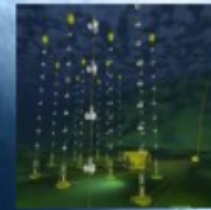


*Recherche conjointe d'ondes  
gravitationnelles et de neutrinos cosmiques  
de haute énergie avec les détecteurs  
VIRGO-LIGO et ANTARES*

Soutenue le 19-12-2012

**Thèse de doctorat réalisée par:  
Bouhou Boutayeb**

**Sous la direction de:  
Kouchner Antoine  
Chassande-Mottin Eric**





**THESE DE DOCTORAT DE L'UNIVERSITE PIERRE ET  
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Spécialité :  
**Astrophysique des hautes énergies**  
Ecole Doctorale : Particules, Noyaux et Cosmos

Presentée par  
**Boutayeb BOUHOU**

Pour obtenir le grade de  
**DOCTEUR de L'UNIVERSITÉ PIERRE ET MARIE CURIE**

Sujet de thèse:

**Recherche conjointe d'ondes gravitationnelles et de  
neutrinos cosmiques de haute énergie avec les détecteurs  
VIRGO-LIGO et ANTARES**

soutenue le 19 décembre 2012

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# INTRODUCTION

High-energy multimessenger astronomy has entered an exciting era with the development and operation of new detectors offering unprecedented opportunities to observe the universe through all kind of cosmic radiations. These includes high-energy ( $\gg$  GeV) neutrinos (HENs) and gravitational waves (GWs) which are on the waiting list for a first detection (see e.g. [1, 2] for recent reviews on these subjects). Contrary to high-energy photons (which are absorbed through interactions in the source and by intervening photon backgrounds) and charged cosmic rays (which are deflected by ambient magnetic fields), both HENs and GWs can escape from the sources and travel at the speed of light through magnetic fields and matter without being altered. They are therefore expected to provide important information about the processes taking place in the core of the production sites and they could even reveal the existence of sources opaque to hadrons and photons, that would have remained undetected so far.

No GW nor cosmic HEN have been individually detected so far. The detection of coincident GW and HEN events would hence be a landmark observation confirming the astrophysical origin of both signals. Coincident searches are also a way to enhance the sensitivity of each individual channel by correlating the HEN and GW significances, considering that the two types of detectors have uncorrelated backgrounds.

*In this thesis, we investigate the potentials of combining GW and HEN observations. We*

*implement and conduct two such analyses using the data of the neutrino telescope ANTARES and the GW interferometric detectors Virgo and LIGO.*

The multimessenger approach followed here could improve our understanding of the properties of the astrophysical processes at the origin of both emissions. While GW emission requires relativistic bulk motion of massive objects such as gravitational collapse or merger of compact objects, the production of HEN arises from the interaction of hadrons in relativistic jets. A joint detection would then sign the presence of accelerated hadrons in the source and constrain the progenitor nature thanks to the GW detection.

The results presented in this thesis is the outcome of a collaborative work. We stress our main contributions in the following list below.

### **First joint search for gravitational wave and high-energy neutrinos using 2007 data**

Late 2007, LIGO and Virgo completed a first joint data taking period. During this period, ANTARES was operating in an incomplete configuration with five active detection strings. We report in Chapter 4 on the analysis of this first concomitant data set.

To allow for a short analysis cycle and the rapid obtaining of results, available tools and methods were re-used. The selection of the neutrino candidates relied on the developments done for a point-source search. The HEN candidates were followed-up in the GW observations with the pipeline originally conceived for GW search triggered by gamma-ray bursts. The outcome of this first search has been submitted for publication and has led to several public presentations.

### **Methodological developments and application to the second search using 2009-2010 data**

LIGO and Virgo completed a second joint data taking period during 2009-2010. During this

period, ANTARES was operating in its complete configuration with twelve detection strings. We report in Chapter 5 on the analysis of this second concomitant data set.

A new and more sophisticated neutrino reconstruction algorithm could be used to analyze this data set, providing reduced error boxes and allowing for more neutrinos candidates. We also developed a new GW search algorithm based on an already existing pipeline (coherent WaveBurst) used for the all-sky burst search. This pipeline searches for the GW signal within the neutrino uncertainty and enables a search in the case of availability of only two GW detectors. This pipeline is much faster than the one used in the first search and includes more sources by extending the search up to 2kHz.

#### *Optimization of the joint search sensitivity*

The selection of neutrino candidates used in the first search was not fully satisfactory since it was performed regardless of the combined sensitivity. This led to a suboptimal search. We proposed and applied a novel optimization procedure for the selection of neutrino candidates taking into account parameters from both GW and HEN data. This optimization, by maximizing the number of detectable sources, is one of the major contributions of this dissertation.

#### *Selection and characterization of the neutrino candidates*

We analysed the ANTARES data and selected a set of neutrino candidates using the optimized cuts. This resulted in a list of 1986 neutrino candidates which we fully characterized in terms of pointing precision and background compatibility. The GW data associated to these neutrino candidates are currently being analyzed.

This thesis is divided into five chapters, structure that reflects the above mentioned contributions. Chapter 1 introduces the main physical concepts associated with GW and HEN along with a description of their joint sources. In Chapters 2 and 3, we give an overview of the experiments and review the data analysis tools. The aim of these three chapters is to bring the

reader to the forefront present-day research, theoretical and experimental, in the field of both GW and HEN physics. Finally, in Chapters [4](#) and [5](#) we give a detailed presentation of the first and second searches respectively.

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# CHAPTER 1

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## MULTIMESSENGER ASTRONOMY

### 1.1 High-energy neutrino astronomy

#### 1.1.1 First steps

Neutrinos are among the most intriguing known elementary particles. Their story started on December 4, 1930, when Wolfgang Pauli postulated the existence of an elusive particle in order to explain the missing amount of energy (and momentum) observed in certain nuclear reactions such as  $\beta$  decays. In mid-1930s papers [1], Enrico Fermi took over Pauli and developed a theory incorporating a neutrino to explain the phenomenology of beta decays. This theory became later the basis of weak interaction physics, but it was only in 1956 that Cowan and Reines directly observed the first neutrinos [2]. Their experiment aimed at detecting the interaction of anti-neutrinos, initially produced in a nuclear reactor, with target protons, according to:

$$\bar{\nu}_e + p \longrightarrow n + e^+ \quad (1.1)$$

This led to the discovery of electron neutrinos ( $\nu_e$ ), more than 25 years after Pauli's proposal. It took even longer to discover the muon neutrinos ( $\nu_\mu$ ), which are of most interest in the scope of this dissertation. This second step was achieved in 1962 in Brookhaven by Schwartz and his collaborators [3]. It was known at that time that pions  $\pi$  and kaons  $K$  produced in atmospheric showers could decay into a muon  $\mu$  and a neutrino, and that this neutrino could differ from the electron neutrino. The idea was thus to study the interactions of a neutrino beam created by the disintegrations of pions produced via the interactions of 15 GeV protons on a Beryllium target. Only the neutrinos could pass through the 13 m thick steel shield placed after the target. The interaction of the produced neutrinos could then be studied with a spark chamber. Muons could then be identified in the product of the interactions but no electrons. This was the signature of a new species of neutrino: the muon neutrino.

The existence of a third species of neutrino was anticipated in 1975 after the discovery of tau ( $\tau$ ) leptons in Stanford [4]. But 25 more years were needed to directly observe these  $\nu_\tau$  neutrinos. This was done by the DONUT collaboration [5]. The used neutrino beam was obtained by the interaction of 800 GeV protons onto a Tungsten target, producing charmed mesons, which in turn decayed into  $\nu_\tau$  neutrinos. The identification of tau leptons in the subsequent neutrino interactions was obtained with the scanning of nuclear emulsions, looking for the specific signature of tau decays.

In parallel to the efforts made towards the direct detection of neutrinos produced on Earth, a first step towards a possible neutrino astronomy was made in the 60's with the detection of MeV neutrinos originating from the Sun [6]. The first observation, by the Homestake experiment, was followed by several others using different complementary techniques which enabled to confirm the solar origin of the observed events. At the same time, these observations gave rise to the famous "solar neutrino anomaly", which is now explained by the theory of neutrino oscillations. This extends beyond the scope of the present dissertation, but an overview of the solar neutrino history can be found in [7]. In the same energy range to that of solar neutrinos, or slightly above, the detection on February 23, 1987, of 25 events arriving within 12 seconds from the Supernova 1987A, was another landmark for neutrino astronomy [8].

Both observations have encouraged the development of large neutrino telescopes as we will see in chapter 2 for the detection of the astrophysical neutrinos, and were rewarded by the Nobel Prize in Physics in 2002. But the extremely low cross section of weak interactions (of order  $6 \times 10^{-44} \text{cm}^2$  for an MeV energy experiment) and the poor angular resolution at nuclear energies represent major obstacles in extending stellar neutrino astronomy much beyond targets like the Sun and a few nearby supernovae. Without denying the important role of the various effects due to neutrino itself, the primary goal of present (experimental and theoretical) investigations remains the astrophysical sources of neutrinos. At present, their detection is currently being challenged by large neutrino telescopes with best sensitivity in the TeV-PeV range.

Keeping these considerations in mind, we begin this chapter with the puzzling question of the origin of the observed cosmic rays (section 1.1.2). We then focus on the possible sources of high-energy neutrinos (HEN).

### 1.1.2 Cosmic rays and neutrinos

One of the main motivations for a neutrino astronomy is to better understand the physics of the observed cosmic rays (CR). In particular, there is a hope that the observation of cosmic neutrinos could unveil the origin of the high-energy cosmic rays observed on Earth. In this section, we briefly describe the current knowledge about cosmic rays. We also describe how

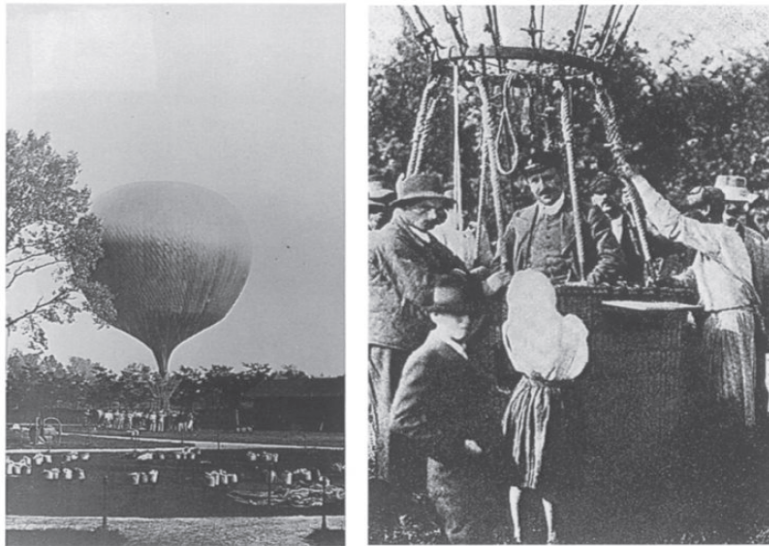
### 1.1.1 High-energy neutrino astronomy

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neutrinos could be produced as by-product of the interactions of CR, in the specific cases of atmospheric and cosmogenic neutrinos. The connection in the production mechanism between cosmic rays and astrophysical neutrinos is described in more details in section 1.1.3.

#### Cosmic rays

Cosmic rays are nuclei and elementary particles originating in the cosmos and reaching the Earth's atmosphere at a rough rate of  $10^4$  per square meter and per second. When penetrating the atmosphere, these CR collide with the N and O nuclei and produce showers of secondary particles (referred to as atmospheric particles), which can be detected at ground level and even underground. The story of CR began in 1912 when the Austrian physicist Victor Francis Hess published results concluding that there was radiation penetrating the atmosphere from outer space. Later in 1925, Robert Millikan confirmed these observations and termed them "cosmic rays". The relative abundances of the different nuclei is shown in Figure 1.2 while the overall



**Figure 1.1** – In 1912 (1913), Hess (Klhorster) started his balloon experiments in which he measured the ionisation of the atmosphere with increasing altitude. Left: Preparation of one of his flights. Right: Hess team after one of the successful balloon flights, Especially the flight of August 7, 1912 when V. Hess reached an altitude of 5 km.

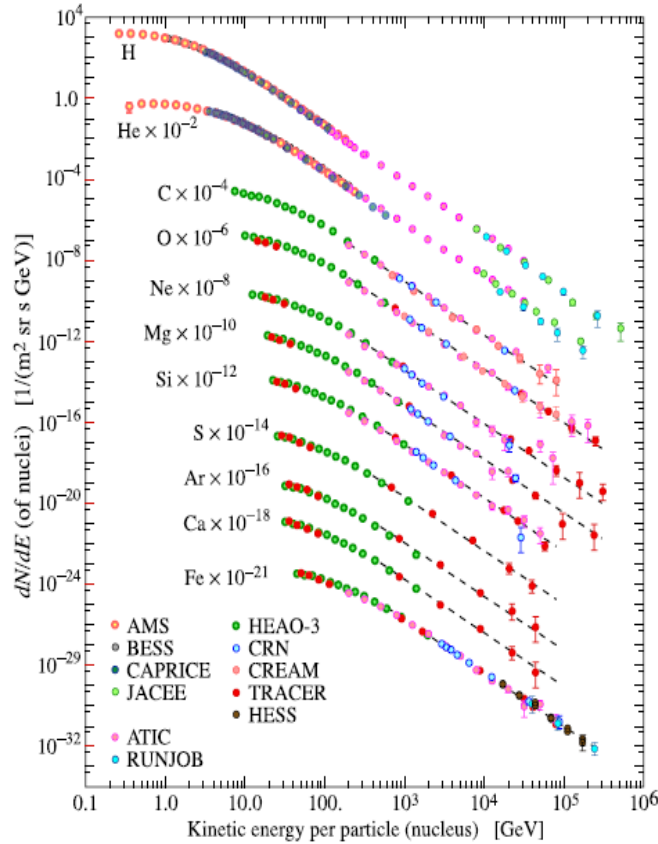
spectrum can be seen in Figure 1.3 [9]. The spectrum of cosmic rays varies slightly with the nucleon species, but at the higher energies the chemical composition shows an enrichment with heavier nuclei from the Iron group, as shown in Figure 1.2. Cosmic rays are divided into two classes:

- Primary cosmic rays: are those particles accelerated at astrophysical sources. This in-

## CHAPTER 1. MULTIMESSENGER ASTRONOMY

cludes electrons, protons, helium, carbon, oxygen and iron.

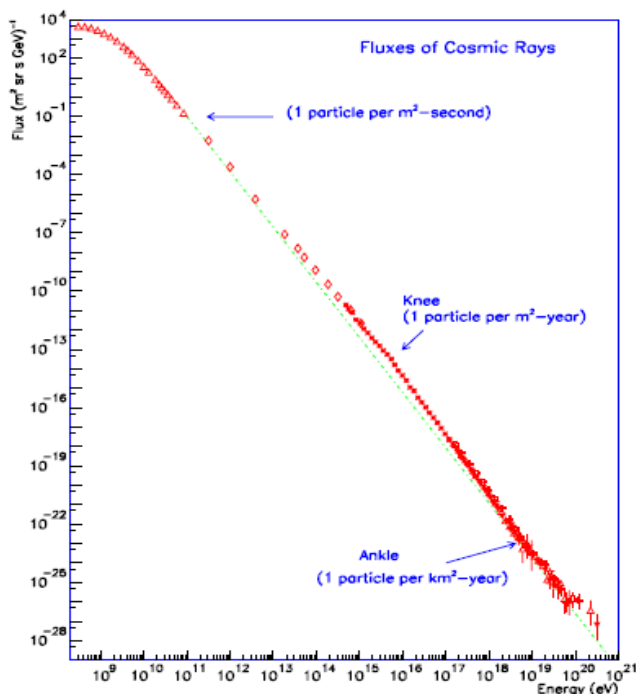
- Secondary cosmic rays: are those particles produced in interaction of the primaries with interstellar gas. This includes lithium, beryllium, boron, and (part of) antiprotons and positrons.



**Figure 1.2** – Composition of cosmic rays at different energies. The curves are shown as fluxes of nuclei against energy-per-nucleus. (Source [10])

Perhaps, the most important characteristic of CR is that the observed energy spectra can be well represented by power-law energy distributions. In the first range of these spectra, extending from  $\text{GeV.nucleon}^{-1}$  to  $\text{PeV.nucleon}^{-1}$  the spectrum is an isotropic power law in  $E^{-\gamma}$ , where  $\gamma = 2.7$ , usually explained as resulting from *galactic* sources such as supernovae. The second energy interval ranging from  $\text{PeV.nucleon}^{-1}$  to  $10 \text{ EeV.nucleon}^{-1}$  is also an isotropic power law spectrum with an index  $\gamma = 3.1$ , possibly originating from *extragalactic* sources, such as active galactic nuclei (AGNs) or sources of gamma-ray bursts (GRBs). Both types of sources

## 1.1.1 High-energy neutrino astronomy



**Figure 1.3** – The differential cosmic ray flux versus energy.

are further discussed in section 1.1.4. The region in between these two energy domains (around  $\sim 10^{15-16}$  eV) is known as *the knee*, which is poorly understood. Some attempts explain this break as the result of changing propagation characteristics within the galaxy, other as the result of the different production sites.

Beyond  $10^{19}$  eV, where one usually calls the particles "Ultra-High Energy Cosmic Rays" (UHECRs), the spectrum flattens to a slope  $\gamma = 2.7$ . Particles are also thought to be from extragalactic origin since, at these energies, they cannot be confined magnetically in the Galaxy. The recorded arrival directions are as well nearly isotropic on the sky. The break at  $\sim 10^{18-19}$  eV is referred to as the *ankle*. Beyond the ankle, the observed flux seems to vanish. This is compatible with the so called GZK (Greisen-Zatsepin-Kuz'min) effect [11, 12] which predicts a suppression in the spectrum of cosmic rays because of their interaction with diffuse (mainly infrared and microwave) radiations, relics of different stages of the formation of the Universe. As an example, extragalactic protons with energy above the pion production threshold ( $5 \times 10^{19}$  eV) lose most of their energy over a distance of about 100 Mpc, small compared to the dimension of the Universe. This implies that cosmic rays can not reach us with an energy of  $10^{20}$  eV unless they originate from a nearby source. This hypothesis remains possible even though there are few sources powerful enough to accelerate particles to such energies at this distance from the

Earth.

The determination of the origin of cosmic rays is also difficult because the arrival directions measured on Earth do not indicate the sources of production. Since they are electrically charged, CR are deflected by interstellar and intergalactic magnetic fields, as opposed to neutrinos. Even at ultra high energy the expected difference between the direction of the source and direction of the particle can reach several degrees. These differences naturally depend on the electric charge carried by cosmic rays, i.e. their composition. This question in the highest energy range remains open. Many experts still favor the hypothesis that highest energy CR are protons, although recent results from the Auger collaboration suggest a transition at around  $10^{19}$  eV, to heavier elements (iron nuclei) [13].

The constraints imposed by the existence of UHECR are related to the size of the potential sources and magnetic field strength prevailing there, which confines charged particles. To acquire a great energy, particles must indeed be confined for some time in the area of acceleration. But the more energetic the particle, the more difficult for magnetic fields (B) to confine it. An upper bound to the maximum energy that can be reached in an acceleration site can be inferred by requiring the Larmor radius ( $r_L = E/qBc$ ) to be smaller than the dimensions of the site, R. The quantities B and R are obtained by the equation:

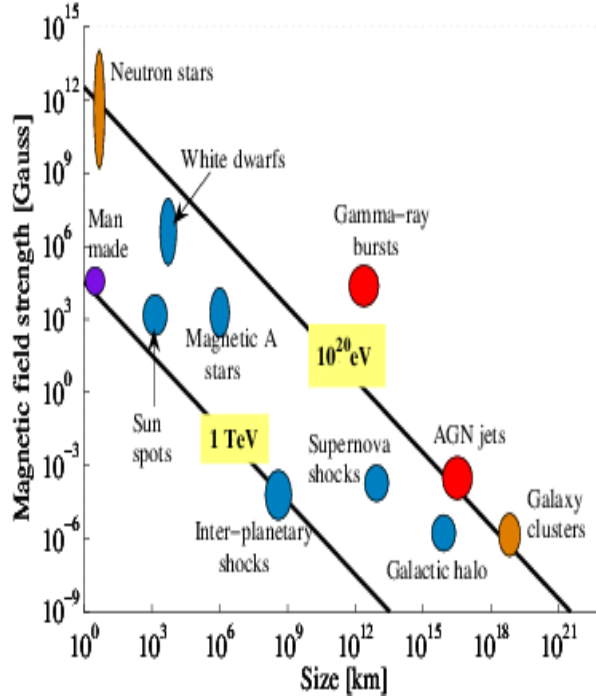
$$E_{\max} = ZecBR \quad (1.2)$$

As a result of this relationship, only certain types of sources are eligible for particle acceleration beyond  $10^{20}$  eV. They are shown in Figure 1.4. A number of these sources are described in more detail in section 1.1.4, as they are all candidates to neutrino production.

### Atmospheric muons and neutrinos

The atmosphere is very rich in particles produced by the interaction of cosmic rays in the air. The vertical flux for different components is shown in Figure 1.5. The most relevant particles for Neutrino Telescopes are atmospheric muons and neutrinos, since they constitute the main physical source of background. The main process responsible for their production is :





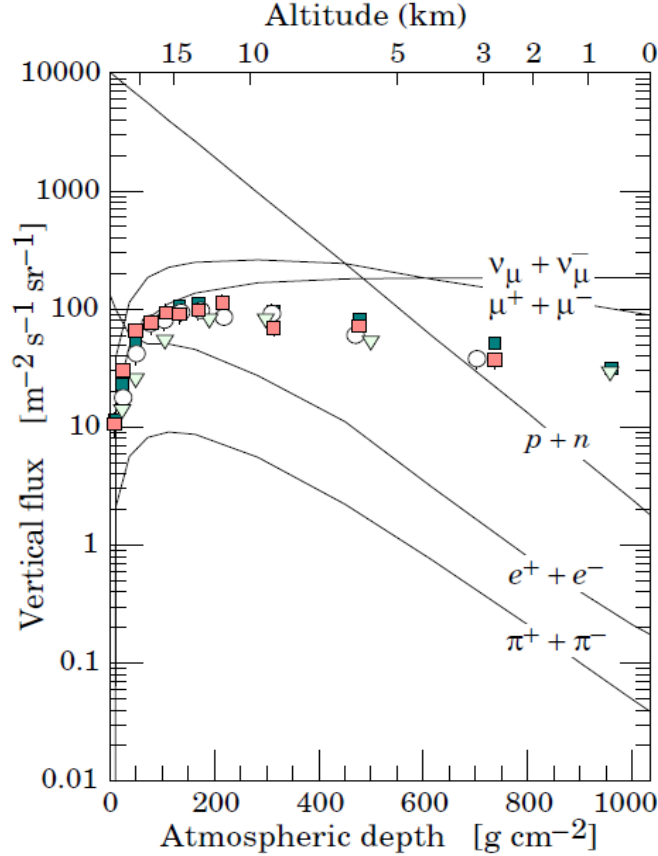
**Figure 1.4** – Hillas diagram (from ([14]) representing the type of sites likely to accelerate cosmic rays to extreme energies. The figure shows the size of the potential sources depending on the intensity of magnetic fields estimated in Gauss units (Earth’s magnetic field is of the order of Gauss). To accelerate protons to energies of 1 TeV ( $10^{20}$  eV), the sources must lie above the corresponding line. This condition, which is necessary, is not necessarily sufficient: accelerating protons  $10^{20}$  eV in clusters of galaxies, for example, requires an acceleration time larger than the age of the universe. As for neutron stars, they are unlikely candidates because of high energy losses associated with the presence of strong magnetic field.

followed by

$$\begin{aligned}\pi^+ &\longrightarrow \mu^+ + \nu_\mu, \\ \mu^+ &\longrightarrow e^+ + \nu_e + \bar{\nu}_\mu\end{aligned}\tag{1.4}$$

Resulting in both muon- and electron-neutrinos. These neutrinos span energies from few MeV to the highest-energy cosmic rays and they are much more abundant at lower energies. Muons are the most numerous charged particles at sea level. They are the remaining of the secondary cosmic rays in the high atmosphere (typically 15 km) and lose about 2 GeV to ionization before reaching the ground. Their energy and angular distributions reflect the convolution of production spectrum, energy loss in the atmosphere and decay [10]. Further discussions on these atmospheric muons and neutrinos follow in section 2.5.





**Figure 1.5** – Components of the cosmic rays in the atmosphere with  $E > 1\text{GeV}$ . The points show measurements of negative muons with energy above 1 GeV. (Source [10])

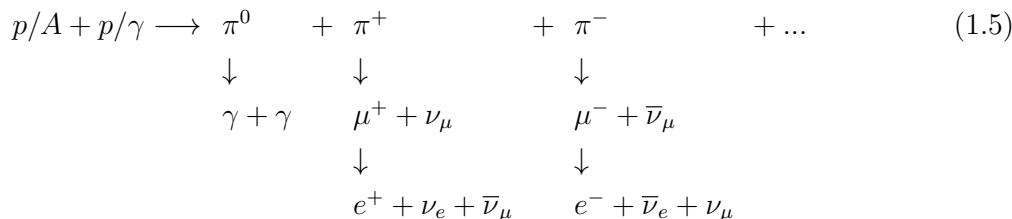
### Cosmogenic neutrinos

As previously stated, as they propagate over cosmological distances, UHECRs may interact with the relic photons fields (GZK effect), These interactions generate pions and neutrons, which decay to produce neutrinos of energy greater than  $10^{17}eV$ . The accumulation of these neutrinos over cosmological time is known as the cosmogenic neutrino flux [15, 16]. Although guaranteed sources, the predicted fluxes of cosmogenic neutrinos are low compared with the sensitivity of current neutrino telescopes. Estimates of these fluxes depend mainly on the properties of the primary cosmic ray flux, particularly in terms of composition. Another important parameter is the variation of the intensity of injected flux (or density of sources) as a function of redshift. All of these parameters lead to predictions that differ substantially. The detection of such cosmogenic neutrinos would represent an important step for neutrino astronomy. An accurate measurement of flux would further constrain the composition and the variation of the density

of sources of cosmic rays with redshift.

### 1.1.3 Neutrinos as cosmic probes

Our current knowledge about astrophysical sources largely rely on observations made using photons (electromagnetic radiation), which are the essential messengers of modern astrophysics. The gamma-ray astronomy (in the TeV range) experienced an unprecedented boom with the advent of new Cherenkov telescopes such as WHIPPLE and more recently HESS. These have demonstrated that TeV photons are actually emitted by number of Galactic and extragalactic sources. The study of these sources has put new constraints on models of cosmic ray production. There is indeed a link between the production of charged cosmic rays and that of photons (or neutrinos) at high energy. Photons and neutrinos can be produced in a beam dump scenario, by the interaction of cosmic rays of high energy with the surrounding matter and background radiation (usually produced by synchrotron radiation of charged particles in magnetic fields) as follows:



In this context, the gamma-rays are produced by the decay of neutral pions ( $\pi^0$ ). This production is necessarily linked to that of high-energy neutrinos from the decay of charged pions. Similarly, the existence of cosmic rays of high energy necessarily implies the production of HEN. This is known as the "cosmic ray connection". As such, sources of cosmic rays could be revealed by observing gamma-rays or HEN which, due to their electrical neutrality, travel in a straight line indicating the location of their production area. The high-energy photons can also be produced in a purely electromagnetic process without hadron. This is the "Synchrotron Self Compton" scenario where electrons accelerated to high energy generate photons by synchrotron radiation. These photons are further accelerated to TeV energies by collision with the high energy electrons. Therefore photons alone can not readily discern the electromagnetic processes from the hadronic ones. On the contrary, the detection of neutrinos would be an unambiguous signature for hadronic mechanisms.

The other limitation of high energy photons is their absorption by matter or radiation, which prevents them from escaping dense sources. Besides, when they do escape, high-energy photons are absorbed by interaction with the interstellar radiations (similarly to cosmic rays in the GZK

effect). As an example for PeV photons, the mean free path is typically restricted to dimension of our Galaxy. Photons can therefore hardly be used at high energies for astronomical survey over cosmological distances.

Neutrinos do not suffer these limitations: they are neutral and weakly interacting. Therefore, if they can be detected with sufficiently high statistics, they appear to be ideal candidates for high energy astronomy, providing access to cosmological distances and inner regions of astrophysical sources. This makes of the neutrino a singular probe able to open a window of observation on the sky.

In this sense, HEN astronomy can address a number of fundamental questions in astrophysics and cosmology. Among these are the nature of dark matter (see section 1.1.4), the origin of the cosmic rays, and the extreme physics responsible for gravitational energy release in the most luminous objects in the universe. The work presented in this dissertation focuses on the detection of neutrinos in coincidence with gravitational waves, following the advocated lines of a multimessenger approach.

### Theoretical upper bounds to the cosmic neutrino flux

If neutrinos of extragalactic origin have not yet been detected, the link (described in the previous paragraph) between cosmic messengers allows to estimate the diffuse neutrino flux produced by the "cosmic accelerators" [17, 18].

The observable spectrum of cosmic rays provides the most restrictive limit. Bahcall and Waxman (WB) have determined a benchmark cosmic neutrino flux, based on the assumption that the observed cosmic rays above  $10^{19}$  eV are protons produced by extragalactic cosmic accelerators. The calculation is based on the production rate (per unit time, volume, and energy) of these ultra high energy protons estimated at:

$$E_p^2 \frac{dN}{dE_p dV dt} \approx 0.65 \times 10^{44} \phi(z) \text{ erg Mpc}^{-3} \text{ year}^{-1} \quad (1.6)$$

where  $\phi(z)$  (with  $\phi(0) = 1$ ) takes into account the evolution of the production rate as a function of redshift (small since following the GZK effect, the protons lose their energy over relatively small distances). The choice, consistent with the Fermi mechanism, of a  $E^{-2}$  differential spectrum is motivated by observations of processes involving shocks (relativistic or not).

The production rate given by equation 1.6 enables to infer an upper limit for the production of HEN from extragalactic sources as AGN or GRBs. The underlying assumption is that the rate of energy injected in the form of neutrinos can not exceed that of the associated protons

### 1.1.1 High-energy neutrino astronomy

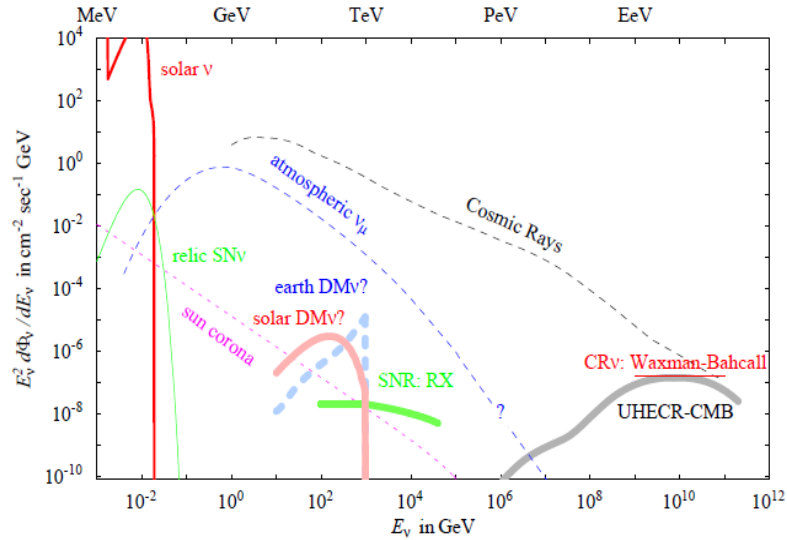
even when all are involved in the production of pions (relation 1.5). The resulting limit is:

$$E_\nu^2 \phi_\nu < 2 \times 10^{-8} \xi_z \left[ \frac{(E_p^2 \frac{dN}{p dE_p dV dt})_{z=0}}{10^{44} \text{ erg/Mpc}^3 \text{ year}} \right] \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \quad (1.7)$$

where  $\xi_z$ , of the order of unity, indicates the evolution of the injection rate following the redshift. Such a flux is being challenged by current neutrino telescopes which have therefore entered a quite exciting era.

### 1.1.4 Astrophysical sources of high-energy neutrinos

In this section we present a selected list of astrophysical sources that are candidates for high-energy neutrino emission. These sources can be sorted into 2 types: *galactic* and *extragalactic*. Based on relation (1.5), estimates of the expected neutrino flux can be achieved relying on the recent observations with gamma-rays with, for example, HESS [19] and FERMI [20]. But these estimates can still vary by orders of magnitude depending on the precise model used to infer them. These estimates of neutrino fluxes at Earth must also be corrected to take into account the flavor mixing occurring during propagation. To the first order, neutrinos are produced in a ratio of flavor (see relation (1.5)) ( $\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$ ) but reach the Earth in the proportions ( $\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$ ).



**Figure 1.6** – Optimistic astrophysical neutrino fluxes from various sources

### Galactic sources

The most promising Galactic sources of neutrinos are briefly reviewed below. Estimates of expected associated neutrino fluxes can be found, for instance, in [21]:

- **Supernova remnants (SNR):** They are the prime candidate sources for accelerating the cosmic rays observed up to  $\sim 10^{15}$ eV thanks to the Fermi mechanism. After the explosion of the star, leading to a supernova, ejected particles can be accelerated to high energies. From the death of the star arises a pulsar with a high magnetic field that contribute to the acceleration of particles. The production of (TeV) neutrinos is expected in the collision of cosmic rays *proton/neutron* with the thermal nucleon in the remnant shell which leads to neutral and charged pions  $\pi^+/\pi^0$ .

The observation by HESS of the southern sky with  $\gamma$  rays at the TeV and above revealed two particularly bright SNR. The first one is Vela Junior (*RX J0852.0 – 4622*). The flux of  $\gamma$  was observed in a region extending up to  $\sim 2^\circ$ . The second is *RX J1713.7 – 3946*. The observed spectra below 10 TeV look like power laws with hard spectral indices:  $\Phi_\gamma = dN_\gamma/dE \propto E^{-\Gamma}$  with  $\Gamma \sim 2$ , the value suggested by the Fermi acceleration mechanism. Various spectral analyses of these sources seem to favor a hadronic origin for the gamma emissions detected, which could lead to an observable flux for a km-scale neutrino telescope.

The flux of neutrinos can be calculated from the flux of  $\pi^+$ . First, we get the flux of  $\pi$  from the  $\gamma$  flux, using the  $\pi^0$  decay and assuming that  $\Phi_\pi^+(E) = \Phi_\pi^-(E) = \Phi_\pi^0(E) = \frac{-Ed\Phi_\gamma}{2dE}$ . Consequently one can deduce the neutrino flux using the  $\pi^+ \rightarrow \mu^+\nu_\mu$  decay:

$$\Phi_{\nu_\mu}(E) = \int_{E/(1-r)}^{\infty} \frac{d\epsilon\Phi_\pi^+(\epsilon)}{(1-r)\epsilon} = \frac{\Phi_\gamma(E/1-r)}{2(1-r)} \quad (1.8)$$

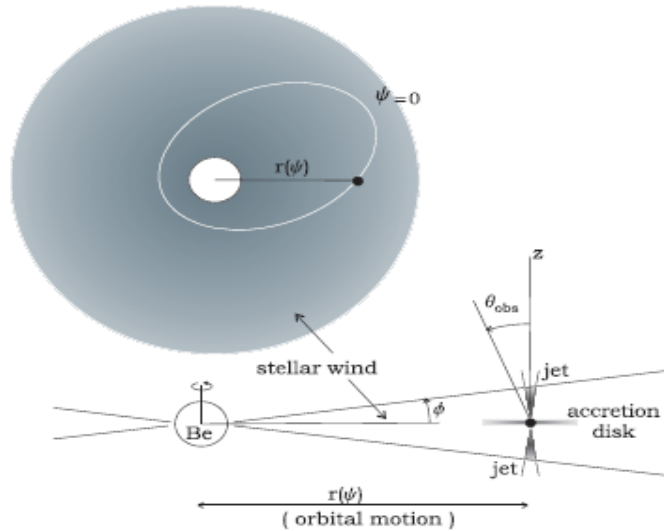
where  $r = (M_\mu/M_\pi)^2$ .

- **Microquasars:** These objects are binary stellar systems with collimated relativistic jets at radio frequencies. They consist of an accreting compact object, either a black hole or a neutron star, and a companion star. The behavior of these systems resembles, to some extent, that presented by extragalactic quasars, hence the origin of the name. The detection of the microquasar Cygnus X-3 above 100 MeV by both Fermi/LAT and AGILE satellites, together with the short flares from Cygnus X-1 reported by AGILE, confirmed that this class of astrophysical objects are interesting candidates for very high energy gamma-ray observations.

### 1.1.1 High-energy neutrino astronomy

Microquasars could produce HEN according to two models. In the first model, inhomogeneities in the jet could generate internal shocks accelerating electrons and protons arising in a power law energy spectrum. Accelerated protons could interact with X-ray emitted by the accretion disc or synchrotron photons generated in the jet by the accelerated electrons [22]. Both Synchrotron self-Compton (SSC) and strong external X-ray fields can cool extremely relativistic protons through pion production. However, the protons should be accelerated up to very high energies ( $10^{16}$  eV) in the inner jet in order to produce a significant flux of multi-TeV neutrinos. It is not established that microquasars can accelerate particles up to such energies at the base of the jets. The high neutrino fluxes predicted by [23] on the basis of this model for different microquasars are in some cases already ruled out by AMANDA II data, and recently by ANTARES [24].

In the second model [25], high-energy gamma-rays and neutrinos could result in matter interactions: accelerated nuclei of the jet could lose neutrons as a result of photo-decay process in collisions with thermal photons from the accretion disk and the massive star. These neutrons propagating toward the disk and the massive star could generate neutrinos by interacting with matter.



**Figure 1.7** – Schematic model of a possible hadronic model of microquasars. (source [26])

- **Soft gamma-ray repeaters (SGRs)** They are X-ray pulsars which have quiescent soft (2–10 keV) periodic X-ray emissions with periods ranging from 5 to 10 s. They exhibit repetitive erratic bursting episodes lasting a few hours each and composed of numerous

very short ( $\sim$  ms) pulses. Every once in a while they emit a giant flare in which a short ( $< 0.5$  s) spike of harder radiation is observed; such flares can reach peak luminosities of  $\sim 10^{47}$  erg/s, in X-rays and  $\gamma$ -rays. A handful of SGR sources are known, most of them in the Milky Way and one in the Large Magellanic Cloud. Three of them have had hard spectrum ( $\sim$  MeV energy) giant flares: one with a luminosity of  $10^{40}$  J/s, the two others being two orders of magnitude weaker.

The favoured *magnetar* model for these objects is a neutron star with a huge magnetic field  $B \gtrsim 10^{15}$  G, which is subject to star-quakes that are thought to fracture the rigid crust, causing outbursts. The giant flares result from the formation and dissipation of strong localized currents due to magnetic field rearrangements associated with the quakes, and liberate a high flux of X- and  $\gamma$ -rays. Sudden changes in the large magnetic fields would accelerate protons or nuclei that produce neutral and charged pions in interactions with thermal radiation. These hadrons would subsequently decay into TeV or even PeV energies  $\gamma$ -rays and neutrinos, making flares from SGRs potential sources of HEN.

An alternative model involving a large scale rearrangement of the magnetic field has also been proposed by [27], which allows for huge energy releases, and detectable HEN fluxes from Galactic magnetars even for relatively small HEN efficiencies.

- ***The Galactic centre:*** Since its observation by the HESS telescope in the TeV domain [28] the centre of our Galaxy has become of particular interest for neutrino astronomy. Indeed, initial observations revealed the presence of two bright sources, one in the direction of Sagittarius A\* (HESS J1745-290), the supermassive black hole at the centre of the Galaxy, and another one, close to supernova Sgr A East. After subtraction of these intense sources, a more diffuse emission has been observed. This diffuse emission of photons of energy greater than 100 GeV is strongly correlated with molecular clouds [29], suggesting a hadronic origin of the observed  $\gamma$ -rays. The associated neutrino emission could be observed with the next generation of neutrino telescopes to be built in the Northern hemisphere.
- ***Pulsar wind nebulae (PWNe):*** They are ejecta of shocked relativistic particles produced when a pulsar emits a relativistic wind further interacting with its environment. The best known among these sources is the Crab Nebula that harbors an energetic pulsar<sup>1</sup> whose spin-down power manifests itself as a synchrotron-emitting source of energetic particles. Recent discoveries of very high energy  $\gamma$ -ray emission associated with PWNe have

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<sup>1</sup>A rapidly rotating, highly-magnetized neutron star, which generates coherent beams of radiation along its magnetic poles.

opened a new channel for investigations of the structure and evolution of these objects. It is thought that this emission in the TeV band probably originates from inverse-Compton scattering of ambient soft photons with energetic electrons in the nebula [30]. Nevertheless, hadronic models have been considered in which the emission is associated with the decay of neutral pions produced in collisions of energetic ions with ambient hadronic material [31], of particular interest is Vela X.

#### Extragalactic sources

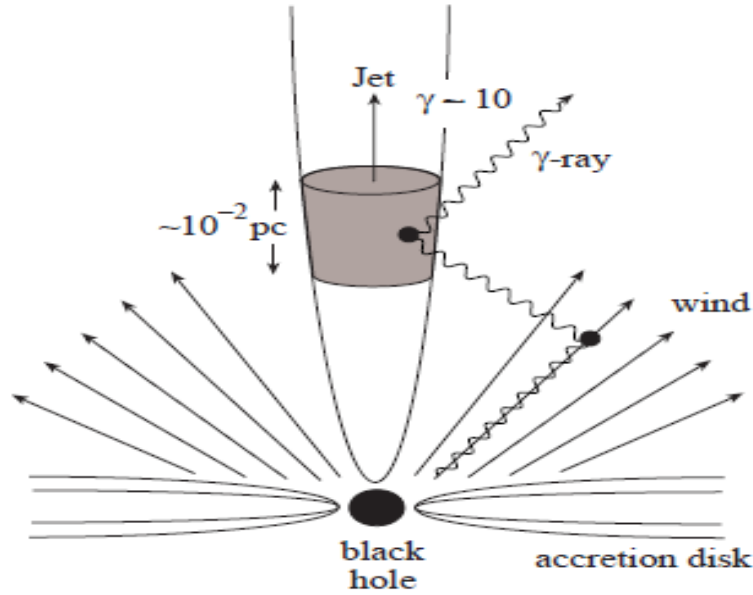
We discussed in section 1.1.2 that extragalactic sources could be at the origin of the cosmic rays (CR) at the highest energies  $E_{CR} > 10^{18}\text{GeV}$ . In this context, several sources are suggested to produce high energy neutrinos:

- **Active galactic nuclei (AGNs):** Active galaxies are galaxies whose center shows increased luminosity with respect to the rest of the galaxy. These galaxies have a concentration of stars, gas and dark matter in the center which make their nucleus active, i.e. gas is being accreted in large quantities and/or stars are being captured, disrupted and swallowed in significant number. AGNs were first observed in 1963 [32] in the radio emission. Some of them are detected in  $\gamma$ -ray range. It has been discovered during the last three decades that these active galaxies have a massive black hole at their center that accretes continuously matter. In the center of the accretion disc, matter is ejected in jet perpendicularly to the accretion disc. Active Galactic nuclei are thought to accelerate electrons in shocks either inside their jets or at the jet termination surface, see Figure 1.8. Certain classes of AGNs (like Blazars) may be capable of accelerating cosmic rays to energies in excess of PeV, which could lead to TeV neutrinos and gamma-rays via photo-meson process. The correlations established by the AUGER collaboration [34] reinforce the hypothesis that AGN could be the source of cosmic rays of ultra high energy, but they are still subject to an intense debate. Searching for neutrinos from known AGN is therefore of particular importance.

An important factor to take into account when predicting neutrino fluxes associated with the observed high-energy gamma rays, for this type of extragalactic sources, is the absorption by the extragalactic background light (EBL). The spectral index of 2.9 observed by the telescope HESS in the case of the blazar 1ES1101 ( $z = 0.186$ ) could, for example, correspond to an index in the source, 1.5 [35], which could therefore lead to a neutrino flux significantly more intense than the gamma flux.

Another feature of blazars is their variability. In the case of PKS2155, an increase of





**Figure 1.8** – Schematic blazar internal shock scenario. Blazars are a subset of AGNs, that emit high-energy radiation in collimated jets pointing at the Earth. (Source [33])

almost a factor of 100 in the gamma flux has been observed by HESS over a one-hour period [36]. Such a flurry of activity in a short period could allow the detection of neutrinos through the significant reduction of associated background noise. This technique is similar to the one adopted to search for neutrinos from sources of gamma-ray burst (GRB).

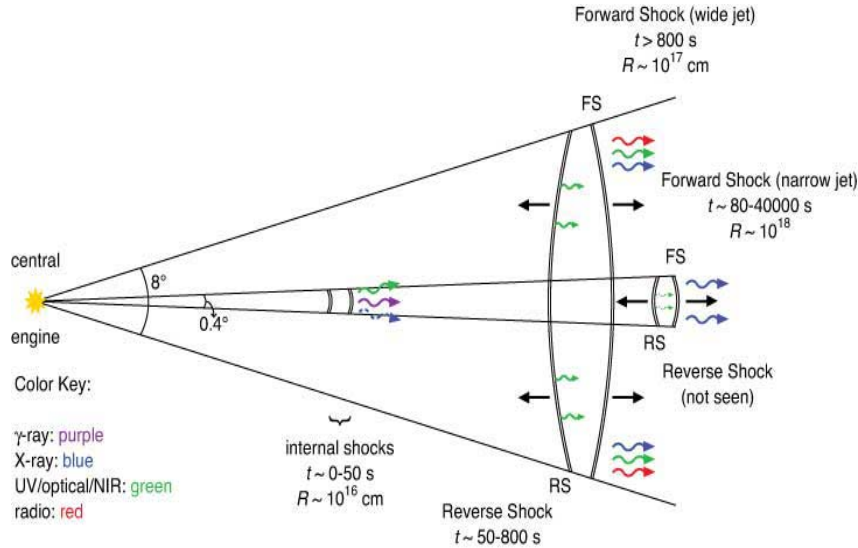
- **Unidentified sources:** Finally, it is interesting to note that a number of sources detected by HESS have no observable counterpart in the electromagnetic spectrum. The origin of this type of source is therefore a theoretical challenge. Observation of high energy neutrinos in the direction of these sources could probably help modeling these objects. The detection of these sources without counterpart underlines once more the possibility of detecting previously unknown sources.
- **Starburst Galaxies:** The observation of synchrotron emission in the radio band from some galaxies (where the star formation rate is unusually high) named "starburst galaxies" implies the presence of a few GeV electrons assuming the existence of intense magnetic fields. The presence in these galaxies of many massive stars in formation phase considerably enriches the interstellar medium with matter. So if protons were accelerated together with the electrons (e.g. supernova explosion), this would result in a significant flow of neutrinos by  $pp$  interactions (on the order of  $dN = 10^{-7}E^{-2}\text{GeV}^{-1}\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$ ),

detectable by the new generation of neutrino telescopes [37].

- ***Gamma-Ray Bursts (GRBs)***: Gamma-ray Bursts (GRBs) (see Figure 1.9) are detected as an intense and short-lived flash of gamma-rays with energies ranging from tens of keVs to tens of GeVs. The morphology of their light curves is highly variable and typically exhibits millisecond variability, suggesting very compact sources and relativistic expansion. GRBs are divided into two classes depending on the duration of their prompt gamma-ray emission, which appears to be correlated with the hardness of their spectra and are believed to arise from different progenitors: short-hard bursts last less than 1–2 seconds while long-soft bursts can last up to dozens of minutes.

The BATSE detector, launched in 1991 on board the Compton Gamma-Ray Observatory, was the first mission to accumulate observations on more than a thousand GRBs, establishing the isotropy of their sky distribution and characterizing their light curve and broken power-law spectra [38]. The detection of X-ray and optical counterparts pertaining to the afterglow phase of several GRBs, triggered by the first observation of an X-ray transient emission from GRB970228 by the BeppoSAX satellite [39], subsequently confirmed their extragalactic origin by allowing a more accurate localization of the source and a redshift determination. Currently operating GRB missions include *Swift*, hosting a wide-field hard X-ray (15 keV–350 keV) burst alert telescope (BAT) coupled to softer X-ray, ultraviolet and optical telescopes and the GBM on the Fermi Gamma-Ray Space Telescope which focuses on the high-energy (15 keV–300 GeV) emission from GRBs. In the standard picture (see e.g. the review by [40]), the mechanism responsible for the enormous, super-Eddington energy release ( $\sim 10^{50} - 10^{52}$  ergs) in the prompt emission and in the afterglow is the dissipation (via internal shocks, magnetic reconnection and external shocks) of bulk kinetic or Poynting flux into highly relativistic particles. The particles are accelerated to a non-thermal energy distribution via the Fermi mechanism in a relativistically expanding fireball ejected by the GRB central engine. The accelerated electrons (and positrons) in the intense magnetic field emit non-thermal photons via synchrotron radiation and inverse Compton scattering.

The plasma parameters inferred from observations to characterize GRB's baryonic fireballs are such that proton acceleration to energies exceeding  $10^{20}$ eV is likely to be possible in these sources. Moreover, the time averaged energy output of GRBs in photons is comparable to the proton energy production rate required to produce the UHECR flux. Therefore, the canonical baryonic fireball also suggests that GRBs are a prime candidate source for the ultra-high-energy cosmic rays (UHECR), observed at energies



**Figure 1.9** – Schematic GRB jet and location of jet photosphere, dissipation (internal shock) and external shock radii.

$E \sim 10^{18} - 10^{20}$  eV. In a baryonic outflow, the internal or external shocks accelerate protons that interact with the gamma-rays and/or other protons inside the fireball producing neutrinos according to the relation 1.5. Such neutrinos are emitted in spatial and temporal coincidence with the GRB prompt electromagnetic signal; their energy is typically in the range  $\sim$  TeV to PeV. Neutrinos with higher (up to  $\sim 10^{10}$  GeV) energy can also be emitted at the beginning of the afterglow phase, when the outflow is decelerated by external shocks with ambient material and the accelerated protons undergo interactions with the matter outside of the jet [41]. An alternative mechanism for neutrino production in fireballs suggested by [42] involves neutral particles that are picked up by the stream when they acquire a charge, such as a decaying neutron, or, further downstream, a neutral atom that is ionized. Such a particle will be extremely energetic in the jet frame, and immediately attains an energy of a PeV. The associated neutrinos would come within an order of magnitude of that energy ( $\sim 100$  TeV), providing a harder spectrum than the one expected from shock acceleration. The sensitivity achieved by neutrino telescopes is such that their observations will allow in a few years to test and distinguish between GRB models with different physics, and to constrain the physical parameters of such models. The current non-detection of neutrinos by IceCube [43] (see also Chapters 4 and 5) already questions the viability of models in which ultra high energy cosmic rays are the decay products of neutrons that have escaped the fireball with high energy. The

current upper limit is still consistent with the "standard" (i.e., following [44]) predictions of neutrino emission from GRB fireballs.

#### Gamma-Ray Burst diffuse flux of Waxman-Bahcall

As stated in the previous section, GRBs are considered to be produced from the collapse of stars or the merger of compact objects with the central object being a black hole (or in case of the magnetar model a fast rotating high-mass neutron star which eventually collapses into a black hole). During the collapse the release of high amounts of gravitational energy during a short time in a small volume leads to an explosion or expansion.

Waxman and Bahcall calculated an upper bound for the diffuse flux [45] of muon-neutrinos produced in GRBs. The shape of this flux is the result of relatively general considerations depending on the photon and proton spectra. The observed spectra can be parametrized as following. First one needs to specify the proton spectrum:

$$N_p(E_p) = N_{p,0} E_p^{-2} \cdot \exp \left[ - \left( \frac{E_p}{\epsilon_{p,max}} \right) \right]; \quad E_p \leq \epsilon_{p,max} \quad (1.9)$$

where  $\epsilon_{p,max}$  is the proton maximum energy. Its value is derived from comparison of acceleration time and synchrotron loss time.  $N_{p,0}$  is the normalization of the spectrum. The photon spectrum  $N_\gamma(E)$  is derived from observed GRB photon spectra and is parametrized by the Band function:

$$N_\gamma(E_\gamma) = N_{\gamma,0} \begin{cases} E_\gamma^{-1} & \text{if } \epsilon_{\gamma,min} \leq E_\gamma < \epsilon_{\gamma,b} \\ \epsilon_{\gamma,b} E_\gamma^{-2} & \text{if } \epsilon_{\gamma,b} \leq E_\gamma < \epsilon_{\gamma,max} \\ 0 & \text{else} \end{cases}$$

where  $N_{\gamma,0}$  is the normalisation factor. The break energy  $\epsilon_{\gamma,b}$  is retrieved from the photon spectrum of a burst. The energy  $\epsilon_{\gamma,max}$  is the maximum photon energy, and  $\epsilon_{\gamma,min}$  is the lower energy cut-off of the photon spectrum.

Using these spectra Waxman and Bahcall (WB) derived a power-law spectrum of the muon-neutrino at Earth:

$$E_{\nu_\mu}^2 dN_{\nu_\mu}(E_{\nu_\mu})/dE_{\nu_\mu} = N_{\nu_\mu,0} \begin{cases} \epsilon_{\nu_\mu,b}^{-1} E_{\nu_\mu} & \text{if } E_{\nu_\mu} \leq \epsilon_{\nu_\mu,b} \\ 1 & \text{if } \epsilon_{\nu_\mu,b} \leq E_{\nu_\mu} < \epsilon_{\nu_\mu,s} \\ \epsilon_{\nu_\mu,s} E_{\nu_\mu}^{-2} & \text{if } E_{\nu_\mu} \geq \epsilon_{\nu_\mu,s} \end{cases}$$

The first break of the WB spectrum  $\epsilon_{\nu_\mu,b} = 10^{14}$  eV is connected to the break in the photon spectrum  $\epsilon_{\gamma,b}$  via the energetics of the  $\Delta$ -resonance. It is determined through the minimal

energy necessary to produce a  $\Delta(1232)$ -resonance in the shock fronts of the bursts.

$$E_\gamma E_p \geq \frac{m_\Delta^2 - m_p^2}{2(1 - \cos(\theta_{p\gamma}))} \quad (1.10)$$

where  $m_\Delta$  and  $m_p$  are the rest mass of the  $\Delta$ -resonance and the proton respectively. We now need an approximation of how much energy is passed from the parent protons to the neutrinos (after pion decay). It is possible to estimate the fraction of energy  $f_\pi = 0.2$  passed on from the protons to the pions. In the subsequent decay of the pions about 1/4 of the pion energy is transformed into neutrinos:

$$\begin{aligned} E_{\nu_\mu} &= \frac{1}{4} f_\pi E_p \\ &= \frac{1}{20} \cdot \frac{m_\Delta^2 - m_p^2}{2(1 - \cos(\theta_{p\gamma}))} E_\gamma \end{aligned} \quad (1.11)$$

This result then has to be boosted to the observer's frame as well as shifted due to cosmological effects to obtain the observed values:

$$E_{\nu_\mu} = \frac{\Gamma^2}{(1+z)^2} \cdot \frac{1}{20} \cdot \frac{m_\Delta^2 - m_p^2}{2(1 - \cos(\theta_{p\gamma}))} E_\gamma \quad (1.12)$$

Using the numerical values given in [46] for the proton mass,  $m_p = 0.94$  GeV, and the  $\Delta$ -mass,  $m_\Delta = 1.23$  GeV, leads to:

$$\epsilon_{\nu_{\mu,b}} = 7 \cdot 10^5 \cdot \frac{\Gamma^2}{(1+z)^2 \epsilon_{\gamma,b}} \text{ GeV} \quad (1.13)$$

The second energy break of the WB spectrum at  $\epsilon_{\nu_{\mu,s}} = 10^{16}$  eV in the neutrino spectrum results from the fact that pions lose energy at very high energy due to synchrotron radiation. It can be obtained by considering synchrotron cooling of the pions. To calculate the energy of this break one has to compare the particle life time  $\tau$  to the synchrotron loss time  $t_{syn}$ .

### Some exotic sources

Another hypothetical source of HEN is related to the presence of dark matter in the universe. It was first in 1933 that Zwicky pointed out that a possibly significant amount of mass was missing from observations [47]. The bulk of this dark matter is non-baryonic. One of the candidates is the neutralino, a stable and neutral particle in the minimal standard super-symmetric model. The Galaxy would lie in a halo consisting of these particles, which would, *inter alia*, help explain the anomalous behavior of the distribution of the velocities of visible objects (constant speed

of about 220 km/s regardless of the distance to the center of the Galaxy).

Subject to the Kepler’s laws, like any other massive object, these particles revolve with the same average speed. Under the influence of gravity, the neutralinos get trapped at the center of massive bodies, such as the Sun and the Galactic center, where they can annihilate. In this scenario, neutrinos would emerge as by product of the annihilations. The discovery potential of a neutrino telescope like ANTARES for such dark matter particles is discussed, for example, in [48].

## 1.2 Gravitational waves

Einstein’s theory of General Relativity introduces the concept of a dynamical and deformable space-time. The dynamics result from the interaction between space-time and its matter contents. In short, “spacetime tells matter how to move; matter tells spacetime how to curve” [49].

General Relativity describes Gravity as a direct effect of space-time curvature. It predicts that the equations of space-time can give rise to radiative solutions, called *gravitational waves*. Gravitational waves (GW) are ripples in the metric of spacetime that propagate at the speed of light.

Here, we give an introduction to GWs in section 1.2.1 and their phenomenology in section 1.2.2. We present in section 1.2.3 the potential astrophysical sources.

### 1.2.1 Basics of gravitational-wave theory

In the theory of General Relativity, gravitation is described as a geometrical effect connected to the curvature of space-time. The geometry of space-time is defined by a metric  $g$  which determines the distance  $ds$  of neighbouring events taking place at space-time coordinates  $x^\alpha$  ( $\alpha = 0, 1, 2, 3$ ) and  $x^\alpha + dx^\alpha$ . We have

$$ds^2 = g_{\mu\nu} dx^\mu dx^\nu \tag{1.14}$$

where Einstein’s summation convention in use here implies the summation over indices  $\mu$  and  $\nu = 0, 1, 2, 3$ . The metric  $g$  used in the above equation through its components  $g_{\mu\nu}$  describes how intervals are measured in space-time and hence the properties of the gravitational field.

The curvature of space-time is determined by the energy-matter distribution through the Einstein equations

$$G_{\mu\nu} = R_{\mu\nu} - \frac{1}{2}R = \frac{8\pi G}{c^4} T_{\mu\nu} \tag{1.15}$$

## CHAPTER 1. MULTIMESSENGER ASTRONOMY

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where  $c$  is the speed of light,  $G$  is the constant of gravitation. The Einstein equations connects the Einstein tensor  $G_{\mu\nu}$  which describes the dynamics of space-time geometry and is directly connected to the metric  $g$  to the stress-energy tensor  $T_{\mu\nu}$  which describes the matter and energy source distribution.

The Einstein equations form a set of 10 non-linear partial differential equations. Finding a solution to those equations is difficult in general. Approximated solutions can be found in the weak field approximation, where the metric results from a small perturbation of the Minkowski metric  $\eta_{\mu\nu} = \text{diag}(-1, 1, 1, 1)$  of special relativity associated to flat space-time

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu} \quad (1.16)$$

where the term  $h_{\mu\nu}$  represents a small (tensor) perturbations with  $|h_{\mu\nu}| \ll 1$ . In this case, the Einstein equations can be linearized. Applying the Lorentz gauge condition, we get

$$\left( \nabla^2 - \frac{1}{c^2} \frac{\partial^2}{\partial t^2} \right) h_{\mu\nu} = 0 \quad (1.17)$$

This is the wave equation. If the propagation direction be  $z$ , the solutions are

$$h_{\mu\nu} = \Re \{ \varepsilon_{\mu\nu} \exp(\omega t - kz) \} \quad (1.18)$$

where  $\omega = kc$  and  $\varepsilon_{\mu\nu}$  is a  $4 \times 4$  symmetric matrix of constants.

This implies the existence of oscillatory wave-like solutions to Einstein's equations: *gravitational waves* (GW). They are predicted to propagate at speed of light.

The freedom to choose a coordinate frame allows us to select one where  $h_{\mu\nu}$  is transverse traceless (also referred to as "TT gauge"). In this frame,  $\varepsilon_{\mu\nu} = h_+ \varepsilon_{\mu\nu}^+ + h_\times \varepsilon_{\mu\nu}^\times$  can be linearly decomposed into two independent polarization tensors  $\varepsilon_{\mu\nu}^+$  and  $\varepsilon_{\mu\nu}^\times$  which define the "+" (plus) and "×" (cross) polarizations respectively.

$$\varepsilon_{\mu\nu}^+ = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \quad \varepsilon_{\mu\nu}^\times = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}. \quad (1.19)$$

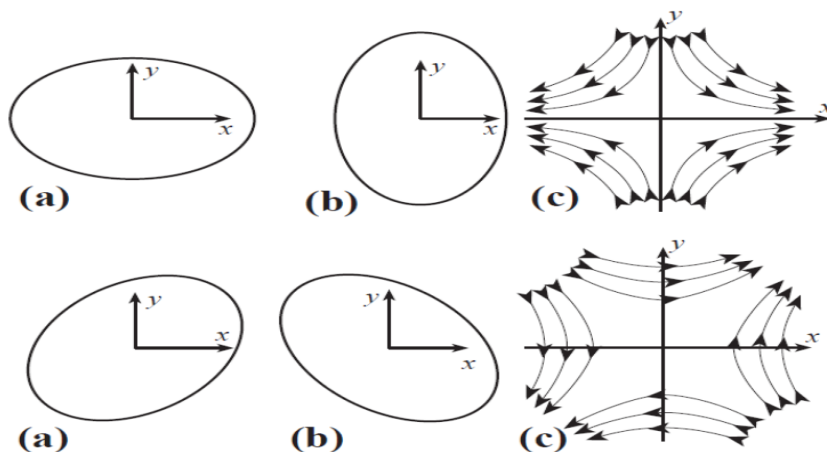
This shows that GW have two independent polarizations.

## 1.2.2 Phenomenology of gravitational waves

### Effect of gravitational waves on matter

Equations (1.18) and (1.19) show that a GW modulates the distance between two nearby objects at the wave frequency  $\omega$  with opposite sign in the plane *transverse* to the direction of propagation.

This is a *differential strain* effect which is illustrated in Figure 1.10 over a ring of free falling test masses submitted to gravity only. We also see that the effect of the + and  $\times$  polarization is the same except a rotation of  $45^\circ$  degrees.



**Figure 1.10** – Deformation of a ring of freely falling test masses due to an impinging GW which propagates in the direction normal to the plane of the ring. (a and b top) effect of the “+” polarization. (a and b bottom) effect of the  $\times$  polarization. (c top) the field lines corresponding to the + polarization (The arrows show the direction of the field). (c bottom), the field lines corresponding to the  $\times$  polarization.

### Production of gravitational waves–Quadrupole formula

Electromagnetic (EM) waves are produced by accelerated charges. Similarly, GW are produced by accelerated masses. The lowest non-vanishing term in the multipole expansion of the source distribution is the quadrupole, since the dipole vanishes due to the conservation of momentum. This is a major difference with respect to EM waves (which are dominated by the dipole). The emission of GW are thus associated to variations of the quadrupolar moment tensor of the mass distribution defined by

$$Q_{ij}(t) = \frac{1}{c^2} \int T_{00}(t, x) x_i x_j d^3x \quad (1.20)$$

where  $T_{00}$  is the time component of the stress-energy tensor which is directly connected to the energy density and hence source rest-mass density. Clearly, a spherically symmetric system



cannot emit GW as its quadrupole does not vary. The so-called *quadrupole formula* obtained in the far field and slow motion approximation ( $v \ll c$ ), connects the GW amplitude to the quadrupole moments defined in Equation (1.20). We have

$$h_{ij} = \frac{2G}{r c^4} \frac{\partial^2}{\partial t^2} Q_{ij}(t - r/c) \quad (1.21)$$

where  $r$  is the distance from the observer to the source. This shows that GW are a *radiation* as its amplitude decreases inversely with the distance  $r$  to the source.

The leading factor  $G/c^4 \approx 8.3 \times 10^{-45} \text{ s}^2/\text{m}/\text{kg}$  is extremely small. To generate GW of sufficient amplitude to be detectable, it has to be compensated by very large variations of  $Q$ .

These variations have typical magnitude  $\ddot{Q} \sim (mv^2)_{\text{non-sph}}$  which is twice the non-spherical part of the kinetic energy inside the source. Let us denote the source characteristic radius  $R$  and  $\epsilon$  the degree of asymmetry of the mass distribution and let us assume that the source evolves over the characteristic time scale  $T$ . We then get the estimate  $\ddot{Q} \approx \epsilon m R^2 / T^2$ . Applying this estimate to systems at the human scale, we see that they are unable to reach a sufficient  $\ddot{Q}$ .

This implies that GW cannot be generated in a laboratory. The sources must involve very massive, dense, relativistic systems and are therefore necessarily high-energy astrophysical processes. To get typical estimates, let us consider a system formed of two compact stars (such as, a neutron-star binary). A detailed discussion of this system as a GW source will be given later in section 1.2.3. For such a source, the above estimate yields  $\ddot{Q} \sim m(\Omega R)^2 \sim m^{5/3} \Omega^{2/3}$  using 3rd Kepler's law. For a binary neutron-star system with  $m = 1.4M_\odot$  located at  $r = 10$  Mpc and orbiting at  $\Omega/(2\pi) \sim 100$  Hz, the above estimate gives  $h \sim 10^{-21}$ . This corresponds to the detectability limits of current GW detectors (as explained in detail in chapter 3).

A consequence of the estimates provided in this section is that GW are produced by the coherent relativistic bulk motion of large mass distributions. This radically differs from EM waves generally produced in Nature by the individual and incoherent motion of charges (atoms or electrons). While EM waves (and neutrino emission) are sensitive to the micro-physics, GW carries information about the global dynamics of the source.

### Radiated GW energy

It is interesting to calculate the energy radiated by a GW away from the source. The GW energy flux (per unit time and unit area) is defined by [50]

$$F_{GW} = \frac{c^3}{16\pi G} \langle \dot{h}_+^2(t) + \dot{h}_\times^2(t) \rangle \quad (1.22)$$

where  $\dot{x}$  designates the time derivative and where the average  $\langle \cdot \rangle$  operates over several periods. This averaging is necessary and arises from the impossibility to define the energy of a gravitational field locally in General Relativity.

For example, the energy flux of a sinusoidal, linearly polarized wave of amplitude  $H_+$  and angular frequency  $\omega$  is

$$F_{GW} = \frac{c^3}{32\pi G} \omega^2 H_+^2 \quad (1.23)$$

Assuming a frequency of  $\omega/(2\pi) = 100$  Hz and amplitude  $H_+ = 10^{-21}$ , one obtains a flux of 3.3 mW/m<sup>2</sup> (or equivalently 3.3 erg/s/cm<sup>2</sup>). This is a considerable energy for astrophysical standard candles. For instance, it is eight orders of magnitude larger than the Crab pulsar luminosity in the  $\sim 10$  keV band.

The GW radiated energy is obtained with

$$E_{GW} = D_L^2 \int d\Omega \int_T F_{GW}(t) dt \quad (1.24)$$

where  $D_L$  is the luminosity distance of the source from the detector,  $\Omega$  is the solid angle and  $F_{GW}$  is measured at the detector.

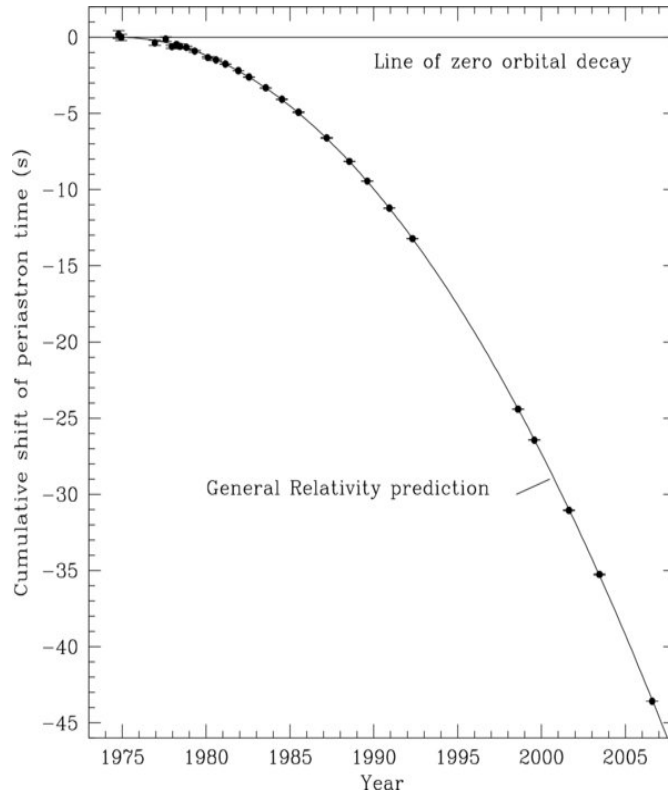
### Indirect evidence of existence

In 1993, the physicists Russel Hulse and Joseph Taylor has been awarded the Nobel Prize in Physics for their experimental observations in 1974. These observations consisted in following the evolution of the orbit of the binary pulsar PSR1913+16 as shown in Figure 1.11 [51, 52]. This system is composed of two neutron stars, of which one is a pulsar and the other is dark, bound in an orbit with period  $P \sim 7hr45min$ .

Hulse and Taylor used their timing measurements of the pulses to infer the details of the orbital motion. The number of pulses received each second increases when the pulsar is moving towards us and is close to its periastron and vice-versa. These observations of the pulse emitted by the pulsar evidenced the orbital decay  $dP/dt < 0$  of the binary (about 40 seconds over 30 years). This implies that the system loses energy.

The measured decay is in remarkably close agreement ( $\sim 0.2\%$ ) [52] with the predictions of General Relativity assuming that the system essentially loses energy by radiating GW away. This provided an indirect evidence for the existence of GW.

Since the discovery of PSR1913+16, other binary pulsars have been detected which includes PSR B1534+12 and PSR J0737-3039A/B [53]. All those newly discovered systems exhibit the same orbital decay as PSR1913+16.



**Figure 1.11** – Cumulative shift of the periastron time for PSR 1913+16 from 1975 to 2007. The continuous curve shows the predictions from the General Relativity. The observations are shown with as points with measurement error bars.

### 1.2.3 Astrophysical sources of gravitational waves

Astrophysical sources of gravitational radiation can be divided into two categories: *permanent* and *transient* sources.

Permanent sources includes *periodic sources* and *stochastic backgrounds*. We refer to periodic sources as sources that emit periodic GW continuously. They are related to isolated rotating neutron stars with some degree of asymmetry (characterized by the ellipticity of the star) that may be due to accretion or pressure from internal magnetic fields for instance. If there is a sufficient degree of asymmetry, such a system is expected to emit a monochromatic GW at twice the rotation period. The wave amplitude is weak (much lower than the noise floor of current detectors). However, since it is permanent, it can be integrated over a long duration. Stochastic GW backgrounds can have an astrophysical or a cosmological origin. Astrophysical backgrounds result from the incoherent superposition of many GW from unresolved faint sources located in the Galaxy or in the nearby Universe. Current cosmological models also predict the existence

of a relic stochastic background from the very early phase of the Universe history. Both types of backgrounds are stochastic GW signals and require at least two detectors in operation to be detected (by the measurement of an excess of correlation).

This thesis focuses on transient sources as they are potentially connected to the emission of high-energy neutrinos. This section discusses into more detail the potential astrophysical sources of transient GW.

### Coalescing compact binaries

A large fraction of stars are in binary systems. If both components of the binary end up forming compact bodies (neutron star or black hole) and if their orbit is sufficient tight, the resulting system will eventually coalesce after losing a considerable amount of energy through GW emission. The coalesce of neutron-star and/or black-hole binaries similar to the Hulse-Taylor binary mentioned previously is often considered the most promising source.

During the inspiralling phase where the two bodies are far apart, the dynamics of such a system (and hence the expected GW waveform) can be predicted with great accuracy by using post-Newtonian expansions [54, 55].

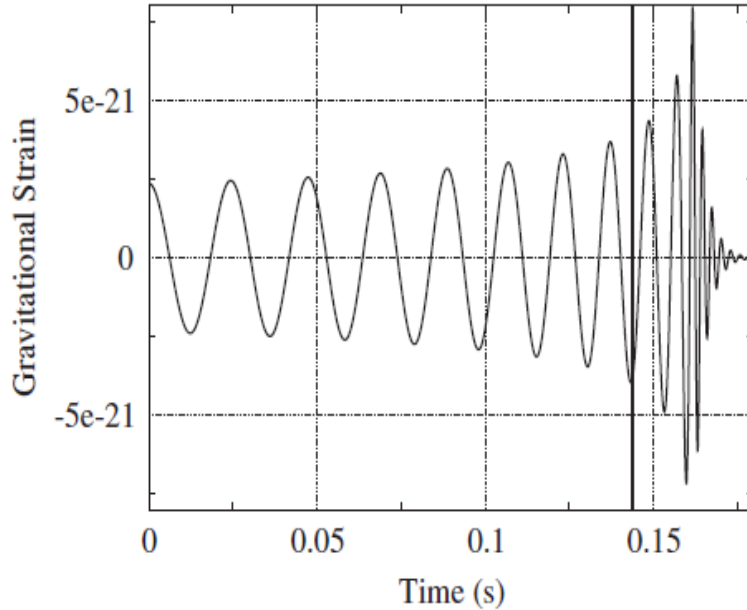
The GW signature consists in a *chirp* signal whose frequency sweeps toward high values according to a power law at first order (see Figure 1.12). A substantial amount of energy is radiated in the following phase when the two bodies merge into a black-hole. In this highly relativistic phase, the perturbative treatment of binary dynamics is not valid anymore and one has to resort to numerical simulations. The process is concluded by the ring-down phase during which the resulting distorted black-hole radiates away its asymmetry down to equilibrium.

During the whole coalescence process, a stellar-mass binary with equal masses radiates away of the order of a percent of its rest mass [56]. This corresponds to a GW amplitude of  $h \sim 10^{-21}$  observable at Earth for a system located at 10 Mpc as estimated above in section 1.2.2. More precise estimates of the detectability horizon can be obtained: GW detectors can ideally observe those binary systems up to a distance of  $\sim 30$  Mpc and  $\sim 440$  Mpc for initial and advanced detectors respectively.

Although binary systems are fairly common, only a small fraction eventually forms a compact binary that is sufficiently tight to coalesce in less than the Hubble time. A survey of population estimates [57] gives a “realistic” rate of one neutron star–neutron star coalescence<sup>2</sup> per 10,000 year per galaxy equivalent in size to the Milky Way. When converted into a rate of *detectable* coalescences, the above horizons lead to  $\sim 0.02$  events per year with the first generation of (initial) detectors and to  $\sim 40$  events for the second generation (advanced). Large

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<sup>2</sup>Similar rates are obtained for the other types of systems mixing neutron-stars and/or black-holes.



**Figure 1.12** – Example of a GW chirp waveform from coalescing compact binaries.

error bars are attached to those estimates reflecting the weakness of the observation constraints we have about those systems. The above stated rates can be 10 times smaller or larger in the “pessimistic” or “optimistic” scenarios respectively.

It is suspected that binary coalescences could be the progenitors of at least a fraction of the short-hard gamma-ray bursts. The “realistic” rates presented above are corroborated by the ones derived from that assumption [57].

### Core collapse supernova

Gravitational stellar-core collapse is another potential source of GW if some degree of non-axisymmetry is exhibited during this process. The simulations required to make reliable predictions of the emission levels are very challenging as they have to incorporate many physical ingredients including relativistic magneto-hydrodynamics and a detailed treatment of neutrino transport and nuclear iterations [58]. The current realistic estimate of the amount of radiated GW energy is of order  $10^{-7} M_{\odot}$  and corresponds approximately [59] to a distance reach of order  $\sim 10$  kpc with the initial detectors,  $\sim 100$  kpc with the advanced detectors. The detectable sources are therefore located in the Galaxy.

A few mechanisms have been suggested in which GW emission associated with gravitational core-collapse is enhanced. This is connected to the collapse of very massive star associated with high rotation rate possibly due to accretion. In that case, bar or fragmentation instabilities

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### 1.1.3 Joint sources of gravitational waves and high-energy neutrinos

[60, 61] may lead to the emission of order  $10^{-2}M_{\odot}$  in GW, leading to similar detectability horizons as the coalescing binaries of neutron-stars. This astrophysical scenario may also be at the heart of long-soft GRB.

#### Star quakes

Several observations indicate that neutron stars may experiment large stress during the course of their life. Although “ordinary” neutron stars are characterized by extremely strong surface magnetic fields ( $\sim 10^{12}$  G), many magnetars appear to have fields 100-1000 times stronger, implying enormous pent-up magnetic energy. Soft gamma ray repeaters (SGRs) and anomalous X-ray pulsars (AXPs) are different observational manifestations of the same underlying system with a highly magnetized star which sporadically converts magnetic field energy into radiation [62].

The sudden release of the magnetic energy may also excite to some extent the fundamental or  $f$ -modes of the star, which radiate GW with damping times of  $\sim 200$  ms.

Detailed predictions about the GW amplitude are difficult to obtain. An upper-limit of  $\sim 10^{49}$  erg on the maximum *total* energy release in an SGR giant flare can be derived from one of the most optimistic models (see [63]), of a giant flare associated with a global reconfiguration of the internal magnetic field. Similarly, [64] estimated a maximum total energy release of  $\sim 10^{48}$ - $10^{49}$  ergs in a fraction of the parameter space, within the model originally proposed by [63].

## 1.3 Joint sources of gravitational waves and high-energy neutrinos

In the previous sections, we described models for the single production of GWs or HENs. In this section, we discuss plausible sources of both GW and HEN emissions. We will see that some of the scenarios leading to joint emissions are tightly connected to gamma-ray bursts (GRBs) [65].

GW emission requires relativistic bulk motion of massive objects such as gravitational collapse or merger of compact objects. Production of HEN requires the formation of a fireball and ejection of relativistic particles with some hadronic load. These two requirements restricts the wide range of sources presented so far. The list of plausible sources gives a global and coherent picture of the astrophysical scenarios from both GW and HEN perspectives. When applicable, we will also mention their connection to observations in the electromagnetic spectrum. Note however, that will be especially interested in the sources that are *not* observed electromagnet-

ically. This may be due to the source opacity (which often arises in the dense media considered here). This may be also due to observational limitations. For instance, a significant fraction of GRBs are missed by current observatories. Swift/BAT and Fermi/GBM miss about 90 % and 40 % of all GRBs respectively. This is due to the limited fields of view, technical downtime, and orbital passes through the South Atlantic Anomaly.

### 1.3.1 Core-collapse supernovae with mildly relativistic jet

One of the promising sources are core-collapse supernovae (CCSN) with mildly relativistic jet [66]. There is evidence for the existence of such jets, observed in radio [67].

The HEN emission for this source is somewhat related to the fireball model for (long) GRB presented in section 1.9. In this model, a jet of plasma is ejected at relativistic velocity. Relying on the assumption that protons are accelerated in the jet through Fermi acceleration in internal shocks,  $pp$  and  $p\gamma$  interactions will produce kaons ( $K$ ) and pions ( $\pi$ ). In these two interactions (non-thermal) neutrinos of TeV energy can be produced through the decay of charged pions and kaons [66, 68]. The charged  $\pi^\pm$  and  $K^\pm$  are expected to follow the proton spectrum falling as  $E^{-2}$ . About 20% of the proton energy is converted into the produced neutrinos. An ejected mass with a kinetic energy of  $3 \times 10^{51}$  erg and a Lorentz factor of 3 at 10 Mpc would generate  $\sim 30$  neutrino events detected in a  $\text{km}^3$  detector [68] which translates to order of few events in ANTARES.

GW emission associated to the gravitational collapse of massive star was already discussed in section 1.2.3. We mentioned that the presence of a high rotation rate (due to accretion for instance) may develop bar-mode instability thus leading to enhanced GW emission. [69] quote upper limits of  $P_{max} = 10^{53}$  erg/s at  $f = 1$  kHz. If the bar remains coherent for  $\sim 100$  cycles, this conducts to a GW emitted energy of order  $10^{-2}M_\odot$ . Under the (unlikely) assumption of extreme rotation, [70] predicts the formation of fragments ( $< 1M_\odot$ ) leading to the emission of an inspiral-like GW chirp. If we estimate that order of one percent of the rest-mass is emitted during merger, we again get a GW emitted energy of order  $10^{-2}M_\odot$ , this time at frequencies of few hundred Hz.

If core collapse supernovae may lead to significant GW and HEN emission, they may also be faint or undetectable electromagnetically. Mildly relativistic jets might not be powerful enough to break out the star hydrogen envelope [68]. This is usually referred to as the “choked GRB” model. Without an emerging jet, the X-ray, optical, IR, and radio afterglows typical of GRB would also be absent. Also, core collapse of massive star may not lead systematically to SN shock breakout. For instance, some of the nearby GRBs (e.g., GRB060505 or GRB060614) miss a supernova. Even if the process succeeds in yielding a supernova, it may not be observable.

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### 1.1.3 Joint sources of gravitational waves and high-energy neutrinos

A significant fraction (up to 15 % with 10 Mpc) of supernovae are missed optically in the local Universe because of selection effects and dust extinction.

Choked GRBs may be at the extreme end of a (potentially large) local population of faint long-soft GRBs. A subclass of GRBs with luminosities lower by a few orders of magnitude than typical luminosities has been identified. Less luminous than typical long GRBs, “low-luminosity GRBs”, are discovered at much smaller distances (SN 1998bw at redshift  $z = 0.0085$ , about 40 Mpc away from Earth, SN 2003lw at  $z = 0.105$ , and SN 2006aj at  $z = 0.033$ ). The event rate per unit volume of those type of events has been estimated to be more than one order of magnitude larger than that of conventional long GRBs.

### 1.3.2 Other sources

Short-hard GRBs are thought to be driven by NS-NS or NS-BH mergers [71, 72]. As discussed in section 1.2.3, coalescing binaries are expected to emit GWs that are detectable to large distances ([73, 74]),  $\sim 30$  Mpc with the initial versions of LIGO and Virgo. Much less is known about the HEN emission from those systems. If the binary merger is associated to a GRB, this implies the presence of an ultrarelativistic jet. If there is significant baryon loading in the jet, this should eventually conduct to the production of HEN.

Other potential galactic sources of GW+HEN joint emission can be considered in this work. Such sources are Soft Gamma Repeaters (SGRs) which are X-ray pulsars with soft gamma-ray bursting activity. According to the magnetar model, SGRs may be associated with star-quakes. The deformation of the star during the outburst could produce GWs (see section 1.2.3), while HENs could potentially emerge from hadron-loaded flares (see section 1.1.4).

A more exotic class of sources are cosmic strings, topological defects formed during phase transitions in the early Universe. Emission of gravitational waves is considered the main channel for cosmic string loops to decay. In particular, cosmic string cusps appear to be potential sources of gravitational waves due to the very large Lorentz factor achieved when they contract. Cosmic strings and topological defects in general are also of interest to high energy neutrino astronomy as they can produce particles, including neutrinos, up to the Planck scale [75].

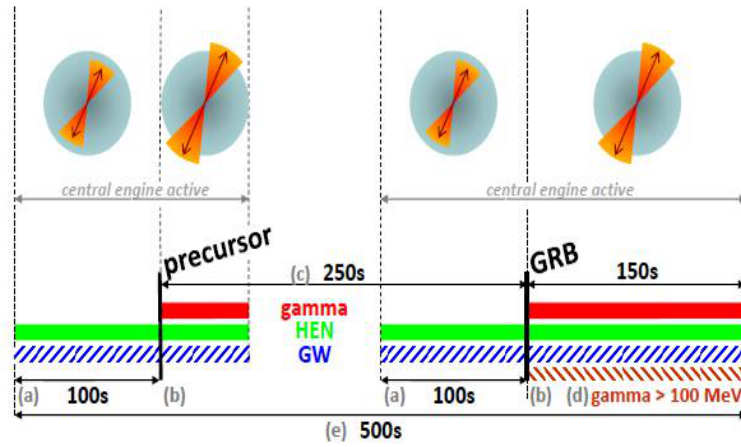
### 1.3.3 Time delay between gravitational wave and high-energy neutrino emissions

The scenarios evoked in the previous sections are connected to GRBs. GRBs provide an interesting astrophysical scenario where the delay between GW and HEN emissions can be characterized. A conservative estimate of this delay determines the baseline duration over which GW and HEN are declared in coincidence. A statistical estimate has been obtained in [76] based



## CHAPTER 1. MULTIMESSENGER ASTRONOMY

on GRBs mainly observed by BATSE, Swift and Fermi LAT. In this article, we considered the duration of the different emission processes to constrain the size of the time search window. Figure 1.13 summarizes the assumptions and modelling of [76]. This leads to an upper bound on the size of  $\Delta t_{GW+HEN} = [-500s, +500s]$  the time search window. The latter is conservative enough to encompass most theoretical models of GW and HEN emissions for GRBs. This time window will be used in both analyses presented in this work, see Chapters 4 and 5 for further details.



**Figure 1.13** – Overview of the GRB emission processes and GW/HEN time search window. (a) Active central engine before the relativistic jet has broken out of star; (b) Active central engine with relativistic jet broken out of star; (c) Delay between onset of precursor and main burst; (d) Duration corresponding to 90% of GeV photon emission; (e) Time span of central engine activity. Possible GW/HEN emission between the precursor and the main GRB (no emission is shown on the figure) has no effect on the estimated time window. Overall, the considered processes allow for a maximum of 500s between the observation of a HEN and a GW transient, setting the time search window to  $[-500s; 500s]$ . (Adapted from [76])

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# CHAPTER 2

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## NEUTRINO TELESCOPES

### 2.1 Summary

With the advent of a new generation of observatories including the ANTARES neutrino telescope observational astrophysics is entering a new era. The ANTARES neutrino telescope gives access to new and unexplored observations of the Universe complementary to the standard photon-based astronomy. This chapter gives an introduction to the neutrino astronomy from an instrumental point-of-view ranging from the general detection principles to the description of the instruments currently in operation. We focus in the most part of this chapter on the ANTARES instrument.

### 2.2 Neutrino telescopes

#### 2.2.1 General principles

The detection rate  $T(E_{\min}, \theta)$  of charged leptons  $l$  ( $e, \mu, \tau$ ) produced by neutrino interactions around the detector can be obtained by convoluting the incoming neutrino flux  $dN/dE_\nu$  and the detection probability of these neutrinos:

$$T(E_{\min}, \theta) = \int_{E_{\min}} P_{\nu \rightarrow l}(E_\nu, E_{\min}) P_{\text{trans}}(\theta, E_\nu) \frac{dN}{dE_\nu} dE_\nu \quad (2.1)$$

where  $P_{\text{trans}}(\theta, E_\nu)$  is the transmissivity coefficient of a neutrino through the Earth and  $P_{\nu \rightarrow l}(E_\nu, E_{\min})$  is the probability that a neutrino of energy  $E_\nu$  creates a detectable lepton of energy greater or equal to  $E_{\min}$ . This latter probability can be written as :

$$P_{\nu \rightarrow l} = \mathcal{N} \int_{E_{\min}}^{E_\nu} dE_l \frac{d\sigma}{dE_l} R_l(E_l, E_{\min}) \quad (2.2)$$

## CHAPTER 2. NEUTRINO TELESCOPES

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where  $\mathcal{N}$  is the Avogadro number,  $\frac{d\sigma}{dE_l}$  is the interaction cross section as a function of the neutrino energy and  $R_l(E_l, E_{min})$  is the path length of the produced lepton. In the case of a muon ( $l = \mu$ ), this distance can be much greater than the detector size, contrarily to electrons and  $\tau$  which are respectively absorbed or quickly desintegrated. This explains why the detection of muon neutrinos is favoured over the other flavors ("golden" channel). However, neutrino telescopes are also sensitive to electron and tau neutrinos and can in principle discriminate between flavors: tau-neutrino with energies  $\geq 1PeV$  can indeed travel several meters before decaying producing a second shower, while electron-neutrino yields an electron which produces an electromagnetic shower.

In the following, we will concentrate on muon neutrino interactions and describe into more details the different terms of relation 2.2.

### 2.2.2 Neutrino interactions

After penetrating the Earth, the neutrino is subject to interactions with electrons and nuclei of atoms and molecules that constitute the rock, the sea or the ice. Neutrinos interact through only the weak interaction and have a small cross section ( $10^{-38}cm^2$  at 1 GeV) [1]. Interactions at higher energy ( $E_\nu > 10GeV$ ) are dominated by deep inelastic scattering onto atomic nuclei. When they interact, neutrinos are subject to two main <sup>1</sup> interaction processes: charged current (CC) interaction or neutral current (NC) interaction. While the former consists in an exchange of charged boson  $W^\pm$ , the second involves the exchange of a neutral boson  $Z^0$  (see Figure 2.1 for illustration):



where  $l$  stands for any kind of leptons ( $e, \mu, \tau$ ),  $N \equiv \frac{n+p}{2}$  can be seen, for simplicity, as an isoscalar nucleon and  $X$  represents the hadronic products of the interaction. In the following we concentrate on the CC interaction which produces a charged lepton that will be later detected.

The differential cross section of the neutrino for this process can be expressed in terms of the parton distribution functions as follow [2, 3]:

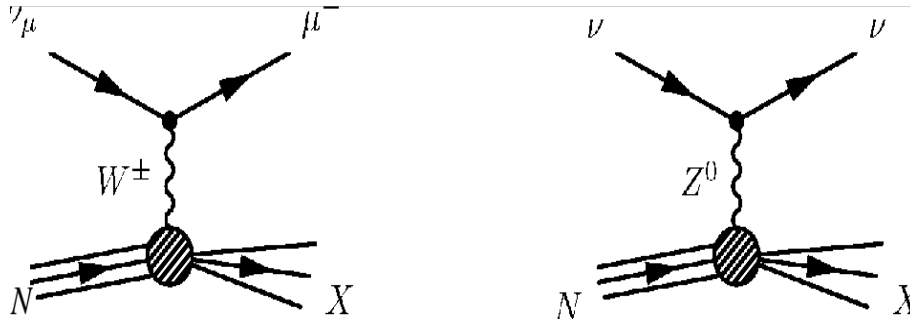
$$\frac{d^2\sigma}{dx dy} = \frac{2G_F^2 M_N E_\nu}{\pi} \left( \frac{M_W^2}{Q^2 + M_W^2} \right)^2 [xq(Q^2, x) + x\bar{q}(Q^2, x)(1-y)^2]\tag{2.4}$$

where:

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<sup>1</sup>we will not treat here the Glashow resonance  $\bar{\nu}e \rightarrow W \rightarrow X$

- $G_F$  is the Fermi constant.
- $Q$  is the invariant momentum transfer.
- $M_N$  and  $M_W$  are the nucleon and the intermediate-boson masses.
- $\nu = E_\nu - E_l$  is the fraction of energy carried by the boson in the laboratory frame.
- $x = \frac{Q^2}{2M_N\nu}$  and  $y = \frac{\nu}{E_\nu}$  are the Bjorken scaling factors.
- $q(Q^2, x)$  and  $\bar{q}(Q^2, x)$  represent the parton distribution functions (PDFs) describing the quark and anti-quark content of nucleon.



**Figure 2.1** – Feynman diagram representation of the CC (left) and NC (right) interactions

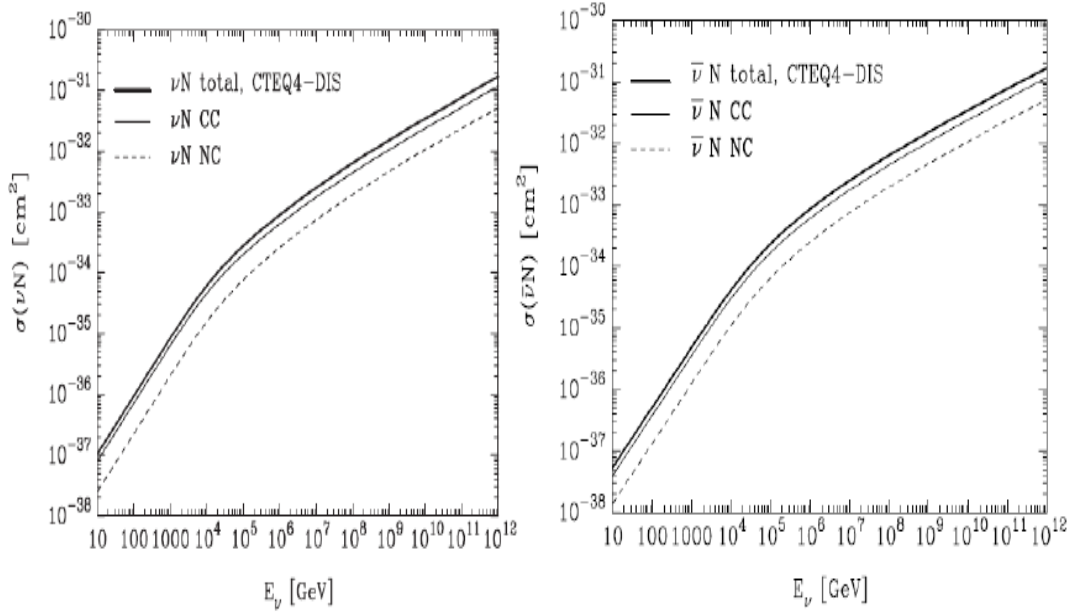
Figure 2.2 left and right show the cross section of the  $\nu$  and  $\bar{\nu}$  interaction respectively. At energies  $E_\nu > 10\text{GeV}$  the cross section increases linearly with energy while it follows a  $\sigma \propto E_\nu^{0.4}$  relation at energies  $E_\nu > 1\text{PeV}$ . These different regimes arise from the non negligible value of  $Q^2$  at high energy with respect to the mass propagator.

For muon neutrino interactions, the angle between the direction of the initial neutrino and the out-going muon in the charged-current channel is very small, the muon track and the parent neutrino are almost collinear. The angular difference between the direction of the primary  $\nu_\mu$  and the induced  $\mu$  can be approximated by [4]:

$$\langle \theta_{\mu\nu} \rangle \approx \frac{0.7^\circ}{(E_\nu/\text{TeV})^{0.6}} \quad (2.5)$$

During the propagation in the medium the muon track is further deflected as the muon undergoes multiple scattering. The mean angular deviation between the initial muon direction and





**Figure 2.2** – The  $\nu$ - $N$  (left) and the  $\bar{\nu}$ - $N$  (right) cross section interaction as function of the energy

the direction after passing a distance  $x$  in the medium is described by [5]:

$$\Delta\theta_{ms} = \frac{13.6 \text{ MeV}}{E_\mu} z \sqrt{\frac{x}{X_0}} \left[ 1 + 0.038 \ln \left( \frac{x}{X_0} \right) \right] \quad (2.6)$$

where  $X_0$  is the radiation length<sup>2</sup> of the medium and  $\Delta\theta_{ms}$  is given in radians and  $z$  is the charge number of the incident particle. The deviations due to the multiple scattering described by Equation (2.6) are generally smaller than the scattering angle in Equation (2.5). Therefore this allows the produced muon to somewhat preserve the original direction of the muon-neutrino. Indeed for neutrino energies larger than 1 TeV, the muon track is aligned with the incident neutrino within a degree. At higher energies ( $\geq 10 \text{ TeV}$ ) the kinematics effects start to be negligible and the biggest uncertainty in the direction estimation comes from the calibration (timing and positioning) of the detector (see section 2.3.6).

### 2.2.3 Propagation of the neutrinos in the Earth

At high energies, as the cross section increases, neutrinos can be absorbed. Typically, the Earth becomes opaque to neutrinos at 70 TeV where the interaction length becomes comparable to the diameter of the Earth.

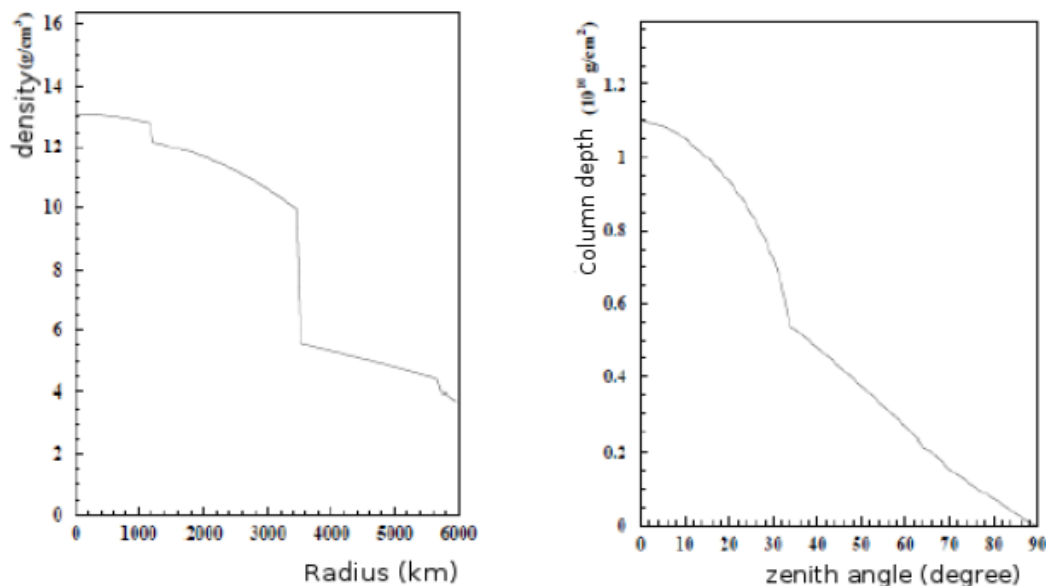
<sup>2</sup>For hadronic projectiles, the strong interactions also contribute to multiple scattering.

## 2.2.2 Neutrino telescopes

To quantify this effect, we take into account the profile of the earth density shown in Figure 2.3 [2]. Using this profile, 10 different layers whose density depends on the distance from the centre of the Earth are considered. The probability of a neutrino traveling a distance  $L$  (referred to as transmissivity coefficient Equation (2.2)), not to be absorbed, can be written in units of water-equivalent-length as:

$$P_{trans}(L) = e^{\frac{-L(\theta)}{\lambda}} \quad (2.7)$$

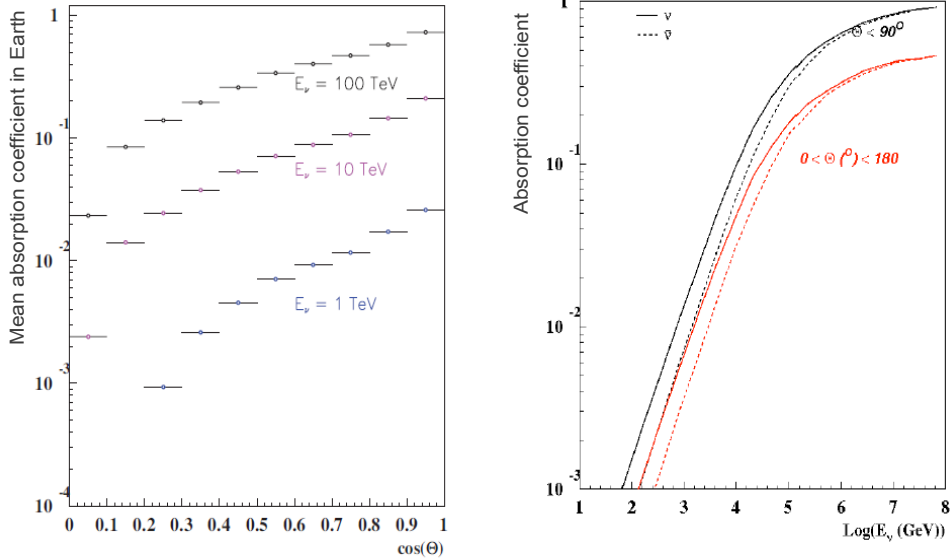
where  $\lambda = 1/(\mathcal{N}\sigma_{tot})$  is the free mean path taking into account the total cross section. Figure 2.4 shows the absorption coefficient  $(1 - P_{trans})$  as a function of energy and zenith angle in the Earth. These plots show that the absorption for neutrinos crossing horizontally a small amount of matter is negligible. Thus high energy neutrino telescopes are sensitive to high energy neutrinos ( $> PeV$ ) mostly in that directions.



**Figure 2.3** – Left: Density profile of the Earth according to the Preliminary Earth Model. Right: Thickness of the Earth as a function of the angle of incidence of the incoming neutrinos

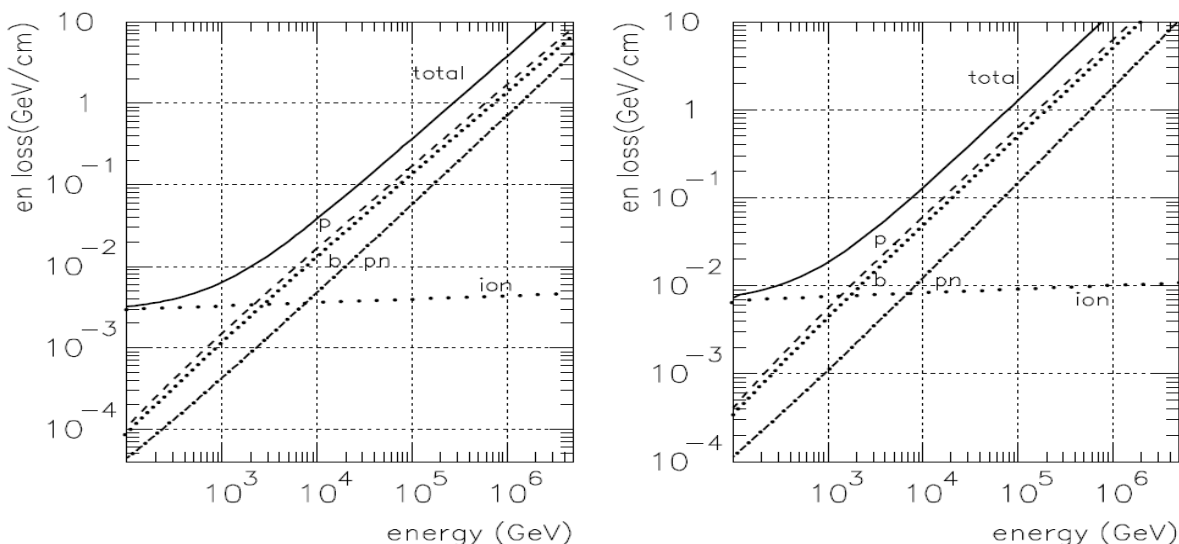
## 2.2.4 Propagation of the muons in water and rocks

Depending on their energy and during their propagation in water or rock, muons lose energy due to various processes (see Figure 2.5). For  $E_\mu < 1$  TeV the dominant process is the ionization, which can be described as a continuous process. At higher energies, muons lose their energy via stochastic phenomena such as bremsstrahlung, pair production and photonuclear interactions.



**Figure 2.4** – Left: Mean absorption effect on neutrinos of energies: 1, 10 and 100 TeV as a function of the zenith angle  $\theta_\nu$ . Right: Absorption coefficient for upgoing neutrinos (black) and for the two hemisphere (red) as function of energy

- **Ionisation:** The continuous energy loss of muons passing through a medium at relatively low energy transfers to atomic electrons, ionising the material along the muon path. The energy loss is calculated using the Bethe-Bloch formula.
- **Bremsstrahlung:** In the electric field of a nucleus or atomic electrons, muons can radiate high energy photons.
- **Pair Production:** A muon can radiate a virtual photon which, again in the electric field of a nucleus, can convert into a real  $e^+e^-$  pair.
- **Photonuclear Interaction:** A muon can radiate a virtual photon which directly interacts with a nucleus in the muon propagation medium. The average energy loss for this process increases almost linearly with energy, and at TeV muon energies constitutes about 10% of the energy loss rate.



**Figure 2.5** – Total and partial energy losses for muons in water (left) and standard rock (right) as a function of muon energy. Total energy loss : solid line; pair production (p): dashed line; bremsstrahlung (b): dotted line; photonuclear interaction (pn): dot-dashes; ionization (ion): large dots

The global contribution of all these processes to the mean energy loss of muons is given by [6]:

$$\left\langle -\frac{dE}{dx} \right\rangle = a(E) + b(E)E \quad (2.8)$$

where  $E$  is the total energy,  $a(E)$  is the contribution due to ionization and  $b(E)$  is due to the radiative processes. Both terms  $a(E)$  and  $b(E)$  are slowly varying functions of  $E$  at high energies. At low energies ( $<1$  TeV) the dominant term comes from the ionization. In the approximation of  $a$  and  $b$  constant, the mean free path of a muon of energy  $E_\mu$  until it reaches an energy  $E_{min}$  can be written as:

$$R_\mu(E_\mu, E_{min}) = \int_{E_{min}}^{E_\mu} \frac{1}{\langle \frac{dE}{dX} \rangle} dE \approx \frac{1}{b} \ln \frac{(a/b) + E_\mu}{(a/b) + E_{min}} \quad (2.9)$$

This gives an estimate of the distances which can be travelled by the muons. Nevertheless, in the high energy regime, the stochastic radiative processes enjoin to use Monte Carlo simulations to better reproduce the high energy losses. (see section 2.5).

### 2.2.5 Detection principle

Neutrino telescopes use sea water or ice as a detection medium to observe cosmic neutrinos. In parallel, these media act as a shield for down going particles of atmospheric origin, since muons

## CHAPTER 2. NEUTRINO TELESCOPES

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and neutrinos are the only particles able to reach deep underground or underwater. Other atmospheric and cosmic particles have either a short lifetime or a short interaction length and can not survive long in dense media.

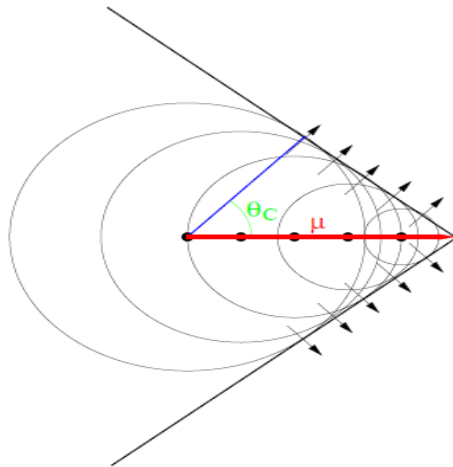
A small fraction of the incoming high energy neutrino flux interacts, (following Equation (2.1)), with the nucleons that make up the matter (water, ice and rock) surrounding the detector. The induced muon-neutrino produces a relativistic muon, with a Lorentz factor  $\beta > 1/n$ . During its propagation, the muon produces an amount of Cherenkov light, see Figure 2.6 [7]. The Cherenkov radiation propagates in a cone whose opening angle  $\theta_c$  depends on the particle velocity as:

$$\cos\theta_c = \frac{1}{\beta n_{water}} \quad (2.10)$$

whith  $n_{water} = 1.35$  for a wavelength of 450 nm and  $\beta=1$ , this formula leads to  $\theta_c = 42^\circ$ . The emitted number of photons per unit of length  $x$  and wavelength  $\lambda$  (Equation (2.11)) increases with frequency [8]:

$$\frac{d^2 N_\gamma}{dx d\lambda} = \frac{2\pi\alpha Z^2}{\lambda^2} \left(1 - \frac{1}{\beta^2 n_{water}^2}\right) \quad (2.11)$$

where  $\alpha$  is the fine structure constant,  $Z$  the charge of the particle causing the emission and  $\lambda$  the wavelength of the emitted photons. Most part of photons is then produced in the ultraviolet region of the electromagnetic spectrum. Integrating Equation (2.11) between 300 nm and 600 nm, for which Cherenkov light contributes most to the signal from a muon, yields a quantity of  $\simeq 350$  photons emitted per centimeter of the track.



**Figure 2.6** – Illustration of the Cherenkov effect. Local distortions of the charge configuration in the medium lead to the emission of electromagnetic waves. Individual contributions along the track (red line) interfere constructively on the envelope which forms a cone. Cherenkov photons (blue line) are emitted under the characteristic angle  $\theta_c$ .

## 2.2.6 Overview of the past and current detectors

### The BAIKAL neutrino telescope

The BAIKAL experiment [9] is a German-Russian collaboration. The detector is deployed at a depth of about 1km in the Siberian Baikal Lake. The experiment has been running since 1993, when three detection strings were immersed and put into operation. Since 1998 the detector was expanded to 18 strings with a total of 192 optical modules (OMs) (NT-200 detector). The detector is arranged around a central unit with the main electronic block and a calibration laser on the top of the layout that provides the support structures for the 18 strings which are distributed on a circular geometry with a radius of 22 m. Each of the strings measures 68.5 m. This setup was extended in 2005 by three additional strings of 200 m length with 36 PMTs at a distance of 100 m (NT-200+) to the detector center in order to increase the effective area for showers. Compared to neutrino telescopes in deep sea, the Baikal setup offers several advantages. Firstly, the operation in fresh water naturally reduces the background contributions from  $^{40}\text{K}$  decays. Secondly, the maintenance of the detector is greatly alleviated by the possibility to use the frozen sea surface as a basis for deployment and recovery operations. The main disadvantages are the reduced absorption length of the water in Lake Baikal and the relatively low depth which leads to a larger atmospheric muon background compared to deep-sea telescopes.

The collaboration published the first limit on the neutrino diffuse flux from the Southern hemisphere using 1038 days of data [10]. The limit  $dN/dE < 8.1 \cdot 10^{-7} E^{-2} \text{GeV}^{-1} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$  is obtained in the range of energy  $20 \text{TeV} \leq E \leq 50 \text{PeV}$ .

In order to further improve the sensitivity to cosmic signals, the collaboration envisages the enhancement of the telescope towards a Gigaton detector. An R&D and prototyping phase has started in this view.

### The Antarctica neutrino telescopes

**AMANDA:** The AMANDA experiment [11] (Antarctica Muon and Neutrino Detector Array) started in 1990. It is located near the Scott-Amundsen South Pole station in Antarctica Ice. The experiment in its final configuration (AMANDA-II) consists of 19 strings immersed in the glacial ice at a depth ranging from 1500 m to 2000 m, carrying 677 OMs. Each OM is a glass pressure vessel, which contains an 8-inches hemispherical PMT and its electronics. AMANDA-B10, the inner core of 302 OMs placed on 10 strings, has been operating since 1997. The high level of light scattering at that depth limits considerably the performance of the detector. This affects especially the angular resolution that remains above few degrees. The optical

## CHAPTER 2. NEUTRINO TELESCOPES

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absorption length in the ice is typically 110 m at 400 nm with a strong wave-length dependence. The ice parameters vary strongly with depth due to horizontal ice layers, i.e. variations in the concentration of impurities which reflect past geological events and climate changes.

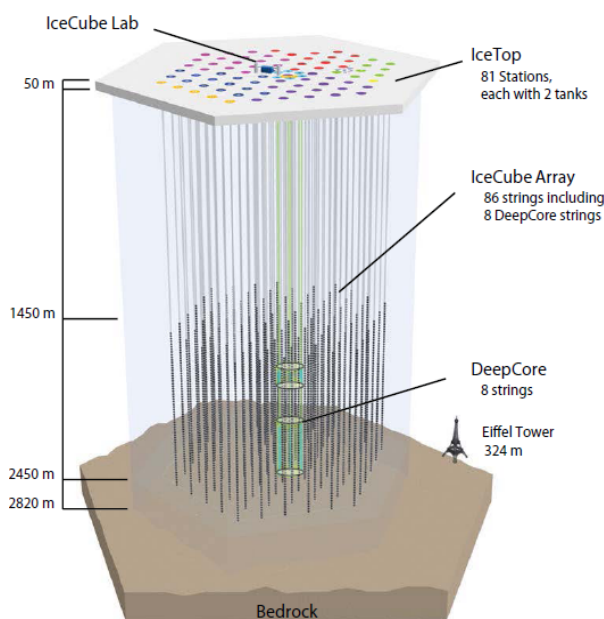
The AMANDA-II has been switched off early 2009 to allow for the extension to km-scale experiment IceCube. With 7 years of data taking, AMANDA-II collected a statistics of 6595 neutrino candidates and measured the spectrum of atmospheric neutrinos up to energies two orders of magnitude higher than in the previous experiments.

**IceCube:** The IceCube Neutrino Observatory is the successor of the AMANDA neutrino telescope. Construction of the IceCube Neutrino Observatory began at the geographic South Pole in the 2004-05 austral summer and was completed during the 2010-11 austral summer. IceCube consists of two parts: IceTop, a surface air shower array [12, 13], and IceCube, a muon and neutrino telescope [14] installed deep in the ice. The final configuration consists of 86 strings (IC86) of over 1000m length separated by 125m, with 5800 PMTs. Each string is comprised of light sensors called Digital Optical Modules (DOMs), which detect Cherenkov photons emitted by relativistic charged particles passing through ice. Each DOM is a spherical, pressure-resistant glass shell containing a 25 cm diameter Hamamatsu photomultiplier tube (PMT), a mu-metal grid for magnetic shielding of the PMT, and electronics for operation and control of the PMT as well as amplification, digitization, filtering, and calibration.

Each IceCube string is associated with an IceTop station, which consists of two cylindrical ice Cherenkov tanks separated by 10 m. Each tank has an inner diameter of 1.82 m, is 1.3 m high, and contains two down-facing DOMs, with center-to-center spacing of 58 cm, frozen in optically clear ice 90 cm in depth.

A large amount of data has already been acquired with smaller configurations throughout the installation period (IC22, IC40, IC59, IC79 and IC86), where for example IC22 denotes the 22-string configuration. Using the data from IC40, the atmospheric neutrino spectrum in the northern hemisphere has been measured up to 100 TeV. No point sources have been identified in a set of more than  $10^5$  neutrino candidates from both hemispheres. Searches for transient sources have set stringent limits on neutrino emission from gamma-ray bursts, and are now accompanied by an extensive neutrino-triggered follow-up program. A very large statistics of cosmic ray events has revealed an anisotropy in the cosmic ray flux at the  $10^{-3}$  level in the 10-100TeV range. While no source of extra-terrestrial neutrinos has been found yet, the physics results obtained so far illustrate the very good performance of the detector.

Some of recent results published by the IceCube collaboration at the moment of writing this thesis can be found in [12, 15–17].



**Figure 2.7** – The IceCube detector with its components DeepCore and IceTop in the final configuration (December 2010)

### The Mediterranean neutrino telescopes

**NESTOR:** The Greek NESTOR (Neutrino Extended Submarine Telescope with Oceanographic Research) collaboration [18] initiated the first project for a neutrino telescope in the Mediterranean sea at a site located 18 km off the coast of Pylos at a depth of 4000 m. The chosen telescope design uses tower-like rigid support structures instead of flexible mooring strings. These towers consist of 12 layers made up of six arms each, which are laid out in a star-shaped form. On each of these arms one upward and one downward looking 13" PMT are mounted. A prototype version of a tower storey has been tested in 2003, and first atmospheric muon data were recorded. Some recent results from the NESTOR collaboration are published in [19].

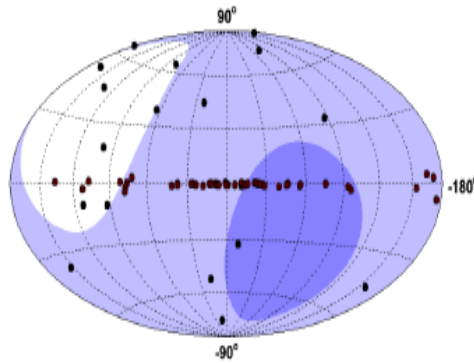
**NEMO:** The Italian NEMO (Neutrino Mediterranean Observatory) project [20] has focused on research and design studies for a future km-scale detector in the Mediterranean sea. The NEMO design concept features a flexible tower structure of horizontal bars of 15 m length which are connected by ropes. At each end of the bars two PMTs are mounted, one looking downwards, the other one in the horizontal direction. The detection towers can be deployed as a compact object together with a socket and self unfurl in the sea. After the unfolding, adjacent bars are aligned perpendicular to each other. NEMO published results from a sample of data recorded in January 2007 [21].



**The KM3NET neutrino telescope:** The KM3NeT consortium [22] is a joint effort of the ANTARES (see next section), NEMO and NESTOR collaborations to construct a cost-effective next generation telescope of cubic-km size. The geometry of the detector [23] consists of a three-dimensional array of OMs attached to vertical structures (Detection Units, DUs). An array of DUs constitutes a detector building block. Several building blocks form the full detector of about 300 DUs. A DU, which is anchored to the sea floor and kept upright by a submerged buoy, could consist of horizontal bars equipped with 2 OMs, one at each end. Alternatively, vertical strings with single optical module could be a simpler design. This should be decided by the end of 2012. The DUs will anyway be connected to shore by an electro-optical cable, and the OMs will consist of 31 3-inch PMTs housed inside a 17-inch pressure-resistant glass sphere covering almost a  $4\pi$  field of view.

### 2.3 The ANTARES neutrino telescope

The ANTARES neutrino telescope [24] is an underwater neutrino detector deployed in the Mediterranean Sea at a depth of 2500 m offshore from Toulon (France) for a design lifetime of about 10 years. It is the most sensitive high energy neutrino observatory studying the Southern Hemisphere, including the Galactic Center 2/3 of the time. The ANTARES field of view has a sky coverage of  $3.5\pi$  sr (see Figure 2.8).



**Figure 2.8** – Sky coverage of the ANTARES neutrino telescope. The blue area is seen 100% of the time by ANTARES while it is completely blind to the white area.

The ANTARES neutrino telescope consists of twelve lines with a sensitive area for high energy muons of more than  $0.05 \text{ km}^2$  for  $E \geq 100 \text{ TeV}$ . Its construction started with the installation of the first lines in 2006, and has been completed on May 30, 2008. The full structure is a three-dimensional array of photo-multipliers (PMT). In addition, a special instrumentation

line (IL), mostly dedicated to environmental studies, was put in operation in January 2008. This makes of the ANTARES detector an interesting observatory for Earth science, oceanographic and acoustic studies. The ANTARES Collaboration is a joint effort of about 29 laboratories from 8 countries (France, Germany, Italy, Morocco, the Netherlands, Romania, Russia and Spain).

### 2.3.1 Detector design

A detailed description of the ANTARES neutrino telescope is given in [24]. The basic elements of the detector are the optical modules (OMs). The later is the assembly of a pressure resistant glass sphere of diameter 43 cm housing a photomultiplier tube and the electronics needed to provide the necessary high voltage [25]. An exhaustive study of PMTs was carried out during the R&D phase, started in 1990, which led to the selection of the 10” Hamamatsu R7081-20 model. Three OMs make up a floor and five floors are grouped to form a sector. One string comprises five sectors.

The layout of the detector consists in a 3-dimensional array of optical modules (OMs) supported by flexible vertical strings anchored to the seabed with the Bottom String Socket (BSS) and are held vertical by a buoy at the top. A schematic overview of the detector string is shown in Figure 2.9. The PMTs are oriented downwards with an angle of  $45^\circ$  below the equator. This orientation gives high efficiency for tracks between upward vertical and horizontal directions, and minimize the effects due to the biofouling. The latter is caused by the adhesion of microorganisms, mostly bacteria, on the external surface.

The detector is operating since 2008 in its complete configuration of 12 strings with 25 floors (75 OMs by string). Eleven strings have a nominal configuration while the twelfth string is equipped with 20 storeys and completed by devices dedicated to acoustic detection. Thus, the total number of the OMs installed in the detector is 885. The strings are about 450m long and separated from each other by at least 60 meters. The distance between two adjacent floors is 14.5m. All strings are connected to a main junction box, which provides the connection to the 40km long cable to the shore station. All the electronics for one storey are housed in a pressure resistant titanium container making up the so-called Local Control Module (LCM). A photon that hits the photo-cathode of a PMT can induce an electrical signal on the anode. If the amplitude of the signal exceeds a certain voltage threshold corresponding typically to 0.3 photo-electron, the signal is read out and digitized by a custom designed front-end chip. Every OM is read out by an electronics board housed in the LCM carrying a pair of Analogue Ring Samplers (ARS). The later provides the time and amplitude of the signal, both essential to reconstruct the muon track direction and estimate its energy (section 2.6). Each sector

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contains a Master Local Control Module (MLCM), that collects the data produced in the floors of a sector and sends them to the main junction box.

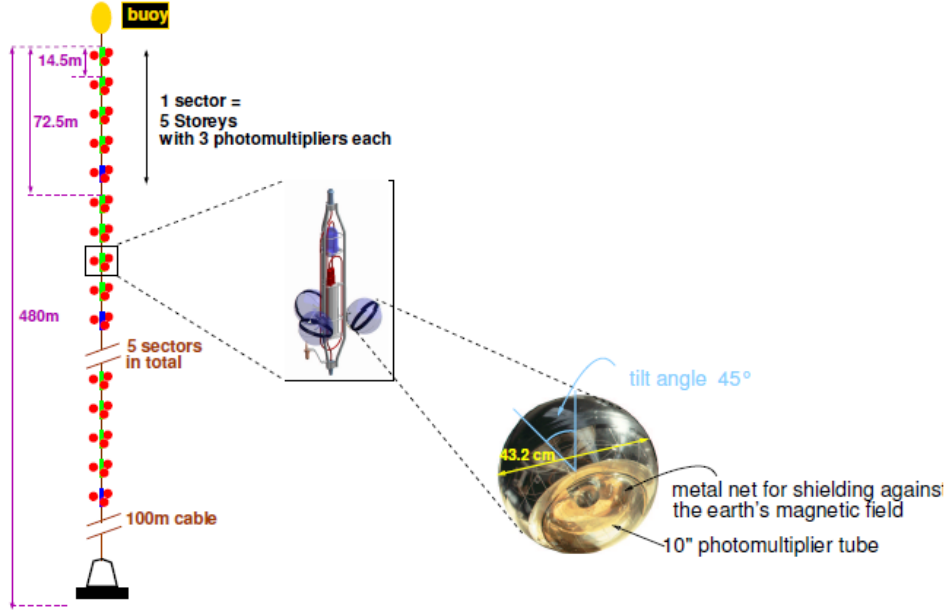


Figure 2.9 – A schematic view of ANTARES string.

### 2.3.2 ANTARES coordinates

The geographic site of ANTARES neutrino telescope is located at Latitude  $42^{\circ}47.935'N$  and Longitude  $6^{\circ}09.942'E$ . The convention for the detector coordinate system (UTM grid) [26, 27], shown in Figure 2.10, is a right-handed system with the x-axis pointing toward the East, the y-axis to the North and the z-axis parallel to the detector line going upwards. The origin is defined on the center of the detector on the sea floor. The direction of the particle track is defined by two angles:

- The angle  $\theta$  is measured from the positive z-axis in a range  $[0, \pi]$ . Upgoing events have  $\theta \leq 90^{\circ}$ ,  $\theta_{\uparrow} = 0^{\circ}$ ,  $\theta_{\rightarrow} = 90^{\circ}$  and  $\theta_{\downarrow} = 180^{\circ}$ .
- The azimuthal angle  $\phi$  is measured from the positive x-axis and it increases counterclockwise towards the positive y-axis (East  $\rightarrow$  North).  $\phi$  is measured in a range  $[-\pi, \pi]$ .

To find the zenith of the source,  $\theta$  should be rotated by  $180^{\circ}$  in space:  $\text{zenith} = 180^{\circ} - \theta$ . Elevation (also called altitude) can be used to denote the position of the source and is defined as "zenith -  $90^{\circ}$ ".

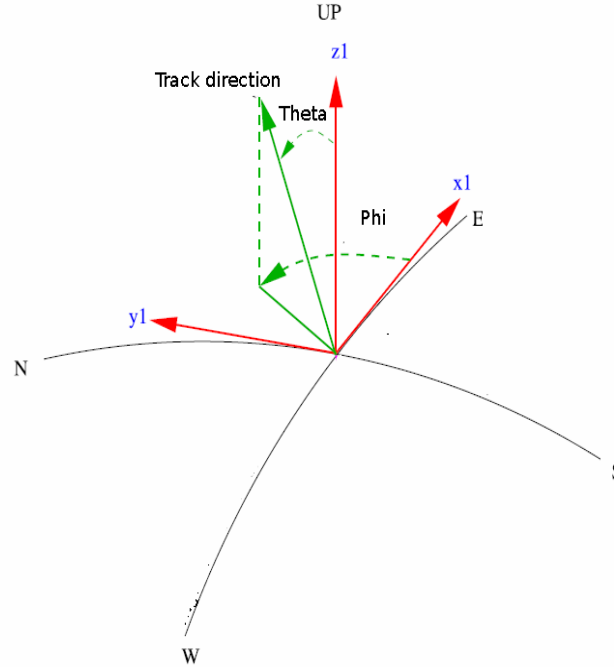


Figure 2.10 – Coordinate system of ANTARES

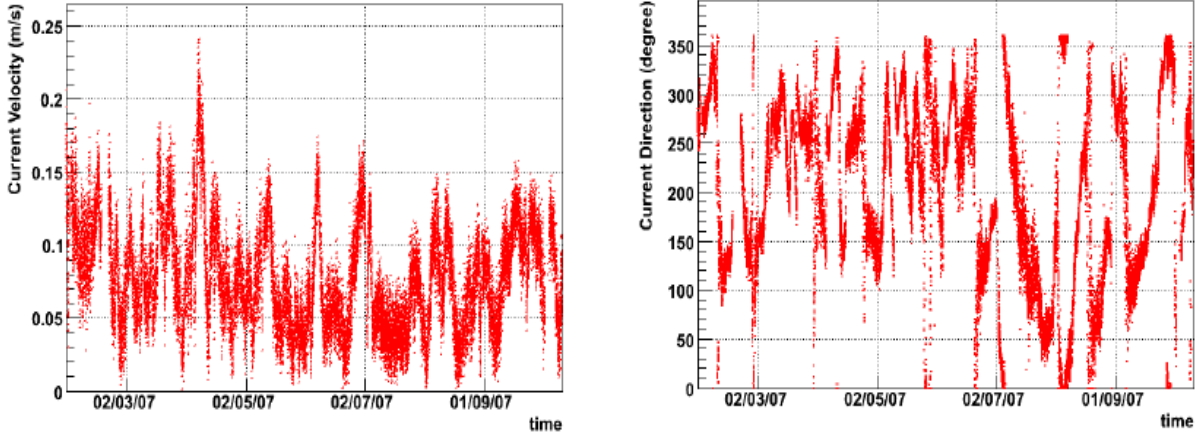
### 2.3.3 Background noise at the ANTARES site

#### Optical background: bioluminescence and $^{40}K$

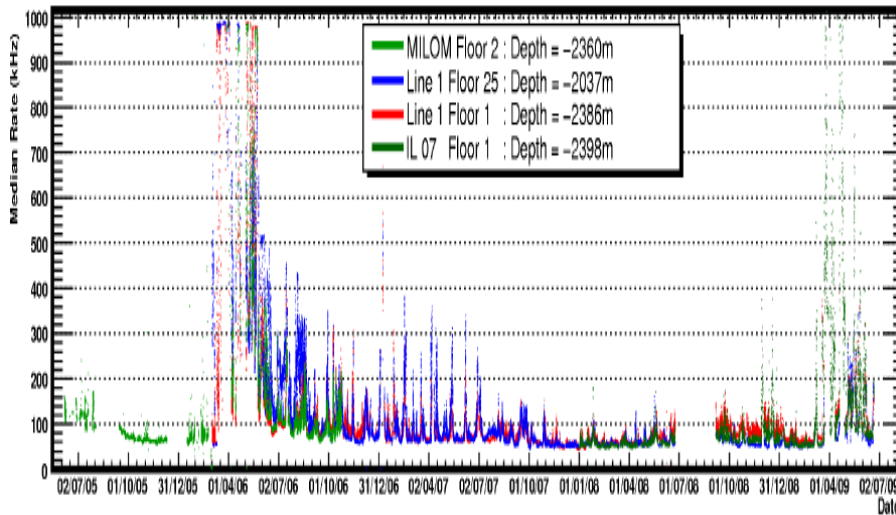
The Cherenkov radiation from  $\nu$ -induced muons is not the only light at the depth of the ANTARES site. Background light is produced by the decay of radioactive potassium-40 ( $^{40}K$ ) and marine microorganisms (bioluminescence). The latter being enhanced in periods of high sea current. Figures 2.11 and 2.12 shows some examples of the sea current and the PMT rates. The  $^{40}K$  decays into two channels:



The first decay channel ( $\beta$  decay) is the dominant decay mode of  $^{40}K$  with a probability of 0.89. The average kinematic energy of the emitted electron is 1.12 MeV, enough to produce



**Figure 2.11** – Sea current velocity (left) and direction (right) in the ANTARES zone during the period going from February to November 2007.



**Figure 2.12** – Median single PMT background rates at different depth levels, monitored over four years of operation from 2005 and 2009.

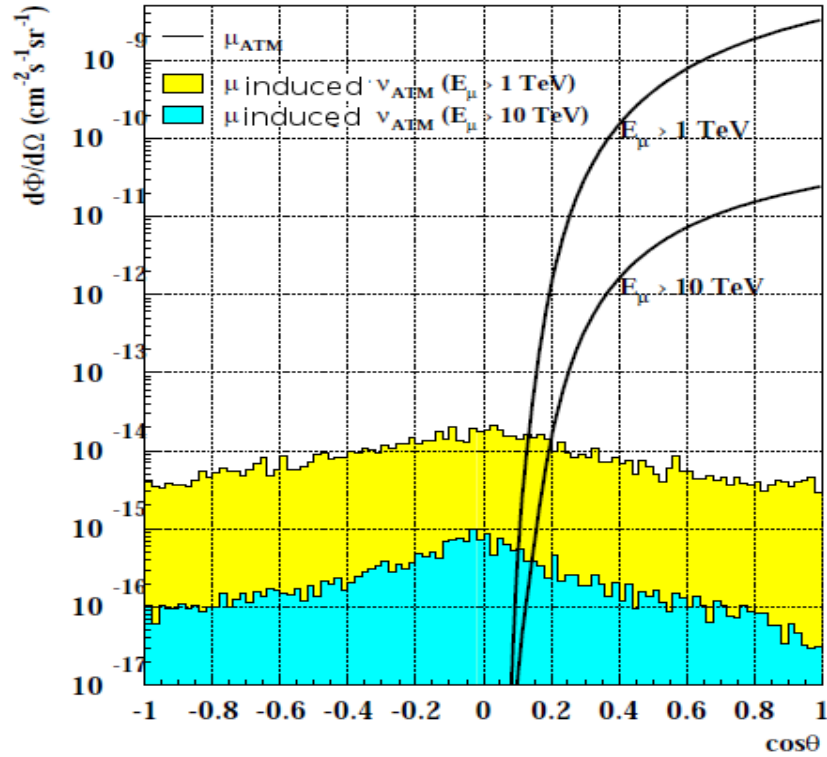
Cherenkov light in water. The decay of the  $^{40}K$  contribute to the PMT rates by a stable rate of around 30 kHz. In the second decay mode, the Cherenkov light comes from the Compton scattering of the 1.4 MeV photon emitted in the desexcitation of the  $^{40}Ar$ .

### 2.3.4 Physical background: atmospheric muons and neutrinos

Cosmic ray interactions in the Earth’s atmosphere above the detector produce energetic atmospheric muons (see section 1.1.2). When the muon energy is high enough, they can travel large

### 2.2.3 The ANTARES neutrino telescope

distances and reach the detector from above. The aim to build the detector in deep sea is to use the water as a shield against the flux of those downward going atmospheric muons. However, upward going atmospheric muons can not travel through the Earth. Everything a part from the desired cosmic neutrinos is considered as background in the detector and should be discarded with filtering algorithms and dedicated predefined cuts in order to increase the sensitivity to cosmic neutrinos. However, upward going atmospheric neutrinos are an irreducible background in the detector. Their flux is several orders of magnitude smaller than atmospheric muons as it is shown in Figure 2.13. As cosmic neutrinos have hard spectrum ( $\frac{dN}{dE} \propto E^{-2}$ ) [28], in contrast with the atmospheric neutrinos ( $\frac{dN}{dE} \propto E^{-3.7}$ ) [29], the neutrino energy could be used to eliminate atmospheric neutrinos (this will be discussed in Chapter 4).



**Figure 2.13** – Flux of atmospheric muons and muon induced by atmospheric neutrinos at 2300m water equivalent depth. In the downgoing direction ( $\cos\theta > 0$ ) the atmospheric muon flux is about  $10^6$  times higher than the neutrino-induced muon flux. The maximum near  $\cos\theta=0$  in the neutrino induced muon spectrum reflects the increased probability of meson decay close to the horizon.

### 2.3.5 Trigger and DAQ systems

#### Data acquisition

The overall data rate being too heavy to be fully written on disk, filtering algorithms must be applied on-line to discard as much as possible the background and save as much as possible the signal events. Several filtering algorithms can be applied depending on the optical background rate, but the basic idea is to search in all directions a time sequence of hits compatible with the passing of a relativistic particle emitting Cherenkov radiation. This is done on shore with a trigger elaborated to process all data coming from the detector in quasi real time [30]. These hits are causally related in time and position, while time-position of hits produced by  $^{40}\text{K}$  decays or bioluminescence are uncorrelated (caused by random processes).

The aim of the trigger is to select correlated hits in the ARS data stream for digitization<sup>3</sup>, readout and transfer to the on-line data processing system on shore. Once the signal has been digitized in the ARS, it is sent to the Data Acquisition (DAQ) board for storage. The DAQ board collects data and sends them to the shore via an Ethernet port. Then, the characteristics of the hits are evaluated in order to discard most background hits, resulting in reduction of data rate by a factor of at least  $10^4$ . Off-shore, the ARS data are organized in data frames. All frames that belong to the same time window are sent to the same processor in the processing farm, as sketched in Figure 2.14. The program buffers the frames in a queue to handle transmission delays in the network. When all frames of a particular time window have been collected, they are passed to the trigger algorithm. The complete collection of frames is referred to as a *time slice*. The time and charge of all hits in the data are determined using the known calibration constants of the detector (see section 2.3.6).

#### Trigger algorithms

The first level of trigger is a simple threshold of about 0.3 photo-electron<sup>4</sup> (pe) equivalent charge applied to the analog signal of the PMT. The corresponding digital data (time and charge) are then referred to as L0 hits.

The detection of two coincident photons by the same PMT generally results in a single hit with a charge that corresponds to  $\simeq 2$  pe. This is unlikely to happen as the result of random background hits, which are mainly produced by single photons and consequently have a charge that corresponds to a single pe. Therefore, the second level of trigger (L1) searches for hits with a large charge (greater than 3 pe or 10 pe depending on the detector's configuration), or

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<sup>3</sup>Because of the length of the optical link to the shore, electrical signals cannot be transmitted in analog form, thus they must be formatted by the ARS.

<sup>4</sup>Equivalent to 45mV.

alternatively for coincidence of hits in the same storey (but different OMs) within 20 ns, (i.e. local coincidence of L0 hits). The time window of 20 ns accommodates the difference in OM positions, uncertainties in the time calibration and some light scattering.

The two most frequently used algorithms both use L1 hits as a starting point:

- The 3N trigger looks for causality relations in space-time between different "L1 hits" in  $\pm 2.2\mu\text{s}$  time window<sup>5</sup>, roughly corresponding to the muon transit time across the detector. A minimum of 5 L1 hits (so at least 10 pe) in coincidence is required to write the event on disk, that is the overall L0 hits sequence during the  $\pm 2.2\mu\text{s}$  time window. The efficiency of the trigger (for the 12 line configuration) rapidly grows with the number of pe in the event. It reaches almost 100% for 40 detected photo-electrons. The purity of this filtering is evaluated at 90% by Monte Carlo simulations.
- The T3 filtering [31] condition can be added in case of low optical background. This algorithm is more open and therefore accepts more background hits, but allows for more efficient shower recognition. Instead of looking for hits that are causally connected, one searches for a T3 trigger cluster within a time window of  $\pm 2\mu\text{s}$ . A T3 trigger cluster is defined as the occurrence of at least 2 L1 hits in two consecutive storeys within a coincidence time window. This time window is 100 ns in the case that the two storeys are adjacent, and 200 ns in the case of next to adjacent storeys.

In this context, it is important to mention that only the 3N trigger will be used in the results obtained with 2007 data presented in Chapter 4. However, in the results obtained with 2009-2010 data presented in Chapter 5 we use the T3 and 3N triggers.

### 2.3.6 Detector calibration and electronics

The precision on the muon track reconstruction (i.e., its time and its direction) requires a precise measurement of the arrival time of the photon, the position of the PMTs, the charge of the hits and the threshold voltage for the readout of the PMTs by associated front end electronics. These PMTs have been calibrated on-shore prior to the deployment. Below, we concentrate on the *in-situ* calibration system of the time and the PMT position. For the threshold and charge calibration, see for example [32].

#### Time calibration

ANTARES is designed to achieve an angular resolution smaller than  $0.3^\circ$  for muons above 10 TeV. This pointing accuracy is closely related to the precision in the determination of the

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<sup>5</sup>More precisely  $2.2\mu\text{s}$  before the time of the first L1 hit up to  $2.2\mu\text{s}$  after the last L1 hit.



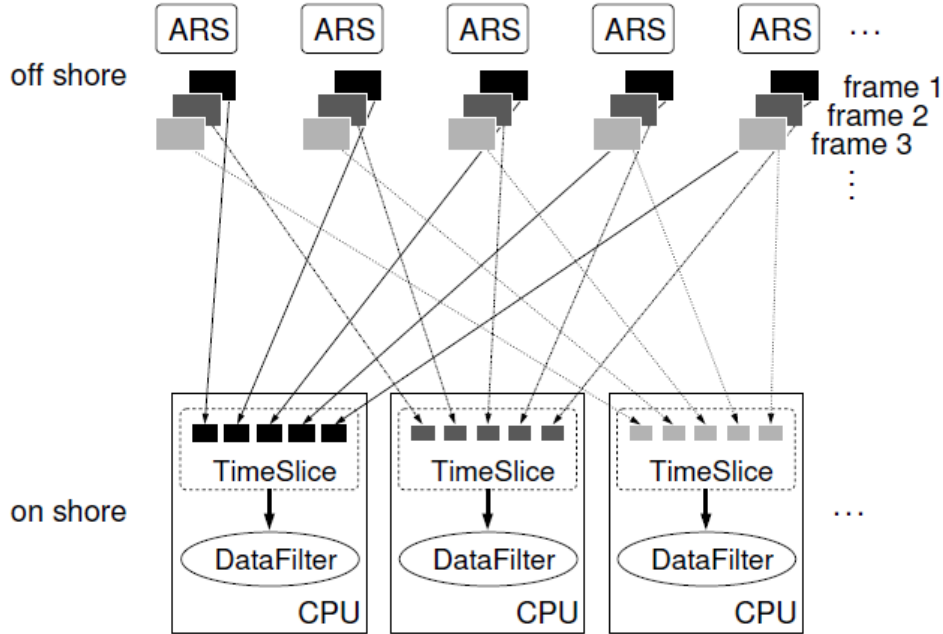


Figure 2.14 – A schematic view of the data collection on shore.

arrival time of the Cherenkov photons at the PMTs. Thus, a time calibration of the detector is necessary [33]. The calibration system includes a 20 MHz reference master clock on shore, LEDs installed inside each OM and Optical Beacons (OBs), equipped with LED or laser devices. The clock system provides a common signal to synchronize the readout of the OMs. Signal received from shore are converted and decoded by an electronics board inside the LCM and are then distributed over an electrical bus to the ARS chips. The relative offset of each local clock can be measured by using a calibration signal sent by the master clock and echoed back. The clock system assigns an absolute event time with a GPS master clock synchronization accuracy of  $100 \mu\text{s}$ .

The optical beacon system is used to calibrate the relative offsets between the PM tubes. Four blue (472 nm) LED beacons on storeys 2, 9, 15 and 21 of each detector line and two green (592 nm) laser beacons on the BSS of L7 and L8 are used for this purpose. The LED beacons are used for intra-line calibration purposes while the laser beacon, being much more powerful and able to illuminate all the lines, is used for inter-line calibration. An initial set of time offsets is determined in the laboratory prior to deployment. After deployment, these values may change due to different factors such as temperature changes or stresses in the cables. Using the optical beacon system they are monitored every month and readjusted as necessary. A

second calibration system consisting of a blue (470 nm) LED inside each OM is used to measure time offsets between the PM tube photo-cathode and the read-out electronics. Internal LED and optical beacon measurements reveal less than 0.5 ns contribution of the electronics to the photon arrival time resolution. Thus, time resolution is dominated by the transit time spread of the PM tubes which is about 1.5 ns, and light scattering and chromatic dispersion, which depends on the distance travelled by the photon. The calibration system just described provides a relative time calibration of better than 1 ns.

### Position calibration

The optical modules are hanged to strings that are freely floating in the sea water. Thus, orientations and positions of each PMT should be measured at every moment to enable their monitoring. This is done, every two minutes, by an acoustic system which is set up on the BSS of each string. A pulse of frequency 40-60 kHz is sent by an acoustic transmitter held on the BSS and is received by the hydrophones situated on each sector along the line allowing a real time localization in space of the OMs by triangulation. The orientation of each optical module frame is measured by a compass and a tilt-meter located inside the LCM container. Together, measurements from the tilt-meters, compasses and acoustic system provide a measurement of the relative position of the OMs with an accuracy of 10-20 cm [34].

## 2.4 Data quality

The selection of data is based on some quality criteria. Each run is tagged by some quality parameters that are stored in the ANTARES data base. The main flags are the 'SCAN' and the Quality-Basic (QB) flags. The former allows to check the run setup of each run as some of them are not write-protected in the database thus they may have been modified during the data taking. In this analysis we select all physics runs which have run setup protected against writing "*SCAN*  $\neq$  1". The second parameter allows to define some crude criteria in order to determine the quality of the data. It can takes the following values (1, 2, 3 and 4), where each number stands for:

- QB = 1 : Defined to perform a basic selection, minimum requirement for a run to be included in the analysis.
- QB = 2 : It requires that at least 80% of the OMs expected to work at the time of the run are effectively working.

- QB = 3 : It requires a mean baseline rate over all active PMT  $\leq 120$  kHz AND a burst fraction  $\leq 40\%$ .
- QB = 4 : Same condition on baseline as in QB = 3 AND a burst fraction  $\leq 20\%$ .

The baseline rate, in kHz, represents the most probable counting rate of a given OM computed from the rate distributions (number of hits divided by the frame duration) in each PMT over the whole (typically few hours long) run. For one PMT the baseline is extracted from a gaussian fit on the left part of the distribution of the rates measured every 15 mn. The burst fraction, in percent, corresponds to the fraction of time during which the OM counting rates are larger than 20 % above the baseline rate [35].

For the analysis of 2007 (2009-2010) data presented in Chapter 4 (Chapter 5) we require a minimum QB value of 3 (1). Requirements about the external conditions (e.g. baseline, burst fraction and sea current), the configuration and behaviour of the detector during a given run (e.g. number of active units, L1 thresholds, alignment), and the properties of the run itself (e.g. duration, number of slices, trigger rates) can also be taken into account for the selection of runs.

## 2.5 Simulation chain

Simulation tools are one of the main ingredients needed to assess the performances of the detector. The simulation chain basically starts with the physics processes occurring in the atmosphere, Earth and underground, that can lead to the production of some detectable light in the detector, taking into account the probability of each process to occur. It also mimics the detector response to these processes. The particles that are simulated are the atmospheric muons and neutrinos induced by interactions of cosmic rays with the Earth's atmosphere, and cosmic neutrinos.

### 2.5.1 Simulation of high-energy neutrinos

These particles are generated using the program GENHEN [36]. The code generates a flux of neutrinos with uniformly distributed directions, within a zenith angle range  $[\theta_{min}, \theta_{max}]$  and according to an arbitrary user input spectrum  $E_\nu^{-\Gamma}$ . The choice adopted in this work is  $\theta \in [0, \pi]$ ,  $\Gamma = 1.4$  and  $E_\nu \in [10^2, 10^8] GeV$ . GENHEN first generates the neutrino position, direction and energy. Neutrino interactions are simulated with LEPTO [37] for deep inelastic scattering (DIS) and RSQ [38] for resonant and quasi-elastic scattering (QES). The secondary particles resulting from the interaction that are able to produce detectable light are stored

## 2.2.5 Simulation chain

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for further usage. We introduce a volume within which the Cherenkov light is generated (see section 2.5.3), named *the can*. A schematic view of the can is shown in Figure 2.15.

The simulated flux of neutrinos arriving at the Earth is given per units of energy  $dE$ , solid angle  $d\Omega$ , area  $dS$  and time  $dt$  by the following relation:

$$\frac{d\Phi_\nu^{sim}}{dE_\nu d\Omega dS dt} = \frac{N_{total}}{t_{gen} V_{gen} I_\theta I_E E^\Gamma} \frac{1}{\sigma(E_\nu) \rho N_A} \frac{1}{P_{Earth}(E_\nu, \theta_\nu)} \quad (2.14)$$

where:

- $N_{total}$  is the total number of generated events.
- $\Gamma$  is the generation spectral index.
- $t_{gen}(s)$  is the arbitrary duration covered by the simulation.
- $V_{gen}(m^3)$  is the total generation volume of the Cherenkov light (in water equivalent units in this case)
- $I_E$  is the energy phase space factor. It depends on the  $\Gamma$  chosen value:

$$I_E = \begin{cases} \frac{E_{max}}{E_{min}} & \text{if } \Gamma = 1 \\ \frac{E_{max}^{1-\Gamma} - E_{min}^{1-\Gamma}}{1 - \Gamma} & \text{otherwise} \end{cases}$$

- $I_\theta(sr) = 2\pi \times (\cos(\theta_{max}) - \cos(\theta_{min}))$  is the angular phase space factor corresponding to the specified range of  $\cos(\theta_\nu)$ .
- $\sigma(E_\nu)(m^2)$  is the charged current neutrino interaction cross-section.
- $\rho N_A(m^{-3})$  the number of target nucleons per unit volume.
- $P_{Earth}(E_\nu, \theta_\nu)$  is the probability of transmission through the Earth for a neutrino of given  $E_\nu$  and  $\theta_\nu$ .

For a given flux model  $\frac{d\Phi_\nu^{model}}{dE_\nu d\Omega dS dt}$  each event is reweighted by the ratio of two fluxes at the point  $(E_\nu, \theta_\nu)$ . That is, the event weight is defined as follow:

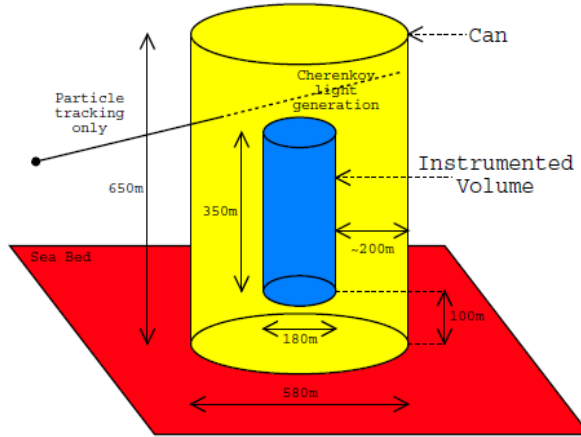
$$w_{event} = \frac{d\Phi_\nu^{model}}{dE_\nu d\Omega dS dt} \times \left( \frac{d\Phi_\nu^{sim}}{dE_\nu d\Omega dS dt} \right)^{-1} \quad (2.15)$$

## CHAPTER 2. NEUTRINO TELESCOPES

The same sample of neutrinos, initially generated following a  $E^{-1.4}$  spectrum, can be re-weighted using any user specified spectrum by assigning a different weight to each event,  $w_{event}$ . Three weighting parameters are introduced in the ANTARES convention of Monte Carlo simulations [39]. First, the weight  $w1$  contains the projected area of the can onto the plane perpendicular to the neutrino direction. Second, the weight  $w2$ , is equal to  $\frac{N_{total}}{t_{gen}} \times \left( \frac{d\Phi_{\nu}^{sim}}{dE_{\nu}d\Omega dS dt} \right)^{-1} \times F$ , where  $F$  is the number of second per year. It has units  $\text{GeV} \cdot \text{m}^2 \cdot \text{sr} \cdot \text{s} \cdot \text{year}^{-1}$ . Third, the global weight  $w3$  equivalent to  $w_{event}$ , is defined as follows:

$$w3 = w2 \times \frac{d\Phi_{\nu}^{model}}{dE_{\nu}d\Omega dS dt} \quad (2.16)$$

where  $\frac{d\Phi_{\nu}^{model}}{dE_{\nu}d\Omega dS dt}$  is the differential flux of neutrinos before penetrating the Earth, in unit of  $\text{GeV}^{-1} \cdot \text{m}^{-2} \cdot \text{sr}^{-1} \cdot \text{s}^{-1}$ . The global weight  $w3$  has unit of  $\text{year}^{-1}$  which can be understood as "rate" per year.



**Figure 2.15** – Schematic view of the can, surrounding the instrumented volume.

### 2.5.2 Simulation of atmospheric muons

Apart from neutrinos, only atmospheric muons, as secondaries from hadronic showers, with energies typically above 500 GeV (1TeV) at the sea level can reach the detector (at a depth larger than 2000 m) for zenith angle  $< 60^\circ$  ( $> 60^\circ$ ) while the others are absorbed. The surviving events at sea level are characterized by a certain energy, direction and muon multiplicity. ANTARES Collaboration uses two independent approaches to simulate this atmospheric muon background:

**Full simulation package:** The program named CORSIKA<sup>6</sup> [40] is used to simulate high energetic primary cosmic radiation (protons,  $\alpha$  particles and heavier nuclei) interactions in the atmosphere and the propagation of the secondary particles to sea level. Most of the particles emerging from these interactions are pions and kaons. The primary cosmic ray flux is generated following a diffuse flux  $dN/dE \propto E^{-\Gamma}$  which allows a later re-weighting with a user specified flux model. CORSIKA offers the choice of the cosmic ray flux and their model of interactions in the atmosphere. To minimize the CPU time, the ANTARES collaboration has chosen to split the flux of the primary cosmic rays into 5 groups including the most abundant particles: proton, helium, carbon, magnesium and iron nuclei in an energy range from few TeV to  $10^2$  PeV and zenith range from  $0^\circ$  to  $85^\circ$ . Secondary particles such as photons, leptons, mesons and nuclei are also propagated to sea level. The development of the hadronic shower in the atmosphere is simulated with the QGSJET01 model [41]. In the analysis presented in chapter 4 we use the Battistoni parametrization of the primary cosmic rays [42]. CORSIKA allows to compare at each step the results of the simulation with data from other experiments which permits a well control of the systematics.

For the propagation of muons from sea level to the detector, the ANTARES collaboration uses the MUSIC<sup>7</sup> package [43]. MUSIC takes into account the interaction processes of muons with matter, i.e. bremsstrahlung, multiple scattering, ionization and pair production (see section 2.2.4). The energetic losses of muons can be modeled by the formula Equation (2.8). Ionization can be considered as a continuous process. As such, it is treated identically over the whole energy range, while the other processes are treated differently when a huge energy loss is induced. Energy losses are thus split into two parts: continuous energy losses (calculated with the Bethe-Bloch formula) and stochastic losses. These latter processes are taken into account when the fraction of energy lost by the muon is greater than  $10^{-3}E$ . In MUSIC, muons are deflected by the three processes quoted above except ionization.

**Fast simulation package:** This program named MUPAGE<sup>8</sup> [44] is based on a predefined parametrization of muon flux measured by several experiments. The parameters include the depth (from 1.5 km to 5 km, the zenith angle  $\theta$  and, for muon showers, the multiplicity  $m$  and the distance of each muon with respect to the direction of the shower). The parametrization has been extracted from the full simulation package HEMAS [45, 46] and the hadronic interaction models were simulated using the DPMJet model [47]. MUPAGE generates events for a user specified data acquisition time, in such a way that no further weighting is needed. This

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<sup>6</sup>COsmic Ray SImulation for KAscade

<sup>7</sup>MUon SImulation Code

<sup>8</sup>Atmospheric MUons from PArametric formulas: a fast GEnerator for neutrino telescopes

simulation provides the best data/MC agreement, hence it is used for the results presented in the Chapter 5.

### 2.5.3 Simulation of the Cherenkov light

The propagation of muons and electrons in water results in the emission of Cherenkov photons. Those are simulated using KM3 [48] and GEASIM codes. The former simulates the propagation of muons using the MUSIC package, the light and secondary particles emitted by these muons. The latter, generates the hits at the OMs by means of a full GEANT (version 3.21) simulation of photon production. In contrast of KM3, GEASIM neglects the photon scattering, thus it assumes their direction as a straight line. This assumption makes GEASIM faster than KM3. Hereafter we concentrate on the KM3 code which simulates the Cherenkov light from muons and electromagnetic showers in three steps:

1. **GEN**: includes a complete GEANT3 simulation of the Cherenkov light. It generates photons produced from short muon track segment (typically one meter) and electromagnetic showers. The Cherenkov photons (direct and scattered) are traced individually through water until absorption takes place. Their positions and times are recorded at concentric spheres of various radii centered on the origin of emission. The program output consists of some tables containing all the photons recorded at each spherical shell.
2. **HIT**: uses the output tables described above to create the hit distributions at the OMs for muon track segments and electron showers. The photon probabilities are computed taking into account the optical properties (absorption and scattering length and refractive index) measured at the ANTARES site [49]. Positions and times of arrival of photons at each OM are stored and used to convert the hit probability into photo-electron number using Poisson statistics. During this step, the orientation of the PMT with respect to the track direction, the position of the lines are taken into account.
3. **KM3MC**: At this level, the propagation of the muons already generated at the can surface is performed. It takes as input the detector description and uses the photon tables to calculate the number of photo-electrons produced in each PMT and their arrival time. Segments of about 1m are examined step by step taking into account the energy losses of the muon. If the energy lost by the muon is greater than the mean energy lost by ionization an electromagnetic shower is produced along the segment. This electromagnetic shower is treated independently using the table of electrons.

Both GEN and HIT programs are run only once to generate the relevant tables of OM hit

probabilities. These tables are then stored on disk for subsequent use by KM3MC which is the program the end-user is most likely to use.

### 2.5.4 Generation of the optical background

The ANTARES neutrino telescope is located in an environment of high optical background produced by  $^{40}\text{K}$  and bioluminescence at rates of about 100kHz per OM. The triggerEfficiency program [50] generates the background hits at the OMs according to the rates found in the raw data files. Then, it applies the same trigger criteria as for data to select candidate events in the Monte Carlo samples.

### 2.5.5 MC run by run approach

Recently the ANTARES collaboration has adopted a new Monte Carlo simulation approach in order to reproduce more realistic conditions of data taking following a run-by-run strategy [51]. The input information (run setup, mean rates, position and orientation of OMs, time and charge calibrations, ARS threshold and run duration) are taken from the data themselves and plugged into the simulation. This approach calls the simulation codes described in section 2.5.

Practically,  $5 \times 10^8$  neutrinos are simulated using GENHEN package in the energy range of 100 GeV and 100 PeV. To simulate downgoing atmospheric muons we generate one tenth of the statistics of the corresponding data run using MUPAGE. The run-by-run MC simulation approach is used in the analysis described in Chapter 5.

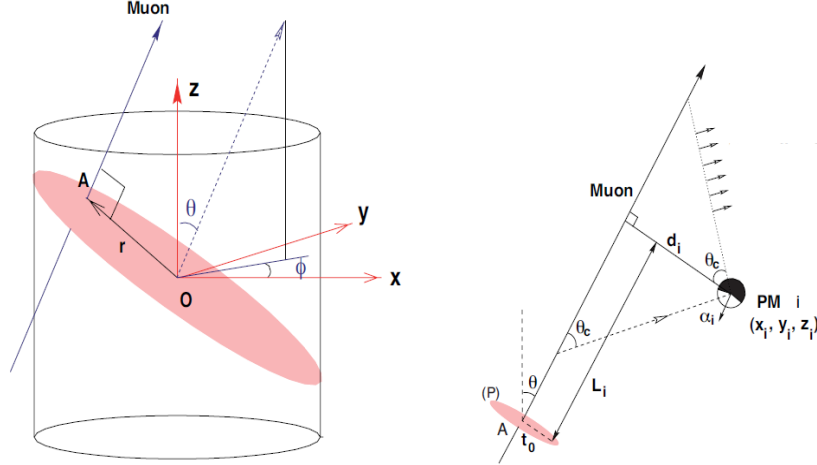
## 2.6 Track reconstruction algorithm

The track reconstruction consists of finding values for the free parameters in the assumed model which most likely caused the outcome of the measurement. In the case of muon track reconstruction, the basic model is a straight line passing through the detector along which a muon moves with the speed of light producing a Cherenkov light on its way as shown in Figure 2.16 (right). The reconstruction takes a set of PMT hits within the three OMs on each storey of each string and deduces the best set of values for the track parameters that are, at a given time  $t_0$ , the position  $\vec{p} = (x, y, z)$  and direction  $\vec{d} = (\sin(\theta)\cos(\phi), \sin(\theta)\sin(\phi), \cos(\theta))$  of the muon. By convention, the time  $t_0$  is defined as the time when the muon passes through the plane perpendicular to its direction and containing the centre of gravity of the detector (see Figure 2.16 on the left).

The muon trajectory is then characterized by  $N_{parameters} = 5$  independent parameters that must be estimated by a given reconstruction algorithm. In practice, an analytical expression



which connects the photon arrival times  $t_i^{th}$  to the track parameters is used:



**Figure 2.16** – Schematic view of the reconstruction strategy. Left: the geometrical description of the *can* and the coordinates used for the reconstruction. Right: the geometrical structure of the muon track induced by a muon-neutrino: definition of variables.

$$t_i^{th} = t_0 + t_{trans} + t_{trav} \quad (2.17)$$

where  $t_{trans}$  is the time it takes for the muon to reach the point where the light is emitted and  $t_{trav}$  is the time it takes for the photon to travel from that point to the OM. Using Figure 2.16 it follows:

$$t_{trans} = \frac{L_i}{c} - \frac{d_i}{c \tan(\theta_c)}$$

$$t_{trav} = \frac{d_i}{v_g \sin(\theta_c)}$$

where  $c$  is the velocity of light in vacuum and  $v_g$  is the group speed in water [52].

In the following we describe the two main reconstruction algorithms adopted by the ANTARES collaboration and used in this thesis. These methods assume that only a single muon crosses the detector. Therefore atmospheric muon bundles will be worse reconstructed and consequently removed by quality cut criteria.

### 2.6.1 In-situ reconstruction algorithm

The fast reconstruction algorithm called BBfit [53], convenient for the online use has been developed as a robust reconstruction method, which produces reliable results without precise

## 2.2.6 Track reconstruction algorithm

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positioning calibration. Its strict hit selection leads to an accurate up-down separation while keeping a good efficiency. In BBfit, the exact geometry of the detector is ignored: the detector lines are straight (i.e lines are supposed unaffected by the sea current) and the 3 OMs of each storey are considered as a single OM centered onto the string. Thus, the hits altitude corresponds to the altitude of the optical modules.

As the first step, time and charge calibration (see section 2.3.6) is applied, the calibrated hit times and amplitudes being given in units of nano-seconds and photo-electrons (pe) respectively. For the selection of hits the algorithm uses the same criteria as those of the T3 trigger (see section 2.3.5). The algorithm requests a coincidence of 2 "L1 hits" in two adjacent floors (next-to-adjacent floors) within 80 ns (160 ns). Then, all hits of the same floor, in coincidence within 20 ns, are merged into one single hit. The time of the merged hit is the earliest time of the participating hits, and the charge is the combined charge of all merged hits. These merged hits are used for the reconstruction. The quality of the reconstruction is measured by a modified- $\chi^2$  function, given by the Equation (2.18):

$$\chi^2 = \frac{Q}{N_{dof}} \quad (2.18)$$

where  $N_{dof} = N_{hit} - N_{parameters}$  is the degrees of freedom,  $N_{hit}$  is the number of merged hits used in the fit, and

$$Q = \sum_{i=1}^{N_{hit}} \left[ \frac{\Delta t^2}{\sigma_i^2} + \frac{q(q_i)d(d_{fit})}{\langle q \rangle d_0} \right] \quad (2.19)$$

where  $\sigma_i$  is the timing error introduced to take into account the applied geometrical approximation and the occasional presence of late hits from small angle scattering or from electromagnetic processes. Its value is set to 10 ns for  $q_i > 2.5$  pe and to 20 ns otherwise. The first term is a time residual, it exploits the difference time  $\Delta t = (t_\gamma - t_i)$  between the hit time  $t_i$  and the expected arrival time of the photons  $t_\gamma$  from the muon track. The second term exploits the fact that an accumulation of storeys with high charges is expected on each detector line at its point of closest approach to the track. It depends on the measured amplitude  $q_i$  and the theoretical distances traveled by the detected photon  $d_{fit}$ . The chosen form gives an empirical penalty to the combination of high charge and large distance. The term  $q(q_i) = q_0 q_i / \sqrt{q_0^2 + q_i'^2}$  is the amplitude of the hit corrected for the angular acceptance of the floor, i.e.  $q' = 2q_i / (\cos(\theta_\alpha) + 1)$ , where  $\theta_\alpha$  is the inclination of the photon track to the detector line, with an artificial saturation at 10pe. The term  $d(d_{fit}) = \sqrt{d_{fit}^2 + d_1^2}$  is protected against small distance travelled by photons. One can assume the constant  $q_0 d_1$  to be around  $50\text{m} \times \text{photoelectron}$  since the intensity

of the Cherenkov light decreases with the distance. The product  $q.d$  is divided by the average corrected amplitude  $\langle q \rangle$ , calculated from all hits which have been selected for the fit, to compensate for the fact that more energetic tracks or showers will produce more light at the same distance. The normalization  $d_0$  balances the weight between the two terms. The value of  $d_0$  has been chosen to be 50m, which is motivated by the fact that at this distance the typical signal in a PMT which points straight into the Cherenkov light front is of the order of one photoelectron.

The same quantity defined in Equation (2.18) is used to estimate a track or a shower (bright point) reconstruction parameters. The two cases differ in the way of calculating the expected arrival time of the photon at the PMT.

In the BBfit algorithm, events are split into four kinds: track reconstructed with a single line, track reconstructed with multiple lines, shower reconstructed with a single line and shower reconstructed with multiple lines. In the case of a single line reconstruction the azimuth information is lost leading to the estimate of only four parameters.

**The azimuth degeneracy:** In the case of tracks reconstructed using only two detector lines, an ambiguity is introduced on the reconstructed azimuth angle of the track,  $\phi_{rec}$ . Thus two muon tracks are reconstructed both having the same zenith angle but different azimuth angle. The distribution of the hit times of the true track and of the track obtained by mirror symmetry with respect to the plane connecting the two lines, are identical. An illustration of this degeneracy is shown in Figure 2.17. The azimuth of the reconstructed original and mirror tracks are connected in the following way:  $\phi_{mirror} = 2\phi_{lines} - \phi_{track}$ , where  $\phi_{lines}$  is the azimuth angle of the plane connecting the two lines.

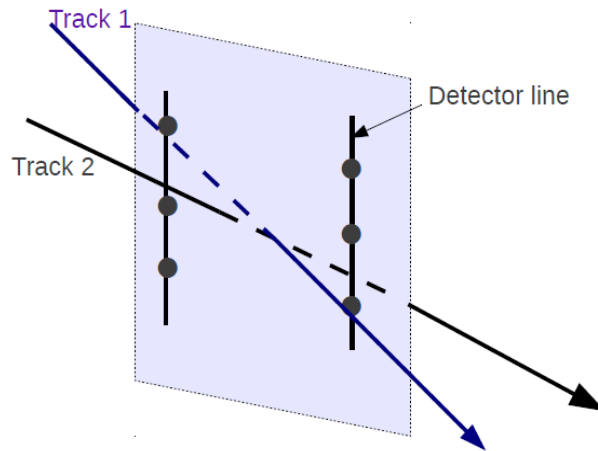


Figure 2.17 – Illustration of the azimuth degeneracy

## 2.2.6 Track reconstruction algorithm

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The version of BBfit used in this thesis is *v3r6*. In this version we added the coordinates of the mirror track (named hereafter  $\text{track}(\phi_{\text{mirror}})$ ) in addition to the original one (named hereafter  $\text{track}(\phi_{\text{track}})$ ). Previous versions provided only one solution randomly chosen among the two mirror tracks. This additional information permits to compare the *best*=Min( $\text{track}(\phi_{\text{track}}), \text{track}(\phi_{\text{mirror}})$ ) and the *random* (the one chosen randomly among the two solutions) track. Further details are presented in Chapter 4.

The choice between the tracks cannot be based on the  $\chi^2$  value since it is the same for both solutions. Thus to resolve the azimuth degeneracy, an intermediate reconstruction step was later introduced to BBfit. It consists of a temporary selection of all (raw) hits with time residuals less than 30ns for both tracks, over the whole detector. The sum of the charges of the two sets of selected hits is calculated and the track corresponding to the highest value is considered to be the correct one. The results presented in this thesis were completed before the implementation of this degeneracy breaking.

**Bright point:** When an electromagnetic or a hadronic shower is produced, it develops itself over a distance small compared to the spacing between detection storeys. As a consequence, light appears as if it was emitted isotropically from a bright point, and expanding with a velocity  $v_g$ . The four bright point parameters are therefore defined by the position of the emission point  $\vec{P} = (x_0, y_0, z_0)$  and the emission time  $t_0$ . The spherical envelop of the light can then be fitted based on the simple relation:

$$v_g(t_i - t_0) = \sqrt{(x_i - x_0)^2 + (y_i - y_0)^2 + (z_i - z_0)^2}$$

where  $t_i$  are the hit times,  $x_i, y_i$  the fixed horizontal positions of the lines and  $z_i$  the altitude of the PMT fired by the hit  $i$ .

The  $\chi^2$  of Equation 2.18 is then referred to as  $b\chi^2$ . Both the track  $\chi^2$  and the bright point  $b\chi^2$  are used in the selection criteria of the final events to reject background: well reconstructed muons have a good  $\chi^2$  but poor  $b\chi^2$  in contrast of background events.

### 2.6.2 Off-line reconstruction algorithm

A second more sophisticated and complex algorithm for the reconstruction of muon tracks, so-called Aafit, is based on the maximum likelihood method. Its full description is given in [54]. It consists of several stages:

**Pre-selection of hits:** This step allows to keep as much as possible hits that are most likely originating from a muon. The hits selected should verify the causality criterion given by the

following relation:

$$\Delta t_{ij} \leq \frac{d_{ij}}{v_g} + 20ns \quad (2.20)$$

where  $\Delta t_{ij}$  is the time difference between a hit  $i$  and the hit  $j$  with the largest amplitude, and  $d_{ij}$  is the distance between the OMs of the two hits. Hits with larger time differences cannot be related to the same muon, unless they have a residual larger than the safety factor 20ns [55], which is unlikely.

In order to reduce the impact of PMT afterpulses on the reconstruction, all the hits selected on the same OM using Equation (2.20) are merged within a time window of 300ns.

**Pre-fit:** The reconstruction procedure starts from a linear pre-fit based on the L1 hits, in order to provide a robust starting point for the further fitting procedure. At this stage, Aafit assumes that the hits occur on points that are located on the muon track, which allows to derive analytically a starting point from the minimization of the  $\chi^2$ , although with a poor precision.

**M-estimator fit:** The M-estimators are a broad class of functions that allow parameter estimation even when the probability distribution that defines the problem is not exactly known. They are referred to as robust estimators when the result is insensitive to small variations of the underlying distribution assumed. The robustness of the M-estimator fit allows better estimate of a set of track parameters, using the residual  $\Delta t_i$ , and reduces the influence of outlier hits.

The output parameters of the prefit are used as seed in the M-estimator fit procedure which considers a sub-set of hits within 100m around the track estimated by the prefit and within a time window  $\pm 150ns$  of the photon arrival times or a charge  $\geq 2.3pe$ . The function that is maximized to estimate the track parameters is:

$$M = \sum_i \lambda \left( -2\sqrt{1 + A_i \frac{(t_i - t_i^{th})^2}{2}} \right) - (1 - \lambda) f_{ang}(\alpha_i) \quad (2.21)$$

where  $A_i$  is the hit amplitude,  $f_{ang}$  is the angular acceptance of the PMT as a function of the incident angle of the photon (with respect to the PMT axis)  $\alpha_i$ . The  $\lambda$  parameter is set to 0.05 as the result of a Monte Carlo based optimization.

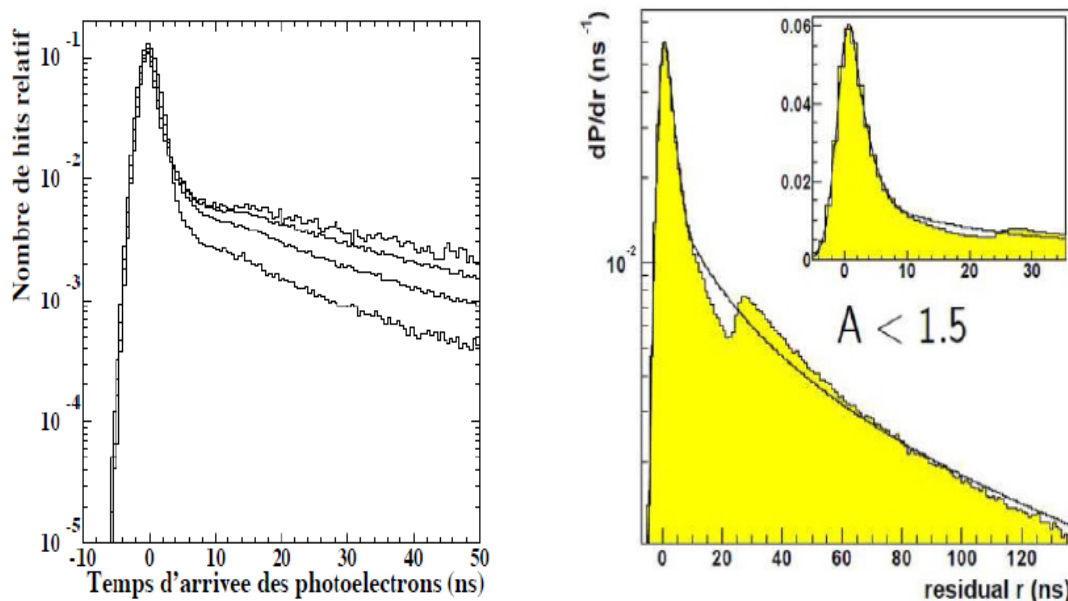
**The maximum likelihood fit:** The final fit procedure uses the principle of Maximum Likelihood (ML). It evaluates the theoretical arrival time of the photon at the OM  $i$ ,  $t_i^{th}$ . Thus the time residual  $\Delta t_i = t_i - t_i^{th}$ , between the measured time and the expected time of the photon, is used to calculate the probability that the photon comes from the track. The track fitter searches for event direction for which the likelihood  $\mathcal{L}$  takes maximum value. Under the

## 2.2.6 Track reconstruction algorithm

muon-like event assumption the following likelihood is calculated:

$$\mathcal{L} = \prod_i P(t_i | t_i^{th}) \quad (2.22)$$

Here  $P(t_i | t_i^{th})$  is the statistical probability of observing  $t_i$  with the expectation of  $t_i^{th}$ . The probability of a hit with a certain residual  $\Delta t_i$  is described by a Probability Density Function (PDF). This PDF is a combination of a signal PDF and a background PDF. The first step



**Figure 2.18** – Distributions of the time residuals used in the ML fit. Left: The curves correspond to four different muon energies, from the top to the bottom: 250, 50, 10 and 2 TeV. These PDFs do not take into account the background hits. The one used in the fit is the one for 10 TeV events. Right: An example of the full PDF used in final ML fit step for hit amplitudes  $< 1.5$ pe. In yellow the histogram obtained by the Monte Carlo, the solid line is the parametrization used by the likelihood fit

of the ML fit is done using a signal only PDF as shown in Figure 2.18 (left). It takes into account the smearing on the hit times introduced by the transit time spread of the PMTs, which impacts the width of the peak around zero, and the scattering of light in water, which causes the long tail at positive values. An unphysical tail is present at values  $< -5$ ns, which was introduced to render the PDF differentiable at negative values. In this step hits with residual  $\Delta t_i \in [-0.5R, R]$ , where  $R$  is the root mean square of the residuals used in the M-estimator, are taken into account. Hits that are part of a coincidence or that have an amplitude larger than 2.5 pe are also selected.

The M-estimator and ML fit steps are repeated 9 times with some initial parameters inferred

## CHAPTER 2. NEUTRINO TELESCOPES

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from the pre-fit. Four starting points are obtained by rotating the pre-fit track by  $25^\circ$ . The rotation is done around the track point which is closest to the center of gravity of the selected hits. Four more trials are obtained by translating the starting point of the track by  $\pm 50$  m in the direction  $\vec{d} \times \hat{z}$  (where  $\vec{d}$  is the track direction) and by  $\pm 50$  m in the direction of  $\hat{z}$ . Among the 9 trials, the track with the best likelihood is stored. The number of the trials,  $N_{comp}$ , giving rise to compatible solutions (i.e with direction within  $1^\circ$  similar to the stored one) is used later in the analysis, as quality selection criterion.

The final fit uses an improved PDF using hits with time residual of  $\pm 250$  ns (in order to add background hits), local coincidences and hits with amplitude larger than  $2.5\text{pe}$ . An example of distribution of this PDF is shown in Figure 2.18 (right). At the output, the algorithm provides two quality parameters of the track. The first given by:

$$\Lambda = \frac{\log \mathcal{L}}{N_{dof}} + 0.1(N_{comp} - 1) \quad (2.23)$$

where  $N_{dof} = (N_{hits} - N_{parameters})$  is the number of degrees of freedom used in the fit. The second term acts as an ad hoc reward for fits with  $N_{comp} > 1$ . The second quality parameter is the angular error estimate,  $\beta$ , of the reconstructed track. This quality parameter is obtained from the fit of the likelihood and is given by:

$$\beta = \sqrt{\sigma_\theta^2 + \sin^2 \theta \sigma_\phi^2} \quad (2.24)$$

where  $\sigma_\theta$  and  $\sigma_\phi$  are the error estimates of the track's zenith and azimuth angles respectively. The use of these quality parameters for the event selection is studied in Chapter 5 for the data recorded during the 2009-2010 data taking period.

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# CHAPTER 3

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## GRAVITATIONAL-WAVE INTERFEROMETRIC DETECTORS

### 3.1 Summary

After the detailed review of neutrino astronomy with the ANTARES neutrino telescope given in the previous chapter, we review in this chapter the observational astrophysics possible with the gravitational wave detectors such as Virgo and LIGO. This chapter first gives an introduction to gravitational-wave astronomy from an instrumental point-of-view ranging from the general detection principles to the description of the instruments currently in operation. Being LIGO and Virgo very similar we will focus on the Virgo detector. The main part of this chapter offers an introduction to the analysis techniques for gravitational wave (GW) data.

### 3.2 Detection principle

The idea of using interferometry to detect gravitational waves was first proposed by two Russian theorists, M. Gertsenshtein and V.I. Pustovoit in 1962 [1]. The applicability of this idea was thoroughly studied by R. Weiss [2] and further by D. Drever [3] leading to the general design followed in today's instruments.

As we have seen in section 1.2.1, gravitational wave exerts a strain on space-time. It thus affect the distances between freely falling test particles. The idea is to sense this deformation thanks to ultra-precise laser interferometry. Let us consider a Michelson-type interferometer in which two laser beams propagate along two orthogonal arms of lengths  $L_1$  and  $L_2$ . An impinging GW is equivalent to a relative displacement of the end mirrors of the interferometer (used as test masses)  $\delta\ell \equiv L_1 - L_2$ . This is related to the GW amplitude  $h = \delta\ell/L$  where  $L$  is the interferometer arm length. The relative displacement of the test masses induces a

## CHAPTER 3. GRAVITATIONAL-WAVE INTERFEROMETRIC DETECTORS

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phase shift between the two interfering beams, measurable at the interferometer output with a photodetection. Three fundamental noises limit the accuracy of this measurement:

- **Seismic noise:** is a *displacement noise* which results from the vibration of the ground below the instrument. The noise comes from the global and large-scale motion of the tectonic plates (including the *micro-seismic* dominated by the interaction of the plates with ocean waves) and from the local anthropic activity. Seismic noise rises rapidly toward low frequencies and limits the sensitivity below 10 Hz. The seismic noise is reduced using suspension systems, as the Virgo *super-attenuator* (see section 3.3).
- **Thermal noise:** is also a *displacement noise* which originates from the Brownian motion of the atoms that compose the mirrors and their suspensions. To reduce this noise both are made of material with a high mechanical quality factor. This noise limits the sensitivity in the frequency band around 100 Hz (where the sensitivity is maximum) and therefore limits the observational horizon of the instrument.
- **Shot noise** is a *sensing noise* which results from the quantum fluctuation of light. Those fluctuations can be interpreted as fluctuations in the phase shift at the photo-detector, thus they can mimic the GWs. The effect of the shot noise is reduced by increasing the number of photons in the interferometer. This is why high-power lasers are used and light is “recycled” thanks to the technique of power recycling. Several kilo-Watts of light power is stored in the initial GW interferometers.

The impact of those three noises can be reduced to reach the accuracy of  $h_{noise} \sim 10^{-21}$ . Several instruments have reached this objective after many years of preparation and construction involving a large number of scientists and engineers coming from many countries. We will describe the Virgo detector in more details in the next section. A next generation of instruments is under way and expected for 2015. The objective is a ten-fold improvement of the sensitivity over the first (and current) generation of instruments. This increases the accessible volume of the Universe (and hence the number of detectable sources) by a factor of 1000.

### 3.3 The Virgo detector

The Virgo interferometer [4] has been built by a collaboration between France and Italy. It is located near Pisa, Italy. The vertex of the Virgo detector is at elevation 53.238 m and at geographic coordinates  $43^{\circ}37'53''\text{N}$  and  $10^{\circ}30'16''\text{E}$ .

### 3.3.4 Response of a gravitational wave interferometer

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In short, Virgo consists in two orthogonal kilometric arms (3 km) illuminated by a laser source. The laser is a Nd:YAG with a wavelength  $\lambda_L = 1064$  nm and output power  $P \sim 10$  W in the initial Virgo design. An initial resonating optical cavity called *mode cleaner* performs both spatial filtering (“mode cleaning”) and frequency stabilization of the input beam. The cleaned laser beam is sent to the beam splitter which separates the light into two identical beams directed to the two arms. To increase the optical path length the interferometer arms are replaced by Fabry-Perot resonating optical cavities. A simplified scheme of Virgo interferometer is shown in Figure 3.1. The relative position of the mirrors of the cavity is controlled so that the light after one round-trip is coherent in phase with the in-coming light from the beam splitter. The equivalent number of round trips or *finesse* is determined by the transmissivity and reflectivity of the input mirrors as well as by their optical losses. The finesse is about 50 in the initial Virgo design. The light beam propagates in an ultra-vacuum system to protect it from air density fluctuations. The two beams recombine and interfere at the beam splitter. The interferometer is tuned on the *dark fringe* by a control system which adjusts the position of the end mirrors accordingly. In the absence of GWs, the small fraction of light power that constitutes the dark fringe goes to a photo-detector that measures its intensity, while all the light that circulates in the arms (bright fringe) is reflected by the beam-splitter back toward the laser. Here, a semi-reflective *power-recycling* mirror feeds the bright fringe back into the interferometer in phase with in the in-coming light from the main laser.

In summary, Virgo is composed of six main mirrors (four large input and end mirrors, the beam splitter and the power recycling mirror) [5] and four resonating optical cavities (mode cleaner, two in the arms and the power recycling cavity). The main optics in the arms are mirrors of 350mm diameter, 100mm thickness and 20kg mass.

All the mirrors are suspended to a specific seismic isolation system, called *super-attenuator* [6]. At its heart is a chain of pendulums, each stage of which provides good attenuation of the vertical and horizontal ground vibrations. The overall attenuation is more than  $10^{10}$  at frequencies  $\leq 10$  Hz.

## 3.4 Response of a gravitational wave interferometer

The response  $h$  of the interferometer to an impinging GW with polarization  $h_+$  and  $h_\times$  can be written as

$$h = F_+(\theta, \phi, \psi)h_+ + F_\times(\theta, \phi, \psi)h_\times \quad (3.1)$$

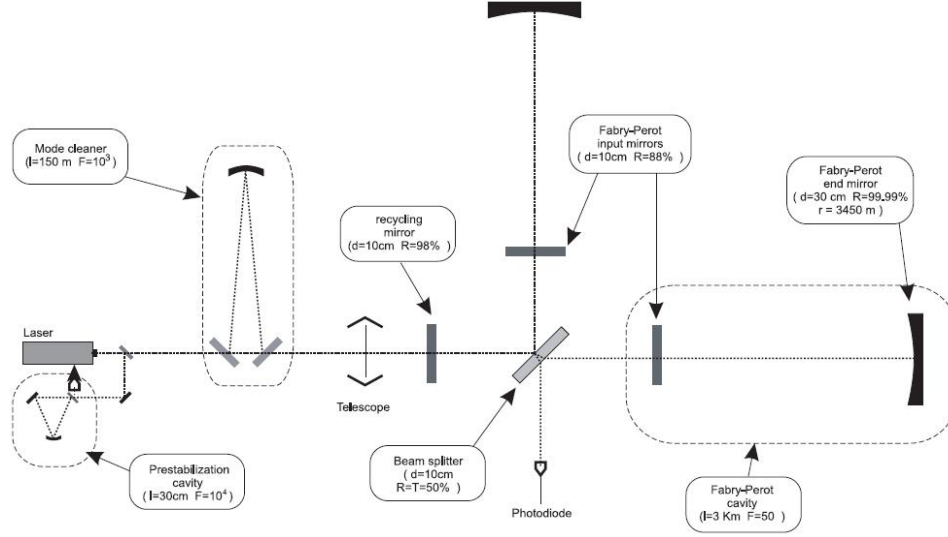


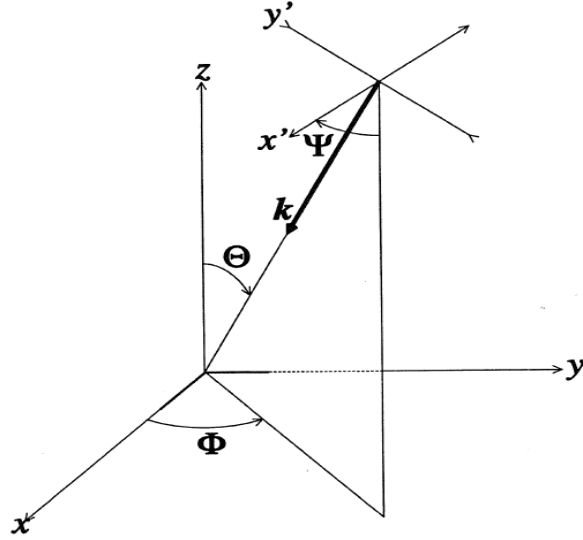
Figure 3.1 – The basic optical scheme of Virgo

where the antenna pattern  $F_+$  and  $F_\times$  are equal to

$$\begin{aligned} F_+(\theta, \phi, \psi) &= \frac{1}{2}(1 + \cos^2 \theta) \cos 2\phi \cos 2\psi - \cos \theta \sin 2\phi \sin 2\psi \\ F_\times(\theta, \phi, \psi) &= \frac{1}{2}(1 + \cos^2 \theta) \cos 2\phi \cos 2\psi + \cos \theta \sin 2\phi \sin 2\psi \end{aligned} \quad (3.2)$$

and are functions of the three angles  $\theta$ ,  $\phi$  and  $\psi$  defined as follows. Let the Cartesian frame  $(x, y, z)$  have the origin on the beam-splitter and the arms of interferometer are along the  $x$  and  $y$  axes. The propagation plane of the GW is characterized by the frame  $(x', y', z')$ . In the prime coordinates the propagation of the GW coincides with the  $z'$  axis. Its sky location is defined by the polar angles  $\theta$  and  $\phi$  with respect to  $(x, y, z)$ , see Figure 3.2. The polarization angle  $\psi$  is between the projection of the  $x$  arm onto the plane orthogonal to the direction of propagation and the  $x'$  axis.

The antenna pattern  $F_+$  and  $F_\times$  in Equations (3.2) encode the detector angular sensitivity (see Figure 3.3). Generally speaking, GW detectors have a very wide aperture and are hence non-directional. We see that the GW detector is blind to certain directions for any value for  $\psi$ , i.e., for  $\phi = \pm\pi/4$  and  $\theta = \pi/2$ . This corresponds to the two bisectors of the detector arms. Conversely, the response  $F_+^2 + F_\times^2$  is maximum for  $\theta = 0$  or  $\pi$  i.e, a GW coming from the zenith.



**Figure 3.2** – The coordinate system used in Virgo in the computation of the antenna pattern functions. The origin coincides with beam-splitter and along the x and y axes. A rotation by an angle  $\theta$  around y axis and  $\phi$  around z axis brings the  $(x', y', z')$  frame onto the  $(x, y, z)$  frame

### 3.5 Astrophysical reach of a gravitational wave detector

An approximate yet realistic estimate of the astrophysical reach of GW detectors can be obtained by considering isotropic monochromatic source of GW [7]. We start from the expression of the GW flux and GW radiated energy given in Equations (1.22) and (1.24) respectively in section 1.2.2.

For monochromatic source emitting at frequency  $f_0$ , we have

$$F_{GW} \approx \frac{\pi c^3}{4GT} f_0^2 h_{rss}^2 \quad (3.3)$$

where  $h_{rss}^2 \equiv \int_T h_+^2(t) + h_\times^2(t) dt$ . Here we integrated over the duration  $T$  which corresponds to the entire duration of the considered GW transient.

Assuming that the source is isotropic, we get from Equation (1.24)

$$E_{GW} = \frac{\pi^2 c^3}{G} D_L^2 f_0^2 h_{rss}^2 \quad (3.4)$$

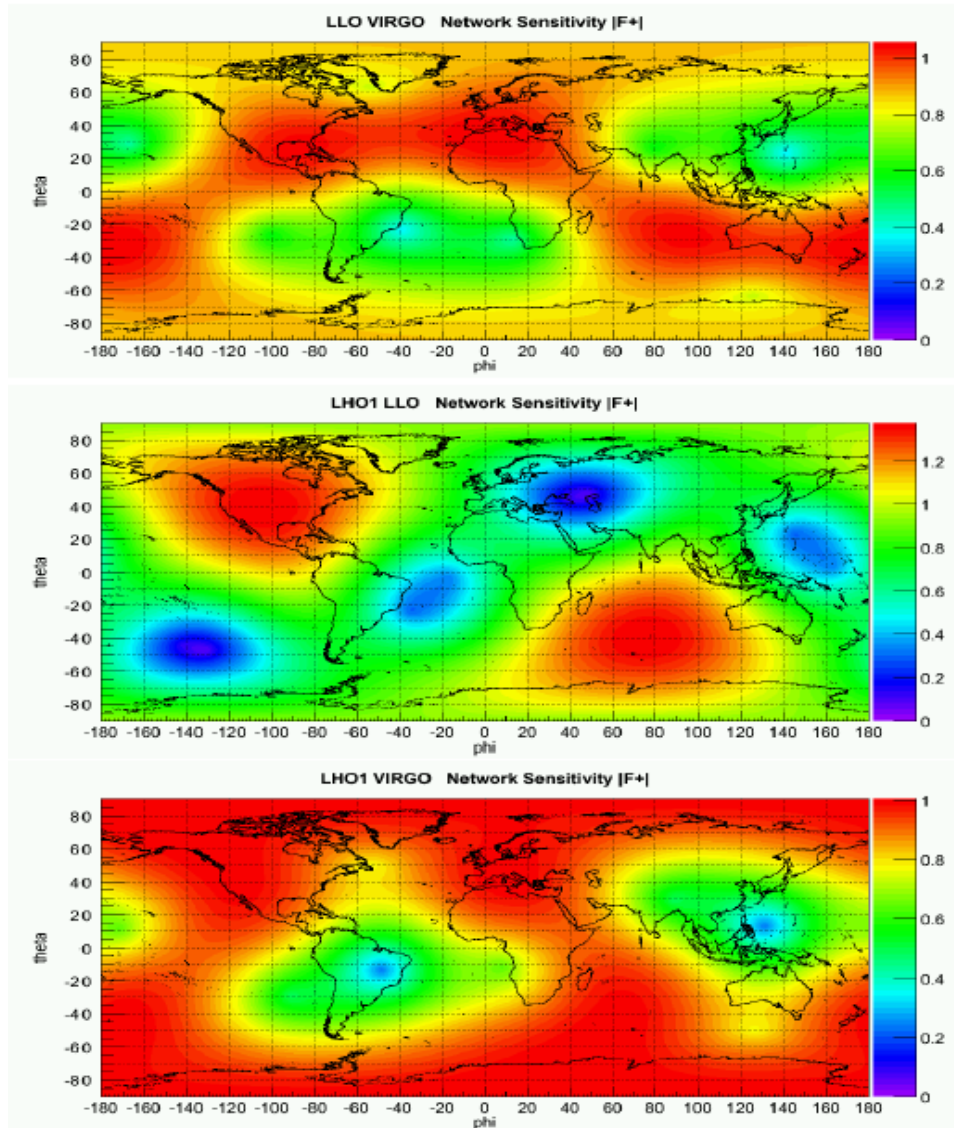


## CHAPTER 3. GRAVITATIONAL-WAVE INTERFEROMETRIC DETECTORS

More realistically, the emission pattern may be linear (e.g., supernova core collapse)

$$h_+(t) \sim \sin^2 \iota s(t) \quad (3.5)$$

$$h_\times(t) \sim 0 \quad (3.6)$$



**Figure 3.3** – The module of the plus component of the network antenna pattern considering the three couples of detectors: H1L1, H1V1, L1V1. The area which network are more sensitive (red colour) increase with respect to the single detector case. This immediately shows the advantage of using more than one detector.

### 3.3.5 Astrophysical reach of a gravitational wave detector

or elliptical (e.g., binary mergers)

$$h_+(t) \sim (1 + \cos^2 \iota)/2A \cos \Phi(t) \quad (3.7)$$

$$h_\times(t) \sim \cos \iota A \sin \Phi(t) \quad (3.8)$$

In that case, it is easy to show that the Equation (3.4) holds

$$E_{GW} = \alpha \frac{\pi^2 c^3}{G} D_L^2 f_0^2 h_{rss}^2 \quad (3.9)$$

with a rescaling factor  $\alpha$  in section 1.2.2 whose value depends on the polarization pattern. We have  $\alpha = 8/15$  and  $\alpha = 2/5$  for linear and elliptical polarization respectively.

Let  $\rho$  define the signal-to-noise ratio (SNR),

$$\rho^2 \equiv \int \frac{|H(f)|^2}{S(f)} df \quad (3.10)$$

where  $H(f)$  is the Fourier transform of the detector response  $h(t) = F_+ h_+(t) + F_\times h_\times(t)$  as defined in Equation (3.1).  $S(f)$  is the two-sided noise power spectral density.

For monochromatic sources, it is easy to show that

$$\rho^2 \approx \beta^2 \frac{h_{rss}^2}{S(f_0)} \quad (3.11)$$

where  $\beta^2 = F_+^2 + F_\times^2$ ,  $\beta^2 = F_+^2 \sin^2 \iota$  and  $\beta^2 = F_+^2 ((1 + \cos^2 \iota)/2)^2 + F_\times^2 \cos^2 \iota$  for the isotropic, linear and elliptical emission patterns respectively as defined in Equations (3.5) and (3.7).

Combining Equations (3.11) and (1.24), we finally get

$$E_{GW} = \frac{\alpha \pi^2 c^3}{\beta^2 G} D_L^2 f_0^2 S(f_0) \rho^2 \quad (3.12)$$

It can be checked numerically that  $\alpha/\beta^2 \approx 2$  for all polarization cases [7].

Consider a burst source that releases  $E_{gw} = 10^{-2} M_\odot$  (which is the typical order-of-magnitude for mergers of stellar-mass compact objects) at frequency  $f = 50$  Hz where Virgo sensitivity is  $S^{1/2}(f) \approx 8 \times 10^{-23}/\text{Hz}^{1/2}$ . By inverting the above Equation (3.12), we can compute that this source is detectable with SNR  $\rho = 10$  at  $D_L \sim 11$  Mpc. This is compatible with the distance estimates for the horizon of binary mergers (see reference [8]).

### 3.6 Worldwide network of gravitational wave detectors

The first generation of interferometric GW detectors includes a total of five large-scale instruments. The French-Italian project Virgo presented earlier. The US-based Laser Interferometer Gravitational-Wave Observatory (LIGO), which includes three kilometeric-scale instruments located in Livingston, Louisiana and Handford, Washington (the latter hosts two interferometers in the same vacuum enclosure). GEO, a German-British detector in operation near Hannover, Germany (see Figure 3.4).



**Figure 3.4** – Geographic location of the interferometric detectors. This world map displays the location of the four sites of the first generation detectors (LIGO H and L, Virgo and GEO).

#### 3.6.1 Source positioning

GW detectors are non-imaging instruments with a nearly omni-directional response. Source localization therefore requires multiple detectors, in order to use the measured time delay between detectors as well as the amplitude of the measured signal in each detector to triangulate a sky location. Several methods of localization have been investigated. The timing accuracy of a GW signal can be written as [9]:

$$\sigma_t \sim \frac{1}{2\pi\sigma_f\rho} \quad (3.13)$$

where  $\sigma_f$  is the effective bandwidth of the source and  $\rho$  is the SNR. For nominal values  $\sigma_f = 100$  Hz and  $\rho = 8$ , timing accuracies are of the order of 0.1 ms. This can be compared to the light travel time between detectors (10–30 ms for the LIGO-Virgo network) to deduce the angular uncertainty for the triangulation of times of arrival. For example, for a binary coalescence signal at the threshold of detectability, [9] estimates a best-case localization of 20 deg<sup>2</sup> (90% containment), and a typical localization of twice this. Additional constraints provided by other

instruments with a better angular accuracy such as HEN telescopes can therefore significantly help improving the source localization.

### 3.6.2 Sensitivities reached so far and coordinated data takings

In 2007, LIGO and Virgo have concluded an agreement which includes the data sharing and coordination of their data takings. The first joint data taking is the LIGO fifth Science Run (or S5) and the first Virgo Science Run (or VSR1). The former started on November 4th, 2005 and ran until October 1, 2007; and the later began on May 18, 2007 until Sep 30, 2007. A second joint data taking with enhanced detectors, S6/VSR2-3, began on 7 July 2009 and ended on 20 October 2010.

We show in Figures 3.5 and 3.6 the strain sensitivity that these detectors reached during S5/VSR1 and S6/VSR2-3 respectively.

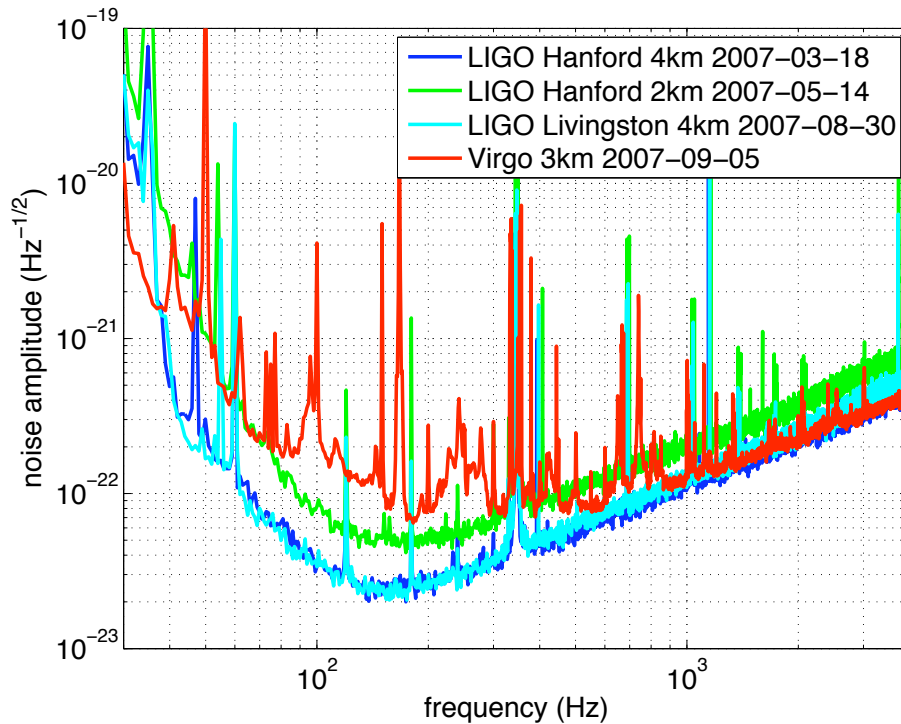
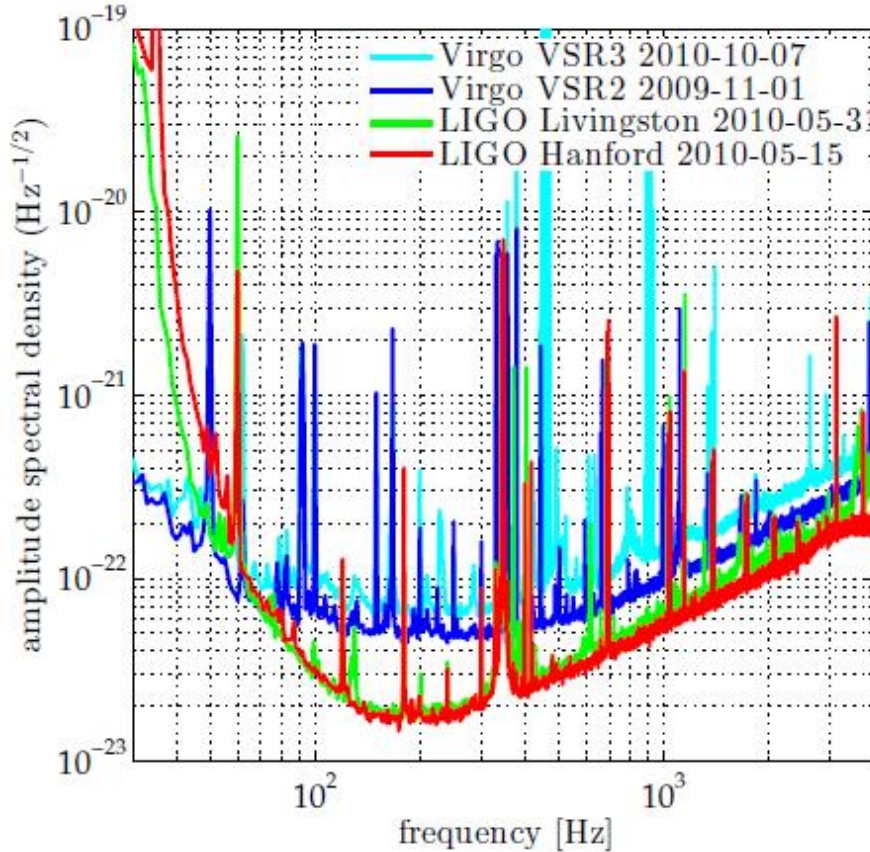


Figure 3.5 – Typical Virgo and LIGO sensitivity curves during the joint science run S5/VSR1

## 3.7 Analysis of gravitational wave data

The output of a GW detector is a time series which contains the response to an impinging GW  $h(t)$  and the instrumental noise  $n(t)$ . The astrophysical sources are expected to be rare



**Figure 3.6** – Typical Virgo and LIGO sensitivity curves during the joint science run S6/VSR2-3

with signature at the limit of detectability. Efficient signal processing methods are thus required to detect the GW signal at low SNR.

Two distinct cases can be considered: (i) the GW signal is known to a good accuracy thanks to reliable astrophysical models; (ii) the GW signal is unknown or poorly known. In the first case, it can be shown that under that the noise is stationary and Gaussian, the optimal detection method is the *matched filtering*. Essentially this consists in cross-correlating the data with the expected signal. A detection is made when an excess of correlation is observed. In the second case (unmodelled burst signals), *time-frequency* techniques are used to extract transient signals from the background noise. We considered that the joint sources of GW and HEN falls in the latter category.

In this section, we give a general overview of the methods and techniques used for the detection of GW bursts. We also introduce in the section two algorithms used to search for GW bursts: the *X-pipeline* and *coherent WaveBurst* (cWB). Both those methods have been

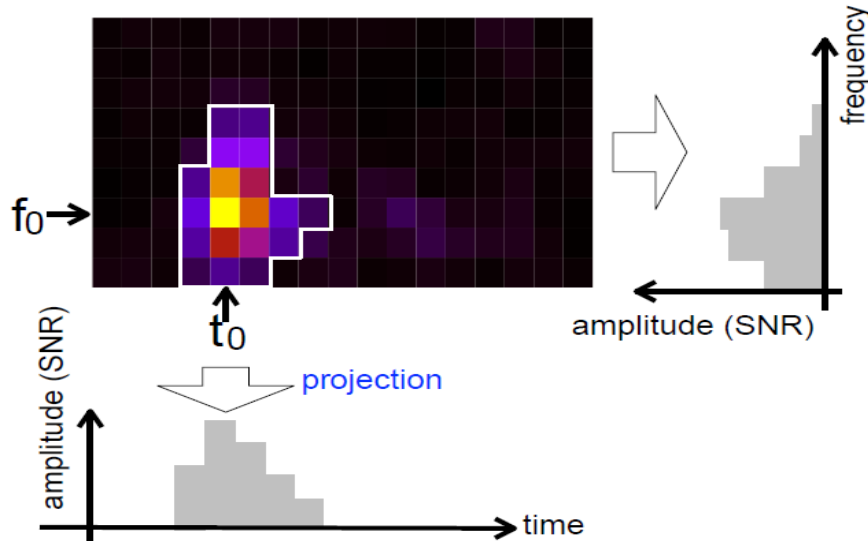
used in the context of the joint GW and HEN searches we present in Chapters 4 and 5.

### 3.7.1 Wavelets and time-frequency analysis

Fourier transform decomposes a signal into its frequency components. The power spectrum provides information about frequency only. The temporal localization is cancelled. A time-frequency distribution is a transform that maps a 1-D signal into a 2-D time-frequency map, which describes the evolution of spectra over time. Each pixel in this map represents the signal power at a given time and frequency.

There exists various ways to produce such representation. Short-term Fourier analysis or wavelet based transforms are the most commonly used. This consists in replacing the Fourier basis composed of long-duration complex exponentials by short duration signals called wavelets concentrated about a given time and frequency. The time-frequency representation results from the projection of the signals on the wavelet basis.

Stationary background noise is associated with a homogeneous wavelet representation while transient signals appears as a localized excess of power. This can be used to detect GW transients by searching for clusters of connected time-frequency pixels (associated with an outstanding power). An example of the time-frequency representation of a transient is given in Figure 3.7.



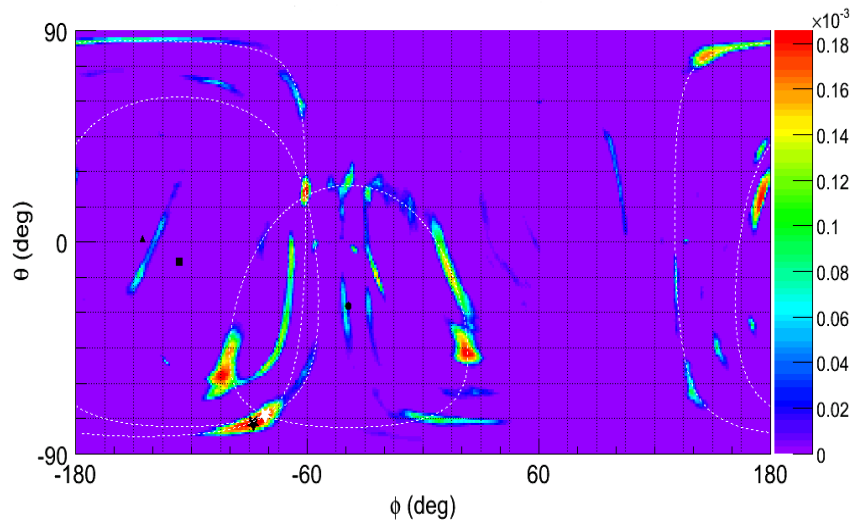
**Figure 3.7** – Time-frequency representation and its projection to time- and frequency-axis respectively. (source: [10])

### 3.7.2 Multi-detector analysis

In the previous section, we described the basic methods used for the analysis of the data stream from a single detector. In the following, we will be interested in aspects specifically related to multiple data streams. The availability of multiple data streams impacts on the way the data are analyzed at different levels.

#### Coherent analysis of multiple data stream

Coherent excess power methods used to search for unmodelled GW bursts require that the signals received by all detectors are *consistent* in time *and* phase. Concretely this is realized by combining the data streams from multiple detectors, taking into account the antenna response and noise level of each detector so that the sum operates constructively for a GW burst from a given sky direction. The data stream which results from this coherent combination maximises the signal-to-noise ratio (SNR). It is used to produce a time-frequency map of the signal energy (equivalently, the SNR), which is then scanned for transient excursions (or *events*) that may be GW signals. Each event is characterised by a measure of significance, based on energy and/or correlation between detectors, as well as its time-frequency properties. Another outcome from this type of analysis is the probability (pseudo-)distribution over the sky usually referred to *sky map* from which the most likely location of the source can be extracted (see Figure 3.8).



**Figure 3.8** – An example of sky map of network statistics for a three detector networks. (source [11])

#### Mitigation of non-Gaussian/non-stationary noise with multiple data

Fundamental noises presented above are expected to be Gaussian and stationary. However, the real instrument noise is dominated by an overwhelming fraction of non-Gaussian non-stationary noises from various origins. It consists in a large number of transient noise excursions commonly called *glitches*. Glitches are produced by a variety of environmental and instrumental processes, such local seismic noise or saturations in feedback control systems. Since glitches occasionally occur nearly simultaneously in separate detectors by chance, they can mimic a gravitational-wave signal.

The population of glitches are difficult to model. The size and the large complexity of GW detectors makes this modelling even more difficult. GW detectors being extended instruments over kilometers, it is hard to completely isolate them from the outside world and the surrounding anthropic activity. Therefore, the accurate modelling of the non-Gaussian/non-stationary noise background is for now out-of-reach. It has to be mitigated and this can be done at least partially by using multiple data.

It is possible to calculate combinings of the data from multiple detectors where the GW signals from all detectors interfere destructively in the sum. The GW signal thus cancels, but not background glitches. The energy in these “null” stream(s) may be used to reject or down-weight events not consistent with a gravitational wave. The success of such tests depend critically on having several independent detectors of comparable sensitivity. The cross-correlation with auxiliary non-GW sensitive channels (which monitors the global status and environment of the GW detector) provides also an important resource for background rejection.

#### Use of multiple data for background estimation

We explained earlier that the accurate modelling of non-Gaussian non-stationary noise is out-of-reach. The remaining part of the glitches that cannot be identified by the coherent techniques described in the previous section constitutes the dominating background noise in burst searches. This background has to be estimated. However, GW signals cannot be turned off: the detectors cannot be shielded from them. Therefore, we don't have “noise-only” data at disposal for background estimation.

Nevertheless, the background can be estimated thanks to the availability of multiple data streams by time shifting one detector's data with respect to the others by a delay much longer than the time-of-flight between detectors. Time shifts only leave triggers due to random coincidences in detector noise and erase the contribution from real GW signals. By repeating the analysis many times with different time-shifts, we get an accurate estimate of the rate of background events.



### 3.7.3 Sensitivity estimate

We test the performance of the search algorithms by repeatedly adding fake gravitational wave signals to the raw data stream and estimating the detection efficiency of each “injected” waveform models. The astrophysical origin and waveform morphology, of the gravitational wave bursts we search for in this work are a priori unknown. A broad range of signal waveforms were considered for the analysis of 2007 data presented in Chapter 4. These include astrophysically-motivated waveforms as well as ad-hoc waveforms. The list of test signals includes:

- ***Sine-Gaussian waveforms*** both linearly polarized

$$h_+(t + t_0) = h_0 \exp(-t^2/(4\tau^2)) \cos(2\pi f_0 t) \quad (3.14)$$

$$h_\times(t + t_0) = 0 \quad (3.15)$$

or circularly polarized

$$h_+(t + t_0) = \frac{1 + \cos^2 \iota}{2} h_0 \exp(-t^2/(4\tau^2)) \cos(2\pi f_0 t) \quad (3.16)$$

$$h_\times(t + t_0) = \cos \iota h_0 \exp(-t^2/(4\tau^2)) \sin(2\pi f_0 t). \quad (3.17)$$

The latter case mimics at least qualitatively the expected GW emission from the final part (merger and ringdown) of the coalescence of a neutron-star and/or black-hole binary. It also provides a reasonable model for the GW emission from some of the extreme scenarios considered for core-collapse supernovae described in section 1.3.1.

In the above equations,  $f_0$  is the central frequency,  $t_0$  is the central time and the decay time  $\tau \equiv Q/(\sqrt{2\pi}f)$ .  $Q$  is the effective number of cycles of the waveforms with values ranging from 2 to 100.

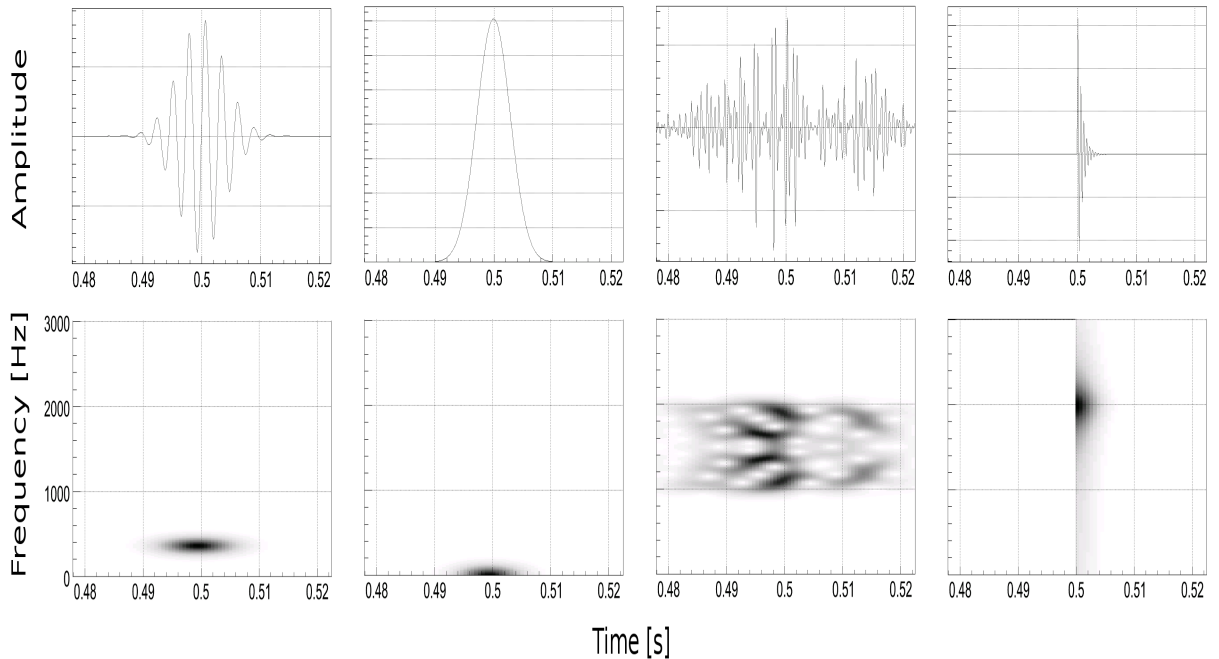
- ***White noise bursts*** are bandpassed random time-series of selected duration with independent polarization amplitudes. White noise bursts can be considered as a limiting case: their waveform does not help to distinguish them from the detector noise. The only discriminant property used to detect them is that they are correlated signatures in the various detector data.
- ***Ring-down waveforms*** are expected from processes like f-modes of NS, or during the ring-down of newly formed BH/NS during the post merger phase after coalescence, or produced in SN star-quakes related to Soft Gamma Repeaters (SGR). They are characterized by their frequency  $f_0$ , duration  $\tau$  or  $Q$  (similarly to SG) and polarization. They

have the following expression:

$$h_+(t + t_0) = \sin(2\pi f_0 t) \exp(-t/\tau) \quad (3.18)$$

$$h_\times(t + t_0) = \cos(2\pi f_0 t) \exp(-t/\tau) \quad (3.19)$$

Figure 3.9 illustrates the various families of waveforms injected into data for simulation studies in time and time-frequency domain.



**Figure 3.9** – Representation of waveforms in the time domain (top row) and a time-frequency domain (the bottom row). From left to right: a 361 Hz  $Q = 9$  sine-Gaussian, a  $\tau = 4.0$  ms Gaussian waveform, a white noise burst with a bandwidth of 1000-2000 Hz and characteristic duration of  $\tau = 20$  ms and, finally, a ringdown waveform with a frequency of 2000 Hz and  $\tau = 1$  ms. (source: [13])

### 3.7.4 Data analysis methods to search for gravitational wave bursts

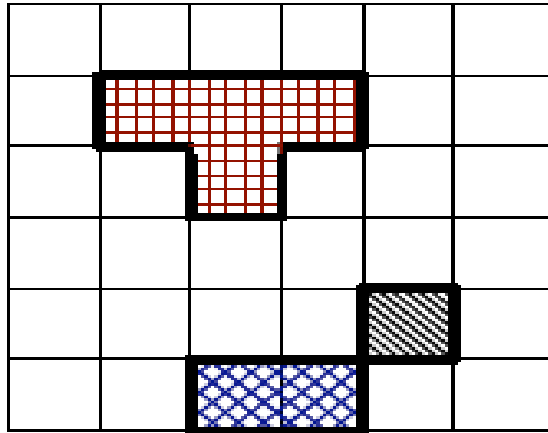
#### The X-pipeline algorithm

*X-pipeline* is an analysis algorithm for interferometric gravitational wave detection. It deals with unmodelled gravitational wave bursts associated with external astrophysical triggers such as gamma rays or neutrinos. The X-pipeline processes data *coherently* from an arbitrary network of GW detectors in the frequency band 64-500 Hz.

## CHAPTER 3. GRAVITATIONAL-WAVE INTERFEROMETRIC DETECTORS

For a specific time and direction, the X-pipeline reads the appropriate GW data and Fourier transforms it. Then for each specified direction it makes a time-frequency map of the time-series data, and computes the different statistics for each time-frequency bin, mainly coherent energies. After that, the X-pipeline looks at a fixed percentage (e.g. 1%) of bins with the highest value of the detection statistics (measured coherent energy) and marks those bins as black bins, see Figure 3.10. Black bins that share a common side are grouped together into clusters which are considered a candidate detection event [12].

X-pipeline algorithm is used, with a slightly modifications that will be discussed later, in this work to analyse the ANTARES, LIGO and Virgo data from 2007. Results are presented in Chapter 4.



**Figure 3.10** – A time frequency map with "black" pixels grouped into 3 clusters. Nearest-neighbor black pixels (those that share an edge) are grouped into a single cluster. Each cluster in this image is denoted by a different color and hatching pattern. (Source [12])

### The coherent WaveBurst algorithm (cWB)

*coherent WaveBurst* (cWB) [14, 15] is, in contrast with the X-pipeline, an un-triggered (all-sky) search algorithm for detecting gravitational wave burst. It uses the constraint likelihood approach [16] to construct a least-squares fit of the two GW polarizations to the combined data from a network of detectors in the frequency band 64-5000 Hz. The cWB analysis is performed in several steps. First, detector data is decomposed into a time-frequency representation and then whitened and conditioned to remove narrow-band noise features. Events are identified by clustering time-frequency pixels with significant energy which is coherent among detectors and characterized using test statistics derived from a constrained (regulated) likelihood (which is also a measure of the signal energy detected in the network and is calculated as described

### 3.3.7 Analysis of gravitational wave data

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in [16]). Two statistics are computed by cWB. The first is a network correlation coefficient  $net_{cc}$ , which is a measure of the degree of correlation between the detectors. The second is the coherent network amplitude  $\rho$  and is proportional to the signal-to-noise ratio. The latter is used to rank events within a homogeneous sub-period.

A triggered version of cWB, named *skymask coherent WaveBurst* (s-cWB), has been developed and used in the analysis presented in Chapter 5. Further details about the s-cWB are discussed in Chapter 5.

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# CHAPTER 4

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## GW+HEN ANALYSIS OF 5L-S5/VSR1

### 4.1 Summary

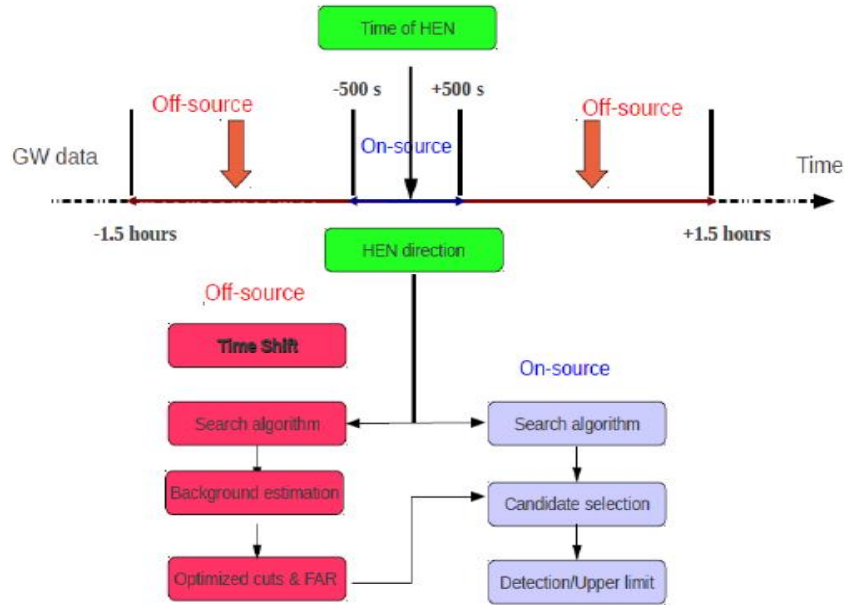
In this chapter we present the first joint search for gravitational-wave bursts associated with high energy neutrinos. Contrarily to the analysis presented in chapter 5, this first search was not jointly optimized: we used the neutrino candidate list obtained for a point source search and looked for possible concomitant, both in time and direction, GW signal using an algorithm specially designed for this kind of *triggered* searches. In this chapter, we describe the method used for this first search and take special care to the description of the neutrino candidate selection using the 2007 data set of ANTARES, LIGO and VIRGO detectors. All detectors were running in their initial sensitivity: ANTARES was running in 5-lines (5L) configuration; LIGO and VIRGO were just finishing their first science runs (S5) and (VSR1) respectively. The outcome of this first search is submitted for publication in the Astrophysical journal [1] and has led to several public presentations [2]. No significant coincident events were observed. We placed limits on the density of joint HEN+GW emission events in the local universe, and compare them with densities of merger and core-collapse events.

### 4.2 High energy neutrino triggered search procedure

The outline of the proposed search procedure [3–6] is shown in diagram 4.1. The GW+HEN joint search is performed by combining GW and HEN data using a *triggered* analysis [7, 8]. Using the latter, the search for GW signals is then restricted to an astrophysically motivated range of arrival times around the neutrino time and in its estimated direction. Compared to a classical method where GW signals are searched for with random arrival time, triggered searches can be run with a lower event detection threshold thanks to the reduction in the volume of analyzed data. This leads to a higher detection probability at a fixed false alarm probability



and better limits in the absence of detection. Similarly, the *a priori* knowledge of the source direction allows for searching only a small part of the sky and vetoing candidate events at times not consistent with the expected GW arrival time. In fact, the number of accidental coincidences between GW detectors decreases as the size of the search window decreases. This part of the sky is referred to as *angular search window* (or ASW) and is described in section 4.4.1. Thus, the use of an external trigger can be a very effective tool for a successful search of GW signals.



**Figure 4.1** – Schematic flow diagram of a HEN-triggered search for GWs. Each neutrino candidate (with its time and directional information) provided by ANTARES acts as an external trigger for the GW algorithm, which searches the combined GW data flow from all active interferometers (ITFs) for a possible concomitant signal. The size of the spatial search window is related to the angular accuracy associated to each HEN candidate. The background estimation and the optimization of the selection strategy are performed using time-shifted data from the off-source region in order to avoid contamination by a potential GW signal. Once the search parameters are tuned, the box is opened and the analysis is applied to the on-source data set.

In the present analysis, the external trigger is a neutrino candidate provided by ANTARES. The neutrino candidate, used as input for the GW+HEN joint search, is characterized by a set of parameters: its sky position  $\vec{d}$ , as given by the direction of the reconstructed muon track, the associated (and possibly direction-dependent) point-spread function of the detector (PSF), the neutrino arrival time, which defines the trigger time  $t_0$ , and the range of possible time delays (positive and negative)  $\Delta t$  between the neutrino signal and the associated GW signal, which is astrophysically motivated, as discussed in section 1.3.3. The latter quantity is referred to as the *on-source* window for the neutrino; this is the time interval which is searched

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### 4.4.3 Selection of High Energy Neutrino candidates

for GW candidate signals. To estimate the significance of the resulting GW candidates, the background rate has to be approximated using time-shift analysis as described in section 3.7.2. This background study is performed in an *off-source* window (shown in red on the diagram of Figure 4.1) around the time of the neutrino candidates.

The GW data used in this thesis are the LIGO S5 runs and VIRGO VSR1 runs (see section 3.2). These data are selected from periods where the detectors H1, H2, and V1 were in science mode, i.e. usable for the detection of GW. The LIGO fifth "science run" (S5) ranges from November 4, 2005 until September 30, 2007 [9, 10]. Over one year of science-quality data were collected with all three LIGO interferometers in simultaneous operation at their design sensitivity, with duty factors of 75%, 76%, and 65% for H1, H2, and L1 respectively. The Virgo detector started its first science run, VSR1 [11], on May 18, 2007. The Virgo duty factor over VSR1 was 78%. The GW data used in this analysis cover the period between January 27 and September 30, 2007.

## 4.3 Selection of High Energy Neutrino candidates

### 4.3.1 The ANTARES data and Monte Carlo sample

The 5L data sample of ANTARES ranges from January 27 to December 4, 2007 [12]. This analysis is restricted to the data taking period overlapping with the science runs of VIRO and LIGO detectors: January 27 to September 30, 2007.

The ANTARES sample is composed of the so-called silver runs selected by data quality criteria applied on all runs. The silver data set is obtained by accepting a baseline rate up to 120 kHz and a burst fraction up to 40% (cf paragraph 2.4). For each detector configuration at least 80% of OMs are required to be active over the full run. This means that among 375 channels a minimum of 300 OMs were active during the 5L period. Taking into account all the above mentioned criteria and the 20% dead time present in the on-line trigger at that period [13, 14], the remaining active time is  $T_{obs} = 104$  days. The final common observation time, considering the duty cycle of the LIGO-Virgo detectors, reduces to  $T_{obs}^{com} = 91.36$  days. The events are triggered with the  $3N$  filter (section 2.3.5). The raw data are processed with the BBfit *v3r6* (section 2.6.1). The set of calibration used for these data are shown in the table 4.1.

In the following we will distinguish between events reconstructed with 2-lines (2L) and those reconstructed with 3-lines and more (3L+). This distinction comes from the presence of two mirror tracks in the case of events reconstructed with 2L, for BBfit *v3r6*. As mentioned in

first run $\rightarrow$ last run	Calibration set
25700 $\rightarrow$ 27640	2007:L5:V4.0
27729 $\rightarrow$ 29763	2007:L5:V4.1

**Table 4.1** – Calibration sets used to calibrate data

section 2.6.1 this version allows access to both mirror tracks. This is a crucial improvement for the present triggered search as it allows to reduce the size of the search window and consequently the background rate. This improvement is illustrated in section 4.4.1

Various Monte Carlo files are simulated as described in section 2.5. In this thesis the neutrino sample is simulated by GENHEN and weighted according to the Bartol flux for atmospheric neutrinos and an  $E^{-2}$  spectrum for cosmic neutrinos. The sample of atmospheric muons is simulated with CORSIKA and weighted with the Battistoni flux. All the MC files used in this analysis are processed by TriggerEfficiency with the 3N trigger. In Figure 4.2 we show the distributions of the nadir angle  $\theta$  (as introduced in section 2.3.2) for data and MC samples. The colour code of the nadir distributions is the following:

- Turquoise curve: the MC truth for down-going atmospheric muons, which have been simulated within  $90^\circ \leq \theta \leq 180^\circ$ .
- Red curve: the reconstructed  $\theta$  for MC atmospheric muons.
- Green curve: the MC truth for atmospheric neutrinos, which have been simulated in the range  $0^\circ \leq \theta \leq 90^\circ$ .
- Blue curve: the reconstructed  $\theta$  for MC atmospheric neutrinos.
- Black curve: data.

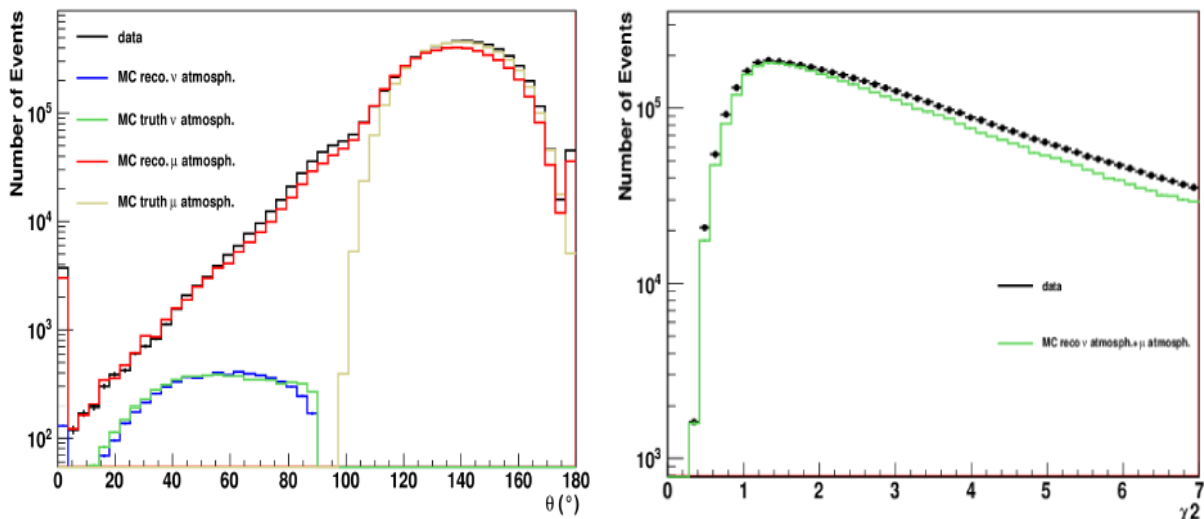
The red curve extends over the whole range of  $\theta$  in contrast of MC truth, showing that the majority of events with  $\theta \leq 90^\circ$  are atmospheric muons misreconstructed as up-going. Cuts based on the above parameters will be studied in the next section to remove these misreconstructed muons and select a sample of data with optimized discovery potential.

### 4.3.2 Event selection criteria

The first step of the selection is to keep only upgoing tracks:

**cut 1:**  $\theta \leq 90^\circ$

### 4.4.3 Selection of High Energy Neutrino candidates



**Figure 4.2** – Left: distributions of nadir  $\theta$  for the data and MC. The colour code is explained in the text. We see that part of the atmospheric muons are reconstructed as upgoing while they are downgoing. Those are known as *misreconstructed* atmospheric muons. Right: distribution of the track  $\chi^2$  for data and MC including all the reconstructed events.

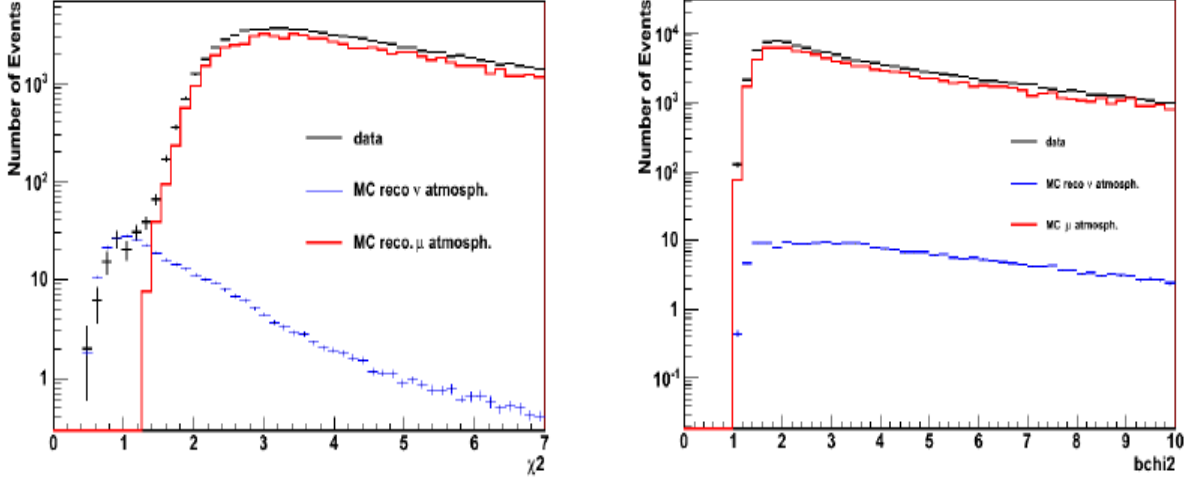
The subsequent steps are motivated by the will to distinguish remaining misreconstructed atmospheric muons from the desired muons originating from the interaction of upgoing neutrinos around the detector. The parameters used for this selection are the quality parameters  $\chi^2$ ,  $b\chi^2$  presented in section 2.6.1, whose distributions are illustrated in Figure 4.3.

After selecting the events passing the cuts, it is easy to compute with the MC simulations, the effective surface that represents the detector sensitivity for the given set of cuts. The neutrinos effective area is defined as the ratio of the rate of selected events to the neutrino flux at Earth:

$$A_{\nu}^{eff}(E_{\nu}, \theta) = \frac{N_{sel}}{N_{gen}} \times V_{generation}(E_{\nu}, \theta) \times (\rho \cdot N_A) \times \sigma(E_{\nu}) \times P_{Earth}(E_{\nu}, \theta_{\nu}) \quad (4.1)$$

Where  $N_{sel}$  and  $N_{gen}$  stand for the selected and generated events respectively. While,  $V_{generation}$ ,  $\rho$ ,  $N_A$ ,  $P_{Earth}$  were introduced in section 2.5. For illustration purposes, we show in Figure 4.9 the neutrino effective area as function of neutrino energy.

In the present analysis, the final cuts on  $\chi^2$  and  $b\chi^2$  are derived in such a way to maximize the chances to discover a point-like source of HEN following the prescriptions detailed in [15, 16]. The objective is to maximize the so-called discovery potential. In order to do so we minimize the model discovery factor (MDF) that is defined, for a point source at declination  $\delta$ , emitting



**Figure 4.3** – Distributions of the track  $\chi^2$  (left) and the bright point  $b\chi^2$  for Data and MC including all the events reconstructed as upgoing.

a power law flux with spectral index  $\gamma$ , as:

$$E^\gamma \frac{d\Phi(\delta)}{dEdSdt} = \frac{N_{sig}(\delta)}{A_{eff}(\delta) \times \Delta t \times \int_{E_{min}}^{E_{max}} E^{-\gamma} dE} \quad (4.2)$$

where:

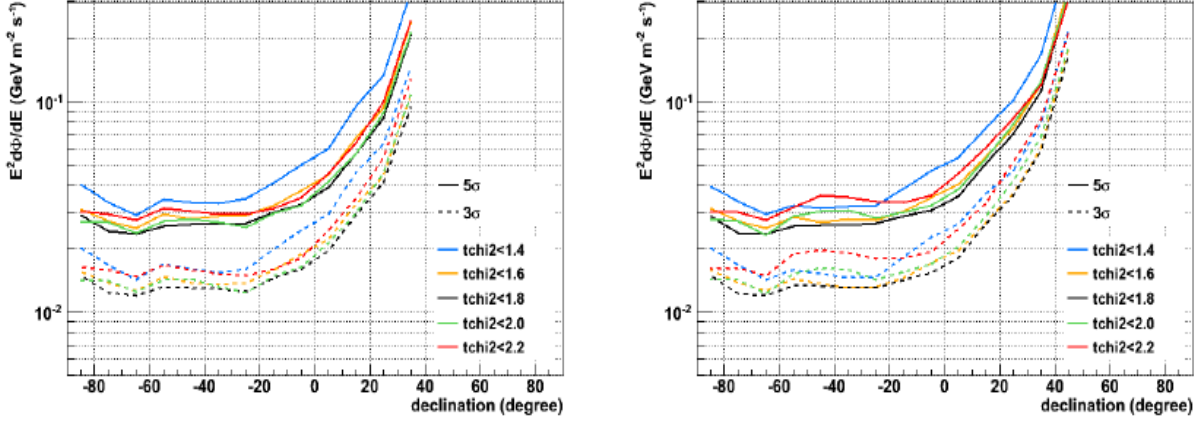
- $N_{sig}(\delta)$  is the average expected number of signal events needed to have a 50% probability to make a discovery at the  $5\sigma$  level.
- $A_{eff}(\delta)$  is the effective area as defined by Equation (4.1).
- $\Delta t$  is the live time of selected runs.
- $[E_{min}; E_{max}]$  is the simulated events energy range.

Several combinations of values were tried for the maximization of the discovery potential:

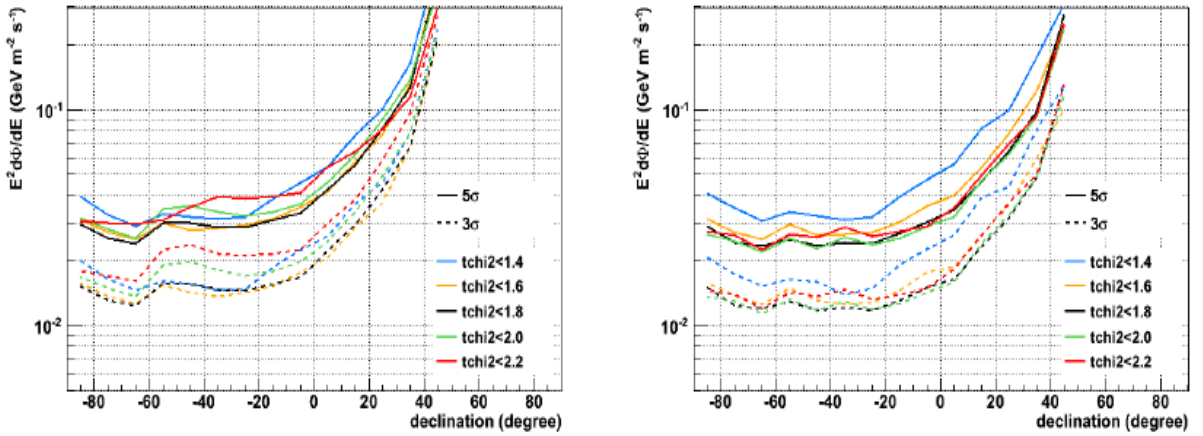
- $\chi^2$ : 1.4, 1.6, 1.8, 2.0, 2.2, 2.4, 2.6.
- $b\chi^2$ : 1.0, 1.4, 1.8, 2.2, 2.6.

Examples are shown in Figure 4.4 for a variety of cuts on  $\chi^2$  and for different nadir angle ranges, applying a cut on  $b\chi^2 \geq 1.8$ . Figure 4.5 shows other examples for 2 other cuts on  $b\chi^2$ .

### 4.4.3 Selection of High Energy Neutrino candidates



**Figure 4.4** – Model discovery factor, for different values of  $\chi^2$  (labeled "tchi2" in the legend), for  $b\chi^2 \geq 1.8$  and  $\theta \leq 80^\circ$  (left),  $\theta \leq 90^\circ$  (right). (Source [16])

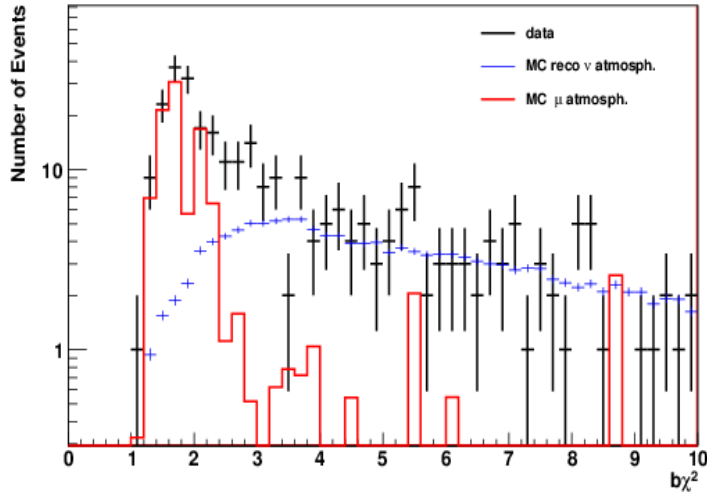


**Figure 4.5** – Model discovery factor, for different values of  $\chi^2$  (labeled "tchi2" in the legend), for  $\theta \leq 90^\circ$  and  $b\chi^2 \geq 1.0$  (left), then  $b\chi^2 \geq 2.6$  (right). (Source [16])

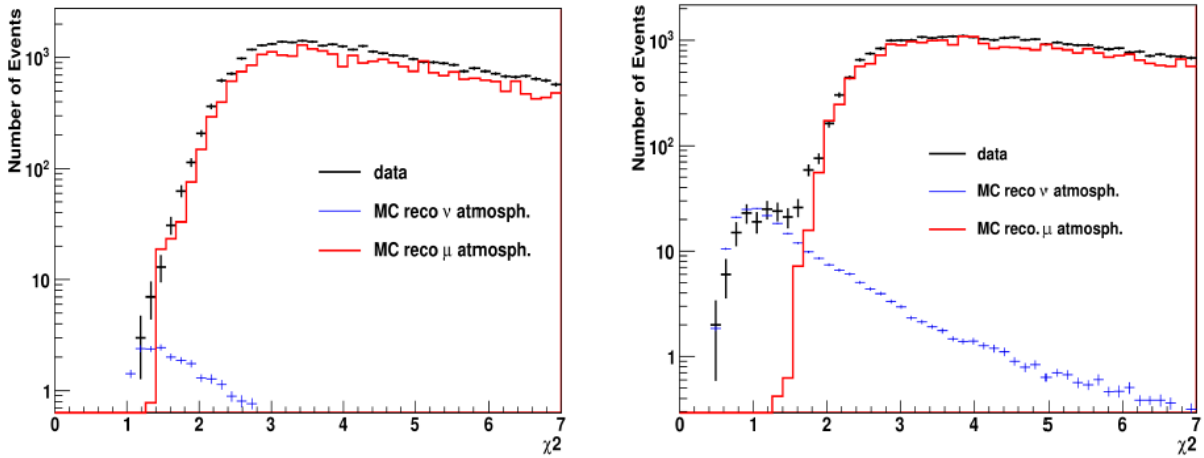
At this stage the following cuts  $\theta \leq 90^\circ$ ,  $\chi^2 \leq 1.8$  and  $b\chi^2 \geq 2.2$  yield one of the best discovery potentials for a large declination band. However, applying these cuts implies a relatively high contamination of atmospheric muons close to the horizon, i.e.  $80^\circ < \theta \leq 90^\circ$ . To reduce this contamination it has been decided to apply a tighter  $\chi^2$  cut in this specific nadir  $\theta$  range. Thus, the final chosen cuts are:

**cut 2:**  $b\chi^2 \geq 2.2$ . This cut is illustrated in Figure 4.6. This rejects events from large electromagnetic showers likely to appear in downgoing muon bundles.

**cut 3:** Further cuts are applied on the track depending on the arrival direction of the candidate:  $\chi^2 \leq 1.8$  when  $\theta \leq 80^\circ$  and  $\chi^2 \leq 1.4$  when  $80^\circ \leq \theta \leq 90^\circ$ . Figure 4.7 illustrates the discrimination power of these cuts for both nadir ranges.



**Figure 4.6** – Bright point fit distributions for up-going events for data and MC where **cut 3** has been applied. Since a bright point is a point-like light source which emits an isotropic light flash at a given moment, events with a very good bright-points fit are not retained as they are not compatible with a muon track. This is more likely to happen with mis reconstructed atmospheric muons.

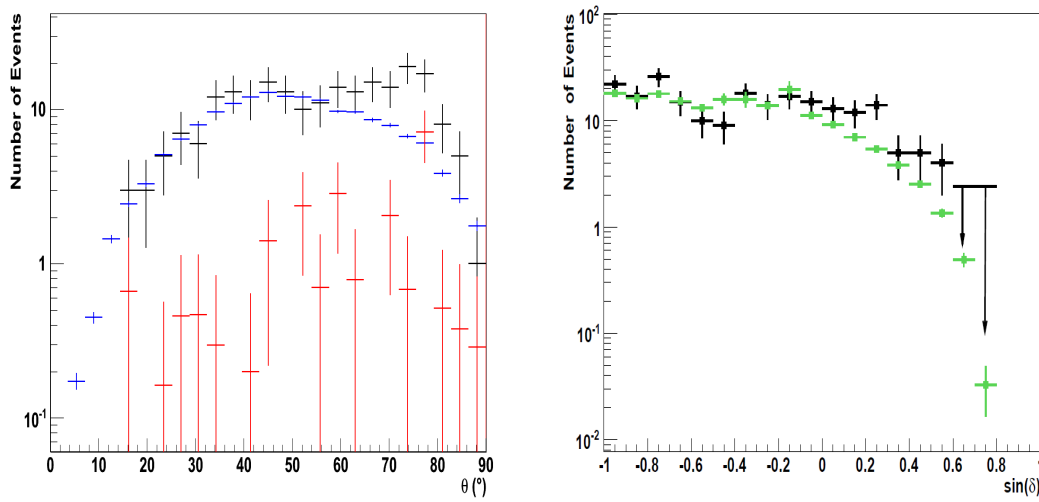


**Figure 4.7** – Quality distributions of the track fit for up-going events for data and MC in the range of  $\theta \leq 80^\circ$  (right) and in the range  $80^\circ \leq \theta \leq 90^\circ$  (left). The cut on  $b\chi^2 \geq 2.2$  is applied in both cases.

### 4.4.3 Selection of High Energy Neutrino candidates

In this section we have described a set of cuts derived from MC sample to discriminate between the true neutrino signal and the background of atmospheric muons. We have shown that using two quality fit values  $\chi^2 \leq 1.8$  when  $\theta \leq 80^\circ$ , and  $\chi^2 \leq 1.4$  when  $80^\circ \leq \theta \leq 90^\circ$  allows to cut out most misreconstructed upward going muons. The percentage of remaining atmospheric muons (or contamination) in the final data sample is estimated to be roughly less than 20%.

Figures 4.8 shows the distributions of the nadir angle and the sine of the declination for the events selected with the final cuts, which are globally consistent with the MC expectations.

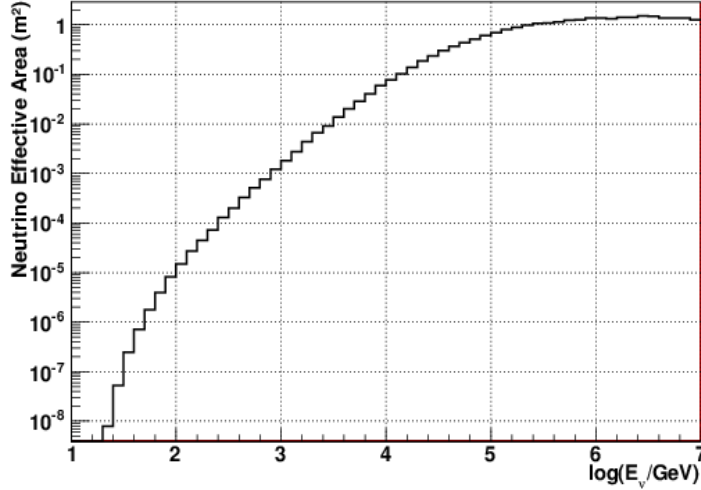


**Figure 4.8** – Left:  $\theta$  distributions for data and MC samples (blue: atmospheric neutrinos, red: atmospheric muons). Right: distributions of the sine of the declination for data (black) and MC (green: total atmospheric background). All cuts are applied.

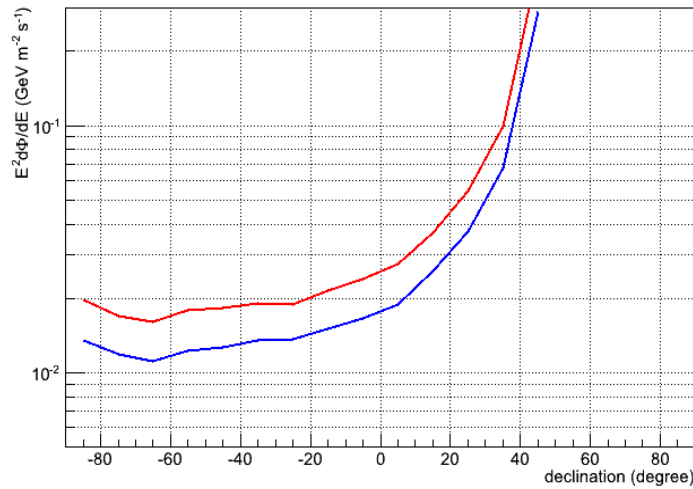
The corresponding effective surface, as defined by Equation (4.1) is shown on Figure 4.9 as a function of the neutrino energy. To characterize further the potential physics yield of the selected sample, we define the sensitivity as the median 90% upper limit obtained over an ensemble of simulated experiments with zero-signal assumption. The sensitivity of the HEN search has been quantified for the whole 5 line data period. It depends on the declination of the potential source. Figure 4.10 shows the sensitivity for the search using the selection criteria described above and assuming an  $E^{-2}$  spectrum. From the curve it's shown that the best sensitivity is estimated to be  $E^2 \frac{dN}{dE} \approx 10^{-6} \text{ GeV cm}^{-2} \text{ s}^{-1}$ .

In the next section, we discuss into details the angular accuracy that can be expected applying the present cuts. This angular accuracy not only depends on the reconstruction parameters, but also on the energy of the selected events. We discussed in chapter 1 that





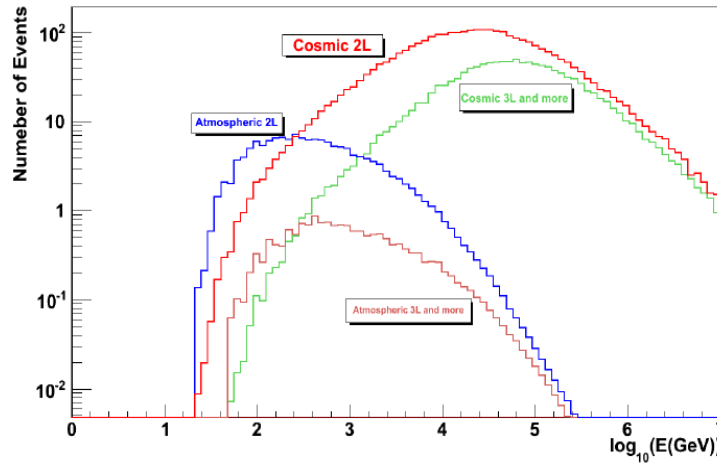
**Figure 4.9** – The effective area for neutrinos as a function of the neutrino energy. The sensitivity of the detector for up-going neutrinos increases with energy due to the rise of neutrino cross-section. Above an energy of 1 PeV the sensitivity saturates at about  $1 \text{ m}^2$  as the increasing neutrino cross-section and the Earth absorption cancel out.



**Figure 4.10** – Sensitivity, after applying all the above described cuts, for the whole 5Line period (blue) and for the GW+HEN joint time of observation (red).

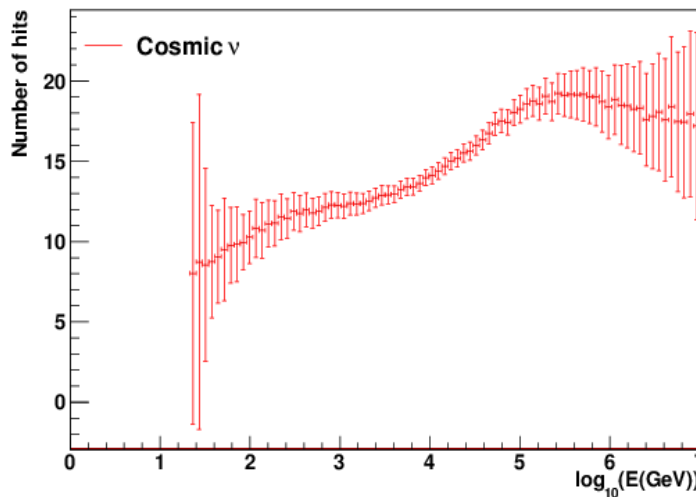
the energy of the high energy neutrino, when correctly reconstructed, can indeed be a good indicator of whether the candidate is of cosmic or atmospheric origin. This is illustrated with the present sample in Figure 4.11.

### 4.4.3 Selection of High Energy Neutrino candidates

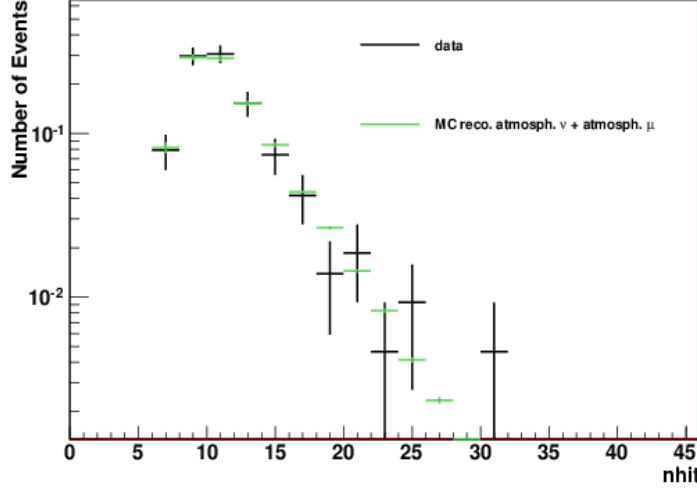


**Figure 4.11** – Distributions of energy for atmospheric and cosmic (according to an  $E^{-2}$  spectrum) neutrinos. The 2L and 3L+ case are presented separately.

The approach used in this analysis is to use the number of hits as an energy estimator of the candidate. Figure 4.12 shows that the number of hits and the MC energy of the neutrino candidate are correlated. On basis of event-by-event selection, we shall associate to each event in the final list an energy (in term of number of hits) in addition to the basic characteristics discussed in section 4.4.2. For illustration purposes the distributions of the number of hits used by the reconstruction for both MC and data, after applying all cuts, are shown in Figure 4.13.



**Figure 4.12** – Number of hits versus neutrino energy for cosmic ( $E^{-2}$ ) neutrinos.



**Figure 4.13** – Number of hits used in the fit for up-going events after applying the cuts described in the text.

## 4.4 High energy neutrino horizon

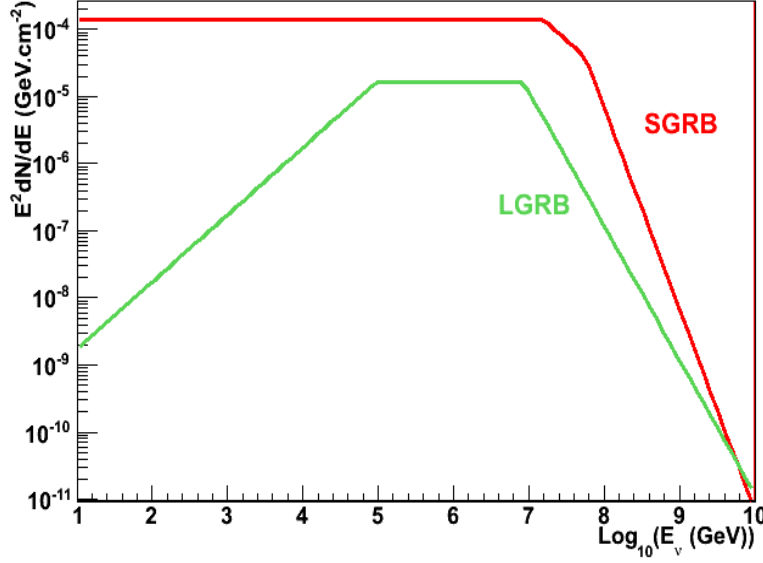
In this section we estimate the horizon  $d_\nu$  of the ANTARES neutrino telescope given the cuts presented above and assuming certain models of sources, namely long-GRBs (LGRB) and short-GRBs (SGRB). These models are presented in section 1.9 and the associated neutrino fluxes are plotted in Figure 4.14. The detectability of each kind of source also depends on its distance to the observer.

Let  $N_\nu(\theta, \phi, d_\nu)$  be the expected number of detected neutrino events from a source located at a distance  $d_\nu$  and with local coordinates  $(\theta, \phi)$ :

$$N_\nu(\theta, \phi, d_\nu) = \left( \frac{d_s}{d_\nu(\theta, \phi)} \right)^2 T \int_{E_\nu^{min}}^{E_\nu^{Max}} A_\nu^{eff}(E_\nu, \theta, \phi) \times \frac{d\Phi(E_\nu, \theta, \phi)}{dE_\nu} dE_\nu, \quad (4.3)$$

where  $A_\nu^{eff}(E_\nu, \theta, \phi)$  is the neutrino effective area of the detector,  $(\Phi_\nu(E_\nu, \theta, \phi))$  the reference theoretical flux at Earth for a source located at a distance  $d_s$ , and  $T$  is the average duration of a GRB in the considered model. Note that we have omitted here the redshift energy loss of neutrinos, which is negligible for sources at  $z < 1$ . Rearranging the Equation (4.3) gives:

$$d_\nu(\theta, \phi, N_\nu) = d_s \cdot \sqrt{\frac{\int_{E_\nu^{min}}^{E_\nu^{Max}} A_\nu^{eff}(E_\nu, \theta, \phi) \cdot \frac{d\Phi(E_\nu, \theta, \phi)}{dE_\nu} \cdot dE_\nu}{N_\nu}} \quad (4.4)$$



**Figure 4.14** – Flux spectrum of LGRB ( $z=2$ ) and SGRB ( $z=1$ ) used in this thesis.

We then define  $d_\nu^{50\%}$  as the distance at which the probability to observe at least one event from the considered source is 50%:

$$P(\geq 1|N_\nu) = 1 - P(0|N_\nu) = 50\% \quad (4.5)$$

where  $N_\nu$  is the number of expected events as given by Equation (4.3) and  $P(0|N_\nu)$  follows the Poisson statistics:

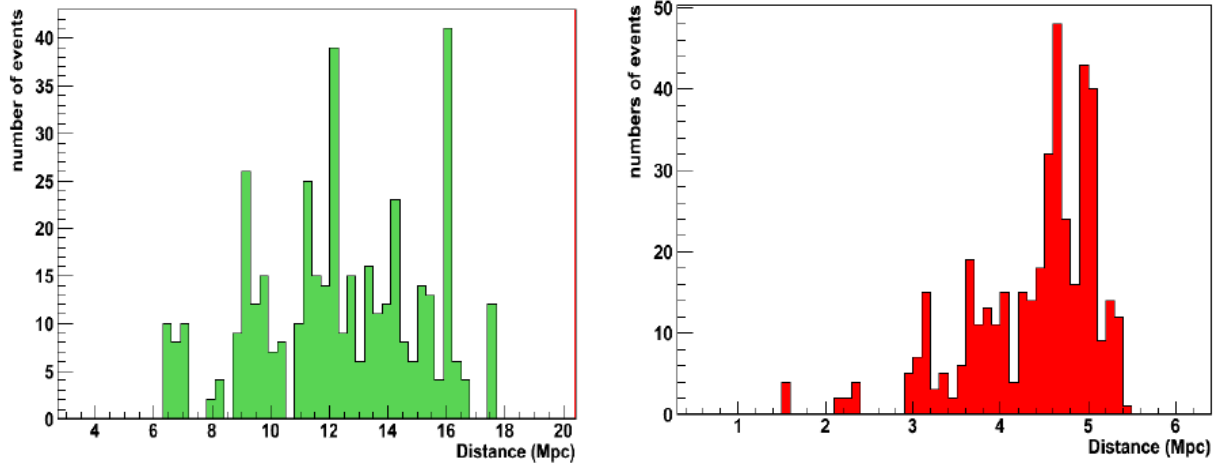
$$P(n|N_\nu) = \frac{(N_\nu)^n \exp(-N_\nu)}{n!} \quad ; n > 0 \quad (4.6)$$

The 50% probability corresponds to the value  $N_\nu = 0.7$ .

Our approach allows the calculation of the HEN horizon on a event-by-event basis. For this we use the effective area  $A_\nu^{eff}(E_\nu, \theta, \phi)$  calculated in bins of  $(\theta, \phi)$  and of in bins of energy (ranging between  $[10, 10^7]$  GeV). We finally compute numerically  $d_\nu^{50\%}$  given  $d_s$ , using Equation (4.4) and  $N_\nu = 0.7$ .

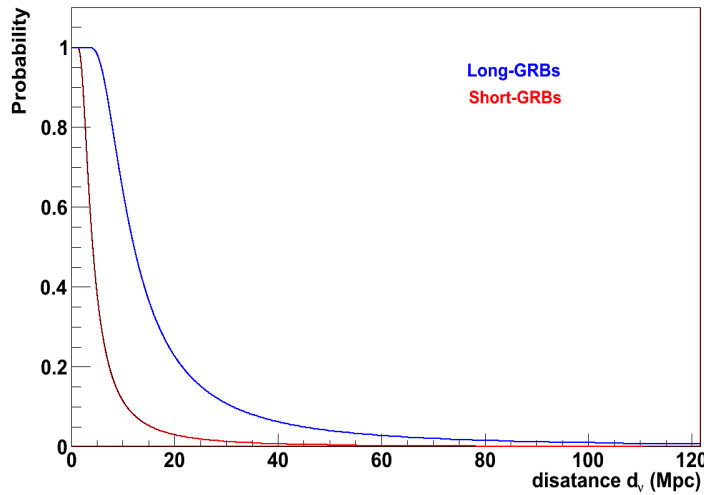
For both cases (LGRB and SGRB), we assume  $d_s = 21$  Mpc (equivalent to  $z = 0.005$ ). We find in average  $d_\nu^{50\%} = 12.4$  Mpc for the former and  $d_\nu^{50\%} = 4.3$  Mpc for the latter. The full distributions of  $d_\nu^{50\%}$  for the selected sample of neutrinos are shown in Figure 4.15.

Alternatively, we show on Figure 4.16 the probability to observe one event at least, as a



**Figure 4.15** – Neutrino horizon calculated for selected sample according to the cuts described in section 4.3.2. On the left is result for long-GRB and on the right for short-GRB.

function of the source distance. This stands for standard LGRB and SGRB. The probability is averaged over all possible locations on the sky.



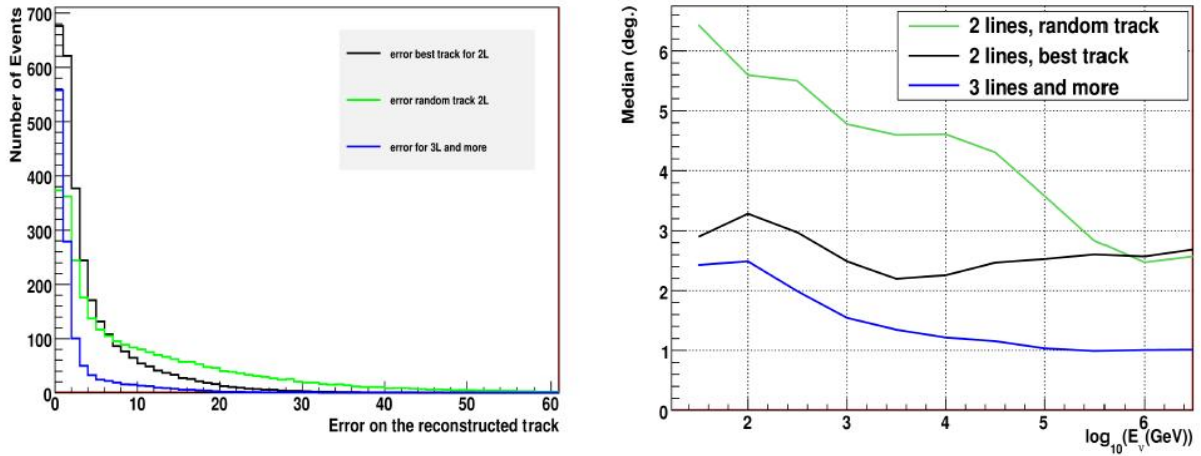
**Figure 4.16** – Probability to detect a source as a function of its distance, for LGRB (blue curve) and SGRB (red curve).

#### 4.4.1 Angular resolution and angular search window

The angular resolution is related to the error on the reconstructed track direction. It is defined as the median of the distribution of the space angle  $\psi$  between the true neutrino direction and

#### 4.4.4 High energy neutrino horizon

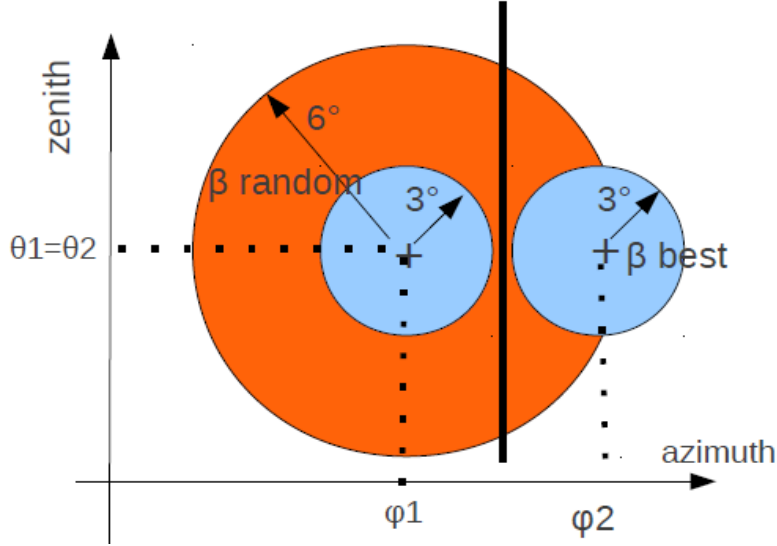
the reconstructed track and is obtained from MC sample obtained with the cuts defined in the previous section and weighted according to an  $E^{-2}$  flux. In the case of events reconstructed with 2 lines, we determine the angular difference of both mirror tracks with respect to the true MC direction. The minimum of those two values, which corresponds to the best track (as defined in section 2.6.1) is used to determine the angular resolution. This method allows to significantly improve the angular resolution as illustrated in Figure 4.17 and sketched in Figure 4.18.



**Figure 4.17** – Left: distribution of angular error between the neutrino direction and the reconstructed track for an  $E^{-2}$  flux. At low energies the error is dominated by the kinematics of neutrino interactions (see section 2.2.2). The median of this distribution is shown on the right plot as function of the neutrino energy (right). Both plots show the values obtained for the best and random tracks in the case of events reconstructed with 2 lines.

The uncertainty on the neutrino arrival direction has to be accounted for in the GW coherent analysis. This is done by defining, on an event-by-event basis, an angular search window (ASW) and the associated  $\psi$  distribution. This distribution is needed by the X-pipeline to compute the significance of an hypothetical signal for the scanned directions inside the ASW. The radius of this window is defined as the 90% (ASW90%) quantile of the  $\psi$  distribution. The following method is used to calculate the ASW90%:

- We calculate the  $\psi$  distribution for the selected MC sample in bins of declination and number of hits. We create 18 bins in declination range with steps of 10 degrees and, for each bin of declination, we create 16 bins in number of hits with step of 1 hit.
- For each distribution error we compute the 90% quantile of the distribution. The corresponding value is the ASW90%.



**Figure 4.18** – Example (arbitrary values) of the projected angular resolution in local coordinates as obtained for the best (blue) and random (orange) track. The black line illustrates the plane containing the 2 detector lines used for reconstruction.

- We fit the  $\psi$  distribution by a log-normal function given by Eq. 4.7:

$$\mathcal{F}(x) = \frac{1}{\sqrt{2}} \frac{e^{-((\ln((x-\theta)/m))^2/2\sigma^2)}}{(x-\theta)\sigma} \quad (4.7)$$

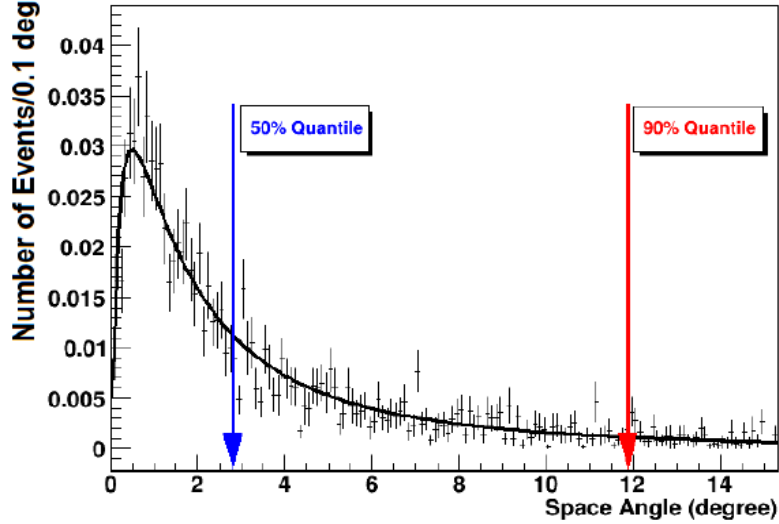
with  $x \geq \theta$  and  $\sigma \geq 0$ .  $\theta$  is the location parameters,  $\sigma$  is related to the shape of the distribution and  $m$  is a scaling parameter.

In Figure 4.19 is shown an example of the  $\psi$  distribution fitted by log-normal distribution for a given bin of declination.

The fit is carried out until the 90% quantiles which is the limit radius used for GW searches. The output fit parameters are added to the HEN candidates list (see section 4.4.2).

In the 2L case, the best track distribution is used to determine the ASW90%. This allows for a substantial reduction of the solid angle to be scanned by the GW search algorithm, as can be deduced from the sketch of Figure 4.18. This can be further quantified by computing the ratio  $R$  as defined by:

$$R = \frac{\Omega_{best}}{\Omega_{random}} \quad (4.8)$$



**Figure 4.19** – Error distribution on the HEN arrival direction for a bin of declination between  $-30^\circ$  and  $-20^\circ$  and number of hits=9 together with the fitted log-normal. The arrows indicate the 50<sup>th</sup> (median) and the 90<sup>th</sup> (ASW90%) of the distribution.

where

$$\Omega_{best} = 2 \times 2\pi(1 - \cos(ASW90_{best})) \quad (4.9)$$

And

$$\Omega_{random} = 2\pi(1 - \cos(ASW90_{random})) \quad (4.10)$$

are the solid angles associated to the  $ASW90_{best}$  and  $ASW90_{random}$  respectively. The ratio between the  $ASW90_{best}$  and  $ASW90_{random}$  is plotted in Figure 4.20. We see from the curve that the size of the best angular search window  $ASW90_{best}$  is in average 44.6% of the size of the random one, which justifies our approach.

The ASW50% (median) and ASW90% are plotted in the Figure 4.21. This Figure shows the improvement on the ASW90% derived from the approach described above. A single circular region of radius  $ASW90\%=30$  degrees encompasses the two mirror tracks, while the individual mirror tracks are contained in a circular region of radius  $ASW90\%=12.5$  degrees. The solid angle to be analyzed is 0.84 sr in the first case while it is  $2 \times 0.15 = 0.30$  in the second case. The distinction of the two mirror tracks allows us to reduce the search window by a factor of almost 3. We show also the Point Spread Function (PSF) in Figure 4.22.



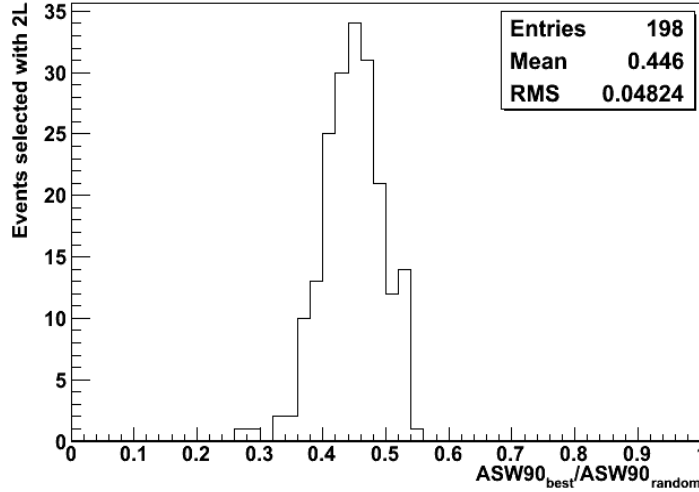


Figure 4.20 – Ratio between  $ASW90_{best}$  and  $ASW90_{random}$ , ignoring any overlap between the search windows associated to each mirror solutions.

#### 4.4.2 List of neutrino candidates

After applying the set of cuts described in the previous sections to the 181 runs corresponding to 104 days equivalent live time to the present analysis period, 414 neutrino candidates remain, which are listed in [17]. In this sample we have separated events reconstructed with exactly 2 lines from those reconstructed with at least 3 lines. This strategy is imposed to take into account the mirror track for events reconstructed with exactly 2 lines. The main informations

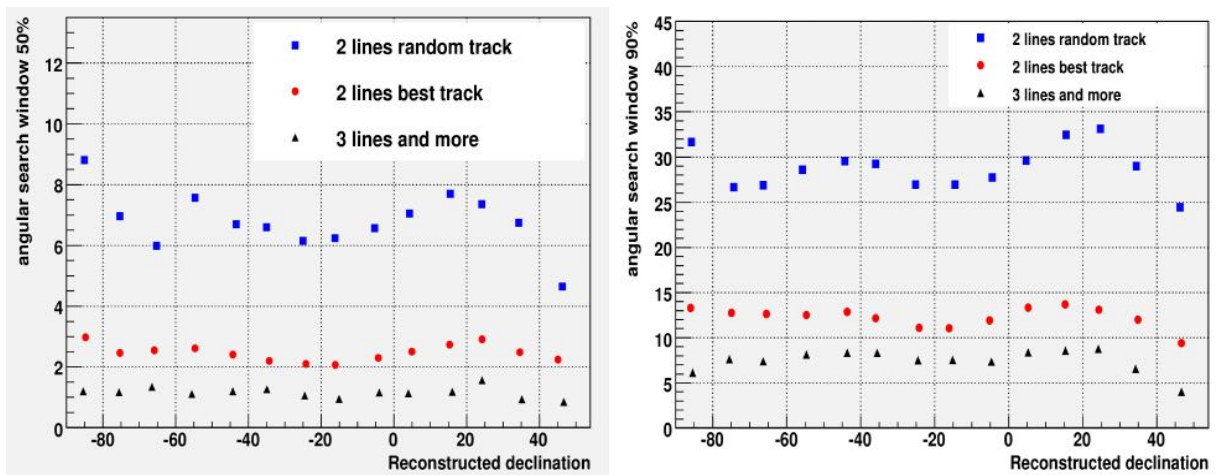
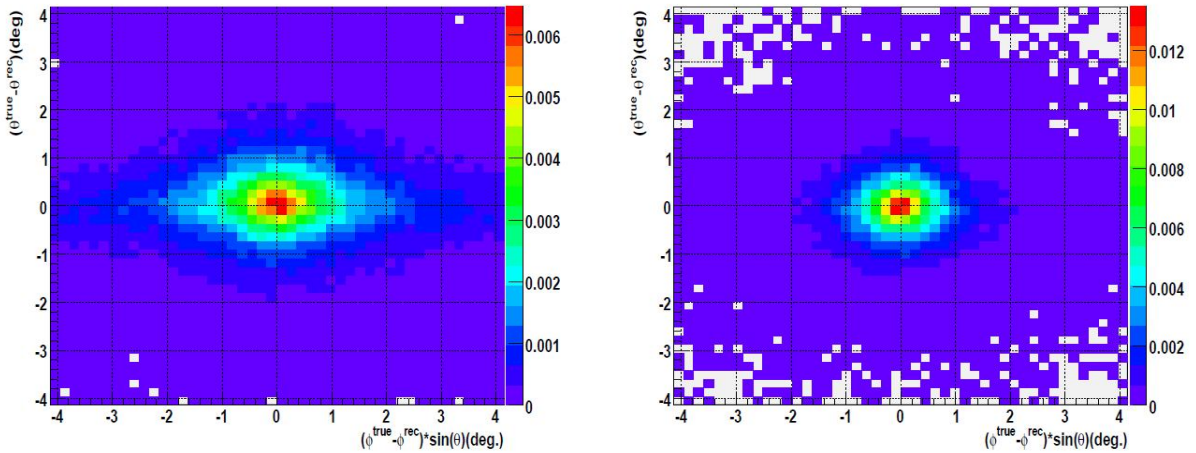


Figure 4.21 – ASW50% (left) and ASW90% (right) as function of declination

in the event list correspond to:

- The neutrino arrival time in Julian Day specified for epoch J2000, which is used also for the computation of the celestial coordinates (right ascension and declination). It is the sum of the UTC event time, computed from the start time of the run, and the product of the frame duration and the frame index;
- The equatorial coordinates  $(\alpha, \delta)$  of each candidate (computed using ConvertCoordinates libraries from the ANTARES local coordinates  $(\theta, \phi)$ );
- The number of lines and the number of hits used in the fit of the track;
- The angular search windows for both 50% and 90% quantiles;
- The log-normal fit parameters obtained by fitting the angular error distribution in bins of event declination and number of hits, as explained in section 4.4.1.

The equatorial coordinates  $(\alpha, \delta)$  and the galactic coordinates of the selected candidates are shown in Figures 4.24 and 4.25 respectively. Due to the geographical location of the detector, the part of the sky with declination greater than  $48^\circ$  is always above the horizon and is thus never observed by the ANTARES telescope. In contrast, the part of the celestial sphere with declination below  $-48^\circ$ , is always visible. The region in between is visible during some fraction of the day. This visibility factor convoluted to the intrinsic acceptance of the detector is shown in galactic coordinates in the Figure 4.26.



**Figure 4.22** – PSF of the ANTARES neutrino telescope, on the left for event selected with 2L (best track) and, on the right for events selected with 3L+.

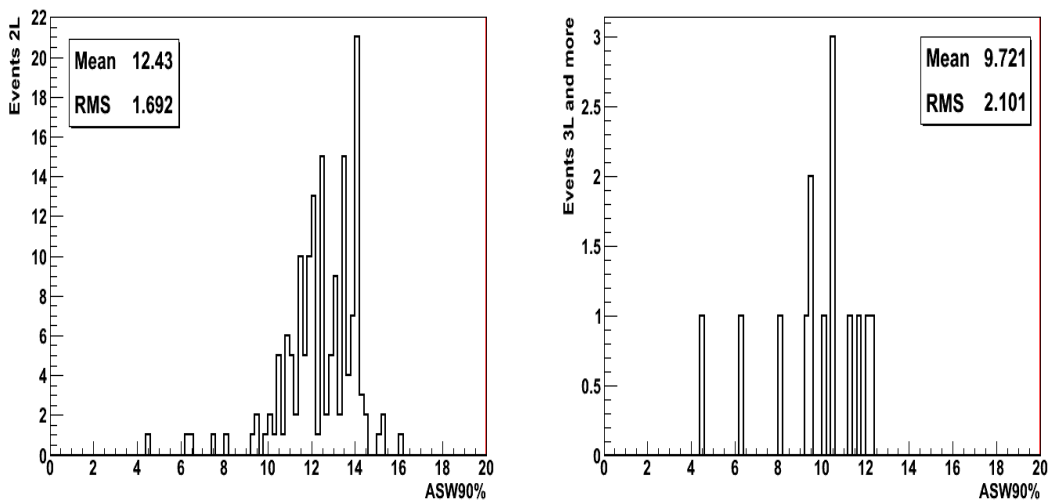
Of the HEN candidate events, 158 occurred at times when at least two gravitational-wave detectors were operating. Since two or more detectors are required to discriminate GW signals from background noise (as described in section 4.5), in the following we consider only these remaining 158 HEN candidates: 144 2-line events and 14 3-line events. We show in Figure 4.23 the distribution of the ASW90% of these events.

## 4.5 Coincidence with gravitational waves

### 4.5.1 Gravitational wave event analysis

Once the list of HEN candidates has been established, they can be fed as external triggers into the X-pipeline to search for GW signals in coincidence with them. The GW dataset used is described in section 4.2. We now concentrate on the preprocessing of the GW dataset using a *coherent triggered* method. The triggered search requires several components provided by the neutrino candidate event, especially time and directional informations. This adopted procedure follows the one used in [18] where the GRB triggers are replaced by neutrino candidates. All the detectors operating at the time of the trigger and passing the data-quality requirements are used in the analysis.

As described in section 4.2 the dataset can be split into two parts: *on-source* and *off-source* data. The former serve to generate GW triggers in coincidence with the neutrino candidates,

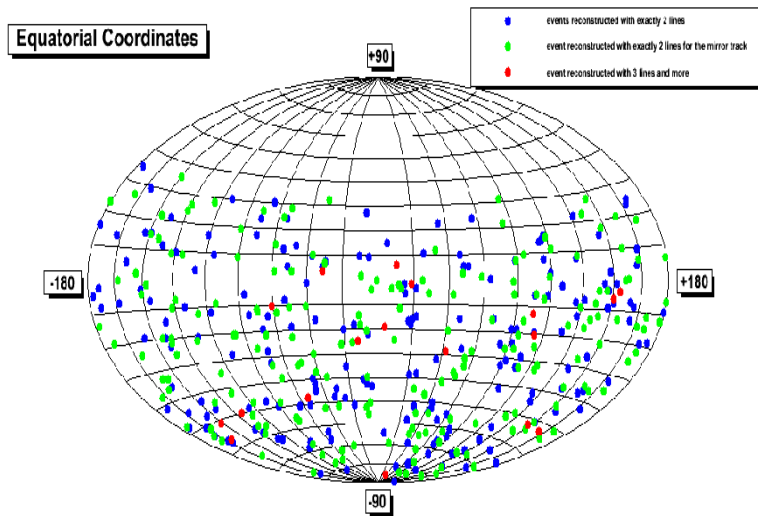


**Figure 4.23** – ASW90% of the remaining 158 neutrino candidates. Left: events reconstructed with 2 lines. Right: events reconstructed with at least 3 lines.

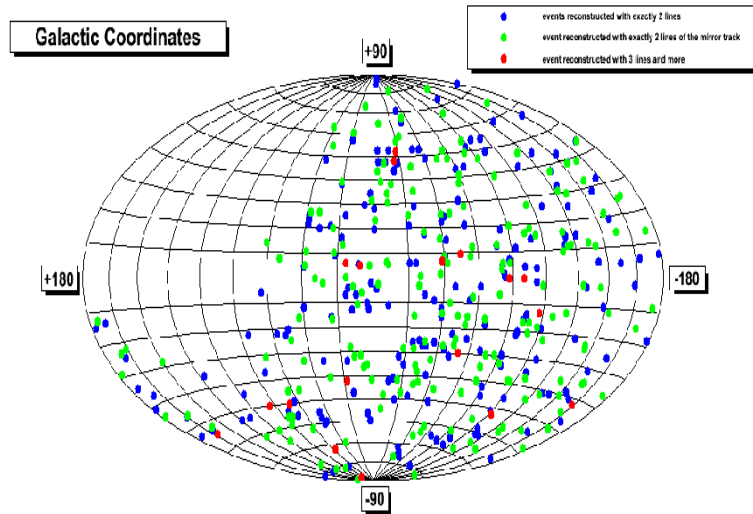
#### 4.4.5 Coincidence with gravitational waves

while the latter are used to optimize the search parameters, to measure the expected false alarm rate and to standardize statistics derived from the on-source window. The on-source data consists of a segment from each interferometer data. The data segments are time-delayed according to the sky location being analysed so that a GW signal from that direction would appear simultaneous in each data stream.

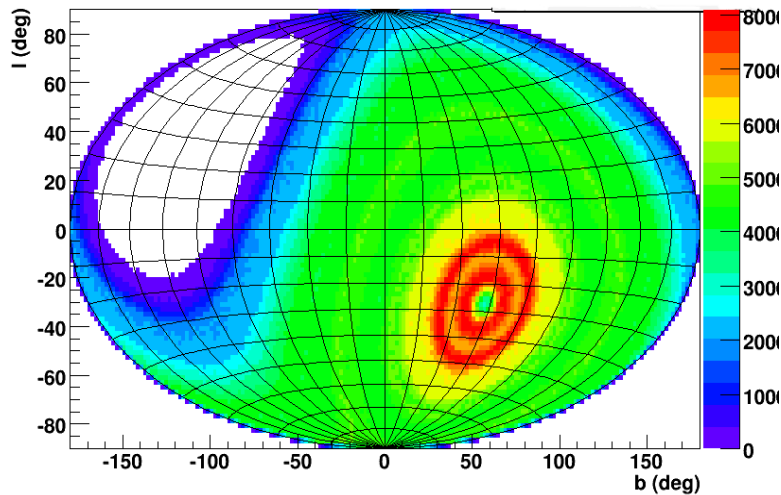
In the context of the joint GW+HEN searches, the source emits a collimated jet pointing to Earth. This gives a quite strong indication about the source core dynamics and its orientation. In particular, it is natural to associate this direction to the source angular momentum. This motivates the assumption of a circular polarization of the incoming gravitational wave to separate the signals from noise. While some of the considered source models do not predict a circularly polarized GW, we expect the loss in sensitivity in that case to be relatively small. In addition to the marginalized circular polarization sum, other combinations of the data are constructed. Of particular importance are the “null” combinations designed to cancel out the GW signal from the given sky location; comparison to corresponding incoherent combinations provides powerful tests for identifying events due to background noise fluctuations glitches, as described in [19]. For each combination, the event cluster is assigned a combined energy as the sum of the energy values of its constituent pixels. This defines a first ranking statistics for the events. In addition, GW events are characterized by their duration, central time, bandwidth, and central frequency. Also, a second ranking statistic is computed based on a



**Figure 4.24** – Sky-map showing the reconstructed declination and right ascension of all the selected events. The blue and green dots correspond to the two possible directions of events reconstructed with exactly 2 lines. The red dots represent the coordinates of the events reconstructed with 3 lines and more.



**Figure 4.25** – Sky-map showing the selected events in galactic coordinates: The blue and green dots correspond to the two possible directions of events reconstructed with exactly 2 lines. The red dots represent the coordinates of the events reconstructed with 3 lines and more.



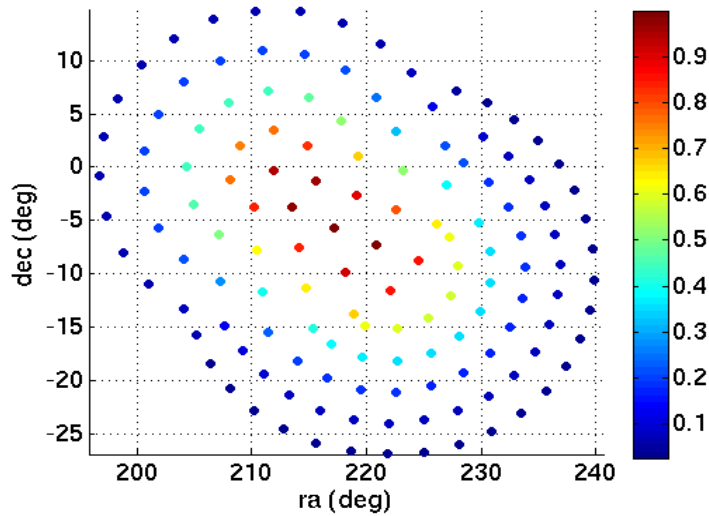
**Figure 4.26** – Acceptance of the ANTARES detector in galactic coordinates, taking into account the visibility factor due to the rotational Earth motion. This quantity is the number of detected events for a given (arbitrary) flux. Only the relative values are relevant.

maximum-likelihood analysis of the event assuming a power-law distributed background noise with no assumption on the GW polarization. In practice this statistic is often found to provide signal-noise separation due to the non-Gaussian nature of the GW detector noise.

#### 4.4.5 Coincidence with gravitational waves

The time-frequency (TF) analysis (see section 3.7.1) is repeated for Fourier transform lengths of 1/128, 1/64, 1/32, 1/16, 1/8, 1/4 s, to maximize the sensitivity to GW signals of different durations. It is also repeated over a discrete grid of sky positions covering most of the source sky location probability distribution. A simple regular grid is used here, composed of concentric circles around the best estimate of the neutrino sky location, which covers 90% of the sky location probability distribution (see Figure 4.27). This grid is designed such that the maximum relative timing error between any pair of GW detectors is less than 0.5 ms. Finally, the events are decimated to a rate of 0.25 Hz before being written to disk.

GW triggers are produced independently for each sky position grid point. The detection statistic, written as a log-likelihood ratio between a signal and a background model, is penalized by the probability  $\mathcal{F}(\vec{d})$  of the trial sky location being the true one, by adding the logarithm of that probability to the detection statistic. The reconstructed source sky position for a given signal is the sky position for which the trigger has the largest penalized detection statistic. Only that maximal trigger is kept by the analysis of the grid of sky positions.



**Figure 4.27** – The estimated neutrino locations and their uncertainties may give rise to overlapping regions on the sky. Searching for one point and its mirror image at once. The color bar shows the probability distribution. (Source [20])

The *off-source* window is defined as all data within  $\pm 1.5$  hours of the neutrino time, excluding the *on-source* interval. The statistical features in the off-source window are similar to the ones in the on-source window. In order to enlarge the background sample, we also repeat the off-source analysis after applying time shifts of multiples of 6 s to the data from one or more detectors. With such time slides, we were able to produce  $O(10^3)$  background trials for

each HEN.

To assess the sensitivity of this joint search, the analysis is repeated with injections of simulated GW signals to the on-source data. The amplitudes and morphologies tested are discussed in section 4.6.2.

## 4.5.2 GW search optimization

As we stated in section 3.7.2, the sensitivity of searches for gravitational-wave bursts is limited by noise (glitches included). The trigger rejection operates in two steps, namely a data preselection followed by a glitch removal procedure. To reduce this background, events that overlap in time within known instrumental and/or environmental disturbances are vetoed. In addition to this, GW consistency tests comparing the coherent and incoherent energies are applied to each event [19]. These tests are applied to the on-source, off-source and injection events. The events failing one or more of these tests are discarded.

The thresholds are optimized by testing a preset range of thresholds and selecting those which give the best overall detection efficiency at a fixed false alarm probability of 1% when applied to a random sample of background and injection events (the on-source events are *not* used; i.e., this is a blind analysis). These tests also determine which of the two ranking statistics discussed in section 4.5 (based on circularly polarized GW energy or power law noise) gives the better detection efficiency. The winner is selected as the final ranking statistic.

Once the thresholds have been fixed, these consistency tests are applied to the on-source events and to the remaining off-source and injection events (those not used for tuning). The surviving on-source event with the largest significance (highest energy or power law statistic) is taken to be the best candidate for a gravitational wave signal and is referred to as the loudest event [21]. All surviving on-source events are assigned a false alarm probability by comparison to the distribution of loudest events from the off-source trials. Any on-source event with probability  $p < 0.01$  is subjected to additional checks to try to determine the origin of the event and additional background time slide trials are performed to improve the accuracy of the false alarm probability estimate. After the  $p$  values have been determined for the loudest events associated with each of the 158 HEN events, the collective set of  $p$  values is tested for consistency with the null hypothesis (no GW signal) using the binomial test, discussed in section 4.5.4. We also set a frequentist upper limit on the strength of gravitational waves associated with each neutrino trigger, as discussed in section 4.6.2.

### 4.5.3 Low-frequency and high-frequency GW analyses

The analysis procedure described in the previous section has been implemented in the X-PIPELINE. Given our knowledge of possible GW sources discussed in chapter 1, the most likely detectable signals at extra-galactic distances are in the low-frequency band (LF,  $f \lesssim 500$  Hz), where the detectors have maximum sensitivity (see Figure 3.5). At the same time, the computational cost of the X-PIPELINE analysis increases at high frequencies. This is due in part to the extra data to be analyzed, but also to the need for finer-resolution sky grids to keep time delay errors much smaller than one GW period. We therefore split the gravitational wave band into two regions: 60-500 Hz and 500-2000 Hz.

The low-frequency band is analyzed for all HEN events. Such a search is computationally feasible while covering the highest-sensitivity region of the GW detectors. However, compact objects such as neutron stars or collapsar cores have characteristic frequencies for GW emission above 500 Hz. Such emissions might be detectable from galactic sources such as soft gamma repeater giant flares, or possibly from nearby galaxies. Since the computational cost in the high-frequency range for all HEN events is prohibitive with the current analysis pipeline, we perform the 500-2000 Hz (high frequency HL) analysis on the 3L+ HEN events only. The 3L+ events are a small subset ( $\sim 10\%$ ) of the total trigger list and have the smallest sky position uncertainties, and therefore the smallest computational cost for processing. To further reduce this cost, we use the same sky grid for the high-frequency search as was used at low frequencies, after determining that the loss of sensitivity is acceptable. The HF analysis is performed independently of the low-frequency analysis (e.g. independent tuning, background estimation) using the identical automated procedure.

### 4.5.4 Binomial test

A quantitative analysis of the significance of any gravitational-wave event must take into account the trial factor due to the number of neutrino events analyzed. We use the *binomial test* [22], as the statistical method to look for a GW signature associated with individual neutrino candidates. Under the null hypothesis, the false alarm probabilities (FAPs)  $p$  for each HEN loudest event are expected to be uniformly distributed between 0 and 1. The binomial test compares the measured  $p$  values (in the on-source window) to the null distribution to determine if there is an excess which may have been due to the cumulative effect of weak GW signals.

The binomial test considers a number of events,  $N_{\text{tail}}$ , among the total number of events in the sample,  $N$ , that have to be tested and sorts their probabilities  $p_{i \in [1, N_{\text{tail}}]}$  in increasing order (i.e. decreasing significance):  $p_1 \leq p_2 \leq p_3 \leq \dots \leq p_N$ . For each of these probabilities,  $p_i$ , we



compute the cumulative binomial probability  $P_{\geq i}(p_i)$  for getting  $i$  or more events at least as significant as  $p_i$ :

$$\begin{aligned} P_{\geq i}(p_i) &= \sum_{j=i}^N P_j(p_i) \\ &= 1 - \sum_{j=0}^{i-1} P_j(p_i) \end{aligned} \tag{4.11}$$

where  $P_j(p_i)$  denotes the probability for getting  $j$  successes in  $N$  trials:

$$P_j(p_i) = \frac{N!}{(N-j)!j!} p_i^j (1-p_i)^{N-j}. \tag{4.12}$$

and  $N$  is the number of neutrino candidates analyzed. The lowest  $P_{\geq i}(p_i)$  for  $i \in [1, N_{\text{tail}}]$  will point to the most significant deviation from the null hypothesis. To assess the significance of the deviation, we repeat the test using  $p$  values drawn from a uniform distribution and count the fraction of such trials which give a lowest  $P_{\geq i}(p_i)$  smaller than that computed from the true measured  $p$  values.

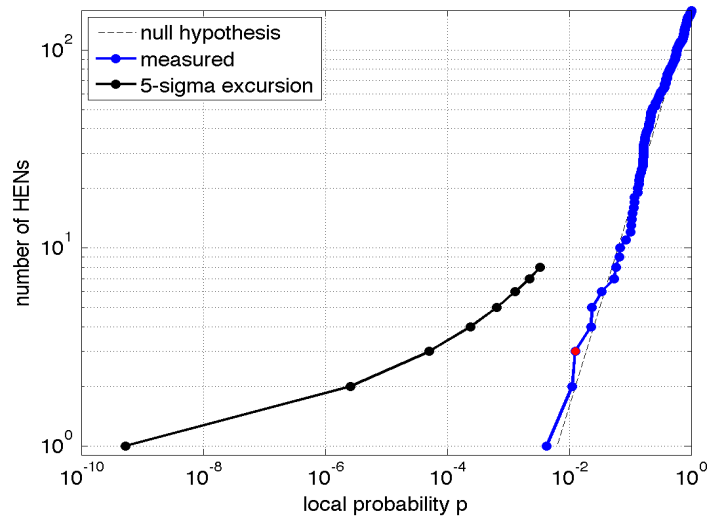
## 4.6 GW+HEN joint search results

### 4.6.1 Individual GW searches

After applying several quality criteria to both the GW and the HEN data a list of neutrino candidates was retained for further search of possible concomitant GW signals. Out of this list, 158 neutrinos (reconstructed with 2L) have been analyzed in the low frequency (LF) range, and 14 (reconstructed with a least 3L) have been analyzed in both the LF and the high frequency (HF) range. We choose  $N_{\text{tail}}$  to be 5% of  $N$ ; i.e.,  $N_{\text{tail}} = 8$  for the low frequency band and  $N_{\text{tail}} = 1$  for the high frequency band.

The smallest FAP was found to be ( $p = 0.01$ ), in the LF range. The corresponding neutrino trigger was localized on the sky by ANTARES telescope in direction  $(\alpha, \delta) = (204.4, -13.03)$  on Wed Sep 12, 2007. Additional time shifts totaling 18064 background trials yielded a refined FAP of  $p = 0.004$ , which is not significant given a trial factor of 158. This event came from the analysis of the H1, H2, and V1 data. Follow-up checks were performed, including checks of detector performance at the time indicated by monitoring programs and operator logs and

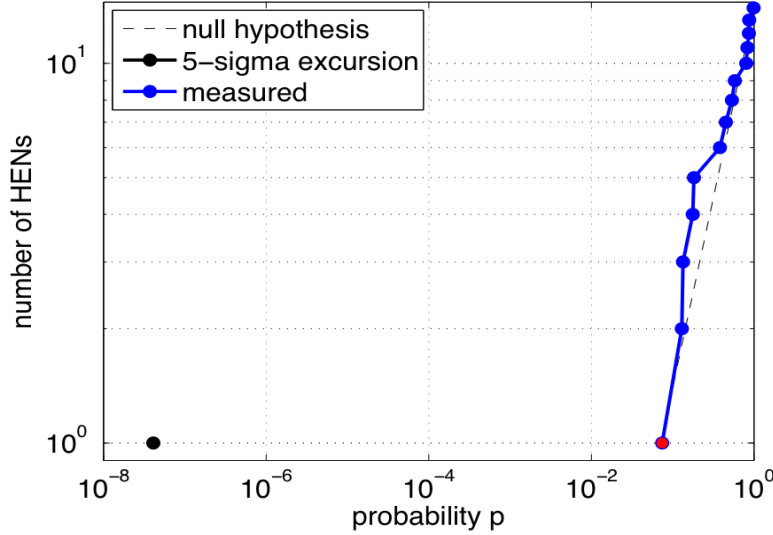
scans of data from detector and environmental monitoring equipment to look for anomalous behavior. While these checks did not uncover a physical cause for the event, they did reveal that it occurred during a glitching period in V1. We conclude that we have no clear gravitational wave burst signal associated with any of our sample of 158 neutrino events. The full analysis is therefore consistent with no GW events being present. Figures 4.28 and 4.29 show the cumulative distribution of  $p$ -values measured in the LF and HF analyses. In both cases the measured  $p$ -values are consistent with the null hypothesis. We also found no candidates in the HF band.



**Figure 4.28** – Distribution of observed  $p$  values for the loudest GW event associated with each neutrino analysed in the low frequency analysis. The red dot indicates the largest deviation of the low  $p$  tail from the uniform distribution null hypothesis; this occurs due to having the three loudest events below  $p_3 \sim 0.013$ . Deviations this large or larger occur in approximately 64% of experiments under the null hypothesis. The black line shows the threshold for a 5-sigma deviation from the null hypothesis.

## 4.6.2 GW upper limits

The sensitivity of the GW search is determined by a Monte-Carlo study. For each neutrino trigger, we add simulated GW signals to the on-source data and repeat the analysis described in section 4.5. We consider that the simulated signal is detected if it produces an event louder than the loudest on-source event after all event tests have been applied. We define a 90% confidence level lower limit on the distance to the source as the maximum distance  $D_{90\%}$  such that for any distance  $D \leq D_{90\%}$  the probability of detection is 0.9 or greater.



**Figure 4.29** – Distribution of observed  $p$  values for the loudest GW event associated with each neutrino analysed in the high frequency analysis. The red dot indicates the largest deviation of the low  $p$  tail from the uniform distribution null hypothesis; since  $N_{\text{tail}} = 1$ , this is constrained to occur for  $p_1$ . Deviations this large or larger occur in approximately 66% of experiments under the null hypothesis. The black dot shows the threshold for a 5-sigma deviation from the null hypothesis.

**Injected waveforms:** We added different burst-type signals to the raw data. The *ad hoc* waveforms are Gaussian-modulated sinusoids already introduced in section 3.7.3:

$$h_+ = \frac{(1 + \cos^2 \iota)}{2} \frac{h_{\text{rss}}}{(2\pi\tau^2)^{\frac{1}{4}}} e^{-\frac{(t-t_0)^2}{4\tau^2}} \cos 2\pi f_0(t - t_0), \quad (4.13)$$

$$h_\times = \cos \iota \frac{h_{\text{rss}}}{(2\pi\tau^2)^{\frac{1}{4}}} e^{-\frac{(t-t_0)^2}{4\tau^2}} \sin 2\pi f_0(t - t_0). \quad (4.14)$$

Here  $f_0$  is the central frequency,  $t_0$  is the central time, and we chose  $\tau = 1/f_0$  as the duration. We use central frequencies of 100 Hz, 150 Hz, and 300 Hz for the low-frequency analysis and 554 Hz and 1000 Hz for the high-frequency search. The quantity  $h_{\text{rss}}$  is the root-sum-square signal amplitude:

$$h_{\text{rss}} \equiv \sqrt{\int h_+^2(t) + h_\times^2(t) dt}. \quad (4.15)$$

This amplitude is related to the total energy  $E_{\text{GW}}$  in the gravitational-wave burst by:

$$E_{\text{GW}} = \frac{2}{5} \frac{\pi^2 c^3}{G} h_{\text{rss}}^2 f_0^2 D^2. \quad (4.16)$$

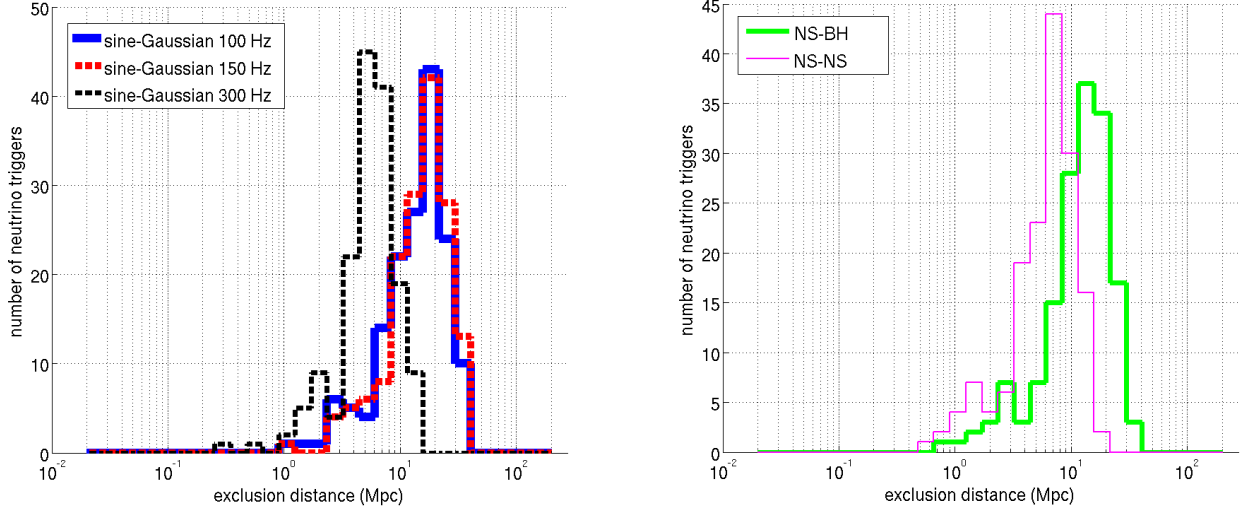
#### 4.4.6 GW+HEN joint search results

This waveform is consistent with the GW emission from a rotating system viewed from an inclination angle  $\iota$  to the rotational axis. We select the inclination uniformly in  $\cos \iota$  with  $\iota \in [0^\circ, 5^\circ]$ . This corresponds to a nearly on-axis system, such as would be expected for association with an observed long GRB. For astrophysical injections we use the gravitational-wave emission of inspiraling neutron star and black hole binaries, which are widely thought to be the progenitors of short GRBs. Specifically, we use the post-Newtonian model for the inspiral of a double neutron star system with component masses  $m_1 = m_2 = 1.35M_\odot$ , and the one for a black-hole-neutron-star system with  $m_1 = 5M_\odot$ ,  $m_2 = 1.35M_\odot$ , as discussed in Chapter 1. We set the component spins to zero in each case. Motivated by estimates of the jet opening angle for short GRBs, we select the inclination uniformly in  $\cos \iota$  with  $\iota \in [0^\circ, 30^\circ]$ .

For each HEN trigger, the injections are distributed uniformly in time over the on-source window. The injection sky positions are selected randomly following the estimated probability distribution (see Eq. 4.7) for the HEN trigger, to account for the uncertainty in the true HEN direction of incidence. The polarization angle (orientation of the rotational axis on the sky) is distributed uniformly. Finally, the amplitude and arrival time at each detector is perturbed randomly to simulate the effect of calibration errors in the LIGO and Virgo detectors.

**Exclusion distances:** For each waveform type (sine-Gaussians at 100, 150, 300, 554, 1000 Hz, and  $1.35M_\odot$ - $1.35M_\odot$  and  $5M_\odot$ - $1.35M_\odot$  inspirals), injections are performed over a range of amplitudes. For the inspiral signals, each amplitude corresponds to a well-defined distance. We can associate a physical distance to each amplitude for the sine-Gaussian waveforms as well, by assuming a fixed energy in gravitational waves. For concreteness, we select  $E_{\text{GW}} = 10^{-2}M_\odot c^2$ . This value corresponds to the optimistic limit of possible gravitational-wave emission by various processes in the collapsing cores of rapidly rotating massive stars [23–26]; more conservative estimates based on 3D simulations have been made in [27–31].

The exclusion distance is defined as the largest distance at which in 90% of the cases the event corresponding to the GW signal would be louder than the loudest on-source event found in the data. For each type of gravitational wave simulated, the distributions of exclusion distances for our neutrino sample are shown in Figures 4.30 and 4.31. For binary neutron star systems of  $(1.35 - 1.35)M_\odot$  and black hole - neutron star systems of  $(5 - 1.35)M_\odot$  typical distance limits are 5 Mpc and 10 Mpc respectively. For the sine-Gaussian waveforms in the low-frequency band the typical distance limits are between 5 Mpc and 17 Mpc, while for those in the high-frequency band the typical limits are of order 1 Mpc.



**Figure 4.30** – Low-frequency analysis: the left plot is the histogram for the sample of analyzed neutrinos of the distance exclusions at the 90% confidence level for the 3 types of circular sine-Gaussian models considered: 100 Hz, 150 Hz and 300 Hz. A standard siren gravitational wave emission of  $E_{GW} = 10^{-2} M_{\odot} c^2$  is assumed. The right plot shows histogram across the sample of analyzed neutrinos of the distance exclusions at the 90% confidence level for the 2 families of binary inspiral models considered: NS-NS and BH-NS.

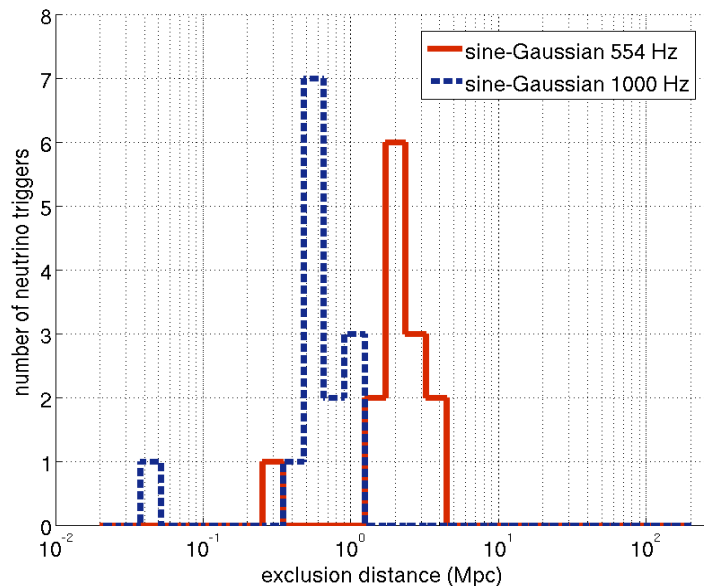
## 4.7 Astrophysical implications

### 4.7.1 Upper limits on joint source populations

The present search for GW and HEN correlations in space and time revealed no evidence for coincident events. In accordance with the Poisson statistics, this implies a 90% confidence level upper limit on the rate of detectable coincidences of  $2.3/T_{\text{obs}}^{\text{com}}$ , where  $T_{\text{obs}}^{\text{com}} \approx 91.36$  days is the duration of coincident observations. This can be expressed as a limit on the rate density (number per unit time per unit volume)  $\rho_{\text{GW-HEN}}$  of objects which would yield coincident GW and HEN signals:

$$\rho_{\text{GW-HEN}} V_{\text{GW-HEN}} \leq \frac{2.3}{T_{\text{obs}}} . \quad (4.17)$$

In this expression,  $V_{\text{GW-HEN}}$  is the volume of universe probed by the present analysis for typical GW-HEN sources and 2.3 is the in accordance with the a Poisson process. This volume is related to the GW and HEN detection efficiencies as a function of distance, and must be estimated for typical emission models. We take as fiducial sources two classes of objects: the final merger phase of the coalescence of two compact objects (short GRB-like), or the collapse



**Figure 4.31** – High-frequency analysis: the histogram for the sample of analysed neutrinos of the distance exclusions at the 90% confidence level for the 2 frequencies of circular sine-Gaussian models considered: 554 Hz and 1000 Hz.

of a massive object (long GRB-like), both followed by the emission of a relativistic hadronic jet. The corresponding HEN and GW detection horizons (or exclusion distances) have been estimated respectively in sections 4.4 and 4.6.2. In the case of short GRBs,  $d_{HEN} \sim 4.41$  Mpc and  $d_{GW} \sim 5$ -10 Mpc depending on the binary masses, while for long GRBs they increase to  $d_{HEN} \sim 12.55$  Mpc and  $d_{GW} \sim 10$ -20 Mpc (under the optimistic assumption of  $E_{GW} = 10^{-2} M_{\odot} c^2$ ). The effective volume probed by the GW+HEN joint analysis can be written as:

$$V_{GWHEN} = \int_0^{\infty} P_{GWHEN}(r) 2\pi r^2 dr \int_{-\pi/2}^{\pi/2} \epsilon_{HEN}(\delta) \cos \delta d\delta \quad (4.18)$$

where  $P_{GWHEN}(r) = P_{HEN}(r) \times P_{GW}(r)$  is the detection probability for a joint emitter and  $\epsilon(\delta)$  is the visibility in ANTARES of a source at declination  $\delta$ . This integral effectively extends until a certain distance  $d_{GWHEN} \simeq \min(d_{HEN}, d_{GW})$ . As  $d_{GW} > d_{HEN}$  for the sources considered hereabove, we approximate  $P_{GW}(r)$  by a step function ( $P_{GW}(r) = 1$  for  $r < d_{GW}$ , 0 elsewhere) and fold it with the probability  $P_{HEN}(r)$  to detect at least one neutrino from the source (as described in section 4.4 and Figure 4.16). From Eq. 4.17 one can then derive approximate limits on the population density of joint GW+HEN emitters:  $\rho_{GW-HEN}^{SGRB} \lesssim 10^{-2} \text{Mpc}^{-3} \text{yr}^{-1}$  for

SGRB-like sources, and  $\rho_{\text{GW-HEN}}^{\text{LGRB}} \lesssim 10^{-3} \text{Mpc}^{-3} \text{yr}^{-1}$  for LGRB-like sources.

### 4.7.2 Comparison of limits with existing estimates

[32, 33] suggest a local rate density of SGRB of  $\rho_{\text{SGRB}} \lesssim 10^{-9} \text{Mpc}^{-3} \text{yr}^{-1}$ , and the abundance of binary neutron star mergers, their assumed progenitors, is estimated to be  $\rho_{\text{NS+NS}} \sim 10^{-6} \text{Mpc}^{-3} \text{yr}^{-1}$  [34], well below the reach of the present search ( $\rho_{\text{GW-HEN}}^{\text{SGRB}} \lesssim 10^{-2} \text{Mpc}^{-3} \text{yr}^{-1}$ ). With  $T_{\text{obs}} = 1$  year, an improvement of a factor 10 on the detection distance is required in order to be able to constrain the fraction of mergers producing coincident GW+HEN signals. [32] estimate a total rate of long GRBs of  $\rho_{\text{LGRB}} \sim 3 \times 10^{-8} \text{Mpc}^{-3} \text{yr}^{-1}$ ; these sources are closely related to Type II and Type Ibc core-collapse supernovae. The local rate of SNIbc is  $\rho_{\text{SNIbc}} \sim 2 \times 10^{-5} \text{Mpc}^{-3} \text{yr}^{-1}$ , whereas  $\rho_{\text{SNII}} \sim 2 \times 10^{-4} \text{Mpc}^{-3} \text{yr}^{-1}$ , relatively close to the obtained limit  $\rho_{\text{GW-HEN}}^{\text{LGRB}} \lesssim 10^{-3} \text{Mpc}^{-3} \text{yr}^{-1}$  under our optimistic assumptions of GW emission in this scenario. A factor 10 only is required in order to constrain the fraction of star collapses producing coincident GW-HEN signals, which translates into a required improvement of 2 on the detection distance.

## 4.8 Conclusions

In this chapter we have described the first joint GW+HEN search using coincident data taken in 2007 from the ANTARES neutrino telescope and the Virgo/LIGO GW interferometers. The absence of GW triggers in coincidence with a list of preselected HEN candidate events has allowed to establish limits on the rate density  $\rho_{\text{GW-HEN}}$  of joint GW+HEN emitting systems. These limits are however not stringent enough to constrain the density of realistic, known candidate GW+HEN progenitors such as binary neutron star mergers or Type II/Ibc core-collapse supernovae. An increased sensitivity can be achieved by performing similar coincidence analyses using other data sets provided by the same instruments. The next chapter presents an improved analysis method applied to the joint data sample collected by ANTARES in its 12L configuration concomitantly with science runs conducted with enhanced Virgo and LIGO interferometers in 2009-2010. This analysis is described in chapter 5.

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# CHAPTER 5

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## GW+HEN ANALYSIS FOR 12L-S6/VSR2-3

### 5.1 Summary

We have presented in the previous chapter results from the first joint search for gravitational-wave bursts associated with high energy neutrinos using the ANTARES, the Virgo and the LIGO data from 2007. In this chapter we present results from the analysis of their 2009-2010 data. A new method is proposed. The neutrinos are selected by a joint optimisation procedure taking into account efficiencies to the neutrino and gravitational-wave signals. The neutrinos have been reconstructed with a more sophisticated reconstruction algorithm, labelled Aafit, in contrast of the robust one (Bbfit) used in the previous search (Chapter 4). The search for GW in coincidence with these neutrinos are done using a specific GW search algorithm, labelled skymask-cWB, specifically prepared for this joint search. Below we describe further these data, the search strategies adopted and the final results.

### 5.2 Data set

#### 5.2.1 Description of ANTARES data

We select from the database 2184 runs from July 7th, 2009 through October 20th, 2010. This list of runs has been selected using data quality (DQ) requirement (see section 2.4). That is, we select all runs with QualityBasic flag greater than 1 ( $QB \geq 1$ ) and runs with run setup "physics". We discard all runs with duration  $< 5$  minutes. Taking into account these DQ criteria we get a duty cycle of 56%. Figure 5.1 shows the distribution of run numbers selected for the analysis. The total observation time (using only neutrino side) is  $T \equiv 266$  days.

A Monte Carlo simulation is performed to match the realistic condition of the data taking following the run by run approach (see section 2.5.5). These information (runsetup, mean rates, alignment, high rate veto, run duration) are taken from the data runs themselves and plugged

into the simulation. This method has been adopted recently by the ANTARES collaboration and is used by all ongoing analyses. A total of  $5 \times 10^8$  neutrinos are simulated using the GENHEN package in the energy range 100 GeV-100 PeV, with an energy spectrum  $dN/dE \propto E^{-\gamma}$ , where  $\gamma = 1.4$ , and in all zenith directions. The spectrum used to simulate neutrinos permits a later re-weighting according to a user specified flux. In this analysis the same neutrino sample is weighted differently to be used as atmospheric neutrinos according to the Bartol flux [2] or as astrophysical signal according to the GRB diffuse flux of Waxman and Bahcall [3] (see section 1.1.4) or  $E^{-2}$  flux [4]. The simulation of atmospheric muons is performed using Mupage package (see section 2.5). In this analysis we select all the events passing the 3N or T3 trigger's condition (see section 2.3.5). These events are then reconstructed with the Aafit reconstruction algorithm (see section 2.6.2).

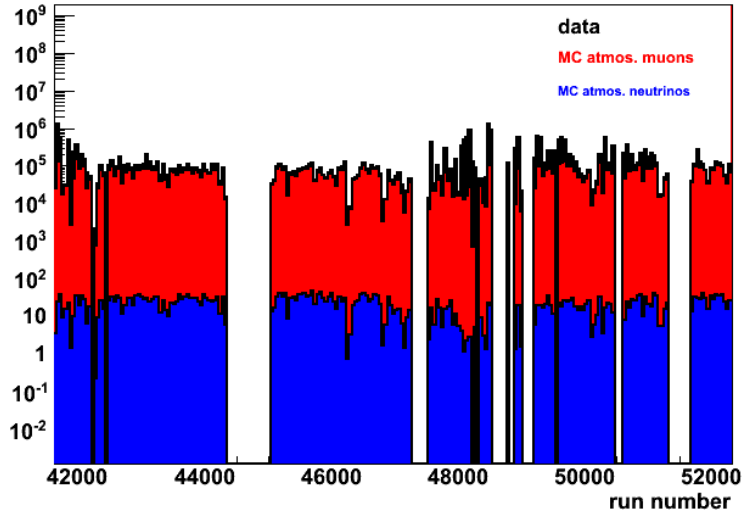


Figure 5.1 – Run numbers that passes the DQ requirements described in the text.

## 5.2.2 Description of Virgo and LIGO data

The GW data used in this search are the S6-VSR2/3 LIGO-Virgo data. Three detectors participated to this data taking namely LIGO-Livingston (L1), LIGO-Hanford (H1) and Virgo (V1). These data were collected between July 07, 2009 and October 21, 2010. LIGO S6 and Virgo VSR data are divided into four parts:

- Period A (S6A-VSR2): running from Tue July 7, 2009 at 21:00 UTC to Tue Sept. 1, 2009 at 00:00 UTC.

### 5.5.3 Gravitational wave event generation

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- Period B (S6B-VSR2): running from Saturday Sep 26, 2009 12:46:33 UTC, Friday Jan 8, 2010 22:00:00 UTC.
- Period C (S6C) : running from Friday Jan 8, 2010 22:00:00 UTC to Saturday Jun 26, 2010 00:00:00 UTC.
- Period D (S6D-VSR3): running from Saturday Jun 26 2010 00:00:00 UTC to Wednesday Oct 20 2010 15:00:00 UTC.

This search aims at detecting bursts of gravitational waves in the frequency range from 64 Hz to 2 kHz. Note that the detectors are most sensitive at about  $\sim 200$  Hz as can be seen from Figure 5.2. The sensitivity in the selected frequency range is within a factor of 10 of the best sensitivity. Each curve in Figure 5.2 shows the amplitude spectral density as a function of frequency. The vertical "spikes" are from mechanical vibrations in parts of the detector. The sensitivity of a detector can be expressed in terms of the amplitude spectral density, which is the square root of the power spectral density, since the strength of a gravitational wave signal is proportional to the strain induced in the interferometer. We use the calibrated data with LSC tag `LDAS_C02` and the Virgo tag `HrecV2` and `HrecV3`. The calibration uncertainty is estimated to be 20% in amplitude and 10 degrees in phase for LIGO and 5.5% in amplitude and 3 degrees in phase for Virgo. The data quality flags [5] aim at eliminating periods where data have poor quality (some or all of the detectors was particularly noisy e.g., due to internal malfunctioning and/or environmental disturbances).

### 5.2.3 The ANTARES, the Virgo and the LIGO joint data set

The search requests at least two GW detectors in operation. The concomitant data taking period between S6VSR2/3 and ANTARES 12L goes from July 7th, 2009 up to October 20th 2010 with some in between periods where one or no interferometer (IFO) was in science mode. In this period, the observation time for each IFO network is: 44.7 days (H1L1V1), 33.5 days (H1L1), 23.1 days (L1V1) and 27.4 days (H1V1). The sum of these partial periods gives the total concomitant observation time of  $\tau \equiv 128.7$  days.

## 5.3 Gravitational wave event generation

For this analysis we rely on a new detection pipeline `skymask coherent WaveBurst` which is a variant of the coherent WaveBurst (cWB) pipeline, presented in section 3.7.4 developed for the purpose of this search.

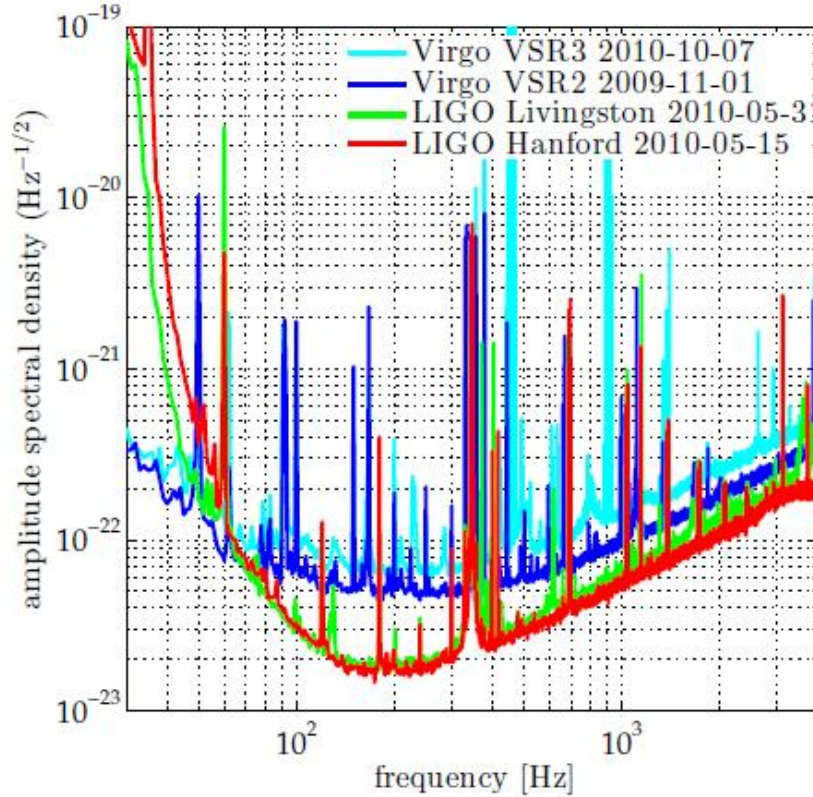


Figure 5.2 – Sensitivity of LIGO-Virgo during the S6-VSR2/3 period.

### 5.3.1 Skymask coherent WaveBurst pipeline

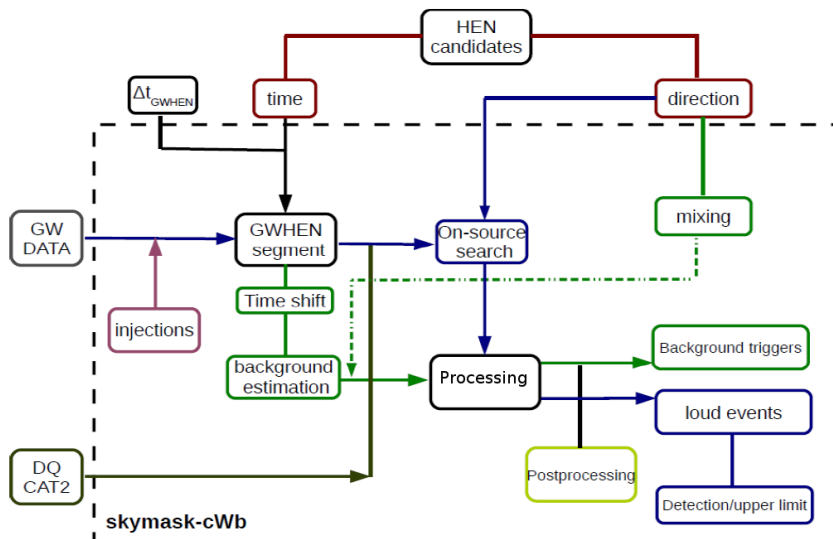
This pipeline has been developed to overcome limitations of earlier analysis schemes presented in section 3.7.4. In particular, it takes into account the lessons learned from the first ANTARES–LIGO/Virgo joint search (see Chapter 4) [6] based on the X-pipeline algorithm.

Core collapse supernovae being one of the potential source targets, the frequency bandwidth should extend to 2 kHz at least. We also expect many more neutrino candidate for this data set, of the order of  $\mathcal{O}(10^3)$ , which is an order-of-magnitude increase with respect to the previous analysis. The current implementation of the X-pipeline used for the first search would require a very large computing power to perform the analysis in a realistic time.

This is why we developed “skymask coherent Wave-Burst” (in short, s-cWB) [7], a variant of the cWB pipeline which reconstructs GW events only in an *a priori* sky area specified by a *sky mask*. This enables the analysis of periods with two GW detectors only (see Figure 5.4 for an illustration). We are thus able to cover the whole livetime. This pipeline is also computationally more efficient than the X-pipeline thus enabling the broadband analysis (up to 2 kHz) for order

### 5.5.3 Gravitational wave event generation

of thousands of neutrino triggers.

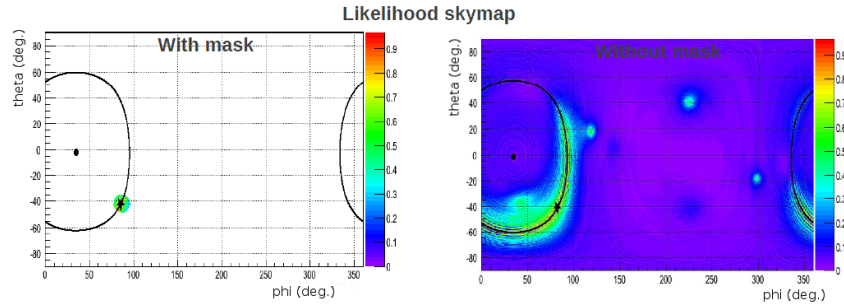


**Figure 5.3** – Schematic outline of the GW+HEN 12LS6VSR2-3 analysis pipeline.

As discussed in section 4.2 the time and direction of the neutrino candidates are exploited as input to the s-cWB pipeline. s-cWB selects GW data segments of length  $\Delta T$  centered about the  $t_\nu$ , i.e. *on-source* window (see section 4.2). It also takes into account the ASW associated to the direction of the neutrino candidate. The search for GW signal is thus restricted to areas on the sky defined by the provided ASW90% instead of scanning the whole sky. A grid, of same resolution as cWB, i.e.  $0.4 \times 0.4$  degree, is used within the ASW90% (see section 4.4.1). The neutrino PSF is taken into account as a probability distribution: each event inside this angular search window is weighted according to the PSF. Figure 5.3 shows a schematic view of the s-cWB pipeline used in this analysis. s-cWB defines the same coherent statistics as cWB, the most relevant ones for this study are the network correlation amplitude  $\rho$ , the network correlation coefficient  $net_{cc}$  and the network energy disbalance  $net_{ED}$ . While cuts on  $net_{cc}$  and  $net_{ED}$  are used to distinguish noise outliers from genuine GW signals, the final event selection is done through a cut over the statistic  $\rho$  which characterises the event significance [8]. We refer the reader to appendix B for the mathematical definition of those statistics.

#### 5.3.2 Background estimation

The method used in the cWB for background study is described in [9]. For completeness, we now describe the general principle. We remind that in a coherent analysis such as s-cWB, time delays are applied to each data streams in order to compensate the time taken by the wave to



**Figure 5.4** – Likelihood skymap of the reconstructed GW events in the case of 2 IFOs, without neutrino skymask (right) and with skymask (left).

propagate from one detector to the other. Thanks to this operation, GW signals from a given source direction are thus aligned in time. The time delays are necessarily smaller than the time-of-flight (at the speed of light) between Virgo and LIGO is about to 27 ms and 10 ms for the Handford and Livingston detector respectively. The method used for background estimation consists in applying additional and non-physical time-shifts to one or more GW data streams as described in section 3.7.2. The time-shifts applied for the background estimation are much larger than the time-of-flight added to the noise auto-correlation time scale (which dominate the sum). These time-shifts erases any correlation between pairs of GW detectors due to any GW signal. The analysis is repeated over several time-shifted data set. The distribution of the resulting events provides an estimate of the experiment background.

In addition to the time-shift analysis s-cWB allows the possibility to estimate background using mixing skymasks and/or combine both methods. While skymask mixing is convenient numerically, we observed that it has limitations because it introduces correlation between trials especially in the case of two-detector network. We consider it as an option for the final analysis. The analysis cuts are tuned based on the estimated background.

We evaluated the background and performance of s-cWB over a simulated neutrino test sample. This study is approximately representative of the final analysis using real neutrino candidate events. The fake neutrino set consisted in 1000 events randomly generated uniformly distributed over the entire sky and during the S6A/VSR2 period. The neutrino localisation uncertainties were chosen to mimick that of 2007 neutrino sample (see chapter 4). We used the modelled 'g'-search which is optimized for circularly polarized GW signals and we disabled regulation. We performed multiple (101) time-shift and (70) skymask mixing experiments between L1, H1 and V1 detectors. This leads to the background estimates presented in Figure 5.5. We adjusted the rejection cuts on  $net_{cc}$  and  $net_{ED}$  to mitigate the long background tails due to the absence of regulation. For an objective FAR of  $10^{-7}$  Hz we therefore need a selection

cut  $\rho \geq \rho_{threshold} = 3.25$ .

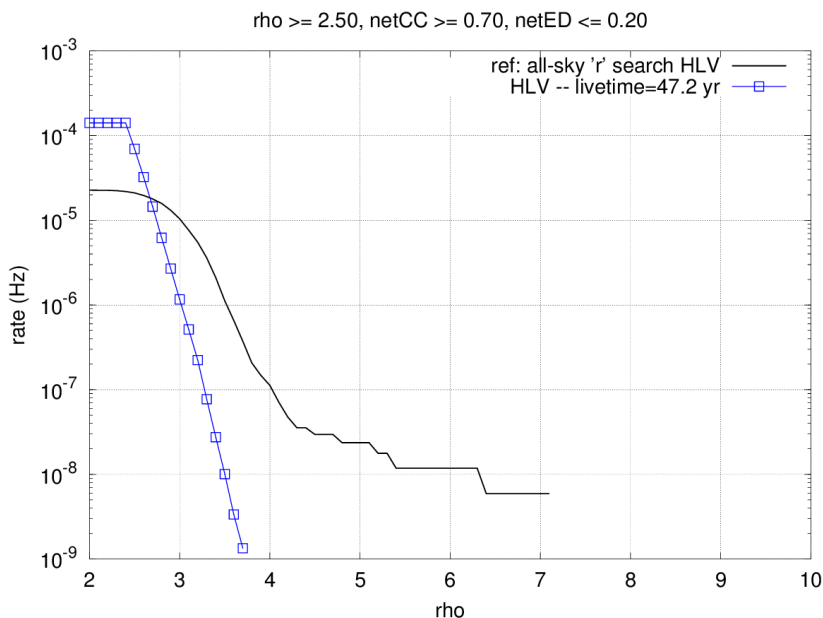
### 5.3.3 Sensitivity estimates

In order to test the performance of the s-cWB we add simulated signals of various amplitudes and waveforms to data (see section 3.7.3). The simulated signals are produced using the Burst-MDC package described in [10].

For each neutrino candidate, we simulate randomly a set of source position according to the PSF. Fake signals are added every  $\sim 100$  seconds mimicking the GW signature from sources at those position. We test the probability of detection and correct recovery for various amplitudes by applying multiplicative factors from weak to strong signals covering the full range from 0 to 100 % efficiency. The resulting data stream is processed identically to the standard analysis.

For each waveform, we evaluate the efficiency for detection as a function of the gravitational wave strain  $h_{rss}$  which is the incoherent sum of the “+” and “ $\times$ ” polarizations defined in Equation (4.15), see Figure 5.6. As expected, the efficiencies are essentially 100% for large values of  $h_{rss}$ , consistent with noise and thus 0% efficiency for small  $h_{rss}$ , and transitioning over a narrow intermediate range of  $h_{rss}$ . The resulting curve is empirically fitted by a sigmoid curve in  $\log_{10}(h_{rss})$ .

We produced the efficiency curves associated to the analysis of the test neutrino sample



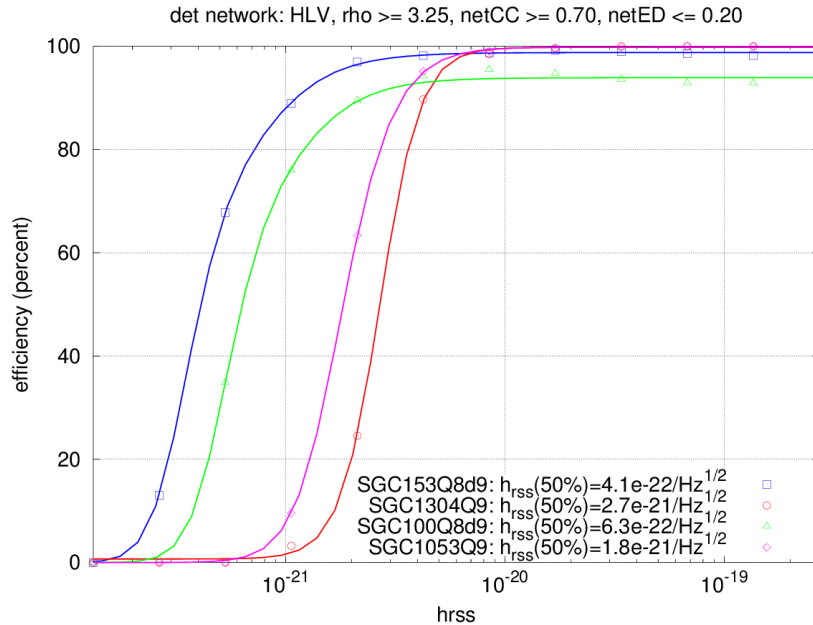
**Figure 5.5** – Background estimate for the test neutrino sample as described in the text and considering triple detector network HLV compared to the all sky background for the same data taking.



introduced in the previous section. We performed multiple injections of circularly polarized Sine-Gaussian waveforms as in Equations (3.16) and (3.17) at four different frequencies i.e., 153, 100, 1053 and 1304 Hz. For selection cut corresponding to the FAR =  $10^{-7}$  Hz we get  $h_{rss}^{50\%} = 4.1 \times 10^{-22}/\sqrt{\text{Hz}}$  at 153 Hz. This can be compared to the result obtained with the X-pipeline in Chapter 4, namely  $h_{rss}^{50\%} = 3 \times 10^{-22}/\sqrt{\text{Hz}}$  at the same frequency and for the same FAR requirement. Despite the absence of the (numerically expensive) event-by-event optimization of the cuts performed by the X-pipeline, the s-cWB performs at a comparable level.

## 5.4 Optimization procedures

The selection of the neutrino events can, in principle, be based on several approaches. Independently from the GW interferometers, the selection can be made in order to discard as much as possible misreconstructed atmospheric muons (resulting in a high purity sample of atmospheric neutrinos). Another criterion would be to filter the events in order to establish the best possible limit on some putative astrophysical neutrino flux (minimizing the so-called model rejection factor MRF). Reversely one can target a discovery by maximizing the model discovery



**Figure 5.6** – Sensitivity estimate obtained with the test neutrino sample as described in the text and for triple detector network HLX.

potential MDP (minimizing the model discovery factor MDF) for this particular neutrino flux.

The third approach is completely dependent of the GW interferometers. This approach maximises a joint figure-of-merit (FOM) by combining the individual efficiencies of HEN and GW. FOM relies on our knowledge on the false alarm probability.

In the following subsections, we describe the three latter options. In the all cases, the signal is assumed to be a diffuse flux (as the sources of interest are distributed anywhere in the sky). We use the Waxman-Bahcall flux for unresolved GRBs, since the energy spectrum is supposed to be representative of generic long- and short-GRBs, (see section 1.1.4).

### 5.4.1 Model rejection factor and Model discovery potential

**Model rejection factor (MRF):** The model rejection factor (MRF) [11] is used in this search to optimize selection criteria in order to place the best upper limit on the signal from an assumed theoretical model. We use in this work the GRB diffuse flux of Waxman-Bahcall. The computation relies **only on Monte Carlo simulation sample** to estimate the expected background events ( $n_b$ ) and true neutrino signal events ( $n_s$ ). The authors in [11] introduce the *average upper limit* at 90% C.L, when  $n_s=0$ , as follows:

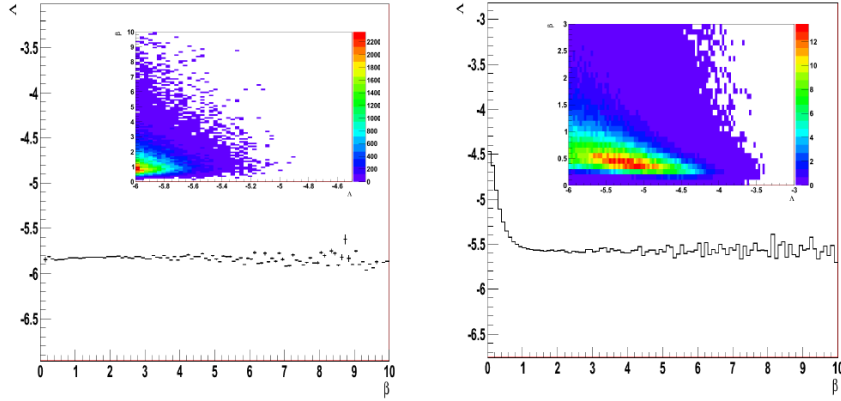
$$\bar{\mu}_{90}(n_b) = \sum_{n_{obs}}^{\infty} \mu_{90}(n_{obs}, n_b) \frac{(n_b)^{n_{obs}}}{n_{obs}!} \exp(-n_b) \quad (5.1)$$

where  $\mu_{90}(n_{obs}, n_b)$  is the Feldman-Cousins (F.C) upper limit [12]. That is, the best upper limit is obtained when the ratio between  $\bar{\mu}_{90}(n_b)$  and  $n_s$ , labeled MRF, is minimum for a set of cuts:

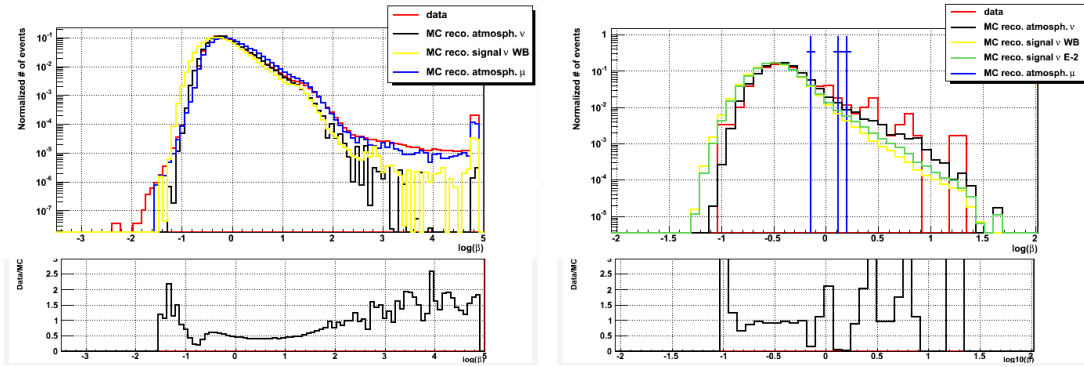
$$MRF(\text{cuts}) = \frac{\bar{\mu}_{90}(n_b(\text{cuts}))}{n_s(\text{cuts})} \quad (5.2)$$

In this work we compute  $n_b$  and  $n_s$  against the reconstruction quality parameter  $\Lambda$ , introduced in section 2.6.2. It's worth noting that  $\Lambda$  and  $\beta$  are correlated as shown in Figure 5.7 right. We show also in Figure 5.8 distributions of  $\beta$  for upgoing events with and without cutting on  $\Lambda$ . Thus we decide not to use  $\beta$  in the optimisation. The distribution of  $\Lambda$  is shown in Figure 5.9 for only upgoing events. It's extrapolated to high  $\Lambda$  values using a Gaussian distribution.

With a number of background events of order of  $10^4$  for small  $\Lambda$ , the computation of  $\bar{\mu}_{90}(n_{obs}, n_b)$  becomes considerably slow because of F.C. algorithm at high statistics. To speed up the computation time we model the upper limit by an analytical parameterization (see



**Figure 5.7** – Distribution of  $\Lambda$  as function of  $\beta$  parameter for atmospheric muons (left), for atmospheric neutrinos (right). Only ongoing events are selected.



**Figure 5.8** – Distributions of  $\beta$  parameter for data and MC without (top) and with (bottom) cut on  $\Lambda$  ( $\Lambda > -5$ ). Only ongoing events are selected.

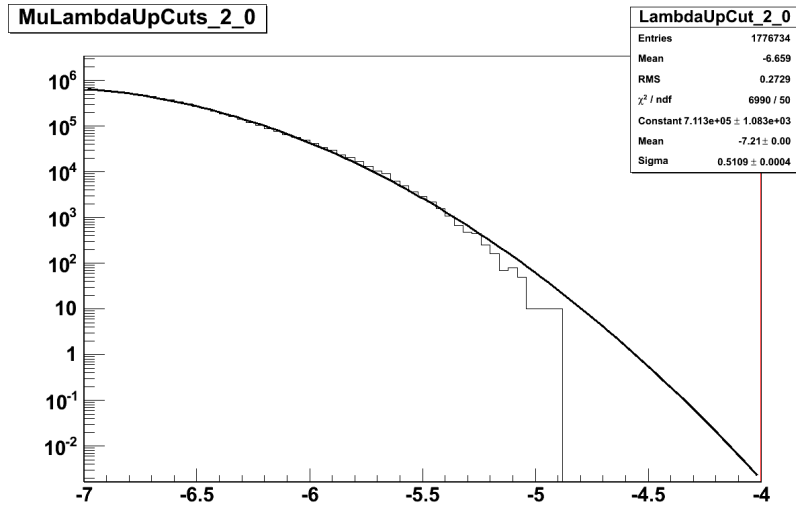
appendix A for further mathematical details):

$$\tilde{\mu}_Q(n_{obs}, n_b) = \left( \frac{-\sqrt{2} \cdot \text{Erf}^{-1}(2Q - 1) + \sqrt{2 \text{Erf}^{-1}(2Q - 1)^2 + 4n_{obs}}}{2} \right)^2 - n_b \quad (5.3)$$

where Erf is the error function and  $Q = 90\%$  is the significance level. In analogy with Equation 5.1,  $\tilde{\mu}_Q(n_{obs}, n_b)$  is weighted with its Poisson probability of occurrence. Thus the model rejection factor becomes:

$$M\tilde{R}F(\text{cuts}) = \frac{\tilde{\mu}_{90\%}(n_b(\text{cuts}))}{n_s(\text{cuts})} \quad (5.4)$$

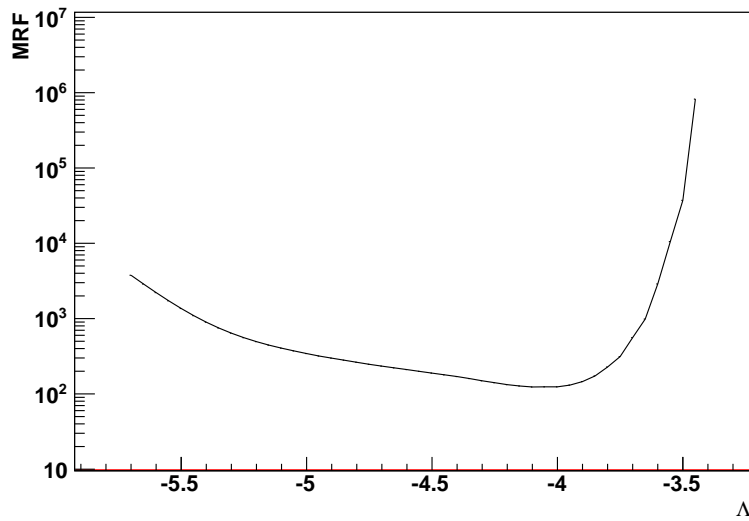
In Figure 5.10 is shown the modified ratio (Equation (5.4)) as function of  $\Lambda$ . We define  $\Lambda_{min}$  in such way the ratio Equation (5.4) is minimum. From the curve 5.10 we find a minimum for



**Figure 5.9** – Distribution of the track quality parameter  $\Lambda$  for misreconstructed atmospheric muons. The distribution is fitted by a Gaussian function.

$\Lambda_{min} = -4.1$ . The final number of events passing  $\Lambda_{min}$  is  $\sim 20$  events.

**Model discovery potential:** We report in this section a commonly used technique in high energy astrophysics, the so-called "Model Discovery Potential" (MDP) [13, 14], for optimizing quality cuts in order to maximize the probability of detecting an excursion of  $n\sigma$  (a "discovery")



**Figure 5.10** – MRF as a function of  $\Lambda$  completed as described in the text. The minimum value is found for  $\Lambda = -4.1$

with a given C.L. We introduce  $n_{crit}$  the smallest number of events needed to claim a detection at a significance level  $\alpha$ . A standard way to quantify this number is to calculate the probability for observing  $\geq n_{crit}$  under the background only hypothesis:

$$\begin{aligned} P(\geq n_{crit}|\mu_b) &= \sum_{n=n_{obs}}^{\infty} P(n|\mu_b) \\ &= 1 - \sum_{n=0}^{n_{obs}-1} P(n|\mu_b) \end{aligned} \quad (5.5)$$

If  $P(\geq n_{crit}|\mu_b) < 5.73 \times 10^{-7}$  we can report that we have a detection at  $5\sigma$  level. This probability is called  $p_{value}$ , i.e  $p = P(\geq n_{crit}|\mu_b)$ . Small  $p_{value}$  is evidence against null hypothesis. If in addition to  $n_b$  a real signal  $\mu_s$  is assumed then the probability that we would observe at least  $n_{crit}$  becomes:

$$\begin{aligned} P(\geq n_{crit}|\mu_b + \mu_s) &= \sum_{n=n_{obs}}^{\infty} P(n|\mu_b + \mu_s) \\ &= 1 - \sum_{n=0}^{n_{obs}-1} P(n|\mu_b + \mu_s) \\ &= 1 - \beta \end{aligned} \quad (5.6)$$

$1 - \beta$  is commonly known as the statistical power. Fixing  $(1 - \beta)$  allows to calculate the corresponding value of  $\mu_s$  for which Equation (5.6) is satisfied, i.e.  $\mu_{lds}$ . We then define the model discovery factor (MDF) as the ratio between  $\mu_{lds}$  and  $\mu_s$ .

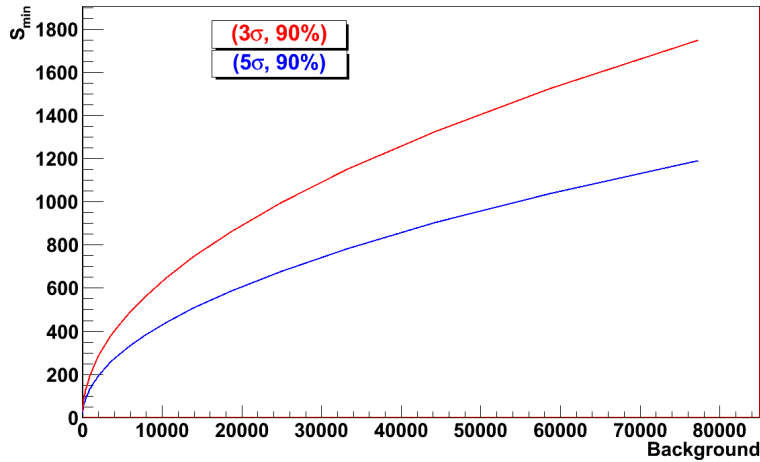
$$MDF(\Lambda) = \frac{\mu_{lds}(\Lambda)}{\mu_s(\Lambda)} \quad (5.7)$$

An optimization of the analysis which aims at minimizing the MDF against  $\Lambda$  for a given statistical power and a given significance (C.L.), has to be done numerically. From other side Punzi derived in [14] an analytical parameterization of  $\mu_{lds}$  by approximation of Poisson distribution by Gaussian one:

$$S_{min} = \frac{cl^2 + 2\sigma\sqrt{n_b} + cl \times \sqrt{cl^2 + 4\sigma\sqrt{n_b} + 4n_b}}{2} \quad (5.8)$$

where  $\sigma$  and  $cl$  are the desired *number* of sigmas and C.L respectively (see Figure 5.11). Thus the MDF can be redefined by Equation (5.9):

$$M\tilde{D}F(\Lambda) = \frac{S_{min}}{\mu_s} \quad (5.9)$$



**Figure 5.11** – Minimum number of signal events versus number of background events.

A study of MDF for a given  $(\sigma, cl)$  as a function of two reconstruction parameters,  $\Lambda$  and  $\beta$  is shown in Figure 5.12. It shows that the MDF has no clear minimum in the accessible parameter space. We confirm this with a 2D distribution of  $\Lambda$  vs  $\beta$  (insert in color in Figure 5.13), which shows the mean value of  $\Lambda$  for each bin in  $\beta$ . Figure 5.13 left shows that there is no minimum of the MDF as a function of  $\beta$ . On the contrary there is a clear minimum of the MDF as a function of  $\Lambda$ . Thus, we restrict this study to the only  $\Lambda$  parameter.

In this work we minimize Equation (5.9) against  $\Lambda$ . Figure 5.14 shows the result for different number of  $\sigma$  and number of  $cl$ . The minimum is obtained for  $\Lambda_{min} = -4.9$  and is roughly the same whatever the assumed number of  $\sigma$  and  $cl$ . The number of events surviving this cut is  $\sim 600$ .

Figure 5.14 shows a rather flat behaviour of the MDF value against  $\Lambda$  (above -5.5). As a consequence the  $\Lambda$  value found to minimize the MRF is not far from the minimum value of the MDF. However, the optimal MRF cut shows a factor 2 loss in the detectable flux (proportional to the MDF) and the optimal cut for the MDF leads to a 3 times worse flux limit (proportional to the MRF). More over, these two approaches do not take into account the fact that we are

looking for common sources of GW and HEN. We conclude that none of these two approaches, often used in neutrino astrophysics, is fully satisfactory for our purpose. In the following section, we present a new optimization method that takes into account parameters from both GW and HEN data, as opposed to MRF and MDP approaches just described.

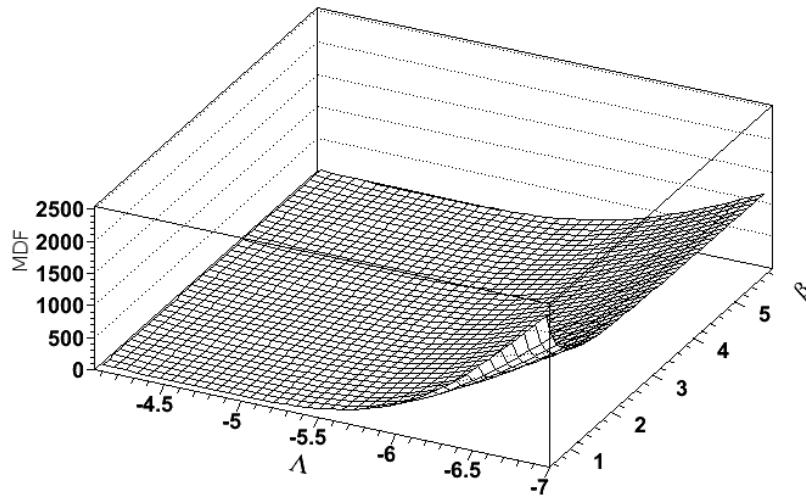


Figure 5.12 – The Model discovery factor in the two parameter space ( $\beta$ ,  $\Lambda$ ) for ( $3\sigma$ , 90%).

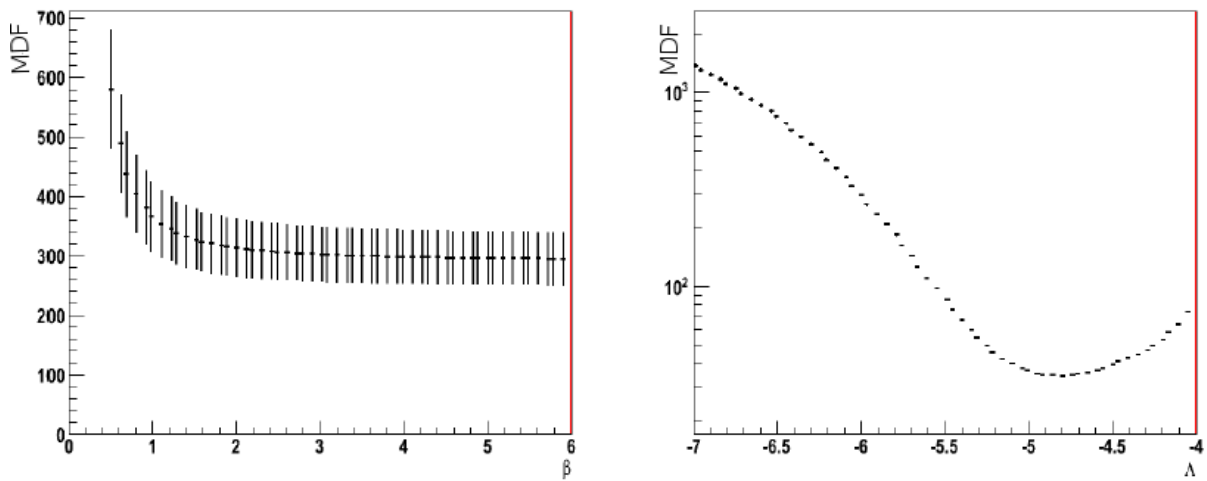
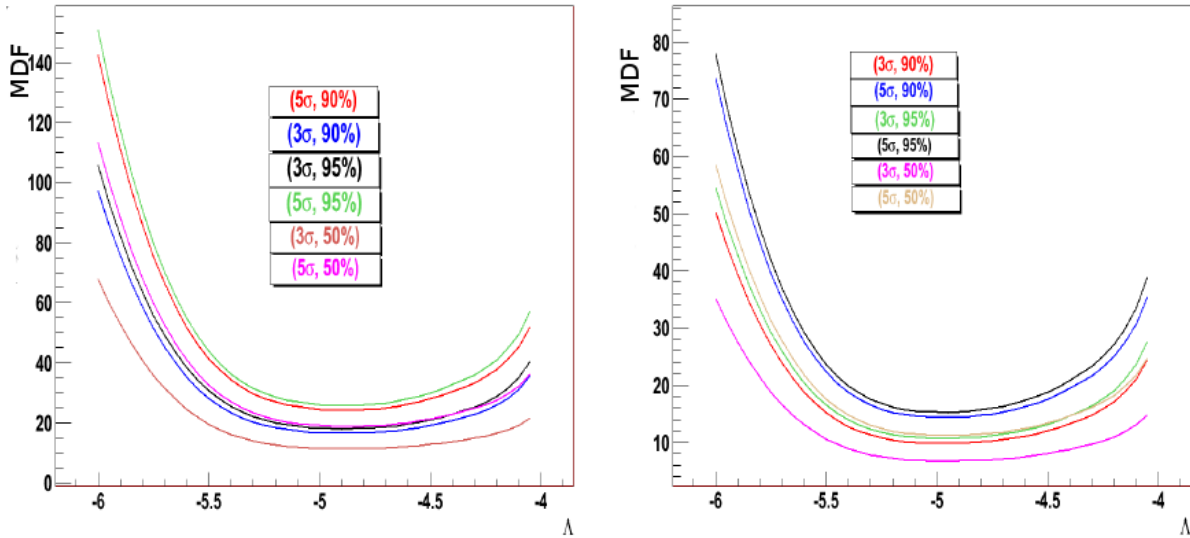


Figure 5.13 – Profile histogram of the MDF on  $\beta$  parameter (Left) and on  $\Lambda$  parameter (right).

### 5.5.5 Description of the joint optimization strategy



**Figure 5.14** – The model discovery factor for different number of  $\sigma$  and  $cl$  as function of  $\Lambda$ , for W&B GRB diffuse flux (left) and  $E^{-2}$  flux (right). The curves show that the minimum of the MDF is independent of the number of sigma  $n\sigma$  and the C.L.

## 5.5 Description of the joint optimization strategy

The two selection procedures described above are not fully satisfactory since they only apply to the neutrino data and do not take into account the impact of the selection onto the GW search. Such independent selection criteria were used in the previous joint searches of HE neutrinos and GW (see chapter 4) leading to suboptimal searches. Here we propose a novel joint optimization procedure. The idea relies on the simple following arguments:

- The rationale behind the concomitant search is to select as much as possible cosmic neutrino candidates and assess their cosmic nature by the observation of GW in time and space coincidence. In this view, the selection should leave large the efficiency to signal neutrinos which can be defined, by means of Monte Carlo simulations, as the ratio of selected events  $N_{selected}$  (after cuts) over triggered events  $N_{triggered}$ :

$$\epsilon_{\nu}(\text{cuts}) = \frac{N_{selected}}{N_{triggered}} \quad (5.10)$$

The cuts considered here are  $\cos\theta_{MC} \geq 0$ ,  $\cos\theta_{rec} \geq 0$ . In order to increase  $\epsilon_{\nu}$ , loose cuts must be applied. This also considerably increases the number of selected background events.



- A too high number of these background events will result in an increased number of accidental coincidences FAR for a fixed set of cuts in the GW search. To avoid this situation, such triggered searches, are usually made with a fixed FAR. In order to keep this FAR constant, the higher the number of neutrino candidates to probe, the tighter the cuts should be applied on the GW side, leading to a poorer efficiency  $\epsilon_{GW}(E_{GW}, r)$  for a given distance  $r$  and a model GW energy release. In other words this leads to a closer horizon for the GW search. In this case the probed distance for GW appears to depend on the neutrino selections cuts and one may write:  $D \equiv D(cuts)$ .

As a consequence, there should be a trade-off in these two approaches, which allows us to stick to the predefined FAR, with cuts that are optimal for the joint search.

### 5.5.1 Definition of the joint figure-of-merit

The approach adopted here is to apply the neutrino cuts to maximize the number  $\mathcal{N}_{\text{GWHEN}}$  of detectable sources emitting both GW and HEN. Let us assume that the sources are all identical and radiate  $E_{GW}$  in GW and emit a fluence  $\varphi_\nu$  in HEN. Let us also assume that their population is isotropic so their density per unit time and volume  $R$  is a constant. The number of detectable sources is

$$\mathcal{N}_{\text{GWHEN}}(\text{cuts}) = \iint dt d^3\Omega \mathcal{R}(r, t) \epsilon_\nu(\text{cuts}) \epsilon_{GW}(\text{cuts}; E_{GW}, r) \quad (5.11)$$

where  $\mathcal{R}(r, t) = R \mathcal{P}(N_\nu > 0 | \varphi_\nu / (4\pi r^2))$  is the density of detectable sources. From Poisson statistics, we get  $\mathcal{P}(N_\nu > 0 | \varphi_\nu / (4\pi r^2)) \propto 1/r^2$  in the limit of small fluxes.

The cuts being applied are connected to the methodologies in use for the muon track reconstruction on the HEN side and for the transient detection on the GW side. Those methodologies are detailed in section 5.3 for GW and in section 2.6 for HEN. We will optimize over the cut thresholds applied to the two following parameters: the quality of the muon track reconstruction  $\Lambda$  and a proxy to the signal-to-noise ratio  $\rho$  for the HEN and GW, respectively. We obtain

$$\mathcal{N}_{\text{GWHEN}}(\Lambda, \rho_{\text{threshold}}) \propto \int_0^\infty 4\pi r^2 dr \frac{1}{r^2} \epsilon_\nu(\Lambda) \epsilon_{GW}(\rho_{\text{threshold}}; E_{GW}, r) \quad (5.12)$$

where we dropped the useless constants such as the global livetime  $\tau$  of the experiment which results from the time integral.

The typical shape of  $\epsilon_{GW}(\rho_{\text{threshold}}; E_{GW}, r)$  as a function of  $r$  for a given threshold and energy  $E_{GW}$  presents a rather sharp transition (less than a decade) from 100% to 0% (see e.g., Figures 3 and 4 of [15]). It can be reasonably well approximated by a step-like function with

## 5.5.5 Description of the joint optimization strategy

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the edge placed at the maximum distance  $D(\rho_{threshold})$  at which a GW source is detectable, i.e., the GW *horizon*. Equation (5.12) can therefore be re-written as:

$$\mathcal{N}_{\text{GWHEN}}(\Lambda, \rho_{threshold}) \propto \epsilon_{\nu}(\Lambda) \int_0^{D(\rho_{threshold})} dr \quad (5.13)$$

The parameter  $\rho_{threshold}$  sets a cut on the minimal detectable GW amplitude. For a GW “standard candle” emitted a given amount of energy in GW, it is inversely proportional to  $D(\rho_{threshold})$ . Therefore, we get

$$\mathcal{N}_{\text{GWHEN}}(\Lambda, \rho_{threshold}) \propto \epsilon_{\nu}(\Lambda) / \rho_{threshold} \quad (5.14)$$

As a conclusion, our aim is to tune the neutrino selection cuts in order to maximize the figure-of-merit given by the ratio  $\epsilon_{\nu}(\Lambda) / \rho_{threshold}$ .

### 5.5.2 Joint optimization procedure

We will now present the procedure for seeking the optimal cuts. Let the false-alarm probability FAP for the combined search be the probability of a fortuitous (time and spatial) coincidence of a GW and HEN background event. We define the working point of the optimization by setting a value for the FAP. Typically, we set FAP to  $4.7 \times 10^{-3}$  (which corresponds to a “ $2\sigma$ ” excursion).

We scan the number  $N$  of neutrino candidates in the total livetime from a minimum to maximum value (typically from  $10^2$  to  $10^4$ ). There is a one-to-one correspondence between each selected  $N$  and a value for  $\Lambda$ . For each value of  $N$ , we compute the target GW false-alarm-rate  $\text{FAR}_{\text{GW}}$  from

$$\text{FAR}_{\text{GW}} = \frac{\text{FAP}}{N\Delta T}, \quad (5.15)$$

where  $\Delta T$  is the duration of the temporal coincidence window (1000s).

We compute the GW background associated to a search triggered by  $N$  neutrino candidates. This is obtained thanks to the approximation using the all-sky GW background described in section 5.6.2. We deduce the value of  $\rho_{threshold}$  for which the resulting background equals the target  $\text{FAR}_{\text{GW}}$ . At this point, the figure-of-merit defined in Equation (5.14) can be computed. The maximum value leads the optimal cuts for the considered range.

### 5.5.3 Dealing with non-stationary backgrounds

While an average signal neutrino efficiency  $\langle \epsilon_{\nu}(\Lambda) \rangle$  valid for the full livetime period can be estimated, the GW background rate and sensitivity instead depends on the exact configuration

of the GW detector network which varies with time.

The whole livetime is divided into segments associated to a single configuration. Each period has a respective livetime  $\tau_n$  such that the total livetime is  $\tau = \sum_n \tau_n$ . If we denote  $f_n = \tau_n/\tau$ , the respective livetime fraction, the average number of neutrino candidates falling in the segment  $n$  is therefore  $N_n = f_n N$ . Correspondingly, we divide the time integral in Equation (5.11) running over the whole livetime into segments

$$\mathcal{N}_{\text{GWHEM}}(\text{cuts}) = \sum_n \int_{\tau_n} dt \int d^3\Omega \mathcal{R}(r, t) \epsilon_\nu(\text{cuts}) \epsilon_{\text{GW},n}(\text{cuts}; E_{\text{GW}}, r) \quad (5.16)$$

Following the same steps described in section 5.5.1, we get

$$\mathcal{N}_{\text{GWHEM}}(\Lambda, \rho_{\text{threshold}}) \propto \langle \epsilon_\nu(\Lambda) \rangle \sum_n f_n / \rho_{\text{threshold},n} \quad (5.17)$$

where the thresholds  $\rho_{\text{threshold},n}$  corresponds to the false-alarm-rate  $\text{FAR}_{\text{GW},n}$  for segment  $n$ .

The initial requirement on the FAP defines a global budget that has to be divided among the different segment analysis i.e.,  $\text{FAP} = \sum_n \text{FAP}_n$ . It is natural to split this budget proportionally to the segment livetime, namely  $\text{FAP}_n = f_n \text{FAP}$ . In this setting, we thus have

$$\text{FAR}_{\text{GW},n} = \frac{\text{FAP}_n}{N_n \Delta T} = \frac{\text{FAP}}{N \Delta T} = \text{constant} \quad (5.18)$$

The overall optimization detailed in section 5.5.2 remains the same with the difference that  $1/\rho_{\text{threshold}}$  is now replaced by  $\sum_n f_n / \rho_{\text{threshold},n}$ .

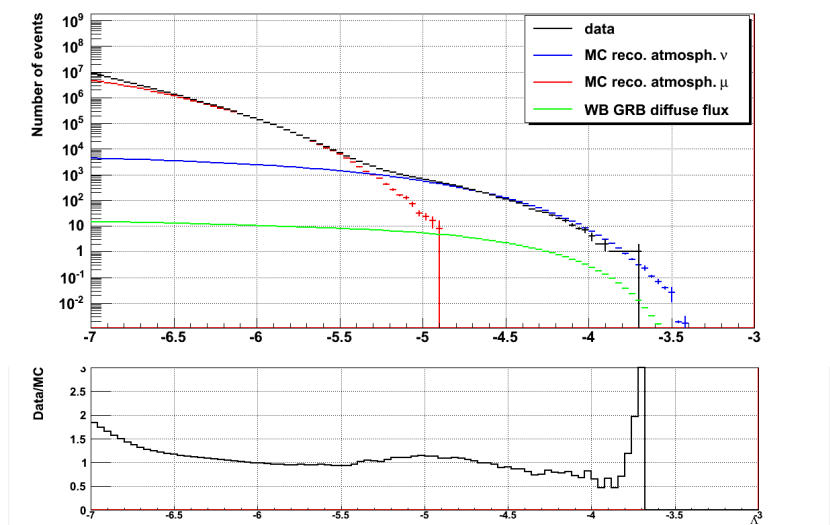
## 5.6 Application of the joint optimization procedure

### 5.6.1 Efficiency to HEN

The first input to the joint optimization described above is the efficiency to neutrino candidates, i.e.  $\epsilon_\nu$ . It is obtained assuming the WB GRB diffuse flux (described in section 1.1.4) by means of MC simulations. The only parameter studied here is the quality of the reconstruction  $\Lambda$ , whose cumulative distributions are shown in Figure 5.15 for atmospheric muons, atmospheric neutrinos, and the studied WB flux of cosmic neutrinos. The MC distributions are compared to the data. The good agreement observed over the full range of  $\Lambda$  values allows us to proceed with the chosen optimization method. This agreement is obtained by applying a scaling factor of 0.8 to the atmospheric muons. Such correction is well within the uncertainty on theoretical

## 5.5.6 Application of the joint optimization procedure

flux (30%) [16]. The obtained efficiency  $\epsilon_\nu$  is shown in Figure 5.16 as a function of the total number of selected events. The cuts considered here are  $\cos\theta_{rec} \geq 0, \cos\theta_{MC} \geq 0$ . The first cut ( $\cos\theta_{rec} \geq 0$ ) permits to select events reconstructed as upgoing, while the second cut ( $\cos\theta_{MC} \geq 0$ ) rejects those that are down-going reconstructed as upgoing (misreconstructed events). The inflection in the curves originates where the number of selected neutrino candidates starts to be dominated by misreconstructed atmospheric muons rather than atmospheric neutrinos.



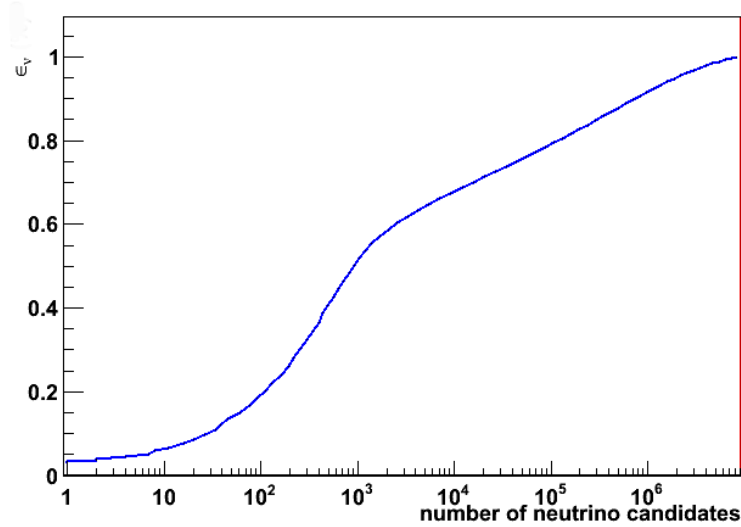
**Figure 5.15** – Cumulative distribution of events, for the overall search period, as a function of  $\Lambda$  for the cuts described in the text. Curves of data and MC atmospheric muons and neutrinos are plotted. The distribution corresponding to the WB GRB diffuse flux is shown in green curve

The contamination (by atmospheric muons) and purity (with respect to the atmospheric neutrino sample) are shown as a function of number of neutrinos candidates in Figure 5.17.

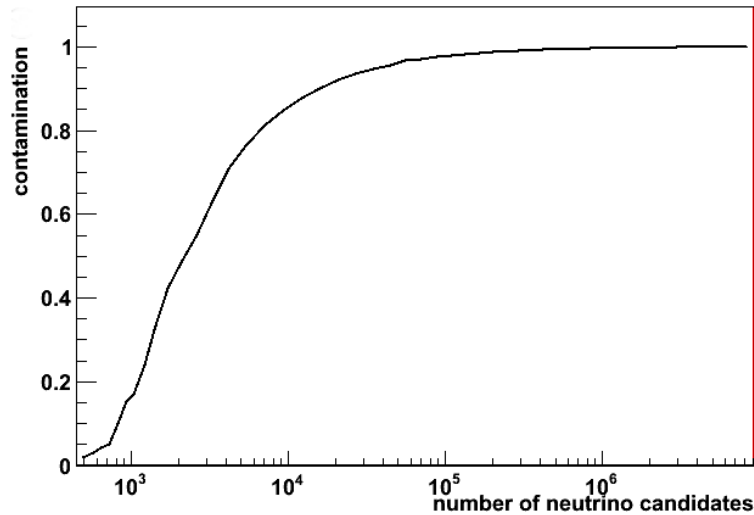
### 5.6.2 Approximation of the GW background

Using s-cWB for the background estimation necessary for the cut optimization would be too much time consuming, due to high number of neutrino trials. Instead, we decided to approximate the background associated to the neutrino candidates by using the all-sky background(s).

If the GW background events are isotropically and Poisson distributed, it is easy to show that the background rate of triggered search should be rescaled by a factor  $\sim (\Omega_{GW}^{1/2} + \Omega_{HEN}^{1/2})^2 / (4\pi)$  where  $\Omega_{GW}$  and  $\Omega_{HEN}$  are the solid angles under the GW and HEN error-boxes (or PSF) respectively. This factor essentially results from an estimate of the probability that those two error boxes overlap if their central directions is chosen at random. The HEN error box



**Figure 5.16** – Efficiency to neutrino candidates for WB GRB diffuse flux.



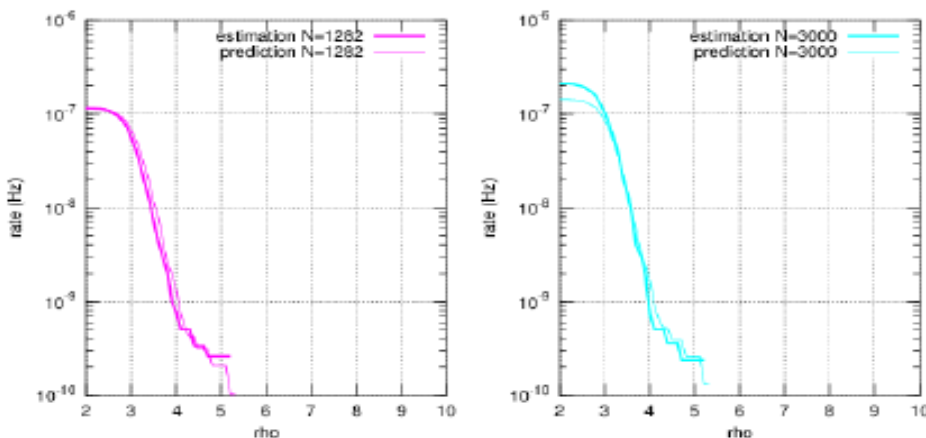
**Figure 5.17** – Muon contamination of the neutrino sample for upgoing events in function of the number of candidates.

$\Omega_{HEN}^{1/2} = \sqrt{\pi}ASW90\%$  depends on the cut applied for the muon track reconstruction. In particular, it is a function of  $\Lambda$  and hence of  $N$ , the number of neutrino candidate.  $\Omega_{GW}$  depends on the configuration of the GW detector network. We estimated that on average the sky map of a background event covers about 425 square degrees, which corresponds to a circular

## 5.5.6 Application of the joint optimization procedure

region of radius about 12 degrees.

We checked this approximation with a Monte-Carlo simulation using a set of GW background triggers obtained for the all-sky S6A/VSR2 analysis. We cross-correlated many times these triggers with a random set of neutrino candidates of variable size. The backgrounds we obtain with this simulation are in rough agreement with the prediction obtained by rescaling the original all-sky background. However an additional factor is necessary to get a good fit of the joint predicted background. This factor estimated heuristically is  $\sim aN + b$  where  $a \approx 10^{-4}$  and  $b \approx 0.5$  and  $N$  is the number of neutrino candidates. The result of background distributions is shown in Figure 5.18.



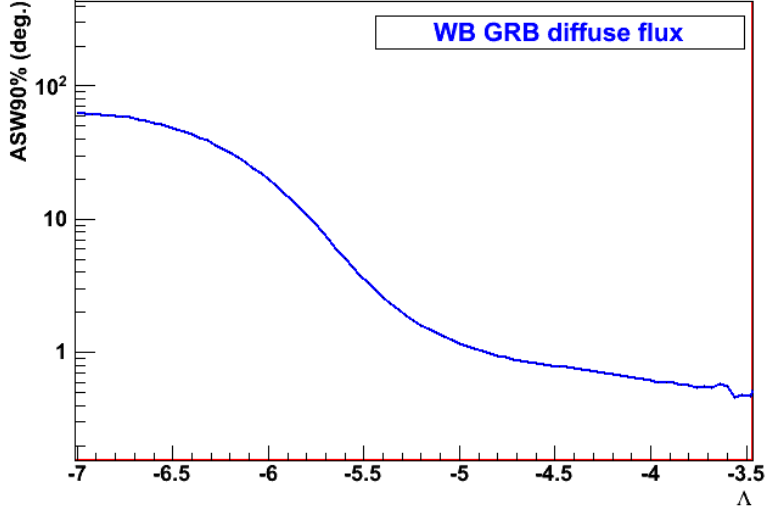
**Figure 5.18** – Background distributions of the network correlated amplitude  $\rho$  for triggered search obtained by rescaling all-sky backgrounds

## 5.6.3 Results of the optimization

### Study without cut on $\beta$

In this section, we summarize the results of the optimization procedure detailed in section 5.5.2. For simplicity, we restricted the optimization to periods with three operating GW detectors which is the most sensitive part of the data set. This corresponds to three separate runs labelled {“S6A/VSR2”, “S6B/VSR2”, “S6D/VSR3”}. This corresponds to the respective live-times  $\tau_n = \{6.9 \text{ days}, 13.7 \text{ days}, 24.1 \text{ days}\}$  and livetime percentages  $f_n = \{5.36 \%, 10.64 \%, 18.72\%\}$ .

We use the approximation scheme described in the previous section 5.6.2 to compute the GW backgrounds for various  $N$ . The rescaling uses the neutrino angular window  $ASW^{90\%}$  as a function of  $\Lambda$  parameter as shown in Figure 5.19. We deduce  $\rho_{threshold,n}$  and the figure-of-merit



**Figure 5.19** – The ASW90% used to estimate the GW background from the all-sky one. No cut on  $\beta$  is applied.

in Equation (5.17). Those quantities are shown as functions of the *total* number  $N$  of neutrino candidates (for the entire ANTARES livetime  $T \approx 266$  days) in Figure 5.21. This number of neutrinos is taken from the data set and not from the MC sample. As such we are less dependent on the MC simulation and avoid problems of low statistics in the atmospheric muon MC sample. We see in Figure 5.20 that  $\rho_{threshold,n}$  increases as a function of  $N$  as expected.

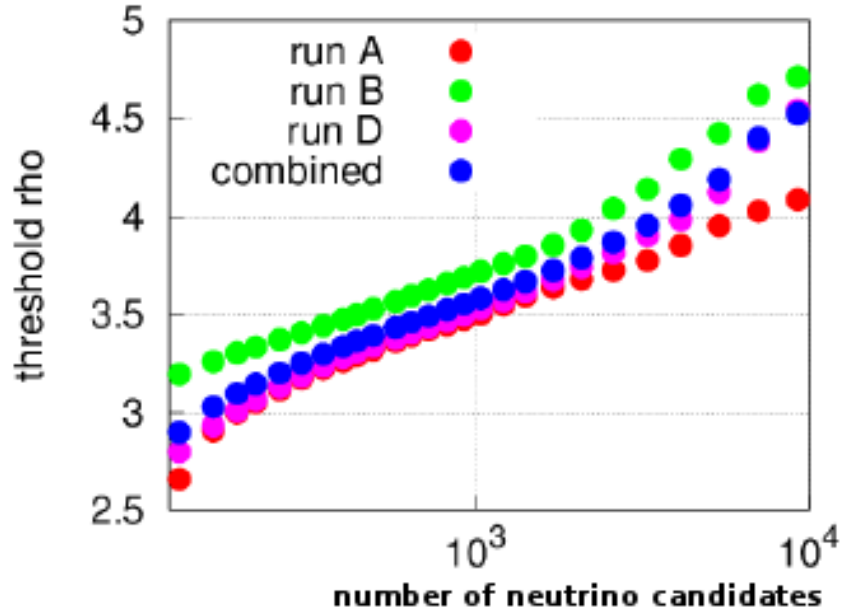
The number  $N$  of candidates ( $\Lambda$ ) for the whole observation time  $\tau$  that maximises the FOM is 3279 (-5.4). The angular search window is significantly better ASW90% = 2.6 degrees than the one used in 2007 joint search. In addition the efficiency  $\epsilon_\nu$  increases to about 62%.

### Study against $\beta$ parameter

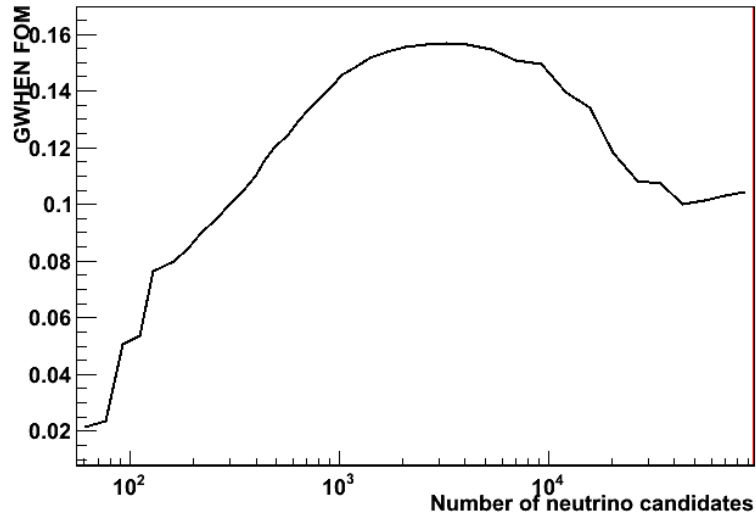
The results presented in the previous section were obtained without any cut on the angular error estimate,  $\beta$ , of the reconstructed track. In this section we present an additional study by considering cuts on  $\beta$ . We choose the following cuts on  $\beta < \{0.6^\circ, 1^\circ, 1.4^\circ\}$  (see Figures 5.22).

The table 5.1 shows the atmospheric muon contamination, FOM and total number of candidates corresponding to the optimal  $\{\Lambda, \beta\}$  cuts. The best FOM and hence sensitivity is obtained with no cut on  $\beta$ . However increasing the number of candidates leads to serious difficulties. Above of the order of 2000 candidates the estimation of GW background gets at the same time computationally very heavy and more difficult to estimate. Indeed, with growing number of candidates, the GW data segments used to estimate the background  $\rho$  distributions will begin

### 5.5.6 Application of the joint optimization procedure



**Figure 5.20** – Distributions of  $\rho$  as function of the number of neutrino candidates for the different GW data taking periods considered.



**Figure 5.21** – FOM as a function of the number of neutrino candidates  $N$  without cut on  $\beta$ .

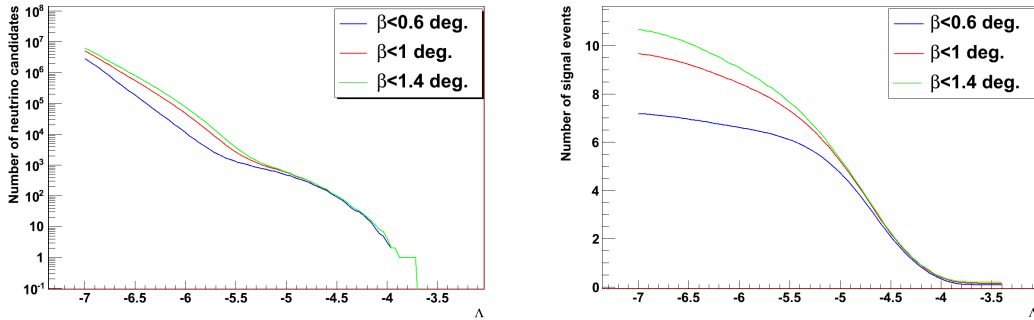
to overlap and correlation will appear. Given that with a  $\beta$  cut at 1 degree the loss in number of detectable sources (which is proportional to FOM) is just 2% with an affordable number of



candidates, we set the final cut values at  $\Lambda > -5.44$  and  $\beta < 1$ . This can also be qualitatively justified by the fact that the contamination by atmospheric muons grows by 20% between  $\beta < 1$  and no  $\beta$  cut. Since meanwhile the neutrino efficiency just marginally grows by 5%, most of the additional neutrino candidates brought by the reduction of the strength of the  $\beta$  cut will be mis-reconstructed atmospheric muons which will just make the GW background estimation more difficult.

$\Lambda >$	$\beta <$	Contamination (%)	$\epsilon_\nu$ (%)	FOM	ASW90% (deg.)	MC $N_\nu$	Data $N_\nu$
-5.60	0.6	40.36	50	0.1358	1.3	1645	1699
-5.44	1.0	44.24	57	0.1525	1.7	1971	1986
-5.44	1.4	57.12	60	0.1547	2.0	2717	2633
-5.40	No cut	63.27	62	0.1564	2.6	3224	3279

**Table 5.1** – Results of the joint optimization in term of FOM for each cut on  $\Lambda$  and  $\beta$ .



**Figure 5.22** – Number of neutrino candidate events (Left) and signal WB GRB diffuse flux events (right) as function of  $\Lambda$  for different cuts on  $\beta$

We compare Figure 5.25(left) the effective areas obtained with these different cuts and the one obtained with the cuts of the Point Source search ( $\Lambda > -5.2$  and  $\beta < 1^\circ$ ). Figure 5.25(right) shows for comparison the ratio between the effective areas obtained in this work to the one obtained with the cuts applied in the search for the point sources [17]. We can see that the final set of cuts of this work gives a gain in effective area between 50% at low energy and almost 20% at high energy.

## 5.7 List of neutrino candidates

We present in this section the result obtained after applying the optimized cuts described in the previous sections. The list obtained consists in  $N = 1986$  neutrino candidates.

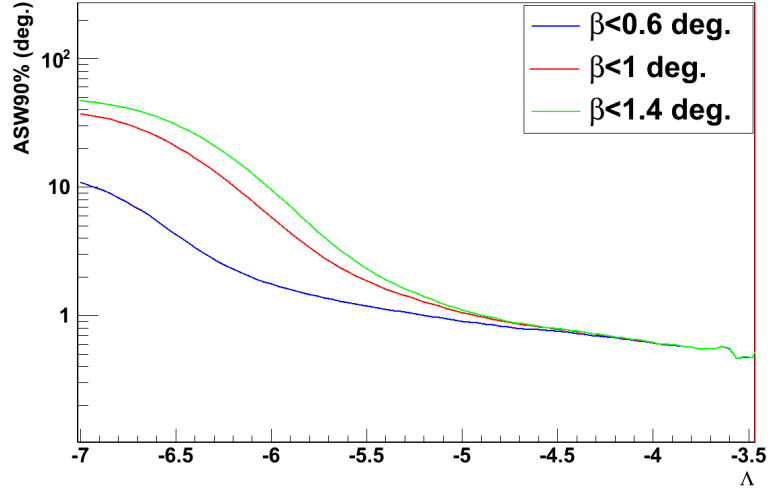


Figure 5.23 – Angular search window ( $ASW_{90\%}$ ) as function of  $\Lambda$  for different cuts on  $\beta$

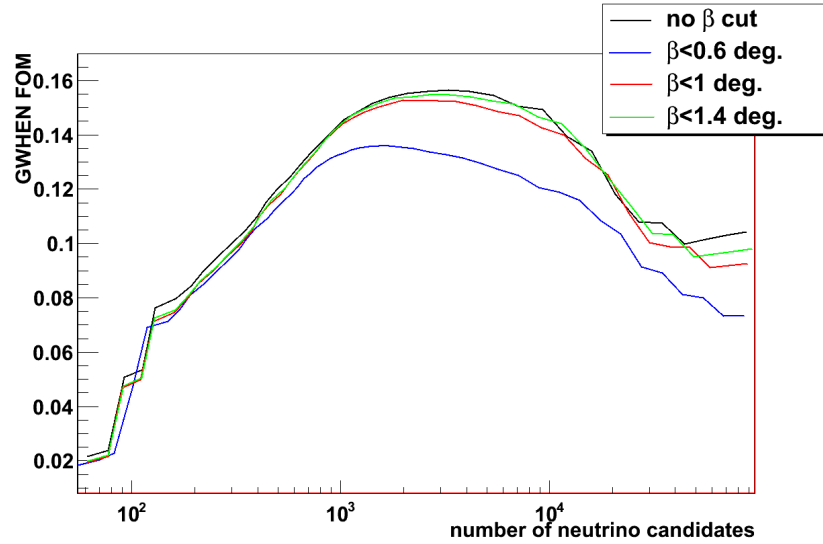
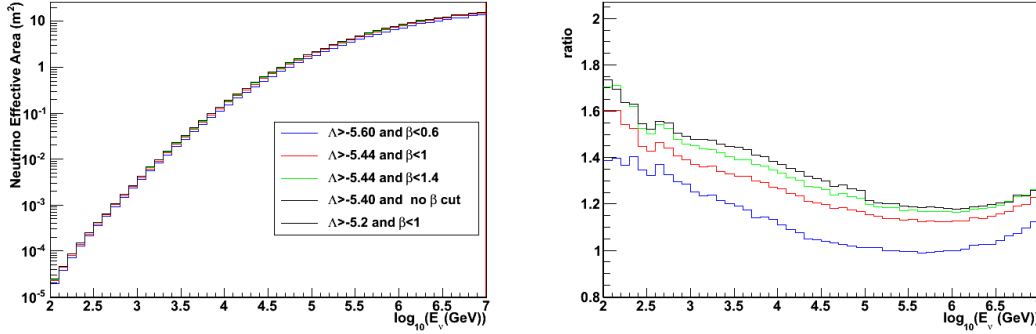


Figure 5.24 – Distribution of GWHEN FOM as a function of the number of neutrino candidates  $N$ , for different cuts on beta

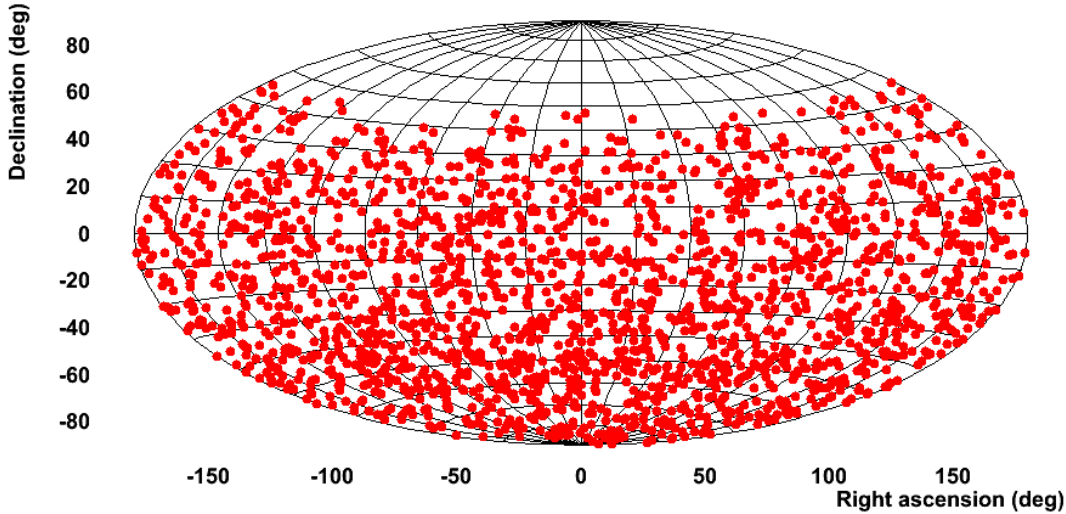
The result consists in a list of neutrino candidates. Each of them is characterized by its arrival time, sky direction and associated error box. The following notations are adopted:

- Time  $t_i$  is given in Julian Day (or GPS)
- Reconstructed direction of the event  $\vec{d}_i = (\alpha_i, \delta_i)$  is given in equatorial coordinates, i.e. right ascension and declination. The skymap of the selected candidates is shown in Figure



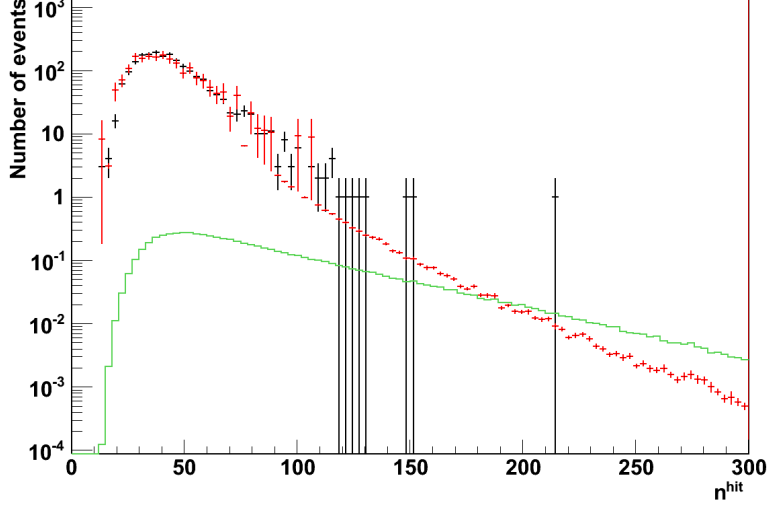
**Figure 5.25** – Left: Neutrino effective areas as a function of neutrino energy. Right: ratio between GWHEN effective areas (corresponding to the different cuts in the text) and point-source one (after applying the corresponding cuts) as a function of neutrino energy.

5.26 in equatorial coordinates.



**Figure 5.26** – Sky map of the final neutrino candidates selected for the analysis. The sky map is shown in equatorial coordinates.

- Energy estimator, given as the number of hits (or  $n^{hit}$ ) used in the track fit. The distribution of the number of hits for data and MC is shown in Figure 5.27.
- $ASW_{GWHEN}^{90}$  is a circle on the sky sphere with radius the 90% percentile of the distribution of space angles  $\psi$  between the reconstructed muon and the MC neutrino direction. It is computed from MC neutrino ANTARES simulation with the same selection cuts applied



**Figure 5.27** – Distribution of the number of hits used as proxy energy in this search. The black curve is the data, the red is the MC atmospheric background and the green is the MC distribution obtained for the WB GRB diffuse flux.

as that for the joint optimization and with an event weighting following the Waxman Bahcall GRB diffuse flux. This distribution is fitted with a log-normal function as defined hereafter:

$$P(\psi) = \frac{1}{\sqrt{2\pi}} \frac{\exp[-\ln(\psi/m)^2/2\sigma^2]}{\sigma\psi} \quad (5.19)$$

where  $m$  and  $\sigma$  are respectively the so called scale and shape parameters. It can be linked to the neutrino bi-dimensional point spread function (PSF),

$$\mathcal{F}_i^{\text{HEN}}(\vec{\mathbf{d}}) \equiv P(\vec{\mathbf{d}}|\vec{\mathbf{d}}_i) \propto \frac{1}{\sin(\psi_i(\vec{\mathbf{d}}))} \frac{\exp[-\ln(\psi_i(\vec{\mathbf{d}})/m)^2/2\sigma^2]}{\sigma\psi_i(\vec{\mathbf{d}})} \quad (5.20)$$

where  $\psi_i(\vec{\mathbf{d}})$  is the space angle between the directions  $\vec{\mathbf{d}}$  and  $\vec{\mathbf{d}}_i$ . An example of this point spread function can be seen on Figure 5.28.

In practice  $ASW_{GWHEN}^{90}$  (or equivalently  $\mathcal{F}_i^{\text{HEN}}$ ),  $m$  and  $\sigma$  can depend on several parameters like  $\Lambda$  (see Figure 5.19), the arrival direction of the neutrino, the number of hits, or the angular reconstruction error parameter  $\beta$ . Figure 5.29 shows the median of the space angle distribution as a function of declination. This quantity is to a good approximation independent of the declination and hence its variation with declination will not be used further to characterize events.

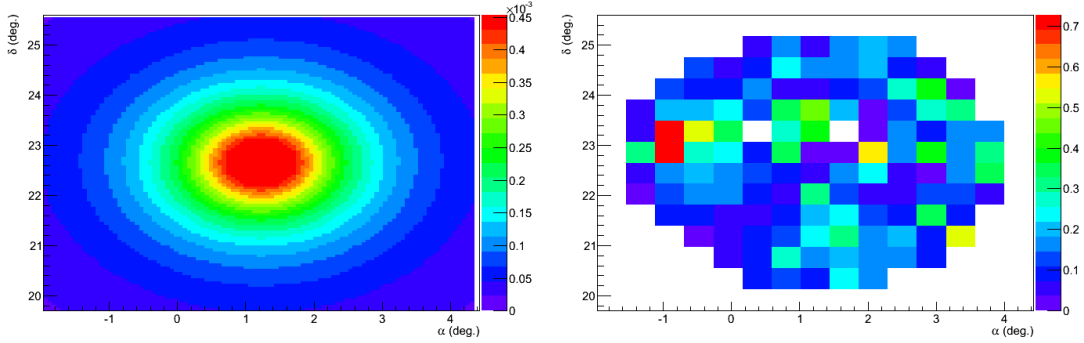


Figure 5.28 – Example of the neutrino PSF (left) and the corresponding GW skymap (right).

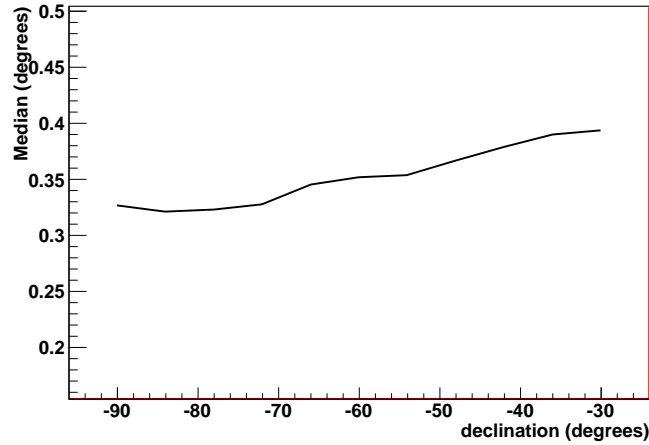


Figure 5.29 – The angular search window for 50% percentile as function of declination.

## 5.8 Procedure for the event post-processing and joint statistical treatment

The statistical analysis of the outcome of the joint search is based on the original proposal from [18], but different aspects are adapted to cope with the specificities of our study, in particular the use of sky masks (with typical size of a few squared degrees) in s-cWB.

Below we describe the different steps and define the relevant quantities that will be used in the final statistical treatment as well as in the estimation of the sensitivity and discovery power of the search.

The goal is to construct a test statistics based on the characteristics of each neutrino event

### 5.5.8 Procedure for the event post-processing and joint statistical treatment

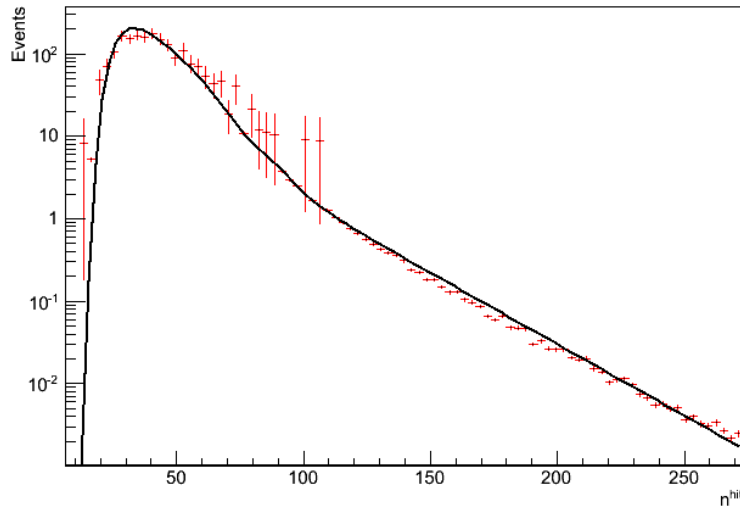
and its associated GW trigger and to compute their joint p-value (or equivalently their excess significance) relying on pseudo-experiment realizations of the search with no signal injected. The discovery potential will then be estimated with the same method but using pseudo experiments containing neutrinos following a WB energy spectrum and associated to GW signal injections. The pseudo experiments will be based on the neutrino characteristics and the combined test statistic described in sections 5.8.1 and 5.8.4.

#### 5.8.1 Statistical characterisation of the neutrino candidates

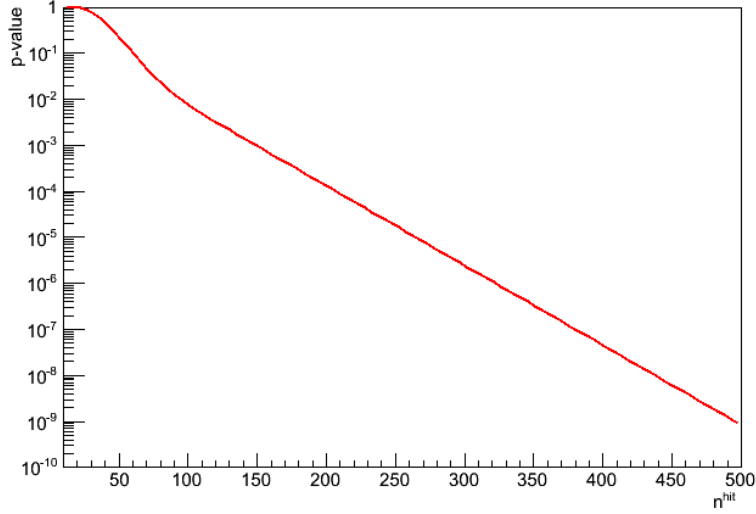
In addition to the neutrino characteristics described above we compute the p-value of the neutrino event, denoted  $p_i^{\text{HEN}}$ . Since these will be considered independently, atmospheric and potential cosmic neutrinos differ only by their energy spectrum. As shown in Figure 5.30, we will use the simple energy estimator given by the number of hits  $n^{\text{hit}}$  of the reconstructed track. The p-value, i.e. the probability that the atmospheric background would produce an event with at least the number of hits of the considered event, is defined as:

$$p_i^{\text{HEN}} = \frac{\int_{n_i^{\text{hit}}}^{\infty} P(n^{\text{hit}}) dn^{\text{hit}}}{\int_0^{\infty} P(n^{\text{hit}}) dn^{\text{hit}}} \quad (5.21)$$

where  $n_i^{\text{hit}}$  is the value corresponding to the event  $i$  and  $P$  the corresponding probability density function (or equivalently the not normalized distribution).



**Figure 5.30** – Distribution (modified as described in the text) of  $n^{\text{hit}}$  together with the function used to fit it and evaluate the corresponding p-values.



**Figure 5.31** – Distribution of the HEN p-value as a function of  $n^{hit}$  estimated from MC simulation as defined in equation 5.21.

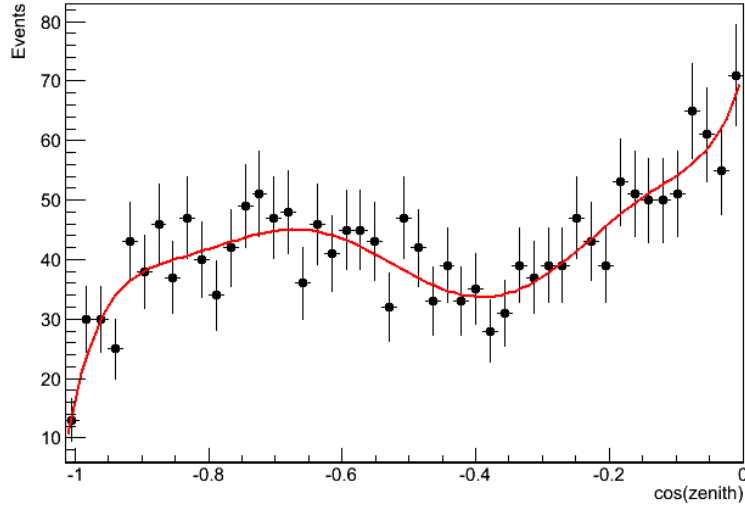
In practice the computation can be made with Monte Carlo simulations extrapolated to high values of  $n^{hit}$  if needed. Considering the overall contamination of atmospheric muons in the final sample (44%) and in order to compensate for the lack of statistics in the atmospheric muon simulation in the  $n^{hit} > 100$  region we conservatively choose to apply a penalty factor for the p-values obtained in the  $n^{hit} > 100$  region. This is achieved by multiplying the atmospheric neutrino distribution by 1.7 in the considered  $n^{hit} > 100$  region. The validity of this approach has been checked by relaxing the cuts and verifying the shape consistency of the muon and neutrino samples. The modified simulated  $n^{hit}$  distribution has been fitted with the following function:

$$P_{n^{hit}}(x) = \exp\left(\sum_{n=0}^4 p_n x^n\right) / (1 + \exp(-p_5(x - p_6))) p_7 \exp(p_8 x) \quad (5.22)$$

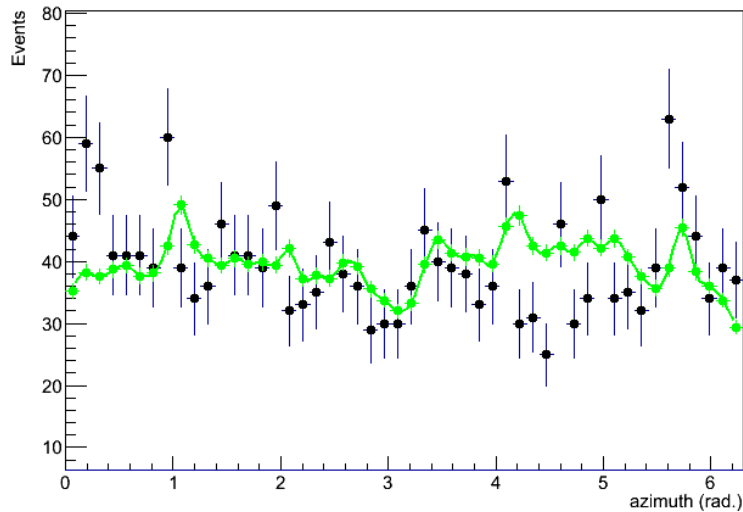
where  $p_n$ ,  $n \in [0, 8]$  are the fit parameters. The result is presented in Figure 5.30. The p-value as a function of  $n^{hit}$  can then be computed by numerical integration and is displayed in Figure 5.31.

Figures 5.32 and 5.33 show the local coordinates of the neutrino triggers together with the fitted functions which will be used to generate the pseudo experiments. The latter also allow us to draw the analysis exposure map, which is presented in Figure 5.34 in galactic coordinates.

## 5.5.8 Procedure for the event post-processing and joint statistical treatment



**Figure 5.32** – Normalized distribution of the zenith angle for data together with the 7 degree polynomial used to fit it.

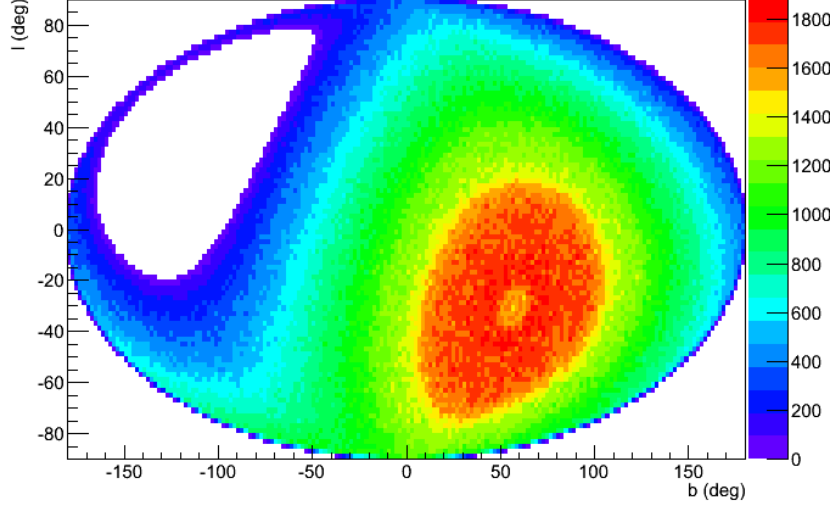


**Figure 5.33** – Distribution of the azimuth for data together with the spline function used to parametrize it. This spline has been fitted on the neutrino Monte Carlo simulation (green points).

### 5.8.2 Statistical characterisation of the GW reconstructed events

For each of the selected neutrino events, s-cWB performs a search for GW around the neutrino time. The whole sky is not scanned but only the region corresponding to ASW90% centered on





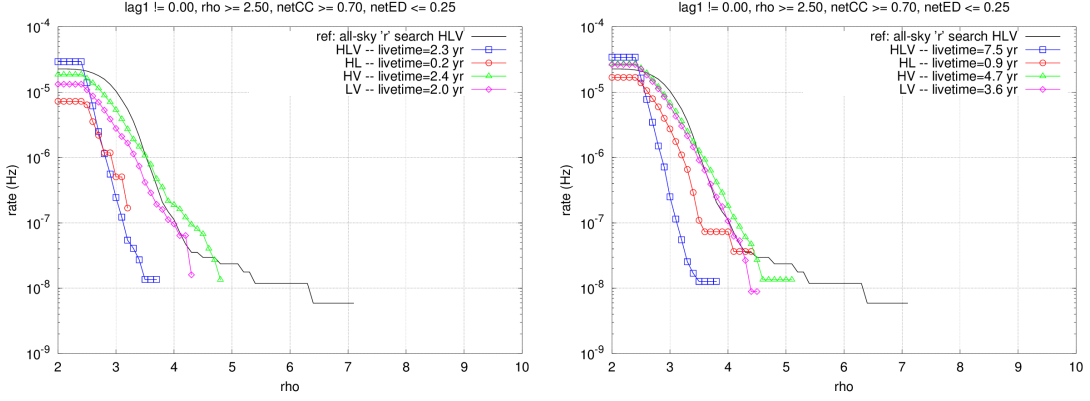
**Figure 5.34** – Relative sky exposure map (arbitrary units) of ANTARES corresponding to the selected neutrino sample in Galactic coordinates.

the reconstructed arrival direction of the neutrino  $\vec{\mathbf{d}}_0$ . For each candidate, s-cWB will provide the GW skymap (SP) labeled hereafter  $\mathcal{F}_i^{\text{GW}}(\vec{\mathbf{d}})$  within ASW90% (see Figure 5.28 right for an example). These ”sky-maps” will be made of pixels of  $0.4^\circ \times 0.4^\circ$  each associated with the probability that a GW is coming from it. The following parameters, of each GW candidate, are provided by the s-cWB. The arrival time, the reconstructed sky location  $(\theta, \phi)$  in the Earth fixed frame with  $\phi = 0^\circ$  corresponding to the Greenwich Meridian,  $\theta = 90^\circ$  corresponding to the equator. Also it provides the value of  $\rho$  for each GW candidates. This latter will correspond to a false alarm rate  $\text{FAR}_i(\rho_i)$  as defined in sections 5.5.2 and 5.5.3. This will lead to a GW p-value indicating what is the probability that coherently combined GW interferometers background produces an event with at least this value of  $\rho_i$ , defined as:

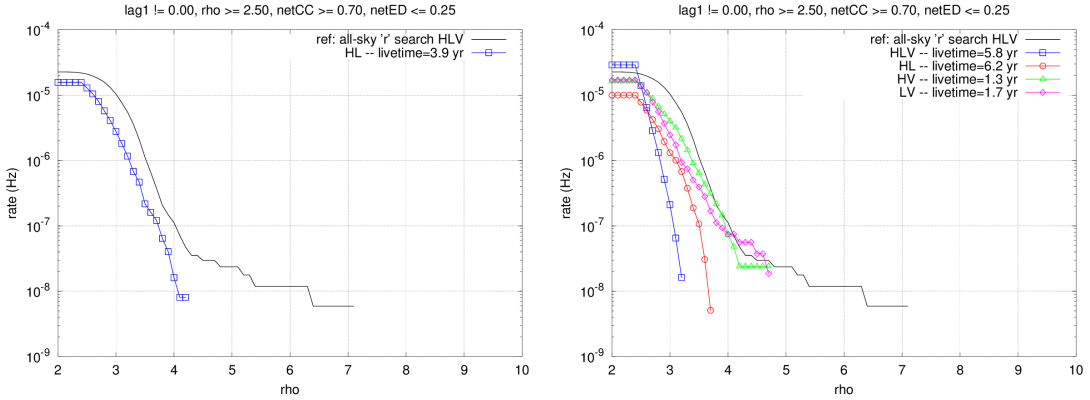
$$p_i^{\text{GW}} = 1 - P(0|\tau_i \times \text{FAR}_i(\rho_i)) \quad (5.23)$$

where  $\tau_i$  is the duration of the GW interferometers run corresponding to event  $i$  (see sections 5.5.2 and 5.5.3). The distributions are computed using  $O(10^3)$  background realisations obtained with time shifts. The background distributions  $\rho$  of all detector configurations and run periods are presented in Figures 5.35 and 5.36. The corresponding p-value evolution for S6A run is shown in Figure 5.37.

## 5.5.8 Procedure for the event post-processing and joint statistical treatment



**Figure 5.35** – Background estimate of the network correlated amplitude  $\rho$  for triggered search. Left: for the S6AVSR2-3 segments. Right: for the S6B segments



**Figure 5.36** – Background estimate of the network correlated amplitude  $\rho$  for triggered search. Left: for the S6C segments. Right: for the S6D segments

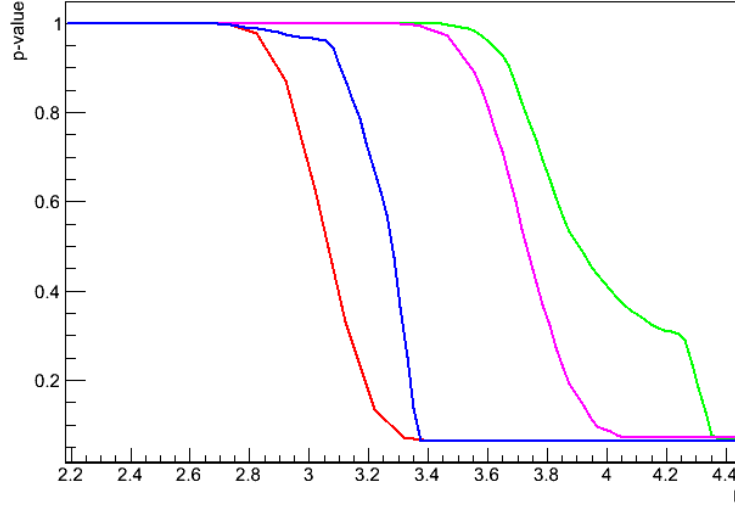
### 5.8.3 Statistical characterisation of the joint candidates

The direction of the joint candidate event can be defined as the one maximizing the product of the HEN PSF and the GW SP:  $\mathcal{F}_i^{\text{GW}} \times \mathcal{F}_i^{\text{HEN}}$ .

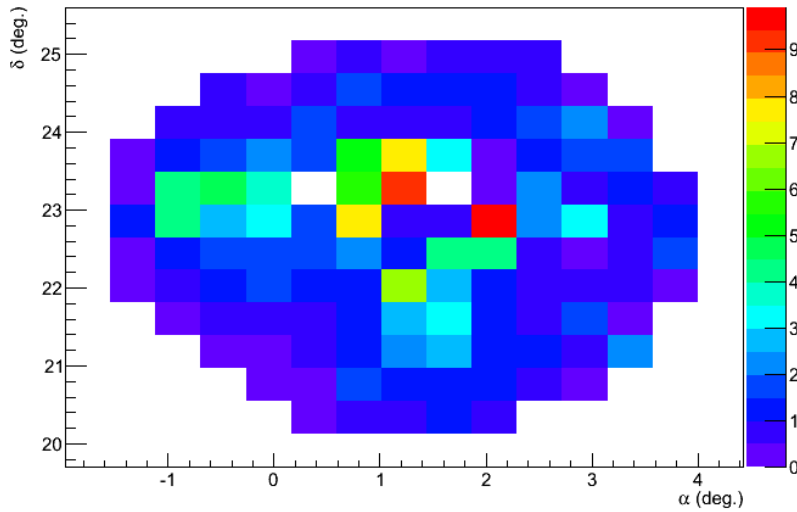
The joint directional test statistic will rely on the marginalized likelihood of the joint event which is defined as:

$$\ln(\mathcal{L}_i) = \int \mathcal{F}_i^{\text{GW}}(\vec{x}) \times \mathcal{F}_i^{\text{HEN}}(\vec{x}) d\vec{x} \quad (5.24)$$

Figure 5.38 shows an example of the joint likelihood. Figure 5.39 shows the distribution of  $P_{bg}$  of  $\ln(\mathcal{L})$  for background estimated with the S6A data for three interferometers together with a Gaussian fit.



**Figure 5.37** – The p-value as a function of  $\rho$  corresponding to S6A data and different detector configurations HLV (blue), HL (red), HV (green) and LV (magenta)

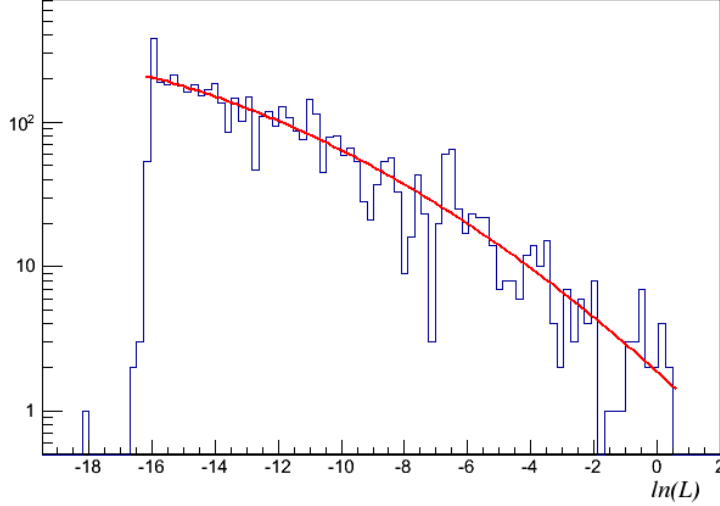


**Figure 5.38** – Example of the joint likelihood obtained with the product of GW SP and HEN PSF

The p-value corresponding to the combined PSF-likelihood will be defined as:

$$p_i^{sky} = \int_{\mathcal{L}_i}^{\infty} P_{bg}(\ln(\mathcal{L})) d\mathcal{L} \quad (5.25)$$

## 5.5.8 Procedure for the event post-processing and joint statistical treatment



**Figure 5.39** – Distribution of  $\ln(\mathcal{L})$  for background estimated with the S6A data for the detector network. The red curve corresponds to a Gaussian fit

and is determined by numerical integration of the fitting function. A dedicated fit will be performed for each S6 period and each interferometer configuration independently.

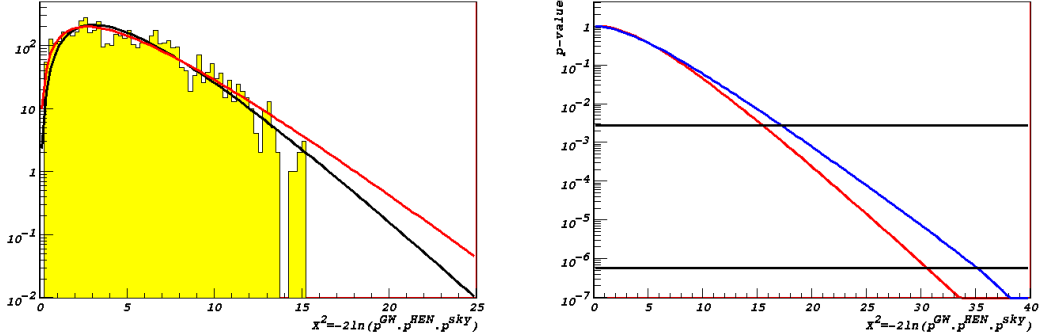
### 5.8.4 Final test statistic

All these p-values can be combined using Fisher’s method [19] to construct a test statistic for each event  $i$ :

$$X_i^2 = -2 \ln(p_i^{sky} \times p_i^{GW} \times p_i^{HEN}) \quad (5.26)$$

This variable behaves like a  $\chi^2$  with 6 degrees of freedom in case variables are independent. But since this is not guaranteed here and since  $p^{GW}$ ,  $p^{HEN}$  and  $p^{sky}$  may not behave as proper p-values (i.e. be independently uniformly distributed in  $[0;1]$ ), the significance of the final outcome of the search will be computed thanks to pseudo-experiment Monte Carlo realisations. In order to do so, the background probability density function of  $X^2$  will be fitted for each S6 period and interferometer configuration. Figure 5.40 shows, for the particular case of S6A run and 3 interferometers configuration, the background distribution of the  $X^2$  variable. It has been fitted with a ”scaled  $\chi^2$ ” with 6 degrees of freedom and a general  $\Gamma$  distribution. The two functions obey to the following formula:

$$f(x; k; \theta) = \frac{1}{\theta^k} \frac{1}{\Gamma(k)} x^{k-1} e^{-x/\theta} \quad (5.27)$$



**Figure 5.40** – Left: Background distribution of the  $X^2$  for S6A with three interferometers. The black line is the scaled  $\chi^2$  and the red one the  $\Gamma$  distribution (see text). Right: corresponding p-value evolution of the  $\Gamma$  distribution (red) and scaled  $\chi^2$  (blue) together with lines corresponding to 3 (upper) and 5 (lower) sigma confidence levels.

The scaled  $\chi^2$  distribution has  $k=3$  (from the 6 degrees of freedom), free  $\theta$  (the scale parameter) and the fit gives a  $\chi^2$  per degree of freedom of 8.2. The general  $\Gamma$  distribution has both parameters free and the fit gives a slightly worse  $\chi^2$  per degree of freedom of 8.5. However, given the corresponding p-values evolution, displayed on the right panel of Figure 5.40, the most conservative choice for the pseudo experiments generation is the  $\Gamma$  distribution. The final result of the search will be the p-value of its most significant event  $i$  and is defined as:

$$p^{\text{GW+HEN}} = \int_{\text{Max}(X_i^2)}^{\infty} P_{bg}(\text{max}(X^2)) dX^2 \quad (5.28)$$

where the probability density function  $P_{bg}(\text{max}(X^2))$  is the result of Monte Carlo simulation of pseudo experiments of 1986 joint triggers.

### 5.8.5 Estimation of the horizon of detection

The detection horizon  $D_{50\%}^{\text{HEN}}$  and  $D_{50\%}^{\text{GW}}$  of each detector for a given model can be defined as the maximum distance for which there is at least a 50% chance probability that the signal would be detected. The common GW+HEN horizon will thus be:

$$D^{\text{GW+HEN}} = \text{Min}(D_{50\%}^{\text{HEN}}, D_{50\%}^{\text{GW}})$$

On the HEN side the horizon corresponds to the maximum distance at which there is a 50% chance probability to have at least one neutrino detected in ANTARES. On the GW side, the procedure is to generate a list of neutrinos with only one having the characteristics of a signal (i.e. with a WB  $n^{\text{hit}}$  distribution as shown by the green curve in Figure 5.27). This neutrino

has to be associated with a  $p_i^{GW}$  corresponding to an injected signal. This is repeated many times and the probability of detection will be the ratio of the number of realisations where  $\max(X_i^2)$  has a p-value lower than the threshold fixed at the end of last section. This detection power will correspond to the intensity of the GW injected in the data. An other interesting quantity would be to inject more and more signal neutrinos at a fixed GW signal intensity and see when the probability is above 50 percent. Once the GWHEN horizon is determined source population limit estimates will be set following the reasoning of section 4.7.

## 5.9 Conclusion

In this chapter we have described the second GW+HEN joint analysis using coincident data taken in 2009-2010 from the ANTARES neutrino telescope and the Virgo/LIGO GW interferometers. In particular we have detailed the methods specifically developed for this search. The joint optimisation procedure on GW and HEN data has led to a list of 1986 neutrino candidates maximizing the number of detectable joint sources. These neutrino events have been completely characterized with the main parameters needed for the coincidence search with GW (see section 5.7). Of these neutrino events, 775 candidates are associated with 2 or 3 interferometer configuration (i.e., HLV: 303, HV: 147, LV: 135 and HL: 190 neutrino candidates).

At the time of submission of this document, the analysis was not completed, some GW data processing being still necessary before launching the pseudo-experiment Monte Carlo simulations needed to set the final joint results. However, all technical steps and ingredients were well defined and presented in this chapter. The final results will be presented in a dedicated paper.

The analysis presented in this chapter has been obtained with improved algorithms and detectors with respect to the analysis of the 2007 data. The global improvement gain expected on the upper limit of population density of common HEN and GW emitters is estimated as follows:

- A gain of a factor 1.4 arises from the observation time (91.36 days and 128.7 days for 2007 and 2009-2010 data respectively).
- A gain of a factor  $\sim 5$  comes from the improvement of the neutrino effective area with respect to 2007 analysis. Indeed, the horizon is imposed by ANTARES and the effective area of the detector has been multiplied by 3 leading to a gain of factor  $\sqrt{3}$  on the distance and hence  $\sqrt{3^3} \sim 5$  on the volume.

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This implies a net improvement by a factor  $\sim 7$  with respect to what is presented in section [4.7.1](#).

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## CONCLUSIONS

By pioneering with the combination of two non-photonic observations, gravitational waves and high-energy neutrinos, this thesis work initiated a new domain in multimessenger astronomy. We designed and assembled a complete pipeline allowing for the combined analysis of ANTARES and LIGO/Virgo data.

We did this in two steps. A first search was conducted on concomitant data taken during 2007. No significant coincident event was detected. This resulted in upper limits on the source population (including potential photon-dark or obscured sources only accessible through GW and HEN observations). To allow rapid progresses, we essentially relied on pre-existing analysis tools. Once the search completed, we identified the limitations and issues of those tools. This has led us to develop new and more sensitive analysis tools that are better suited to the observations at hand. These tools are now integrated in a new pipeline which we applied in the context of a second search using 2009-2010 data currently in progress. The improvements brought to this second search includes a new neutrino selection strategy relying on a combined figure of merit, which maximizes the number of common observable sources.

Some of the methodologies proposed here could be developed in other contexts, and even beyond the GW and HEN context. For instance, the pipeline skymask coherent WaveBurst could serve as a basis to other types of “triggered” GW follow-up burst searches (e.g., in coincidence with gamma-ray bursts). Another example is the optimization scheme which is fairly generic and may be used to optimize the other types of joint searches combining GW or HEN with other cosmic messengers (gamma-rays for instance).

The pathfinder developments done in this thesis pave the way for future collaborations involving the next generation of detectors. These projects include KM3NeT, the future  $\text{km}^3$  neutrino telescope in the Mediterranean sea and the second generation of interferometric GW

## Conclusions

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detectors (advanced LIGO and advanced Virgo). The sensitivity of those instruments will be significantly improved with respect to their predecessors. There are reasonable chances that they will lead to actual observation in their respective channel.

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# APPENDIX A

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## DEMONSTRATION OF THE MRF APPROXIMATION

We follow Neymann's construction of confidence interval to have an estimation of the upper limit in case the computing time of Feldman Cousin limit is prohibitive. For a normal distribution, the probability that a measurement  $n_{obs}$  falls within the interval  $[\mu + c, \mu + d]$ , where  $\mu$  is the mean and  $c < 0$ , is equivalent to the probability that a measurement  $\mu$  falls within the interval  $[n_{obs} - d, n_{obs} - c]$ . Thus we write:

$$\begin{aligned} P(\mu + c_Q \leq n_{obs} \leq \mu + d) &= P(n_{obs} - d \leq \mu \leq n_{obs} - c_Q) \\ &= Q \\ &= erf(d) - erf(c_Q) \end{aligned} \tag{A.1}$$

where erf is the error function and Q is the significance level.

$$erf(x) \equiv \frac{1}{\sqrt{2\pi}} \int_{-\infty}^x e^{-t^2/2} dt \tag{A.2}$$

If  $d \equiv \infty$

$$\begin{aligned} Q &= erf(\infty) - erf(c_Q) \\ &= 1 - erf(c_Q) \\ \Rightarrow c_Q &= erf^{-1}(1 - Q) \end{aligned} \tag{A.3}$$

## DEMONSTRATION OF THE MRF APPROXIMATION

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From Eqs. A.1 and A.3 we write:

$$\mu \leq n_{obs} - erf^{-1}(1 - Q) \quad (\text{A.4})$$

Thus,

$$\mu_{max} = n_{obs} - erf^{-1}(1 - Q) \quad (\text{A.5})$$

Using the following relation [1]:

$$erf\left(\frac{x}{\sigma}\right) = \frac{1}{2} + \frac{1}{2}Erf\left(\frac{x}{\sqrt{2}\sigma}\right) \quad (\text{A.6})$$

where  $\sigma$  is the standard deviations and  $Erf$  is given by:

$$Erf(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-t^2} dt \quad (\text{A.7})$$

we find that:

$$\mu_{max} = n_{obs} - \sqrt{2\mu}Erf^{-1}(1 - 2Q) \quad (\text{A.8})$$

we can also write  $\mu_{max} = n_s + n_b$  where  $n_s$  and  $n_b$  are the number of signal and background events respectively. We put  $x = \sqrt{\mu_{max}} > 0$ , thus

$$x^2 + \sqrt{2}Erf^{-1}(2Q - 1)x - n_{obs} = 0 \quad (\text{A.9})$$

resolving this equation we find:

$$\begin{aligned} x &= \frac{-\sqrt{2}Erf^{-1}(1 - 2Q) + \sqrt{2(Erf^{-1}(1 - 2Q))^2 + 4n_{obs}}}{2} \\ &= \sqrt{n_s + n_b} \end{aligned} \quad (\text{A.10})$$

Finally:

$$n_s \equiv \tilde{\mu}_Q(n_{obs}, n_b) = \left[ \frac{-\sqrt{2}Erf^{-1}(2Q - 1) + \sqrt{2(Erf^{-1}(2Q - 1))^2 + 4n_{obs}}}{2} \right]^2 - n_b \quad (\text{A.11})$$

This approximation should be weighted with the Poisson probability of its occurrence to get the new parametrization of *the average upper limit*:

$$\bar{\mu}_Q(n_b) = \sum_{n_{obs}}^{\infty} \tilde{\mu}_Q(n_{obs}, n_b) \frac{(n_b)^{n_{obs}}}{(n_{obs})!} exp(-n_b) \quad (\text{A.12})$$

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note that this approximation is applied for large values of  $n_{obs} > n_{obs}^{crit}$  such that  $|FC_{ul} - n_s|/FC_{ul} \leq 10\%$ , where  $FC_{ul}$  is FC upper limit. Thus for  $n_{obs} > n_{crit}$  we redefine the ratio to be minimized, in section 5.4.1 as follow:

$$M\tilde{R}F(\text{cuts}) = \frac{\tilde{\mu}_Q(n_b(\text{cuts}))}{n_s(\text{cuts})} \quad (\text{A.13})$$

## DEMONSTRATION OF THE MRF APPROXIMATION

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## REFERENCES

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# APPENDIX B

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## COHERENT WAVEBURST STATISTICS

We have discussed the coherent WaveBurst and the skymask-coherent WaveBurst pipelines in chapters 3 and 5 respectively. In this appendix we define the coherent statistics used in the identification of the GW triggers, i.e  $net_{cc}$ ,  $net_{ED}$  and  $\rho$ .

We consider that we project the time-aligned data onto a complete wavelet basis. Let us denote  $w[i, j]$  is the corresponding wavelet coefficients where  $i, j$  are the time-frequency indices. We do the same for the detector response  $\xi[i, j] = F_+(\theta, \phi)w_+[i, j] + F_\times(\theta, \phi)w_\times[i, j]$  where  $w_{+(\times)}[i, j]$  denotes the wavelet coefficients of the GW polarizations  $h_{+(\times)}$ . The antenna patterns  $F_{+(\times)}$  are defined in Sec. 3.4. Let  $\sigma[i, j]$  be the RMS noise in the time-frequency bin  $(i, j)$ .

The log-likelihood functional is obtained assuming a Gaussian quasi-stationary noise and can be expressed in the wavelet domain as

$$L_{noise} = \sum_{i,j \in \Omega_{TF}} \left[ \frac{w^2[i, j]}{\sigma^2[i, j]} - \frac{(w[i, j] - \xi[i, j])^2}{\sigma^2[i, j]} \right] \quad (\text{B.1})$$

where  $\Omega_{TF}$  is the time-frequency area selected for the analysis.

This expression in the case of a one-detector analysis. Eq. (B.1) can be generalized to  $K$  detectors

$$L_{noise} = \sum_{k=1}^K \sum_{i,j \in \Omega_{TF}} \left[ \frac{w_k^2[i, j]}{\sigma_k^2[i, j]} - \frac{(w_k[i, j] - \xi_k[i, j])^2}{\sigma_k^2[i, j]} \right]. \quad (\text{B.2})$$

Coherent WaveBurst relies on the maximum likelihood ratio statistic i.e., maximizing Eq. (B.2) over all sky locations  $(\theta, \phi)$ . This quantity is a quadratic form of  $w$ , thus it can be expressed in a matrix form as follows

$$L_{noise}^{max}(\theta, \phi) = \sum_{n,m} L_{nm}, \quad (\text{B.3})$$

where  $L_{nm} = \sum_{i,j \in \Omega_{TF}} w_n[i, j]w_m[i, j]P_{nm}[i, j]$  and  $P$  is the orthogonal projector onto the  $GW$

## COHERENT WAVEBURST STATISTICS

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plane spanned by normalized antenna pattern vectors  $f_+$  and  $f_\times$  defined as follows

$$f_{+(\times)} = \left\{ \frac{F_{1+(\times)}(\theta, \phi)}{\sigma_1[i, j]}, \dots, \frac{F_{K+(\times)}(\theta, \phi)}{\sigma_K[i, j]} \right\}. \quad (\text{B.4})$$

We refer to *coherent energy*

$$E_c = \sum_{m \neq n} L_{mn} \quad (\text{B.5})$$

as the sum of the off-diagonal terms of the log-likelihood matrix.  $E_c$  measures the correlation between the detector responses to a common GW signal. We also defined the *reduced coherent energy*  $e_c = \sum_{n \neq m} L_{nm} |r_{nm}|$  where the terms are weighted by the Pearson's coefficients

$$r_{nm} = \frac{L_{nm}}{\sqrt{L_{nn}L_{mm}}}. \quad (\text{B.6})$$

By projecting the data onto the *null space* complementary to the GW plane, we define the null matrix  $N_{nm} = E_{nm} - L_{nm}$  with  $E_{nn} = w_n^2$  and the associated null energy

$$N_{null} = \sum_{n,m} N_{nm}. \quad (\text{B.7})$$

Instrumental glitches have a small  $E_c$  and large  $N_{null}$ .

Finally, given these ingredients we can define the *network correlation coefficient*

$$net_{cc} = \frac{E_c}{N_{null} + |E_c|}, \quad (\text{B.8})$$

the *coherent network amplitude*

$$\rho = \sqrt{\frac{e_c}{K} net_{cc}}, \quad (\text{B.9})$$

and the *network energy disbalance*

$$net_{ED} = \sum_k \frac{|\Delta_k|}{E_c}, \quad (\text{B.10})$$

where  $\Delta_k$  is the energy disbalance for detector  $k$ .

While cuts on  $net_{cc}$  and  $net_{ED}$  are used to distinguish noise outliers from genuine GW signals, the final event selection is done through a cut over the statistic  $\rho$  which characterises the event significance (see chapter 5 for the application of these statistics).

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# APPENDIX C

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## LIST OF HIGH ENERGY NEUTRINO CANDIDATES FOR THE 2009-2010 DATA

1	#	ID	JD	GPS RA[deg.]	DEC[deg.]	radius[deg.]	location[deg.]	scale[deg.]	shape	normalization	nhit	ASW_90[
2	##	start	S6A									
3	0001	2455021.06199646	931094971	317.666	4.358	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	51	0.9	
4	0002	2455021.76038040	931155311	138.462	5.235	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	30	2.4	
5	0003	2455021.95309485	931171962	205.006	3.064	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	44	1.4	
6	0004	2455022.13148593	931187375	278.683	1.967	-1.2873e-01	4.3155e-01	4.6595e-01	3.9162e-02	57	0.7	
7	0005	2455022.31313315	931203069	255.984	-46.786	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	67	1.4	
8	0006	2455022.44211534	931214213	118.664	28.874	-1.1909e-01	7.2127e-01	6.0423e-01	3.7507e-02	27	1.8	
9	0007	2455022.45728516	931215524	157.294	-39.769	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	53	1.4	
10	0008	2455022.94472038	931257638	168.102	-42.850	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	47	1.4	
11	0009	2455023.18653782	931278531	272.997	-21.999	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	50	1.4	
12	0010	2455023.18998930	931278830	1.531	-28.790	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	45	1.4	
13	0011	2455023.37019701	931294400	334.105	-10.712	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	48	1.4	
14	0012	2455023.39396068	931296453	69.937	-17.854	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	38	1.4	
15	0013	2455023.40570083	931297467	32.350	-40.431	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	45	1.4	
16	0014	2455023.89575708	931339808	237.065	42.325	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	67	1.4	
17	0015	2455024.96057196	931431808	206.881	-5.697	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	27	2.4	
18	0016	2455028.74935072	931759158	192.449	-49.417	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	46	1.4	
19	0017	2455029.82388645	931851998	45.763	-56.811	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	42	1.4	
20	0018	2455030.16800912	931881730	74.591	14.647	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	36	1.4	
21	0019	2455030.27551389	931891019	29.548	7.599	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	41	0.9	
22	0020	2455030.33532665	931896187	51.484	-12.502	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	62	0.9	
23	0021	2455030.38375704	931900371	70.987	39.204	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	31	0.9	
24	0022	2455030.93817457	931948273	308.219	-48.184	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	72	1.4	
25	0023	2455031.60103568	932005544	206.992	-38.656	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	38	1.4	
26	0024	2455031.91920714	932033034	270.687	-44.455	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	65	1.4	
27	0025	2455032.08877353	932047685	2.736	-63.554	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	57	1.4	
28	0026	2455032.42253465	932076521	164.843	16.811	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	43	1.4	
29	0027	2455033.33583128	932155430	351.912	-40.016	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	58	1.4	
30	0028	2455033.57360678	932175974	174.370	43.050	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	29	2.4	
31	0029	2455033.61363238	932179432	227.699	-29.385	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	38	1.4	
32	0030	2455033.66610532	932183966	101.450	-43.373	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	53	1.4	
33	0031	2455034.45436583	932252072	109.591	-13.022	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	87	1.4	
34	0032	2455035.07953033	932306086	281.293	23.853	-1.1909e-01	7.2127e-01	6.0423e-01	3.7507e-02	22	1.8	
35	0033	2455035.18161884	932314906	29.890	-63.436	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	56	0.9	

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36	0034	2455035.40957799	932334602	101.450	32.177	-1.7861e+00	6.7827e+00	8.6368e-01	3.8440e-01	30	1.4
37	0035	2455035.64492418	932354936	247.231	-26.876	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	35	1.4
38	0036	2455035.70030035	932359720	227.842	42.919	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	46	1.4
39	0037	2455035.97026079	932383045	211.009	-59.338	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	34	1.4
40	0038	2455036.00870766	932386367	242.953	-39.003	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	67	1.4
41	0039	2455036.60298826	932437713	62.518	-47.951	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	53	0.9
42	0040	2455036.60985464	932438306	102.326	15.432	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	44	1.4
43	0041	2455036.63224016	932440240	272.965	-8.272	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	59	1.4
44	0042	2455036.70911771	932446882	140.991	-37.795	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	45	1.4
45	0043	2455036.71386641	932447293	197.929	-9.068	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	72	0.9
46	0044	2455036.97629850	932469967	49.100	-45.947	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	26	0.9
47	0045	2455036.99191191	932471316	260.728	1.668	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	42	0.9
48	0046	2455037.07504211	932478498	181.562	-44.687	-5.8944e-02	2.9333e-01	5.7306e-01	3.8834e-02	110	0.6
49	0047	2455037.09645452	932480348	266.521	-55.111	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	79	1.4
50	0048	2455037.42636007	932508852	135.162	-42.375	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	45	0.9
51	0049	2455037.54148144	932518798	166.903	36.240	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	38	1.4
52	0050	2455037.85645194	932546012	210.049	-5.290	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	44	1.4
53	0051	2455038.44163643	932596572	120.888	13.742	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	47	1.4
54	0052	2455038.95829055	932641211	278.848	31.341	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	50	1.4
55	0053	2455038.97211600	932642405	163.861	-45.126	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	37	1.4
56	0054	2455039.30290420	932670985	138.019	-66.930	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	64	1.4
57	0055	2455041.87228627	932892980	323.880	-62.866	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	53	1.4
58	0056	2455041.97123183	932901529	333.888	17.928	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	29	2.4
59	0057	2455042.17163841	932918844	349.430	-6.478	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	46	1.4
60	0058	2455042.35897386	932935030	124.059	6.046	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	33	1.4
61	0059	2455042.45033082	932942923	3.545	-71.453	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	30	2.4
62	0060	2455042.87758885	932979838	303.584	-28.374	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	40	0.9
63	0061	2455042.89936669	932981720	250.252	-30.276	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	37	1.4
64	0062	2455043.89864128	933068057	316.089	4.421	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	36	1.4
65	0063	2455050.32408157	933623215	72.132	1.396	-5.8944e-02	2.9333e-01	5.7306e-01	3.8834e-02	114	0.6
66	0064	2455050.38858959	933628789	356.053	-31.259	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	42	1.4
67	0065	2455050.40529145	933630232	313.438	-51.861	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	55	1.4
68	0066	2455050.44870235	933633982	38.167	-55.362	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	23	2.4
69	0067	2455052.47328426	933808906	115.206	-18.798	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	47	0.9
70	0068	2455052.58433722	933818501	206.041	-45.213	-1.2873e-01	4.3155e-01	4.6595e-01	3.9162e-02	42	0.7
71	0069	2455052.85057939	933841505	166.502	-25.475	-1.2873e-01	4.3155e-01	4.6595e-01	3.9162e-02	60	0.7
72	0070	2455052.95932832	933850900	253.817	-75.759	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	60	1.4
73	0071	2455052.97455143	933852216	286.417	37.666	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	65	1.4
74	0072	2455053.41821454	933890548	20.185	-23.592	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	59	1.4
75	0073	2455053.48363661	933896201	49.990	-19.411	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	40	1.4
76	0074	2455053.53529934	933900664	187.949	-6.248	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	52	0.9
77	0075	2455053.53684889	933900798	44.865	-25.779	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	67	1.4
78	0076	2455053.74347266	933918651	163.514	13.204	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	37	1.4
79	0077	2455053.74875280	933919107	78.440	-60.862	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	34	1.4
80	0078	2455053.81557582	933924880	276.507	28.587	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	85	1.4
81	0079	2455053.83153518	933926259	186.604	-39.316	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	32	1.4
82	0080	2455054.19238734	933957437	79.365	-26.764	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	29	1.4
83	0081	2455054.30248002	933966949	211.712	-45.529	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	29	2.4
84	0082	2455054.32037523	933968495	41.278	31.473	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	52	1.4
85	0083	2455054.65740359	933997614	289.824	-23.322	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	34	1.4
86	0084	2455055.01582708	934028582	273.787	-44.754	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	38	1.4
87	0085	2455057.10660147	934209225	355.481	-47.229	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	40	0.9

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88	0086	2455057.72174617	934262373	197.766	37.641	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	32	1.4
89	0087	2455057.73197650	934263257	343.302	-21.717	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	62	1.4
90	0088	2455057.77638293	934267094	18.317	-71.965	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	36	0.9
91	0089	2455057.99678427	934286137	338.646	-57.019	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	36	0.9
92	0090	2455058.10416152	934295414	25.851	14.336	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	26	2.4
93	0091	2455058.18834888	934302688	178.236	-41.215	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	46	1.4
94	0092	2455058.76158587	934352216	246.087	-39.107	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	42	0.9
95	0093	2455058.86341465	934361014	3.491	-27.687	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	72	1.4
96	0094	2455058.91450708	934365428	288.617	39.340	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	30	1.4
97	0095	2455059.05793775	934377820	78.537	-81.132	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	36	0.9
98	0096	2455059.14860678	934385654	296.207	-56.333	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	35	0.9
99	0097	2455059.39256684	934406732	86.229	-5.943	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	42	1.4
100	0098	2455059.55834199	934421055	110.022	-52.160	-1.2873e-01	4.3155e-01	4.6595e-01	3.9162e-02	41	0.7
101	0099	2455059.60484498	934425073	348.050	-74.294	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	29	2.4
102	0100	2455059.72044919	934435061	88.907	-77.196	-1.2873e-01	4.3155e-01	4.6595e-01	3.9162e-02	59	0.7
103	0101	2455059.87421622	934448347	259.574	7.695	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	25	2.4
104	0102	2455059.91445785	934451824	224.493	10.941	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	49	1.4
105	0103	2455059.98885820	934458252	241.941	-37.187	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	35	1.4
106	0104	2455060.09424206	934467357	323.311	-40.725	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	42	1.4
107	0105	2455060.18410076	934475121	205.068	-72.845	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	38	1.4
108	0106	2455060.25954351	934481639	9.288	-7.403	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	42	1.4
109	0107	2455060.35331136	934489741	179.878	-53.666	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	57	1.4
110	0108	2455060.52726260	934504770	47.437	-33.261	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	55	1.4
111	0109	2455061.31263711	934572626	192.544	-55.694	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	50	1.4
112	0110	2455061.44684815	934584222	72.470	-28.046	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	42	1.4
113	0111	2455061.51759585	934590335	237.226	-9.551	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	37	1.4
114	0112	2455061.55946493	934593952	202.888	33.499	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	37	1.4
115	0113	2455061.73849454	934609420	19.756	-50.560	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	51	1.4
116	0114	2455061.74870241	934610302	152.932	-6.469	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	34	1.4
117	0115	2455061.83503097	934617761	298.604	-42.499	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	25	1.4
118	0116	2455061.88976534	934622490	214.252	-34.716	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	41	1.4
119	0117	2455061.94754236	934627482	357.669	13.929	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	43	1.4
120	0118	2455062.02194877	934633911	172.194	-63.516	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	32	1.4
121	0119	2455062.08912358	934639715	101.379	-14.331	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	40	1.4
122	0120	2455062.21500284	934650591	295.537	-40.361	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	33	1.4
123	0121	2455062.82701440	934703469	300.123	35.695	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	34	1.4
124	0122	2455062.85720530	934706077	323.861	-6.029	-1.1909e-01	7.2127e-01	6.0423e-01	3.7507e-02	20	1.8
125	0123	2455062.88545185	934708518	263.884	8.358	-1.1909e-01	7.2127e-01	6.0423e-01	3.7507e-02	66	1.8
126	0124	2455062.89821627	934709620	245.558	16.387	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	32	1.4
127	0125	2455062.97267542	934716054	285.690	27.039	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	26	2.4
128	0126	2455063.17559712	934733586	25.934	-60.307	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	43	0.9
129	0127	2455063.48054315	934759933	162.308	-30.704	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	37	1.4
130	0128	2455063.57841217	934768389	314.799	-37.629	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	35	1.4
131	0129	2455063.60847560	934770987	173.670	45.183	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	57	0.9
132	0130	2455063.63467694	934773251	170.213	-13.859	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	31	0.9
133	0131	2455063.68940751	934777979	233.357	-1.269	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	37	0.9
134	0132	2455063.77603876	934785464	260.557	-19.652	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	80	0.9
135	0133	2455063.78605218	934786329	138.906	-50.654	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	58	1.4
136	0134	2455063.88720217	934795069	212.069	-22.876	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	35	1.4
137	0135	2455064.04774615	934808940	335.759	44.453	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	39	1.4
138	0136	2455064.14454310	934817303	288.283	-49.621	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	36	1.4
139	0137	2455064.26502570	934827713	161.003	-8.728	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	46	1.4

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140	0138	2455064.56062293	934853252	38.039	-52.296	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	74	1.4
141	0139	2455064.65752250	934861624	281.452	-16.760	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	39	1.4
142	0140	2455064.78114668	934872306	257.829	-0.921	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	35	1.4
143	0141	2455064.88179257	934881001	22.451	-15.508	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	47	1.4
144	0142	2455064.95292887	934887148	146.216	-65.464	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	40	1.4
145	0143	2455064.99601715	934890870	11.022	8.344	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	41	1.4
146	0144	2455065.36133282	934922434	169.335	-47.674	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	40	0.9
147	0145	2455065.60217816	934943243	165.957	-25.904	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	56	0.9
148	0146	2455065.93864074	934972313	62.855	-28.983	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	59	1.4
149	0147	2455066.39089495	935011388	176.976	-11.310	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	36	0.9
150	0148	2455066.57591951	935027374	193.704	-21.759	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	49	1.4
151	0149	2455066.61269078	935030551	3.471	-59.062	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	71	1.4
152	0150	2455066.75797386	935043103	211.403	-49.385	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	45	1.4
153	0151	2455066.77956388	935044969	235.841	17.491	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	40	1.4
154	0152	2455067.01314266	935065150	289.079	-74.713	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	44	1.4
155	0153	2455067.08142308	935071049	54.618	-13.711	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	35	1.4
156	0154	2455067.11560343	935074003	234.943	-63.137	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	29	2.4
157	0155	2455067.12042047	935074419	304.395	-12.814	-1.1909e-01	7.2127e-01	6.0423e-01	3.7507e-02	27	1.8
158	0156	2455067.15376586	935077300	21.271	-27.720	-1.2873e-01	4.3155e-01	4.6595e-01	3.9162e-02	45	0.7
159	0157	2455067.30991995	935090792	105.702	-6.759	-1.2873e-01	4.3155e-01	4.6595e-01	3.9162e-02	52	0.7
160	0158	2455070.47703972	935364431	265.930	-75.124	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	41	1.4
161	0159	2455070.94445264	935404815	296.500	12.771	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	39	0.9
162	0160	2455070.96791834	935406843	329.554	17.101	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	45	0.9
163	0161	2455070.99781936	935409426	35.999	-50.428	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	67	1.4
164	0162	2455071.13297930	935421104	91.198	-60.854	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	25	2.4
165	0163	2455071.26768616	935432743	60.807	27.094	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	51	1.4
166	0164	2455071.29632968	935435217	294.982	-48.854	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	25	2.4
167	0165	2455071.32881274	935438024	197.670	-19.309	-1.1909e-01	7.2127e-01	6.0423e-01	3.7507e-02	28	1.8
168	0166	2455071.39038574	935443344	110.555	-56.593	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	37	1.4
169	0167	2455071.40315053	935444447	60.000	19.101	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	47	1.4
170	0168	2455071.76877458	935476037	285.997	1.892	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	42	0.9
171	0169	2455071.82952120	935481285	6.548	-1.611	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	32	1.4
172	0170	2455072.02111240	935497839	332.166	-27.354	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	26	2.4
173	0171	2455072.08589852	935503436	267.489	-18.082	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	53	1.4
174	0172	2455072.10148270	935504783	71.396	-42.301	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	28	2.4
175	0173	2455072.42031869	935532330	42.345	-50.906	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	50	1.4
176	0174	2455072.85751870	935570104	151.015	-64.369	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	81	1.4
177	0175	2455072.87929551	935571986	302.403	-2.080	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	38	0.9
178	0176	2455073.03755802	935585660	341.378	26.213	-1.2873e-01	4.3155e-01	4.6595e-01	3.9162e-02	38	0.7
179	0177	2455073.04830593	935586588	333.750	6.568	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	73	1.4
180	0178	2455073.21274276	935600795	28.475	20.486	-1.1909e-01	7.2127e-01	6.0423e-01	3.7507e-02	28	1.8
181	0179	2455073.43171108	935619714	191.985	29.561	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	34	1.4
182	0180	2455073.44068156	935620489	148.114	-0.467	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	70	1.4
183	0181	2455073.46909432	935622944	195.280	-21.809	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	32	1.4
184	0182	2455073.64250209	935637927	98.395	-50.232	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	69	1.4
185	0183	2455073.64388251	935638046	264.339	28.544	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	47	1.4
186	0184	2455073.69052558	935642076	180.486	-21.394	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	38	1.4
187	0185	2455073.76116355	935648179	298.854	36.684	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	48	1.4
188	0186	2455073.97565402	935666711	283.507	-12.569	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	26	2.4
189	0187	2455074.16081558	935682709	1.175	-18.999	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	34	1.4
190	0188	2455074.21222119	935687150	108.559	-53.956	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	71	1.4
191	0189	2455074.32623248	935697001	298.966	-58.654	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	37	1.4

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192 0190 2455074.56496007 935717627 84.393 -37.166 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 62 1.4  
193 0191 2455074.57640119 935718616 79.034 -30.771 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 38 1.4  
194 0192 2455074.60422679 935721020 272.659 4.576 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 75 1.4  
195 0193 2455074.79432343 935737444 67.313 -48.050 -1.1724e-01 4.7983e-01 5.2936e-01 3.8897e-02 51 0.9  
196 0194 2455075.10189846 935764019 8.468 1.425 -1.3370e-01 8.5313e-01 6.3102e-01 3.7539e-02 15 2.4  
197 0195 2455075.17740608 935770542 14.325 29.555 -1.1724e-01 4.7983e-01 5.2936e-01 3.8897e-02 46 0.9  
198 0196 2455075.21724744 935773985 348.538 -50.641 -1.3370e-01 8.5313e-01 6.3102e-01 3.7539e-02 29 2.4  
199 0197 2455075.28702876 935780014 150.807 0.342 -1.3370e-01 8.5313e-01 6.3102e-01 3.7539e-02 30 2.4  
200 0198 2455075.36731093 935786950 159.178 -34.961 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 36 1.4  
201 0199 2455075.38729420 935788677 26.551 -9.824 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 66 1.4  
202 0200 2455075.41695957 935791240 50.676 -64.237 -1.1909e-01 7.2127e-01 6.0423e-01 3.7507e-02 30 1.8  
203 ## stop S6A -- start  
204 0201 2455075.56390515 935803936 186.645 -78.234 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 39 1.4  
205 0202 2455075.77641224 935822297 26.229 -51.325 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 35 1.4  
206 0203 2455075.99417841 935841112 42.364 11.601 -1.1909e-01 7.2127e-01 6.0423e-01 3.7507e-02 22 1.8  
207 0204 2455075.99462135 935841150 292.792 -26.328 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 35 1.4  
208 0205 2455076.01741383 935843119 315.405 34.672 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 44 1.4  
209 0206 2455076.15557493 935855056 253.920 -64.226 -1.1724e-01 4.7983e-01 5.2936e-01 3.8897e-02 46 0.9  
210 0207 2455076.18136926 935857285 160.419 -29.016 -1.1724e-01 4.7983e-01 5.2936e-01 3.8897e-02 34 0.9  
211 0208 2455076.23681134 935862075 113.337 -57.305 -1.3370e-01 8.5313e-01 6.3102e-01 3.7539e-02 25 2.4  
212 0209 2455076.27127798 935865053 307.233 -60.805 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 72 1.4  
213 0210 2455076.32513939 935869707 134.496 38.062 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 51 1.4  
214 0211 2455076.33399198 935870471 208.913 -12.640 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 32 1.4  
215 0212 2455076.35855125 935872593 147.308 -15.700 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 32 1.4  
216 0213 2455076.57486298 935891283 251.261 -16.281 -1.1724e-01 4.7983e-01 5.2936e-01 3.8897e-02 34 0.9  
217 0214 2455076.58392926 935892066 118.896 2.822 -1.3370e-01 8.5313e-01 6.3102e-01 3.7539e-02 24 2.4  
218 0215 2455076.77056074 935908191 274.193 -63.643 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 47 1.4  
219 0216 2455077.08998965 935935790 232.891 -61.107 -1.3370e-01 8.5313e-01 6.3102e-01 3.7539e-02 28 2.4  
220 0217 2455077.29565244 935953559 99.410 -5.291 -1.3370e-01 8.5313e-01 6.3102e-01 3.7539e-02 32 2.4  
221 0218 2455077.76187250 935993840 342.896 -9.615 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 37 1.4  
222 0219 2455077.79683288 935996861 196.981 -12.760 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 38 1.4  
223 0220 2455077.91146154 936006765 342.016 -46.411 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 37 1.4  
224 0221 2455078.11485758 936024338 41.640 46.071 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 32 1.4  
225 0222 2455078.14156621 936026646 282.452 -45.117 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 54 1.4  
226 0223 2455078.24965750 936035985 337.977 -49.741 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 73 1.4  
227 0224 2455078.31163506 936041340 182.403 -12.568 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 28 1.4  
228 0225 2455078.66255429 936071659 224.546 14.682 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 53 1.4  
229 0226 2455079.09997850 936109453 220.691 -78.436 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 67 1.4  
230 0227 2455079.14743735 936113553 235.278 -66.087 -1.3370e-01 8.5313e-01 6.3102e-01 3.7539e-02 24 2.4  
231 0228 2455079.23722766 936121311 183.940 -49.505 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 42 1.4  
232 0229 2455079.30866599 936127483 21.285 -38.030 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 53 1.4  
233 0230 2455079.40743016 936136016 170.021 -12.730 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 59 1.4  
234 0231 2455079.47519614 936141871 63.018 -27.148 -1.1909e-01 7.2127e-01 6.0423e-01 3.7507e-02 25 1.8  
235 0232 2455079.47590578 936141933 109.353 -43.789 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 48 1.4  
236 0233 2455079.56121105 936149303 132.409 1.719 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 34 1.4  
237 0234 2455079.57961689 936150893 219.567 44.493 -1.1724e-01 4.7983e-01 5.2936e-01 3.8897e-02 32 0.9  
238 0235 2455079.60719435 936153276 105.653 -38.931 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 37 1.4  
239 0236 2455079.63811721 936155948 243.927 -85.337 -1.3370e-01 8.5313e-01 6.3102e-01 3.7539e-02 30 2.4  
240 0237 2455079.78572540 936168701 340.634 -31.464 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 49 1.4  
241 0238 2455079.86039597 936175153 16.488 -32.619 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 36 1.4  
242 0239 2455079.91700502 936180044 241.291 -33.317 -1.1909e-01 7.2127e-01 6.0423e-01 3.7507e-02 20 1.8  
243 0240 2455079.96408156 936184111 53.170 -4.564 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 33 1.4



# LIST OF HIGH ENERGY NEUTRINO CANDIDATES FOR THE 2009-2010 DATA

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244	0241	2455079.99178393	936186505	53.833	-46.456	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	23	2.4
245	0242	2455080.26754240	936210330	304.848	-63.157	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	65	2.4
246	0243	2455080.30098932	936213220	200.562	-14.125	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	33	1.4
247	0244	2455080.50745682	936231059	131.300	-53.602	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	47	0.9
248	0245	2455080.61428536	936240289	171.795	19.682	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	79	1.4
249	0246	2455080.65172297	936243523	346.127	-38.193	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	25	2.4
250	0247	2455080.78975878	936255450	140.283	-42.237	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	37	1.4
251	0248	2455080.81326229	936257480	153.269	-48.309	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	56	1.4
252	0249	2455080.86532787	936261979	239.266	22.131	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	32	1.4
253	0250	2455081.03265593	936276436	316.385	-27.710	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	36	1.4
254	0251	2455081.17430312	936288674	145.492	-65.358	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	29	2.4
255	0252	2455081.17518076	936288750	310.872	-35.986	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	28	2.4
256	0253	2455081.27522467	936297394	33.006	-20.002	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	51	1.4
257	0254	2455081.36548723	936305193	352.796	-38.440	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	55	1.4
258	0255	2455081.42963220	936310735	172.399	-46.444	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	44	0.9
259	0256	2455081.43810186	936311467	119.039	16.706	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	42	0.9
260	0257	2455081.46934234	936314166	141.511	43.768	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	41	1.4
261	0258	2455081.75732313	936339047	350.102	-7.725	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	30	2.4
262	0259	2455081.87184067	936348942	2.549	24.156	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	59	2.4
263	0260	2455082.03341998	936362902	8.738	-11.288	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	37	1.4
264	0261	2455082.23583768	936380391	122.853	10.639	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	37	1.4
265	0262	2455082.28760713	936384864	21.450	-56.564	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	63	0.9
266	0263	2455082.53515656	936406252	197.978	-64.291	-1.2873e-01	4.3155e-01	4.6595e-01	3.9162e-02	44	0.7
267	0264	2455082.61202671	936412894	250.676	-9.426	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	35	1.4
268	0265	2455082.63848570	936415180	187.983	16.341	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	32	0.9
269	0266	2455082.67468045	936418307	274.678	-8.183	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	38	1.4
270	0267	2455082.76755631	936426331	283.751	-21.164	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	34	1.4
271	0268	2455082.92962440	936440334	316.109	-67.492	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	42	1.4
272	0269	2455083.03701931	936449613	37.804	-45.552	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	83	0.9
273	0270	2455083.05275481	936450973	5.566	-53.262	-1.2873e-01	4.3155e-01	4.6595e-01	3.9162e-02	60	0.7
274	0271	2455083.06745450	936452243	312.436	-15.372	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	41	1.4
275	0272	2455083.18404952	936462316	355.395	-3.458	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	62	1.4
276	0273	2455083.42293132	936482956	103.993	28.368	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	44	0.9
277	0274	2455083.50672955	936490196	196.316	36.018	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	29	2.4
278	0275	2455083.73577995	936509986	320.376	-43.986	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	36	0.9
279	0276	2455083.73592252	936509998	195.708	8.432	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	56	0.9
280	0277	2455083.73668266	936510064	314.963	23.670	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	36	1.4
281	0278	2455083.80856309	936516274	220.616	-58.925	-1.1909e-01	7.2127e-01	6.0423e-01	3.7507e-02	31	1.8
282	0279	2455084.13393384	936544386	359.862	-42.770	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	45	1.4
283	0280	2455084.29535617	936558333	149.835	-40.793	-1.1909e-01	7.2127e-01	6.0423e-01	3.7507e-02	29	1.8
284	0281	2455084.47954483	936574247	250.232	-29.542	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	98	1.4
285	0282	2455084.52238013	936577948	86.300	-15.433	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	50	1.4
286	0283	2455084.70065469	936593351	193.669	16.403	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	36	1.4
287	0284	2455084.73734402	936596521	272.373	-12.385	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	46	1.4
288	0285	2455084.93151646	936613298	11.085	-31.666	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	44	1.4
289	0286	2455085.02272638	936621178	284.122	-4.322	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	80	1.4
290	0287	2455085.17644877	936634460	39.562	4.080	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	36	1.4
291	0288	2455085.39207416	936653090	149.682	-9.064	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	33	1.4
292	0289	2455085.53667003	936665583	238.313	3.530	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	42	1.4
293	0290	2455085.63388097	936673982	223.456	-13.145	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	68	1.4
294	0291	2455085.81000029	936689199	258.033	28.657	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	63	0.9
295	0292	2455085.81627549	936689741	181.333	-81.504	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	44	1.4

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296	0293	2455085.94696772	936701033	355.609	12.623	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	37	1.4
297	0294	2455085.99814372	936705454	334.364	-73.035	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	46	1.4
298	0295	2455086.33772210	936734794	51.412	-50.081	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	41	1.4
299	0296	2455086.35776611	936736525	115.358	-1.712	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	43	1.4
300	0297	2455086.40197481	936740345	212.435	-52.563	-5.8944e-02	2.9333e-01	5.7306e-01	3.8834e-02	101	0.6
301	0298	2455086.40866353	936740923	112.413	-1.239	-5.8944e-02	2.9333e-01	5.7306e-01	3.8834e-02	47	0.6
302	0299	2455086.48541717	936747555	131.185	-55.889	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	28	2.4
303	0300	2455086.51202936	936749854	91.114	-85.172	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	61	0.9
304	0301	2455086.81907830	936776383	272.525	-6.543	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	56	1.4
305	0302	2455087.24479815	936813165	63.225	-16.889	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	56	1.4
306	0303	2455087.38036137	936824878	215.603	-52.496	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	33	0.9
307	0304	2455088.42721201	936915326	91.969	-36.275	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	40	1.4
308	0305	2455088.46528086	936918615	132.251	-56.236	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	66	1.4
309	0306	2455088.57025334	936927684	168.350	-16.421	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	79	1.4
310	0307	2455089.41468143	937000643	245.913	-65.604	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	45	1.4
311	0308	2455090.05202632	937055710	343.455	24.853	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	38	1.4
312	0309	2455090.07066954	937057320	330.588	-13.538	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	44	1.4
313	0310	2455090.07539159	937057728	2.778	6.638	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	33	1.4
314	0311	2455090.08057983	937058177	328.174	16.945	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	37	1.4
315	0312	2455090.11482057	937061135	307.431	-35.535	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	42	1.4
316	0313	2455090.17635614	937066452	129.887	-15.388	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	80	1.4
317	0314	2455090.26020686	937073696	99.595	-63.557	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	50	1.4
318	0315	2455090.32316510	937079136	159.295	34.297	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	47	1.4
319	0316	2455090.41727628	937087267	202.391	7.376	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	45	1.4
320	0317	2455090.44945331	937090047	18.880	-41.386	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	80	1.4
321	0318	2455090.46335818	937091249	271.916	-31.743	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	58	1.4
322	0319	2455090.50333907	937094703	159.524	-15.889	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	46	1.4
323	0320	2455091.11569909	937147611	181.766	-46.886	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	39	1.4
324	0321	2455091.22797368	937157311	189.470	-64.559	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	28	2.4
325	0322	2455091.24194602	937158519	93.087	-30.725	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	45	1.4
326	0323	2455091.28544568	937162277	48.500	19.241	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	31	2.4
327	0324	2455091.41615599	937173570	324.521	-48.735	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	24	2.4
328	0325	2455091.44493275	937176057	229.094	-26.141	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	42	1.4
329	0326	2455091.46355564	937177666	197.124	6.631	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	23	2.4
330	0327	2455091.64030714	937192937	91.279	-40.405	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	40	2.4
331	0328	2455091.76433502	937203653	187.982	-38.231	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	36	0.9
332	0329	2455091.77363468	937204457	287.123	43.801	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	42	1.4
333	0330	2455092.26310601	937246747	312.379	-64.703	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	29	2.4
334	0331	2455092.38553911	937257325	43.981	-23.647	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	55	2.4
335	0332	2455092.57538687	937273728	293.416	-31.917	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	57	1.4
336	0333	2455092.63911316	937279234	260.435	27.843	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	42	1.4
337	0334	2455092.81691255	937294596	353.786	12.035	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	30	2.4
338	0335	2455092.82023761	937294883	186.894	-32.649	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	33	1.4
339	0336	2455092.90980427	937302622	315.280	-0.447	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	46	0.9
340	0337	2455092.94552705	937305708	298.898	-61.532	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	88	1.4
341	0338	2455093.05334004	937315023	3.893	-7.564	-1.2873e-01	4.3155e-01	4.6595e-01	3.9162e-02	55	0.7
342	0339	2455093.29306832	937335736	193.268	-17.158	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	22	2.4
343	0340	2455093.32564608	937338550	90.124	-5.205	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	44	1.4
344	0341	2455093.40926251	937345775	317.116	-75.871	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	33	1.4
345	0342	2455093.47608774	937351548	118.676	19.345	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	57	0.9
346	0343	2455093.48161499	937352026	172.275	24.961	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	70	1.4
347	0344	2455093.72319728	937372899	210.676	-15.984	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	42	1.4

## LIST OF HIGH ENERGY NEUTRINO CANDIDATES FOR THE 2009-2010 DATA

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348	0345	2455093.85862360	937384600	289.632	28.662	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	63	1.4
349	0346	2455094.04037710	937400303	45.899	30.911	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	26	2.4
350	0347	2455094.09017880	937404606	73.479	-7.003	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	40	0.9
351	0348	2455094.29038023	937421903	25.237	-8.833	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	42	1.4
352	0349	2455094.43607690	937434492	210.009	-52.230	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	54	1.4
353	0350	2455094.78884488	937464971	3.674	-48.582	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	34	1.4
354	0351	2455094.92212449	937476486	353.805	-48.761	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	51	0.9
355	0352	2455094.96444620	937480143	268.251	-11.069	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	35	1.4
356	0353	2455095.02124958	937485050	21.663	1.555	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	73	1.4
357	0354	2455095.08594664	937490640	95.314	-40.052	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	37	1.4
358	0355	2455095.31074892	937510063	5.839	-69.210	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	44	1.4
359	0356	2455095.40141202	937517896	51.941	-13.238	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	58	1.4
360	0357	2455096.24040858	937590386	136.272	-47.028	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	64	1.4
361	0358	2455096.29589030	937595179	146.780	-9.331	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	40	1.4
362	0359	2455096.41449365	937605427	104.963	-33.021	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	55	1.4
363	0360	2455096.52800333	937615234	128.593	-29.992	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	32	1.4
364	0361	2455096.68391567	937628705	141.312	-39.629	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	70	1.4
365	0362	2455097.45008271	937694902	228.978	-38.159	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	32	1.4
366	0363	2455097.56872116	937705152	193.538	-2.264	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	56	1.4
367	0364	2455098.16288293	937756488	148.194	-4.399	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	35	1.4
368	0365	2455098.54092366	937789150	192.691	14.963	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	40	1.4
369	0366	2455098.68646128	937801725	240.770	35.351	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	48	1.4
370	0367	2455098.91636730	937821589	351.543	3.824	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	36	1.4
371	0368	2455099.24073472	937849614	18.588	-14.617	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	30	2.4
372	0369	2455099.59653242	937880355	296.078	0.247	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	52	1.4
373	0370	2455099.63512643	937883689	175.922	0.378	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	45	1.4
374	0371	2455099.79334823	937897360	93.697	-49.992	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	40	0.9
375	0372	2455102.27178044	938111496	200.139	-27.965	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	75	1.4
376	0373	2455102.27805785	938112039	67.798	22.646	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	37	1.4
377	0374	2455102.35356275	938118562	132.628	-14.614	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	40	1.4
378	0375	2455102.39752847	938122361	175.148	35.082	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	41	1.4
379	0376	2455103.04918244	938178664	356.482	-3.559	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	32	1.4
380	0377	2455103.40413438	938209332	278.252	-36.117	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	38	1.4
381	0378	2455103.58586945	938225034	282.729	-79.220	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	29	2.4
382	0379	2455103.78034553	938241836	204.419	-18.149	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	36	1.4
383	0380	2455103.88545957	938250918	15.509	1.608	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	52	1.4
384	0381	2455103.94084063	938255703	45.803	30.019	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	47	1.4
385	0382	2455104.04120529	938264375	53.910	-56.310	-1.2873e-01	4.3155e-01	4.6595e-01	3.9162e-02	60	0.7
386	0383	2455104.16566846	938275128	288.279	-56.157	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	74	1.4
387	0384	2455104.20894439	938278867	210.871	-51.328	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	59	0.9
388	0385	2455104.23098445	938280772	63.085	-23.178	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	33	1.4
389	0386	2455104.48051724	938302331	226.405	-28.934	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	38	1.4
390	0387	2455104.68229967	938319765	288.159	-42.235	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	75	0.9
391	0388	2455104.70328215	938321578	307.095	-6.614	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	37	0.9
392	0389	2455104.90458370	938338971	8.751	-29.573	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	51	1.4
393	0390	2455105.26904169	938370460	135.057	-0.240	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	52	1.4
394	0391	2455105.47162534	938387963	76.853	-23.921	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	24	2.4
395	0392	2455105.47359406	938388133	169.350	6.763	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	37	0.9
396	0393	2455105.69289356	938407081	331.632	-21.688	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	62	1.4
397	0394	2455106.09898691	938442167	349.394	-64.148	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	30	2.4
398	0395	2455106.10501045	938442687	97.016	-14.779	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	17	2.4
399	0396	2455106.13841955	938445574	20.880	-34.063	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	18	2.4

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400 0397 2455106.15760056 938447231 111.651 -66.684 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 33 1.4  
401 0398 2455106.15804839 938447270 308.309 -35.751 -1.1724e-01 4.7983e-01 5.2936e-01 3.8897e-02 55 0.9  
402 0399 2455106.33725387 938462753 69.956 18.560 -1.3370e-01 8.5313e-01 6.3102e-01 3.7539e-02 29 2.4  
403 0400 2455106.33770698 938462792 35.802 -64.301 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 57 1.4  
404 0401 2455106.38053544 938466493 230.019 -43.933 -1.1724e-01 4.7983e-01 5.2936e-01 3.8897e-02 35 0.9  
405 0402 2455106.41301495 938469299 303.756 -66.111 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 67 1.4  
406 0403 2455106.43796736 938471455 173.146 22.524 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 35 1.4  
407 0404 2455106.59420504 938484954 267.949 15.123 -1.3370e-01 8.5313e-01 6.3102e-01 3.7539e-02 30 2.4  
408 0405 2455106.59899067 938485367 186.962 -13.071 -1.3370e-01 8.5313e-01 6.3102e-01 3.7539e-02 20 2.4  
409 0406 2455106.67855854 938492242 28.342 -53.398 -1.3370e-01 8.5313e-01 6.3102e-01 3.7539e-02 24 2.4  
410 0407 2455106.68526612 938492821 183.389 -35.410 -1.3370e-01 8.5313e-01 6.3102e-01 3.7539e-02 27 2.4  
411 0408 2455106.75716598 938499034 204.453 -8.382 -1.3370e-01 8.5313e-01 6.3102e-01 3.7539e-02 27 2.4  
412 0409 2455106.93284884 938514213 6.804 17.120 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 41 1.4  
413 0410 2455106.94926794 938515631 275.171 -49.706 -1.3370e-01 8.5313e-01 6.3102e-01 3.7539e-02 31 2.4  
414 0411 2455107.06586108 938525705 200.162 -51.684 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 50 1.4  
415 0412 2455107.06993162 938526057 89.805 -19.215 -1.3370e-01 8.5313e-01 6.3102e-01 3.7539e-02 26 2.4  
416 0413 2455107.16309664 938534106 113.966 -2.746 -1.3370e-01 8.5313e-01 6.3102e-01 3.7539e-02 29 2.4  
417 0414 2455107.22904195 938539804 47.678 -1.816 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 33 1.4  
418 0415 2455107.24446919 938541137 29.501 5.593 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 52 1.4  
419 0416 2455107.73067877 938583145 163.598 -27.937 -1.3370e-01 8.5313e-01 6.3102e-01 3.7539e-02 30 2.4  
420 0417 2455107.74286200 938584198 15.701 -15.867 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 52 1.4  
421 0418 2455108.09088190 938614267 210.184 -75.982 -1.1909e-01 7.2127e-01 6.0423e-01 3.7507e-02 26 1.8  
422 0419 2455108.13113839 938617745 76.988 -27.793 -1.1909e-01 7.2127e-01 6.0423e-01 3.7507e-02 27 1.8  
423 0420 2455108.65188488 938662737 302.757 8.166 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 34 1.4  
424 0421 2455108.72213116 938668807 254.230 -49.669 -1.1724e-01 4.7983e-01 5.2936e-01 3.8897e-02 69 0.9  
425 0422 2455108.77672014 938673523 233.790 16.947 -1.3370e-01 8.5313e-01 6.3102e-01 3.7539e-02 19 2.4  
426 0423 2455108.93658872 938687336 88.782 -11.029 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 38 1.4  
427 0424 2455108.94028716 938687655 302.904 11.418 -1.3370e-01 8.5313e-01 6.3102e-01 3.7539e-02 30 2.4  
428 0425 2455109.04694551 938696871 277.608 -35.585 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 34 1.4  
429 0426 2455109.27708373 938716755 42.313 12.270 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 63 1.4  
430 0427 2455109.27978510 938716988 81.125 24.193 -1.1724e-01 4.7983e-01 5.2936e-01 3.8897e-02 60 0.9  
431 0428 2455109.30529717 938719192 245.768 -54.777 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 48 1.4  
432 0429 2455109.32126382 938720572 111.881 7.221 -1.1724e-01 4.7983e-01 5.2936e-01 3.8897e-02 46 0.9  
433 0430 2455109.50827962 938736730 97.654 -76.296 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 37 1.4  
434 0431 2455109.64102689 938748199 150.037 -53.125 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 28 1.4  
435 0432 2455109.70997371 938754156 240.039 -55.760 -1.3370e-01 8.5313e-01 6.3102e-01 3.7539e-02 28 2.4  
436 0433 2455109.78012252 938760217 191.092 -76.308 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 48 1.4  
437 0434 2455109.95262540 938775121 307.876 27.691 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 38 1.4  
438 0435 2455110.35278849 938809695 0.831 -83.787 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 36 1.4  
439 0436 2455110.39121065 938813015 231.918 -15.213 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 70 1.4  
440 0437 2455110.75548297 938844488 15.339 -17.305 -1.3370e-01 8.5313e-01 6.3102e-01 3.7539e-02 24 2.4  
441 0438 2455110.76066198 938844936 77.634 -68.946 -1.1724e-01 4.7983e-01 5.2936e-01 3.8897e-02 58 0.9  
442 0439 2455110.80497928 938848765 314.592 -2.379 -1.1724e-01 4.7983e-01 5.2936e-01 3.8897e-02 85 0.9  
443 0440 2455110.91119889 938857942 262.753 2.770 -1.3370e-01 8.5313e-01 6.3102e-01 3.7539e-02 25 2.4  
444 0441 2455110.99633956 938865298 78.485 25.500 -1.3370e-01 8.5313e-01 6.3102e-01 3.7539e-02 45 2.4  
445 0442 2455111.07609910 938872189 62.979 -7.400 -1.1724e-01 4.7983e-01 5.2936e-01 3.8897e-02 42 0.9  
446 0443 2455111.29796803 938891359 209.033 -50.034 -1.3370e-01 8.5313e-01 6.3102e-01 3.7539e-02 25 2.4  
447 0444 2455111.31306605 938892663 224.628 -12.990 -1.3370e-01 8.5313e-01 6.3102e-01 3.7539e-02 26 2.4  
448 0445 2455111.34094428 938895072 177.023 -21.854 -1.1724e-01 4.7983e-01 5.2936e-01 3.8897e-02 43 0.9  
449 0446 2455111.52696723 938911144 221.214 -20.684 -1.2873e-01 4.3155e-01 4.6595e-01 3.9162e-02 77 0.7  
450 0447 2455112.40857237 938987315 233.452 -14.584 -1.2873e-01 4.3155e-01 4.6595e-01 3.9162e-02 45 0.7  
451 0448 2455112.49756440 938995004 126.204 -2.166 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 35 1.4

## LIST OF HIGH ENERGY NEUTRINO CANDIDATES FOR THE 2009-2010 DATA

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452	0449	2455112.67848511	939010636	173.150	-48.876	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	54	1.4
453	0450	2455112.80672018	939021715	200.152	-36.498	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	54	1.4
454	0451	2455112.94746167	939033875	107.088	-34.198	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	42	1.4
455	0452	2455113.29913474	939064260	146.416	39.410	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	49	1.4
456	0453	2455113.52092373	939083422	170.341	6.919	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	46	1.4
457	0454	2455113.66173084	939095588	356.420	-35.023	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	40	1.4
458	0455	2455113.74950718	939103172	24.051	-14.475	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	25	1.4
459	0456	2455113.87727032	939114211	72.400	-22.222	-1.1909e-01	7.2127e-01	6.0423e-01	3.7507e-02	29	1.8
460	0457	2455114.02079491	939126611	14.529	-34.800	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	41	1.4
461	0458	2455114.08210711	939131909	131.171	-56.990	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	39	1.4
462	0459	2455114.10003122	939133457	149.562	-23.916	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	46	1.4
463	0460	2455114.47014329	939165435	171.940	-58.800	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	72	0.9
464	0461	2455114.48221273	939166478	330.533	-41.798	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	23	2.4
465	0462	2455114.61945104	939178335	299.100	-24.130	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	46	0.9
466	0463	2455114.96373037	939208081	23.482	-38.374	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	56	1.4
467	0464	2455115.20252461	939228713	7.009	-12.443	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	33	1.4
468	0465	2455115.25815626	939233519	122.012	5.774	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	40	1.4
469	0466	2455115.69694165	939271430	243.642	-31.468	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	45	1.4
470	0467	2455115.73724370	939274912	339.596	30.885	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	34	1.4
471	0468	2455115.77108010	939277836	251.583	-16.284	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	29	2.4
472	0469	2455115.85696732	939285256	14.422	1.130	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	34	1.4
473	0470	2455115.96788788	939294840	278.270	-83.675	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	41	1.4
474	0471	2455115.96792188	939294843	237.923	-69.630	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	30	2.4
475	0472	2455116.24429123	939318721	194.052	-28.568	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	40	1.4
476	0473	2455116.42582425	939334406	351.379	-55.731	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	56	1.4
477	0474	2455116.42960646	939334732	209.405	-17.414	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	57	1.4
478	0475	2455116.59190139	939348755	164.209	-70.024	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	53	1.4
479	0476	2455116.66839094	939355363	205.711	-67.549	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	46	1.4
480	0477	2455116.72638818	939360374	89.399	-46.879	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	41	1.4
481	0478	2455116.75696082	939363016	217.008	-18.117	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	87	1.4
482	0479	2455116.91970536	939377077	299.273	-34.680	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	40	1.4
483	0480	2455116.96917723	939381351	297.645	-0.251	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	54	1.4
484	0481	2455117.11302713	939393780	58.528	-35.957	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	44	0.9
485	0482	2455117.13440548	939395627	220.053	-52.071	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	37	0.9
486	0483	2455117.30518671	939410383	87.764	-69.789	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	42	1.4
487	0484	2455117.39428554	939418081	51.843	-27.383	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	23	2.4
488	0485	2455117.41056783	939419488	62.812	-23.353	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	42	1.4
489	0486	2455117.43264564	939421395	86.844	-31.075	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	36	1.4
490	0487	2455117.44347119	939422330	222.113	-20.451	-1.2873e-01	4.3155e-01	4.6595e-01	3.9162e-02	46	0.7
491	0488	2455117.47784299	939425300	147.514	33.030	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	58	1.4
492	0489	2455117.58490281	939434550	301.777	10.870	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	37	1.4
493	0490	2455117.99339341	939469844	291.060	-38.797	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	32	1.4
494	0491	2455118.09652087	939478754	339.369	-46.066	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	37	1.4
495	0492	2455118.18926273	939486767	89.990	-53.063	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	53	1.4
496	0493	2455118.71224171	939531952	10.798	-7.637	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	40	1.4
497	0494	2455118.78390243	939538144	353.904	15.452	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	61	1.4
498	0495	2455118.82267344	939541493	283.496	-49.890	-1.1909e-01	7.2127e-01	6.0423e-01	3.7507e-02	27	1.8
499	0496	2455118.83480135	939542541	31.539	-29.662	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	69	0.9
500	0497	2455118.93664650	939551341	345.681	-26.193	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	56	0.9
501	0498	2455118.95626420	939553036	0.772	26.750	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	44	1.4
502	0499	2455118.98722376	939555711	31.086	44.150	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	28	2.4
503	0500	2455119.06038976	939562032	107.194	-46.814	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	43	0.9

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504 0501 2455119.10381960 939565785 111.700 -29.431 -1.1724e-01 4.7983e-01 5.2936e-01 3.8897e-02 52 0.9

505 0502 2455119.23430143 939577058 98.321 19.419 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 79 1.4

506 0503 2455119.50723823 939600640 117.050 -25.781 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 36 1.4

507 0504 2455119.54814882 939604175 128.668 -73.127 -1.3370e-01 8.5313e-01 6.3102e-01 3.7539e-02 31 2.4

508 0505 2455119.60944940 939609471 103.082 -79.016 -1.3370e-01 8.5313e-01 6.3102e-01 3.7539e-02 26 2.4

509 0506 2455119.66618321 939614373 288.891 10.154 -1.3370e-01 8.5313e-01 6.3102e-01 3.7539e-02 27 2.4

510 0507 2455119.80532641 939626395 339.224 -13.088 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 55 1.4

511 0508 2455119.85847406 939630987 13.254 -22.584 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 32 1.4

512 0509 2455119.87126979 939632092 301.247 -15.812 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 100 1.4

513 0510 2455120.14462516 939655710 38.322 27.279 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 73 1.4

514 0511 2455120.43275522 939680605 214.461 -53.564 -1.1724e-01 4.7983e-01 5.2936e-01 3.8897e-02 53 0.9

515 0512 2455120.47931155 939684627 333.194 -46.537 -1.1724e-01 4.7983e-01 5.2936e-01 3.8897e-02 77 0.9

516 0513 2455120.49385715 939685884 227.452 45.373 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 39 1.4

517 0514 2455120.69817599 939703537 6.947 -61.248 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 35 1.4

518 0515 2455120.73808635 939706985 234.113 -47.606 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 38 1.4

519 0516 2455120.81641992 939713753 294.394 24.516 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 35 1.4

520 0517 2455120.89703852 939720719 256.611 -70.079 -1.1724e-01 4.7983e-01 5.2936e-01 3.8897e-02 33 0.9

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522 0519 2455121.18227442 939745363 162.392 -43.568 -1.3370e-01 8.5313e-01 6.3102e-01 3.7539e-02 31 2.4

523 0520 2455121.33633591 939758674 90.349 5.215 -1.1724e-01 4.7983e-01 5.2936e-01 3.8897e-02 34 0.9

524 0521 2455121.77626935 939796684 280.168 -57.413 -1.1724e-01 4.7983e-01 5.2936e-01 3.8897e-02 72 0.9

525 0522 2455121.92770574 939809768 46.175 -18.464 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 41 1.4

526 0523 2455122.35754073 939846906 121.636 5.775 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 36 1.4

527 0524 2455122.53895372 939862580 233.077 -7.957 -1.1724e-01 4.7983e-01 5.2936e-01 3.8897e-02 37 0.9

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530 0527 2455123.17154615 939917236 250.627 -48.299 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 68 1.4

531 0528 2455123.31624400 939929738 165.563 -5.823 -1.1909e-01 7.2127e-01 6.0423e-01 3.7507e-02 30 1.8

532 0529 2455123.43635652 939940116 273.038 -58.888 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 53 1.4

533 0530 2455123.50894756 939946388 121.026 -53.723 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 34 1.4

534 0531 2455123.77341984 939969238 242.247 -78.692 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 42 1.4

535 0532 2455123.81395575 939972740 0.505 -50.354 -1.1724e-01 4.7983e-01 5.2936e-01 3.8897e-02 58 0.9

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542 0539 2455124.99847915 940075083 51.269 -66.319 -1.3370e-01 8.5313e-01 6.3102e-01 3.7539e-02 21 2.4

543 0540 2455125.05026863 940079558 3.031 -9.007 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 32 1.4

544 0541 2455125.13125508 940086555 31.563 8.618 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 34 1.4

545 0542 2455125.17651380 940090465 346.590 -53.355 -1.1909e-01 7.2127e-01 6.0423e-01 3.7507e-02 31 1.8

546 0543 2455125.54695083 940122471 210.268 -65.801 -1.3370e-01 8.5313e-01 6.3102e-01 3.7539e-02 23 2.4

547 0544 2455125.67692770 940133701 243.164 16.606 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 39 1.4

548 0545 2455125.78264708 940142835 9.373 -49.397 -1.1724e-01 4.7983e-01 5.2936e-01 3.8897e-02 58 0.9

549 0546 2455125.82050078 940146106 271.614 -68.371 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 36 1.4

550 0547 2455125.86797558 940150208 26.170 39.099 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 40 1.4

551 0548 2455126.16958920 940176267 26.159 -3.051 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 44 1.4

552 0549 2455126.57395115 940211204 277.858 31.085 -1.1724e-01 4.7983e-01 5.2936e-01 3.8897e-02 45 0.9

553 0550 2455126.84745015 940234834 42.955 21.035 -1.1909e-01 7.2127e-01 6.0423e-01 3.7507e-02 26 1.8

554 0551 2455126.89342438 940238806 104.686 -34.039 -1.1724e-01 4.7983e-01 5.2936e-01 3.8897e-02 53 0.9

555 0552 2455126.90883151 940240138 40.048 -63.297 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 41 1.4

# LIST OF HIGH ENERGY NEUTRINO CANDIDATES FOR THE 2009-2010 DATA

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556	0553	2455127.62431524	940301955	276.272	9.594	-1.2873e-01	4.3155e-01	4.6595e-01	3.9162e-02	64	0.7
557	0554	2455127.70146982	940308621	40.170	-42.834	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	37	0.9
558	0555	2455127.78941914	940316220	317.629	37.671	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	47	0.9
559	0556	2455128.37791950	940367067	226.634	-67.325	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	41	1.4
560	0557	2455128.48421007	940376250	332.441	-29.655	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	45	1.4
561	0558	2455128.49604244	940377273	222.078	42.240	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	57	1.4
562	0559	2455128.87890660	940410352	33.977	-13.513	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	34	1.4
563	0560	2455128.94782299	940416306	82.861	-28.278	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	45	0.9
564	0561	2455128.99911445	940420738	28.863	39.702	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	48	1.4
565	0562	2455129.23151505	940440817	63.399	-53.583	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	36	1.4
566	0563	2455129.24410961	940441906	6.151	-58.770	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	21	2.4
567	0564	2455129.42888012	940457870	165.708	-58.167	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	25	2.4
568	0565	2455129.46803809	940461253	26.096	-57.126	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	47	2.4
569	0566	2455129.63331953	940475533	260.848	-32.698	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	36	2.4
570	0567	2455129.74693742	940485350	166.756	-58.293	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	52	1.4
571	0568	2455129.85060141	940494306	65.732	-60.227	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	43	1.4
572	0569	2455129.97996590	940505484	212.346	-48.187	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	34	0.9
573	0570	2455130.04261403	940510896	313.204	-18.608	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	21	2.4
574	0571	2455130.71697979	940569162	276.164	0.823	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	44	0.9
575	0572	2455130.73928354	940571089	342.991	-32.316	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	42	0.9
576	0573	2455130.90883162	940585738	90.482	-23.827	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	94	1.4
577	0574	2455131.04302858	940597332	149.284	-3.053	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	26	2.4
578	0575	2455131.09322920	940601670	25.112	15.380	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	46	1.4
579	0576	2455131.09736405	940602027	330.097	-22.425	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	26	2.4
580	0577	2455131.10132227	940602369	70.967	24.886	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	40	1.4
581	0578	2455131.13305411	940605110	21.637	-26.976	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	61	0.9
582	0579	2455131.46665416	940633933	27.225	-51.185	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	84	0.9
583	0580	2455131.50656328	940637382	218.474	32.134	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	45	1.4
584	0581	2455131.73572846	940657181	268.470	29.503	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	67	1.4
585	0582	2455132.41269022	940715671	91.722	-16.046	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	52	1.4
586	0583	2455132.71350595	940741661	230.084	-2.542	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	40	1.4
587	0584	2455133.24511799	940787593	34.831	-10.815	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	36	1.4
588	0585	2455133.86701904	940841325	181.531	-53.320	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	29	2.4
589	0586	2455133.87178621	940841737	346.348	-25.473	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	79	0.9
590	0587	2455133.93840643	940847493	359.884	-8.175	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	66	1.4
591	0588	2455133.94025409	940847652	217.462	-56.767	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	70	1.4
592	0589	2455133.94301469	940847891	317.600	-33.199	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	66	1.4
593	0590	2455134.88193759	940929014	334.006	10.852	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	42	1.4
594	0591	2455135.17944633	940954719	171.056	-40.090	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	29	2.4
595	0592	2455135.27592074	940963054	136.558	34.198	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	39	1.4
596	0593	2455135.30288916	940965384	134.181	-41.672	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	51	0.9
597	0594	2455136.66749813	941083286	251.830	22.254	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	42	1.4
598	0595	2455136.73338158	941088979	267.951	-18.728	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	43	1.4
599	0596	2455136.90881518	941104136	325.566	29.975	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	39	1.4
600	0597	2455137.01383289	941113210	107.265	-21.099	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	89	0.9
601	0598	2455137.05125840	941116443	356.996	18.432	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	14	2.4
602	0599	2455137.40940642	941147387	194.166	38.150	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	53	0.9
603	0600	2455138.07224381	941204656	45.023	-73.484	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	29	0.9
604	0601	2455138.22964691	941218256	187.377	22.481	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	54	1.4
605	0602	2455138.49297261	941241007	319.308	-68.022	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	41	1.4
606	0603	2455138.66407874	941255791	259.420	15.133	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	32	1.4
607	0604	2455138.70878856	941259654	305.961	-56.371	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	53	1.4

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608	0605	2455138.80484908	941267953	267.146	6.146	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	44	1.4
609	0606	2455139.17659348	941300072	188.397	-18.520	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	33	1.4
610	0607	2455139.38663643	941318220	301.403	-39.883	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	33	1.4
611	0608	2455139.55354005	941332640	120.588	-45.707	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	32	1.4
612	0609	2455139.67658649	941343272	288.496	-10.161	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	48	1.4
613	0610	2455139.84273192	941357627	30.147	4.845	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	37	1.4
614	0611	2455139.93447511	941365553	288.410	-34.817	-1.2873e-01	4.3155e-01	4.6595e-01	3.9162e-02	38	0.7
615	0612	2455139.97019810	941368640	65.107	37.544	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	54	1.4
616	0613	2455140.06783770	941377076	11.931	19.418	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	39	1.4
617	0614	2455140.20084105	941388567	10.769	-43.905	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	56	1.4
618	0615	2455140.23956732	941391913	108.903	-17.148	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	38	1.4
619	0616	2455140.25011695	941392825	200.972	-60.354	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	36	0.9
620	0617	2455140.56937111	941420408	289.436	-42.581	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	48	0.9
621	0618	2455140.62746823	941425428	348.550	-19.841	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	38	1.4
622	0619	2455140.99363963	941457065	38.911	23.479	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	24	2.4
623	0620	2455176.36060023	944512770	195.011	-32.392	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	46	1.4
624	0621	2455176.40237466	944516380	359.823	-65.837	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	46	1.4
625	0622	2455176.46654245	944521924	257.082	4.281	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	46	0.9
626	0623	2455176.60589619	944533964	303.881	-8.242	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	49	0.9
627	0624	2455177.03758351	944571262	72.237	24.741	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	44	1.4
628	0625	2455177.29581319	944593573	250.629	-28.328	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	36	1.4
629	0626	2455177.37983646	944600832	264.444	2.125	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	31	1.4
630	0627	2455177.47043999	944608661	185.947	16.929	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	25	2.4
631	0628	2455177.49870100	944611102	257.049	-46.286	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	42	0.9
632	0629	2455177.68067624	944626825	328.826	1.137	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	49	1.4
633	0630	2455177.73889666	944631855	48.550	-8.711	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	26	2.4
634	0631	2455177.96495108	944651386	250.890	-56.828	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	36	0.9
635	0632	2455178.07888863	944661230	162.809	0.994	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	42	0.9
636	0633	2455178.08458527	944661723	104.357	21.695	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	33	1.4
637	0634	2455178.65448253	944710962	285.130	-27.855	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	67	0.9
638	0635	2455178.66430116	944711810	301.419	-0.560	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	68	0.9
639	0636	2455178.76675491	944720662	318.784	-31.718	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	32	1.4
640	0637	2455178.87802147	944730276	13.866	32.173	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	53	1.4
641	0638	2455179.05028598	944745159	10.291	-78.284	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	42	1.4
642	0639	2455179.40395461	944775716	93.361	-46.081	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	39	1.4
643	0640	2455179.40550306	944775850	97.663	-46.538	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	40	1.4
644	0641	2455179.56627066	944789740	301.081	32.891	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	48	1.4
645	0642	2455179.58936774	944791736	212.966	-3.599	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	27	2.4
646	0643	2455179.73058975	944803937	87.161	-14.830	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	45	1.4
647	0644	2455179.84496806	944813820	310.268	-36.443	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	34	1.4
648	0645	2455179.85397646	944814598	207.057	-49.995	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	73	1.4
649	0646	2455180.06707255	944833010	74.832	19.767	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	31	2.4
650	0647	2455180.27510587	944850984	30.776	-51.459	-1.2873e-01	4.3155e-01	4.6595e-01	3.9162e-02	66	0.7
651	0648	2455180.32389121	944855199	175.448	18.109	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	46	0.9
652	0649	2455180.64733940	944883145	128.707	-53.534	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	35	0.9
653	0650	2455180.87835807	944903105	127.231	-43.494	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	56	1.4
654	0651	2455180.88672615	944903828	334.541	-32.892	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	37	1.4
655	0652	2455180.98455891	944912280	53.371	-21.714	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	36	0.9
656	0653	2455181.06941845	944919612	169.837	-35.463	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	33	1.4
657	0654	2455181.10539858	944922721	98.553	14.371	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	37	1.4
658	0655	2455181.11092318	944923198	197.227	-62.747	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	42	1.4
659	0656	2455181.25572826	944935709	54.726	-75.030	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	43	1.4



# LIST OF HIGH ENERGY NEUTRINO CANDIDATES FOR THE 2009-2010 DATA

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660	0657	2455181.26114534	944936177	224.202	15.433	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	35	0.9
661	0658	2455181.27213487	944937127	221.375	-39.836	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	39	1.4
662	0659	2455181.39615310	944947842	331.913	-18.848	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	63	1.4
663	0660	2455181.43261759	944950993	249.079	-9.585	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	42	1.4
664	0661	2455181.52212712	944958726	203.664	4.713	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	35	1.4
665	0662	2455181.52726115	944959170	303.200	15.620	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	29	2.4
666	0663	2455181.68452047	944972757	66.048	-55.284	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	44	1.4
667	0664	2455181.80611859	944983263	93.140	-38.941	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	46	1.4
668	0665	2455181.81130490	944983711	278.108	-41.385	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	49	1.4
669	0666	2455181.88721786	944990270	50.770	1.863	-1.1909e-01	7.2127e-01	6.0423e-01	3.7507e-02	27	1.8
670	0667	2455181.96213342	944996743	256.497	-62.777	-1.1909e-01	7.2127e-01	6.0423e-01	3.7507e-02	52	1.8
671	0668	2455182.25901530	945022393	280.095	-52.426	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	41	1.4
672	0669	2455182.37235249	945032186	280.887	-0.198	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	46	1.4
673	0670	2455182.42272247	945036538	180.013	-86.062	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	21	2.4
674	0671	2455182.55033348	945047563	359.212	-53.044	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	53	0.9
675	0672	2455182.88636941	945076597	20.025	14.276	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	30	2.4
676	0673	2455182.91177126	945078792	340.218	-37.075	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	32	1.4
677	0674	2455182.92972610	945080343	175.828	-26.912	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	42	1.4
678	0675	2455182.95503343	945082529	27.317	28.658	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	52	1.4
679	0676	2455182.99577626	945086050	163.523	3.164	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	46	1.4
680	0677	2455183.31495369	945113626	107.294	-16.030	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	27	1.4
681	0678	2455183.60883661	945139018	198.168	-27.954	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	46	1.4
682	0679	2455183.72978068	945149468	293.436	-33.187	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	39	1.4
683	0680	2455183.75057692	945151264	295.289	-49.467	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	35	1.4
684	0681	2455184.30304891	945198998	131.205	1.572	-5.8944e-02	2.9333e-01	5.7306e-01	3.8834e-02	101	0.6
685	0682	2455184.30656651	945199302	155.365	-12.477	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	19	2.4
686	0683	2455184.44487798	945211252	175.855	-48.298	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	33	1.4
687	0684	2455184.47752719	945214073	225.544	35.043	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	51	1.4
688	0685	2455184.48765474	945214948	119.704	-52.224	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	46	1.4
689	0686	2455184.53726252	945219234	323.409	-52.930	-1.2873e-01	4.3155e-01	4.6595e-01	3.9162e-02	54	0.7
690	0687	2455184.69114048	945232529	333.907	-3.422	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	50	0.9
691	0688	2455184.73246867	945236100	307.564	17.928	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	55	1.4
692	0689	2455184.99949594	945259171	267.437	-73.667	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	44	1.4
693	0690	2455185.01604326	945260601	37.022	6.420	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	39	1.4
694	0691	2455185.02234563	945261145	176.017	16.588	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	22	2.4
695	0692	2455185.05988826	945264389	130.558	33.827	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	31	2.4
696	0693	2455185.07594380	945265776	212.062	-44.087	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	37	1.4
697	0694	2455185.16263358	945273266	334.567	-52.112	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	54	1.4
698	0695	2455185.19185599	945275791	357.646	-51.206	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	29	2.4
699	0696	2455185.19297753	945275888	92.645	-35.479	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	33	1.4
700	0697	2455185.25821923	945281525	215.916	-2.103	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	31	1.4
701	0698	2455185.31207878	945286178	218.766	11.076	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	97	0.9
702	0699	2455185.32505852	945287300	307.682	-27.176	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	35	1.4
703	0700	2455185.70732004	945320327	302.210	-34.967	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	40	1.4
704	0701	2455185.77454881	945326136	281.345	-11.892	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	43	1.4
705	0702	2455185.92937998	945339513	332.200	-25.898	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	34	1.4
706	0703	2455186.02294166	945347597	85.141	10.661	-1.2873e-01	4.3155e-01	4.6595e-01	3.9162e-02	65	0.7
707	0704	2455186.02409992	945347697	174.475	-21.966	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	31	2.4
708	0705	2455186.05520124	945350384	216.031	-58.688	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	49	1.4
709	0706	2455186.22819540	945365331	193.511	-23.269	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	56	0.9
710	0707	2455186.30411782	945371890	225.989	13.623	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	48	0.9
711	0708	2455186.30578811	945372035	55.800	-61.690	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	38	1.4

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712	0709	2455186.31640317	945372952	232.495	3.022	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	48	1.4
713	0710	2455186.31770412	945373064	111.159	-45.507	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	51	1.4
714	0711	2455186.41036246	945381070	269.648	-24.735	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	42	1.4
715	0712	2455186.45940630	945385307	209.129	-64.340	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	35	1.4
716	0713	2455186.49715197	945388568	264.619	3.712	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	68	0.9
717	0714	2455186.56137737	945394118	157.661	-49.228	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	39	1.4
718	0715	2455186.57689280	945395458	117.489	-49.812	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	54	1.4
719	0716	2455186.59625851	945397131	55.495	-22.319	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	41	1.4
720	0717	2455186.66107419	945402731	51.556	-41.455	-1.1909e-01	7.2127e-01	6.0423e-01	3.7507e-02	27	1.8
721	0718	2455186.69145344	945405356	86.896	-59.383	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	24	2.4
722	0719	2455186.69459665	945405628	75.712	-43.954	-1.2873e-01	4.3155e-01	4.6595e-01	3.9162e-02	34	0.7
723	0720	2455186.75393546	945410755	297.910	15.664	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	26	2.4
724	0721	2455186.78126233	945413116	313.747	-52.164	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	31	2.4
725	0722	2455186.81286299	945415846	150.491	-45.271	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	40	0.9
726	0723	2455186.81826188	945416312	358.520	12.668	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	49	0.9
727	0724	2455186.86866401	945420667	75.767	-57.310	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	39	1.4
728	0725	2455188.19673582	945535412	89.244	-42.022	-1.1909e-01	7.2127e-01	6.0423e-01	3.7507e-02	29	1.8
729	0726	2455188.22021508	945537441	245.781	-69.885	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	37	1.4
730	0727	2455188.23699775	945538891	110.626	-36.628	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	18	2.4
731	0728	2455188.26880437	945541639	163.605	-65.409	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	66	0.9
732	0729	2455188.31900133	945545976	186.434	37.369	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	18	2.4
733	0730	2455188.43355275	945555873	216.759	20.508	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	53	2.4
734	0731	2455188.60491998	945570680	313.066	-6.654	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	58	1.4
735	0732	2455188.62120062	945572086	293.448	-2.703	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	43	1.4
736	0733	2455188.71726245	945580386	295.426	-16.357	-1.1909e-01	7.2127e-01	6.0423e-01	3.7507e-02	23	1.8
737	0734	2455189.17977206	945620347	135.221	8.397	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	27	2.4
738	0735	2455189.19309817	945621498	154.937	4.552	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	58	1.4
739	0736	2455189.21772394	945623626	240.573	-12.974	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	71	1.4
740	0737	2455189.30541555	945631202	109.819	-50.505	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	52	1.4
741	0738	2455189.33156785	945633462	98.313	-55.134	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	41	1.4
742	0739	2455189.34552145	945634668	291.811	-13.060	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	58	1.4
743	0740	2455189.43989452	945642821	261.356	4.773	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	75	1.4
744	0741	2455189.50517487	945648462	318.110	0.333	-1.1909e-01	7.2127e-01	6.0423e-01	3.7507e-02	22	1.8
745	0742	2455189.53259519	945650831	292.638	-28.398	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	56	0.9
746	0743	2455189.54650895	945652033	227.451	18.216	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	28	2.4
747	0744	2455189.56117206	945653300	241.954	-34.181	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	33	1.4
748	0745	2455189.56900697	945653977	12.139	-26.821	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	38	1.4
749	0746	2455189.58712903	945655542	84.859	-41.621	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	41	1.4
750	0747	2455189.61079032	945657587	23.576	11.120	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	32	1.4
751	0748	2455189.67531367	945663162	260.686	3.375	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	40	1.4
752	0749	2455189.76234013	945670681	333.358	24.397	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	62	1.4
753	0750	2455189.84112265	945677487	295.226	-24.967	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	48	1.4
754	0751	2455189.86724503	945679744	28.891	3.611	-1.2873e-01	4.3155e-01	4.6595e-01	3.9162e-02	43	0.7
755	0752	2455189.88137404	945680965	30.357	-60.141	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	32	0.9
756	0753	2455190.06489370	945696821	105.702	4.303	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	41	1.4
757	0754	2455190.23295942	945711342	271.920	-16.015	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	86	1.4
758	0755	2455190.26165361	945713821	113.719	-33.912	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	24	2.4
759	0756	2455190.30101956	945717223	253.703	-20.745	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	57	1.4
760	0757	2455190.36577198	945722817	280.345	14.397	-1.1909e-01	7.2127e-01	6.0423e-01	3.7507e-02	27	1.8
761	0758	2455190.43494695	945728794	173.296	3.863	-1.1909e-01	7.2127e-01	6.0423e-01	3.7507e-02	50	1.8
762	0759	2455190.43802490	945729060	15.382	-37.340	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	28	2.4
763	0760	2455190.58809914	945742026	230.744	-67.190	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	44	1.4

## LIST OF HIGH ENERGY NEUTRINO CANDIDATES FOR THE 2009-2010 DATA

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764	0761	2455190.64852638	945747247	257.281	-43.345	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	35	0.9
765	0762	2455190.75656885	945756582	26.679	39.333	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	41	1.4
766	0763	2455190.77666783	945758319	346.528	-55.446	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	31	2.4
767	0764	2455190.90073477	945769038	353.761	-10.056	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	22	2.4
768	0765	2455191.07954270	945784487	94.727	-59.338	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	47	1.4
769	0766	2455191.09109280	945785485	169.178	-26.613	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	45	0.9
770	0767	2455191.13633636	945789394	239.339	-47.795	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	33	1.4
771	0768	2455191.15140879	945790696	228.930	15.437	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	30	2.4
772	0769	2455191.20783708	945795572	138.246	-37.687	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	80	0.9
773	0770	2455191.21603047	945796280	285.247	-19.755	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	30	2.4
774	0771	2455191.24990460	945799206	85.087	-27.823	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	59	1.4
775	0772	2455191.27287725	945801191	132.431	16.119	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	38	1.4
776	0773	2455191.43364389	945815081	301.206	-3.407	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	31	2.4
777	0774	2455191.49072895	945820013	241.216	-50.228	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	36	1.4
778	0775	2455191.52547335	945823015	217.600	-3.941	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	42	1.4
779	0776	2455191.53177773	945823560	330.378	27.810	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	39	1.4
780	0777	2455192.15463775	945877375	289.784	-45.262	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	42	0.9
781	0778	2455192.24410402	945885105	105.900	-41.732	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	45	0.9
782	0779	2455192.26786255	945887158	121.622	-0.163	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	60	1.4
783	0780	2455192.38032764	945896875	42.982	-52.148	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	37	1.4
784	0781	2455192.49069143	945906410	210.878	-11.458	-1.1909e-01	7.2127e-01	6.0423e-01	3.7507e-02	22	1.8
785	0782	2455192.55556949	945912016	209.560	-39.589	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	42	1.4
786	0783	2455192.61748737	945917365	339.288	-0.221	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	47	1.4
787	0784	2455192.74176696	945928103	120.755	-39.027	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	29	2.4
788	0785	2455192.77533777	945931004	22.964	6.706	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	46	1.4
789	0786	2455192.79055565	945932319	214.877	-62.088	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	34	1.4
790	0787	2455192.85197386	945937625	45.151	-14.234	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	50	1.4
791	0788	2455192.86945414	945939135	217.271	-71.745	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	41	1.4
792	0789	2455192.93074785	945944431	18.933	28.914	-5.8944e-02	2.9333e-01	5.7306e-01	3.8834e-02	214	0.6
793	0790	2455193.12625274	945961323	117.358	42.733	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	32	1.4
794	0791	2455193.23920794	945971082	157.049	-11.993	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	30	2.4
795	0792	2455193.25177703	945972168	177.245	-38.820	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	49	1.4
796	0793	2455193.49933465	945993557	169.553	-26.928	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	66	1.4
797	0794	2455193.76033573	946016108	299.098	7.281	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	56	1.4
798	0795	2455193.77183890	946017101	175.039	-73.664	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	27	2.4
799	0796	2455193.88955972	946027272	2.766	-58.139	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	61	1.4
800	0797	2455194.21847979	946055691	154.212	24.974	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	40	1.4
801	0798	2455194.24334194	946057839	207.659	-3.927	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	38	1.4
802	0799	2455194.34810904	946066891	224.203	9.163	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	44	1.4
803	0800	2455194.43836779	946074689	253.304	-36.764	-1.2873e-01	4.3155e-01	4.6595e-01	3.9162e-02	48	0.7
804	0801	2455194.68717315	946096186	42.081	28.673	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	45	1.4
805	0802	2455194.68736318	946096203	250.934	-16.820	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	51	1.4
806	0803	2455194.83326808	946108809	81.804	7.745	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	85	1.4
807	0804	2455194.94157086	946118166	342.996	-41.451	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	31	2.4
808	0805	2455195.04014714	946126683	11.335	-32.386	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	42	1.4
809	0806	2455195.05106900	946127627	81.040	28.972	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	26	2.4
810	0807	2455195.33607486	946152251	205.709	-74.502	-5.3660e-02	3.7117e-01	6.4893e-01	3.6677e-02	72	1.2
811	0808	2455195.49918680	946166344	60.392	-84.483	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	71	0.9
812	0809	2455195.65716034	946179993	233.724	-33.022	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	42	1.4
813	0810	2455195.86609631	946198045	195.789	-87.647	-1.2873e-01	4.3155e-01	4.6595e-01	3.9162e-02	60	0.7
814	0811	2455195.87305563	946198647	359.106	7.661	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	64	0.9
815	0812	2455196.03698362	946212810	36.351	7.189	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	36	1.4

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816	0813	2455196.09357134	946217699	128.368	1.391	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	35	1.4
817	0814	2455196.10573781	946218750	133.970	36.838	-1.1909e-01	7.2127e-01	6.0423e-01	3.7507e-02	27	1.8
818	0815	2455196.20104784	946226985	112.585	21.455	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	76	1.4
819	0816	2455196.20195120	946227063	229.146	-35.530	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	34	1.4
820	0817	2455196.32910411	946238049	270.230	-1.033	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	34	0.9
821	0818	2455196.34582890	946239494	355.325	-42.724	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	27	2.4
822	0819	2455196.51730728	946254310	347.485	31.268	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	49	1.4
823	0820	2455196.68476378	946268778	276.091	12.169	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	45	1.4
824	0821	2455196.77623850	946276682	153.640	-70.377	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	34	1.4
825	0822	2455196.81660113	946280169	310.156	-69.503	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	47	1.4
826	0823	2455197.01356936	946297187	14.566	-9.847	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	68	1.4
827	0824	2455197.11318555	946305794	66.453	-0.840	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	27	2.4
828	0825	2455197.22022673	946315042	139.423	-23.609	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	21	2.4
829	0826	2455197.22654436	946315588	160.856	-0.828	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	50	0.9
830	0827	2455197.62020656	946349600	54.788	-44.624	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	37	0.9
831	0828	2455197.72030308	946358249	213.686	-52.286	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	39	1.4
832	0829	2455197.73813817	946359790	51.332	25.007	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	45	1.4
833	0830	2455197.90974396	946374616	90.680	-0.331	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	43	1.4
834	0831	2455198.20461957	946400094	115.214	6.246	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	47	1.4
835	0832	2455198.48822306	946424597	299.902	18.907	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	40	1.4
836	0833	2455198.49936446	946425560	214.464	-38.282	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	45	1.4
837	0834	2455198.75505946	946447652	20.804	3.496	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	39	0.9
838	0835	2455198.80386155	946451868	29.893	36.624	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	42	1.4
839	0836	2455198.84553438	946455469	325.184	-17.620	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	35	1.4
840	0837	2455199.11695812	946478920	60.294	-46.073	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	35	1.4
841	0838	2455199.32165197	946496605	177.612	-43.608	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	61	0.9
842	0839	2455199.50425473	946512382	174.596	-26.646	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	29	2.4
843	0840	2455199.65344042	946525272	315.545	-14.142	-1.1909e-01	7.2127e-01	6.0423e-01	3.7507e-02	30	1.8
844	0841	2455199.67326995	946526985	342.880	11.294	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	22	2.4
845	0842	2455199.73837464	946532610	300.436	-17.084	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	22	2.4
846	0843	2455199.80482370	946538351	346.532	-9.574	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	23	2.4
847	0844	2455199.97867064	946553372	118.522	5.126	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	43	1.4
848	0845	2455200.19836435	946572353	156.136	17.143	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	41	0.9
849	0846	2455200.21128236	946573469	281.206	-27.685	-5.8944e-02	2.9333e-01	5.7306e-01	3.8834e-02	111	0.6
850	0847	2455200.24253147	946576169	158.037	-30.857	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	34	1.4
851	0848	2455200.39128406	946589021	233.851	-18.053	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	40	1.4
852	0849	2455200.40955362	946590600	333.699	-33.135	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	42	1.4
853	0850	2455200.49801000	946598243	115.394	-61.523	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	29	2.4
854	0851	2455200.50295737	946598670	118.432	-73.416	-1.1909e-01	7.2127e-01	6.0423e-01	3.7507e-02	24	1.8
855	0852	2455200.63914878	946610437	257.750	-18.706	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	36	0.9
856	0853	2455200.73664624	946618861	68.630	-46.294	-5.8944e-02	2.9333e-01	5.7306e-01	3.8834e-02	114	0.6
857	0854	2455200.82720896	946626685	43.219	-18.838	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	52	0.9
858	0855	2455200.85383520	946628986	4.746	-61.413	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	42	0.9
859	0856	2455200.86111443	946629615	351.922	-8.619	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	53	1.4
860	0857	2455200.91682470	946634428	155.629	2.871	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	39	1.4
861	0858	2455201.27852597	946665679	135.621	15.304	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	52	1.4
862	0859	2455201.50119943	946684918	272.419	-5.337	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	46	1.4
863	0860	2455201.51964677	946686512	182.276	-25.628	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	25	2.4
864	0861	2455201.57071479	946690924	118.513	-77.902	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	53	2.4
865	0862	2455201.62218506	946695371	300.067	18.551	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	32	0.9
866	0863	2455201.71330061	946703244	310.037	-9.823	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	46	0.9
867	0864	2455201.90501365	946719808	56.506	15.541	-1.1909e-01	7.2127e-01	6.0423e-01	3.7507e-02	31	1.8

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868	0865	2455202.56619047	946776933	226.425	-26.198	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	43	1.4
869	0866	2455202.57824478	946777975	48.026	-3.908	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	48	1.4
870	0867	2455202.89990655	946805766	32.564	-22.498	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	54	1.4
871	0868	2455203.00614741	946814946	9.277	-20.964	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	25	2.4
872	0869	2455203.13391412	946825985	89.082	-11.646	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	52	0.9
873	0870	2455203.28664686	946839181	214.259	-0.251	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	44	0.9
874	0871	2455203.64317126	946869984	311.290	-22.788	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	63	0.9
875	0872	2455203.79039468	946882705	76.056	12.364	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	32	1.4
876	0873	2455203.95790065	946897177	186.720	-16.253	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	24	2.4
877	0874	2455204.07717164	946907482	44.618	-23.035	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	49	1.4
878	0875	2455204.08132679	946907841	167.712	33.081	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	34	0.9
879	0876	2455204.16160983	946914778	177.142	-20.882	-1.1210e-01	3.5816e-01	4.5437e-01	4.0298e-02	130	0.5
880	0877	2455204.24444168	946921934	73.211	-55.726	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	54	1.4
881	0878	2455204.91856534	946980179	101.313	27.139	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	42	1.4
882	0879	2455205.34927857	947017392	334.347	-45.866	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	63	1.4
883	0880	2455205.37763531	947019842	103.421	-58.168	-8.8598e-02	3.3283e-01	5.3278e-01	3.9884e-02	126	0.6
884	##	stop S6B	--	start							
885	0881	2455205.59201854	947038365	267.264	-51.054	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	48	0.9
886	0882	2455205.75899046	947052791	118.043	-18.373	-1.1909e-01	7.2127e-01	6.0423e-01	3.7507e-02	30	1.8
887	0883	2455205.97940864	947071835	115.109	16.753	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	37	0.9
888	0884	2455206.00180145	947073770	130.615	-21.946	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	51	1.4
889	0885	2455206.26931457	947096883	332.136	-37.905	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	27	2.4
890	0886	2455206.36533759	947105180	237.271	-52.013	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	56	1.4
891	0887	2455206.40668835	947108752	345.728	-52.192	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	29	2.4
892	0888	2455206.52609776	947119069	80.905	-44.259	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	23	2.4
893	0889	2455206.63121873	947128152	325.758	-9.835	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	41	0.9
894	0890	2455206.66747144	947131284	1.693	19.163	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	41	0.9
895	0891	2455206.67259082	947131726	329.613	-44.847	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	33	0.9
896	0892	2455206.73749282	947137334	67.664	7.449	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	55	0.9
897	0893	2455206.74643766	947138107	203.141	-64.683	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	56	0.9
898	0894	2455206.74980613	947138398	87.173	26.354	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	50	1.4
899	0895	2455206.75151176	947138545	26.082	-22.605	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	56	0.9
900	0896	2455206.87608301	947149308	7.058	-47.541	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	32	1.4
901	0897	2455206.91583704	947152743	212.966	-38.042	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	48	1.4
902	0898	2455207.01591151	947161389	152.202	15.928	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	58	0.9
903	0899	2455207.08166584	947167070	86.772	14.539	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	32	0.9
904	0900	2455207.20778341	947177967	117.999	14.092	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	37	0.9
905	0901	2455207.22579561	947179523	129.025	19.866	-1.1909e-01	7.2127e-01	6.0423e-01	3.7507e-02	31	1.8
906	0902	2455207.33615105	947189058	139.241	-22.835	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	26	2.4
907	0903	2455207.47513383	947201066	227.609	-3.938	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	28	2.4
908	0904	2455207.64567817	947215801	4.079	4.212	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	42	1.4
909	0905	2455207.79742100	947228912	81.020	17.226	-1.2873e-01	4.3155e-01	4.6595e-01	3.9162e-02	42	0.7
910	0906	2455208.19976877	947263675	241.253	-47.750	-1.2873e-01	4.3155e-01	4.6595e-01	3.9162e-02	48	0.7
911	0907	2455208.24828695	947267866	94.459	-22.668	-1.2873e-01	4.3155e-01	4.6595e-01	3.9162e-02	73	0.7
912	0908	2455208.27795336	947270430	183.964	31.182	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	46	0.9
913	0909	2455208.46690315	947286755	11.208	-2.795	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	43	1.4
914	0910	2455208.65447656	947302961	240.837	-83.941	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	38	1.4
915	0911	2455208.82690760	947317859	45.053	-35.434	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	58	0.9
916	0912	2455208.94043913	947327668	74.696	1.665	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	21	2.4
917	0913	2455208.95740231	947329134	33.176	7.278	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	43	1.4
918	0914	2455208.95959556	947329324	310.556	-56.006	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	26	2.4
919	0915	2455209.13629385	947344590	230.622	-33.109	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	23	2.4

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920 0916 2455209.22185271 947351983 277.762 -52.548 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 39 1.4

921 0917 2455209.30528449 947359191 14.398 -54.989 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 56 1.4

922 0918 2455209.33191709 947361492 149.062 -29.658 -1.3370e-01 8.5313e-01 6.3102e-01 3.7539e-02 25 2.4

923 0919 2455209.35135004 947363171 253.749 -52.798 -1.1724e-01 4.7983e-01 5.2936e-01 3.8897e-02 50 0.9

924 0920 2455209.38793623 947366332 311.044 32.084 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 56 1.4

925 0921 2455209.44853596 947371568 339.721 -27.964 -1.1724e-01 4.7983e-01 5.2936e-01 3.8897e-02 37 0.9

926 0922 2455209.47386163 947373756 263.659 13.193 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 52 1.4

927 0923 2455209.77249363 947399558 131.683 -28.552 -1.1724e-01 4.7983e-01 5.2936e-01 3.8897e-02 76 0.9

928 0924 2455209.79083373 947401143 44.297 27.973 -1.1724e-01 4.7983e-01 5.2936e-01 3.8897e-02 80 0.9

929 0925 2455209.83807158 947405224 28.661 -36.461 -1.3370e-01 8.5313e-01 6.3102e-01 3.7539e-02 23 2.4

930 0926 2455209.86684556 947407710 205.102 -56.088 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 81 1.4

931 0927 2455209.96111612 947415855 108.564 -16.082 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 43 1.4

932 0928 2455210.05777507 947424206 23.435 -36.751 -1.3370e-01 8.5313e-01 6.3102e-01 3.7539e-02 31 2.4

933 0929 2455210.16938478 947433849 219.044 34.427 -1.3370e-01 8.5313e-01 6.3102e-01 3.7539e-02 26 2.4

934 0930 2455210.18549947 947435242 173.028 36.944 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 37 1.4

935 0931 2455210.21484370 947437777 123.166 -37.100 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 59 1.4

936 0932 2455210.21804241 947438053 264.968 -49.697 -1.2873e-01 4.3155e-01 4.6595e-01 3.9162e-02 50 0.7

937 0933 2455210.43937220 947457176 270.955 -6.792 -1.3370e-01 8.5313e-01 6.3102e-01 3.7539e-02 29 2.4

938 0934 2455210.50426152 947462783 228.357 7.854 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 45 1.4

939 0935 2455210.58498972 947469758 267.813 22.353 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 32 1.4

940 0936 2455210.63097229 947473731 305.927 26.076 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 19 1.4

941 0937 2455210.67885656 947477868 6.182 -25.268 -1.1724e-01 4.7983e-01 5.2936e-01 3.8897e-02 36 0.9

942 0938 2455210.75309901 947484282 336.174 -26.774 -1.7861e+00 6.7827e+00 8.6368e-01 3.8440e-01 28 1.4

943 0939 2455210.78665557 947487182 32.647 -50.787 -1.3370e-01 8.5313e-01 6.3102e-01 3.7539e-02 14 2.4

944 0940 2455210.81492192 947489624 53.093 6.017 -1.1724e-01 4.7983e-01 5.2936e-01 3.8897e-02 36 0.9

945 0941 2455210.88302667 947495508 159.777 -43.026 -1.3370e-01 8.5313e-01 6.3102e-01 3.7539e-02 21 2.4

946 0942 2455210.95532939 947501755 121.446 21.508 -1.3370e-01 8.5313e-01 6.3102e-01 3.7539e-02 47 2.4

947 0943 2455210.96064258 947502214 17.852 -5.590 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 59 1.4

948 0944 2455211.02021087 947507361 117.161 -30.028 -1.7861e+00 6.7827e+00 8.6368e-01 3.8440e-01 31 1.4

949 0945 2455211.17875483 947521059 152.515 23.840 -1.7861e+00 6.7827e+00 8.6368e-01 3.8440e-01 37 1.4

950 0946 2455211.19979930 947522877 263.441 -47.207 -1.7861e+00 6.7827e+00 8.6368e-01 3.8440e-01 50 1.4

951 0947 2455211.23356536 947525795 177.446 -20.883 -1.1724e-01 4.7983e-01 5.2936e-01 3.8897e-02 49 0.9

952 0948 2455211.23625788 947526027 179.400 -5.439 -1.3370e-01 8.5313e-01 6.3102e-01 3.7539e-02 30 2.4

953 0949 2455211.35794080 947536541 225.210 -32.172 -1.3370e-01 8.5313e-01 6.3102e-01 3.7539e-02 30 2.4

954 0950 2455211.39414760 947539669 158.473 -15.134 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 75 1.4

955 0951 2455211.49668203 947548528 62.133 -47.866 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 33 1.4

956 0952 2455211.53471177 947551814 292.684 34.166 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 61 1.4

957 0953 2455211.55099228 947553220 353.837 14.121 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 39 1.4

958 0954 2455211.57554351 947555341 32.428 -57.857 -1.1724e-01 4.7983e-01 5.2936e-01 3.8897e-02 37 0.9

959 0955 2455211.59760908 947557248 197.748 -54.015 -1.1724e-01 4.7983e-01 5.2936e-01 3.8897e-02 39 0.9

960 0956 2455211.65511459 947562216 100.629 -24.442 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 57 1.4

961 0957 2455211.76506830 947571716 32.353 40.097 -1.1724e-01 4.7983e-01 5.2936e-01 3.8897e-02 40 0.9

962 0958 2455212.20425262 947609662 183.042 45.535 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 41 1.4

963 0959 2455212.27313993 947615614 49.168 -51.723 -1.1724e-01 4.7983e-01 5.2936e-01 3.8897e-02 93 0.9

964 0960 2455212.28904463 947616988 148.081 2.273 -1.1724e-01 4.7983e-01 5.2936e-01 3.8897e-02 33 0.9

965 0961 2455212.37899045 947624759 350.098 -69.949 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 63 1.4

966 0962 2455212.41061837 947627492 298.791 -28.302 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 42 1.4

967 0963 2455212.46859616 947632501 36.526 -67.883 -1.1724e-01 4.7983e-01 5.2936e-01 3.8897e-02 32 0.9

968 0964 2455212.56806648 947641095 359.404 -60.557 -1.2873e-01 4.3155e-01 4.6595e-01 3.9162e-02 53 0.7

969 0965 2455212.58355032 947642433 32.563 3.851 -1.1909e-01 7.2127e-01 6.0423e-01 3.7507e-02 30 1.8

970 0966 2455212.59013134 947643002 203.433 -45.794 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 58 1.4

971 0967 2455212.77125714 947658651 50.658 -59.275 -1.1724e-01 4.7983e-01 5.2936e-01 3.8897e-02 49 0.9

# LIST OF HIGH ENERGY NEUTRINO CANDIDATES FOR THE 2009-2010 DATA

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972	0968	2455212.79352479	947660575	69.802	-16.268	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	50	0.9
973	0969	2455212.81448302	947662386	124.386	17.047	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	34	1.4
974	0970	2455212.88081398	947668117	166.762	-22.996	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	23	2.4
975	0971	2455212.88892148	947668817	166.939	-31.081	-1.1909e-01	7.2127e-01	6.0423e-01	3.7507e-02	28	1.8
976	0972	2455212.92046770	947671543	122.686	4.647	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	19	2.4
977	0973	2455212.92471797	947671910	74.808	-75.830	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	61	1.4
978	0974	2455213.15414407	947691733	238.454	25.548	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	14	2.4
979	0975	2455213.19806784	947695528	160.430	-1.371	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	32	1.4
980	0976	2455213.21381213	947696888	200.820	-38.225	-1.2873e-01	4.3155e-01	4.6595e-01	3.9162e-02	77	0.7
981	0977	2455213.35664608	947709229	276.946	-23.016	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	34	1.4
982	0978	2455213.39821696	947712820	234.501	34.173	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	36	1.4
983	0979	2455213.40174958	947713126	67.726	-53.436	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	24	2.4
984	0980	2455213.43431247	947715939	211.552	13.112	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	56	1.4
985	0981	2455213.48770472	947720552	250.051	-5.168	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	64	0.9
986	0982	2455213.49114798	947720850	261.905	-20.117	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	20	2.4
987	0983	2455213.50139438	947721735	299.654	33.847	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	46	1.4
988	0984	2455213.51991054	947723335	209.996	-14.521	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	39	0.9
989	0985	2455213.53946560	947725024	200.485	-29.139	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	27	0.9
990	0986	2455213.53971454	947725046	109.252	-46.437	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	37	1.4
991	0987	2455213.54156747	947725206	320.335	-68.918	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	55	1.4
992	0988	2455214.01182564	947765836	175.032	-4.417	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	34	1.4
993	0989	2455214.11136989	947774437	114.048	-11.184	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	29	2.4
994	0990	2455214.28131093	947789120	223.097	-28.813	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	40	1.4
995	0991	2455214.30593188	947791247	277.461	-9.760	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	61	1.4
996	0992	2455214.36089245	947795996	178.073	-27.653	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	30	2.4
997	0993	2455214.42798763	947801793	301.777	24.406	-1.1909e-01	7.2127e-01	6.0423e-01	3.7507e-02	30	1.8
998	0994	2455214.87267737	947840214	299.101	-41.611	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	51	1.4
999	0995	2455214.89370262	947842030	35.968	5.427	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	69	1.4
1000	0996	2455215.50331896	947894701	283.750	-77.656	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	25	2.4
1001	0997	2455215.56109982	947899694	276.305	-55.215	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	35	0.9
1002	0998	2455215.65139634	947907495	357.315	13.840	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	28	2.4
1003	0999	2455215.78045199	947918646	349.378	16.011	-1.2873e-01	4.3155e-01	4.6595e-01	3.9162e-02	47	0.7
1004	1000	2455215.90226208	947929170	8.882	-52.036	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	29	2.4
1005	1001	2455216.01085793	947938553	41.373	-84.886	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	27	2.4
1006	1002	2455216.34873897	947967746	203.507	30.062	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	47	1.4
1007	1003	2455216.36133052	947968833	201.399	-26.520	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	31	2.4
1008	1004	2455216.45310313	947976763	249.040	10.568	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	32	1.4
1009	1005	2455216.59292969	947988844	98.494	-30.628	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	30	2.4
1010	1006	2455216.72955620	948000648	333.831	7.730	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	32	1.4
1011	1007	2455216.86105434	948012010	341.944	-11.576	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	47	1.4
1012	1008	2455216.88993180	948014505	26.279	-39.408	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	42	1.4
1013	1009	2455216.89107169	948014603	31.229	-15.565	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	62	1.4
1014	1010	2455216.89991008	948015367	208.509	-31.749	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	20	1.4
1015	1011	2455216.91641982	948016793	76.145	-33.772	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	41	1.4
1016	1012	2455217.20964166	948042128	197.893	16.200	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	26	1.4
1017	1013	2455217.30659437	948050504	140.939	-33.050	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	78	1.4
1018	1014	2455217.37064803	948056038	153.145	-27.790	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	79	1.4
1019	1015	2455217.38352752	948057151	267.267	-3.638	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	53	0.9
1020	1016	2455217.43662342	948061739	70.824	-44.897	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	44	1.4
1021	1017	2455217.48114018	948065585	35.632	-14.867	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	44	1.4
1022	1018	2455217.63457306	948078842	318.290	1.948	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	28	2.4
1023	1019	2455217.68534775	948083229	73.186	-66.497	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	45	1.4

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1024	1020	2455217.69372588	948083952	76.056	-24.998	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	37	1.4
1025	1021	2455217.72233598	948086424	22.124	-41.139	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	58	1.4
1026	1022	2455217.77375757	948090867	258.509	-50.920	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	34	1.4
1027	1023	2455217.79942390	948093085	79.440	-10.827	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	40	1.4
1028	1024	2455217.93751951	948105016	209.026	-29.980	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	32	0.9
1029	1025	2455217.96018590	948106975	158.933	-9.470	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	37	1.4
1030	1026	2455218.00320179	948110691	297.851	-71.415	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	36	1.4
1031	1027	2455218.04921834	948114667	66.443	-9.481	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	33	1.4
1032	1028	2455218.06026285	948115621	136.881	-48.062	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	45	1.4
1033	1029	2455218.12468535	948121187	212.250	-21.730	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	30	2.4
1034	1030	2455218.14745146	948123154	207.128	3.288	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	52	1.4
1035	1031	2455218.16159433	948124376	306.424	-76.348	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	40	0.9
1036	1032	2455218.23743555	948130929	203.209	4.090	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	37	0.9
1037	1033	2455218.28351038	948134910	146.554	6.006	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	36	1.4
1038	1034	2455218.37466473	948142786	246.216	-25.287	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	53	1.4
1039	1035	2455218.52024679	948155364	263.409	0.566	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	26	2.4
1040	1036	2455218.71965313	948172593	54.200	-18.294	-1.1909e-01	7.2127e-01	6.0423e-01	3.7507e-02	28	1.8
1041	1037	2455218.80594342	948180048	113.978	-7.262	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	21	2.4
1042	1038	2455219.09213103	948204775	244.287	5.275	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	23	2.4
1043	1039	2455219.14023248	948208931	246.829	-84.491	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	22	2.4
1044	1040	2455219.15124774	948209882	122.980	23.331	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	51	1.4
1045	1041	2455219.18000458	948212367	117.554	-7.495	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	74	1.4
1046	1042	2455219.22247143	948216036	186.590	-6.019	-1.2873e-01	4.3155e-01	4.6595e-01	3.9162e-02	50	0.7
1047	1043	2455219.23366936	948217004	223.687	-36.116	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	38	1.4
1048	1044	2455219.25388962	948218751	255.211	-29.602	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	28	2.4
1049	1045	2455219.33250068	948225543	306.654	-6.792	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	41	1.4
1050	1046	2455219.33472768	948225735	350.803	-62.116	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	41	1.4
1051	1047	2455219.48966383	948239121	250.112	-13.580	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	21	2.4
1052	1048	2455219.63133488	948251362	286.211	10.829	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	36	1.4
1053	1049	2455219.75108672	948261708	324.316	-55.637	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	36	0.9
1054	1050	2455219.75716941	948262234	4.511	9.788	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	31	2.4
1055	1051	2455219.78046755	948264247	85.081	24.757	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	95	2.4
1056	1052	2455219.80331319	948266221	72.520	-3.493	-1.1210e-01	3.5816e-01	4.5437e-01	4.0298e-02	108	0.5
1057	1053	2455219.96904028	948280540	194.174	-73.655	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	24	2.4
1058	1054	2455220.04206527	948286849	162.689	-53.608	-8.8598e-02	3.3283e-01	5.3278e-01	3.9884e-02	150	0.6
1059	1055	2455220.36821775	948315029	335.818	12.849	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	37	1.4
1060	1056	2455220.44918721	948322024	305.047	22.556	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	23	2.4
1061	1057	2455220.49848040	948326283	289.880	32.873	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	55	2.4
1062	1058	2455220.57302099	948332724	246.263	-8.464	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	56	1.4
1063	1059	2455220.66813892	948340942	39.348	38.839	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	44	1.4
1064	1060	2455220.74677507	948347736	107.446	-65.438	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	61	0.9
1065	1061	2455220.77984676	948350593	183.238	-45.749	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	28	2.4
1066	1062	2455220.81694154	948353798	99.911	-60.413	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	42	0.9
1067	1063	2455220.99541059	948369218	51.487	13.658	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	24	2.4
1068	1064	2455221.06080764	948374868	38.067	-24.461	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	39	2.4
1069	1065	2455221.13791954	948381531	294.711	-29.451	-5.8944e-02	2.9333e-01	5.7306e-01	3.8834e-02	119	0.6
1070	1066	2455221.27910554	948393729	158.171	-2.711	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	36	1.4
1071	1067	2455221.30351473	948395838	129.469	-24.215	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	23	2.4
1072	1068	2455221.33926419	948398927	124.093	-72.093	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	35	1.4
1073	1069	2455221.50481393	948413230	347.248	37.295	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	27	2.4
1074	1070	2455221.54215549	948416457	52.033	-5.111	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	63	1.4
1075	1071	2455221.57922778	948419660	137.678	-78.180	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	33	0.9



## LIST OF HIGH ENERGY NEUTRINO CANDIDATES FOR THE 2009-2010 DATA

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1076	1072	2455221.64028048	948424935	357.852	47.000	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	41	0.9
1077	1073	2455221.75557236	948434896	279.748	-56.149	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	42	1.4
1078	1074	2455222.32131253	948483776	165.999	5.048	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	37	1.4
1079	1075	2455222.62123264	948509689	286.165	18.345	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	33	1.4
1080	1076	2455222.69290437	948515881	118.419	-13.132	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	48	1.4
1081	1077	2455222.74576054	948520448	266.505	-62.370	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	84	0.9
1082	1078	2455222.75772050	948521482	112.018	1.505	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	32	0.9
1083	1079	2455222.91335717	948534929	270.682	-56.529	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	33	0.9
1084	1080	2455223.16058157	948556289	148.651	-61.979	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	25	2.4
1085	1081	2455223.29012699	948567481	234.251	-28.644	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	58	0.9
1086	1082	2455223.31370597	948569519	207.332	-25.654	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	39	1.4
1087	1083	2455223.34636204	948572340	204.991	-24.691	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	33	1.4
1088	1084	2455223.62032678	948596011	322.678	-0.872	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	47	1.4
1089	1085	2455223.95972438	948625335	65.928	3.770	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	33	0.9
1090	1086	2455224.01295691	948629934	137.206	-14.028	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	32	1.4
1091	1087	2455224.05723229	948633759	243.915	-18.892	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	27	2.4
1092	1088	2455224.37403218	948661131	196.278	-23.099	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	74	1.4
1093	1089	2455224.46085038	948668632	235.820	19.710	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	34	1.4
1094	1090	2455224.66861514	948686583	346.007	-26.315	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	28	1.4
1095	1091	2455224.79992182	948697928	156.004	-64.575	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	89	1.4
1096	1092	2455224.89850966	948706446	21.848	5.295	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	38	1.4
1097	1093	2455225.09116564	948723091	251.221	-41.631	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	23	2.4
1098	1094	2455225.11815454	948725423	190.873	-1.819	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	92	2.4
1099	1095	2455225.19082410	948731702	192.131	11.316	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	34	1.4
1100	1096	2455225.30049046	948741177	91.608	-48.254	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	84	0.9
1101	1097	2455225.33291445	948743978	229.733	-75.828	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	60	0.9
1102	1098	2455225.55116786	948762835	342.094	35.552	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	43	1.4
1103	1099	2455225.55806497	948763431	262.072	11.086	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	32	1.4
1104	1100	2455225.65571585	948771868	37.747	18.739	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	33	1.4
1105	1101	2455225.78345525	948782905	77.575	-0.047	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	36	1.4
1106	1102	2455225.86544796	948789989	162.560	-38.927	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	35	1.4
1107	1103	2455225.98945937	948800704	208.863	-42.351	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	23	2.4
1108	1104	2455226.49592804	948844463	12.922	-67.977	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	52	0.9
1109	1105	2455226.62185065	948855342	244.096	-32.250	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	48	1.4
1110	1106	2455226.62876391	948855940	30.090	-24.777	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	57	1.4
1111	1107	2455226.63261844	948856273	326.561	-9.564	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	29	2.4
1112	1108	2455226.69199090	948861403	317.119	-29.785	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	32	1.4
1113	1109	2455227.38304052	948921109	274.256	-10.089	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	43	1.4
1114	1110	2455227.58180827	948938283	88.182	-36.395	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	33	1.4
1115	1111	2455227.71621039	948949895	65.838	-38.510	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	39	1.4
1116	1112	2455228.22342598	948993719	230.812	27.397	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	32	1.4
1117	1113	2455228.55535479	949022397	136.282	-49.505	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	63	1.4
1118	1114	2455231.82649058	949305023	44.587	-9.319	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	32	1.4
1119	1115	2455231.96039399	949316593	89.812	-31.333	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	29	2.4
1120	1116	2455232.01008270	949320886	208.901	6.636	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	40	1.4
1121	1117	2455232.04375434	949323795	187.660	-66.270	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	52	1.4
1122	1118	2455232.15063248	949333029	180.283	15.690	-1.2873e-01	4.3155e-01	4.6595e-01	3.9162e-02	59	0.7
1123	1119	2455232.20247236	949337508	1.888	-46.375	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	26	2.4
1124	1120	2455232.23740823	949340527	221.282	-35.734	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	80	0.9
1125	1121	2455232.36926152	949351919	195.137	-1.809	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	43	1.4
1126	1122	2455232.38524317	949353300	167.865	-28.090	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	24	2.4
1127	1123	2455232.40058797	949354625	9.860	-56.106	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	40	1.4

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1128	1124	2455232.59851963	949371727	0.104	-46.954	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	40	0.9
1129	1125	2455232.60584214	949372359	65.585	-33.839	-1.2873e-01	4.3155e-01	4.6595e-01	3.9162e-02	34	0.7
1130	1126	2455232.63352183	949374751	345.528	17.806	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	68	1.4
1131	1127	2455232.77243470	949386753	89.698	37.040	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	72	1.4
1132	1128	2455232.79390368	949388608	125.976	22.166	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	35	1.4
1133	1129	2455232.89347699	949397211	82.098	-83.428	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	33	1.4
1134	1130	2455232.96587954	949403466	102.746	1.604	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	42	1.4
1135	1131	2455233.27333710	949430031	294.057	-0.258	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	88	1.4
1136	1132	2455233.37104961	949438473	294.315	-12.876	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	57	1.4
1137	1133	2455233.38794543	949439933	38.527	-41.127	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	38	0.9
1138	1134	2455233.49782838	949449427	358.312	31.742	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	34	0.9
1139	1135	2455233.60557642	949458736	116.915	-41.156	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	64	1.4
1140	1136	2455233.78372019	949474128	264.184	-56.082	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	31	1.4
1141	1137	2455233.79082307	949474742	81.396	-8.198	-1.2873e-01	4.3155e-01	4.6595e-01	3.9162e-02	60	0.7
1142	1138	2455233.99792775	949492635	178.429	-8.704	-1.2873e-01	4.3155e-01	4.6595e-01	3.9162e-02	47	0.7
1143	1139	2455234.05581226	949497637	304.342	-55.041	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	32	0.9
1144	1140	2455234.06206055	949498177	203.235	-24.044	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	50	0.9
1145	1141	2455234.10329669	949501739	203.033	42.253	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	88	0.9
1146	1142	2455234.11349118	949502620	144.672	-25.741	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	37	1.4
1147	1143	2455234.17226805	949507698	116.168	-36.173	-1.1909e-01	7.2127e-01	6.0423e-01	3.7507e-02	31	1.8
1148	1144	2455234.17458007	949507898	232.149	-73.066	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	32	1.4
1149	1145	2455234.20308039	949510361	288.287	17.564	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	44	1.4
1150	1146	2455234.23349760	949512989	274.625	-85.271	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	62	1.4
1151	1147	2455234.27105166	949516233	338.716	-11.411	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	35	1.4
1152	1148	2455234.28405659	949517357	206.358	5.535	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	22	2.4
1153	1149	2455234.35606033	949523578	291.066	32.423	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	41	2.4
1154	1150	2455234.43237098	949530171	255.404	-22.884	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	38	1.4
1155	1151	2455234.43997151	949530828	250.749	-82.903	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	46	1.4
1156	1152	2455234.46632278	949533105	161.252	-56.190	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	34	1.4
1157	1153	2455234.50218369	949536203	178.883	-51.967	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	36	1.4
1158	1154	2455235.00724824	949579841	101.607	-74.960	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	30	1.4
1159	1155	2455235.48053110	949620732	255.276	21.010	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	31	2.4
1160	1156	2455235.60015703	949631068	344.160	35.564	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	54	2.4
1161	1157	2455235.66886048	949637004	91.296	14.301	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	45	2.4
1162	1158	2455235.90736161	949657611	346.345	-35.238	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	41	1.4
1163	1159	2455236.09782212	949674066	216.286	-28.671	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	43	0.9
1164	1160	2455236.51118661	949709781	21.396	-58.381	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	22	2.4
1165	1161	2455236.65832392	949722494	311.032	-37.363	-1.1909e-01	7.2127e-01	6.0423e-01	3.7507e-02	29	1.8
1166	1162	2455236.69194154	949725398	151.987	-57.454	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	38	0.9
1167	1163	2455236.79559207	949734354	0.681	-37.195	-1.1909e-01	7.2127e-01	6.0423e-01	3.7507e-02	29	1.8
1168	1164	2455237.05170999	949756482	330.298	-50.913	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	37	0.9
1169	1165	2455237.05319009	949756610	278.469	-23.573	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	31	2.4
1170	1166	2455237.05822559	949757045	54.677	-31.165	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	63	1.4
1171	1167	2455237.27419539	949775705	250.101	1.844	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	37	1.4
1172	1168	2455237.67022373	949809922	87.573	27.633	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	37	1.4
1173	1169	2455237.90749359	949830422	194.588	-80.618	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	40	1.4
1174	1170	2455238.04709435	949842483	129.891	-10.447	-1.2873e-01	4.3155e-01	4.6595e-01	3.9162e-02	41	0.7
1175	1171	2455238.29850840	949864206	268.915	-41.544	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	48	0.9
1176	1172	2455238.54279775	949885312	233.262	-22.124	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	22	2.4
1177	1173	2455238.80680592	949908123	318.764	-52.914	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	30	2.4
1178	1174	2455238.83067321	949910185	16.152	8.161	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	49	1.4
1179	1175	2455238.84593511	949911503	35.966	17.808	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	51	1.4

## LIST OF HIGH ENERGY NEUTRINO CANDIDATES FOR THE 2009-2010 DATA

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1180	1176	2455238.86708216	949913330	308.956	-60.607	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	42	1.4
1181	1177	2455239.15188527	949937937	133.415	2.981	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	59	1.4
1182	1178	2455239.42988479	949961957	338.995	5.574	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	44	1.4
1183	1179	2455239.67181225	949982859	67.722	-54.693	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	56	1.4
1184	1180	2455239.96451713	950008149	172.860	-14.823	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	52	1.4
1185	1181	2455240.18513263	950027210	284.347	-23.086	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	49	1.4
1186	1182	2455240.21007501	950029365	242.480	-3.892	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	34	1.4
1187	1183	2455240.21160765	950029497	211.312	-45.305	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	36	1.4
1188	1184	2455240.23034532	950031116	185.137	-73.085	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	58	0.9
1189	1185	2455240.34505034	950041027	272.662	-37.470	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	63	0.9
1190	1186	2455240.41802997	950047332	351.348	-19.590	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	55	1.4
1191	1187	2455240.66495751	950068667	21.024	-3.372	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	35	1.4
1192	1188	2455240.80404601	950080684	130.577	-17.357	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	43	1.4
1193	1189	2455240.91853798	950090576	91.702	-67.632	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	39	0.9
1194	1190	2455240.93571007	950092060	44.912	-12.529	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	29	2.4
1195	1191	2455241.09773842	950106059	266.207	-53.110	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	34	2.4
1196	1192	2455241.13957804	950109674	196.043	-4.553	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	50	0.9
1197	1193	2455241.65199051	950153946	69.486	30.920	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	32	1.4
1198	1194	2455241.72682003	950160412	212.961	-69.030	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	36	0.9
1199	1195	2455241.96851666	950181294	58.341	8.207	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	22	2.4
1200	1196	2455242.14205350	950196288	159.121	-46.988	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	54	0.9
1201	1197	2455242.21229851	950202357	331.966	-59.103	-1.1909e-01	7.2127e-01	6.0423e-01	3.7507e-02	30	1.8
1202	1198	2455242.39309355	950217978	232.213	0.320	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	27	2.4
1203	1199	2455242.50935854	950228023	216.341	-30.679	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	58	1.4
1204	1200	2455242.53919763	950230601	248.625	-35.295	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	29	2.4
1205	1201	2455242.62830058	950238300	267.614	-27.172	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	50	2.4
1206	1202	2455242.64813353	950240013	304.941	5.364	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	46	1.4
1207	1203	2455242.69406945	950243982	101.511	-44.945	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	41	1.4
1208	1204	2455242.74461460	950248349	331.102	-37.505	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	54	1.4
1209	1205	2455242.98259308	950268911	166.229	9.696	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	38	1.4
1210	1206	2455242.98397481	950269030	266.530	-63.085	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	43	0.9
1211	1207	2455243.02402614	950272490	153.353	17.113	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	44	1.4
1212	1208	2455243.26316068	950293152	273.627	13.975	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	31	2.4
1213	1209	2455244.04238785	950360477	105.430	-19.063	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	25	2.4
1214	1210	2455244.11037502	950366351	309.510	-35.744	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	57	0.9
1215	1211	2455244.18681015	950372955	110.253	-58.106	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	42	0.9
1216	1212	2455244.34751617	950386840	49.400	-46.820	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	65	1.4
1217	1213	2455244.70301797	950417555	49.645	-6.026	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	56	1.4
1218	1214	2455245.06326866	950448681	206.368	-49.273	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	46	1.4
1219	1215	2455245.08729539	950450757	144.462	-25.738	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	21	2.4
1220	1216	2455245.11403893	950453067	159.365	32.917	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	52	0.9
1221	1217	2455245.27470075	950466949	164.540	-60.394	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	59	0.9
1222	1218	2455245.44499140	950481662	231.172	-85.484	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	24	2.4
1223	1219	2455245.44966551	950482066	244.638	-4.769	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	83	1.4
1224	1220	2455245.45975074	950482937	300.302	14.171	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	33	1.4
1225	1221	2455245.60601843	950495574	106.127	-65.269	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	38	1.4
1226	1222	2455245.71563288	950505045	53.773	13.446	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	54	1.4
1227	1223	2455246.02217481	950531530	97.378	-16.582	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	57	1.4
1228	1224	2455246.03158917	950532344	233.263	-46.073	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	35	1.4
1229	1225	2455246.09805670	950538087	174.332	-1.822	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	25	2.4
1230	1226	2455246.11528234	950539575	214.466	17.640	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	70	1.4
1231	1227	2455246.28998500	950554669	197.475	9.682	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	64	1.4

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1232	1228	2455246.33228058	950558324	312.487	-16.123	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	50	1.4
1233	1229	2455246.42955897	950566728	165.777	-50.785	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	33	1.4
1234	1230	2455246.75944578	950595231	25.761	15.246	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	99	1.4
1235	1231	2455246.88573043	950606142	159.477	36.232	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	65	1.4
1236	1232	2455246.91716358	950608857	111.797	21.931	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	58	1.4
1237	1233	2455247.21308151	950634425	209.838	-49.177	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	50	0.9
1238	1234	2455247.24815218	950637455	349.328	-72.661	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	24	2.4
1239	1235	2455247.38435043	950649222	300.730	-81.634	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	58	0.9
1240	1236	2455247.64487348	950671732	333.654	-35.879	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	38	0.9
1241	1237	2455248.12800971	950713475	244.347	6.203	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	30	2.4
1242	1238	2455248.15882571	950716137	189.658	-63.631	-1.2873e-01	4.3155e-01	4.6595e-01	3.9162e-02	83	0.7
1243	1239	2455248.37754314	950735034	216.336	5.409	-1.2873e-01	4.3155e-01	4.6595e-01	3.9162e-02	53	0.7
1244	1240	2455248.70727778	950763523	298.895	-33.968	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	52	1.4
1245	1241	2455248.87771300	950778249	99.719	-15.781	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	51	0.9
1246	1242	2455248.91453510	950781430	239.154	-23.460	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	32	0.9
1247	1243	2455249.05170480	950793282	109.860	-2.231	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	31	2.4
1248	1244	2455249.07433209	950795237	288.527	-70.925	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	65	1.4
1249	1245	2455249.32470947	950816869	352.745	-11.411	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	50	1.4
1250	1246	2455249.48498370	950830717	331.292	-45.173	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	48	1.4
1251	1247	2455249.53726233	950835234	104.269	-29.206	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	36	1.4
1252	1248	2455249.90214154	950866760	88.128	-32.685	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	61	0.9
1253	1249	2455249.94436753	950870408	133.525	39.457	-1.1909e-01	7.2127e-01	6.0423e-01	3.7507e-02	31	1.8
1254	1250	2455250.04090446	950878749	147.859	-28.125	-1.1909e-01	7.2127e-01	6.0423e-01	3.7507e-02	28	1.8
1255	1251	2455250.04838391	950879395	147.227	22.454	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	39	1.4
1256	1252	2455250.47216235	950916009	223.921	-39.904	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	54	1.4
1257	1253	2455250.50063640	950918469	316.257	-3.098	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	28	2.4
1258	1254	2455250.54714032	950922487	246.636	-32.686	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	35	0.9
1259	1255	2455250.70674558	950936277	25.209	21.320	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	36	1.4
1260	1256	2455251.06517422	950967246	171.914	42.818	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	60	1.4
1261	1257	2455251.11415422	950971477	183.872	-24.055	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	55	1.4
1262	1258	2455251.13918401	950973640	354.176	-81.250	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	43	0.9
1263	1259	2455251.19776064	950978701	280.767	-6.270	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	58	0.9
1264	1260	2455251.28195543	950985975	355.240	-7.914	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	33	1.4
1265	1261	2455251.37408099	950993935	257.172	25.183	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	44	1.4
1266	1262	2455251.43607378	950999291	273.004	-26.267	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	44	0.9
1267	1263	2455251.45271221	951000729	242.559	-48.993	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	27	2.4
1268	1264	2455251.53134595	951007523	120.158	-52.530	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	31	2.4
1269	1265	2455254.56912428	951269987	300.560	-22.486	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	38	0.9
1270	1266	2455254.83440150	951292907	113.376	-39.305	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	50	1.4
1271	1267	2455255.15049270	951320217	334.300	-27.545	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	30	2.4
1272	1268	2455255.19945811	951324448	305.669	8.883	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	54	1.4
1273	1269	2455255.21161200	951325498	299.542	-66.919	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	52	0.9
1274	1270	2455255.27759747	951331199	239.712	-50.950	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	76	0.9
1275	1271	2455255.28326351	951331688	341.809	-38.533	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	29	2.4
1276	1272	2455255.43858706	951345108	104.708	-49.112	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	34	2.4
1277	1273	2455255.75018716	951372031	32.381	-24.453	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	27	2.4
1278	1274	2455255.83863293	951379672	198.367	-22.289	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	45	1.4
1279	1275	2455255.90554189	951385453	95.598	-57.626	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	30	2.4
1280	1276	2455256.15353235	951406880	265.867	-14.570	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	33	0.9
1281	1277	2455256.29602770	951419191	153.135	-27.213	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	62	1.4
1282	1278	2455256.40462749	951428574	272.305	34.817	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	47	0.9
1283	1279	2455256.60036258	951445486	113.578	-58.128	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	27	2.4

## LIST OF HIGH ENERGY NEUTRINO CANDIDATES FOR THE 2009-2010 DATA

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1284	1280	2455256.60499258	951445886	40.650	28.305	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	50	1.4
1285	1281	2455256.71003407	951454961	68.124	16.054	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	47	1.4
1286	1282	2455256.79754508	951462522	122.853	-74.560	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	42	0.9
1287	1283	2455256.89157759	951470647	137.086	37.464	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	47	0.9
1288	1284	2455256.91242316	951472448	92.657	-35.438	-1.1909e-01	7.2127e-01	6.0423e-01	3.7507e-02	31	1.8
1289	1285	2455256.93188579	951474129	186.059	-27.492	-1.1909e-01	7.2127e-01	6.0423e-01	3.7507e-02	29	1.8
1290	1286	2455257.31602508	951507319	247.774	28.999	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	57	1.4
1291	1287	2455257.47023293	951520643	251.381	-6.165	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	66	1.4
1292	1288	2455257.66049793	951537082	152.998	-27.867	-1.2873e-01	4.3155e-01	4.6595e-01	3.9162e-02	58	0.7
1293	1289	2455257.70898795	951541271	137.758	-63.620	-1.2873e-01	4.3155e-01	4.6595e-01	3.9162e-02	59	0.7
1294	1290	2455257.73587488	951543594	29.546	27.063	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	31	2.4
1295	1291	2455257.79489538	951548693	61.982	2.317	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	88	2.4
1296	1292	2455258.03068668	951569066	244.968	-5.899	-1.1909e-01	7.2127e-01	6.0423e-01	3.7507e-02	30	1.8
1297	1293	2455258.06352406	951571903	252.012	-74.408	-1.1909e-01	7.2127e-01	6.0423e-01	3.7507e-02	32	1.8
1298	1294	2455258.08327040	951573609	224.081	-12.926	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	80	0.9
1299	1295	2455258.10306321	951575319	112.776	-2.369	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	97	1.4
1300	1296	2455258.16277478	951580478	311.195	-16.847	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	43	1.4
1301	1297	2455258.25098552	951588100	199.424	-68.796	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	45	1.4
1302	1298	2455259.94614591	951734562	147.978	14.078	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	52	1.4
1303	1299	2455259.96364018	951736073	32.567	-41.438	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	28	2.4
1304	1300	2455260.02215769	951741129	189.316	-66.285	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	35	1.4
1305	1301	2455260.12224479	951749776	157.221	30.385	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	46	1.4
1306	1302	2455260.18633076	951755313	232.560	18.338	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	30	2.4
1307	1303	2455260.32220811	951767053	288.229	-11.089	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	30	2.4
1308	1304	2455260.43713780	951776983	38.091	14.978	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	71	1.4
1309	1305	2455260.44574146	951777727	252.298	5.147	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	46	1.4
1310	1306	2455260.53491109	951785431	322.231	-40.597	-1.1909e-01	7.2127e-01	6.0423e-01	3.7507e-02	31	1.8
1311	1307	2455260.60643335	951791610	137.134	-63.994	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	31	2.4
1312	1308	2455260.75423916	951804381	38.562	-31.526	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	40	1.4
1313	1309	2455261.19588286	951842539	315.265	-7.455	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	35	1.4
1314	1310	2455261.31298374	951852656	230.839	16.296	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	35	1.4
1315	1311	2455261.34274907	951855228	286.390	-75.079	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	35	1.4
1316	1312	2455261.76379208	951891606	339.817	-33.331	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	60	1.4
1317	1313	2455261.78229491	951893205	154.027	10.076	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	30	2.4
1318	1314	2455261.80862669	951895480	138.568	-13.318	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	31	2.4
1319	1315	2455261.89353787	951902816	33.102	-15.791	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	35	2.4
1320	1316	2455261.93239698	951906174	95.193	11.129	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	35	1.4
1321	1317	2455263.29721293	952024094	210.043	3.714	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	82	1.4
1322	1318	2455267.62379628	952397910	83.137	-15.107	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	40	0.9
1323	1319	2455267.67307166	952402168	132.980	-18.113	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	33	1.4
1324	1320	2455267.67338965	952402195	3.705	-35.560	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	28	2.4
1325	1321	2455267.67367323	952402220	100.637	37.467	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	60	2.4
1326	1322	2455267.81031033	952414025	159.353	32.380	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	30	2.4
1327	1323	2455267.84146818	952416717	233.180	-26.350	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	29	2.4
1328	1324	2455268.35150423	952460784	189.398	-60.340	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	24	2.4
1329	1325	2455268.35481495	952461071	214.756	-29.087	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	30	2.4
1330	1326	2455268.40013440	952464986	301.321	-50.569	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	49	0.9
1331	1327	2455280.29903374	953493051	274.970	-70.396	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	37	1.4
1332	1328	2455283.30609960	953752862	198.173	-42.956	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	38	1.4
1333	1329	2455283.43377335	953763893	18.049	-35.932	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	33	1.4
1334	1330	2455283.47959317	953767851	66.466	-22.341	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	52	1.4
1335	1331	2455283.77032782	953792971	131.524	-17.652	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	52	0.9

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1336	1332	2455284.90541283	953891042	71.241	-33.435	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	37	1.4
1337	1333	2455284.91821652	953892148	227.039	-65.340	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	31	1.4
1338	1334	2455285.01907694	953900863	155.875	-29.601	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	61	1.4
1339	1335	2455285.22608287	953918748	316.749	-64.999	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	61	1.4
1340	1336	2455285.32338085	953927155	232.948	-29.647	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	54	1.4
1341	1337	2455285.45588485	953938603	111.069	-50.826	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	47	1.4
1342	1338	2455285.50638051	953942966	43.810	0.722	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	35	1.4
1343	1339	2455285.63365691	953953962	342.064	-46.721	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	42	1.4
1344	1340	2455285.78249703	953966822	78.165	30.326	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	37	1.4
1345	1341	2455285.84646996	953972350	166.717	23.895	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	52	0.9
1346	1342	2455286.05485091	953990354	76.126	-71.186	-5.8944e-02	2.9333e-01	5.7306e-01	3.8834e-02	106	0.6
1347	1343	2455286.12994036	953996841	272.941	33.026	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	42	1.4
1348	1344	2455286.19644749	954002588	333.943	-54.377	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	94	1.4
1349	1345	2455286.45788897	954025176	265.583	-7.233	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	36	1.4
1350	1346	2455286.65496167	954042203	117.467	-31.204	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	46	0.9
1351	1347	2455286.68027402	954044390	34.538	-83.079	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	43	1.4
1352	1348	2455286.69960489	954046060	60.444	-40.071	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	83	0.9
1353	1349	2455286.70877901	954046853	347.634	-31.890	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	43	0.9
1354	1350	2455286.83997087	954058188	124.098	-20.895	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	38	1.4
1355	1351	2455287.02338135	954074035	163.752	-62.606	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	23	2.4
1356	1352	2455287.08176524	954079079	277.041	-13.477	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	28	2.4
1357	1353	2455287.61673736	954125301	83.916	32.279	-1.1909e-01	7.2127e-01	6.0423e-01	3.7507e-02	31	1.8
1358	1354	2455287.86721703	954146942	104.179	-35.902	-5.8944e-02	2.9333e-01	5.7306e-01	3.8834e-02	107	0.6
1359	1355	2455287.88643340	954148602	105.853	32.275	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	27	2.4
1360	1356	2455288.20731313	954176326	242.669	-7.154	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	25	2.4
1361	1357	2455288.21580076	954177060	164.575	-21.435	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	35	1.4
1362	1358	2455288.42881651	954195464	335.653	-1.559	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	44	1.4
1363	1359	2455288.59563127	954209877	95.769	-49.679	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	42	1.4
1364	1360	2455288.62424942	954212350	108.890	23.990	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	36	1.4
1365	1361	2455288.68381763	954217496	165.791	-20.770	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	65	0.9
1366	1362	2455289.15006982	954257781	270.689	-28.074	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	36	1.4
1367	1363	2455291.12335500	954428272	262.101	20.130	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	47	0.9
1368	1364	2455291.46249512	954457574	343.776	-15.150	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	48	0.9
1369	1365	2455291.69763300	954477890	54.094	19.770	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	37	1.4
1370	1366	2455292.22765110	954523684	247.471	-29.202	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	31	2.4
1371	1367	2455292.24820815	954525460	234.509	21.605	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	94	0.9
1372	1368	2455292.29463392	954529471	270.203	8.486	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	39	1.4
1373	1369	2455292.49014666	954546363	359.652	-10.742	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	29	2.4
1374	1370	2455292.52128847	954549054	33.260	14.021	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	36	1.4
1375	1371	2455292.57108652	954553356	51.280	-35.735	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	66	1.4
1376	1372	2455292.68902117	954563546	96.097	-32.419	-8.8598e-02	3.3283e-01	5.3278e-01	3.9884e-02	111	0.6
1377	1373	2455292.73629607	954567630	91.906	10.251	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	30	2.4
1378	1374	2455292.75246910	954569028	203.231	-3.709	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	36	1.4
1379	1375	2455292.81947784	954574817	127.065	12.601	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	31	2.4
1380	1376	2455292.89357225	954581219	44.004	-29.827	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	31	2.4
1381	1377	2455293.11053481	954599965	2.780	-40.146	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	35	1.4
1382	1378	2455293.11912271	954600707	292.842	17.945	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	43	1.4
1383	1379	2455293.17125132	954605211	262.566	-41.919	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	41	1.4
1384	1380	2455293.27960597	954614572	256.933	0.180	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	30	2.4
1385	1381	2455293.28418842	954614968	91.264	-78.875	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	45	1.4
1386	1382	2455293.30188583	954616497	18.778	-34.856	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	28	2.4
1387	1383	2455293.41606072	954626362	6.602	2.667	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	32	0.9

## LIST OF HIGH ENERGY NEUTRINO CANDIDATES FOR THE 2009-2010 DATA

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1388	1384	2455293.41668533	954626416	325.188	37.603	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	61	1.4
1389	1385	2455293.44424809	954628798	77.478	11.282	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	43	1.4
1390	1386	2455293.45458253	954629690	31.232	-9.580	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	44	0.9
1391	1387	2455293.49485037	954633170	101.306	-2.677	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	47	0.9
1392	1388	2455293.57516357	954640109	4.230	-29.401	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	40	1.4
1393	1389	2455293.60671236	954642834	255.412	-46.157	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	41	1.4
1394	1390	2455293.63365788	954645163	103.551	19.820	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	31	2.4
1395	1391	2455293.69882299	954650793	41.047	-30.233	-1.2873e-01	4.3155e-01	4.6595e-01	3.9162e-02	80	0.7
1396	1392	2455293.75432706	954655588	292.463	-47.971	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	47	0.9
1397	1393	2455293.76192011	954656244	219.685	-27.691	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	25	2.4
1398	1394	2455293.92012988	954669914	164.733	-37.380	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	41	1.4
1399	1395	2455294.13527096	954688502	140.999	-32.182	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	29	1.4
1400	1396	2455294.38711661	954710261	316.658	8.995	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	33	1.4
1401	1397	2455295.03622396	954766344	25.019	-57.540	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	41	1.4
1402	1398	2455297.80116550	955005235	232.497	-15.102	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	48	1.4
1403	1399	2455298.00370654	955022735	31.428	-47.200	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	68	1.4
1404	1400	2455298.18076100	955038032	300.351	-16.365	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	81	1.4
1405	1401	2455299.04094349	955112352	209.653	29.951	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	85	1.4
1406	1402	2455299.89983036	955186560	231.575	-24.476	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	37	1.4
1407	1403	2455300.09199446	955203163	313.716	-61.118	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	23	2.4
1408	1404	2455300.10737209	955204491	323.104	-32.401	-1.1909e-01	7.2127e-01	6.0423e-01	3.7507e-02	30	1.8
1409	1405	2455300.117100524	955204805	312.823	-44.083	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	36	1.4
1410	1406	2455300.13246019	955206659	225.520	-44.910	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	62	0.9
1411	1407	2455316.80675897	956647318	231.896	-23.457	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	42	1.4
1412	1408	2455316.85196370	956651224	122.597	15.279	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	48	1.4
1413	1409	2455316.94276806	956659070	254.038	26.451	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	67	1.4
1414	1410	2455317.02226984	956665939	232.771	-44.501	-1.2873e-01	4.3155e-01	4.6595e-01	3.9162e-02	50	0.7
1415	1411	2455317.08609056	956671453	352.206	-74.182	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	51	0.9
1416	1412	2455317.11340286	956673813	1.290	-25.203	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	36	1.4
1417	1413	2455317.73010541	956727096	280.399	-79.105	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	34	0.9
1418	1414	2455317.76486827	956730099	152.380	7.549	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	32	1.4
1419	1415	2455320.27713519	956947159	33.757	-0.495	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	48	1.4
1420	1416	2455322.80545293	957165606	174.047	-55.550	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	41	1.4
1421	1417	2455322.84338650	957168883	158.385	-71.000	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	59	1.4
1422	1418	2455322.91332532	957174926	249.189	-28.790	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	46	1.4
1423	1419	2455322.91586188	957175145	181.247	5.545	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	46	1.4
1424	1420	2455344.35894043	959027827	63.679	-65.365	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	28	2.4
1425	1421	2455344.42181101	959033259	47.194	-38.129	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	62	1.4
1426	1422	2455345.19932765	959100436	259.712	-78.579	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	67	1.4
1427	1423	2455358.21125349	960224667	234.974	-37.476	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	50	1.4
1428	1424	2455358.35228472	960236852	17.868	8.193	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	42	1.4
1429	1425	2455358.37698580	960238986	120.692	-7.779	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	60	1.4
1430	1426	2455358.41296782	960242095	73.628	-61.822	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	48	1.4
1431	1427	2455358.47477294	960247435	109.298	-53.125	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	42	1.4
1432	1428	2455358.95643379	960289050	202.414	28.594	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	42	1.4
1433	1429	2455359.00592964	960293327	129.586	-41.588	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	32	1.4
1434	1430	2455359.19807954	960309929	56.894	-74.614	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	80	1.4
1435	1431	2455359.26808122	960315977	10.652	-49.793	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	53	1.4
1436	1432	2455361.23326367	960485768	274.802	-67.332	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	22	2.4
1437	1433	2455363.94296776	960719887	180.786	-46.451	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	47	0.9
1438	1434	2455364.48756816	960766940	127.780	-27.446	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	47	0.9
1439	1435	2455364.82054339	960795709	56.488	-75.717	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	45	1.4

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1440	1436	2455364.82141812	960795785	189.450	-24.416	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	47	1.4
1441	1437	2455365.38584119	960844551	115.391	23.256	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	28	2.4
1442	1438	2455365.55524306	960859188	219.344	-31.908	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	42	1.4
1443	1439	2455365.63625495	960866187	74.309	-9.347	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	53	1.4
1444	1440	2455365.72809334	960874122	118.809	9.255	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	43	1.4
1445	1441	2455366.08878634	960905286	7.788	25.082	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	24	2.4
1446	1442	2455366.15344437	960910872	334.794	11.446	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	43	2.4
1447	1443	2455366.17056137	960912351	118.883	-43.657	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	71	1.4
1448	1444	2455366.26401931	960920426	137.585	-38.630	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	33	1.4
1449	1445	2455366.32874271	960926018	63.457	-16.829	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	54	1.4
1450	1446	2455366.67018804	960955519	221.094	-11.824	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	48	1.4
1451	1447	2455366.68754250	960957018	242.556	-36.774	-8.8598e-02	3.3283e-01	5.3278e-01	3.9884e-02	148	0.6
1452	1448	2455366.78625159	960965547	29.983	-84.119	-8.8598e-02	3.3283e-01	5.3278e-01	3.9884e-02	29	0.6
1453	1449	2455366.86441567	960972300	341.787	-51.758	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	65	0.9
1454	1450	2455366.94538879	960979296	334.229	-21.182	-5.8944e-02	2.9333e-01	5.7306e-01	3.8834e-02	115	0.6
1455	1451	2455366.96332096	960980845	55.272	-46.520	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	41	1.4
1456	1452	2455367.37588935	961016491	71.926	-29.398	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	48	1.4
1457	1453	2455367.99364515	961069865	284.757	-37.977	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	41	1.4
1458	1454	2455368.26262811	961093106	38.030	-5.528	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	48	1.4
1459	1455	2455368.36648407	961102079	6.572	-49.199	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	60	1.4
1460	1456	2455368.70294318	961131149	113.119	-33.695	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	44	1.4
1461	1457	2455368.89872659	961148064	248.170	-19.935	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	43	1.4
1462	1458	2455368.99524298	961156403	291.187	-54.659	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	56	1.4
1463	1459	2455369.10473938	961165864	300.718	-28.056	-1.2873e-01	4.3155e-01	4.6595e-01	3.9162e-02	60	0.7
1464	1460	2455369.18190296	961172531	59.854	4.334	-1.2873e-01	4.3155e-01	4.6595e-01	3.9162e-02	46	0.7
1465	1461	2455369.98898602	961242263	207.260	-35.786	-1.2873e-01	4.3155e-01	4.6595e-01	3.9162e-02	76	0.7
1466	1462	2455371.69582045	961389733	266.951	-9.712	-1.2873e-01	4.3155e-01	4.6595e-01	3.9162e-02	76	0.7
1467	1463	2455371.91391682	961408577	235.455	40.263	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	54	1.4
1468	1464	2455371.91509862	961408679	203.451	11.810	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	38	1.4
1469	1465	2455372.02870194	961418494	354.329	-2.969	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	61	1.4
1470	1466	2455372.75174290	961480965	184.012	-22.011	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	55	0.9
1471	1467	2455372.83658108	961488295	176.420	-1.942	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	39	1.4
1472		# stop S6C -- start									
1473	1468	2455373.90313579	961580445	5.989	-70.629	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	63	1.4
1474	1469	2455374.49172512	961631300	123.617	4.409	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	66	0.9
1475	1470	2455375.14686582	961687904	44.359	-3.731	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	86	0.9
1476	1471	2455375.51446072	961719664	67.031	-6.509	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	56	1.4
1477	1472	2455375.76383908	961741210	175.990	-2.733	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	53	0.9
1478	1473	2455376.04986419	961765923	358.947	13.176	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	40	1.4
1479	1474	2455376.07209754	961767844	306.986	-18.809	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	60	1.4
1480	1475	2455376.60249931	961813670	358.852	-50.026	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	33	1.4
1481	1476	2455379.12838555	962031907	288.827	35.383	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	41	0.9
1482	1477	2455379.16635990	962035188	302.257	-19.197	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	50	1.4
1483	1478	2455379.45978149	962060540	108.331	9.730	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	35	1.4
1484	1479	2455379.73571086	962084380	281.294	-46.943	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	51	1.4
1485	1480	2455380.12874386	962118338	265.592	-52.702	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	34	0.9
1486	1481	2455380.21582264	962125862	41.444	2.236	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	58	1.4
1487	1482	2455381.26283730	962216324	46.290	-22.895	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	38	1.4
1488	1483	2455381.32268154	962221494	36.502	4.215	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	39	1.4
1489	1484	2455381.52888911	962239311	170.937	16.473	-8.8598e-02	3.3283e-01	5.3278e-01	3.9884e-02	121	0.6
1490	1485	2455381.55279714	962241376	210.295	-3.444	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	31	2.4
1491	1486	2455383.34716509	962396410	41.078	-1.939	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	56	1.4



# LIST OF HIGH ENERGY NEUTRINO CANDIDATES FOR THE 2009-2010 DATA

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1492	1487	2455384.07014133	962458875	268.290	11.144	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	44	1.4
1493	1488	2455384.14838615	962465635	280.349	-0.236	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	43	1.4
1494	1489	2455384.50147035	962496142	141.142	-51.345	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	39	1.4
1495	1490	2455384.58535537	962503389	34.387	-72.951	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	50	1.4
1496	1491	2455384.58735360	962503562	82.034	-5.806	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	51	0.9
1497	1492	2455384.67206094	962510881	211.819	-59.991	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	53	0.9
1498	1493	2455384.84454509	962525783	340.199	-18.425	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	27	2.4
1499	1494	2455385.01038952	962540112	255.698	-17.156	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	39	1.4
1500	1495	2455385.04728529	962543300	226.310	-24.719	-1.1909e-01	7.2127e-01	6.0423e-01	3.7507e-02	31	1.8
1501	1496	2455385.26635610	962562228	136.573	-39.175	-1.1909e-01	7.2127e-01	6.0423e-01	3.7507e-02	94	1.8
1502	1497	2455385.42705640	962576112	84.338	33.769	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	48	0.9
1503	1498	2455385.84846503	962612522	350.902	-58.961	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	48	1.4
1504	1499	2455385.87065587	962614439	209.722	-9.175	-1.2873e-01	4.3155e-01	4.6595e-01	3.9162e-02	57	0.7
1505	1500	2455386.64829265	962681627	204.374	38.929	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	59	1.4
1506	1501	2455386.68276354	962684605	219.334	24.891	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	26	2.4
1507	1502	2455387.02261932	962713969	246.653	-45.851	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	34	1.4
1508	1503	2455387.19454592	962728823	318.334	-14.532	-1.7861e+00	6.7827e+00	8.6368e-01	3.8440e-01	26	1.4
1509	1504	2455387.22718896	962731644	217.429	-61.109	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	41	1.4
1510	1505	2455387.23182377	962732044	309.818	-56.973	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	32	1.4
1511	1506	2455387.42003623	962748306	122.565	-0.590	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	31	2.4
1512	1507	2455387.66092453	962769118	109.719	11.035	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	39	1.4
1513	1508	2455387.79549742	962780745	317.174	-8.815	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	37	1.4
1514	1509	2455388.25188769	962820178	336.079	-41.845	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	46	0.9
1515	1510	2455388.27647286	962822302	239.542	-45.034	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	34	1.4
1516	1511	2455388.45725814	962837922	75.514	-64.535	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	42	1.4
1517	1512	2455388.49139560	962840871	77.617	-26.651	-1.2873e-01	4.3155e-01	4.6595e-01	3.9162e-02	49	0.7
1518	1513	2455388.64444318	962854094	147.968	14.852	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	82	1.4
1519	1514	2455388.76476178	962864490	185.579	8.436	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	41	1.4
1520	1515	2455388.76672677	962864660	94.380	-61.145	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	53	1.4
1521	1516	2455388.85713631	962872471	208.389	-14.968	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	40	1.4
1522	1517	2455388.88175389	962874598	305.962	-51.989	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	38	0.9
1523	1518	2455389.18574832	962900863	286.138	-18.429	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	48	0.9
1524	1519	2455389.49712053	962927766	130.908	11.714	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	45	1.4
1525	1520	2455389.52152963	962929875	160.448	-42.283	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	52	0.9
1526	1521	2455389.53943972	962931422	165.847	29.750	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	69	1.4
1527	1522	2455389.63683500	962939837	179.316	-20.342	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	31	2.4
1528	1523	2455389.87726054	962960610	336.881	-38.636	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	32	1.4
1529	1524	2455390.02402431	962973290	151.515	-62.033	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	52	1.4
1530	1525	2455390.54528381	963018327	27.766	-41.501	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	41	1.4
1531	1526	2455390.68555944	963030447	222.228	8.629	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	28	2.4
1532	1527	2455390.69935538	963031639	254.640	-10.566	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	29	2.4
1533	1528	2455390.93820683	963052276	210.622	3.885	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	41	1.4
1534	1529	2455391.26882551	963080841	332.910	-13.269	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	32	1.4
1535	1530	2455391.29238911	963082877	150.464	-48.353	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	48	0.9
1536	1531	2455391.29684010	963083261	33.686	-80.121	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	41	1.4
1537	1532	2455391.44676429	963096215	346.265	-23.497	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	62	1.4
1538	1533	2455391.51726329	963102306	101.889	-71.360	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	54	1.4
1539	1534	2455391.98485833	963142706	312.346	7.081	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	85	1.4
1540	1535	2455392.09837487	963152514	313.628	-65.214	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	48	0.9
1541	1536	2455392.11320869	963153796	105.445	-41.411	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	38	1.4
1542	1537	2455392.19615406	963160962	7.207	46.000	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	19	2.4
1543	1538	2455392.48761505	963186144	93.162	-11.278	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	88	1.4

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1544 1539 2455392.51090710 963188157 96.435 36.323 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 44 1.4  
1545 1540 2455392.68417985 963203128 239.970 -0.784 -1.3370e-01 8.5313e-01 6.3102e-01 3.7539e-02 29 2.4  
1546 1541 2455396.07159846 963495801 296.094 17.169 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 40 1.4  
1547 1542 2455396.29105526 963514762 57.010 6.188 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 54 1.4  
1548 1543 2455396.42950057 963526723 133.517 8.850 -1.3370e-01 8.5313e-01 6.3102e-01 3.7539e-02 24 2.4  
1549 1544 2455396.44622235 963528168 59.009 -3.628 -5.8944e-02 2.9333e-01 5.7306e-01 3.8834e-02 101 0.6  
1550 1545 2455396.53987868 963536260 75.075 3.888 -1.3370e-01 8.5313e-01 6.3102e-01 3.7539e-02 25 2.4  
1551 1546 2455396.59061666 963540644 112.253 2.542 -1.3370e-01 8.5313e-01 6.3102e-01 3.7539e-02 38 2.4  
1552 1547 2455396.69411137 963549586 256.047 20.499 -1.3370e-01 8.5313e-01 6.3102e-01 3.7539e-02 23 2.4  
1553 1548 2455397.05813910 963581038 78.141 -60.199 -1.1724e-01 4.7983e-01 5.2936e-01 3.8897e-02 38 0.9  
1554 1549 2455397.06047488 963581240 215.015 -42.034 -1.3370e-01 8.5313e-01 6.3102e-01 3.7539e-02 23 2.4  
1555 1550 2455397.19554695 963592910 329.391 -16.566 -1.1724e-01 4.7983e-01 5.2936e-01 3.8897e-02 47 0.9  
1556 1551 2455397.64009648 963631319 48.756 -64.158 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 76 1.4  
1557 1552 2455397.69566175 963636120 54.397 -41.147 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 33 1.4  
1558 1553 2455397.95582273 963658598 19.932 -21.140 -1.3370e-01 8.5313e-01 6.3102e-01 3.7539e-02 30 2.4  
1559 1554 2455398.07279179 963668704 30.381 15.265 -1.3370e-01 8.5313e-01 6.3102e-01 3.7539e-02 23 2.4  
1560 1555 2455398.16670441 963676818 47.179 -59.568 -1.3370e-01 8.5313e-01 6.3102e-01 3.7539e-02 28 2.4  
1561 1556 2455398.20316353 963679968 28.490 -4.236 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 41 1.4  
1562 1557 2455398.36393923 963693859 54.360 4.932 -1.1724e-01 4.7983e-01 5.2936e-01 3.8897e-02 48 0.9  
1563 1558 2455398.44059353 963700482 77.734 -21.196 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 44 1.4  
1564 1559 2455398.46876191 963702916 63.192 10.778 -1.1724e-01 4.7983e-01 5.2936e-01 3.8897e-02 52 0.9  
1565 1560 2455398.54297531 963709328 145.348 -51.806 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 56 1.4  
1566 1561 2455398.73030620 963725513 263.267 0.649 -1.3370e-01 8.5313e-01 6.3102e-01 3.7539e-02 25 2.4  
1567 1562 2455398.82056218 963733311 65.161 -49.828 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 41 1.4  
1568 1563 2455398.90865081 963740922 165.275 -61.816 -1.3370e-01 8.5313e-01 6.3102e-01 3.7539e-02 29 2.4  
1569 1564 2455399.07744975 963755506 326.980 12.709 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 49 1.4  
1570 1565 2455399.17494927 963763930 277.281 -57.701 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 35 1.4  
1571 1566 2455399.75873374 963814369 157.299 -40.395 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 33 1.4  
1572 1567 2455405.34960546 964297420 50.755 -62.232 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 92 1.4  
1573 1568 2455405.53609605 964313533 97.317 -35.782 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 37 1.4  
1574 1569 2455405.98854355 964352625 328.322 -77.202 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 42 1.4  
1575 1570 2455406.26117066 964376180 89.769 -36.885 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 34 1.4  
1576 1571 2455406.63367816 964408364 187.842 17.240 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 44 1.4  
1577 1572 2455406.79152398 964422002 54.867 -61.780 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 48 1.4  
1578 1573 2455407.00565888 964440503 286.714 -13.592 -1.1724e-01 4.7983e-01 5.2936e-01 3.8897e-02 55 0.9  
1579 1574 2455407.11088480 964449595 285.558 -53.702 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 44 1.4  
1580 1575 2455407.25114877 964461714 354.543 -33.245 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 47 1.4  
1581 1576 2455407.40058597 964474625 140.357 -29.592 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 35 1.4  
1582 1577 2455407.58625397 964490667 138.391 -19.949 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 64 1.4  
1583 1578 2455407.79421643 964508635 171.837 7.523 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 44 1.4  
1584 1579 2455407.89173694 964517061 235.571 27.482 -1.3370e-01 8.5313e-01 6.3102e-01 3.7539e-02 24 2.4  
1585 1580 2455408.60103370 964578344 165.047 26.423 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 34 1.4  
1586 1581 2455409.54893676 964660243 122.521 -8.117 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 53 1.4  
1587 1582 2455409.71998793 964675021 213.815 -14.903 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 50 1.4  
1588 1583 2455410.34271102 964728825 118.803 -21.503 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 36 1.4  
1589 1584 2455410.65032080 964755402 189.118 27.898 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 77 1.4  
1590 1585 2455410.72016895 964761437 186.235 42.879 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 47 1.4  
1591 1586 2455410.95517517 964781742 278.609 20.398 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 99 1.4  
1592 1587 2455410.98121297 964783991 278.015 -0.243 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 49 1.4  
1593 1588 2455411.20149212 964803023 328.739 22.200 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 47 1.4  
1594 1589 2455411.29430793 964811043 131.155 -41.499 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 58 1.4  
1595 1590 2455411.40650879 964820737 240.098 -49.745 -9.2963e-02 5.6770e-01 6.3052e-01 3.8106e-02 50 1.4

## LIST OF HIGH ENERGY NEUTRINO CANDIDATES FOR THE 2009-2010 DATA

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1596	1591	2455411.44335445	964823920	150.859	21.608	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	39	1.4
1597	1592	2455411.68580267	964844868	138.110	-3.563	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	35	0.9
1598	1593	2455411.72122069	964847928	201.585	43.448	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	40	0.9
1599	1594	2455411.82257757	964856685	1.722	-59.887	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	52	0.9
1600	1595	2455411.89406440	964862862	54.756	-49.620	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	74	0.9
1601	1596	2455411.94043781	964866868	182.167	-30.453	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	57	1.4
1602	1597	2455412.05739074	964876973	340.269	24.848	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	44	1.4
1603	1598	2455412.06133395	964877314	231.903	-26.820	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	40	1.4
1604	1599	2455412.06920058	964877993	25.985	26.147	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	42	1.4
1605	1600	2455412.09714234	964880408	82.909	-74.640	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	47	1.4
1606	1601	2455412.23159644	964892024	81.573	-54.420	-1.2873e-01	4.3155e-01	4.6595e-01	3.9162e-02	47	0.7
1607	1602	2455412.31984813	964899649	355.591	5.232	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	38	1.4
1608	1603	2455412.45190219	964911059	219.013	-20.328	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	77	1.4
1609	1604	2455412.47150470	964912753	5.474	-43.144	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	40	1.4
1610	1605	2455412.67484742	964930321	121.704	5.153	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	49	1.4
1611	1606	2455413.24667944	964979728	126.881	-30.190	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	23	2.4
1612	1607	2455413.26990541	964981734	100.996	7.694	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	48	1.4
1613	1608	2455413.62293001	965012236	202.157	9.644	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	45	1.4
1614	1609	2455413.62309067	965012250	197.447	-53.627	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	46	1.4
1615	1610	2455413.65482573	965014991	65.591	-47.281	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	37	1.4
1616	1611	2455413.84677035	965031575	238.036	-8.435	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	55	1.4
1617	1612	2455413.86081947	965032789	304.777	14.607	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	45	1.4
1618	1613	2455413.88250034	965034663	2.283	-62.468	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	43	1.4
1619	1614	2455414.06564428	965050486	34.480	-19.110	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	54	1.4
1620	1615	2455414.19301958	965061491	51.291	13.925	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	26	2.4
1621	1616	2455414.20250958	965062311	124.313	-3.286	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	51	1.4
1622	1617	2455414.81650328	965115360	189.228	5.082	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	45	1.4
1623	1618	2455414.88050599	965120890	313.700	-33.401	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	38	1.4
1624	1619	2455415.32265675	965159092	127.642	5.416	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	28	2.4
1625	1620	2455415.79980090	965200317	230.472	-23.253	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	55	1.4
1626	1621	2455416.24052251	965238396	32.097	9.841	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	45	1.4
1627	1622	2455416.39728093	965251940	93.417	-2.898	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	64	1.4
1628	1623	2455416.41189513	965253202	39.306	-51.194	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	58	1.4
1629	1624	2455416.85135381	965291171	228.601	27.528	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	31	1.4
1630	1625	2455416.99133890	965303266	325.211	18.155	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	48	1.4
1631	1626	2455418.11804856	965400614	51.357	-38.619	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	65	1.4
1632	1627	2455419.17279374	965491744	334.367	-19.407	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	47	1.4
1633	1628	2455419.66193775	965534006	274.301	-2.131	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	40	1.4
1634	1629	2455420.58188819	965613490	134.184	-9.965	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	50	1.4
1635	1630	2455420.64478845	965618924	140.585	25.252	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	37	1.4
1636	1631	2455421.01842883	965651207	52.057	-20.234	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	24	2.4
1637	1632	2455421.13481522	965661263	47.267	-17.304	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	41	1.4
1638	1633	2455421.17550090	965664778	341.923	-30.664	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	28	2.4
1639	1634	2455421.18388006	965665502	356.147	-54.737	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	44	1.4
1640	1635	2455421.20734816	965667529	193.559	-59.953	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	49	1.4
1641	1636	2455421.26966946	965672914	33.709	-8.258	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	55	0.9
1642	1637	2455421.31489924	965676822	145.228	-6.521	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	32	1.4
1643	1638	2455421.50370376	965693135	61.422	-22.894	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	71	1.4
1644	1639	2455421.64049105	965704953	162.548	38.503	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	33	1.4
1645	1640	2455421.64943180	965705725	305.359	-28.389	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	40	1.4
1646	1641	2455421.70295410	965710350	121.166	-24.871	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	34	1.4
1647	1642	2455421.97428930	965733793	290.181	-41.123	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	44	1.4

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1648	1643	2455422.01567384	965737369	285.616	-20.758	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	65	1.4
1649	1644	2455422.10703200	965745262	325.751	-38.644	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	28	2.4
1650	1645	2455422.19272734	965752666	322.679	-41.813	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	38	2.4
1651	1646	2455422.20932694	965754100	63.902	17.355	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	31	2.4
1652	1647	2455422.34728654	965766020	61.990	-29.209	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	26	2.4
1653	1648	2455422.37016411	965767997	168.206	-14.173	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	46	0.9
1654	1649	2455422.54721552	965783294	0.807	-50.504	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	23	2.4
1655	1650	2455422.70648059	965797054	300.507	7.048	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	49	1.4
1656	1651	2455422.93377367	965816693	300.421	17.063	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	35	1.4
1657	1652	2455423.07352596	965828767	320.854	-18.990	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	34	1.4
1658	1653	2455423.09972906	965831031	294.205	15.139	-1.2873e-01	4.3155e-01	4.6595e-01	3.9162e-02	59	0.7
1659	1654	2455423.10299524	965831313	50.049	-47.905	-1.2873e-01	4.3155e-01	4.6595e-01	3.9162e-02	60	0.7
1660	1655	2455423.61643567	965875675	309.142	-28.397	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	50	1.4
1661	1656	2455423.80698012	965892138	350.920	-31.017	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	51	1.4
1662	1657	2455423.83849925	965894861	199.005	-61.231	-1.2873e-01	4.3155e-01	4.6595e-01	3.9162e-02	57	0.7
1663	1658	2455423.84040886	965895026	190.940	-61.557	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	37	1.4
1664	1659	2455423.87209296	965897763	196.226	-0.480	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	25	1.4
1665	1660	2455424.21539309	965927424	73.948	-35.590	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	39	0.9
1666	1661	2455424.23310282	965928955	164.980	-22.524	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	33	1.4
1667	1662	2455424.52232128	965953943	272.523	-67.829	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	33	1.4
1668	1663	2455425.06198192	966000570	23.139	-42.407	-1.1909e-01	7.2127e-01	6.0423e-01	3.7507e-02	31	1.8
1669	1664	2455425.56386018	966043932	177.165	-45.668	-1.2873e-01	4.3155e-01	4.6595e-01	3.9162e-02	92	0.7
1670	1665	2455425.95365897	966077611	10.359	24.096	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	45	1.4
1671	1666	2455426.00529824	966082072	260.094	9.219	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	32	1.4
1672	1667	2455426.02304114	966083605	267.758	-16.403	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	30	2.4
1673	1668	2455426.02816909	966084048	2.878	12.071	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	31	2.4
1674	1669	2455426.18466108	966097569	300.647	-74.729	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	24	2.4
1675	1670	2455426.27978837	966105788	104.893	-46.328	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	33	1.4
1676	1671	2455426.68160543	966140505	284.851	-81.391	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	60	1.4
1677	1672	2455427.03499794	966171038	316.091	22.544	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	39	1.4
1678	1673	2455427.07843445	966174791	62.896	-45.680	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	41	1.4
1679	1674	2455427.21933358	966186965	85.067	-51.409	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	44	1.4
1680	1675	2455427.40387959	966202910	158.621	-34.187	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	53	1.4
1681	1676	2455427.44496192	966206459	298.221	-50.612	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	29	2.4
1682	1677	2455427.65459995	966224572	293.625	-51.197	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	36	0.9
1683	1678	2455427.66846274	966225770	30.561	-59.887	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	32	1.4
1684	1679	2455428.08346722	966261626	341.423	-26.854	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	51	1.4
1685	1680	2455428.11037461	966263951	109.837	-10.540	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	34	1.4
1686	1681	2455428.21922358	966273355	332.675	5.883	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	27	2.4
1687	1682	2455428.23824451	966274999	122.614	-42.221	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	34	1.4
1688	1683	2455441.45374207	967416818	94.562	-25.760	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	41	0.9
1689	1684	2455441.48969199	967419924	67.477	-35.895	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	58	1.4
1690	1685	2455441.56147618	967426126	104.308	-48.963	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	27	2.4
1691	1686	2455441.56792120	967426683	158.748	-35.408	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	54	1.4
1692	1687	2455442.03270271	967466840	295.604	-58.742	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	50	1.4
1693	1688	2455442.21609640	967482685	9.822	12.791	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	46	0.9
1694	1689	2455442.31723545	967491424	192.412	-78.016	-1.1909e-01	7.2127e-01	6.0423e-01	3.7507e-02	29	1.8
1695	1690	2455442.36213883	967495303	155.833	17.577	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	58	1.4
1696	1691	2455442.70921974	967525291	27.780	-81.366	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	43	1.4
1697	1692	2455442.71087246	967525434	327.359	-45.899	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	31	1.4
1698	1693	2455442.87448866	967539570	294.521	40.132	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	64	1.4
1699	1694	2455442.89214633	967541096	230.263	-66.383	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	54	0.9

# LIST OF HIGH ENERGY NEUTRINO CANDIDATES FOR THE 2009-2010 DATA

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1700	1695	2455443.02464581	967552544	1.238	44.416	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	35	1.4
1701	1696	2455443.20190358	967567859	191.607	-49.942	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	61	0.9
1702	1697	2455443.20944823	967568511	28.412	-57.455	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	52	1.4
1703	1698	2455443.28496185	967575035	22.892	-15.778	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	36	1.4
1704	1699	2455443.28555079	967575086	89.108	13.049	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	21	2.4
1705	1700	2455443.78091011	967617885	99.606	-55.991	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	29	2.4
1706	1701	2455444.11103544	967646408	28.467	8.555	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	42	1.4
1707	1702	2455444.81675966	967707383	338.543	2.164	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	34	1.4
1708	1703	2455444.89938478	967714521	17.411	9.451	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	30	2.4
1709	1704	2455444.98906271	967722270	7.528	-20.007	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	36	1.4
1710	1705	2455445.24470879	967744357	86.630	33.205	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	44	1.4
1711	1706	2455445.26592067	967746190	22.609	-71.529	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	52	1.4
1712	1707	2455445.28335692	967747697	160.296	-69.197	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	53	1.4
1713	1708	2455445.85291538	967796906	358.180	-31.748	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	25	2.4
1714	1709	2455445.87460896	967798781	230.756	6.897	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	44	1.4
1715	1710	2455446.05589751	967814444	314.241	-32.061	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	40	1.4
1716	1711	2455446.46786945	967850038	117.580	-46.652	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	70	0.9
1717	1712	2455446.54708421	967856883	279.306	-11.358	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	35	1.4
1718	1713	2455446.75667797	967874991	140.782	-63.664	-1.1909e-01	7.2127e-01	6.0423e-01	3.7507e-02	30	1.8
1719	1714	2455446.80403547	967879083	1.952	-23.709	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	63	1.4
1720	1715	2455446.94695755	967891432	59.918	-8.642	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	49	1.4
1721	1716	2455446.99029482	967895176	59.824	14.294	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	68	1.4
1722	1717	2455447.03362027	967898919	308.926	-22.196	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	105	1.4
1723	1718	2455447.26917945	967919272	52.097	-41.938	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	40	1.4
1724	1719	2455447.27743756	967919985	134.272	2.371	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	54	1.4
1725	1720	2455447.83084432	967967799	350.188	23.967	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	51	1.4
1726	1721	2455447.97088409	967979899	61.608	-35.476	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	40	1.4
1727	1722	2455448.08618777	967989861	49.698	-3.116	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	35	1.4
1728	1723	2455448.31741339	968009839	179.983	-35.432	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	30	1.4
1729	1724	2455448.39402879	968016459	200.622	12.571	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	67	1.4
1730	1725	2455448.42772426	968019370	217.913	2.598	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	29	2.4
1731	1726	2455448.68787973	968041847	282.067	-29.940	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	36	1.4
1732	1727	2455448.77399536	968049288	24.896	-48.870	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	49	1.4
1733	1728	2455448.79541924	968051139	219.211	-0.092	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	20	1.4
1734	1729	2455448.83752018	968054776	193.173	-35.721	-1.1909e-01	7.2127e-01	6.0423e-01	3.7507e-02	30	1.8
1735	1730	2455448.87335538	968057872	43.387	-84.199	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	42	0.9
1736	1731	2455449.00031679	968068842	44.362	2.314	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	39	1.4
1737	1732	2455449.38702265	968102253	98.425	-39.494	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	46	1.4
1738	1733	2455449.54458668	968115867	117.406	-59.687	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	34	1.4
1739	1734	2455449.78084109	968136279	252.108	43.031	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	32	1.4
1740	1735	2455449.78381254	968136536	280.903	-39.117	-1.2873e-01	4.3155e-01	4.6595e-01	3.9162e-02	37	0.7
1741	1736	2455449.84177884	968141544	262.672	-48.550	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	40	1.4
1742	1737	2455449.98687581	968154081	285.448	-51.109	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	33	1.4
1743	1738	2455450.08299150	968162385	33.874	6.552	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	39	1.4
1744	1739	2455450.08345315	968162425	313.492	-21.837	-1.1909e-01	7.2127e-01	6.0423e-01	3.7507e-02	29	1.8
1745	1740	2455450.13989163	968167301	258.531	-67.610	-1.1909e-01	7.2127e-01	6.0423e-01	3.7507e-02	45	1.8
1746	1741	2455450.29677551	968180856	285.437	-87.541	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	21	2.4
1747	1742	2455450.83399792	968227272	238.619	23.875	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	94	1.4
1748	1743	2455450.86255113	968229739	266.493	-69.117	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	75	0.9
1749	1744	2455450.87407838	968230735	67.154	-33.516	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	43	0.9
1750	1745	2455451.07600479	968248181	339.338	18.516	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	79	1.4
1751	1746	2455451.23133647	968261602	53.617	-31.862	-1.1909e-01	7.2127e-01	6.0423e-01	3.7507e-02	25	1.8

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1752	1747	2455451.28454823	968266199	67.115	33.041	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	48	1.4
1753	1748	2455451.50674469	968285397	115.947	-2.447	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	48	1.4
1754	1749	2455451.78208613	968309187	184.436	-52.226	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	41	0.9
1755	1750	2455451.80424182	968311101	197.555	0.462	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	27	2.4
1756	1751	2455452.07326191	968334344	65.706	-4.102	-1.1909e-01	7.2127e-01	6.0423e-01	3.7507e-02	29	1.8
1757	1752	2455452.08551482	968335403	28.354	-49.227	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	52	1.4
1758	1753	2455452.10731938	968337287	343.683	-79.519	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	24	2.4
1759	1754	2455452.20449255	968345683	57.043	-1.560	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	38	0.9
1760	1755	2455452.22965164	968347856	250.902	-83.167	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	42	1.4
1761	1756	2455452.23154252	968348020	151.291	-35.510	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	30	2.4
1762	1757	2455452.36088703	968359195	162.197	12.472	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	49	0.9
1763	1758	2455452.36702477	968359725	176.041	29.863	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	24	2.4
1764	1759	2455452.57756140	968377916	294.351	-54.310	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	57	0.9
1765	1760	2455453.24560289	968435635	90.253	-58.855	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	63	0.9
1766	1761	2455453.25190889	968436179	211.328	-67.028	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	33	1.4
1767	1762	2455453.25259588	968436239	35.524	-70.161	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	34	1.4
1768	1763	2455453.36087261	968445594	53.510	-16.938	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	28	2.4
1769	1764	2455453.41293734	968450092	206.813	15.460	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	45	1.4
1770	1765	2455453.41348776	968450140	162.361	42.798	-1.1210e-01	3.5816e-01	4.5437e-01	4.0298e-02	114	0.5
1771	1766	2455453.42685768	968451295	143.073	25.880	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	40	0.9
1772	1767	2455453.86968999	968489556	320.407	24.216	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	34	1.4
1773	1768	2455453.93808666	968495465	265.853	3.678	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	46	1.4
1774	1769	2455454.30271870	968526969	282.908	-51.377	-1.7861e+00	6.7827e+00	8.6368e-01	3.8440e-01	26	1.4
1775	1770	2455454.37953530	968533606	72.904	-37.762	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	48	0.9
1776	1771	2455454.43112392	968538064	204.179	-38.790	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	30	2.4
1777	1772	2455454.46976008	968541402	82.501	-53.496	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	38	1.4
1778	1773	2455454.48323023	968542566	133.147	-46.521	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	30	2.4
1779	1774	2455454.50385255	968544347	124.003	-30.084	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	89	0.9
1780	1775	2455454.77093044	968567423	249.674	-4.856	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	57	1.4
1781	1776	2455454.91359343	968579749	89.688	-42.864	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	33	1.4
1782	1777	2455454.96372225	968584080	52.293	4.365	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	28	2.4
1783	1778	2455454.98309502	968585754	253.150	-27.544	-1.1909e-01	7.2127e-01	6.0423e-01	3.7507e-02	23	1.8
1784	1779	2455455.20882833	968605257	0.276	8.491	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	28	2.4
1785	1780	2455455.51356785	968631587	102.524	-7.292	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	51	1.4
1786	1781	2455455.80973056	968657175	20.353	-55.592	-1.7861e+00	6.7827e+00	8.6368e-01	3.8440e-01	29	1.4
1787	1782	2455455.90317996	968665249	225.192	-52.217	-1.1909e-01	7.2127e-01	6.0423e-01	3.7507e-02	28	1.8
1788	1783	2455455.99218813	968672940	77.351	-4.361	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	45	1.4
1789	1784	2455456.15787180	968687255	129.863	-65.277	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	34	0.9
1790	1785	2455456.20172689	968691044	44.735	5.830	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	27	2.4
1791	1786	2455456.20605460	968691418	191.833	-57.155	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	44	1.4
1792	1787	2455456.59749667	968725238	172.467	9.421	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	42	1.4
1793	1788	2455456.61395583	968726660	223.122	-33.374	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	72	0.9
1794	1789	2455457.12617472	968770916	62.516	30.053	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	46	0.9
1795	1790	2455457.27603636	968783864	149.913	-57.385	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	44	1.4
1796	1791	2455457.70004021	968820498	311.329	-24.458	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	30	1.4
1797	1792	2455457.74421786	968824315	315.362	-83.810	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	34	1.4
1798	1793	2455457.76773135	968826346	261.090	-43.762	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	47	1.4
1799	1794	2455457.81715868	968830617	216.741	-3.327	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	44	1.4
1800	1795	2455458.27230883	968869942	13.094	-10.294	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	69	1.4
1801	1796	2455458.32611694	968874591	7.234	-62.816	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	32	1.4
1802	1797	2455458.45893698	968886067	182.219	39.801	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	36	0.9
1803	1798	2455458.61452063	968899509	246.751	12.499	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	36	1.4

## LIST OF HIGH ENERGY NEUTRINO CANDIDATES FOR THE 2009-2010 DATA

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1804	1799	2455458.81424959	968916766	118.206	-48.445	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	31	2.4
1805	1800	2455458.86849402	968921452	189.228	-35.980	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	40	1.4
1806	1801	2455458.94910179	968928417	264.027	-44.981	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	30	2.4
1807	1802	2455459.05437309	968937512	42.274	30.380	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	45	1.4
1808	1803	2455459.13172550	968944196	340.949	13.071	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	40	1.4
1809	1804	2455459.18837762	968949090	122.851	5.024	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	48	1.4
1810	1805	2455459.35471725	968963462	124.037	45.249	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	25	2.4
1811	1806	2455459.52773436	968978411	319.930	-54.225	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	54	1.4
1812	1807	2455459.70348314	968993595	271.569	44.217	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	42	1.4
1813	1808	2455459.70862106	968994039	2.090	-36.578	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	39	0.9
1814	1809	2455459.93289750	969013417	315.066	-64.835	-8.8598e-02	3.3283e-01	5.3278e-01	3.9884e-02	125	0.6
1815	1810	2455460.12238082	969029788	215.906	-49.693	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	18	2.4
1816	1811	2455460.34336759	969048881	155.483	-5.338	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	49	1.4
1817	1812	2455460.35634849	969050003	135.241	0.318	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	44	1.4
1818	1813	2455460.37567663	969051673	101.999	-1.694	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	58	1.4
1819	1814	2455461.16192720	969119605	152.141	-9.531	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	57	1.4
1820	1815	2455461.87336644	969181073	287.104	-2.908	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	40	1.4
1821	1816	2455461.89217576	969182698	43.941	13.215	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	53	0.9
1822	1817	2455461.98280990	969190529	6.948	34.909	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	39	1.4
1823	1818	2455462.02469139	969194148	337.255	25.388	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	36	1.4
1824	1819	2455462.31736533	969219435	105.227	-43.216	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	40	1.4
1825	1820	2455462.38022886	969224866	35.947	-54.463	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	42	1.4
1826	1821	2455462.40710516	969227188	152.609	16.647	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	87	0.9
1827	1822	2455462.52875500	969237699	124.849	-24.464	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	39	1.4
1828	1823	2455462.58753144	969242777	173.333	-7.415	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	48	1.4
1829	1824	2455462.65078916	969248243	174.637	-45.211	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	33	1.4
1830	1825	2455462.91259969	969270863	63.928	2.929	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	41	1.4
1831	1826	2455462.95610410	969274622	125.749	-65.055	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	35	1.4
1832	1827	2455463.78877374	969346565	277.962	-0.582	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	48	0.9
1833	1828	2455463.92620325	969358438	3.320	24.990	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	36	1.4
1834	1829	2455463.94571679	969360124	355.573	4.437	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	37	0.9
1835	1830	2455464.18784837	969381045	342.251	-38.295	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	64	0.9
1836	1831	2455464.24919048	969386345	102.662	-29.369	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	48	0.9
1837	1832	2455464.25432507	969386788	63.376	-33.042	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	22	2.4
1838	1833	2455464.47117015	969405524	117.889	-12.746	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	40	2.4
1839	1834	2455464.52591589	969410254	149.584	29.662	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	60	1.4
1840	1835	2455464.59014824	969415803	329.730	-41.640	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	43	1.4
1841	1836	2455464.76883134	969431242	286.862	28.859	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	31	2.4
1842	1837	2455464.98477664	969449899	336.140	-53.616	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	68	1.4
1843	1838	2455465.20217247	969468682	300.366	-64.441	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	24	2.4
1844	1839	2455465.22110820	969470318	9.733	-66.005	-1.2873e-01	4.3155e-01	4.6595e-01	3.9162e-02	45	0.7
1845	1840	2455465.26766302	969474341	3.905	-54.082	-1.2873e-01	4.3155e-01	4.6595e-01	3.9162e-02	50	0.7
1846	1841	2455465.34250419	969480807	61.534	-9.946	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	23	2.4
1847	1842	2455465.71727566	969513187	163.475	-77.000	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	25	2.4
1848	1843	2455465.81941184	969522012	336.446	-10.660	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	41	1.4
1849	1844	2455465.98171801	969536035	264.668	-15.524	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	21	2.4
1850	1845	2455466.06624986	969543338	15.199	-68.529	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	44	0.9
1851	1846	2455466.18644652	969553723	16.764	26.422	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	36	1.4
1852	1847	2455466.21055843	969555807	40.706	-3.228	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	34	1.4
1853	1848	2455466.42180381	969574058	181.618	15.791	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	67	1.4
1854	1849	2455466.51320002	969581955	234.615	-47.282	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	41	0.9
1855	1850	2455466.51323532	969581958	31.811	-47.983	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	55	1.4

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1856	1851	2455466.73762422	969601345	295.242	19.950	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	44	1.4
1857	1852	2455466.76198870	969603450	90.070	-54.647	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	32	1.4
1858	1853	2455466.78865597	969605754	335.481	17.898	-1.1909e-01	7.2127e-01	6.0423e-01	3.7507e-02	29	1.8
1859	1854	2455466.88795078	969614333	302.620	-83.652	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	51	1.4
1860	1855	2455466.93633213	969618514	39.241	-67.012	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	37	0.9
1861	1856	2455466.98716546	969622906	100.356	-3.848	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	60	1.4
1862	1857	2455467.42747723	969660949	49.092	-81.461	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	49	1.4
1863	1858	2455467.43249122	969661382	224.770	6.317	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	75	1.4
1864	1859	2455467.76027688	969689702	299.915	19.464	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	34	1.4
1865	1860	2455467.80525130	969693588	267.331	-54.250	-1.2873e-01	4.3155e-01	4.6595e-01	3.9162e-02	46	0.7
1866	1861	2455468.01548934	969711753	57.472	-1.745	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	37	1.4
1867	1862	2455468.12238422	969720988	47.996	-10.893	-1.1909e-01	7.2127e-01	6.0423e-01	3.7507e-02	19	1.8
1868	1863	2455468.40786635	969745654	54.319	-58.179	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	27	2.4
1869	1864	2455468.51448225	969754866	180.319	-5.392	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	56	0.9
1870	1865	2455468.52250588	969755559	264.080	20.810	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	36	1.4
1871	1866	2455468.53763206	969756866	91.030	-50.021	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	31	2.4
1872	1867	2455468.57377213	969759988	267.644	-10.242	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	39	0.9
1873	1868	2455468.76184332	969776238	189.447	-36.529	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	38	1.4
1874	1869	2455468.89205756	969787488	0.389	-16.059	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	75	1.4
1875	1870	2455470.45784087	969922772	180.031	-11.653	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	22	2.4
1876	1871	2455470.55339879	969931028	222.317	38.197	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	44	1.4
1877	1872	2455470.60049885	969935098	144.127	-39.135	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	37	1.4
1878	1873	2455470.61300779	969936178	54.832	-48.685	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	68	1.4
1879	1874	2455471.09057801	969977440	301.358	-26.443	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	26	1.4
1880	1875	2455471.12168407	969980128	21.267	20.121	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	28	2.4
1881	1876	2455471.19216048	969986217	348.237	-17.299	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	23	2.4
1882	1877	2455471.27659978	969993513	56.015	-18.756	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	31	2.4
1883	1878	2455471.44108016	970007724	141.301	27.161	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	43	1.4
1884	1879	2455471.44284181	970007876	103.697	13.652	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	38	1.4
1885	1880	2455471.48984280	970011937	75.428	-34.192	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	35	1.4
1886	1881	2455472.15431079	970069347	47.518	-15.983	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	37	1.4
1887	1882	2455472.22932264	970075828	108.595	1.605	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	63	1.4
1888	1883	2455472.29622119	970081608	61.476	-26.025	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	22	2.4
1889	1884	2455472.32062918	970083717	145.591	-6.634	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	47	1.4
1890	1885	2455472.41634610	970091987	138.004	11.225	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	23	2.4
1891	1886	2455472.57447945	970105650	136.947	-81.216	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	40	1.4
1892	1887	2455472.70844984	970117225	204.603	10.738	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	66	1.4
1893	1888	2455472.88317258	970132321	248.890	0.717	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	42	1.4
1894	1889	2455473.04086075	970145945	284.629	-24.863	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	27	2.4
1895	1890	2455473.30473971	970168744	106.459	-24.086	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	24	2.4
1896	1891	2455474.02785861	970231221	10.296	6.186	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	28	2.4
1897	1892	2455474.41903012	970265019	114.811	23.813	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	71	1.4
1898	1893	2455474.46438909	970268938	130.208	13.199	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	28	2.4
1899	1894	2455474.52924379	970274541	209.702	-19.198	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	22	2.4
1900	1895	2455474.85116494	970302355	2.157	20.246	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	57	1.4
1901	1896	2455474.95486273	970311315	41.393	6.314	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	41	1.4
1902	1897	2455475.03581629	970318309	48.341	25.042	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	81	1.4
1903	1898	2455475.05119788	970319638	303.291	-10.743	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	41	1.4
1904	1899	2455475.25459109	970337211	103.881	18.048	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	41	1.4
1905	1900	2455475.33083298	970343798	95.339	-23.100	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	64	1.4
1906	1901	2455475.69275791	970375069	357.122	-22.579	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	48	1.4
1907	1902	2455475.83398988	970387271	330.954	-55.084	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	46	0.9



## LIST OF HIGH ENERGY NEUTRINO CANDIDATES FOR THE 2009-2010 DATA

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1908	1903	2455476.17378727	970416630	90.707	19.135	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	25	2.4
1909	1904	2455476.61735227	970454954	311.182	-11.663	-1.1909e-01	7.2127e-01	6.0423e-01	3.7507e-02	26	1.8
1910	1905	2455476.69835011	970461952	324.323	-55.779	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	47	0.9
1911	1906	2455476.84185180	970474350	169.516	-51.599	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	42	0.9
1912	1907	2455476.86915061	970476709	67.844	-9.655	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	26	2.4
1913	1908	2455476.87110898	970476878	114.738	-54.099	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	33	1.4
1914	1909	2455477.13119858	970499350	107.767	-5.724	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	77	1.4
1915	1910	2455477.26743633	970511121	269.986	-48.508	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	49	1.4
1916	1911	2455478.54320654	970621348	339.811	-49.212	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	33	1.4
1917	1912	2455478.66409797	970631793	276.690	-0.243	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	52	0.9
1918	1913	2455478.69726989	970634659	13.426	-79.916	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	27	2.4
1919	1914	2455478.95793565	970657180	271.367	-68.747	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	34	1.4
1920	1915	2455478.98190327	970659251	332.564	2.512	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	46	1.4
1921	1916	2455479.00982090	970661663	263.958	-46.564	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	38	1.4
1922	1917	2455479.02115066	970662642	44.158	-9.799	-1.2873e-01	4.3155e-01	4.6595e-01	3.9162e-02	59	0.7
1923	1918	2455479.03418574	970663768	10.564	-15.409	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	44	1.4
1924	1919	2455479.03642127	970663961	110.156	-44.611	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	25	1.4
1925	1920	2455479.06134852	970666115	311.090	-26.609	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	29	2.4
1926	1921	2455479.10224807	970669649	345.468	-10.674	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	75	1.4
1927	1922	2455479.34993596	970691049	65.110	-22.549	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	23	2.4
1928	1923	2455479.95994526	970743754	6.694	-59.147	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	33	0.9
1929	1924	2455479.97126507	970744732	18.951	18.034	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	33	1.4
1930	1925	2455480.00556085	970747695	129.718	-33.692	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	26	1.4
1931	1926	2455480.04324654	970750951	145.303	-17.009	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	75	1.4
1932	1927	2455480.08674619	970754709	181.854	-49.848	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	43	0.9
1933	1928	2455480.12686491	970758176	158.766	-22.579	-1.1724e-01	4.7983e-01	5.2936e-01	3.8897e-02	25	0.9
1934	1929	2455480.19020144	970763648	258.119	-61.760	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	62	1.4
1935	1930	2455480.31483632	970774416	215.226	-53.528	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	29	2.4
1936	1931	2455480.38875956	970780803	119.721	-24.317	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	38	1.4
1937	1932	2455480.43083866	970784439	119.501	-71.390	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	36	1.4
1938	1933	2455480.49024313	970789572	96.431	-37.780	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	38	1.4
1939	1934	2455480.52861682	970792887	228.597	27.745	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	56	1.4
1940	1935	2455480.53011919	970793017	120.579	-18.015	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	38	1.4
1941	1936	2455480.75810719	970812715	222.309	6.494	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	43	1.4
1942	1937	2455481.15369736	970846894	36.564	26.380	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	58	1.4
1943	1938	2455481.49201310	970876124	223.065	7.969	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	35	1.4
1944	1939	2455481.49501402	970876384	216.875	-33.004	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	32	1.4
1945	1940	2455481.69228371	970893428	341.109	-71.517	-1.2873e-01	4.3155e-01	4.6595e-01	3.9162e-02	65	0.7
1946	1941	2455481.76719164	970899900	244.308	10.344	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	30	2.4
1947	1942	2455481.90847431	970912107	64.283	18.936	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	49	2.4
1948	1943	2455482.06437262	970925576	79.706	-31.700	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	35	1.4
1949	1944	2455482.06639273	970925751	19.136	-66.978	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	57	1.4
1950	1945	2455482.36233079	970951320	190.485	26.391	-1.1909e-01	7.2127e-01	6.0423e-01	3.7507e-02	26	1.8
1951	1946	2455482.38583820	970953351	172.135	-6.447	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	47	1.4
1952	1947	2455482.55774061	970968203	160.126	-41.528	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	37	1.4
1953	1948	2455482.62741040	970974223	150.044	-38.405	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	34	1.4
1954	1949	2455483.09039424	971014225	274.654	-44.501	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	93	1.4
1955	1950	2455483.11543480	971016388	308.764	-47.814	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	47	1.4
1956	1951	2455483.16705295	971020848	135.085	-17.001	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	44	1.4
1957	1952	2455483.55215420	971054121	189.108	-29.403	-1.3370e-01	8.5313e-01	6.3102e-01	3.7539e-02	29	2.4
1958	1953	2455483.58125118	971056635	252.514	-8.394	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	43	1.4
1959	1954	2455483.75950707	971072036	171.680	-44.441	-9.2963e-02	5.6770e-01	6.3052e-01	3.8106e-02	38	1.4

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1960 1955 2455483.76670481 971072658 75.469 -40.554 -1.1724e-01 4.7983e-01 5.2936e-01 3.8897e-02 35 0.9  
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1991 1986 2455489.87829766 971600699 26.194 -11.058 -1.2873e-01 4.3155e-01 4.6595e-01 3.9162e-02 58 0.7  
1992 ## stop S6D

**LIST OF HIGH ENERGY NEUTRINO CANDIDATES FOR THE 2009-2010  
DATA**

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**Résumé:** L'objectif de ce travail est la détection conjointe d'ondes gravitationnelles et de neutrinos cosmique de haute énergie à travers une approche multi-messagers. Les astronomies neutrinos et ondes gravitationnelles sont encore en phase de développement, mais elles sont appelées à jouer un rôle fondamental dans le futur. En effet, ces messagers peuvent parcourir de grandes distances grâce à leur faible interaction avec la matière (contrairement aux photons qui, à haute énergie, sont rapidement absorbés), sans être affectés par les champs magnétiques (contrairement aux rayons cosmiques chargés). Ils peuvent également s'échapper de milieux denses et fournir des informations sur les processus qui ont lieu au coeur des sources astrophysique (les photons s'échappent des couches périphériques des objets célestes). En un mot, ces astronomies sont susceptibles d'ouvrir une nouvelle fenêtre d'observation sur le cosmos.

La collaboration ANTARES a construit en Méditerranée un télescope sous-marin de neutrino de haute énergie d'une surface de détection proche de  $0.1 \text{ km}^2$ . C'est le télescope le plus sensible pour la partie du ciel observée. Les interféromètres Virgo et LIGO sont des détecteur terrestres pour l'observation directe d'ondes gravitationnelles, installés en Europe et aux États-Unis d'Amérique respectivement. Les instruments ANTARES, Virgo et LIGO offrent une sensibilité inégalée dans la zone de recherche commune.

Le premier chapitre de cette thèse introduit les motivations théoriques pour une recherche jointe d'ondes gravitationnelles et de neutrinos de haute énergies en développant les différents scénarios d'émission. Le deuxième et troisième chapitres sont consacrés à l'étude des techniques de détection avec les interféromètres Virgo-LIGO et le télescope à neutrinos ANTARES. Les quatrième et cinquième chapitres de ce travail présentent les résultats d'analyses de données combinées d'ANTARES, Virgo et LIGO prises séparément pendant les années 2007 et 2009-2010.

Mots clés : Neutrinos de haute énergie, ondes gravitationnelles, sursauts gamma, astronomie multi-messenger, ANTARES, Virgo, LIGO.

**Abstract:** The aim of this work is the joint detection of gravitational waves and high energy neutrinos in a multi-messengers context. The neutrino and gravitational waves astronomies are still in the phase of development, but they are expected to play a fundamental role in the future. In fact, these messengers can travel big distances because of their weak interaction with matter (contrary to photons that at high energy are rapidly absorbed) without being affected by magnetic fields (contrary to charged cosmic rays). They can also escape dense media and provide informations on the processes taking place in the heart of astrophysics sources. Particularly, GW+HEN multi-messenger astronomy may open a new observational window on the Universe. ANTARES collaboration has built a telescope of area  $0.1 \text{ km}^2$  in the Mediterranean Sea for the detection of high energy neutrinos. This is the most sensitive telescope for the observed part of the sky. LIGO and Virgo interferometers are ground-based detectors for direct observation of gravitational waves, installed in Europe and the USA respectively. Instruments ANTARES, Virgo and LIGO offer unrivaled sensitivity in the area of joint observation. The first chapter of this thesis introduces the theoretical motivations for GW+HEN search by developing different emission scenarios. The second and third chapters give an overview of the experiments and review the data analysis tools. The fourth and fifth chapters of this work present the results of the analysis of the combined data from ANTARES, Virgo and LIGO taken separately in 2007 and 2009-2010.

Keywords: High-energy neutrino, Gravitational waves, Gamma-ray Burst, multimessenger astronomy, ANTARES, Virgo, LIGO.