Gravitational Waves in the European Strategy for Particle Physics

ET Steering Committee
http://www.et-gw.eu/

with the key contribution of the
"Gravitational Wave International Committee
3G subcommittee"
https://gwic.ligo.org/3Gsubcomm/

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Abstract

This document briefly describes some of the scientific and technological synergies that are possible between the nascent field of Gravitational Waves (GWs) and High Energy Particle Physics (HEPP). It is submitted by the ET steering committee under the supervision of GWIC-3G (a team of the Gravitational Wave International Committee (GWIC)) as contribution to the European Strategy for Particle Physics and in view of the submission of the Einstein telescope (ET) observatory project to the ESFRI Roadmap.

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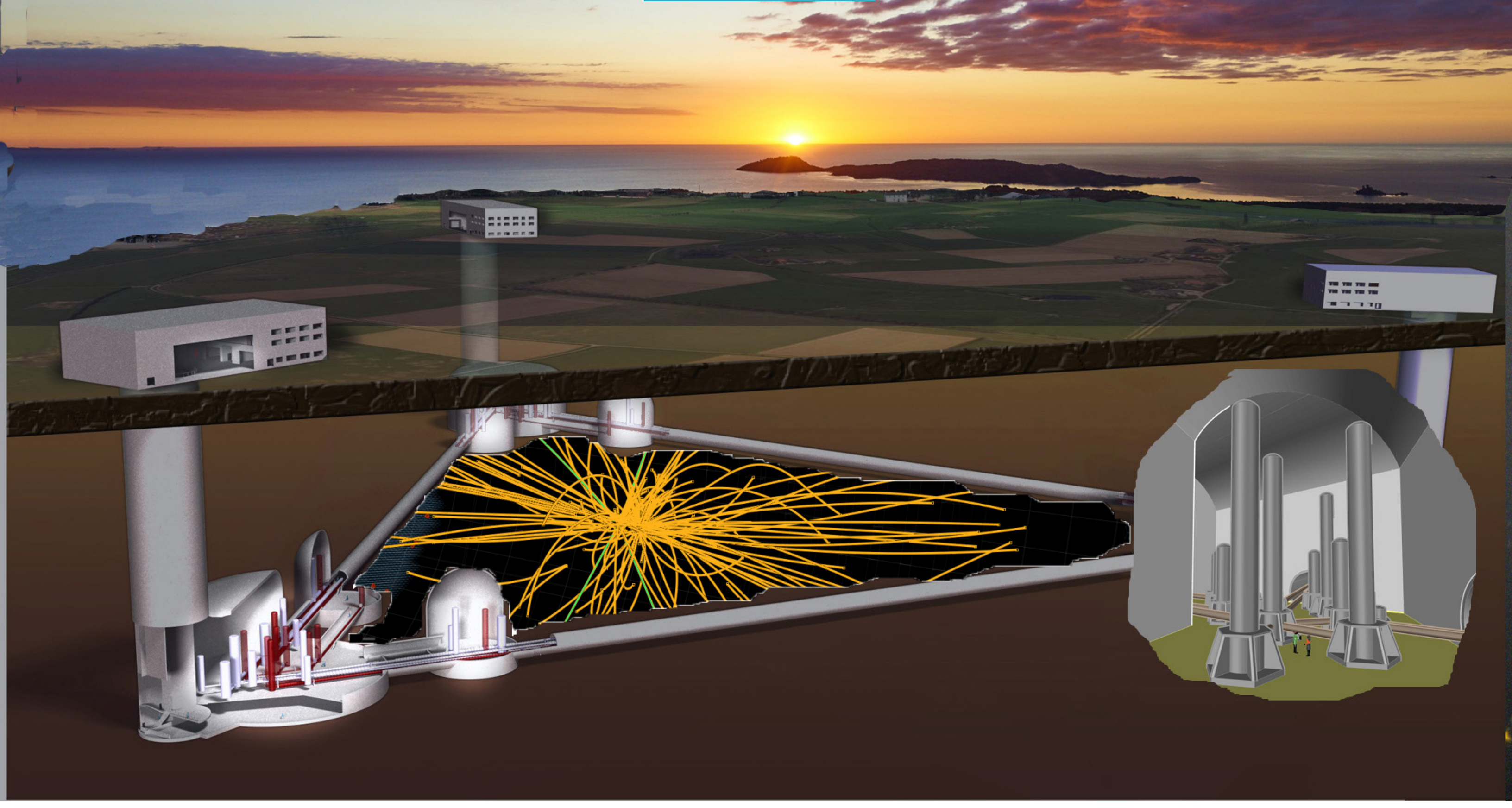
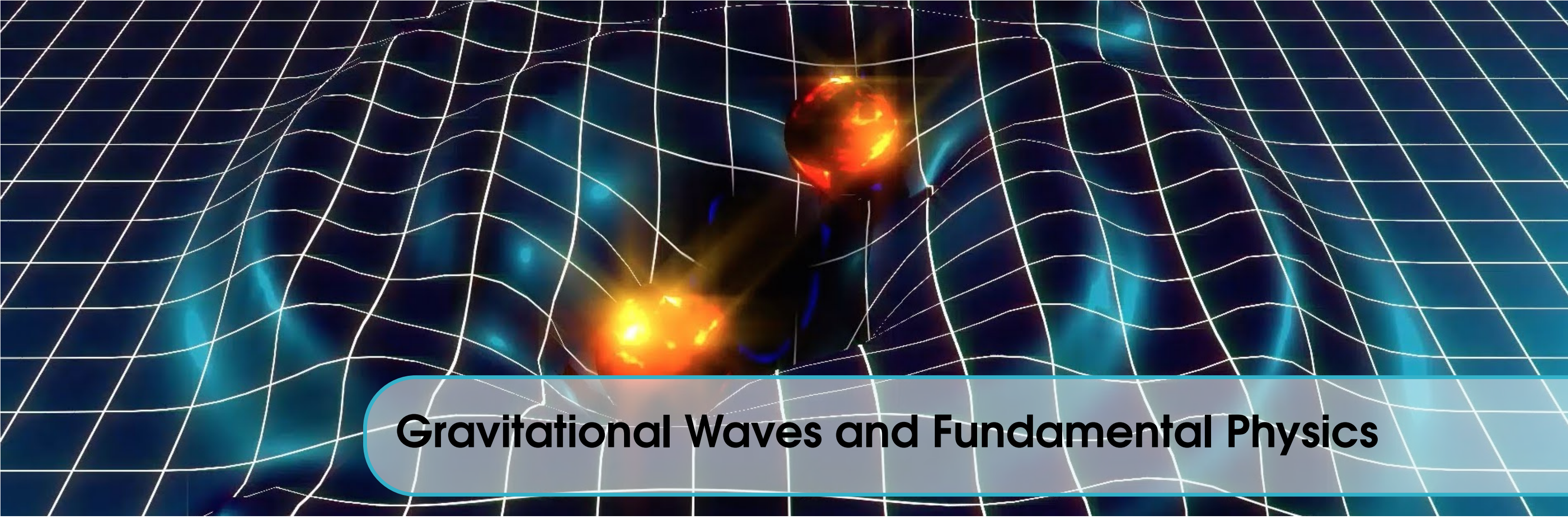




Gravitational Waves and Fundamental Physics

Introduction

Gravity assembles structures in the Universe from the smallest scale of planets to galaxy clusters and the largest scale of the Universe itself. Yet, until recently gravity played only a passive role in observing the Universe. Almost everything we know about the universe, from its hot primeval phase to recent accelerated expansion, the most powerful explosions such as hypernovae and brightest objects like quasars, comes from electromagnetic waves. Important exceptions include cosmic rays and neutrinos that have allowed to probe complementary phenomena.

September 14, 2015 forever changed the role of gravity in our exploration of the Universe, when two detectors (located in Livingston LA and Hanford WA) comprising the US Laser Interferometry Gravitational Observatory (LIGO) observed gravitational waves (GWs) from a pair of colliding black holes. Since then LIGO and the Virgo detector (located in Pisa) have observed nine more binary black hole merger events, firmly establishing a new window on to the Universe. Moreover, the joint discovery of a merging binary neutron star by LIGO, Virgo and the Fermi gamma ray and INTEGRAL satellites on August 17, 2017 triggered an electromagnetic follow-up of the source and generated a treasure trove of data that helps, for example, to understand the origin of heavy elements and constrain extreme nuclear matter and theories with extra spatial dimensions.

Advanced LIGO and Virgo will only be first steps in this new endeavor that is guaranteed to change our perception of the Universe in the coming decades. Indeed, the next generation of GW observatories, such as the Einstein Telescope and Cosmic Explorer (referred to as 3G), will witness merging black holes and neutron stars when the Universe was still in its infancy assembling its first stars and black holes. At such sensitivity levels we can expect to witness extremely bright events that could reveal subtle signatures of new physics. 3G observatories promise to deliver data that could transform the landscape of physics, addressing some of the most pressing problems in fundamental physics and cosmology.

Future GW observations will enable unprecedented and unique science in extreme gravity and fundamental physics. They will allow us to explore and address an impressive set of questions in these topics, which will affect future science at profound levels. The next generation of GW observatories will address:

- ⋆ **The nature of dark matter.** *Is dark matter composed of particles, dark objects or modifications of gravitational interactions?*
- ⋆ **The nature of gravity.** *Is Einstein (still) right? What building-block principles and symmetries in nature invoked in the description of gravity can be challenged?*
- ⋆ **The nature of compact objects.** *Are black holes and neutron stars the only astrophysical extreme compact objects in the Universe? Are there subtle signatures of quantum gravity in the spacetime geometry of these compact objects?*
- ⋆ **Cosmology and the early unniverse** *What phase transitions took place in the early history of the Universe and what are their energy scales? How do cosmological parameters vary with redshift?*

Nature of dark matter

Harnessing deep insights on gravity at scales accessible by GW detectors, as well as gaining knowledge of the population of electromagnetically dark objects in our Universe, can help reveal the nature of dark matter. Unique as well as complementary insights can be obtained from 3G detectors with their exquisite ability to probe compact objects and their dynamics, throughout the Universe. In particular, 3G detectors can help answer key questions about the origin of dark matter.

Black holes as dark matter candidates. LIGO and Virgo discoveries have revived interest in the possibility that dark matter could be composed, in part, of black holes of masses ~ 0.1–$100 M_{\odot}$. Such black holes might have been produced from the collapse of large primordial density fluctuations in the very early Universe. The exact distribution of masses depends on the model of inflation, and might be further affected by processes in the early Universe such as the quantum-chromodynamic phase transition.

The detection of GWs from binary systems composed of objects much lighter than stellar mass black holes, or with a mass distribution demonstrating an excess within a certain range, could point towards the existence of primordial black holes. The detection of very high redshift sources would be another hint towards this formation channel. With a sensitivity to observe stellar mass black holes at redshifts of $\sim$ 10-20, 3G detectors will be uniquely positioned to determine their mass and spatial distribution, which will be crucial to test this hypothesis.

Detection of dark matter with compact objects. Beyond probing whether dark matter can be partially made up of black holes, GWs can also scrutinize models where dark matter interacts with standard model particles. Indeed, binary black holes evolving in a dark-matter rich environment will not only accrete the surrounding material, but also exert a gravitational drag on the dark matter medium, which affects the inspiral dynamics. Even though their magnitude is small, drag and accretion could have a cumulative effect that piles up over a large number of orbits that could be detected by a combination of observatories in space and 3G detectors.

Additionally, dark matter that interacts with standard model particles can scatter, lose energy, and be captured in astrophysical objects. The dark-matter material eventually thermalizes with the star, and accumulates inside a finite-size core. It is conceivable that the dark-matter core might imprint a signature on the merger phase of two of these objects. In certain models, asymmetric dark matter can accumulate and collapse to a black hole in the dense interiors of neutron stars. The core can grow by accumulating the remaining neutron star material, in effect turning neutron stars into light black holes in regions of high dark-matter density such as galactic centers. This provides a mechanism for creating light black holes that could be observed by 3G detectors.

Bosonic clouds. Ultralight bosons have been proposed in various extensions of the Standard Model. Most notably, a pseudo-scalar axion has been proposed to solve the strong CP problem in QCD. If the axion mass is in a suitable range, it could also account for dark matter. When the Compton wavelength of such light bosons (masses of 10^{-21}–10^{-11} eV) is comparable to the horizon size of a stellar or supermassive rotating black hole, superradiance can cause the spin to decay, populating bound Bohr orbits around the black hole with an exponentially large number of particles. Such bound states, in effect “gravitational atoms", have bosonic “clouds" with masses up to $\sim 10\%$ of the mass of the black hole. Once formed, the clouds annihilate over a longer timescale through the emission of coherent, nearly-monochromatic, GWs.

Alternatively, measuring the spin and mass distribution of binary black holes can provide evidence for characteristic spin down from superradiance, and explore the parameter space for ultralight bosons with 3G detectors. GWs will, therefore, provide a unique window into the ultralight, weakly coupled regime of particle physics that cannot be easily probed with terrestrial experiments.

Nature of dynamical gravity

Astrophysical black holes and relativistic stars exhibit the largest curvatures of spacetime geometry we know of. New physics, arising as a consequence of failure of general relativity (GR), could reveal itself in high signal-to-noise ratio GW events.

New fields, particles and polarizations. Lovelock’s uniqueness theorem in 4-dimensions implies that departures from GR that preserve locality necessarily requires the presence of extra degrees of freedom, which, in turn, leads to additional polarizations. The presence of such fields often lead to violations of the strong equivalence principle through the fields’ nonminimal coupling with matter. Among possible theories, those with an additional scalar field are relatively simple and yet could exhibit exciting new strong-field phenomenology. They also serve as excellent examples of the type of new physics we can hope to detect. In particular, if a binary’s components can become “dressed" with a scalar configuration, the system emits scalar waves, with the dominant component being dipolar emission, in addition to tensorial ones. Additional polarization can be detected directly, or indirectly inferred from its effects on the system’s dynamics and consequent impact on the GR polarizations.

Graviton mass. Recently, the possibility that gravitons could have a mass has resurfaced in theoretical physics within extensions of GR. The current best bound on the graviton mass from LIGO through modified dispersion relations is $m_g < 7.7 \times 10^{-23}\,\mathrm{eV/c^2}$ and improvements of two orders of magnitude would be possible with 3G detectors.

Lorentz violations. Lorentz symmetry is regarded as a fundamental property of the Standard Model of particle physics, tested to spectacular accuracy in particle experiments. In the gravitational sector, constraints are far less refined. Theories with Lorentz invariance violation have been invoked (e.g., Horava-Lifschitz and Einstein-Aether theories) which can be greatly constrained by 3G detectors which would observe sources at redshifts of $z \sim$ 10-20.

Parity violations. Parity violations in gravity arise naturally within some flavors of string theory, loop quantum gravity and inflation. Effective gravitational theories incorporating such effects are known, and, to some degree, associated phenomenologies have been understood. For instance, solutions with nontrivial pseudo-scalar configurations that violate spatial parity have been constructed. The resulting scalar dipole leads to a correction of a binary's quadrupole and hence the GWs produced through merger. Additionally, parity violating theories can exhibit birefringence, thus impacting the characteristics of GWs tied to their handedness.

Nature of compact objects

Observational evidence so far suggests that compact massive objects in the Universe exist in the form of black holes and neutron stars. Binary systems composed of such objects provide ideal scenarios to unravel both astrophysical and fundamental puzzles, elucidating strong gravitational connections with the most energetic phenomena in our Universe, exploring the "final state" conjecture (i.e., that the end option of collapse is a Kerr black hole), the existence of horizons, etc.

Nature of black holes. Black holes in isolation are the simplest objects in the Universe. Astrophysical black holes are electrically neutral and are described by just two parameters — their mass and spin angular momentum. A perturbed black hole returns to its quiescent state by emitting a series of quasi-normal modes, whose frequency and decay time are uniquely determined by the two parameters. By detecting several quasi-normal modes 3G detectors can facilitate multiple null-hypothesis tests of the Kerr metric.

Nature of neutron stars. General relativity, with input from nuclear physics, can describe the structure of ultra-dense neutron stars. However, the neutron star equation of state is currently poorly known, especially at supra-nuclear densities and hot temperatures. Knowledge of the equation of state of supranuclear densities will provide unprecedented insights on the behavior of matter in regimes not accessible to laboratory experiments.

Signatures of matter in GWs from the inspiral stage manifest as differences in the phase and amplitude of the signal compared to that of binary black holes. These include rotational and tidal deformations, excitation of internal oscillation modes of the star, spin-tidal couplings, gravito-magnetic interactions, nonlinear tidal effects, and the presence of a surface instead of an event horizon. Significant matter signatures could show up in the waveform during the tidal disruption in a neutron star-black hole binary, or the merger and post-merger epochs in binary neutron star collisions. Signals from these regimes have high frequencies and are therefore difficult to measure with current detectors. Exploiting finite-size effects in the inspiral and post-merger regimes, 3G detectors will improve current measurements of tidal effects by a factor of ~ 10 and determine the equation of state significantly better and probe new physics encountered during the merger and post-merger phases of the signal.

Beyond black holes and neutron stars. From a phenomenological standpoint, black holes and neutron stars are just two "species" of a larger family of compact objects. More exotic species are theoretically predicted in extensions to GR, but also in particular scenarios within GR. For instance, in the presence of beyond-standard model fundamental fields minimally coupled to gravity (e.g., boson stars), Grand Unified Theories in the early Universe (e.g., cosmic strings), exotic states of matter or "dressed" compact objects with further structure stemming from quantum gravitational origin. Arguments have been put forward that propose horizonless compact objects (e.g., fuzzballs, gravastars, and dark stars), or new physics at the horizon scale (e.g., firewalls).

GW observations provide a unique discovery opportunity in this context, since exotic matter/dark matter might not interact electromagnetically or any electromagnetic signal from the surface of the compact object might be highly redshifted. Example GW signatures include dipole radiation, spin-induced quadrupole moment, tidal heating and tidal deformability.

Additionally, while the ringdown signal can be qualitatively similar to that of a black hole, quasi normal modes of, e.g. gravastars, axion stars and boson stars, are different from Kerr black holes. 3G detectors will have unprecedented ability to extract such modes. In addition to gravitational modes, matter modes might be excited in the ringdown of an extremely compact object, akin to fluid modes excited in a remnant neutron star. In the case of certain black hole mimickers the prompt ringdown signal is identical to that of a black hole; however, these objects generically support quasi-bound trapped modes which produce a modulated train of pulses at late time. These modes appear after a delay time whose characteristics are key to test Planckian corrections at the horizon scale that could be explored with 3G detectors.

Cosmology and phase transitions in the early Universe

GW observations may inform us about the history and structure of the Universe in at least two ways: by studies of individual sources at cosmological distances that give information about its geometry and kinematics and by direct observation of a GW stochastic background of cosmological origin. In turn, a stochastic background could either be astrophysical in origin, generated by any of a myriad of astrophysical systems or it could come from the Big Bang itself, generated by quantum processes associated with inflation or with spontaneous symmetry breaking in the early Universe. Cosmic background is probably the most fundamentally important observation that GW detectors can make. However, the astrophysical background may mask the primordial background over much of the accessible spectrum and techniques are being developed to subtract foreground signals to dig deeper.

Inflation. The background expected from inflation, assuming the standard slow-roll model, is likely below the sensitivity of 3G detectors. If the equation of state of the Universe immediately after inflation is stiff, the spectral index is modified with a large tilt in the high frequency end of the spectrum, the background might be detectable with 3G detectors.

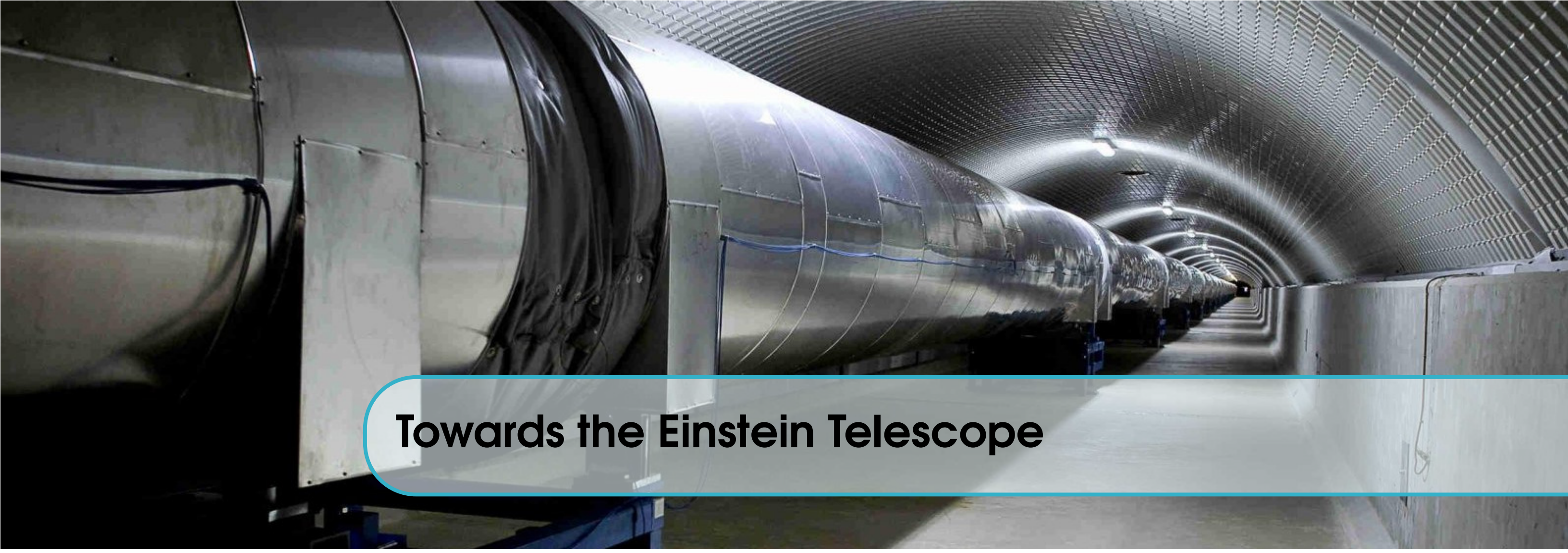
First order phase transitions.

Following the end of inflation, the Universe might have undergone the QCD and the electroweak phase transitions. The standard model of particle physics fails at energies higher than the electroweak symmetry breaking scale, where several proposed extensions of the standard model predict the occurrence of phase transitions. Any experimental confirmation that such phase transitions took place in the early Universe would therefore constitute an invaluable piece of information for our understanding of particle theory underlying the Universe at very high energies. To be an efficient direct source of GWs, a phase transition must be of first order. First order phase transitions proceed through the nucleation of bubbles of the true vacuum, energetically more favourable, in the space-filling false vacuum.

The dynamics of the bubble expansion and collision is phenomenologically very rich, and the sources of GWs are the tensor anisotropic stresses generated by these multiple phenomena: the bubble wall's expansion, the sound waves in the plasma, and the subsequent magnetohydrodynamic turbulence. If the borken vacuum manifold is topologically nontrivial, topological defects such as cosmic strings may arise in the aftermath of a phase transition. Networks of such defects are expected to emit GWs independently of the type and origin of the defects. Cosmic strings predominantly decay by the formation of loops and the subsequent GW emission by cosmic string cusps and kinks. 3G detectors will be able to either detect cosmic string sources or substantially improve current bounds by as much as 8 orders of magnitude.

Dark Photons. Dark photon is a proposed to be a light but massive gauge boson of a U(1) extension of the standard model. If sufficiently light, the local occupation number of the dark photon could be much larger than one, so it can then be treated as a coherently oscillating background field that imposes an oscillating force on objects that carry dark charge. The oscillation frequency is determined by the mass of the dark photon. Such effects could result in a stochastic background that could be measured by 3G detectors, potentially exploring large fractions of the parameter space of such models.

Standard Sirens. Additionally, gravitational waves from compact binary coalescences are standard sirens and hence their observation could provide an accurate measurement of the luminosity distance to their host galaxies. This feature was already exploited in the first measurement of the Hubble constant with the binary neutron star merger event GW170817. Observations of such sources in third generation detectors can help measure the various cosmological parameters, in particular the dark energy equation of state and its variation with redshift.



Towards the Einstein Telescope

Introduction

The *Einstein gravitational–wave Telescope* (ET) will be a GW *observatory* of the third generation aiming to reach a sensitivity for signals emitted by astrophysical and cosmological sources about a factor of ten better than the design sensitivity of the advanced detectors currently in operation. To reduce the effects of the residual seismic motion, ET will be located underground at a depth of about 100 m to 200 m and, in the complete configuration, it will consist of three nested detectors, each in turn composed of two interferometers. The topology of each interferometer will be the dual-recycled Michelson layout with Fabry–Perot arm cavities, with an arm–length of about 10 km. The configuration of each detector devotes one interferometer to the detection of the low-frequency components of the GW signal (2–40 Hz) while the other one is dedicated to the high-frequency components. In the former (ET-LF), operating at cryogenic temperature, the thermal, seismic, gravity gradient and radiation pressure noise sources will be particularly suppressed; in the latter (ET-HF) the sensitivity at high frequencies will be improved by high laser light power circulating in the Fabry–Perot cavities, and by the use of frequency-dependent squeezed light technologies.

The first direct detection of gravitational waves (GW) by the LIGO and Virgo detectors, and the multi-messenger observation of GW170817-GRB 170817A-SSS17a/AT2017gfo marked the birth of multi-messenger astronomy. These cornerstone achievements came after more than three decades of experimental efforts, finalized with the conception, design and realization of large interferometric detectors in USA (Laser Interferometer Gravitational Wave Oservatory, LIGO), Europe (Virgo in Italy; GEO600 in Germany) and Japan (TAMA 300). While the present advanced detectors do not fully exploit their potential for sensitivity and bandwidth yet, technically feasible concepts for a third generation of ground-based interferometer detectors have been developed, improving the sensitivity by a factor of ten beyond the design of the current advanced detectors as well as yielding a ten times lower cut-in frequency to exploit the full potential of multi-messenger astronomy. Currently, the only operational second-generation gravitational wave detectors are in the US (LIGO) and in Italy (Virgo). The Kamioka Gravitational Wave Detector (KAGRA), in Japan, is currently under construction and is planned to come online in late 2019. KAGRA pioneers new, crucial technologies that have never been applied in large scale detectors: it is built underground, in the Kamioka mine, to suppress seismic and Newtonian noise, and its test masses will be cooled down to 20 K to reduce thermal noise.

Planning for a network of future GW observatories already started, under the coordination of the Gravitational Wave International Committee on Third Generation Ground-based Detectors. In the US, a third generation detector in a new facility is being planned under the name "Cosmic Explorer" (CE). The Einstein Telescope (ET) is Europe's vision of a third generation (3G) gravitational wave observatory that will enable routine gravitational wave astronomy for several decades.

In order to realize a third-generation GW observatory with a significantly enhanced sensitivity, some technological limitations adopted in the advanced interferometers must be overcome and new solutions must be developed. Several of these technological challenges posed by these new infrastructures require expertise, which is available in the High-Energy Particle Physics (HEPP) community.

This report briefly describes areas in which the development of synergies with the HEPP community in the construction and operation of the next generation of gravitational wave detectors would be highly desirable and profitable. In particular, there is great synergy potential in the infrastructure aspects: underground facilities, vacuum technology, and cryogenics. High intensity computing is another “infrastructure” issue, were solutions can be found in synergy. Additional topics where a collaboration would be beneficial are electronics, data acquisition, controls and automation. Finally, the global character of the 3G infrastructure would profit enormously from the great experience gained in the HEPP community on the governance schemes for large research infrastructures.

Underground facilities

The Einstein Telescope observatory has a triangular topology. The three corner stations are connected by 10 km long tunnels. Each corner station consists of a collection of surface buildings. The main assembly building gives access to the underground infrastructure. At each corner there are three large experimental caverns; the main cavern houses the laser injection systems, the main detection systems and the beam splitters, while the test masses of the interferometers as well as optical auxiliary systems occupy the auxiliary caverns. Tunnels house the interferometer arms and have an inner diameter of several meters, depending on the details of technical design.

The characteristics of the site location and of the infrastructure have a direct impact on the final sensitivity and robustness of the detector. Ground vibrations not only directly affect the sensitivity, through seismic and Newtonian noise couplings, but can also have indirect effects (e.g. though scattered light or making the overall control more difficult). Therefore, local seismic noise (of natural or anthropic origin) is one of the key parameters for the assessment of a candidate site. Moreover, the nature of the rock, abundance of water, long-term geological stability are aspects that can influence the infrastructure cost and stability. These aspects are particularly relevant for an underground infrastructure such as the one planned for hosting the ET detector.

Minimizing the site facility and infrastructure influence on detector performance is only one aspect of the R&D work required. Civil infrastructure costs will account for a large share (more than, 50%) of the total cost of building and operating the next generations of particle accelerators and gravitational wave observatories.

Particle physics (for a long time) and astroparticle physics (more recently) share a common interest of studying and developing very large civil and vacuum infrastructures. Hence, there is a strong demand that scientists and engineers working in particle and astroparticle physics share their efforts and expertise and pay particular attention to innovation and cost optimization in this domain (e.g. underground infrastructure monitoring, natural risk minimization, excavation methods). Developing synergies with the HEPP community in an effort to minimize costs, cost uncertainties, and other collateral impacts on society will reap rewards, potentially pivotal, in approval and sponsorship and will minimize the risk of e.g. planning delays, large cost fluctuations, anomalies in contract documentation, lack of thorough safety and/or environmental control.

Vacuum technology

In laser interferometers for GW detection most of the instrument has to be kept under High-Vacuum (HV) or ultra-High-Vacuum (UHV) for several reasons:

- reduce the noise due to residual gas density fluctuations along the beam path to an acceptable level
- isolate test masses and other optical elements from acoustic noise
- reduce test mass motion excitation due to residual gas fluctuations
- reduce friction losses in the mirror suspensions
- contribute to thermal isolation of test masses and of their support structures
- contribute to preserve the cleanliness of optical elements.

A vacuum system of this kind is composed of several UHV pipes with kilometre length and several cylindrical vertical HV/UHV tanks (towers) containing the optical elements and their support structures. The laser beam must travel in a single vacuum volume, i.e. without any physical separation (windows) along the beam path. Short HV volumes (the towers, which are not bakeable) are tolerable along the beam path. The towers are separated from the UHV part of the long tubes by differential pumping and cryo traps, stopping the migration of water and other high vapor pressure components from the HV sections into the tubes. Materials incompatible with HV and UHV can either be encapsulated in containers or kept in separate vacuum sections connected by small apertures and differentially pumped. Large gate valves are needed at each end of the arm pipes to maintain UHV when venting a tower. For the same reason, each tower can be separated from the rest of the vacuum enclosure by suitable gate valves.

The residual gas composition should be dominated by hydrogen outgassing from the beam tube material with a target base pressure of $\leq 10^{-10}$ hPa. The vacuum system must be extremely clean from heavy organic molecules, both to limit the phase noise and to prevent pollution of the optical components. Hydrocarbon partial pressure shall be at the level of $\leq 10^{-14}$ hPa.

Vacuum systems for planned 3G detectors will be the largest man-made UHV systems ever conceived (total volume $\sim 1.5 \times 10^5\,\mathrm{m}^3$; surface $\sim 5 \times 10^5\,\mathrm{m}^2$), and and will account for a substantial fraction of the cost of implementing the observatory. Substantial innovation and research went into designing and building the LIGO, Virgo, GEO600 and KAGRA vacuum systems within economic constraints; the more stringent technical requirements and much larger size needed for 3G vacuum envelopes ask for innovative technical strategies to minimise the overall costs, while maintaining reliability and longevity. Several such avenues have been proposed and should be explored together with the high energy particle physics community.

For several decades the HEPP community developed expertise on the design, construction, operation and maintenance of high and ultra-high vacuum systems for accelerators and detectors. Examples of areas in which the exploitation of synergies with the HEPP community would be highly beneficial are:

- ⋆ Design of vacuum components
- ⋆ Vacuum instruments and calibration, leak detection
- ⋆ Gas-density profile simulation and identification of contaminants
- ⋆ Physics of gas-surface interaction, surface treatments and thin-film coatings
- ⋆ Innovative pumping schemes
- ⋆ Longevity of mechanically actuated devices, e.g. large gate valves
- ⋆ Compatibility of UHV and cryogenic requirements
- ⋆ Ionization, electrostatic charge measurement and mitigation strategies
- ⋆ Control, operation and monitoring of distributed vacuum systems
- ⋆ Safety issues

Cryogenics

A feature of most designs for future interferometers is the cryogenic operation of the test mass mirrors for the reduction of thermal noise. The heat is extracted from the mirror via the suspension fibers connected to the seismic isolation system, which attenuates the seismic noise up to few hertz. The system must be designed to provide an efficient thermal link, through which the heat can be extracted, and, at the same time, not to spoil the seismic isolation of the test mass.

The cryogenic cooler, based on refrigerators or on liquefiers, must deliver an extremely low noise, steady cooling power of ~ 100 mW at 10 K to the mirror, and must be sufficiently flexible to operate in different modes: cool-down, steady-state and warm-up, each with specific requirements. The cryo-baffles for shielding the cold mirrors from environmental thermal radiation require significantly higher cooling powers (on the order of several 10 W each) although with reduced vibration requirements.

The HEPP community developed decade-long expertise on the design, construction, operation and maintenance of cryogenic systems and plants for accelerators and detectors. Examples of areas in which the development of synergies with the HEPP community would be highly beneficial are:

- ⋆ Design of low-noise, thermally efficient refrigerators and/or liquifiers
- ⋆ Logistics of large, cryogenic underground plant/distribution systems
- ⋆ Controls, operation and monitoring of large-scale cryogenic systems
- ⋆ Storage, handling and distribution of large volumes of cryogenic fluids in a confined environment; general safety issues

Controls and automation

Control systems for gravitational wave detectors and particle accelerators share the need to control multiparameter systems with a high degree of complexity. For a gravitational wave detector, the control system must meet three basic requirements: Starting from a random initial state, it must first bring the device to a predefined operating point (“lock acquisition”). Secondly, it must prevent any type of disturbance from causing the instrument to deviate from its working point by more than a specified amount. Finally, it must provide a sufficiently low-noise electronic signal, which contains the GW signal. Both control systems must cover all operational scenarios (commissioning, operation, development/upgrade) and share high-level requirements:

⋆ Provide controls to operators to act and affect changes to the machine
⋆ Automatic process control, feedback and sequence control
⋆ Display of operator information
⋆ Monitoring, recording and logging of machine status
⋆ Prevention of automatic or manual control actions which may initiate a hazard
⋆ Fault diagnostic and recovery
⋆ Machine protection (including failure analysis)

The development of a control system architecture and a control software architecture (possibly based on innovative control/automation schemes) that allows to meet all these requirements is a challenging and stimulating task. The exchange of skills and experience in these areas between the GW and HEPP communities would be highly desirable and mutually beneficial.

Electronics, DAQ

Gravitational wave interferometers are complex opto-mechanical systems, which need to be complemented with vast amounts of electronics to operate successfully. The experiment contains many optical photodiodes, quadrant-detectors and cameras to monitor the optical beams, position sensors and accelerometers to monitor the seismic isolation systems and various environmental sensors to measure outside disturbances. Various actuators are used to act on the laser frequency, the suspensions positions, cavity lengths and mirror alignment using piezos, voice-coils and electro-static actuators. For the most critical parts of the instrument, this requires state-of-the-art low-noise electronics.

Low noise digital demodulation techniques and sampling rates of up to $1\,GHz$ are required, outperforming analog electronics in terms of versatility, feasibility of complex filters and flexible customization during commissioning. Sky localisation of the GW source through triangulation and multi-messenger astronomy require an absolute timing accuracy of better than $1\,\mu s$. Digital demodulation places even higher demands on the relative timing between the fast ADCs distributed over the entire experiment with a timing jitter at the level of $1\,ps$, which is why fibre based timing distribution systems such as the White Rabbit timing network developed for CERN are of great interest for future GW detectors.

Computing

CERN and WLCG are examining the LHC computer models and infrastructures for the future high-luminosity runs of the LHC, which will increase the data volume and computing requirements by large factors. At the same time, it became clear that the global facilities supporting the WLCG would also conduct other large-scale scientific experiments such as SKA, LSST, CTA and 3G-GW experiments. It is obvious that a common data management and computing infrastructure that can support all this would be desirable for the projects, the computing facilities and the funding agencies. Exabyte data management capabilities are being explored that can efficiently deliver data to heterogeneous and globally distributed computing resources such as HTC clusters, HPC clusters and commercial clouds. We see the need to support a wide variety of processors covering CPUs, accelerators (e.g. GPU, MIC) as well as FPGA and other innovative architectures.

GW community is strongly interested in the CERN/WLCG strategy based on three areas of investment:

⋆ A federated data cloud ("data lake") capable of curating and delivering exabyte-scale data on a long-term basis, complemented by tools and services that allow experiments to manage these data and content delivery tools to efficiently serve the data to remote computing resources. This data lake would also provide an effective mechanism for hosting and serving data to the broader community, including public open access, potentially involving commercial interests.
⋆ The ability to take full advantage of available resources in the coming years requires the development of software skills and the ability to transfer applications agilely and flexibly to appropriate computing architectures as they evolve. The infrastructure will also depend on a clearing house for software tools and services for

scientific communities. With the HEP Software Foundation (HSF) the HEP community has provided a vehicle to discuss the long-term software investment as well as the location for a software tool clearing house. It is not necessarily specific to HEP and could also be strengthened by involving other scientific communities.

⋆ Networks to support the infrastructure and the use of appropriate technologies to handle data management both within the lake and externally.

GW communities are interested in the CERN "openlab" concept, which is a vehicle for collaboration with industry, independent from any expectations of procurement. This provides a mechanism for financing and staffing projects of common interest between CERN and various industry partners. In recent years, this concept has spread to other research institutions. This is another way of potential technology transfer into the 3G-GW community, allowing new computer technologies to be explored in collaboration with companies and access to their expertise. The GW community is strongly interested in finding cooperation and synergies with CERN in some or all of these areas. The associated technologies are very interesting and could contribute to the development of a broad set of tools useful for a broad scientific base.

Governance

The current GW detectors, GEO in Germany, LIGO in US, Virgo in Italy and KAGRA in Japan are born as independent scientific collaborations, but the specific nature of GW research privileges collaboration rather than competition between all these infrastructures. For this reason a process of convergence developed in the last decade resulting in a stringent agreement between the LIGO Scientific Collaboration (LSC, including the GEO collaboration) and the Virgo collaboration; essentially we have a collaboration of collaborations: LVC – the LIGO Virgo Collaboration. When KAGRA will be operative (end of 2019) it will make a similar trilateral agreement with the LIGO and the Virgo collaborations. Future infrastructures such as ET and CE, which are still starting independently from each other due to different framework conditions and time constraints in Europe and the USA, will tend to very strong integration. Hence, ET and CE would profit enormously from the large experience of the HEPP community on what concerns the governance schemes of large research infrastructures. The relationship between CERN and ET first, and then CE, could be of different nature and from a different level: it can start from the minimal support given by CERN and HEPP community on management of world-class infrastructures and on technology transfer, to get to cover different forms of integration, involving some CERN infrastructures in the realisation and management of ET.

Recommendations

- We recommend that the **existing and potential synergies between high-energy particle physics and the gravitational wave** community in regard to science and common technologies be analysed, promoted and developed, and exploited for the mutual benefit of both communities.
- The gravitational wave community encourages a **strong participation** of Europe's leading particle physics institutions in future gravitational wave observatories, in particular in the fields of **engineering and computer science**.
- We recommend to **jointly develop governance schemes** for the installation and operation of a global network of third-generation gravitational wave detectors.