Python in Gravitational Waves communities

Elena Cuoco (elena.cuoco@ego-gw.it)
European Gravitational Observatory
on behalf of Virgo Collaboration

VIR-0346A-16

Elena Cuoco's bio

Something about me

http://www.elenacuoco.com

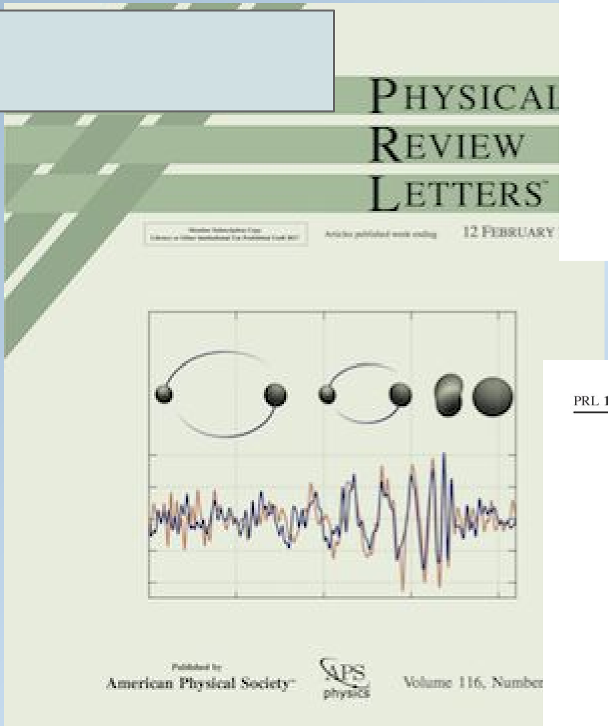
- Ph.D in Physics, working at EGO
- Physicist of LIGO-Virgo Collaboration (http://www.virgo-gw.eu/ http://www.ligo.org/)
- GraWIToN Scientific coordinator (http://www.grawiton-gw.eu/)
- Kaggle Master (http://www.kaggle.com/elenacuoco)
- Science outreach passionate

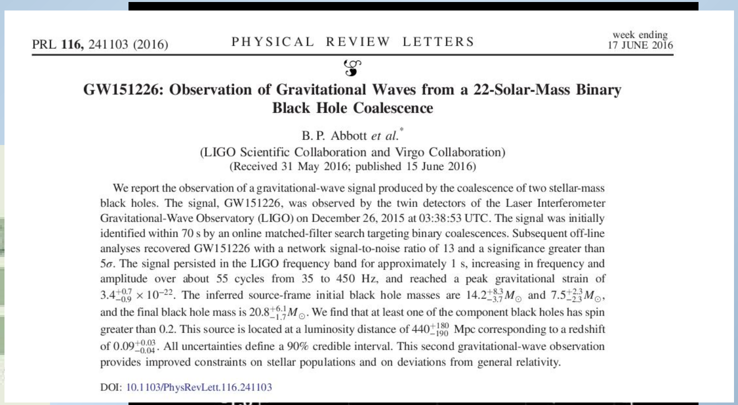
Why Gravitational Waves?

We can look at the Universe
with ‘different eyes’

New era in Astronomy

Spoiler of J. Rollins talk



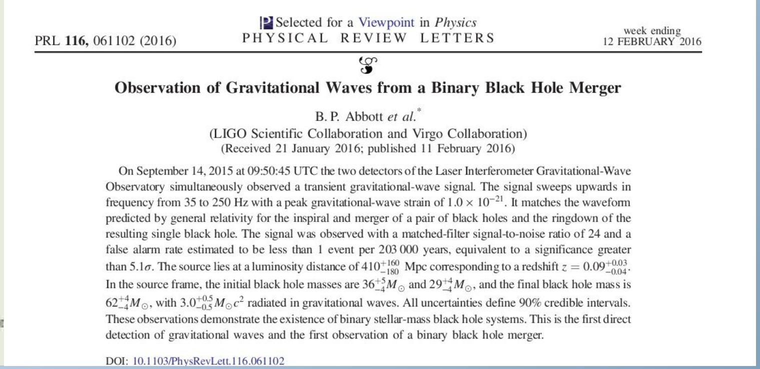

PRL 116, 241103 (2016) PHYSICAL REVIEW LETTERS week ending 17 JUNE 2016

GW151226: Observation of Gravitational Waves from a 22-Solar-Mass Binary Black Hole Coalescence

B. P. Abbott *et al.**
(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 31 May 2016; published 15 June 2016)

We report the observation of a gravitational-wave signal produced by the coalescence of two stellar-mass black holes. The signal, GW151226, was observed by the twin detectors of the Laser Interferometer Gravitational-Wave Observatory (LIGO) on December 26, 2015 at 03:38:53 UTC. The signal was initially identified within 70 s by an online matched-filter search targeting binary coalescences. Subsequent off-line analyses recovered GW151226 with a network signal-to-noise ratio of 13 and a significance greater than 5σ. The signal persisted in the LIGO frequency band for approximately 1 s, increasing in frequency and amplitude over about 55 cycles from 35 to 450 Hz, and reached a peak gravitational strain of $3.4^{+0.7}_{-0.9} \times 10^{-22}$. The inferred source-frame initial black hole masses are $14.2^{+8.3}_{-3.7} M_\odot$ and $7.5^{+2.3}_{-2.3} M_\odot$, and the final black hole mass is $20.8^{+6.1}_{-1.7} M_\odot$. We find that at least one of the component black holes has spin greater than 0.2. This source is located at a luminosity distance of 440^{+180}_{-190} Mpc corresponding to a redshift of $0.09^{+0.03}_{-0.04}$. All uncertainties define a 90% credible interval. This second gravitational-wave observation provides improved constraints on stellar populations and on deviations from general relativity.

DOI: 10.1103/PhysRevLett.116.241103


Selected for a Viewpoint in *Physics*
PRL 116, 061102 (2016) PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2016

Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.**
(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 21 January 2016; published 11 February 2016)

On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 to 250 Hz with a peak gravitational-wave strain of 1.0×10^{-21}. It matches the waveform predicted by general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting single black hole. The signal was observed with a matched-filter signal-to-noise ratio of 24 and a false alarm rate estimated to be less than 1 event per 203 000 years, equivalent to a significance greater than 5.1σ. The source lies at a luminosity distance of 410^{+160}_{-180} Mpc corresponding to a redshift $z = 0.09^{+0.03}_{-0.04}$. In the source frame, the initial black hole masses are $36^{+5}_{-4} M_\odot$ and $29^{+4}_{-4} M_\odot$, and the final black hole mass is $62^{+4}_{-4} M_\odot$, with $3.0^{+0.5}_{-0.5} M_\odot c^2$ radiated in gravitational waves. All uncertainties define 90% credible intervals. These observations demonstrate the existence of binary stellar-mass black hole systems. This is the first direct detection of gravitational waves and the first observation of a binary black hole merger.

DOI: 10.1103/PhysRevLett.116.061102

Warnings

- In 45′ I will try to explain everything about GW
  - If you are interested I'm here at the end of the talk and in the following days
- This talk is meant for Beginners, but I cannot avoid to introduce many technical details

Why @Europython 2016?

We used also python to achieve this big result!

Python is used daily in our communities, in control room for our control system, in our Signal Processing pipelines, in parameter estimation…

I'm going to show some of the places in which we use it, while explaining the big discovery we made, and the 'TOOL' we used.

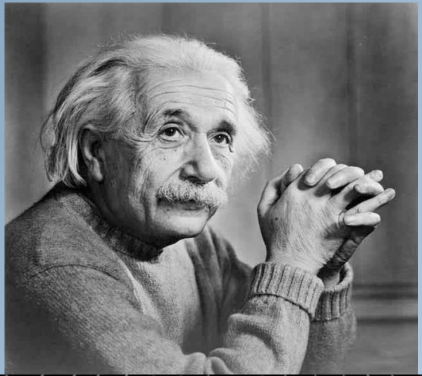
It is sure a not exhaustive list of python usage in our field!

Let's start

The Challenge

What are Gravitational Waves? How we discovered them?

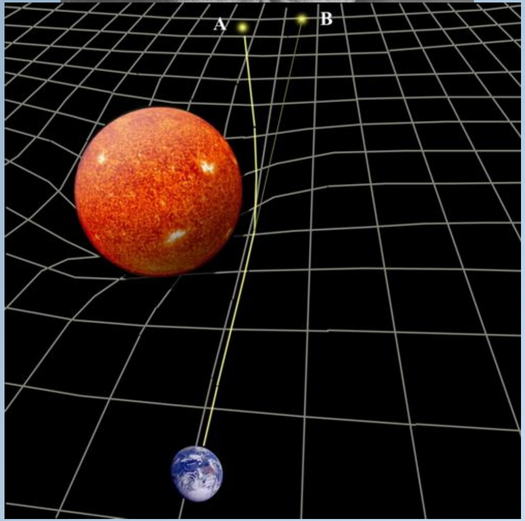
General Relativity (1915)

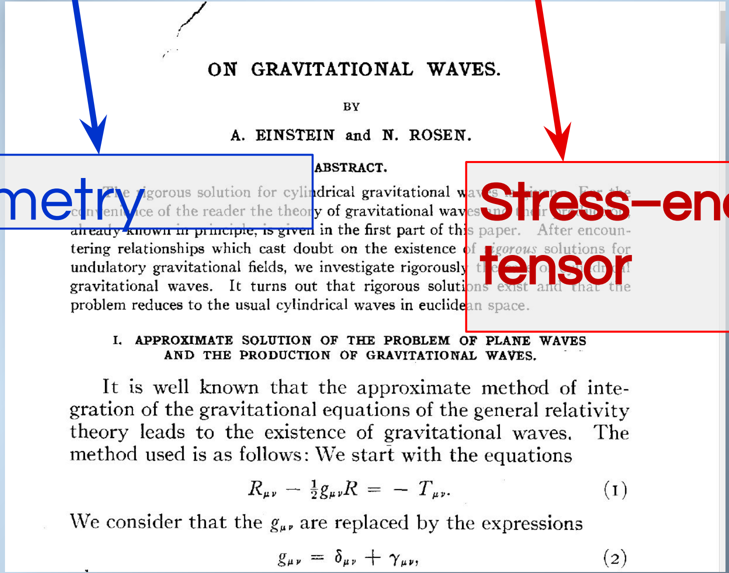


$$\mathbf{G}_{\mu\nu} = \frac{8\pi G}{c^4}\mathbf{T}_{\mu\nu}$$

Geometry

Stress–energy tensor





ON GRAVITATIONAL WAVES.

BY

A. EINSTEIN and N. ROSEN.

ABSTRACT.

The rigorous solution for cylindrical gravitational waves is given. For the convenience of the reader the theory of gravitational waves and their production, already known in principle, is given in the first part of this paper. After encountering relationships which cast doubt on the existence of *rigorous* solutions for undulatory gravitational fields, we investigate rigorously the case of cylindrical gravitational waves. It turns out that rigorous solutions exist and that the problem reduces to the usual cylindrical waves in euclidean space.

I. APPROXIMATE SOLUTION OF THE PROBLEM OF PLANE WAVES AND THE PRODUCTION OF GRAVITATIONAL WAVES.

It is well known that the approximate method of integration of the gravitational equations of the general relativity theory leads to the existence of gravitational waves. The method used is as follows: We start with the equations

$$R_{\mu\nu} - \tfrac{1}{2}g_{\mu\nu}R = -T_{\mu\nu}. \quad (1)$$

We consider that the $g_{\mu\nu}$ are replaced by the expressions

$$g_{\mu\nu} = \delta_{\mu\nu} + \gamma_{\mu\nu}, \quad (2)$$

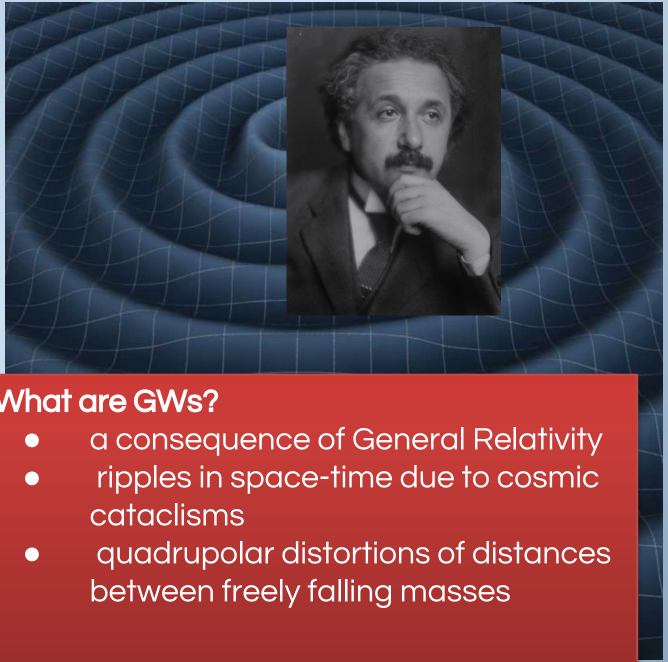
Do you want to play with me?

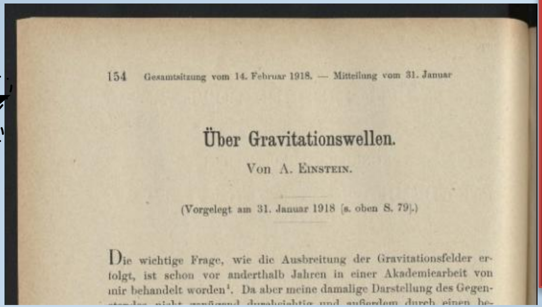
What happen to the space-time if masses accelerate?

Gravitational Waves (1916)

- Very small effect!
  - We need Huge mass involved
- Tiny interaction with matter:
  - Extremely difficult to detect
- Ideal messengers from remote space-time regions
  - *Can bring a whole new view of the Universe*

… when Einstein firstly predicted the gravitational waves





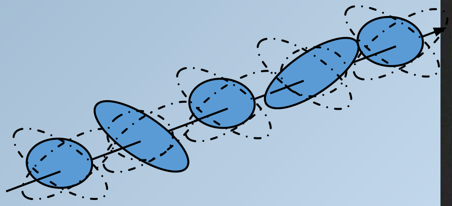
154 Gesamtsitzung vom 14. Februar 1918. — Mitteilung vom 31. Januar

Über Gravitationswellen.

Von A. Einstein.

(Vorgelegt am 31. Januar 1918 [s. oben S. 79].)

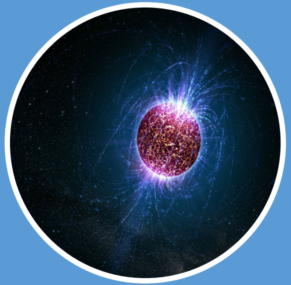
Die wichtige Frage, wie die Ausbreitung der Gravitationsfelder erfolgt, ist schon vor anderthalb Jahren in einer Akademiearbeit von mir behandelt worden[1]. Da aber meine damalige Darstellung des Gegen-



What are GWs?

- a consequence of General Relativity
- ripples in space-time due to cosmic cataclisms
- quadrupolar distortions of distances between freely falling masses

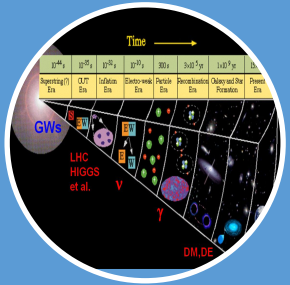
Astrophysical sources



Rotating Neutron Stars

Supernovae

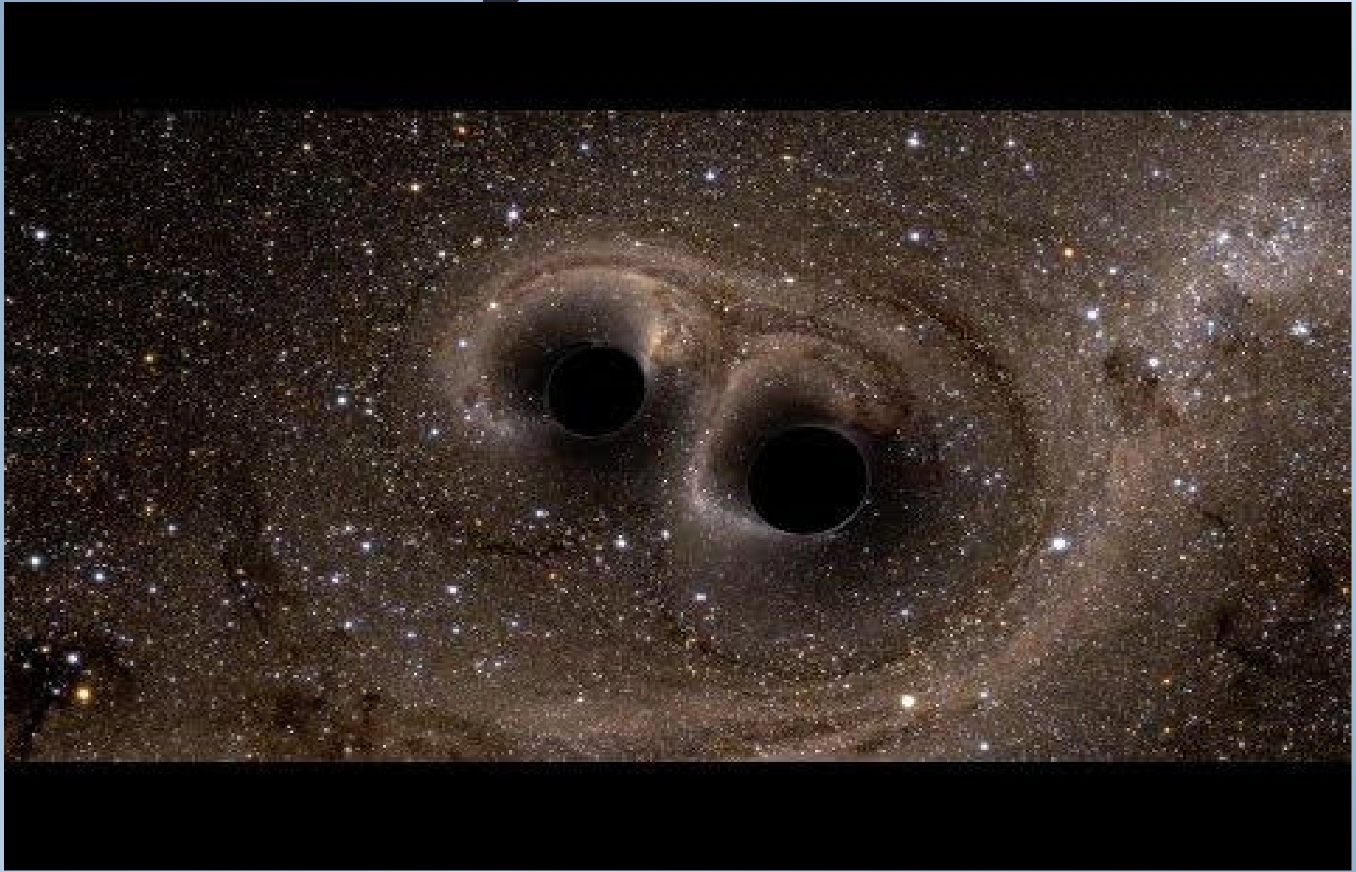
Compact Coalescing Binaries



Stochastich GW background

Main topic!

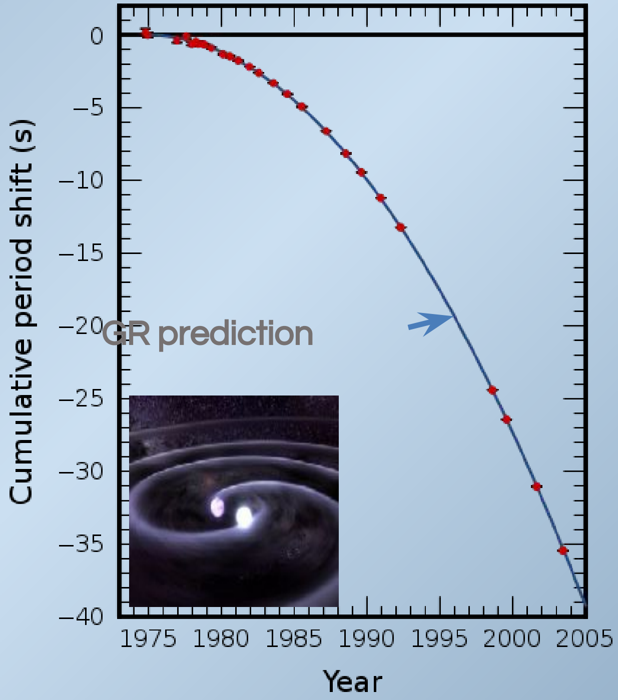
Coalescing Binaries



How did we know GWs exist?

The Nobel Prize in Physics 1993
Russell A. Hulse, Joseph H. Taylor Jr.

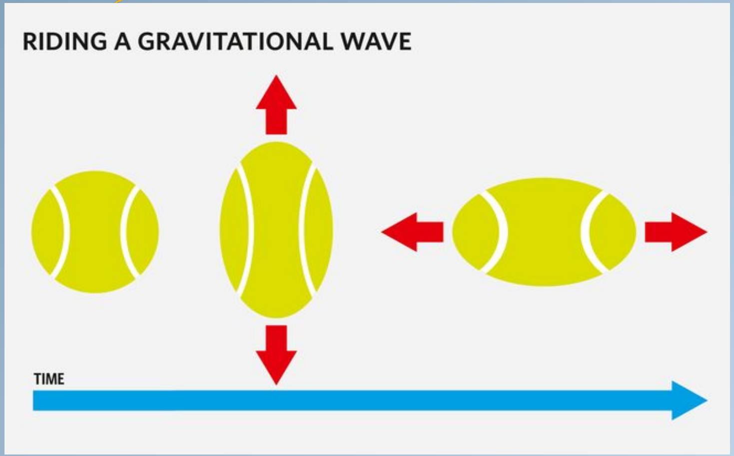
Binary Pulsar 1913+16

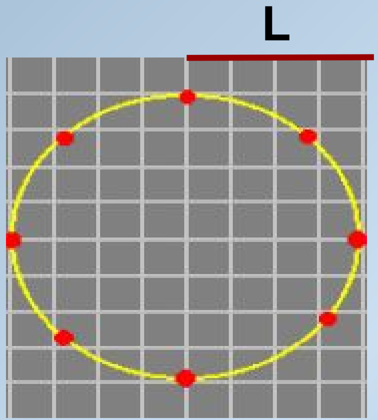


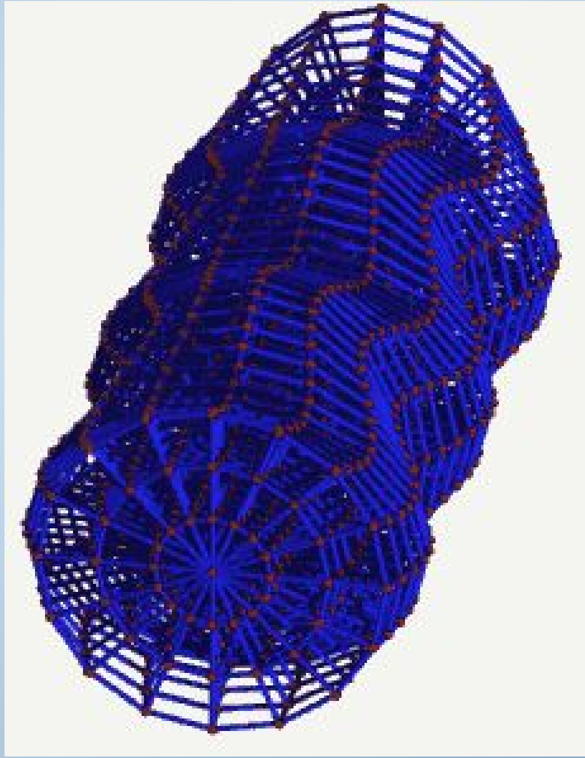
J. M. Weisberg, J. H. Taylor,
http://arxiv.org/abs/astro-ph/0407149

How we detect them?

...revealing the effect of GW







© Markus Pössel, Max Planck Institute

What is the plausible “strain” $h = \Delta L/L$

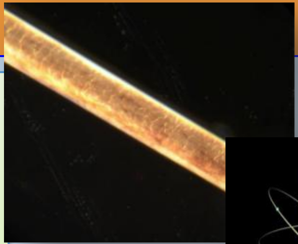
Even for the most tremendous events in Universe, $h \sim 10^{-21}$

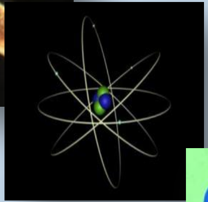
The challenge

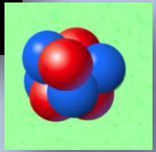
With $h = \Delta L/L \sim 10^{-21}$,

- even with test masses L~km far apart,
- displacement is $\Delta L \sim 10^{-18}$m

- Diameter of human hair: 10^{-5} m
- Diameter of atom: 10^{-10} m
- Diameter of atomic nucleus: 10^{-14} m
- Diameter of proton: 10^{-15} m



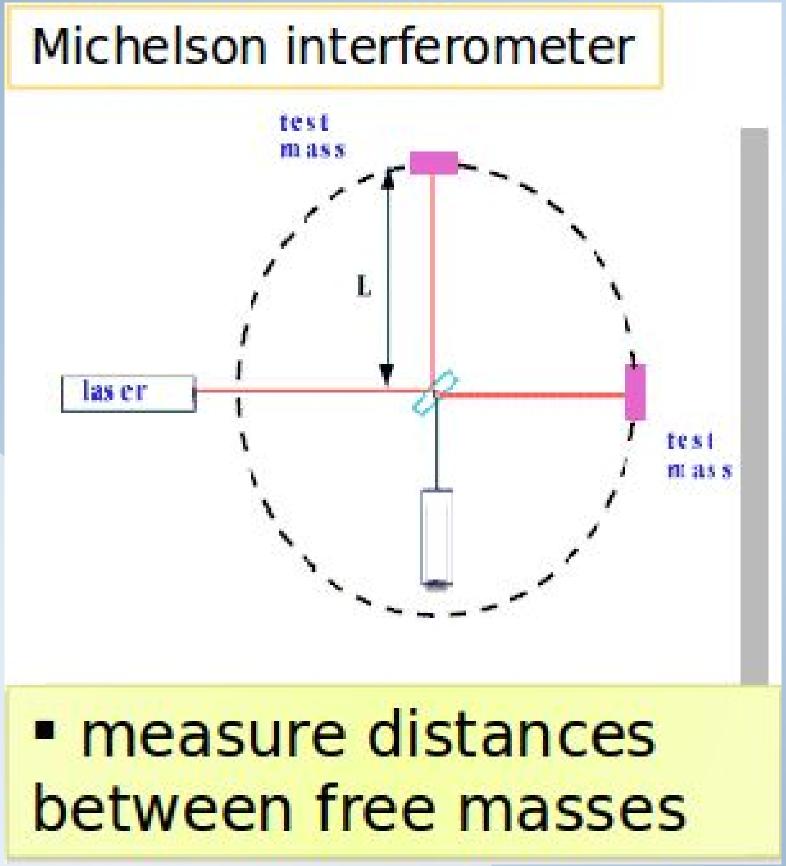


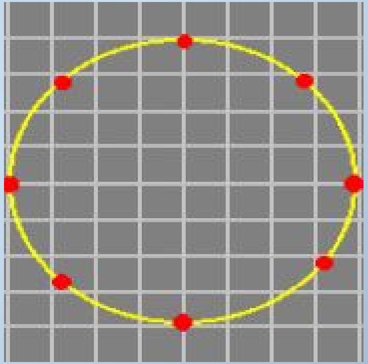


$\Delta L \sim 10^{-18}$m looks rather small

The 'TOOL'

Which kind of instrument can we use to detect such a small displacement?

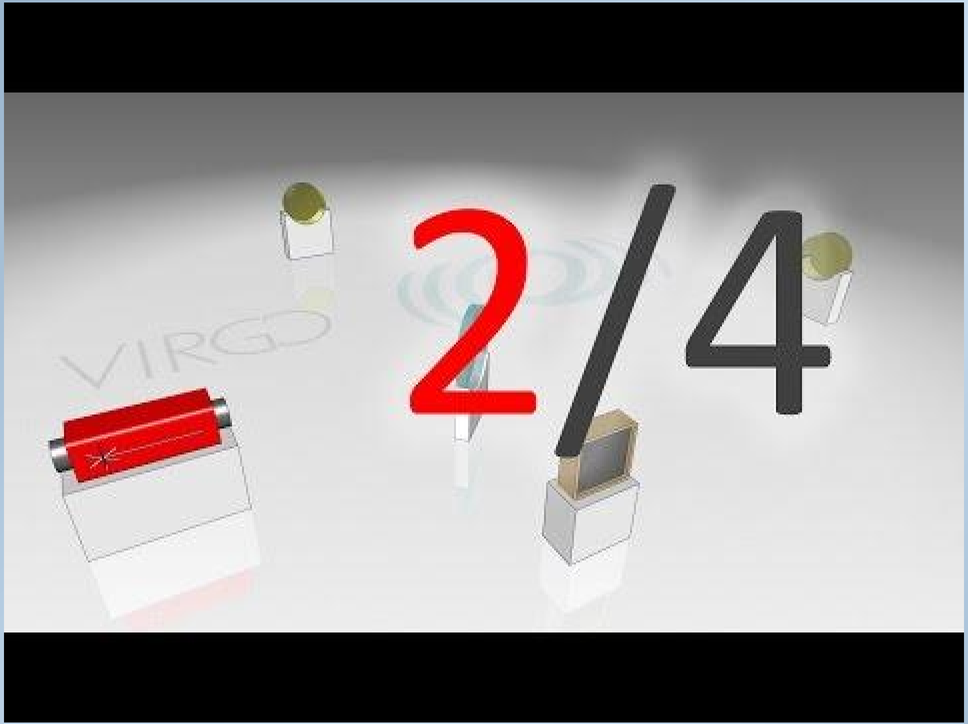




How it works…

Credits: Marco Kraan - Nikhef

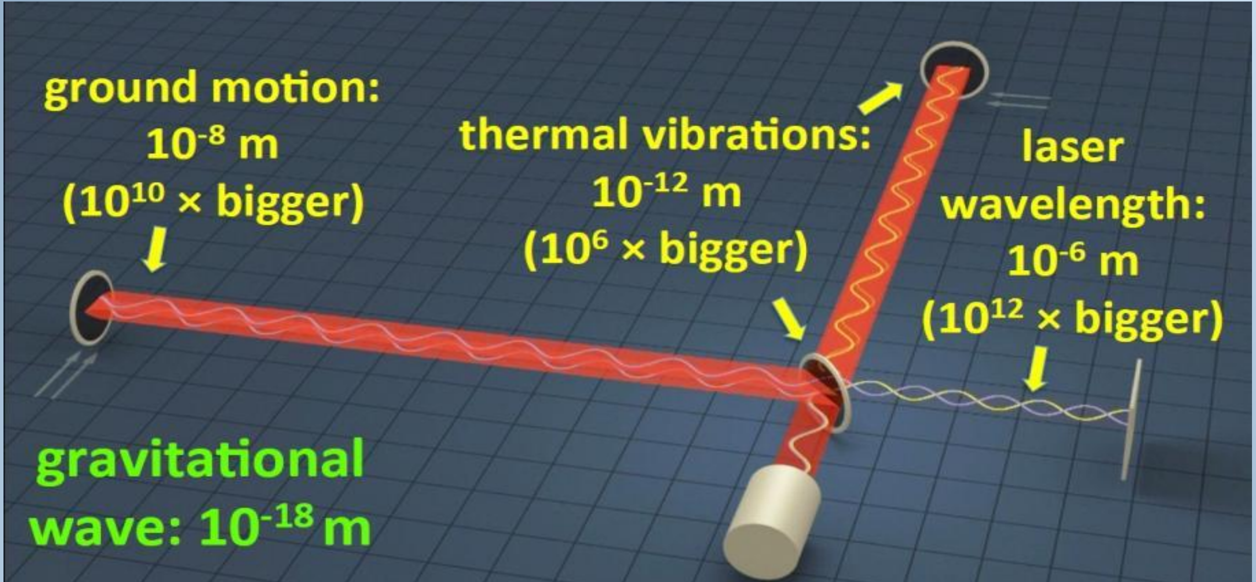
How it works...



Credits: Marco Kraan - Nikhef

How to deal with the noise??

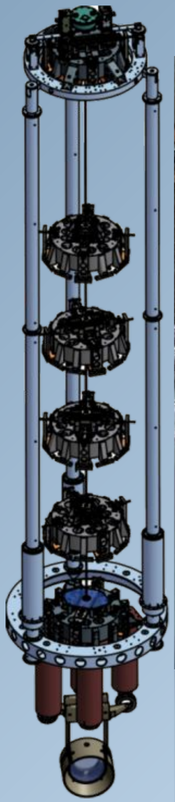
Doesn't matter how sensitive you are, if your noise is billions of times your signal

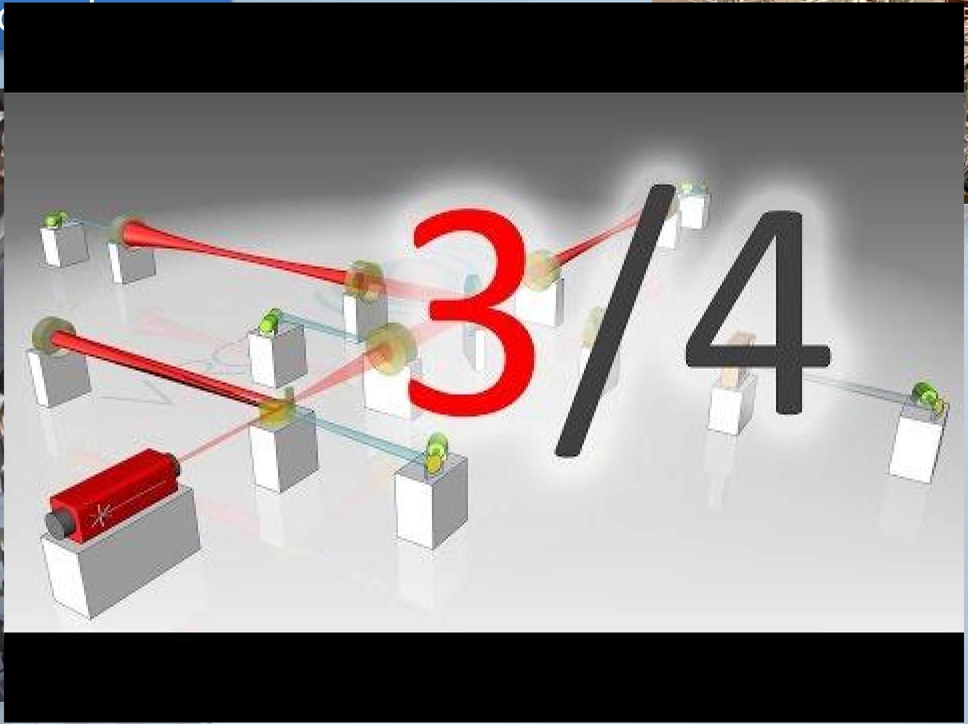


Credits: Stephen Fairhurst

Coping with Noise

Seismi

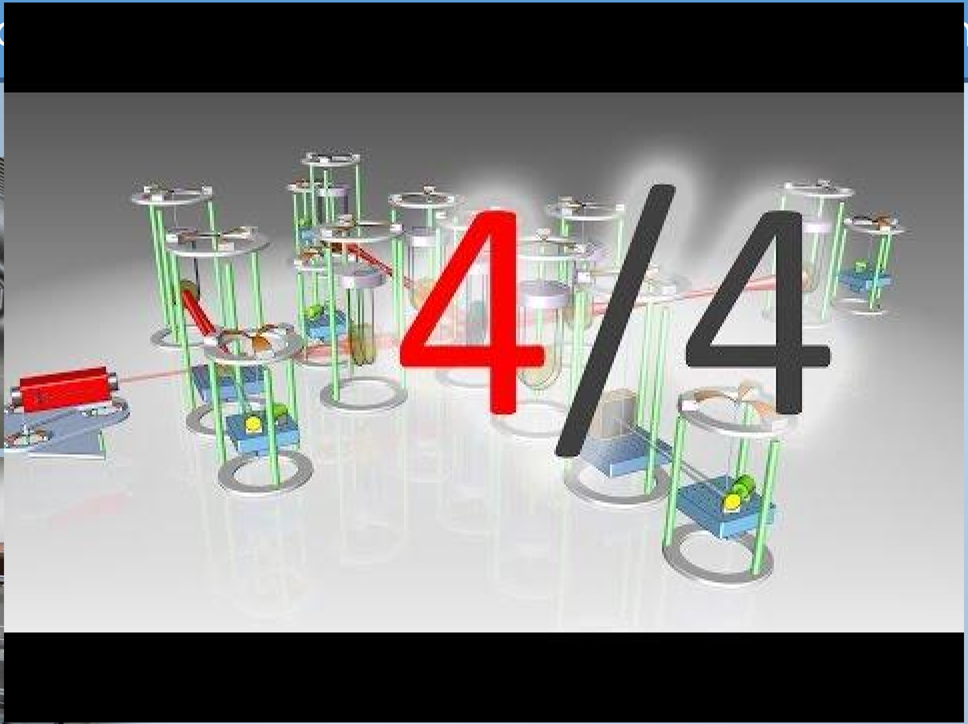




Credits: Marco Kraan - Nikhef

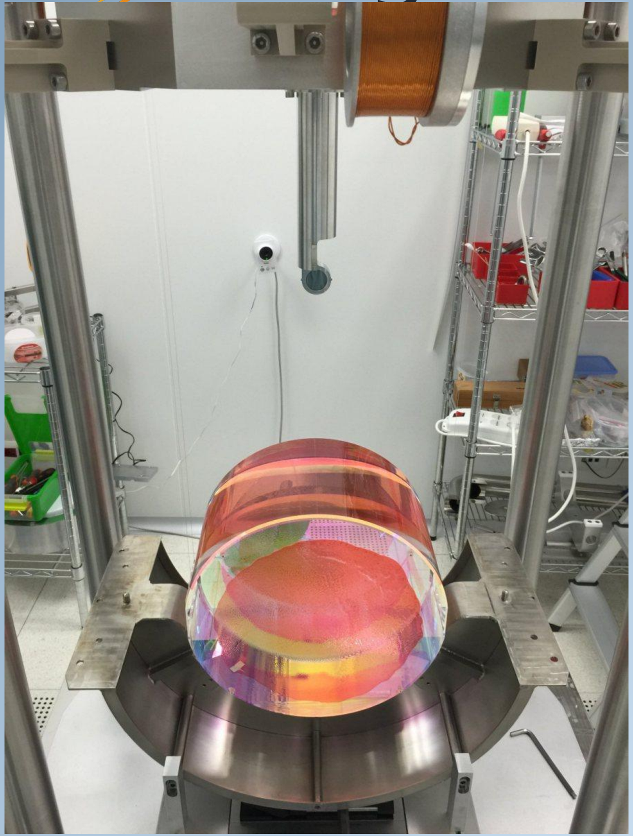
Coping with Noise

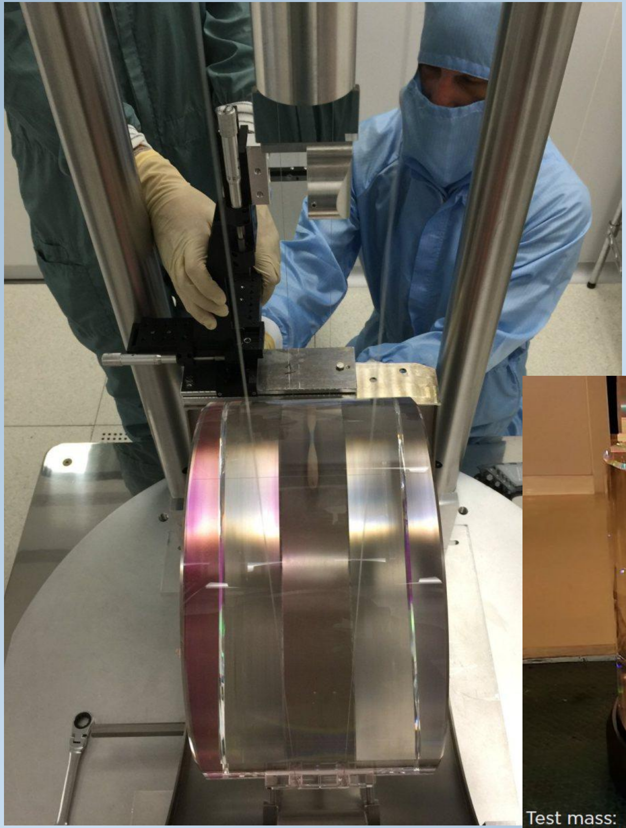
Gas pressure n … bar



Credits: Marco Kraan - Nikhef

Virgo mirrors





Reducing thermal noise

Virgo

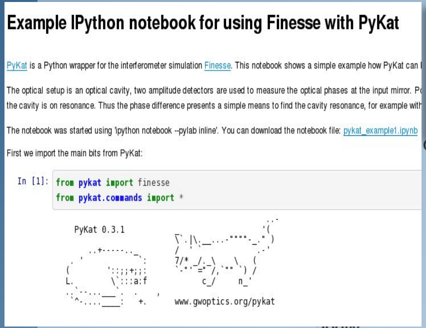
Credits N. Baldocchi

Python in Gravitational Waves Communities

Where and how?

The sensitivity curve

Virgo, LIGO are very complex instruments!


Example IPython notebook for using Finesse with PyKat

PyKat is a Python wrapper for the interferometer simulation Finesse. This notebook shows a simple example how PyKat can

The optical setup is an optical cavity, two amplitude detectors are used to measure the optical phases at the input mirror. P
the cavity is on resonance. Thus the phase difference presents a simple means to find the cavity resonance, for example wit

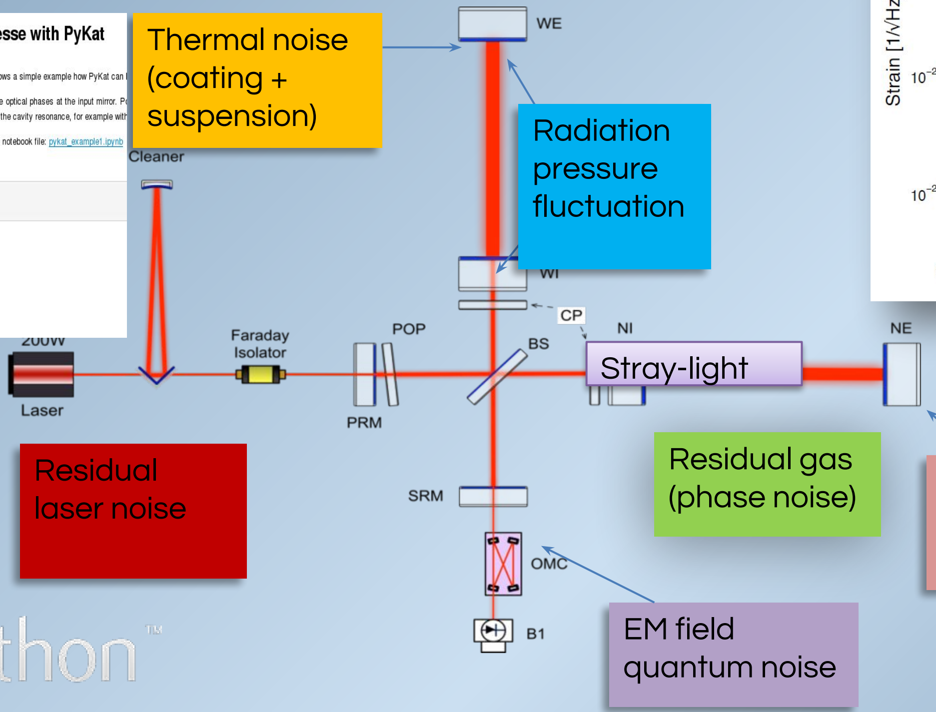
The notebook was started using 'ipython notebook --pylab inline'. You can download the notebook file: pykat_example1.ipynb

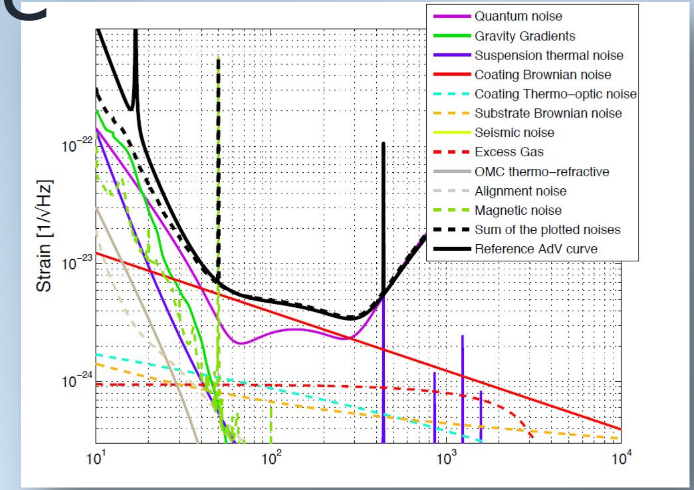
First we import the main bits from PyKat:

```
In [1]: from pykat import finesse
        from pykat.commands import *
```

PyKat 0.3.1

www.gwoptics.org/pykat





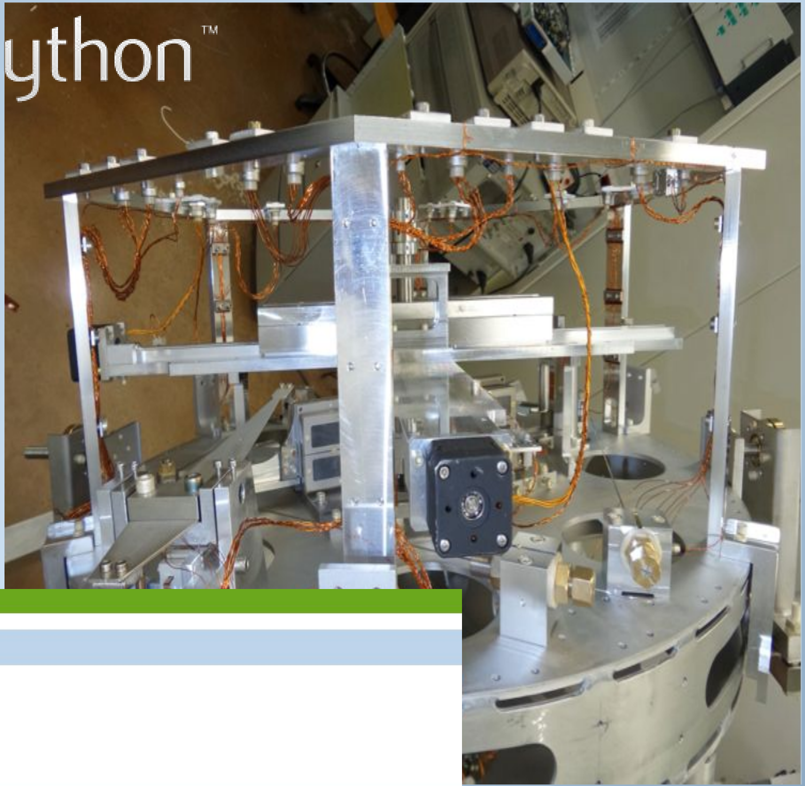
http://www.gwoptics.org/pykat/

credits A. Chiummo

Active Controls

- RingHeaterPR: Monitor and control of Power Supply (TCS)
- PyINJ: Automation for INJ
- PyFlags: DQ flags computation
- PyDMS: Python server to support DMS
- PyDAQ: Monitoring of DAQ properties
- PyHVAC: Top level automation of INJ and DET Labs temperature control
- PySFP: Scanning Fabry-Perot automation

python™



VIRGO Python PythonDoc documentation »

Table Of Contents

Welcome to Python for Virgo Detector Control documentation!
Indices and tables

Next topic

Python Cascina Setup

This Page

Show Source

Quick search

Go

Welcome to Python for Virgo Detector Control documentation!

- Python Cascina Setup
- Python for VIRGO Detector Control Guidelines
- Graphical User Interfaces (GUI) Development Guidelines
- PythonVirgoTools documentation
- TangoDAQSmsBridge documentation

Indices and tables

- Index
- Search Page

VIRGO Python PythonDoc documentation »

Credits F. Carbognani and B. Swinkels

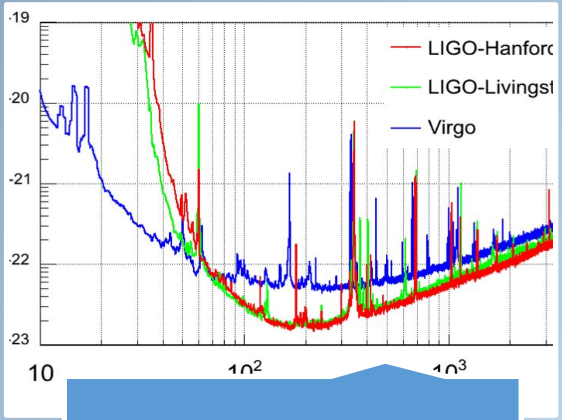
How can we extract from our detector data a Gravitational Wave Event?

The Data Analysis

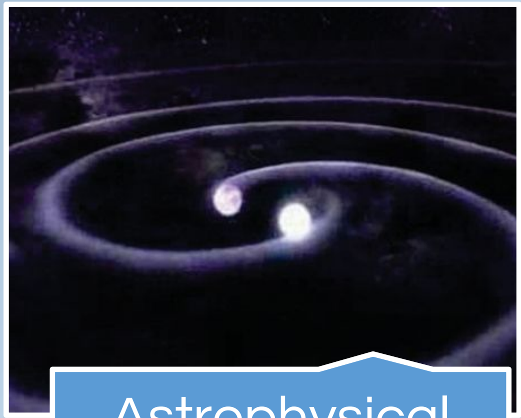
Using...

python™

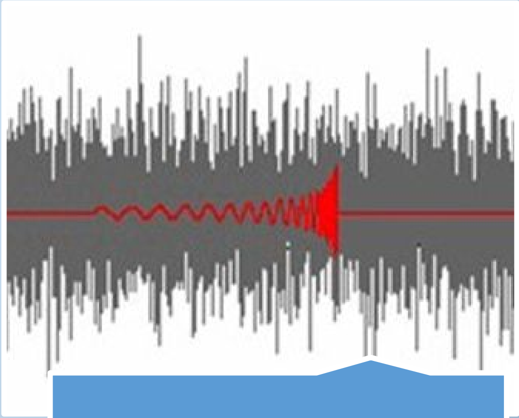
What is a GW detection



Detector

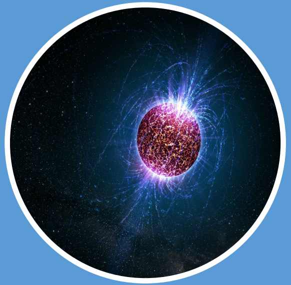


Astrophysical signal



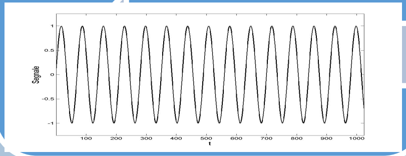
Signal extraction

GW Signals



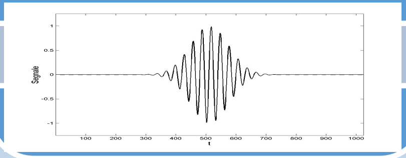
Periodic signals

- Rotating Neutron Stars



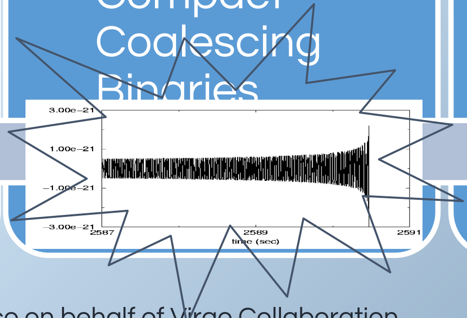
Short transient signals

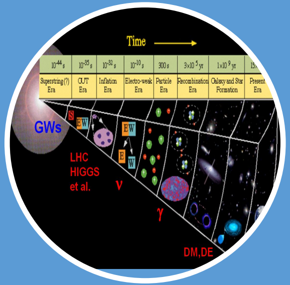
- Supernovae



Transient signals

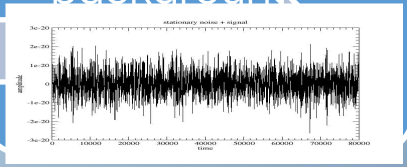
- Compact Coalescing Binaries





BroadBand signals

- Stochastich GW background



Ideal world: Optimal filter

The detector output

$x = n + \xi$

+

Our noise is Gaussian distributed

→

How we can extract the signal?

Matched Filter: a bit of formulae

python™

The data

$$x(t) = n(t) + \hat{h}(t)$$

$$\rho(t) = 4 \int_0^\infty \frac{\tilde{x}(f)\ \tilde{h}^*(f)}{S_n(f)} e^{2\pi i f t} df$$

Look for maxima of $|\rho(t)|$ above some threshold ➔ trigger

pycbc.filter package

Submodules

pycbc.filter.matchedfilter module

This modules provides functions for matched filtering along with associated utilities.

`pycbc.filter.matchedfilter.match`(*vec1, vec2, psd=None, low_frequency_cutoff=None, high_frequency_cutoff=None, v1_norm=None, v2_norm=None*) [source]

Return the match between the two TimeSeries or FrequencySeries.

Return the match between two waveforms. This is equivalent to the overlap maximized over time and phase.

generation

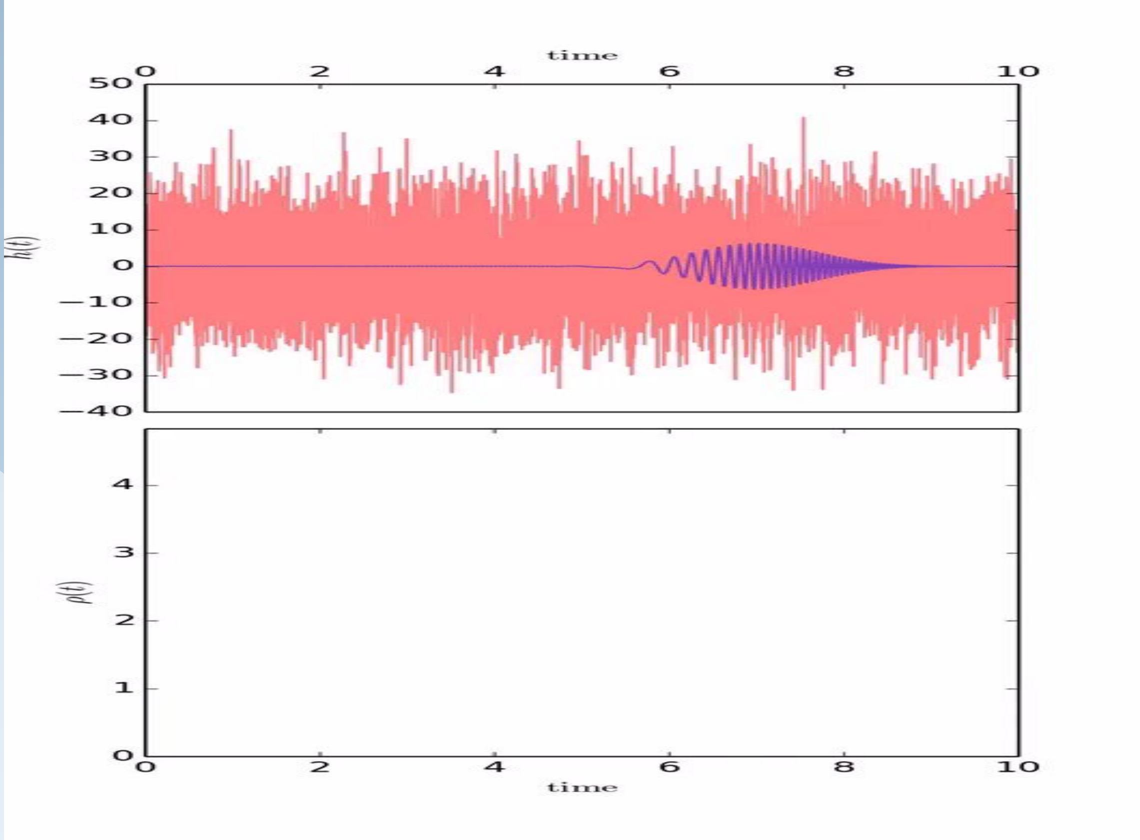
Calculating the Effectualness (Fitting Factor) of Template Banks

Dag Generator for Doing Faithfulness Comparisons

(1,2), Marcel Kehl (11), Drew Keppel (4), Badri Krishnan (4), Prayush Kumar (2,11), Amber Lenon (2), Andrew Lundgren (4), Duncan Macleod (6), Thomas Massinger (2), Adam Mercer (7), Andrew Miller (8), Saeed Mirshekari (9), Alex Nitz (1,2), Laura Nuttall (2), Francesco Pannarale (10), Larne Pekowsky (2), Harald Pfeiffer (11), Samantha Usman (2), Karsten Wiesner (4), Andrew Williamson (10), Josh Willis (8).

Matched filter search in action

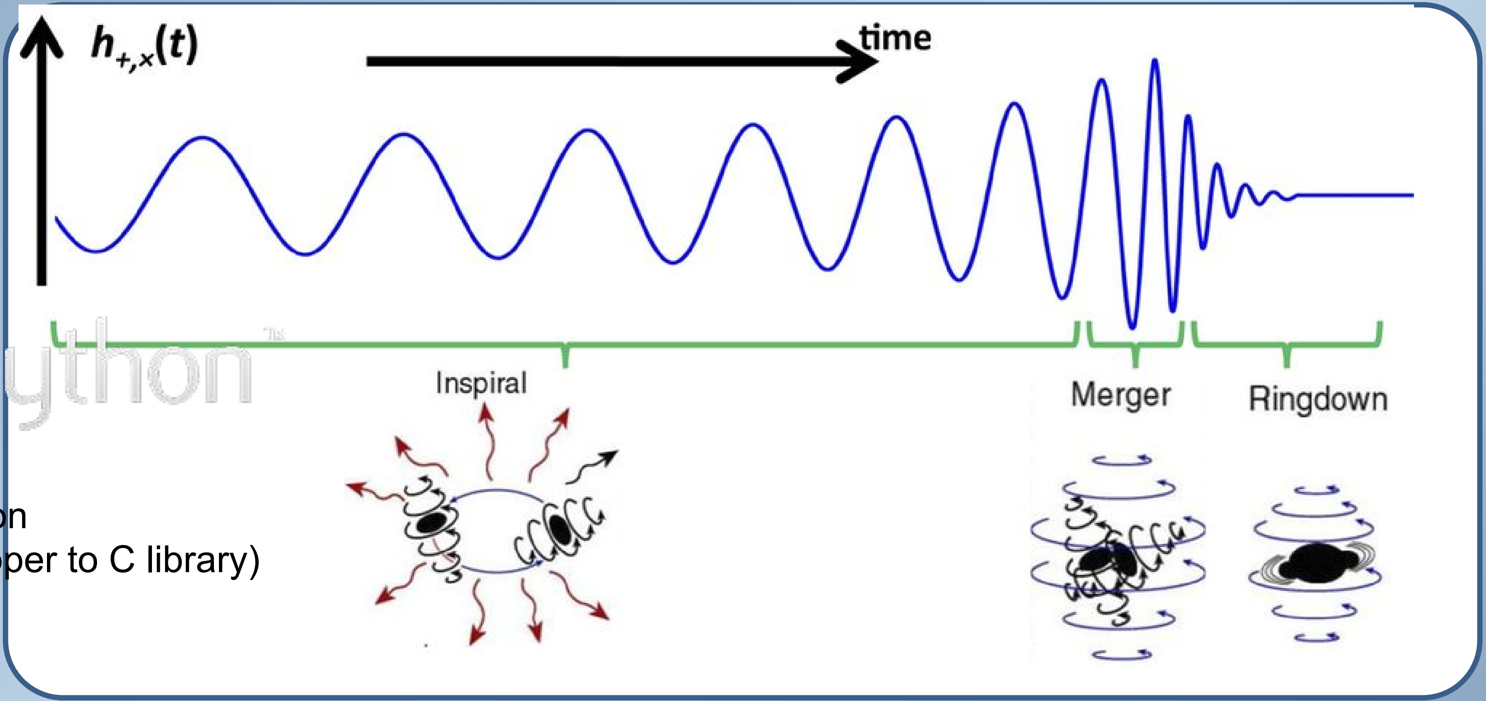
PyCBC



http://ligo-cbc.github.io/pycbc/latest/html/

CBC Matched Filtering

We need a **template waveforms** to use to extract the signal from the background



LALsimulation
pyLAL (wrapper to C library)

Signal to Noise Ratio

A key definition for the signal in the detector noise is its SNR:
How much the signal is intense with respect to the noise?

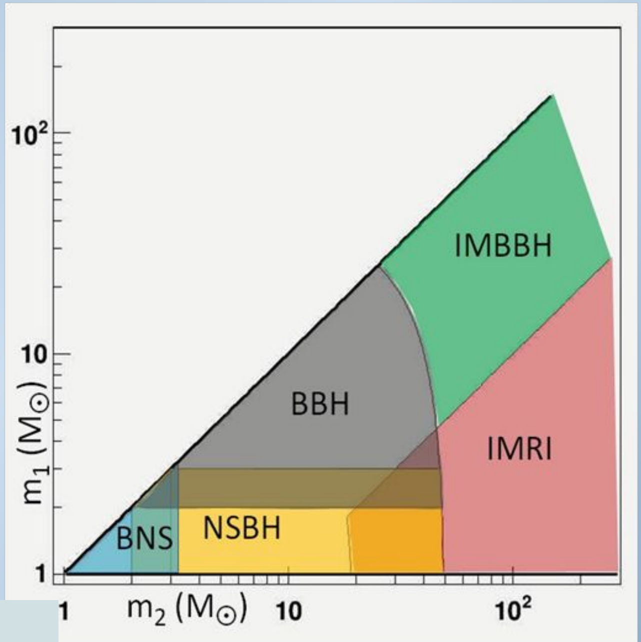
$$SNR = 2\left[\int_0^{\infty} \frac{|\tilde{h}(f)|^2}{S_n(f)} df\right]^{1/2}$$

Noise power spectral density

<u>We use a threshold on SNR value to build our templates bank</u>

Building template bank

- To cover in efficient way the parameters space, we build a *template bank* requiring that the signal can be detected with a maximum loss of 3% of its SNR



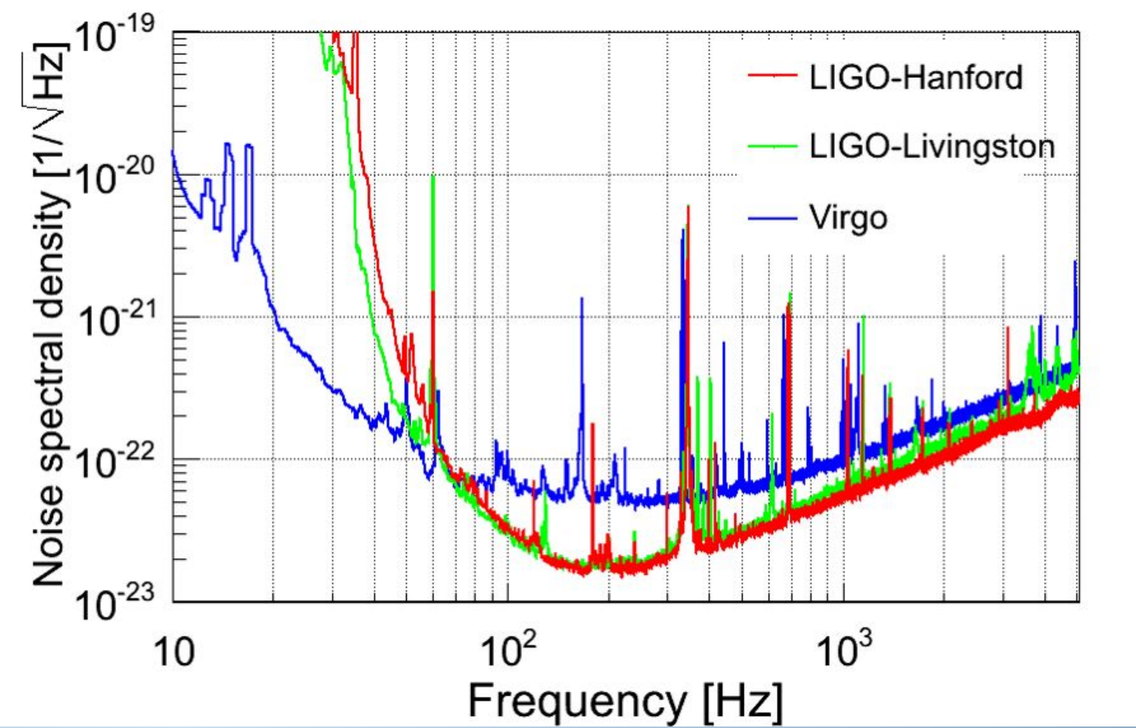
pyCBC

~250000 waveforms used for GW150914

credits G. Guidi

The noise

How to deal with noise, while analyzing data



The detector noise

The noise is not as ideal as we want…
It is:

- Not stationary
- Not Gaussian
- Contaminated by a lot of spurious events

Python used in many software package to clean data:
GWpy, GWpySoft, LALDetchar, pyLAL,pyNAP

Generic transient signals search

What if we don't know the signal

What to do if our noise is not Gaussian

We need some pipeline which does not rely on the knowledge of waveform

Different triggers generator

python™

Find excess of power with respect the background noise

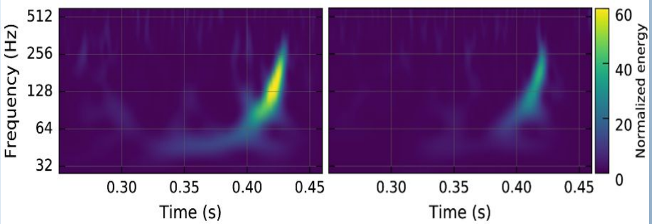
Look for transient signals

Use generic ‘template bank’ :

- sine-gaussian waveforms
- wavelets

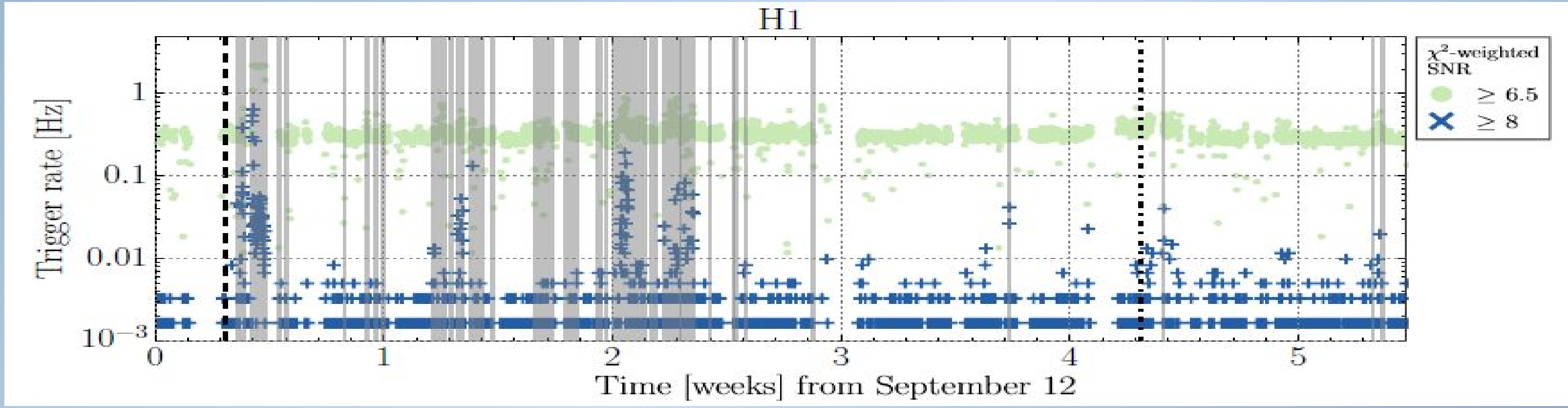
Omicron, Klein-Welle, WDF, coherent WaveBurst

The cWB pipeline produced online the first trigger for GW event!



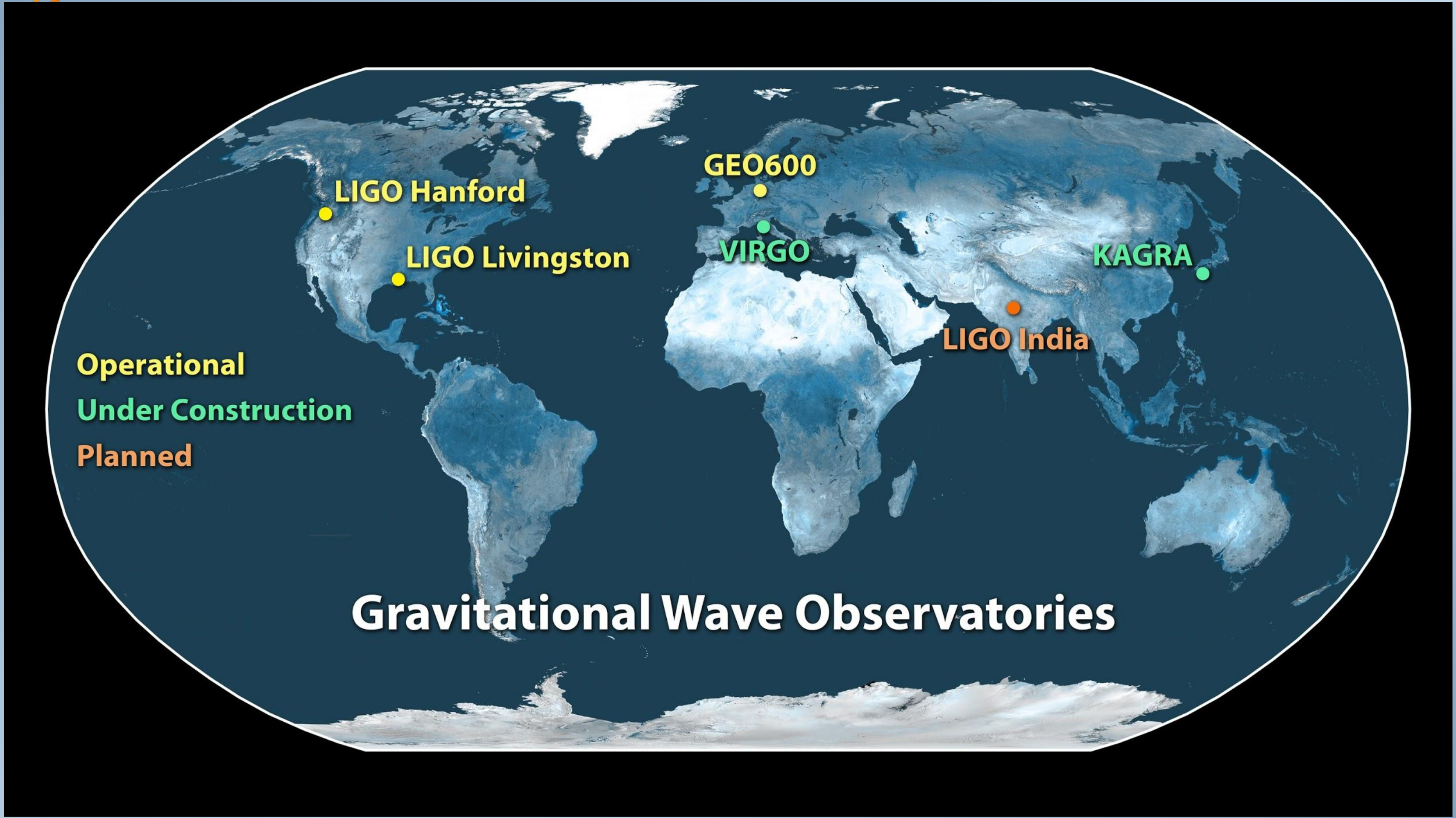
Why glitch identification?

- Transient noise (**glitches**) can occur within the targeted frequency range
- More than **200000 auxiliary channels** are recorded to monitor instrument behaviour and environmental conditions
- In the case of clear correlation within glitches in gravitational wave channel and auxiliary ones, data are discarded from the analysis (**vetoed**)

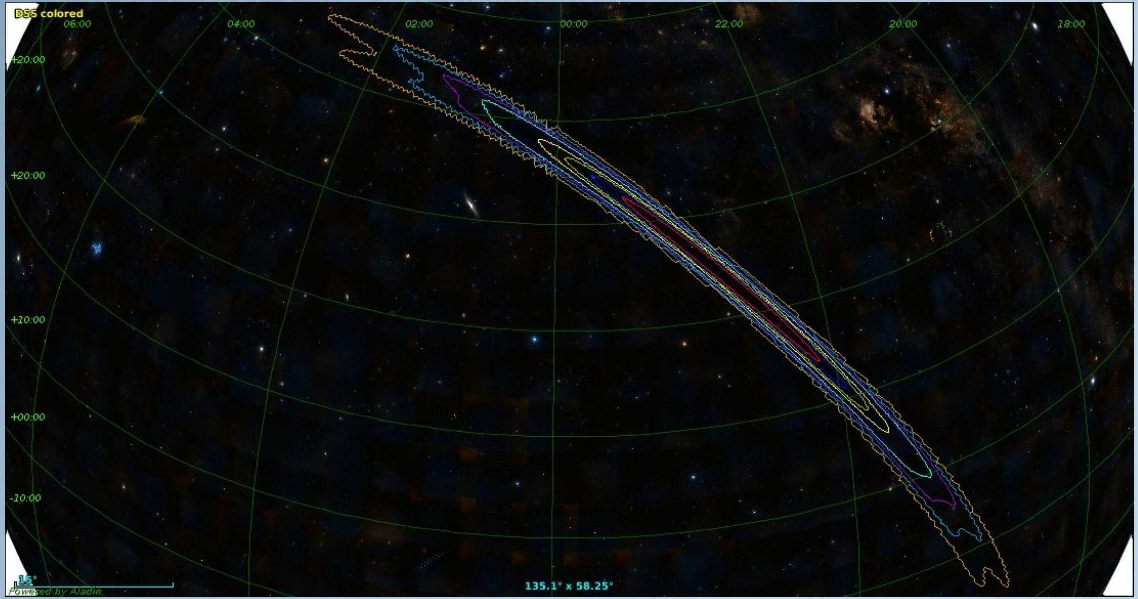


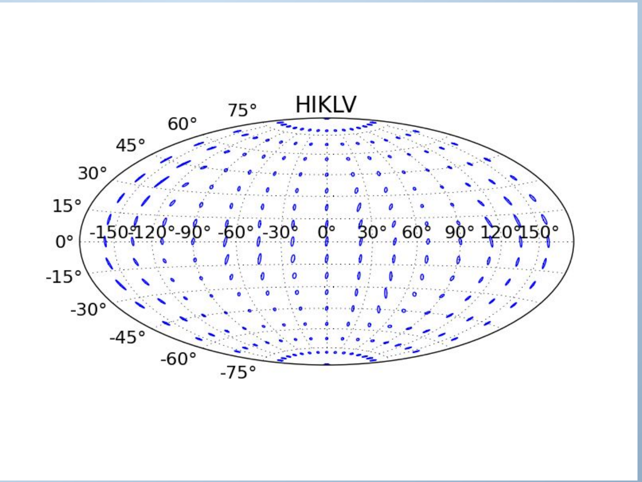
arXiv:1602.03844

A network


GEO600
LIGO Hanford
LIGO Livingston
VIRGO
KAGRA
LIGO India
Operational
Under Construction
Planned
Gravitational Wave Observatories

Localization in The Sky





Tutorial and code links

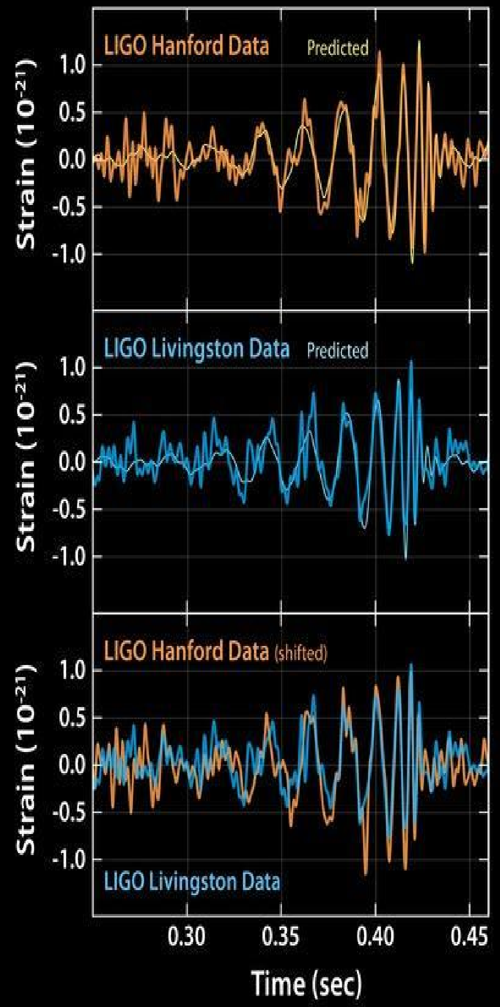
Credits G. Greco

https://github.com/ggreco77/GWsky
https://vimeo.com/153202019

http://nbviewer.jupyter.org/gist/ggreco77/d43e5a1141b99f918672e70adc05864d python™

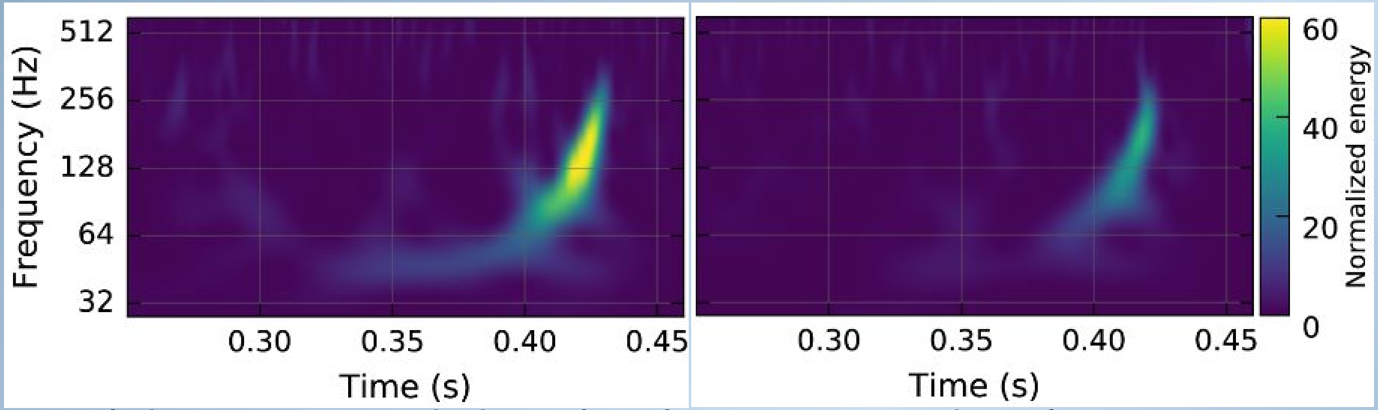
The Gravitational Waves have been detected!

The guest star: 14 September 2015
The special guest: 26 December 2015



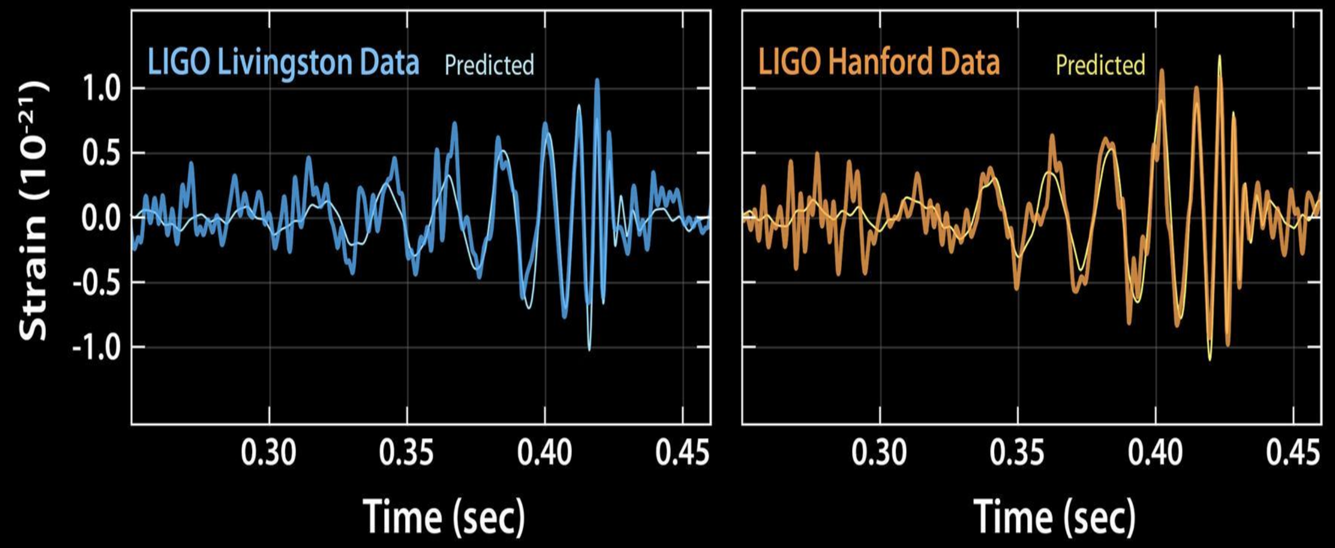
September 14, 2015 – 11:50:45 CET

LIGO Hanford Observatory LIGO Livingston Observatory

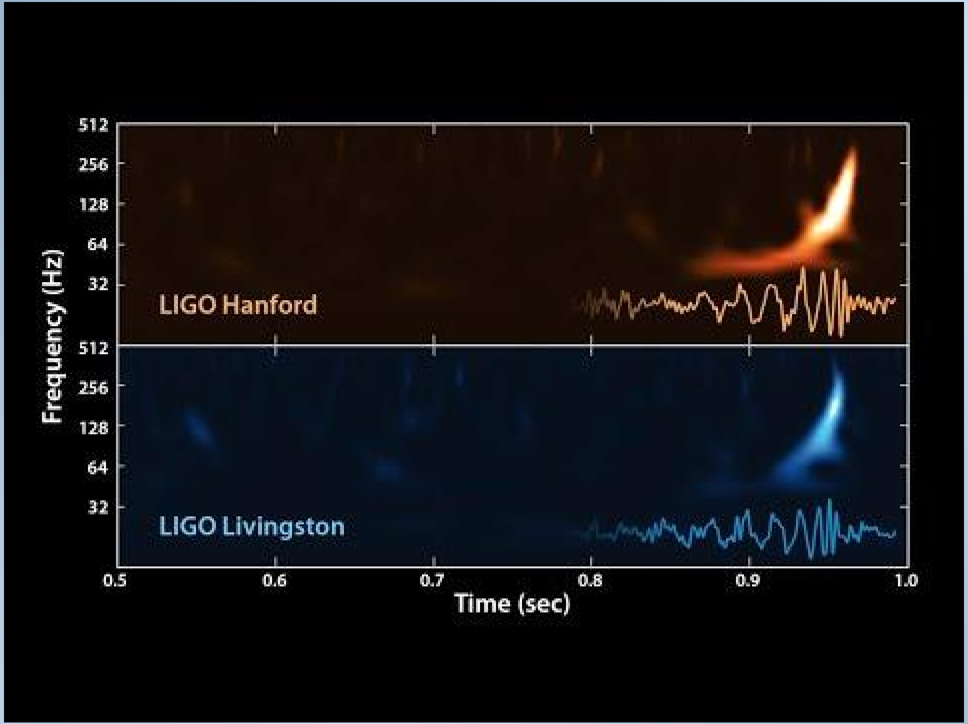


Initial detection made by a low latency searches for generic GW transients: **Coherent WaveBurst**

Reported within 3 minutes after data acquisition!


LIGO Livingston Data
Predicted
LIGO Hanford Data
Predicted
Strain (10⁻²¹)
1.0
0.5
0.0
-0.5
-1.0
0.30
0.35
0.40
0.45
Time (sec)
Time (sec)

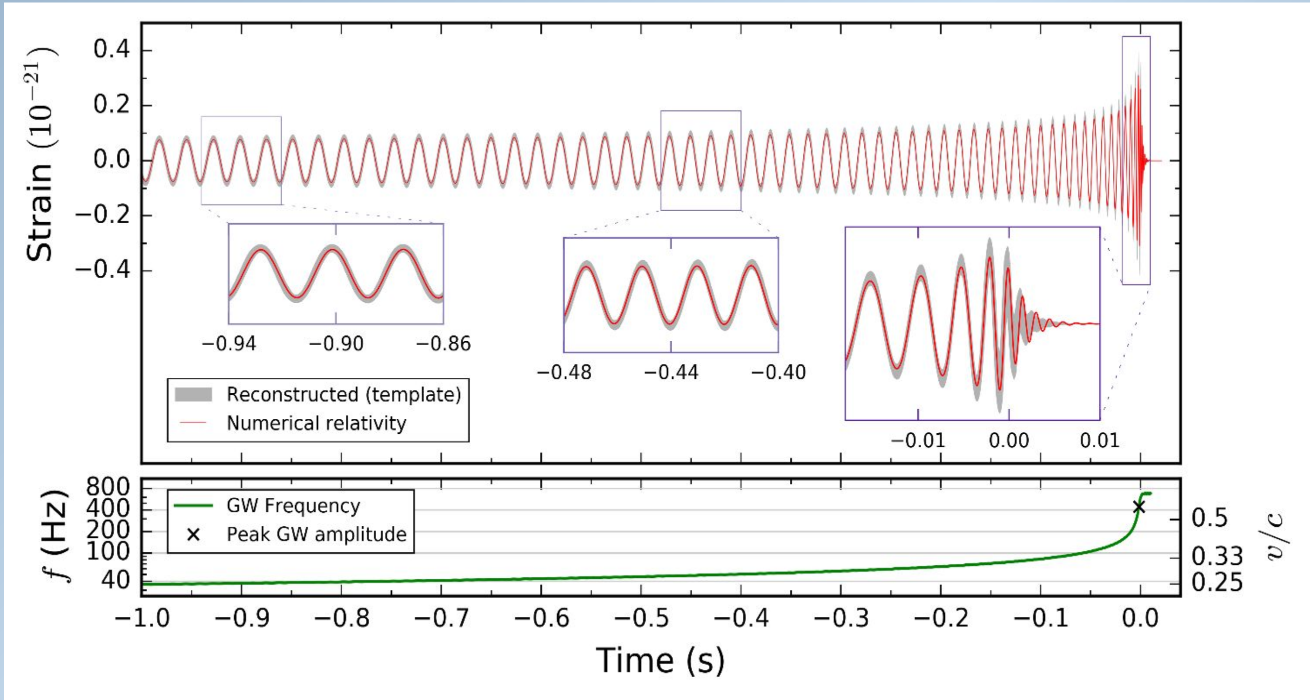
The GW sound



512
256
128
64
32
LIGO Hanford
512
256
128
64
32
LIGO Livingston
Frequency (Hz)
0.5
0.6
0.7
0.8
0.9
1.0
Time (sec)

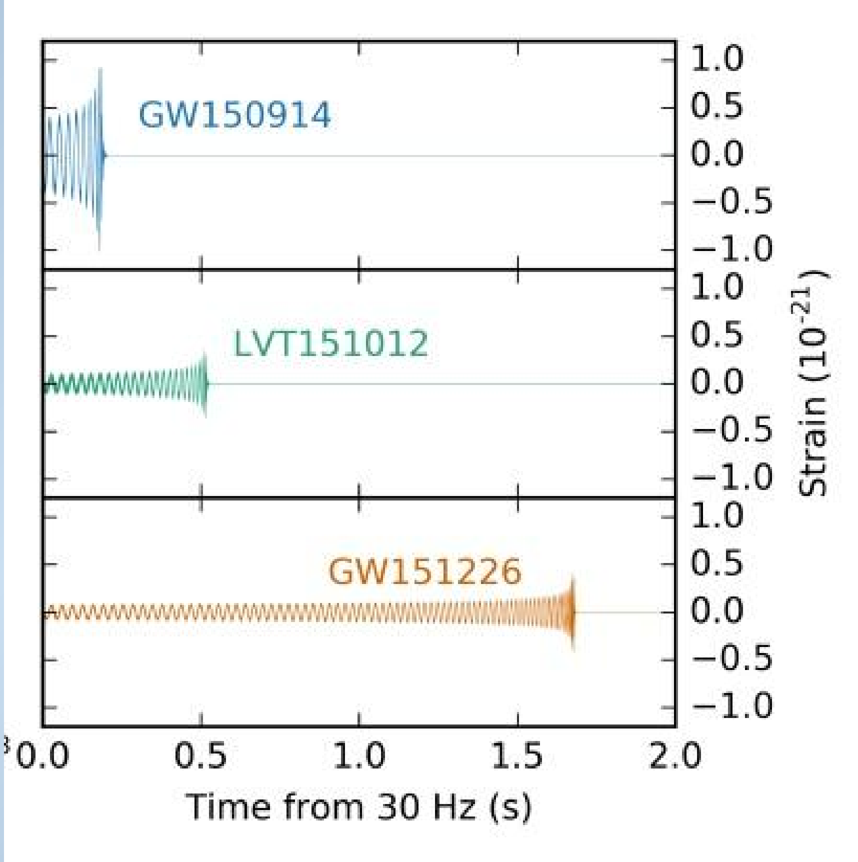
On December 26th 2015
We did it…AGAIN!

GW151226



Detection Summary

EVENT	GW150914	GW151226	LVT151012
SNR	23.7	13	9.7
DISTANCE	420Mpc (1.3 billion ly)	440Mpc (1.44 billion ly)	1000Mpc (3.26 billion ly)
FAR /yr	$<6.0x10^{-7}$	$<6.0x10^{-7}$	0.37
M1 (solar mass)	36.2	14	23
M2 (solar mass)	29.1	7.5	13
Mtot (solar mass)	62.3	20.8	35



Personal experience

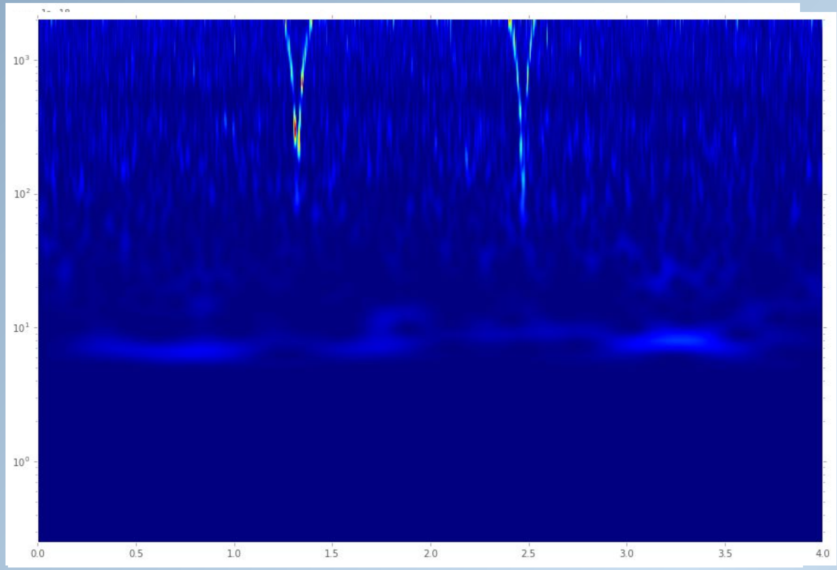
- Working on noise identification and data characterization.
  - Noise Analysis Package (C++ library)
  - Swig used to embed the code in python
  - pynap (generic noise analysis toolkit)
  - pyWDF (ETG based on wavelets)
  - pyWDFML (Machine learning tool to classify signals)

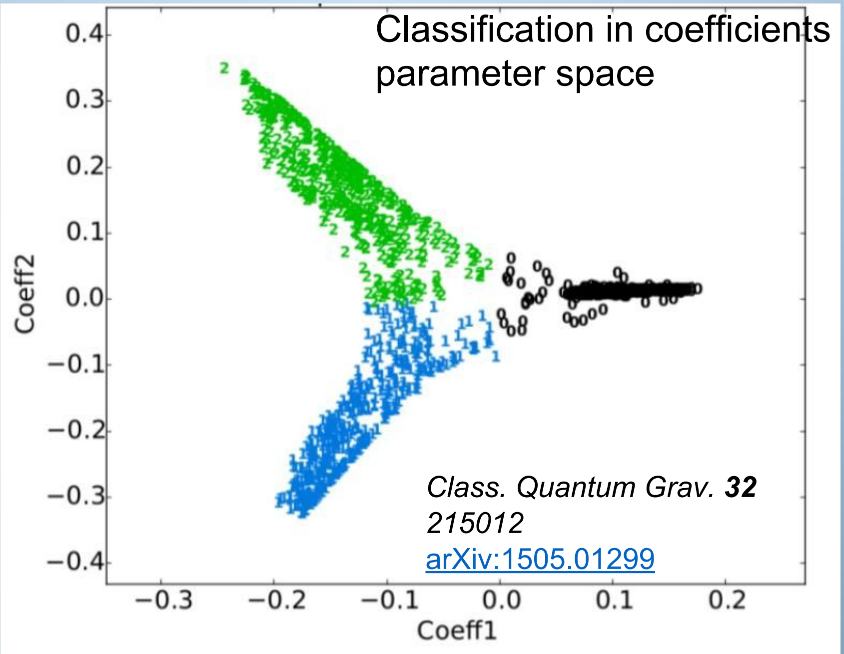
The environment: python 2.7.5, scikit-learn, scipy, numpy, matplotlib, pandas,pyCharm

Glitch Classification

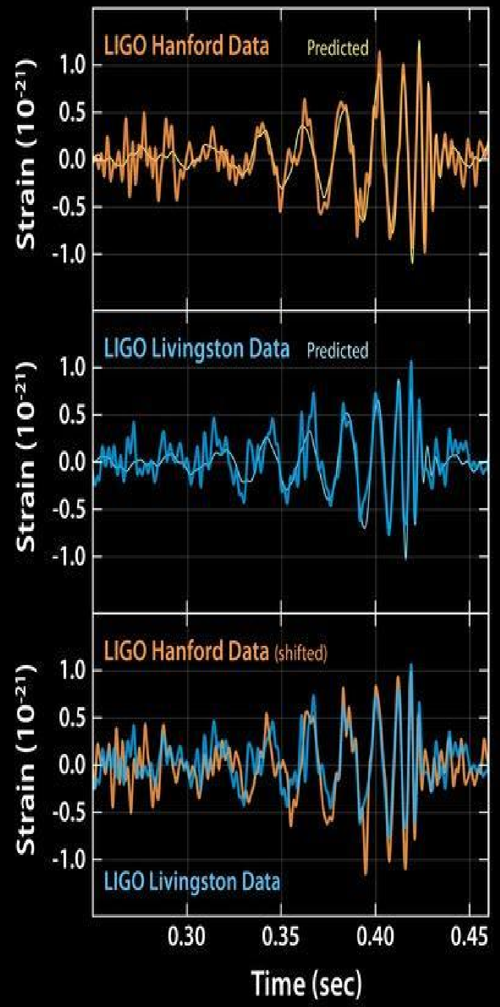
numpy, pynap, matplotlib,scikit-learn, pandas

- Starting from raw data, find transient signals, extract waveforms and classify them





Let’s play with the data



LIGO Open Science Center

https://losc.ligo.org/

LIGO

LIGO Open Science Center

LIGO is operated by California Institute of Technology and Massachusetts Institute of Technology and supported by the U.S. National Science Foundation.

- Getting Started
- Tutorials
- Data & Catalogs
- Timelines
- My Sources
- Software
- GPS ↔ UTC
- About LIGO
- Student Projects
- Acknowledgement

Data release for event GW150914

This page has been prepared by the LIGO Scientific Collaboration (LSC) and the Virgo Collaboration to inform the broader community about a confirmed astrophysical event observed by the gravitational-wave detectors, and to make the data around that time available for others to analyze. There is also a **technical details** page about the data linked below, and feel free to **contact us**. This dataset has the Digital Object Identifier (doi) http://dx.doi.org/10.7935/K5MW2F23

Summary of Observation

The event occurred at GPS time 1126259462.39 == September 14 2015, 09:50:45.39 UTC. The false alarm rate is estimated to be less than 1 event per **203,000 years**, equivalent to a significance of **5.1 sigma**. The event was detected in data from the LIGO Hanford and LIGO Livingston observatories.

- There are Science Summaries, covering the information below in ordinary language.
- There is a one page factsheet about GW150914, summarizing the event.

Ipython Notebook

- Playing with GW event data
  - Let’s move to the tutorial on my notebook

jupyter notebook GW150914_tutorial-SHORT.ipynb

SIGNAL PROCESSING WITH GW150914 OPEN DATA

Welcome! This ipython notebook (or associated python script GW150914_tutorial.py) will go through some typical signal processing tasks on strain time-series data associated with the LIGO GW150914 data release from the LIGO Open Science Center (LOSC):

- https://losc.ligo.org/events/GW150914/
- View the tutorial as a web page - https://losc.ligo.org/s/events/GW150914/GW150914_tutorial.html/
- Download the tutorial as a python script - https://losc.ligo.org/s/events/GW150914/GW150914_tutorial.py/
- Download the tutorial as iPython Notebook - https://losc.ligo.org/s/events/GW150914/GW150914_tutorial.ipynb/

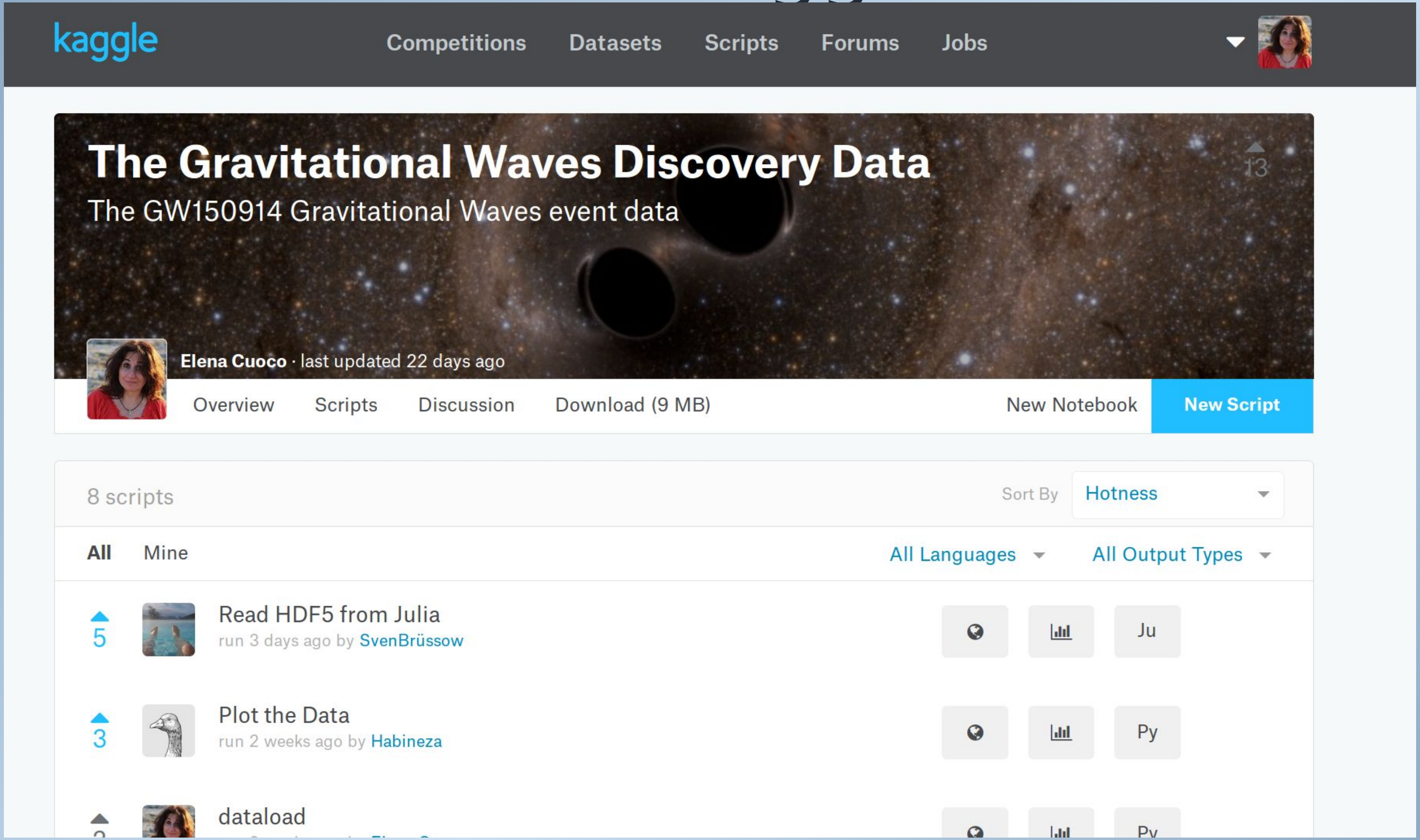
To begin, download the ipython notebook, readligo.py, and the data files listed below, into a directory / folder, then run it. Or you can run the python script GW150914_tutorial.py. You will need the python packages: numpy, scipy, matplotlib, h5py.

On Windows, or if you prefer, you can use a python development environment such as Anaconda (https://www.continuum.io/why-anaconda) or Enthought Canopy (https://www.enthought.com/products/canopy/).

Questions, comments, suggestions, corrections, etc: email losc@ligo.caltech.edu

v20160208b

...now also on Kaggle



A new ERA for Astronomy has just began …thanks also to python

With Gravitational Regards

Elena Cuoco