EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY

The Gravitational wave search

COST ACTION CA17137
A NETWORK FOR GRAVITATIONAL WAVES, GEOPHYSICS AND MACHINE LEARNING

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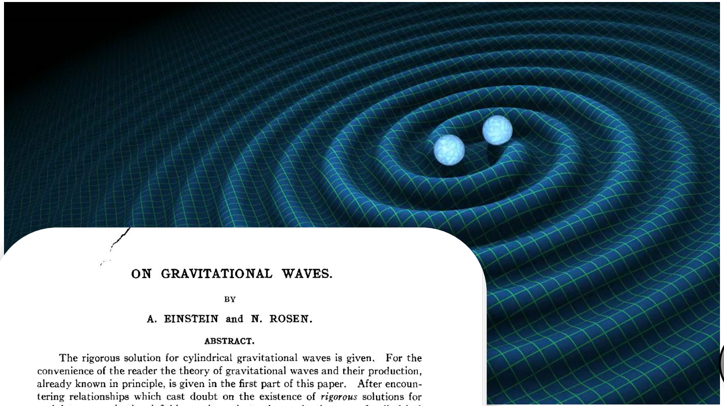
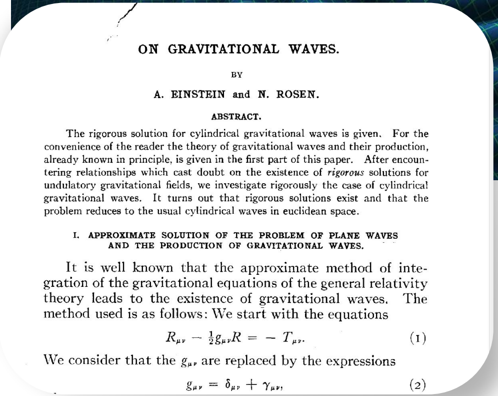
4th G2net Training School, Thessaloniki, 28-31 March-2023

What are Gravitational Waves (GWs)?





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.

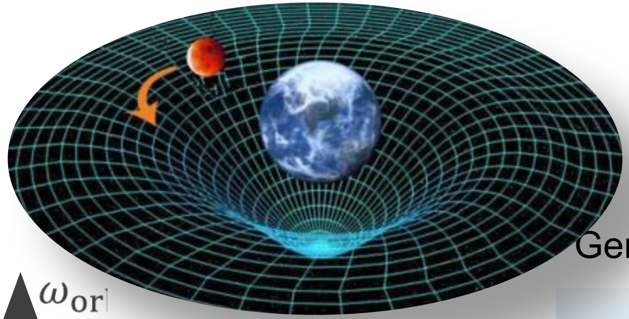
It is well known that the approximate method of integration of the gravitational equations of the general relativity theory leads to the existence of gravitational waves. The method used is as follows: We start with the equations

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

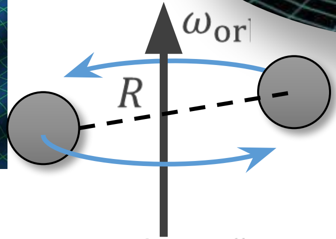
We consider that the $g_{\mu\nu}$ are replaced by the expressions

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

Gravitational Waves (1916)



More in the next lectures

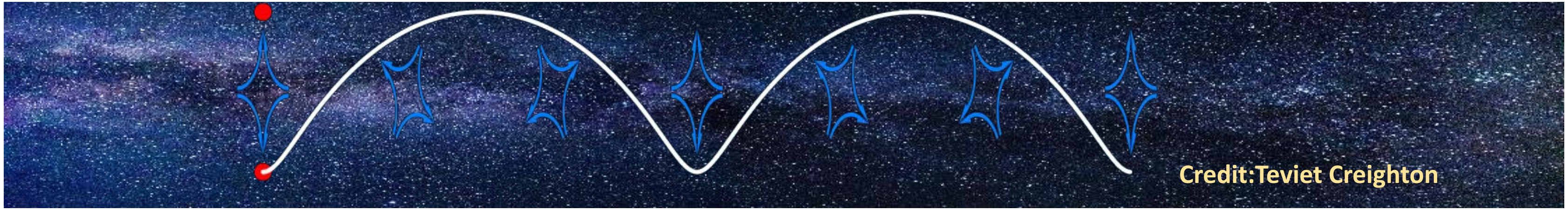


General Relativity (1915)

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

Free propagation along "z-axis" in vacuum ($T_{\mu\nu} = 0$):

$$\Box h_{\mu\nu} = 0 \quad \Rightarrow h_{\mu\nu}(t,z) = h_{\mu\nu}e^{i(kz-\omega t)} \quad \text{with} \quad \omega/c = k$$



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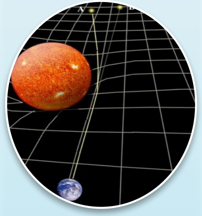
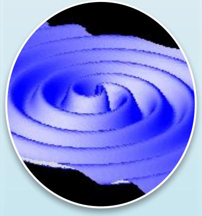
credits F. Di Renzo

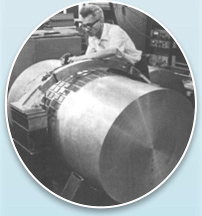
The Gravitational Wave science: a long history...started 100 years ago



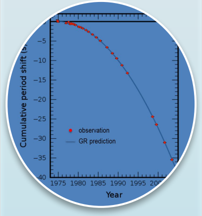
1915
- General Relativity



1916
- Gravitational Waves



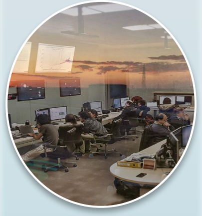
1966
- Weber and Resonant Bars



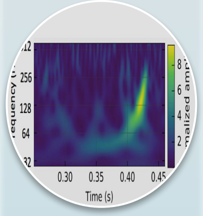
1974
- Hulse-Taylor:Observing the pulsar binary PSR B1913+16

1980-1990
- Cryogenic Resonant Bars

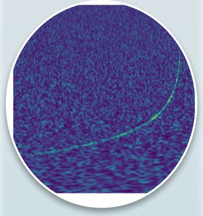
1993
- The approval of Virgo Experiment



1999+
- Data taking from LIGO and Virgo

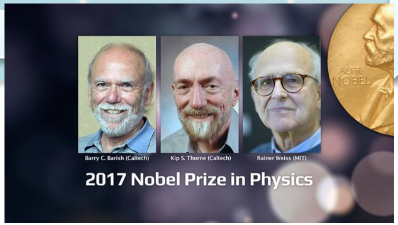


2015
- GW BHBH detection



2017
- BNS detection: Multi-messenger Astronomy

~100 years



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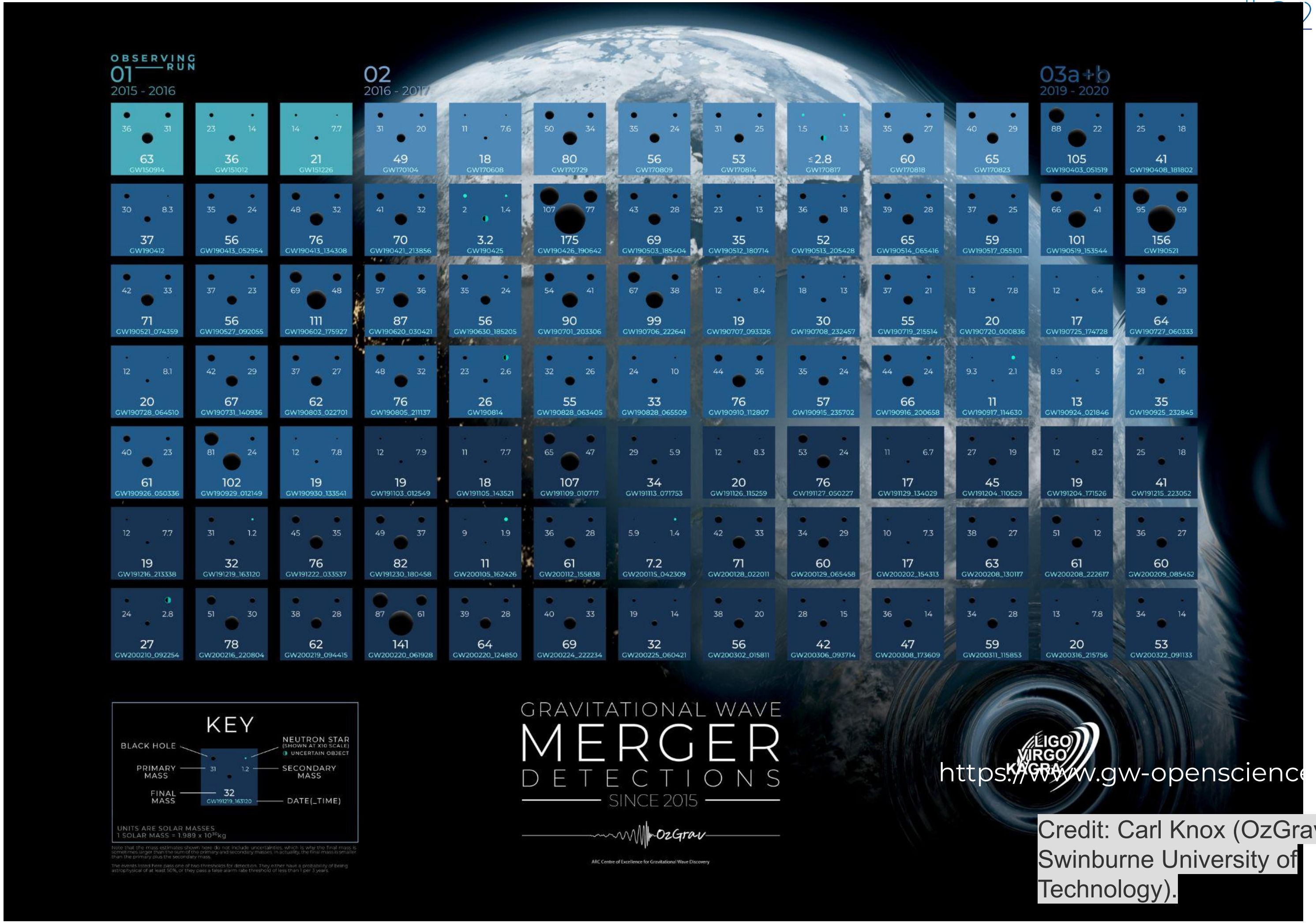
So Far...

91 events!!!



https://www.gw-openscience

Credit: Carl Knox (OzGrav, Swinburne University of Technology).

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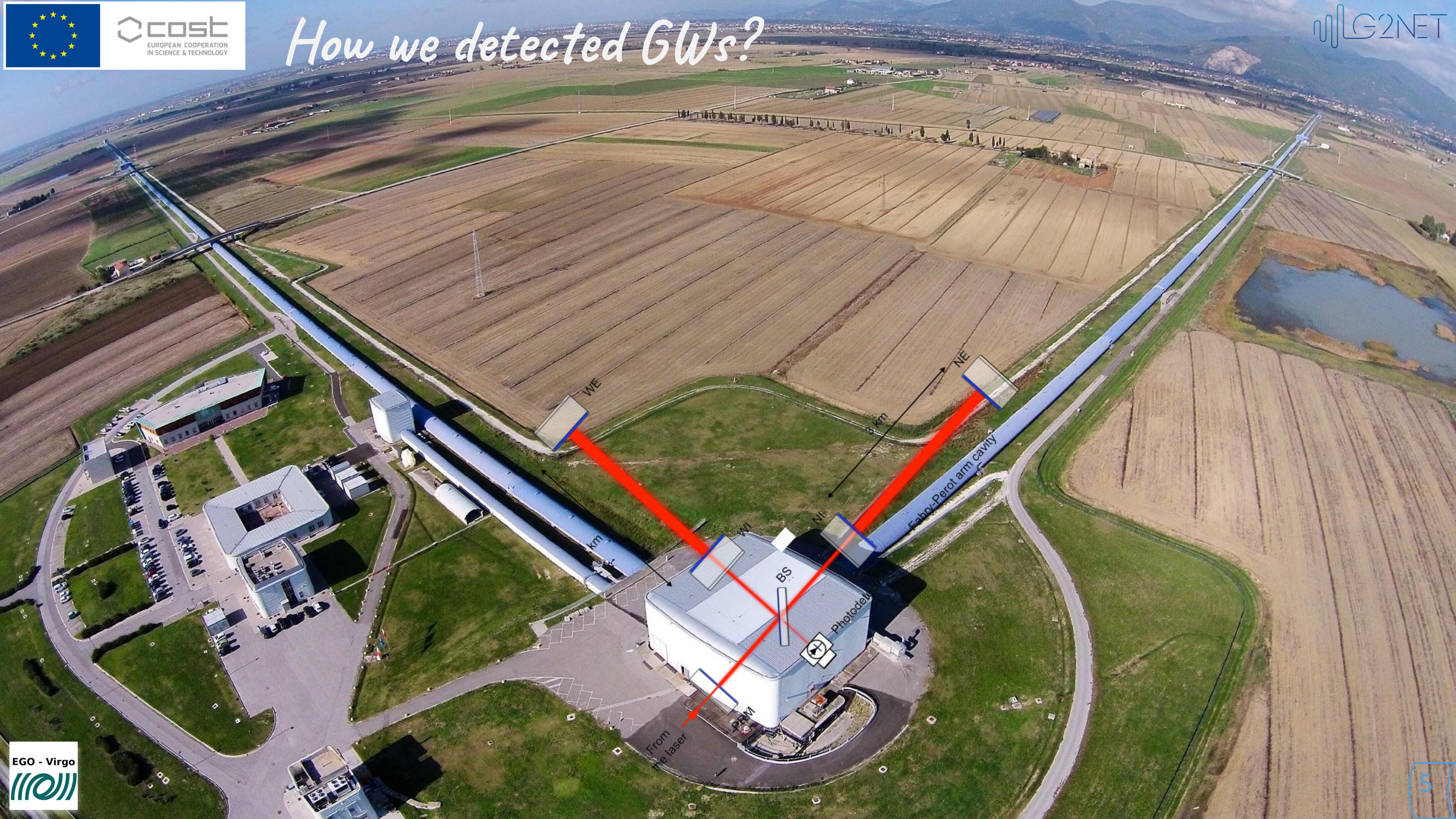
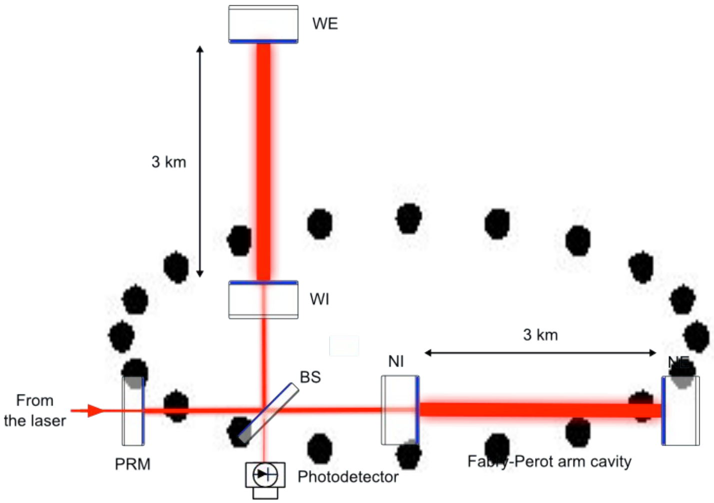
How we detected GWs?



GW detectors: a simple Michelson interferometer

1. Laser light is split in two orthogonal paths by a beam-splitter (BS). These are reflected back toward the BS by mirrors at the ends of the arms;
2. When recombined at the BS, **they interfere**. If the arms are exactly the same length (up to $n\lambda_L$), the light returns entirely toward the laser: destructive interference;
3. If the arms differ by an amount that is not an integer number of wavelengths, then the destructive interference will be incomplete: light passes to the photodiode (PD)



Estimated sensitivity (I):

Nd:YAG laser:
$\lambda_L = 1064$ nm

$$h \approx \frac{\Delta L}{L} \sim \frac{\lambda_L}{L} \sim 10^{-9}$$

$L \sim 1$ km

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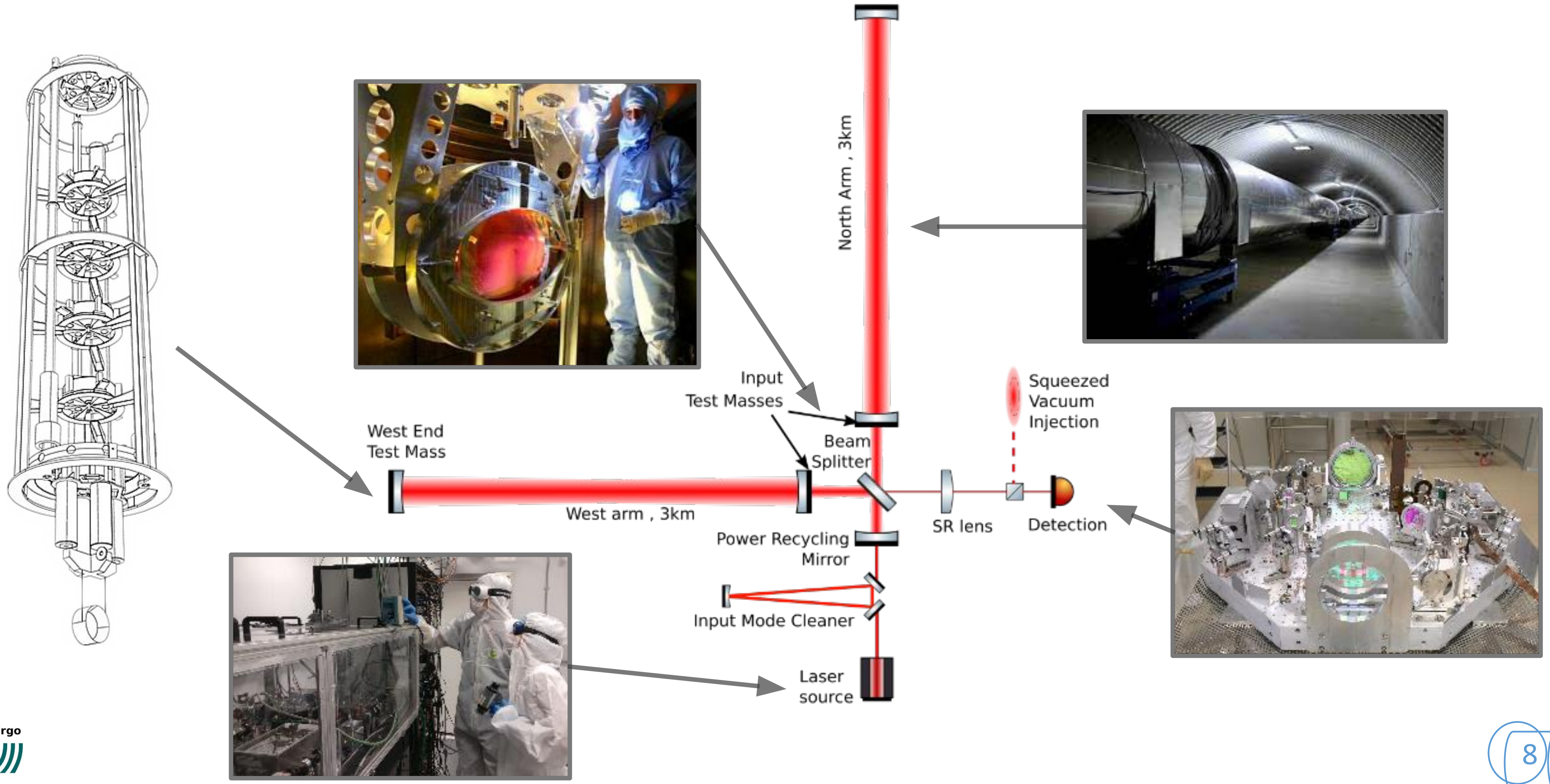
How we detected GWs?

The Advanced Virgo detector



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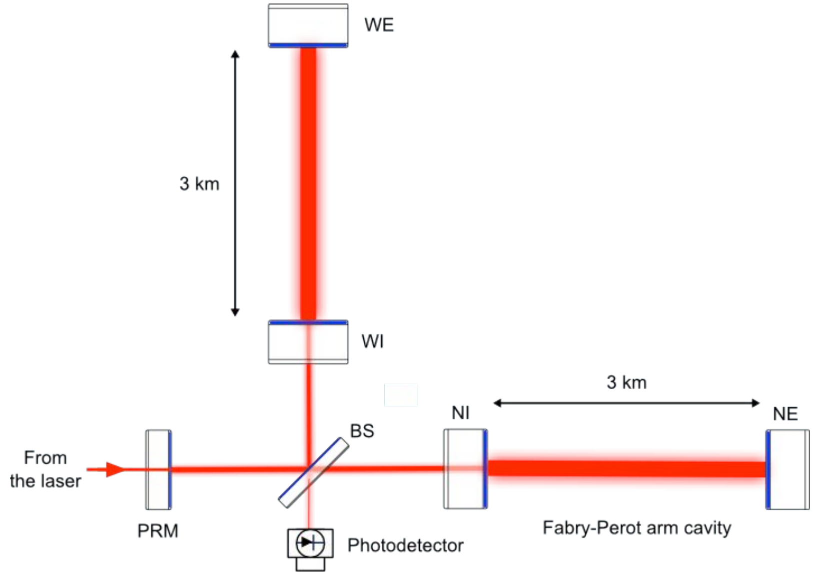
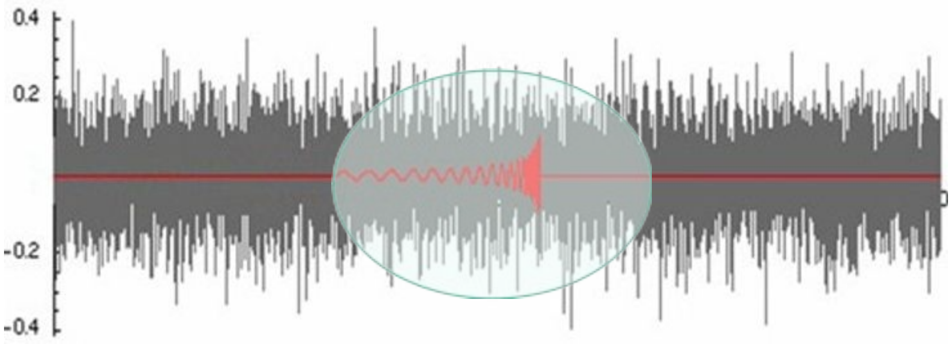
GW detector data



Time series sequences… noisy time series with low amplitude GW signal buried in



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Frequency dependent strain sensitivity

Detector noise is conveniently described as a **stochastic process.** Its dominant contributions can be overall assumed to be **stationary and Gaussian**.

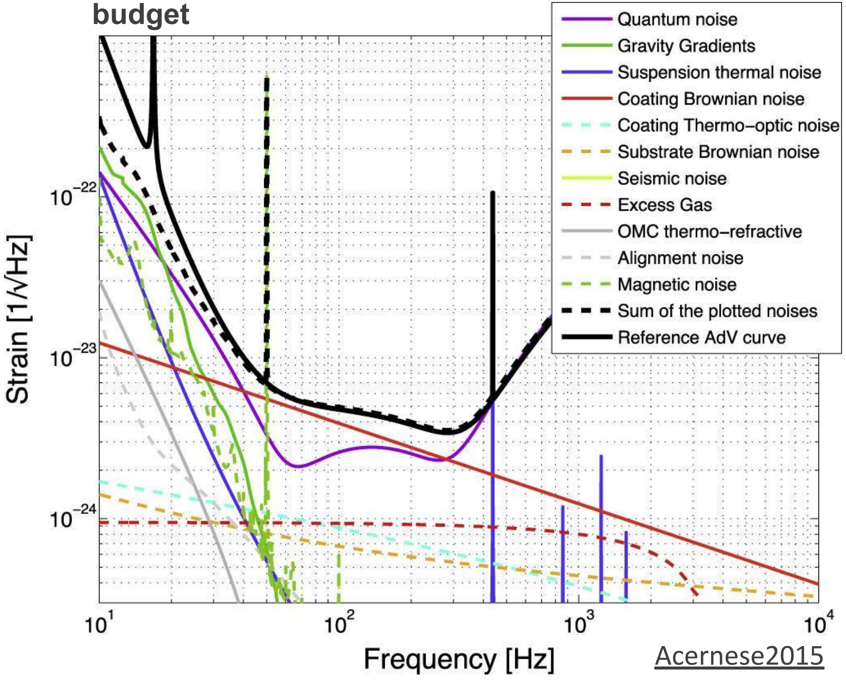
⇒ Its statistical properties are fully characterized by its **correlation matrix**, or, equivalently, by the **Power Spectral Density (PSD)**;

⇒ Its Amplitude Spectral Density (ASD, square root of the PSD) provides a frequency-dependent measure of the detector sensitivity.

Noise sources and limitations to the sensitivity

- Fundamental noises: from the physical limitation of the detection principle and its implementation (continuous lines);
- Technical noises: from the actual implementation of the detector with components that are *not optimal*, have imperfections (dashed lines, only for ~stationary ones);

Advanced Virgo reference sensitivity and noise budget



Acernese2015

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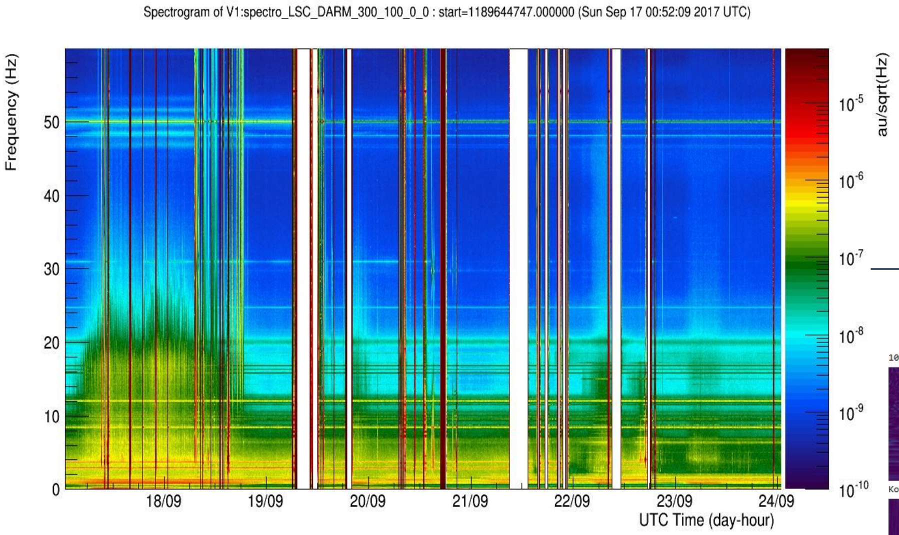
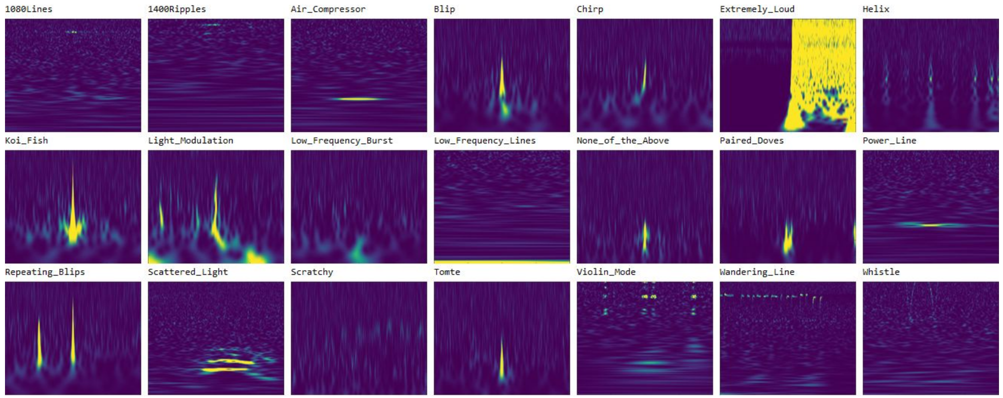
Detector Noise



Broadband



Glitches

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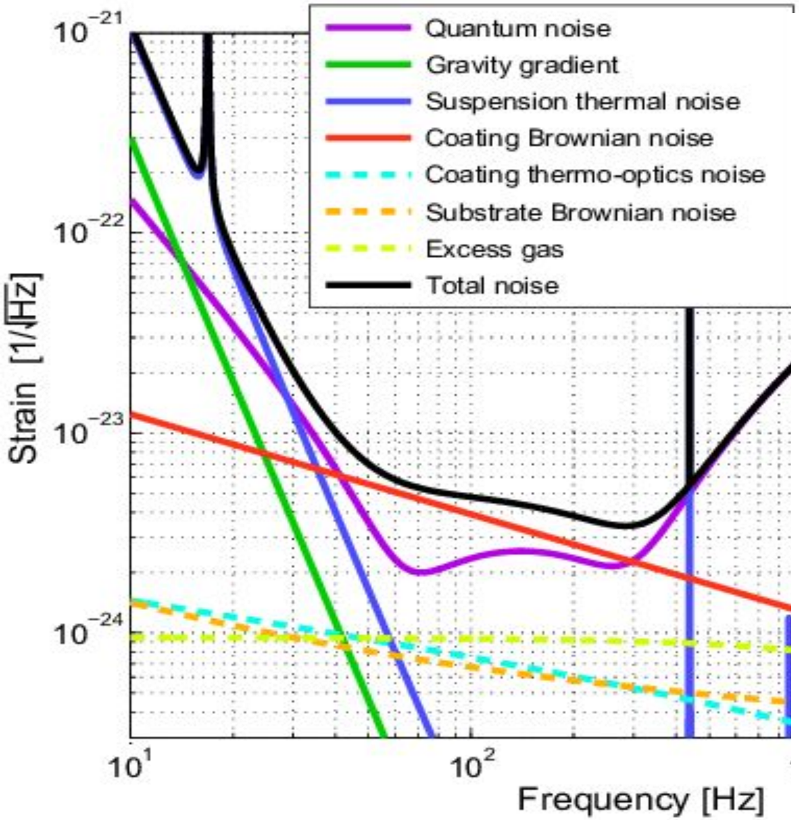
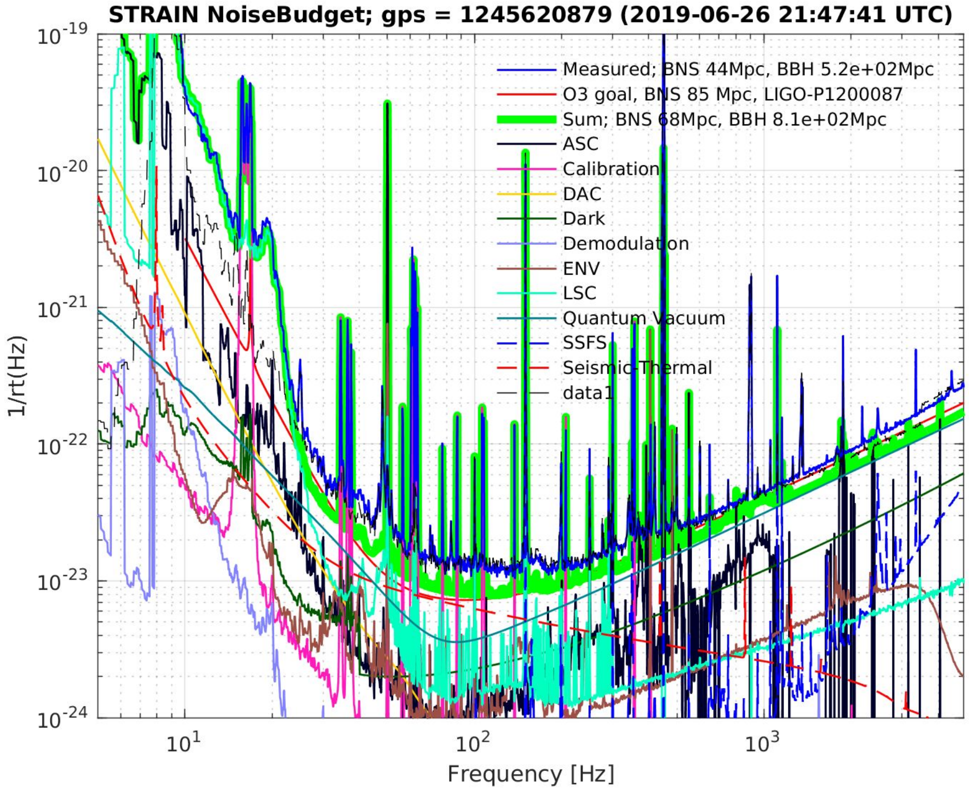
Gravity Spy, Zevin et al (2017) https://www.zooniverse.org/projects/zooniverse/gravity-spy

Noise budget: fundamental vs. actual





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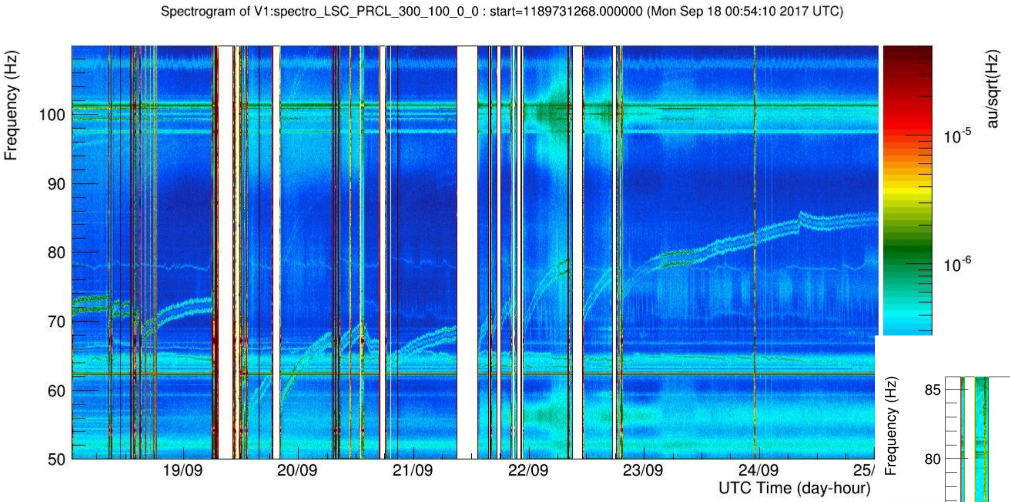
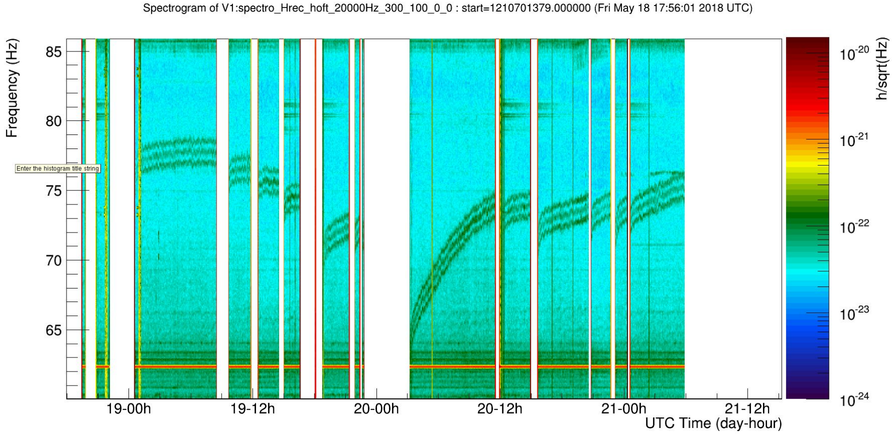
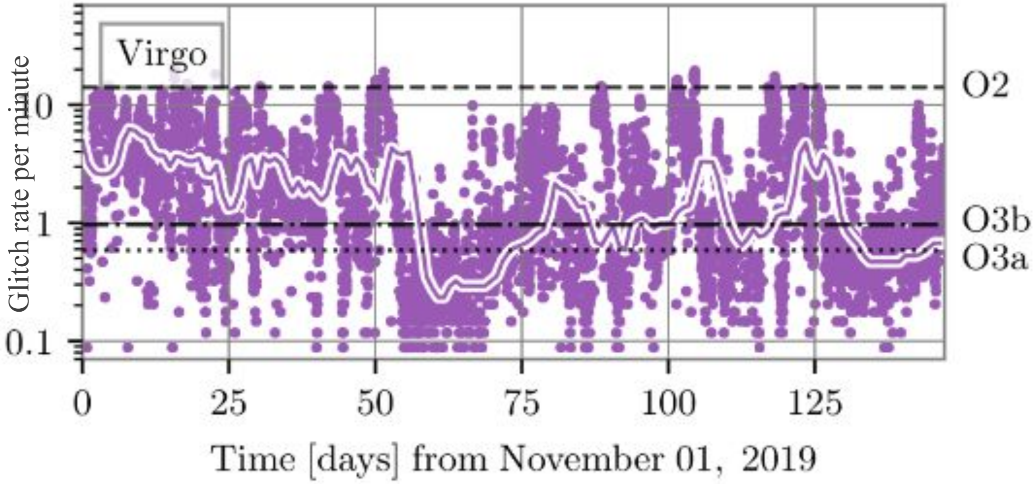
Non linear noise...

Here Machine Learning can help

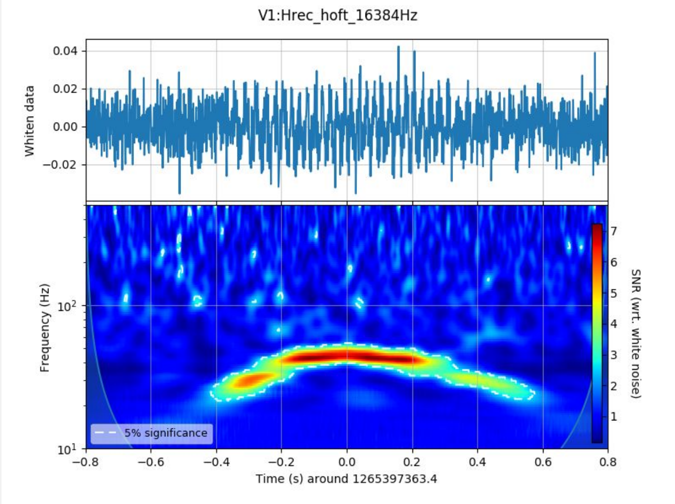




Non-stationary and transient noise



Example of Scattered light glitch



Here Machine Learning can help

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The matched filter technique and the BNS range

Additive noise model:

$$\underbrace{x(t)}_{\text{detector data}} = \underbrace{n(t)}_{\text{noise}} + \underbrace{s(t)}_{\text{signal}}$$

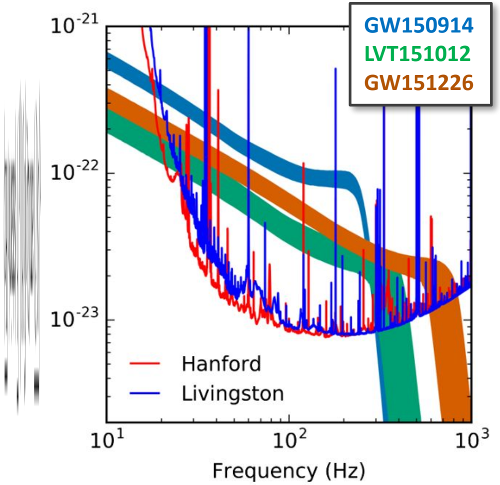
Signal model:

$$s(t) \approx \varrho h(t)$$

with ϱ the amplitude and $h(t) = h(t;\boldsymbol{\theta})$ the waveform model ($(\boldsymbol{h}|\boldsymbol{h}) = 1$).

Optimal detection statistic: likelihood ratio, in stationary and Gaussian noise equivalent to:

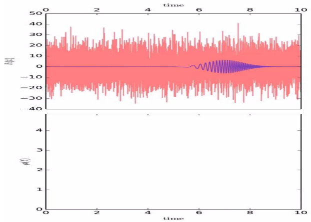
$$\boxed{(\boldsymbol{x}|\boldsymbol{h}) = 4\,\Re \int_0^\infty \frac{\tilde{x}(f)\tilde{h}^*(f)}{S(f)}\,df}$$



Phys. Rev. X 6, 041015

Compact binary inspiral range [Bassan2014]:

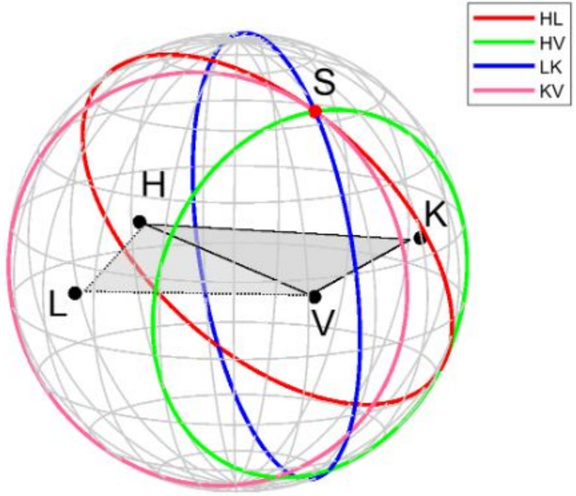
$$\frac{d_{\text{range}}}{1\ \text{Mpc}} = \frac{1}{2.26} \times 1.95 \times 10^{-20} \left(\frac{\mathcal{M}}{M_\odot}\right)^{5/6} \sqrt{\int_{f_{\min}}^{f_{\text{ISCO}}} \frac{f^{-7/3}}{S(f)}\,df}$$



International Collaboration: ground based detectors

Why more than 1 detector?

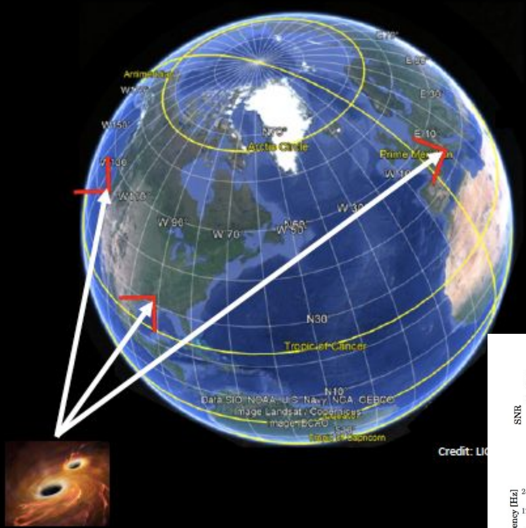
- Source localization using only timing for a two-site network yields an annulus on the sky.
- For three detectors, the time delays restrict the source to two sky regions which are mirror images with respect to the plane passing through the three sites.
- <u>With four or more detectors</u>, timing information alone is sufficient to localize to <u>a single sky region</u>, and the additional baselines help to limit the region to under 10 <u>deg^2 for some signals.</u>



arXiv:1304.0670

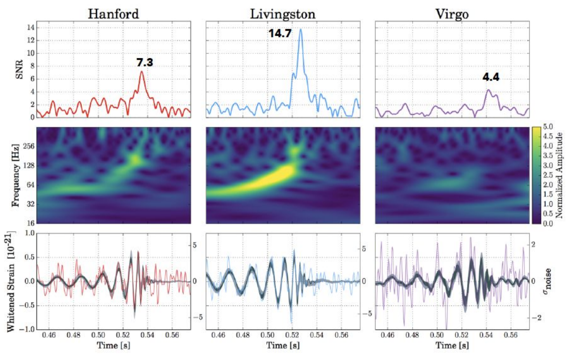
- 2 detector → 100 -1000 deg^2
- 3 detector → 10 - 100 deg^2
- 4 detector → < 10 deg^2

GW170814: The first triple detection



Credit: LIG

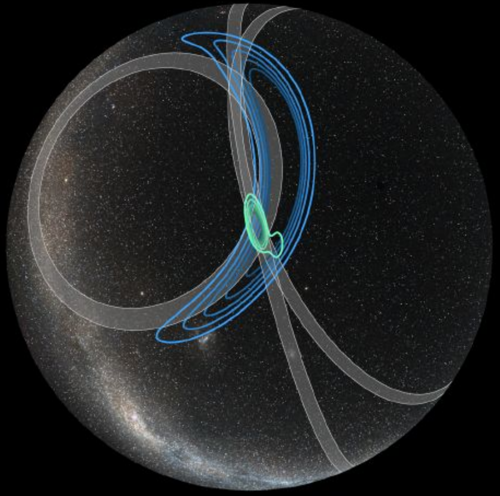
Virgo observed its first BBH coalescence ,GW170814



3-detector network SNR: 18.3

PRL, 119, 141101 (2017)

IFAE MiB, April 4th, 2018 G Losurdo - INFN Pisa 18

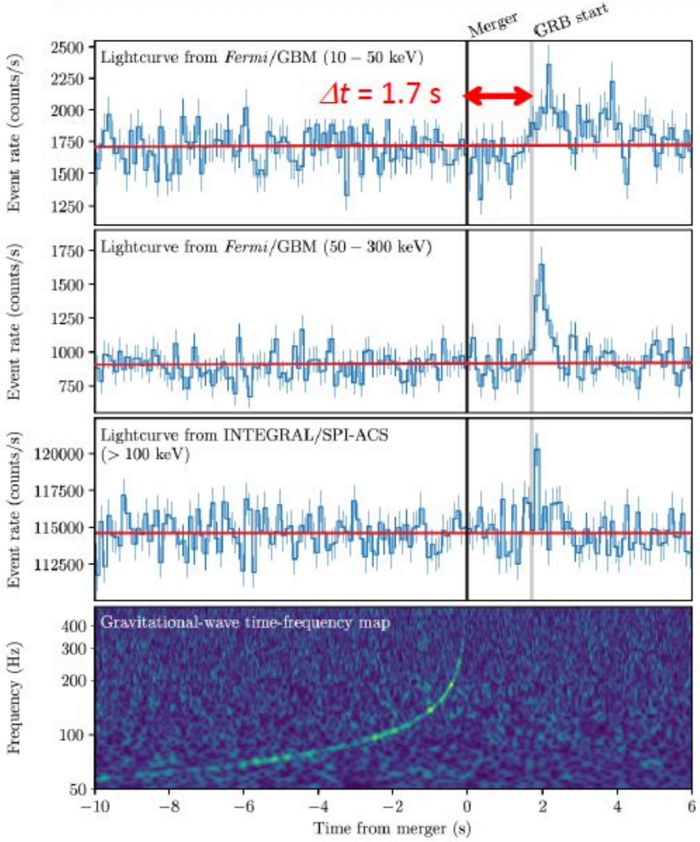


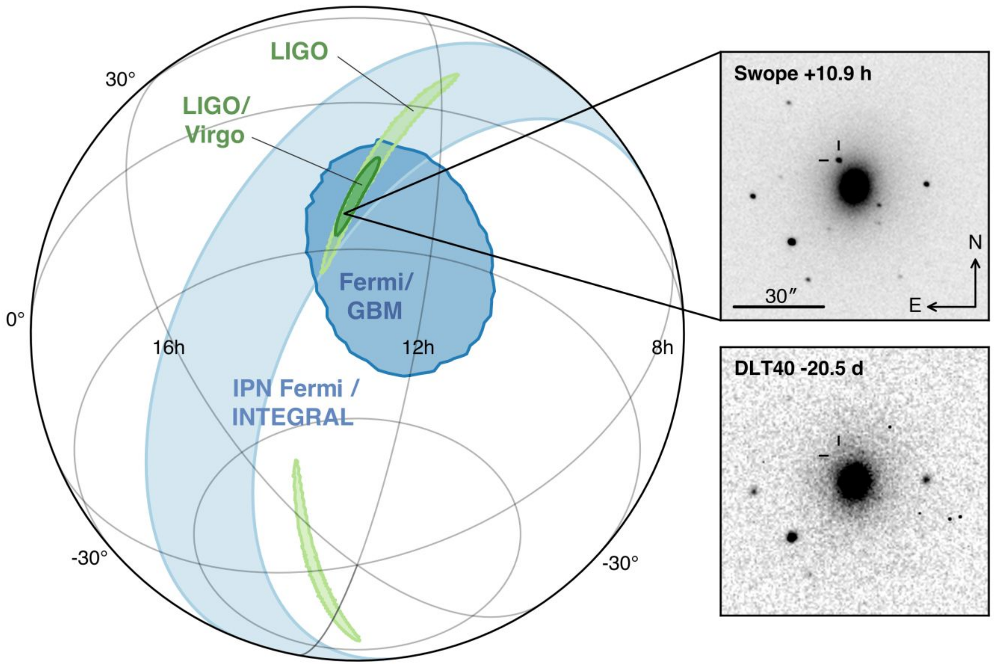
Credit: Leo Singer

LH 1160 square degrees
LHV 60 square degrees

Phys. Rev. Lett. 119, 141101 (2017)

GW170817: 17 August 2017, 12:41:04 UT: The Multi-Messenger Astronomy





B.P. Abbott et al. (LIGO Scientific Collaboration and Virgo Collaboration)
Phys. Rev. Lett. 119, 161101 – Published 16 October 2017

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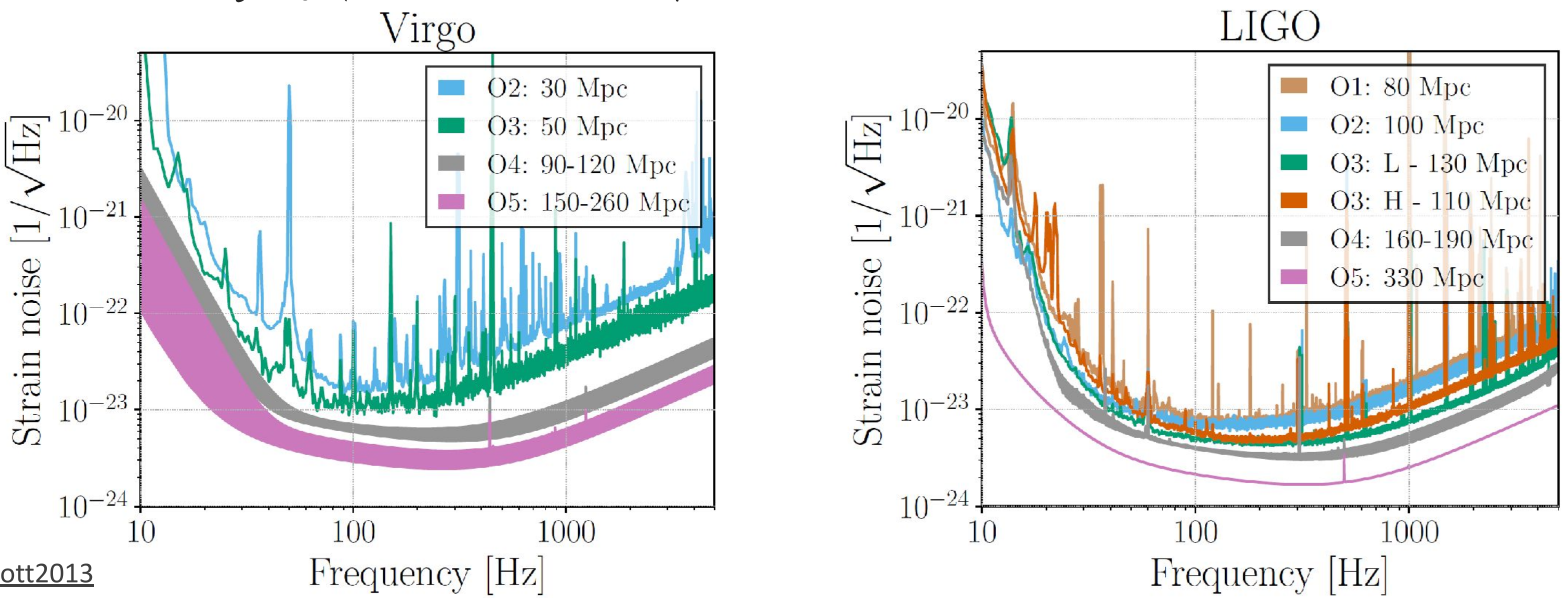
Detector sensitivities and their evolution

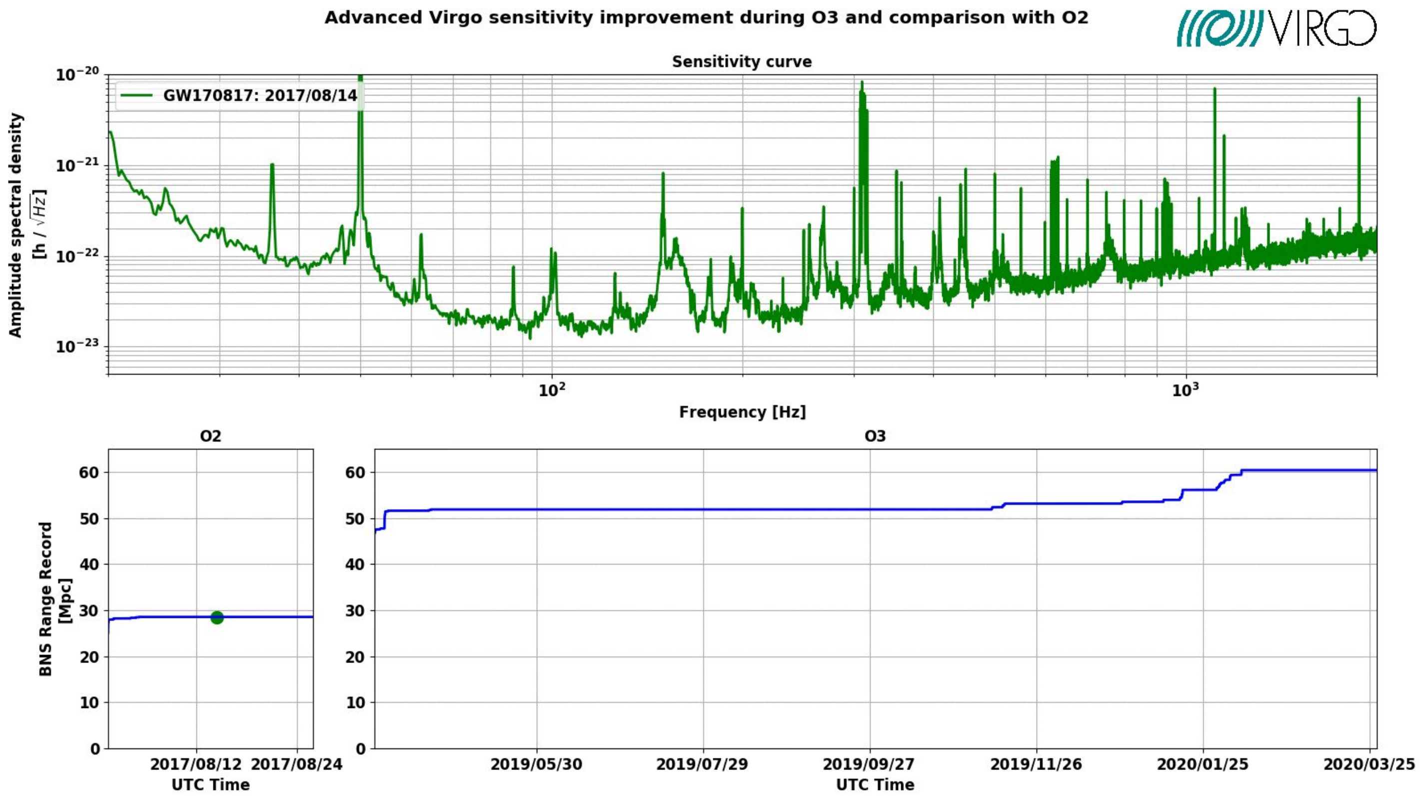
"Spikes" (spectral lines) in the strain sensitivity include technical noises not included in the noise budget at the previous page;

"Bumps" are usually a symptom of non-stationary or non-linear contributions to the noise.



Abbott2013

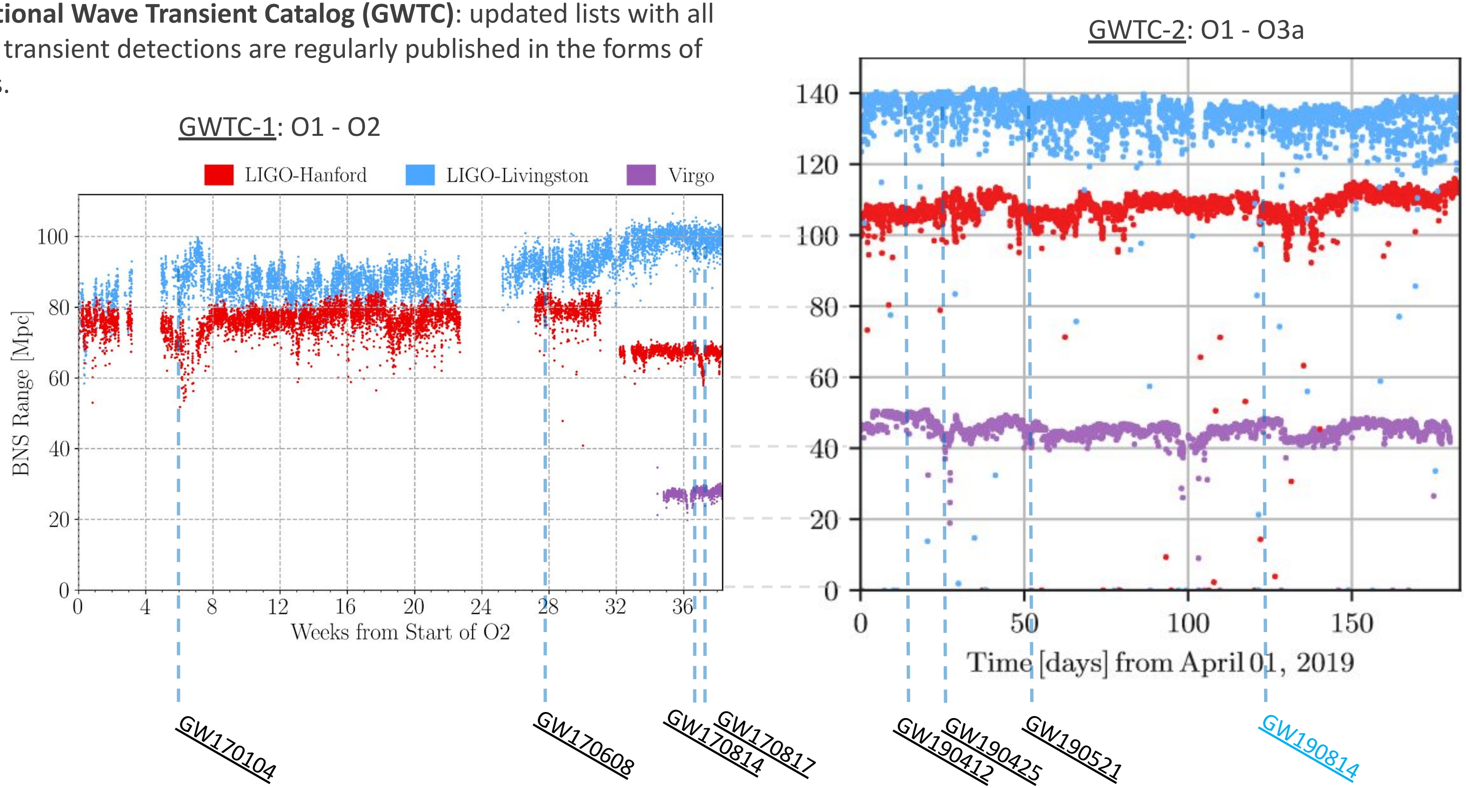
Advanced Virgo sensitivity from O2 to O3b



VIR-0462A-20

Increase in BNS range from O2 to O3a

Gravitational Wave Transient Catalog (GWTC): updated lists with all the GW transient detections are regularly published in the forms of catalogs.



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The effective BNS Volume

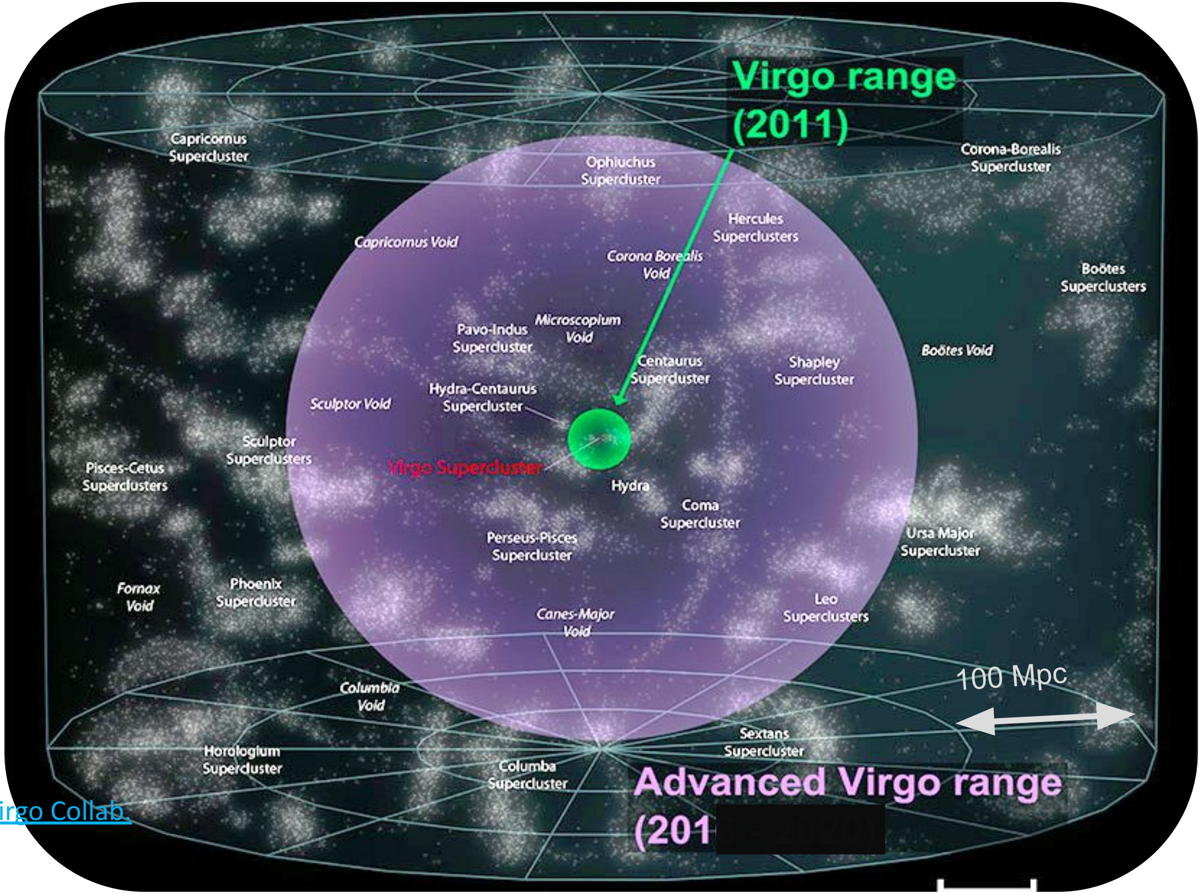

Image Credit: [Virgo Collab.]

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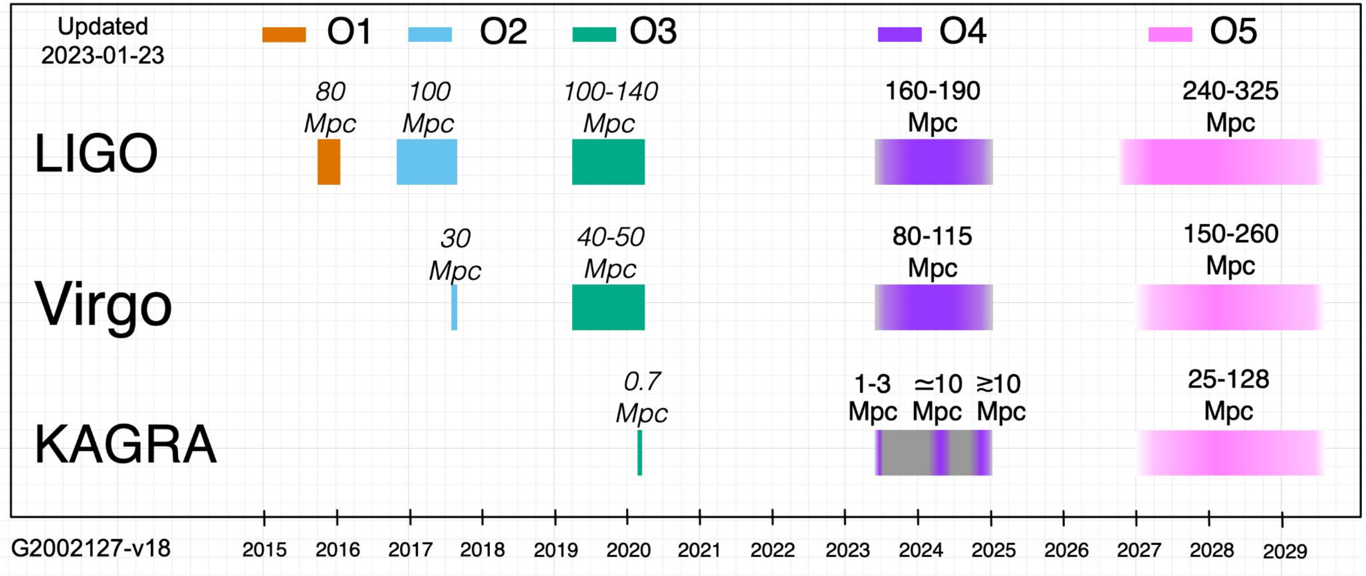
Quantifying the detector performance

The detector **strain sensitivity** is the minimum *detectable* value of the strain produced by an incoming GW:

⇒ It is determined by the **detector noise**.

BNS inspiral range: the distance, averaged over GW polarizations and directions in the sky, at which a single detector can observe with matched-filter Signal-to-noise Ratio (SNR) of 8 the inspiral of two neutron stars.



https://observing.docs.ligo.org/plan/

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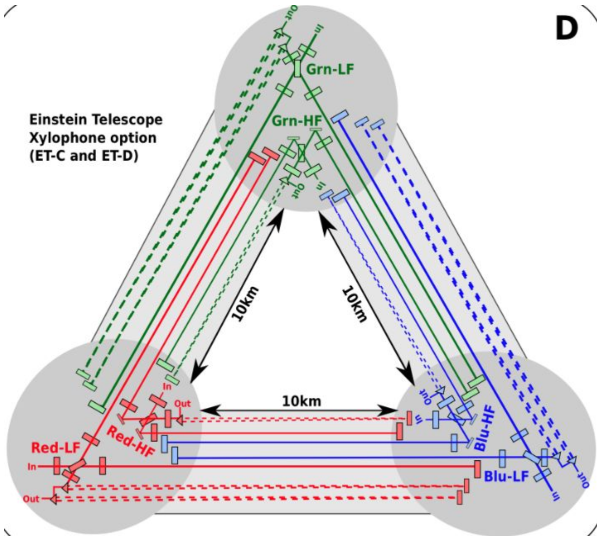
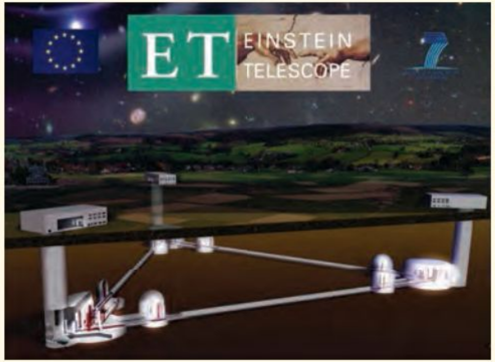
The European 3G idea

In Europe we developed the idea of a 3G GW observatory



The Einstein gravitational–wave Telescope (ET)



ET [7] is a concept for a third generation gravitational-wave *observatory* likely with a location in Europe. To reduce the effects of seismic motion, the ET concept calls for the site to be located at a depth of about 100 m to 200 m below ground. In its final configuration it shall be arranged as an equilateral triangle of three interlaced detectors, each consisting of two interferometers. The configuration of each detector dedicates one interferometer (ET-LF) to detecting the **L**ow **F**requency components of the gravitational-wave signal (2–40 Hz), while the other one (ET-HF) is dedicated to the **H**igh **F**requency components. Each interferometer will have a dual-recycled Michelson layout with about 10 km long Fabry-Perot arm cavities. In ET-LF, which operates at cryogenic temperature, thermal, seismic, gravity gradient and radiation pressure noise sources are particularly suppressed; in ET-HF, sensitivity at high frequencies is improved by high laser light power circulating in the Fabry–Perot cavities and the use of frequency-dependent squeezed light technologies.

https://gwic.ligo.org/3Gsubcomm

The European 3G idea

Euregio Meuse-Rhin

SOS Enattos
Sardaigne (Italy)

https://gwic.ligo.org/3Gsubcomm

3G effort worldwide

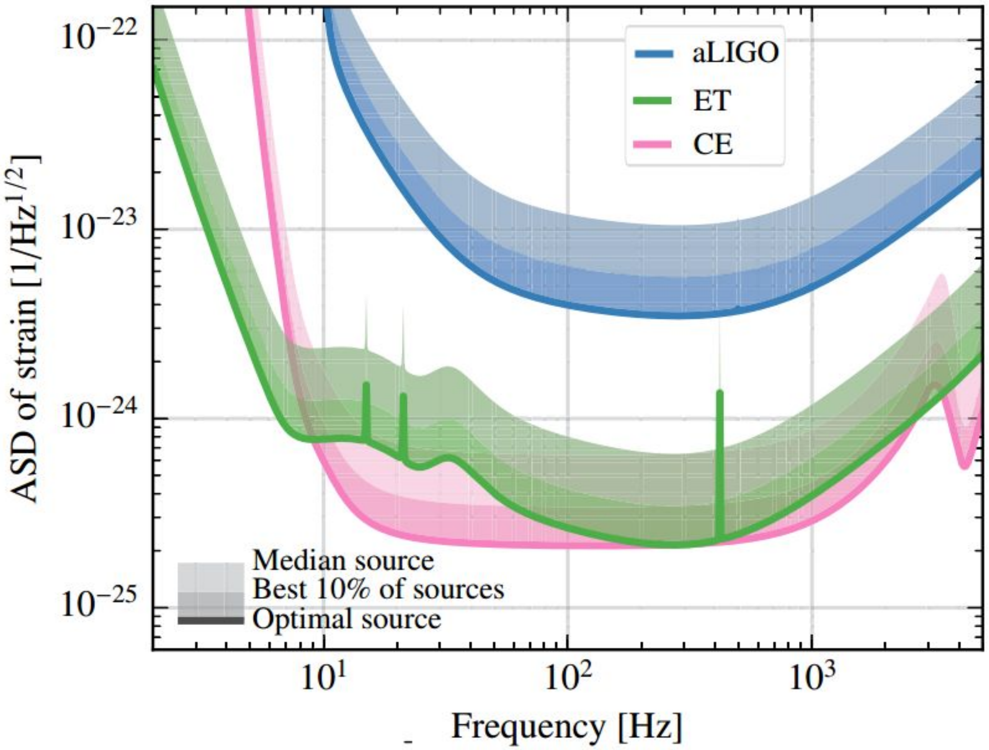
Cosmic Explorer (CE)

CE [8] is a concept for an L-shaped above-ground observatory with 40 km arm-length, operating a dual recycled Michelson interferometer with Fabry–Perot arm cavities, with possible site location in the US or/and in Australia. Its initial phase, called CE1, will employ scaled-up *Advanced LIGO technology* including 320 kg fused silica test masses, 1.4 MW of optical power, and frequency-dependent squeezing. A major upgrade, CE2, will exploit the full potential of the new facility by using *Voyager technology* such as silicon test masses and amorphous silicon coatings operating at 123 K, with 1.5 or 2 μm laser light and 3 MW of optical power in its arm cavities.

NSF funded in 2018 the Conceptual Design Study of a 3G facility: Cosmic Explorer: 40km – L shaped detector

ET and CE sensitivity

[3G R&D: Research and Development for the Next Generation of Groundbased Gravitational-wave Detectors]()



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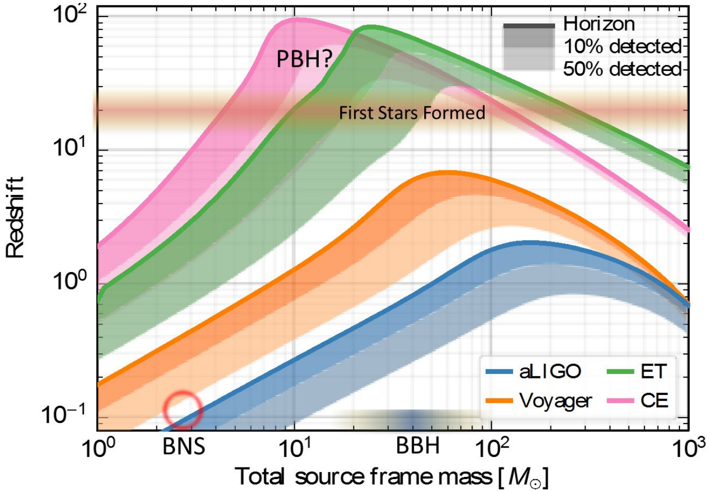
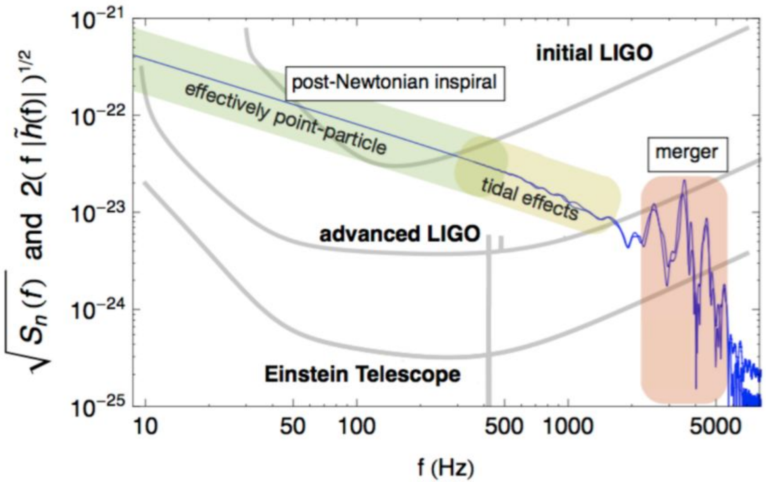
Science case with 3G detectors

From [The Next-Generation Global Gravitational-Wave Observatory: New Astrophysics with the Farthest, Oldest, and Most Violent Events in the Universe](#) : With 3G GW observatories ten times more sensitive than current instruments we will investigate the fundamental physics of the primeval Universe and probe its dark sectors

- Primordial BH
- BBH merger from globular clusters
- Intermediate massive BH
- Star formations
- GRB from BNS/BHNS at high z
- Post merger phase



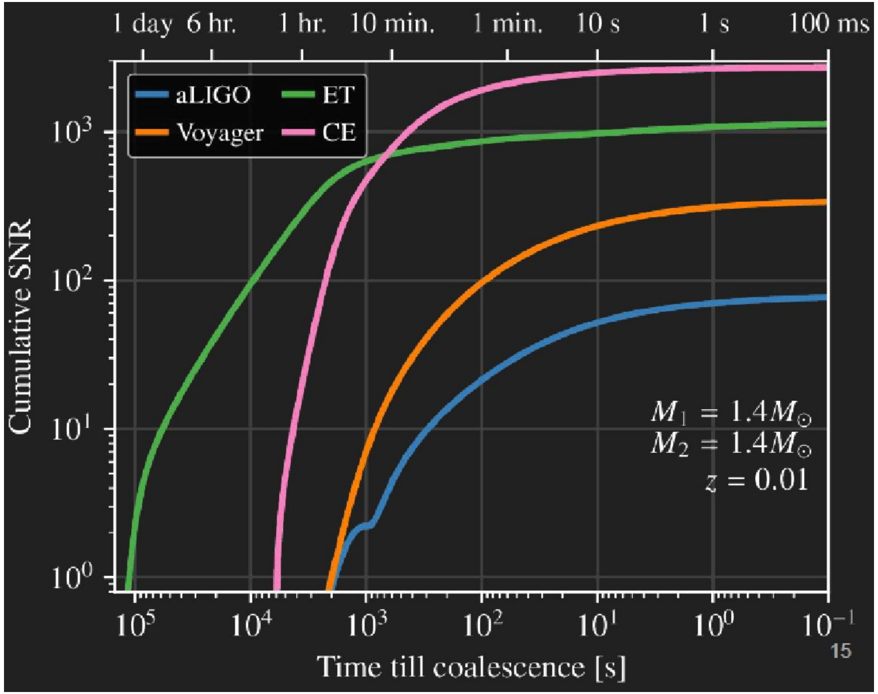


https://arxiv.org/pdf/1912.02622 M.Maggiore et al.

Early warning

Time before the merger

This will enhance the Multimessenger physics



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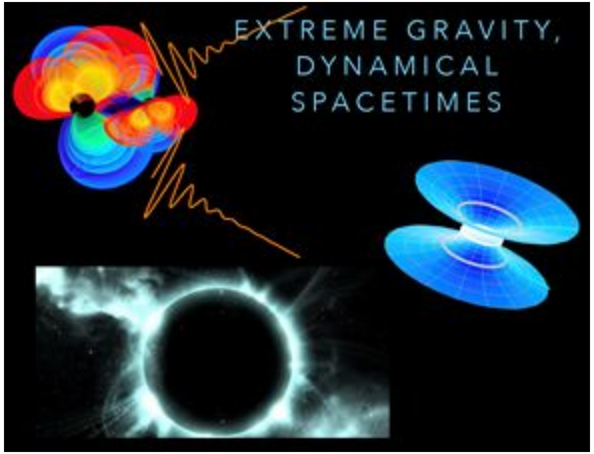
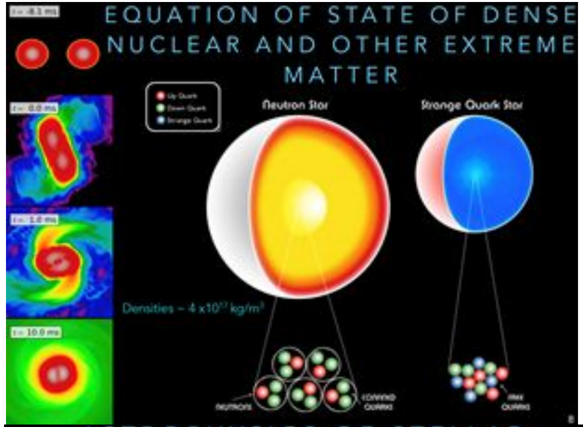
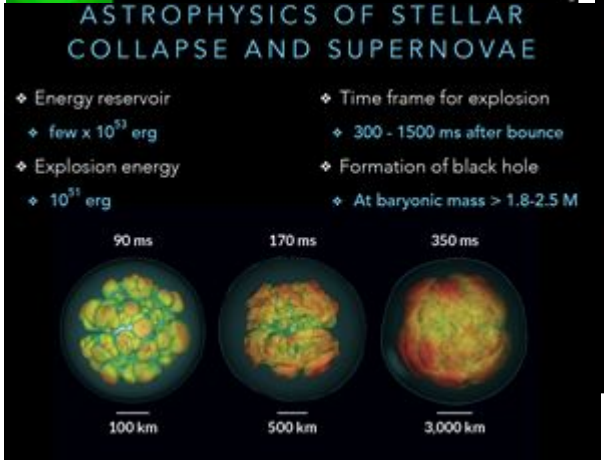
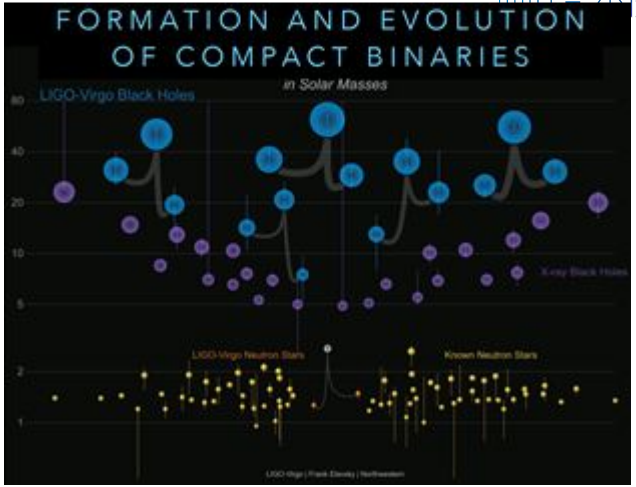
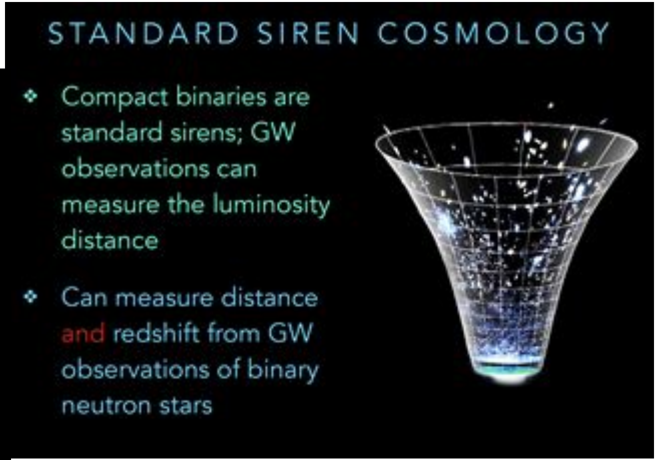
GW and Fundamental science









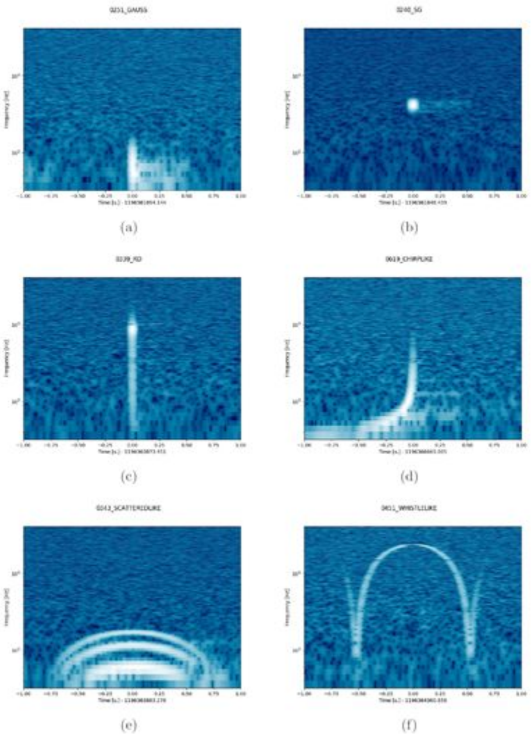


How Machine learning could help Gravitational Wave Science?

Control system and noise cancellation

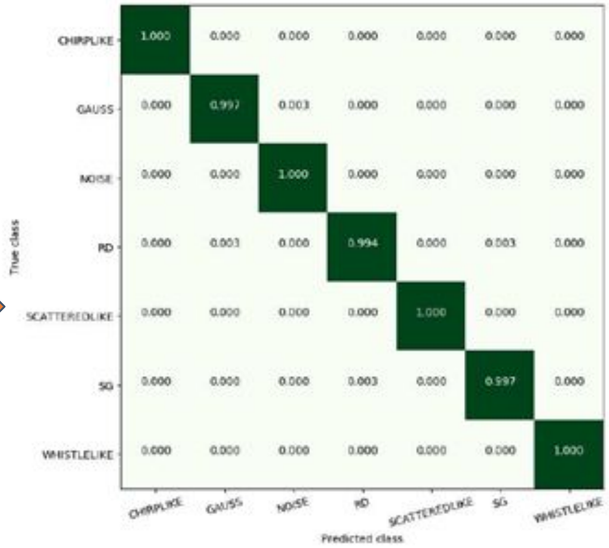
- Adaptive control
- Newtonian Noise removal
- Not stationary and Not linear noise identification
- Relation among main channels and auxiliary channels

Signal classification instead of Human vetting



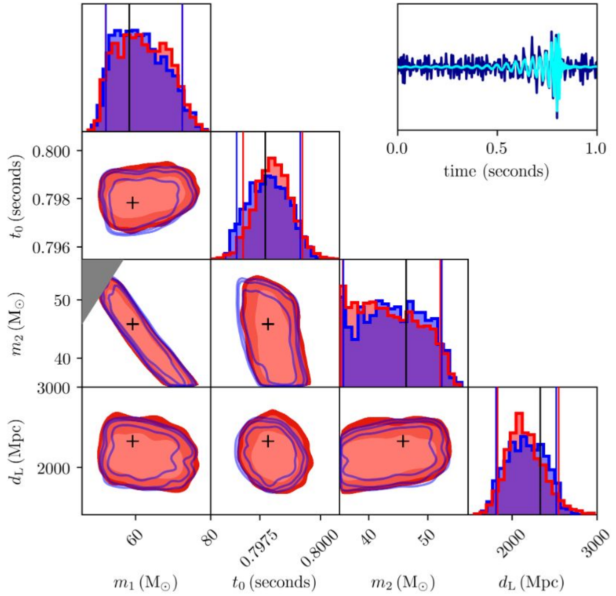
ML

More details in
Razzano & Cuoco 2018, CQG,35,9



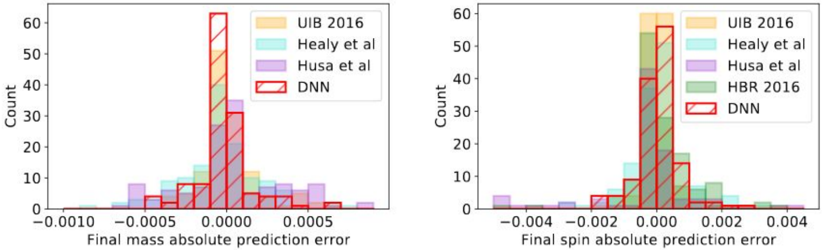
Faster in identifying noise versus signals

Fast Parameter estimation



Bayesian parameter estimation using conditional variational autoencoders for gravitational-wave astronomy

[Gabbard, Hunter](#) *et al.* arXiv:1909.06296



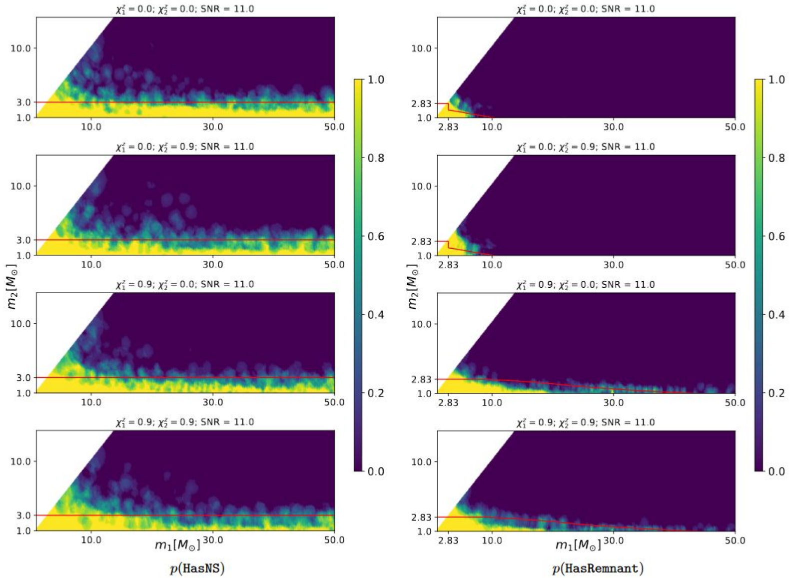
(a) $M_f^{DNN} - M_f^{NR}$ (b) $\chi_f^{DNN} - \chi_f^{NR}$

Figure 2: Residual error on the remnant mass $M_f(\eta, S_{eff}, \Delta\chi)$ (a) and spin $\chi_f(\eta, S_{eff}, \Delta\chi)$ (b) as predicted by the DNN for the non-precessing BBHs. Our error is compared with the fits performed by the UIB group in 2016 [6], Healy et al [34], Husa et al [12] and Hofmann, Barausse and Rezzolla (HBR) [13].

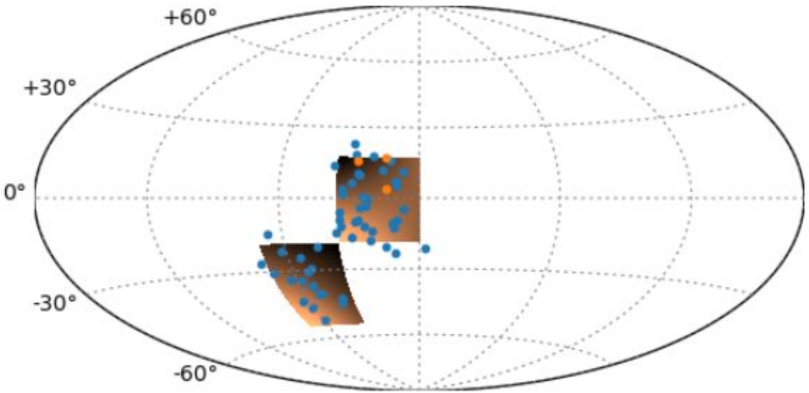
Predicting the properties of black holes merger remnants with Deep Neural Networks

[Leïla Haegel](#), [Sascha Husa](#), [arXiv:1911.01496](#)

Parameter estimation



and much more...



A Machine Learning Based Source Property Inference for Compact Binary Mergers

Deep Chatterjee, et al arXiv:1911.00116

Using Deep Learning to Localize Gravitational Wave Sources

Chayan Chatterjee, Linqing Wen, Kevin Vinsen, Manoj Kovalam, Amitava Datta
arXiv:1909.06367

EGO - Virgo

The future: Artificial Intelligence for 3G detectors

Many low SNR signals (overlapping signals)

Many transient noise disturbances (glitches)

Not stationary/not linear noise (strange noise coupling)

Many monitoring auxiliary channels ("big" data)

Computational and timing efficiency (Fast alert system)

We should think to new approach for our data analysis

Thank you

COST ACTION CA17137
A NETWORK FOR GRAVITATIONAL WAVES, GEOPHYSICS AND MACHINE LEARNING