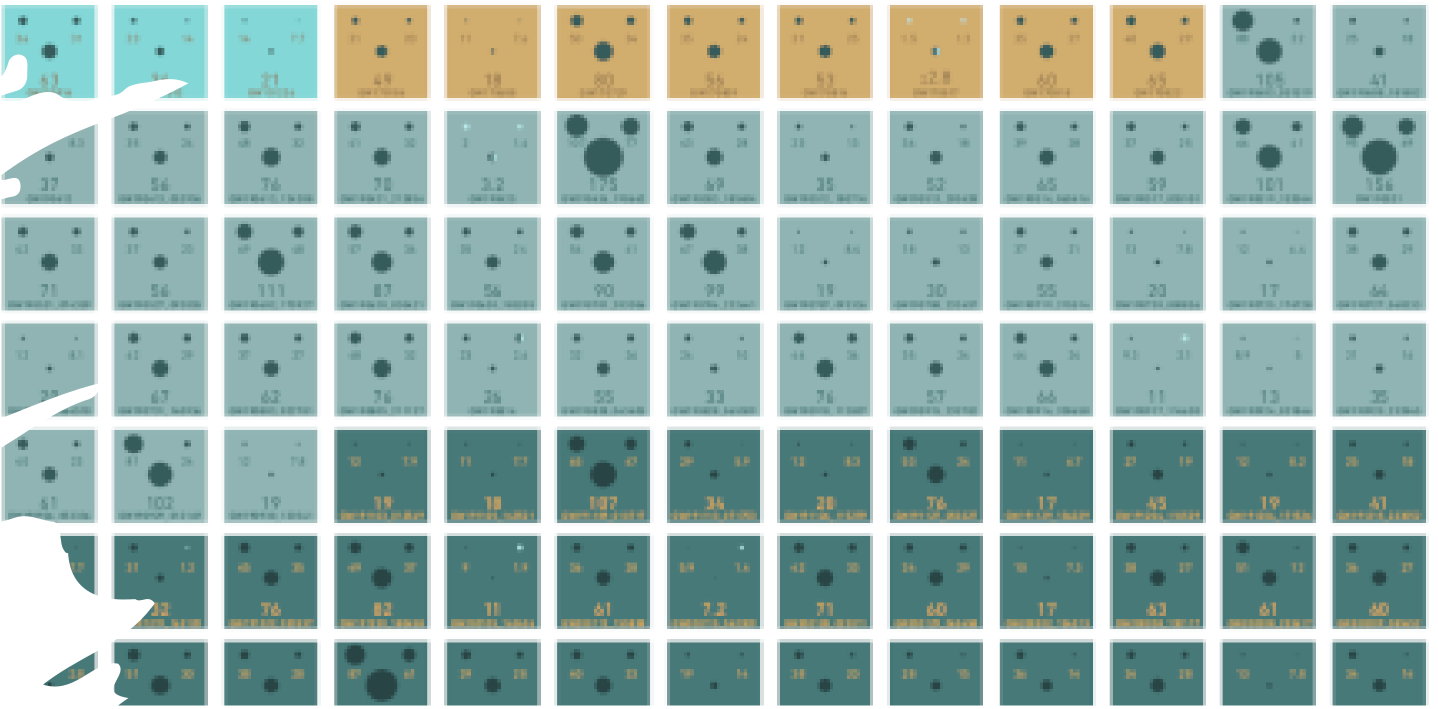
Gravitational waves and their role in multimessenger astrophysics



N. Sorrentino on behalf of the LVK collaborations

University of Pisa and INFN Pisa

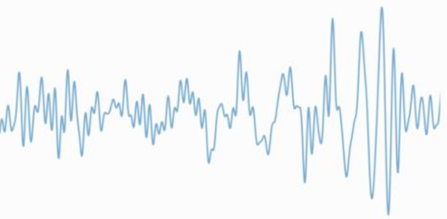
LSC LIGO Scientific Collaboration VIRGO KAGRA

SEXTEN HANDS ON THE EXTREME UNIVERSE
WITH HIGH ENERGY GAMMA RAYS
21/07/2022

SEXTEN CENTER FOR ASTROPHYSICS

UNIVERSITÀ DI PISA

INFN Istituto Nazionale di Fisica Nucleare



OUTLINE

1. GW theoretical background:
   1) Spacetime curvature and its perturbation;
   2) Wave solution and its effect on test masses;
   3) Accelerating massive objects and GW emission.
2. GW detectors and observations:
   1) First generation: from Michelson interferometer to Advanced GW detectors;
   2) Second generation: Advanced LIGO , Advanced Virgo and GW170817;
   3) Improvement of sensitivity and GW catalogues.
3. Updates and work in progress:
   1) Get ready for the future data collection;
   2) Way to the third-generation detector: the Einstein Telescope.

«The gravitational field is not diffuse in space: the gravitational field is space. This is the idea of the theory of general relativity.» (C. Rovelli)

EINSTEIN EQUATION

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Spacetime curvature

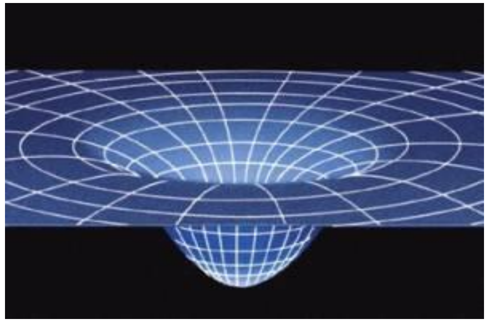
Dimensional scale factor:
$\sim 2 \times 10^{-43} \frac{s^2}{kg\ m}$

Energy Density Tensor

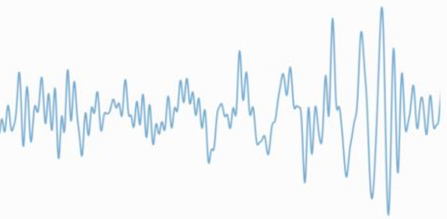
LINEARIZED PERTURBATION THEORY

$$g_{\mu\nu} \approx \eta_{\mu\nu} + h_{\mu\nu} \ ; h_{\mu}^{\mu} \ll 1 \quad \longrightarrow \quad \Box h_{\mu\nu} = -\frac{16\pi G}{c^4} T_{\mu\nu}$$

D'Alembert Operator



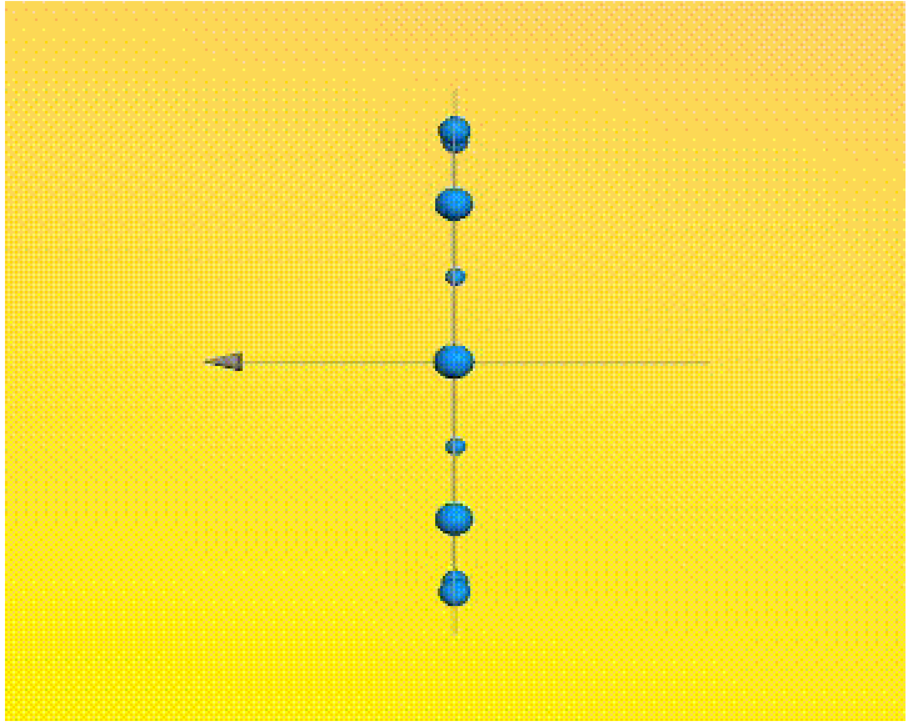
The metric perturbation is traveling at speed of light (**c**) along $\vec{k}$ direction.
This wave solution is what we call **Gravitational Wave (GW)**.



GW PHYSICAL PROPERTIES

Consider **free propagation** in spacetime $x^{\mu} = (ct, \vec{x})$ in vacuum ($T_{\mu\nu} = 0$):

$$\square h_{\mu\nu} = 0 \implies h_{\mu\nu} = A_{\mu\nu} e^{ik^{\mu}x_{\mu}} \quad \text{where} \;\; k^{\mu} = (\omega/c\,, \vec{k})$$



The linearized Einstein equation results in a wave equation in **Lorenz Gauge**:

$$\frac{\partial h^{\mu\alpha}}{\partial x^{\mu}} = 0$$

$A_{\mu\nu}$ is the amplitude tensor factor, which perturbation affect spacetime geodetics on **transverse plane**.
Are GW physical or artifacts of the gauge choice?

- $h_{+} = \frac{1}{2}(A_{11} - A_{22});$
- $h_{\times} = A_{12} = A_{21};$

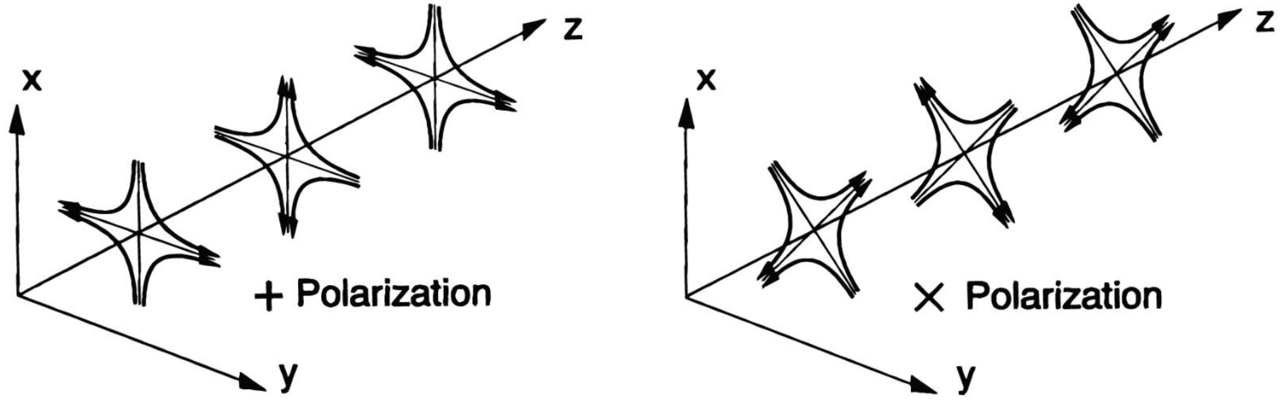
$\ddot{h}_{+,\times}$ are gauge-invariant quantities **[1, 2]**

TRANSVERSE TRACELESS (TT) GAUGE

The remaining gauge freedom is chosen to be traceless and purely spatial (assume **z-propagation**):

$$h_{ij}^{\mathrm{TT}}(t,z) = \begin{pmatrix} h_+ & h_\times & 0 \\ h_\times & -h_+ & 0 \\ 0 & 0 & 0 \end{pmatrix} \cos[\omega(t - z/c)] \qquad \textit{if} \qquad \vec{k} = (0,0,\omega/c)$$

"Free falling" geodetics of test masses: $\left.\frac{d^2x^i}{d\tau^2}\right|_{\tau=0} = 0$, remain at rest even after wave passage **[2].**



TT gauge $\longrightarrow h_{ij}^{\mathrm{TT}}$ valid for generic superposition of monochromatic plane waves with 2 independent polarization modes (h_+, $h_\times$);

GW EFFECT ON TEST MASSES

h_+ propagating in Z direction, masses free on X-Y plane:

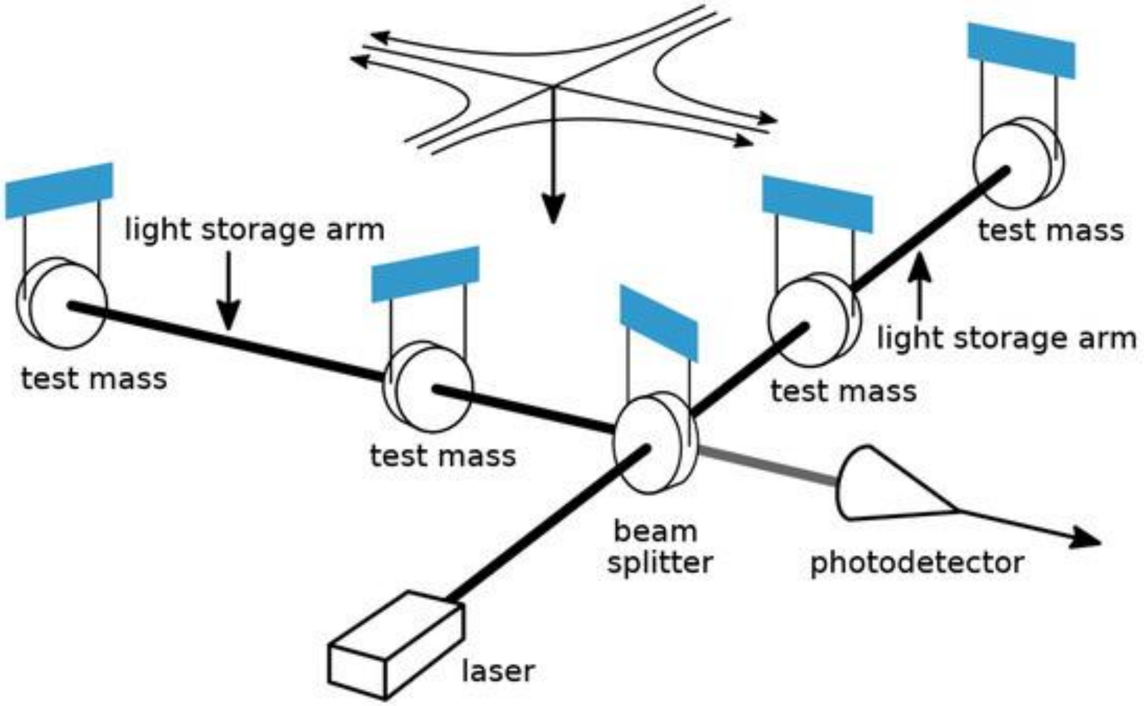


Image from [3]

In **DETECTOR REFERENCE FRAME**, mass coordinate separation is proportional to $\ddot{h}_+$ [2]. In TT gauge GW affect the light propagation for masses at distance L. Propagation on x axis and then back again:

$$\overset{\to 0}{ds^2} = -c^2dt^2 + [1 + h_+ \cos[\omega(t - z/c)]]dx^2$$

$$1/\omega \gg L \quad \longrightarrow \quad \Delta t \cong \frac{L}{c} h_+ \cos(\omega t)$$

Phase difference at photodetector in case of two interferometric light rays (Michelson):

$$\Delta\phi_{\ Mich} = \Delta\phi_{\ x} - \Delta\phi_{\ y} = 2\Delta\phi_{\ x} = \frac{2\pi}{\lambda_{laser}} 2\Delta t c = \frac{4\pi L}{\lambda_{laser}} h_+ \cos(\omega t)$$

GW EMISSION FROM ENERGY DISTRIBUTION

- GW emission of non-relativistic sources ($v \ll c$) with size R ($1/\omega \gg R$) at distance r **[1, 2]**:

$$h_{\mu\nu}(t) \approx \frac{2}{r}\frac{G}{c^4}\ddot{I}_{\mu\nu}(t - \tfrac{r}{c})$$

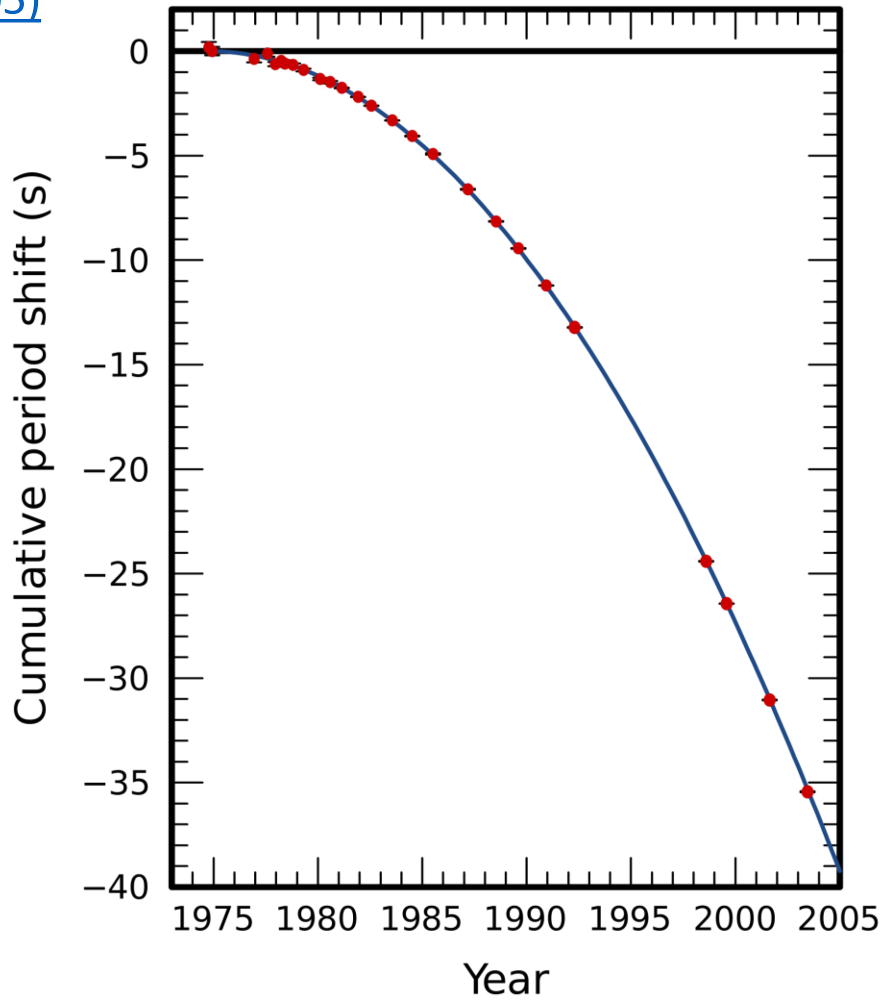
- Energy tensor leaded by mass density;
- GW leaded by **quadrupole moment** $\ddot{I}_{\mu\nu}$ **radiation**;

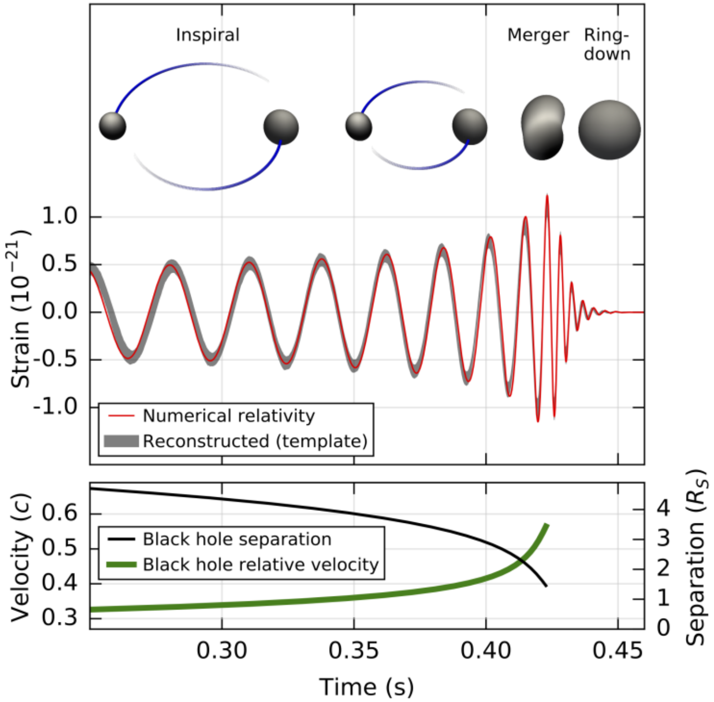
For an orbiting binary pulsar systems (right figure):

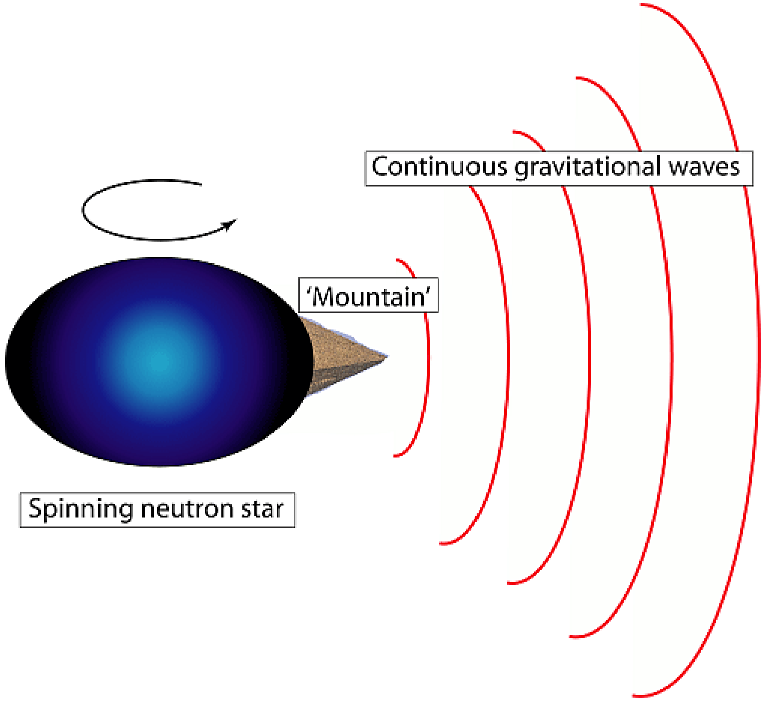
$$I \approx MR^2, \ddot{I} \approx 4MR^2\omega_{orb}^2,$$

$$h \approx \frac{8G}{c^4}\frac{M}{r}R^2\omega_{orb}^2 \approx 10^{-21} \quad \text{at} \quad \omega = 2\omega_{orb}$$

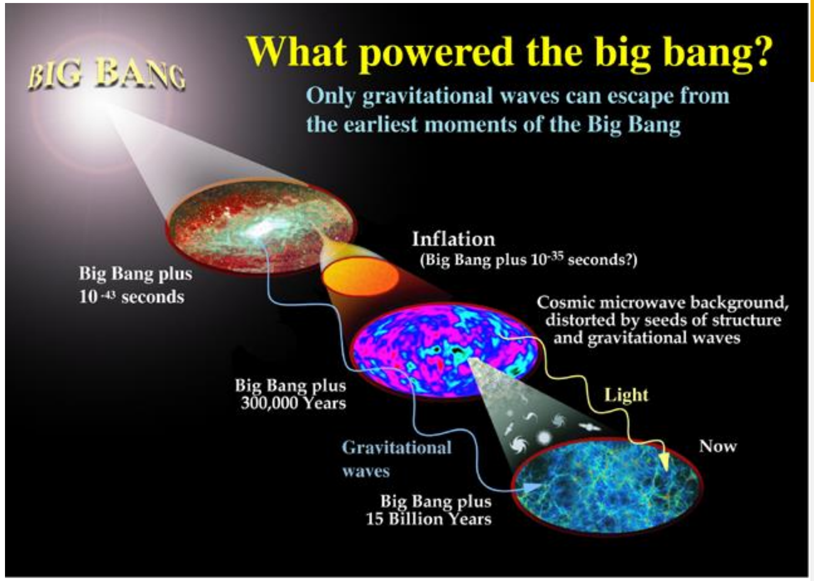
Binary Pulsar B1913+16 – [Weisberg, J.M., Taylor, J.H. (2005)]







Images from https://www.ligo.org/science/



GW EMISSION MECHANISMS

- **Binary Compact Objects** (BH or NS): inspiral, merger ringdown (last for BHs);
- Non-spherical **spinning NSs:** narrow frequency band signal with well defined spectral components;
- GW **stochastic background,** cosmological origin or superposition of unresolved astrophysical sources: continuous GW with broad-band spectra;

A MODERN MICHELSON INTERFEROMETER FOR GW DETECTION

Estimated sensitivity :

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

Using photon count:

$$N_{ph} \xrightarrow{variance} \sqrt{N_{ph}}$$

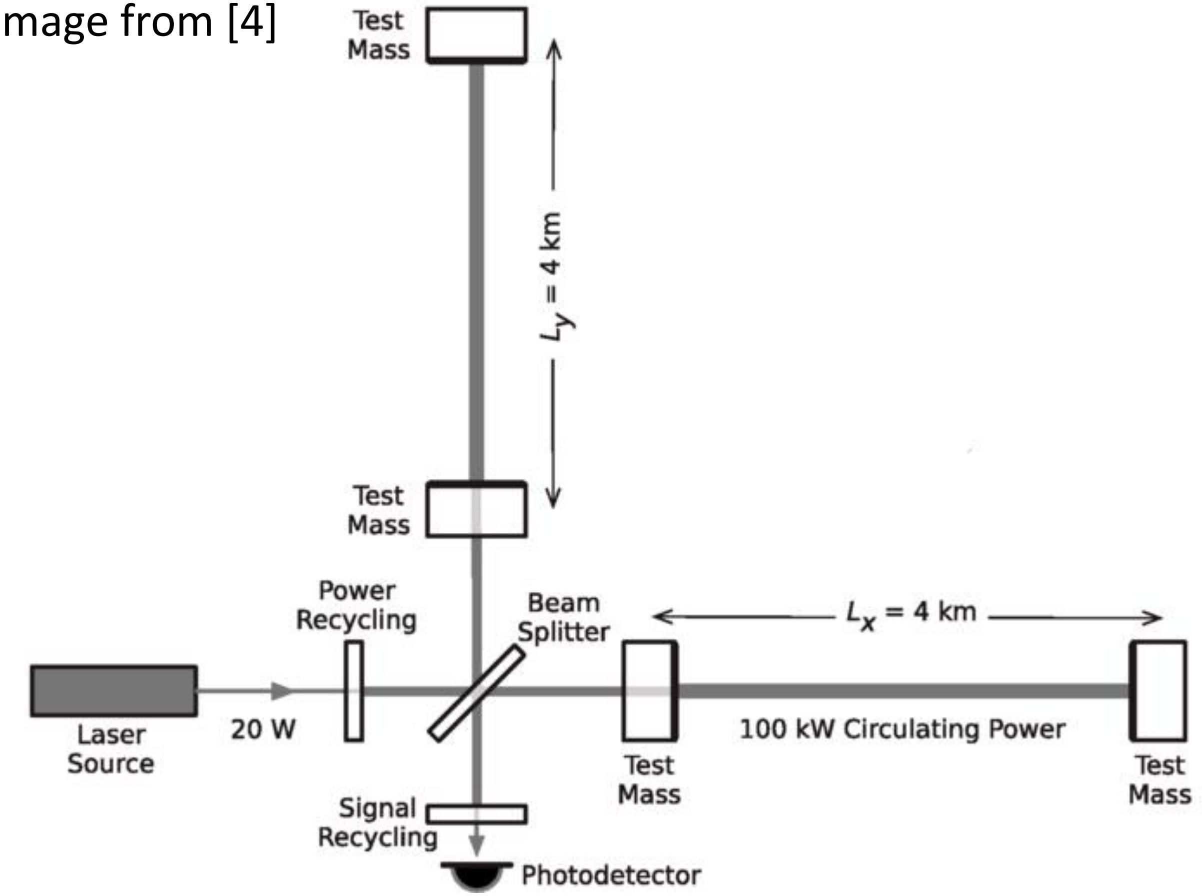
$P_{Laser} = 1$ W, $f_{gw} = 300$ Hz:

$$h \approx \frac{\Delta L}{L} \sim \frac{\lambda_L}{\sqrt{N_{ph}} L} \sim 10^{-17}$$

[5]

GW signal reconstructed from variation of destructive interferometry of splitting laser beams:

Image from [4]



ADVANCED MICHELSON INTERFEROMETER FOR GW DETECTION

Fabry-Perot Cavities:

GW passage ⟶ more power leaks out of the cavity

$$h \sim 10^{-20}$$

Power Recycling:

More the N_{ph}⟶ lower the shot-noise ⟶ more the radiation pressure;

Signal Recycling:

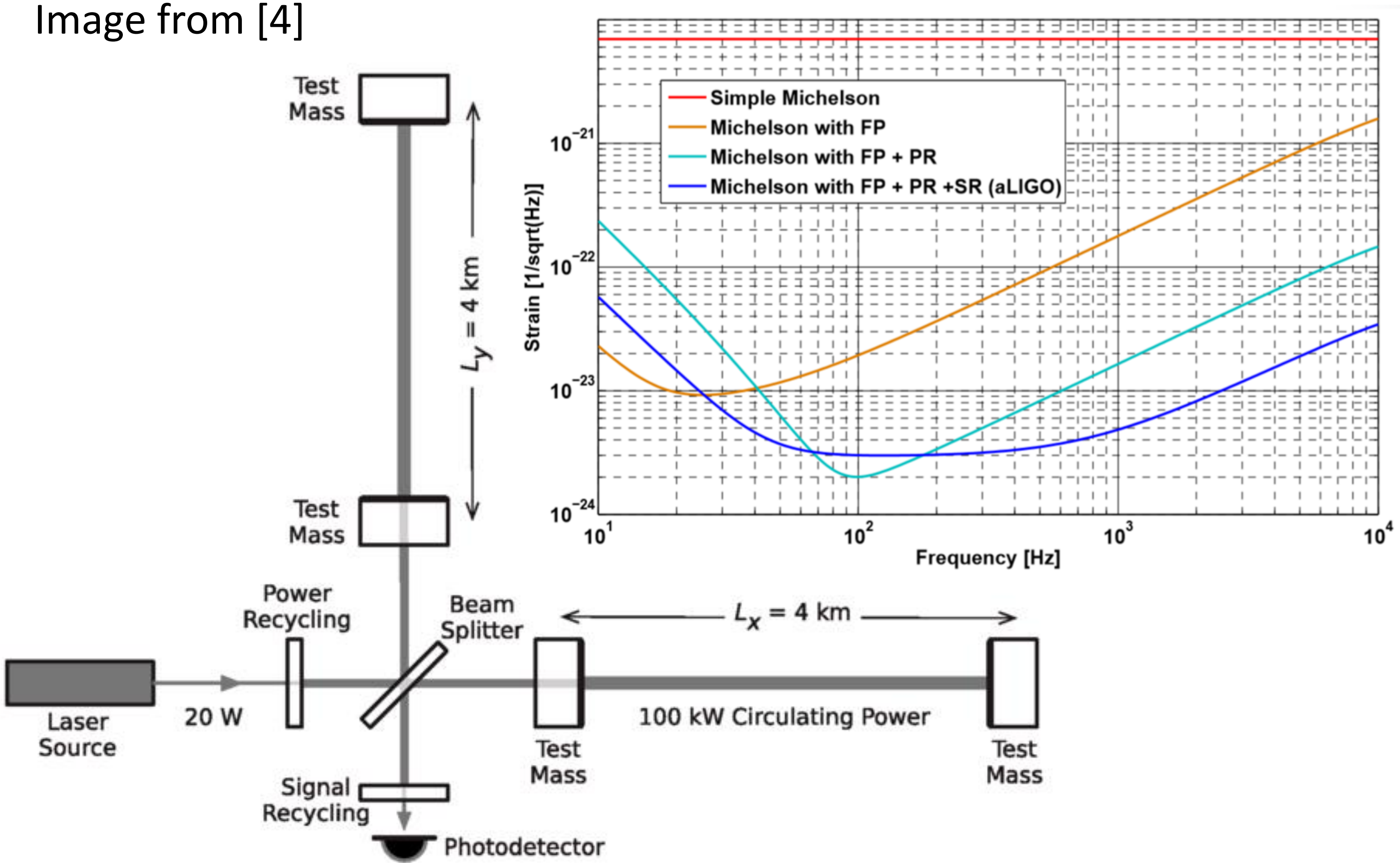
resonant tuning of the signal increases the signal sideband amplitude in a certain frequency band.

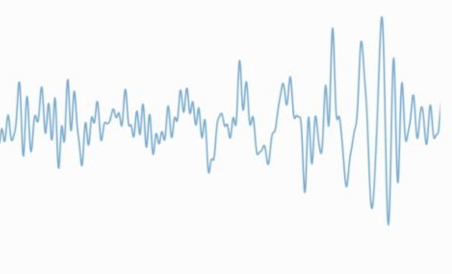
[5]

Advanced LIGO interferometer design

Image from [5]

Image from [4]



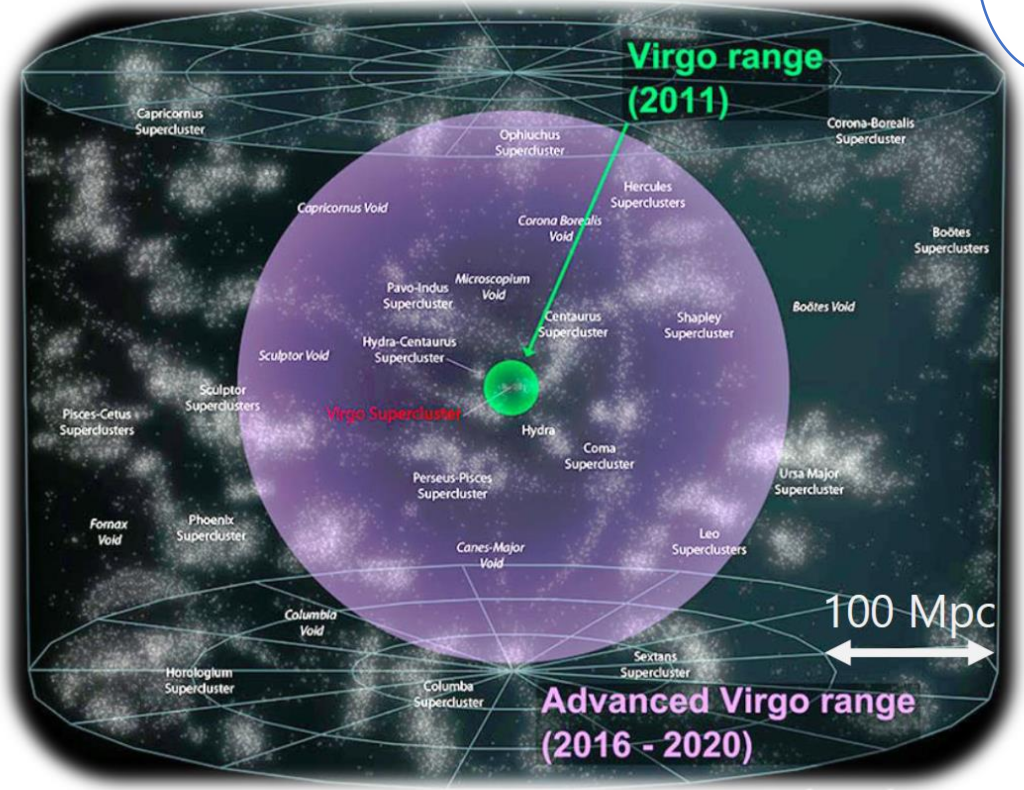


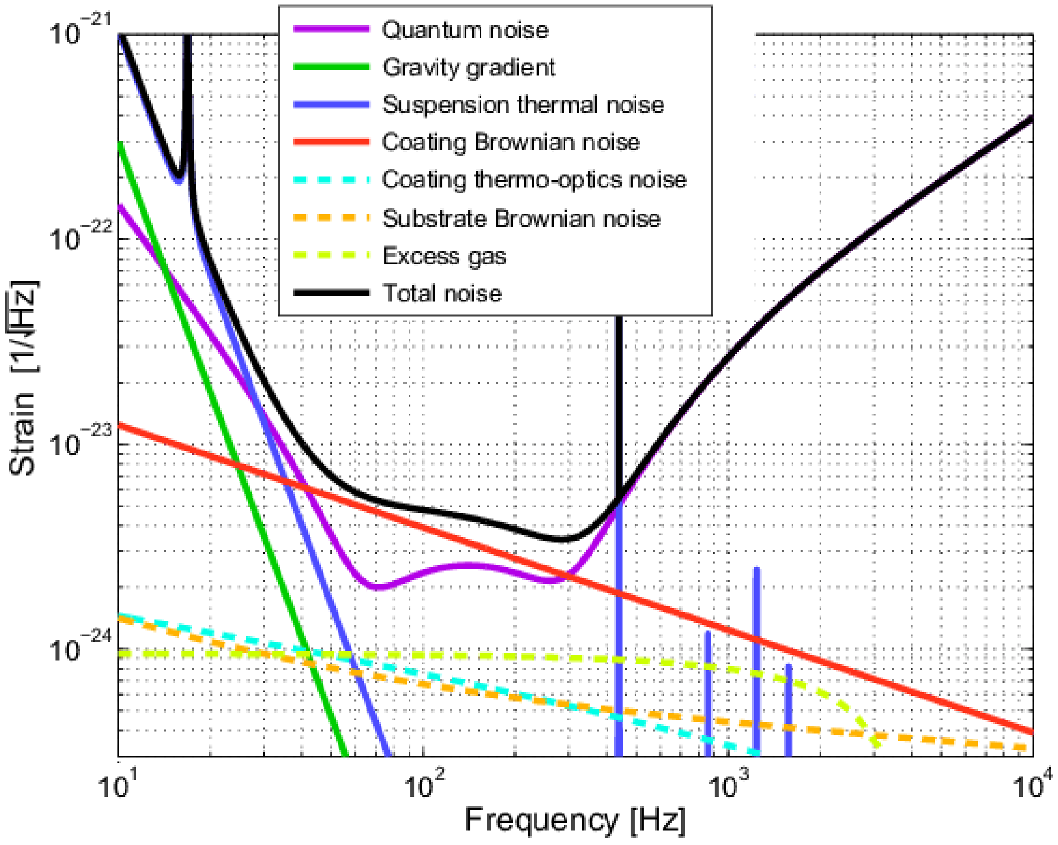
Detector sensitivity to GWs

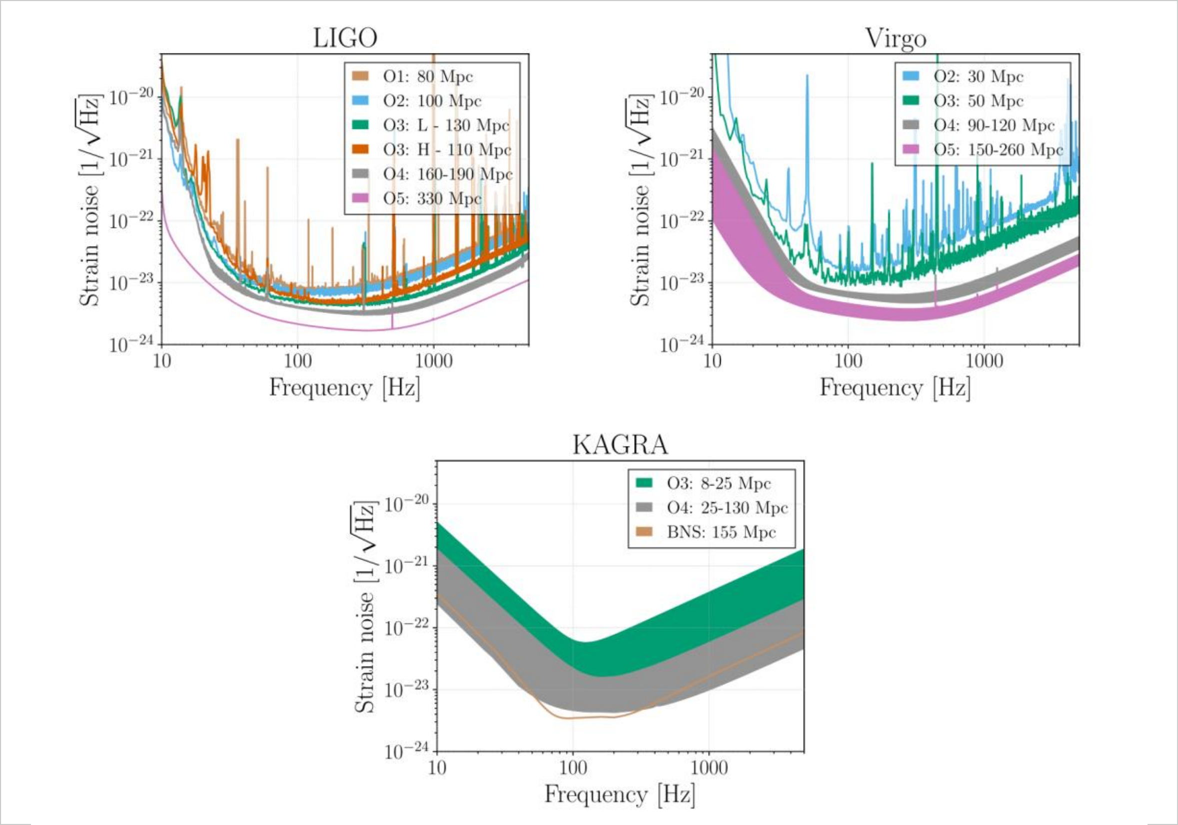
BNS range [Bassan 2014]:

$$\frac{d_{\text{range}}}{1\ \text{Mpc}} = 0.86 \times 10^{-20} \left(\frac{\mathcal{M}}{M_\odot}\right)^{5/6} \sqrt{\int_{f_{\min}}^{f_{\text{ISCO}}} \frac{f^{-7/3}}{|h(f)|^2}\, df}$$

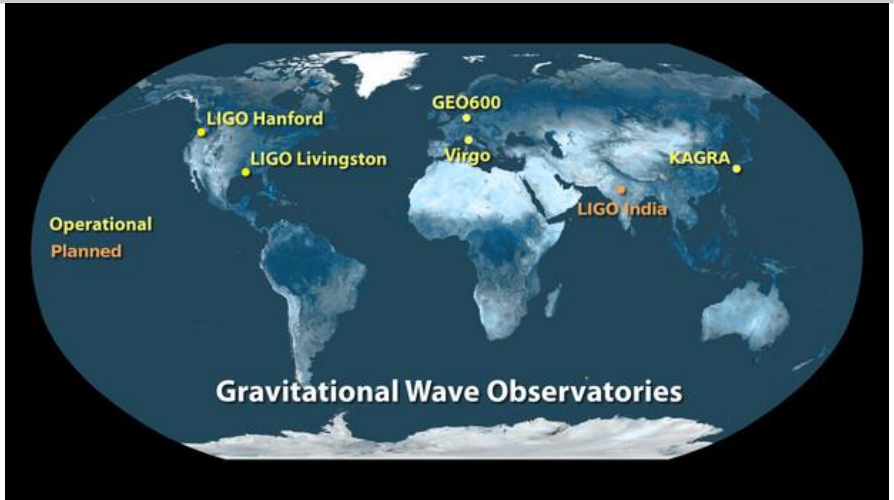
Strain $[1/\sqrt{Hz}]$







ADVANCED INTERFEROMETERS NETWORK

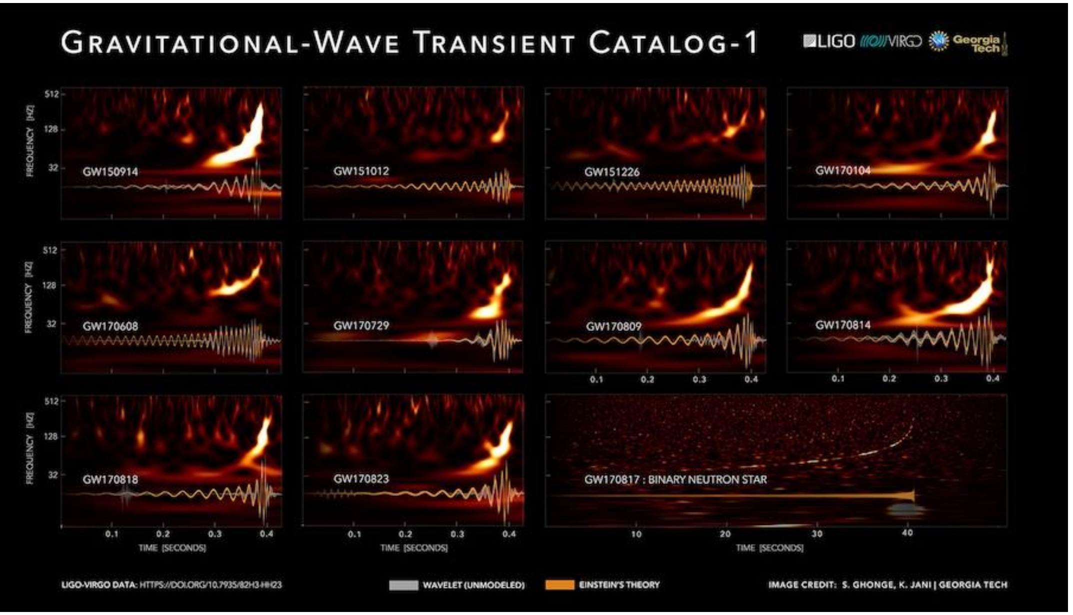


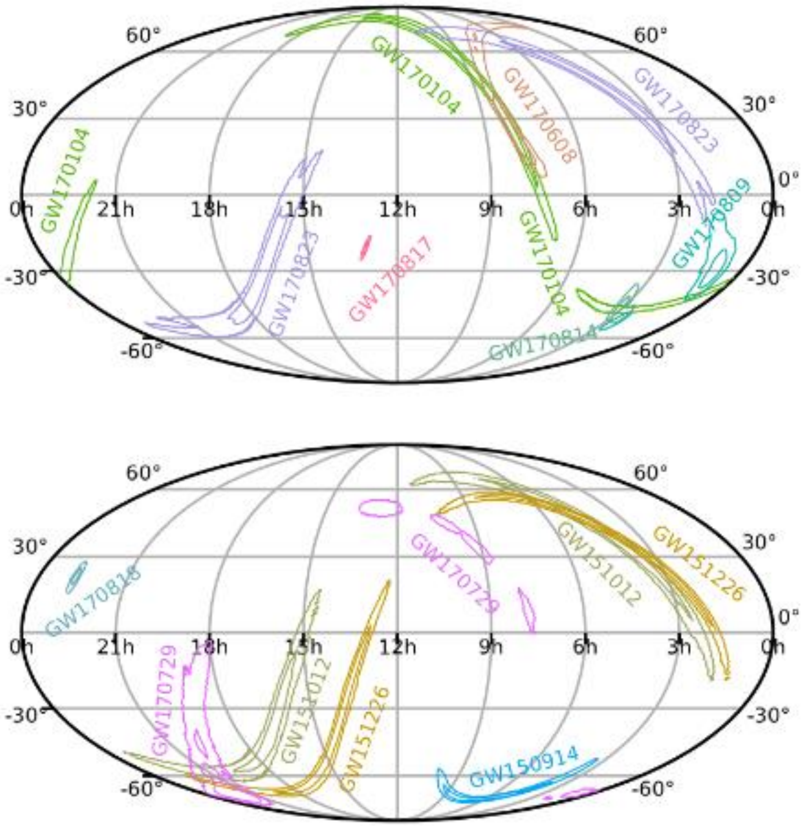
Images from [6]

O1 AND O2 OBSERVATIONS (GWTC-1)

O1: **Advanced LIGO** Livingston (L1) and Hanford (H1) [3, 4];

O2: **Advanced Virgo** joined Advanced LIGO in August 2017⟶ restricting area of sky localization [7];





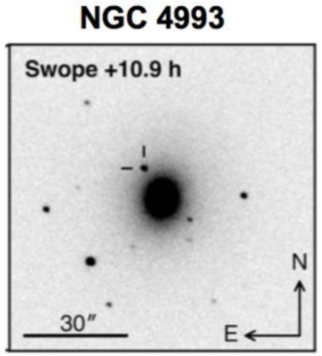
- **11 events detected**, including:
- GW150914: first GW observation, with higher energy emitted ($3M_{\odot}$);
- GW170814: coherently observed with three interferometers: **1160 deg2** ⟶ (LIGOs) **60 deg2** (LIGOs + Virgo);
- **GW170817**: first observation of **binary NS merger** and relative electromagnetic counterparts;

GW170817 AND GRB170817A

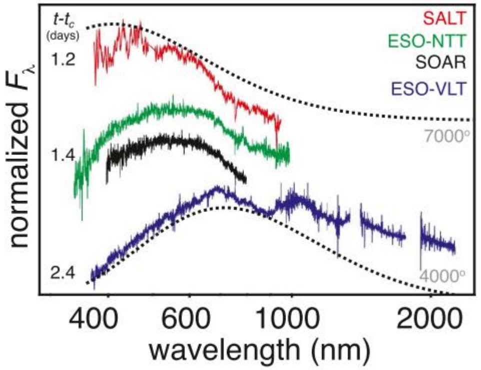
Probability of $\sim 5 \times 10^{-8}$ that GW170817 occurred close in time and with a certain level of location agreement with a **short GRB** [11, 12, 21].

Time delay $\sim 1{,}7\ s$, burst duration $T_{90} \approx 2{,}0\ s$.

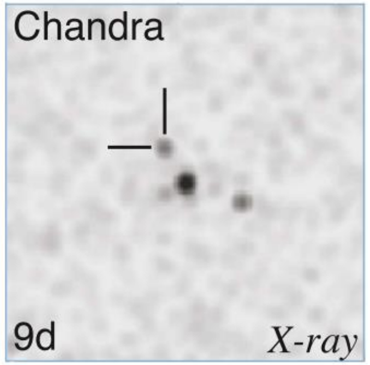
GRB 170817A prompt **sub-luminous**, **bright optical transient** identified it in **NGC 4993** host galaxy:

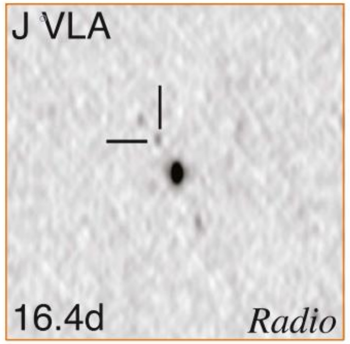


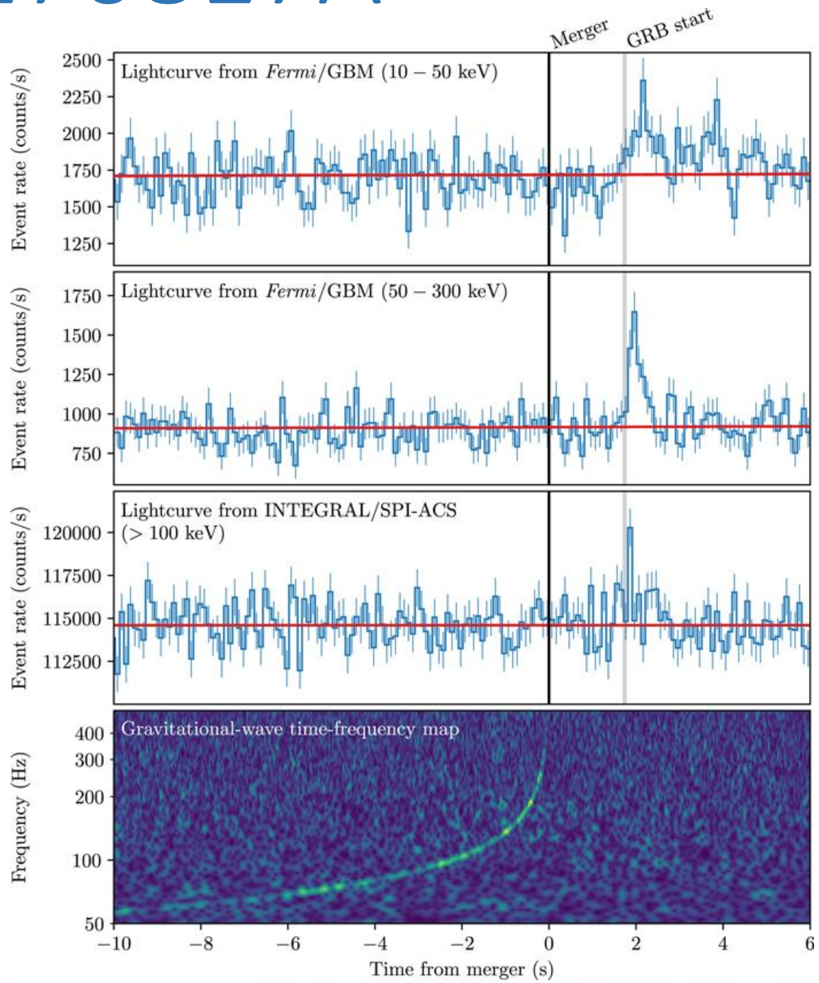
Kilonova radioactive decay of r-process nuclei



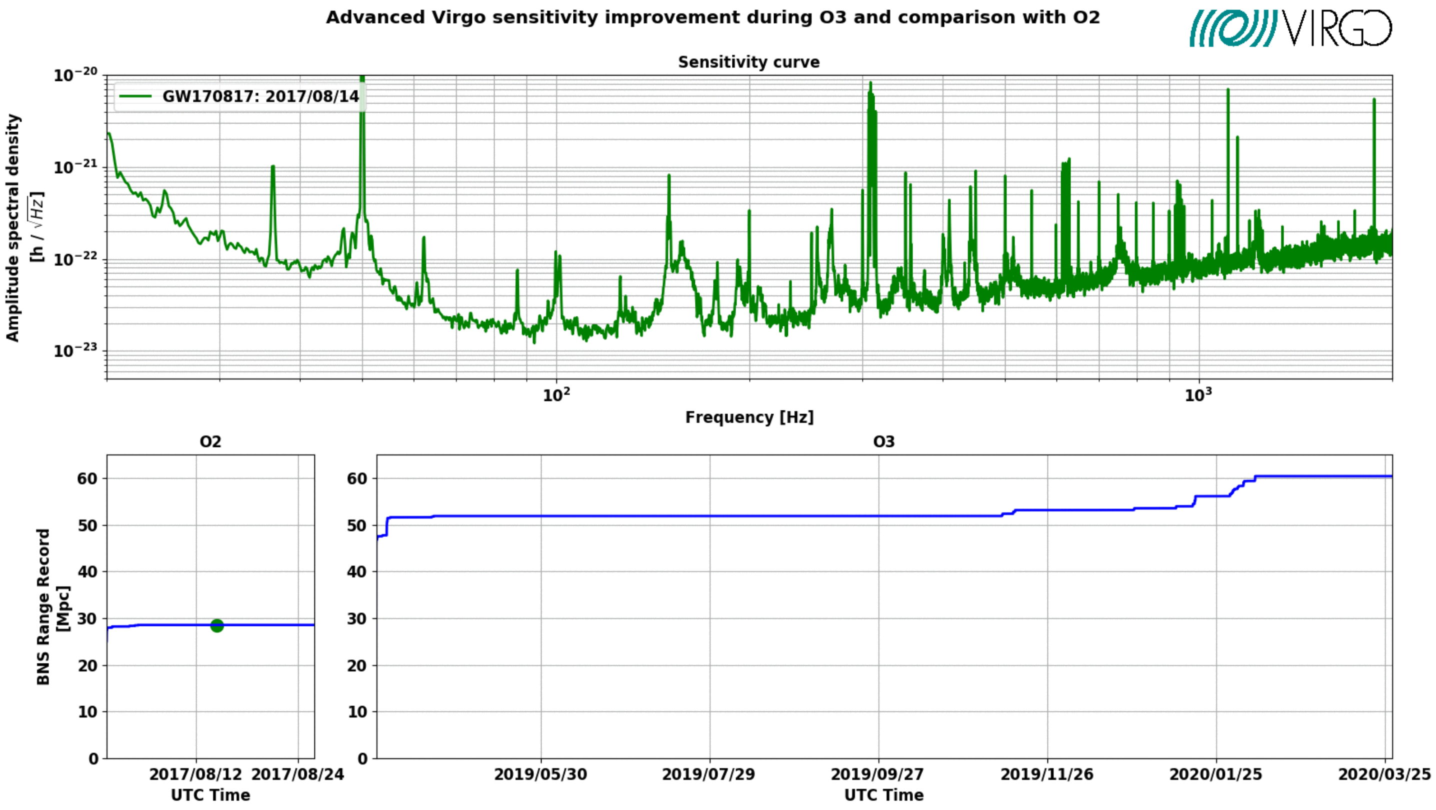
$\xrightarrow{afterglow}$



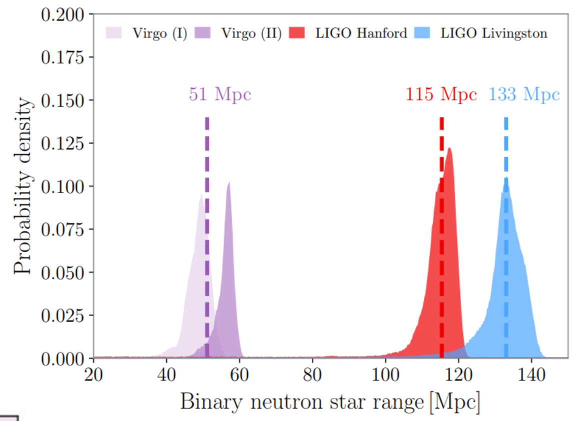


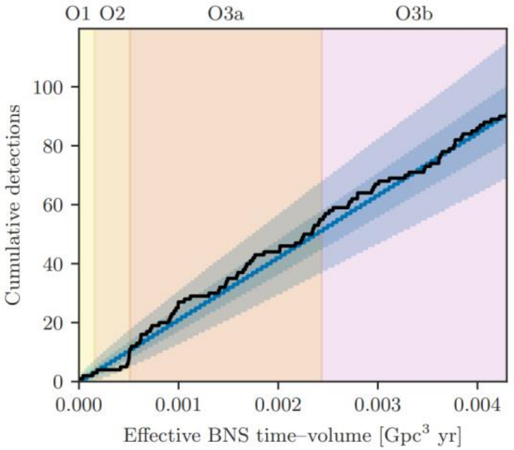


SENSITIVITY INCREMENT DURING O3



During O3 Advanced Virgo installed new increased laser power and **new wires suspending the mirrors** [8, 10]:

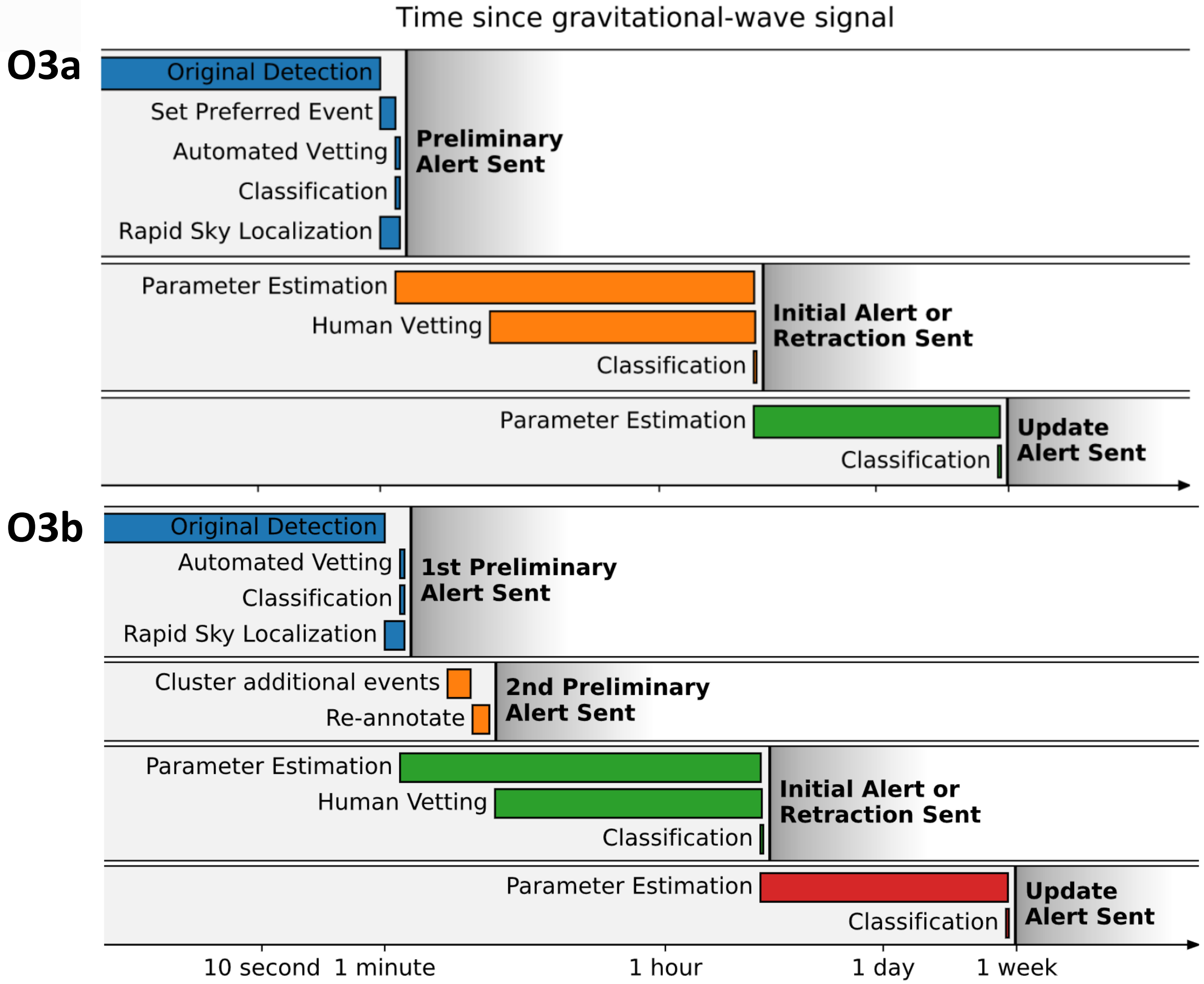


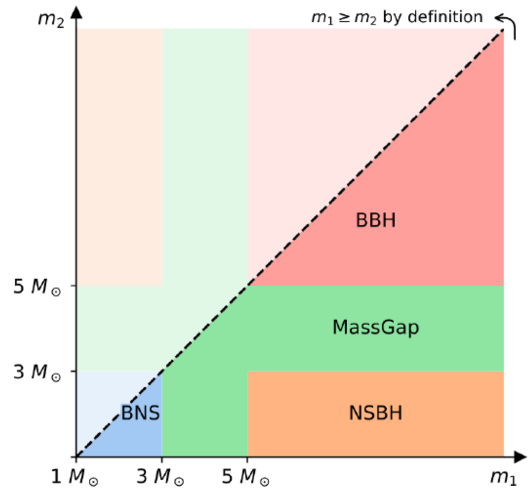


Maintenance activities increased Virgo BNS range during O3b
VIR-0462A-20

ALERTS SYSTEM

During O3 **alerts** to astronomers were **public** [6]:





Contents:
- False Alarm Rate ;
- Sky localization;

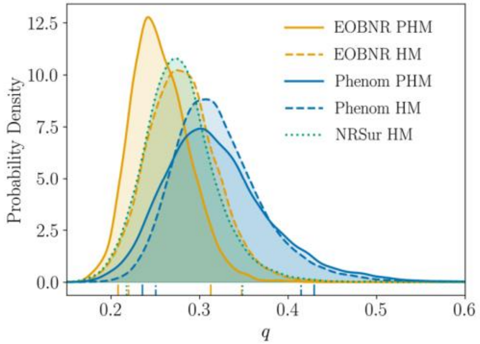
For bursts:
- Central frequency;
- Duration;
- GW fluence;

For compact binary coalescences:
- Luminosity distance;
- **Classification**: BNS, mass gap, NS-BH, BBH, Terrestrial;
- **Properties**: source classifier (prob. at least one NS), remnant classifier (prob. the system ejected a non-zero amount of NS matter);

For more information see also:
https://emfollow.docs.ligo.org/userguide/index.html

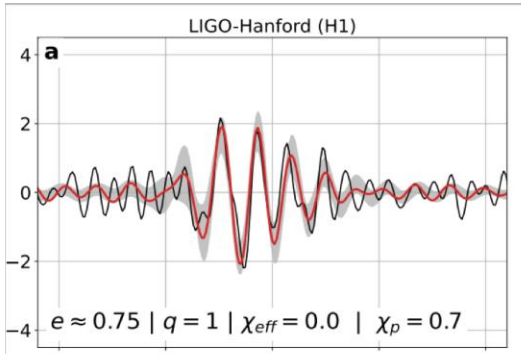
O3 MOST RELEVANT GW EVENTS

- **GW190412**: BBH with asymmetric masses (q):



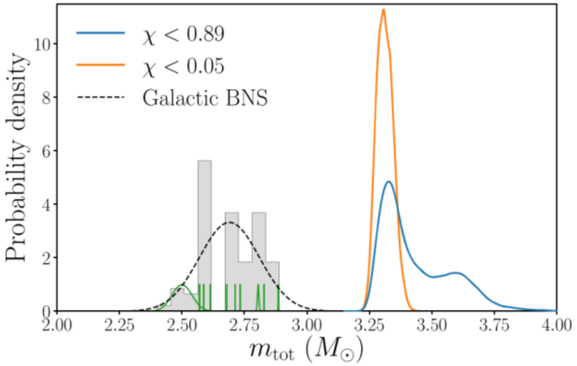
Strong evidence of emission beyond quadrupole approximation [18];

- **GW190521**: BBH with final mass $150\ M_{\odot}$:



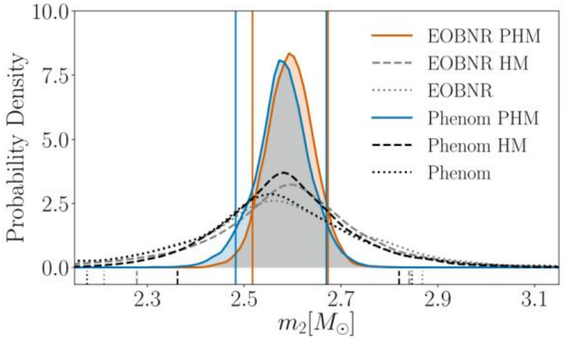
Very short inspiral $\longrightarrow$ estimated to be a high eccentric merger [19, 20];

- **GW190425**: consistent BNS, BH components cannot be ruled out:



Total mass: significantly larger than any observed BNS system ($\sim 3.4\ M_{\odot}$) [14]

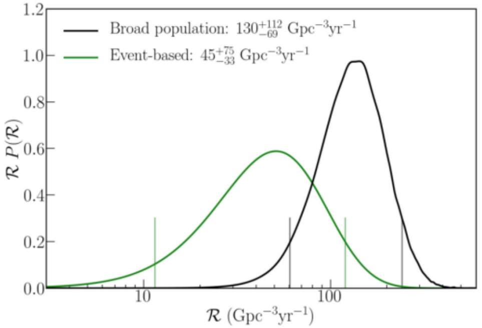
- **GW190814**: $23\ M_{\odot}$ BH and $2.6\ M_{\odot}$ compact object:



Does the system contain the lightest BH or the heaviest NS ever discovered, or a strange star? [15, 16]

- **GW200105** and **GW200115**: first two **NS-BH events** detected:

probably coming from the same NS-BH population [17]



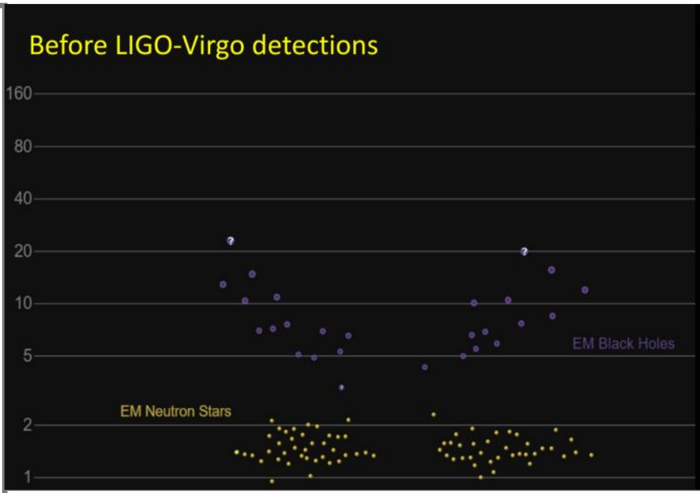
GWTC-2, GWTC-2.1 and GWTC-3

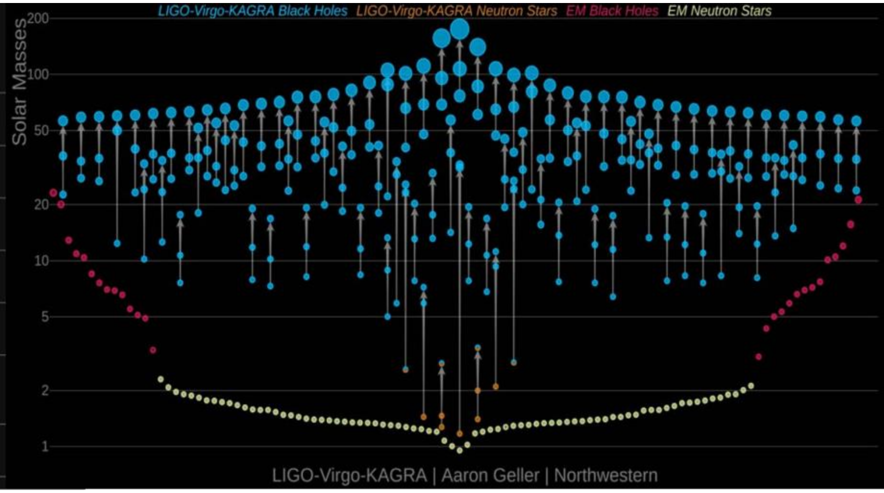
90 candidates found with $p_{astro\ source} > 0.5$

Looking forward to check the remaining sources of GWs:

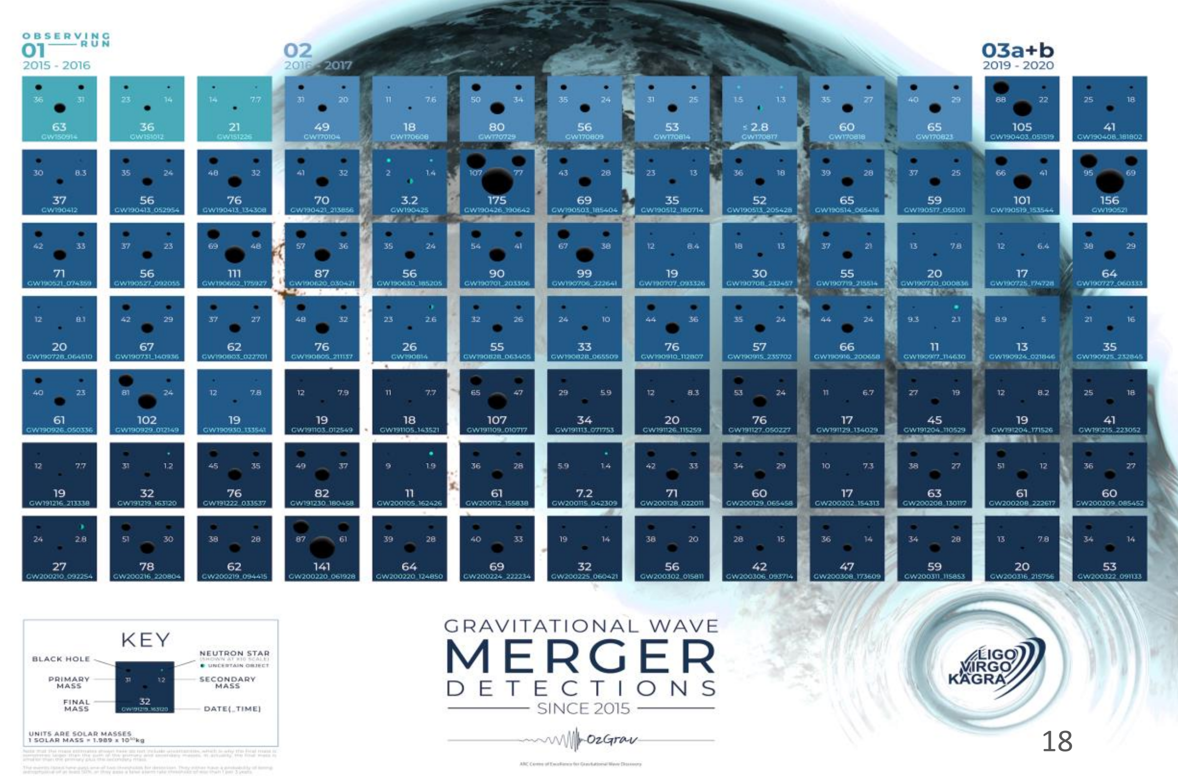
spinning NSs and stochastic background

21/07/2022

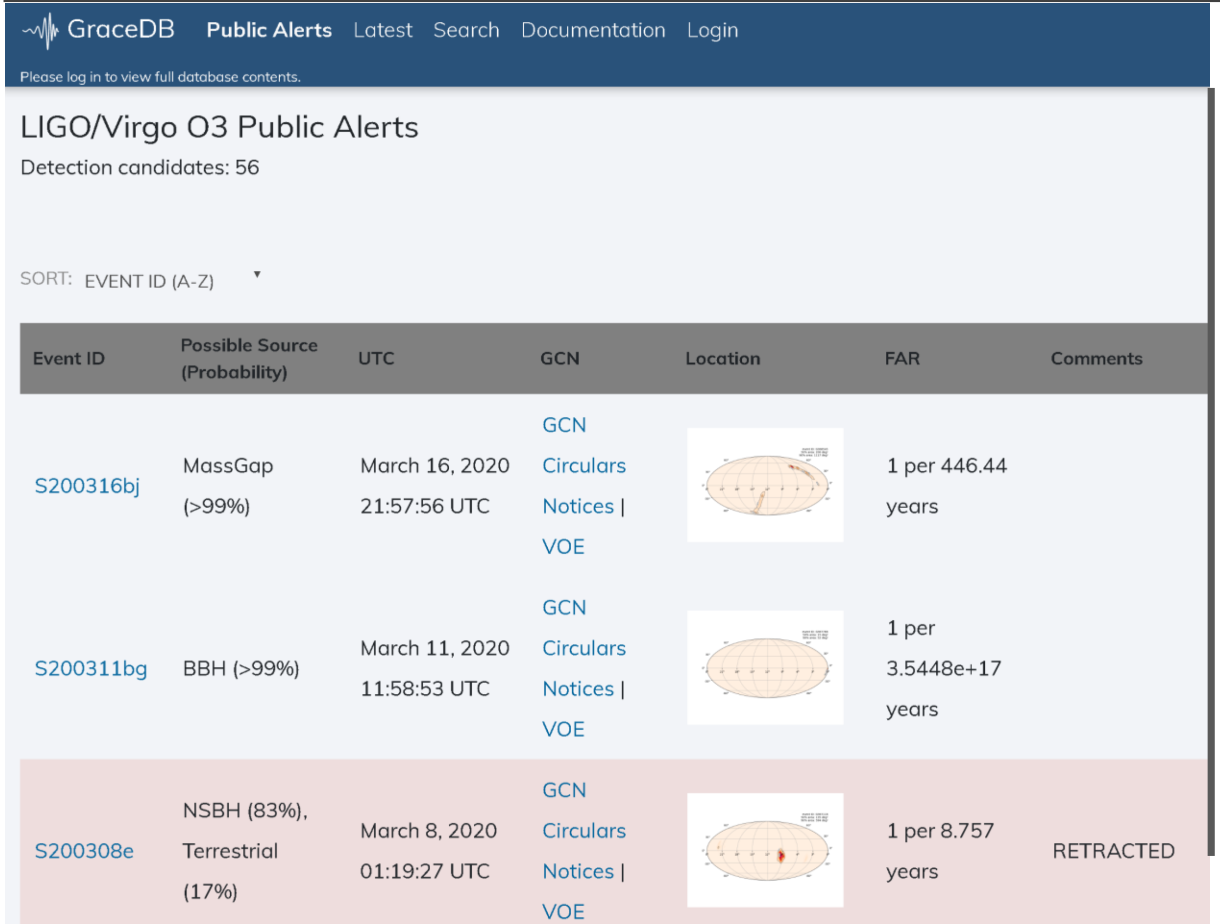




https://www.ligo.org/detections/O3bcatalog/files/gwmerger-poster-white-md.jpg



GWOSC OPEN SOURCE AND GRACEDB PUBLIC ALERTS



GraceDB Public Alerts Latest Search Documentation Login

Please log in to view full database contents.

LIGO/Virgo O3 Public Alerts

Detection candidates: 56

SORT: EVENT ID (A-Z)

Event ID	Possible Source (Probability)	UTC	GCN	Location	FAR	Comments
S200316bj	MassGap (>99%)	March 16, 2020 21:57:56 UTC	GCN Circulars Notices | VOE		1 per 446.44 years	
S200311bg	BBH (>99%)	March 11, 2020 11:58:53 UTC	GCN Circulars Notices | VOE		1 per 3.5448e+17 years	
S200308e	NSBH (83%), Terrestrial (17%)	March 8, 2020 01:19:27 UTC	GCN Circulars Notices | VOE		1 per 8.757 years	RETRACTED

LIGO-Virgo data become public after an initial proprietary period:

- Around a relevant event after article published;
- Chunks of 6 months after the end of the data taking (e.g. O3);

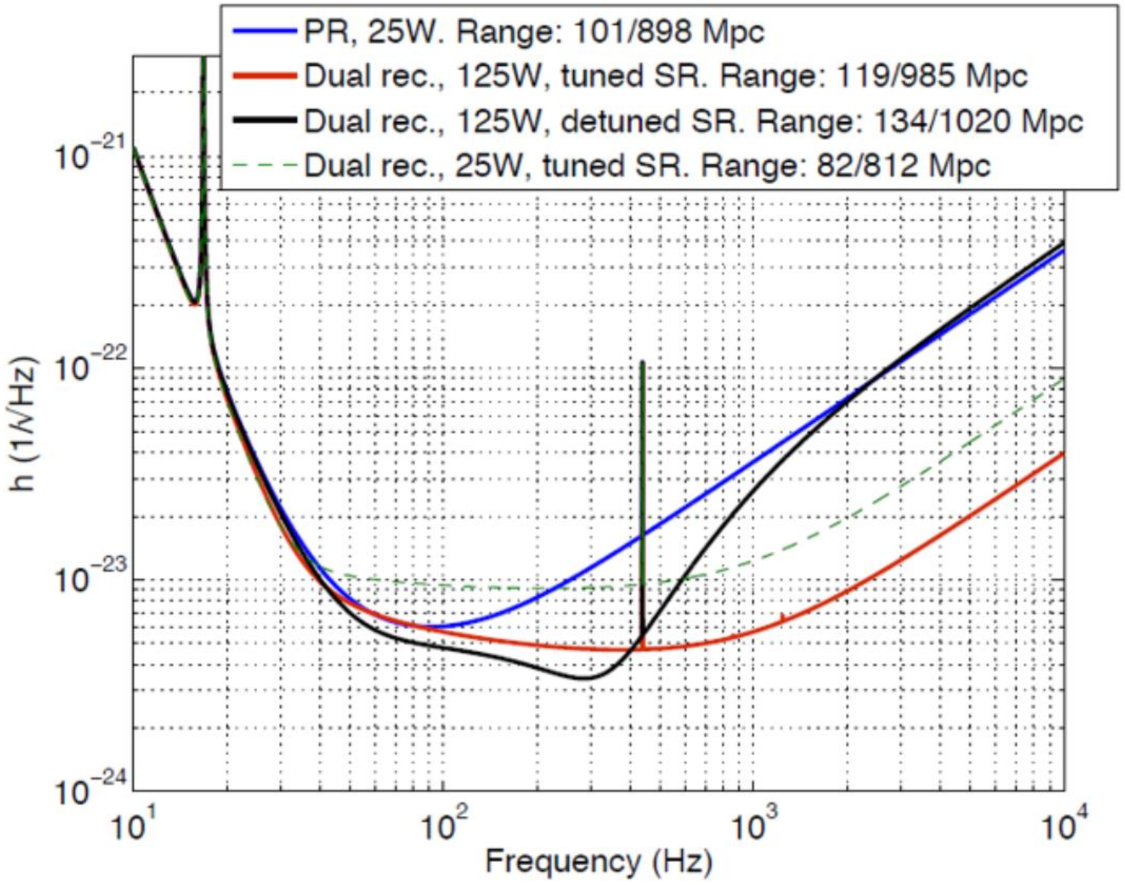
https://www.gw-openscience.org

ADVANCED VIRGO+ BEFORE AND AFTER O4

Main updates for Advanced Virgo Plus [13]:
- **Signal recycling mirror**: enhance middle/high frequency sensitivity band (right figure);
- **Frequency dependent squeezing**: light squeezed on output with different angles on a certain frequency band. Reduce shot noise and radiation pressure;

Additional updates:
- **New laser system**: inject ~75 W in the interferometer, reducing shot-noise;
- **Newtonian Noise Cancellation**: array of seismic sensors around the main mirrors, expected to be relevant in low-frequency band.

These and other updates are almost ready for O4, which should start on March 2023, with the goal of $\mathbf{100\ Mpc}$ **BNS range** reached.



O5 PRESPECTIVES

Towards the limit of second-generation detectors [13]:

- Large beam area inside arm cavities ⟶ smaller thermal noise effects;
- Larger test masses (40 →105 kg, 35 →55 cm diameter) ⟶ better free-falling condition;
- New suspensions and seismic insulation mechanisms ⟶ reduce thermal noise;
- New coatings with lower mechanical losses;

Aim to work for O5 (maybe 2026) at **200 Mpc BNS range**.

EINSTEIN TELESCOPE (ET) AND LOW-FREQUENCY GW

10 times more sensitive than second-generation detectors;

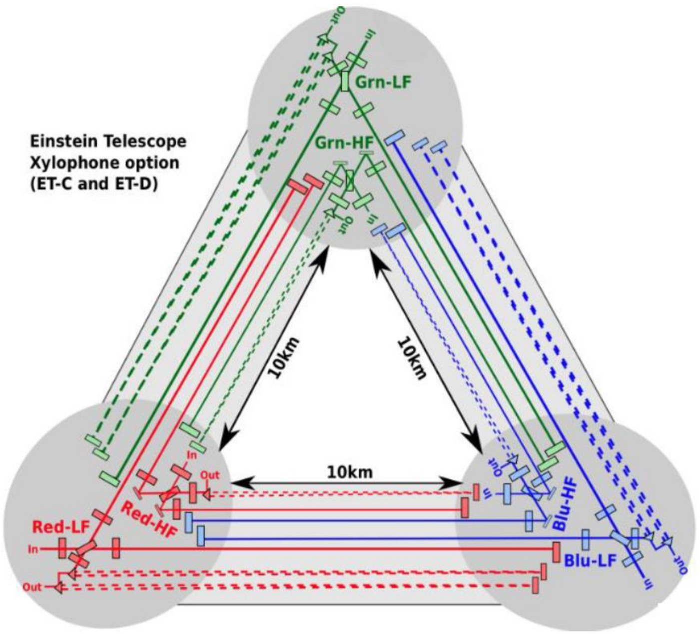
Three detector with shared arms;

Located underground ⟶ reduce seismic and Newtonian noise;

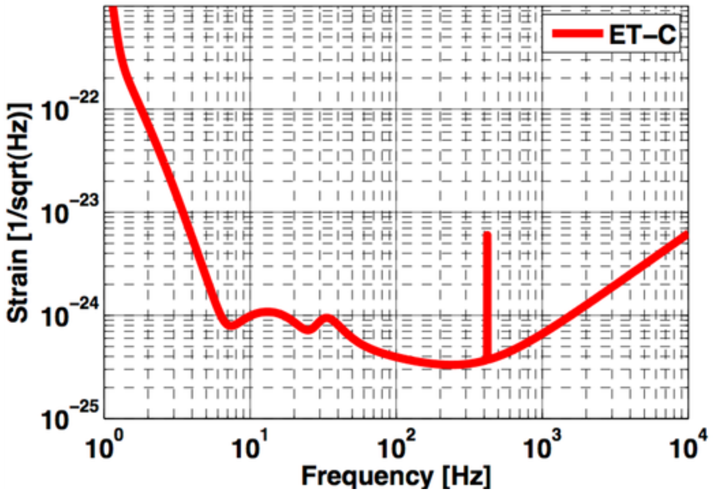
10 km long arms, in an equilateral triangle configuration: resolve GW polarization and make self localization;

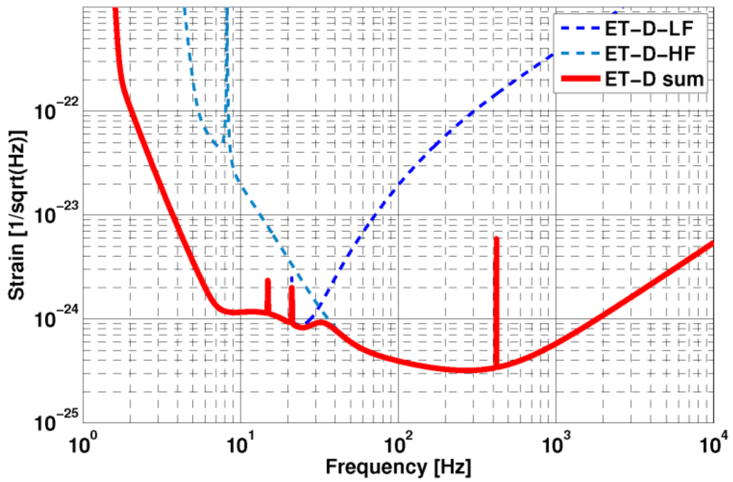
Xylophone configuration: three nested detectors, each composed of two interferometers, one optimized for operation below 30Hz and one optimized for operation at higher frequencies;

ET DESIGN



GW below 30 Hz: higher mass mergers, tidal effects on NSs, BHs close encounters.





Details about ET project: http://www.et-gw.eu/index.php/etsensitivities

Photo wall from Racconti dal BarAonda:
https://www.asimmetrie.it/archivio

THANK YOU FOR THE ATTENTION

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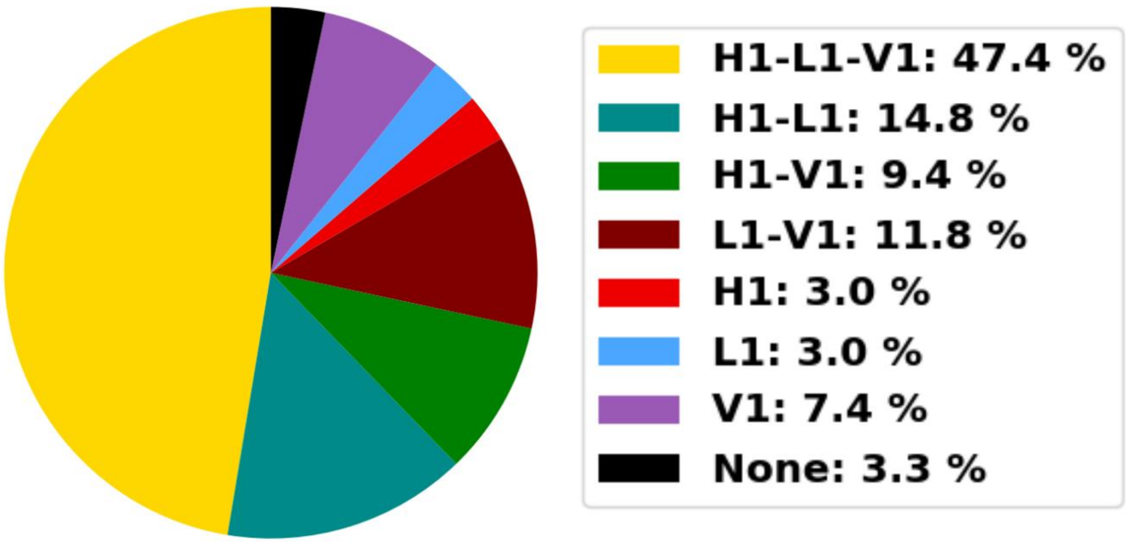
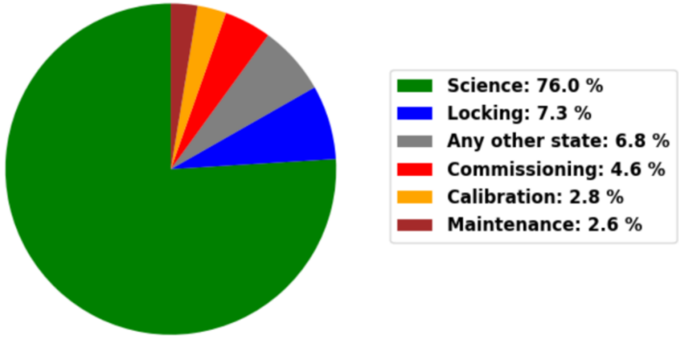
O3 DUTY CYCLE

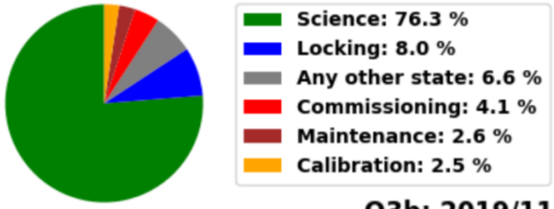
Network Duty Cycle



Advanced Virgo Duty Cycle during O3



O3a: 2019/04/01 -> 2019/10/01



O3b: 2019/11/01 -> 2020/03/27