Gravitational waves: Opening a new window on the universe

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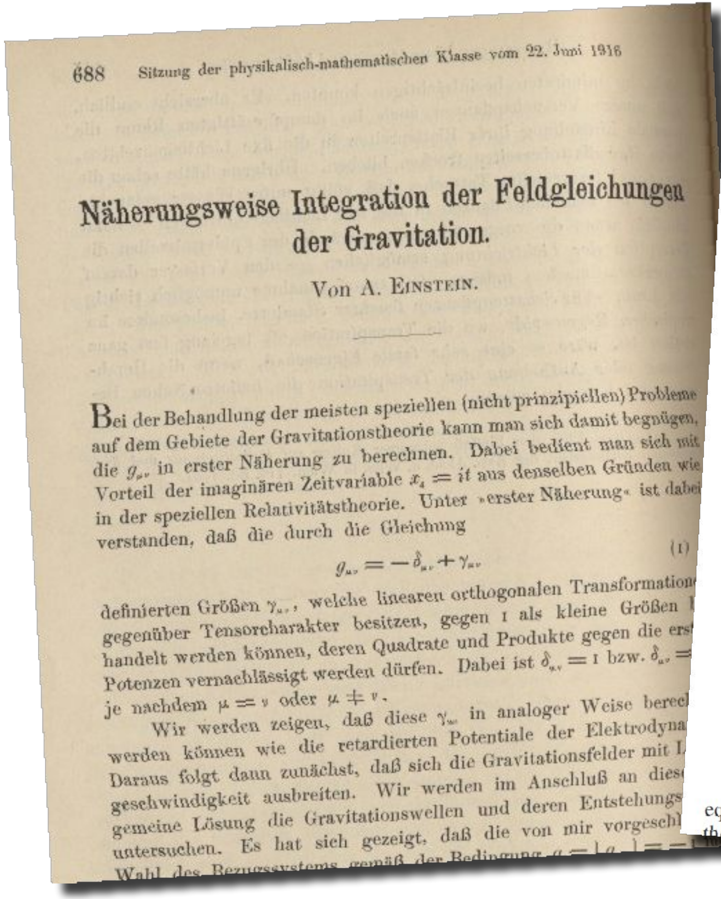
MONT BLANC

Gravitational Waves



688 Sitzung der physikalisch-mathematischen Klasse vom 22. Juni 1916

Näherungsweise Integration der Feldgleichungen der Gravitation.

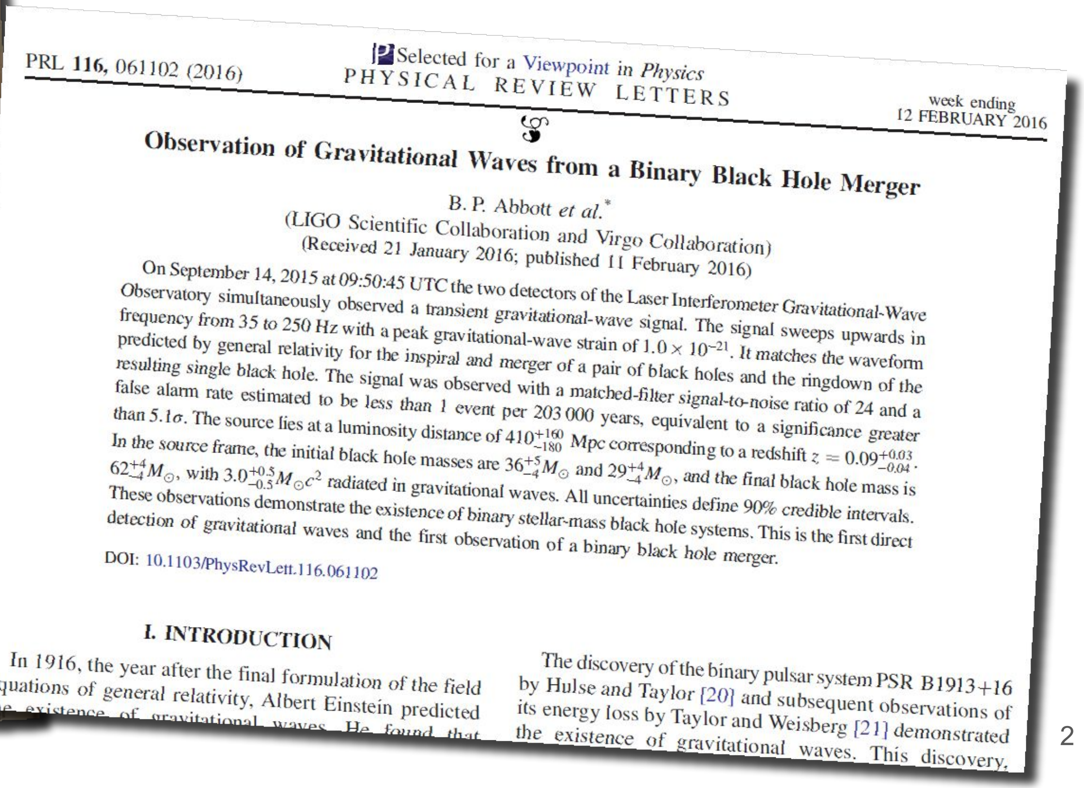
Von A. Einstein.

Bei der Behandlung der meisten speziellen (nicht prinzipiellen) Probleme auf dem Gebiete der Gravitationstheorie kann man sich damit begnügen, die $g_{\mu\nu}$ in erster Näherung zu berechnen. Dabei bedient man sich mit Vorteil der imaginären Zeitvariable $x_4 = it$ aus denselben Gründen wie in der speziellen Relativitätstheorie. Unter »erster Näherung« ist dabei verstanden, daß die durch die Gleichung

$$g_{\mu\nu} = -\delta_{\mu\nu} + \gamma_{\mu\nu} \tag{1}$$

definierten Größen $\gamma_{\mu\nu}$, welche linearen orthogonalen Transformation
gegenüber Tensorcharakter besitzen, gegen 1 als kleine Größen
handelt werden können, deren Quadrate und Produkte gegen die ers
Potenzen vernachlässigt werden dürfen. Dabei ist $\delta_{\mu\nu} = 1$ bzw. $\delta_{\mu\nu} =$
je nachdem $\mu = \nu$ oder $\mu \neq \nu$.

Wir werden zeigen, daß diese $\gamma_{\mu\nu}$ in analoger Weise berec
werden können wie die retardierten Potentiale der Elektrodyna
Daraus folgt dann zunächst, daß sich die Gravitationsfelder mit L
geschwindigkeit ausbreiten. Wir werden im Anschluß an dies
gemeine Lösung die Gravitationswellen und deren Entstehungs
untersuchen. Es hat sich gezeigt, daß die von mir vorgeschl
Wahl des Bezugssystems gemäß der Bedingung



PRL **116,** 061102 (2016)

Selected for a Viewpoint in *Physics*

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

I. INTRODUCTION

In 1916, the year after the final formulation of the field equations of general relativity, Albert Einstein predicted the existence of gravitational waves. He found that

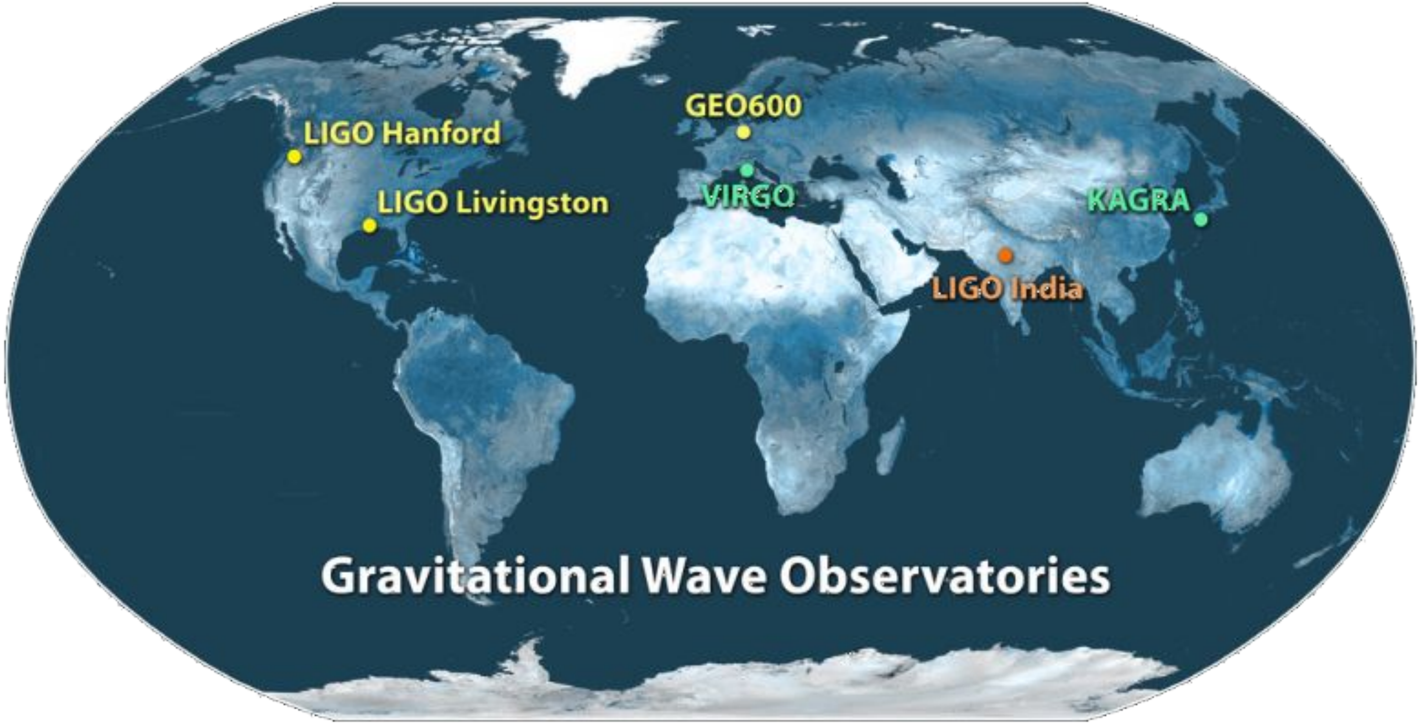
The discovery of the binary pulsar system PSR B1913+16 by Hulse and Taylor [20] and subsequent observations of its energy loss by Taylor and Weisberg [21] demonstrated the existence of gravitational waves. This discovery,

Gravitational wave observatories

LSC : ~1400+ members
~127 institutions
from ~19 countries

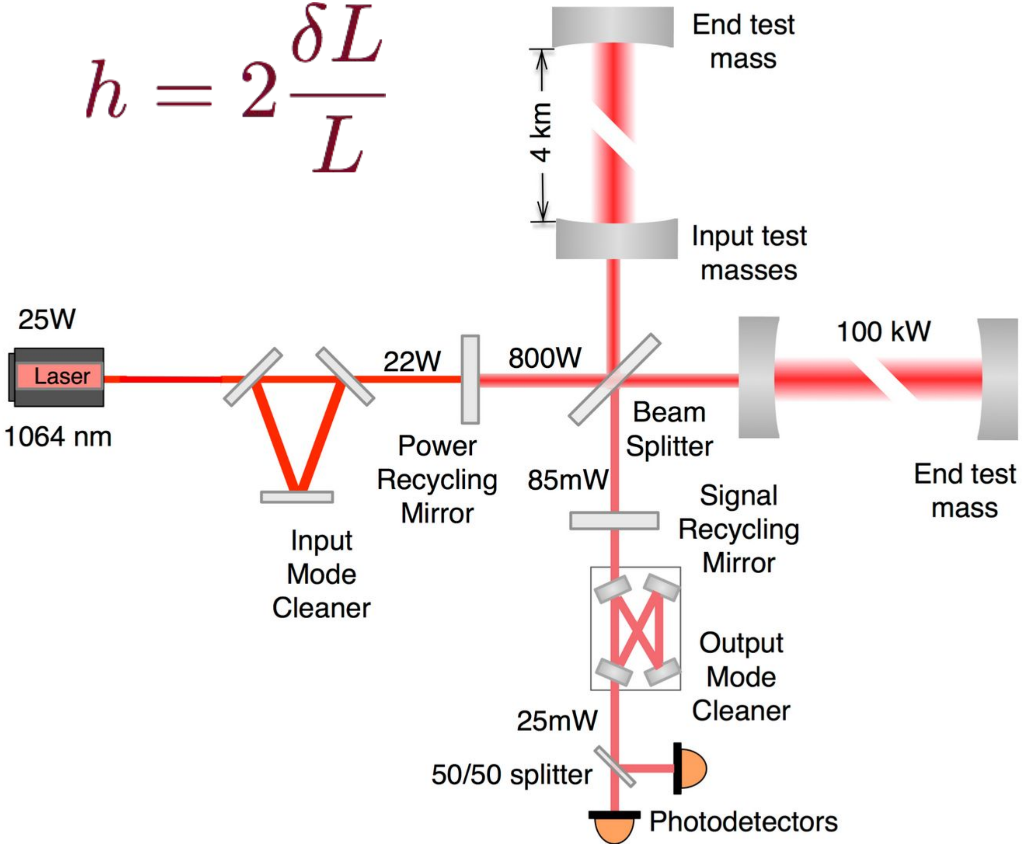
Virgo : ~800+ membres
129 institution
from 16 countries

KAGRA : ~400+ membres
110 institution
from 15 countries



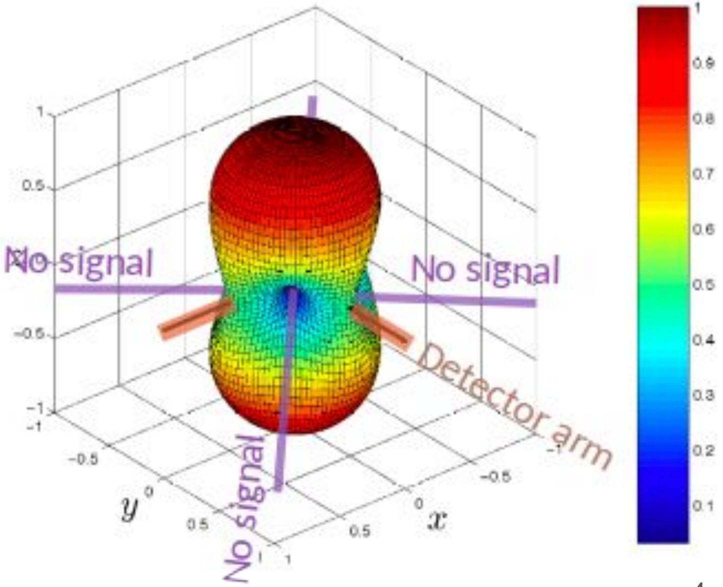
Michelson interferometer :
a “sensor” of gravitational waves

$$h = 2\frac{\delta L}{L}$$



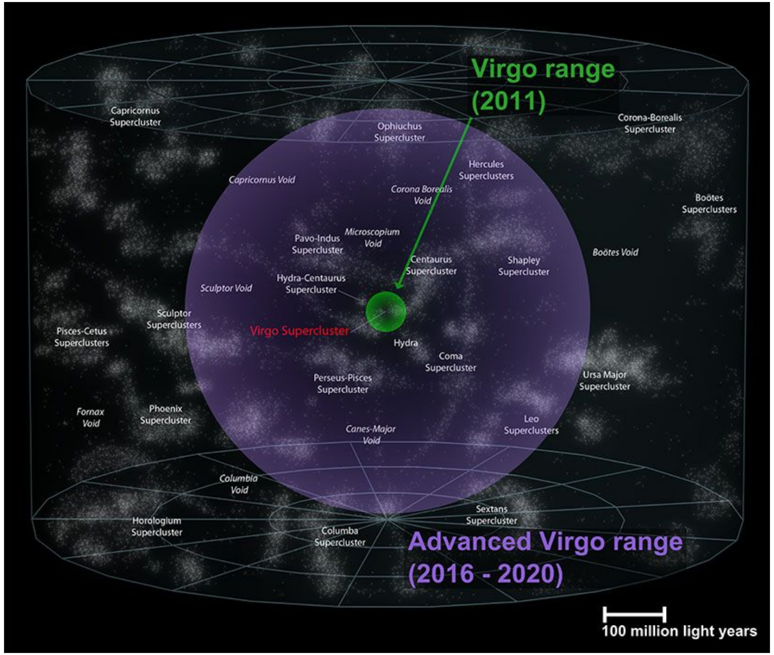
$$h \approx 10^{-23}$$

$$\Rightarrow \quad \delta L \approx 10^{-20}\ \mathrm{m}$$



Horizon distance

- “Horizon” distance:
  - Distance at which a particular standard source emitted a signal which can be detected with a Signal-to-Noise Ratio (SNR)=8
  - Standard source = binary Neutron Star (BNS) coalescence with 1.4 $M_\odot$ for each component



Improving the sensitivity (or horizon) by a factor 10

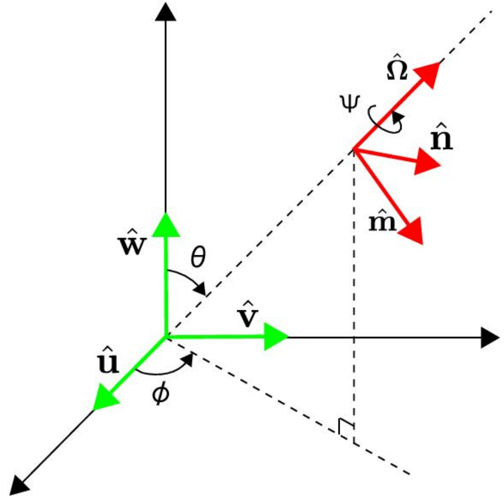
↓

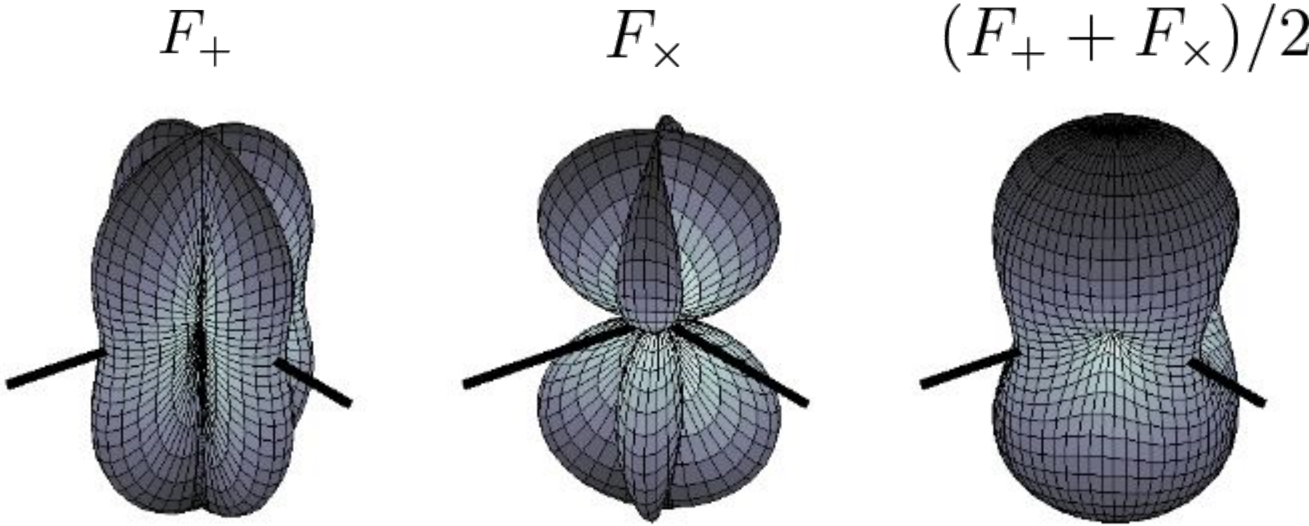
Increase the volume (or event rate) by 1000

Range distance

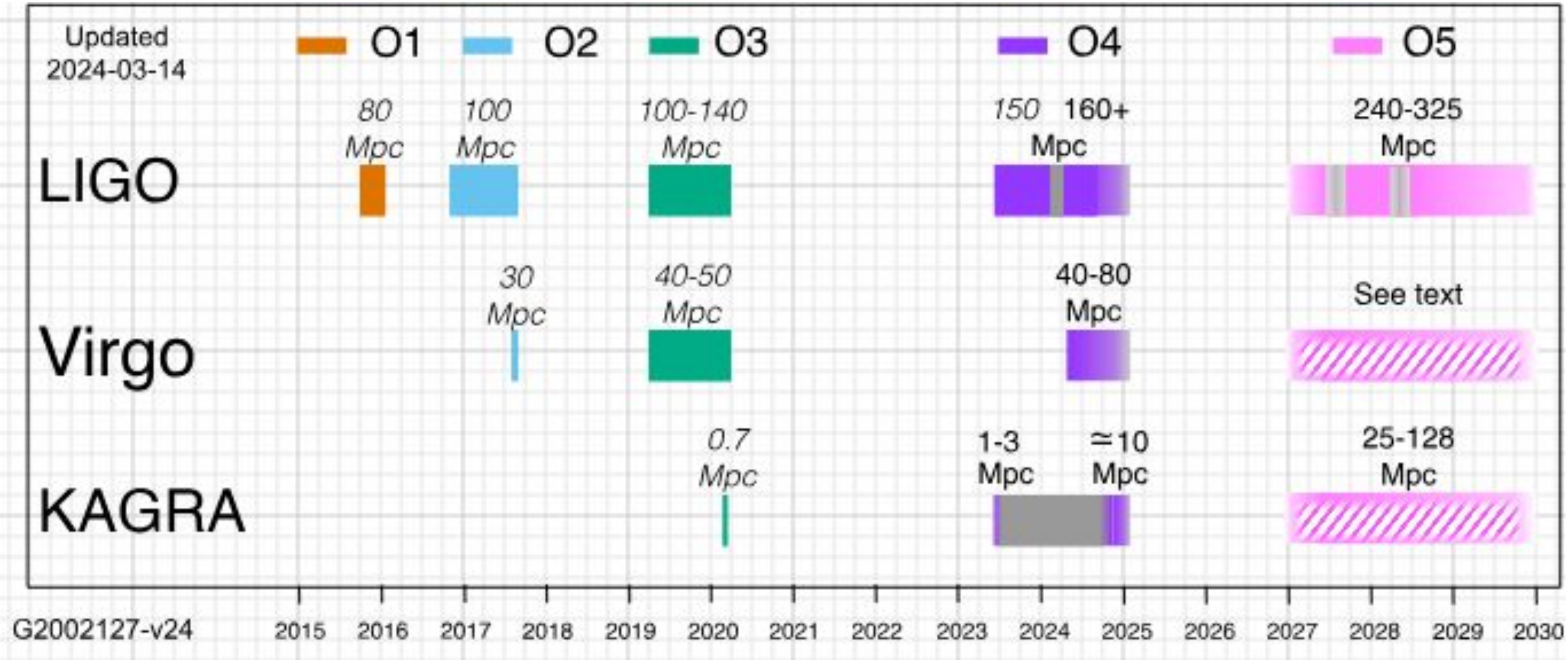
- The “Range” is the horizon averaged over the antenna factor: R=H/2.264

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





Past and future science runs



CBC Analysis : The Matched Filtering

- In time domain:

data stream

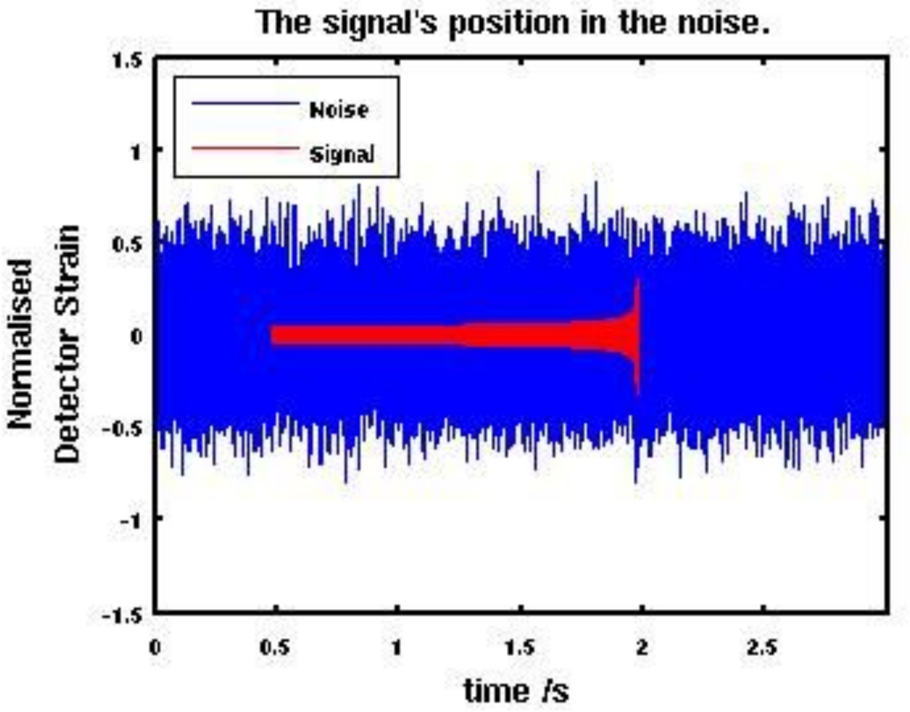
$$s(t) = n(t) + h(t)$$

noise

GW signal

- In Frequency domain
  - Fourier transform

$$\tilde{s}(f) = \tilde{n}(f) + \tilde{h}(f)$$

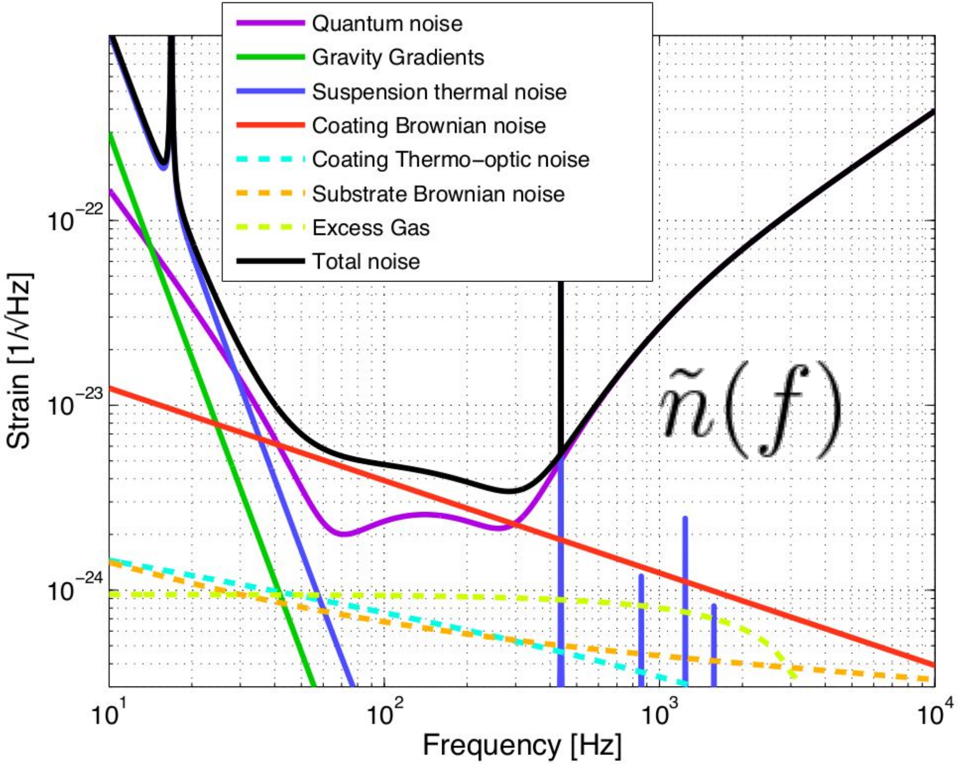


CBC Analysis: Power Spectral Density

- The PSD is the autocorrelation of the noise $S_n(f)$:

$$< \tilde{n}(f)\tilde{n}^*(f') >= \frac{1}{2}S_n(f)\delta(f-f')$$

- The Amplitude Spectral Density (ASD) is $\tilde{n}(f)$ and PSD=ASD^2



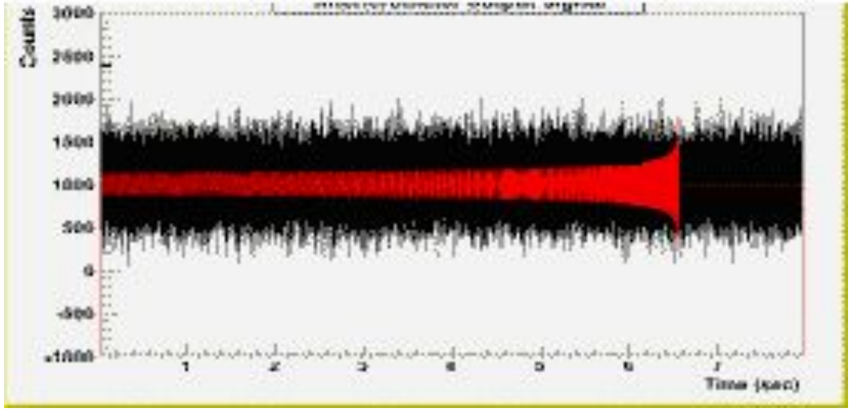
CBC Analysis: Filters

Optimal filter is :

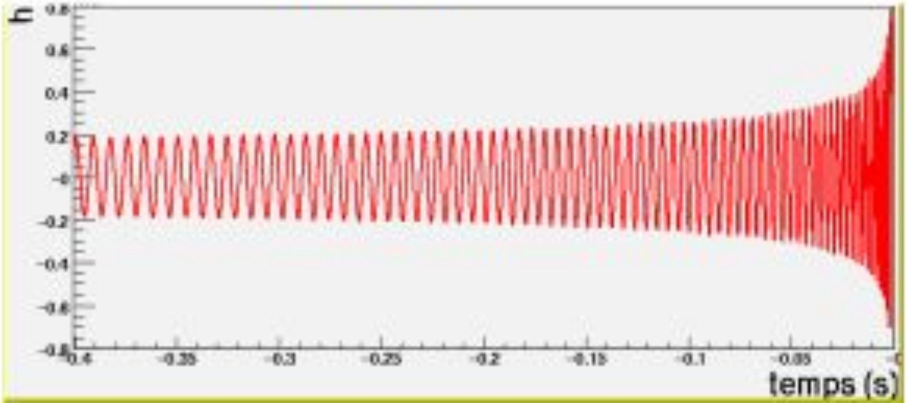
$$\tilde{Q}(f) = 2\alpha \frac{\tilde{T}(f)}{S_n(f)} e^{2i\pi f t_0}$$

$$h(t) \propto T(t)$$

Signal buried into noise



Template



CBC Analysis: Filtering

- The filtered stream of data is :

$$S = \int_{-\infty}^{+\infty} \tilde{s}(f)\tilde{Q}^*(f)\mathrm{d}f$$

- The filtered noise is :

$$N = \int_{-\infty}^{+\infty} \tilde{n}(f)\tilde{Q}^*(f)\mathrm{d}f = S - < S >$$

- Similar to a scalar product :

The bigger S is, the more the stream fits to the filter

CBC Analysis: Signal-to-Noise Ratio

- Let build a Signal-to-Noise Ratio (SNR) :

$$SNR = \frac{<S>}{\sigma_N}$$

- With the filtered noise standard deviation :

$$\sigma_N = \sqrt{<N^2> - \cancel{<N>}^2} = \sqrt{<N^2>}$$

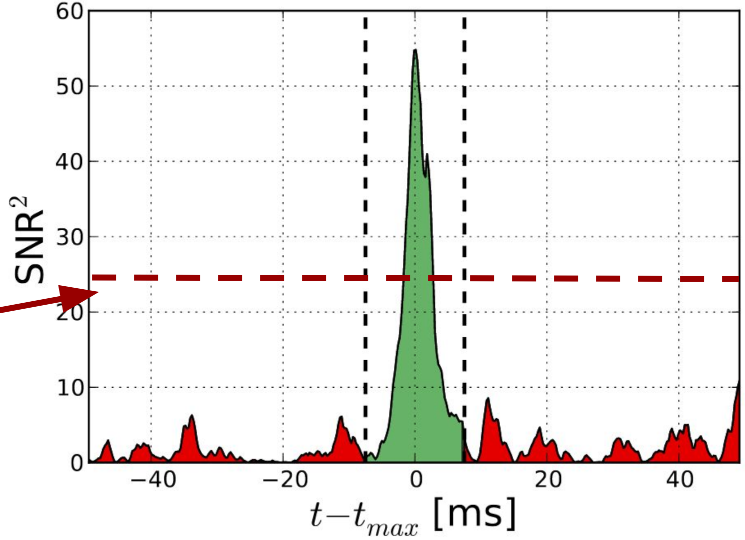
- **SNR = 8 means signal times greater than the gaussian noise std**

CBC Analysis: Signal-to-Noise Ratio

- With an optimal filter such that : $\tilde{h}(f) = \alpha \tilde{T}(f) e^{2i\pi f t}$

- The SNR is

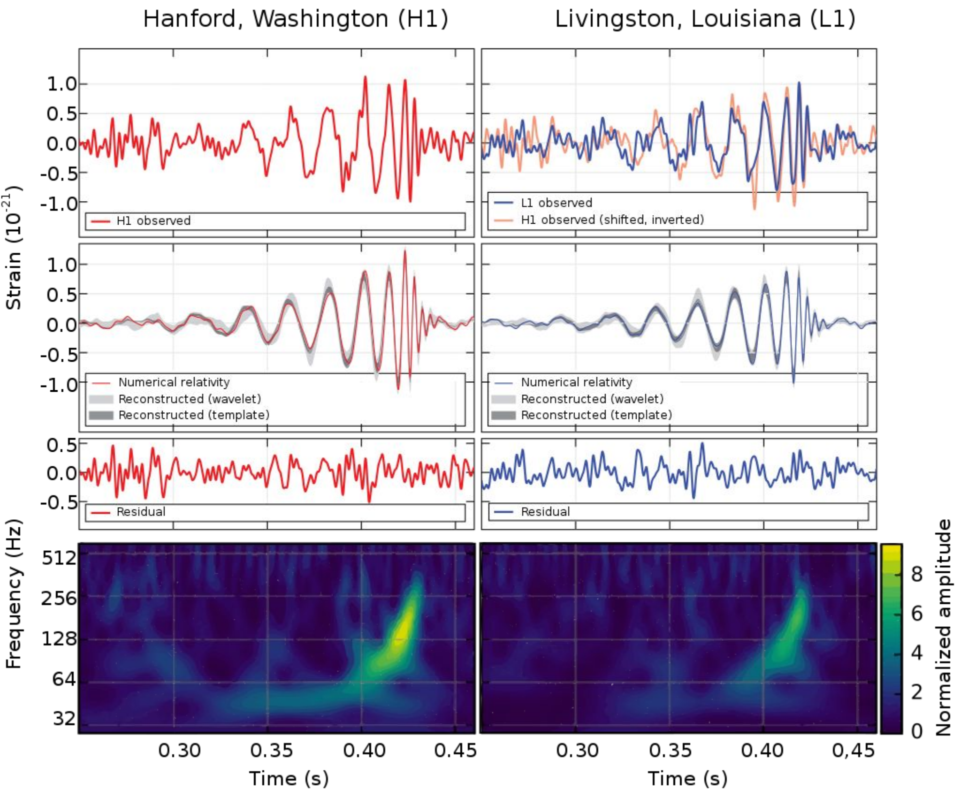
$$SNR^2(t) = 2\alpha^2 \int_0^{+\infty} \frac{|\tilde{T}(f)|^2}{S_n(f)} e^{-2i\pi f(t_0 - t)} \mathrm{d}f$$



SNR threshold at 5 (or 4.8)

CBC Analysis: Combined SNR

- For multiple detector triggers:



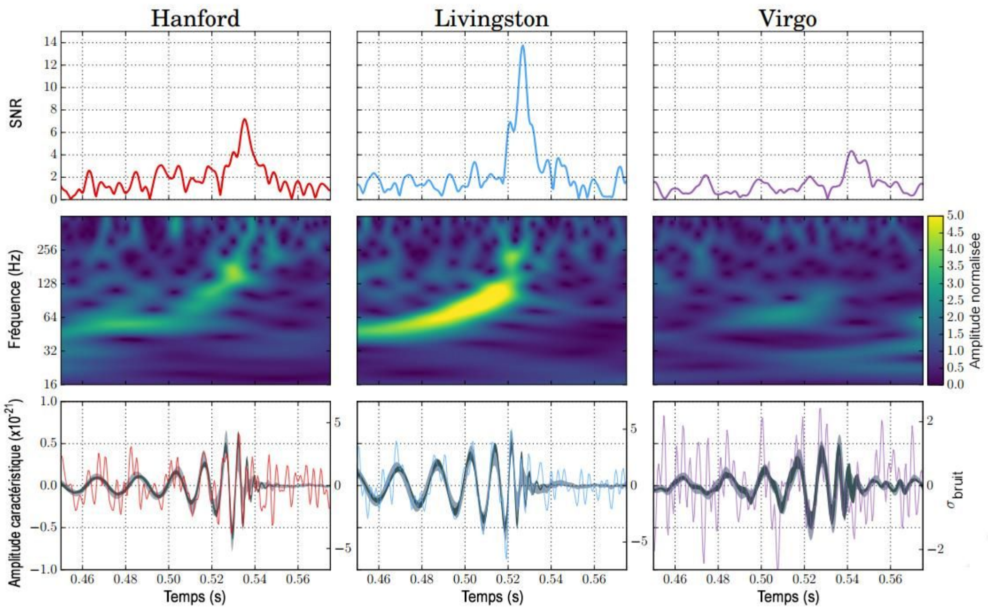
$$cSNR = \sqrt{\sum_{itf} SNR_{itf}^2}$$

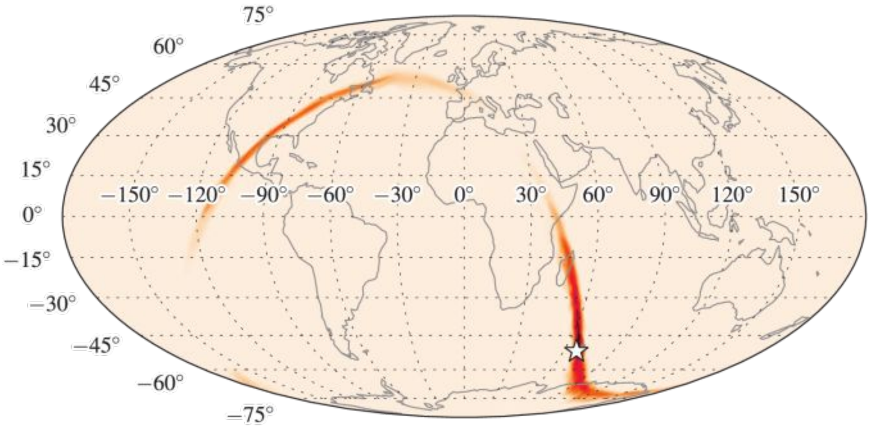
Time of Flight limits for coincidences:

- HL: 15ms
- HV: 35ms
- LV: 35ms

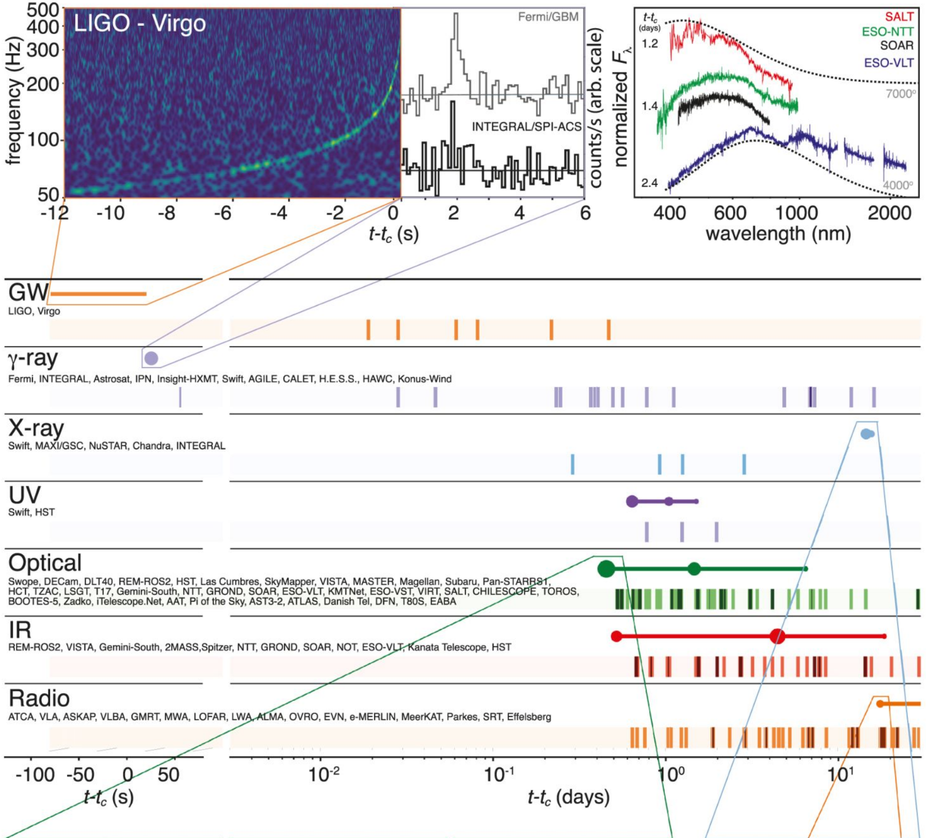
CBC Analysis: Localization

- Triangularization from SNR peaks:





First BNS : GW170817

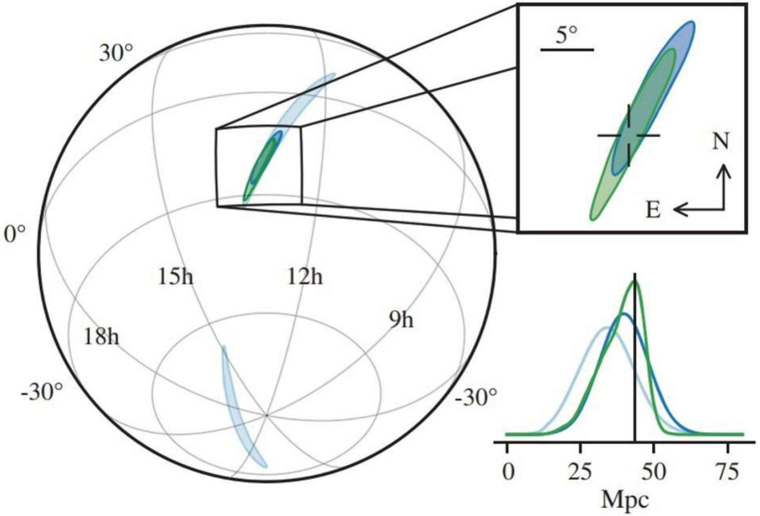


First and only multi-messenger detection

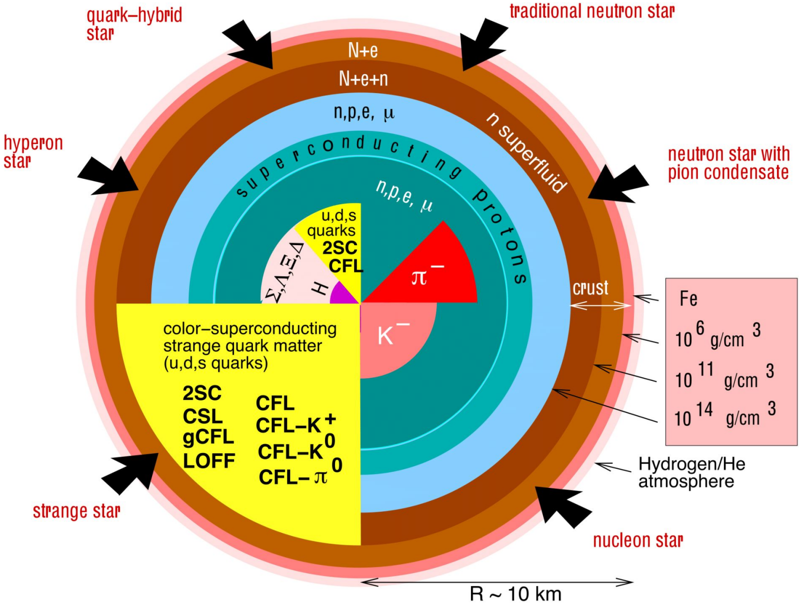
Observed on August the 17th, 2017

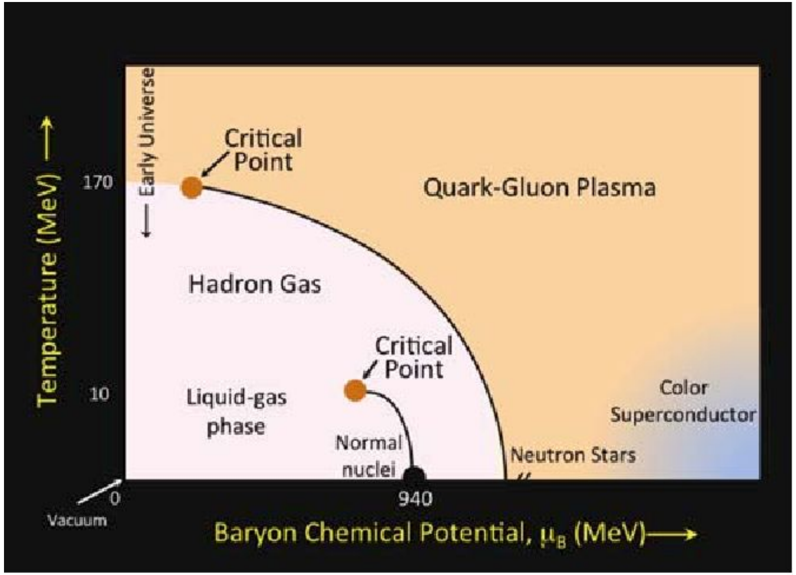
Binary Neutron Star

Localized in NGC4993

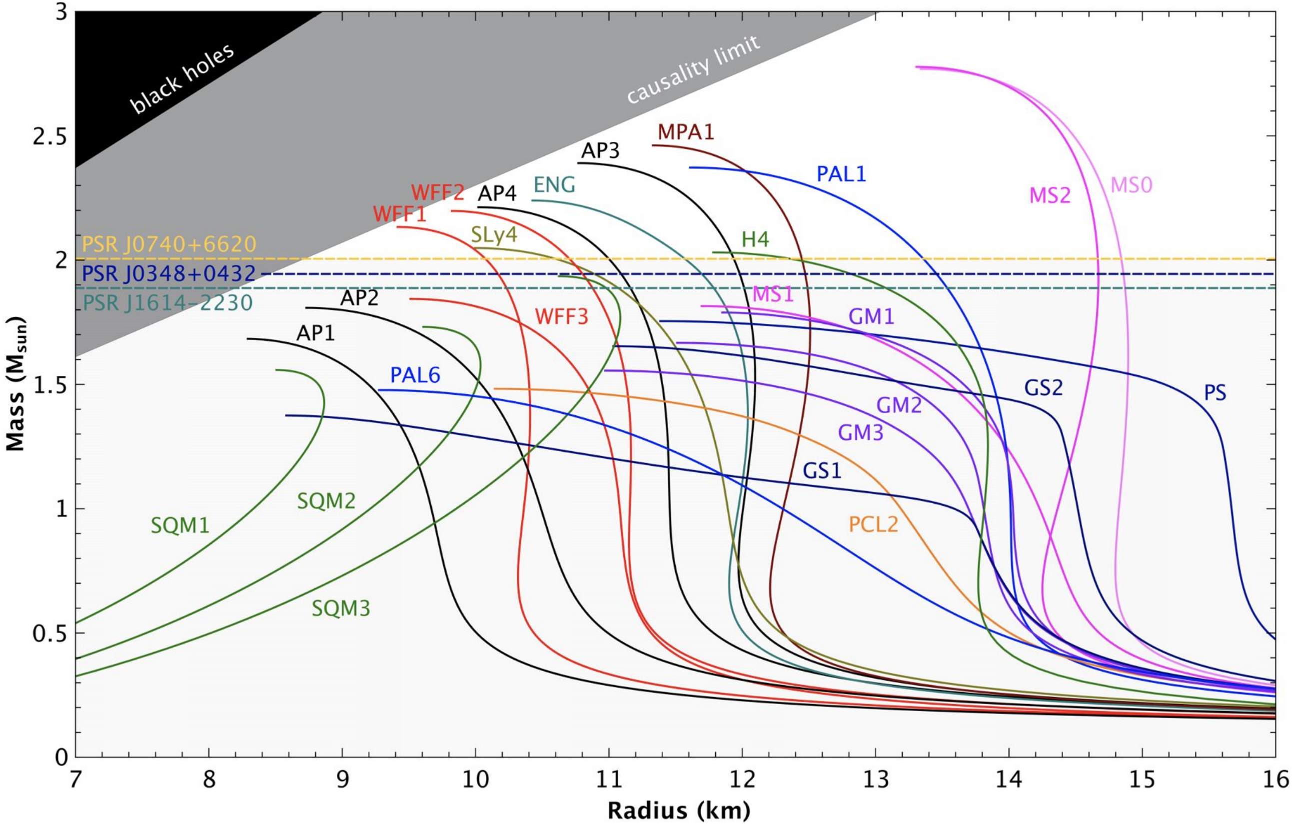


Neutron Stars internal structure

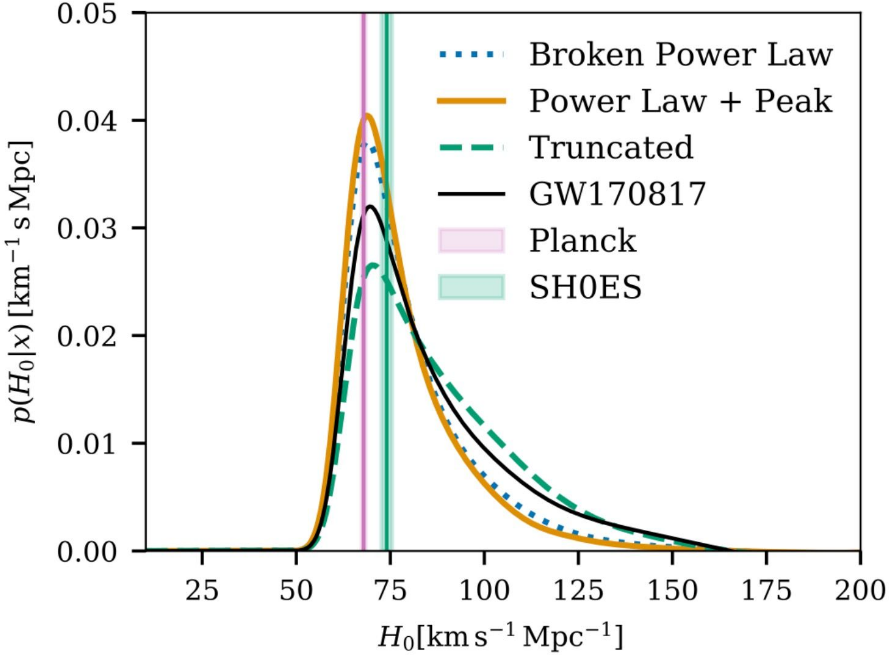




Neutron Stars internal structure



Hubble Constant Measurements



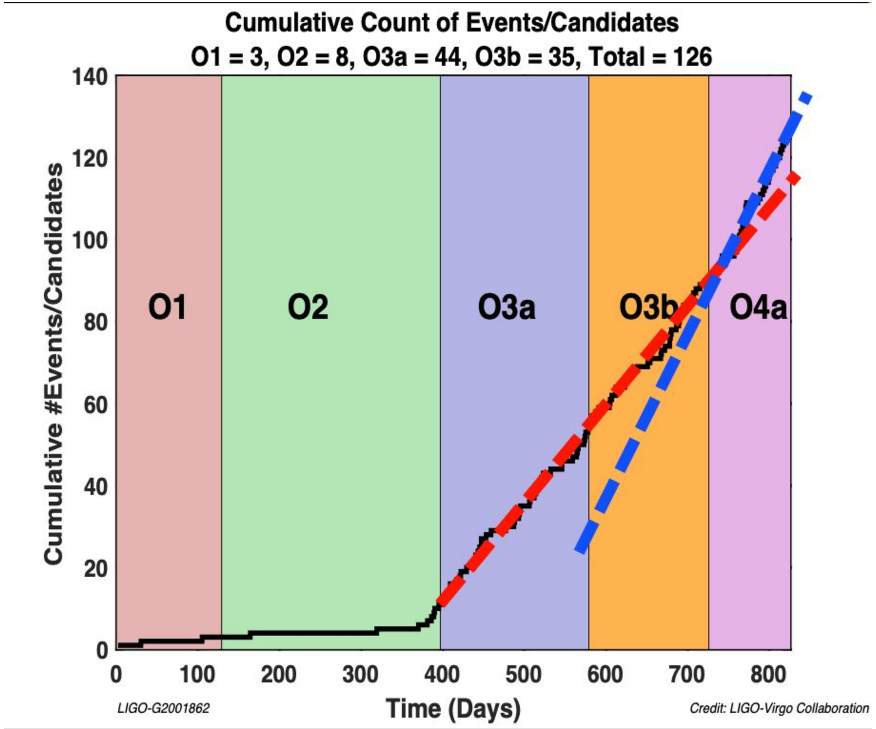
Contribution des BBH
à la mesure de H_0

Méthode d’association :

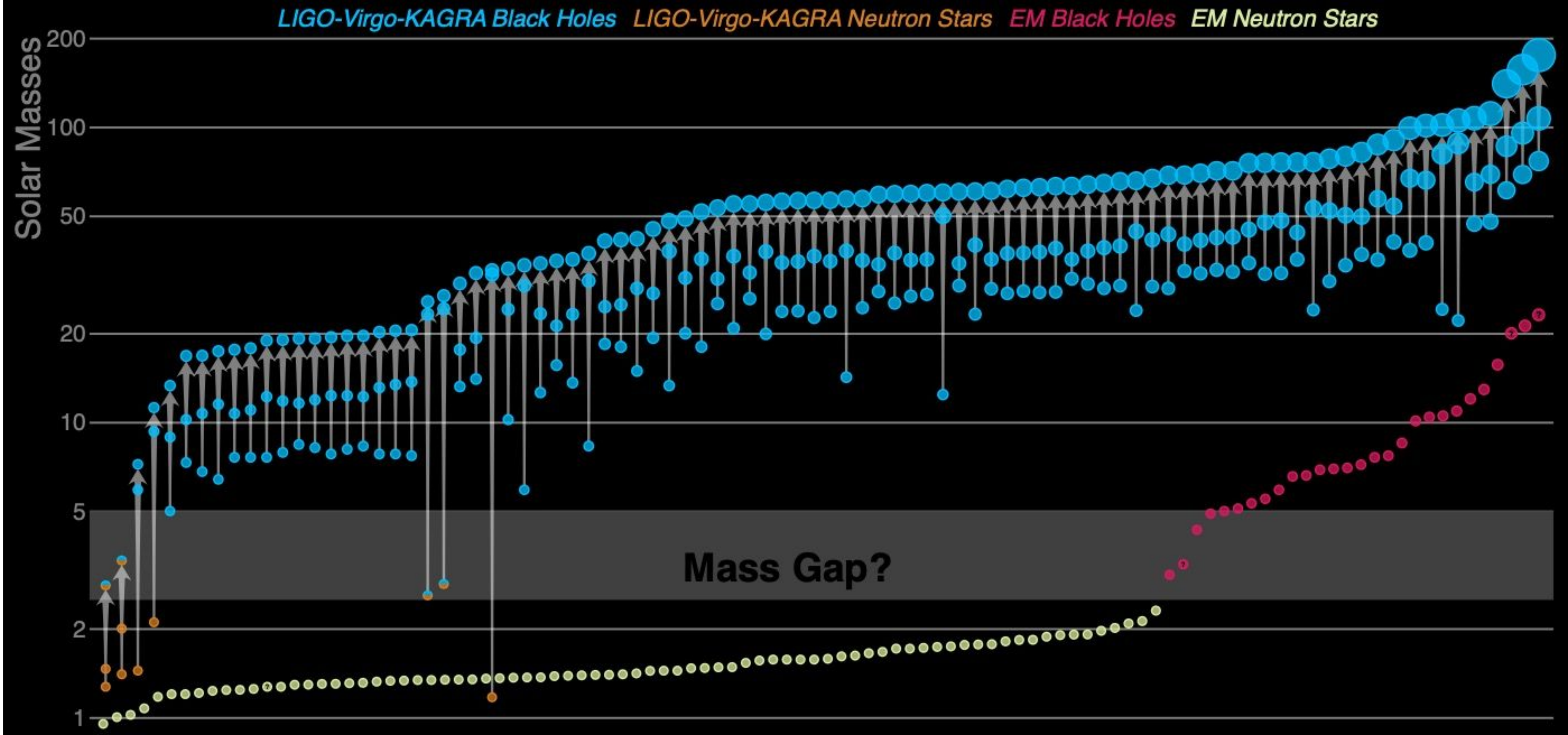
- Evt associé à sa galaxie hôte probable (catalogue GLADE+)
- Marginalise sur les redshifts des hôtes potentiels de chaque évt.

$$H_0 = 68^{+8}_{-6}\, km.\, s^{-1}.\, Mpc^{-1}$$

Rate of events



Masses in the Stellar Graveyard



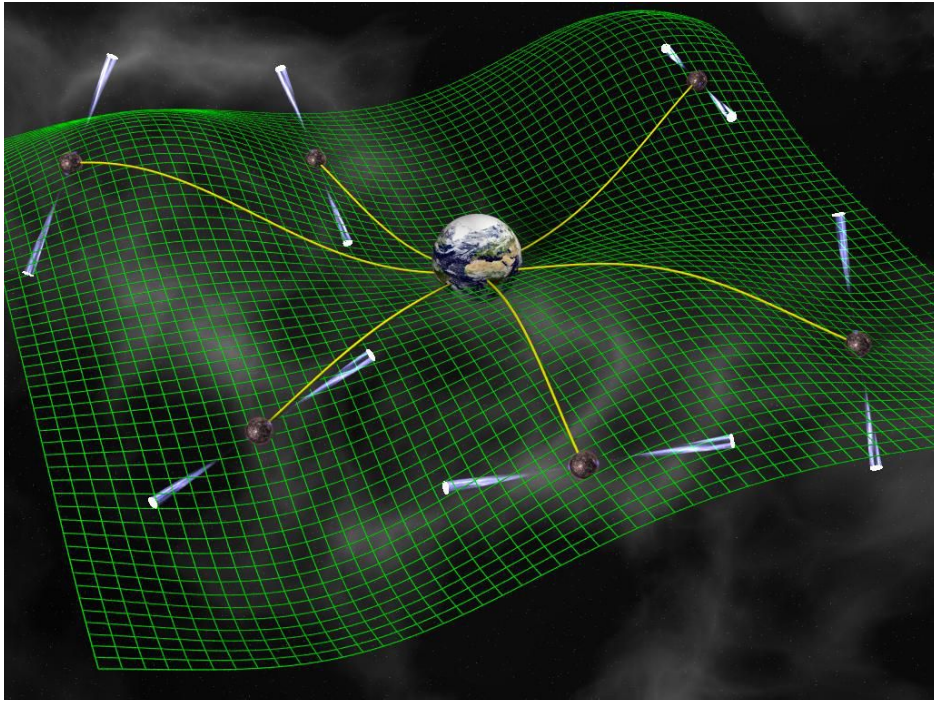
LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

End of the second part

Weber bars and Mass-resonant detectors

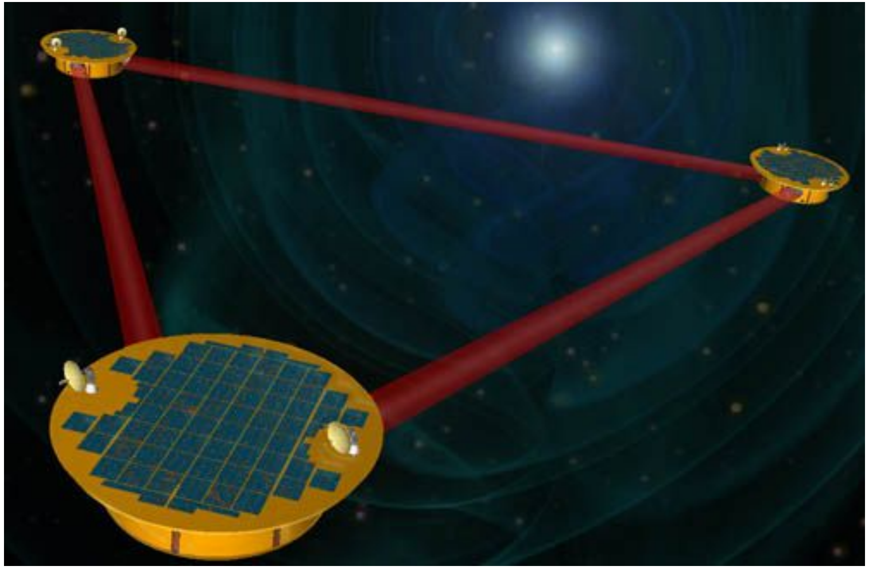
- Weber bars:
  - University of Maryland;
- ALLEGRO:
  - Louisiana State University;
  - 4.2K;
- NIOBE:
  - Western Australia;
  - 2-5K;
- AURIGA:
  - Italy;
  - 0.1K;
- Explorer:
  - CERN;
  - 2-5K;
- NAUTILUS:
  - INFN;
  - 1.5K;
- GRAIL:
  - Leiden University;
  - 20mK;

Pulsar Timing Array



- International Pulsar Timing Array:
  - NANOGrav ;
  - European Pulsar Timing Array;
  - Chinese Pulsar Timing Array;
  - Parkes Pulsar Timing Array;
- Sources :
  - Stochastic background;
  - Supermassive binaries;
- Evidence for gravitational wave background (3 to 4.6 σ);

Space-based interferometer: LISA



- Frequency bandwidth : 0.1mHz - 1Hz;
- 2.5 millions of km;
- Lagrange point L3;
- Launched 2035 (?);
- Sources:
  - Massive binaries;
  - Resolvable galactic binaries;
  - Extreme Mass Ratio Inspirals;