Detectors Evolution for Gravitational Waves Observations

F. Frasconi – INFN Pisa

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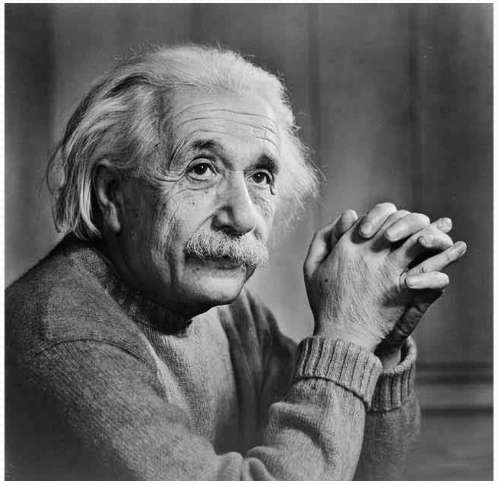
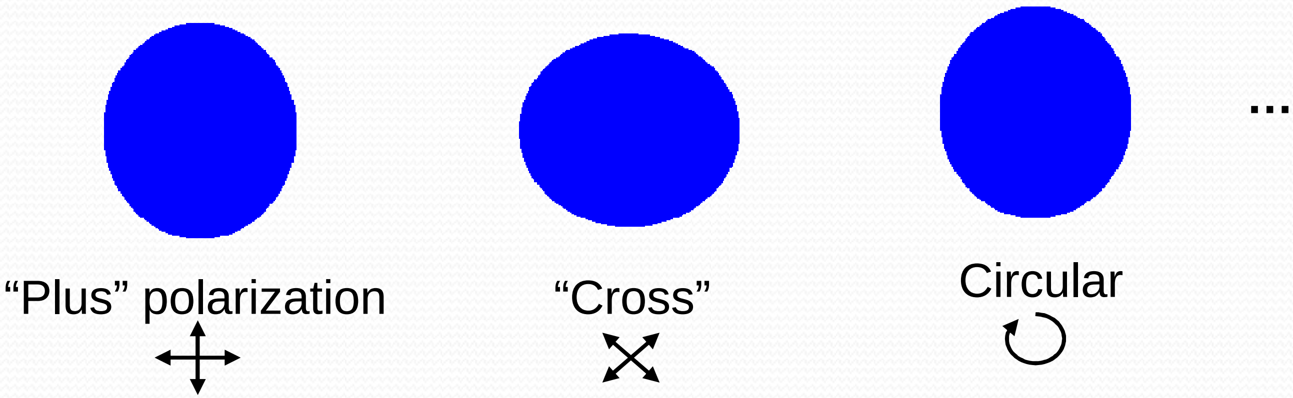
Gravitational Waves

- According to the Einstein's theory of General Relativity (1915), **Gravitational Waves (GW)** are perturbations of the "space-time" metric traveling in the Universe at the speed of light;
- They are expected to be emitted by astrophysical processes in which accelerated coherent motions of large masses take place (supernova explosions, pulsars, black holes, etc.);
- The aim of modern detectors (ground based interferometric detectors - ITF) is the direct observation of GW together with the possibility to localize their source in the sky (detectors network).

GW interaction

- When such a wave interacts with an object, this is **"stretched"** and **"compressed"** in alternative way

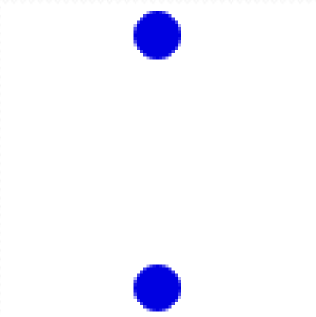


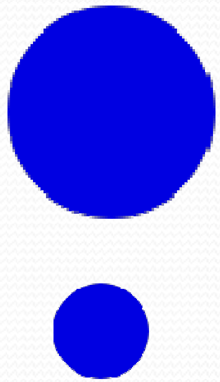


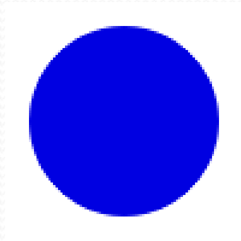
How can GWs be produced?

Two compact objects in close orbit

Deform space, and objects embedded in it, at a frequency twice their orbital frequency







The deformation is measured by the "strain", $h = \Delta L / L$

h is inversely proportional to the source distance

Ripples in the cosmic sea

- Linearized Einstein equations admit wave solutions as perturbations to a background geometry

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

$$\mathbf{g} = \eta + \mathbf{h} \ \text{ with} \left|h_{\mu\nu}\right| << 1 \ \Rightarrow \ \left(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right)h_{\mu\nu} = 0$$

- **Gravitational Waves:**

  transverse space-time distortions propagating at the speed of light, described by 2 independent polarization

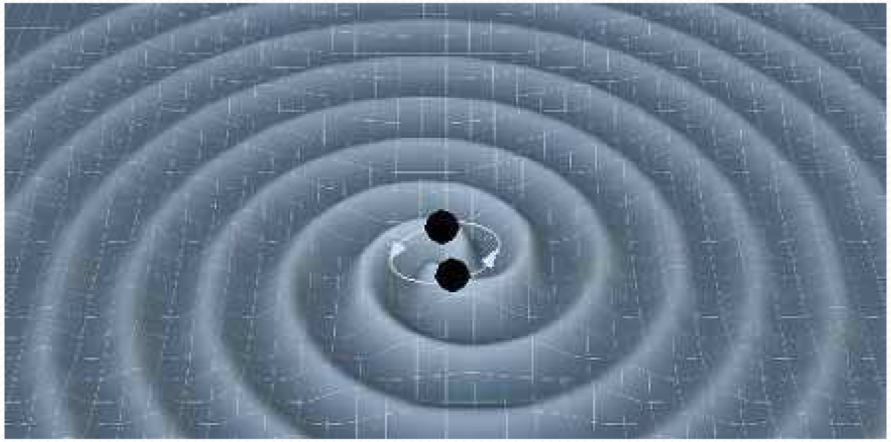
$$\mathbf{h}(z,t) = e^{i(\omega t - kz)}\begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & h_+ & h_\times & 0 \\ 0 & h_\times & -h_+ & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

Target GW amplitude

- Efficient sources of GW must be **asymmetric**, **compact** and **fast**;
- GW detectors are sensitive to amplitude **h**: 1/r attenuation !

Amplitude

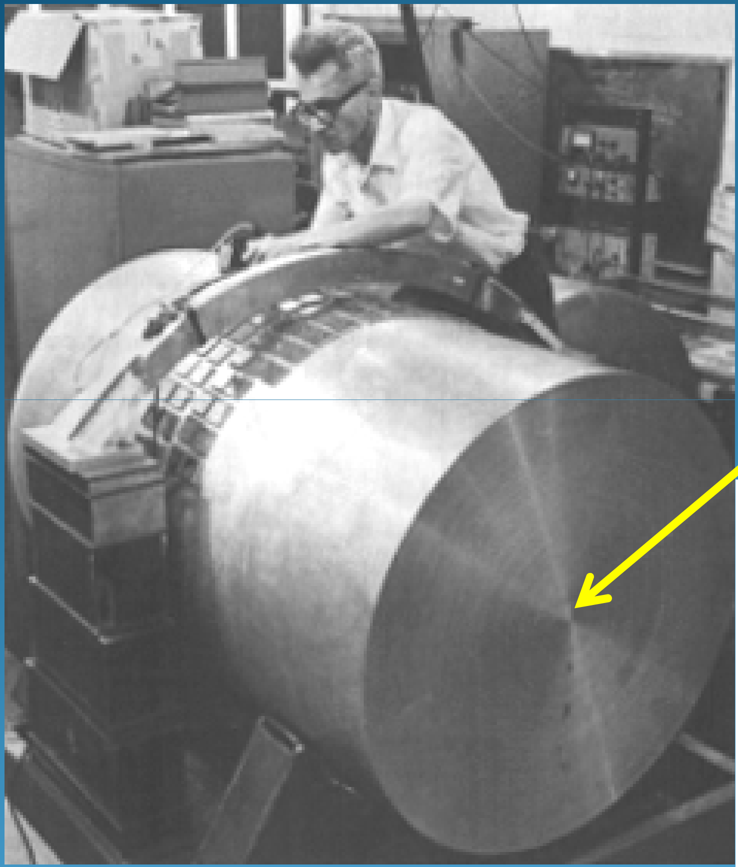
$$h_{\mu\nu} = \frac{2G}{c^4} \cdot \frac{1}{r} \ddot{Q}_{\mu\nu}$$



Target Amplitude:
coalescing NS/NS in the Virgo cluster (r ~ 10 Mpc)

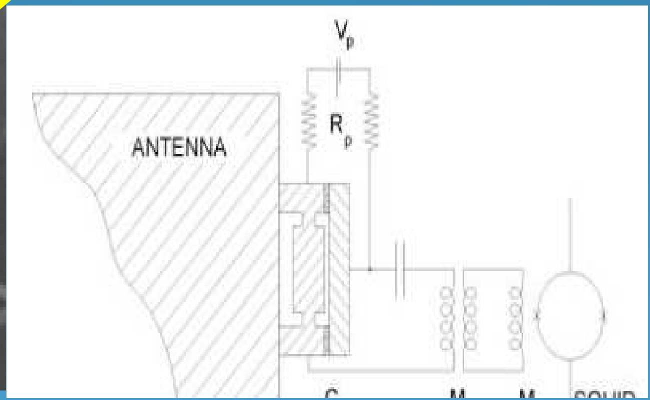
→ $h \sim 10^{-21}$

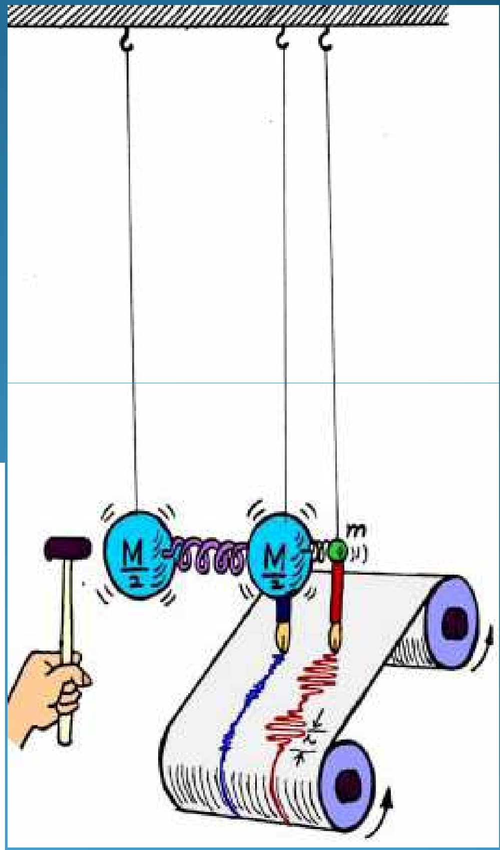
Fist Attempt: the resonant bars



Joseph Weber
(~1960)

Resonant bar
suspended in
the middle

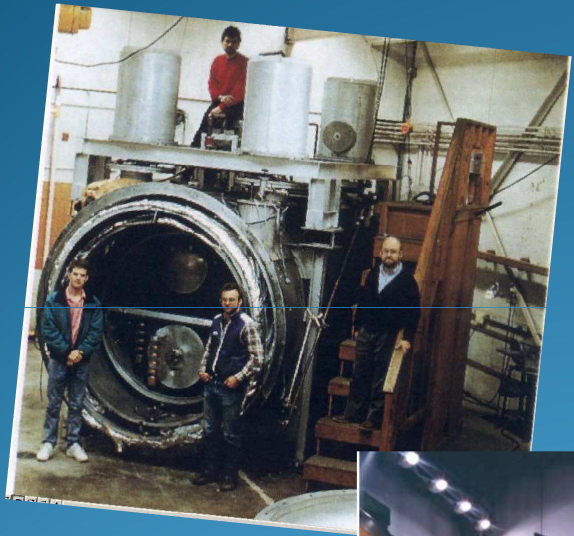


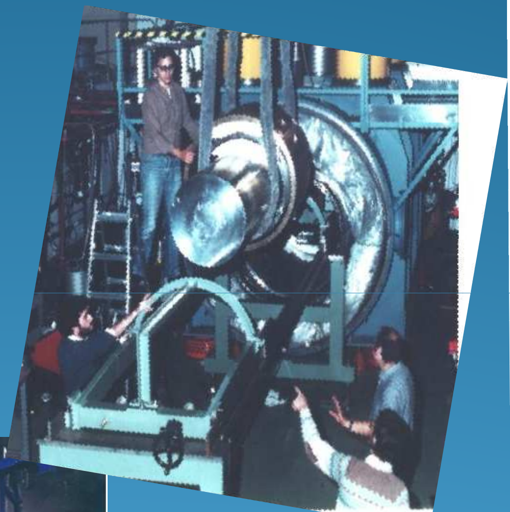


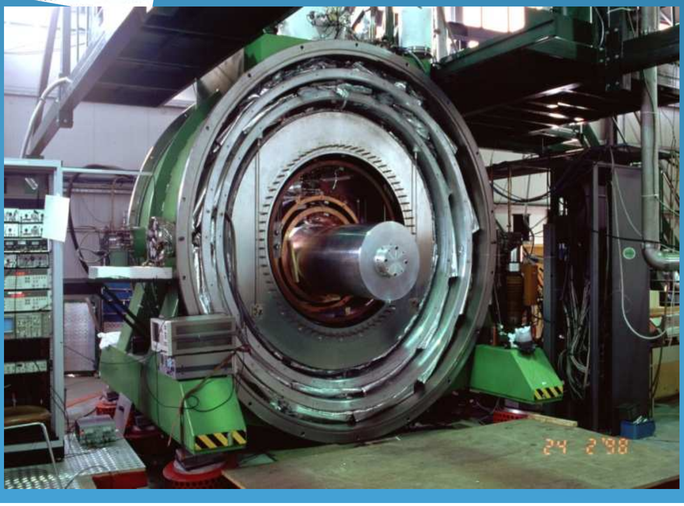
- The passage of GW having a frequency in the range of the bar resonance, excites its longitudinal mode;
- A coupled smaller mass would vibrate with a larger amplitude

GW Detectors: the resonant bars

Narrow band Detectors for a feeble signal

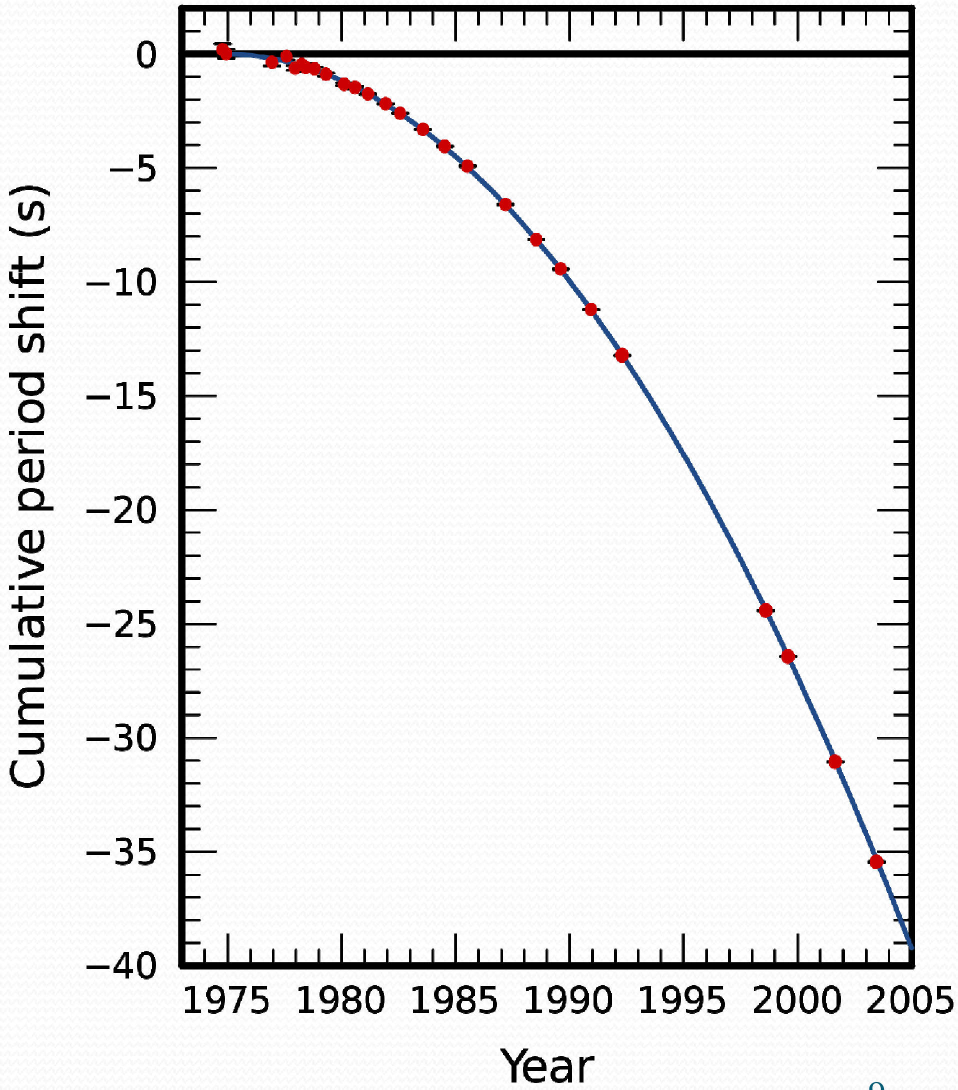






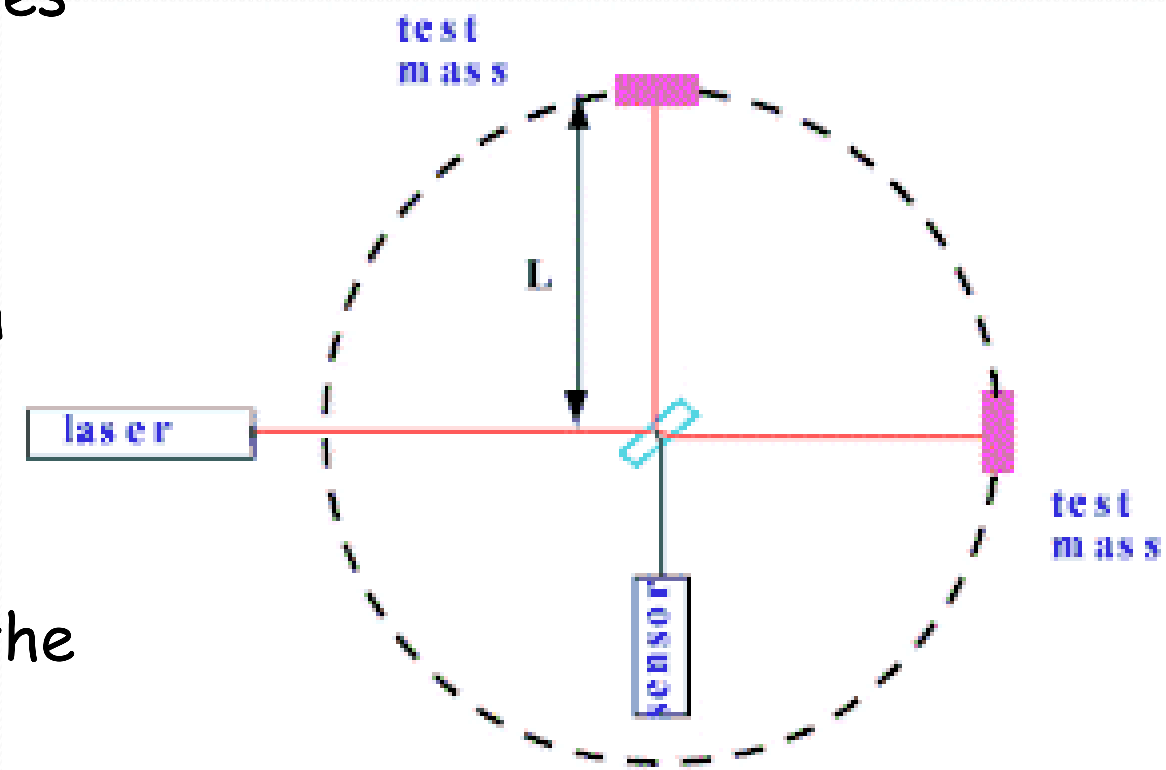
The indirect proof of GW existence: PSR 1916+13

- This binary system is loosing energy (gravitational waves emission) as predicted by General Relativity: orbital period decreases;
- Coalescence of the two bodies within 400 million of years;
- Nobel Prize on Physics 1993: R. A. Hulse e J. H. Taylor



The Interferometric Detectors

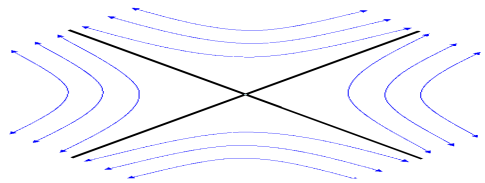
- GW impinging on masses distribution with "L" shape induce a space-time deformation;
- The space-time strain can be measured by using light;
- A very complex instrument based on the working principle of a Michelson interferometer.

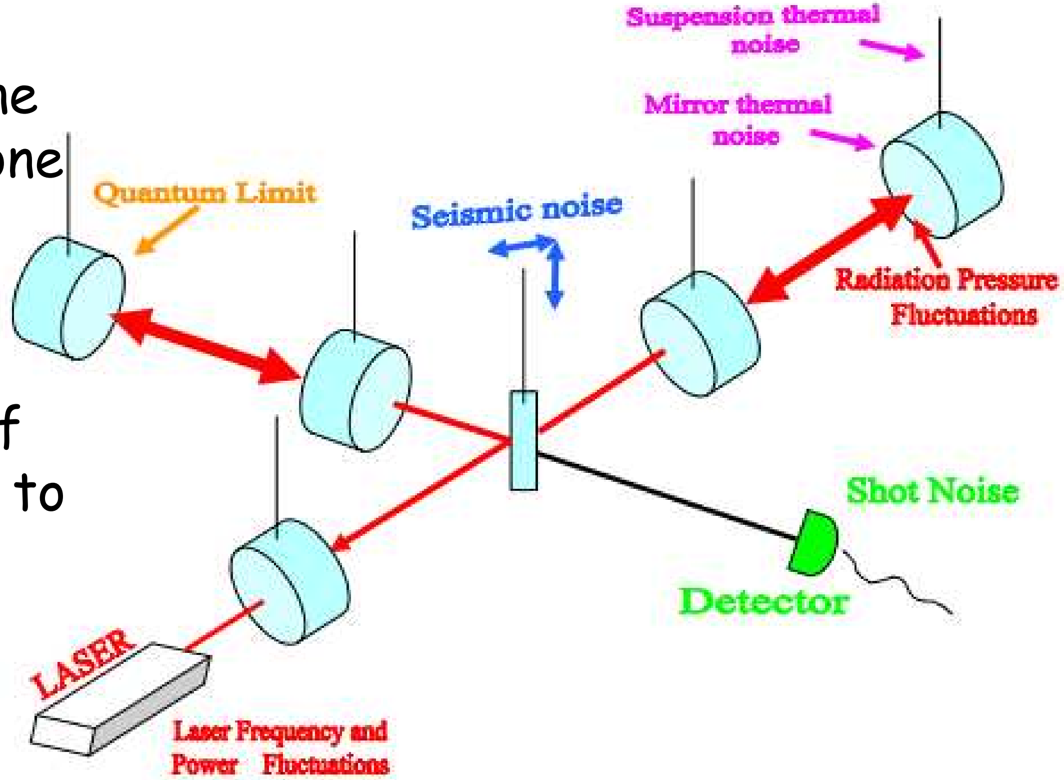


The broadband GW Interferometers

- The detector is sensitive to **h** the Gravitational Wave strain amplitude (a GW impinging on the plane of a suspended interferometer stretches one arm compressing the other one alternatively)
- The detector sensitivity is expressed in terms of the amplitude spectral density of the detector noise referred to its input

  H(f) $[(Hz)^{-1/2}]$





Target Sensitivity of ITFs

- Mirror displacement hit by GW:

$$\Delta L \approx \frac{1}{2} h L$$

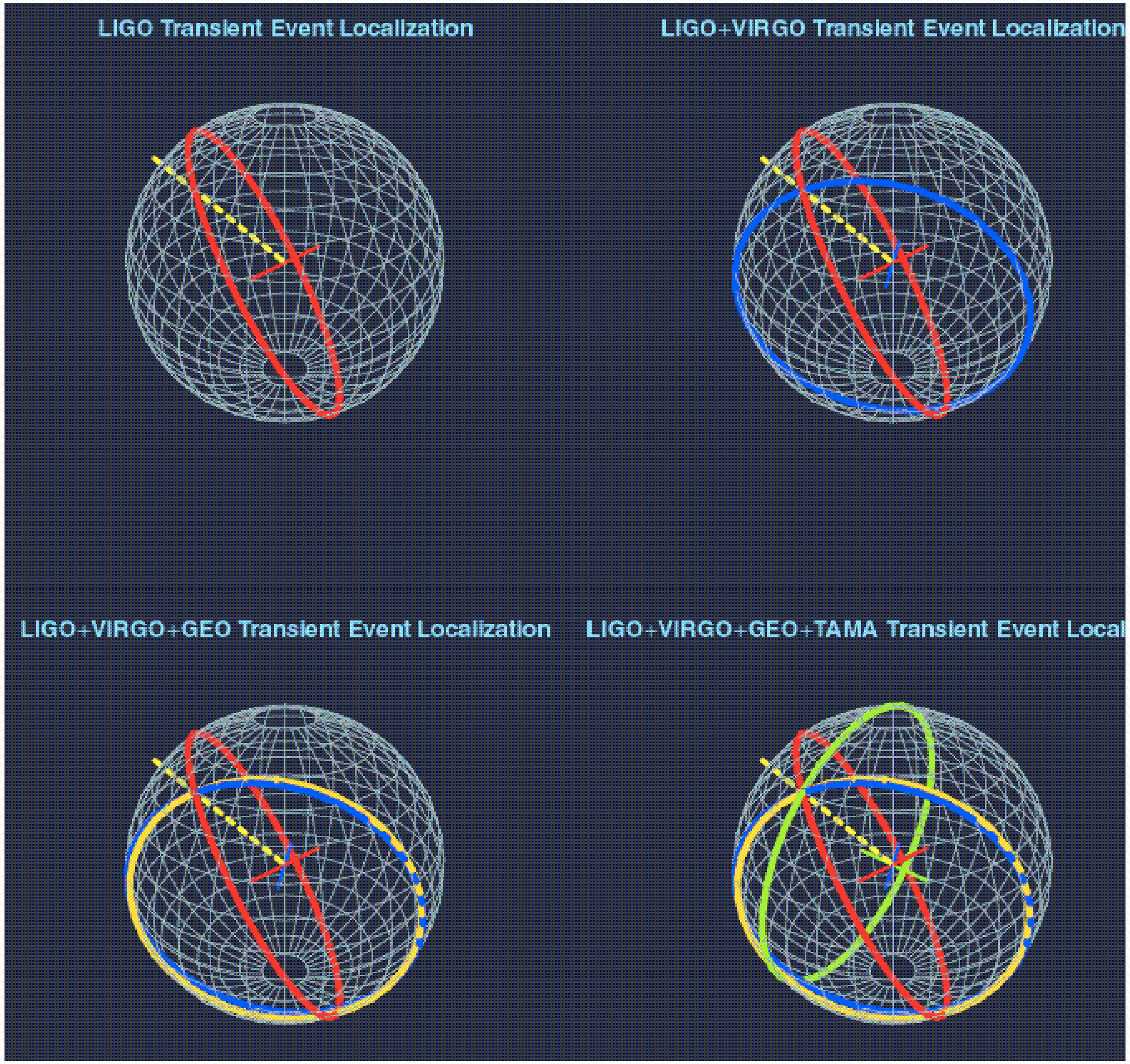
Mirror Displacement (ΔL) — GW Amplitude (h) — Interferometer arm length (L)

- Coalescing binary NS system @ Virgo cluster: h~ 10^{-21}
- Interferometer arm length L on Earth: a few km (10^3m)
- Need to measure: $\Delta L \sim 10^{-18}$ m

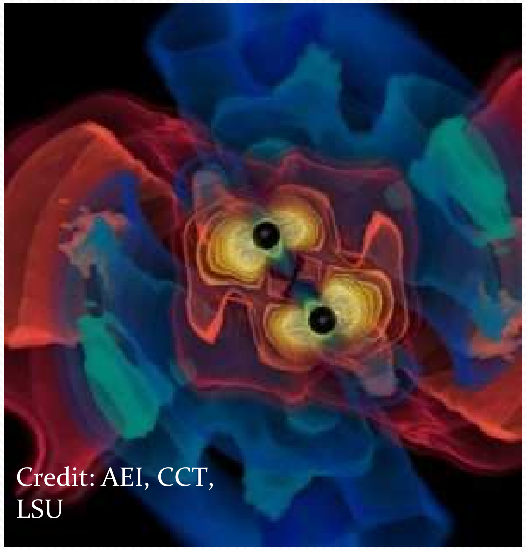
ITFs of the 1st Generation and Network

Importance of a detectors Network

- False alarm rejection require coincidence;
- Triangulation allows to pinpoint the source;
- The Network allows to deconvolve detector response and signal wave form -> measurement of the signal parameters;
- Longer observation time better sky coverage.

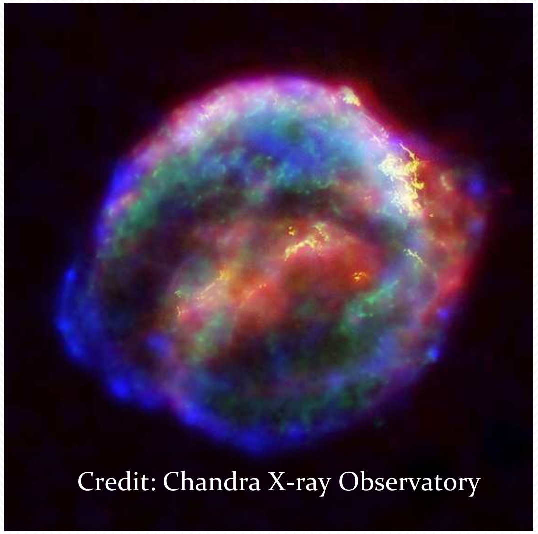


GW Sources



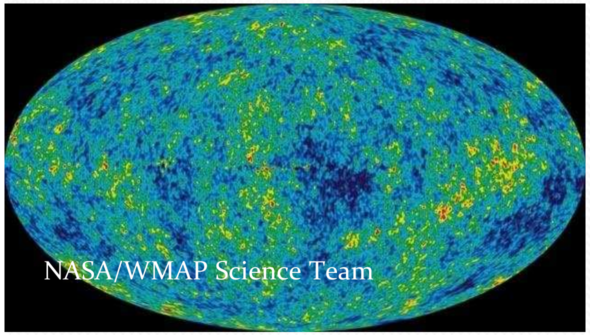
Coalescing Binary Systems

- Neutron stars, low mass black holes, and NS/BS systems



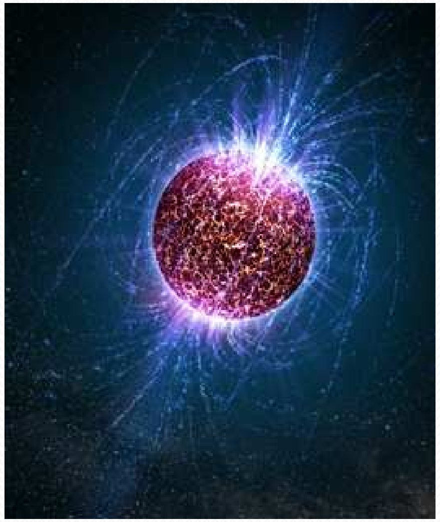
'Bursts'

- galactic asymmetric core collapse supernovae
- cosmic strings
- ???



Cosmic GW background

- Stochastic, incoherent background
- unlikely to detect, but can bound in the 10-10000 Hz range

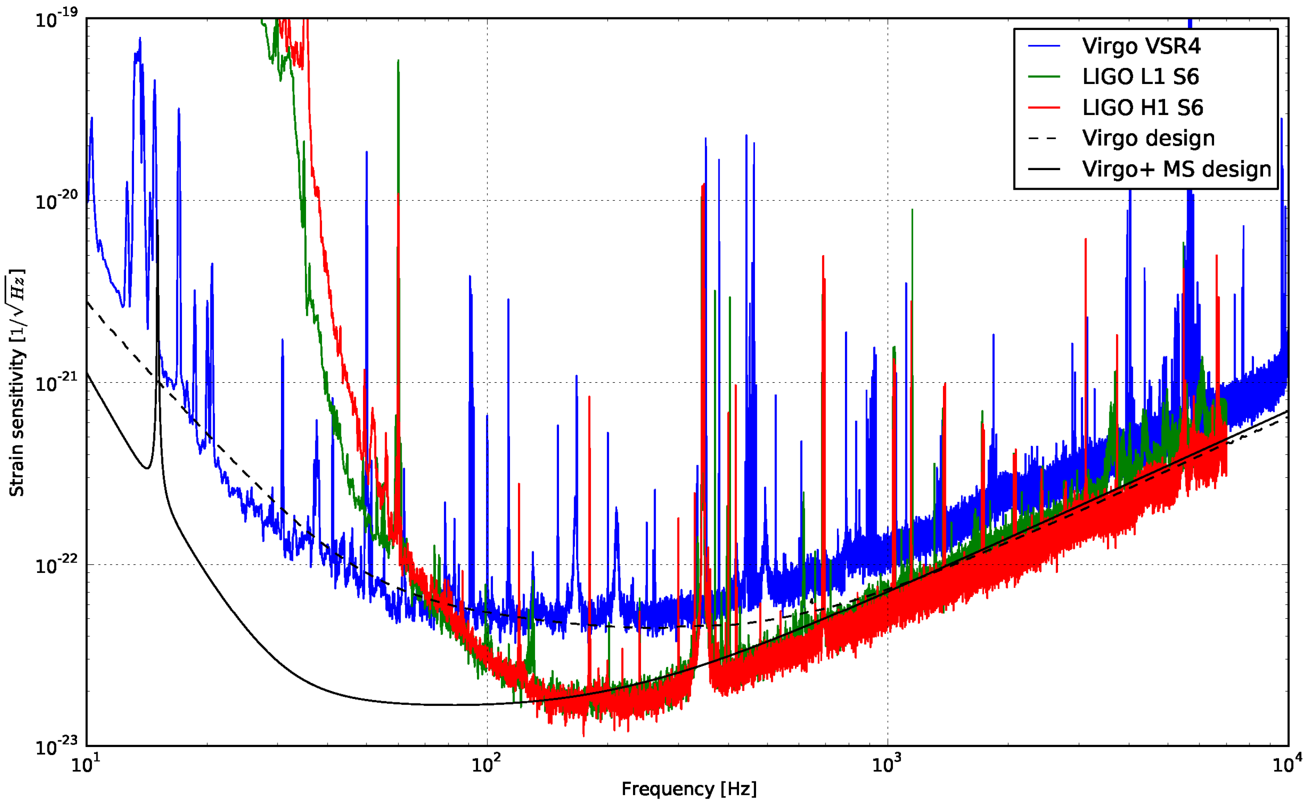


Continuous Sources

- Spinning neutron stars
- probe crustal deformations, 'quarki-ness'

Achived Sensitivities: 1st Generation ITF

- LIGO and VIRGO reached the design sensitivity;
- Robust and reliable instruments realized.



Some Scientific Papers

PHYSICAL REVIEW D **85**, 082002 (2012)

Search for gravitational waves from low mass compact binary coalescence in LIGO's sixth science run and Virgo's science runs 2 and 3

THE ASTROPHYSICAL JOURNAL, 760:12 (18pp), 2012 November 20 doi:10.1088/0004-637X/760/1/12

SEARCH FOR GRAVITATIONAL WAVES ASSOCIATED WITH GAMMA-RAY BURSTS DURING LIGO SCIENCE RUN 6 AND VIRGO SCIENCE RUNS 2 AND 3

PHYSICAL REVIEW D 85, 122007 (2012)

All-sky search for gravitational-wave bursts in the second joint LIGO-Virgo run

THE ASTROPHYSICAL JOURNAL, 737:93 (16pp), 2011 August 20 doi:10.1088/0004-637X/737/2/93

BEATING THE SPIN-DOWN LIMIT ON GRAVITATIONAL WAVE EMISSION FROM THE VELA PULSAR

nature Vol 460 | 20 August 2009 | doi:10.1038/nature08278

LETTERS

An upper limit on the stochastic gravitational-wave background of cosmological origin

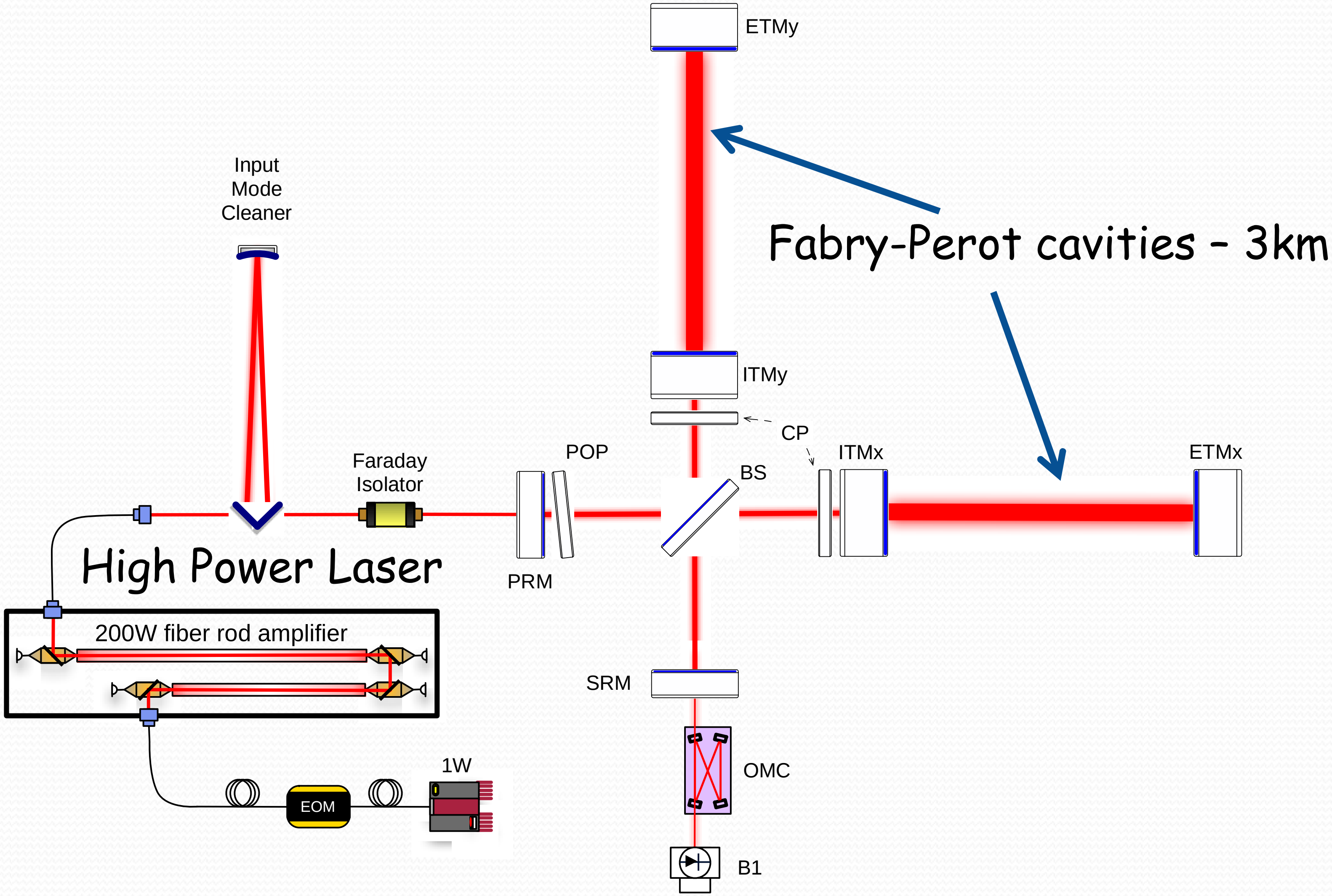
The LIGO Scientific Collaboration* & The Virgo Collaboration*

No signal detected by 1st Generation Instruments

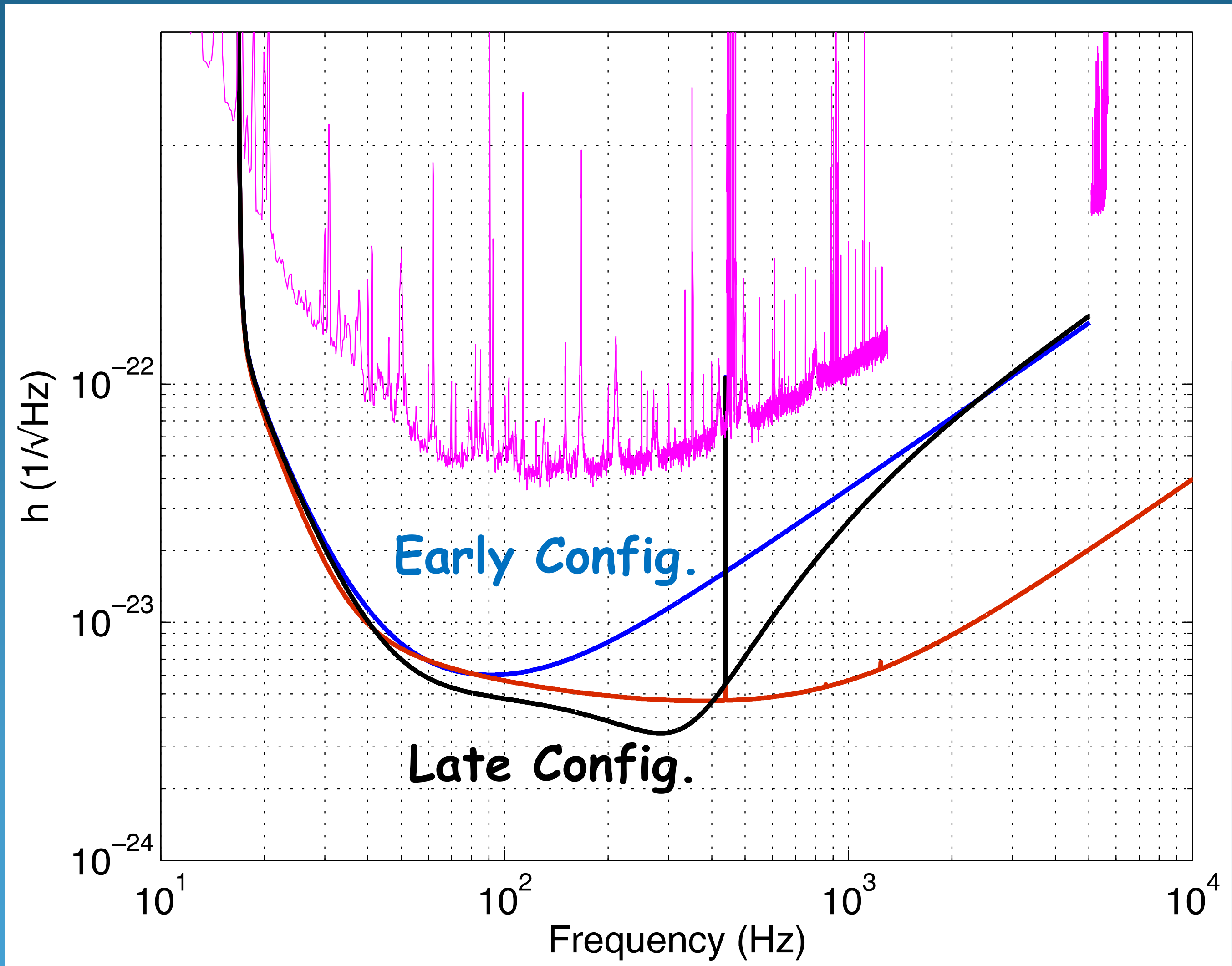
The Advanced Interferometers

- 2nd Generation detectors based on the same infrastructures;
- Advanced VIRGO (AdV): upgrade of the ground based VIRGO interferometer;
- Michelson Interferometer with two Fabry-Perot cavities along the arms 3 km long each one.

Optical layout: AdV



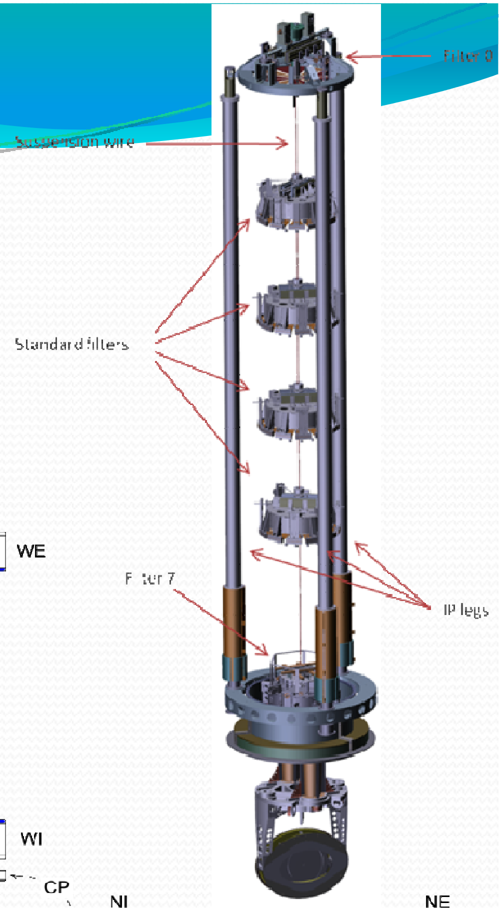
Evolution of the AdV Interferometer Sensitivity

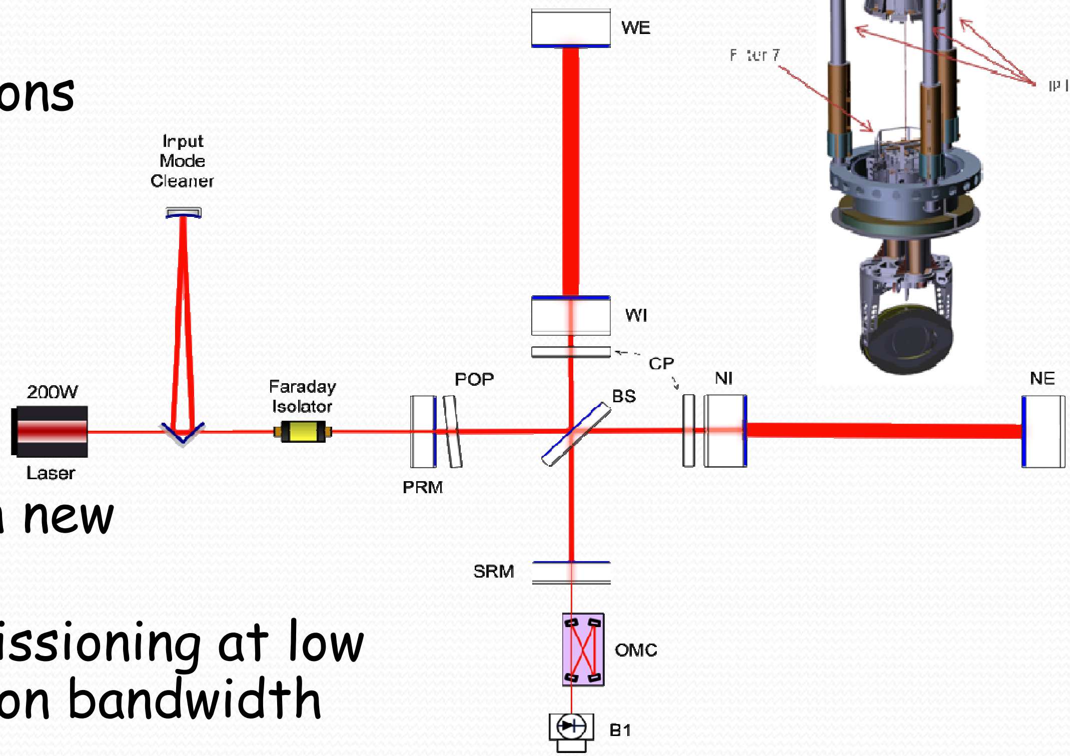


AdV Design

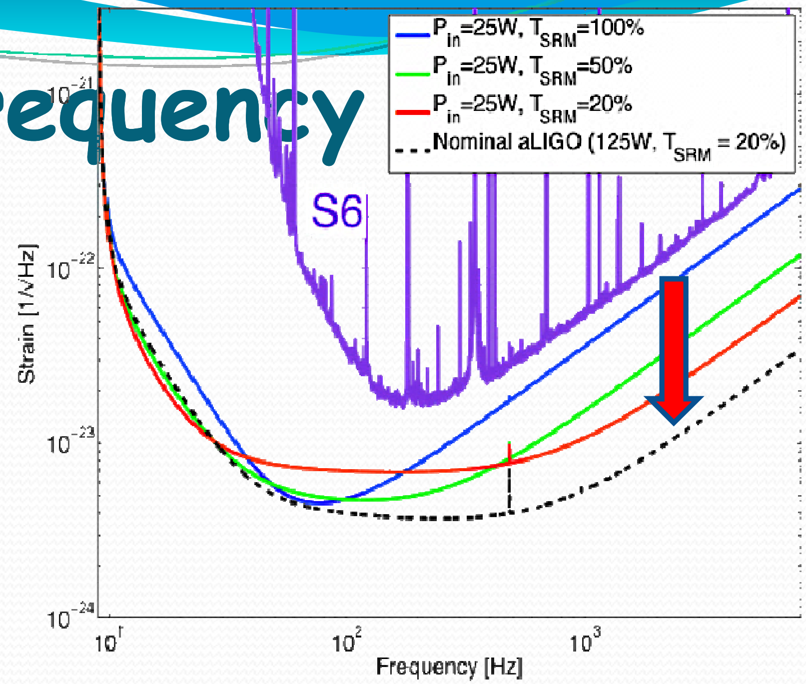
- Main changes with respect to VIRGO:
  - larger beam
  - heavier mirrors
  - higher quality optics
  - thermal control of aberrations
  - 200W fiber laser
  - Signal Recycling

- Vibration isolation by VIRGO Superattenuators:
  - performance compliant with new requirements
  - wide experience with commissioning at low frequency (extended detection bandwidth at low frequency)





Noise budget: high frequency

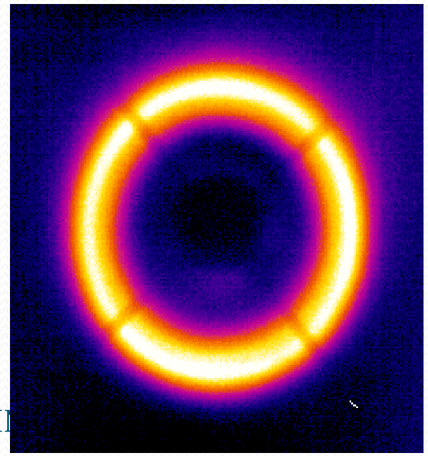


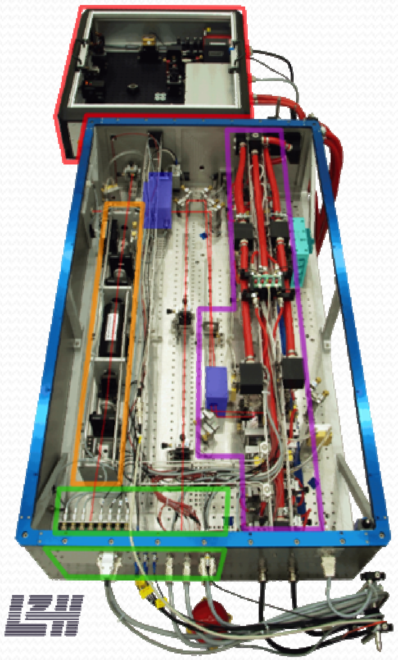
- Dominated by laser shot noise.

- Improved by increasing the power:
  > 100W input, ~1 MW in the cavities.

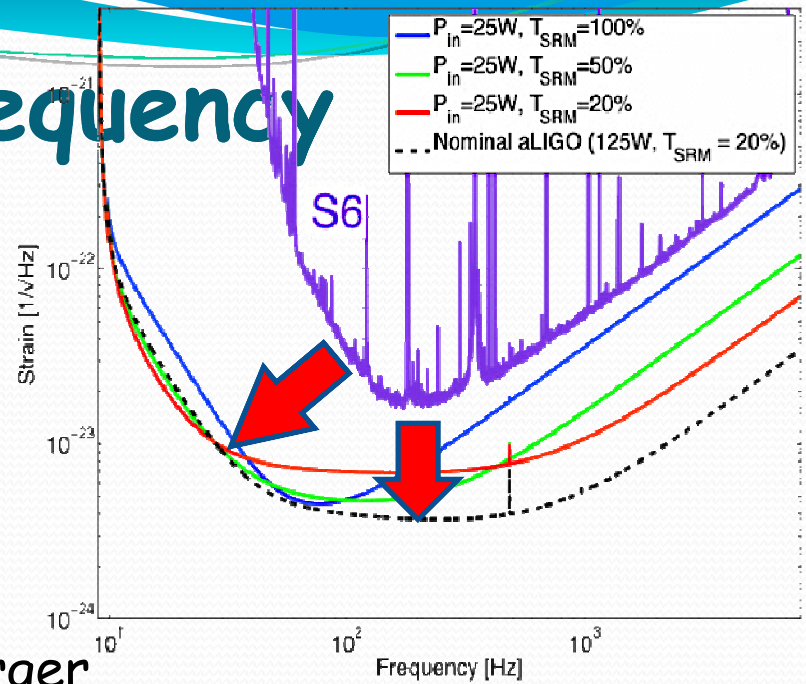
- Requires:

- New laser amplifiers (solid state, fiber);
- Heavy, low absorption optics (substrates, coatings);
- Sophisticated systems to correct thermal aberration.





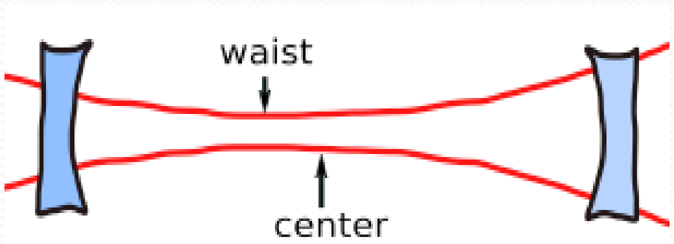
Noise budget: mid frequency

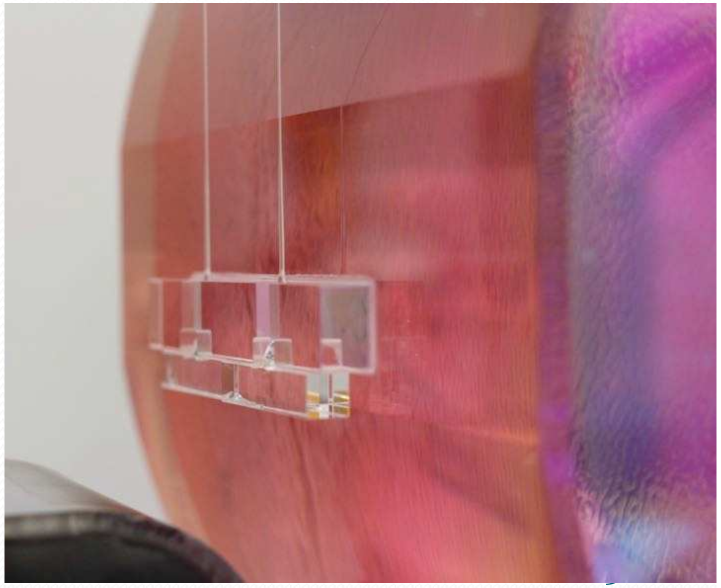


- Dominated by thermal noise of:
  - Mirror coatings
  - Mirror Suspensions

- Reduced by:

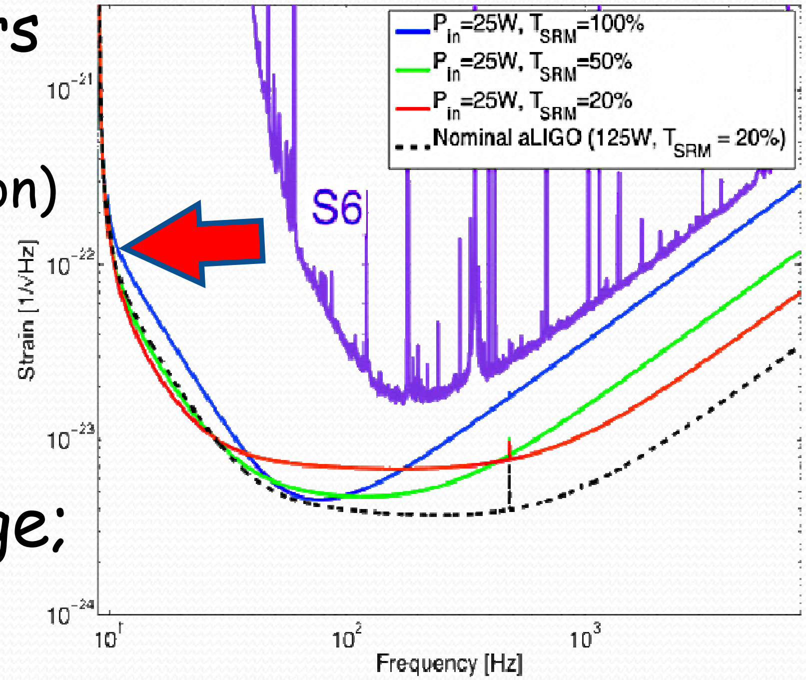
- An improved optical configuration with larger beam spot;
- Test masses suspended by fused silica fibers (low mechanical losses);
- Mirror coatings engineered for low losses





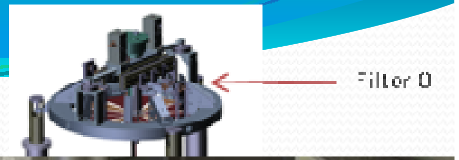
Noise budget: low frequency

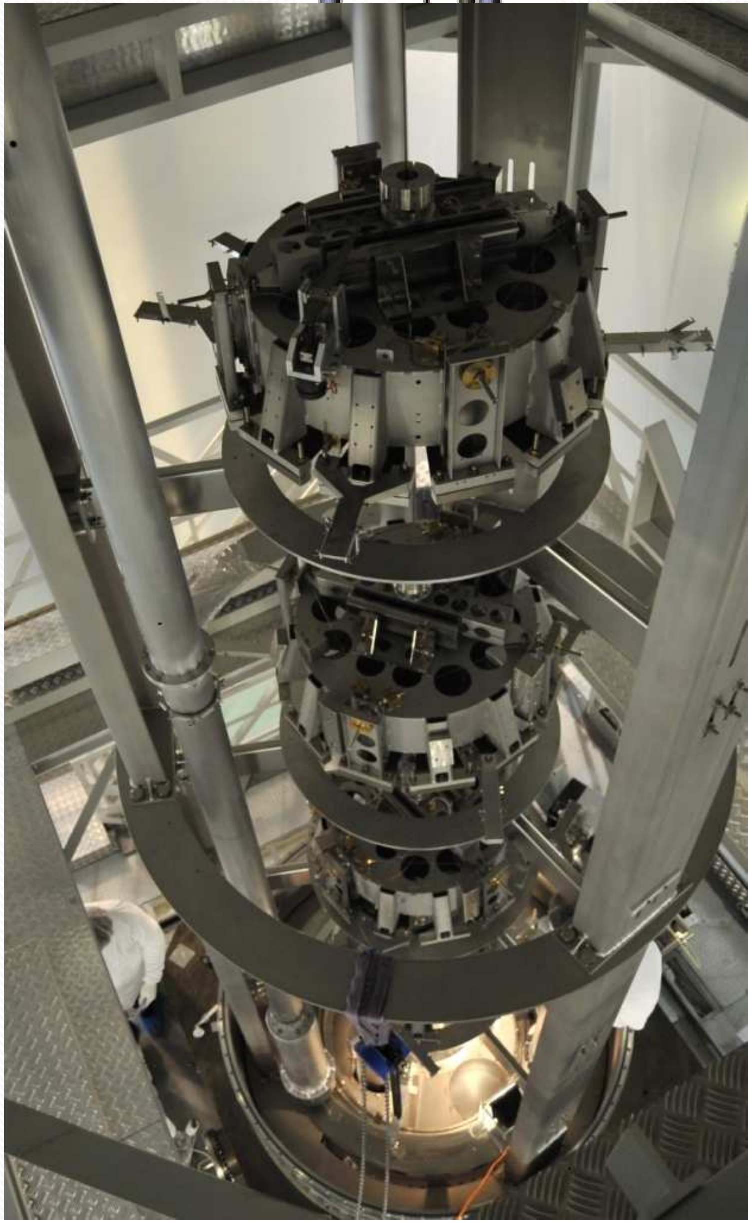
- Dominated by seismic noise;
- Managed by suspending the mirrors from complex vibration isolators
  - VIRGO Superattenuators (1st Generation)
  - LIGO active system
- Technical noise sources of different nature are the real challenge in this frequency range;
- Ultimate limit for ground based detectors: gravity gradient noise.



AdV Sueperattenuators

- The **Superattenuator (SA)** is the mechanical system adopted to isolate the optical components from seismic activities (local disturbances). It is based on the working principle of a **multistage pendulum**;
- Hybrid system: **active** control below 4 Hz and **passive** attenuation starting from 4 Hz;
- Detection bandwidth extended in the low frequency range.





aLIGO Seismic Isolation

Hydraulic exte
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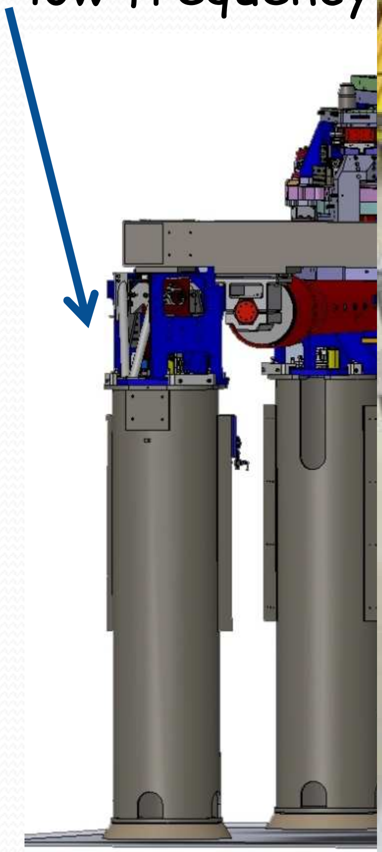
low frequency



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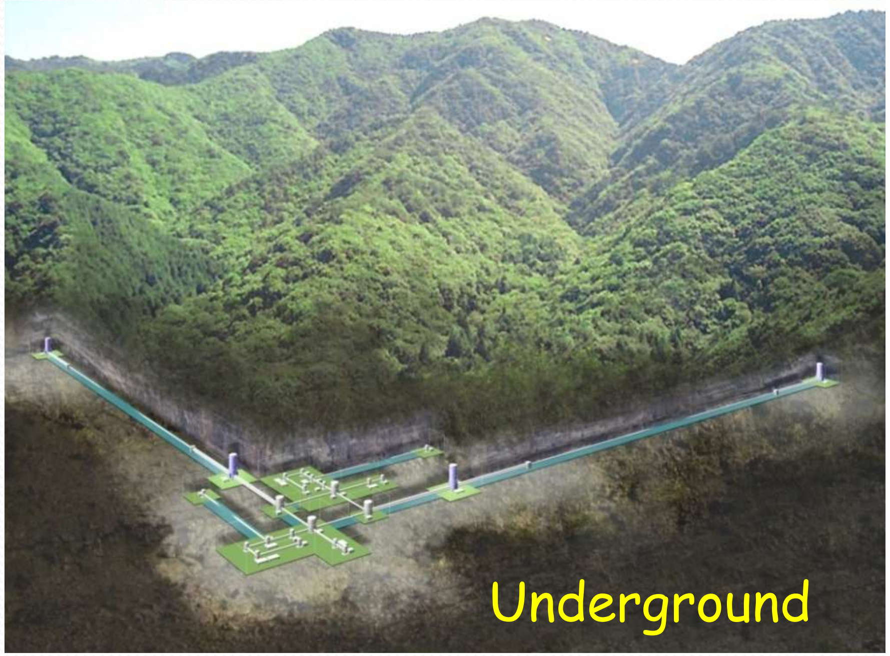
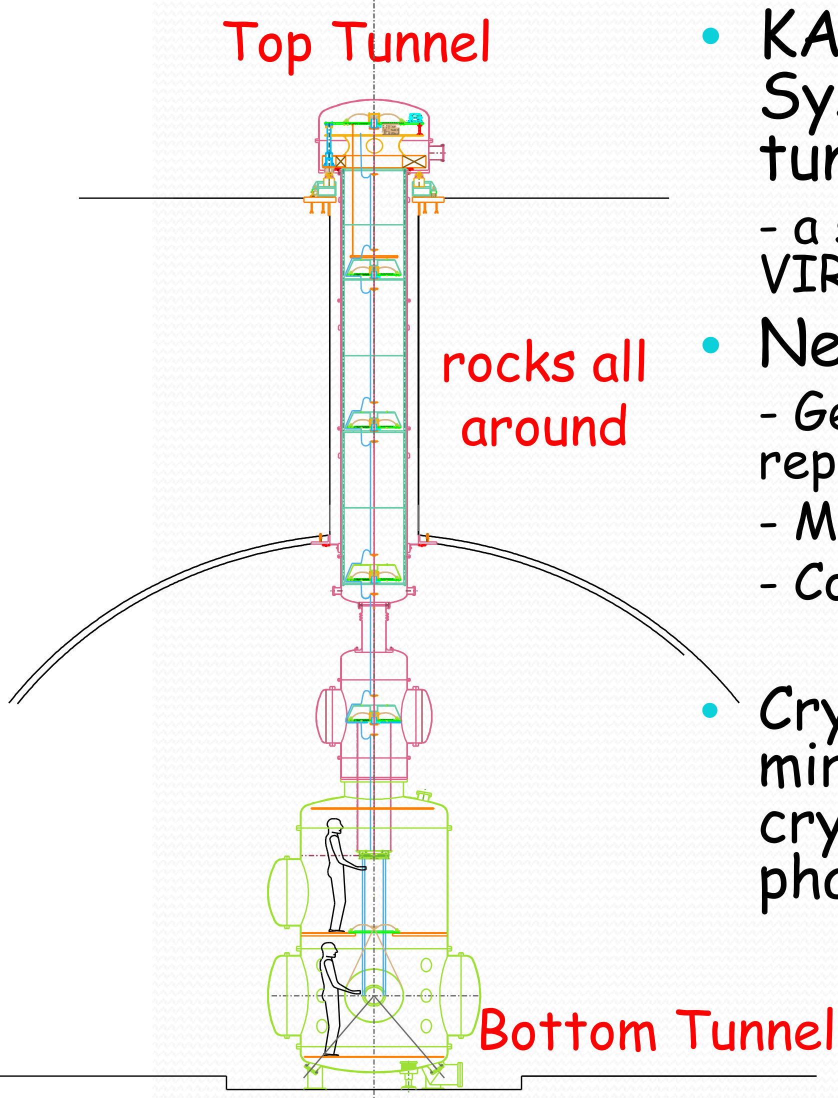
KAGRA: underground detector

- Underground ITF located in the Kamioka mine (Japan) with 3 km orthogonal arms:
  - reduced seismic noise (about a factor 50 @ 10 Hz) and gravity noise
  - simplified seismic isolation system;
- Second phase: cryogenic cooling of test masses:
  - reduced thermal noise

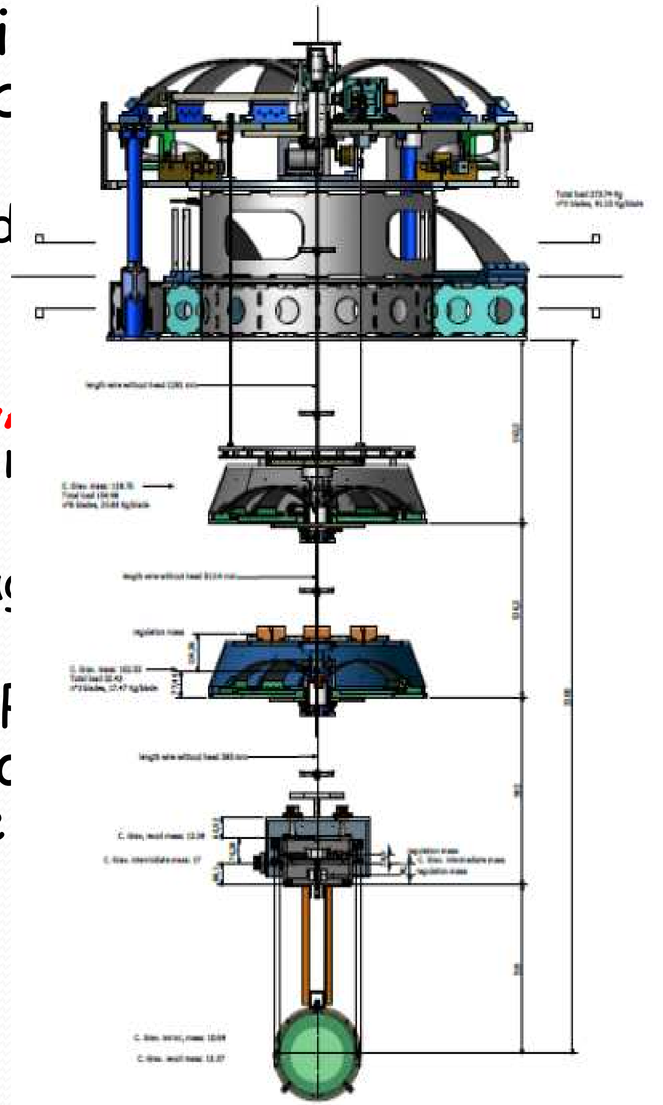
KAGRA



KAGRA Vibration Isolation

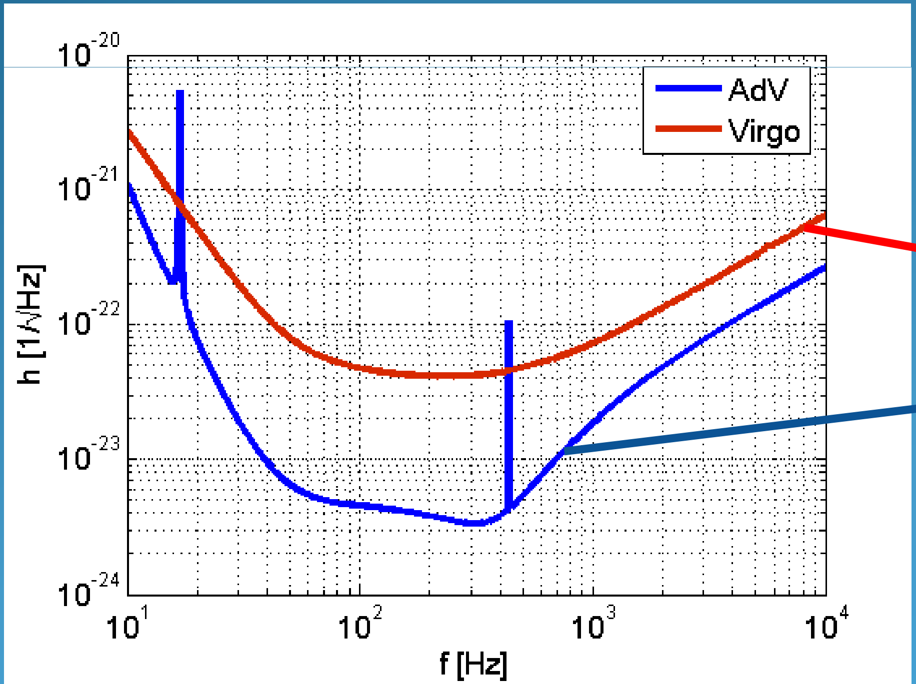


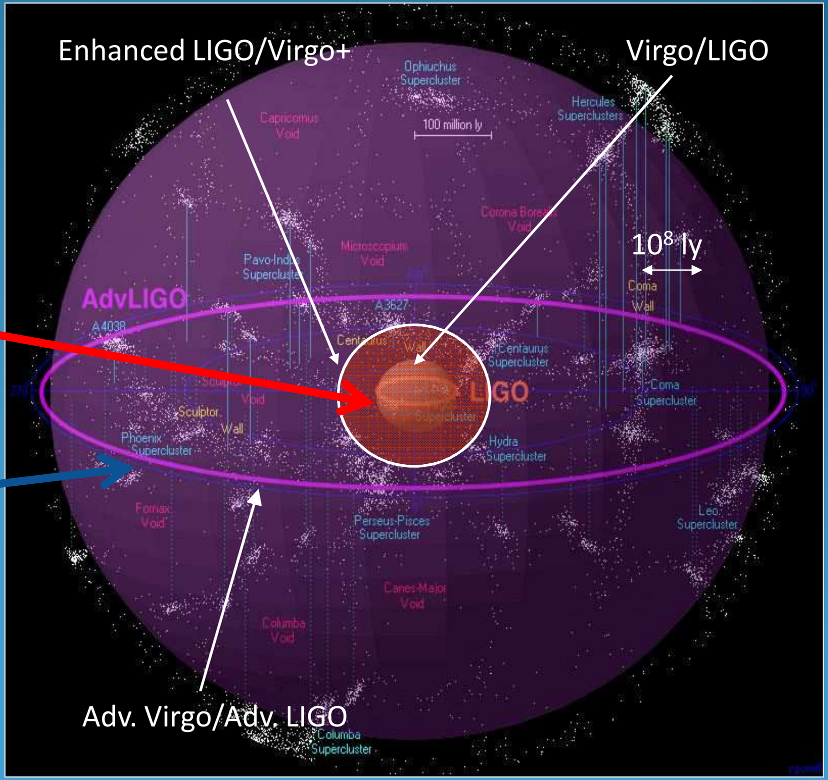
- KAGRA **SAS** (Seismi System) is mounted b tunnels:
  - a simplified and improved VIRGO SA
- New features:
  - Geometric anti-spring (G replace Magnetic anti-sprii
  - Magnetic damping stage
  - Compact pre-isolator sta
- Cryostat in the Fabry-I mirrors to be cooled d cryogenic temperature phase.



Advanced Detectors

- The upgrades to advanced instruments (2nd generation) are almost completed. They will be in commissioning phase in 2016;
- Advanced detectors are promising an improvement of a factor 10 in sensitivity.

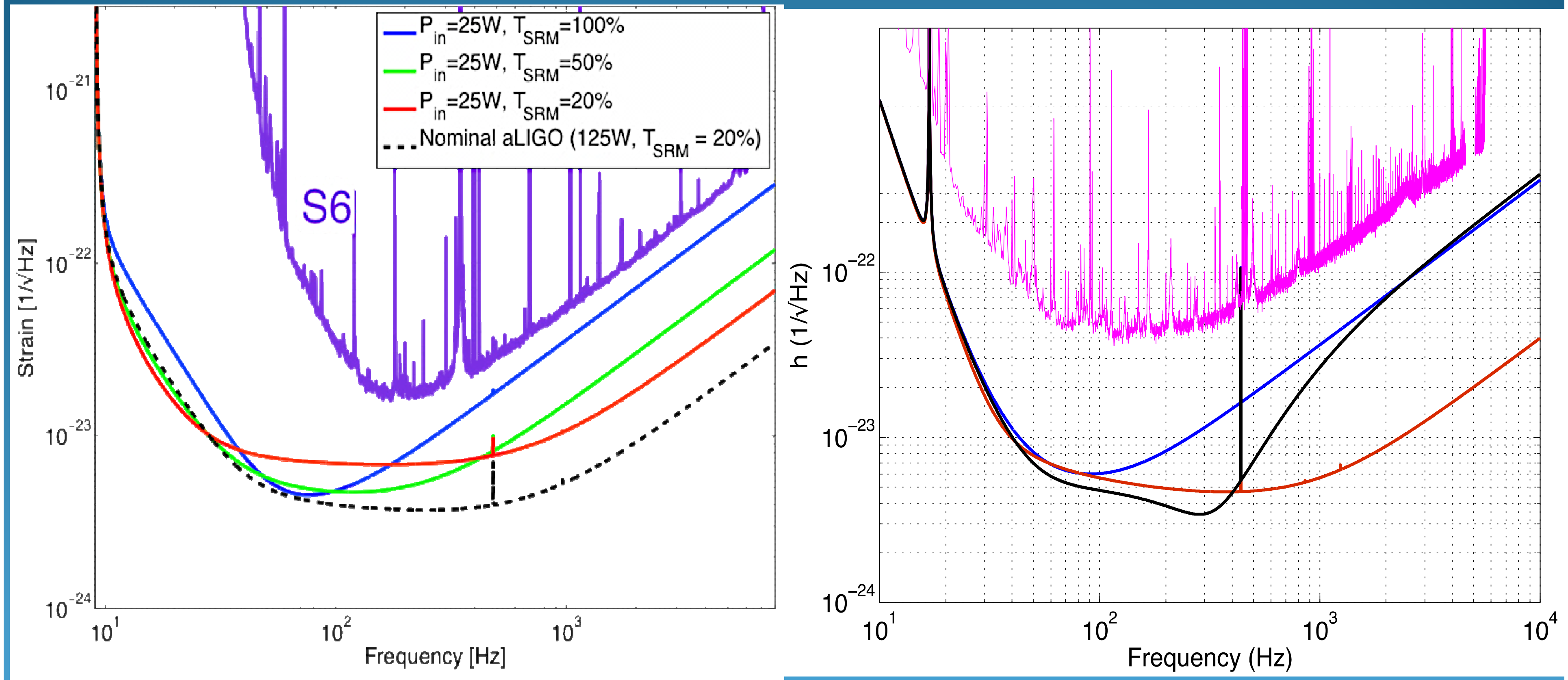




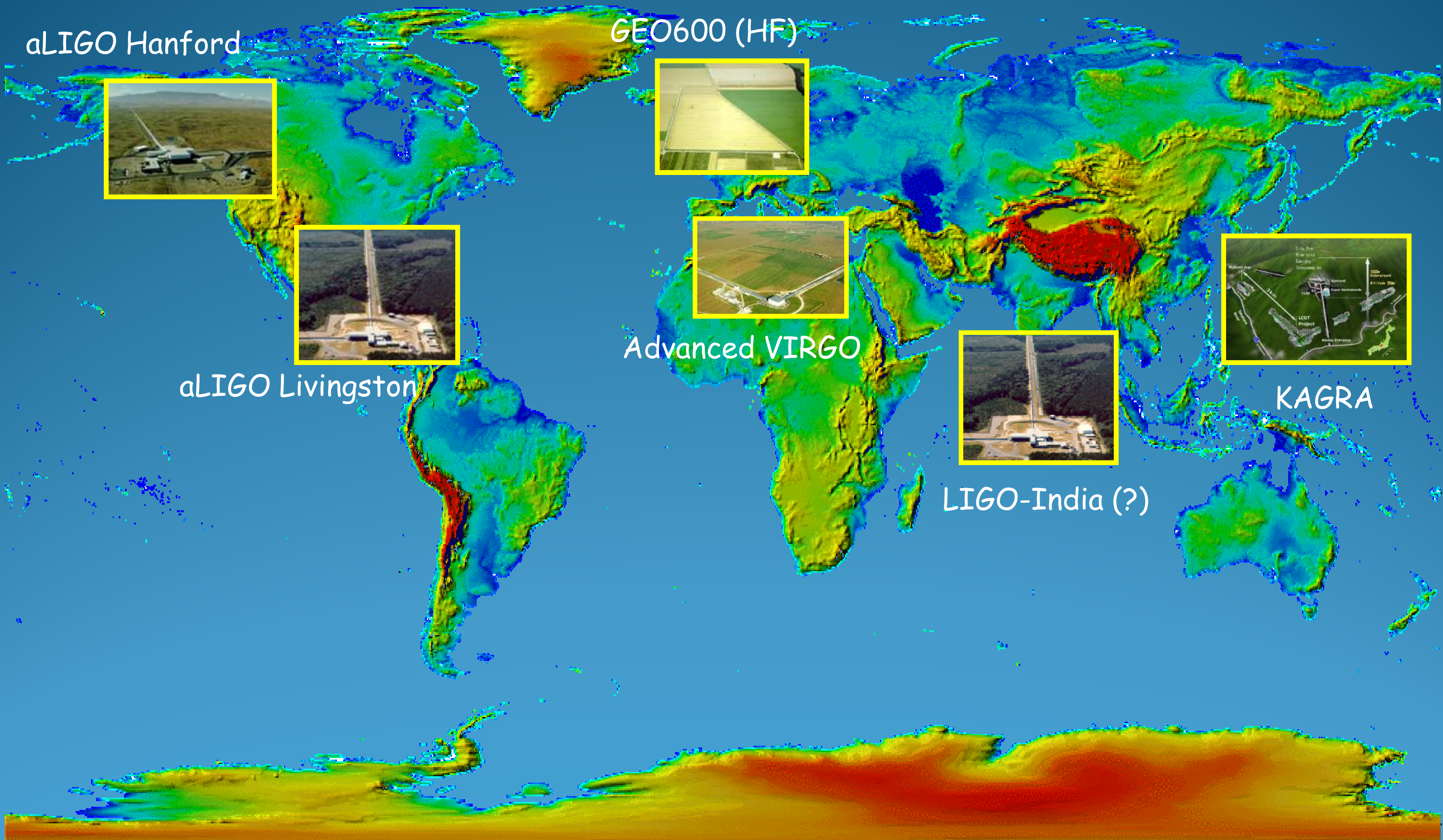
Credit: R.Powell, B.Berger

Advanced Detectors Sensitivity Goals

- Advanced detectors are tunable for different sources;
- Typical benchmarks include BNS and 10+10 BBH.



The Advanced Detectors Network

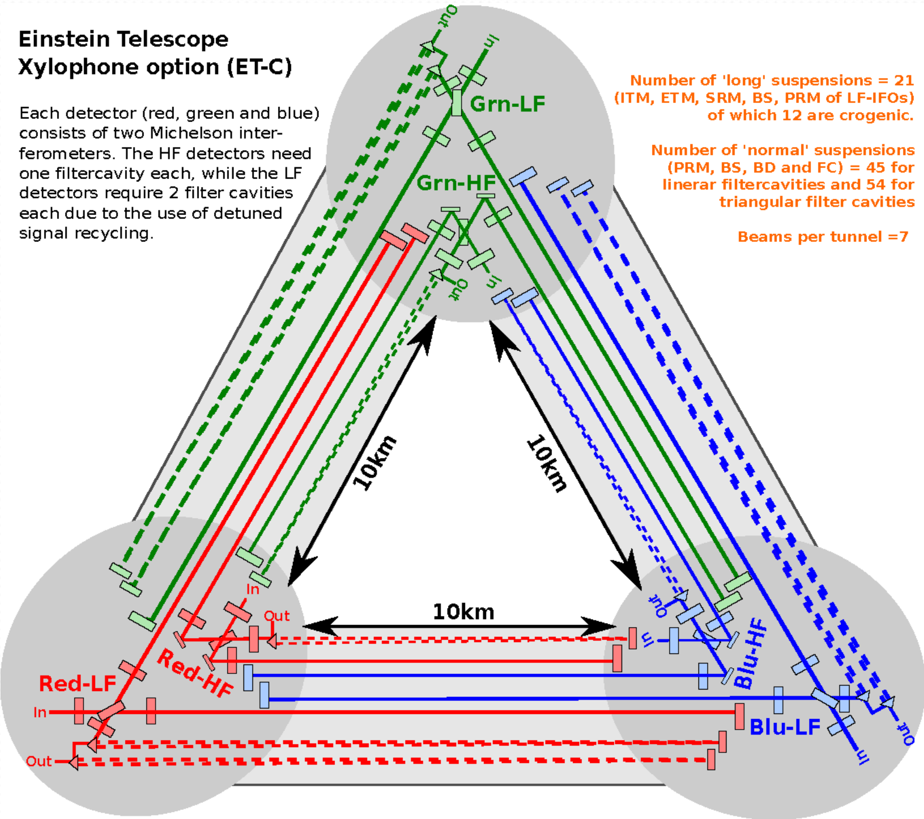


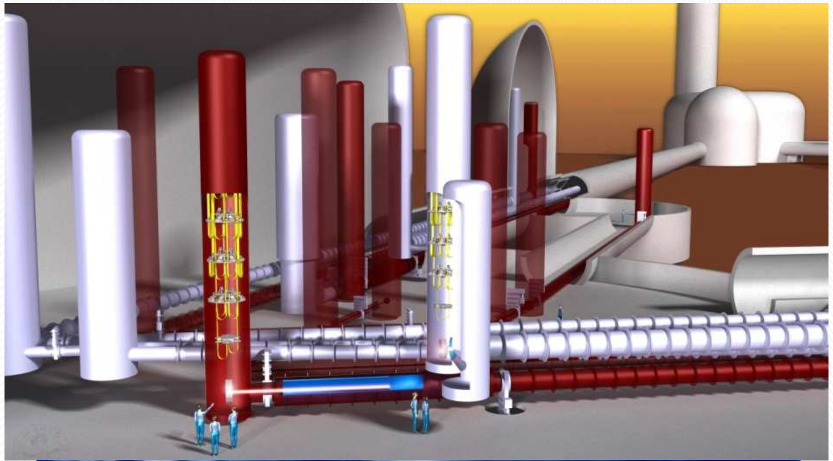
GW Observations: the future

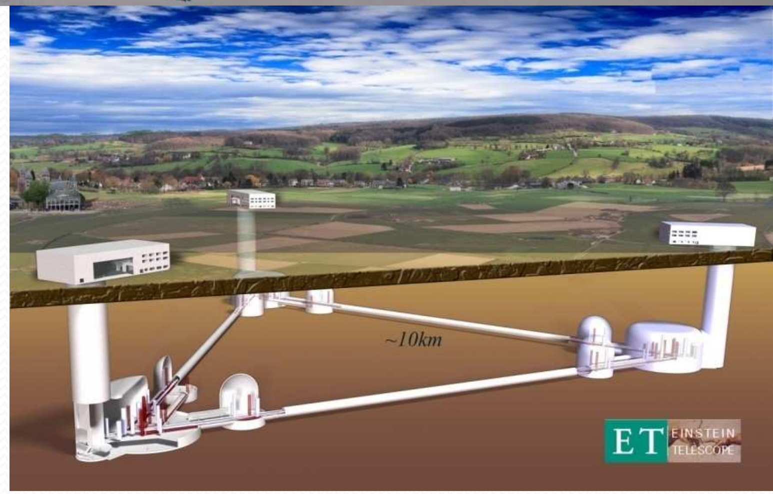
- The aim of the ET Project (Einstein Telescope) is the realization of a large scale GW Observatory in Europe (3rd generation detector);
- The ET design built up a pan-European community (ET Science Team) supporting the project;
- ET conceptual design study document delivered in 2011.

The Research Infrastructure

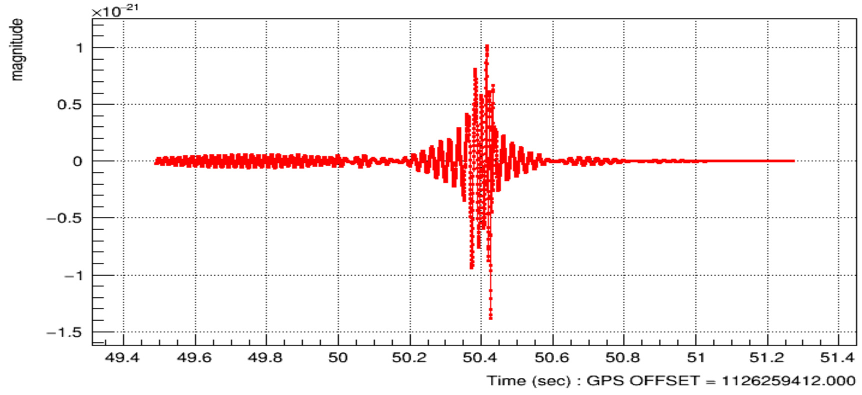
- The ET research infrastructure is a giant scale GW interferometer, cryogenic and underground.





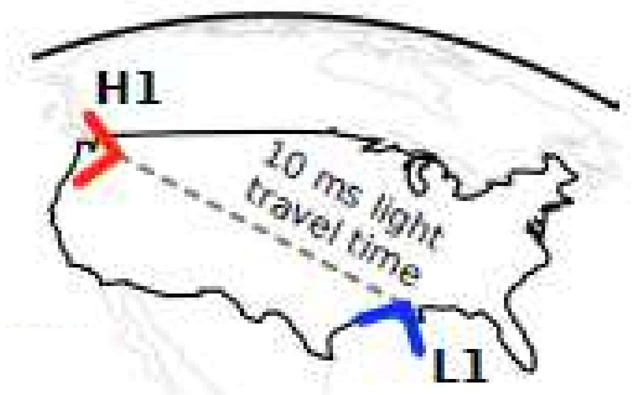


The First GW Detection

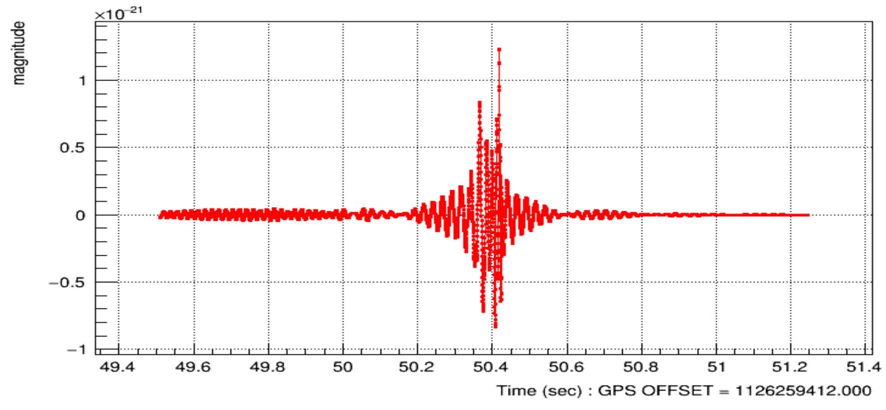


September 14, 2015 at 11:50:45 in Central European Time

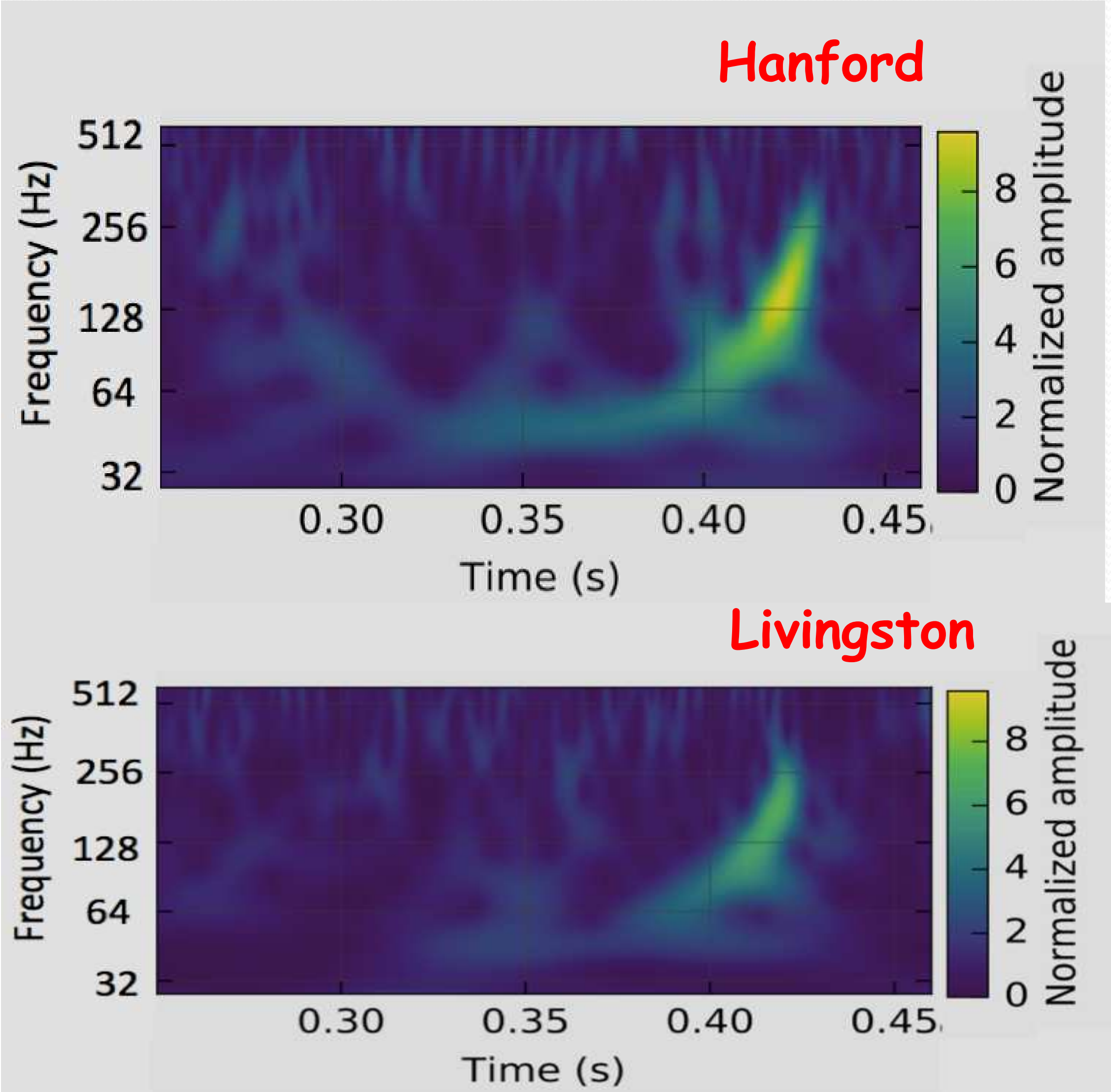
Alarm reported by the on-line algorithm for generic transient search



SNR = 24



The signals on aLIGO ITFs /1



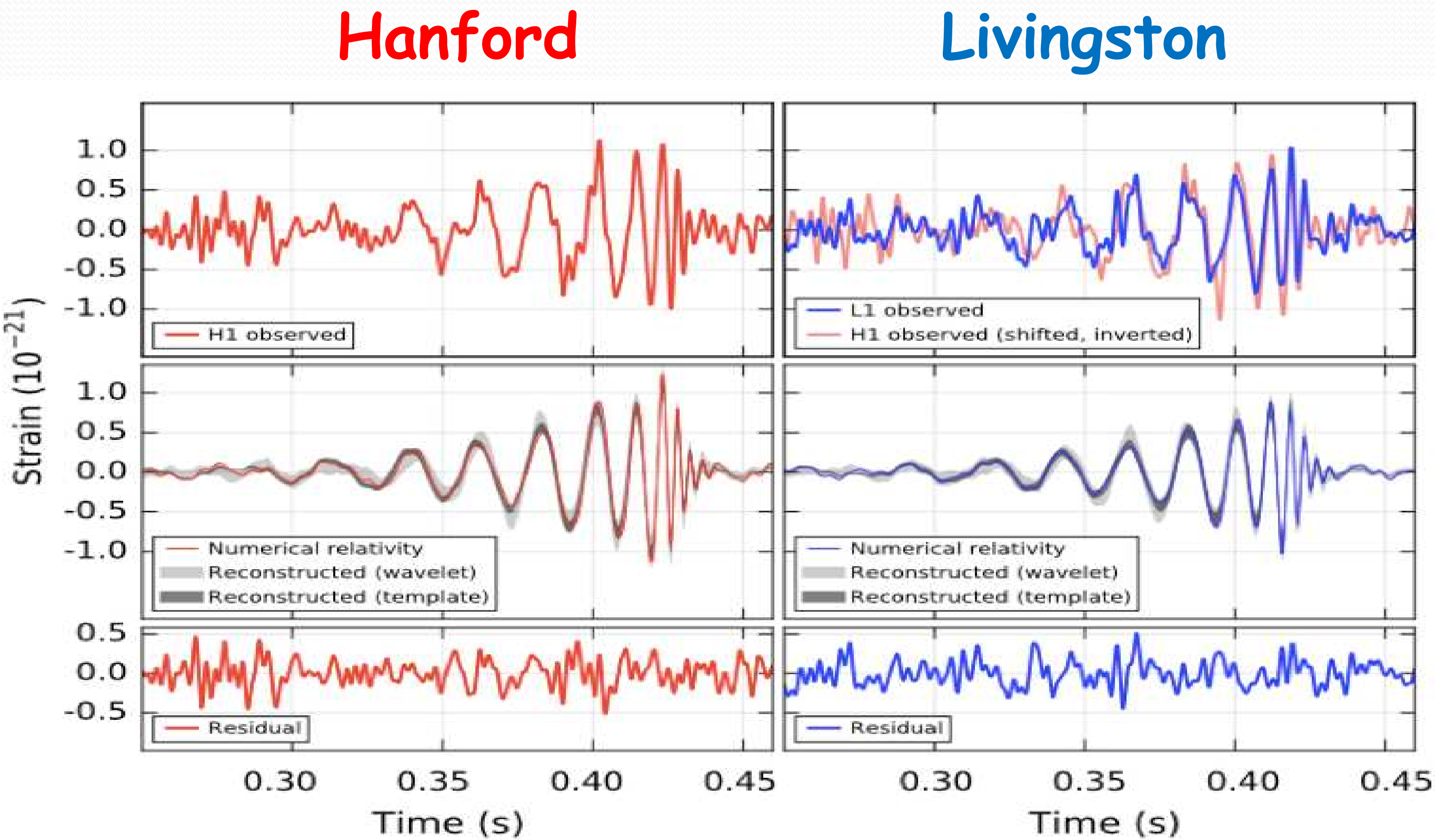
- The False Alarm rate bound to **1** event each **203,000 years**
- False Alarm Probability

  $< 2*10^{-7}$
- Statistical Significance of the Signal

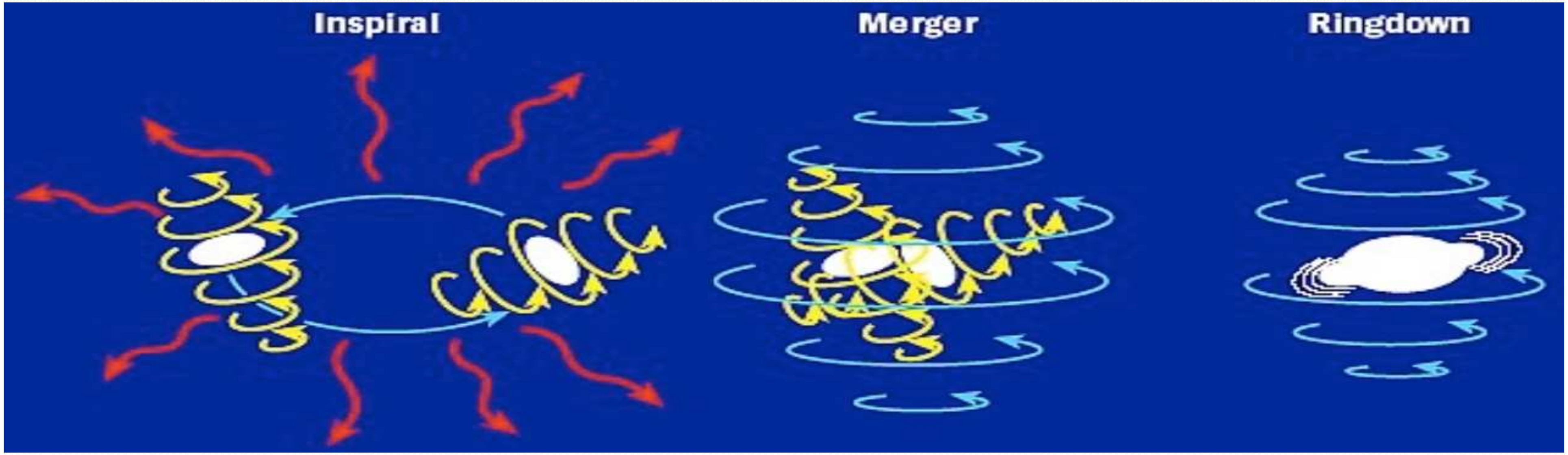
  5.1σ

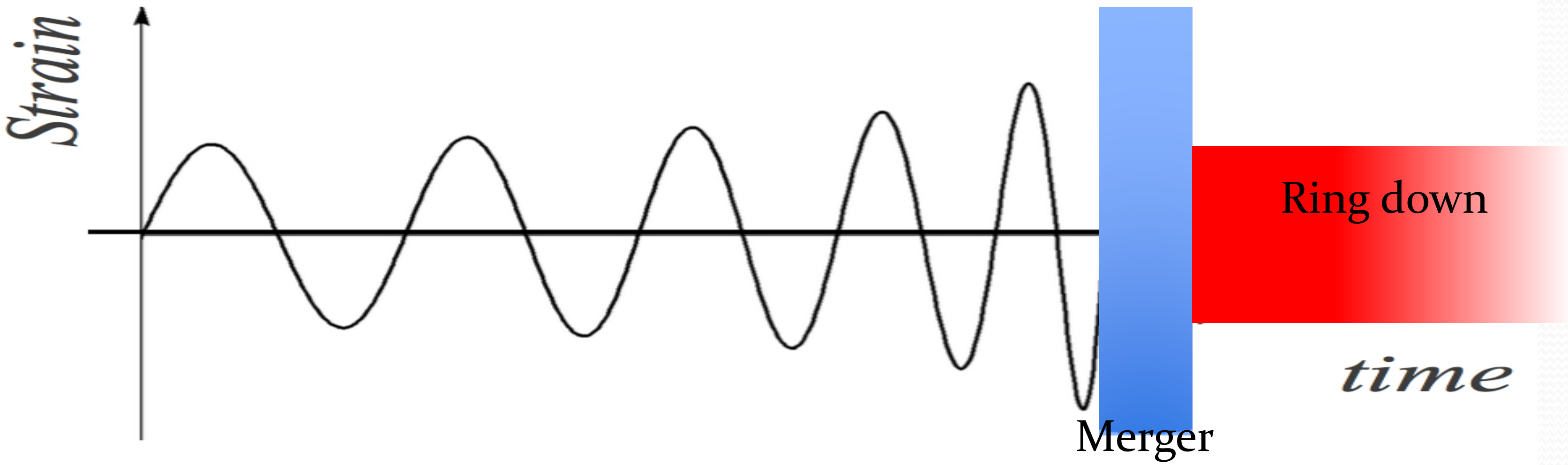
(5.1 Standard deviation)

The signals on aLIGO ITFs /2

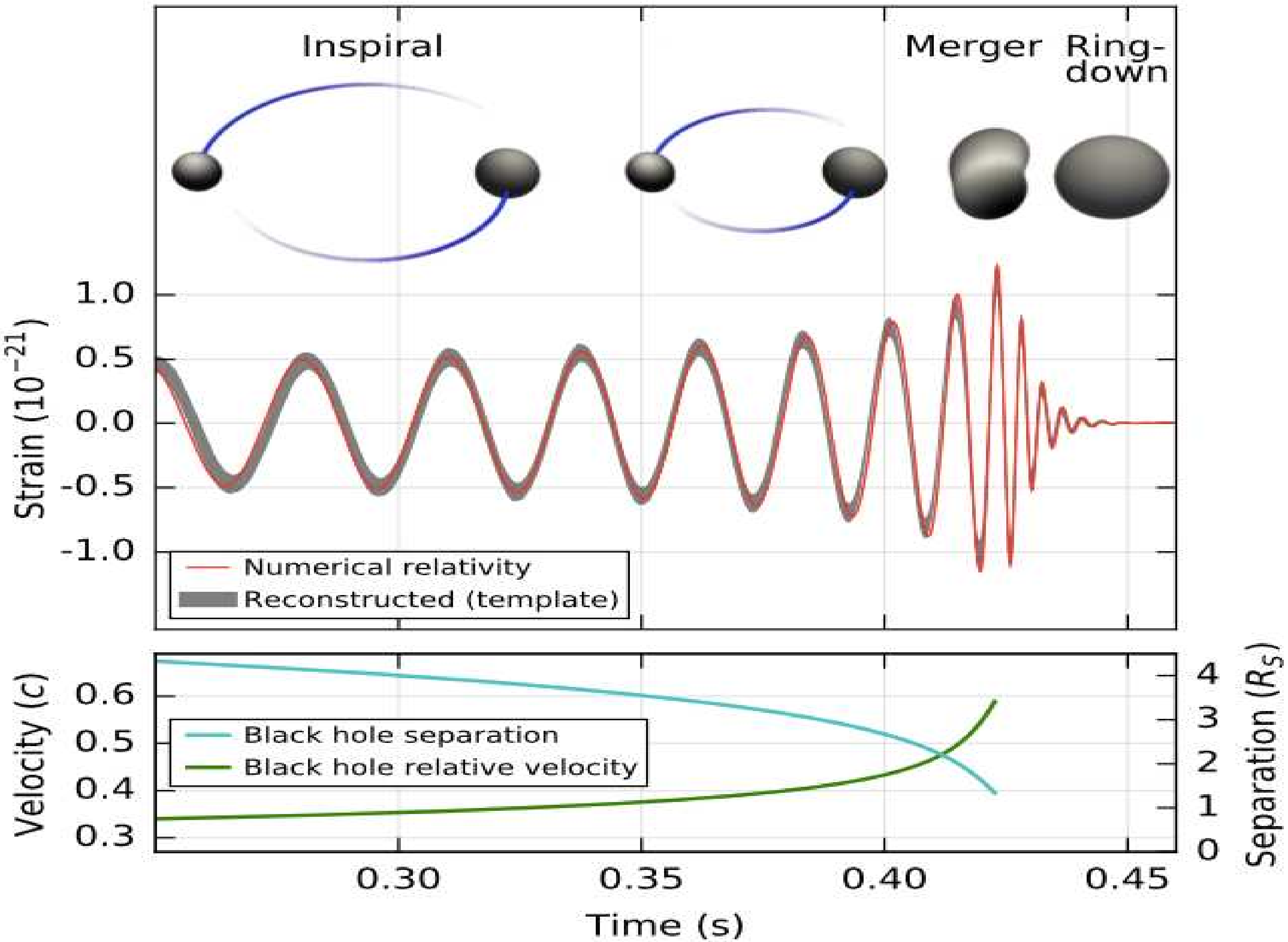


The time evolution: BH formation



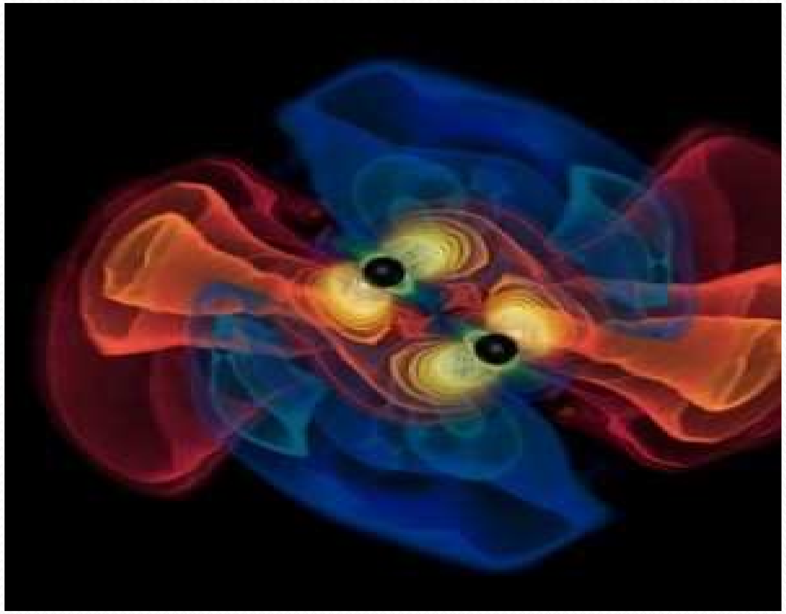


A signal from a BBH merger



Some parameters

- The event took place approximately 1.3 billion years ago



Primary black hole mass	36^{+5}_{-4} $M_\odot$
Secondary black hole mass	29^{+4}_{-4} $M_\odot$
Final black hole mass	62^{+4}_{-4} $M_\odot$
Final black hole spin	$0.67^{+0.05}_{-0.07}$
Luminosity distance	410^{+160}_{-180} Mpc
Source redshift, z	$0.09^{+0.03}_{-0.04}$

The Paper

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

http://link.aps.org/doi/10.1103/PhysRevLett.116.061102

Conclusions

- The upgrade of ground based ITF detectors to a 2^{nd} generation instruments, is almost concluded;
- Following the VIRGO experience a big effort has been done implementing complex systems for seismic noise isolation:

  - detector bandwidth extended in the low frequency range, below 100 Hz

  - improved sensitivity of a factor 10;
- A network of 2^{nd} generation detectors will play a crucial role to localize GW source in the sky;
- The **first direct detection** of GW (**GW150914**) is opening the era of Gravitational Waves astronomy.

Thank you for your attention !!