DIPARTIMENTO DI FISICA
SAPIENZA
UNIVERSITÀ DI ROMA

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Sezione di Roma

Gravitational waves. Detector concepts and future perspective.

E. Majorana

Motivations, experience, observations and R&D

CRIS-MAC 2024

13th Cosmic-Ray International Studies and Multi-Messenger Astroparticle Conference

The network of present interferometric detectors

LSC LIGO Scientific Collaboration

LIGO VIRGO KAGRA

KAGRA

VIRGO

What do we measure ?

The strain is associated to a metric deformation propagating at the speed of light as a wave with two polarizations at 45°

$$R^{\alpha\beta} - \frac{1}{2} g^{\alpha\beta} R = \frac{8\pi G}{c^4} T^{\alpha\beta}$$

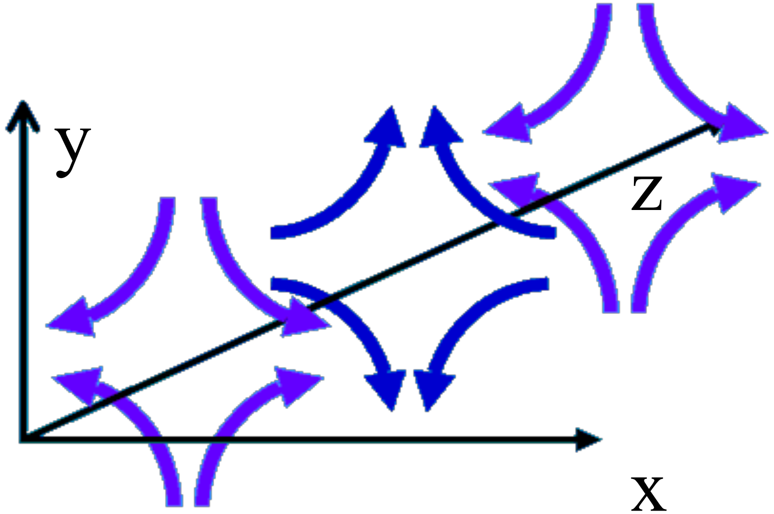
A. Einstein 1916

$$g_{\alpha\beta} = \eta_{\alpha\beta} + h_{\alpha\beta} \qquad \left| h_{\alpha\beta} \right| << 1$$

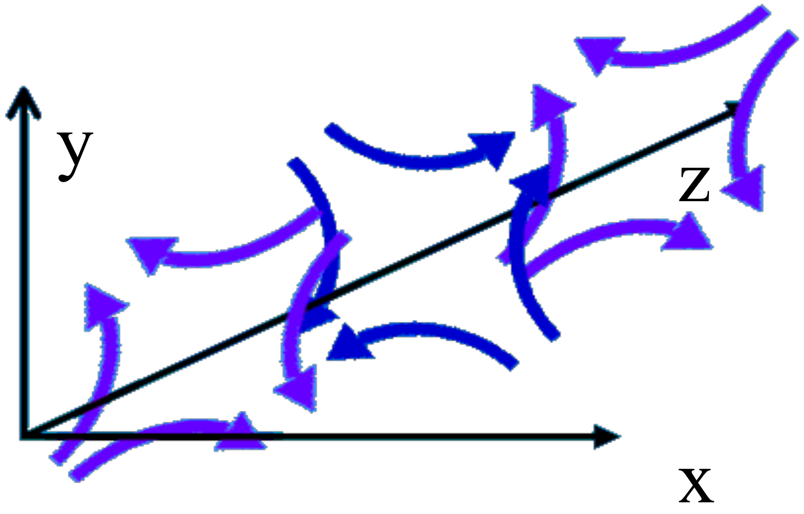
Linearization and gauge choice

$$R^{\alpha\beta} - \frac{1}{2} g^{\alpha\beta} R = -\frac{\Box h^{\alpha\beta}}{2} = 0$$

Wave equation set (in absence of the source)



$\hat{k} = \hat{z}$



Energetics → astrophysics

Luminosity [W]

$$L = \frac{G}{45c^5}\left|\dddot{Q}_{\mu\nu}\right|^2$$

- A very small coefficient
- Mass quadrupole emission

Supernova 1987a 1.6 10^5 ly

<ins>A very small coupling</ins>

Example: a Supernova in the Milky Way
Distance: 10 kpc = 3 10^{20} m
Energy: 10^{40} Joule
Expected strain at the Earth h = 10^{-21}

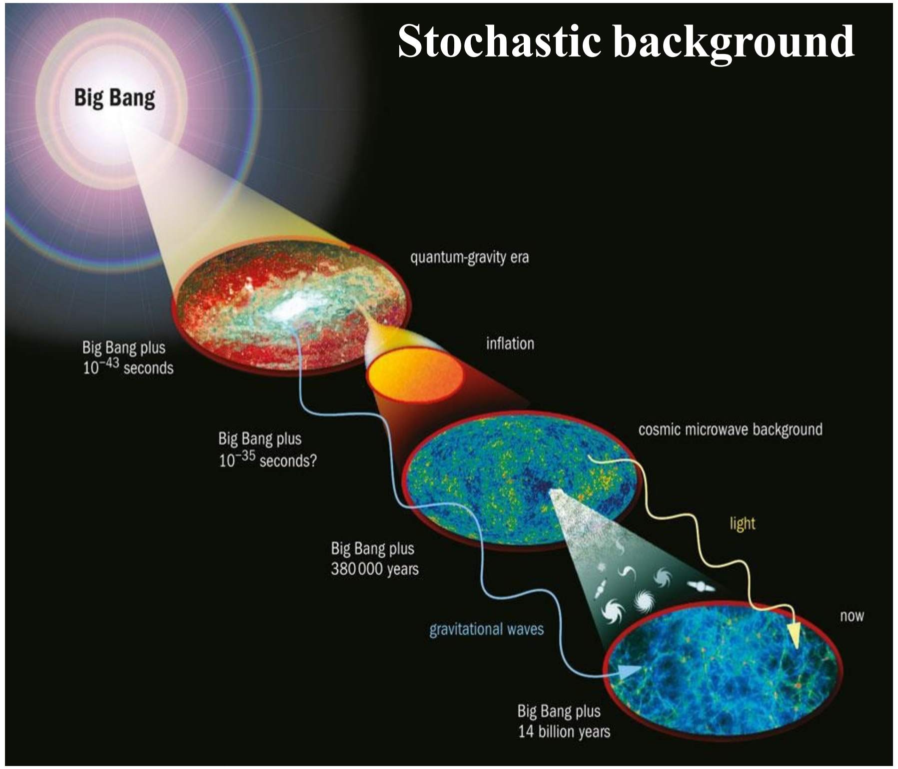
<ins>Galactic SNovae (1 event/30-50 y), a very small rate</ins>

We aim to detect various sources

PERIODIC

CIRPS & BURST

STOCHASTIC

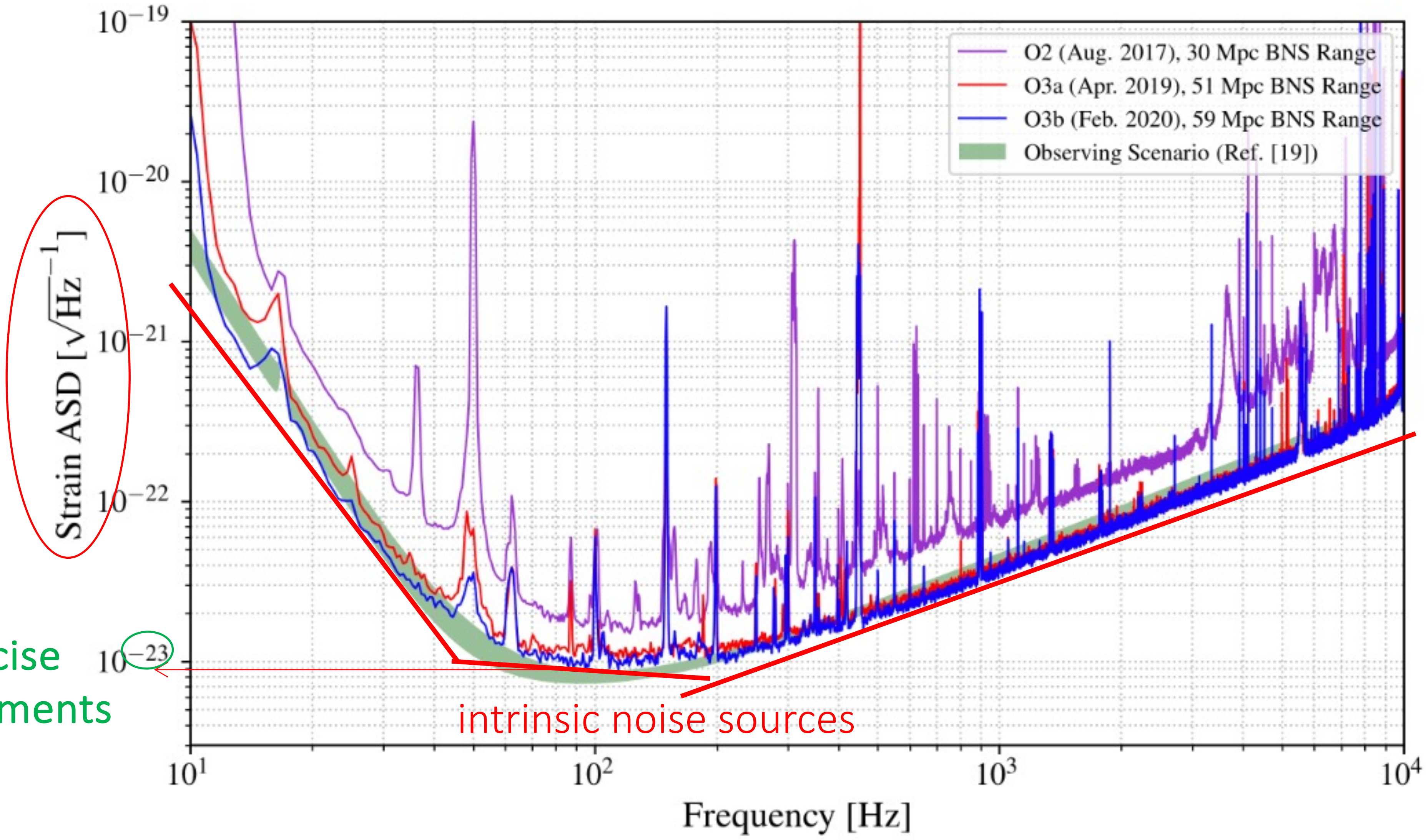


Modeled waveform

Unmodeled waveform

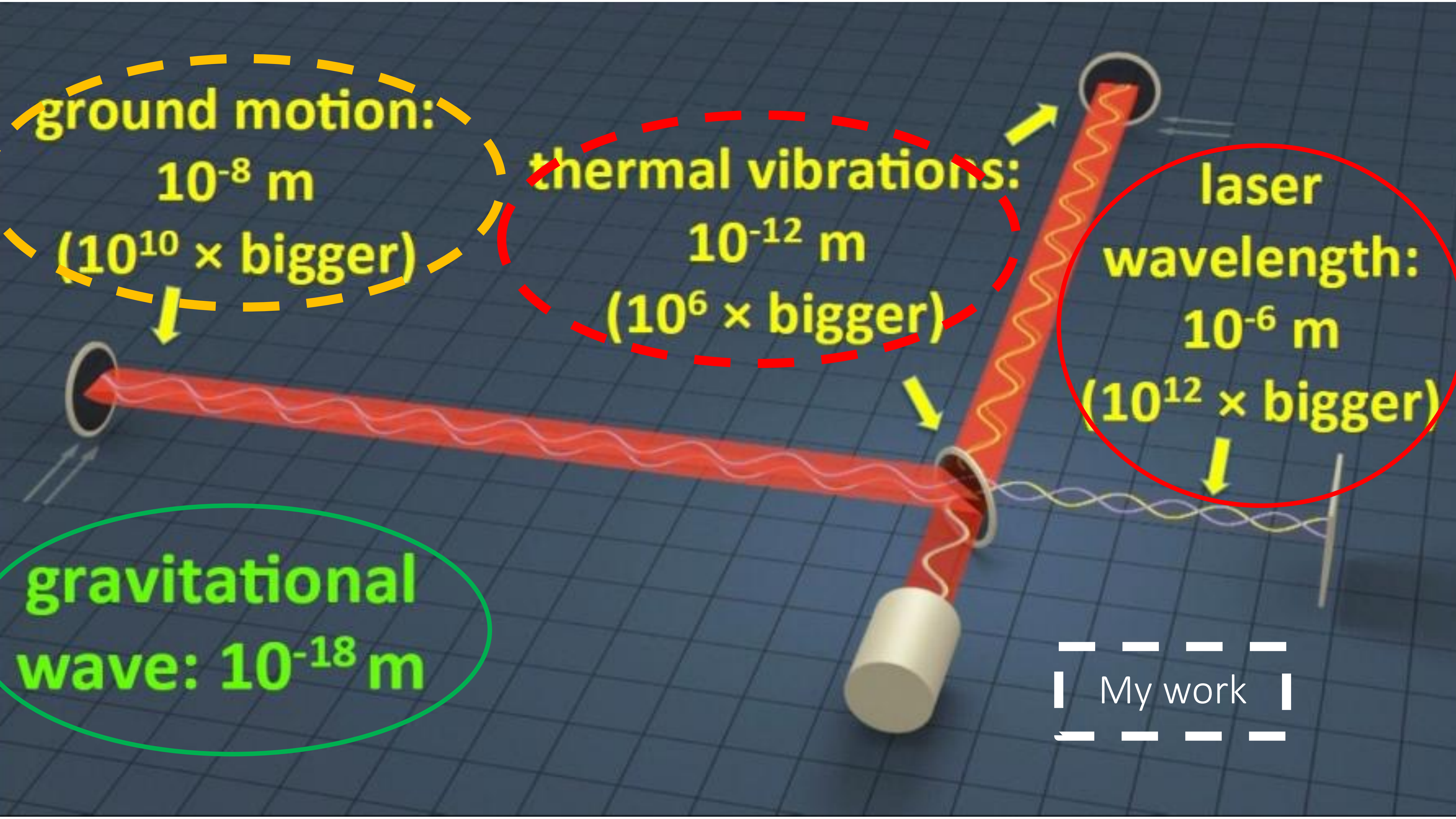
Still to be observed: SuperNovae, isolated Neutron Stars, Stochastic background

GW interferometers sense the strain, their sensitivity is expressed by the **strain spectral density** $\tilde{h}(\omega) = \sqrt{S(\omega)}$



Very precise measurements

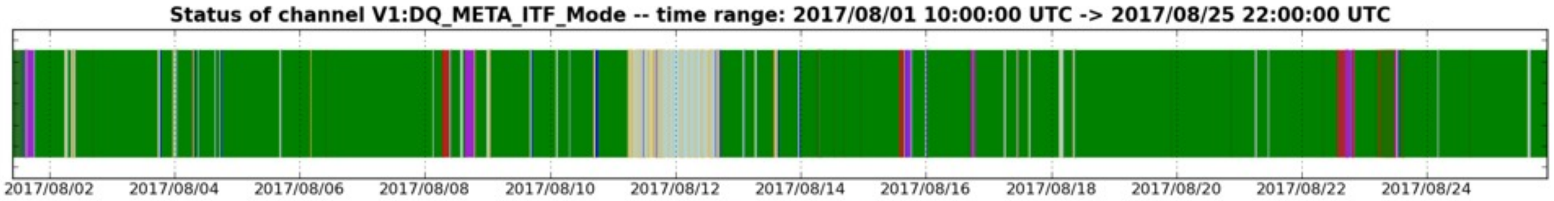
intrinsic noise sources


ground motion:
10-8 m
(1010 × bigger)
thermal vibrations:
10-12 m
(106 × bigger)
laser
wavelength:
10-6 m
(1012 × bigger)
gravitational
wave: 10-18 m

My work

The *network* detecotr

Concept: O2, just 16 days in coincidence with LIGO, the power of the network



- 🟩 Science: 85.08 %
- 🟦 Locking: 8.71 %
- 🟪 Calibration: 1.86 %
- 🟥 Maintenance: 1.28 %
- 🟧 Not locked: 1.26 %
- 🟦 Locked: 1.15 %
- 🟪 Adjusting: 0.41 %
- 🟥 Unknown: 0.25 %

Quiet weather conditions (summer)

Good duty-cycle (85.5% in spite of some technical bug…)

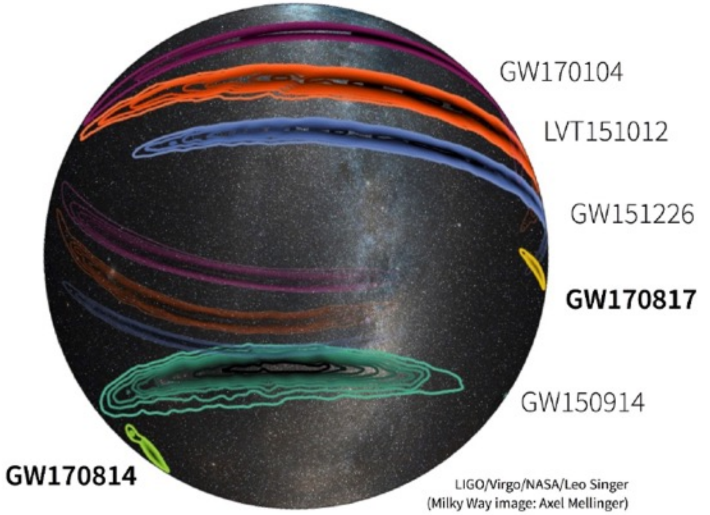
Highest BNS range: 28.2 Mpc

Average ranges: BNS 26 - BBH$_{10}$ 134 - BBH$_{30}$ 314 Mpc

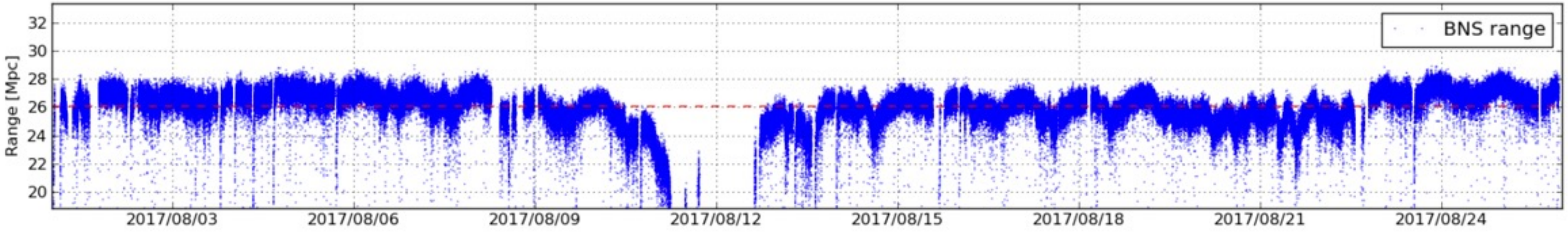
➔O2 Glitchness had to be reduced **(done for O3!)**

➔Automatic Alignment accuracy to be improved **(done for O3!)**

➔Several other technical noise issues **(done for O3!)**



LIGO/Virgo/NASA/Leo Singer (Milky Way image: Axel Mellinger)

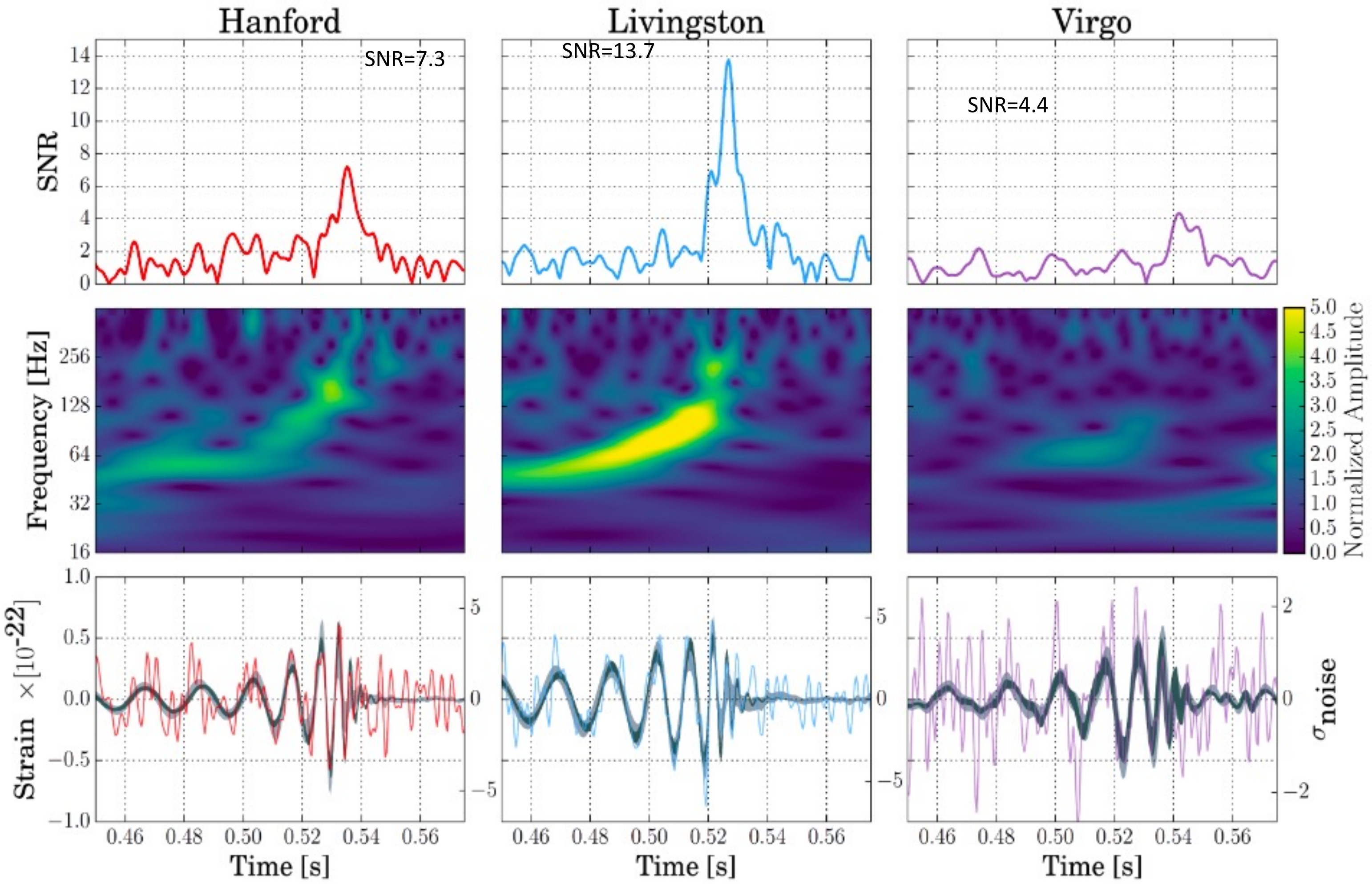


Phys. Rev. Lett. 119, 141101, 2017
Phys. Rev. Lett., 119, 161101, 2017

Bad sensitivity on one detector… nevertheless, three events detected produced a lot of science

GW170814 BBH, TRIPLE !!! A new life

August 14, 2017**: a Three-Detector Observation** of Gravitational Waves from a coalescing Binary Black Hole with 31 and 25 solar mass, while the final black hole figure is 53 solar mass, ~3 solar masses radiated as pure GWs (Phys. Rev. Lett. 119, 141101, 2017)

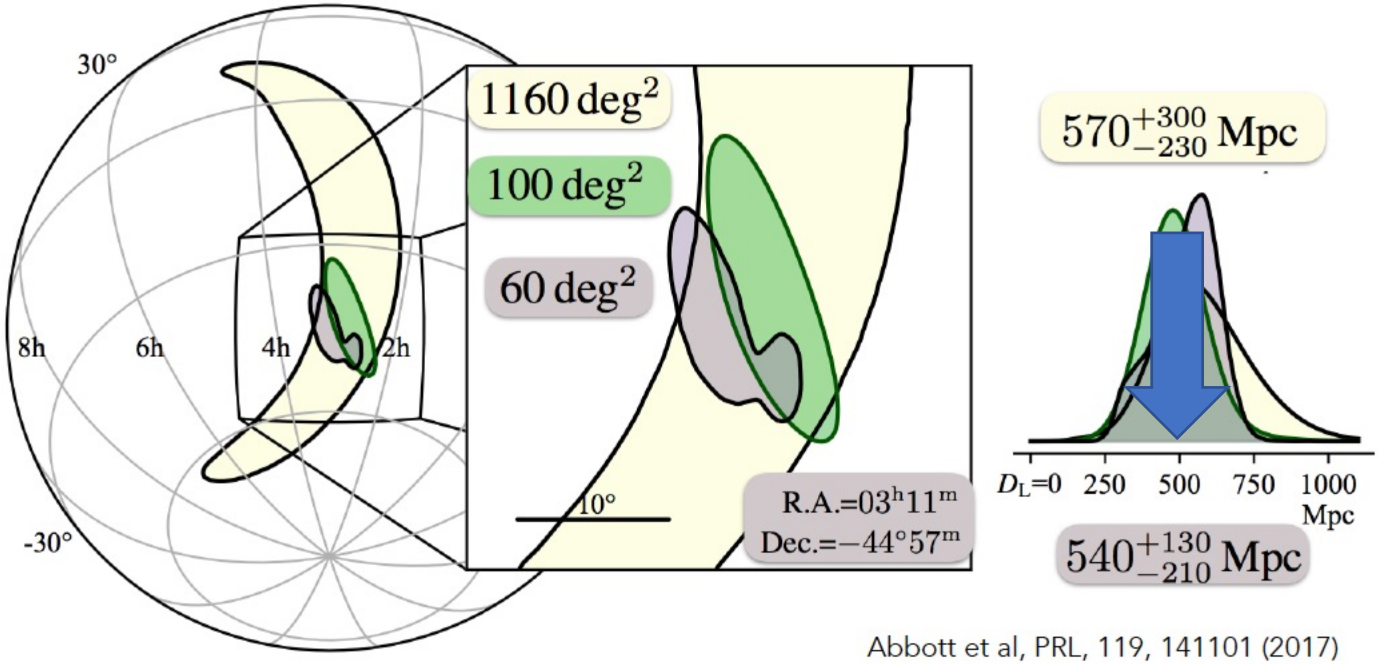


Sky position localization for GW170814 is within an area of **~100 deg^2**

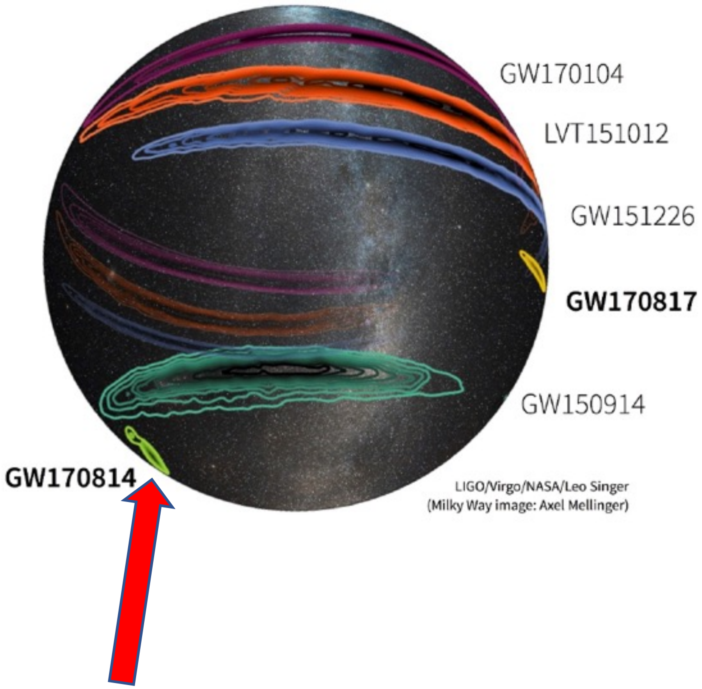
Radiated GW energy ~ **2.7 M$_o$ c^2**

GW170814 BBH TRIPLE !!!

August 14, 2017**: a Three-Detector Observation** of Gravitational Waves from a coalescing Binary Black Hole with 31 and 25 solar mass, while the final black hole figure is 53 solar mass, ~3 solar masses radiated as pure GWs (Phys. Rev. Lett. 119, 141101, 2017)



Abbott et al, PRL, 119, 141101 (2017)

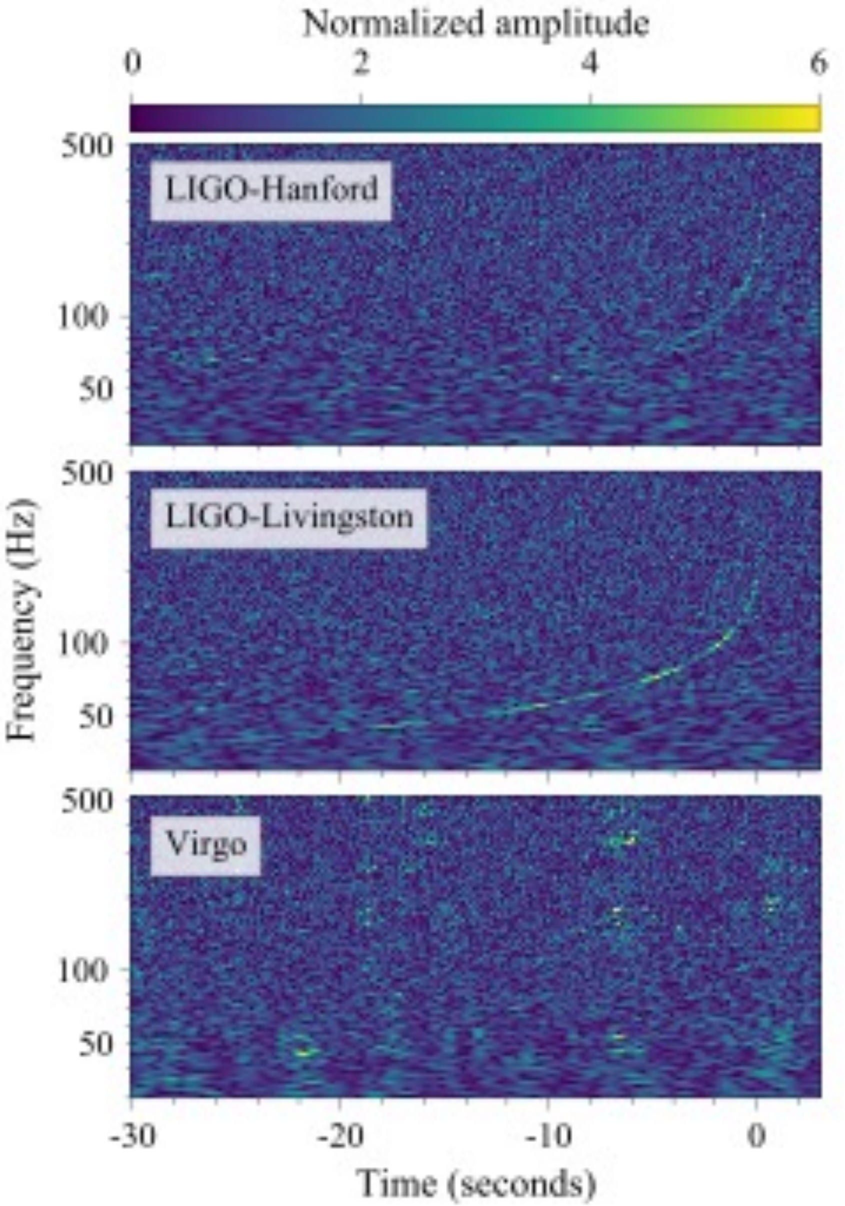


LIGO/Virgo/NASA/Leo Singer
(Milky Way image: Axel Mellinger)

ERROR IN SKY AREA: 20x
ERROR IN DISTANCE: 1.5x
ERROR BOX ON THE SKY: 30x
(from 70 to 2 Mpc3)

GW170817: from pure geometry to matter and multi-messenger physics

GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral, Phys. Rev. Lett., 119, 161101 (2017)



LIGO and the Virgo detectors were operational at the time of the binary neutron star inspiral **12:41:04.4 UTC**

GW170817 swept through the detectors' sensitive band in **~60s.**

f_{start} ~ 24Hz, Radiated energy > **0.025 M_o c^2**

Loudest (network SNR of **32.4**), closest and best localized signal signal ever observed by LIGO and Virgo

$$\mathcal{M}_c^{\rm det} = 1.1977^{+0.0008}_{-0.0003}\, M_\odot \qquad D_L = 40^{+8}_{-14}\ \mathrm{Mpc}$$

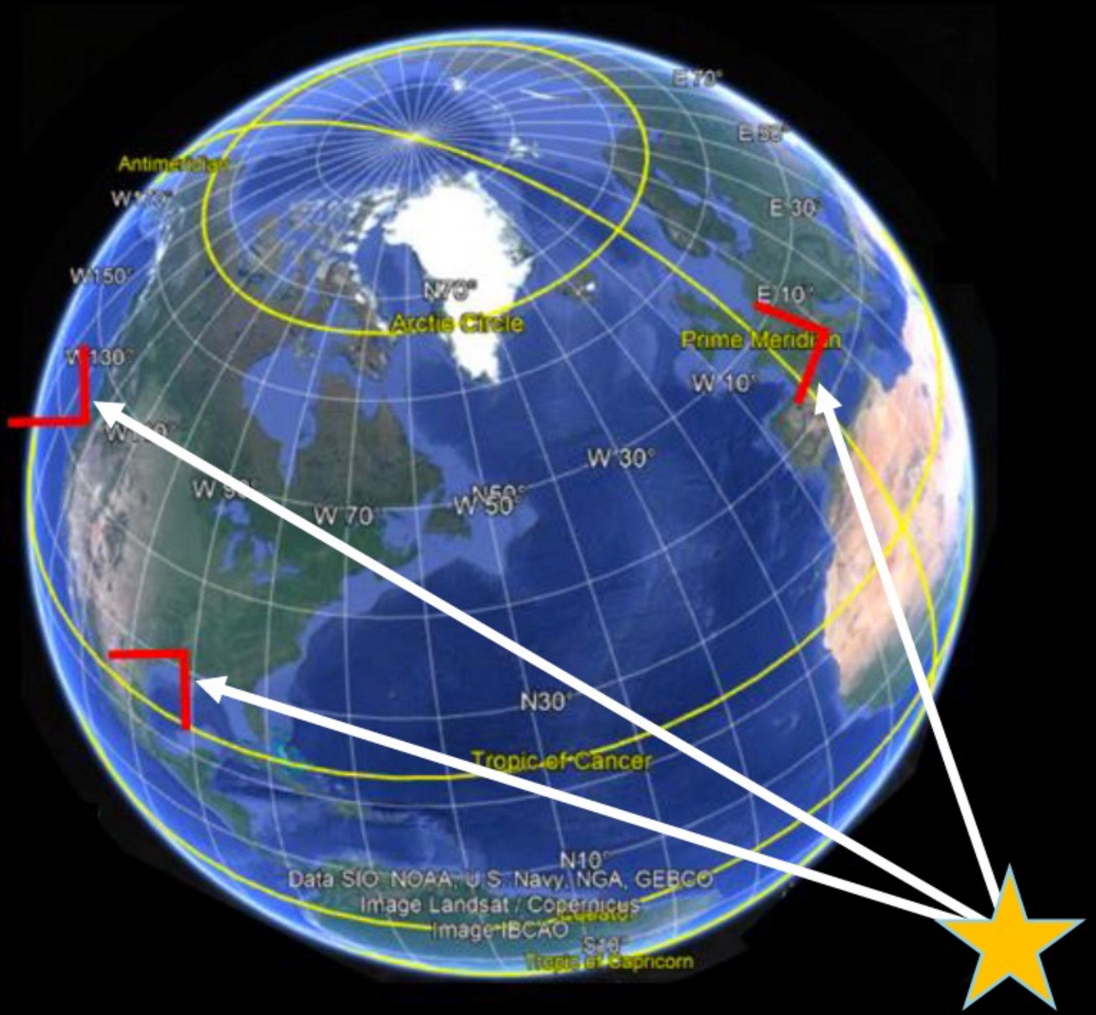
$$2.73 < M_{\rm Total} < 3.29\ \mathrm{M}_\odot \quad 0.86 < m_i < 2.26\ \mathrm{M}_\odot$$


Virgo, Cascina, Italy


LIGO, Livingston, LA

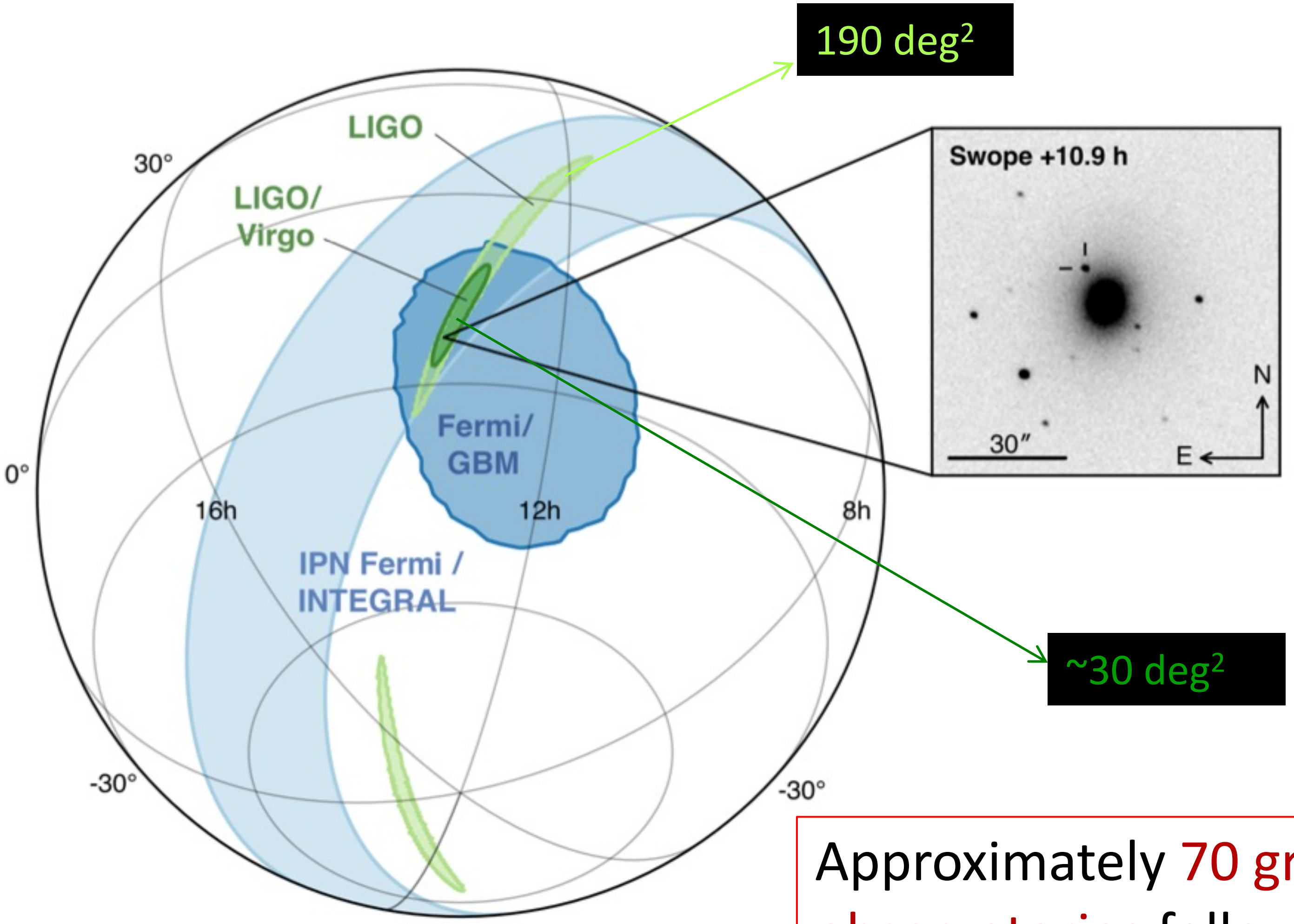

LIGO, Hanford, WA

BNS



GW170817 first arrived at Virgo, after 22 ms it reached LLO, and another 3 ms later LLH detected it

Sky Localization
GW170817



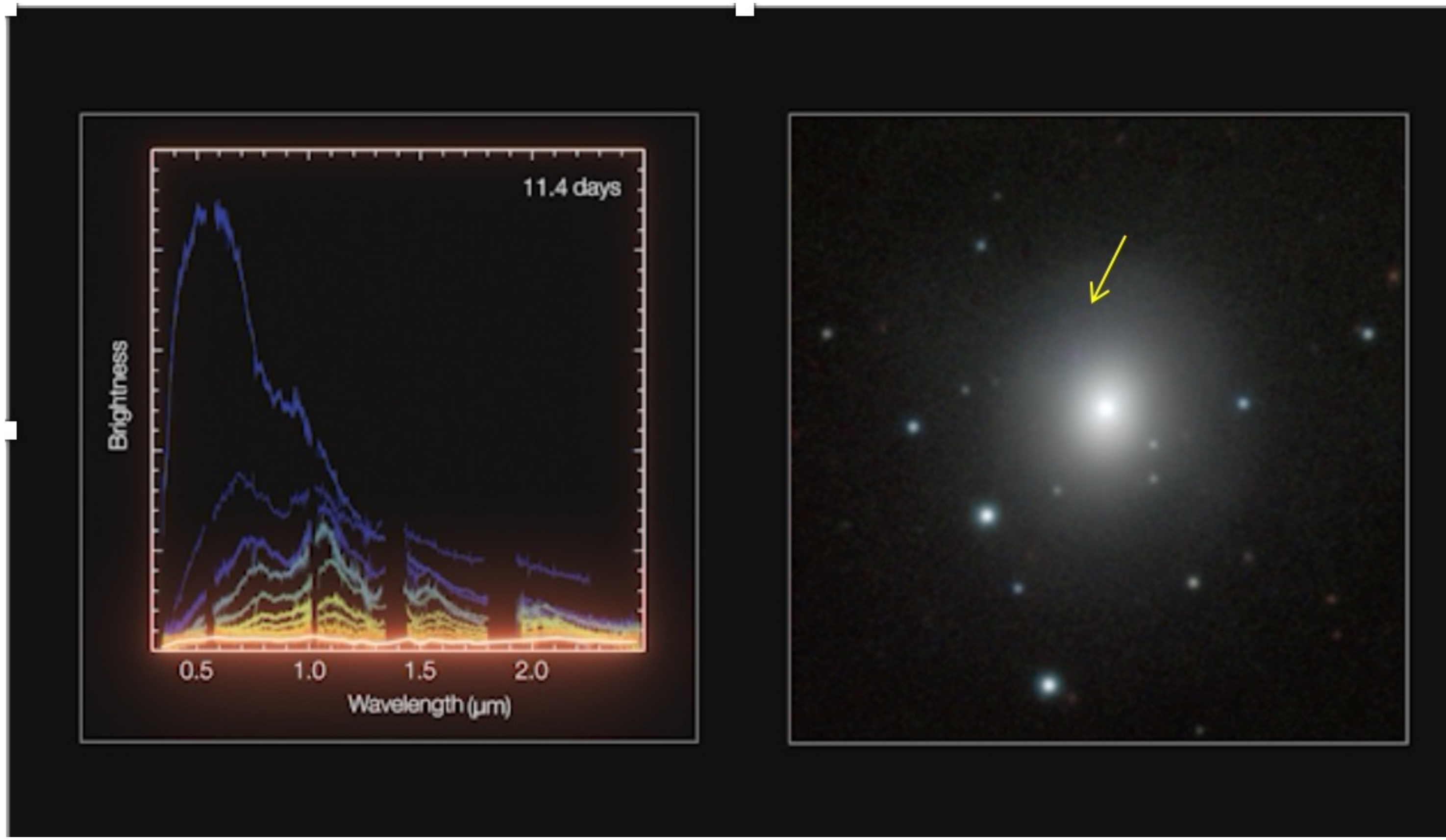
Location of the apparent host *galaxy NGC 4993 in the* ***Swope optical discovery*** *image at 10.9 h after the merger*

Approximately 70 ground- and space- based observatories followed-up on this event !

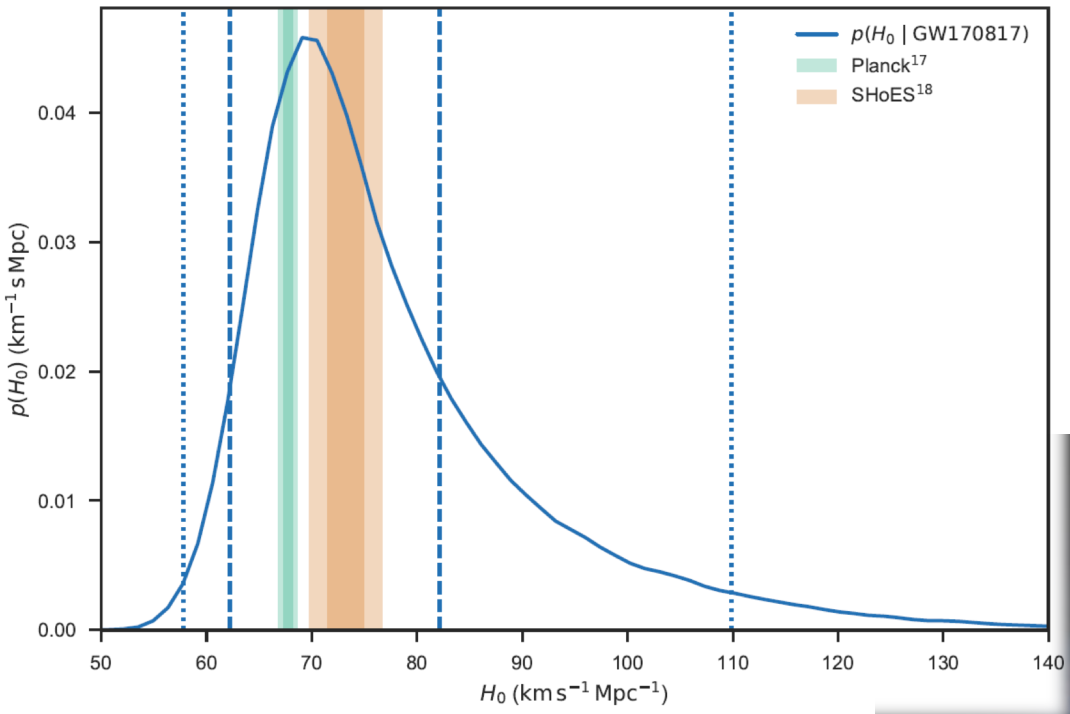
Kilonova interpretation

The evolution of the spectral energy distribution, **rapid fading** and emergence of **broad spectral features** indicated that the source had physical evolution similar kilonovae models (Metzger et al (2010)):

- Rapid shift of the spectral energy distribution from the optical to the near-IR
- **Signatures of the radioactive decay of *r*-process nucleosynthesis elements**
- **Features consistent with the production of lanthanides within the ejecta**

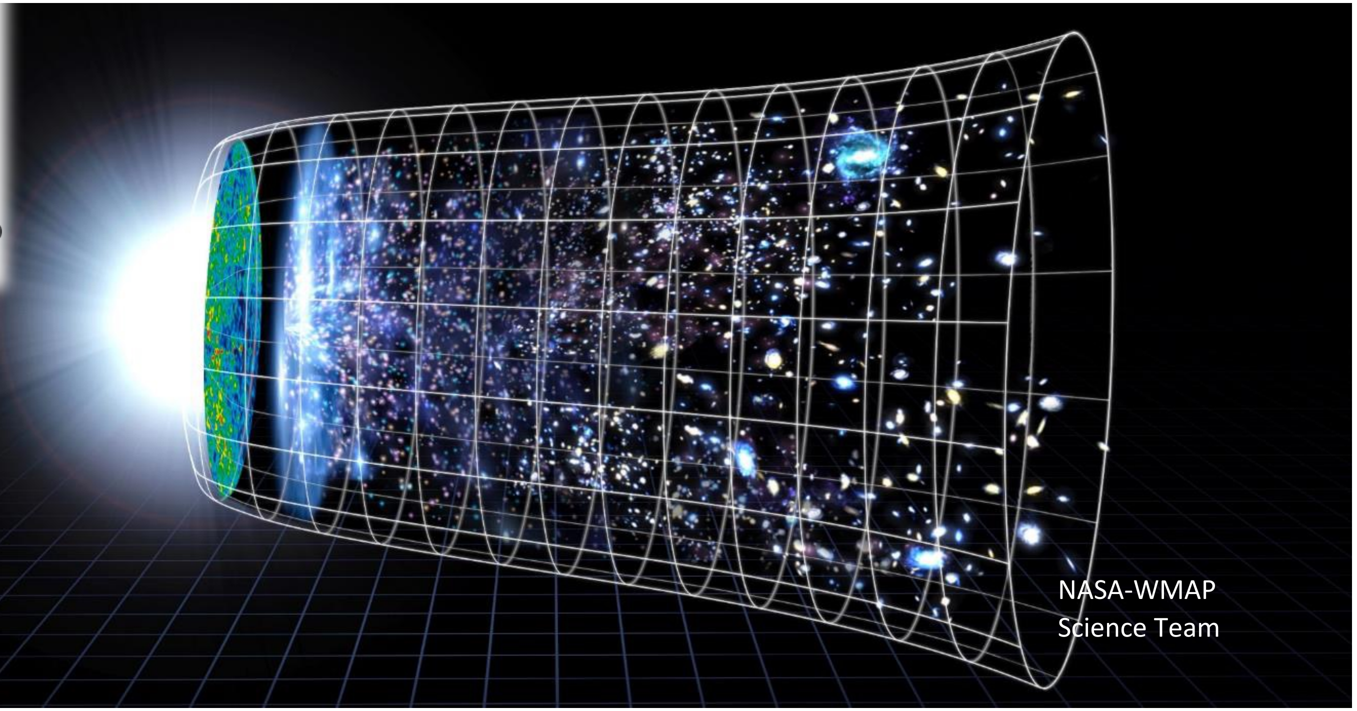


Hubble constant measurements:
a new astronomy was born



$$H_0 = 70.0^{+12.0}_{-8.0}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$

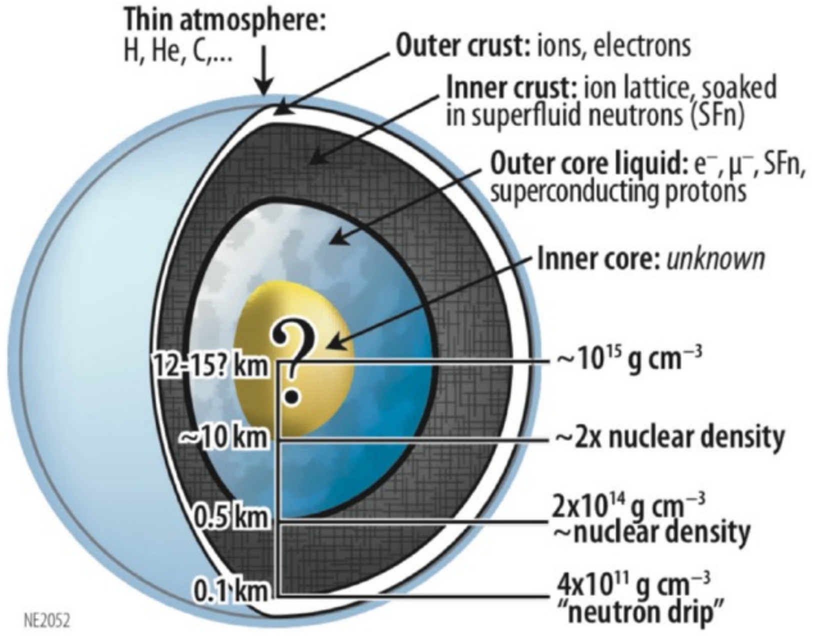
"A Gravitational-Wave Standard Siren Measurement of the Hubble Constant", Nature [https://doi.org/10.1038/nature24471]

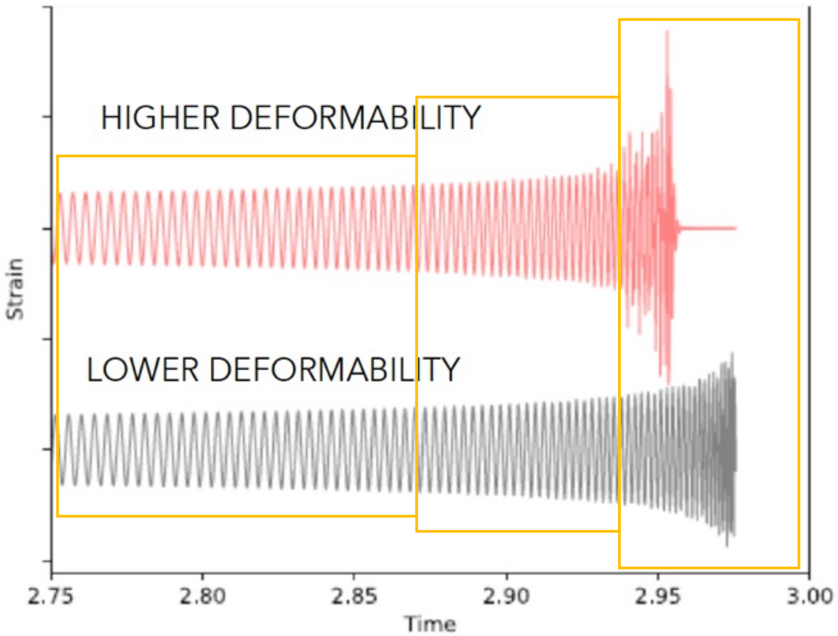


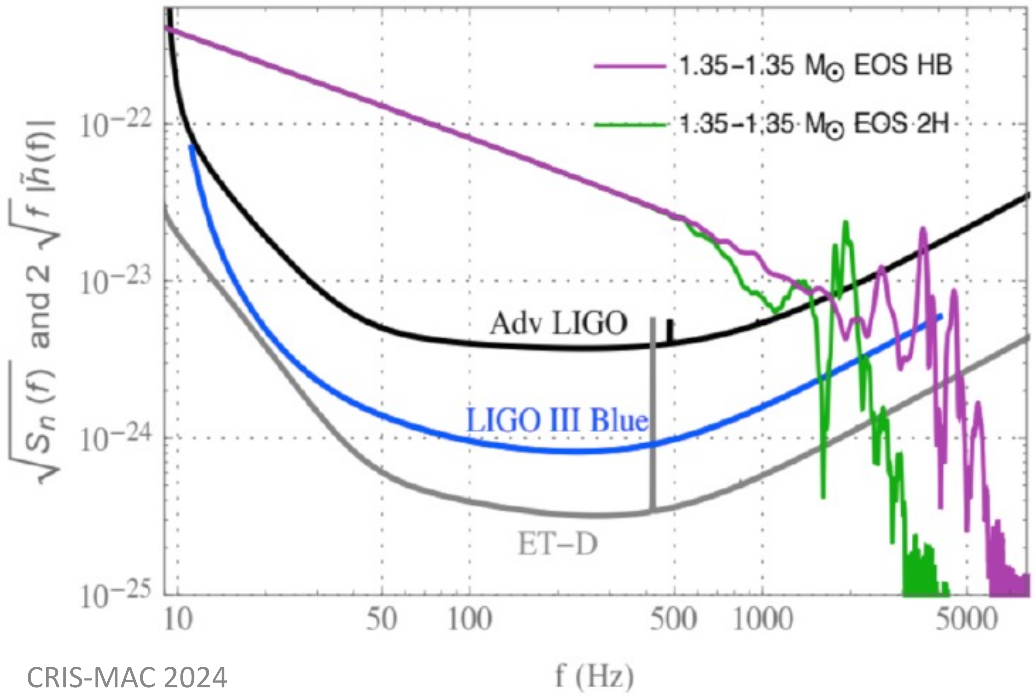
NASA-WMAP Science Team

We really need much more to reconstruct NS composition through EOS

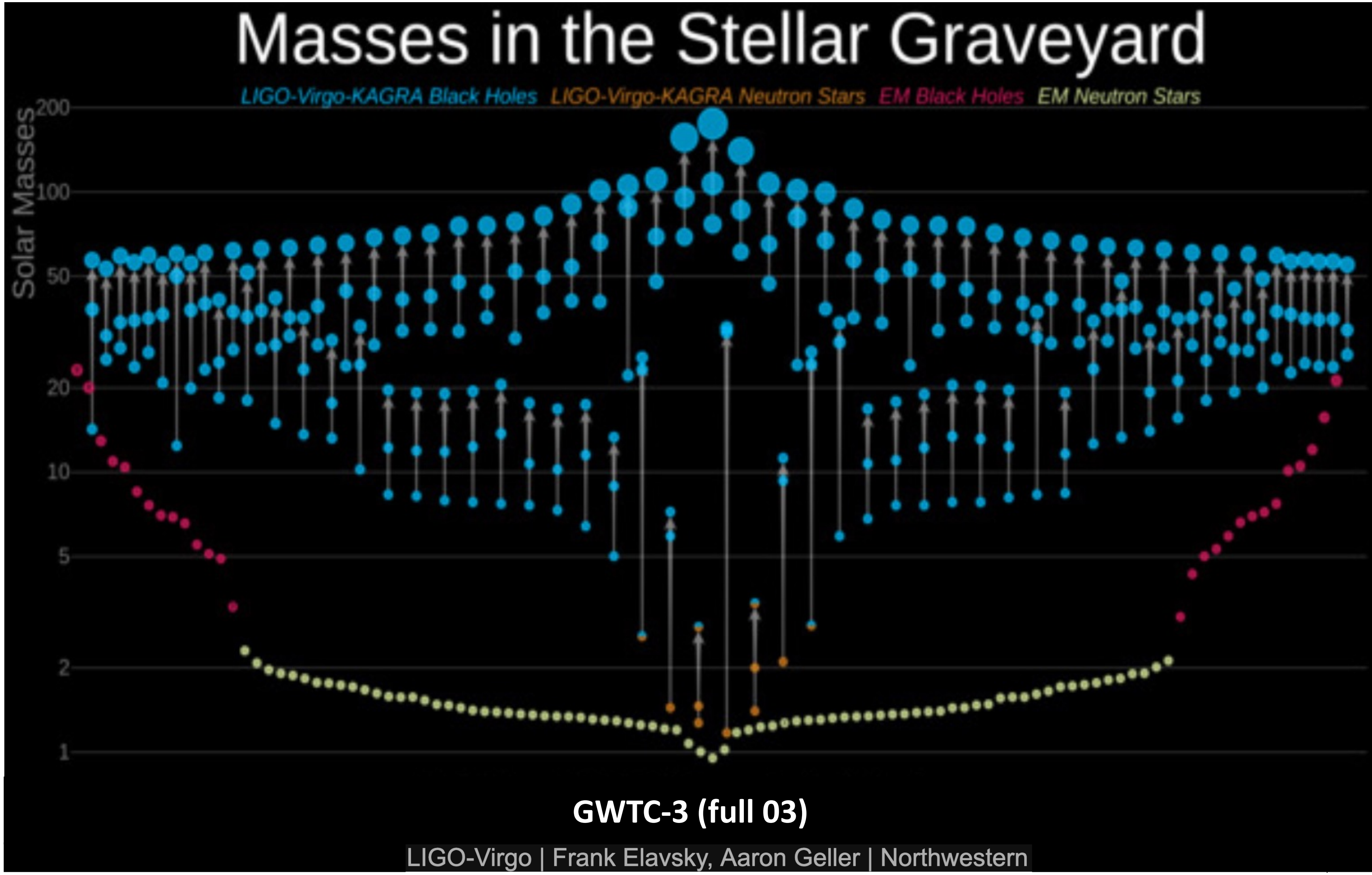
More events, higher sensitivity !







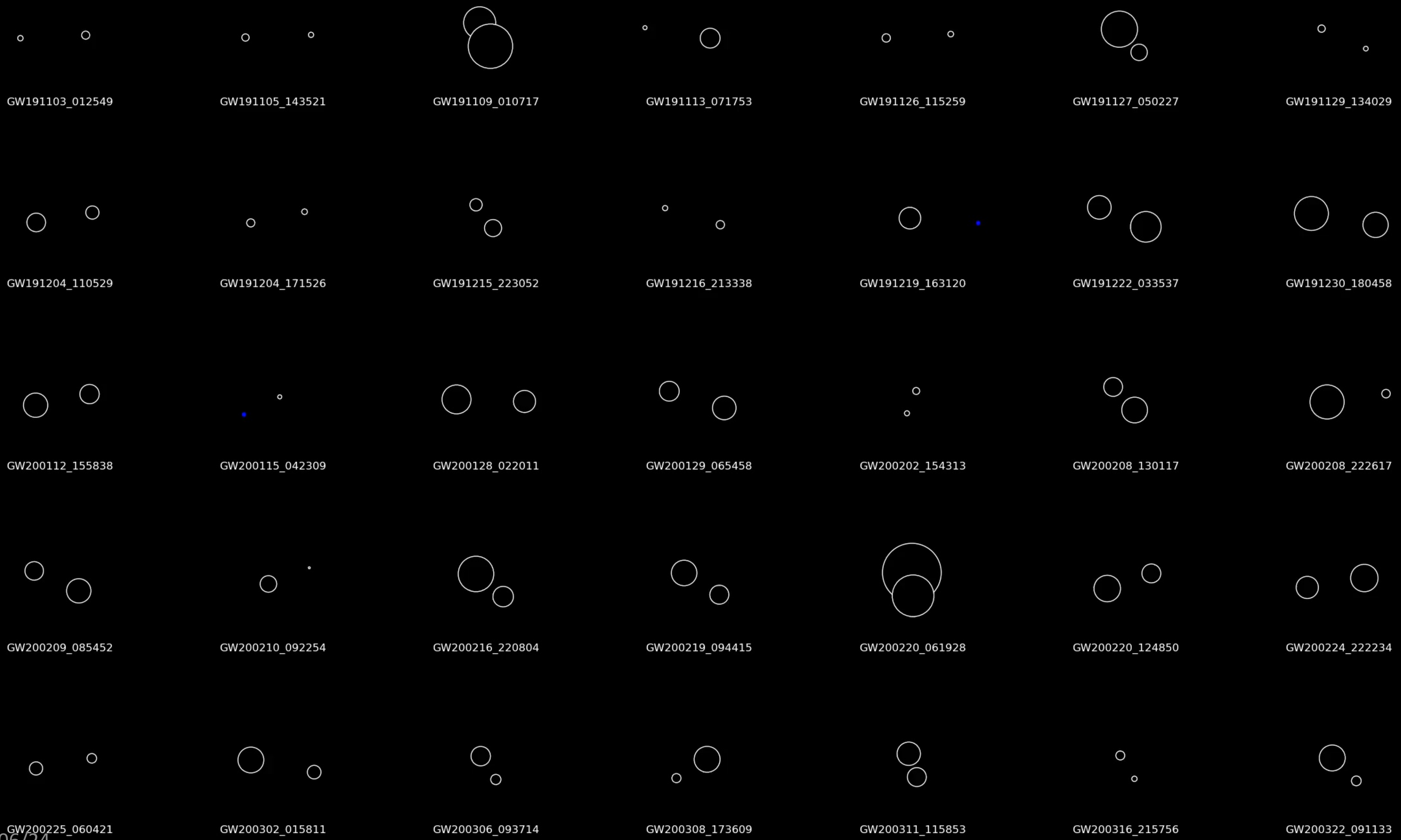
CBCs, a lot of events BUT MOSTLY BBH



GWTC-3 (full 03)

LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern

Credit: Zoheyr Doctor / CIERA / LIGO-Virgo Collaboration



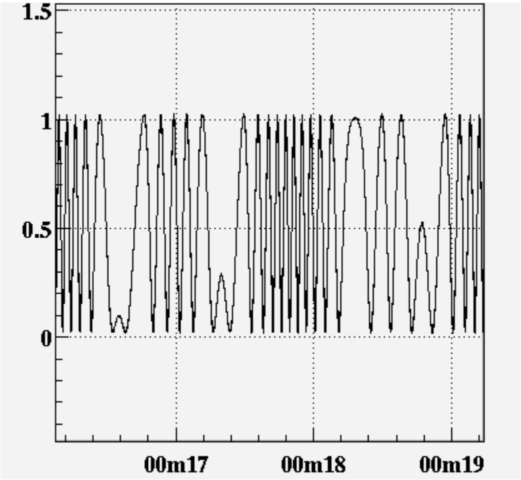
Zoheyr Doctor / CIERA / LIGO-Virgo Collaboration

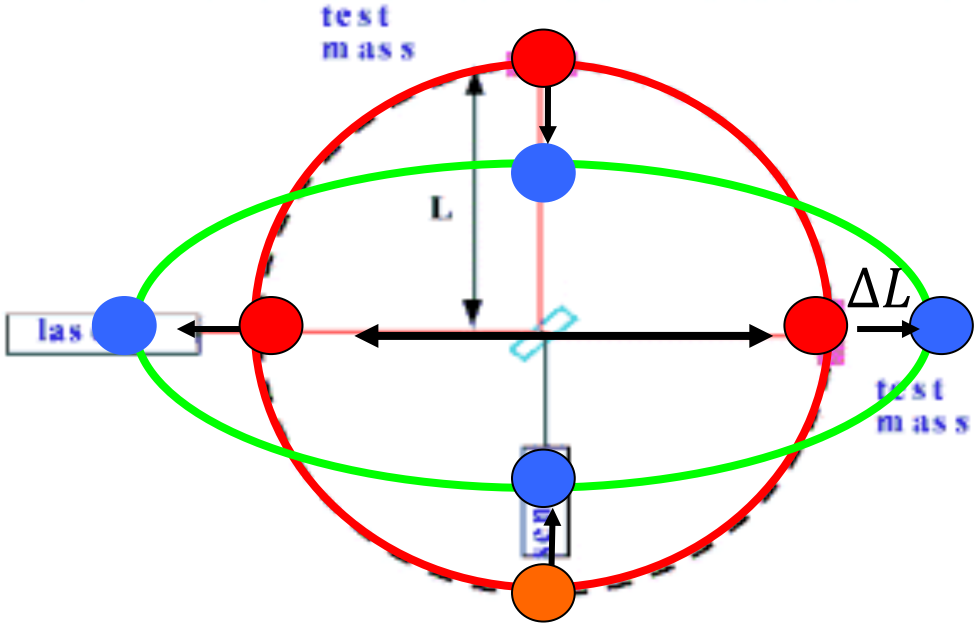
How do we measure ?

Free-mass (wide band) detectors VS Old technology of mechanically resonant detectors

Wide-band detection possible using interferometry:

Interference fringes

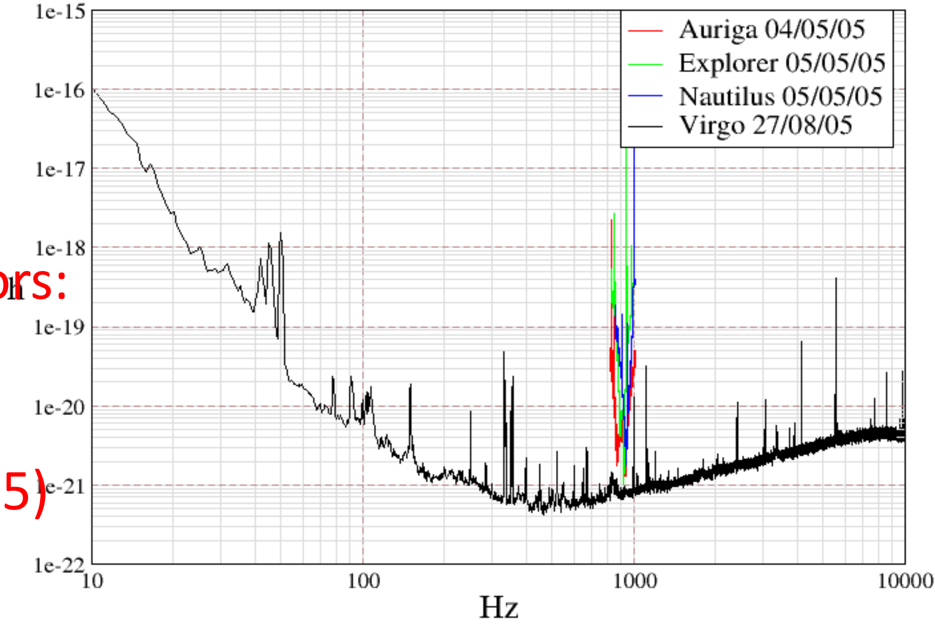




$$h \approx \frac{\Delta L}{L}$$

Compared to Weber resonant detectors:

- higher sensitivity
- many more detectable sources !!
- Resonant detectors abandoned (2005)



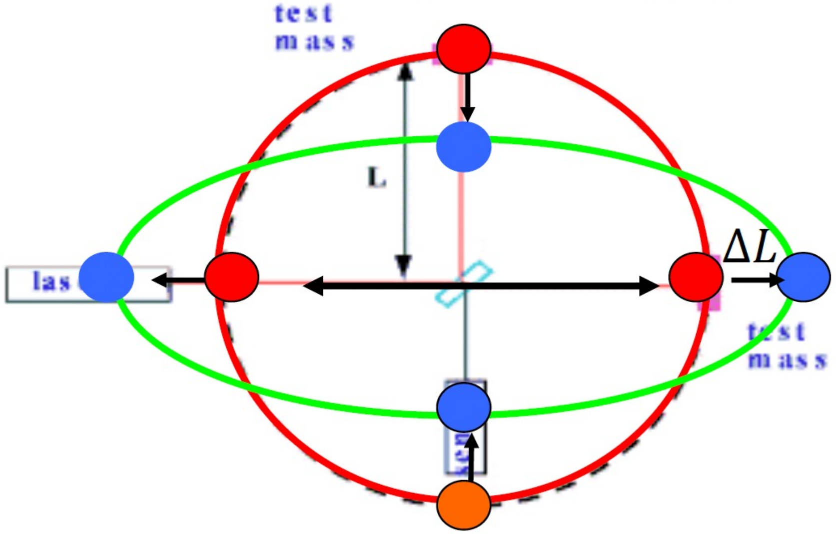
Michelson ITF, basic formalism

Given a GW source at distance r
the effect due to optimal coupling
of polarization "+" is:

$$l_1 \rightarrow l_1\left(1+\frac{1}{2}h_+\right)$$

$$l_2 \rightarrow l_2\left(1-\frac{1}{2}h_+\right)$$

$$\boxed{\delta P_{GW} \propto Amplitude_{GW}}$$

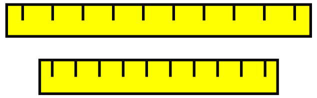


The detected ITF power signal is sensitive to the amplitude of gravitational waves (and not to their **power**, as in e.m. wave detection).

ITF GW signal fades as 1/r (and not as 1/r^2 as in e.m. telescopes):
If $\tilde{h}(f)$ is the detector noise LSD, the number detectable sources increases as $\Delta\tilde{\boldsymbol{h}}^3$

The detection is intrinsically limited by (A) quantum noise (shot noise), but also by the mechanical thermal noise and, if the detector is on the Earth, by (B) seismic background and (C) gravity gradients

“Observational feasibility” adopting km baseline



$$\Delta l = \int \sqrt{|g_{\mu\nu} dx^{\mu} dx^{\nu}|} = \int_0^l |g_{xx}|^{1/2} dx \approx l\, |g_{xx}(x=0)|^{\frac{1}{2}} \approx l\left[1 + \frac{1}{2} h_{xx}^{TT}\right]$$

- a small deformation of the flat metric

$$\rightarrow \quad dt = \frac{1}{c}\sqrt{1 + h_{xx}}\; dx$$

- Time differential due to the perturbation

$$\int_0^{T_{out}} dt = \frac{1}{c}\int_0^L \sqrt{1 + h_{xx}}\; dx \approx \frac{1}{c}\int_0^L \left(1 + \frac{1}{2} h_{xx}\right) dx$$

- time elapsed to travel along one arm of the interferometer

$$T^x_{tot} = \frac{2L}{c} + \frac{1}{2c}\left[\int_0^L h_{xx} dx - \int_L^0 h_{xx} dx\right] = \frac{2L}{c} + \frac{1}{c}\int_0^L h_{xx} dx$$

- in the acoustic band (low freq.) the amplitude of the wave can be roughly considered constant during travel in the arm → we can just multiply by 2 the forward term

$$T^x_{tot} - T^y_{tot} = \left[\frac{2L}{c} + \frac{1}{c}\int_0^L h\, dx\right] - \left[\frac{2L}{c} - \frac{1}{c}\int_0^L h\, dy\right]$$

$$h_{xx} = h_{yy} = h$$

- It does not apply for LISA as L is 10^6 larger

“Observational feasibility” on km-scale

$$\Delta\phi = \omega\Delta T = \omega\frac{2L}{c}h = \frac{4\pi}{\underset{1.0610^{-6}m}{\lambda}}\overset{3\ km}{L}\underset{10^{-22}}{\boxed{h}}$$

long armlength L helps **but even adopting km baseline,** h is too small and GW-observation level $\Delta\phi$ would result impossible due to the shot noise

➔ using Fabry-Perot cavities further enhances L through the Finesse $\mathfrak{f}$

$$\Delta\phi_{PF} = \overbrace{\overset{\sim 300}{\boxed{\frac{2\mathfrak{f}}{\pi}}}\frac{1}{\sqrt{1+\left(\frac{\omega_{GW}}{\omega}\right)^2}}}^{L_{opt}(\omega)}\Delta\phi$$

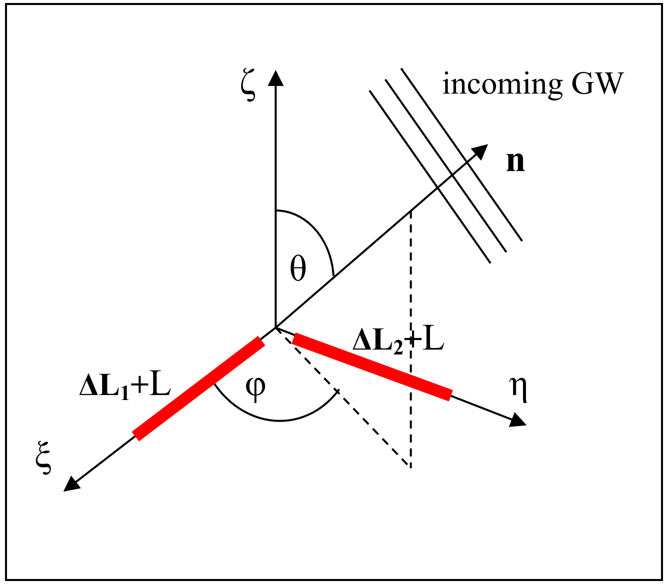
Amplitude of a phase signal due to strain $h=\frac{\Delta L}{L}$ detected

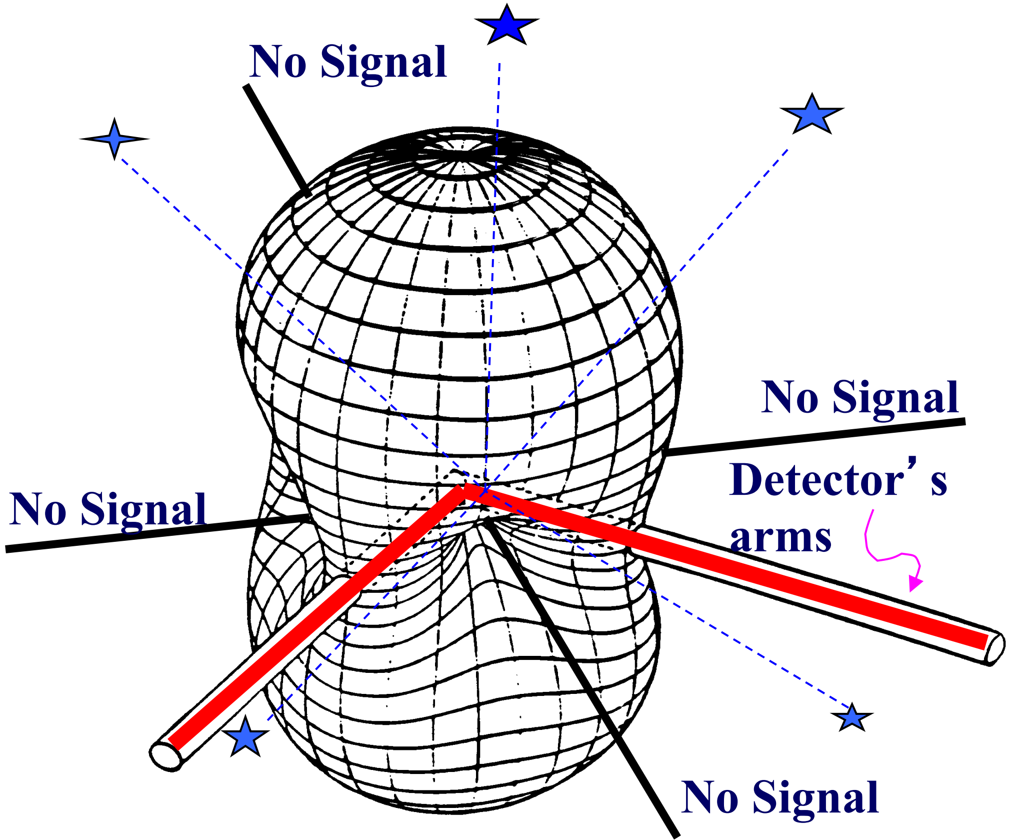
$$\tilde{\phi}_{FP} = \frac{1}{8L\mathfrak{f}}\sqrt{\frac{2\hbar\omega}{\eta P_{in}}}\sqrt{1+\left(\frac{\omega_{GW}}{\omega}\right)^2}$$

The shot noise is reduced by increasing Laser power and FP finesse

Antenna Pattern for Michelson interferometer

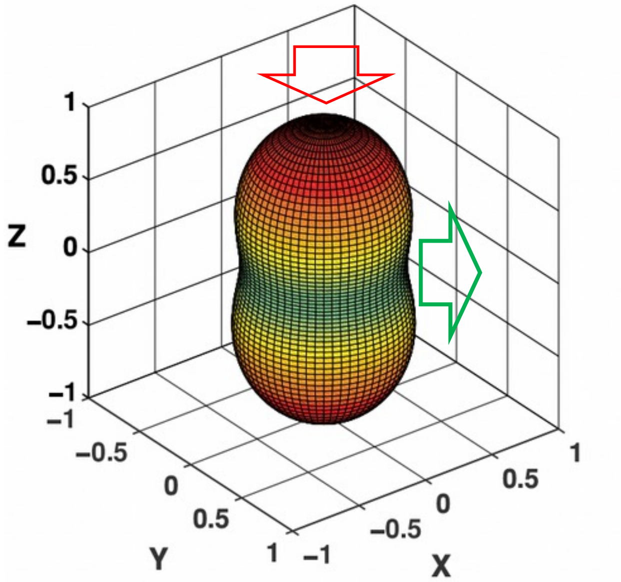
$$\frac{\Delta L}{L} = \frac{\Delta L_1 + \Delta L_2}{L} = \frac{1+\cos^2\theta}{2}\cos(2\varphi)h^+ + \cos\theta\,\sin(2\varphi)h^x$$





A glance to *km-scale* triangle shape

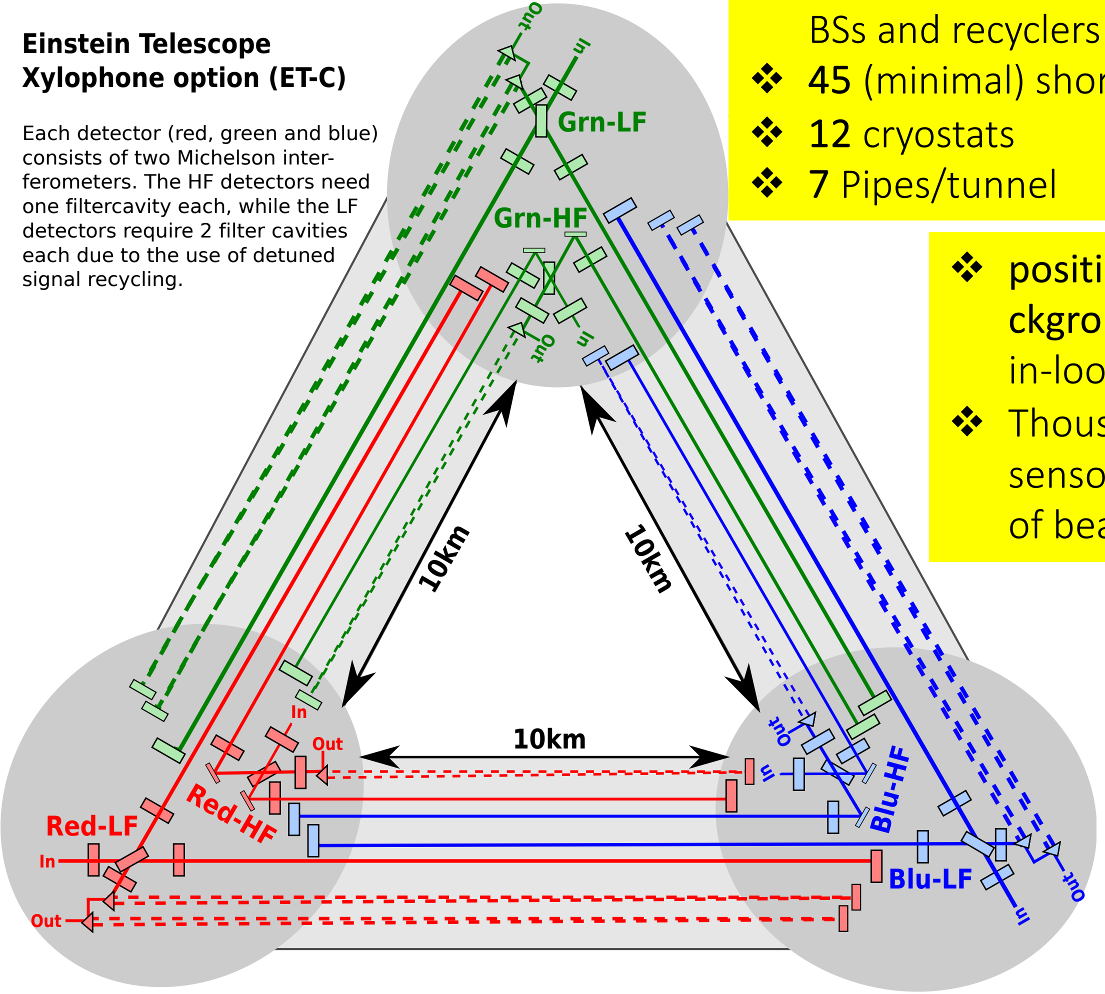
- Start with a “single” hybrid detector
- Add a 2nd one to fully resolve polarization
- Add a 3rd one aimed to provide *null stream*
- *Notice: omnidirectional*



Minimal numbers

- ❖ 21 Long suspensions for Test masses BSs and recyclers (signal and power)
- ❖ 45 (minimal) shorter towers
- ❖ 12 cryostats
- ❖ 7 Pipes/tunnel

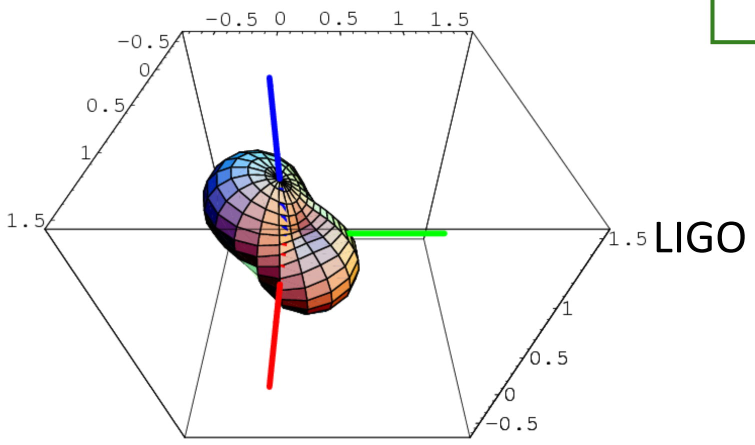
- ❖ **position/acceleration/background:** thousands of in-loop sensors for
- ❖ Thousands of global sensors for optical D.O.F of beams

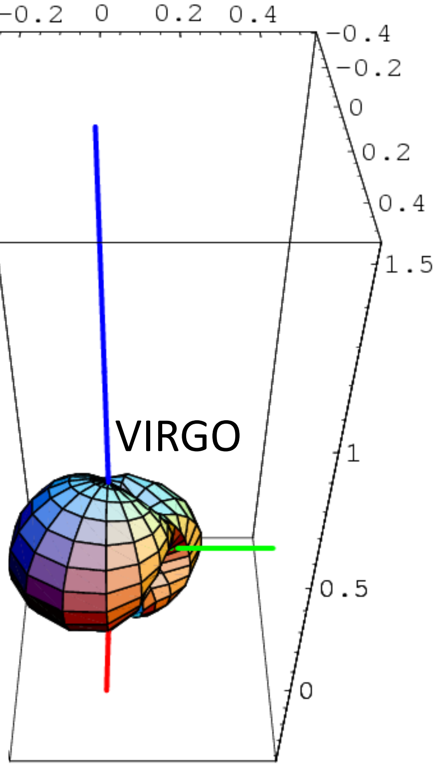


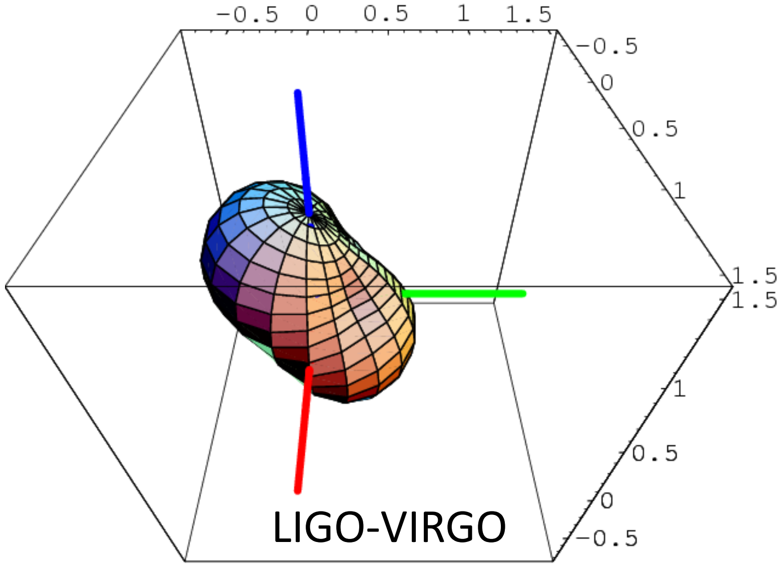
Einstein Telescope
Xylophone option (ET-C)

Each detector (red, green and blue) consists of two Michelson interferometers. The HF detectors need one filtercavity each, while the LF detectors require 2 filter cavities each due to the use of detuned signal recycling.

Network patterns







(A. Viceré)

- Environmental monitoring and engineering signals are used to veto on environmental noise
- Coincidence analysis is essential to further identify false alarms at the level of the residual noise affecting the single detectors.
- but also to constitute a “single” detector ➔ location and orientation are relevant parameters

For example, coherent combination advanced LIGO-H/LIGO-L/Virgo (SNR=8, eff. 90%), enlarges the BNS detection distance at which BNS from 150-170 Mpc of single antennas ➔ 270 Mpc

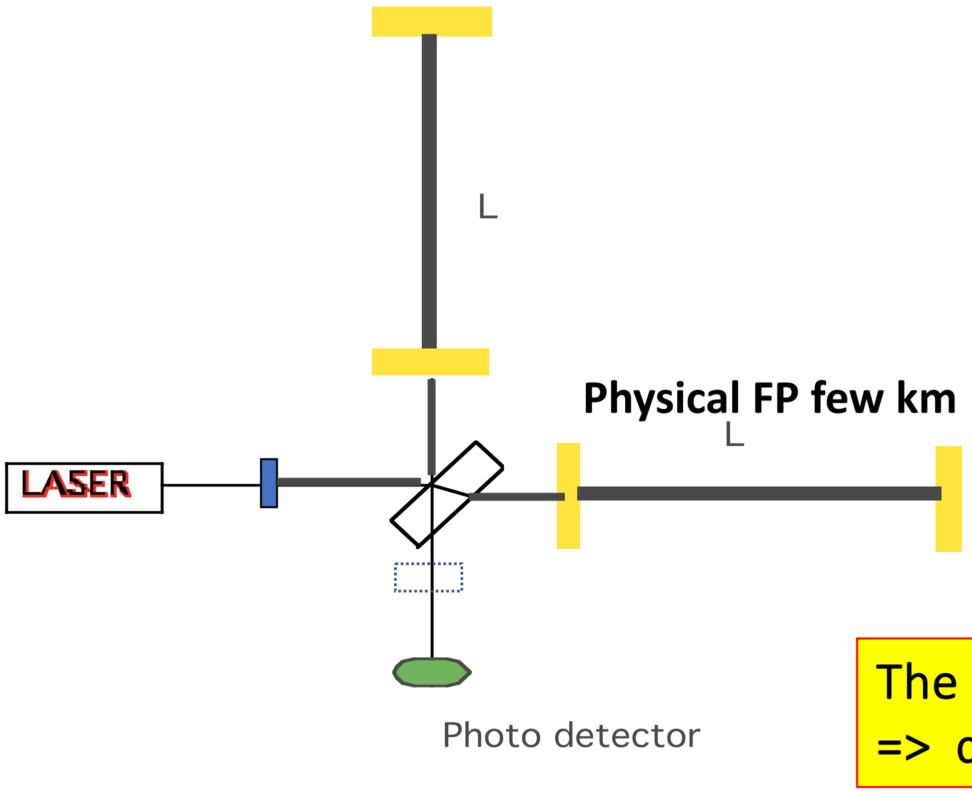
Standard layout used in ground-based detectors

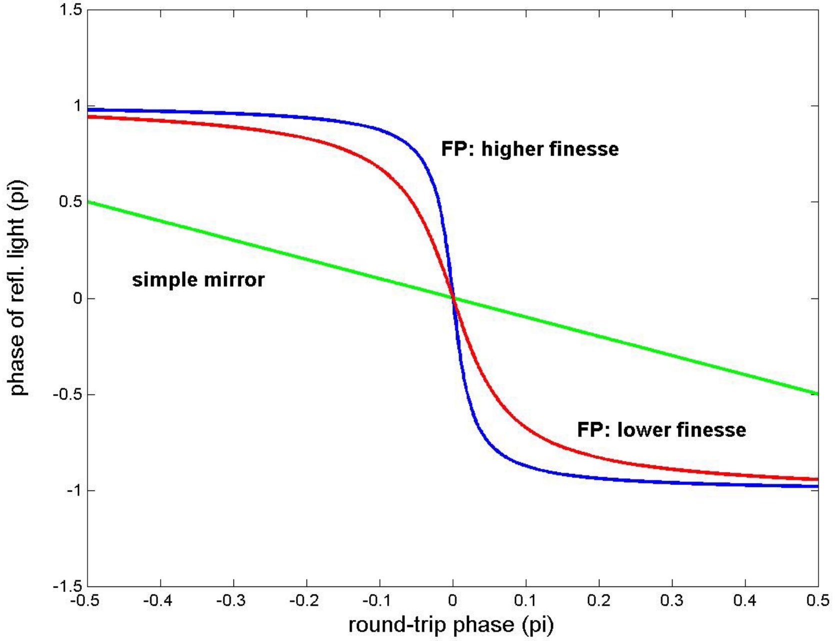
I) The optical path where the GW-induced phase shift is accummulated can be enhanced by means of Fabry-Perot resonant cavities.

II) Dark fringe detection to reduce read-out noise.

III) Power and Signal recycling.

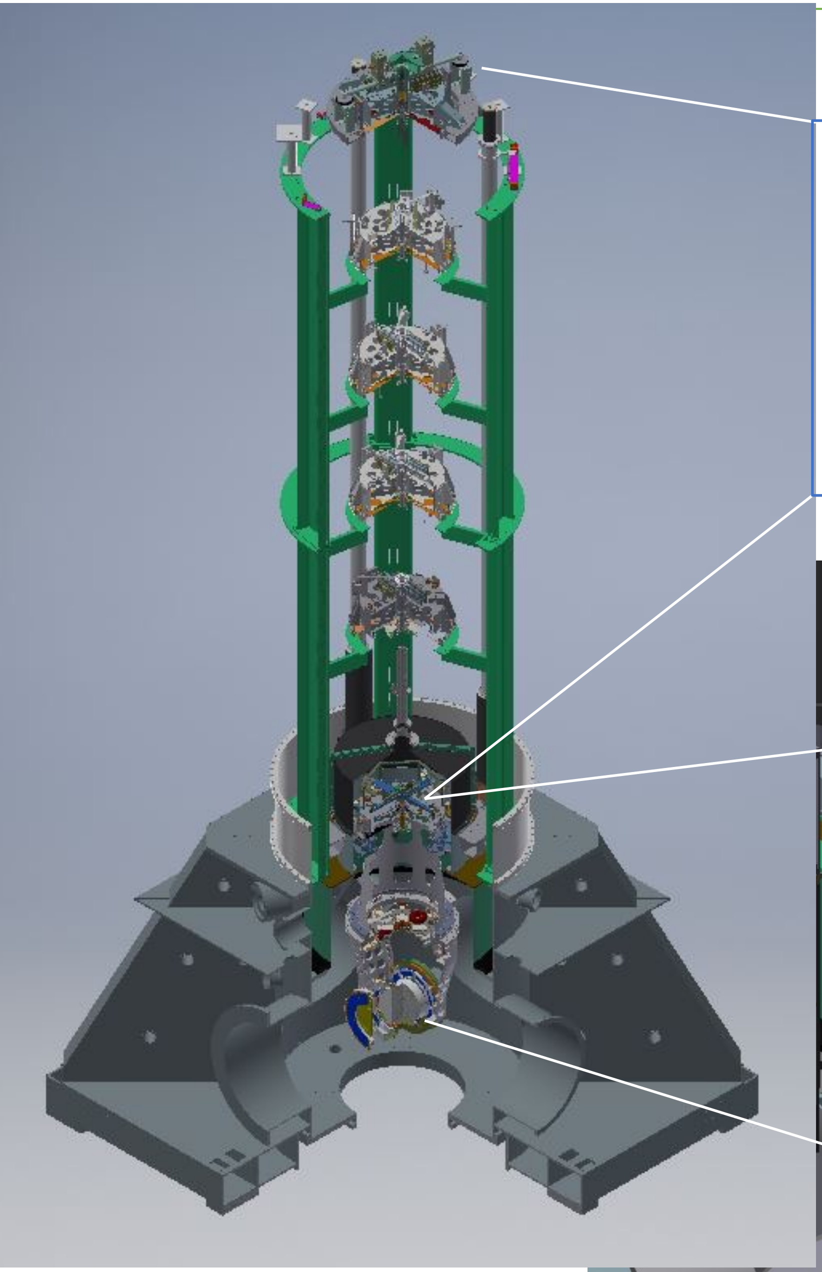
Effective optical path ~300 km



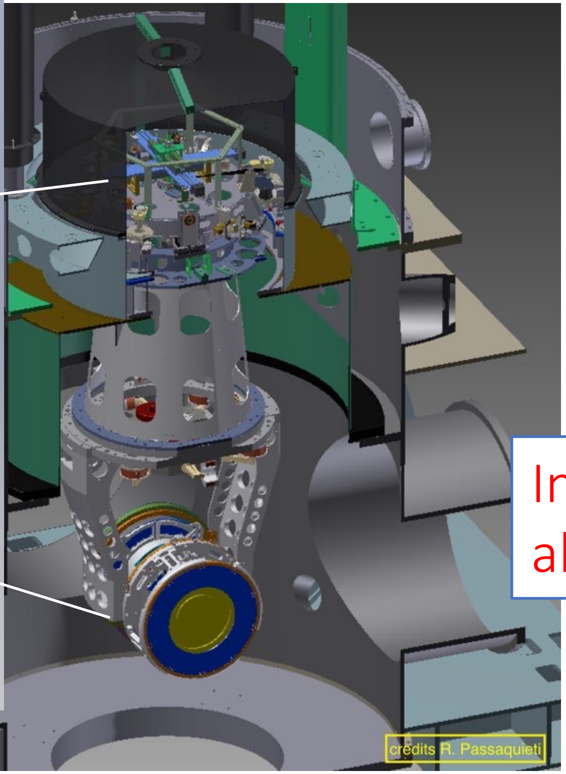


The response of the resonant ITF is much steeper
=> demanding attenuation and control system are needed

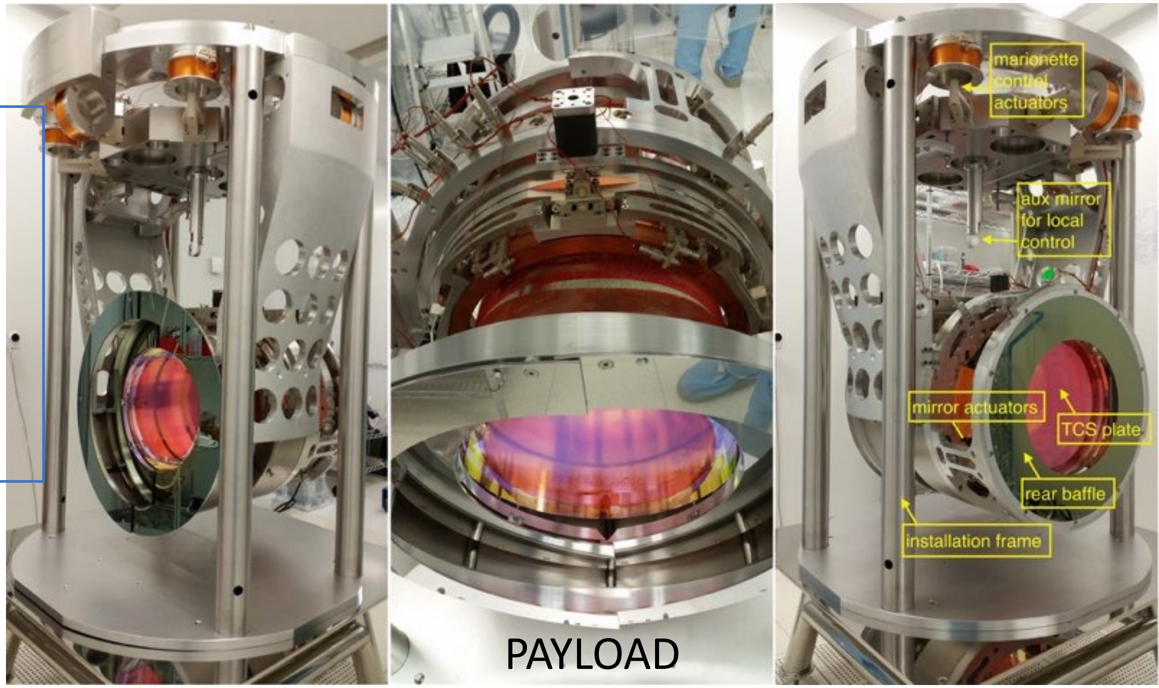
Test mass suspensions and seismic isolator in Virgo: overall system



In AdV the first 5 stages of the Super-attenuator (horizontal and vertical) are roughly the same **designed ~30 years ago**



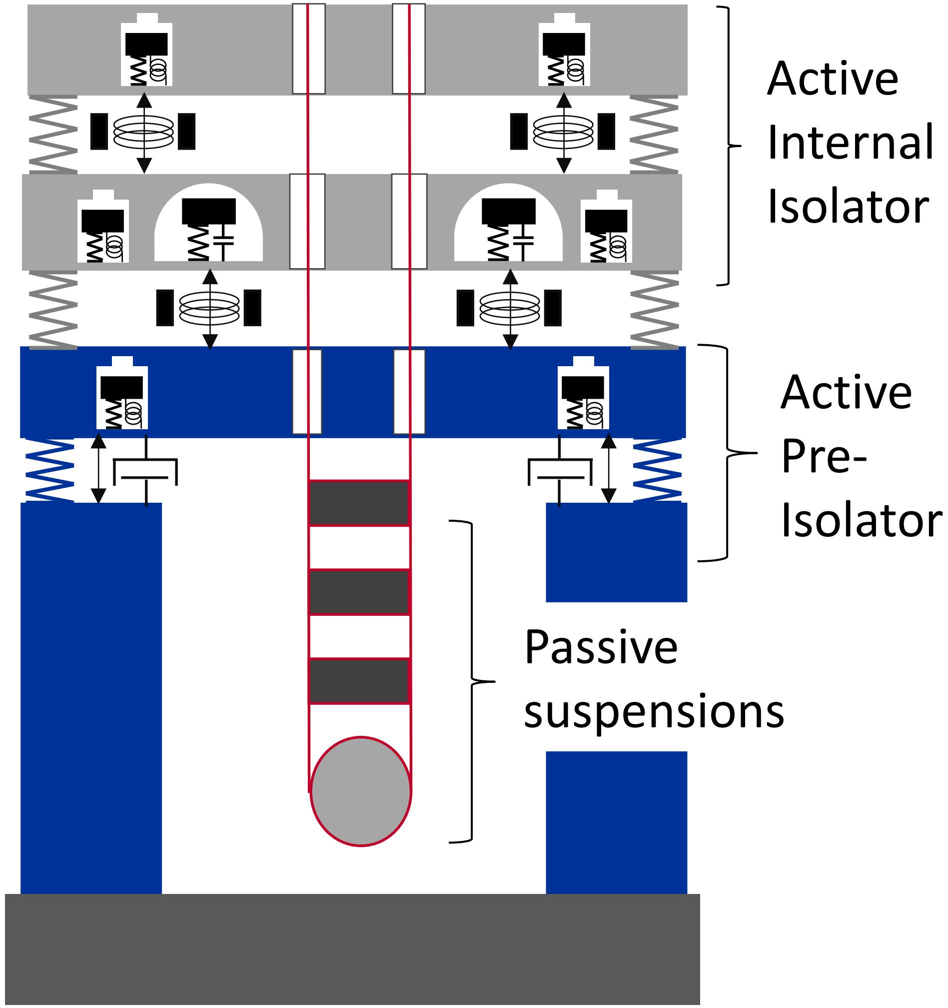
credits R. Passaquieti



Indeed, the seismic suspension is already there almost ready for ET (!!)

Test mass suspensions and seismic isolator in LIGO: overall system

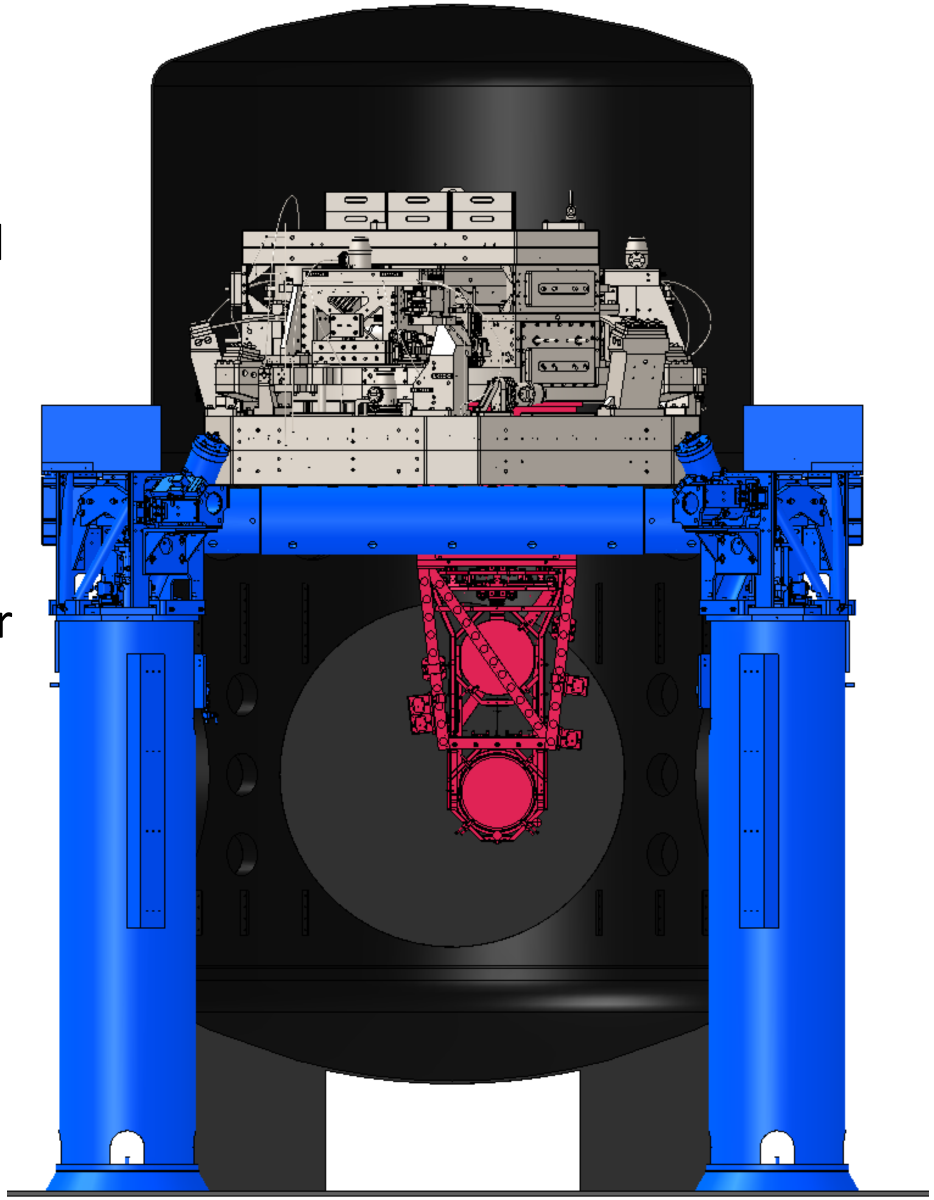
Purely active (wide band control on a more rigid mechanics)



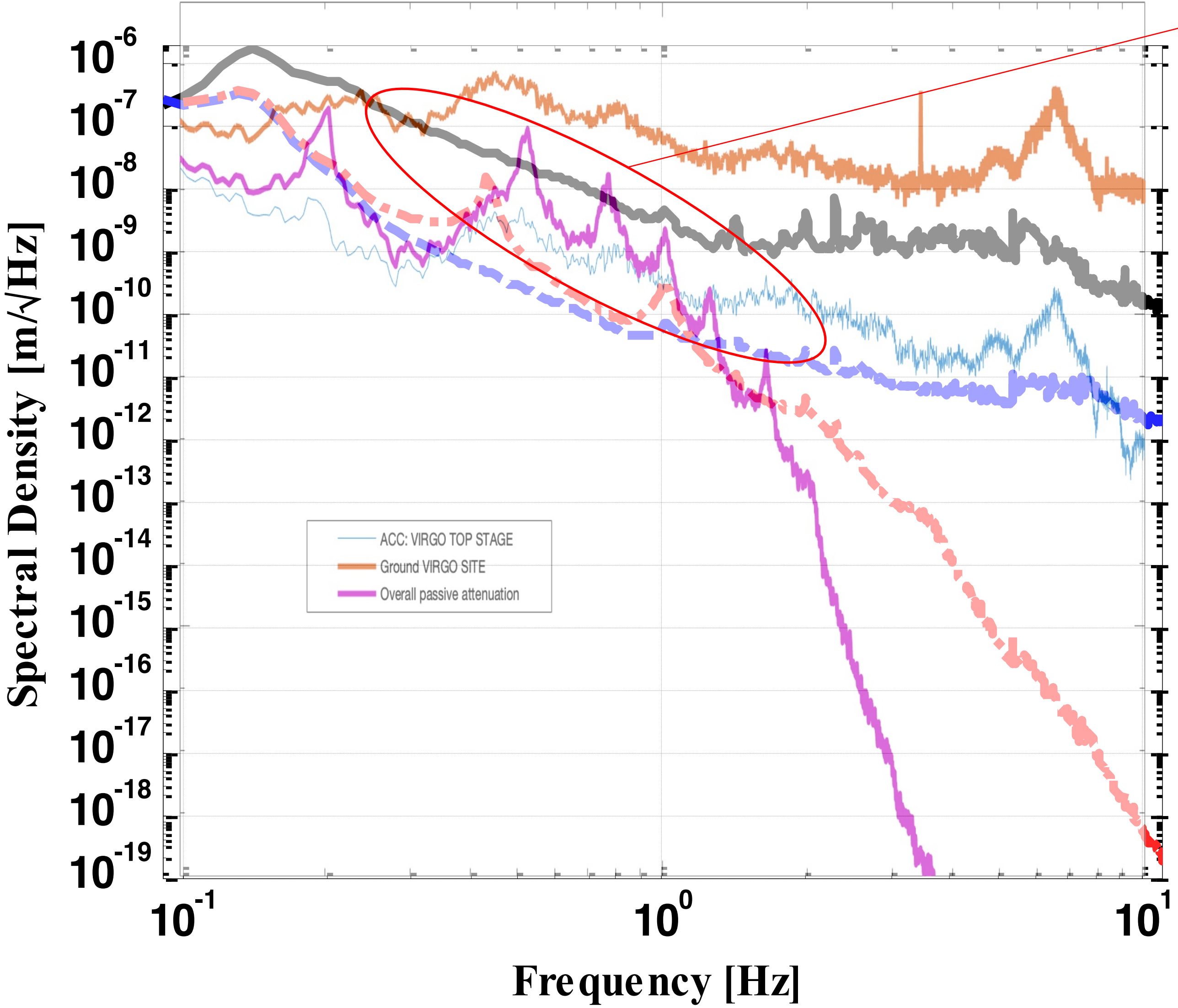
Active Internal Isolator

Active Pre-Isolator

Passive suspensions



Both LIGO and Virgo/KAGRA are equipped performance attenuators of seismic background



Need of chain mode damping

GROUND noise at Virgo

GROUND noise at LIGO

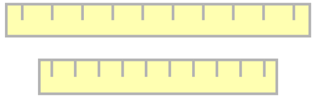
ACTIVE SUPPRESSION
@ payload suspension point

~10^{-9}
SUPPRESSION
@10 Hz for LIGO,
@3 Hz for Virgo

PASSIVE FILTERING in LIGO

PASSIVE USING LONG CHAIN (Virgo, KAGRA)

Let’s avoid the seismic background
What about *Mkm* baseline ?



notice how the ticks on a ruler affected by GW

$$\Delta l = \int \sqrt{|g_{\mu\nu}dx^{\mu}dx^{\nu}|} = \int_0^l |g_{xx}|^{1/2}dx \approx l\,|g_{xx}(x=0)|^{\frac{1}{2}} \approx l\left[1+\frac{1}{2}h_{xx}^{TT}\right]$$

- a small deformation of the flat metric

$$\rightarrow \quad dt = \frac{1}{c}\sqrt{1+h_{xx}}\;dx$$

- Time differential due to the perturbation

$$\int_0^{T_{out}} dt = \frac{1}{c}\int_0^L \sqrt{1+h_{xx}}\;dx \approx \frac{1}{c}\int_0^L \left(1+\frac{1}{2}h_{xx}\right)dx$$

- time elapsed to travel along one arm of the interferometer

$$T_{tot}^{x} = \frac{2L}{c} + \frac{1}{2c}\left[\int_0^L h_{xx}dx - \int_L^0 h_{xx}dx\right] \xcancel{=} \frac{2L}{c} + \frac{1}{c}\int_0^L h_{xx}dx$$

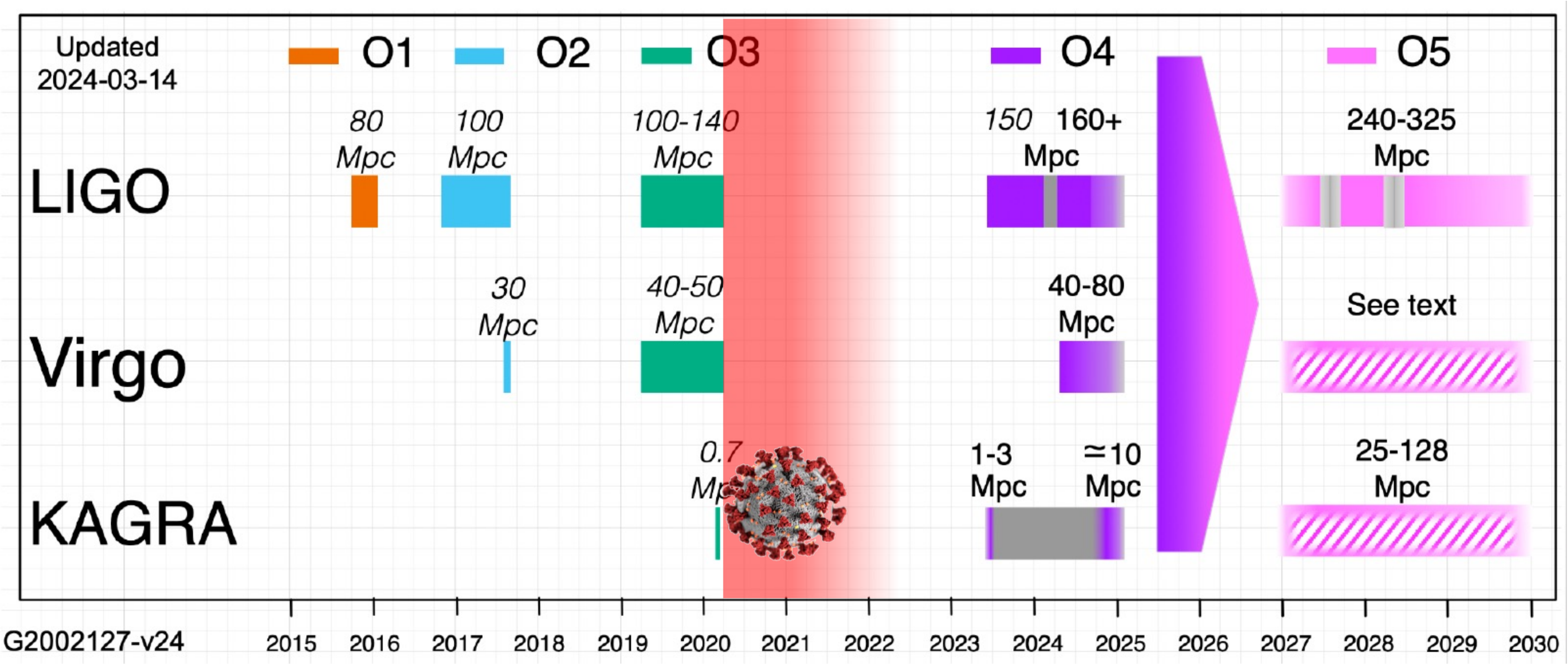
- It does not apply for LISA, as L is 10^6 larger

Real time optical recombination (phase reconstruction)

Off-line Doppler (frequency) shift observation and metric reconstruction

Where do we go ?

LVK Observation runs



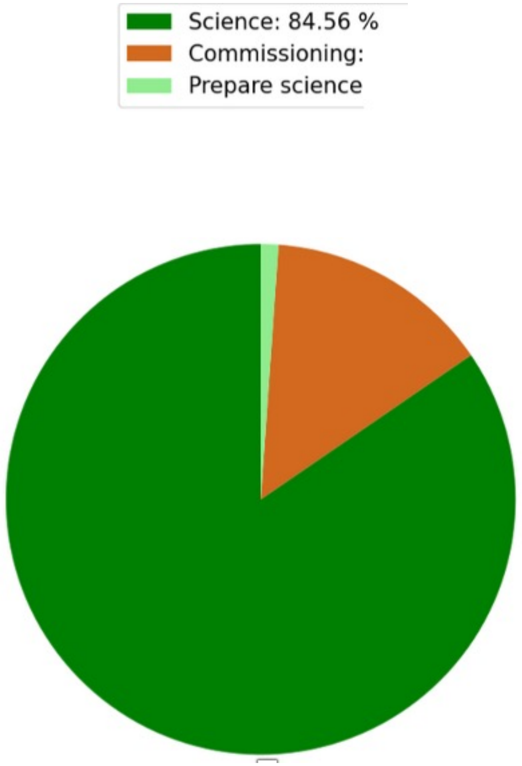
https://gwdoc.icrr.u-tokyo.ac.jp/DocDB/0116/L2011619/003/KSCnewsletter_202004H.pdf

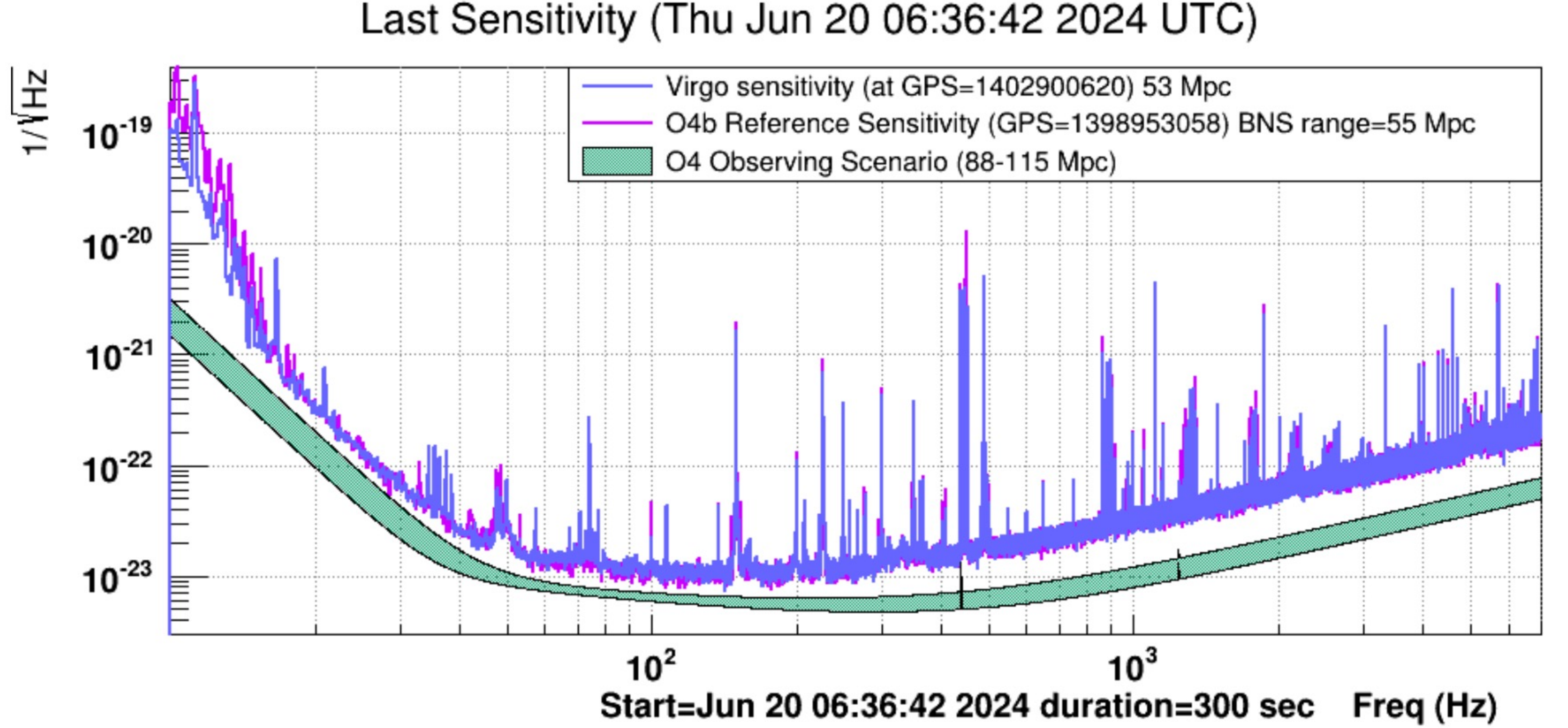
Post O5 planning
= just started

The hard life of commissioning

O4b: we have the same sensitivity of O3,

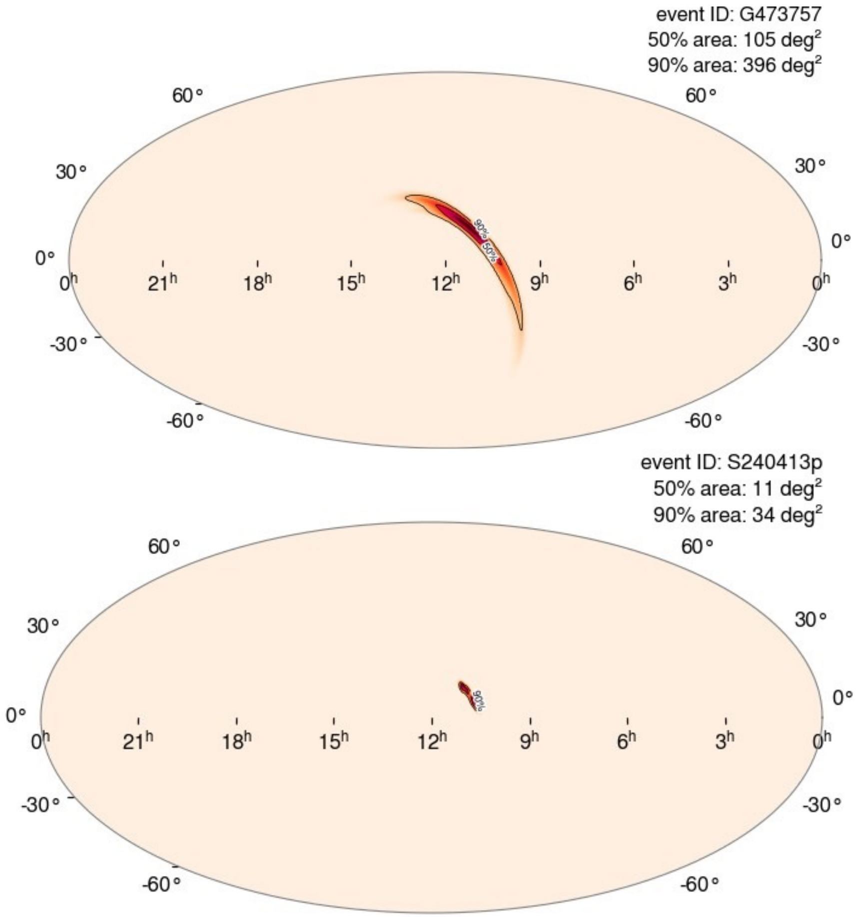
- At low frequency technical noise, a typical issue affecting the interferometers. ET will dedicate further and major improving efforts
- The power injected is nowadays low in Virgo. The machine is very stable, but tuning at high power is a time consuming activity
- We must improve the optical configuration





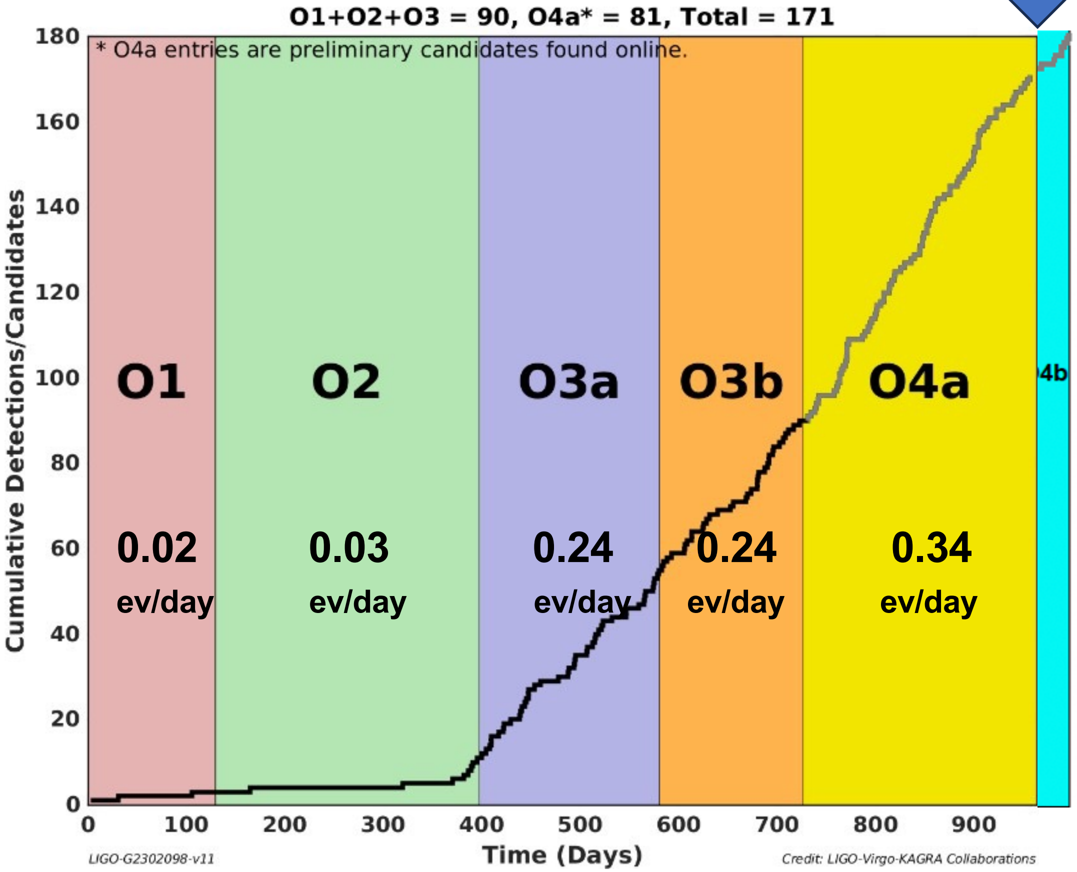
O4, the current run: the importance of being there

BBH candidate S240413p (2024) W W/O VIRGO



We just joined O4(b)

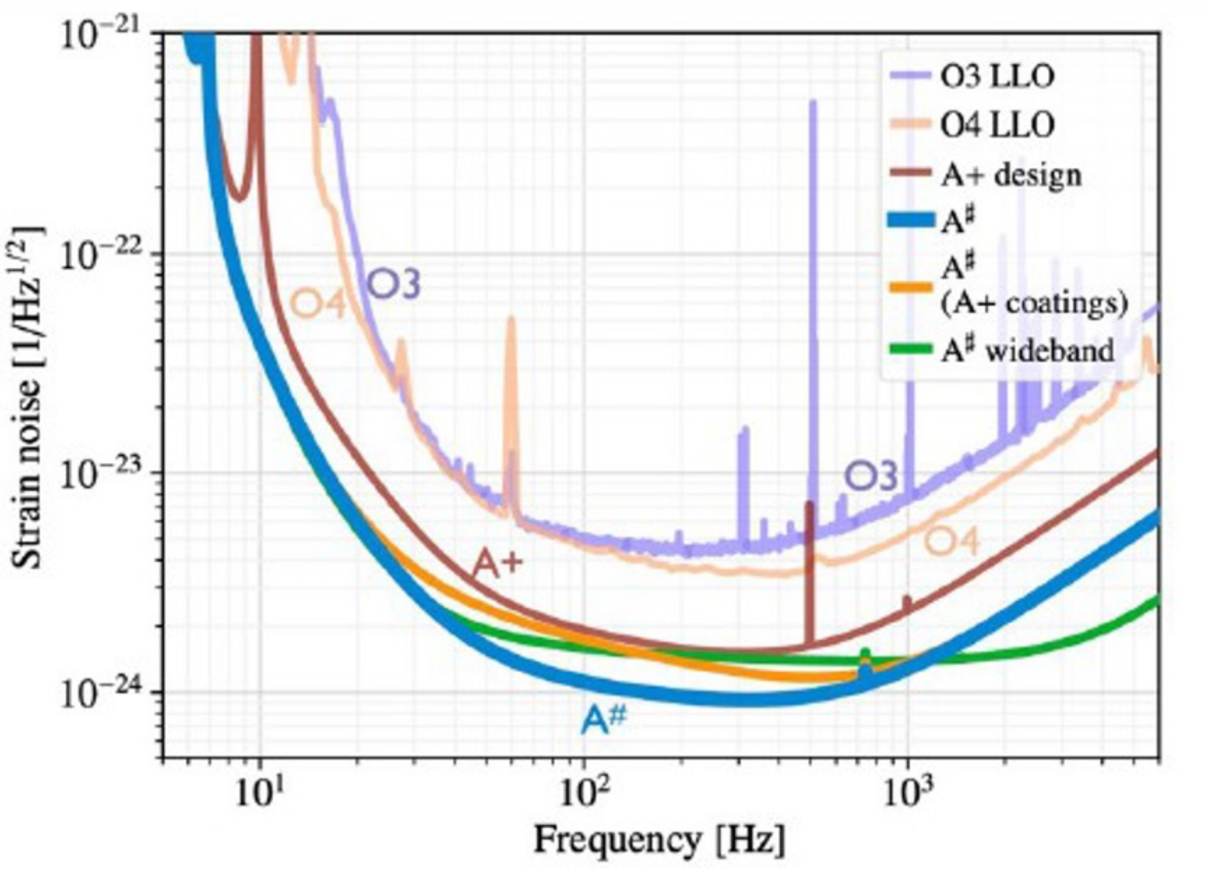
- 15 events (using LIGO trigger)
- a few discarded

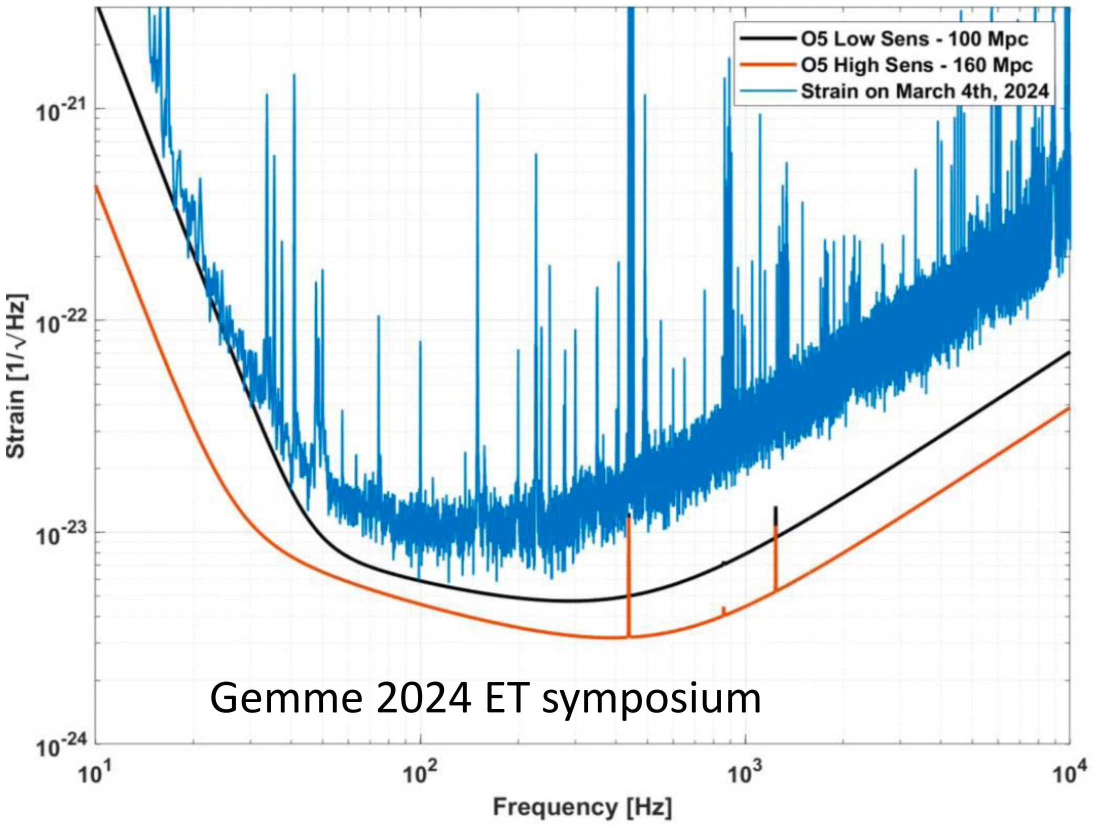


Total O4 significant detection candidates: ~**100** (~10% rejected)

A major effor to recover triggering sensitivity WRT LIGO

We cannot perform another observation run with 1/3 LIGO sensitivity



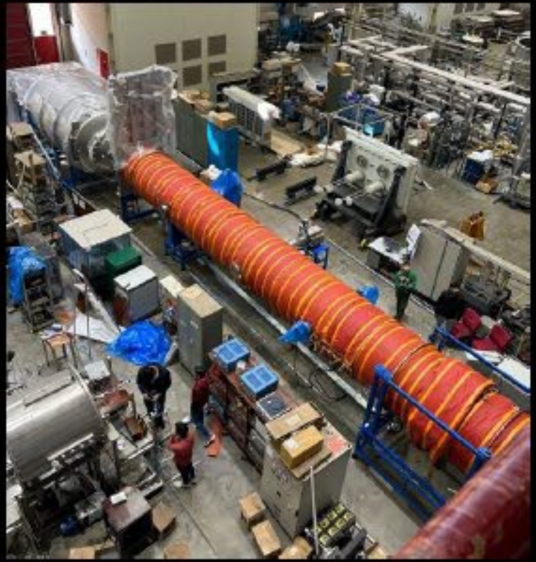


Gemme 2024 ET symposium

Progress on LIGO-India

- LIGO Aundha Observatory (LAO aka LIGO-India) was approved for funding in April 2023!
- Most of the major activities are now happening in India, eg:
  - LIGO-India Vacuum System Prototyping 'LI-VISTA' @IPR
  - Final facility design @DCSEM
  - Expression of Interest for LAO facility construction @RRCAT
  - Human resource development @IUCAA
- Activities on US/LIGO Lab side:
  - Export license for shipment of critical detector components to India
  - Finalization of DAE-Caltech-MIT MOU
  - Joint LIGO US – LIGO-India Systems Meetings

LI-VISTA



Brian & Dave visit IPR, Dec 2023

LI-VISTA BT+GV+Cryopump Inspection

SLIDE: Dave Reitze

KAGRA

Large-scale Cryogenic Gravitational-wave Telescope

2nd generation GW detector in Japan, started in 2010.

Artwork Image of KAGRA

Large-scale Detector

- Baseline length: 3km
- High-power Interferometer

Cryogenic interferometer

- Mirror temperature: 20K

Underground site

- Kamioka site dedicated
- L-shaped tunnel

SLIDE: Masaki Ando

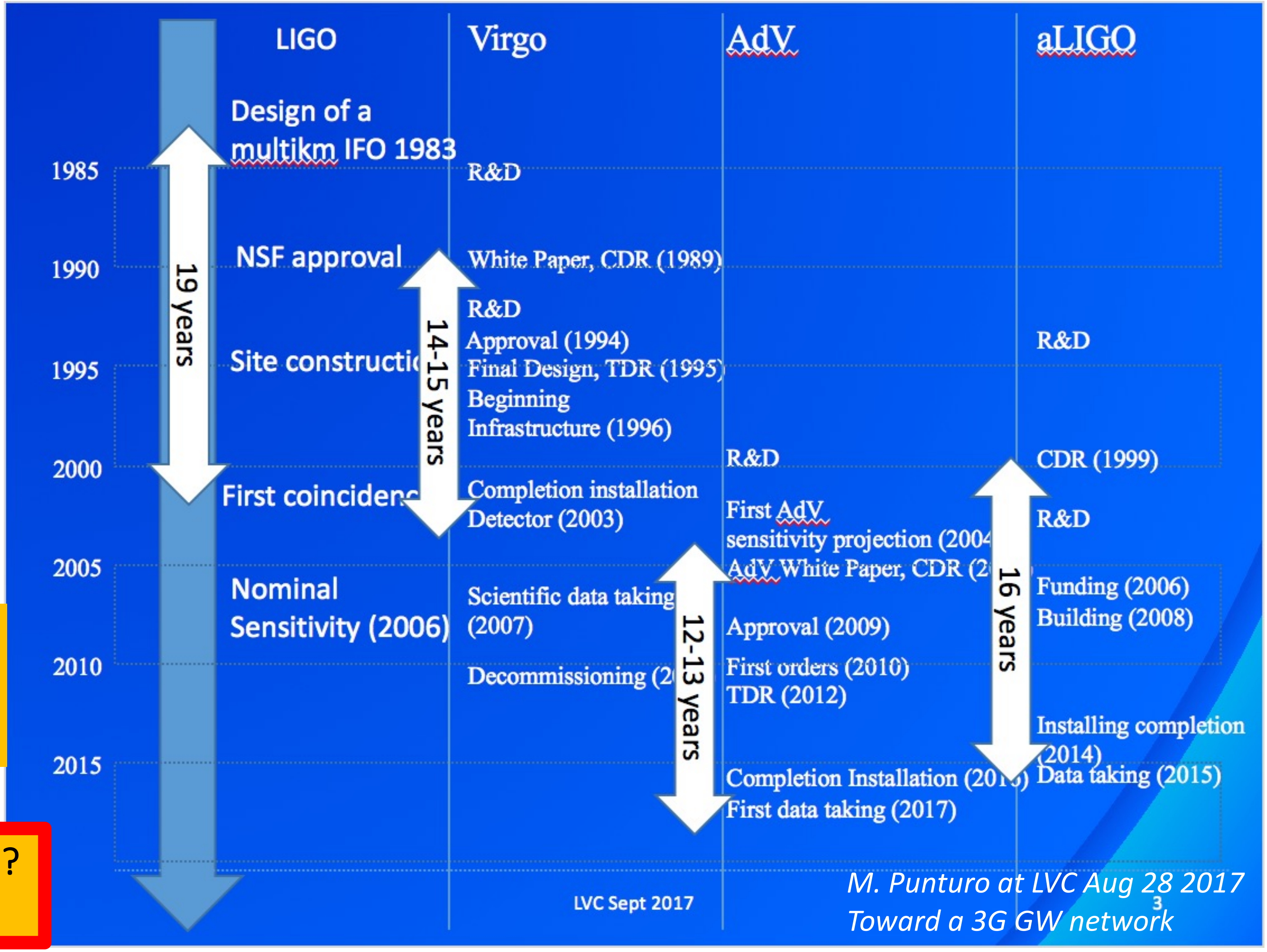
Conclusion: “the factory of water” (until ET is in operation)

- GW detectors are scientific infrastructures with a long “time constant”
  - Ideas in the ’70s
  - Projects in the ‘80
  - 1G integration, end of ‘90s
- The typical timeline (CDR-to-realisation) for a GW detector is ~15 years

➔ how long building a 2G detector would it take? (INDIGO approval 2016…)

➔ Something must change for ET !
❖ **The infrastructure** is the main issue
❖**Timeline** to **have the whole ITF** operation

➔ **Who produces scientific data meanwhile?**
❖ LVK (20-25 y?)



	LIGO	Virgo	AdV	aLIGO
	Design of a multikm IFO 1983			
1985		R&D		
1990	NSF approval	White Paper, CDR (1989)		
1995	Site constructi	R&D Approval (1994) Final Design, TDR (1995) Beginning Infrastructure (1996)		R&D
2000	First coinciden	Completion installation Detector (2003)	R&D	CDR (1999)
2005	Nominal Sensitivity (2006)	Scientific data taking (2007)	First AdV sensitivity projection (2004 AdV White Paper, CDR (2	R&D Funding (2006) Building (2008)
2010		Decommissioning (2	Approval (2009) First orders (2010) TDR (2012)	
2015			Completion Installation (201 First data taking (2017)	Installing completion (2014) Data taking (2015)

M. Punturo at LVC Aug 28 2017
Toward a 3G GW network

PLEASE HELP US !