Gravitational-wave astronomy

Matteo Barsuglia
(AstroParticule et Cosmologie, CNRS/Université Paris Cité)

With contributions and credits from many LIGO-Virgo-KAGRA colleagues

Scope and outline of the lectures

- The *big picture*
- Some historical elements
- Gravitational-wave detector basic structure
- Experimental techniques, challenges, and opportunities
- Detector noise sources and related physics
- Some of the astrophysical results of the LIGO-Virgo-KAGRA network
- The future of GW astronomy

The big picture

Gravitational-waves (GW) in GR

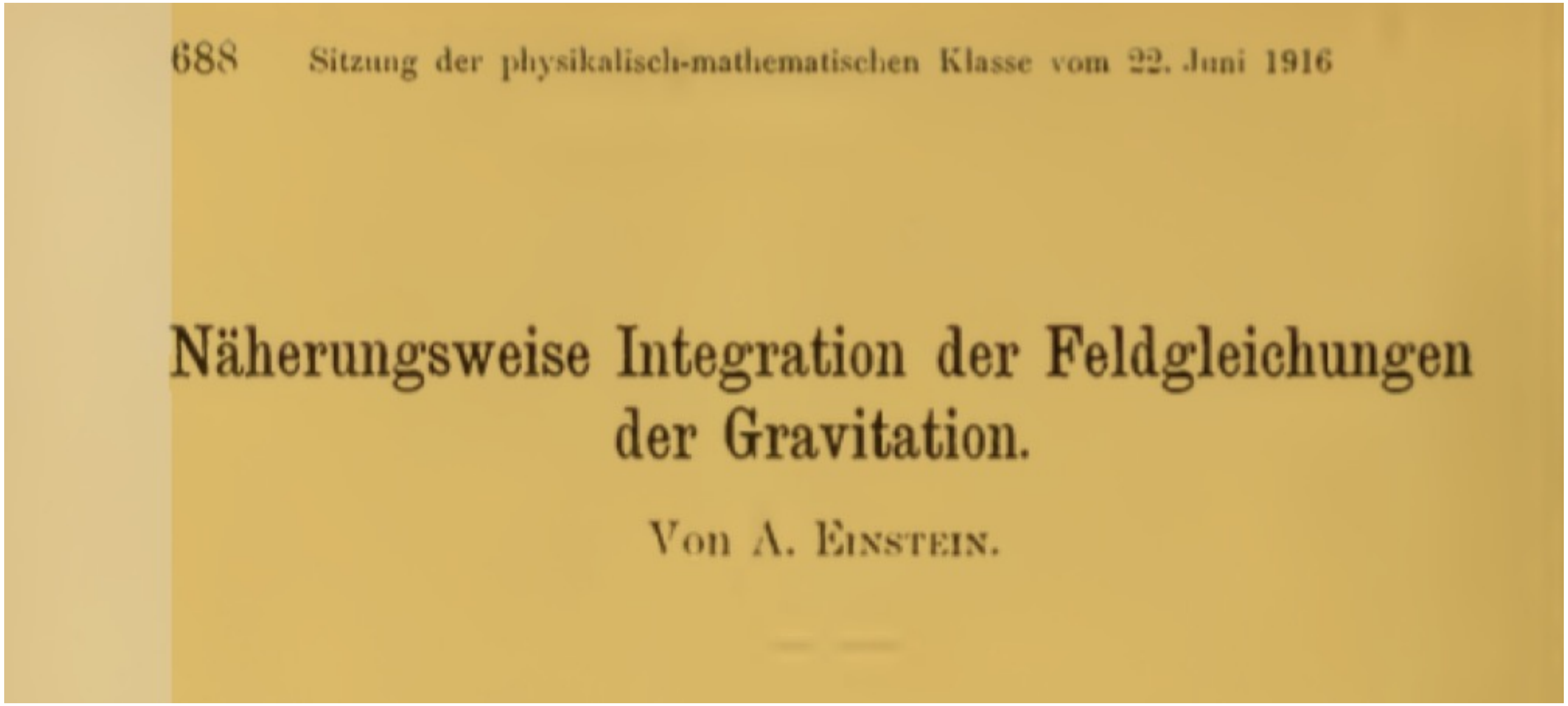
- Consequence of general relativity
- Oscillatory small perturbation of the metric
- Speed of light
- 2 transverse polarizations
- Produced by acceleration of the mass quadrupole moment

$$h_{ij}(t) = \frac{2}{r}\frac{G}{c^4}\ddot{Q}_{ij}(t - r/c) \qquad \mathcal{L} = \epsilon \frac{c^5}{G}\left(\frac{R_S}{R}\right)^2 \left(\frac{v}{c}\right)^6$$

$h \sim 10^{-21}$

Einstein 1916

"Approximative integration of the field equation of gravitation"

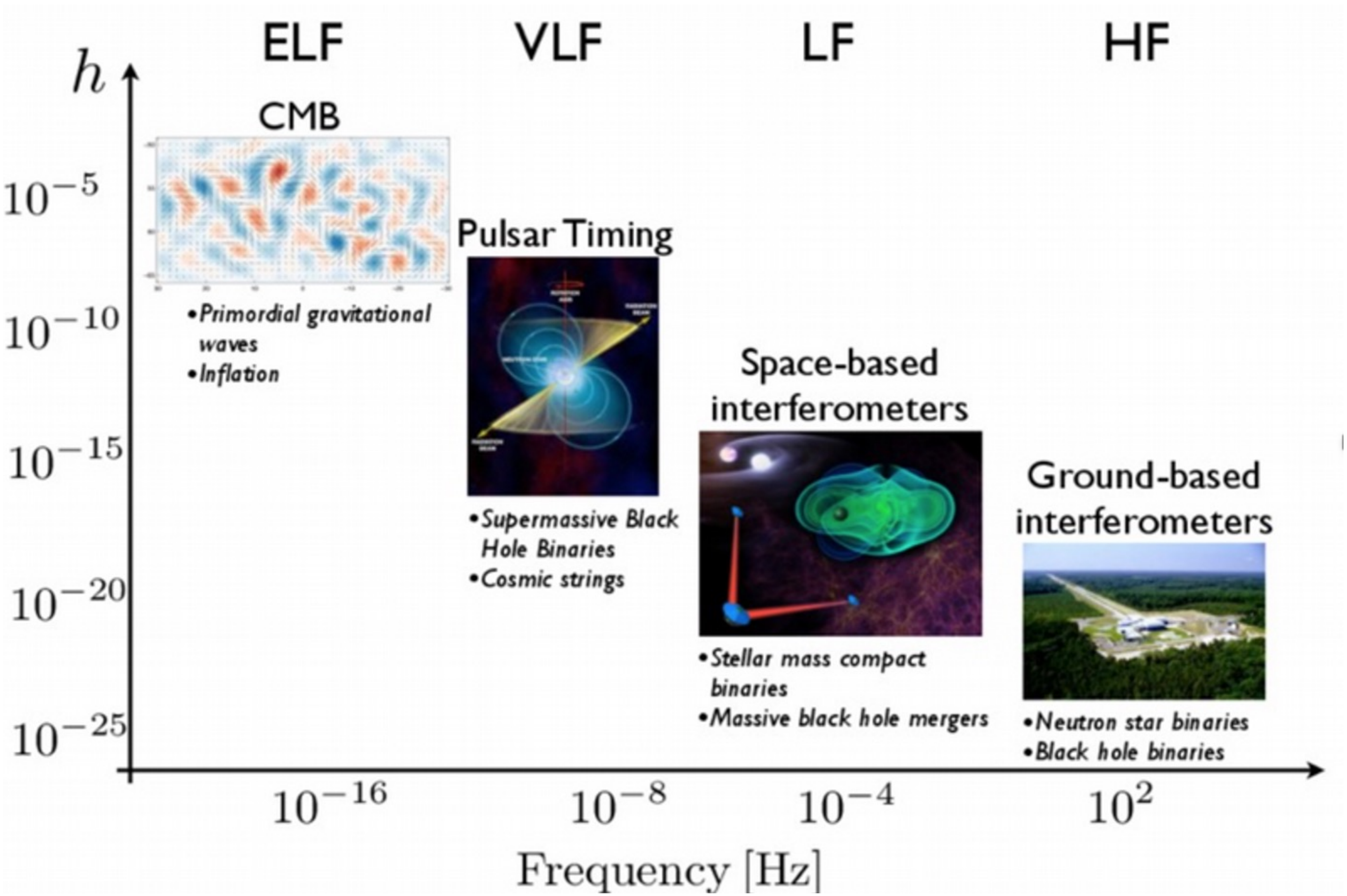


688 Sitzung der physikalisch-mathematischen Klasse vom 22. Juni 1916

Näherungsweise Integration der Feldgleichungen der Gravitation.

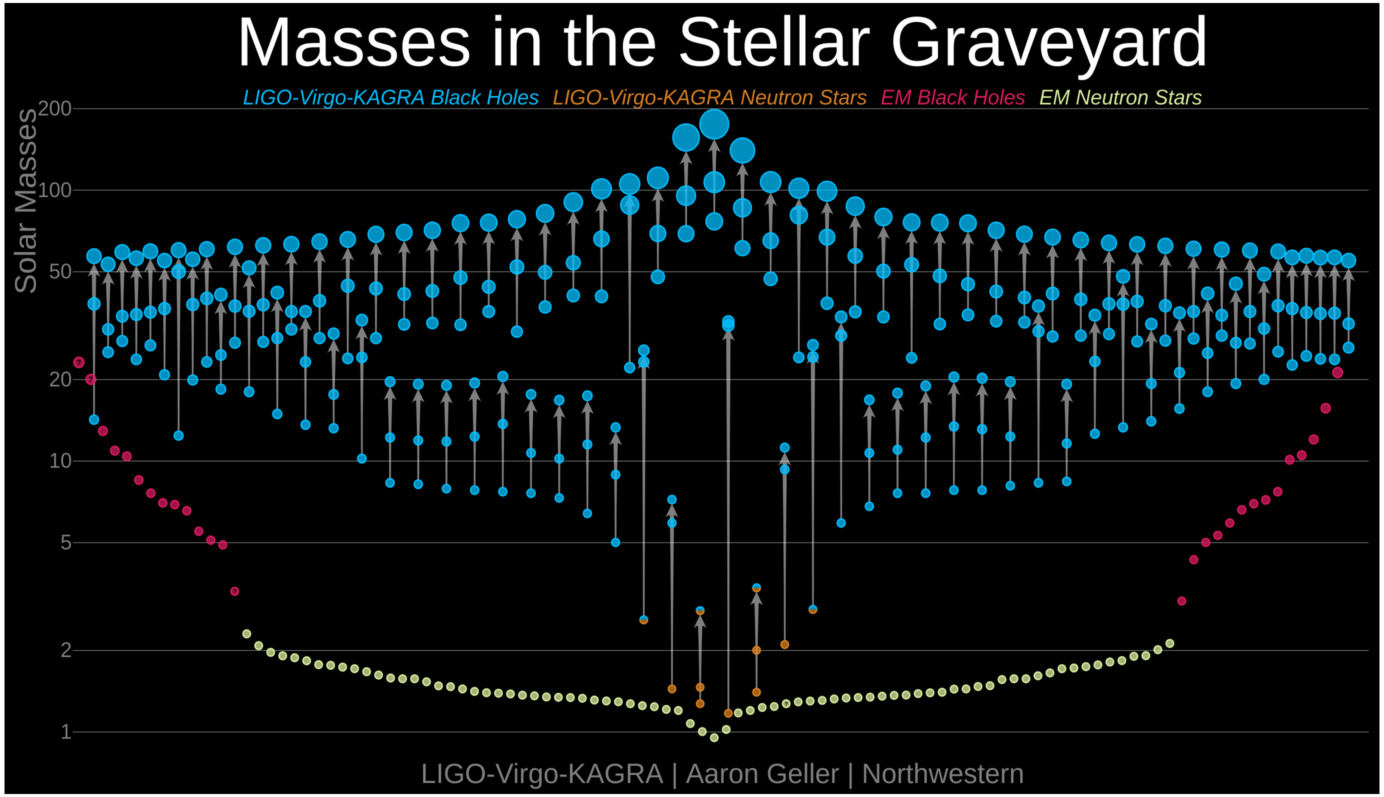
Von A. Einstein.

Detectors/projects and science goals



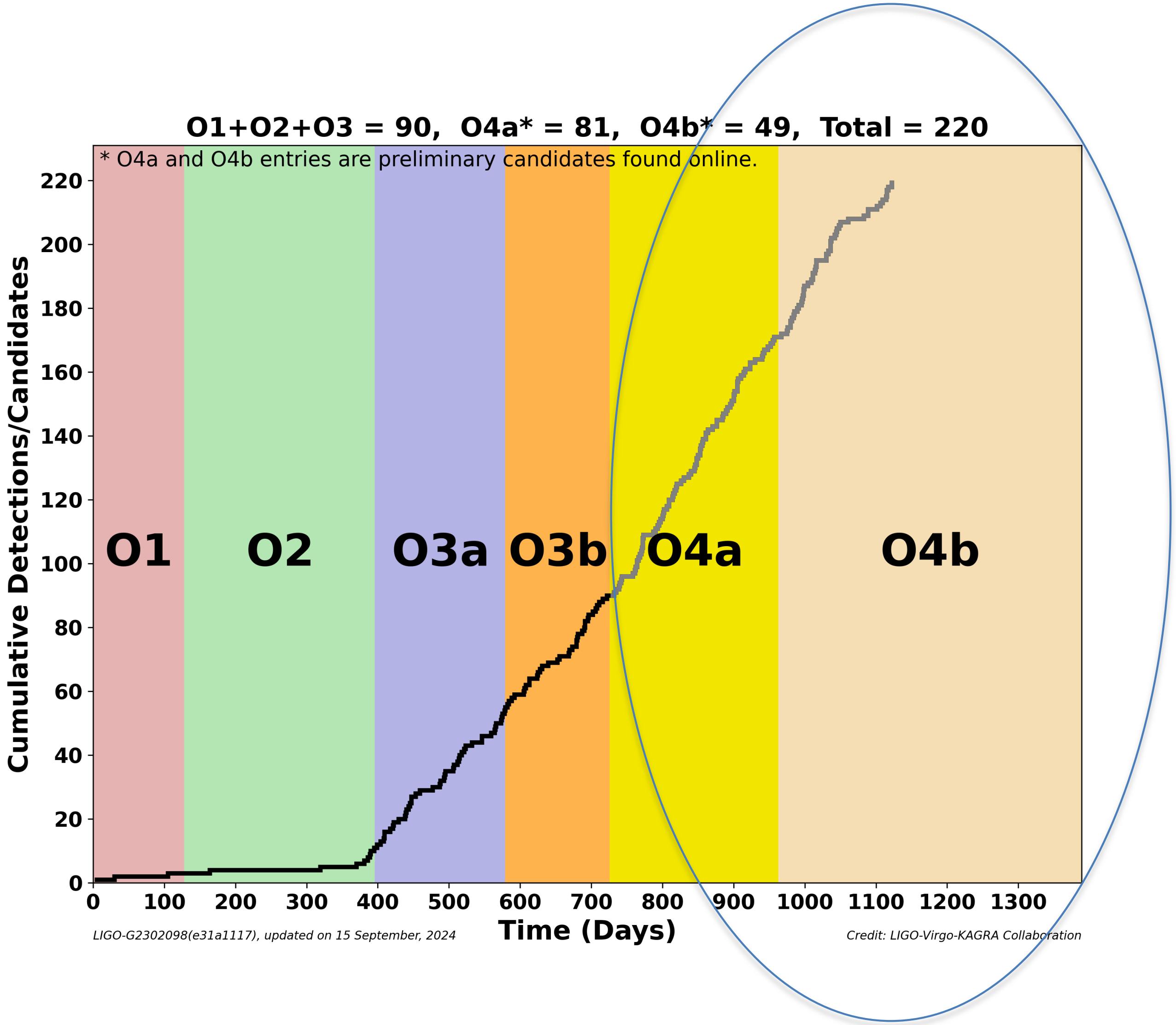
Gravitational-wave observatory network

Detections so far by LIGO-Virgo-KAGRA



GWTC-3: Compact Binary Coalescences Observed by LIGO and Virgo During the Second Part of the Third Observing Run; LIGO-Virgo-KAGRA collaborations, https://arxiv.org/abs/2111.03606

Detections and online candidates so far by LIGO-Virgo-KAGRA

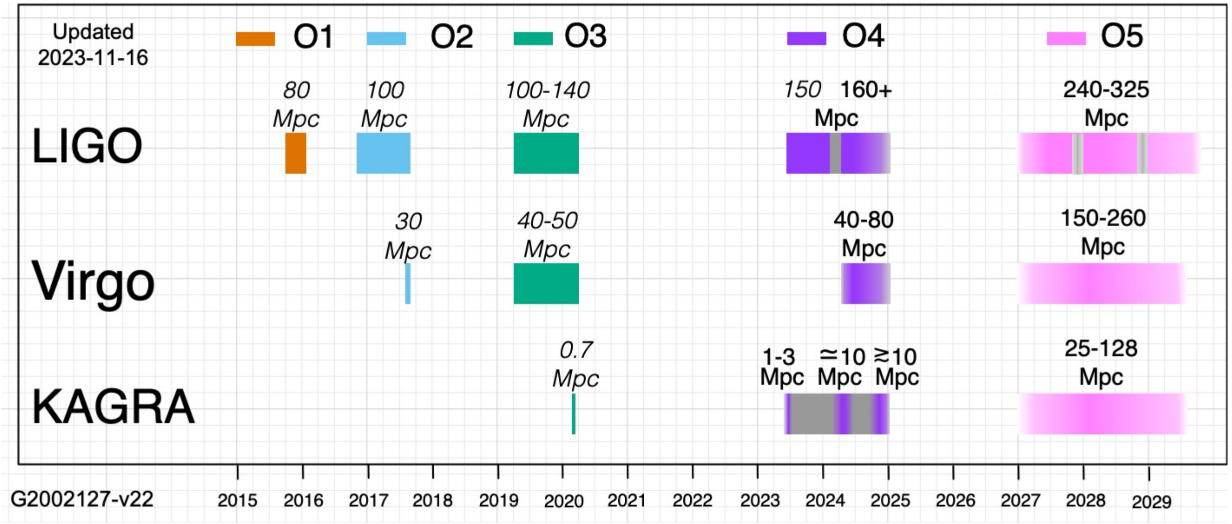


Online candidates

Ground based GW detectors: possible roadmap

Current infrastructures

New infrastructures

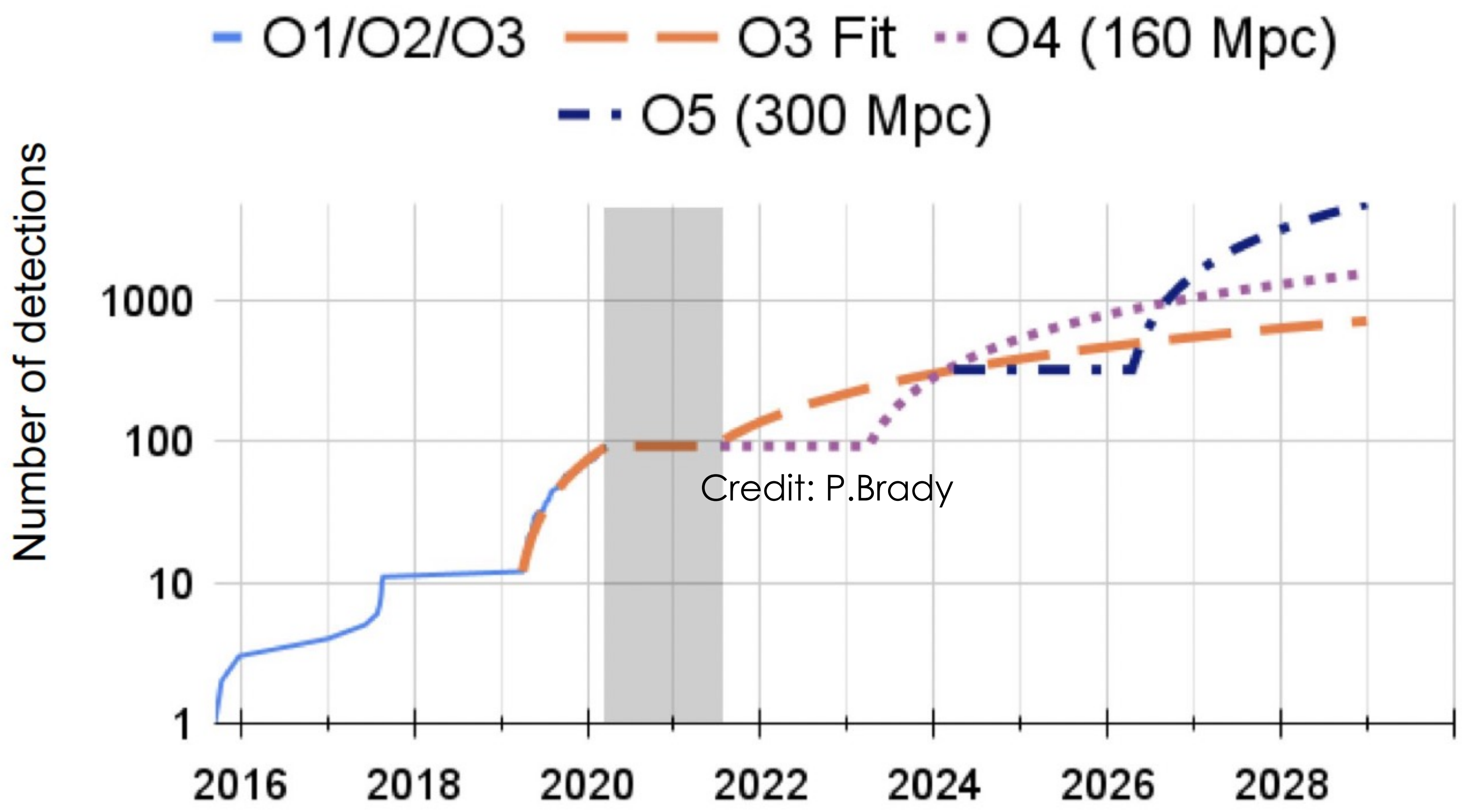


- A#
- Virgo_nEXT

Decade 2030

- Cosmic Explorer
- EinsteinTelescope

Alternate observing periods with upgrades

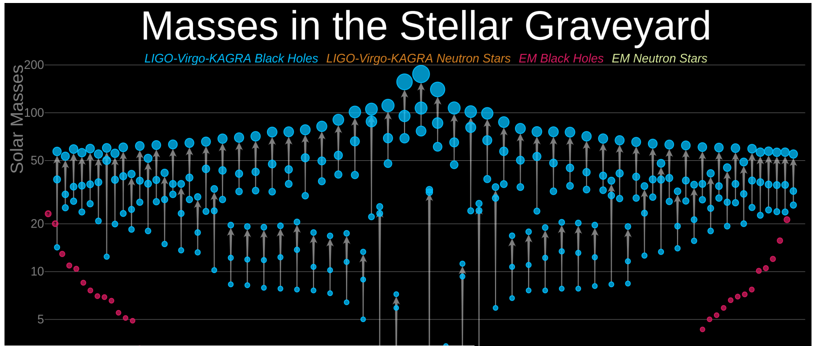


Credit: P.Brady

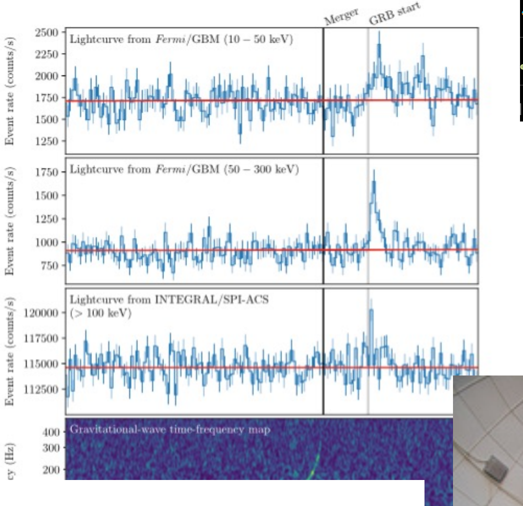
Credit:P.Brady

Why GW with (ground-based) detectors science?

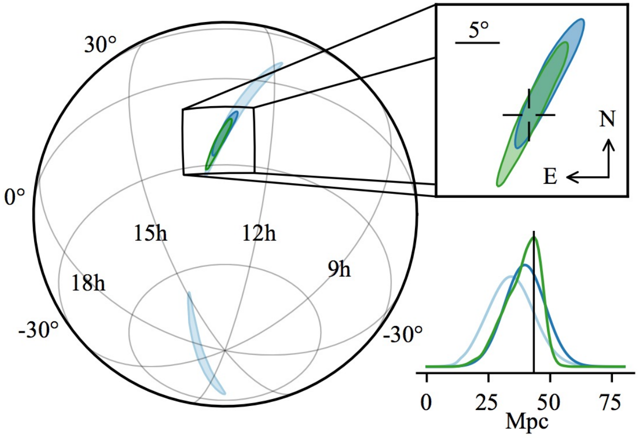
New objects, new populations

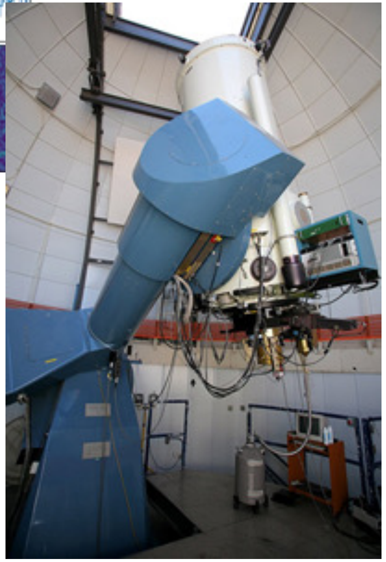


Same objects observed in a new way



Alerts for electromagnetic observatories





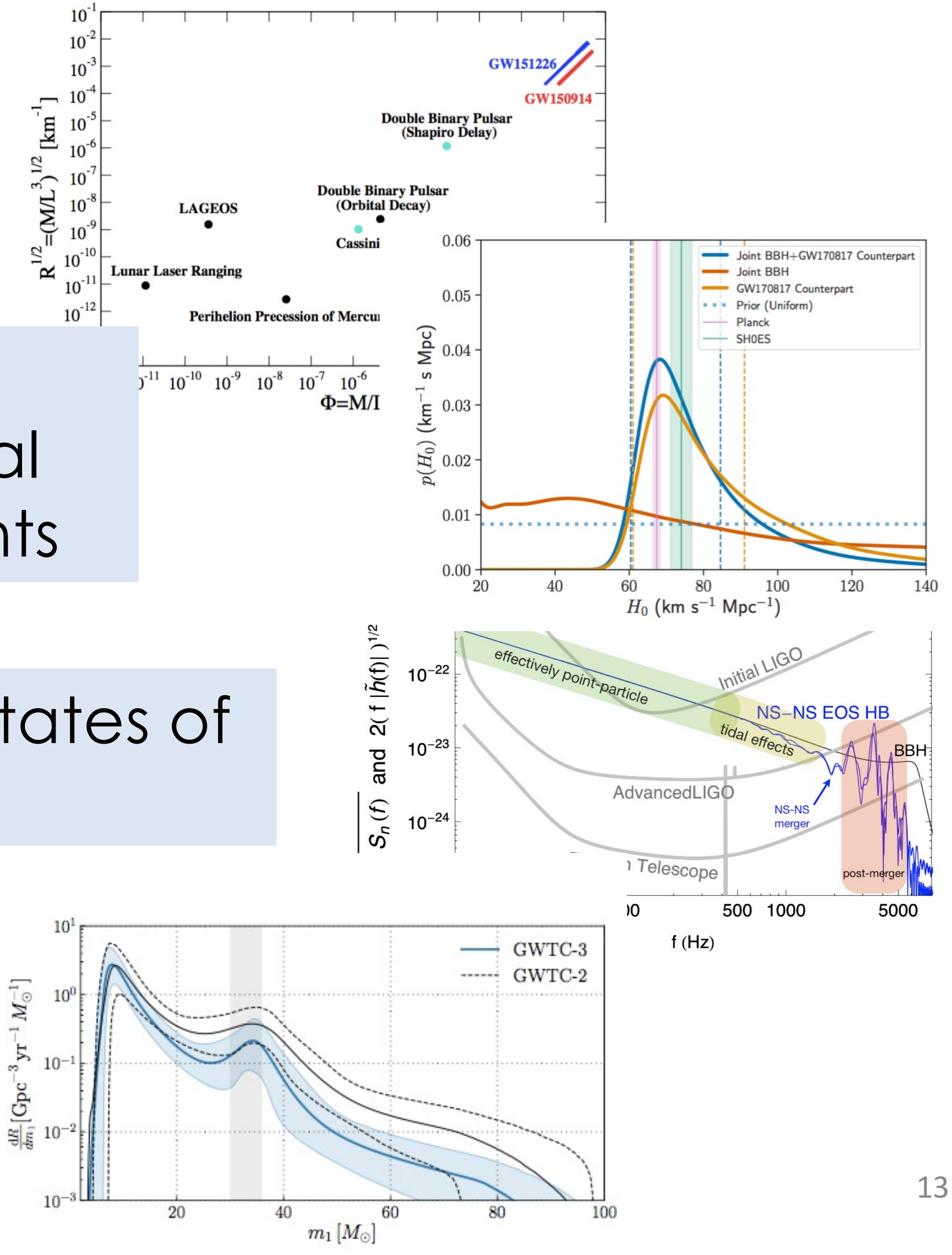
Why GW with (ground-based) detectors science?

New tests of gravity

New cosmological measurements

Study of extreme states of matter

Populations of compact objects

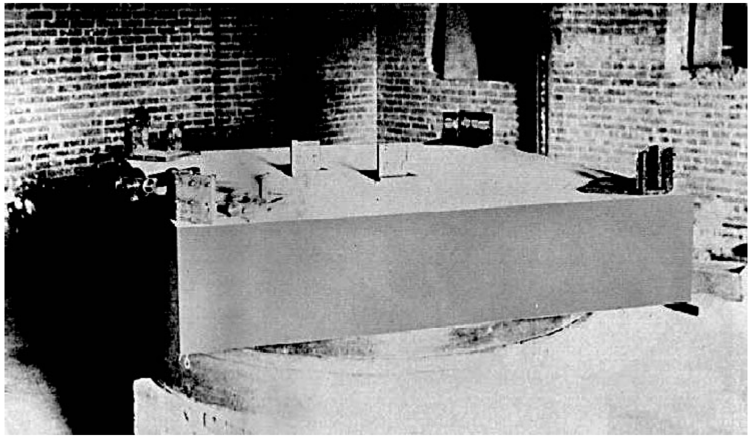


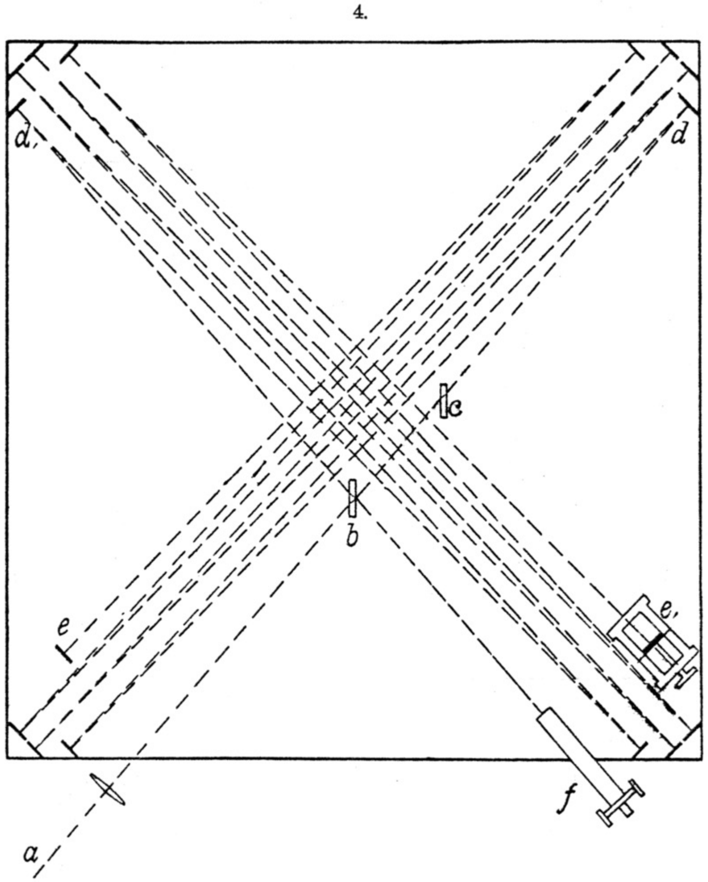
Some history

Weber’s bars

- Sensitive around the resonance frequency
- ~ 1 kHz
- Limitation: size of the bar, and narrow-band detector
- Max sensitivity: $h \sim 10^{-19}$

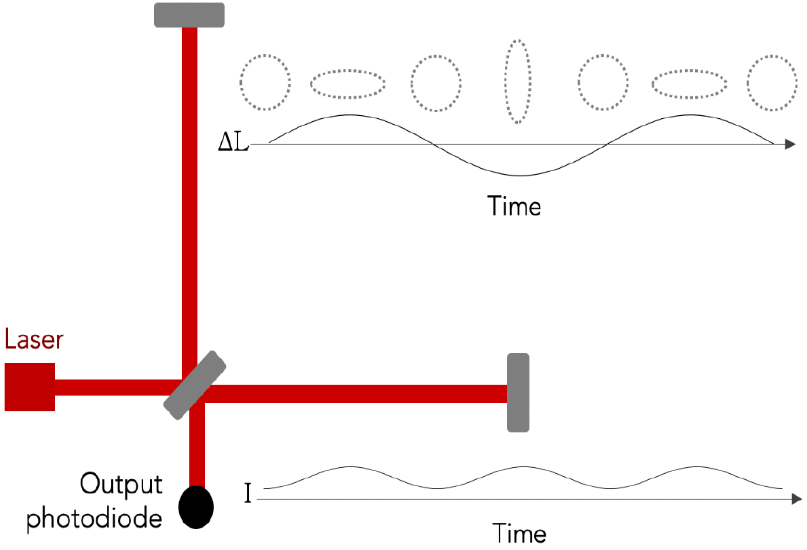
Michelson and Morley experiment (1887)





Already some concepts of the modern GW interferometric detectors: multiple beams and seismic isolation

Interferometric detectors: the early years



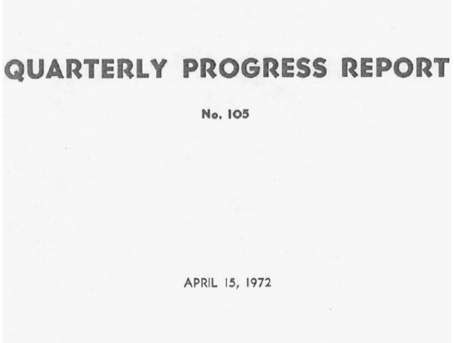
- Concept/ideas: Gertsenshtein and V. I. Pustovoit (1962), Pirani (1962)

- Unpublished work by Weber and Forward (Weber's student), foreground for Forward experiment in Malibù

- First prototype: E. Moss, L. R. Miller, and R. L. Forward (1971) ~ 10^{-14} m$\text{Hz}^{-1/2}$

- R. Weiss (1972) – realistic study of the noises

Weiss: Quarterly progress report



QUARTERLY PROGRESS REPORT

No. 105

APRIL 15, 1972

'S INSTITUTE OF TECHNOLOGY
ABORATORY OF ELECTRONICS
IDGE, MASSACHUSETTS 02139

LIGO-P720002-00-R

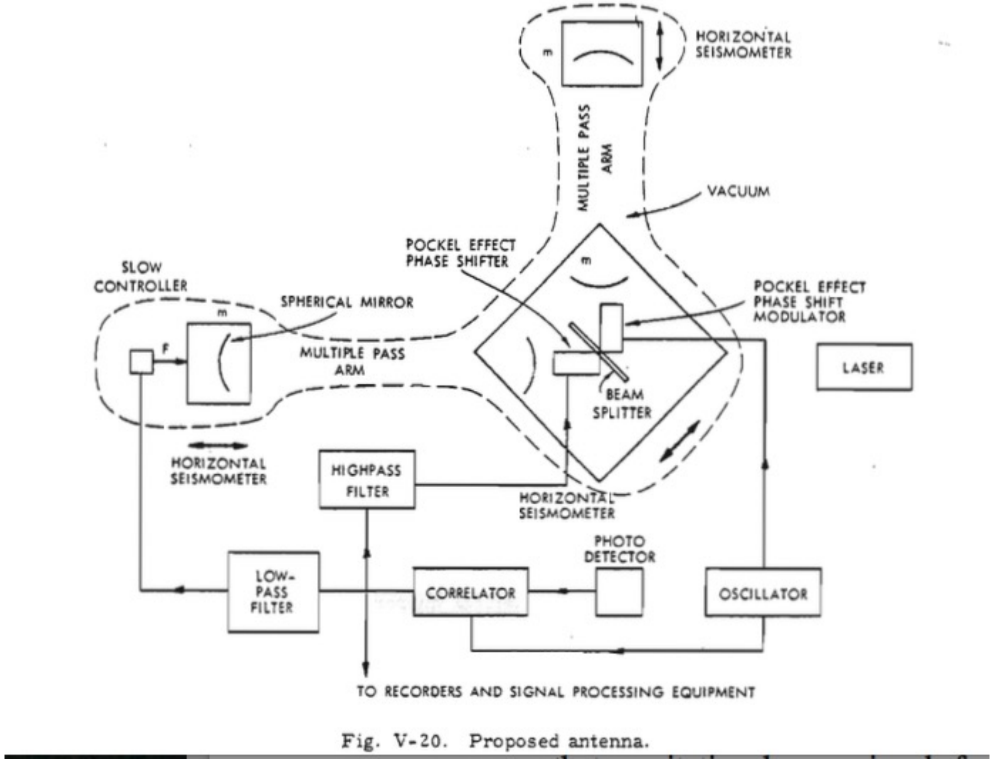


Fig. V-20. Proposed antenna.

http://www.sciencemag.org/news/2016/08/meet-college-dropout-who-invented-gravitational-wave-detector

https://dcc.ligo.org/LIGO-P720002/public

Virgo

Adalberto Giazotto (INFN)

Alain Brillet (CNRS)

Some of the Conditions to build Virgo and LIGO

Theoretical developments (GW are real, waveforms, estimation of the amplitudes)

Technology: lasers (~ 1960), control systems (>1945)

Discovery of black-holes and neutron stars (~ 1970)

Hulse and Taylor binary pulsar (GW exist)

Motivated community
To detect $h=10^{-21}$

Kilometric detectors (~ 2000)

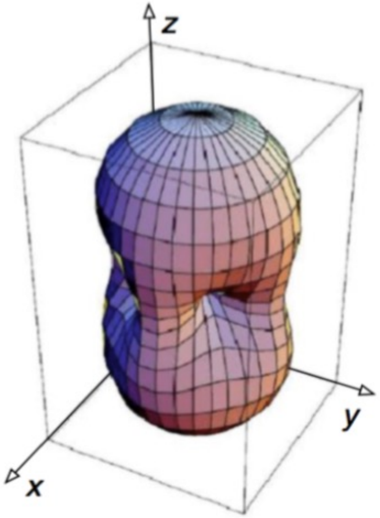
+ TAMA (300 m) in Japan

The LIGO-Virgo network (~ 2007)

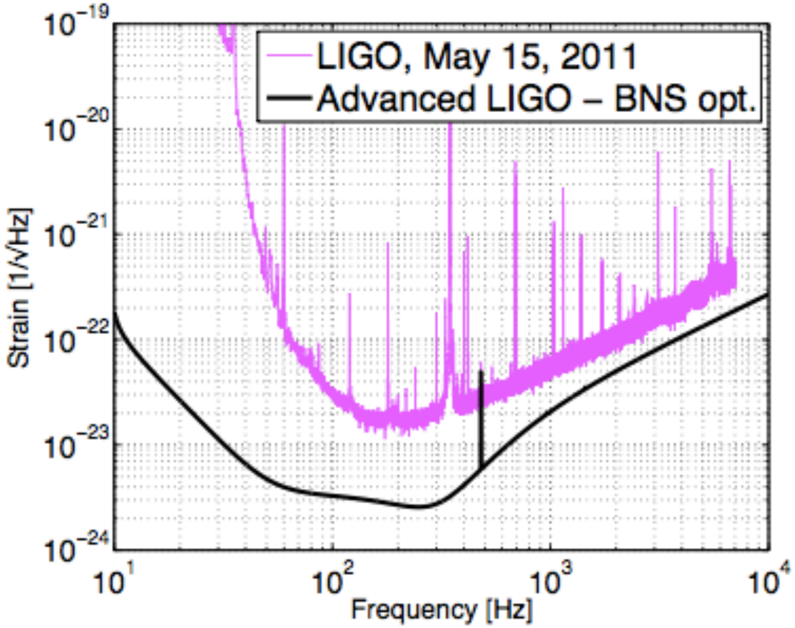
Agreement : data exchange, common publication of results

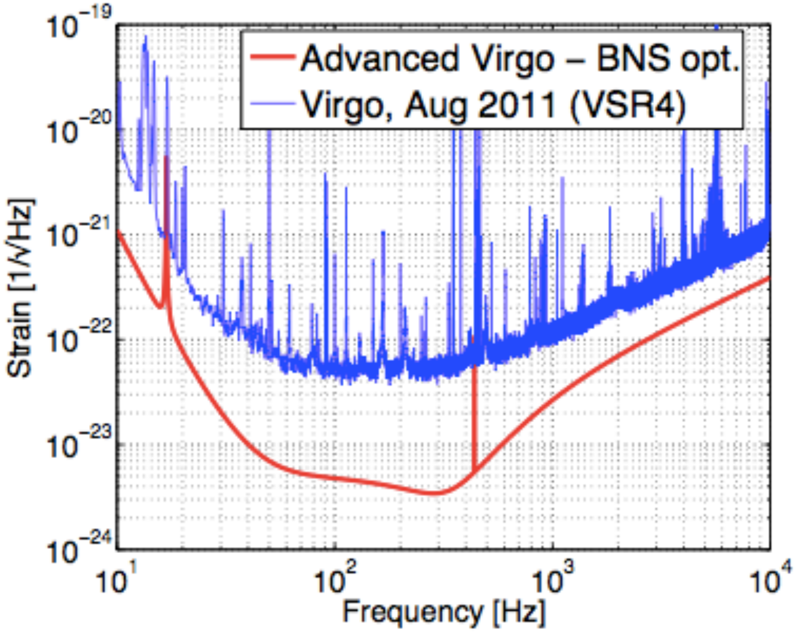
Benefits:

- Confidence in detection
- Sky coverage
- Duty cycle
- Sky position localization



Advanced detectors

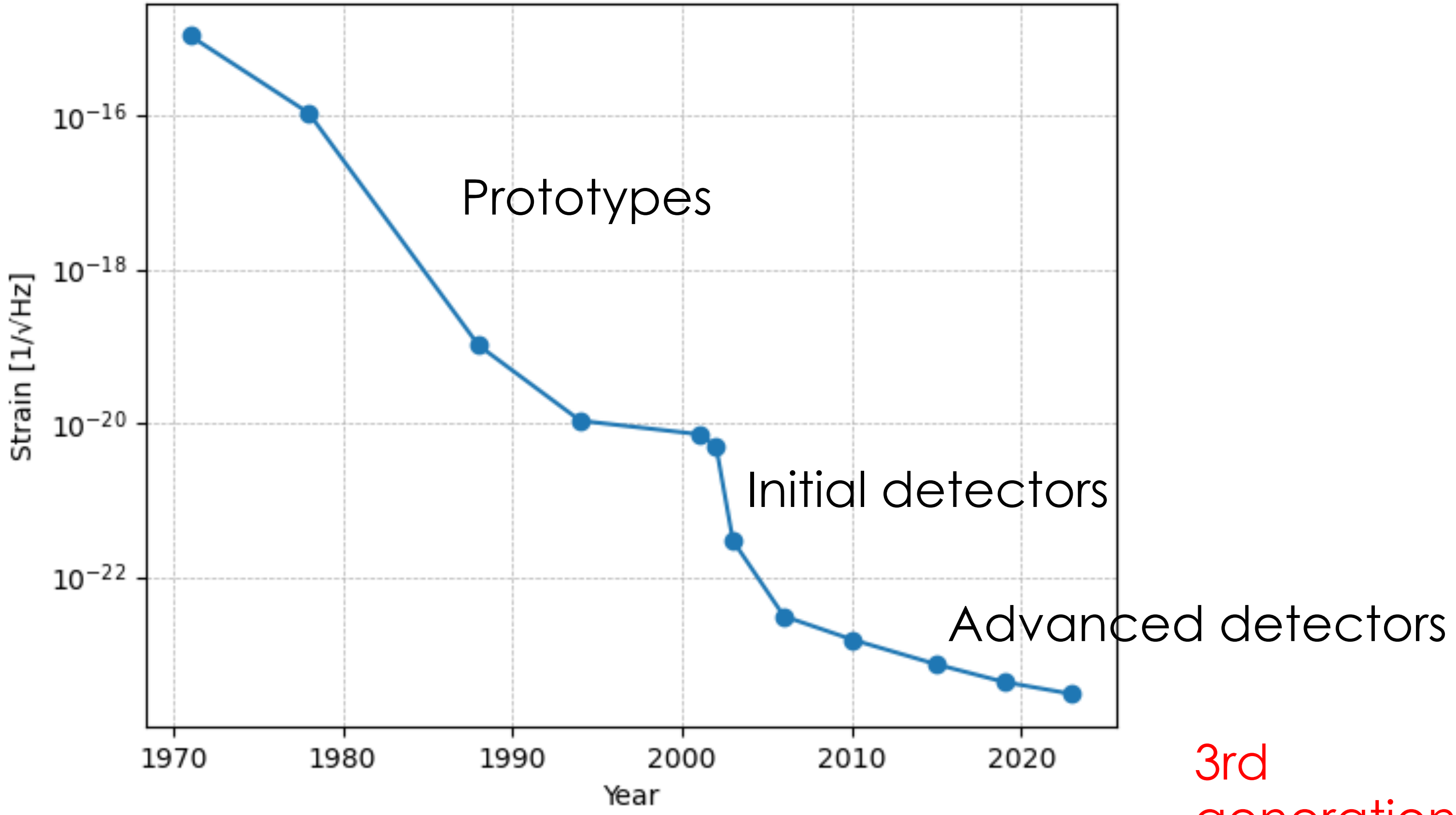

Advanced LIGO


Advanced Virgo

X 10 sensitivity increase → x1000 rate increase

1 day of AdVirgo/aLIGO = 3 years of Virgo/LIGO

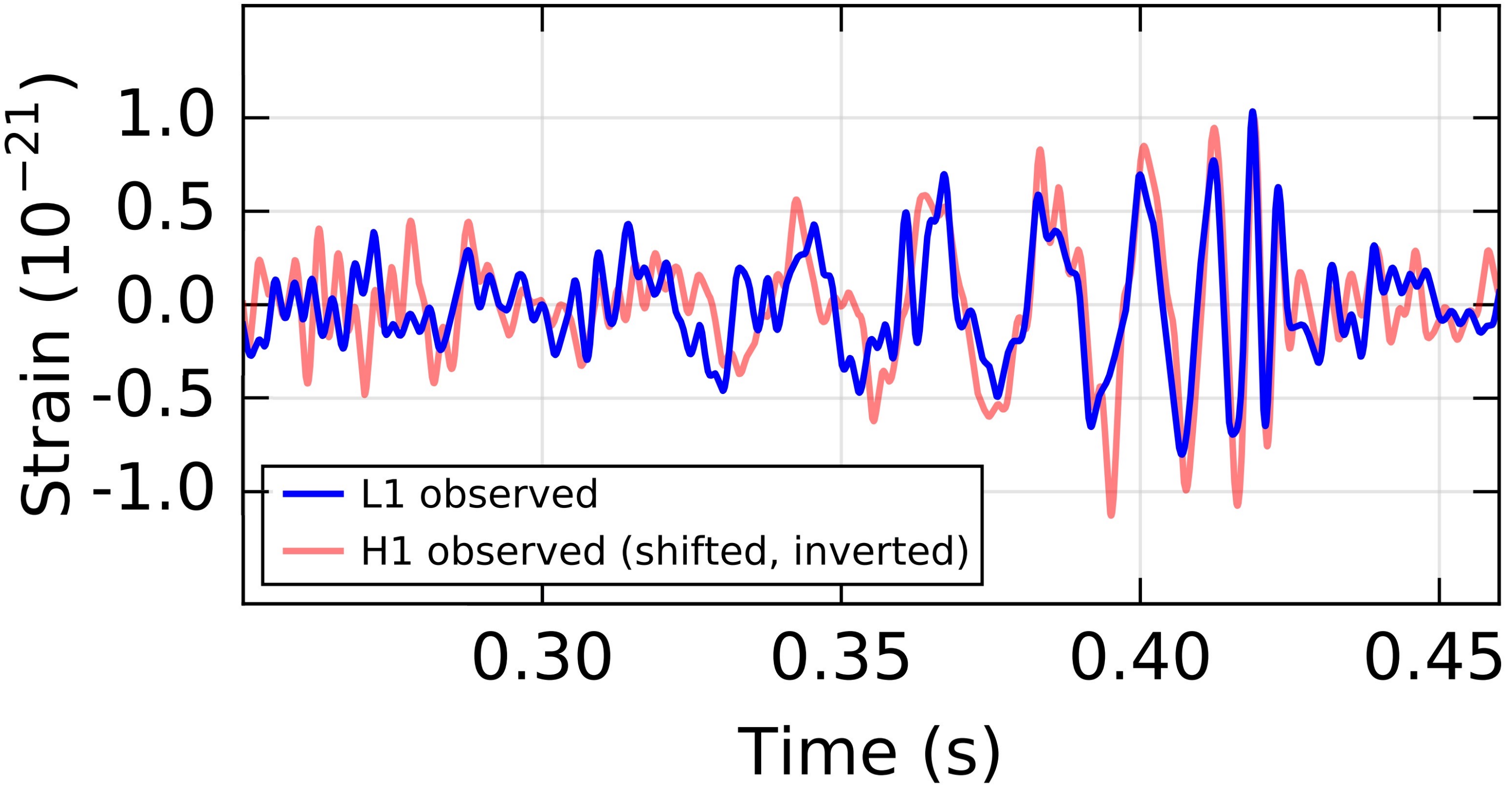
Interferometer progress in the last 40 years

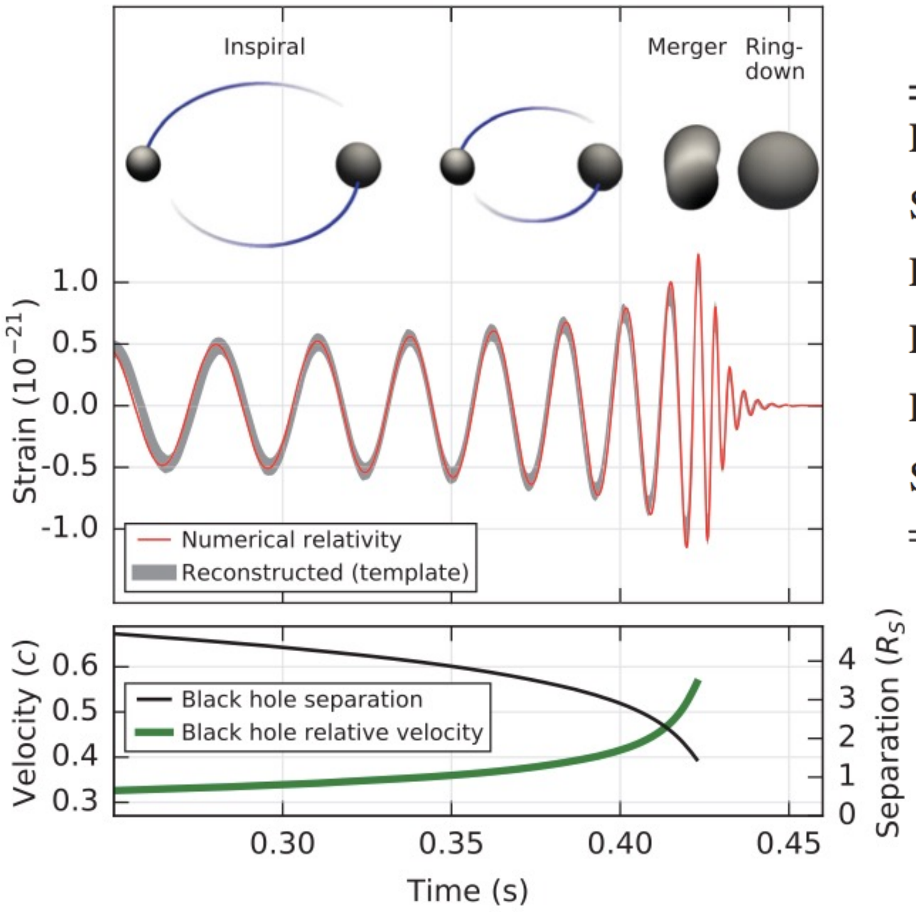


3rd
generation
detectors

Figure modified by E.Capocasa from R.Adhikari, Gravitational Radiation Detection with Laser Interferometry, arXiv:1305.5188, 2013 credit:LIGO

14 September 2015: GW150914

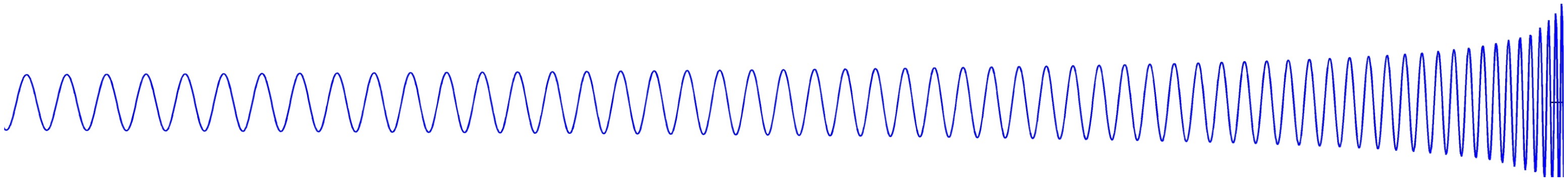


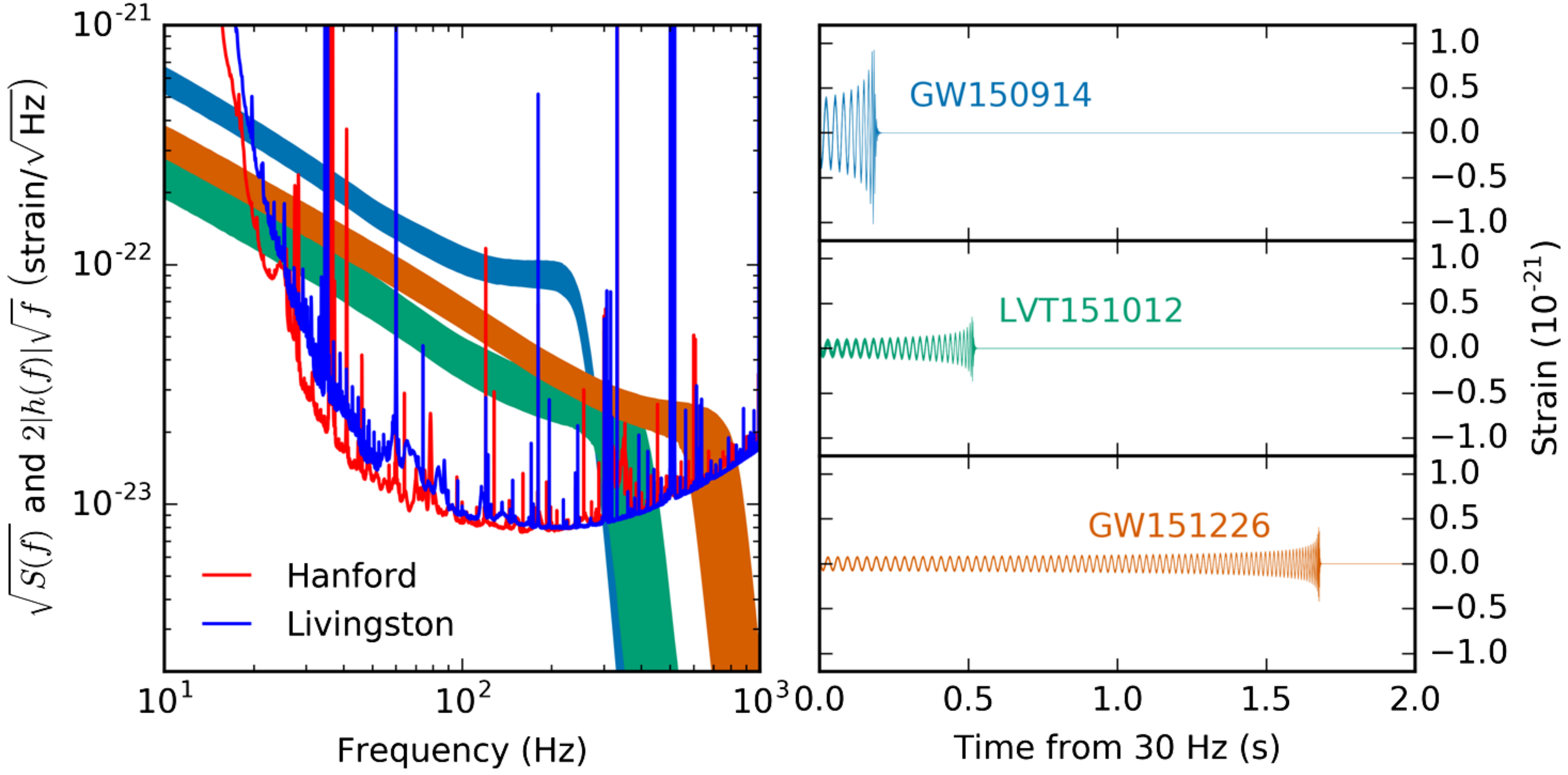


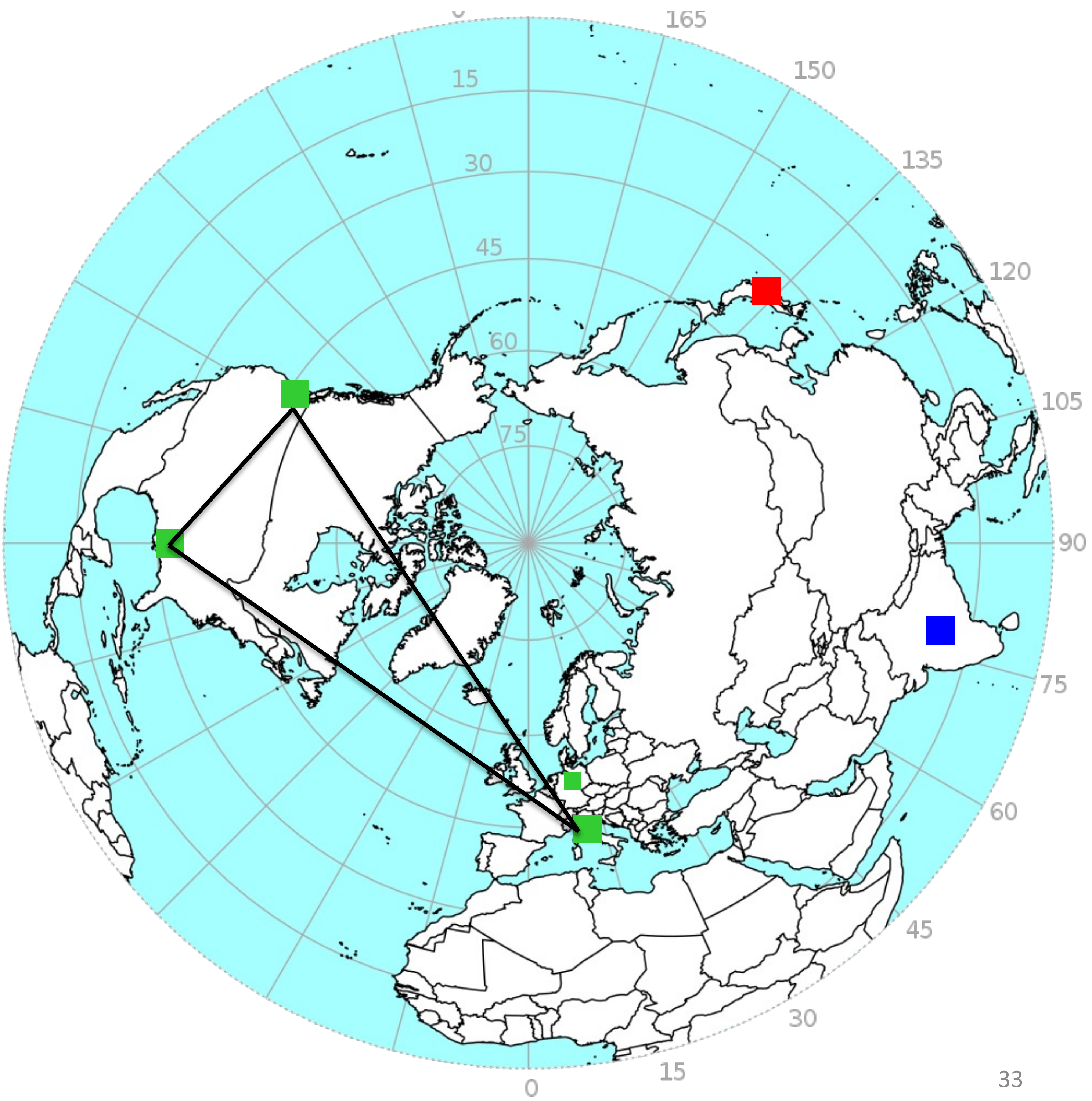
Primary black hole mass	$36^{+5}_{-4} M_\odot$
Secondary black hole mass	$29^{+4}_{-4} M_\odot$
Final black hole mass	$62^{+4}_{-4} M_\odot$
Final black hole spin	$0.67^{+0.05}_{-0.07}$
Luminosity distance	410^{+160}_{-180} Mpc
Source redshift z	$0.09^{+0.03}_{-0.04}$

Energy in GW	$3.0^{+0.5}_{-0.5} M_\odot c^2$
Luminosity	$3.6^{+0.5}_{-0.4} \times 10^{56}$ erg/s

BNS Inspiral vs detector sensitivity





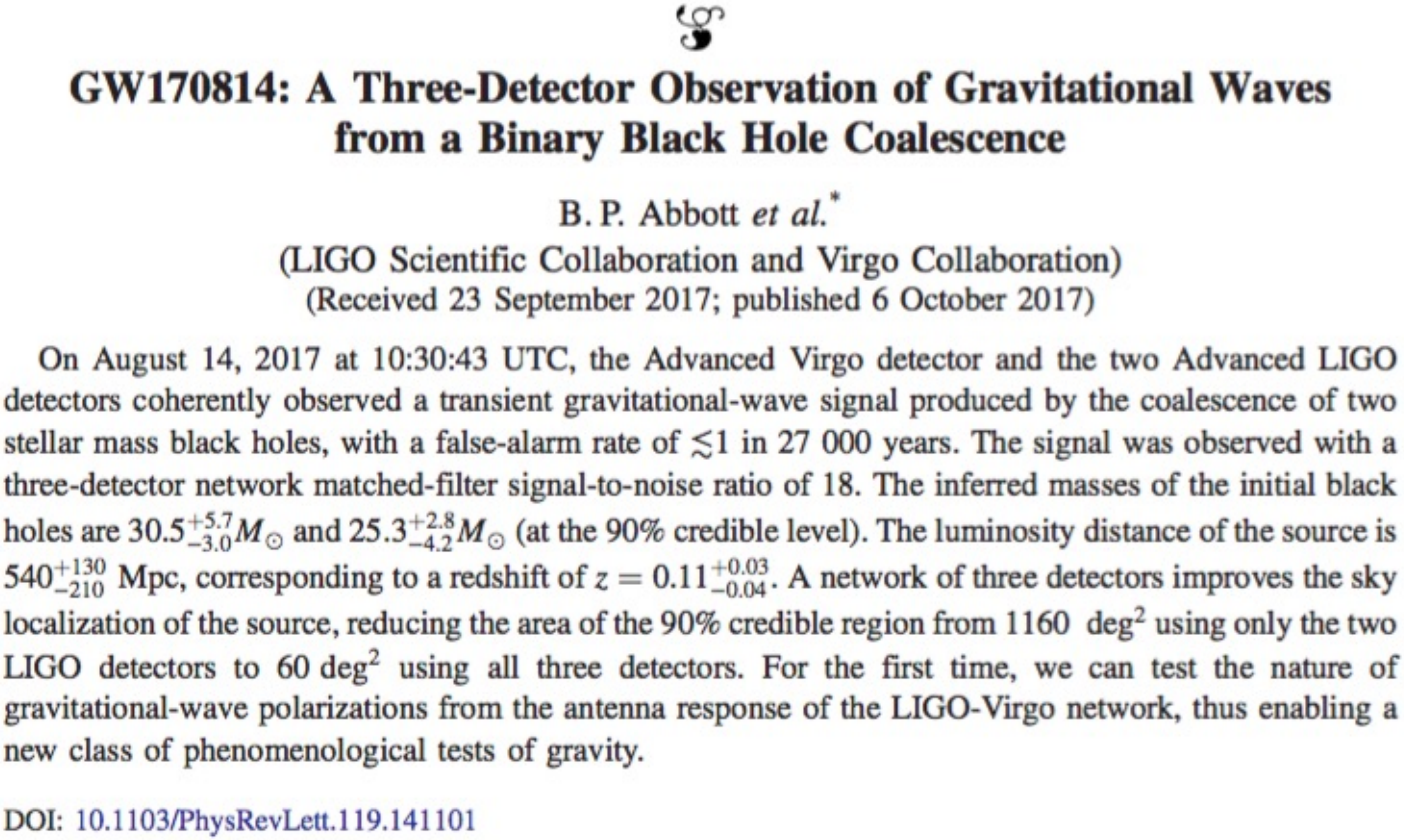


🟩 OPERATION

🟧 COMMISSIONING

🟥 CONSTRUCTION

🟦 APPROVED



GW170814: A Three-Detector Observation of Gravitational Waves from a Binary Black Hole Coalescence

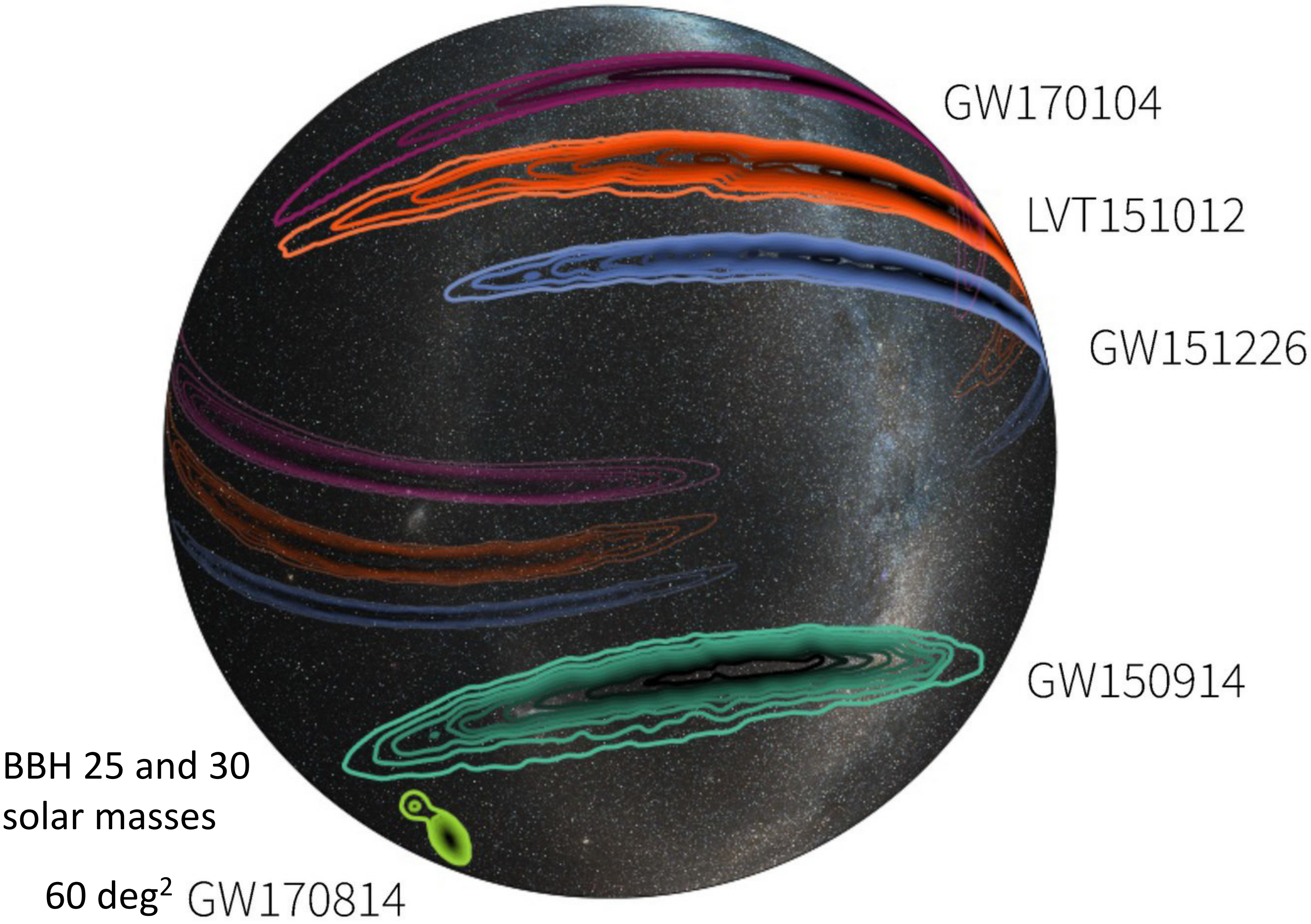
B. P. Abbott *et al.*[*]
(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 23 September 2017; published 6 October 2017)

On August 14, 2017 at 10:30:43 UTC, the Advanced Virgo detector and the two Advanced LIGO detectors coherently observed a transient gravitational-wave signal produced by the coalescence of two stellar mass black holes, with a false-alarm rate of $\lesssim 1$ in 27 000 years. The signal was observed with a three-detector network matched-filter signal-to-noise ratio of 18. The inferred masses of the initial black holes are $30.5^{+5.7}_{-3.0} M_{\odot}$ and $25.3^{+2.8}_{-4.2} M_{\odot}$ (at the 90% credible level). The luminosity distance of the source is 540^{+130}_{-210} Mpc, corresponding to a redshift of $z = 0.11^{+0.03}_{-0.04}$. A network of three detectors improves the sky localization of the source, reducing the area of the 90% credible region from 1160 deg^2 using only the two LIGO detectors to 60 deg^2 using all three detectors. For the first time, we can test the nature of gravitational-wave polarizations from the antenna response of the LIGO-Virgo network, thus enabling a new class of phenomenological tests of gravity.

DOI: 10.1103/PhysRevLett.119.141101

Triple detection – 14 August 2017



PRL **119,** 161101 (2017)

Selected for a Viewpoint in *Physics*
PHYSICAL REVIEW LETTERS

week ending
20 OCTOBER 2017

GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral

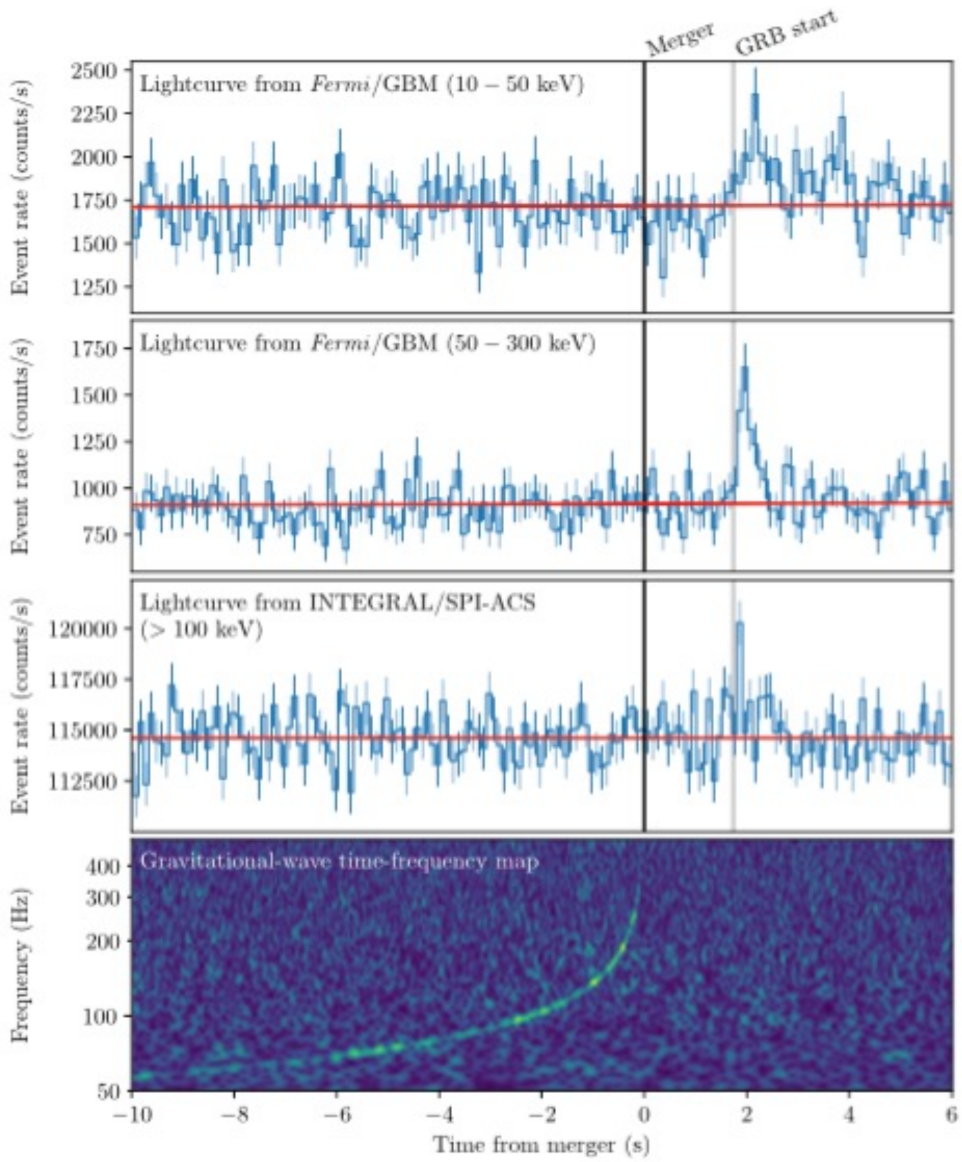
B. P. Abbott *et al.*[*]
(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 26 September 2017; revised manuscript received 2 October 2017; published 16 October 2017)

On August 17, 2017 at 12:41:04 UTC the Advanced LIGO and Advanced Virgo gravitational-wave detectors made their first observation of a binary neutron star inspiral. The signal, GW170817, was detected with a combined signal-to-noise ratio of 32.4 and a false-alarm-rate estimate of less than one per 8.0×10^4 years. We infer the component masses of the binary to be between 0.86 and 2.26 $M_\odot$, in agreement with masses of known neutron stars. Restricting the component spins to the range inferred in binary neutron stars, we find the component masses to be in the range 1.17–1.60 $M_\odot$, with the total mass of the system $2.74^{+0.04}_{-0.01} M_\odot$. The source was localized within a sky region of 28 deg^2 (90% probability) and had a luminosity distance of 40^{+8}_{-14} Mpc, the closest and most precisely localized gravitational-wave signal yet. The association with the γ-ray burst GRB 170817A, detected by Fermi-GBM 1.7 s after the coalescence, corroborates the hypothesis of a neutron star merger and provides the first direct evidence of a link between these mergers and short γ-ray bursts. Subsequent identification of transient counterparts across the electromagnetic spectrum in the same location further supports the interpretation of this event as a neutron star merger. This unprecedented joint gravitational and electromagnetic observation provides insight into astrophysics, dense matter, gravitation, and cosmology.

DOI: 10.1103/PhysRevLett.119.161101

GW170817: Binary neutron star merger

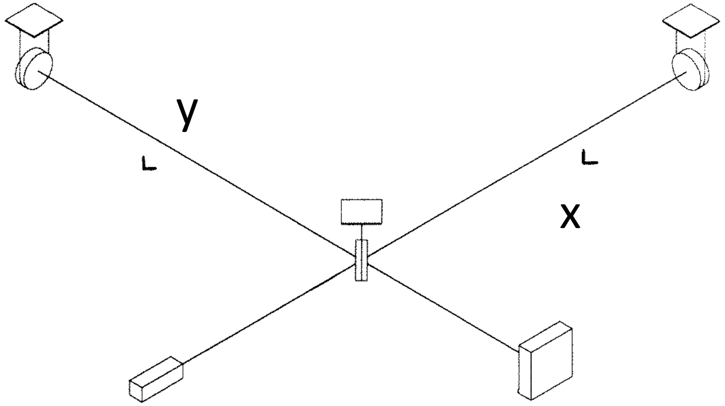


GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral, B.P.Abbott, Phys. Rev. Lett. 119, 161101 (2017)

The gravitational-wave detectors principle and optical scheme

Light detectors

$$
\begin{aligned}
ds^2 \quad = 0 \quad &= g_{\mu\nu} dx^\mu dx^\nu \\
&= (\eta_{\mu\nu} + h_{\mu\nu})\, dx^\mu dx^\nu \\
&= -c^2 dt^2 + (1 + h_{11}(2\pi f t - kz))\, dx^2.
\end{aligned}
$$



$$\int_0^{\tau_{out}} dt = \frac{1}{c}\int_0^L \sqrt{1 + h_{11}} dx \approx \frac{1}{c}\int_0^L \left(1 + \frac{1}{2} h_{11}\left(2\pi f t - kz\right)\right) dx,$$

$$\int_{\tau_{out}}^{\tau_{rt}} dt = -\frac{1}{c}\int_L^0 \left(1 + \frac{1}{2} h_{11}(2\pi f t - kz)\right) dx.$$

$$\tau_{rt} = \frac{2L}{c} + \frac{1}{2c}\int_0^L h_{11}(2\pi f t - kz)dx - \frac{1}{2c}\int_L^0 h_{11}(2\pi f t - kz)dx.$$

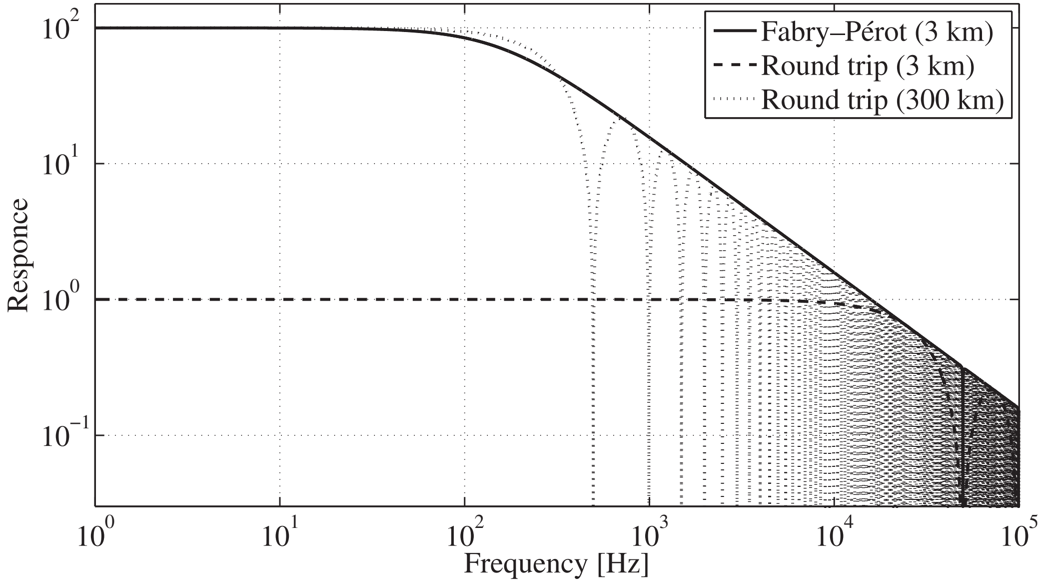
Light detectors

$$\tau_{rt} = \frac{2L}{c} + \frac{1}{2c}\int_0^L h_{11}(2\pi f t - kz)dx - \frac{1}{2c}\int_L^0 h_{11}(2\pi f t - kz)dx.$$

$$2\pi f_{gw}\tau_{rt} \ll 1.$$

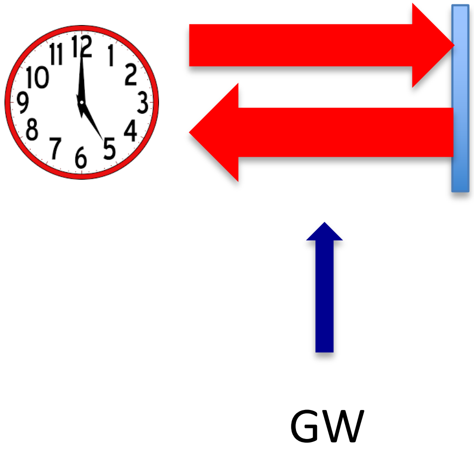
$$\Delta\tau(t) = h(t)\frac{2L}{c} = h(t)\tau_{rt0}$$

$$\Delta\phi(t) = h(t)\tau_{rt0}\frac{2\pi c}{\lambda}$$



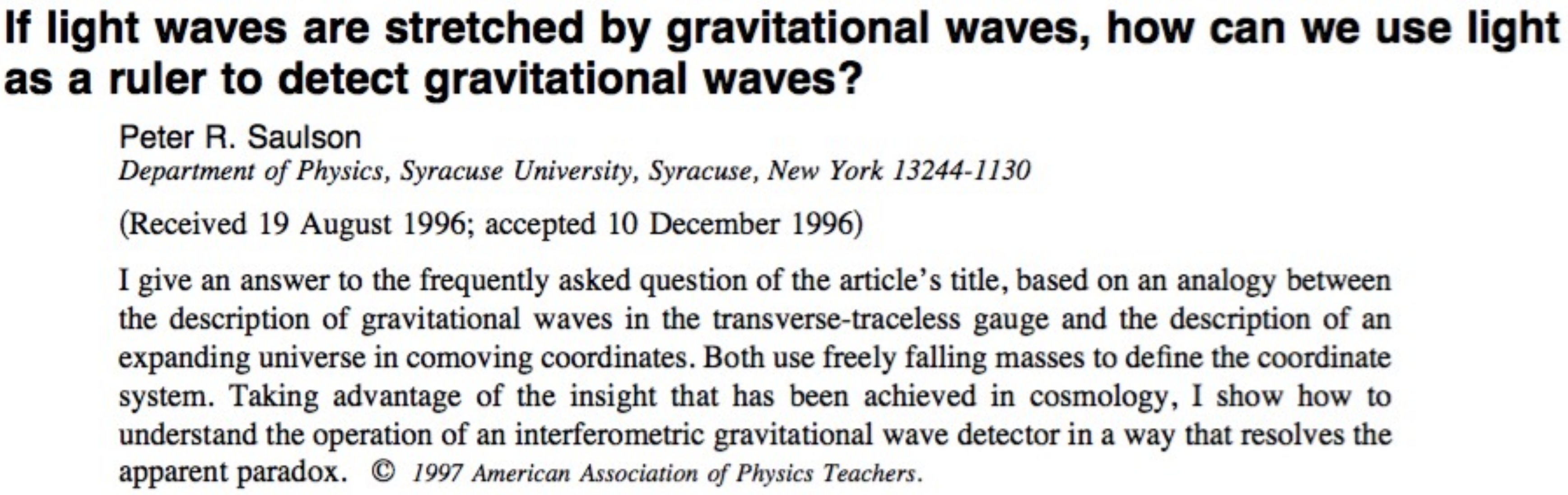
Response of a Michelson interferometer to a GW

- Why we don’t use only one arm?



The *rubber ruler puzzle*

- Question: if a GW stretches space, doesn't it also stretch the light traveling in that space? If the « ruler » is stretched by the same amount, how can we use this ruler?



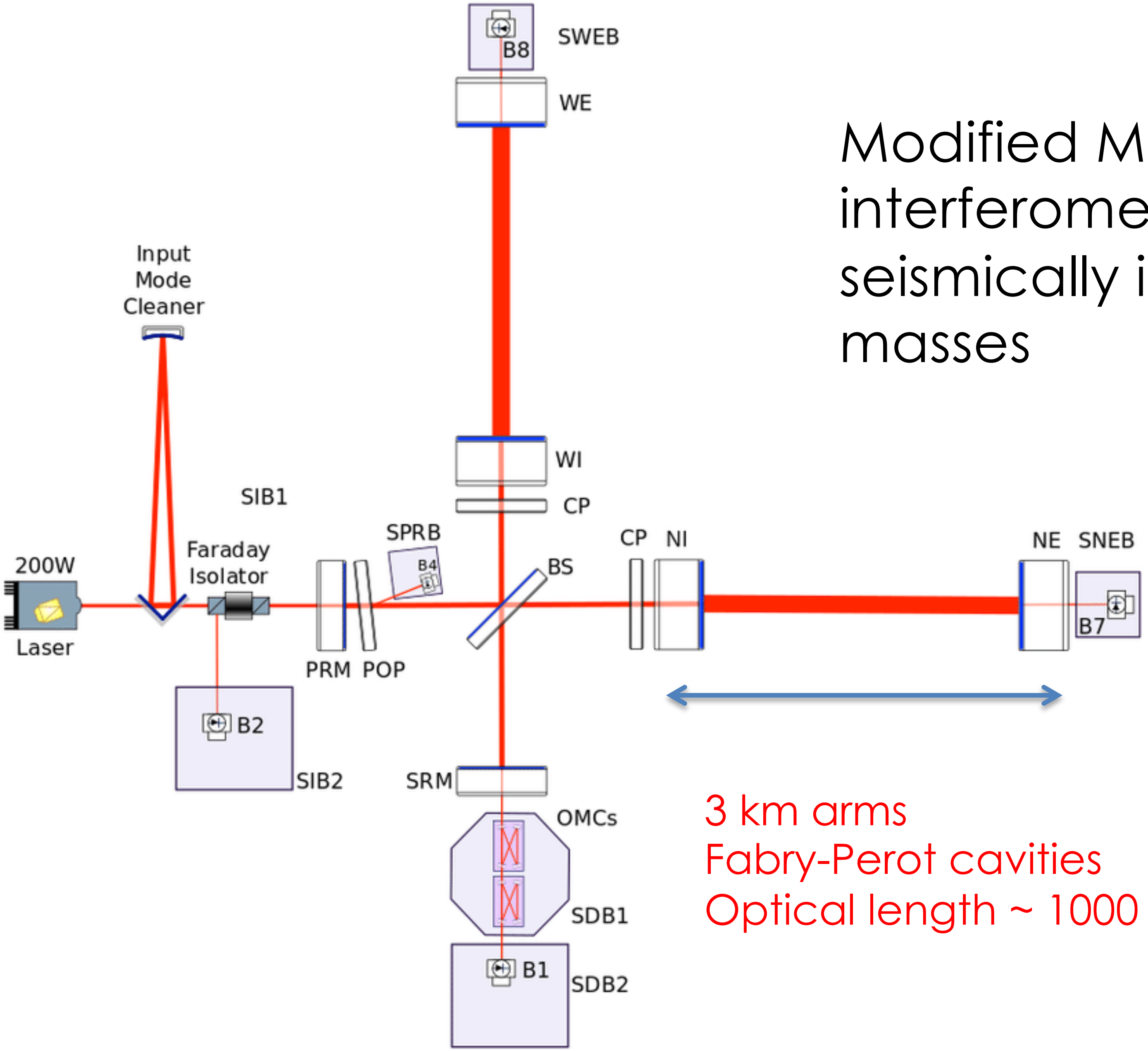
If light waves are stretched by gravitational waves, how can we use light as a ruler to detect gravitational waves?

Peter R. Saulson
Department of Physics, Syracuse University, Syracuse, New York 13244-1130

(Received 19 August 1996; accepted 10 December 1996)

I give an answer to the frequently asked question of the article's title, based on an analogy between the description of gravitational waves in the transverse-traceless gauge and the description of an expanding universe in comoving coordinates. Both use freely falling masses to define the coordinate system. Taking advantage of the insight that has been achieved in cosmology, I show how to understand the operation of an interferometric gravitational wave detector in a way that resolves the apparent paradox. © *1997 American Association of Physics Teachers.*

Advanced Virgo

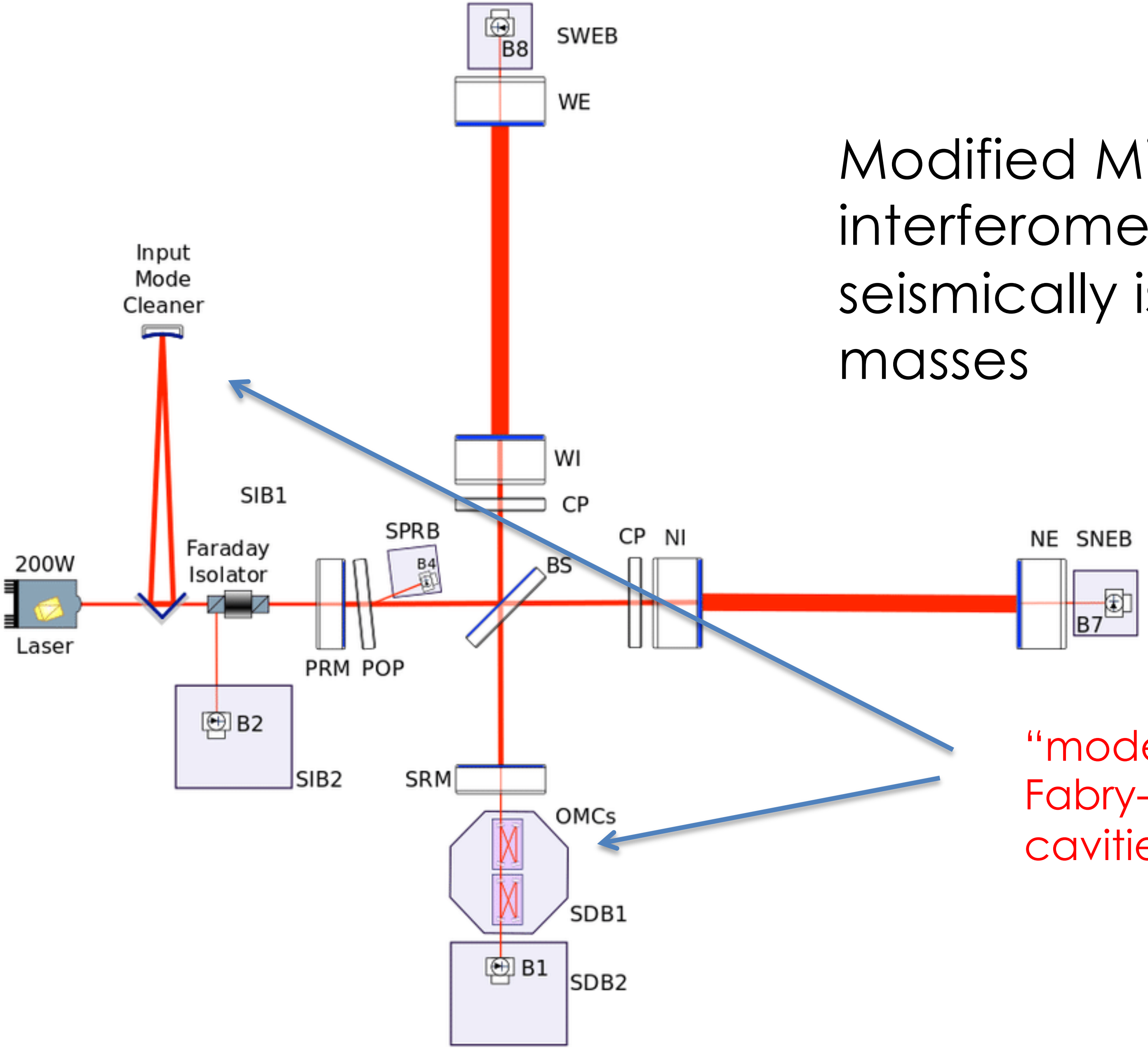


Modified Michelson interferometer with seismically isolated test masses

3 km arms
Fabry-Perot cavities
Optical length ~ 1000 km

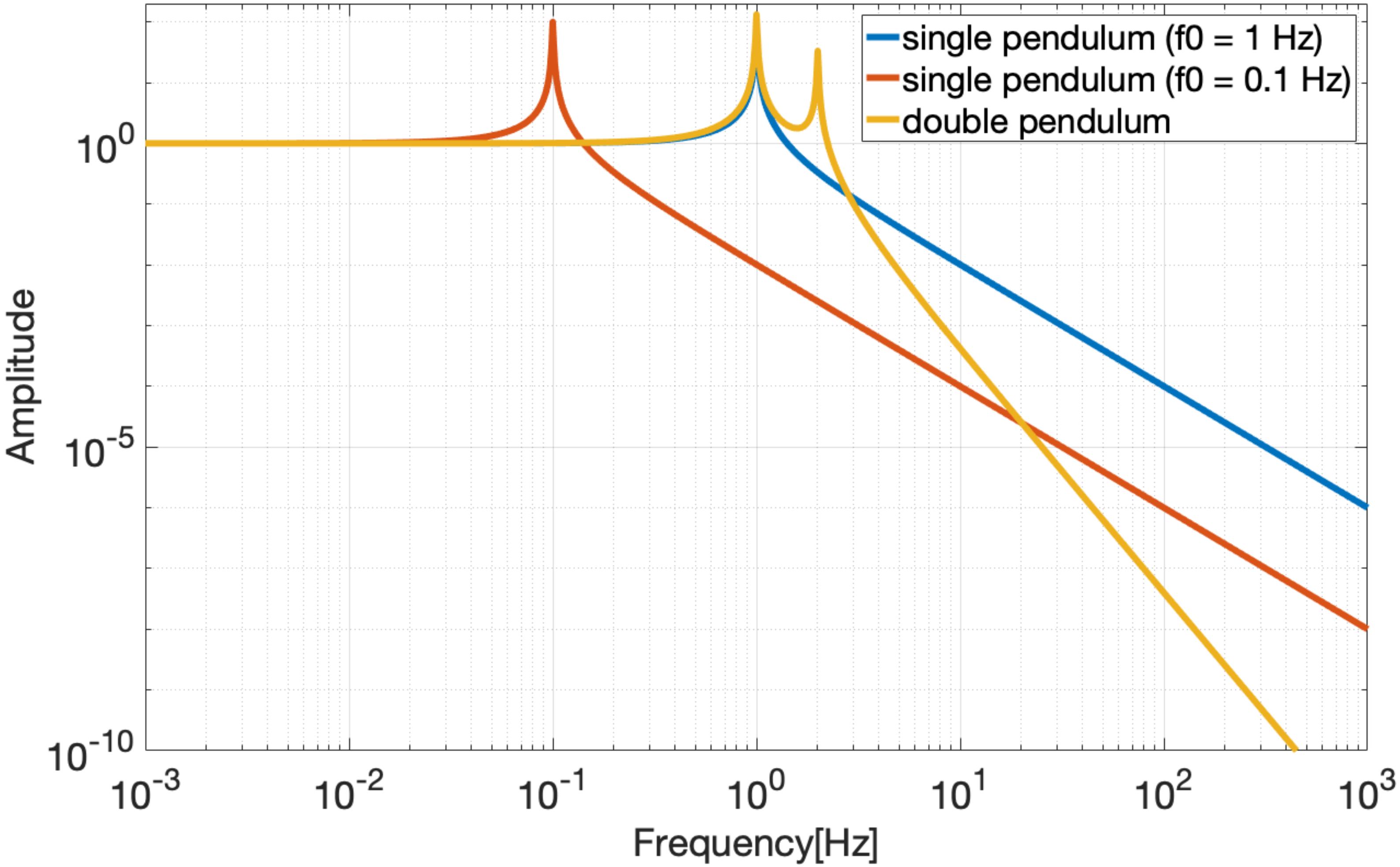
Advanced Virgo

Modified Michelson interferometer with seismically isolated test masses

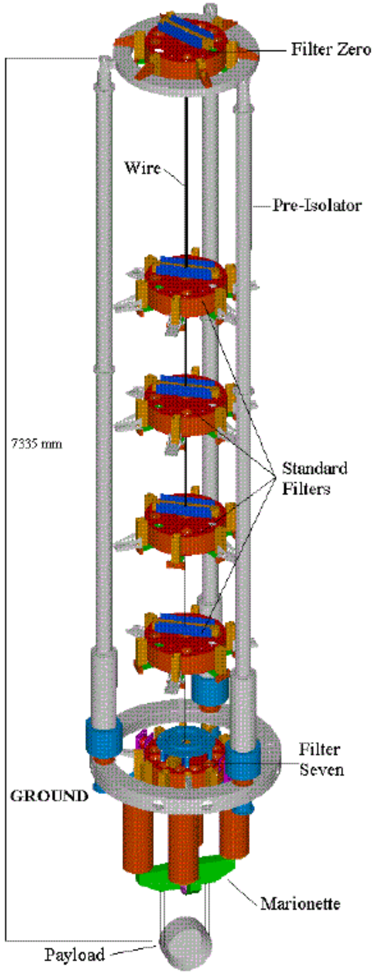


“mode cleaners”
Fabry-Perot
cavities

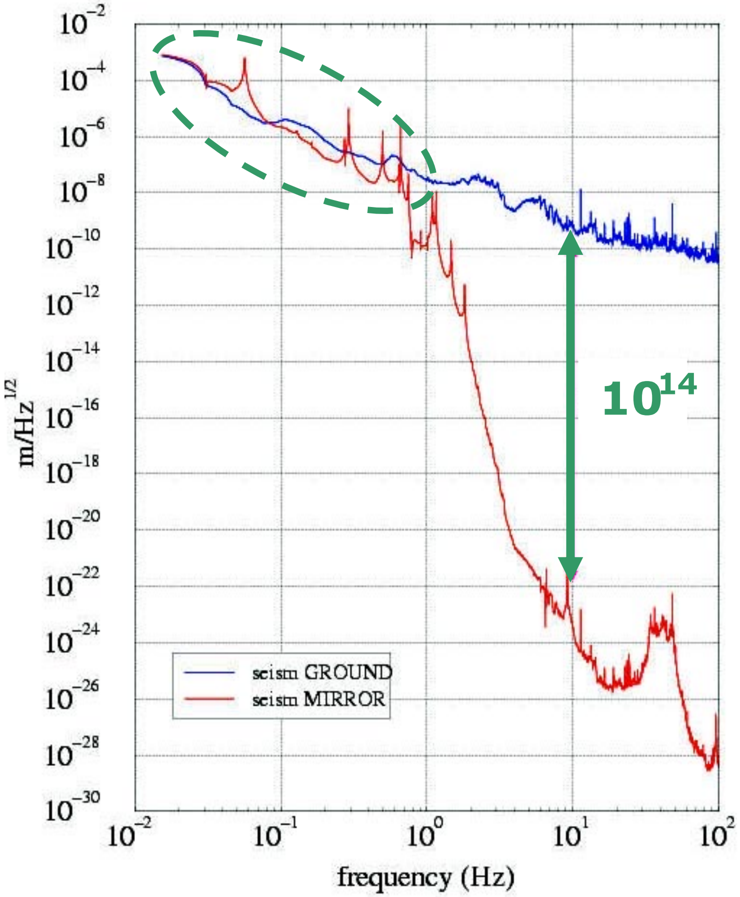
Building blocks: pendula



Building blocks: Suspensions



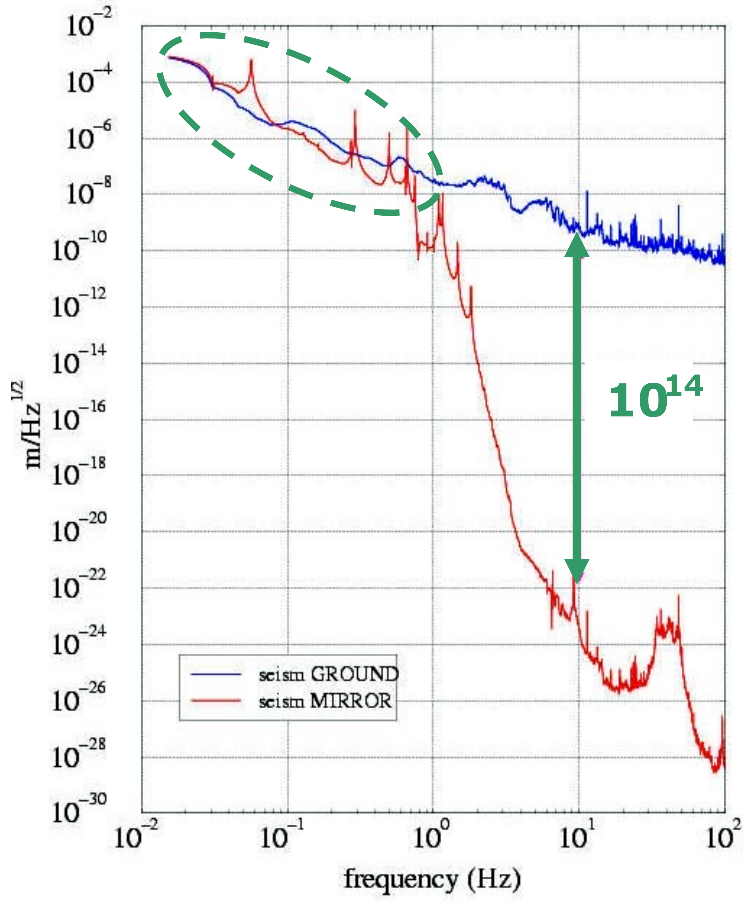
Virgo *superattenuator*



Virgo *superattenuator transfer function*

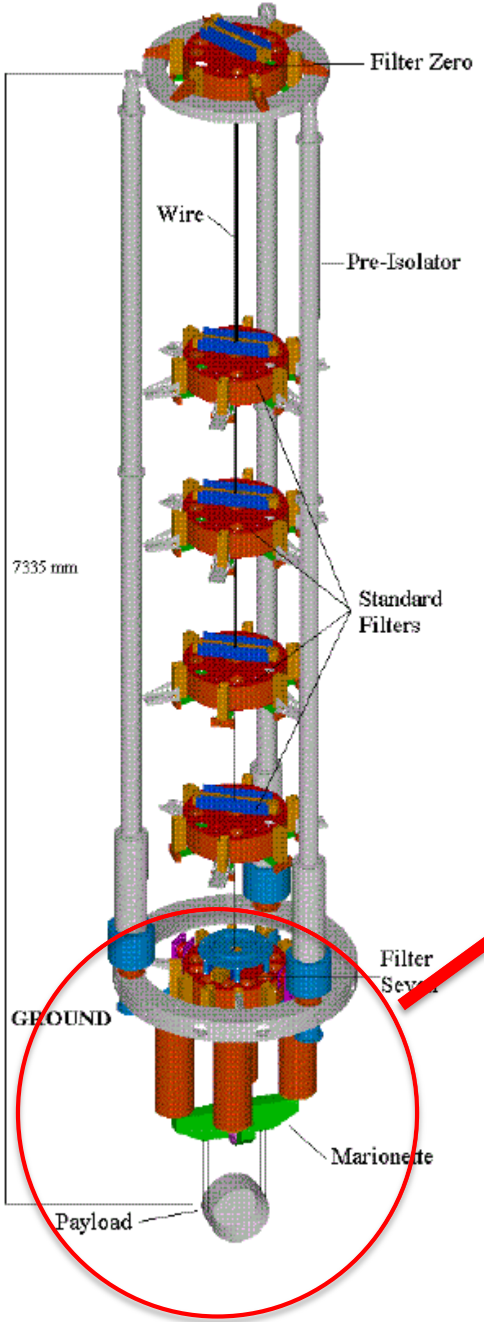
Bulding blocks: Suspensions

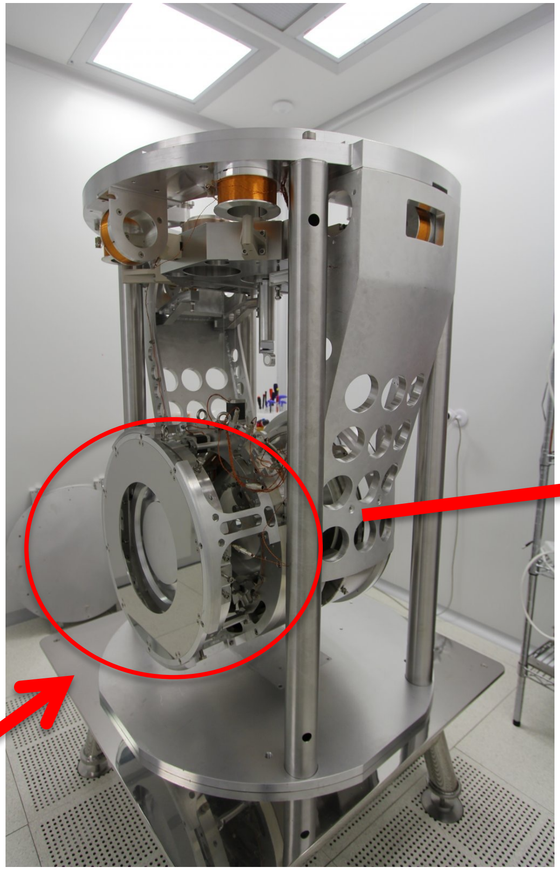
$$\frac{x}{x_{\mathrm{sus}}} = \frac{f_0^2}{f_0^2 - f^2}$$



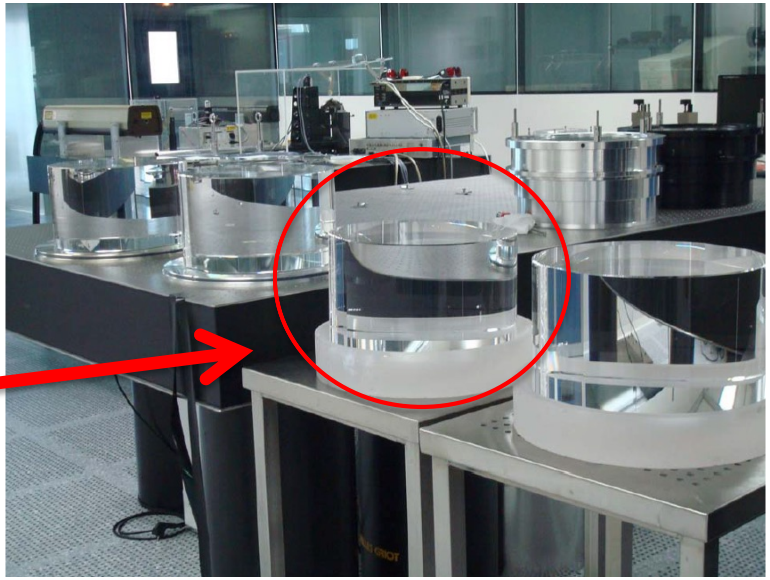
Active controls needed

Bulding blocks: mirrors

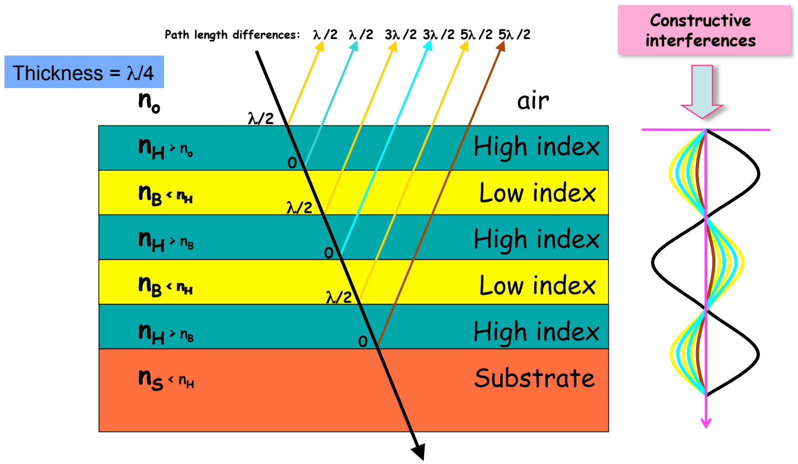


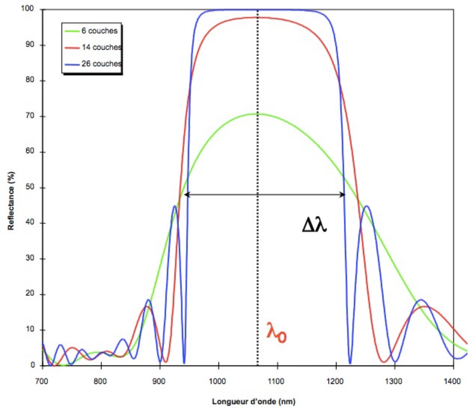


Credit Virgo



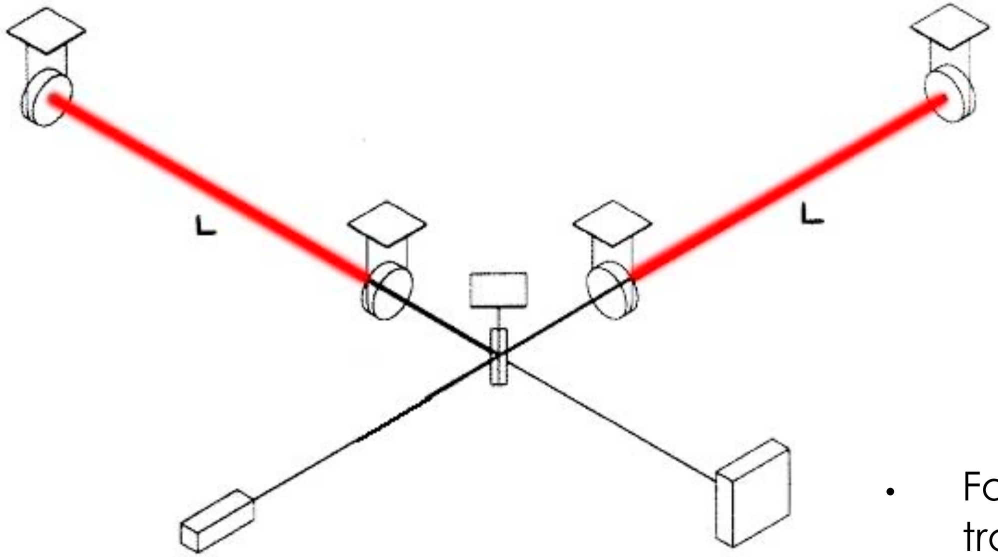
Bulding blocks Mirror = substrate + coating

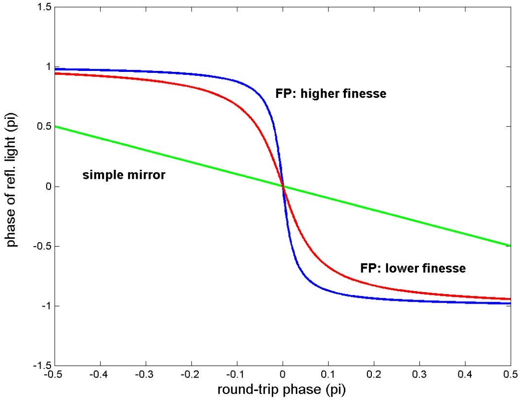




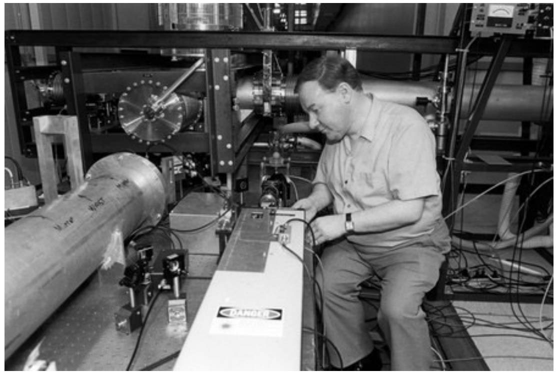
Credit: LMA, www.lma.in2p3.fr

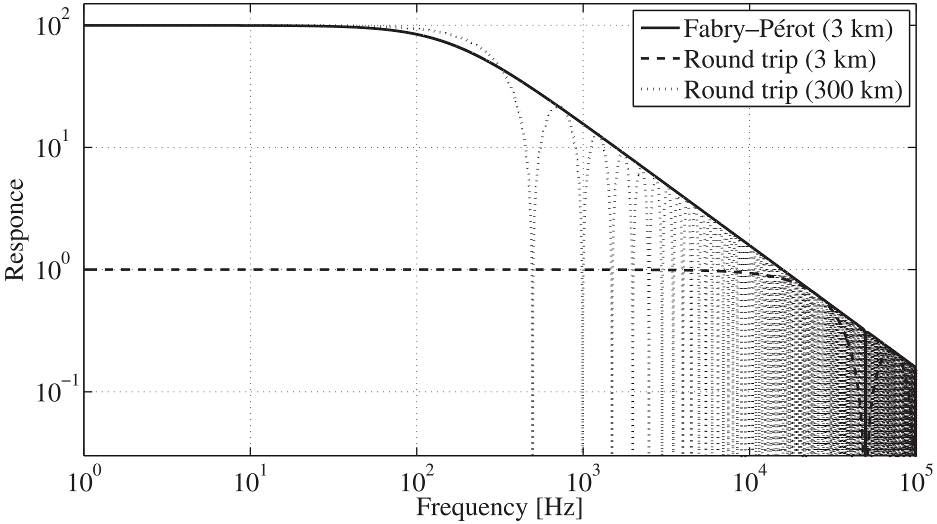
Bulding blocks: Fabry-Perot cavities



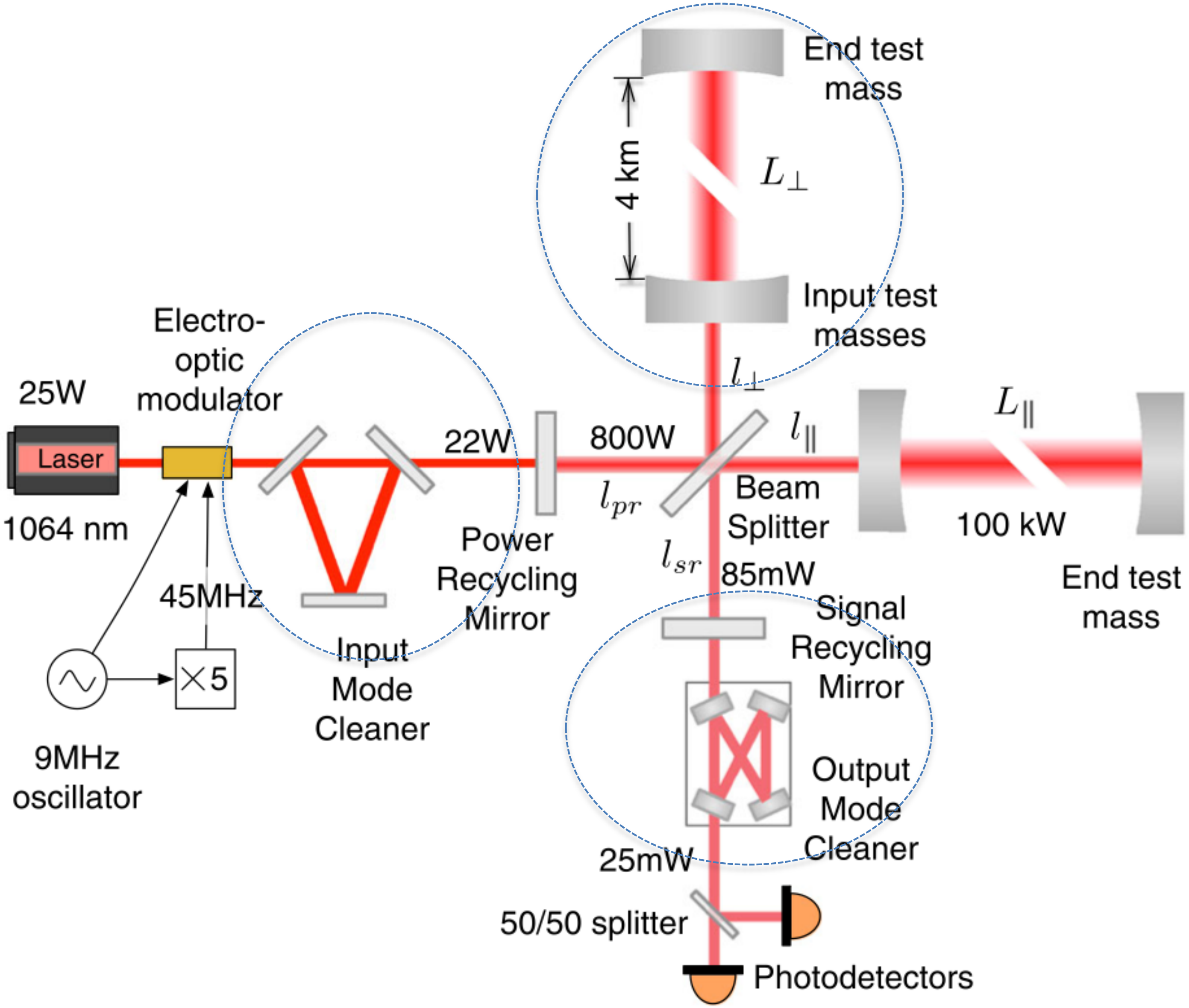


- Fabry-Perot cavities: amplify the length-to-phase transduction
- Drawback: works only at resonance

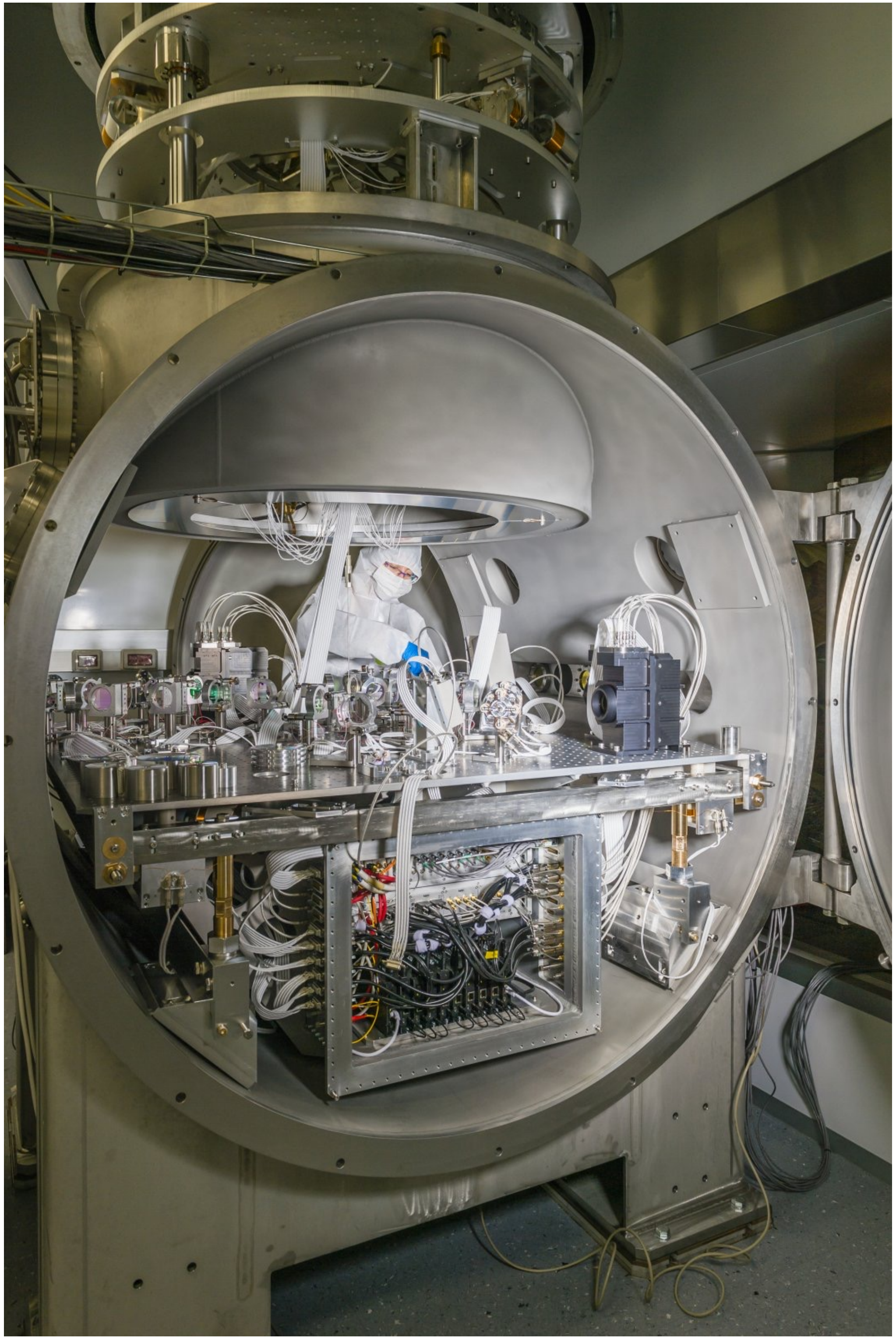


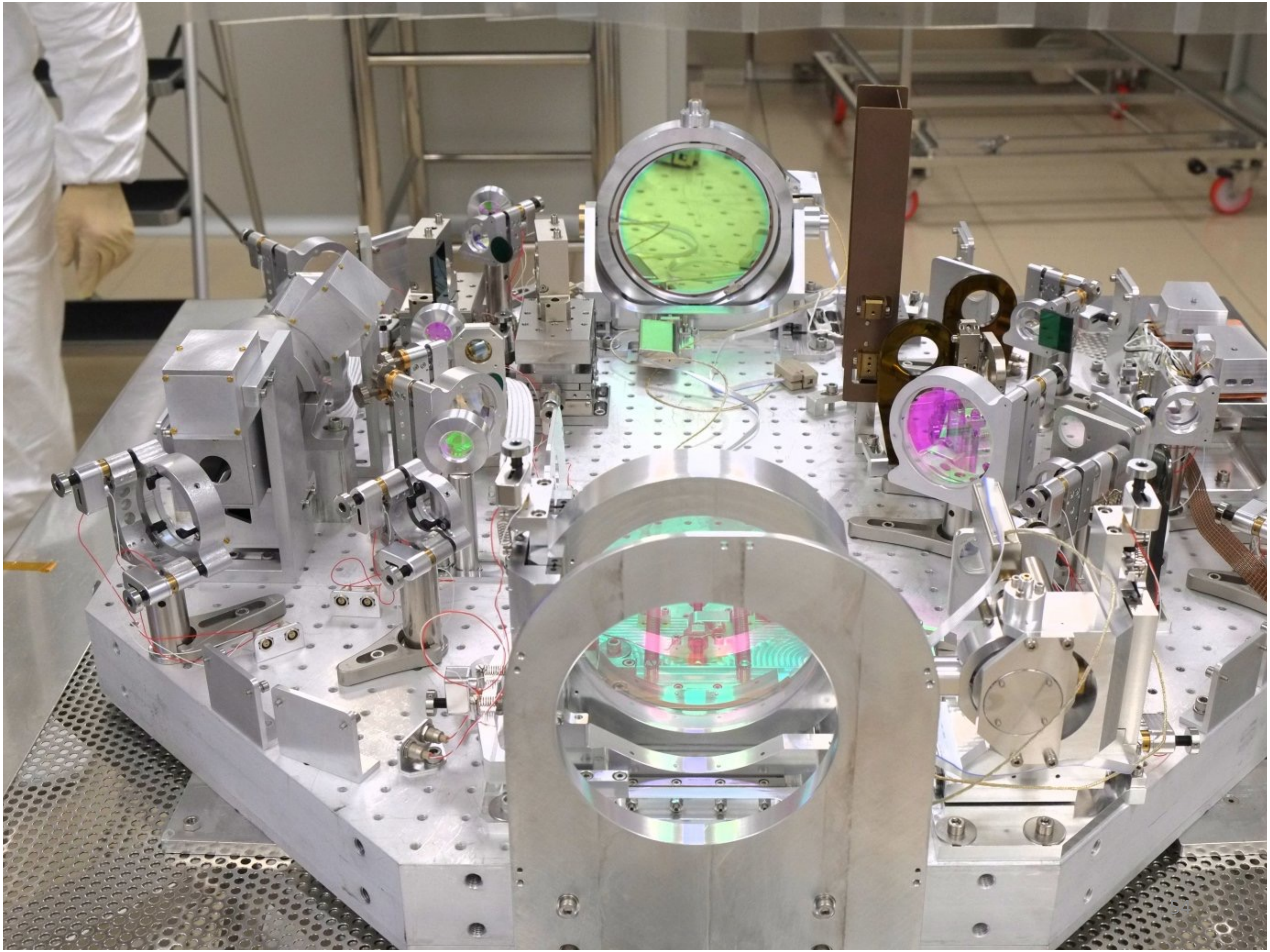


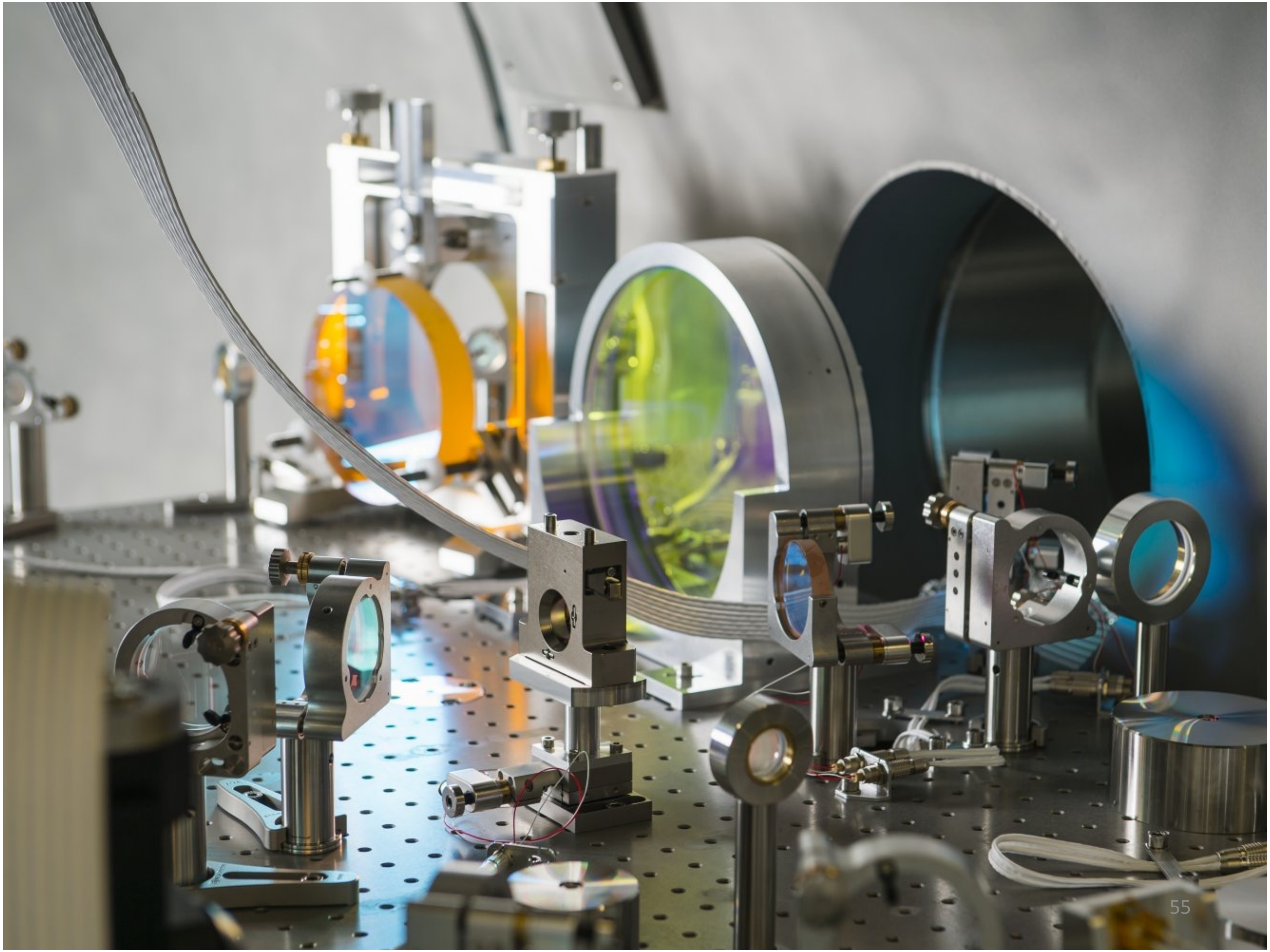
Fabry-Perot cavities



LASERVISION
FJW Optical Systems, Inc.







Noise sources

A possible classification:

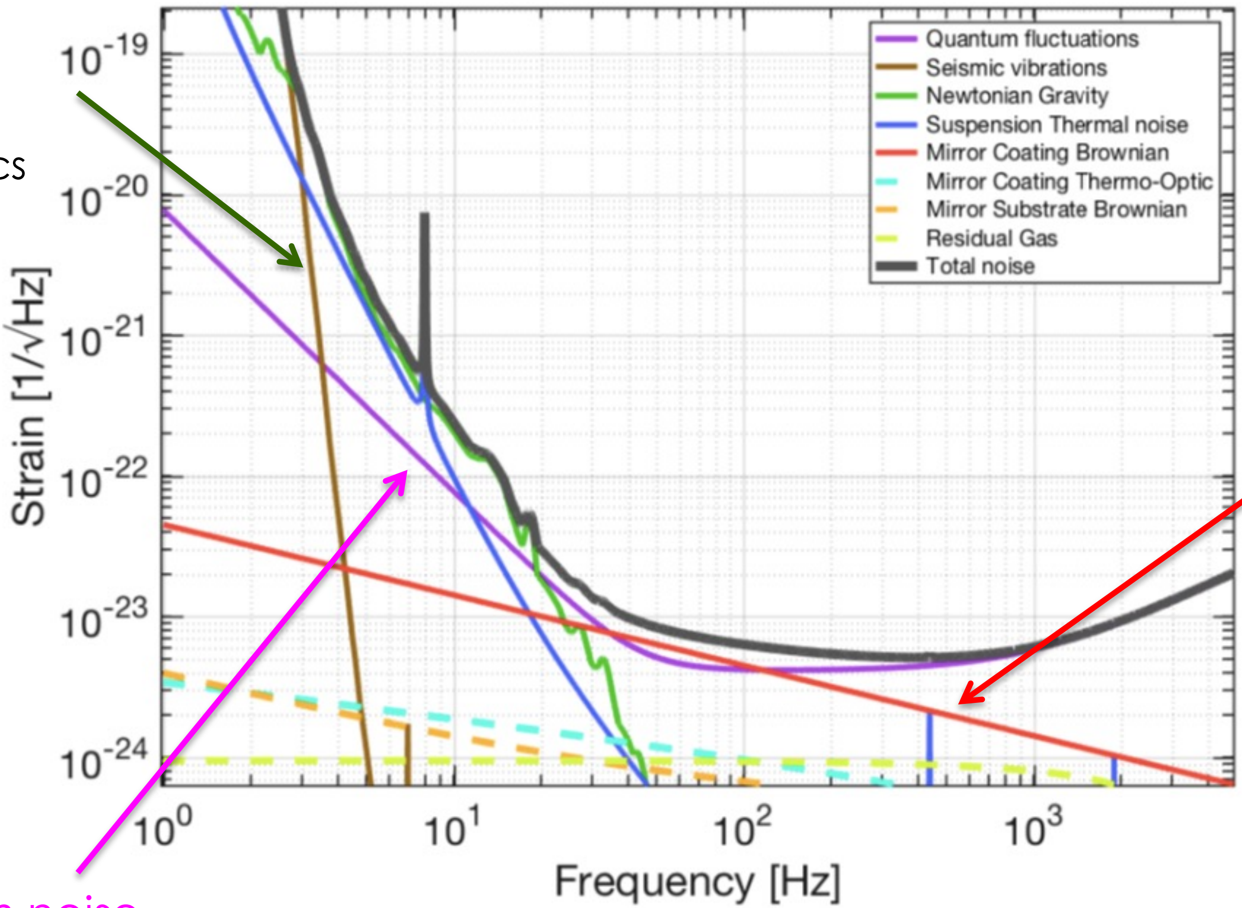
- Fundamental noises (from *first principles*)
  - Quantum, thermal
- Technical noises
  - Laser, electronics, vacuum pressure
- Enviromental noises (from the environment)
  - Seismic, acoustic, magnetic

Another classification:

- Displacement noises (create a real displacement): seismic, thermal
- Read-out noises (ability of the instrument to sense test-mass mition) quantum, electronic noises of the readout

Advanced Virgo sensitivity curve

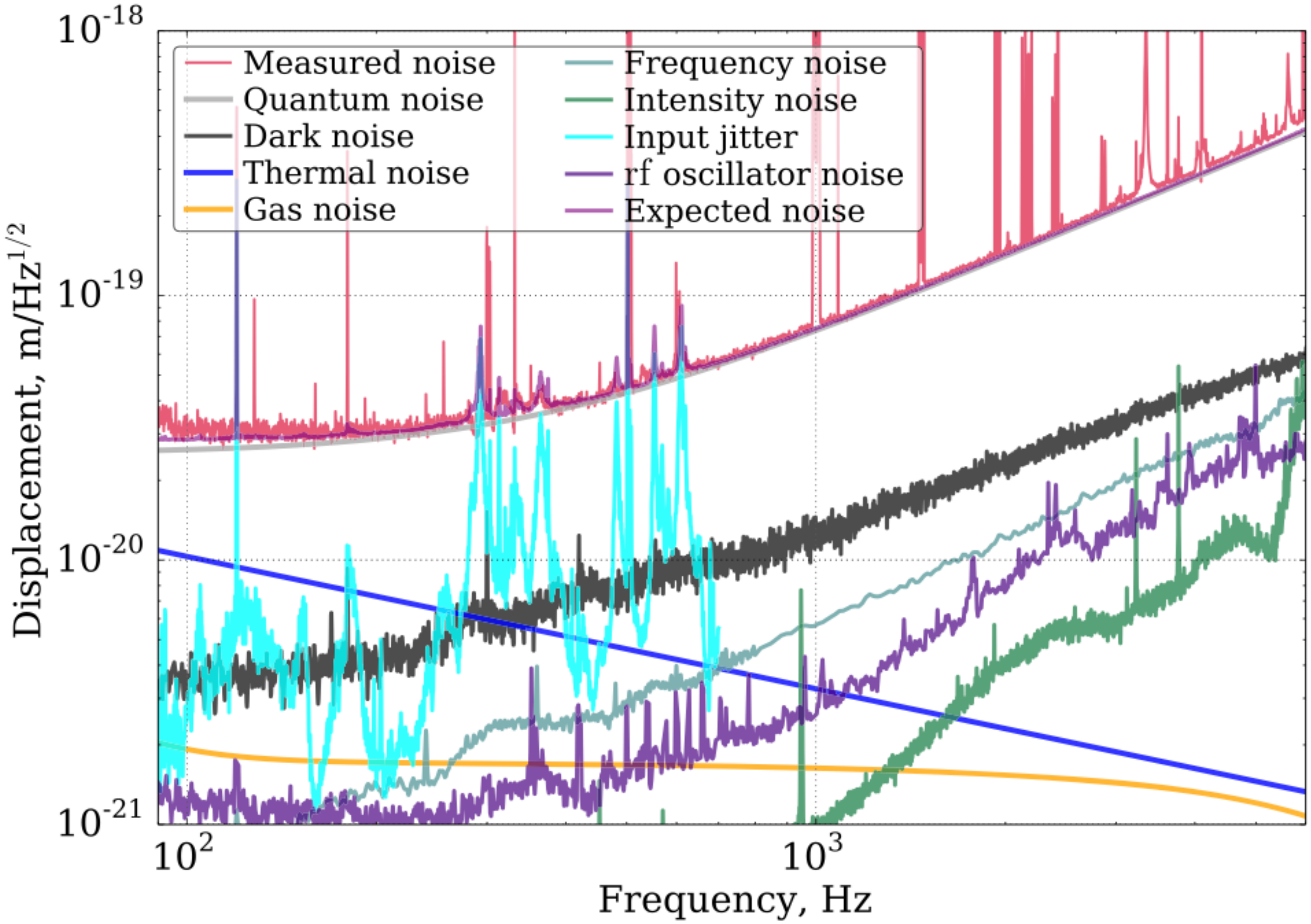
Seismic and gravity gradient noise
Geophysics



Thermal noise
Thermodynamics

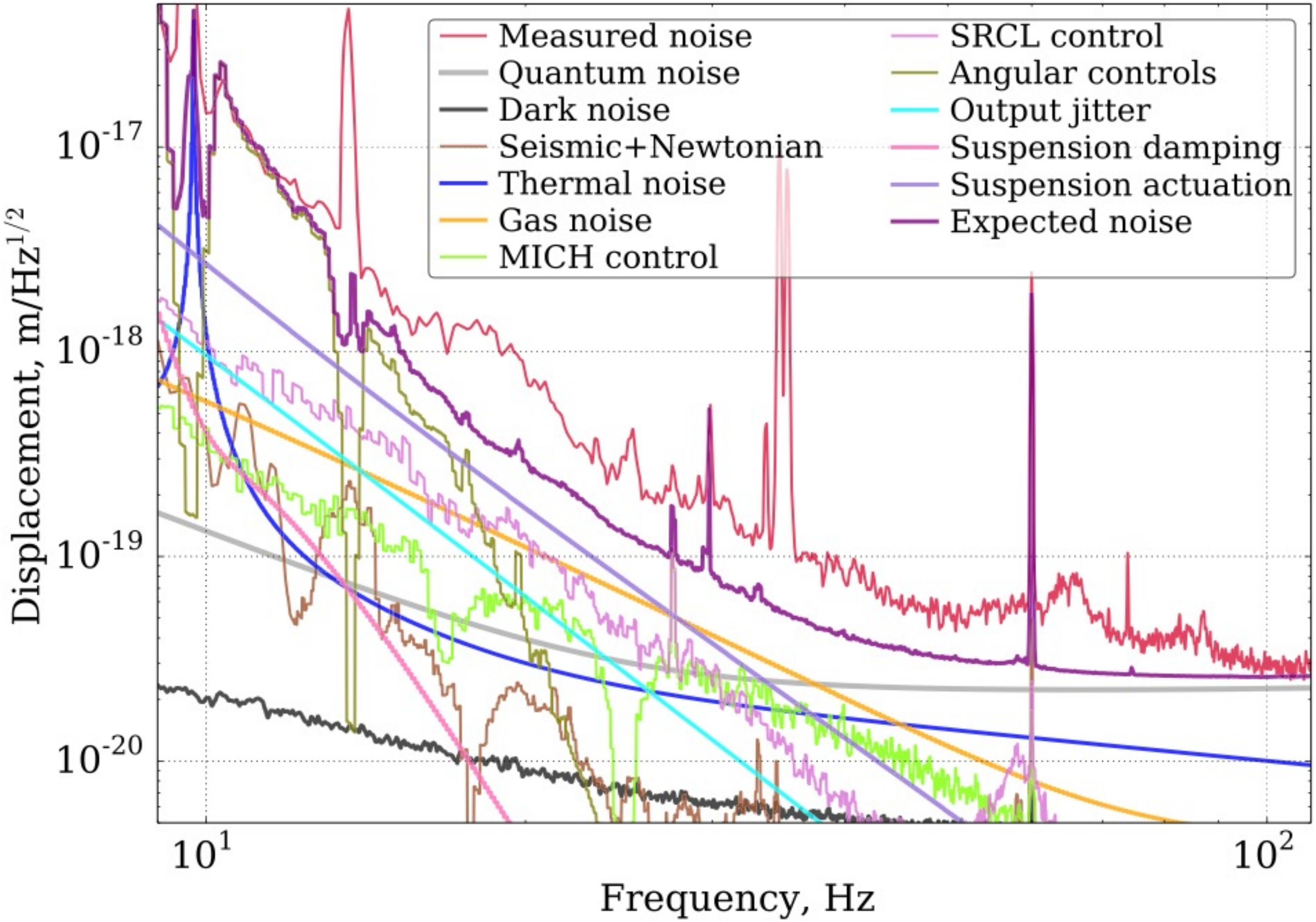
Quantum noise
Quantum mechanics

The real sensitivity curve



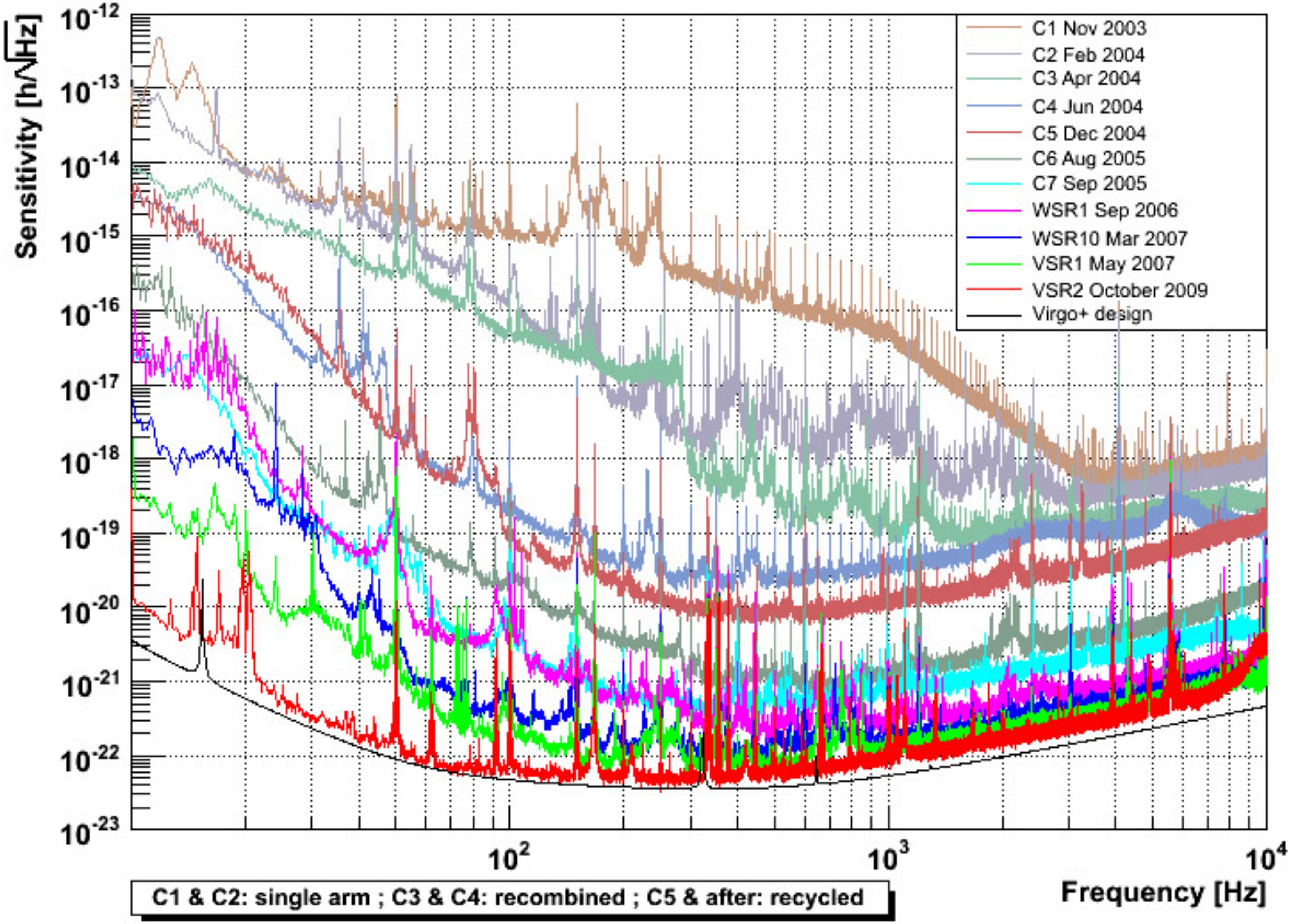
Sensitivity of the Advanced LIGO detectors at the beginning of gravitational wave astronomy
D. V. Martynov *et al.* Phys. Rev. D **93**, 112004 – (2016)

The real sensitivity curve



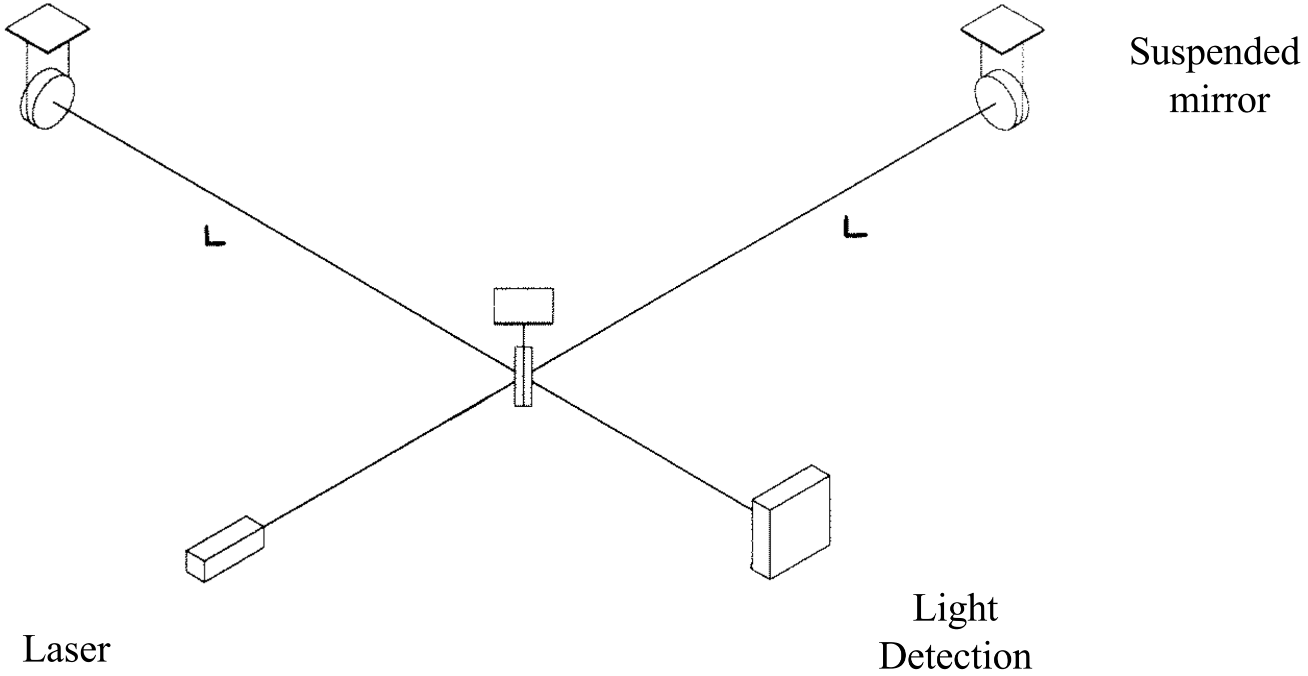
Sensitivity of the Advanced LIGO detectors at the beginning of gravitational wave astronomy
D. V. Martynov *et al.* Phys. Rev. D **93**, 112004 – (2016)

Example of sensitivity evolution



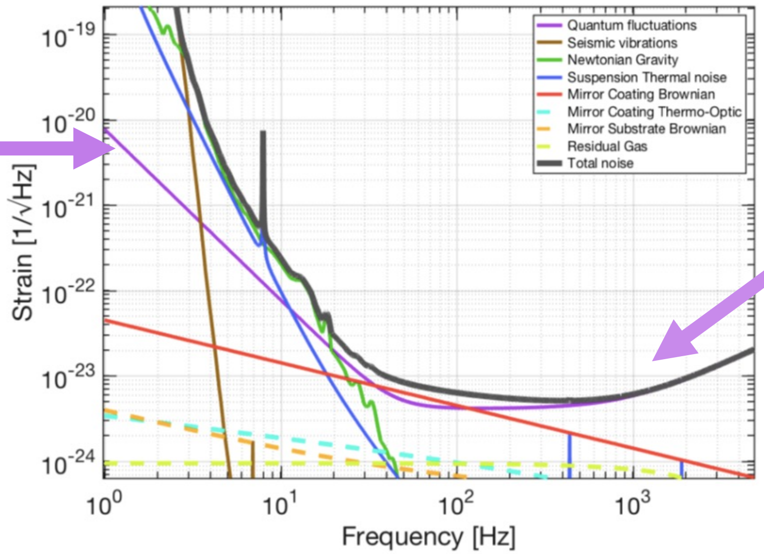
The quantum noise

Which is the intrinsic limitation of an interferometric measurement ?



Quantum noise: a semiclassical picture

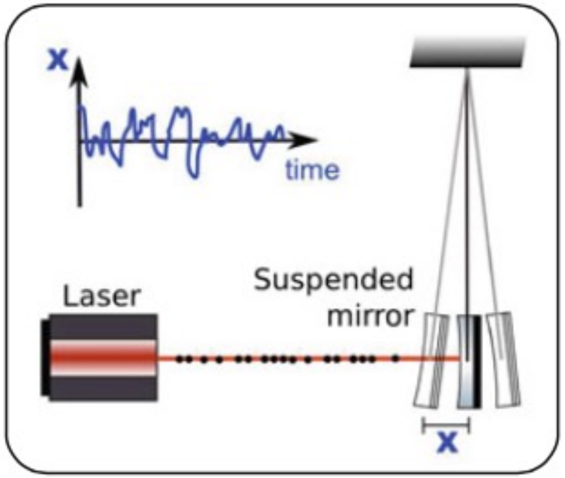
Radiation pressure noise

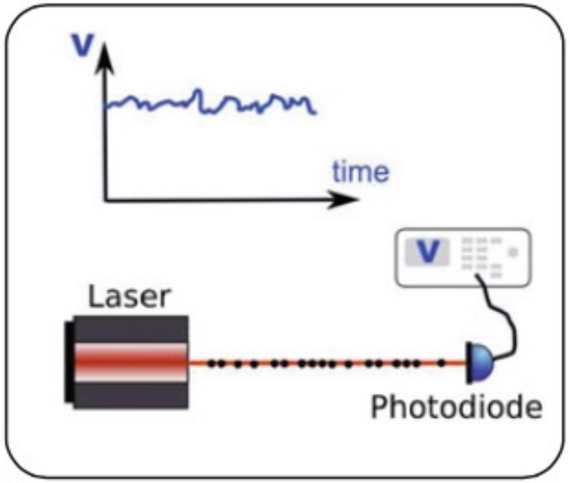


Shot noise

$$h_{\mathrm{rp}}(f) = \frac{1}{mf^2L}\sqrt{\frac{\hbar P}{2\pi^3 c\lambda}}$$

$$h_{\mathrm{sn}}(f) = \frac{1}{L}\sqrt{\frac{\hbar c\lambda}{2\pi P}}$$



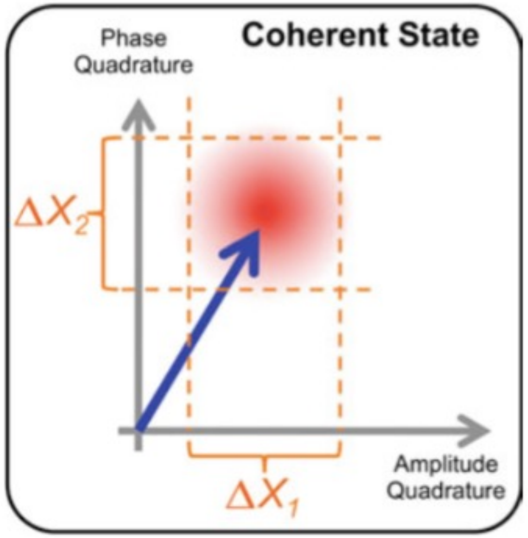


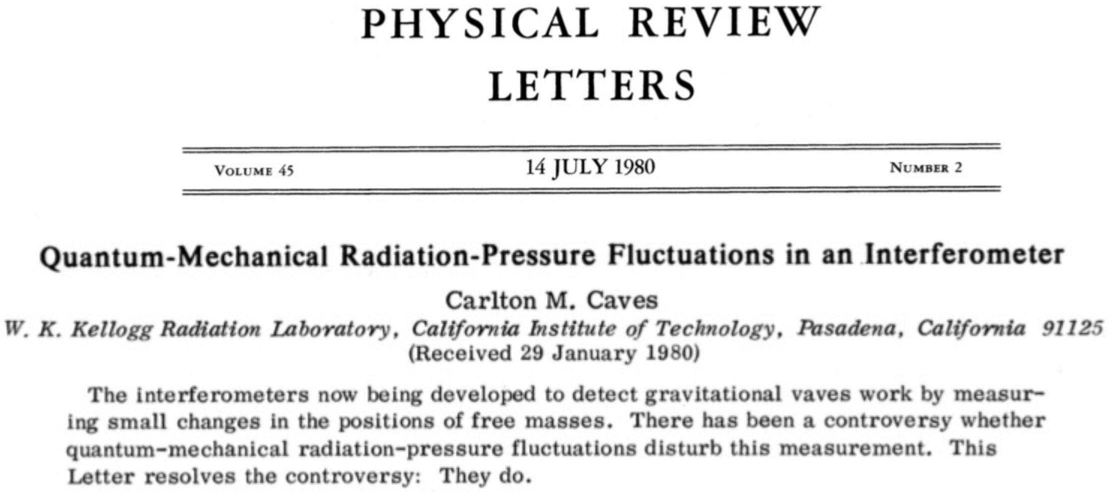
- Fluctuation in the momentum transferred to the mirror

- Poissonian statistics on the photon arrival time

Full quanto-mechanical treatement : Quantization of e.m. fields

- Quantum noise: consequence of quantization of e.m. field
- Quantization of e.m. field: rersponsible for spontaneous emission and Lamb shift
- Existence of zero-point fluctuations





PHYSICAL REVIEW LETTERS

VOLUME 45 | 14 JULY 1980 | NUMBER 2

Quantum-Mechanical Radiation-Pressure Fluctuations in an Interferometer

Carlton M. Caves

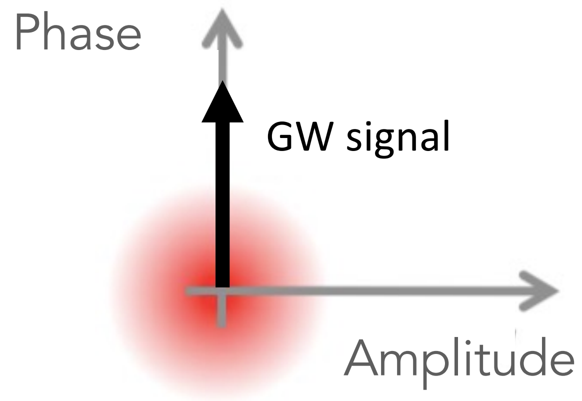
W. K. Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California 91125

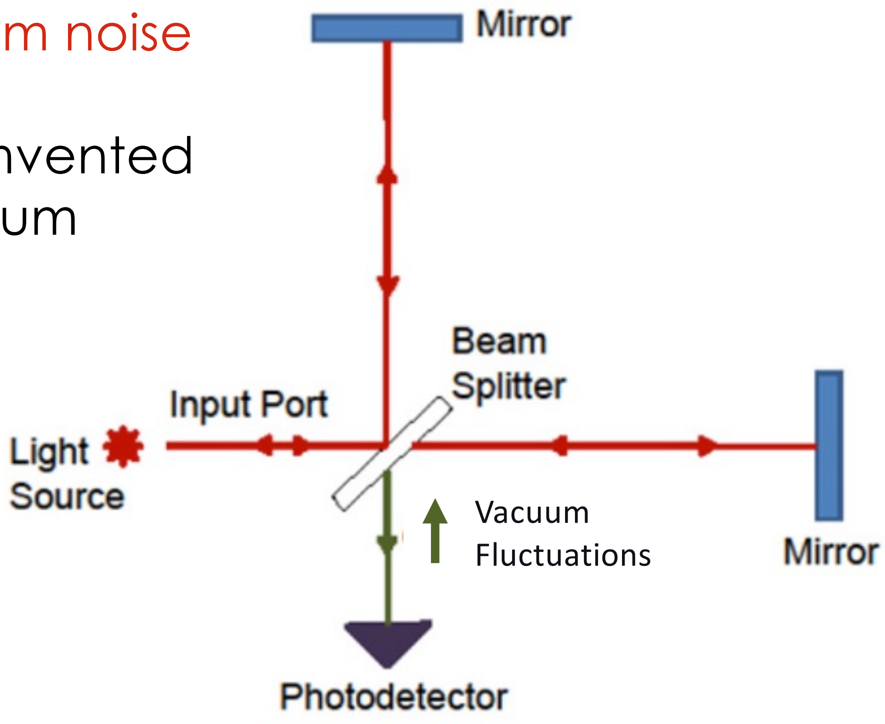
(Received 29 January 1980)

The interferometers now being developed to detect gravitational vaves work by measuring small changes in the positions of free masses. There has been a controversy whether quantum-mechanical radiation-pressure fluctuations disturb this measurement. This Letter resolves the controversy: They do.

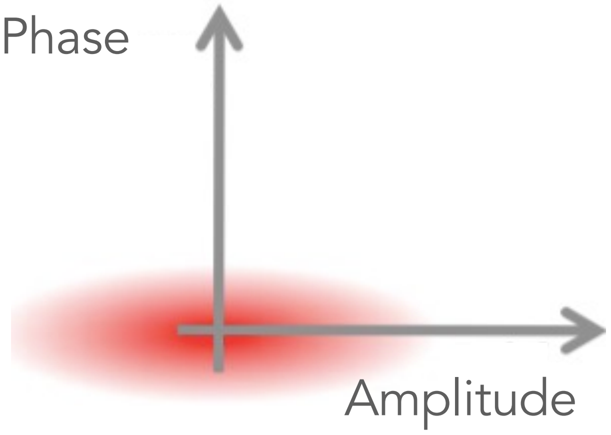
Quantum noise in GW interferometers

- If the cavities are symmetric, only vacuum fluctuations are responsible for quantum noise
- Standard quantum limit can be circumvented introducing correlation between vacuum fluctuations





Squeezed states



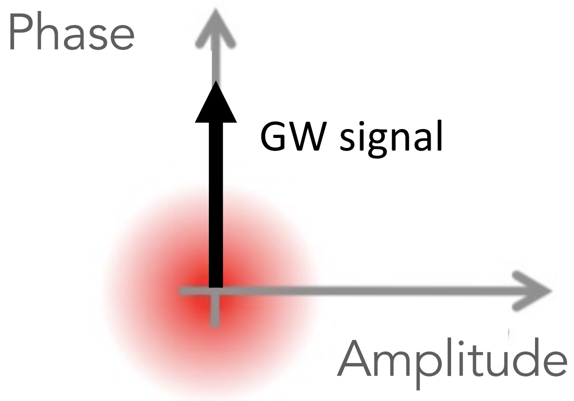
- Non classical light state
- Noise in one quadrature is reduced with respect to the one of a coherent stat

Each state is characterized by:

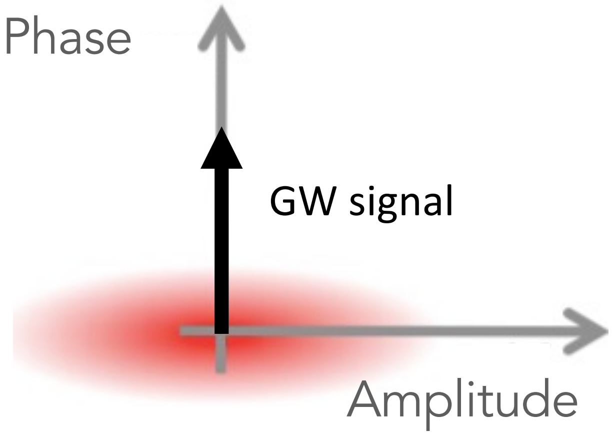
- Squeezing factor (magnitude of the squeezing)
- Squeezing angle (orientation of the ellipse)

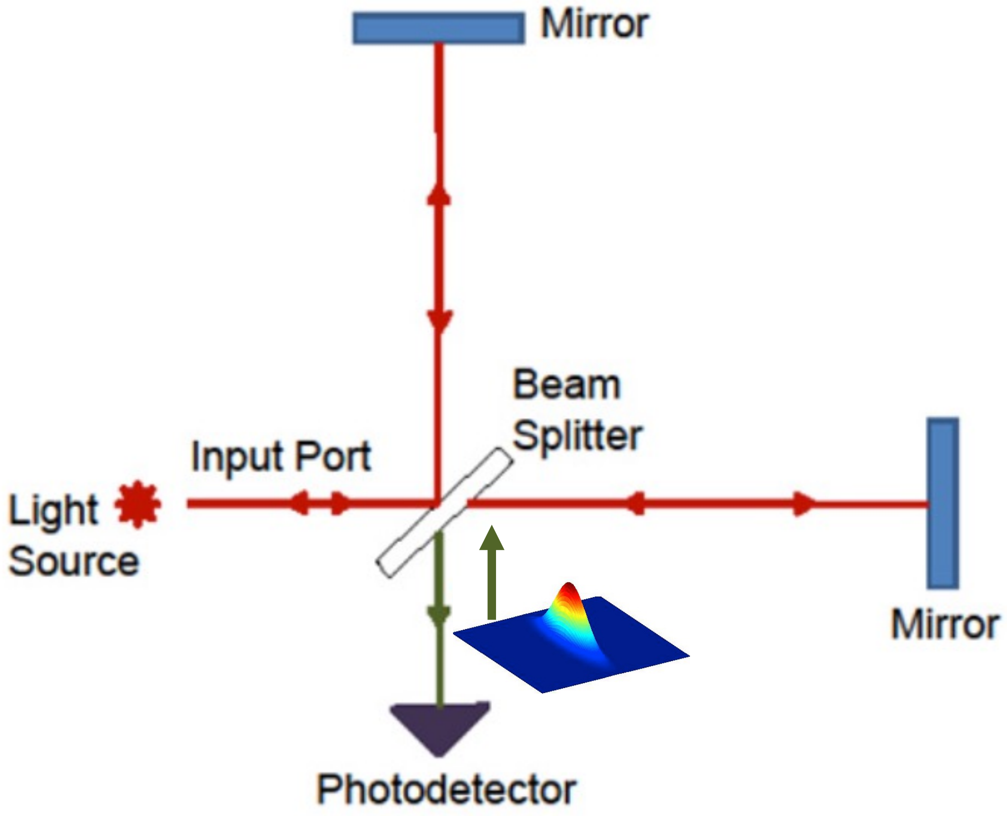
Quantum noise reduction using squeezed vacuum

Ordinary vacuum state

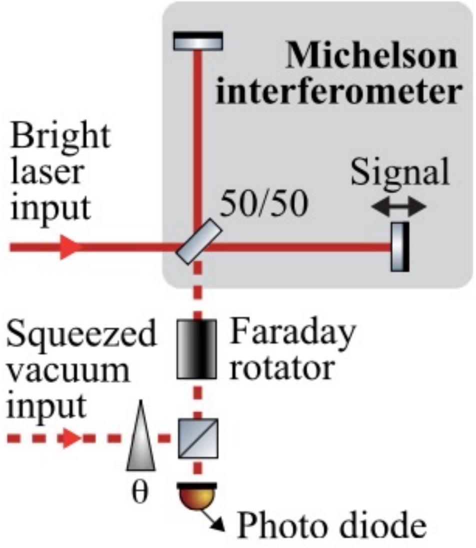


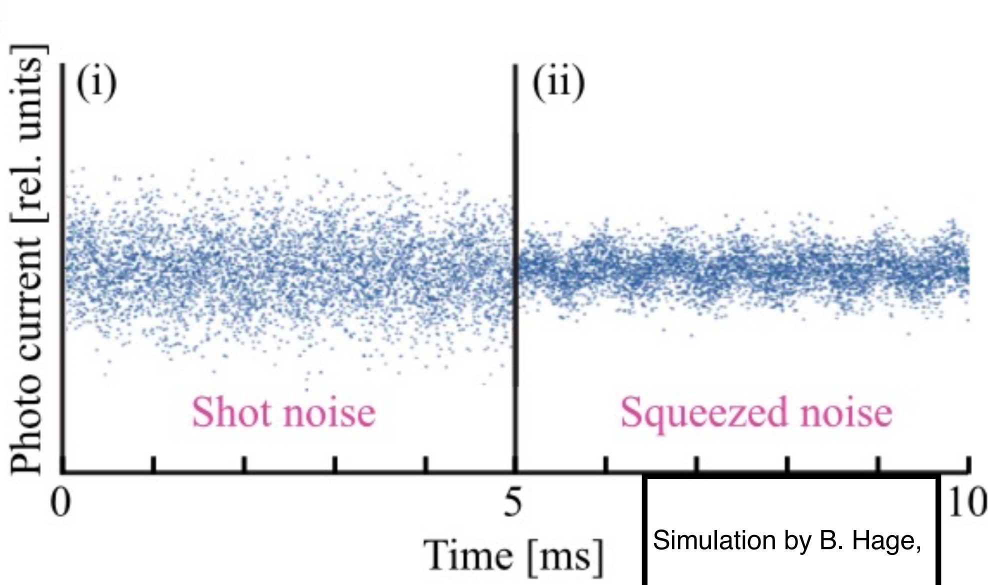
Squeezed vacuum state





Quantum noise reduction using squeezed light



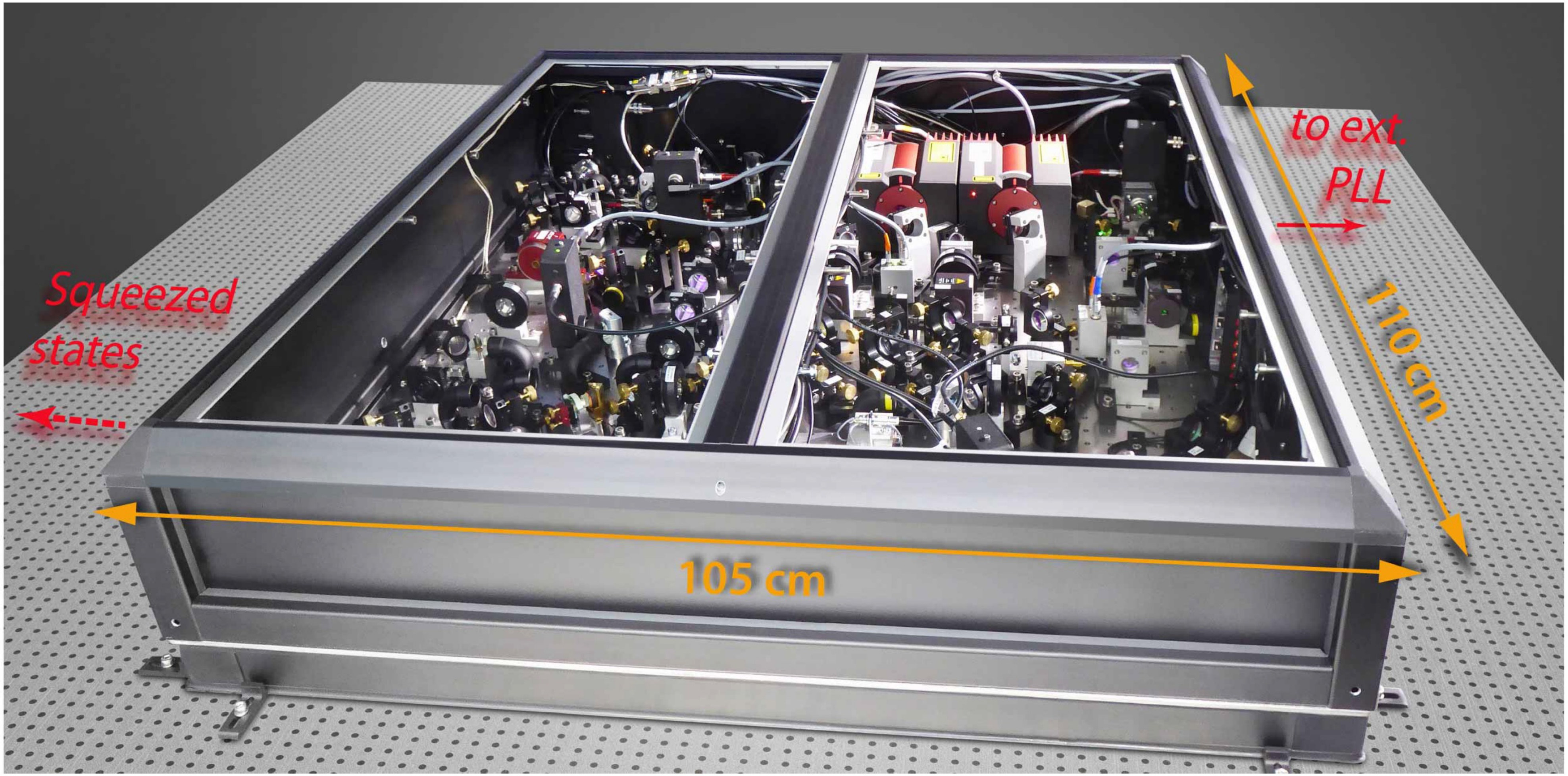


Simulation by B. Hage,

Albert Einstein Institute

- Simulated output of Michelson interferometer where a signal is produced by modulating the relative arm length
- With squeezing the shot noise is reduced and a sinusoidal signal is visible

Vacuum squeezed source for Virgo

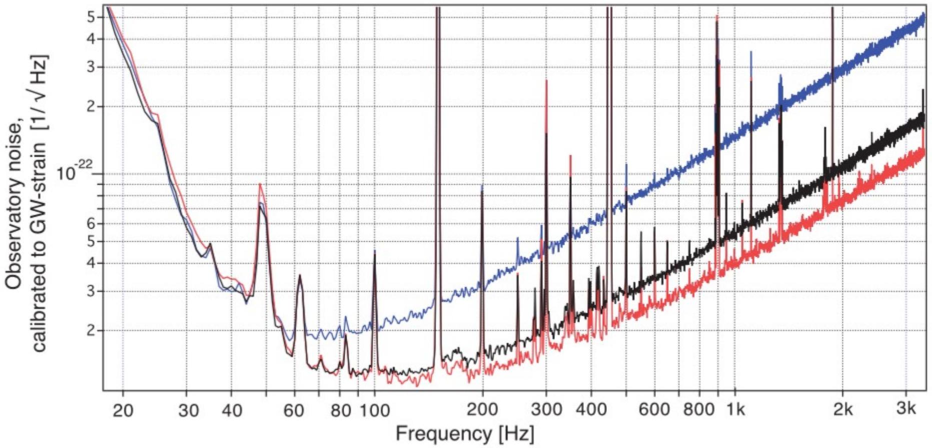


The Squeezed Light Source for the Advanced Virgo Detector in the Observation Run O3
M.Mehmet, H.Vahlbruch, Galaxies 2020, 8(4), 79.

Application to LIGO and Virgo: results

Advanced Virgo

- Best measured ~3dB
- Detection rate improvement: 16-26%

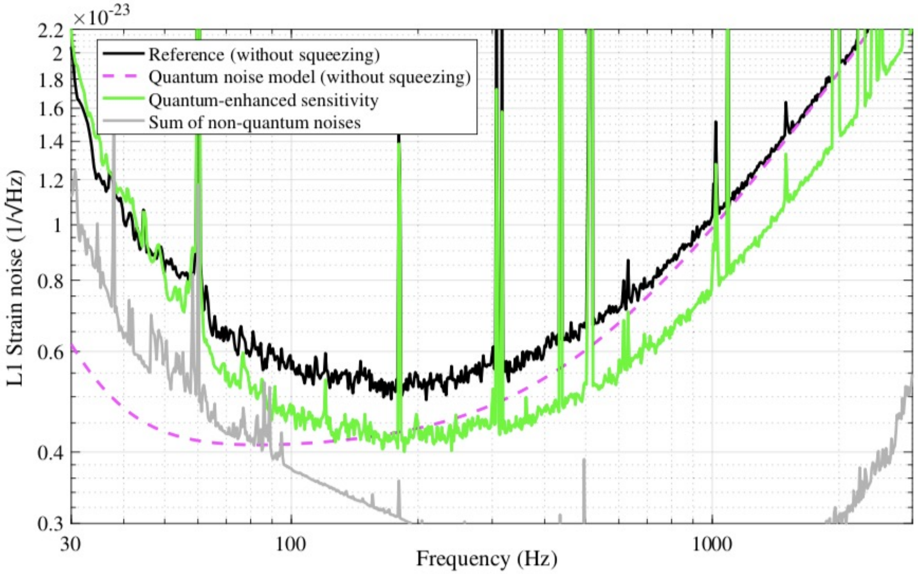


Increasing the Astrophysical Reach of the Advanced Virgo Detector via the Application of Squeezed Vacuum States of Light

F. Acernese *et al.* (Virgo Collaboration)
Phys. Rev. Lett. **123**, 231108 – Published 5 December 2019

Advanced LIGO

- Best measured ~3 dB
- Detection rate improvement: 50%



Quantum-Enhanced Advanced LIGO Detectors in the Era of Gravitational-Wave Astronomy

M. Tse *et al.*
Phys. Rev. Lett. **123**, 231107 – Published 5 December 2019

Summary quantum noise

- Quantum noise originated by vacuum fluctuations is the main limitation of GW detector sensitivity

- Most effective mitigation strategy: squeezed vacuum injection

- After 40 year of developments squeezing is routinely used in GW detectors with relevant impact on sensitivity

- Key technology also for 3rd generation: ongoing work to optimise its performances: loss reduction, complex rotation od the squeezing ellipse, etc..

The thermal noise

The thermal noise: bibliography

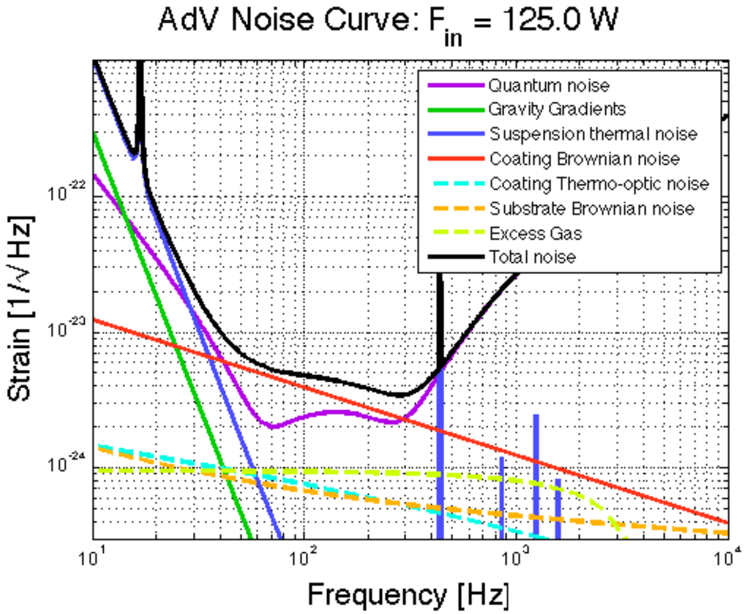
For a review on the thermal noise:
Optical Coatings and Thermal Noise in Precision Measurement, Cambridge University Press, 2012

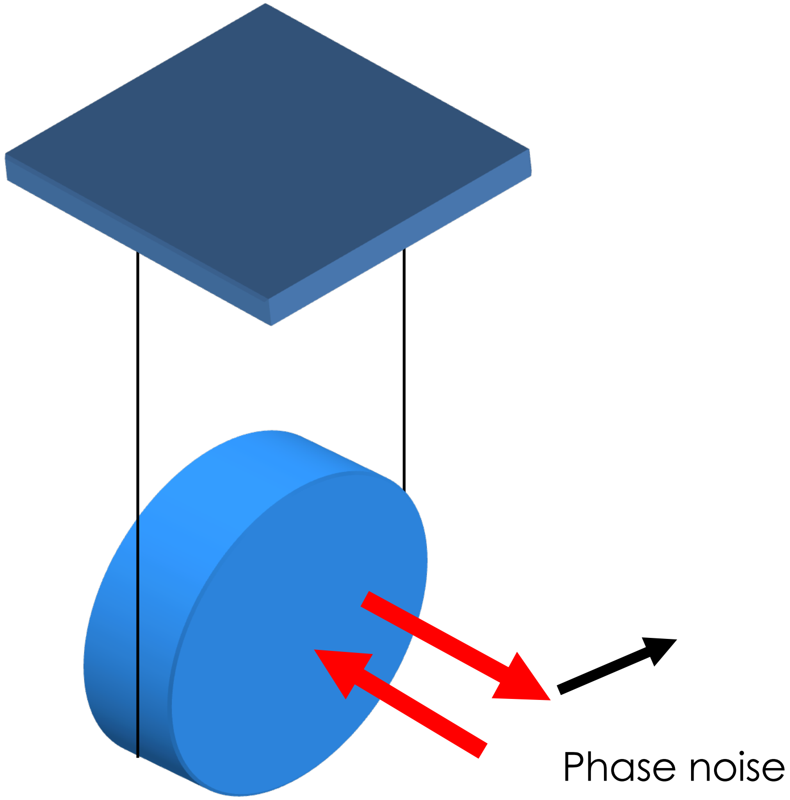
For an introduction of thermal noise see: P.R.Saulson, *Thermal noise in mechanical experiments*, Phys Rev D 42 8 (1990)

Introduction

What is the distribution of thermal energy versus the frequency? How this energy is converted in displacement?

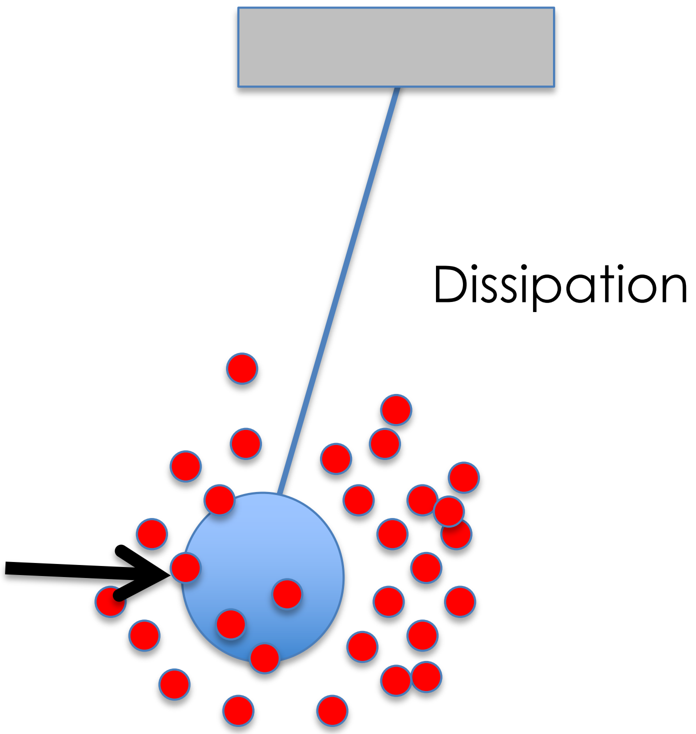
What is the *power spectrum* of thermal noise?

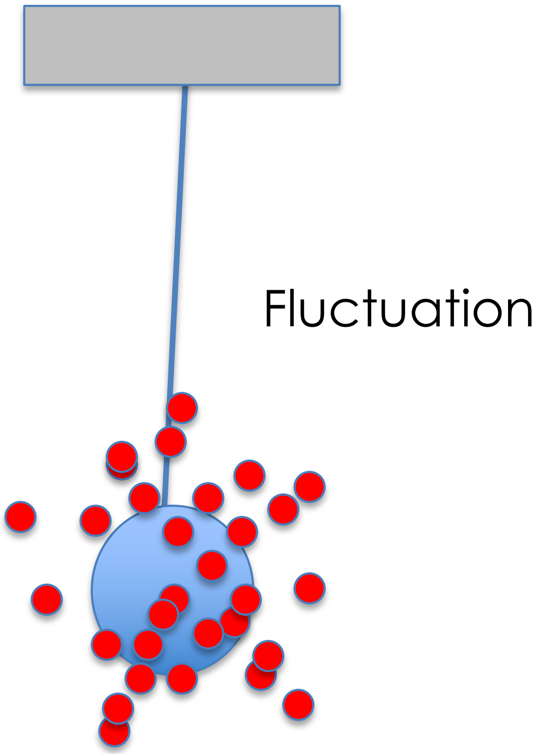




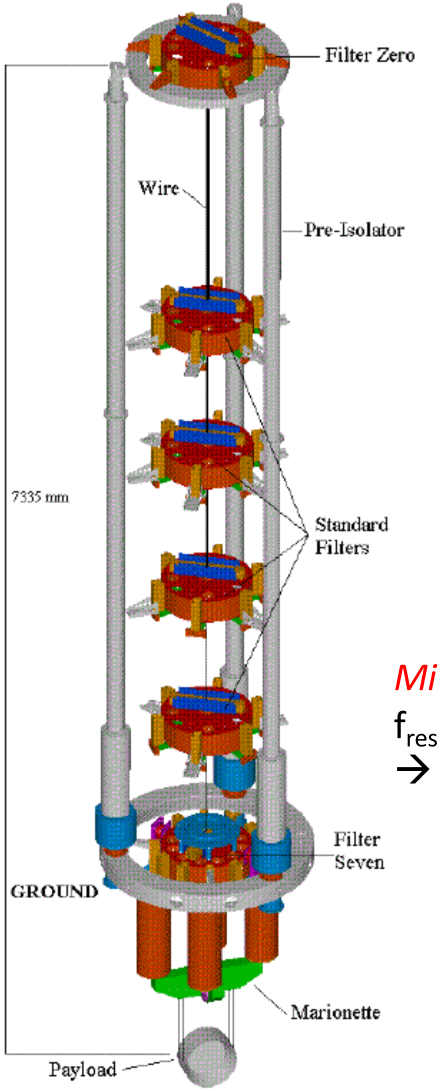
The fluctuation-dissipation theorem

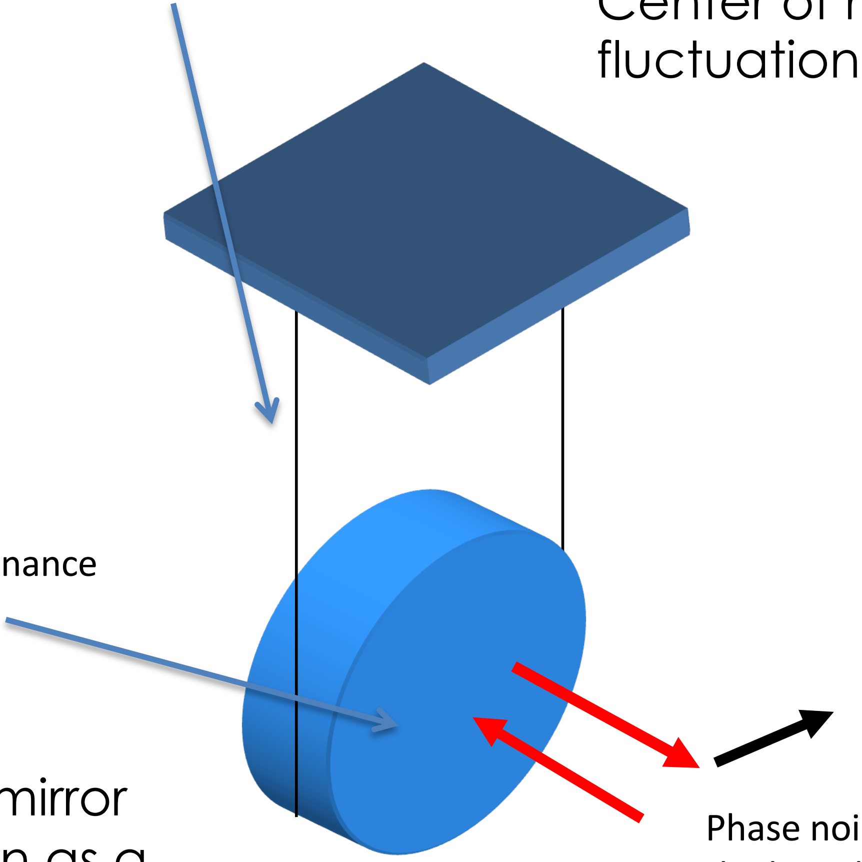
- There is a relation between the response of a driven dissipative system and the spontaneous fluctuations of a generalized variable (i.e. the position) of the system in equilibrium: the fluctuation dissipation-stheorem (Callen 1951).





Types of thermal noise in GW detectors





Pendulum thermal noise
f_{res} ~ 1 Hz
→ thermal noise above resonance

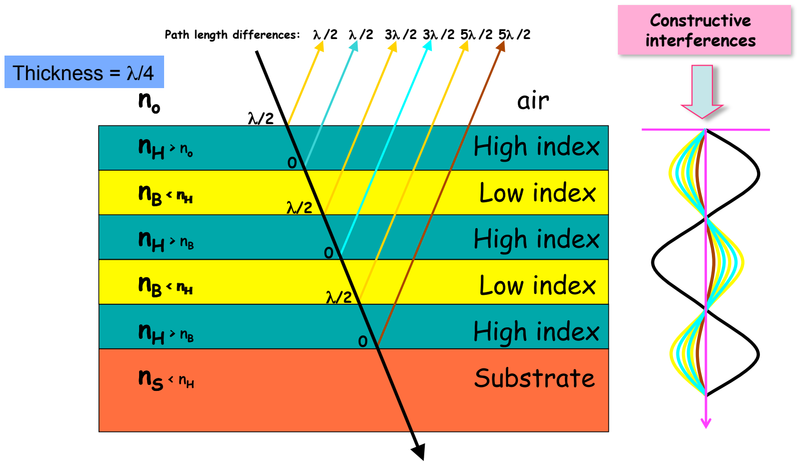
Center of mass fluctuation

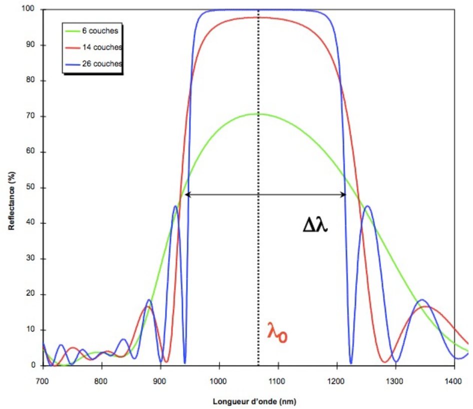
Mirror thermal noise
f_{res} ~ a few kHz
→ thermal noise below resonance

Apparent fluctuation of mirror surface as seen as a laser beam

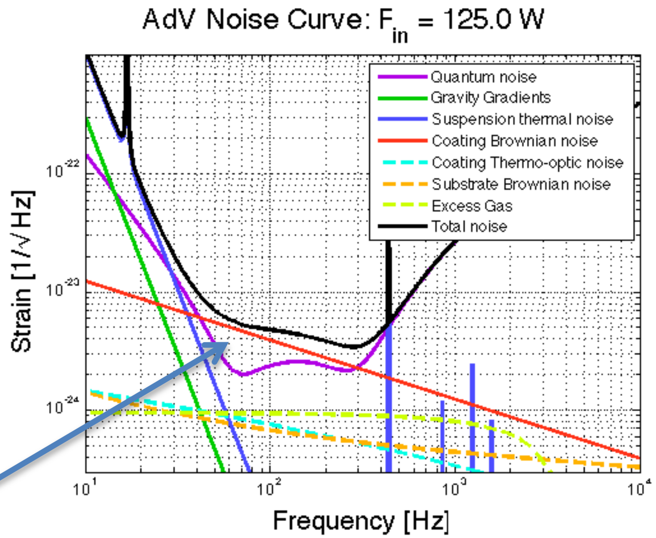
Phase noise of the laser beam

Mirror = substrate + coating





Credit: LMA, www.lma.in2p3.fr



The performances of a km scale interferometer are limited by ~ 5 micron surface coating !

Virgo-LIGO-KAGRA network results

Intro: Gravitational-wave observatory network

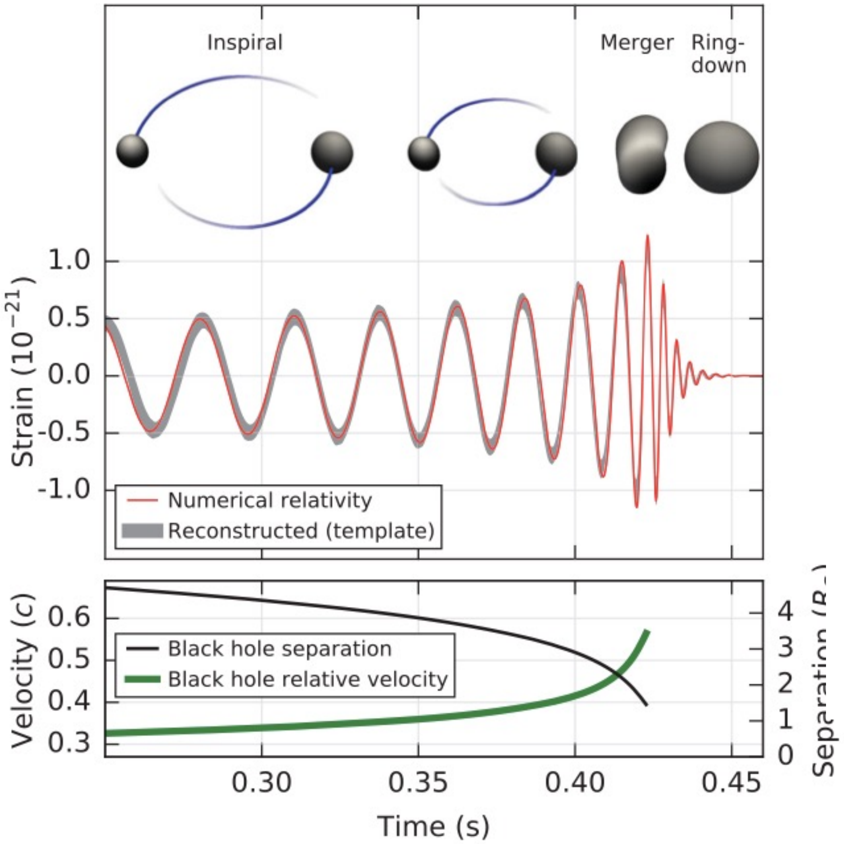
Summary of the results

- First detection of gravitational-waves
- First test of gravitational-wave polarisation
- Gravitational waves travel at the speed-of-light
- Tests of the emission at higher harmonics of GW
- Tests of GR in strong field regime

- First observations of a NS-NS merger
- First observations of BH-BH mergers
- A new population of BH with high masses
- First measurements on NS tidal deformability
- Link between GRB and neutron star mergers
- Kilonova powered by binary NS merger

- Alternative measurement of Hubble constant
- Speed of gravity → consequences on gravity alternative theories

GW150914: a binary black-hole system



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	$0.09^{+0.03}_{-0.04}$

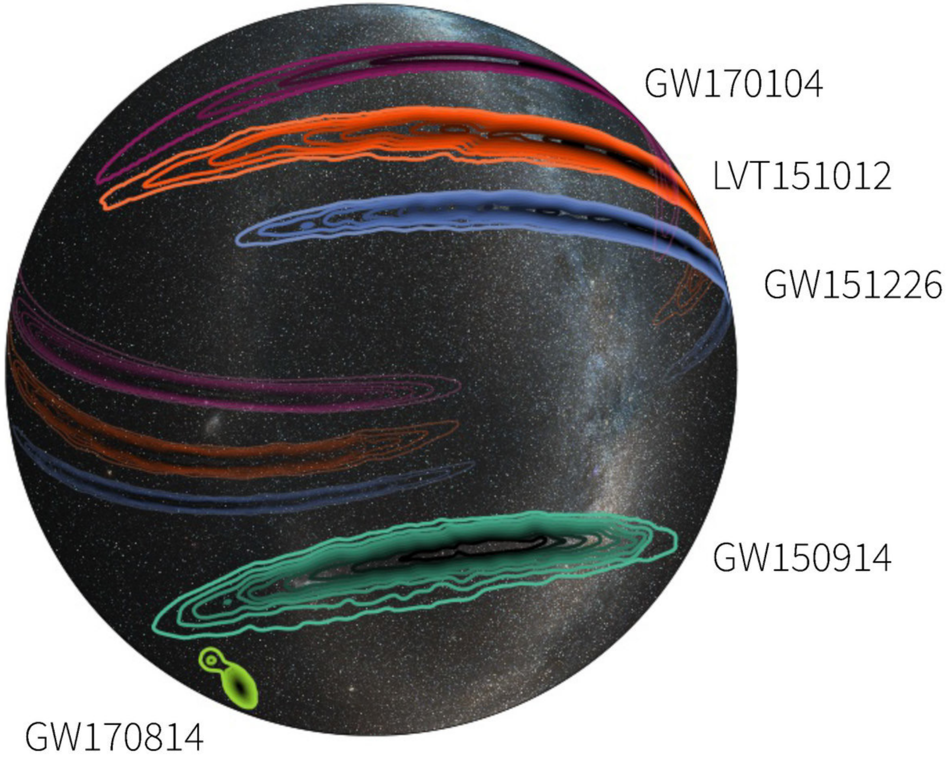
Energy in GW $3.0^{+0.5}_{-0.5} M_\odot c^2$

Luminosity $3.6^{+0.5}_{-0.4} \times 10^{56}$ erg/s

Solar luminosity 3 x 10^{33} erg/s

First triple detection: GW170814

GW170814: A Three-Detector Observation of Gravitational Waves from a Binary Black Hole Coalescence, B.P. Abbott et al, Phys. Rev. Lett. 119, 141101 (2017)

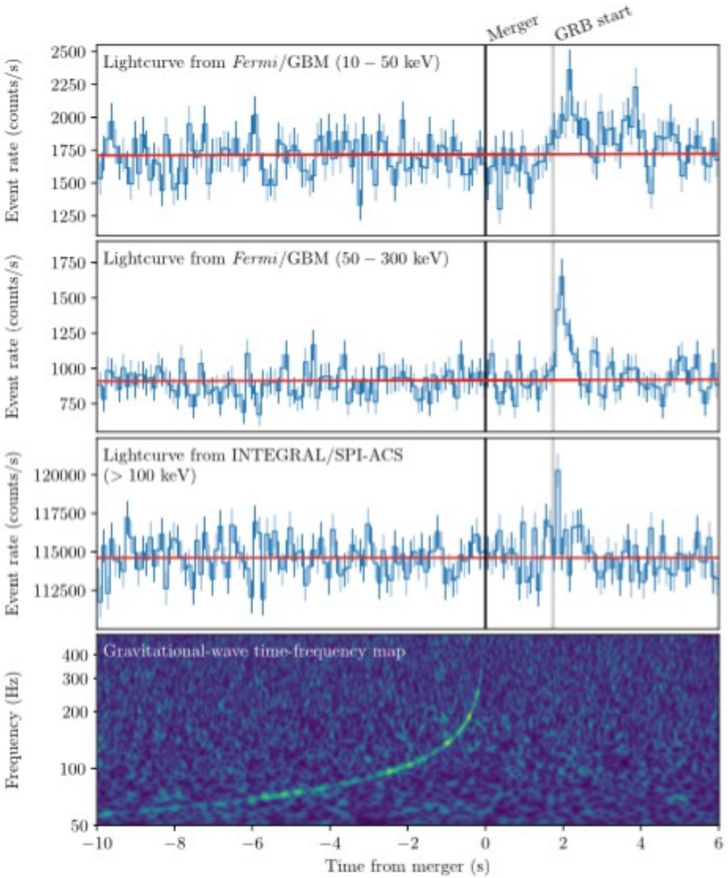


~ 60 deg^2

- ~ x 10 better localization
- first tests of GW polarization

Tests of GR : gravitational-wave properties

~ 130 millions light-year travel (at the speed of light)
~ 1.7 seconds delay betwen GRB and GW



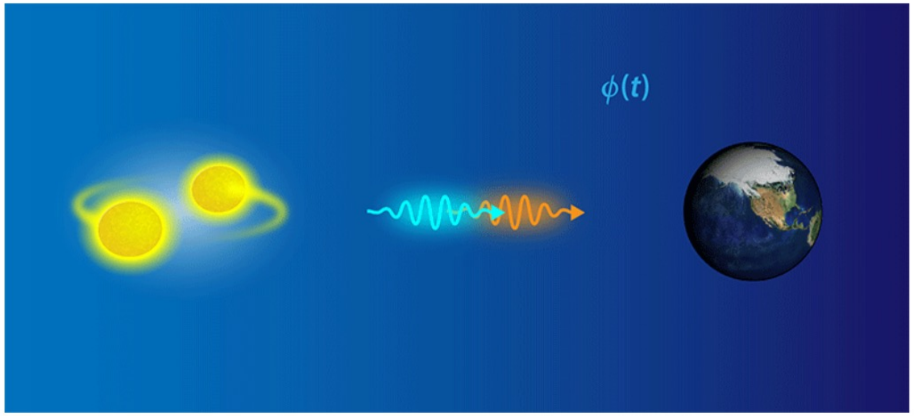
$$-3 \times 10^{-15} \leqslant \frac{\Delta v}{v_{\mathrm{EM}}} \leqslant +7 \times 10^{-16}$$

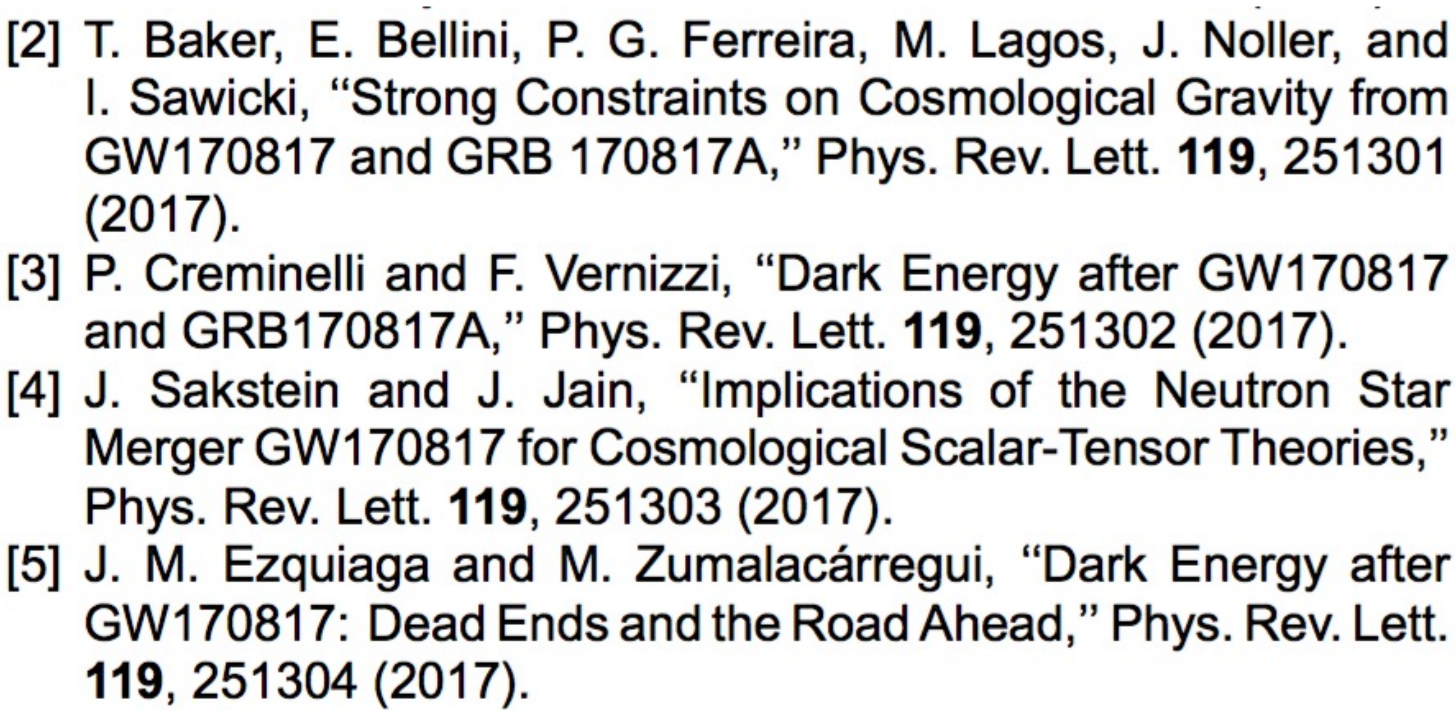
Photons
emitted 10
seconds after

GW and photons
emitted at the
same time

Test of GR: impact of GW170817 on modified gravity theories

Credit
American Physical Society





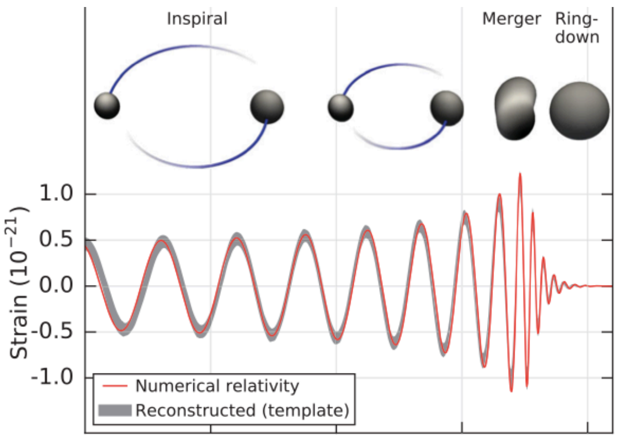
[2] T. Baker, E. Bellini, P. G. Ferreira, M. Lagos, J. Noller, and I. Sawicki, “Strong Constraints on Cosmological Gravity from GW170817 and GRB 170817A,” Phys. Rev. Lett. **119**, 251301 (2017).

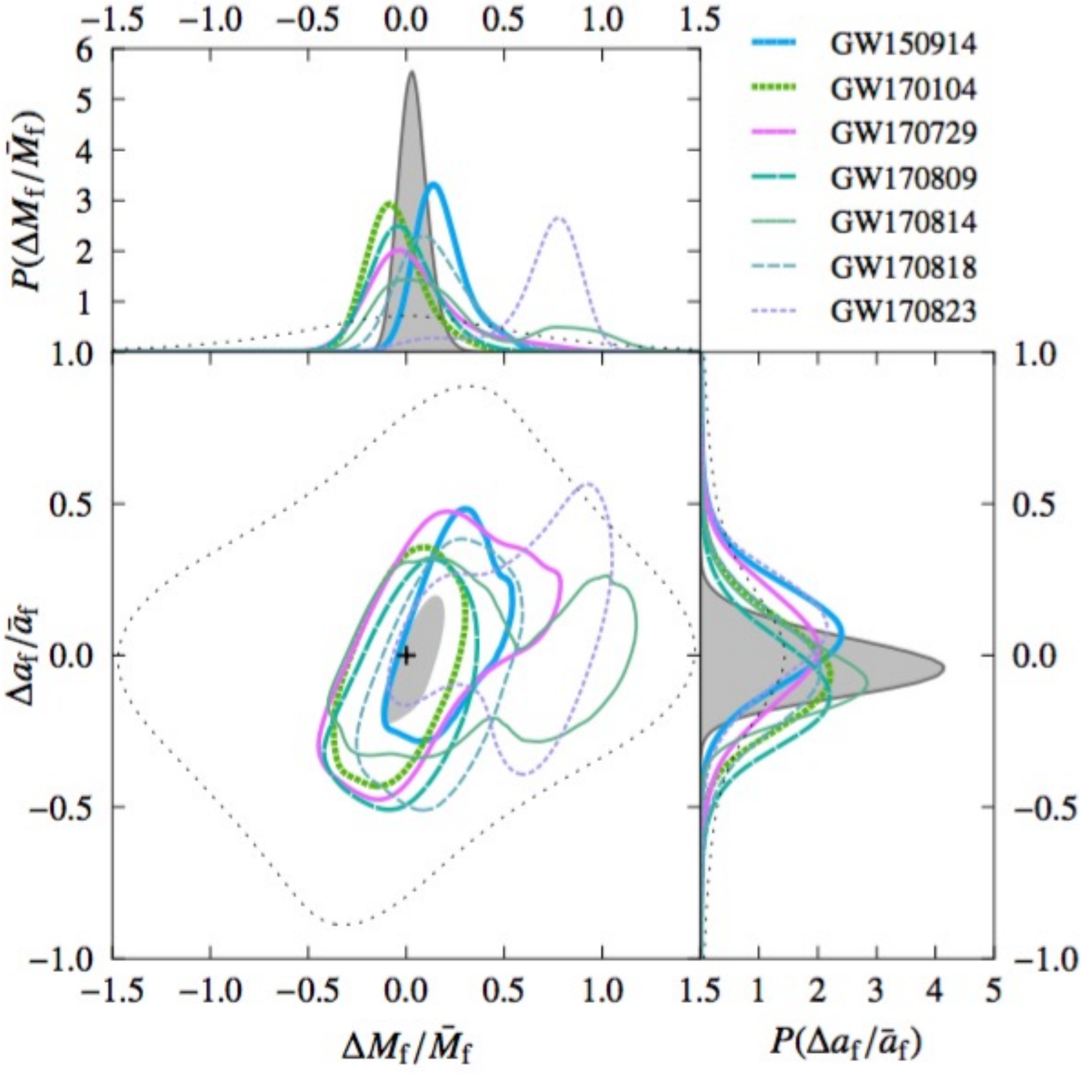
[3] P. Creminelli and F. Vernizzi, “Dark Energy after GW170817 and GRB170817A,” Phys. Rev. Lett. **119**, 251302 (2017).

[4] J. Sakstein and J. Jain, “Implications of the Neutron Star Merger GW170817 for Cosmological Scalar-Tensor Theories,” Phys. Rev. Lett. **119**, 251303 (2017).

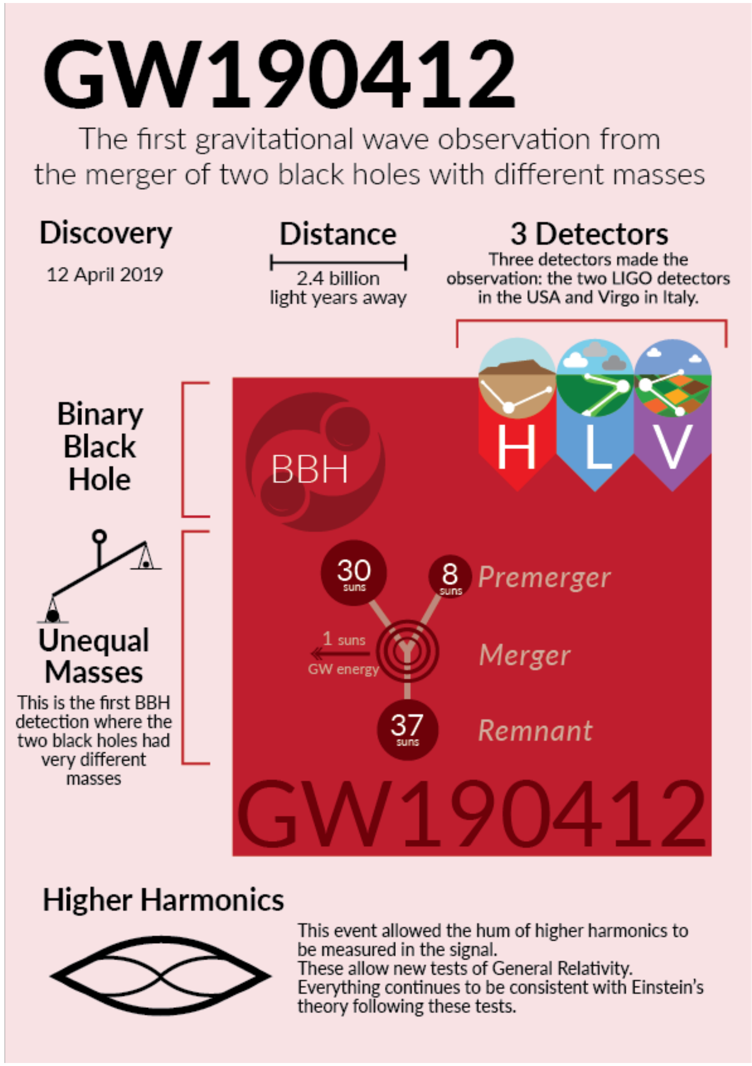
[5] J. M. Ezquiaga and M. Zumalacárregui, “Dark Energy after GW170817: Dead Ends and the Road Ahead,” Phys. Rev. Lett. **119**, 251304 (2017).

Consistency check: high and low waveform





GW190412: BBH with unequal masses



GW190412

The first gravitational wave observation from the merger of two black holes with different masses

Discovery

12 April 2019

Distance

2.4 billion light years away

3 Detectors

Three detectors made the observation: the two LIGO detectors in the USA and Virgo in Italy.

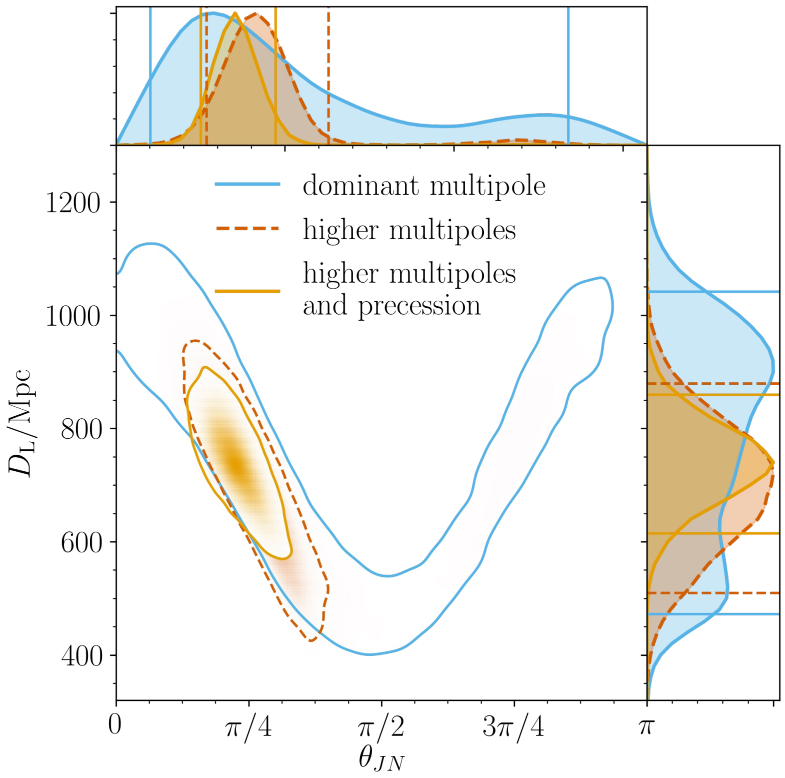
Binary Black Hole

Unequal Masses

This is the first BBH detection where the two black holes had very different masses

Higher Harmonics

This event allowed the hum of higher harmonics to be measured in the signal.
These allow new tests of General Relativity.
Everything continues to be consistent with Einstein's theory following these tests.



GW190412: Observation of a Binary-Black-Hole Coalescence with Asymmetric Masses, LIGO and Virgo Collaborations, arXiv:2004.08342

Summary of the results

- First detection of gravitational-waves
- First test of gravitational-wave polarisation
- Gravitational waves travel at the speed-of-light
- Tesf of the emission at higher harmonics of GW
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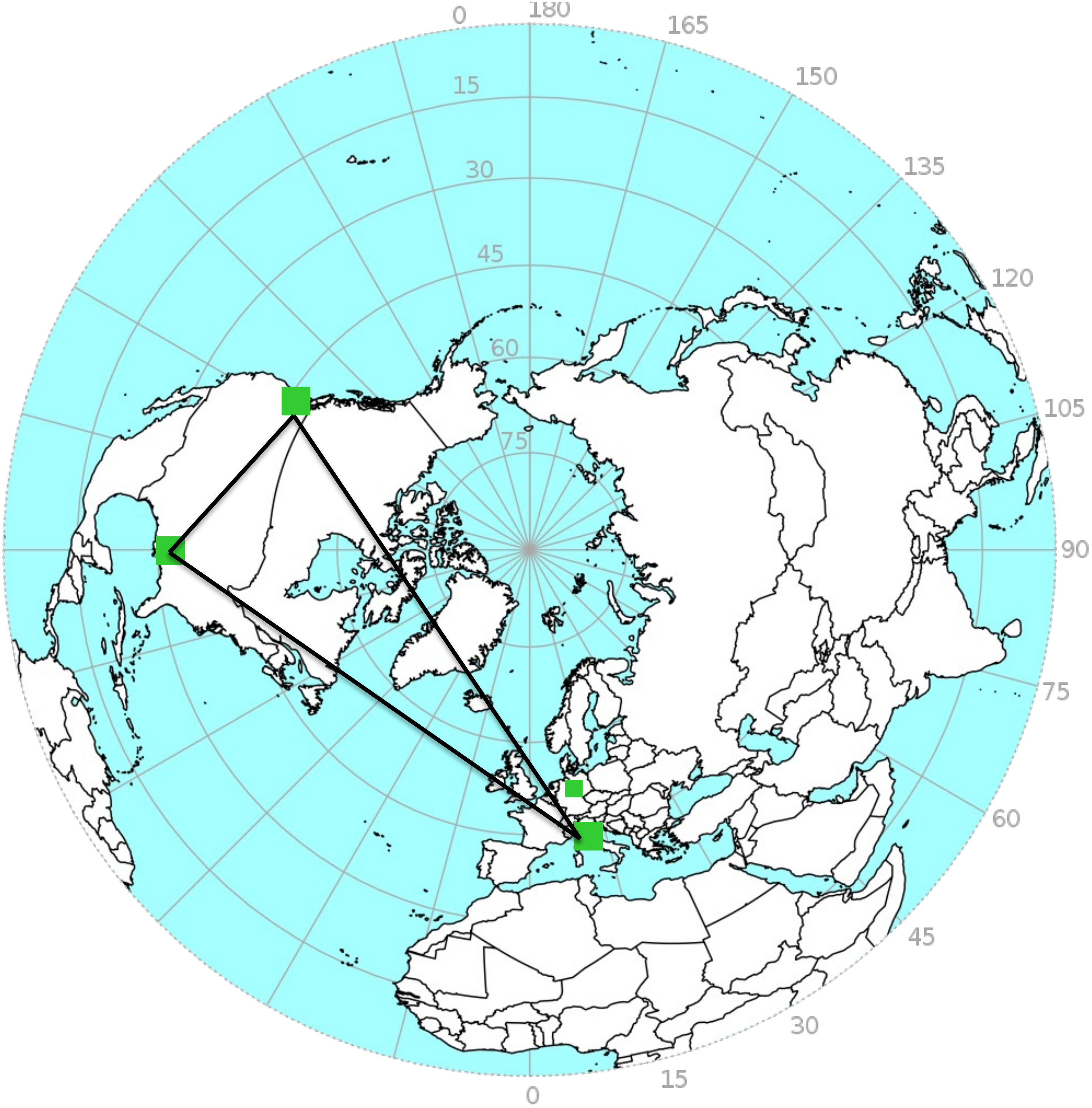
- First measurements on NS tidal deformability
- Link between GRB and neutron star mergers
- Kilonova powered by binary NS merger

- Alternative measurement of Hubble constant
- Speed of gravity → consequences on gravity alternative theories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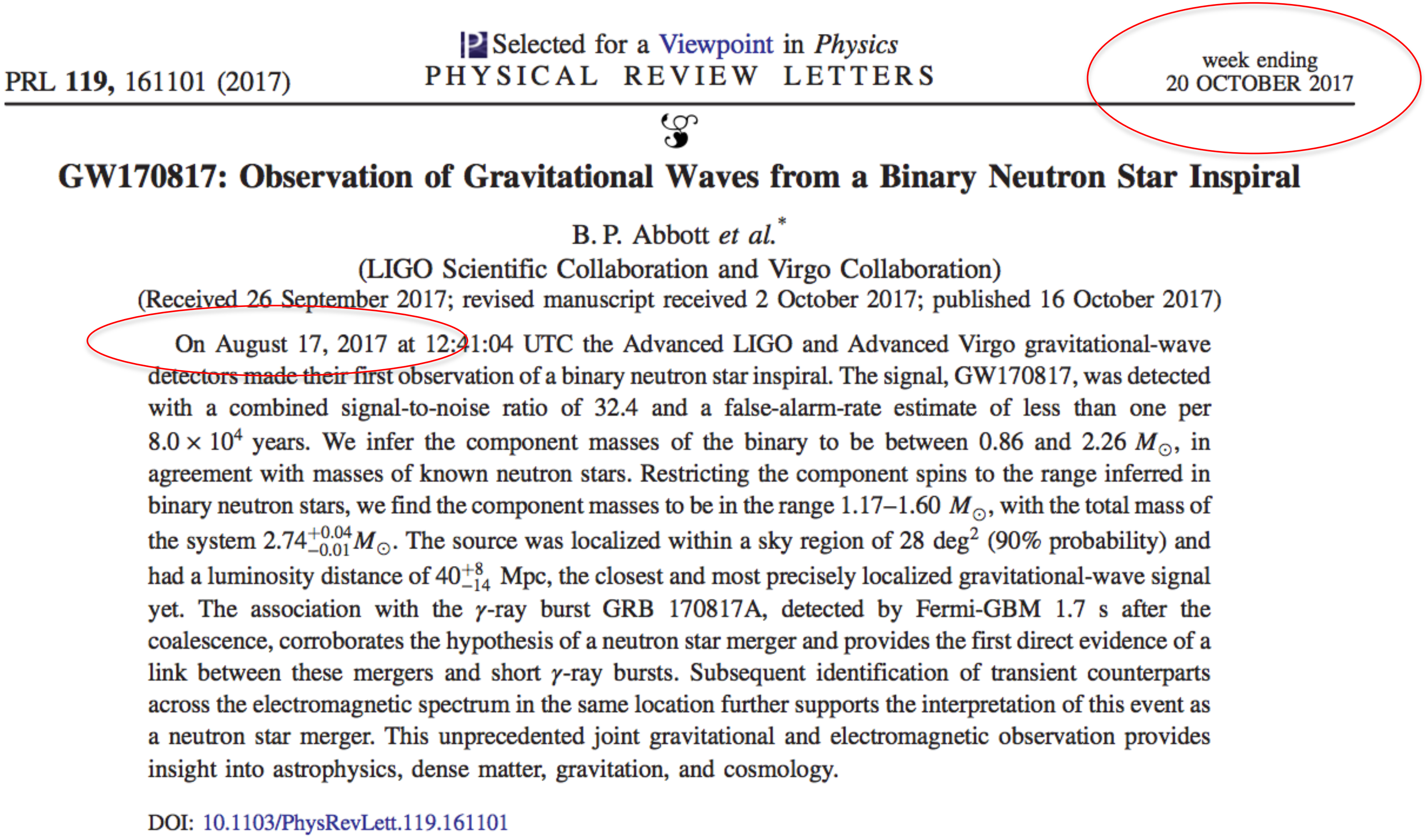


Selected for a Viewpoint in *Physics*

PRL **119,** 161101 (2017) PHYSICAL REVIEW LETTERS week ending 20 OCTOBER 2017

GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral

B. P. Abbott *et al.*[*]

(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 26 September 2017; revised manuscript received 2 October 2017; published 16 October 2017)

On August 17, 2017 at 12:41:04 UTC the Advanced LIGO and Advanced Virgo gravitational-wave detectors made their first observation of a binary neutron star inspiral. The signal, GW170817, was detected with a combined signal-to-noise ratio of 32.4 and a false-alarm-rate estimate of less than one per 8.0×10^4 years. We infer the component masses of the binary to be between 0.86 and 2.26 $M_\odot$, in agreement with masses of known neutron stars. Restricting the component spins to the range inferred in binary neutron stars, we find the component masses to be in the range 1.17–1.60 $M_\odot$, with the total mass of the system $2.74^{+0.04}_{-0.01} M_\odot$. The source was localized within a sky region of 28 deg^2 (90% probability) and had a luminosity distance of 40^{+8}_{-14} Mpc, the closest and most precisely localized gravitational-wave signal yet. The association with the γ-ray burst GRB 170817A, detected by Fermi-GBM 1.7 s after the coalescence, corroborates the hypothesis of a neutron star merger and provides the first direct evidence of a link between these mergers and short γ-ray bursts. Subsequent identification of transient counterparts across the electromagnetic spectrum in the same location further supports the interpretation of this event as a neutron star merger. This unprecedented joint gravitational and electromagnetic observation provides insight into astrophysics, dense matter, gravitation, and cosmology.

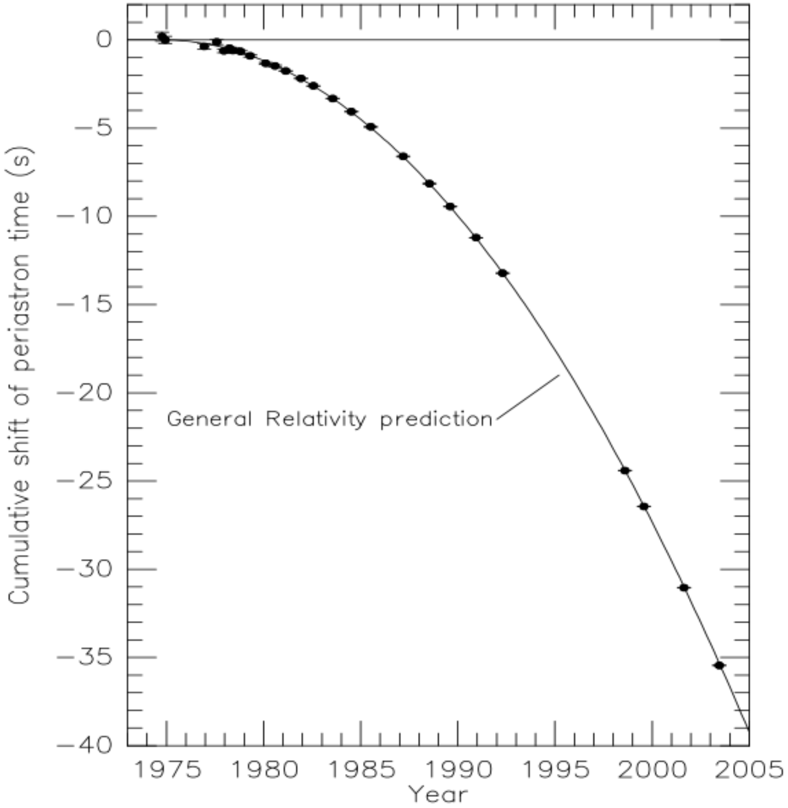
DOI: 10.1103/PhysRevLett.119.161101

Proof of existence of gravitational-waves Observation of NS binary inspirals

Hulse and Taylor
Prix Nobel 1993

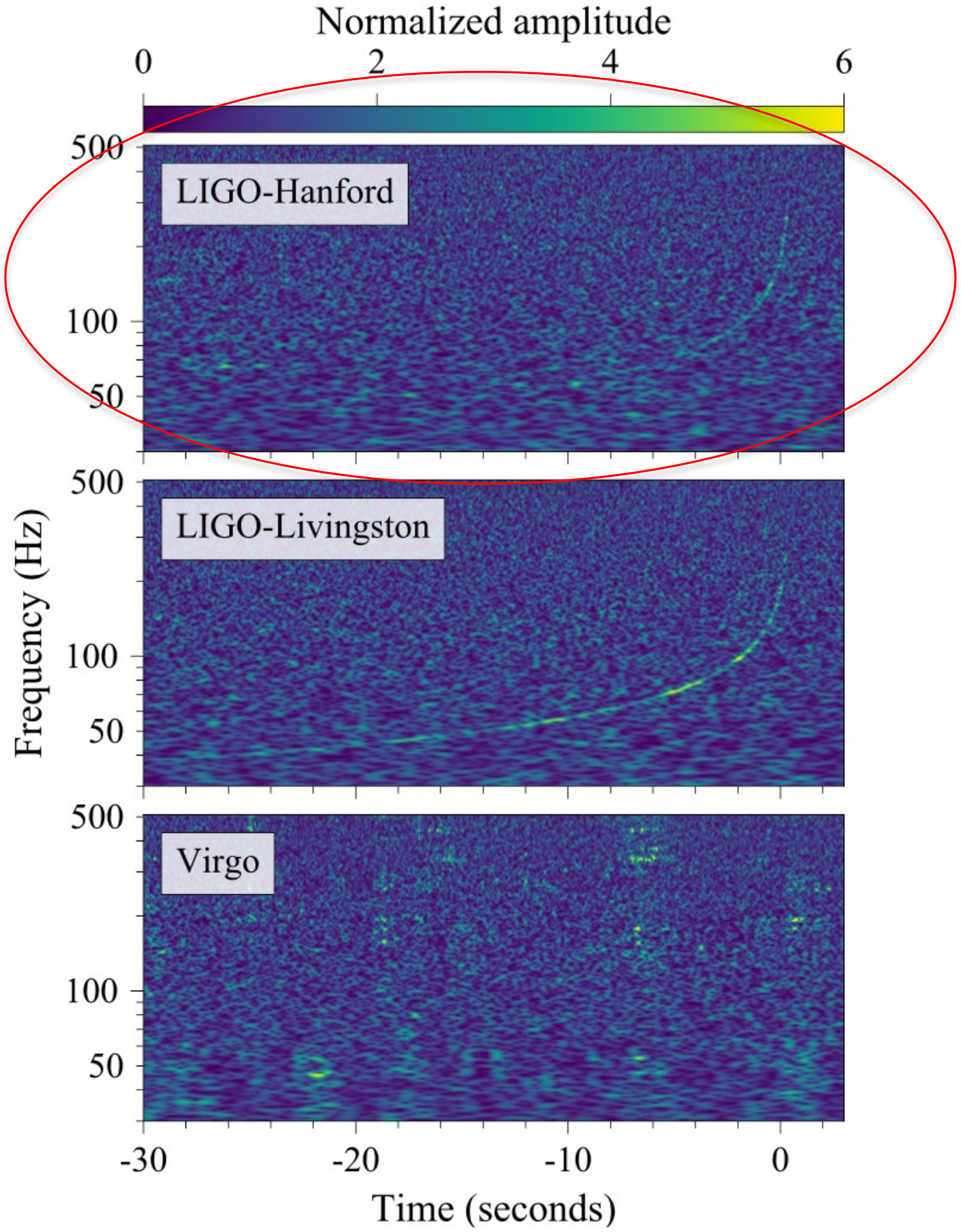
« for the discovery of a new type of pulsar, a discovery that has opened up new possibilities for the study of gravitation »

Binary Pulsar P1913+16
energy loss

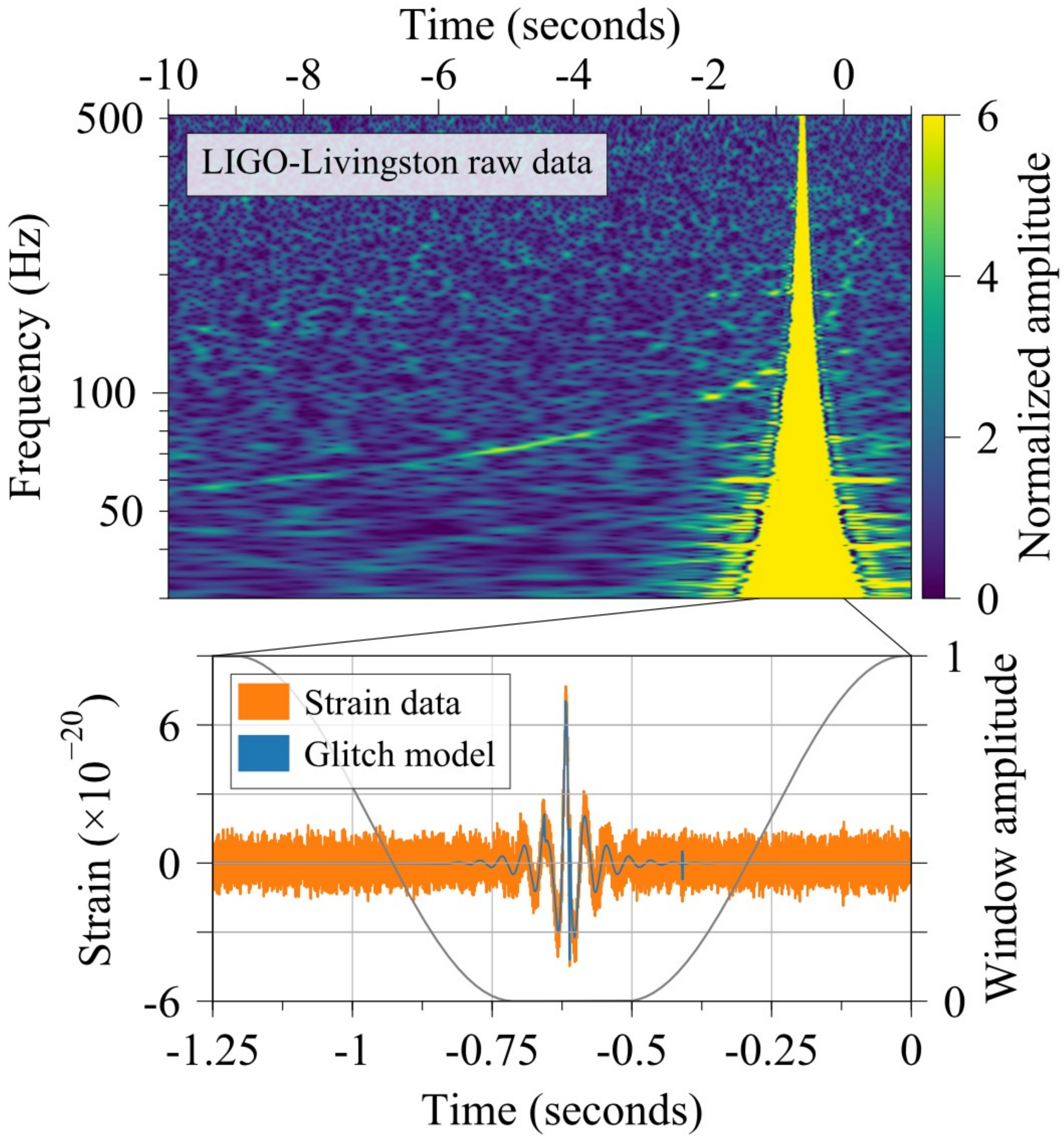


Weisberg et Taylor

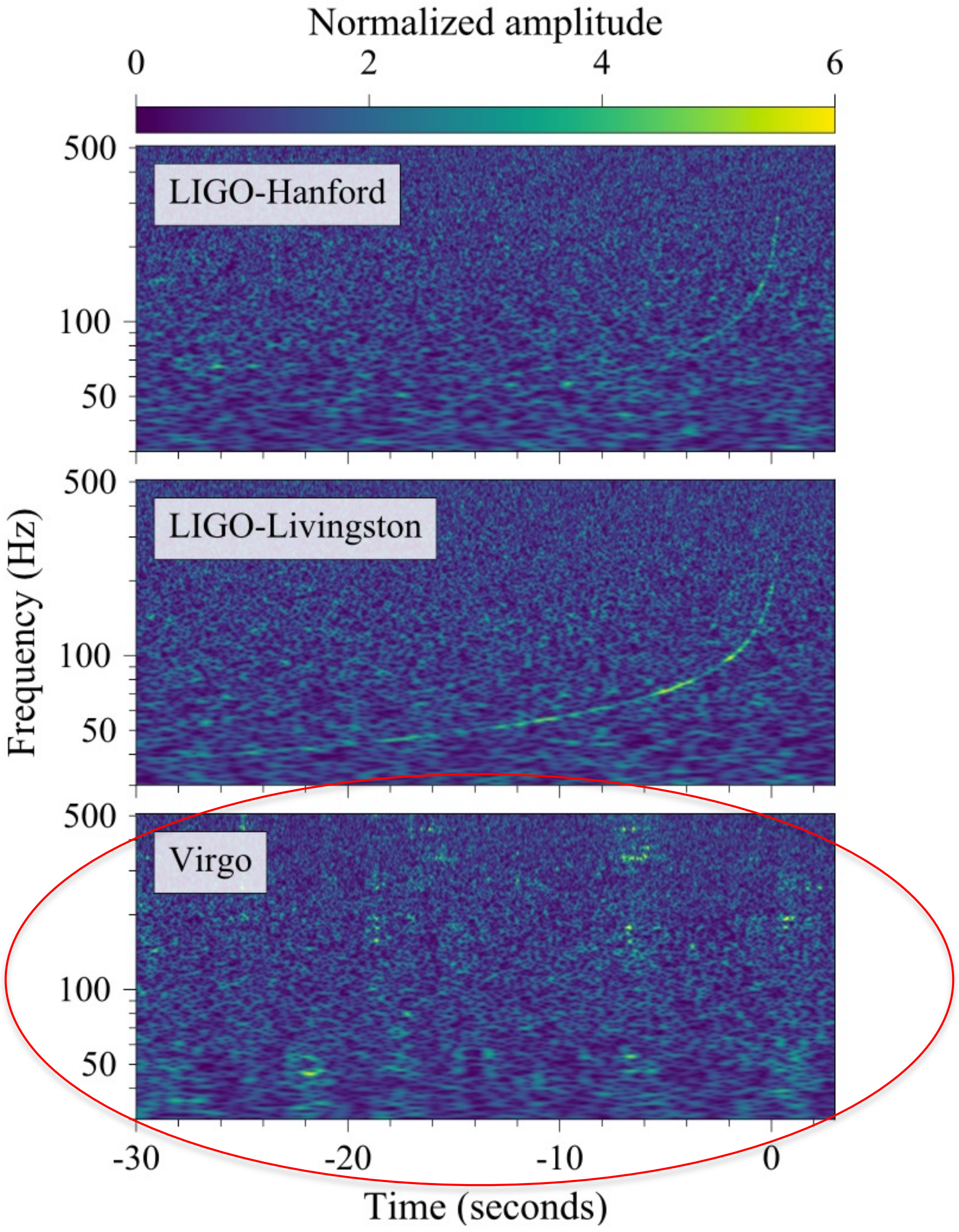
The signal in Hanford

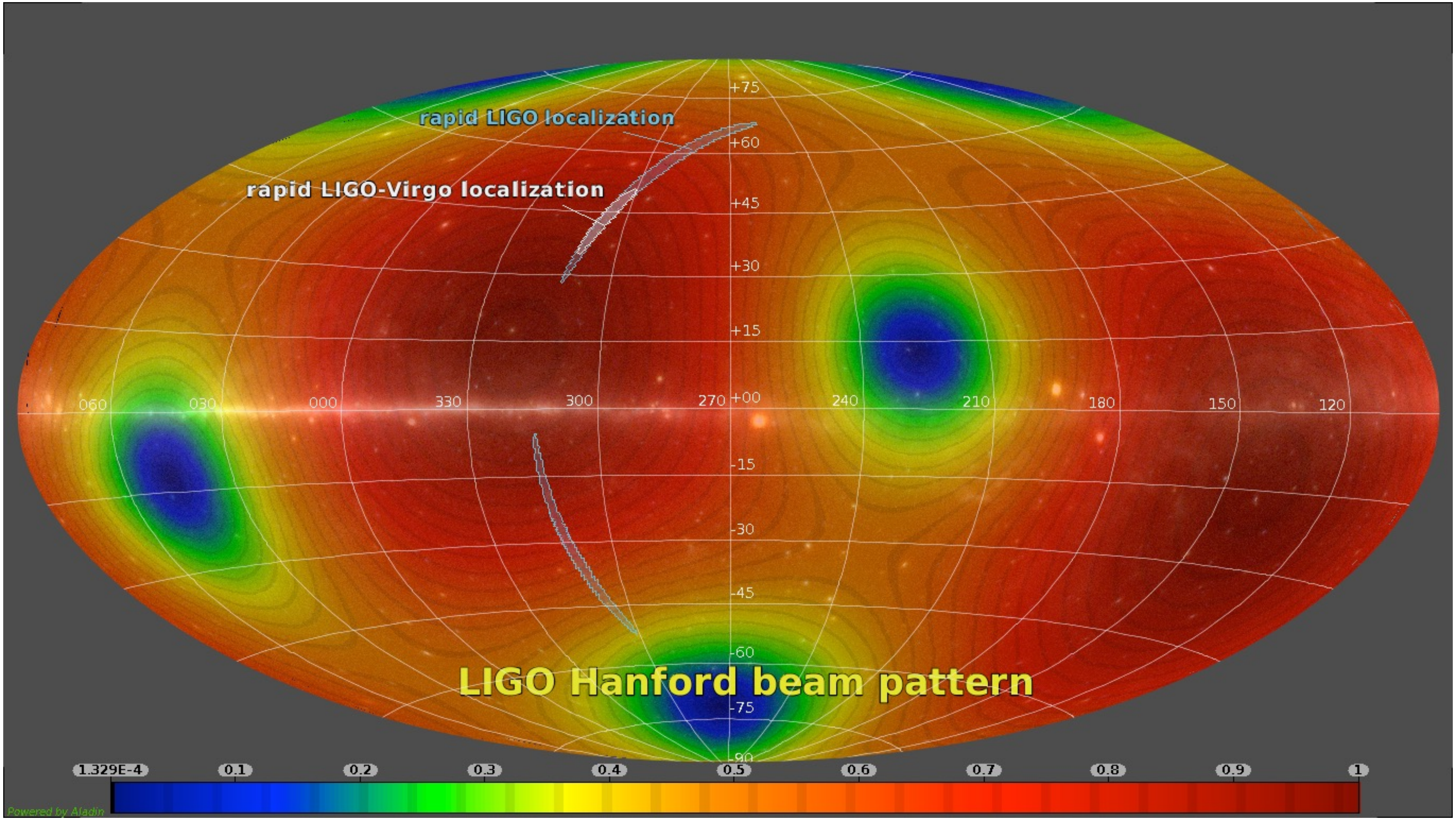


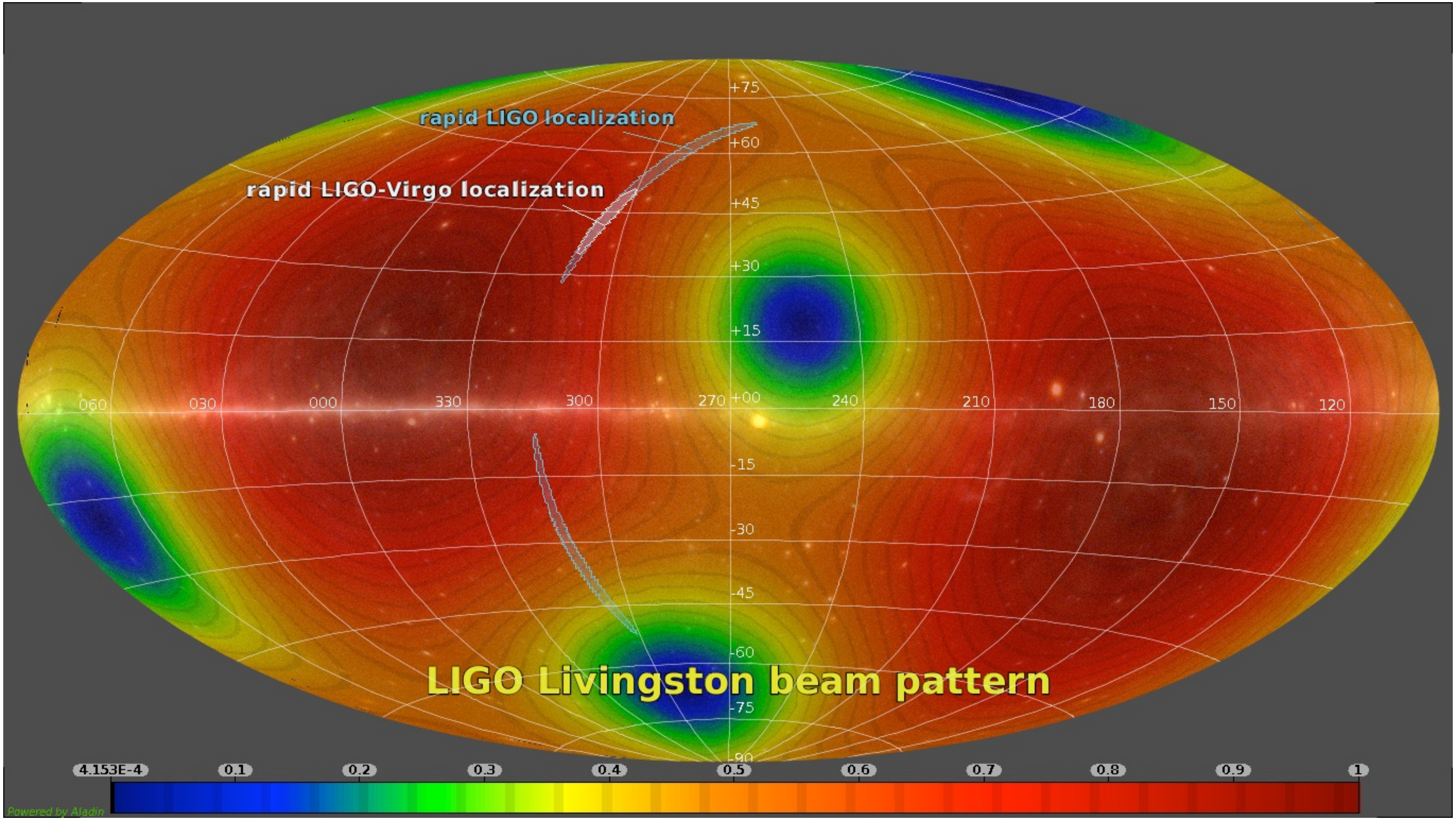
The instrumental glitch in Livingston



The signal in Virgo




rapid LIGO localization
rapid LIGO-Virgo localization
LIGO Hanford beam pattern
+75
+60
+45
+30
+15
+00
-15
-30
-45
-60
-75
-90
060
030
000
330
300
270
240
210
180
150
120
1.329E-4
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Powered by Aladin


rapid LIGO localization
rapid LIGO-Virgo localization
+75
+60
+45
+30
+15
+00
-15
-30
-45
-60
-75
-90
060
030
000
330
300
270
240
210
180
150
120
LIGO Livingston beam pattern
4.153E-4
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0.3
0.4
0.5
0.6
0.7
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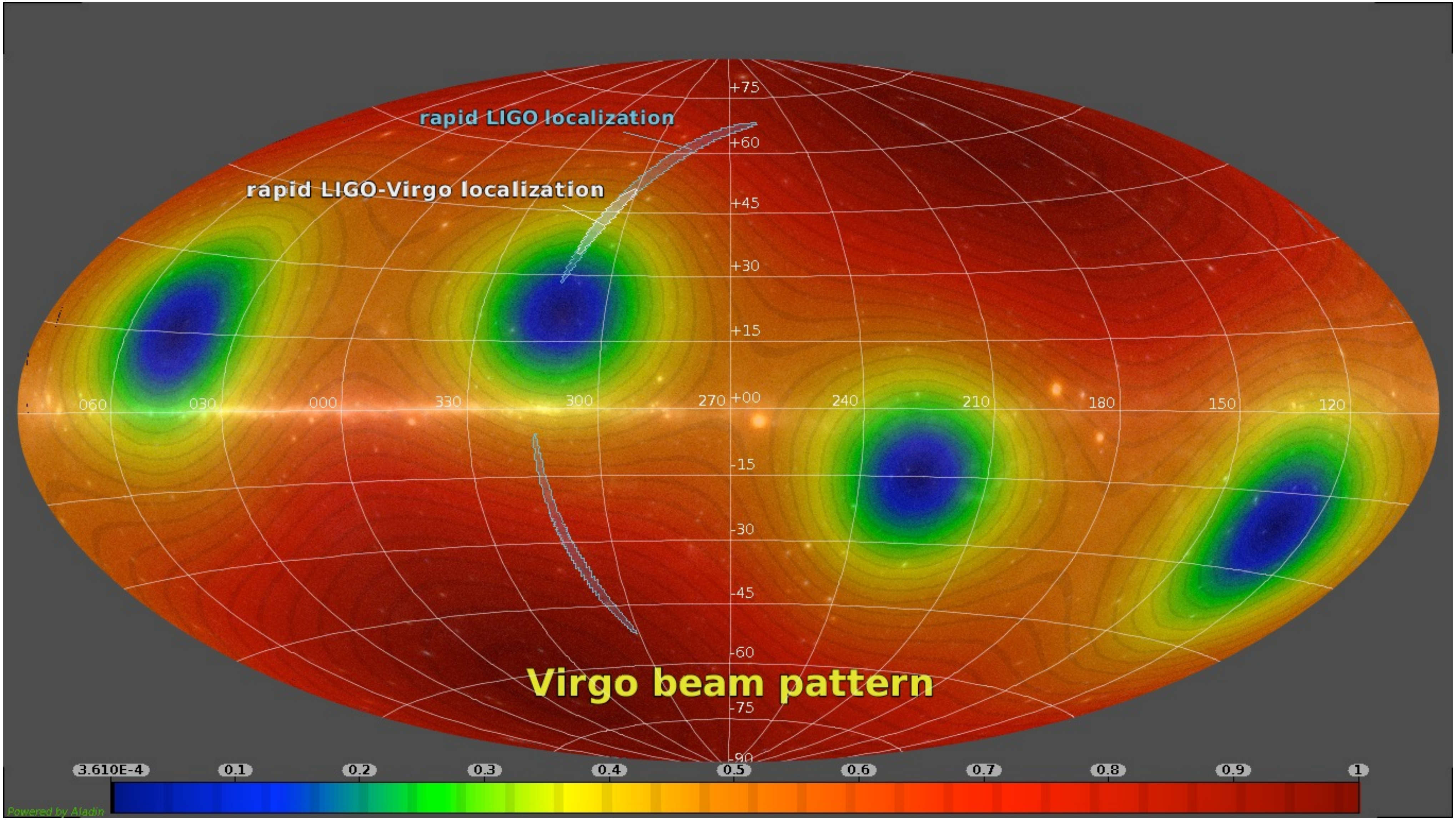
Powered by Aladin


rapid LIGO localization
rapid LIGO-Virgo localization
Virgo beam pattern
+75
+60
+45
+30
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+00
-15
-30
-45
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-75
-90
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330
300
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240
210
180
150
120
3.610E-4
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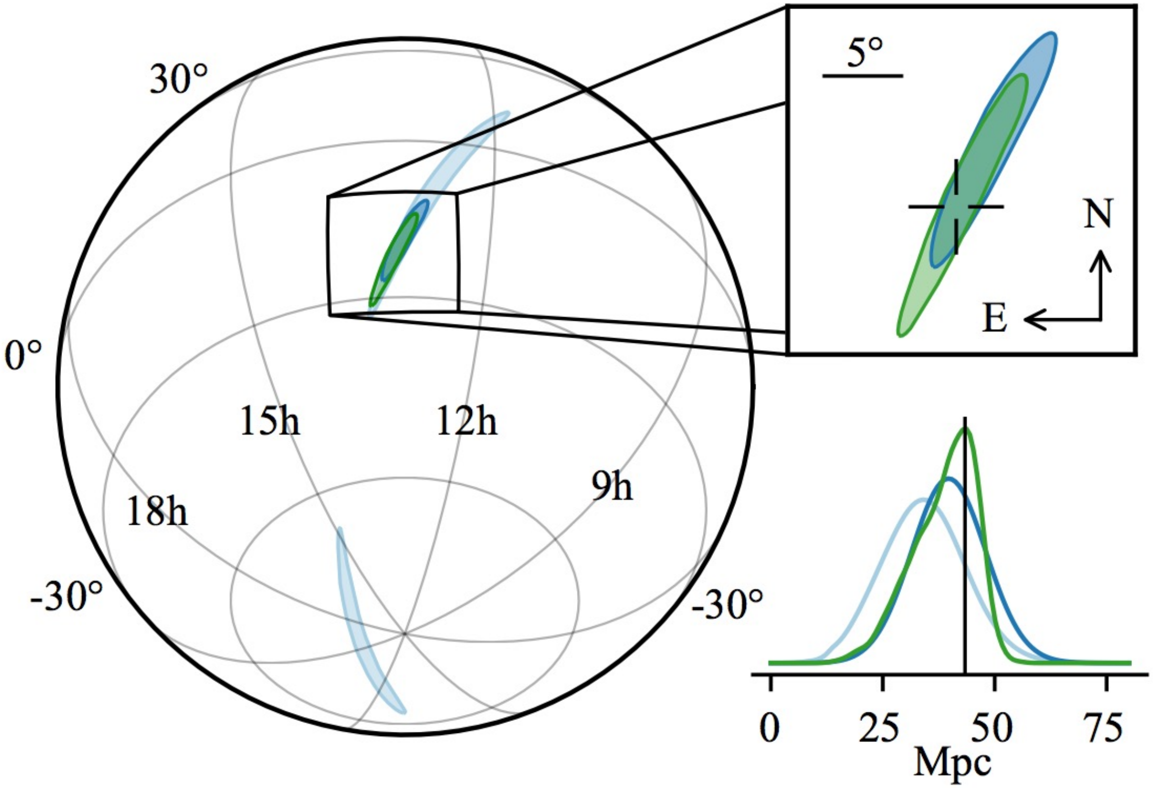
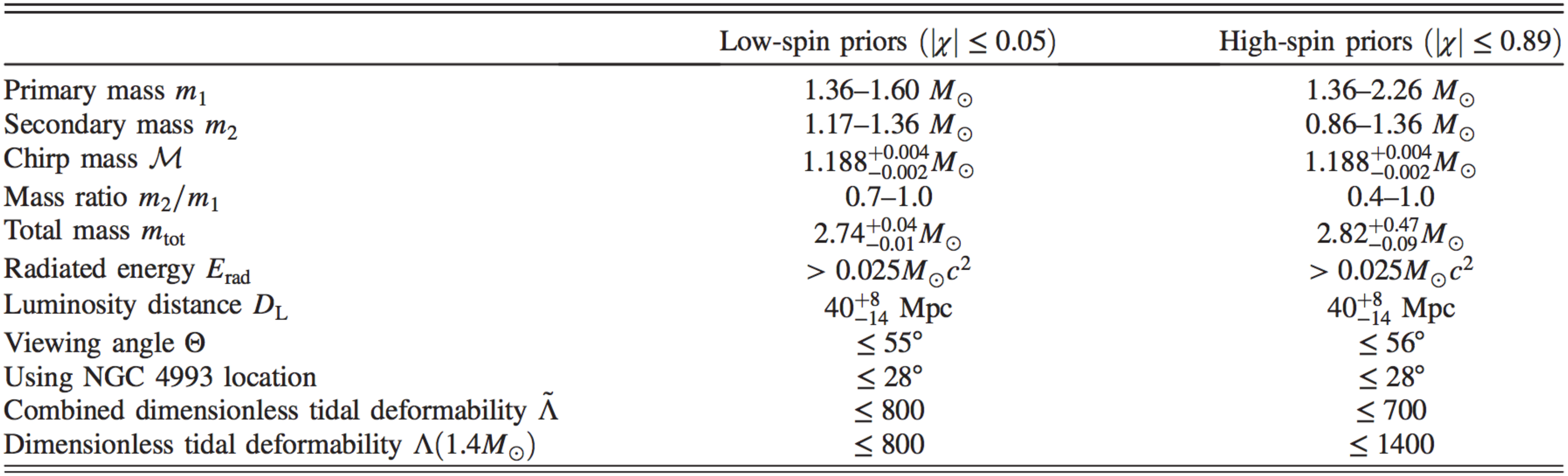
0.5
0.6
0.7
0.8
0.9
1
Powered by Aladin

Final localization



Distance with Virgo/LIGO = 40 +/- 8 Mpc
Distance with Galaxy NGC4993 identification = 40.4 +/- 3.4 Mpc

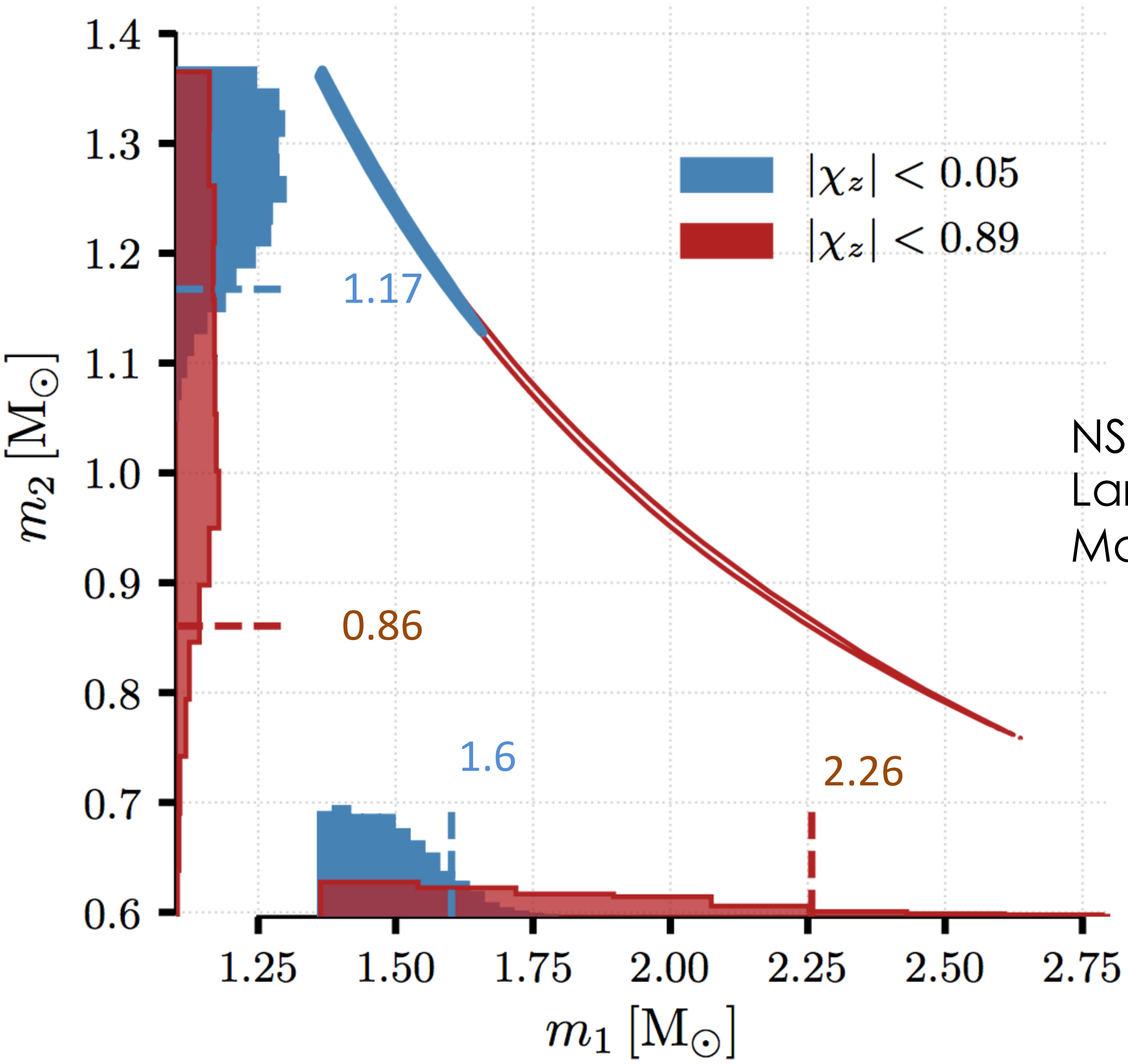
Source parameters



	Low-spin priors ($\|\chi\| \leq 0.05$)	High-spin priors ($\|\chi\| \leq 0.89$)
Primary mass m_1	1.36–1.60 $M_\odot$	1.36–2.26 $M_\odot$
Secondary mass m_2	1.17–1.36 $M_\odot$	0.86–1.36 $M_\odot$
Chirp mass $\mathcal{M}$	$1.188^{+0.004}_{-0.002} M_\odot$	$1.188^{+0.004}_{-0.002} M_\odot$
Mass ratio m_2/m_1	0.7–1.0	0.4–1.0
Total mass m_{tot}	$2.74^{+0.04}_{-0.01} M_\odot$	$2.82^{+0.47}_{-0.09} M_\odot$
Radiated energy E_{rad}	$> 0.025 M_\odot c^2$	$> 0.025 M_\odot c^2$
Luminosity distance D_{L}	40^{+8}_{-14} Mpc	40^{+8}_{-14} Mpc
Viewing angle Θ	$\leq 55°$	$\leq 56°$
Using NGC 4993 location	$\leq 28°$	$\leq 28°$
Combined dimensionless tidal deformability $\tilde{\Lambda}$	≤ 800	≤ 700
Dimensionless tidal deformability $\Lambda(1.4 M_\odot)$	≤ 800	≤ 1400

NS masses in BNS [1.17, ~1.6]
Largest NS mass 2.01
Masses BH in Binaries > 5

Masses : Black-holes or neutron stars



NS masses in BNS [1.17, ~1.6]
Largest NS mass 2.01
Masses BH in Binaries > 5

Source localization and 1^{st} optical detection

t_c + 40 min: 1st LV announcement

candidate BNS associated with GRB

t_c + 1h05 : Fermi report

preliminary localization = 1100 deg^2

t_c + 1h30 min: LV update

H1-only loc. and distance = 37 ± 12 Mpc

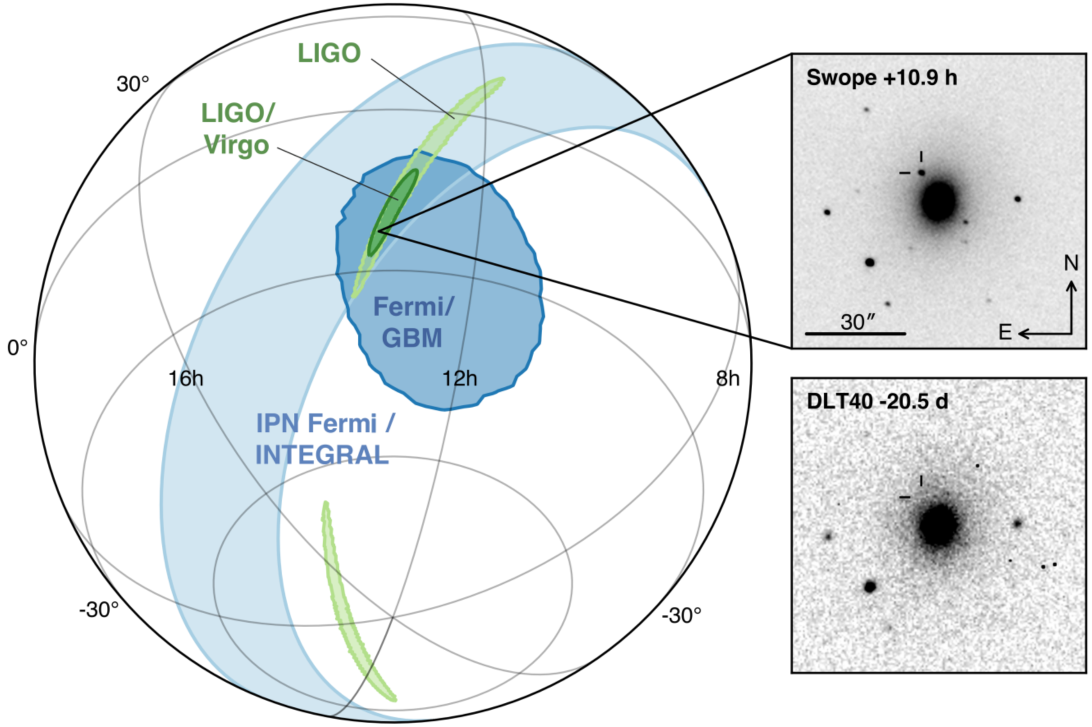
t_c + 5h : LIGO Virgo loc. = 30 deg^2
distance = 40 ± 8 Mpc

Too late for Australia and South Africa

t_c + 11h : Swope detects SSS17a and its host galaxy NGC4993

9th field taken at 20:33 LT, Las Campanas Obs

+ 5 more independent detections in the following hour



t_c + 13h: Swope announcement

GCN Circular #21529

t_c + 17h: 1st report on spectroscopic obs.

(GCN Circular #21547)

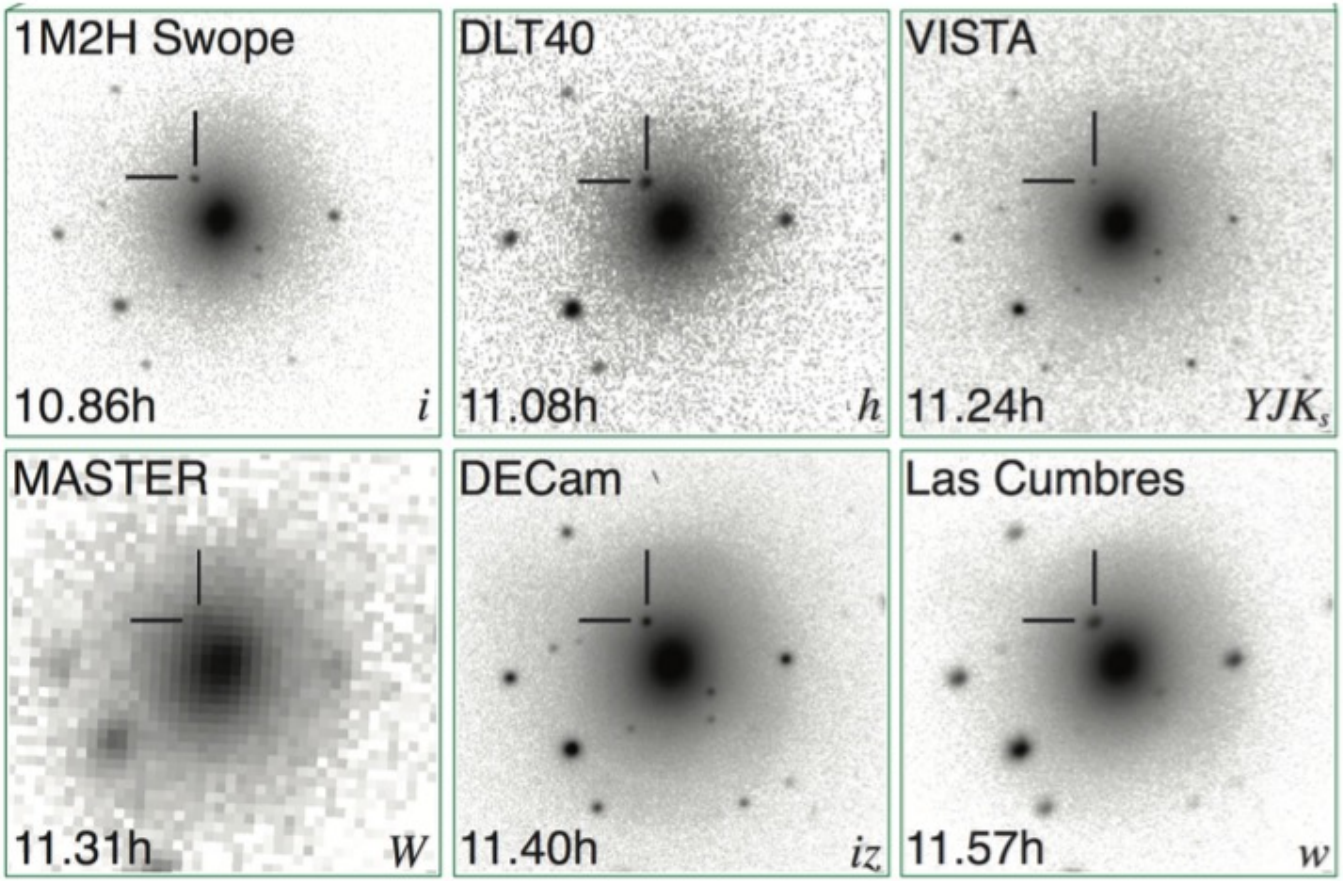
Credit: Eric Chassande-Mottin

The optical counterpart discovery

1m Swope, 3 sq deg
Las Campanas, Chile

PROMPT 0.4m
CTIO, Chile

ESO VISTA 4.1m, ≥ 2 sq deg
Paranal Obs, Chile

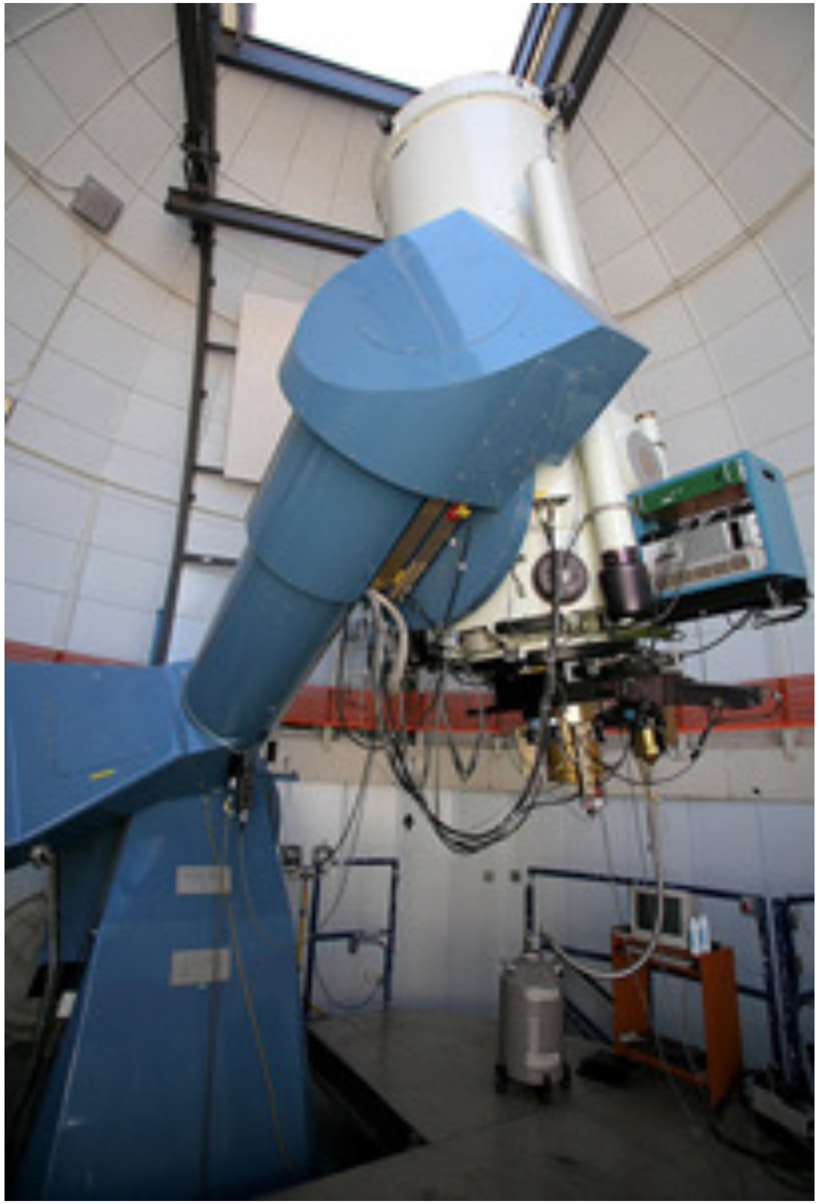


0.4m
OAFA, Argentina

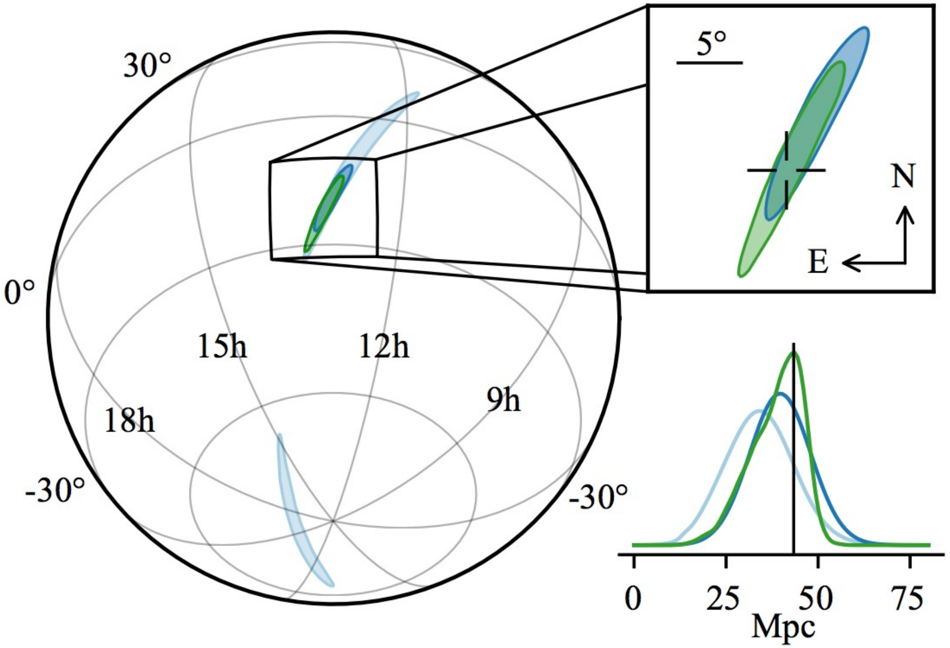
Blanco 4m – 3 sq deg
CTIO, Chile

1m – 0.2 sq deg
CTIO, Chile

Swope telescope – Las campanas

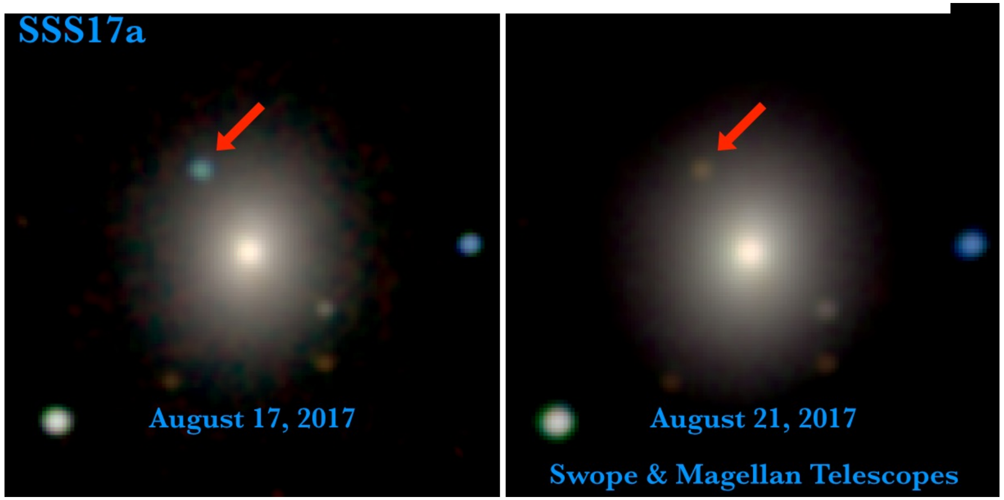


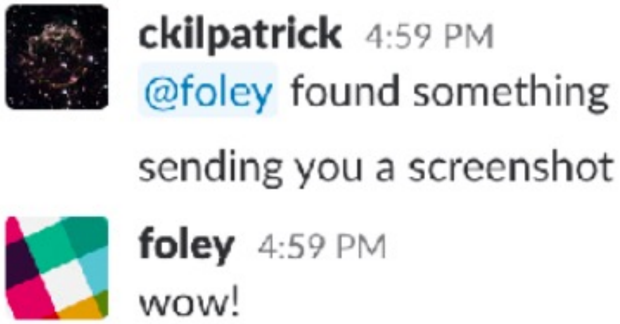
The galaxy identification and the kilonova



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

Properties of the Binary Neutron Star Merger GW170817, B. P. Abbott et al., Phys. Rev. X 9, 011001 (2019)





ckilpatrick 4:59 PM
@foley found something
sending you a screenshot

foley 4:59 PM
wow!

https://ziggy.ucolick.org/sss17a/

HST images of the kilonova

THE ASTROPHYSICAL JOURNAL LETTERS, 848:L27 (9pp), 2017 October 20 Tanvir et al

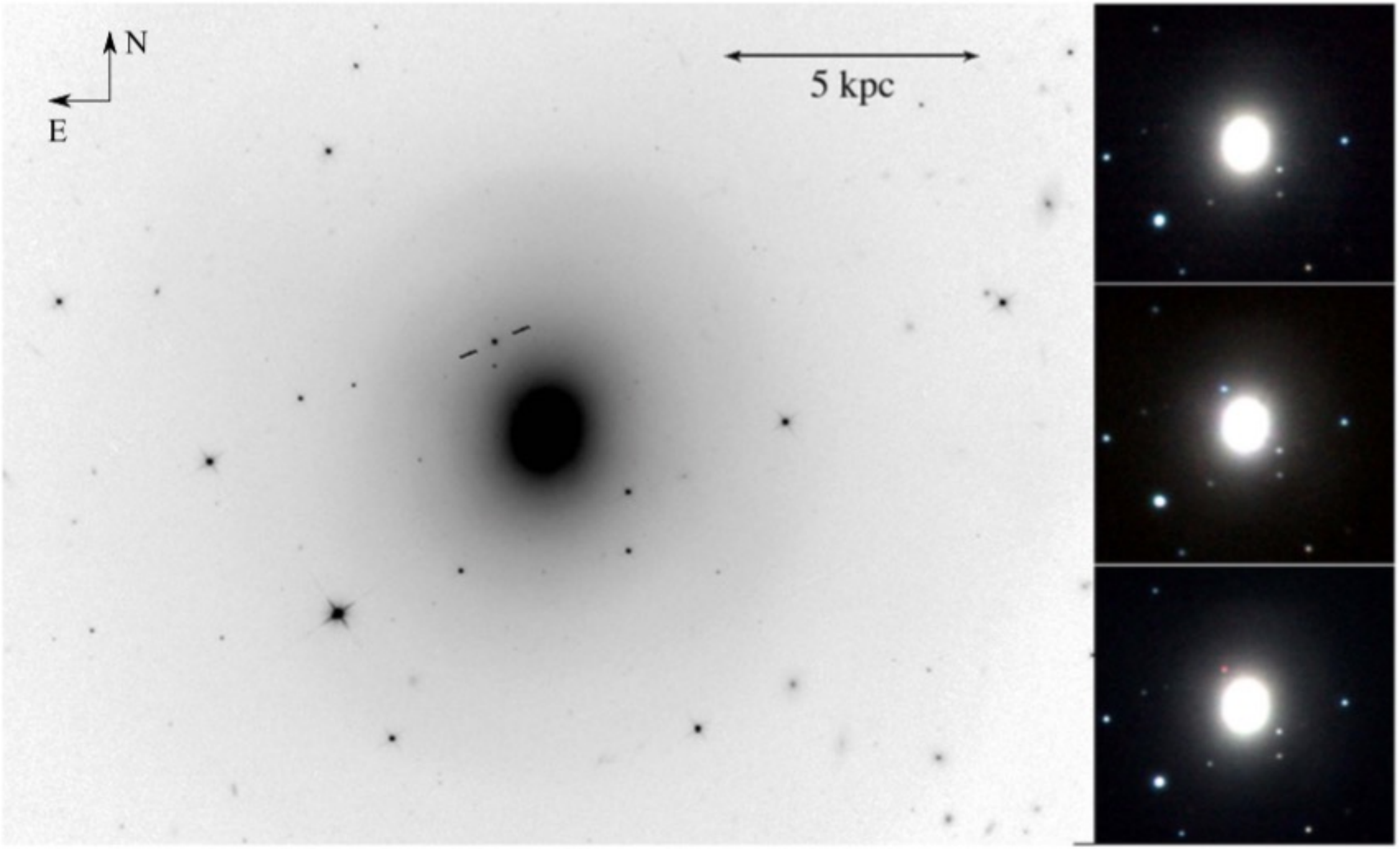
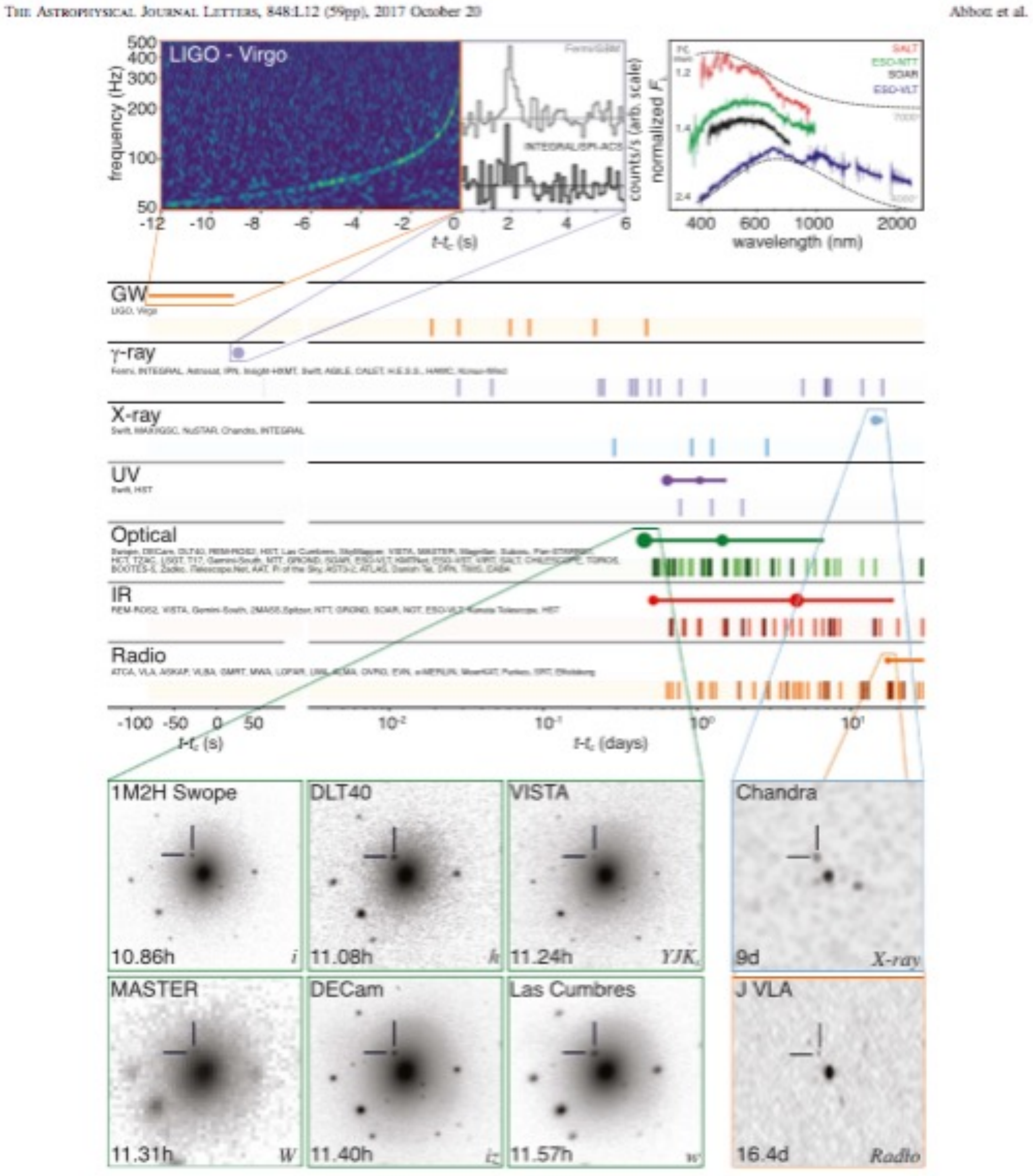


Figure 1. Main panel shows the first-epoch F110W *HST*/WFC3-IR image of the field of AT2017gfo indicating its location within NGC 4993. The physical scale assuming a distance of 40 Mpc is shown. The sequence of panels on the right shows VISTA imaging (RGB rendition created from *Y*, *J*, K_s images) from pre-discovery (2014; top), discovery (middle), and at 8.5 days post-merger as the transient was fading and becoming increasingly red (bottom).

A planetary observation



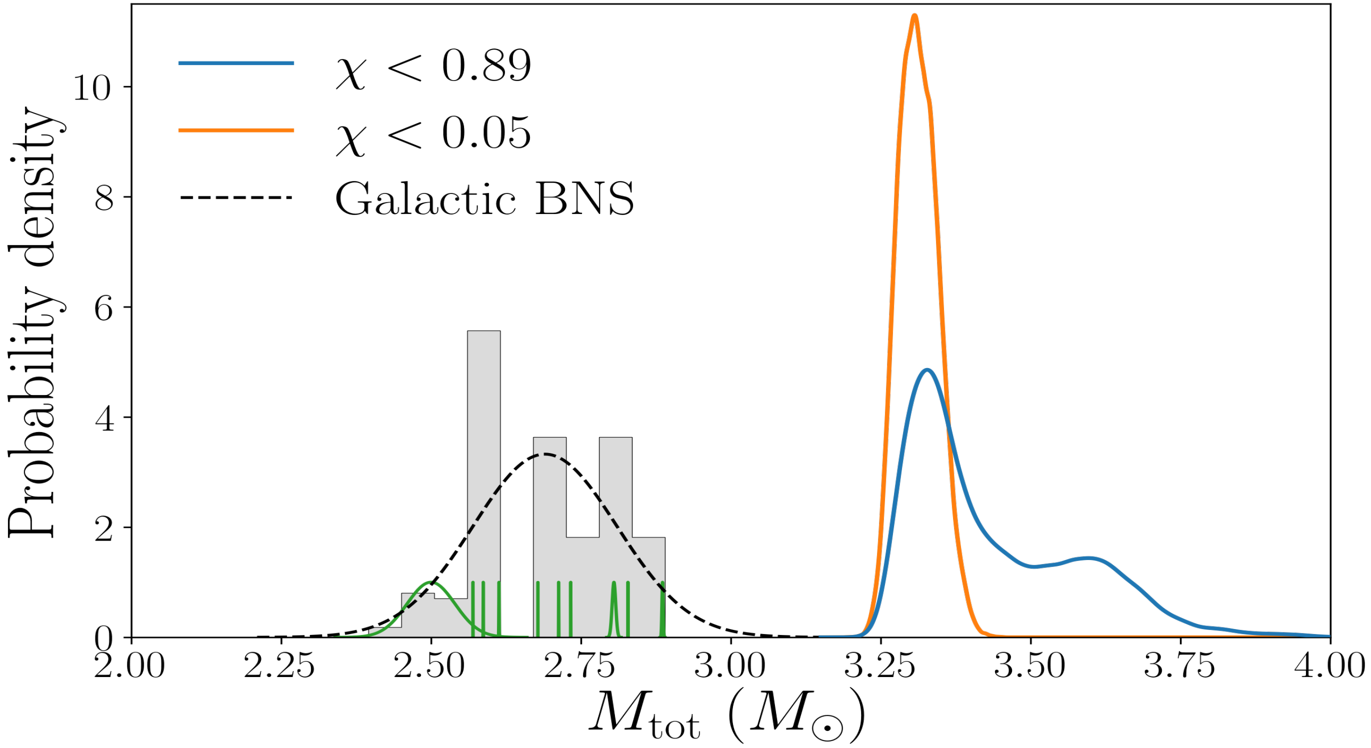
The Astrophysical Journal Letters, 848:L12 (59pp), 2017 October 20

Abbott et al.

Multi-Messenger Observations of a Binary Neutron Star Merger,
B.P.Abbott, et al. (Virgo and LIGO and other astrophysics group)
Astrophys. J. Lett. 848, L12 (2017)

56 teams and collaborations,
3600 authors

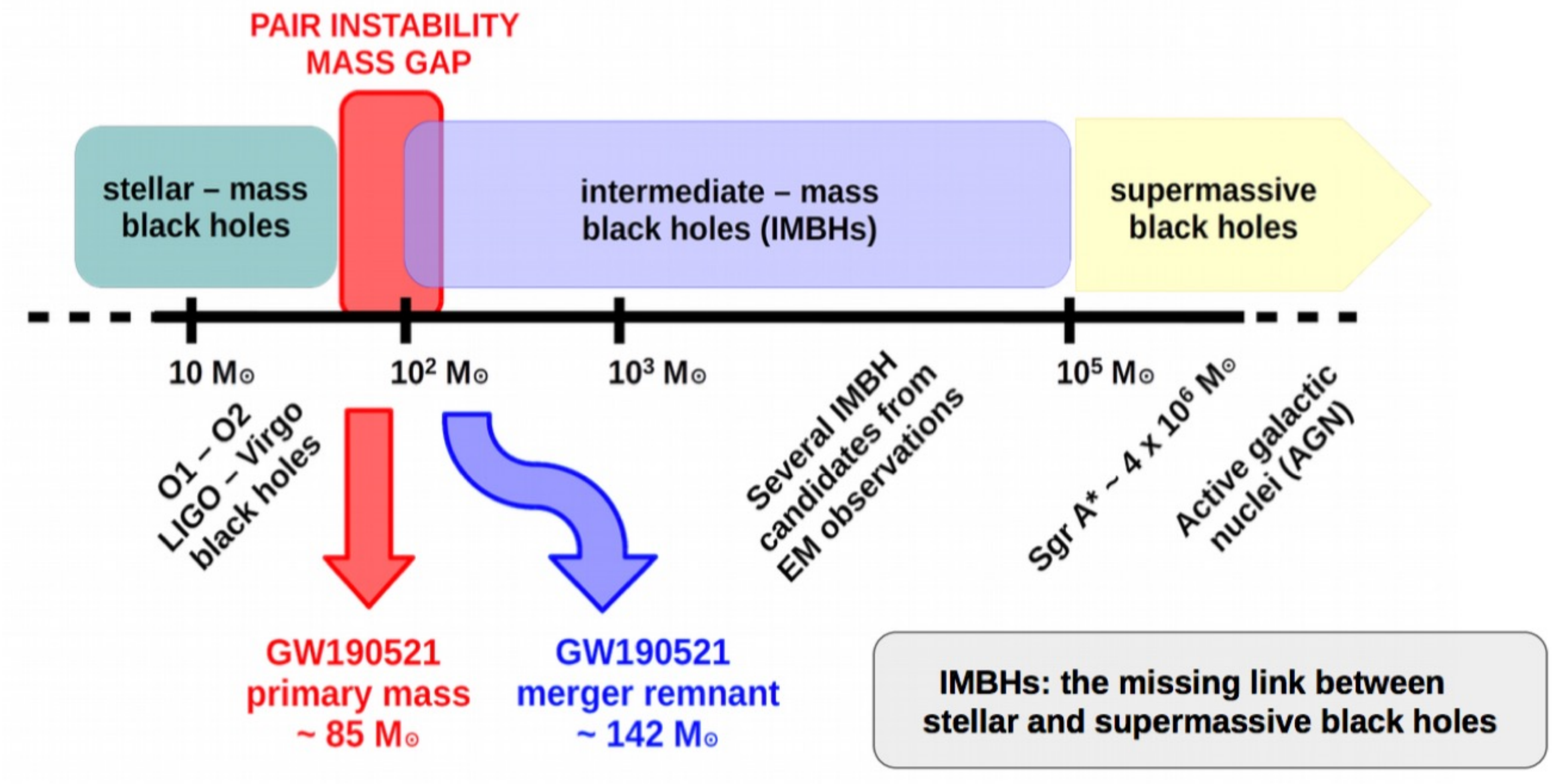
A second BNS
with total mass ~ 3.4 solar masses



GW190425: Observation of a Compact Binary Coalescence with Total Mass ~ 3.4 M, LIGO and Virgo Collaborations, The Astrophysical Journal Letters, 892:L3, 2020

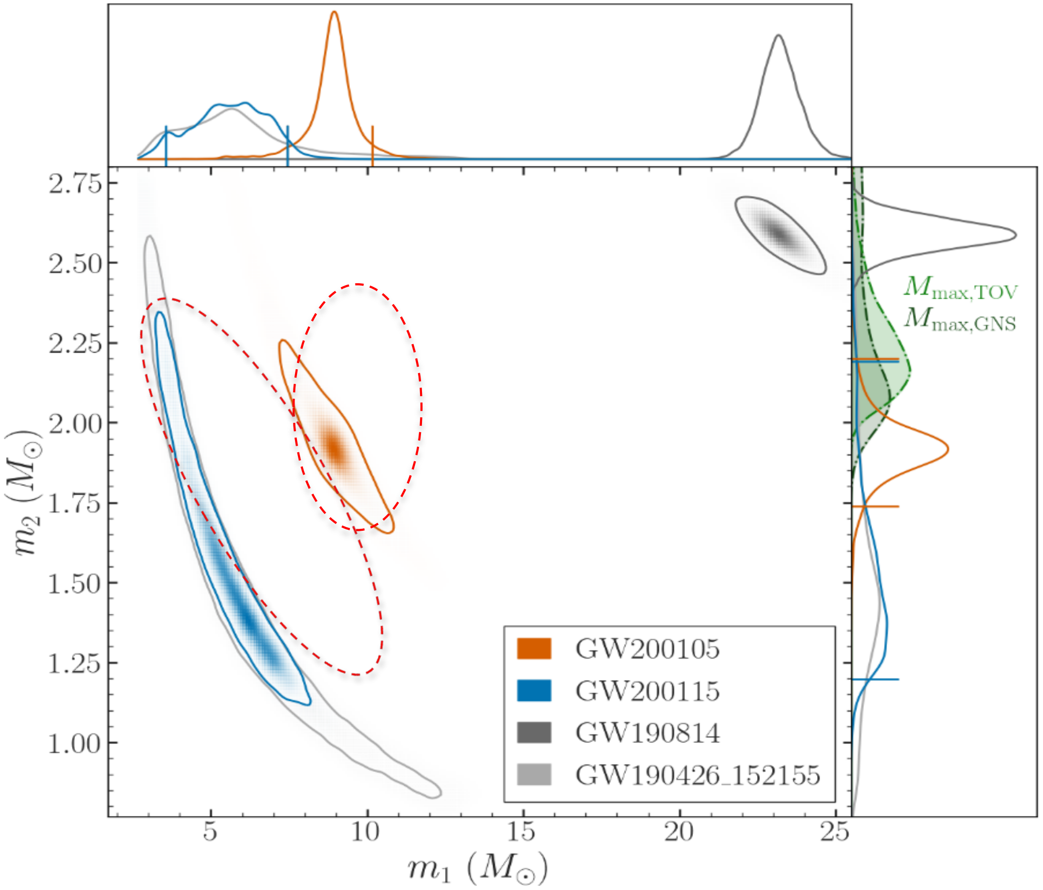
First IMBH and a black-hole in the mass gap

GW190521: BBH merger with component masses ~ 66M⨀ and ~ 85M⨀. The final BH is 142 M⨀ - the first intermediate-mass black-hole



Credit: LIGO/Virgo

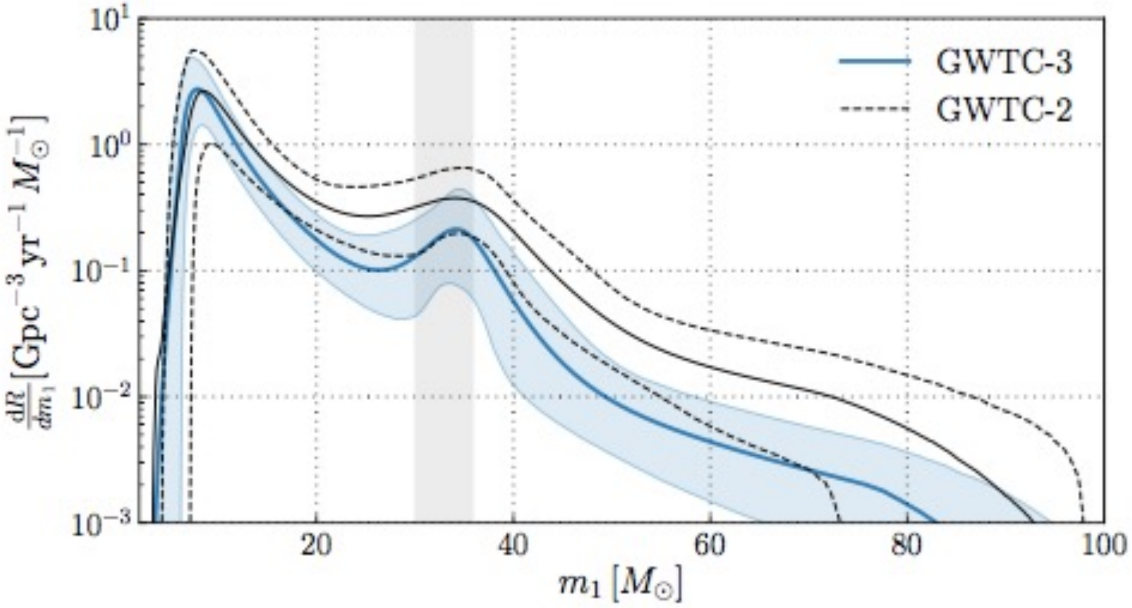
NS-BH systems



Observation of Gravitational Waves from Two Neutron Star–Black Hole Coalescences,
LIGO/Virgo/KAGRA Collaborations
The Astrophysical Journal Letters,
Volume 915, Number 1 (2021)

- GW200105 - 8.9 and 1.9 solar masses
- GW200115 – 5.7 and 1.5 solar masses

Black-hole populations

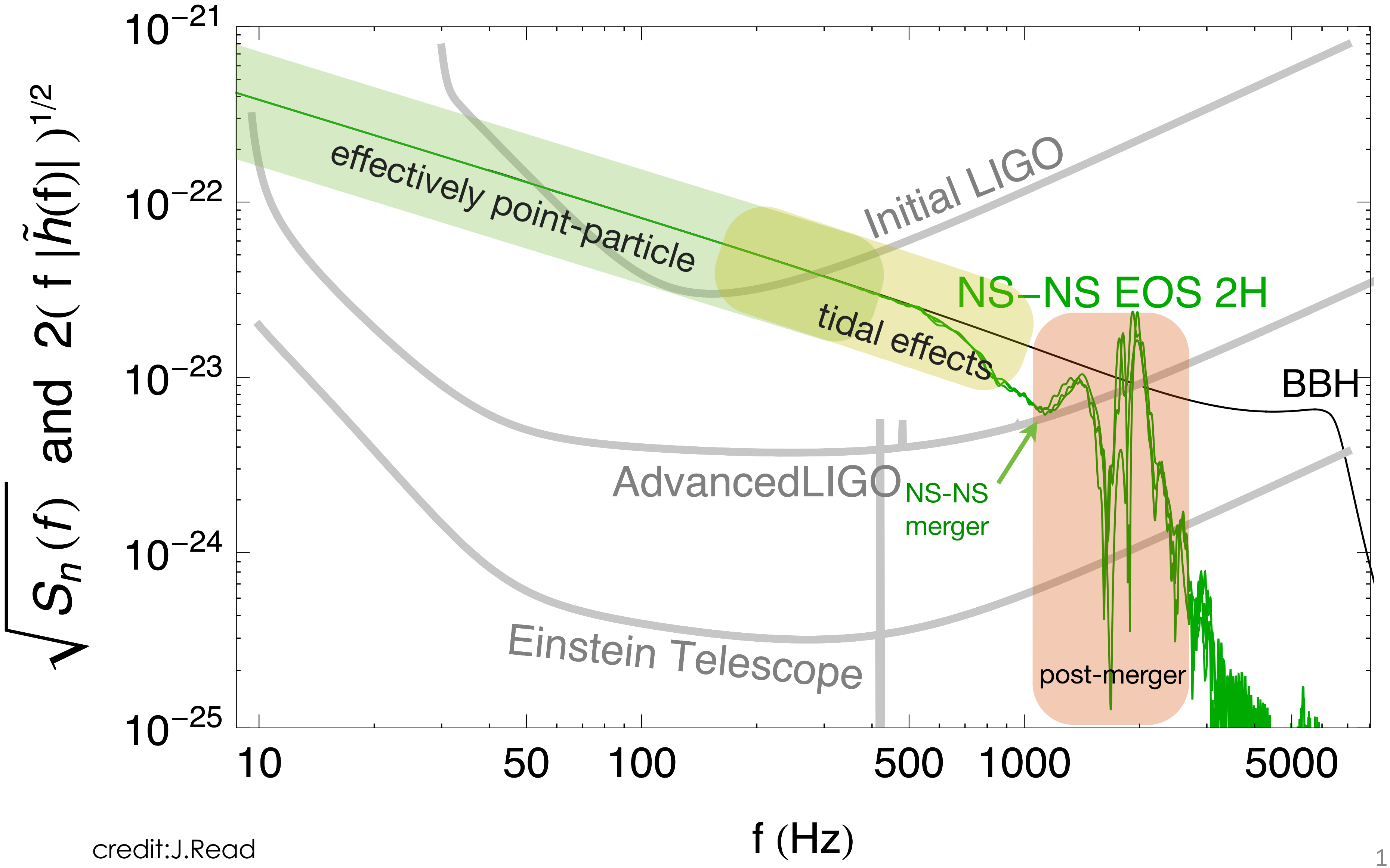


The population of merging compact binaries inferred using gravitational waves through GWTC-3, LIGO/Virgo/KAGRA Collaborations, arXiv:2111.03634

Next data takings:

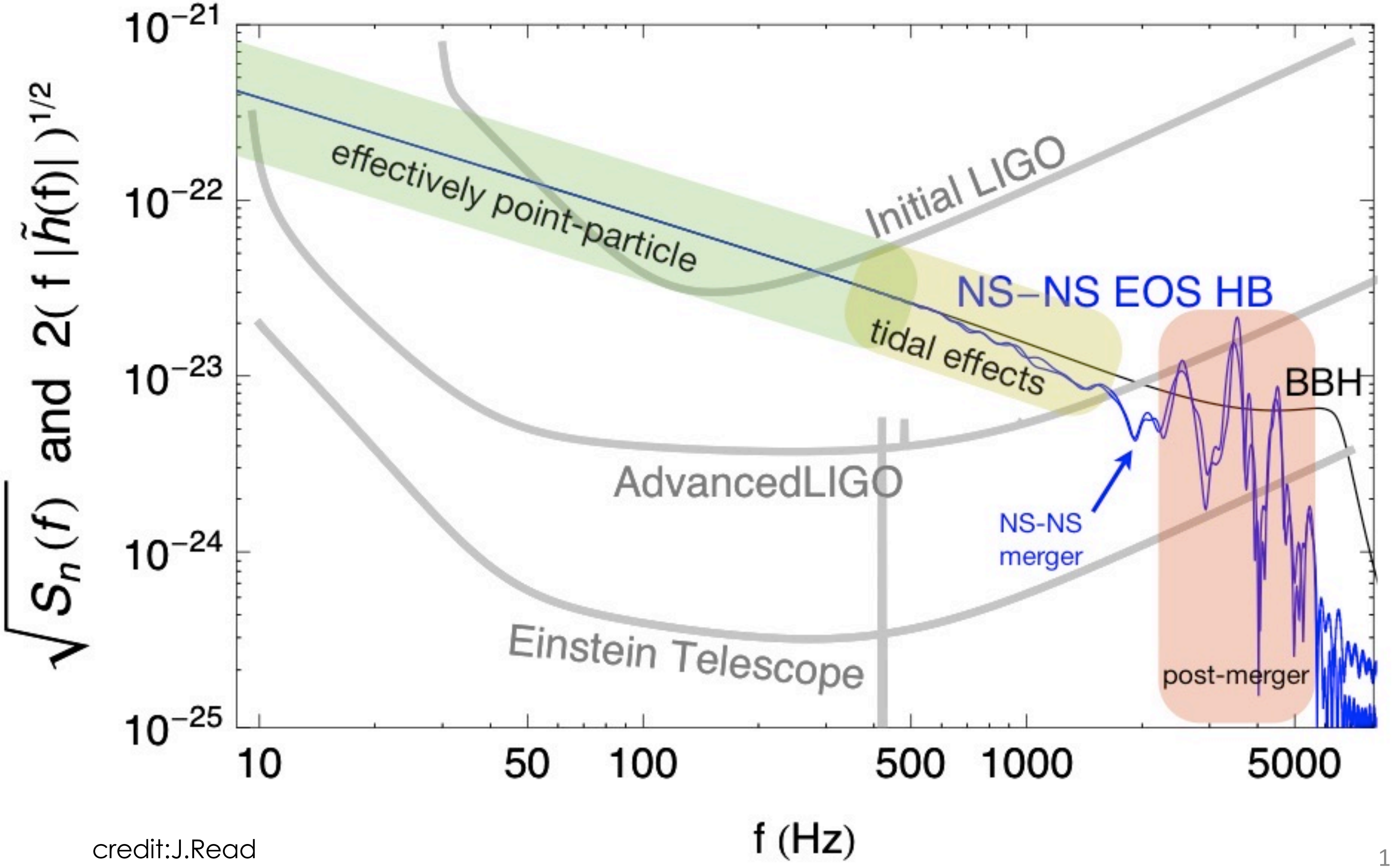
~ hundreds of events in O4
~ 10^3 events/year for O5

Nuclear matter: GW for different equations of state



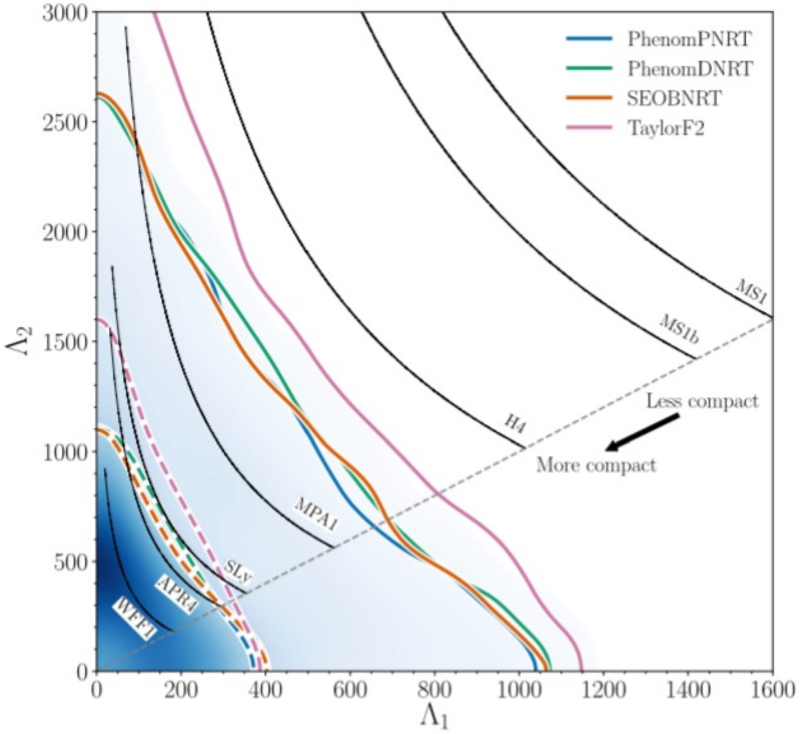
credit:J.Read

Nuclear matter: GW for different equations of state



credit:J.Read

Nuclear matter: Measurements of EoS equation of state



Properties of the Binary Neutron Star Merger GW170817, B. P. Abbott et al., Phys. Rev. X 9, 011001 (2019)

Measurements of Neutron Star Radii and Equation of State, B. P. Abbott et al, Phys. Rev. Lett. 121, 161101 (2018)

Tidal interactions between neutron-stars give their imprint in the gravitational-wave signal

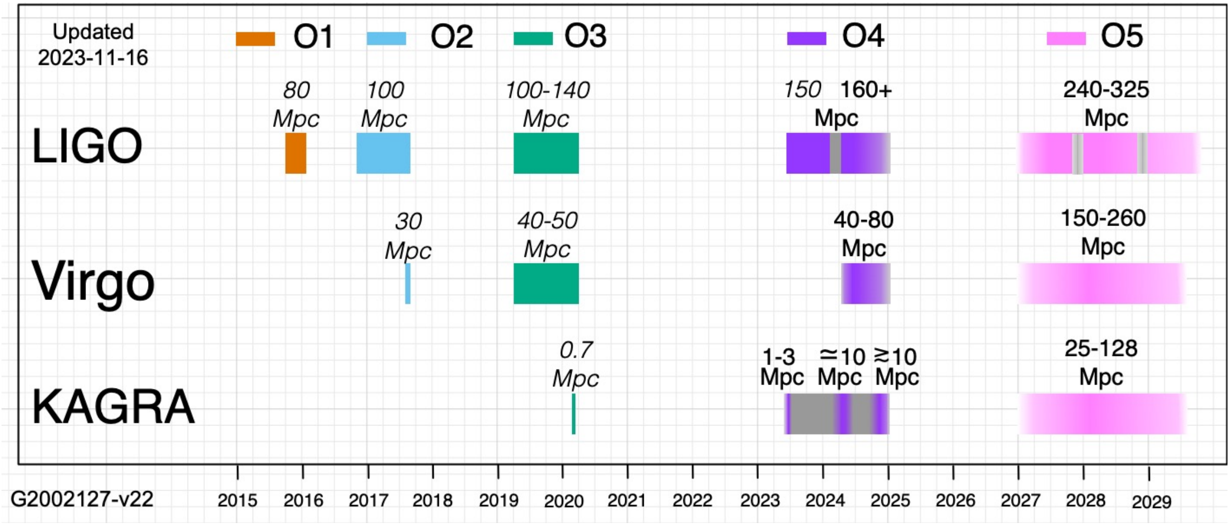
This allows to put constraints on the radii and EoS of the stars

The future

Ground based GW detectors: possible roadmap

Current infrastructures

New infrastructures



- A#
- Virgo_nEXT

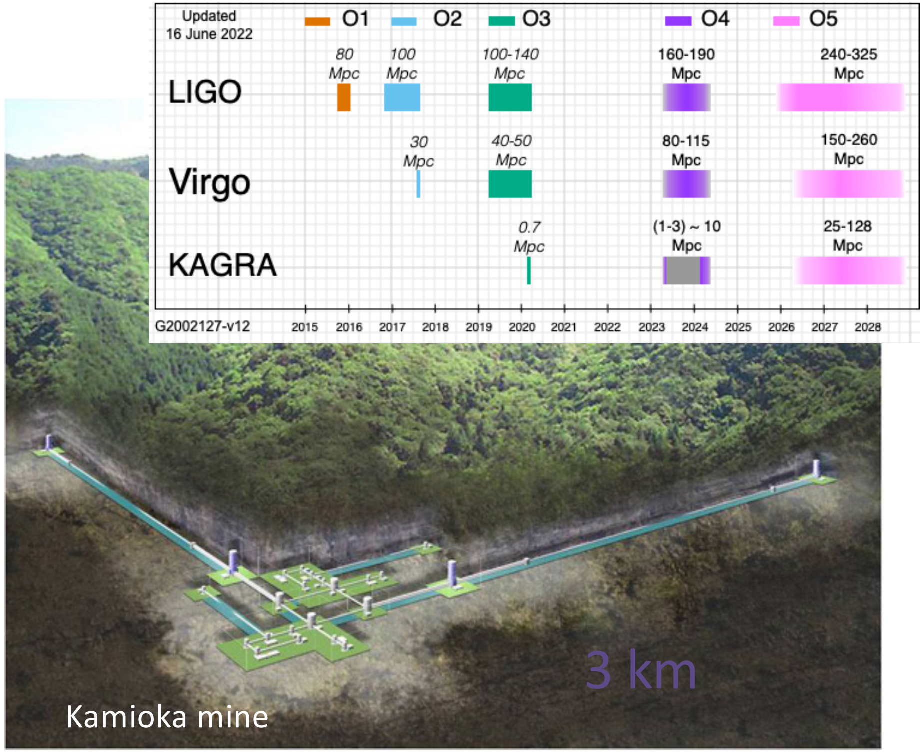
Decade 2030

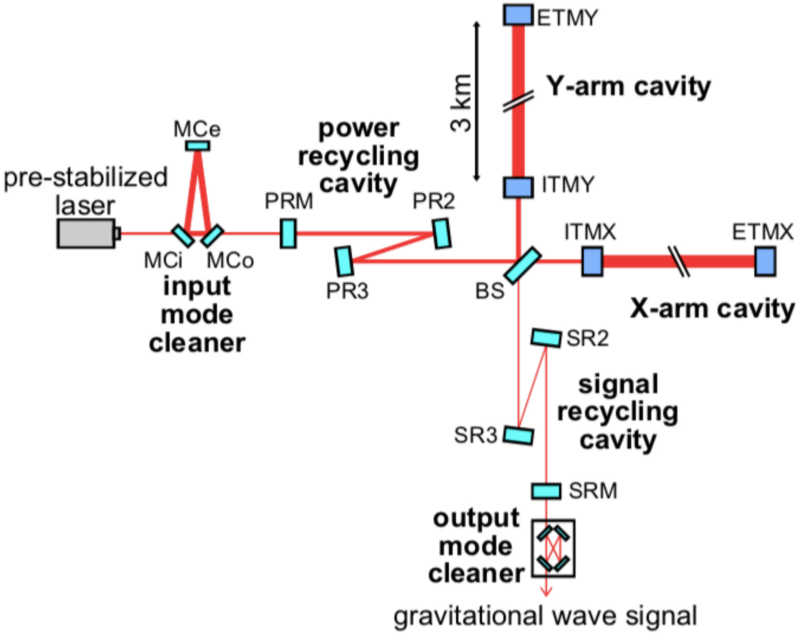
- Cosmic Explorer
- EinsteinTelescope

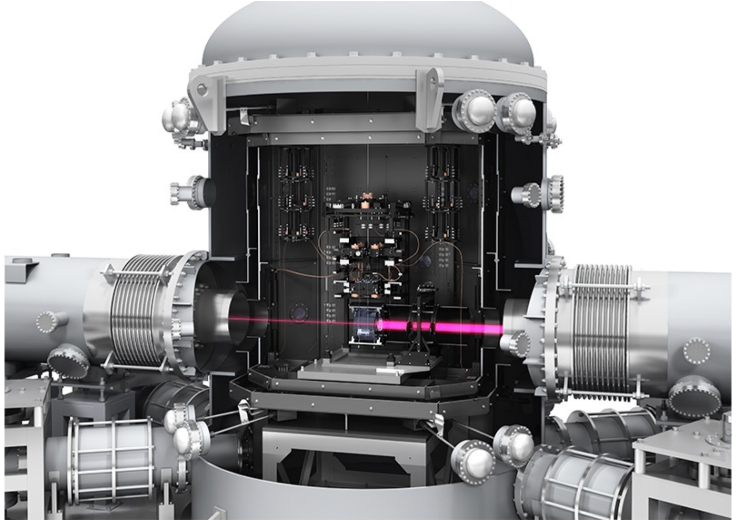
KAGRA

Japanese "2.5" Generation detector

- Undeground
- Cryogenic







The period 2030-2035
New Virgo/LIGO upgrades under study

- Reach the limit of the infrastructures with 2G detectors
- Continue the science program

- Ultimate goal ~ x2 with respect to AdVanced Virgo+ and Advanced LIGO+

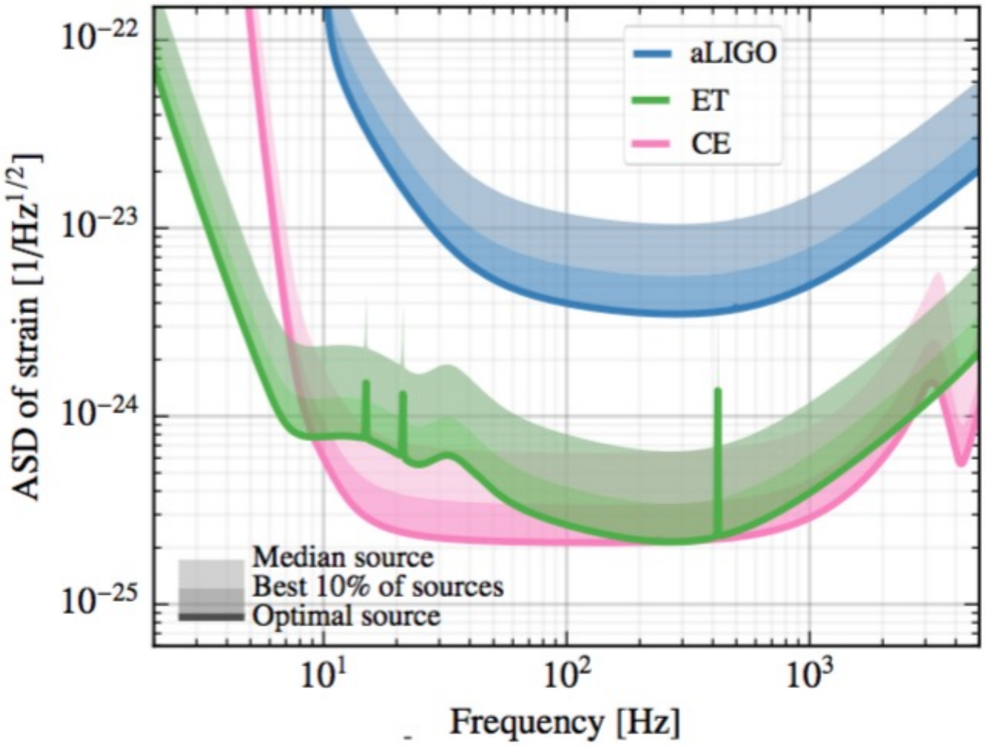
- Testbench for 3G detectors

- Technologies

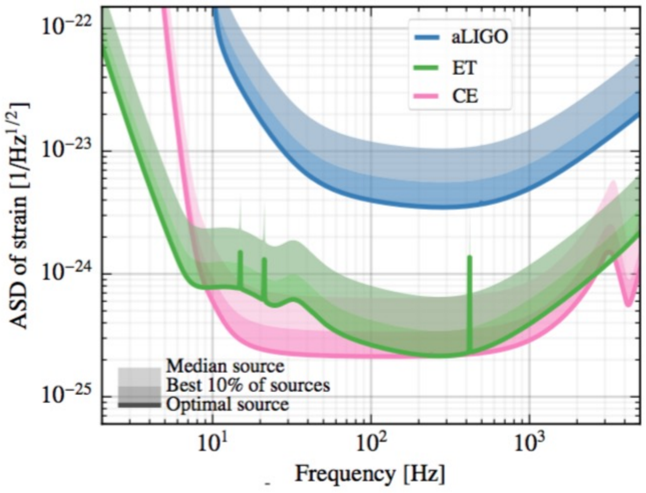
    - Better coatings
    - Higher laser powers
    - Higher squeezing level
    - Reduce technical noises at low frequency
    - Reduce Newtonian noise

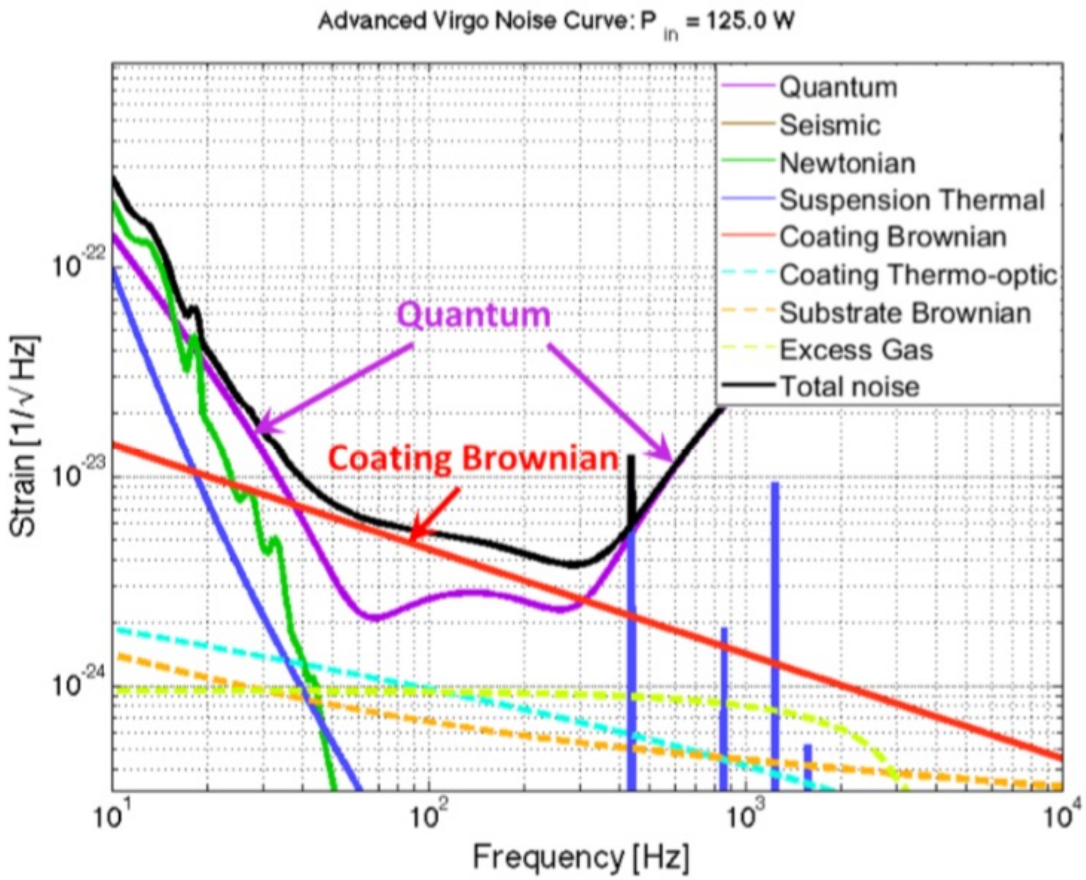
Einstein Telescope
a 3G detector

- An order of magnitude better than current detectors
- Pushing down to ~ 2 Hz the observational bandwdith (compared to ~ 10-20 Hz today

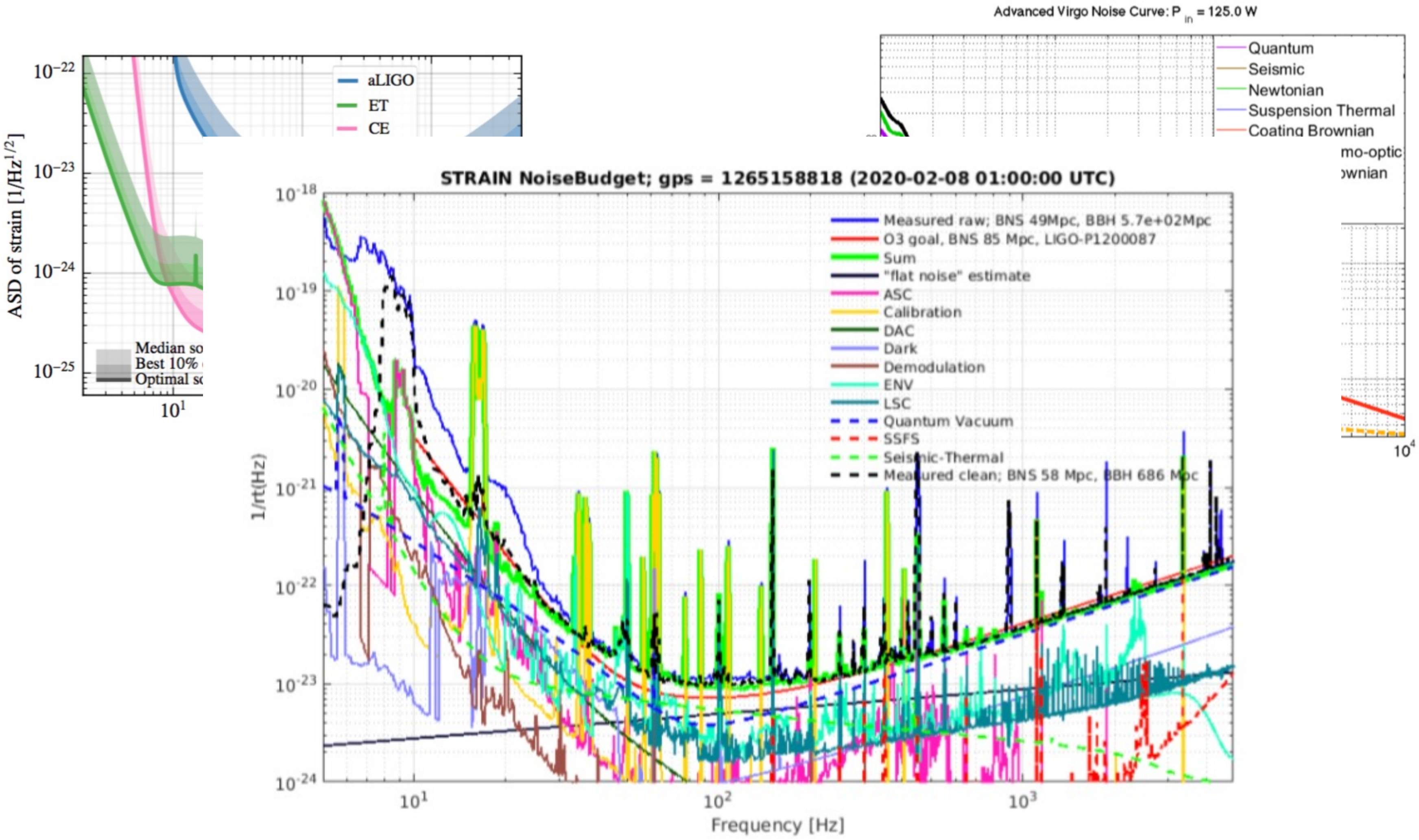


Gain one order of magnitude in sensitivity





Gain one order of magnitude in sensitivity



ET science

- Black-holes evolution
  - Black-hole mergers in the entire Universe and before the first galaxies
  - Intermediate-mass black-holes

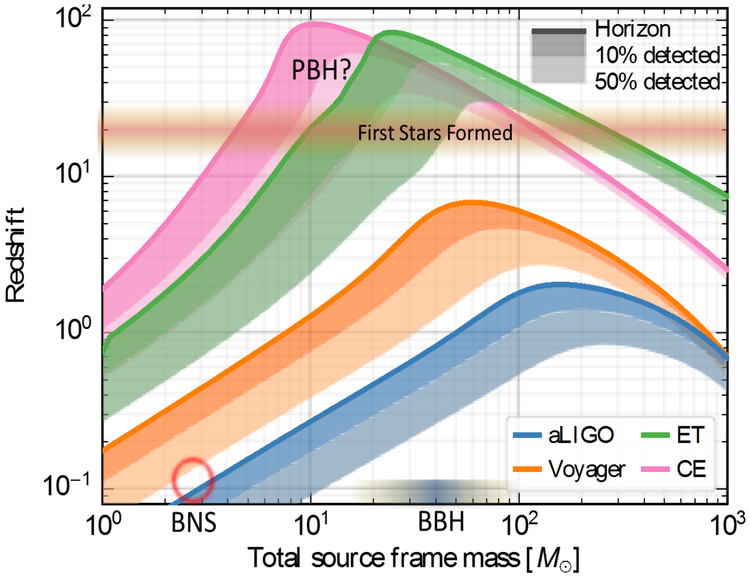
- Nature of gravitation
  - Nature of black-holes
  - Process in the primordial Universe
  - Signs of quantum gravity (i.e. échos)

- Cosmology Nature of dark eneregy
  - An alternative cosmology
  - Test of modified gravity theories with new observables

- Nature of matter at the smaller scales
  - Study of nuclear matter

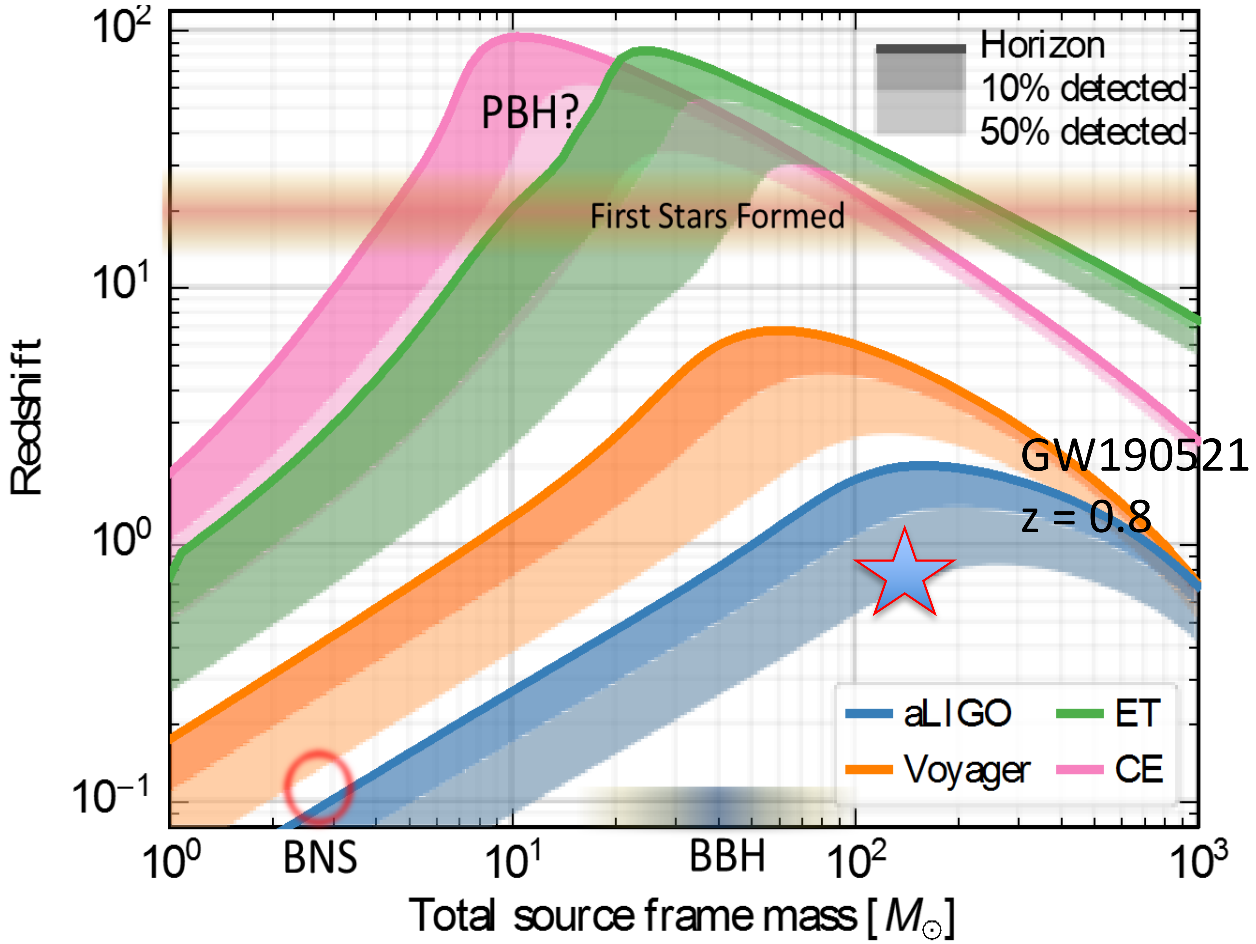
- Physics of Supernovae

- Multi-messenger astrophysics



https://arxiv.org/pdf/1912.02622
ET science case

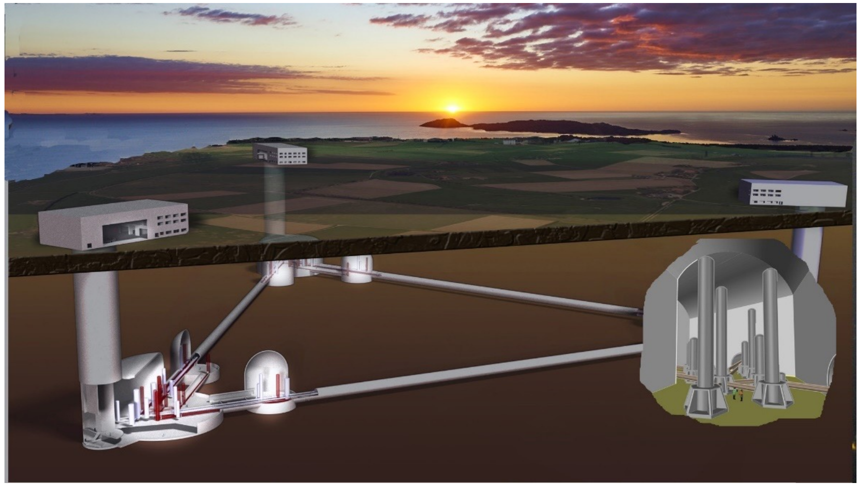
Horizon for compact objects

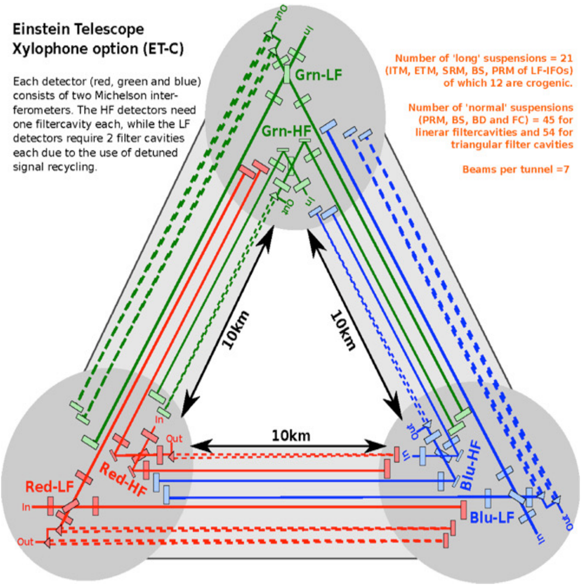


https://arxiv.org/pdf/1912.02622
ET science case

ET design

- Underground (seismic noise reduction)
- 10- km long arms (signal increase)
- Triangle configuration → polarisation
- « Xylophone » (two combined detectors)
- Cryogenics (20 K) (thermal noise reduction)





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.

Number of 'long' suspensions = 21 (ITM, ETM, SRM, BS, PRM of LF-IFOs) of which 12 are crogenic.

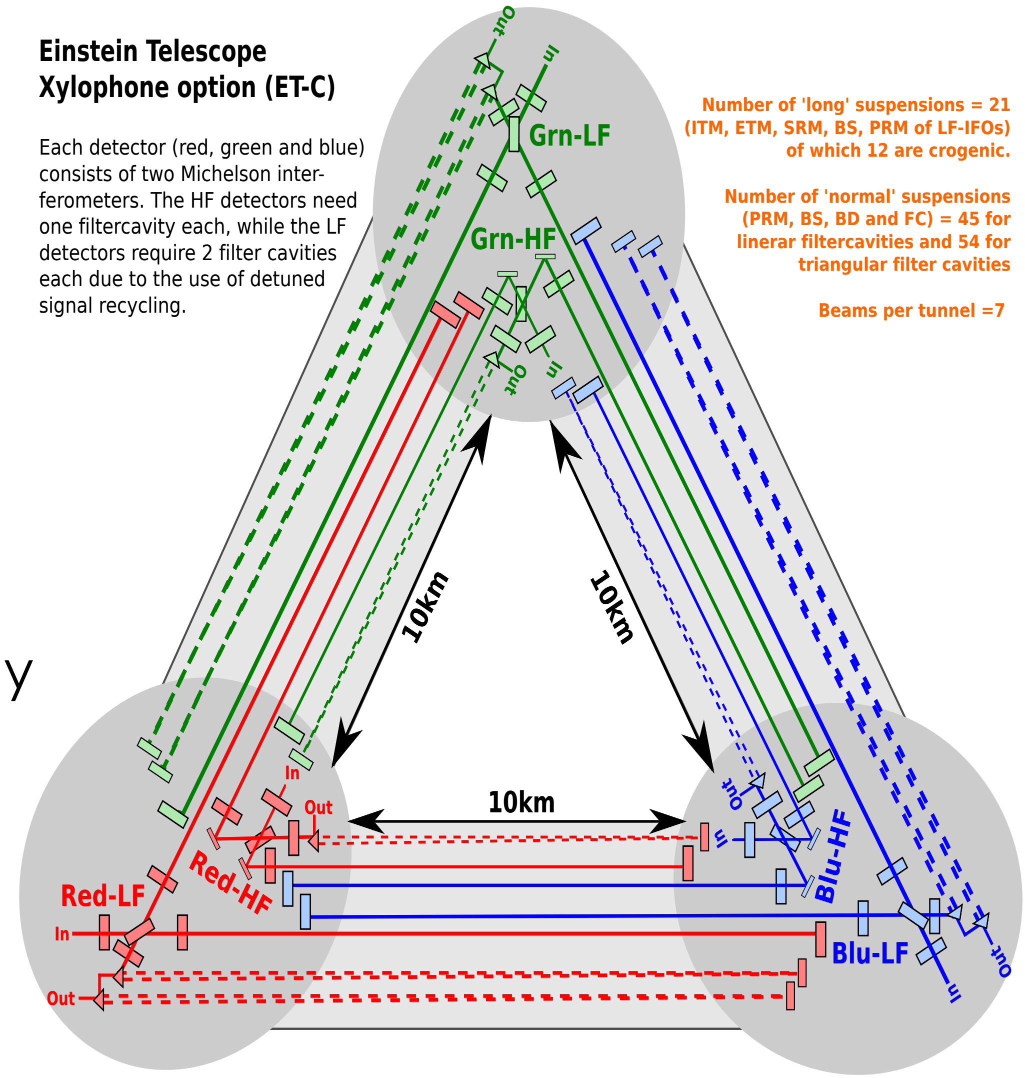
Number of 'normal' suspensions (PRM, BS, BD and FC) = 45 for linerar filtercavities and 54 for triangular filter cavities

Beams per tunnel =7

http://www.et-gw.eu/

Triangle shaped detector

- Start with a single (xylophone) detector
- Add a 2nd one to fully resolve polarization
- Add a 3rd one for null stream and redundancy



Einstein Telescope
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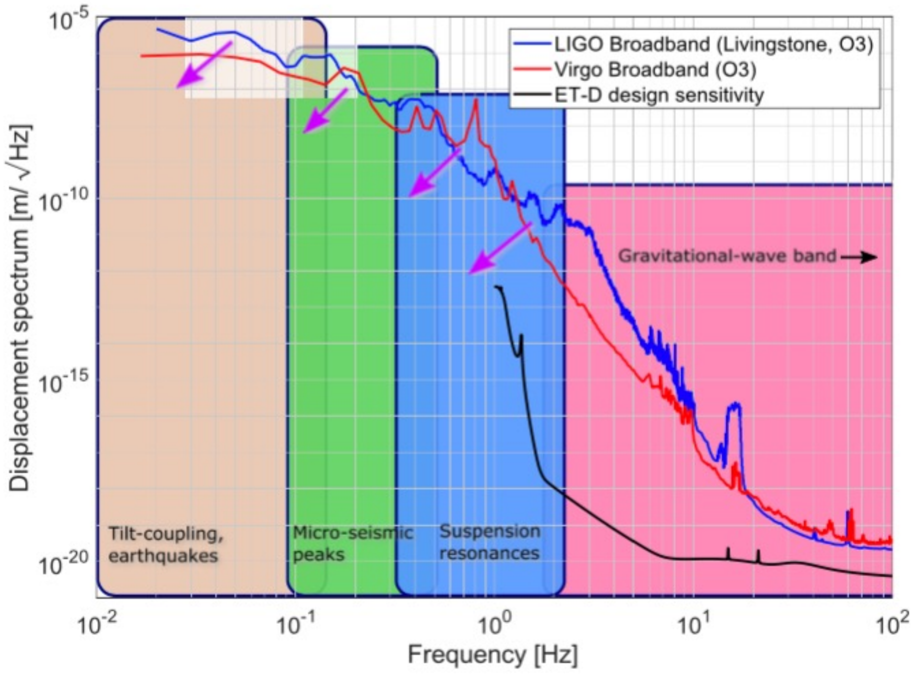
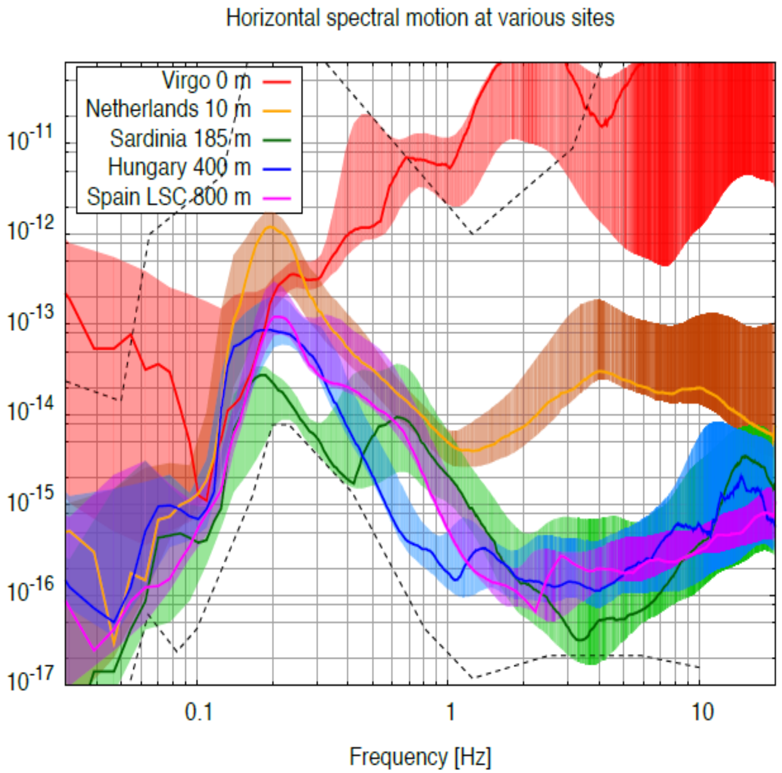
Beams per tunnel =7

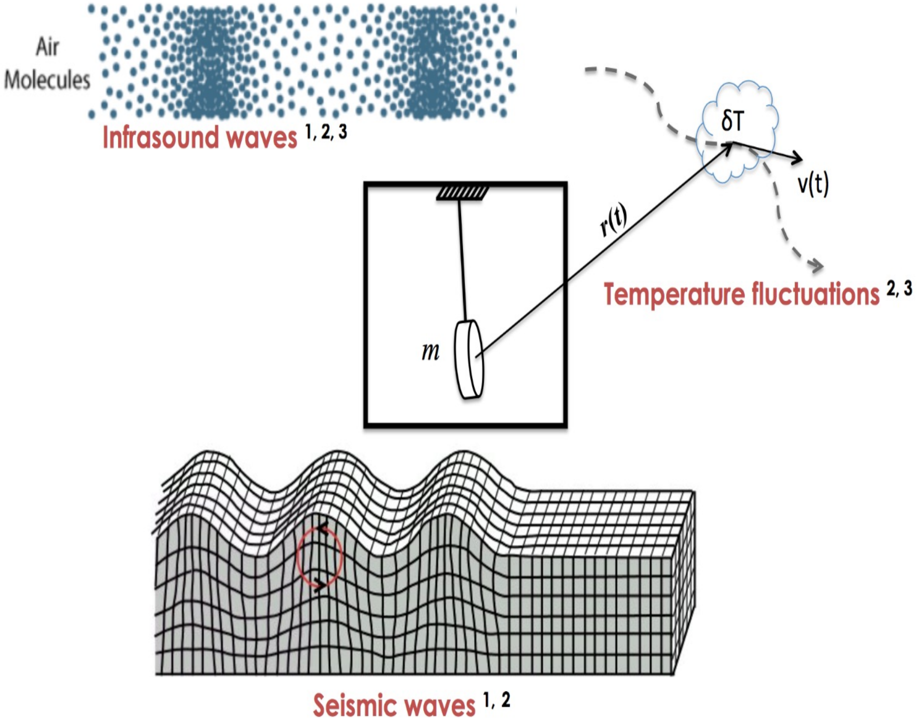
Widening the band at low frequency

- Low frequency limitation for GW detectors is given by the seismic noise and Newtonian noise → going underground
- Other benefits: less in-band noise (scattered light, etc...



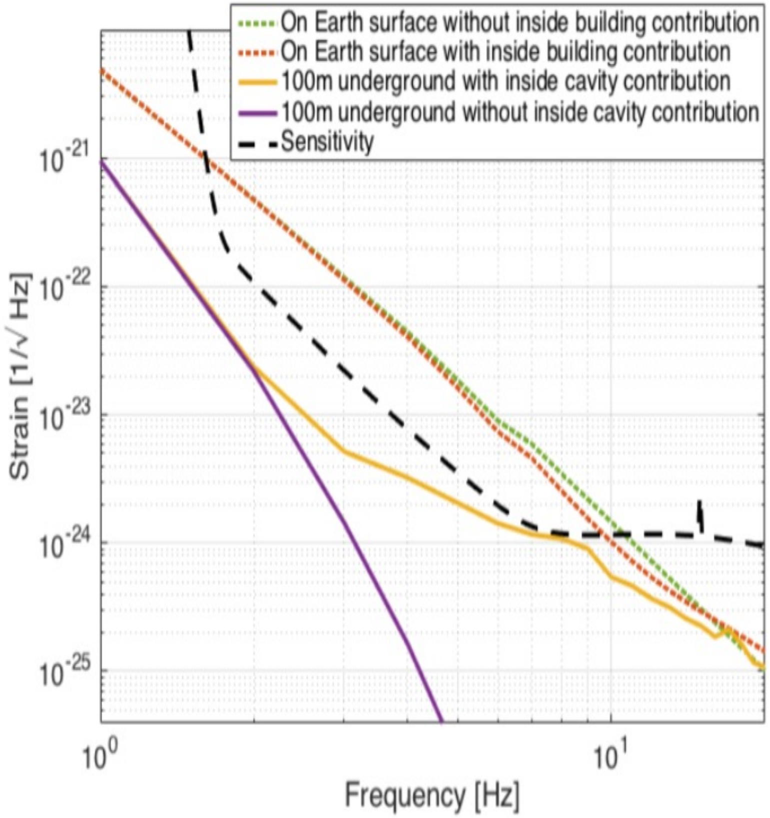


Atmospheric Newtonian Noise



[1] Saulson Phys. Rev. D **30**, 732, [2] J. Harms Terrestrial Gravity Fluctuations,
[3] Creighton CQG. **25** (2008) 125011, C.Cafaro, S. A. Ali arXiv:0906.4844 [gr-qc]

2

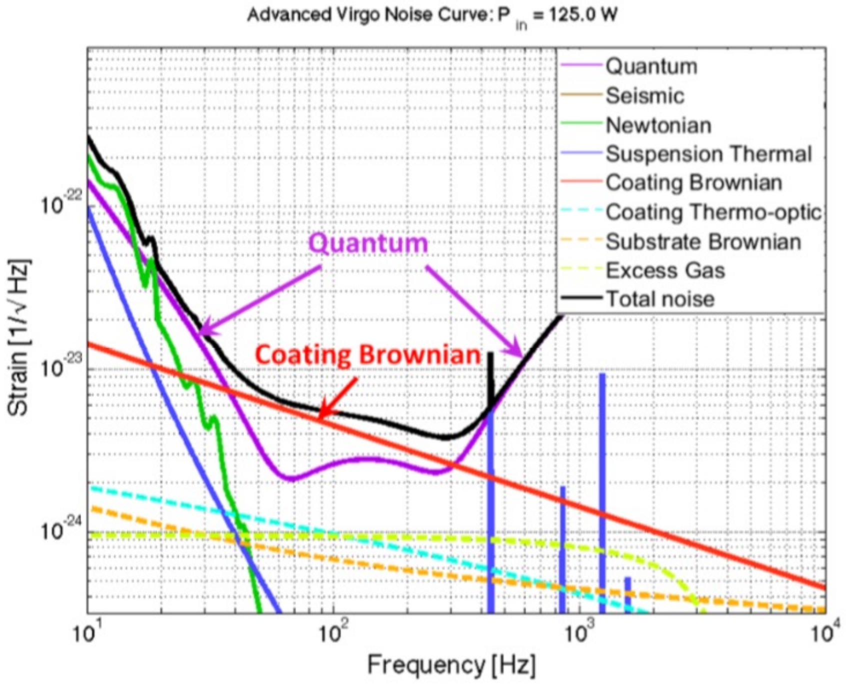


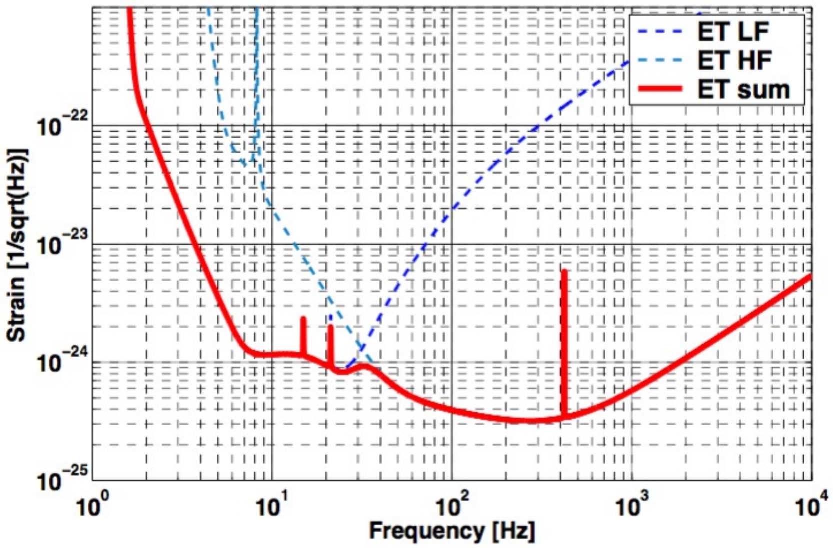
Impact of infrasound atmospheric noise on gravity detectors used for astrophysical and geophysical applications

Donatella Fiorucci[1], Jan Harms[2,3], Matteo Barsuglia[1], Irene Fiori[4], and Federico Paoletti[4,5]

Xylophone

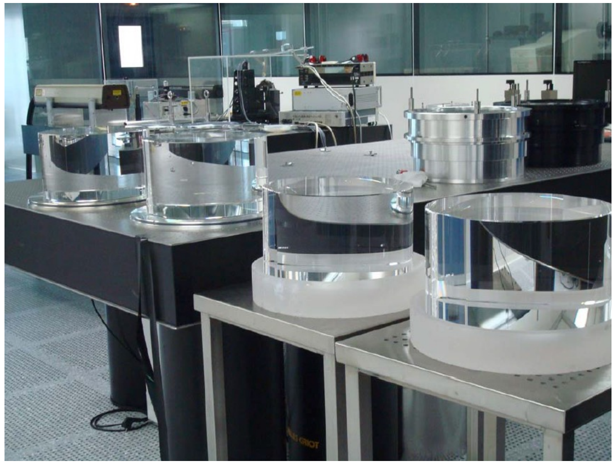
- Improving al low and high frequency with a single detector is very challenging
  - HF requires more laser power
  - LF requires cold mirrors
- Split the detection band over 2 “specialized” instruments instruments





The ET technologies and challenges

- Extrapolation of current or planned technologies for Virgo and LIGO
  - Squeezing (non classical states of light)
  - High-power lasers
  - Large mirrors
  - New mirror's coatings
  - Thermal compensation techniques
  - Seismic suspension systems



- Technologies not tested in Virgo and LIGO
  - Cryogenics (also in KAGRA)
  - New cryogenic materials
  - New laser wavelengths
- R&D program needed
- Challenges in building a complex underground facilities