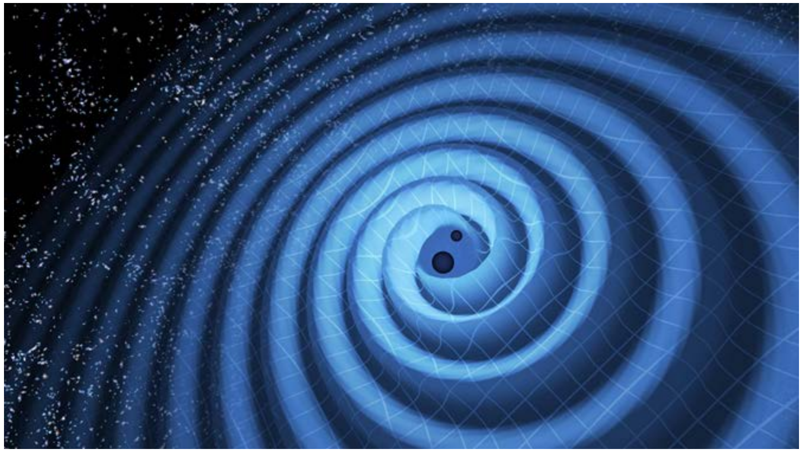


Detecting gravitational waves with kilometric interferometers

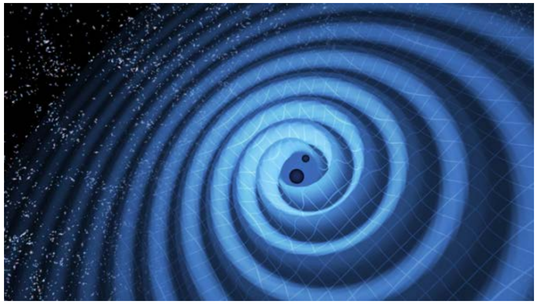
R. Gouaty
LAPP - Annecy

Seminar at the European School of Instrumentation in Particle & Astroparticle Physics

Virgo web site: http://public.virgo-gw.eu/
LIGO web site: http://www.ligo.org/

Outline

- Gravitational waves
- How to detect them ?
- First detections



PHYSICAL
REVIEW
LETTERS

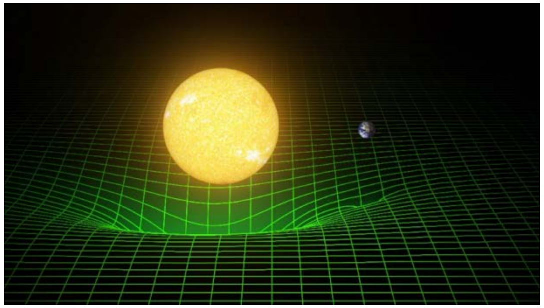
12 FEBRUARY 2016

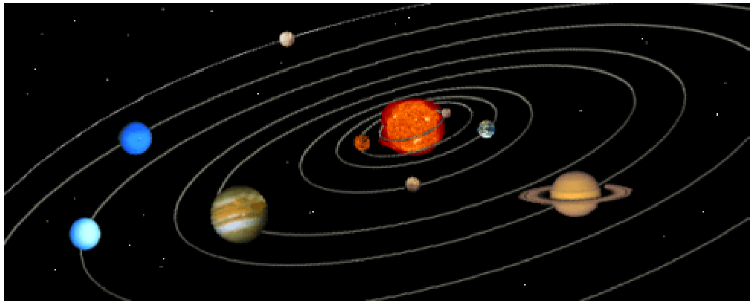
Published by
American Physical Society

APS physics

Volume 116, Number 6

Gravitation and space time



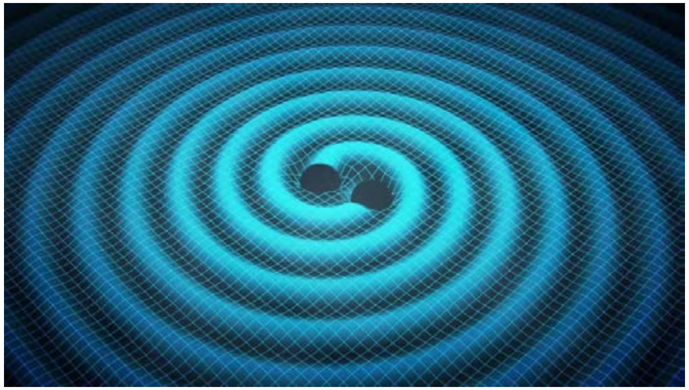


General relativity:

- Mass curves space
- Gravitational force: effect of space curvature
- J. A. Wheeler : "***Space tells matter how to move and matter tells space how to curve***"
- Extreme case: black hole

➢ **Gravitational Waves: fluctuations of space time deformations that propagate**

- Ripples in the curvature of space-time

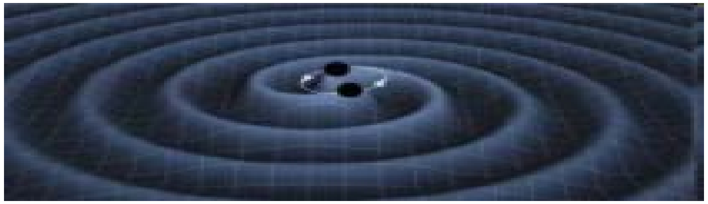


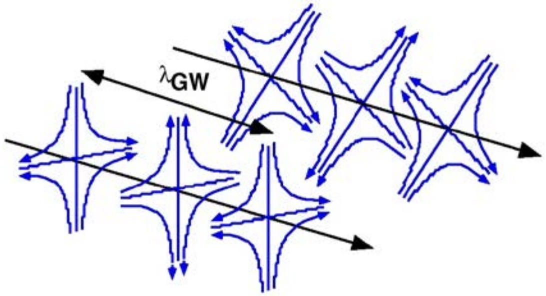
Gravitational waves

GW origin

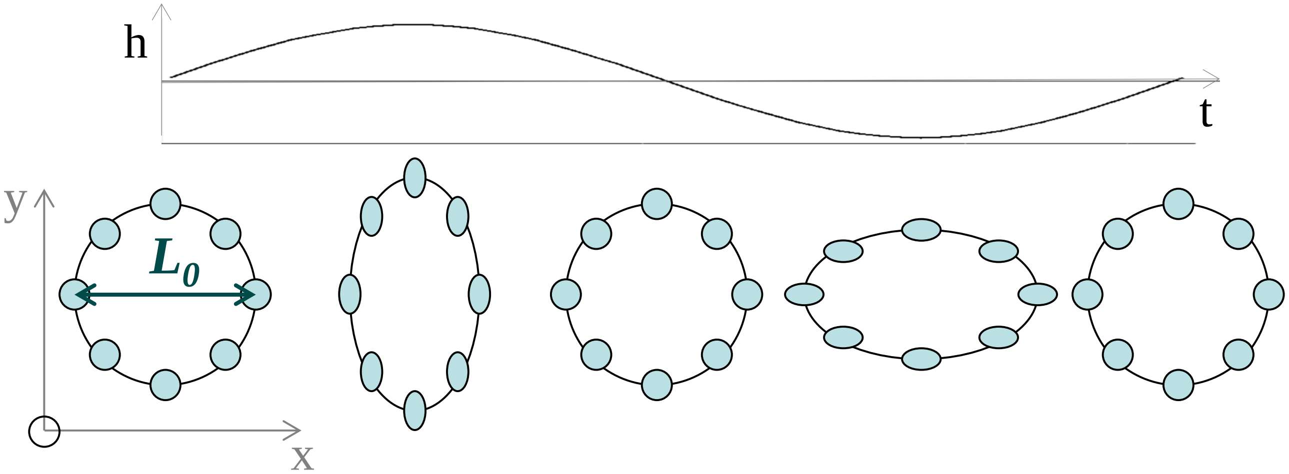
Masses in motion
↓
Space-time deformation
↓
Gravitational wave

- transversal plane wave
- propagation at the light speed c
- Two polarisation states (+ and x)





Detectable effect on free fall masses



$$\delta L_x(t) = \frac{1}{2}\, h(t)\, L_0$$

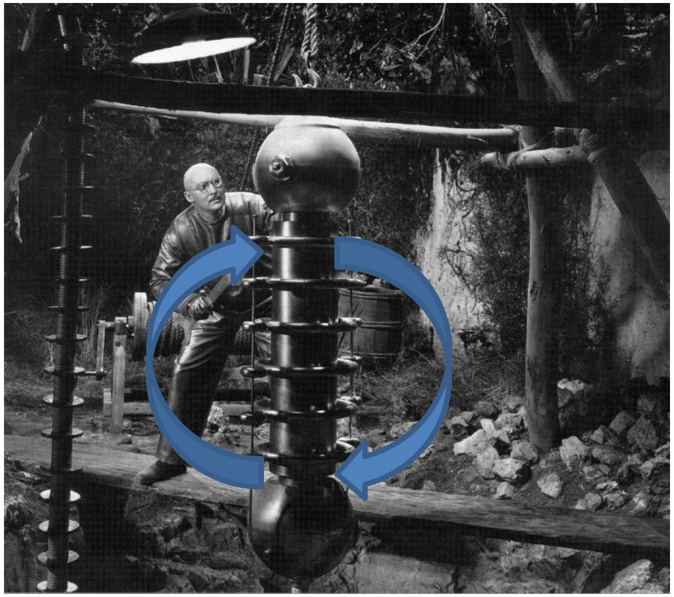
h(t): amplitude of the GW

(*h* has no dimension)

Illustration of the metric variation with free fall masses initially located along a circle, for a + polarised GW propagating along z

GW generation

- ➢ Accelerated masses, quadrupolar momentum



$$h \approx \frac{G}{c^4} \frac{E_{ns}}{r}$$

"Non spherical" kinetic energy

distance to the source

$\sim 10^{-44}\ \mathrm{m^{-1}\ kg^{-1}\ s^{2}}$

Examples with 2 orbiting objects:

$$h \approx \frac{32\pi^2 G M R^2 f_{orb}^2}{r c^4}$$

- ▸ M = 1000 kg, R = 1 m, f = 1 kHz, r = 300 m

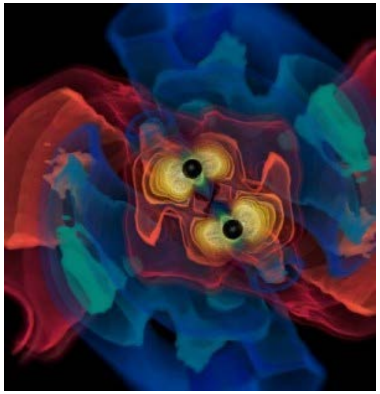
  $h \sim 10^{-35}$

- ▸ $M = 1.4\ M_{\odot}$, R = 20 km, f = 400 Hz, $r = 10^{23}$ m (15 Mpc = 48,9 Mlyr)

  $h \sim 10^{-21}$

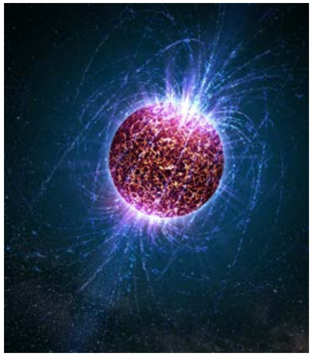
- ➢ Which detectable sources?
  - No way for lab generation
  - Astrophysical sources(high masses and velocities)
    - Despite the distance penalty
    - Typical sources: orbiting objects

Astrophysical sources of GW



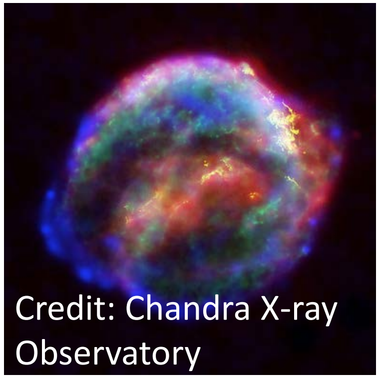
Credit: AEI, CCT, LSU

- **Binary system**
  - Need to be compact to be observed by ground based detectors
    → Neutron stars, black holes
  - Signal well modeled but rates not well known



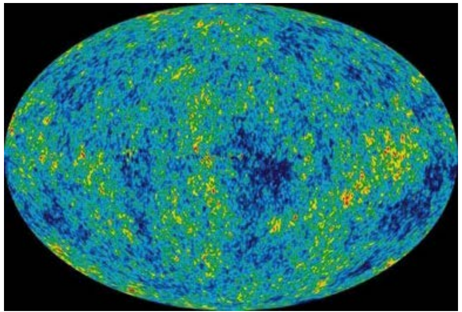
Casey Reed, Penn State

- **Spinning neutron stars**
  - Nearly monotonic signals
  - Long duration
  - Strength not well known



Credit: Chandra X-ray Observatory

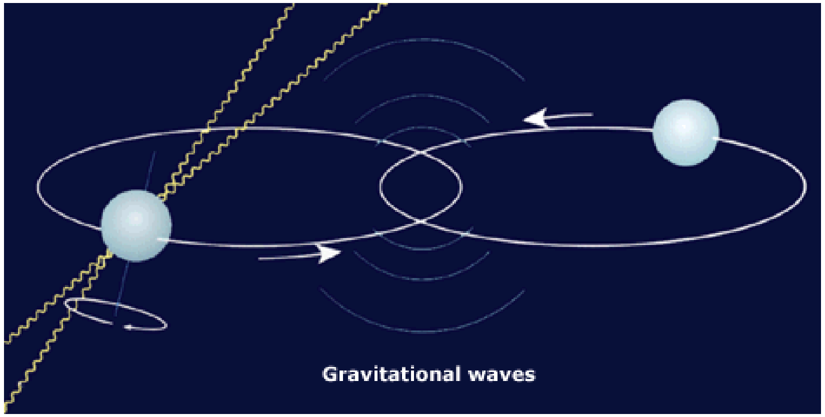
- **Asymmetric explosion**
  - Like supernovae core collapse
  - "burst" transient
  - Not well modeled

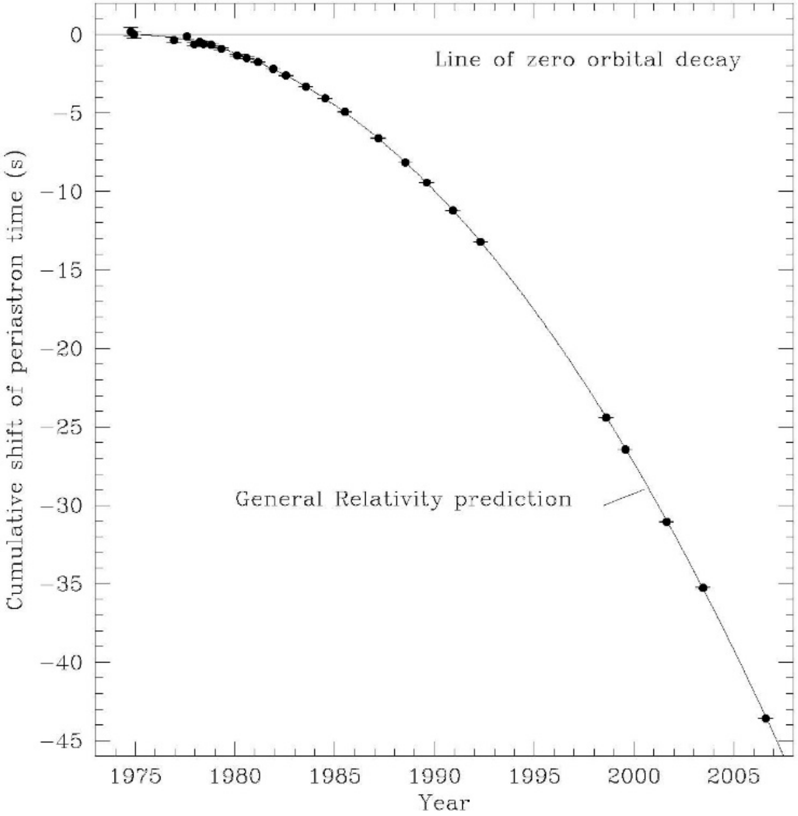


NASA/WMAP Science Team

- **Cosmic gravitational wave background**
  - Residual of the big bang/inflation
  - Stochastic background
  - Could be overlapped by superposition of transients

Indirect evidence: PSR 1913+16



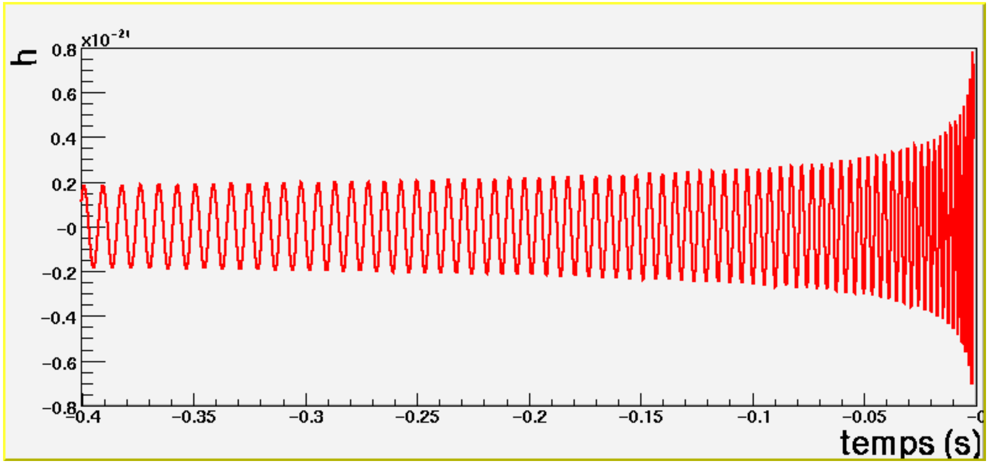


$$\dot{P}_{observe} / \dot{P}_{predit} = 1.0013 \pm 0.0021$$

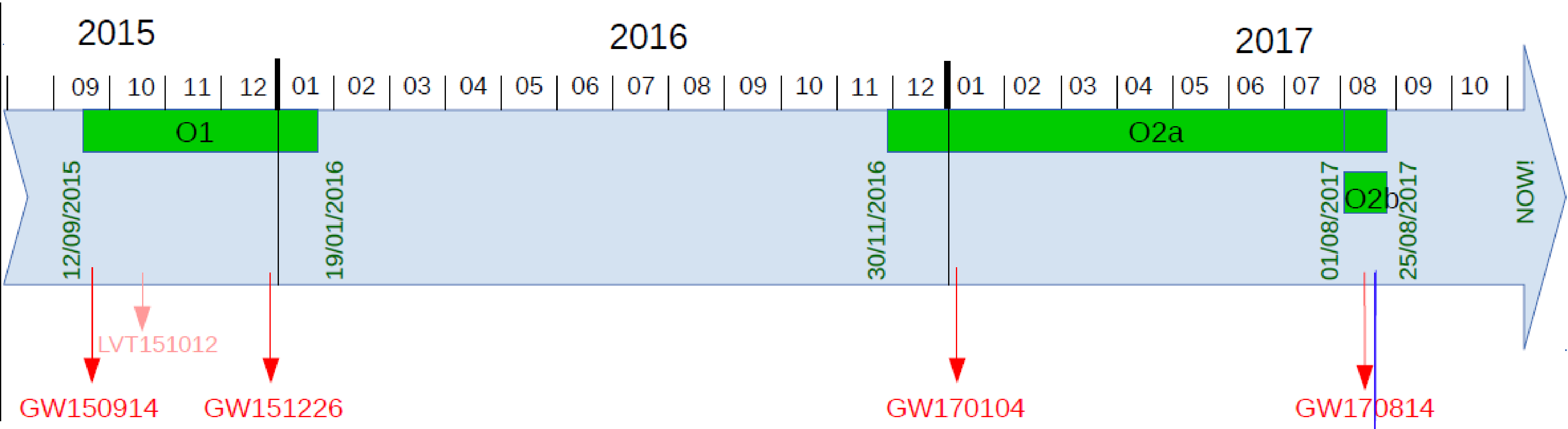
- Binary system of neutron stars
- One neutron star is a radio pulsar
- Discovered in 1975 by Hulse and Taylor
- Studied by Taylor, Weisberg and co.
- **Decay of the orbital period compatible with GW emission**
- Frequency of GW emitted by PSR 1913+16: ~ 0.07 mHz
  Undetectable by ground-based detectors (bandwidth 10 Hz- 10 kHz)

Coalescing binaries

- Binary systems of compact stars at the end of their evolution
  - Neutron stars and black holes
- Very rare phenomenum in our Galaxy
  - A few tens per million years
- Typical amplitude (for neutron stars)
  - h ~ 10^{-22} à 20 Mpc
- Very distinctive waveform



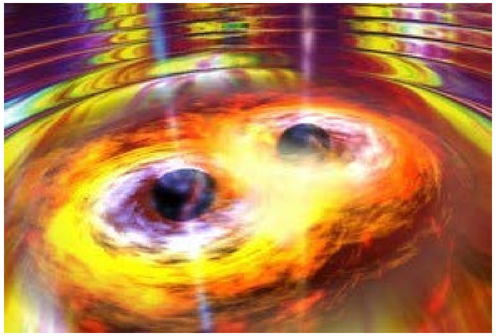
First detections!



First GW detection !

First detection in triple coincidence

GW170817 + multi-messengers detections



Sources = Coalescing binaries

- **Black holes**
- **Neutron Stars**

Detected amplitude:

Example for GW170814: h = 5×10^{-22} → **δL (Virgo) = ± 0.8×10^{-18} m**

→ **experimental challenge**

An experimental challenge

- ❑ A lot of technical challenges to detect:
  - ➢ Measure a relative variation of length **h ~ 10^{-23}**

  ≡ Measure the distance Earth – Moon with an accuracy roughly equal to the size of a proton!

  - ➢ Happening rarely
  - ➢ During short times

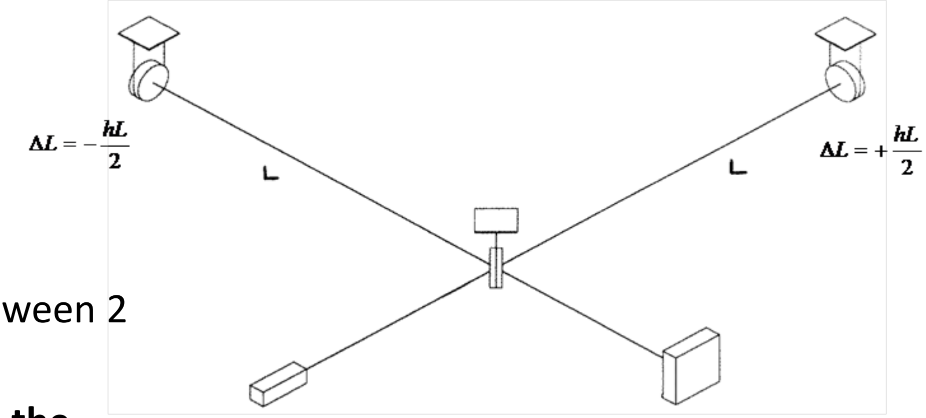
GW quest: a bit of history

- Joseph Weber invents the bar detector
  - First claim for detection in 1969… but contested
  - Triggered large interest, at least 18 bars in 8 countries
- Evolve to cryogenic resonant bars (80-90)
- Bar not enough sensitivity:
  - h : few 10^{-21} 1/sqrt(Hz) @ 900Hz

- ITF started in the 70's (Germany, Rai Weiss)
  - Broad band instrument
- Few ITF prototypes in the 80's
  - MIT, Glasgow, Garching, Caltech,...
  - ~10m long
  - Not made for detection
- Jump to km scale in early 90
  - LIGO, Virgo, GEO, TAMA

Gravitational Wave Interferometer

- Measure a variation of distance between masses
  - Measure the light travel time to propagate over this distance
  - Laser interferometry is an appropriate technique
    - Comparative measurement
    - Suspended mirrors = free fall test masses



- Michelson interferometer well suited:
  - Effect of a gravitational wave is in opposition between 2 perpendicular axes
  - **Light intensity of interfering beams is related to the difference of optical path length in the 2 arms**

We need a big interferometer:

ΔL proportional to L

➔ need several km arms!

How interferometers detect GW?

How interferometers detect GW?

- **Virgo optical configuration, or how to measure 10^{-20} m?**
  - Simple Michelson interferometer
  - How do we improve the detector sensitivity?

- **How do we measure the GW strain, h(t), from this detector?**

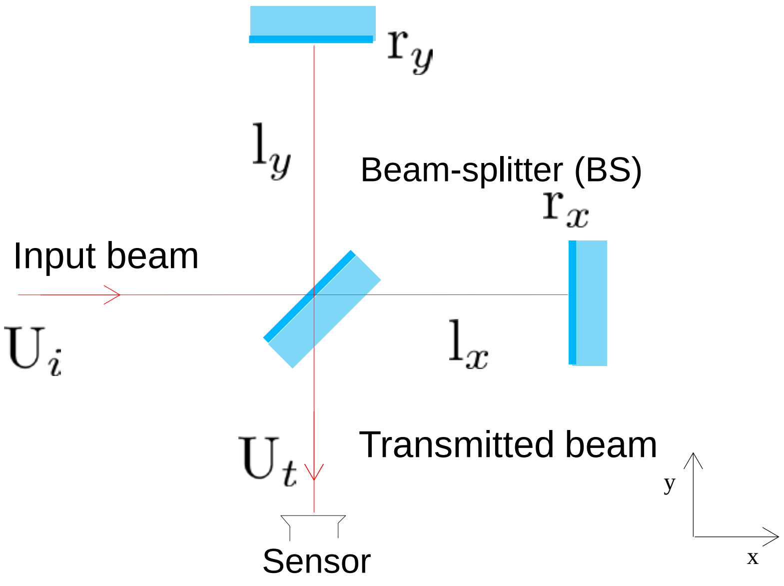
- **Some noises of the Virgo detector**
  - What is noise?
  - Main noise sources – how to mitigate them?

Simple Michelson interferometer: transmitted power

Field transmitted by the interferometer

$$U_t = \frac{\mathcal{A}_i}{2}\left(r_y\, e^{2\jmath k l_y} \;-\; r_x\, e^{2\jmath k l_x}\right)$$

k is the wave number, k = 2π/λ
λ is the laser wavelength (λ=1064 nm)

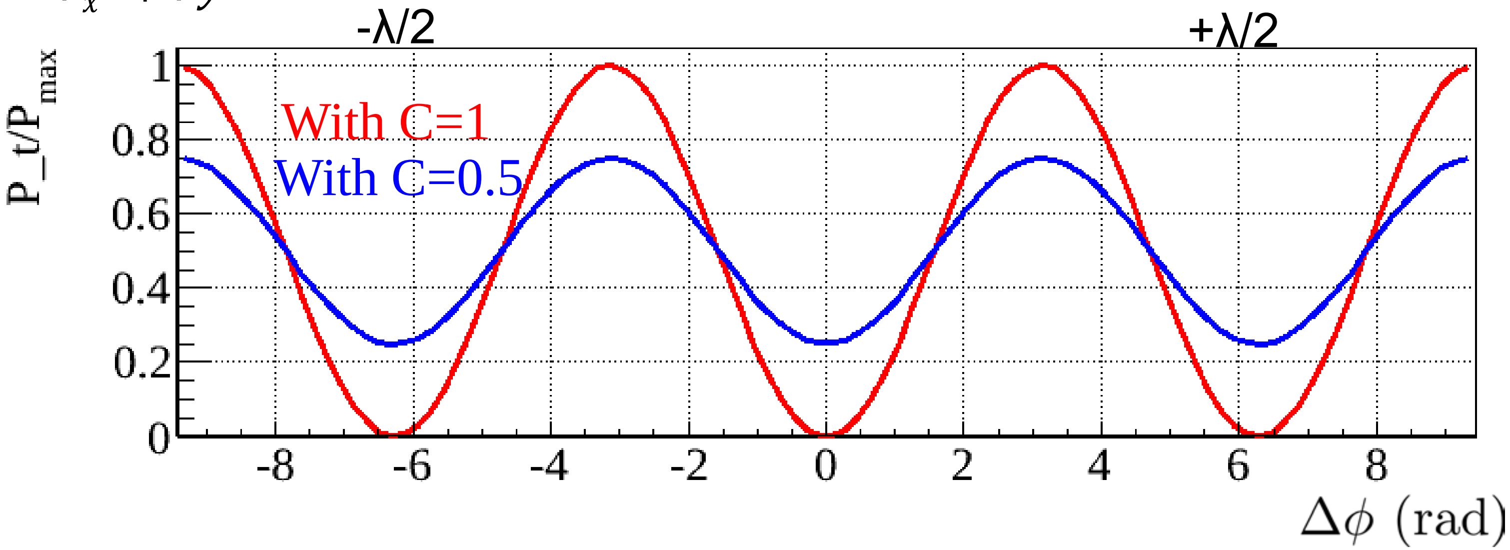


Transmitted power

$$P_t \propto |U_t|^2 \;=\; \frac{P_{max}}{2}\left(1 \;-\; C\,\cos(\Delta\phi)\right)$$

where $\Delta\phi \;=\; 2k(l_y - l_x)$

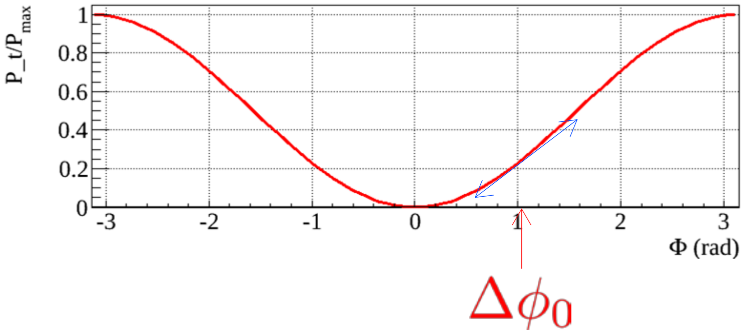
ITF contrast: $C = \dfrac{2rxry}{r_x{}^2 + ry^2}$



From the power to the gravitational wave strain h(t)

Interferometer set around a working point

$$\Delta\phi_0 = 2\,k\,(l_y - l_x) = 2\,k\,\Delta L_0$$

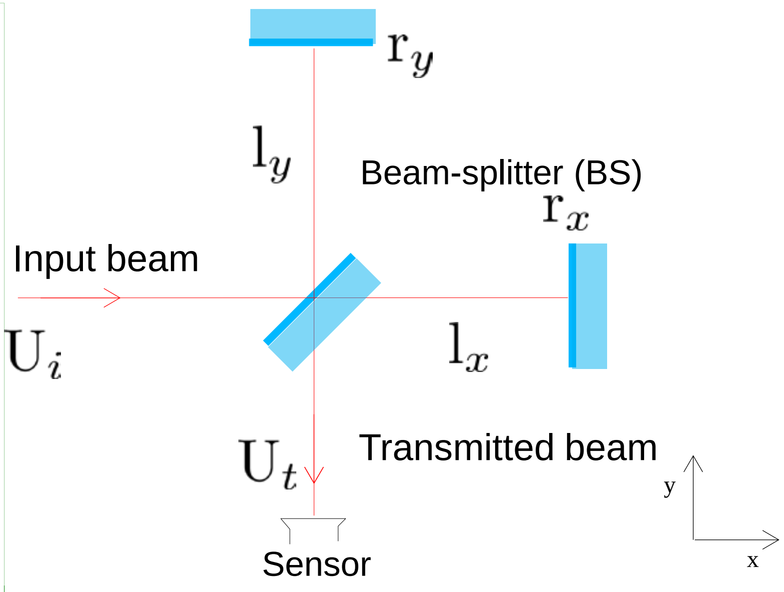


$$\delta P_t = \underbrace{P_i\, C\, \frac{2\pi}{\lambda} \sin\left(\frac{4\pi}{\lambda}\Delta L_0\right)} \times \delta\Delta L$$

$$\delta P_t = (\text{Interferometer response}) \times \delta\Delta L$$

(W/m)

Measured physical quantity Physical effect to be detected



Around the working point:

$$\delta P_t \propto \delta\Delta L = h L_0$$

$$\delta P_t \propto h$$

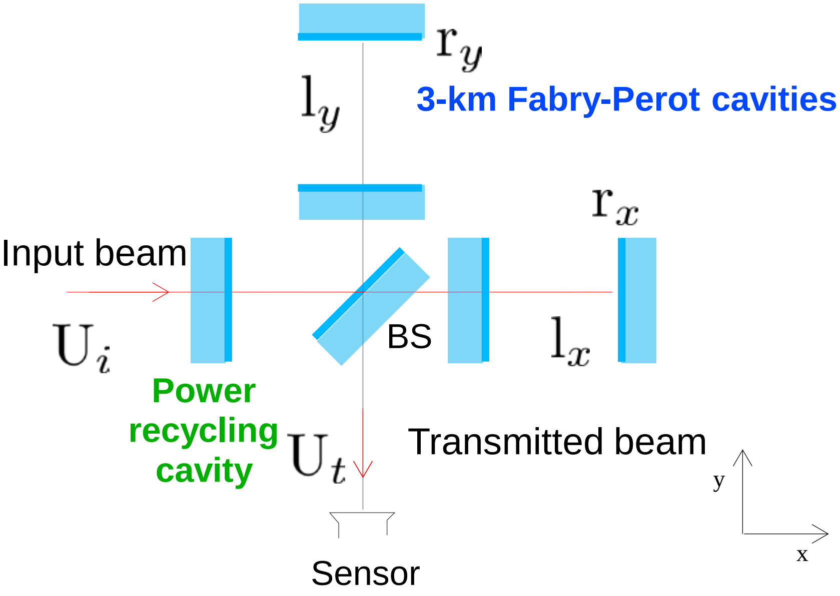
Improved interferometer response

More mirrors to form cavities:

- 3-km Fabry-Perot **cavities** in the arms
- power recycling **cavity**

$$\delta P_t = \underbrace{\underset{\sim 38}{G_{PR}}\, P_i\, C\, \frac{2\pi}{\lambda} \sin\left(\frac{4\pi}{\lambda}\Delta L_0\right) \underset{\sim 300}{\frac{2\mathcal{F}}{\pi}}} \times \delta\Delta L$$

$$\delta P_t = \underset{\text{(W/m)}}{(\text{Interferometer response})} \times \delta\Delta L$$

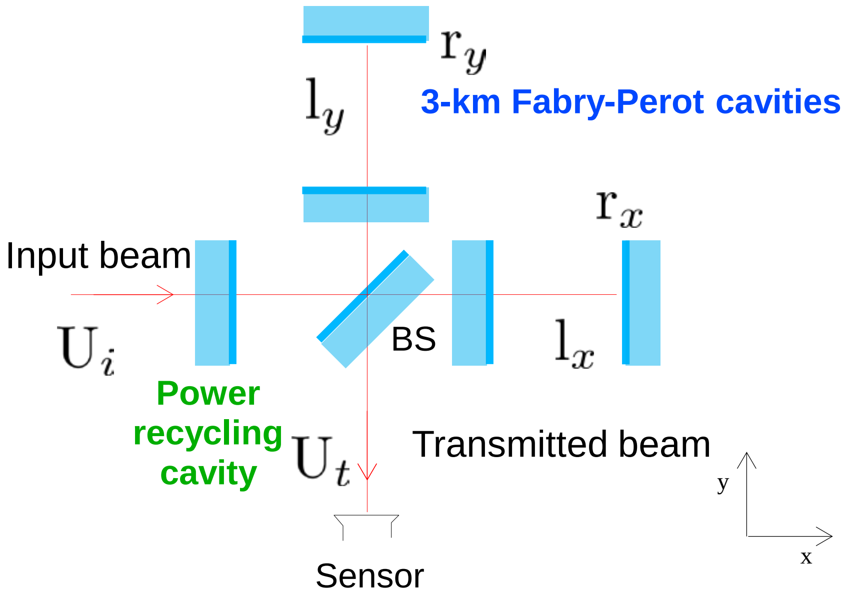


For the same $\delta\Delta L$,
δP_t has been increased by a factor 12000

Order of magnitude of the « sensitivity »

$$\delta P_t = G_{PR}\, P_i\, C\, \frac{2\pi}{\lambda} \sin\left(\frac{4\pi}{\lambda}\Delta L_0\right) \frac{2\mathcal{F}}{\pi}\, \delta\Delta L$$

Laser wavelength	$\lambda = 1064$ nm
Input power	$P_i \sim 100$ W
Interferometer contrast	$C \sim 1$
Cavity finesse	$\mathcal{F} \sim 450$
Power recycling gain	$G_{PR} \sim 38$
Working point	$\Delta L_0 \sim 10^{-11}$ m



Shot noise due to output power of $\sim 50\,\mathrm{mW}$
$\rightarrow \delta P_{t,min} \sim 0.1\,\mathrm{nW}$ ⟶ $\delta\Delta L_{min} \sim 5 \times 10^{-20}$ m

$$\rightarrow h_{min} = \frac{\delta\Delta L_{min}}{L} \sim 10^{-23}$$

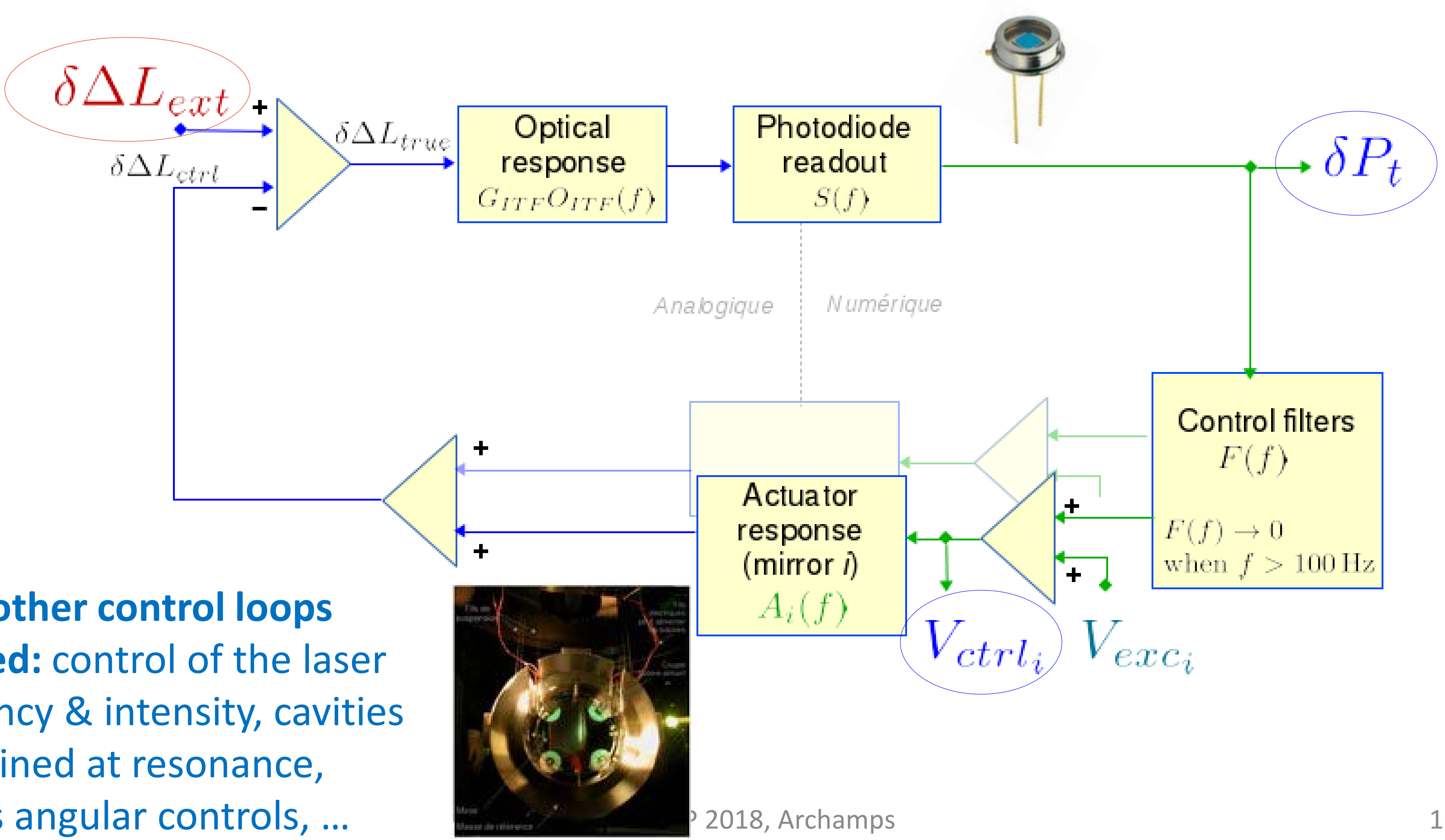
⚠ *In reality, the detector response depends on frequency...*

How do we control the working point?

Small offset from a dark fringe: $\Delta L_0 = n\frac{\lambda}{2} + 10^{-11}\,\mathrm{m}$

- Controls to reduce the motion up to ~100 Hz
- Precision of the control $\delta\Delta L_{true}$ ~ 10^{-15} m

$$\delta\Delta L_{ext} = \delta\Delta L_{noise} + \delta\Delta L_{GW}$$



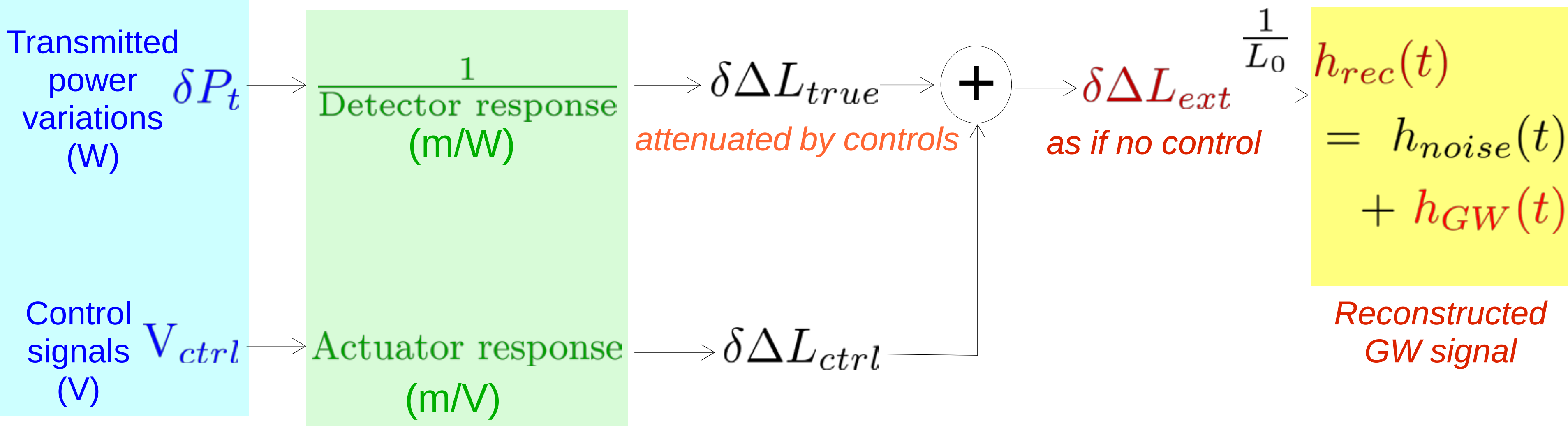
Many other control loops required: control of the laser frequency & intensity, cavities maintained at resonance, mirrors angular controls, …

From the detector data to the GW strain h(t)

- High frequency (>100 Hz): mirrors behave as free falling masses

$$\rightarrow \quad h(t) = \frac{\delta \Delta L_{true}(t)}{L_0}$$

- Lower frequency: the controls attenuate the noise... but also the GW signal!
  → the control signals contain information on *h(t)*



Transmitted power variations (W) δP_t → $\frac{1}{\text{Detector response}}$ (m/W) → $\delta \Delta L_{true}$

attenuated by controls

Control signals (V) V_{ctrl} → Actuator response (m/V) → $\delta \Delta L_{ctrl}$

$\delta \Delta L_{true} + \delta \Delta L_{ctrl}$ → $\delta \Delta L_{ext}$ $\xrightarrow{\frac{1}{L_0}}$

as if no control

$$h_{rec}(t) = h_{noise}(t) + h_{GW}(t)$$

Reconstructed GW signal

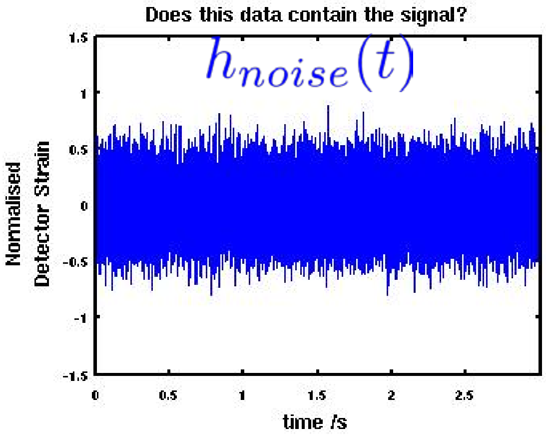
Input signals

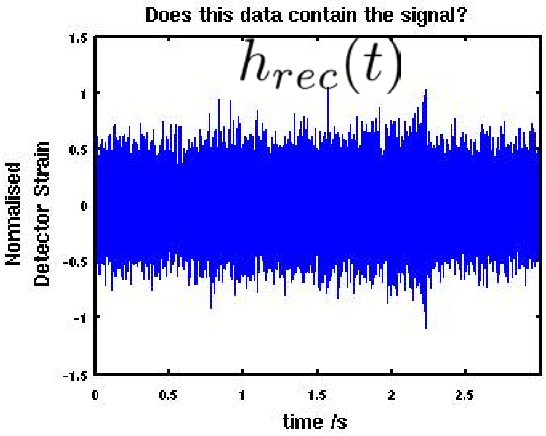
Responses to be measured (calibrated) in dedicated dataset

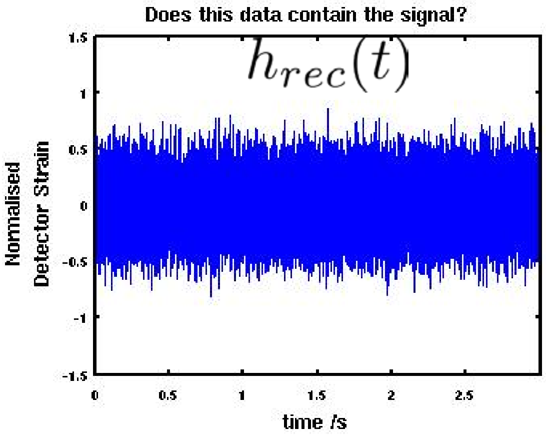
What is noise in Virgo?

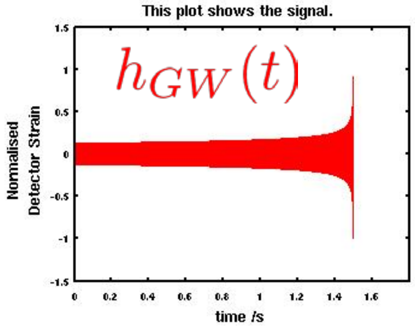
- Stochastic (random) signal that contributes to the signal $h_{rec}(t)$ but does not contain information on the gravitational wave strain $h_{GW}(t)$

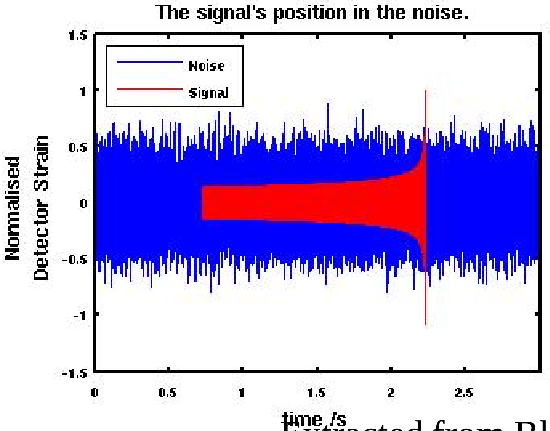
$$h_{rec}(t) = h_{noise}(t) + h_{GW}(t)$$

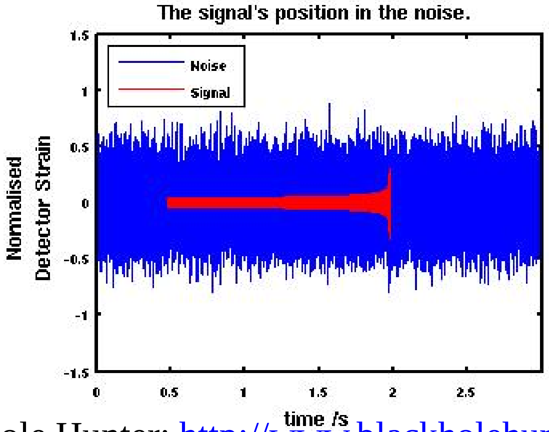

Does this data contain the signal?


Does this data contain the signal?


Does this data contain the signal?


This plot shows the signal.

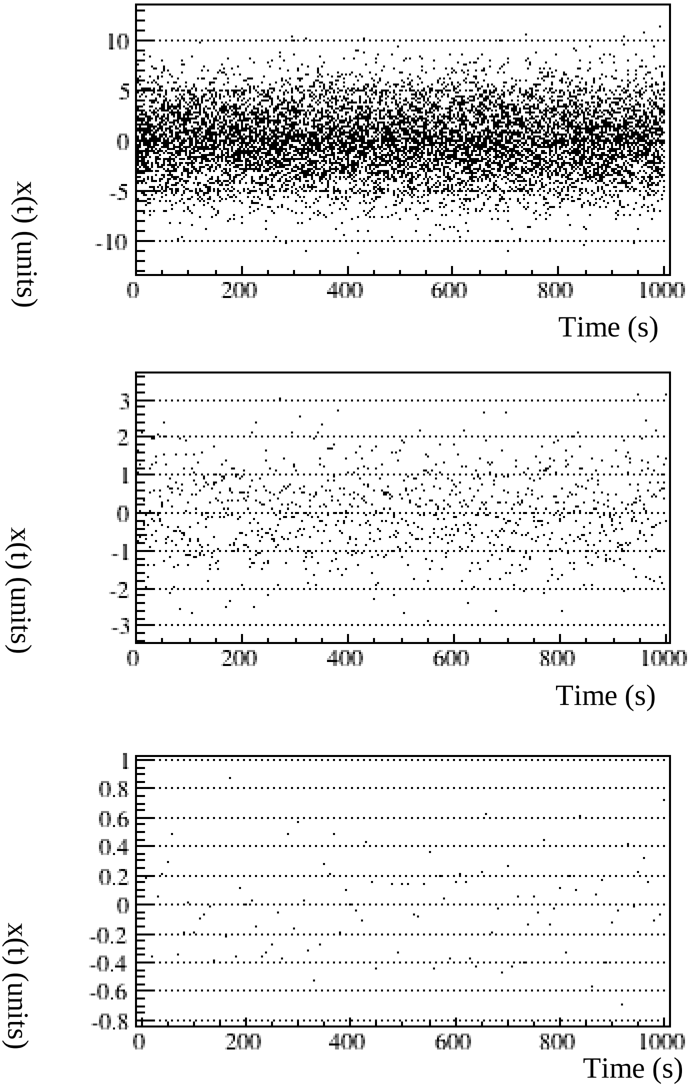

The signal's position in the noise.


The signal's position in the noise.

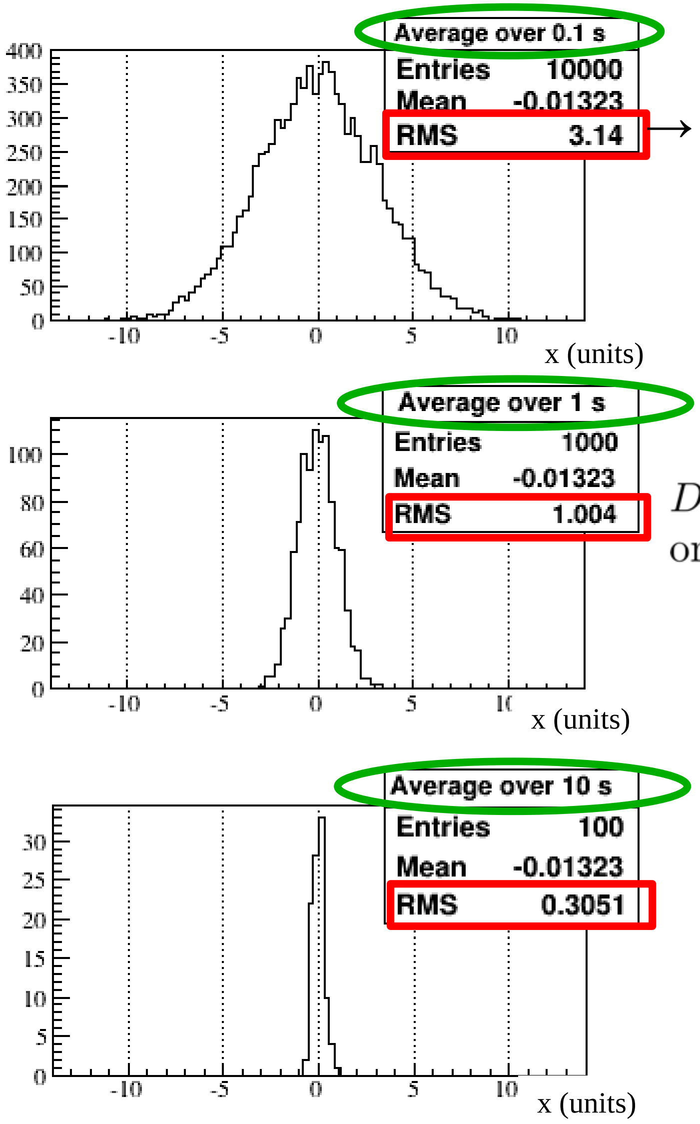
Extracted from Black Hole Hunter: http://www.blackholehunter.org/

How do we characterize noise?

Data points (noise)



Distribution of the data



→ Noise characterised by its standard deviation σ_x

$$\sigma_x = \frac{D}{\sqrt{\text{average duration}}}$$

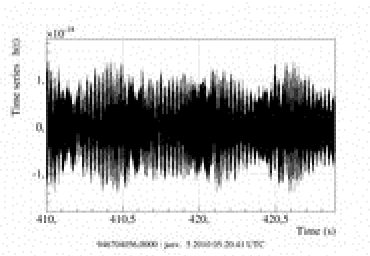
D is in (Data units $\times \sqrt{\text{s}}$) or $\frac{\text{Data units}}{\sqrt{\text{Hz}}}$

→ D = 1 units/√Hz

From hrec(t) to Virgo sensitivity curve

1/ Reconstruction of h(t)

$$h_{rec}(t) = h_{noise}(t) + \cancel{h_{GW}(t)}$$



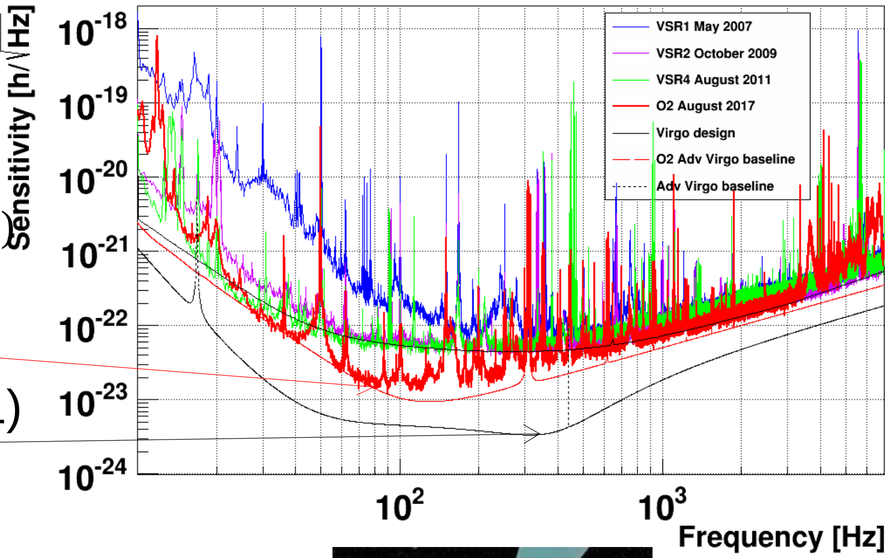
2/ Amplitude spectral density of *h(t)*
(noise standard deviation over 1 s)

$$ASD = \sqrt{PSD} = \sqrt{\frac{|DFT|^2}{T}}$$

Discrete Fourier Transform (DFT)

~5 x10^{-20} m/√Hz (Advanced Virgo O2, 2017)

~10^{-20} m/√Hz (Advanced Virgo nominal, ~2021)



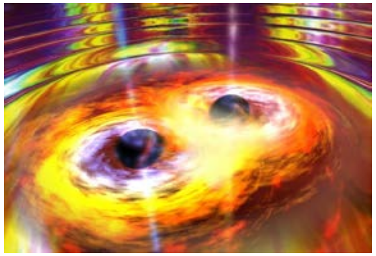


Image: Danna Berry/SkyWorks/NASA

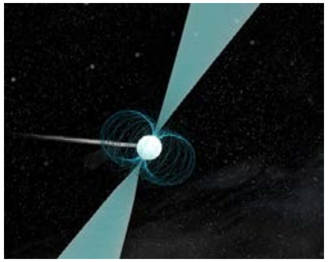


Image: B. Saxton (NRAO/AUI/NSF)

Compact Binary Coalescences

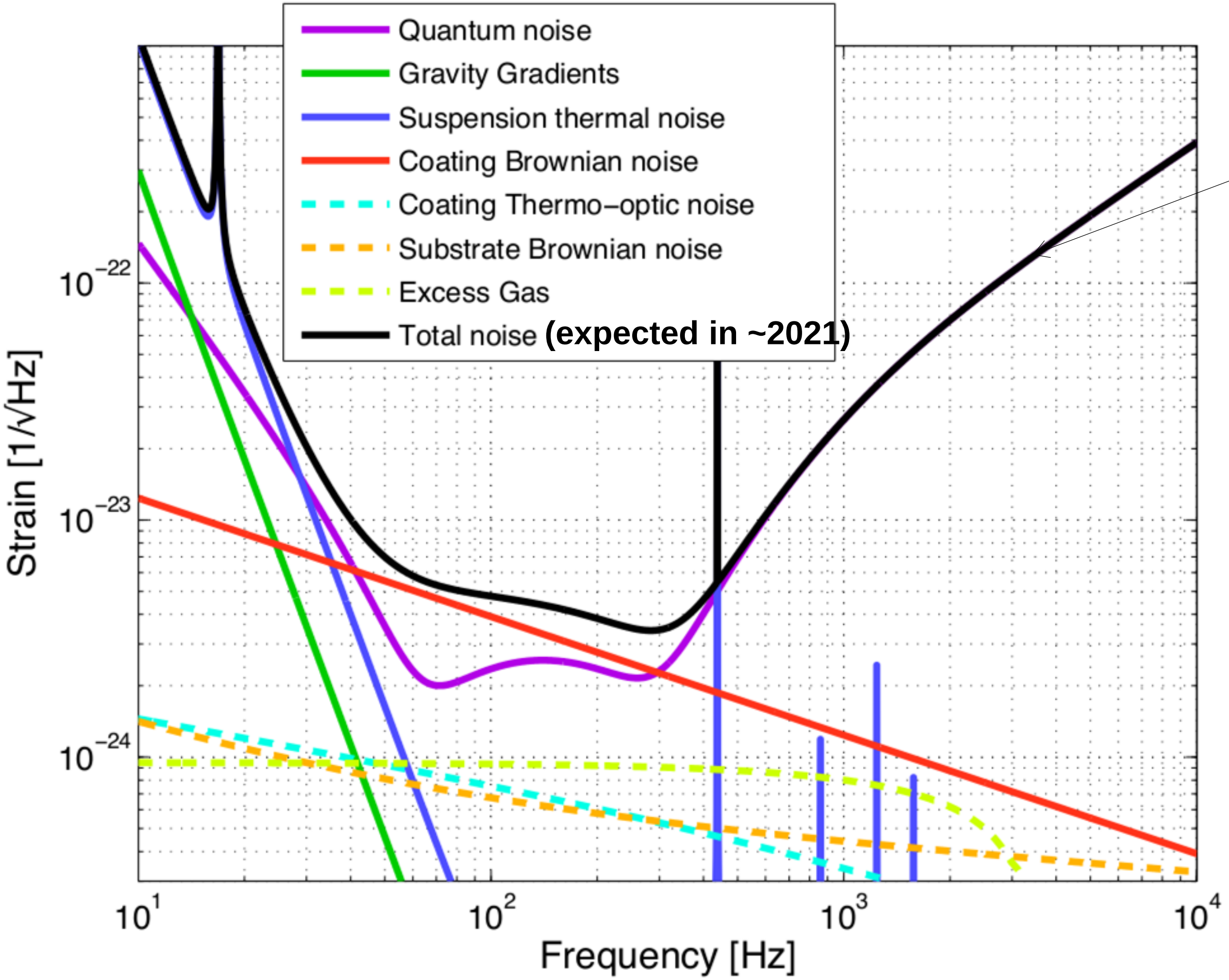
Signal lasts for a few seconds
→ can detect h ~ 10^{-23}

Rotating neutron stars

Signal averaged over days (~10^{6} s)
→ can detect h ~ 10^{-26}

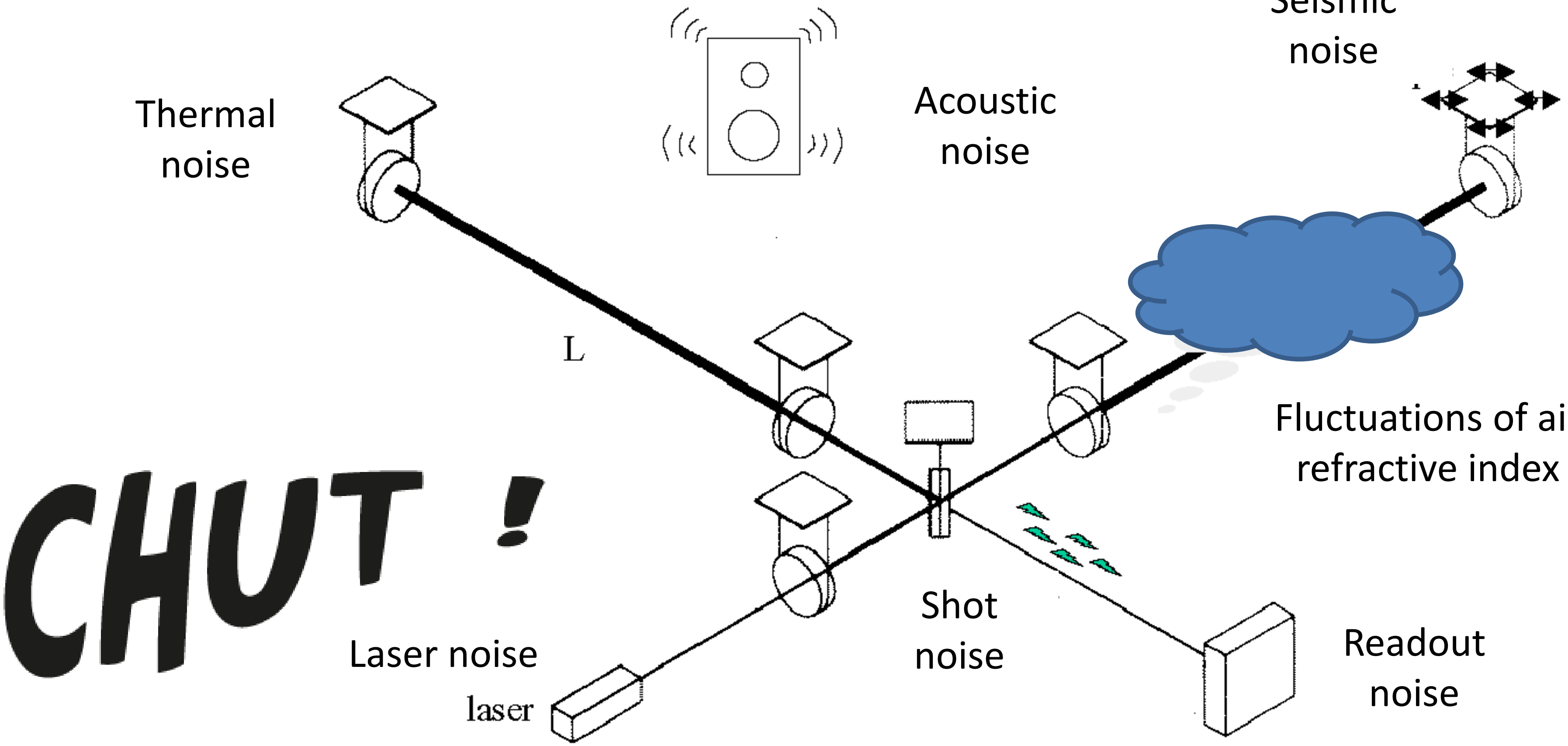
Nominal sensitivity of Advanced Virgo

Fundamental noise only
Possible technical noise not shown



Sum of all the noises

Fundamental noise sources



Seismic noise

Thermal noise

Acoustic noise

Fluctuations of air refractive index

Laser noise

Shot noise

Readout noise

Shot noise

Fluctuations of arrival times of photons (quantum noise)

Arrival time of single photons

$$\text{Power received by the photodiode: } P_t$$

$$\rightarrow \quad N = \frac{P_t}{\mathrm{h}\nu} \text{ photons/s on average.}$$

$$\text{Standard deviation on this number: } \sigma_N = \sqrt{N}$$

$$\rightarrow \quad \sigma_{P_t} = \sigma_N \times \mathrm{h}\nu = \sqrt{\frac{P}{\mathrm{h}\nu}}\mathrm{h}\nu = \sqrt{P_t \mathrm{h}\nu}$$

$$\text{Virgo laser: } \lambda = 1.064\,\mu\text{m} \rightarrow \nu = \frac{\mathrm{c}}{\lambda} \sim 2.8 \times 10^{14}\,\text{Hz}$$

$$\text{Working point: } P_t \sim 80\,\text{mW} \quad \rightarrow \quad \sigma_{P_t} = 0.1\,\text{nW}/\sqrt{\text{Hz}}$$

$$\rightarrow \quad \text{a variation of power is interpreted as a variation of distance } \delta\Delta L$$

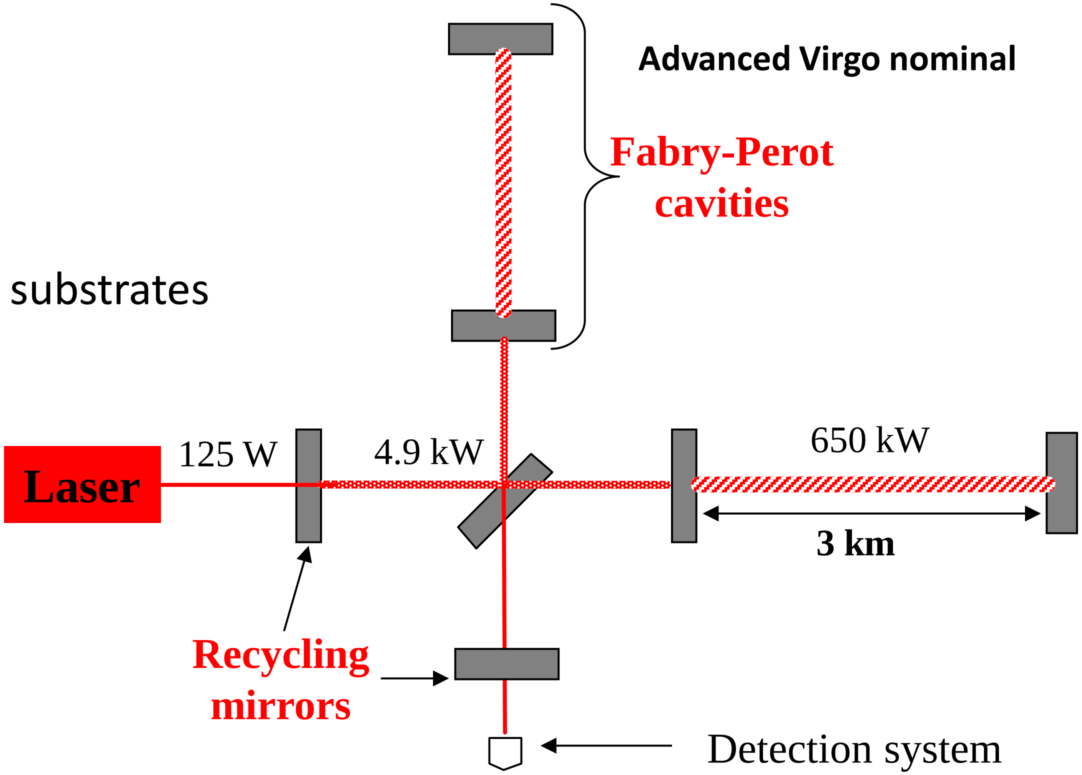
$$\delta P_t = (\text{Virgo response}) \times L_0 \times h \qquad h_{equivalent} = \frac{1}{L_0}\frac{\sigma_{P_t}}{(\text{Virgo response})}$$

(in W/m)

→ $h_{equivalent} \propto 1/\sqrt{P_{in}}$

Minimizing impact of shot noise

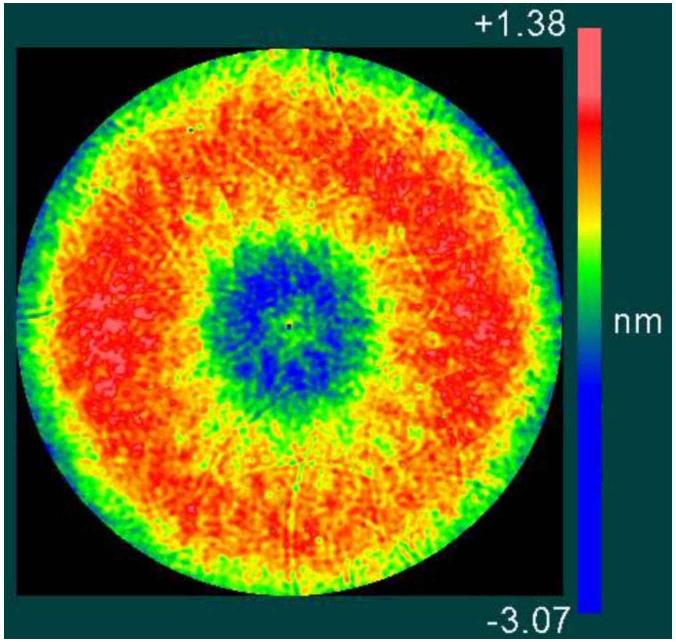
- Drives **optical configuration**
- **Use high power laser**
  → limited by side-effects:
    - radiation pressure noise
    - thermal absorption in mirror substrates

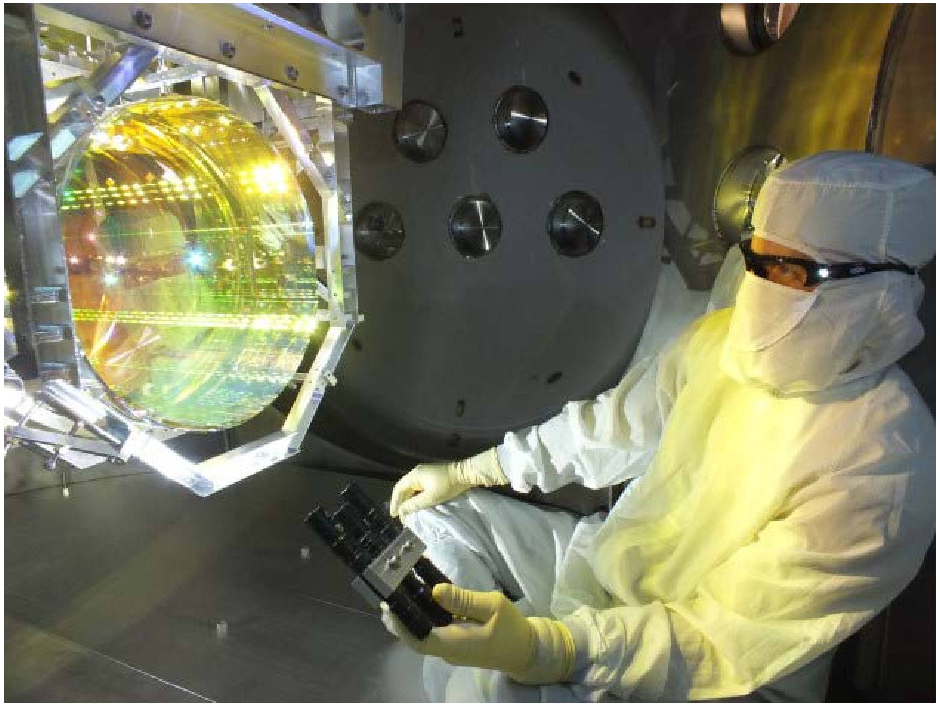


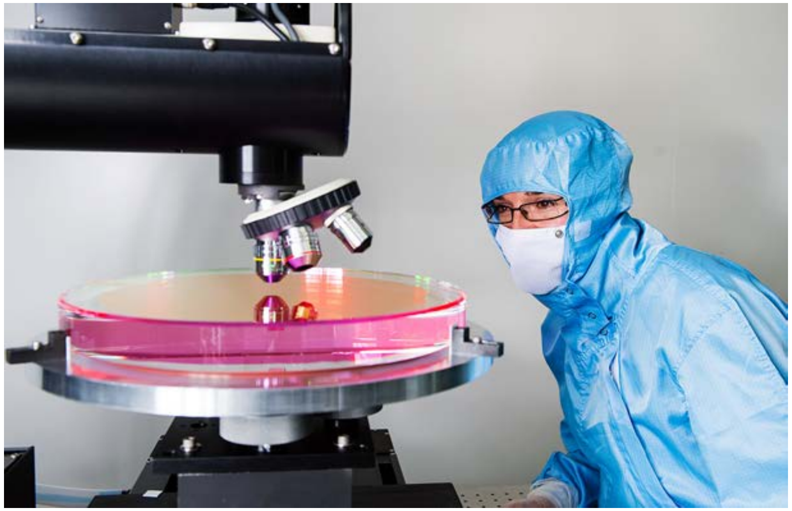
- Avoid optical losses > **high quality mirrors**
- Optimize contrast defect (C≈1) > **Output Mode Cleaner Cavity**

« Perfect » mirrors

- 40 kg, 35 cm diameter, 20 cm thickness in ultra pure silica
- Uniformity of mirrors is unique in the world:
  - a few nanometers peak-to-valley
  - flatness < 0.5 nm RMS (over 150mm diameter)

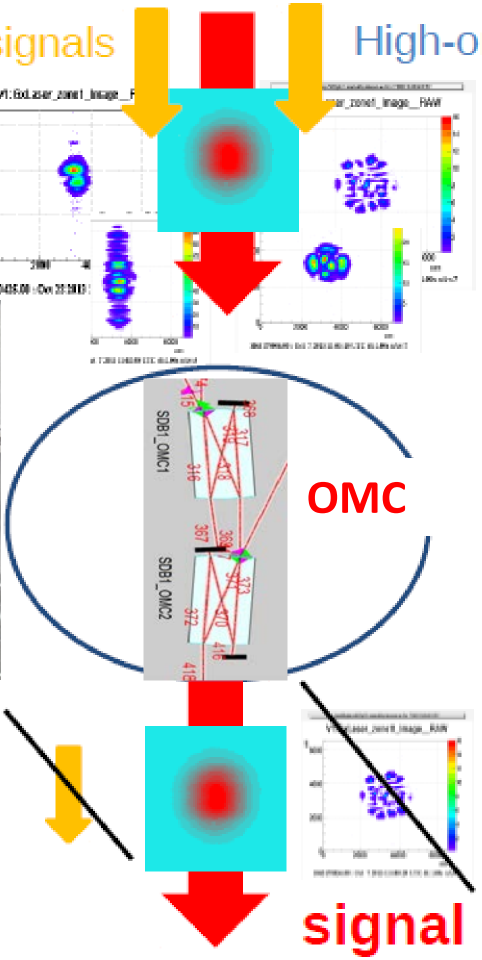






Output Mode Cleaner

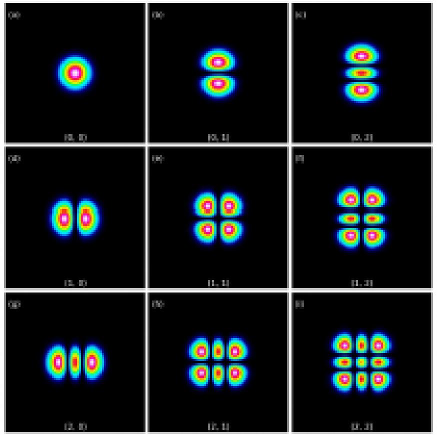
- 2 bow-tie Fabry Perot cavities:
  - Get rid of high order modes and controls signals.

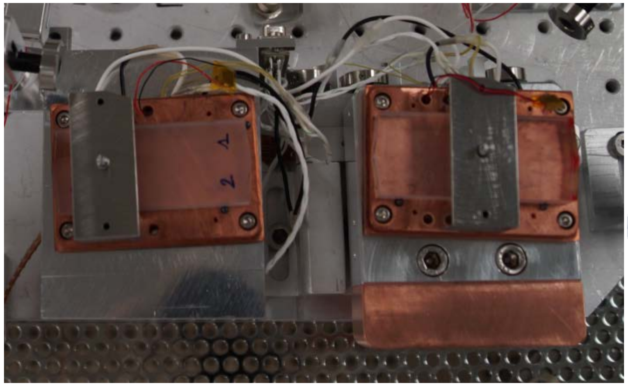

Control signals

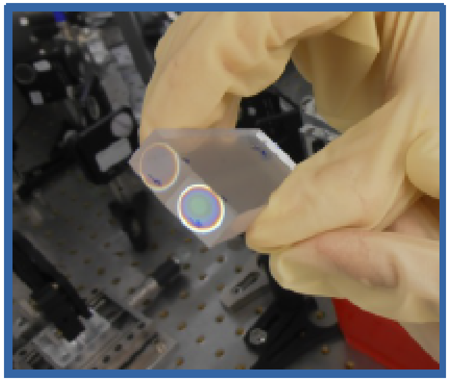
High-order modes

OMC

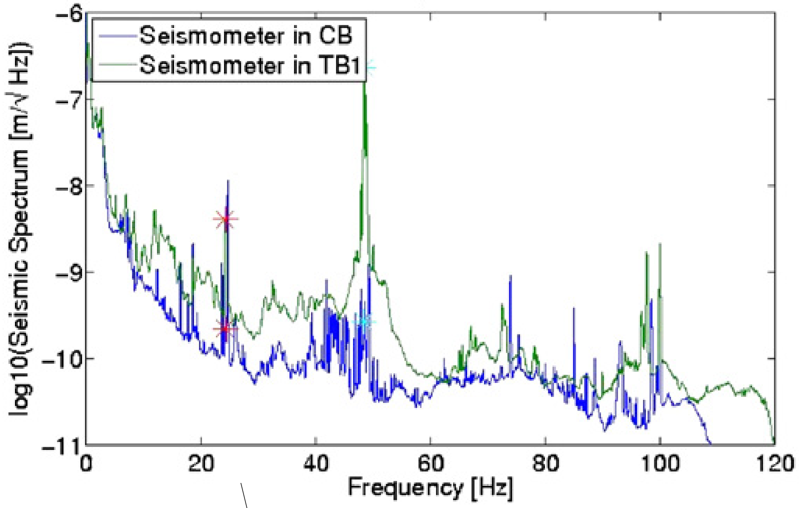
signal





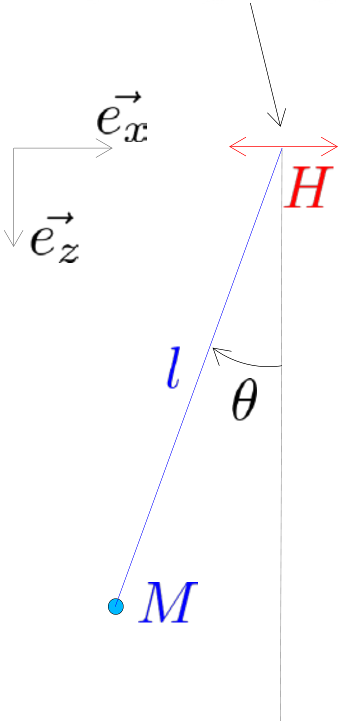


Seismic noise and suspended mirrors



Ground vibrations up to ~1 µm/√Hz at low frequency decreasing down to ~10 pm/√Hz at 100 Hz

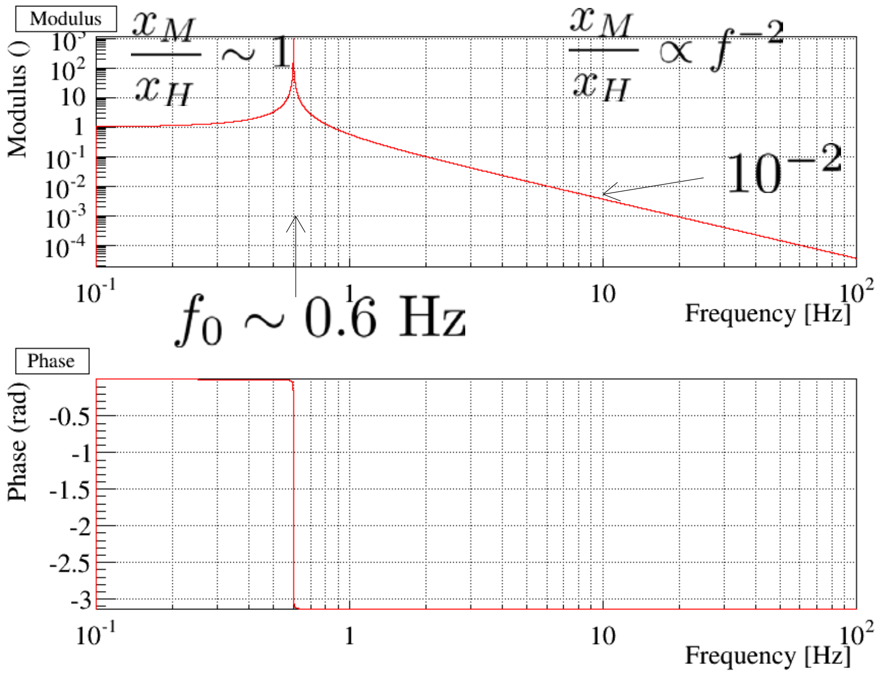
$$\gg 10^{-19}\,\mathrm{m}/\sqrt{\mathrm{Hz}} \text{ needed to detect GW !!}$$



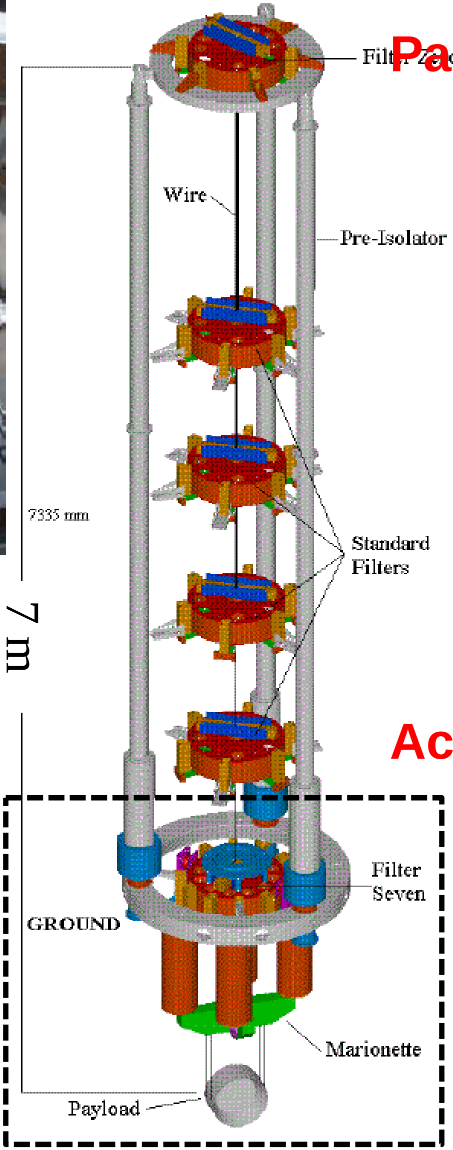
Assuming δx_H small and sinusoidal and θ small:

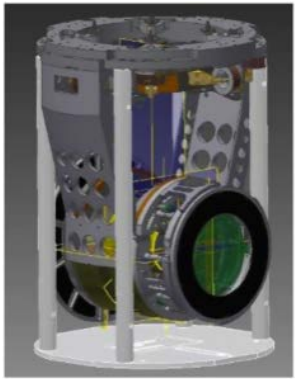
$$\underline{x_M} = \underline{\mathcal{H}} \times \underline{x_H}$$

Transfer function



Seismic noise: Virgo super-attenuators





Passive attenuation: 7 pendulum in cascade

$$\text{At 10 Hz: } \frac{x_{mirror}}{x_{ground}} \sim \left(10^{-2}\right)^{7} = 10^{-14}$$

$$x_{ground} \sim 10^{-9}\,\mathrm{m}/\sqrt{\mathrm{Hz}}$$

$$\rightarrow x_{mirror} \sim 10^{-23}\,\mathrm{m}/\sqrt{\mathrm{Hz}}$$

This noise directly modifies the positions of the mirror surfaces, and thus $\delta\Delta L$ and $h_{rec}(t)$!

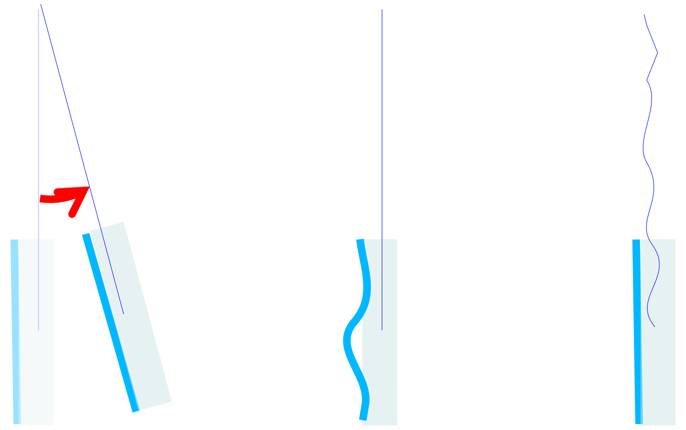
Active controls at low frequency

- Accelerometers or interferometer data
- Electromagnetic actuators
- Control loops

Thermal noise (pendulum and coating)

Microscopic thermal fluctuations

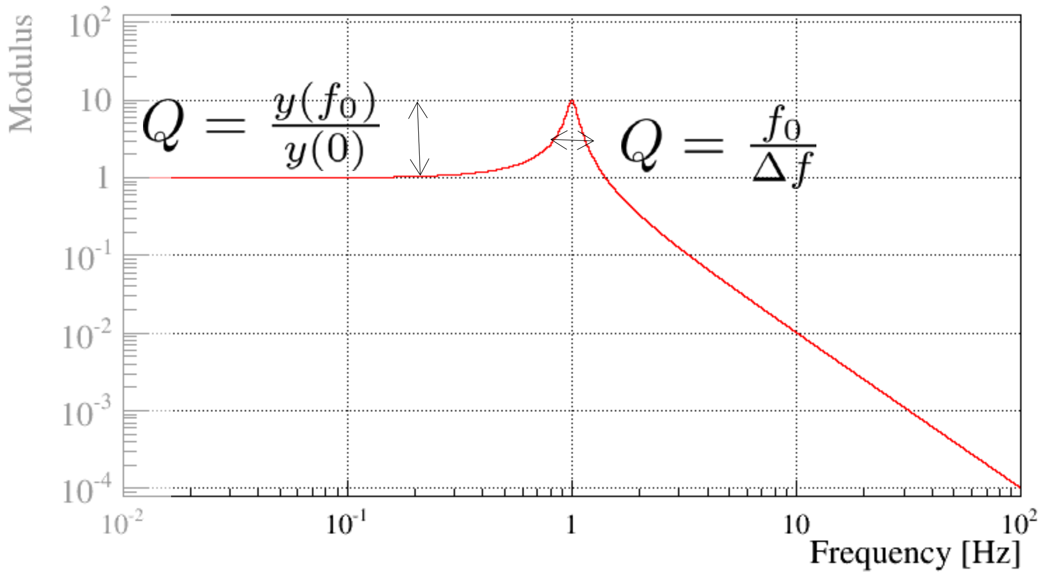
→ dissipation of energy through excitation of the macroscopic modes of the mirror



Pendulum mode
f < 40 Hz

“Mirror” mode
f> few kHz

“Violin” modes
f > 40 Hz

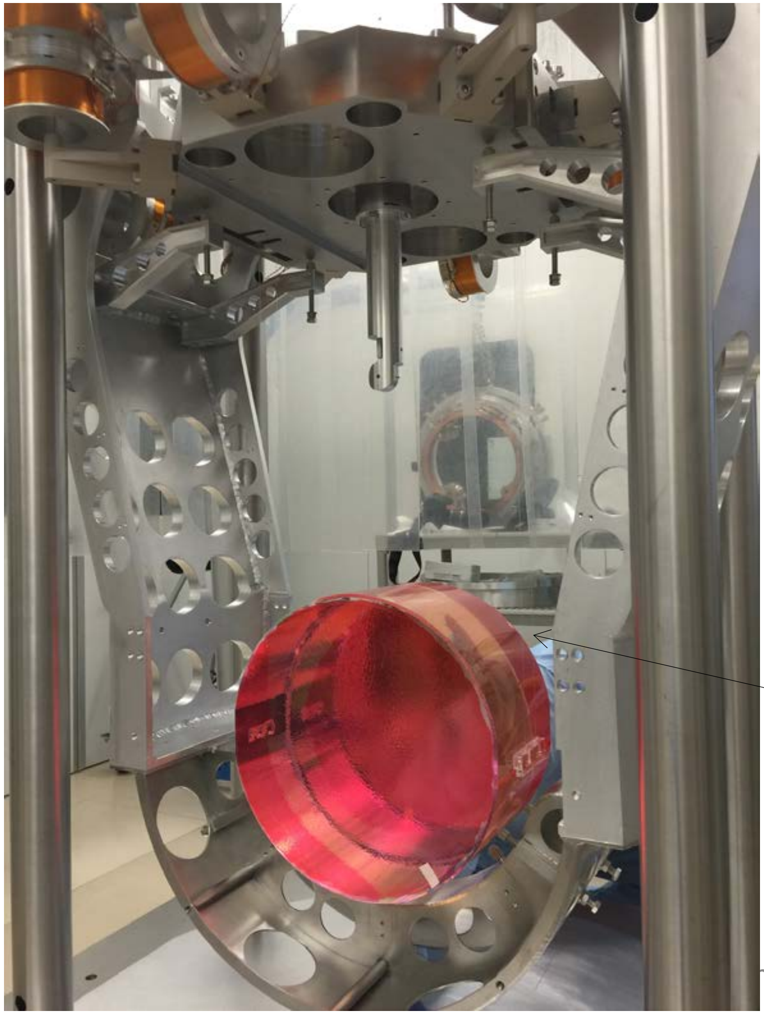


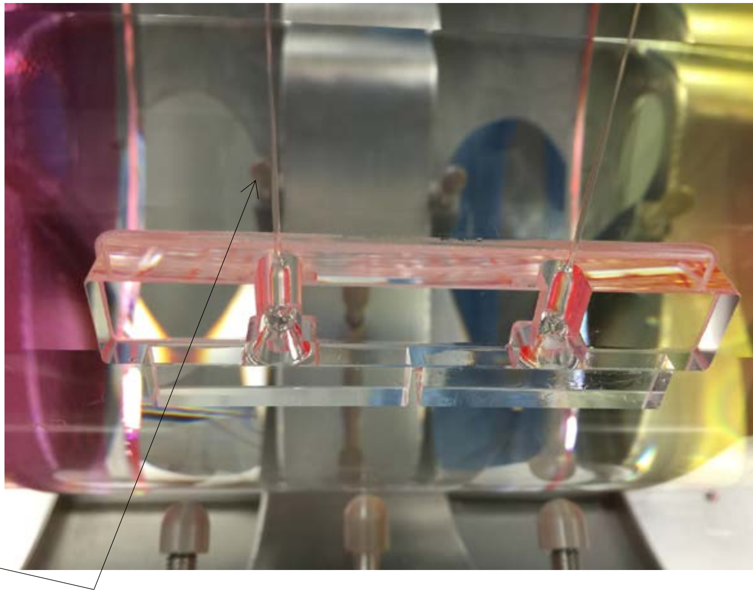
This noise directly modifies the positions of the mirror surfaces, and thus $\delta\Delta L$ and $h_{rec}(t)$!

We want high quality factors Q to concentrate all the noise in a small frequency band

Thermal noise: improving Q

- **Very high quality mirror coating** developed in a lab close to Lyon (Laboratoire des Matériaux Avancés)
- **Monolithic suspension** developed in labs in Perugia and Rome

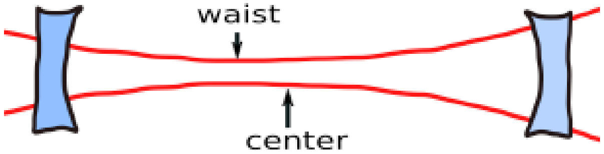




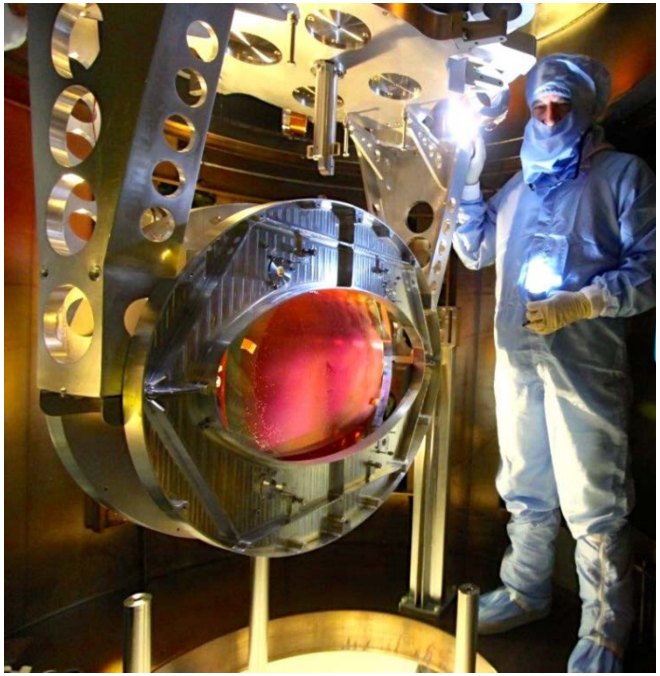
Fused-silica fibers
(diameter of 400 µm and length of 0.7 m)

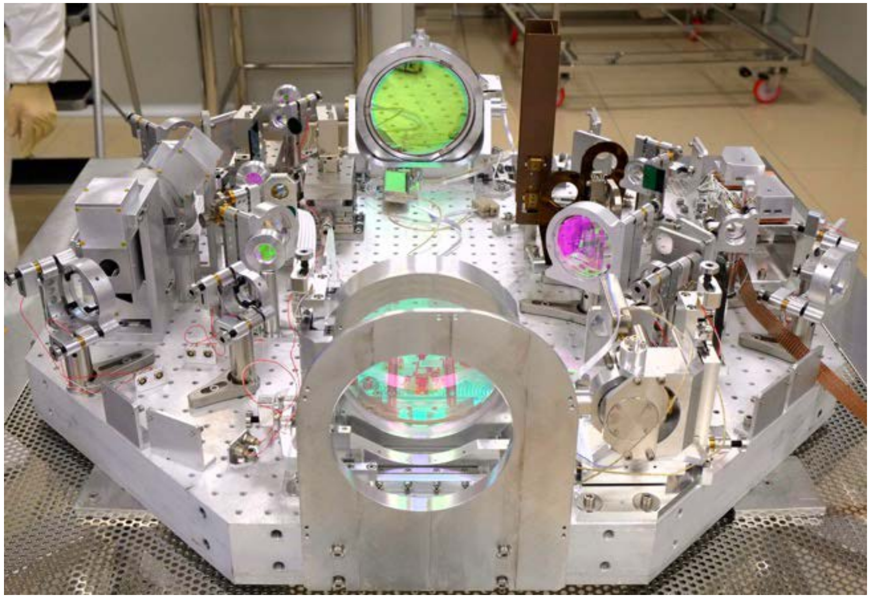
Thermal noise: coupling reduction

- Reduce the coupling between the laser beam and the thermal fluctuations
  → **use large beams**: fluctuations averaged over larger area
  → Thermal Noise ~1/D, with D = beam diameter



- Impact of large beams:
  - Require beam splitter (diameter = 55 cm)
  - High magnification telescopes to adapt beam size to photodetectors (from w=50 mm on mirrors to w=0.3 mm on sensors) > require optical benches





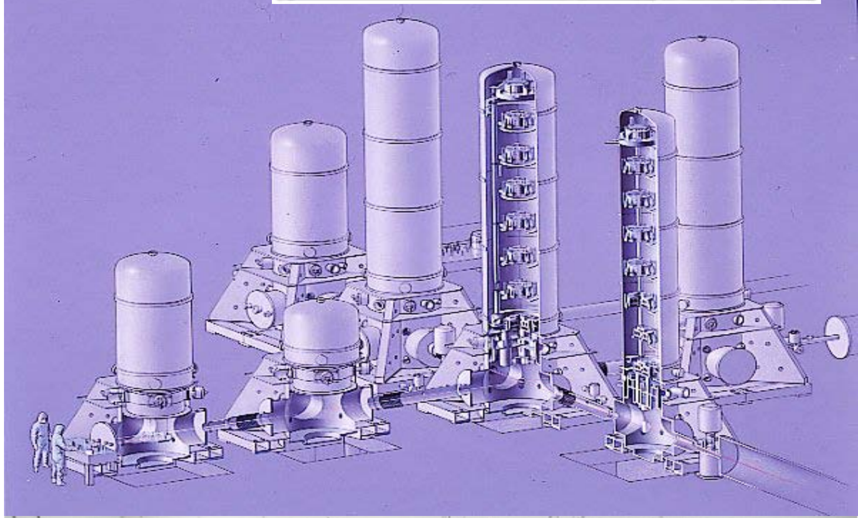
Under vacuum

Goals

- Isolation against acoustic noise
- Avoid measurement noise due to fluctuations of air refractive index
- Keep mirrors clean

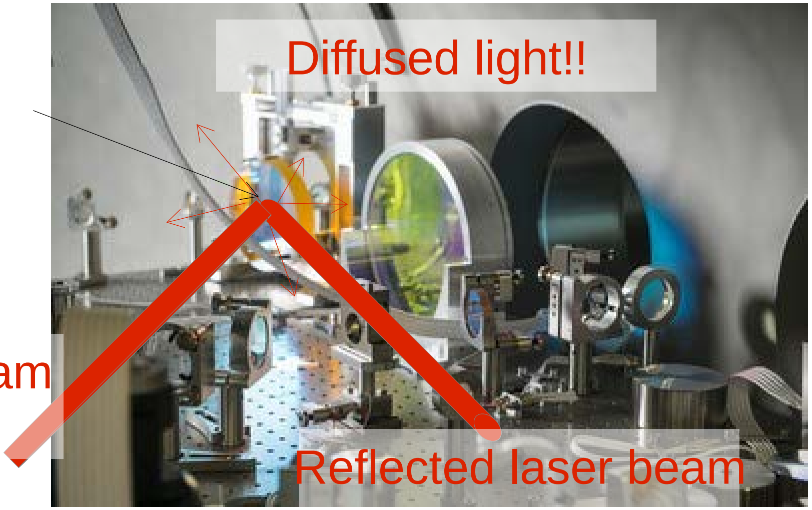
Advanced Virgo vacuum in a few numbers:

- Volume of vacuum system: 7000 m^3
- Different levels of vacuum:
  - 3 km arms designed for up to 10^{-9} mbar (Ultra High Vacuum)
  - ~10^{-6} - 10^{-7} mbar in mirror vacuum chambers (« towers »)
- Separation between arms and towers with cryotrap links



Example of technical noise: Diffused light

Optical element
(mirror, lens, ...)
vibrating due to
seismic or
acoustic noises



Diffused light!!

Incident laser beam

Reflected laser beam

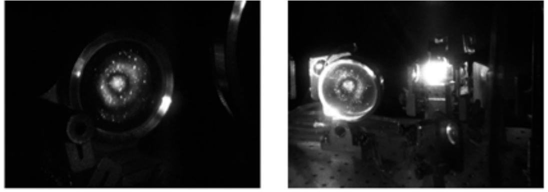
some photons of the diffused
light gets recombined with the
interferometer beam

↓

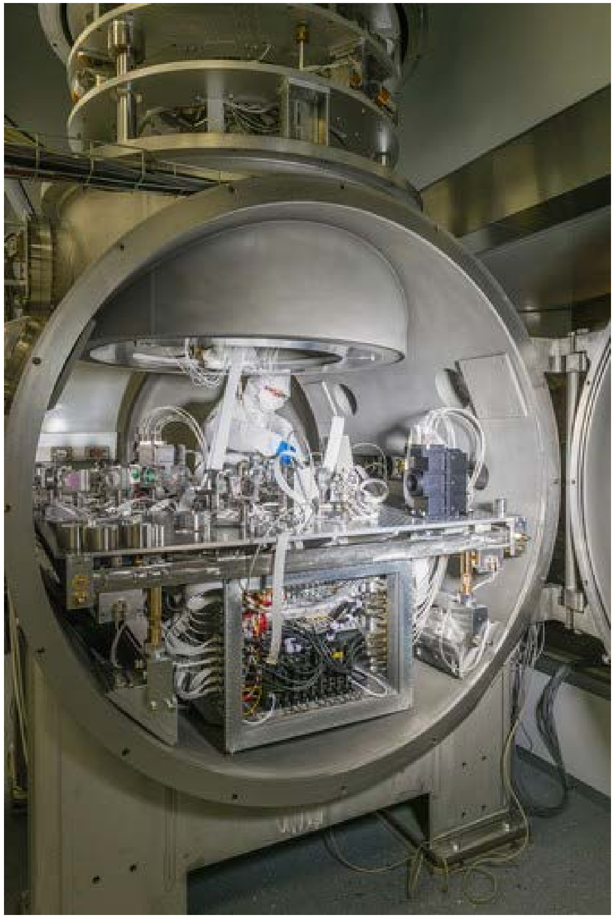
phase noise

↓

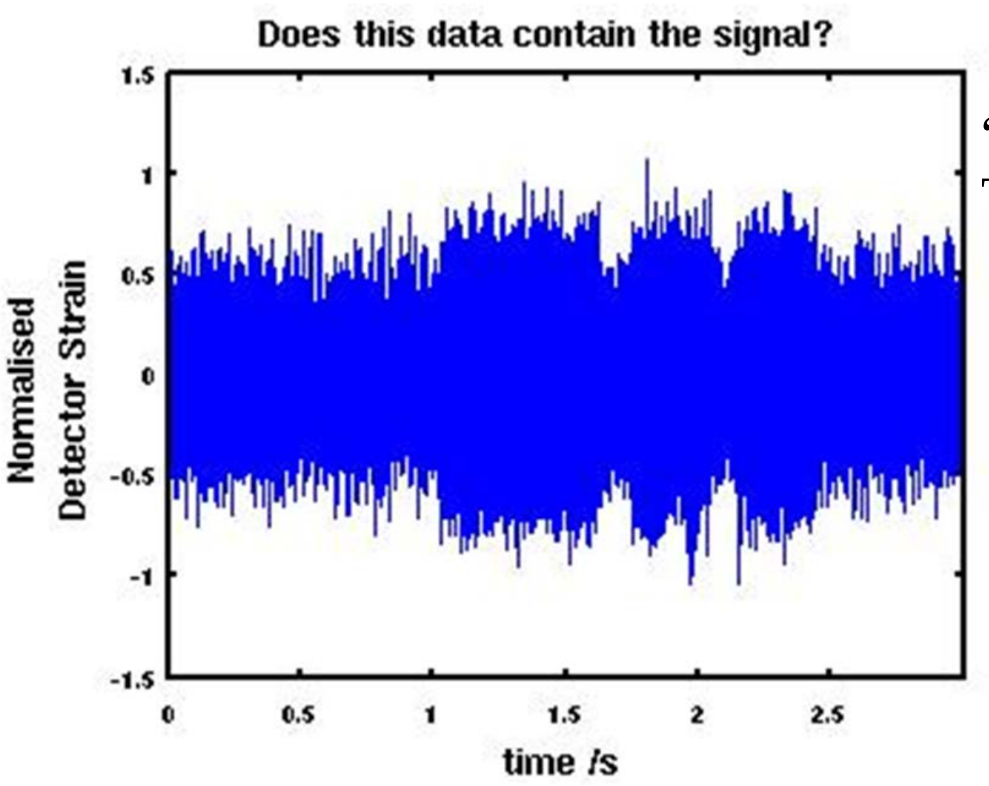
extra power fluctuations
(imprint of the optical element vibrations)



Evolution for AdVirgo: suspend
the optical benches and place
them under vacuum



Noises are not always stationary

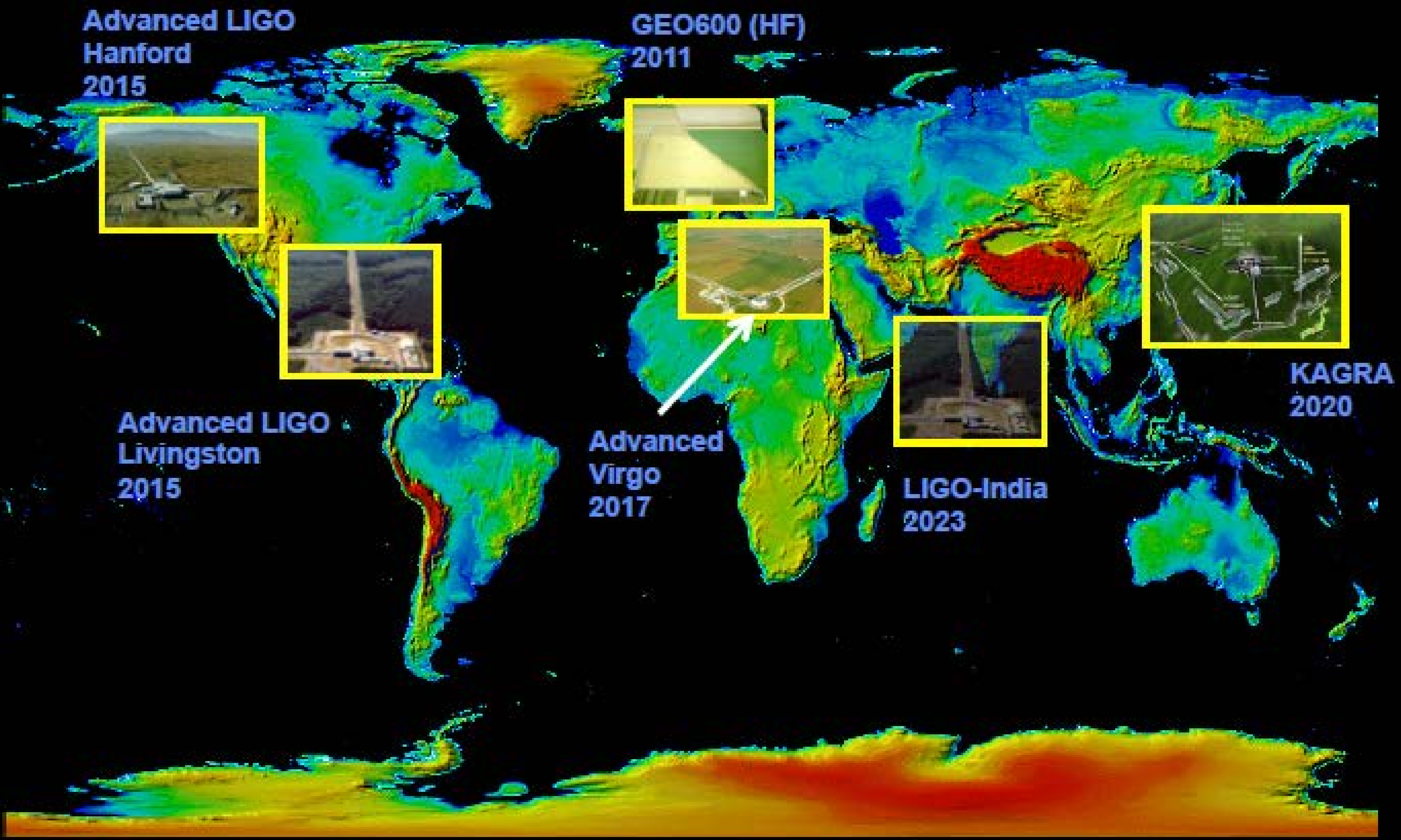


Does this data contain the signal?

“Glitches” are impulses of noise.
They might look like a transient GW signal

- environmental disturbances monitored with an array of sensors: seismic activities, magnetic perturbations, acoustic noises, temperature, humidity → used to veto false alarm triggers due to instrumental artifacts
- requires coincidence between 2 detectors to reduce false alarm rate

The detector network

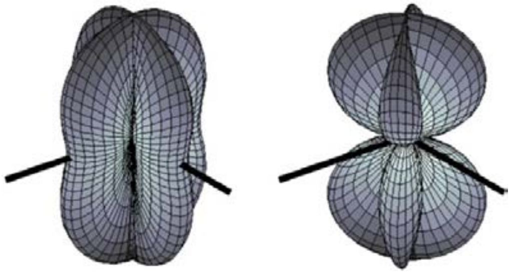


LIGO

2 interferometers - 4 km arms

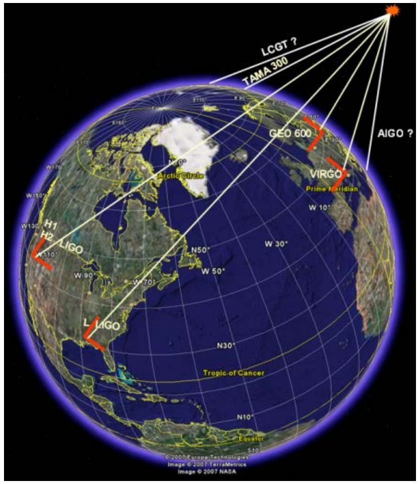
- Louisiana
- Washington State
- A third one will be installed in India

The benefits of the network



- ❑ A GW interferometer has a wide beam antenna
  - A single detector cannot localize the source
  - Need to compare the signals found in coincidence between several detectors (triangulation):

→ **allow to point towards the source position in the sky**

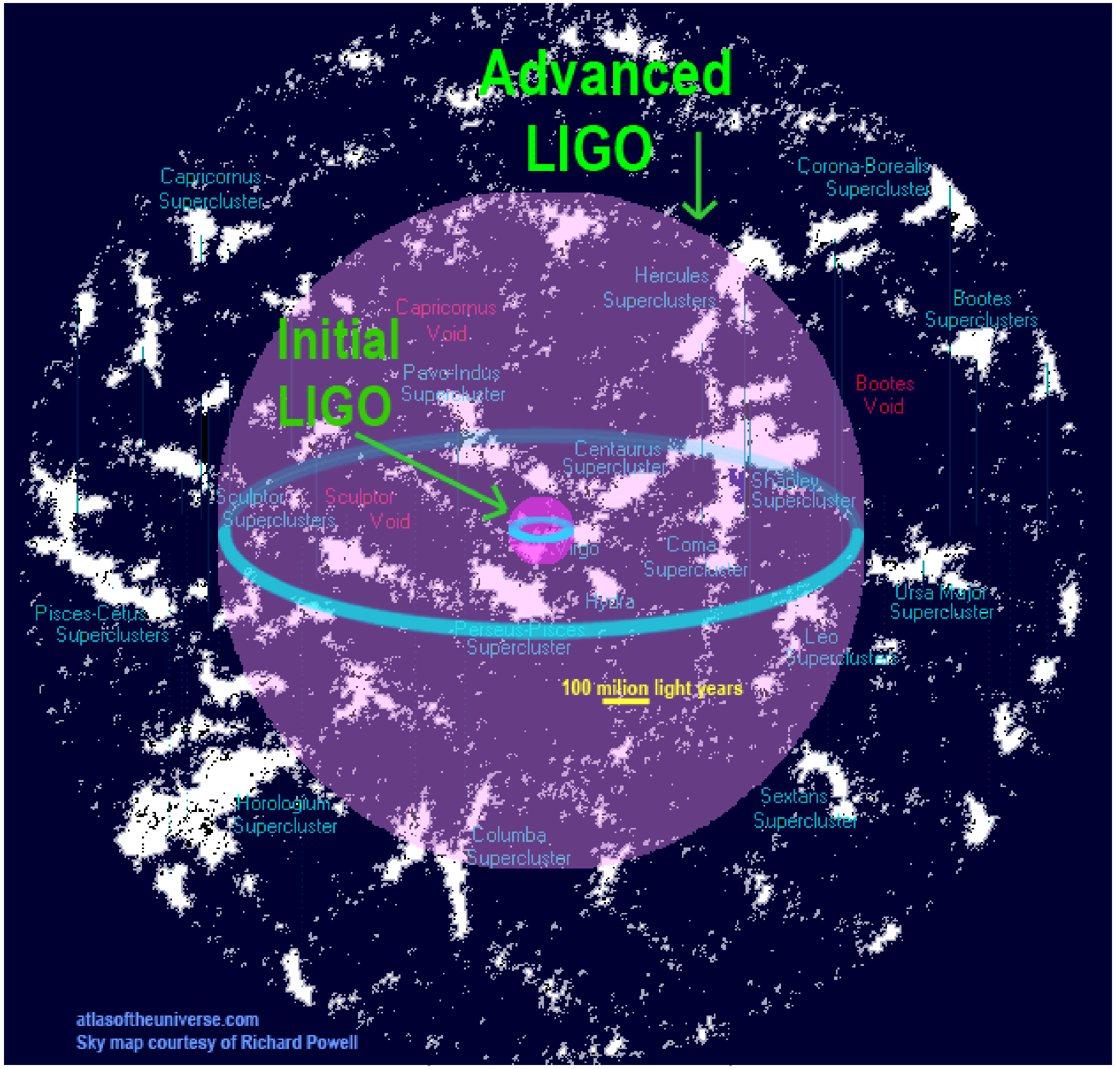


- ❑ Looking for rare and transient signals: can be hidden in detector noise

→ requires observation in coincidence between at least 2 detectors

- ❑ Since 2007, Virgo and LIGO share their data and analyze them jointly

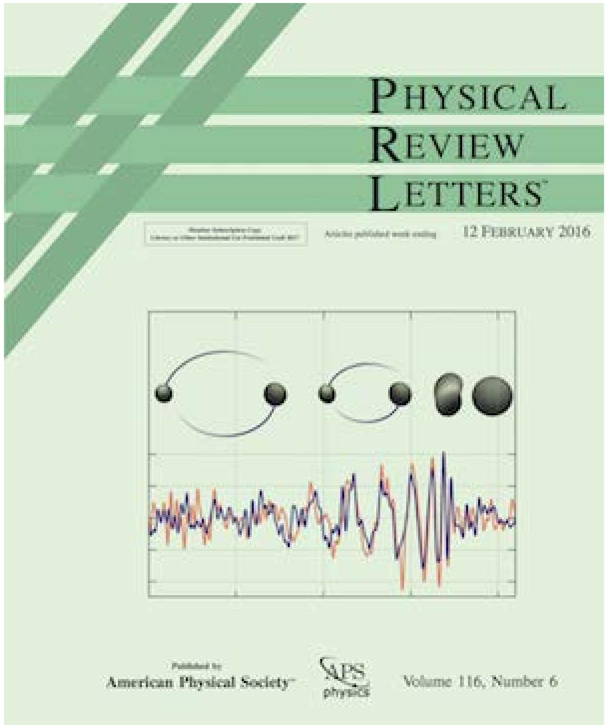
From the first to the second generation of detectors



atlasoftheuniverse.com
Sky map courtesy of Richard Powell

O1: First science run of Advanced LIGO
Sep 2015 – Jan 2016

First event called GW150914

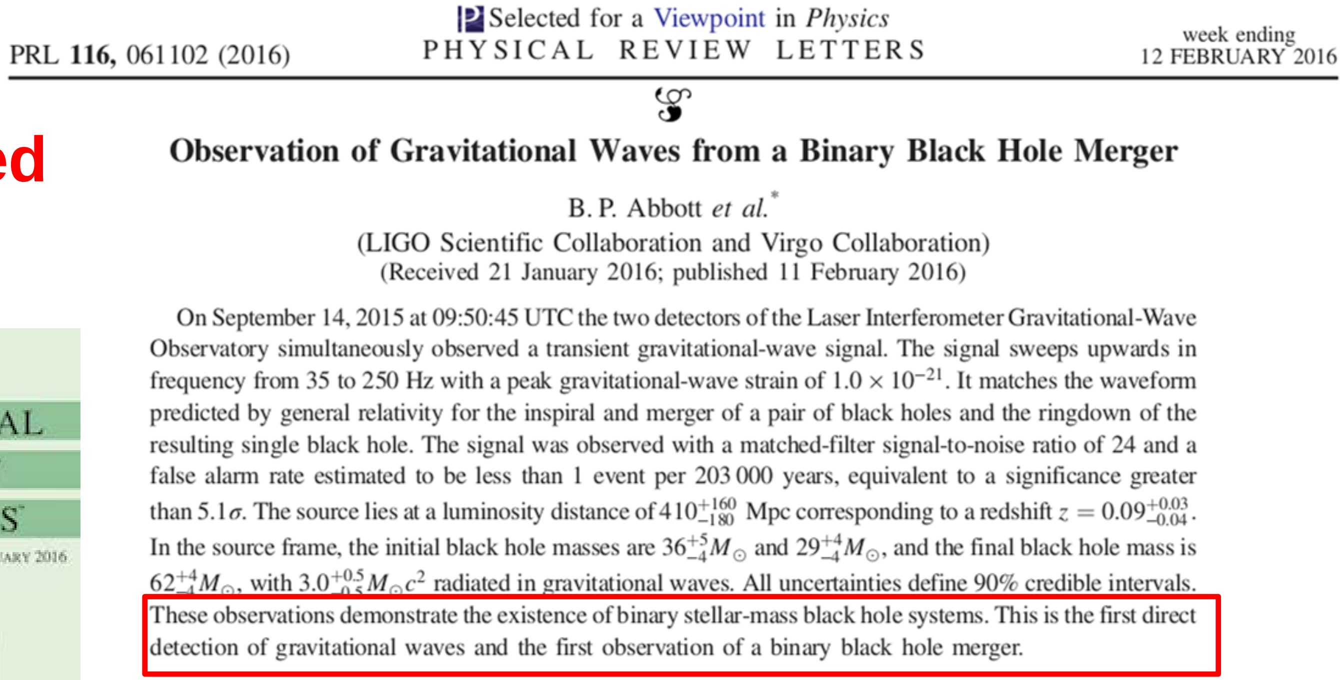


PHYSICAL REVIEW LETTERS

12 FEBRUARY 2016

American Physical Society

Volume 116, Number 6



Selected for a Viewpoint in *Physics*

PRL **116,** 061102 (2016) 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)

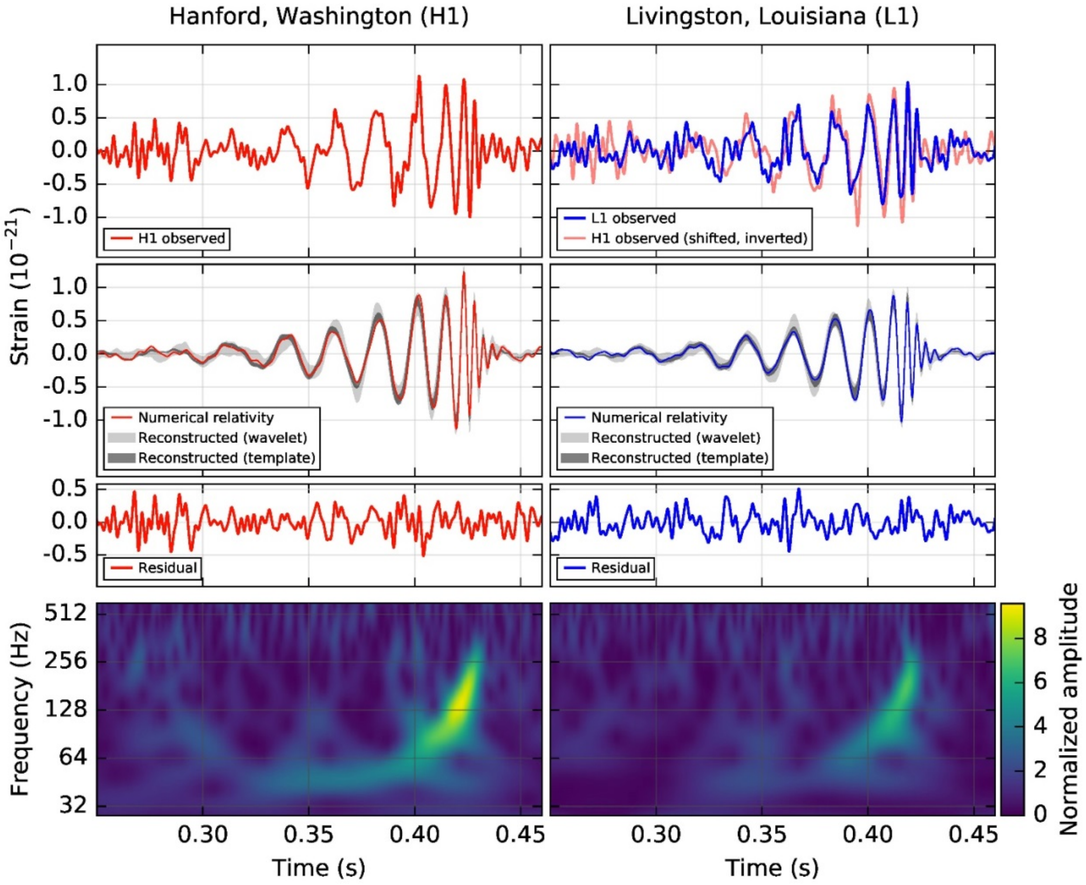
On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 to 250 Hz with a peak gravitational-wave strain of 1.0×10^{-21}. It matches 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.

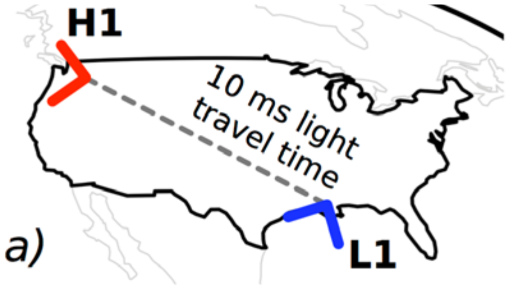
On Feb 11 2016, the LIGO and Virgo collaborations have announced the detection of

GW150914

On September 14th, 2015 at 09:50:45 UTC | 29 + 36 $M_\odot$

The first direct detection of GW

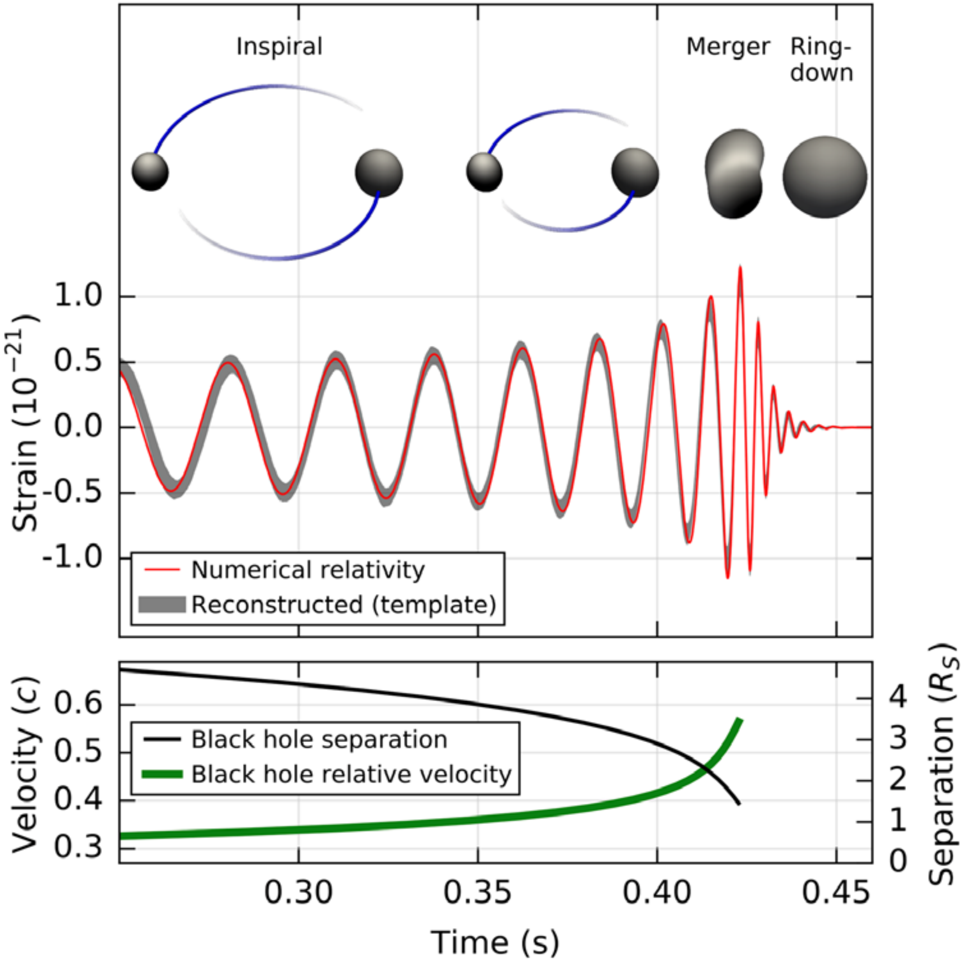


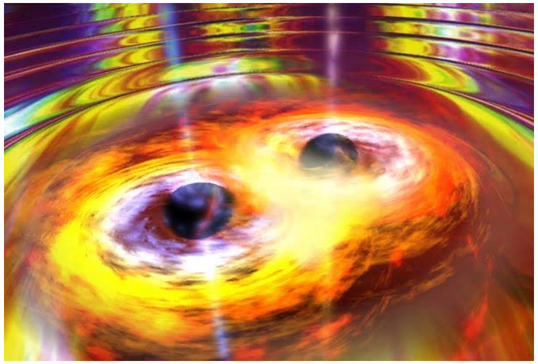


- Same signal in the 2 LIGO detectors, with a time difference = 7 ms
- Signal evolution = Typical signature of a coalescence
- Signal seen from 30 Hz:
  - Duration ~200 ms
  - Number of cycle ~10
- Signal-to-noise ratio: 24
  False alarm rate: <1 in 200,000 years
- Signal extracted from data matches the expected waveform for the coalescence of 2 black holes:

  36 et 29 solar masses

First observation of binary black hole merger (GW150914)





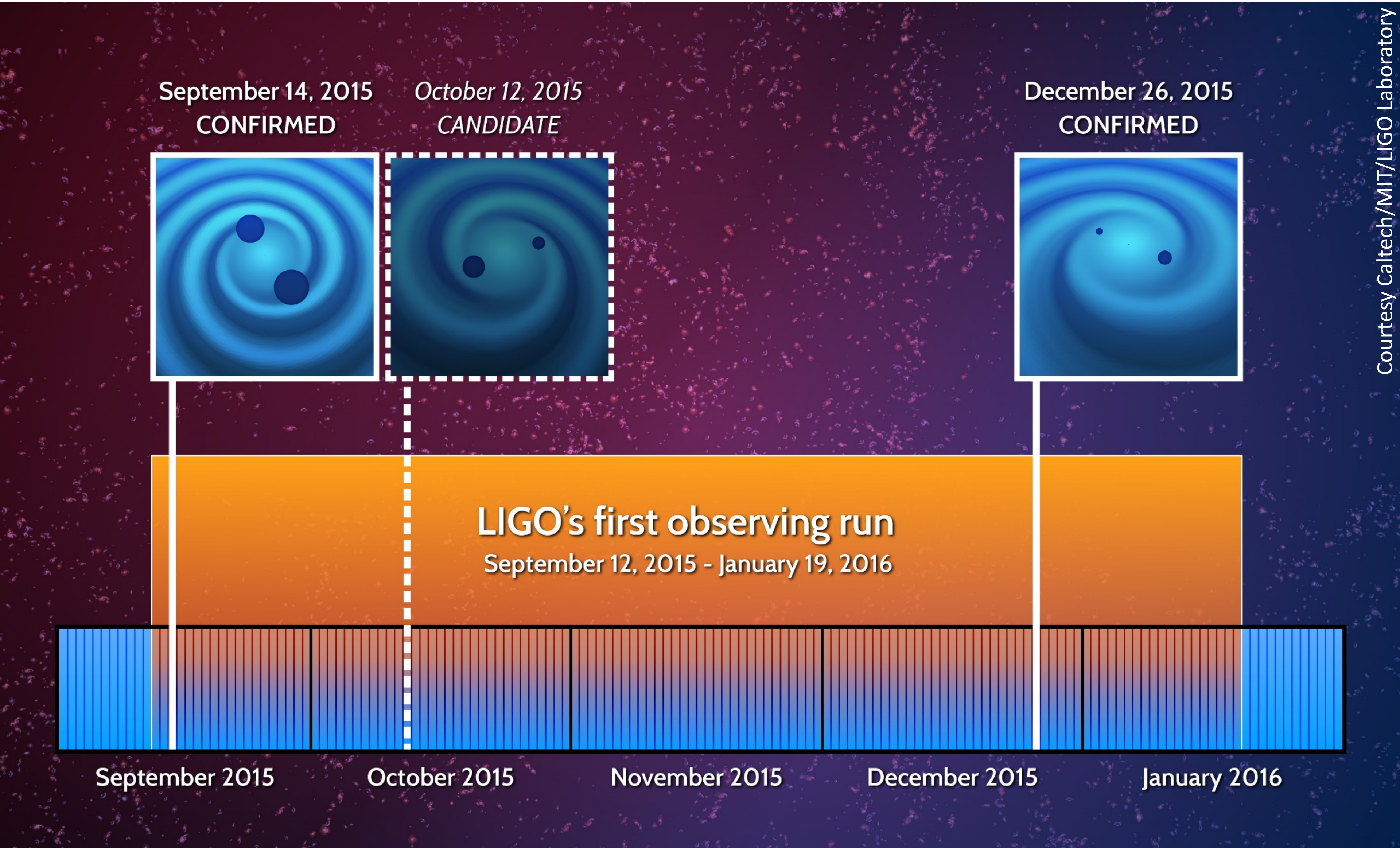
Distance ~$1.3\text{x}10^9$ light-years (z~0.1)

Initial black holes (total mass ~65 $M_\odot$)
~36 $M_\odot$ and 29 $M_\odot$
peak speed of BH's: ~0.6 c

Remnant black hole
mass ~62 $M_\odot$
spin ~70% of maximum
horizon ~ 180 km

Energy radiated into GW (in 200 ms): 3 $M_\odot$

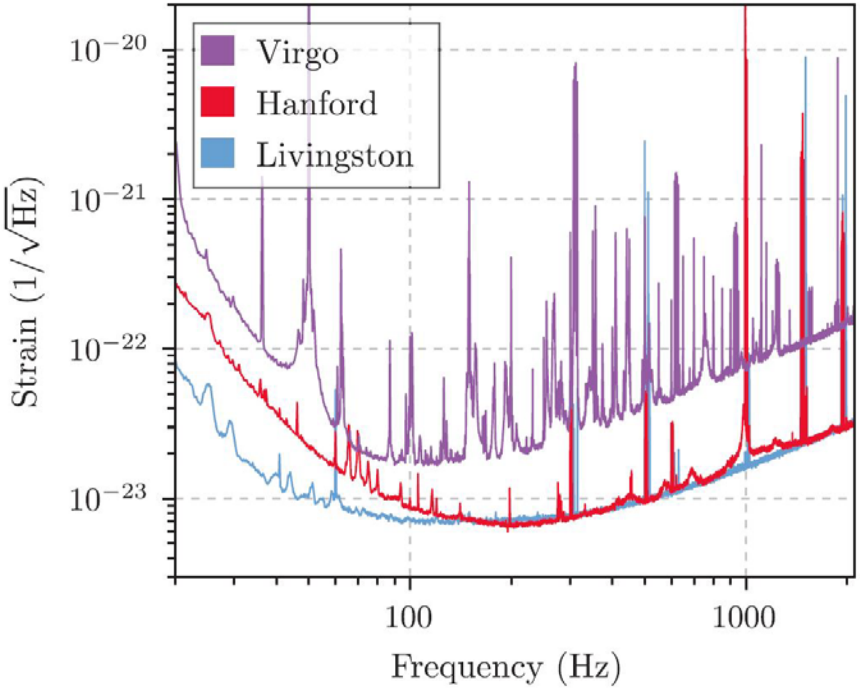
Recap from O1

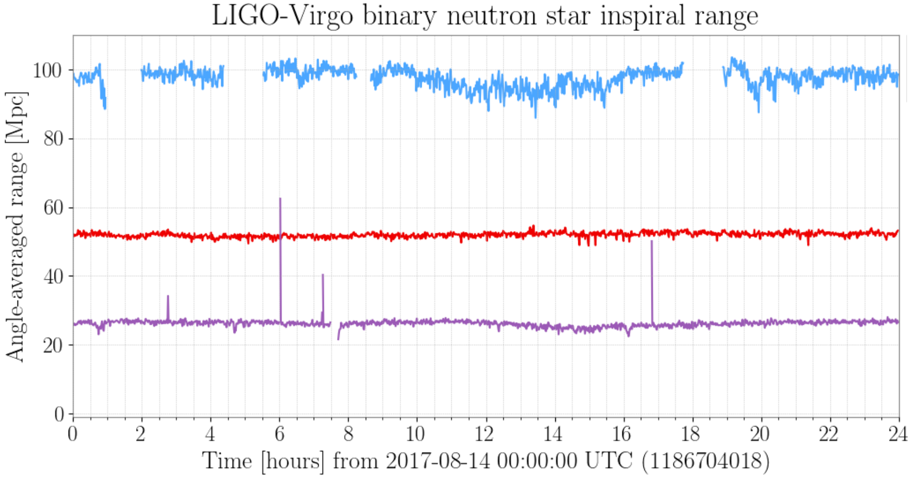


Courtesy Caltech/MIT/LIGO Laboratory

O2 science run (LIGO-Virgo detectors)

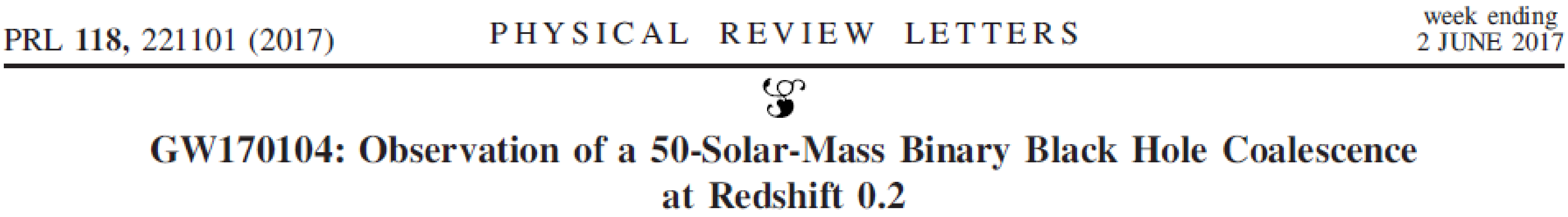
- LIGO
  - 37 weeks, 120 days of coincident operation
- Virgo joined for last month
  - Only 3.5 weeks
  - Very good stability, 82% duty cycle: 20 days of data
  - Sensitivity 2-3 times lower than LIGO





- Binary neutron star range ~ average detection distance
- Horizon ~ 2.26 x range

O2 BBH so far...



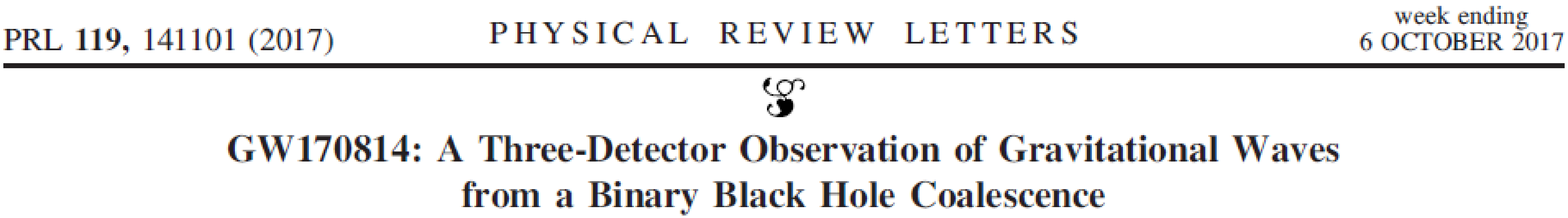
PRL 118, 221101 (2017) PHYSICAL REVIEW LETTERS week ending 2 JUNE 2017

GW170104: Observation of a 50-Solar-Mass Binary Black Hole Coalescence at Redshift 0.2

arXiv.org > astro-ph > arXiv:1711.05578

Astrophysics > High Energy Astrophysical Phenomena

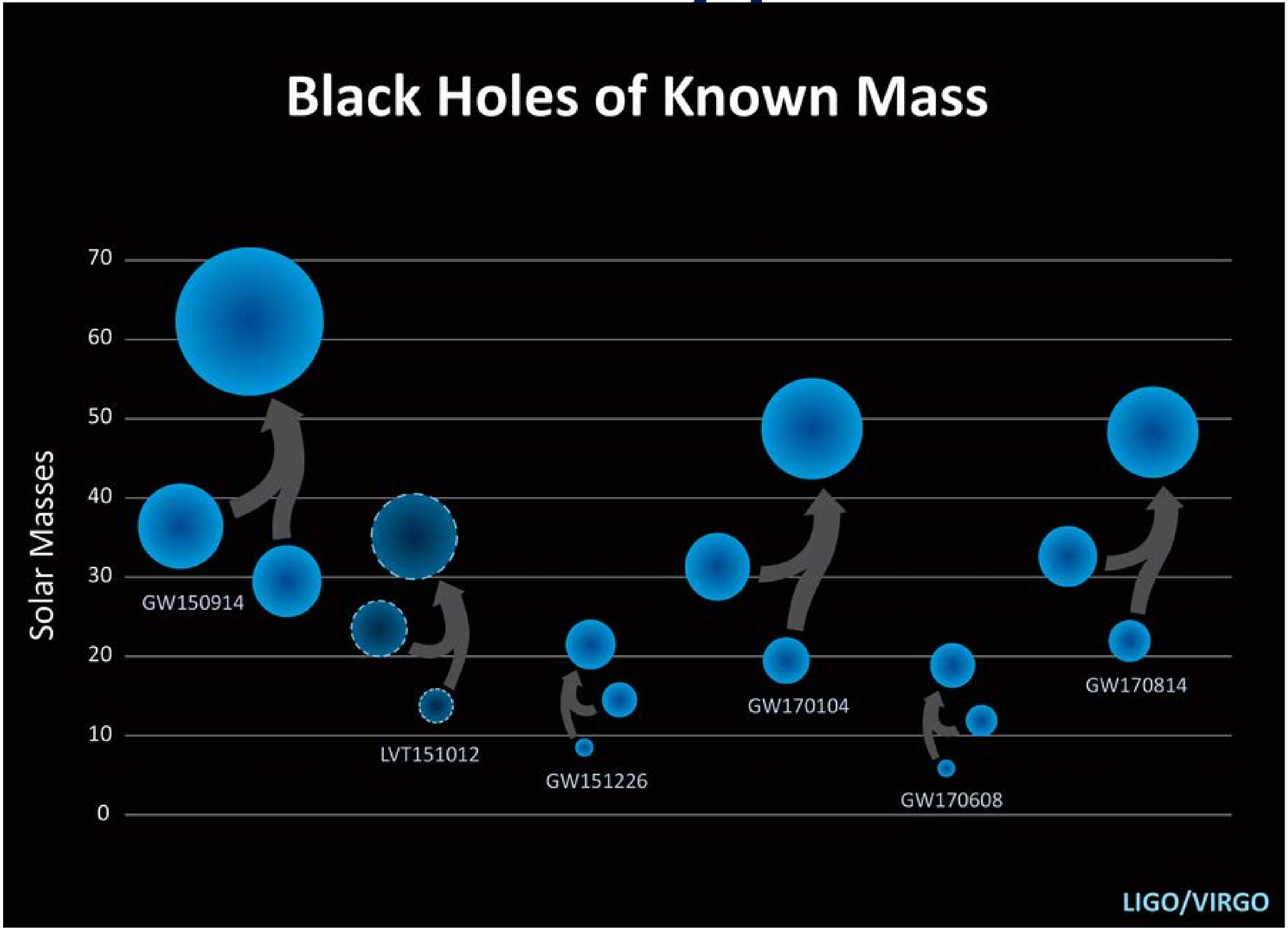
GW170608: Observation of a 19-solar-mass Binary Black Hole Coalescence



PRL 119, 141101 (2017) PHYSICAL REVIEW LETTERS week ending 6 OCTOBER 2017

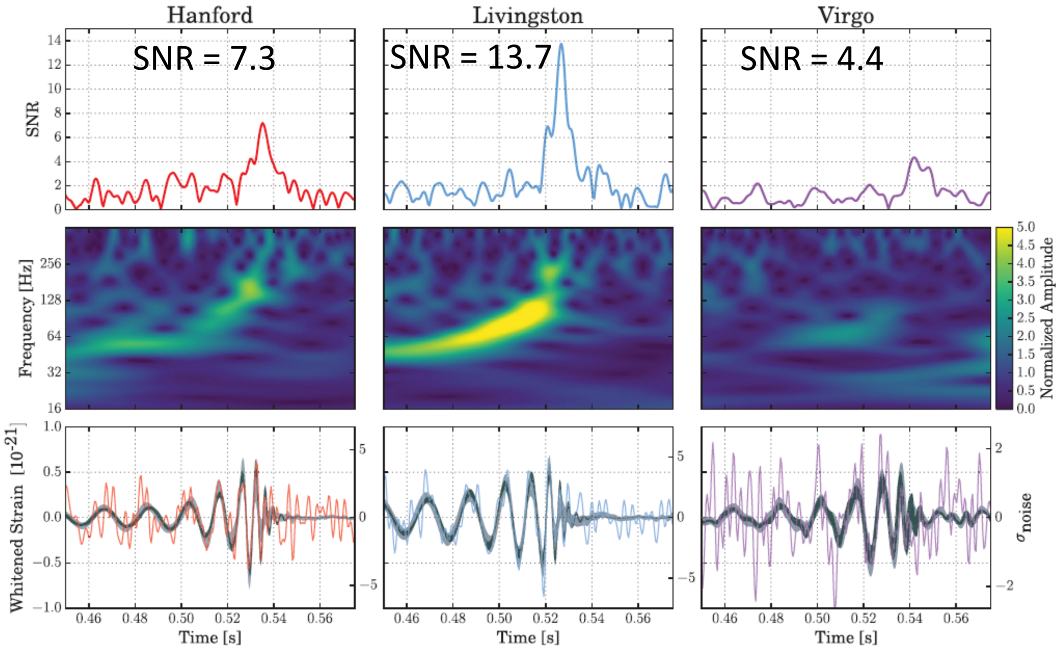
GW170814: A Three-Detector Observation of Gravitational Waves from a Binary Black Hole Coalescence

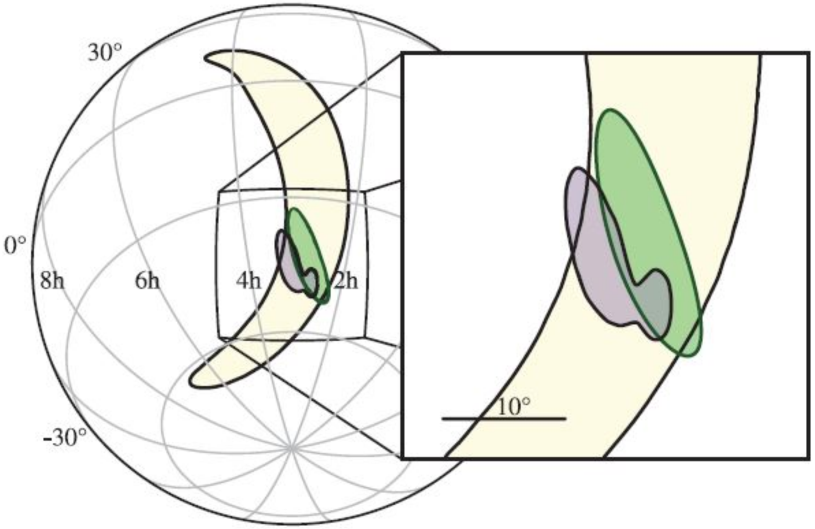
BBH family picture

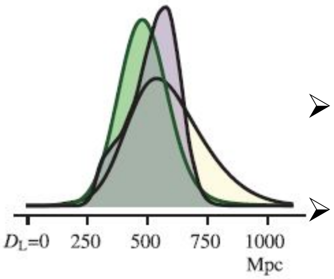


GW170814

- ❑ First GW signal ever measured by Virgo
- ❑ SNRs consistent with average expectations from relative detector sensitivities

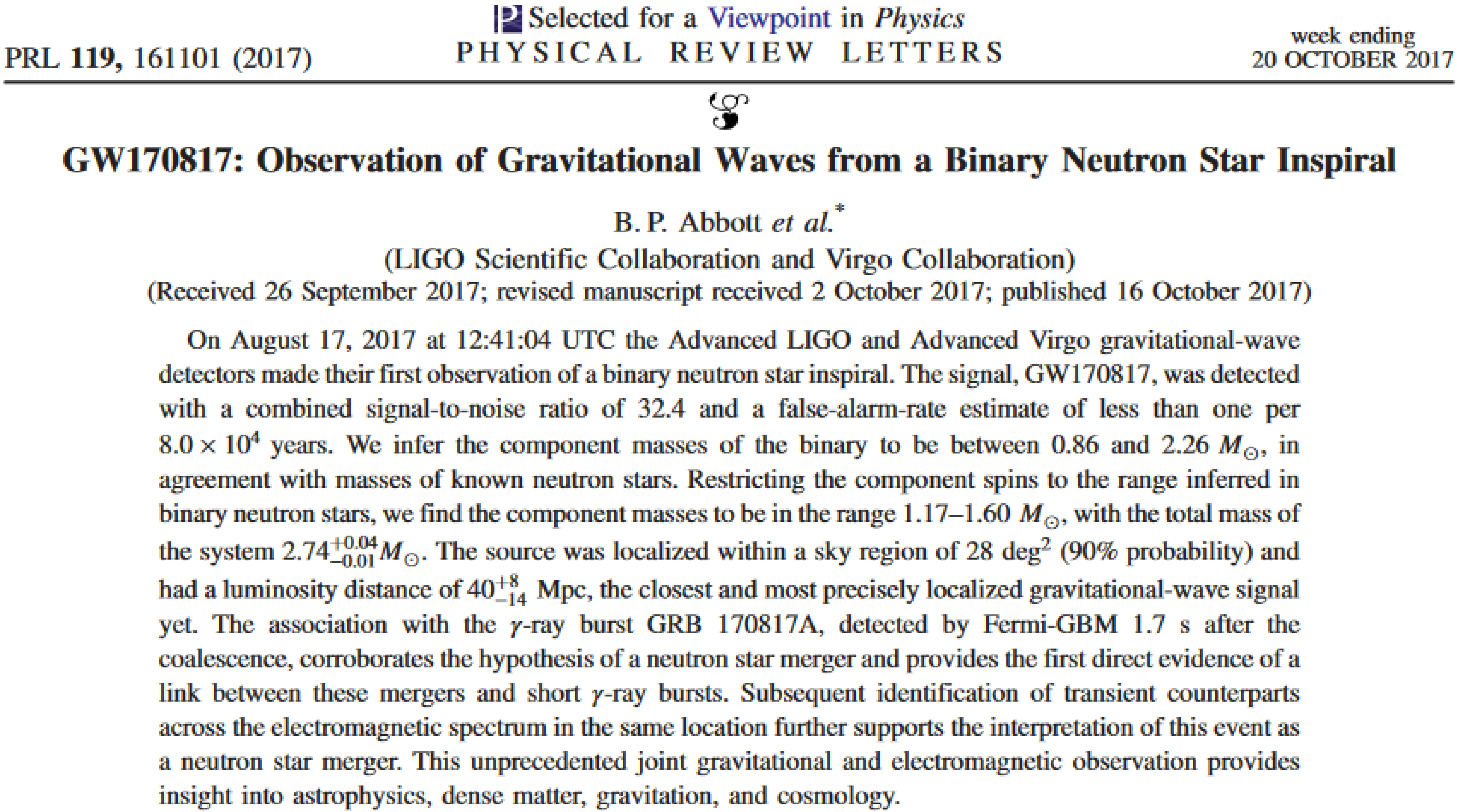






- ❑ Virgo is a game changer for sky localization
  - ➢ Sky position inferred from time differences, phase differences, amplitude ratios at the 3 sites
  - ➢ LIGO 90% CL area 1160 deg^2 ➔ 60 deg^2 with Virgo
  - ➢ 3D localization
    - ▪ 71 × 106 Mpc^3 ➔ 2.1 × 106 Mpc^3
    - ▪ number of possible host galaxies reduced by an order of magnitude

First observation of GW from a Binary Neutron Star coalescence



Selected for a Viewpoint in *Physics*
PRL **119,** 161101 (2017) PHYSICAL REVIEW LETTERS week ending 20 OCTOBER 2017

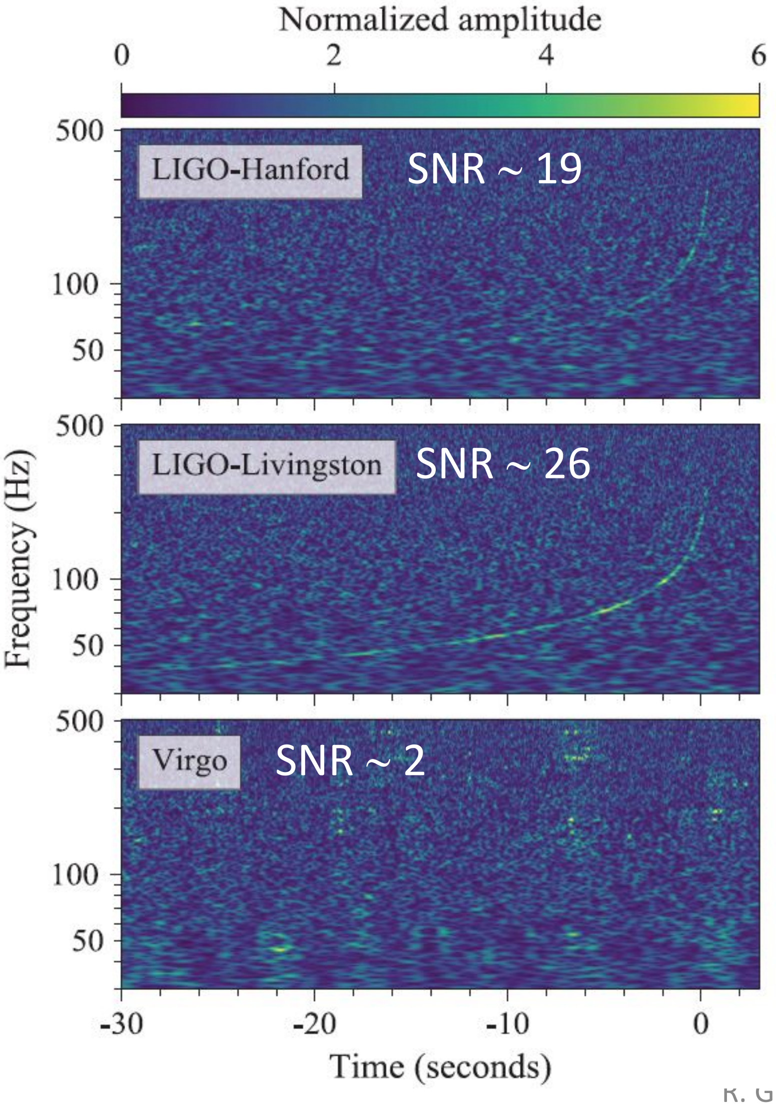
GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral

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

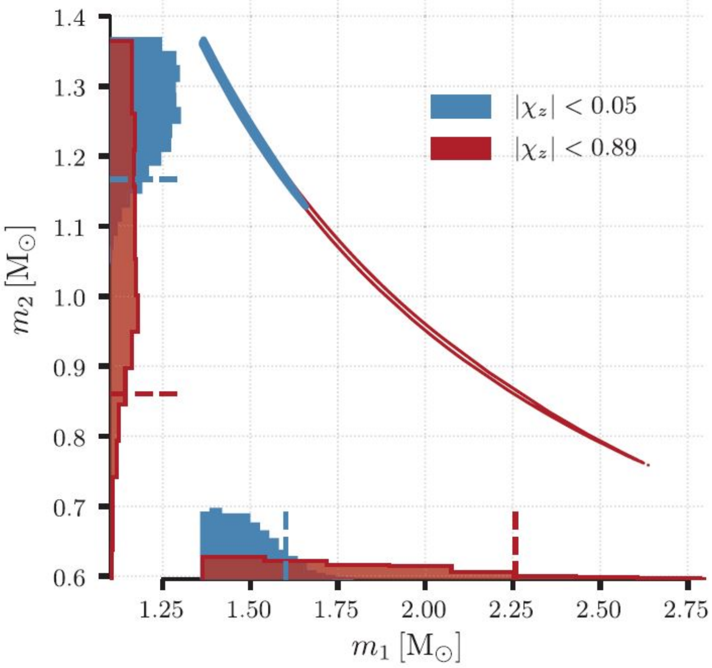
(Received 26 September 2017; revised manuscript received 2 October 2017; published 16 October 2017)

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.

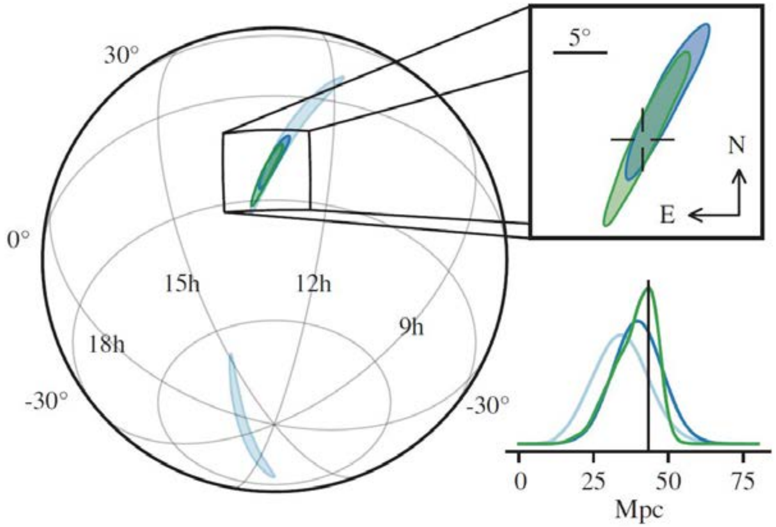
GW170817



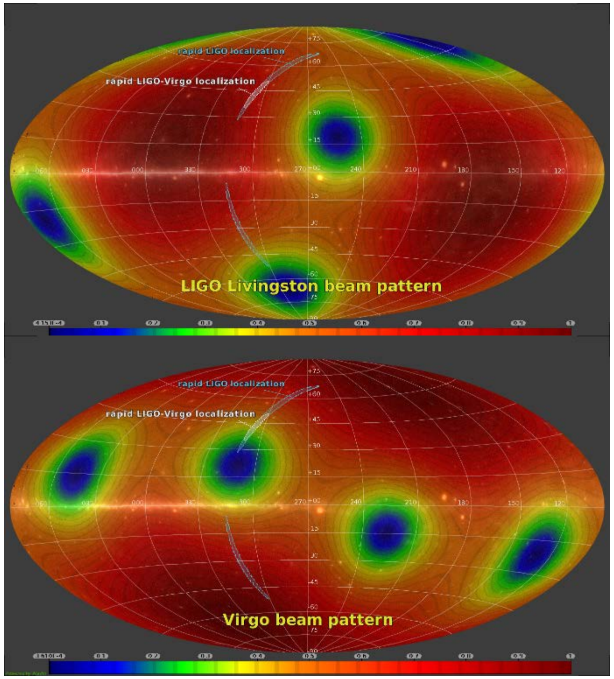
- ☐ Combined SNR 32.4
  - ➢ Loudest signal so far
  - ➢ False alarm rate < 1 / 80000 years
- ☐ Luminosity distance 40^{+8}_{-14} Mpc
  - ➢ Closest source so far
- ☐ Measured masses consistent with known neutron star masses

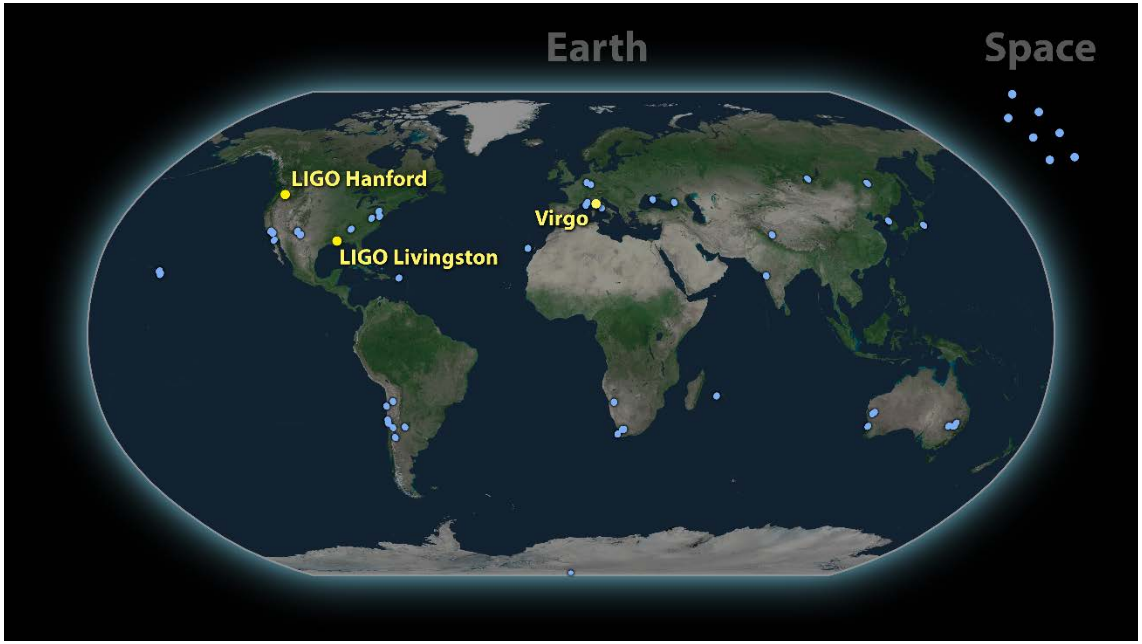


GW170817 Localization & Follow-up

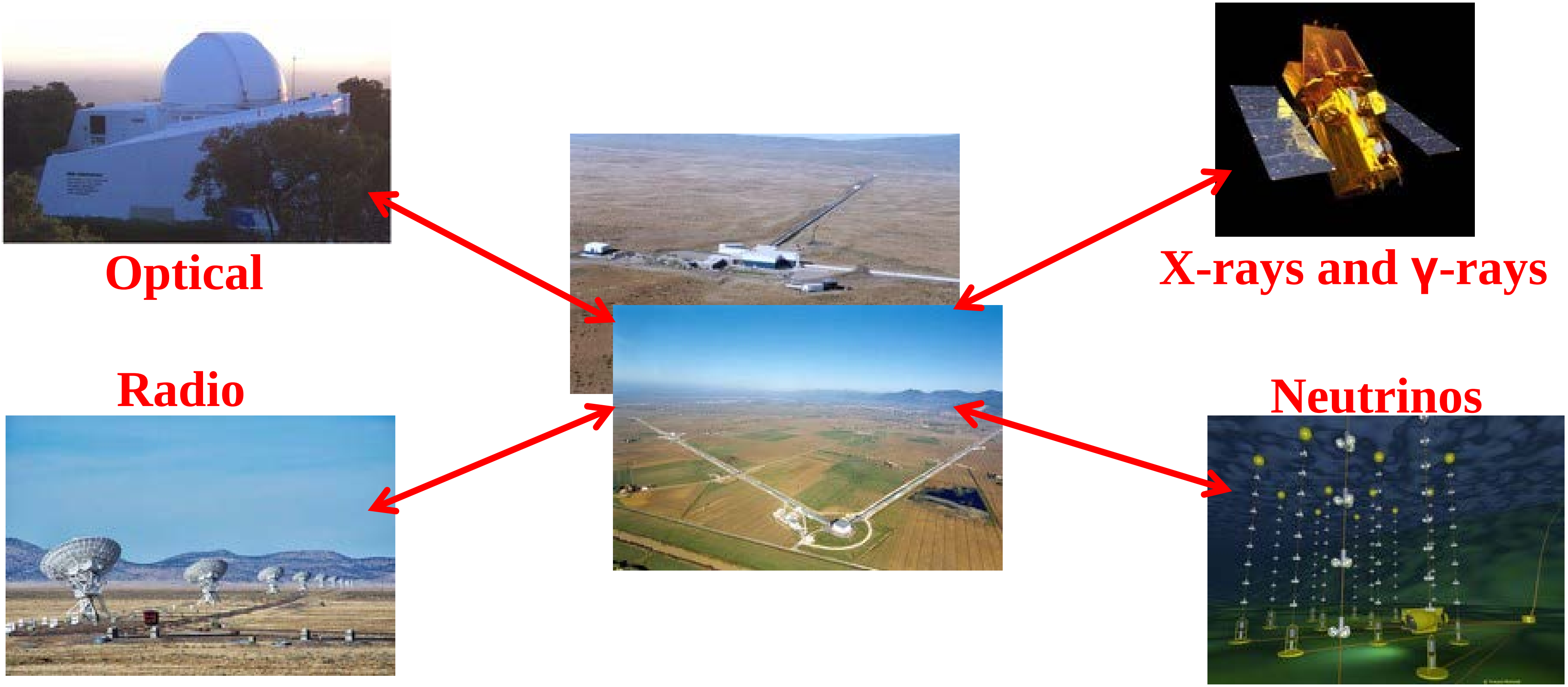


- ❑ Most precisely localized GW source so far
  - ➢ Rapid HL localization: 190 deg^2
  - ➢ Rapid HLV localization: 31 deg^2
  - ➢ Final HLV localization: 28 deg^2
  - ➢ 3D localization: 380 Mpc^3
- ❑ Triggered multi-wavelength follow-up observations
  - ➢ Identification of NGC4993 as host galaxy





Alerts for multi-messenger observations



Optical

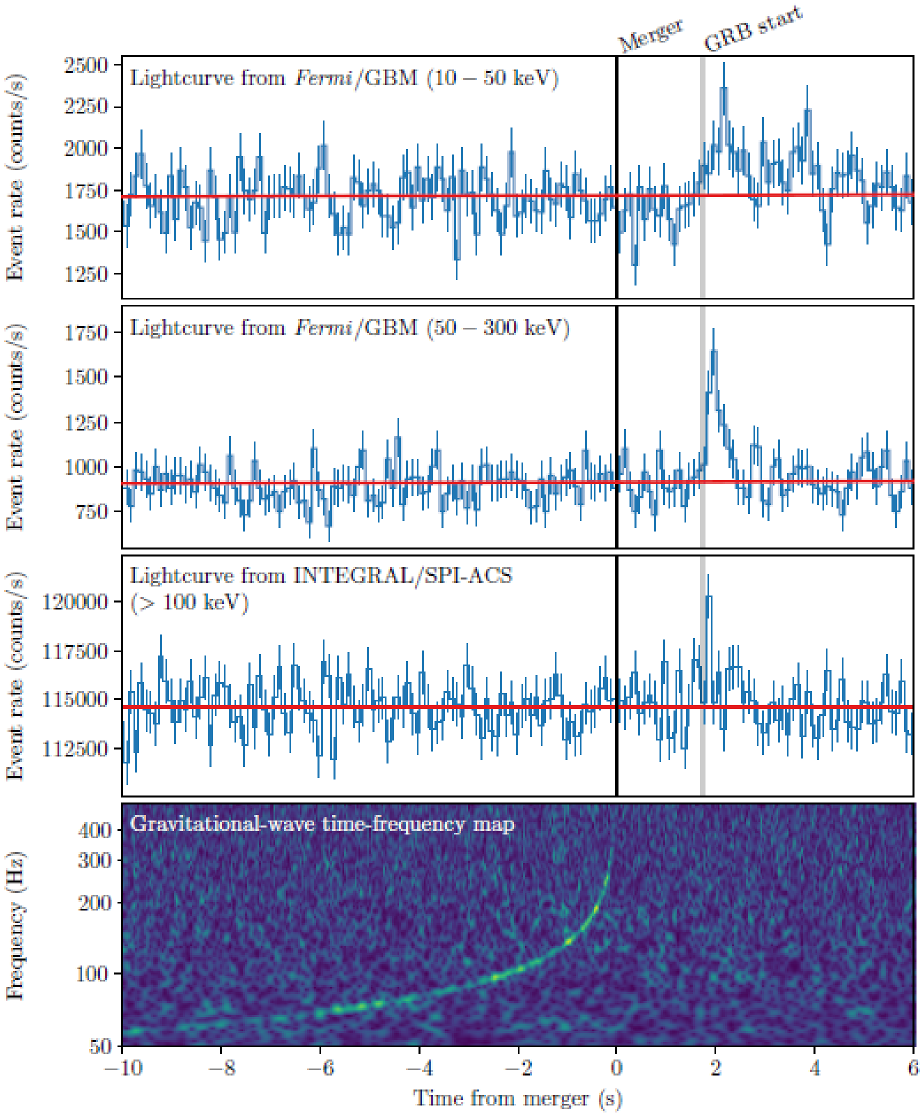
X-rays and γ-rays

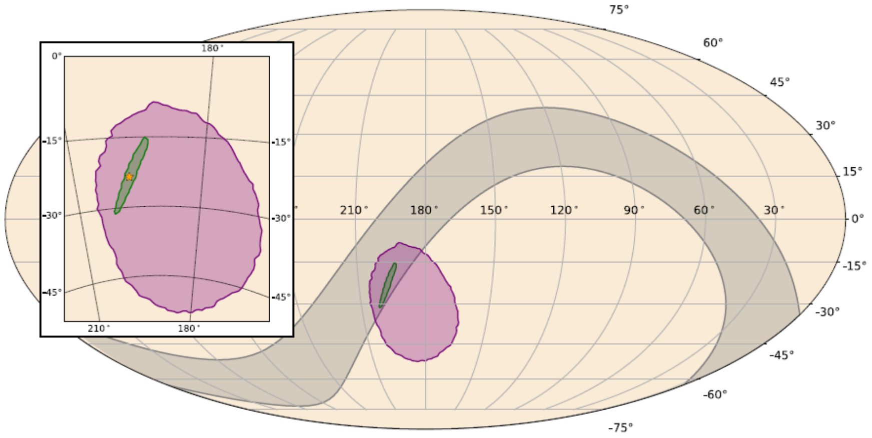
Radio

Neutrinos

- ➢ **Increase event significance**
- ➢ **Better understand the physics of the detected sources**

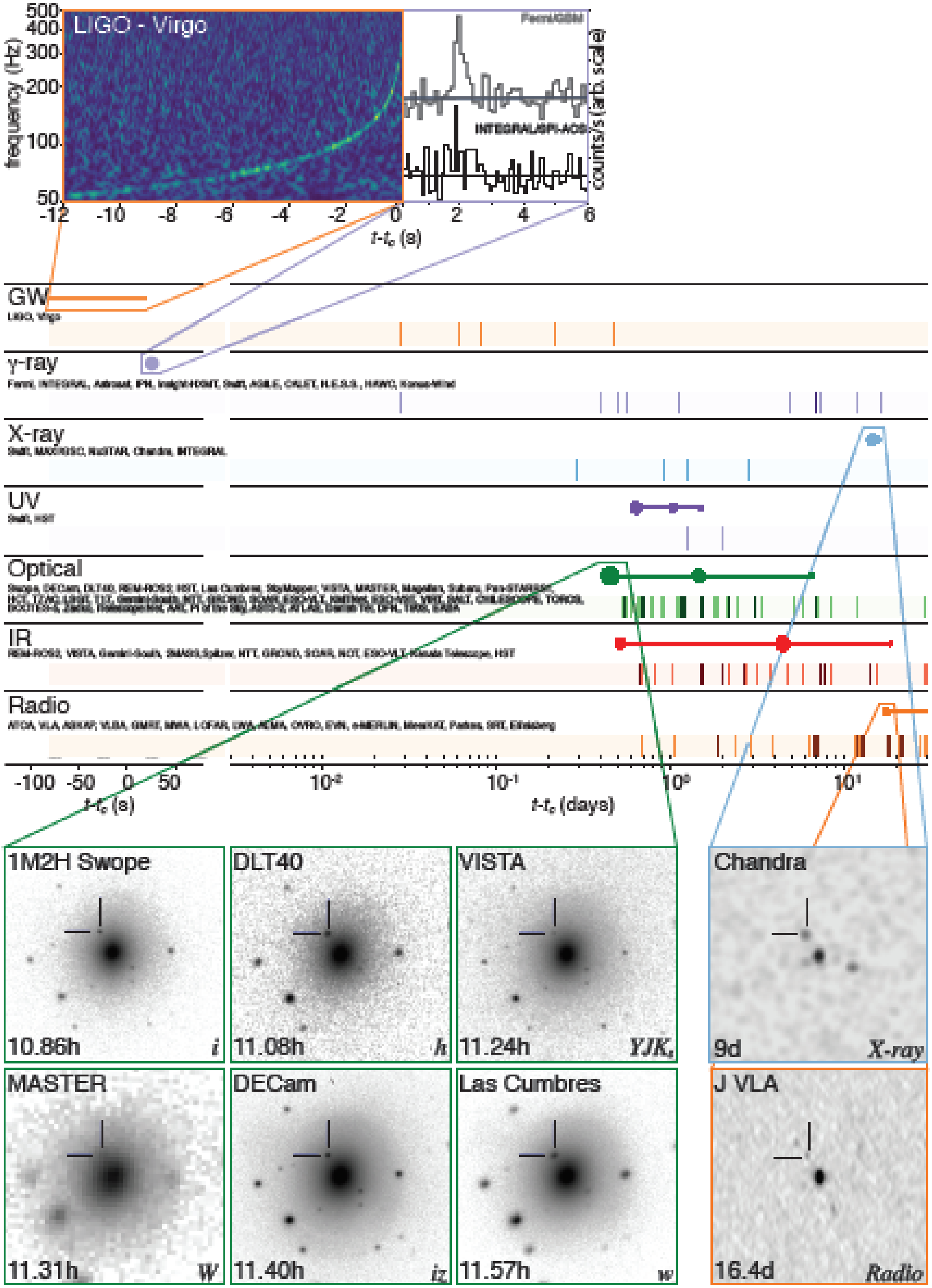
GRB 170817A





- ❑ GRB 170817A detected by Fermi-GBM and INTEGRAL SPI-ACS
  - ➢ ~ 1.7s after merger
  - ➢ Closest short GRB with a known distance
  - ➢ 2-6 orders of magnitude less energetic than other bursts with measured redshift
- ❑ Probability of temporal and spatial coincidence occurring by chance is $5 \cdot 10^{-8}$
  - ➢ Confirms BNS mergers as a progenitor of short GRBs

AT2017gfo



- Kilonova/macronova observed in UV/optical/near IR
- X-ray and radio afterglow
- An observational fiesta, a theoretical feat

Extracting the science from CBC sources

Fundamental physics

- Strong field tests of General Relativity
- Tests of GR cornerstones
  - GW polarization & speed, Lorentz invariance, equivalence principle, graviton mass…
- Equation of state of ultra-dense matter in neutron stars

Astrophysics

- Population studies, rates and formation scenarios
- Connection to short gamma-ray bursts
- Origin of heavy elements in Universe

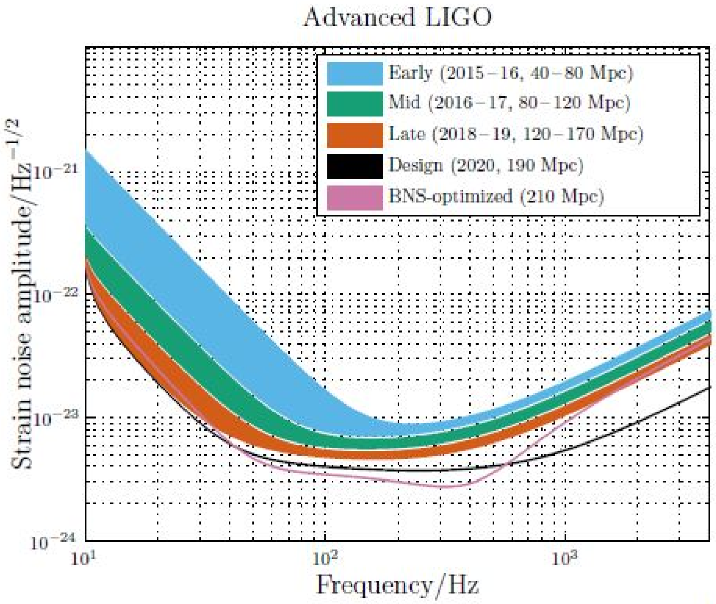
Cosmology

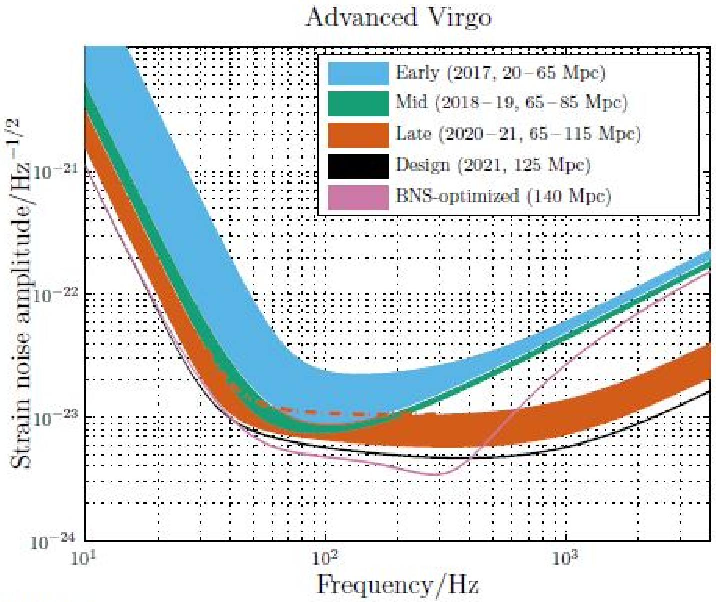
- Standard sirens to measure local expansion rate of Universe
- Clues for dark matter ??

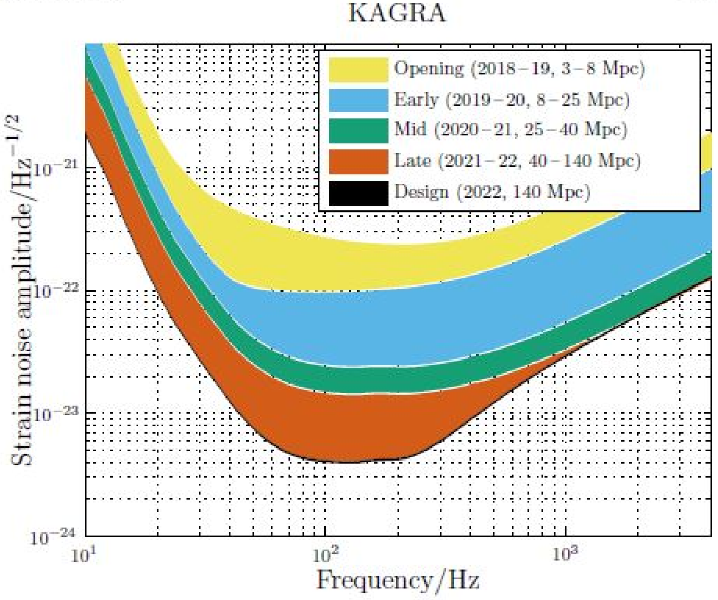
More in the future with

- Rare, golden events at high SNR
- Larger sample

A wider network of more sensitive detectors

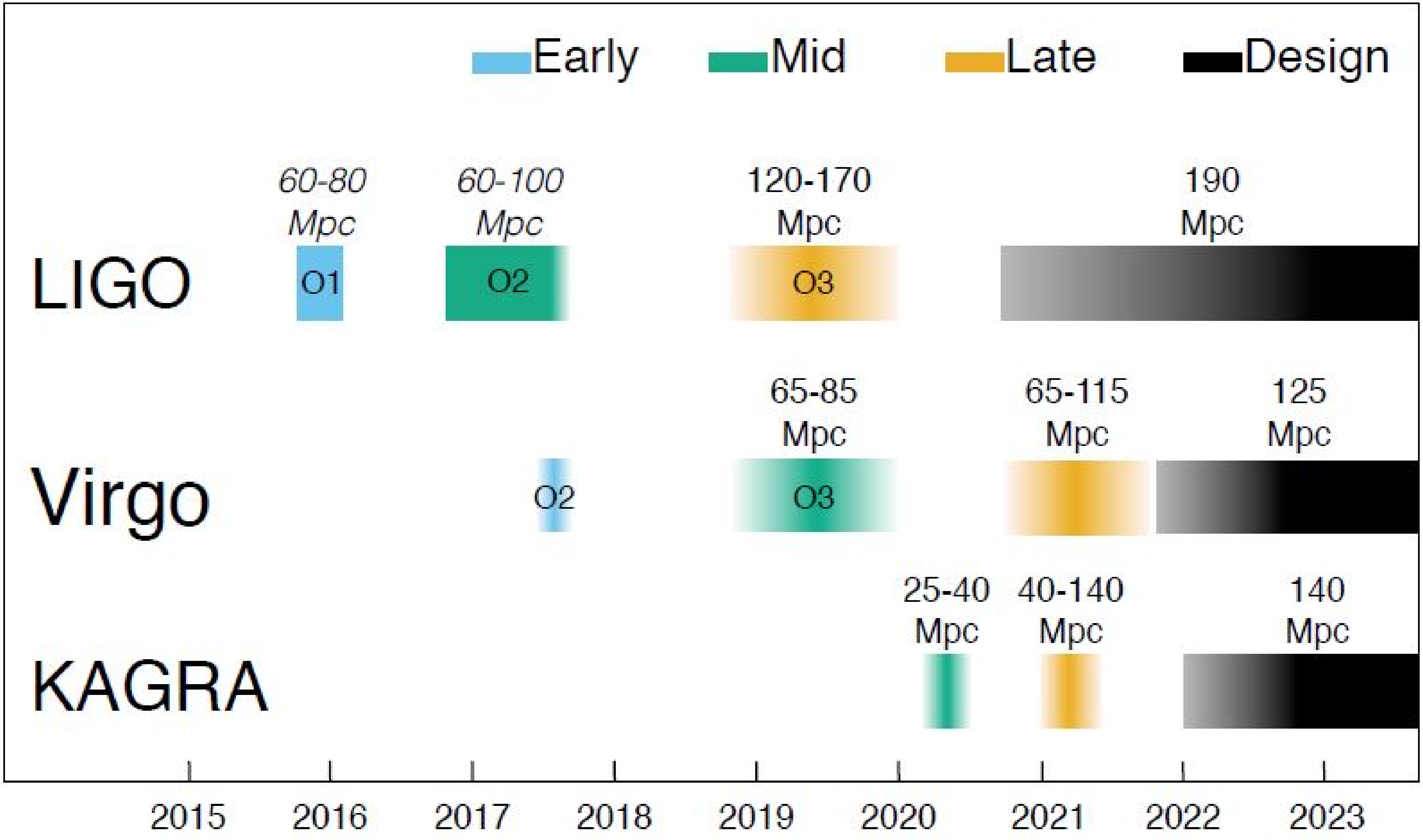

Advanced LIGO


Advanced Virgo


KAGRA

+ 3rd LIGO detector to be installed in India, operations > 2024

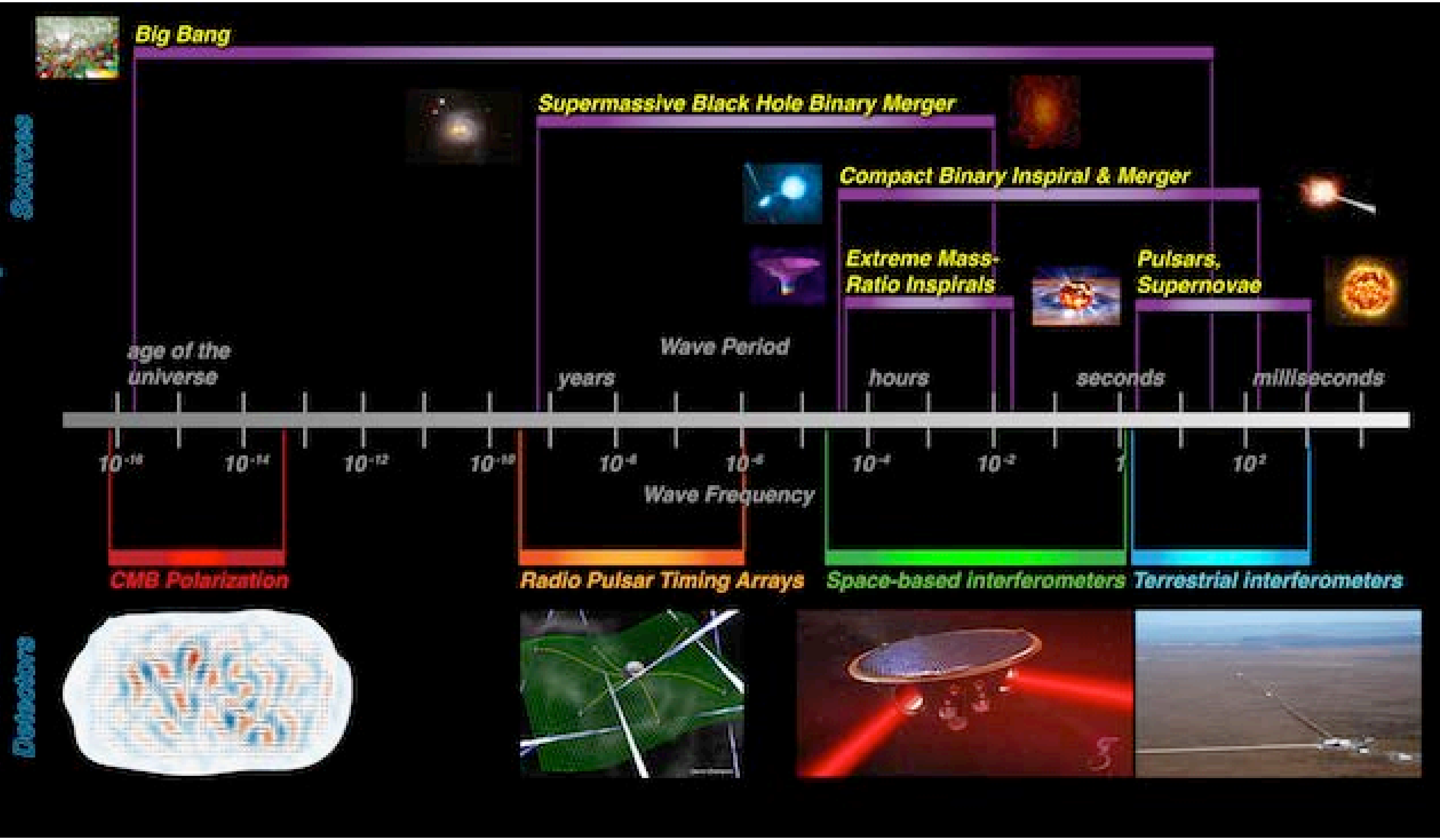
Future observing runs



+ Plans starting for 2.5G and 3G detectors

SPARES

Extending the spectrum



Noise characterized in frequency domain

$$s(n) \xrightarrow{\text{Discrete Fourier Transform (DFT)}} S(k) = A(k)\mathrm{e}^{\mathrm{j}\Phi(k)}$$

Sampled signal

Fourier spectrum

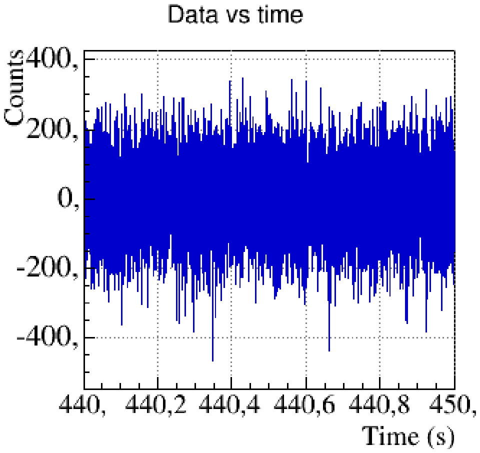
→ Noise characterised by the fluctuations of its Fourier spectrum

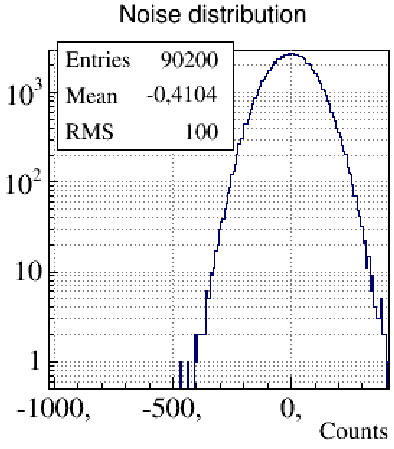
$\longrightarrow D(k)$ in units/√Hz

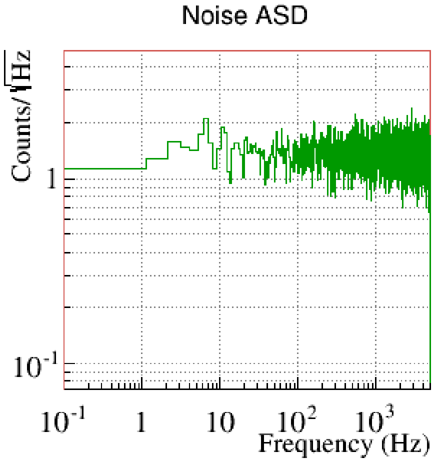
Assumption: noise is random and ergodic

→ noise characterised by its amplitude spectral density (ASD) $ASD = \sqrt{PSD} = \sqrt{\frac{|DFT|^2}{T}}$

Random gaussian noise
1 count/√Hz
Sampled at 10 kHz



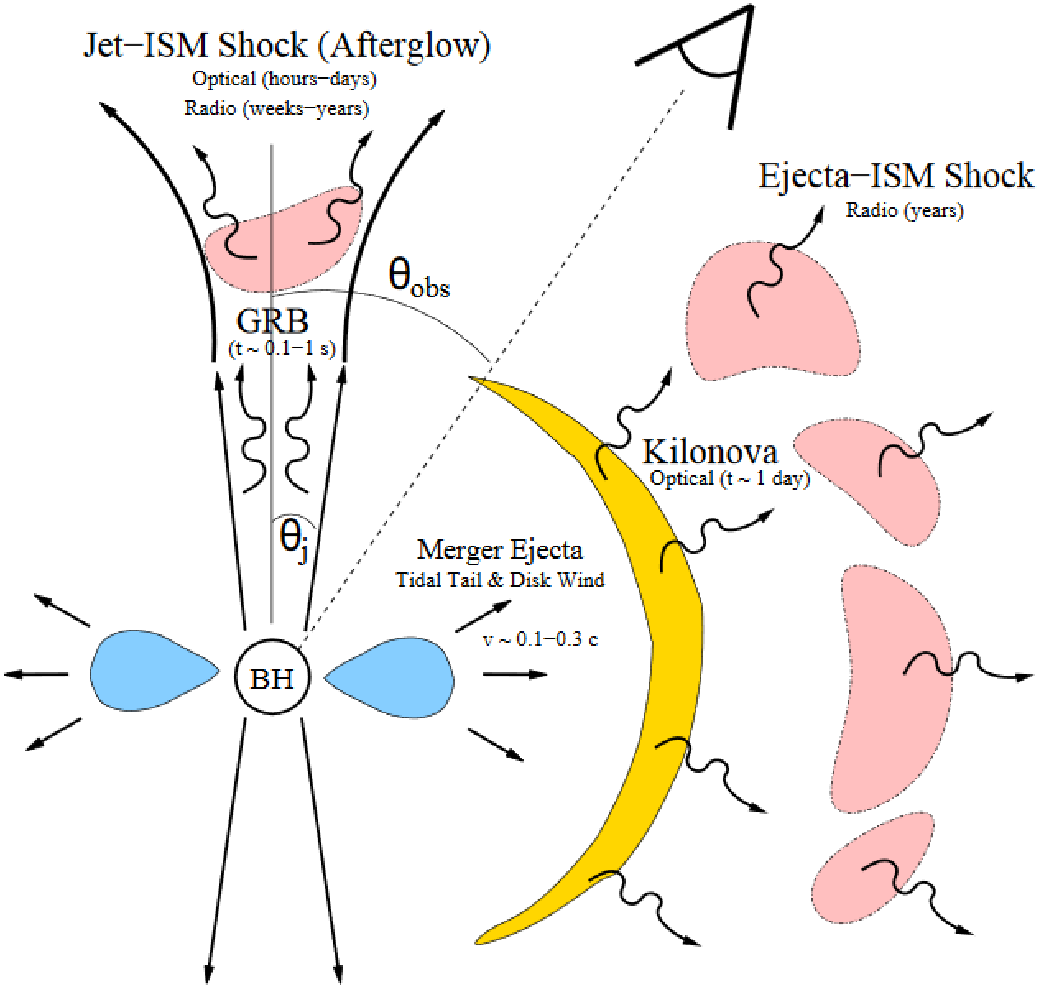




Coalescence of the 2 black holes

Let’s go there!

Expected Electromagnetic Counterparts



- GRB from jet
- Afterglow from jet – ISM interaction
- Kilonova / Macronova powered by radioactive decay of r-process nuclei synthesized in ejecta

Measuring H0 from GW170817/AT2017gfo

- GW sources are standard sirens
  - Masses encoded in waveform
  - Once masses are know, amplitude gives distance
    - From GW only, luminosity distance = at 90% CL ➔ at 68% CL, assuming sky position of AT2017gfo
    - Uncertainty from statistics and geometrical degeneracy with system inclination

$$v_H = H_0 d$$

Hubble flow velocity from host galaxy NGC4993

Distance from GW

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

Independent of any cosmic distance ladder