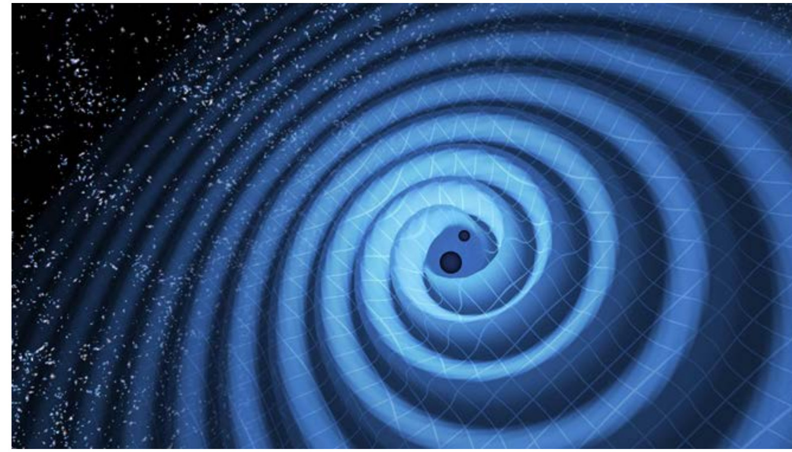
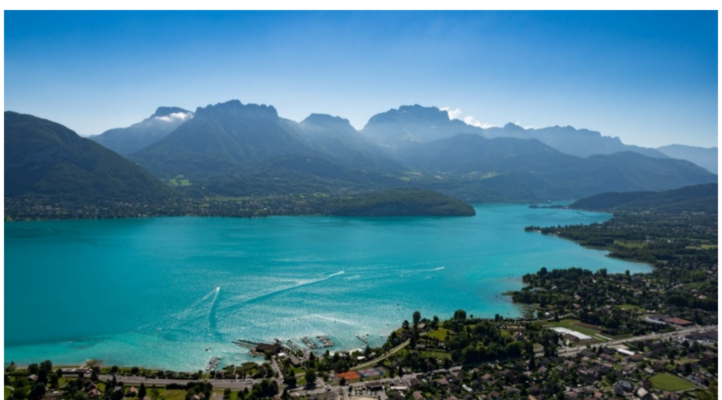


Detecting gravitational waves with kilometric interferometers

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/

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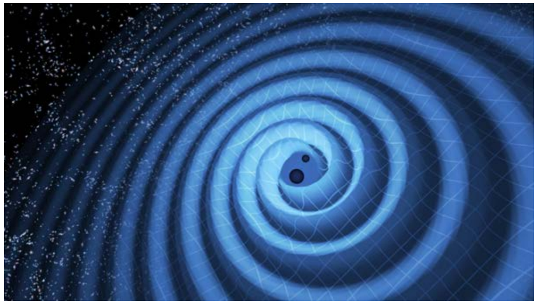
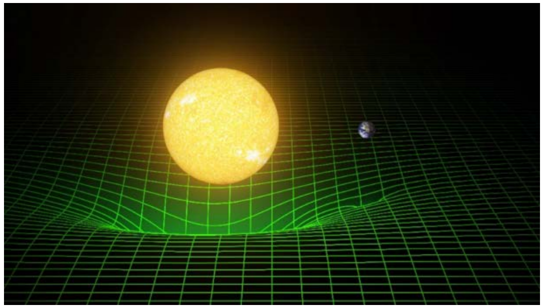
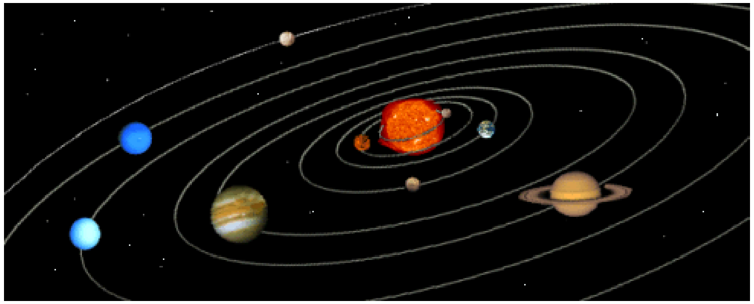


- **What are gravitational waves?**
- How can we detect gravitational waves?
- How do terrestrial interferometers work?
- Prospectives for interferometers and other detectors

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***"
- Mathematical formalism with Einstein Field Equations:

$$\left(R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R\right) = 8\pi G \left(T_{\mu\nu}\right)$$

with c = 1 ! would be $\frac{8\pi G}{c^4}$.

curvature term

energy-momentum term (includes mass)

$g_{\mu\nu}$ **metric tensor**

$R_{\mu\nu}$ **Ricci tensor (depends on $g_{\mu\nu}$ and derivatives)**

From Einstein Field Equations to Gravitational Waves

$$\eta_{\mu\nu} = \begin{pmatrix} -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

- Flat space-time = Minkowski metric
  - Add a perturbation $h_{\mu\nu}$ to the metric of a flat space
  - Linearize Einstein Field Equations

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}, \quad h_{\mu\nu} \ll 1$$

- Obtain a wave equation

$$(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2})h_{\mu\nu} = 0$$ (in vacuum, no $T_{\mu\nu}$)

- Solution (in vacuum): **waves propagating at speed of light**

$$h_{\mu\nu} = A_{\mu\nu} \cdot e^{-i(\vec{k}\cdot\vec{x}-\omega\cdot t)}$$

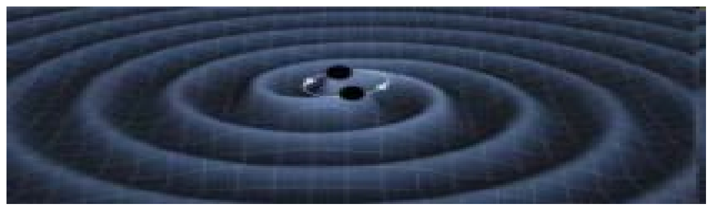
- Tensorial waves:
  - 10 degrees of freedom (symmetric tensor)
  - Choose a coordinate system (« Transverse Traceless » (TT) gauge): 2 polarizations

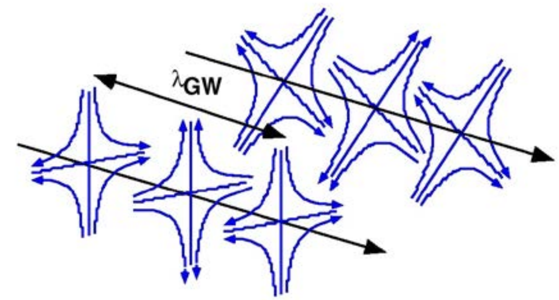
Gravitational waves

GW origin

Masses in motion
↓
Space-time deformation
↓
Gravitational wave

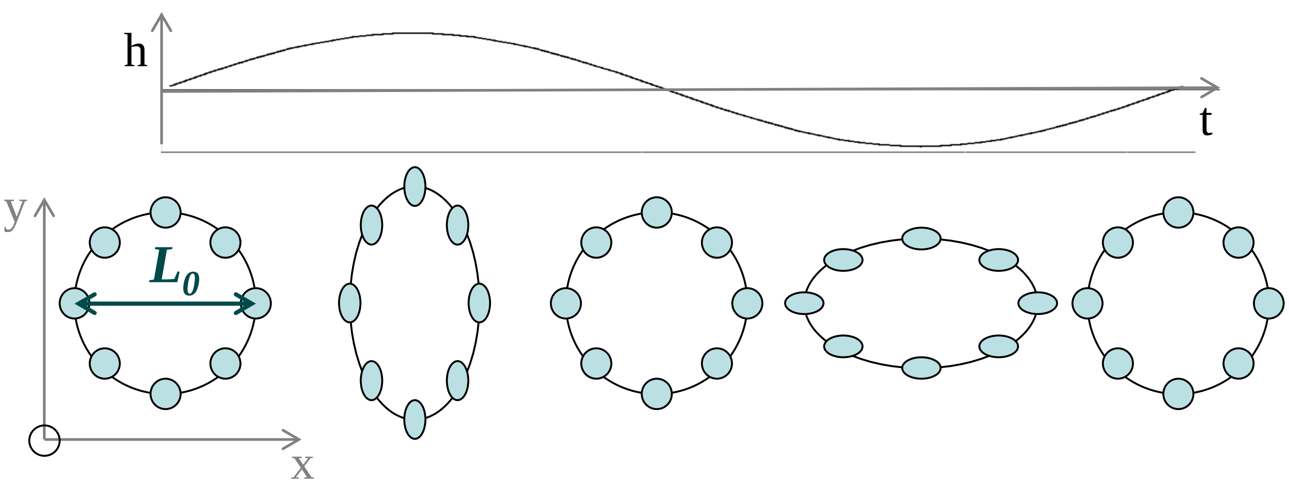
- transversal plane wave
- propagation at the light speed c
- Two polarisation states (+ and x)





$$h_{\mu\nu} = h_+(t - z/c) + h_x(t - z/c)$$

Detectable effect on free fall masses



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

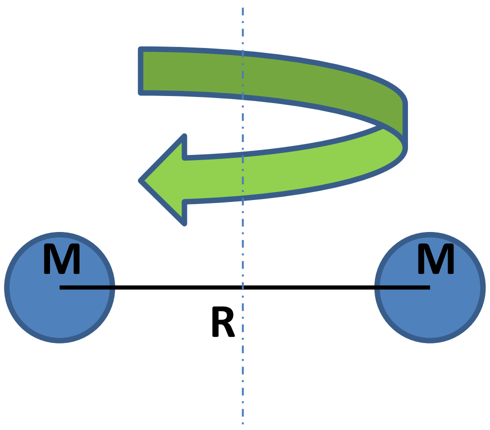
h(t): amplitude of the GW

(*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

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

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

$h \sim 10^{-35}$

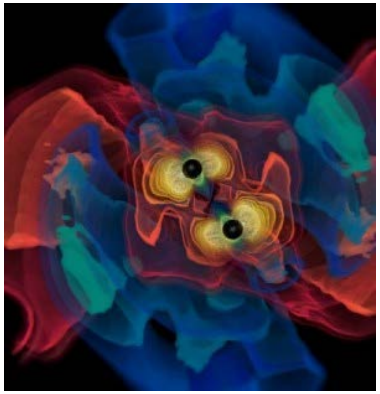
▶ $M = 1.4\ M_\odot$, R = 20 km, f = 400 Hz, $r = 10^{23}$ m (15 Mpc = 48,9 Mlyr)

$h \sim 10^{-21}$

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

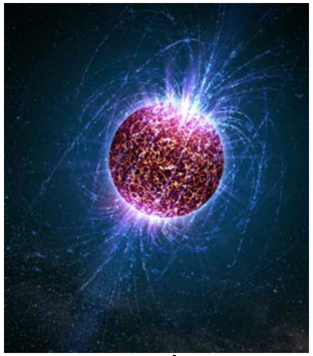
Astrophysical sources of GW

- **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



Credit: AEI, CCT, LSU

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

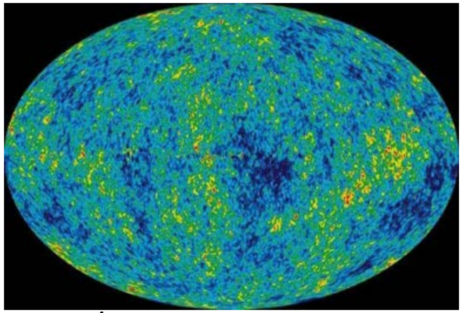


Casey Reed, Penn State

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

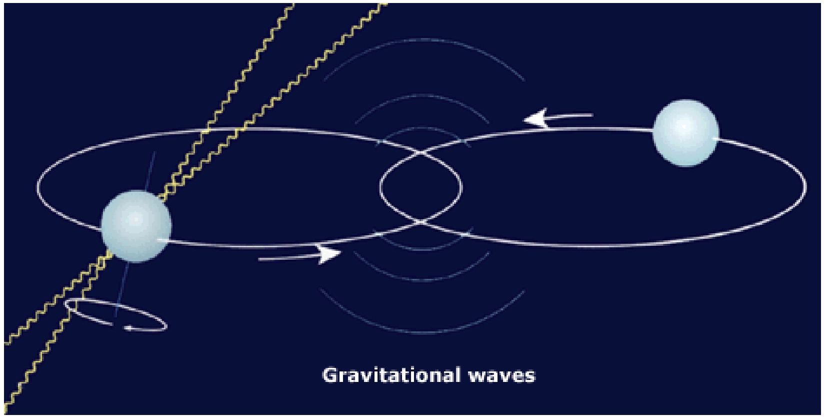
Crab Nebula, Hubble

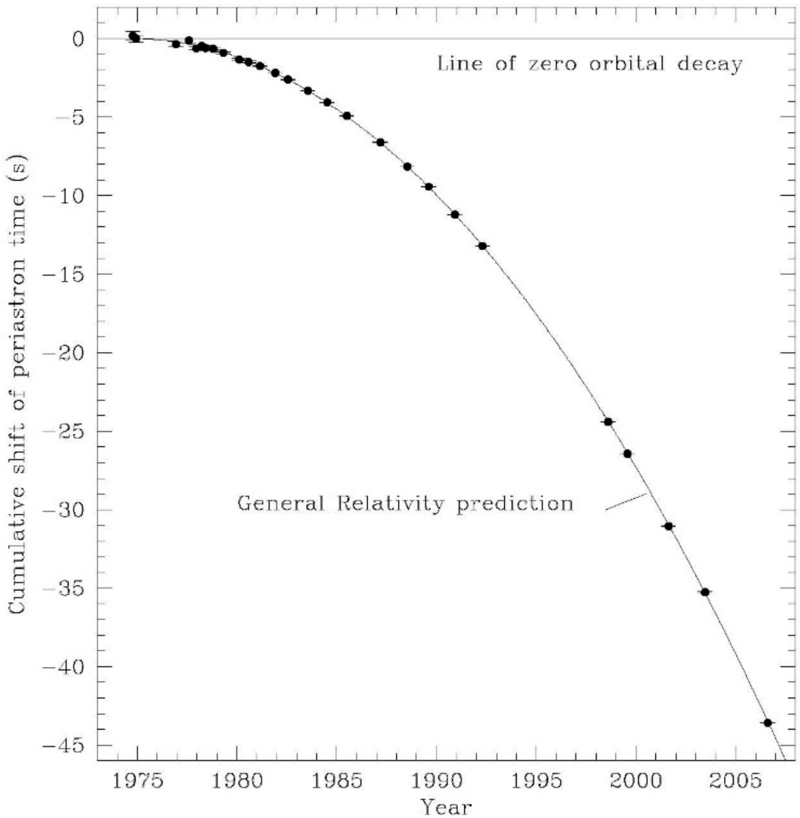
- **Gravitational wave stochastic background**
  - Astrophysical background:
    From large population of transients signals from distant sources
  - Cosmological background: Residual of the big bang/inflation



NASA/WMAP Science Team

Indirect evidence: PSR 1913+16



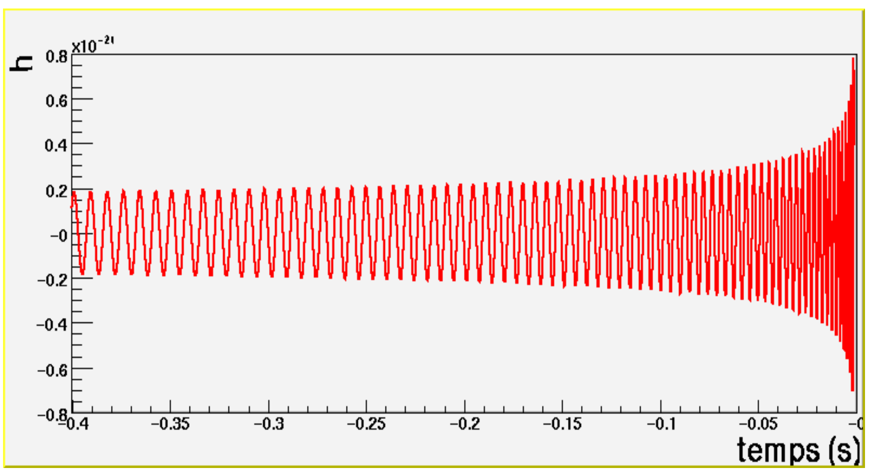


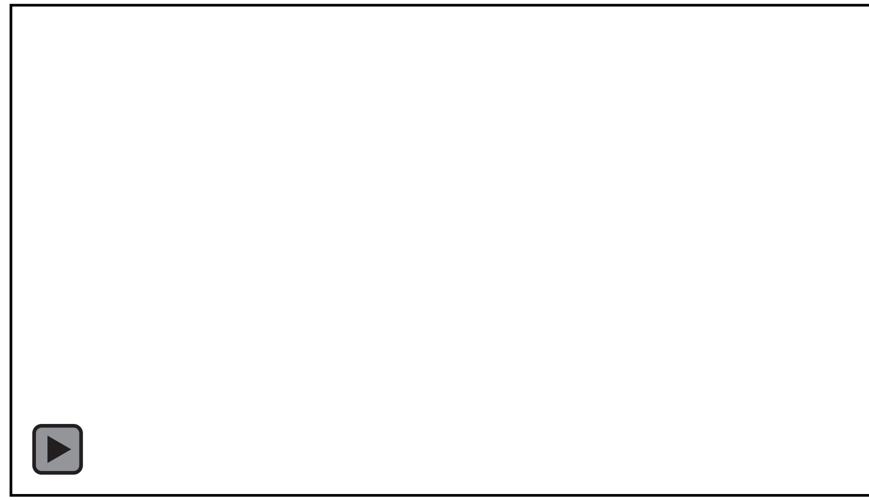
$$\dot{P}_{observe} / \dot{P}_{predit} = 1.0013 \pm 0.0021$$

- 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

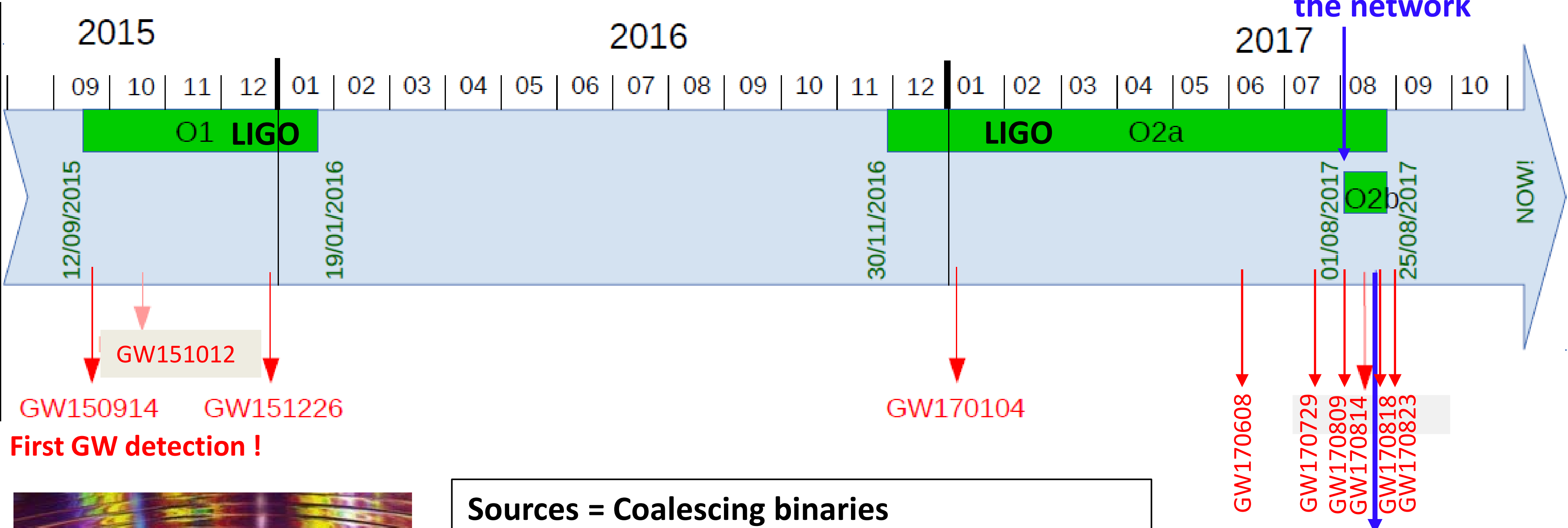
- Binary systems of compact stars at the end of their evolution
  - Neutron stars and black holes
- Very rare phenomenum in our Galaxy
  - A few tens per million years
- Typical amplitude (for neutron stars)
  - $h \sim 10^{-22}$ à 20 Mpc
- Very distinctive waveform

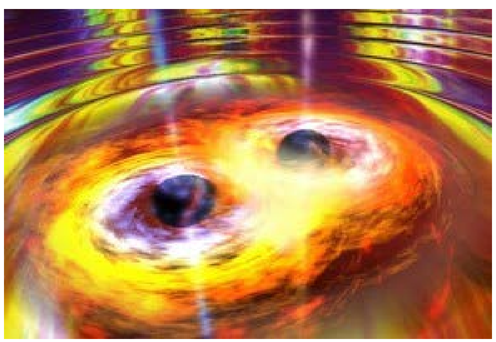




Courtesy Caltech/MIT/LIGO Laboratory

First detections with LIGO & Virgo: O1 and O2 runs

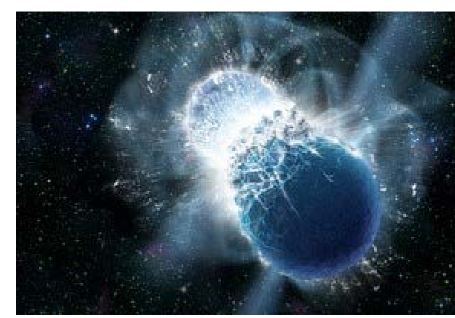




Sources = Coalescing binaries

- Black holes (10 detections)
- Neutron Stars (1 detection)

GW170817 + multi-messengers detections



2017 Nobel Prize awarded to Rainer Weiss, Barry C. Barish et Kip S. Thorne

LIGO & Virgo O3 run

- O3 run: LIGO/Virgo joint data taking from April 2019 to April 2020

- Already ~50 detection candidates > low-latency public alerts:
https://gracedb.ligo.org/superevents/public/O3/

- Recently published: “GW190425: Observation of a Compact Binary Coalescence with Total Mass~3.4M⊙”
  → Likely to be a second binary neutron star coalescence

LIGO/Virgo O3 Public Alerts

Detection candidates: 51

SORT: EVENT ID (A-Z)

Event ID	Possible Source (Probability)	UTC	GCN	Location	FAR	Comments
S200219ac	BBH (96%), Terrestrial (4%)	Feb. 19, 2020 09:44:15 UTC	GCN Circulars Notices | VOE		1 per 2.3819 years	
S200213t	BNS (63%), Terrestrial (37%)	Feb. 13, 2020 04:10:40 UTC	GCN Circulars Notices | VOE		1 per 1.7934 years	
S200208q	BBH (99%)	Feb. 8, 2020 13:01:17 UTC	GCN Circulars Notices | VOE		1 per 12.587 years	
S200129m	BBH (>99%)	Jan. 29, 2020 06:54:58 UTC	GCN Circulars Notices | VOE		1 per 4.7313e+23 years	
S200128d	BBH (97%), Terrestrial (3%)	Jan. 28, 2020 02:20:11 UTC	GCN Circulars Notices | VOE		1 per 1.9238 years	

Science to be extracted from coalescing binaries

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 ??

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- What are gravitational waves?
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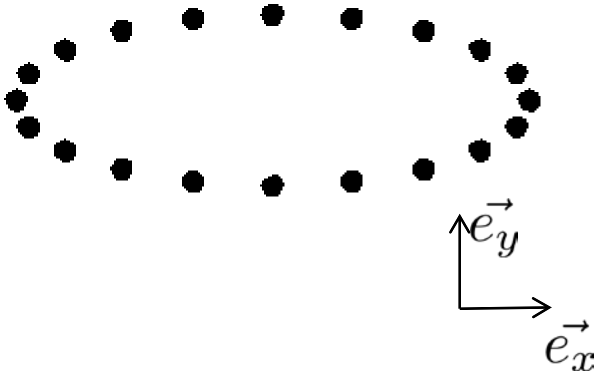
- How do terrestrial interferometers work?
- Prospectives for interferometers and other detectors

Reminder: effect of a GW on free fall masses

A gravitational wave (GW) modifies the distance between free-fall masses

$$\delta x(t) = -\delta y(t) = \frac{1}{2} h(t) L_0$$

h(t): amplitude of the GW

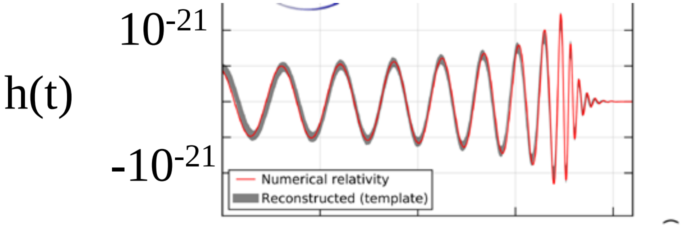


Typical amplitude of a GW crossing the Earth: $h \sim 10^{-23}$

(h has no dimension/unit)

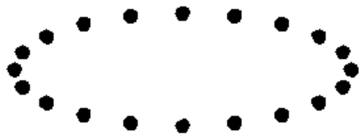
Case of a GW with polarisation + propagating along z

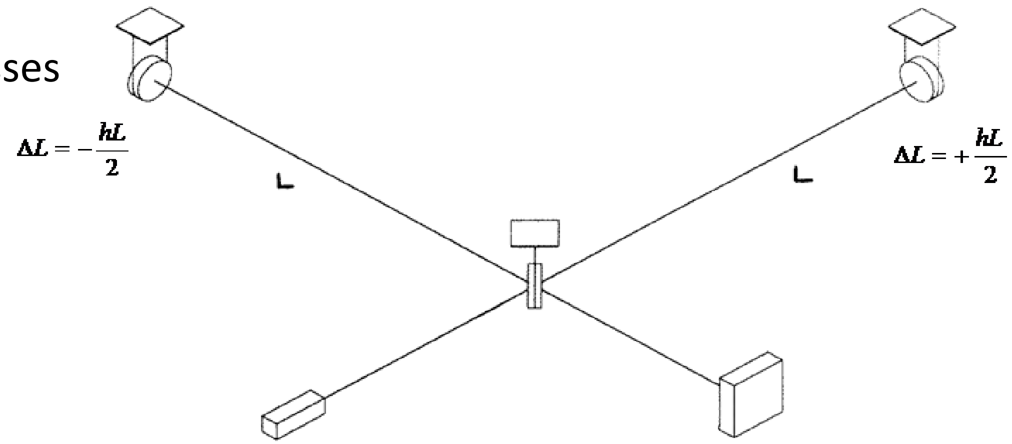
Reconstructed strain of GW150914



Terrestrial GW Interferometer: basic principle

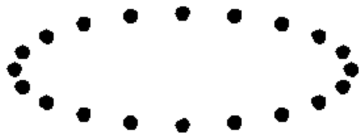
- Measure a variation of distance between masses
  - Measure the light travel time to propagate over this distance
  - Laser interferometry is an appropriate technique
    - Comparative measurement
    - Suspended mirrors = free fall test masses





Terrestrial GW Interferometer: basic principle

Terrestrial GW Interferometer: basic principle



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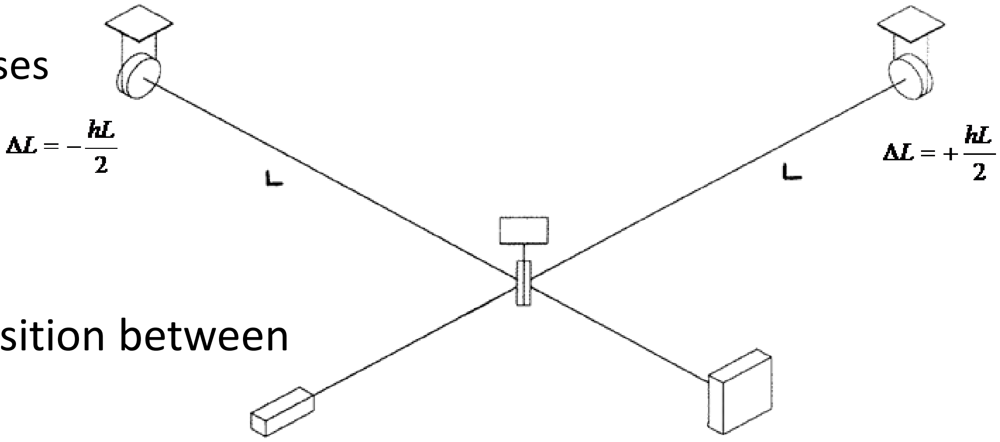


- Michelson interferometer well suited:
  - Effect of a gravitational wave is in opposition between 2 perpendicular axes
  - **Light intensity of interfering beams is related to the difference of optical path length in the 2 arms**

We need a big interferometer:

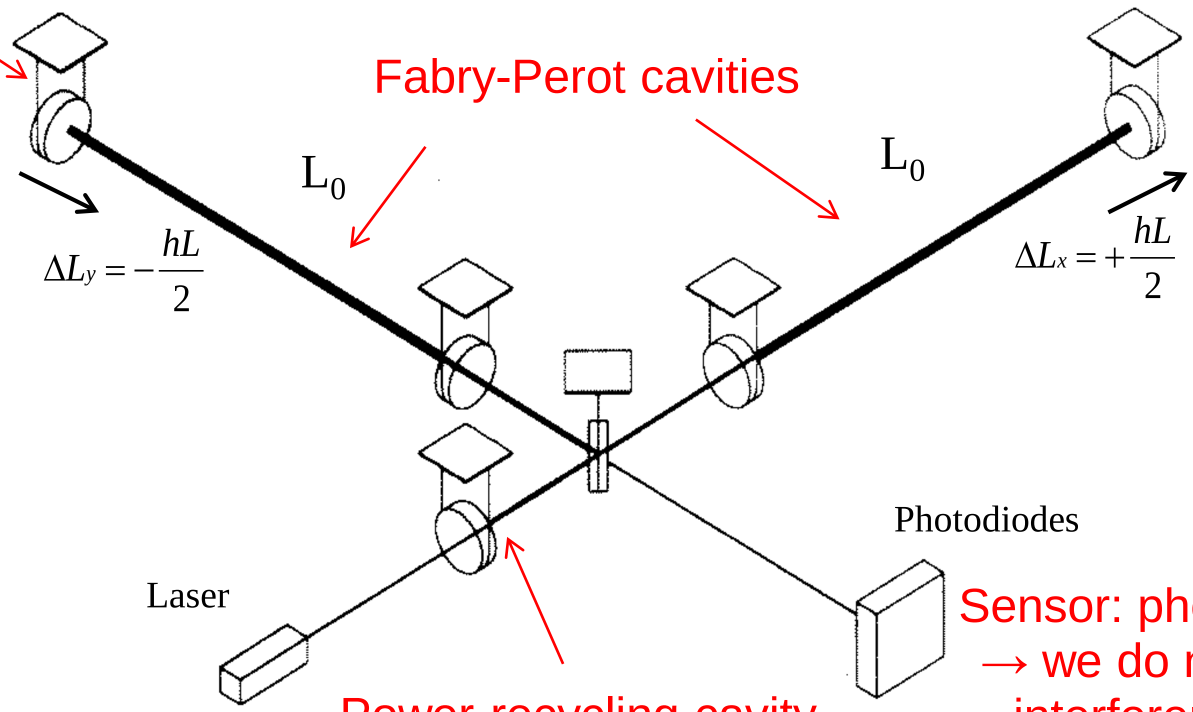
ΔL proportional to L
➔ need several km arms!

Bandwidth: 10 Hz to few kHz

LIGO/Virgo: more complicated interferometers

Suspended mirrors → Mirrors can be considered as free-falling in the ITF plane for frequencies larger than ~10 Hz

Fabry-Perot cavities



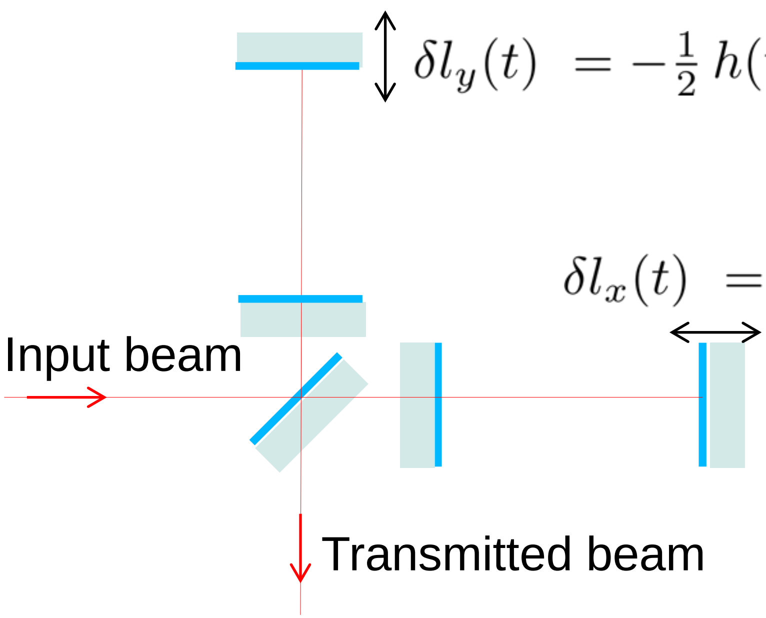
Sensor: photodiode → we do not image the interference pattern!

Power-recycling cavity

Infrared laser
P ~ 100 W

WARNING: STILL VERY SIMPLIFIED SCHEME!

Orders of magnitude



$$\delta l_y(t) = -\tfrac{1}{2}\, h(t)\, L_y$$

$$\delta l_x(t) = \tfrac{1}{2}\, h(t)\, L_x$$

Typical amplitude of differential arm length variations when a GW crosses the Earth:

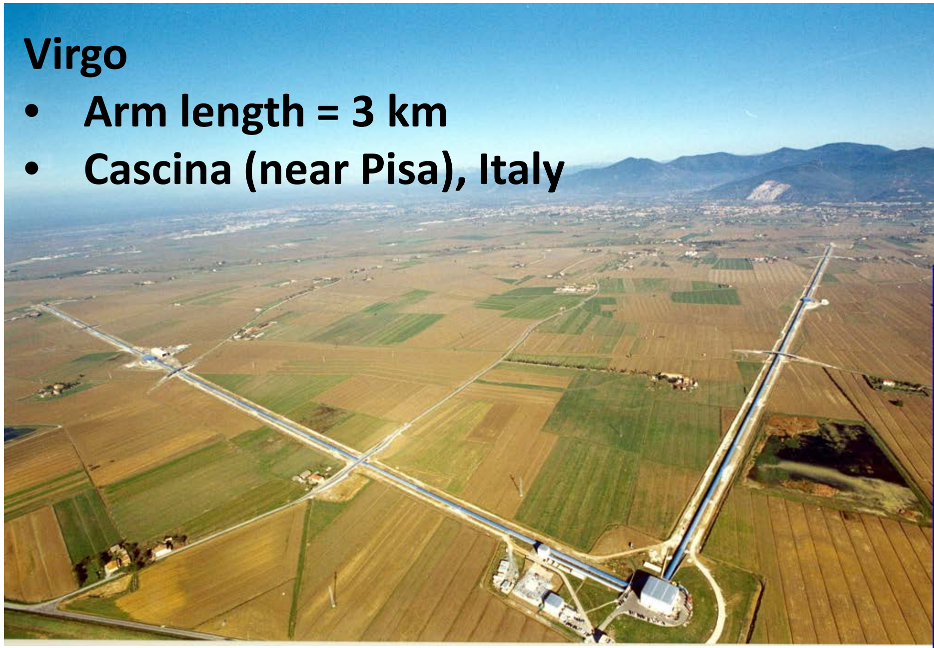
$$\delta \Delta L = \delta l_x(t) - \delta l_y(t) = h(t)\, L_0$$

$$\mathrm{h} \sim 10^{-23} \qquad L_0 = 3\,\mathrm{km}$$

$$\rightarrow \delta \Delta L \sim 3 \times 10^{-20}\,\mathrm{m}$$

$$\sim \frac{\text{size of a proton}}{100000}$$

Km scale interferometers

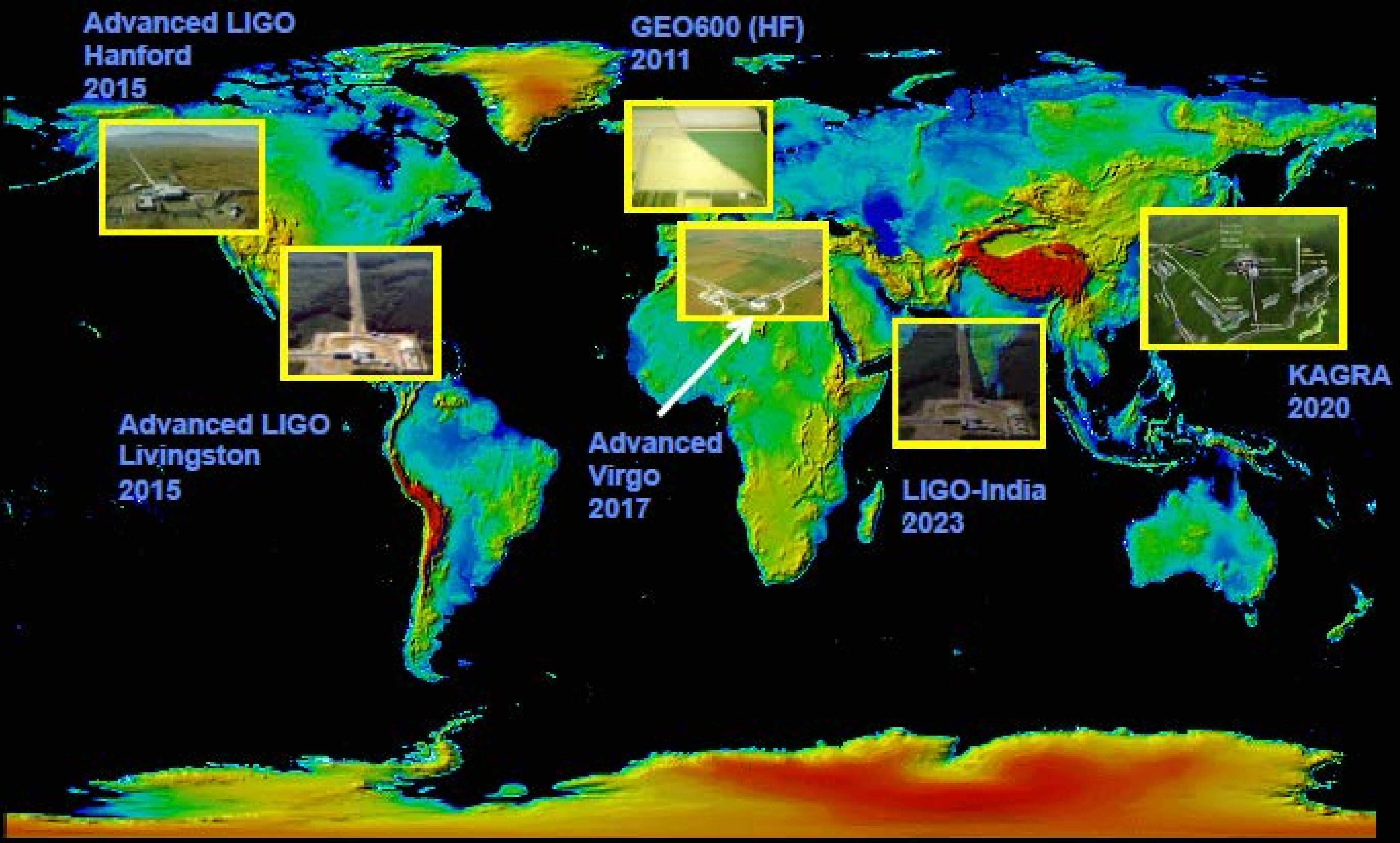


Virgo
- **Arm length = 3 km**
- **Cascina (near Pisa), Italy**

LIGO Livingston
- **Arm length = 4 km**
- **Louisiana**

LIGO Hanford
- **Arm length = 4 km**
- **Washington State**

The detector network



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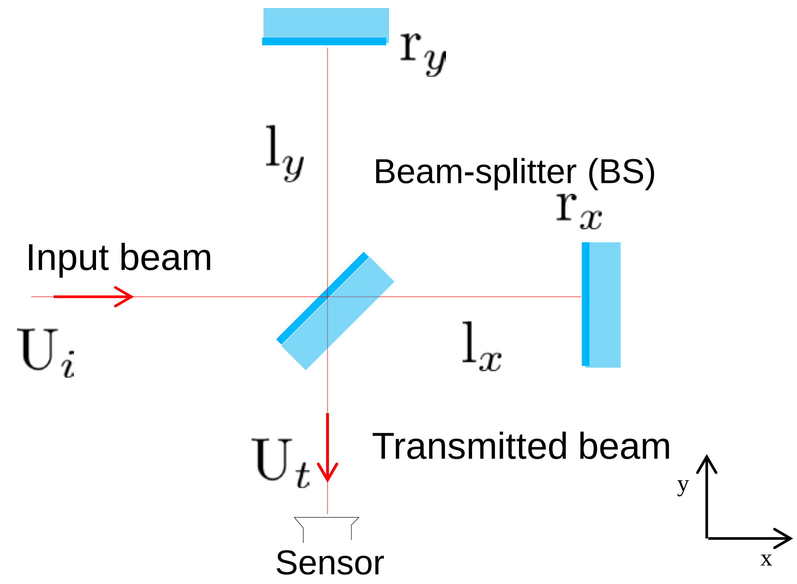
- What are gravitational waves?
- How can we detect gravitational waves?
- **How do terrestrial interferometers work?**
  - The Virgo optical configuration or how to measure 10^{-20} m
  - How to maintain the ITF at its working point?
  - How to measure the GW strain h(t) from this detector?
  - Noises limiting the ITF sensitivity: how to tackle them?
  - From interferometers to a “gravitational-wave telescope”
- Prospectives for interferometers and other detectors

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)



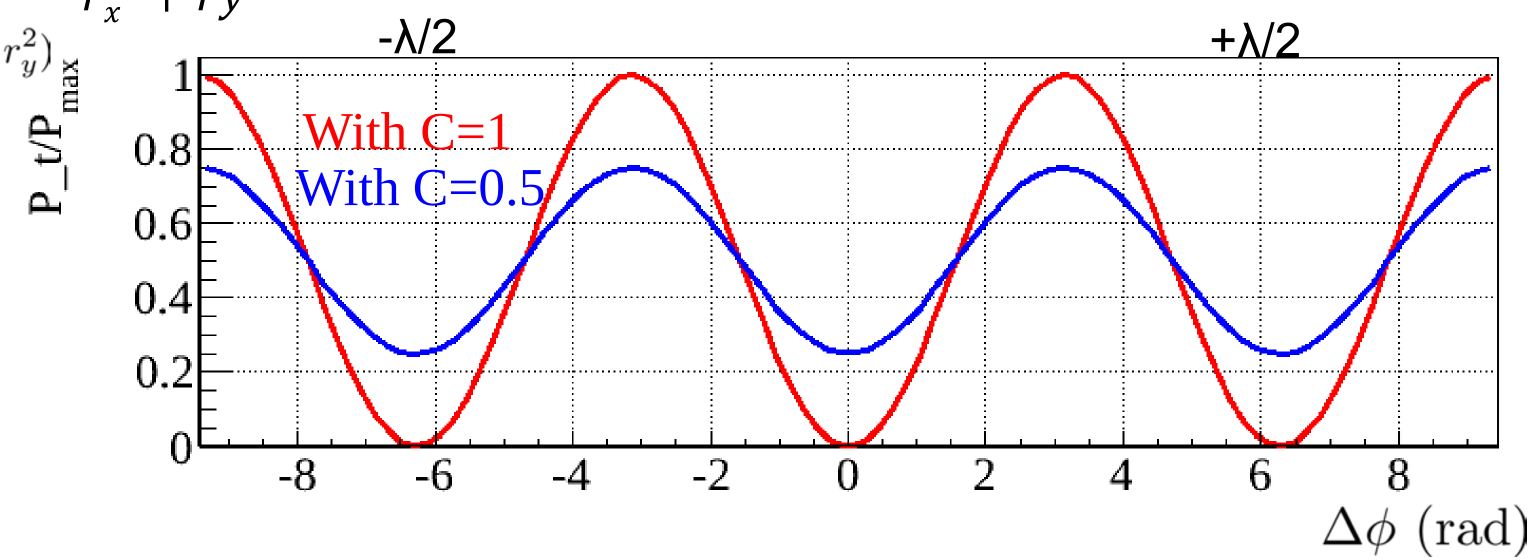
Transmitted power

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

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

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

$$P_{max} = \frac{P_i}{2}(r_x^2 + r_y^2)$$



What power does Virgo measure?

- In general, the beam is not a plane wave but a spherical wave

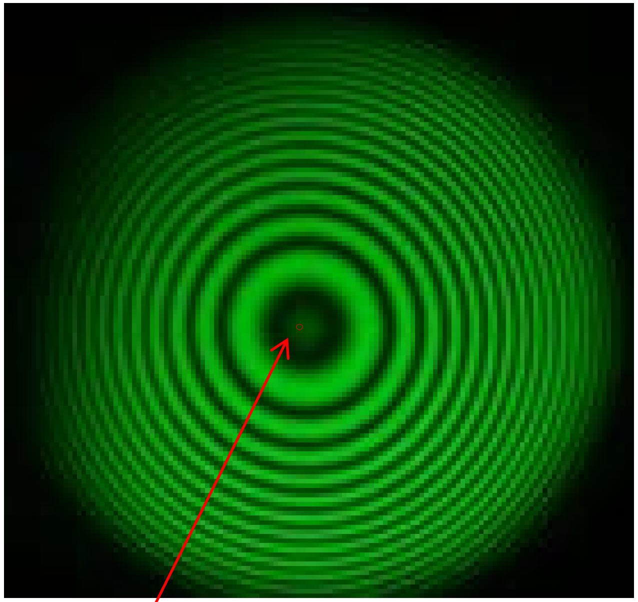
  → interference pattern

  (and the complementary pattern in reflection)

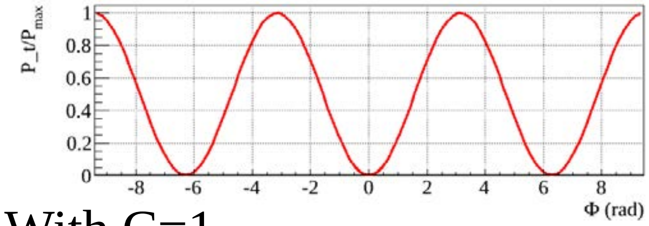
- Virgo interference pattern much larger than the beam size:

  ~1 m between two consecutive fringes

  → we do not study the fringes in nice images !



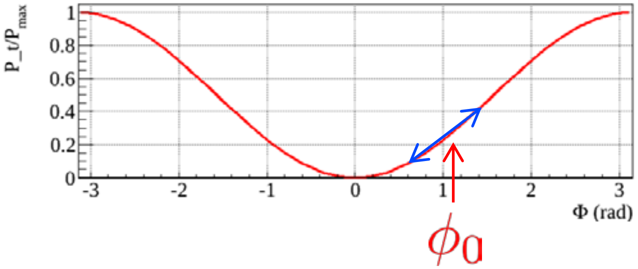
Equivalent size of Virgo beam



With C=1

Freely swinging mirrors

Setting a working point →



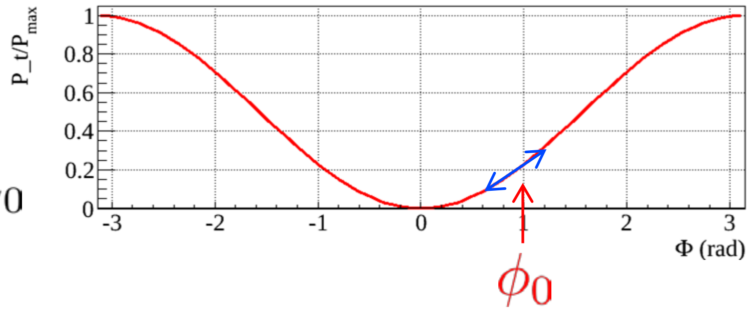
Controlled mirror positions

From the power to the gravitational wave

$$P_t = \frac{P_i}{2}\left(1 - C\cos(\phi)\right) \quad \text{where } \phi = 2\frac{2\pi}{\lambda}(l_y - l_x)$$

- Around the working point:

$$\left.\frac{\mathrm{d}P_t}{d\phi}\right|_{\phi_0} = \frac{P_i}{2} C \sin(\phi_0) \quad \text{where } \phi_0 = \frac{4\pi}{\lambda}\Delta L_0$$



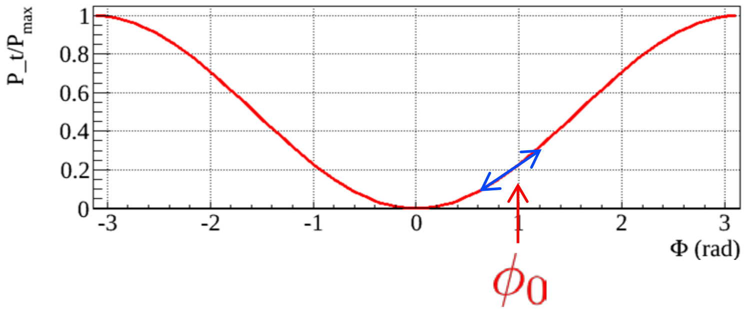
- Power variations as function of small differential length variations:

$$\delta P_t = \frac{P_i}{2} C \sin(\phi_0)\delta\phi$$

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

$$\delta P_t \propto \delta\Delta L = h L_0 \quad \text{around the working point !}$$

From the power to the gravitational wave



- Around the working point:

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

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

(W/m)

Measurable physical quantity

Physical effect to be detected

Improving the interferometer sensitivity

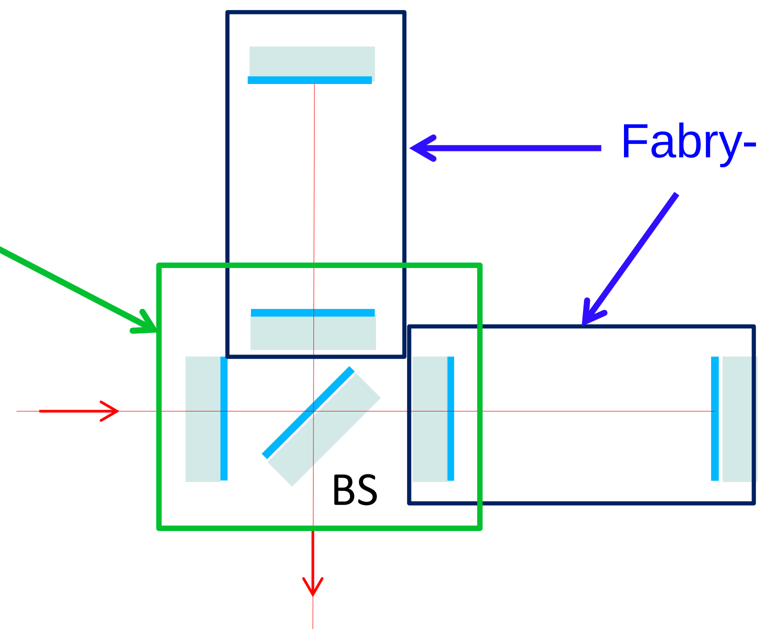
$$\delta P_t = P_i C \sin\left(\frac{4\pi}{\lambda}\Delta L_0\right) \underbrace{(k\,\delta\Delta L)}_{\propto\, \delta\phi}$$

Increase the input power on BS

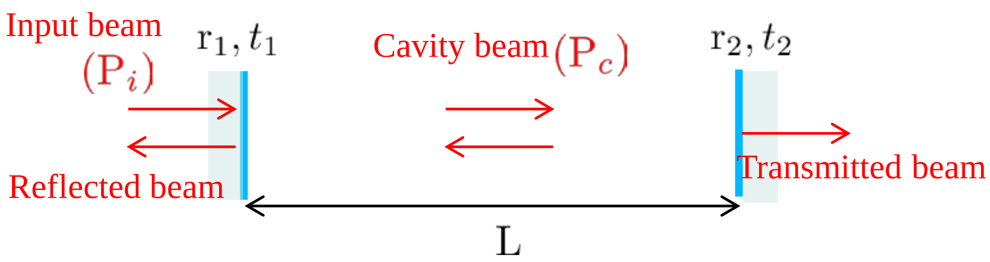
Increase the phase difference between the arms for a given differential arm length variation

Recycling **cavity**

Fabry-Perot **cavities** in the arms

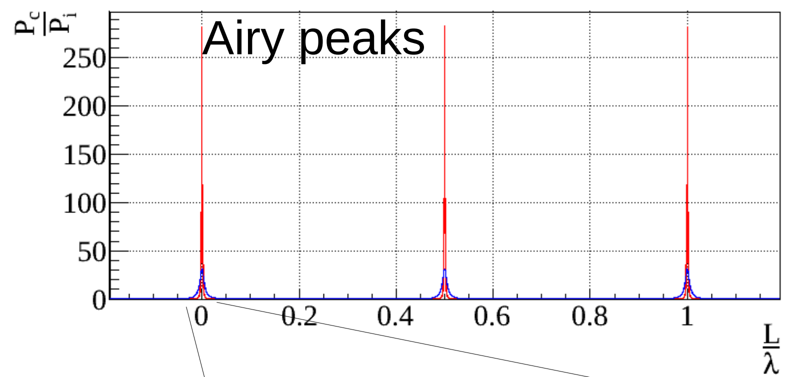


Beam resonant inside the cavities

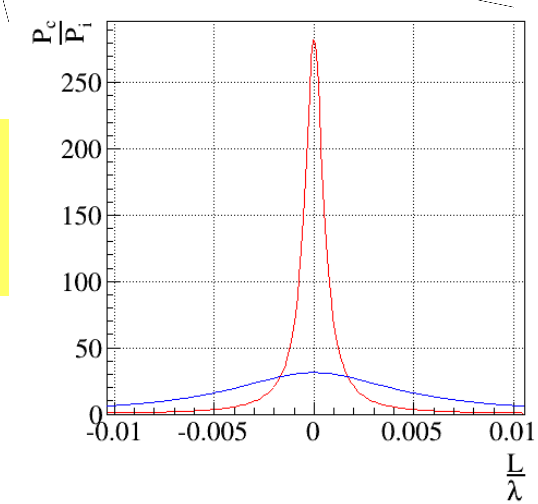


$$P_c = P_i \frac{t_1^2}{(1 - r_1 r_2)^2} \frac{1}{1 + \left(\frac{2\mathcal{F}}{\pi}\right)^2 \sin^2(kL)}$$

$$\text{Finesse } \mathcal{F} = \frac{\pi\sqrt{r_1 r_2}}{1 - r_1 r_2}$$



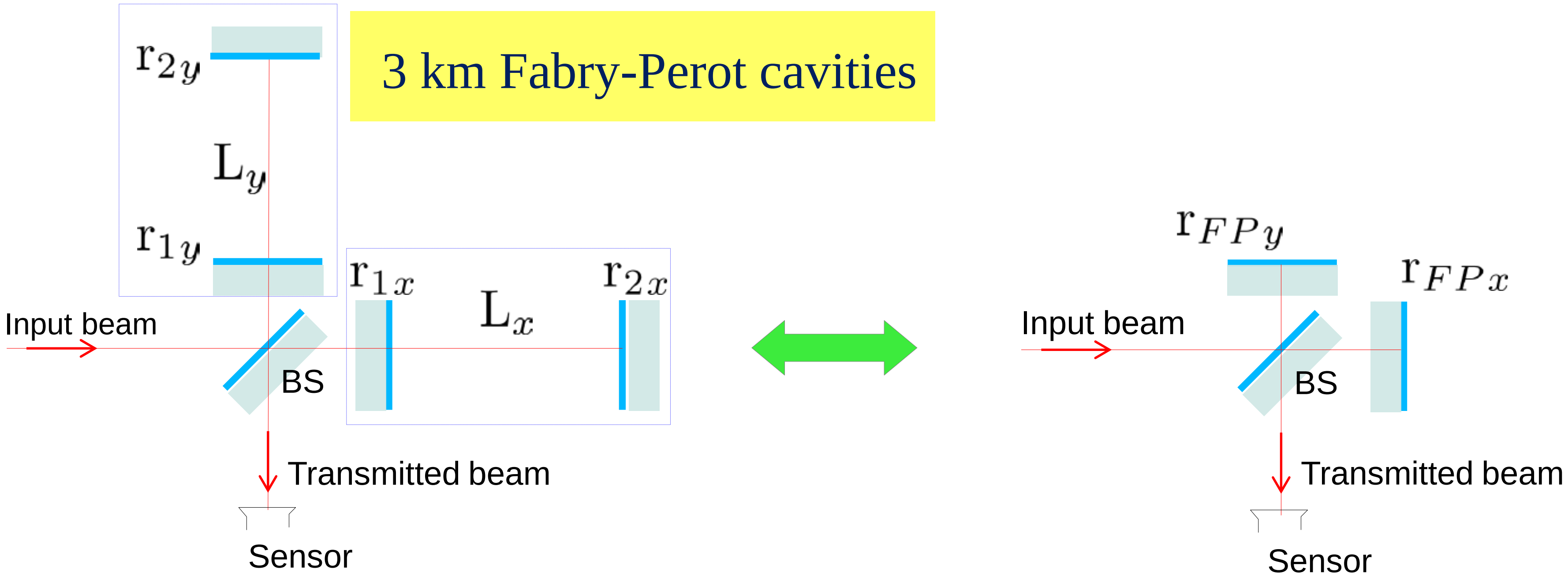
Virgo cavity at resonance: $L = n\frac{\lambda}{2} \quad (n \in \mathbb{N})$



Virgo F = 50
AdVirgo F = 443

Average number of light round-trips in the cavity: $N = \frac{2\mathcal{F}}{\pi}$

How do we amplify the phase offset?



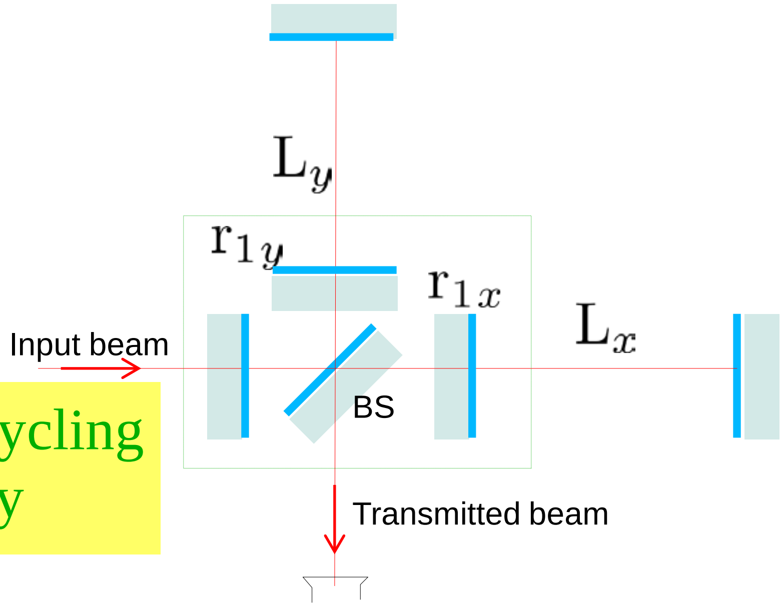
$$r_{FPx} = -1 \times e^{J \frac{2\mathcal{F}}{\pi} 2\, k\, \delta L_x}$$

~number of round-trips in the arm
~300 for AdVirgo

(instead of $r_{armx} = -1 \times e^{J 2k(L_x + \delta L_x)}$ in the arm of a simple Michelson)

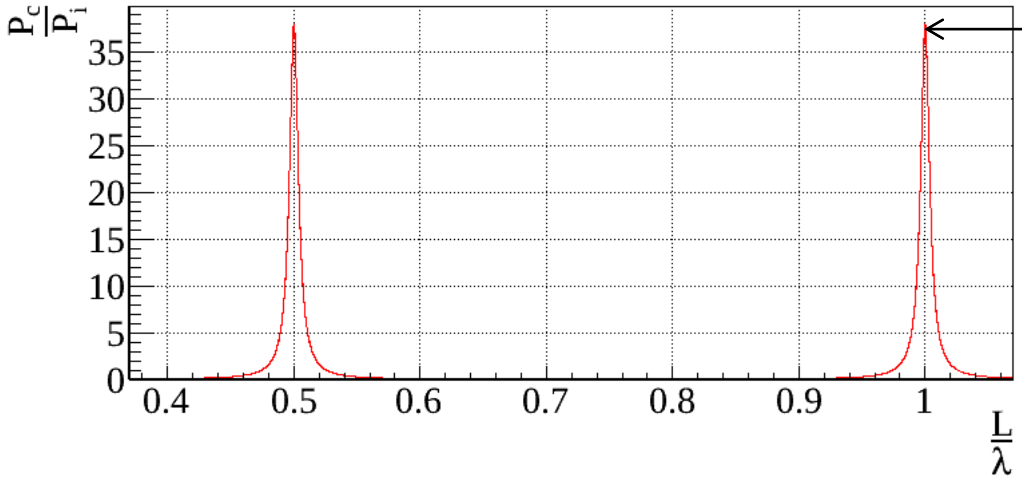
How do we increase the power on BS?

Detector working point close to a dark fringe
→ most of power go back towards the laser



Power recycling cavity

Resonant power recycling cavity



$G_{PR} = 38 \quad (r_{PR}^2 = 0.95)$

→ input power on BS increased by a factor 38!

Improved interferometer response

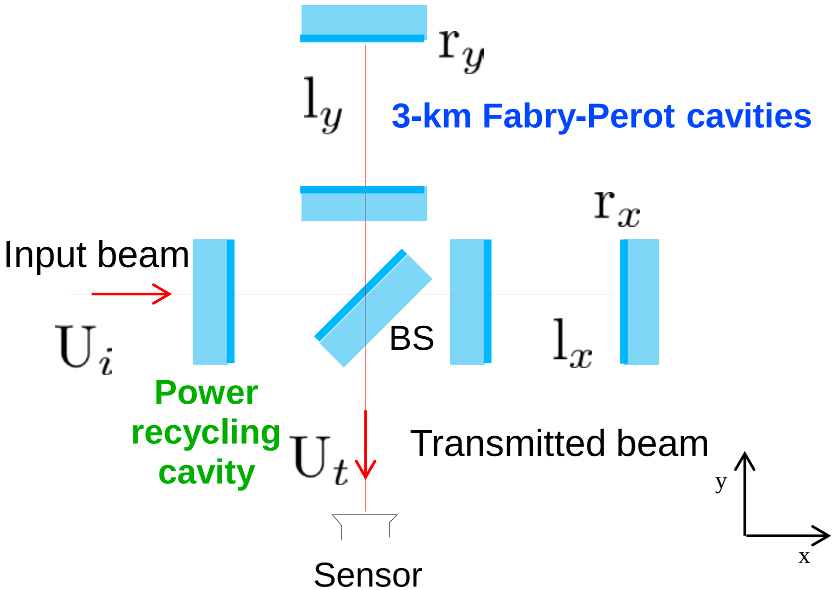
- **Response of simple Michelson:**

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

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

(W/m)

- **Response of recycled Michelson with Fabry-Perot cavities:**



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

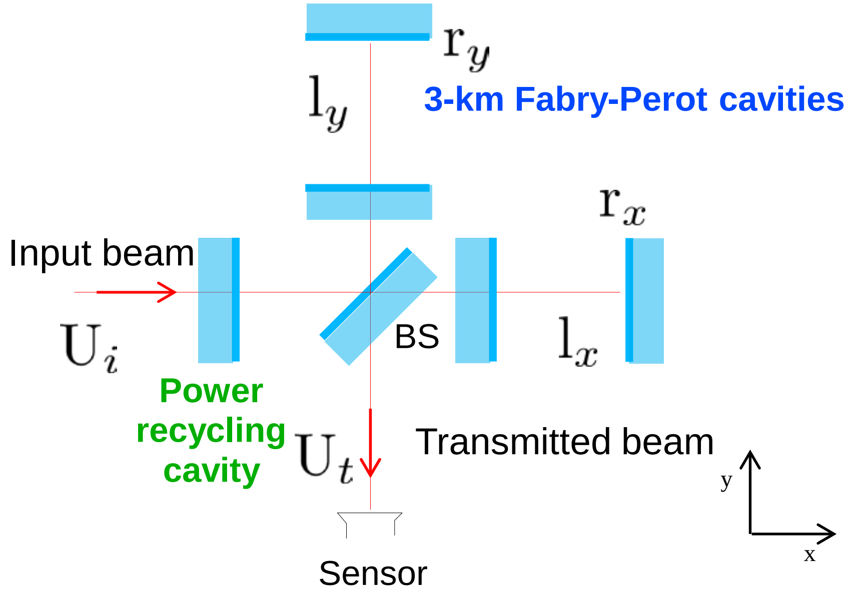
G_{PR} ~38 $\qquad$ $\frac{2\mathcal{F}}{\pi}$ ~300

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 $\sim 50\,\text{mW}$

$\rightarrow \delta P_{t,min} \sim 0.1\,\text{nW}$ $\longrightarrow$ $\delta\Delta L_{min} \sim 5 \times 10^{-20}$ m

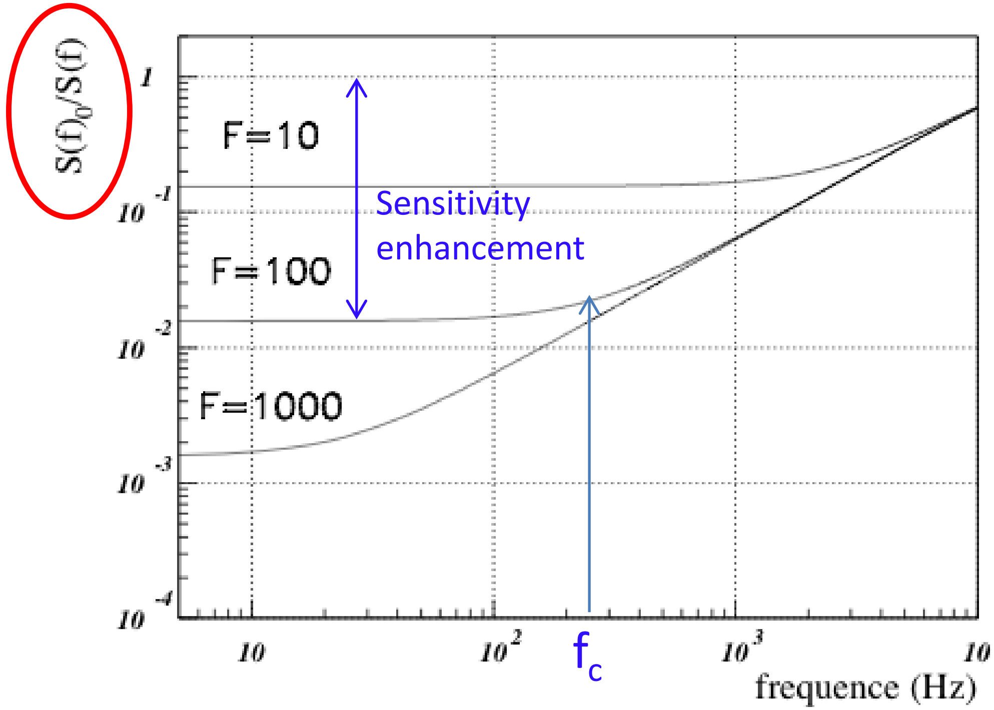
$$\rightarrow h_{min} = \frac{\delta\Delta L_{min}}{L} \sim 10^{-23}$$

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

Example of frequency dependency of the ITF response

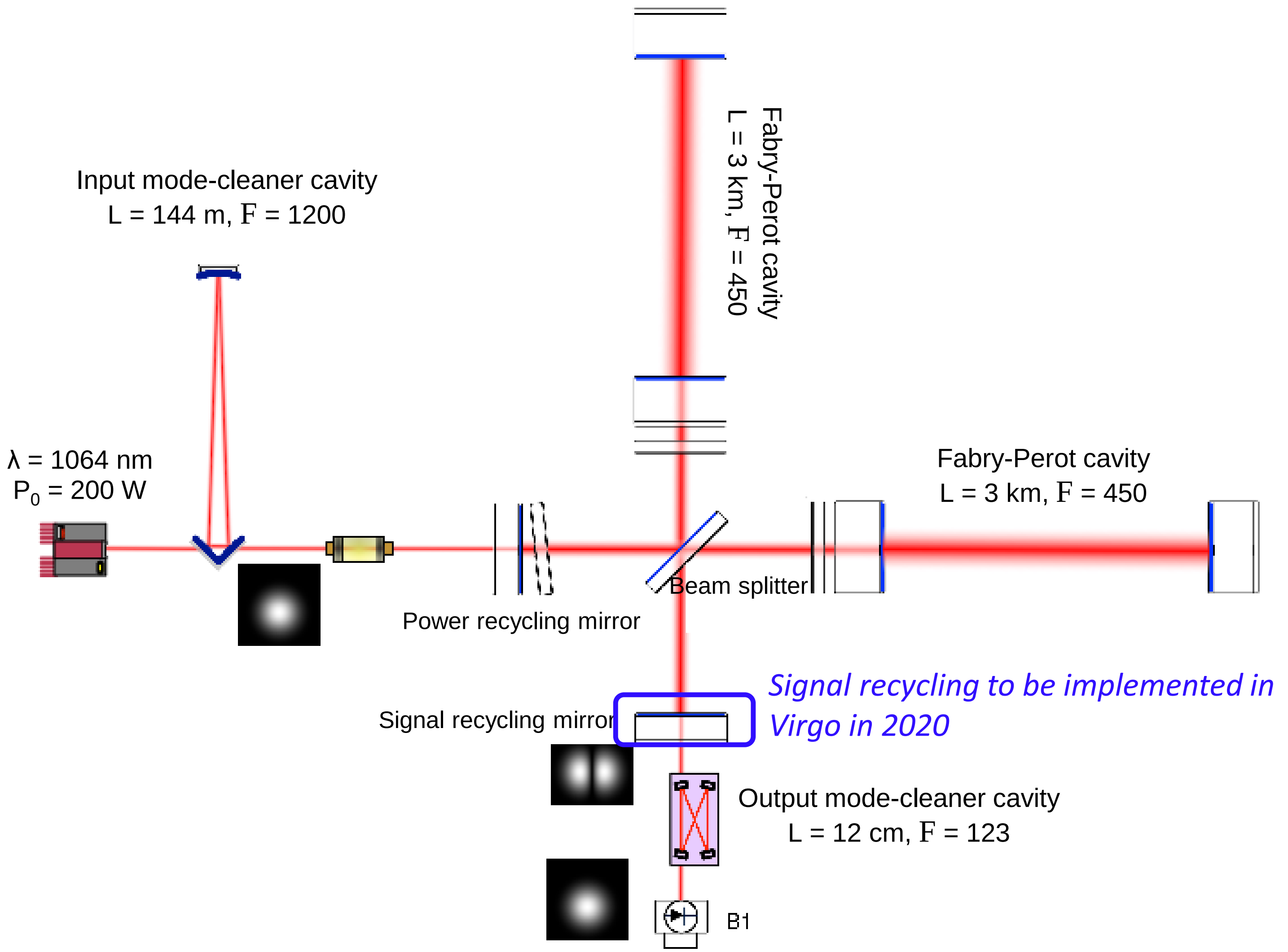
- Light travel time in the cavities must be taken into account
- Fabry-Perot cavities behave as a low pass filter
- Frequency cut-off: $$f_c = \frac{c}{4\mathcal{F}L}$$

Ratio between the sensitivity of an interferometer with Fabry-Perot cavities versus the sensitivity of an interferometer without cavities

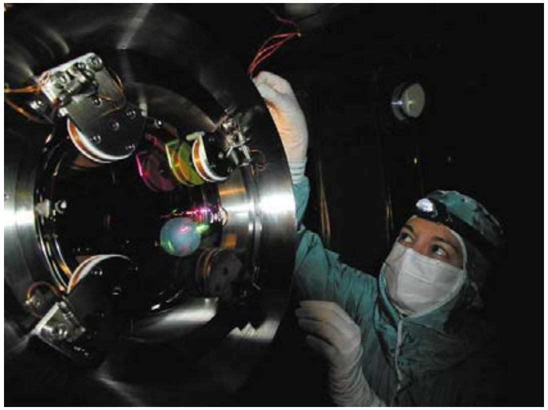


- Finesse of Virgo Fabry Perot cavities: F = 450, L= 3 km → f_c = 55 Hz

Optical layout of Advanced Virgo

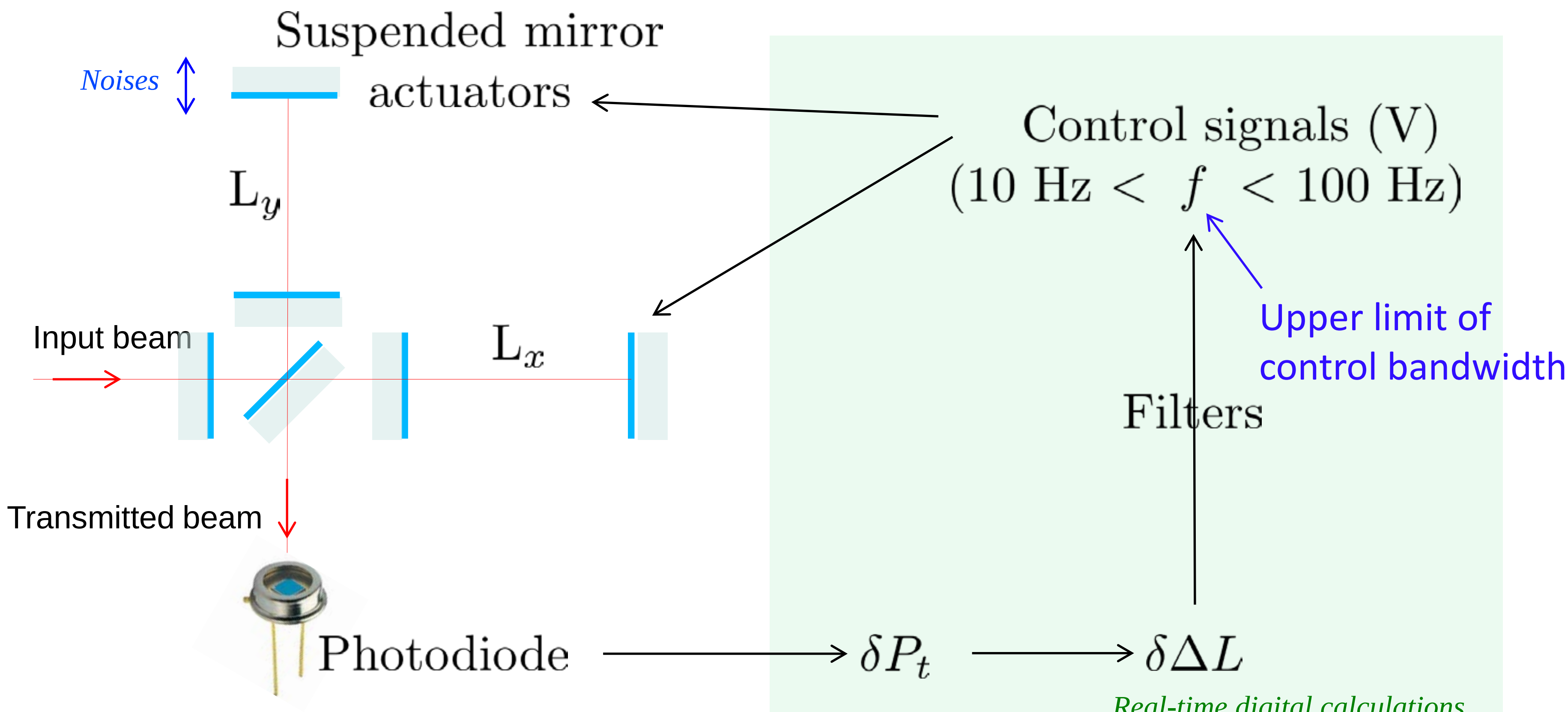


How do we control the working point?



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

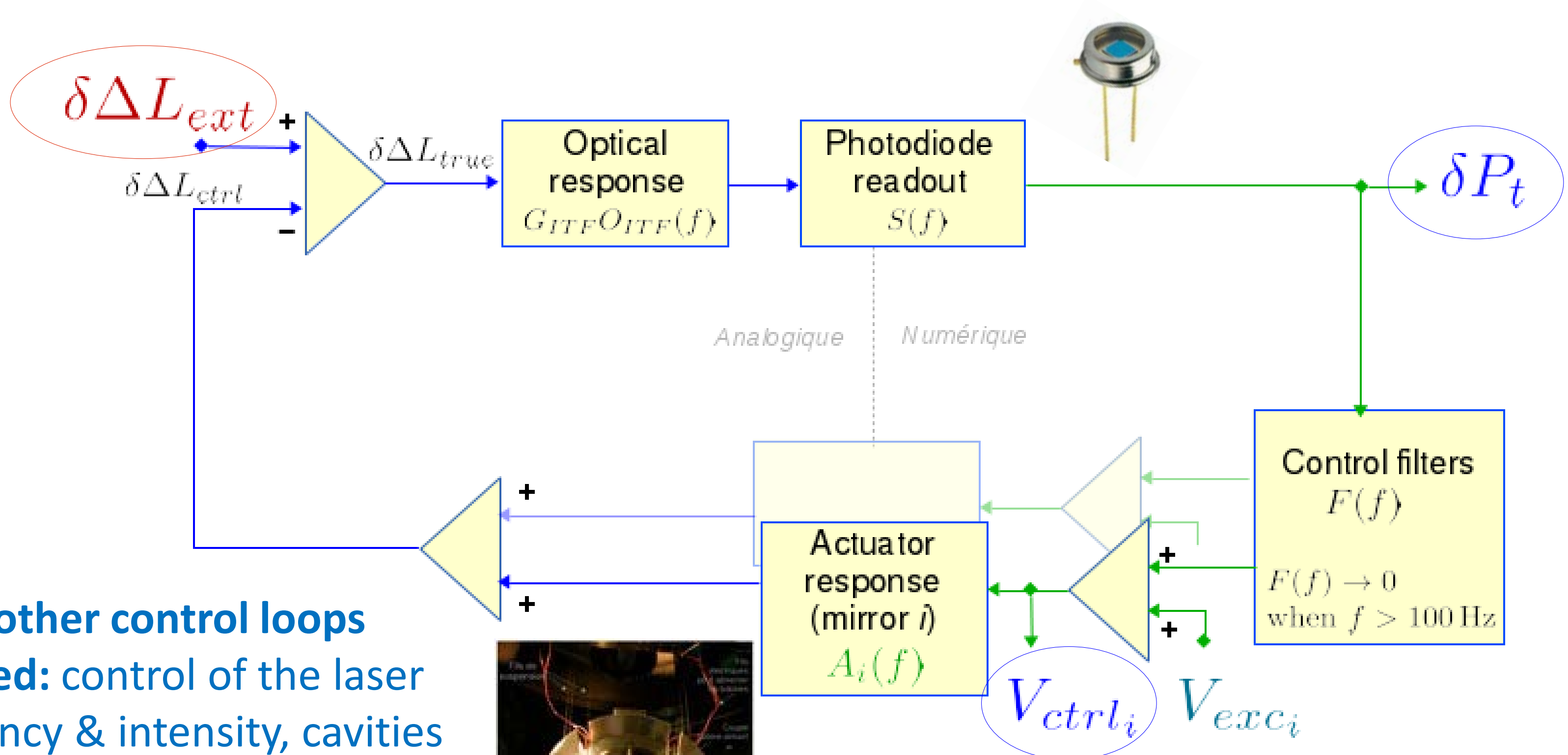


How do we control the working point?

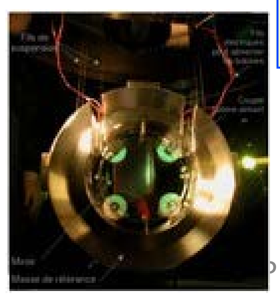
Small offset from a dark fringe: $\Delta L_0 = n\frac{\lambda}{2} + 10^{-11}\,\mathrm{m}$

- 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, …



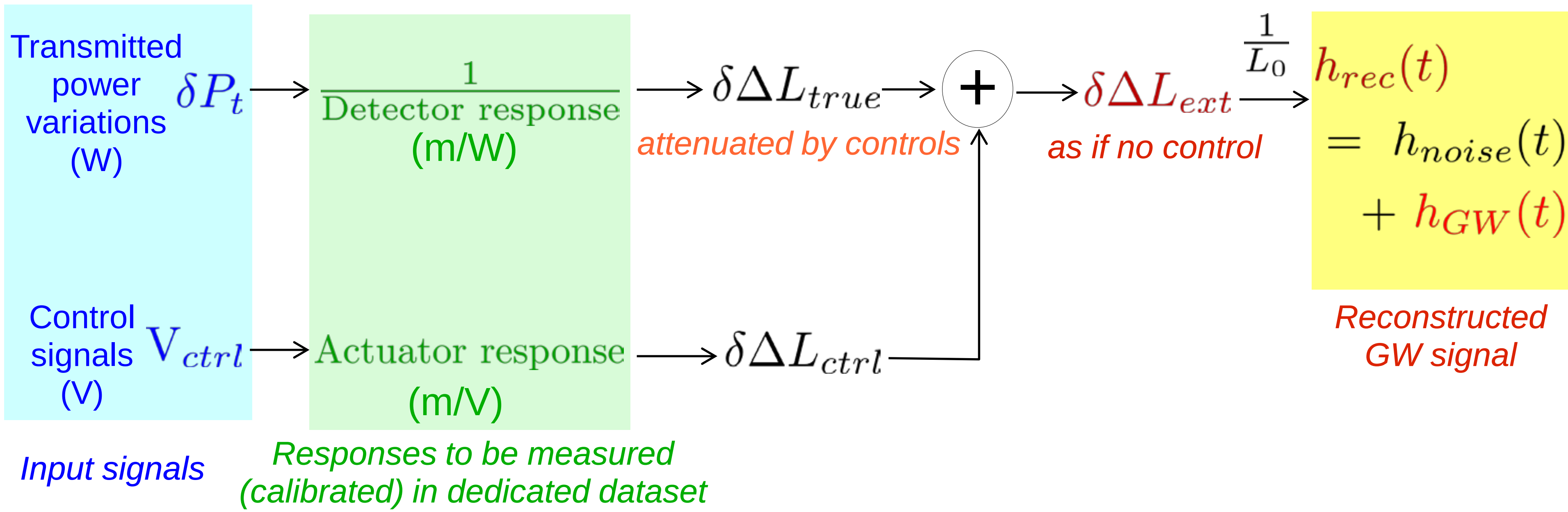
From the detector data to the GW strain h(t)

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

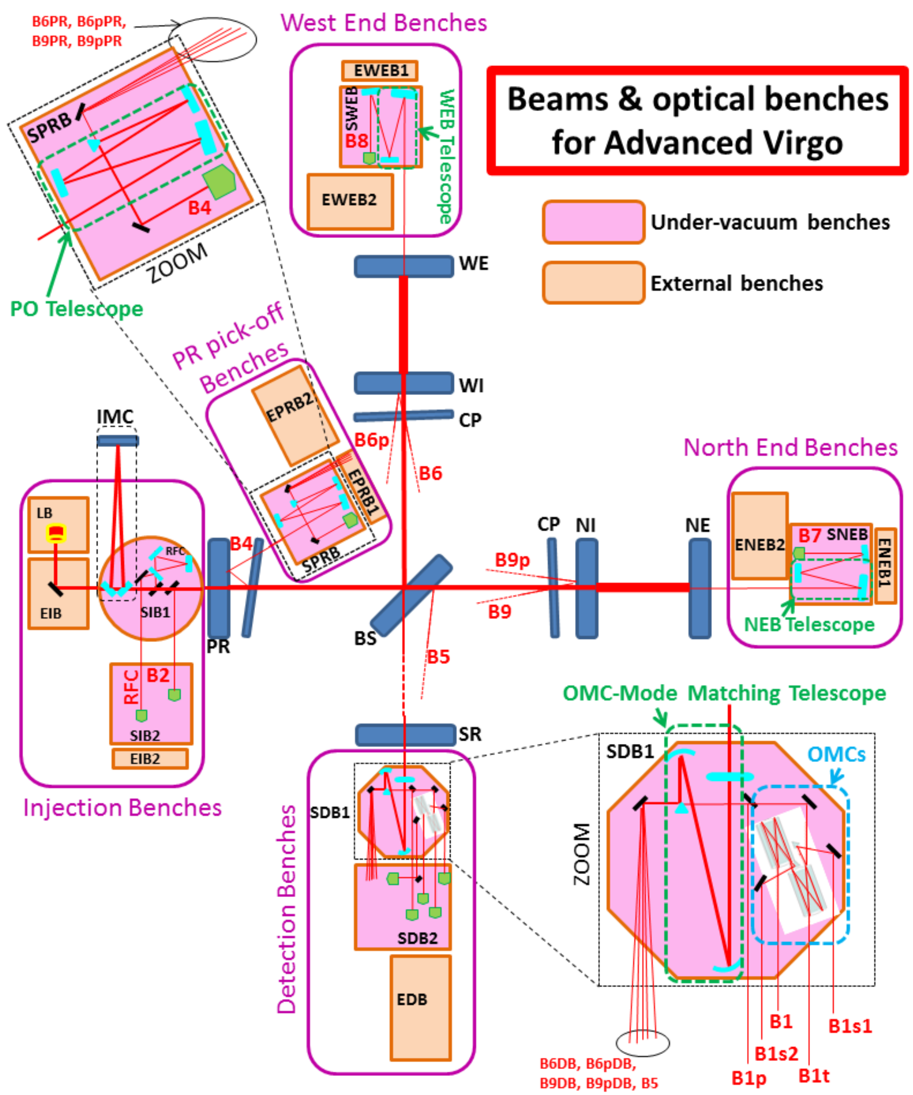
  $\rightarrow \quad h(t) = \frac{\delta\Delta L_{true}(t)}{L_0}$

- Lower frequency: the controls attenuate the noise... but also the GW signal!

  → the control signals contain information on *h(t)*



How to extract all error signals? Interferometer optical ports

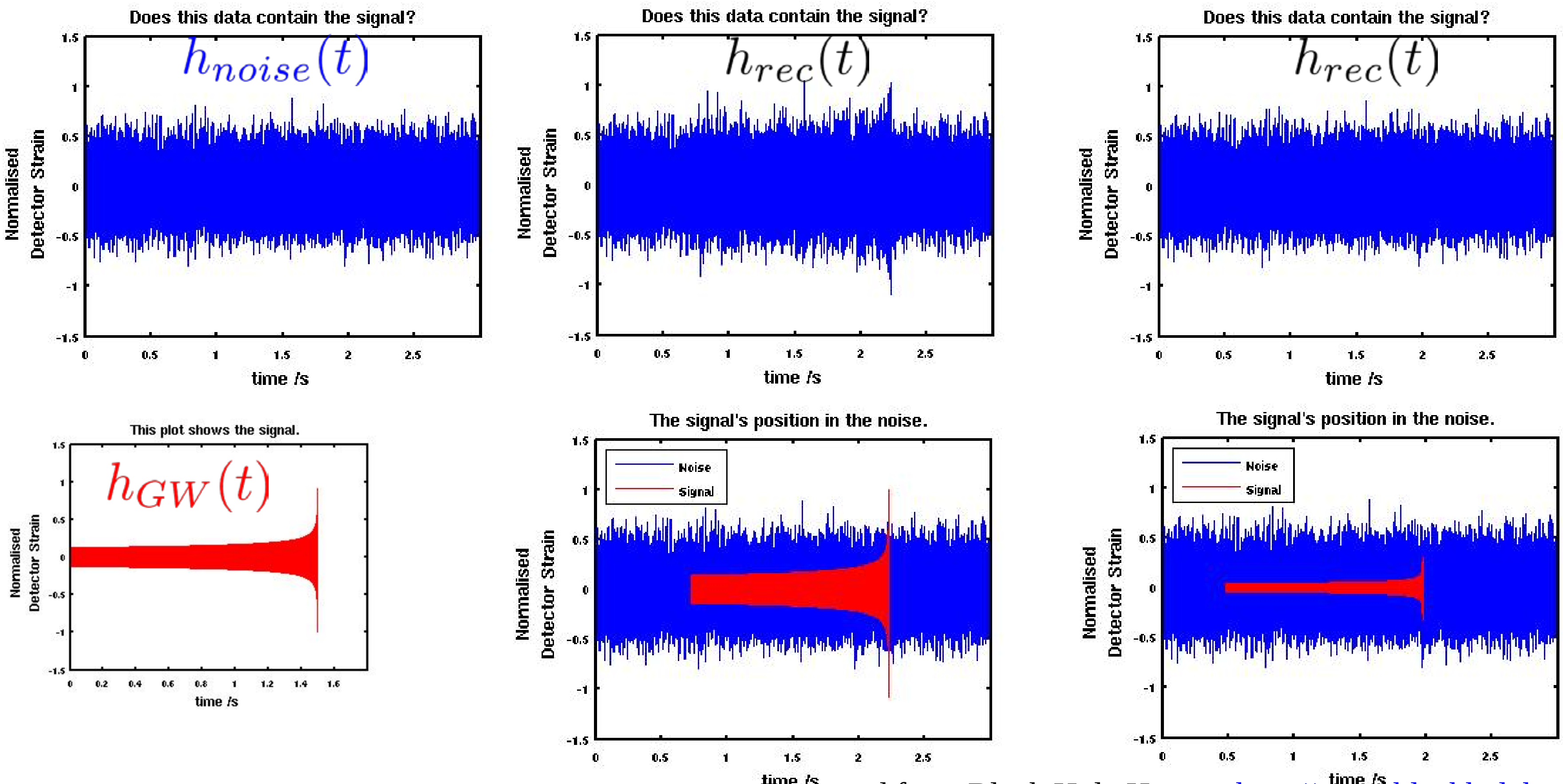


Noises limiting interferometer sensitivity: How to mitigate them ?

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 $h_{GW}(t)$

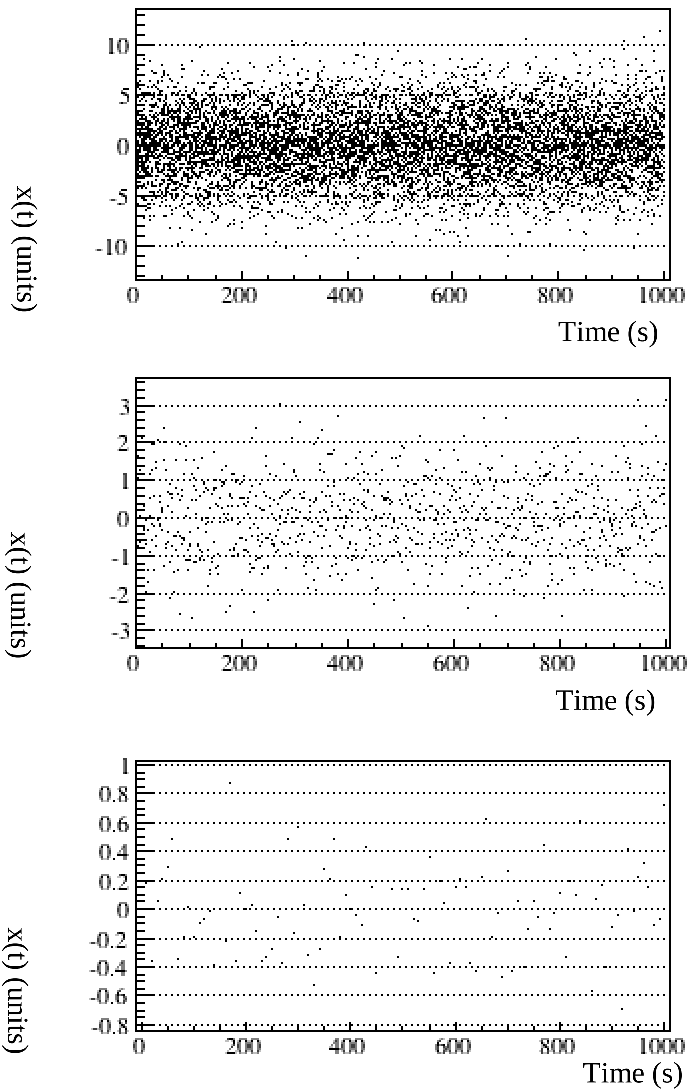
$$h_{rec}(t) = h_{noise}(t) + h_{GW}(t)$$



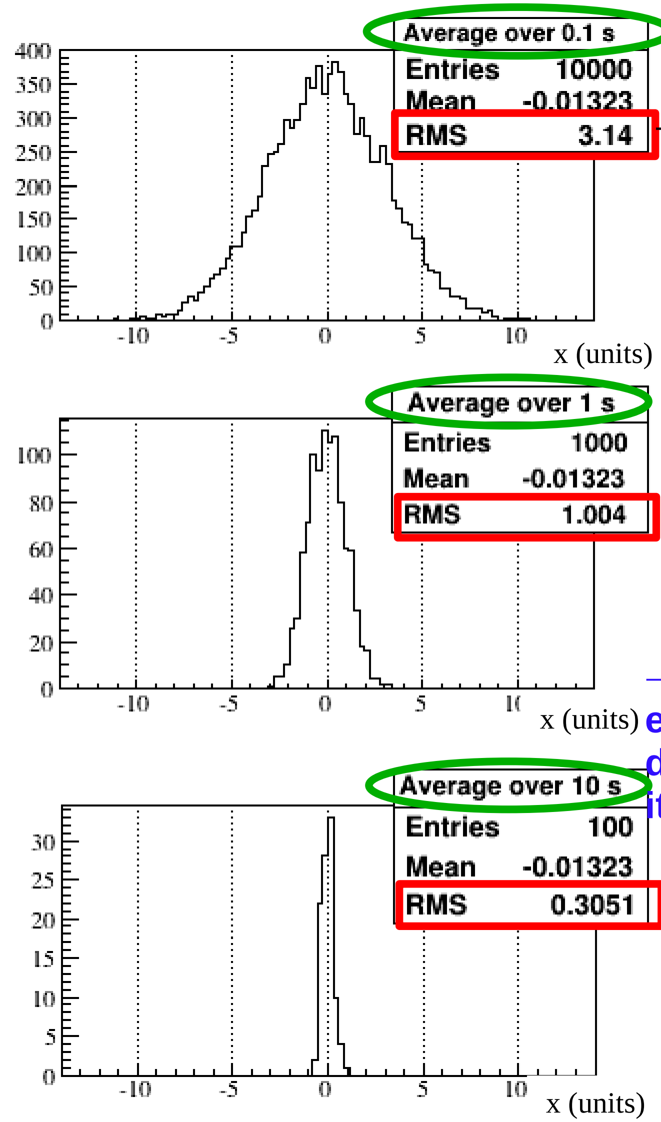
Extracted from Black Hole Hunter: http://www.blackholehunter.org/

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 $\frac{\text{Data units}}{\sqrt{\text{Hz}}}$

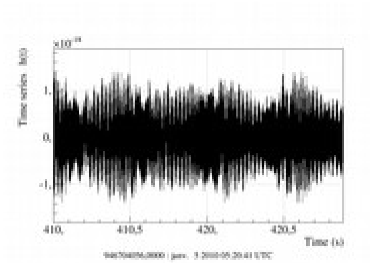
→ its absolute value is equal to the standard deviation of the noise when it is averaged over 1 s

→ D = 1 units/√Hz

From hrec(t) to Virgo sensitivity curve

1/ Reconstruction of h(t)

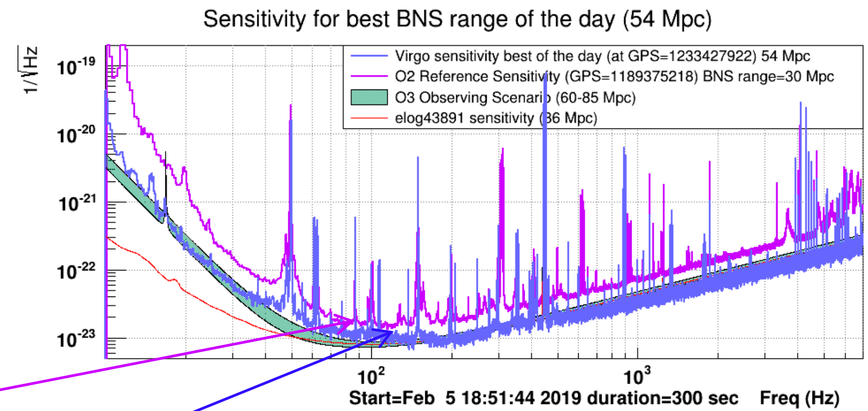
$$h_{rec}(t) = h_{noise}(t) + h_{GW}(t)$$



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)

~3 x10^{-20} m/√Hz (Advanced Virgo in Feb 2019)

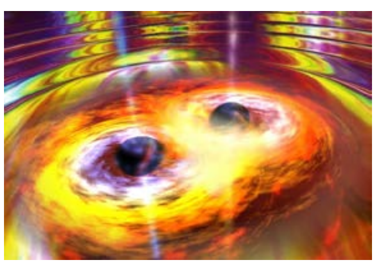


Image: Danna Berry/SkyWorks/NASA

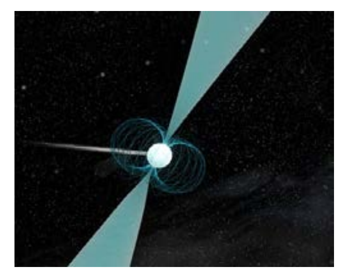


Image: B. Saxton (NRAO/AUI/NSF)

Compact Binary Coalescences

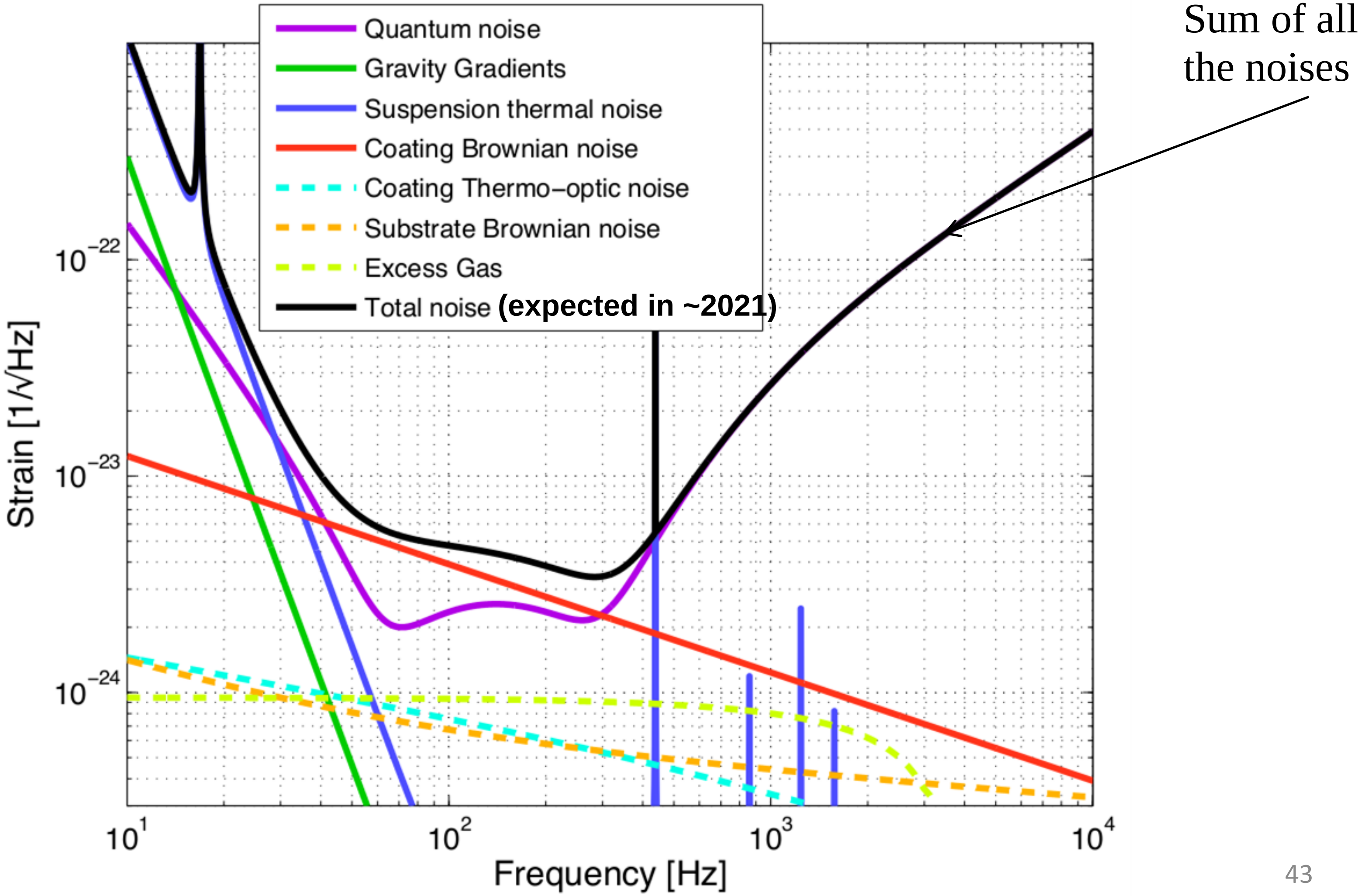
Signal lasts for a few seconds
→ can detect h ~ 10^{-23}

Rotating neutron stars

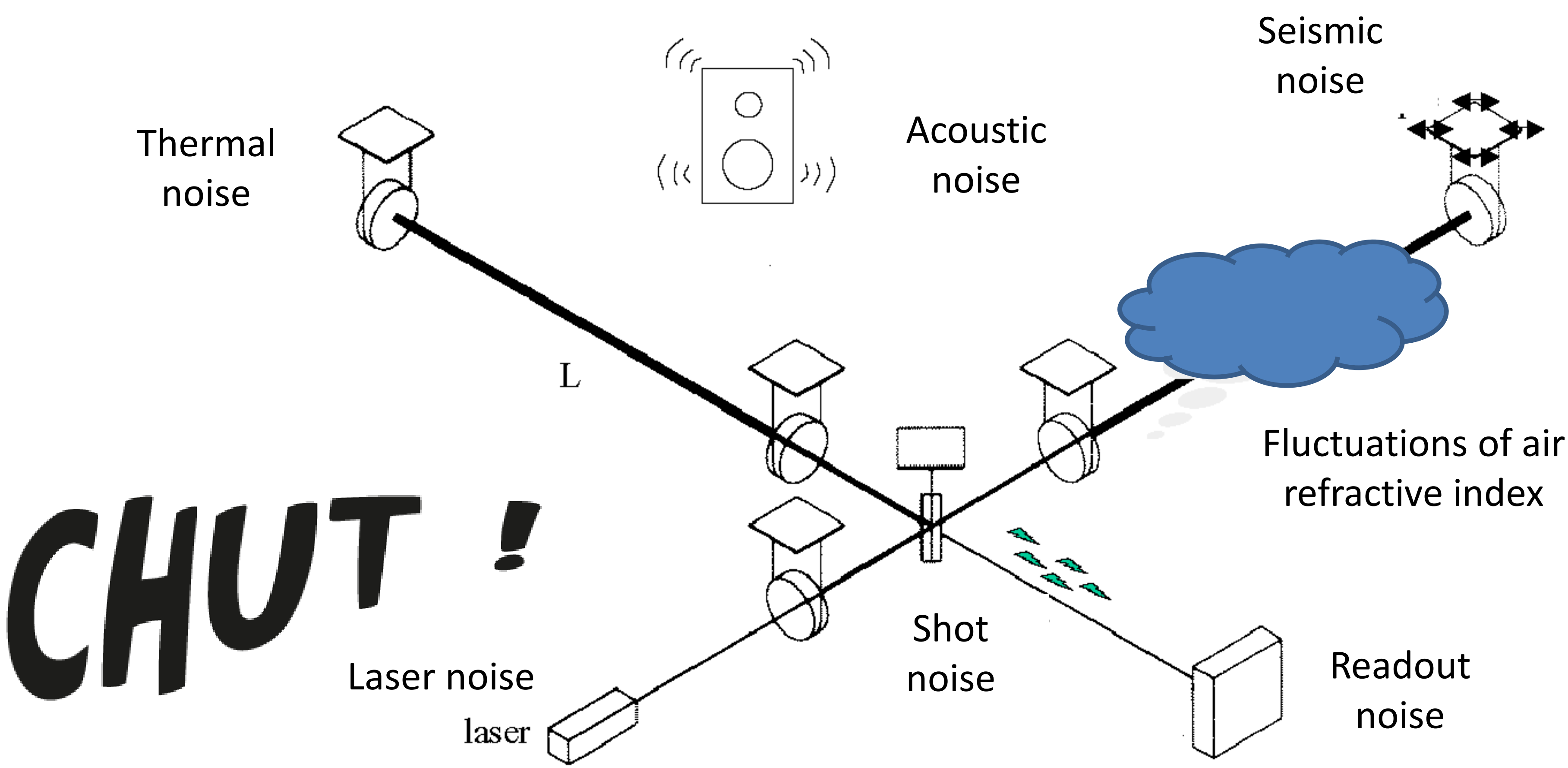
Signal averaged over days (~10^{6} s)
→ can detect h ~ 10^{-26}

Nominal sensitivity of Advanced Virgo

Fundamental noise only
Possible technical noise not shown



Fundamental noise sources



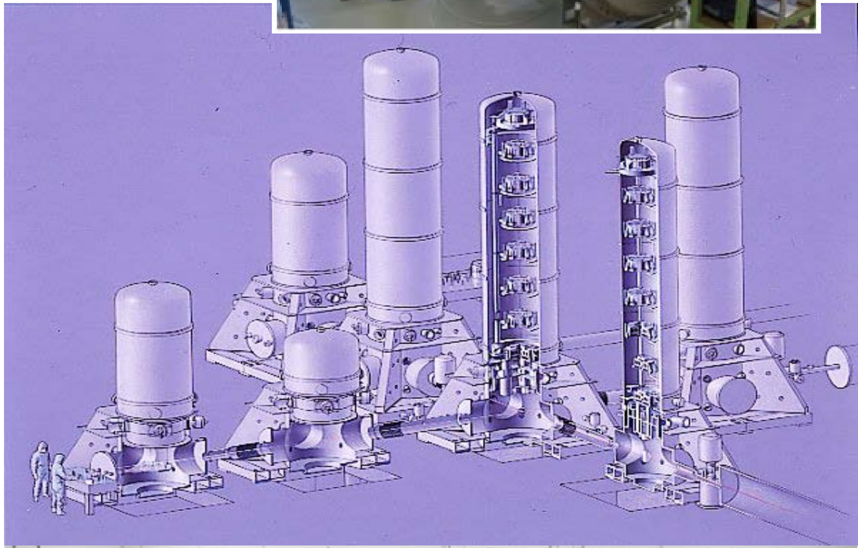
Under vacuum

Goals

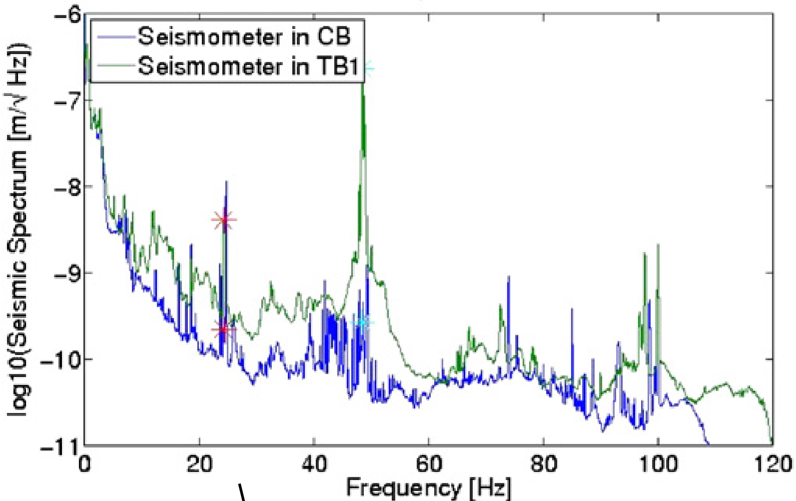
- Isolation against acoustic noise
- Avoid measurement noise due to fluctuations of air refractive index
- Keep mirrors clean

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

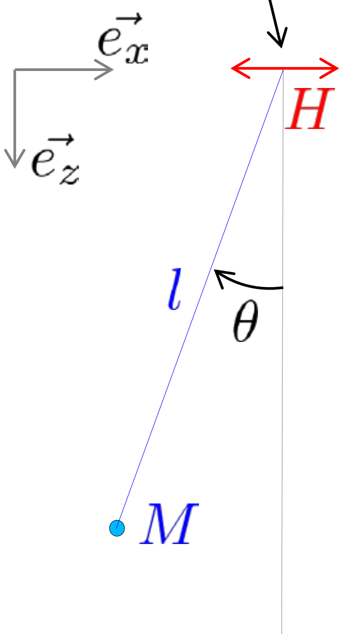


Seismic noise and suspended mirrors



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

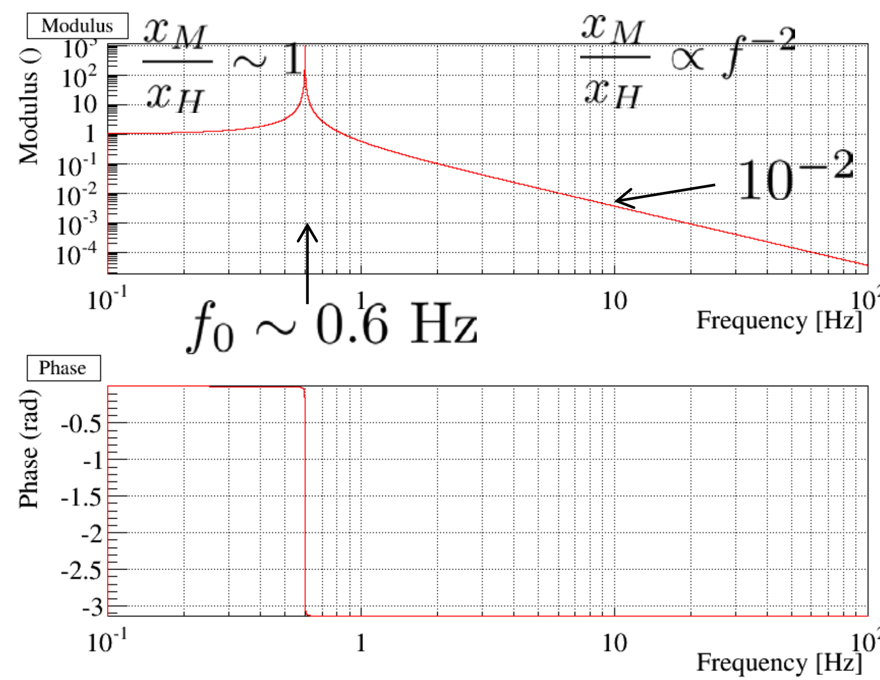
$$\gg 10^{-19}\,\mathrm{m}/\sqrt{\mathrm{Hz}} \text{ needed to detect GW !!}$$



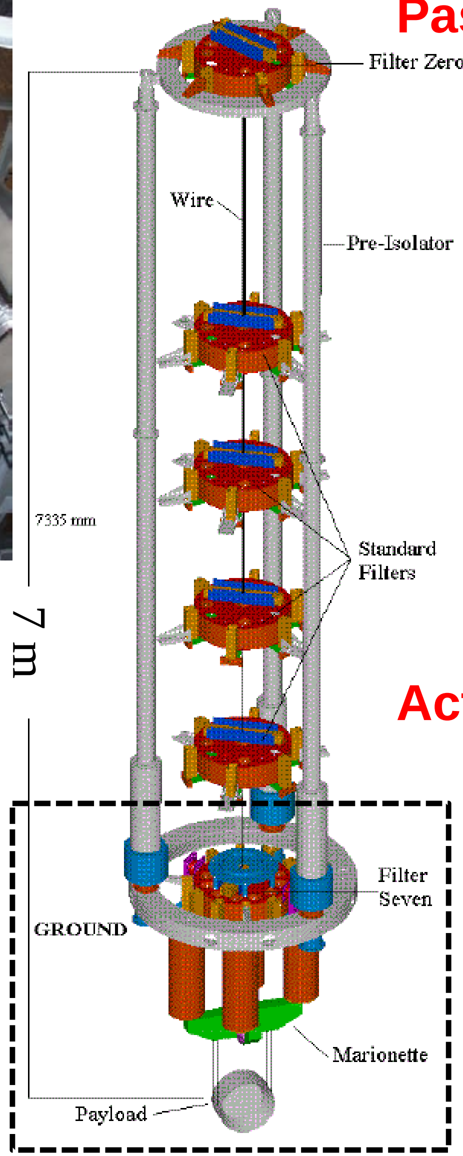
Assuming δx_H small and sinusoidal and θ small:

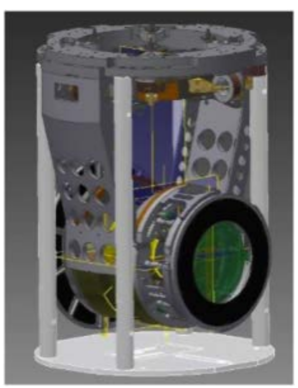
$$\underline{x_M} = \underline{\mathcal{H}} \times \underline{x_H}$$

Transfer function



Seismic noise: Virgo super-attenuators





Passive attenuation: 7 pendulum in cascade

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

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

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

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

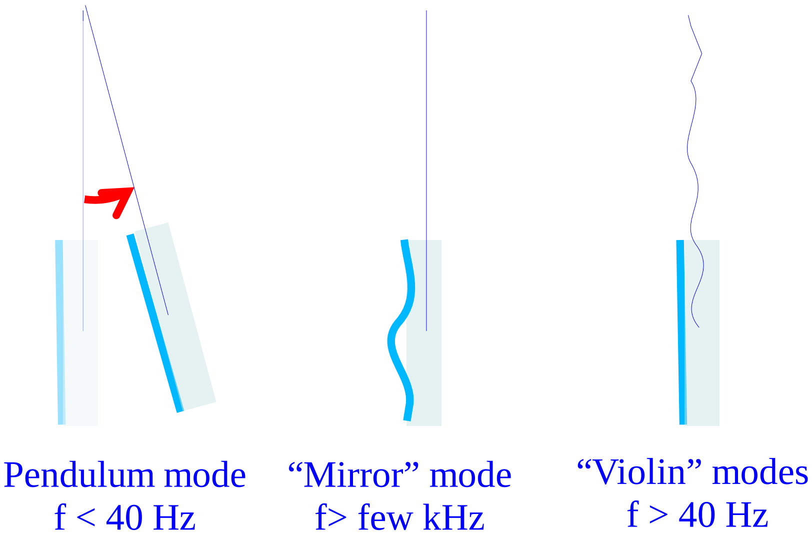
Active controls at low frequency

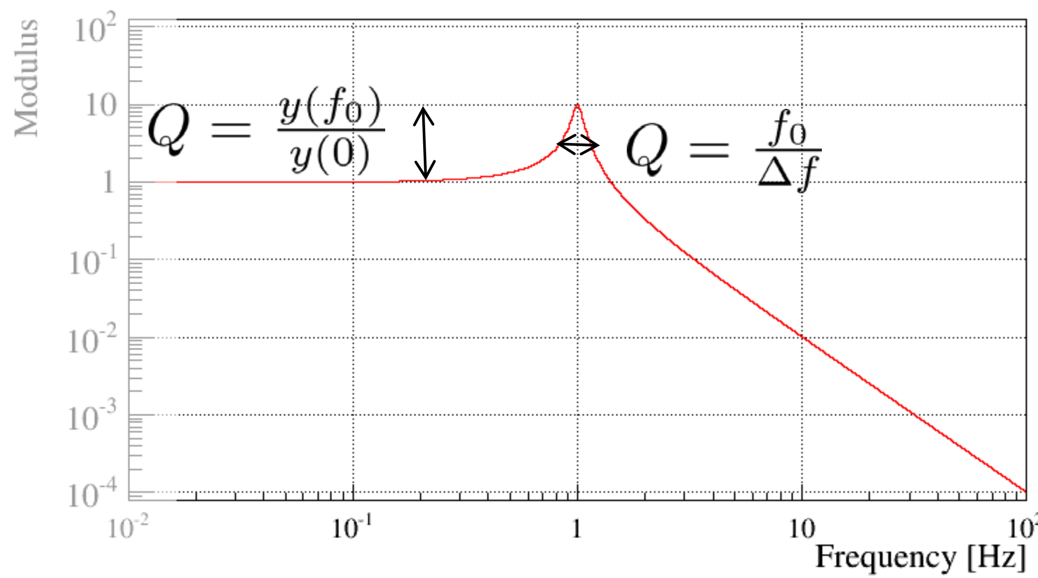
- Accelerometers or interferometer data
- Electromagnetic actuators
- Control loops

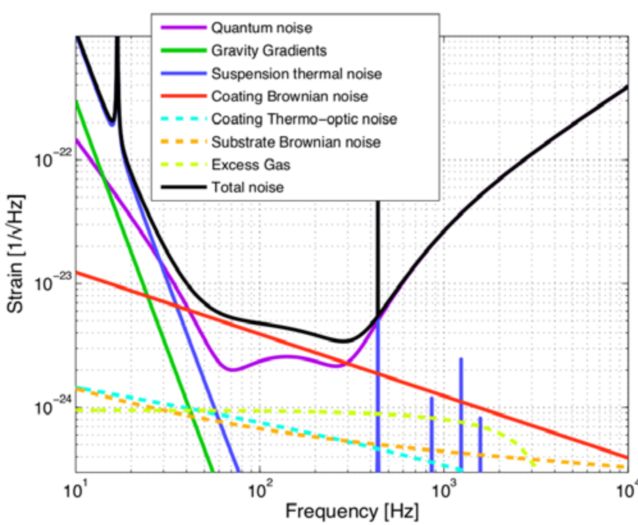
Thermal noise (pendulum and coating)

Microscopic thermal fluctuations

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





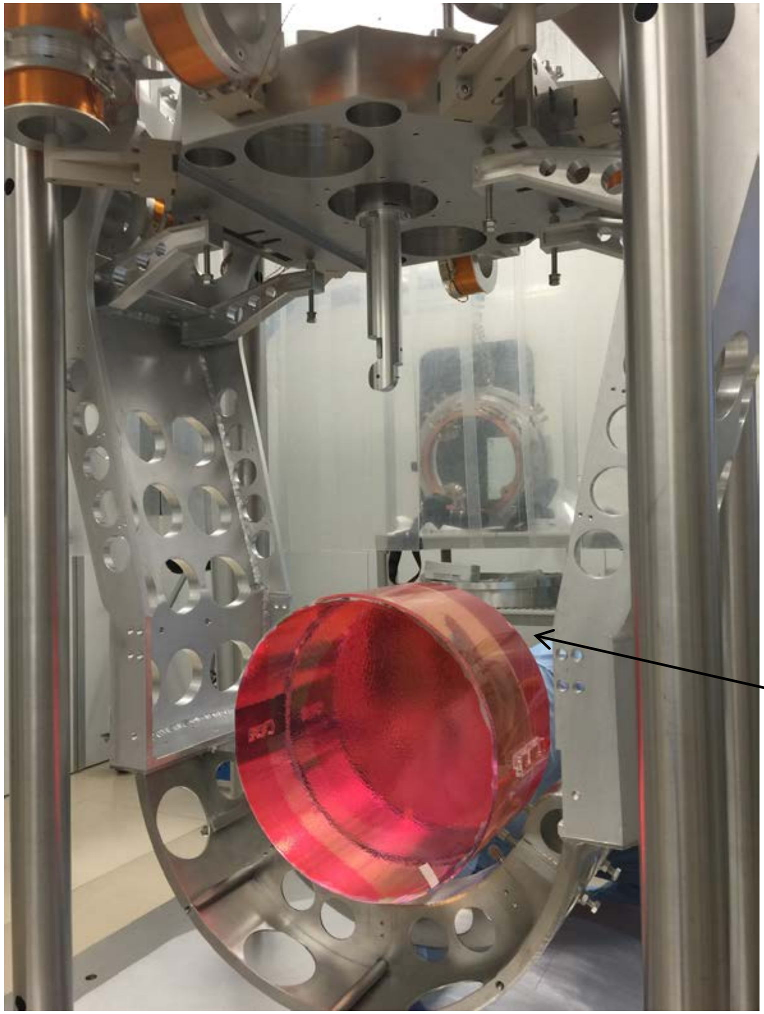


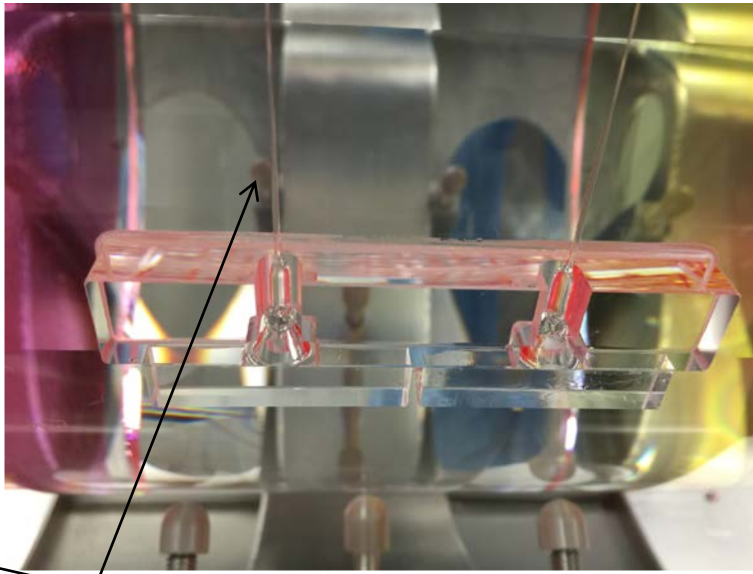
This noise directly modifies the positions of the mirror surfaces, and thus $\delta\Delta L$ and $h_{rec}(t)$!

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

Reduction of thermal noise: monolithic suspensions

- Increase the quality factor of the mirrors (with respect to steel wires)
- **Monolithic suspension** developed in labs in Perugia and Rome





Fused-silica fibers:
- Diameter of 400 µm
- length of 0.7 m
- Load stress: 800 Mpa

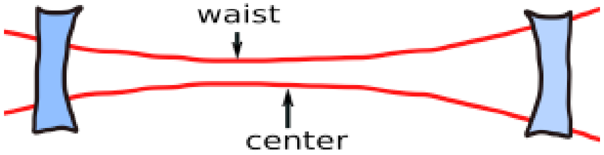
Reduction of thermal noise: mirror coating

40 kg mirrors of Advanced Virgo
35 cm diameter, 40 cm width
Suprasil fused silica

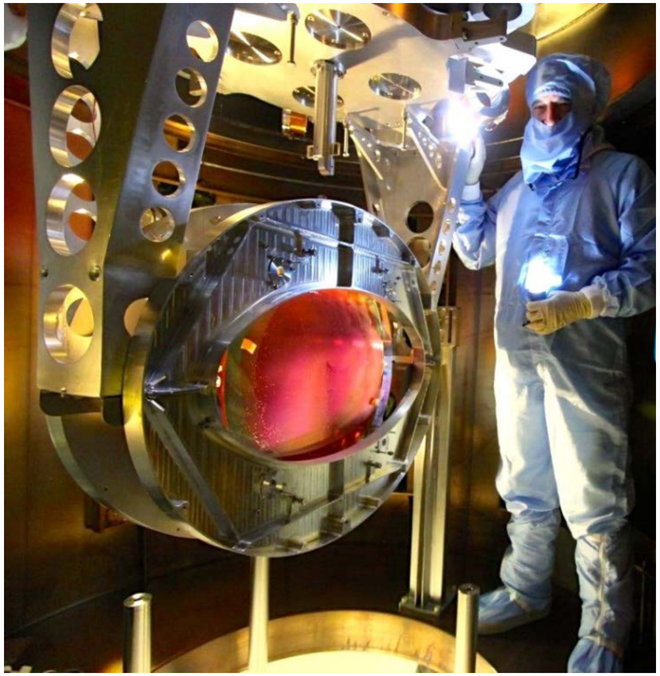
- Currently the main source of thermal noise
- Very high quality mirror coating developed in a lab close to Lyon (Laboratoire des Matériaux Avancés)
- R&D to improve mechanical properties of coating
- Cryogenics mirrors (at Kagra, future detectors)
  - other substrate
  - other coating
  - other wavelength

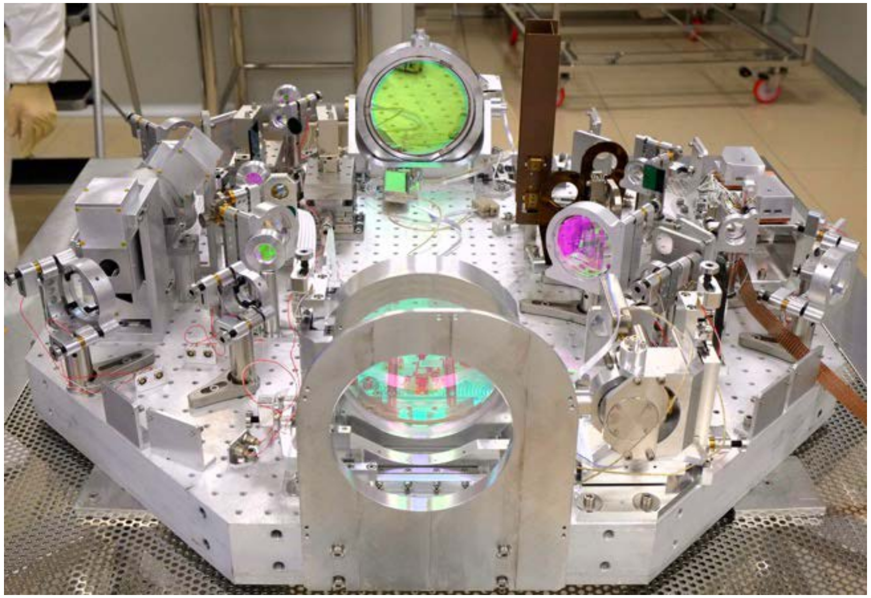
Thermal noise: coupling reduction

- 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 large mirrors (and heavier):
    > Advanced Virgo 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





Shot noise

Fluctuations of arrival times of photons (**quantum noise**)

Power received by the photodiode: P_t

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

Arrival time of single photons

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

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

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

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

$\rightarrow$ 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)

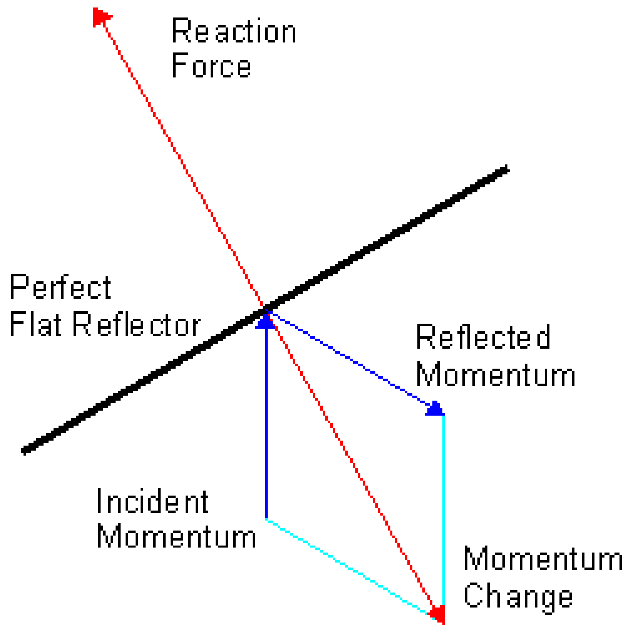
$\rightarrow h_{equivalent}\ \alpha\ 1/\sqrt{P_{in}}$

Radiation pressure noise

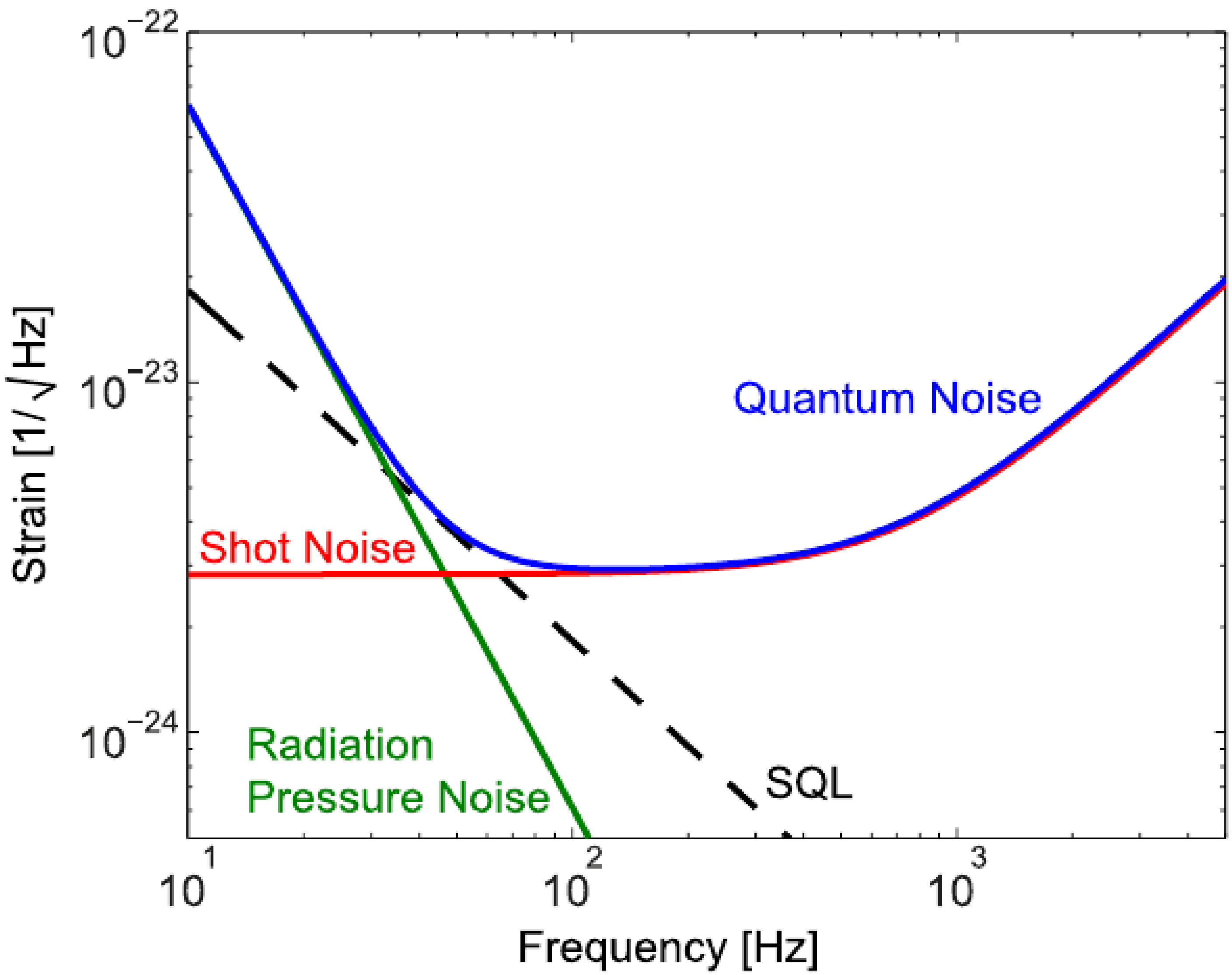
- Radiation pressure: transfer of photon's momentum to the reflective surface (recoil force)
- Radiation pressure noise: due to fluctuations of number of photons hitting the mirror surfaces > mirror motion noise
- Radiation pressure noise impact at low frequency:

  > Mirror motion filtered by pendulum mechanical response

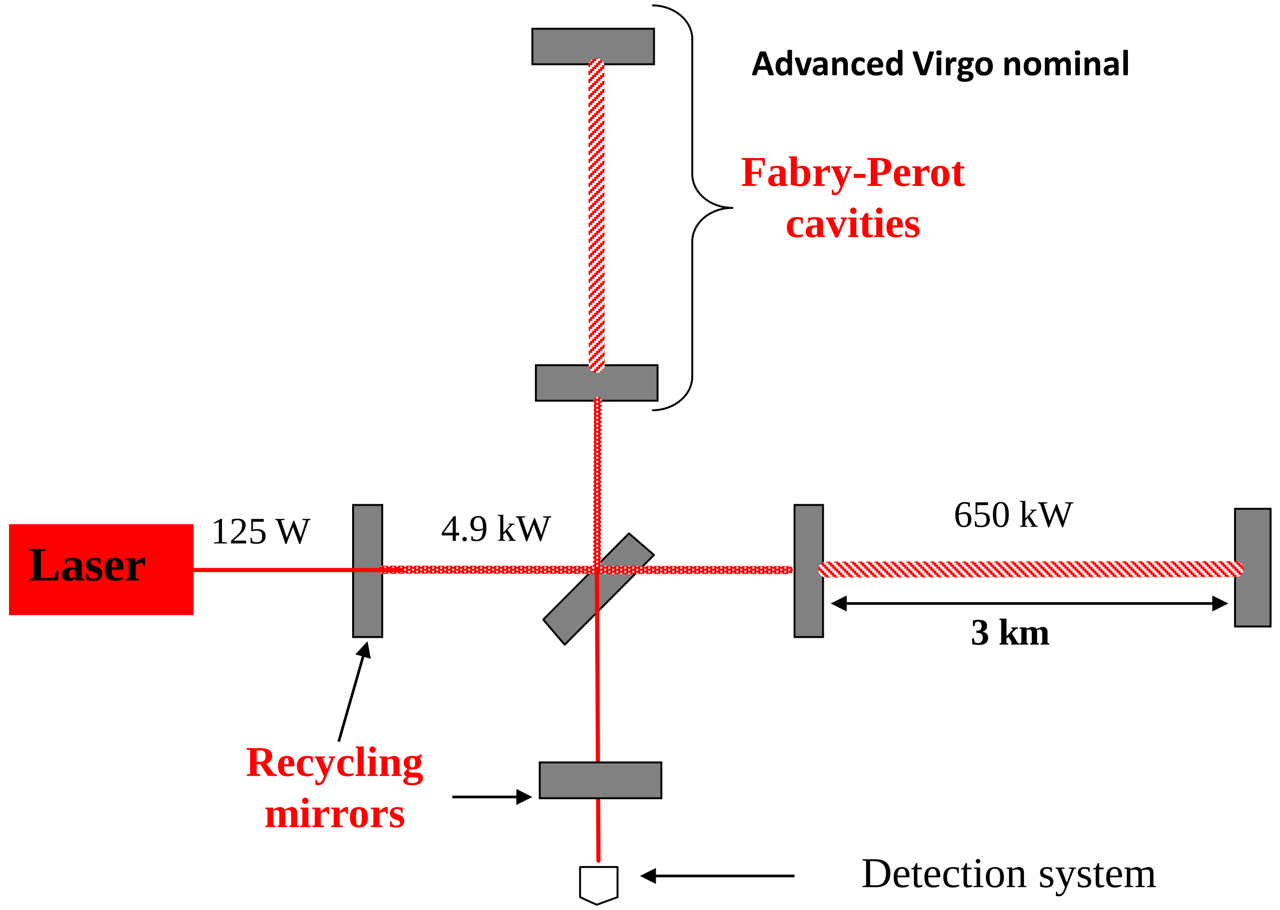
$\rightarrow h_{equivalent} \; \alpha \; \sqrt{P}_{in}$



Quantum noise in the sensitivity



Minimizing shot noise with optical configuration



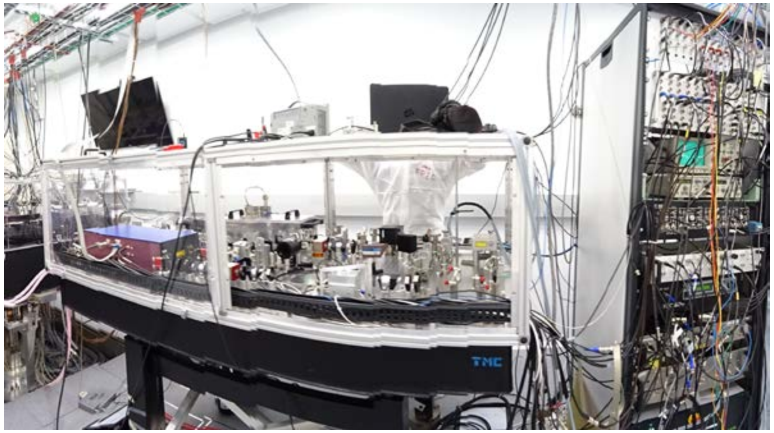
Reduction of shot noise: high power laser

Goal for AdV (nominal):

- continuous 200 W laser, stable monomode beam (TEM00), 1064 nm

Only 25W currently injected in Advanced Virgo

→ decrease shot noise contribution



But limited by side-effects:

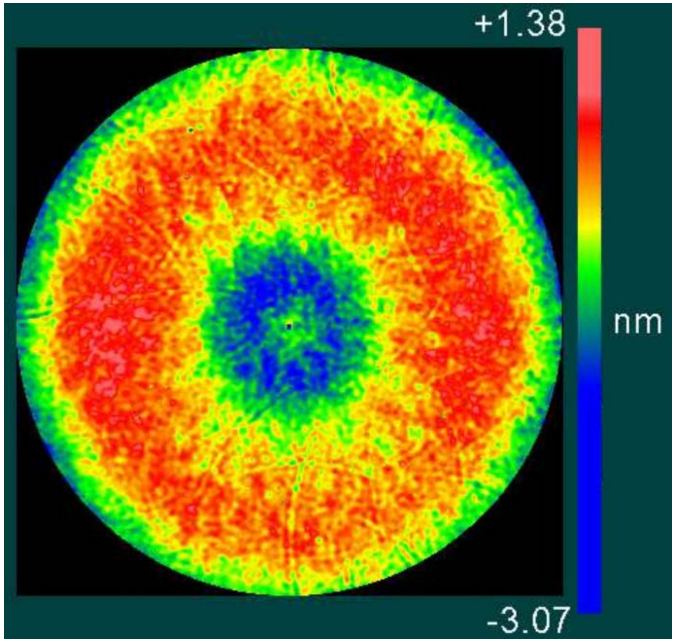
- **Radiation pressure**
  - Increase of radiation pressure noise
  - Cavities more difficult to control
  - Parametric instabilities: coupling of laser high order modes with mirrors mechanical modes

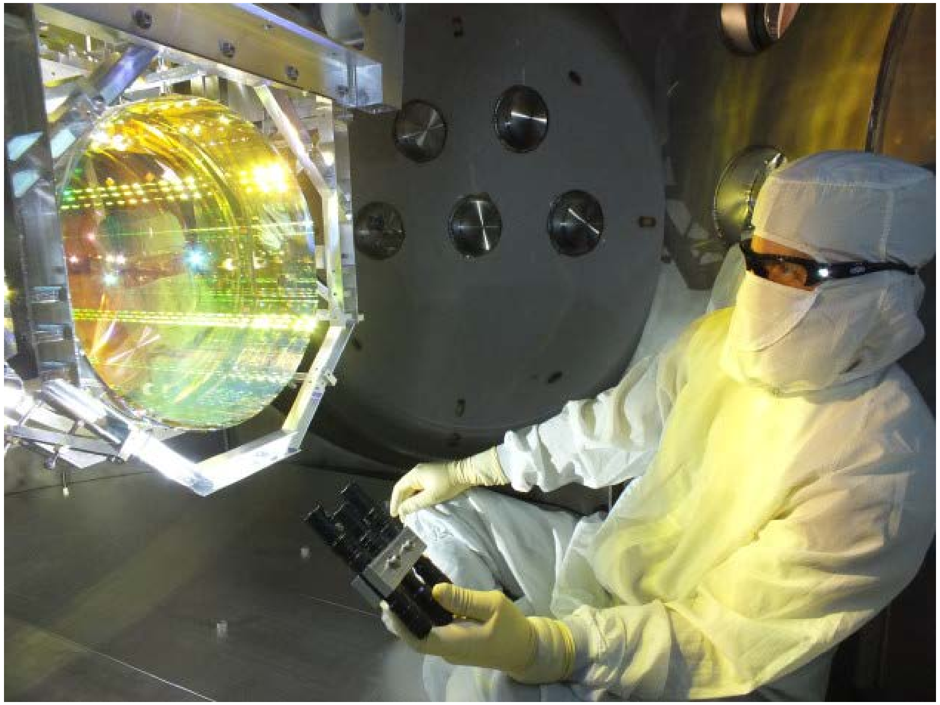
- **Thermal absorption in the mirrors (optical lensing)**
  → Need of thermal compensation system

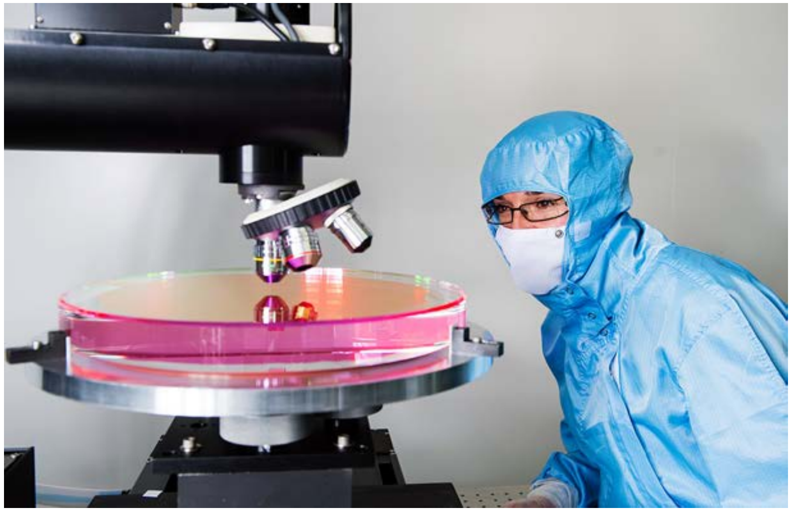
Avoid optical losses to not spoil high power → high quality mirrors

« 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)

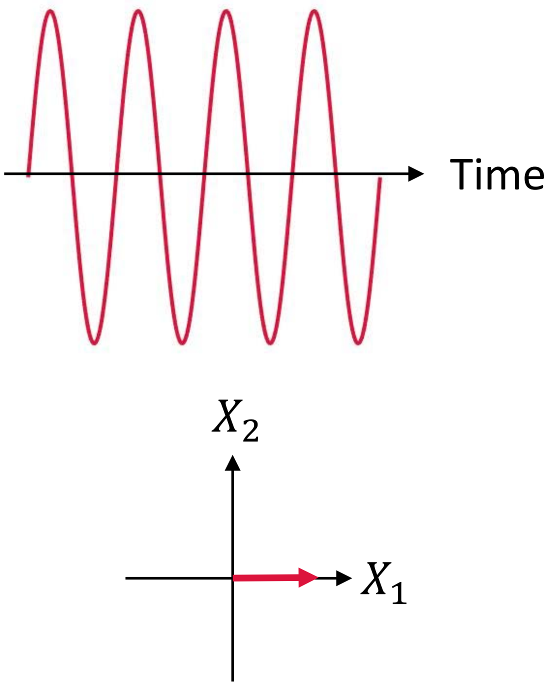




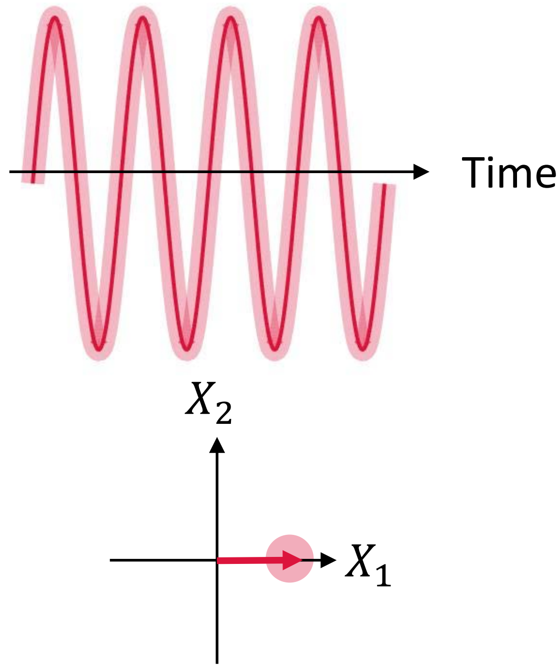


Optical field models

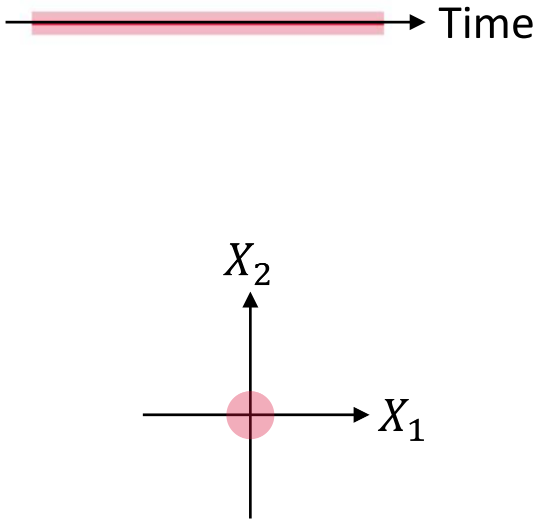
Classical picture



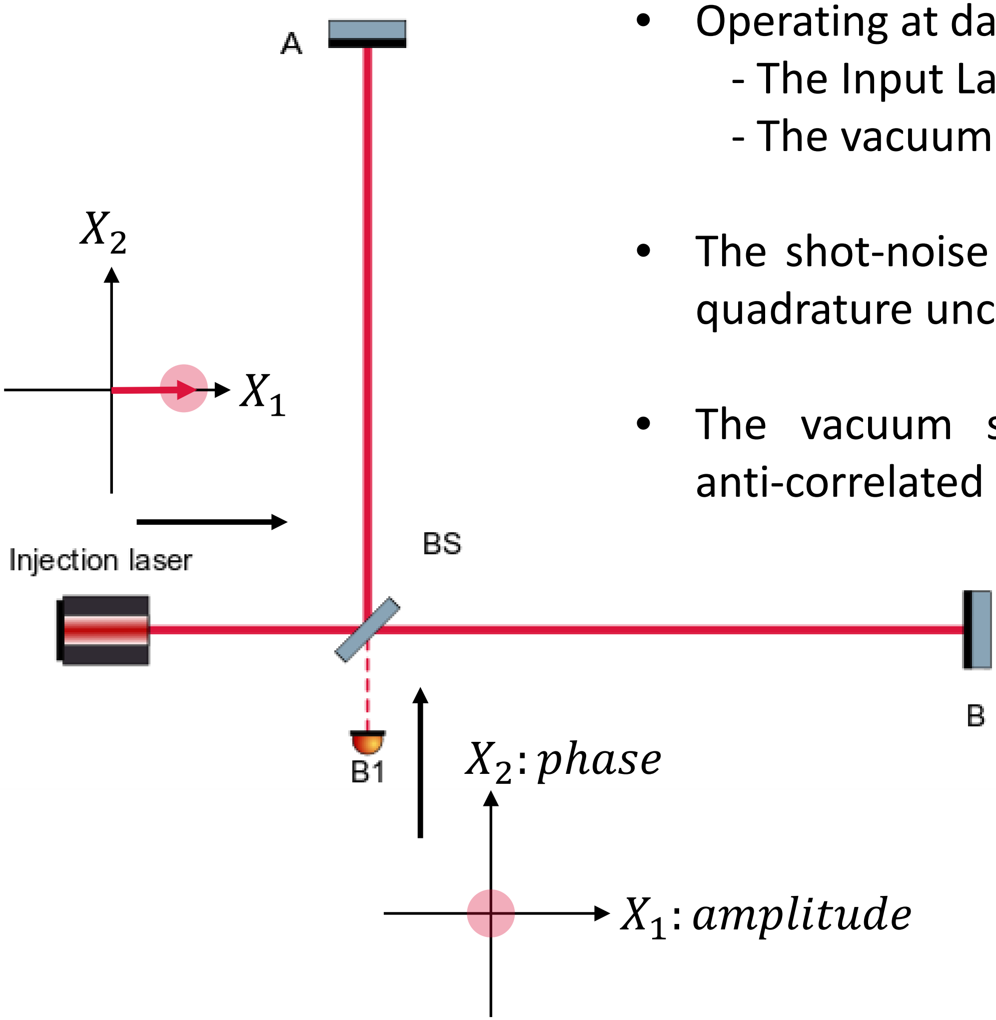
Coherent State



Vacuum State



Michelson interferometer at dark fringe and quantum noises

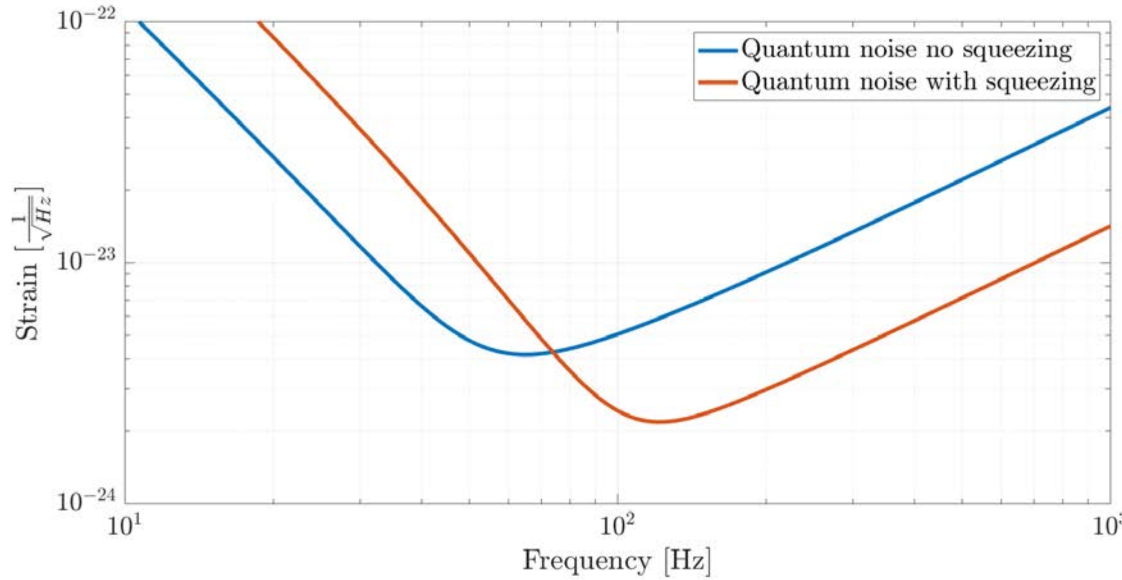


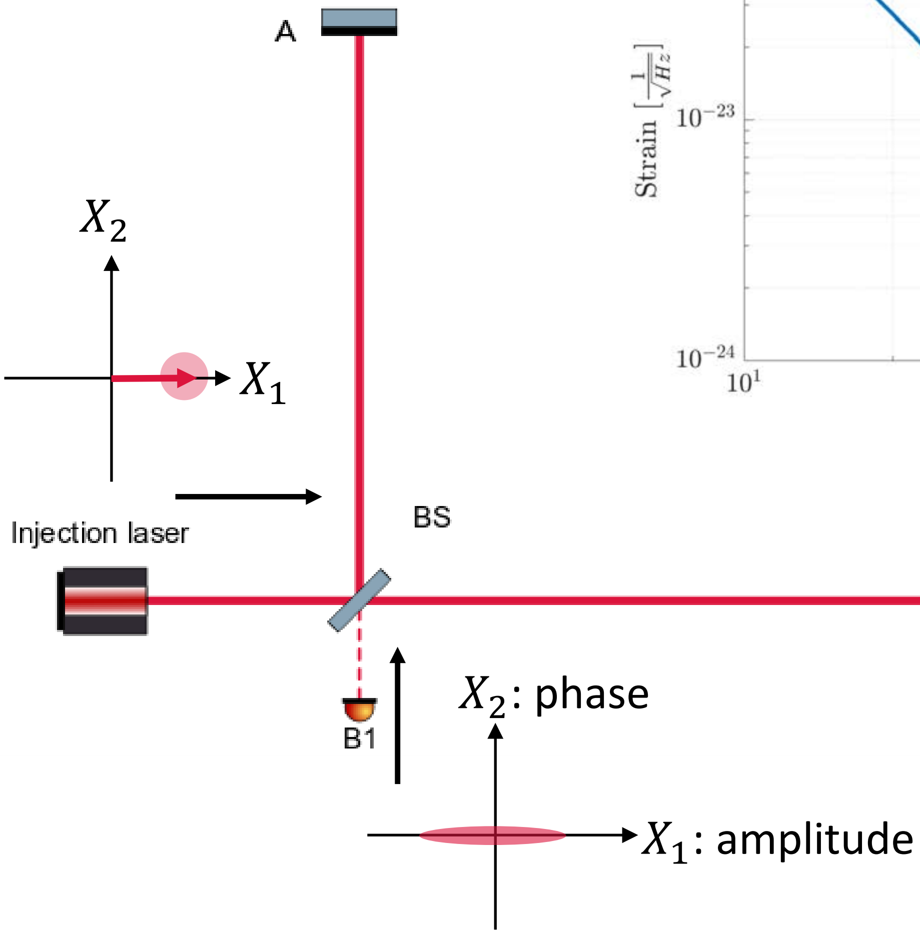
- Operating at dark-fringe :
  - The Input Laser is reflected back to the injection
  - The vacuum field is reflected to the detection

- The shot-noise arises from the vacuum state phase quadrature uncertainty

- The vacuum state amplitude-quadrature induces anti-correlated radiation-pressure in the arms

Reduction of shot noise: squeezing





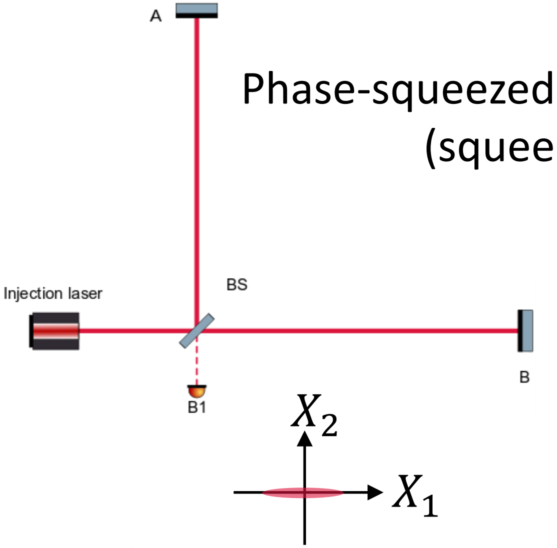
Inject a phase-squeezed vacuum state in the interferometer (squeezing)

Installed in Virgo and LIGO

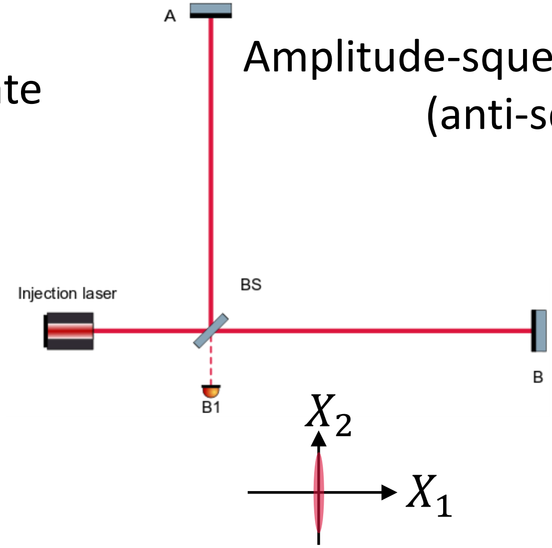
→ **Decrease shot noise**

But increase radiation pressure noise

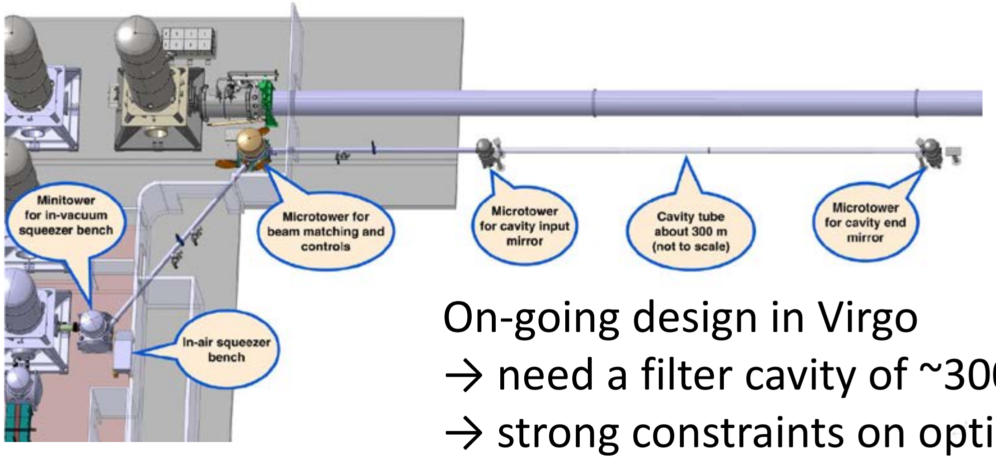
Reduction of quantum noise: frequency dependent squeezing



Phase-squeezed vacuum State
(squeezing)



Amplitude-squeezed vacuum State
(anti-squeezing)



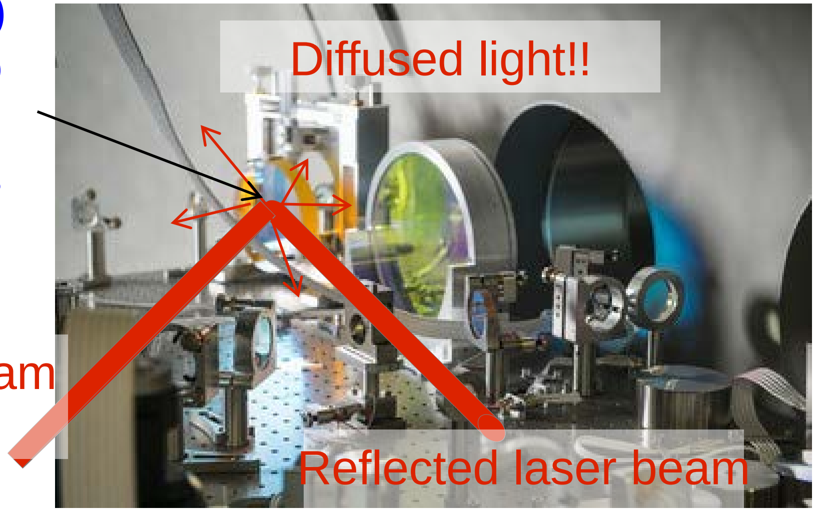
→ **Decrease shot noise AND radiation pressure noise**

On-going design in Virgo
→ need a filter cavity of ~300 m, with finesse ~10000
→ strong constraints on optical losses, beam matching and alignment, …
(suspended in vacuum optical benches)

Example of technical noise: Diffused light

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

Incident laser beam



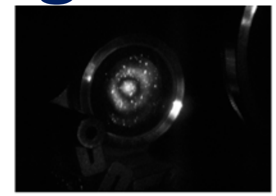
some photons of the diffused light gets recombined with the interferometer beam

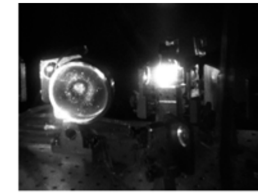
↓

phase noise

↓

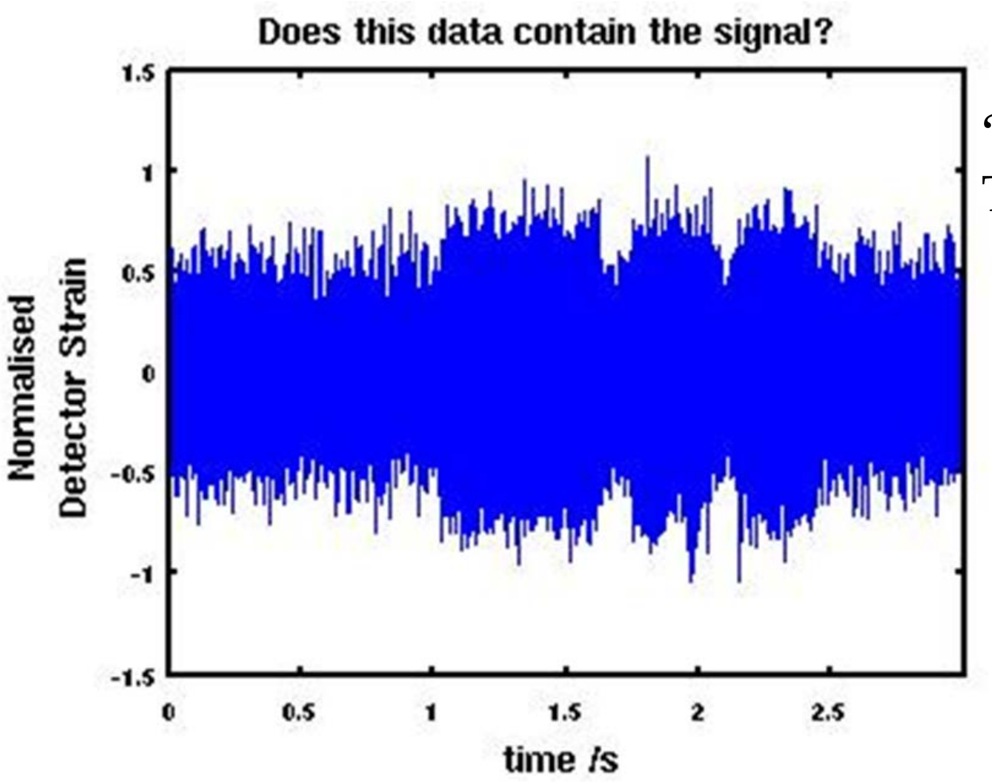
extra power fluctuations
(imprint of the optical element vibrations)





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

Noises are not always stationary



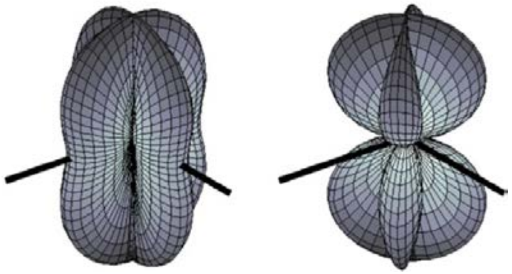
"Glitches" are impulses of noise.
They might look like a transient GW signal

- 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

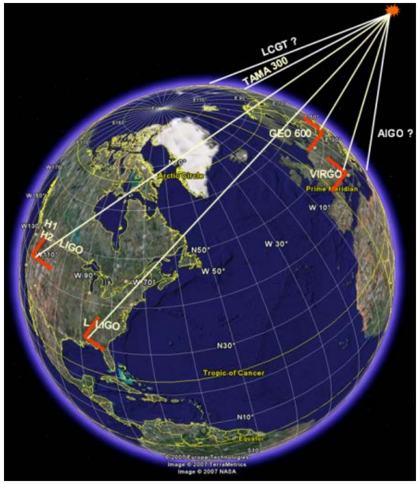
From interferometers to a « gravitational-wave telescope »

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):

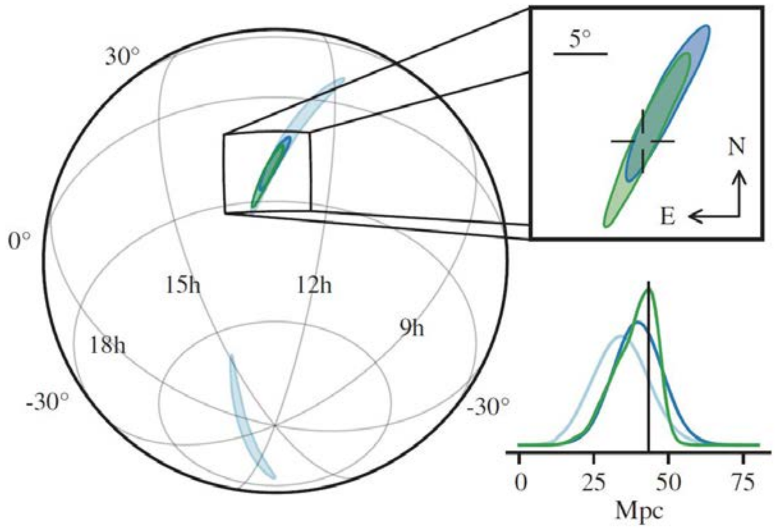
    → **allow to point towards the source position in the sky**



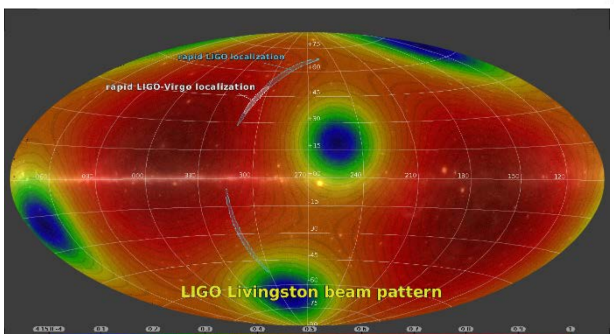
- Looking for rare and transient signals: can be hidden in detector noise

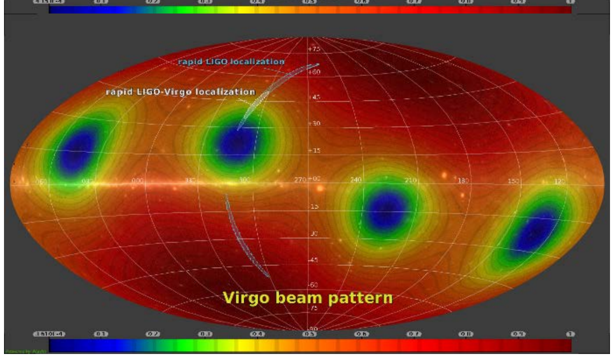
  → requires observation in coincidence between at least 2 detectors
- Since 2007, Virgo and LIGO share their data and analyze them jointly
- KAGRA will be soon joining the network

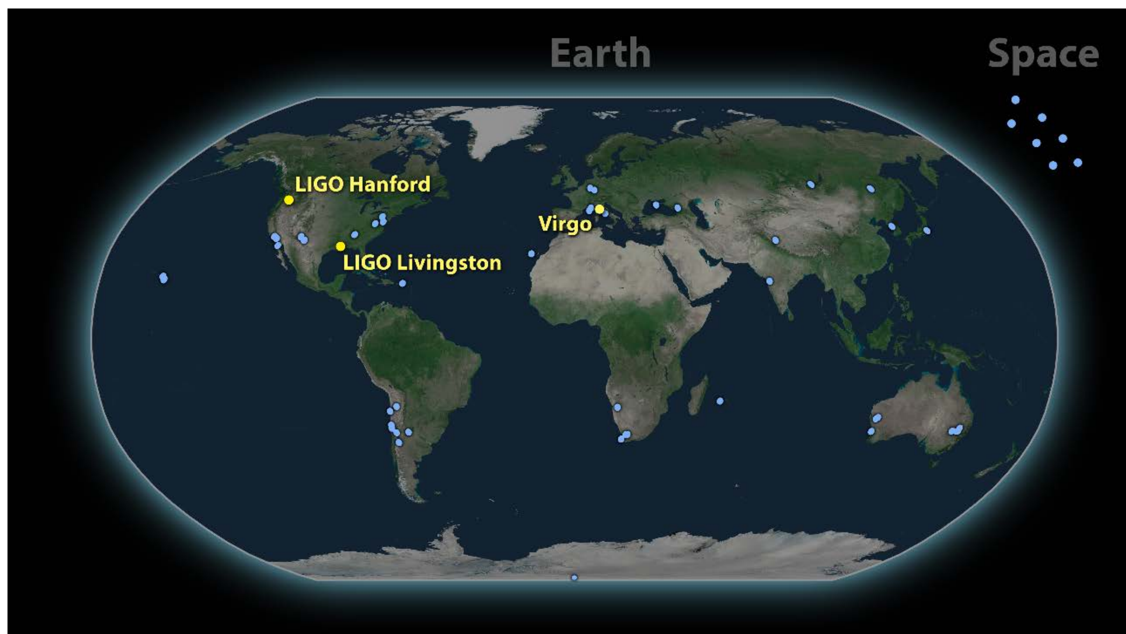
GW170817 Localization & Follow-up



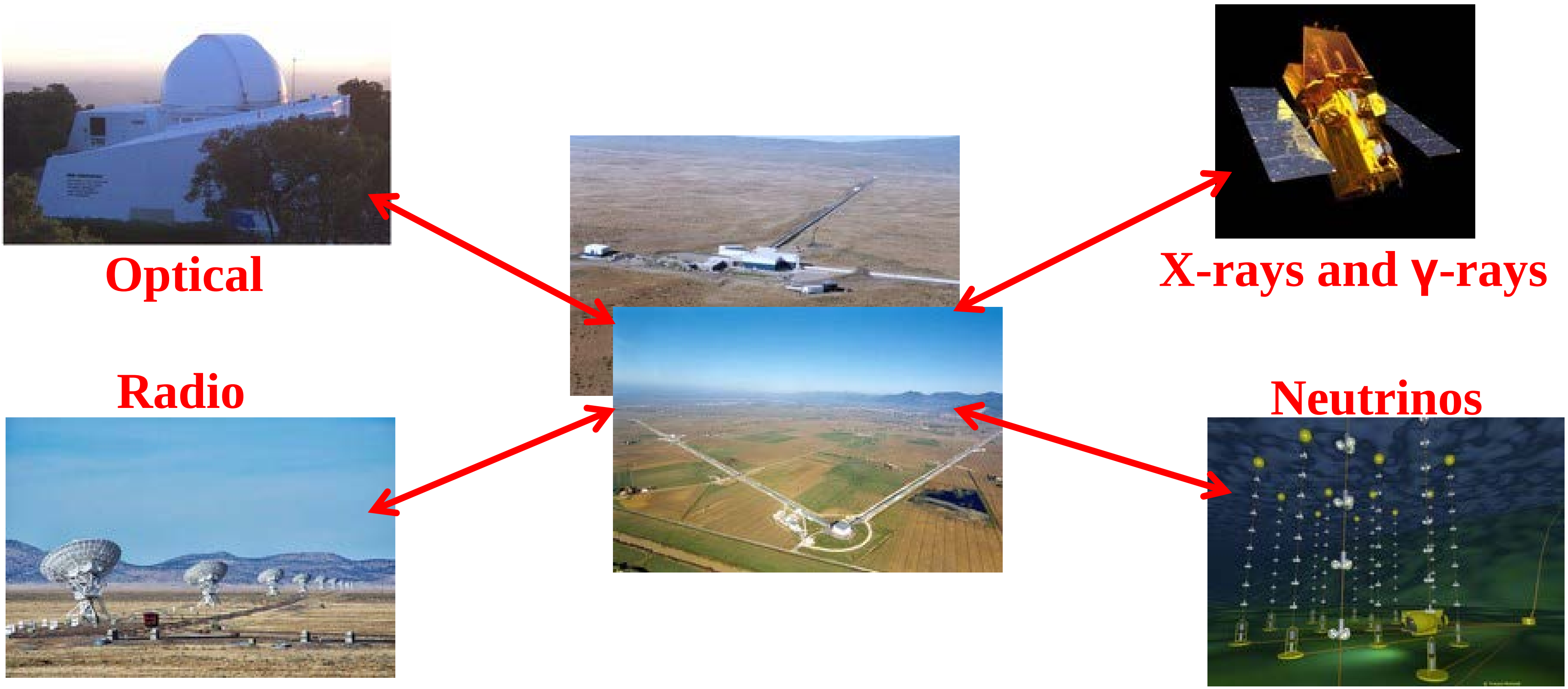
- ❑ Most precisely localized GW source so far
  - ➢ Rapid HL localization: 190 deg^2
  - ➢ Rapid HLV localization: 31 deg^2
  - ➢ Final HLV localization: 28 deg^2
  - ➢ 3D localization: 380 Mpc^3
- ❑ Triggered multi-wavelength follow-up observations
  - ➢ Identification of NGC4993 as host galaxy







Alerts for multi-messenger observations



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

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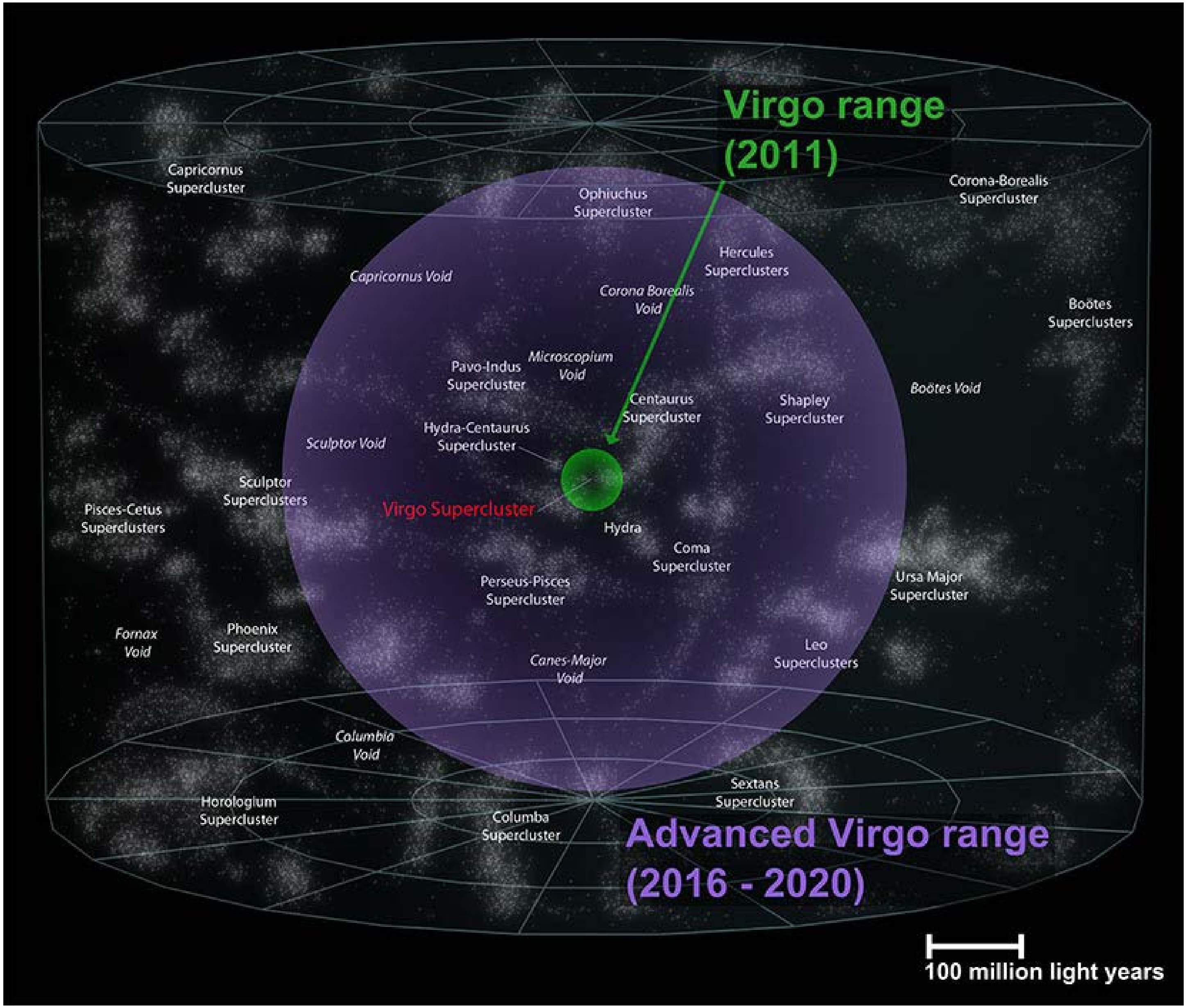
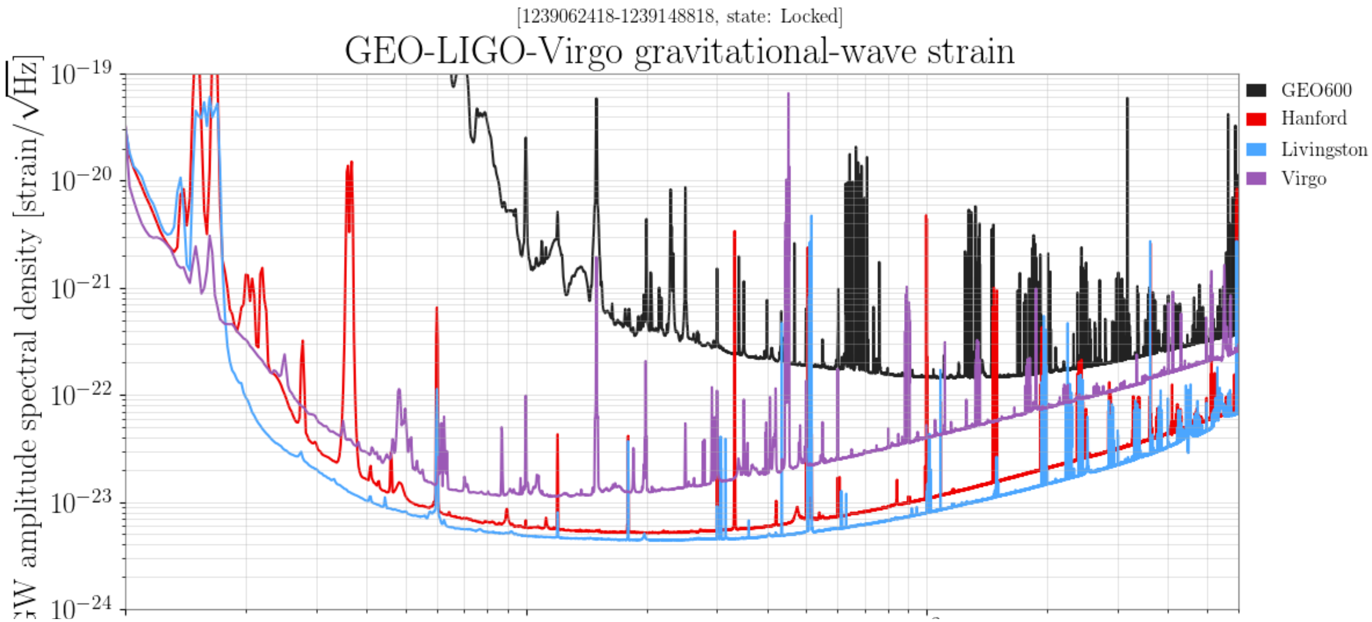
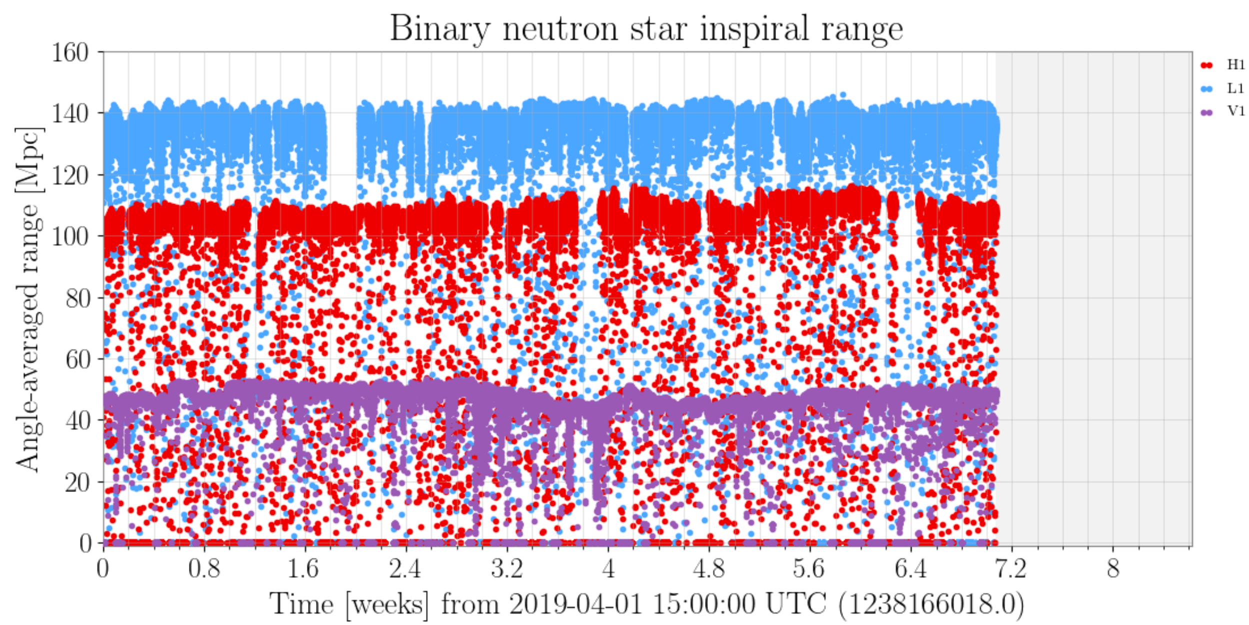
- What are gravitational waves?
- How can we detect gravitational waves?
- How do terrestrial interferometers work?
- **Prospectives for interferometers and other detectors**

From initial to advanced detectors



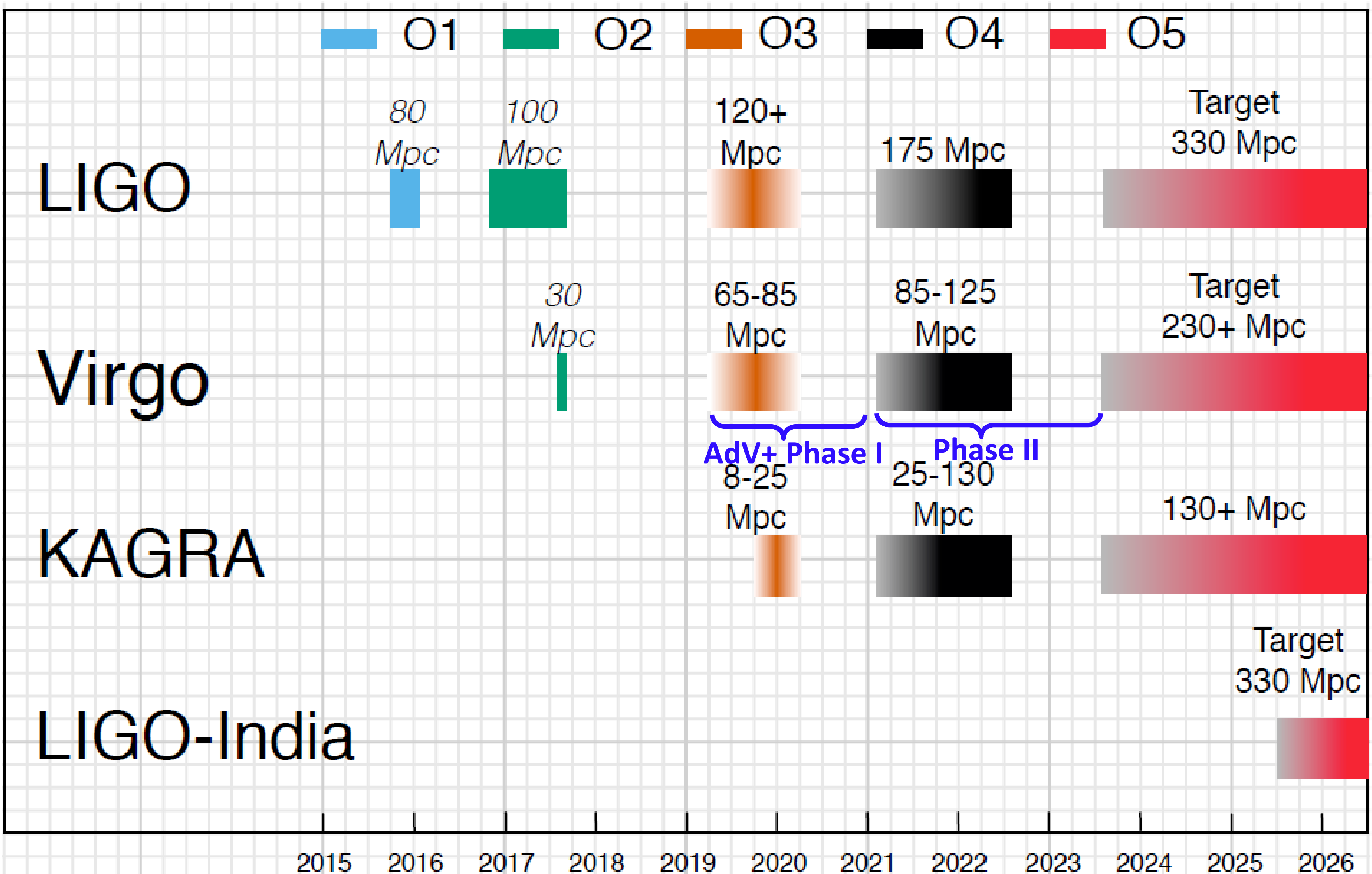
Current interferometers sensitivity





BNS Range:
Distance at which a neutron star binary coalescence with averaged orientation over the sky can be seen with signal-to-noise ratio of 8

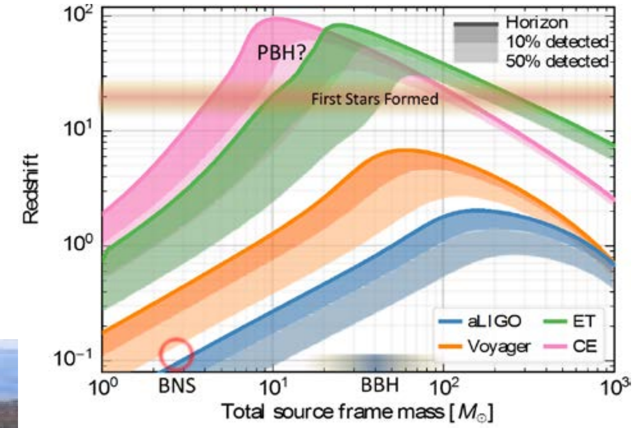
Future observing runs

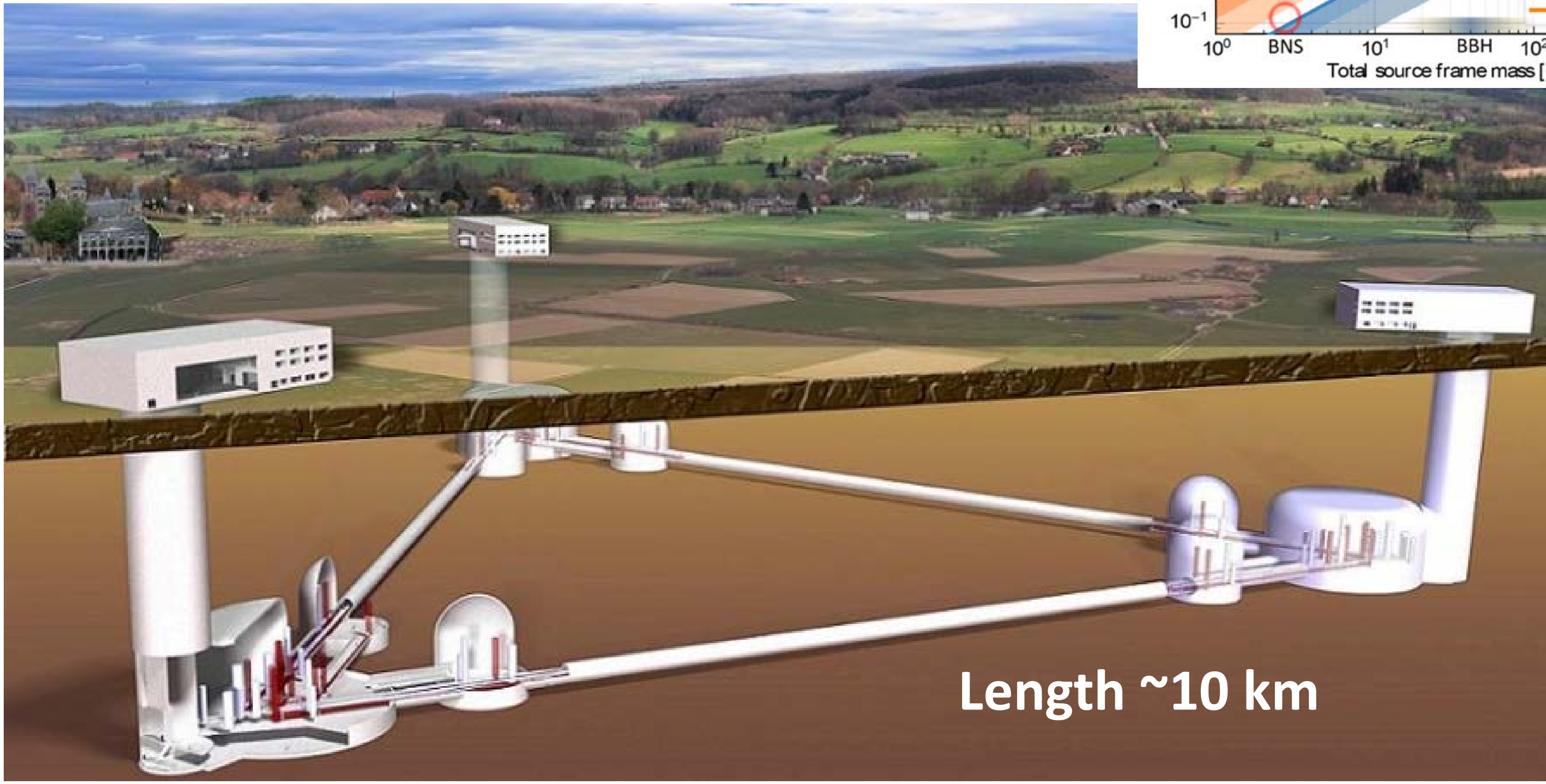


Einstein Telescope

- Third generation interferometer: gain another factor 10 in sensitivity and enlarge bandwidth
- Located underground, ~10 km arms
- Thermal noise reduction with cryogenics
- Xylophone detector
- In operation after 2030?

Could probe CBC signals from a large fraction of the Universe



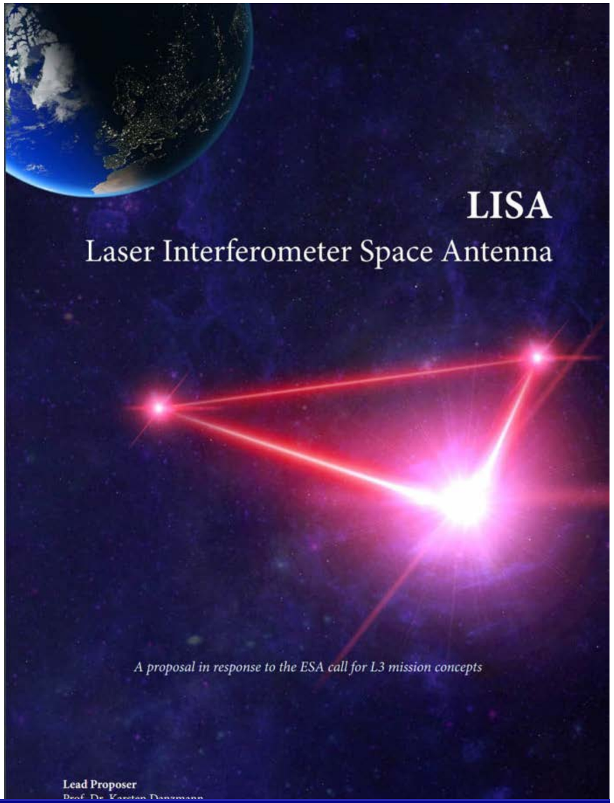


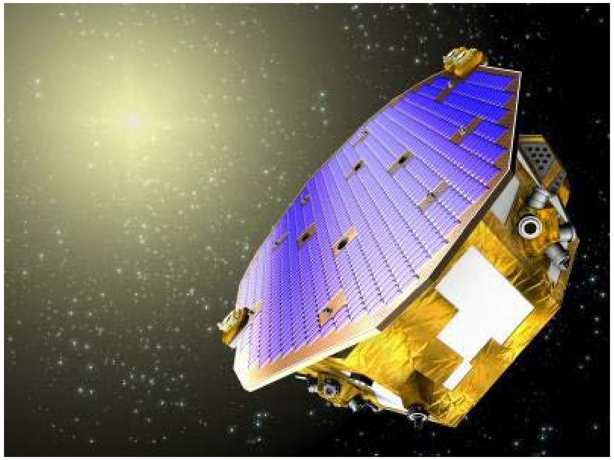
Spatial interferometer: LISA

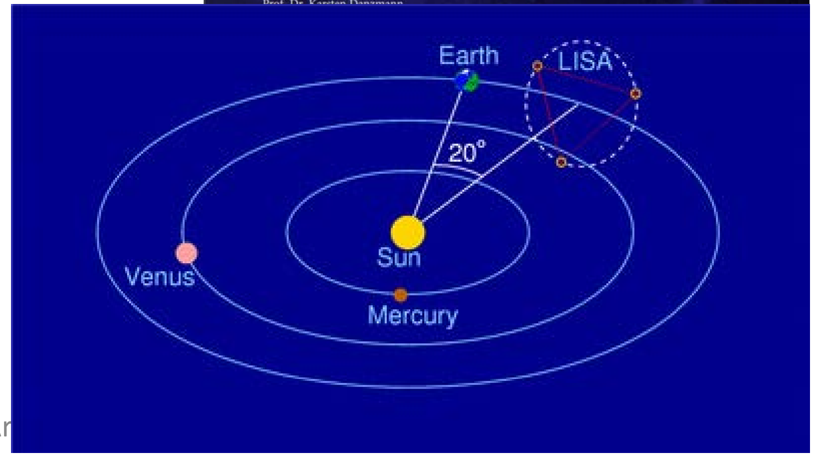
- **Bandwidth: 0.1 mHz to 1 Hz (2.5 million km arm length)**
- Launch of LISA in the years 2030?

  → operation for 5 to 10 years

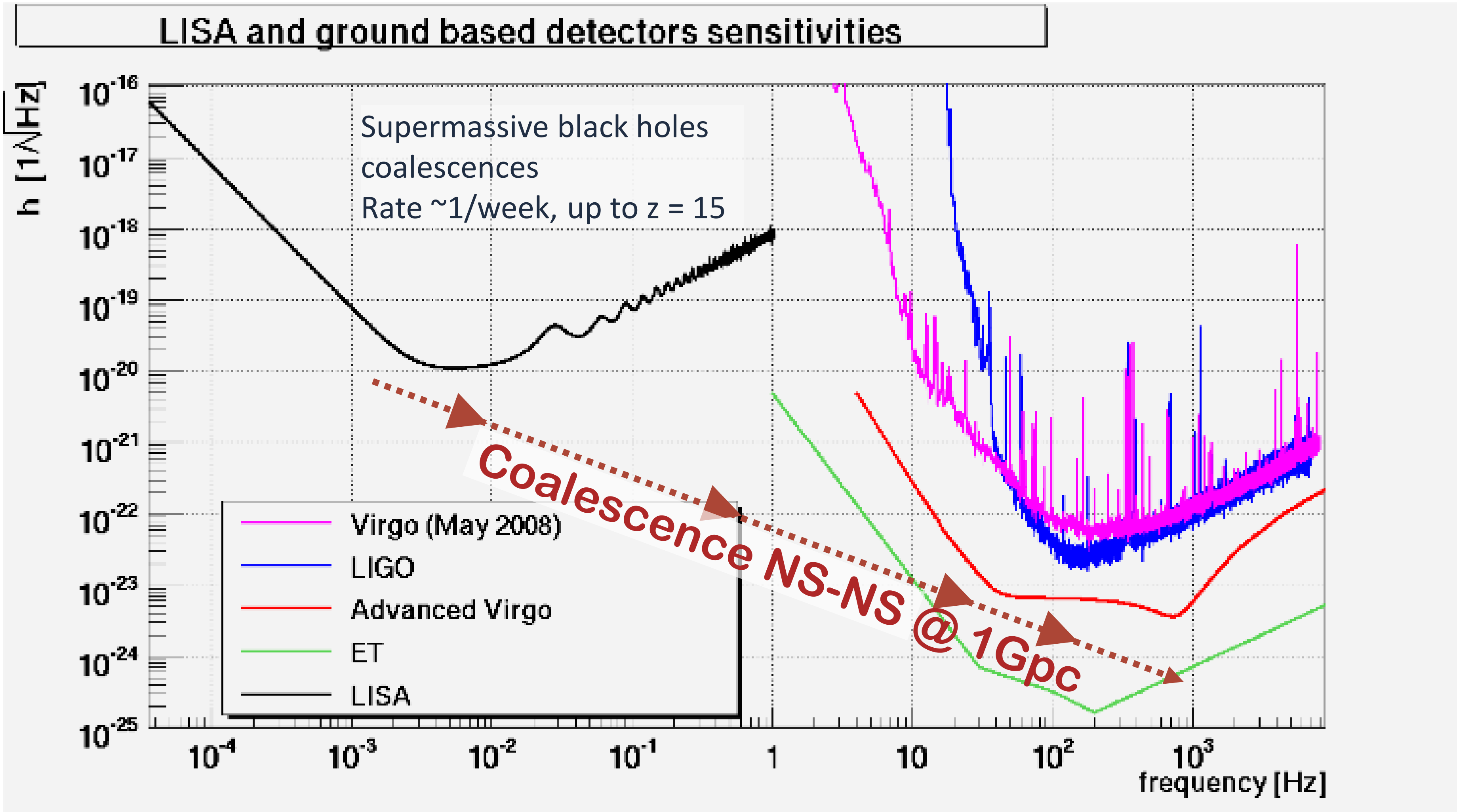
- Successful intermediate step: LISA Pathfinder
  - ➢ launched end 2015
  - ➢ test of free-fall masses
  - ➢ validation of differential motion measurements



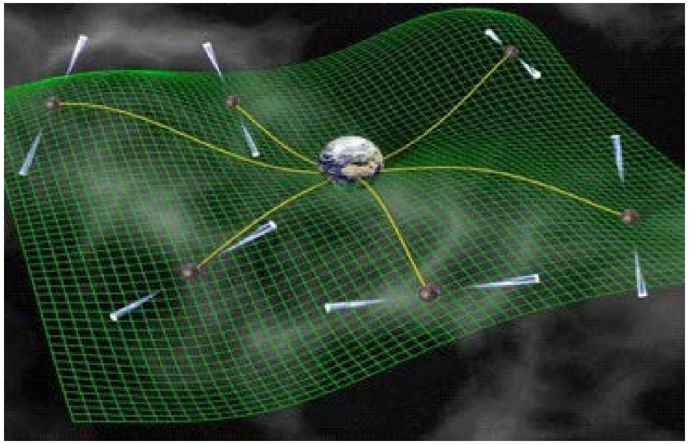




ET and LISA performances



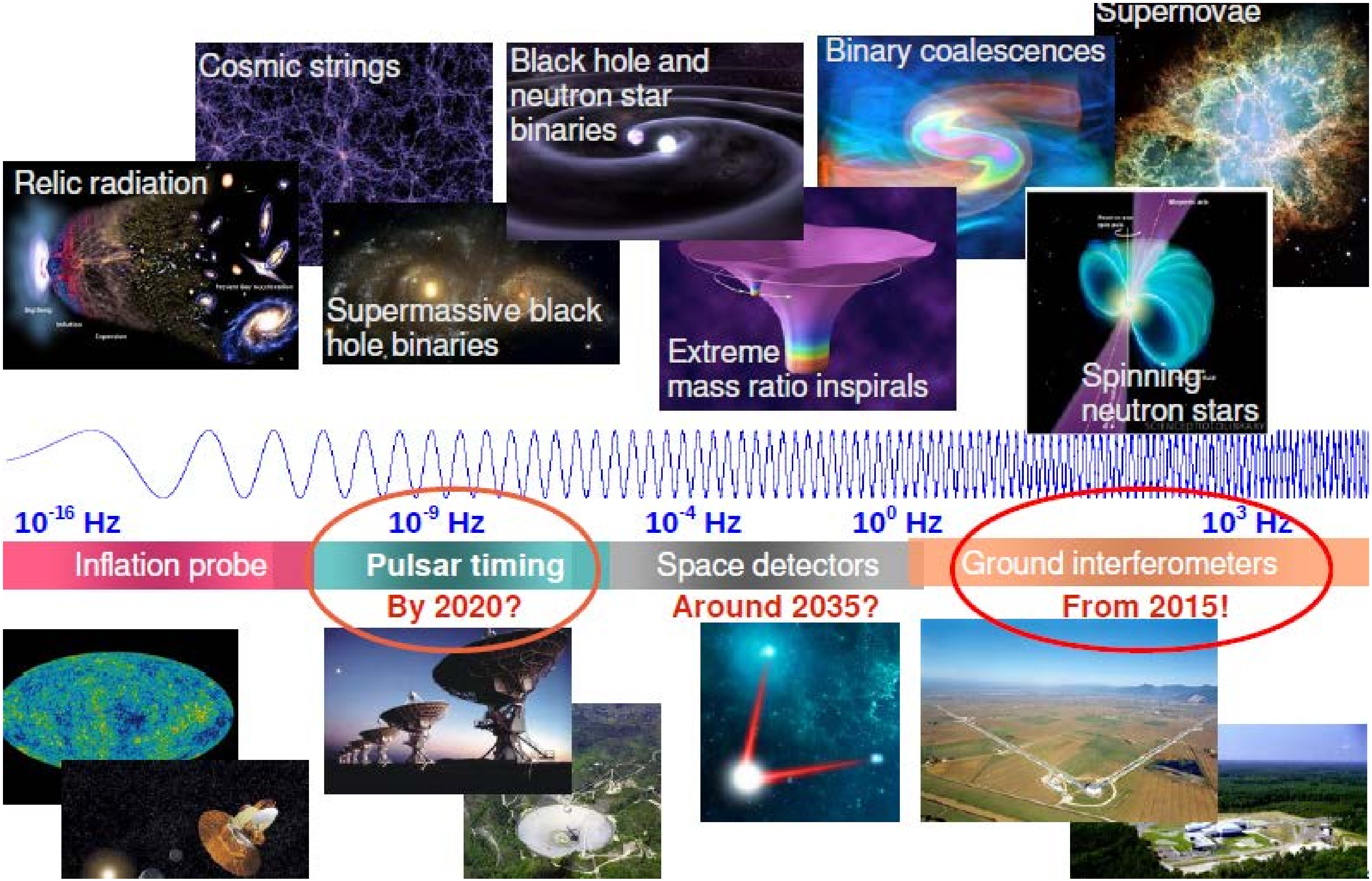
Pulsars timing arrays



- **Bandwidth: 1 nHz to 1000 nHz**
- Observation of 20 ms pulsars in radio
  - GW cause the time of arrival of the pulses to vary by a few tens of nanoseconds over their wavelength
  - Weekly sampling over 5 years

- International network
  - Parkes PTA
  - North American NanoHertz Gravitationnal Wave Observatory
  - European PTA
- **First detections expected in the coming years!**

A large GW spectrum to be studied…



SPARES

Noise characterized in frequency domain

Discrete Fourier Transform (DFT)

$$s(n) \longrightarrow S(k) = A(k)e^{j\Phi(k)}$$

Sampled signal — Fourier spectrum

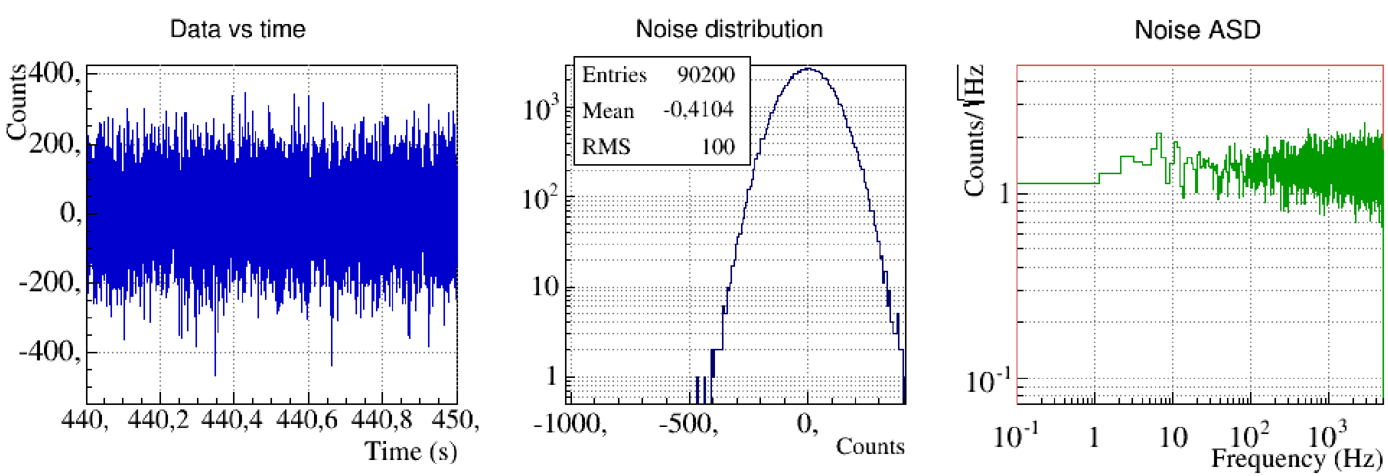
→ Noise characterised by the fluctuations of its Fourier spectrum

→ $D(k)$ 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

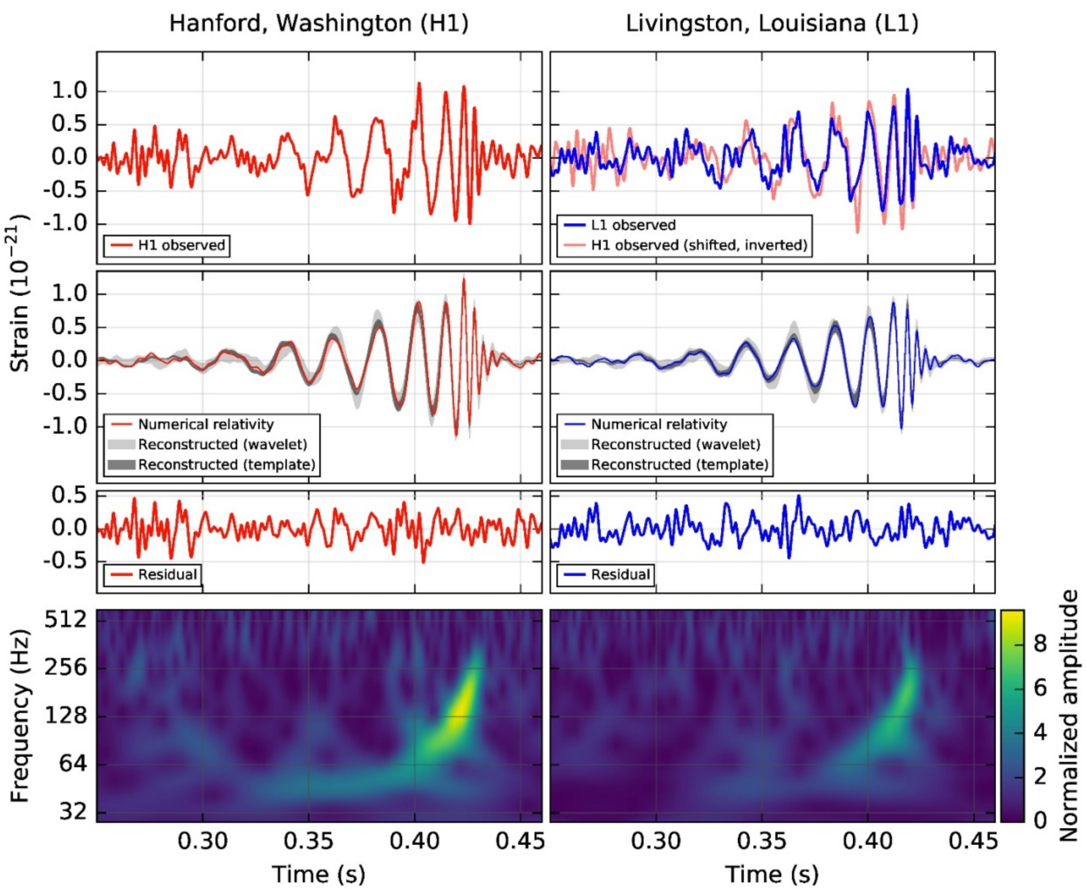


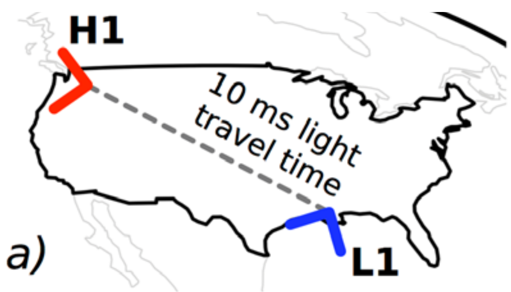
On Feb 11 2016, the LIGO and Virgo collaborations have announced the detection of

GW150914

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

The first direct detection of GW

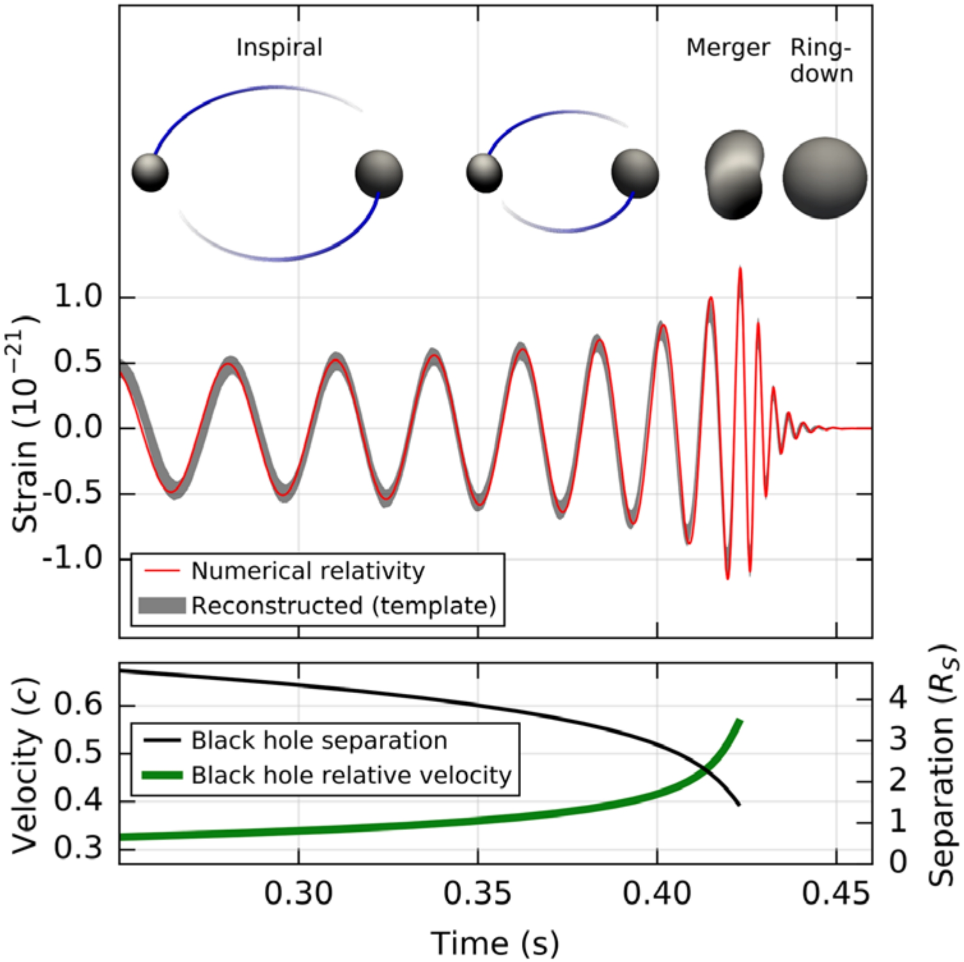


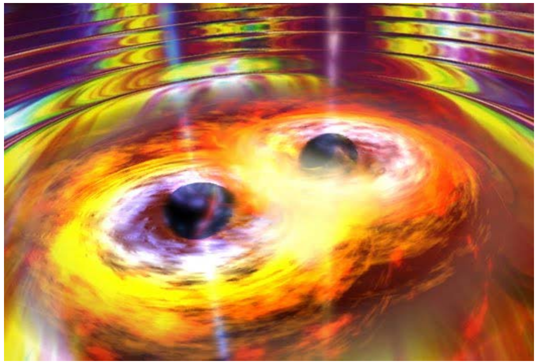


- Same signal in the 2 LIGO detectors, with a time difference = 7 ms
- Signal evolution = Typical signature of a coalescence
- Signal seen from 30 Hz:
  - Duration ~200 ms
  - Number of cycle ~10
- Signal-to-noise ratio: 24
False alarm rate: <1 in 200,000 years
- Signal extracted from data matches the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

  36 et 29 solar masses

First observation of binary black hole merger (GW150914)





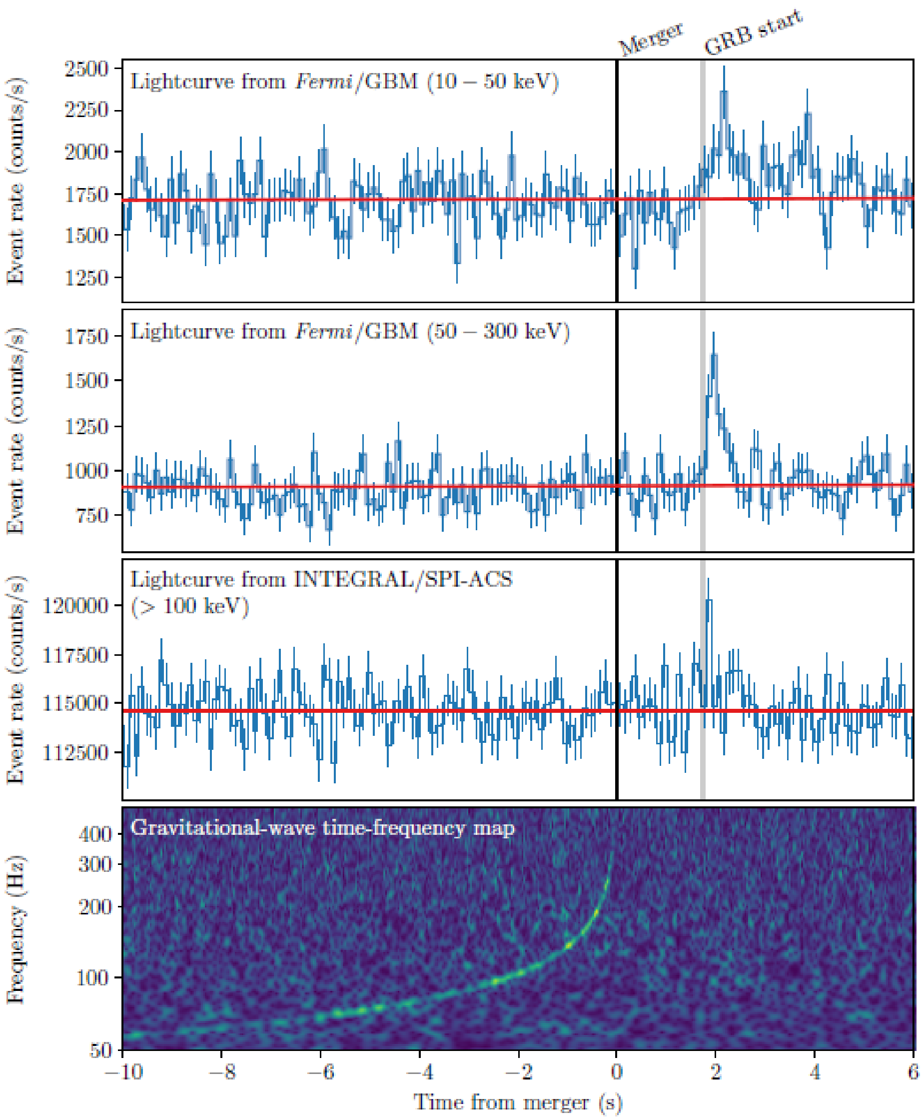
Distance ~1.3×10^9 light-years (z~0.1)

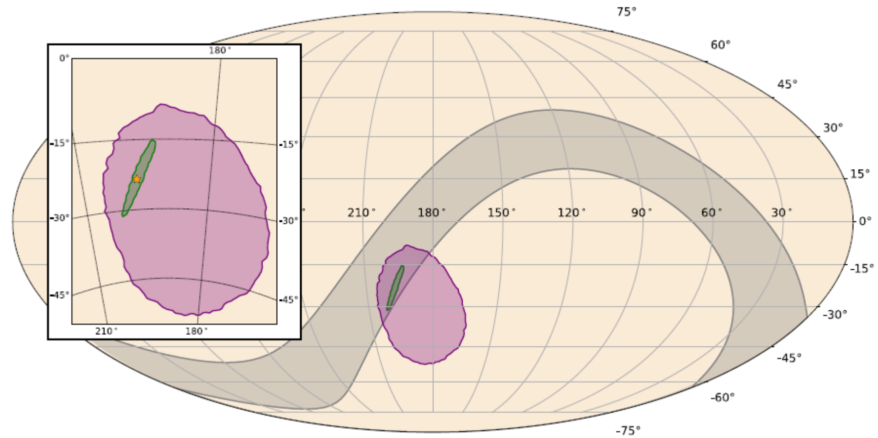
Initial black holes (total mass ~65 $M_\odot$)
~36 $M_\odot$ and 29 $M_\odot$
peak speed of BH's: ~0.6 c

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

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

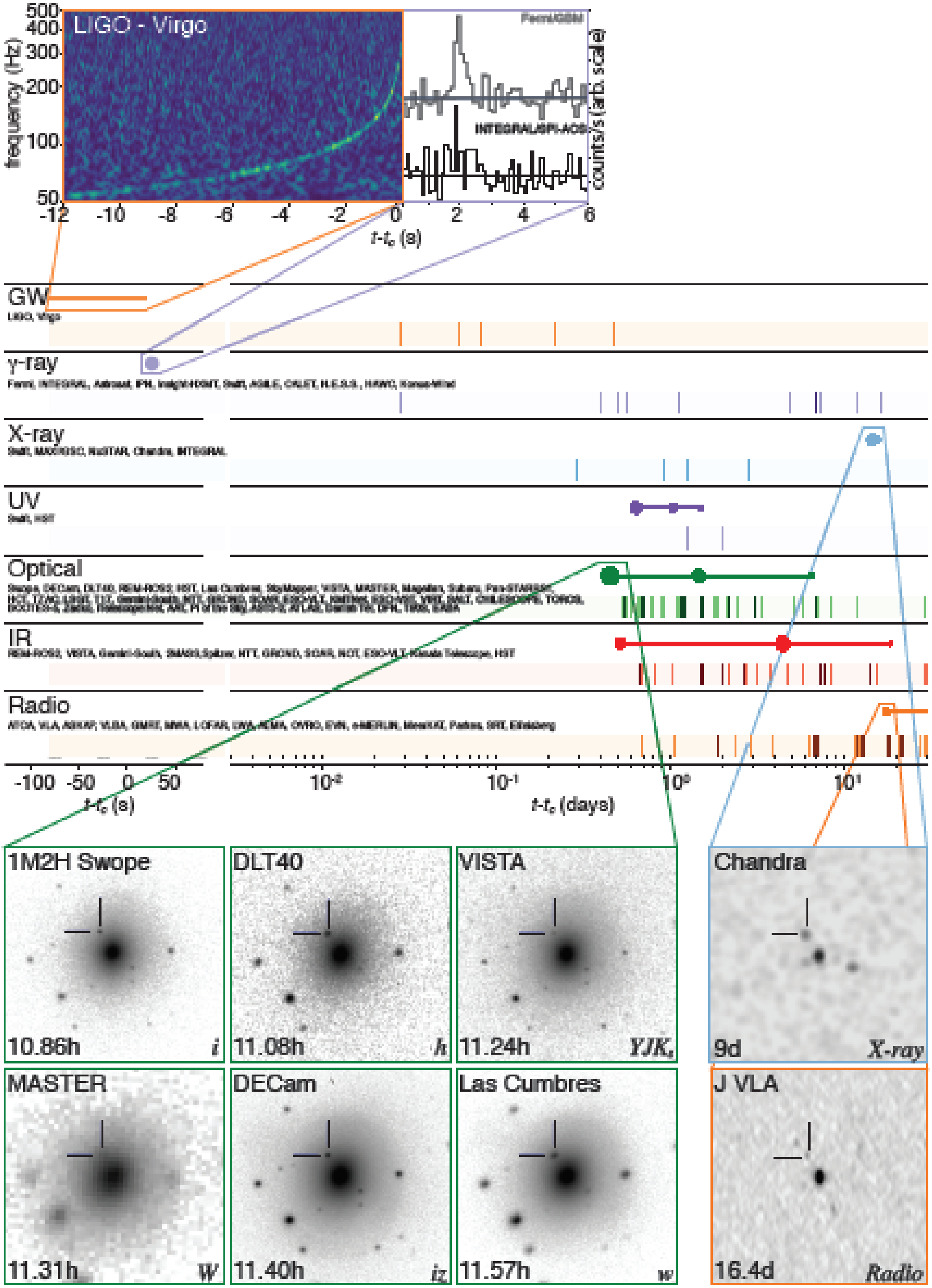
GRB 170817A





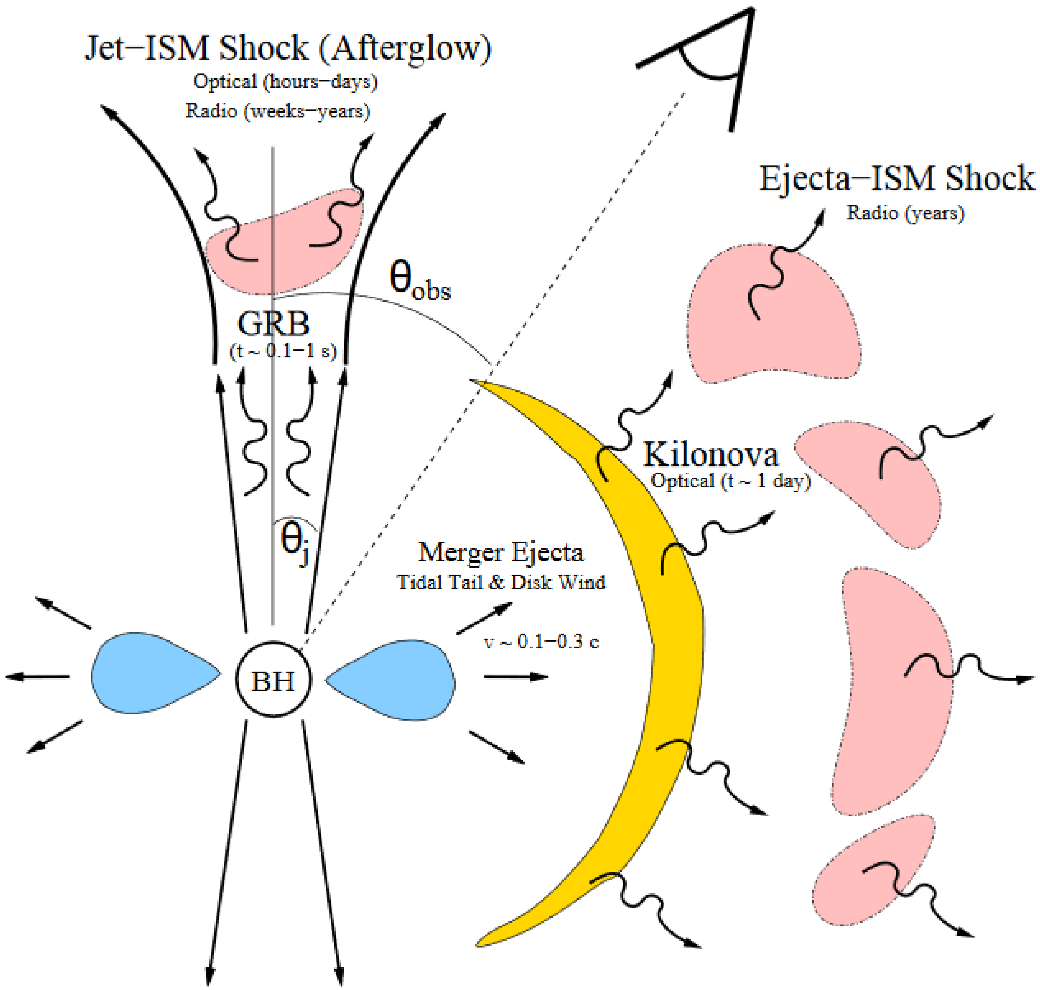
- GRB 170817A detected by Fermi-GBM and INTEGRAL SPI-ACS
  - ~ 1.7s after merger
  - Closest short GRB with a known distance
  - 2-6 orders of magnitude less energetic than other bursts with measured redshift
- Probability of temporal and spatial coincidence occurring by chance is $5 \cdot 10^{-8}$
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

AT2017gfo



- Kilonova/macronova observed in UV/optical/near IR
- X-ray and radio afterglow

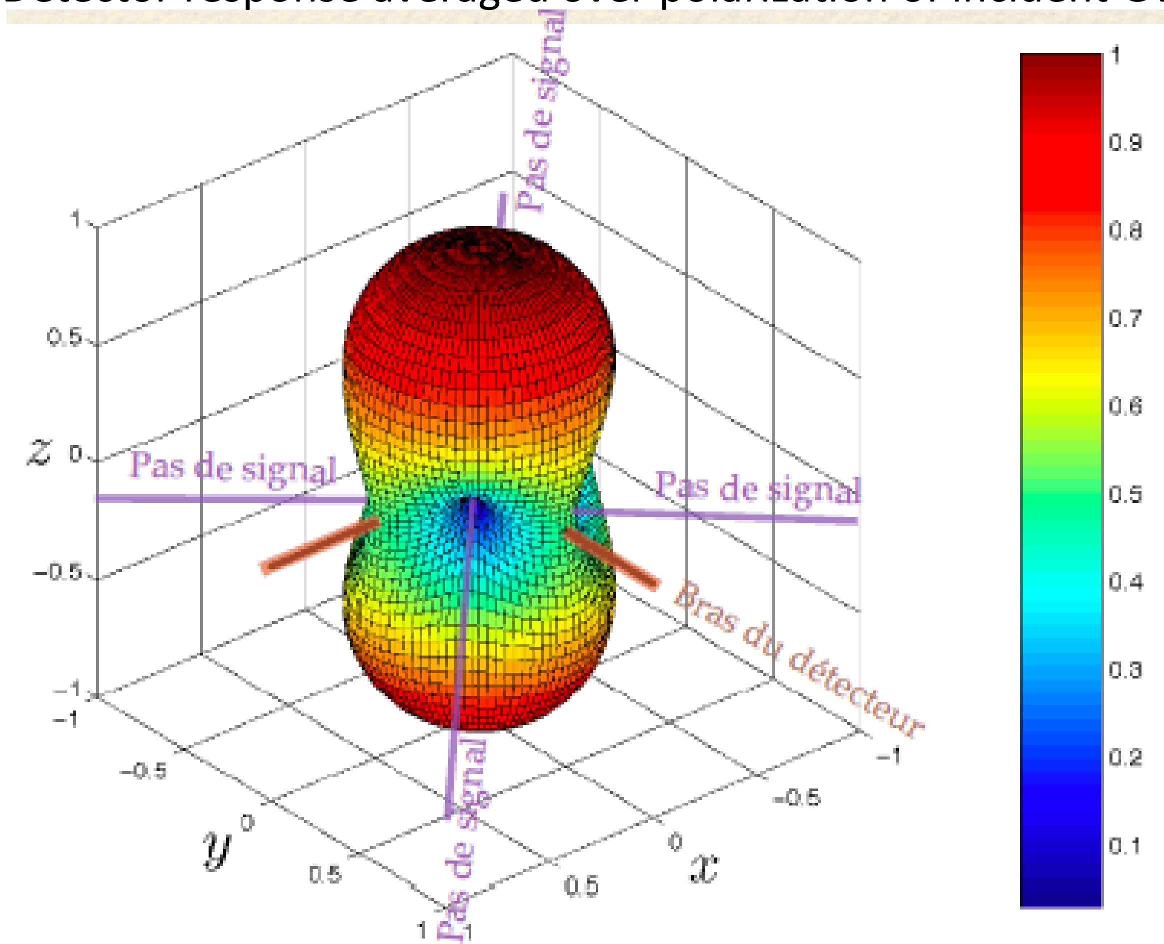
Expected Electromagnetic Counterparts



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

Angular response of the interferometer

Detector response averaged over polarization of incident GW



- Interferometers have a broad angular response: behave more like an antenna than a traditional telescope
- A few blind spots

Output Mode Cleaner

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