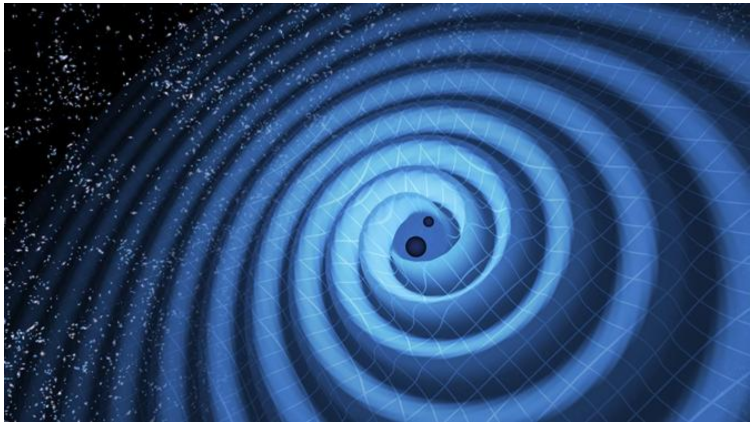
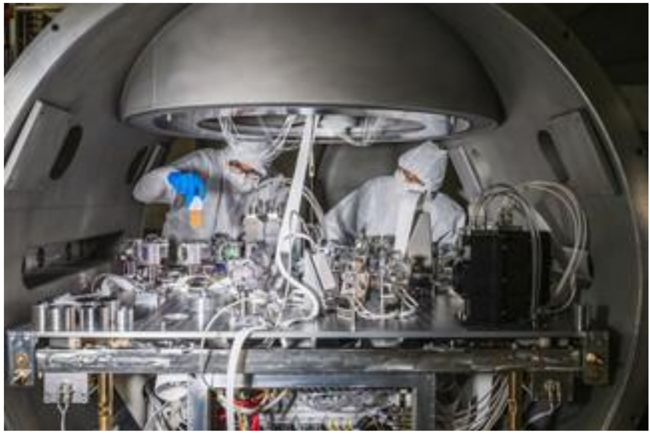




Gravitational Waves:

The instrumental challenges of the detection

Romain Gouaty
LAPP – Annecy
GraSPA summer school





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- **Principles:**
  - Effect of GW on free-fall masses
  - Basic detection principle overview

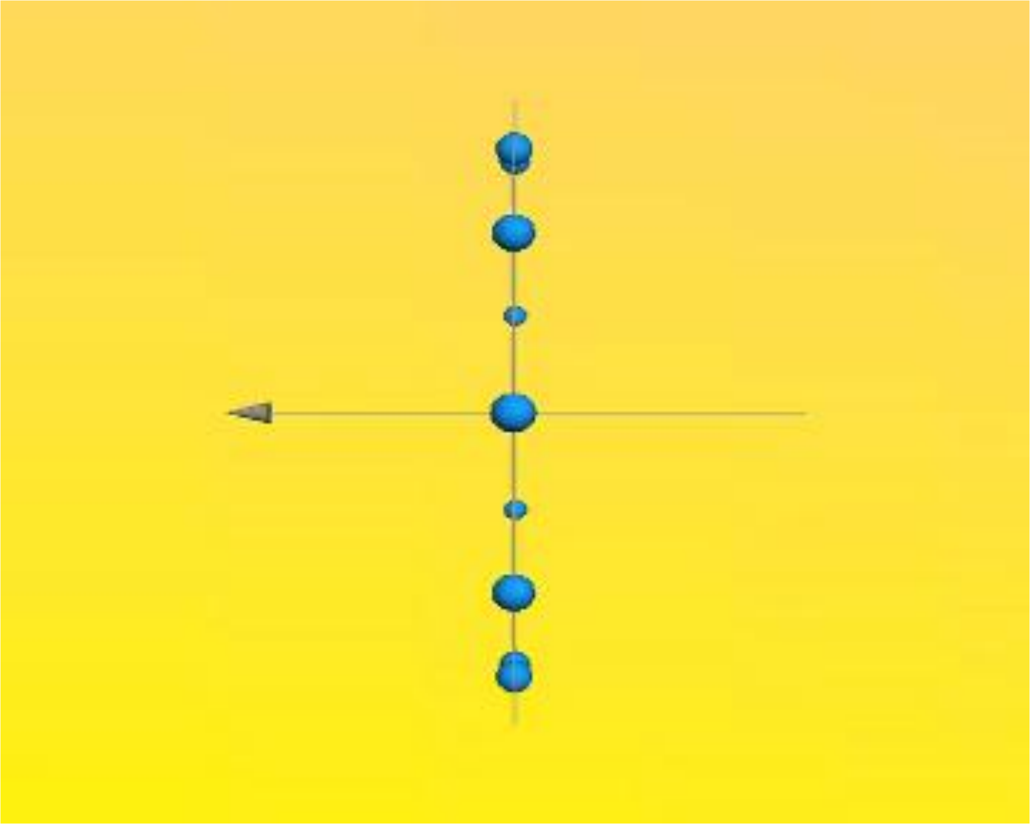
- **Virgo optical configuration or how to measure 10^{-20} m**
  - Simple Michelson interferometer
  - How do we improve the detector sensitivity?
  - How to measure the GW strain h(t) from this detector?

- **Noises limiting the ITF sensitivity: how to tackle them?**

- **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

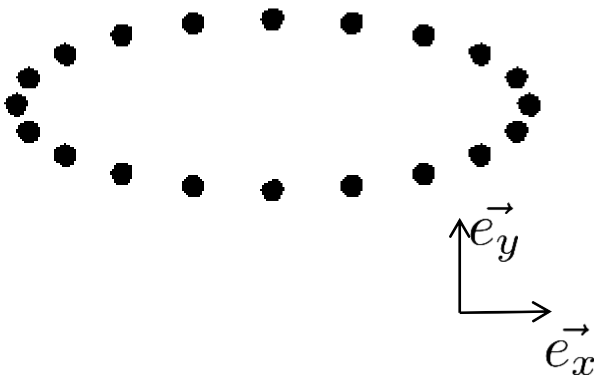


Reminder: effect of a GW on free fall masses

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

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

h(t): amplitude of the GW (= strain)

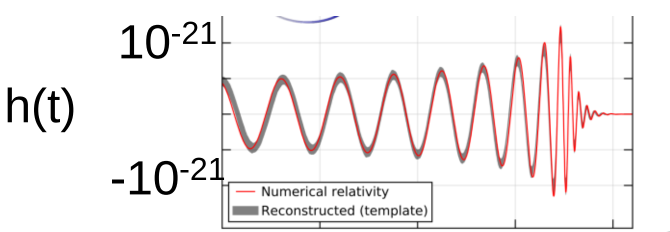


Typical amplitude of a GW crossing the Earth: $h \sim 10^{-23}$

(*h* has no dimension/unit)

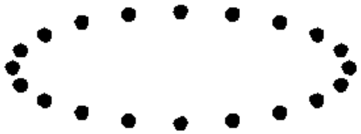
Case of a GW with polarisation + propagating along z

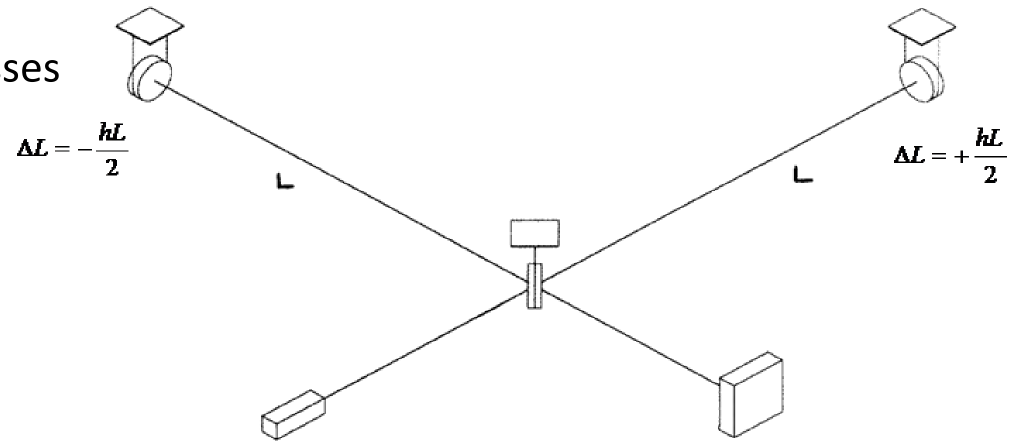
Reconstructed strain of GW150914



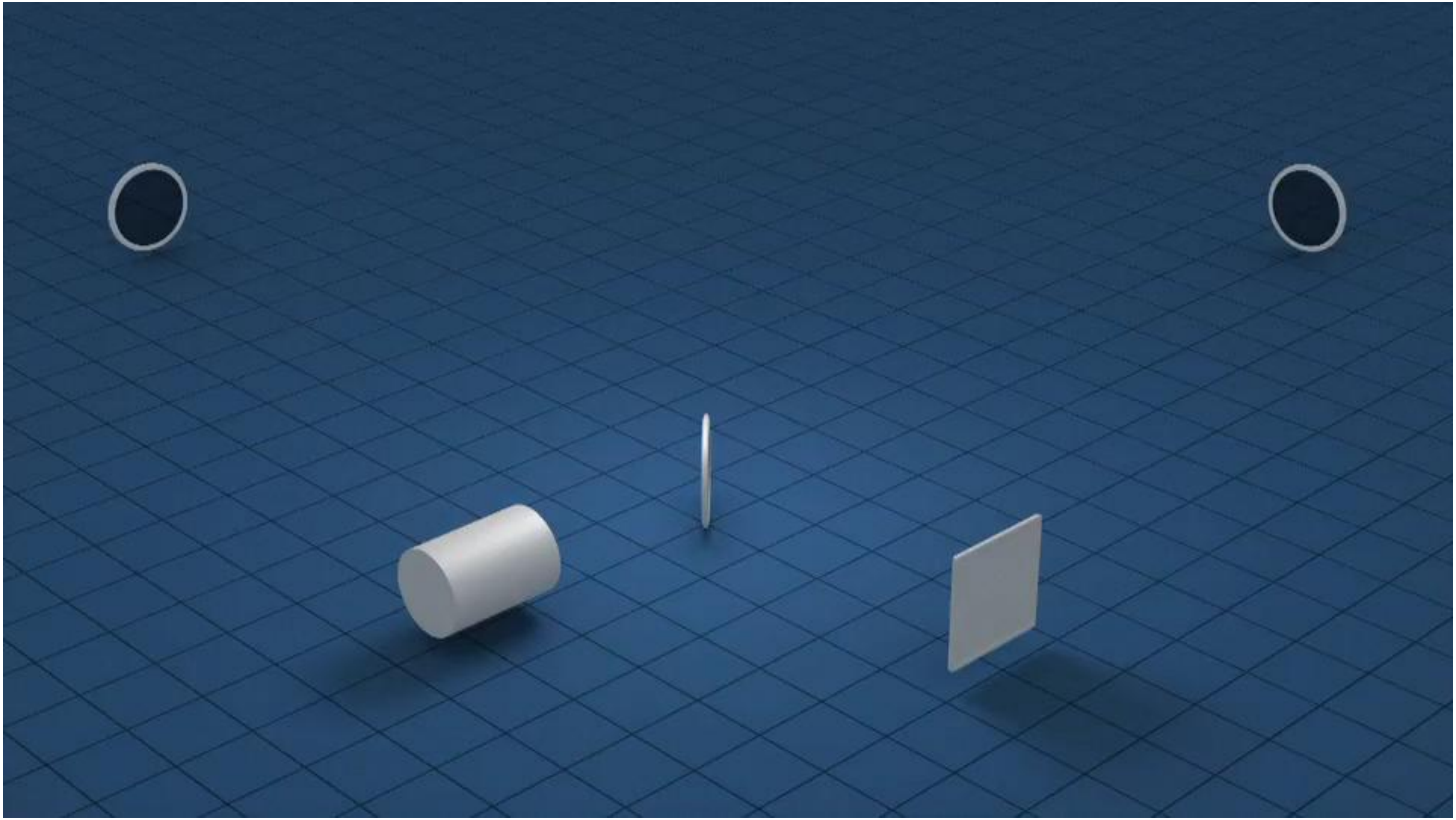
Terrestrial GW Interferometer: basic principle

- 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

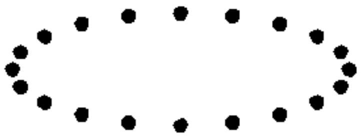




Terrestrial GW Interferometer: basic principle



Terrestrial GW Interferometer: basic principle



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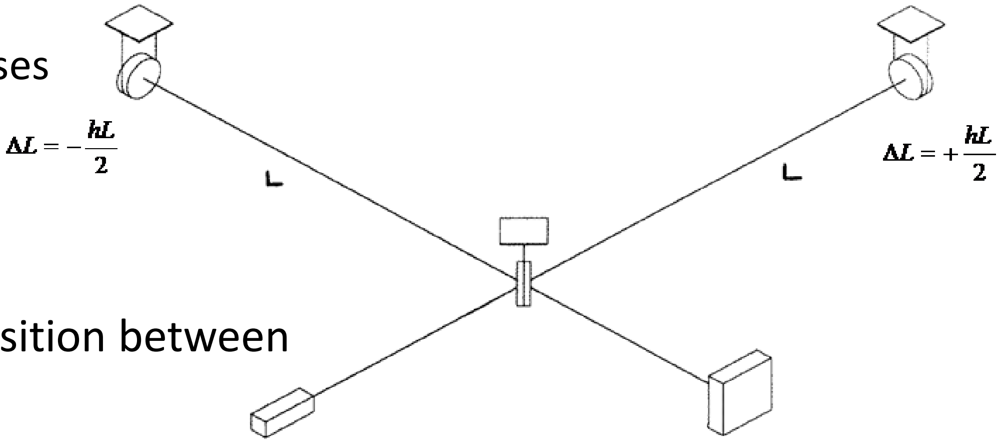


- Michelson interferometer well suited:
  - Effect of a gravitational wave is in opposition between 2 perpendicular axes
  - **Light intensity of interfering beams is related to the difference of optical path length in the 2 arms**

We need a big interferometer:

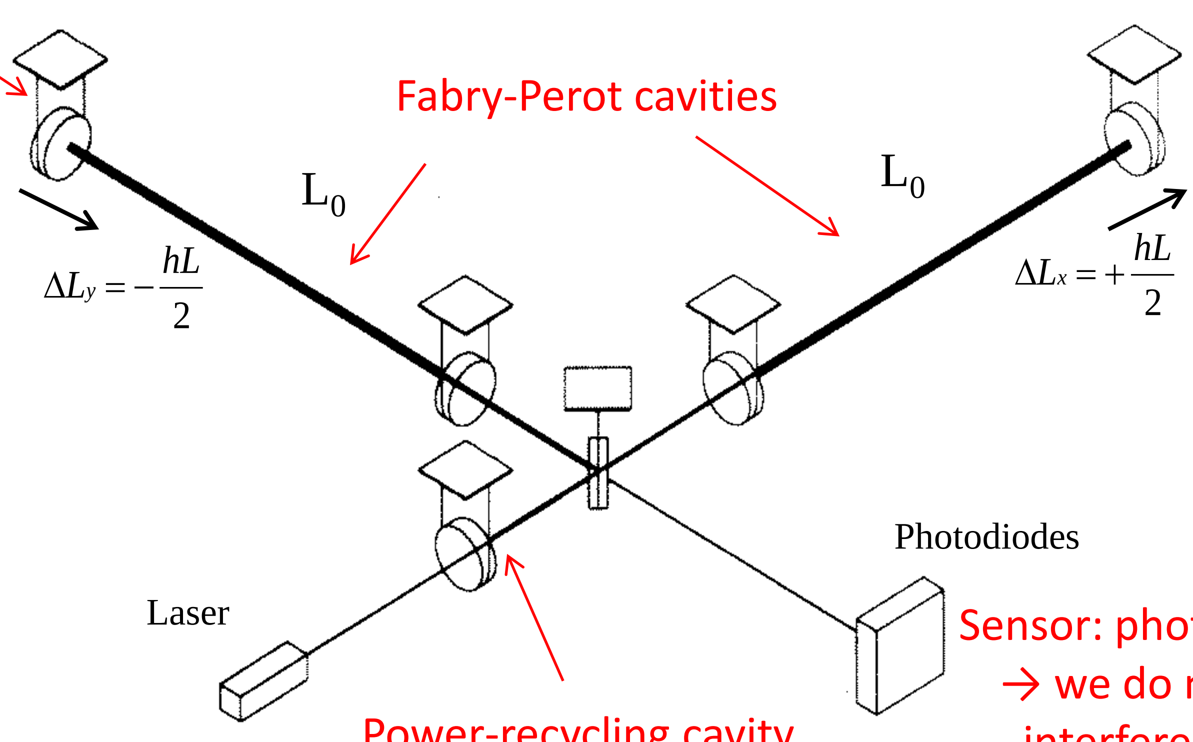
ΔL proportional to L

→ need several km arms!

Bandwidth: 10 Hz to few kHz

Virgo/LIGO: more complicated interferometers

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

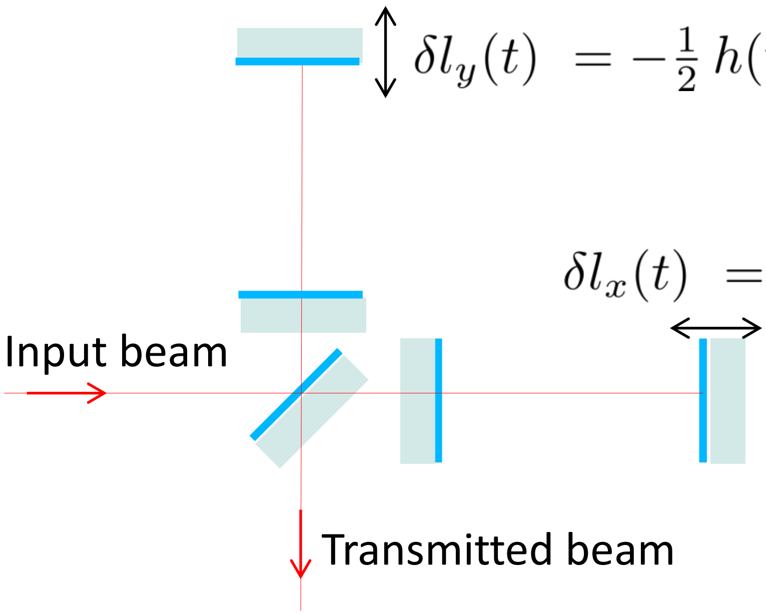


Sensor: photodiode
→ we do not image the interference pattern!

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:

$$\begin{aligned} \delta \Delta L &= \delta l_x(t) - \delta l_y(t) \\ &= h(t)\, L_0 \end{aligned}$$

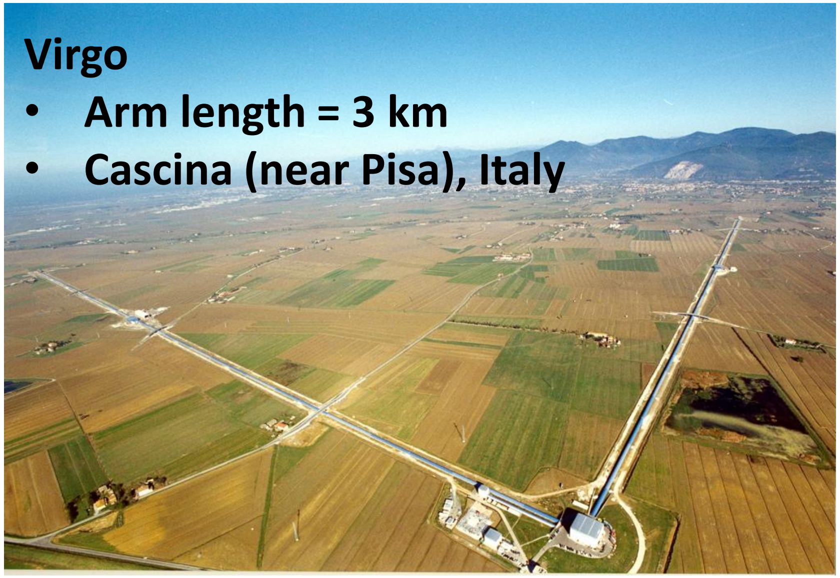
$$\mathrm{h} \sim 10^{-23} \qquad L_0 = 3\,\mathrm{km}$$

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

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

Km scale interferometers

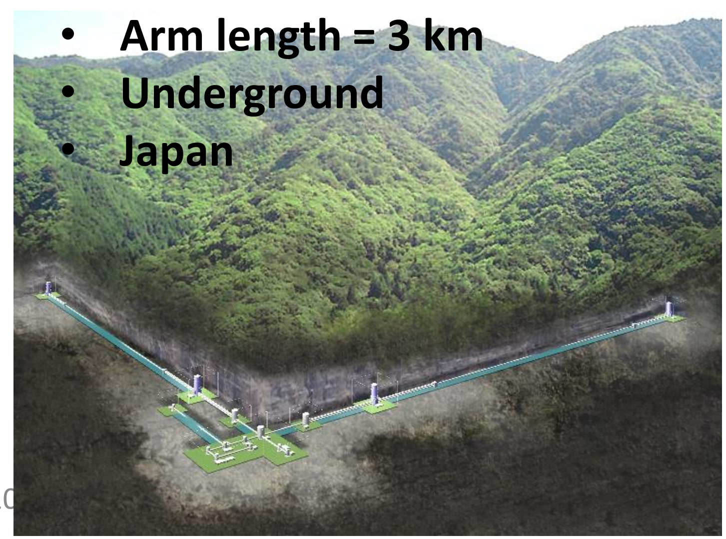
Virgo
- Arm length = 3 km
- Cascina (near Pisa), Italy



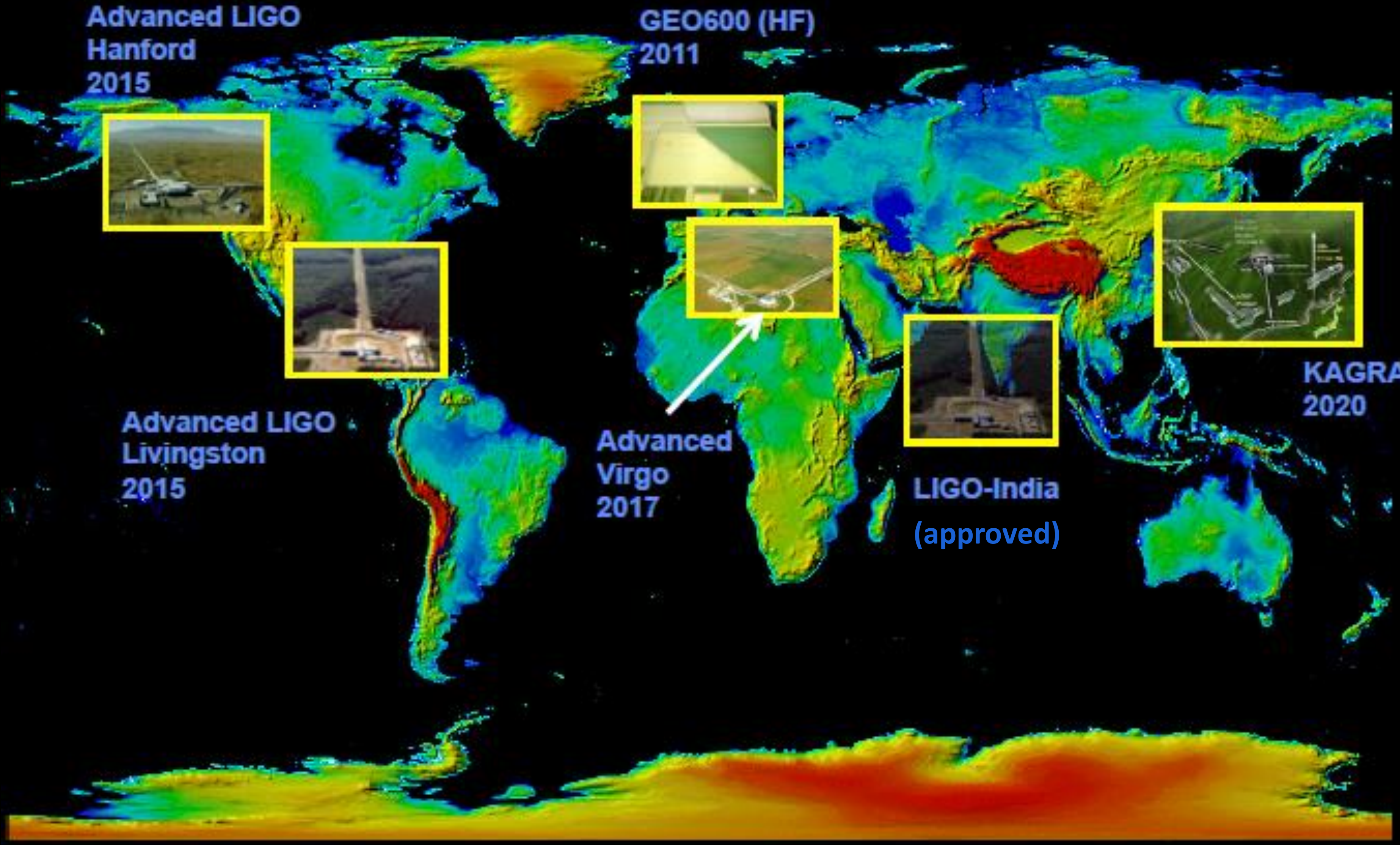
LIGO Livingston
- Arm length = 4 km
- Louisiana

LIGO Hanford
- Arm length = 4 km
- Washington State

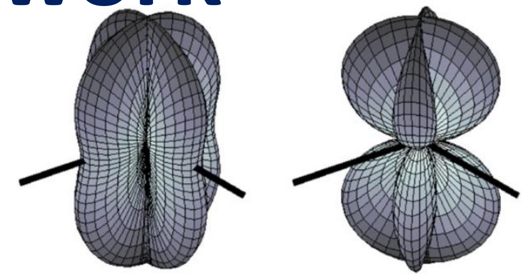
KAGRA
- Arm length = 3 km
- Underground
- Japan



The detector network



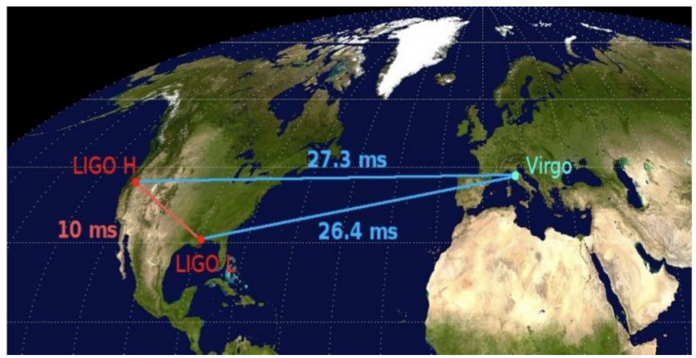
The benefits of the network

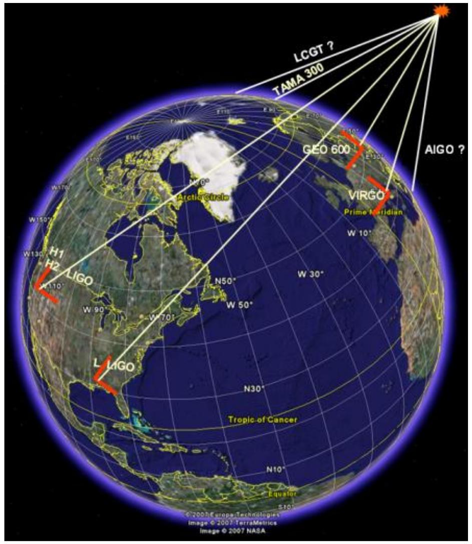


- A GW interferometer acts as a wide beam antenna
  - A single detector cannot localize the source
  - Need to compare the signals found in coincidence between several detectors (triangulation):

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

    → **the telescope is obtained by a network of interferometers**



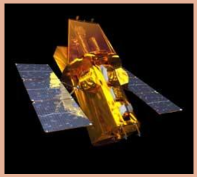


- Looking for rare and transient signals: can be hidden in detector noise

  → requires observation in coincidence between at least 2 detectors
- Since 2007, Virgo and LIGO share their data and analyze them jointly
- Now building the International Gravitational-Wave Network with KAGRA and LIGO India

Multi-messenger astronomy

Astrophysical alerts



GCN (GRBs)

Swift, Fermi, INTEGRAL, ...

SNEWS (supernova)

IceCube, Super-K, SNO, LVD

Alerts in LIGO-Virgo control rooms

Specific analysis (on-line and later)

Online GW candidates (LIGO-Virgo)

+ checks by rapid response team
(operators on sites + remote scientists on shift)

Few minutes

Alerts for the observatories

Radio and optical telescopes

ROTSE, TAROT, SkyMapper, QUEST,
Pi of the Sky, Zadko, Liverpool Telescope, LOFAR

X-ray satellites

Swift/XRT

γ-ray telescopes

HESS, CTA

- ➢ Increase the significance of the events
- ➢ Better understand the physics of the sources

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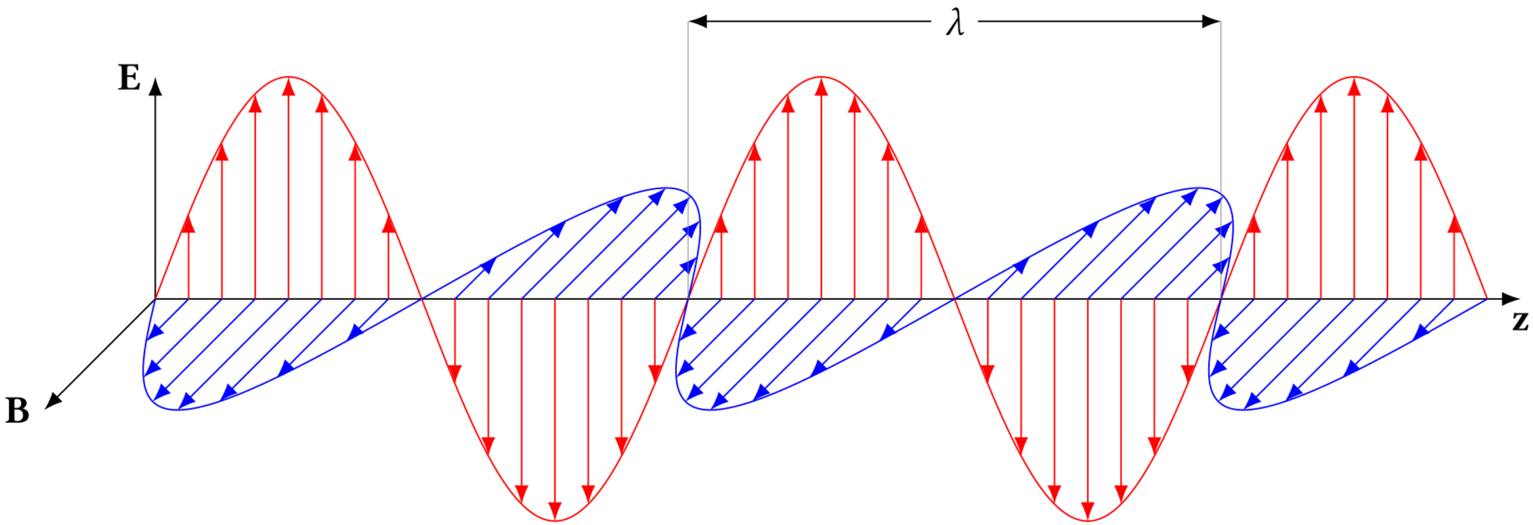
Electromagnetic waves



- Propagation of a perturbation of electric and magnetic fields
- Direction of propagation: along k
- E and B are in phase, and with perpendicular directions
- E and B are perpendicular to the direction of propagation of the wave (transverse wave)
- Amplitude: amplitude of the E (or B) field,
- Two polarisations: defined by the direction of E (or B)

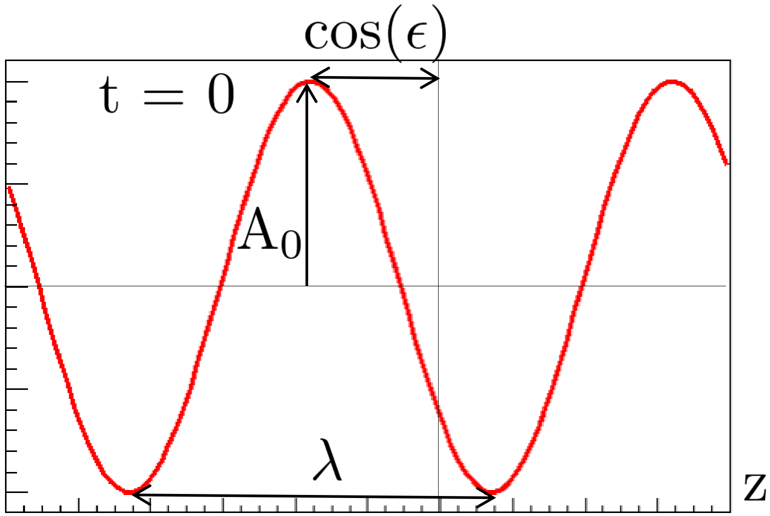
$$\vec{B} = \frac{\vec{k} \times \vec{E}}{c}$$

Description of plane waves

- Plane wave propagating along z, with speed c

$$A(z,t) = A_0 \cos(kz - \omega t + \epsilon) \qquad (\text{since } \vec{k}\vec{r} = k\, z)$$

$$\begin{cases} A_0 & \text{amplitude} \\ \lambda & \text{wavelength (m)} \\ k = \frac{2\pi}{\lambda} & \text{wave number (rad/m)} \\ \omega = kc & \text{angular frequency (rad/s)} \end{cases}$$



- Average power: $\mathrm{P} \propto A_0^2$

- Complex form

$$U(z,t) = A_0 e^{\jmath(kz-\omega t+\epsilon)}$$

$$= \underline{A_0} e^{\jmath(kz+\epsilon)} \qquad \text{with} \quad \underline{A_0} = A_0 e^{-\jmath\omega t}$$

--> simpler algebraic calculations, for example $\mathrm{P} \propto |U|^2 = UU^*$

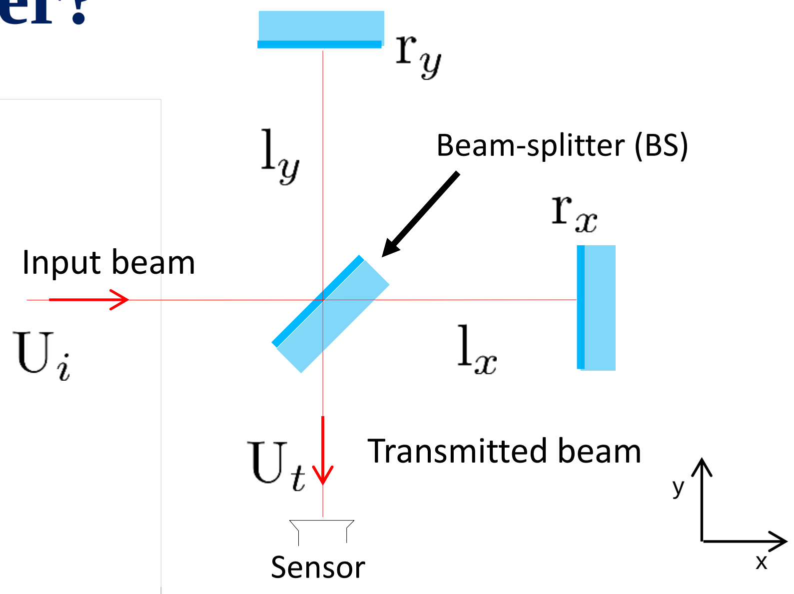
--> real plane wave is the real part: $\Re\big(U(z,t)\big) = A(z,t)$

- Plane waves do not exist but they are a good approximation of many waves in localized region of space

How do we « observe » ΔL with a Michelson interferometer?

- Input wave $$U_i(x,t) = \underline{A}_i e^{\jmath kx} = \underline{A}_i \quad \text{on BS}$$
- BS located at (0,0)
- Sensor located at $(0,-y_s)$
- Amplitude reflection and transmission coefficients: r and t

→ We are interested in the beam transmitted by the interferometer: it is the sum of the two beams (fields) that have propagated along each arm



Around the mirrors:

- Radius of curvature of the beam ~ 1400 m
- Size of the beam ~ few cm

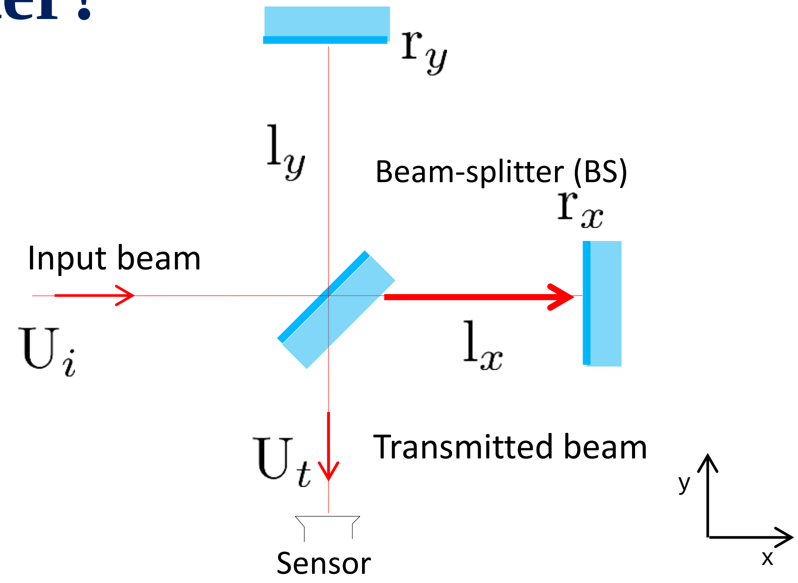
→ The beam can be approximated by plane waves

How do we « observe » ΔL with a Michelson interferometer?

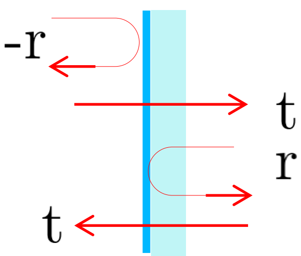
- Input wave $$U_i(x,t) = \underline{A}_i e^{jkx}$$ $$= \underline{A}_i \quad \text{on BS}$$

- Beam propagating along x-arm:

$$U_{tx} = \underline{A}_i \, t_{BS} \, e^{jkl_x} \ \ldots\ldots$$



Sign convention for amplitude reflection and transmission coefficients



Without losses:
$t^2 + r^2 = 1$

How do we « observe » ΔL with a Michelson interferometer?

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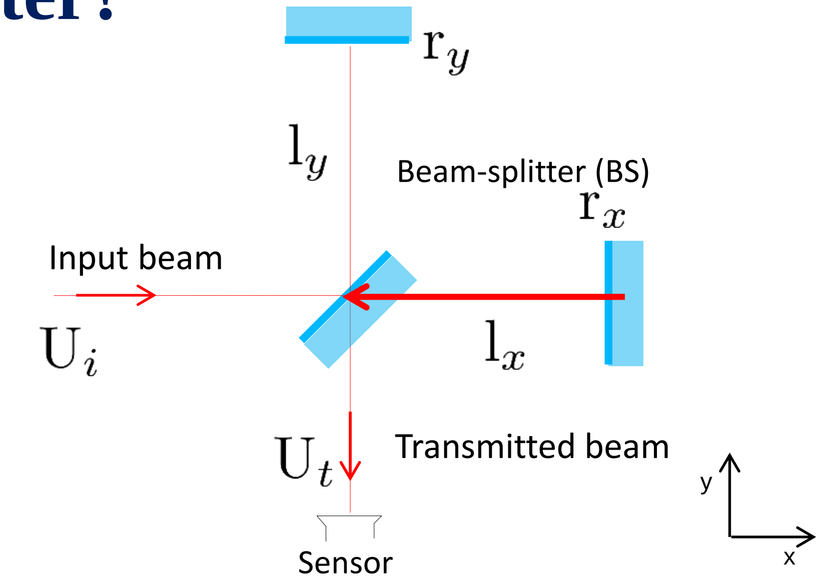

- Beam propagating along x-arm:

$$U_{tx} = \underline{\mathcal{A}}_i \, t_{BS} \, e^{\jmath k l_x} \quad (-r_x) e^{\jmath k l_x} \ldots\ldots$$

Sign convention for amplitude reflection and transmission coefficients

Without losses:
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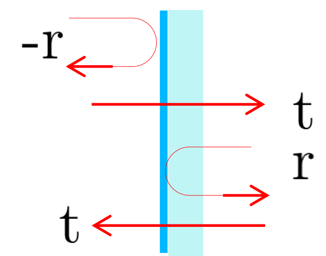

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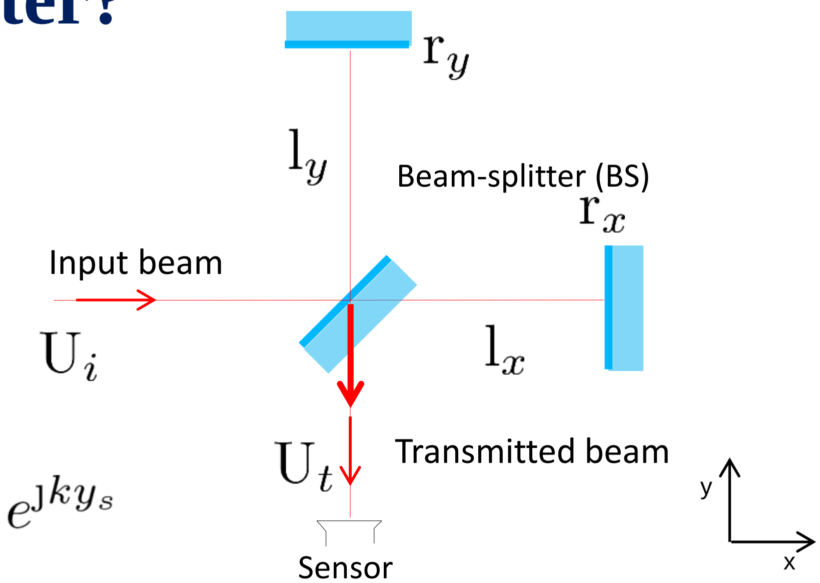

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- Beam propagating along x-arm:

$$U_{tx} = \underline{\mathcal{A}_i}\, t_{BS}\, e^{jkl_x} \quad (-r_x) e^{jkl_x} \quad r_{BS}\, e^{jky_s}$$

Sign convention for amplitude reflection and transmission coefficients

Without losses:
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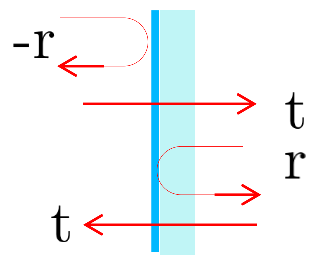

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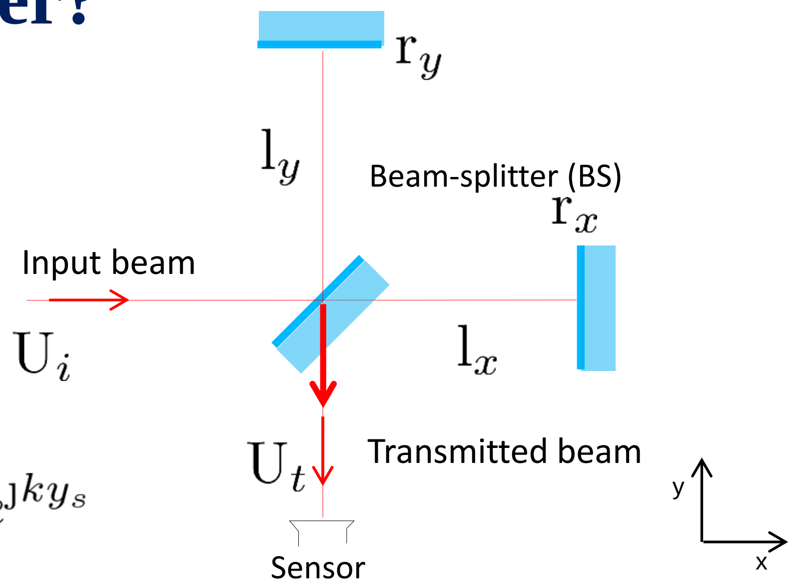

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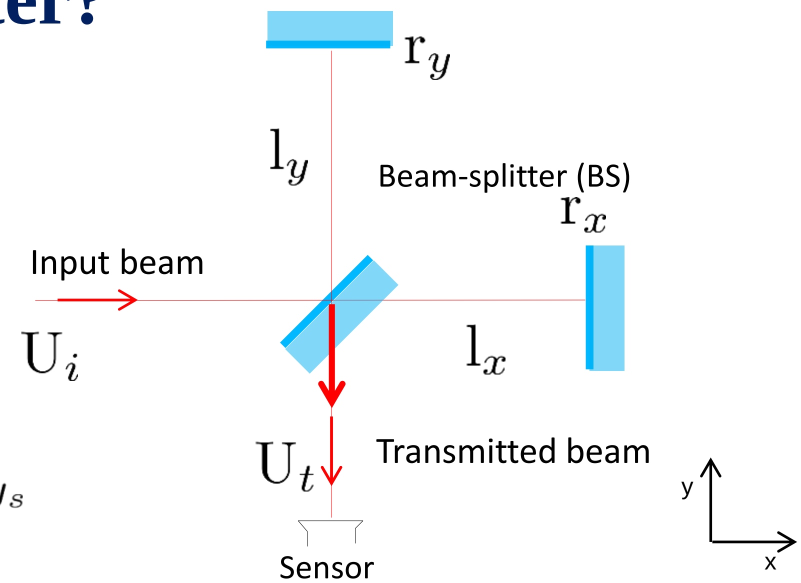
- Beam propagating along x-arm:

$$\begin{aligned} U_{tx} &= \underline{A}_i\, t_{BS}\, e^{\jmath k l_x} \quad (-r_x) e^{\jmath k l_x} \quad r_{BS}\, e^{\jmath k y_s} \\ &= \underline{A}_i\, t_{BS}\, r_{BS}\, (-r_x)\, e^{2\jmath k l_x}\, e^{\jmath k y_s} \\ &= \frac{\underline{A}_i}{2} \times \underbrace{\left(-\, r_x\, e^{2\jmath k l_x}\right)}_{\text{Complex reflection of the x-arm}} e^{\jmath k y_s} \qquad \text{with } t_{BS} = r_{BS} = \tfrac{1}{\sqrt{2}} \end{aligned}$$

How do we « observe » ΔL with a Michelson interferometer?



- Input wave $$U_i(x,t) = \underline{A}_i e^{\jmath kx}$$ $$= \underline{A}_i \quad \text{on BS}$$

- Beam propagating along x-arm:

$$U_{tx} = \underline{A}_i\, t_{BS}\, e^{\jmath kl_x} \quad (-r_x) e^{\jmath kl_x} \quad r_{BS}\, e^{\jmath ky_s}$$
$$= \underline{A}_i\, t_{BS}\, r_{BS}\, (-r_x)\, e^{2\jmath kl_x}\, e^{\jmath ky_s}$$
$$= \frac{\underline{A}_i}{2} \times \underbrace{\left(-\, r_x\, e^{2\jmath kl_x} \right)}_{\text{Complex reflection of the x-arm}} e^{\jmath ky_s}$$

- Beam propagating along y-arm:

$$U_{ty} = -\frac{\underline{A}_i}{2} \times \underbrace{\left(-\, r_y\, e^{2\jmath kl_y} \right)}_{\text{Complex reflection of the y-arm}} e^{\jmath ky_s}$$

+

Transmitted field:

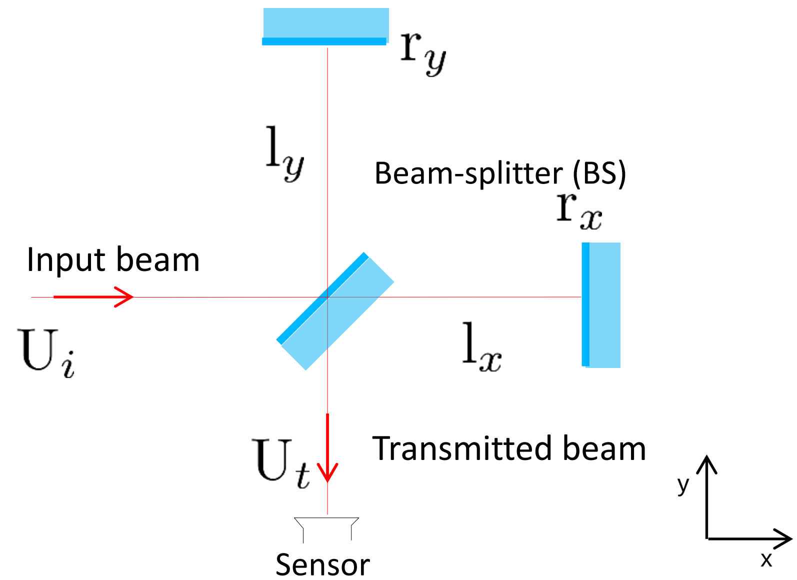
$$U_t = U_{tx} + U_{ty}$$
$$= \frac{\underline{A}_i}{2} e^{\jmath ky_s} \left(r_y\, e^{2\jmath kl_y} - r_x\, e^{2\jmath kl_x} \right)$$

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)



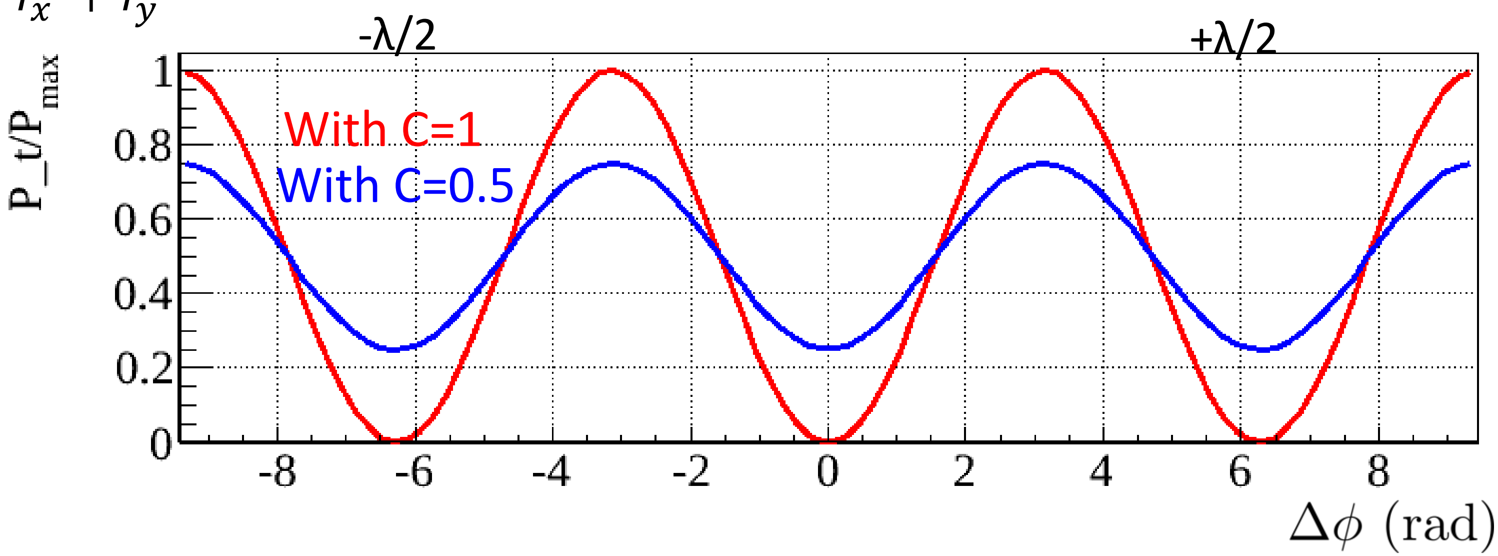
Transmitted power

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

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

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

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



What power does Virgo measure?

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

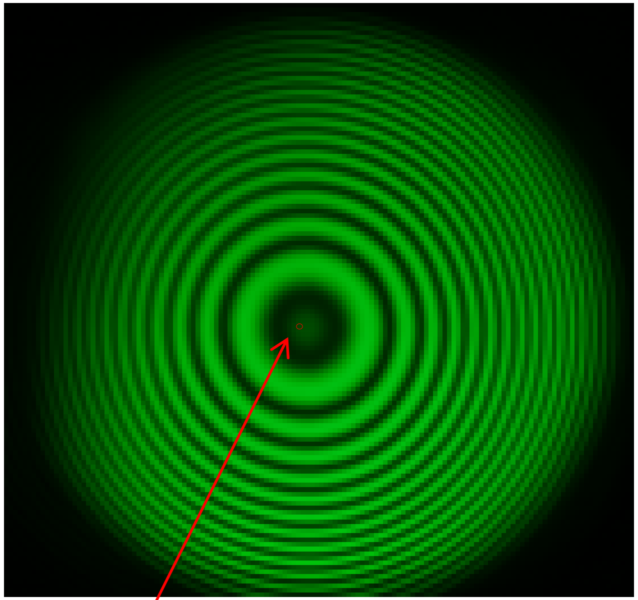
  → interference pattern

  (and the complementary pattern in reflection)

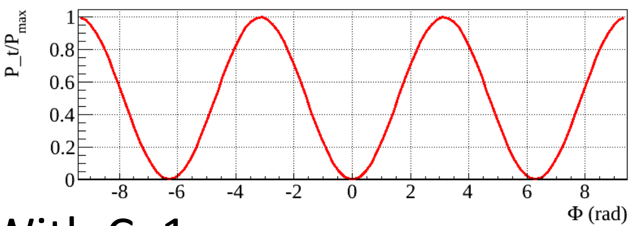
- Virgo interference pattern much larger than the beam size:

  ~1 m between two consecutive fringes

  → we do not study the fringes in nice images !



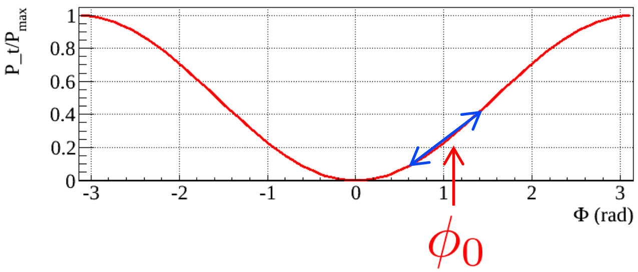
Equivalent size of Virgo beam



With C=1

Freely swinging mirrors

Setting a working point



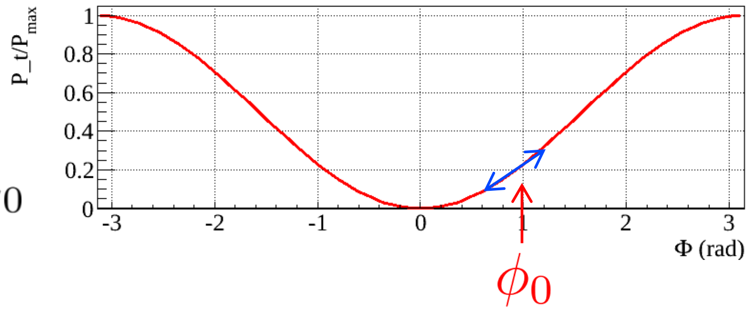
Controlled mirror positions

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:

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



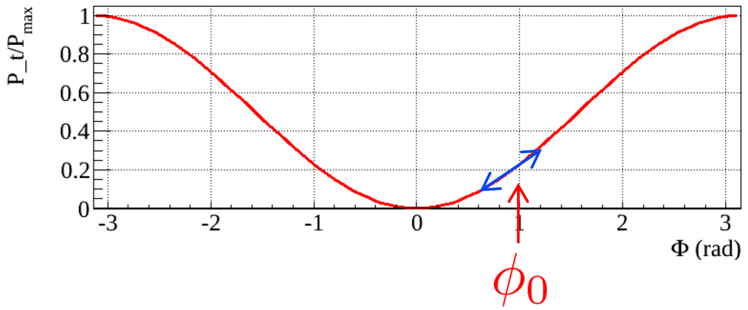
- Power variations as function of small differential length variations:

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

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

$$\boxed{\delta P_t \propto \delta\Delta L = hL_0 \quad \text{around the working point !}}$$

From the power to the gravitational wave



- Around the working point:

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

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

(W/m)

Measurable physical quantity

Physical effect to be detected

Improving the interferometer sensitivity

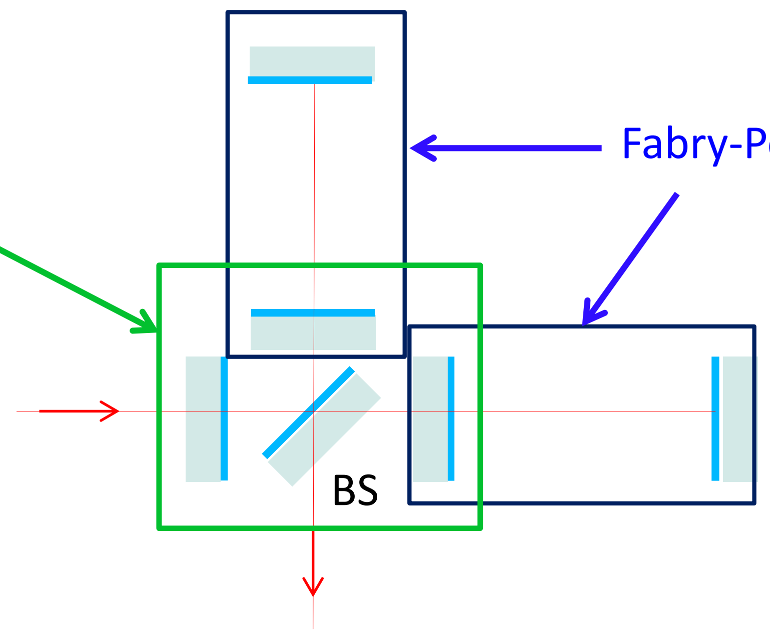
$$\delta P_t = P_i C \sin\left(\frac{4\pi}{\lambda}\Delta L_0\right)\underbrace{(k\,\delta\Delta L)}_{\propto\,\delta\phi}$$

Increase the input power on BS

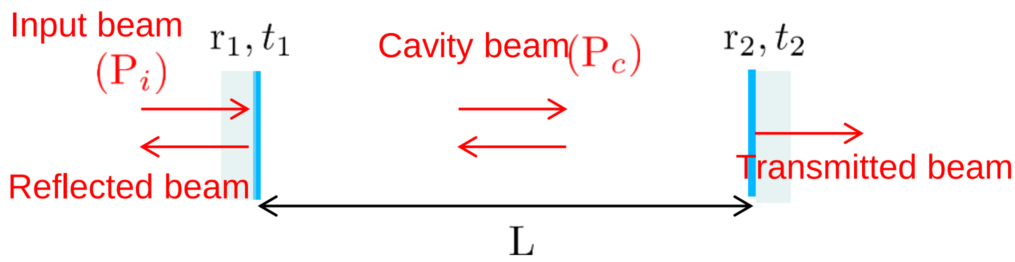
Increase the phase difference between the arms for a given differential arm length variation

Recycling **cavity**

Fabry-Perot **cavities** in the arms

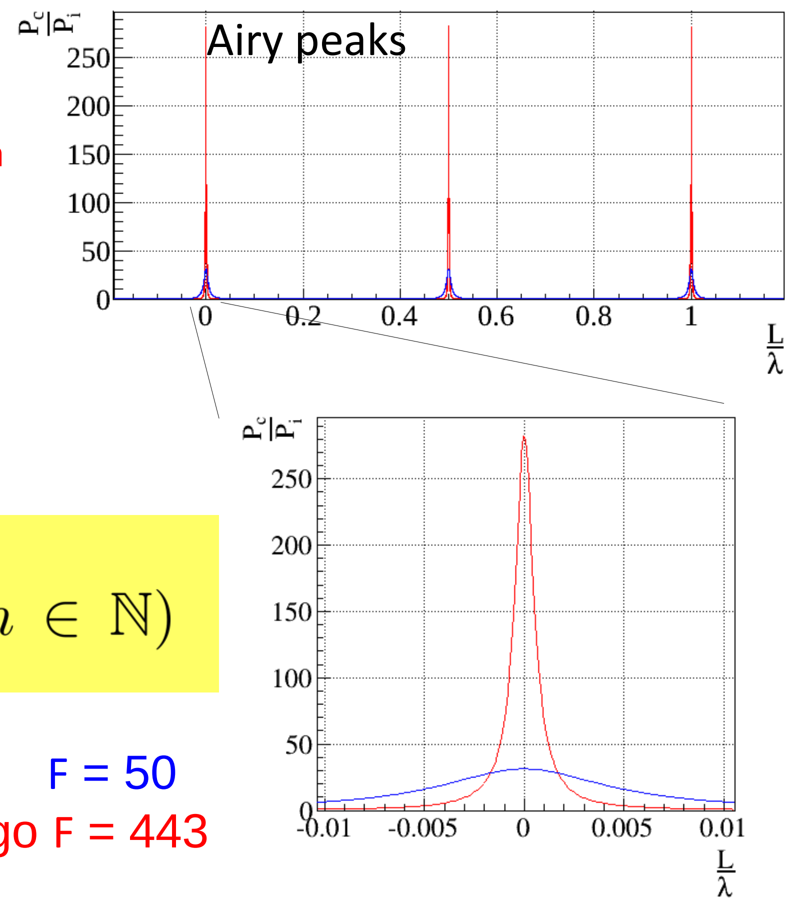


Beam resonant inside the cavities



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

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



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

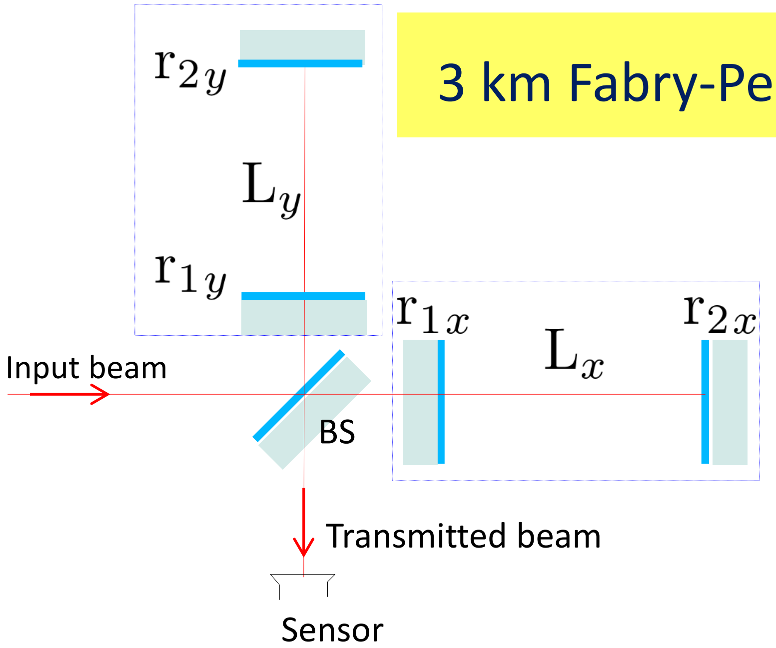
Virgo F = 50

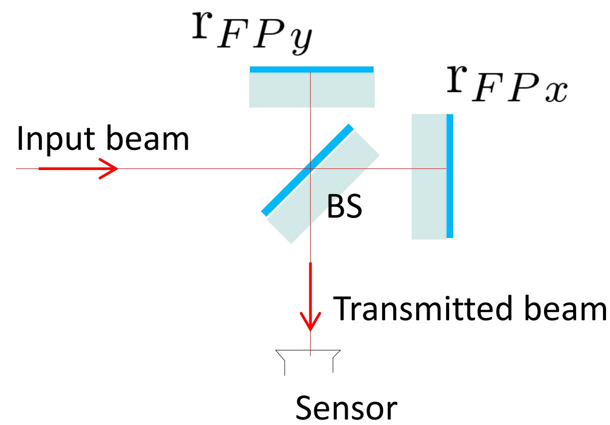
AdVirgo F = 443

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

How do we amplify the phase offset?

3 km Fabry-Perot cavities





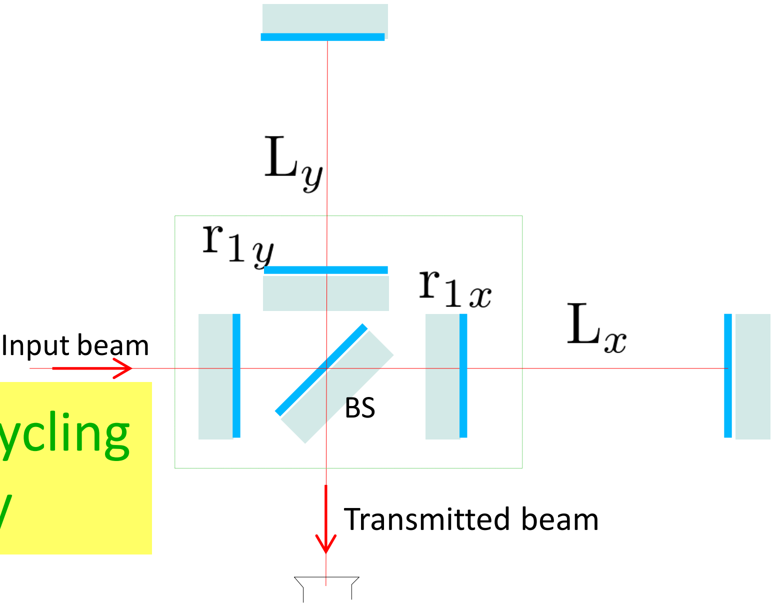
$$r_{FPx} = -1 \times e^{\mathrm{J}\,\frac{2\mathcal{F}}{\pi}\,2\,k\,\delta L_x}$$

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

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

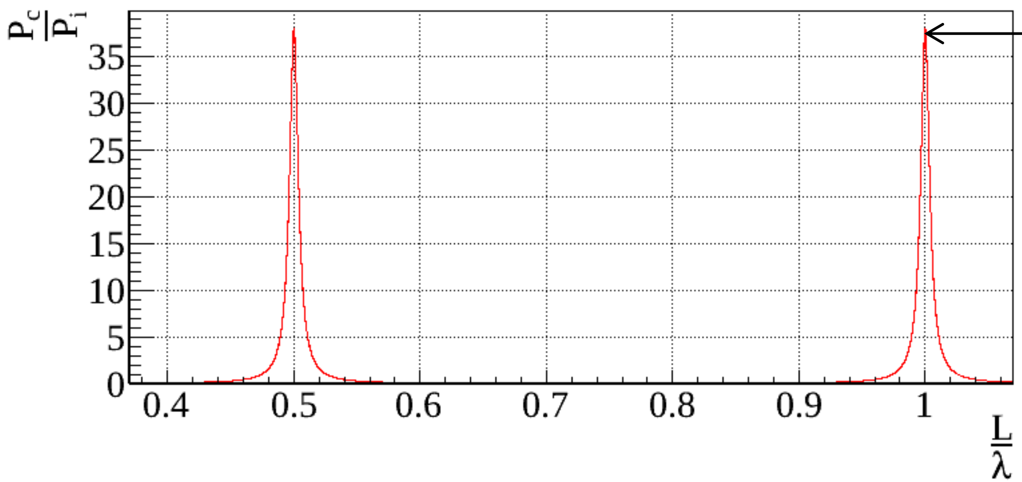
How do we increase the power on BS?

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



Power recycling cavity

Resonant power recycling cavity



$$\mathrm{G}_{PR} = 38 \quad (r_{PR}^2 = 0.95)$$

→ input power on BS increased by a factor 38!

Improved interferometer response

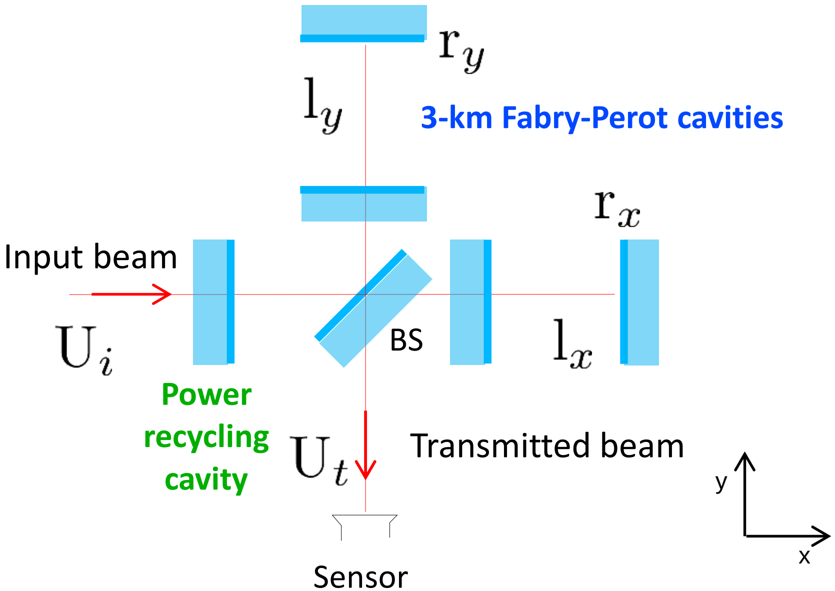
- **Response of simple Michelson:**

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

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

(W/m)

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



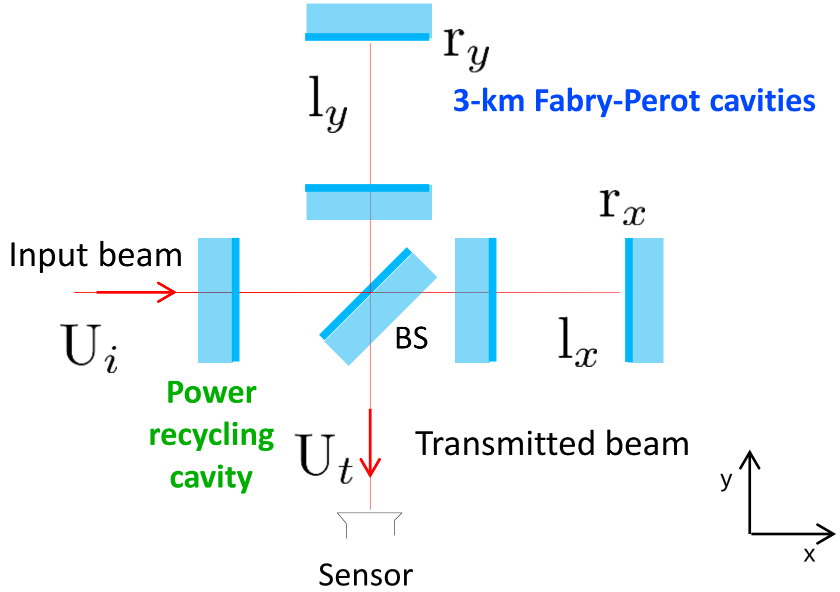
$$\delta P_t = \underbrace{G_{PR}}_{\sim 38}\, P_i\, C\, \frac{2\pi}{\lambda} \sin\left(\frac{4\pi}{\lambda}\Delta L_0\right) \underbrace{\frac{2\mathcal{F}}{\pi}}_{\sim 300} \delta\Delta L$$

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

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

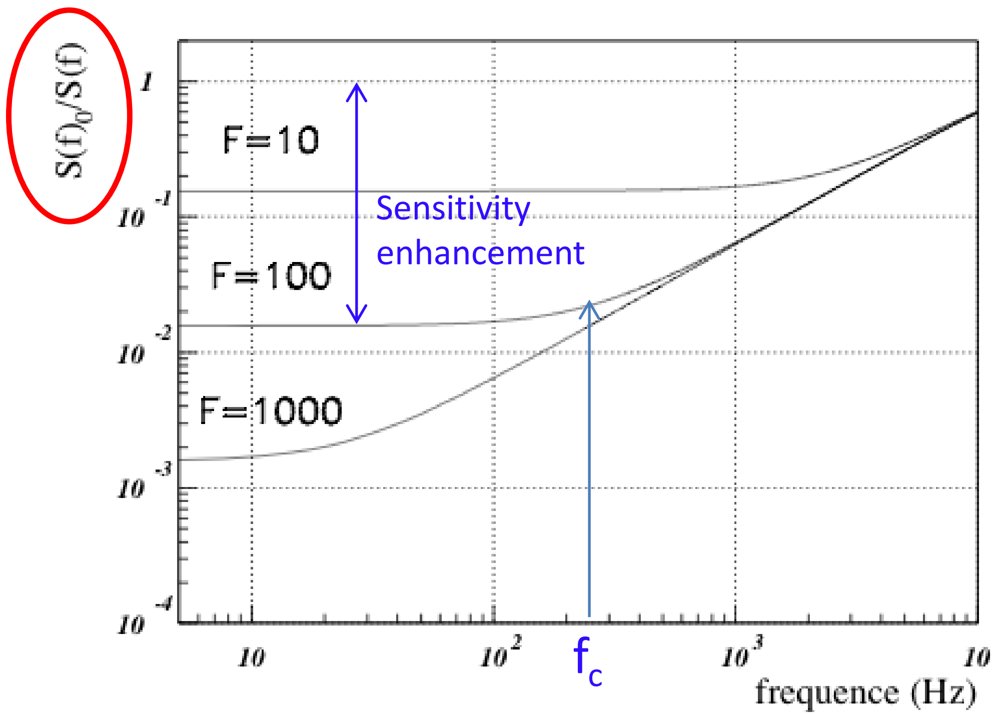
$$\rightarrow h_{min} = \frac{\delta\Delta L_{min}}{L} \sim 10^{-23}$$

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

Example of frequency dependency of the ITF response

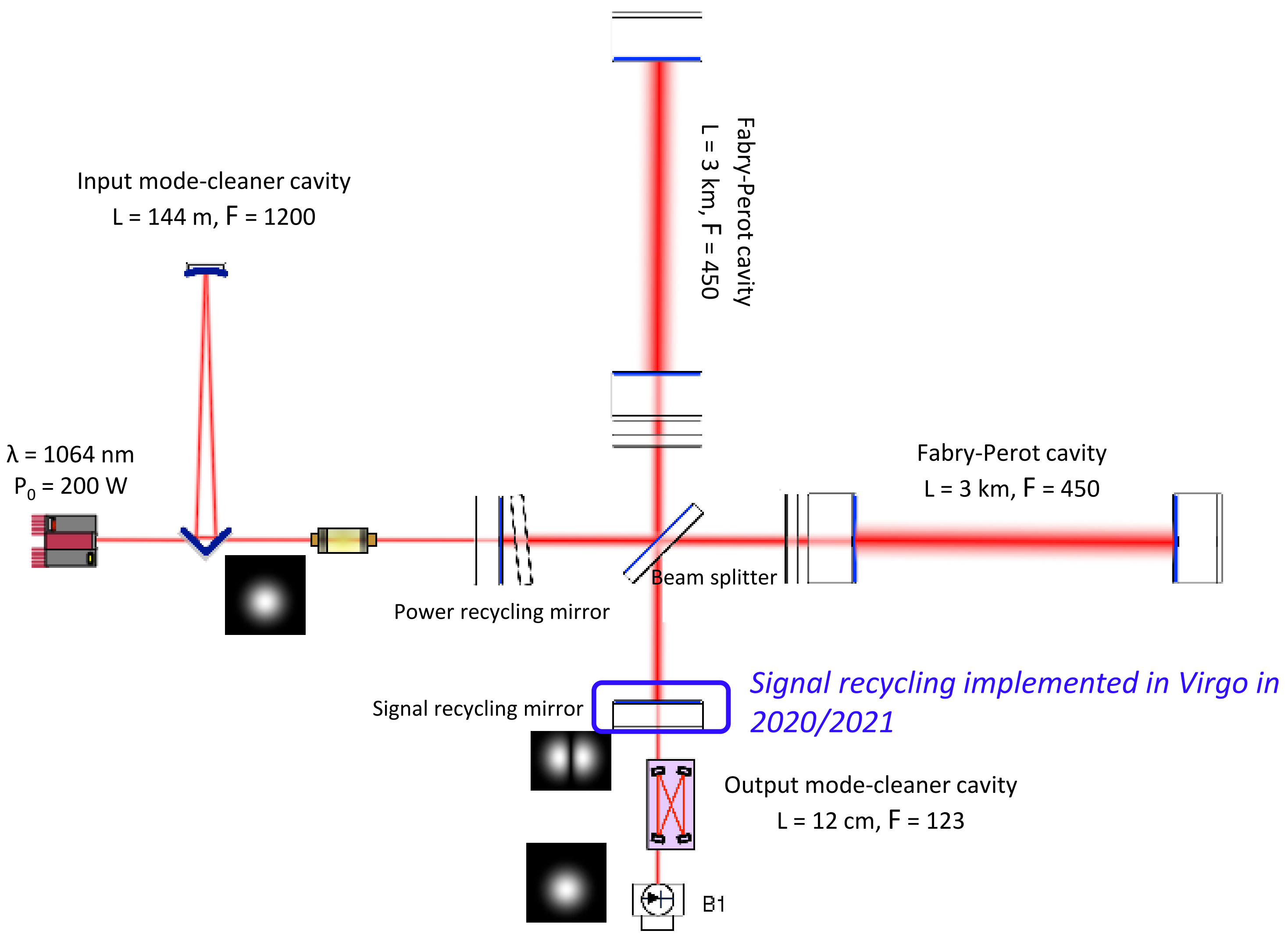
- Light travel time in the cavities must be taken into account
- Fabry-Perot cavities behave as a low pass filter
- Frequency cut-off: $$f_c = \frac{c}{4\mathcal{F}L}$$

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

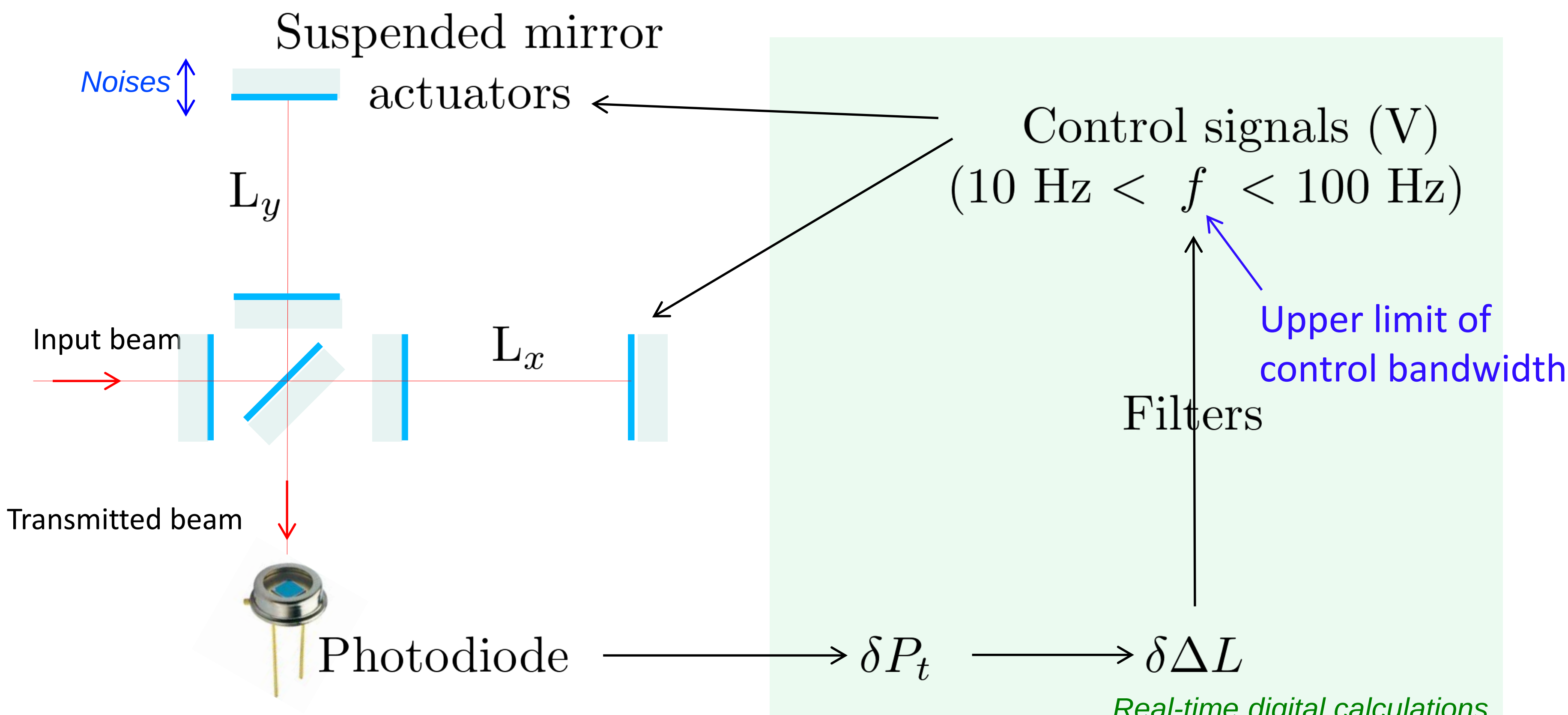
Optical layout of Virgo



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

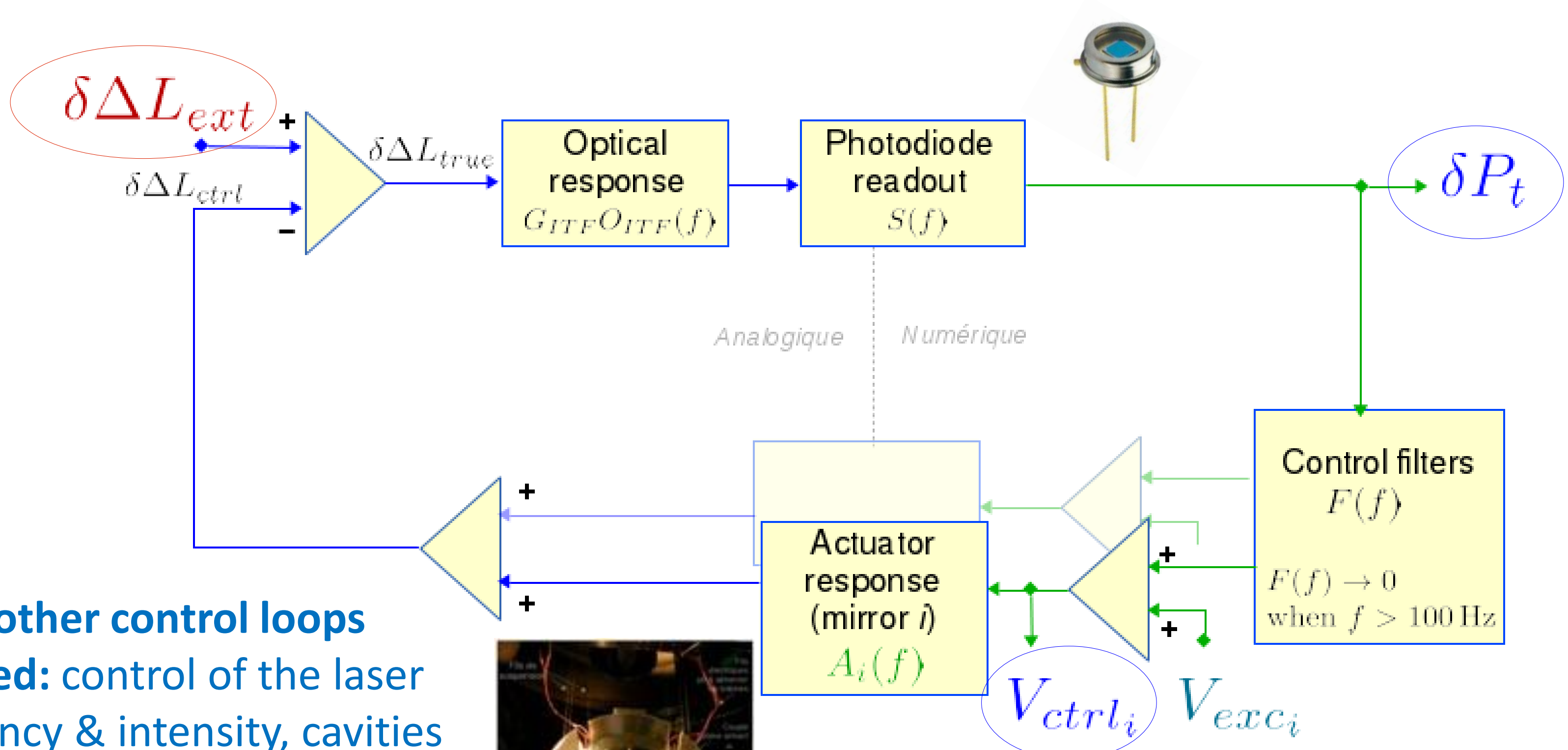


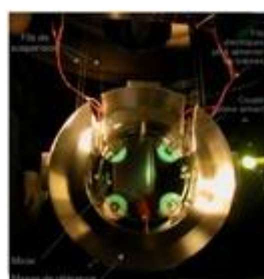
How do we control the working point?

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, …

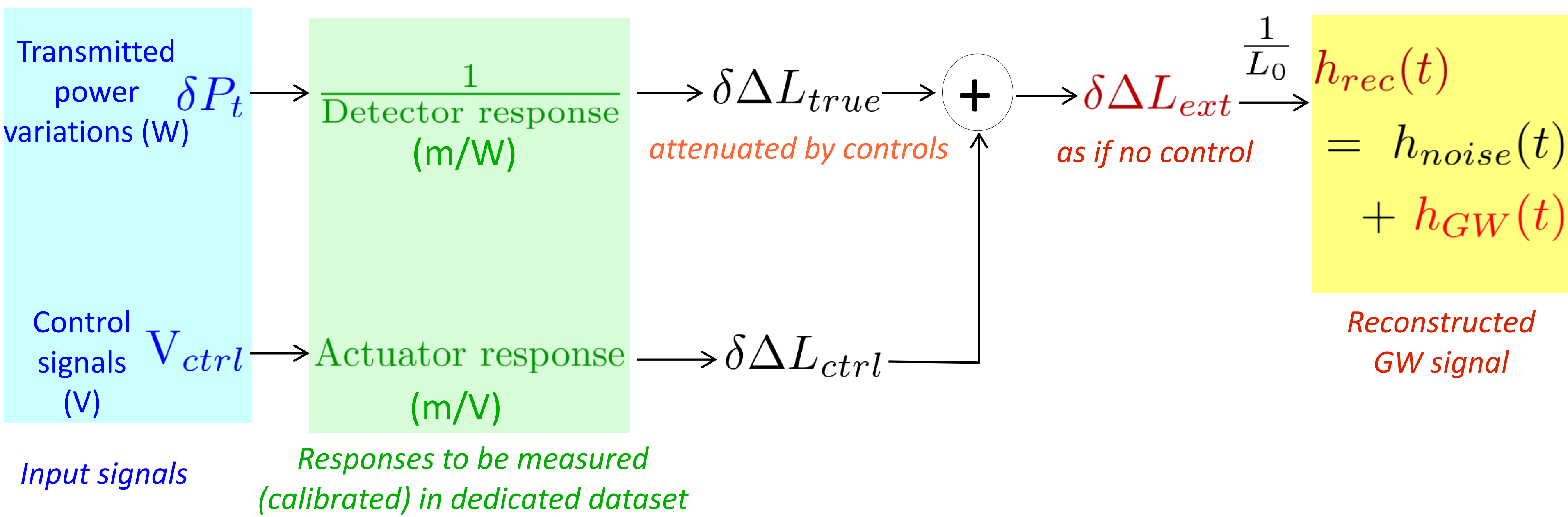
From the detector data to the GW strain h(t)

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

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

- 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

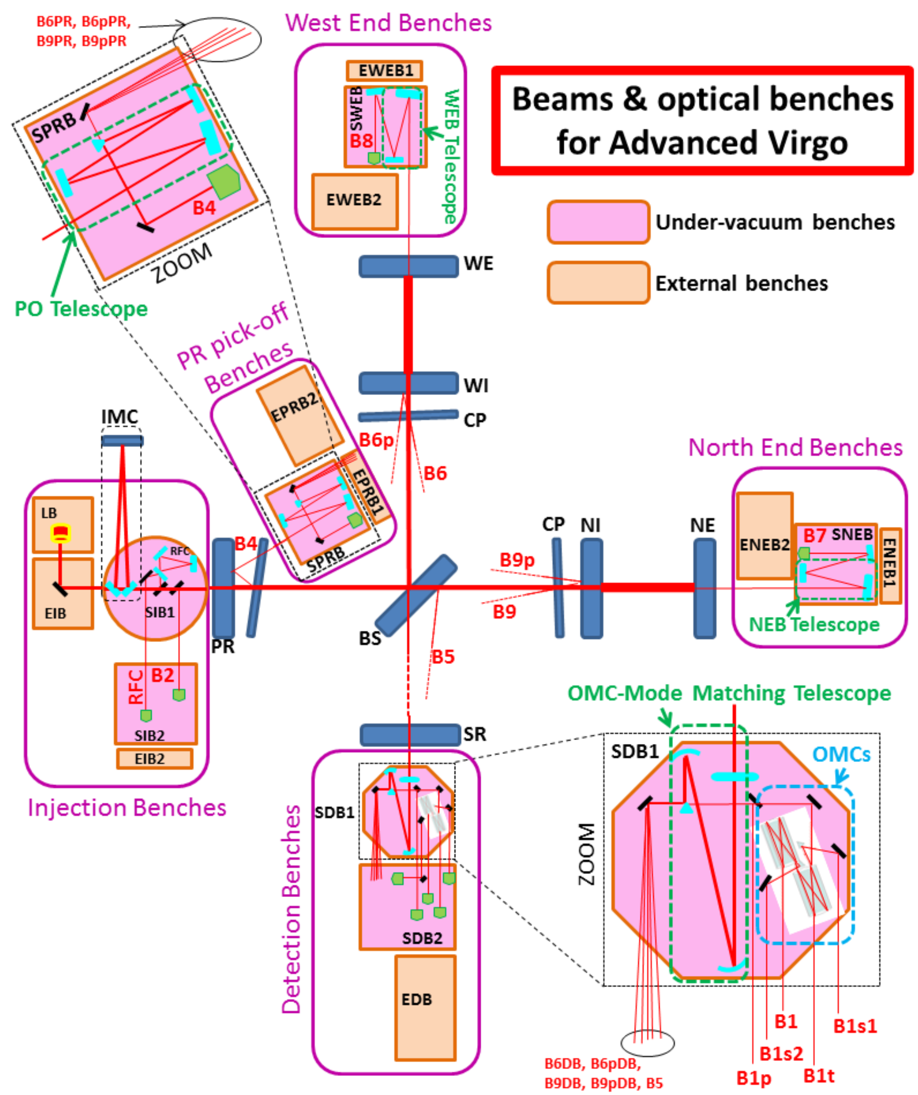


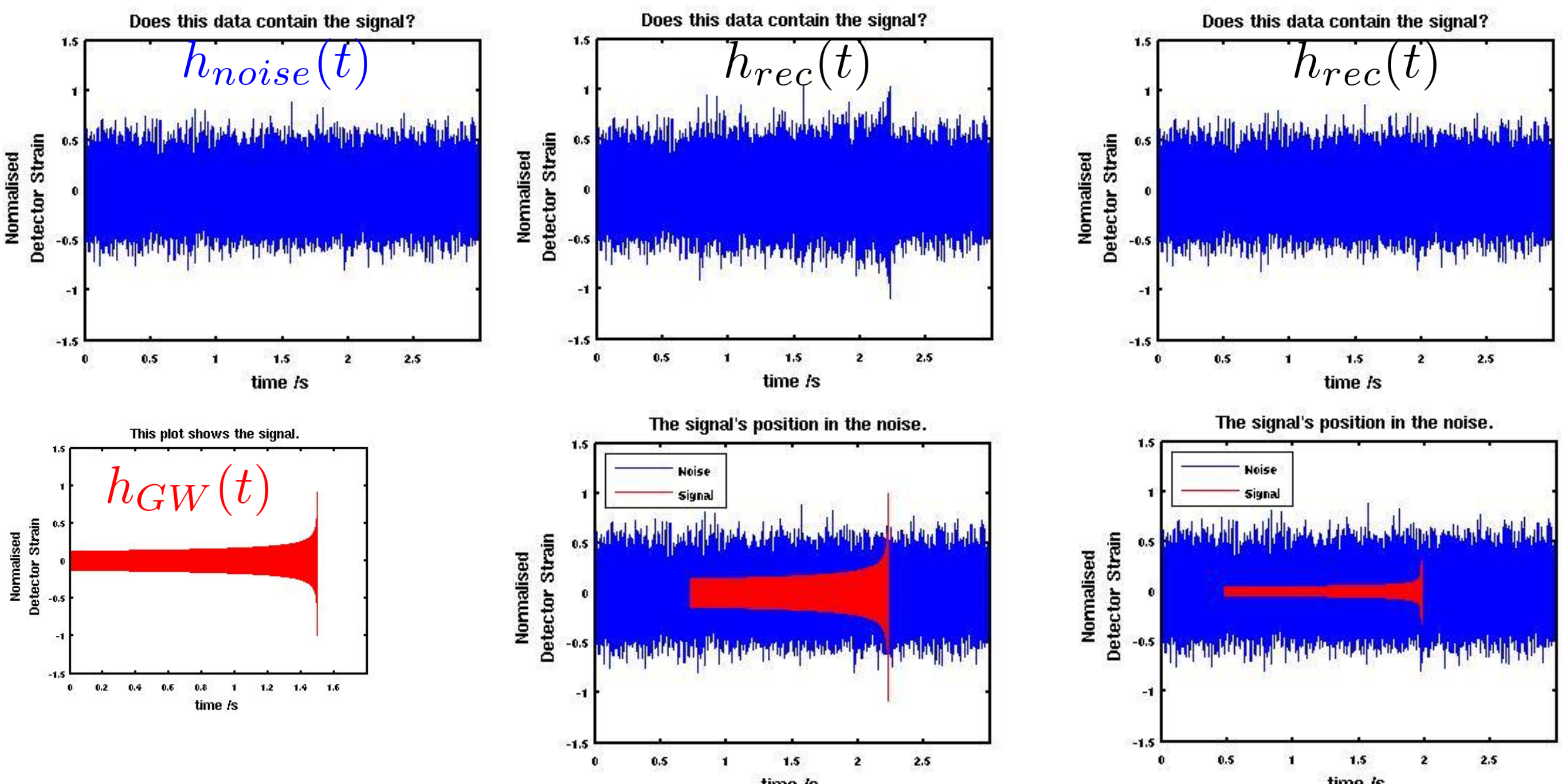
Table of Contents

- **Principles:**
  - ➢ Effect of GW on free-fall masses
  - ➢ Basic detection principle overview
- **Virgo optical configuration or how to measure 10^{-20} m**
  - ➢ Simple Michelson interferometer
  - ➢ How do we improve the detector sensitivity?
  - ➢ How to measure the GW strain h(t) from this detector?
- **Noises limiting the ITF sensitivity: how to tackle them?**
- **Prospectives for interferometers and other detectors**

What is noise in GW detectors ?

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

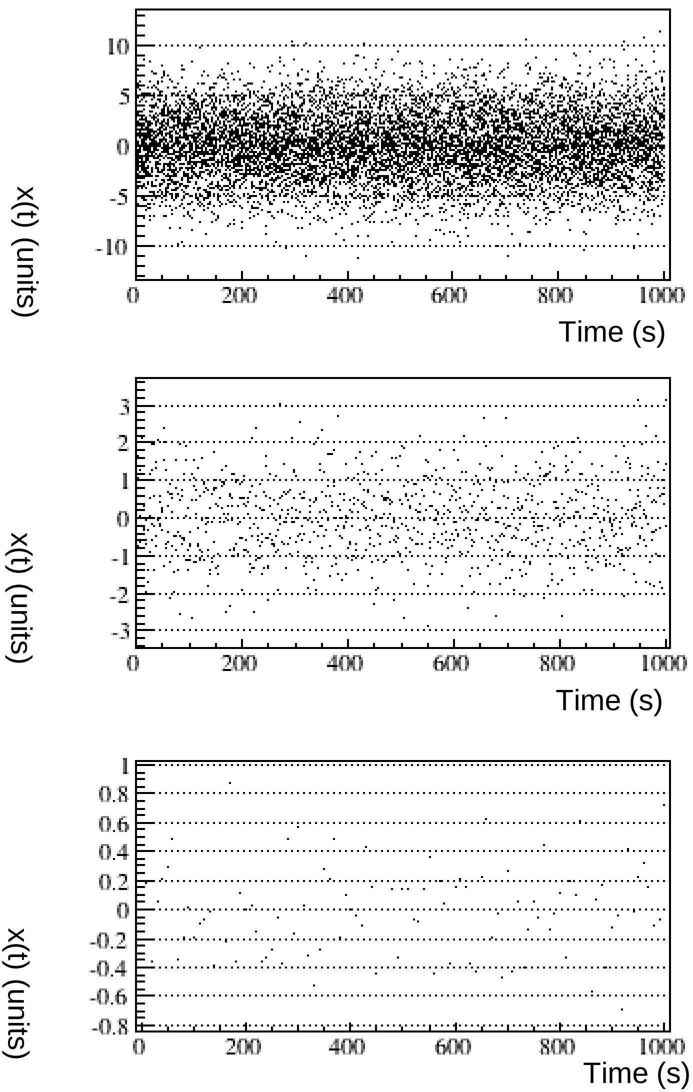
$$h_{rec}(t) = h_{noise}(t) + h_{GW}(t)$$



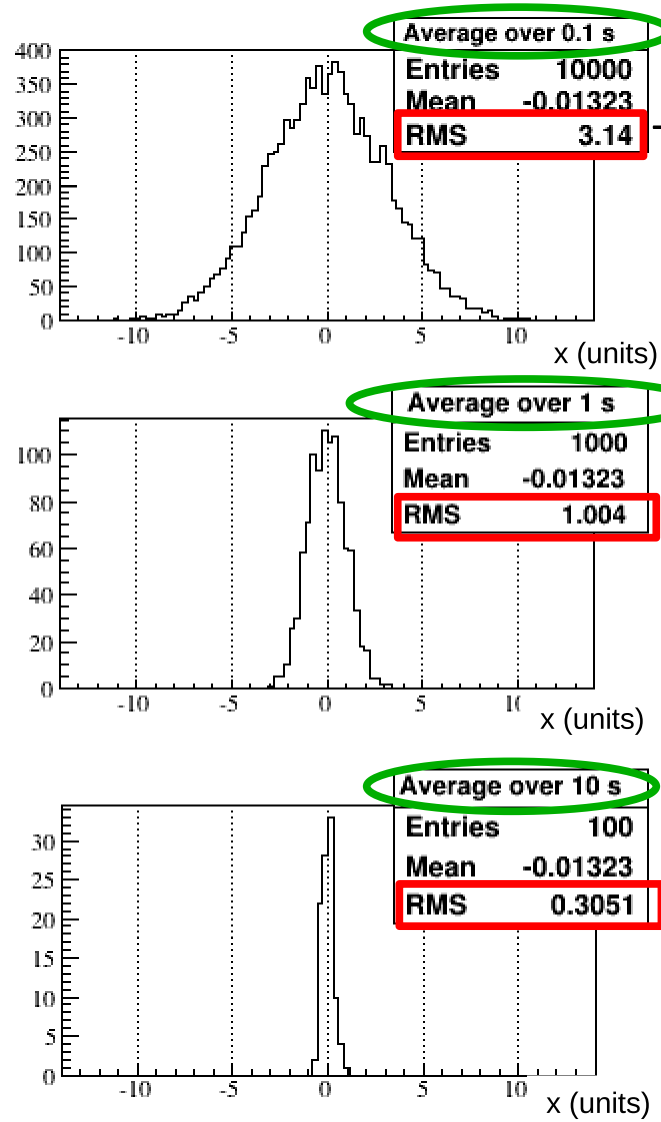
Extracted from Black Hole Hunter: http://www.blackholehunter.org/

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 $(\text{Data units} \times \sqrt{\text{s}})$ 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

How do we characterize a noise… 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

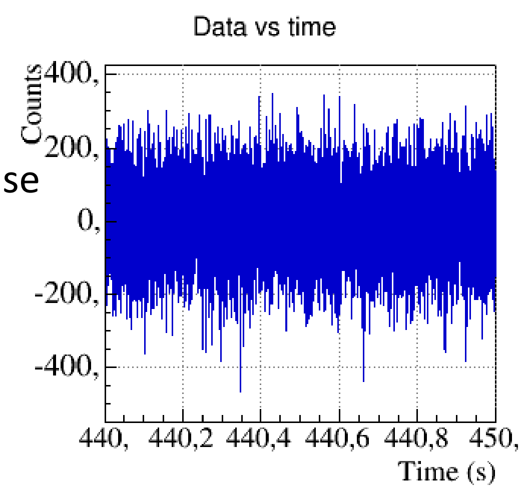
Assumption: noise is random and ergodic

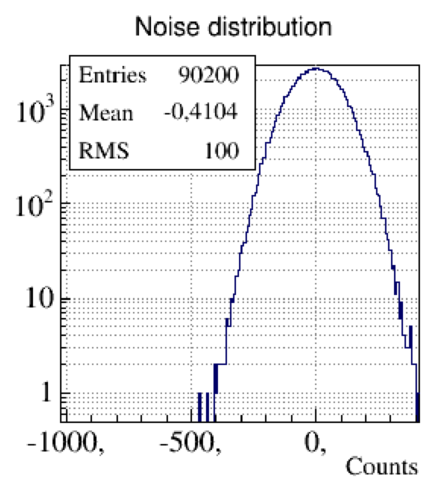
→ noise characterised by its amplitude spectral density (ASD)

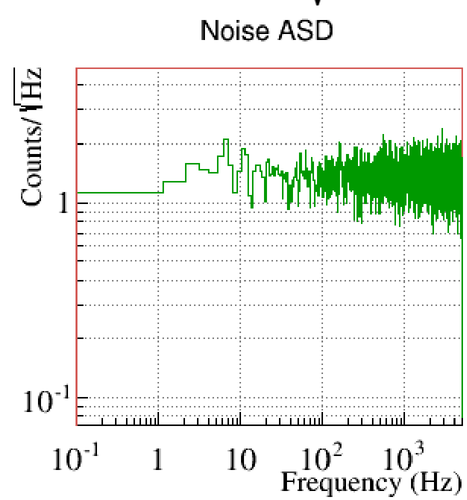
$$ASD = \sqrt{PSD} = \sqrt{\frac{|DFT|^2}{T}}$$

Random gaussian noise
1 count/√Hz

Sampled at 10 kHz



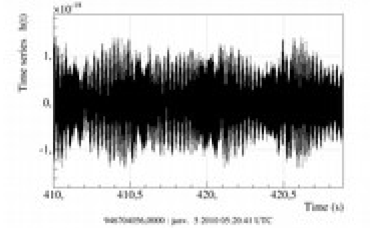




From hrec(t) to Virgo sensitivity curve

1/ Reconstruction of h(t)

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



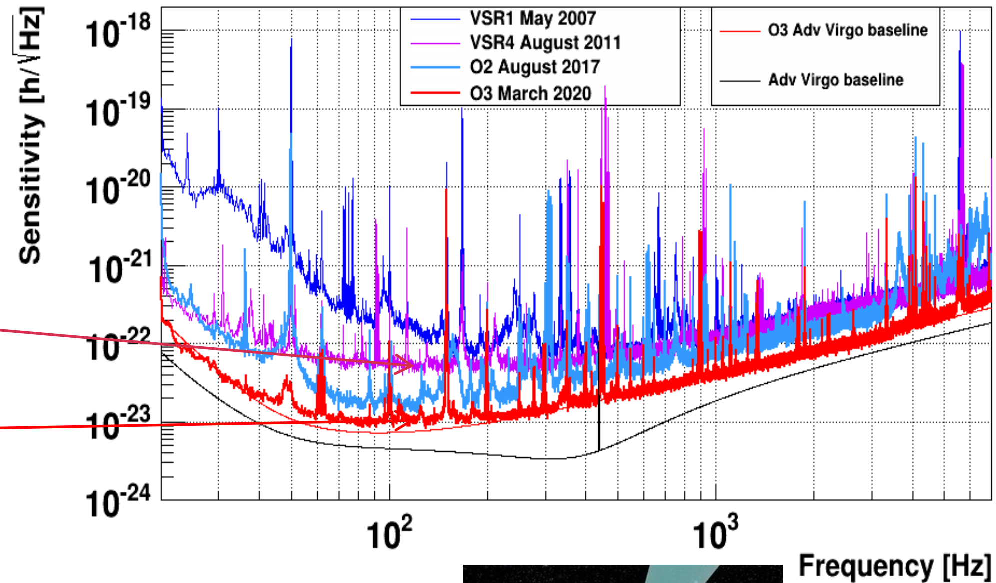
2/ Amplitude spectral density of *h(t)*
(noise standard deviation over 1 s)

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

Discrete Fourier Transform (DFT)

~10^{-19} m/√Hz (Virgo, 2011)

~10^{-20} m/√Hz (Advanced Virgo, 2020)



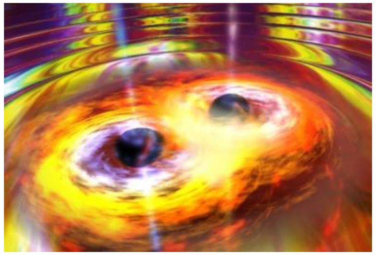


Image: Danna Berry/SkyWorks/NASA

Compact Binary Coalescences

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

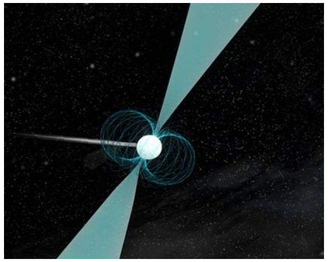


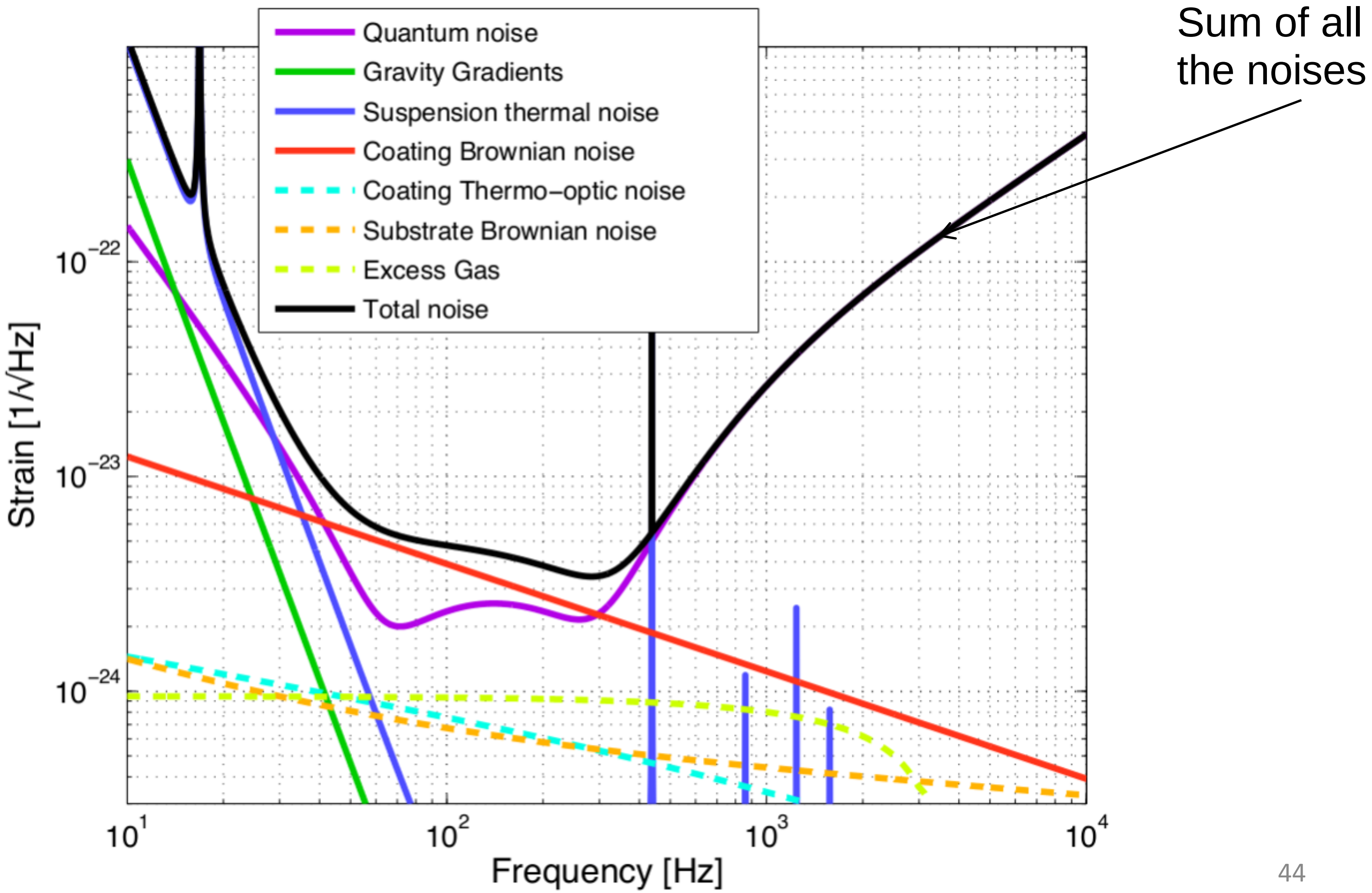
Image: B. Saxton (NRAO/AUI/NSF)

Rotating neutron stars

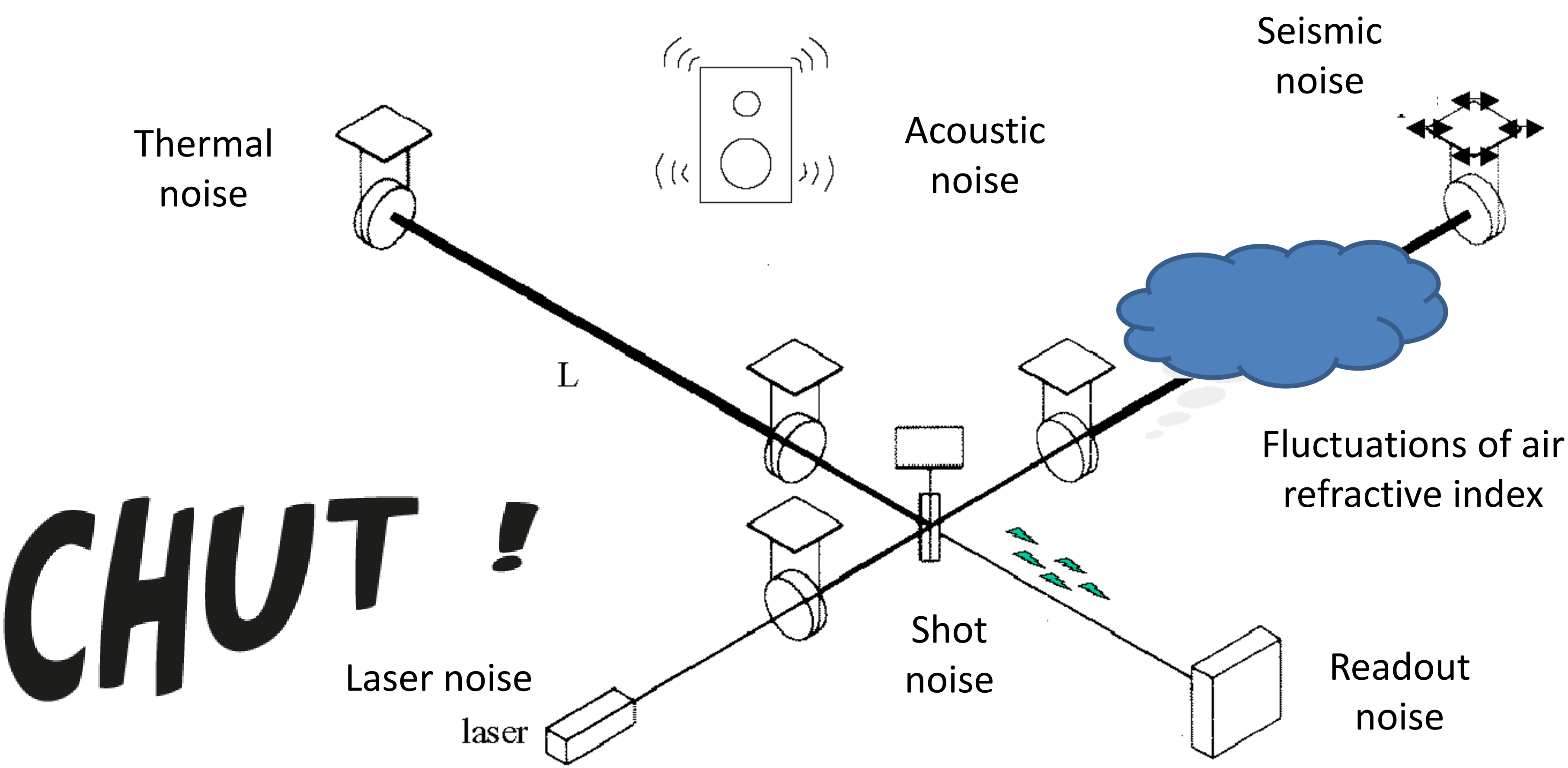
Signal averaged over days (~10^6 s)
→ can detect h ~ 10^{-26}

Nominal sensitivity of Advanced Virgo

Fundamental noise only
Possible technical noise not shown



Fundamental noise sources



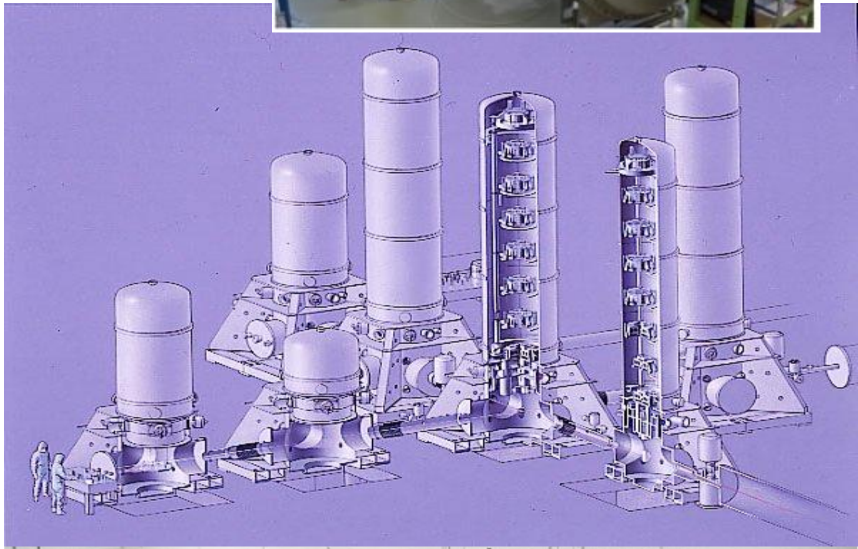
Under vacuum

Goals

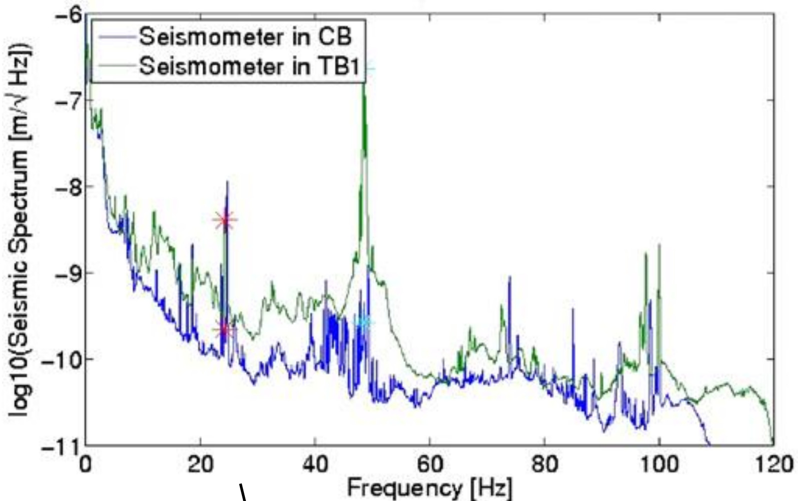
- Isolation against acoustic noise
- Avoid measurement noise due to fluctuations of air refractive index
- Keep mirrors clean

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

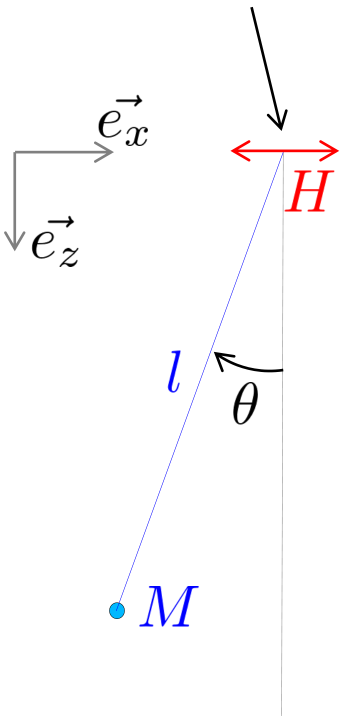


Seismic noise and suspended mirrors



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

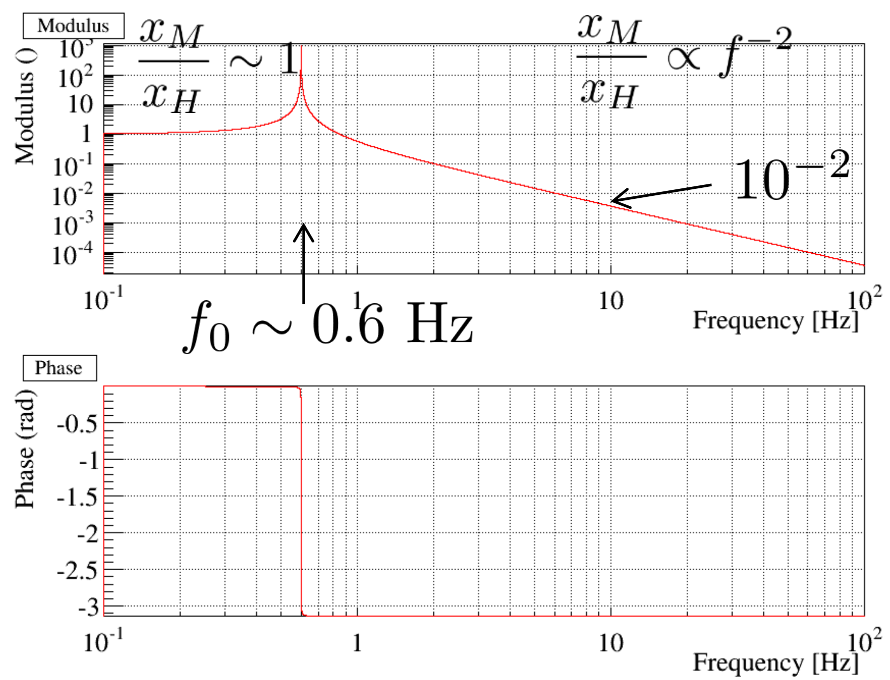
$\gg 10^{-19}\,\mathrm{m}/\sqrt{\mathrm{Hz}}$ needed to detect GW !!



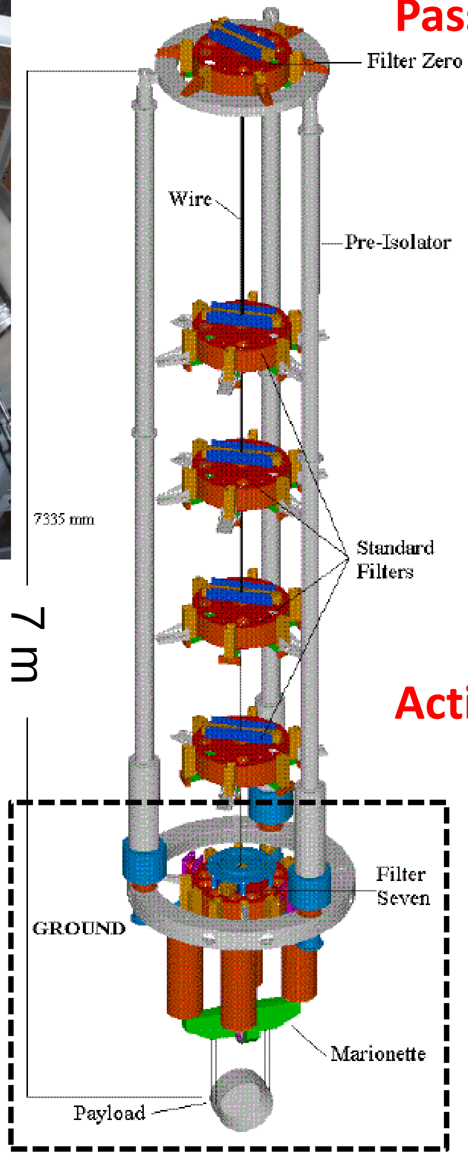
Assuming δx_H small and sinusoidal and θ small:

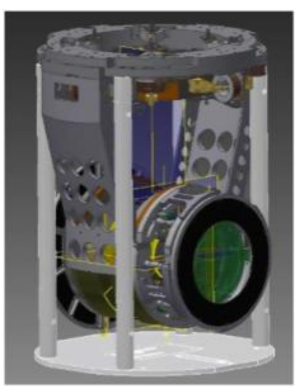
$$\underline{x_M} = \underline{\mathcal{H}} \times \underline{x_H}$$

Transfer function



Seismic noise: Virgo super-attenuators





Passive attenuation: 7 pendulum in cascade

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

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

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

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

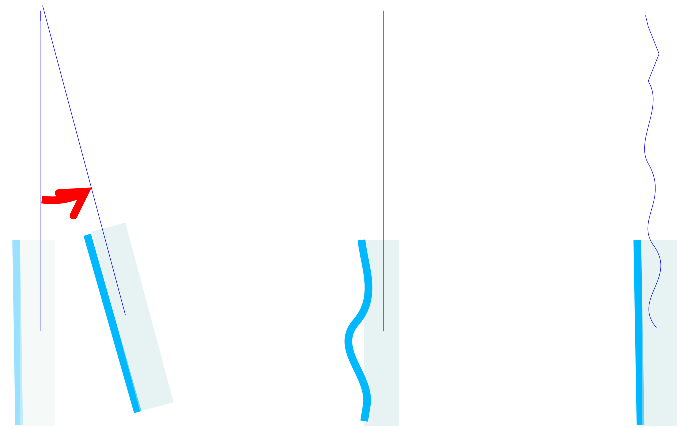
Active controls at low frequency

- Accelerometers or interferometer data
- Electromagnetic actuators
- Control loops

Thermal noise (pendulum and coating)

Microscopic thermal fluctuations

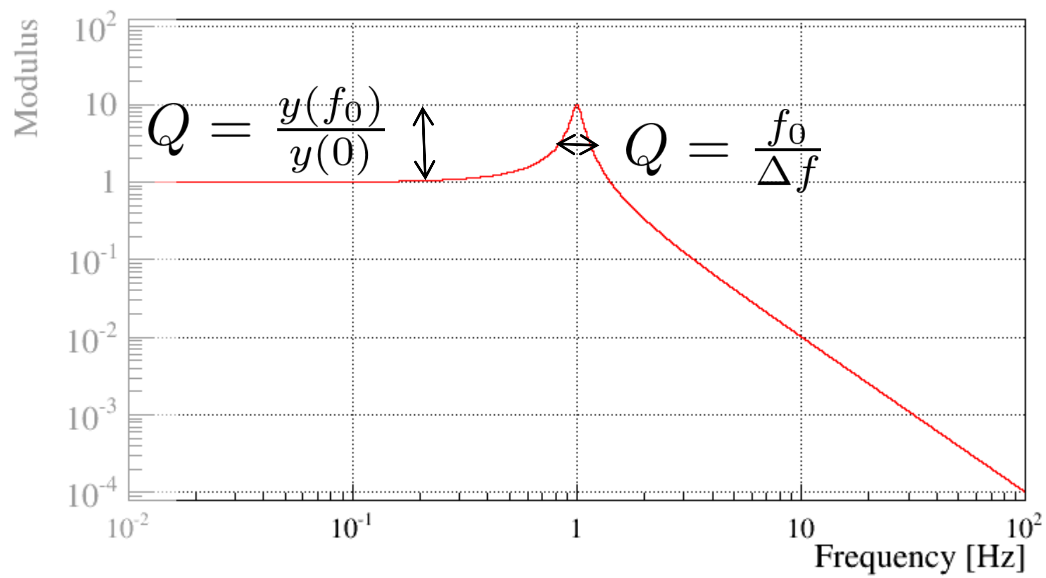
→ dissipation of energy through excitation of the macroscopic modes of the mirror

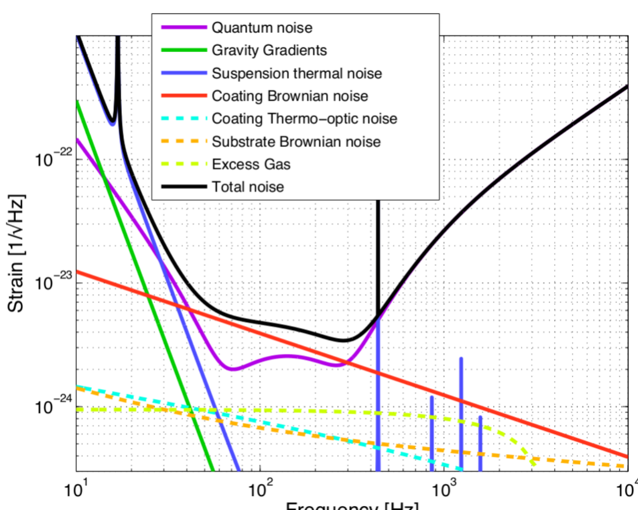


Pendulum mode
f < 40 Hz

"Mirror" mode
f> few kHz

"Violin" modes
f > 40 Hz



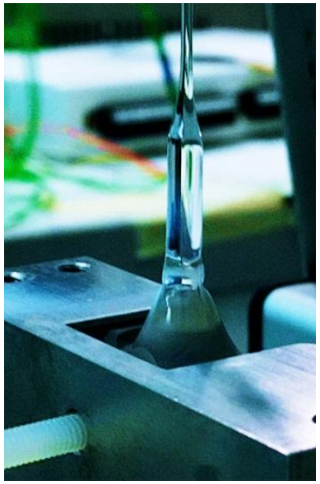


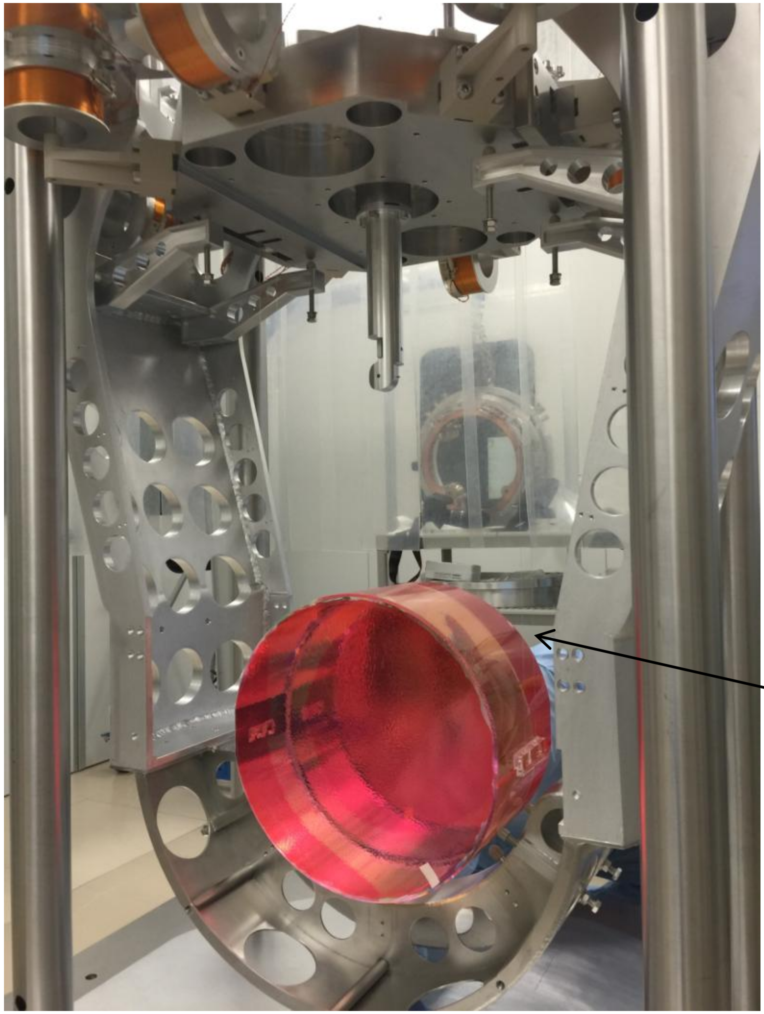
This noise directly modifies the positions of the mirror surfaces, and thus $\delta\Delta L$ and $h_{rec}(t)$!

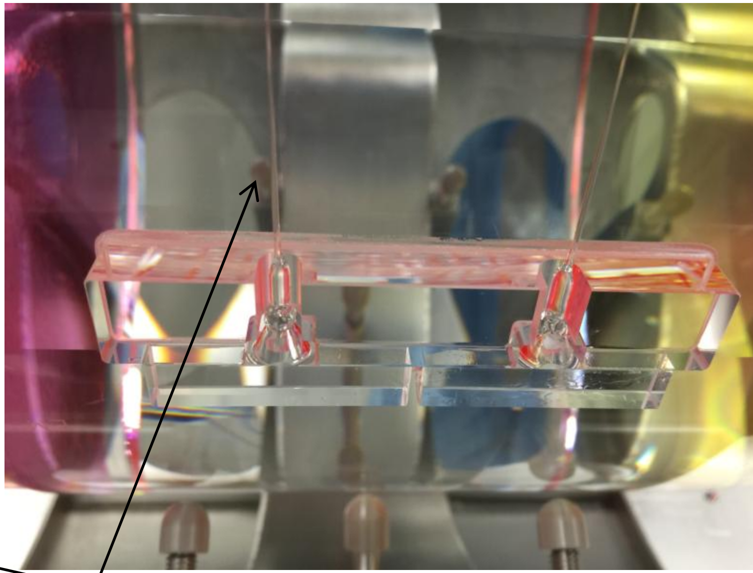
We want high quality factors Q to concentrate all the noise in a small frequency band

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

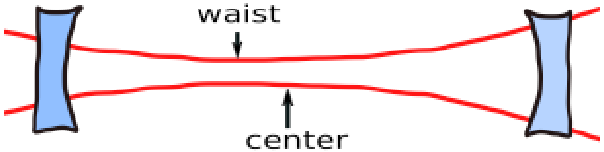
Reduction of thermal noise: mirror coating

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

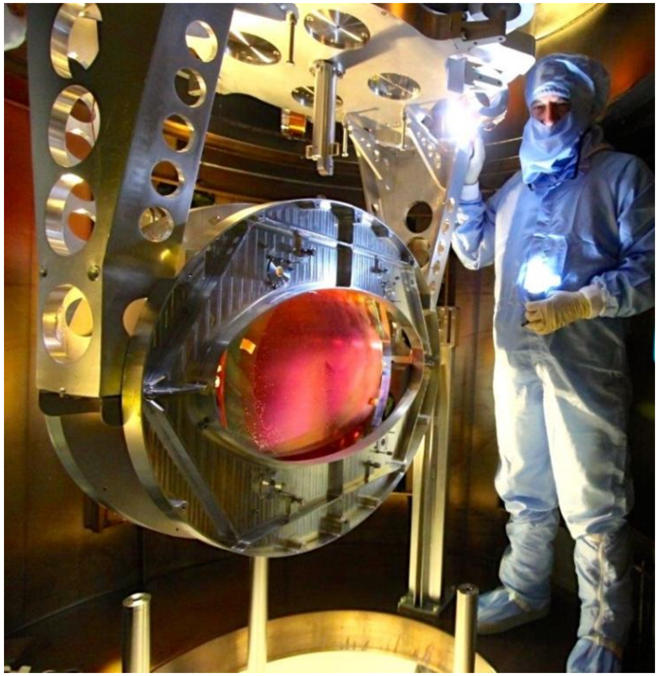
- Currently the main source of thermal noise
- Very high quality mirror coating developed in a lab close to Lyon (Laboratoire des Matériaux Avancés)
- R&D to improve mechanical properties of coating
- Cryogenics mirrors (at Kagra, future detectors)
  - other substrate
  - other coating
  - other wavelength

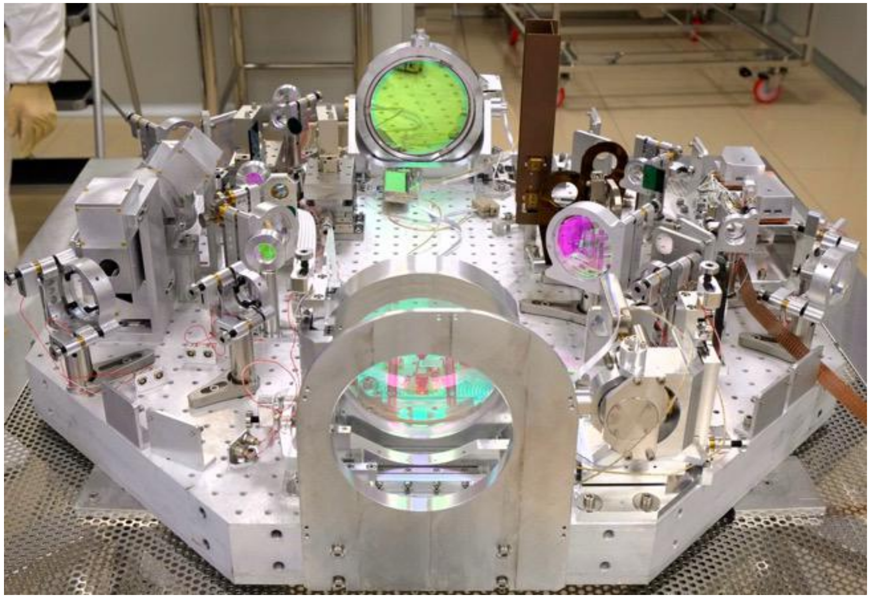
Thermal noise: coupling reduction

- Reduce the coupling between the laser beam and the thermal fluctuations
  → **use large beams**: fluctuations averaged over larger surface
  → 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



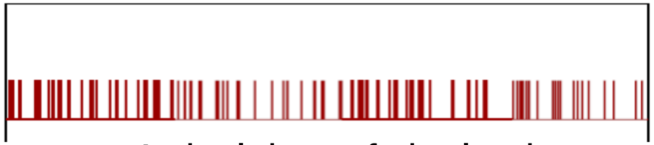


Shot noise

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.



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

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 $\delta\Delta L$

$$\delta P_t = (\text{Virgo response}) \times L_0 \times h$$

(in W/m)

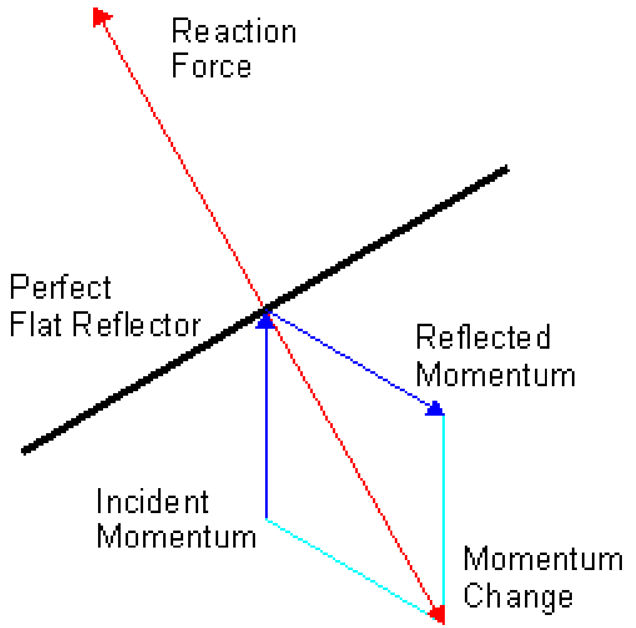
$$h_{equivalent} = \frac{1}{L_0}\frac{\sigma_{P_t}}{(\text{Virgo response})}$$

$\rightarrow h_{equivalent}\ \alpha\ 1/\sqrt{P}$

Radiation pressure noise

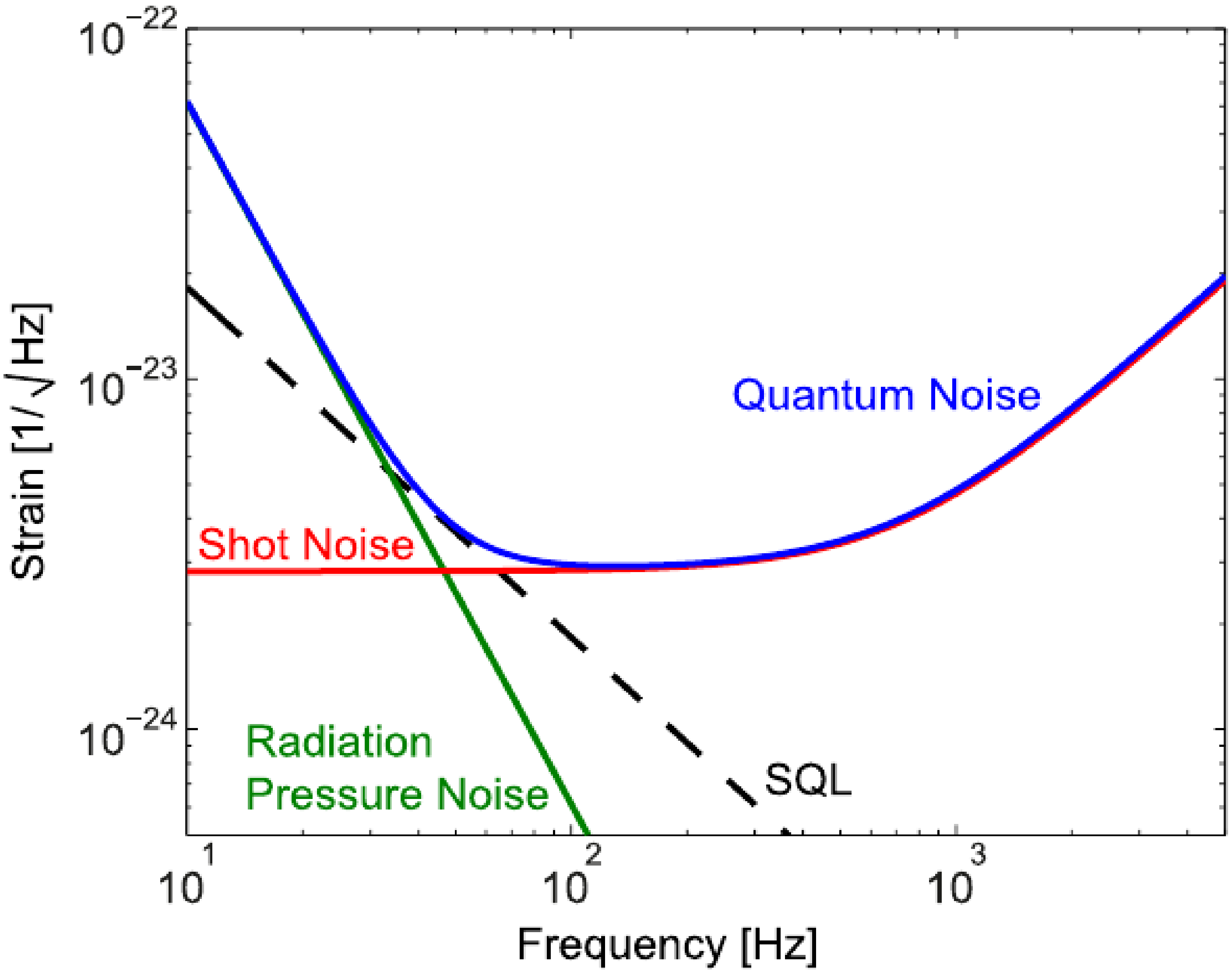
- Radiation pressure: transfer of photon's momentum to the reflective surface (recoil force)
- Radiation pressure noise: due to fluctuations of number of photons hitting the mirror surfaces > mirror motion noise
- Radiation pressure noise impact at low frequency:

  > Mirror motion filtered by pendulum mechanical response

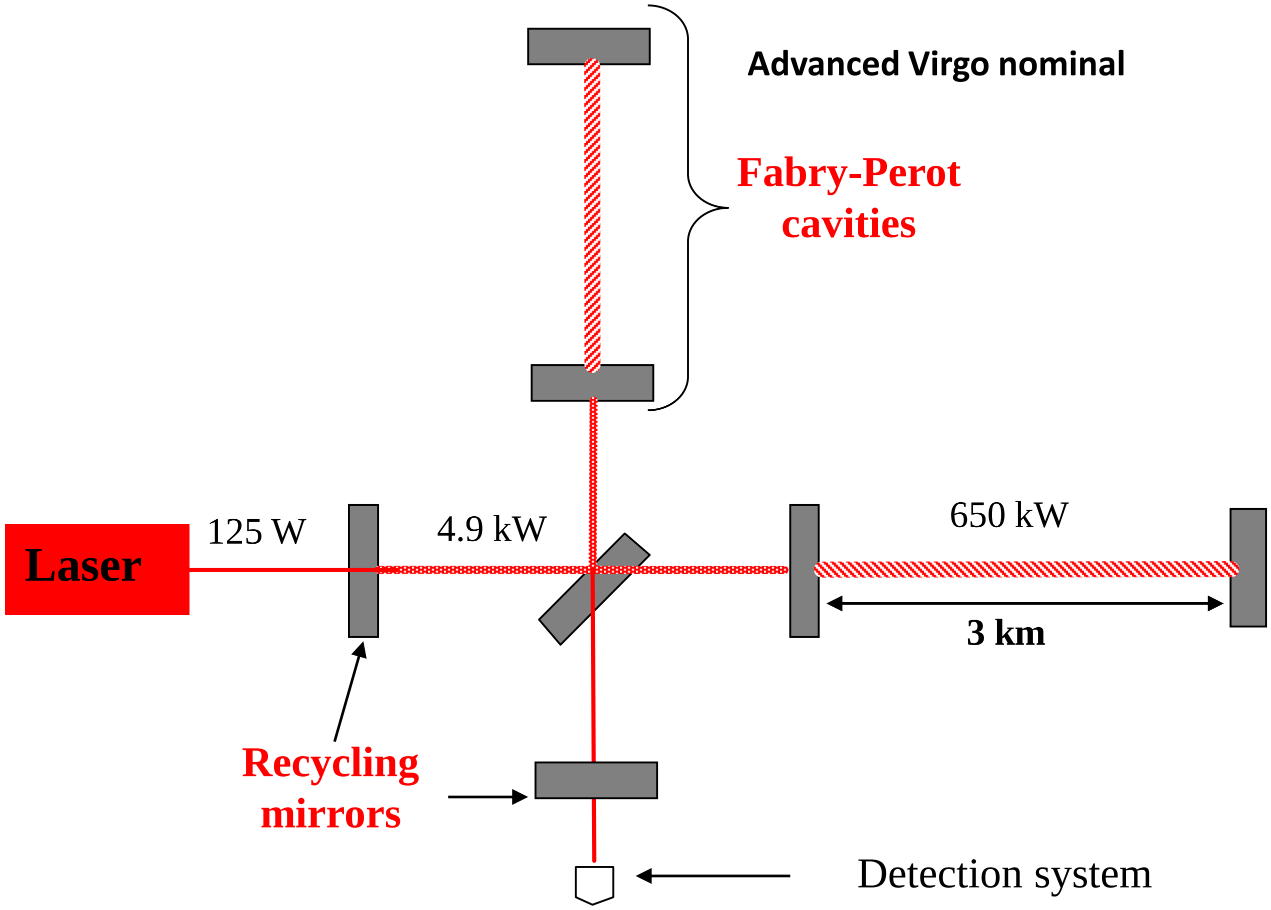


$\rightarrow h_{equivalent}\ \alpha\ \sqrt{P}$

Quantum noise in the sensitivity



Minimizing shot noise with optical configuration

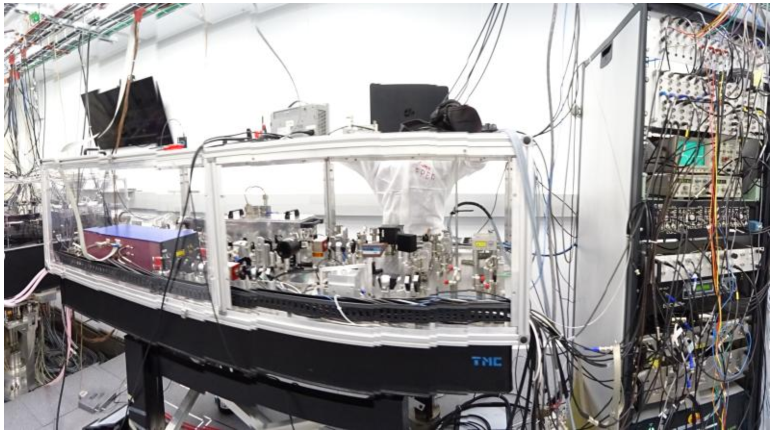


Reduction of shot noise: high power laser

Goal for AdV (nominal):

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

→ 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

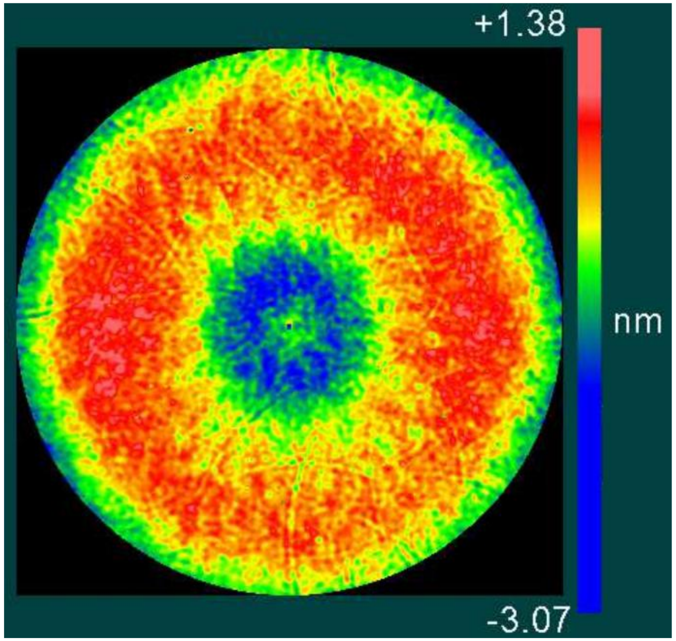
- **Thermal absorption in the mirrors (optical lensing)**

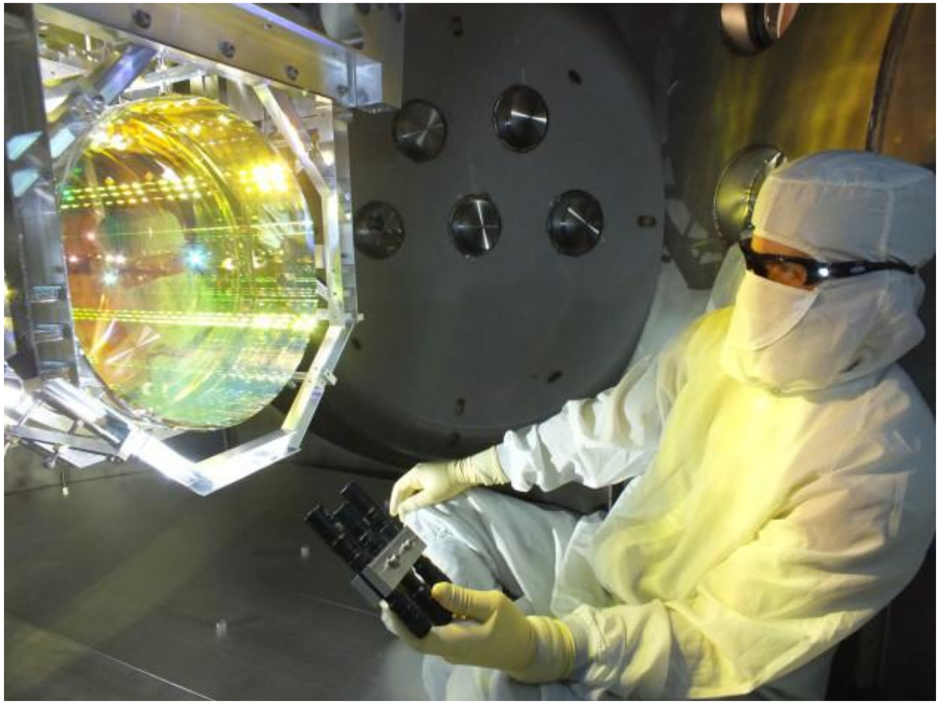
  → Need of thermal compensation system

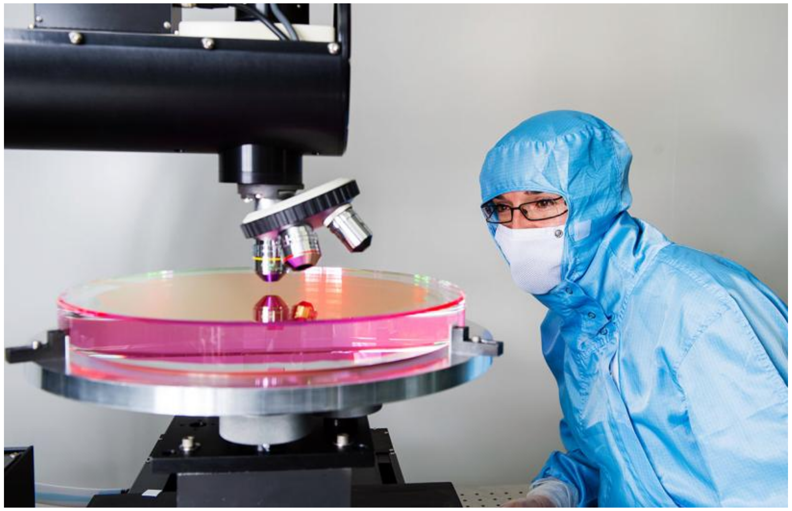
Avoid optical losses to not spoil high power → high quality mirrors

« 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)

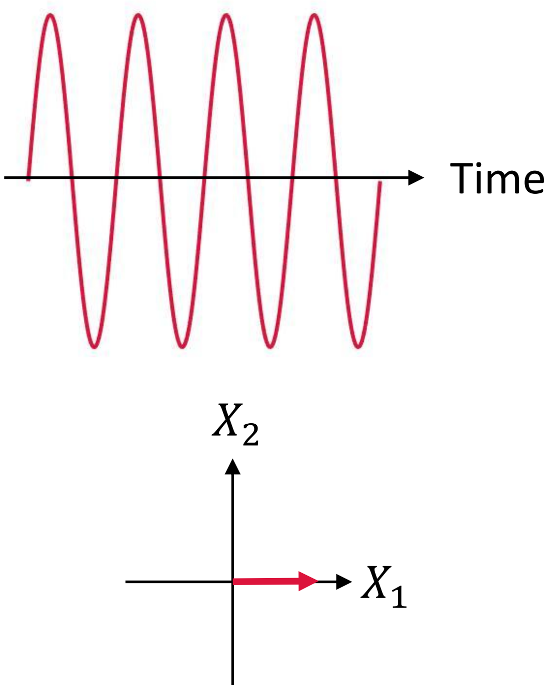




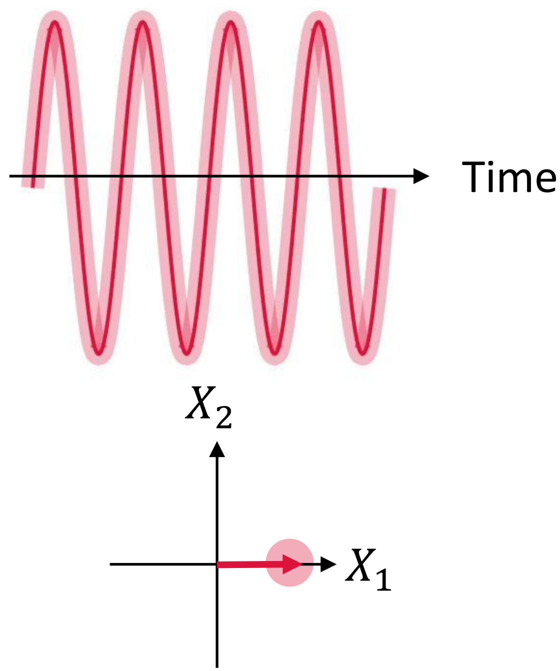


Optical field models

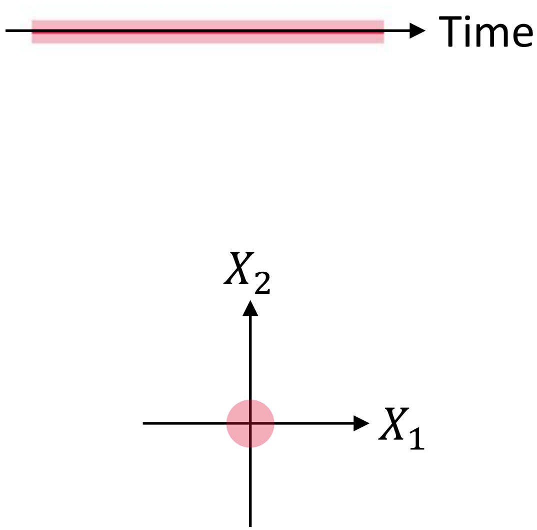
Classical picture



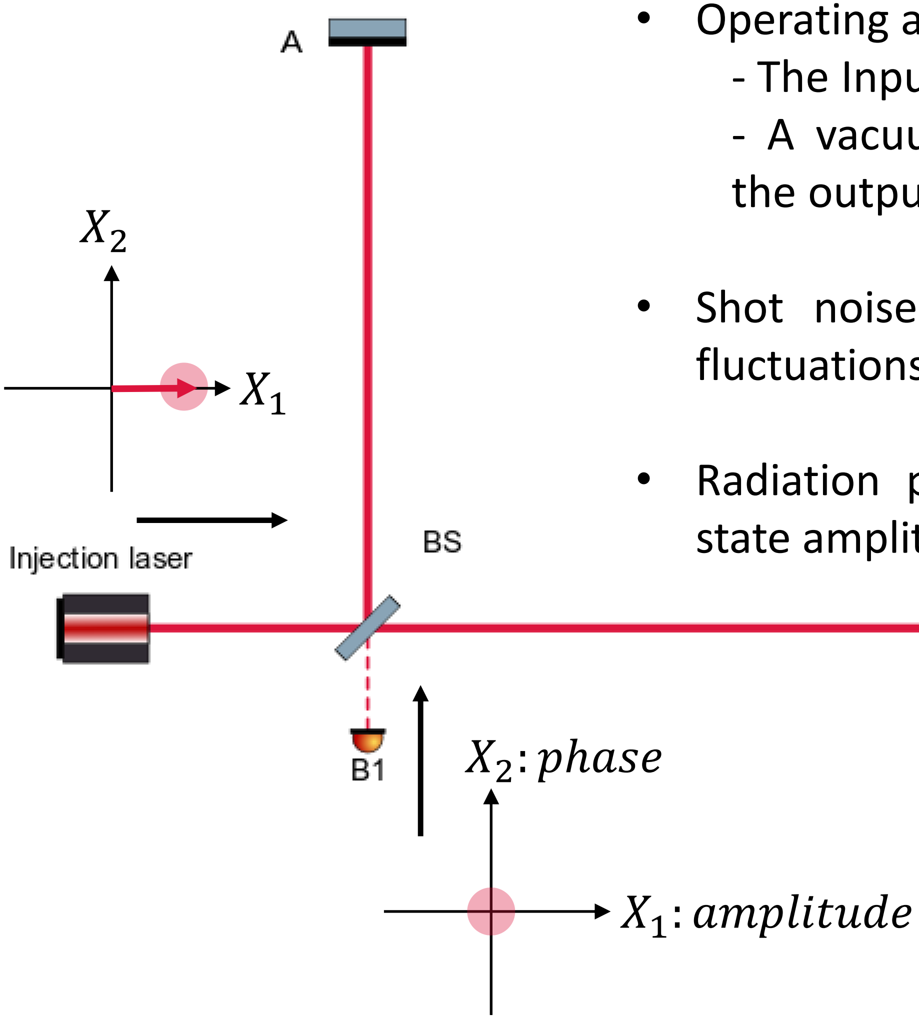
Coherent State



Vacuum State

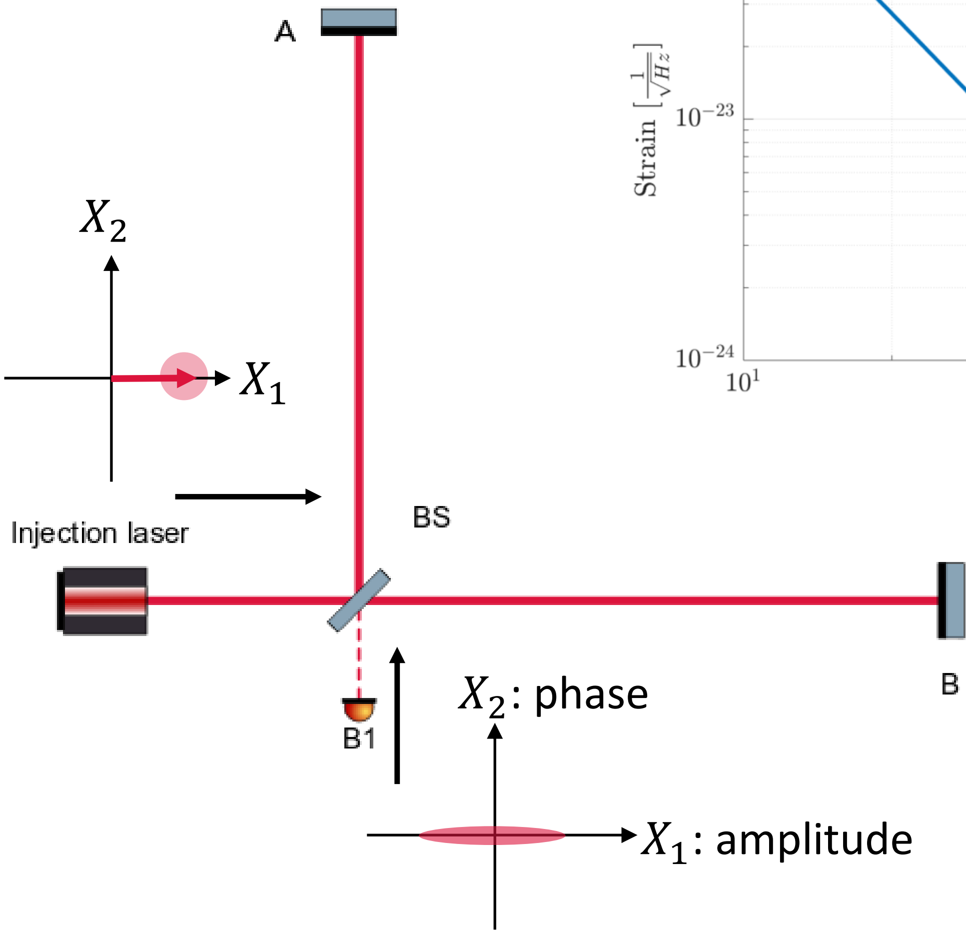


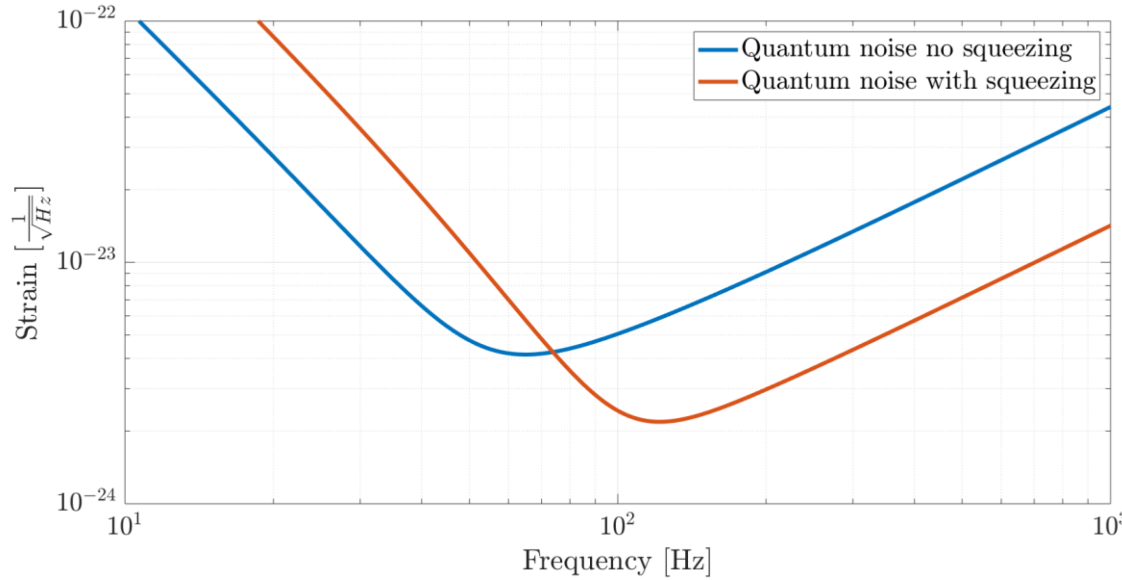
Michelson interferometer at dark fringe and quantum noises



- Operating at dark-fringe :
  - The Input Laser is reflected back to the injection
  - A vacuum field enters the interferometer from the output port
- Shot noise arises from the vacuum state phase fluctuations (ΔX_2)
- Radiation pressure noise arises from the vacuum state amplitude fluctuations (ΔX_1)

Reduction of shot noise: squeezing





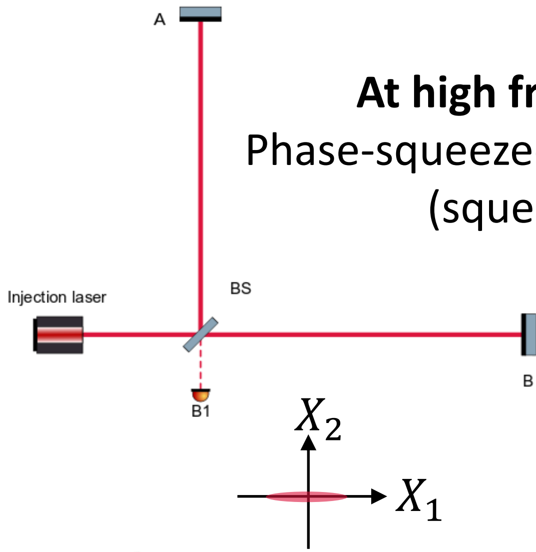
Inject a phase-squeezed vacuum state in the interferometer (squeezing)

Already in place during O3 run

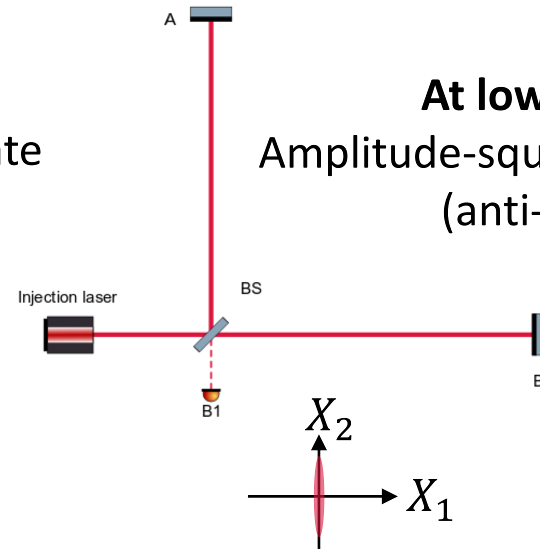
→ **Decrease shot noise**

But increase radiation pressure noise

Reduction of quantum noise: frequency dependent squeezing

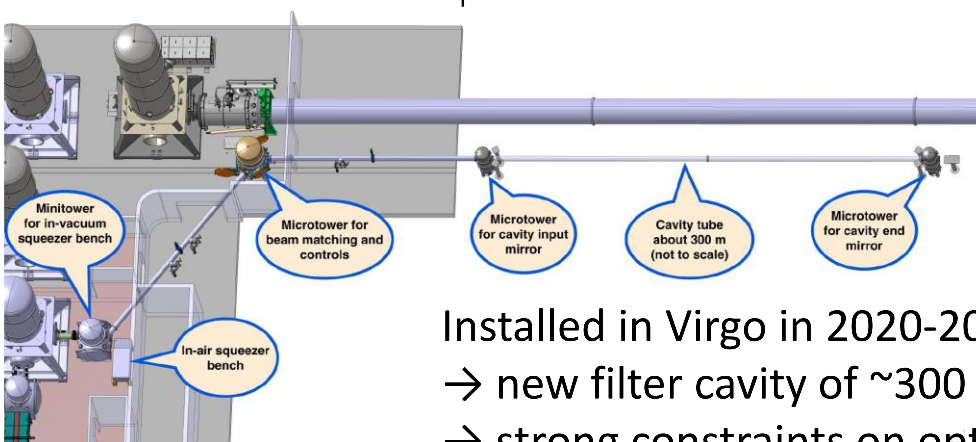


At high frequency:
Phase-squeezed vacuum State
(squeezing)



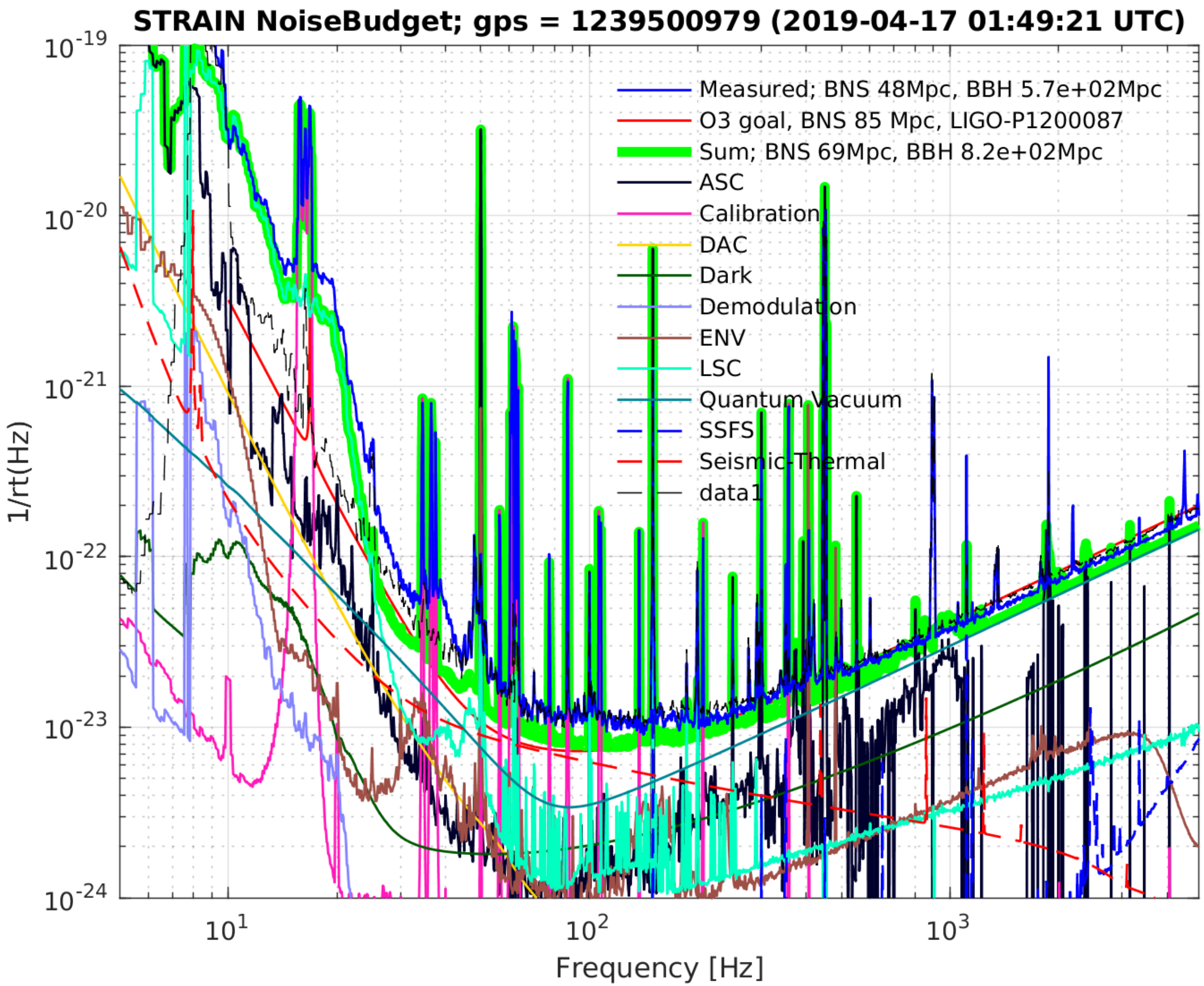
At low frequency:
Amplitude-squeezed vacuum State
(anti-squeezing)

→ Decrease shot noise at high freq
AND radiation pressure noise at low freq



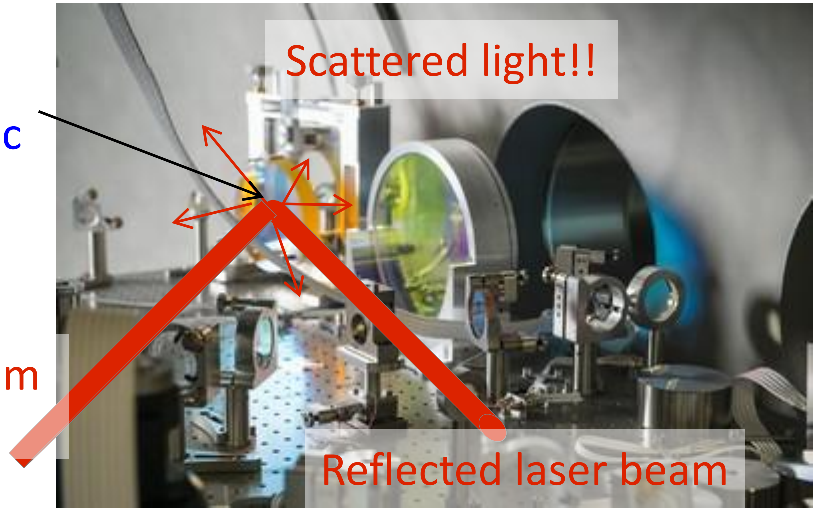
Installed in Virgo in 2020-2021
→ new filter cavity of ~300 m, with finesse ~10000
→ strong constraints on optical losses, beam matching and alignment, …
(suspended in vacuum optical benches)

Example of Advanced Virgo noise budget (O3 run)



Example of technical noise: Scattered light

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



Incident laser beam

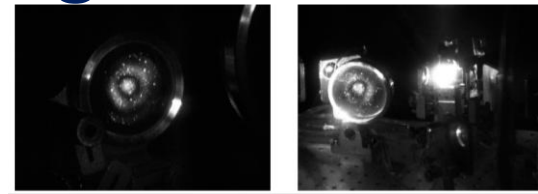
some photons of the scattered light gets recombined with the interferometer beam

↓

phase noise

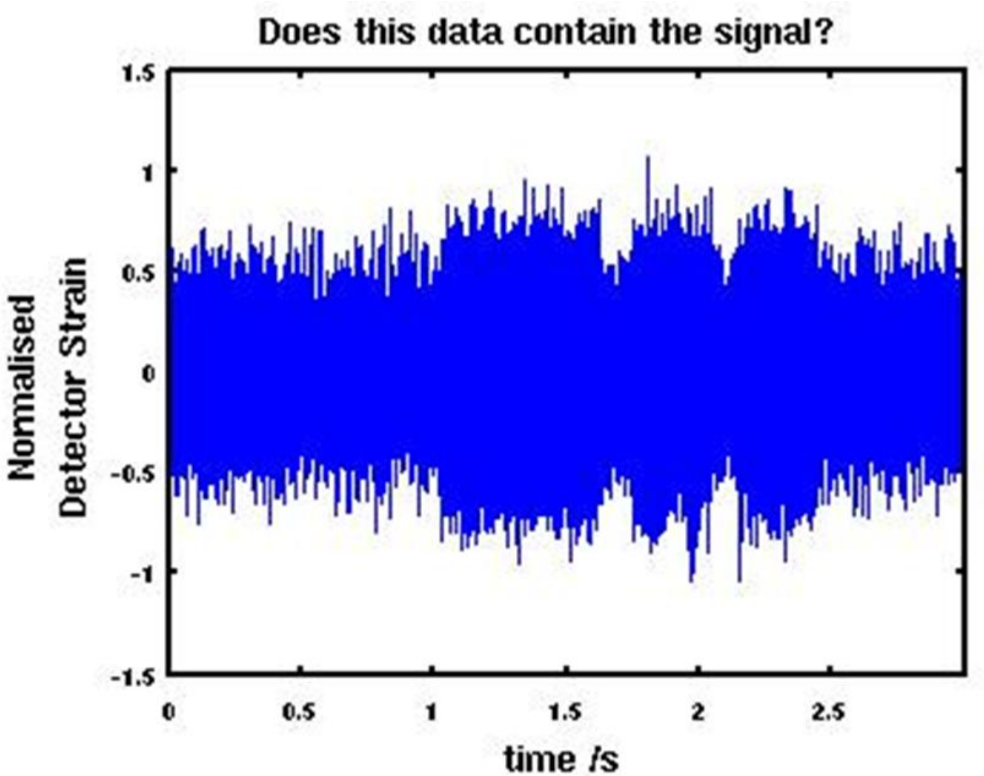
↓

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

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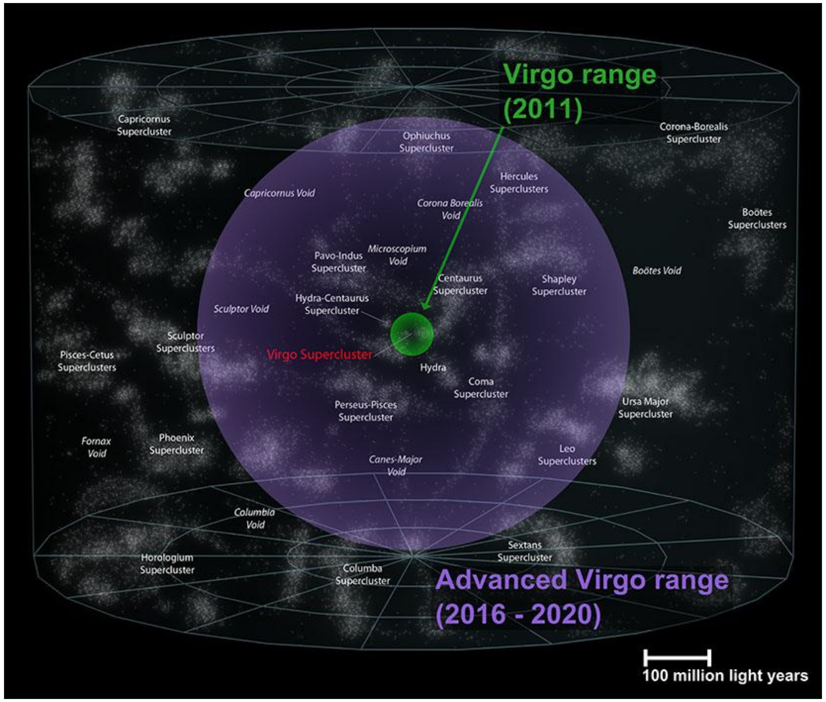
Range of Advanced detectors



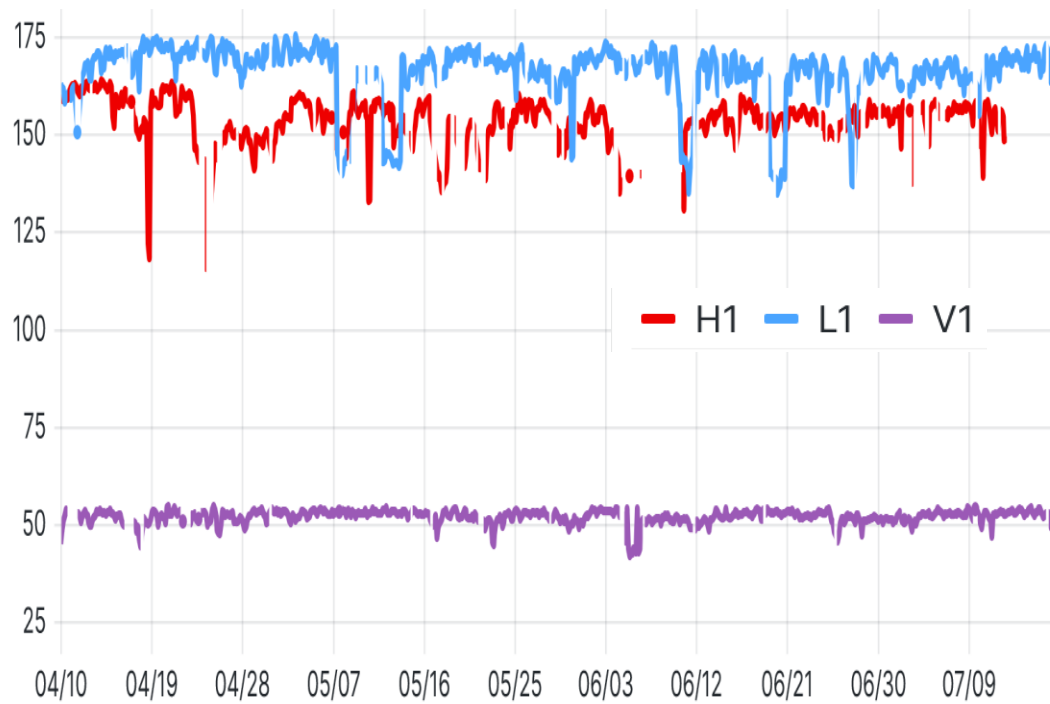
Distance at which a neutron star binary coalescence ($1.4\ M_\odot$ - $1.4\ M_\odot$) can be seen with signal-to-noise ratio of 8

Improving the sensitivity (or range) by a factor 10

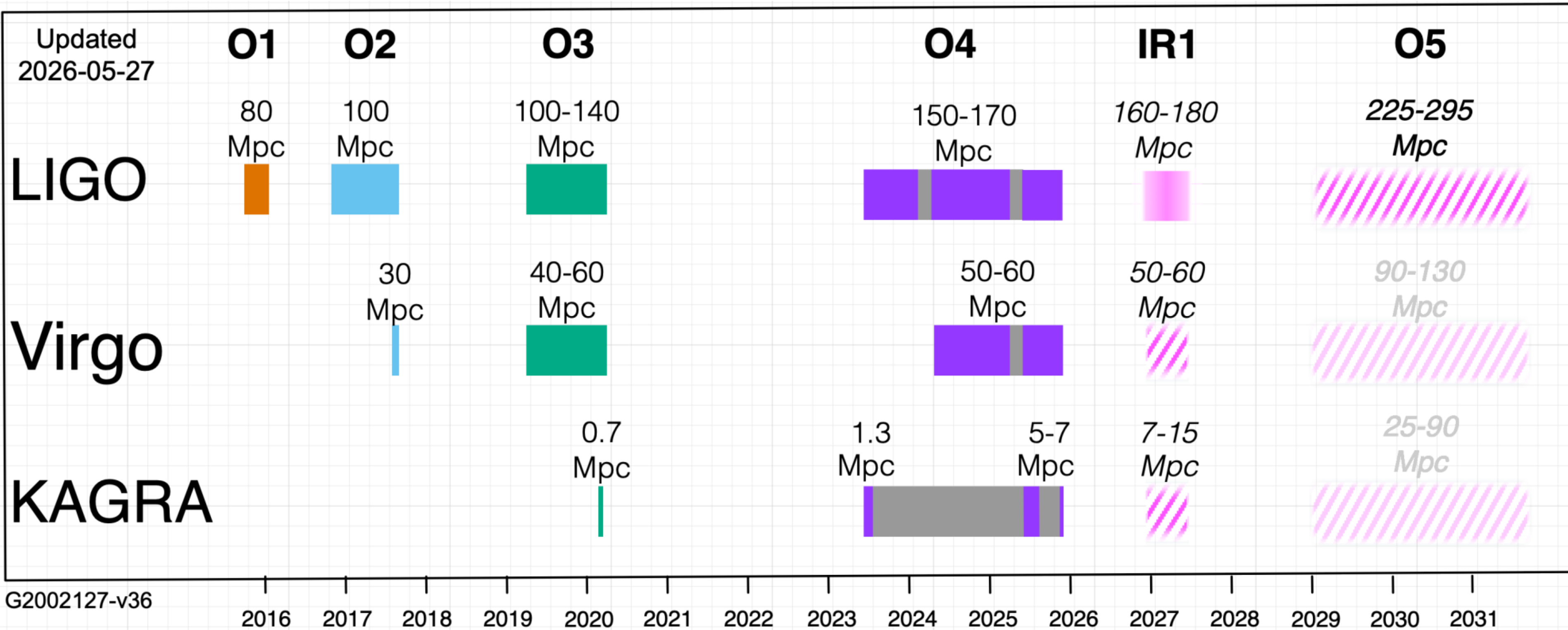
↓

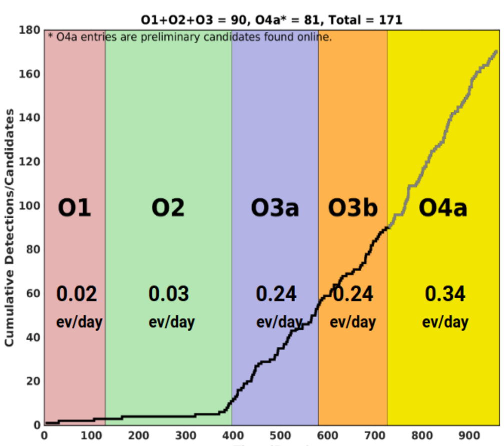
Increase the volume (or event rate) by $10^3 = 1000$

LIGO-Virgo ranges (Mpc) during the O4 run (2024) →



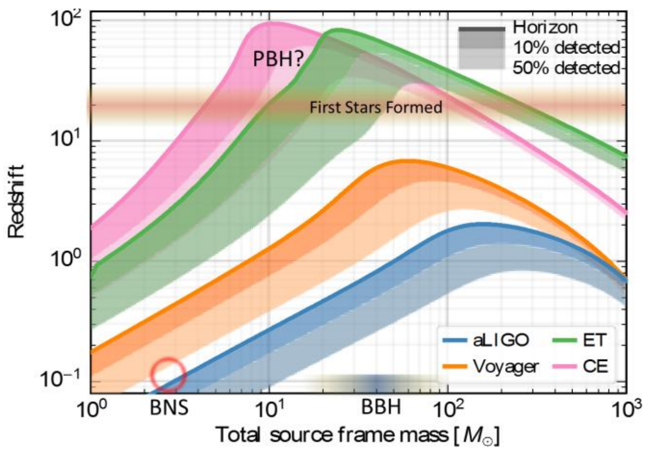
Observing runs





Einstein Telescope and Cosmic Explorer

- **Third generation interferometer: gain another factor 10 in sensitivity and enlarge bandwidth**

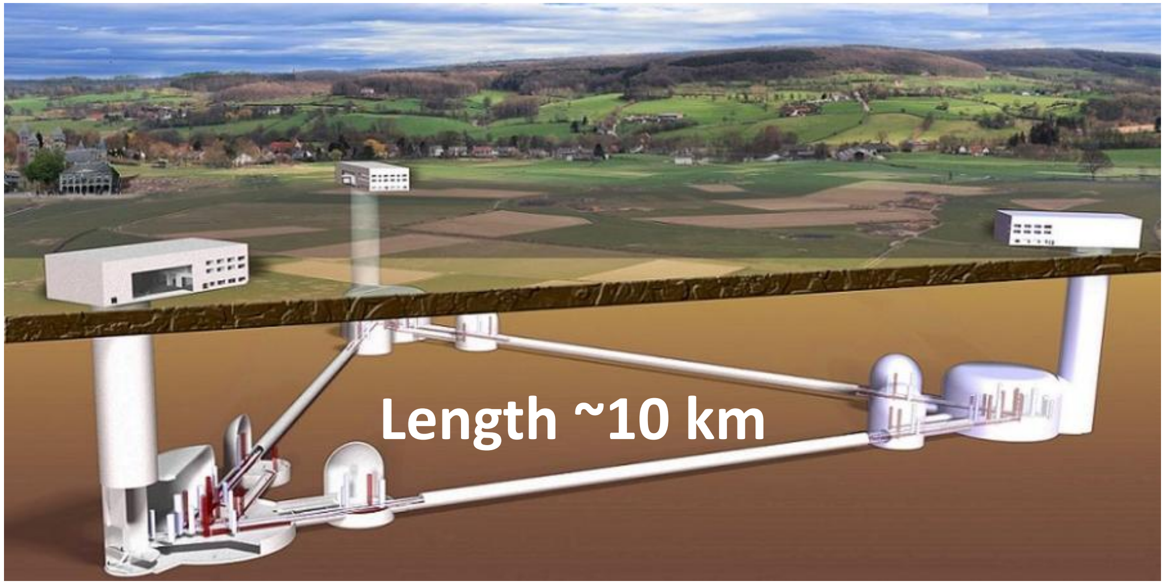


Einstein Telescope (Europe):
Located underground, with ~10 km arms
Cryogenics to reduce thermal noise
Xylophone configuration?
cold + hot interferometers in parallel

Cosmic Explorer (US):
With ~40 km arms

Could probe CBC signals from a large fraction of the Universe

In operation after 2036+?

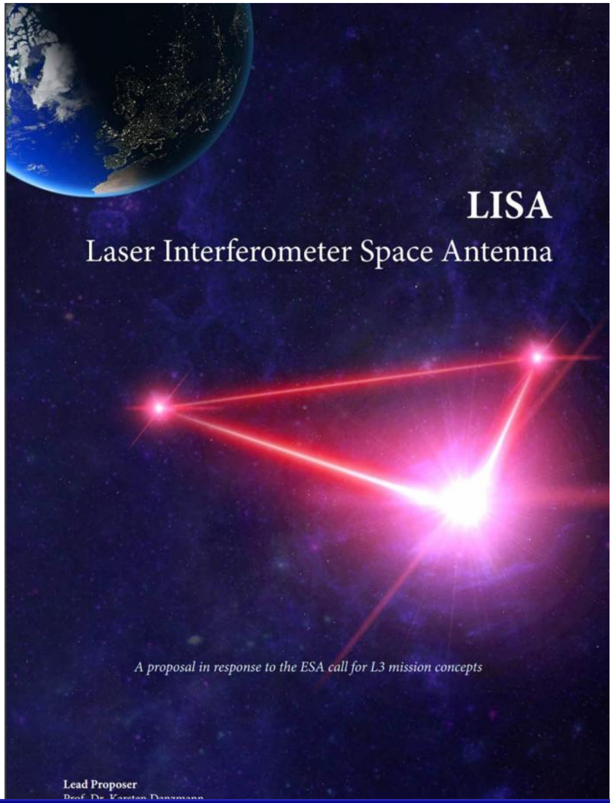


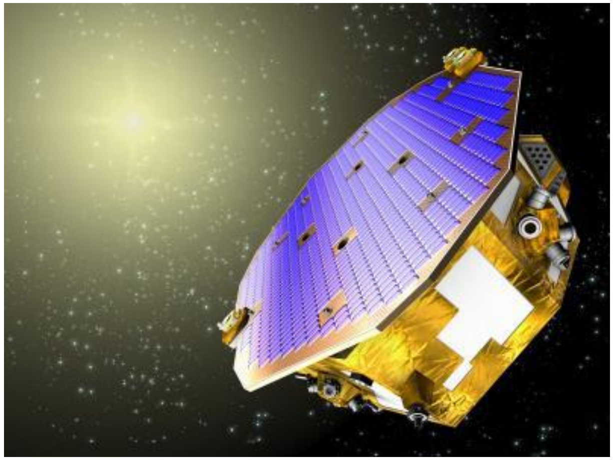
Spatial interferometer: LISA

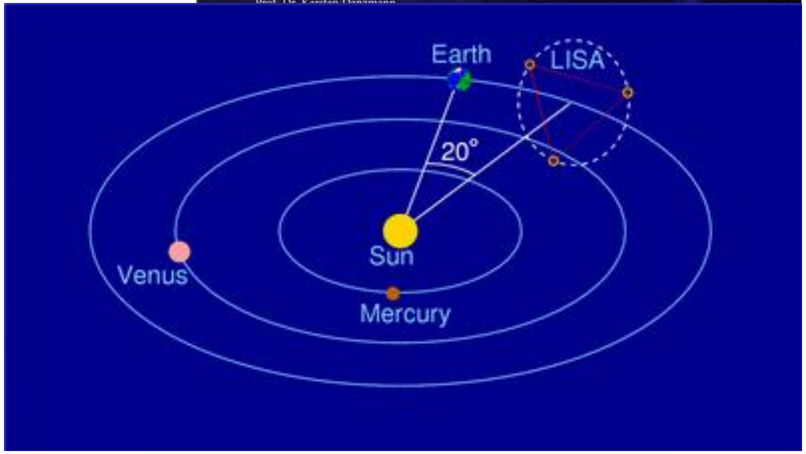
- **Bandwidth: 0.1 mHz to 1 Hz (2.5 million km arm length)**
- Launch of LISA around 2035?

  → operation for 5 to 10 years

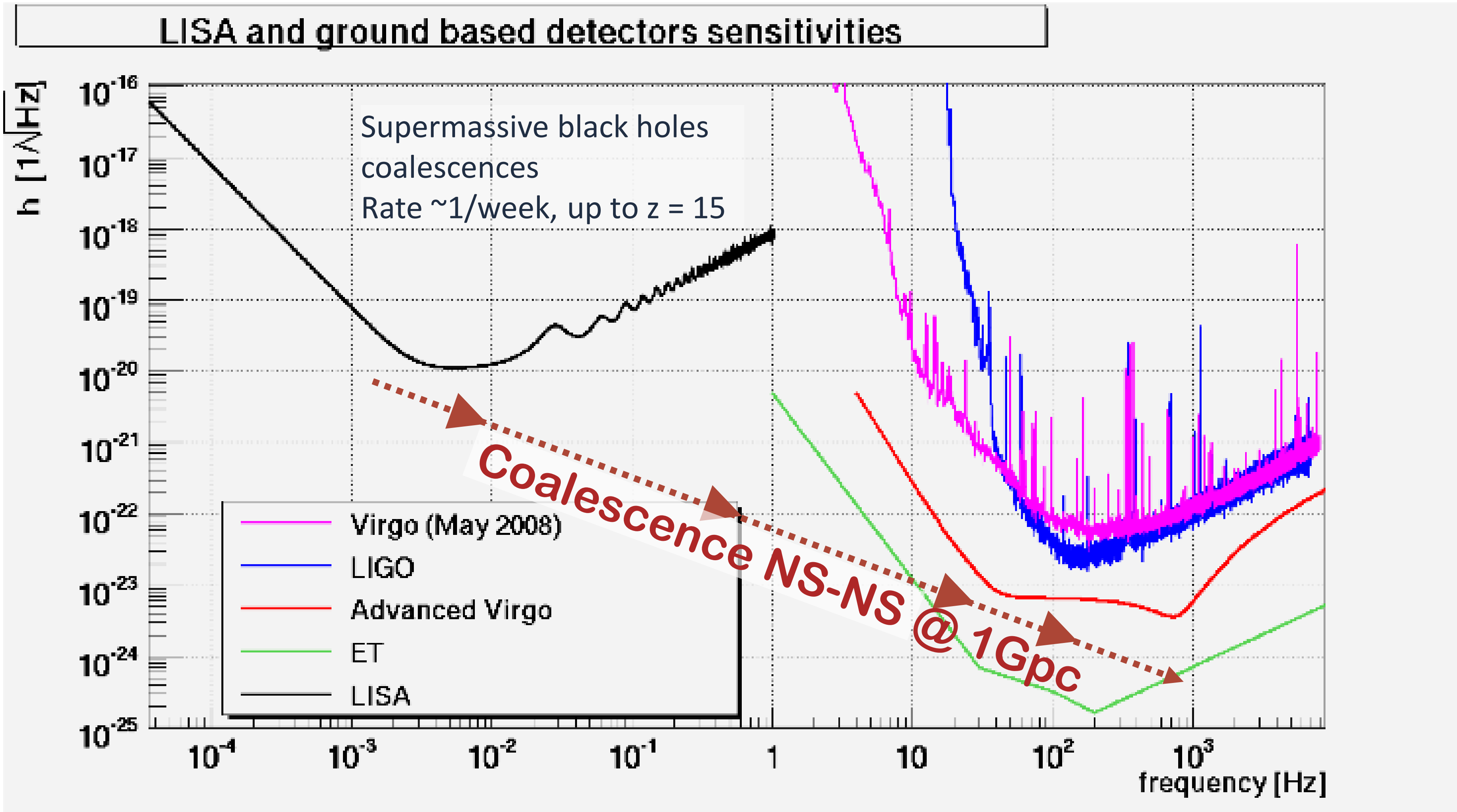
- Successful intermediate step: LISA Pathfinder
  - ➢ launched end 2015
  - ➢ test of free-fall masses
  - ➢ validation of differential motion measurements





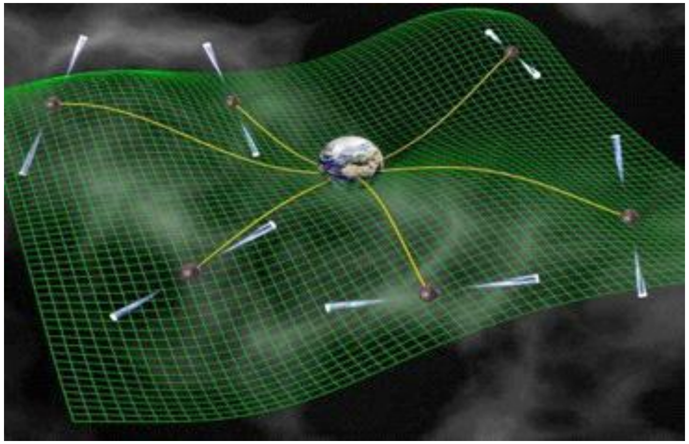


ET and LISA performances



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 to be confirmed**

A large GW spectrum to be studied…