

The Virgo detector

L. Rolland
LAPP-Annecy
GraSPA summer school

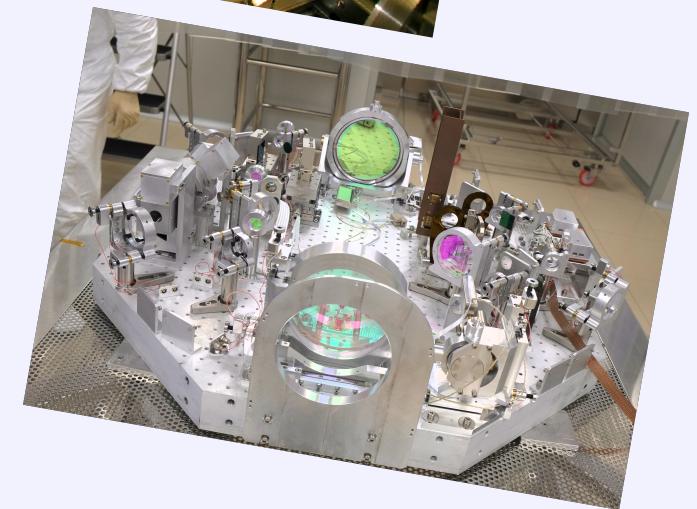


Table of contents

- **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 do we measure the GW strain, $h(t)$, from this detector?**
- **Some noises of the Virgo detector**
 - What is a noise?
 - The fundamental noises: seismic, thermal, and shot noises
 - History of Virgo noise

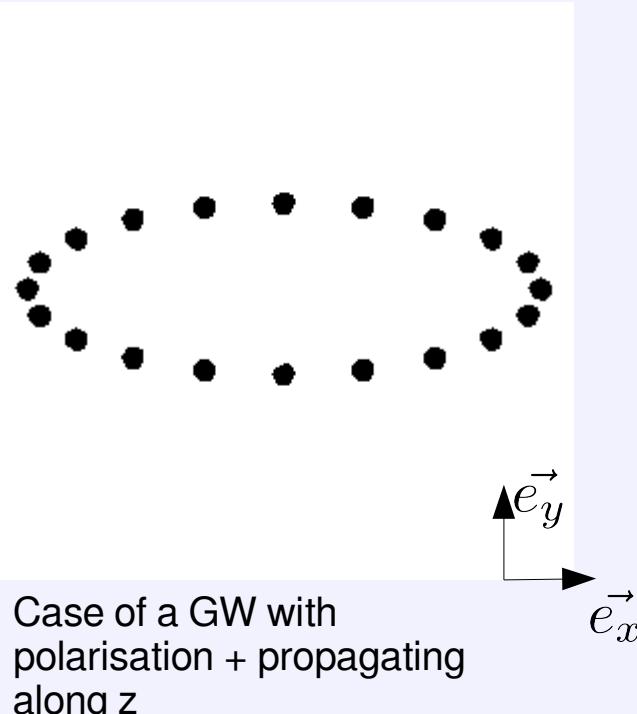
Reminder: effect of a GW on free masses

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

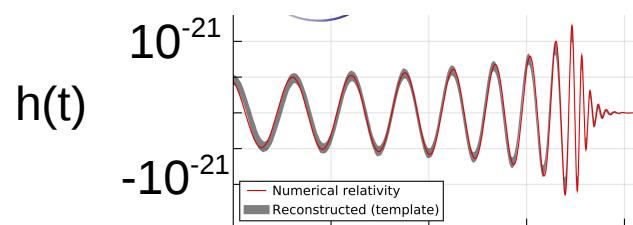
$$\delta x(t) = -\delta y(t) = \frac{1}{2} h(t) L_0$$

h(t): amplitude of the GW

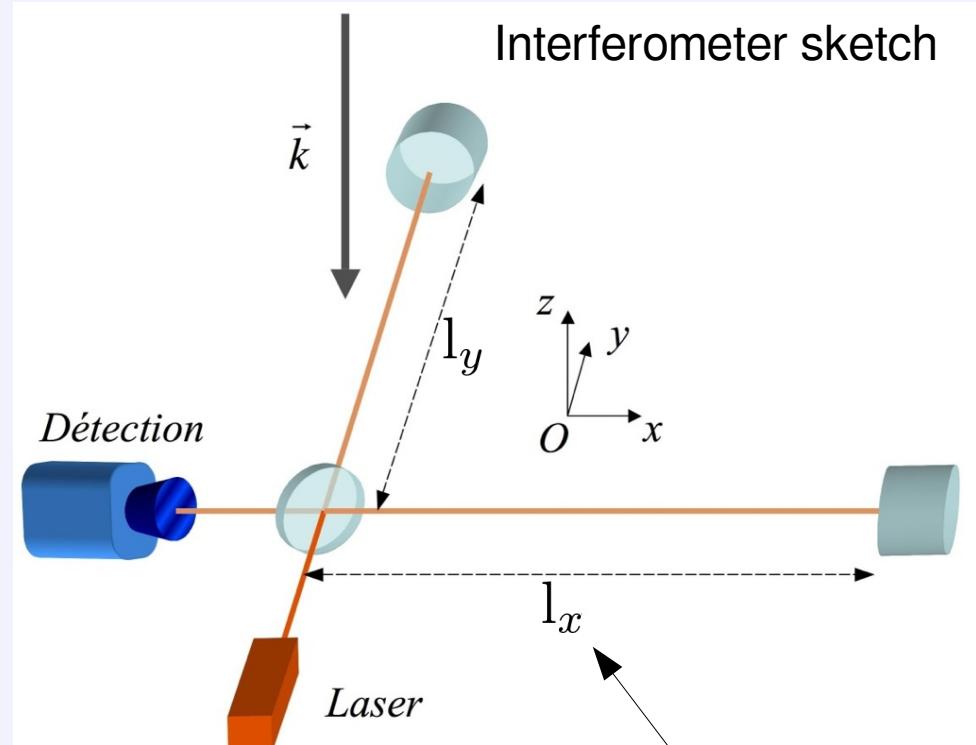
Typical amplitude of a GW crossing the Earth:
 $h \sim 10^{-23}$ (h has no dimension/unit)



Reconstructed strain of GW150914



A general overview of the Virgo detector

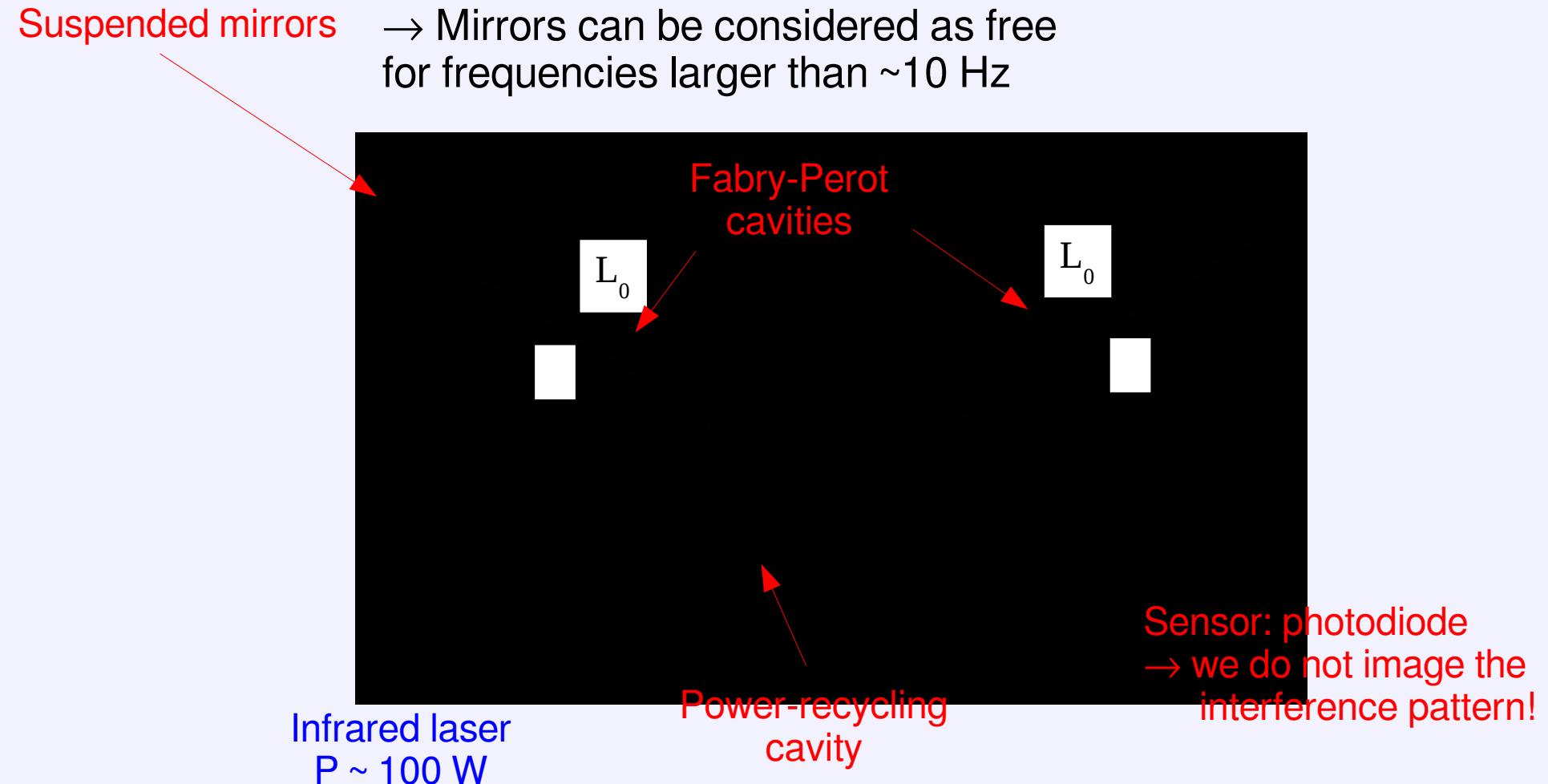


The interference pattern depends on ΔL :

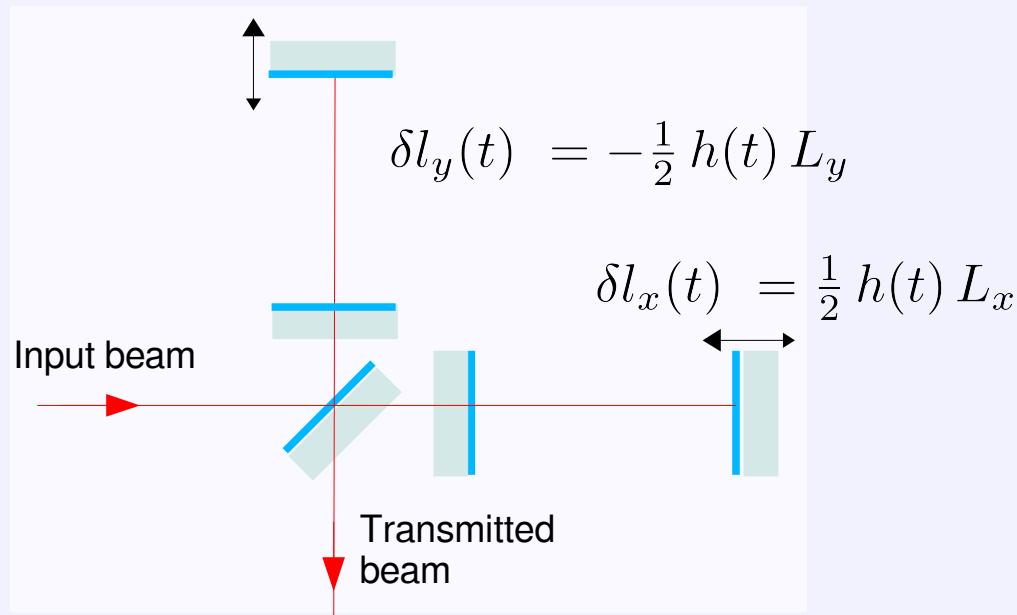
$$\Delta L(t) = l_x(t) - l_y(t)$$

Length of the arms: $L_0 = 3 \text{ km}$

Virgo: a more complicated interferometer



Orders of magnitude

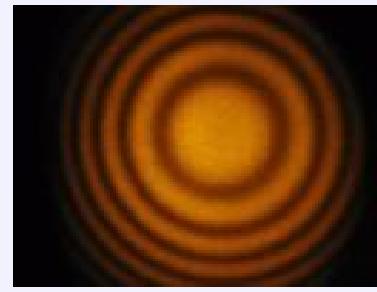
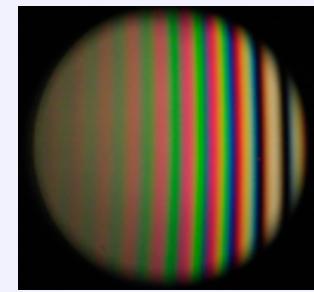
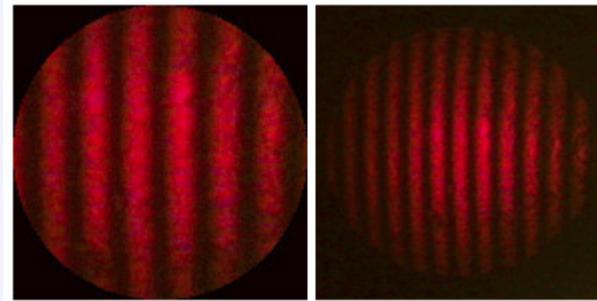


Typical amplitude of differential arm length variations when a GW crosses the Earth:

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

$$\begin{aligned}h &\sim 10^{-23} & L_0 &= 3 \text{ km} \\ \rightarrow \delta\Delta L &\sim 3 \times 10^{-20} \text{ m} \\ &\sim \frac{\text{size of a proton}}{100000}\end{aligned}$$

How and for what did you use interferometers?



Wavelength of monochromatic source

Sodium doublet wavelength separation

Classroom interferometer



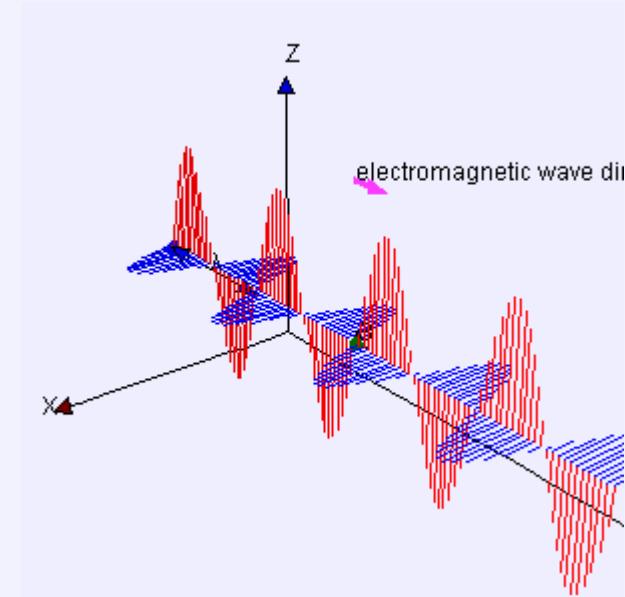
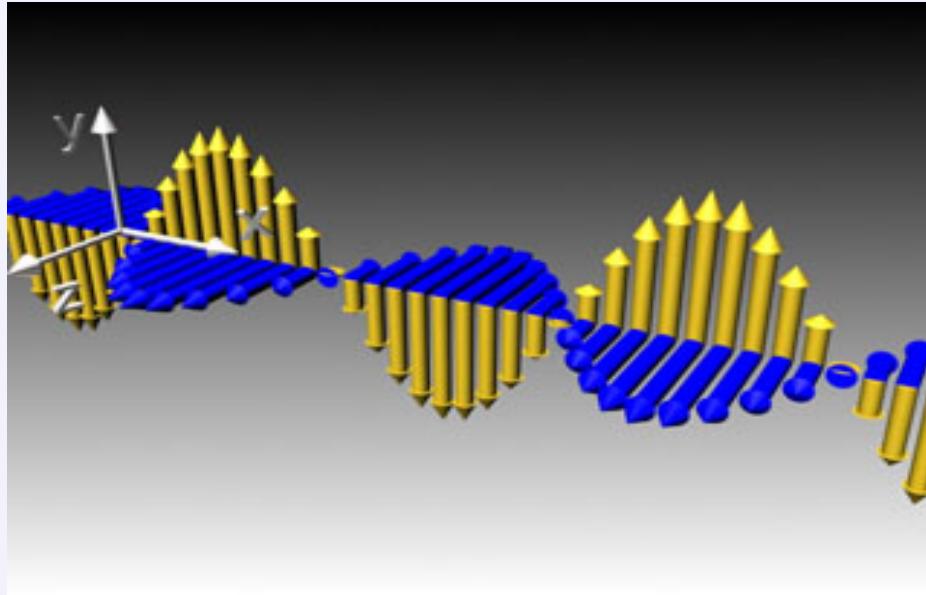
Virgo interferometer
Pisa, Italy



Part 2: Virgo optical configuration

- Reminder about electromagnetic waves and planes waves
- How do we “observe” ΔL with a Michelson interferometer?
 - Measurement of a power variations
 - From power variations to ΔL (or to gravitational wave amplitude h)
- Improving the interferometer
 - How do we increase the power on the beam-splitter mirror?
 - How do we amplify the phase offset between the arms?

Electromagnetic waves



- Propagation of a perturbation of electric and magnetic fields
 - Direction of propagation: along \vec{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

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

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

- Average power: $P \propto A_0^2$

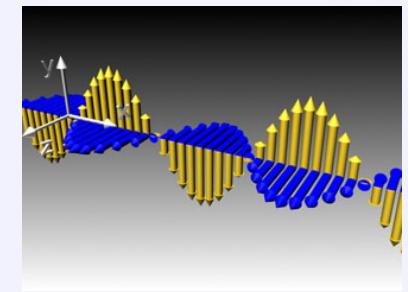
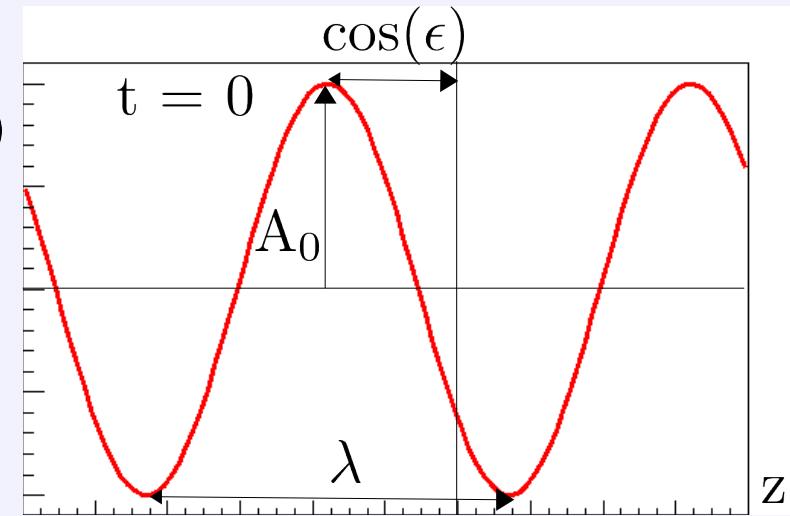
- Complex form

$$\begin{aligned} U(z, t) &= A_0 e^{j(kz - \omega t + \epsilon)} \\ &= \underline{\mathcal{A}_0} e^{j(kz + \epsilon)} \quad \text{with} \quad \underline{\mathcal{A}_0} = A_0 e^{-j\omega t} \end{aligned}$$

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

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

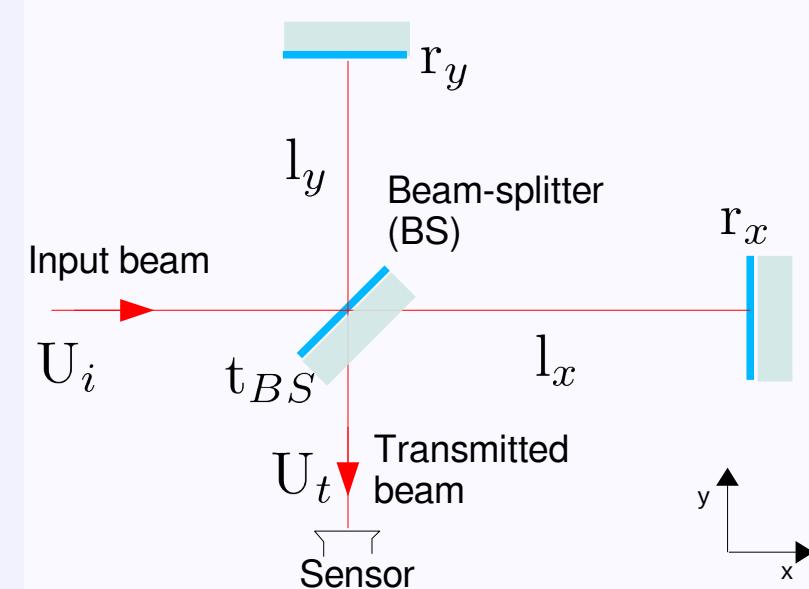
- Plane waves do not exist but they are a good approximation of many waves in localised region of space



How do we “observe” ΔL with a Michelson interferometer?

- Input wave $U_i(x, t) = \underline{A}_i e^{jkx}$
 $= \underline{A}_i$ 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 \sim few cm

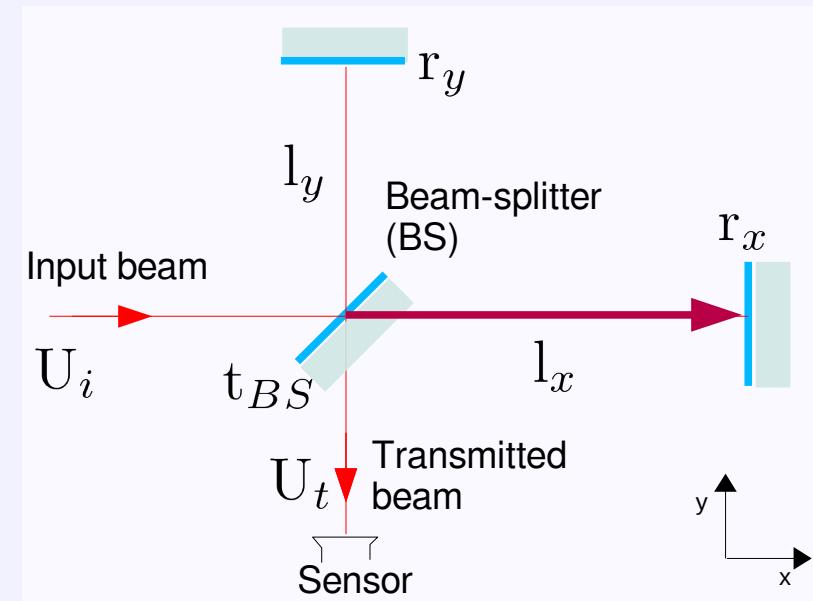
→ The beam can be approximated by plane waves

How do we “observe” ΔL with a Michelson interferometer?

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

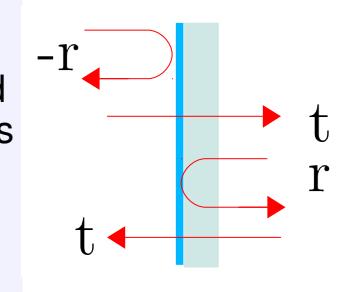
- Beam propagating along x-arm:

$$U_{tx} = \underline{\mathcal{A}}_i t_{BS} e^{\jmath kl_x} \dots$$



Sign convention for
amplitude reflection and
transmission coefficients

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

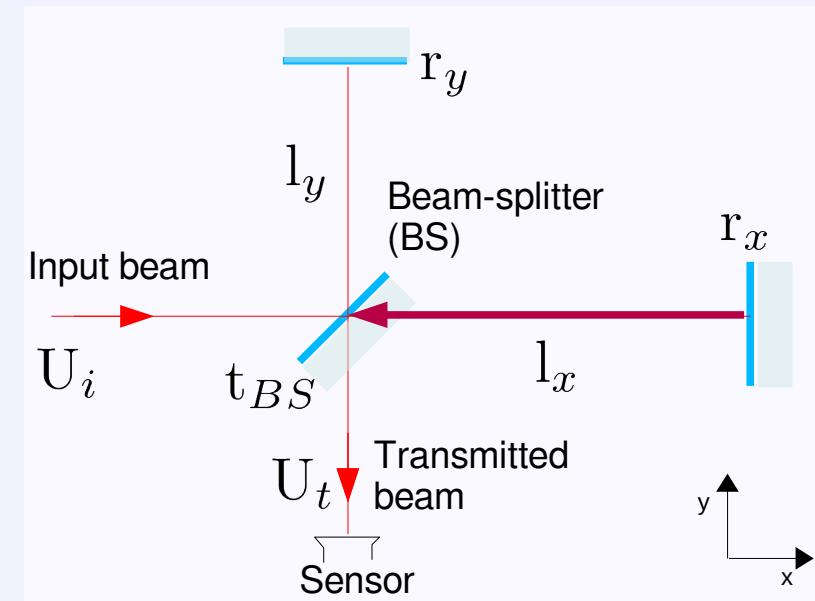


How do we “observe” ΔL with a Michelson interferometer?

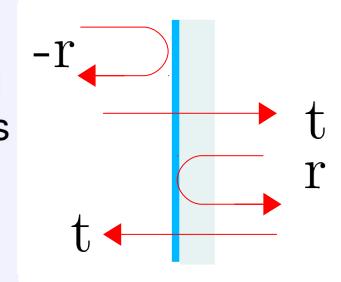
- Input wave $U_i(x, t) = \underline{\mathcal{A}}_i e^{\jmath kx}$
 $= \underline{\mathcal{A}}_i$ on BS

- Beam propagating along x-arm:

$$U_{tx} = \underline{\mathcal{A}}_i t_{BS} e^{\jmath kl_x} (-r_x) e^{\jmath kl_x} \dots$$



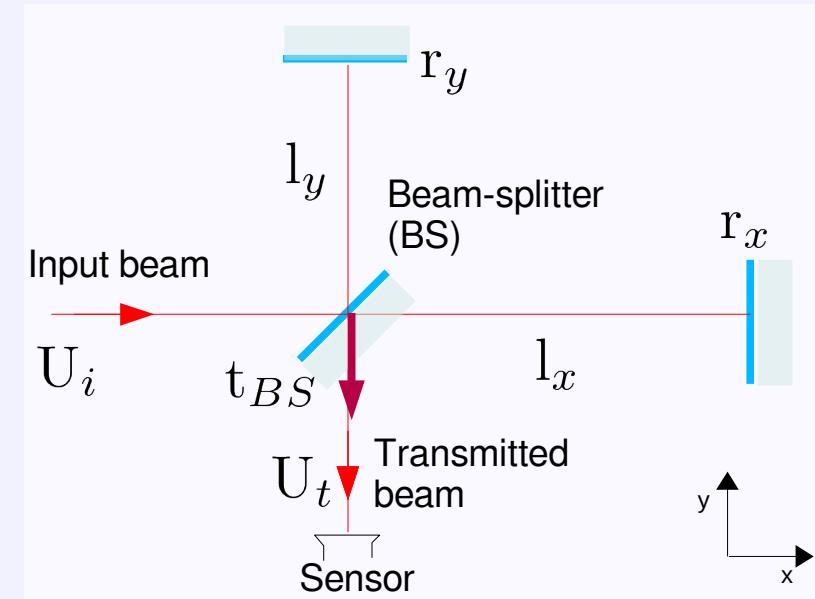
Sign convention for
amplitude reflection and
transmission coefficients



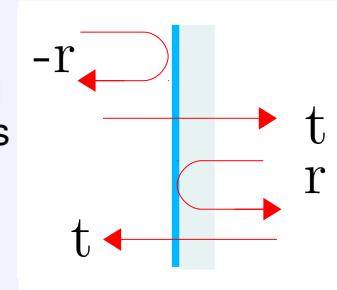
How do we “observe” ΔL with a Michelson interferometer?

- Input wave $U_i(x, t) = \underline{\mathcal{A}}_i e^{\jmath kx}$
 $= \underline{\mathcal{A}}_i$ on BS
- Beam propagating along x-arm:

$$U_{tx} = \underline{\mathcal{A}}_i t_{BS} e^{\jmath kl_x} (-r_x) e^{\jmath kl_x} r_{BS} e^{\jmath ky_s}$$



Sign convention for amplitude reflection and transmission coefficients

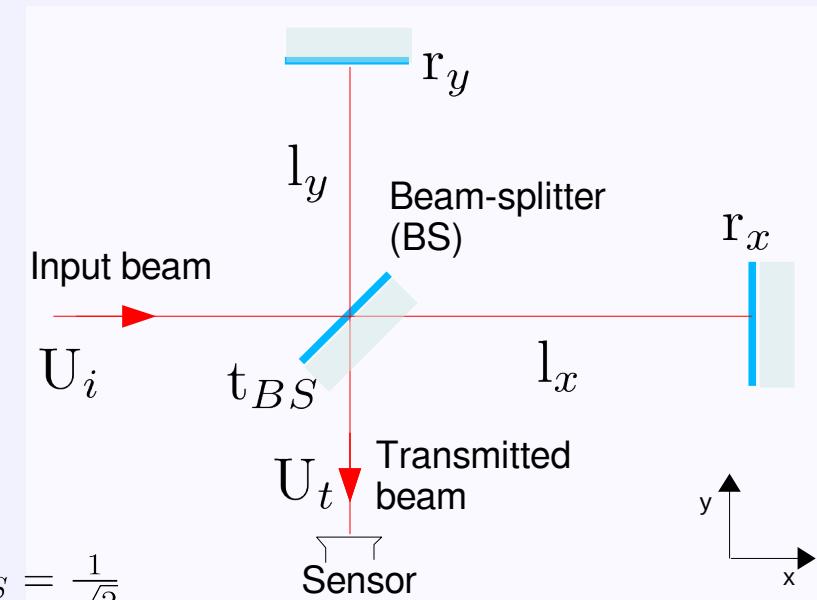


How do we “observe” ΔL with a Michelson interferometer?

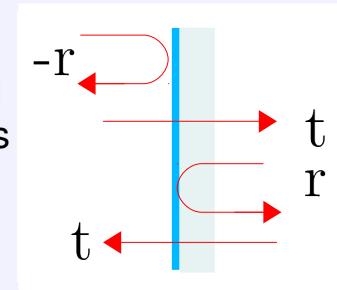
- Input wave $U_i(x, t) = \underline{\mathcal{A}}_i e^{\text{j} kx}$
 $= \underline{\mathcal{A}}_i$ on BS

- Beam propagating along x-arm:

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



Sign convention for amplitude reflection and transmission coefficients



How do we “observe” ΔL with a Michelson interferometer?

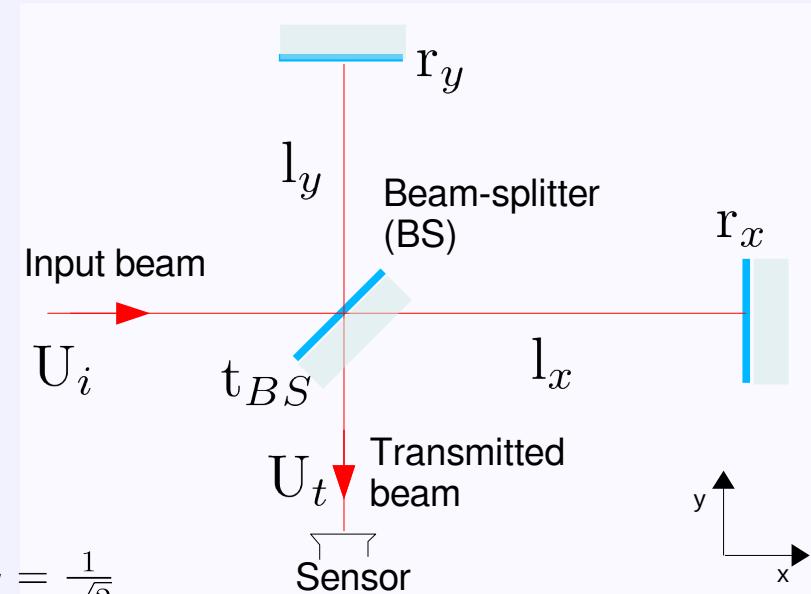
- Input wave $U_i(x, t) = \underline{\mathcal{A}}_i e^{\text{j} kx}$
 $= \underline{\mathcal{A}}_i$ on BS

- Beam propagating along x-arm:

$$\begin{aligned} U_{tx} &= \underline{\mathcal{A}}_i t_{BS} e^{\text{j} kl_x} (-r_x) e^{\text{j} kl_x} r_{BS} e^{\text{j} ky_s} \\ &= \underline{\mathcal{A}}_i t_{BS} r_{BS} (-r_x) e^{2\text{j} kl_x} e^{\text{j} ky_s} \\ &= \frac{\underline{\mathcal{A}}_i}{2} \times \underbrace{(-r_x e^{2\text{j} kl_x})}_{\text{Complex reflection of the x-arm}} e^{\text{j} ky_s} \quad \text{with } t_{BS} = r_{BS} = \frac{1}{\sqrt{2}} \end{aligned}$$

- Beam propagating along y-arm:

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



- Transmitted field:

$$\begin{aligned} U_t &= U_{tx} + U_{ty} \\ &= \frac{\underline{\mathcal{A}}_i}{2} e^{\text{j} ky_s} (r_y e^{2\text{j} kl_y} - r_x e^{2\text{j} kl_x}) \end{aligned}$$

Power transmitted by a simple Michelson

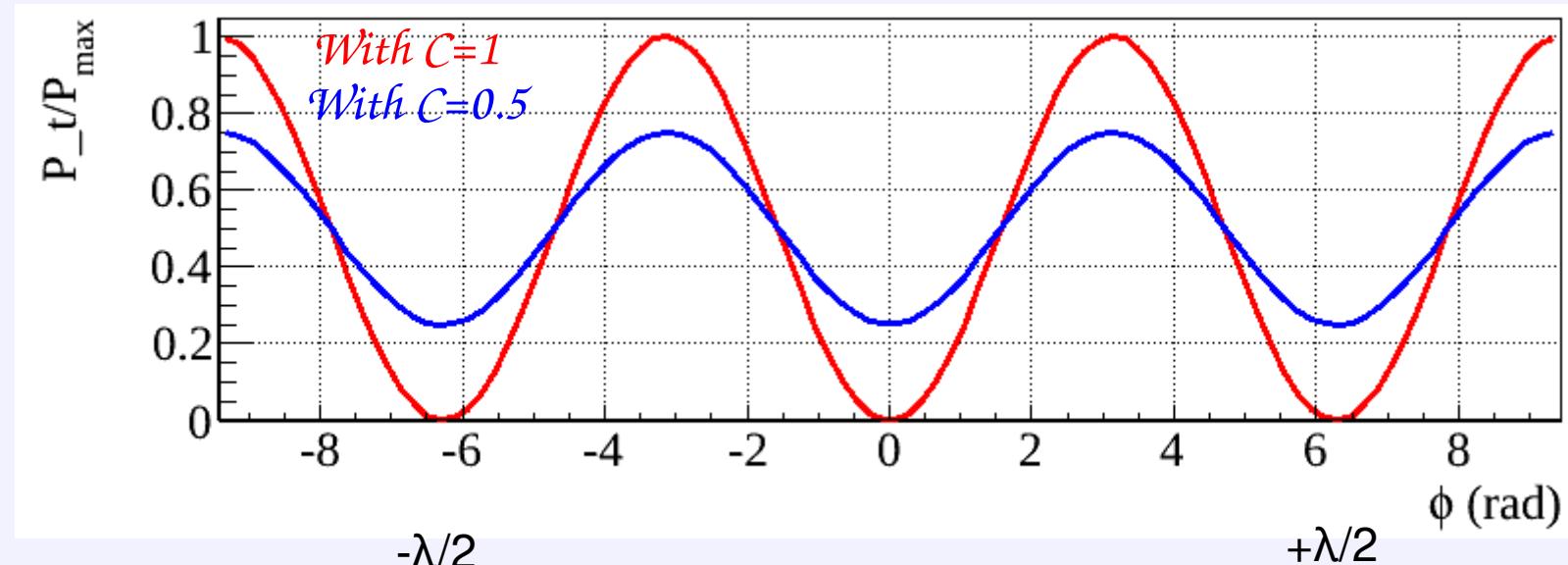
- Transmitted field: $U_t = \frac{A_i}{2} e^{jk y_s} (r_y e^{2jkl_y} - r_x e^{2jkl_x})$

- Calculation of the transmitted power:

$$P_t \propto |U_t|^2 = \frac{P_{max}}{2} (1 - C \cos(\phi)) \quad \text{where } \phi = 2k(l_y - l_x)$$

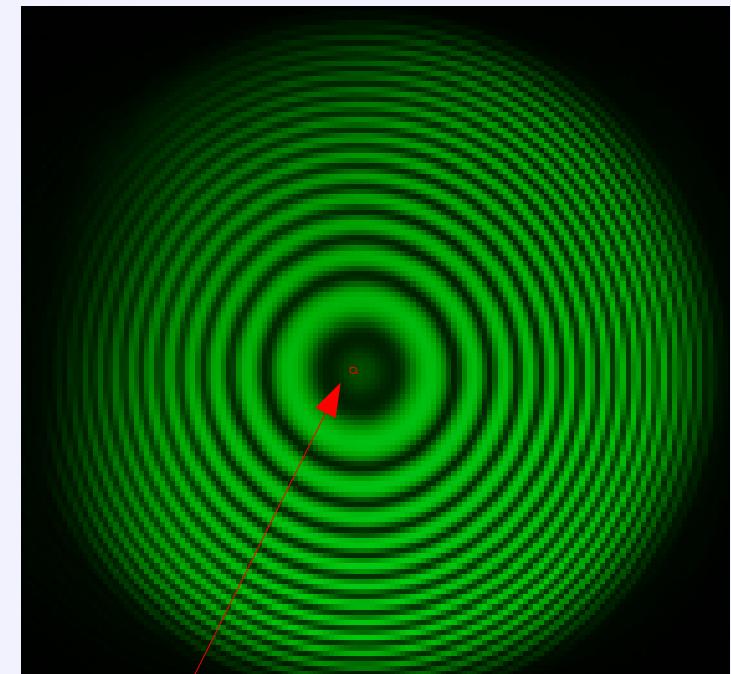
$$C = 2 \frac{r_x r_y}{r_x^2 + r_y^2}$$

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

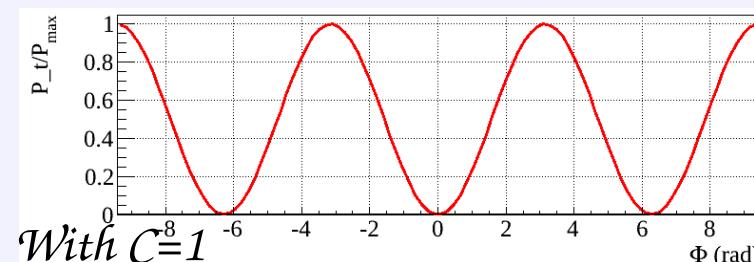


What power does Virgo measure?

- 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 !

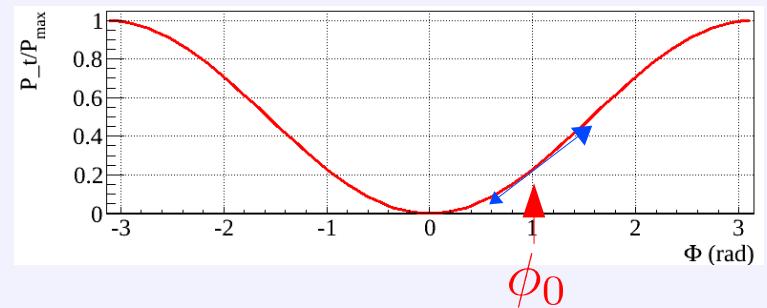


Equivalent size of Virgo beam



Freely swinging mirrors

Setting a working point



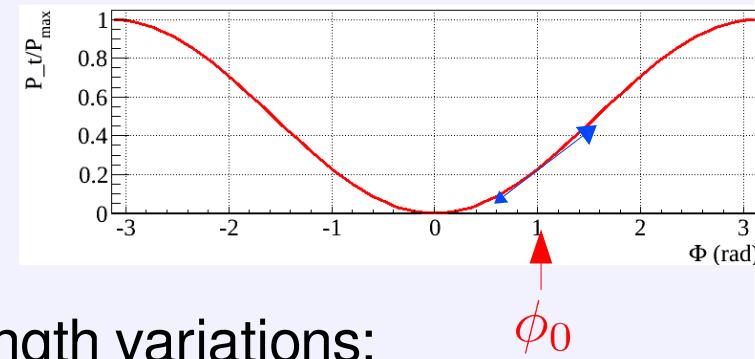
Controlled mirror positions

From the power to the gravitational wave

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

- Around the working point:

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



- Power variations as function of small differential length variations:

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

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

$\delta P_t \propto \delta\Delta L = hL_0$ around the working point !

From the power to the gravitational wave

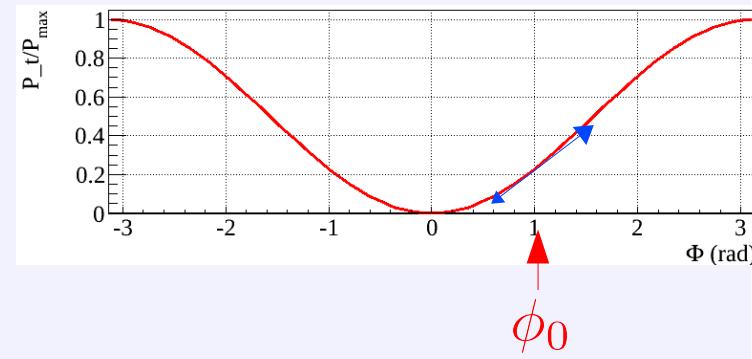
- Around the working point:

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

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

Measurable
physical quantity

Physical effect to be detected



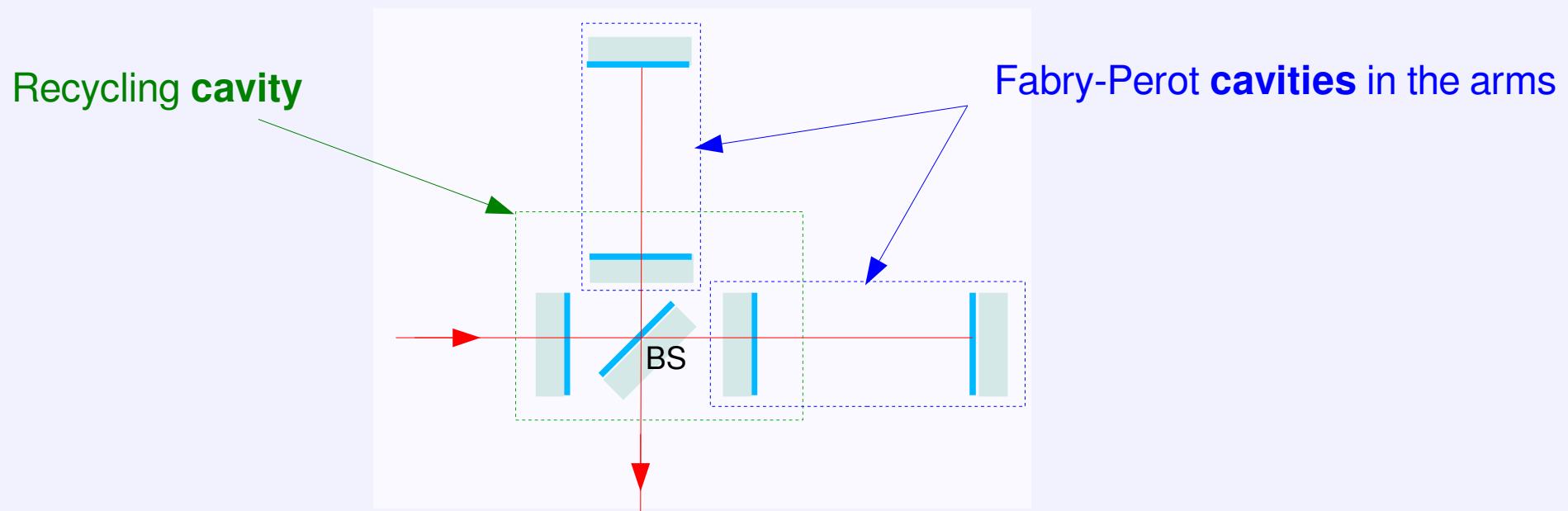
Improving the interferometer sensitivity

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

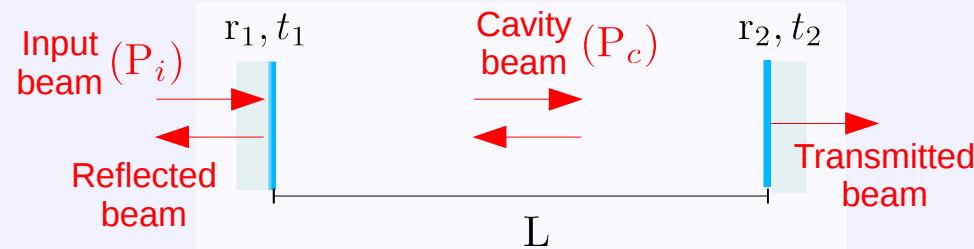
$\propto \delta \phi$

Increase the input power
on BS

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



In Virgo, the beam is resonant inside the cavities



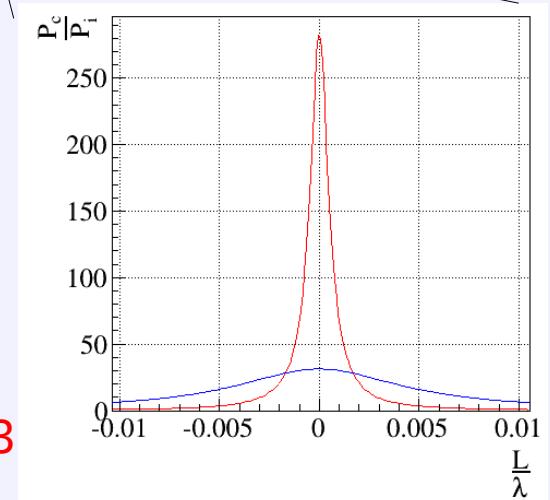
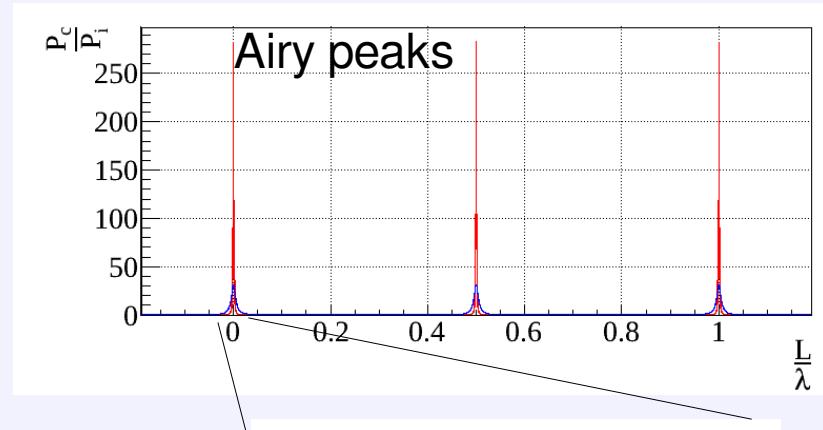
$$P_c = P_i \frac{t_1^2}{(1 - r_1 r_2)^2} \frac{1}{1 + \left(\frac{2\mathcal{F}}{\pi}\right)^2 \sin^2(kL)}$$

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

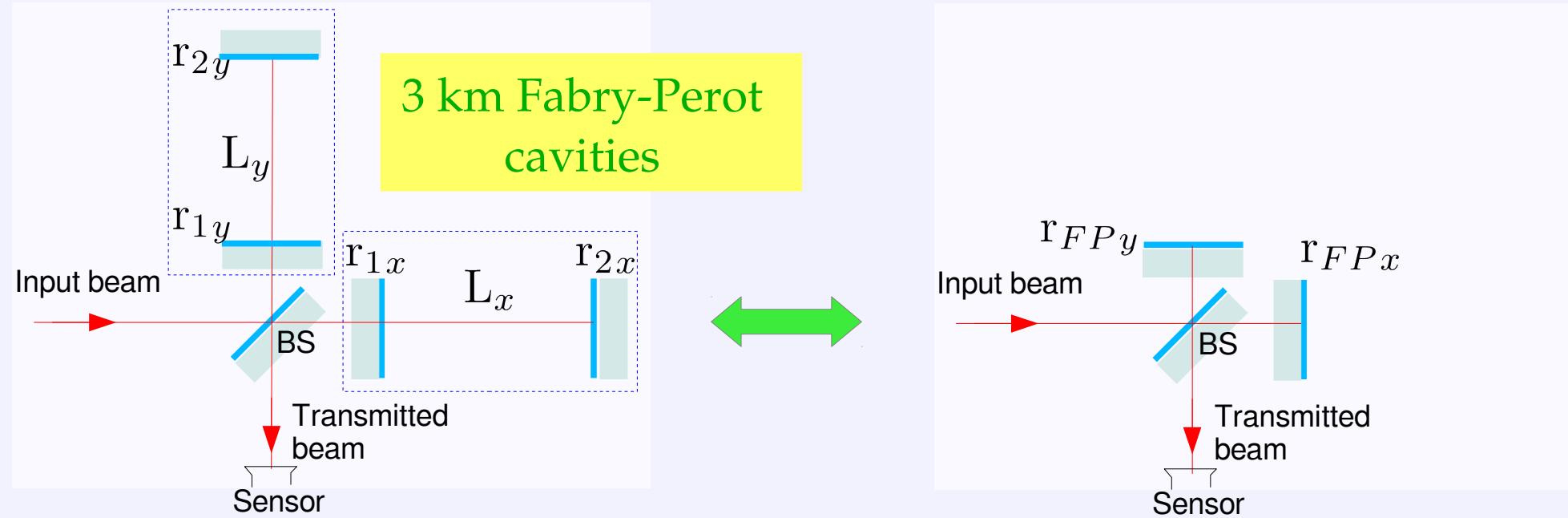
Virgo cavity at resonance: $L = n \frac{\lambda}{2}$ ($n \in \mathbb{N}$)

Virgo $\mathcal{F} = 50$
AdVirgo $\mathcal{F} = 443$

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



How do we amplify the phase offset?



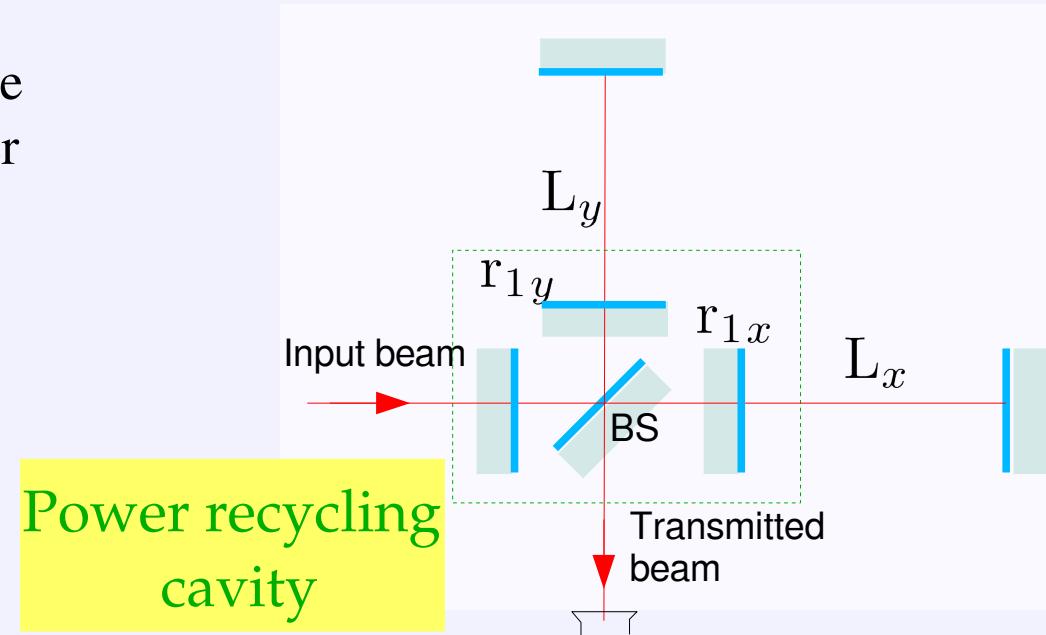
$$r_{F Px} = -1 \times e^{j\frac{2\mathcal{F}}{\pi} 2 k \delta L_x}$$

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

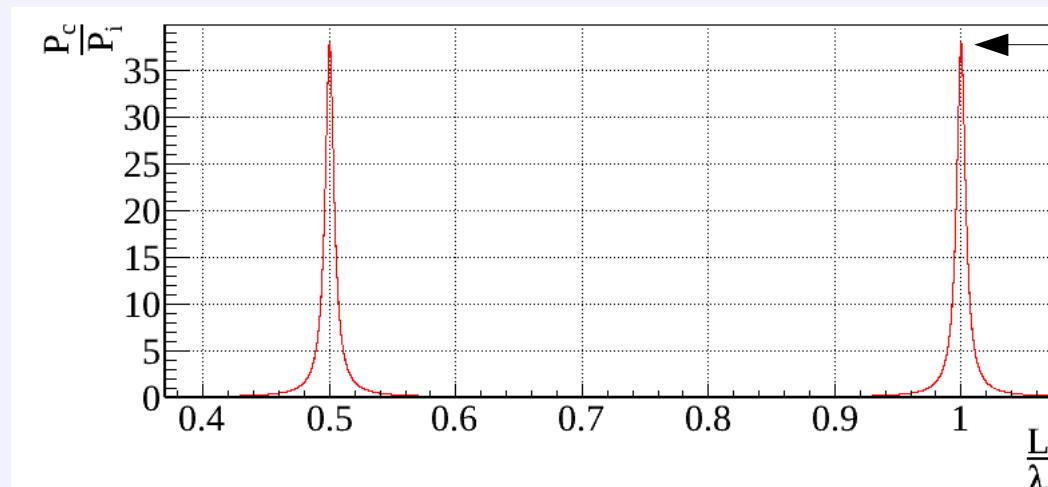
(instead of $r_{armx} = -1 \times e^{j2k(L_x + \delta L_x)}$ in the arm of a simple Michelson)

How do we increase the power on BS?

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



Resonant power recycling cavity



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

→ input power on BS increased by a factor 38!

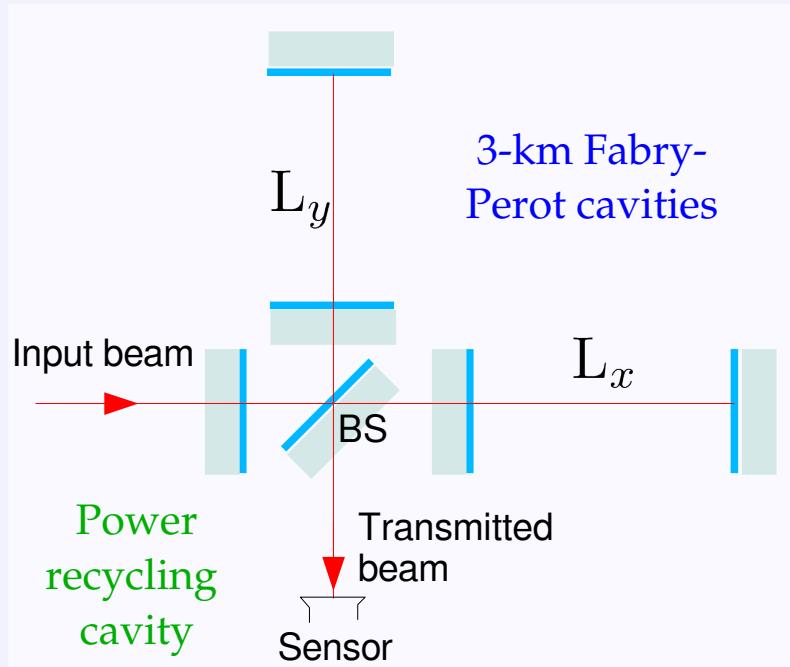
The improved interferometer response

- **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:**

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

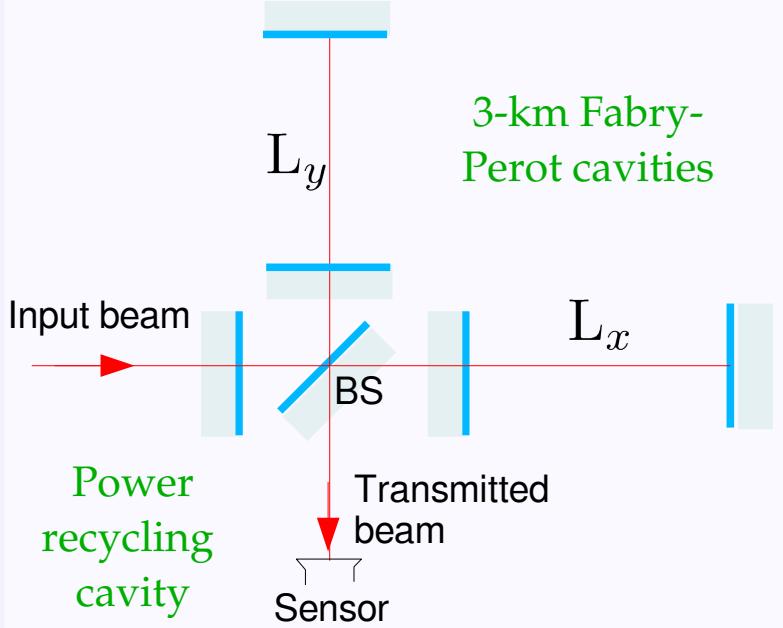
~ 38 ~ 300

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

A hint of AdvancedVirgo sensitivity

- Response of recycled Michelson with Fabry-Perot cavities:

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



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

Shot noise due to output power of $\sim 50 \text{ mW}$

$$\rightarrow \delta P_{t,min} \sim 0.1 \text{ nW}$$



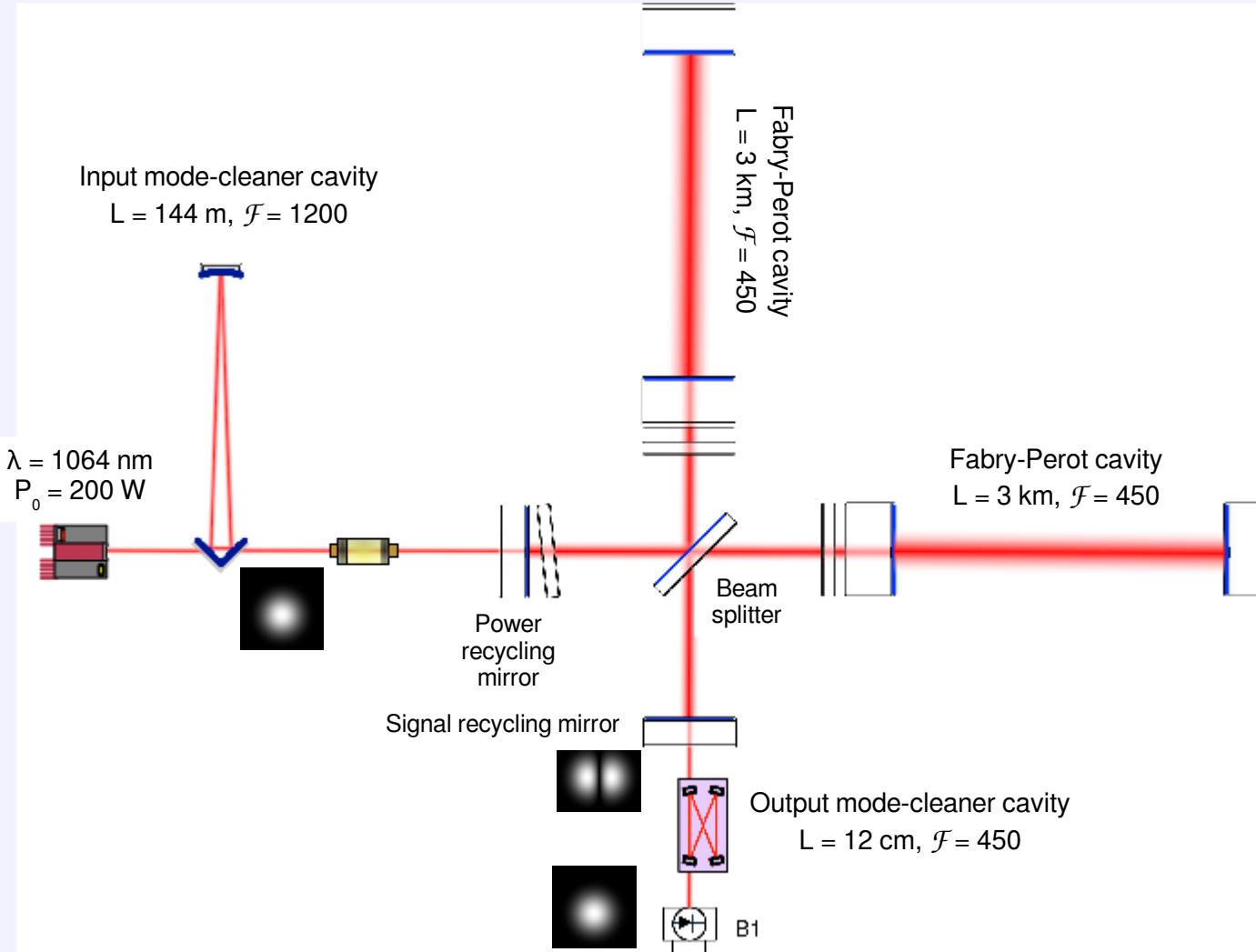
$$\rightarrow \delta \Delta L_{min} \sim 5 \times 10^{-20} \text{ m}$$

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



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

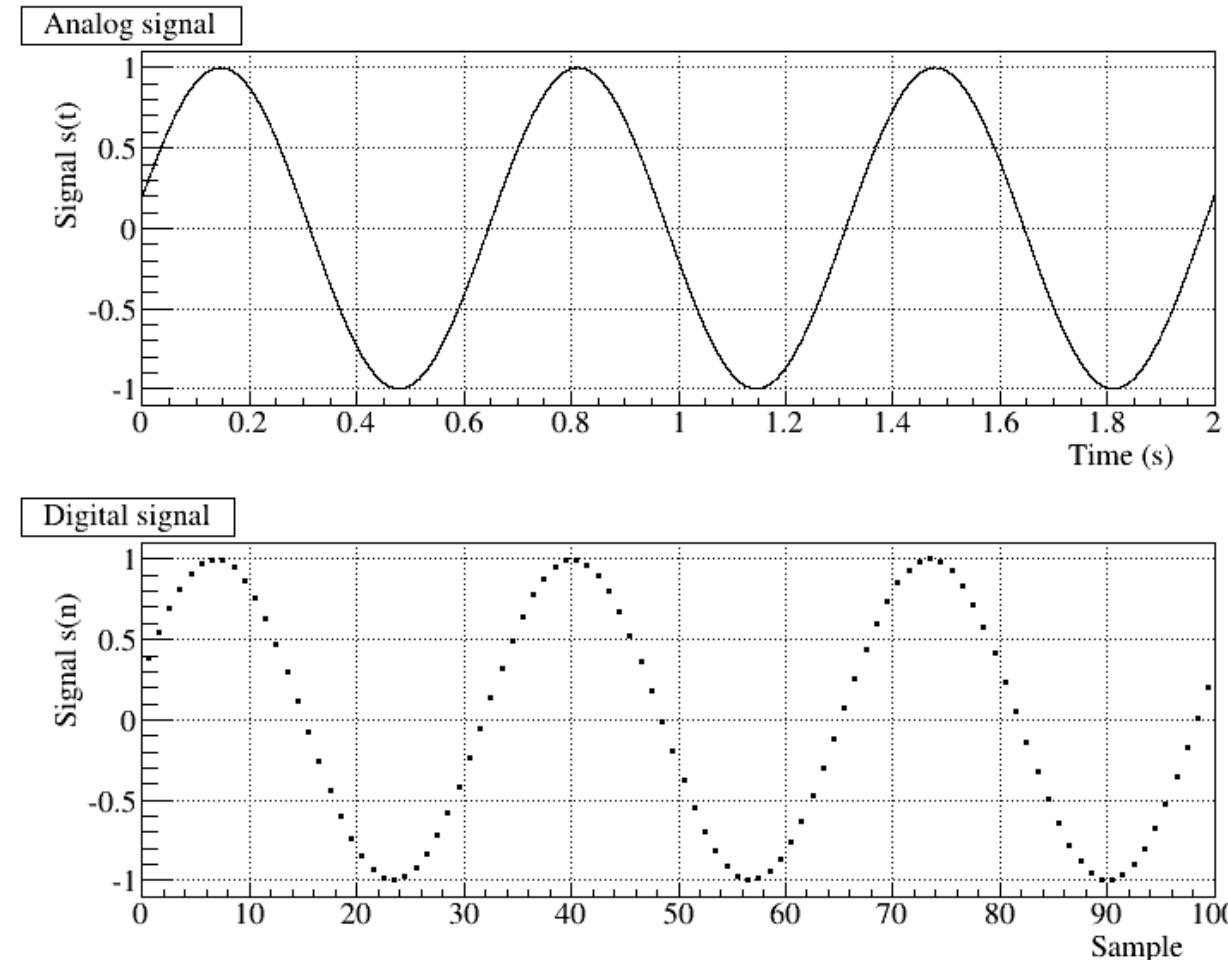
Optical layout of Virgo



Part 3: How do we measure the GW strain, $h(t)$, from this detector?

- Notes about data processing
- Controlling the interferometer working point
- A glimpse on the calibration and $h(t)$ reconstruction
- Data collection

Notes about data processing: digitisation



Analog signal $s(t)$
Continuous
A voltage in general

ADC DAC



Digital signal $s(n)$
Discrete (sampling frequency)
Can be stored numerically
Can be processed numerically
Warnings:
Nyquist frequency
Aliasing

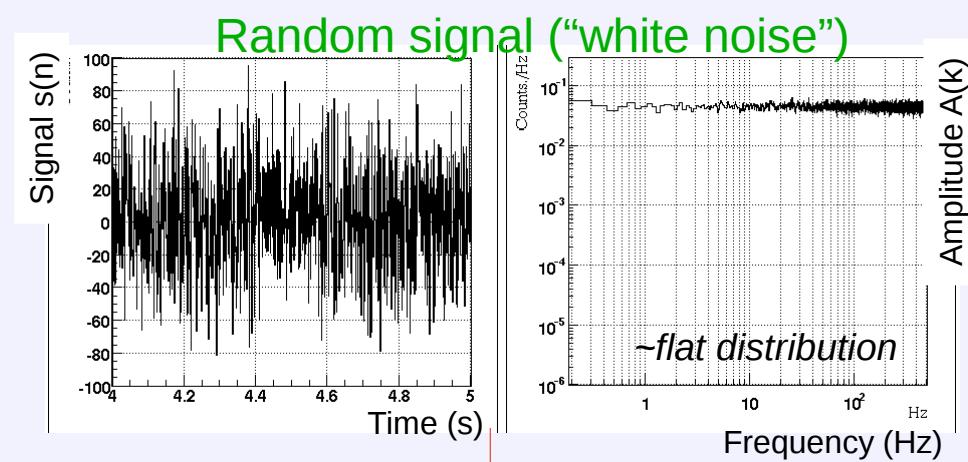
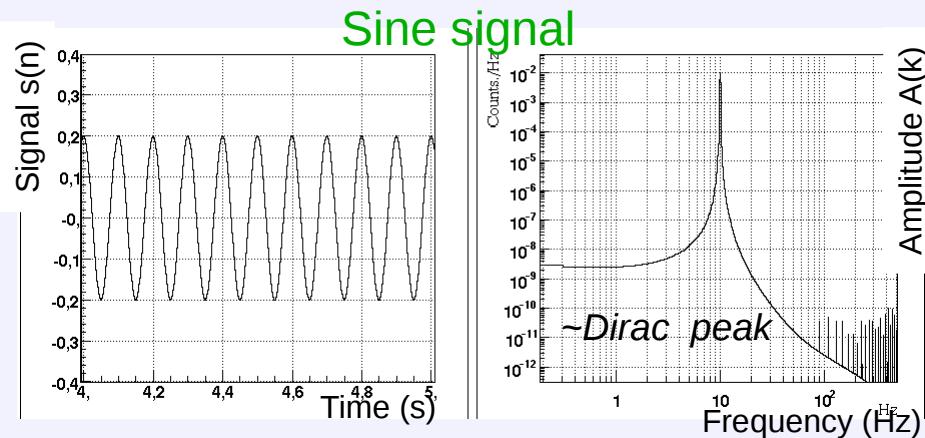
Notes about data processing: spectral analysis

A signal can be decomposed in different frequency components.



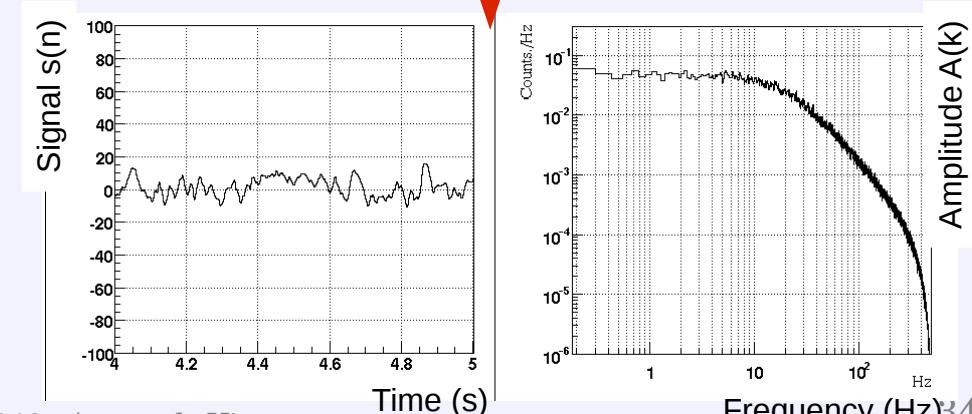
$A(k)$ and $\Phi(k)$

$$\begin{aligned} S(k) &= \sum_{n=1}^N s(n)e^{-j2\pi k \frac{n}{N}} \\ &= A(k)e^{\Phi(k)} \end{aligned}$$



Apply a low-pass filter
on the signal

Filtering the data
= modifying the frequency components

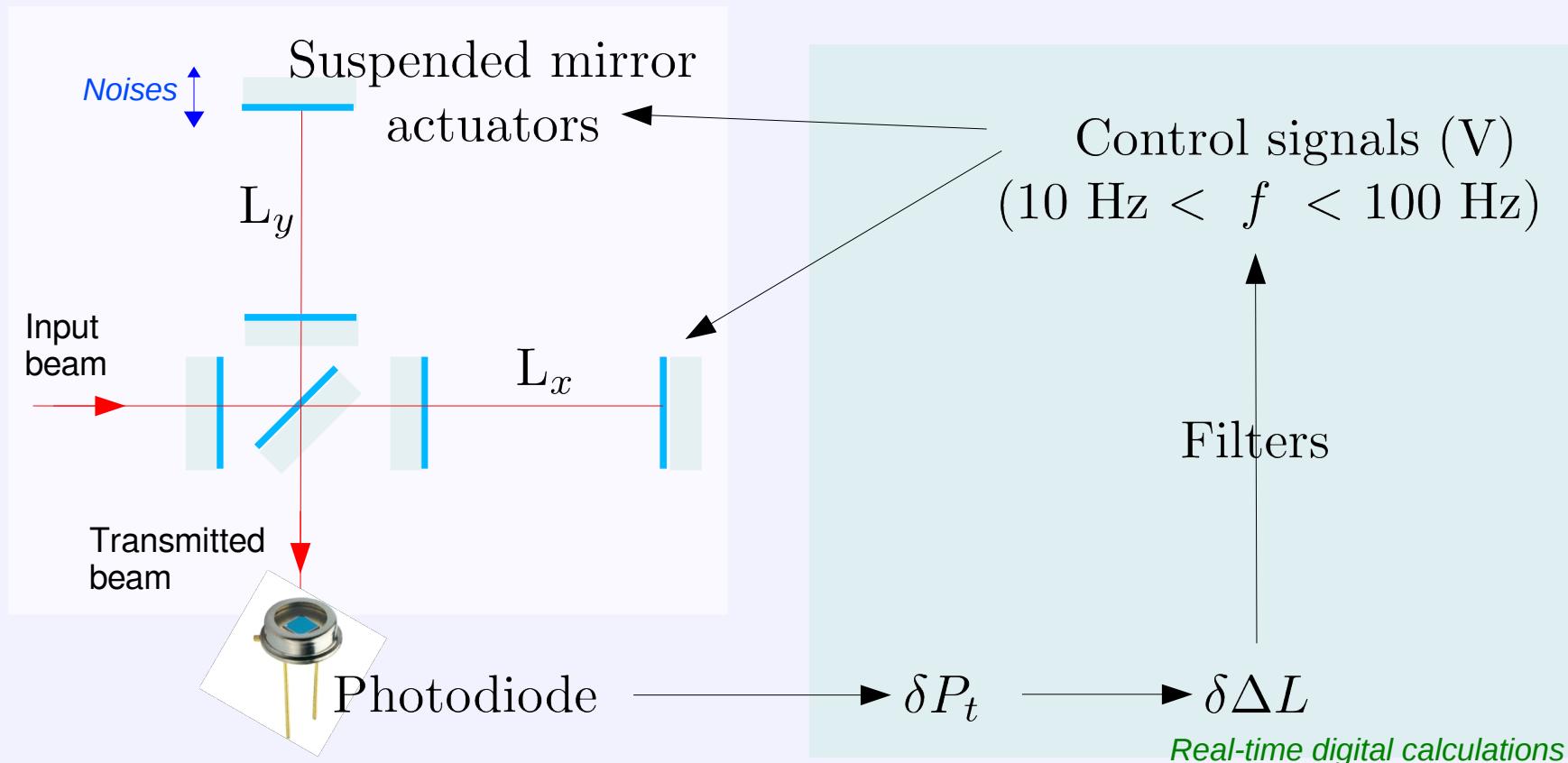


How do we control the working point?



We want $\Delta L_0 = n \frac{\lambda}{2} + 10^{-11} \text{ m}$ to be (almost) fixed!

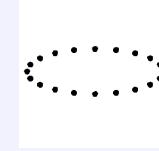
Control loop done for noises with f between $\sim 10 \text{ Hz}$ and $\sim 100 \text{ Hz}$
Precision of the control $\sim 10^{-16} \text{ m}$



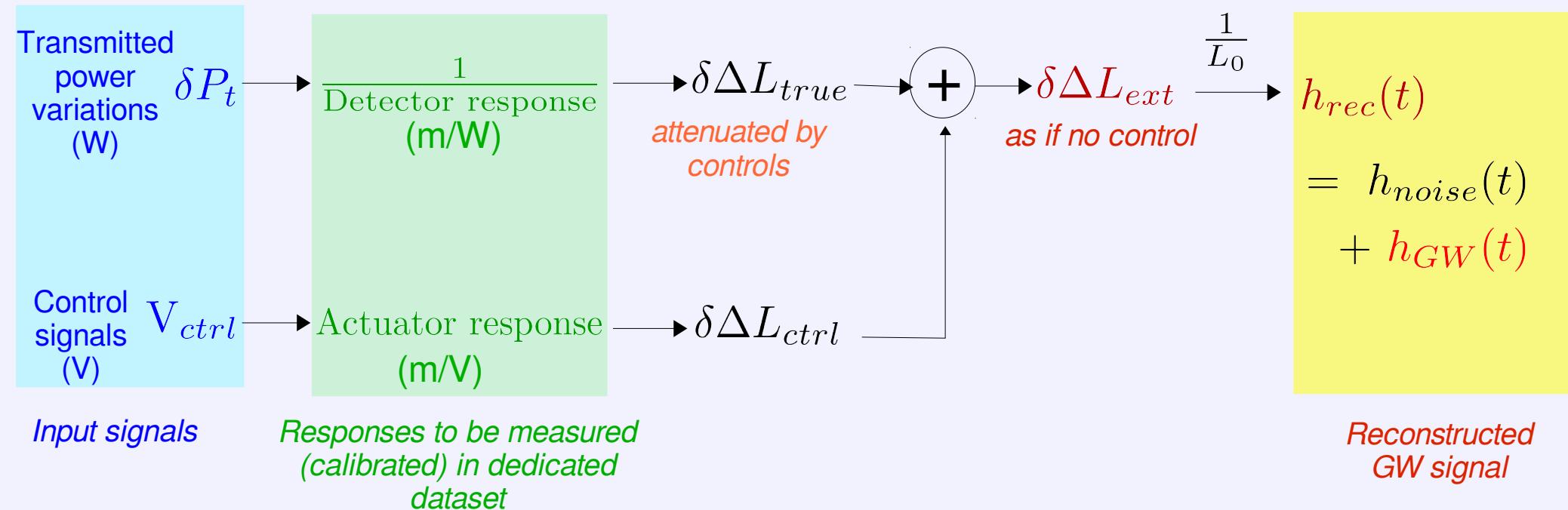
From the detector data to the GW strain $h(t)$

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

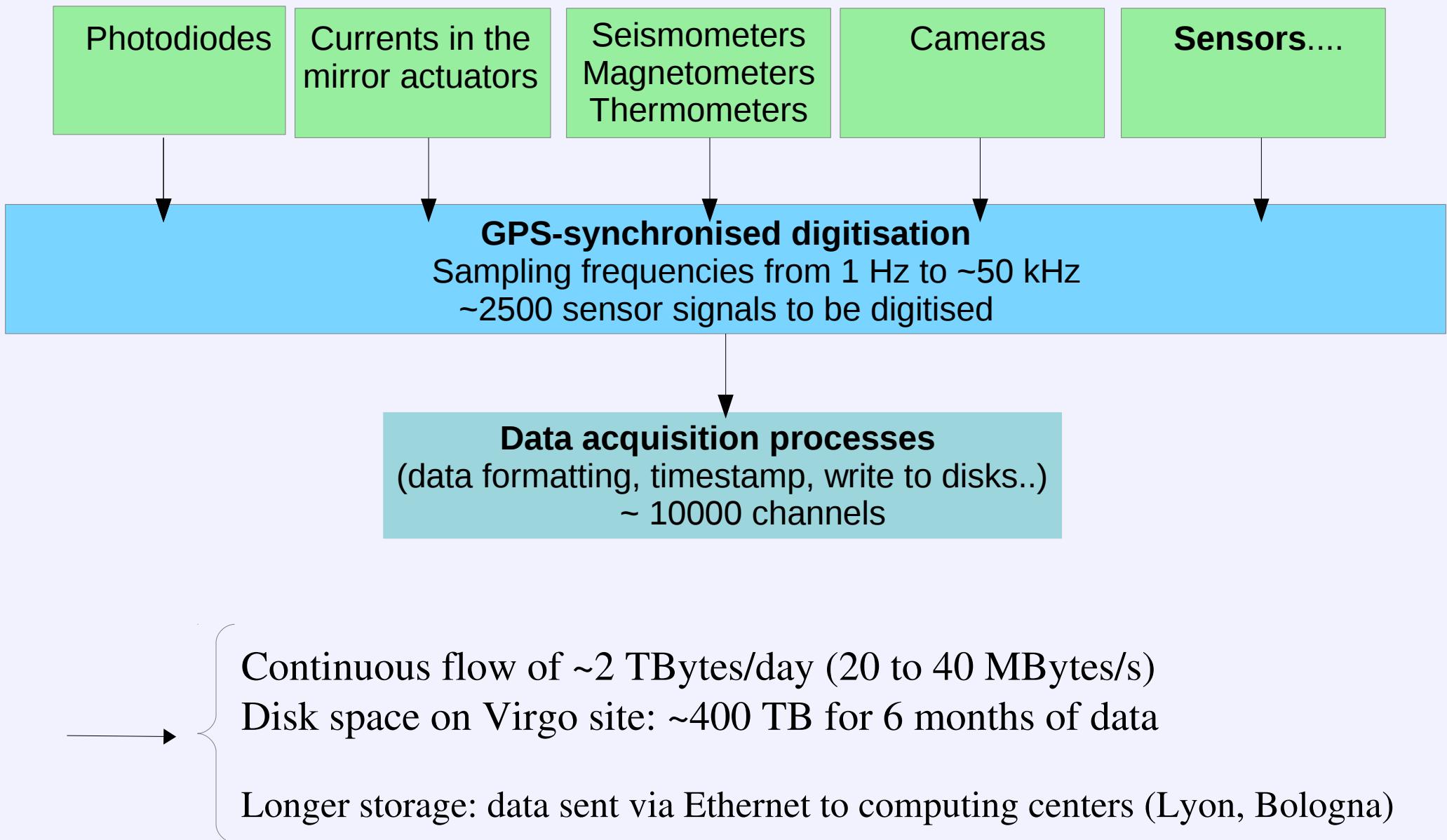
$$\rightarrow h(t) = \frac{\delta\Delta L_{true}(t)}{L_0}$$



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



AdVirgo data acquisition summary



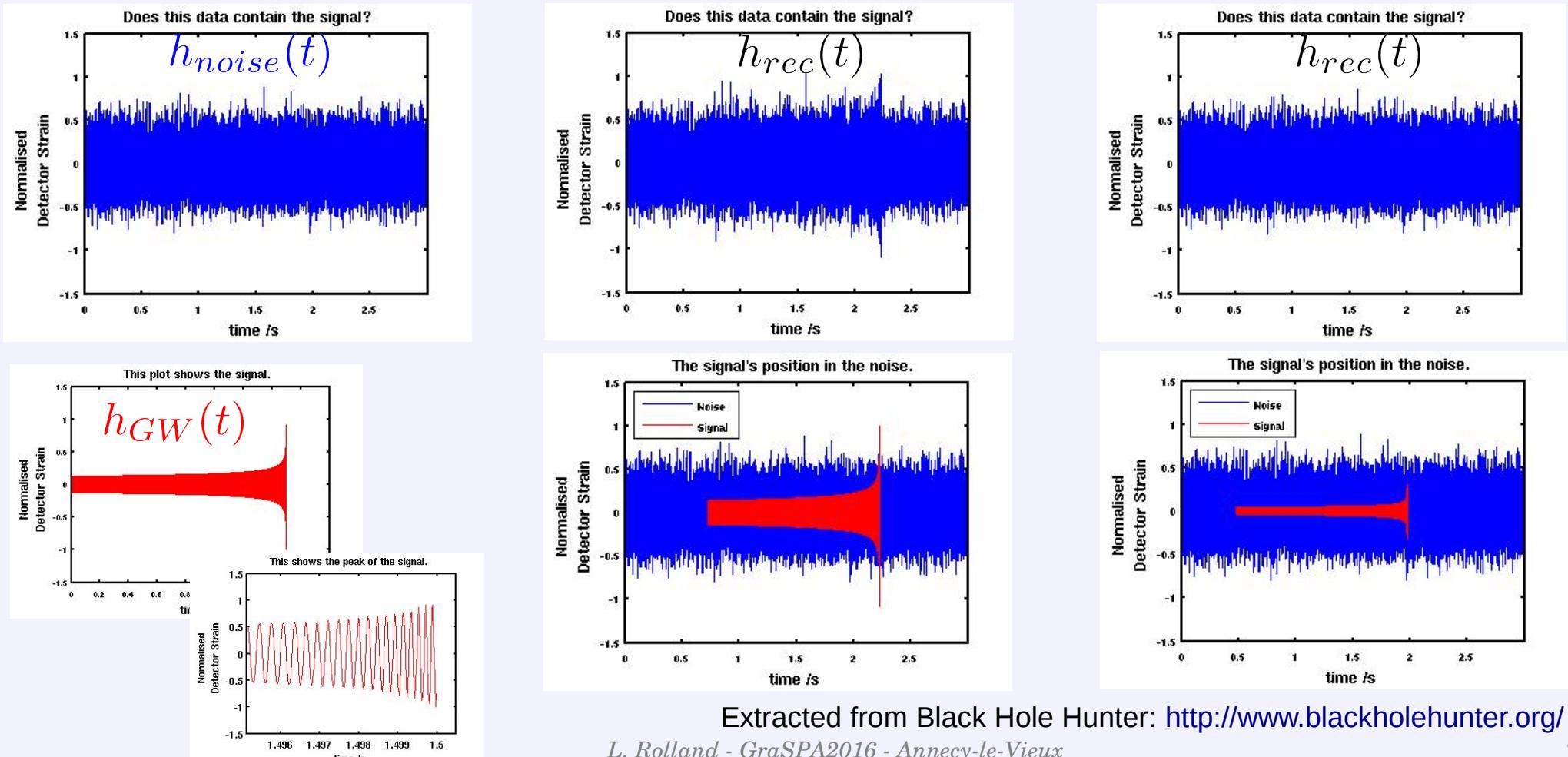
Part 4: Virgo noises



What is noise in Virgo?

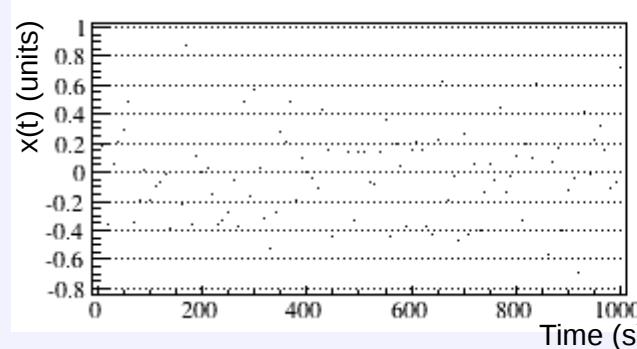
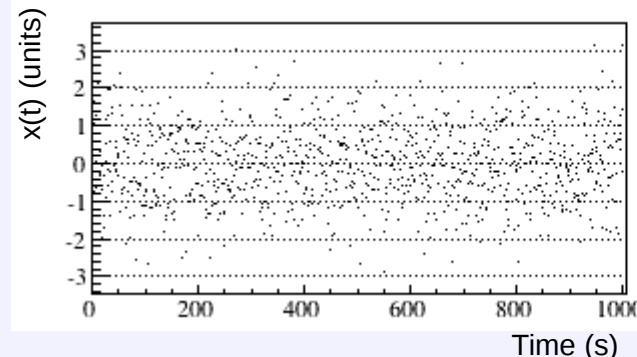
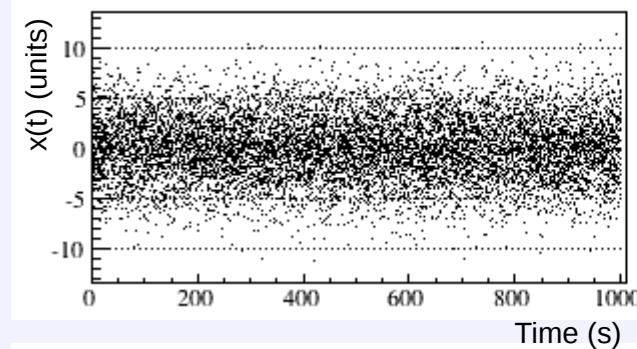
- Stochastic (random) signal that contributes to the signal $h_{\text{rec}}(t)$ but does not contain information on the gravitational wave strain $h_{\text{GW}}(t)$

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

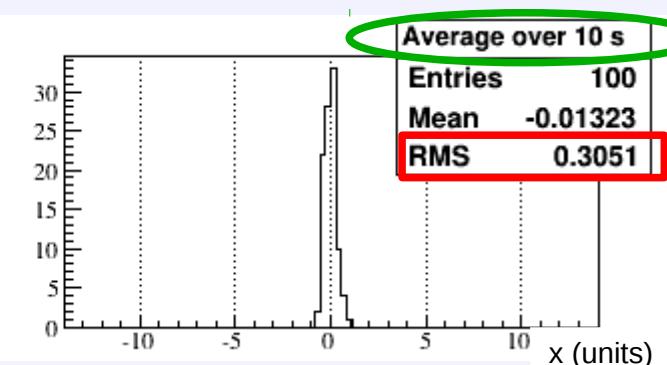
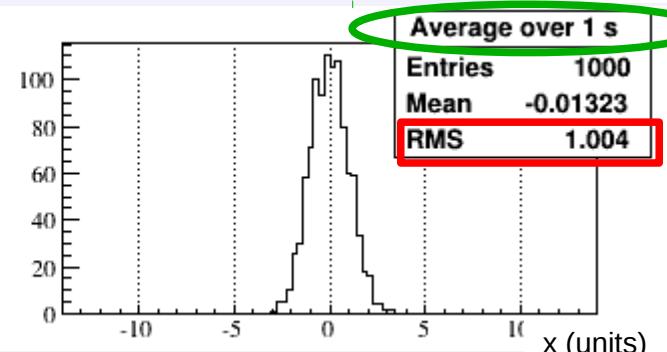
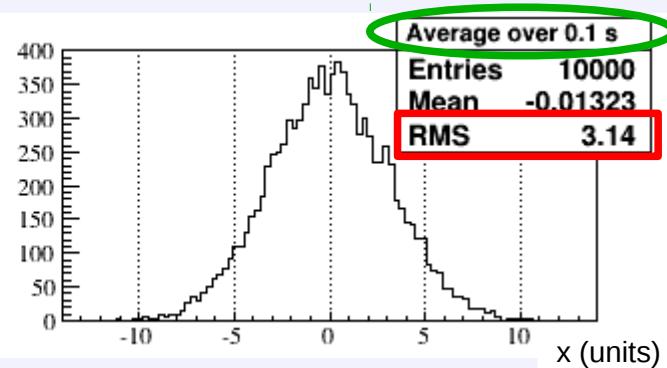


How do we characterise noise?

Data points (noise)



Distribution of the data



Gaussian distribution:

$$N e^{-\frac{1}{2} \frac{(x - \langle x \rangle)^2}{\sigma_x^2}}$$

→ Noise measurement characterised by its standard deviation σ_x

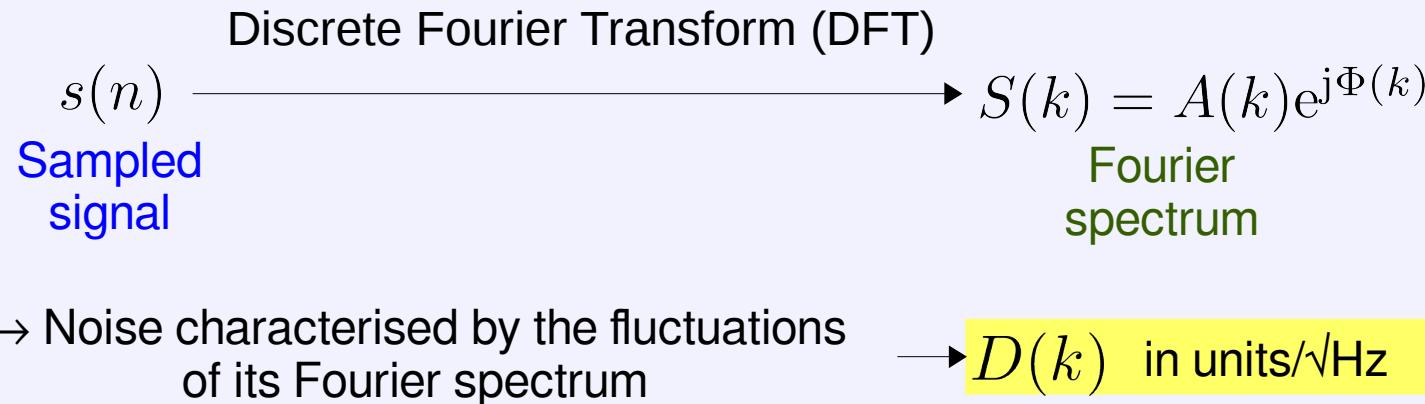
$$\sigma_x = \frac{D}{\sqrt{\text{average duration}}}$$

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

→ Noise characterised by D

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

How do we characterise a noise ... in frequency-domain?



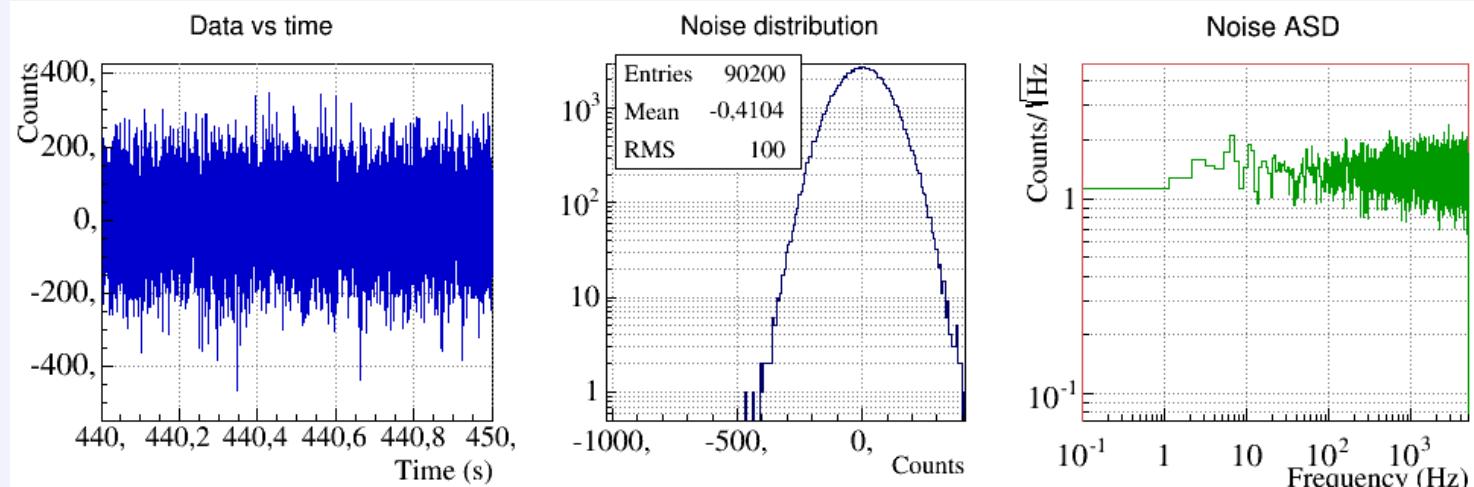
Assumption: noise is random and ergodic

→ noise characterised by its amplitude spectral density (ASD)

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

Random gaussian noise
1 count/ $\sqrt{\text{Hz}}$

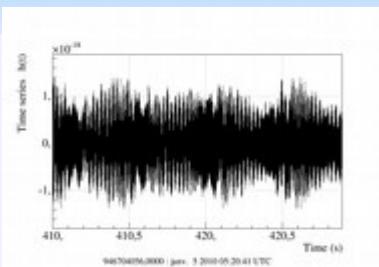
Sampled at 10 kHz



From $h_{rec}(t)$ 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)

$\sim 10^{-19} \text{ m}/\sqrt{\text{Hz}}$ (Virgo, 2011)

$\sim 10^{-20} \text{ m}/\sqrt{\text{Hz}}$ (Advanced Virgo, ~2021)

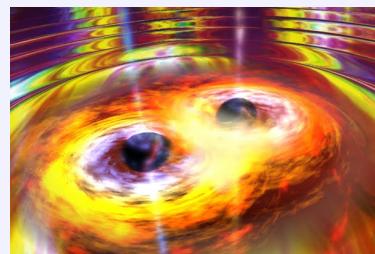


Image: Danna Berry/SkyWorks/NASA

Compact Binary Coalescences

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

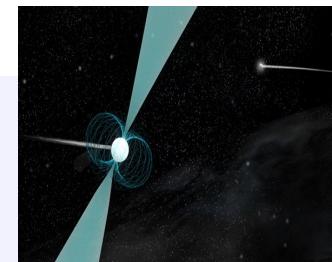
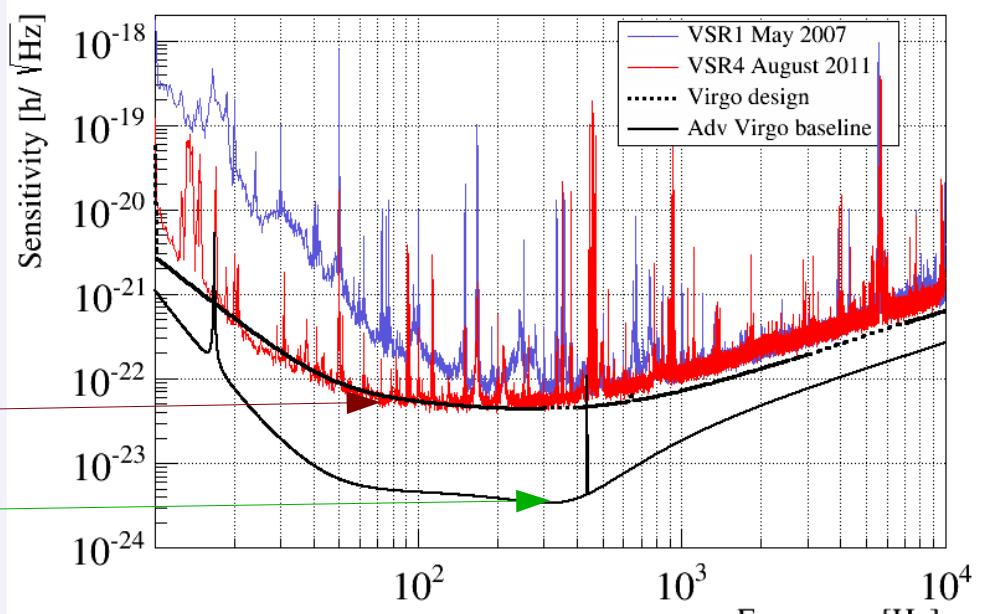
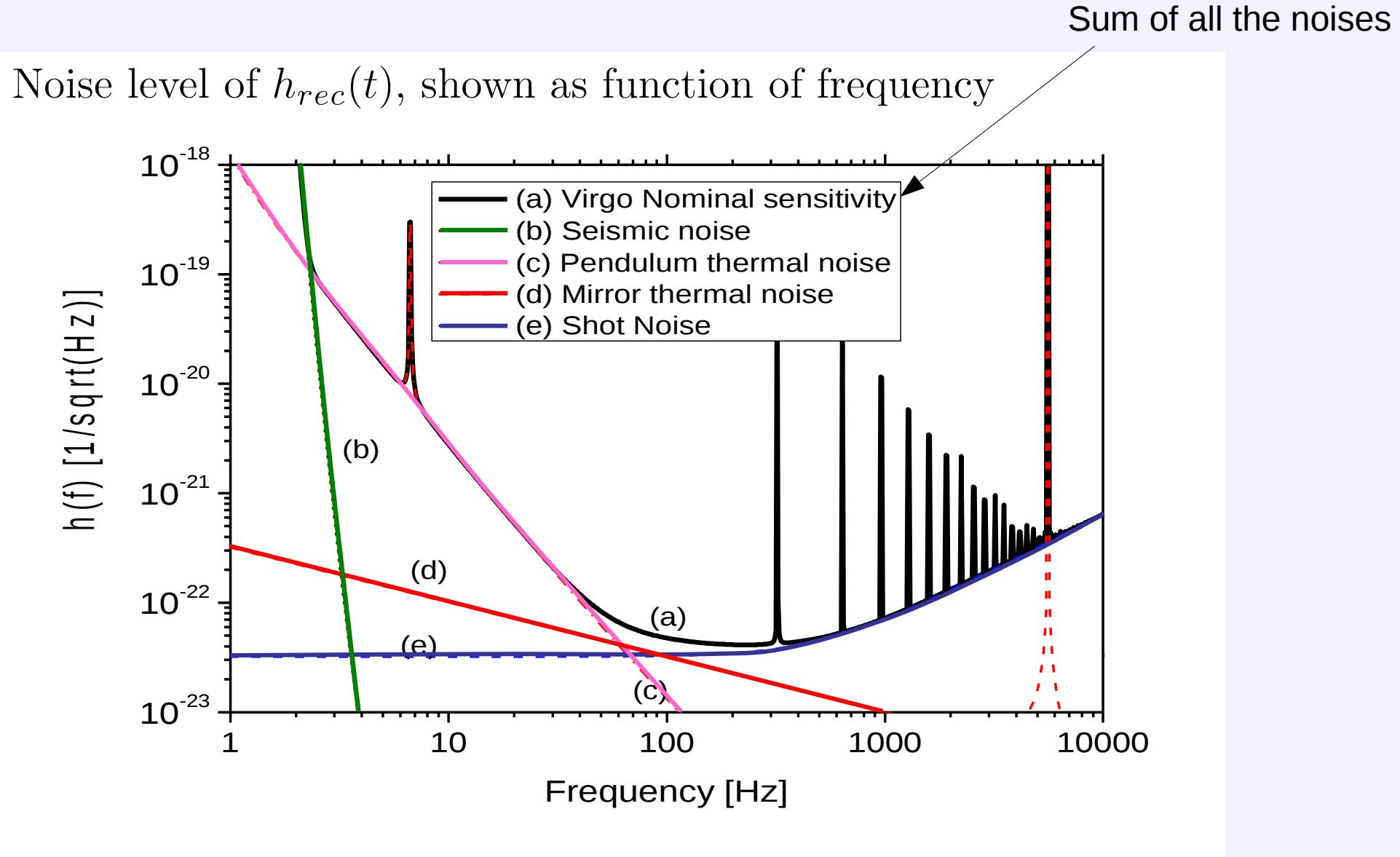


Image: B. Saxton
(NRAO/AUI/NSF)

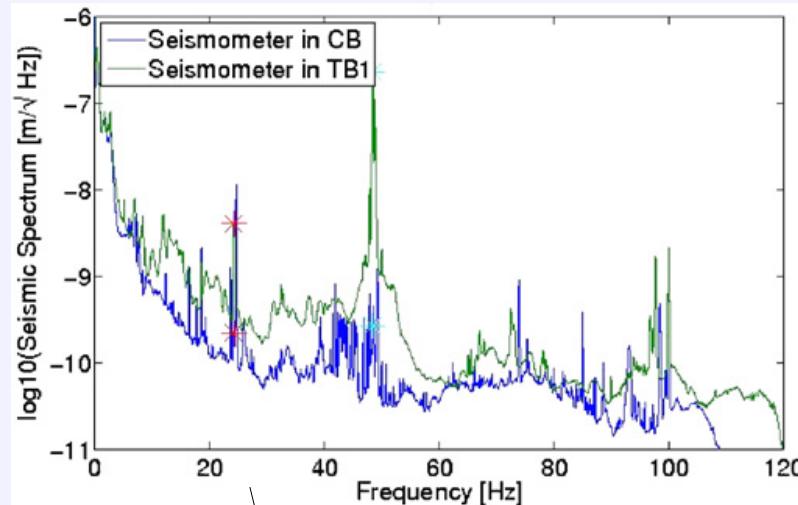
Rotating neutron stars

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

What is the noise level of Virgo?

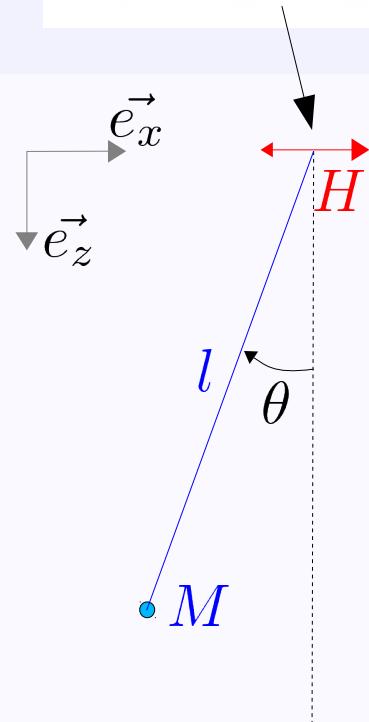


Seismic noise and suspended mirrors



Ground vibrations up to $\sim 1 \text{ }\mu\text{m}/\sqrt{\text{Hz}}$ at low frequency
decreasing down to $\sim 10 \text{ pm}/\sqrt{\text{Hz}}$ at 100 Hz

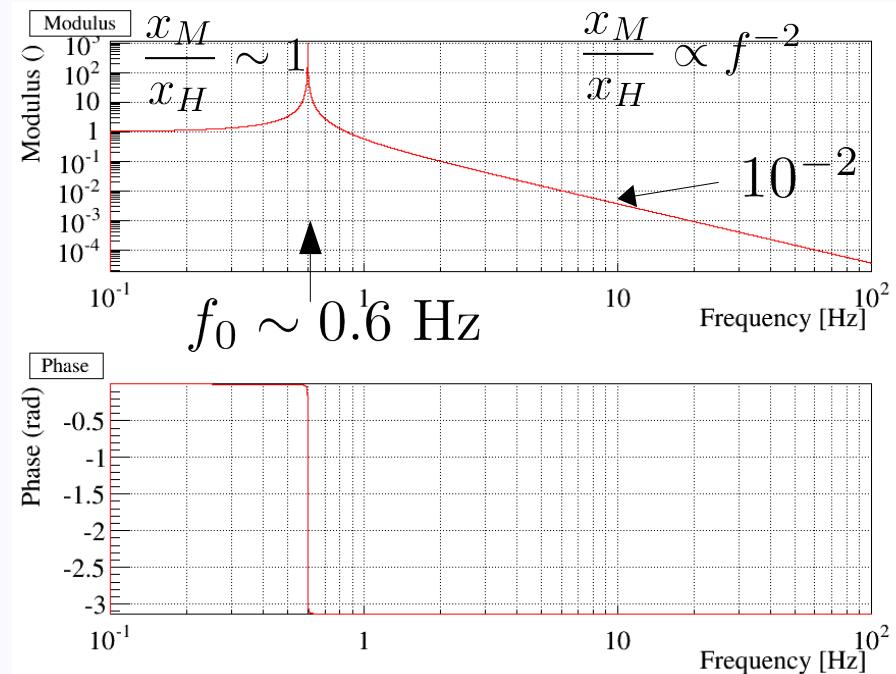
$\gg 10^{-19} \text{ m}/\sqrt{\text{Hz}}$ needed to detect GW !!



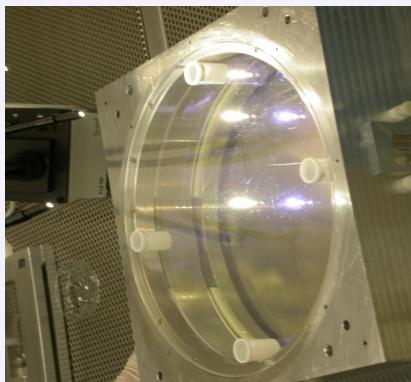
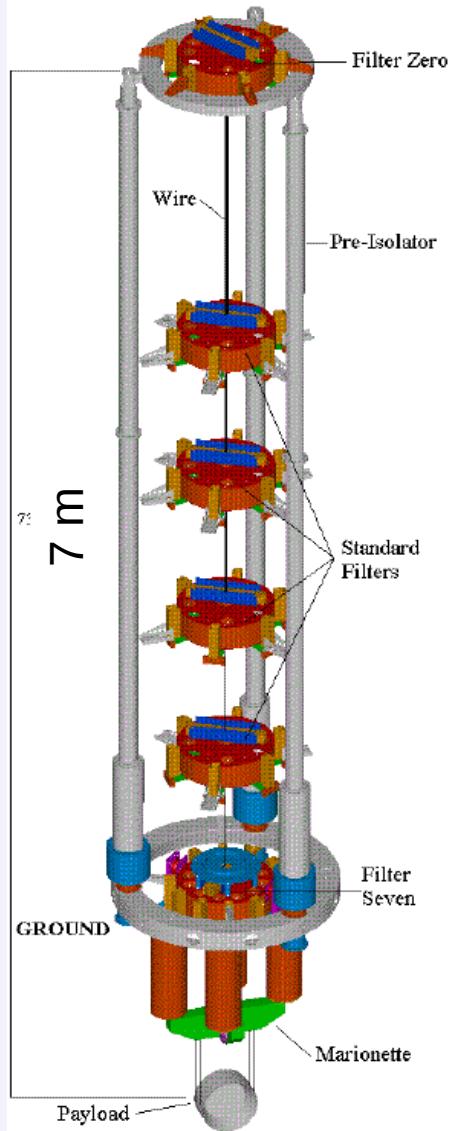
Assuming
 δx_H small and sinusoidal
and θ small:

$$\underline{x}_M = \underline{\mathcal{H}} \times \underline{x}_H$$


Transfer function



Seismic noise and the Virgo suspension



- **Passive attenuation:** 7 pendulum in cascade

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

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

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

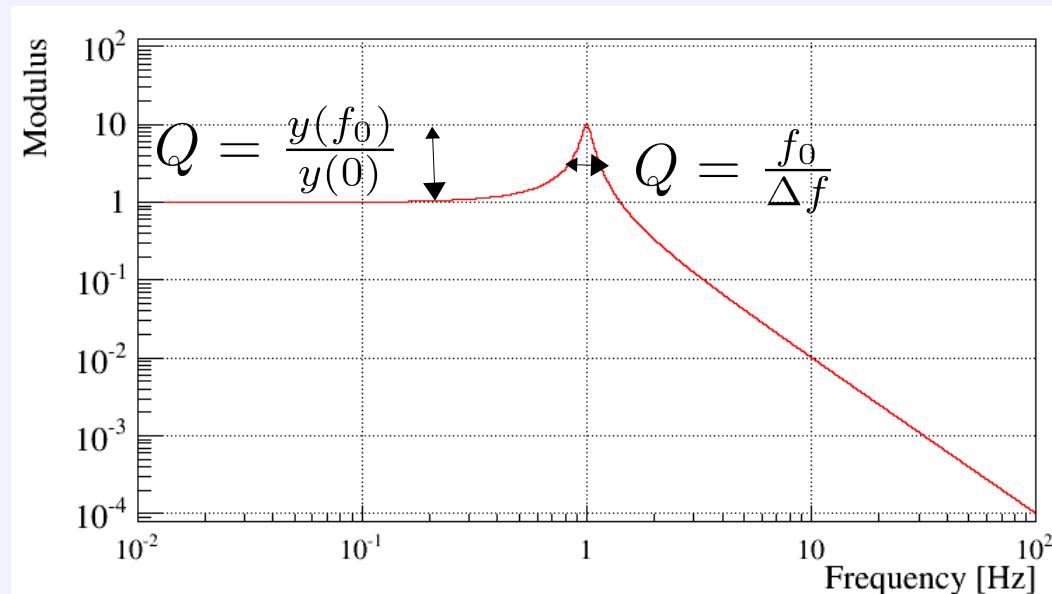
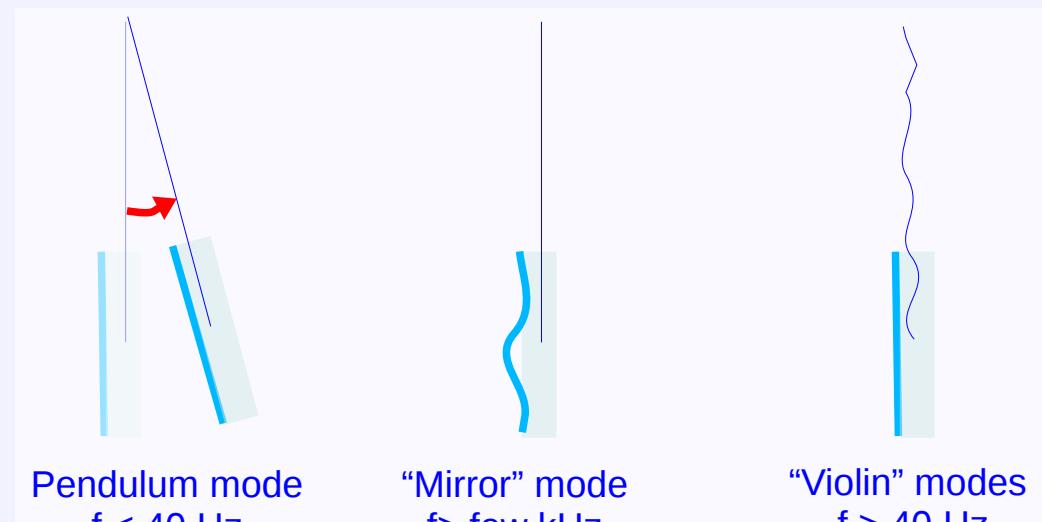
This noise directly modifies the positions of the mirror surfaces, and thus $\delta\Delta L$ and $h_{\text{rec}}(t)$!

- **Active controls** at low frequency

- Accelerometers or interferometer data
- Electromagnetic actuators
- Control loops

Some noises: thermal noise

- Microscopic thermal fluctuations
 - > dissipation of energy through excitation of the macroscopic modes of the mirror

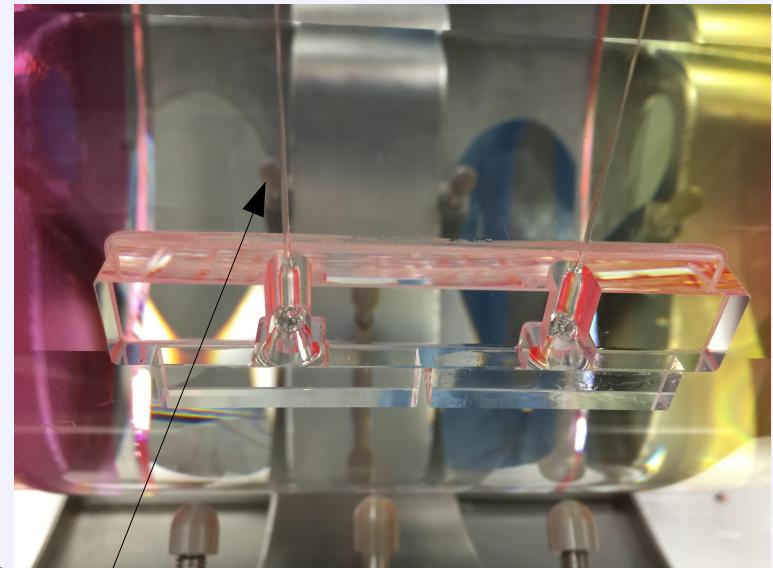
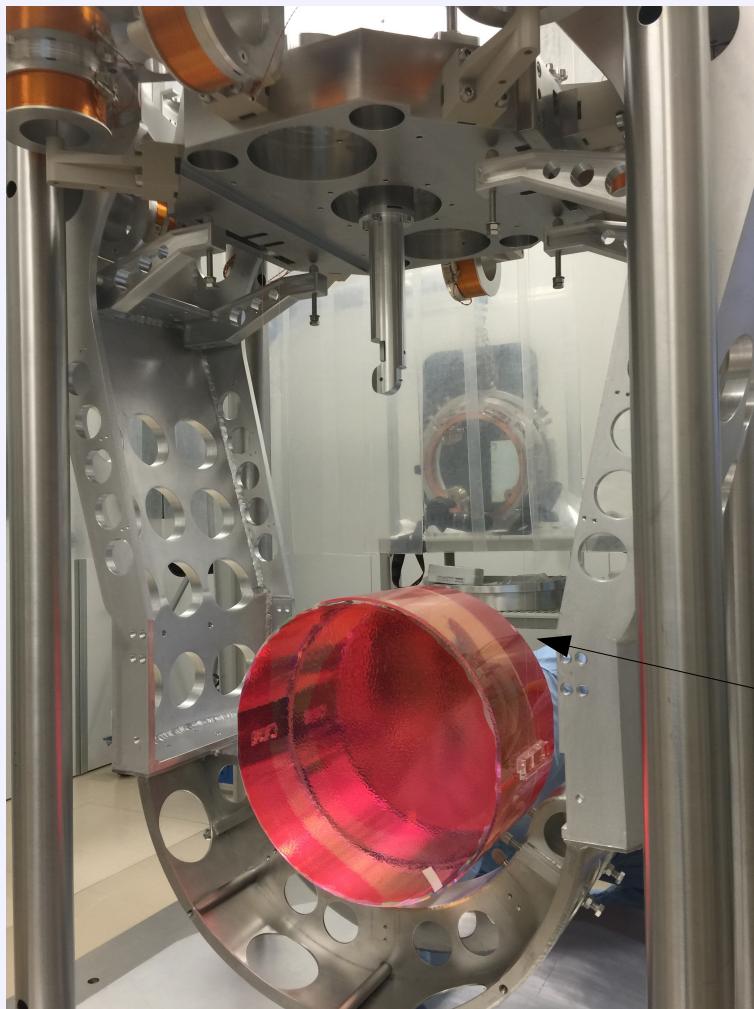


This noise directly modifies the positions of the mirror surfaces, and thus $\delta\Delta L$ and $h_{rec}(t)$!

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

Thermal noise: monolithic suspensions

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



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

What is the shot noise?



The PARTICLE ZOO
Subatomic Particle Plush Toys FROM THE STANDARD MODEL OF PHYSICS & beyond!

- Fluctuations of arrival times of photons (quantum noise)

Power received by the photodiode: P_t
 $\rightarrow N = \frac{P_t}{h\nu}$ photons/s on average.



Standard deviation on this number: $\sigma_N = \sqrt{N}$
 $\rightarrow \sigma_{P_t} = \sigma_N \times h\nu = \sqrt{\frac{P}{h\nu}} h\nu = \sqrt{P_t h\nu}$

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

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

\rightarrow a variation of power is interpreted as a variation of distance $\delta\Delta L$

$$\delta P_t = (\text{Virgo response}) \times L_0 \times h \\ (\text{in W/m})$$

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

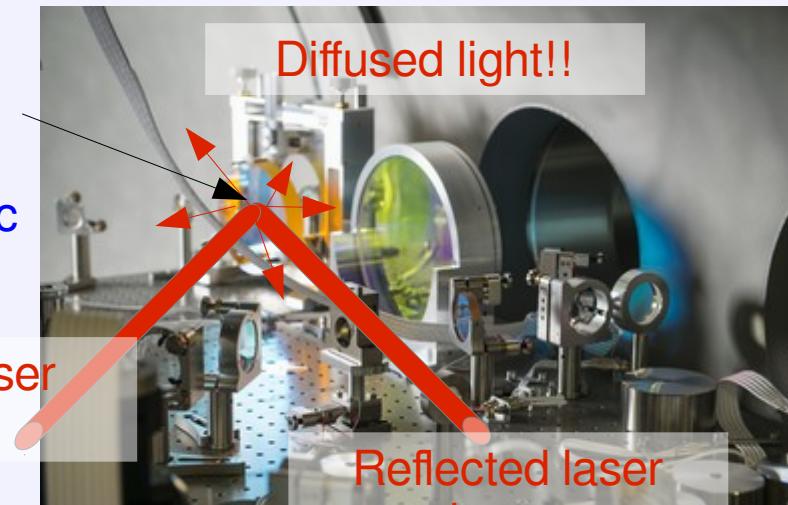
Some other gaussian noises

- Acoustic vibrations and refraction index fluctuations
 - Main elements installed in vacuum
- Laser: amplitude, frequency, jitter noise
 - Lots of control loops to reduce these noises
- Electronics noise 
 - Challenge for the electronics engineers to measure down to $0.1 \text{ nW}/\sqrt{\text{Hz}}$
- Non-linear noise from diffuse light
 - Need dedicated optical elements with specific mechanical modes

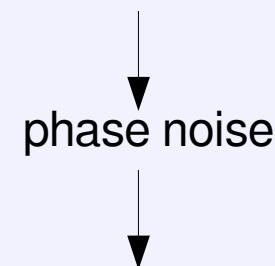


Another source of noise: diffused light

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

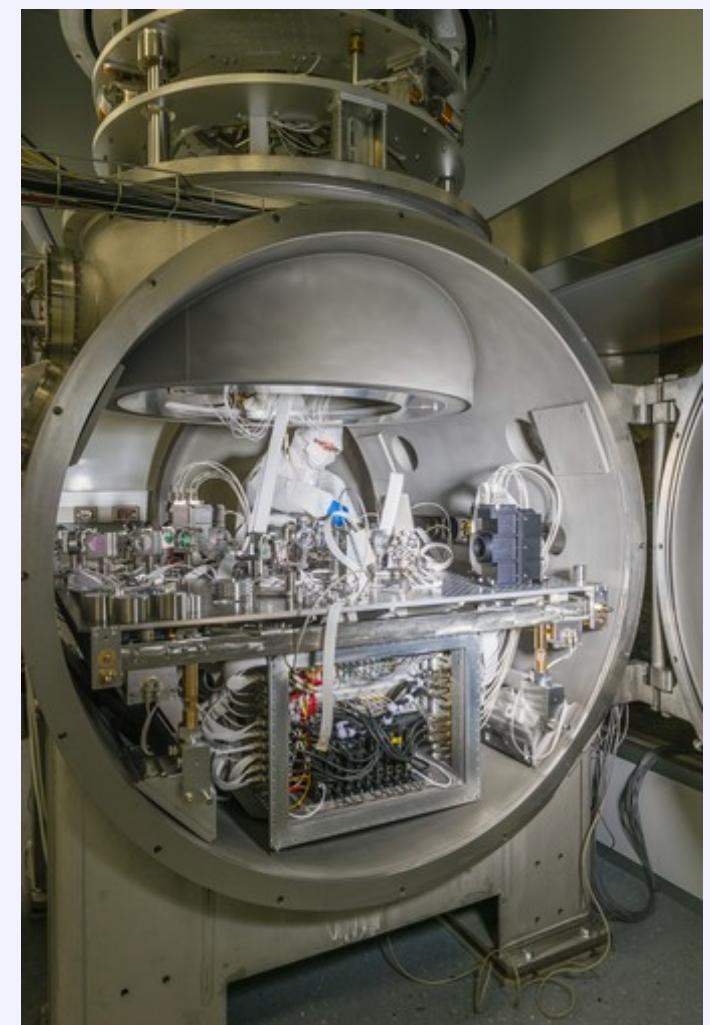


some photons of the diffused light gets recombined with the interferometer beam



extra power fluctuations
(imprint of the optical element vibrations)

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



Interpretation of the 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)

$\sim 10^{-19} \text{ m}/\sqrt{\text{Hz}}$ (Virgo, 2011)

$\sim 10^{-20} \text{ m}/\sqrt{\text{Hz}}$ (Advanced Virgo, ~2021)

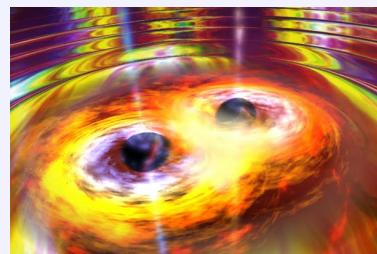
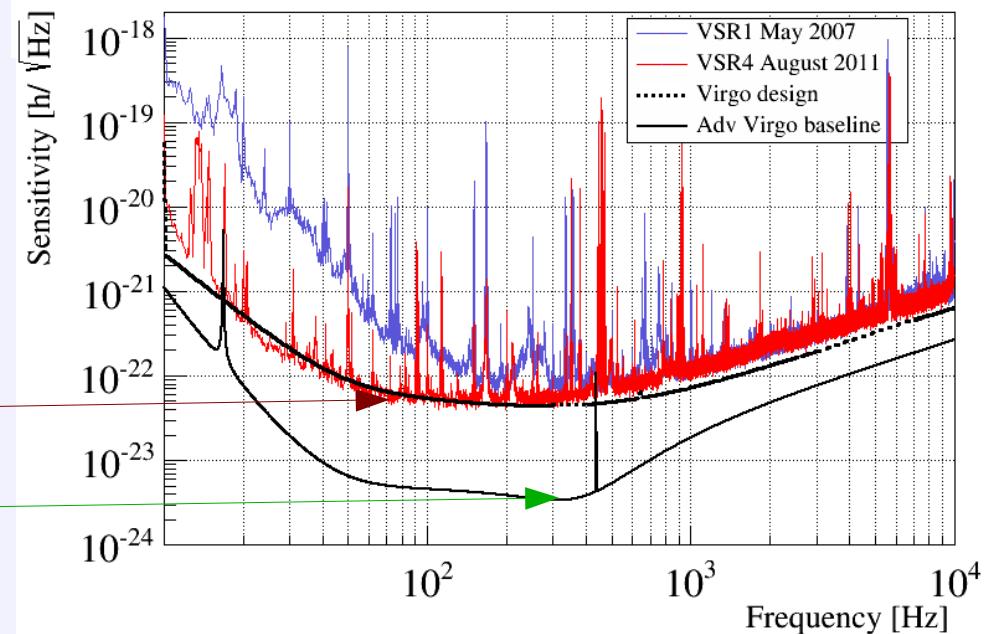


Image: Danna Berry/SkyWorks/NASA

Compact Binary Coalescences

Signal lasts for a few seconds

→ can detect $h \sim 10^{-23}$

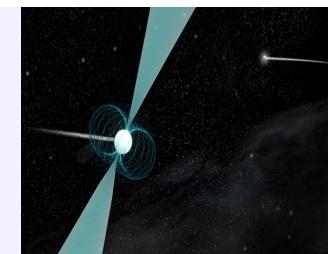


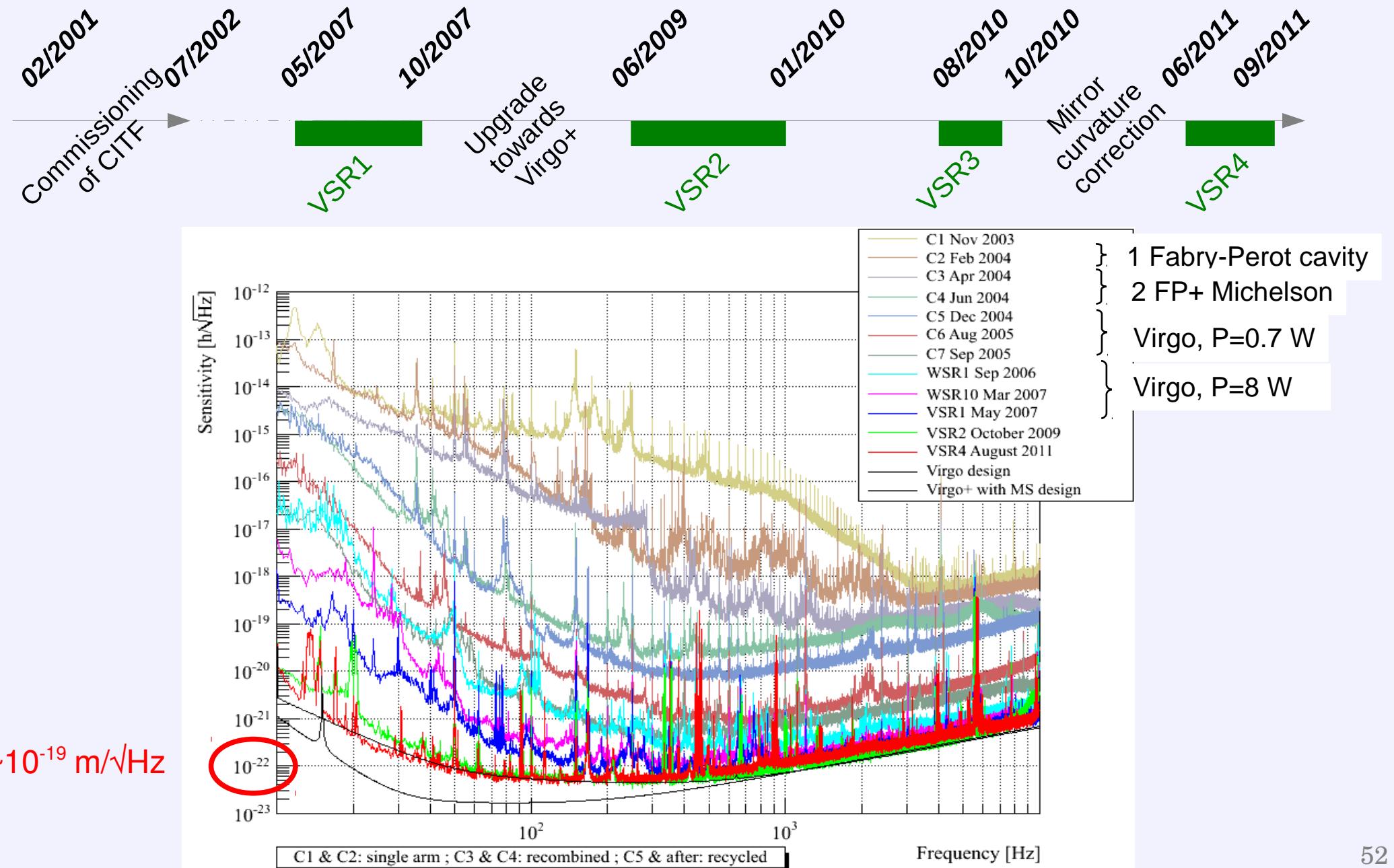
Image: B. Saxton
(NRAO/AUI/NSF)

Rotating neutron stars

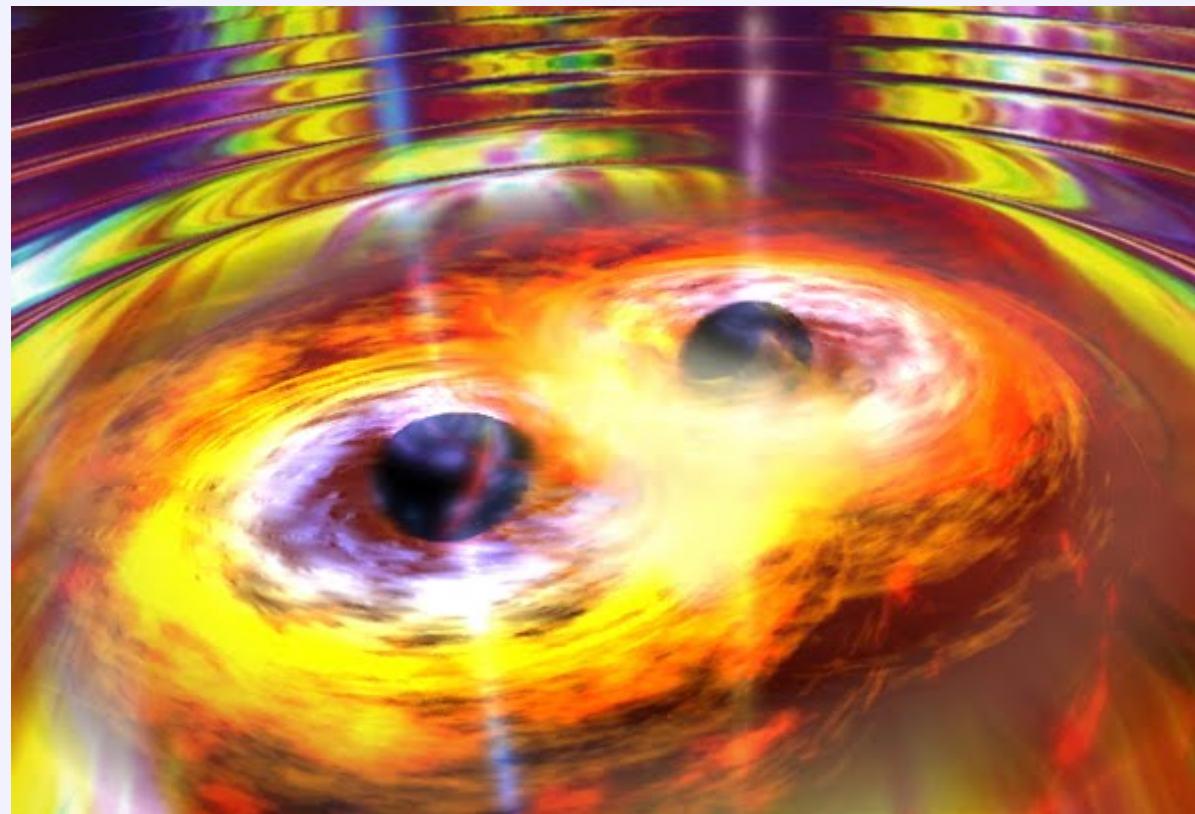
Signal averaged over days ($\sim 10^6$ s)

→ can detect $h \sim 10^{-26}$

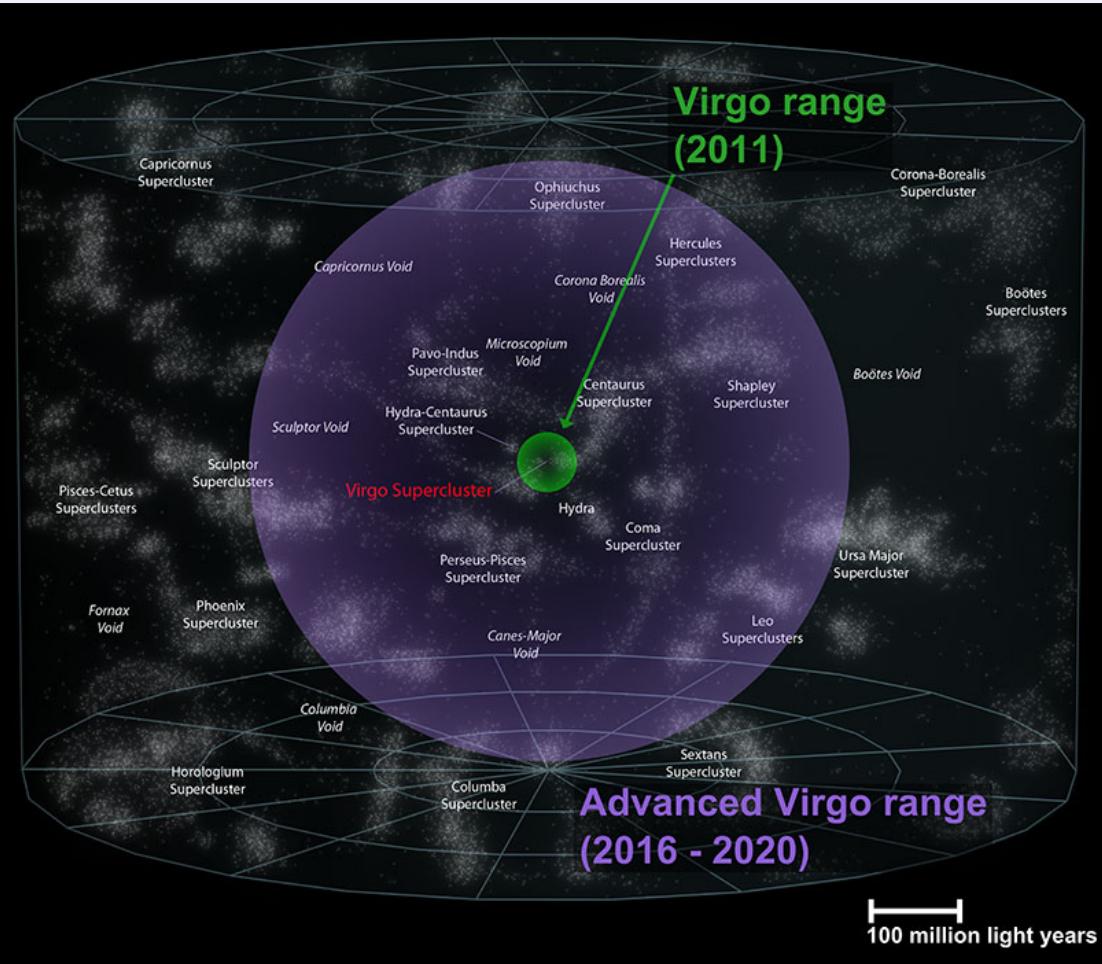
History of Virgo noise curve



Part 5: towards Advanced Virgo



Horizon of Advanced detectors



Expected neutron star binary coalescence detection rate (event/year)

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

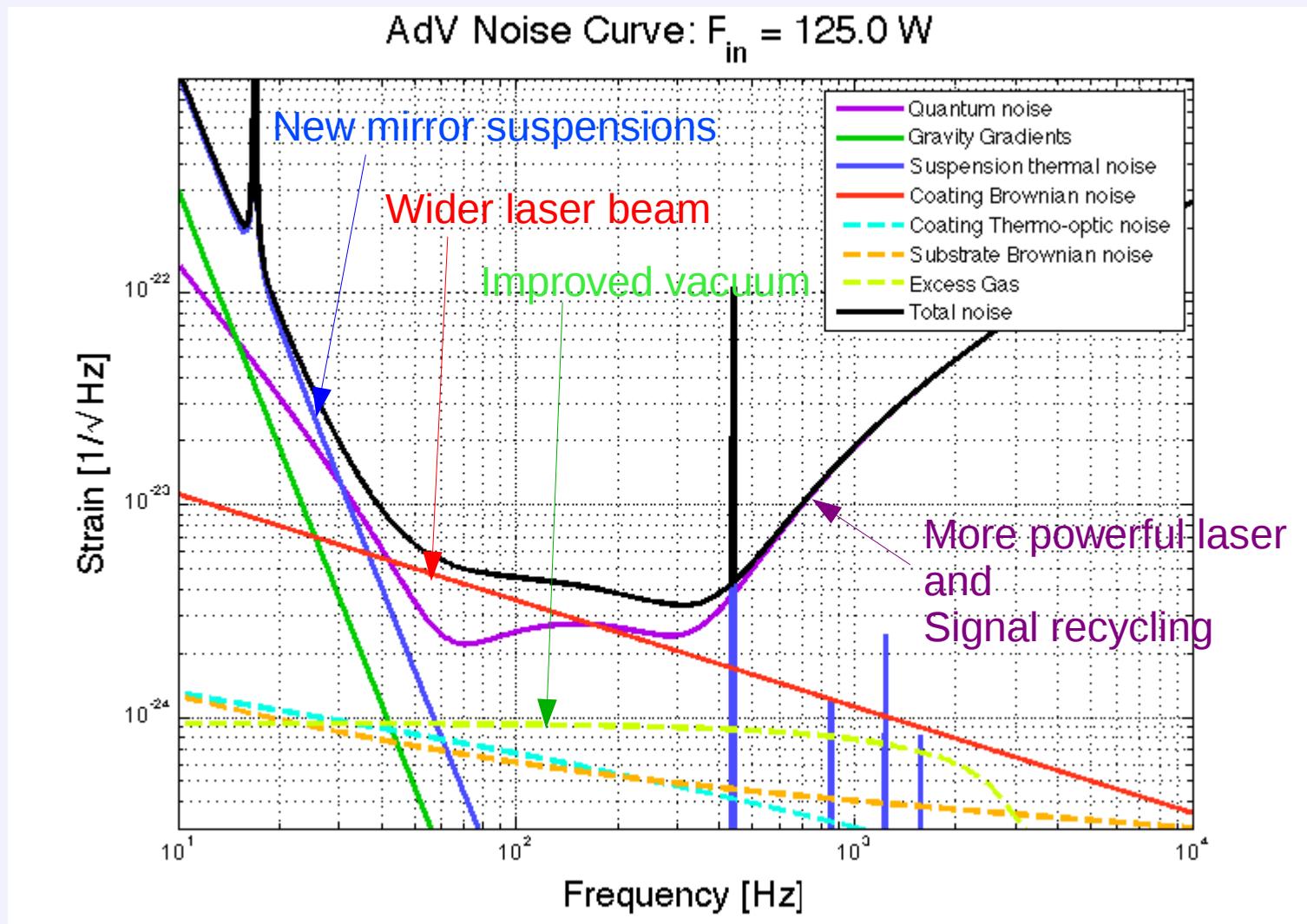
Improving the sensitivity (or horizon) by a factor 10



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

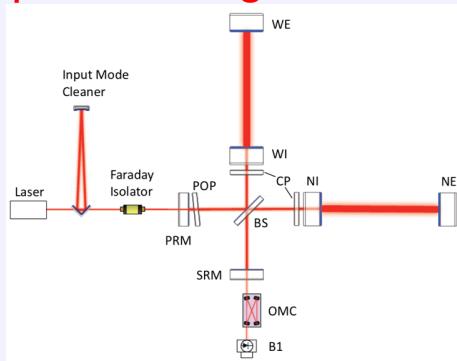
	low	realistic	high
Initial Virgo/LIGO	0.0002	0.02	0.2
Advanced Virgo/LIGO	0.4	40	400

Towards the Advanced Virgo sensitivity

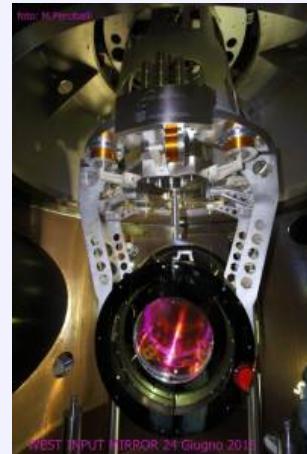


Advanced Virgo installation almost completed...

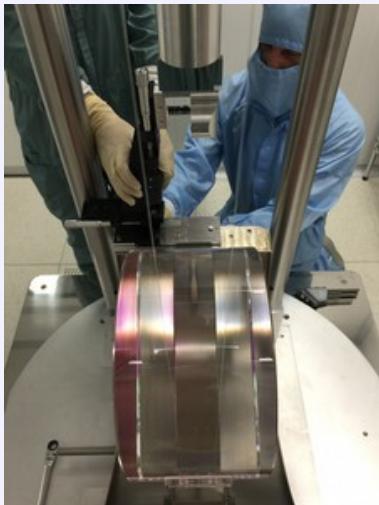
New optical configuration



Better and heavier mirrors



Monolithic silica mirror suspension



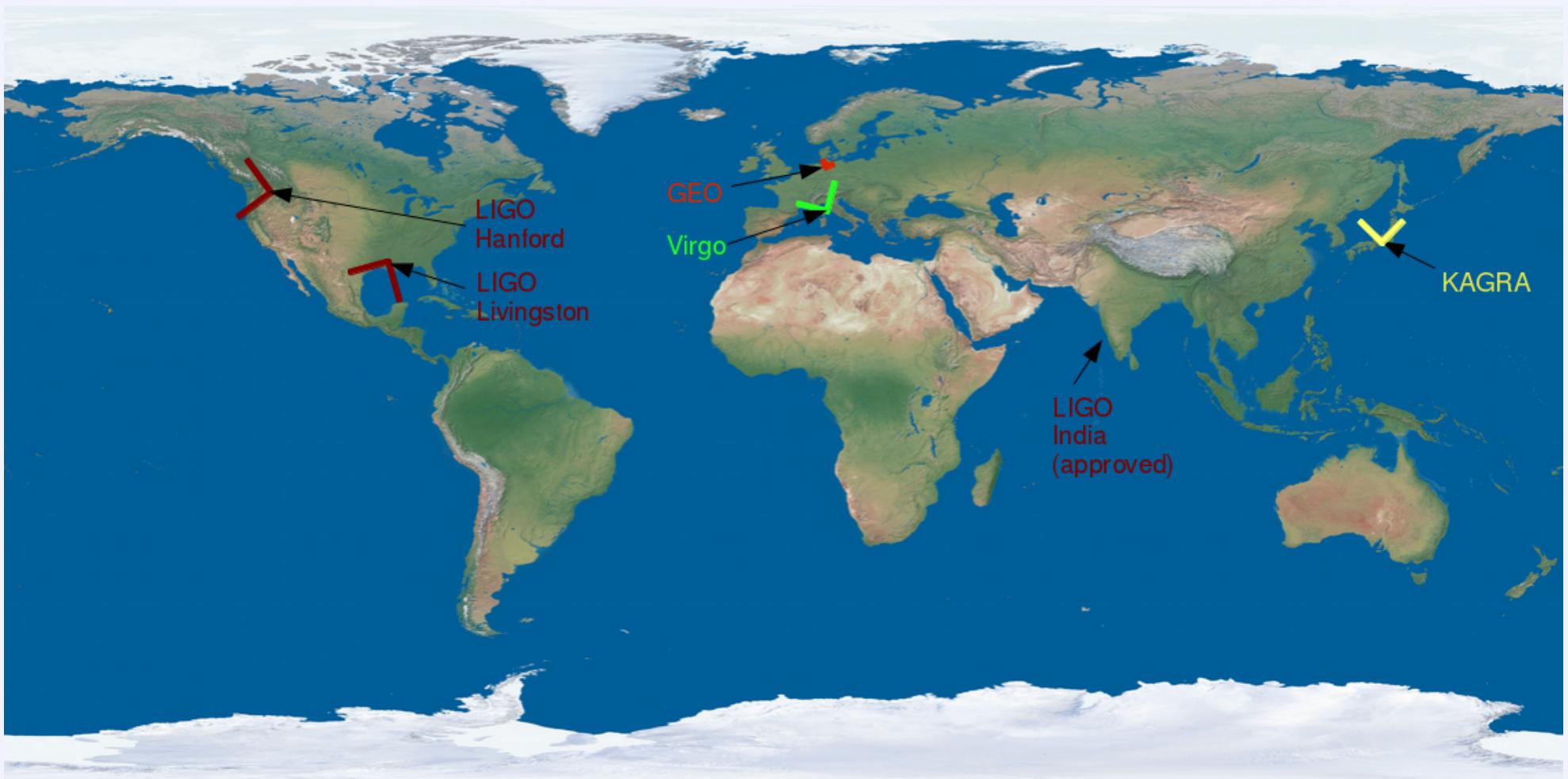
More in vacuum
suspended benches



New electronics boards

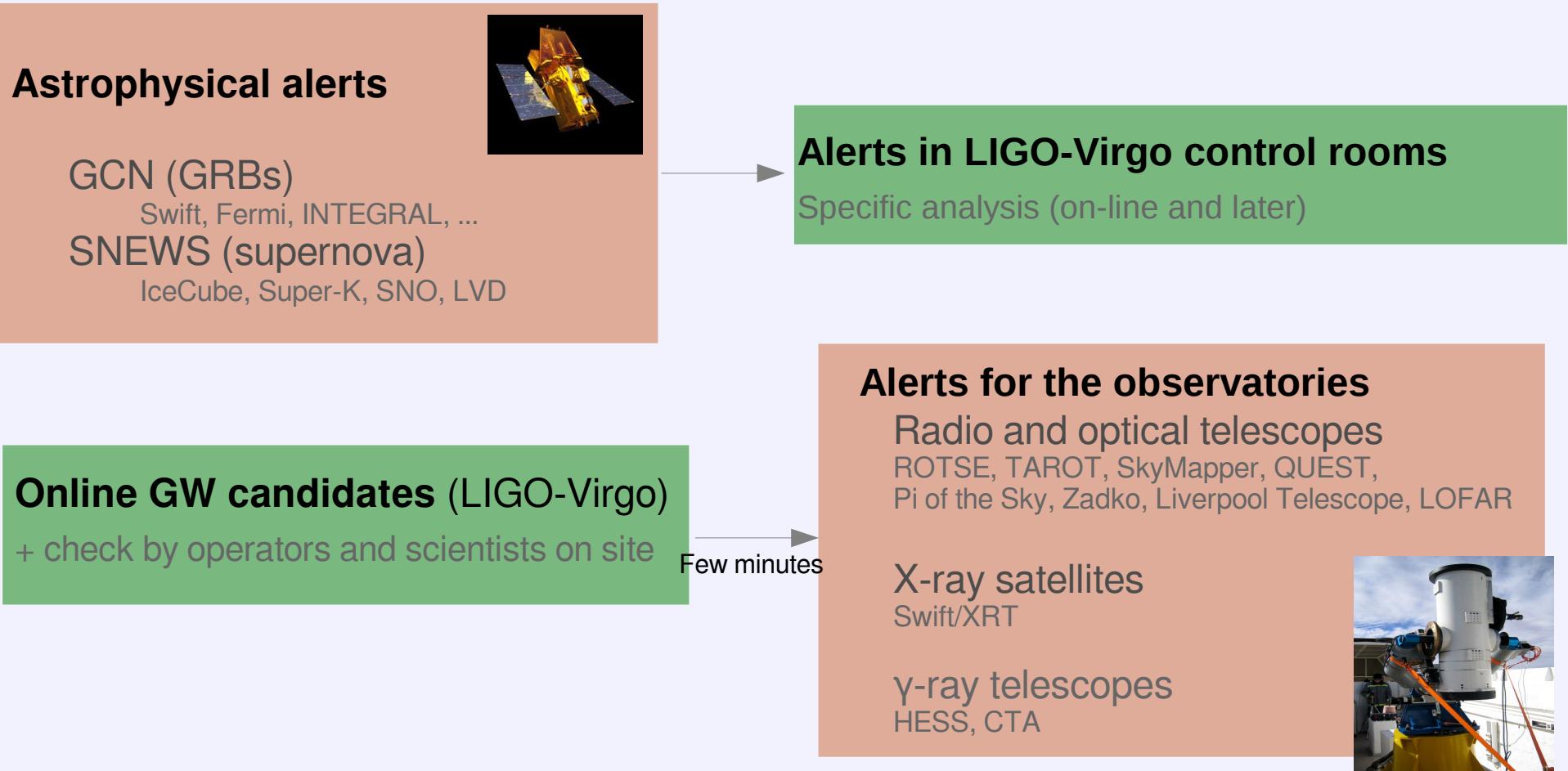


A worldwide network of interferometers



- ▶ Confirm a detection
- ▶ Determine the position of a GW source
- ▶ Decompose the GW polarisation

Multi-messenger astronomy



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

Towards more GW detections!

