The Virgo detector

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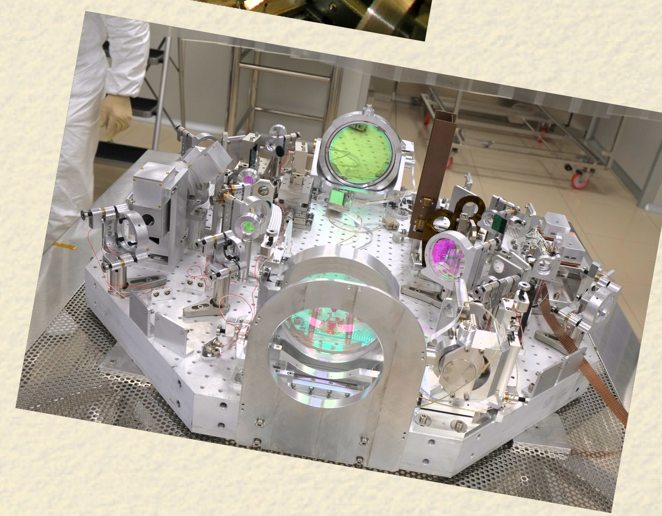

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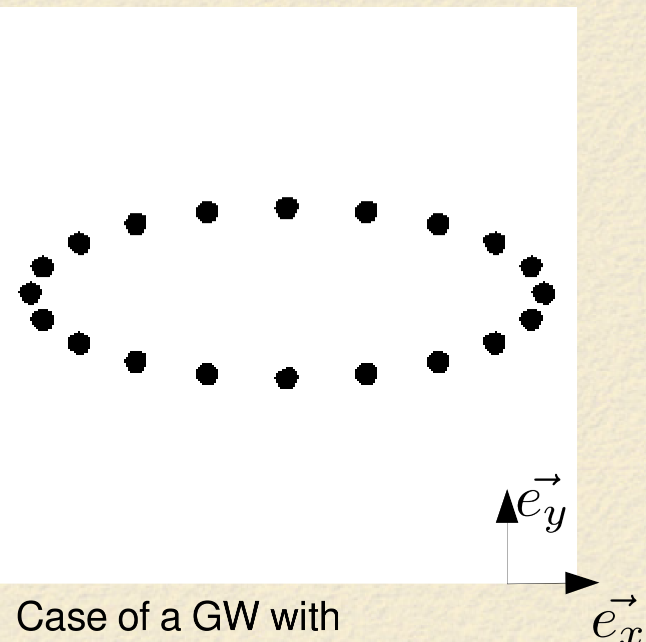
  - Simple Michelson interferometer
  - How do we improve the detector sensitivity?

- **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



Case of a GW with polarisation + propagating along z

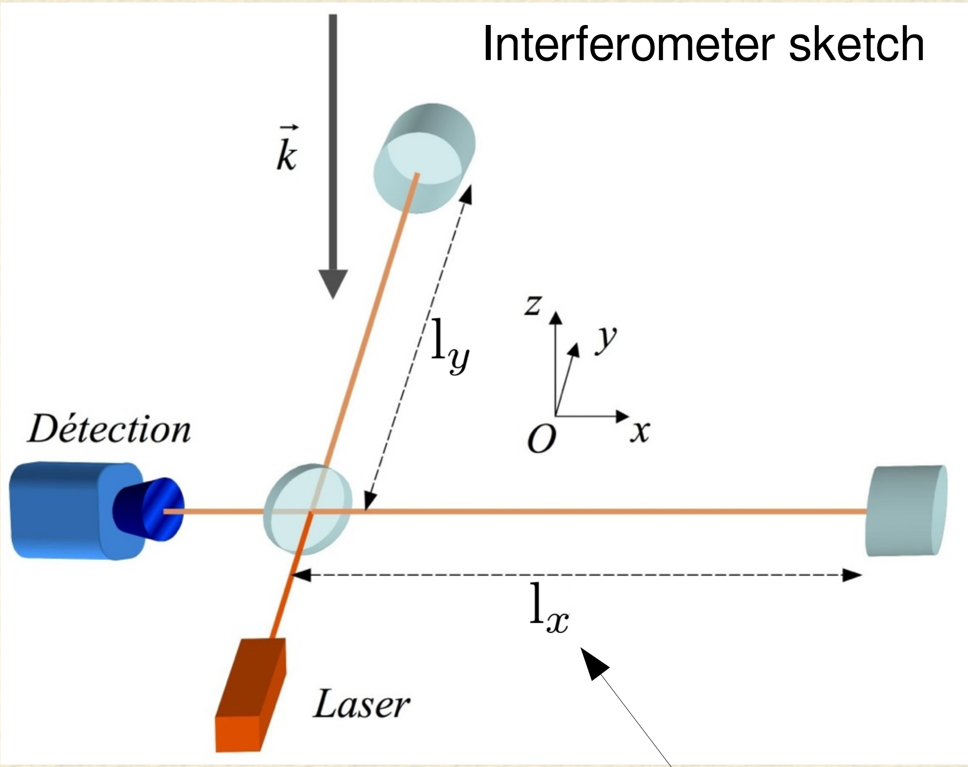
$$\delta x(t) \;=\; -\delta y(t) \;=\; \tfrac{1}{2}\, h(t)\, L_0$$

h(t): amplitude of the GW

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

(*h* has no dimension/unit)

A general overview of the Virgo detector



The interference pattern depends on ΔL:

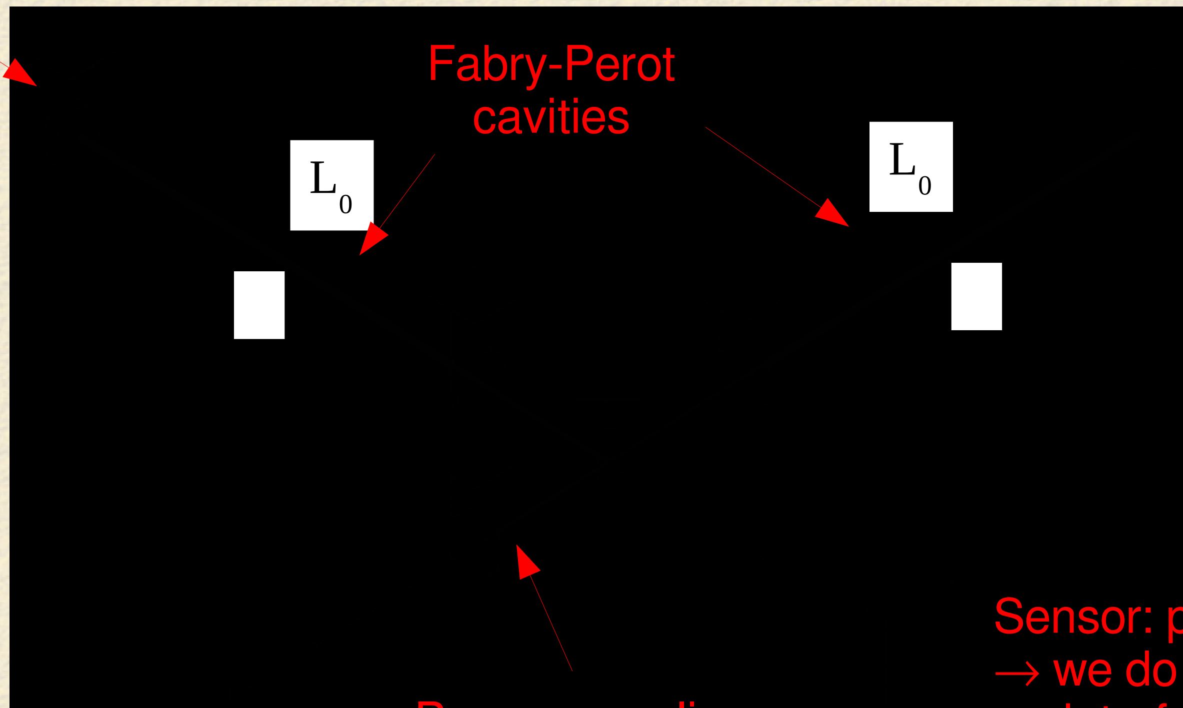
$\Delta L(t) = l_{x}(t) - l_y(t)$

Length of the arms: $L_0 = 3$ km

Virgo: a more complicated interferometer

Suspended mirrors

→ Mirrors can be considered as free for frequencies larger than ~10 Hz

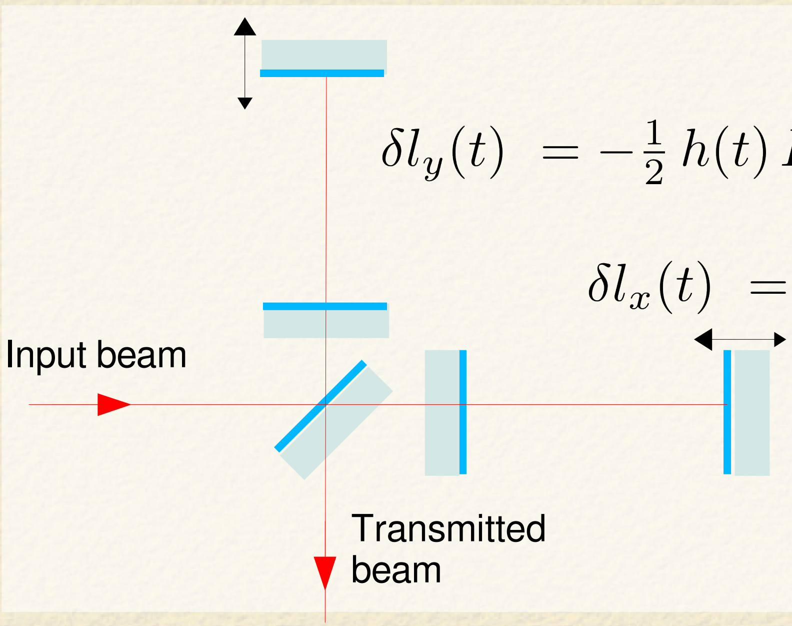


Sensor: photodiode
→ we do not image the interference pattern!

Infrared laser
P ~ 100 W

Power-recycling cavity

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:

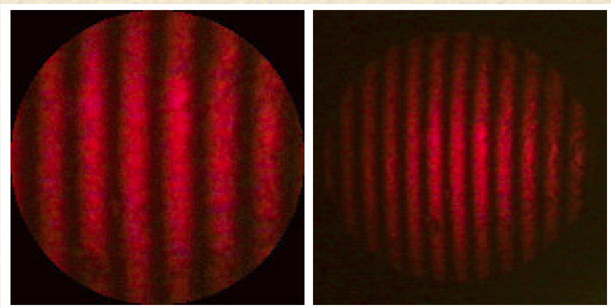
$$\begin{aligned}\delta\Delta L &= \delta l_x(t) - \delta l_y(t)\\ &= h(t)\, L_0\end{aligned}$$

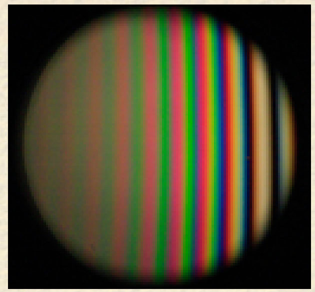
$$\mathrm{h} \sim 10^{-23} \qquad L_0 = 3\,\mathrm{km}$$

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

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

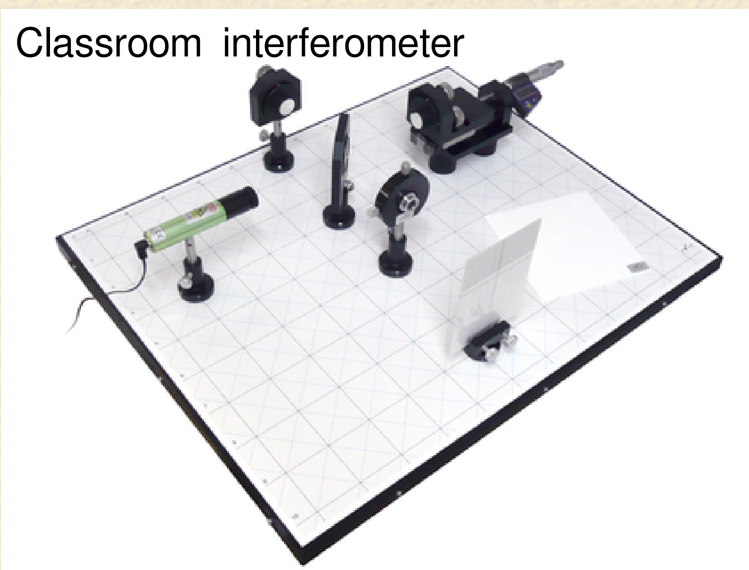
How and for what did you use interferometers?





Wavelength of monochromatic source

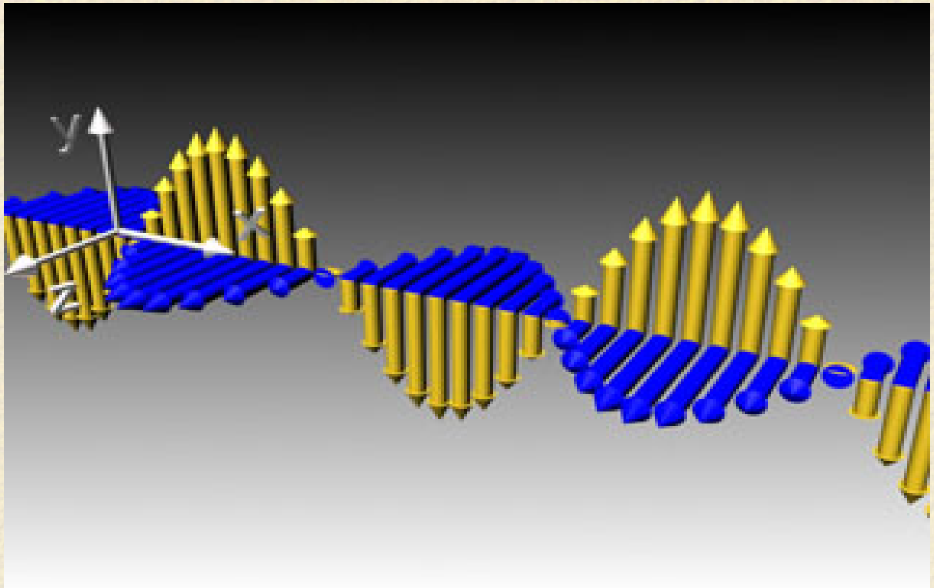
Sodium doublet wavelength separation

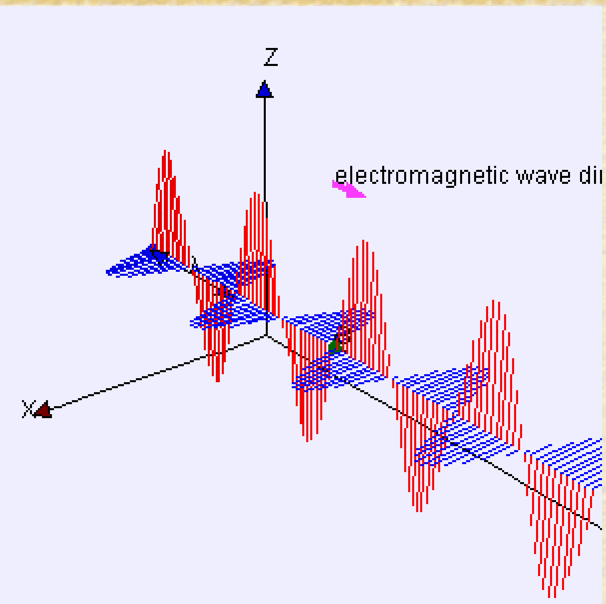


Part 2: Virgo optical configuration

- 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 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)

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

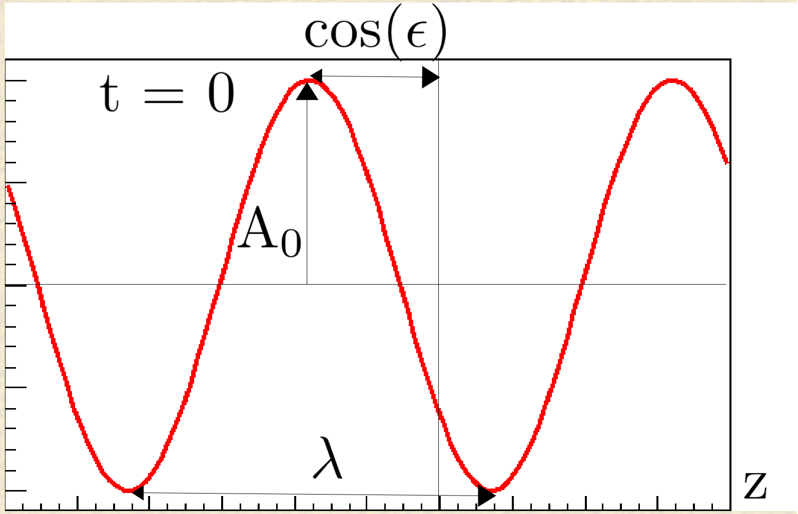
Description of plane waves

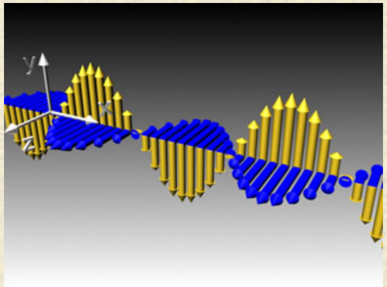
- Plane wave propagating along z, with speed c

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

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

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





- Complex form

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

$$= \underline{A}_0 e^{\jmath(kz+\epsilon)} \qquad \text{with} \qquad \underline{A}_0 = A_0 e^{-\jmath\omega t}$$

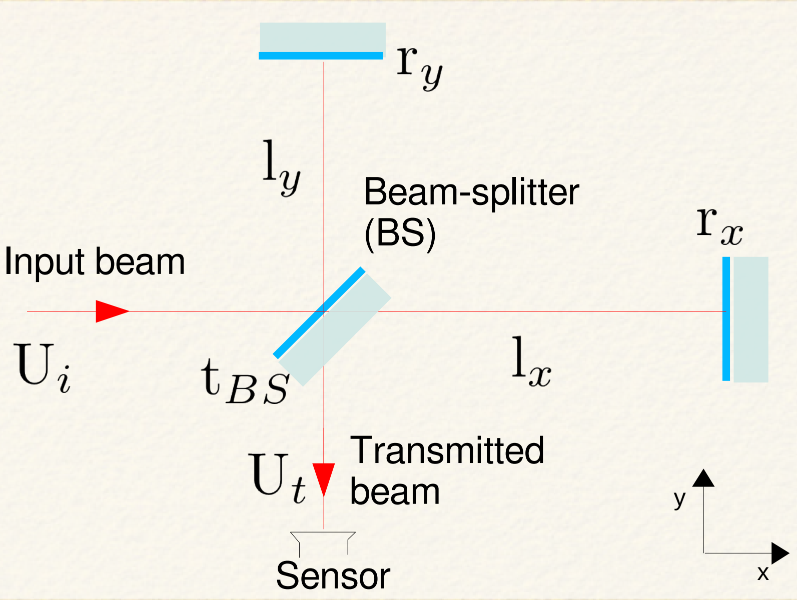
--> simpler algebraic calculations, for example $\mathrm{P} \propto |U|^2 = UU^*$

--> 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 localised region of space

How do we "observe" ΔL with a Michelson interferometer?

- Input wave $U_i(x,t) = \underline{A_i} e^{\jmath kx}$
  $= \underline{A_i}$ 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

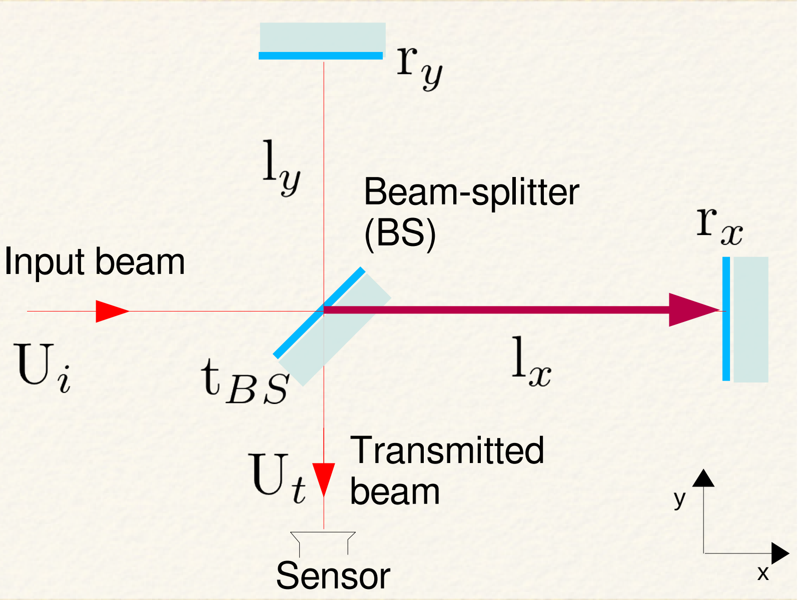
How do we “observe” ΔL with a Michelson interferometer?

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

$$= \underline{A}_i \quad \text{on BS}$$

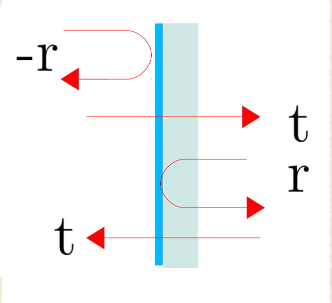
- Beam propagating along x-arm:

$$U_{tx} = \underline{A}_i \, t_{BS} \, e^{\jmath k l_x} \;\ldots\ldots$$



Sign convention for amplitude reflection and transmission coefficients

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

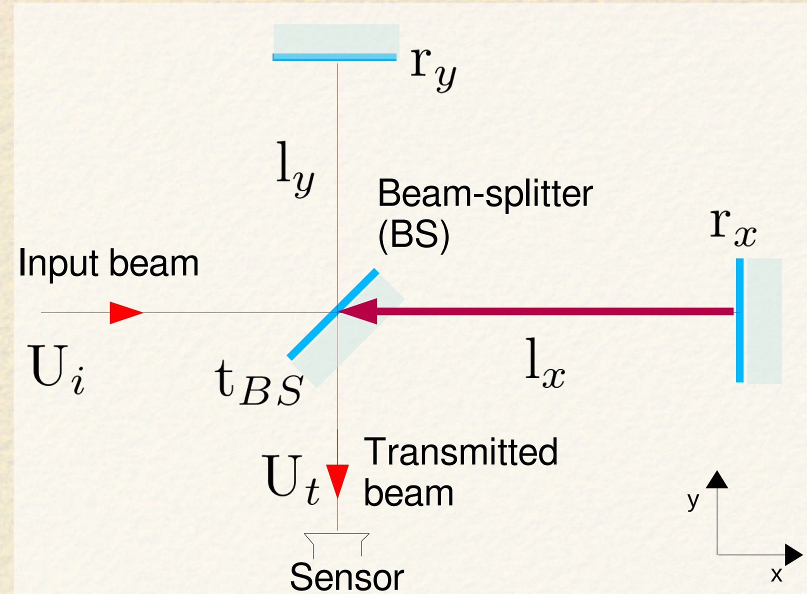


How do we "observe" ΔL with a Michelson interferometer?

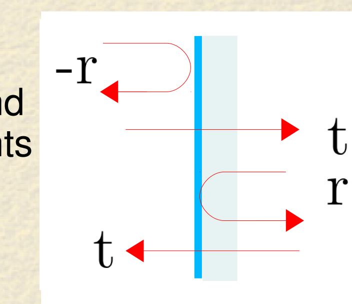
- Input wave $U_i(x,t) = \underline{A}_i e^{\jmath kx}$
  $= \underline{A}_i$ on BS

- Beam propagating along x-arm:

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



Sign convention for amplitude reflection and transmission coefficients

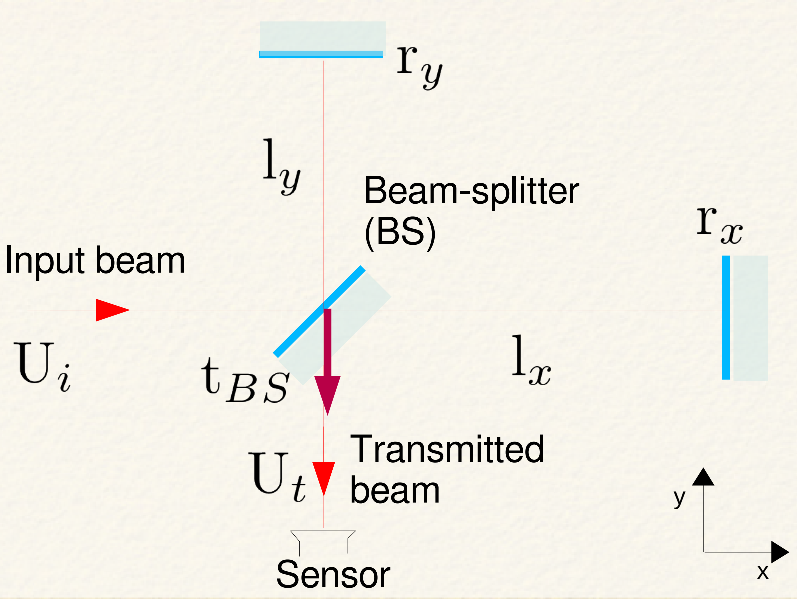


How do we “observe” ΔL with a Michelson interferometer?

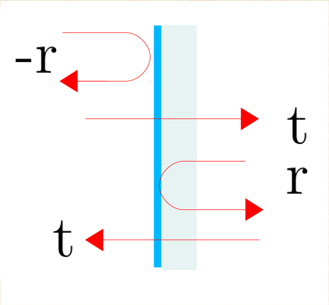
- Input wave $$U_i(x,t) = \underline{A}_i e^{\jmath kx}$$ $$= \underline{A}_i \quad \text{on BS}$$

- Beam propagating along x-arm:

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



Sign convention for amplitude reflection and transmission coefficients



How do we "observe" ΔL with a Michelson interferometer?

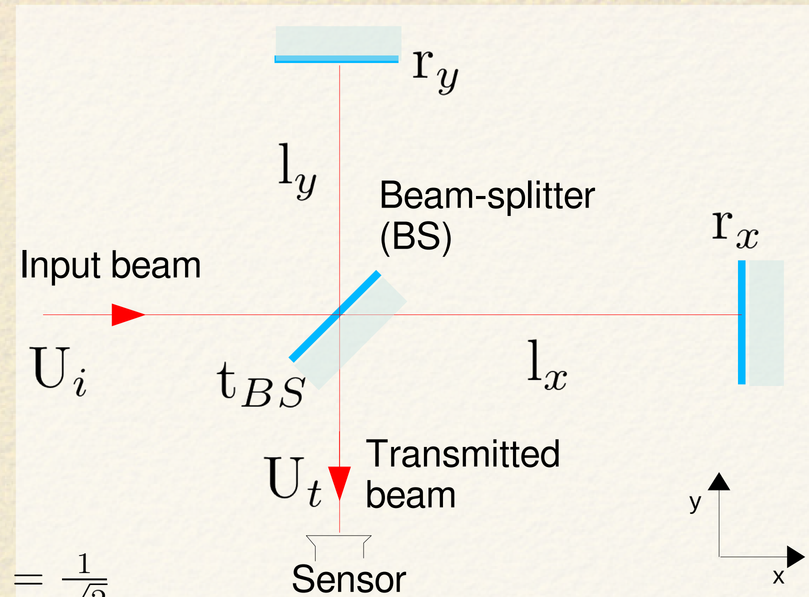
- Input wave $U_i(x,t) = \underline{A}_i e^{\jmath kx}$

$$= \underline{A}_i \quad \text{on BS}$$

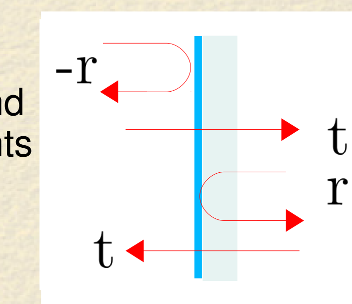
- Beam propagating along x-arm:

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

with $\mathrm{t}_{BS} = r_{BS} = \frac{1}{\sqrt{2}}$



Sign convention for amplitude reflection and transmission coefficients



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

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

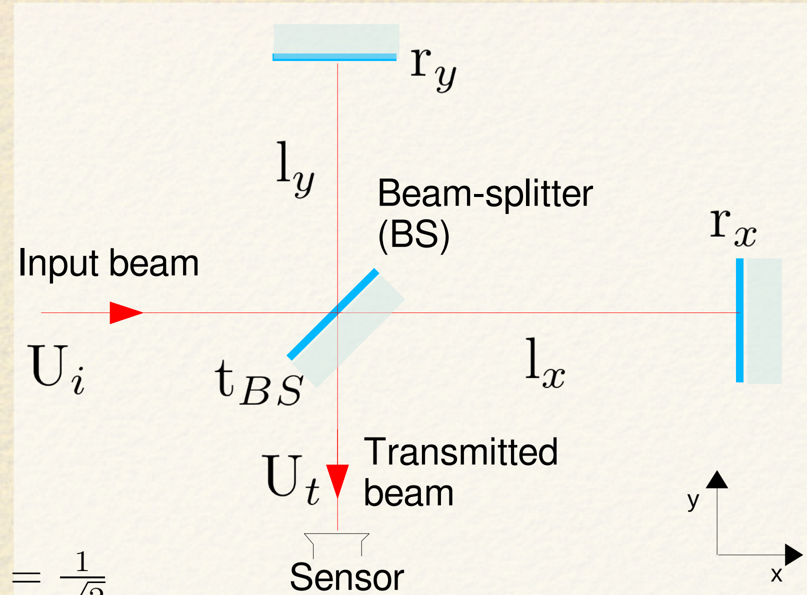
$$= \underline{\mathcal{A}_i} \quad \text{on BS}$$

- Beam propagating along x-arm:

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

$$= \underline{\mathcal{A}_i}\, t_{BS}\, r_{BS}\, (-r_x)\, e^{2\jmath k l_x}\, e^{\jmath k y_s}$$

$$= \frac{\mathcal{A}_i}{2} \times \underbrace{\left(- r_x\, e^{2\jmath k l_x} \right)}_{\text{Complex reflection of the x-arm}} e^{\jmath k y_s} \qquad \text{with } t_{BS} = r_{BS} = \frac{1}{\sqrt{2}}$$



- Beam propagating along y-arm:

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

$+$

- Transmitted field:

$$U_t = U_{tx} + U_{ty}$$

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

Power transmitted by a simple Michelson

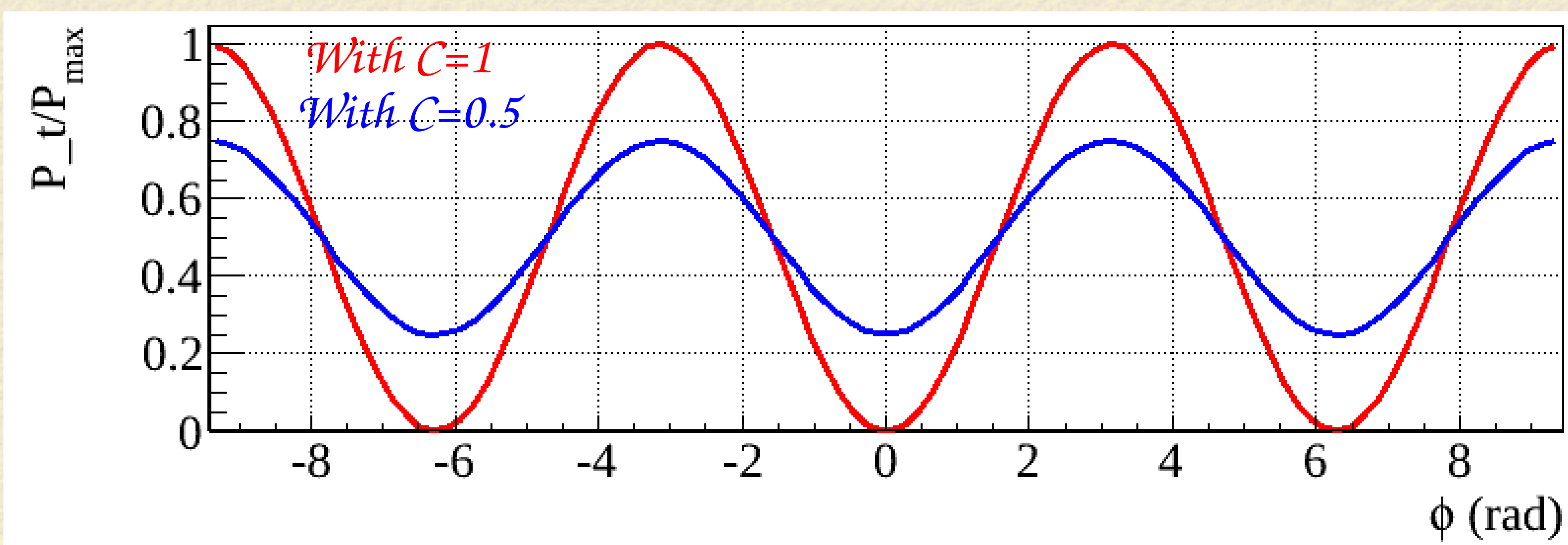
- Transmitted field: $U_t = \frac{\mathcal{A}_i}{2} e^{\jmath k y_s} \left(r_y\, e^{2\jmath k l_y} - r_x\, e^{2\jmath k l_x} \right)$

- Calculation of the transmitted power:

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

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

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

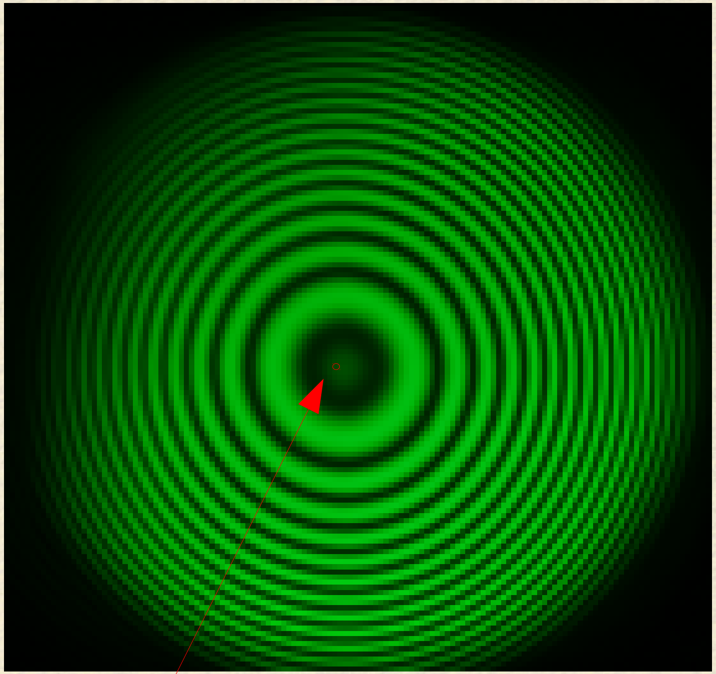


What power does Virgo measure?

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

  → interference pattern

  (and the complementary pattern in reflection)

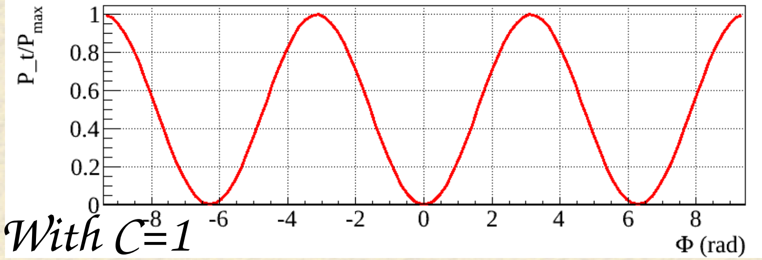


Equivalent size of Virgo beam

- Virgo interference pattern much larger than the beam size:

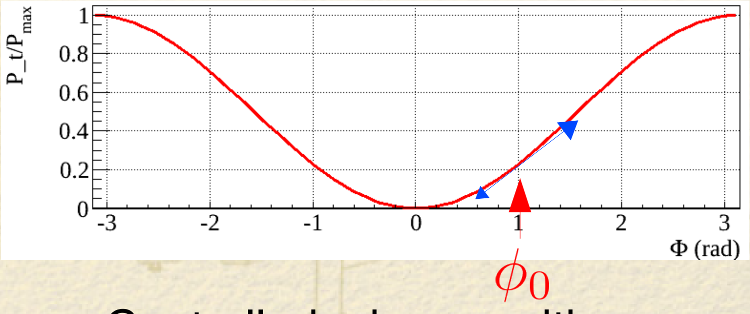
  ~1 m between two consecutive fringes

  → we do not study the fringes in nice images !



Freely swinging mirrors

Setting a working point



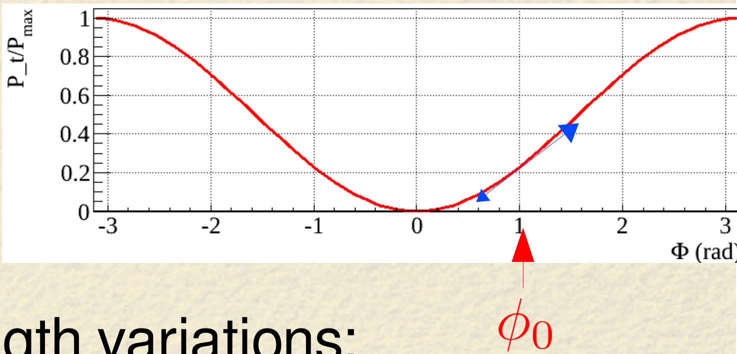
Controlled mirror positions

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:

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

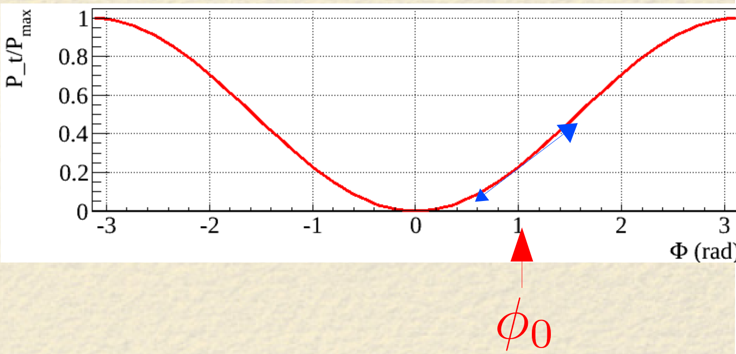
$$\delta P_t = P_i\, C\, \frac{2\pi}{\lambda} \sin\left(\frac{4\pi}{\lambda}\Delta L_0\right) \delta\Delta L$$

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

From the power to the gravitational wave

- Around the working point:

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



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

(W/m)

Measurable physical quantity

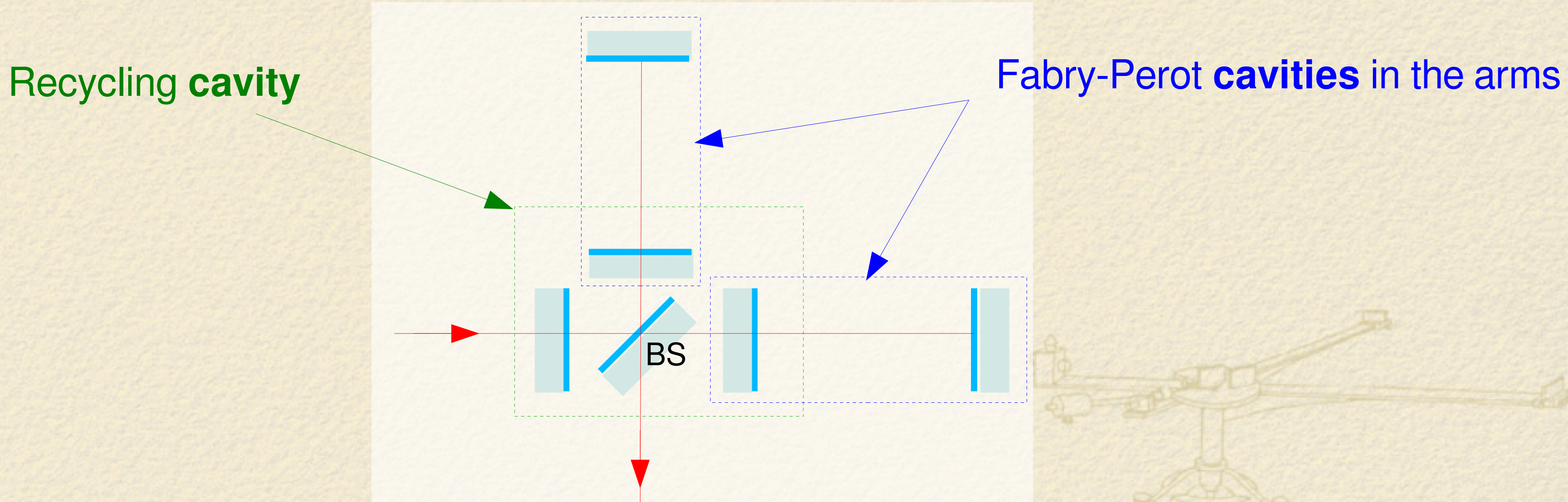
Physical effect to be detected

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

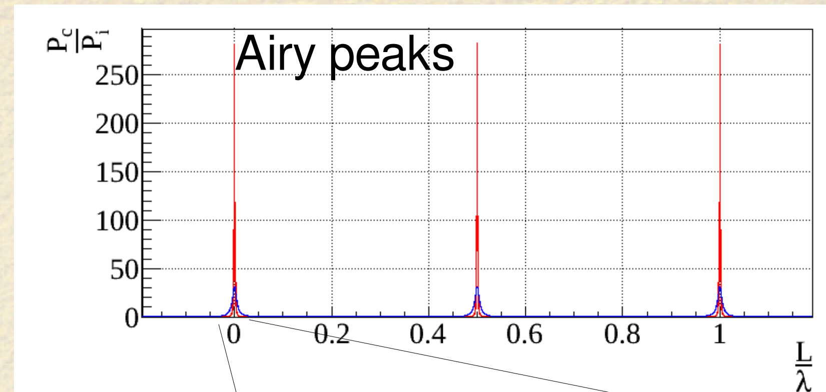
Increase the phase difference between the arms for a given differential arm length variation



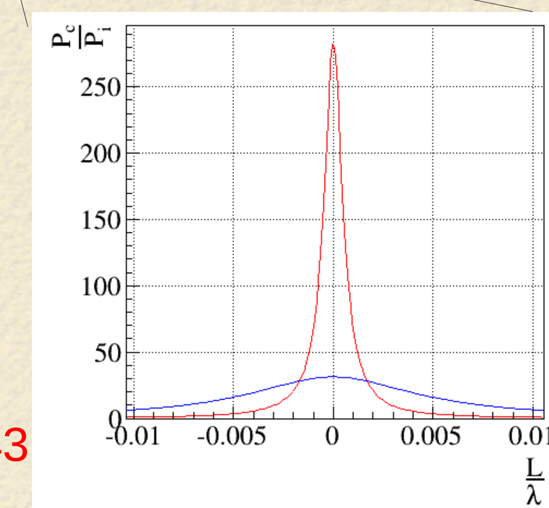
In Virgo, the beam is resonant inside the cavities

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

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



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

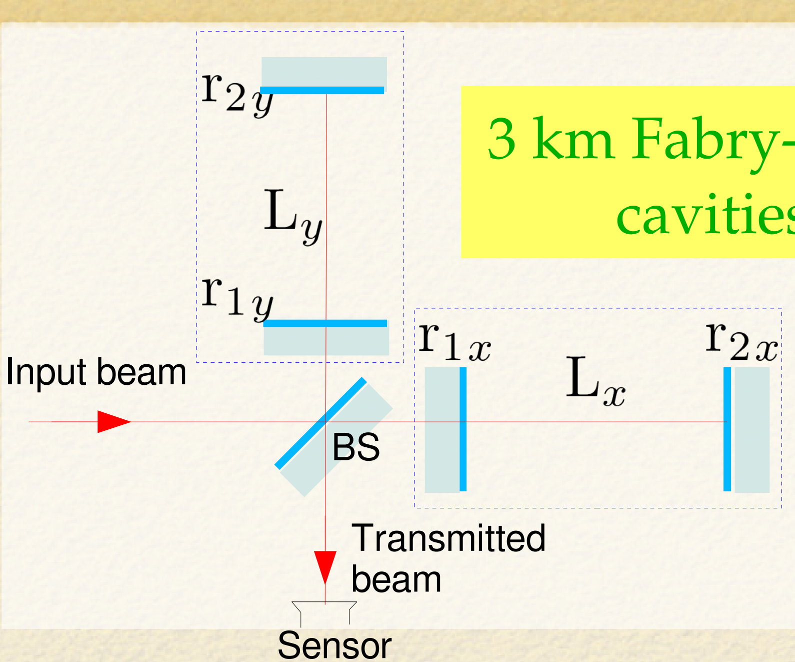


Virgo $\mathcal{F} = 50$

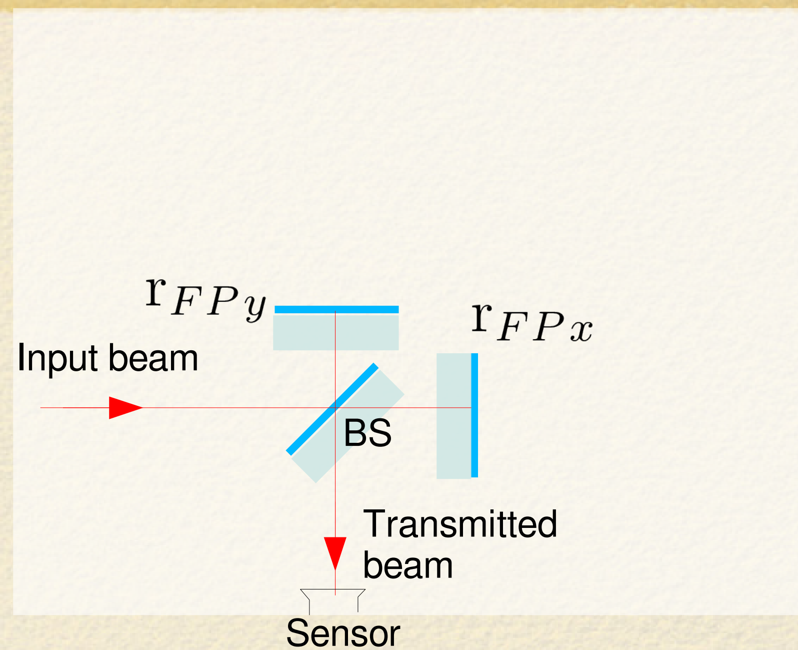
AdVirgo $\mathcal{F} = 443$

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

How do we amplify the phase offset?



3 km Fabry-Perot cavities



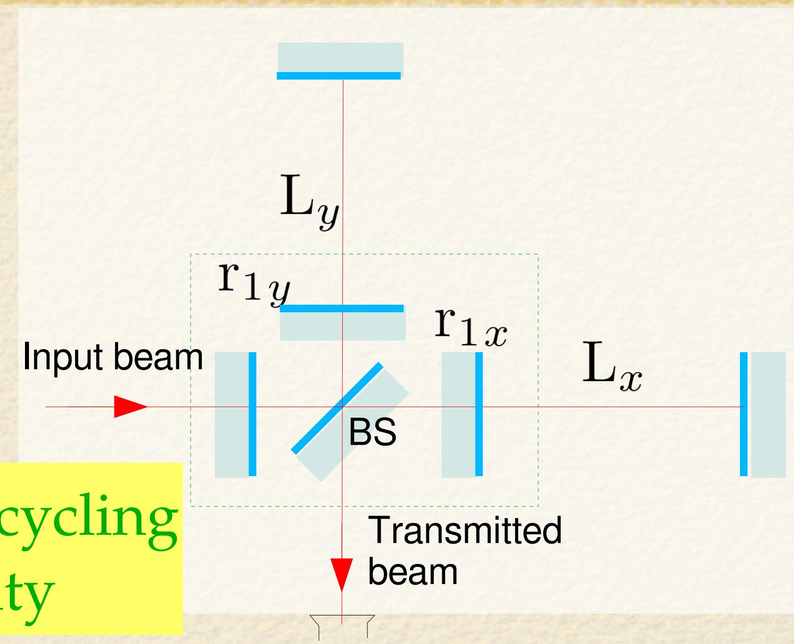
$$r_{FPx} = -1 \times e^{\mathrm{j}\,\frac{2\mathcal{F}}{\pi}\,2\,k\,\delta L_x}$$

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

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

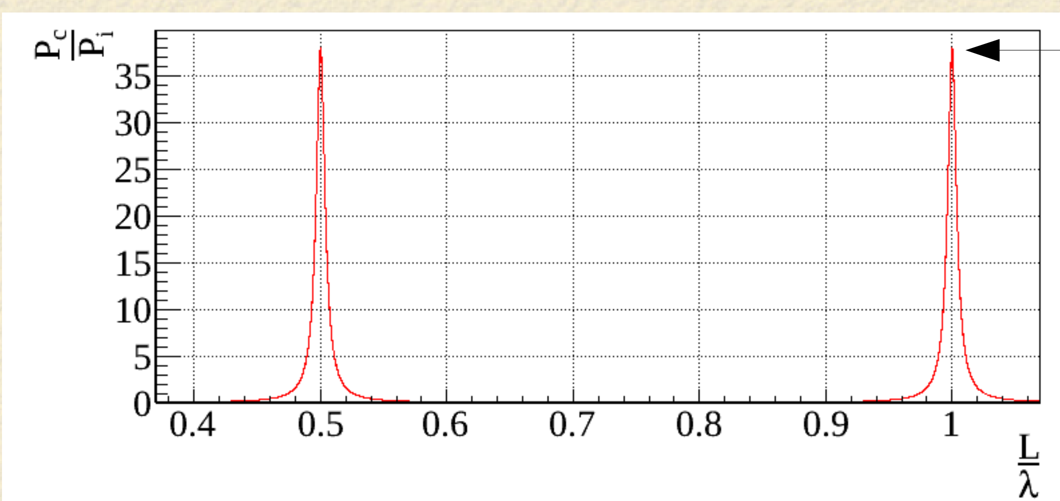
How do we increase the power on BS?

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



Power recycling cavity

Resonant power recycling cavity



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

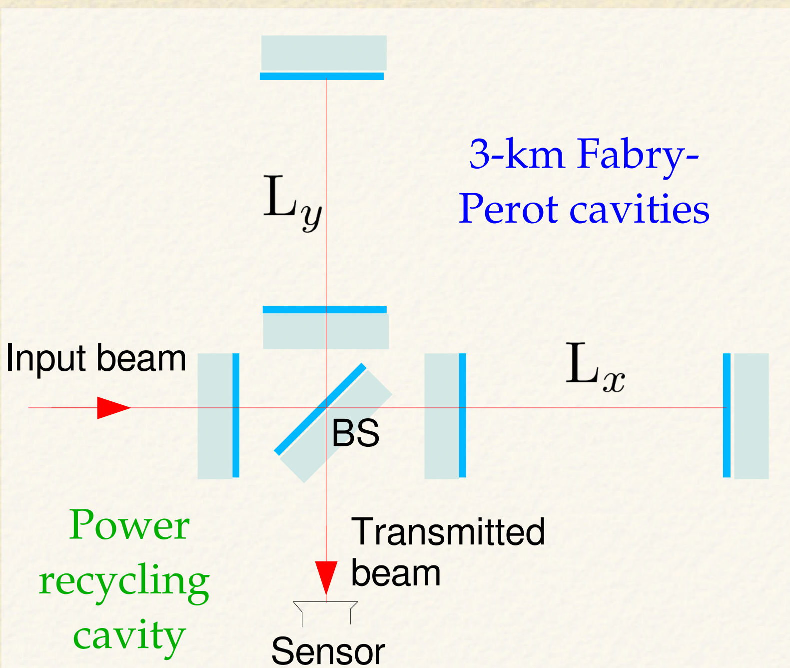
→ input power on BS increased by a factor 38!

The improved interferometer response

- **Response of simple Michelson:**

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

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

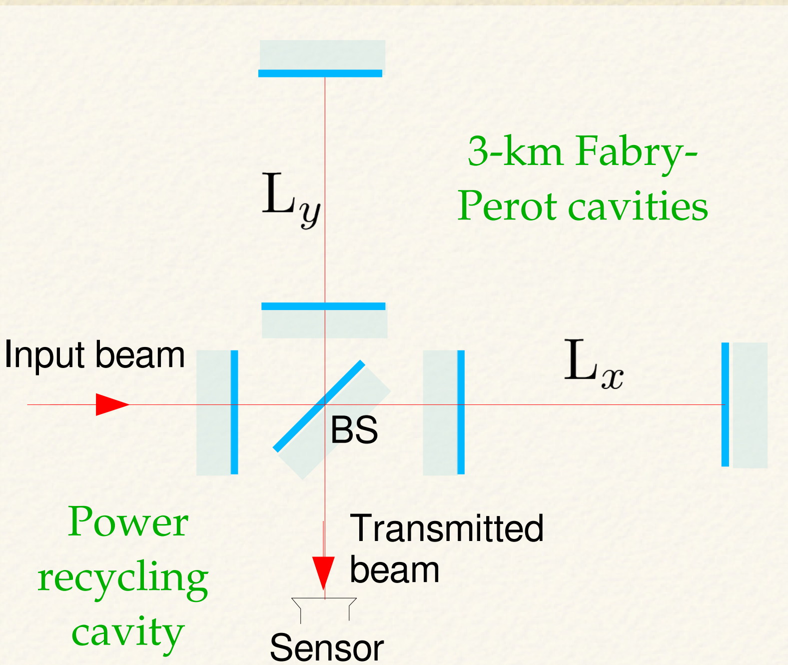


- **Response of recycled Michelson with Fabry-Perot cavities:**

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

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

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	$\lambda = 1064$ 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

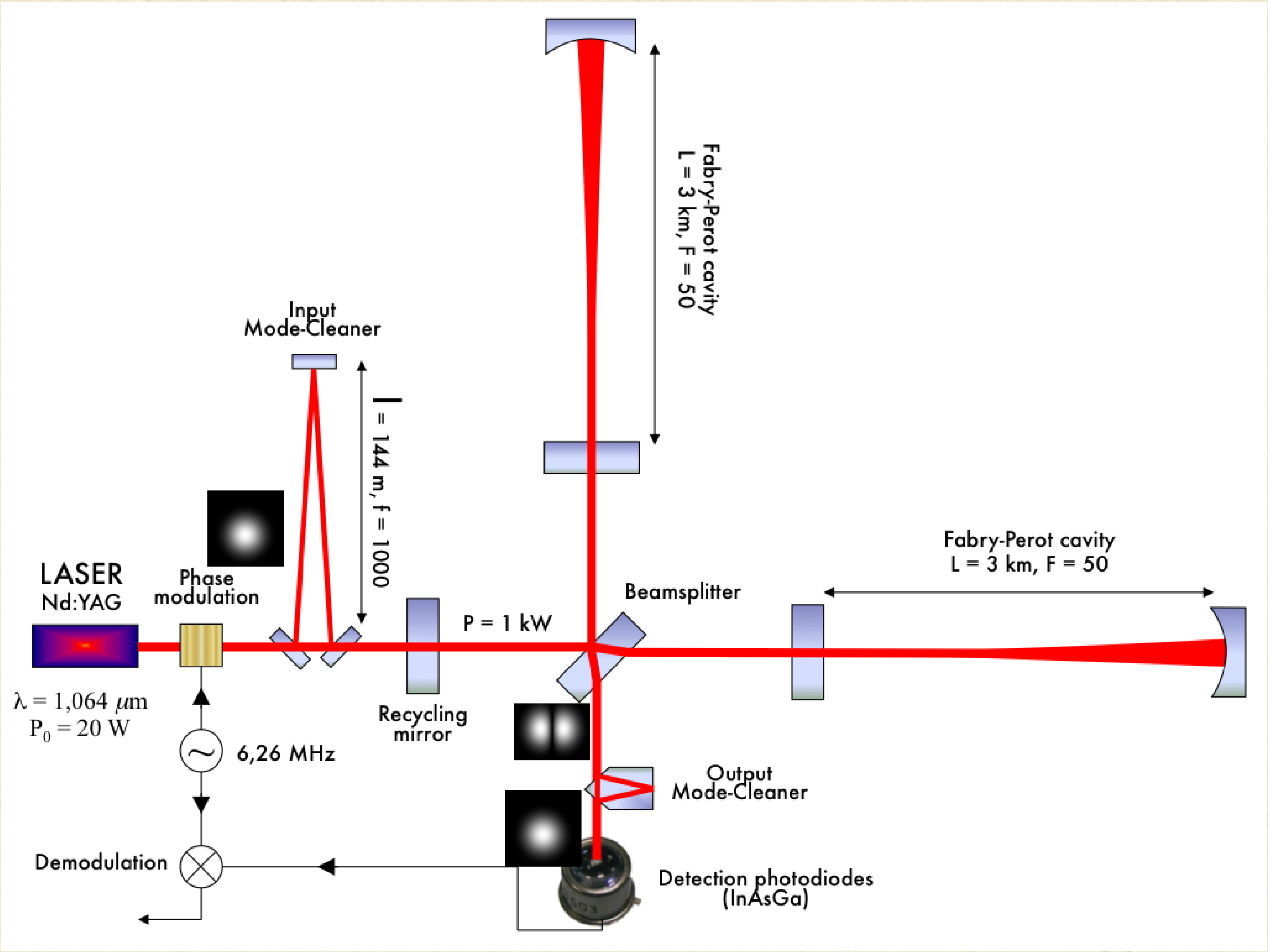
Shot noise due to output power of ~ 50 mW

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

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

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

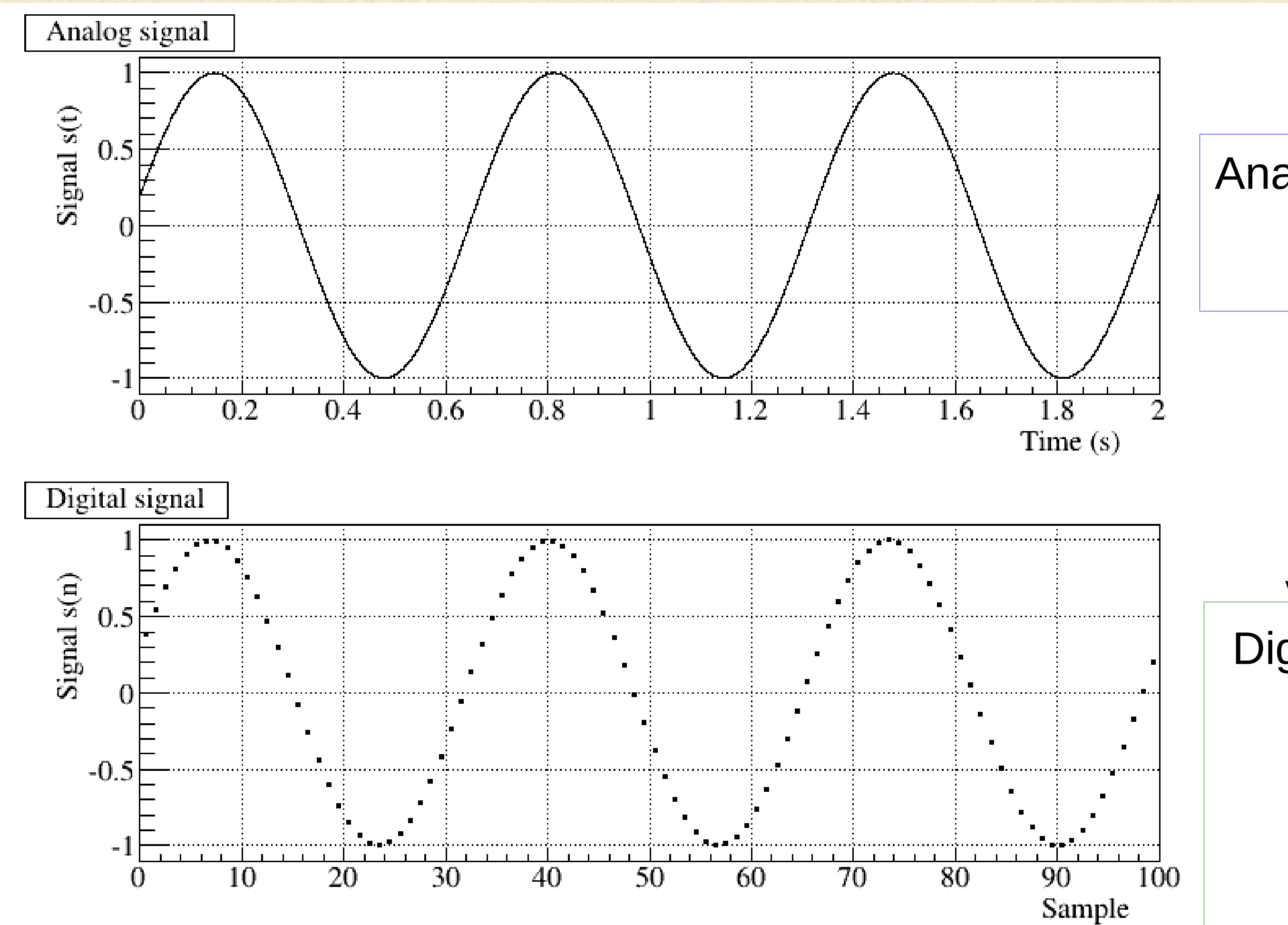
Optical layout of Virgo



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.

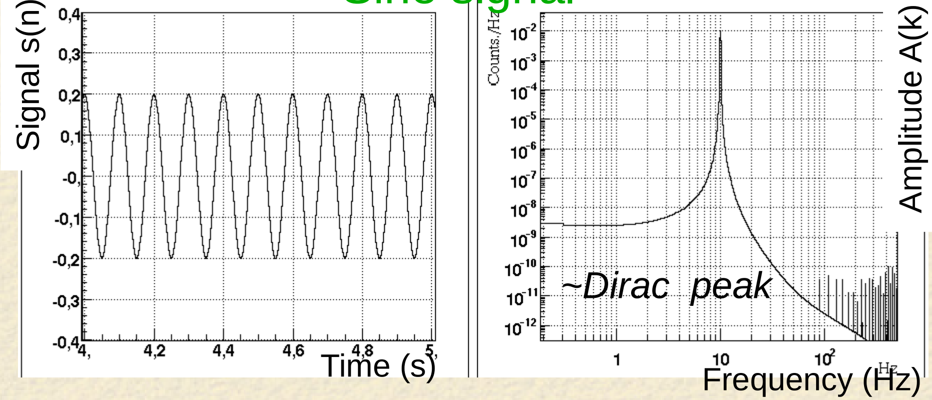
(Discrete) Fourier transform

$$s(n) \rightleftarrows A(k) \text{ and } \Phi(k)$$

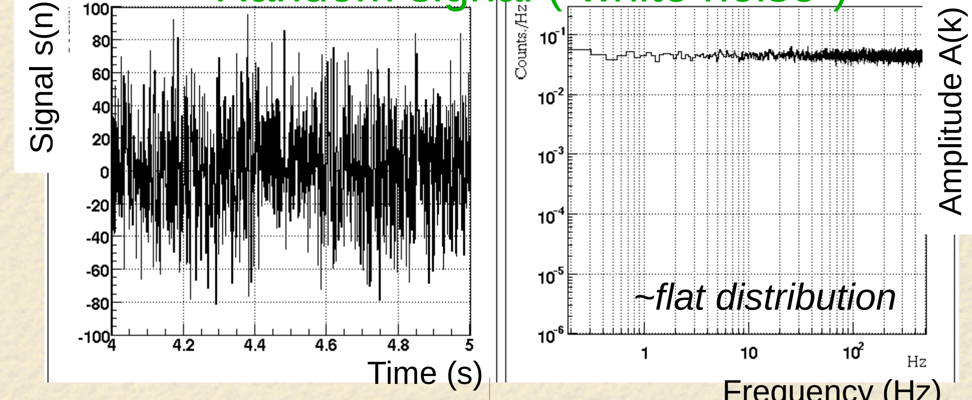
Inverse Fourier transform

$$S(k) = \sum_{n=1}^{N} s(n) e^{-\jmath 2\pi k \frac{n}{N}}$$
$$= A(k) e^{\Phi(k)}$$

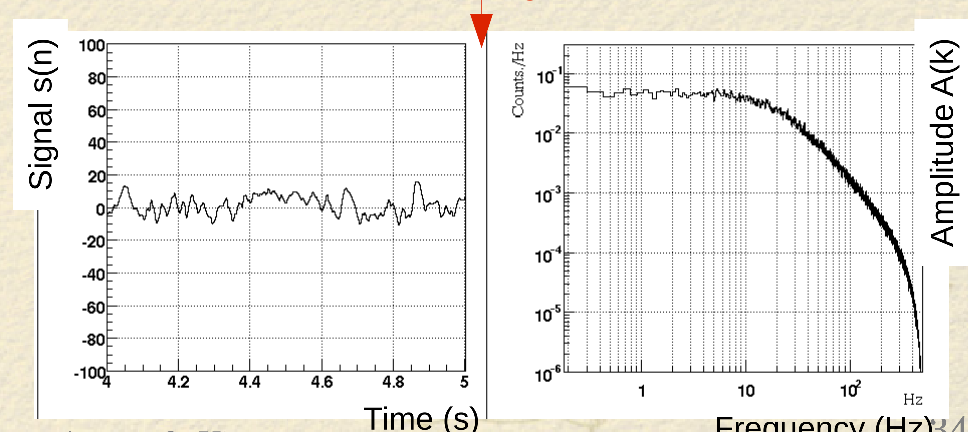
Sine signal



Random signal (“white noise”)



Apply a low-pass filter on the signal



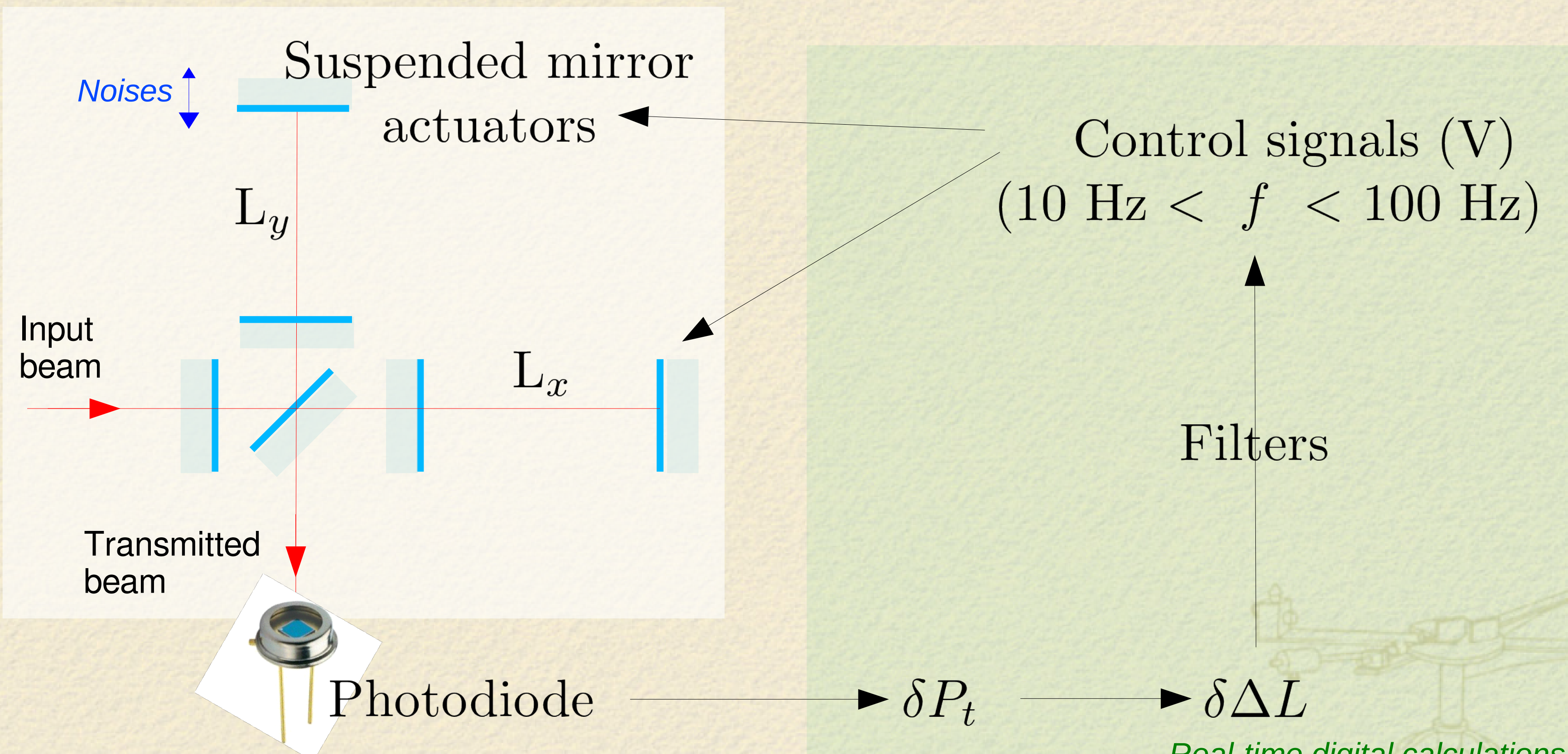
Filtering the data
= modifying the frequency components

How do we control the working point?

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

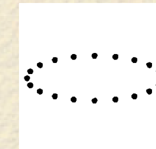
Control loop done for noises with f between ~10 Hz and ~100 Hz

Precision of the control ~ 10^{-16} m

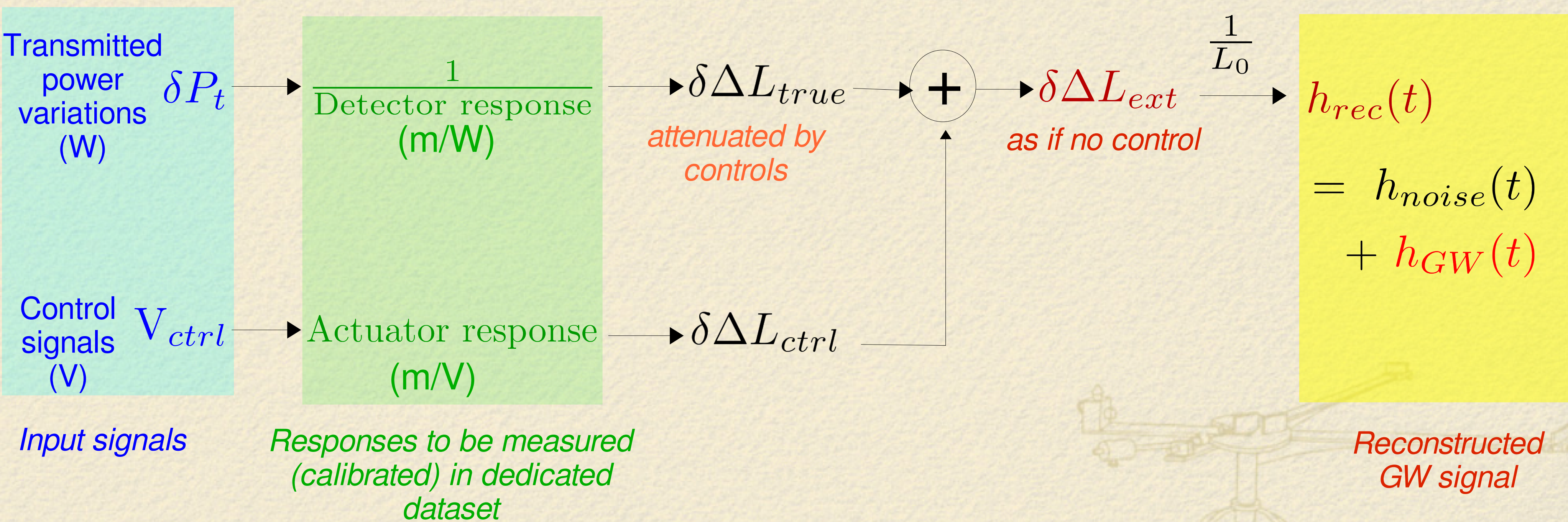


From the detector data to the GW strain h(t)

- 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!
  $\rightarrow$ the control signals contain information on *h(t)*



AdVirgo data acquisition summary

Photodiodes

Currents in the mirror actuators

Seismometers
Magnetometers
Thermometers

Cameras

Sensors....

↓

GPS-synchronised digitisation
Sampling frequencies from 1 Hz to ~50 kHz
~2500 sensor signals to be digitised

↓

Data acquisition processes
(data formatting, timestamp, write to disks..)
~ 10000 channels

→

Continuous flow of ~2 TBytes/day (20 to 40 MBytes/s)
Disk space on Virgo site: ~400 TB for 6 months of data

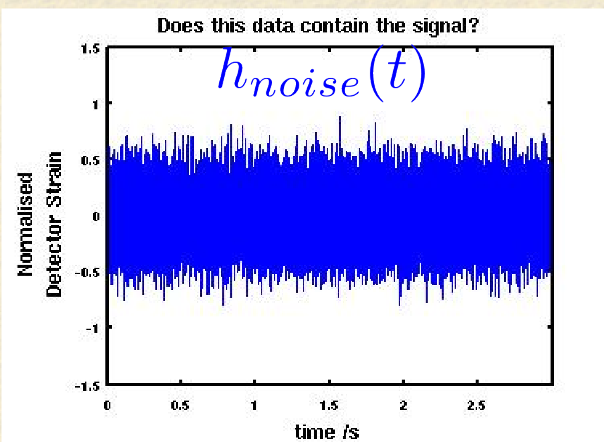
Longer storage: data sent via Ethernet to computing centers (Lyon, Bologna)

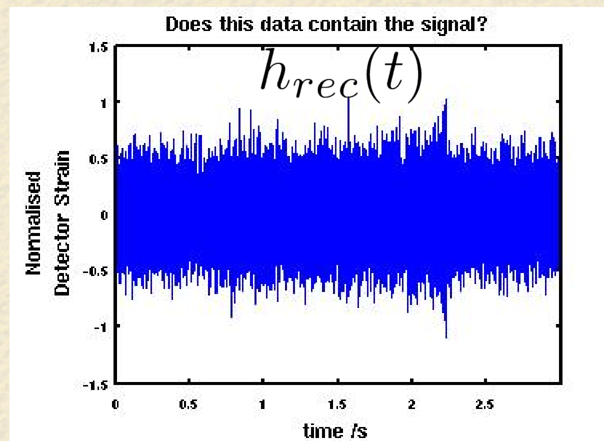
Part 4: Virgo noises

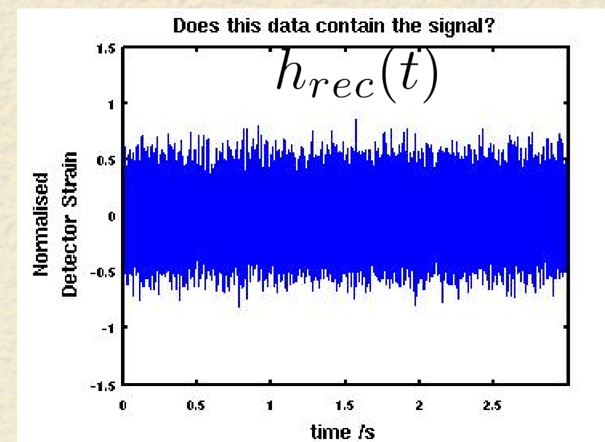
What is a noise in Virgo?

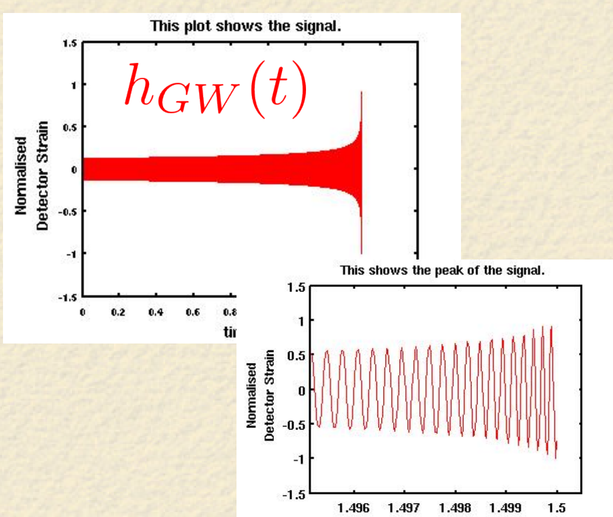
- Stochastic (random) signal that contributes to the signal $h_{rec}(t)$ but does not contain information on the gravitational wave strain $h_{GW}(t)$

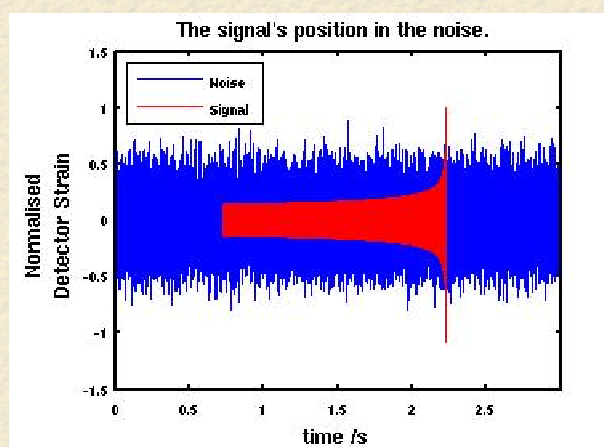
$$h_{rec}(t) = h_{noise}(t) + h_{GW}(t)$$

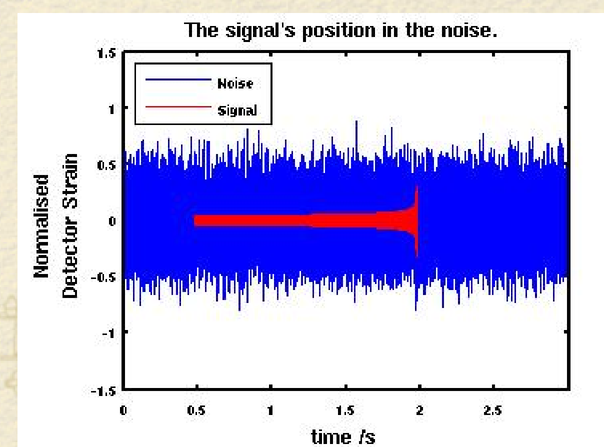








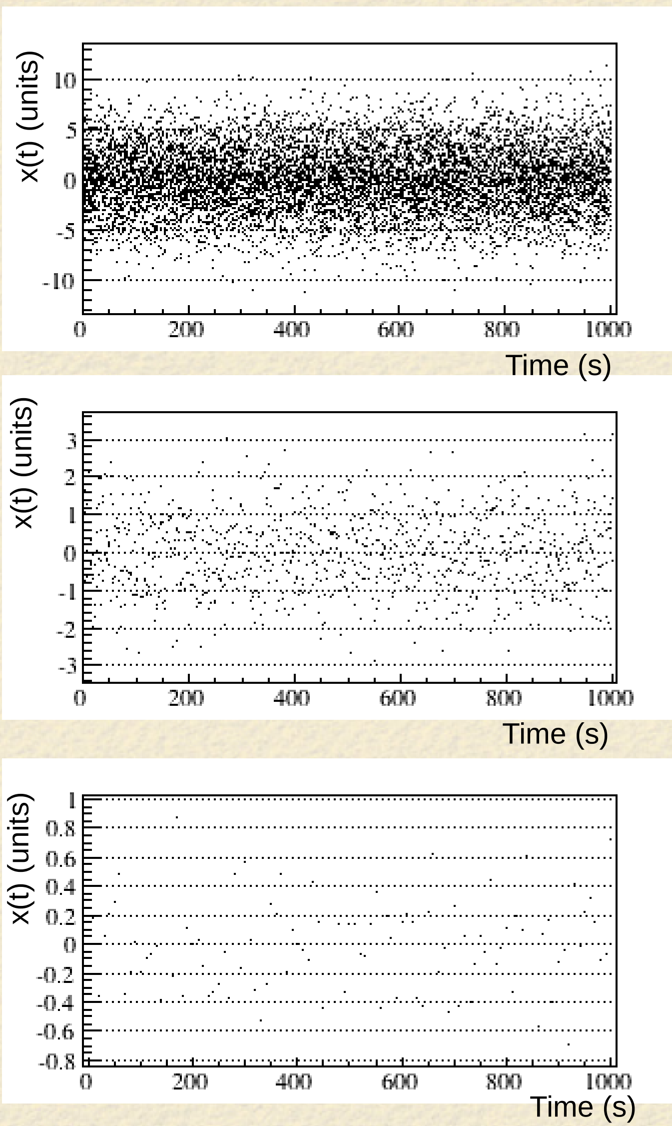




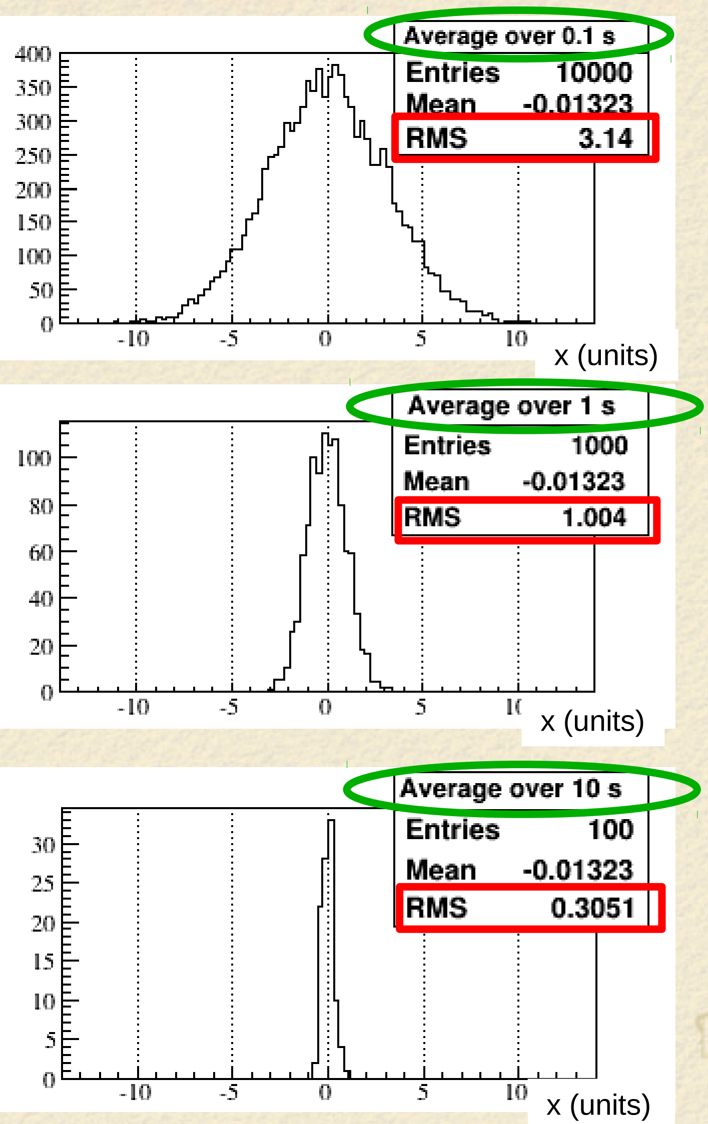
Extracted from Black Hole Hunter: http://www.blackholehunter.org/

How do we characterise a noise?

Data points (noise)



Distribution of the data



Gaussian distribution:

$$N\,e^{-\frac{1}{2}\frac{(x-<x>)^2}{\sigma_x^2}}$$

→ 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

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

Discrete Fourier Transform (DFT)

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

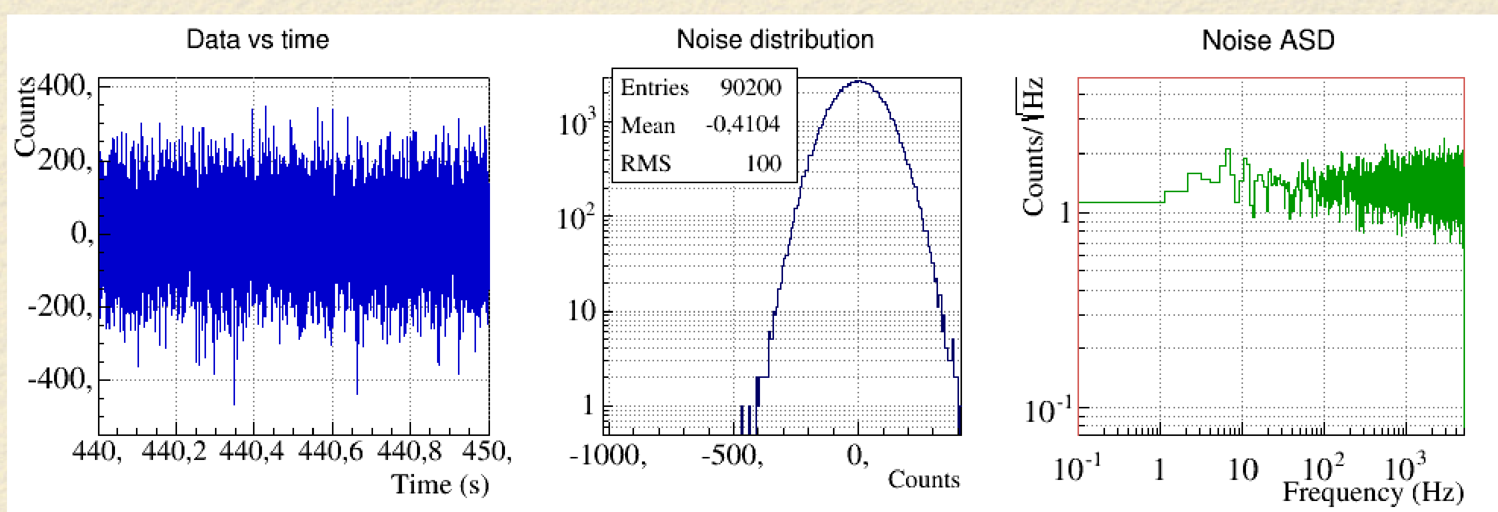
Sampled signal → Fourier spectrum

→ Noise characterised by the fluctuations of its Fourier spectrum → $D(k)$ in units/√Hz

Assumption: noise is random and ergodic

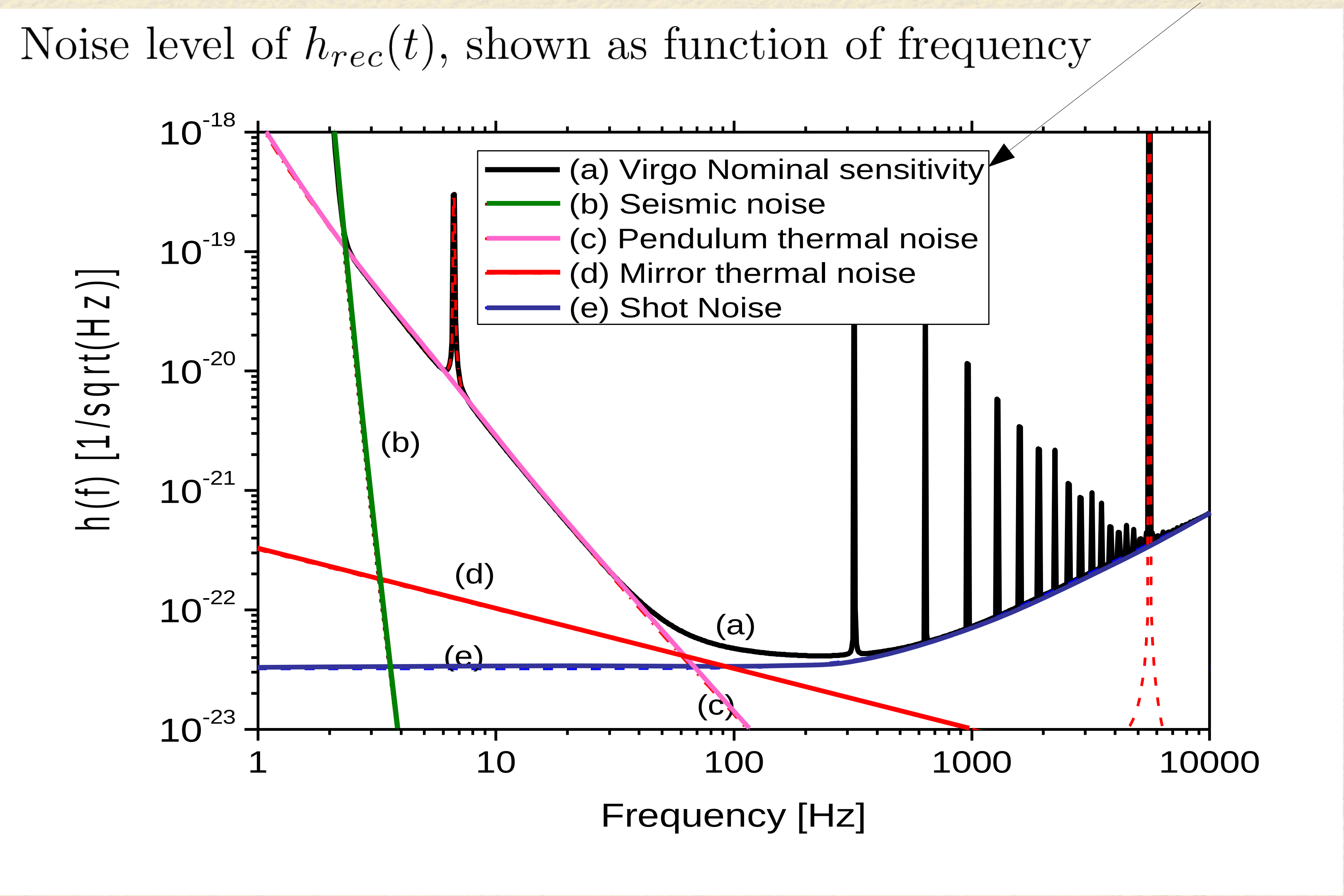
→ noise characterised by its amplitude spectral density (ASD) $ASD = \sqrt{PSD} = \sqrt{\frac{|DFT|^2}{T}}$

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

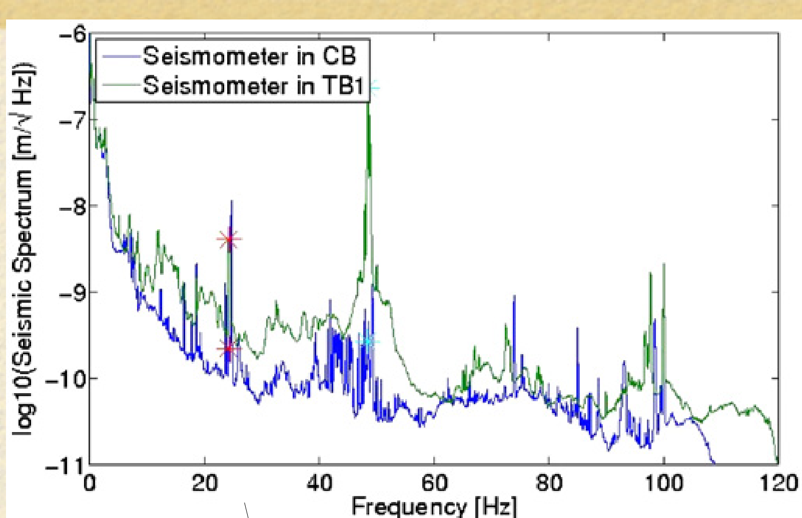


What is the noise level of Virgo?

Sum of all the noises

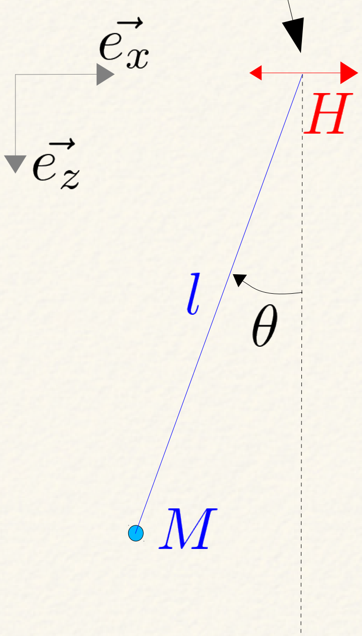


Seismic noise and suspended mirrors



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

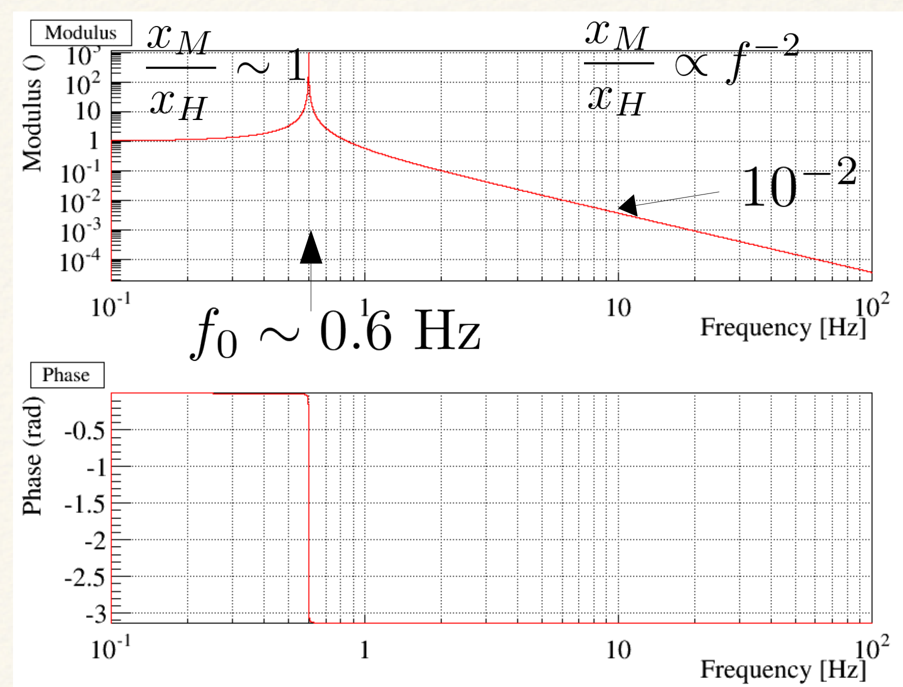
$$\gg 10^{-19}\ \mathrm{m}/\sqrt{\mathrm{Hz}} \text{ needed to detect GW !!}$$



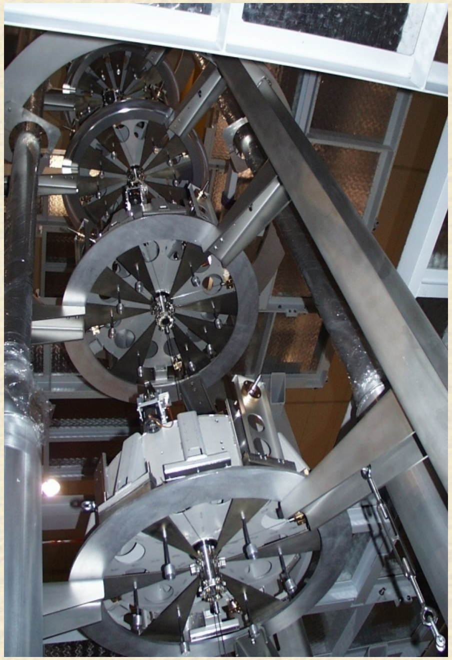
Assuming
δx_H small and sinusoidal
and θ small:

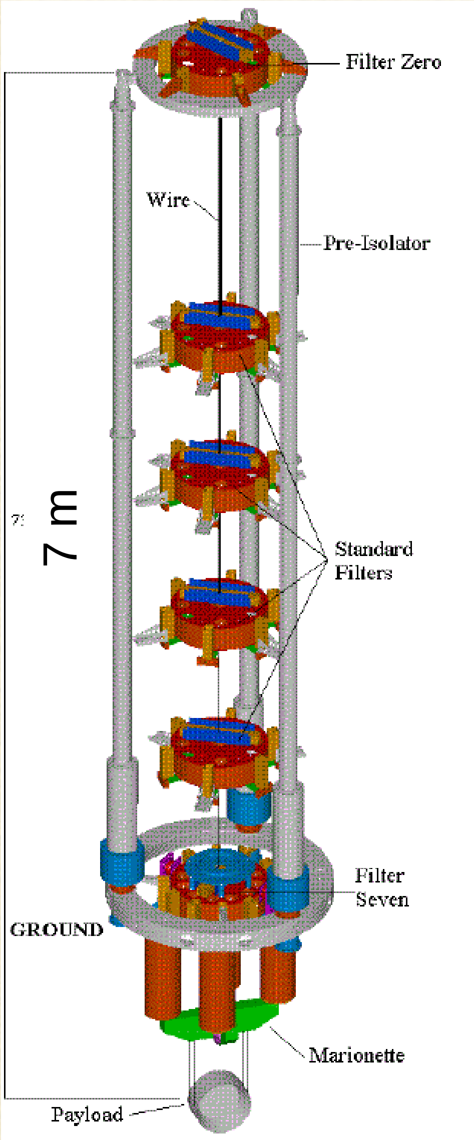
$$\underline{x_M} = \underline{\mathcal{H}} \times \underline{x_H}$$

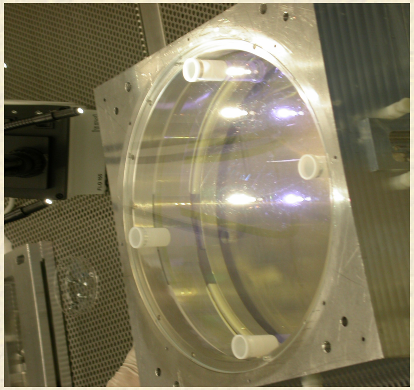
Transfer function



Seismic noise and the Virgo suspension







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

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

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

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

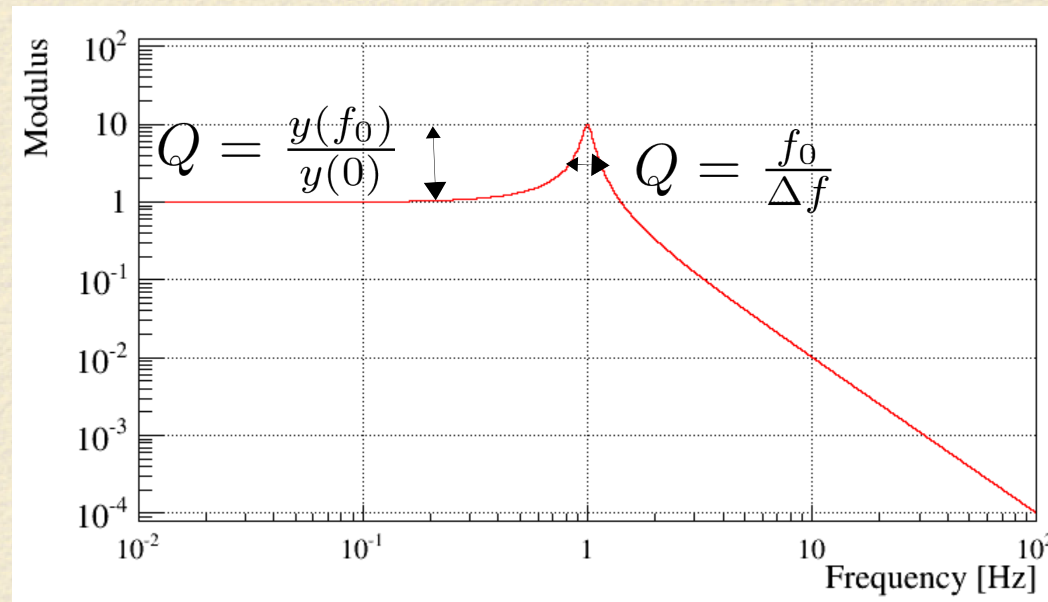
This noise directly modifies the positions of the mirror surfaces, and thus $\delta\Delta L$ and $h_{rec}(t)$!

- **Active controls** at low frequency
  - Accelerometers or interferometer data
  - Electromagnetic actuators
  - Control loops

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

What is the 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 $\delta\Delta L$

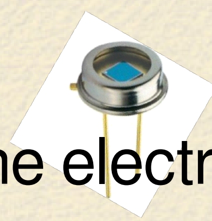
$$\delta P_t = (\text{Virgo response}) \times L_0 \times h$$

(in W/m)

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

Some other noises

- Acoustic vibrations and refraction index fluctuation
  - Main elements installed in vacuum
- Laser: amplitude, frequency, jitter noise
  - Lots of control loops to reduce these noises
- Electronics noise



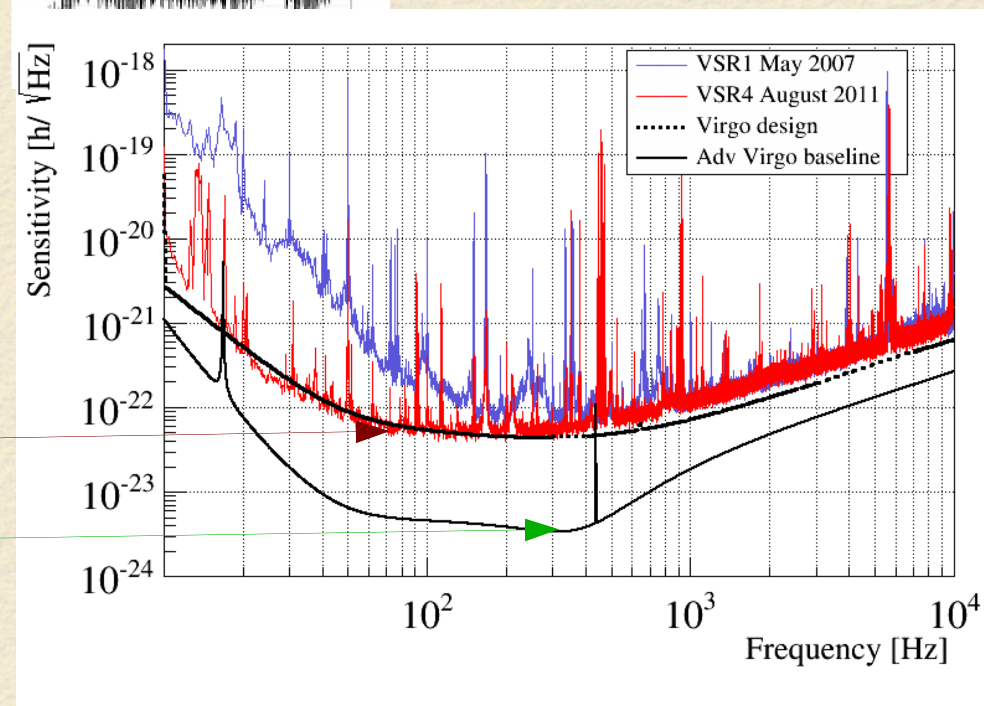
  - Challenge for the electronicians to measure down to 0.1 nW/sqrt(Hz)
- Non-linear noise from diffuse light
  - Need dedicated optical elements with specific mechanical modes

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)



~10^{-19} m/√Hz (Virgo, 2011)

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

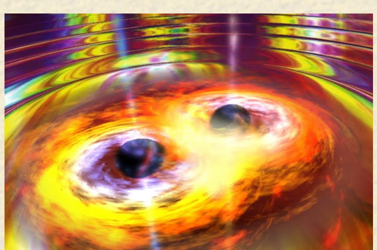


Image: Danna Berry/SkyWorks/NASA

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

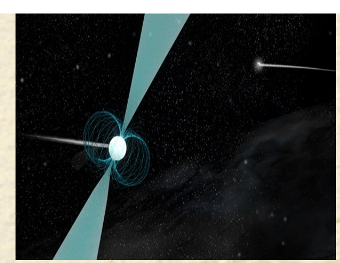
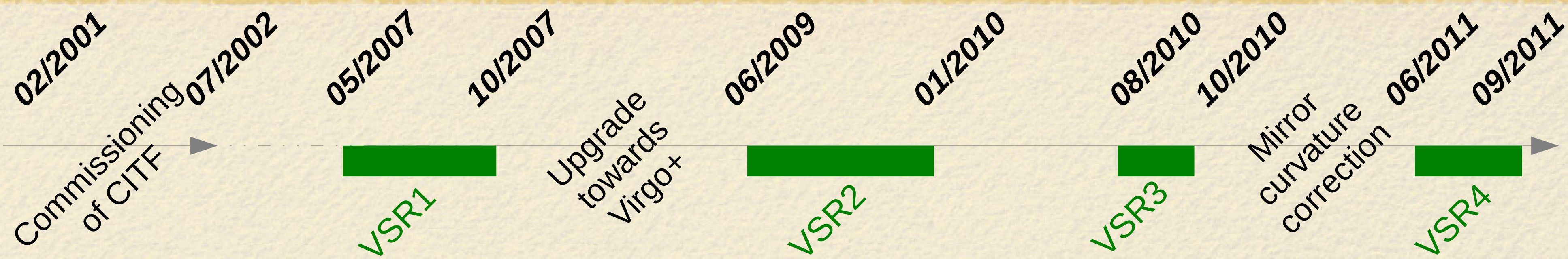
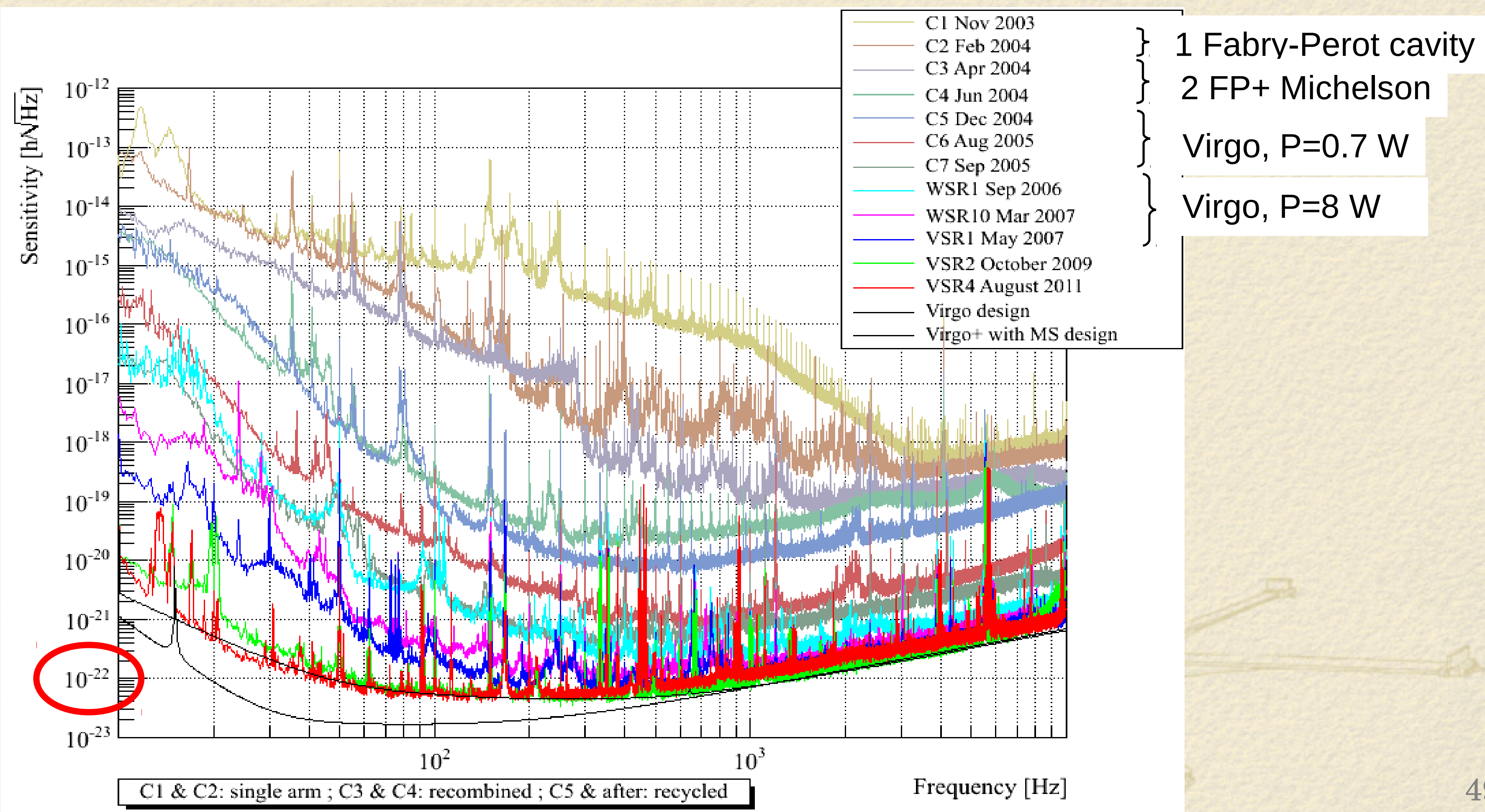


Image: B. Saxton (NRAO/AUI/NSF)

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

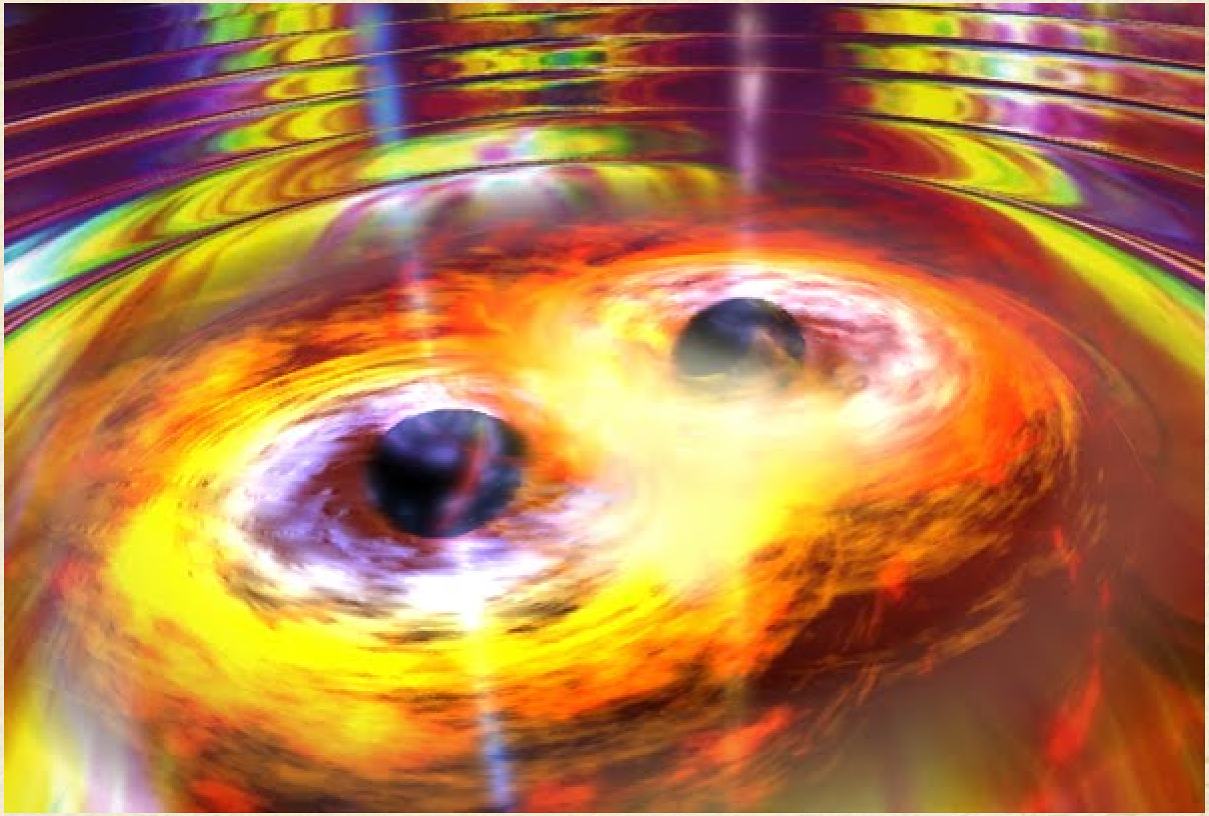
History of Virgo noise curve



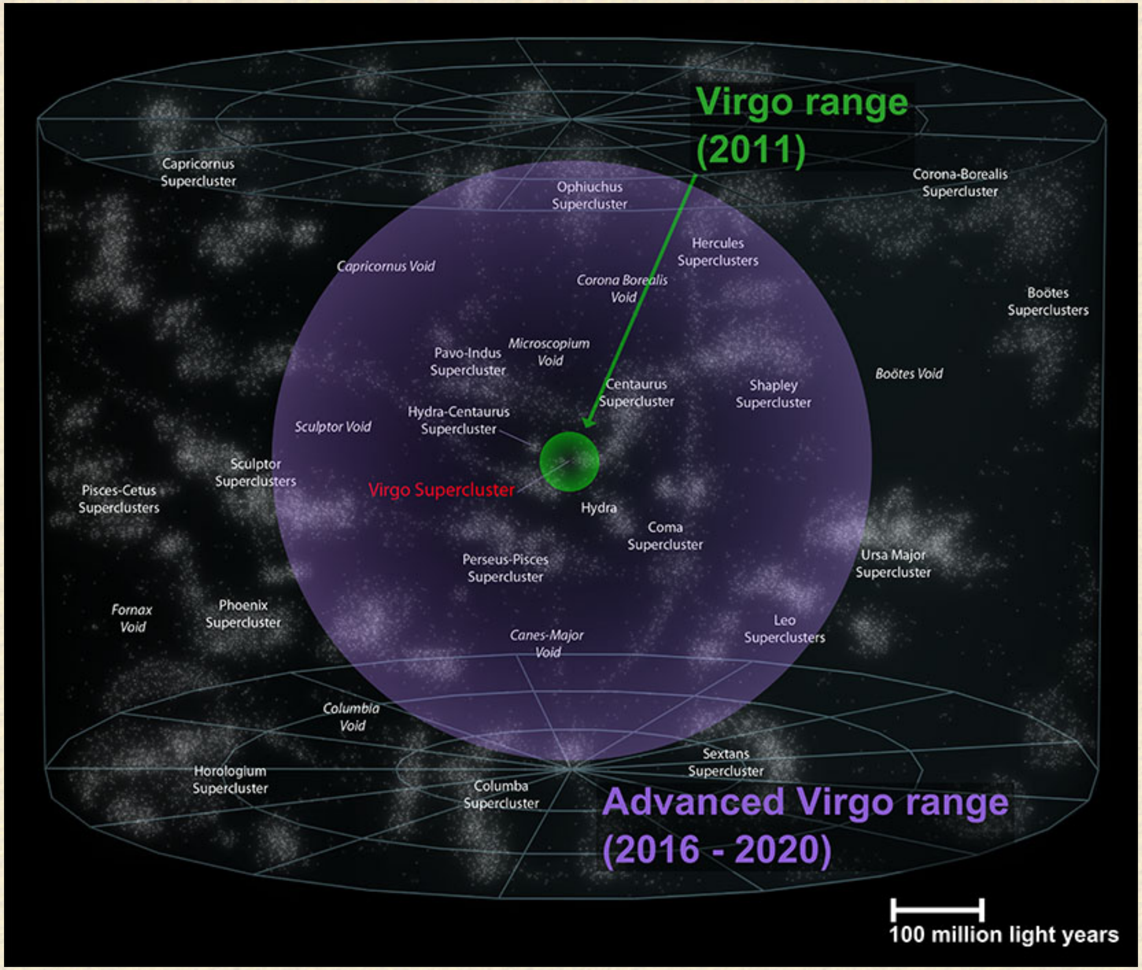


~10^{-19} m/√Hz

Part 5: towards Advanced Virgo



Horizon 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 horizon) by a factor 10

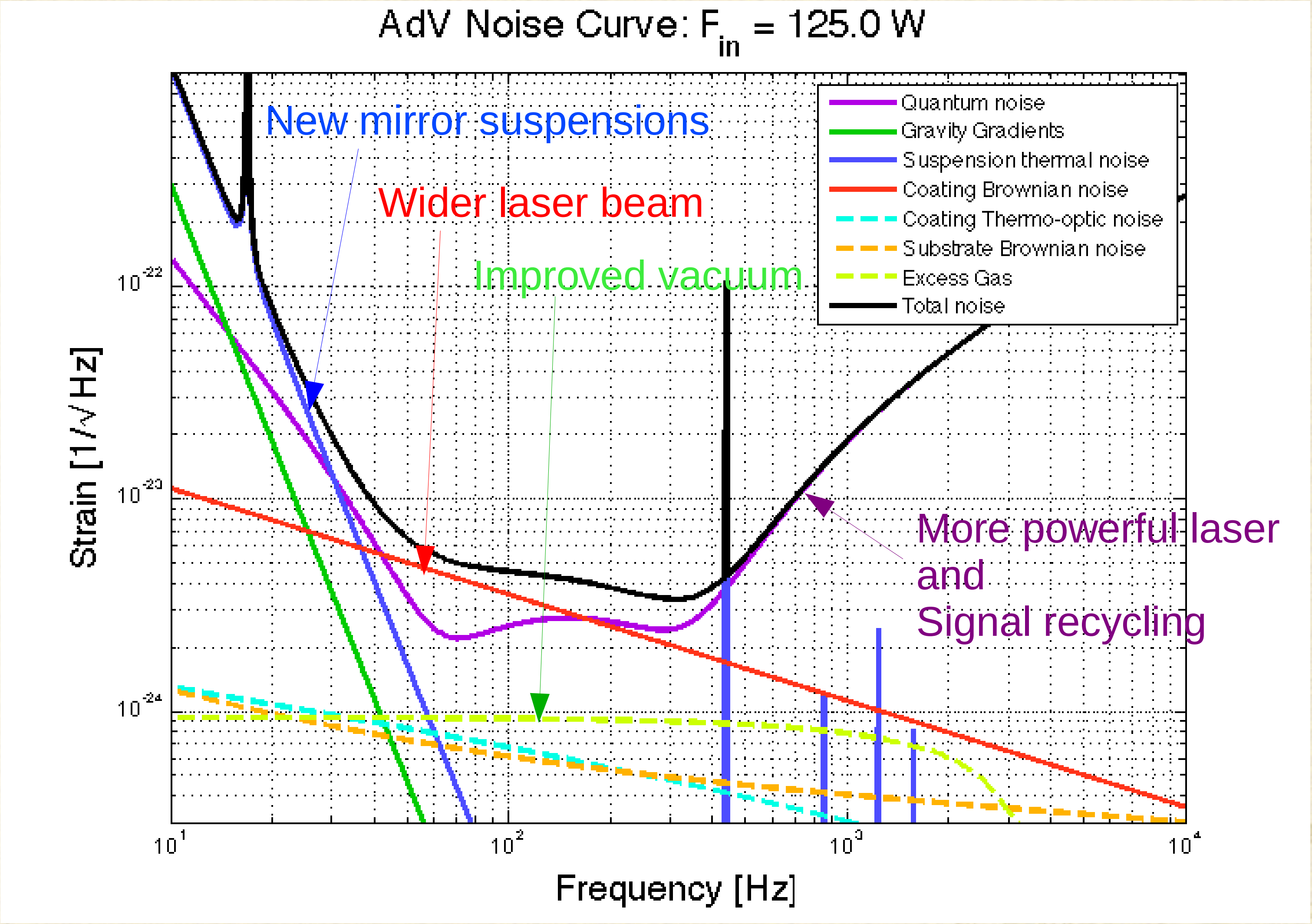
↓

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

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

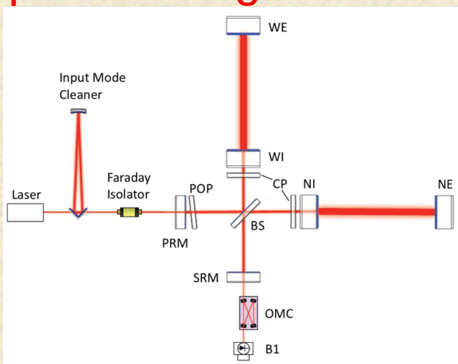
	low	realistic	high
Initial Virgo/LIGO	0.0002	**0.02**	0.2
Advanced Virgo/LIGO	0.4	**40**	400

Towards the Advanced Virgo sensitivity

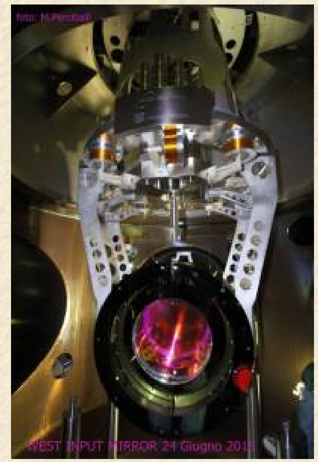


Advanced Virgo is being built

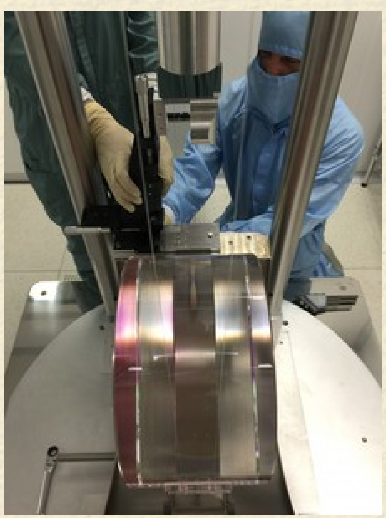
New optical configuration



Better and heavier mirrors

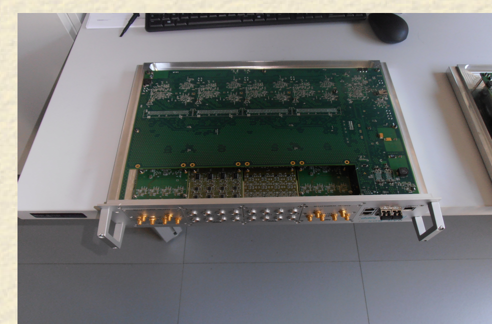


Monolithic silica mirror suspension

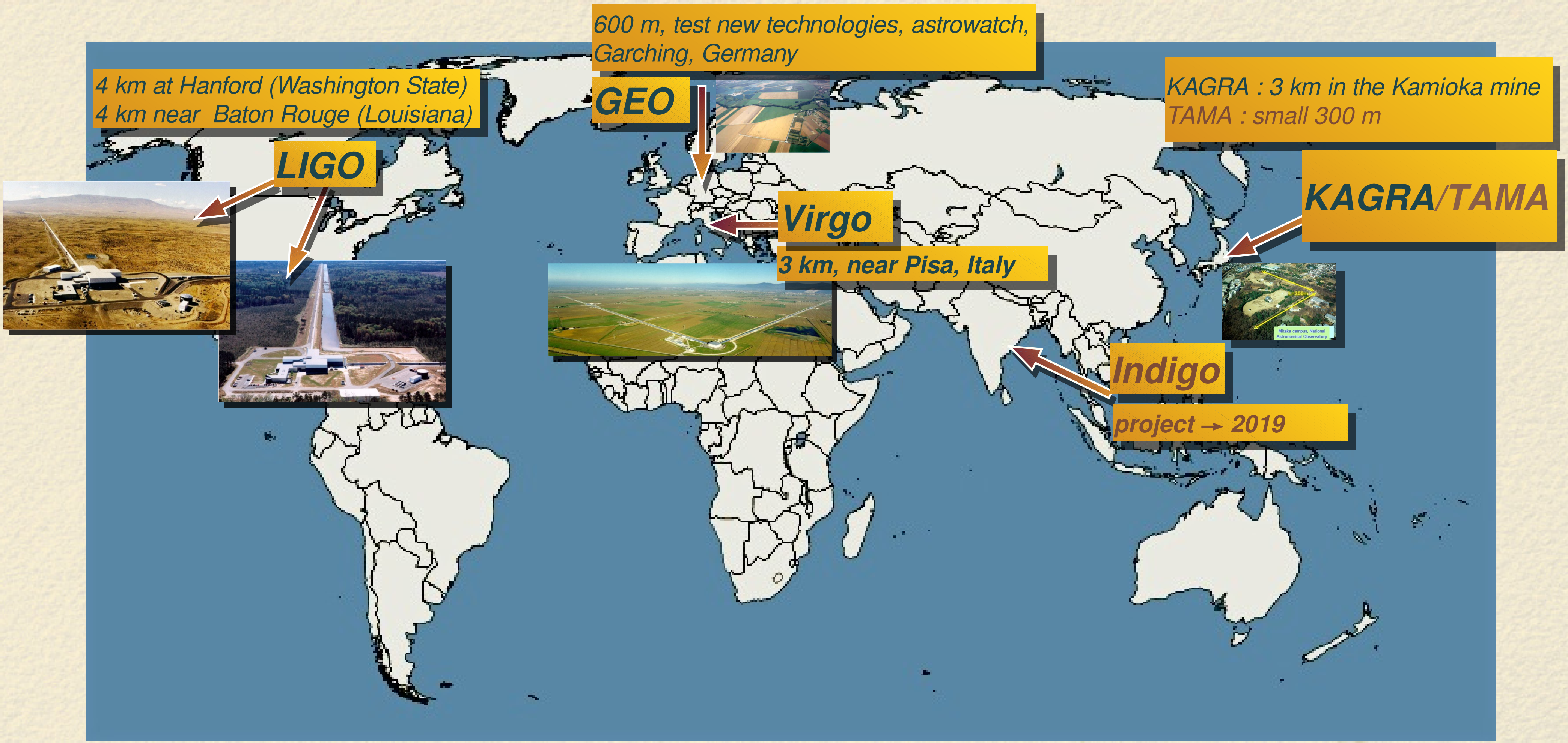


More in vacuum
suspended benches

New electronics boards



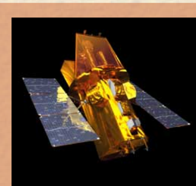
A worldwide network of interferometers



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

Multi-messenger astronomy

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)
+ check by operators and scientists on site

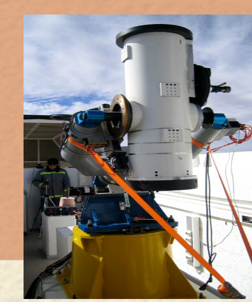
Few minutes

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 telescomes
HESS, CTA



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

Towards the first GW detections!

Completing the Advanced LIGO and Virgo interferometers

Starting the network observation periods

Increasing the size of the network