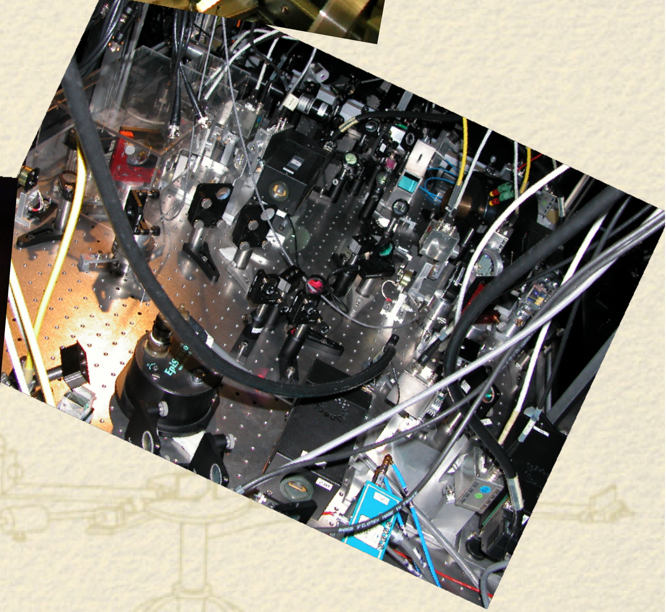
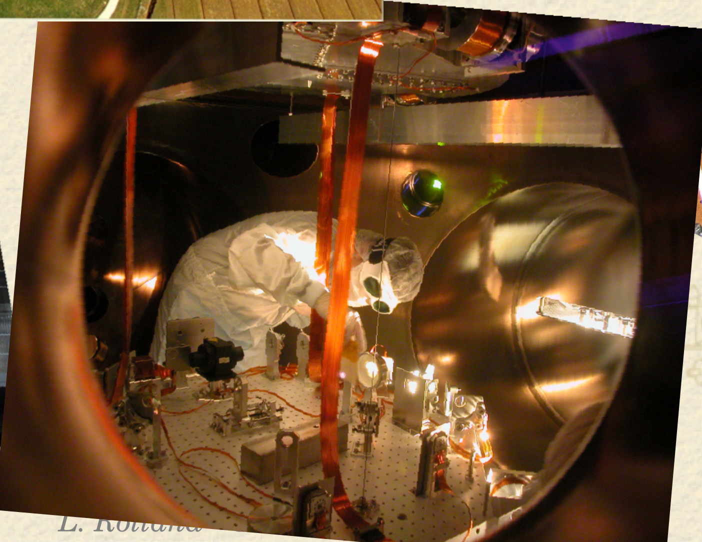
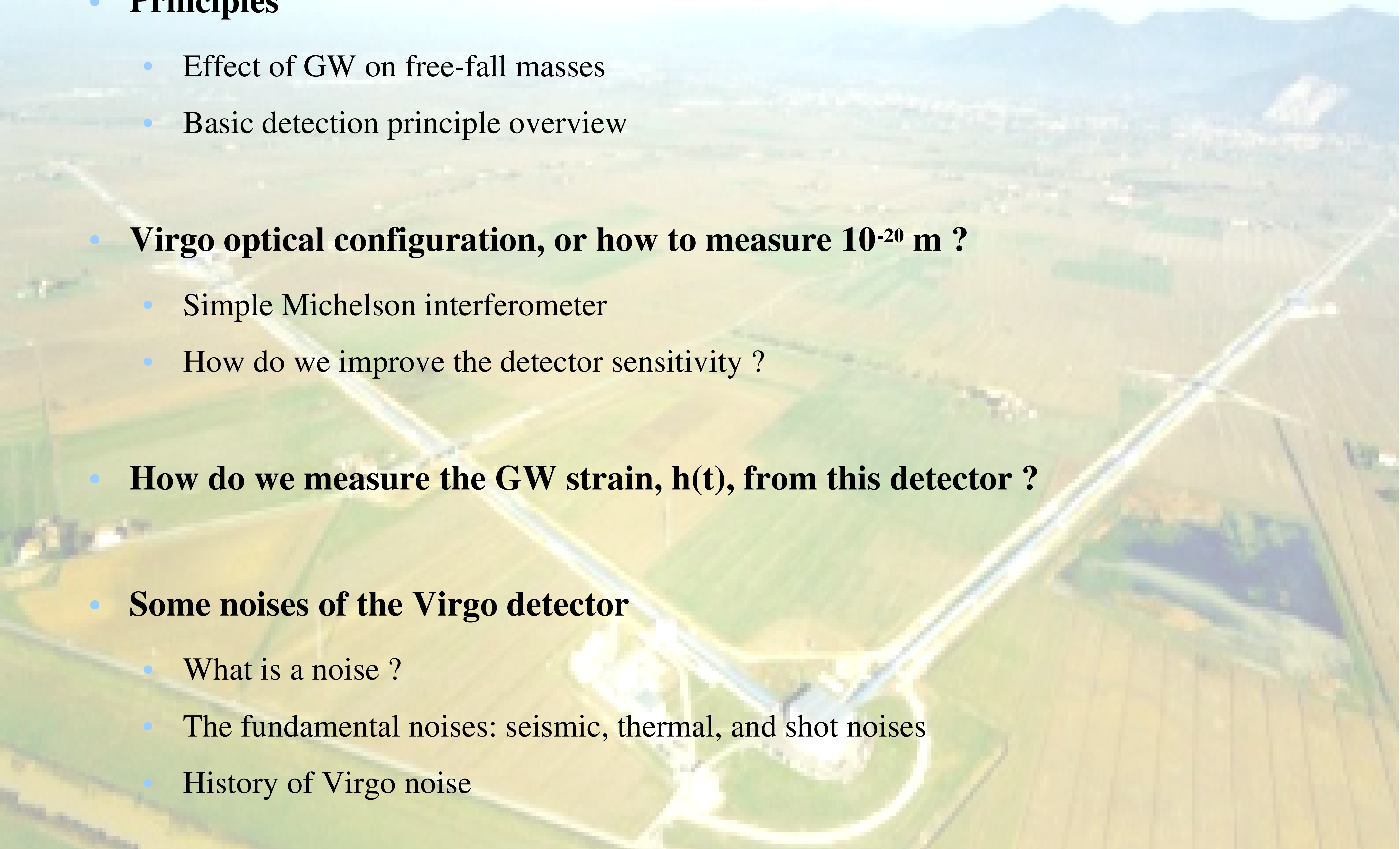
# The Virgo detector

L. Rolland
LAPP-Annecy
GraSPA summer school



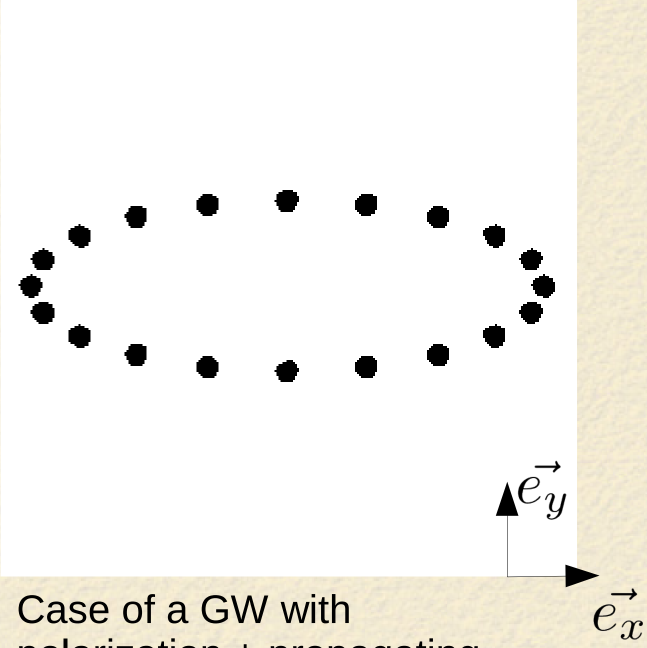


# Table of contents



# Reminder: effect of a GW on free masses

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



Case of a GW with polarization + propagating along z

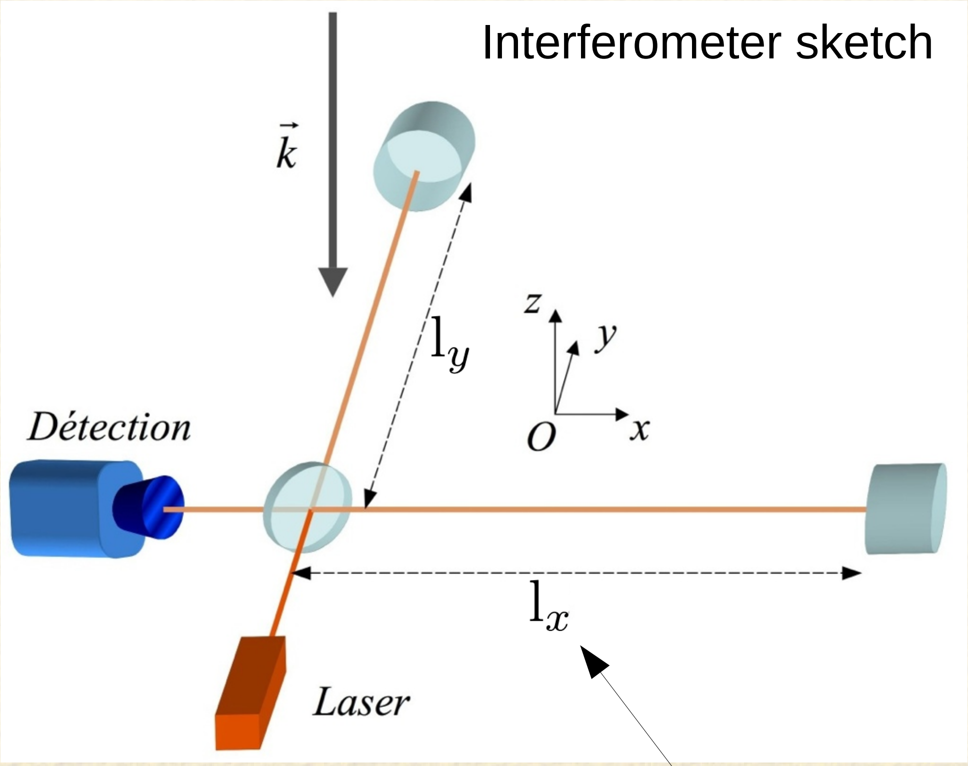
$$\delta x(t) \;=\; -\delta y(t) \;=\; \tfrac{1}{2}\, h(t)\, L_0$$

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 $\Delta L$:

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

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

# Virgo: a more complicated interferometer

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

Fabry-Perot cavities

$L_0$

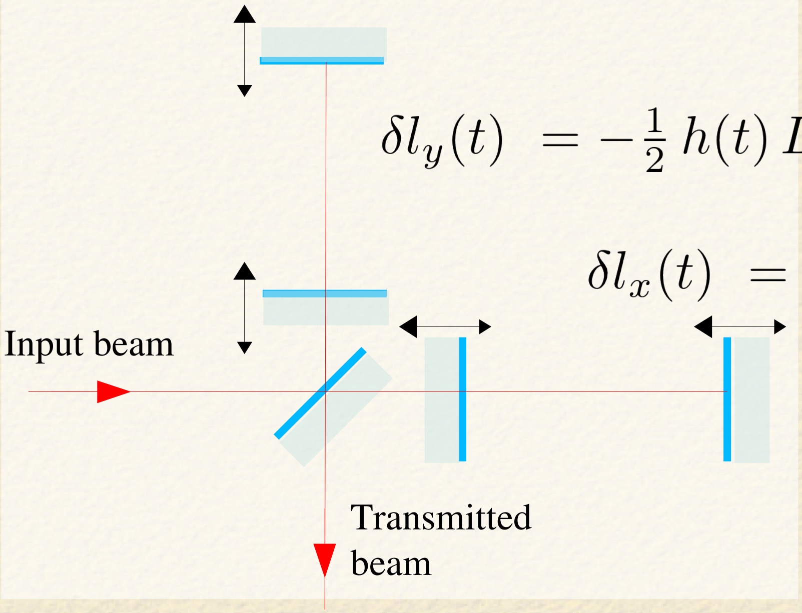
$L_0$

Power-recycling cavity

Infra-red laser
P ~ 100 W

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

# 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:

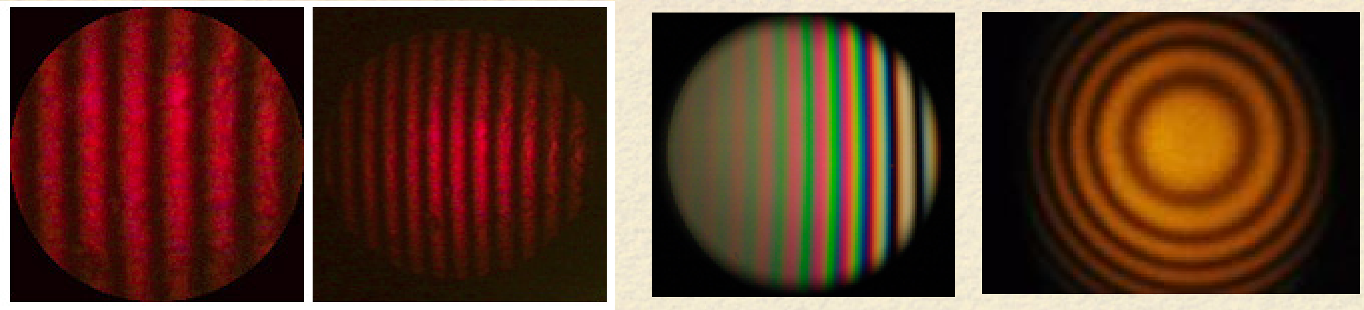
$$\begin{aligned}\delta\Delta L &= \delta l_x(t) - \delta l_y(t)\\ &= h(t)\,L_0\end{aligned}$$

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

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

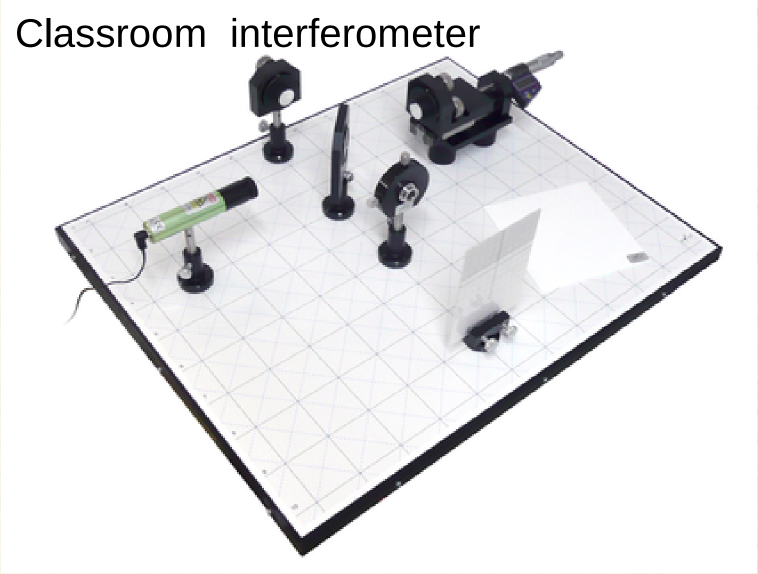
$$\sim \frac{\text{size of a proton}}{100000}$$

# How and for what did you use interferometers ?



Wavelength of monochromatic source

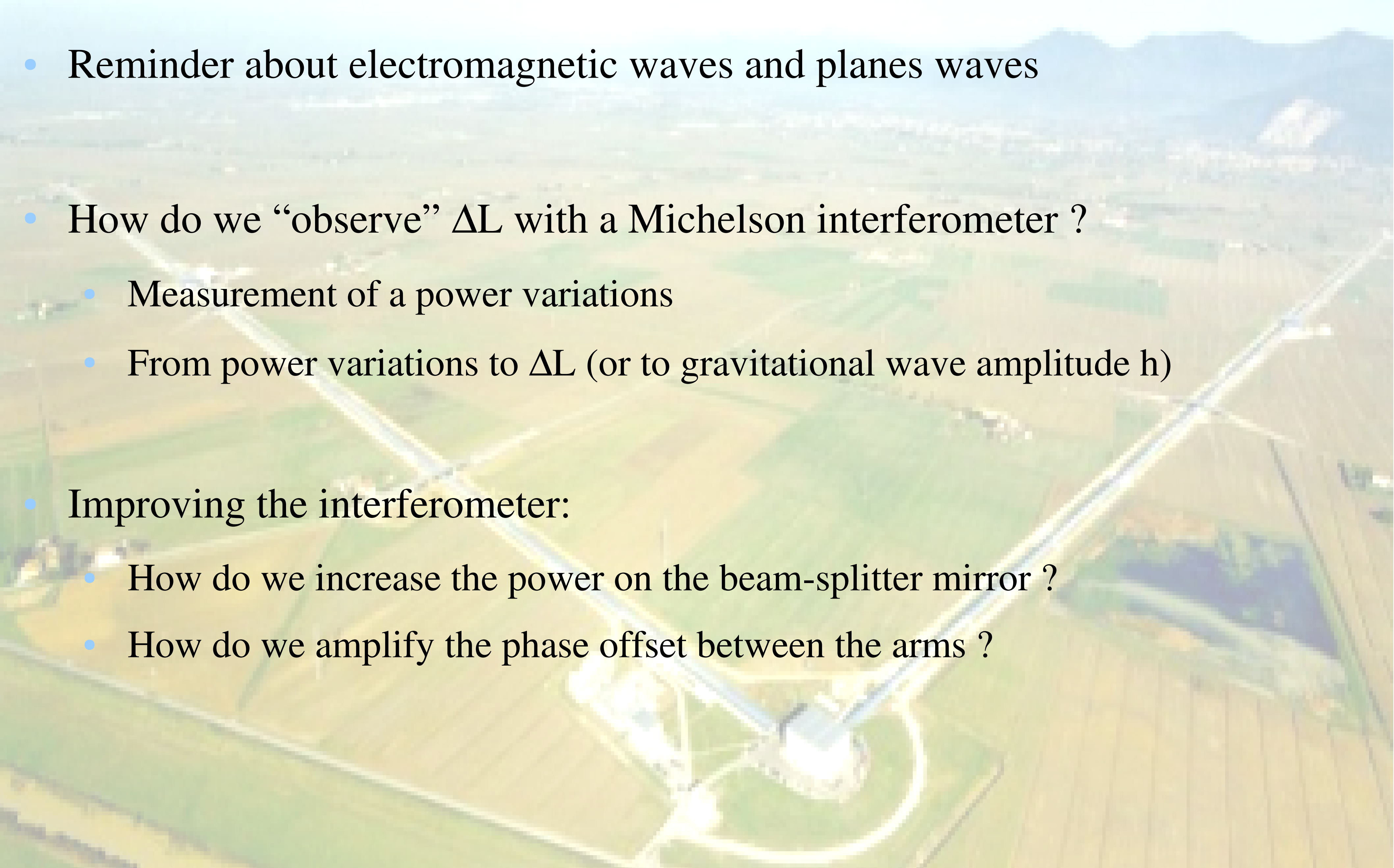
Sodium doublet wavelength separation



Classroom interferometer

Virgo interferometer
Pisa, Italy

# Part 2: Virgo optical configuration

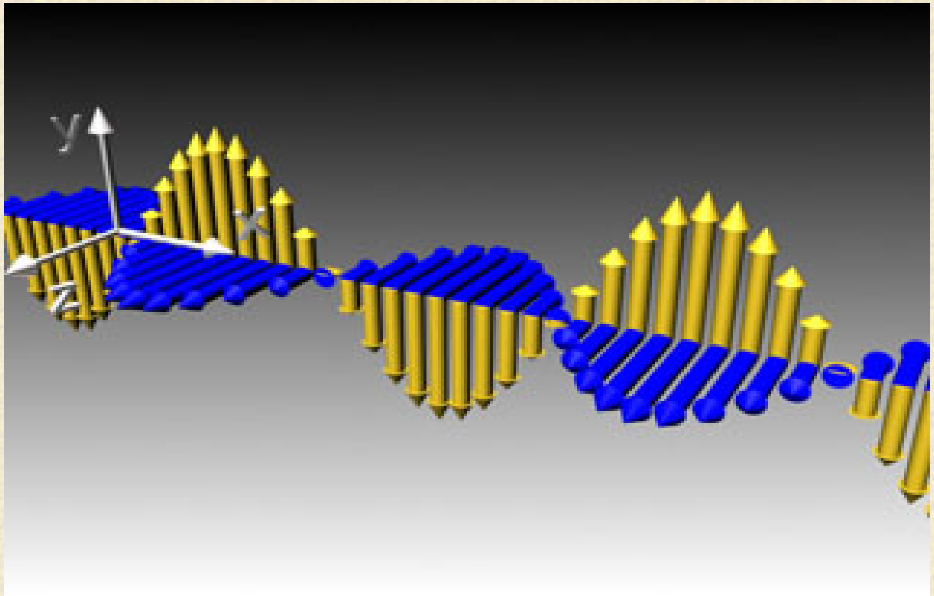


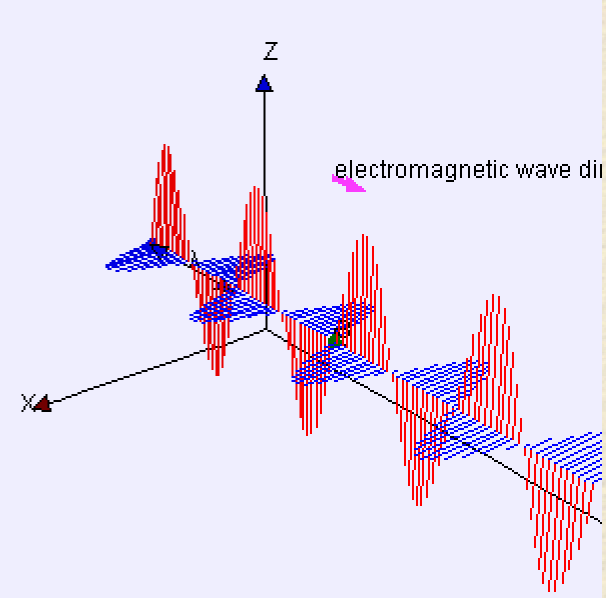
- Reminder about electromagnetic waves and planes waves

- 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





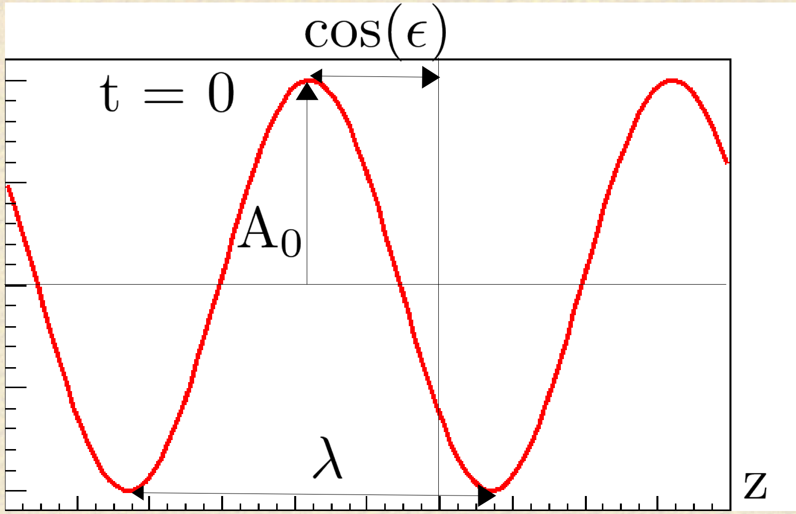
- Propagation of a perturbation of electric and magnetic fields
    - Direction of propagation: along k
    - E and B are in phase, and with perpendicular directions
    - E and B are perpendicular to the direction of propagation of the wave (transverse wave)
- Amplitude: amplitude of the E (or B) field,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

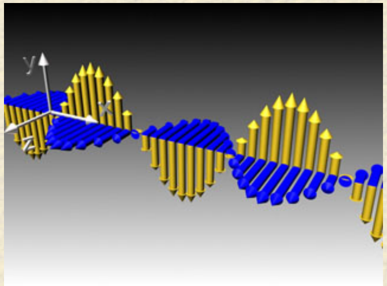
$$A(z,t) = A_0 \cos(kz - \omega t + \epsilon) \qquad (\text{since } \vec{k}\vec{r} = k\,z)$$



| | |
|---|---|
| $A_0$ | amplitude |
| $\lambda$ | wavelength (m) |
| $k = \frac{2\pi}{\lambda}$ | wave number (rad/m) |
| $\omega = kc$ | angular frequency (rad/s) |

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

- 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 $P \propto |U|^2 = UU^*$

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

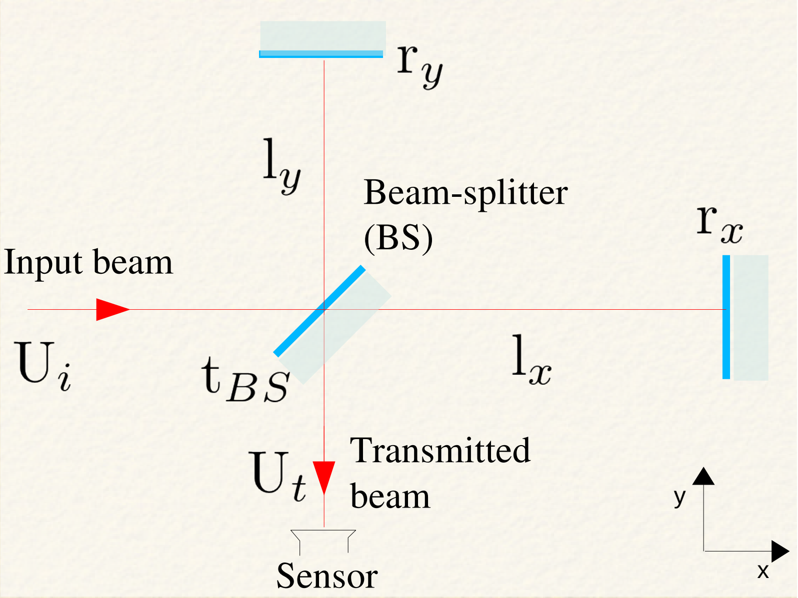
- Plane waves do not exist but they are a good approximation of many waves in localized region of space

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

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

  $= \underline{A_i}$ 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 ~ few cm

→ The beam can be approximated by plane waves

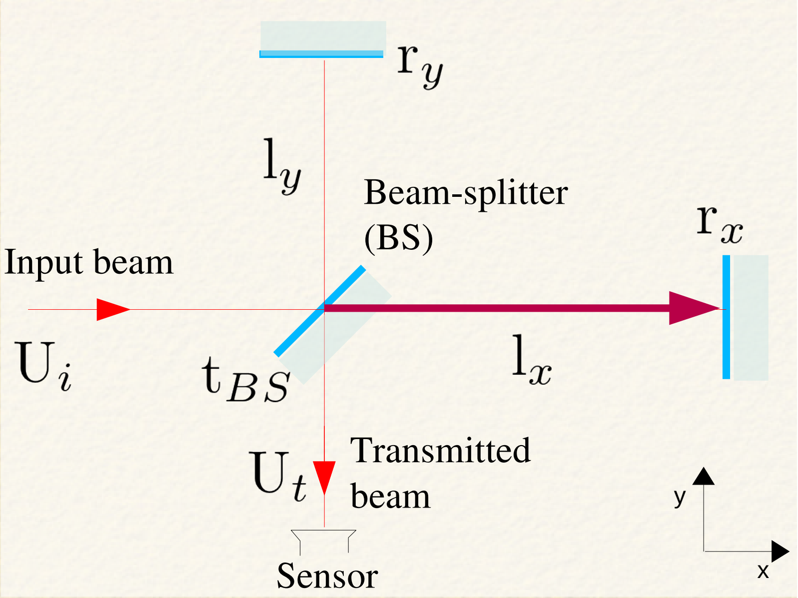
# How do we "observe" ΔL with a Michelson interferometer ?

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

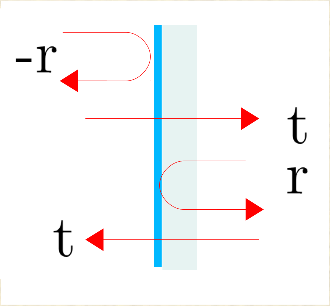
  $= \underline{\mathcal{A}}_i$ on BS

- Beam propagating along x-arm:

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



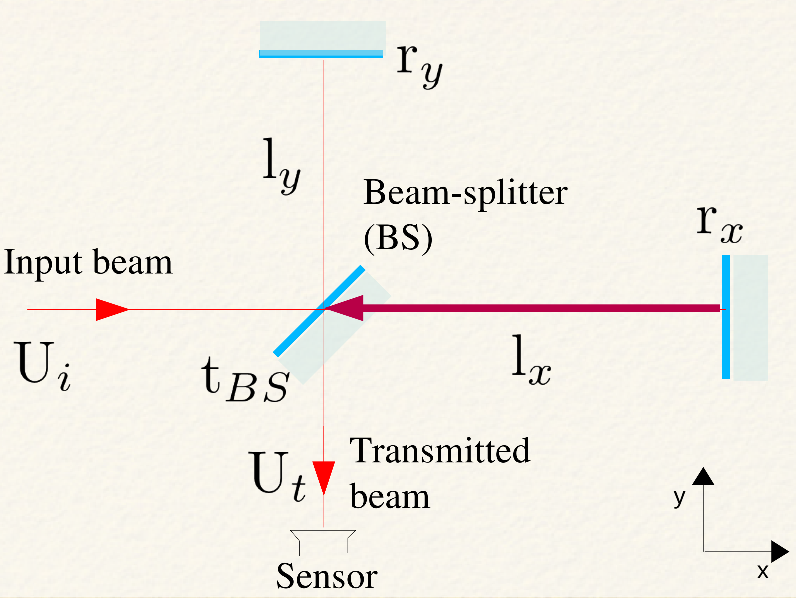
Sign convention for amplitude reflection and transmission coefficients



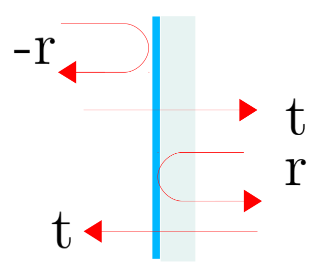
# How do we “observe” ΔL with a Michelson interferometer ?

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

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



Sign convention for amplitude reflection and transmission coefficients

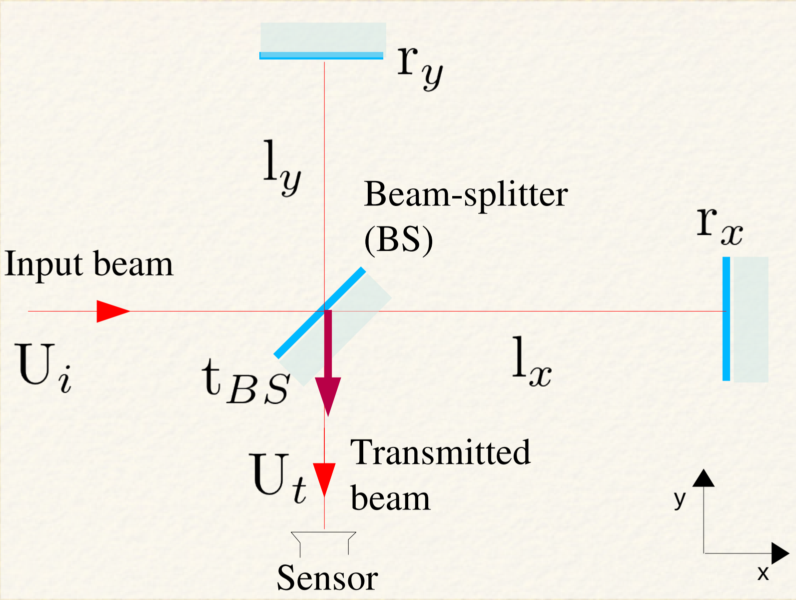


# How do we "observe" ΔL with a Michelson interferometer ?

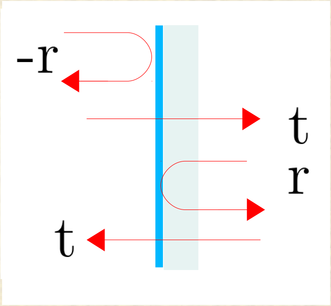
- Input wave $$U_i(x,t) = \underline{A}_i e^{\jmath kx}$$ $$= \underline{A}_i \quad \text{on BS}$$

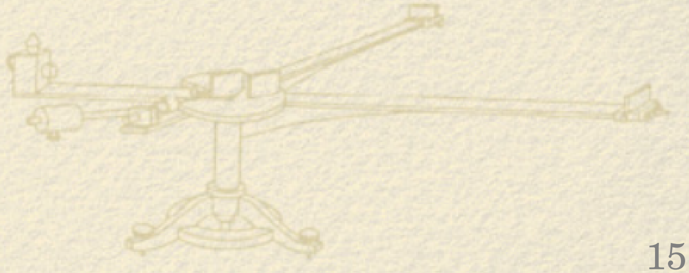
- Beam propagating along x-arm:

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



Sign convention for amplitude reflection and transmission coefficients





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

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

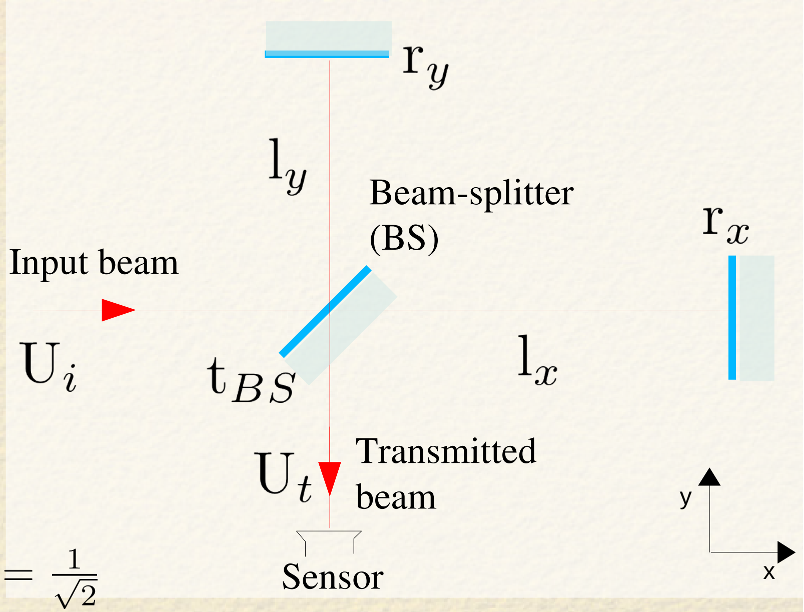
  $= \underline{A}_i$ on BS

- Beam propagating along x-arm:

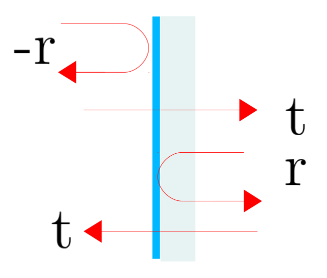
$$U_{tx} = \underline{A}_i\, t_{BS}\, e^{\jmath k l_x} \quad (-r_x) e^{\jmath k l_x} \quad r_{BS}\, e^{\jmath k y_s}$$

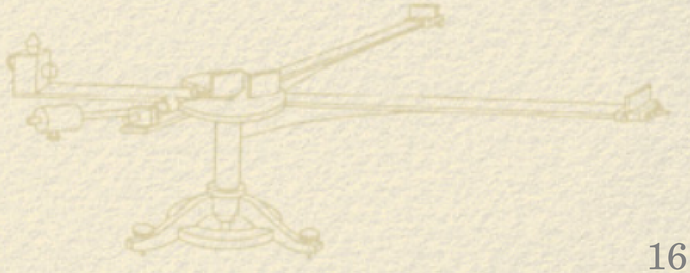
$$= \underline{A}_i\, t_{BS}\, r_{BS}\, (-r_x)\, e^{2\jmath k l_x}\, e^{\jmath k y_s}$$

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

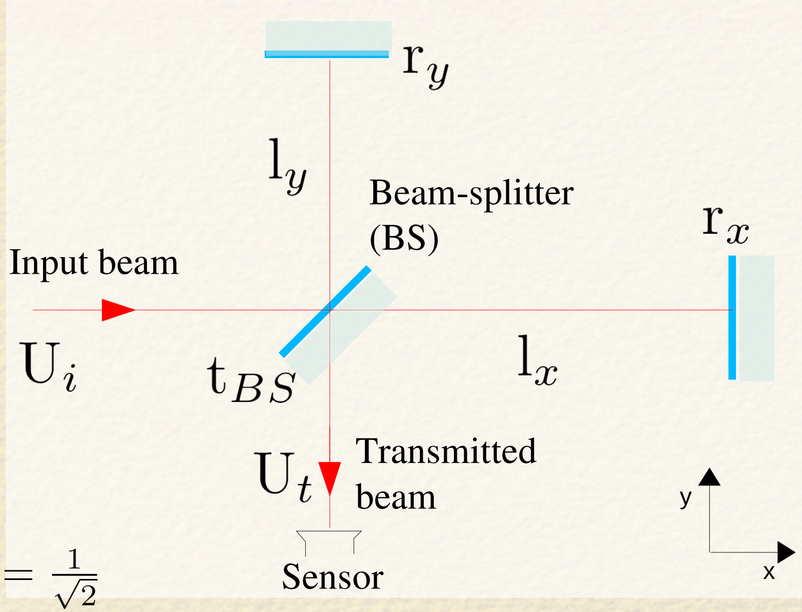


Sign convention for amplitude reflection and transmission coefficients





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



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

- Beam propagating along x-arm:

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

$$= \underline{A}_i\, t_{BS}\, r_{BS}\, (-r_x)\, e^{2\jmath kl_x}\, e^{\jmath ky_s}$$

$$= \frac{\underline{A}_i}{2} \times \underbrace{\left( -\, r_x\, e^{2\jmath kl_x} \right)}_{\text{Complex reflection of the x-arm}} e^{\jmath ky_s} \qquad \text{with } \mathrm{t}_{BS} = r_{BS} = \tfrac{1}{\sqrt{2}}$$

+

- 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:

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

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

# Power transmitted by a simple Michelson

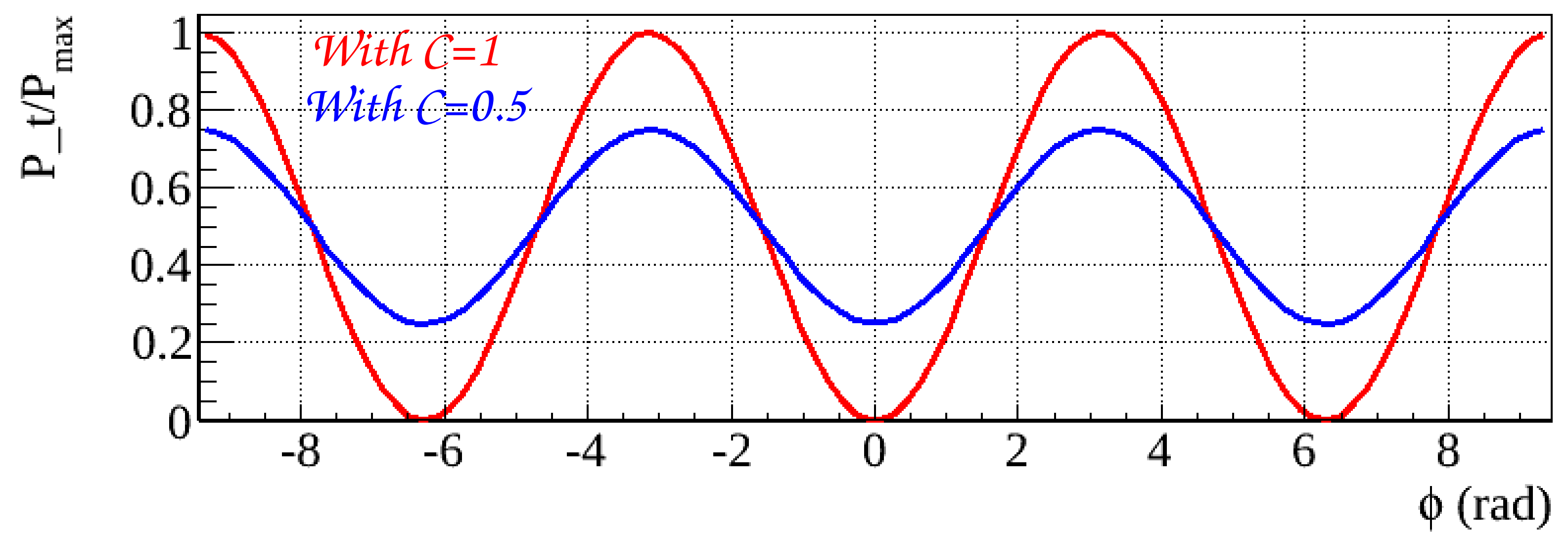
- Transmitted field: $U_t = \frac{\mathcal{A}_i}{2}\, e^{\jmath k y_s} \left( r_y\, e^{2\jmath k l_y} \;-\; r_x\, e^{2\jmath k l_x} \right)$

- Calculation of the transmitted power:

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

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

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

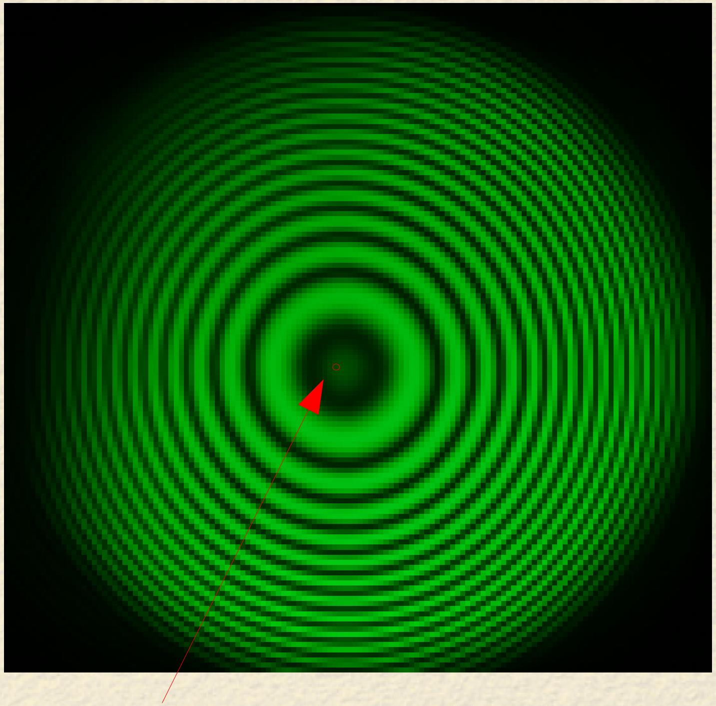


# What power does Virgo measure ?

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

  → interference pattern

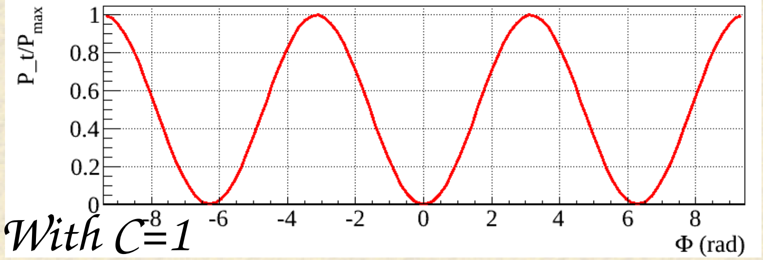
  (and the complementary pattern in reflection)



Equivalent size of Virgo beam

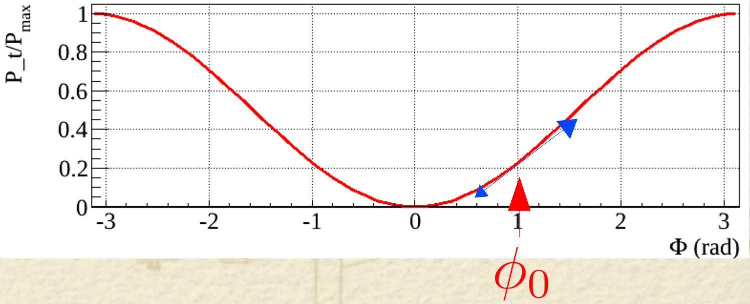
- Virgo interference pattern much larger than the beam size: ~1 m between 2 two consecutive fringes

  → we do not study the fringes in nice  images !



Freely swinging mirrors

Setting a working point →



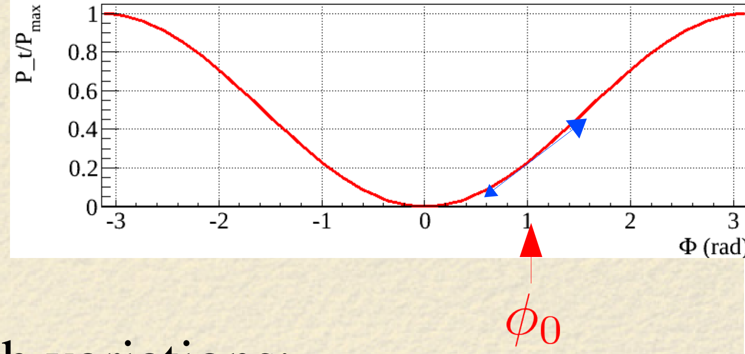
Controlled mirror positions

# From the power to the gravitational wave

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

- Around the working point:

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



- Power variations as function of small differential length variations:

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

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

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

# From the power to the gravitational wave

- Around the working point:

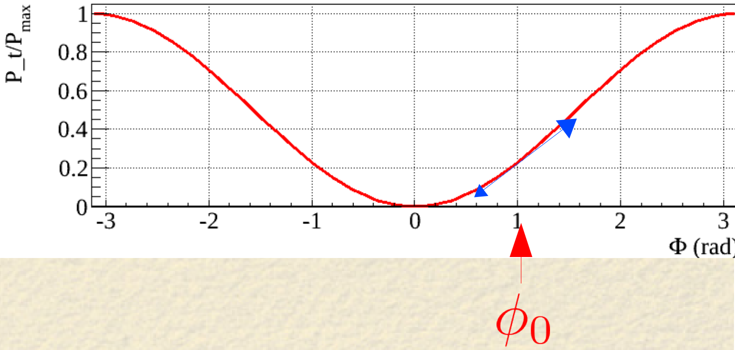
$$\delta P_t = \underbrace{P_i \, C \, \frac{4\pi}{\lambda} \sin\left(\frac{4\pi}{\lambda}\Delta L_0\right)}\, \delta\Delta L$$

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

(W/m)

Measurable physical quantity

Physical effect to be detected



# Improving the interferometer sensitivity

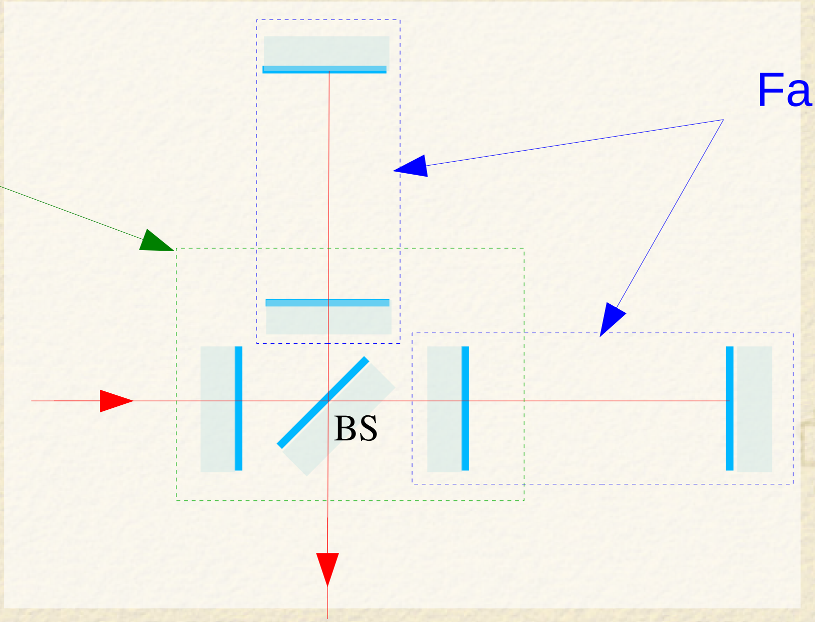
$$\delta P_t = P_i\, C \,\sin\left(\frac{4\pi}{\lambda}\Delta L_0\right) \underbrace{\left(2\,k\,\delta\Delta L\right)}_{\delta\phi}$$

Increase the input power on BS

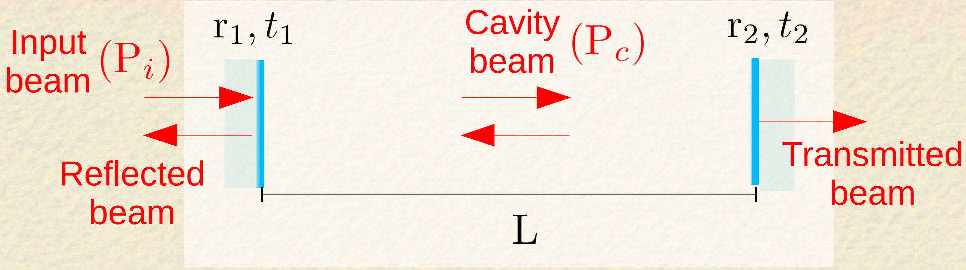
Increase the phase difference between the arms for a given differential arm length variation

Recycling **cavity**

Fabry-Perot **cavities** in the arms

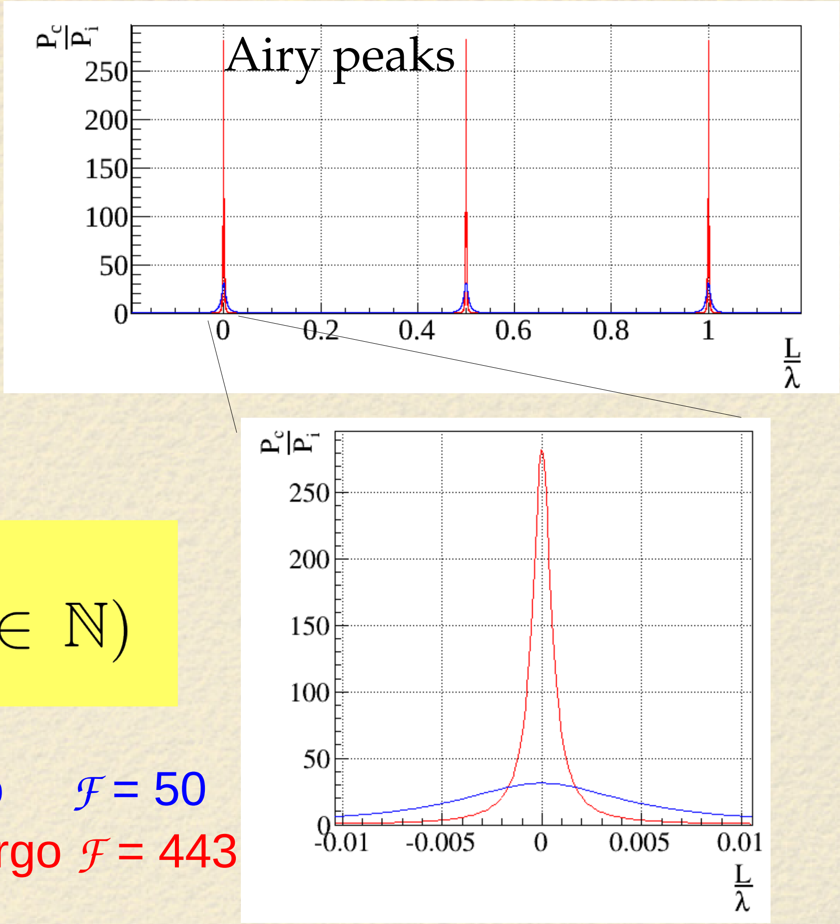


# In Virgo, the beam is resonant inside the cavities



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

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

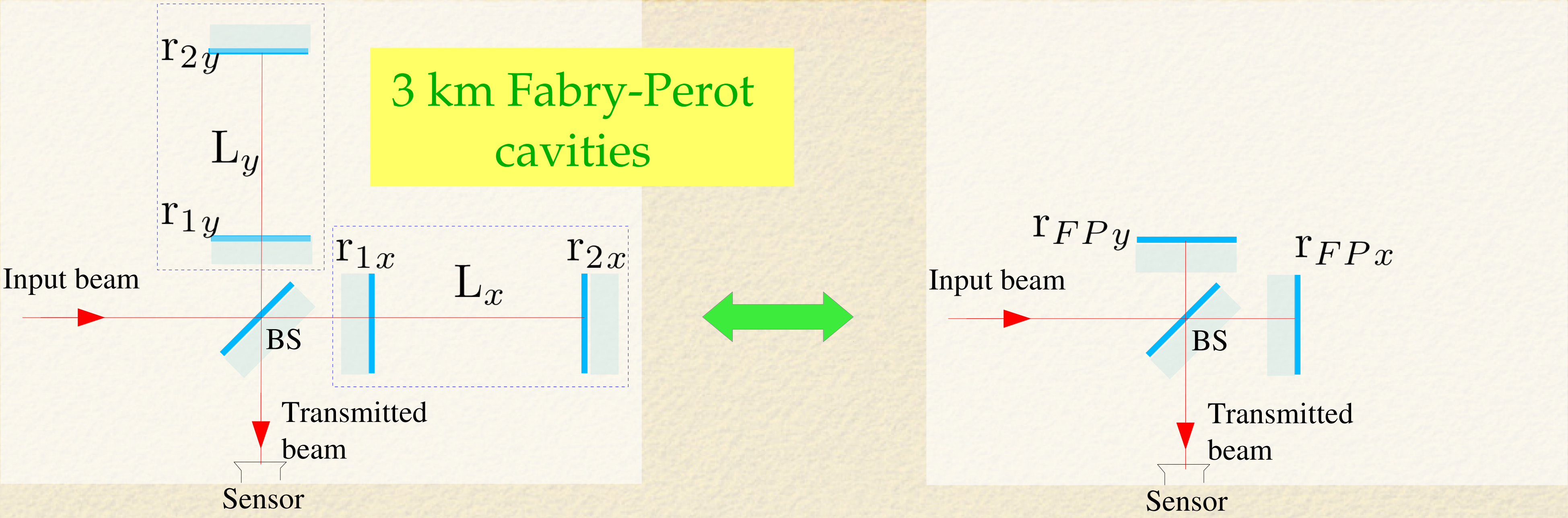


Virgo $\mathcal{F} = 50$
AdVirgo $\mathcal{F} = 443$

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

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

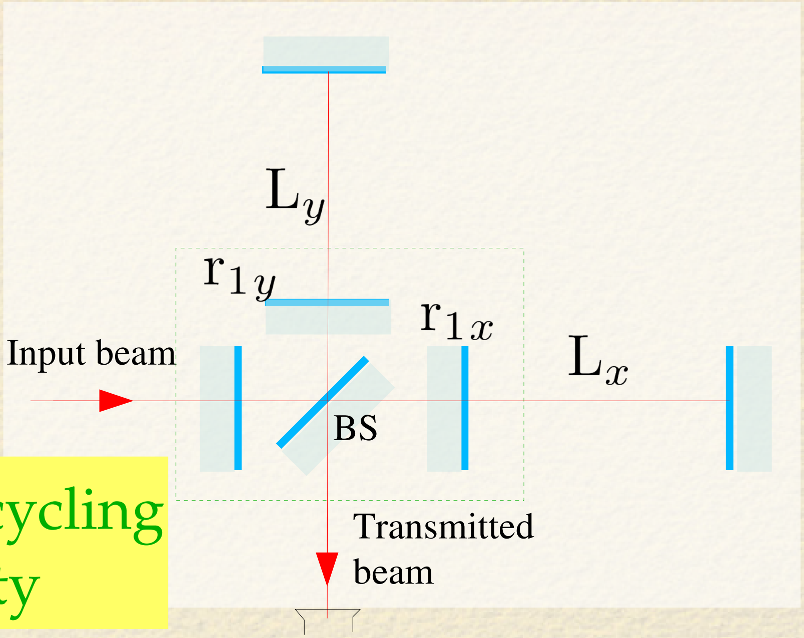
$$r_{FPx} = -1 \times e^{\mathrm{J}\frac{2\mathcal{F}}{\pi}2\,k\,\delta L_x}$$

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

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

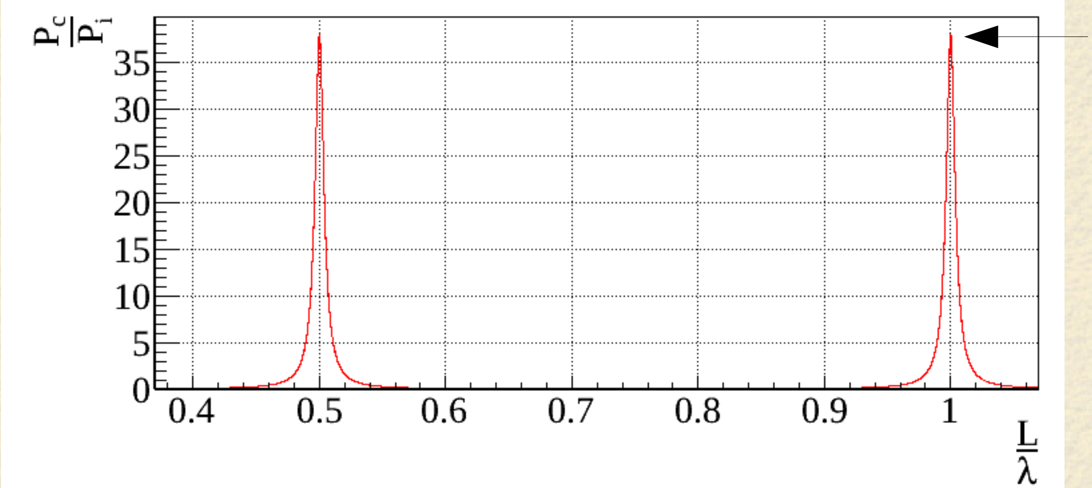
# How do we increase the power on BS ?

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 !

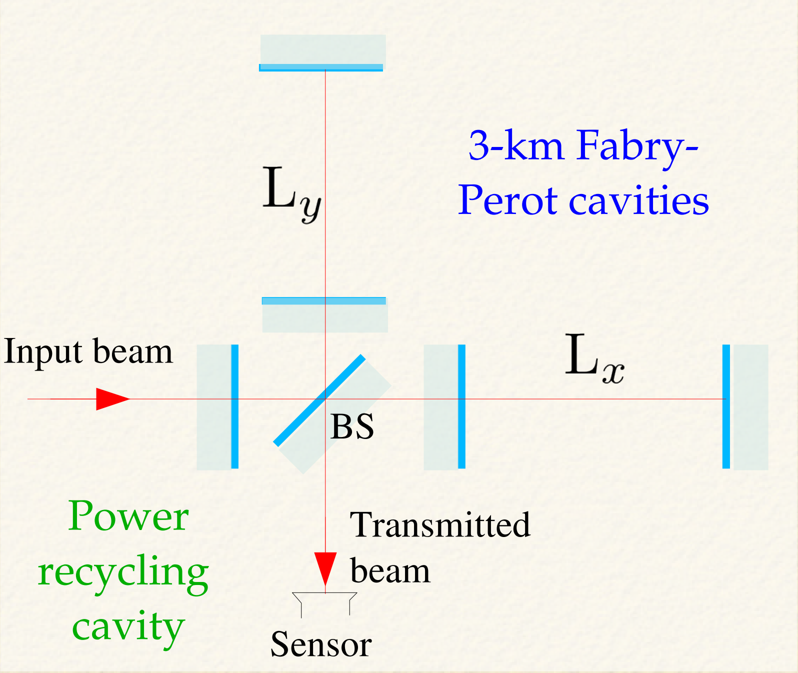
# The improved interferometer response

- **Response of simple Michelson:**

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

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

(W/m)



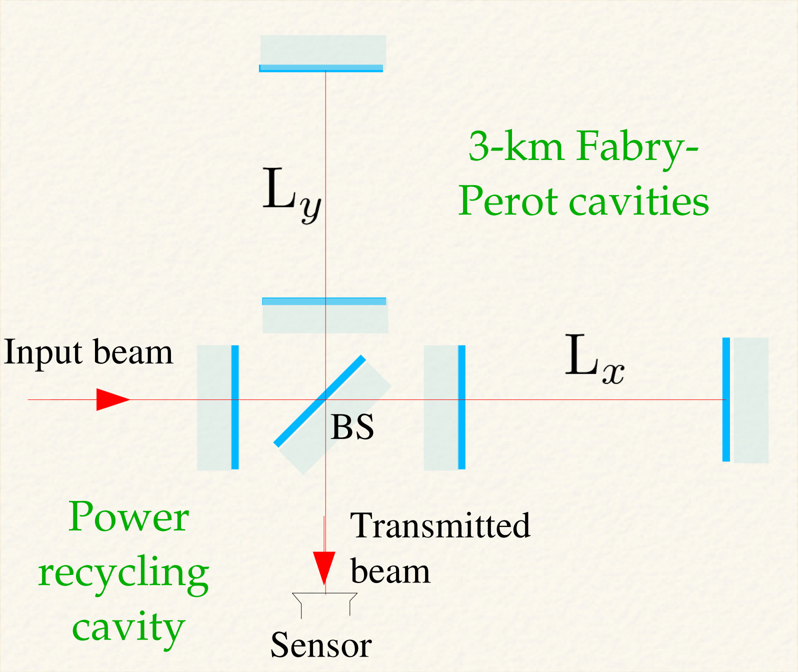
- **Response of recycled Michelson with Fabry-Perot cavities:**

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

~38 ~300

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

# 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: $\lambda = 1.064\,\mu\mathrm{m}$
Input power: P$_i \sim 100$ W
Interferometer contrast: $C \sim 1$
Input mirror reflection: $r_1 = \sqrt{0.986}$
Working point: $\Delta L_0 \sim 10^{-11}$ m
Power recycling gain: $G_{PR} \sim 38$

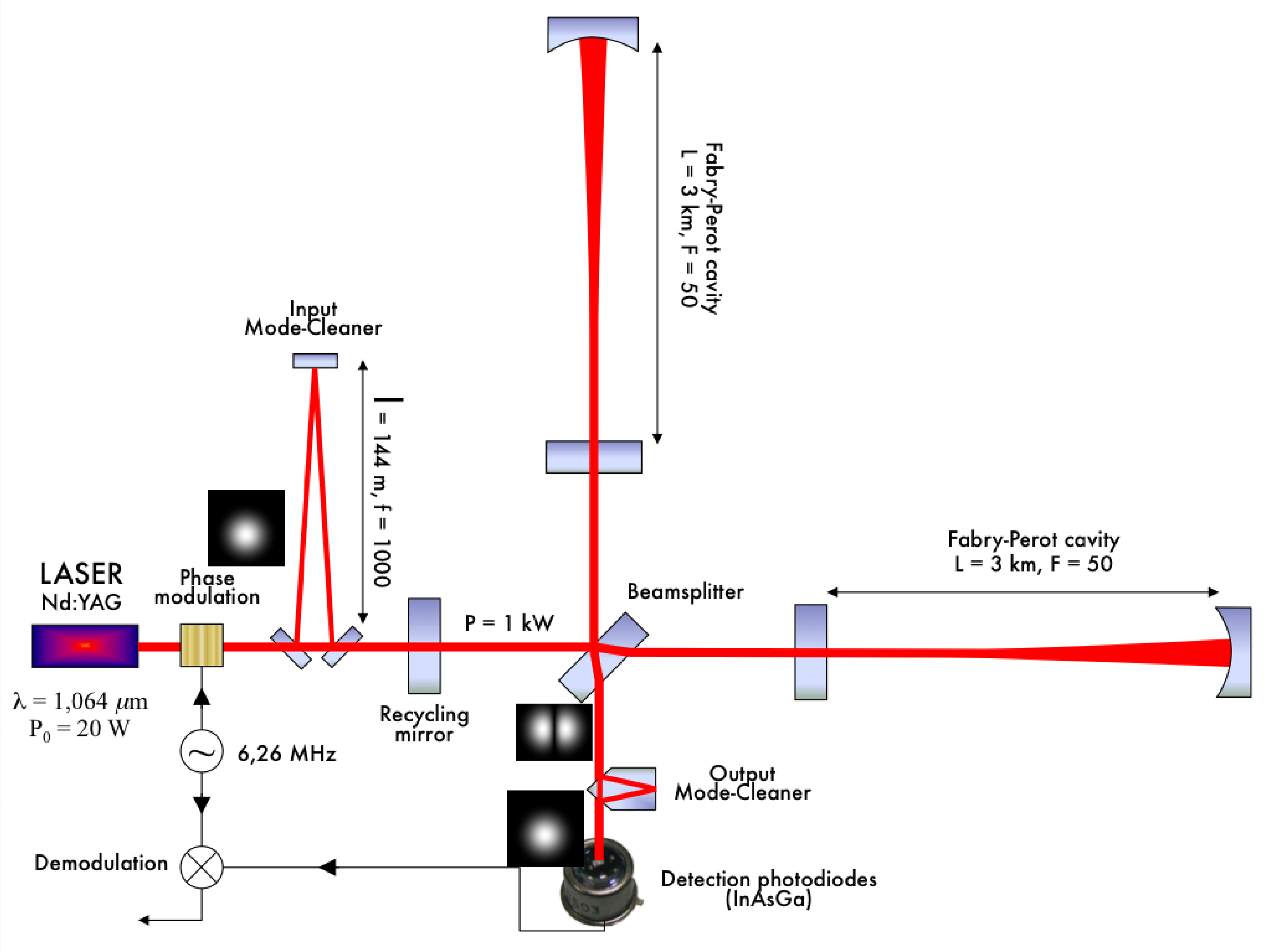
Power noise: $\delta P_{t,min} \sim 0.1\,\mathrm{nW}$ →

$$\delta\Delta L_{min} \sim 5\times10^{-20}\ \mathrm{m}$$

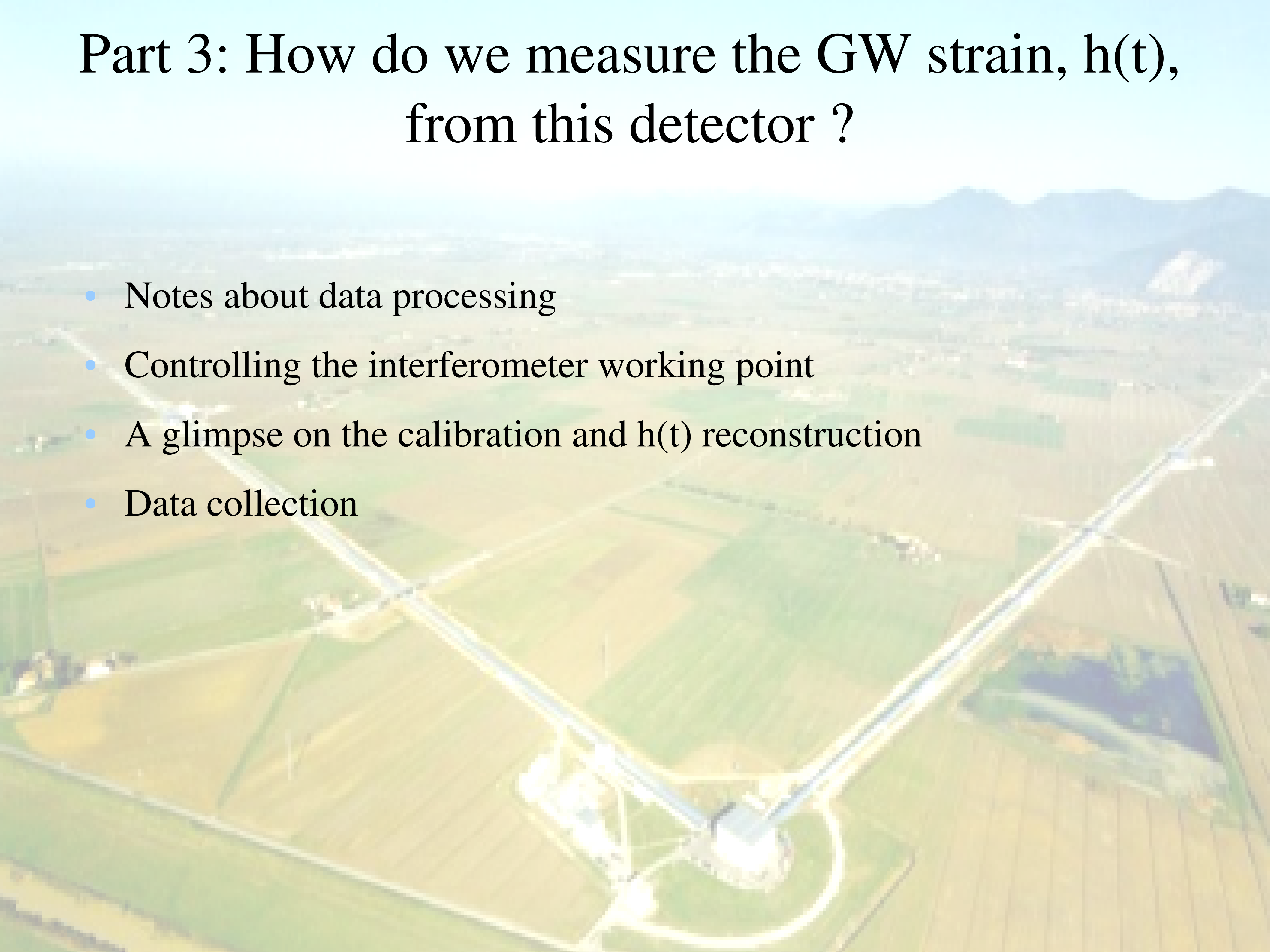
$$\rightarrow h_{min} = \frac{\delta\Delta L_{min}}{L} \sim 10^{-23}$$

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

# Optical layout of Virgo

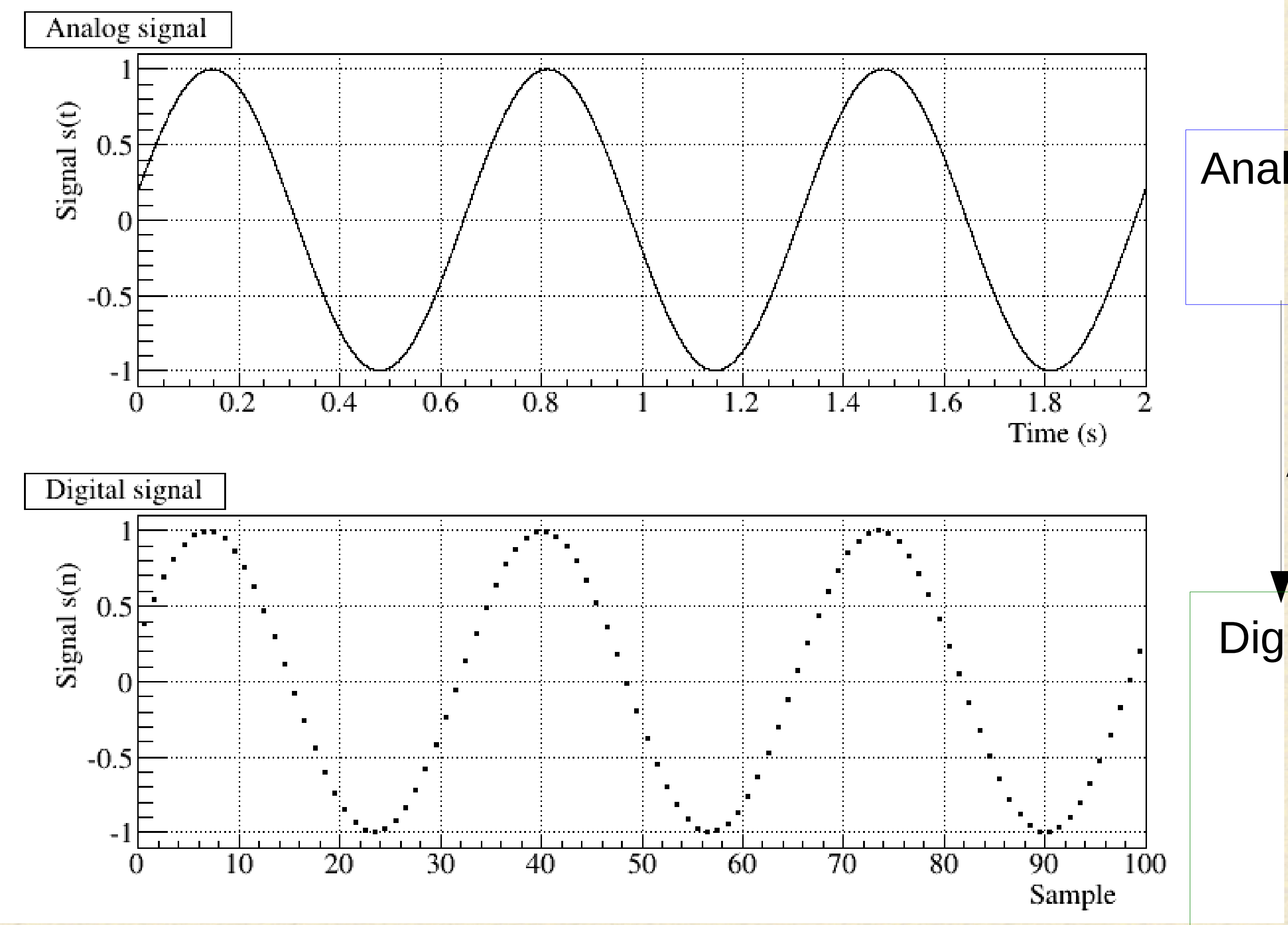


# Part 3: How do we measure the GW strain, h(t), from this detector ?



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

# Notes about data processing: digitization



## 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

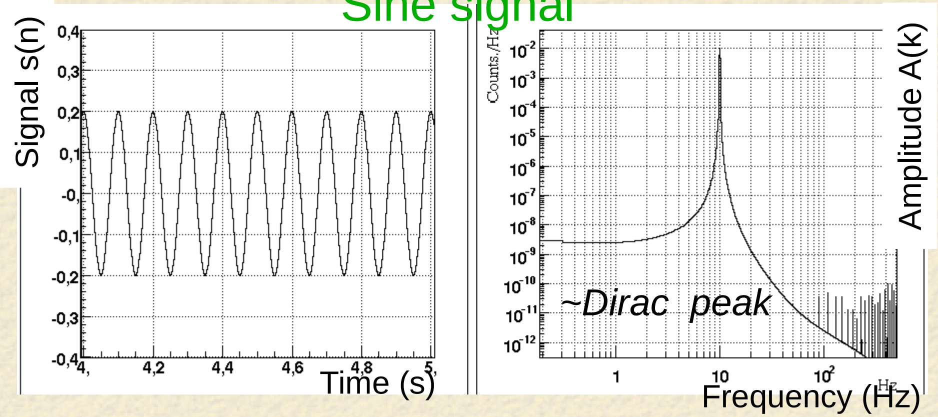
# Notes about data processing: spectral analysis

A signal can be decomposed in different frequency components.

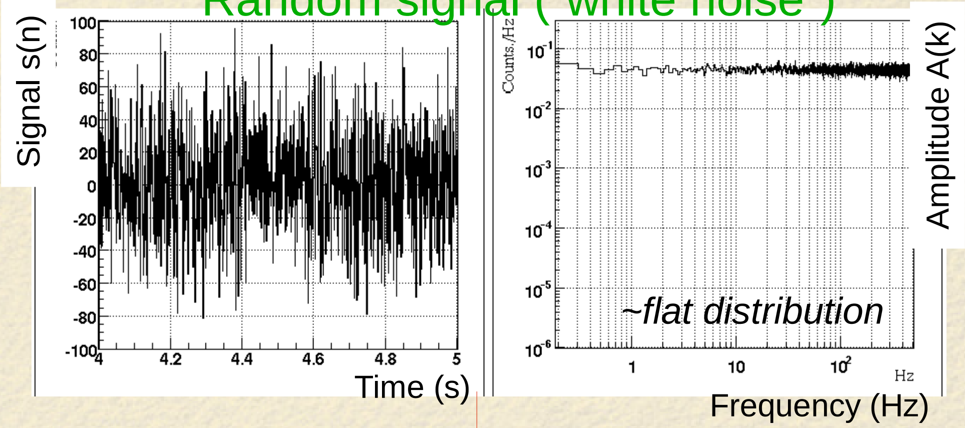
$$s(n) \xrightleftharpoons[\text{Inverse Fourier transform}]{\text{(Discrete) Fourier transform}} A(k) \text{ and } \Phi(k)$$

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

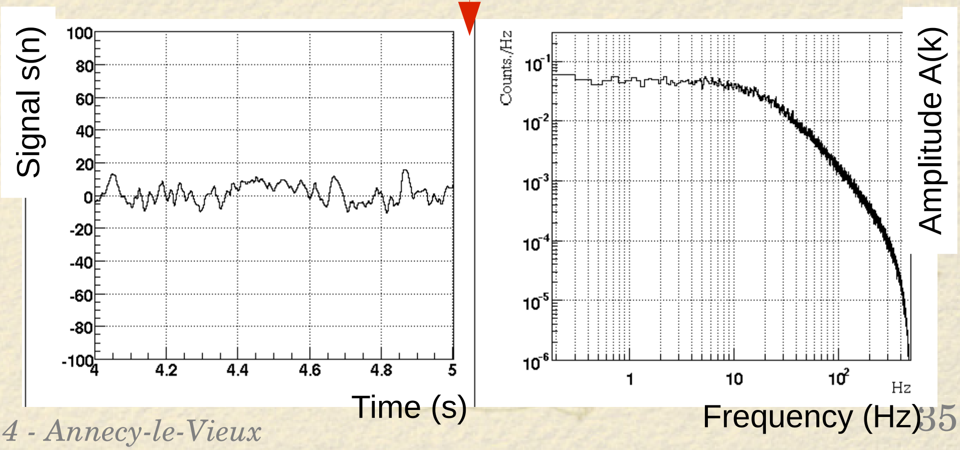
Sine signal



Random signal (“white noise”)



Apply a low-pass filter
on the signal



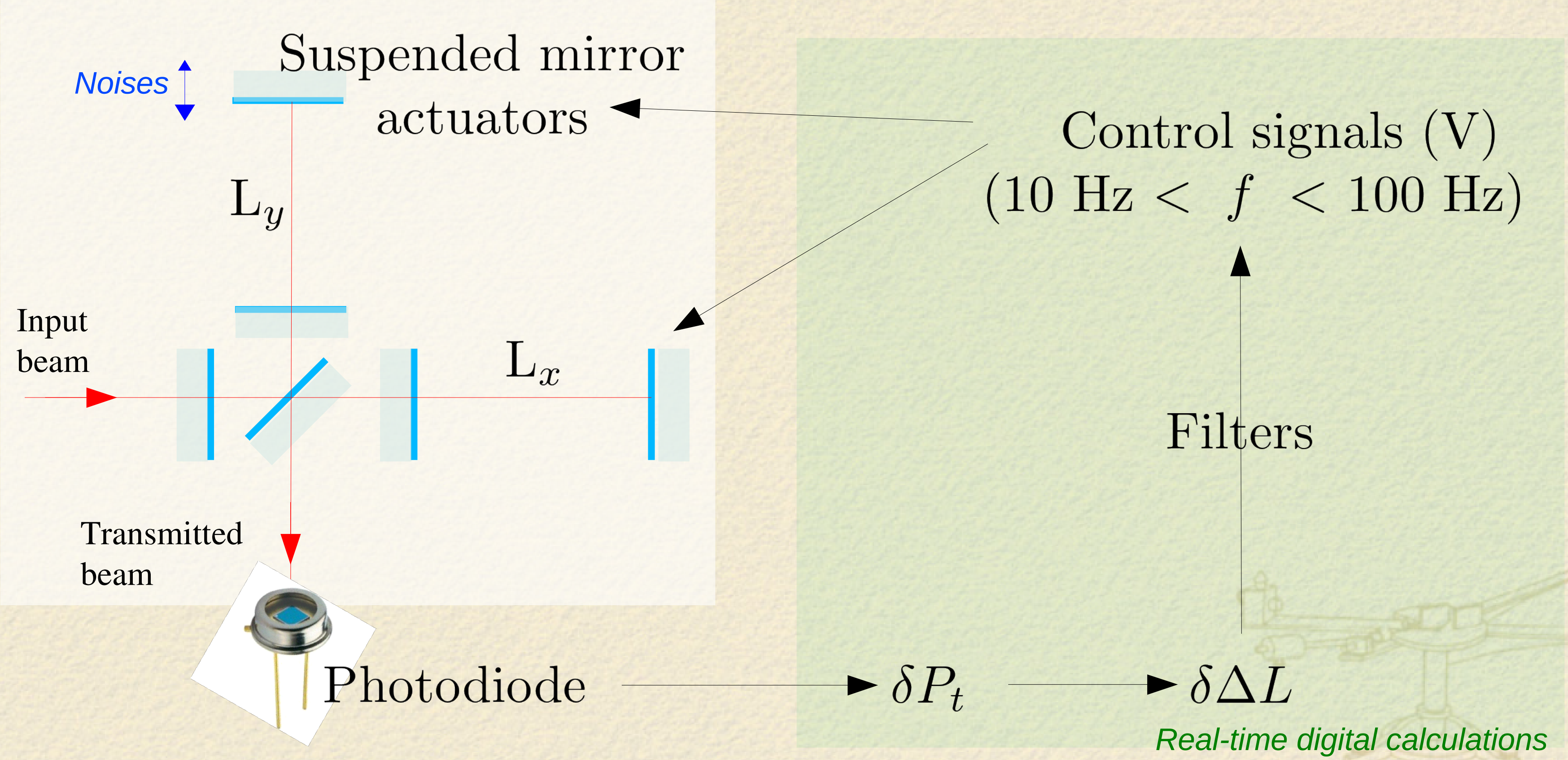
Filtering the data
= modifying the frequency components

# How do we control the working point ?

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

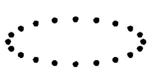
Control loop done for noises with f between ~10 Hz and ~100 Hz

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



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

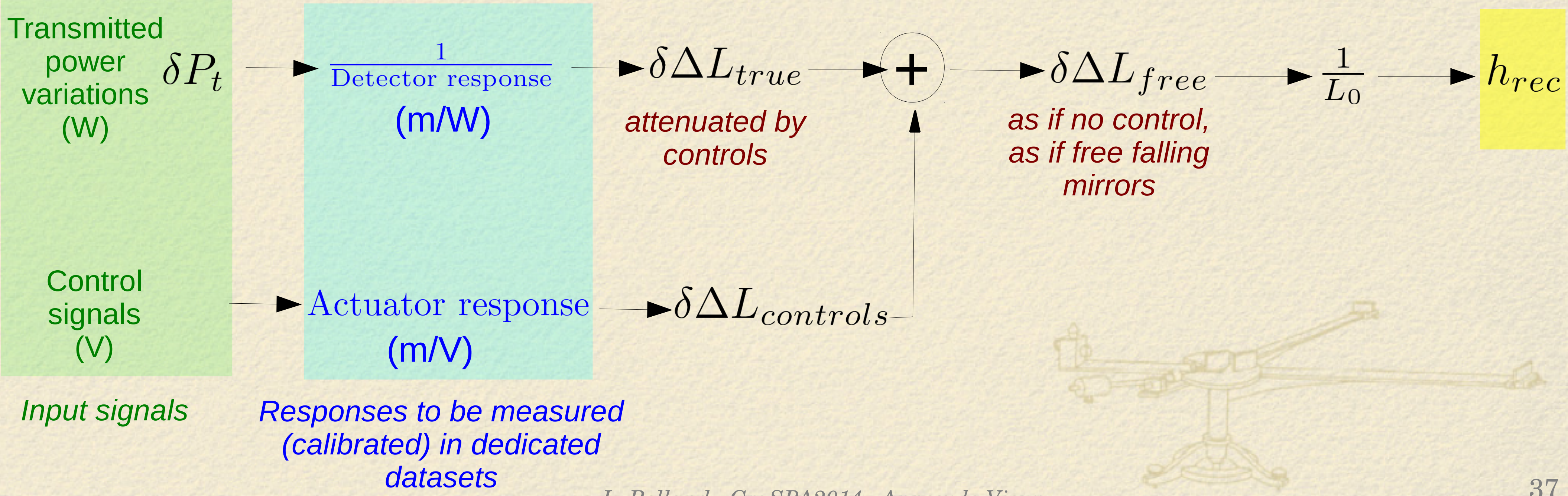
For free falling masses, $h(t) = \frac{\delta\Delta L(t)}{L_0}$



→ this condition is valid for the suspended mirrors above $\sim$ 100 Hz (no control signal)

At lower frequencies, the controls attenuate the noise... but also the gravitational wave signal !

→ the control signals contain information on h(t)



Transmitted power variations (W) $\delta P_t$ → $\frac{1}{\text{Detector response}}$ (m/W) → $\delta\Delta L_{true}$ → + → $\delta\Delta L_{free}$ → $\frac{1}{L_0}$ → $h_{rec}$

*attenuated by controls*

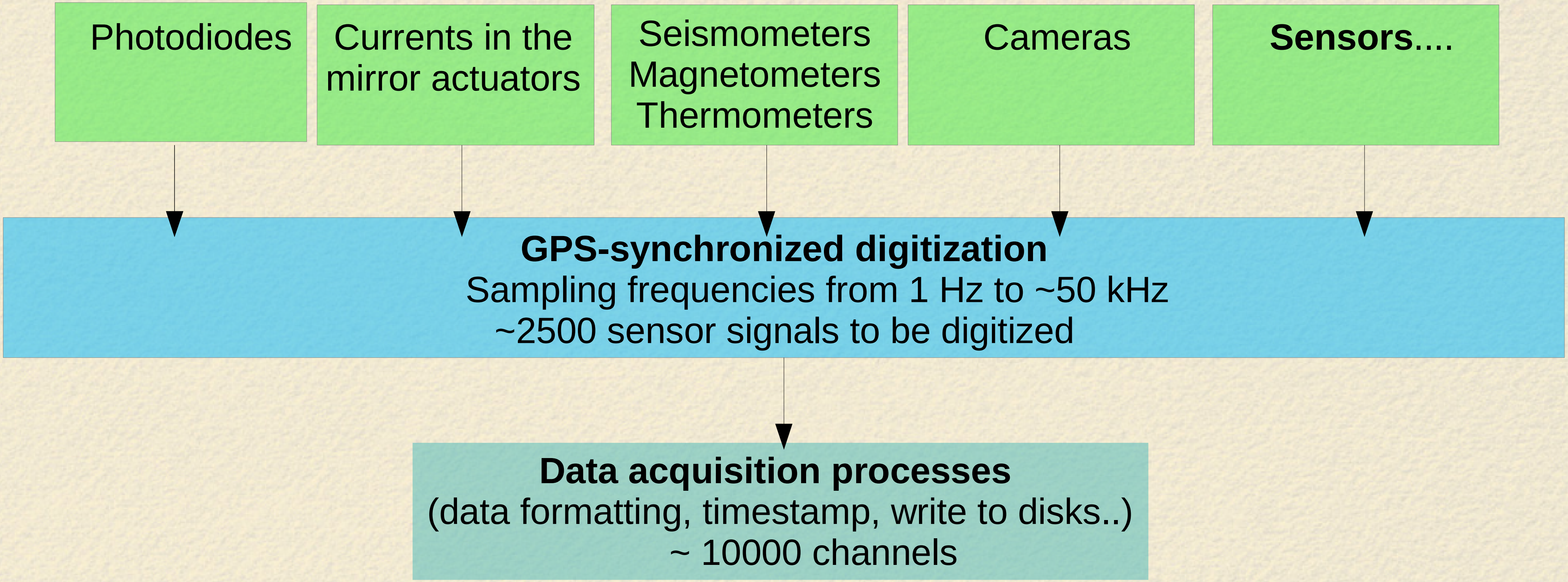
*as if no control, as if free falling mirrors*

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

*Input signals*

*Responses to be measured (calibrated) in dedicated datasets*

# AdVirgo data acquisition summary



Photodiodes

Currents in the mirror actuators

Seismometers
Magnetometers
Thermometers

Cameras

**Sensors....**

**GPS-synchronized digitization**
Sampling frequencies from 1 Hz to ~50 kHz
~2500 sensor signals to be digitized

**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

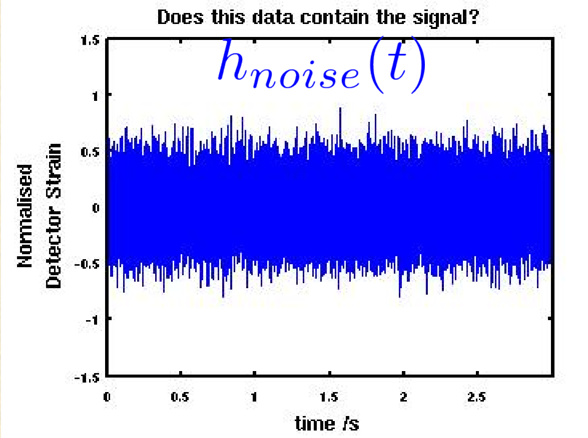
Longer storage: data sent via Ethernet to computing centers (Lyon, Bologna)

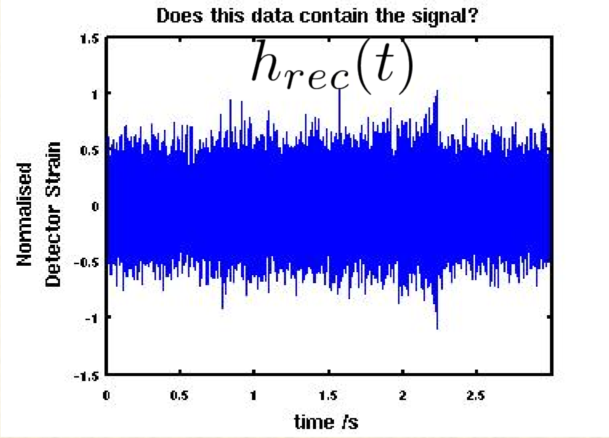
# Part 4: Virgo noises

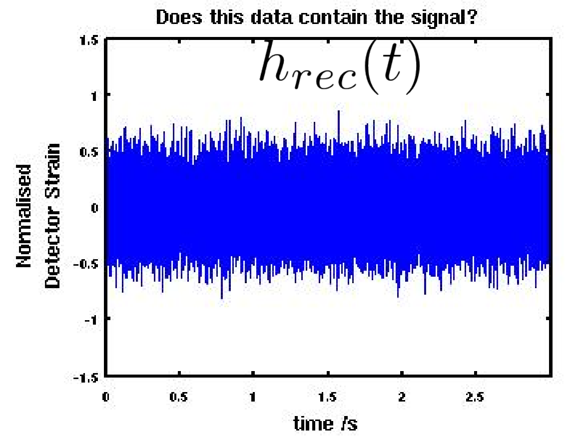
# What is a noise in Virgo ?

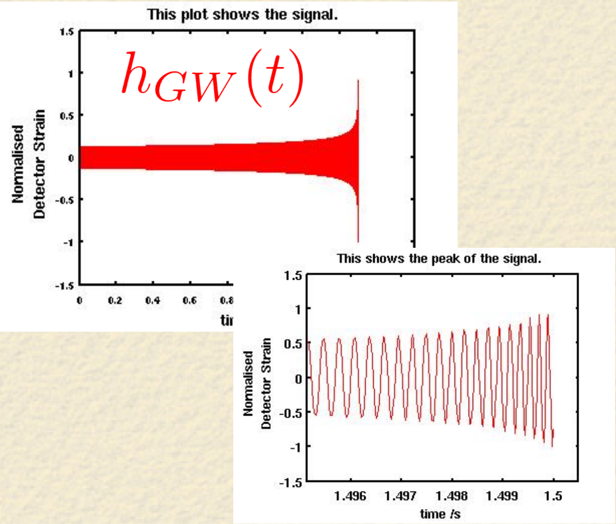
- Stochastic (random) signal that contributes to the signal $h_{rec}(t)$ but does not contain information on the gravitational wave strain $h_{GW}(t)$

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

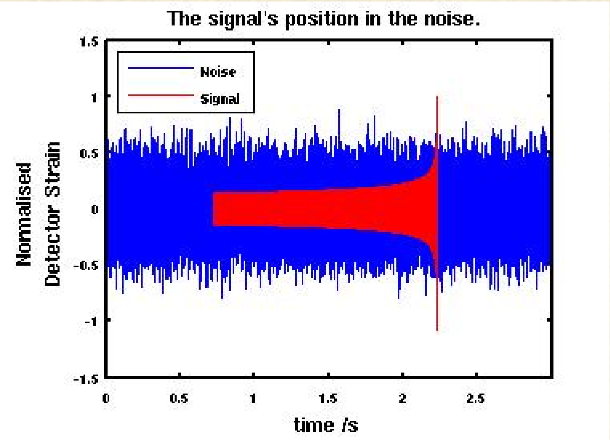

Does this data contain the signal?

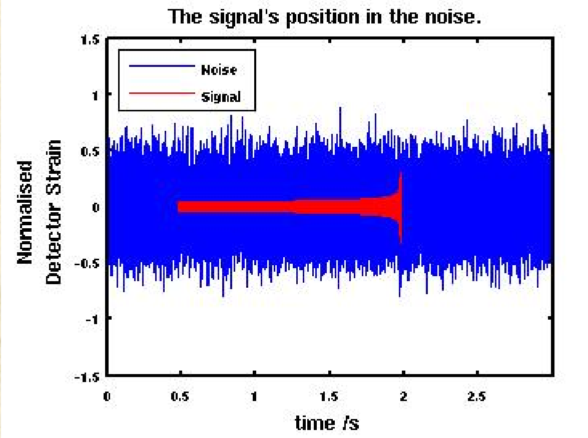

Does this data contain the signal?


Does this data contain the signal?


This plot shows the signal.

This shows the peak of the signal.


The signal's position in the noise.


The signal's position in the noise.

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

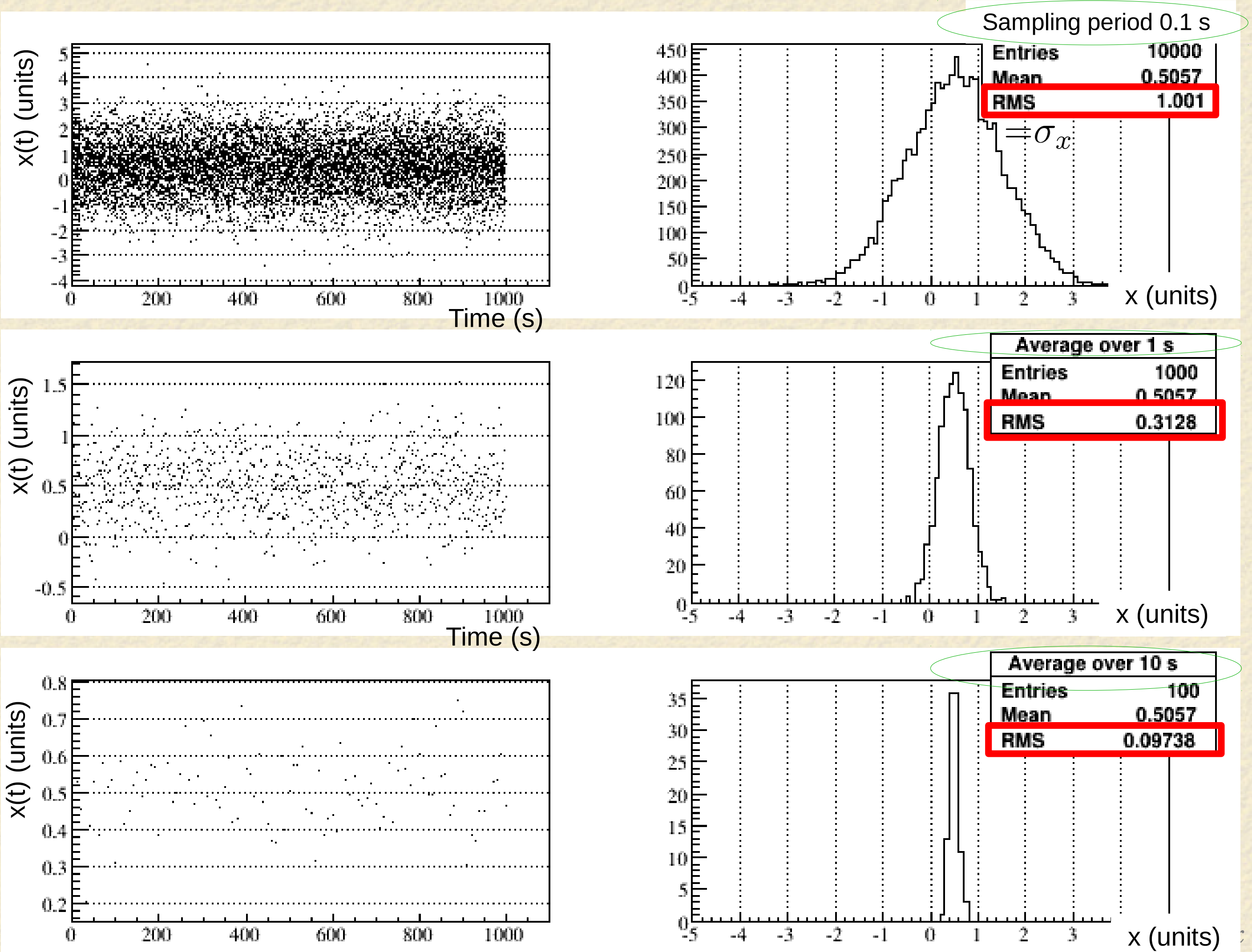
# How do we characterize a noise ?

Hypothesis: - we are looking for a constant signal $S_0$ (=0.5) in the data

- data are noisy (Gaussian noise)

$$x(t) = S_0 + Noise(t)$$

**Data points** **Distribution of the data**



Gaussian distribution:

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

The mean value of the noise stays around 0
The mean value of the signal stays around $S_0$.

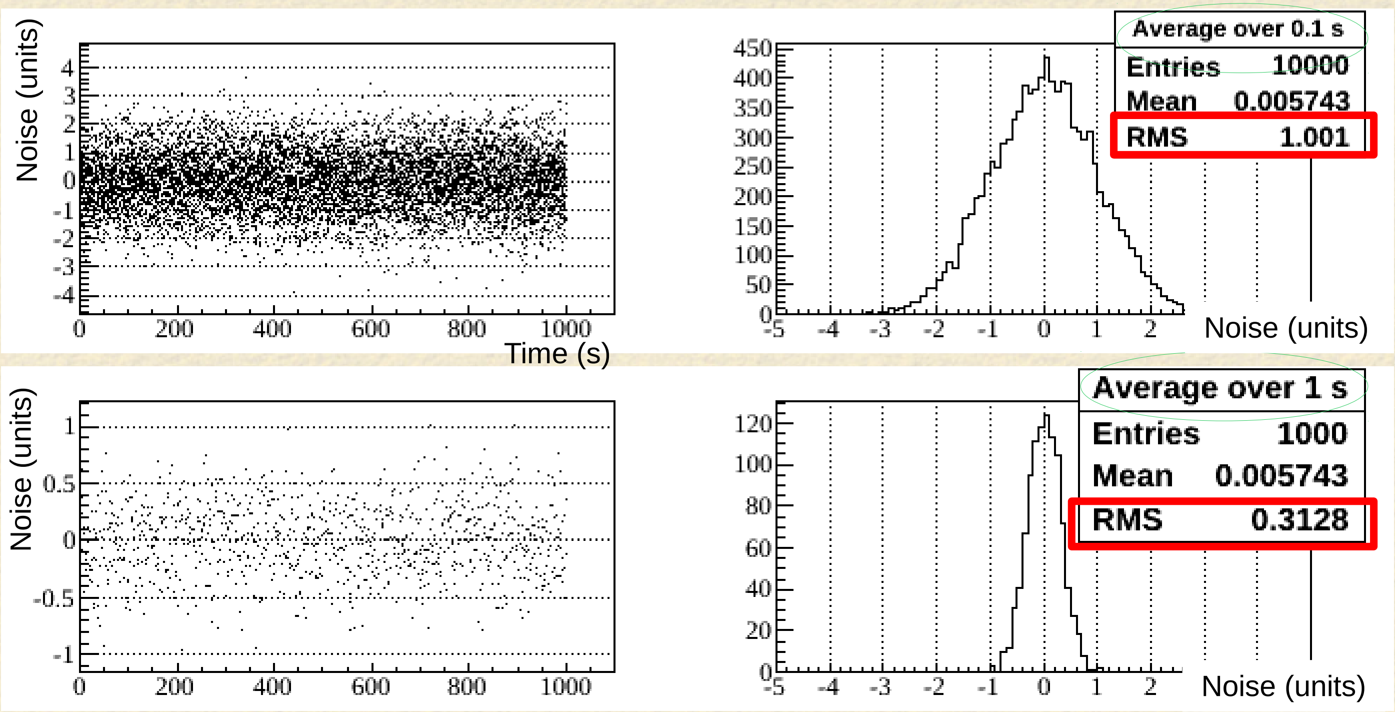
The variations of the noise decrease when the data are averaged over longer time

$$\sigma_x \propto \frac{1}{\sqrt{\text{average duration}}}$$

→ What is important to characterize a noise is it dispersion $\sigma_x$ !

# How do we characterize a noise ?

**Data points of noise only** **Projection of noise data**



The variations of the noise decrease when the data are averaged over longer time

$$\sigma_x \propto \frac{1}{\sqrt{\text{average duration}}}$$

$$\downarrow$$

The noise can be characterized by the coefficient of proportionality D

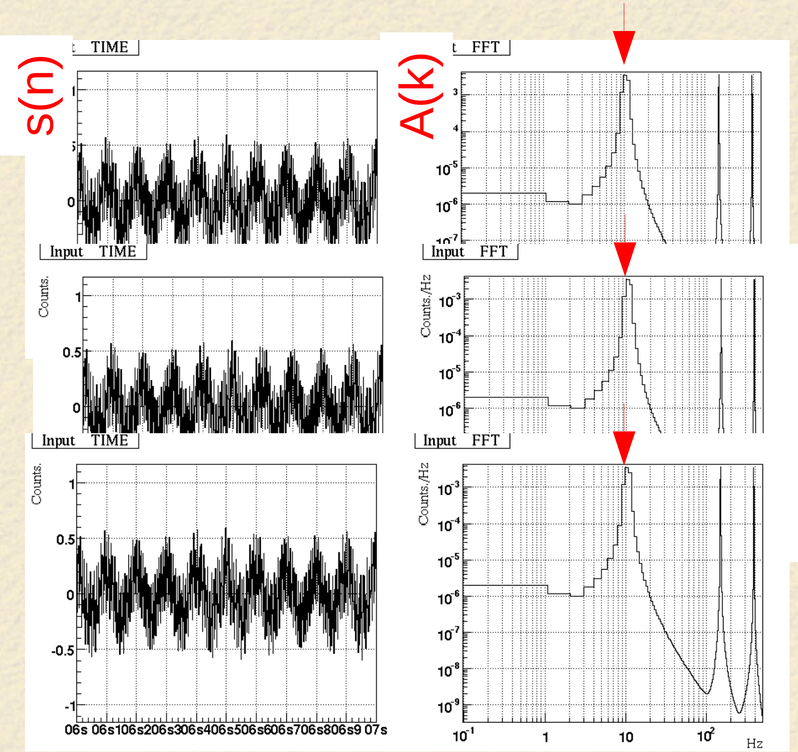
$$\underbrace{\sigma_x = \frac{D}{\sqrt{\text{average duration}}}}$$

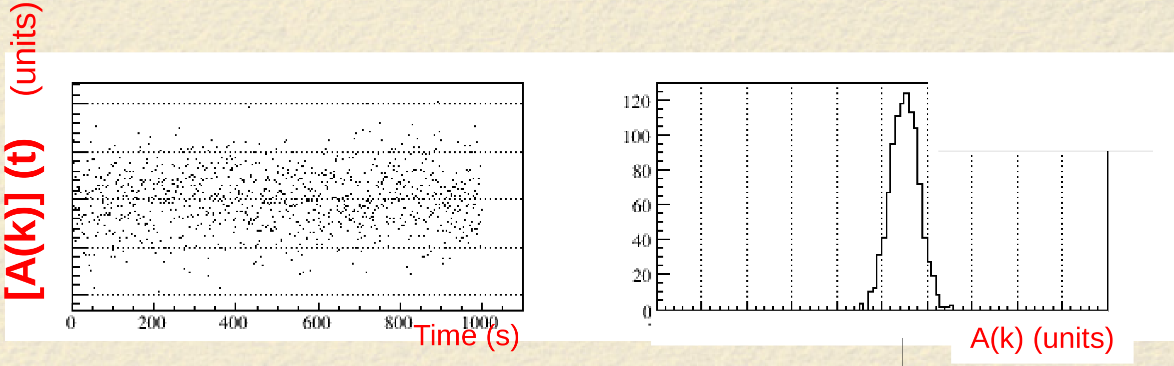
$D$ is in (Data units $\times \sqrt{\text{s}}$) or $\frac{\text{Data units}}{\sqrt{\text{Hz}}}$

its absolute value is equal to the dispersion of the noise when it is averaged over 1 s.

# How do we characterize a noise ...in frequency-domain ?

$$s(n) \xrightarrow[\text{transform}]{\text{Discrete Fourier}} A(k) \text{ (and } \Phi(k))$$





$$\sigma_{A(k)}$$

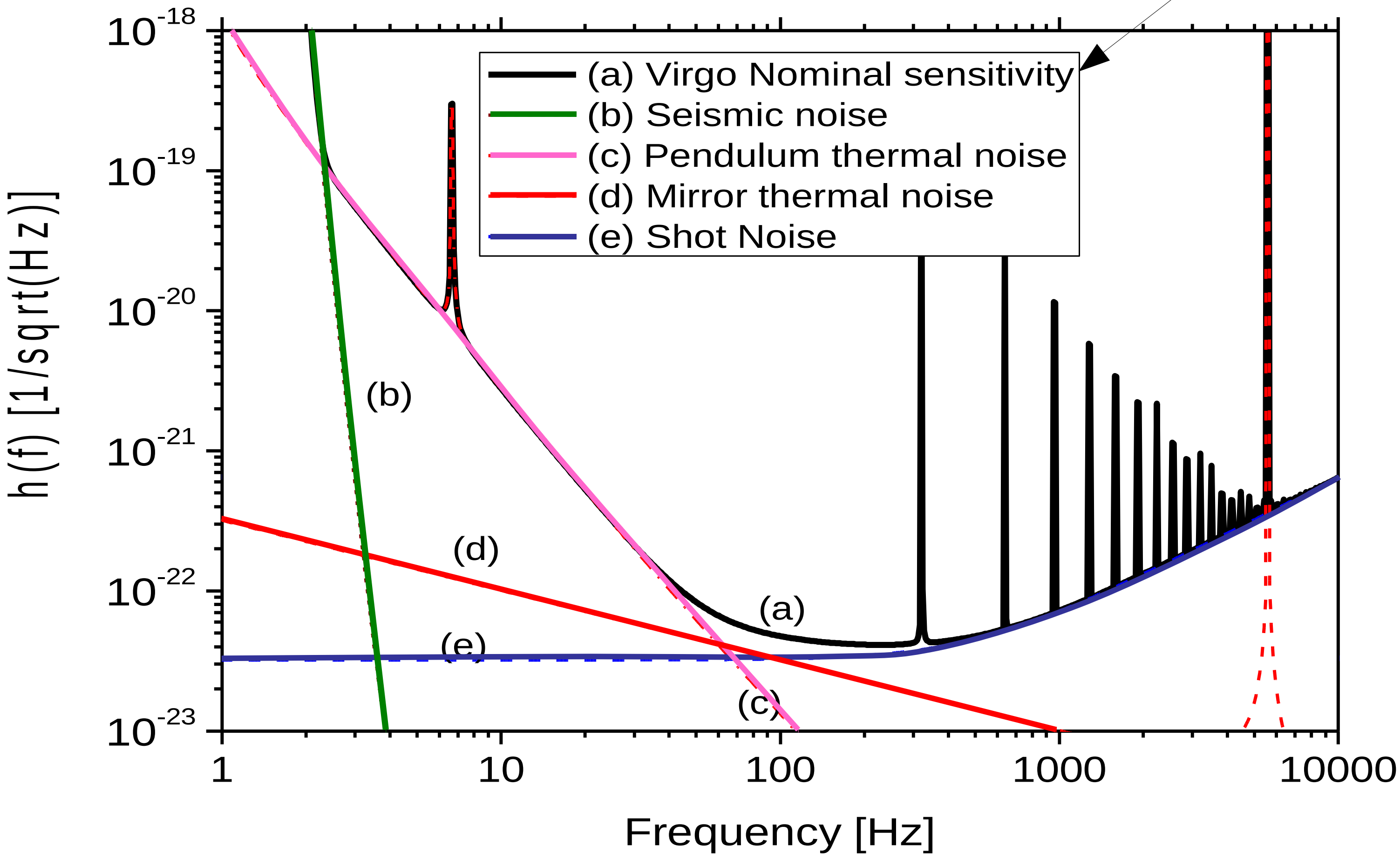
$$\boxed{D(k) \text{ also in } \frac{\text{Data units}}{\sqrt{\text{Hz}}}}$$

D(k) (amplitude spectral density) is
a curve that characterizes the noise dispersion as function of frequency

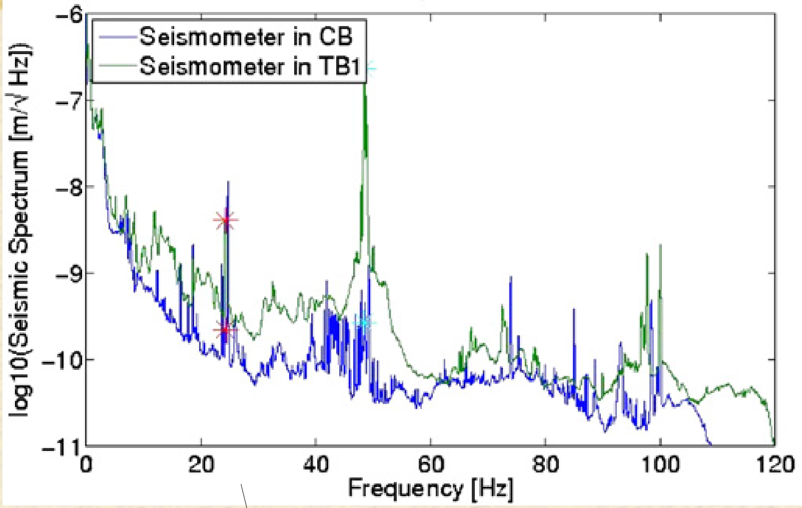
# What is the noise level of Virgo ?

Sum of all the noises

Noise level of $h_{rec}(t)$, shown as function of frequency

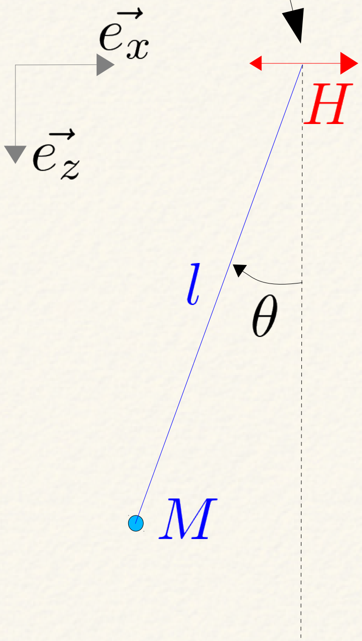


# Seismic noise and suspended mirrors



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

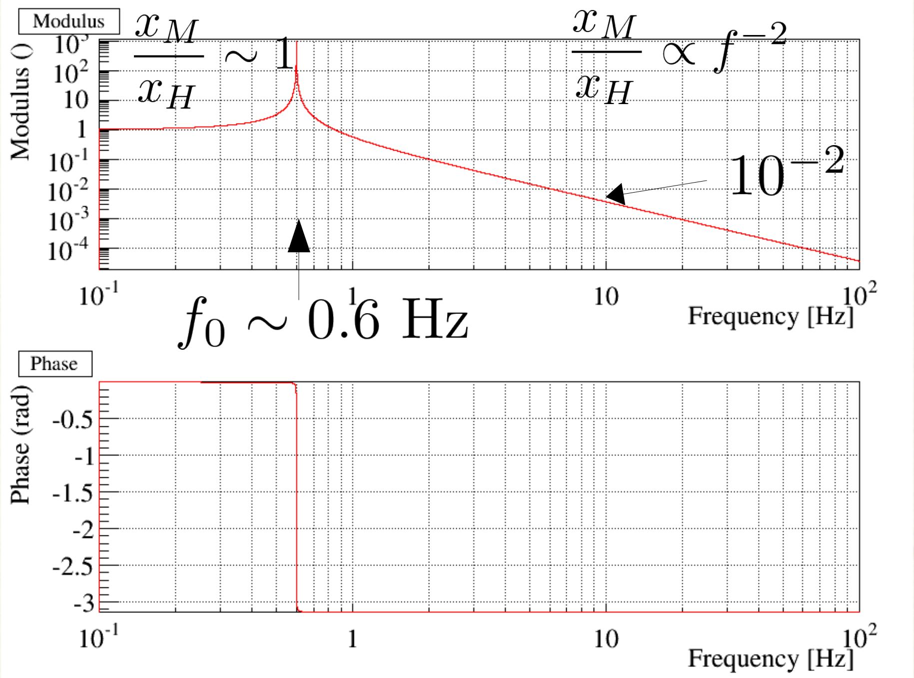
$\gg 10^{-19}\,\mathrm{m}/\sqrt{\mathrm{Hz}}$ needed to detect GW !!



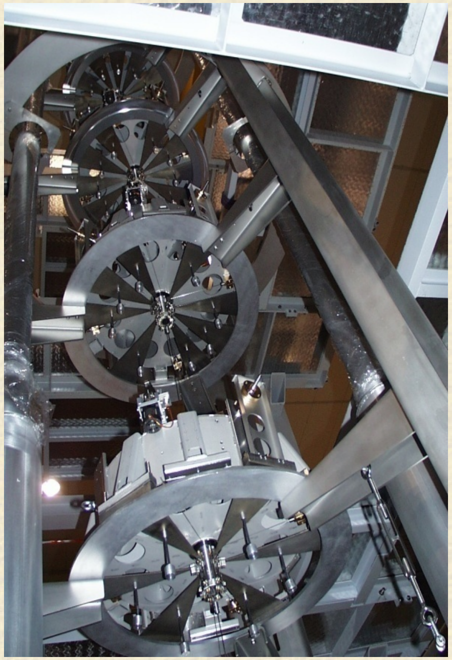
Assuming $\delta x_H$ small and sinusoidal and $\theta$ small:

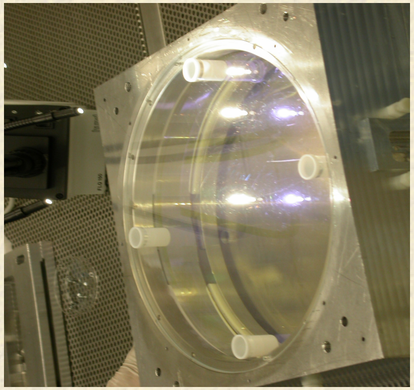
$$\underline{x_M} = \underline{\mathcal{H}} \times \underline{x_H}$$

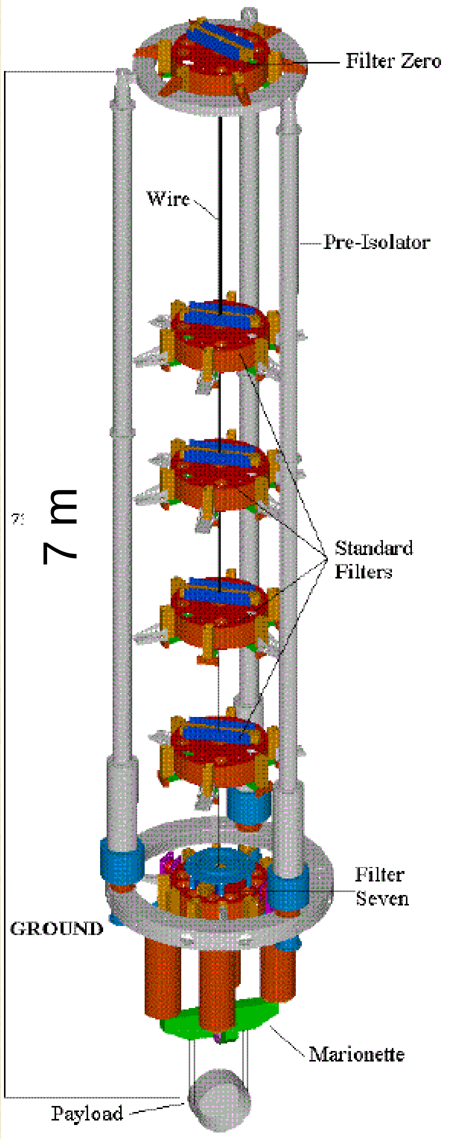
Transfer function



# Seismic noise and the Virgo suspension







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

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

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

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

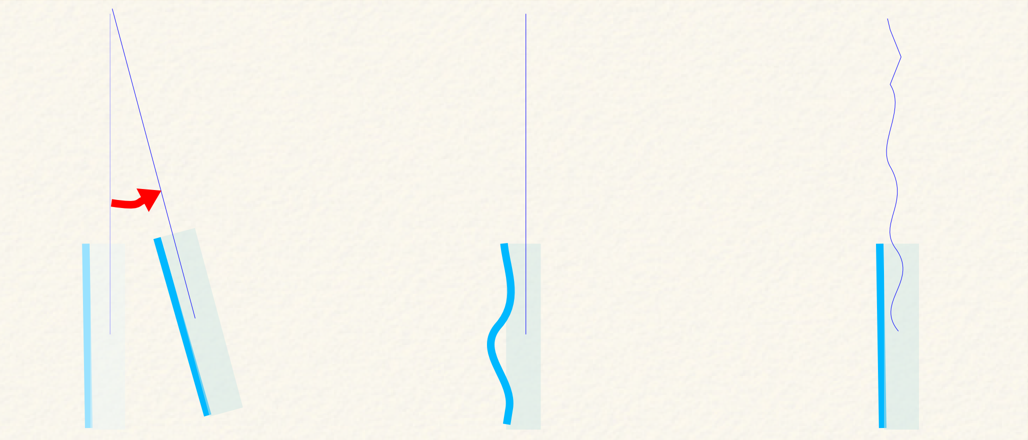
This noise directly modifies the positions of the mirror surfaces, and thus $\delta\Delta L$ and $h_{rec}(t)$ !

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

# Some noises: thermal noise

- Microscopic thermal fluctuations

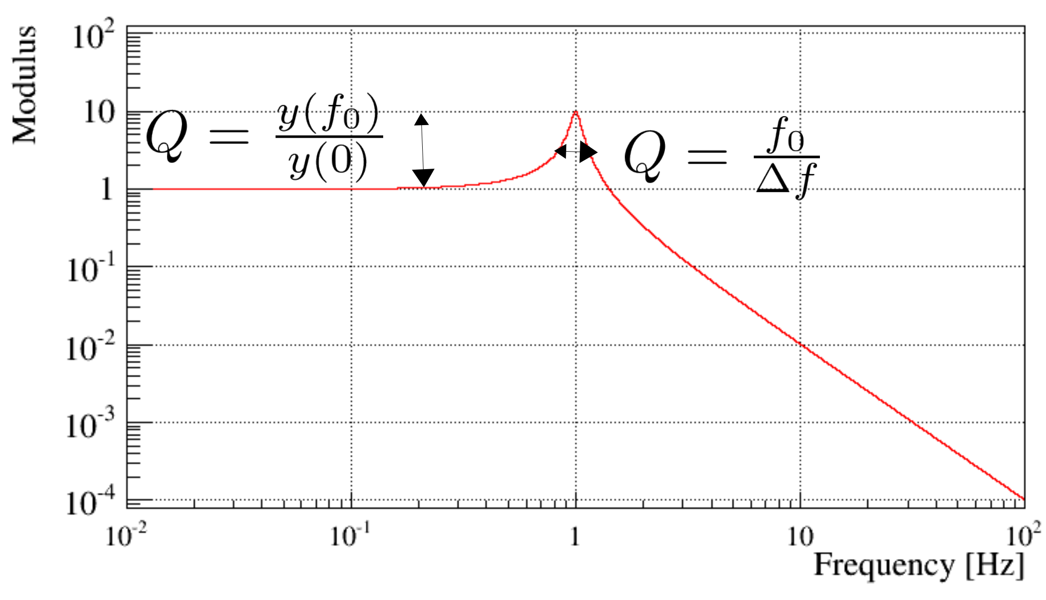
--> dissipation of energy through excitation of the macroscopic modes of the mirror



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 $h_{rec}(t)$ !

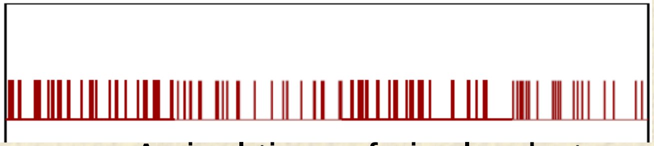
- We want high quality factors Q to concentrate all the noise in a small frequency band

# 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 $\delta\Delta L$

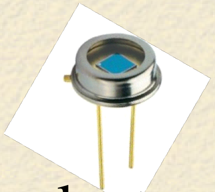
$$\delta P_t = (\text{Virgo response}) \times L_0 \times h$$

(in W/m)

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

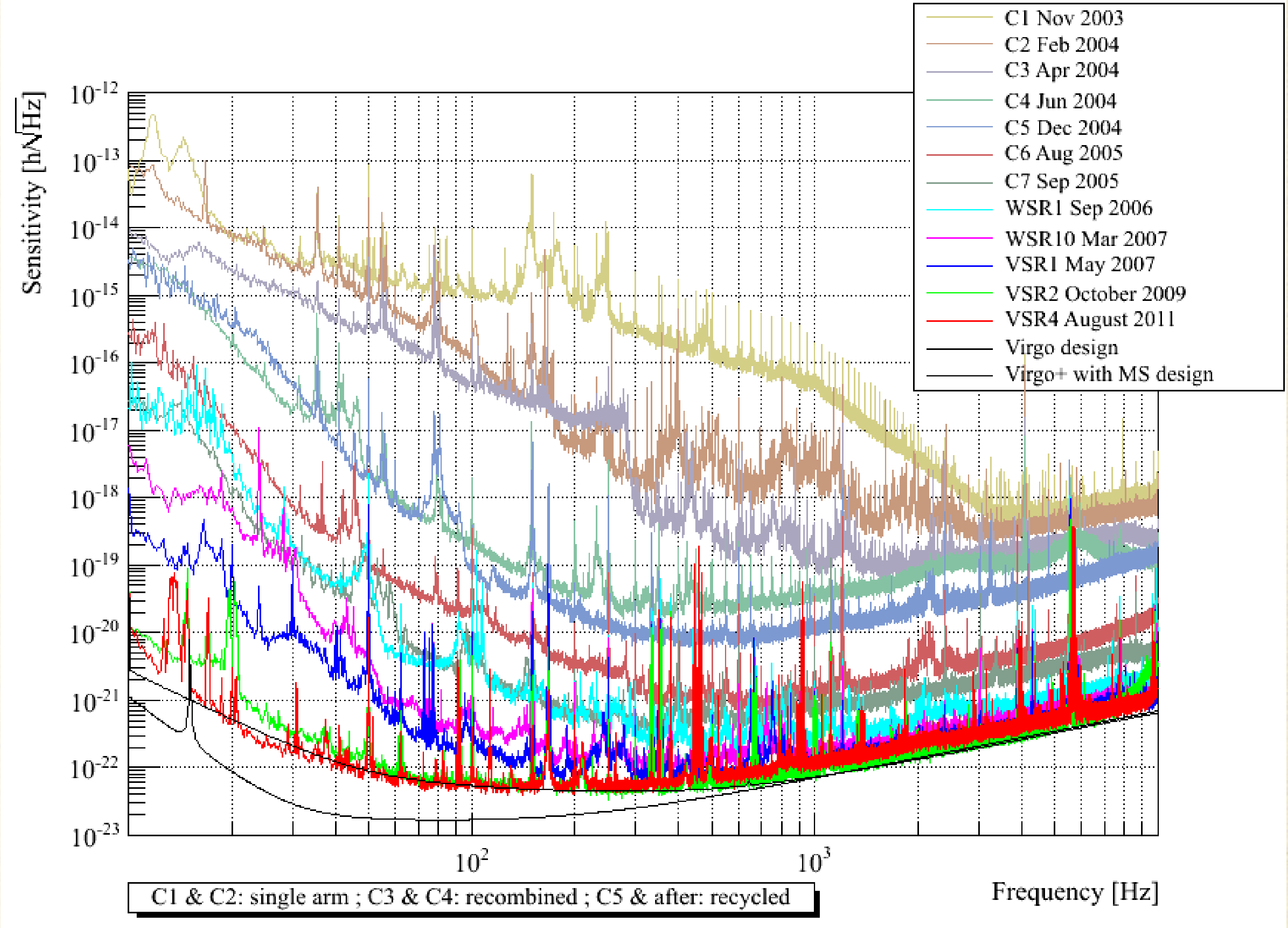
# Some other noises

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

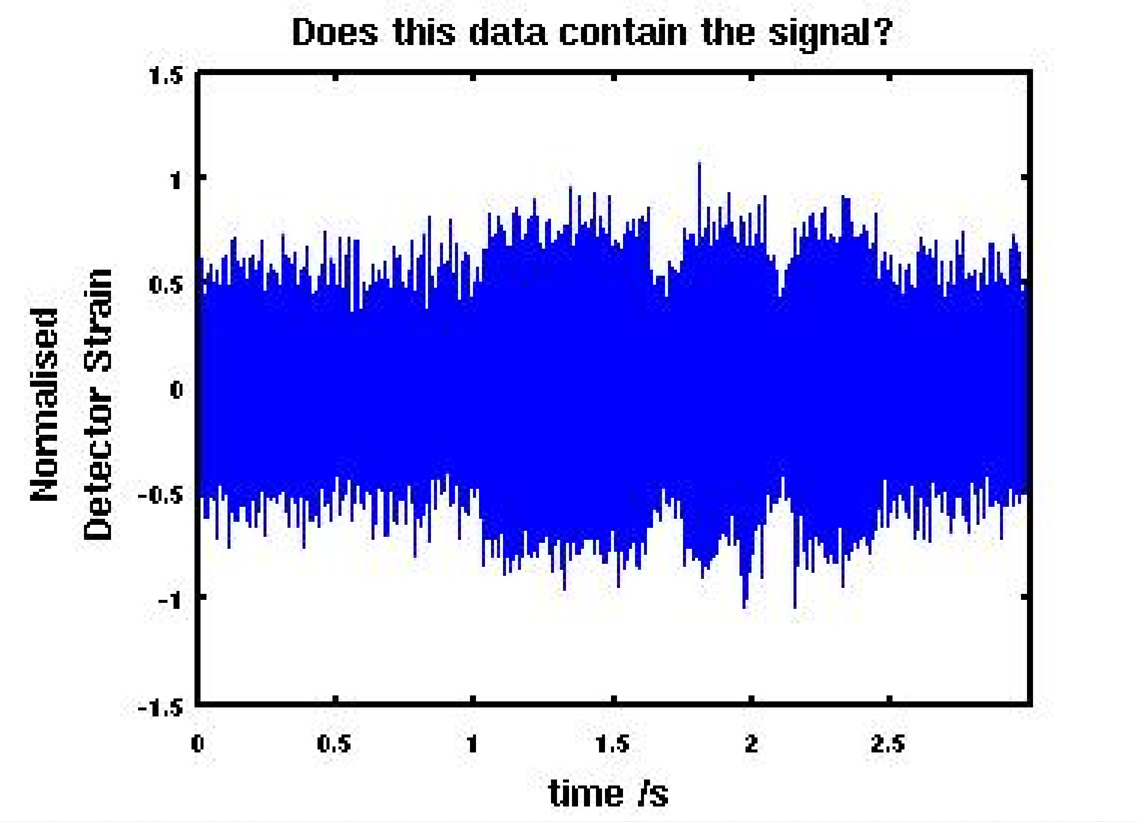


- Electronics noise
  - Challenge for the electronicians to measure down to 0.1 nW/sqrt(Hz)
- Non-linear noise from diffuse light
  - Need dedicated optical elements with specific mechanical modes

# History of Virgo noise curve



# Noises are not always stationary...



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

**➔ Now it is time to play with the data analysis !**