The Virgo detector

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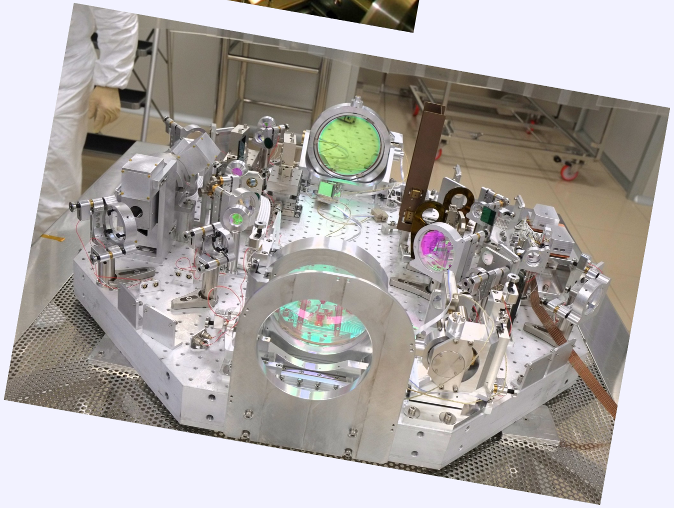

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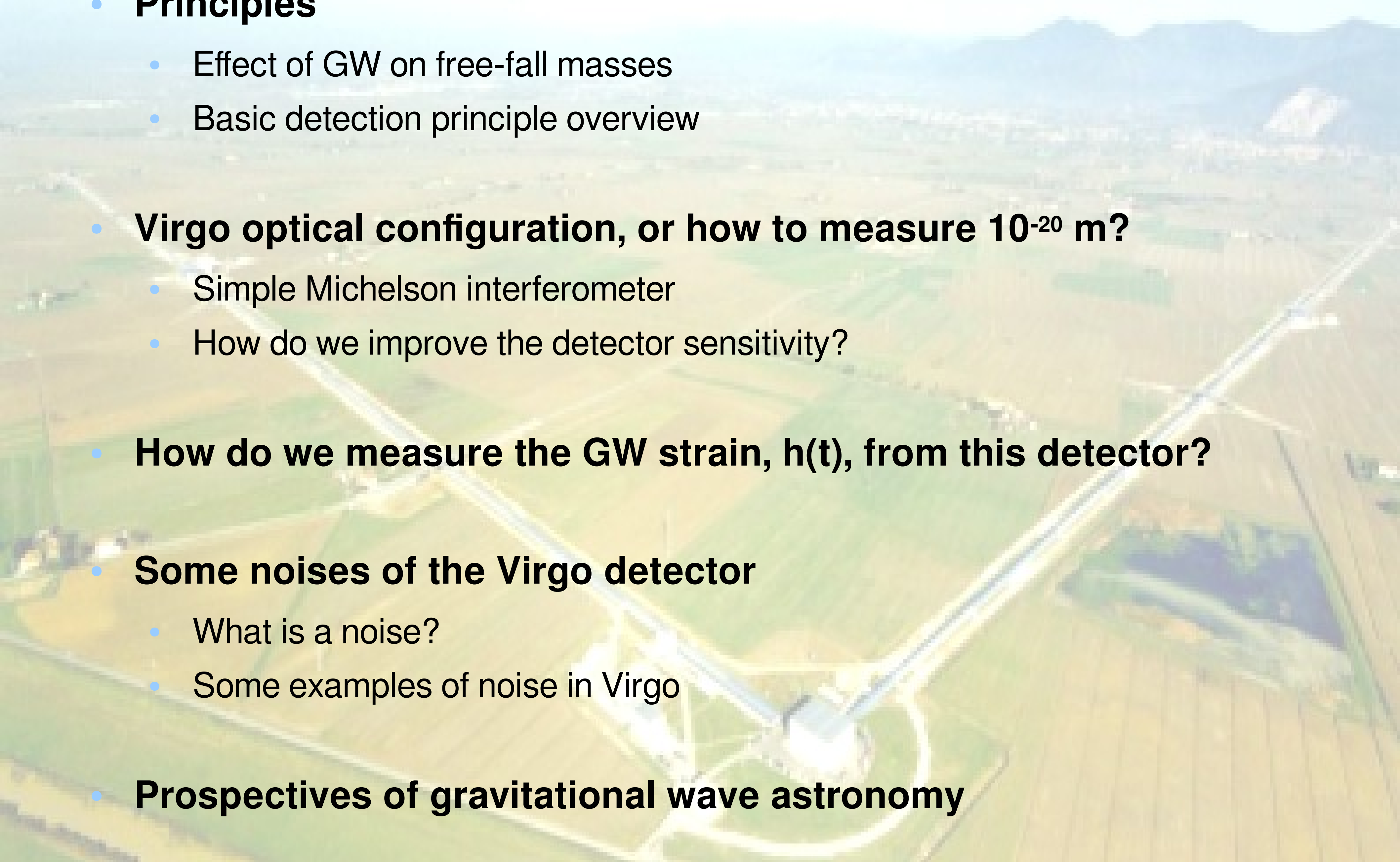
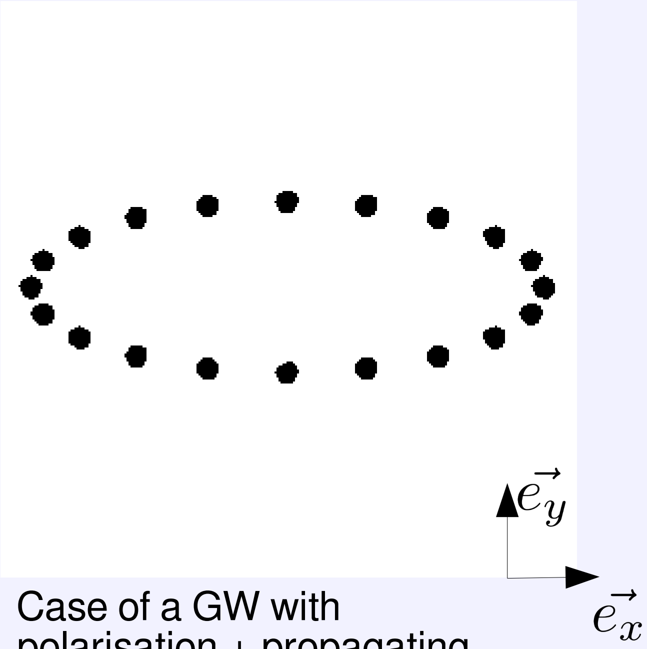


Reminder: effect of a GW on free masses

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



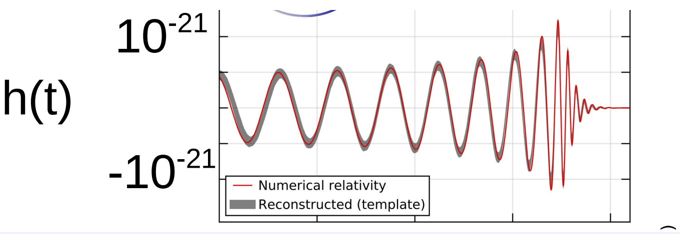
Case of a GW with polarisation + propagating along z

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

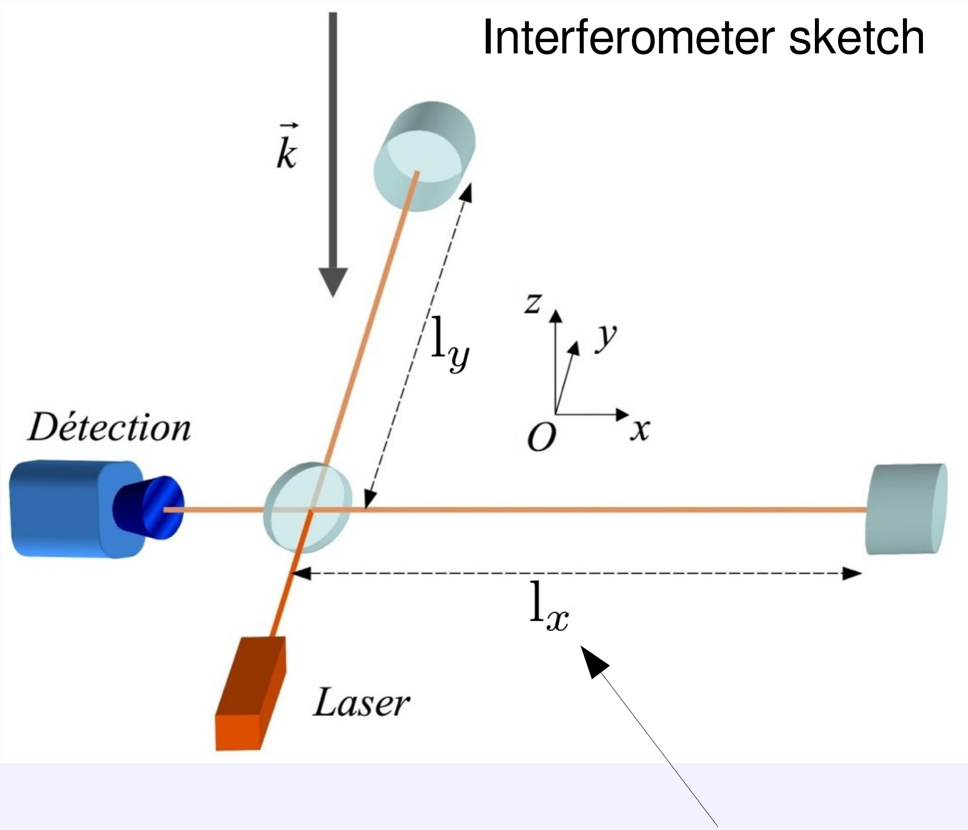
h(t): amplitude of the GW

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

Reconstructed strain of GW150914



A general overview of the Virgo detector



The interference pattern depends on ΔL:

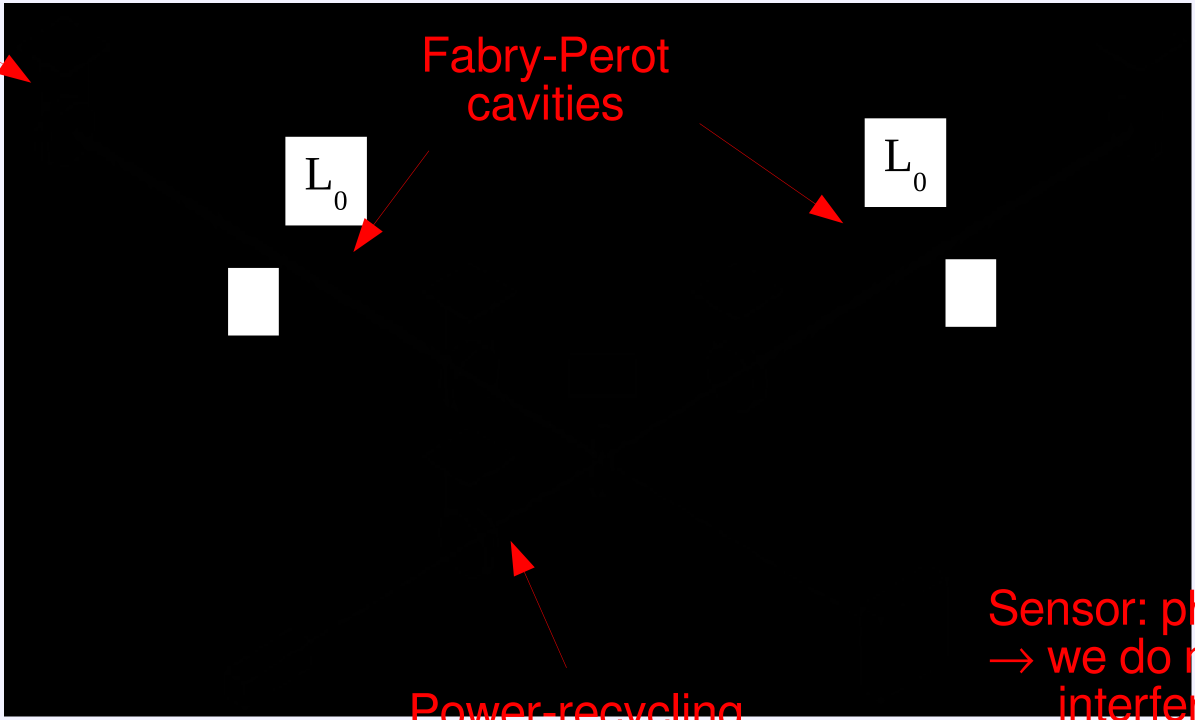
$$\Delta L(t) = \ l_{x(}t) - l_y(t)$$

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

Virgo: a more complicated interferometer

Suspended mirrors

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



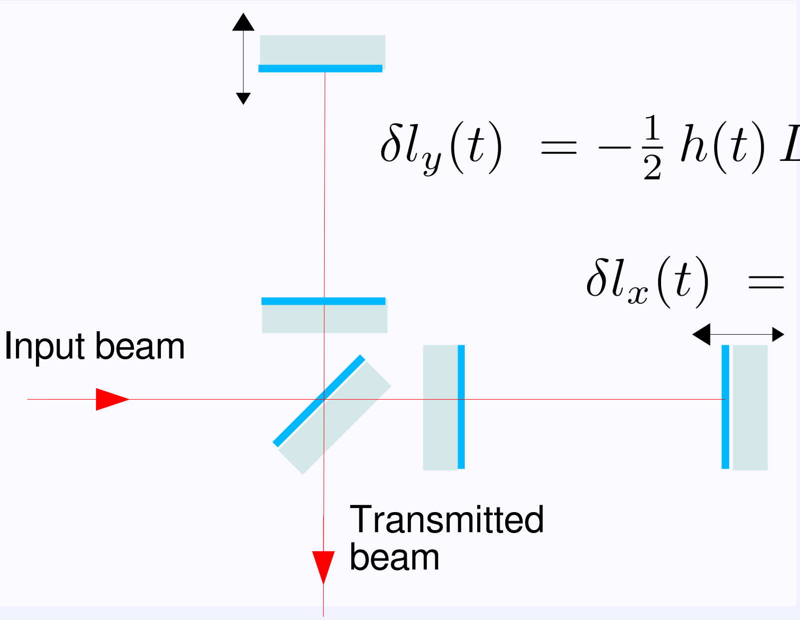
Fabry-Perot cavities

Power-recycling cavity

Infrared 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:

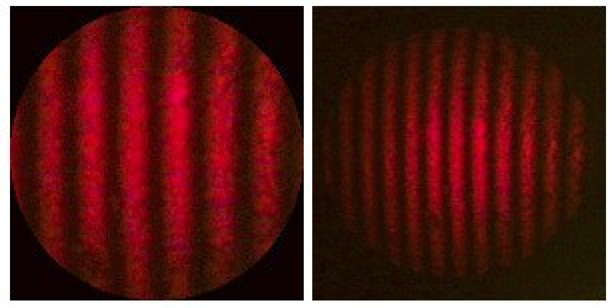
$$\begin{aligned}\delta\Delta L &= \delta l_x(t)-\delta l_y(t)\\ &= h(t)\,L_0\end{aligned}$$

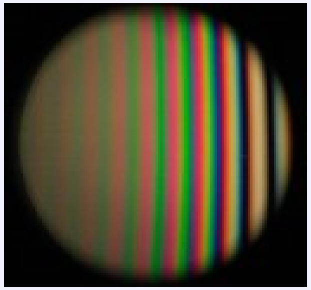
$$\mathrm{h}\sim 10^{-23} \qquad L_0 = 3\,\mathrm{km}$$

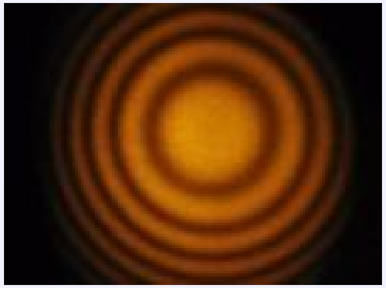
$$\rightarrow\ \delta\Delta L \sim 3\times 10^{-20}\,\mathrm{m}$$

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

How and for what did you use interferometers?

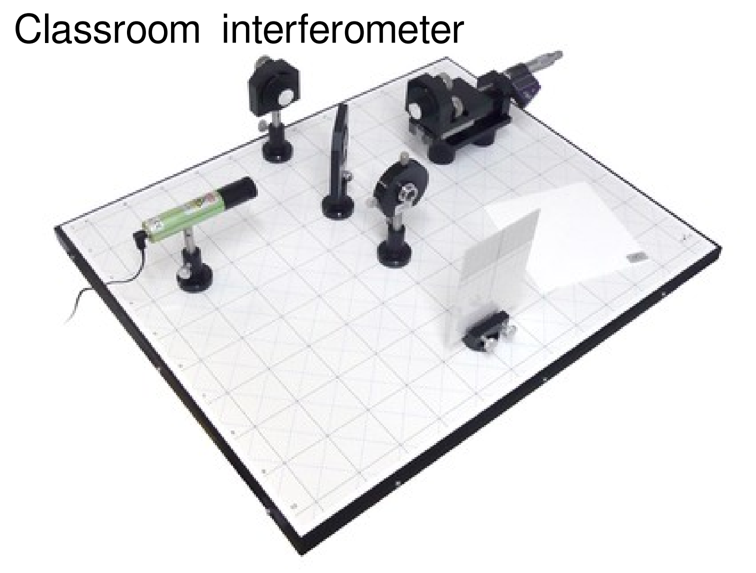






Wavelength of monochromatic source

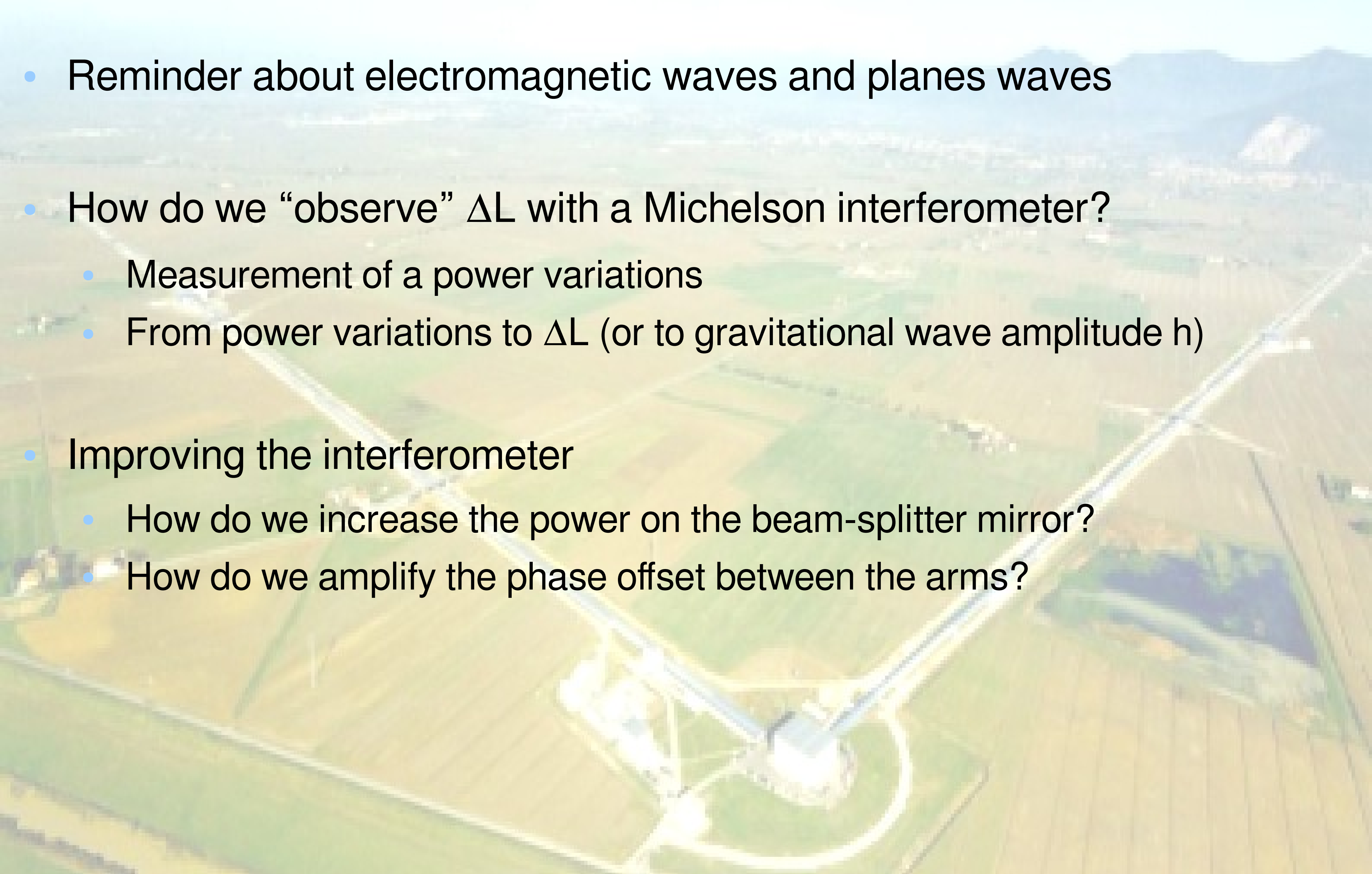
Sodium doublet wavelength separation



Classroom interferometer

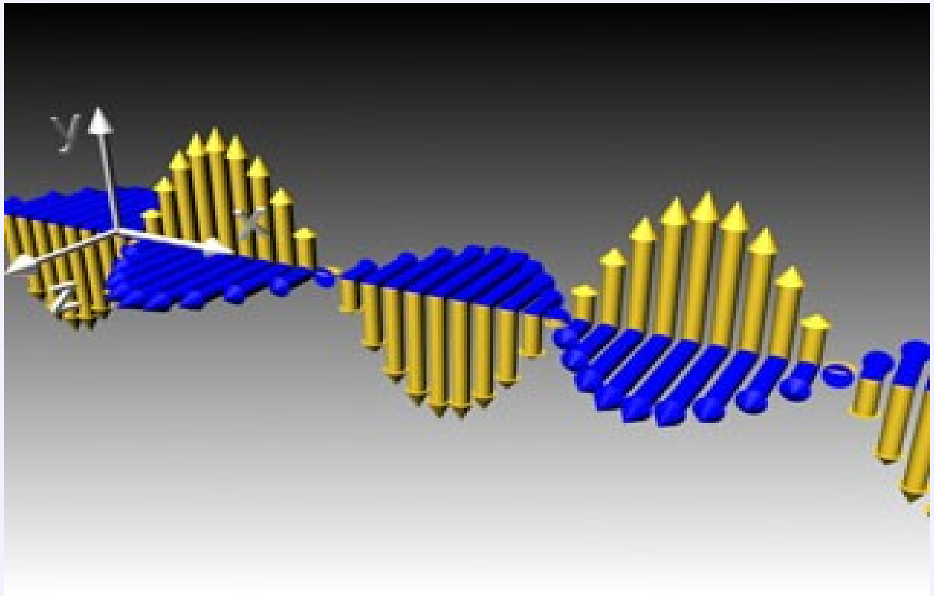
Virgo interferometer
Pisa, Italy

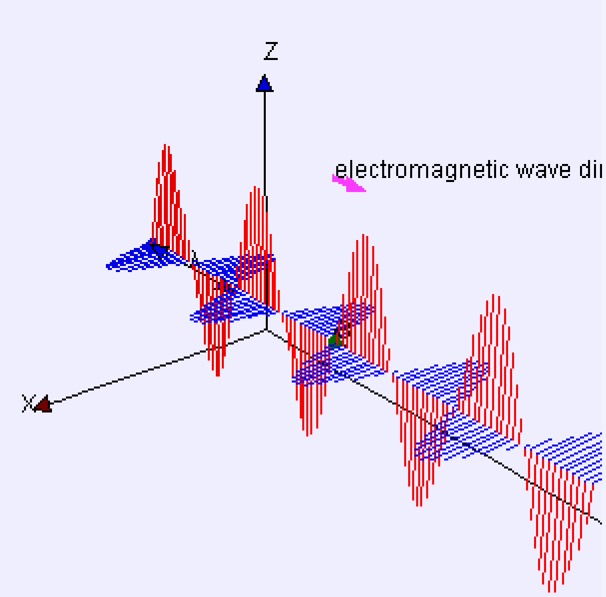
Part 2: Virgo optical configuration



- 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 polarisations: defined by the direction of E (or B)

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

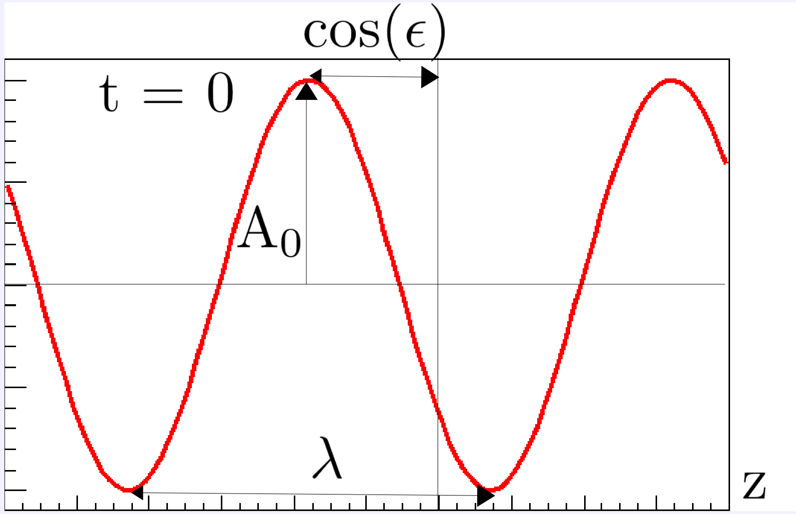
Description of plane waves

- Plane wave propagating along z, with speed c

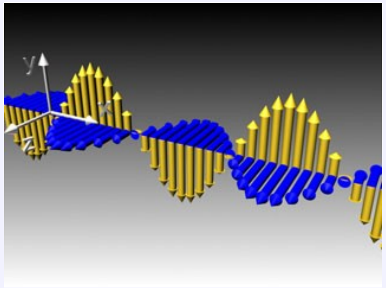
$$A(z,t) = A_0 \cos(kz - \omega t + \epsilon) \qquad (\text{since } \vec{k}\vec{r} = k\, z)$$

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

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



- Complex form



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

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

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

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

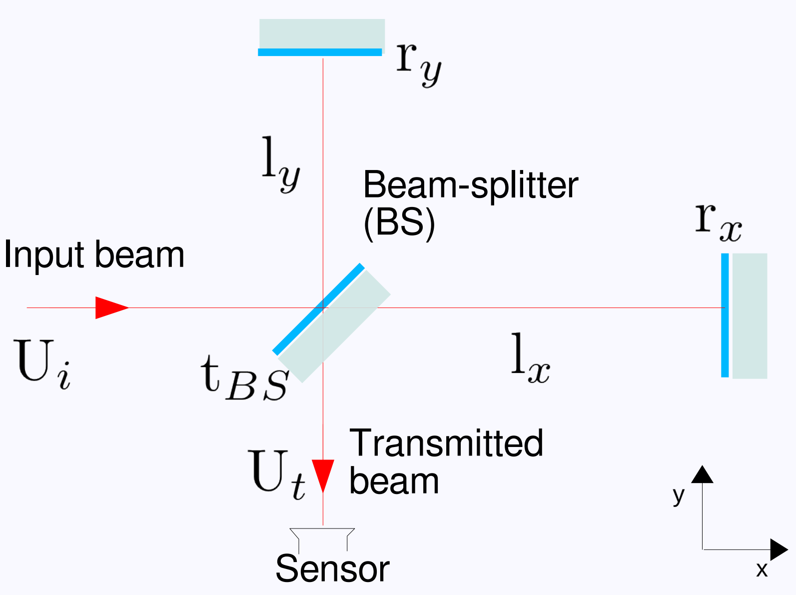
- Plane waves do not exist but they are a good approximation of many waves in localised region of space

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 ~ few cm

→ The beam can be approximated by plane waves

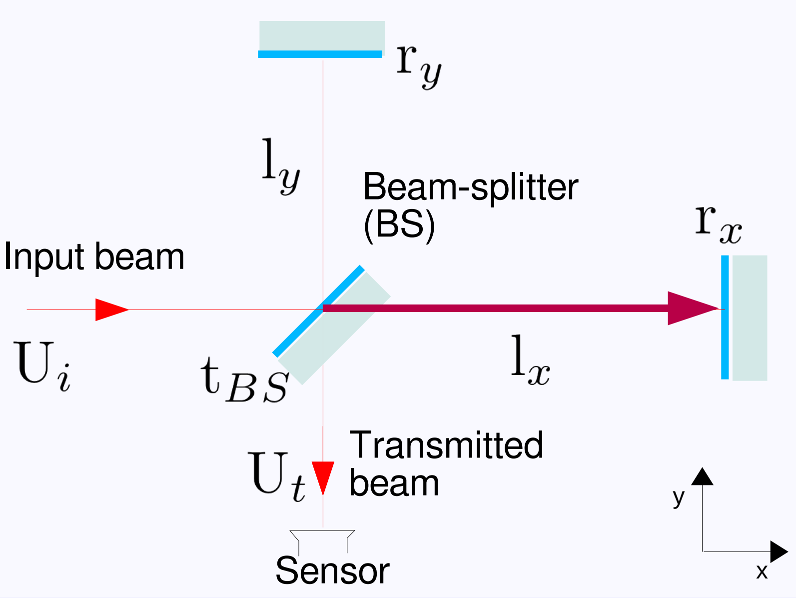
How do we “observe” ΔL with a Michelson interferometer?

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

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

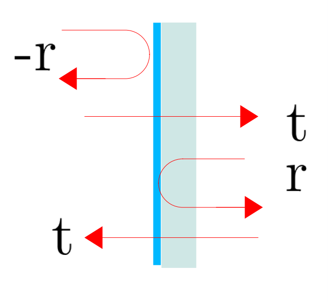
- Beam propagating along x-arm:

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



Sign convention for amplitude reflection and transmission coefficients

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



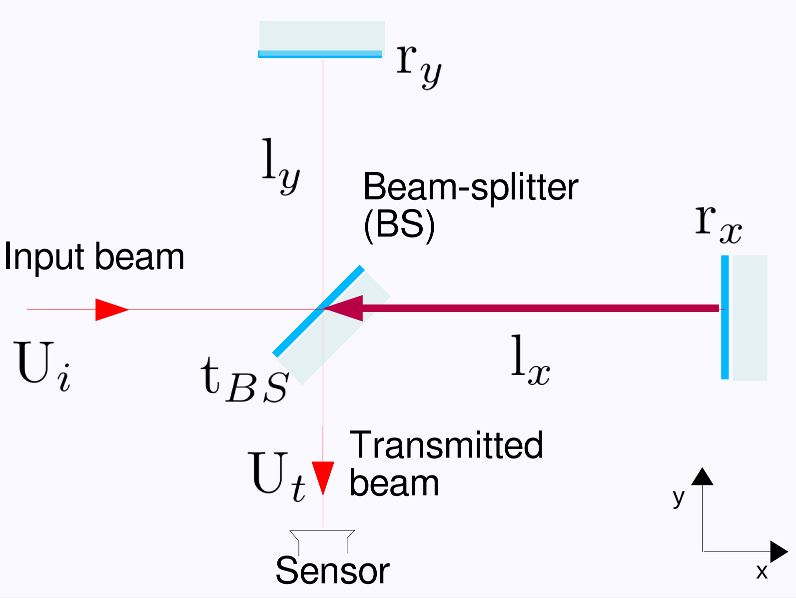
How do we “observe” ΔL with a Michelson interferometer?

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

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

- Beam propagating along x-arm:

$$U_{tx} = \underline{\mathcal{A}_i}\, t_{BS}\, e^{\mathrm{J}kl_x} \quad (-r_x) e^{\mathrm{J}kl_x} \ldots\ldots$$



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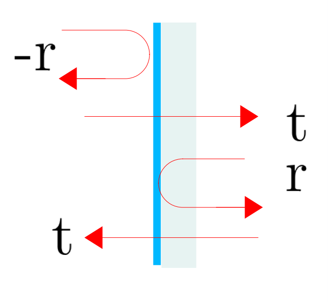

How do we "observe" ΔL with a Michelson interferometer?

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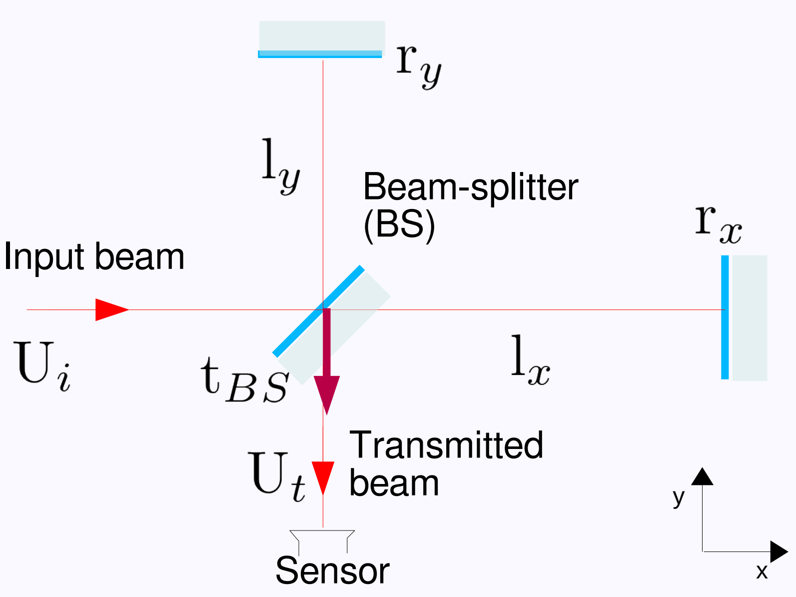
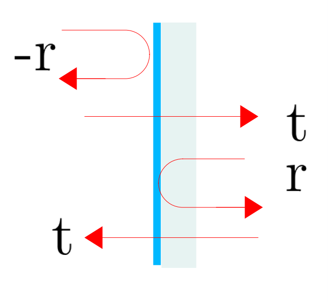
$$U_{tx} = \underline{A}_i \, t_{BS} \, e^{\jmath k l_x} \quad (-r_x) e^{\jmath k l_x} \quad r_{BS} \, e^{\jmath k y_s}$$



Sign convention for amplitude reflection and transmission coefficients



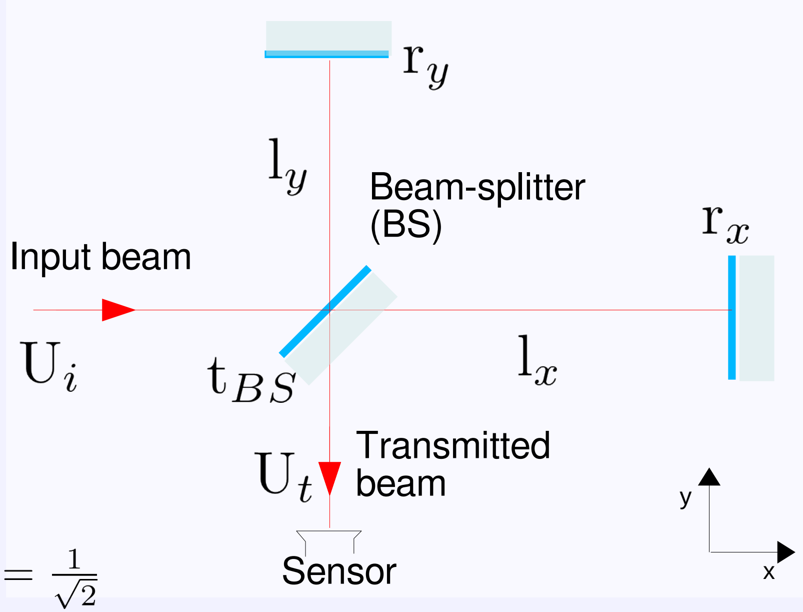
How do we “observe” ΔL with a Michelson interferometer?

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

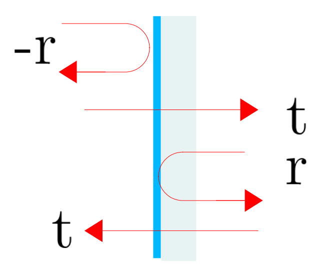
$$U_{tx} = \underline{\mathcal{A}}_i \, t_{BS} \, e^{\jmath k l_x} \quad (-r_x) e^{\jmath k l_x} \quad r_{BS} \, e^{\jmath k y_s}$$

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

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



Sign convention for amplitude reflection and transmission coefficients



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

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

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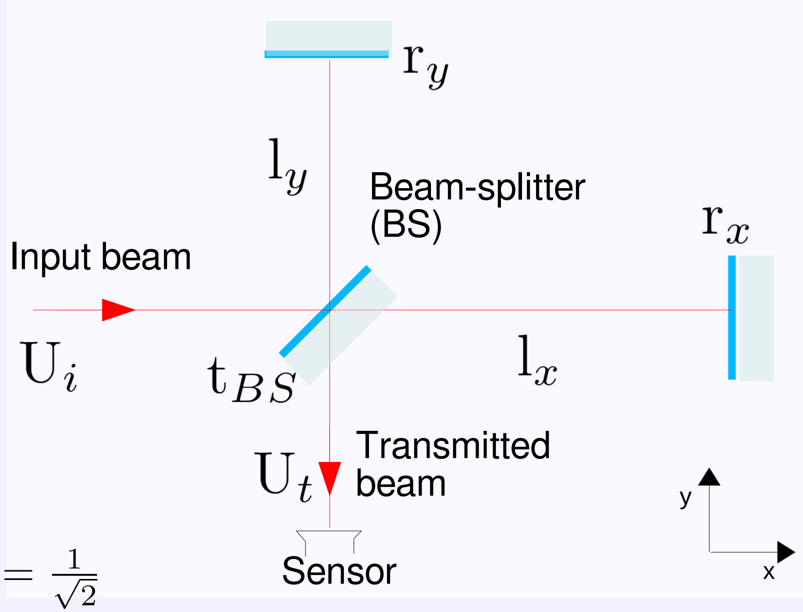


- Beam propagating along x-arm:

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

- Beam propagating along y-arm:

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

- Transmitted field:

$$\begin{aligned} U_t &= U_{tx} + U_{ty} \\ &= \frac{\underline{\mathcal{A}_i}}{2}\, e^{\jmath k y_s} \left(r_y\, e^{2\jmath k l_y} \;-\; r_x\, e^{2\jmath k l_x}\right) \end{aligned}$$

Power transmitted by a simple Michelson

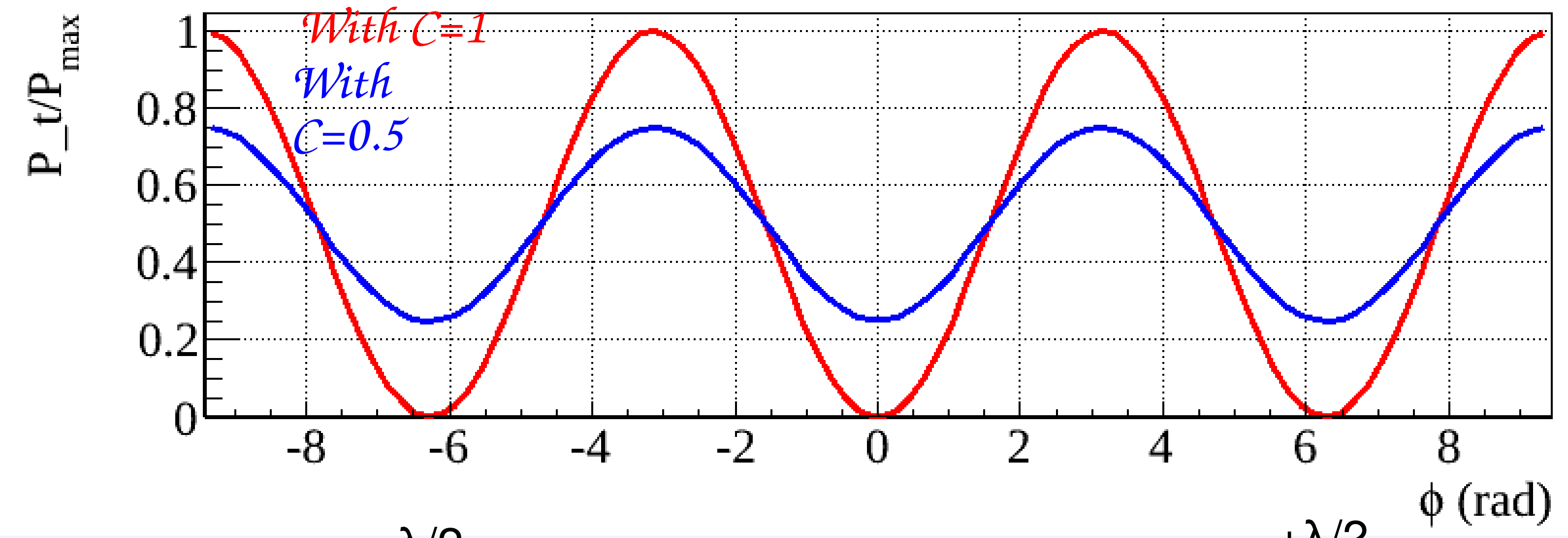
- Transmitted field: $U_t = \frac{\mathcal{A}_i}{2} e^{\jmath k y_s} \left(r_y \, e^{2\jmath k l_y} - r_x \, e^{2\jmath k l_x}\right)$

- Calculation of the transmitted power:

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

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

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



-λ/2 +λ/2

What power does Virgo measure?

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

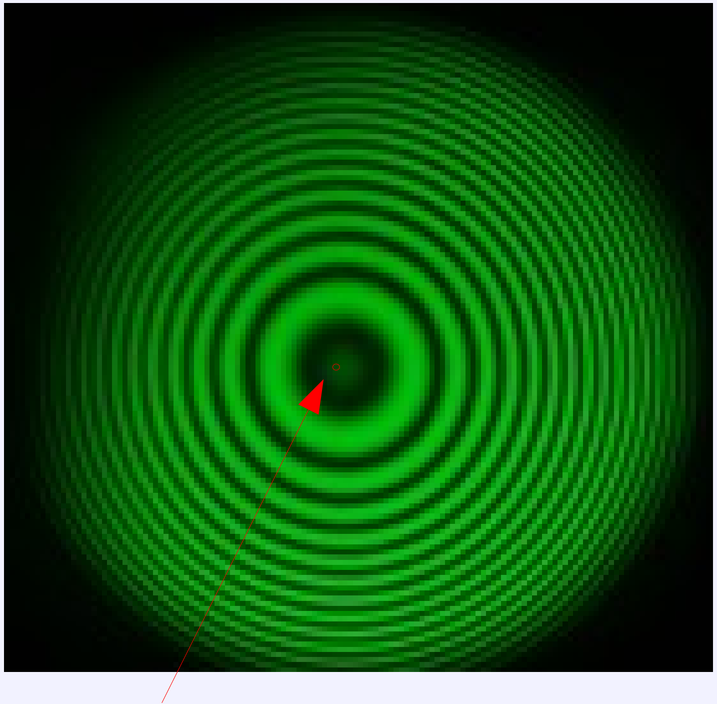
  → interference pattern

  (and the complementary pattern in reflection)

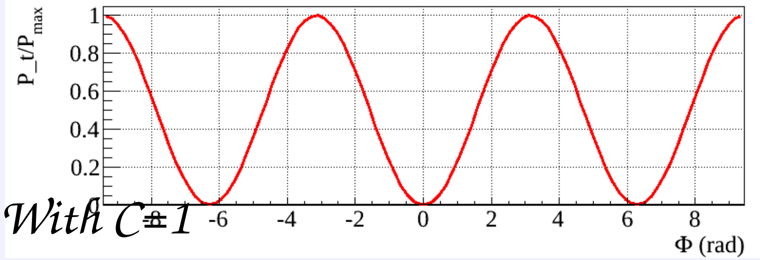
- Virgo interference pattern much larger than the beam size:

  ~1 m between two consecutive fringes

  → we do not study the fringes in nice images !



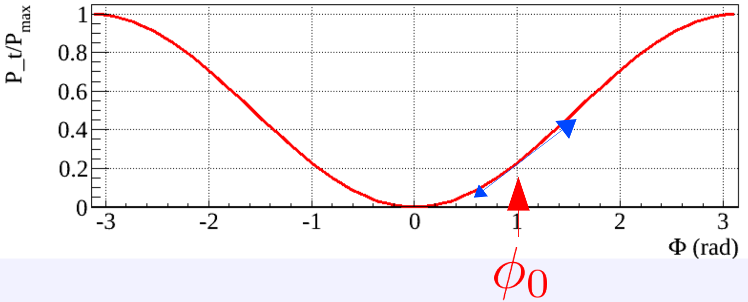
Equivalent size of Virgo beam



With $C=1$

Arm length regularly increasing

Setting a working point →



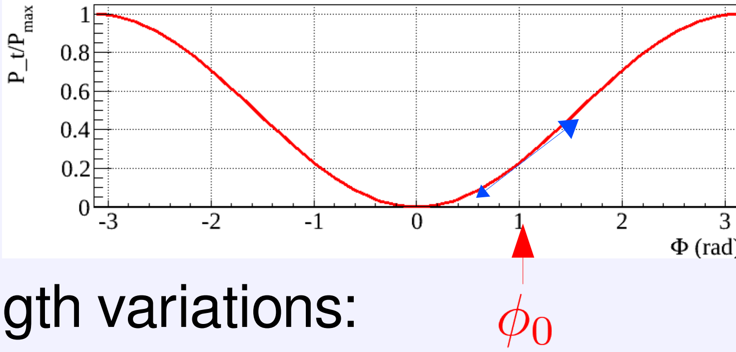
Controlled mirror positions

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:

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

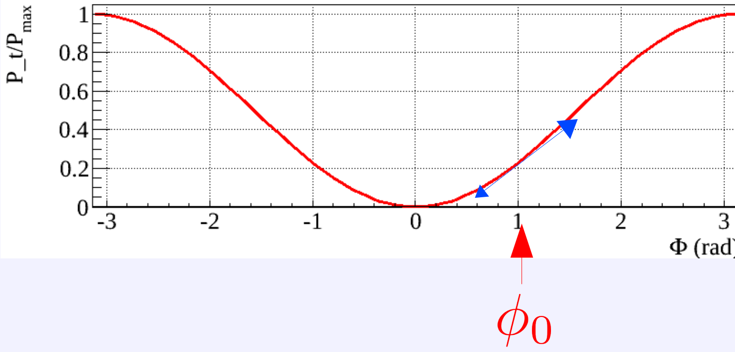
$$\delta P_t = P_i\,C\,\frac{2\pi}{\lambda}\sin\left(\frac{4\pi}{\lambda}\Delta L_0\right)\delta\Delta L$$

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

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

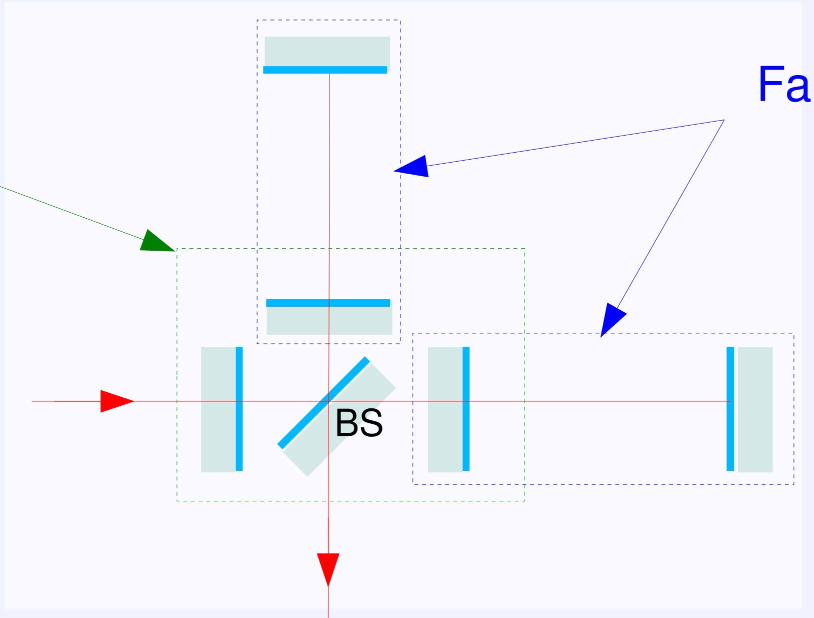
$$\delta P_t = P_i\, C\, \sin\left(\frac{4\pi}{\lambda}\Delta L_0\right) \underbrace{\left(k\,\delta\Delta L\right)}_{\propto\,\delta\phi}$$

Increase the input power on BS

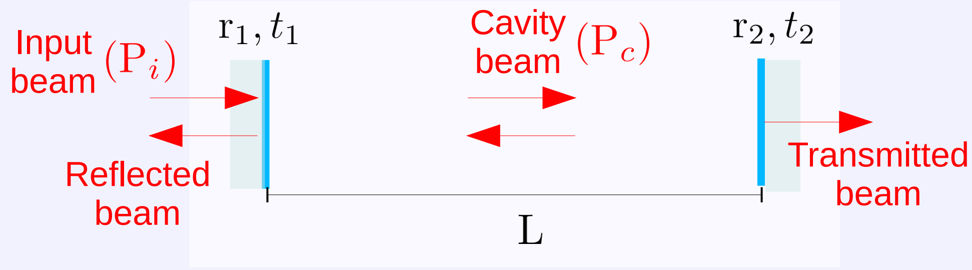
Increase the phase difference between the arms for a given differential arm length variation

Recycling **cavity**

Fabry-Perot **cavities** in the arms

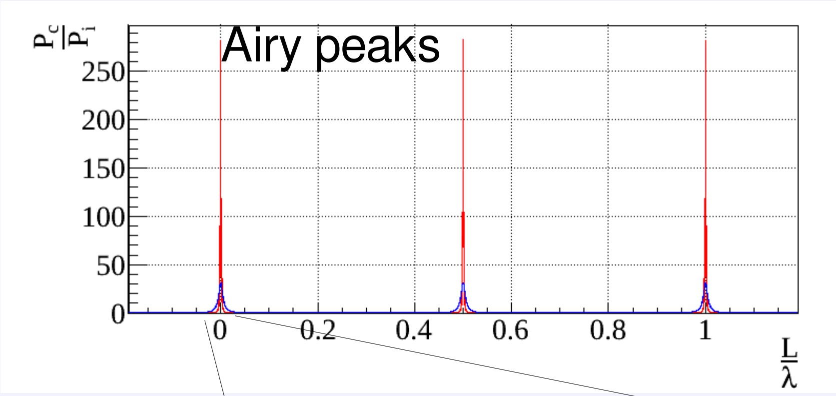


In Virgo, the beam is resonant inside the cavities

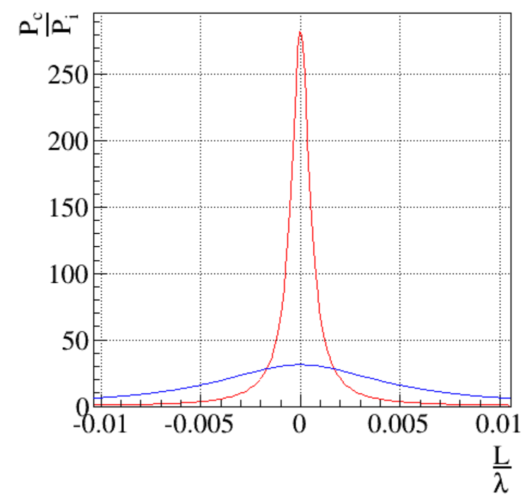


$$P_c = P_i \frac{t_1^2}{(1-r_1r_2)^2} \frac{1}{1+\left(\frac{2\mathcal{F}}{\pi}\right)^2 \sin^2(kL)}$$

$$\text{Finesse } \mathcal{F} = \frac{\pi\sqrt{r_1r_2}}{1-r_1r_2}$$



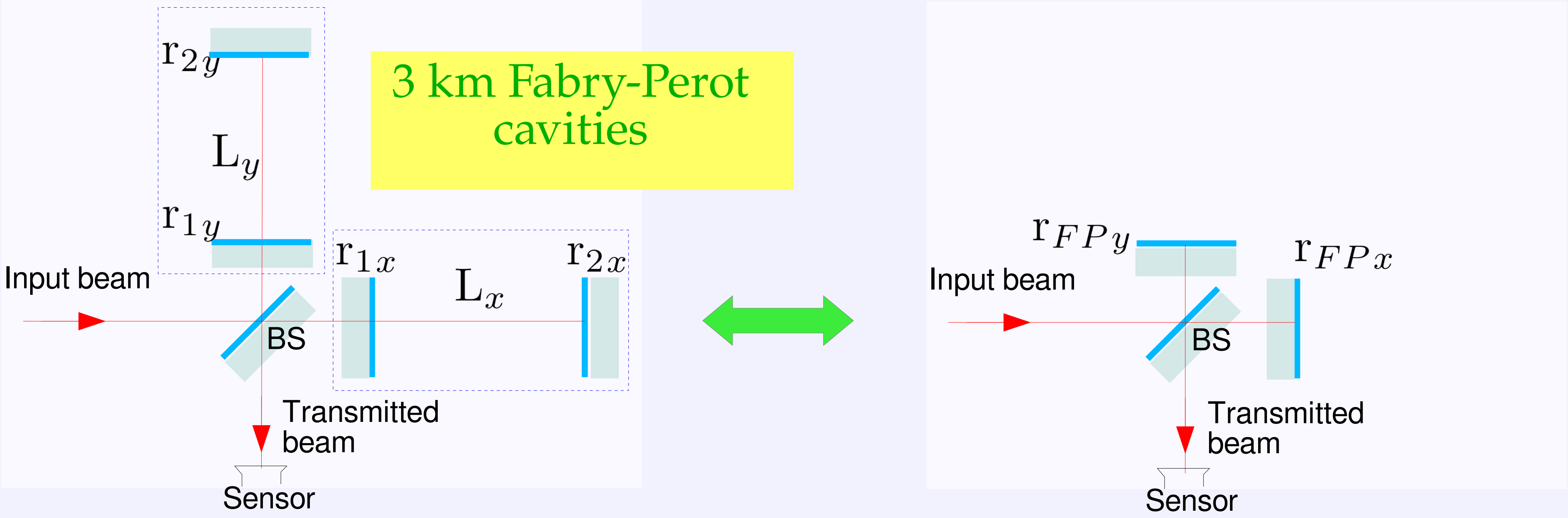
Virgo cavity at resonance: $L = n\frac{\lambda}{2} \quad (n \in \mathbb{N})$



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

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

How do we amplify the phase offset?



3 km Fabry-Perot cavities

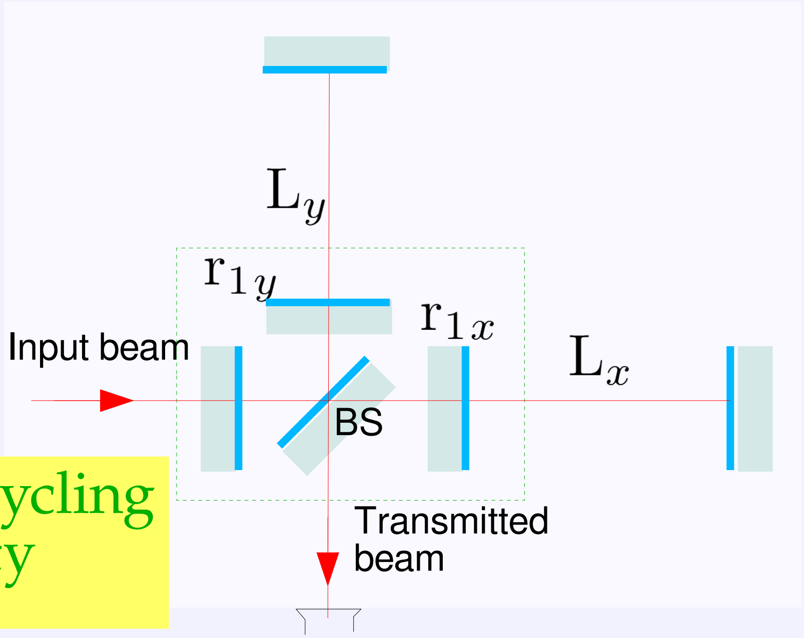
$$r_{FPx} = -1 \times e^{\jmath \frac{2\mathcal{F}}{\pi} 2\, k\, \delta L_x}$$

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

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

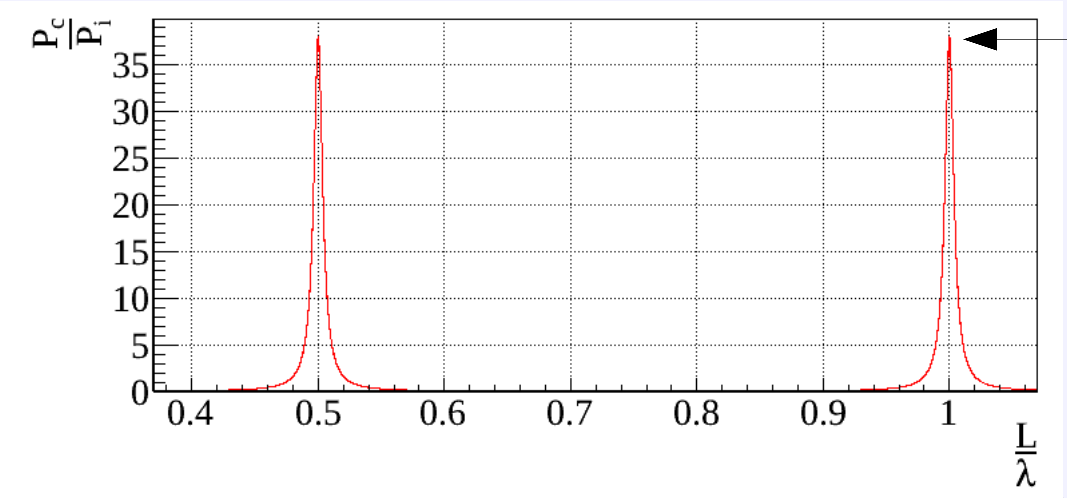
How do we increase the power on BS?

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



Power recycling cavity

Resonant power recycling cavity



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

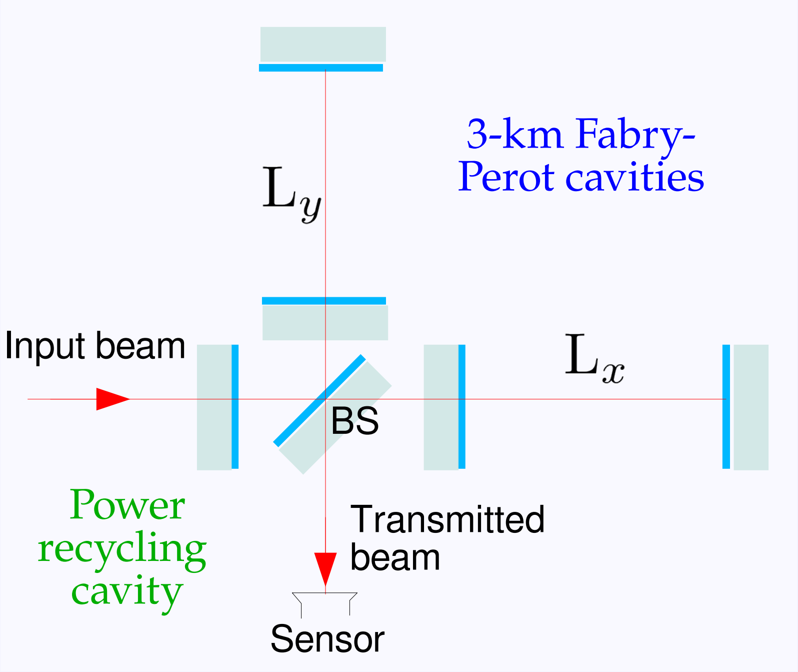
→ input power on BS increased by a factor 38!

The improved interferometer response

- **Response of simple Michelson:**

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

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

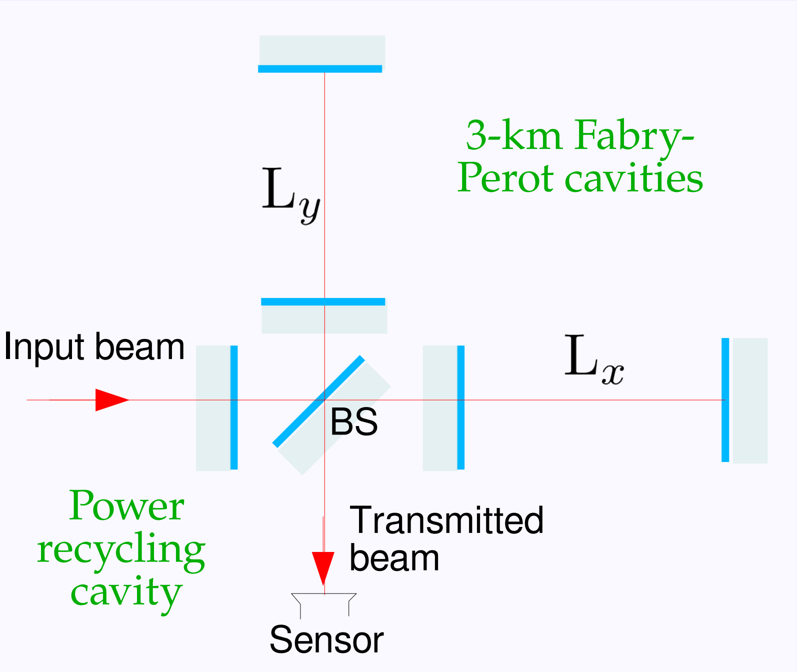


- **Response of recycled Michelson with Fabry-Perot cavities:**

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

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

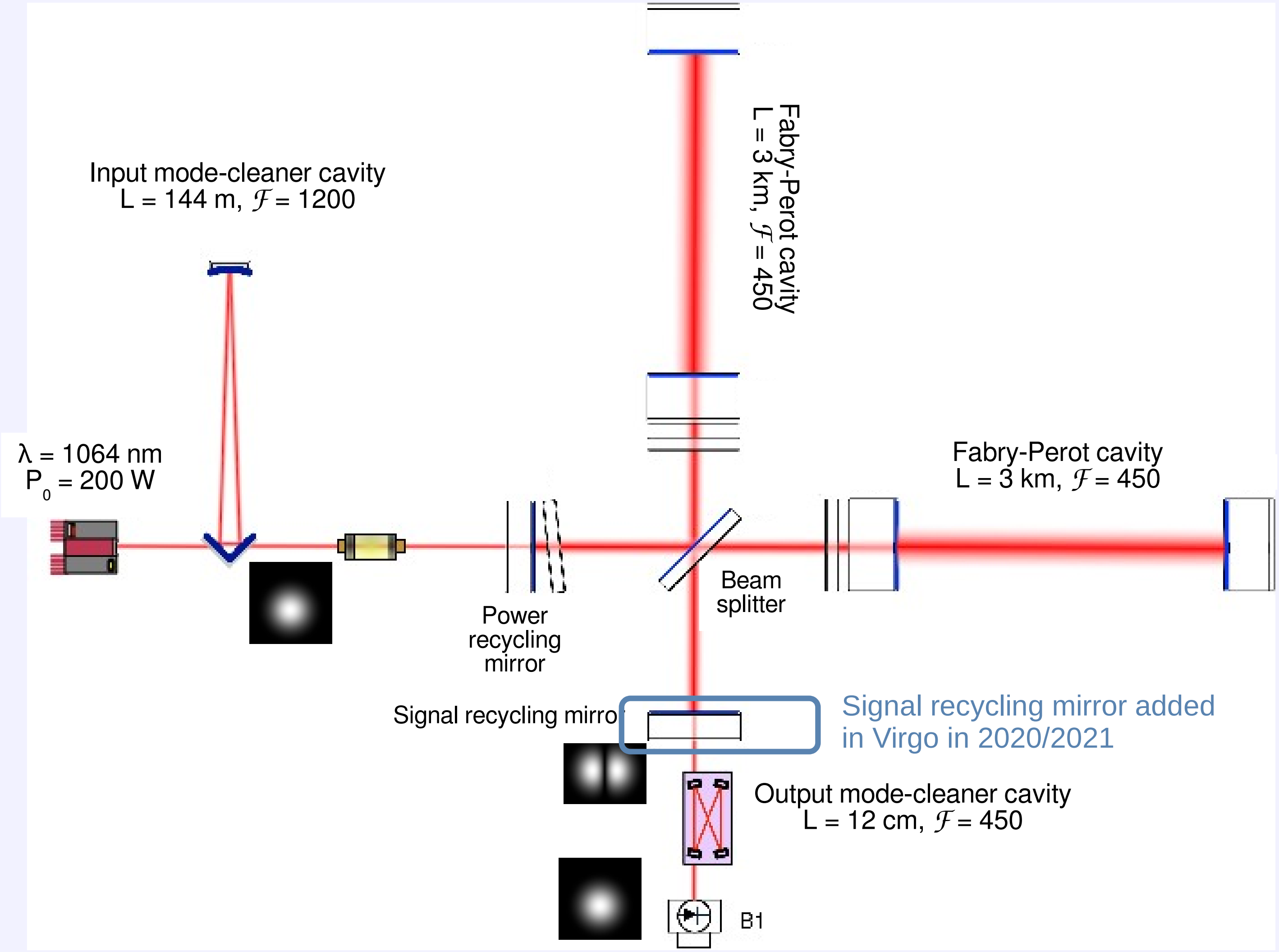
$\rightarrow \delta P_{t,min} \sim 0.1\,\text{nW}$ ⟶

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

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

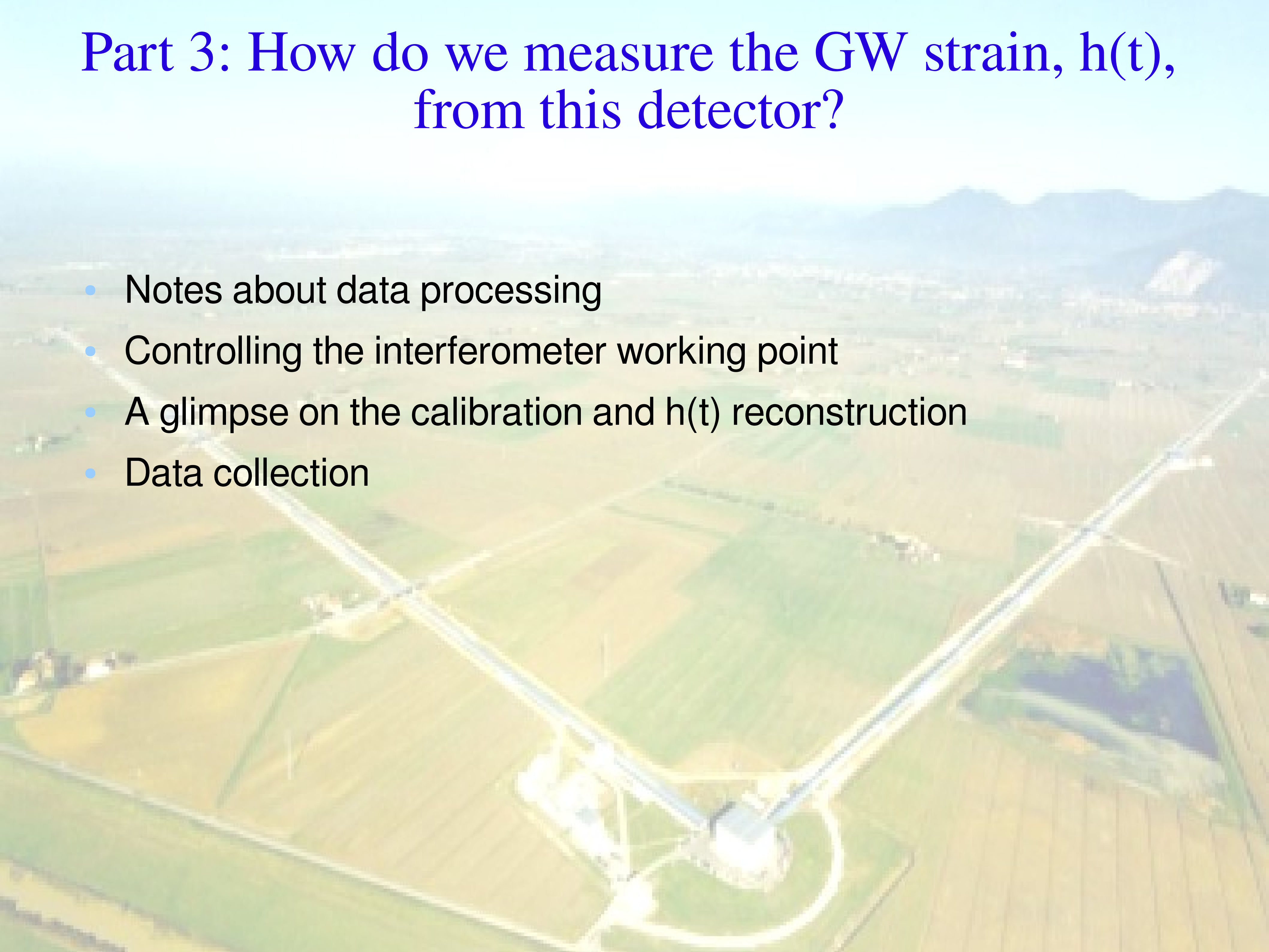
In reality, the detector response depends on frequency...

Optical layout of Virgo



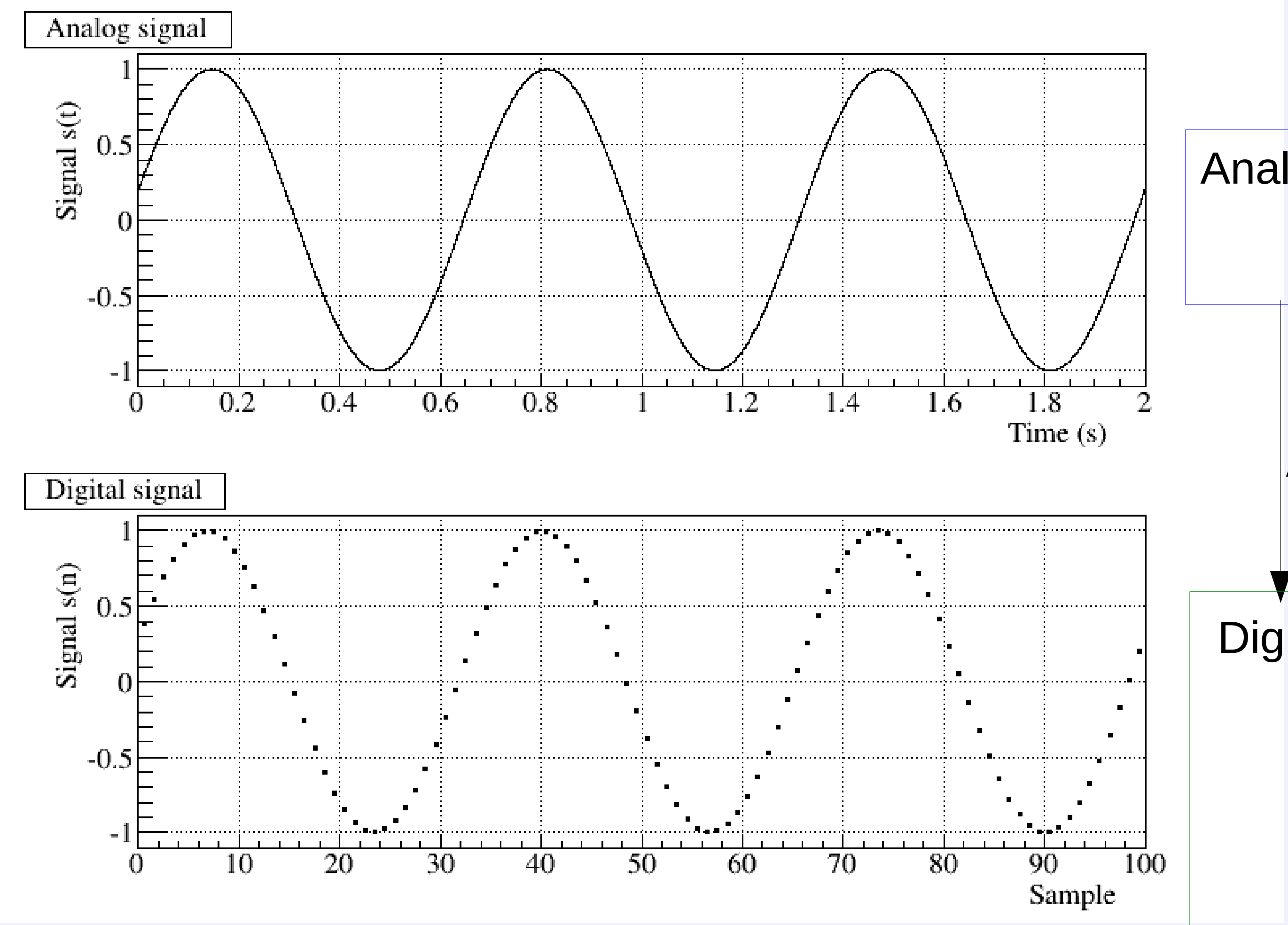
Signal recycling mirror added in Virgo in 2020/2021

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

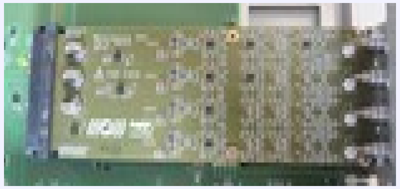


Analog signal s(t)

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

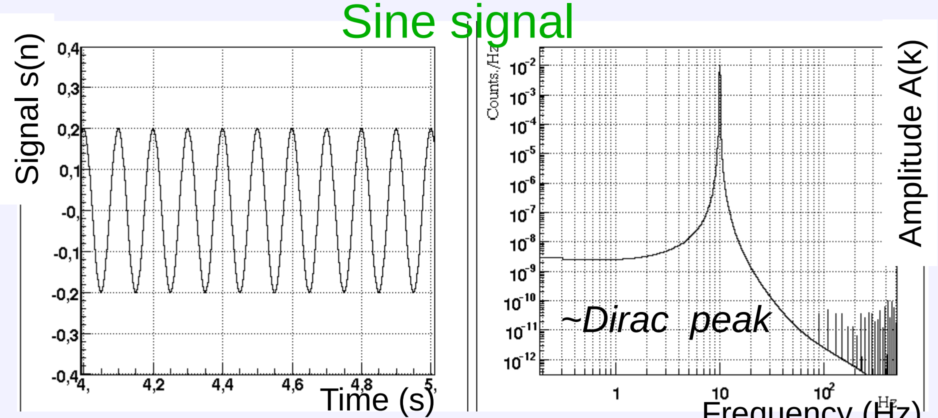
Notes about data processing: spectral analysis

A signal can be decomposed in different frequency components.

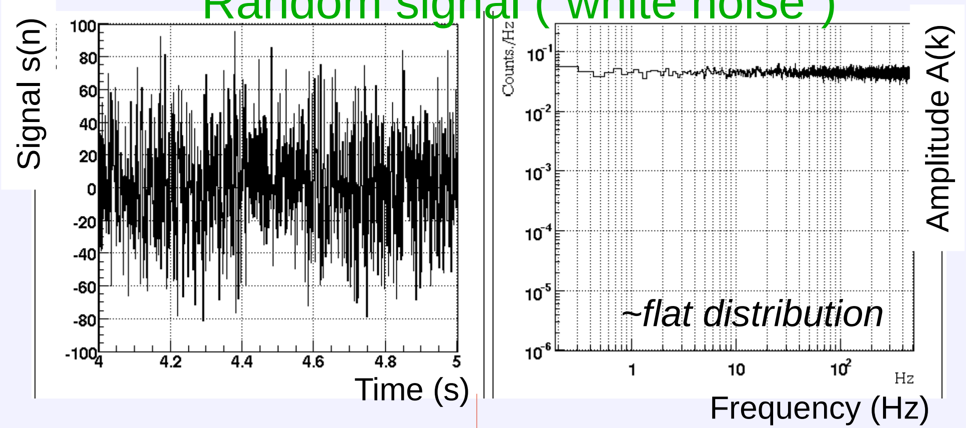
$$s(n) \underset{\textit{Inverse Fourier transform}}{\overset{\textit{(Discrete) Fourier transform}}{\rightleftarrows}} A(k) \text{ and } \Phi(k)$$

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

Sine signal

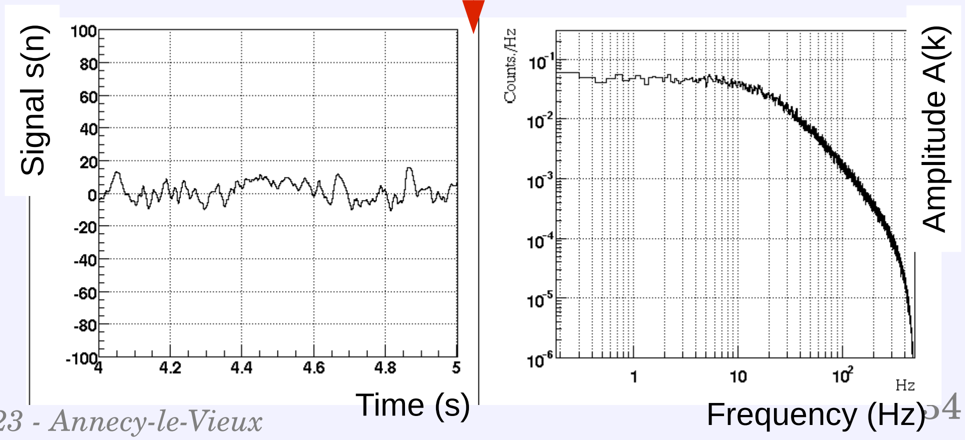


Random signal ("white noise")

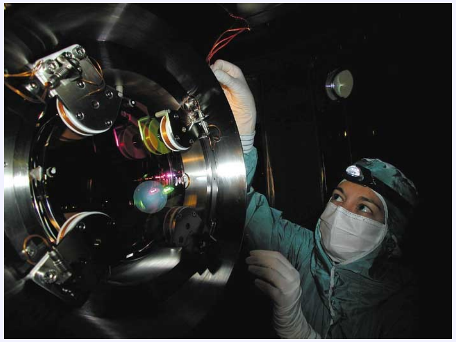


Apply a low-pass filter on the signal

Filtering the data
= modifying the frequency components



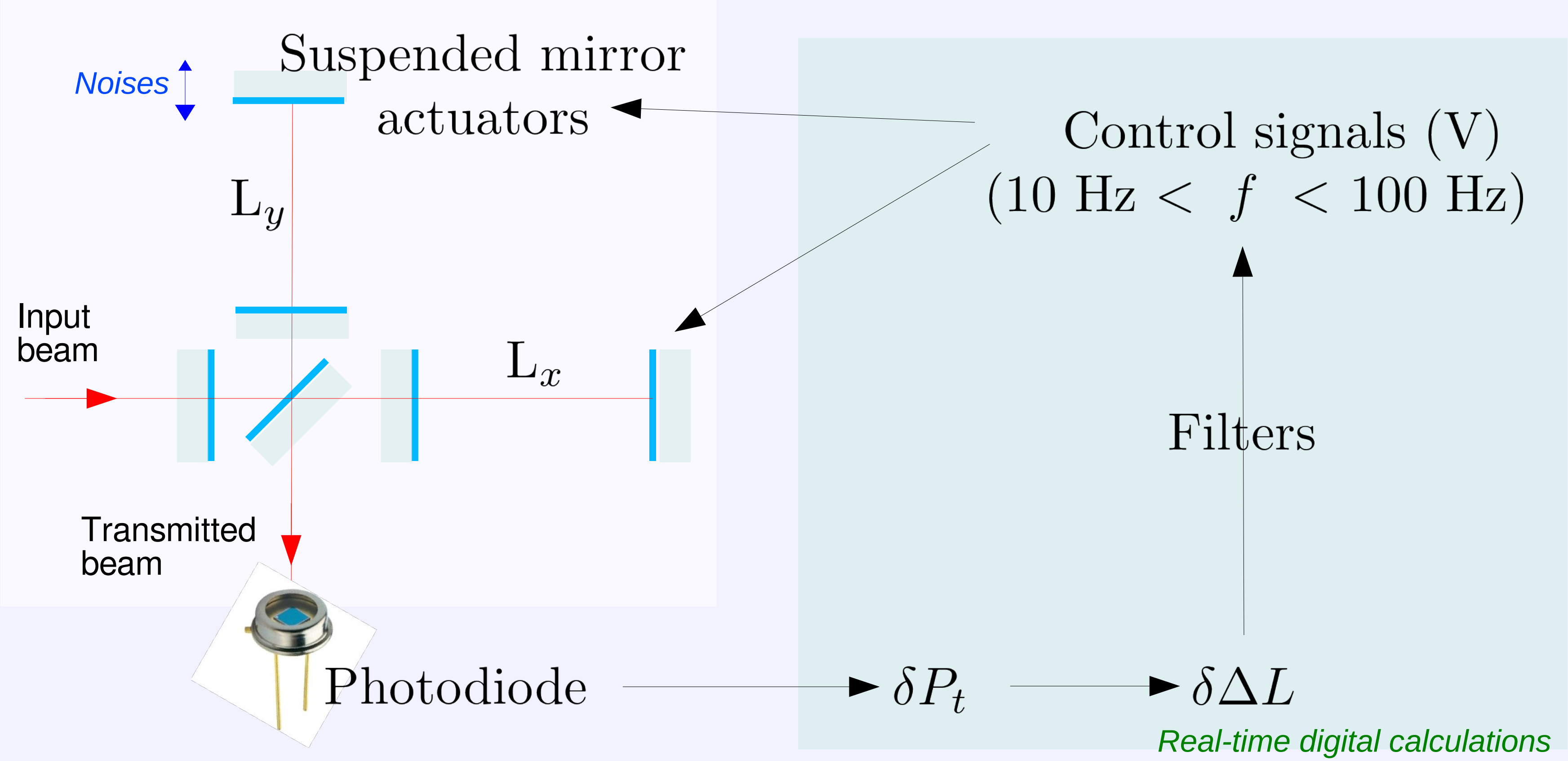
How do we control the working point?



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



Control signals (V)
$(10\ \mathrm{Hz} < f < 100\ \mathrm{Hz})$

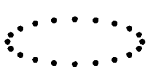
Filters

$\delta P_t \rightarrow \delta \Delta L$

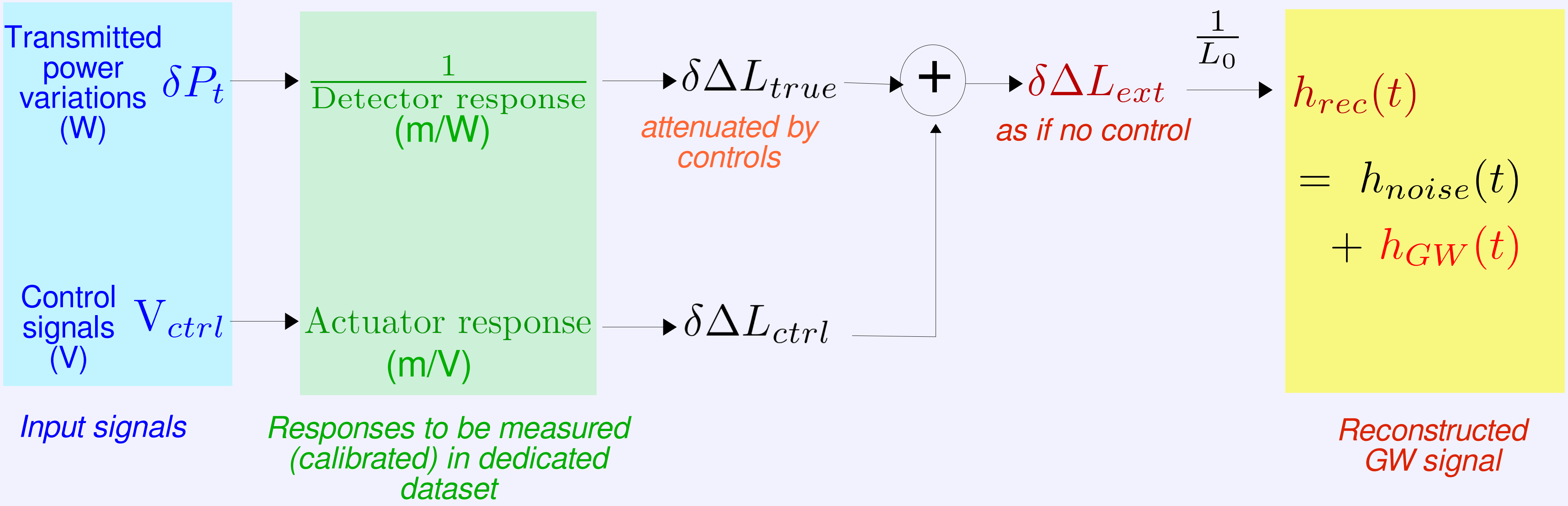
Real-time digital calculations

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)*

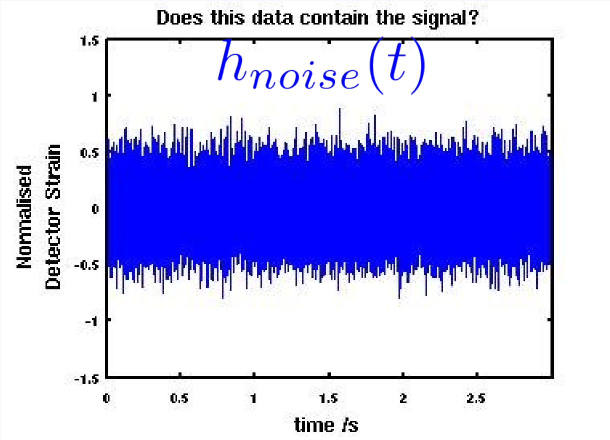


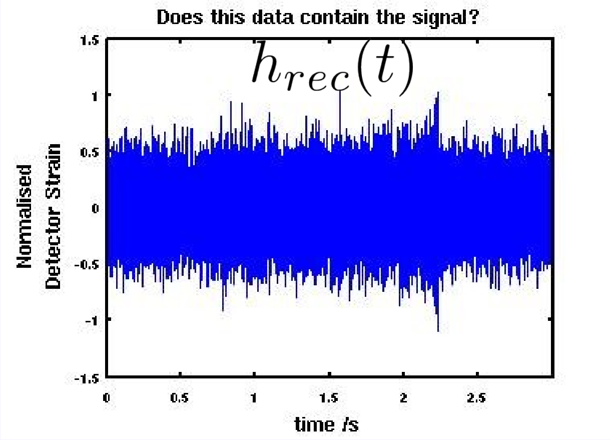
Part 4: Virgo noises

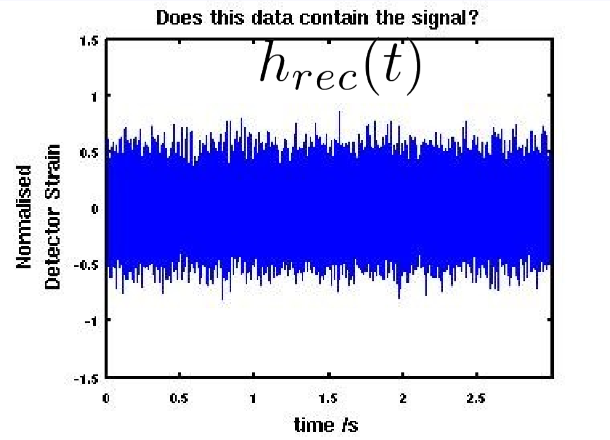
What is noise in Virgo?

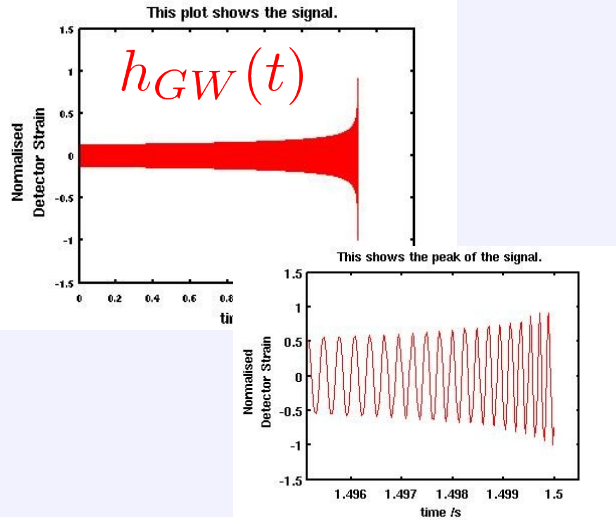
- Stochastic (random) signal that contributes to the signal $h_{rec}(t)$ but does not contain information on the gravitational wave strain $h_{GW}(t)$

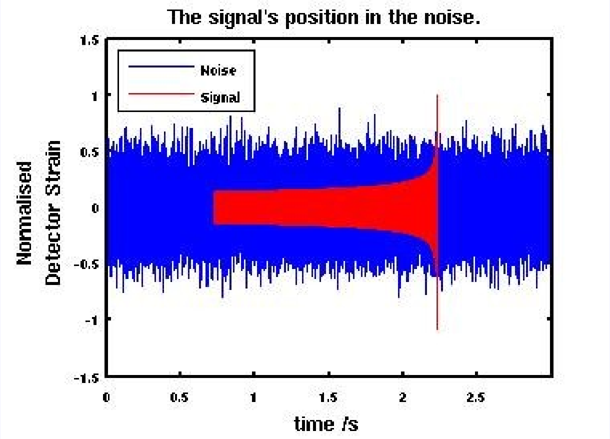
$$h_{rec}(t) = \color{blue}{h_{noise}(t)} + \color{red}{h_{GW}(t)}$$

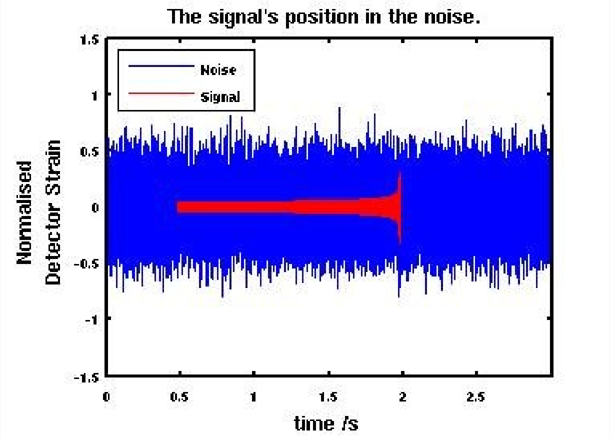










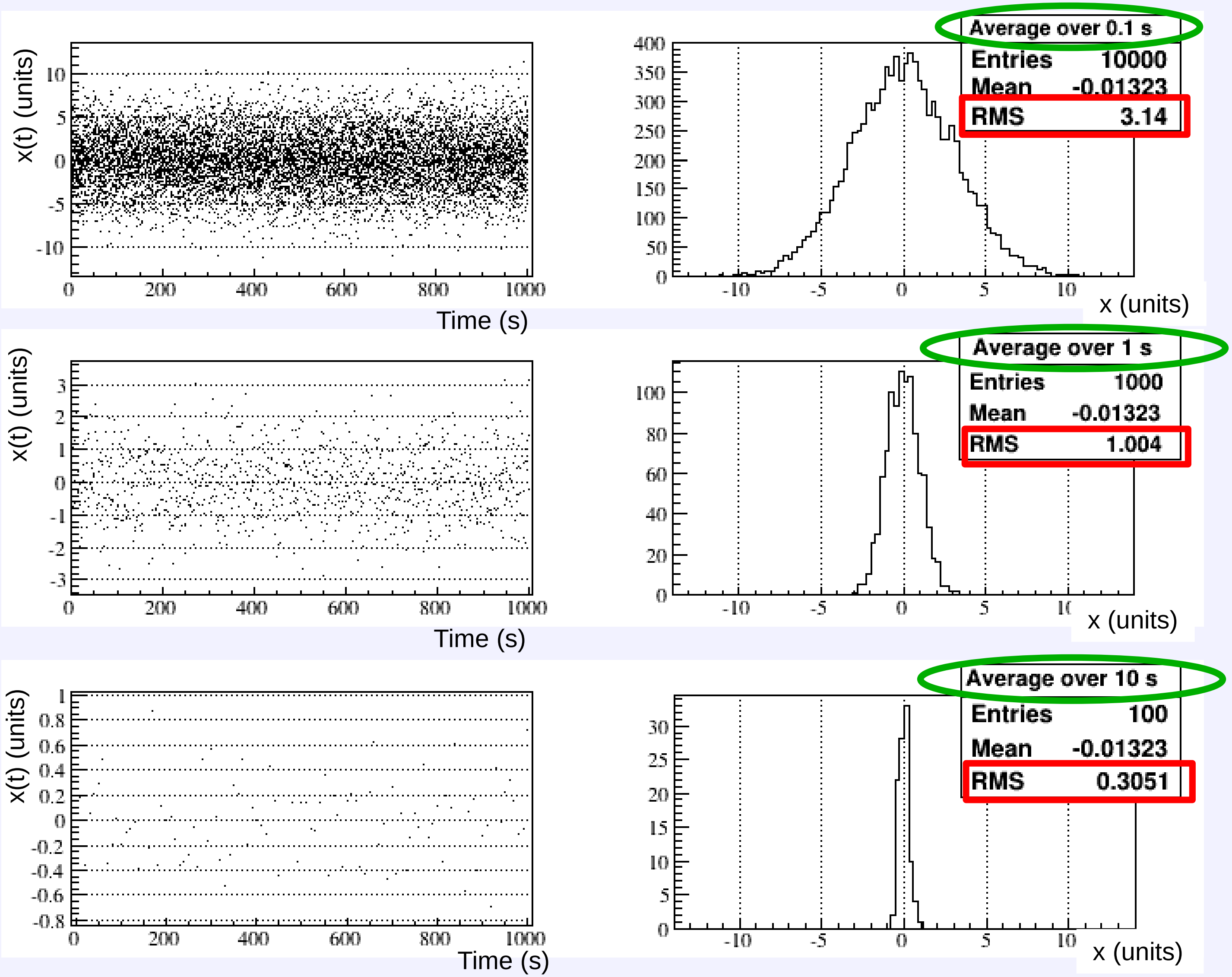


Extracted from Black Hole Hunter: http://www.blackholehunter.org/

How do we characterise noise?

Data points (noise)

Distribution of the data



Gaussian distribution:

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

→ Noise measurement characterised by its standard deviation σ_x

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

D is in $(\text{Data units} \times \sqrt{\text{s}})$ 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?

Discrete Fourier Transform (DFT)

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

Sampled signal

Fourier spectrum

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

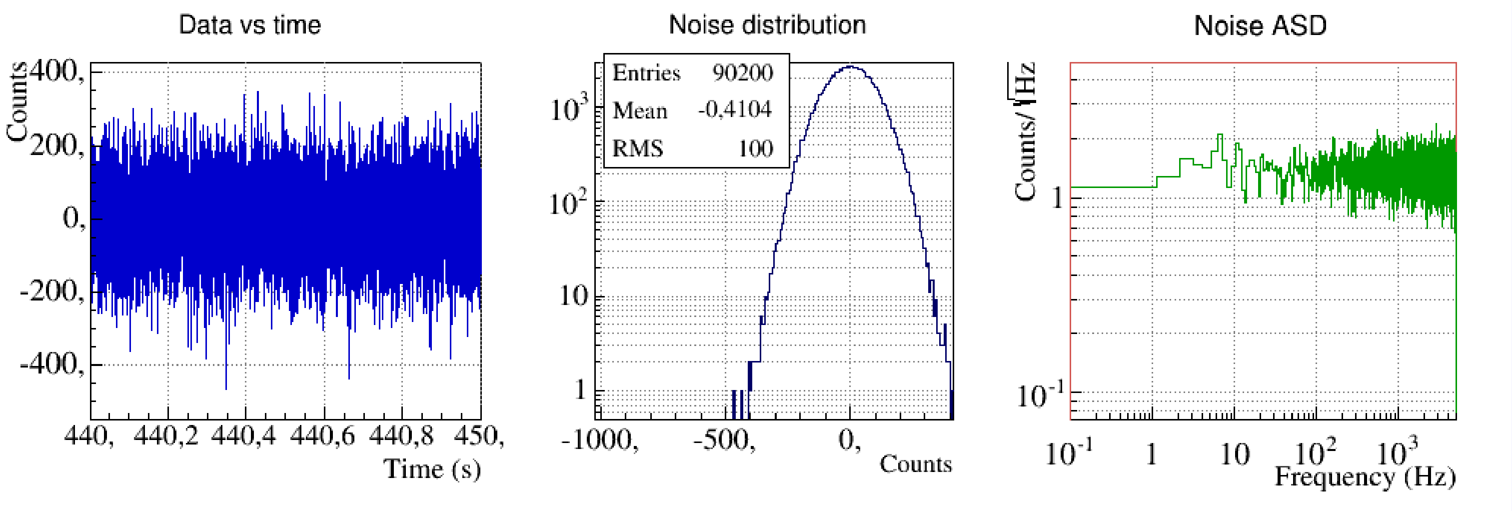
Assumption: noise is random and ergodic

→ noise characterised by its amplitude spectral density (ASD)

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

Random gaussian noise
1 count/√Hz

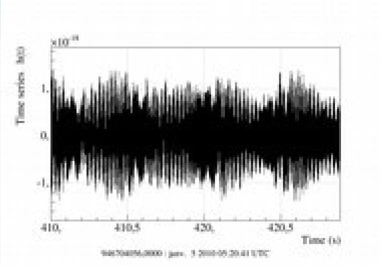
Sampled at 10 kHz



From $h_{rec}(t)$ to Virgo sensitivity curve

1/ Reconstruction of h(t)

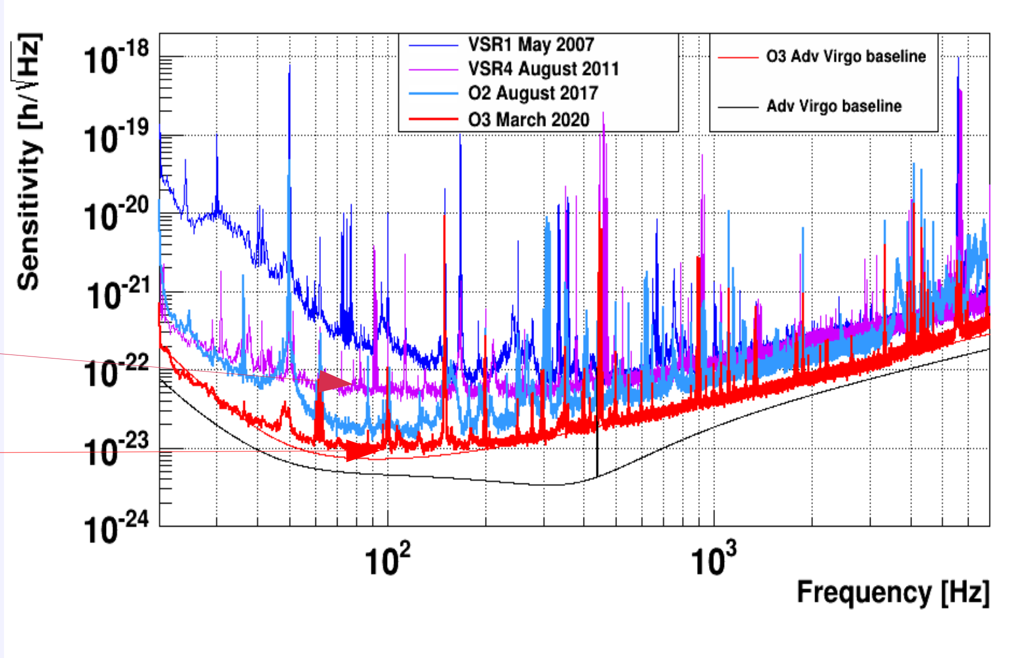
$$h_{rec}(t) = h_{noise}(t) + \cancel{h_{GW}(t)}$$



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

~10^{-19} m/√Hz (Virgo, 2011)

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



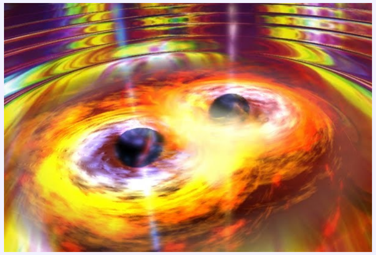


Image: Danna Berry/SkyWorks/NASA

Compact Binary Coalescences

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

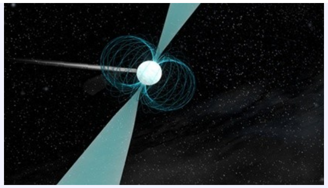
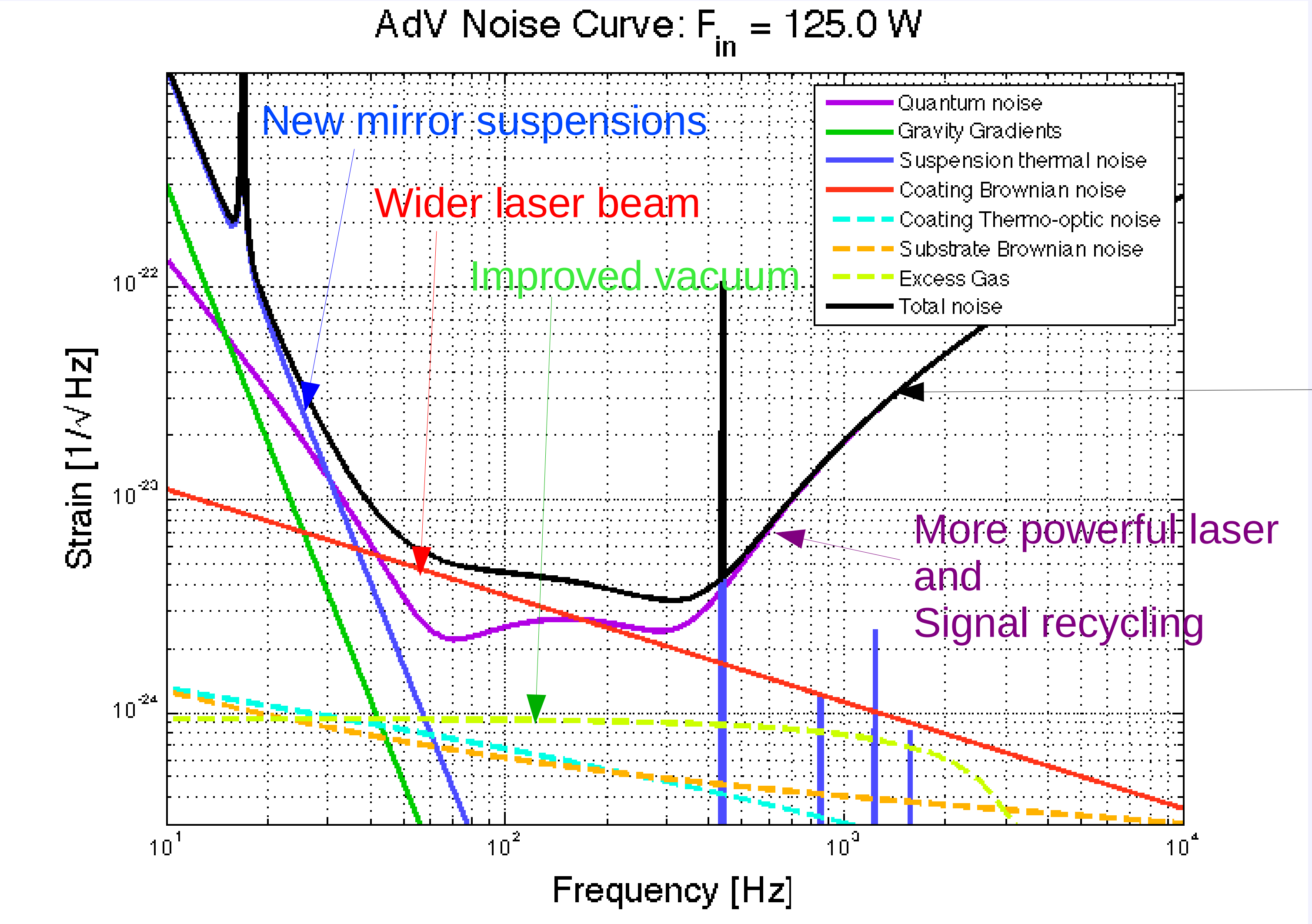


Image: B. Saxton (NRAO/AUI/NSF)

Rotating neutron stars

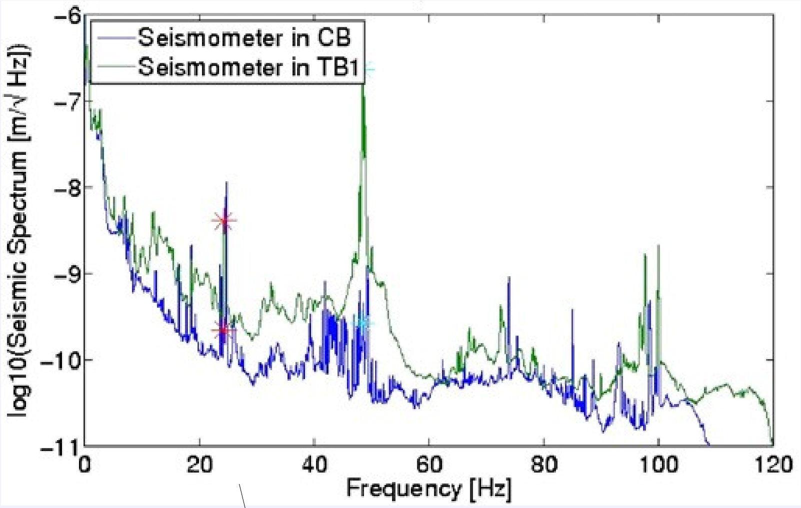
Signal averaged over days (~10^6 s)
→ can detect h ~ 10^{-26}

What is the noise level in Virgo?
Fondamental noises



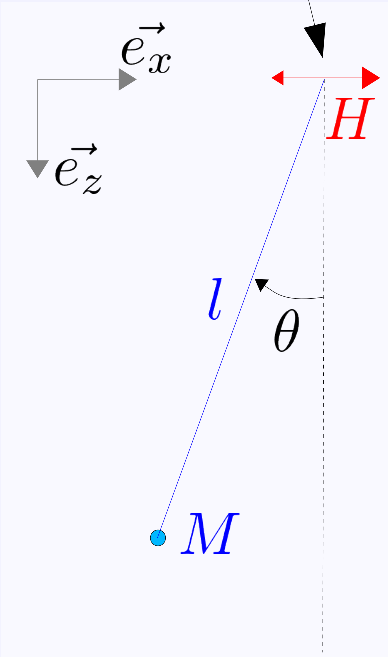
Sum of all the noises

Seismic noise and suspended mirrors



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

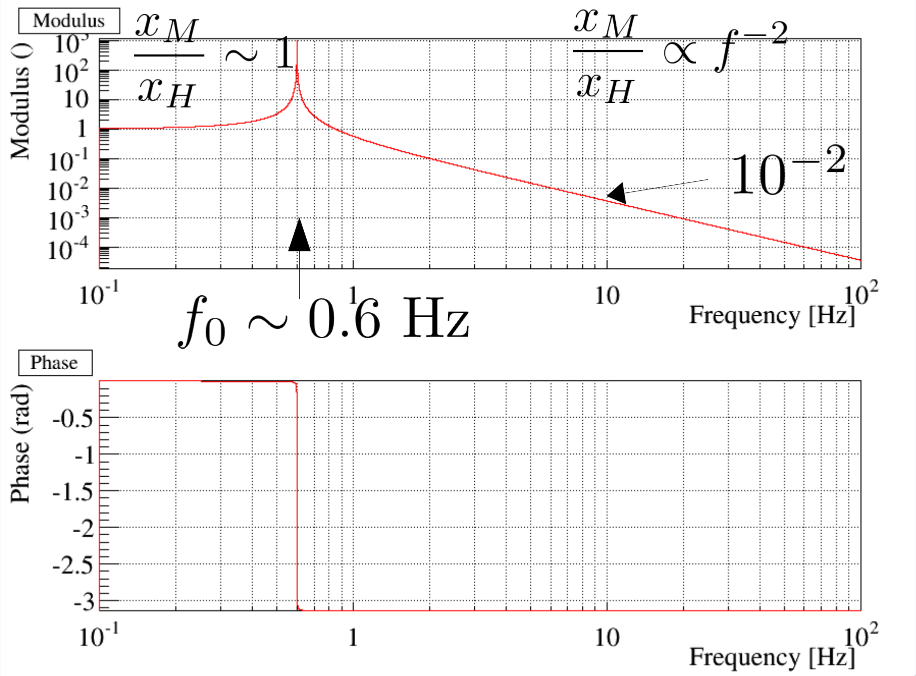
$$\gg 10^{-19}\,\mathrm{m}/\sqrt{\mathrm{Hz}}\ \text{needed to detect GW !!}$$



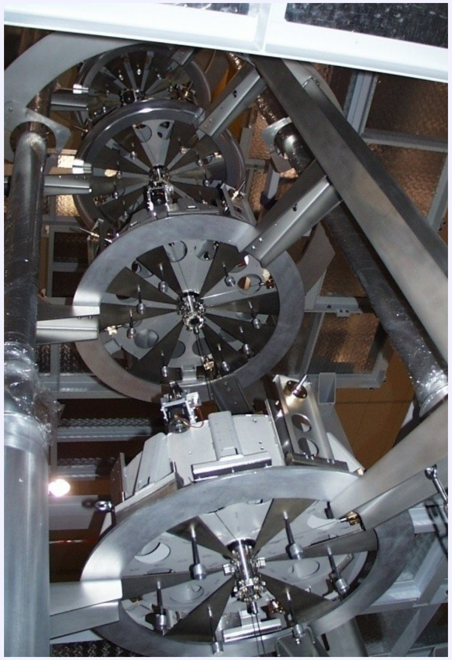
Assuming δx_H small and sinusoidal and θ small:

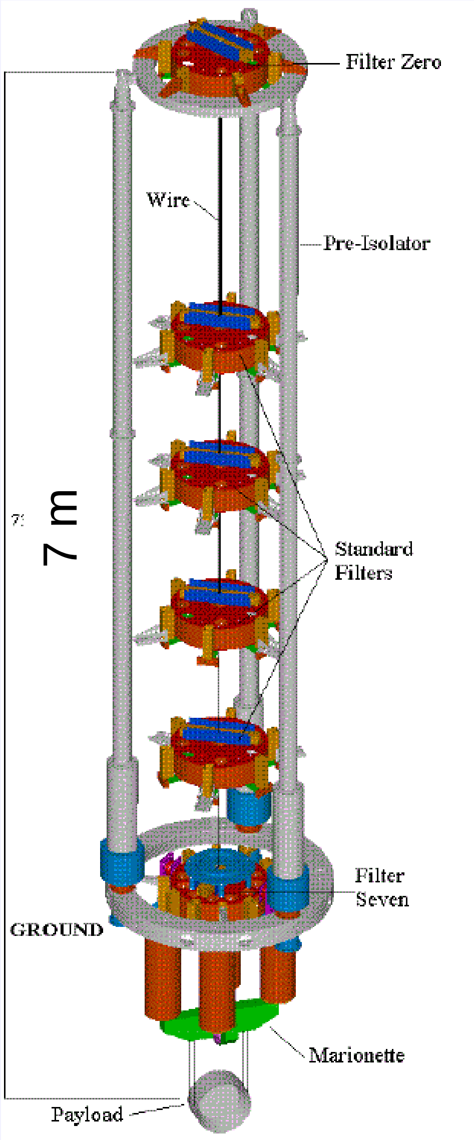
$$\underline{x_M} = \underline{\mathcal{H}} \times \underline{x_H}$$

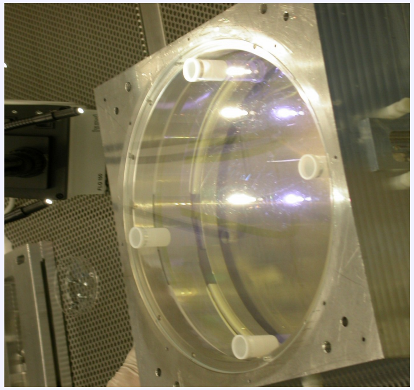
Transfer function



Seismic noise and the Virgo suspension







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

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

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

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

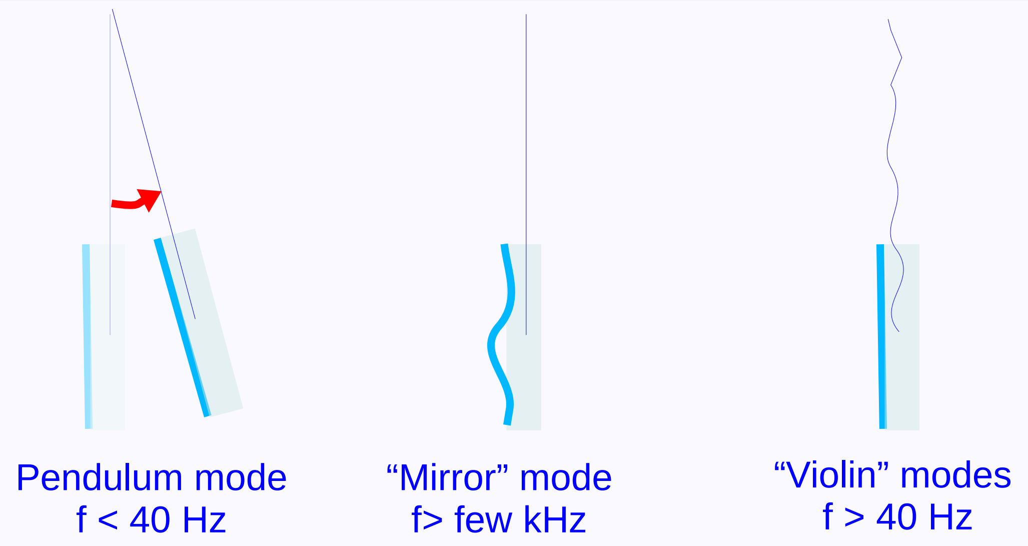
This noise directly modifies the positions of the mirror surfaces, and thus $\delta\Delta L$ and $h_{rec}(t)$!

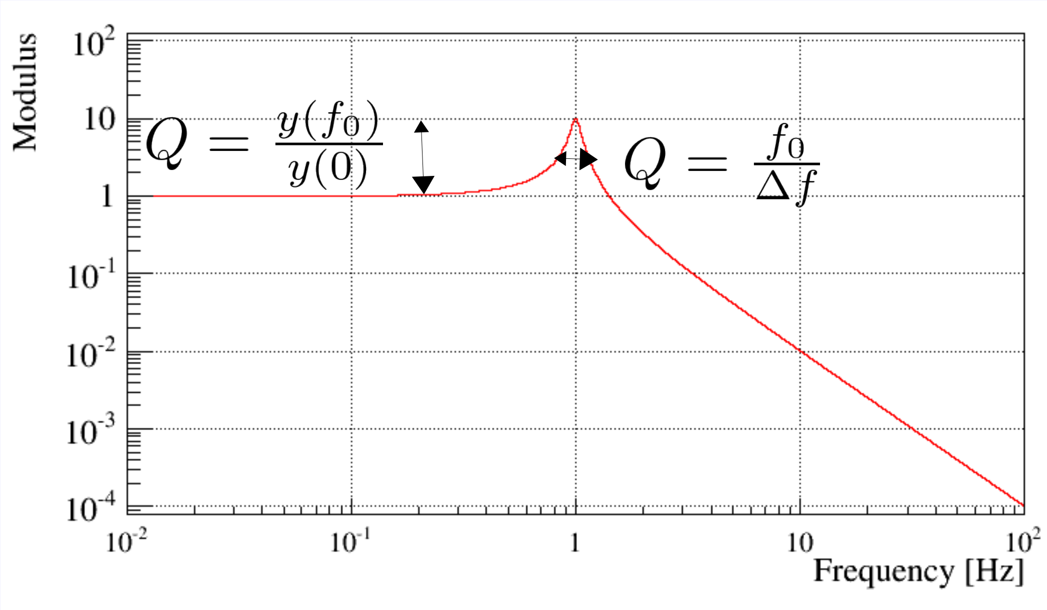
- **Active controls** at low frequency
  - Accelerometers or interferometer data
  - Electromagnetic actuators
  - Control loops

What is 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 $h_{rec}(t)$!

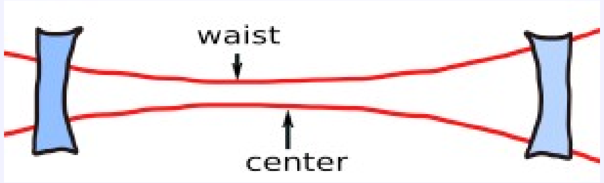
We want high quality factors Q to concentrate all the noise in a small frequency band

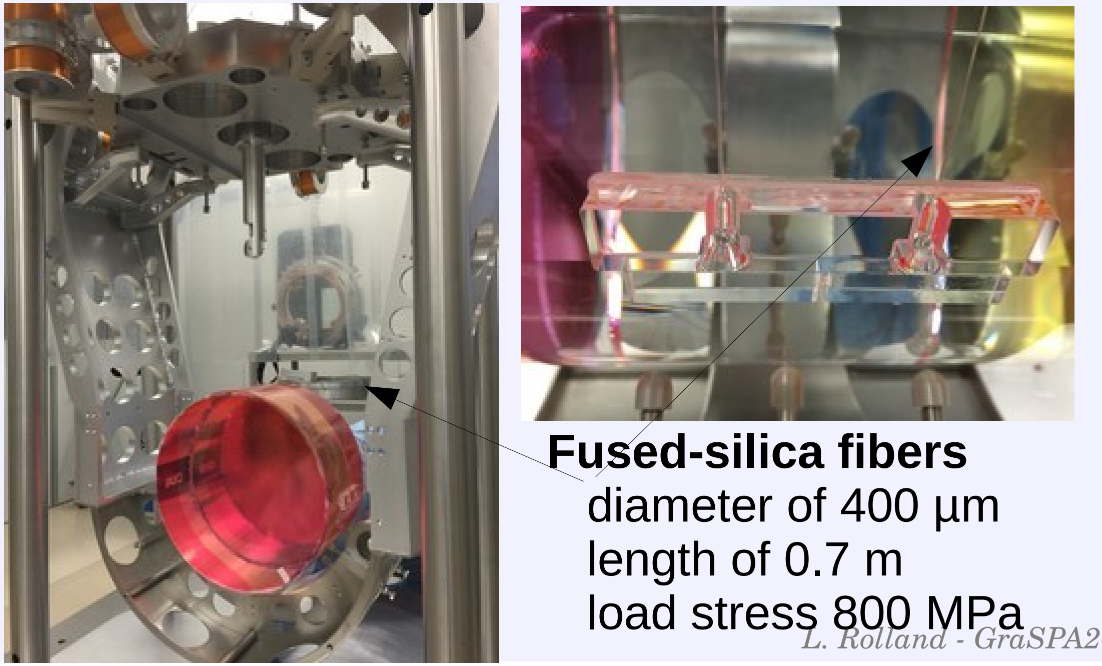
Thermal noise mitigation

Monolithic suspensions
- Monolithic suspension developed in labs in Perugia and Rome

Mirror coatings
- currently main source of thermal noise
- very high quality mirror coatings developed at Lyon (LMA)
- active R&D activities to improve performances, new materials, ...
- cryogenic mirrors to be used at Kagra + future detectors

Reduction of noise coupling with the beam
- use of larger laser beams (thermal noise ~1/laser beam)





Fused-silica fibers
diameter of 400 µm
length of 0.7 m
load stress 800 MPa

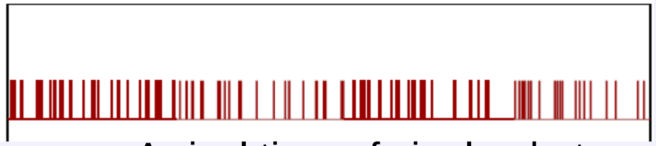
40 kg mirrors
35 cm diameter
40 cm width
Suprasil fused silica

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 $\delta\Delta L$

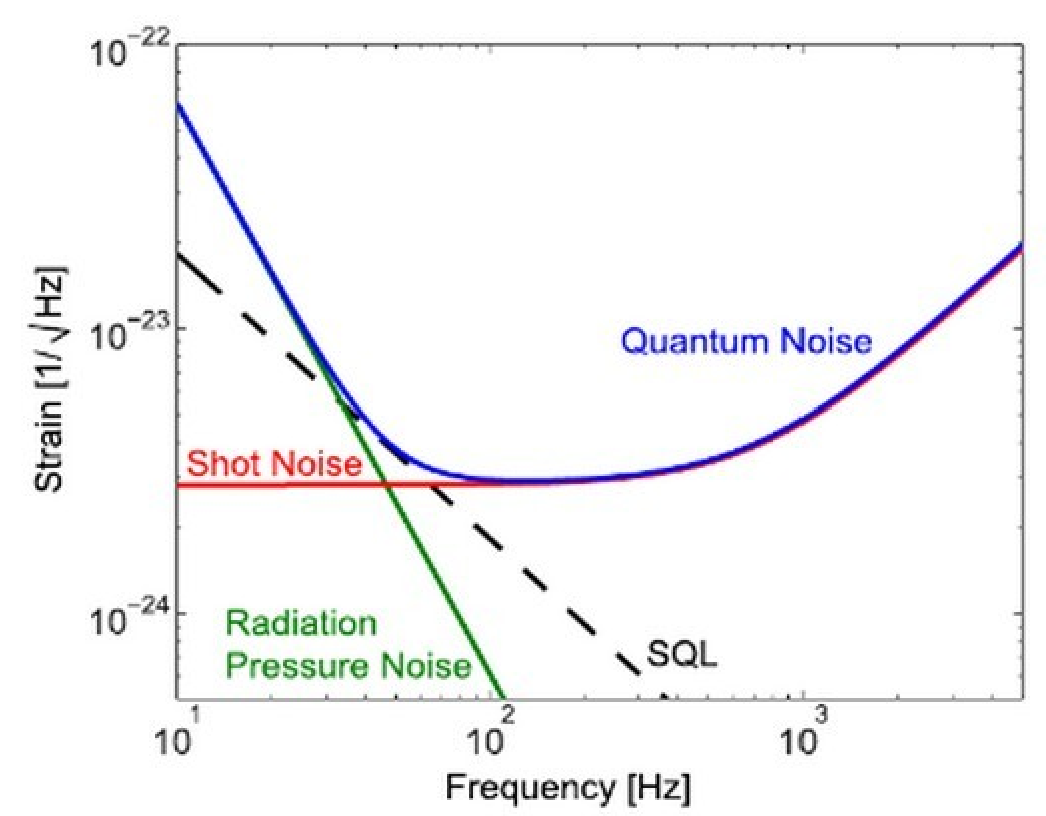
$$\delta P_t = (\text{Virgo response}) \times L_0 \times h$$

(in W/m)

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

$$h_{equivalent} \propto \frac{1}{\sqrt{P}}$$

Increasing the power to reduce shot noise?



Increasing input laser power:

- decreasing of shot noise at high frequency

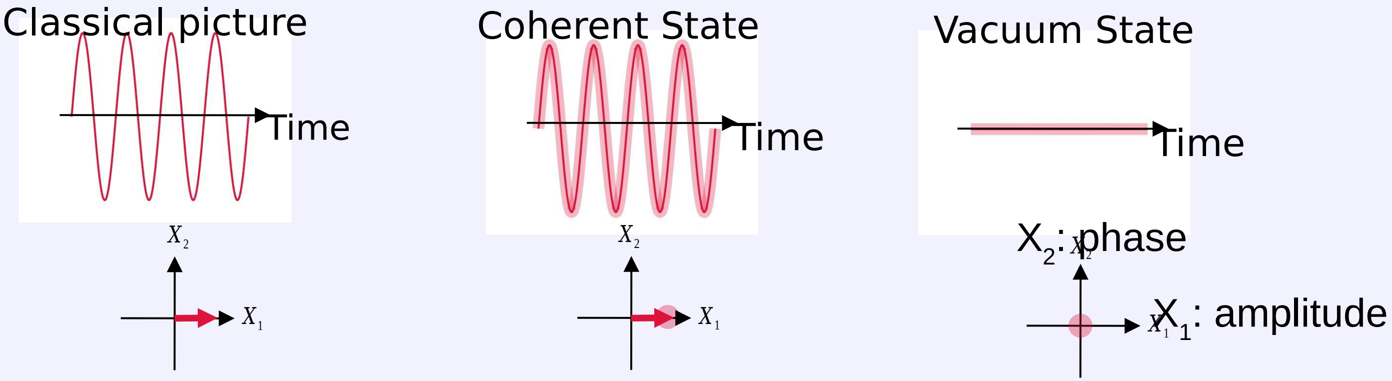
But a lot of side effects

- ...increasing the radiation pressure noise at low frequency
- recycling cavities more difficult to control
- thermal absorption in the mirrors: optical lensing
  - → need of complex thermal compensation system
  - → high quality mirrors to reduce absorption
- parametric instabilities: coupling of laser high order modes with mirror mechanical modes

Reduction of quantum noise: with squeezing

→ **How to reduce quantum noise without increasing laser power?**

Optical field models



with Heisenberg relation

Interferometer operating close to a dark fringe

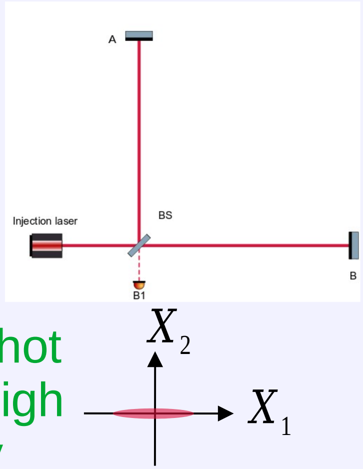
- The laser is reflected back to the injection
- A vacuum fied enters the interferometer from the output port

} interferences

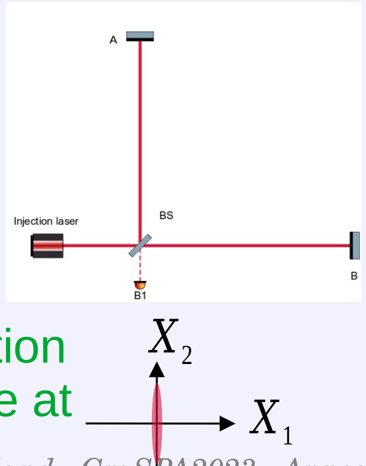
→ shot noise arises from the vacuum state phase variations

→ radiation pressure noise arises from the vacuum state amplitude variations

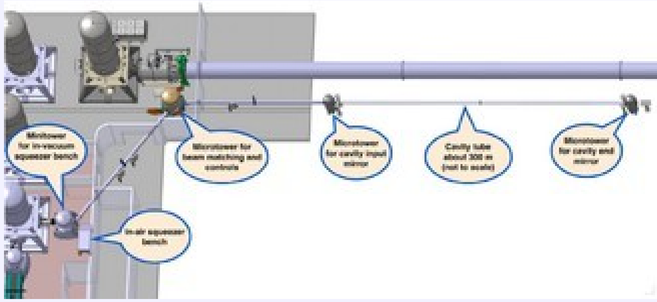
Injecting squeezed vacuum states in the interferometer



Reduce shot noise at high frequency



Reduce radiation pressure noise at low frequency

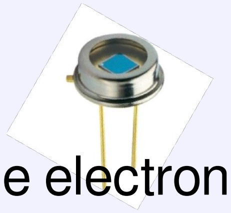


→ Installed in Virgo in 2020-2021
New filter cavity of 300 m
Strong constraints on optical losses, beam matching, alignment,...

Some other gaussian noises

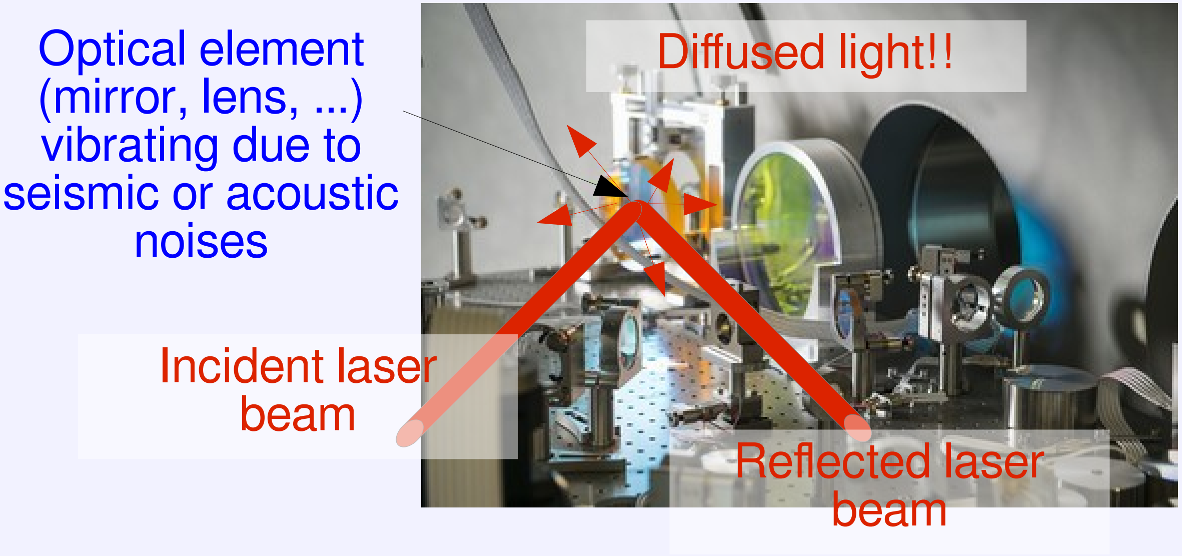
- Acoustic vibrations and refraction index fluctuations
  - Main elements installed in vacuum

- 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 nW/sqrt(Hz)
- Non-linear noise from diffuse light
  - Need dedicated optical elements with specific mechanical modes

Another source of noise: diffused light

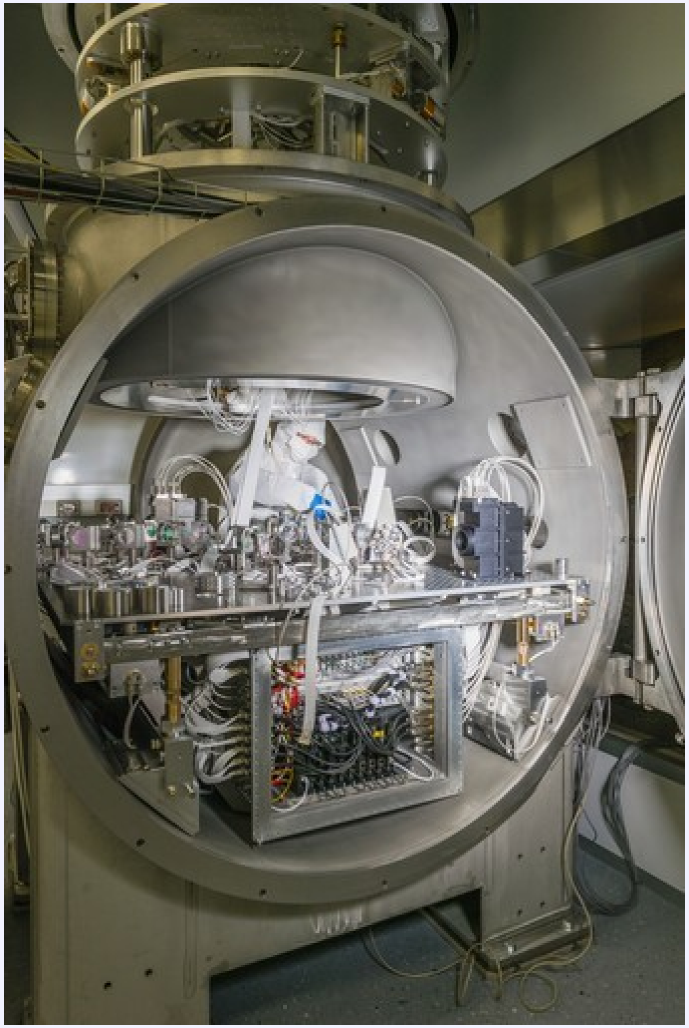


some photons of the diffused light get recombined with the interferometer beam

phase noise → extra power fluctuations

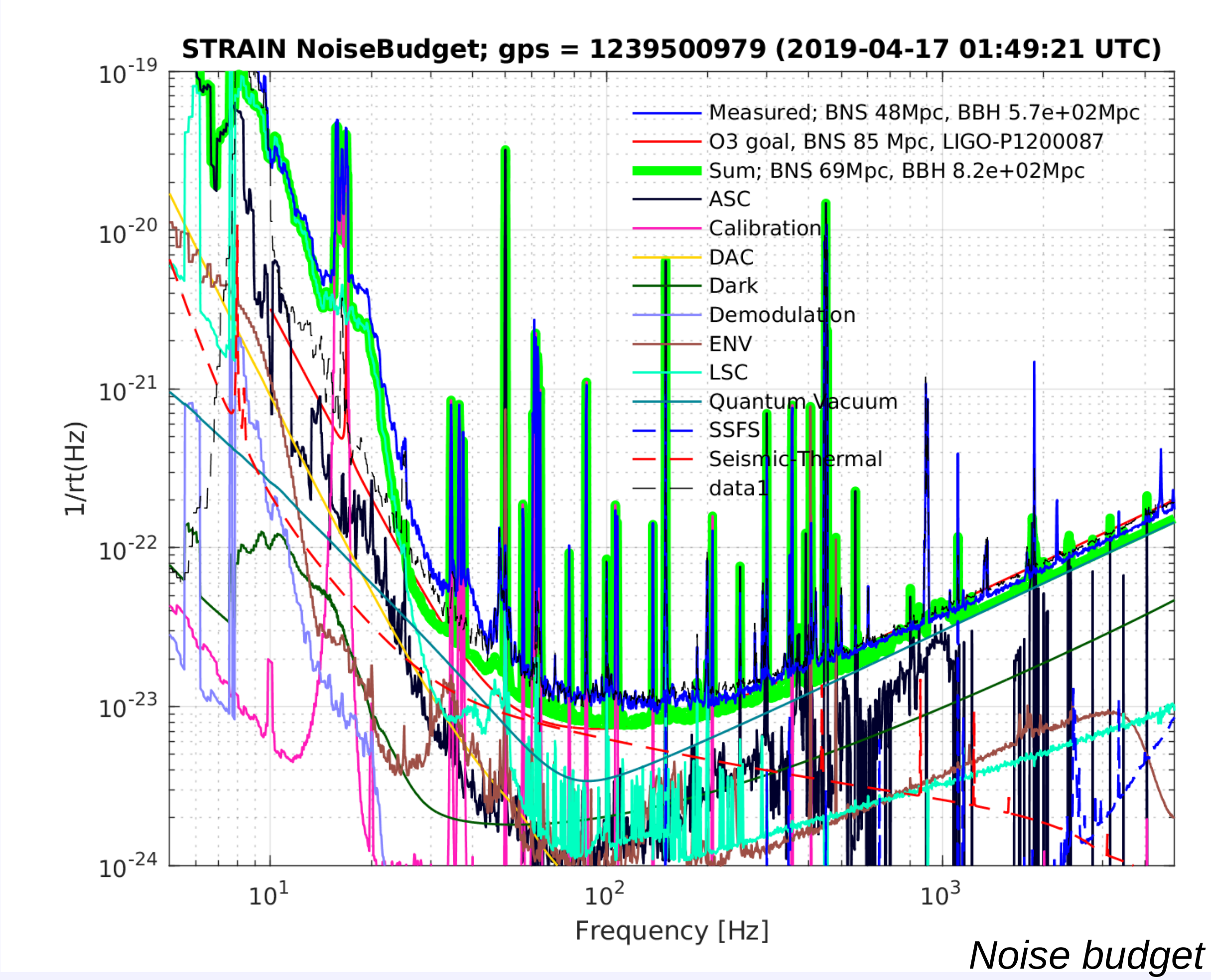
radiation pressure noise in the Fabry-Perot cavities → extra fluctuations of mirror positions

Evolutions done since ~2015: suspend the optical benches and place them under vacuum



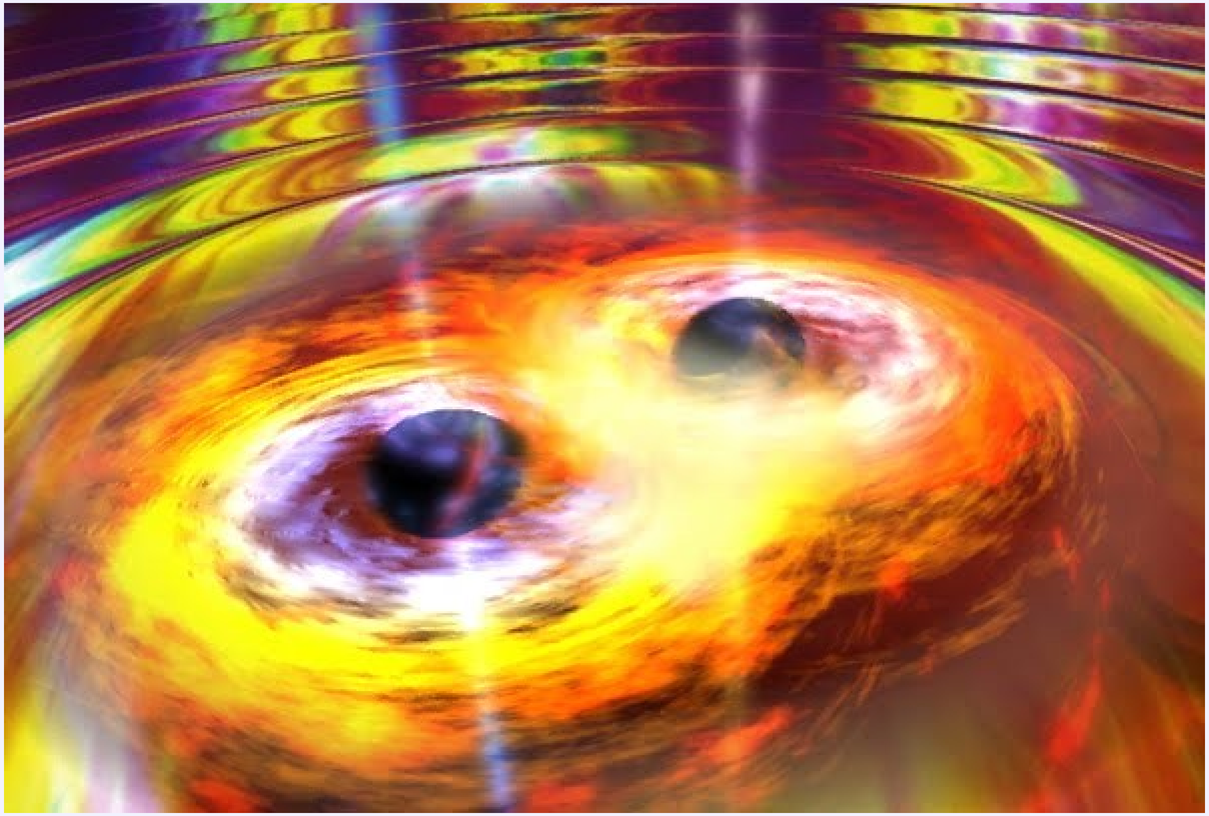
Example of a Virgo noise budget

Goal: modelize and/or measure all known noises
check if their sum matches the sensitivity curve…
…. or if there is still unexplained sources of noise

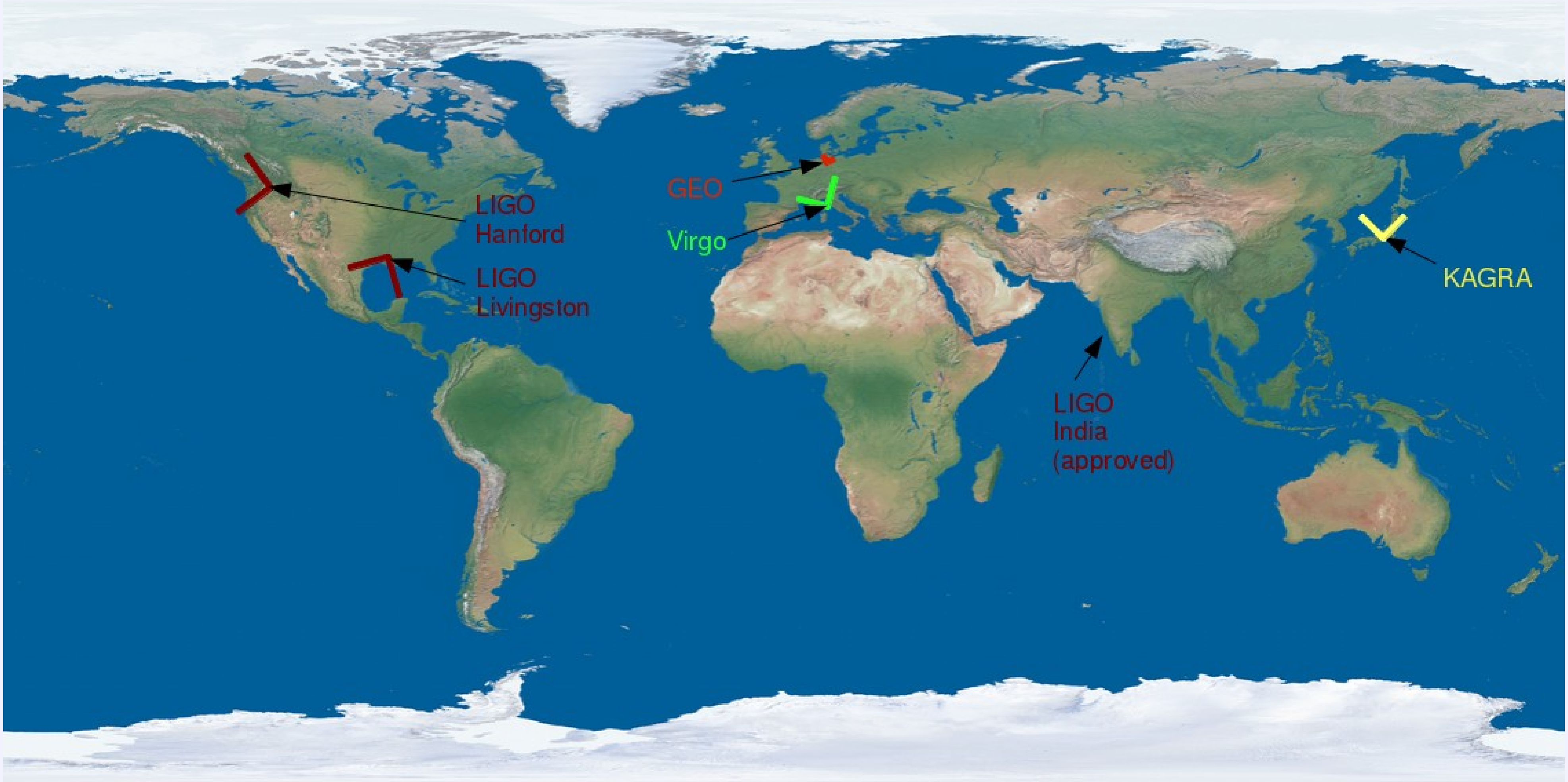


Noise budget from O3 run (April 2019)

Part 5: prospectives for gravitationnal wave astronomy



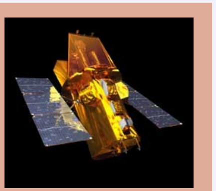
A worldwide network of interferometers: LIGO-Virgo-KAGRA



- ►(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)

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

Few minutes

Alerts for the observatories

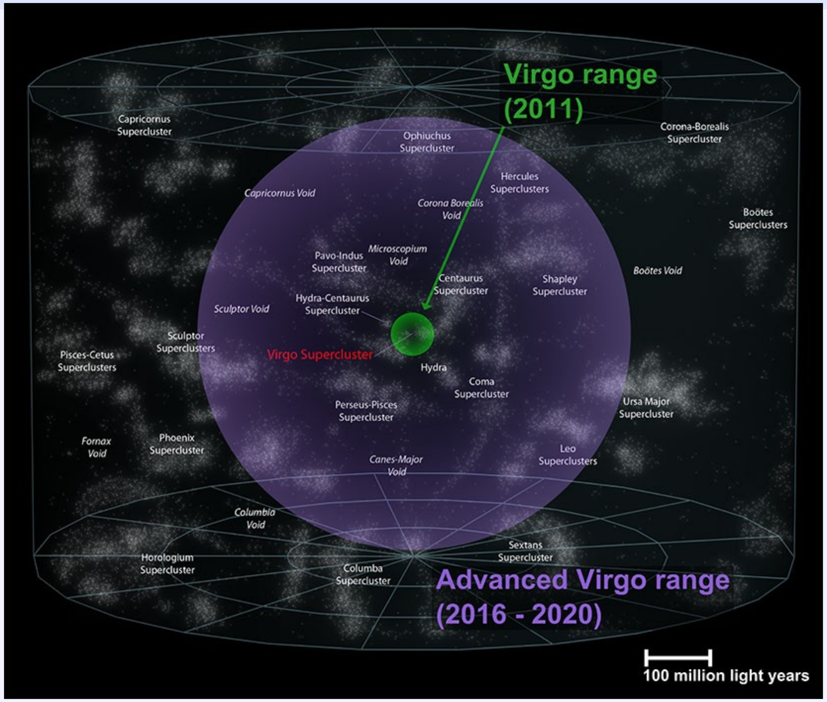
Radio and optical telescopes
ROTSE, TAROT, SkyMapper, QUEST,
Pi of the Sky, Zadko, Liverpool Telescope, LOFAR

X-ray satellites
Swift/XRT

γ-ray telescopes
HESS, CTA

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

Range of Advanced detectors



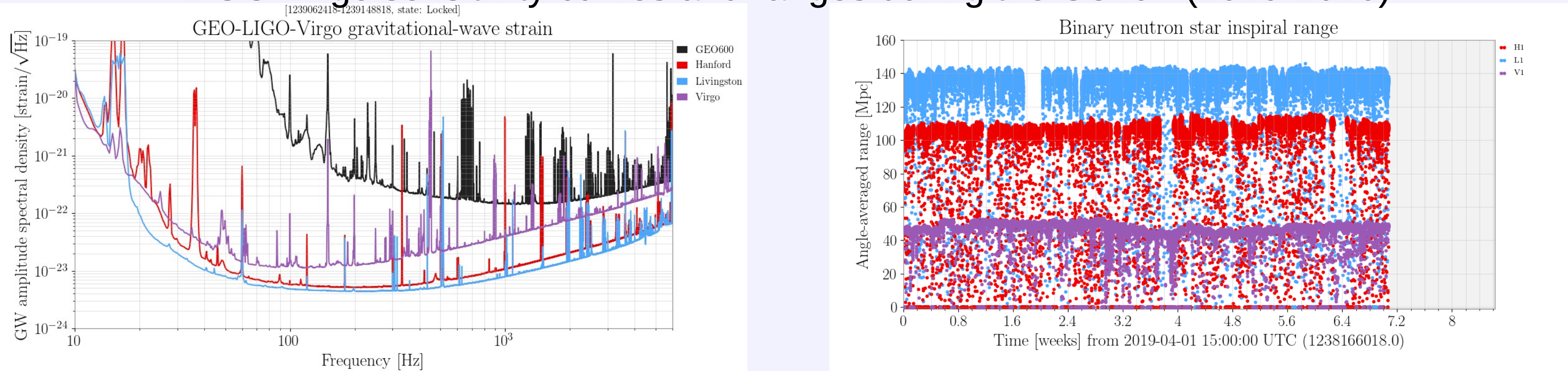
Distance at which a neutron star binary coalescence (1.4 $M_\odot$ - 1.4 $M_\odot$) can be seen with signal-to-noise ratio of 8

Improving the sensitivity (or range) by a factor 10

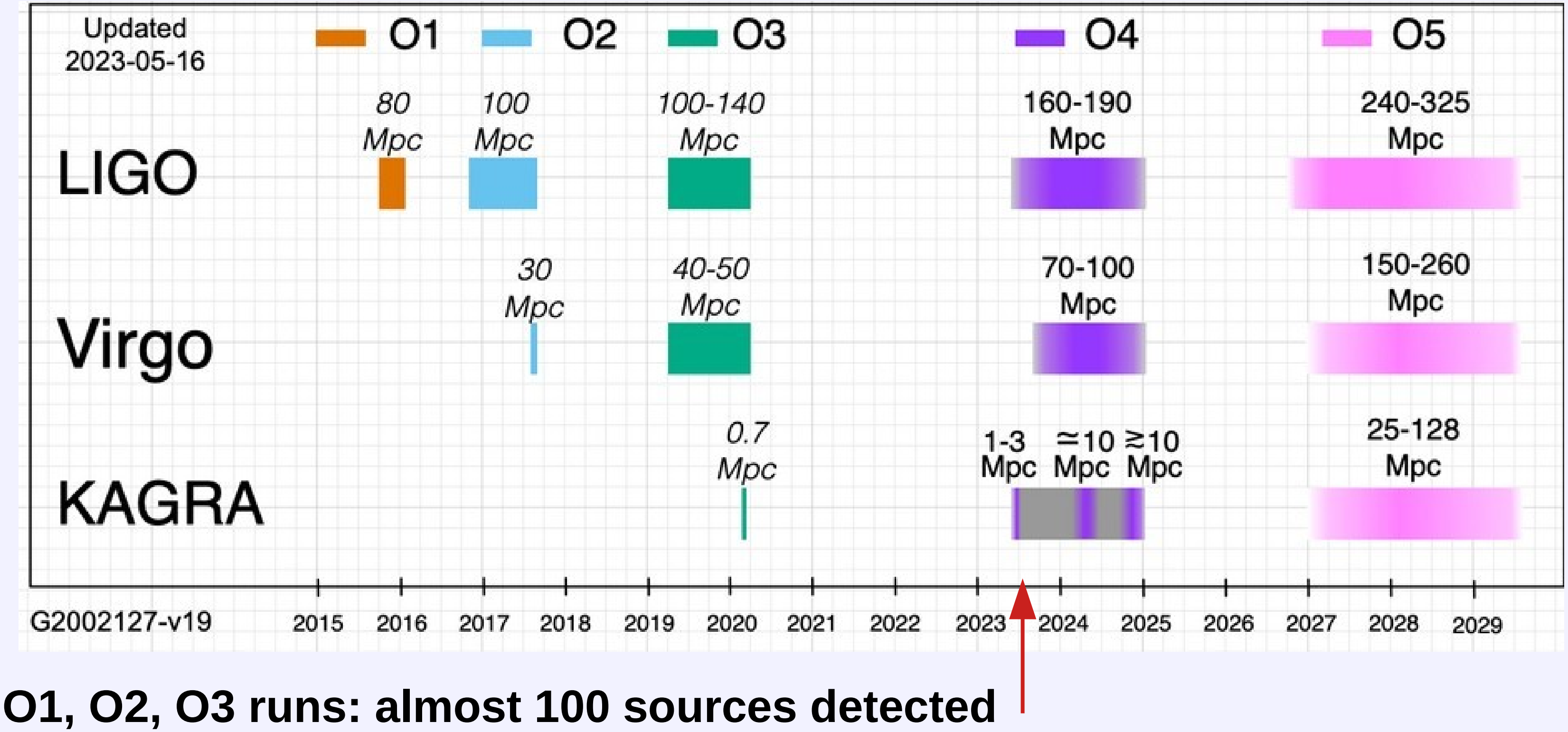
↓

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

LIGO-Virgo sensitivity curves and ranges during the O3 run (2019-2020)



LIGO-Virgo-KAGRA have started observations



O1, O2, O3 runs: almost 100 sources detected

mainly coalesces of binary black holes
a few coalescences of binary neutron stars, GW170817 with multimessenger observations!
a few coalescences of neutron star-black hole

discoveries of particular events (high mass black holes, objects of type unclear, ….)
starting population studies (statistical studies)

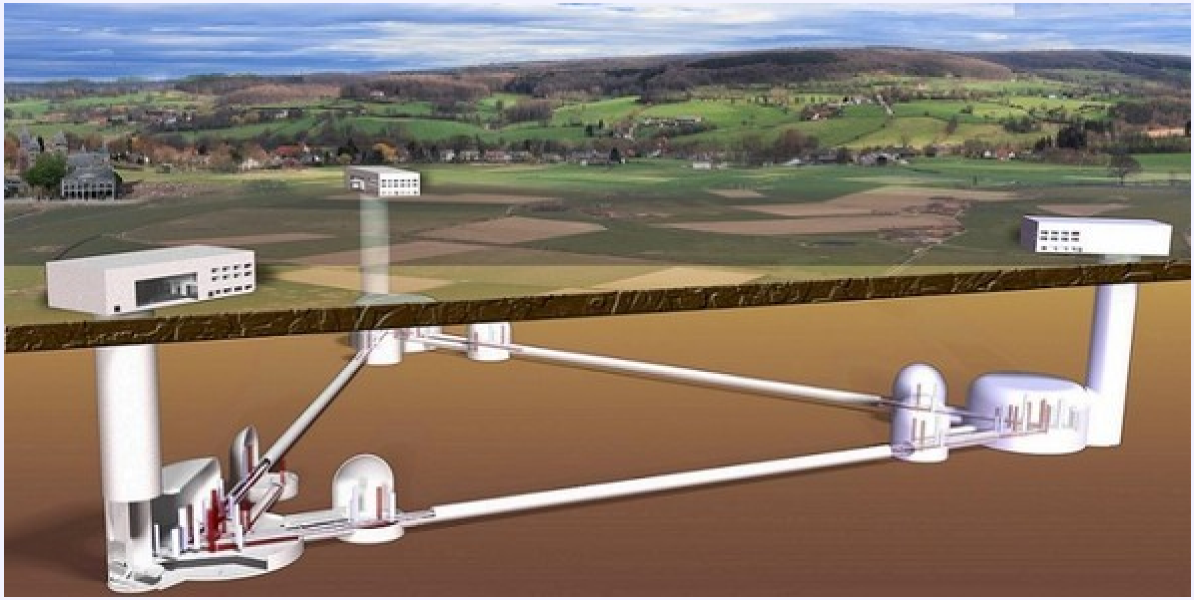
O4 started on May 24th

regular detections + daily public alerts of sub-threshold events

Starting construction of hardware to be installed in 2025, for O5 run

Einstein Telescope and Cosmic Explorer projects

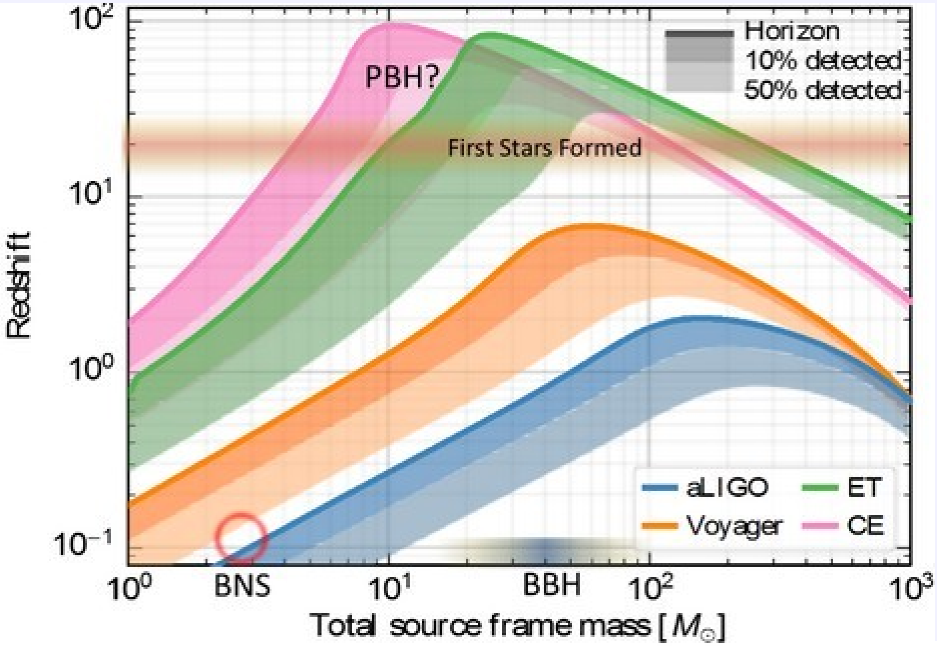
Third generation interferometer: gain another factor 10 in sensitivity and enlarge bandwidth



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

Cosmic Explorer (US):
With ~40 km arms

In operation after 2036+?



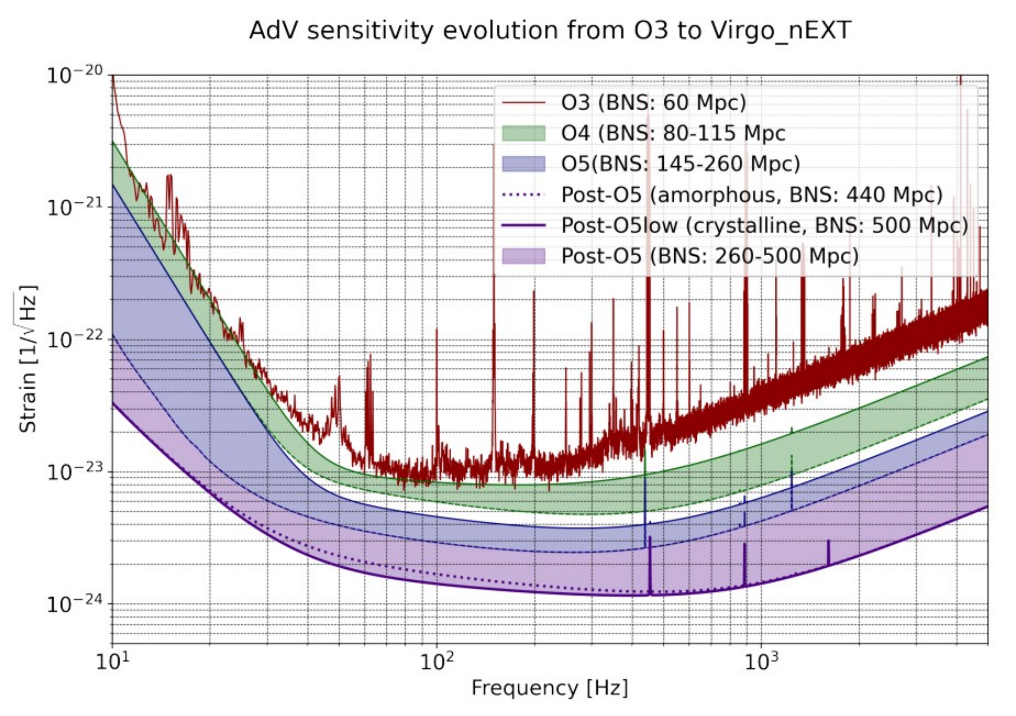
At design sensitivity, could probe CBC signals from a large fraction of the Universe

From Virgo to Einstein Telescope

Some urgent technical and design issues to tackle in Virgo
+ work on optical simulations to understand complex effects

Thinking to Virgo_nEXT project
use the Virgo infrastructure to its best scientific potential
seen as a R&D exploration towards E.T., to bridge Virgo to E.T.
R&D of new technologies for E.T., to be tested on Virgo in the next decade

→ **a lot of interesting experimental and data analysis developments for the next years!**

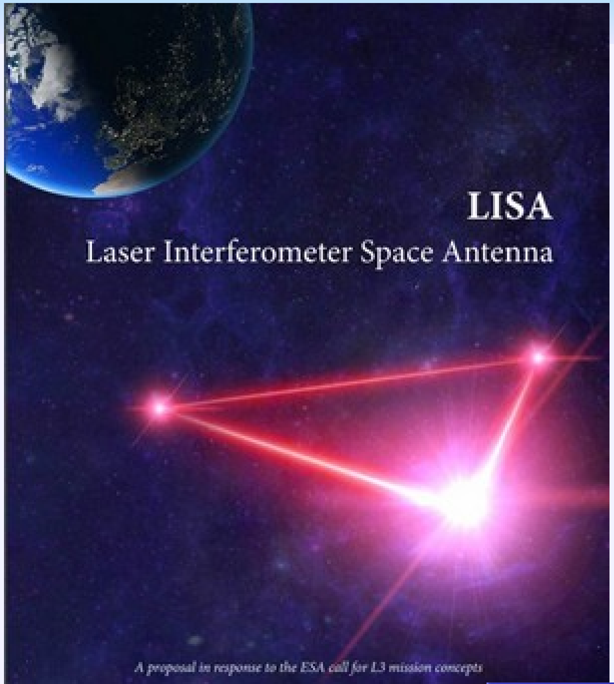


LISA: a spatial interferometer in construction

Bandwidth: 0.1 mHz to 1 Hz

Triangle with 2.5 million km arm length

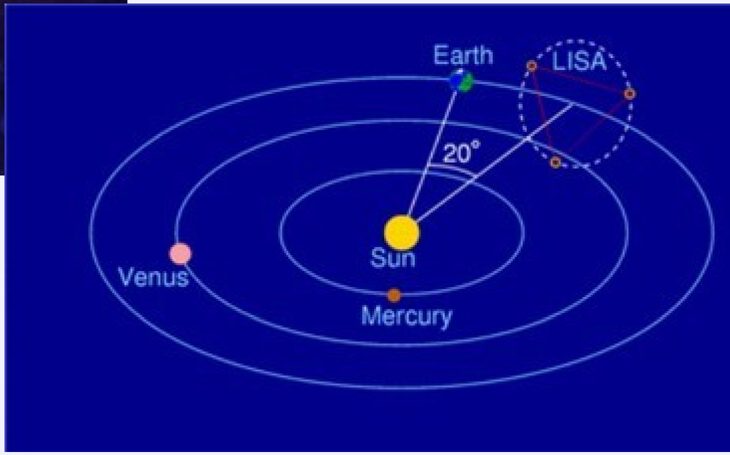
Launch of LISA around 2035?
→ opration for 5 to 10 years



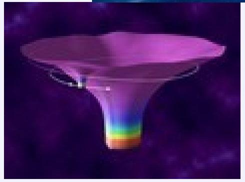
LISA
Laser Interferometer Space Antenna

A proposal in response to the ESA call for L3 mission concepts

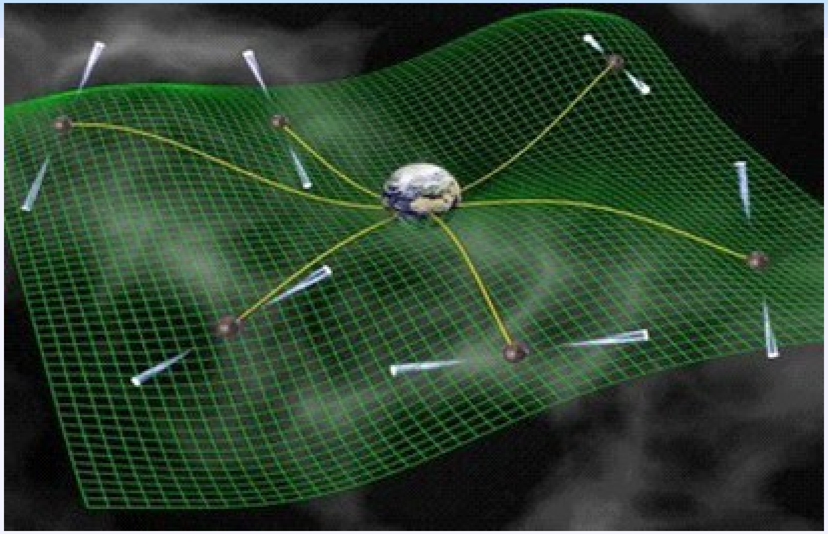
Lead Proposer
Prof. Dr. Karsten Danzmann



massive black hole binaries
galactic binaries
extreme mass-ratio inspirals
...



Pulsar Timing Arrays



Bandwidth: nHz to 100 nHz

Observation of ~20 pulsars in radio

- weekly sampling over years
- GW cause the time of arrival of the pulses
  to vary by a few tens of nanoseconds
  over their wavelength

International network

- Parkes PTA
- North American NanoHertz Gravitational Wave Observatory
- European PTA

Super massive black hole binaries

…

→ First hints of signals in the last years….

Still a lot of gravitational fun in front of us!

… but right now I have to work with my students
to complete the Virgo calibration for the O4 run