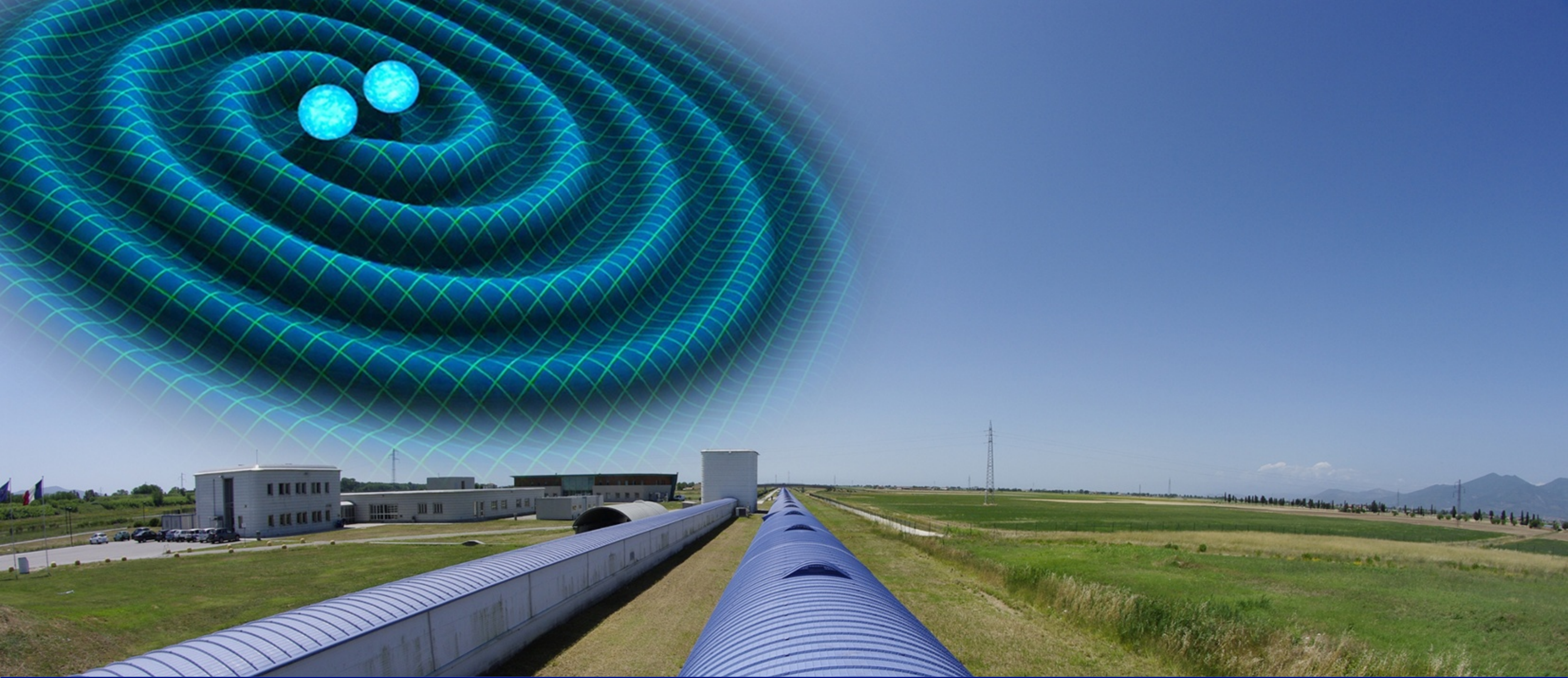


Ground Detectors (LIGO/Virgo and ET)

Jerome Degallaix

1st MaNiTou summer school

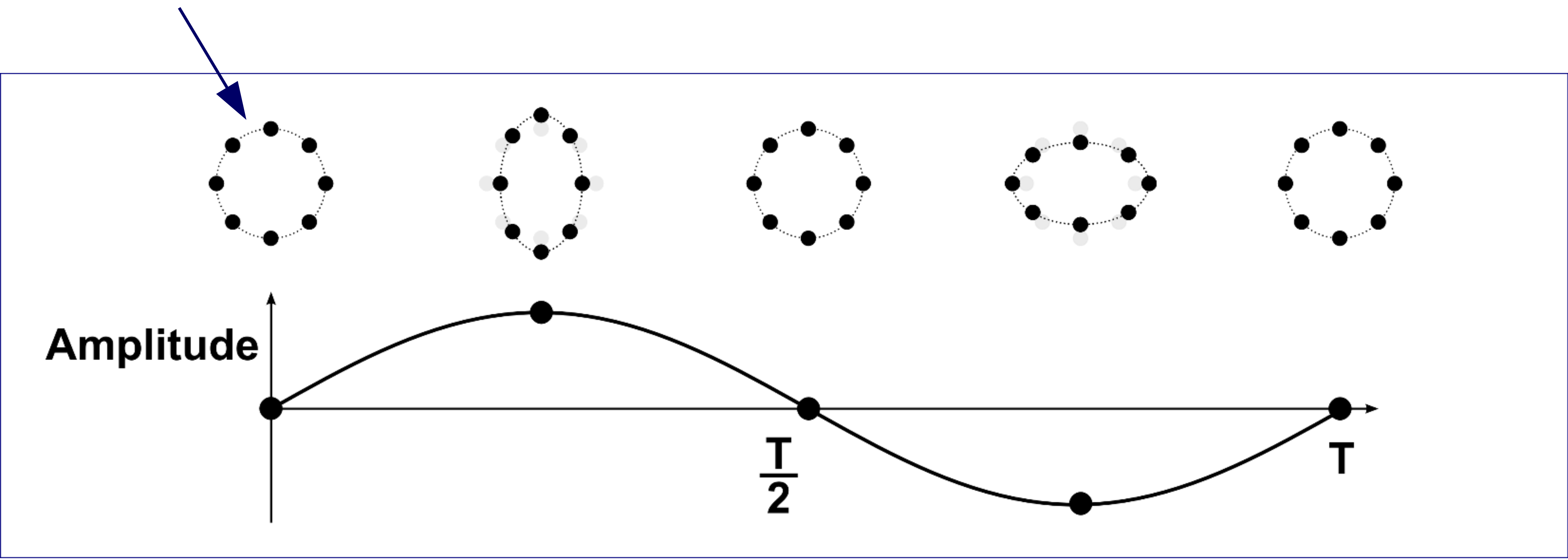
Menu

- Principle of detection
- Beating the noise
- Selected technologies
- Now and future detectors

I.
Principle of detection

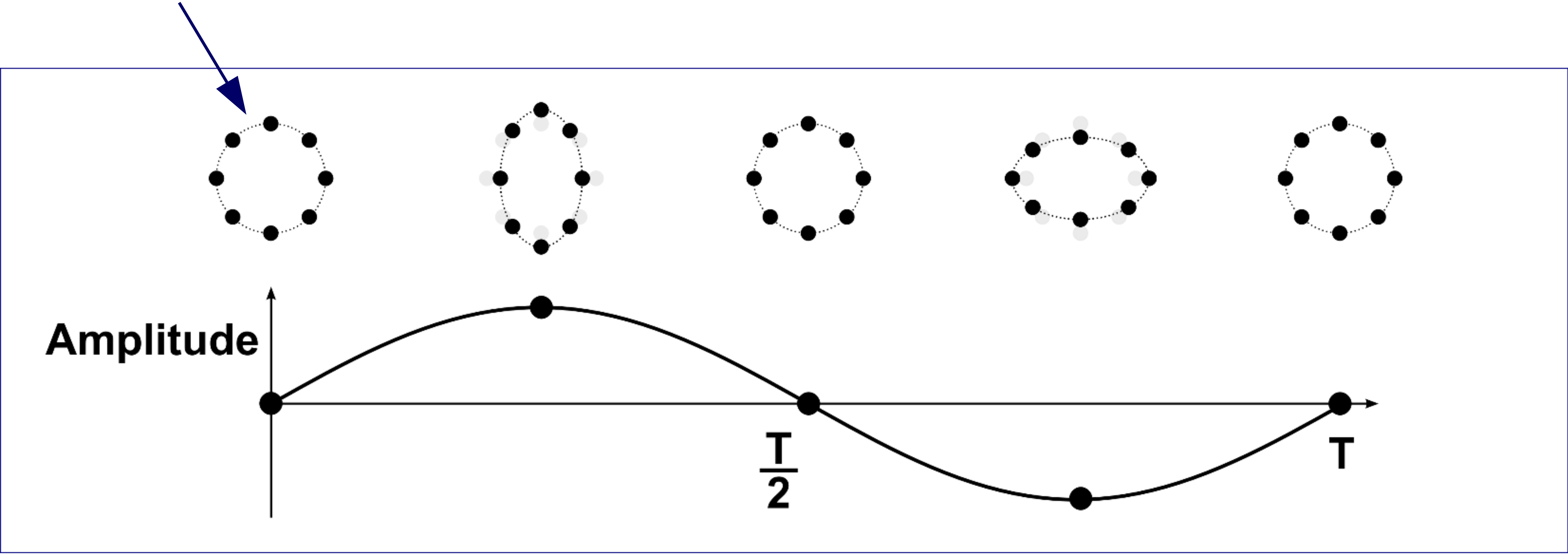
Effect of gravitational waves

Free falling masses



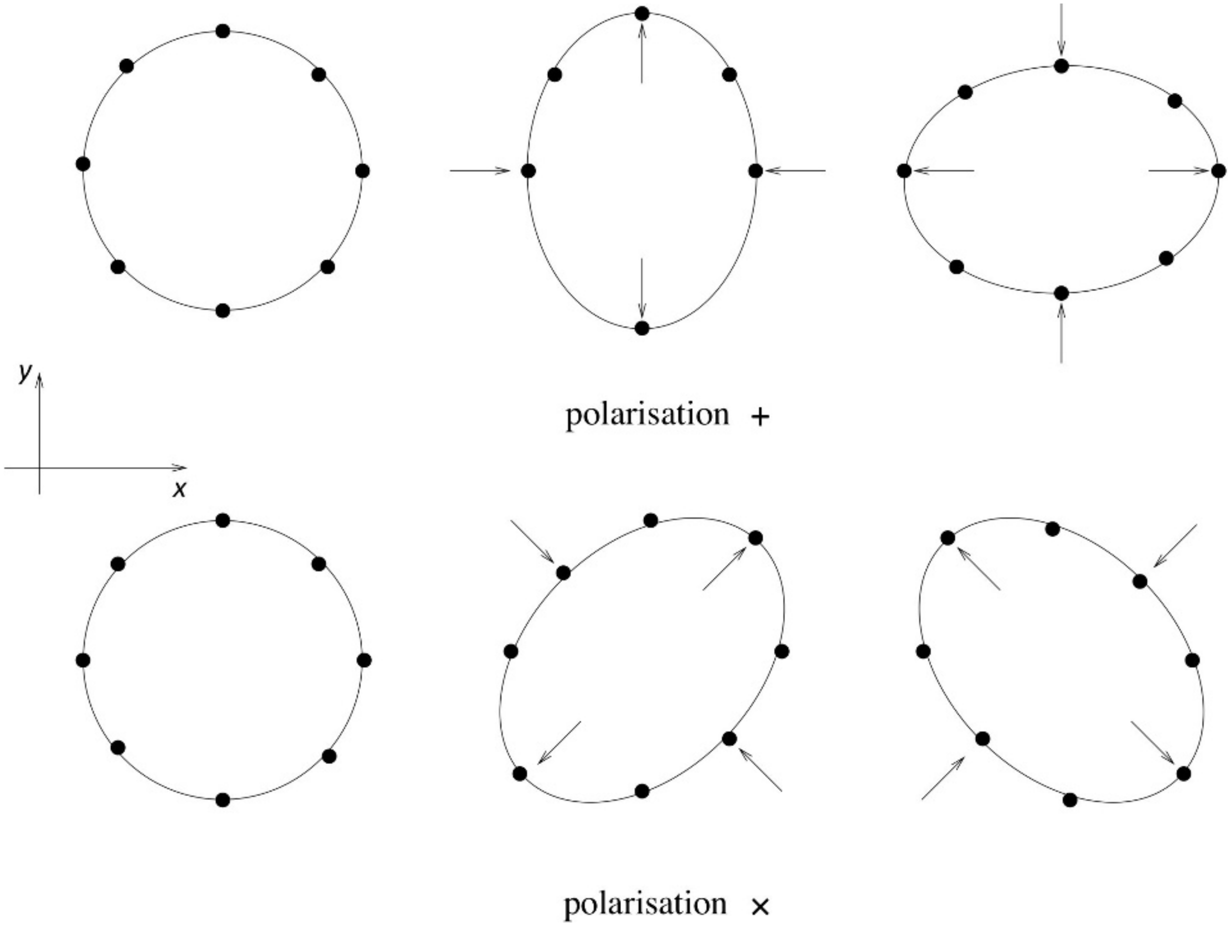
Effect of gravitational waves

Free falling masses



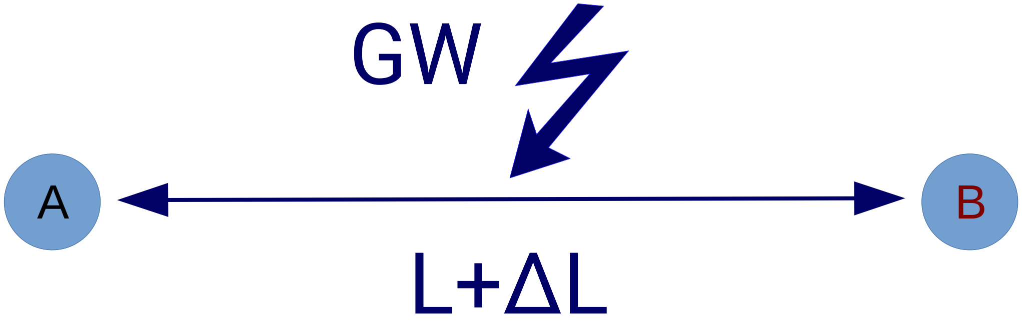
Example for
one polarisation

2 kind of polarisations



Gravitational wave amplitude

2 free falling masses



Amplitude of the deformation
$\Delta L = (1/2)\, h \times L$

Gravitational wave amplitude

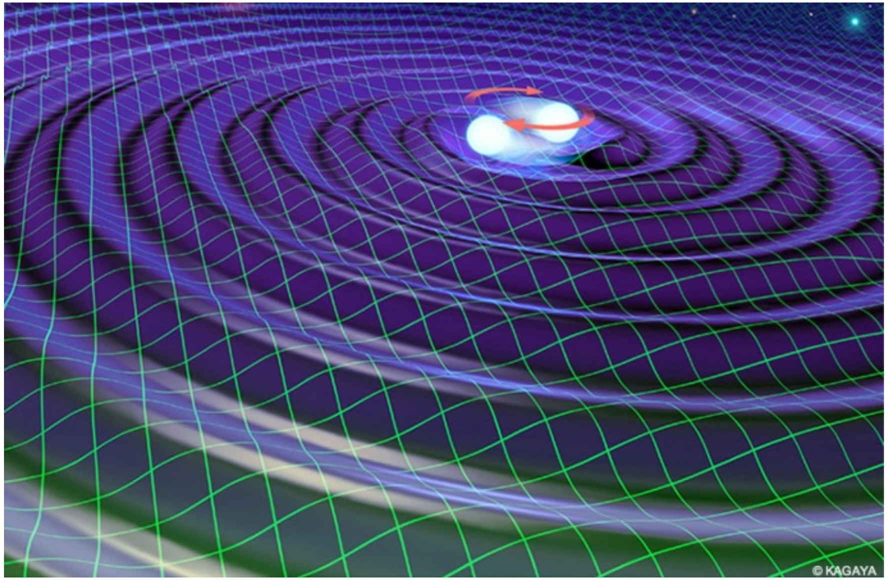
Quadrupole formula :

$$h = \frac{2G}{c^4 r}\ddot{I}$$

Amplitude

Distance

Mass quadrupole moment



Typical amplitude for the fusion of 2 black holes

$$h = 1,5 \times 10^{-21} \left(\frac{\text{Mass}}{30\ M_\odot}\right) \left(\frac{400\ \text{Mpc}}{\text{Distance}}\right) \left(\frac{\text{Frequency GW}}{50\ \text{Hz}}\right)^{\frac{2}{3}}$$

Freq. GW = 2 × orbital frequency

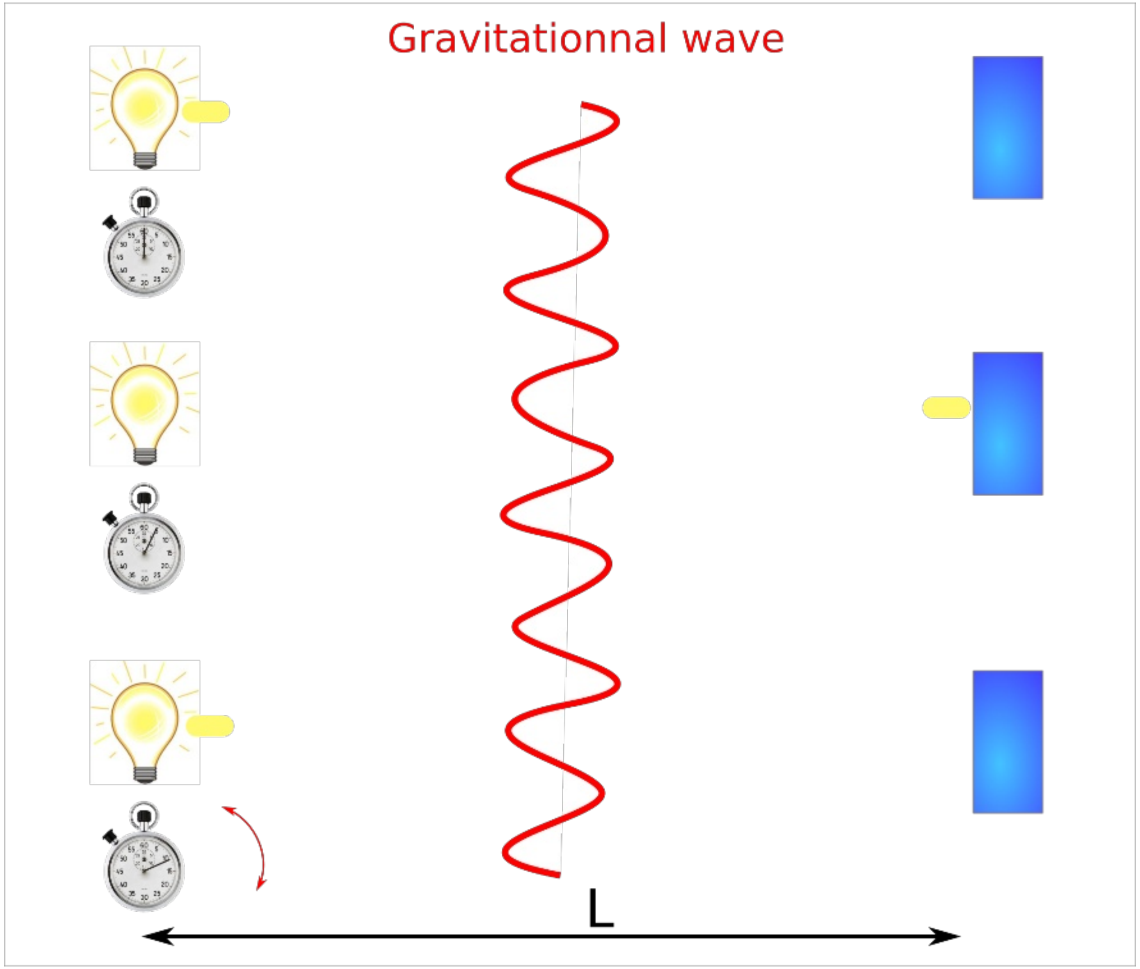
Order of magnitude $\Delta L = 0.5\, h \times L$

If $h \sim 10^{-21}$ so we should measure :

The distance Sun – Proxima Centauri with an accuracy of 0.02 mm

Or 2 km with an accuracy of 10^{-18} meter !

A more rigorous approach



Starting from the Einstein equation and calculating the round trip time of the light.

Assuming a plane wave monochromatic GW:

$$h(t) = h_0 \cos(\omega_{GW} t)$$

Modulation of the round trip time

$$\mathrm{Time}_{RT} = \frac{2L}{c} + \frac{h_0}{\omega_{GW}} \sin\left(\frac{\omega_{GW} L}{c}\right) \cos\left(\omega_{GW}\left(t - L/c\right)\right)$$

usual round trip time

Amplitude of the modulation

frequency of the modulation

1. For low frequency, we found the usual formula
2. The modulation sign is reversed for the other transverse direction (with + polarisation)
3. No effect for certain GW frequencies
4. RT time change could be seen as a length change or light phase shift

II.
Michelson interferometer

A brief history

1916 – first calculation

1957 – accepted reality of GW

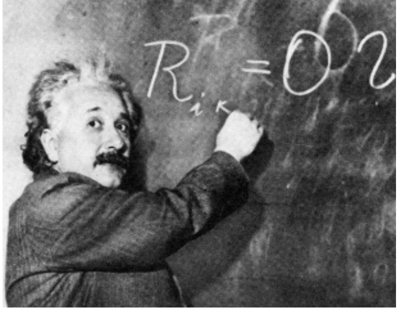
1960 – first detector

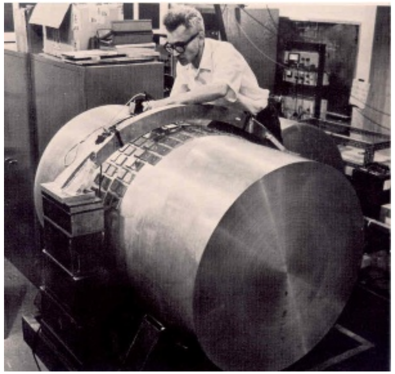
1970 – idea of laser interferometers

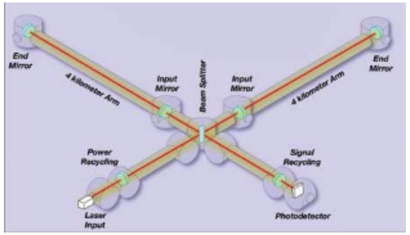
2008 – data taking with giant interferometers

2015 – first detection

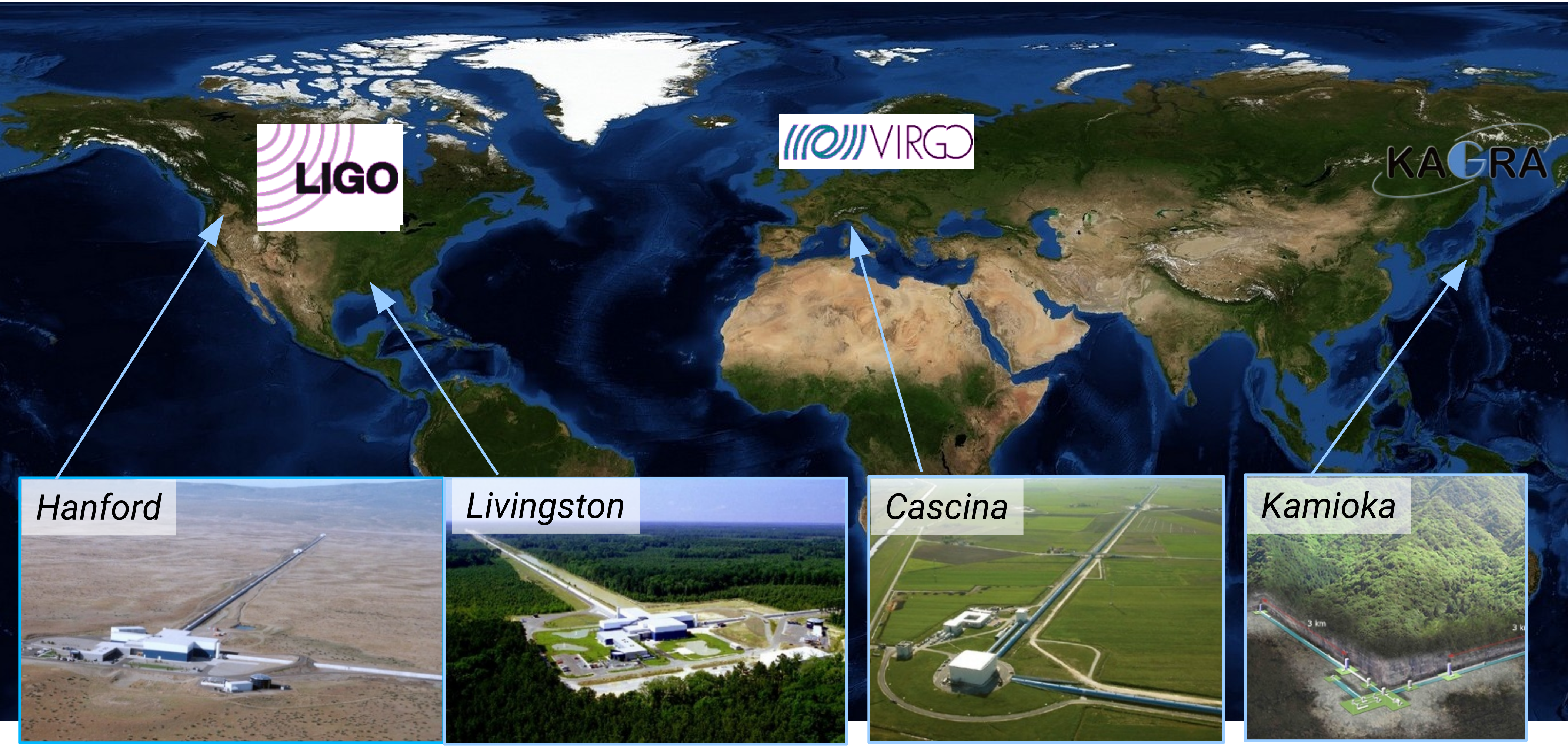
2020 – weekly detections of GW sources



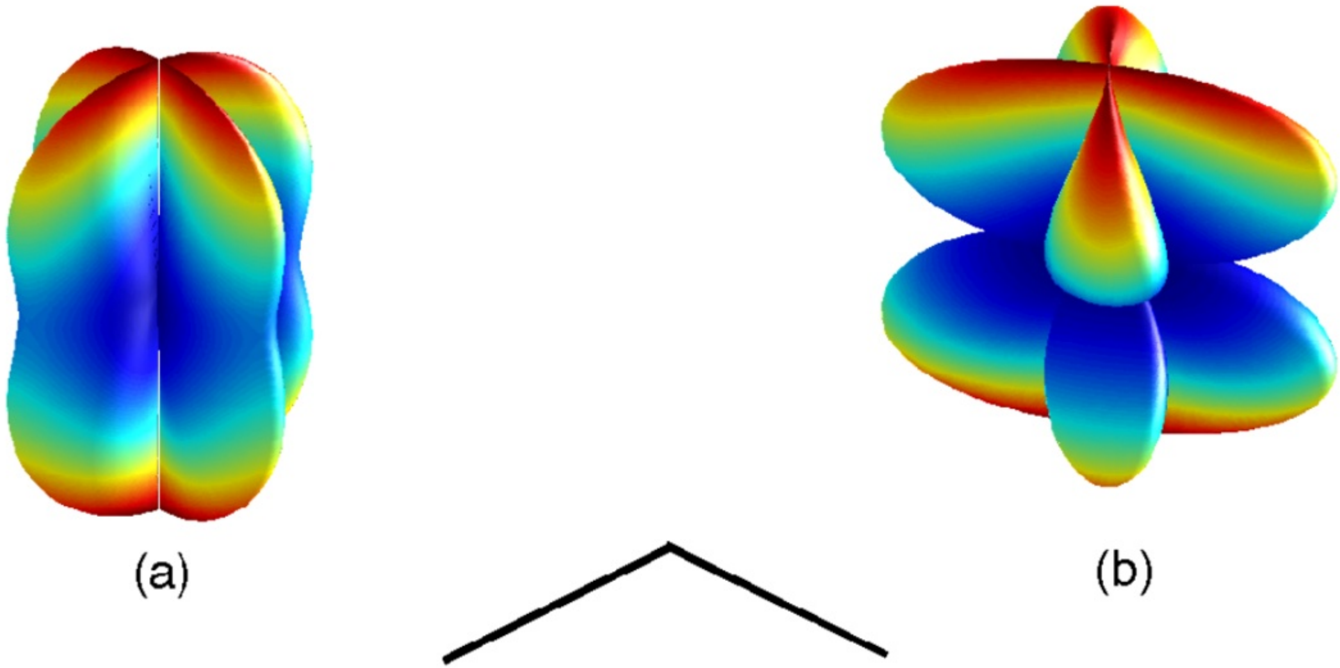




A network of detectors



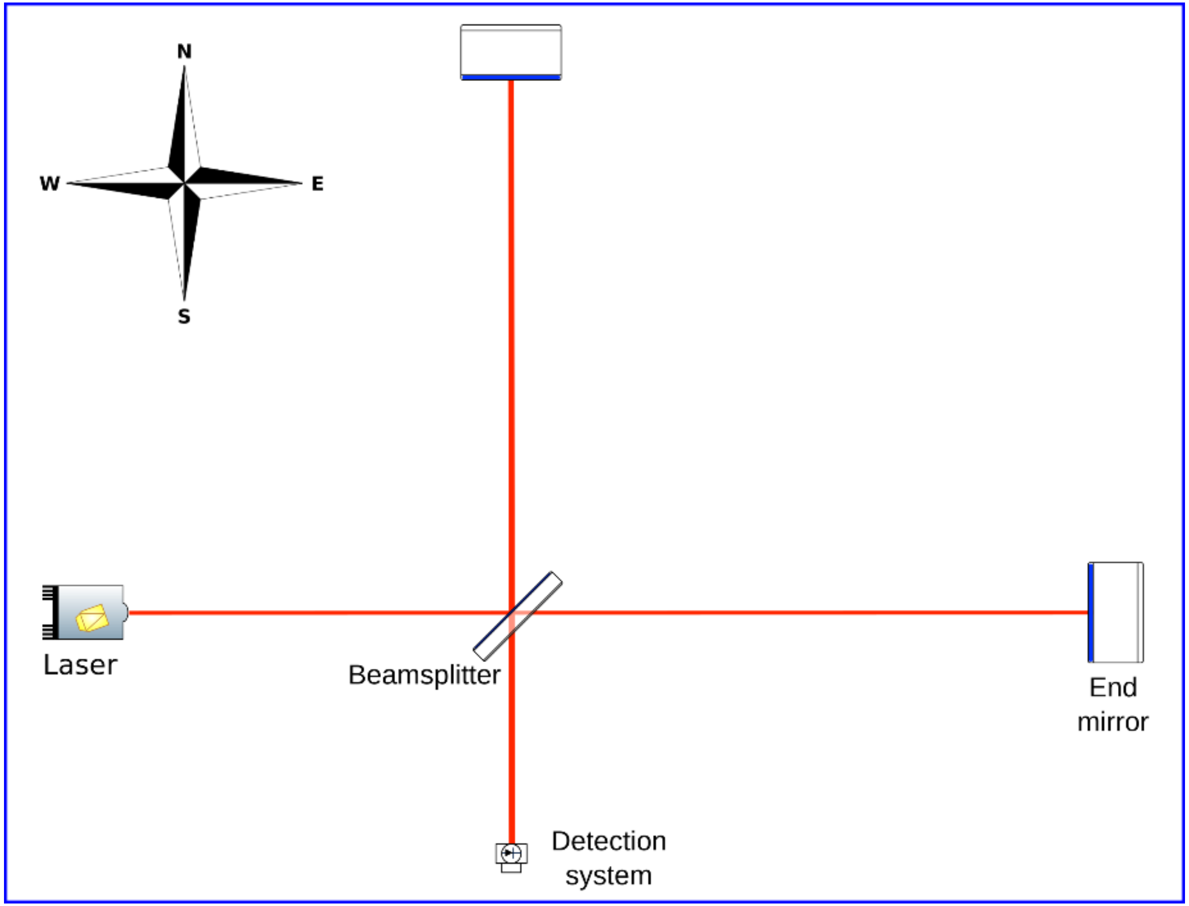
Antenna pattern of the detector



+ polarisation × polarisation

You have some blind spots !

The simplest Michelson interferometer



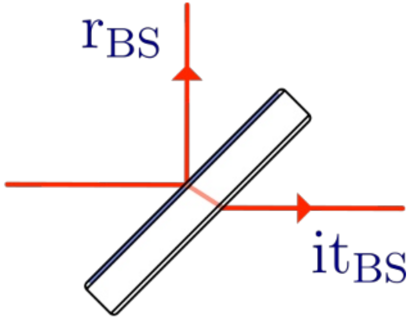
2 arms along the North and East directions (N and E index)

Propagating the electric field

Starting field : E_0

After propagating along a distance L : $E_1 = e^{-ikL} E_0$

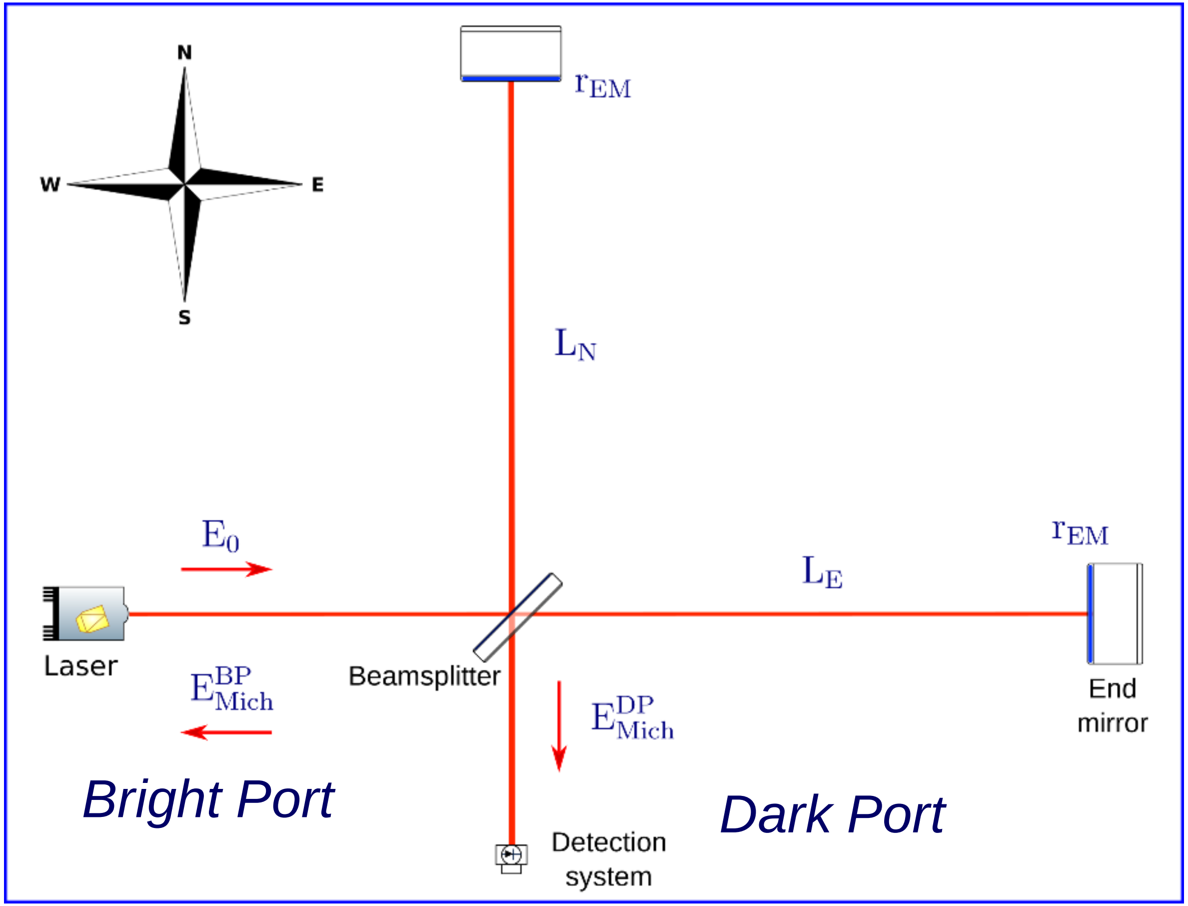
Dealing with the beam splitter (separating the light 50/50):



Beamsplitter

$$r_{BS} = t_{BS} = \frac{1}{\sqrt{2}}$$

Convention name for the electric fields



Field equations

$$E_{Mich}^{BP} = \left(r_{BS}^2 r_{EM} e^{-i2kL_N} - t_{BS}^2 r_{EM} e^{-i2kL_E}\right) E_0$$

$$E_{Mich}^{DP} = \left(i r_{BS} t_{BS} r_{EM} e^{-i2kL_N} + i r_{BS} t_{BS} r_{EM} e^{-i2kL_E}\right) E_0$$

Introducing differential and common lengths for the arms :

$$L_- = \frac{L_N - L_E}{2} \qquad L_+ = \frac{L_N + L_E}{2}$$

$$\Longleftrightarrow$$

$$L_N = L_+ + L_- \qquad L_E = L_+ - L_-$$

Finally, we arrived at :

$$E_{Mich}^{BP} = \left(-ie^{-2kL_+} \sin(2kL_-)\right) r_{EM} E_0$$

$$E_{Mich}^{DP} = \left(-ie^{-2kL_+} \cos(2kL_-)\right) r_{EM} E_0$$

Field equations

$$E_{\mathrm{Mich}}^{\mathrm{BP}} = \left(-ie^{-2kL+}\sin(2kL-)\right) r_{\mathrm{EM}} E_0$$
$$E_{\mathrm{Mich}}^{\mathrm{DP}} = \left(-ie^{-2kL+}\cos(2kL-)\right) r_{\mathrm{EM}} E_0$$

From the two above equations :

1. Energy is preserved between the 2 ports
2. Common motion induces only a phase shift
3. Differential motion modulates the powers

The differential phase between the 2 arms due to the GW signal is converted to a variation of power at the dark port.

Increase the phase difference to increase the signal !

Finding the right operating point

Adding a differential length modulation due to a passing GW

$$\Delta L_- = \frac{1}{2}\left(L_N\left(1+\frac{h_0}{2}\cos\left(\omega_{GW}t\right)\right) - L_E\left(1-\frac{h_0}{2}\cos\left(\omega_{GW}t\right)\right)\right)$$

$$\Delta L_- = L_- + h_0 L_+ \cos\left(\omega_{GW}t\right)$$

Since the amplitude of the GW is very small :

$$\cos(a + x\cos b) \simeq \cos(a) - x\sin(a)\cos(b)$$
$$\sin(a + x\cos b) \simeq \sin(a) - x\cos(a)\cos(b)$$

$$E_{Mich}^{BP} \simeq \left(-ie^{-2kL+}\left(\sin(2kL-) + 2kh_0L_+\cos(2kL_-)\cos\left(\omega_{GW}t\right)\right)\right) r_{EM}E_0$$

$$E_{Mich}^{DP} \simeq \left(ie^{-2kL+}\left(\cos(2kL-) - 2kh_0L_+\sin(2kL_-)\cos\left(\omega_{GW}t\right)\right)\right) r_{EM}E_0$$

Need to be on the dark fringe to maximise the signal on the south port !

Finding the right operating point

But, I do not measure an amplitude but a power with my photodiode...

$$\left|E^{DP}_{Mich}\right|^2 \propto \left|\cos(2kL_-) - 2kh_0L_+ \sin(2kL_-) \cos(\omega_{GW}t)\right|^2$$
$$\propto \cos^2(2kL_-) - 4kh_0L_+ \cos(2kL_-) \sin(2kL_-) \cos(\omega_{GW}t) + \mathcal{O}(h_0^2)$$

If perfectly on the dark fringe, signal proportional to h_0^2,

Need to add a slight dark fringe offset to have a signal proportional to h_0

A closer look at the differential phase

Signal proportional to : $\mathrm{kh_0L_+}$

For a simple Michelson, to increase the detectable signal :

1. Lower the wavelength
2. Increase the length of the arm

Wavelength depends on laser availability and optics, it is fixed at 1064 nm for current interferometers.

Some typical lengths for experiments

Type of experiments	Length
Optomechanics	~ 1 mm
Large table top experiments	~ 1m
GW prototypes	~ 10 m
Current GW detectors	~ 1 km
Next generation GW detectors	~ 10 km

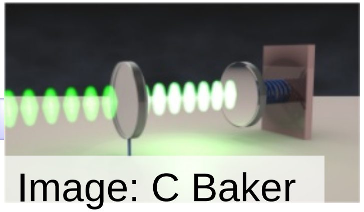
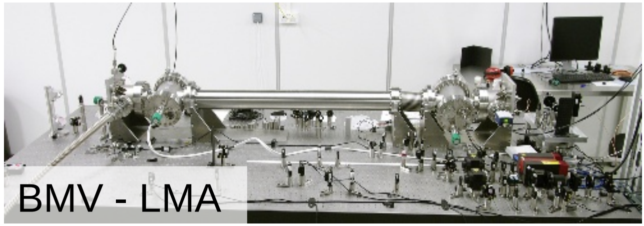
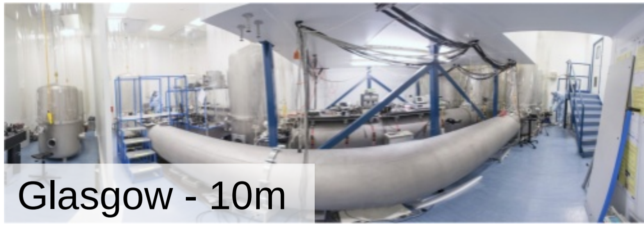
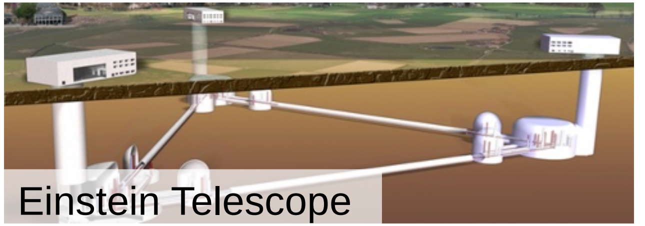


Image: C Baker


BMV - LMA


Glasgow - 10m

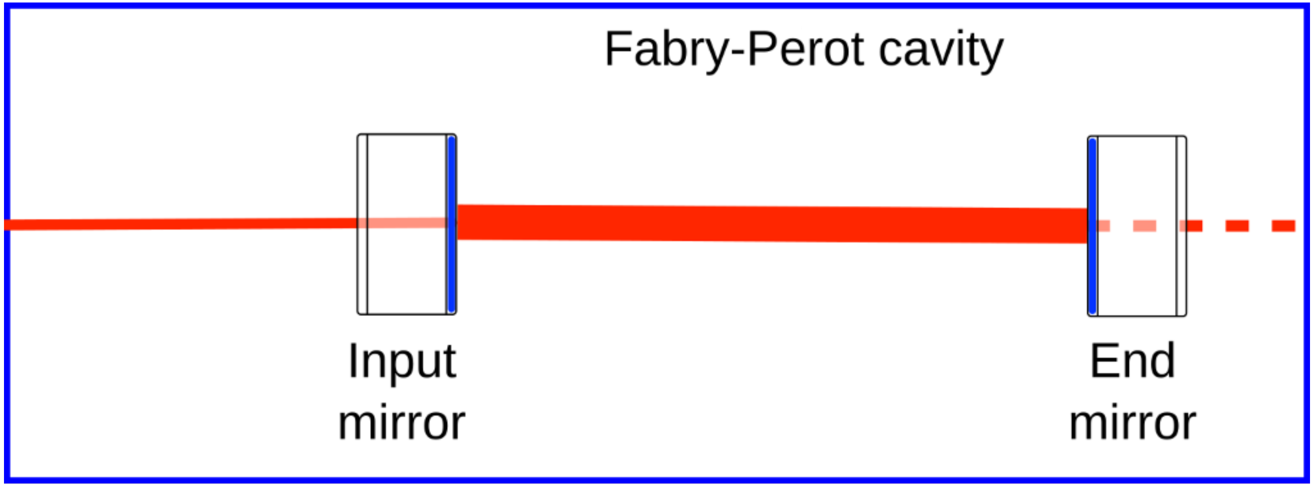

Virgo


Einstein Telescope

III.
More than just a Michelson
(or how to increase the sensitivity ?)

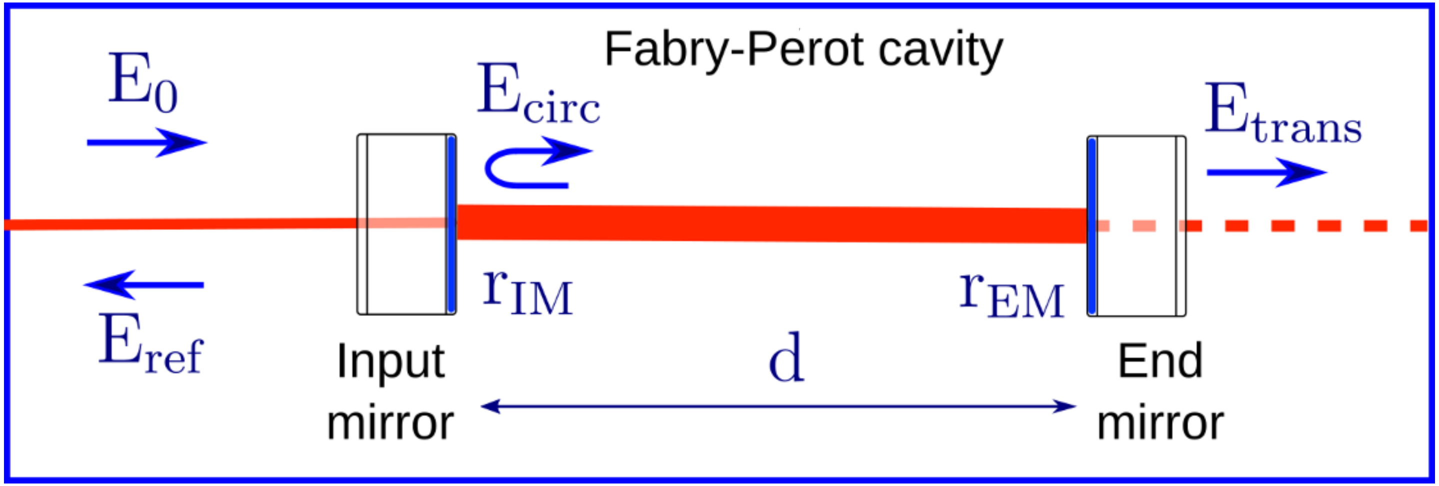
The Fabry-Perot cavity

Two mirrors facing each other separated by a certain distance.



Presence of light interferences inside the cavity, enhancing or destroying the electric field between the 2 mirrors.

Cavity electric fields



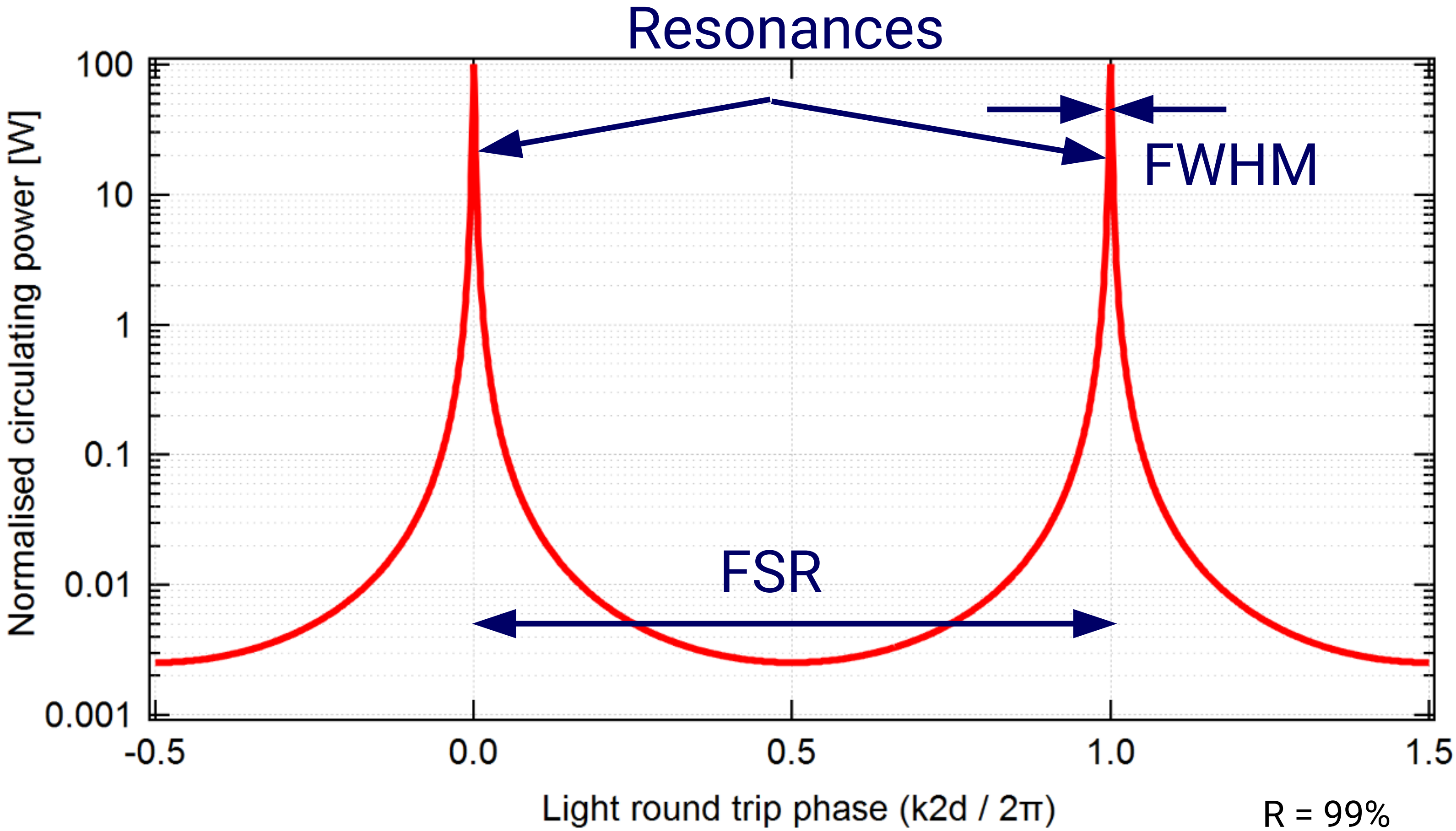
$$E_{circ} = \frac{i t_{IM}}{1 - r_{IM} r_{EM} e^{-ik2d}} E_0$$

$$r_{xx}^2 + t_{xx}^2 = 1$$

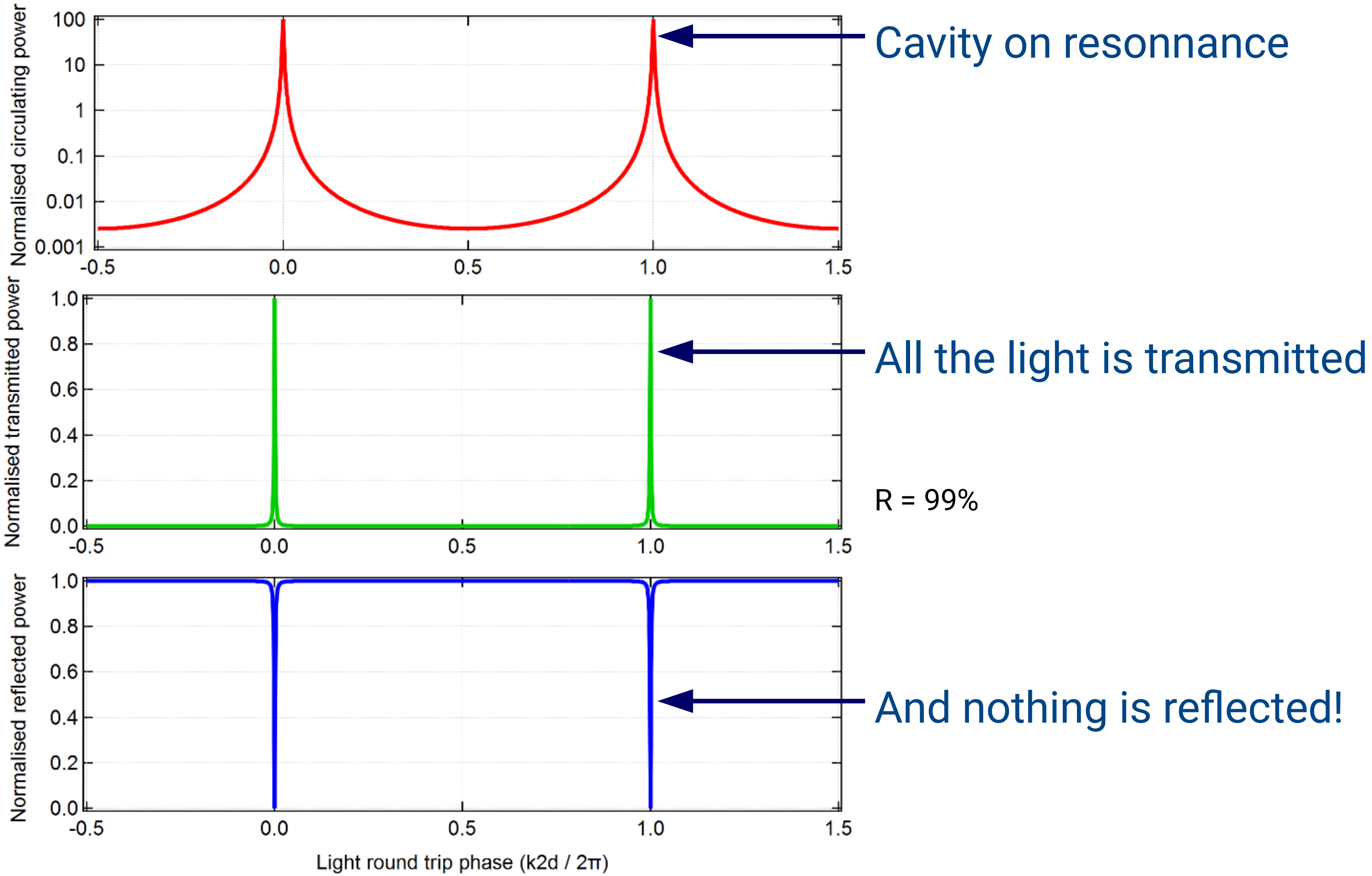
$$E_{trans} = \frac{-t_{IM} t_{EM} e^{-ik2d}}{1 - r_{IM} r_{EM} e^{-ik2d}} E_0$$

$$E_{ref} = \left(r_{IM} - \frac{t_{IM}^2 r_{EM} e^{-ik2d}}{1 - r_{IM} r_{EM} e^{-ik2d}} \right) E_0$$

Circulating power a function of the detuning



R = 99%


Normalised circulating power
100
10
1
0.1
0.01
0.001
-0.5
0.0
0.5
1.0
1.5
Normalised transmitted power
1.0
0.8
0.6
0.4
0.2
0.0
Normalised reflected power
Light round trip phase (k2d / 2π)
Cavity on resonnance
All the light is transmitted
R = 99%
And nothing is reflected!

Some key numbers

The cavity gain $$G = \frac{T_{IM}}{\left(1 - \sqrt{R_{IM} R_{EM}}\right)^2}$$

The finesse $$\mathfrak{F} = \frac{\pi \sqrt[4]{R_{IM} R_{EM}}}{1 - \sqrt{R_{IM} R_{EM}}}$$

The FSR $$\frac{c}{2L}$$

The FWHM $$\frac{FSR}{\mathfrak{F}}$$

Some key numbers

For Advanced Virgo

$T_{IM} = 1.4\ \%$

$T_{EM} = 5\ ppm$

The cavity gain $$G = \frac{T_{IM}}{\left(1 - \sqrt{R_{IM} R_{EM}}\right)^2}$$ 280

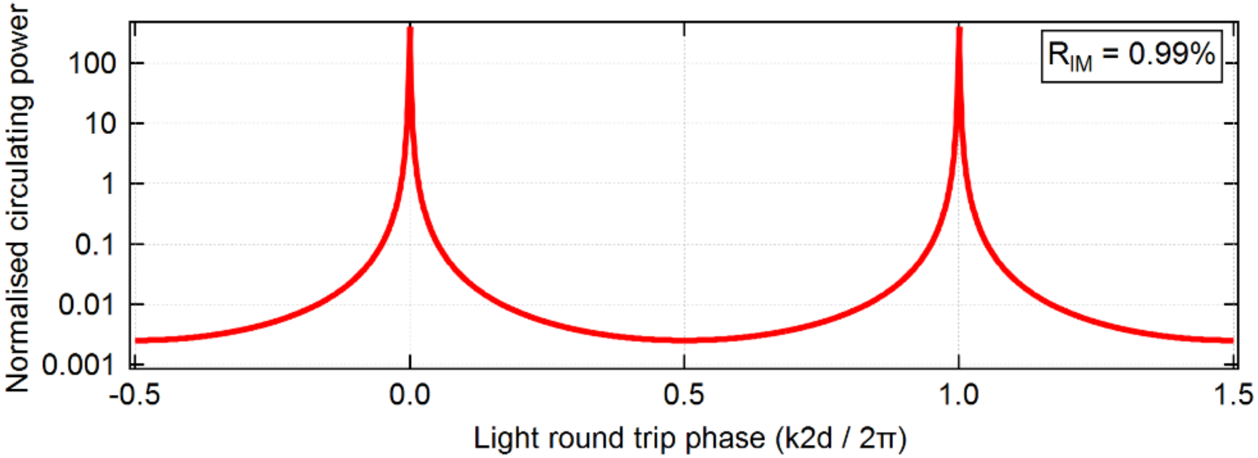
The finesse $$\mathfrak{F} = \frac{\pi \sqrt[4]{R_{IM} R_{EM}}}{1 - \sqrt{R_{IM} R_{EM}}}$$ 450

The FSR $$\frac{c}{2L}$$ 50 kHz

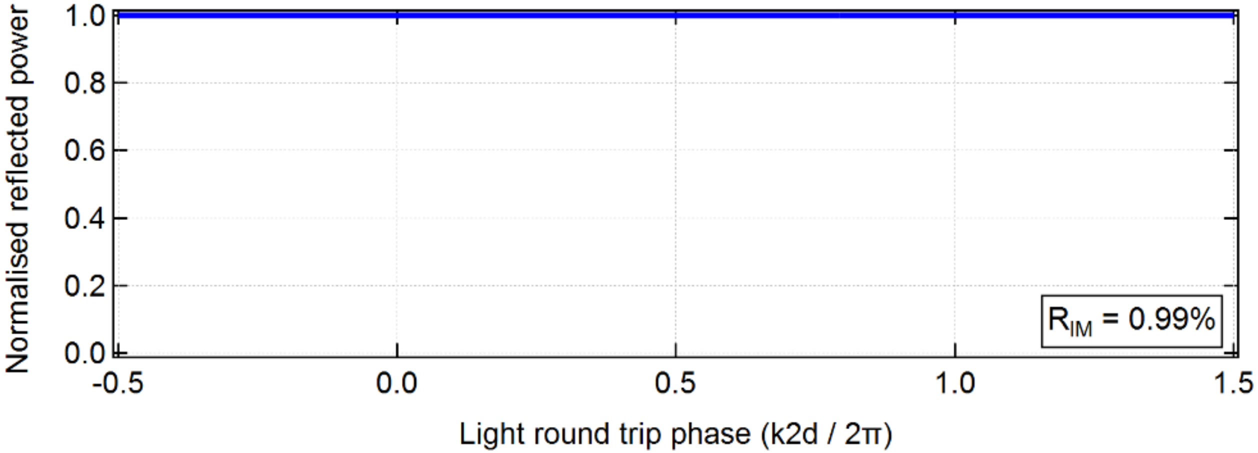
The FWHM $$\frac{FSR}{\mathfrak{F}}$$ 110 Hz

(2 xbandwidth of the cavity)

Special case of the arm cavity of GW detectors

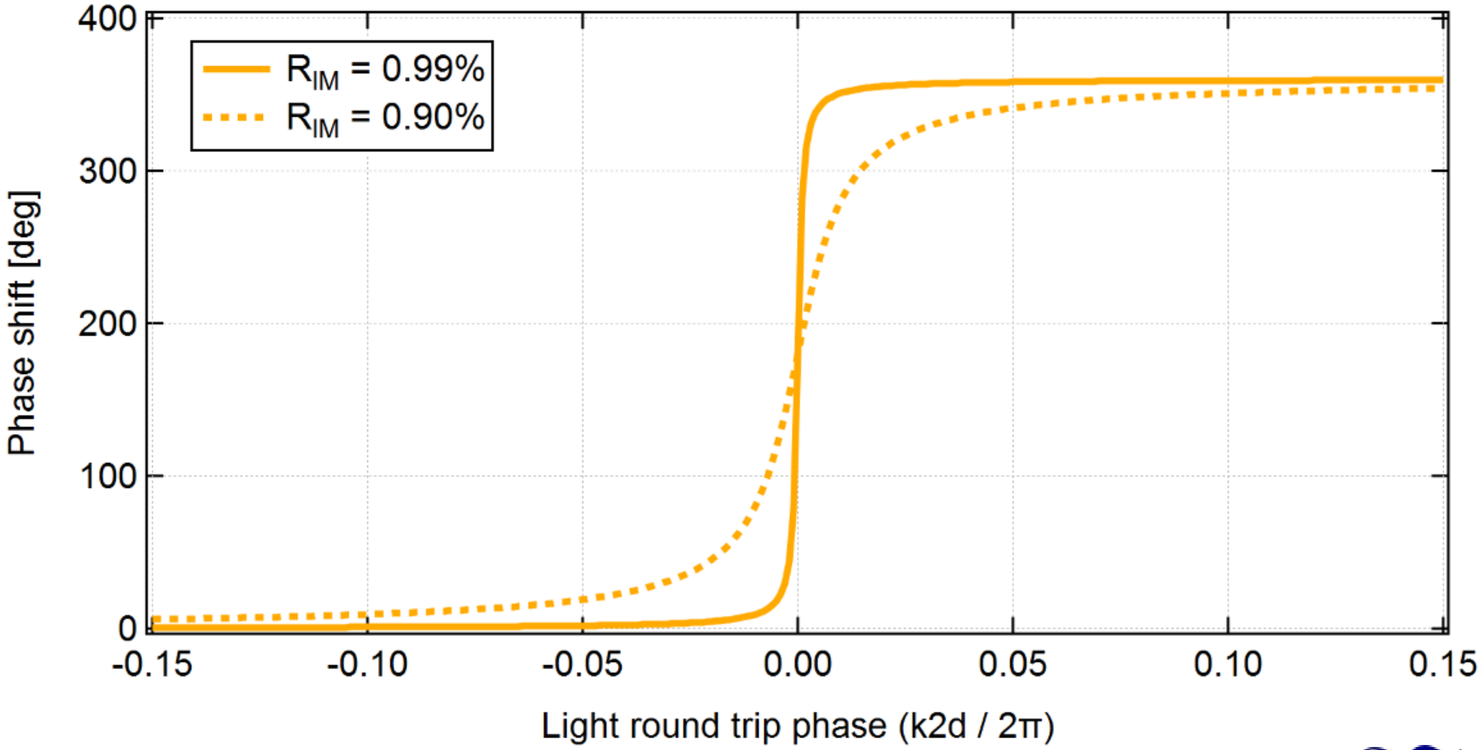


The end mirror is almost perfectly reflective



All the light is reflected by the cavity

The cavity can amplify the light phase shift



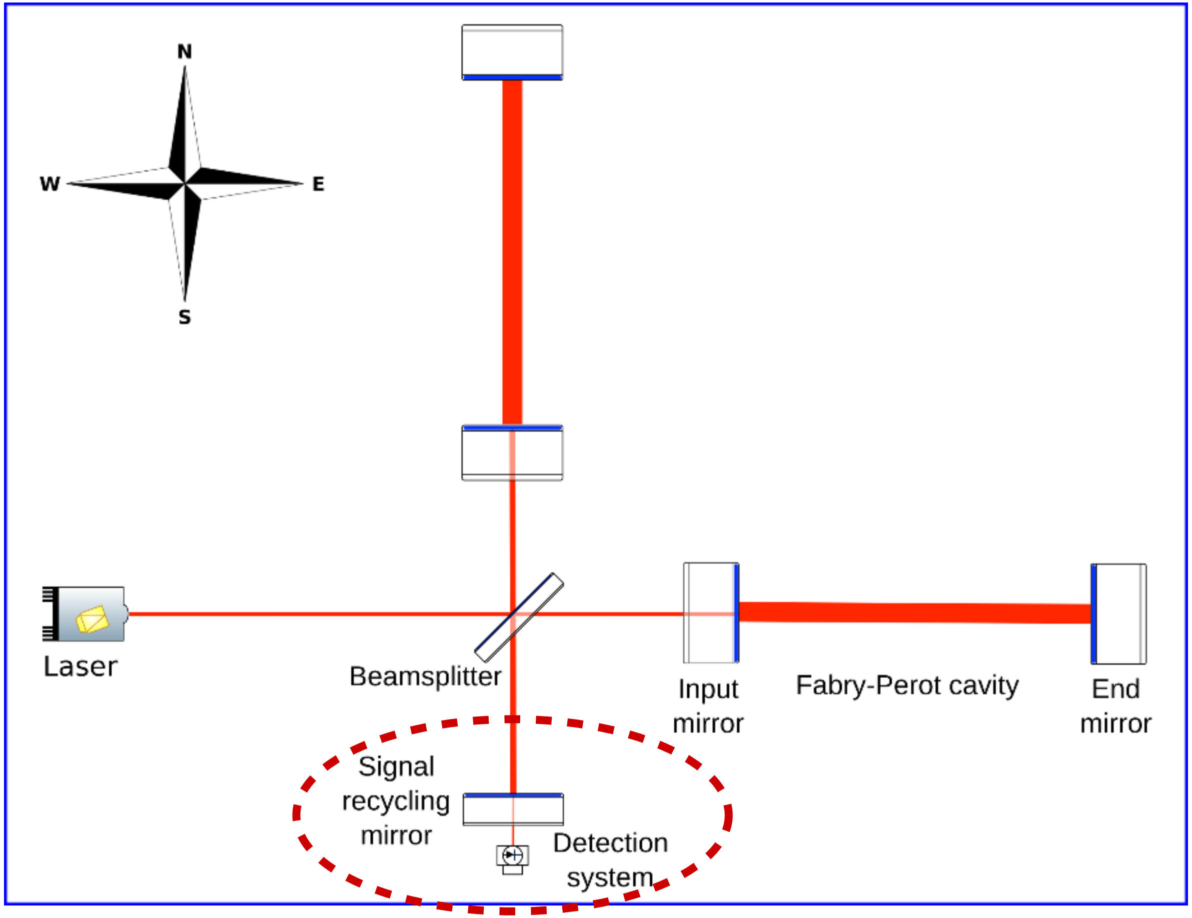
But only when the cavity is on resonance!

$$G = \frac{4}{T_{IM}}$$

$$\mathfrak{F} = \frac{2\pi}{T_{IM}}$$

Amplification of the GW phase shift by a factor : $\frac{2\mathfrak{F}}{\pi}$ ~ 280

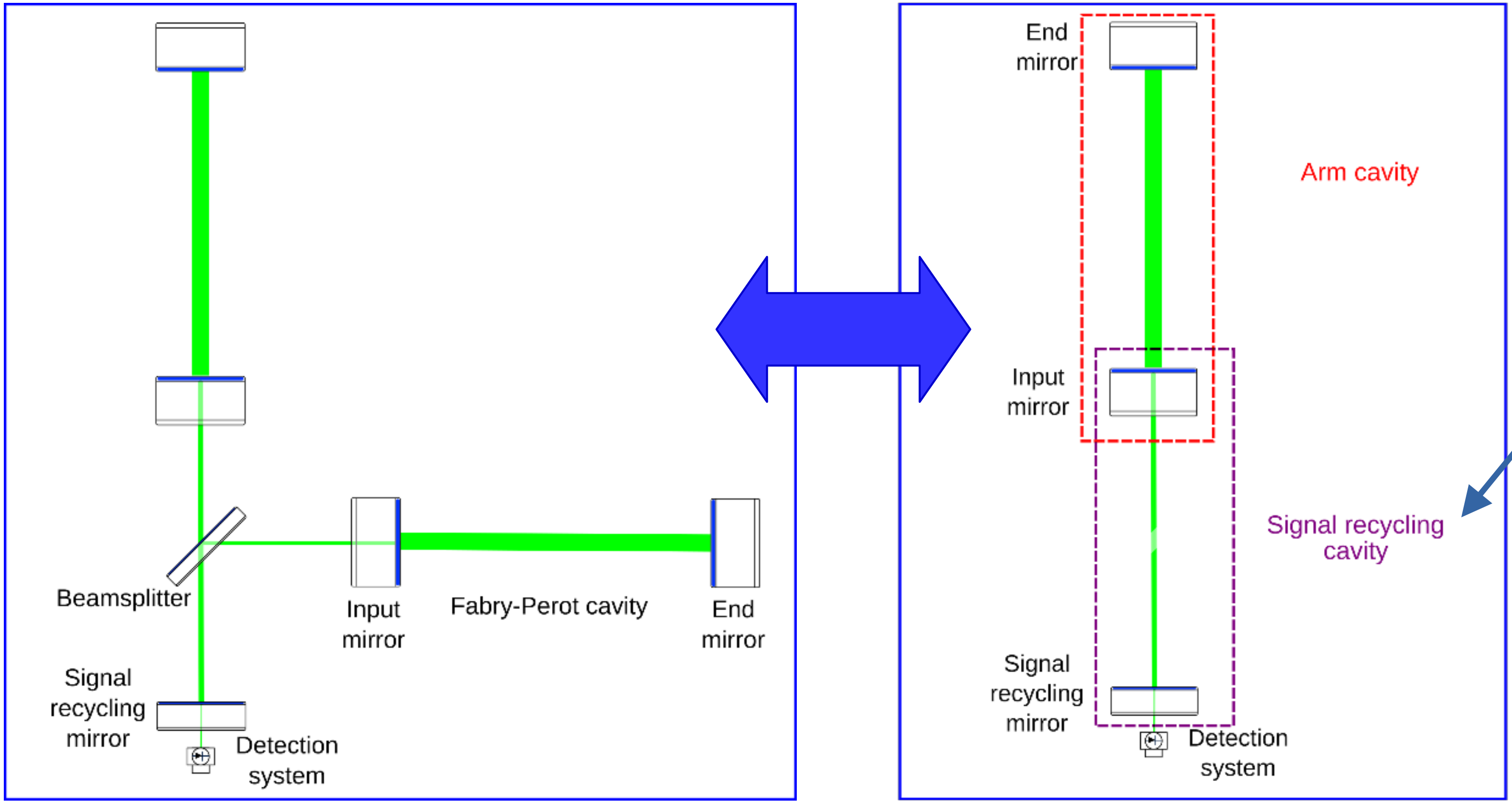
The signal recycling cavity



New mirror at the detection port to form the signal recycing cavity

Create a new cavity with the arm cavities

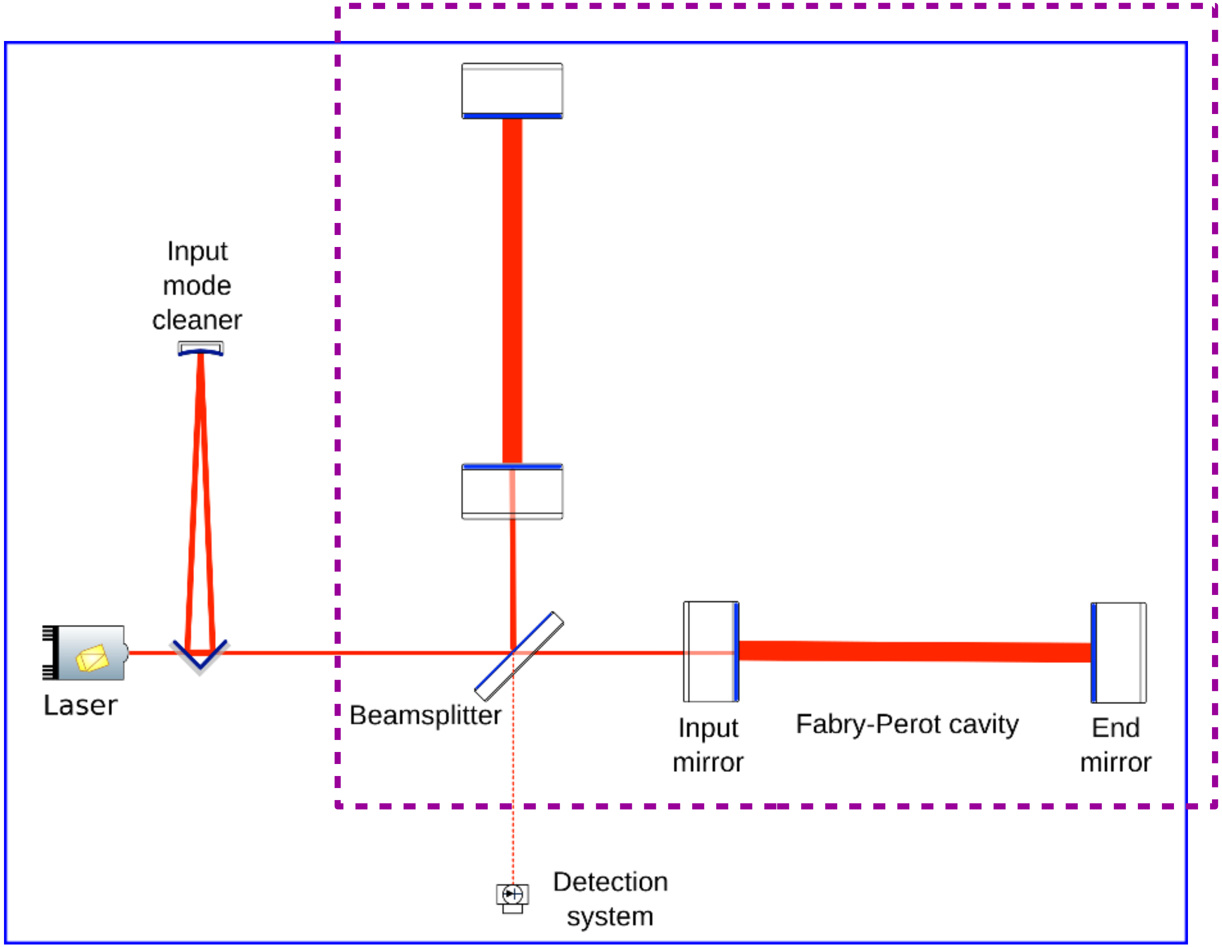
For the GW signal sidebands



View from the end mirror, the SR cavity could be seen as a mirror.

Possibility to tune the apparent transmission of input mirror for the GW signal → could tune the bandwidth of the detector

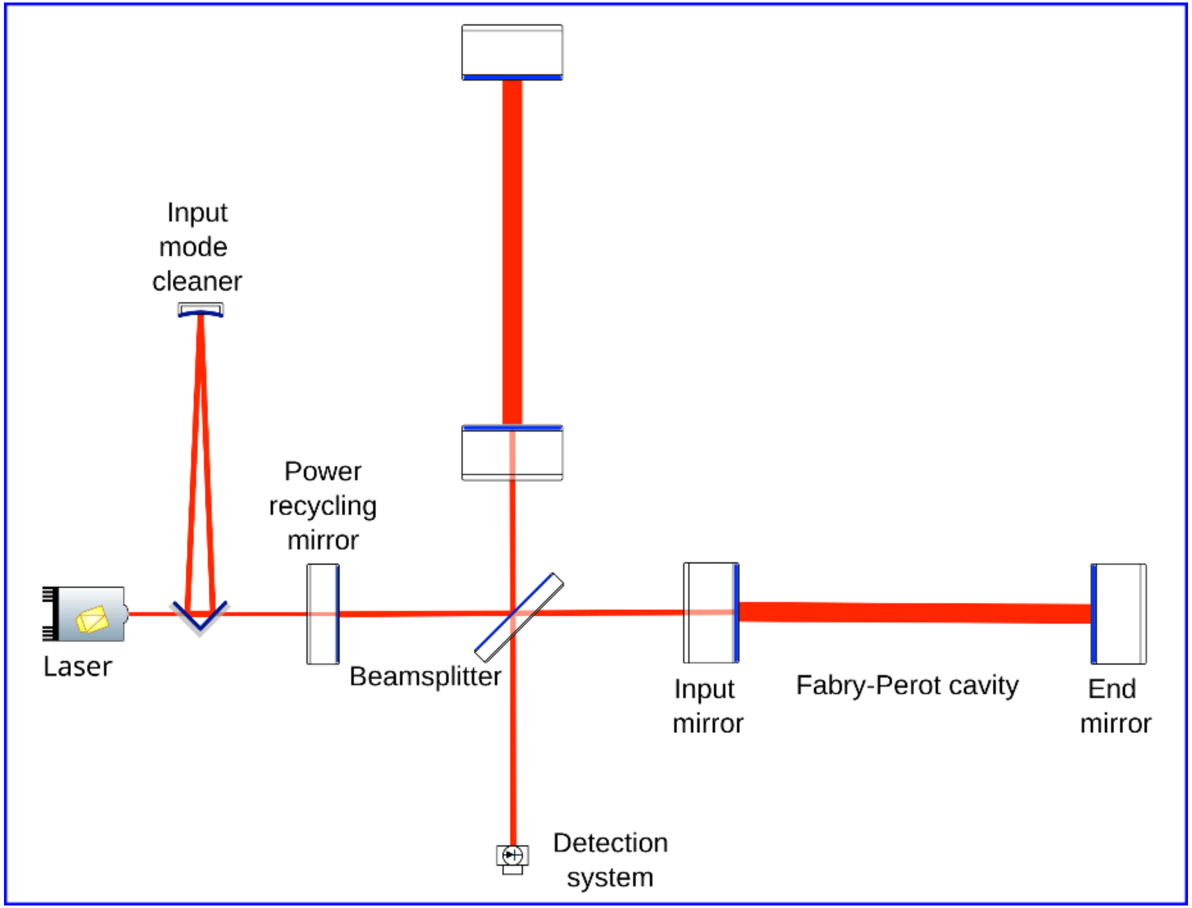
The power recycling cavity



View from the laser, all the power is reflected back.

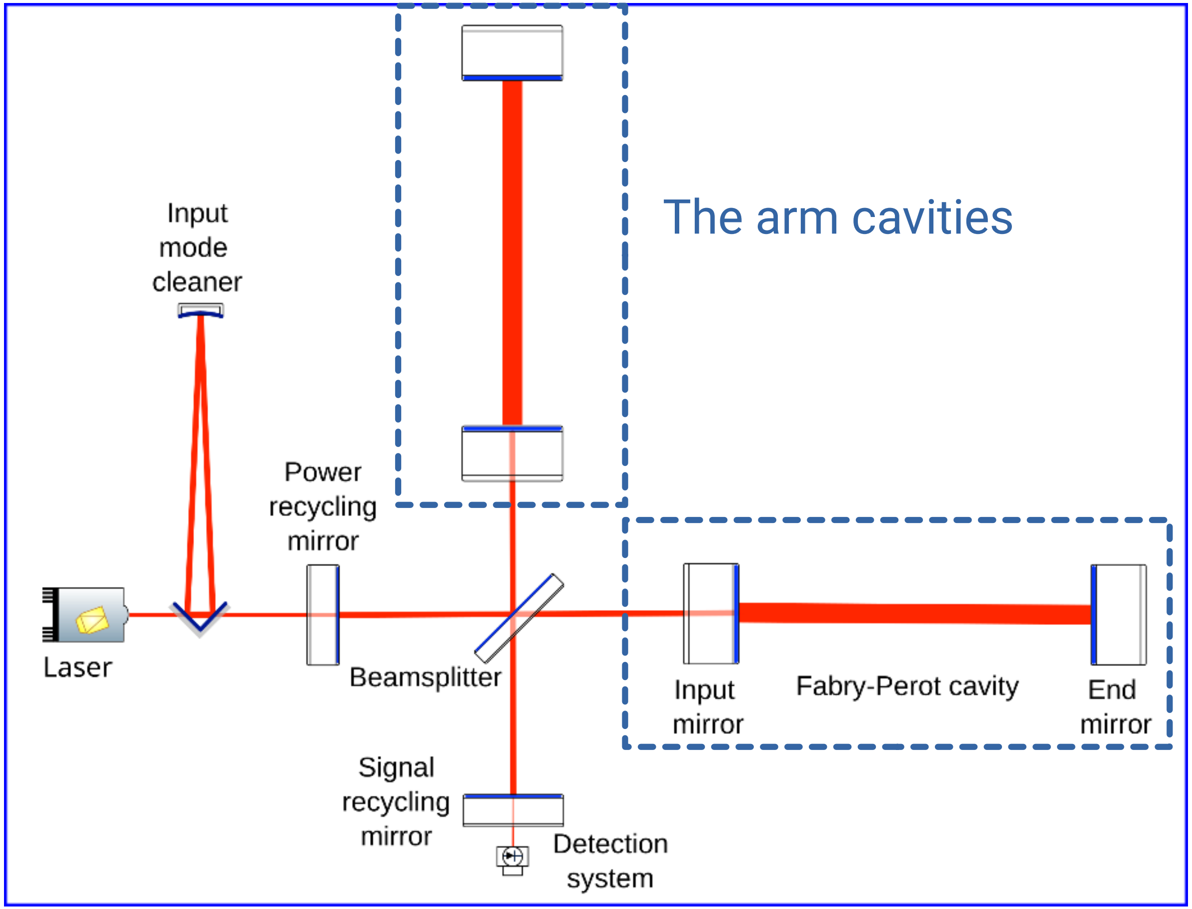
Could be the end mirror of a cavity

The power recycling cavity

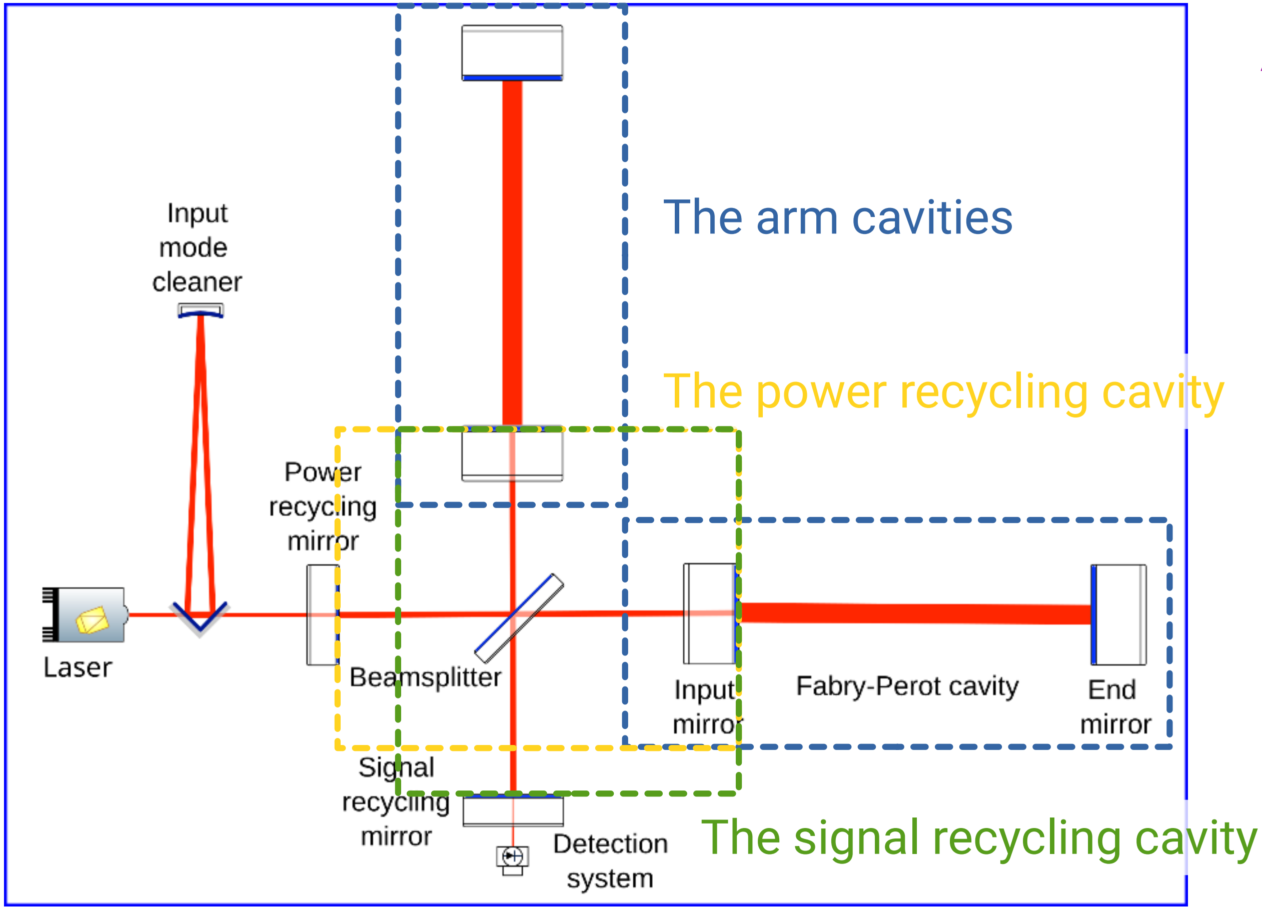


Possibility to enhance the laser power by a factor 40.

The layout of a GW detector



The layout of a GW detector



A system of coupled cavities...

IV.
The fundamental limiting noises

How to quantify the noise ?

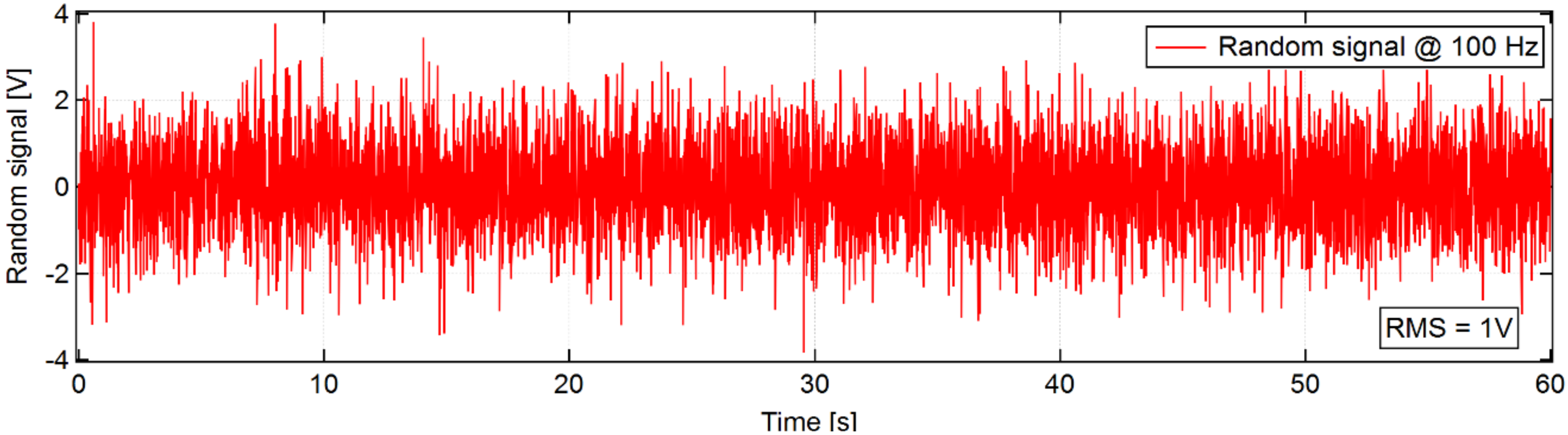
Use the power spectral density : S_V

$$S_V(\omega) = \lim_{T\to\infty} \frac{1}{2T} \left| \int_{-T}^{+T} V(t) e^{-i\omega t} dt \right|^2$$

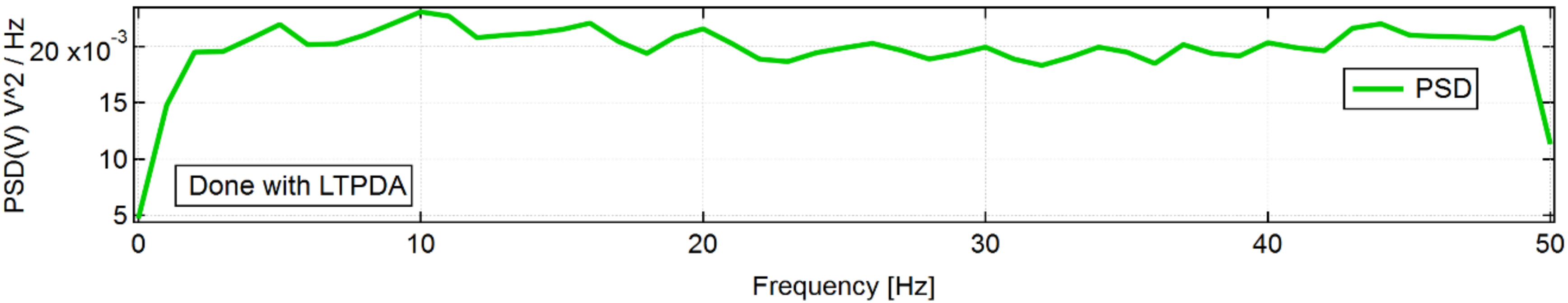
In unit of : $\frac{[V]^2}{Hz}$, that represents the noise power density in a given bandwidth as a function of the frequency.

More frequently, we use the noise **Amplitude** Spectral Density (ASD): $\sqrt{S_V(\omega)}$

Ok, that definition does not really help!



White noise during 60 seconds

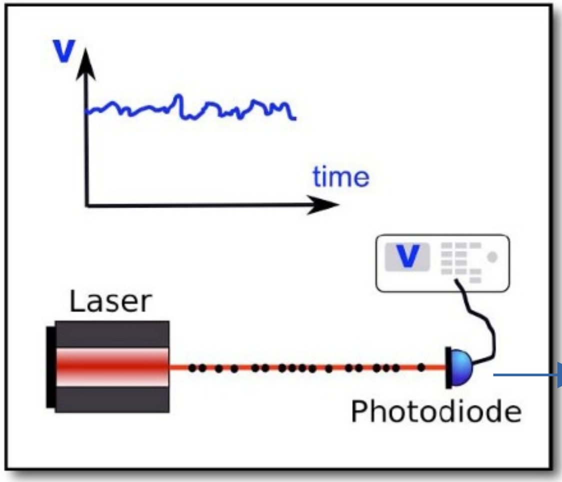


$$\mathrm{RMS_V} = \lim_{T\to\infty}\sqrt{\frac{1}{T}\int_0^T V^2(t)dt}$$

$$\mathrm{RMS_V^2} = \int_0^\infty S_V(\omega)d\omega$$

The intrinsic shot noise

Measuring an optical power is counting the number of photon for a given time.



P the optical power

Due to the discrete nature of light, arrival time of photons follows a Poisson statistics :

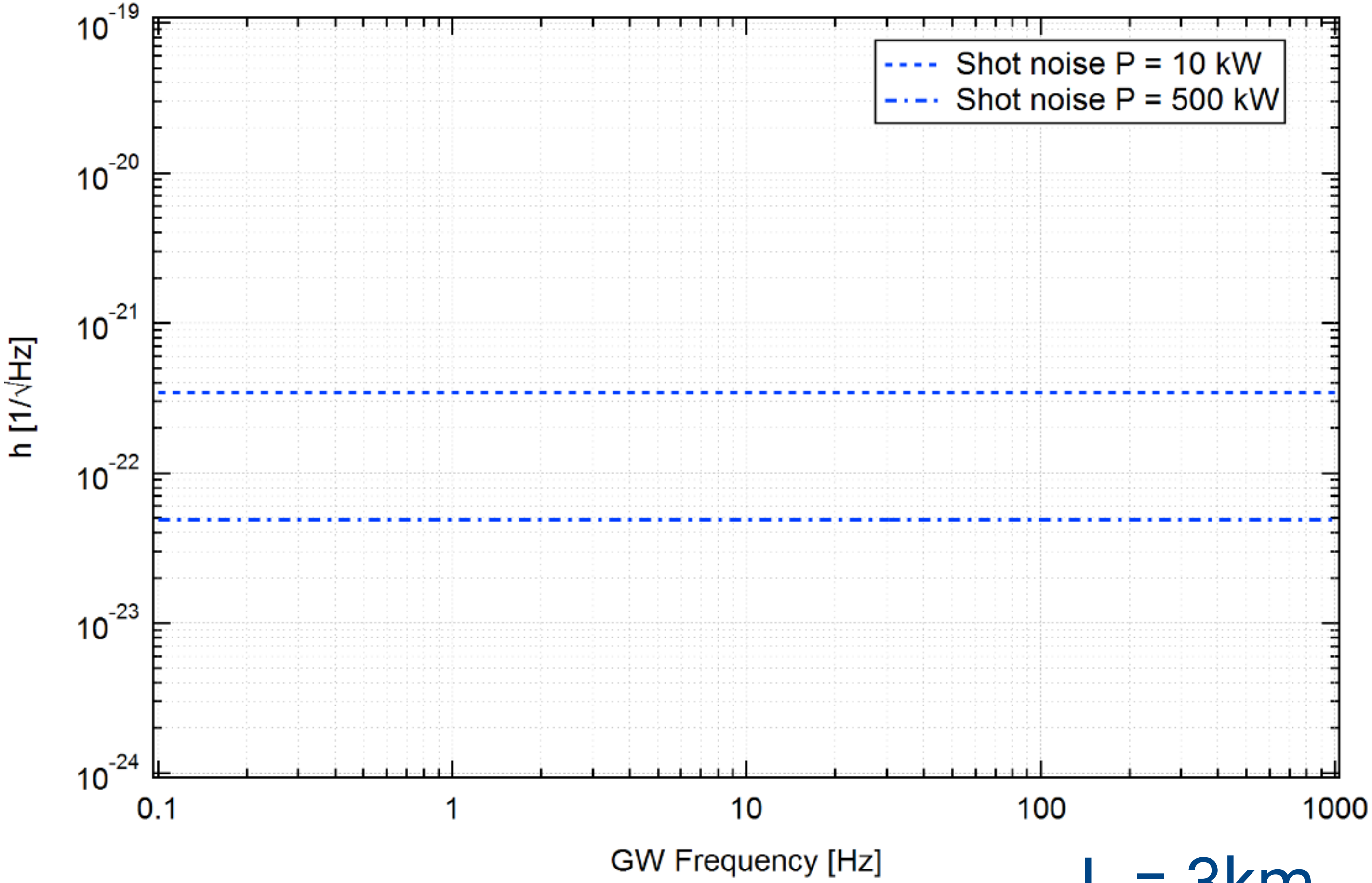
$$S_{SN}(\omega) = 2Ph_p\frac{c}{\lambda}$$

Formula will determine the minimum possible differential displacement to measure

Shot noise limited (simple) Michelson

$\Delta L = (1/2)\, h \times L$

ASD output power of my signal proportional to h and laser input power.



L = 3km

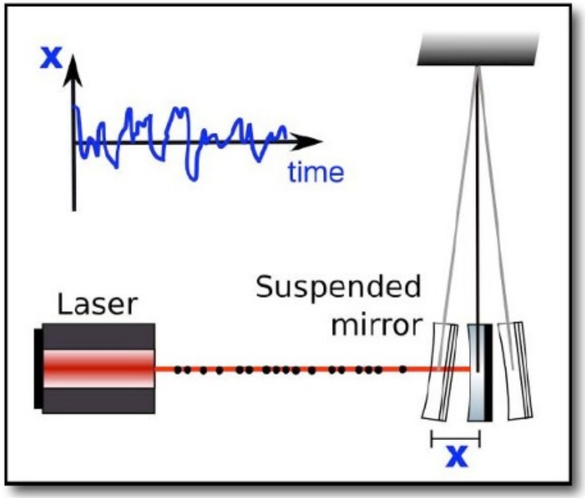
From the minimum displacement we can measure (SNR = 1), we can calculate the minimum h observable (GW amplitude)

$$S_h^{min}(\omega) = \frac{1}{(2\pi L_+)^2} \frac{h_p \lambda c}{P_0}$$

$$\sqrt{S_h^{min}(\omega)} = \frac{2 \times 10^{-20}}{\sqrt{P_0}} [1/\sqrt{Hz}]$$

Radiation pressure noise

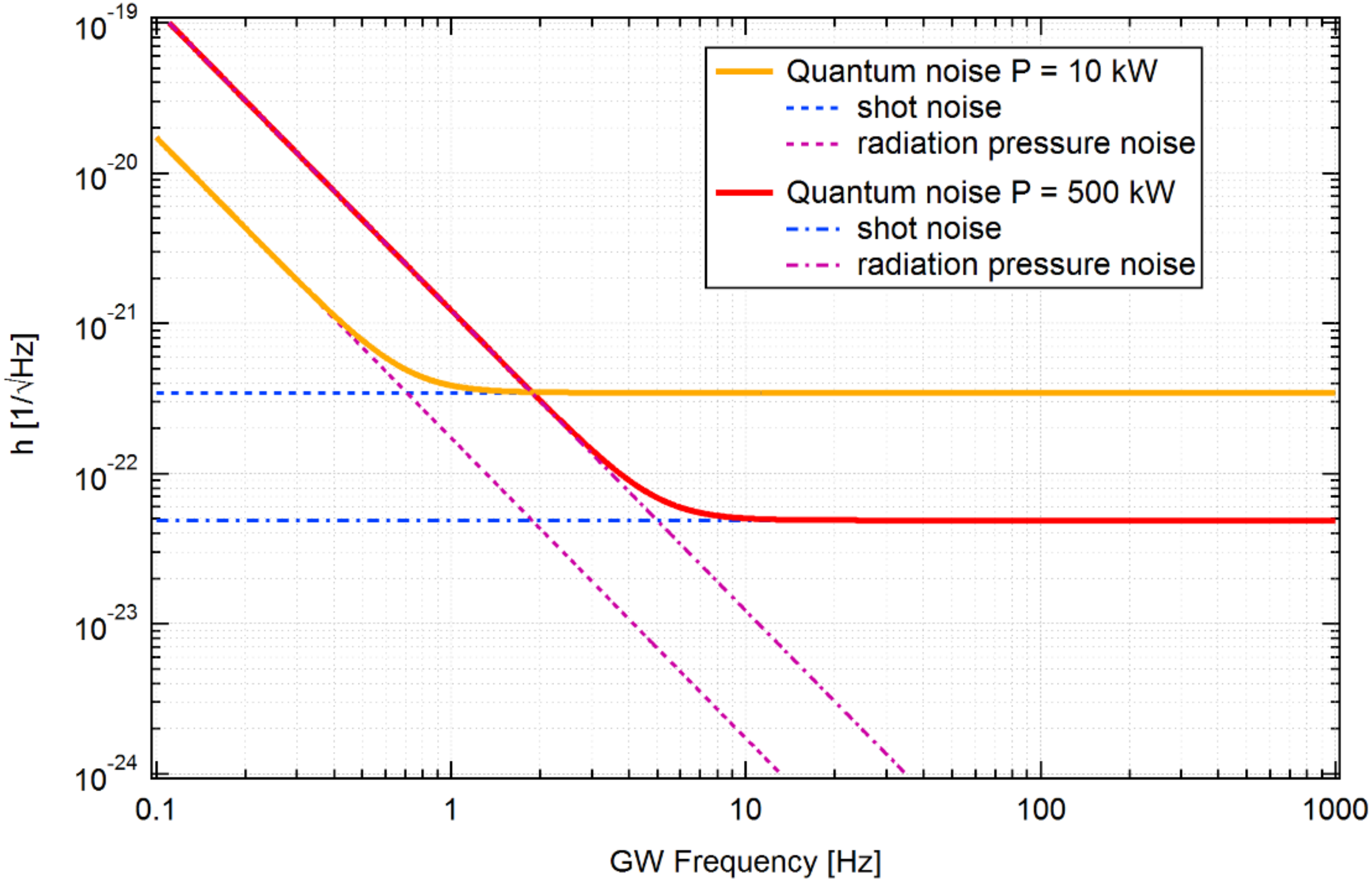
Measuring the mirror position with light, induced a back action : the radiation pressure noise.



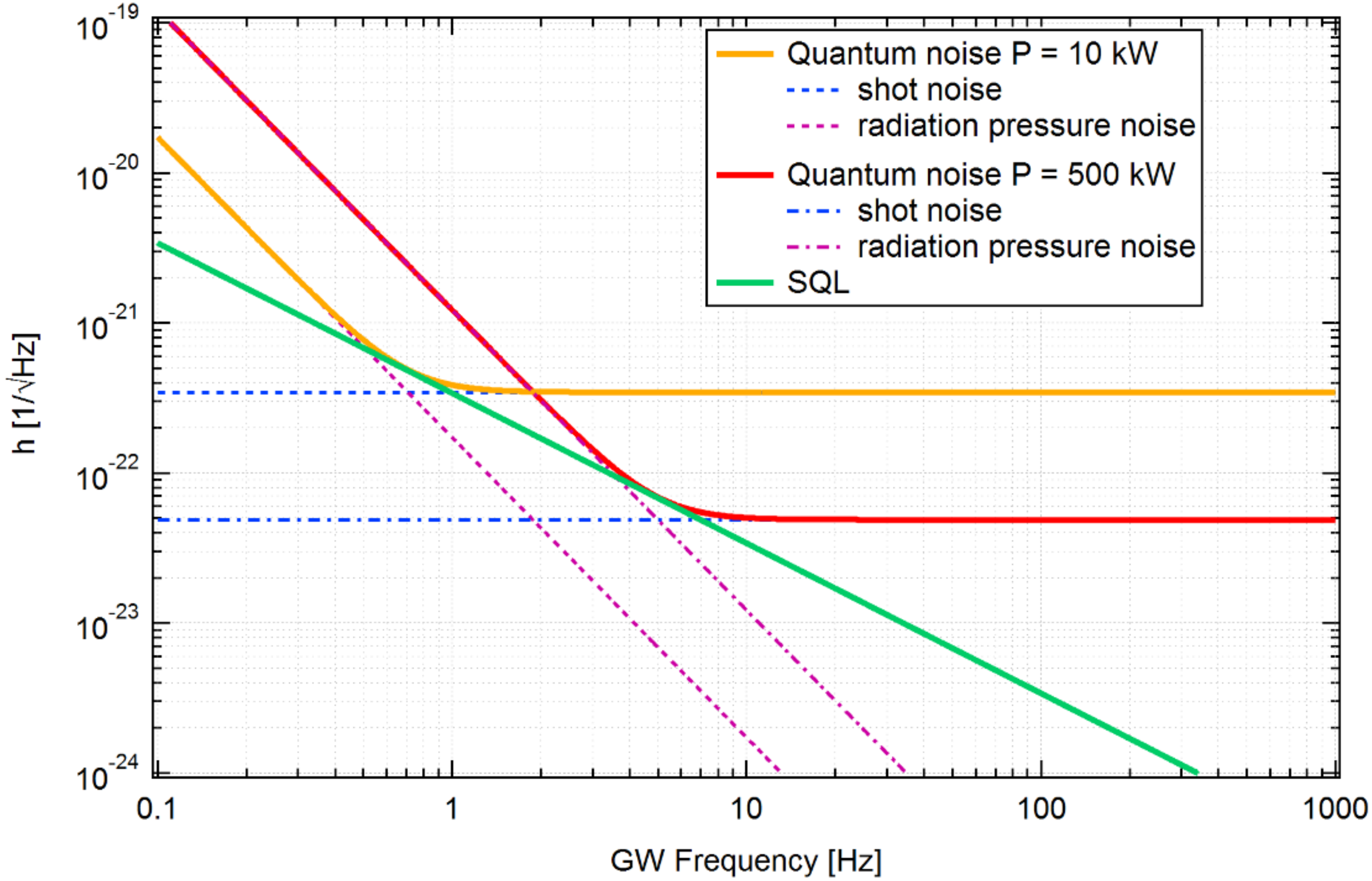
$$F = 2\frac{P_{inc}}{c}$$

Noise PSD for a simple Michelson : $S_{RP}(\omega) = \frac{1}{mL\omega^2}\sqrt{\frac{4hP}{c\lambda}}$

Quantum noise limited (simple) Michelson



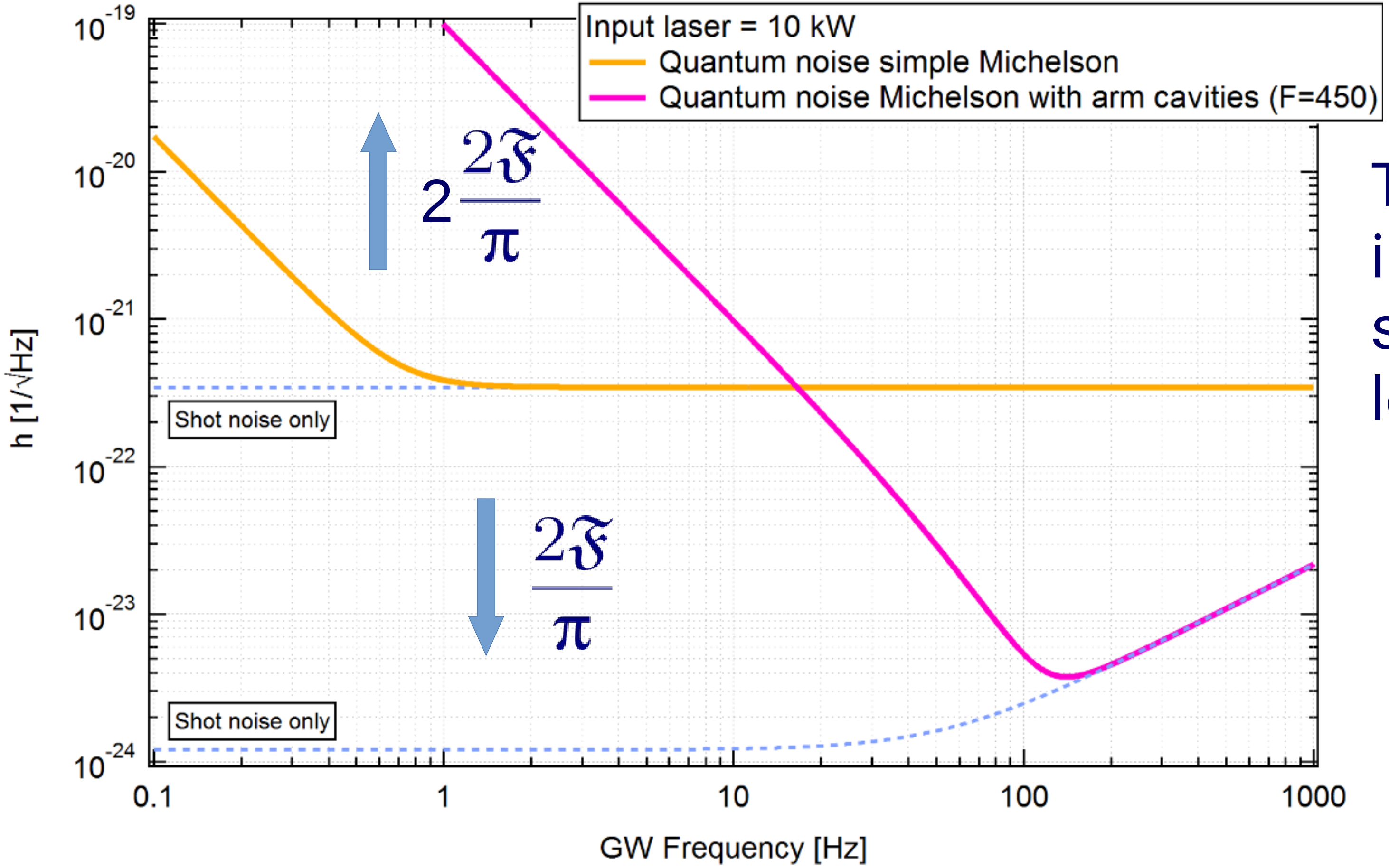
Quantum noise limited (simple) Michelson



SQL = standard quantum limit

$$h_{SQL}(\omega) = \sqrt{\frac{2h}{\pi m L^2 \omega^2}}$$

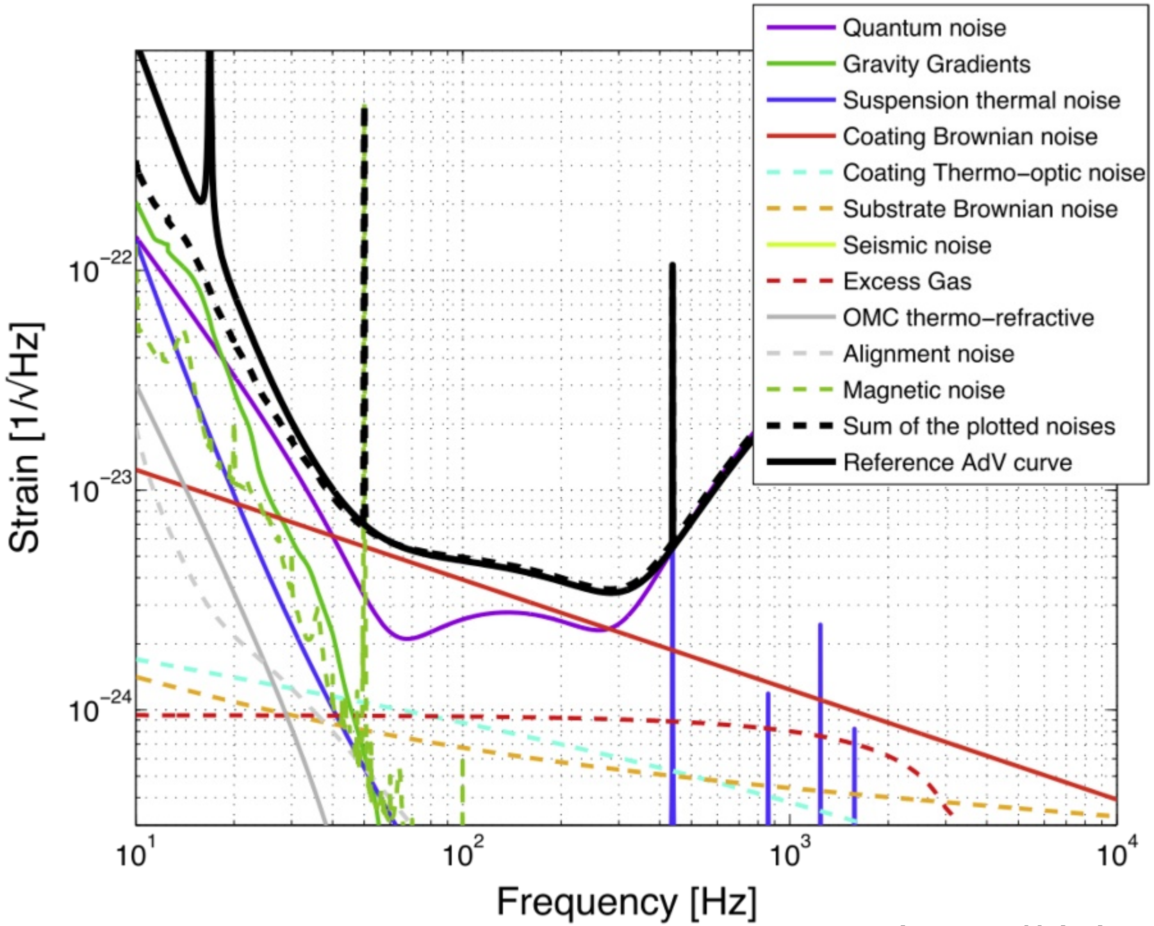
Quantum noise with FP arm cavities



The FP arm cavity, increases the signal but act as a low-pass filter

V.
The technial limiting noises

The Advanced Virgo noise budget

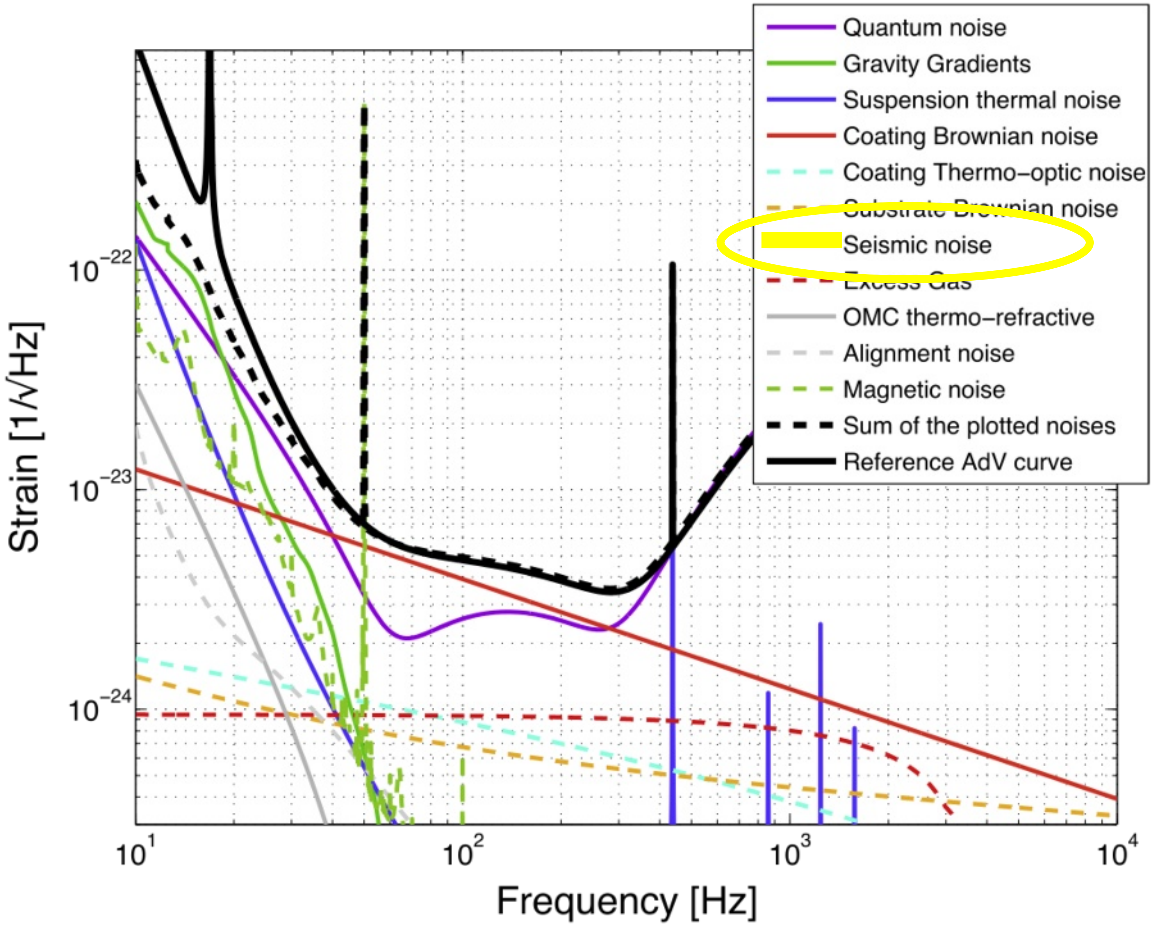


Done in 2012 for the expected final configuration of AVirgo

Similar noise budget for Advanced LIGO

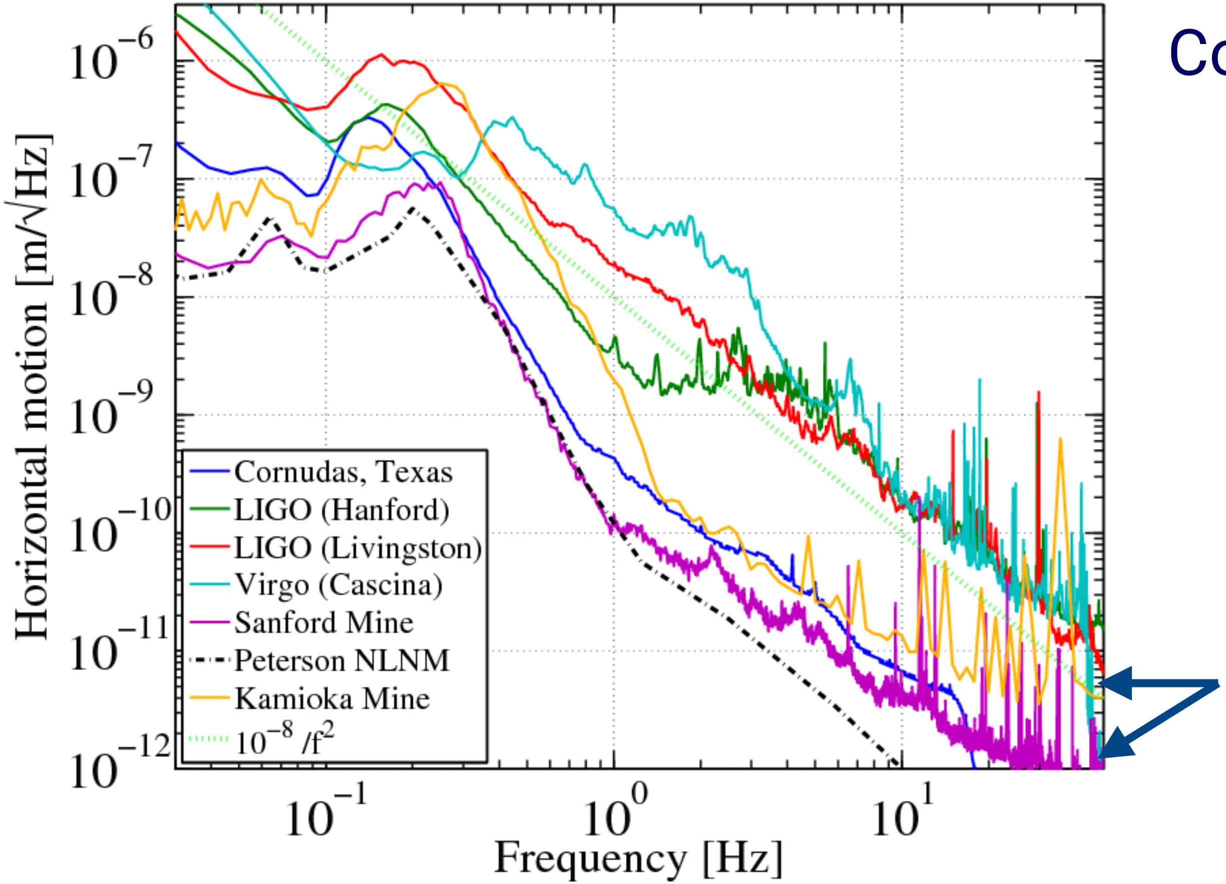
https://doi.org/10.1088/0264-9381/32/2/024001

The Advanced Virgo noise budget



Not limiting :
the seismic noise

The ground is never still!



Comparison of different sites

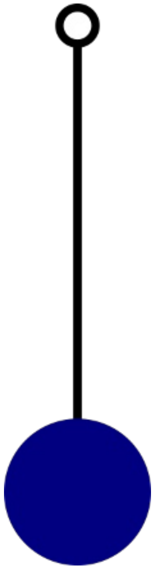
Underground

Gravitational radiation detection with laser interferometry – R. Adhikari - Rev. Mod. Phys. 86, 121

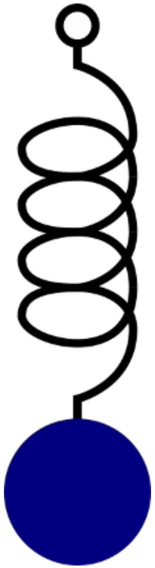
Isolate the mirror from the seismic motion

- Must isolate all degrees of freedom
- Suspension based on pendula :

https://doi.org/10.1063/1.1150645

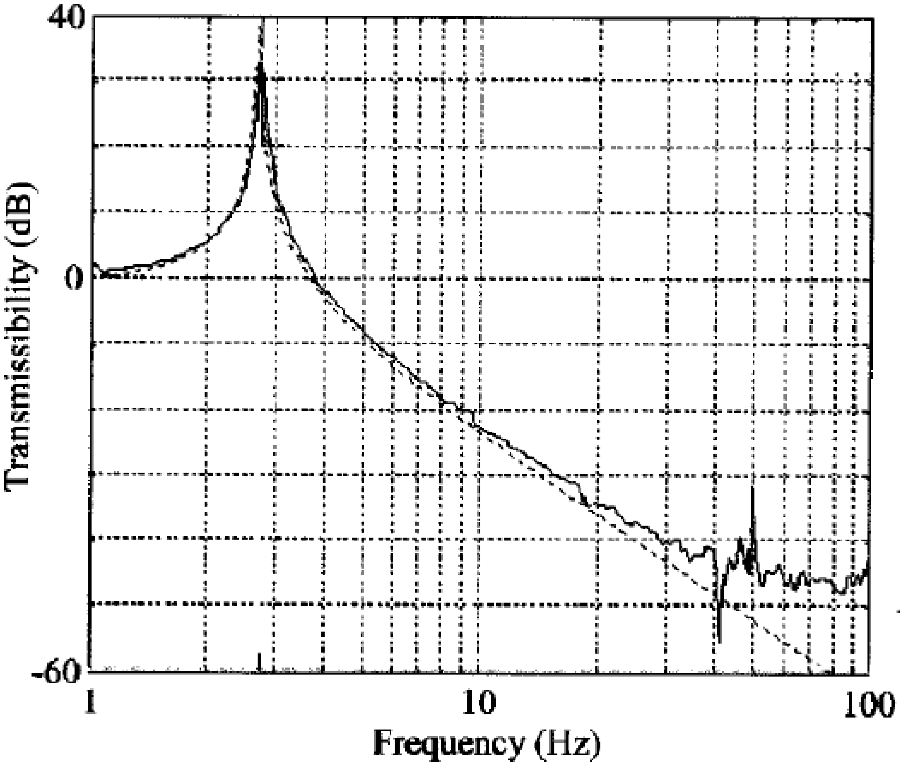


My mirror



Horizontal isolation

Vertical isolation



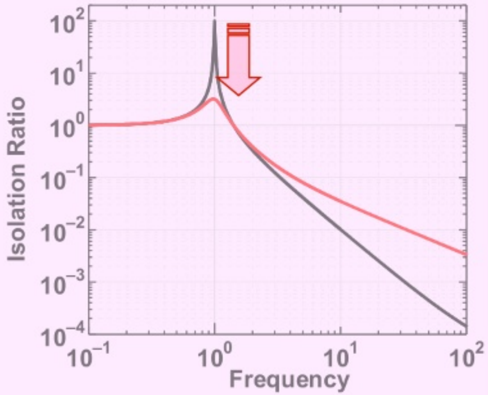
Transfer function

Possibility to tune the isolation

- How to get more isolation?

Damping

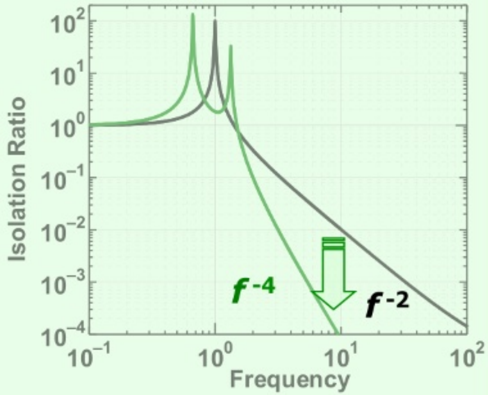
Lower the peak height



Worse isolation

Multi stage

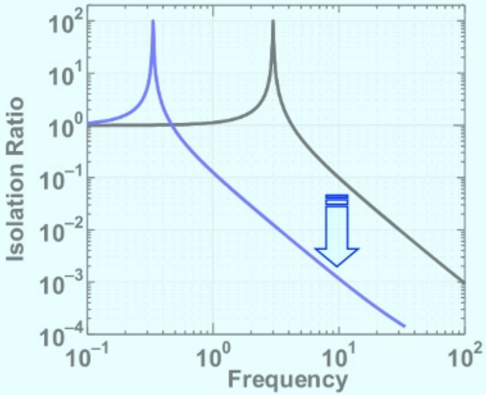
Steeper isolation curve



More peaks

Lower resonant freq

Better isolation



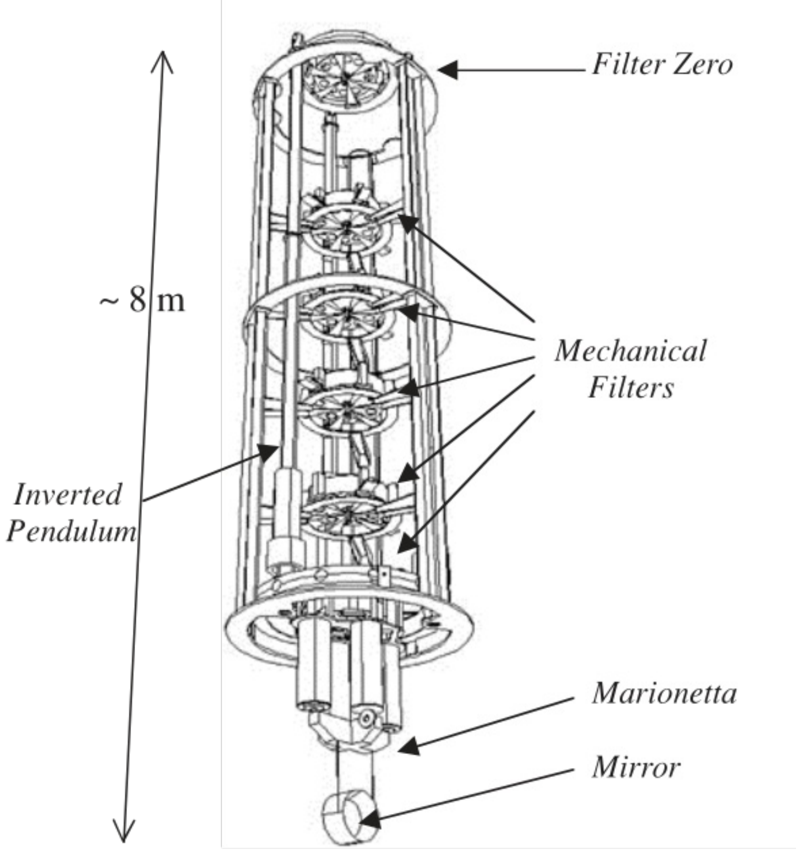
Complex to realize

- In practice: employ combination of these measures

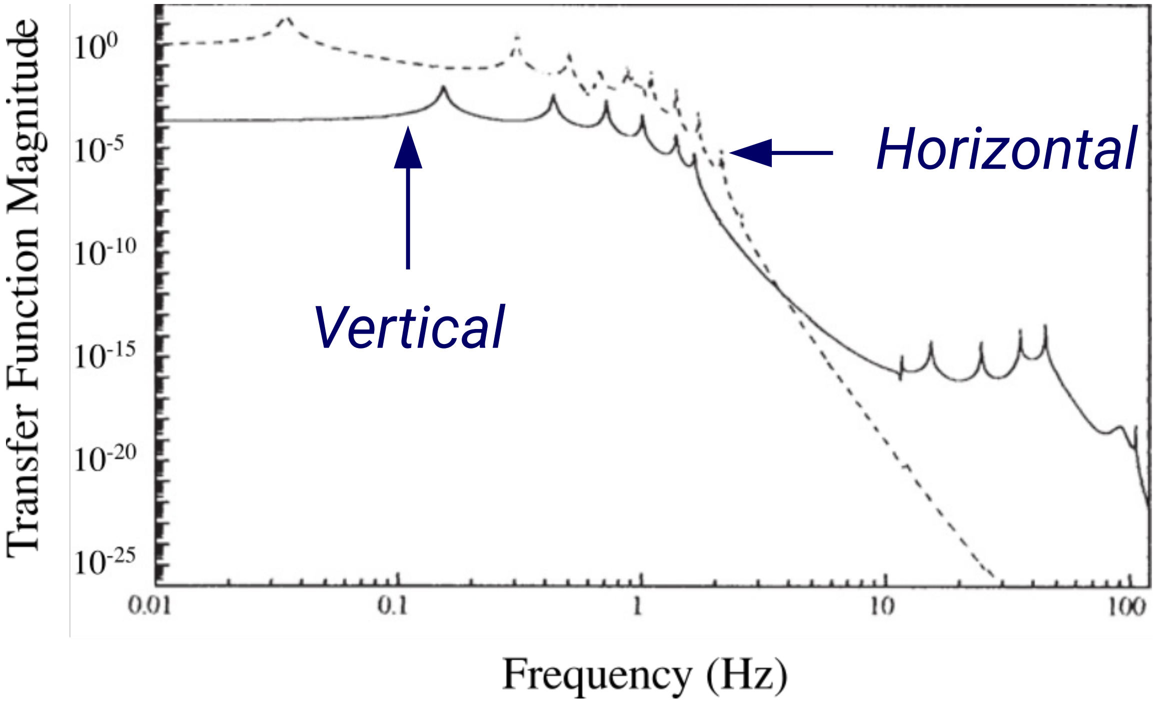
Taken from: Noises in Gravitational Wave Detectors, K. Arai, LIGO Document G1401145-v2

The Virgo supper attenuator

https://doi.org/10.1088/0264-9381/19/7/353



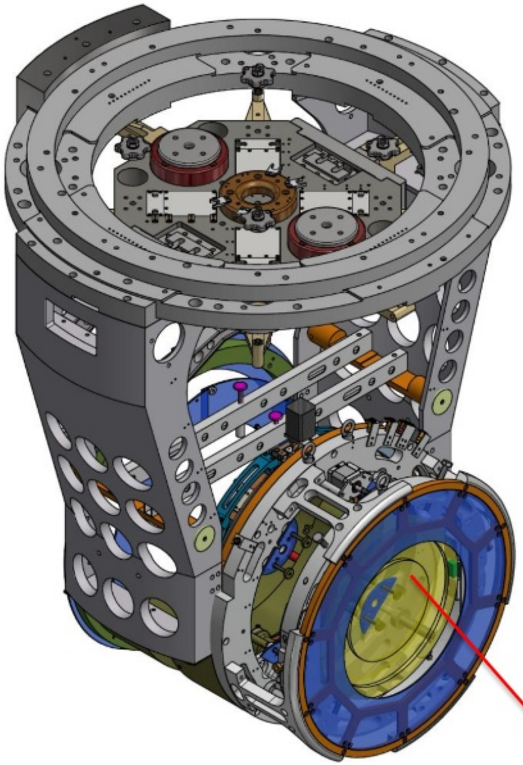
Virgo supper attenuator

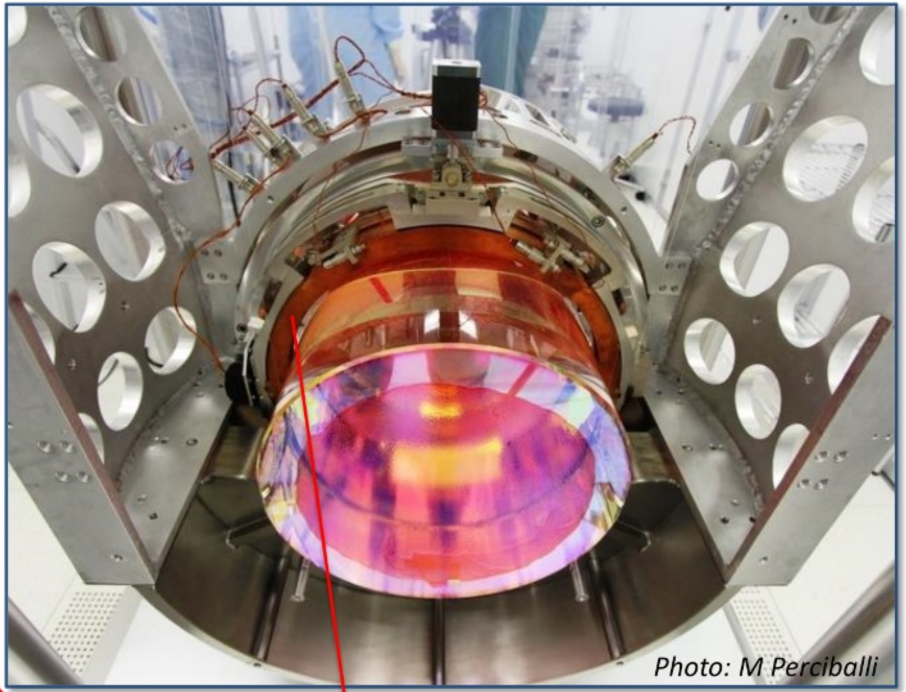


Isolation transfert function

The last stage of the suspension

Where the mirror is attached



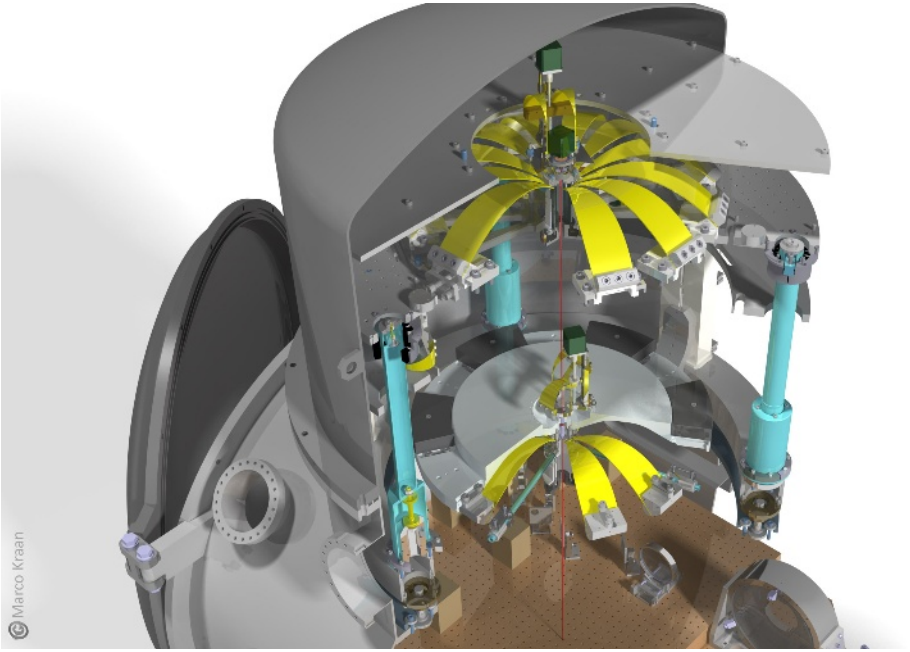


TCS: thermal compensation
(Compensation Plate and Ring Heater)

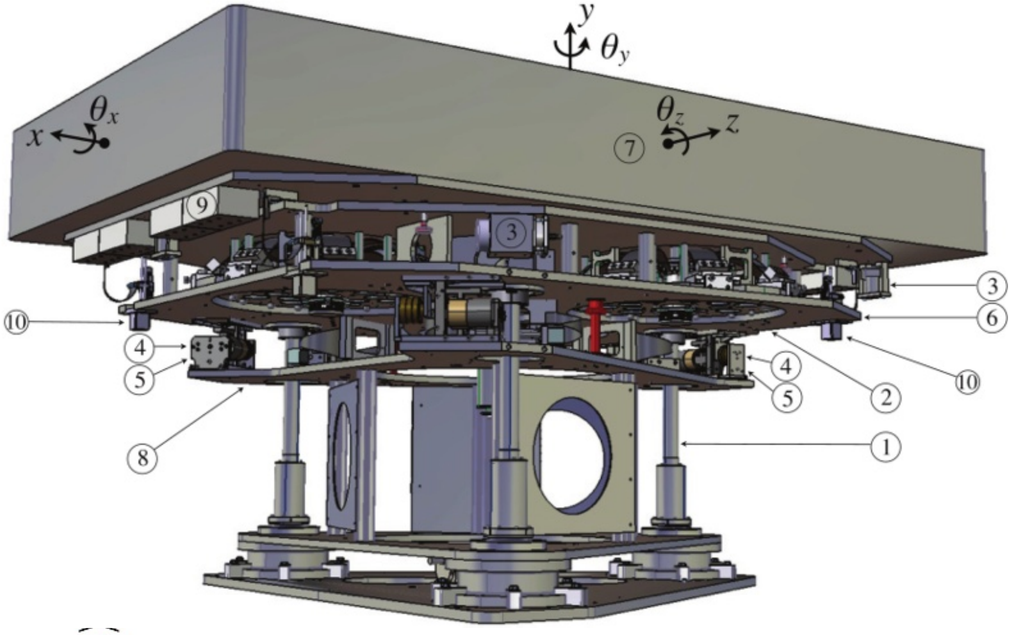
Taken from: The payloads of Advanced Virgo: current status and upgrades – Naticchioni – Amaldi 12

Not only for the main mirrors

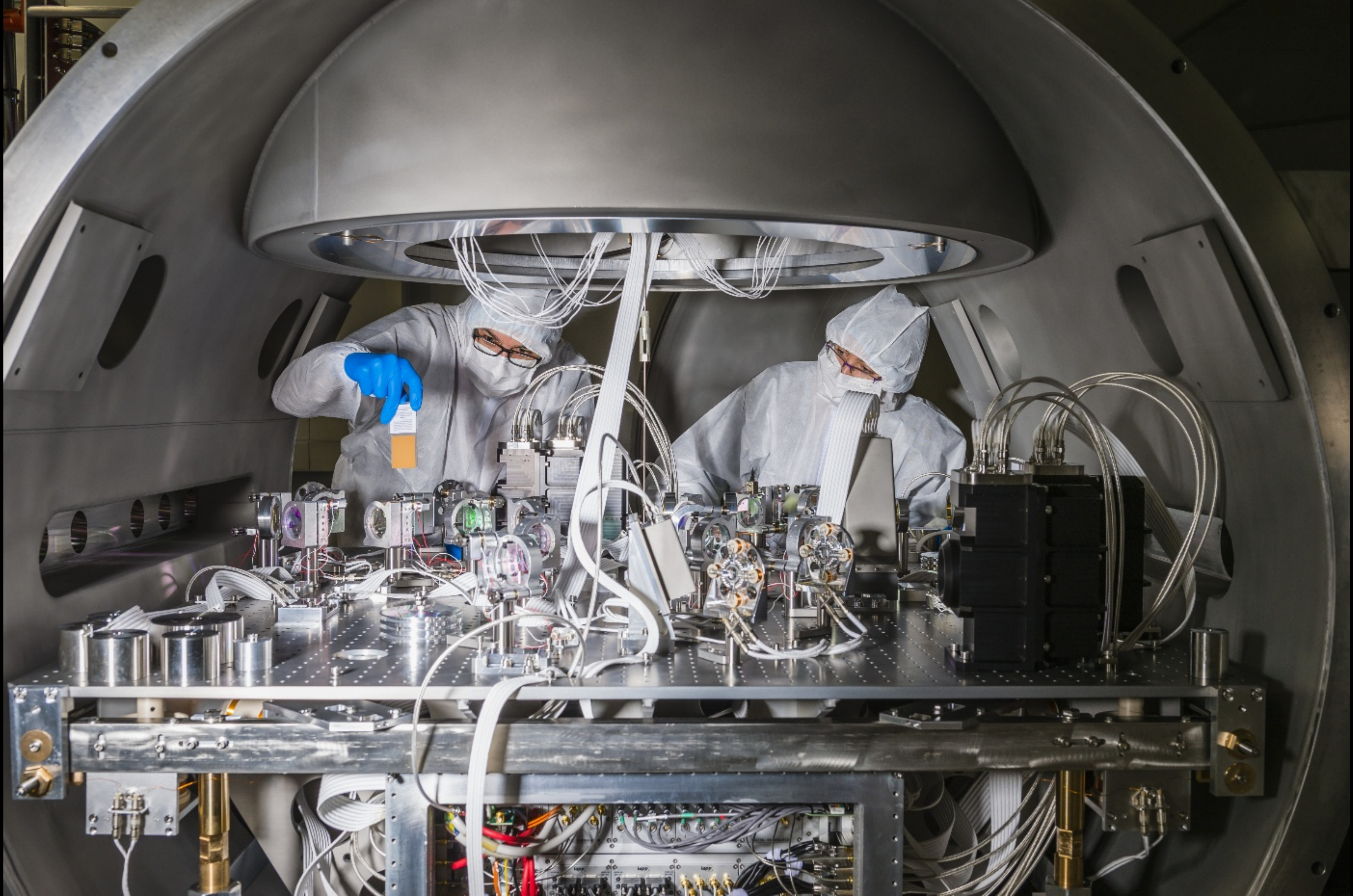
But also for the benches with critical optics !



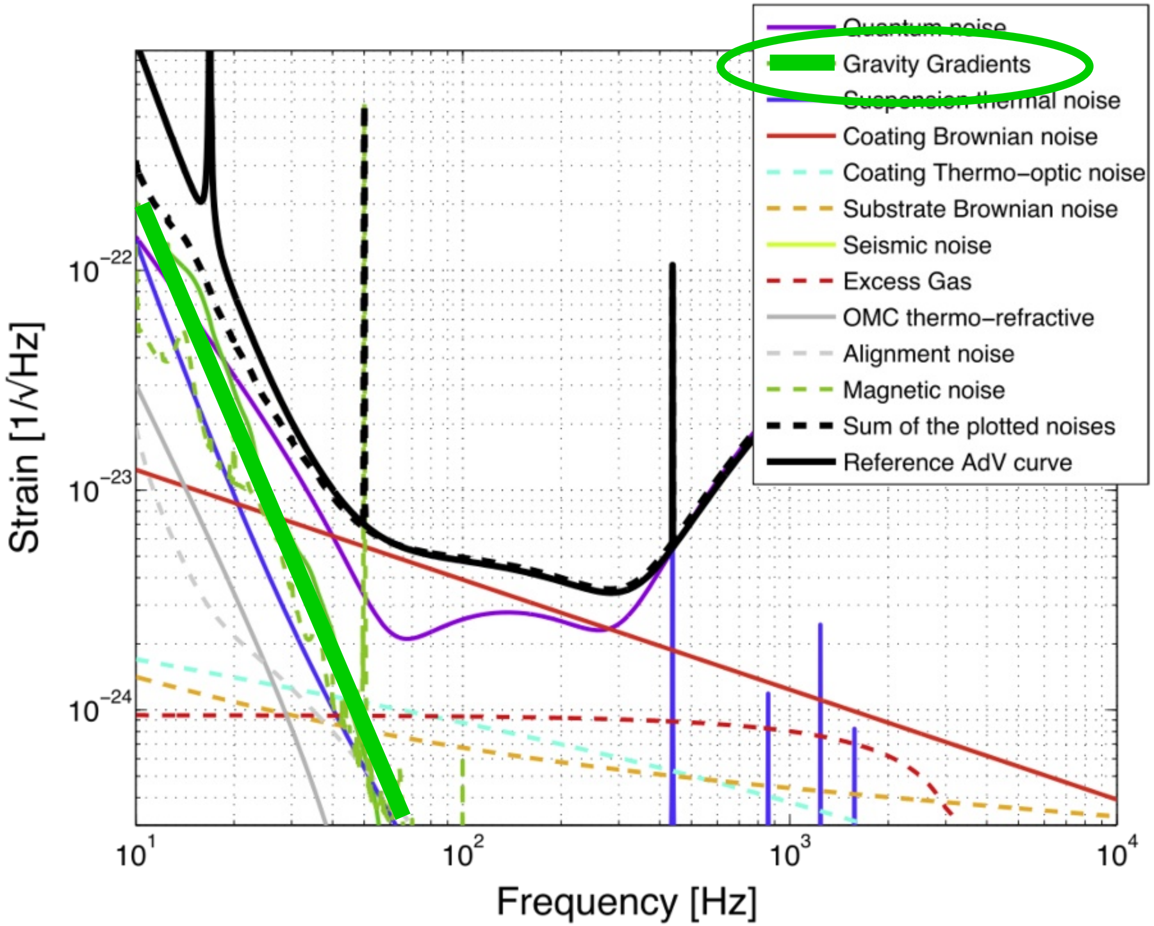
Compact suspension for mini tower



External bench



The Advanced Virgo noise budget



At low frequency :
gravity gradient noise

Gravity gradient (or Newtonian) noise

Due to local density variation in the surrounding of the mirror (from Earth or atmosphere). Can not be shielded.

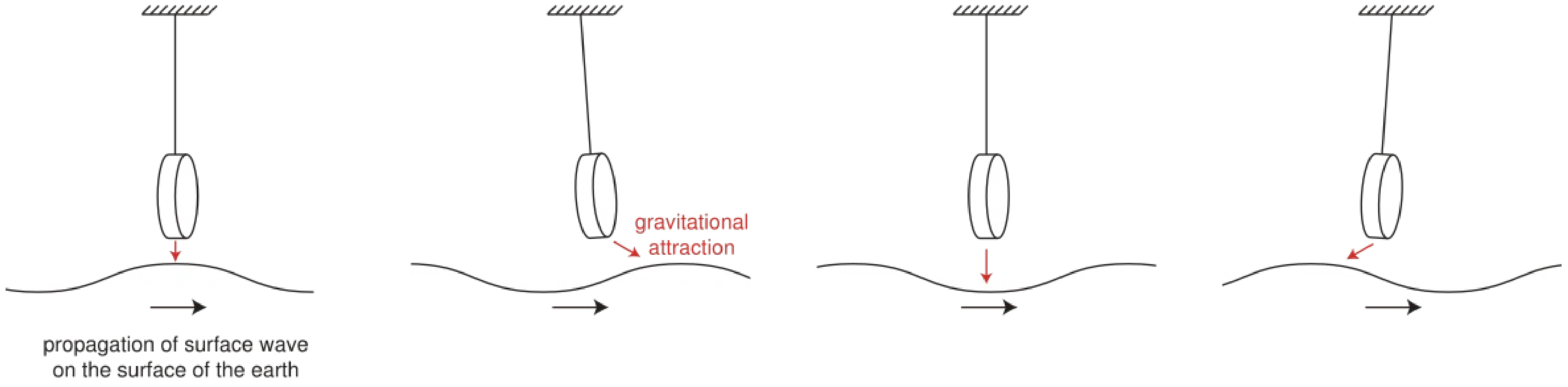
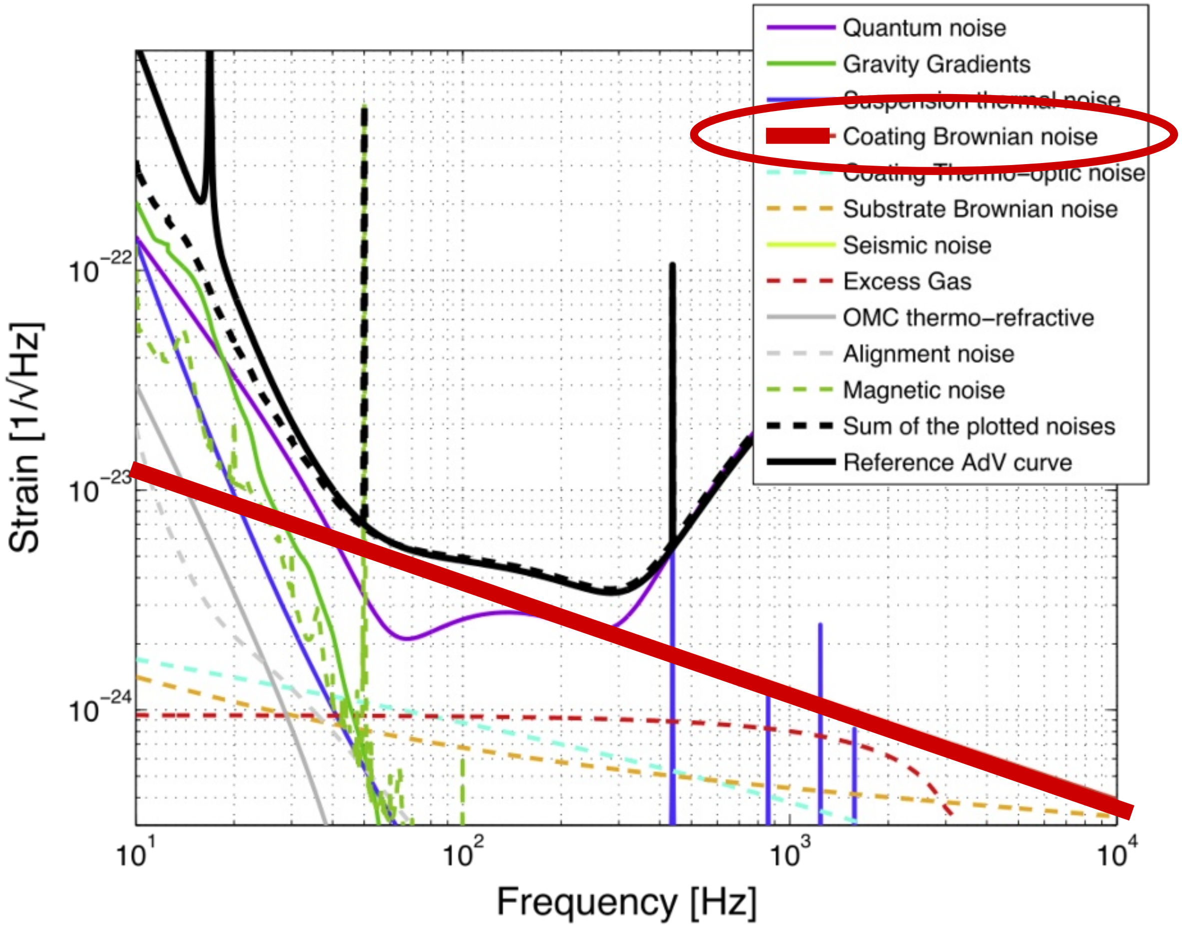


Figure 7: Time-lapsed schematic illustrating the fluctuating gravitational force on a suspended mass by the propagation of a surface wave through the ground.

Illusatration from: Gravitational Wave Detection by Interferometry - *Living Review*

The Advanced Virgo noise budget



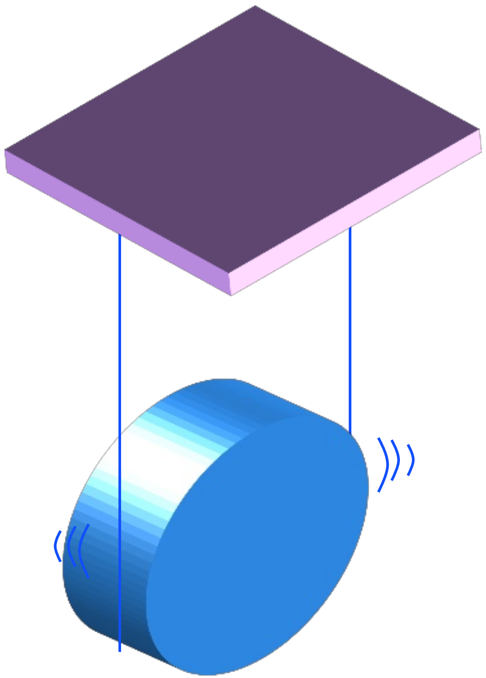
Middle frequencies :
coating thermal noise

Thermal noise(s)

Not only one thermal noise but several responsible for displacement noises:

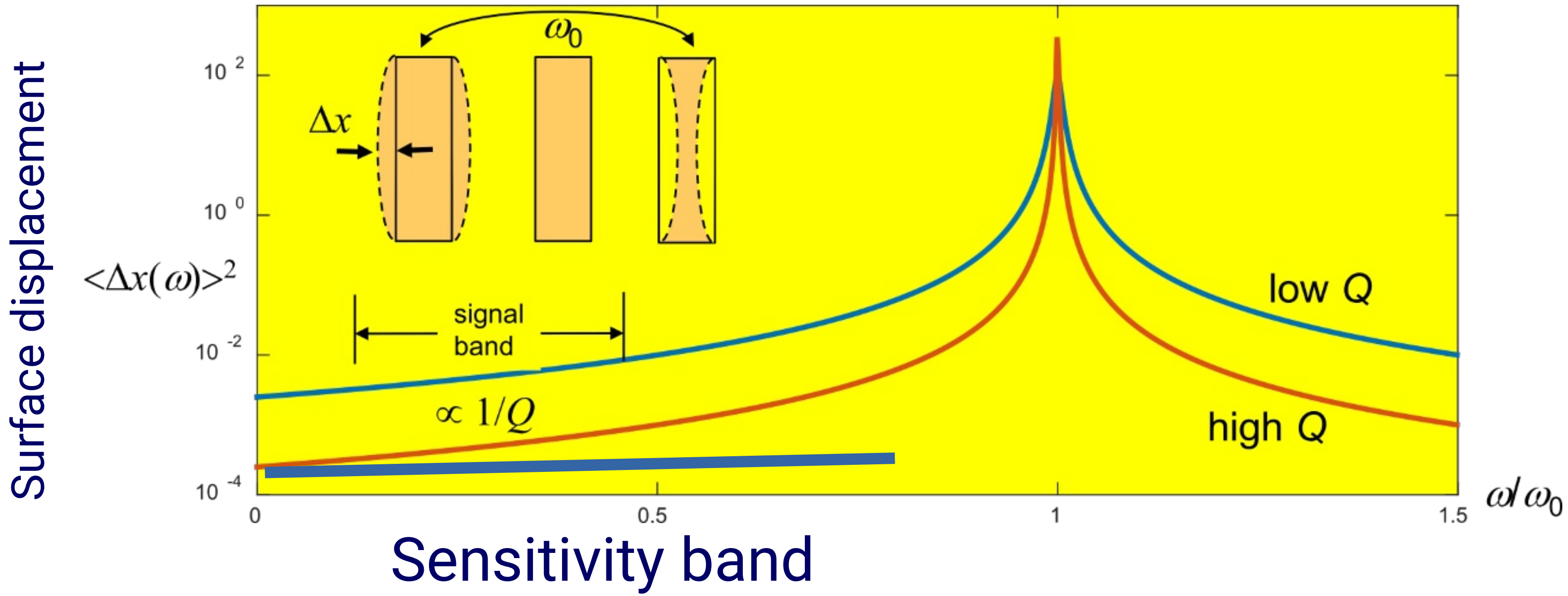
- Suspension thermal noise
- Thermo-optic noise
- Substrate Brownian noise
- Coating Brownian noise

Currently the worst offender



A closer look at it:

https://doi.org/10.1364/CLEO_AT.2017.JF1D.2



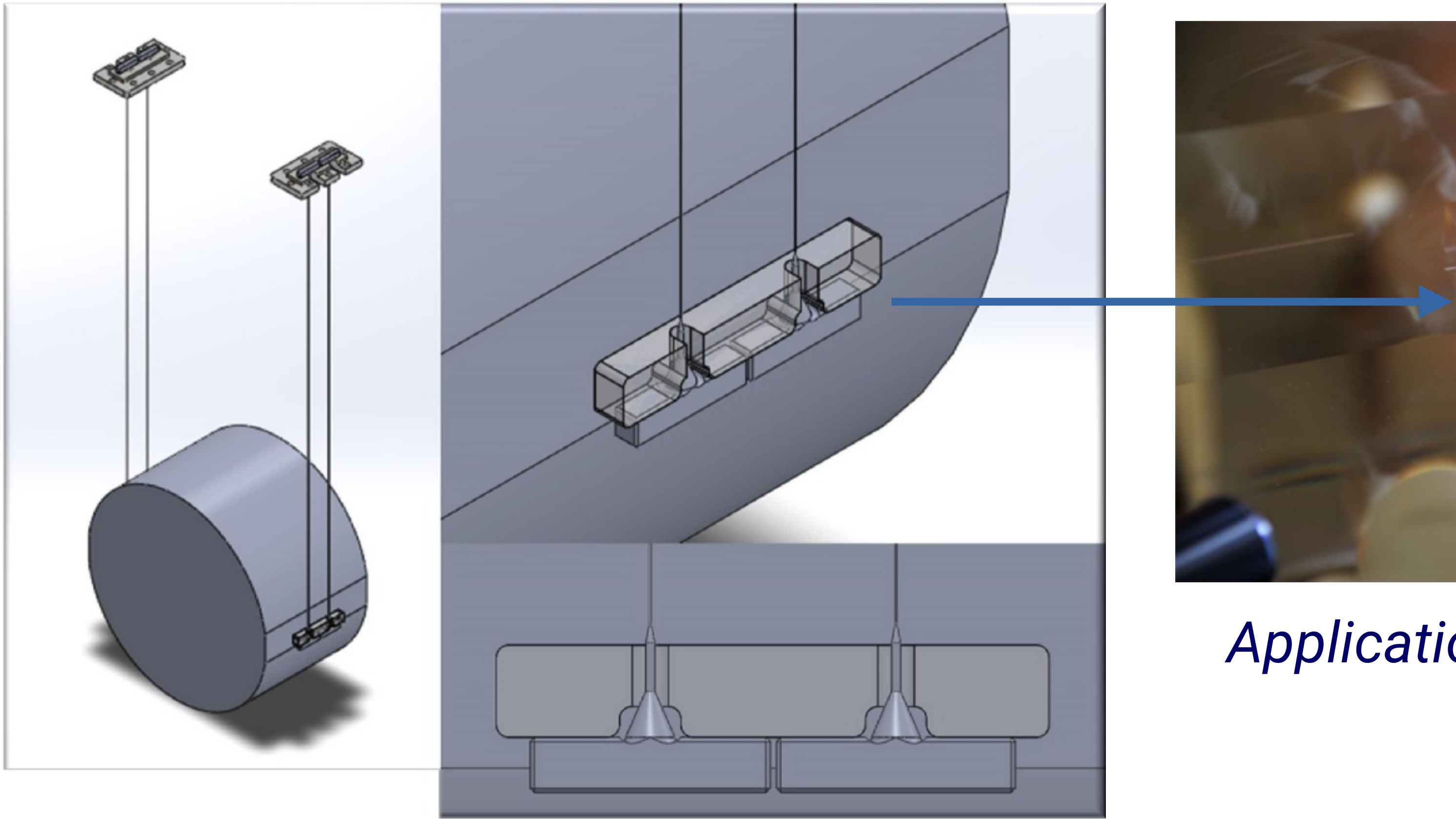
Depend on:

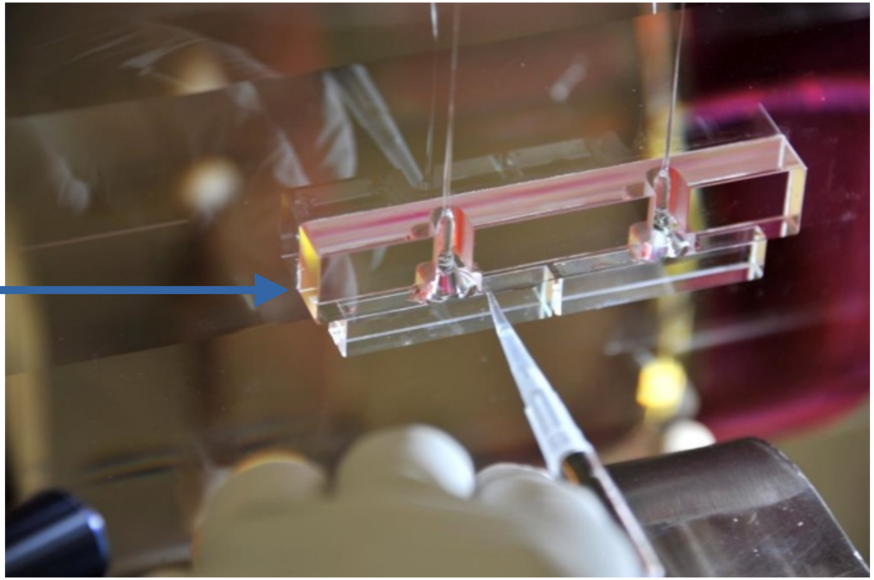
- The temperature
- The mechanical loss (prop to 1/Q)

Use very high Q material, interfaces are critical

Monolithic suspension

Mirror, attachment, fiber: all made of glass.





Application of silicate bonding

Coating thermal noise

Intensive worlwide research to reduce this noise :

coating thickness

coating loss angle

temperature

$$S_{\mathrm{CTN}} \propto T \frac{d\phi}{w^2}$$

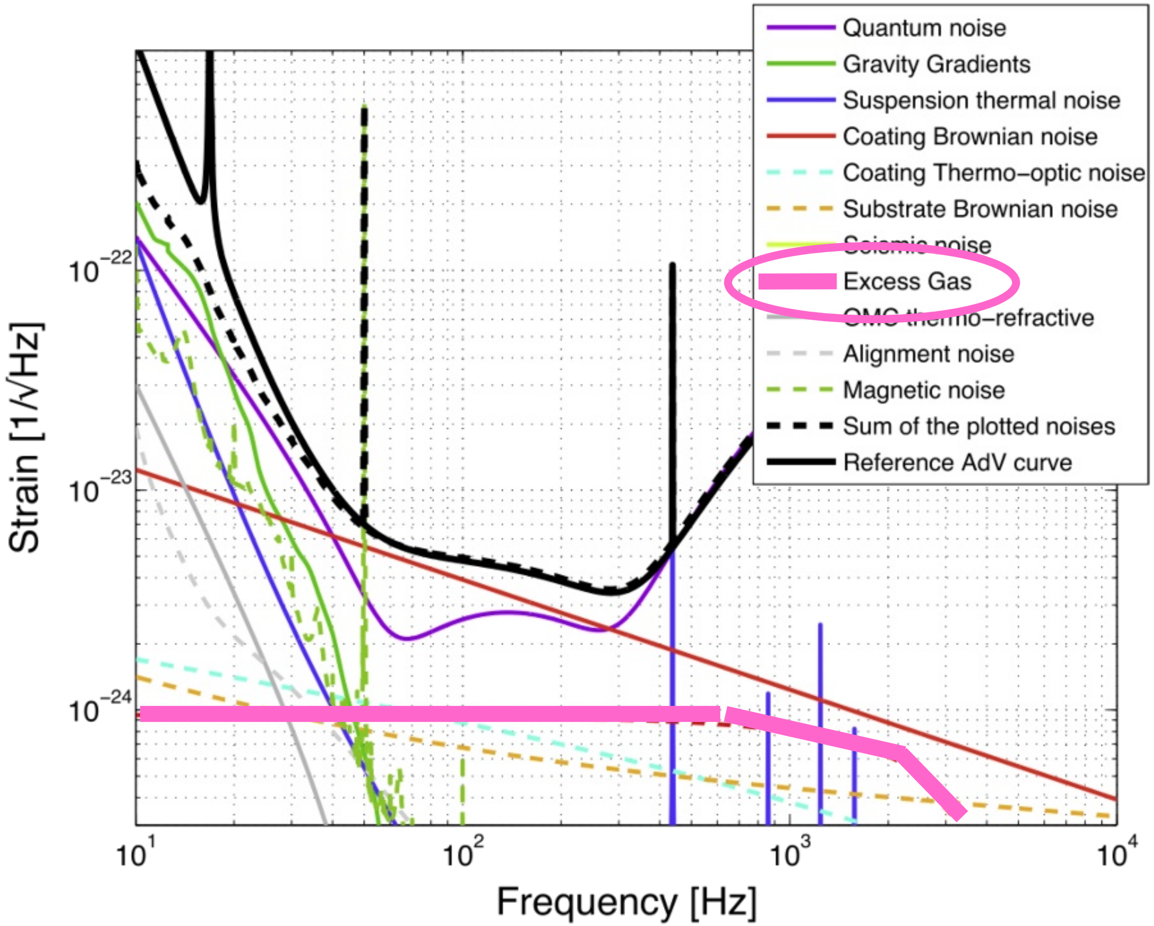
beam size

Optimised
Coating materials

Large beams

Not possible in current
infrastructure

Phase noise from imperfect vacuum



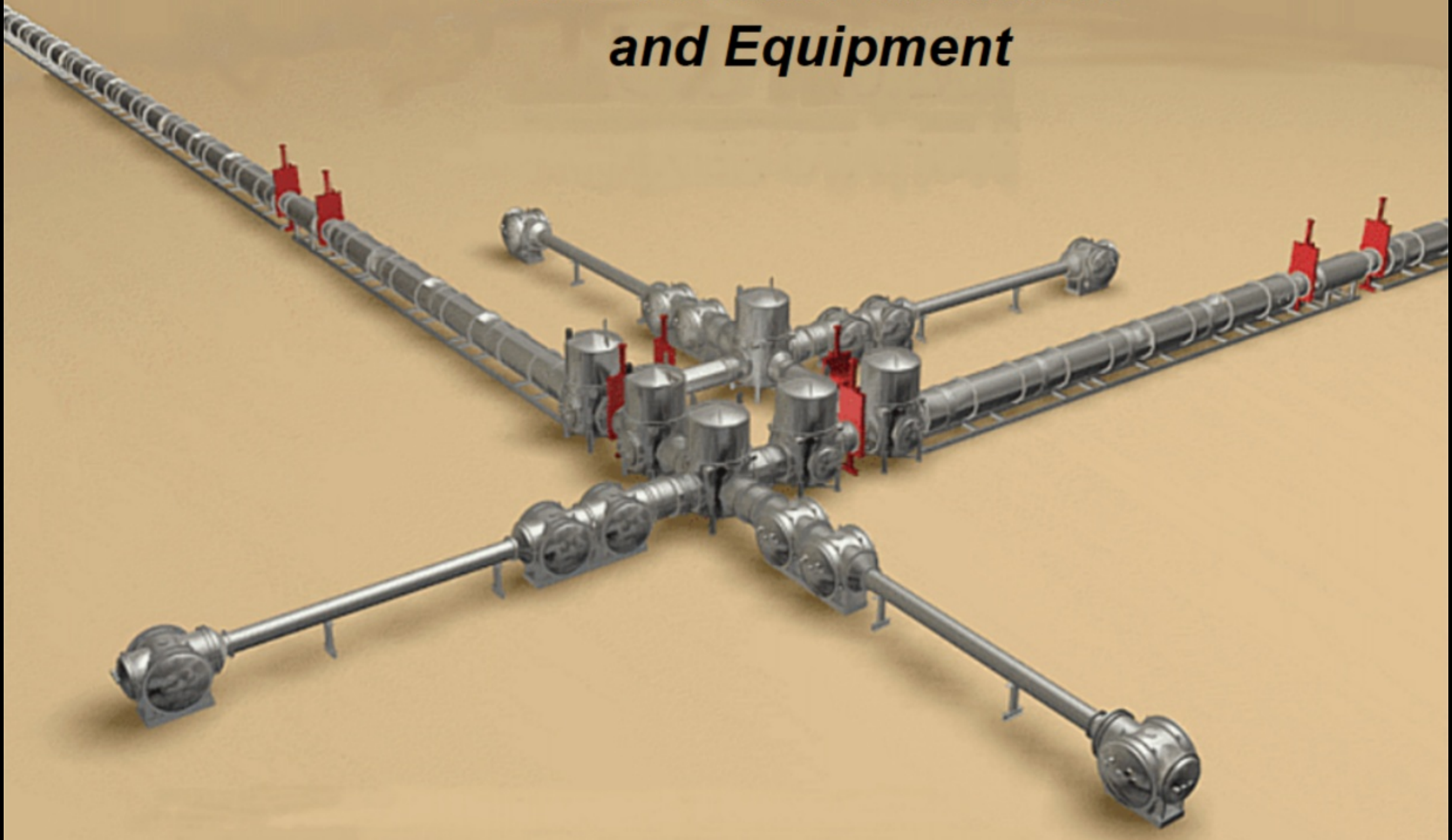
Turbulences in gas, creates variation of the refractive index

The critical path of light is under vaccum.
Limit of the facility

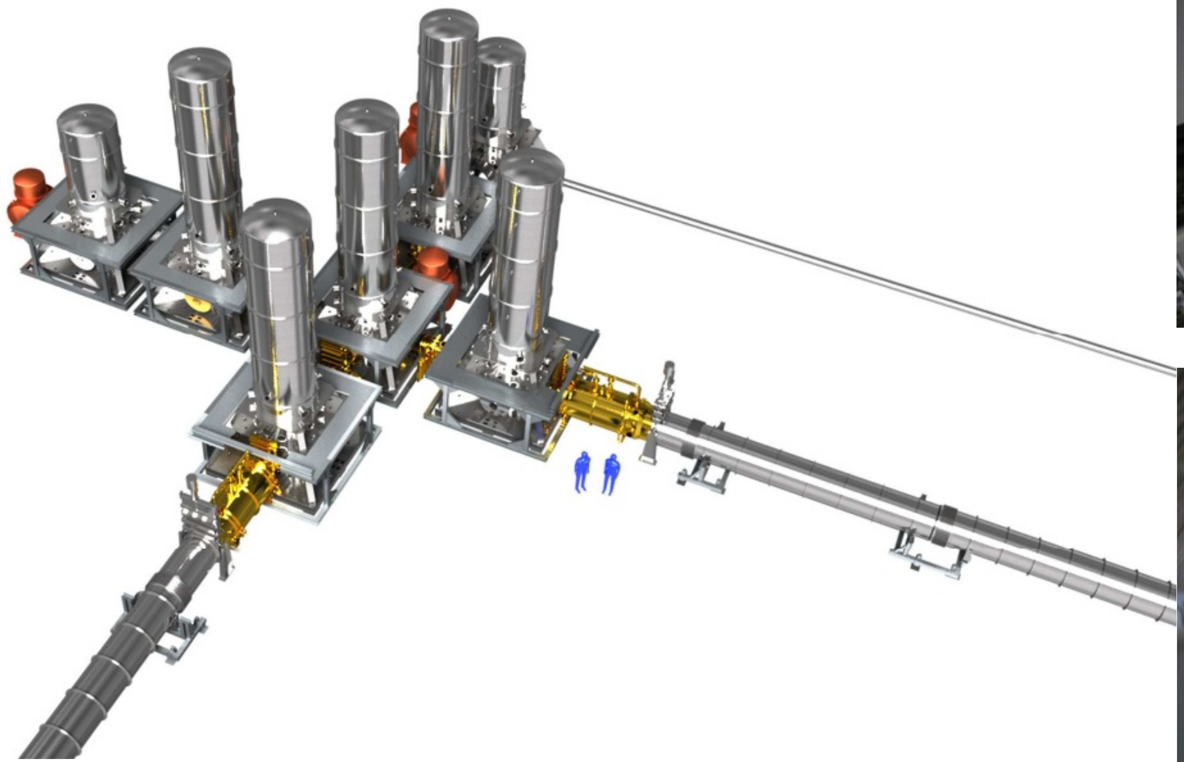
LSC LIGO Scientific Collaboration

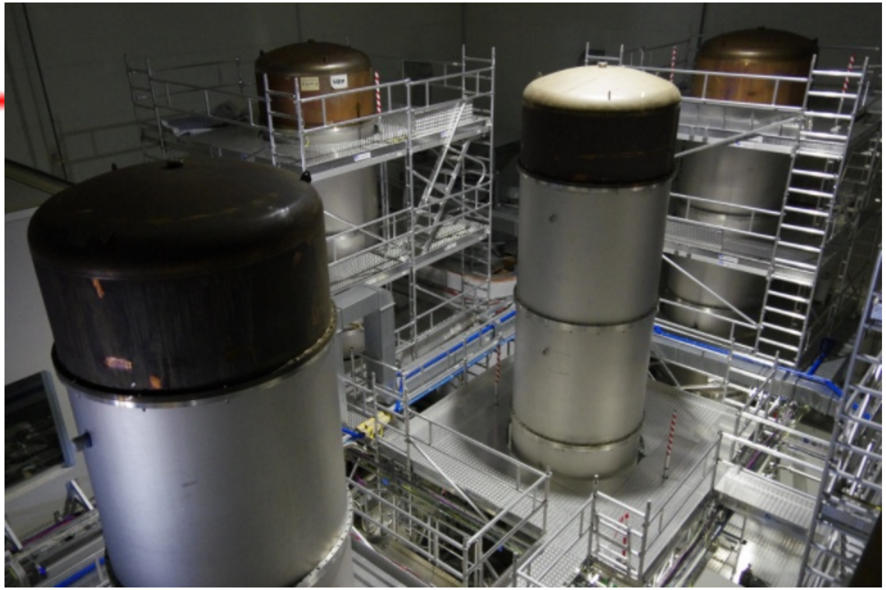
G1701480

LIGO Vacuum Chambers and Equipment



The Virgo chambers





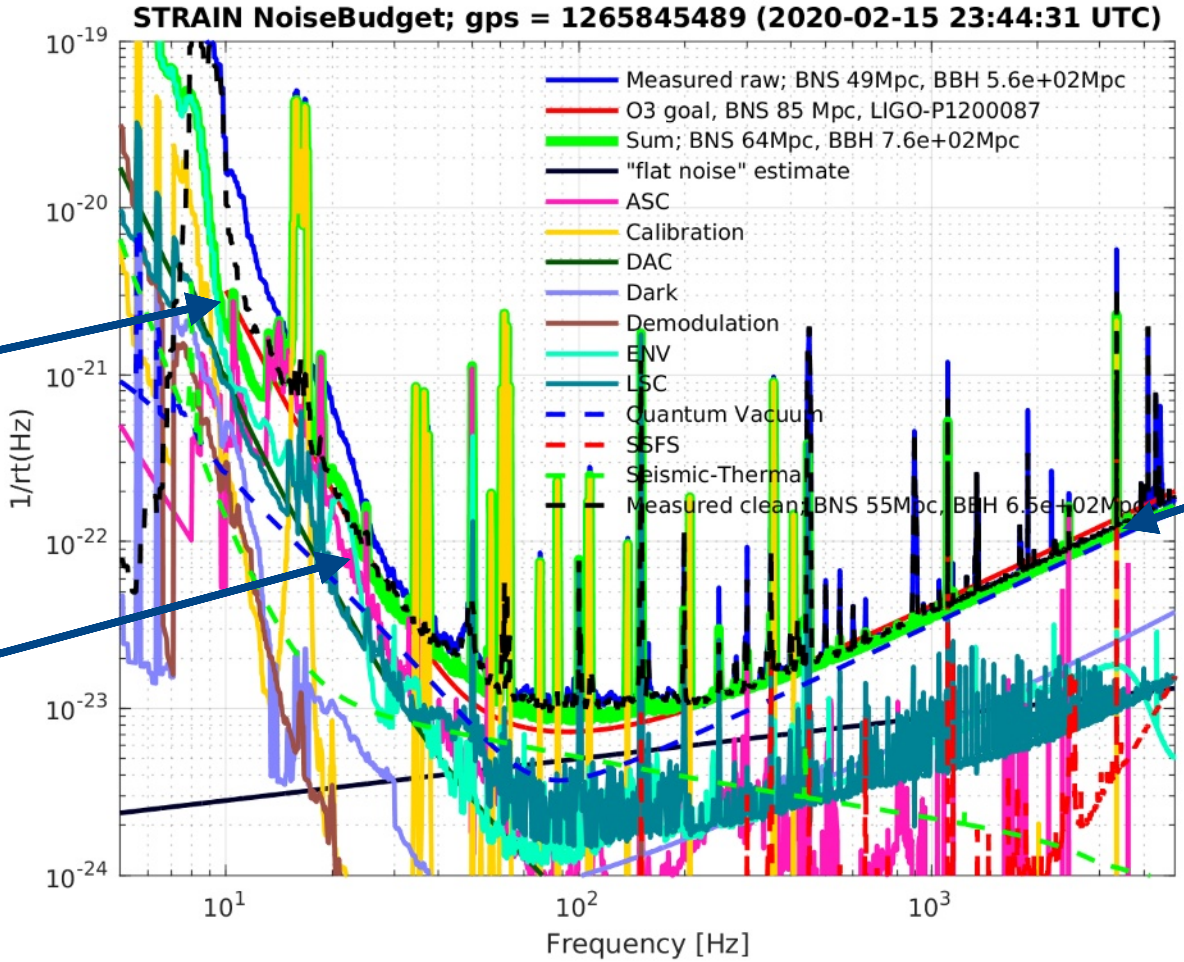
Pressure < 10^{-9} mbar

Total volume : 7000 m^3

Advanced Virgo measured (real) noise budget

Control noise

Suspension thermal noise



Shot noise

VI.
Selected technologies

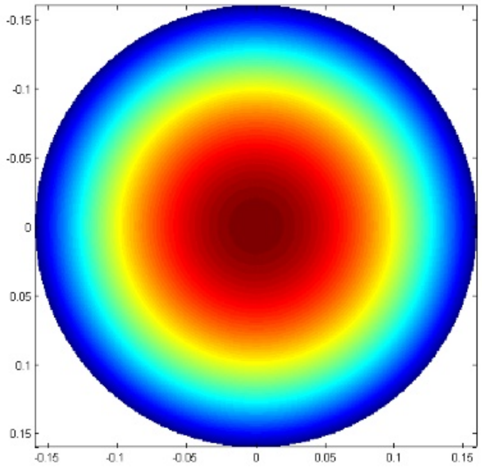
- mirrors
- thermal compensation
- diffused light mitigation
- control

The arm cavity mirrors

- arm cavity where the optical losses are the most critical
- optical cavity round trip loss < 0.01%
- give tight constraints on the mirror quality surface:

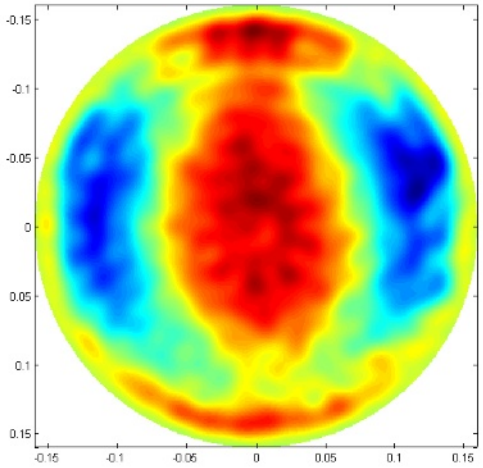
Mirror surface height as color scale

Radius error



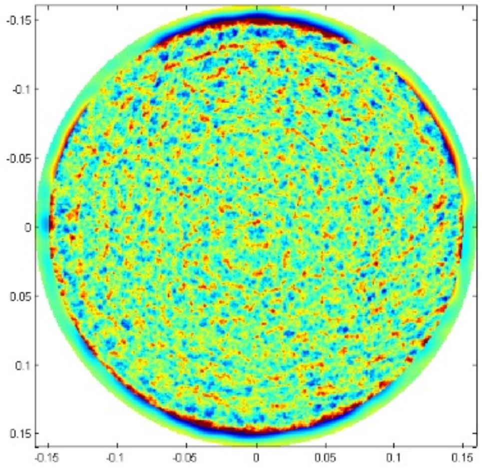
bad contrast
(could be corrected)

Low frequency error
(f <50 m^{-1})



bad contrast
distorted beam

High frequency error
(f >50 m^{-1})



light lost

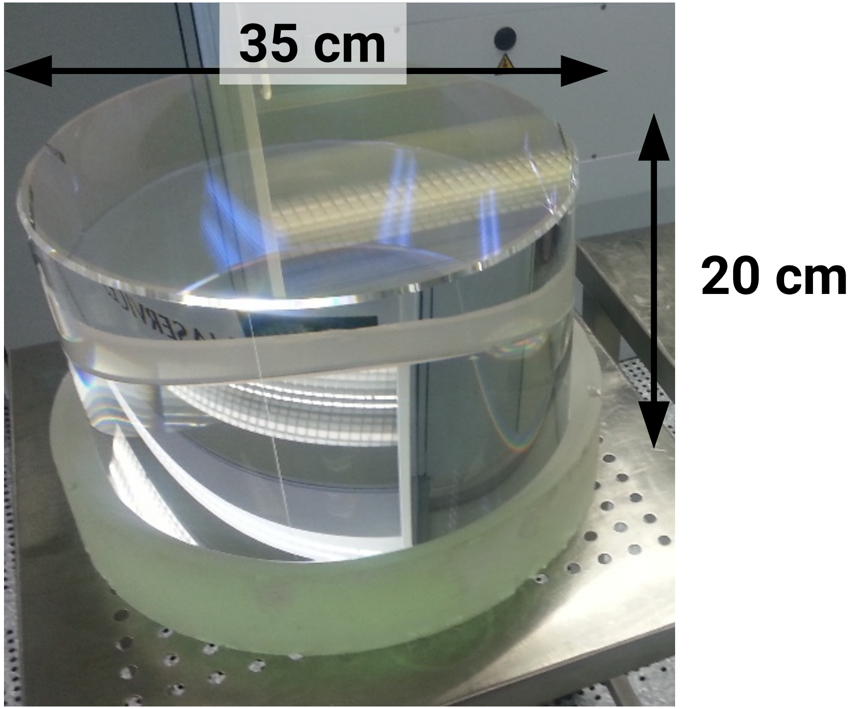
The arm cavity mirrors

- arm cavity where the optical losses are the most critical
- optical cavity round trip loss $< 0.01\%$
- give tight constraints on the mirror quality surface:

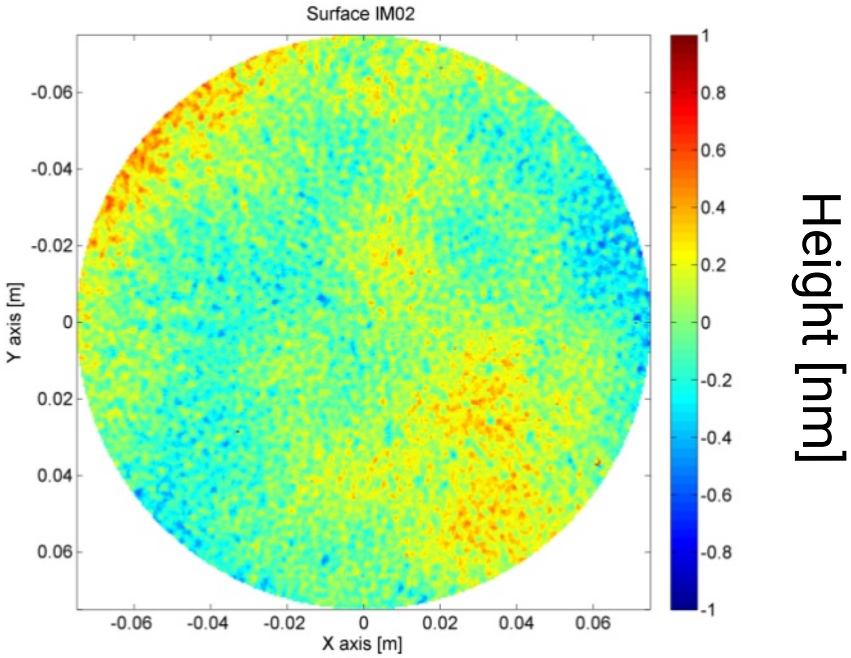
Very stringent requirement on the polishing and coating

The mirrors for the 3 km long cavities

- mirrors weighting 40 kg made of the purest fused silica
- state of the art polishing (flatness RMS ~ 0.3 nm)
- coated using Ion Beam Sputerring (IBS) technology

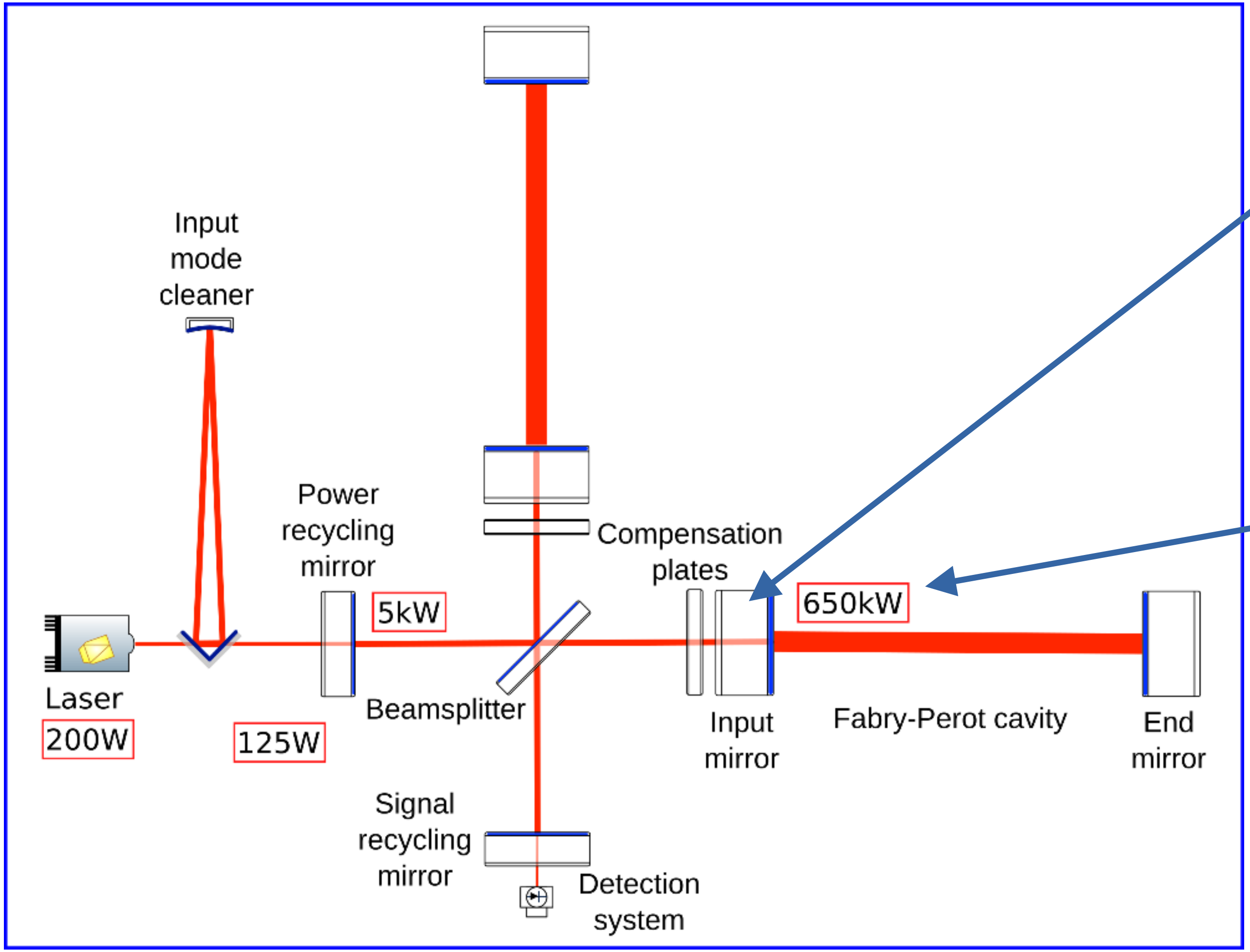


Polished substrate



Mirror surface height

A story of power

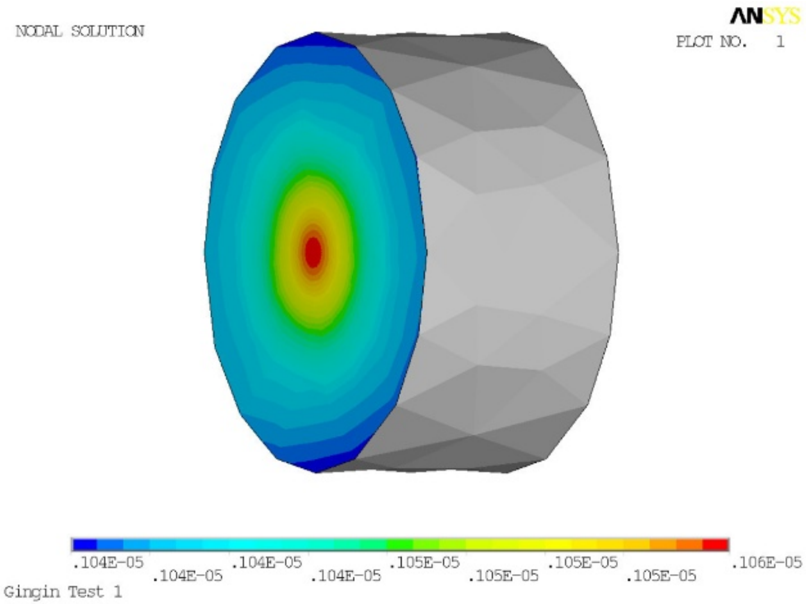


kW of light in the substrate

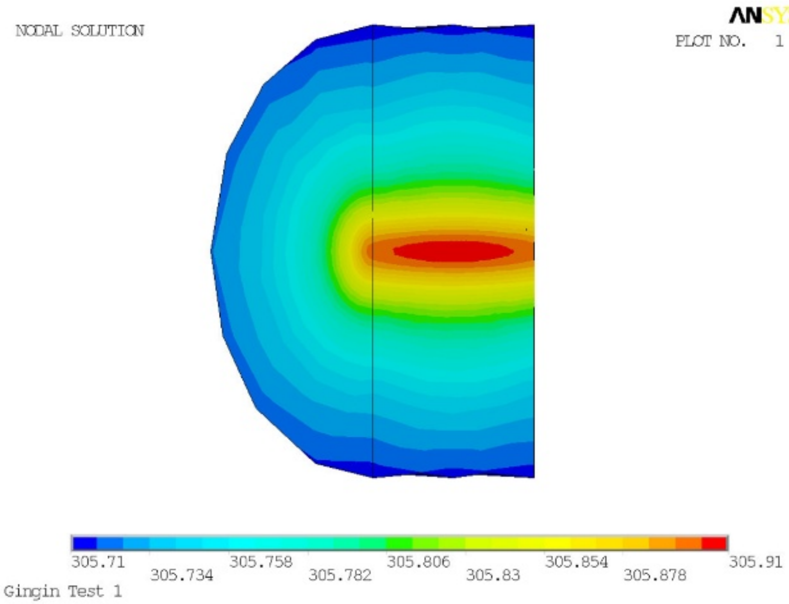
Huge amount of optical power

Effect of the optical absorption

- even if very good substrate / coating, still residual absorption (< ppm)
- part of the laser beam will be absorbed
- and converted to heat



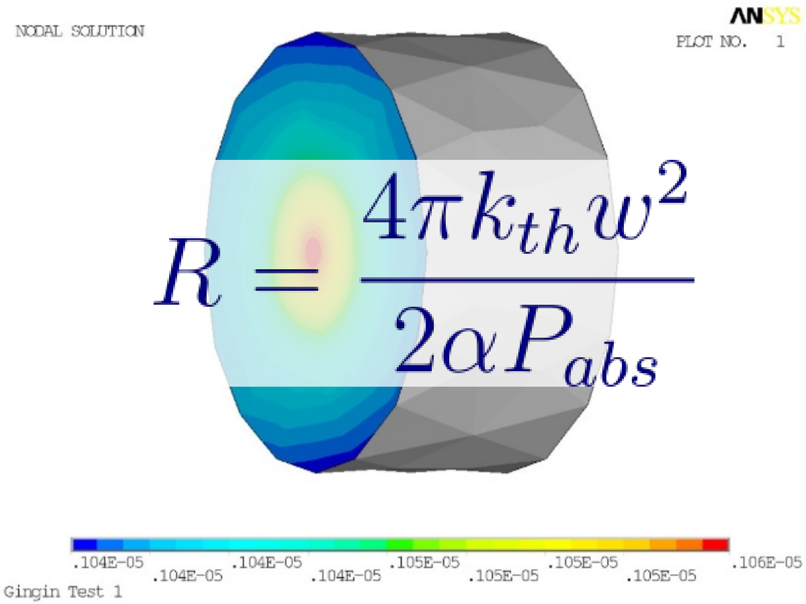
Coating absorption



Substrate absorption

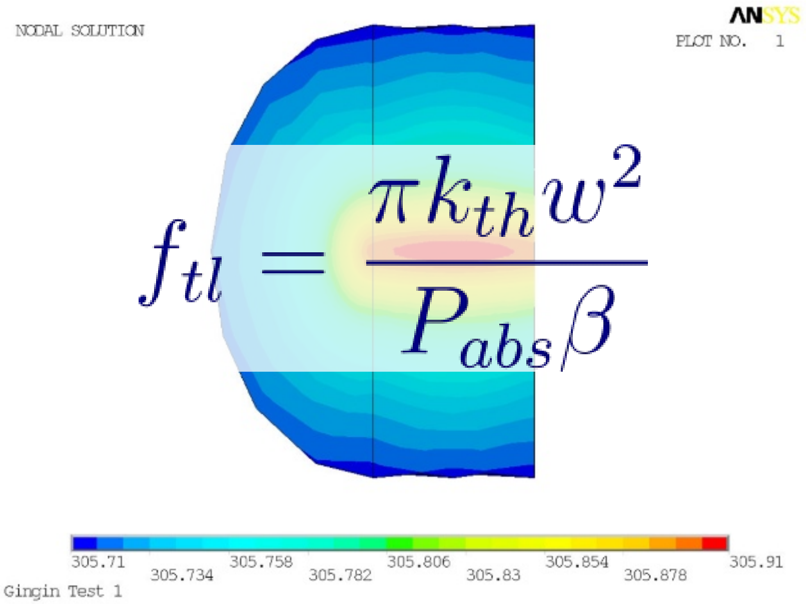
Effect of the optical absorption

- even if very good substrate / coating, still residual absorption (< ppm)
- part of the laser beam will be absorbed
- and converted to heat



$$R = \frac{4\pi k_{th} w^2}{2\alpha P_{abs}}$$

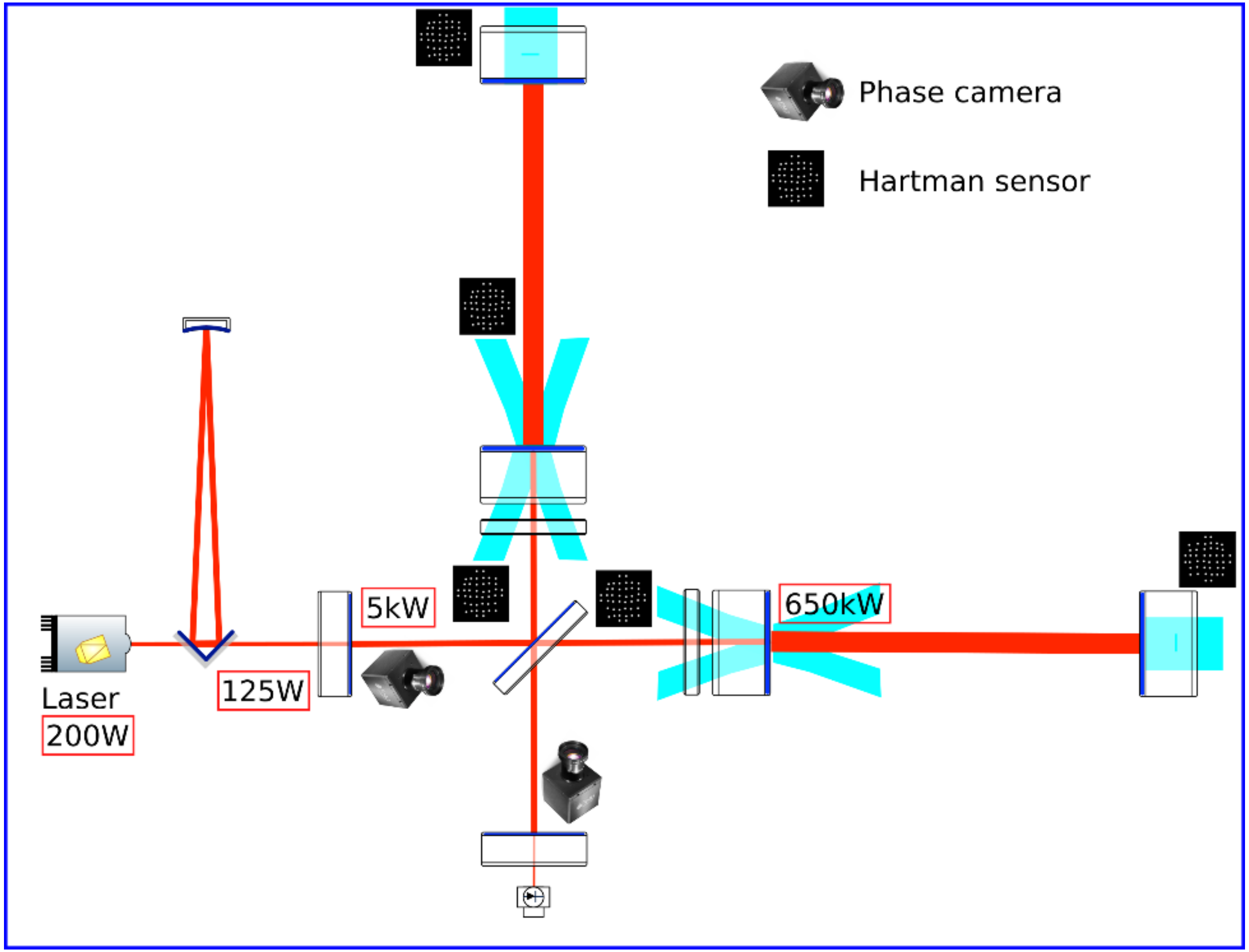
Coating absorption



$$f_{tl} = \frac{\pi k_{th} w^2}{P_{abs} \beta}$$

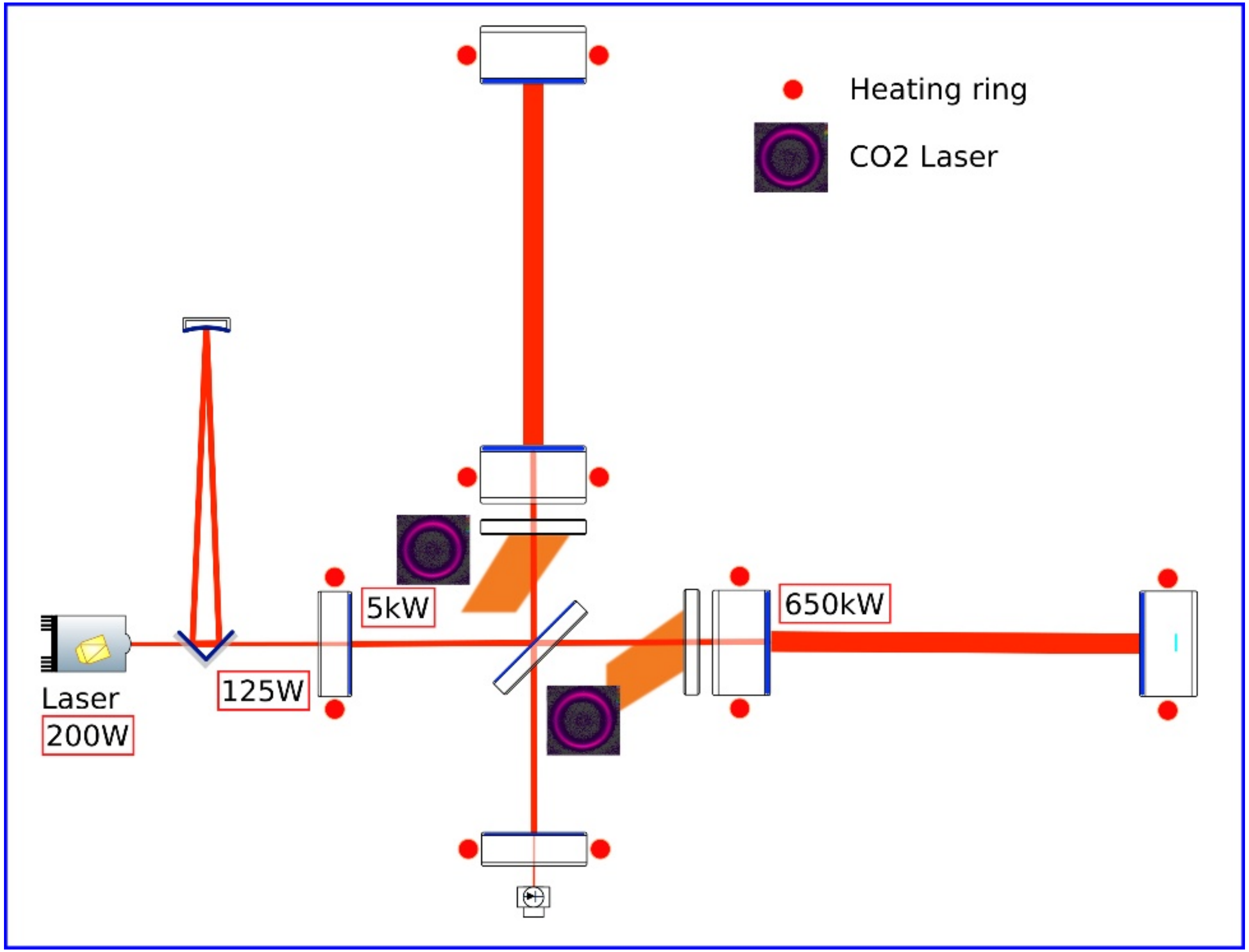
Substrate absorption

The thermal compensation system



Sensing the thermal aberrations

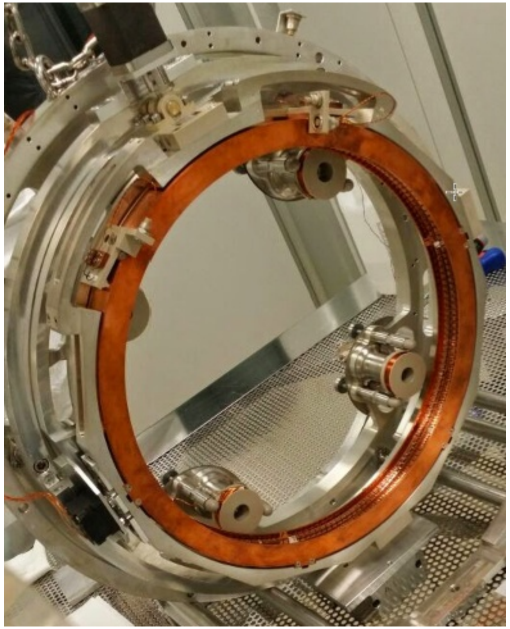
The thermal compensation system



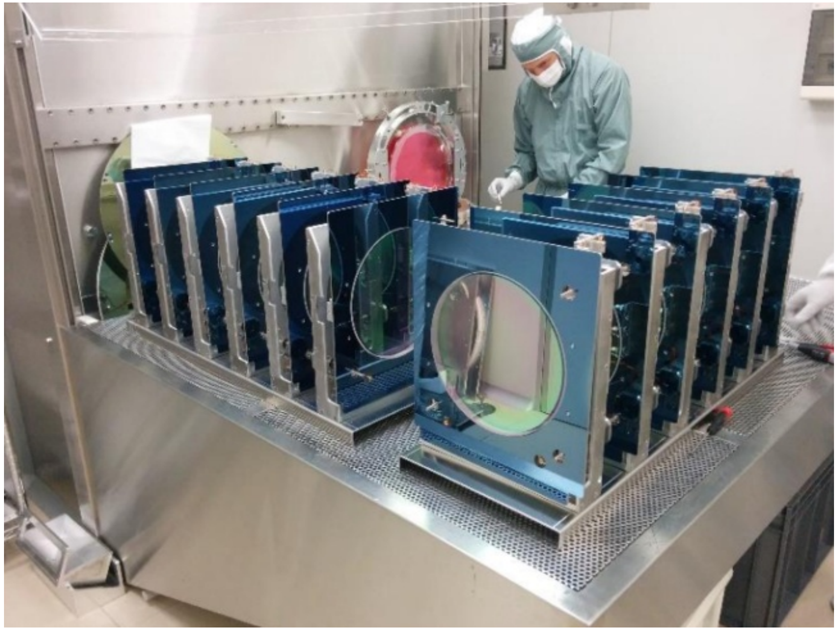
Toward an aberration free interferometer

Applying heat to induce or correct a thermal gradient

Thermal compensation system in photos

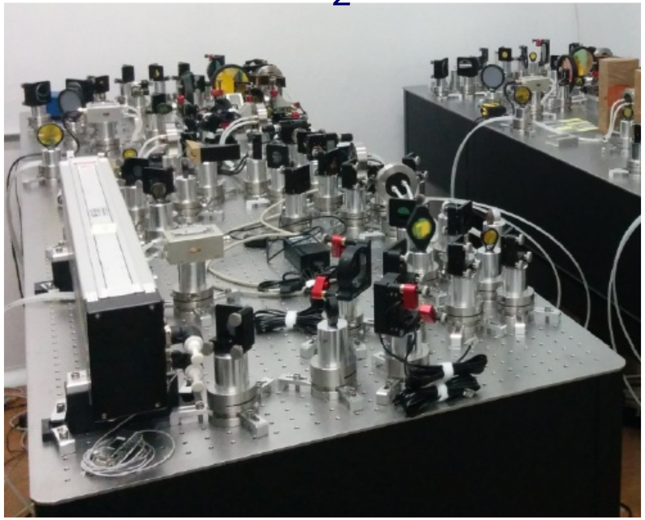


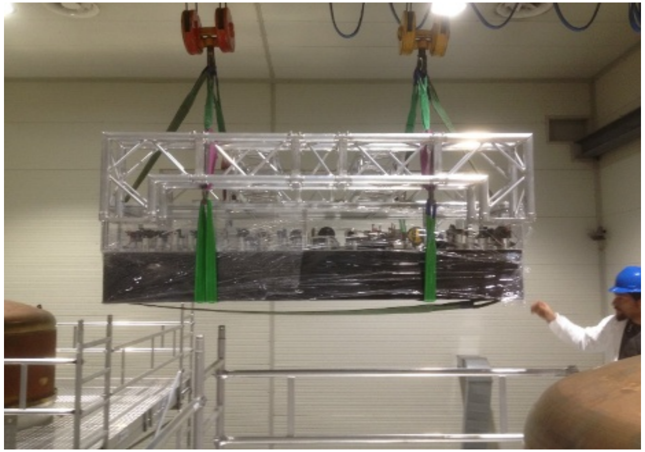
Heating ring



Steering mirror for Hartman sensors

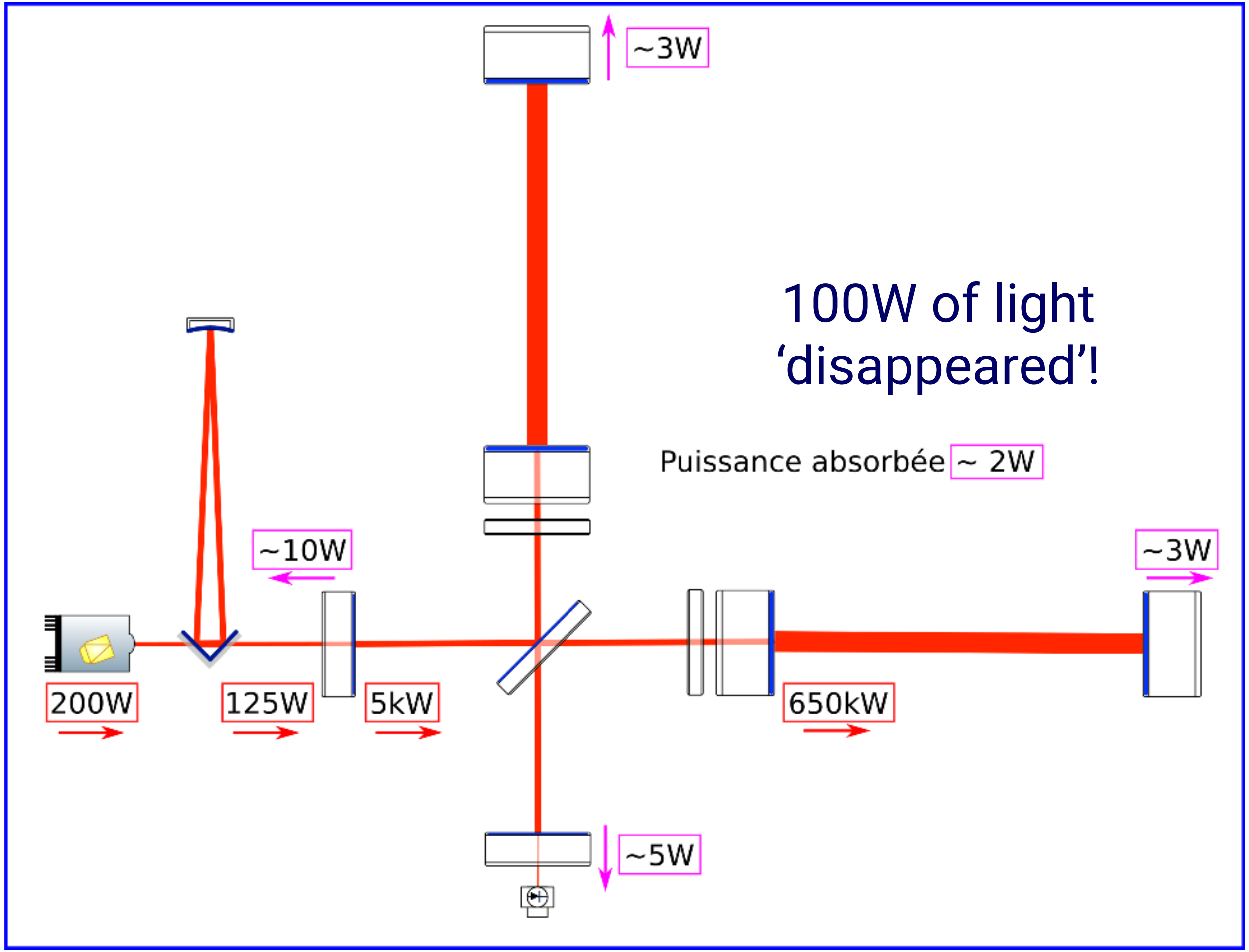
CO_2 laser bench





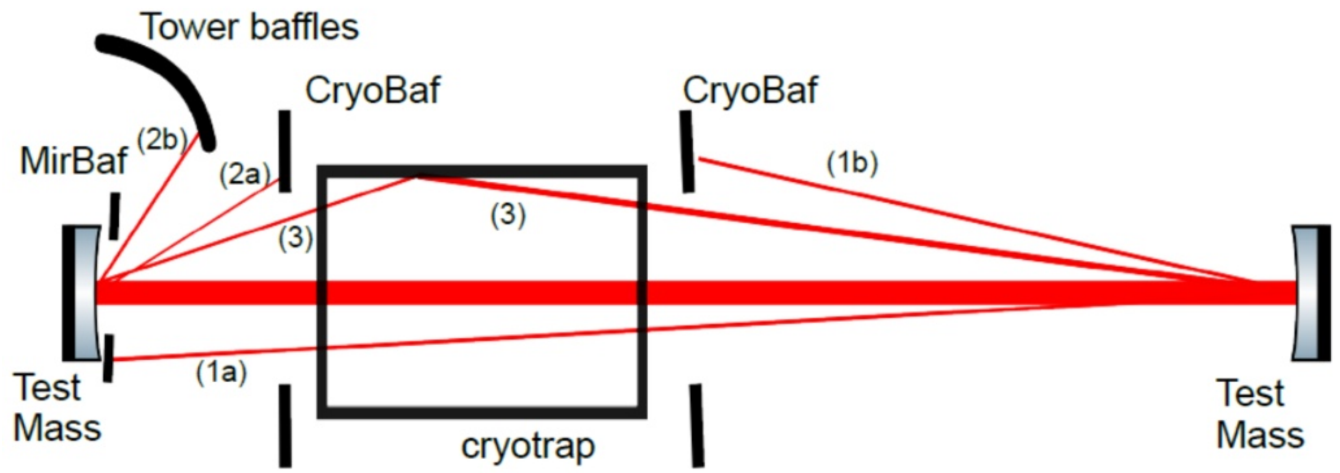
Installation on the site

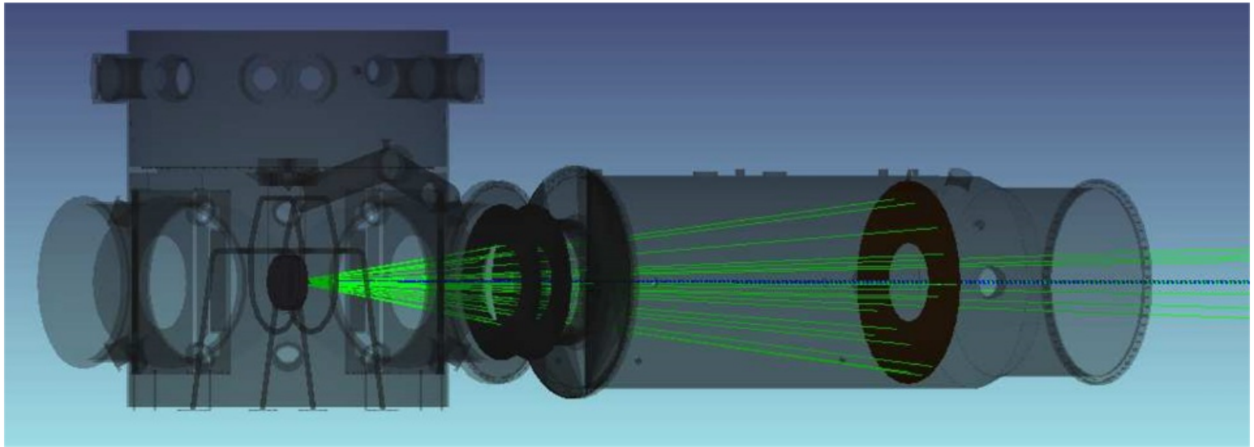
The diffused light



Where my light is lost ?

Diffused light: an extra phase noise

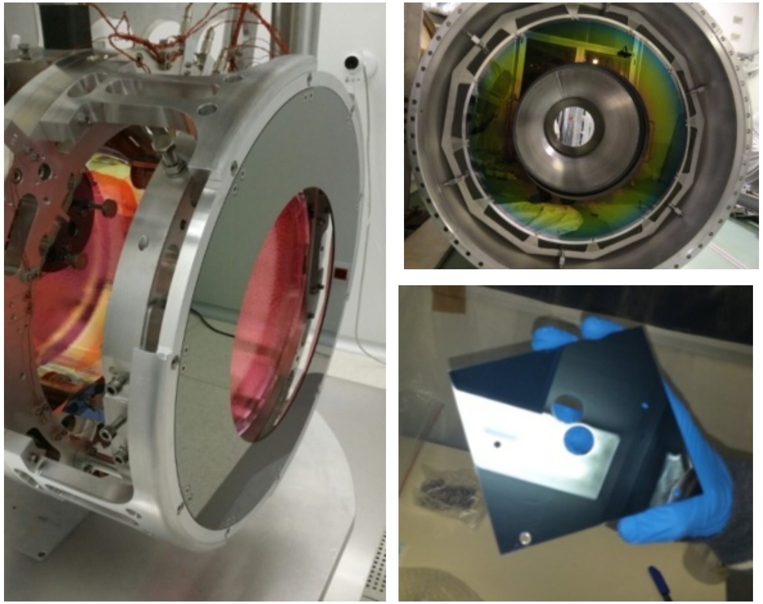




A complex problem with different path for the scattered light.

Could add extra phase noise if recombined with the main beam

Dumping the diffused light



Light baffles around the mirrors and in the vacuum tubes

All the critical optics are suspended and under vacuum

Must keep everything under control!

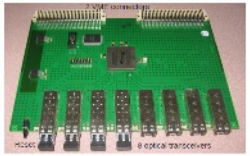
- A complex machine with a lot of subsystems...

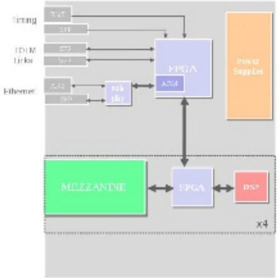


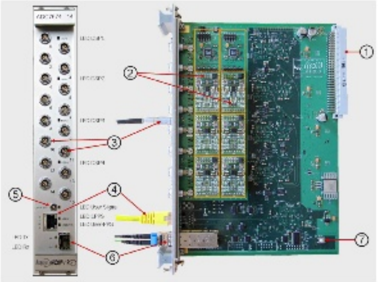

- … all interconnected
- needs to developed home made systems (hardware and software) for real time control, data monitoring and storage.


(a) TOLM-PMC mezzanine.

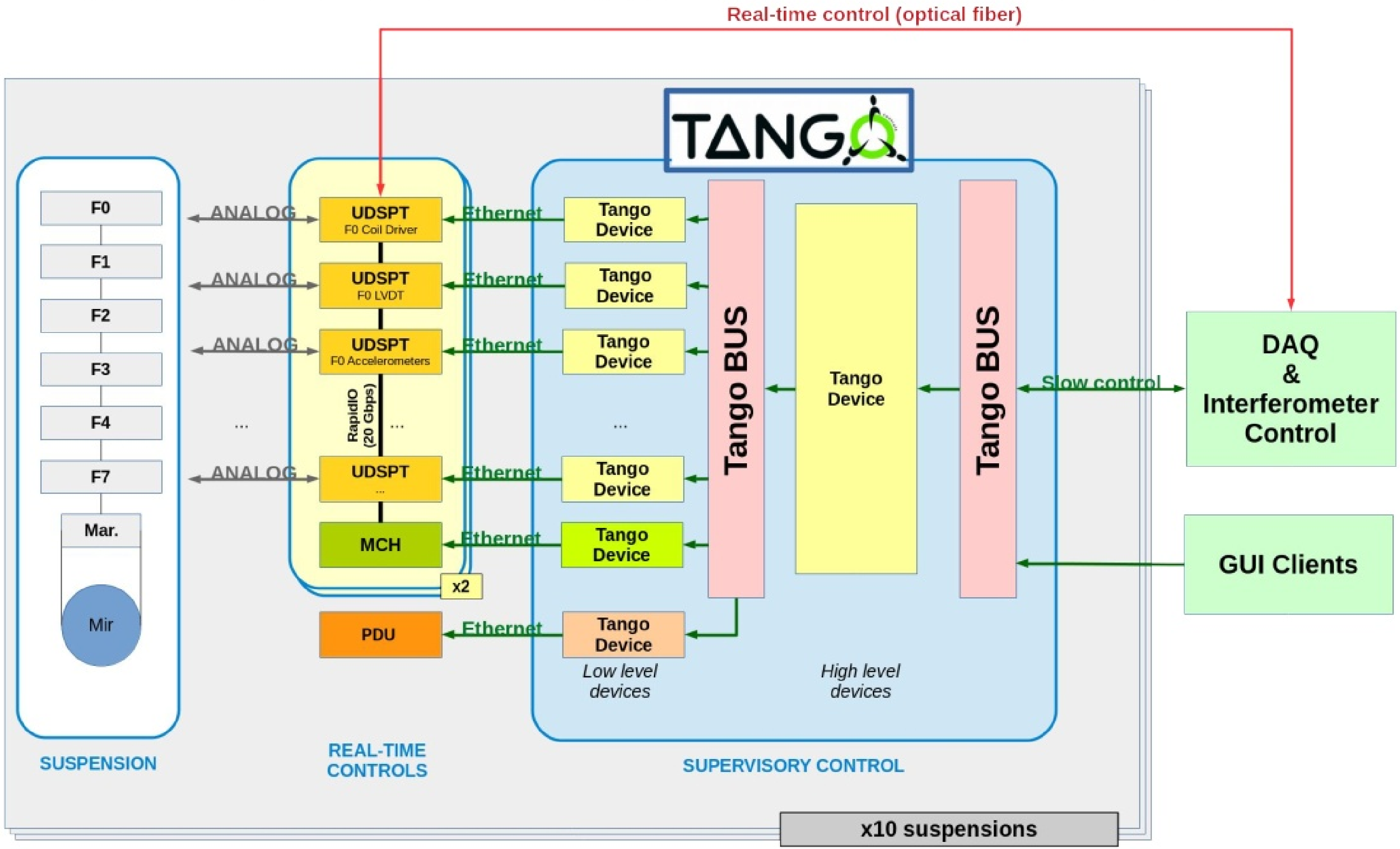

(b) TOLM-PCI mezzanine.


(c) Mux/Demux board.

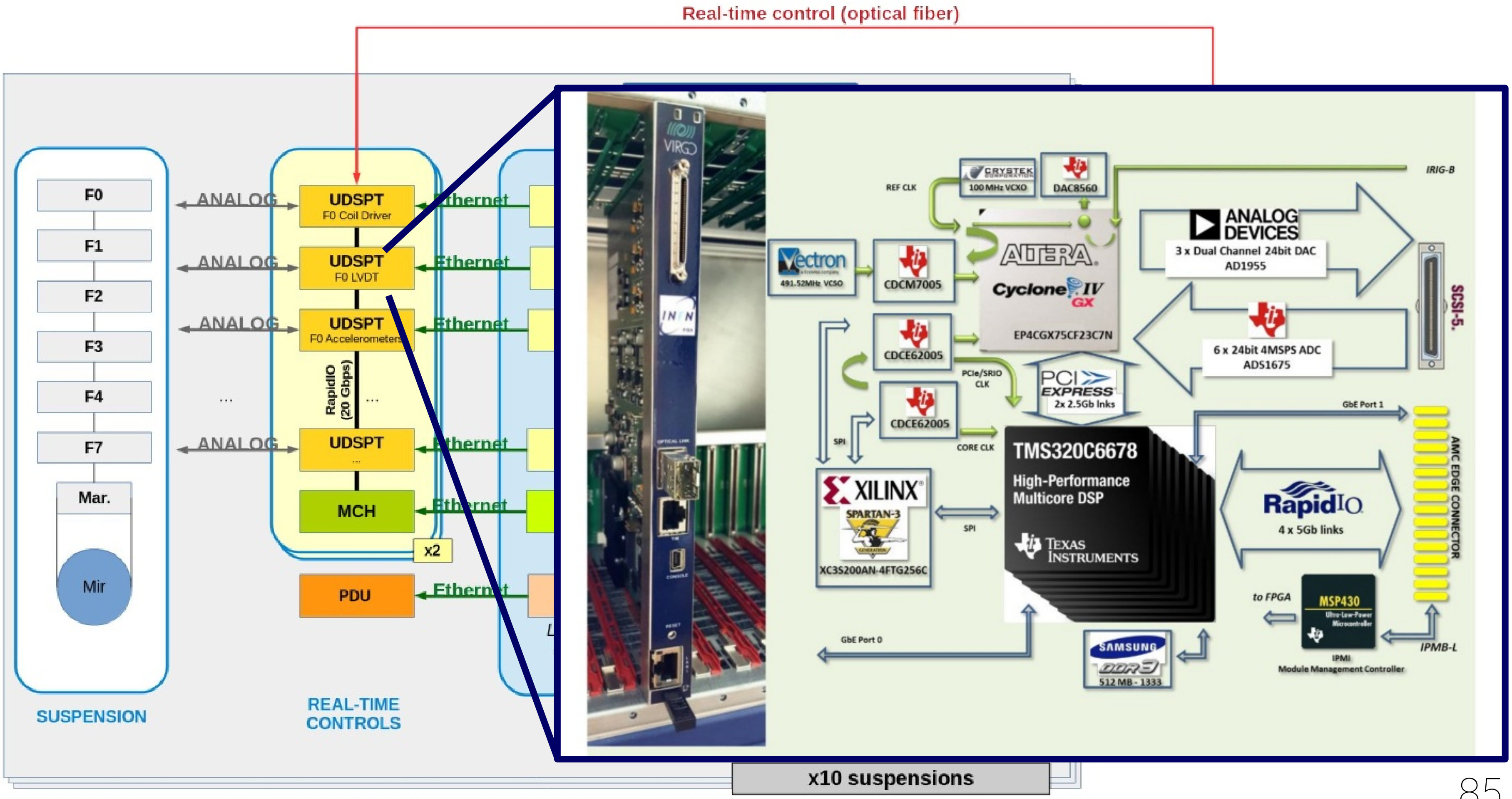




Example: control of the suspension

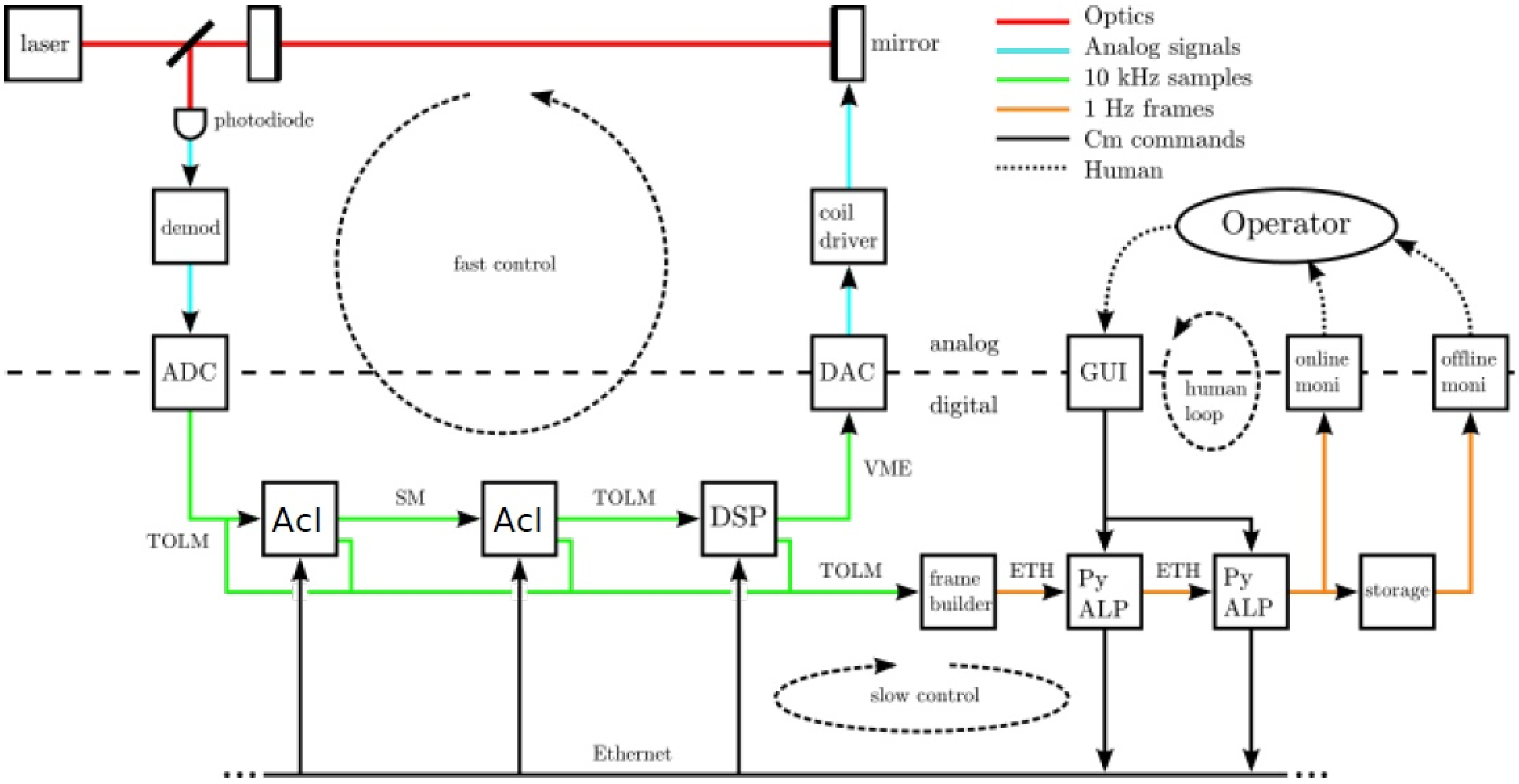


Example: control of the suspension



Example: the arm cavities

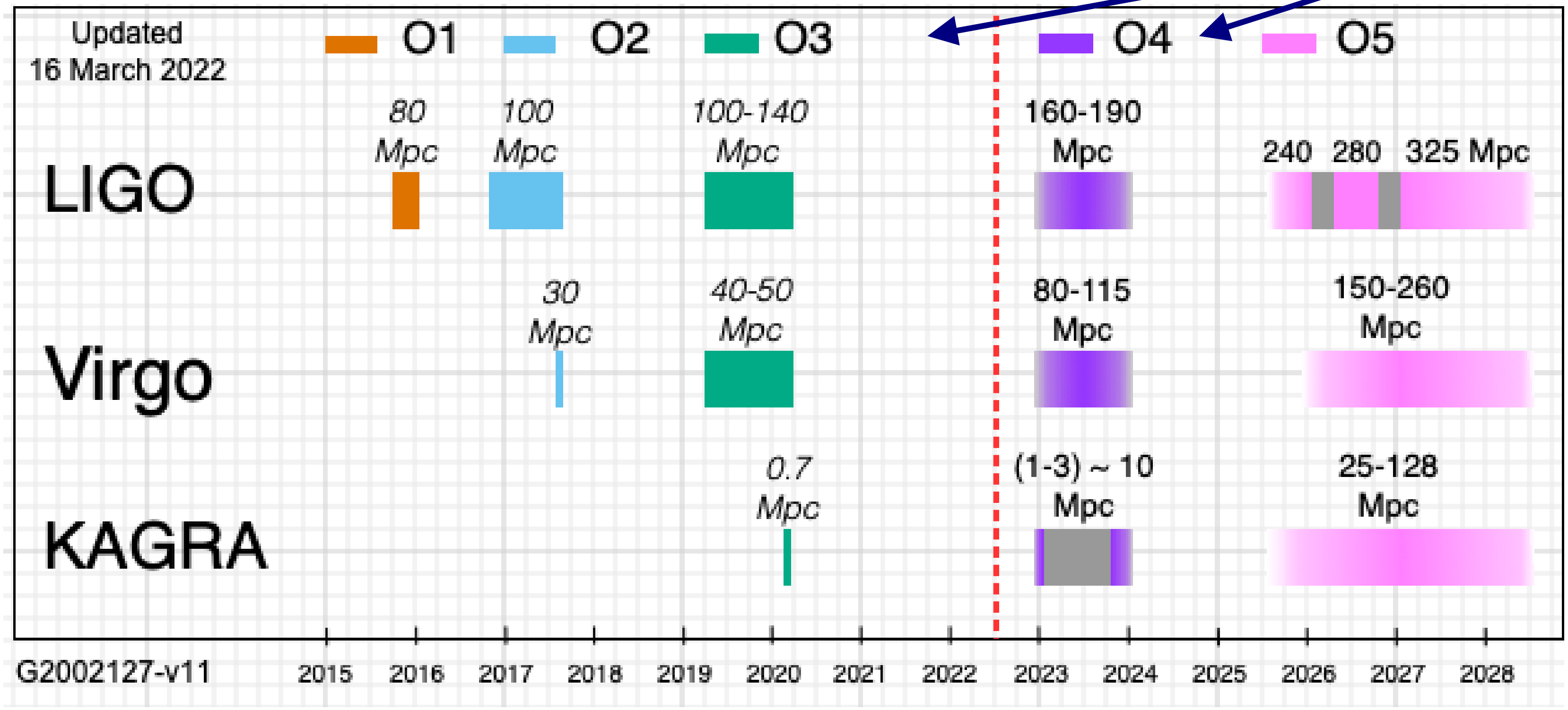
Not always obvious to have a proper error signal



VII.
The next upgrades
(with a Virgo focus)

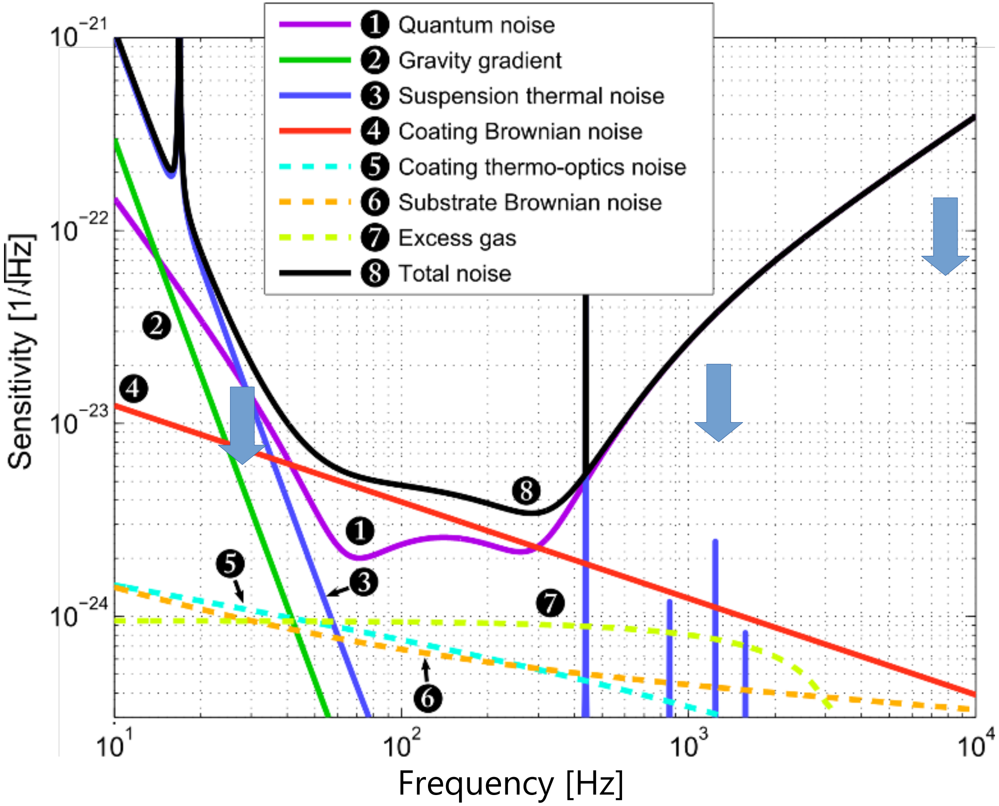
Timeline

The '+ upgrades' (Advanced Virgo+, Advanced LIGO+)



More and more sensitive instruments

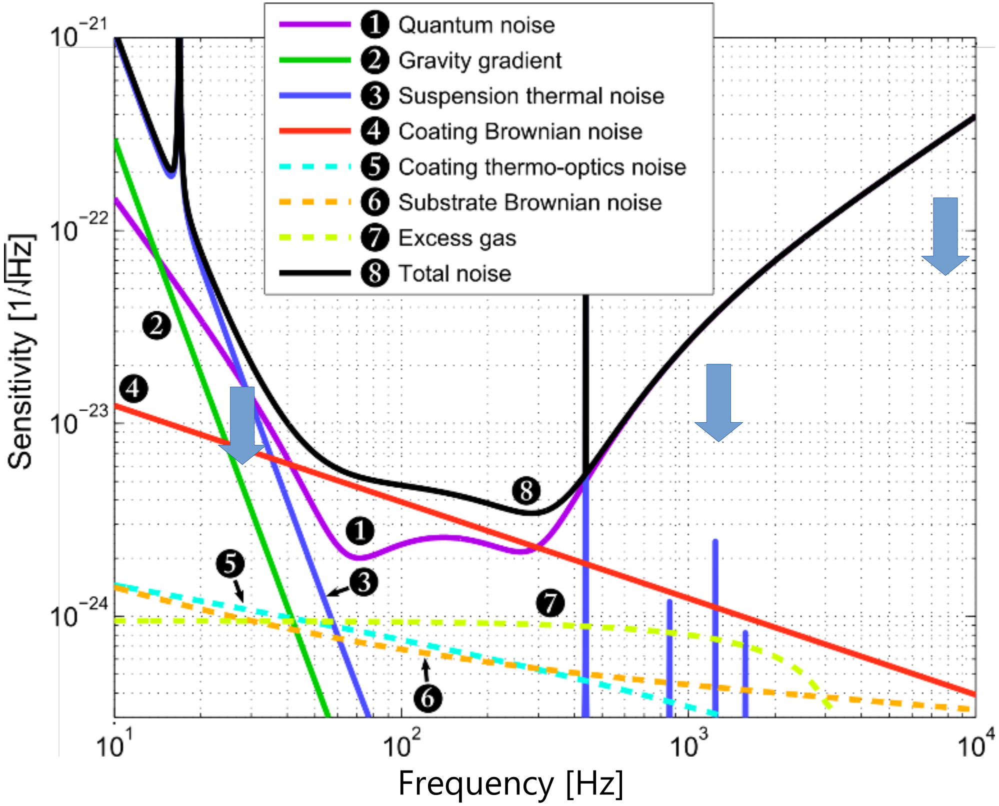
Advanced Virgo+



Advanced Virgo noise budget

- Phase I *before O4*
  - ❶ 25-40W input power
  - ❶ signal recycling mirror
  - ❷ Newtonian noise cancellation
  - ❶ frequency depend squeezing
  - preparatory work for phase II

Advanced Virgo+

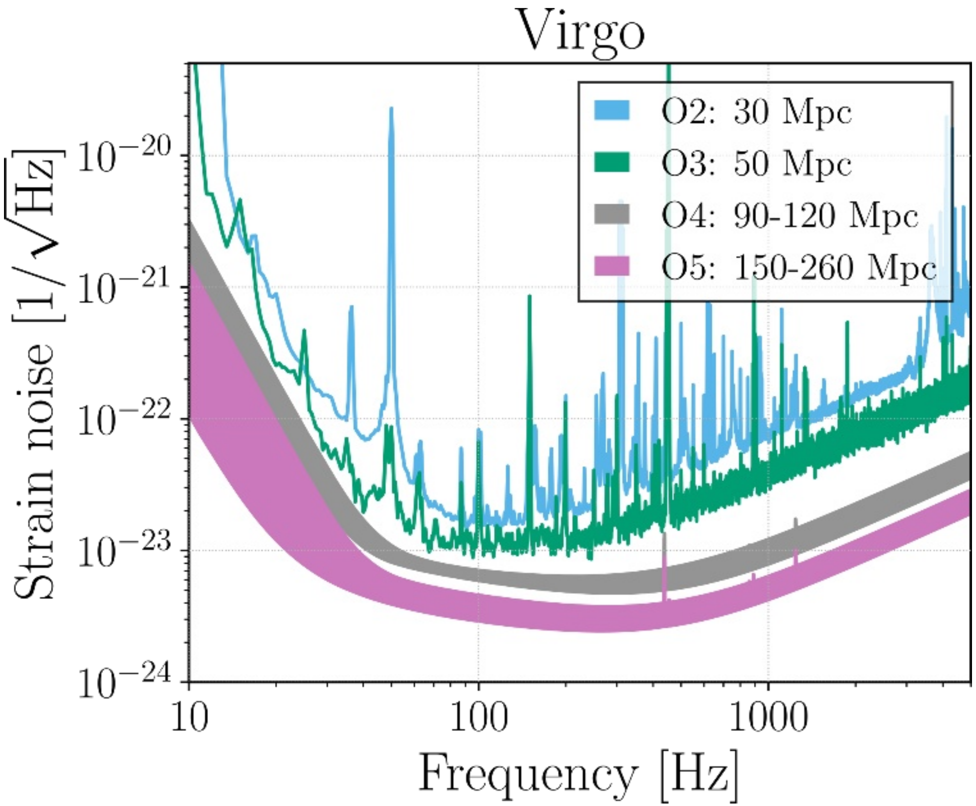


Advanced Virgo noise budget

- **Phase I** *before O4*
  - ❶ 25-40W input power
  - ❶ signal recycling mirror
  - ❷ Newtonian noise cancellation
  - ❶ frequency depend squeezing
  - preparatory work for phase II

- **Phase II** *before O5*
  - ❶ 60-80W input power
  - ❶ lower optical loss
  - ❹ larger mirror with better coating

Advanced Virgo+



Advanced Virgo noise budget

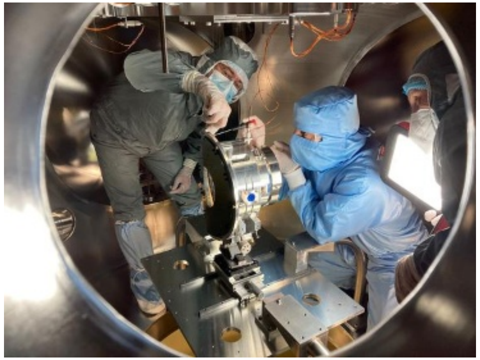
(similar improvement for LIGO)

- Phase I *before O4*
  - ❶ 25-40W input power
  - ❶ signal recycling mirror
  - ❷ Newtonian noise cancellation
  - ❶ frequency depend squeezing
  - preparatory work for phase II

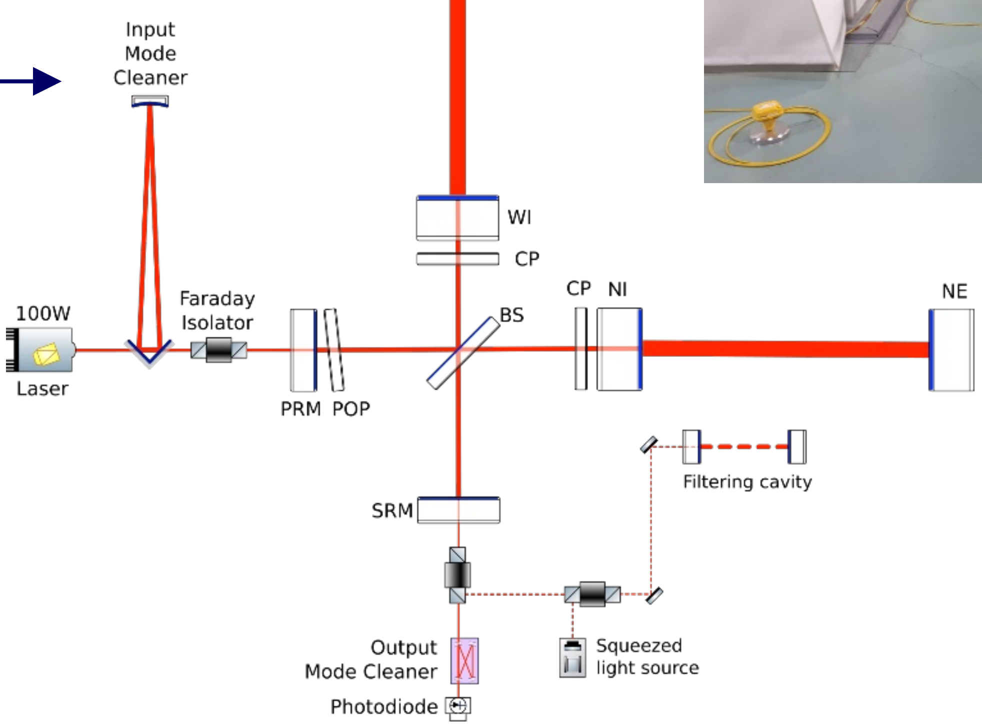
- Phase II *before O5*
  - ❶ 60-80W input power
  - ❶ lower optical loss
  - ❹ larger mirror with better coating

Phase I: installation highlights

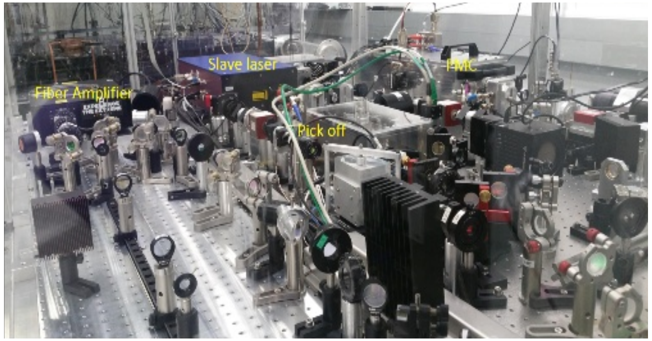
New IMC mirror with instrumented baffle



Seismometers array for Newtonian noise subtraction

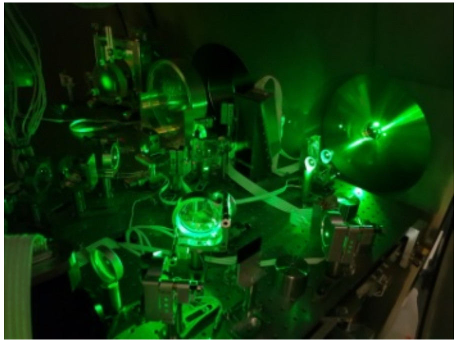


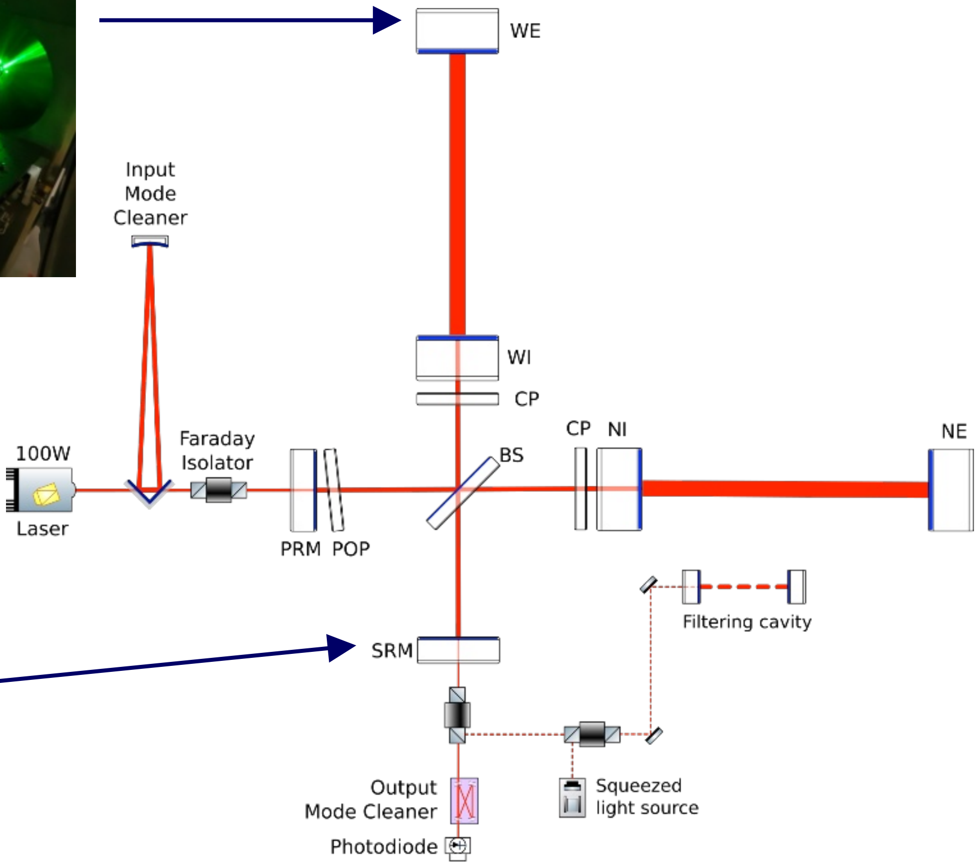
New fiber laser ~ 100W



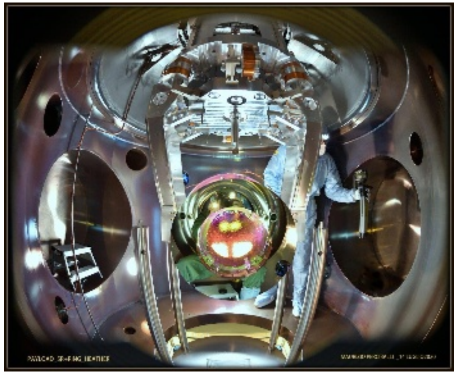
Phase I: installation highlights

Auxiliary green lasers for lock acquisition with signal recycling

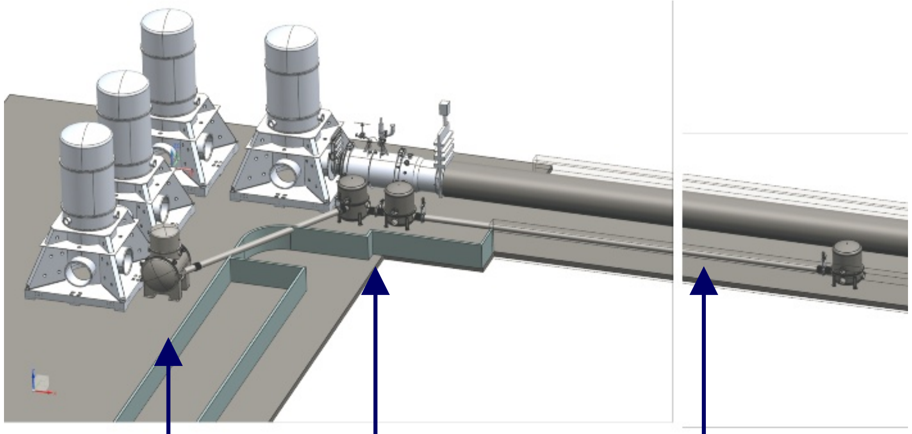




Suspended signal recycling mirror

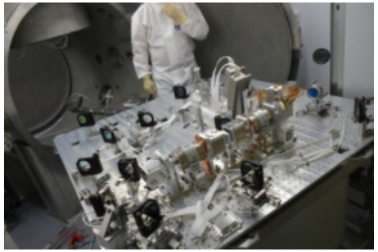


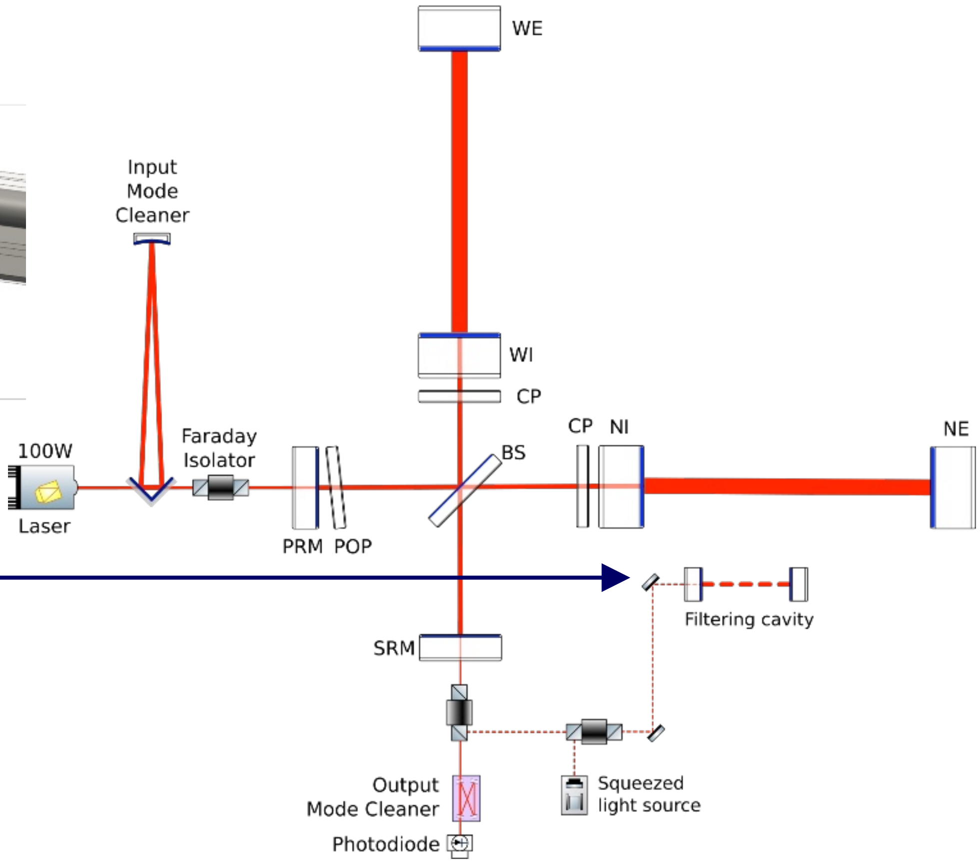
Phase I: installation highlights



New in vacuum suspended optical benches

New 300m long optical cavity

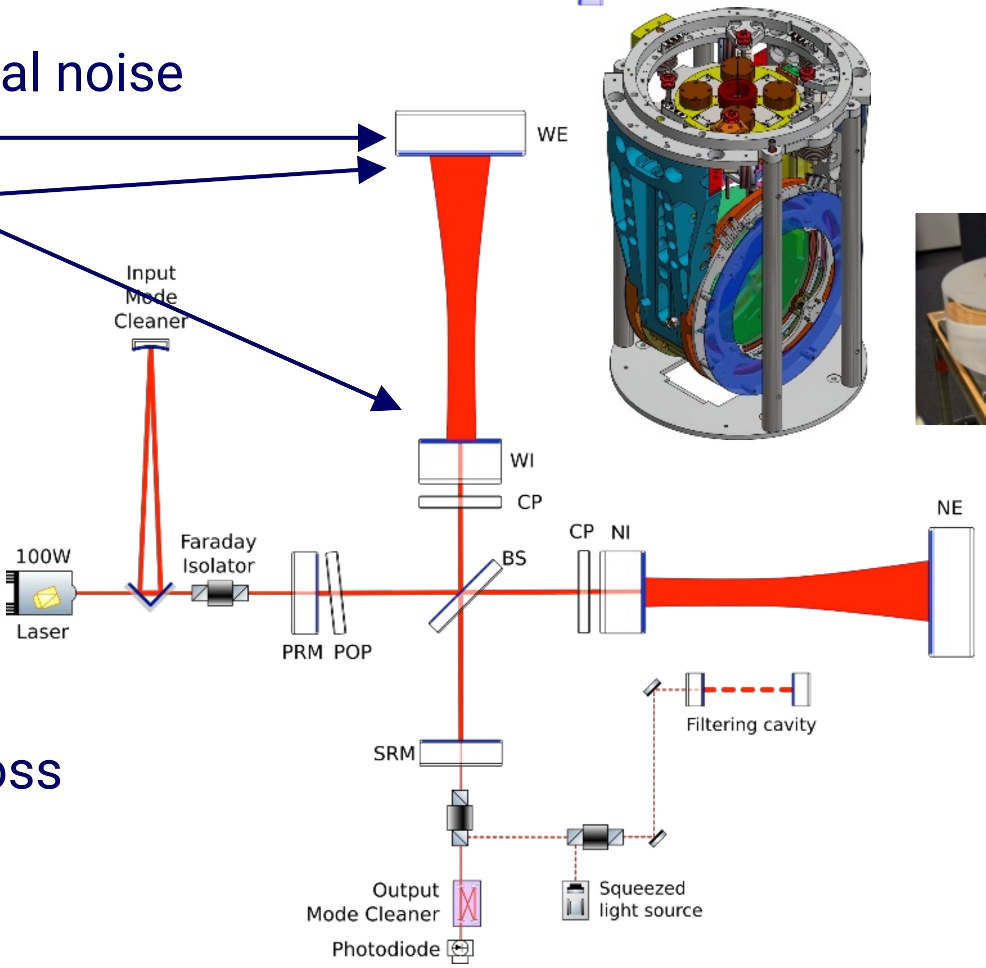


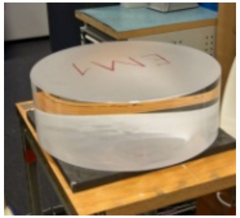


The filtering cavity

The AdV+ phase II (installation after O4)

- 2 actions to reduce coating thermal noise
  - larger end mirrors (+60%)
  - new coating material

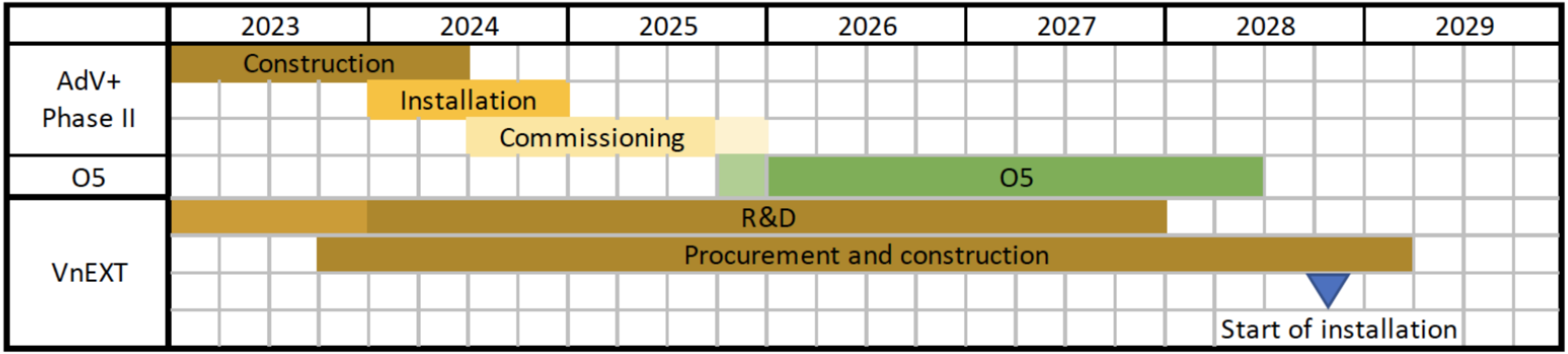




- upgraded laser (more power)
- lower detection and squeezing loss
- improved thermal compensation
- instrumented baffles

And after O5 ?

- Virgo nEXT: the ultimate upgrade
  - doubling the sensitivity
  - more laser power, less optical losses, better mirrors, more squeezing
  - closing the gap with the next generation

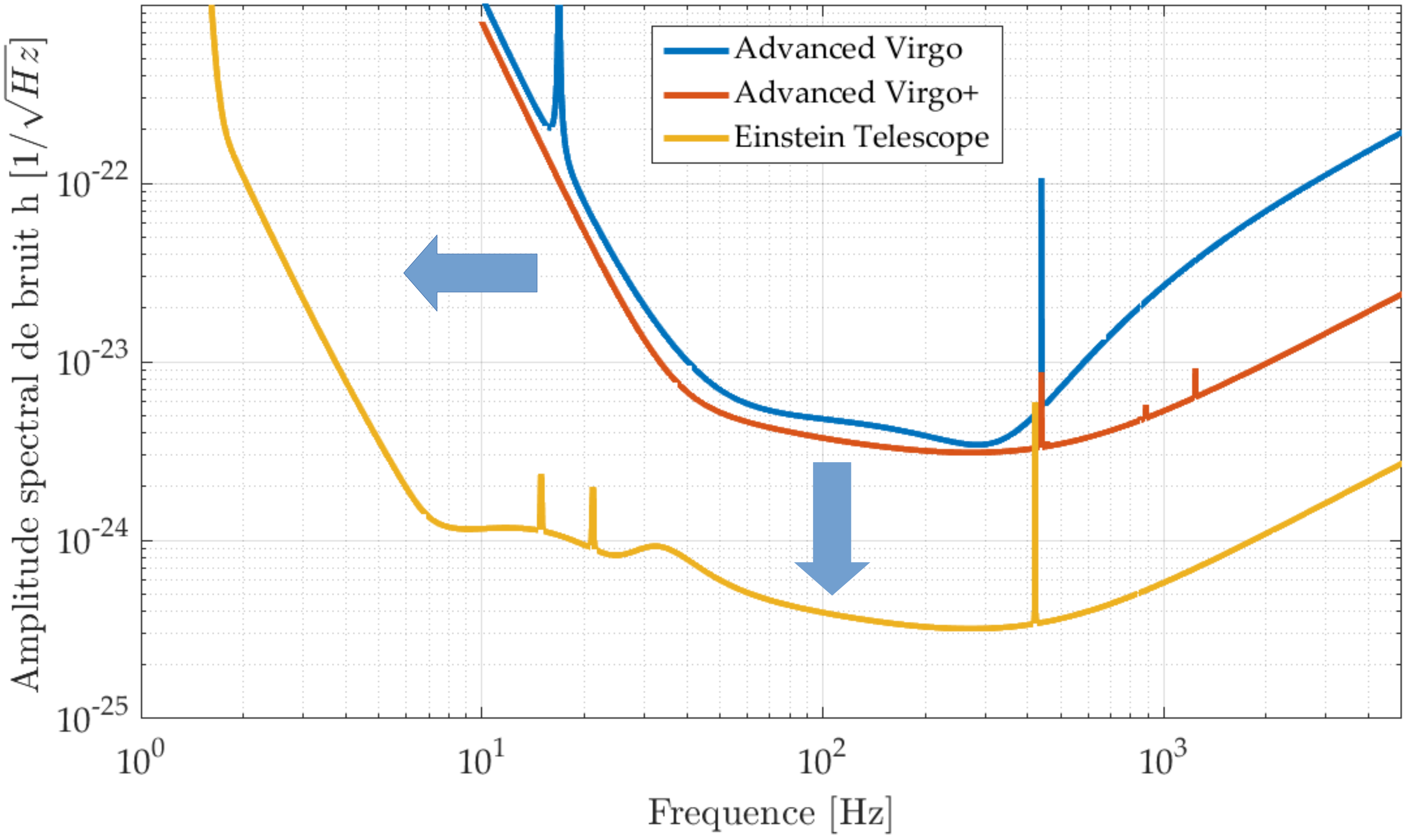


(similar plan/timeline for LIGO)

VIII.
The next generation

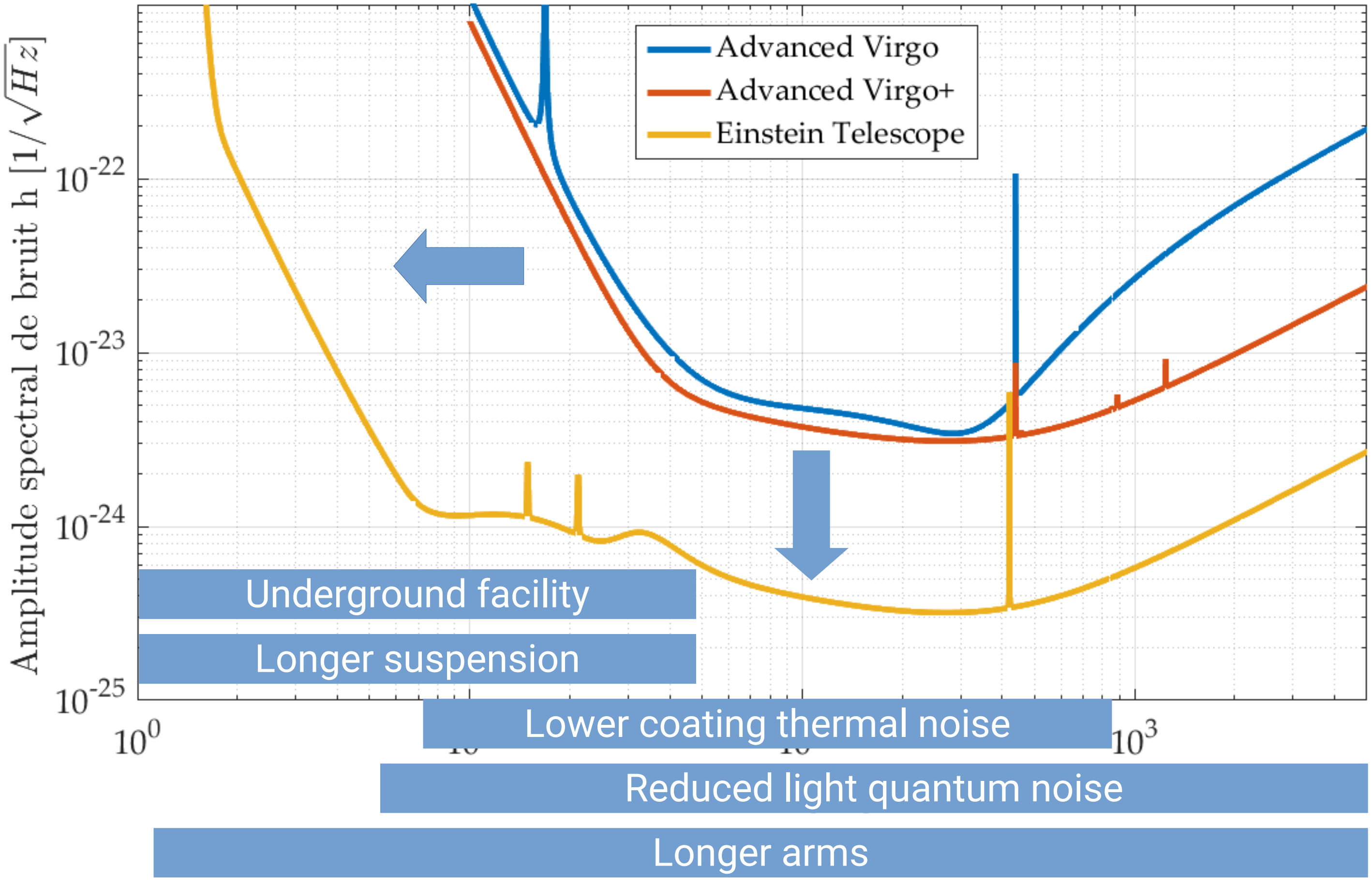
The Virgo successor: the Einstein Telescope

Goal: to be 10 times more sensitive, new infrastructure



The Virgo successor: the Einstein Telescope

Goal: to be 10 times more sensitive

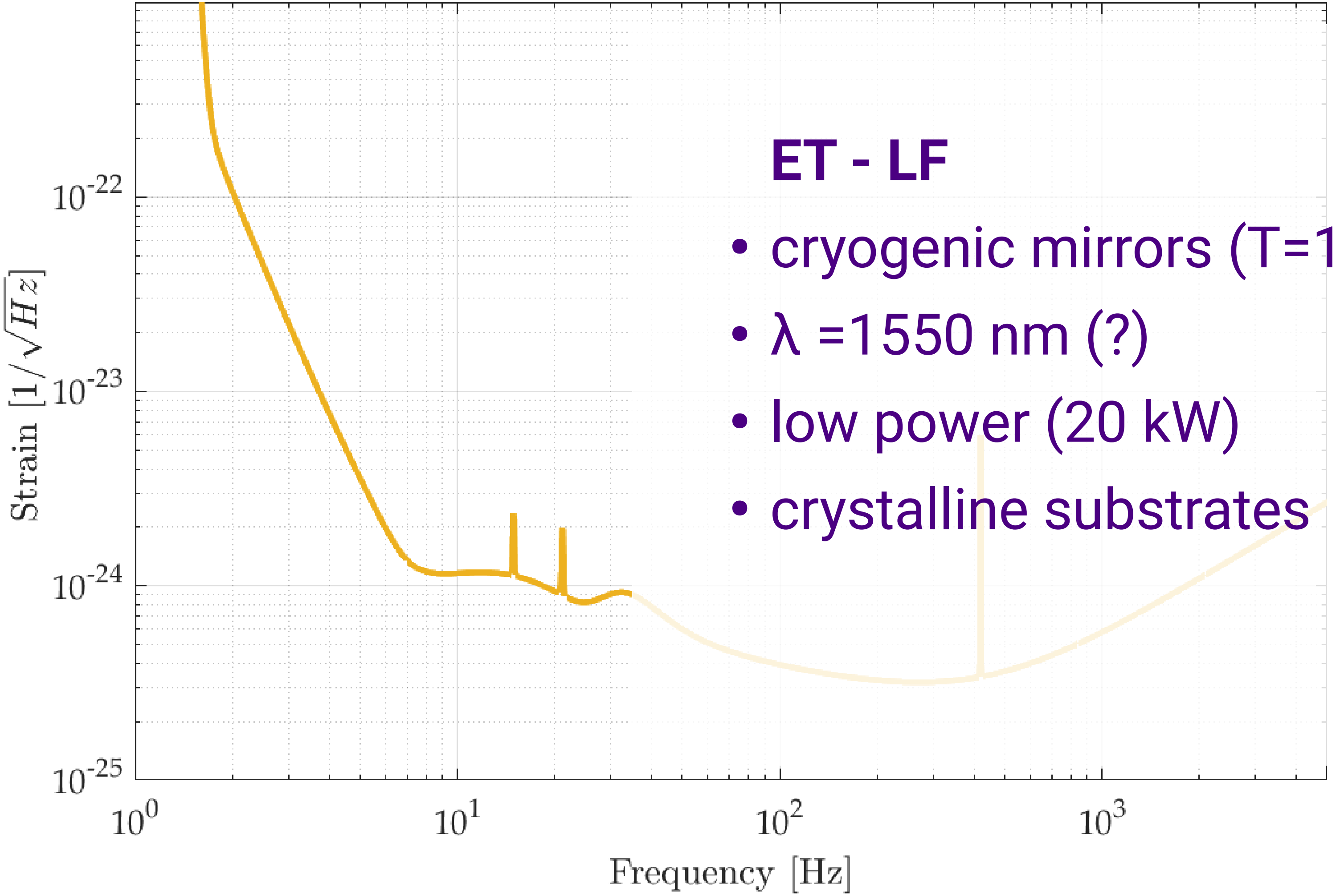


The challenge of increasing the bandwidth

- conflicting requirement at low and high frequencies
  - high optical power required at high frequency to lower the shot noise
  - but high power also degrades the low frequency due to radiation pressure noise

- the sensitivity could be achieved by 2 interferometers dedicated to low frequency (ET-LF) and high frequency (ET-HF)

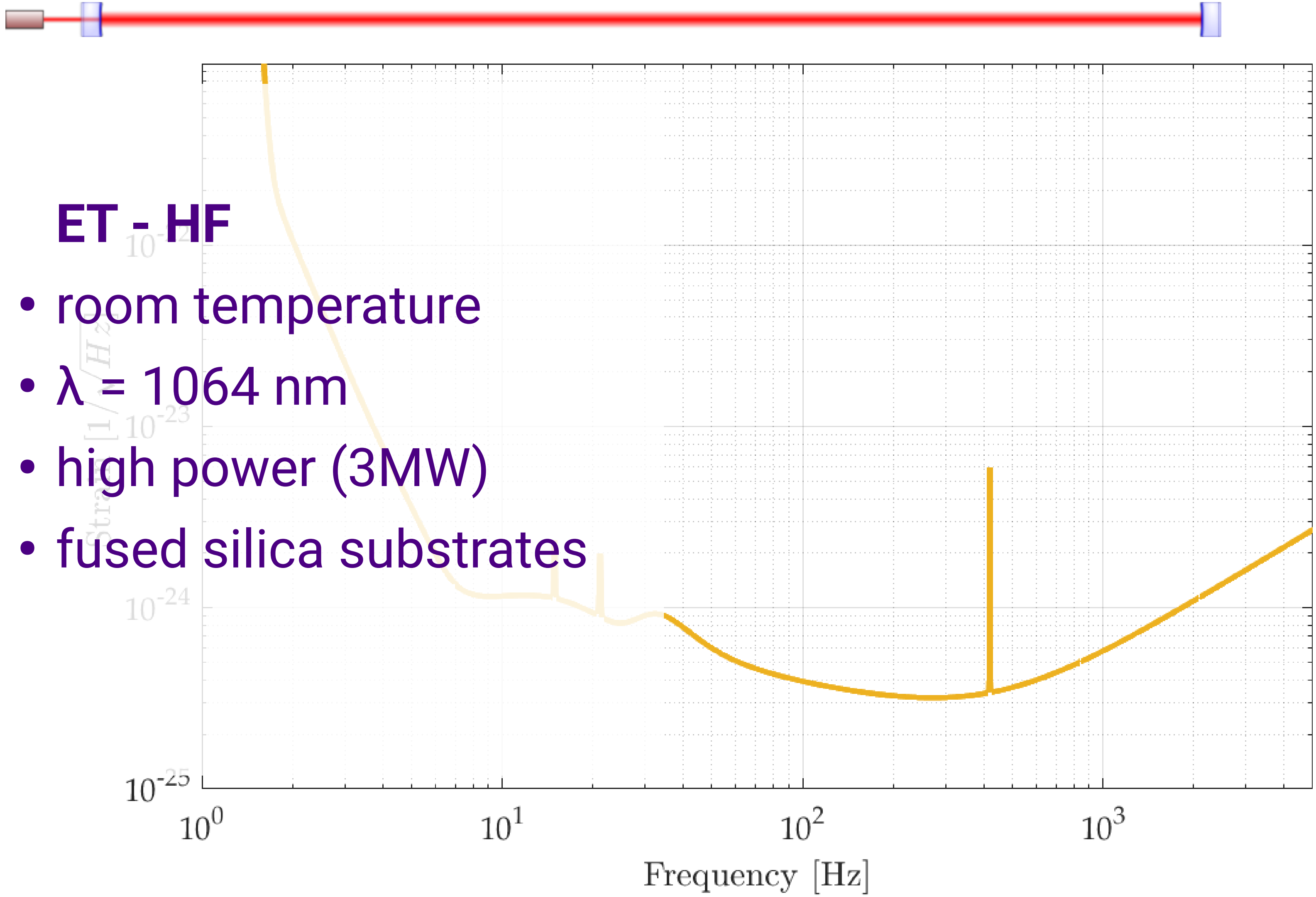
The xylophone strategy



ET - LF

- cryogenic mirrors (T=10-20K)
- λ =1550 nm (?)
- low power (20 kW)
- crystalline substrates

The xylophone strategy



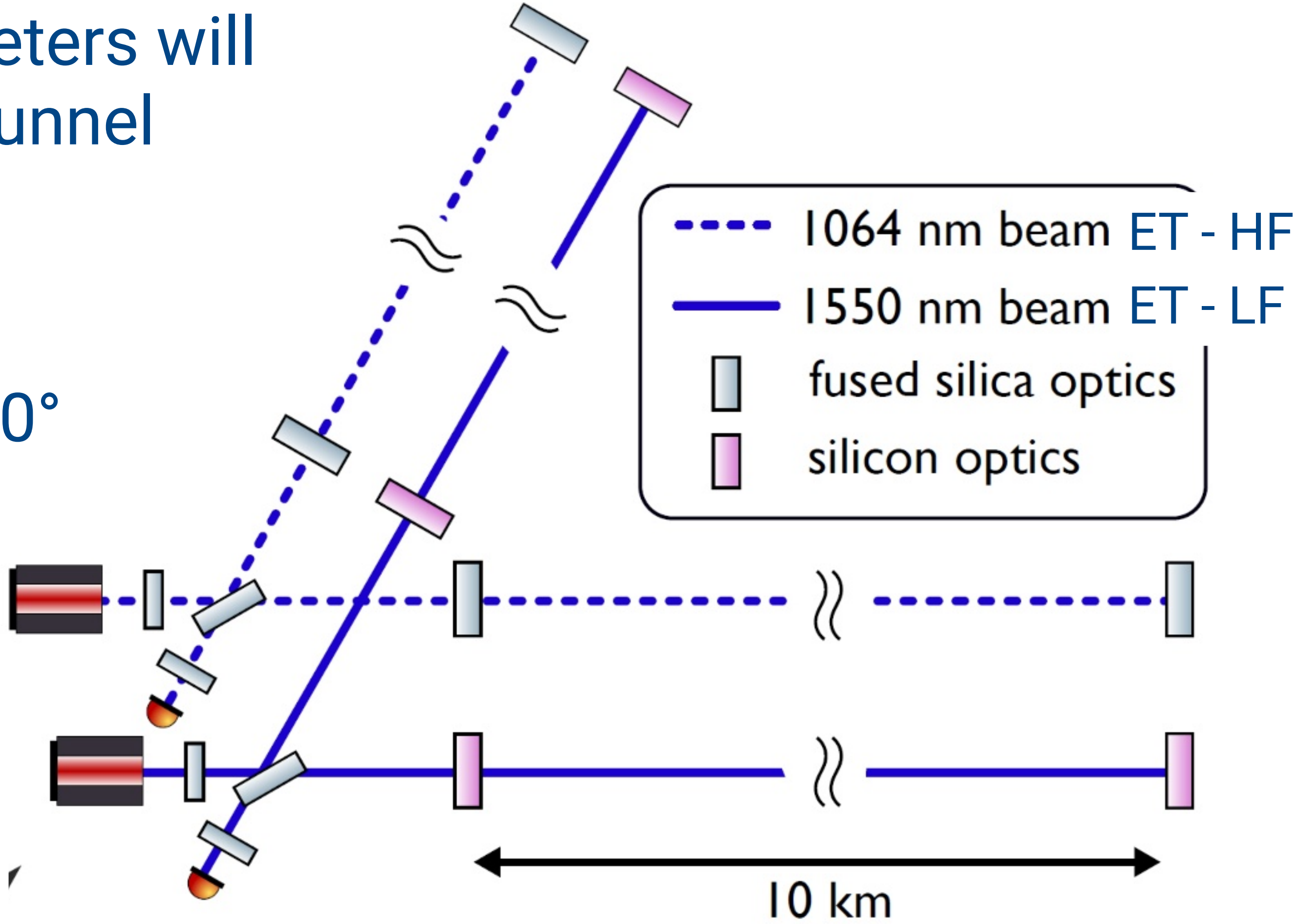
ET - HF

- room temperature
- λ = 1064 nm
- high power (3MW)
- fused silica substrates

1 detector = 2 interferometers

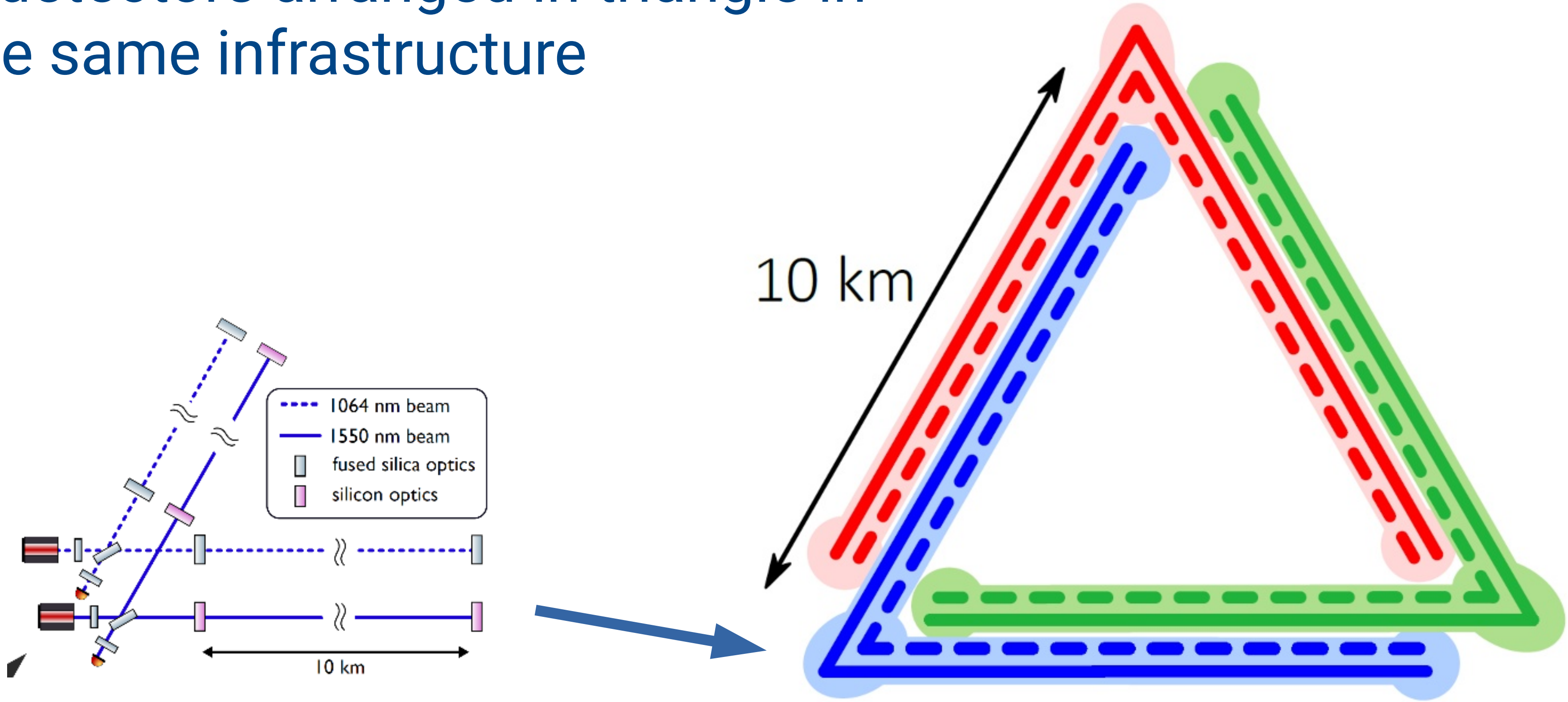
The 2 interferometers will share the same tunnel

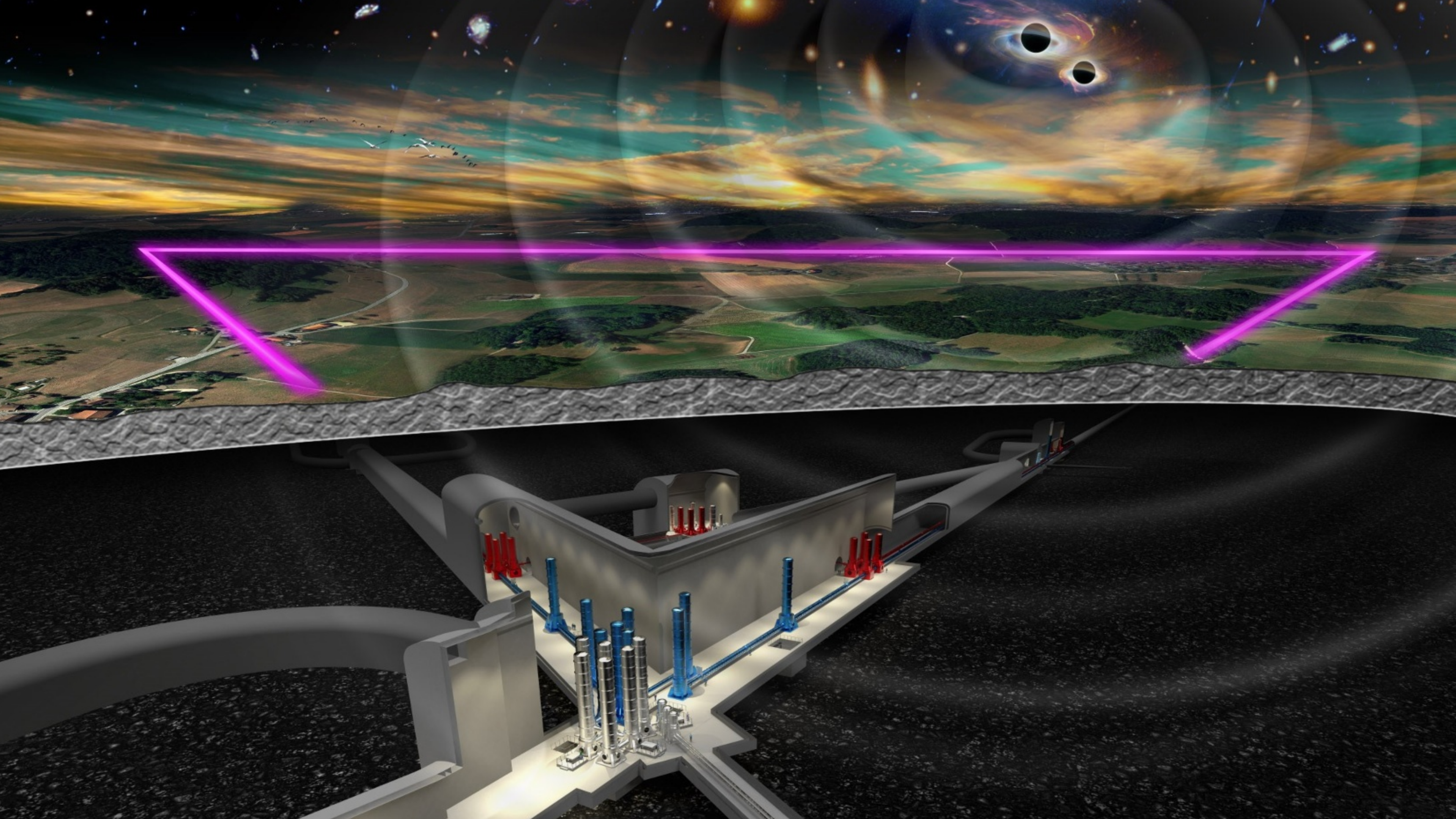
Michelson with 60° arm cavities



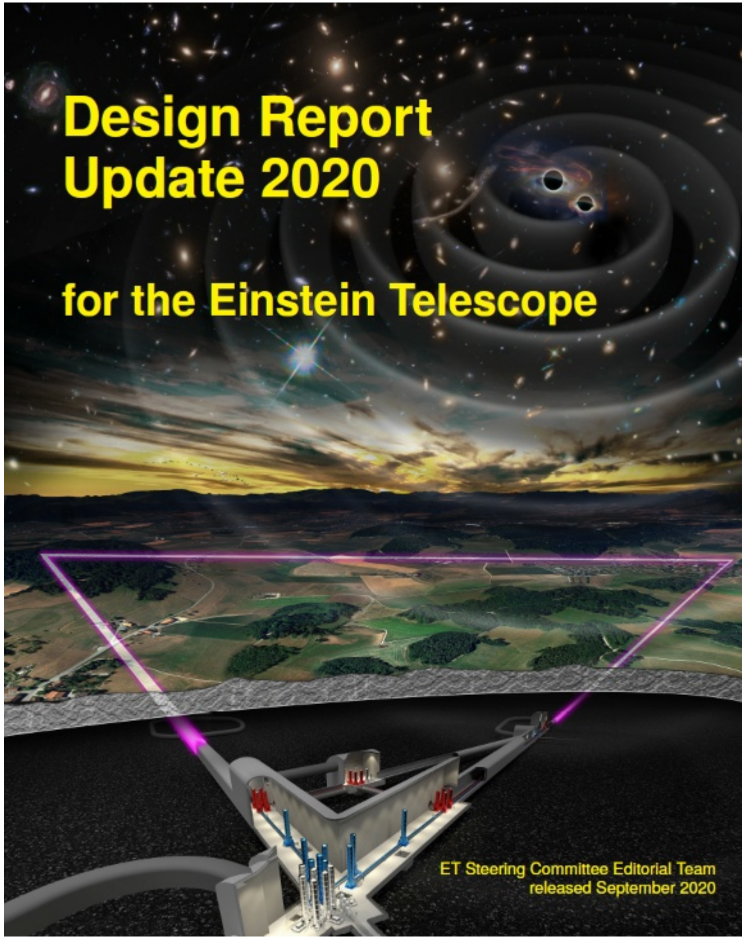
Not one but 3 detectors

3 detectors arranged in triangle in the same infrastructure





The key parameters



https://apps.et-gw.eu/tds/ql/?c=15418

Parameter	ET-HF	ET-LF
Arm length	10 km	10 km
Input power (after IMC)	500 W	3 W
Arm power	3 MW	18 kW
Temperature	290 K	10-20 K
Mirror material	fused silica	silicon
Mirror diameter / thickness	62 cm / 30 cm	45 cm/ 57 cm
Mirror masses	200 kg	211 kg
Laser wavelength	1064 nm	1550 nm
SR-phase (rad)	tuned (0.0)	detuned (0.6)
SR transmittance	10 %	20 %
Quantum noise suppression	freq. dep. squeez.	freq. dep. squeez.
Filter cavities	1×300 m	2×1.0 km
Squeezing level	10 dB (effective)	10 dB (effective)
Beam shape	TEM_{00}	TEM_{00}
Beam radius	12.0 cm	9 cm
Scatter loss per surface	37 ppm	37 ppm
Seismic isolation	SA, 8 m tall	mod SA, 17 m tall
Seismic (for $f > 1$ Hz)	$5 \cdot 10^{-10}\, m/f^2$	$5 \cdot 10^{-10}\, m/f^2$
Gravity gradient subtraction	none	factor of a few

The American cousin: Cosmic Explorer