About gravitational wave detectors

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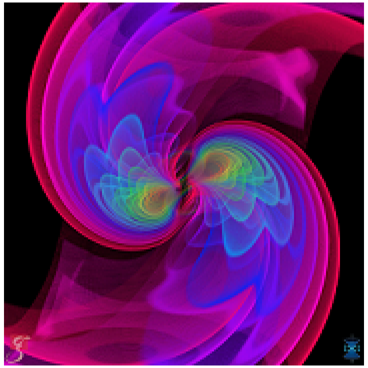
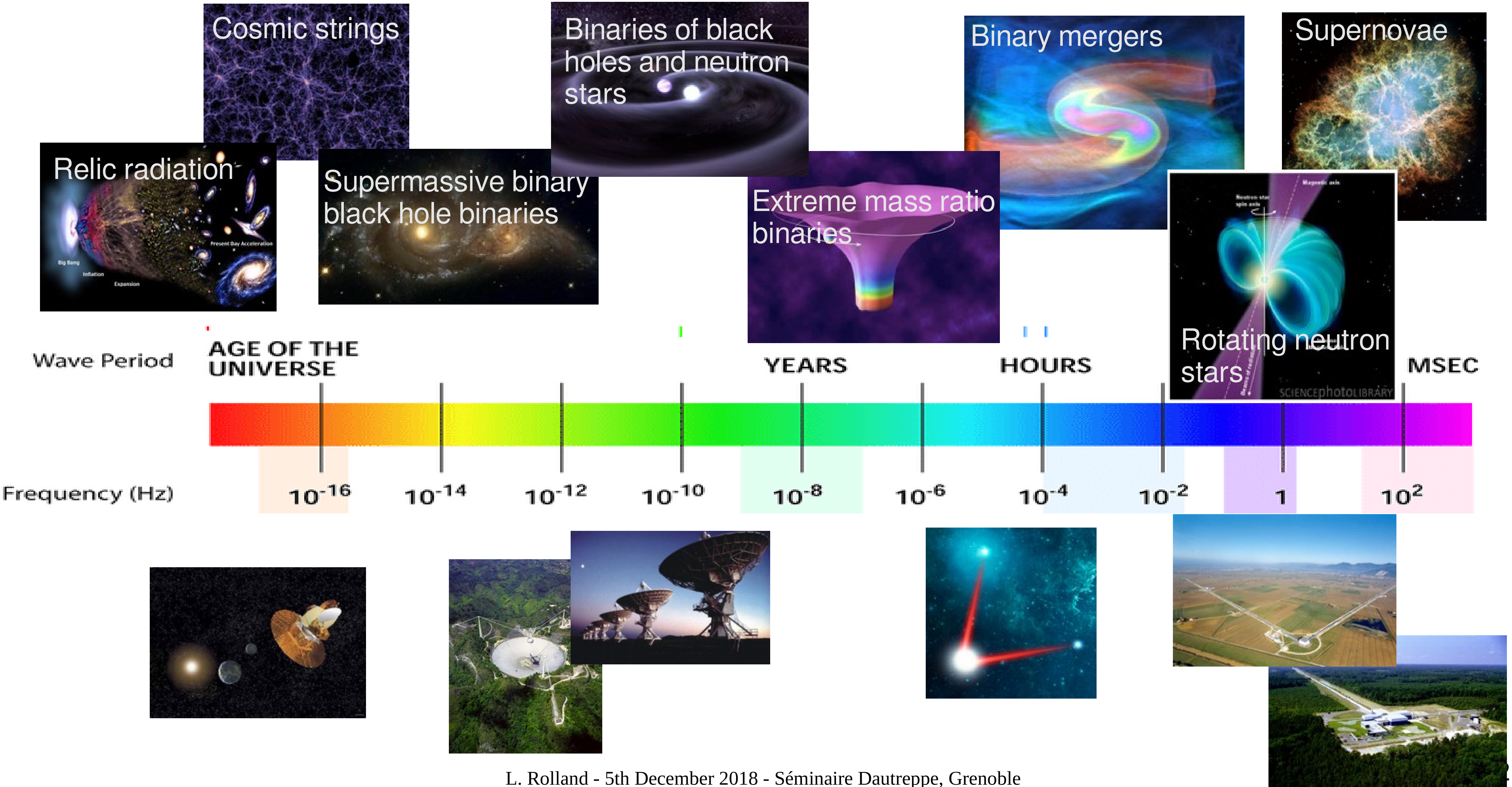


DAUTREPPE 2018
Dernières nouvelles de l'univers

Université Grenoble-Alpes
Saint Martin d'Hères

December 5th 2018

The gravitational wave (GW) spectrum



Cosmic strings

Binaries of black holes and neutron stars

Binary mergers

Supernovae

Relic radiation

Supermassive binary black hole binaries

Extreme mass ratio binaries

Rotating neutron stars

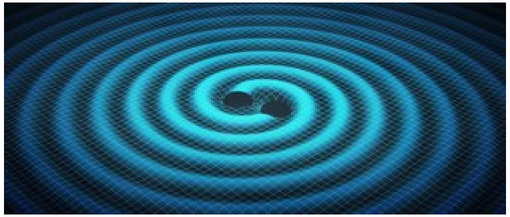
Wave Period: AGE OF THE UNIVERSE, YEARS, HOURS, MSEC

Frequency (Hz): 10^{-16}, 10^{-14}, 10^{-12}, 10^{-10}, 10^{-8}, 10^{-6}, 10^{-4}, 10^{-2}, 1, 10^{2}

Ground-based interferometers

(GW in the range 10 Hz to few kHz)

Detecting gravitational waves with ground-based interferometers



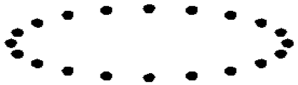
Masses in motion

↓

Space-time deformation

↓

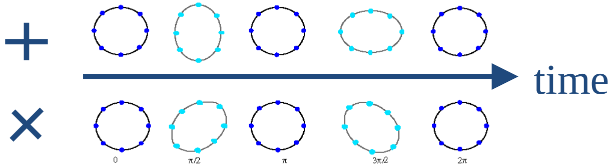
Gravitational wave

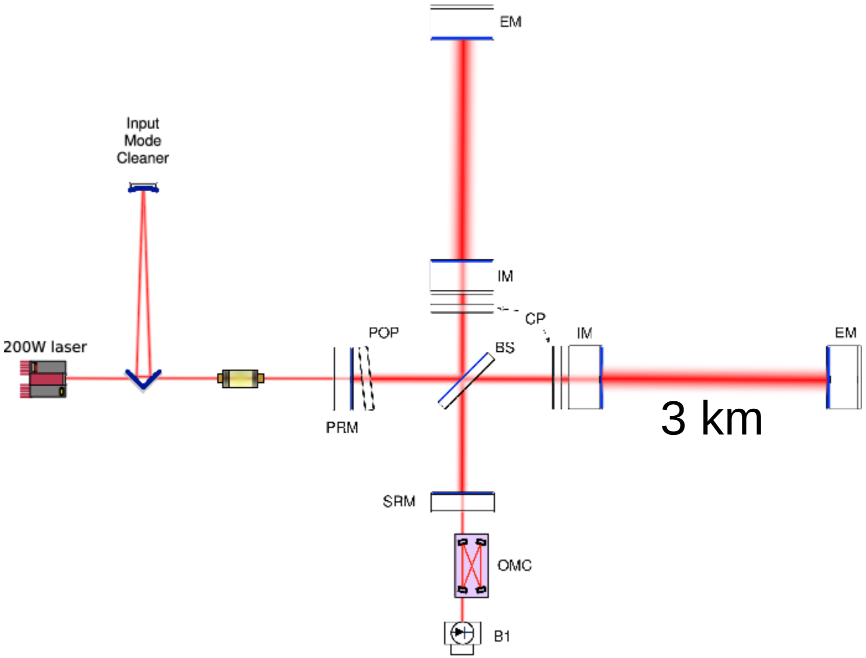


$$\delta L_x(t) = \frac{1}{2}\, h(t)\, L_0$$

h(t): amplitude of the GW

(*h* has no dimension)

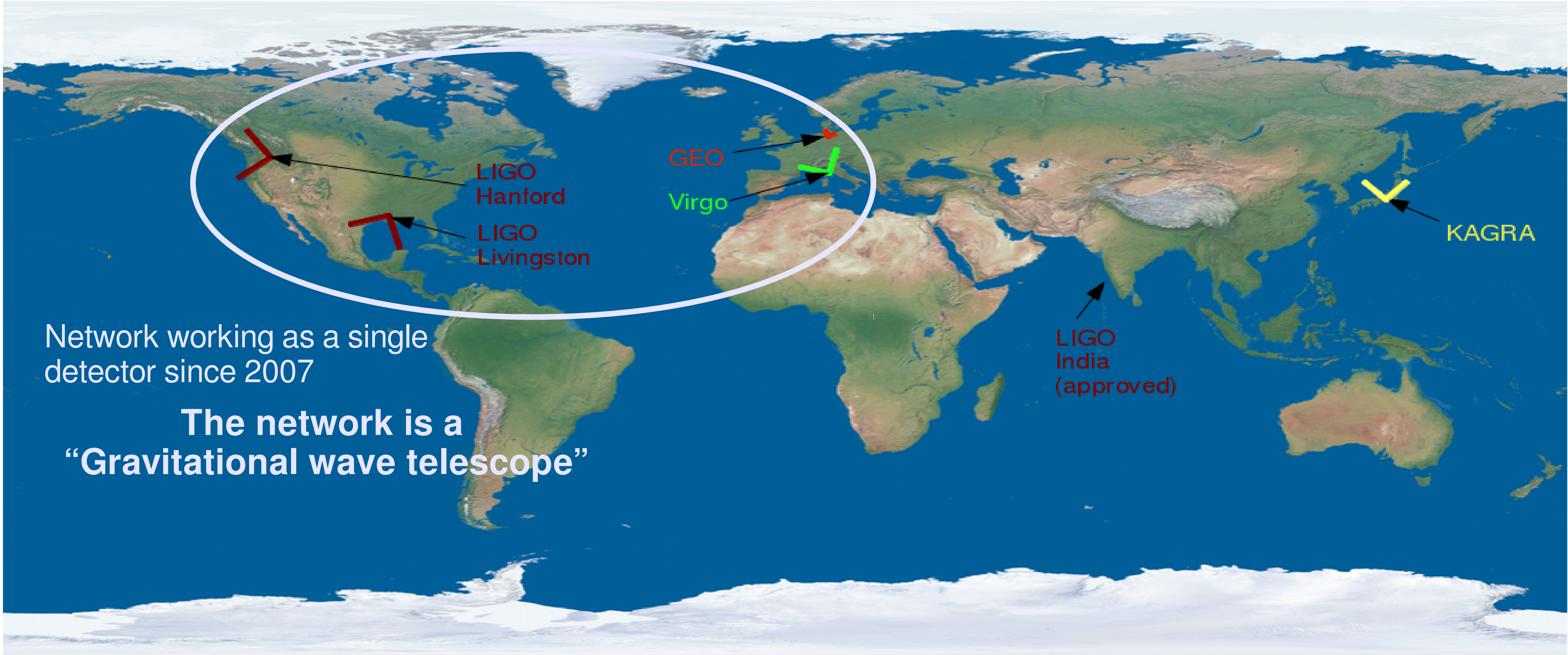




For GW170814, first Virgo detected event:

$h = 5\times10^{-22}$ → $\delta L = \pm\, 0.8 \times 10^{-18}$ m

An international network of detectors

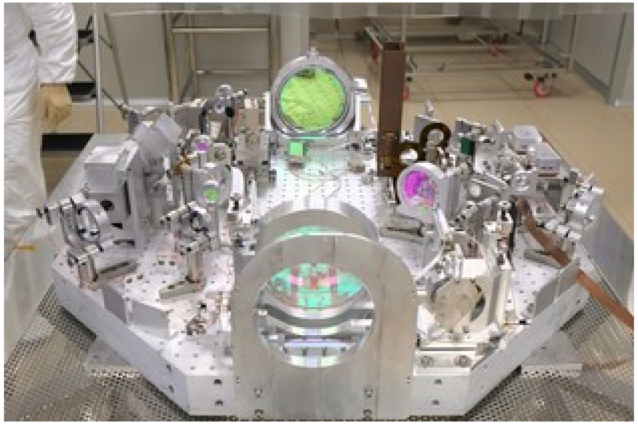


Network working as a single detector since 2007

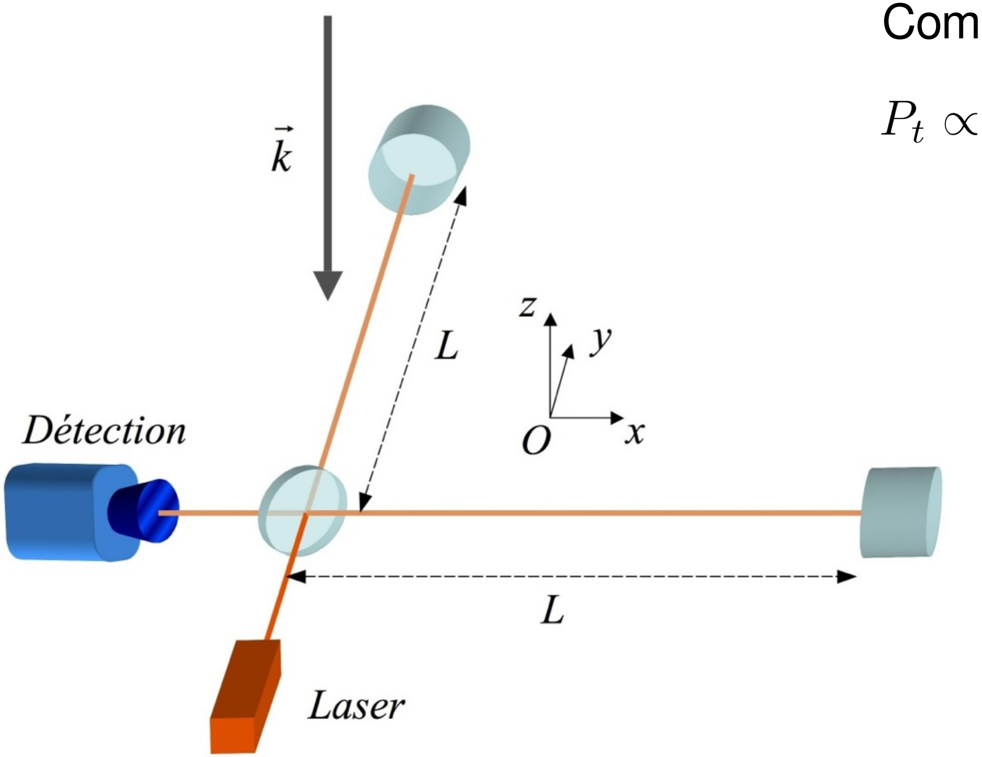
The network is a "Gravitational wave telescope"

- ✔ Rejection of spurious local noise (coincidence) → better sensitivity
- ✔ Source localisation (triangulation) → astronomy
- ✔ Wave polarization

Optical configuration, detector controls and hints of detectors sensitivity

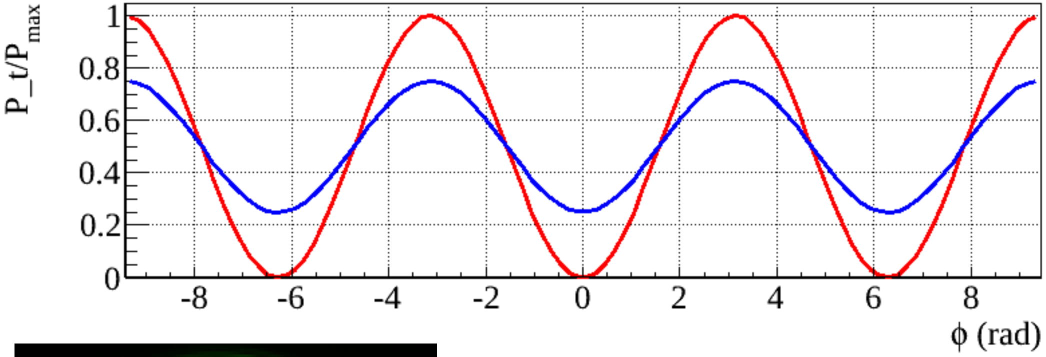


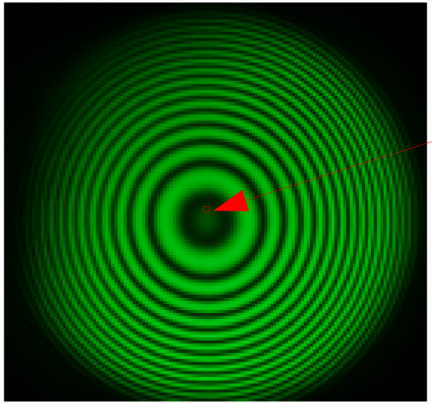
Simple Michelson interferometer



Computation of power output assuming plane waves:

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

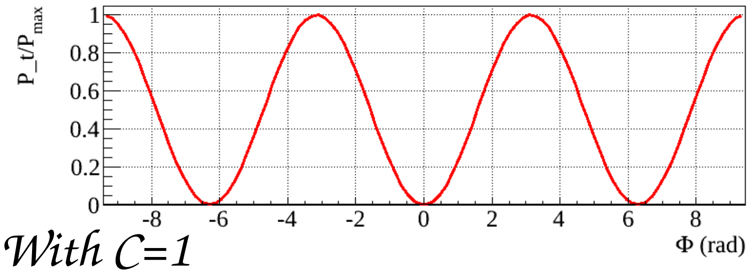




Equivalent size of Virgo beam

We do not measure nice fringe images !

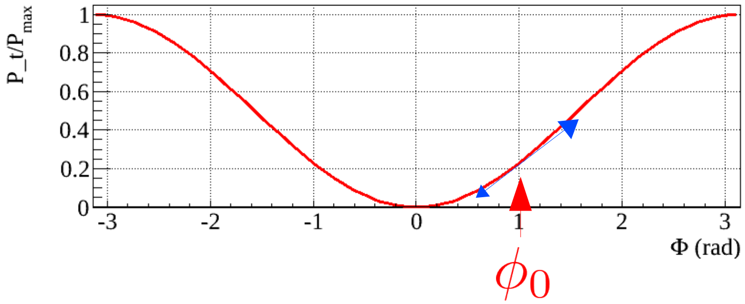
Longitudinally-controlled Michelson interferometer



With C=1

Freely swinging mirrors

Setting a working point →



Controlled mirror positions

Power variations as a function of small differential length variations

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

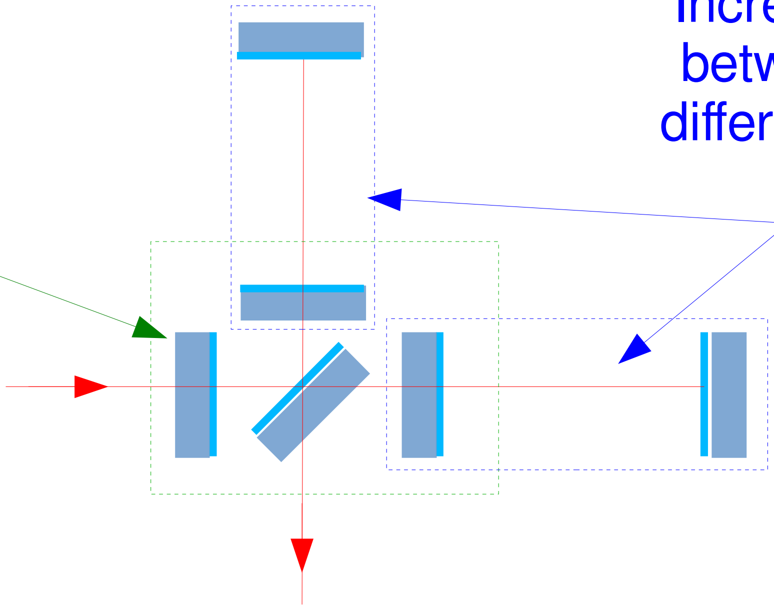
$\delta P_t \propto \delta\Delta L = hL_0$ around the working point !

Improving the sensitivity with resonant cavities

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

Increase the input power on BS

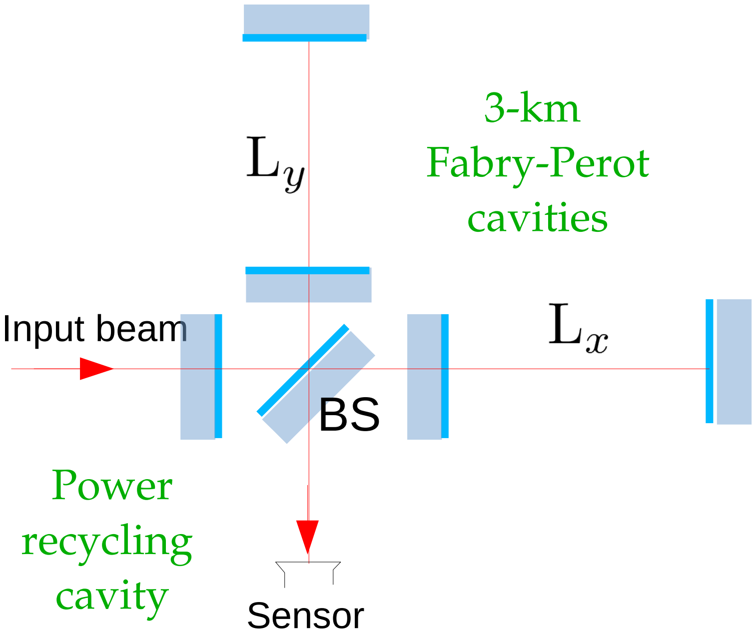
Increase the phase difference between the arms for a given differential arm length variation



Recycling **cavity**

Fabry-Perot **cavities** in the arms

A hint of (shot-noise limited) 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

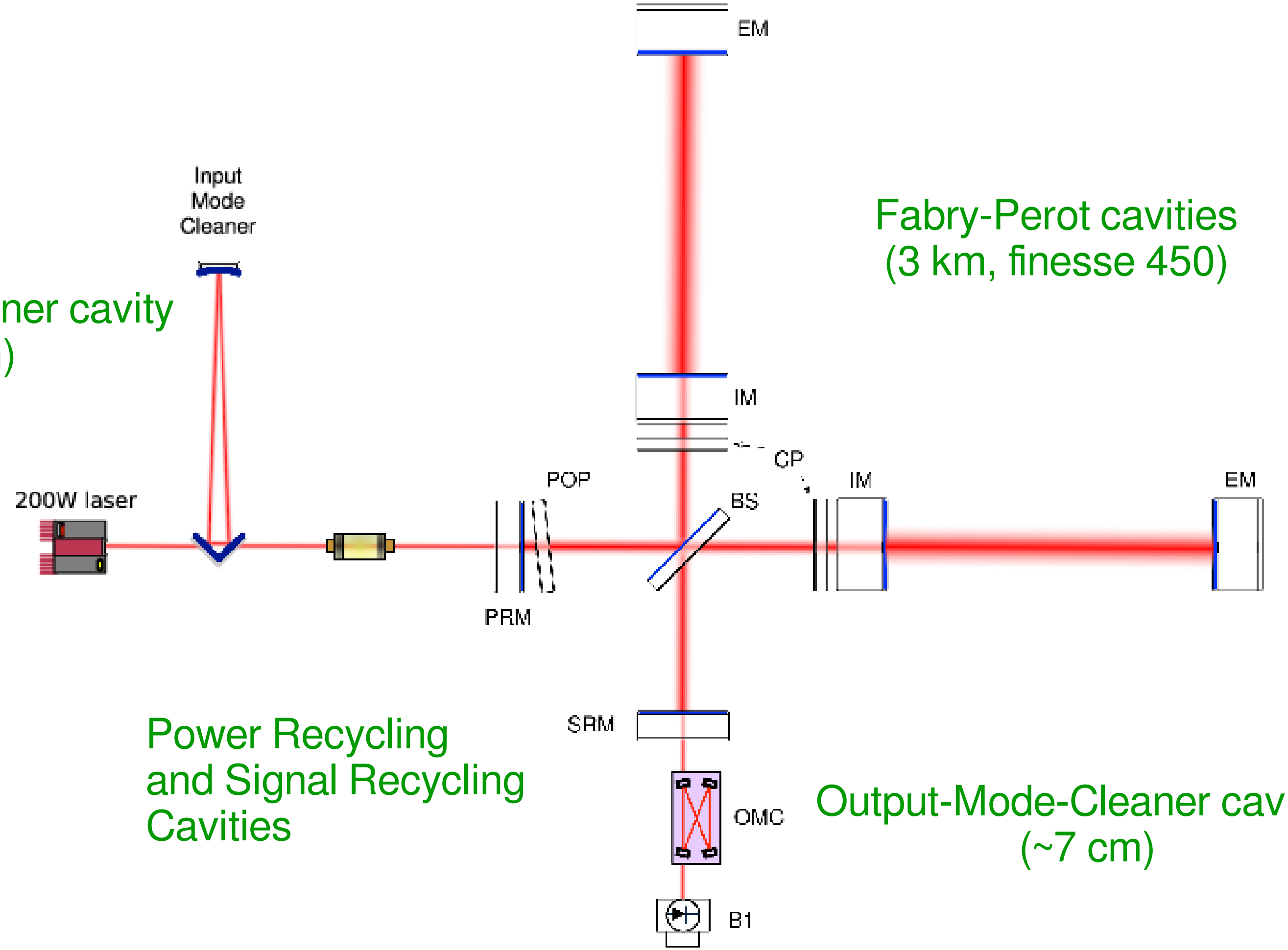
Shot noise due to output power of ~ 50 mW

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

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

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

Advanced Virgo optical layout



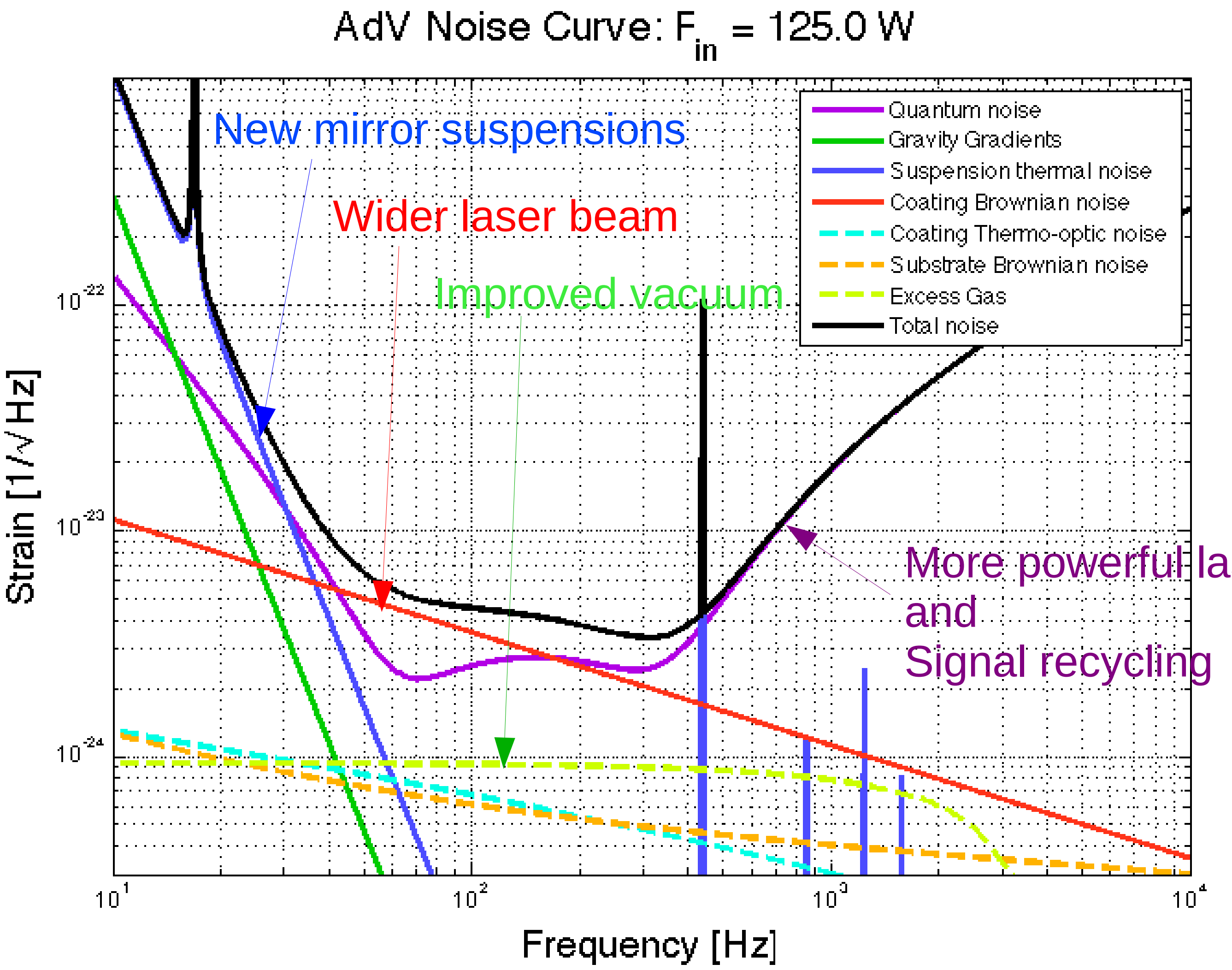
Fabry-Perot cavities
(3 km, finesse 450)

Input-Mode-Cleaner cavity
(~100 m)

Power Recycling
and Signal Recycling
Cavities

Output-Mode-Cleaner cavities
(~7 cm)

Detector nominal sensitivity



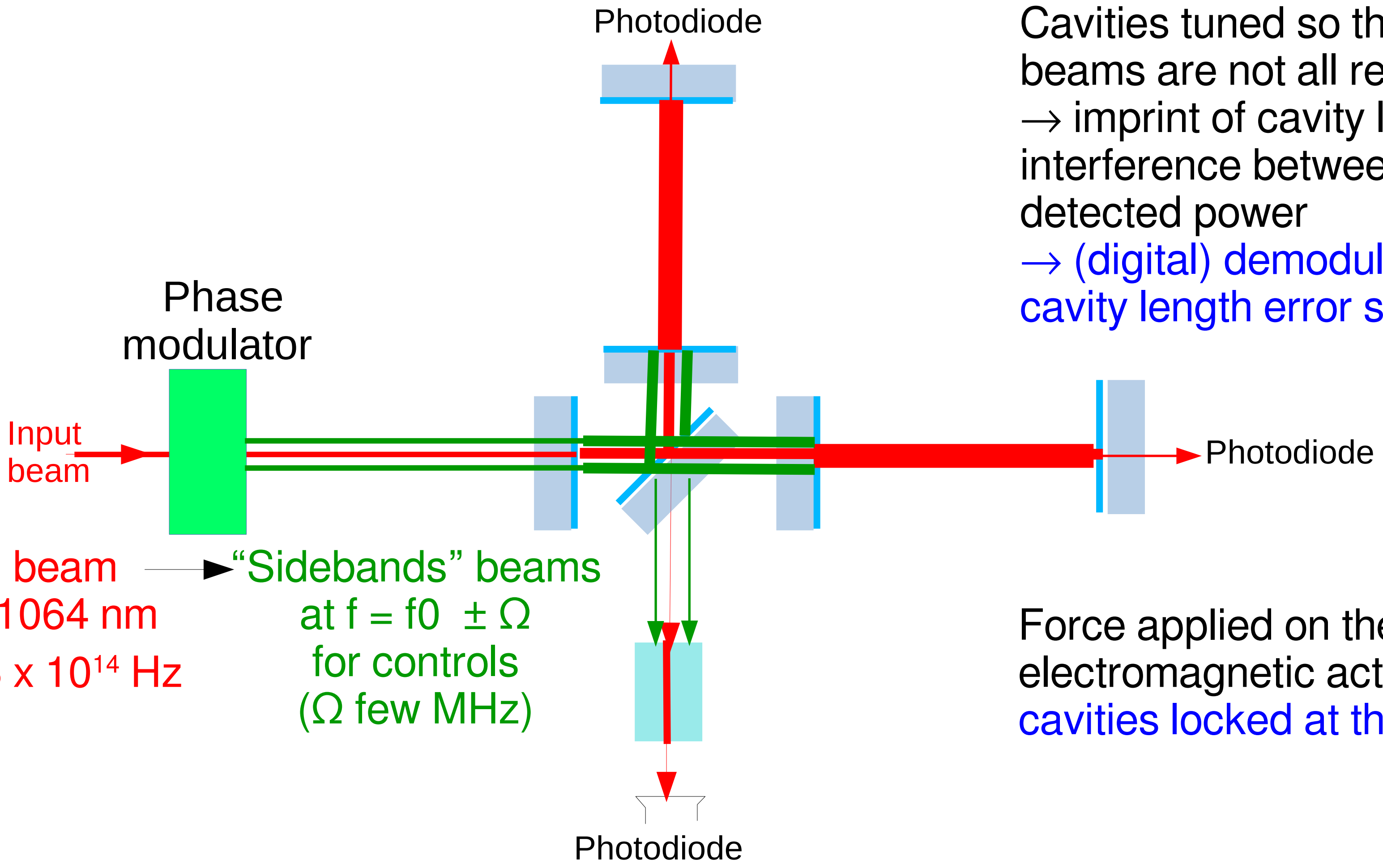
New mirror suspensions

Wider laser beam

Improved vacuum

More powerful laser
and
Signal recycling

Controlling the working point of the interferometer



Main beam ⟶ "Sidebands" beams

λ_0 = 1064 nm

$f_0 \sim 3 \times 10^{14}$ Hz

at f = f0 ± Ω

for controls

(Ω few MHz)

Cavities tuned so that the different beams are not all resonant in all

→ imprint of cavity lengths in the interference between beams, hence in detected power

→ (digital) demodulation at Ω to extract cavity length error signal

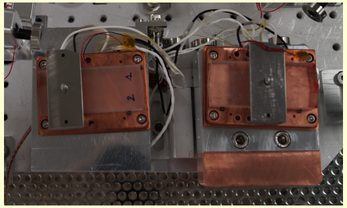
Force applied on the mirrors via electromagnetic actuators to keep the cavities locked at their nominal length

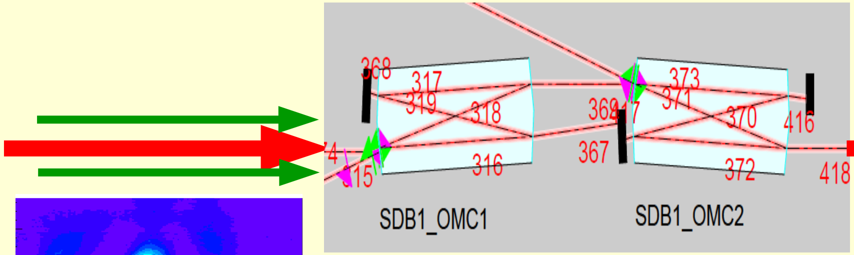
A cavity to clean the interferometer output beam

Beam wavelength selection

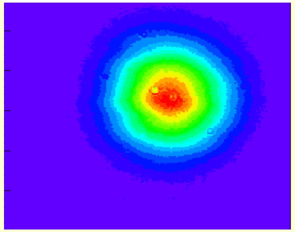
Main beam

Sidebands



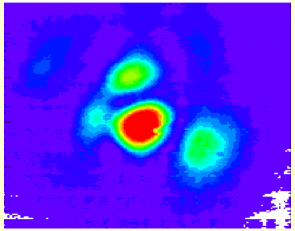


2 bow-tie cavities in series

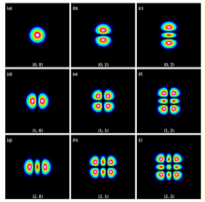


Gaussian beam, the one sensitive to gravitational waves

Beam geometry selection

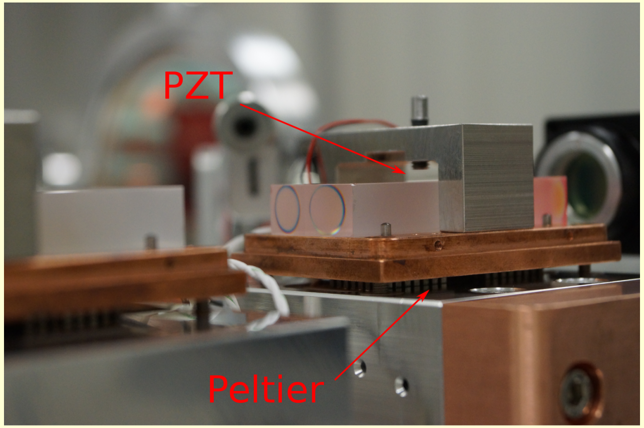


Higher order modes in the output beam (due to interferometer imperfections)



Control of the cavity length to keep resonance of the Gaussian mode of main beam

- Peltier cell
- Piezo actuator



Main features of the output mode cleaner cavities

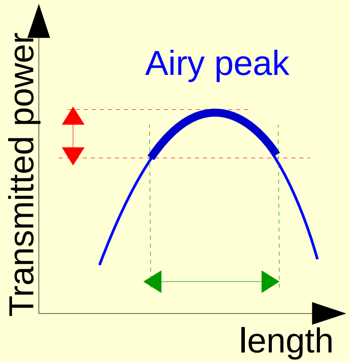
Cavity length noise

↓

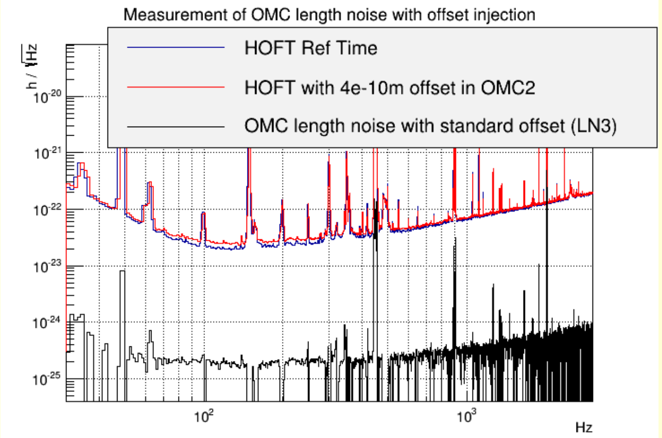
Photodiode power variations

↓

Noise in h(t) sensitivity



→ Need a precise control the cavity length:
lock precision: few 10^{-12} m
limited by thermo-refractive noise (40-900 Hz)



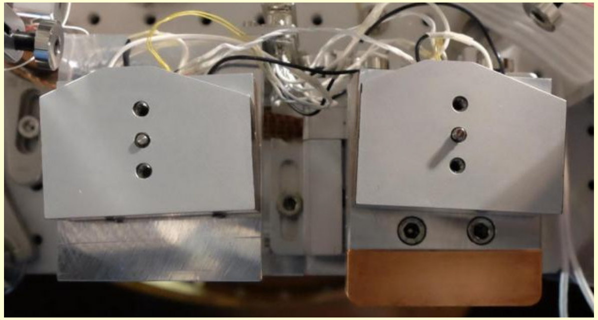
Optical losses

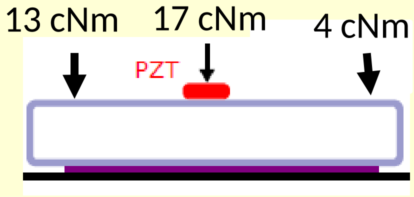
Absorption in the substrate ~0.06 %
- negligible

Scattering (1% for each OMC)
- polishing of reflective surfaces

Beam matching on first OMC (2%)
- mode matching and alignment

Beam matching between both OMCs (0.85%)
- mode matching, polarization, alignment



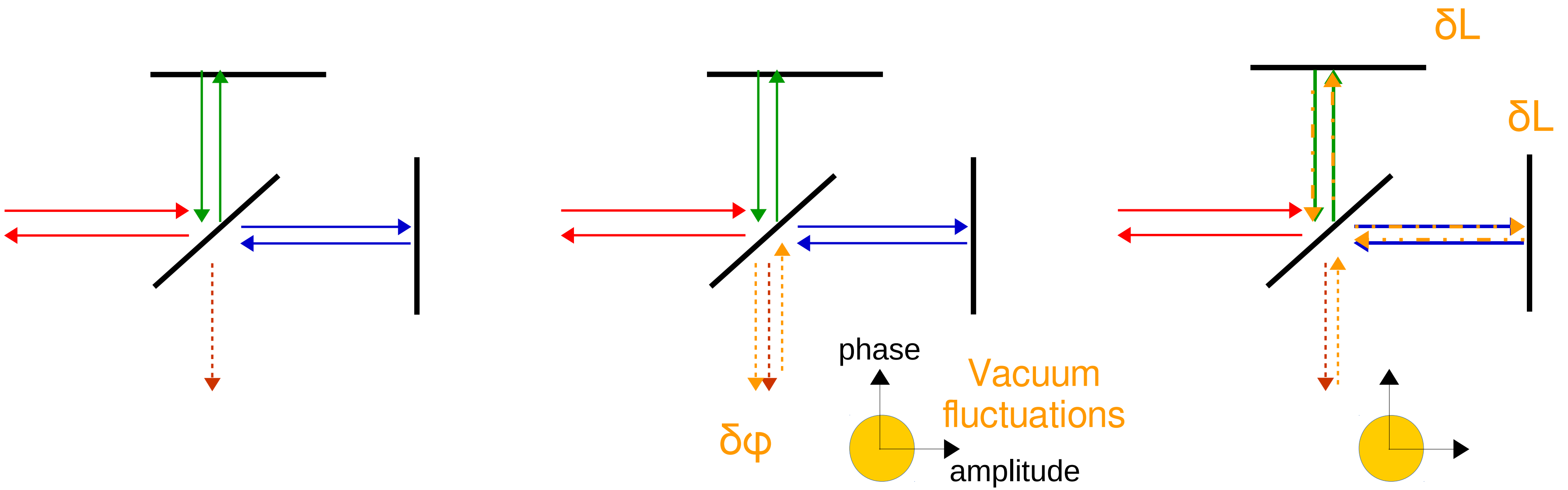


Current technological challenges

- Reducing quantum noise
- Reducing thermal noise
- Reduction of technical noise

Reducing quantum noise

Quantum noise: shot noise and radiation pressure noise



Working point close to a dark fringe

Signal related to phase offset

→ fluctuations of the phase

Photon shot noise

$$\propto \frac{\text{Phase fluctuation}}{\text{Laser power}}$$

→ fluctuations of the mirror positions

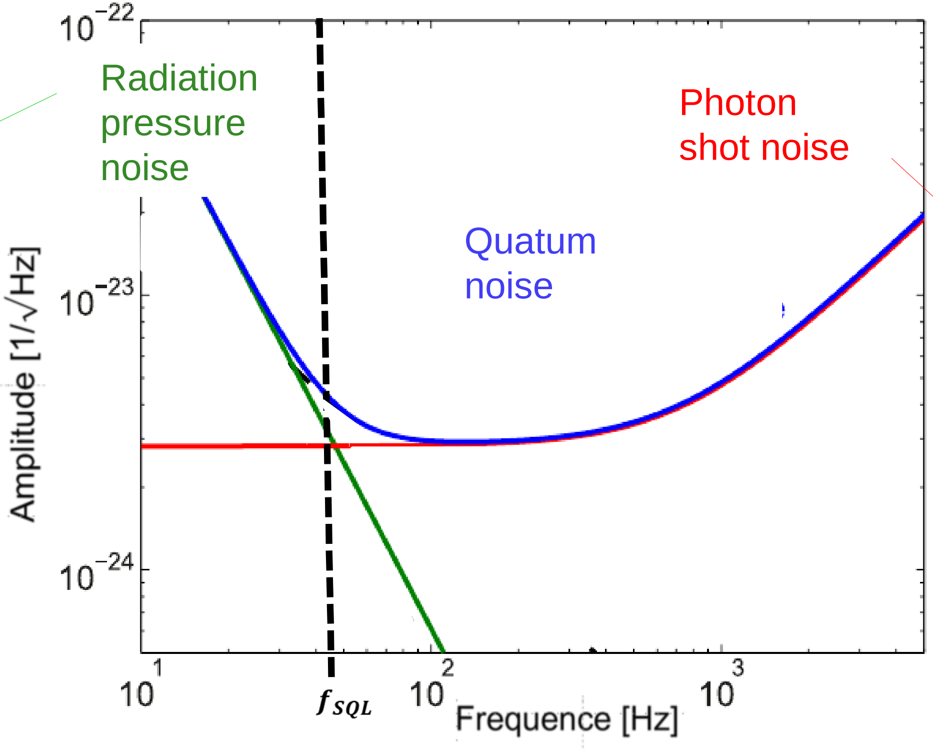
Radiation pressure noise

$\propto$ Amplitude fluctuation x Laser power

Quantum noise in the sensitivity

Fluctuation of differential length

Fluctuation of measured power

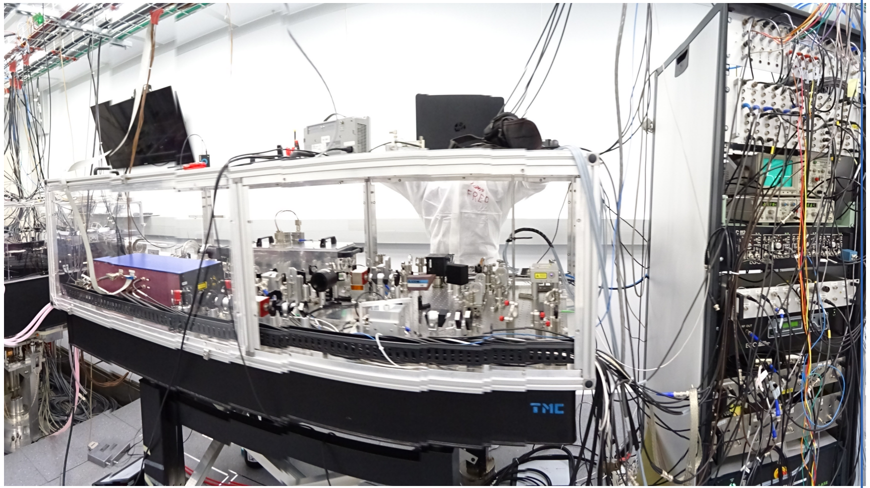


Fluctuation of measured power

Reduction of photon shot noise: high power laser

Goal for AdV:

continuous 200 W laser, stable monomode beam (TEM00), 1064 nm
frequency pre-stabilisation 1 Hz linewidth
low power noise (~10^{-9} /sqrt(Hz) in AdV bandwidth)
low beam jitter <10^{-11} rad/sqrt(Hz) at 10 Hz



R&D

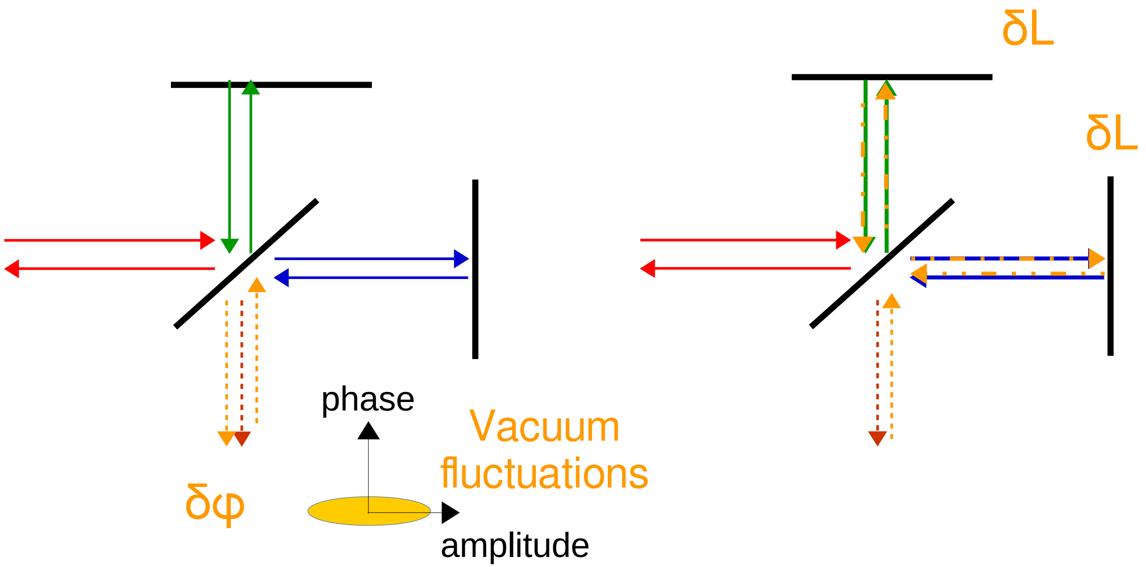
1 W seed, amplified to 100 or 200 W
- Two 100 W laser with coherence addition?
- A direct 200 W laser?

→ decrease shot noise contribution,
but increase radiation pressure noise contribution

Thermal effects in the interferometer mirrors
→ need of thermal compensation system

Parametric instabilities
coupling of laser high order modes with mirror modes

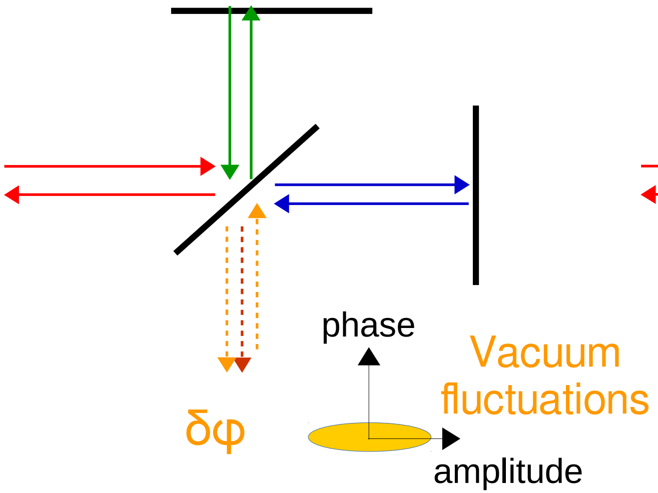
Reduction of photon shot noise: squeezing

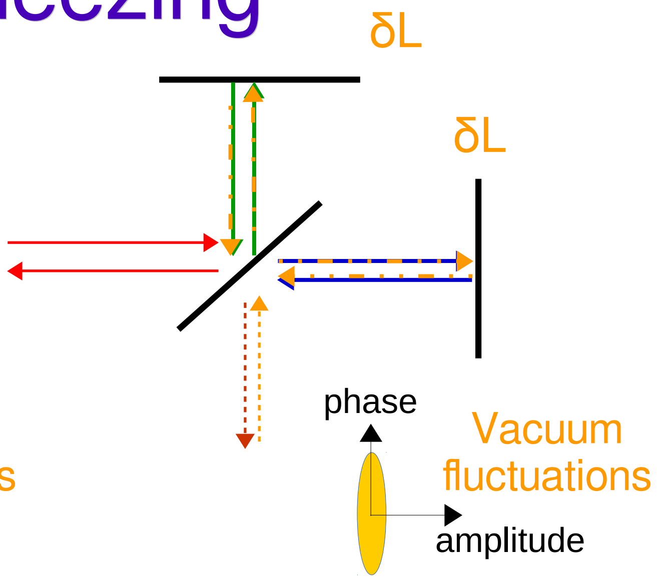


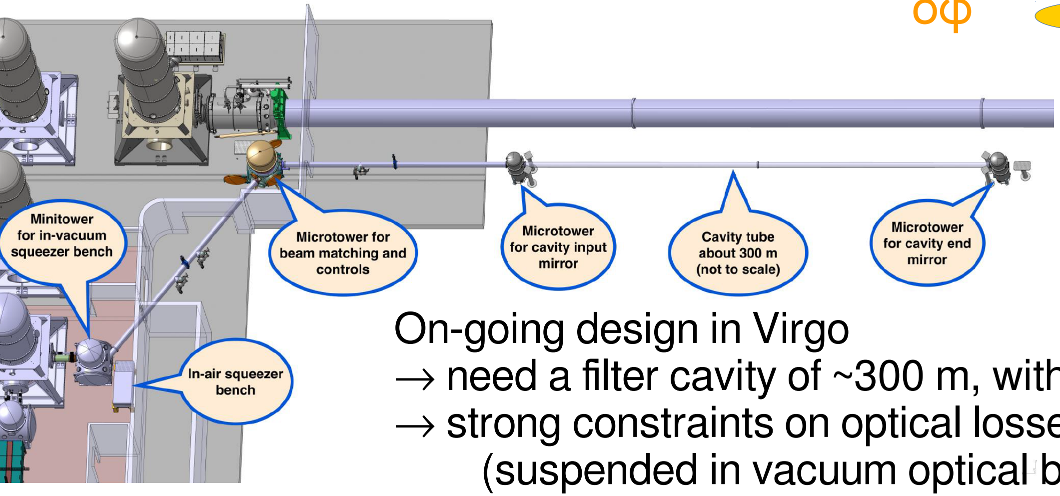
→ decrease photon shot noise
but increase radiation pressure noise

Installed in Virgo and LIGO
Commissioning on-going (currently 0.5 dB improvement)
→ constraints on optical losses, beam matching and alignment, ...

Reduction of quantum noise: frequency-dependent squeezing







→ decrease photon shot noise
AND radiation pressure noise

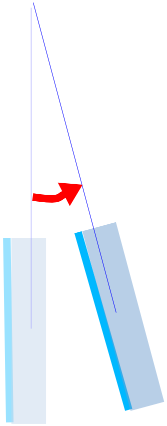
On-going design in Virgo
→ need a filter cavity of ~300 m, with finesse ~10000
→ strong constraints on optical losses, beam matching and alignment, …
(suspended in vacuum optical benches)

Reducing thermal noise

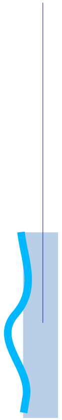
Thermal noise

Microscopic thermal fluctuations

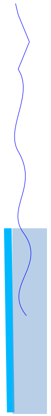
→ dissipation of energy through excitation of the macroscopic modes of the mirror



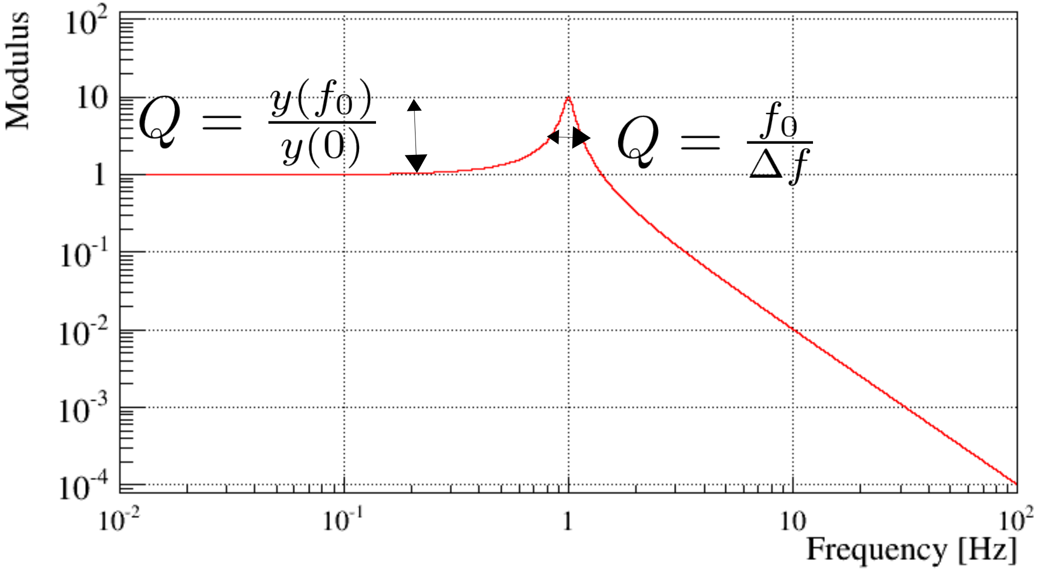
Pendulum mode
f < 40 Hz



“Mirror” mode
f> few kHz



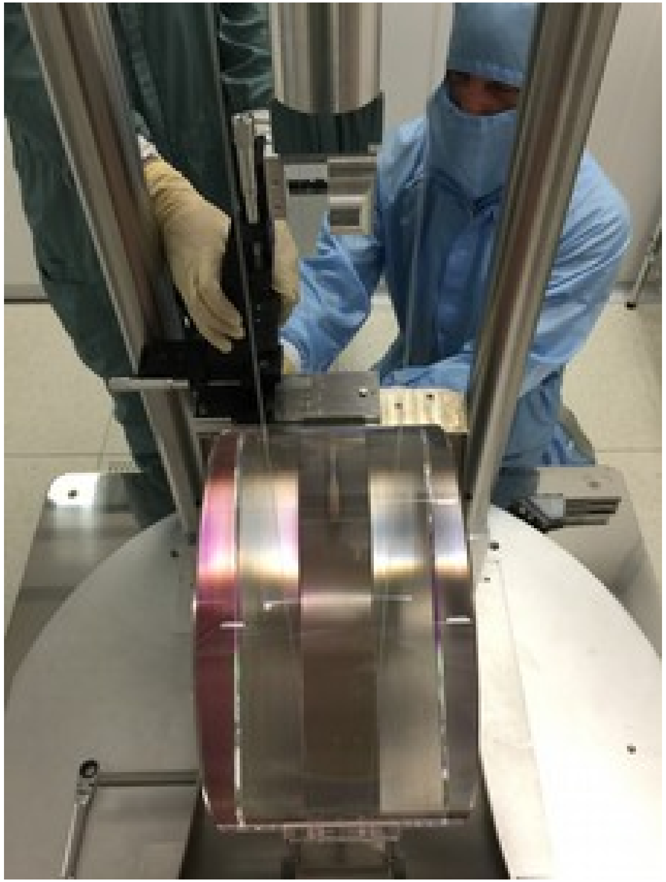
“Violin” modes
f > 40 Hz



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

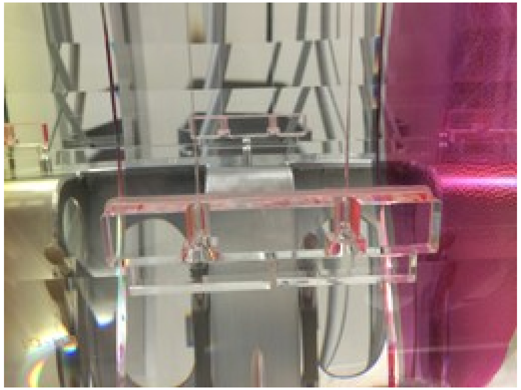
Thermal fluctuation of mirror surface position → Fluctuation of differential length → Fluctuation of measured power

Reduction of thermal noise: monolithic suspensions



Increase the quality factor of the mirrors (wrt to steel wires)

Fused silica
400 µm diameter, increasing to ~ 1 mm at both ends
0.7 m length
Load stress: 800 Mpa



Installed in Virgo in 2010
But failures in 2015/2016… (vacuum cleanliness issues)
… now fixed, re-installed beginning 2017

Reduction of thermal noise: mirror coating

40 kg mirrors of Advanced Virgo
35 cm diameter, 40 cm width

Currently the main source of thermal noise

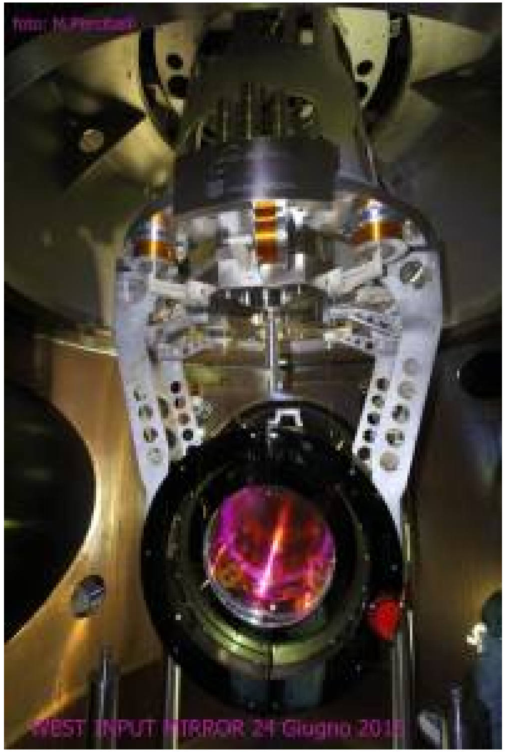
Substrate at room temperature: Suprasil fused silica

- R&D to improve mechanical properties of coating
  - still controlling optical properties
  - larger coating size

Cryogenics mirrors (at Kagra, future detectors)
- other substrate
- other coating
- other wavelength

→ talk by J. Degallaix!

Reduction of thermal noise: larger beams... and mirrors



Larger beam (currently 5-6 cm radius on mirrors) → Average mirror fluctuations on larger surface → Lower noise from surface fluctuations

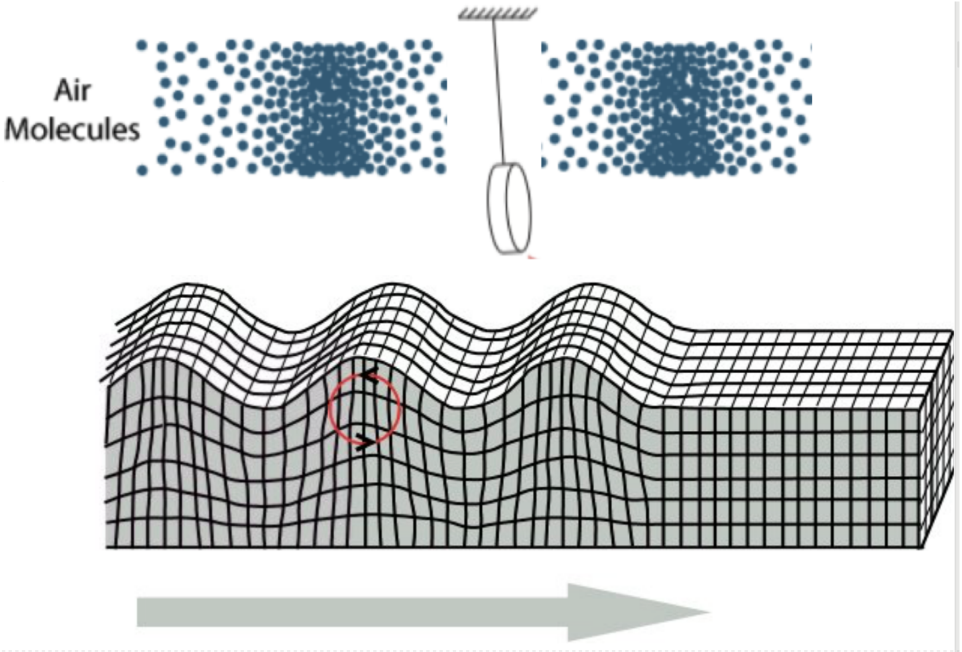
Need of R&D for larger beams
- → larger mirrors (and heavier)
  - → mechanical constraints on mirror suspensions
  - → larger size of coating
  - → upgrade of optical benches to detect output beams

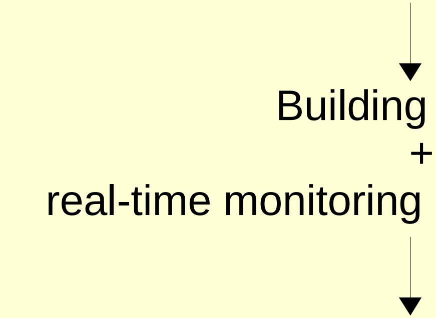
- → use high-order modes instead of TEM00 Gaussian mode?

(Heavier mirrors → reduce the radiation pressure quantum noise)

Two last examples

Newtonian noise cancellation and smart infrastructure





Newtonian noise cancellation

Array of seismometers and microphones

↓

Building model
+
real-time monitoring of Newtonian noise

↓

Noise subtracted from h(t)
(contribution at low frequency)

Reduction of Newtonian noise

→ **R&D for "smart infrastructure"**
(low noise air conditioning, fans, ...)

A “technical noise”: scattered light

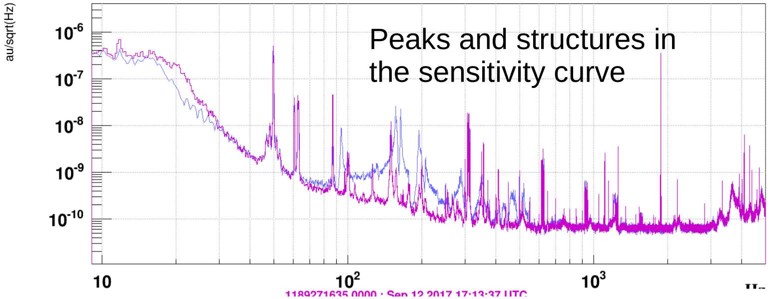
Scattered light
+
Vibrated parts
(seismic/acoustic)

→

Light recombination in the interferometer

→

Phase noise in the detected beam

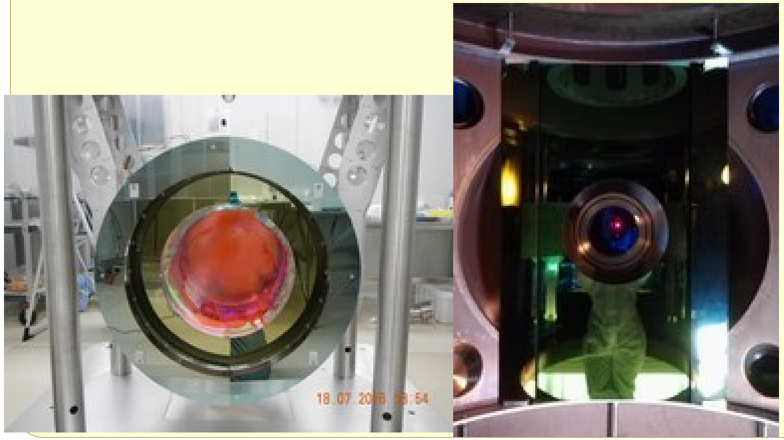


Peaks and structures in the sensitivity curve

Reducing the amount of scattered light

Better optics (polishing) and beam dumps

New baffles to absorb light and ghost beams
in the tubes and towers, around the mirrors

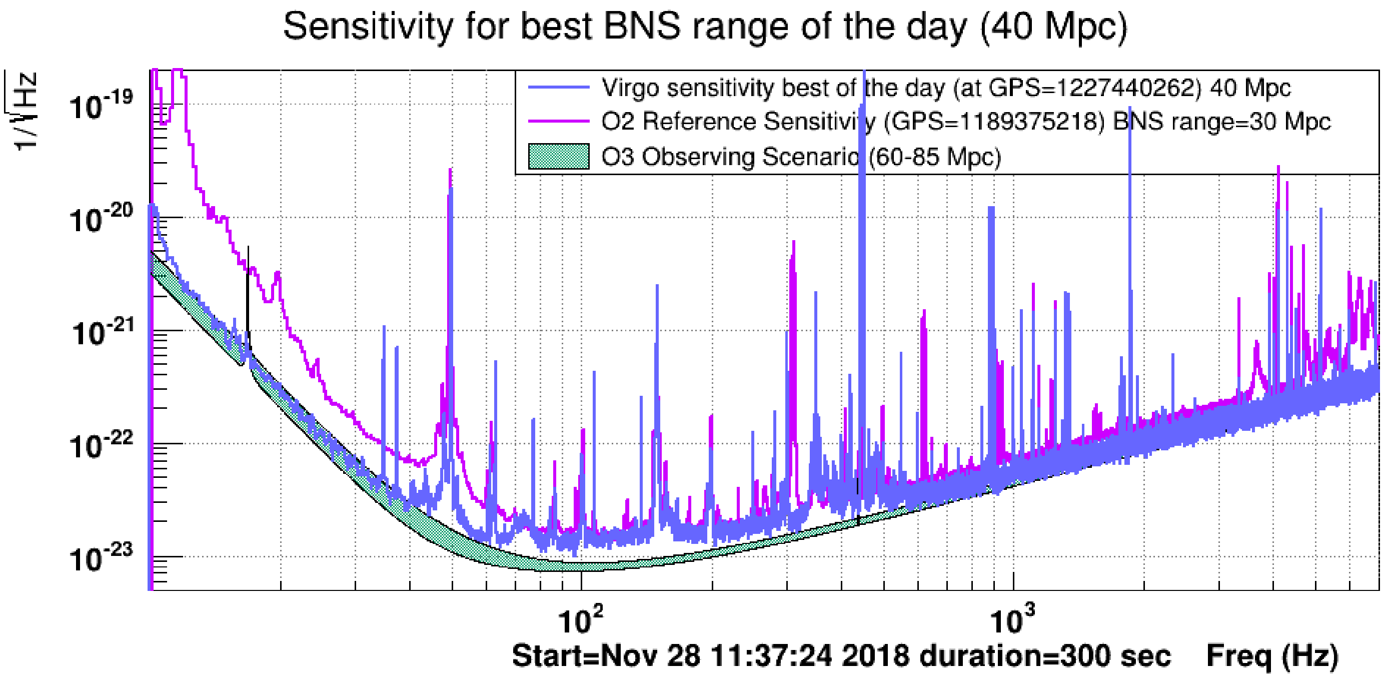


Reduce the coupling with seismic/acoustic noise

Optical benches suspended and placed in vacuum

- limited number of cables (power, data)
- space and load constraints, thermal constraints
- bench position control
- →integrated electronics

On-going commissioning... towards O3



Run O3 starts ...
“not before end of March”

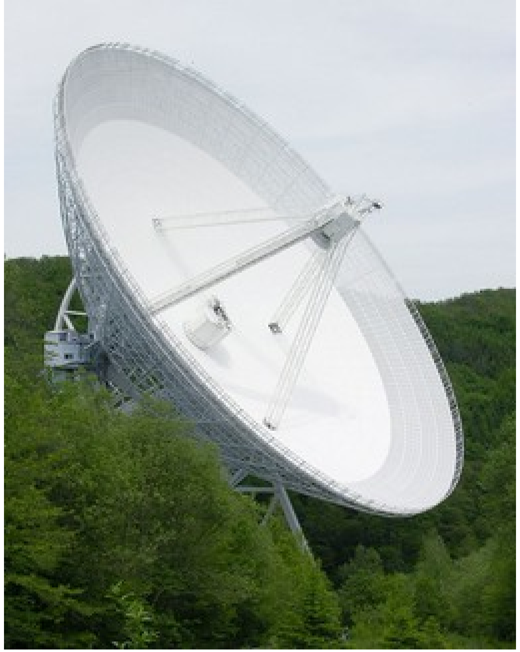
Goal is 60 Mpc range

Mystery flat noise...

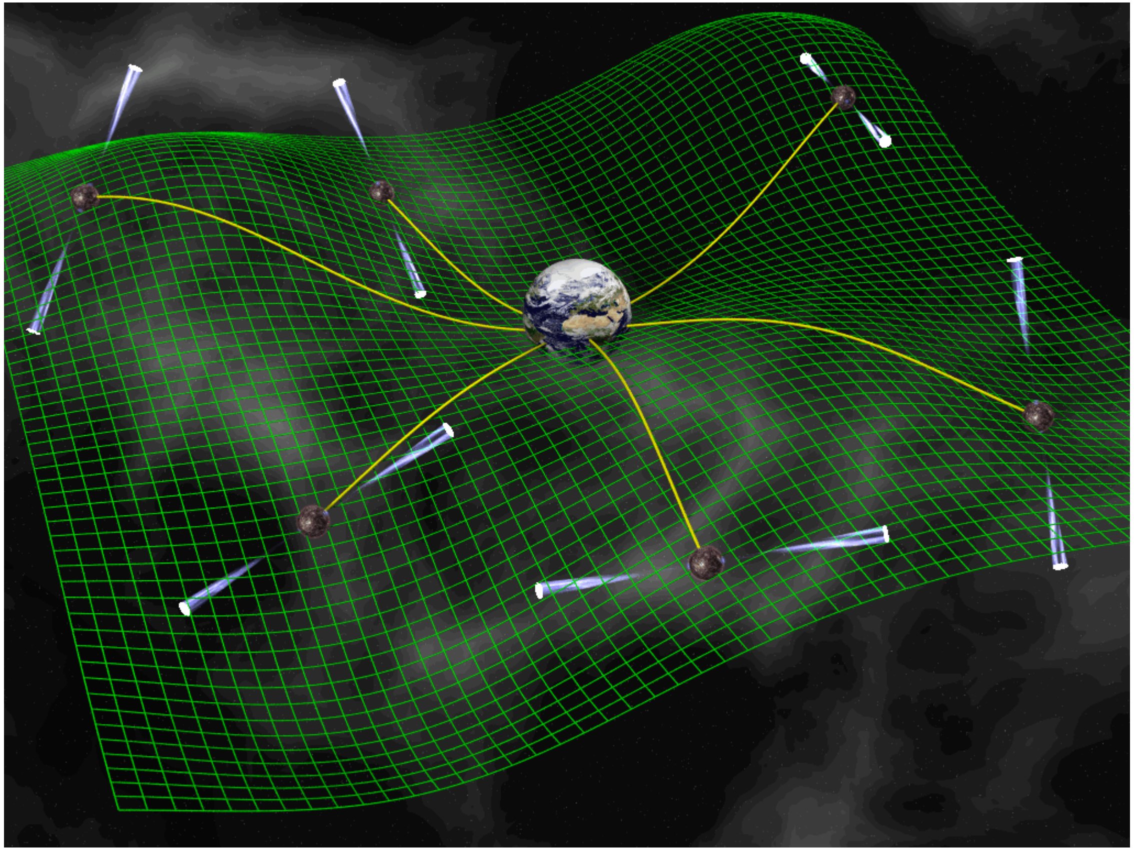
We have worked for improving the sensitivity since years…
now we start to also improve the precision !

→ talk by D. Estevez !

Pulsar Timing Arrays



GW detection principle with pulsar timing arrays



GW search in the range 1 nHz to 1 μHz

→ coalescence of supermassive black holes, ...

Arrays of radio telescopes

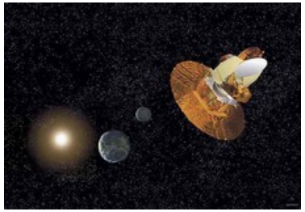
→ monitoring of ~20 millisecond pulsars

→ pulse timing deviation of ~10's ns over a year

systematic uncertainties to be reduced!

Data taking on-going
Adding new telescopes/new pulsars
→ stay tuned for GW detection!

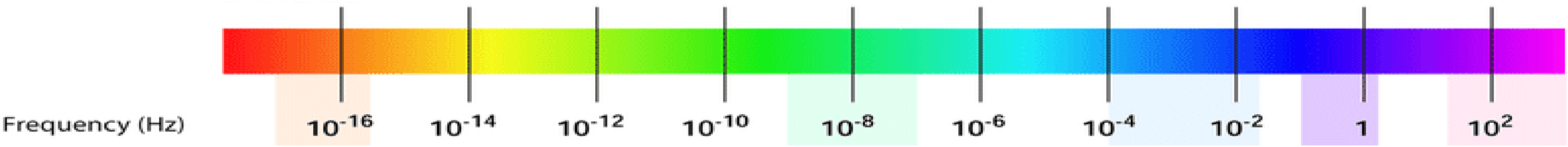
Probing the gravitational wave spectrum!

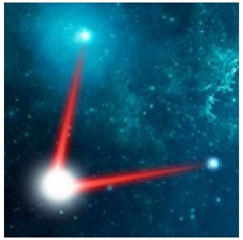


Cosmological Microwave Background

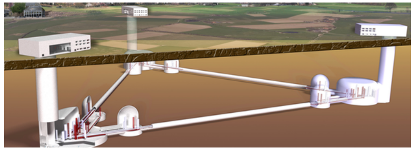
Pulsar Timing Arrays

Virgo
LIGO

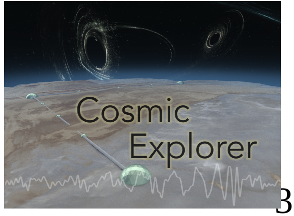




LISA



Einstein Telescope
Cosmic Explorer



→ talk by R. Bonnand!