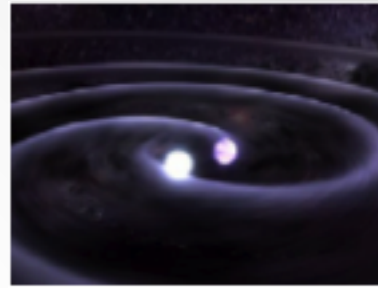


Survival kit to ground based detectors

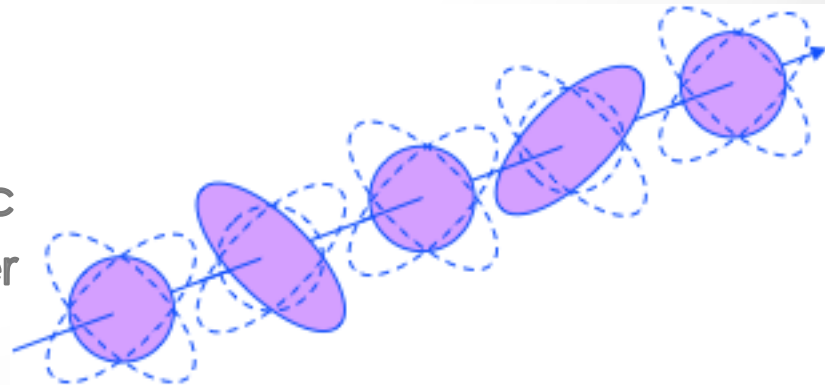
Nicolas Leroy
Laboratoire de l'accélérateur
linéaire d'Orsay



What are Gravitational waves ?

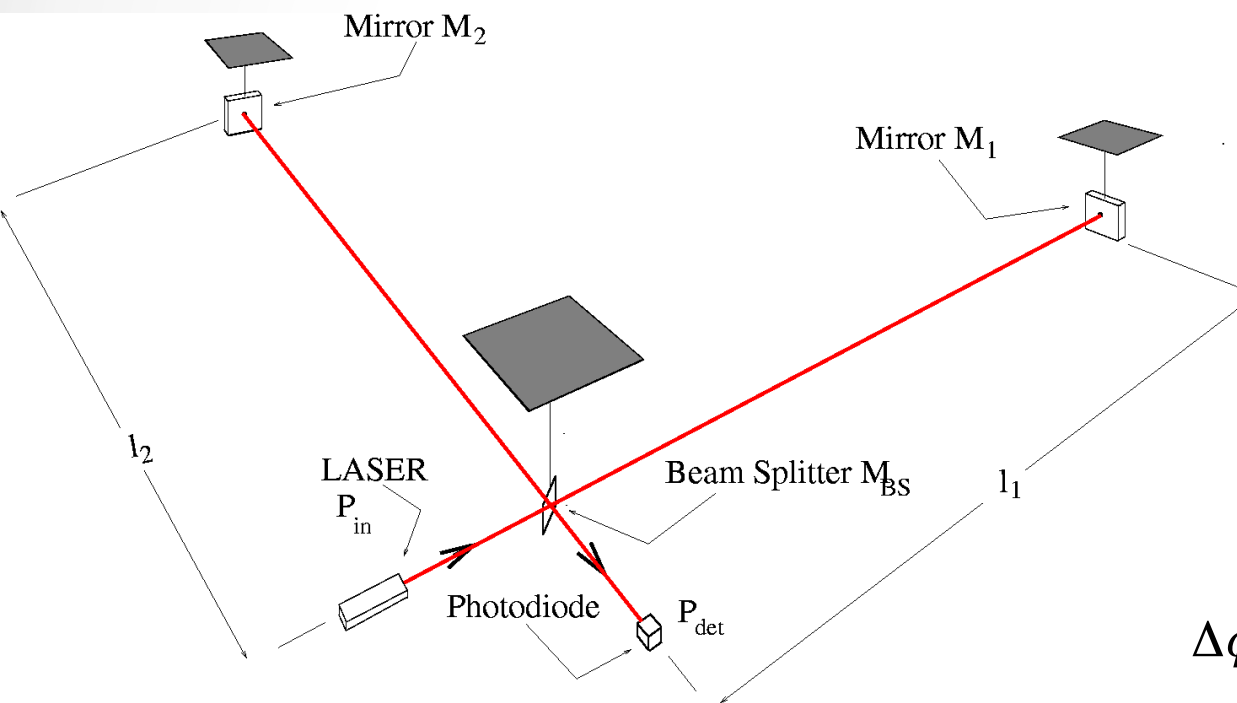


- Solution from General Relativity derived by A. Einstein in 1916
- Far from sources they can be seen as a perturbation of the metrics ie :
 - They are ripples of space-time produced by rapidly accelerating mass distributions
 - Provide info on mass displacement
 - Weakly coupled – access to very dense part of objects
- Main proprieties:
 - Propagate at speed of light
 - Two polarizations '+' and 'x'
 - Produce a differential effect on metric
 - Emission is quadrupolar at lowest order



Suspended interferometer

- Mirrors act as test masses of the metric
- Using differential effect -> variation of detected light at output ports



$$P_{\text{det}} = \frac{P_{\text{in}}}{2} (1 + C \cos(\Delta\phi))$$

$$C = \frac{2r_1 r_2}{r_1^2 + r_2^2}$$

$$\equiv \Delta\phi_{\text{OP}} \quad \equiv \delta\phi_{\text{GW}}$$

$$\Delta\phi = \frac{2\pi(l_2 - l_1)}{\lambda} + \frac{2\pi(l_2 + l_1)h(t)}{\lambda}$$

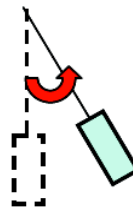
$$P_{\text{det}} = \frac{P_{\text{in}}}{2} (1 + C \cos(\Delta\phi_{\text{OP}}) - C \sin(\Delta\phi_{\text{OP}}) \times \delta\phi_{\text{GW}}(t))$$

Limiting noises

- Seismic noise
 - Waves, human activity, Earth activity
- Newtonian noise
 - Fluctuation of Earth gravitationnal field
- Thermal noise:
 - Brownian excitation for suspension wires, pendulum mode, mirror surface, and mirror coating



- Quantum noise



Pendulum
noise



Mirror thermal
noise



Violin mode, resonances
from the wire

Quantum noise

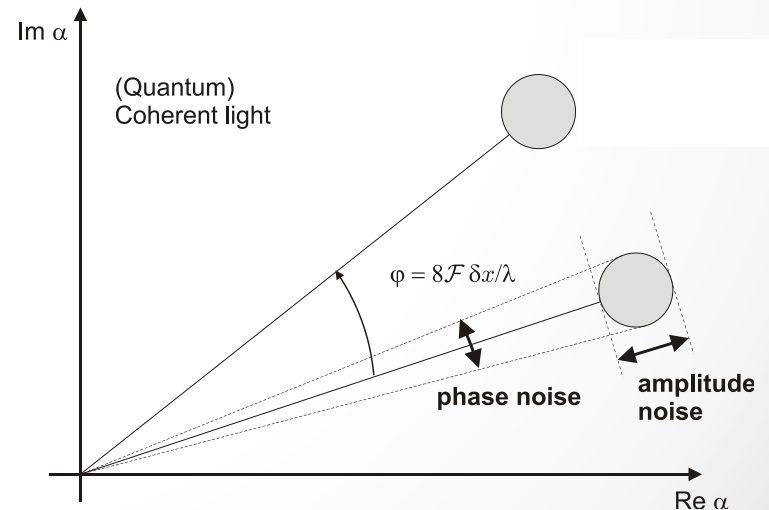
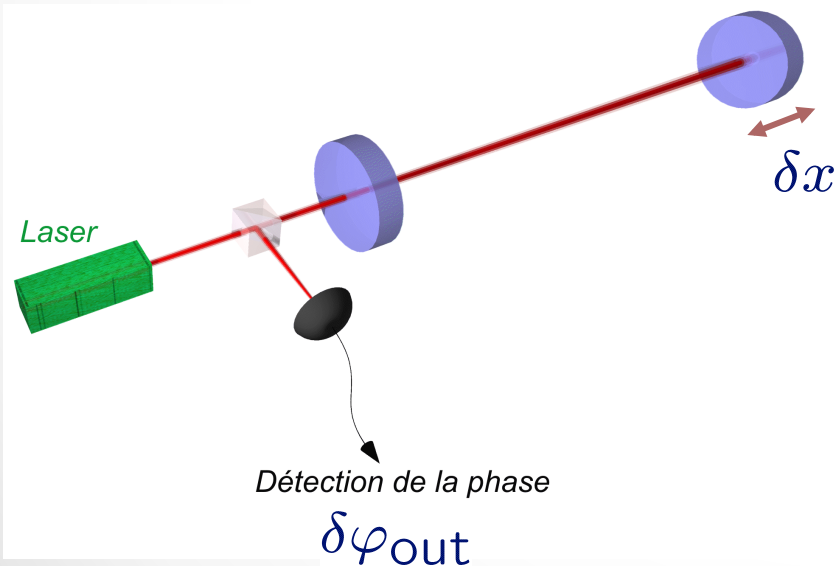
thermal noise

$$\delta\varphi_{\text{out}} = \delta\varphi_{\text{in}} + \frac{8\mathcal{F}}{\lambda} (\delta x + \delta x_{\text{cl}} + \delta x_{\text{rad}})$$

phase
noise

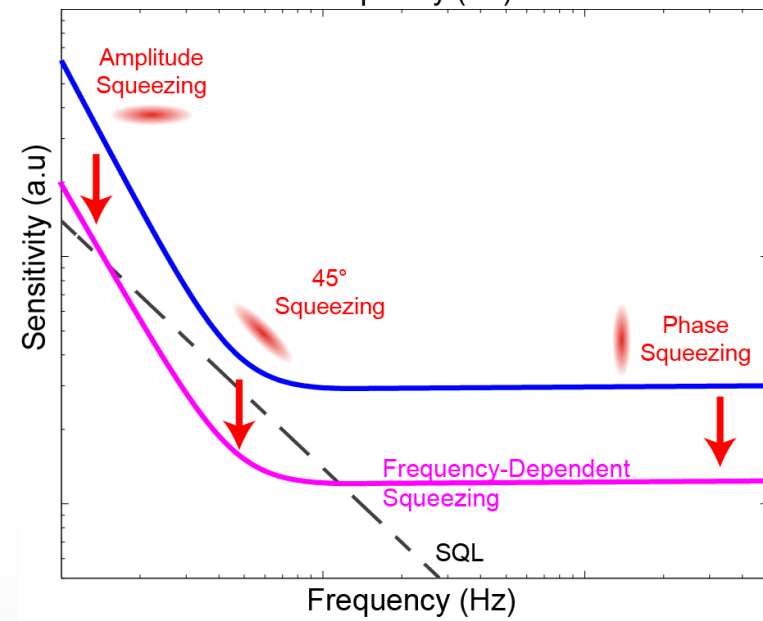
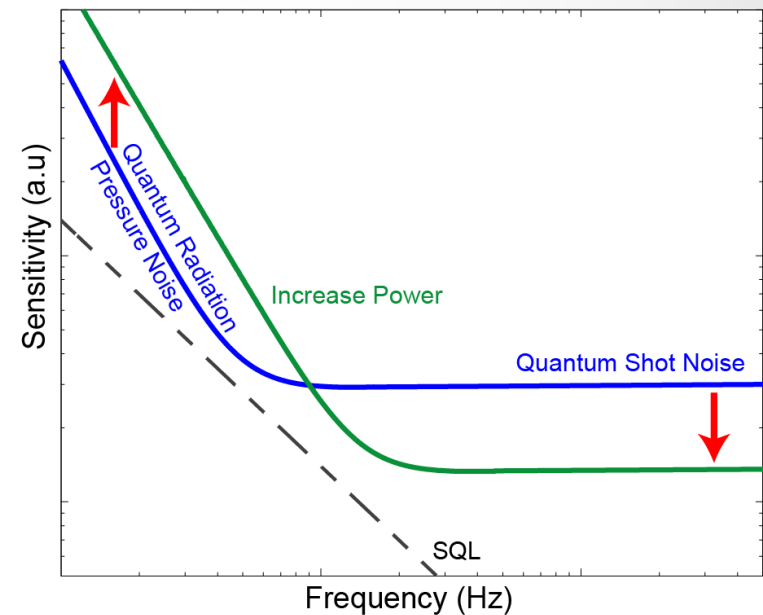
signal

radiation
pressure noise



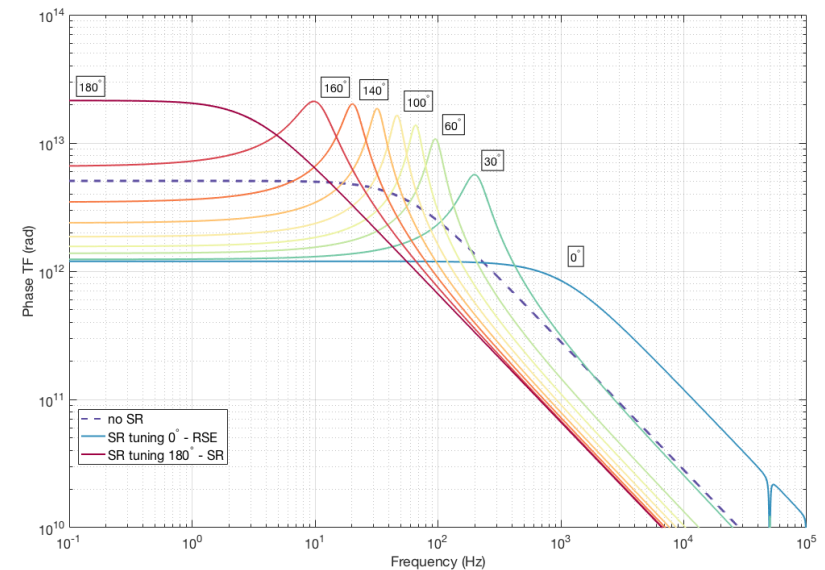
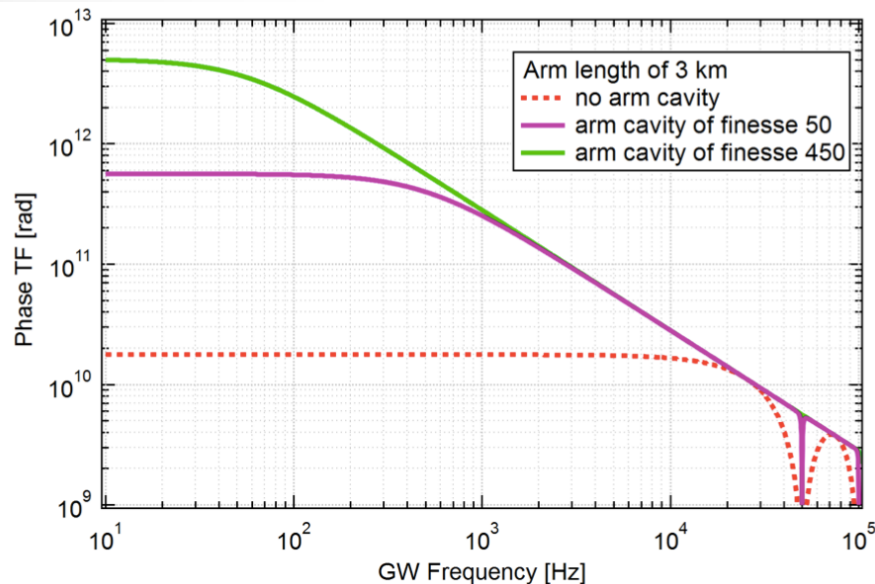
Quantum noise in GW detector

- Shot noise $\approx 1/\sqrt{P}$
- Radiation Pressure noise $\approx \sqrt{P}$
- Increasing laser power is not the only solution – you can also squeeze the light field



Increase sensitivity : optical path

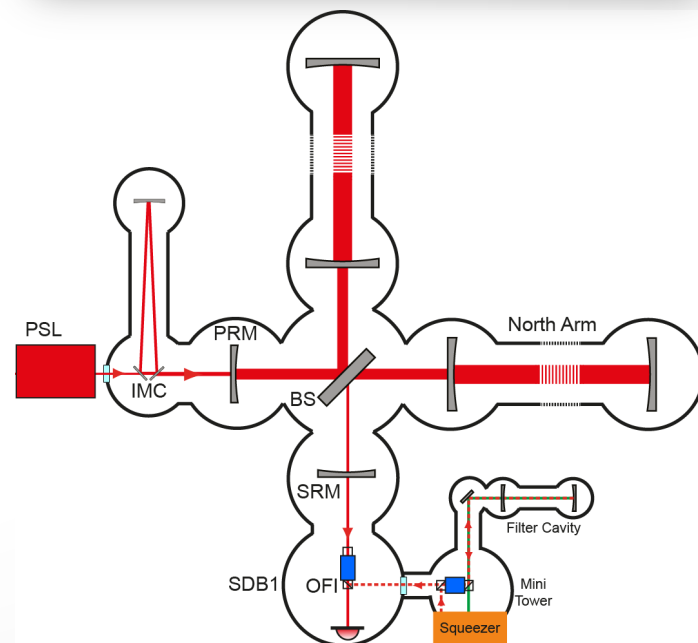
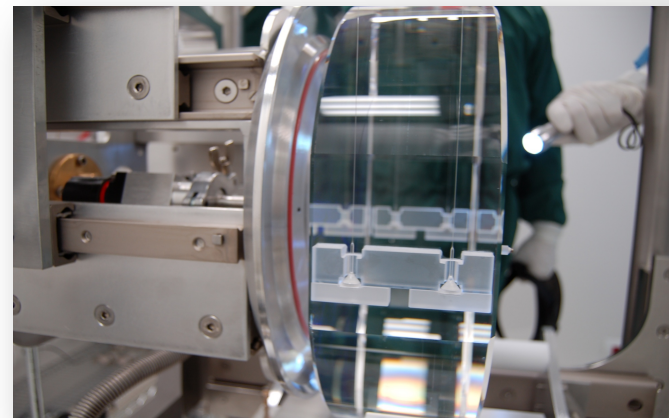
- Using Fabry-Perot cavities
 - Increase optical path – but modify the frequency bandwidth
- Recycling cavities
 - Increase optical path with power recycling (between laser source and beam splitter) – modify frequency bandwidth
 - Increase SNR and tune response with signal recycling (between beam splitter and output port)



Increase sensitivity :

location, materials and quantum noise

- Underground -> KAGRA
- Large and massive optics with large Q material ie reduced mechanical losses
- Improve coating to also reduce mechanical losses
- Suspended optics and material for suspension wires
- Cryogenics -> KAGRA
- Improve quantum noise : larger laser power and squeezing



Main challenges for a detector on Earth

- Maximizing length of the detector -> kilometric optical cavities
- Avoid perturbation on optical path -> everything under high vacuum ie 7000 m³ for Virgo
- Mirrors as free falling masses ie decoupled from external perturbations -> suspended optics
- Precise control of the length between the different suspended optics
- Precise ruler -> stable high power laser both in power and frequency
- Reduce at maximum technical noises

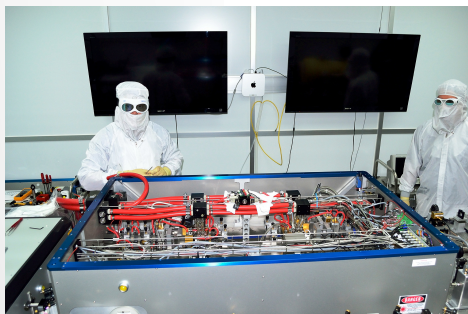
Advanced generation detector

Michelson interferometer

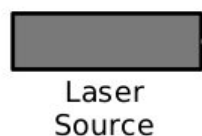
Goal : $(L_x - L_y)/L_x = 10^{-23}$

Feedback loops from
few Hz to few kHz

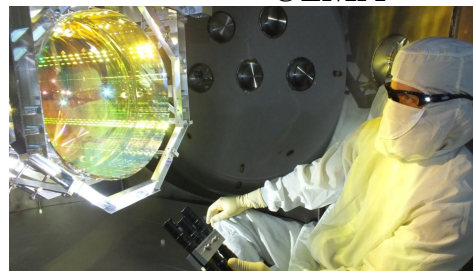
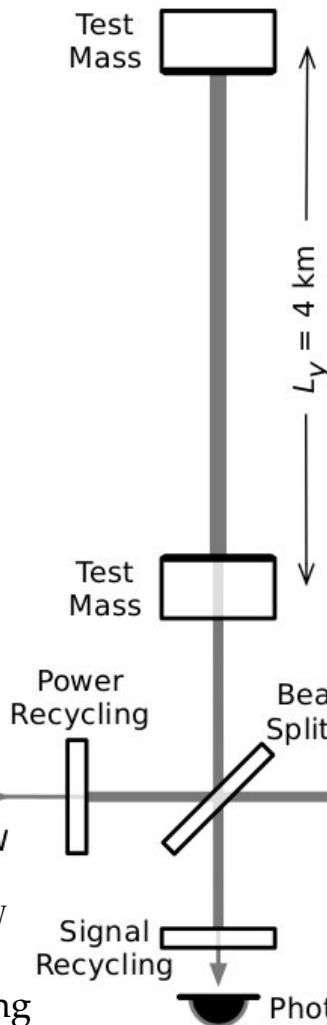
High power laser



@ARTEMIS



@APC Mode matching
Spatial filtering

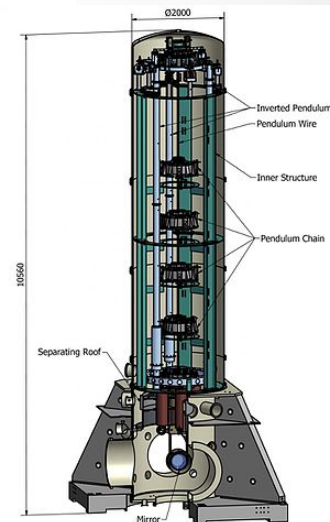


@LMA

High quality
optics – 40 kg
Surface RMS ~nm

Fabry-Perot
cavities

Full system under
vacuum $\sim 10^{-12}$ atm



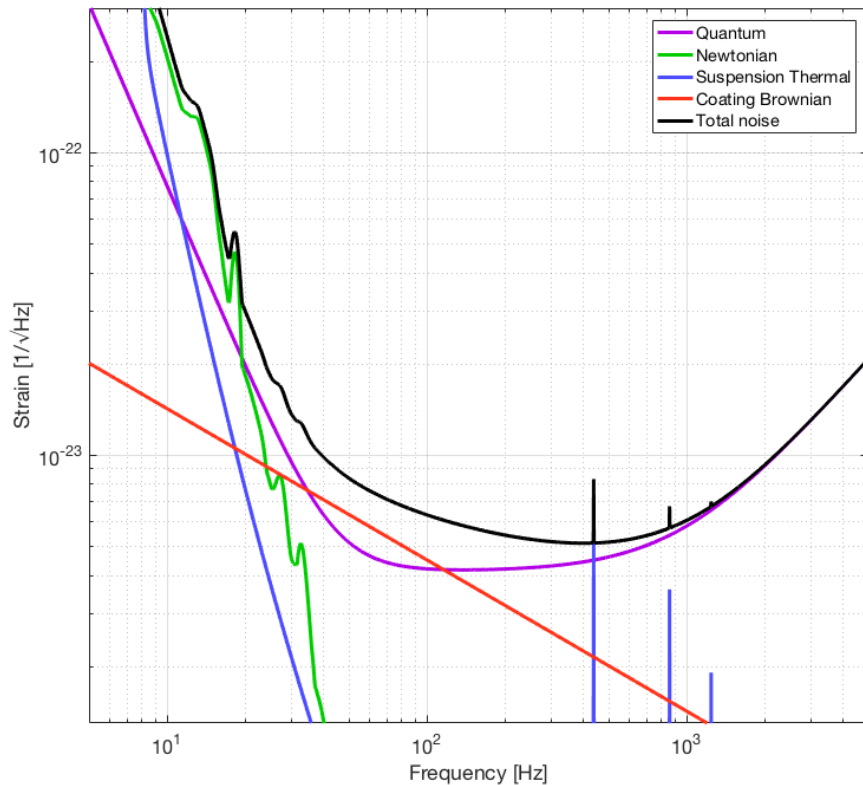
Suspended
Optics

Attenuation
 10^{14} @ 10 Hz

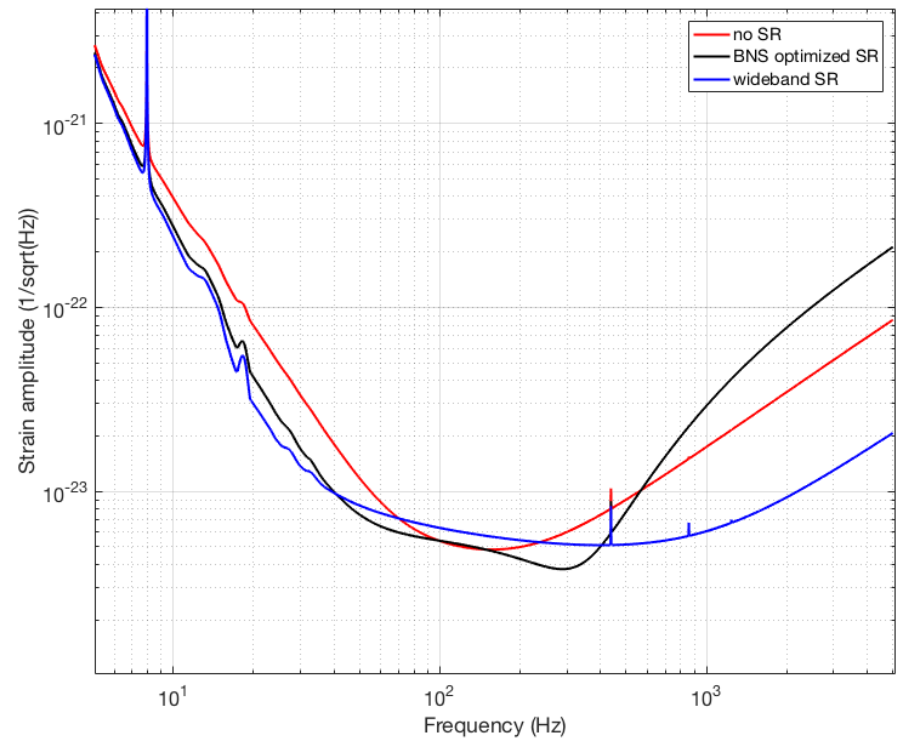
@LAPP

Targeted sensitivity

Contribution of main sources of noise

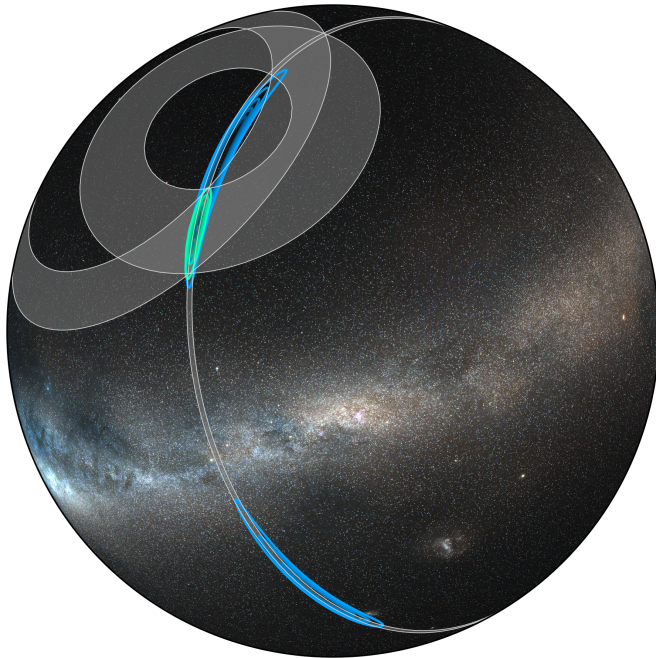
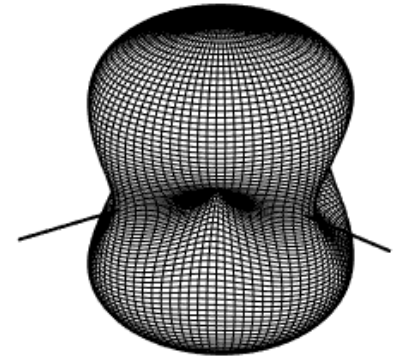


Different SR configurations



All-sky detector

- Beam pattern for antenna response
- Need a network to perform sky localization

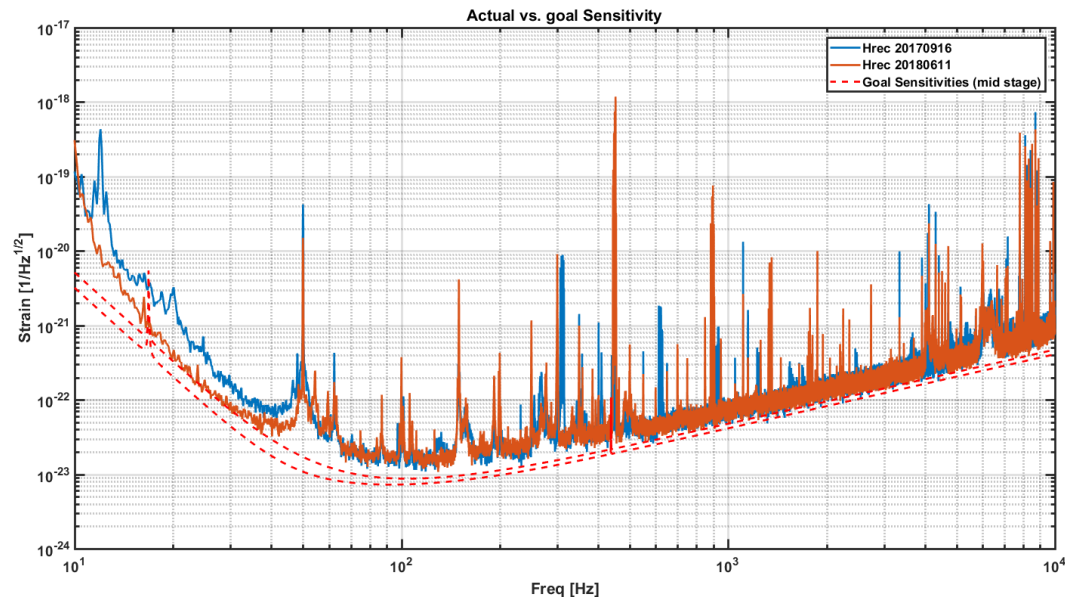


Credit: LIGO/Virgo/NASA/Leo Singer (Milky Way image: Axel Mellinger)



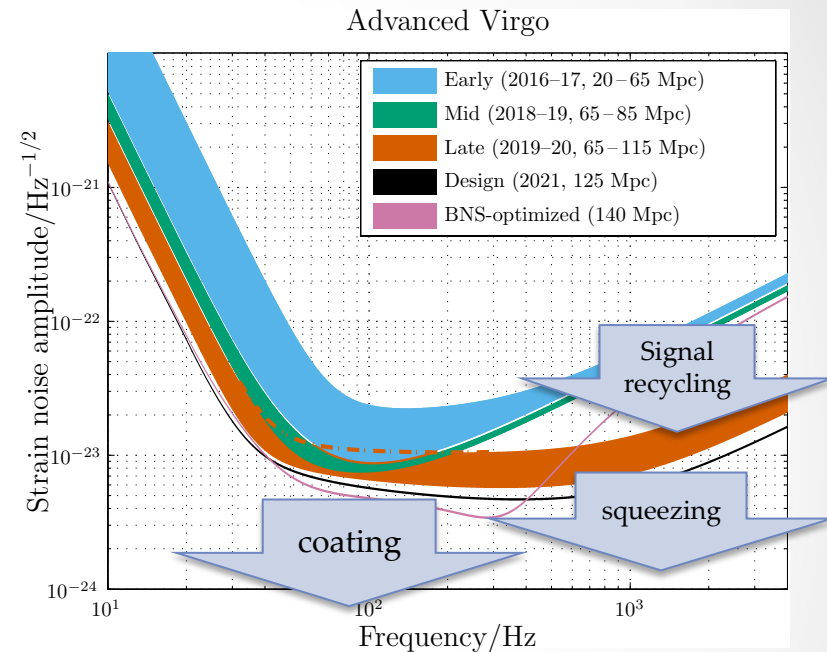
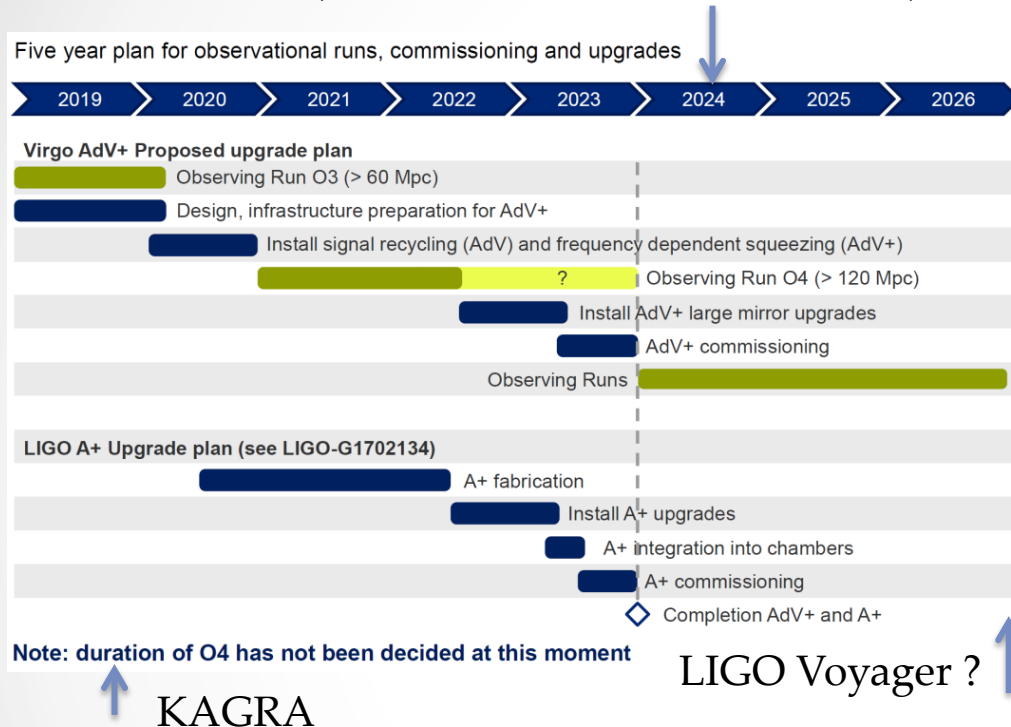
Current status

- After O2 start upgrades on the different sites:
 - LIGO : increase laser power, change mirrors, reduce diffuse light, install frequency independent squeezing
 - Virgo : move back to monolithic suspensions, new laser system, frequency independent squeezing
- LIGO is still performing some installations
- Virgo back to low noise beginning of May



Post O3 program: Advanced Virgo +

LIGO India (same as LIGO at the same time)

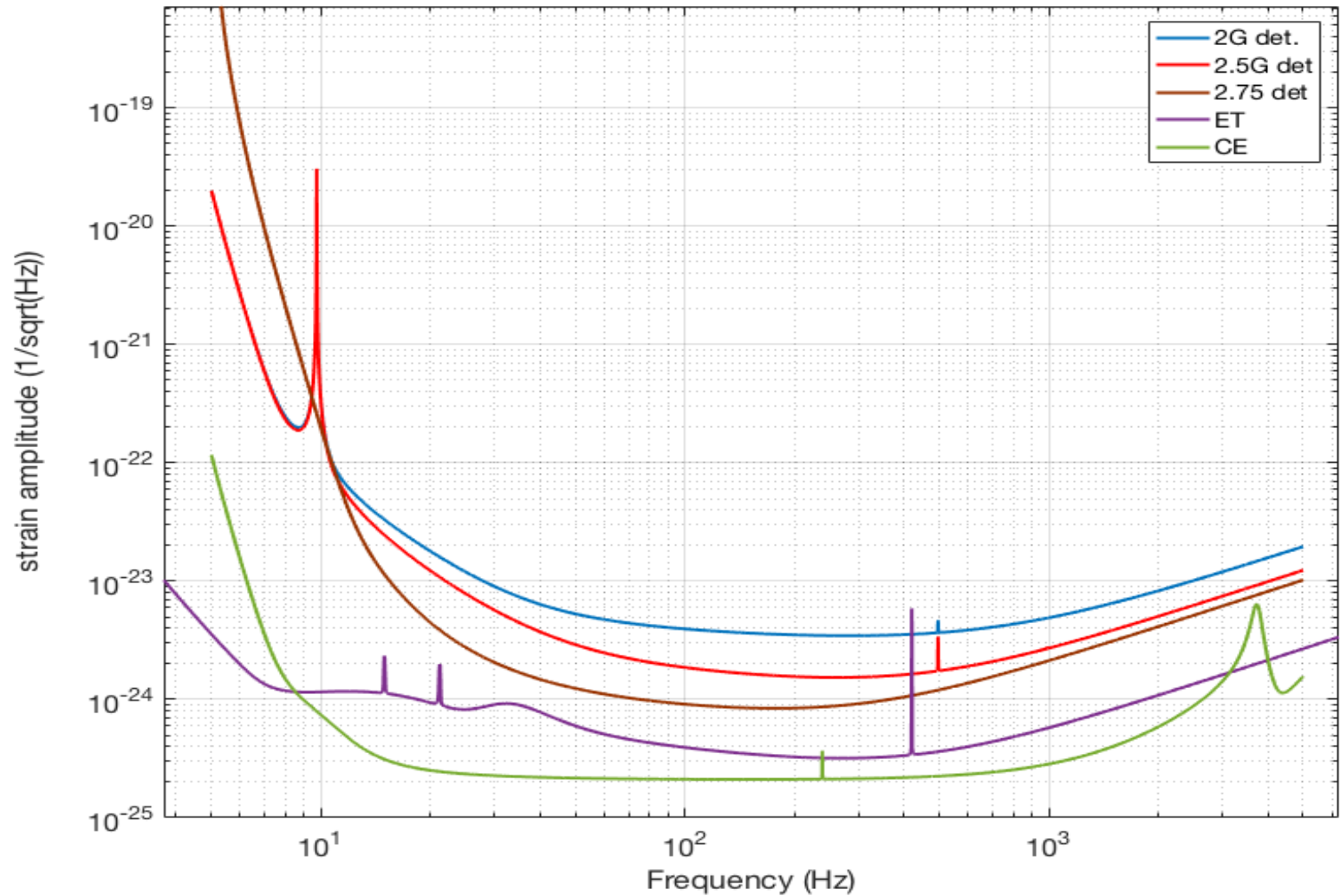


- 2 steps program : interlace data taking and upgrades
 - O4 : signal recycling + frequency independent squeezing
 - O5 : reduce thermal noise -> new mirrors and coatings

Moving to next generation

- **2.5 G**: a set of upgrades capable of enhancing the sensitivities of the current detectors (event rate 5-10x)
 - A+ at LIGO, AdV+ at Virgo - Timeline:~2023
- **2.75G ?** : use the current infrastructure to its maximum and prepare 3 G
- **3 G**: new infrastructures/detectors capable of reaching the early universe. One order of magnitude gained in sensitivity wrt 2G
 - Timeline: ~2030 - Cost > 1 Geuros
 - Einstein Telescope: European project for a nested assembly of 6 co-located interferometers, 10 km long underground
 - Cosmic Explorer: US project for a 40 km interferometer surface detector

Possible scenario



Conclusions

- Ground based detectors have shown their ability to perform detection
- Next run will start beginning of next year for one year
- Lot of activities on Virgo's side to prepare shutdown in 2020:
 - Signal recycling mirror
 - Frequency dependent squeezing
- Preparation of Advanced Virgo+ : testbed for Einstein telescope
 - New mirrors with new coatings
 - Deal with Newtonian noises
 - Fight against technical noise sources