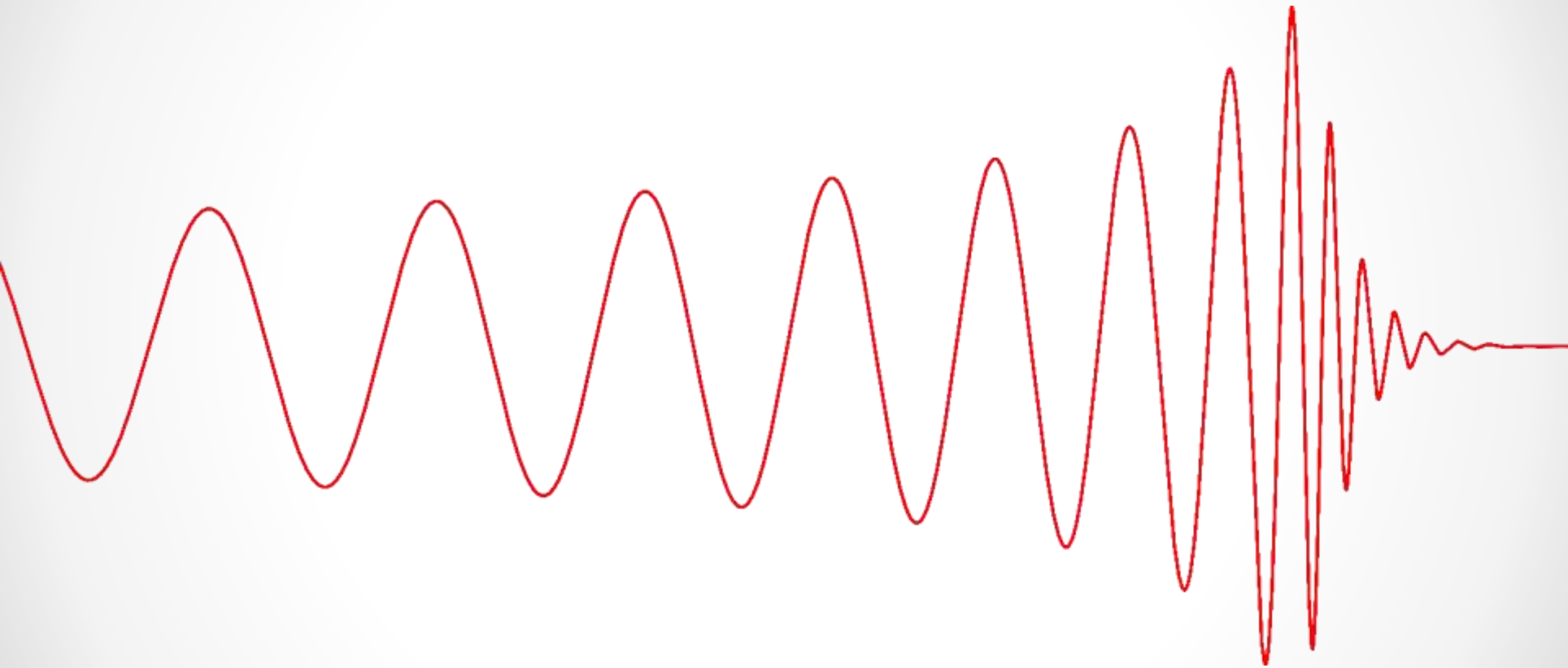
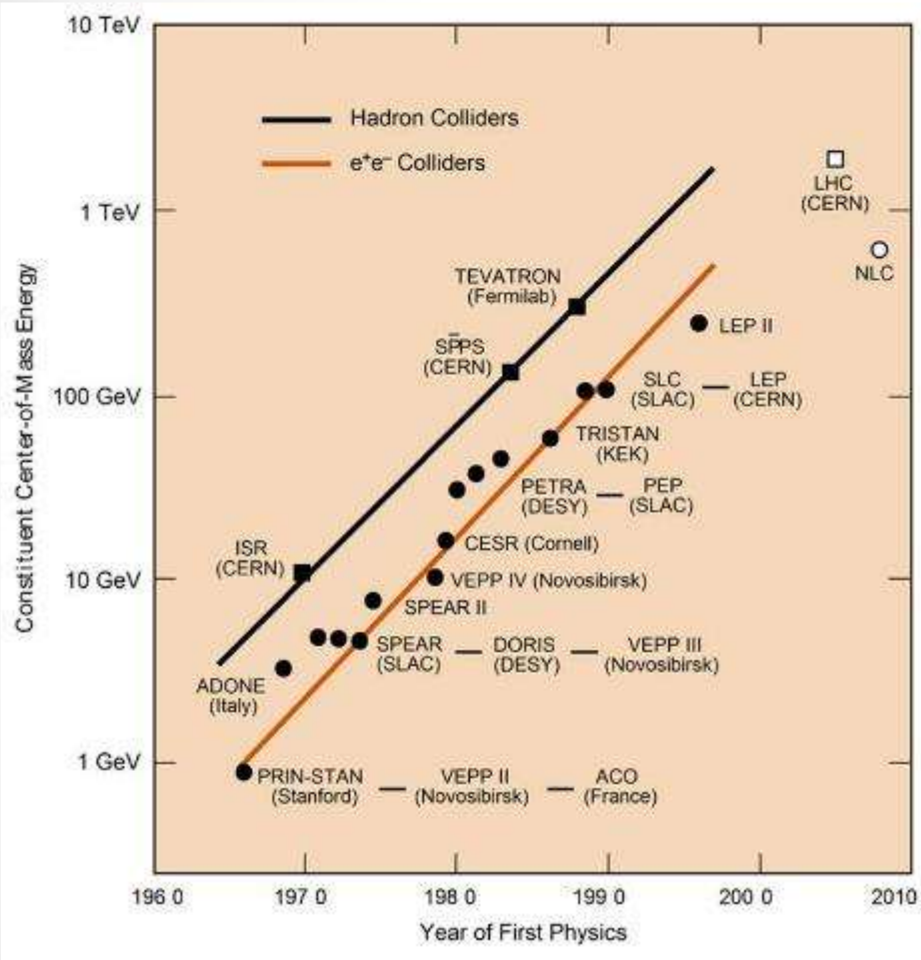
Avanced Virgo Gravitational-Wave Detector



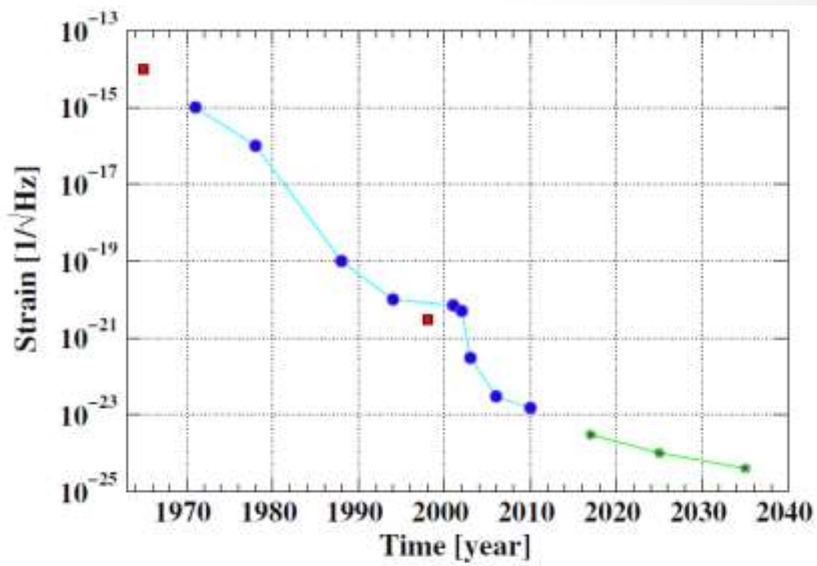
Jan Harms
Gran Sasso Science Institute (GSSI)
INFN LNGS

A History of Two Fields

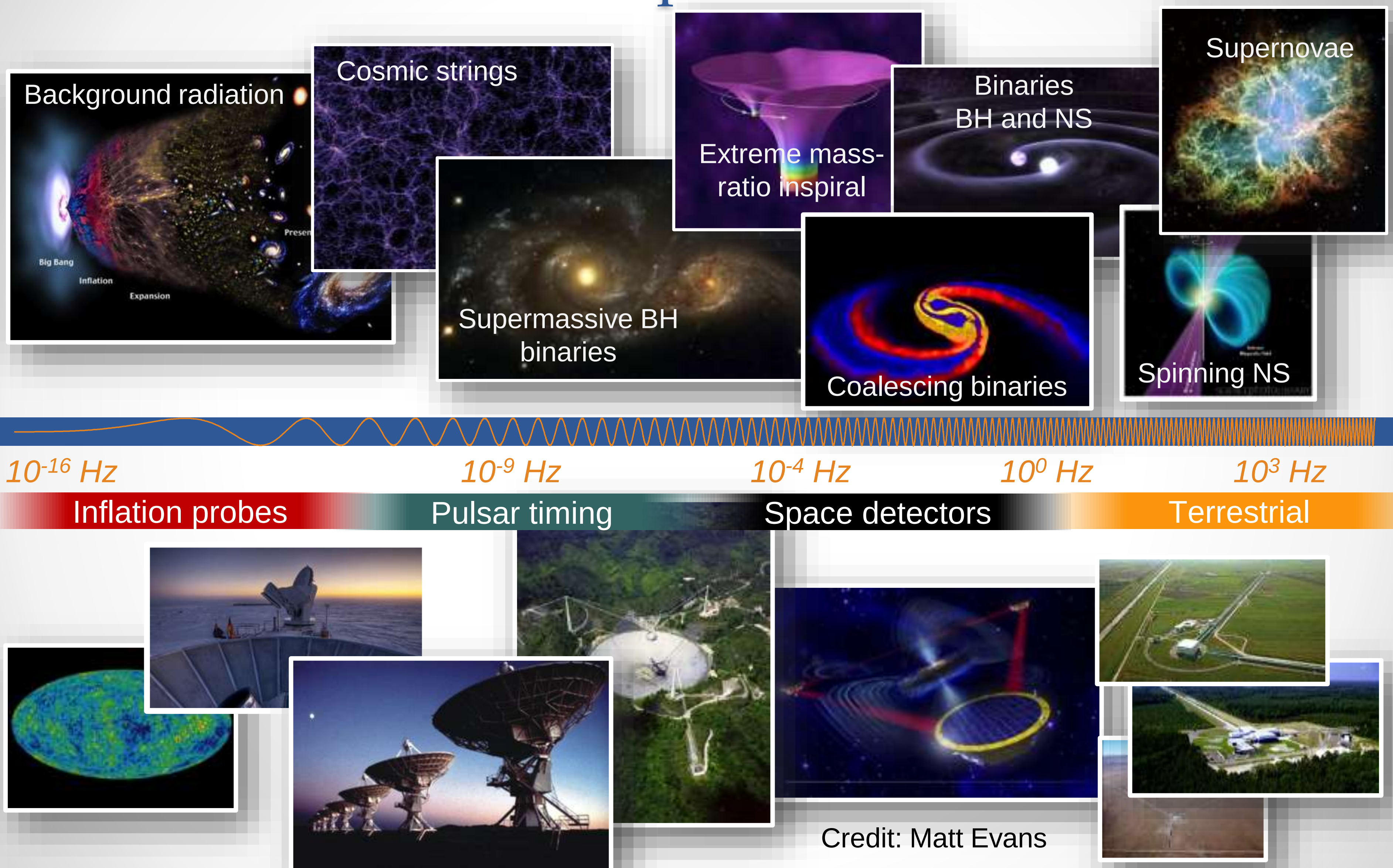
Particle Accelerators



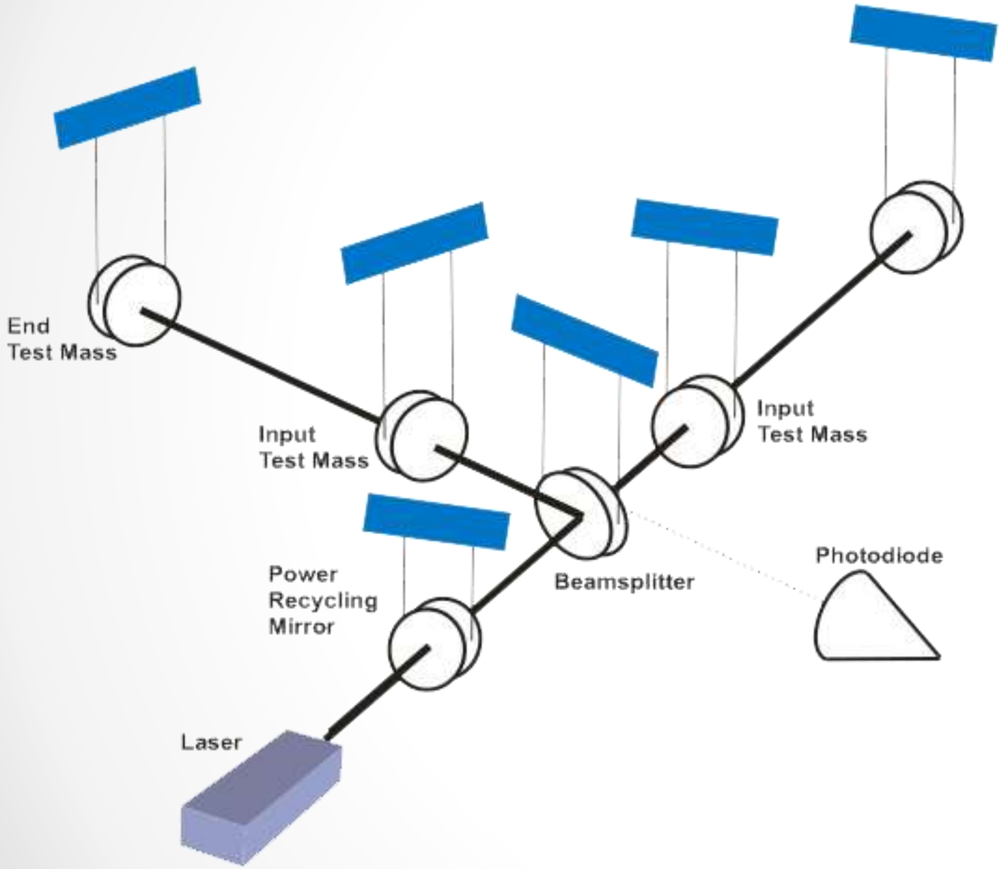
GW Detectors



GW Spectrum


Background radiation
Big Bang
Inflation
Expansion
Cosmic strings
Supermassive BH binaries
Extreme mass-ratio inspiral
Binaries BH and NS
Coalescing binaries
Supernovae
Spinning NS
10^{-16} Hz
10^{-9} Hz
10^{-4} Hz
10^{0} Hz
10^{3} Hz
Inflation probes
Pulsar timing
Space detectors
Terrestrial
Credit: Matt Evans

Interferometric GW Detectors

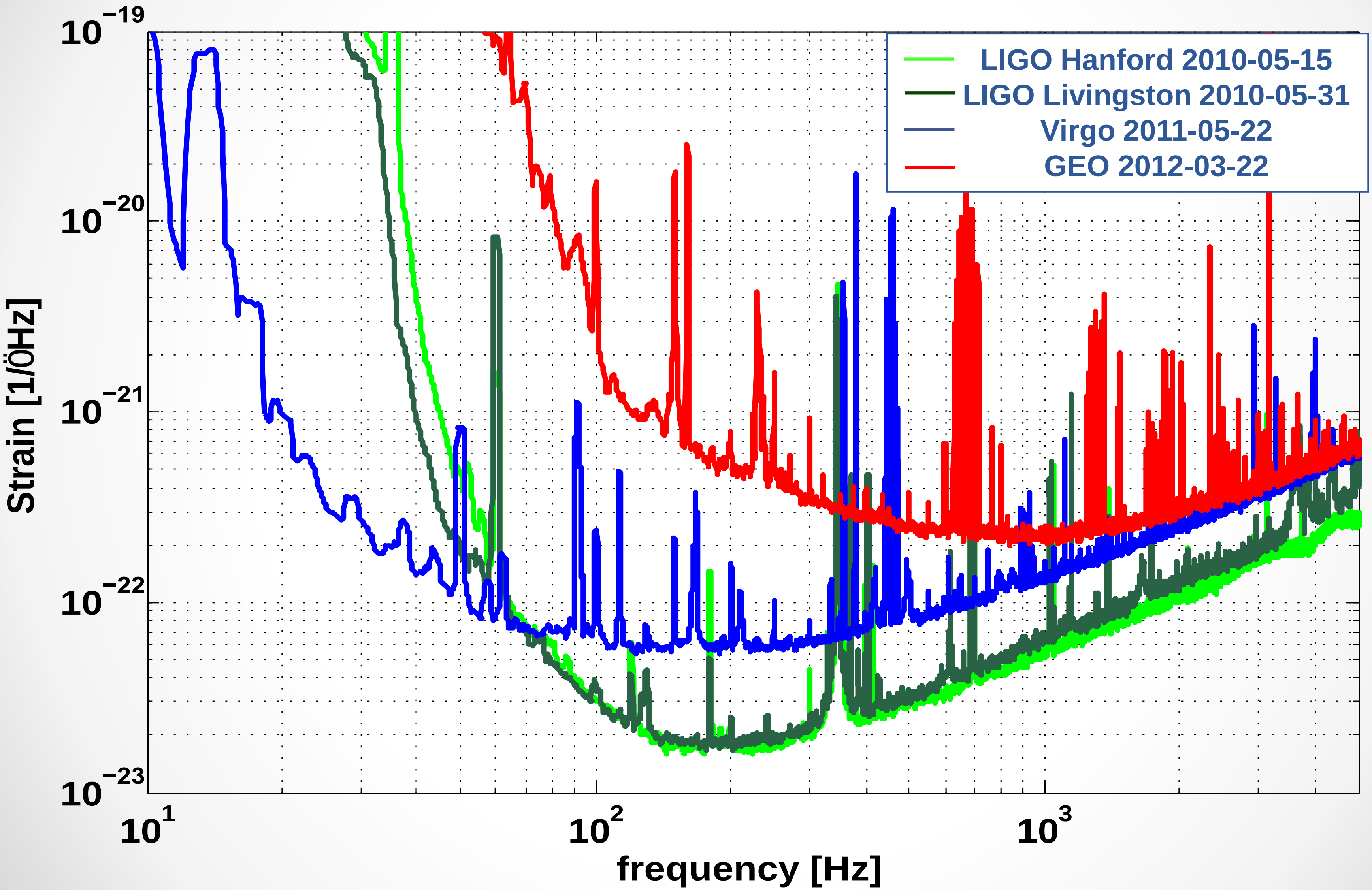


$$h = \frac{2\Delta L}{L}$$

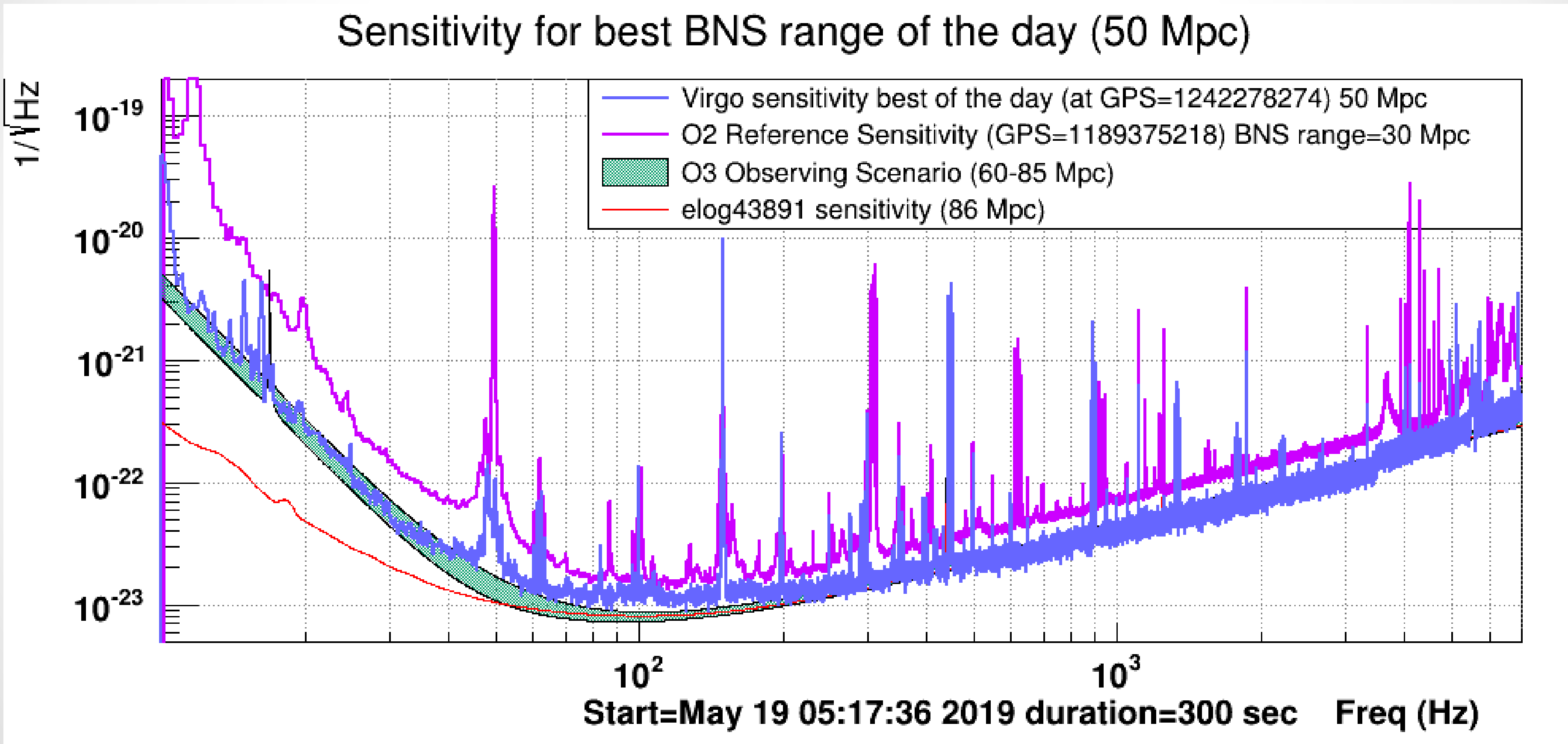
Amplitude h on Earth:

- h ~ 10^{-21} (GW150914)
- L = 1m, ΔL= 10^{-21} m
- L = 3km, **ΔL= 10^{-18} m**

Final Sensitivities of the First Generation

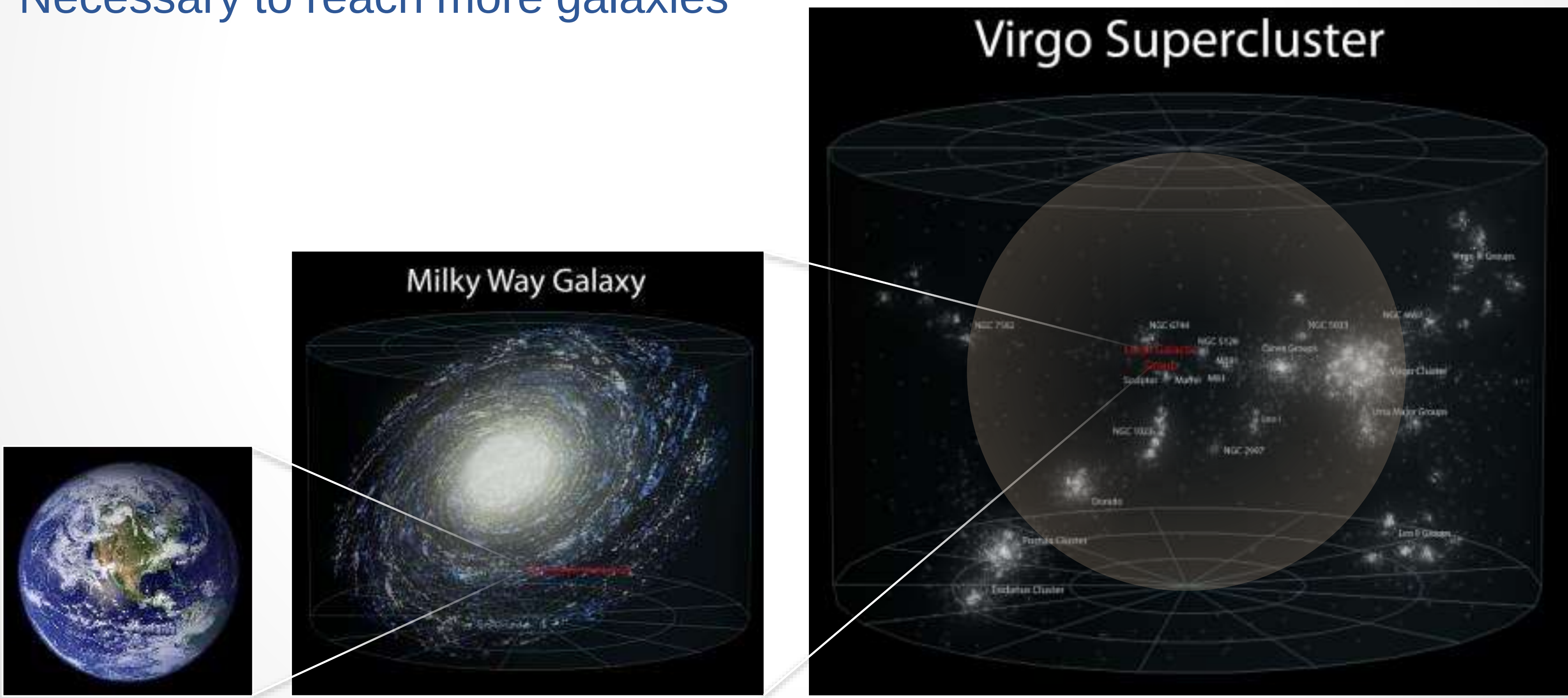


Sensitivity progress of Advanced Virgo



The first generation

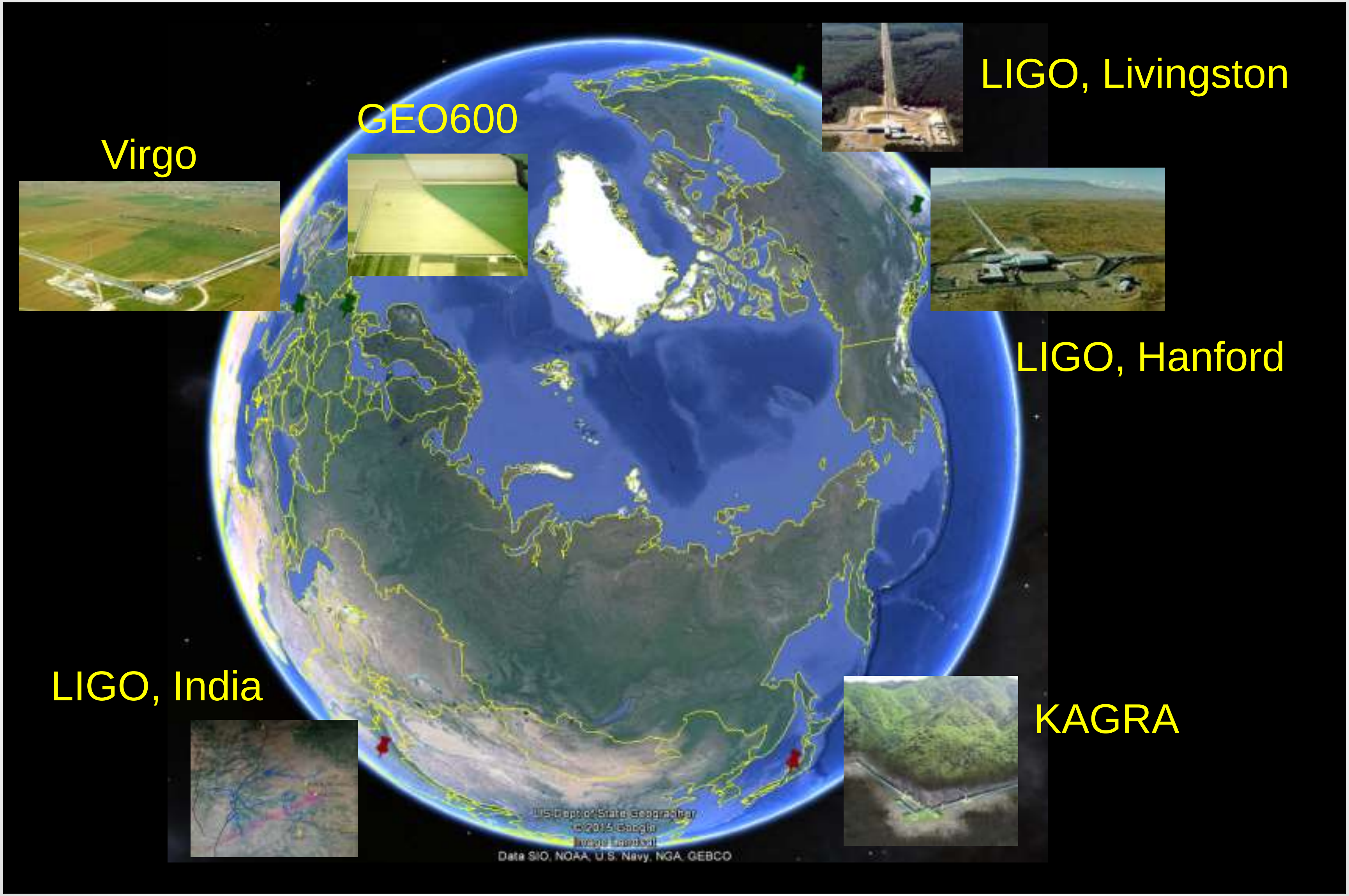
- The first generation detectors were constructed between the mid 90s and 2000s; they reached the design sensitivity; observations for some years
- Sensitivity sufficient to reach 200 galaxies, but…
- Compact-object mergers occur only once per 10.000 years per galaxy…
- Necessary to reach more galaxies



The second generation

- During observations with the first generation, more advanced technologies were developed for the second generation
- Advanced detectors will be about 10x more sensitive, reach of order 100,000 galaxies
- Accordingly, one should see several tens of signals per year

Global Network of Detectors

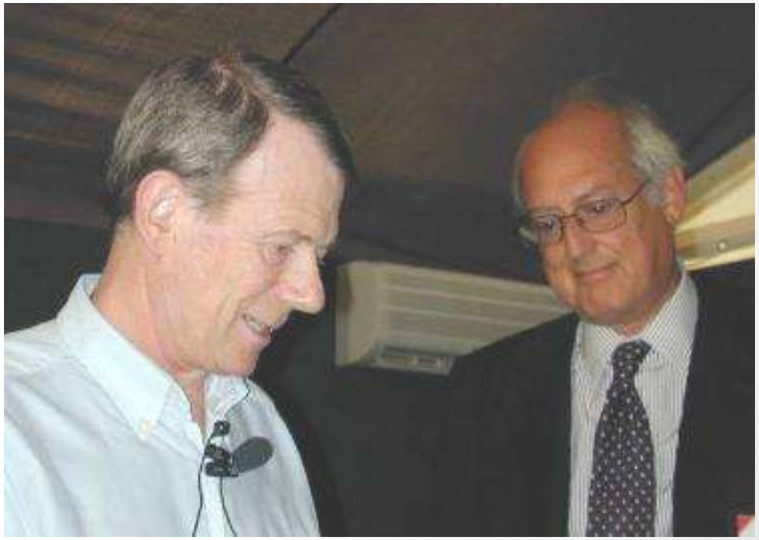


The Birth of Virgo

Virgo was conceived in
the 80s

Construction completed in July 2003

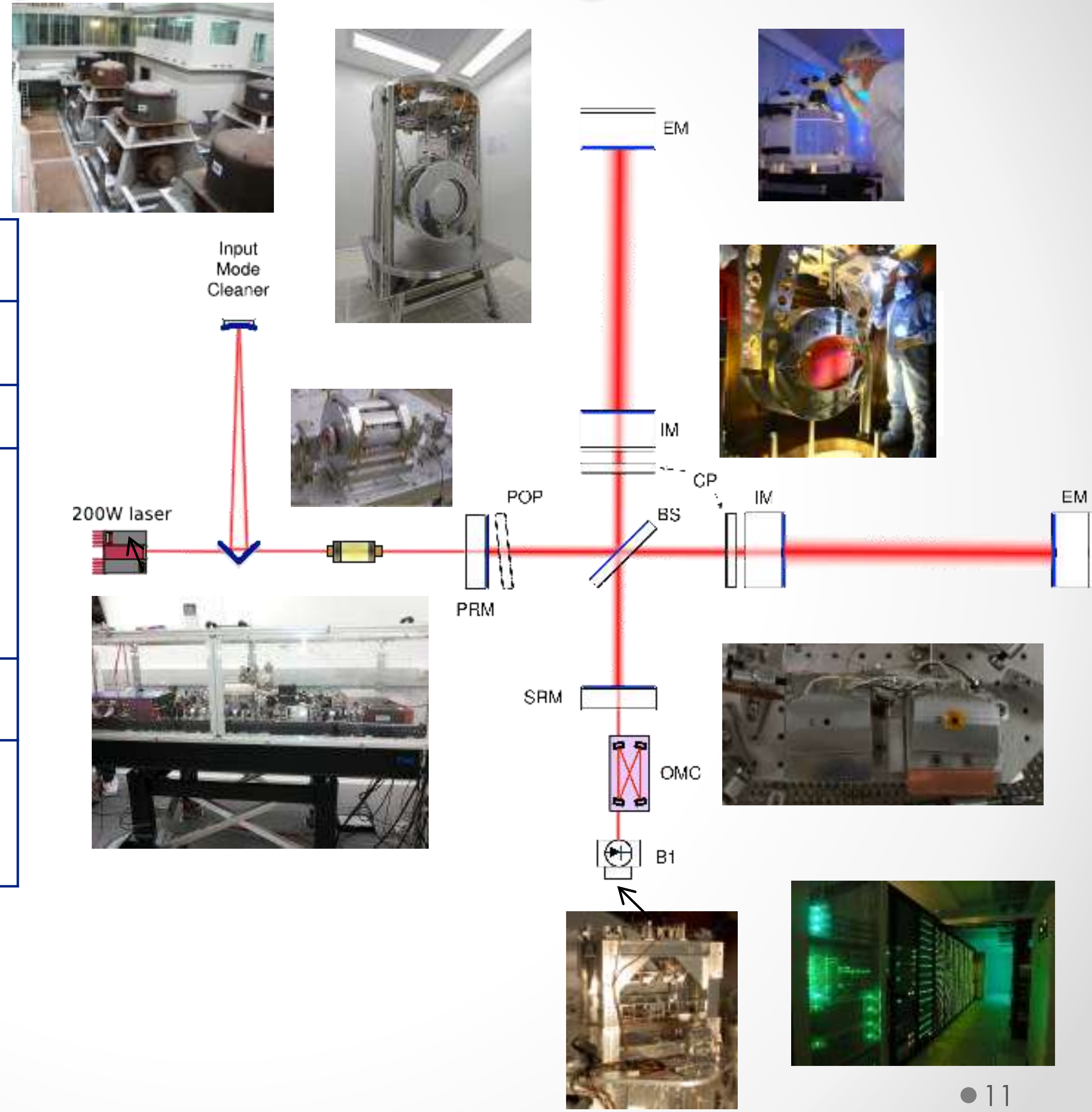
Founding fathers of Virgo:
Alain Brillet and Adalberto Giazotto



Summary: Advanced Virgo

What's Advanced?

Parameter	*Initial Virgo*	*Advanced Virgo*
Laser power	20 W, input 20 kW, arm	125 W, input 700 kW, arm
Test mass	20 kg	42 kg
Interferometer topology	Power-recycled Fabry-Perot Michelson with arm cavities	Dual-recycled Fabry-Perot Michelson with arm cavities
GW Readout Method	RF heterodyne	DC homodyne
Best sensitivity	5×10^{-23} / rHz	Tunable, better than 5×10^{-24} / rHz in wide band



Virgo Infrastructure: 3km Vacuum Tube

Light travels in ultra-high vacuum.

Only few molecules crossing the laser beam cause an observable change in path length masking GWs

Cover the tube:
stop roaming cars and projectiles of hunters

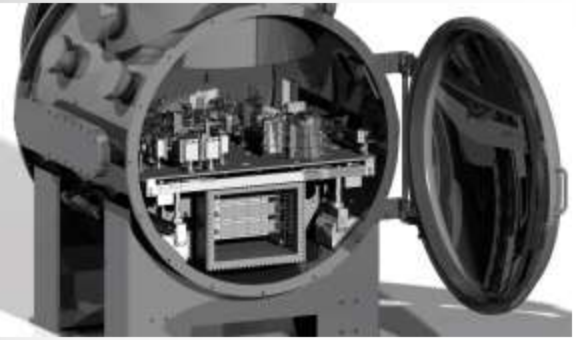
Dangers at LIGO

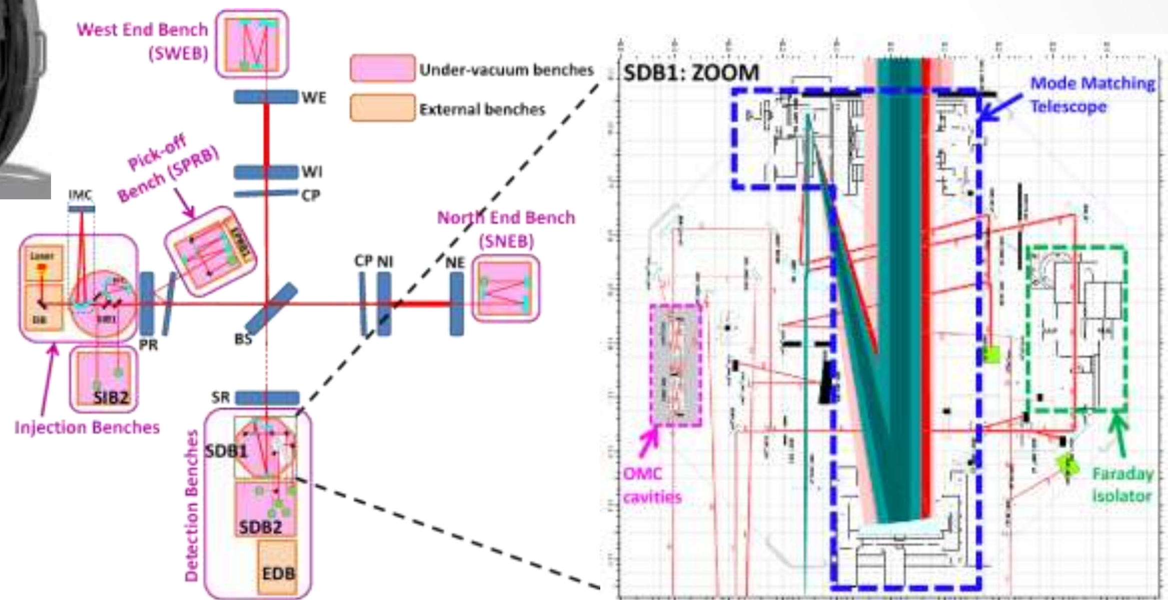
Vacuum Chambers

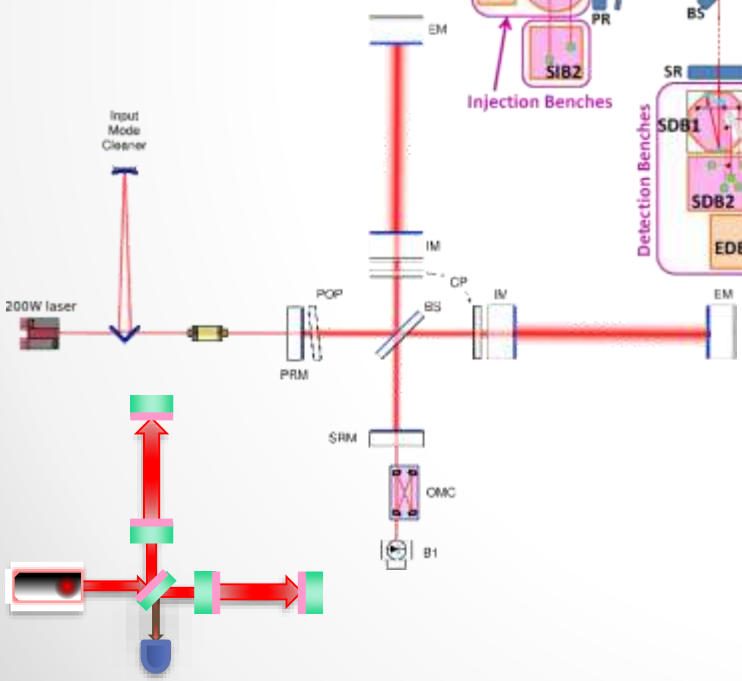
Central building

Work inside the chamber

Levels of Representation

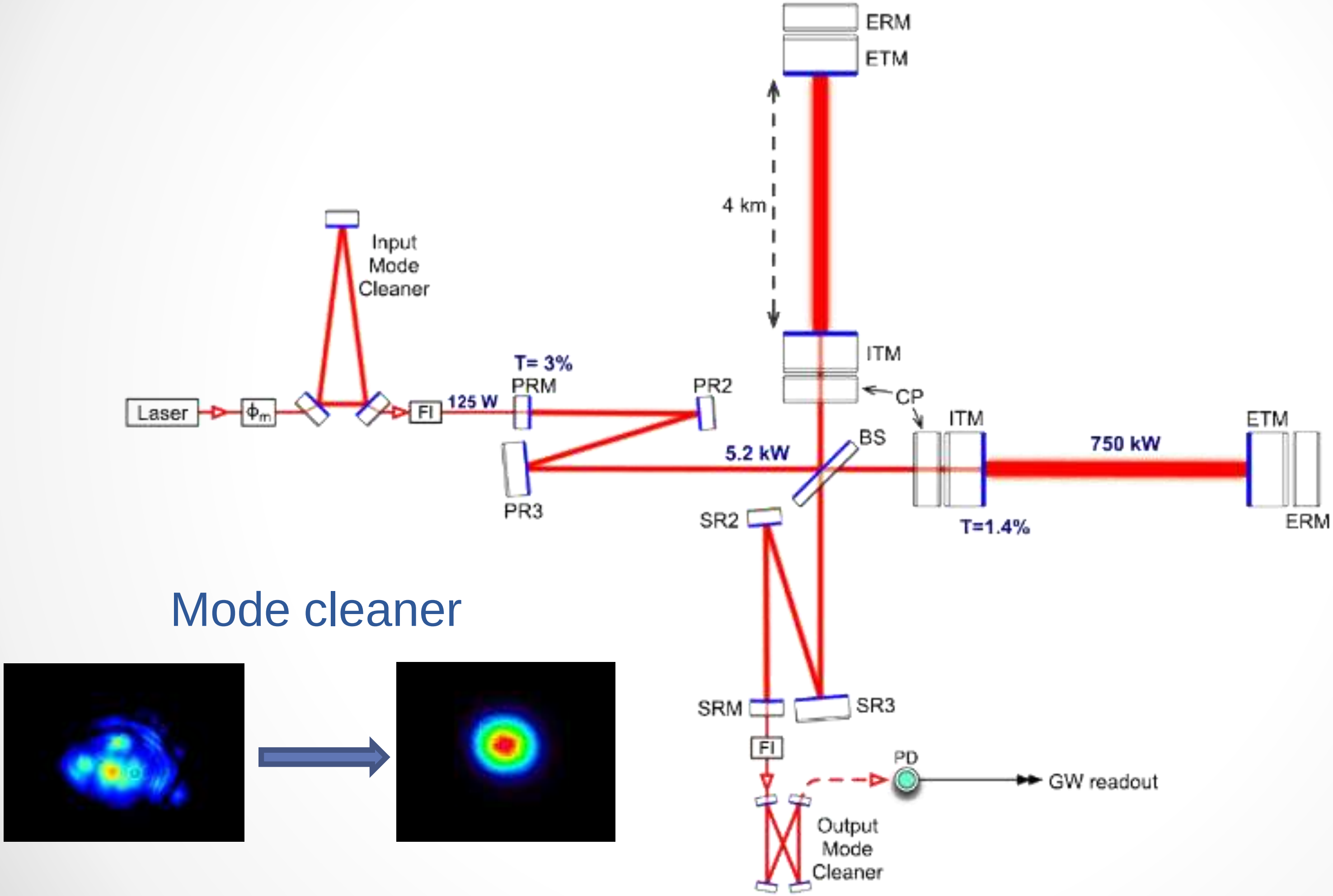




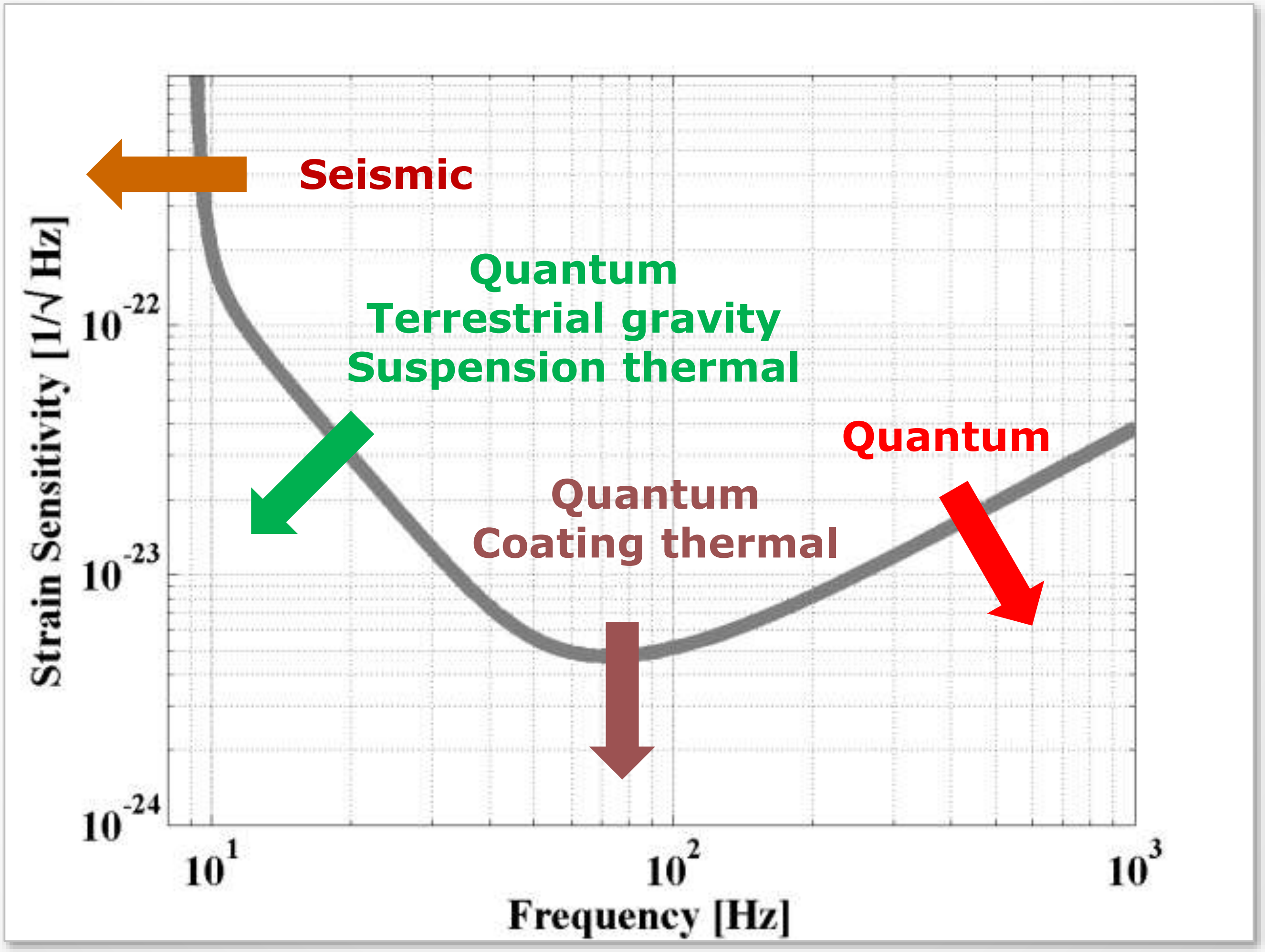


Interferometric GW detectors
are very complex

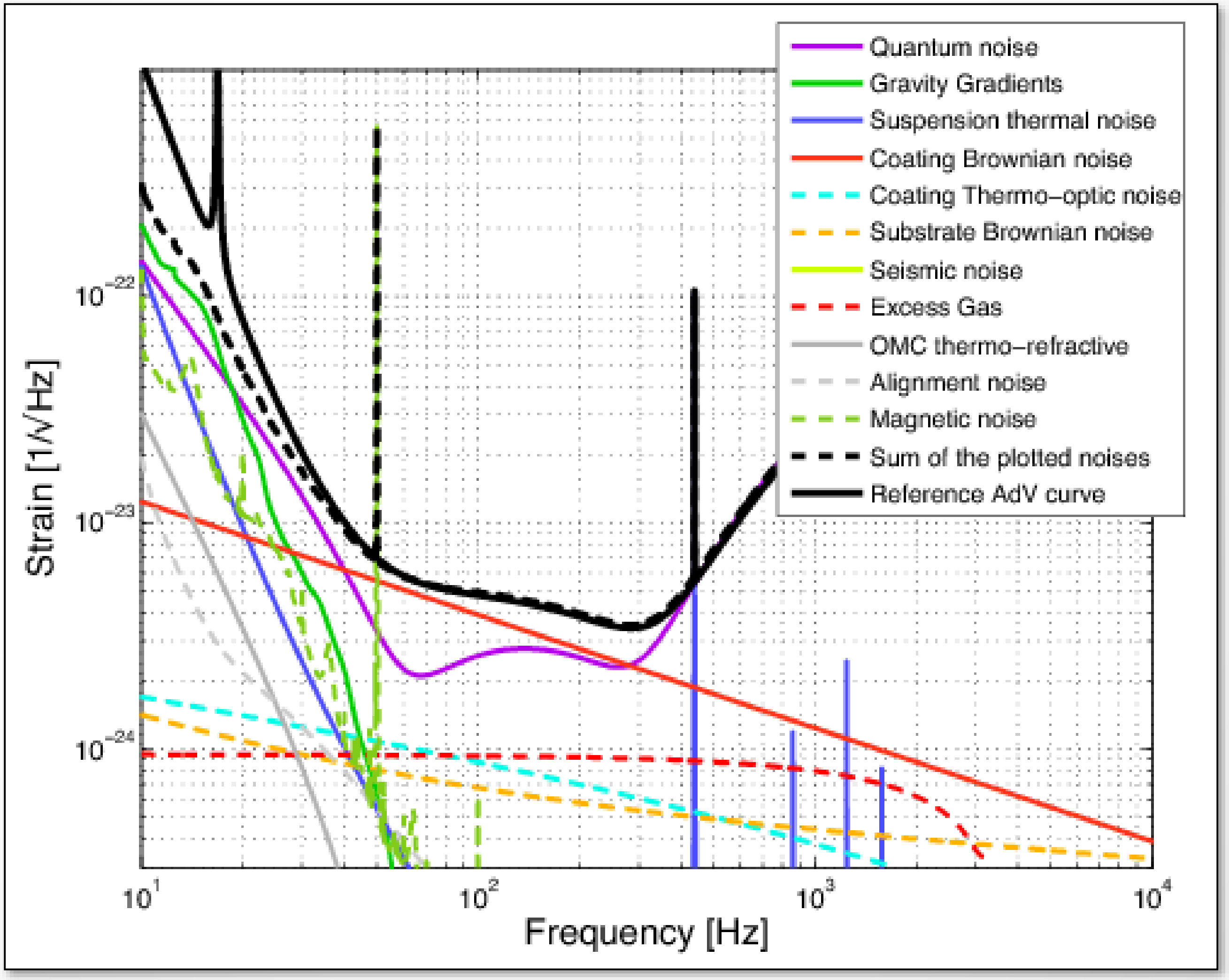
Virgo Configuration



Main Noise Sources



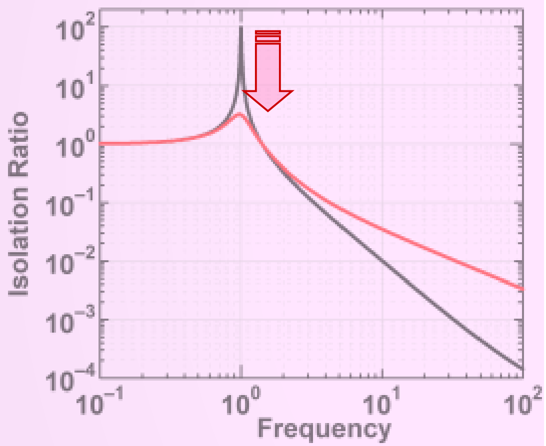
Adv Virgo Noise Budget



Principles of Seismic Isolation

Damping

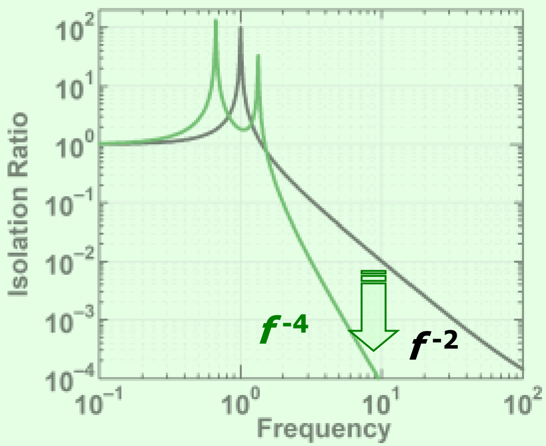
Lower peak height



Less isolation

Cascaded

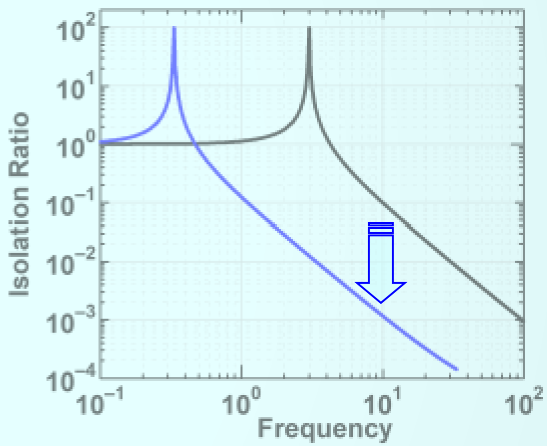
Steeper isolation curve



More peaks

Larger structure

Lower resonance frequency



Difficult to realize

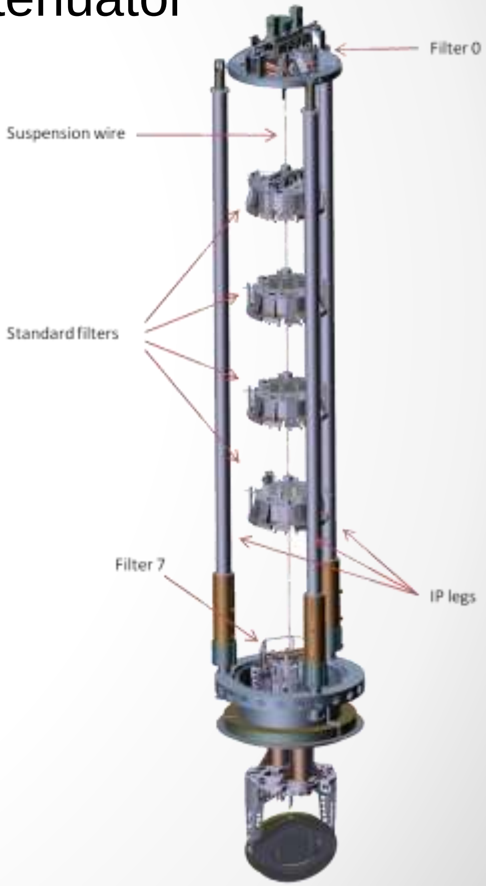
In pratice: use combination of these methods

Seismic Isolation of Adv Virgo

Mechanical filters

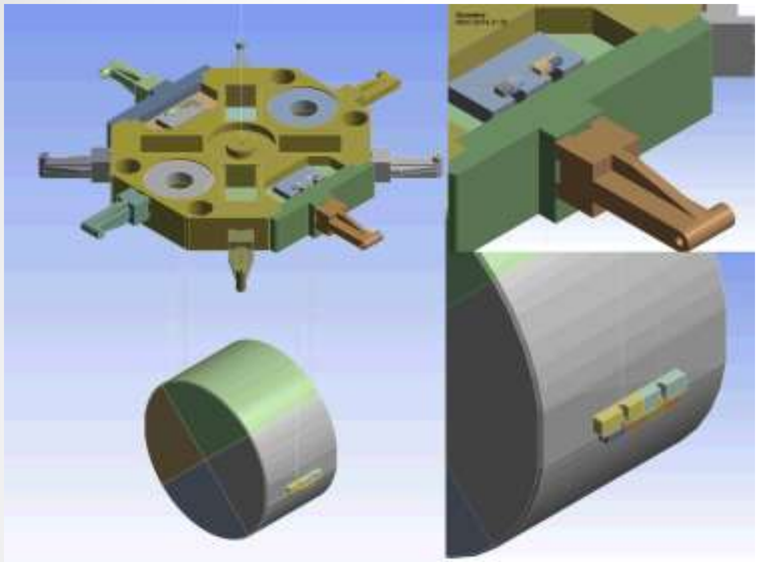
Passive isolation

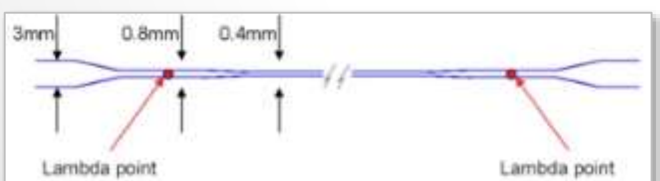
Superattenuator



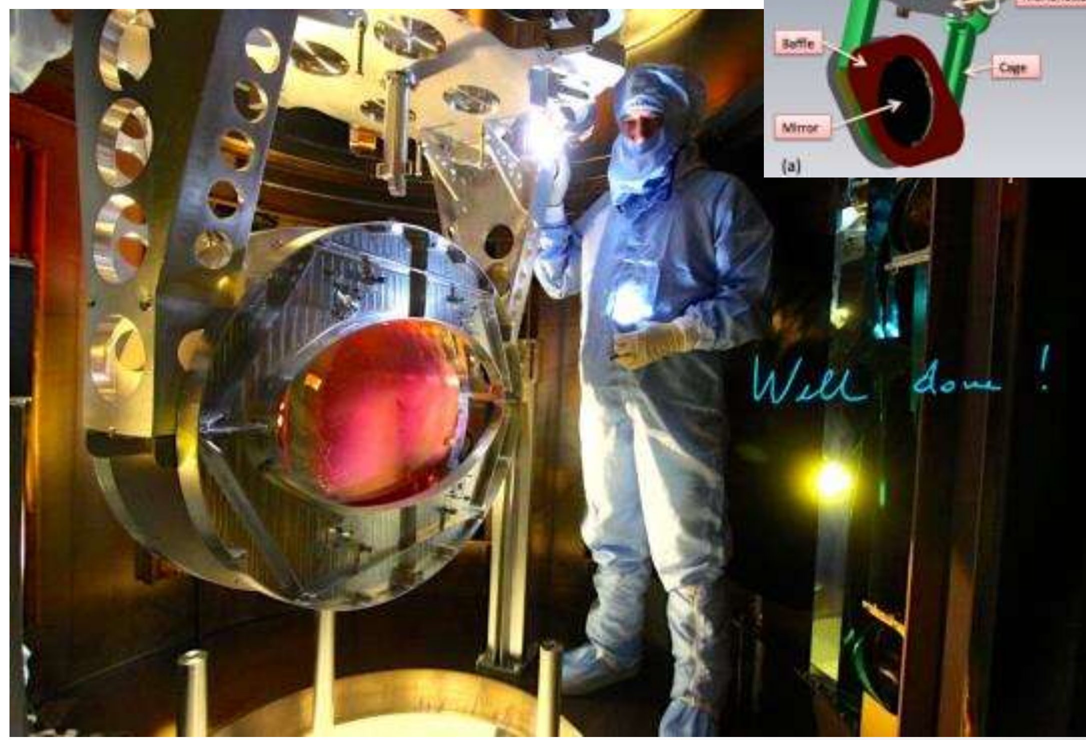
Suspension System of Adv Virgo

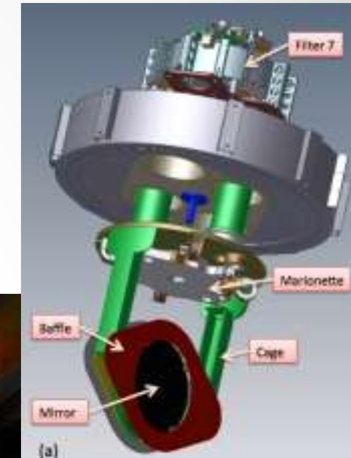
Test mass





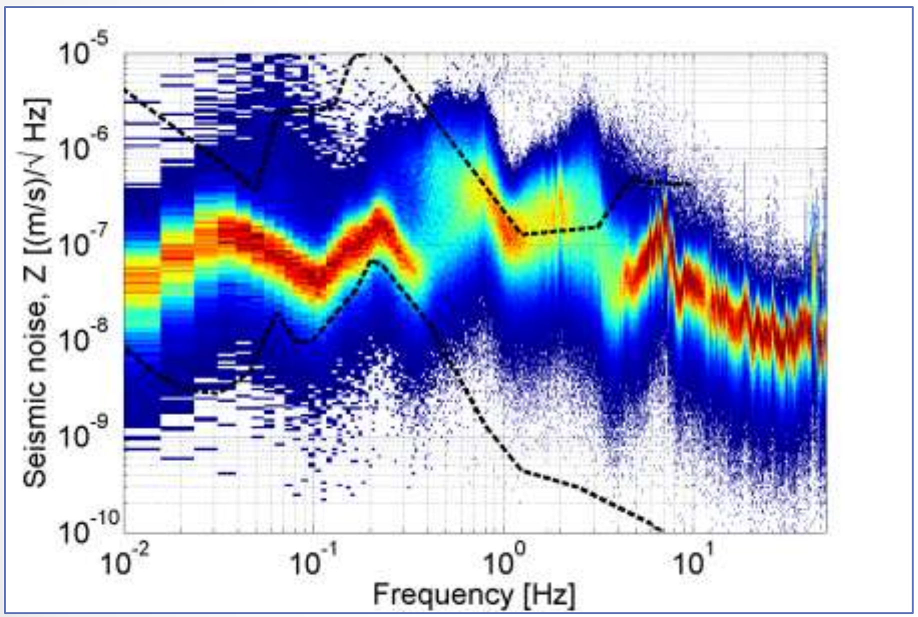
Beam splitter



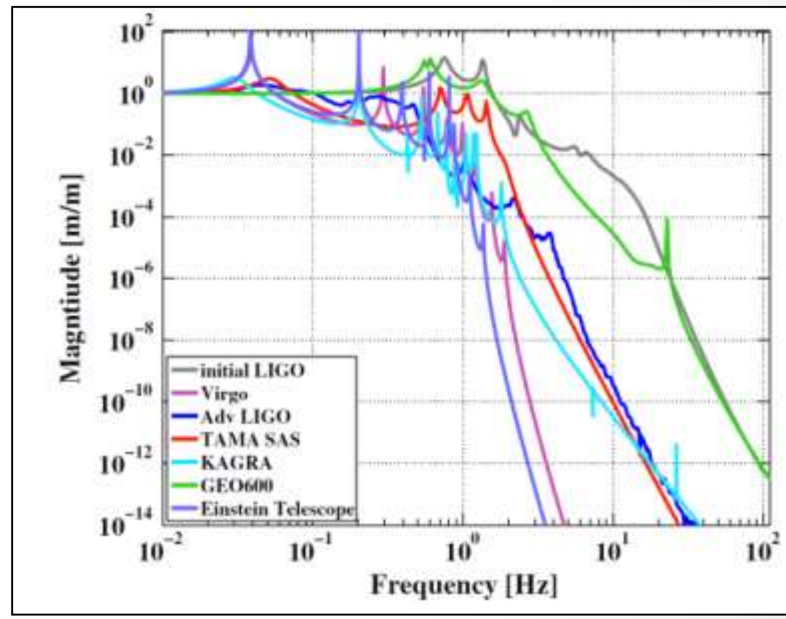


Seismic Noise

Ground motion at the Virgo site



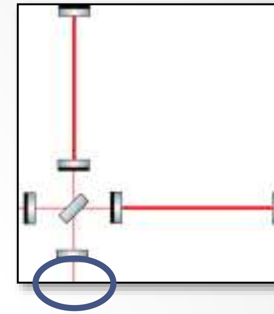
Modelled seismic isolation performance



Quantum Noise

Heisenberg uncertainty principle

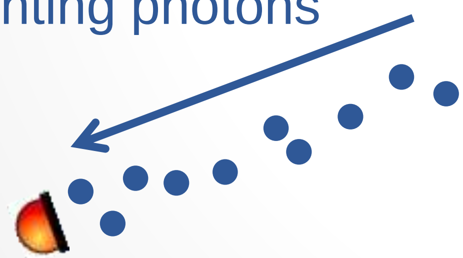
$$\Delta p \, \Delta x \geq \frac{\hbar}{2}$$



Caves: it is the state of the field incident from the output that determines the photon statistics

What are the position and momentum variables in the case of light?

Fundamental measurement in Virgo: Counting photons

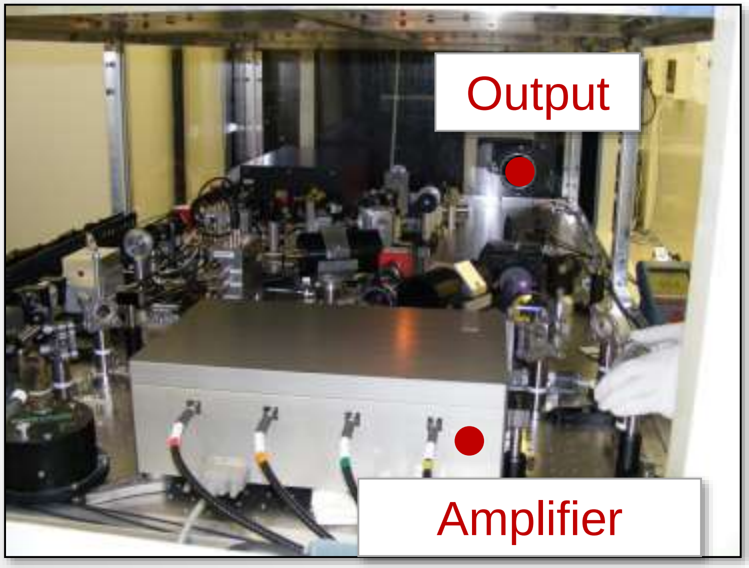


Multiple answers, but for GW detectors, the conjugate variables are the **quadratures of the EM field**:

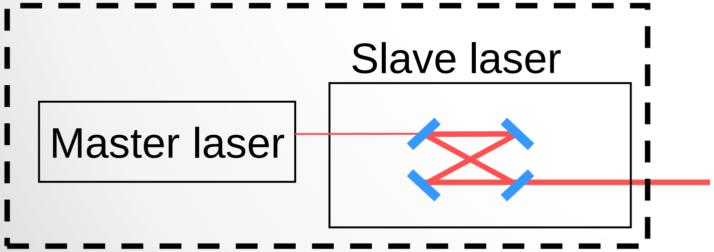
$$E(t) = E_1(t)\cos(\omega_0 t) + E_2(t)\sin(\omega_0 t)$$

High-Power Laser

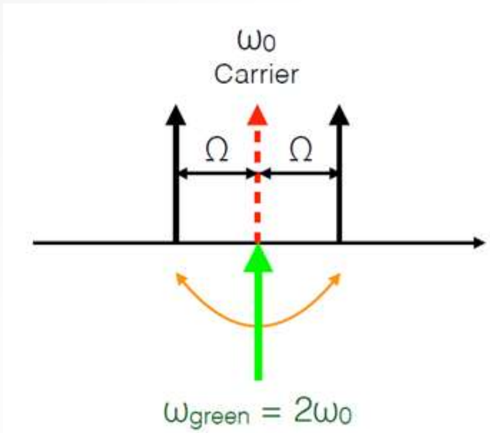
- Stabilized in power and frequency
- Master-slave configuration

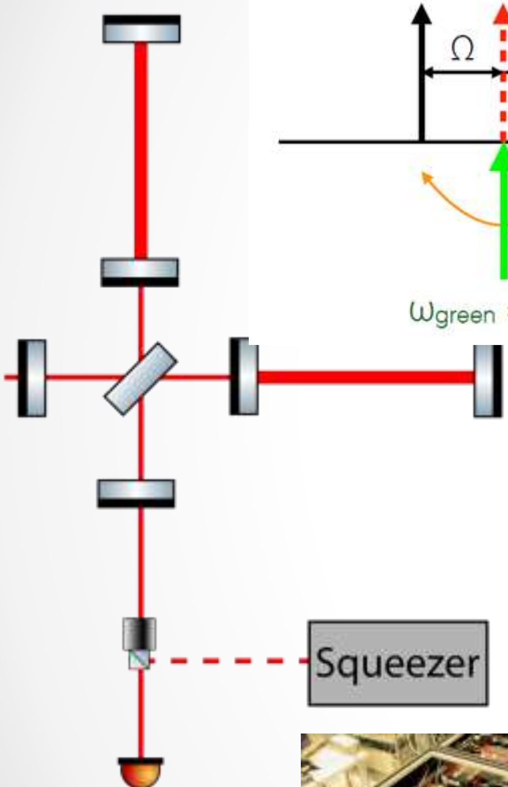


A new laser is being developed.

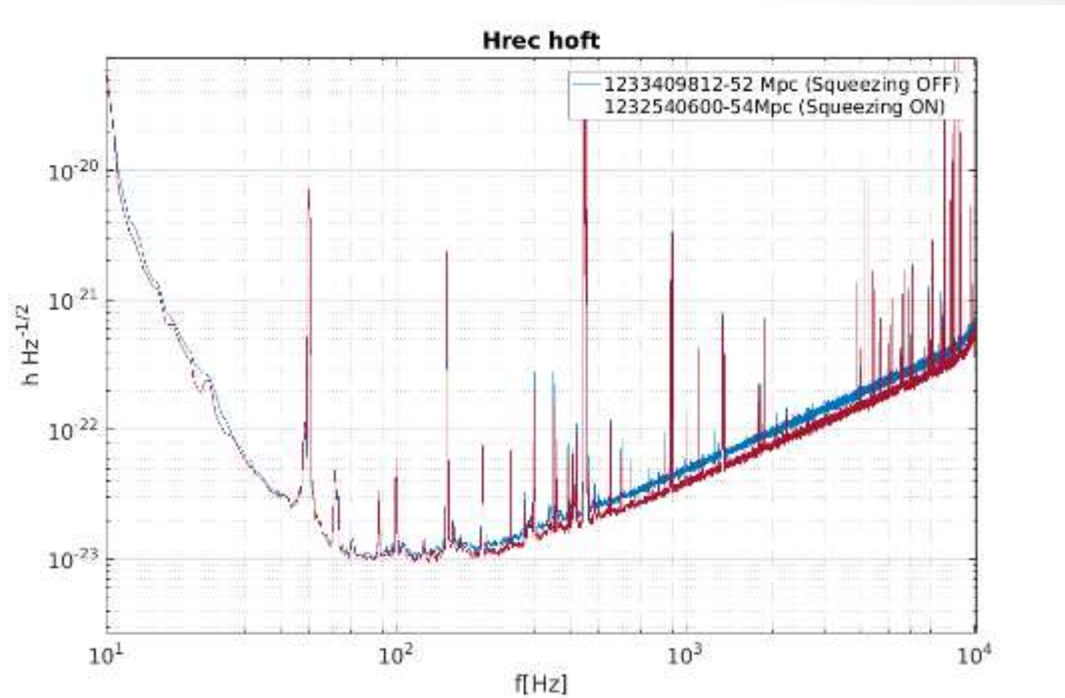


Squeezed-Light Technology

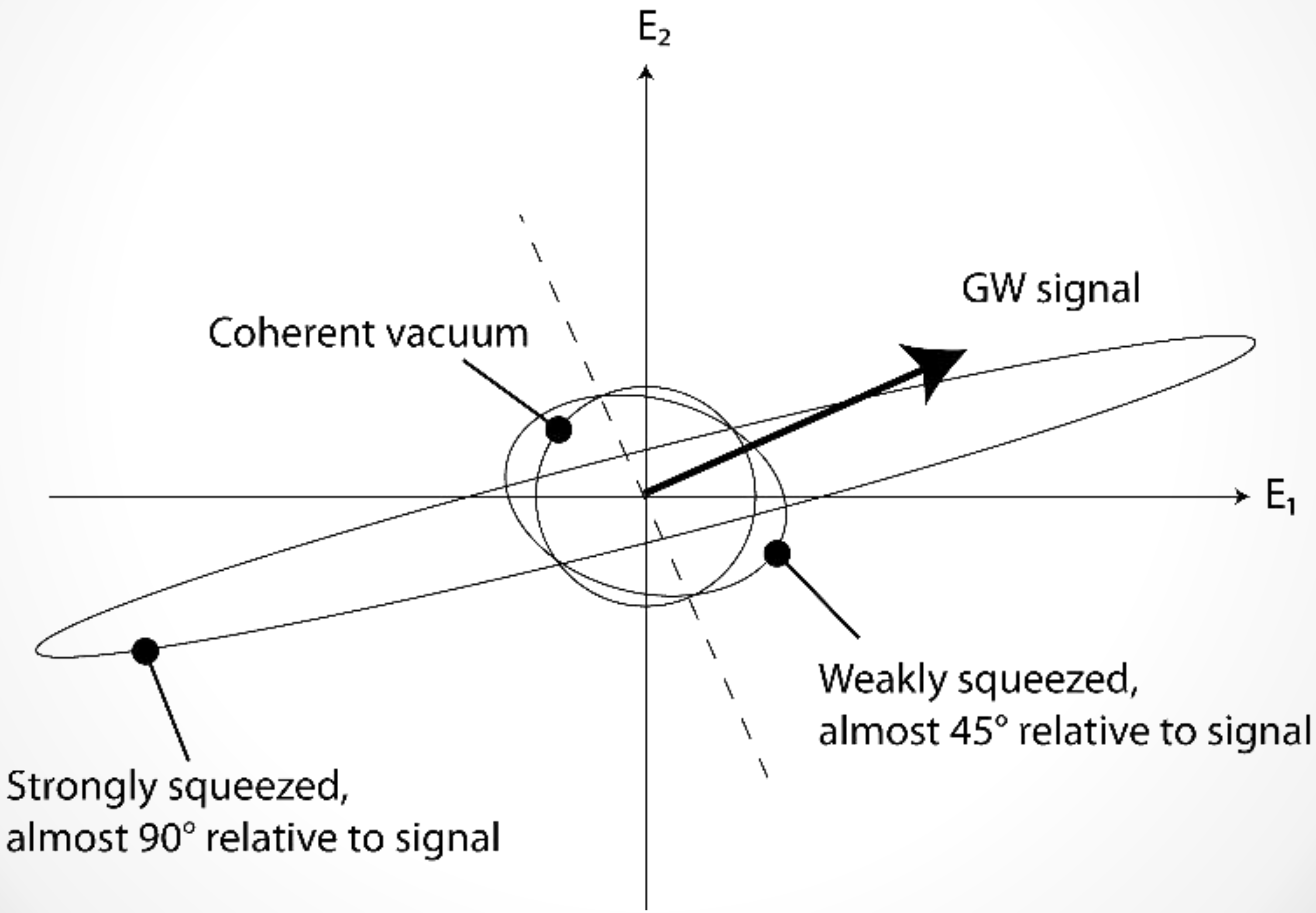




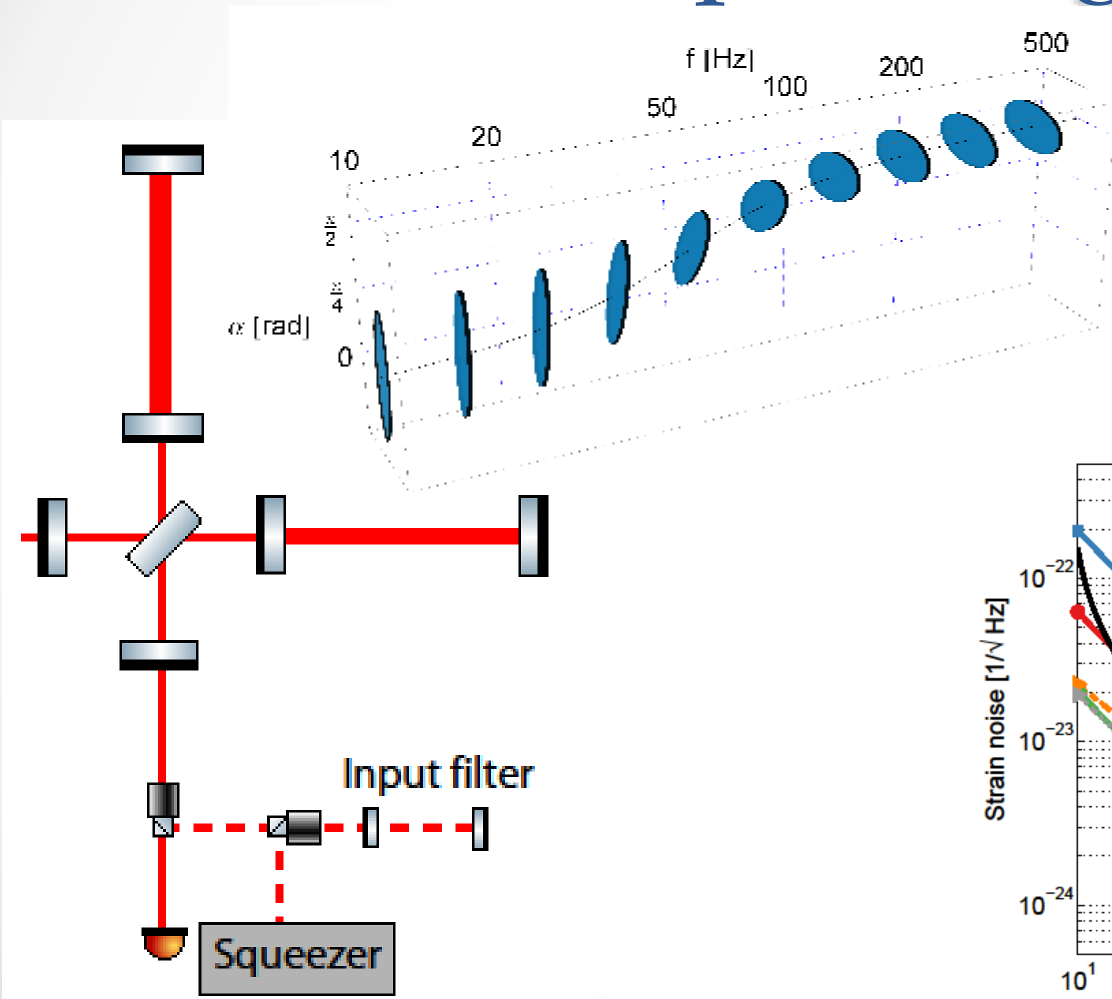
Squeezed light is produced by parametric down-conversion in non-linear crystals



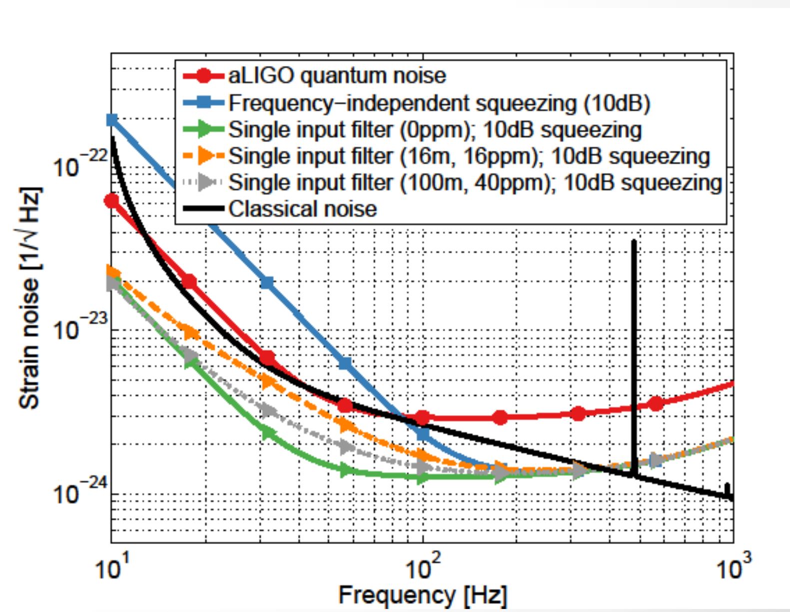
Squeezing Ellipses



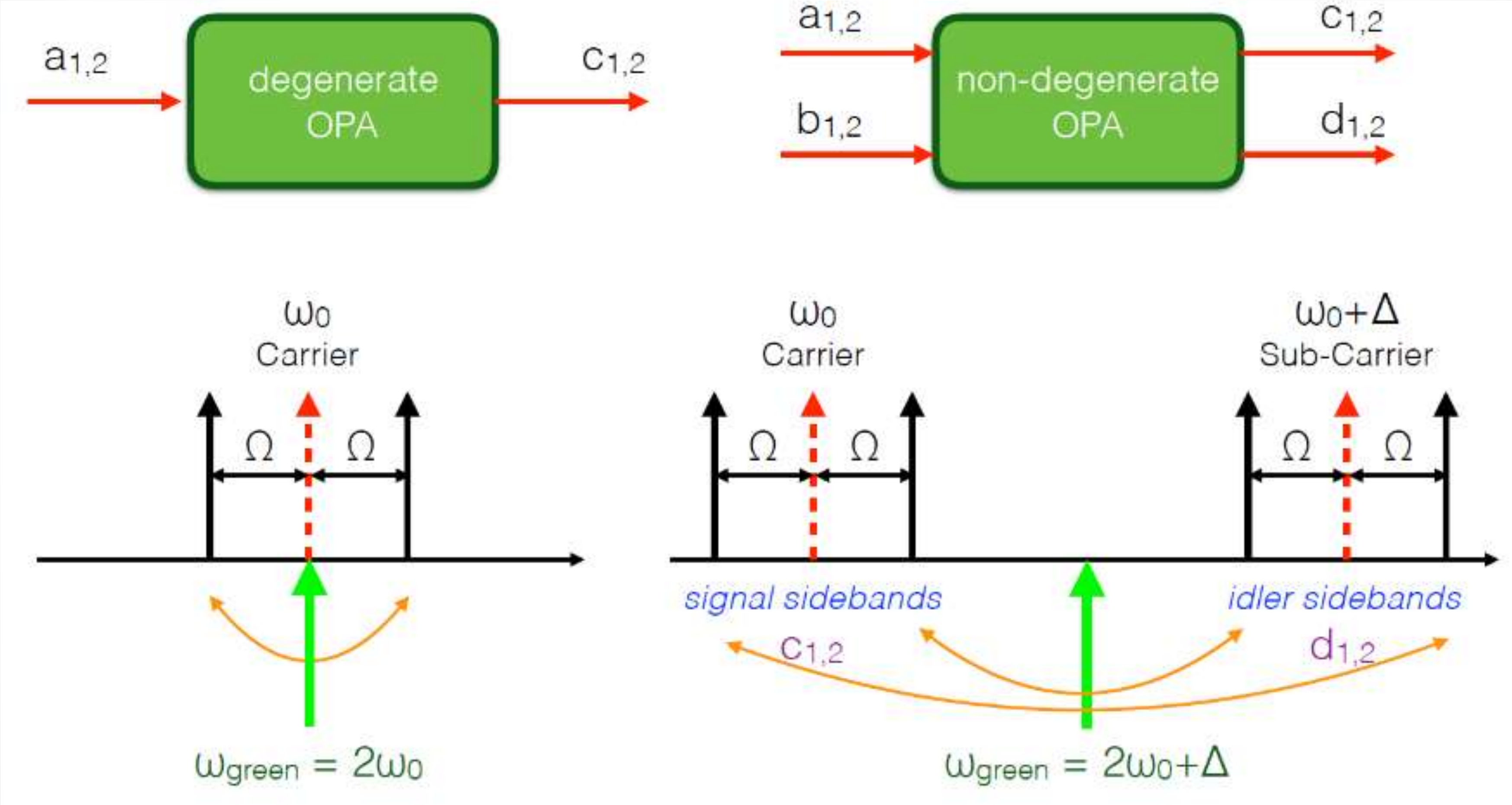
Frequency-Dependent Squeezing



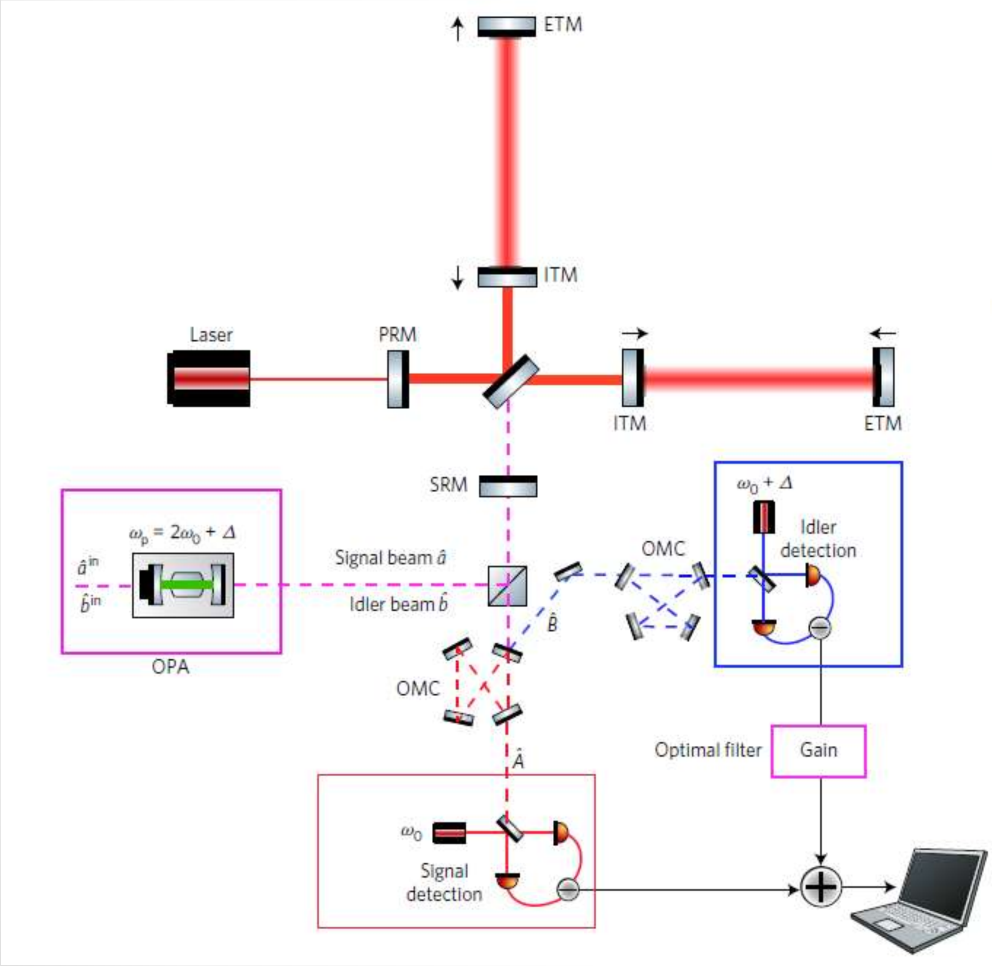
Rotation of the squeezing ellipse by the interferometer needs to be compensated using a filter cavity.

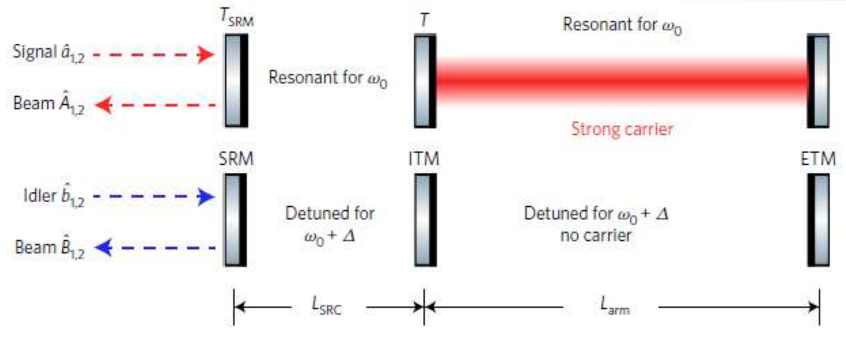


Down-conversion



EPR Scheme

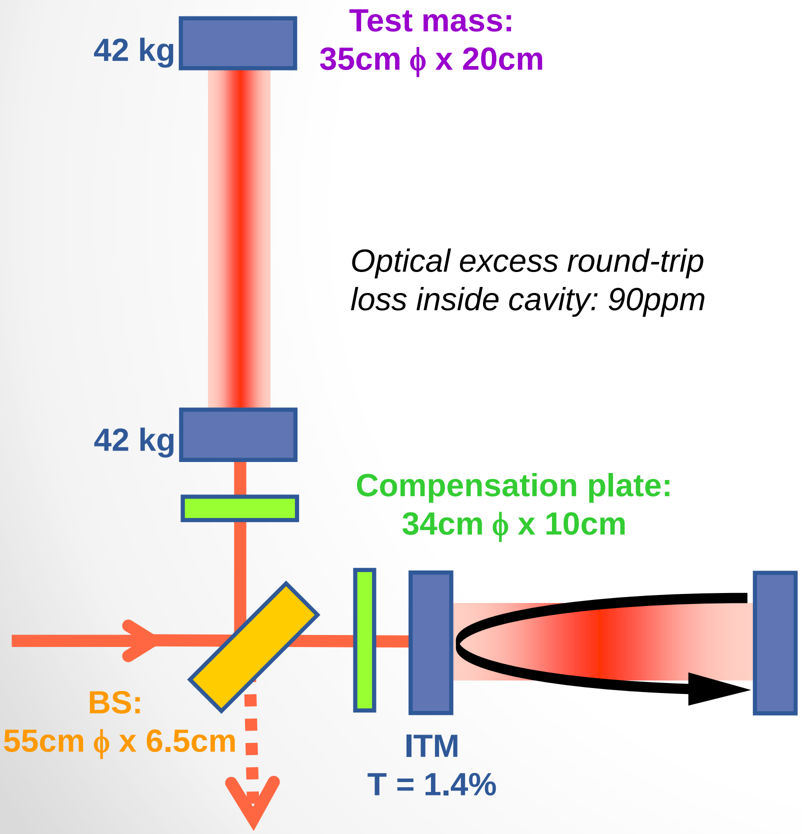


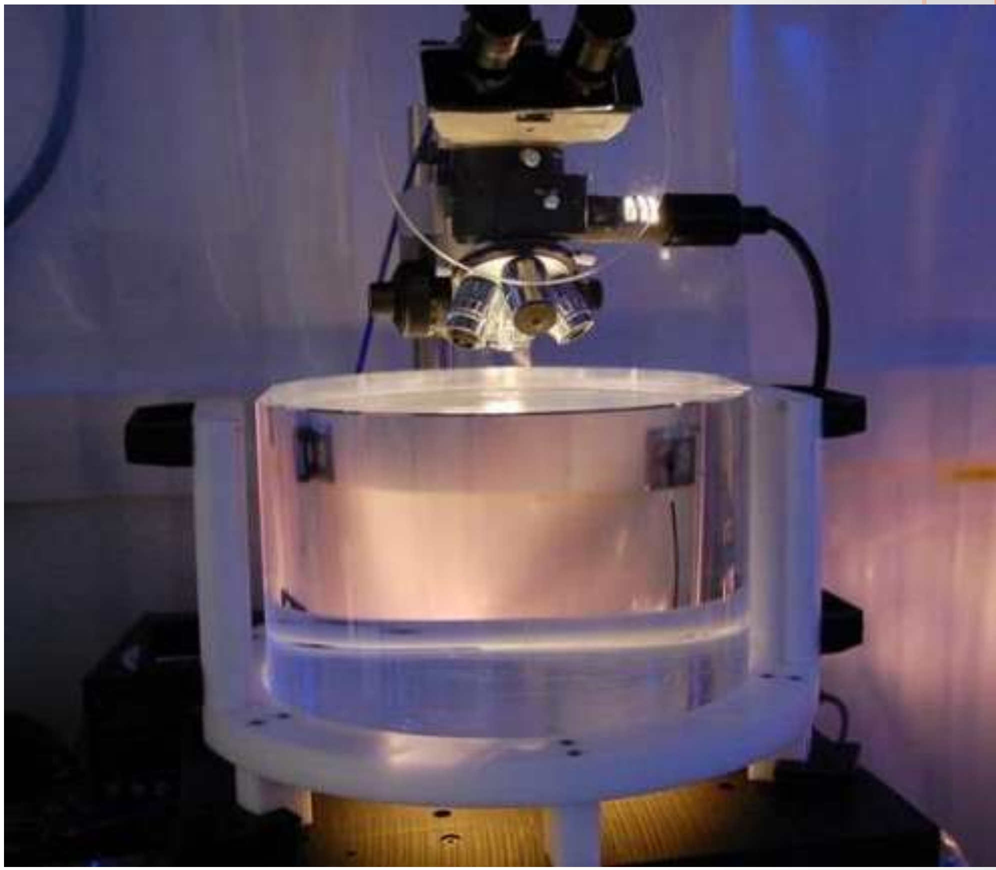


Signal and idler beams are detected individually and optimally combined electronically.

Test Mass

- Requires advanced technologies for substrates and polishing
- Coating deposition pushes current technology limits
- Sub-nm profile errors over 30cm



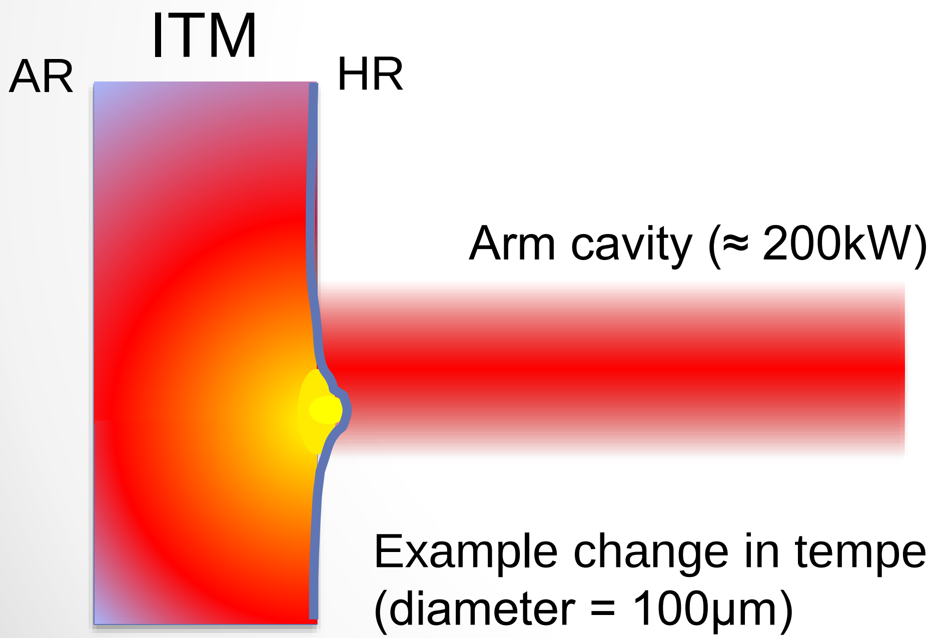


Designed to

- Have ultra low mechanical loss and high resonance frequencies (vibration)
- Have extremely low absorption, low scattering, high homogeneity, precise curvature and profile

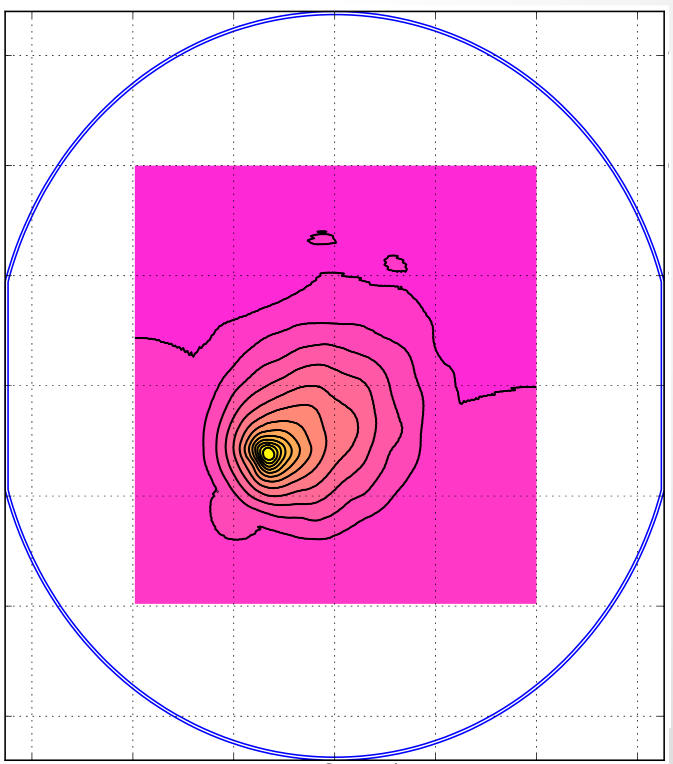
Point Absorbers

- Localized small (≤ 100μm),
- highly absorbing (> 10^4 ppm)
- on test mass high-reflectivity surface



Example change in temperature
(diameter = 100μm)
Then ΔT = **800K**

Resulting thermal lens/surface deformation (example)



A Brooks (2019)

absorber: 155 μm across bright center

er: 155 μm across bright center

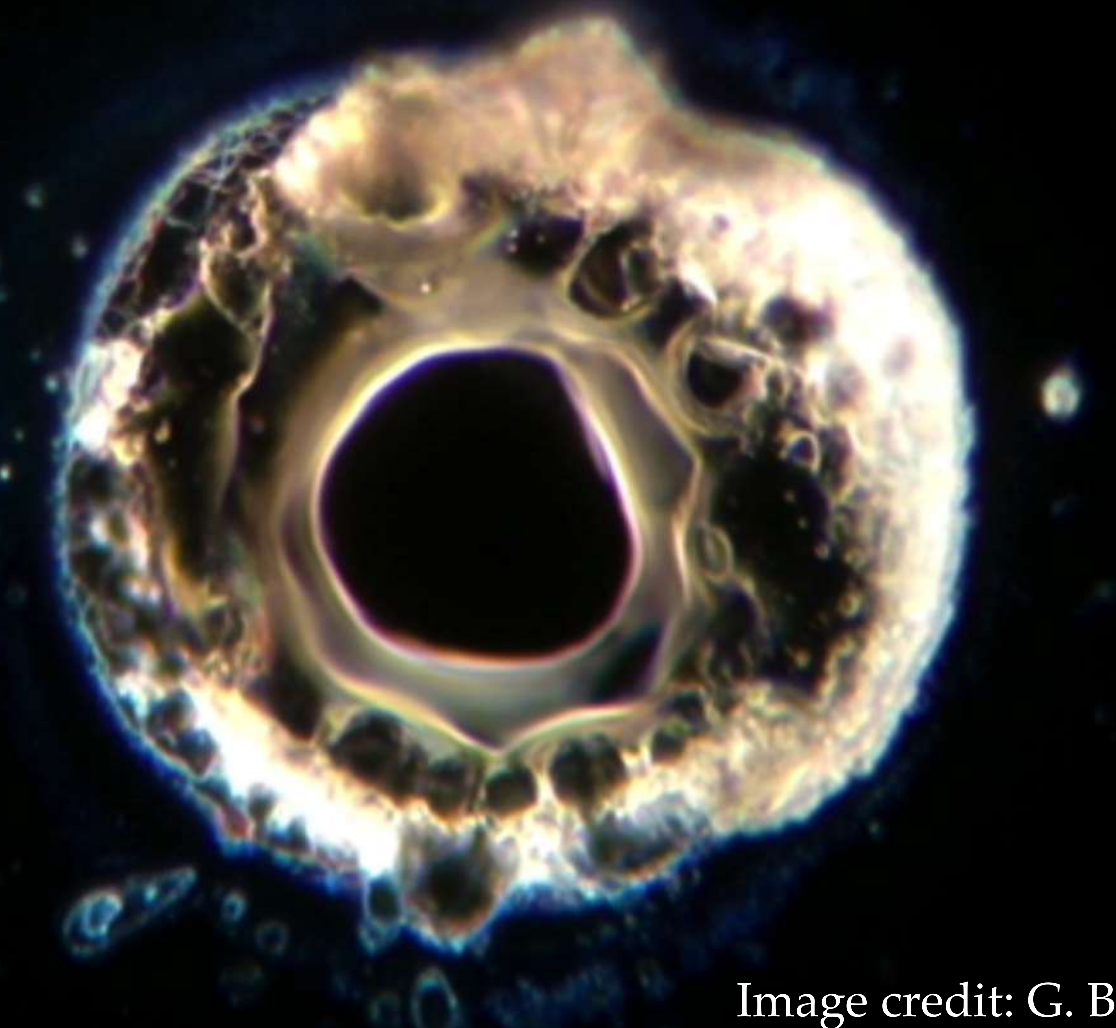
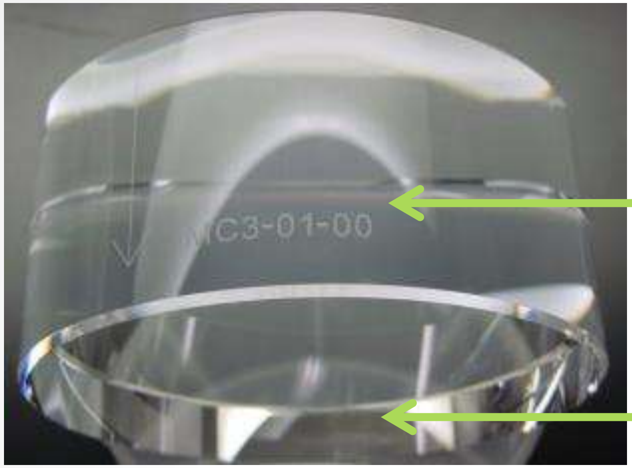
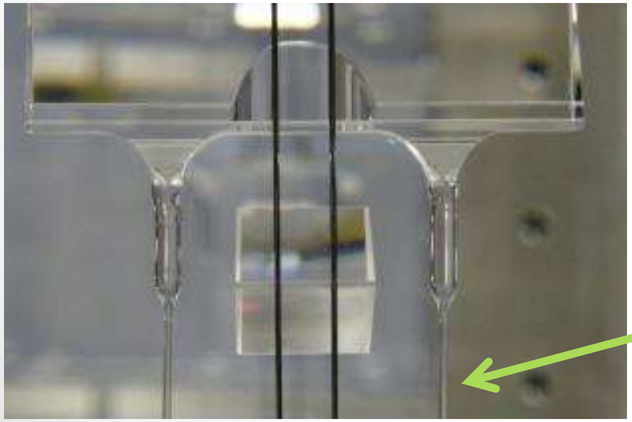


Image credit: G. Billingsley et al.

Thermal Noise



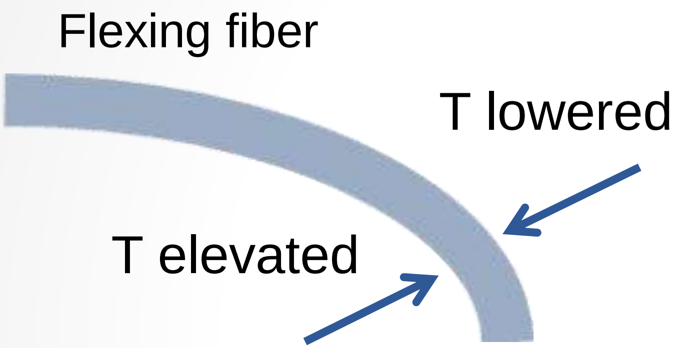


Substrate thermal noise
- ***Thermo-elastic noise***
- Brownian noise

Coating thermal noise
- ***Brownian noise***
- Thermo-refractive noise
- Thermo-elastic noise
- Photothermal noise

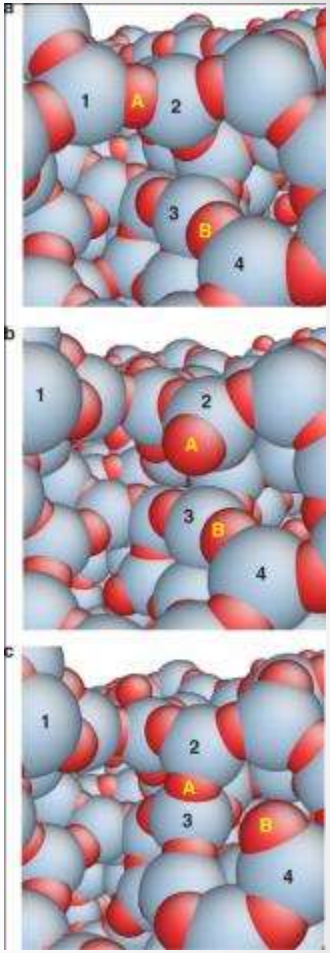
Suspension thermal noise
- Brownian noise
- ***Thermo-elastic noise***

Dissipation and Thermal Noise



Thermo-elastic noise:
Irreversible heat flux across temperature gradients

Brownian noise:
Many possible causes (for example, change in silicon bonds)

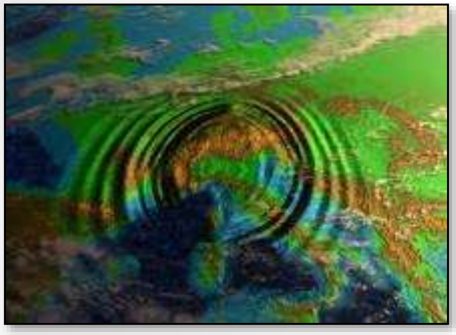

Zheng et al 2010

Fluctuation-dissipation theorem:
Thermal-noise spectrum proportional to mechanically dissipated power

$$S_x(\Omega) = \frac{8\pi kT}{\Omega^2}\frac{W_{\text{diss}}}{F_p^2}$$

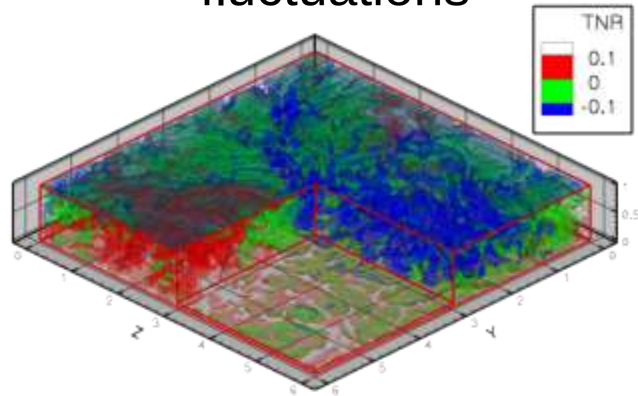
Newtonian Gravitational Noise

Seismic noise



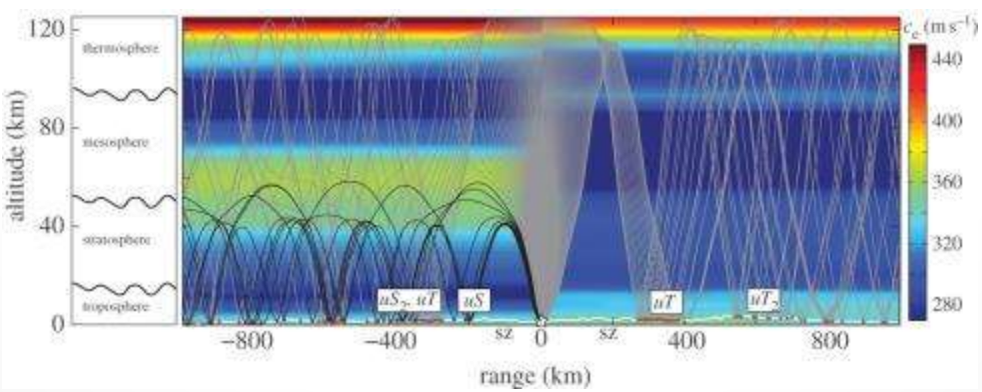
$$\frac{\xi(f)\, e^{-\frac{2\pi f h}{c_{\mathrm{hor}}}}}{f^2}$$

Advected temperature fluctuations



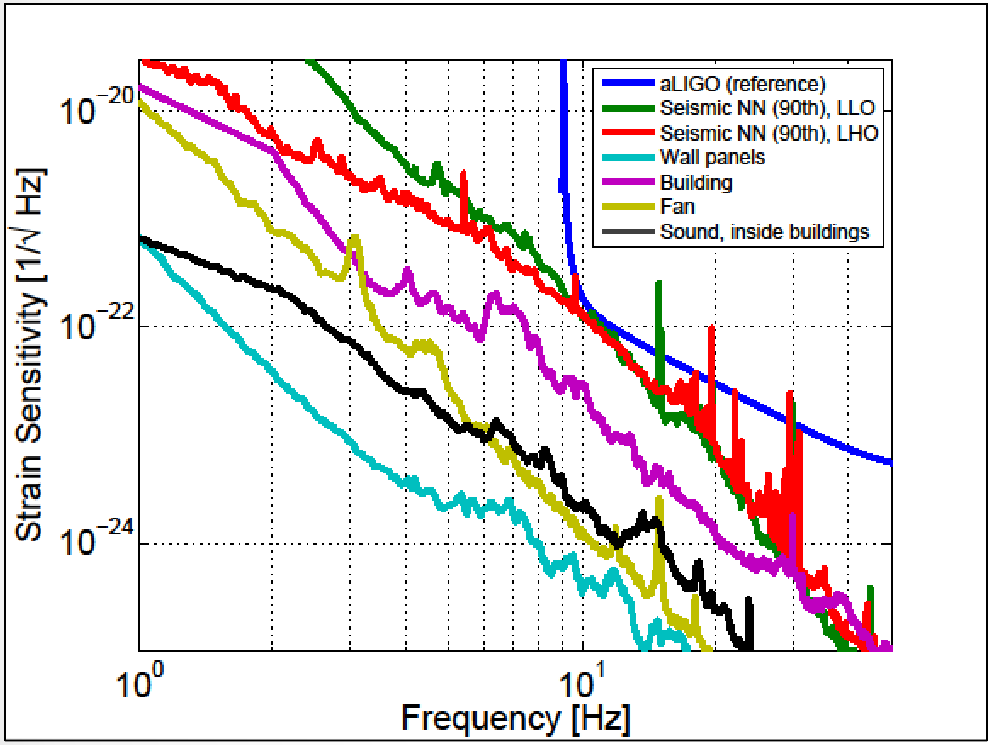
$$\frac{\delta \mathrm{T}(f)\, e^{-\frac{2\pi f r}{v}}}{f^{10/3}}$$

Infrasound



$$\frac{p(f)\, e^{-\frac{2\pi d f}{c_{\mathrm{hor}}}}}{f^3}$$

Newtonian Noise in LIGO

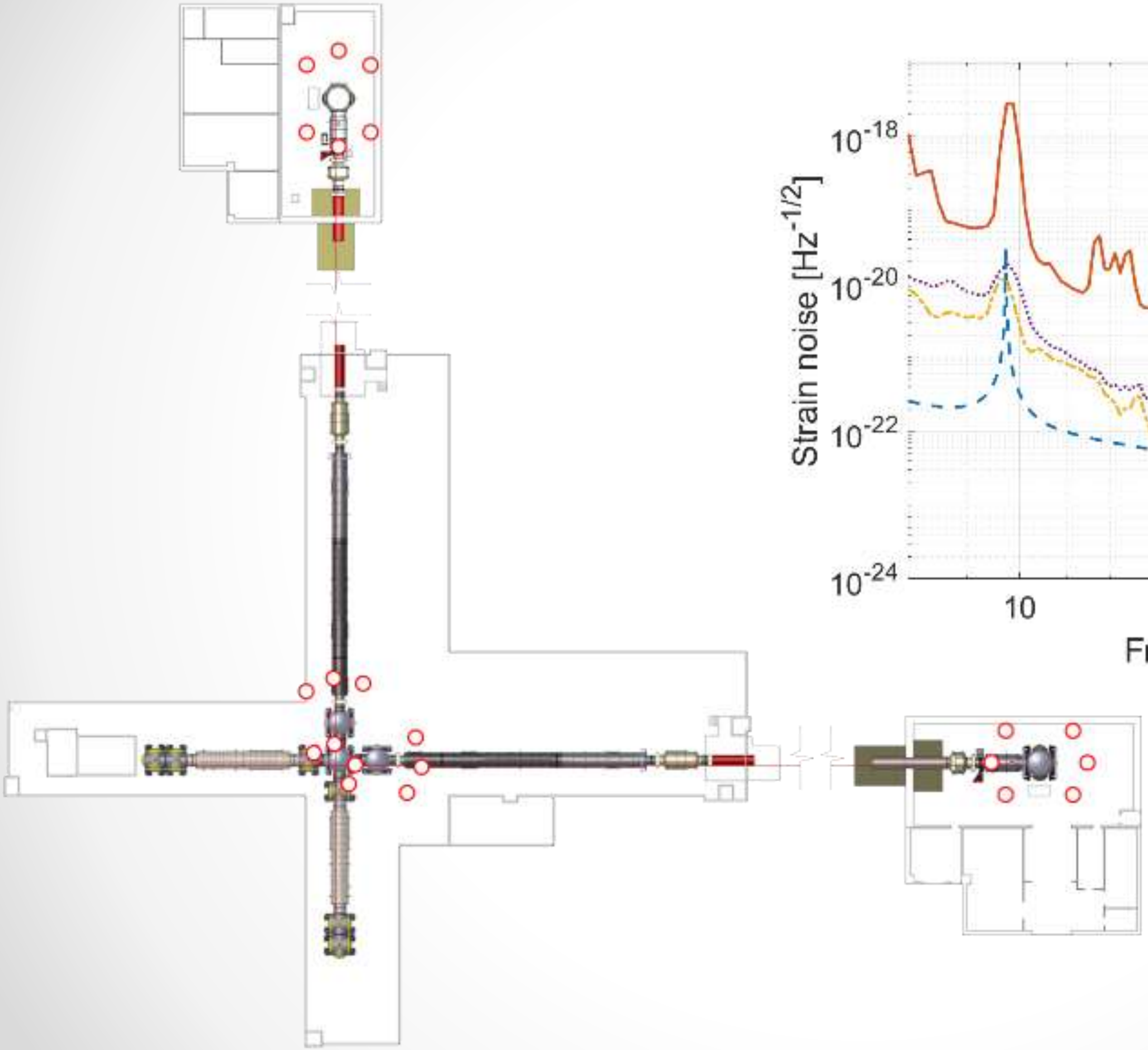


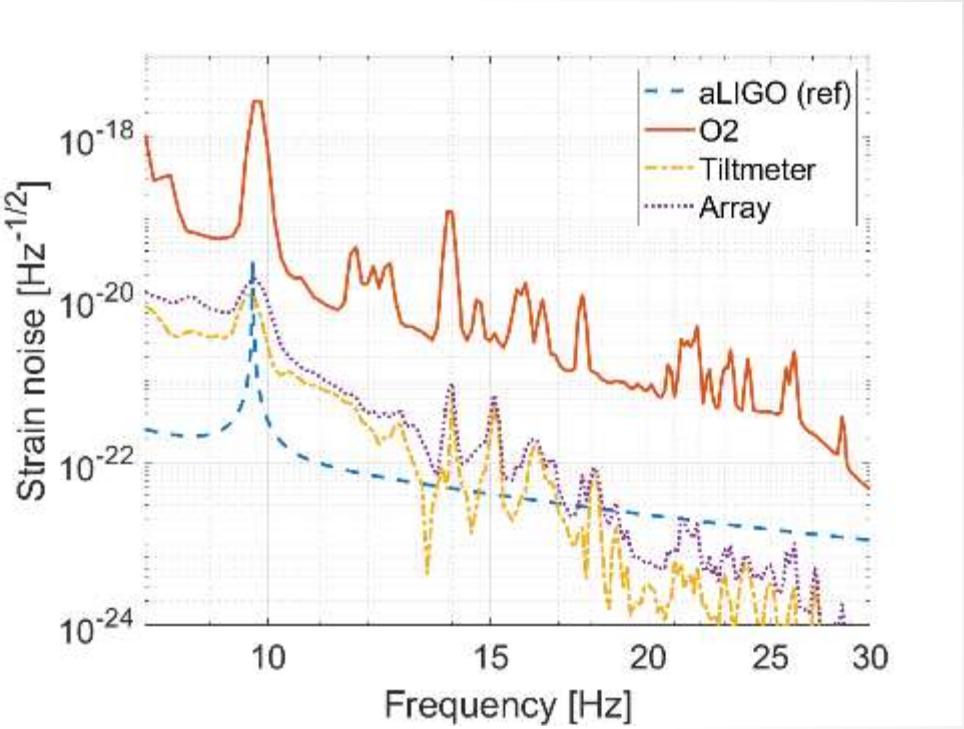
- Seismic surface waves

- Vibrations of buildings
- Vibration of water tubes
- Vibration of vacuum system
- Ventilation fan

- Sound inside and outside laboratory building

Newtonian-Noise Cancellation



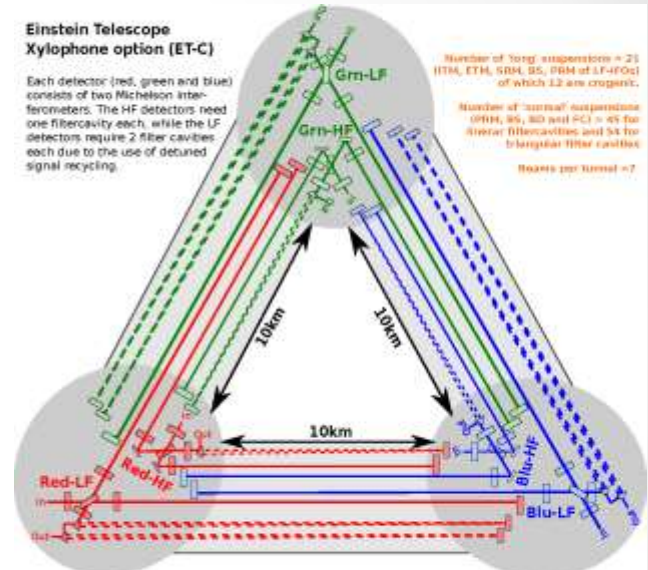


Future Key Technologies

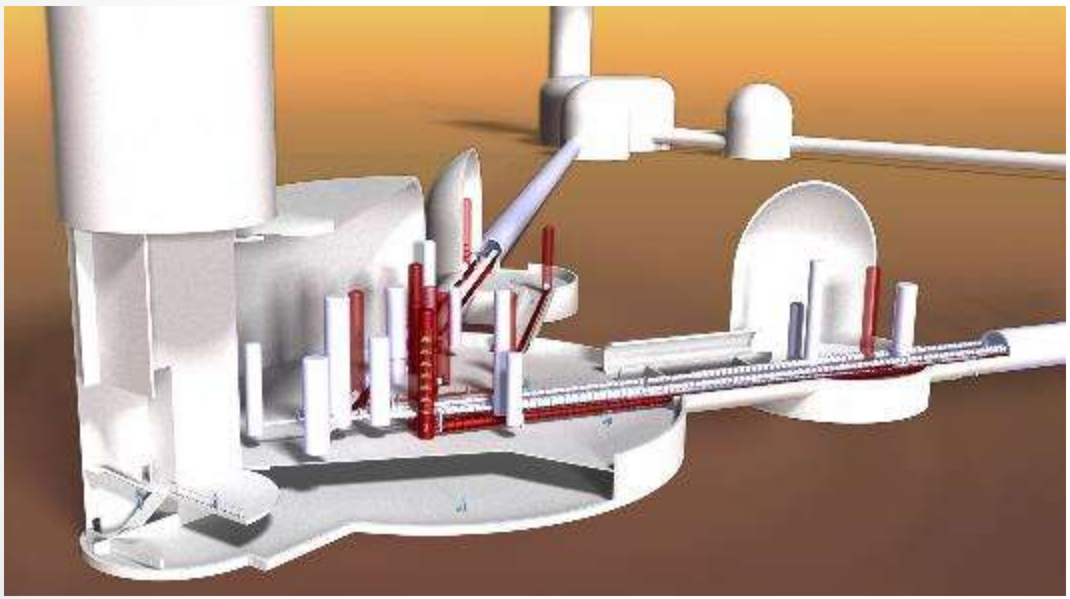
- Quantum-noise reduction by squeezing and QND
- Interferometer control to address non-linear couplings and non-stationary noise
- Adaptive optics to reduce optical loss
- Coating thermal-noise reduction
- Cryogenics for mirror and suspension cooling
- Suppressing parametric instabilities due to high laser power
- Coherent cancellation of environmental noise

Einstein Telescope

Triangular xylophone



Constructed a few 100m underground



ET parameters

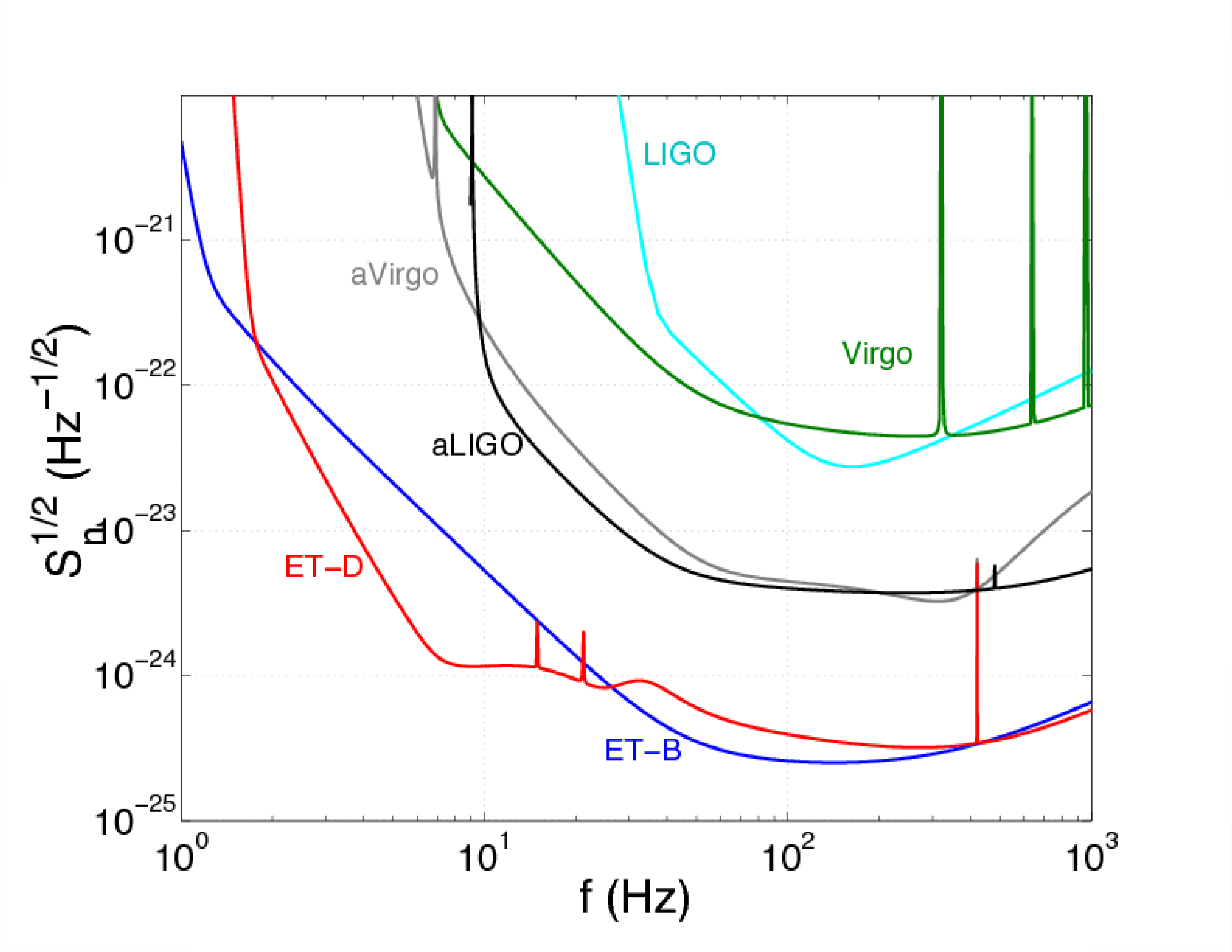
10km arm length

200kg mirrors

3MW light power (high tone)

10K substrates (low tone)

ET Sensitivity

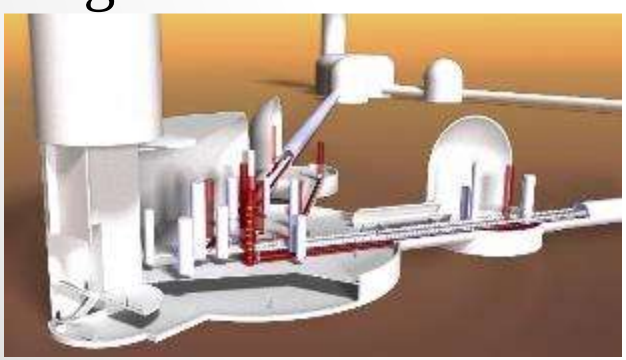


Future Scenario I

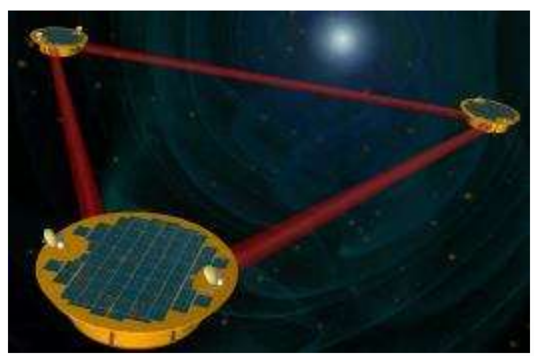
A Facilities of advanced detectors

B

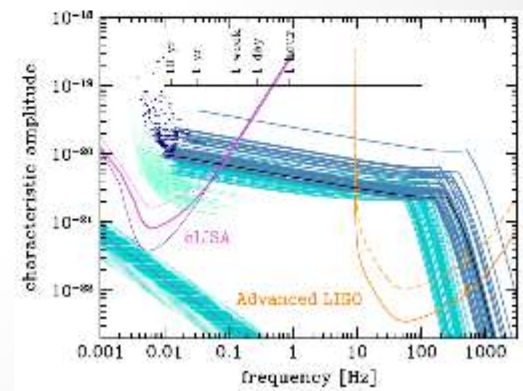
3rd generation



LISA



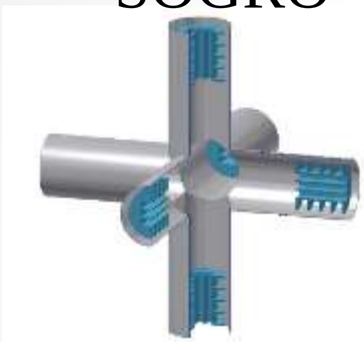
Bonus: synergy



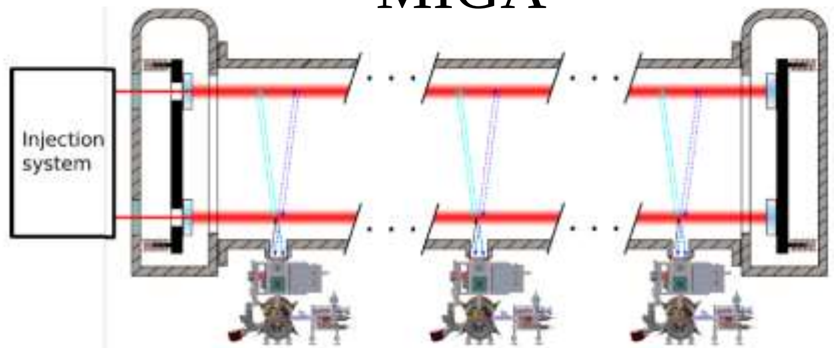
Future Scenario II

C

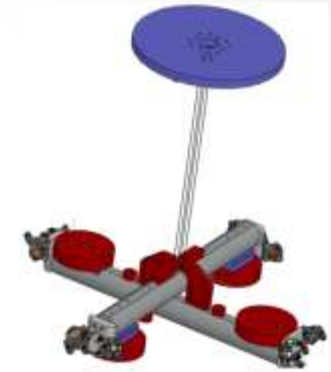
SOGRO



MIGA



Torsion bar



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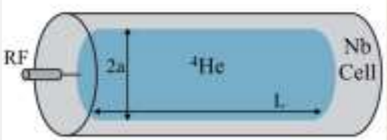
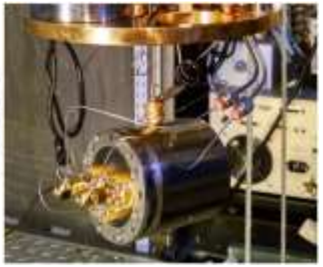


Liquid He



Earth/Moon vibrations

Ultimate Decigo / Big Bang Observer

E