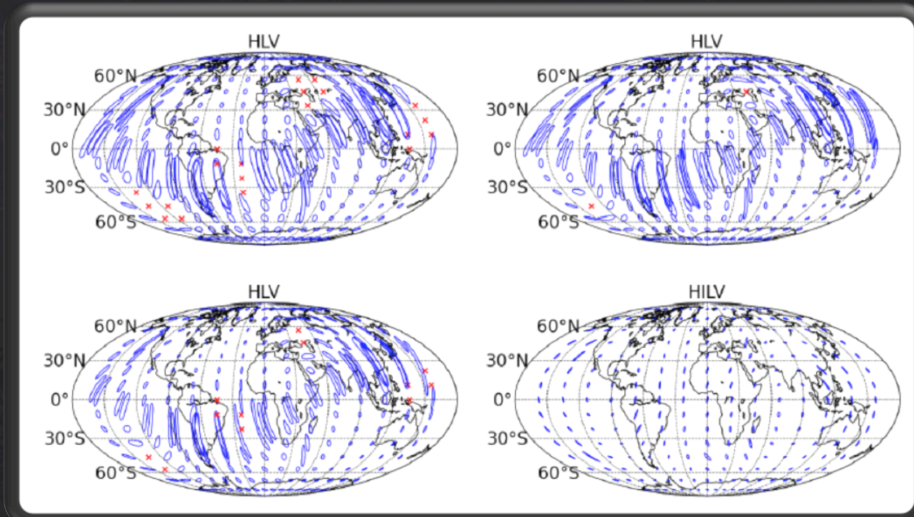

Advanced detectors of gravitational waves: status and perspectives

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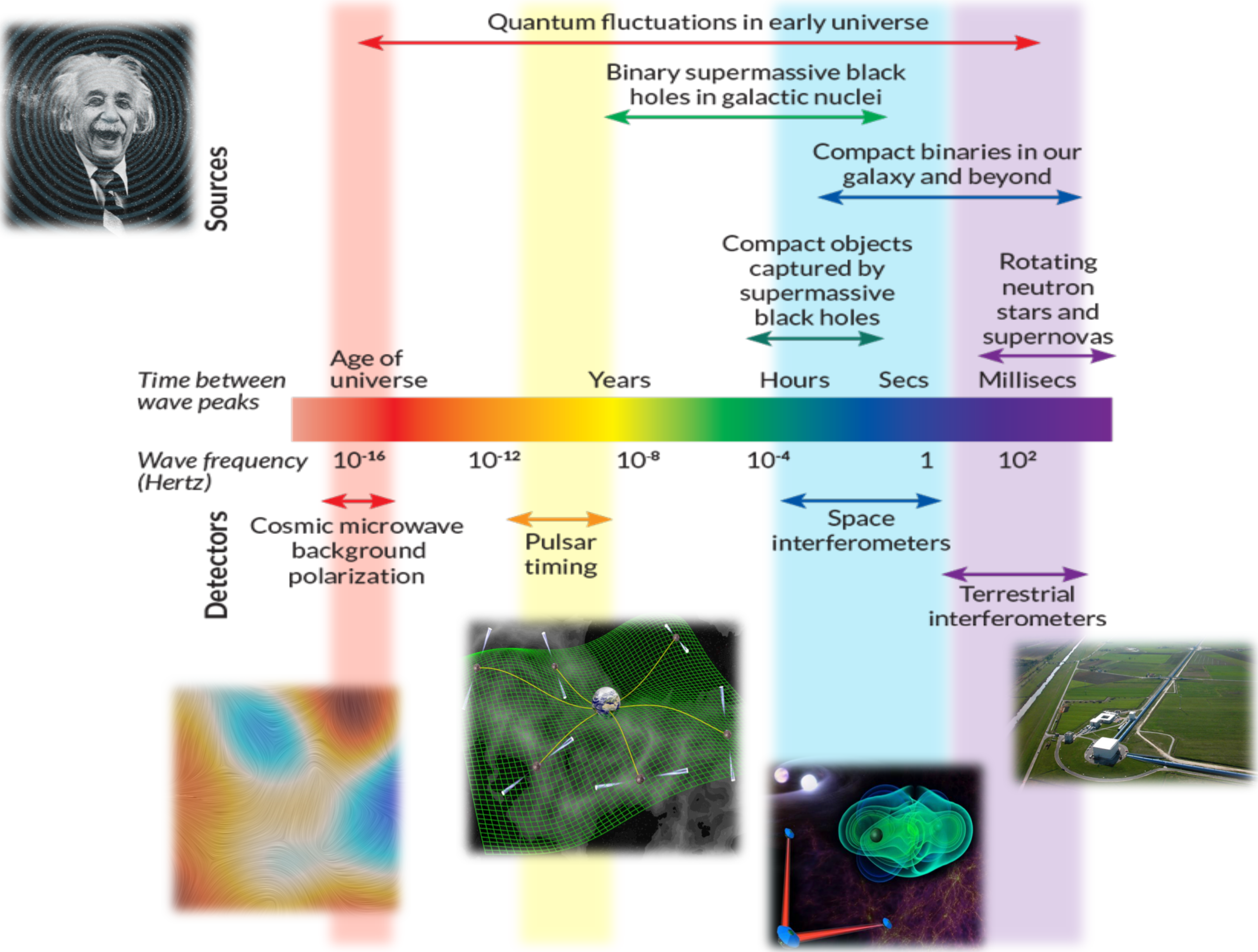
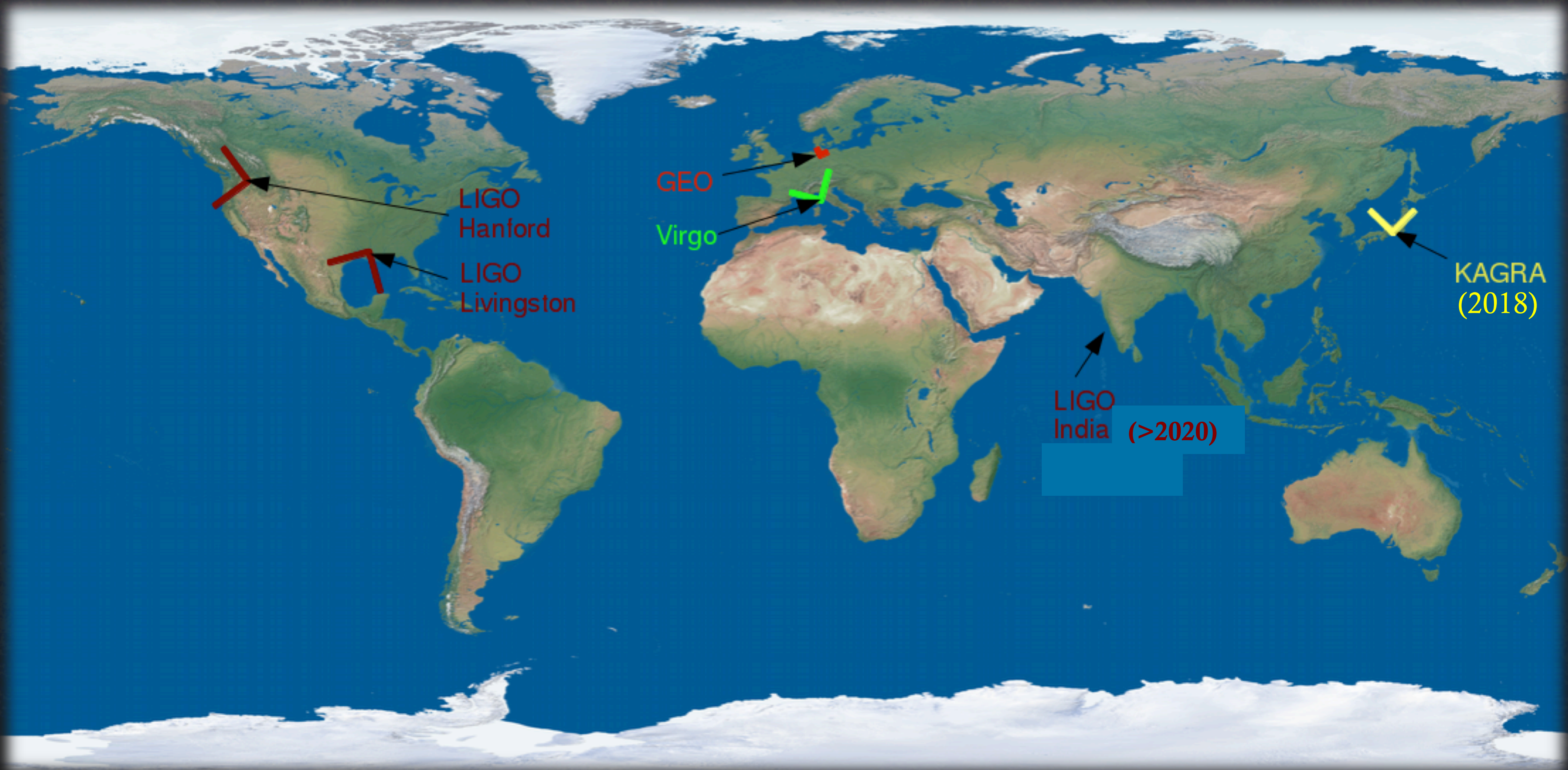
Istituto Nazionale Fisica Nucleare Sezione di Pisa

New Frontiers in *Theoretical Physics - XXXV Convegno Nazionale di Fisica Teorica* and *GGI 10th anniversary*. 17-20 May 2016. Galileo Galilei Institute, Firenze.



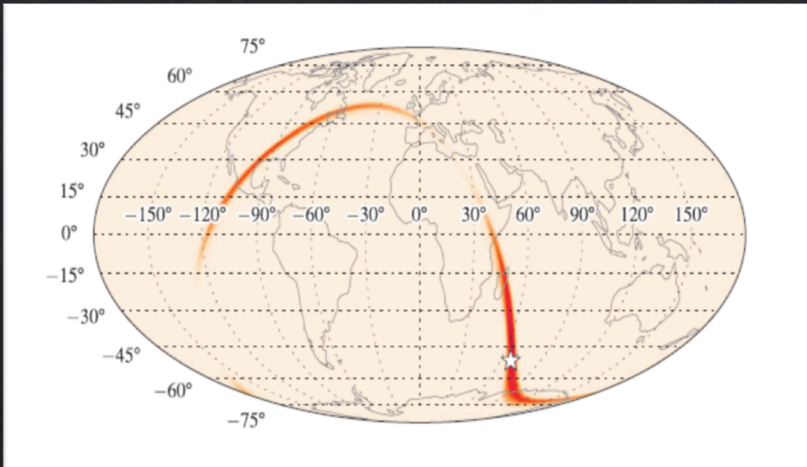
Quantum fluctuations in early universe
Binary supermassive black holes in galactic nuclei
Compact binaries in our galaxy and beyond
Compact objects captured by supermassive black holes
Rotating neutron stars and supernovas
Sources
Time between wave peaks
Age of universe
Years
Hours
Secs
Millisecs
Wave frequency (Hertz)
10^{-16}
10^{-12}
10^{-8}
10^{-4}
1
10^{2}
Detectors
Cosmic microwave background polarization
Pulsar timing
Space interferometers
Terrestrial interferometers

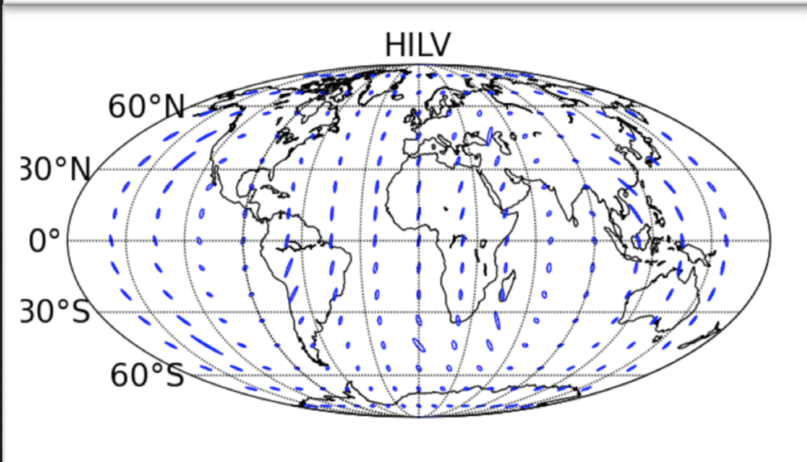
The Gravitational Wave Detectors Network

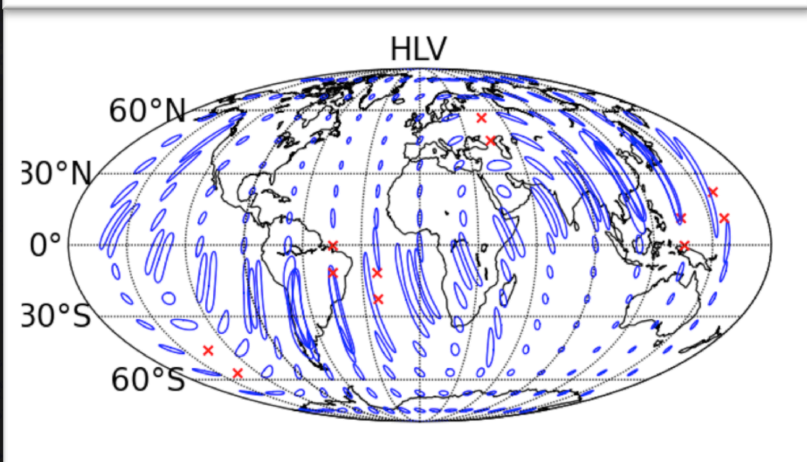


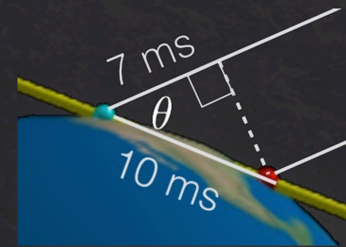
- Currently LIGO-H & LIGO-V operative (first scientific run ended, now stopped until the end of the year for upgrade)
- Virgo will join at the next scientific run.
- This will be important to improve sentitivity, coverage and estimation of parameters

Localization





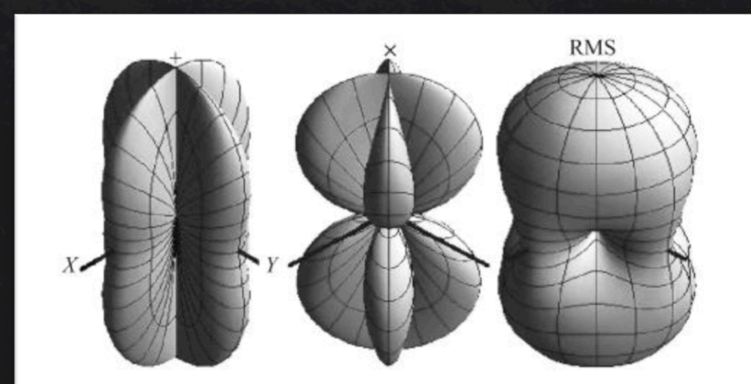




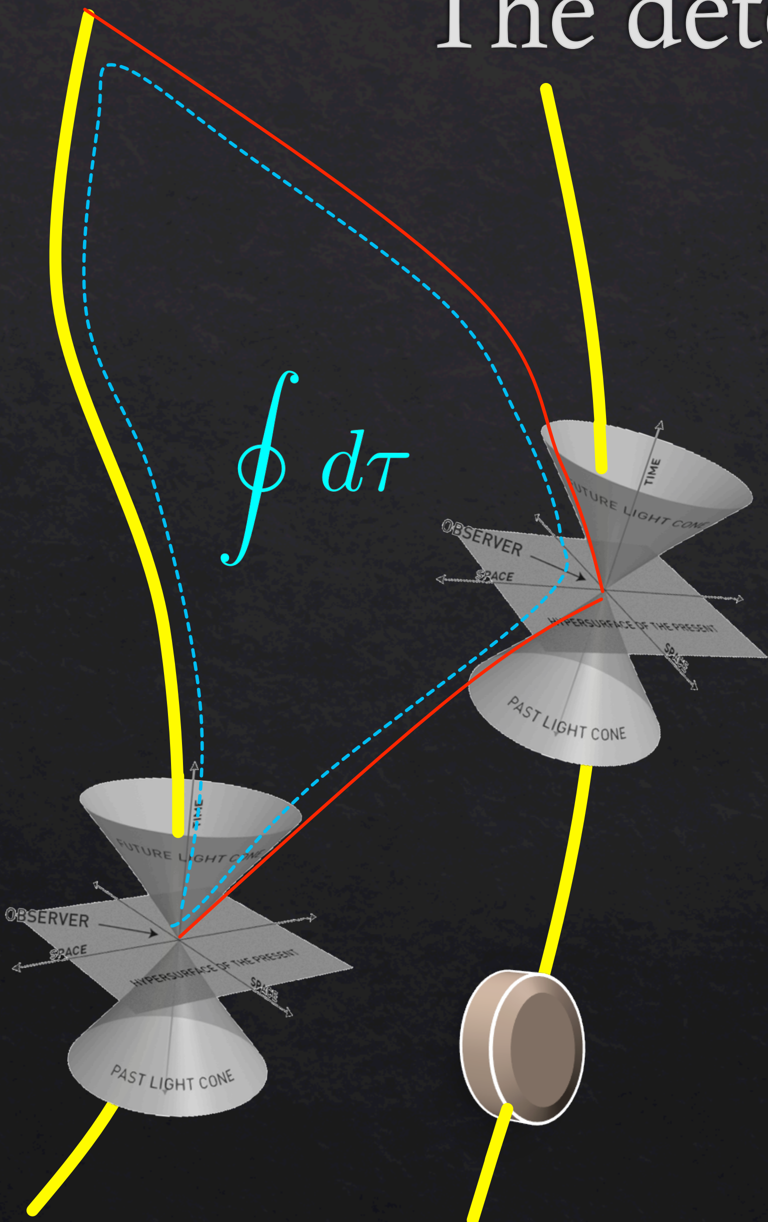
- Localization is roughly proportional to the timing accuracy $\Delta\tau$,

$$\Delta\tau = \frac{1}{2\pi\,\mathrm{SNR}\,\Delta f}$$

- Phase and amplitude consistency are taken into account also.



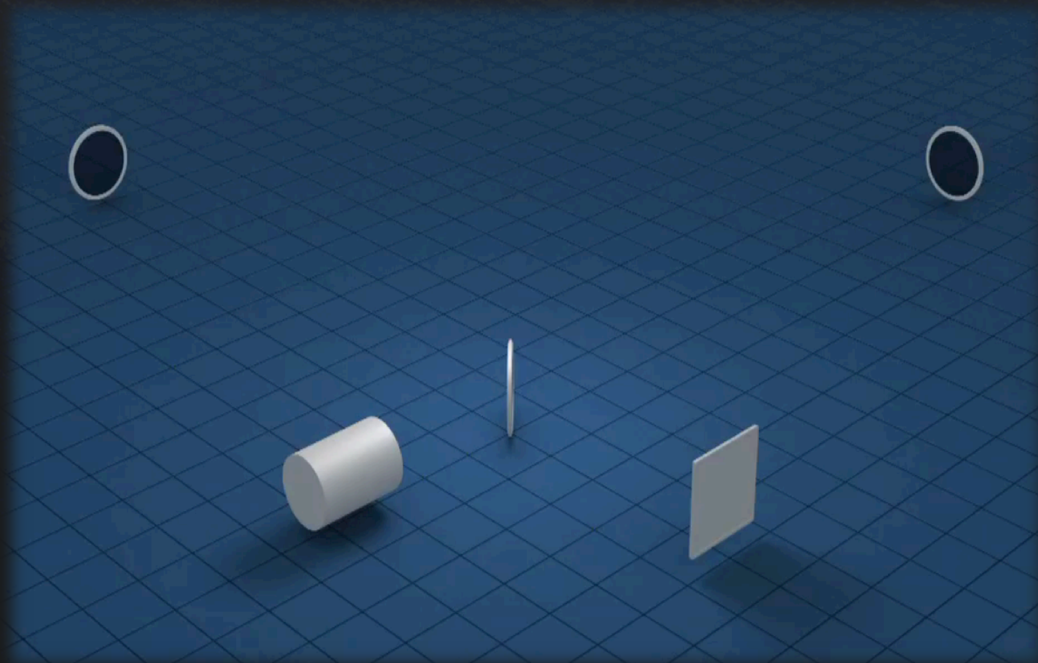
The detector principle



- Description can be coordinate dependent
- Physical observable is not
- Intuitive picture (when $\lambda_{GW} \gg L$): tidal force

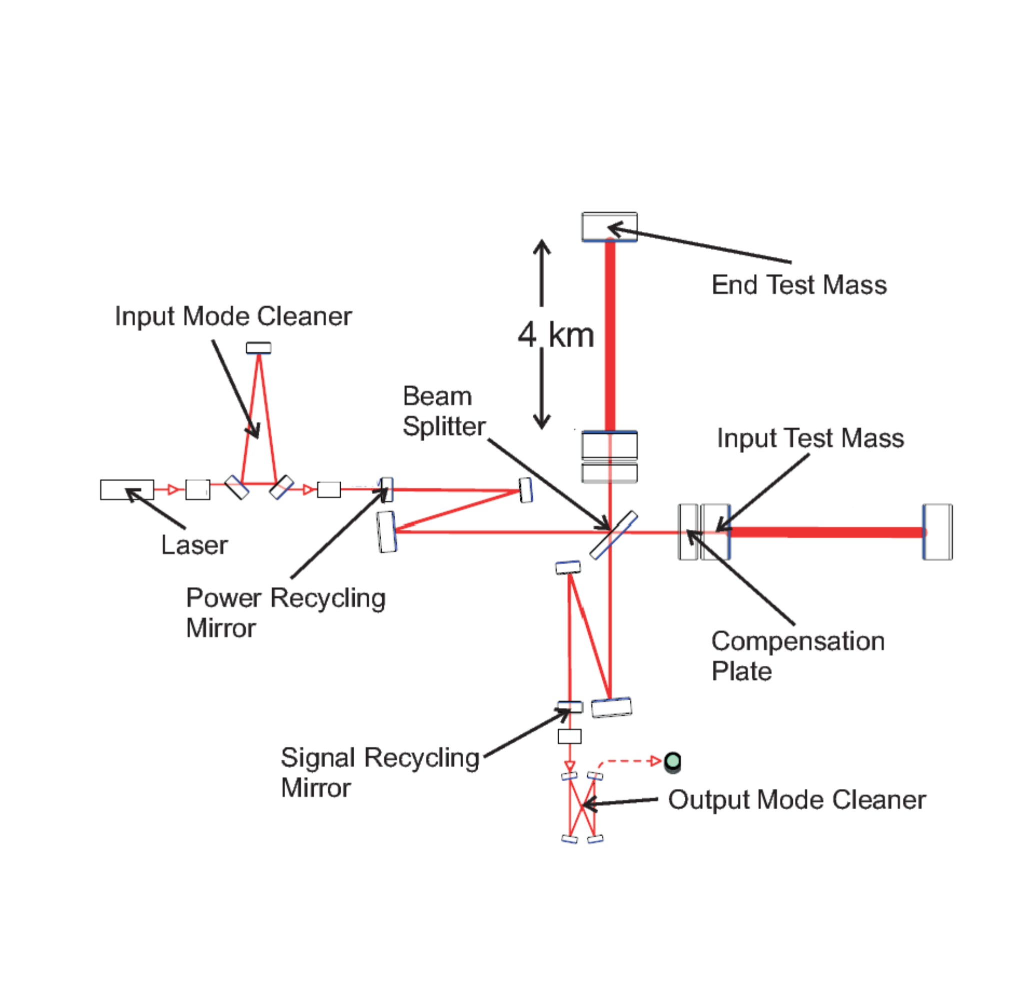
$$F_i = \frac{1}{2} m \frac{d^2 h_{ij}^{TT}}{dt^2} L_j$$

on the end mirrors.

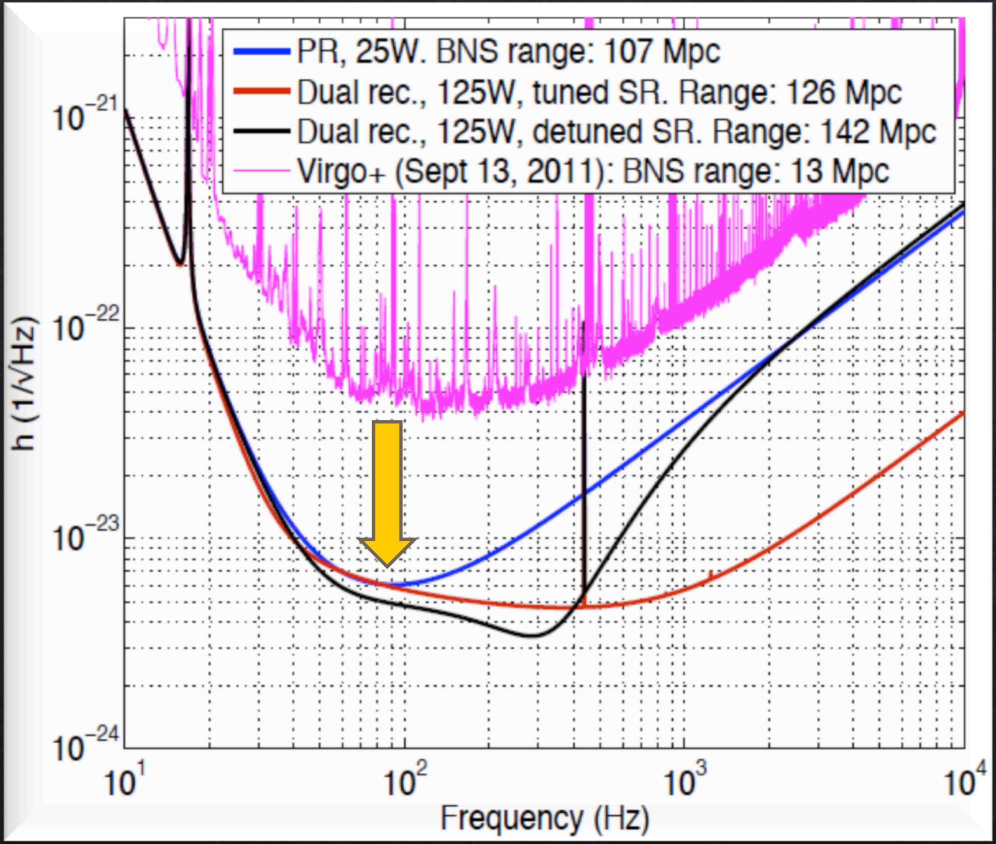


A more realistic optical scheme

- Resonant cavities to increase the effective arm length
- Power recycling mirror
- Signal recycling mirror
- ....



Advanced detectors: a sensitivity jump



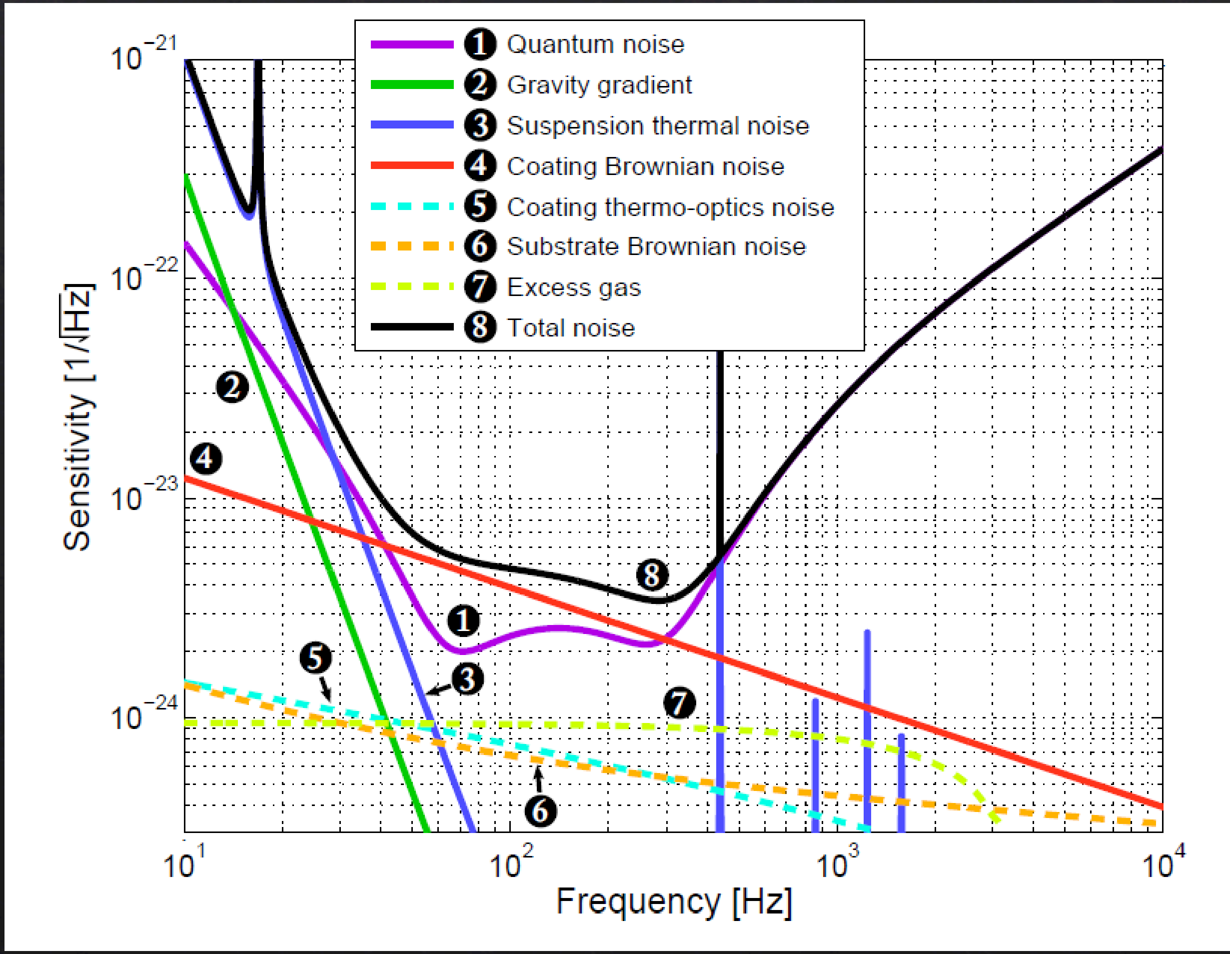
Strain sensitivity ×10

Range ×10

Events rate ×10^3

- Larger beams
- Heavier mirrors: 42 kg (×2)
- New payload
- Higher quality optics
- Larger finesse: $\mathcal{F} \simeq 450$ (×3)
- Improved thermal control of aberrations
- Improved vacuum
- 200W fiber laser
- Signal recycling

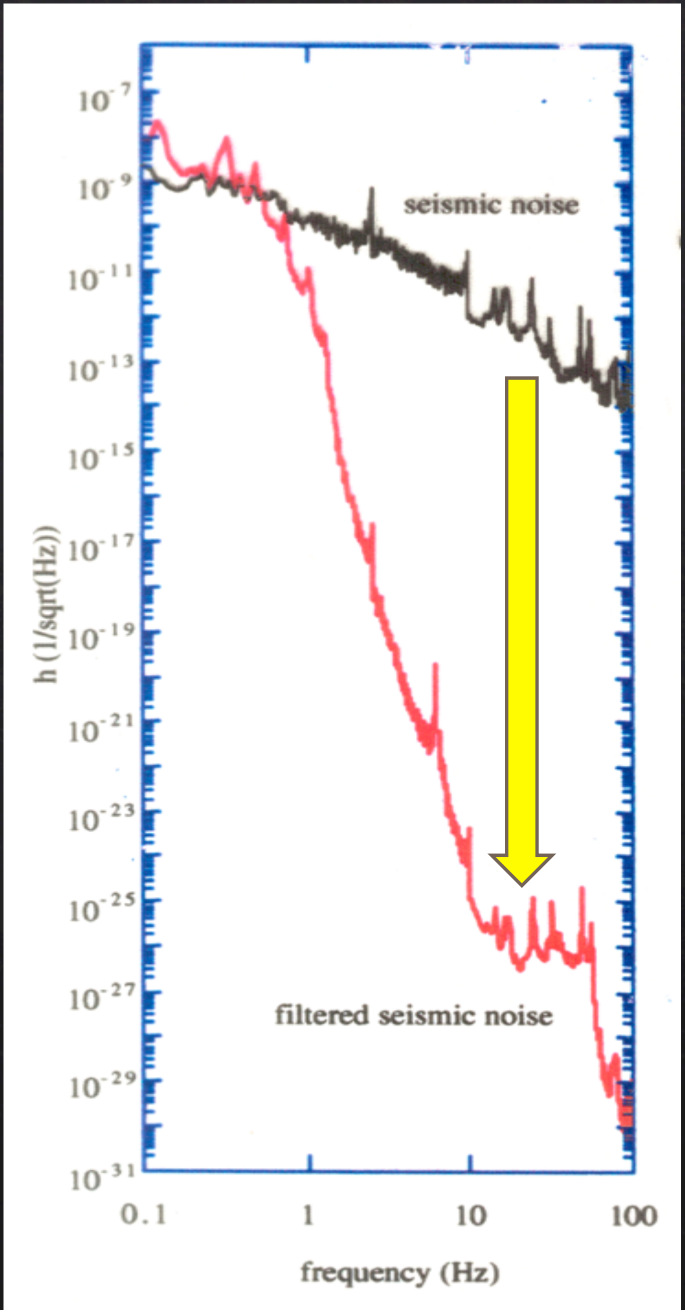
A fight with the noise

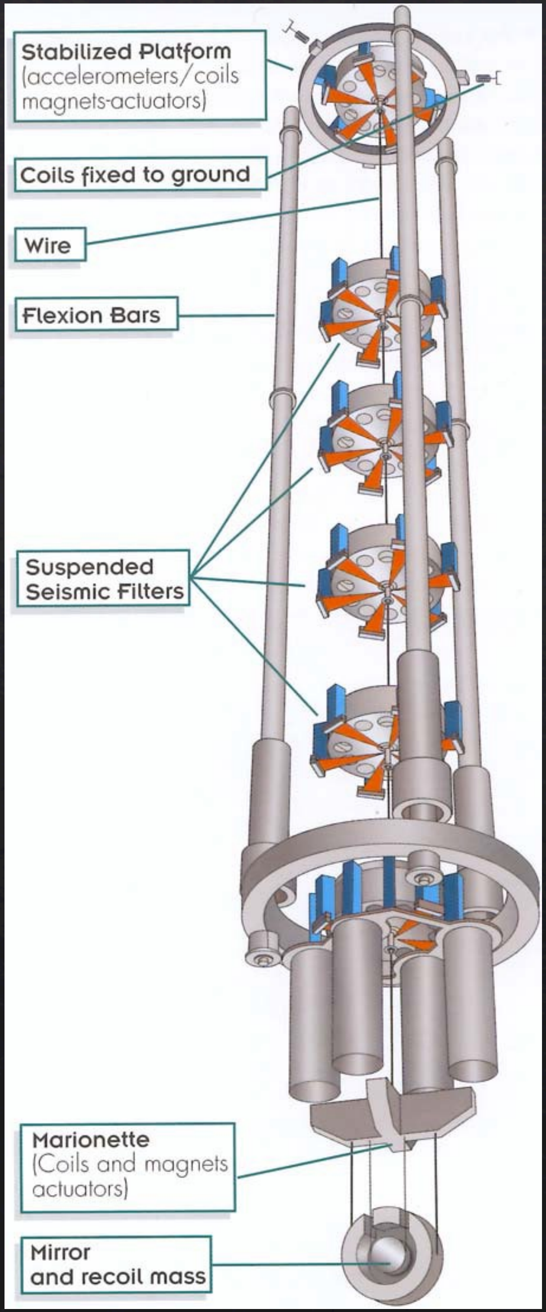


- Fundamental noises
  - Seismic
    - Direct
    - Newtonian
  - Thermal
    - Suspension
    - Mirror Coating
    - Mirror Bulk
  - Quantum
    - Shot noise
    - Radiation pressure
  - ……….
- Technical noises
  - Laser frequency & intensity
  - Scattered light
  - Residual gas
  - Length and alignment control systems
  - Magnetic actuation
  - Acoustic couplings
  - Nonlinear couplings (up-conversion)

Seismic noise

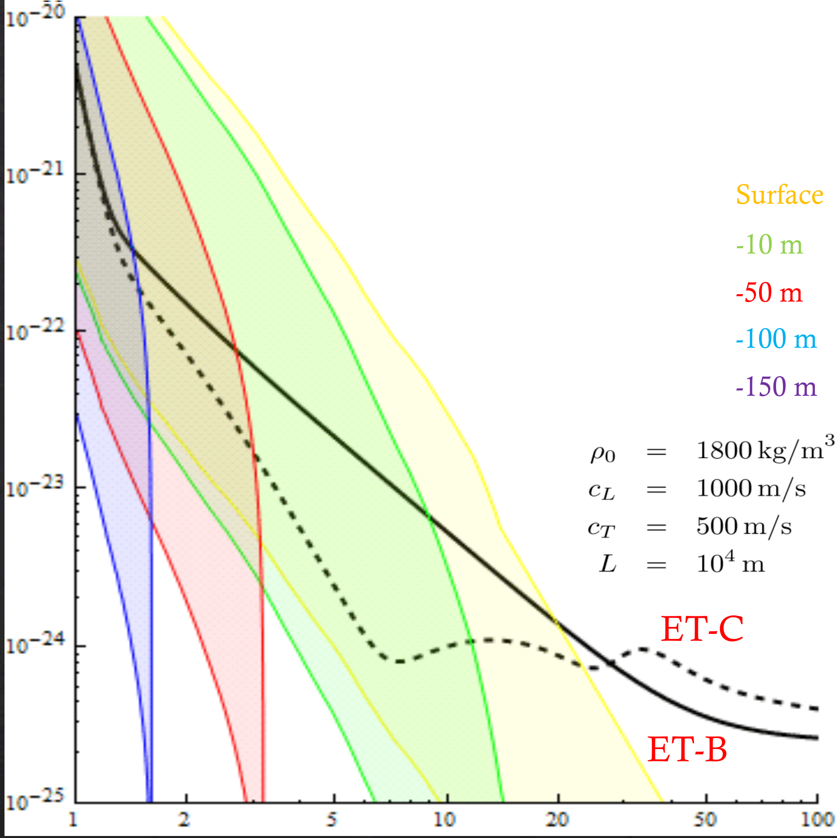
- Seismic motion is much larger than the expected mirror displacement by GW
- Must be attenuated in the sensitivity band
- Basic idea: an oscillator act as a low pass filter above its resonance
- Attenuation ineffective below the resonance(s): active control needed

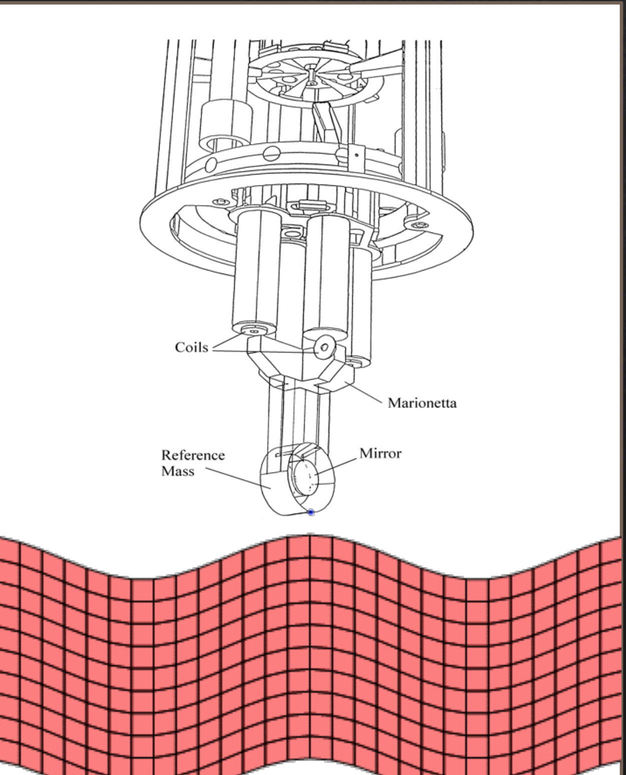


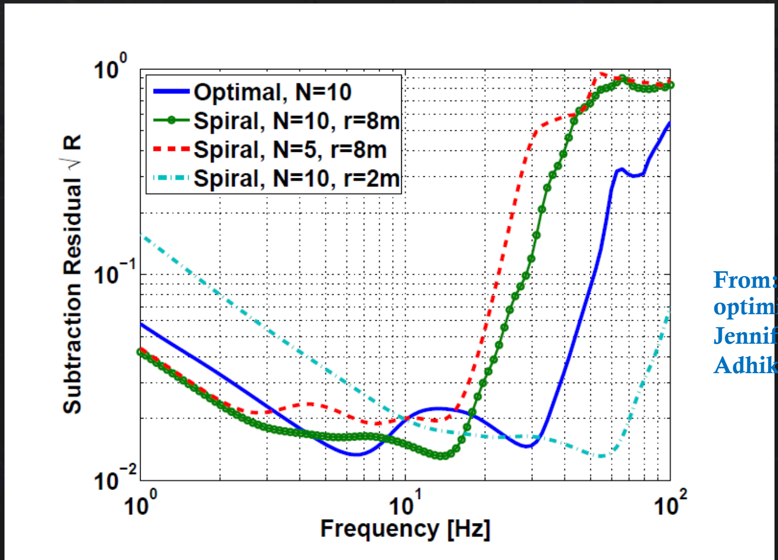


Gravity Gradient Noise

- Direct coupling to gravity field produced by mass density fluctuations
- Fundamental limit for earth-bound detectors. Marginally relevant for Advanced detectors.
- Mitigation:
  - Go underground
  - Subtract

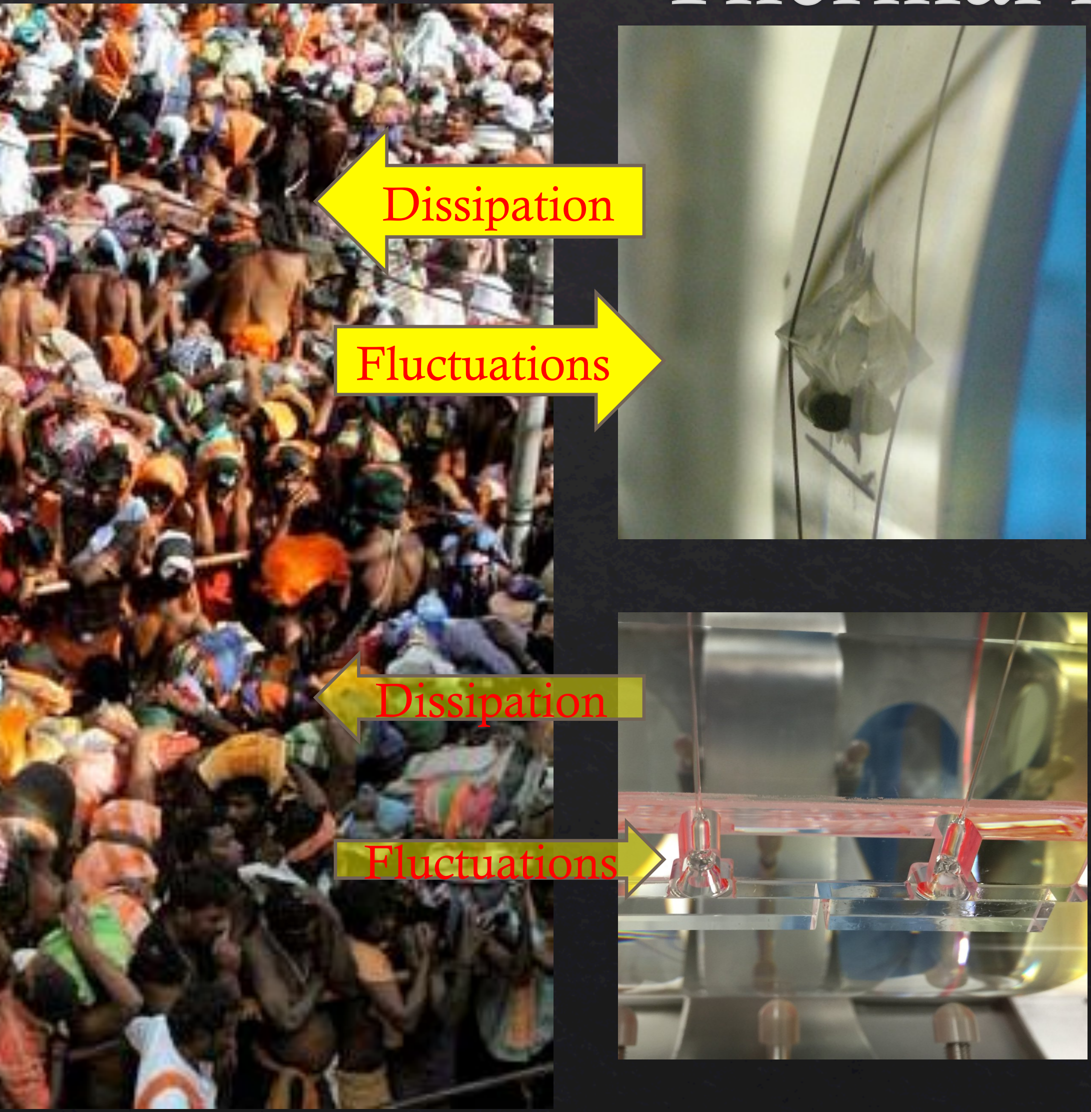




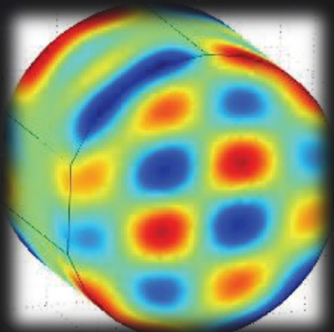


From: Subtraction of Newtonian noise using optimized sensor arrays
Jennifer C. Driggers, Jan Harms, and Rana X. Adhikari Phys. Rev. D 86, 102001

Thermal noise

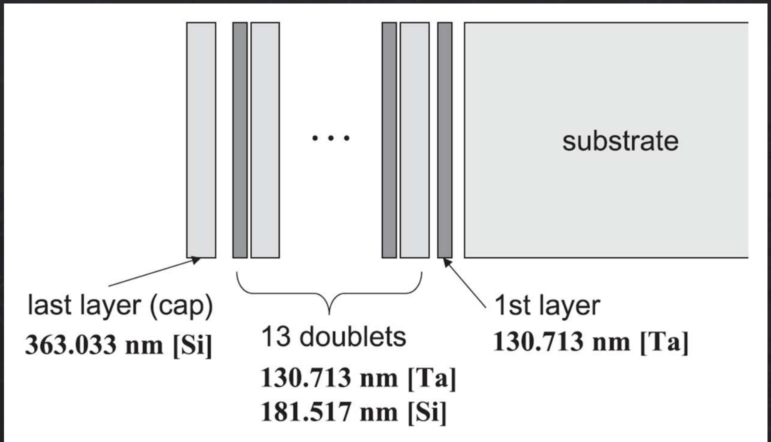


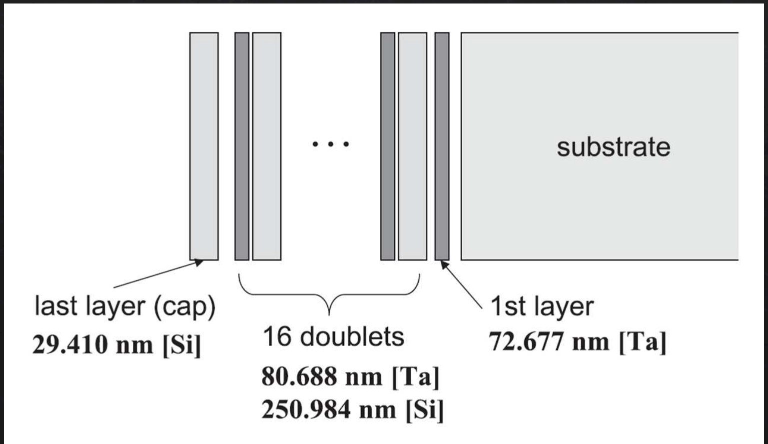
- Dominated by thermal fluctuations of mirrors and suspensions
- Handles:
    - Larger beam spot (statistical effect)
    - Fused silica fiber suspensions (low losses)
    - Improved mirror coatings (low losses)
    - Cryogeny (not foreseen in LIGO & Virgo)



$$S_F^{(m)} = 4k_B T \frac{\omega^{(m)}}{Q^{(m)}}$$

Coating thermal noise

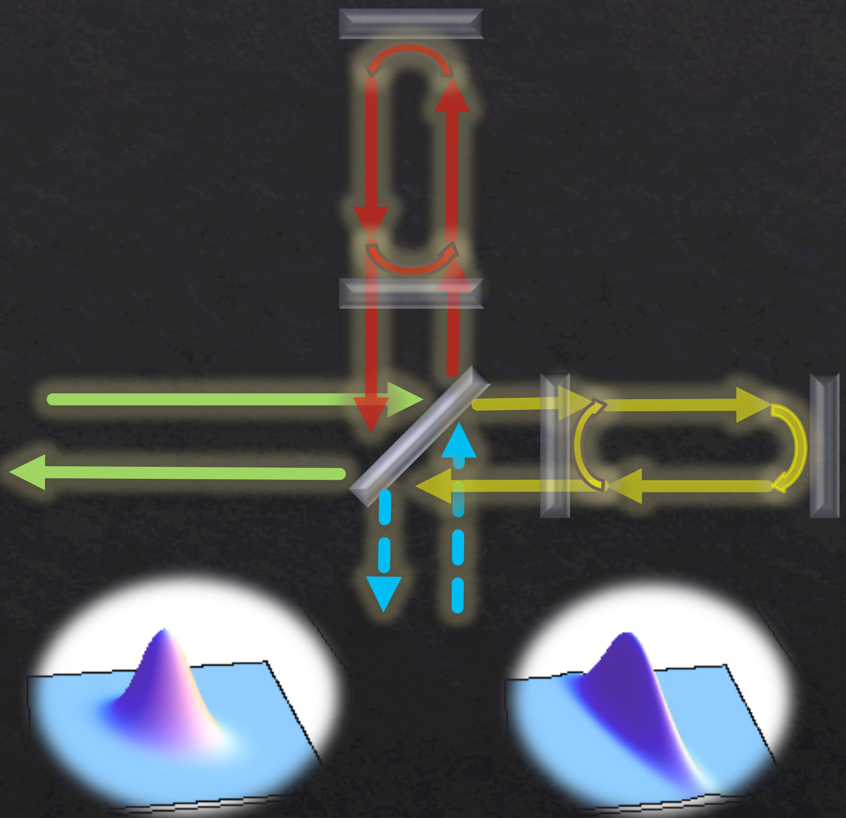




- A difficult problem
- Constraint: good optical properties of materials
- Complex theoretical modelization of dissipation mechanisms
- Phenomenological approach: parameter optimization (genetic algorithms, ….)
- Experimental approach: test new materials (new kind of dopings)
- Currently the limit in the intermediate frequency region

Quantum noise

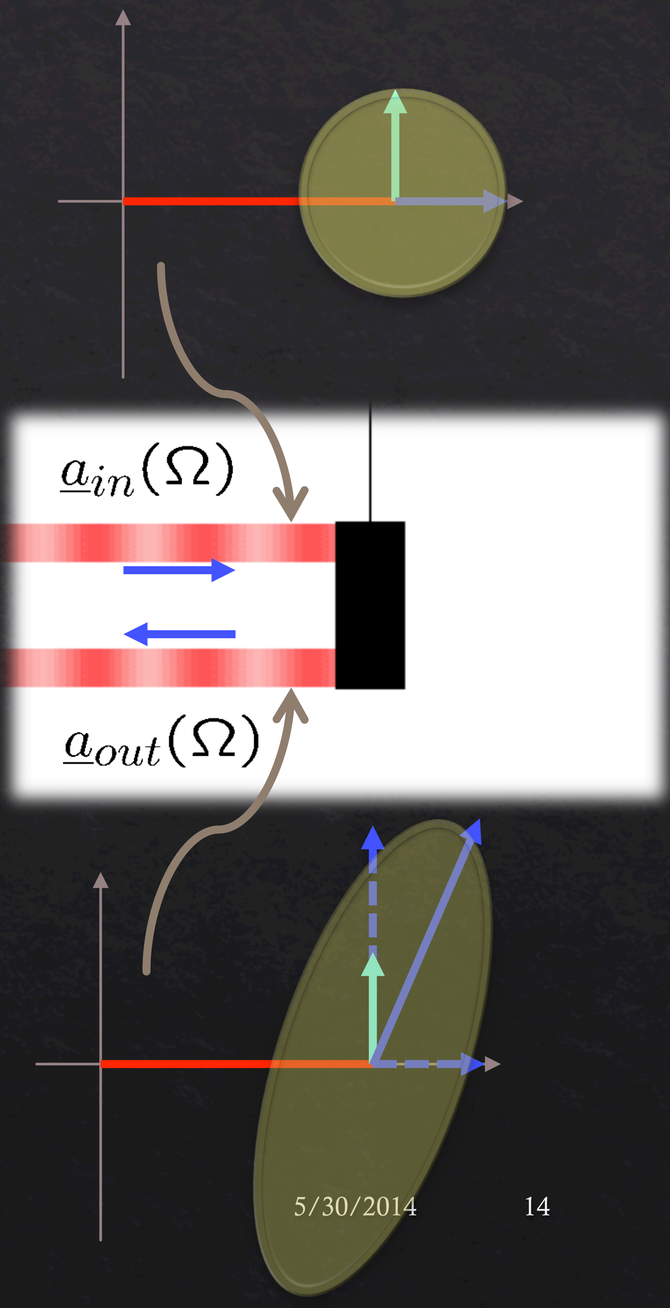
- Quantum noise comes from quantization of electromagnetic field, not of the test masses
- Source: quantum fluctuations of the vacuum, entering the interferometer across the «dark port»
- Non-classical fields can have a modified variance
- Non-classical fields can be used to improve measurement sensitivity

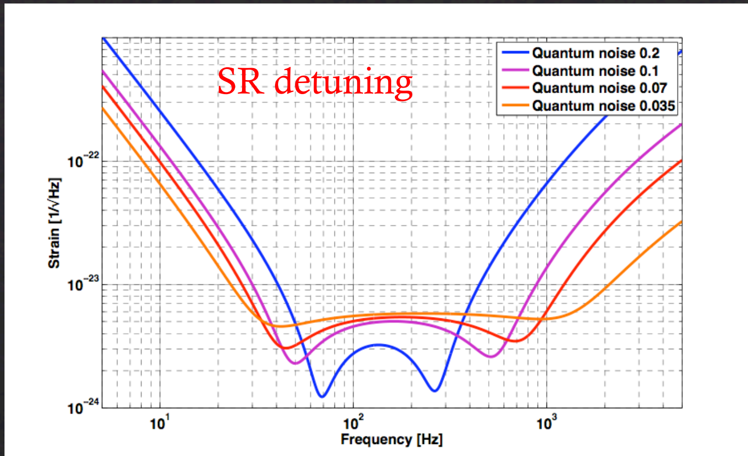


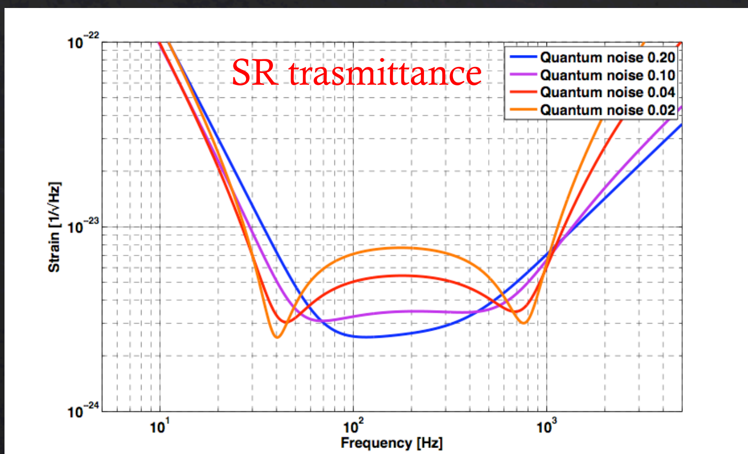
Non-classical states are generated by the interferometer itself

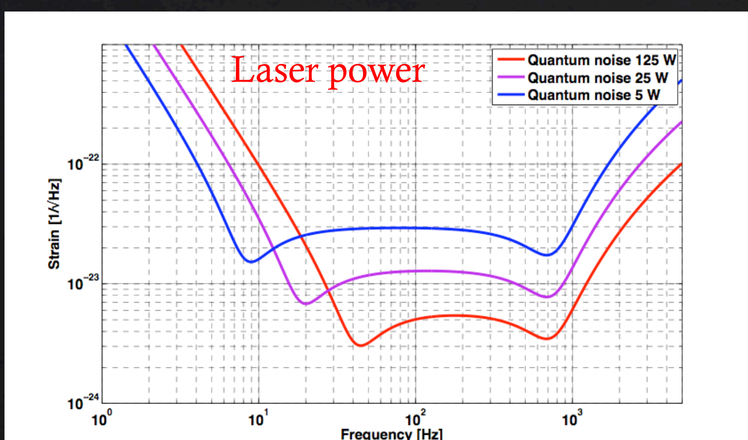
Ponderomotive squeezing

- In a coherent state phase and amplitude noise are uncorrelated
- Quasiprobability distribution: isotropic Gaussian
- Back action induced by radiation pressure generate a correlation between phase and amplitude fluctuations
- Fluctuations are increased along a direction, but decreased along another one: a squeezed state «Optomechanical Kerr effect»
- *(■δa↓a @δa↓p)↓out =(■1&0@−2I↓ℓ ω↓ℓ /mΩ↑2 c↑2 &1)(■δa↓a @δ a↓p)↓in*

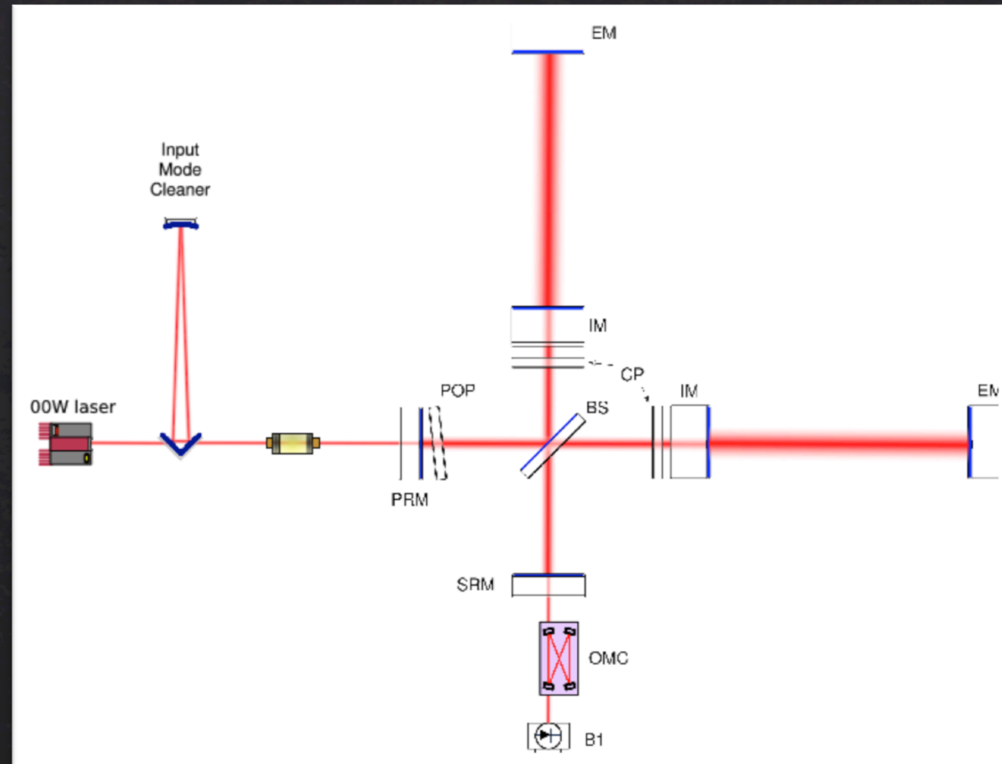






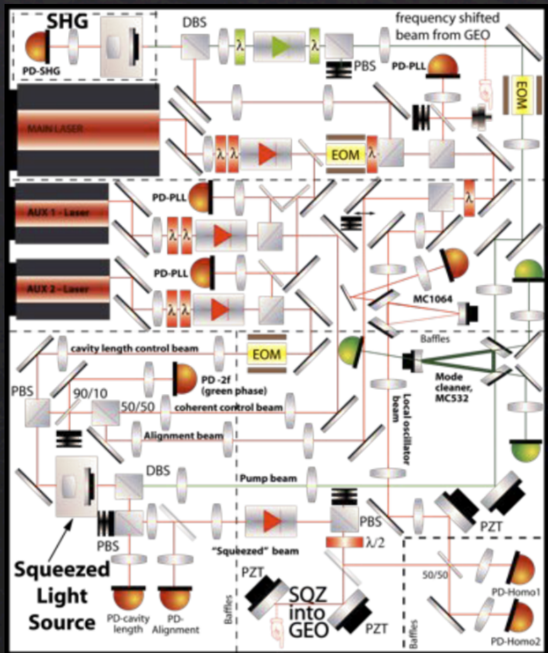


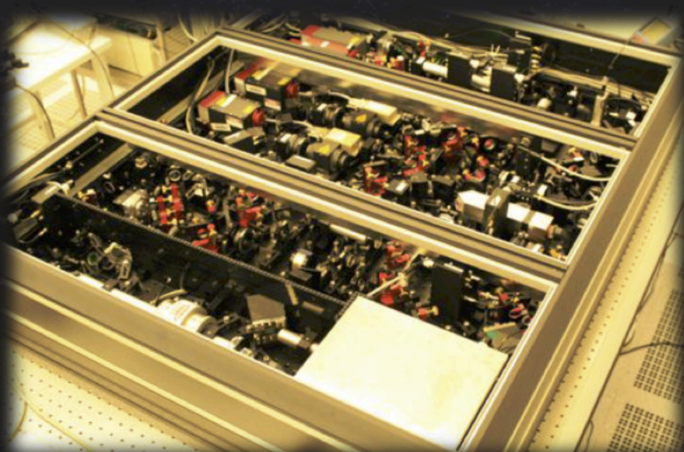
Effect of optomechanical coupling



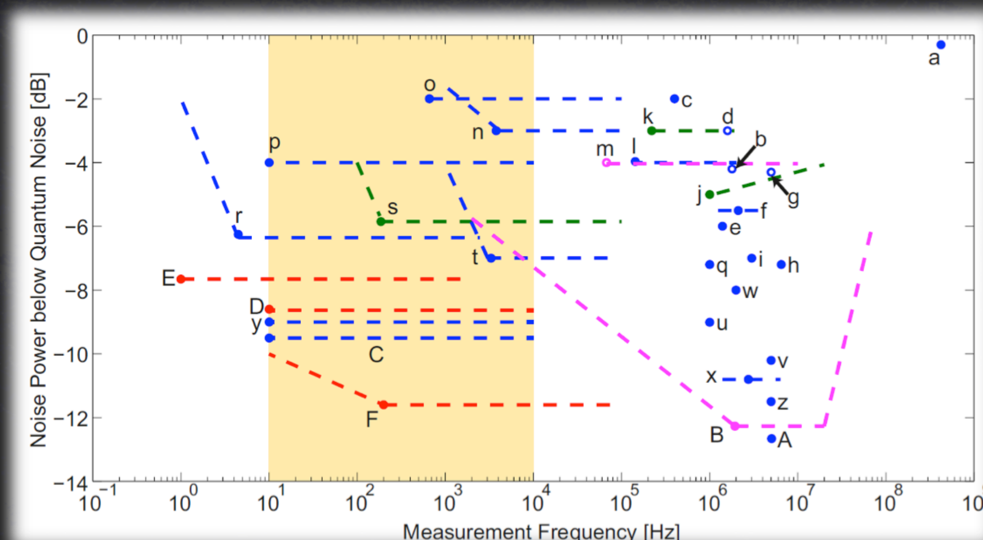
- By changing the optical parameter the sensitivity curve can be tuned….
- …and maybe adapted to a specific source.
- Quantum limit: radiation pressure noise and shot noise are dual aspects of quantum fluctuations

Squeezing vacuum generation





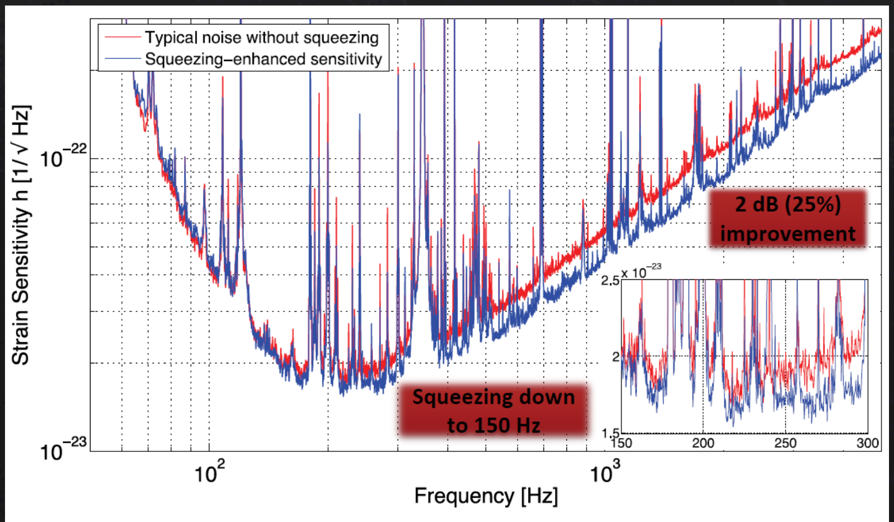
- Standard way: nonlinear crystals and optical parametric amplification
- Over past decade, squeezing made incredible progresses
- Squeezing at low frequencies (as low as 1Hz)
- Squeezing factor 10dB (QN reduction by a factor 3)



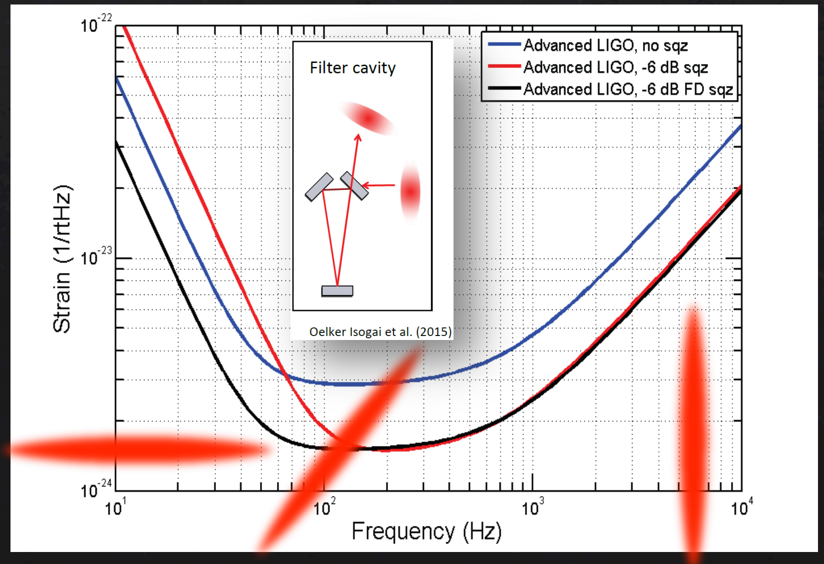
Courtesy: S.Y.Chua, Ph.D. Thesis (2013)

Take advantage of squeezed states

- Injection of a squeezed vacuum state in the dark port
- Measure of an optimized quadrature of the output ponderomotively squeezed state
- Both
- Optimal solution: squeezing angle must be frequency dependent

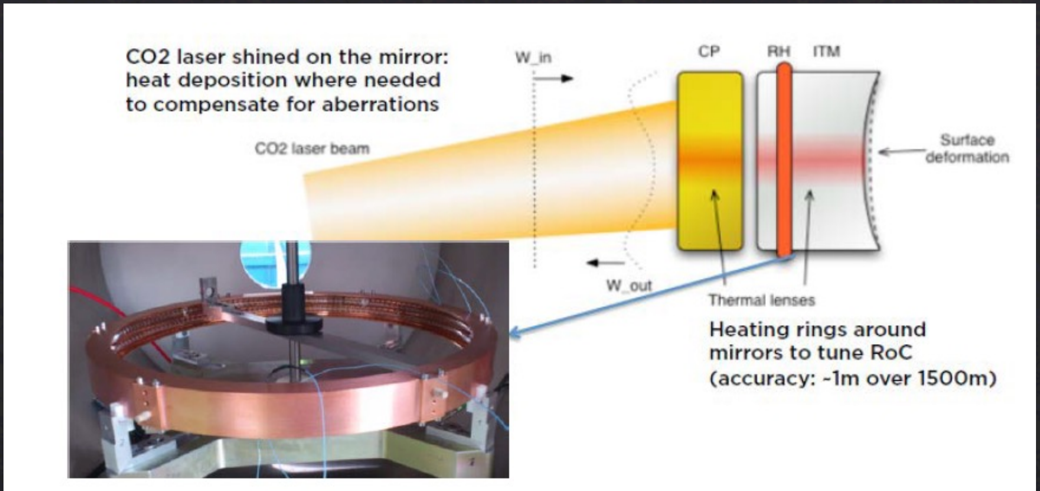


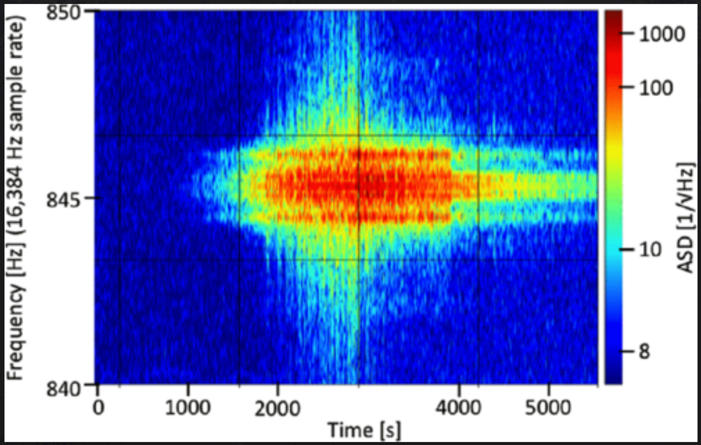
LIGO Scientific Collaboration, Nature Photonics (2013)

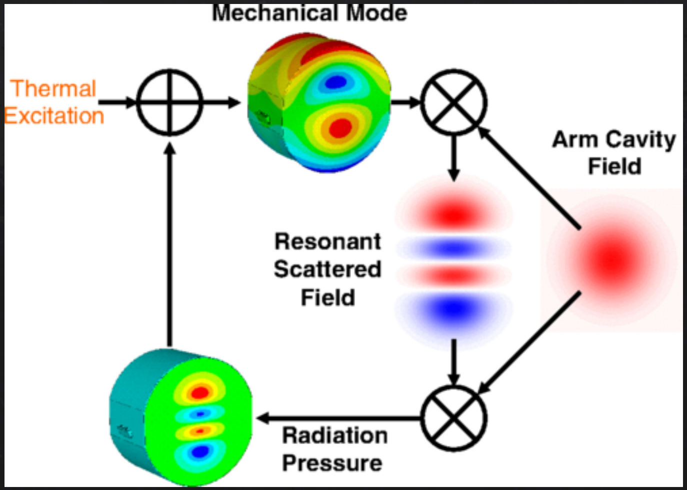


High power lasers

- Brute force approach to reduce shot noise
- With squeezing, in principle an handle to reduce optical noise at will
- Hower, there is not a free lunch:
  - Thermal lensing effects
  - Thermo-optic noise
  - Parametric instabilities

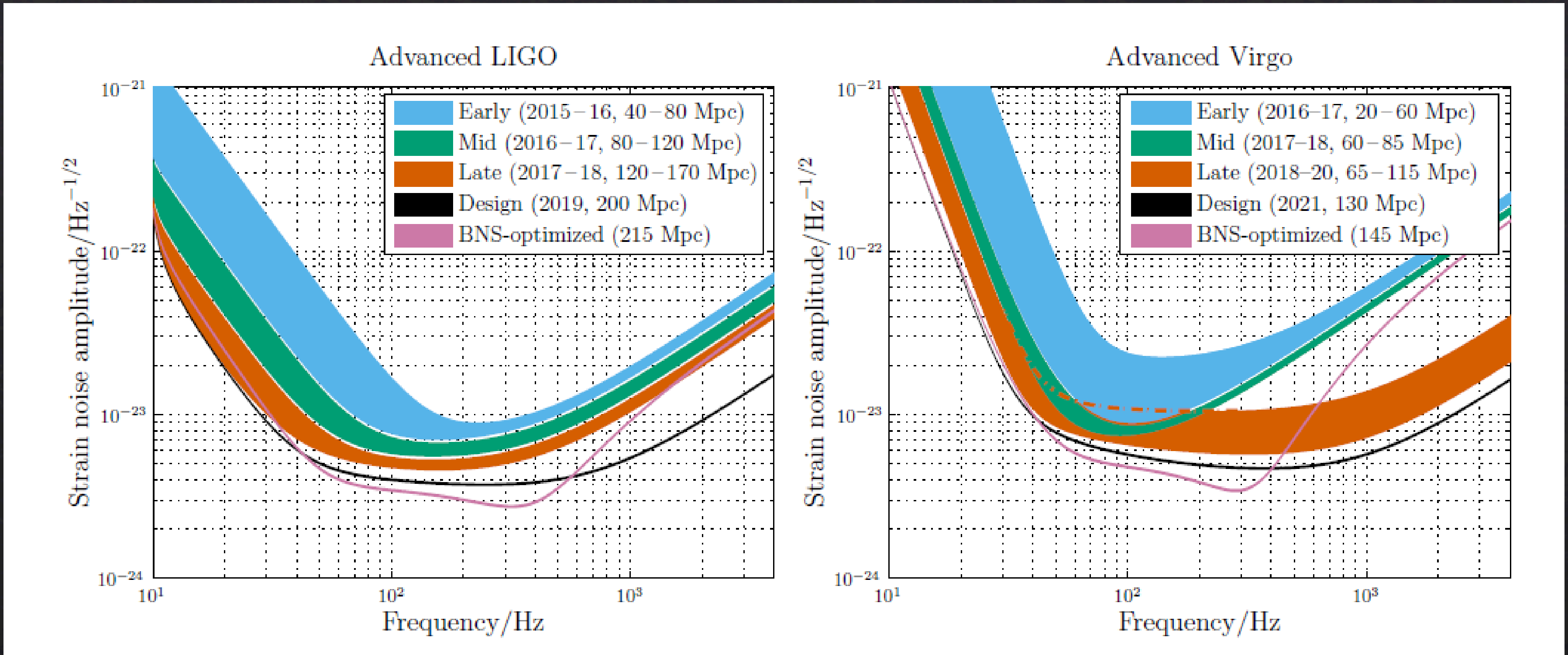




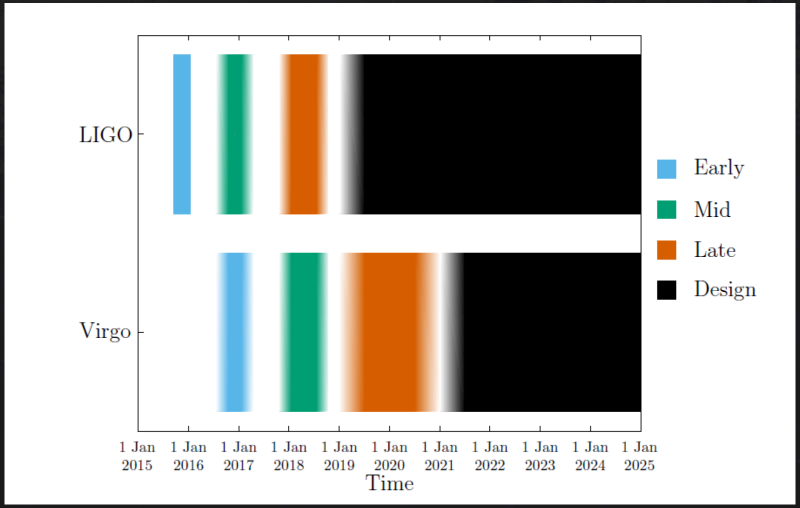


Evans et al., PRL 114, 161102 (2015)

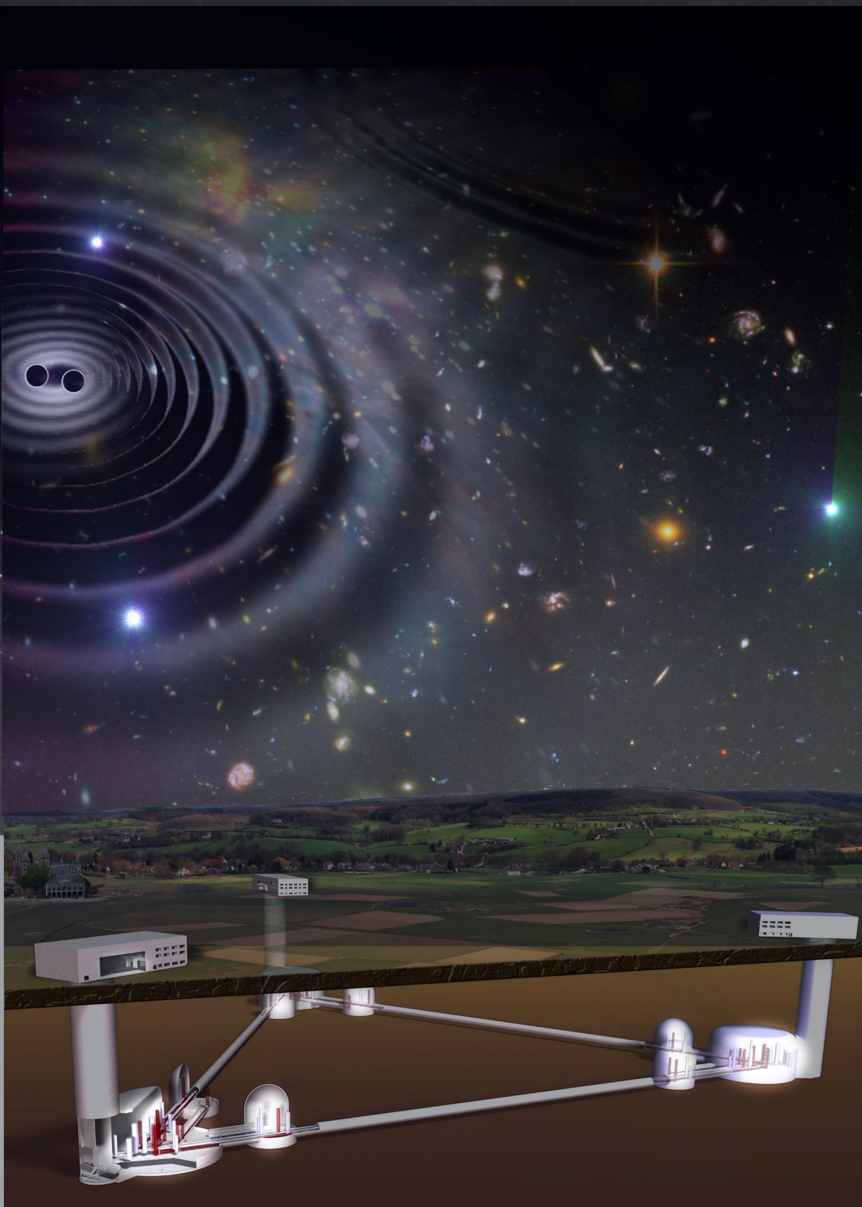
The observing scenario

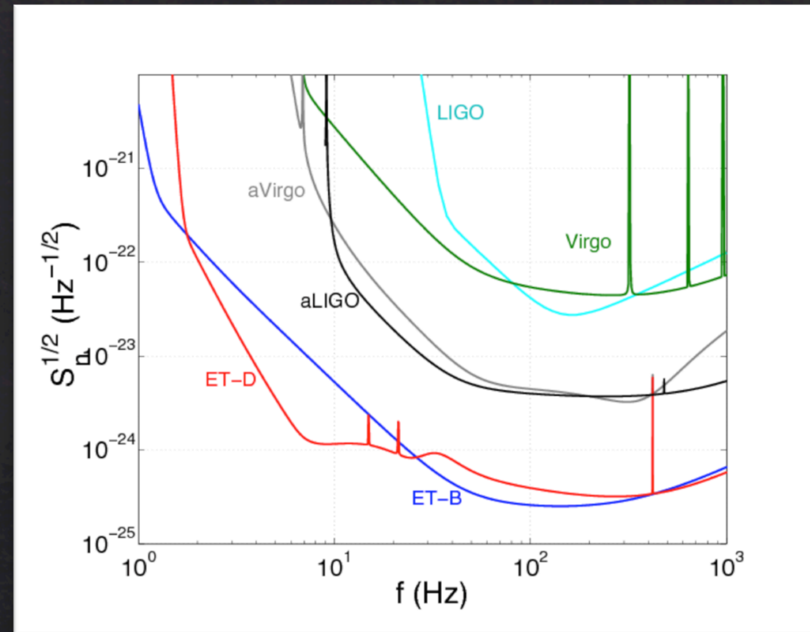


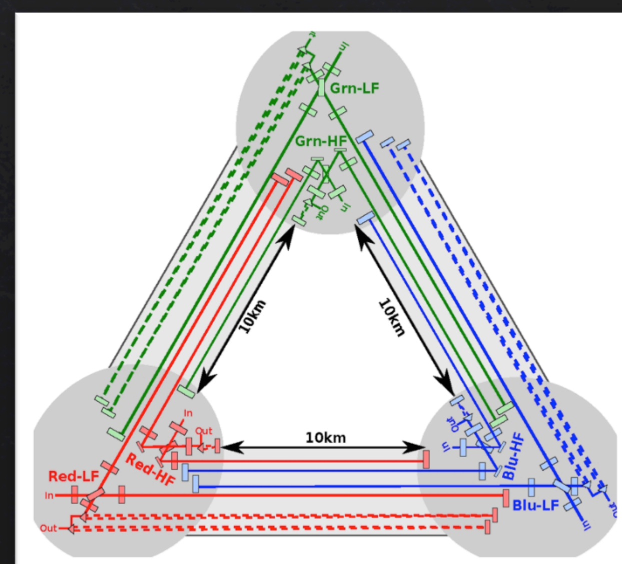
- Plan: a series of scientific runs with intermediate commissioning interruptions
- Sensitivity will increase in steps toward the design one
- Quite successful until now….



What next? The third generation detectors



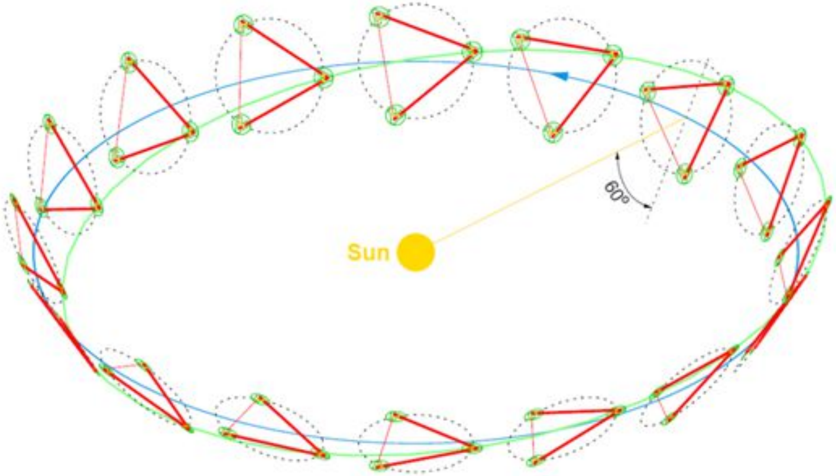




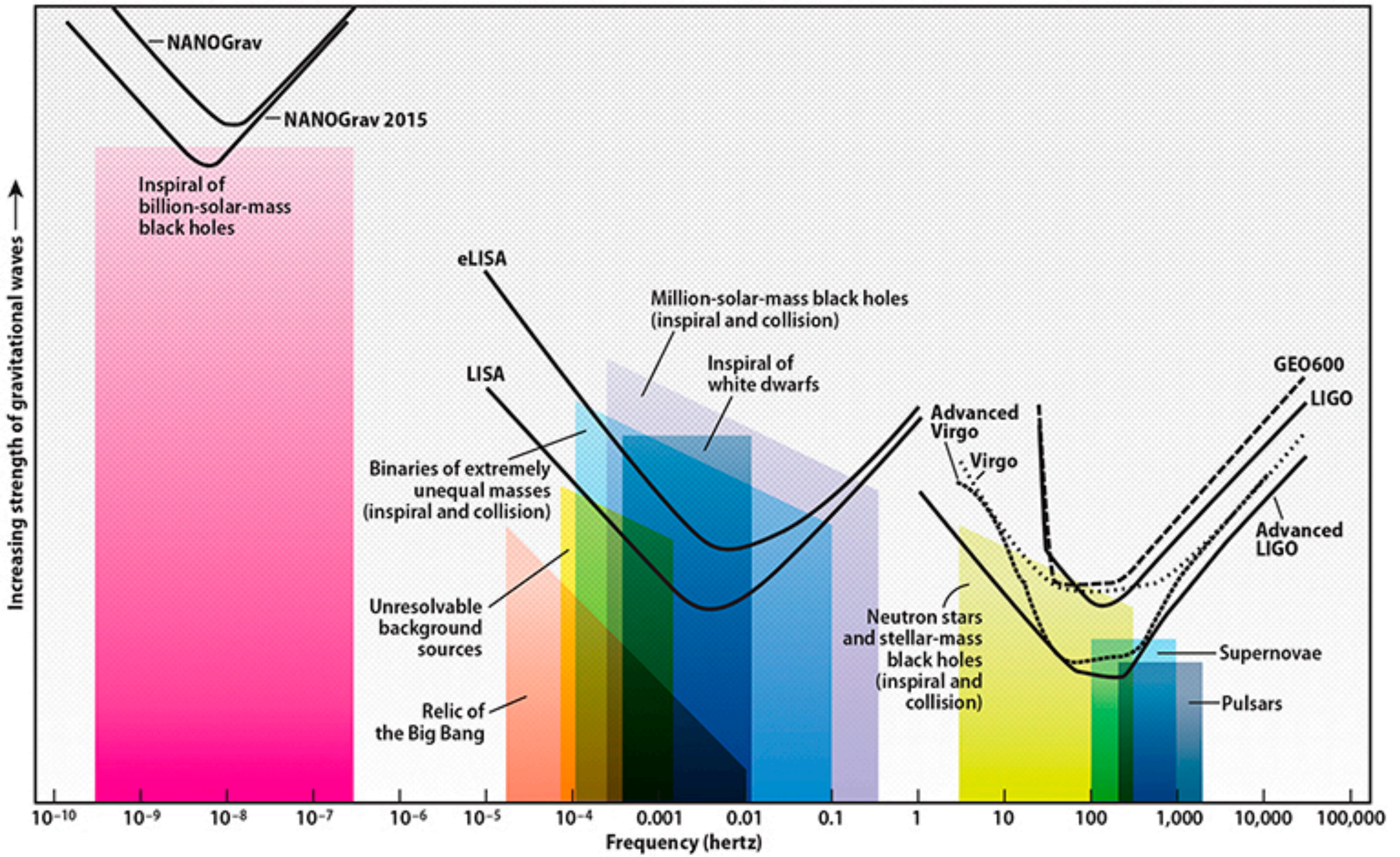
What next? Space detectors

eLISA Space Based GW Detector

- Laser Interferometer in Space Antenna, LISA, provides unique capabilities
  - Immune to seismic noise
  - Long baseline provides 0.001 - 1Hz GW spectrum sensitivity needed for observing massive black hole mergers
- Multiple identical or similar detectors to improve detection confidence



LISA: a mission to detect and observe gravitational waves, O Jennrich, in Gravitational Wave and Particle Astrophysics, Proc SPIE v5500



Thank you for your attention….