Development of ground based laser interferometers for the detection of gravitational waves

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Outline

1. Gravitational waves, nature & their sources
2. Gravitational wave detectors (GWD)
    a) Ground based
    b) Space based
3. Noise sources
4. Thermal noise
5. Current status of detectors
    a) Advanced LIGO
    b) GEO-HF
    c) KAGRA
6. Conclusions

What are Gravitational waves?

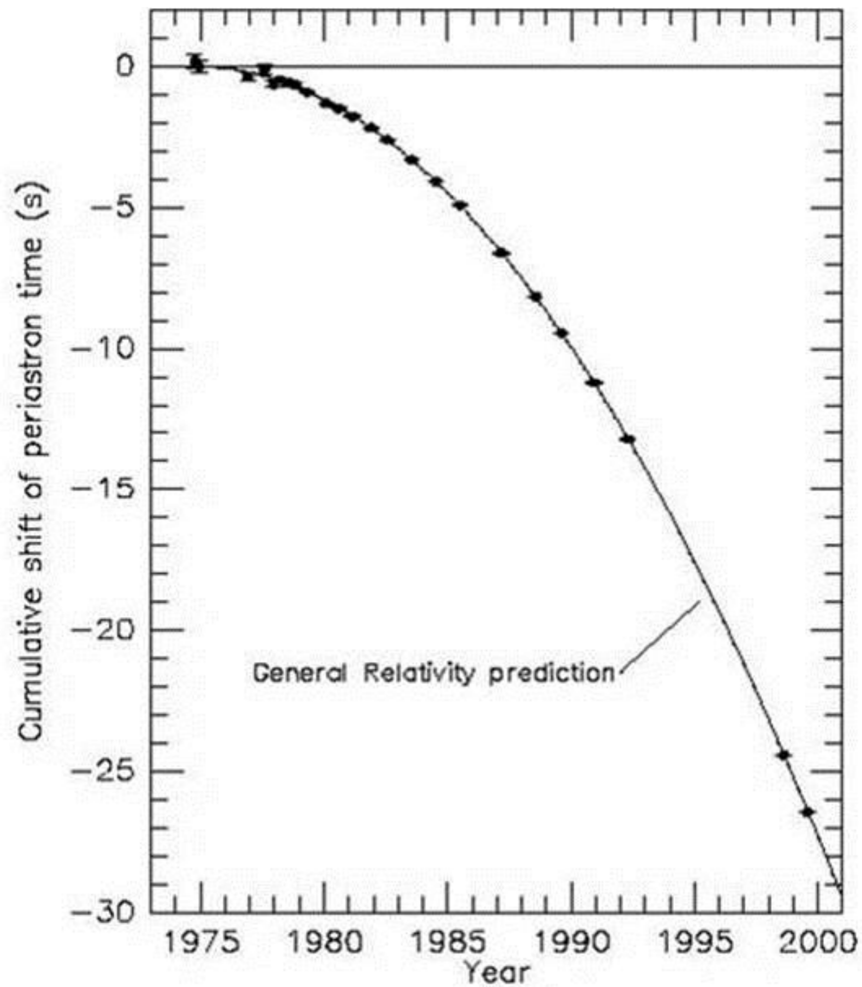
- Proposed by Einstein in 1916
- Described as ripples in the curvature of space-time

- Propagates as a wave in the universe at the speed of light
- GW are yet to be detected

Image courtesy:- University of Glasgow

Evidence of existence

- Hulse and Taylor were awarded Nobel prize in 1993
- Discovery of binary pulsar PSR 1913+16



Decay of the orbital period of binary pulsar PSR 1913+16 with time

Nature of GW

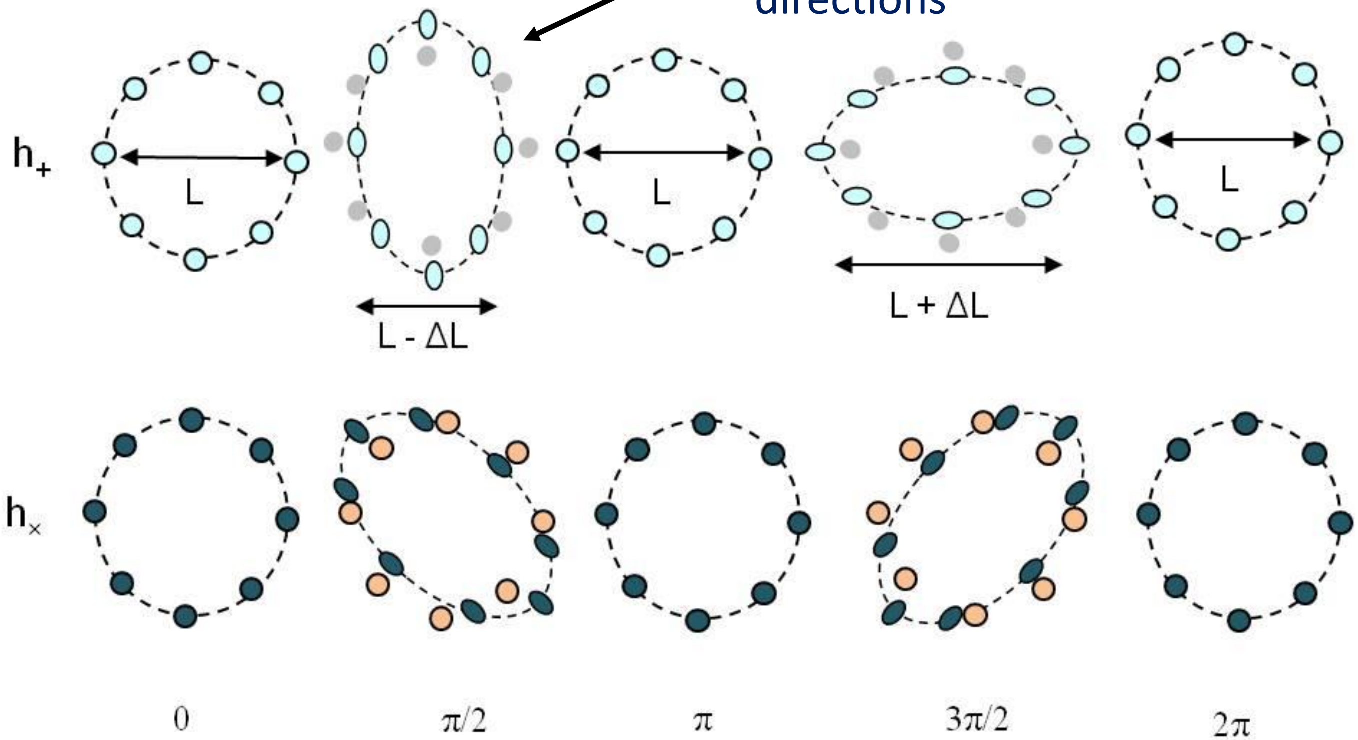
- Weakest among all forces
- Produced when matter is accelerated in an asymmetrical way
- Quadrupole in nature – which means it has varying moment of inertia
- The amplitude *'h'* of the GW can be defined as,

$$\boldsymbol{h = \frac{2\Delta L}{L} \sim 10^{-23}}\ \textit{\textbf{(rms)}}$$

where $\frac{\Delta L}{L}$ is the strain

Polarisations: h_+ and $h_\times$

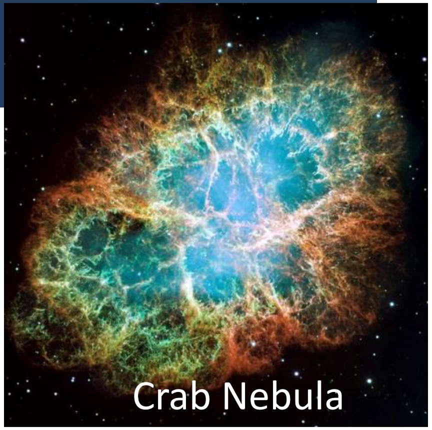
Particles are stretched and squeezed in the orthogonal directions

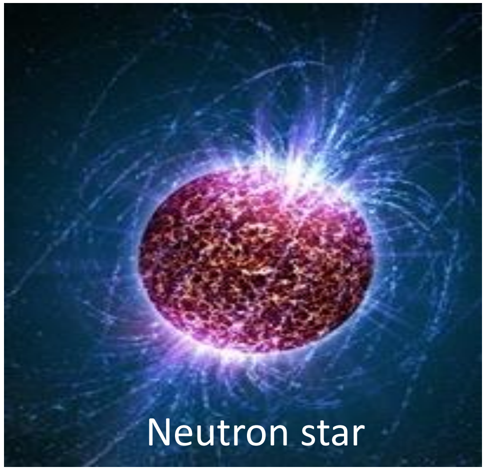


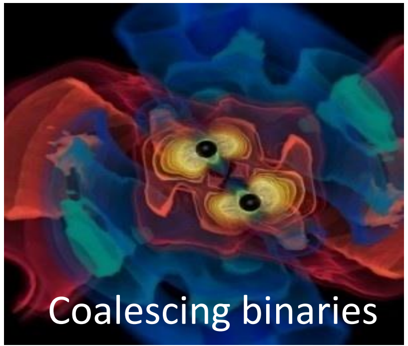
Effect of two polarisations of gravitational waves on a ring of test particles

Sources

- Burst sources
  - Supernovae (Crab Nebula)
  - Coalescing compact binaries
- Periodic sources
  - Pulsars (rapidly rotating neutron stars)
- Stochastic sources
  - Superposition of waves from many sources







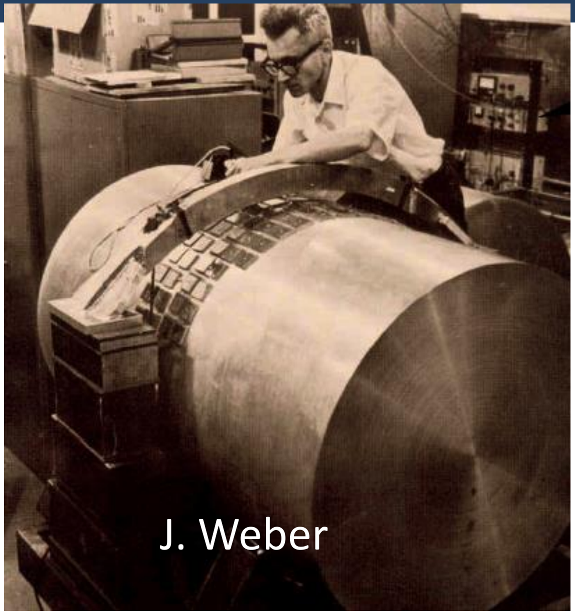
Detection of GW

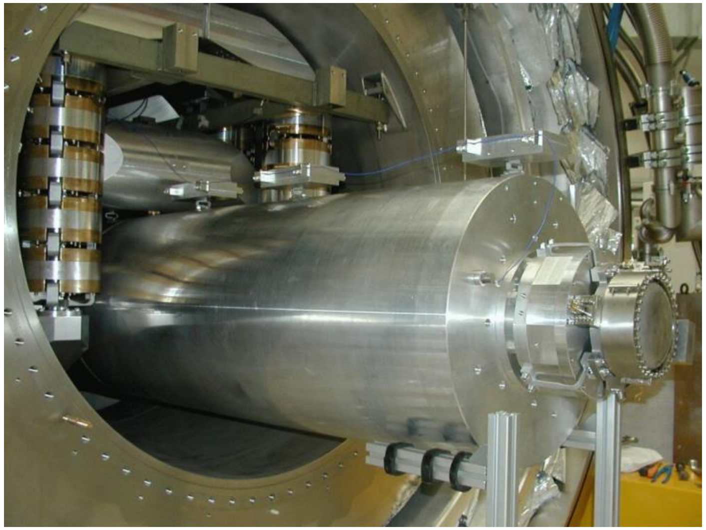
<u>Designs currently being developed around the world includes:-</u>

- Bar Detectors
- Ground based interferometers (frequency greater than 10Hz)
- Space based interferometer (Millihertz range)

Bar detectors

- Started by Joseph Weber in 1960
- Resonant bar detectors were not successful

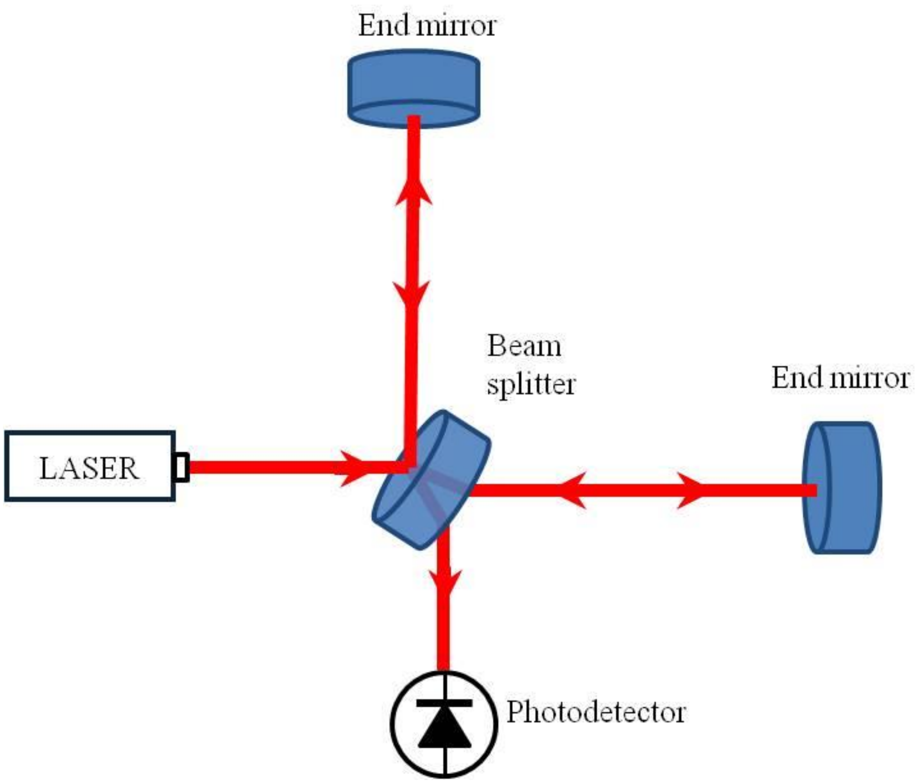




Low temperature bar detectors in Italy (Rome), CERN, Australia (Perth) and Netherlands

Laser interferometry

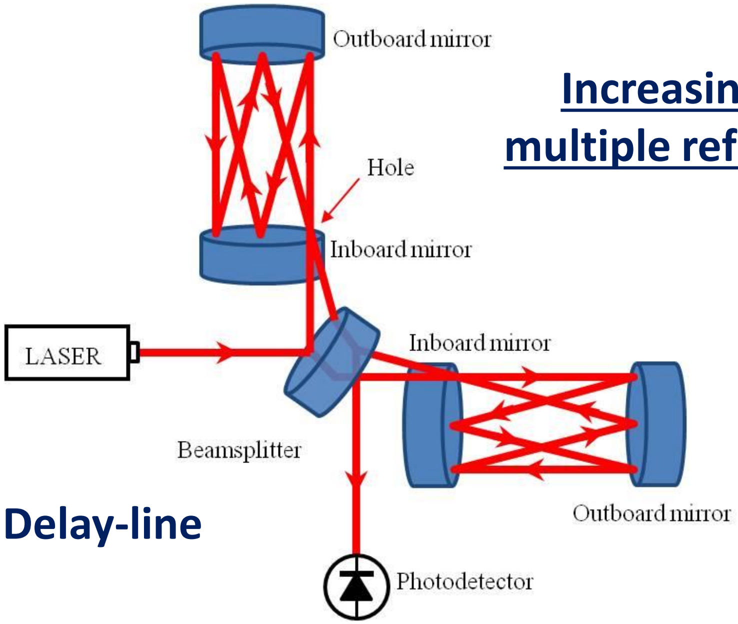
- Proposed by R. L. Forward and R. Weiss
- Based on Michelson interferometer
- Offers high sensitivity over a wide range of frequencies
- Longer armlength improves the sensitivity



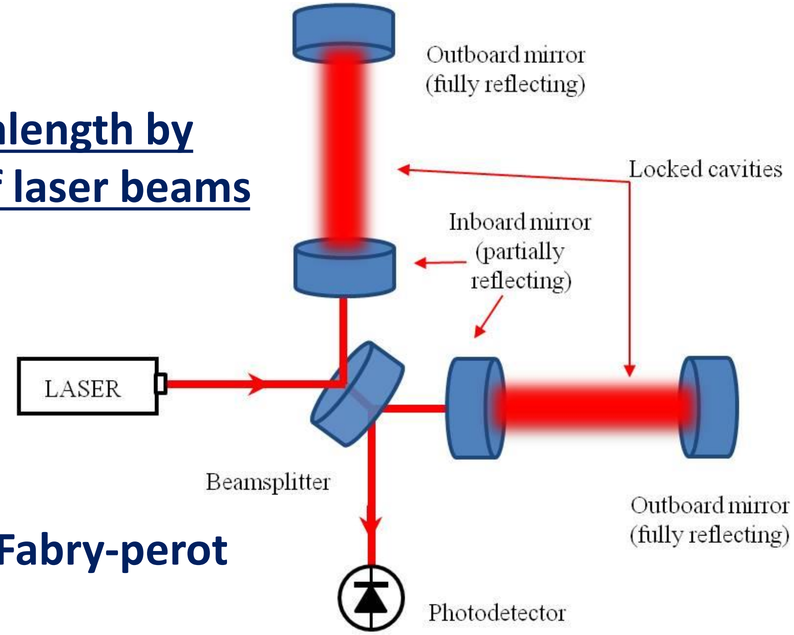
Michelson interferometer

Increasing the armlength by multiple reflection of laser beams

Delay-line

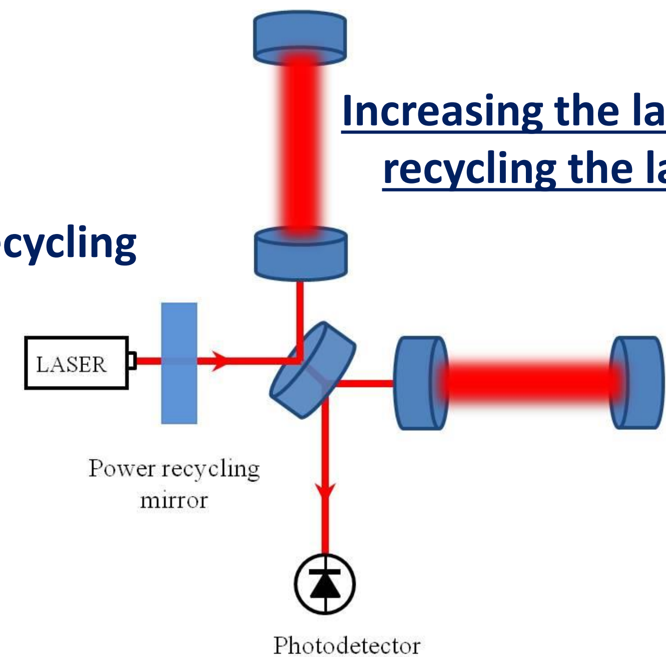


Fabry-perot

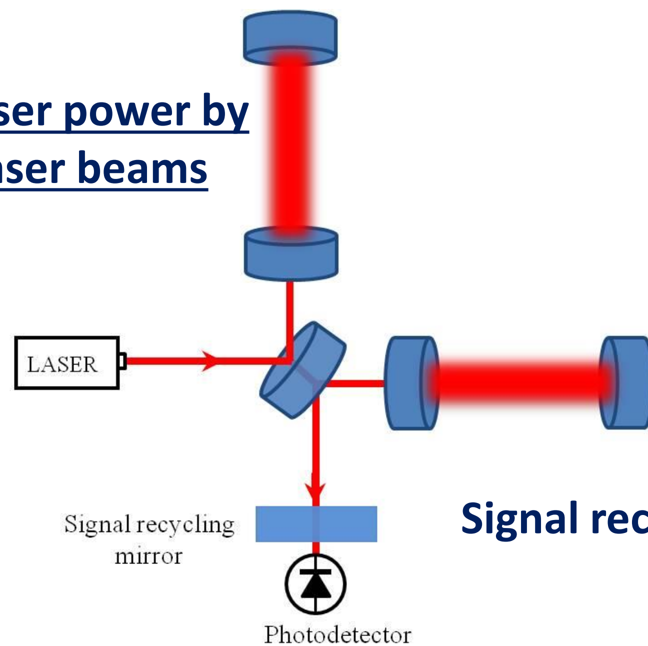


Increasing the laser power by recycling the laser beams

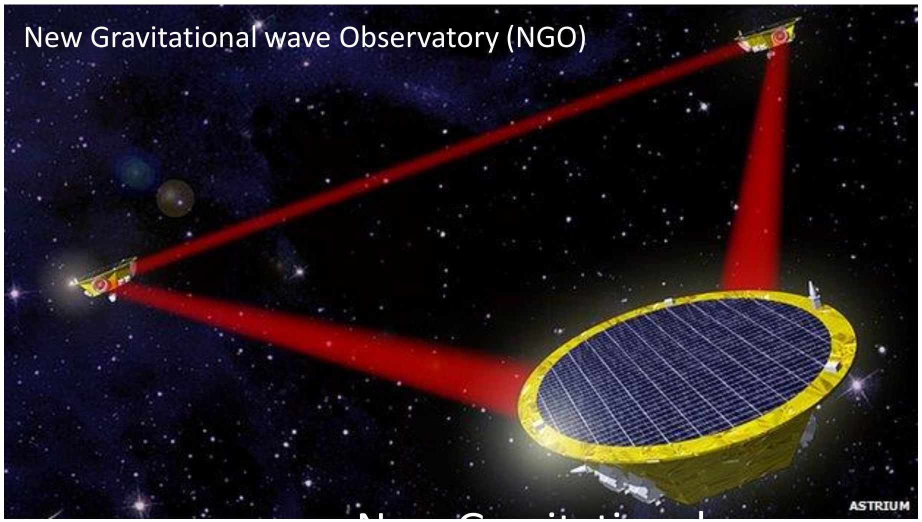
Power recycling



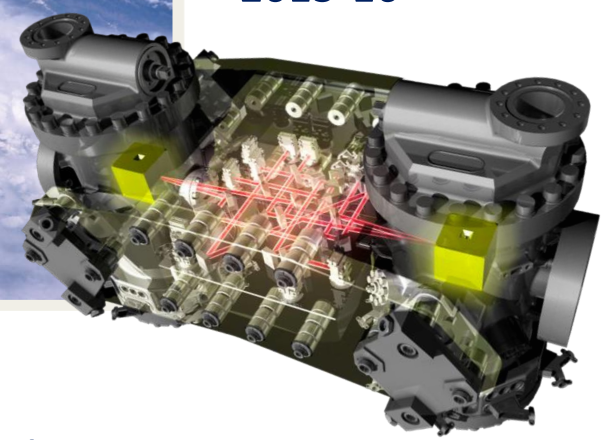
Signal recycling



Space based detector



LISA pathfinder launch date 2015-16



- Earlier called as LISA (laser interferometer space antenna
- Armlength: 1 million km
- Low frequency detector: $h \approx \frac{10^{-21}}{\sqrt{Hz}}$ at 1 mHz

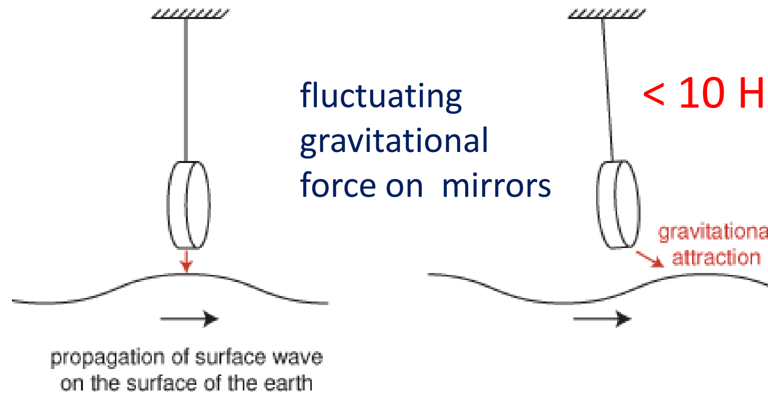
Noise sources

Seismic noise



< 10 Hz

Gravity gradient noise

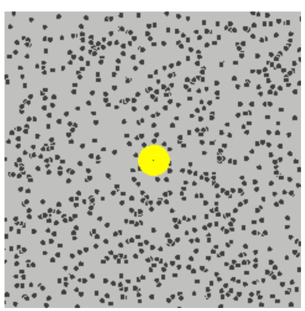


fluctuating
gravitational
force on mirrors

< 10 Hz

Thermal noise

Random
vibrations of
atoms &
molecules

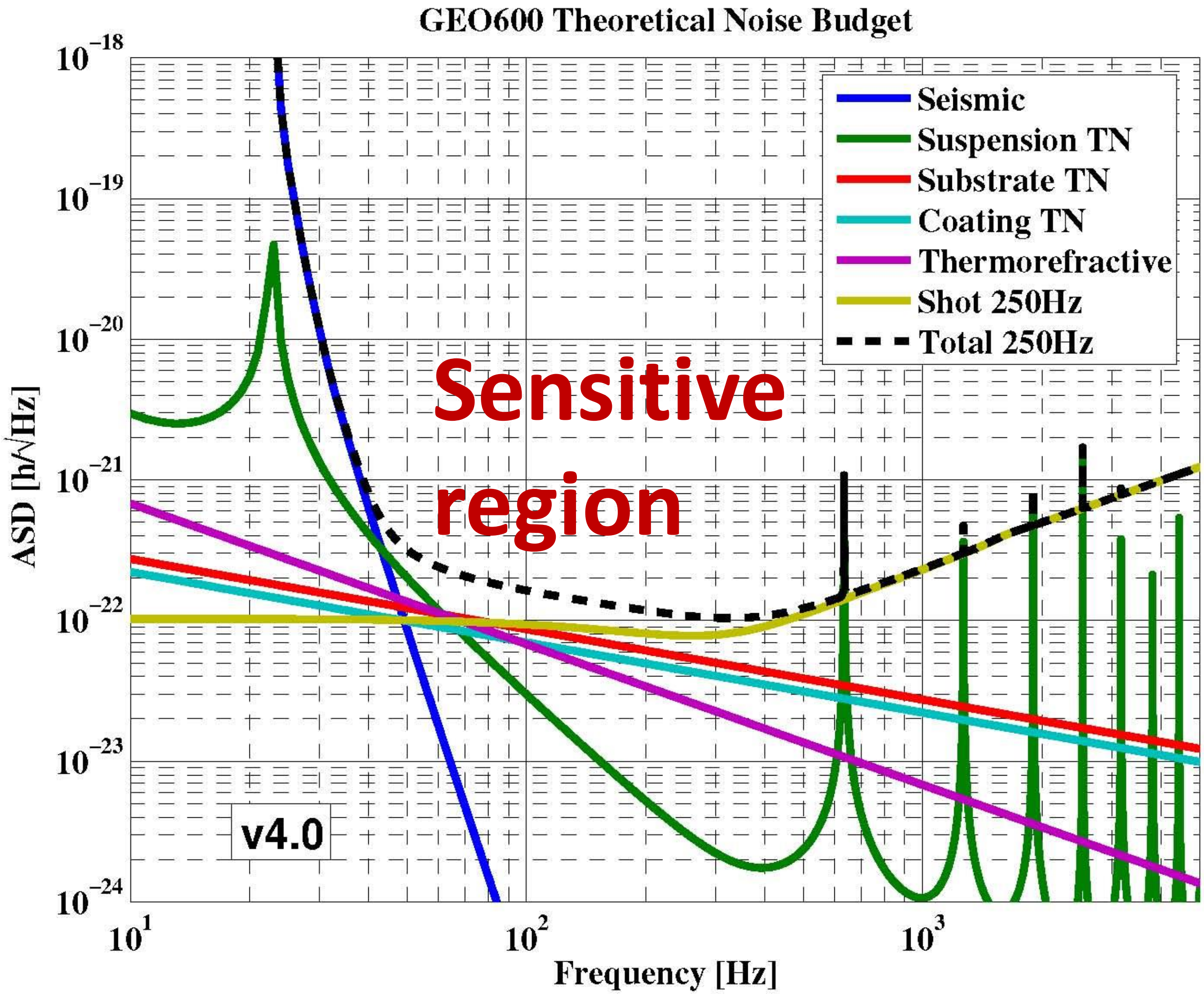


Few Hz to
> 100 Hz

Quantum noise

- Photon shot noise (HF)
- Radiation pressure noise (LF)

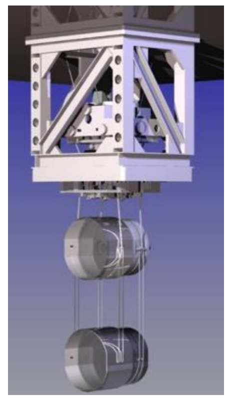
Strain sensitivity



How to reduce the noise?

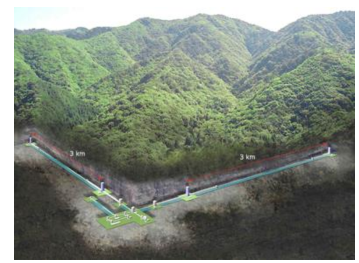
Seismic noise

- Quiet location
- Multi stage pendulum suspension



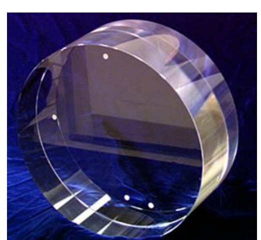
Gravity gradient noise

- Going underground (mines)
- Space based detector



Thermal noise

- High quality (low mechanical loss)materials (ex. fused silica, sapphire)



Quantum noise

- Increased laser power
- Bigger test mass

Thermal noise (TN)

- TN is the most significant noise sources below 100 Hz
- TN in the system reveals itself in two ways:
  – Brownian motion
  – Temperature fluctuations
- In GW detectors study of TN is important in the suspension elemenst:
  – Test mass mirrors, fibres etc

Suspension thermal noise

Fluctuation dissipation theorem

Mechanical loss

$$S_x(\omega) = \frac{4k_B T \omega_0 \phi(\omega)}{2\pi^3 \omega m[(\omega_0^2 - \omega^2)^2 + \omega_0^4 \phi^2(\omega)]}$$

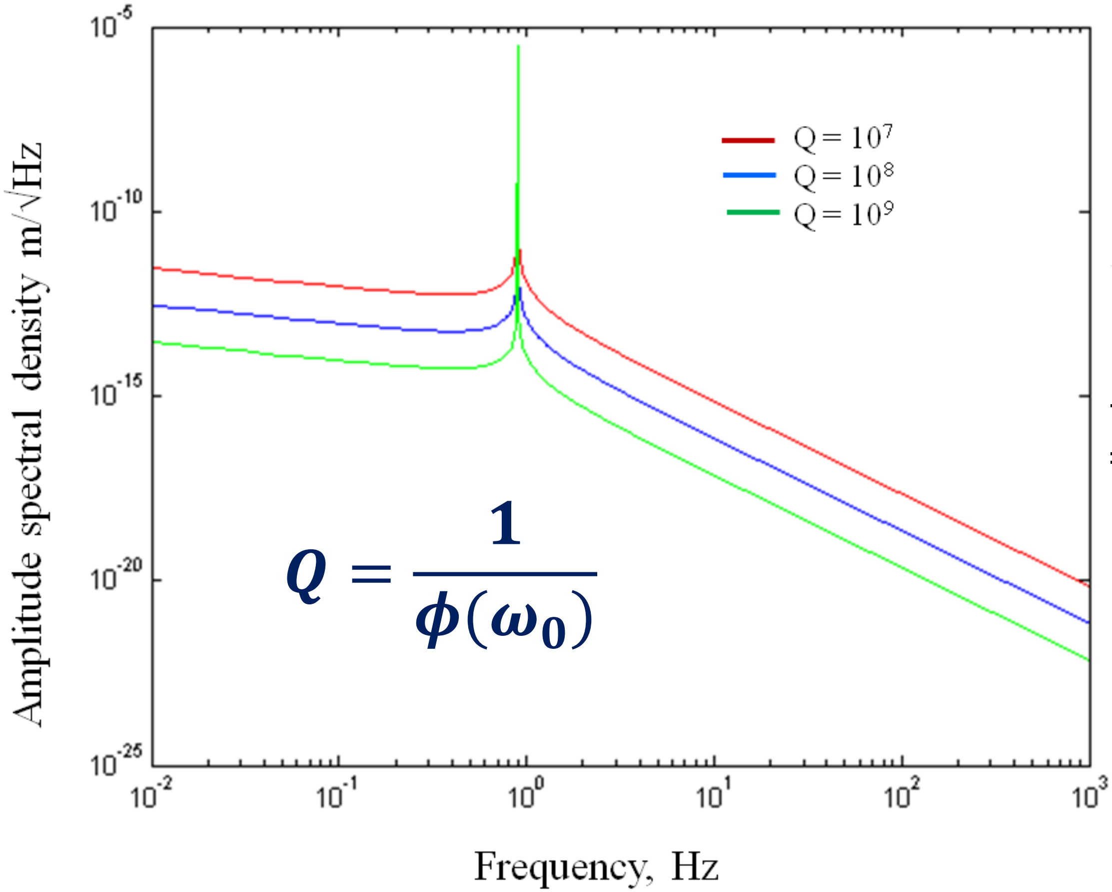
Sources of dissipation

- Thermoelastic
- Surface loss
- Bulk loss
- Weld loss

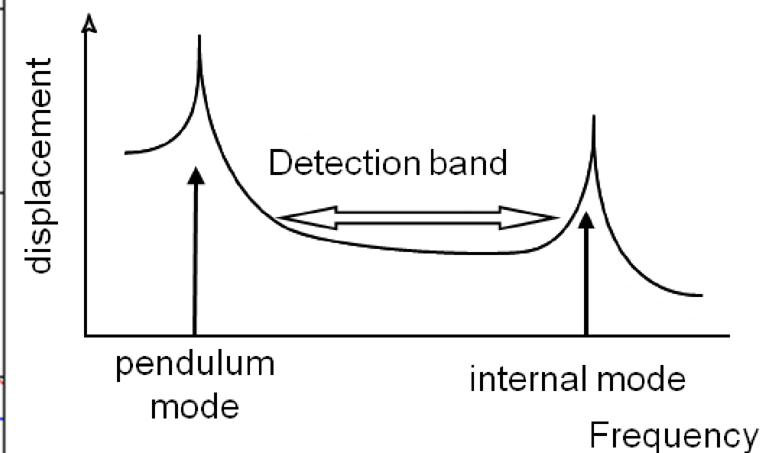
In addition, the loss can be reduced by storing energy in the lossless gravity which is known as the **dissipation dilution factor, D**.

D is the ratio of total gravitational energy of the suspension pendulum motion to the elastic energy stored in the wires

Mechanical loss

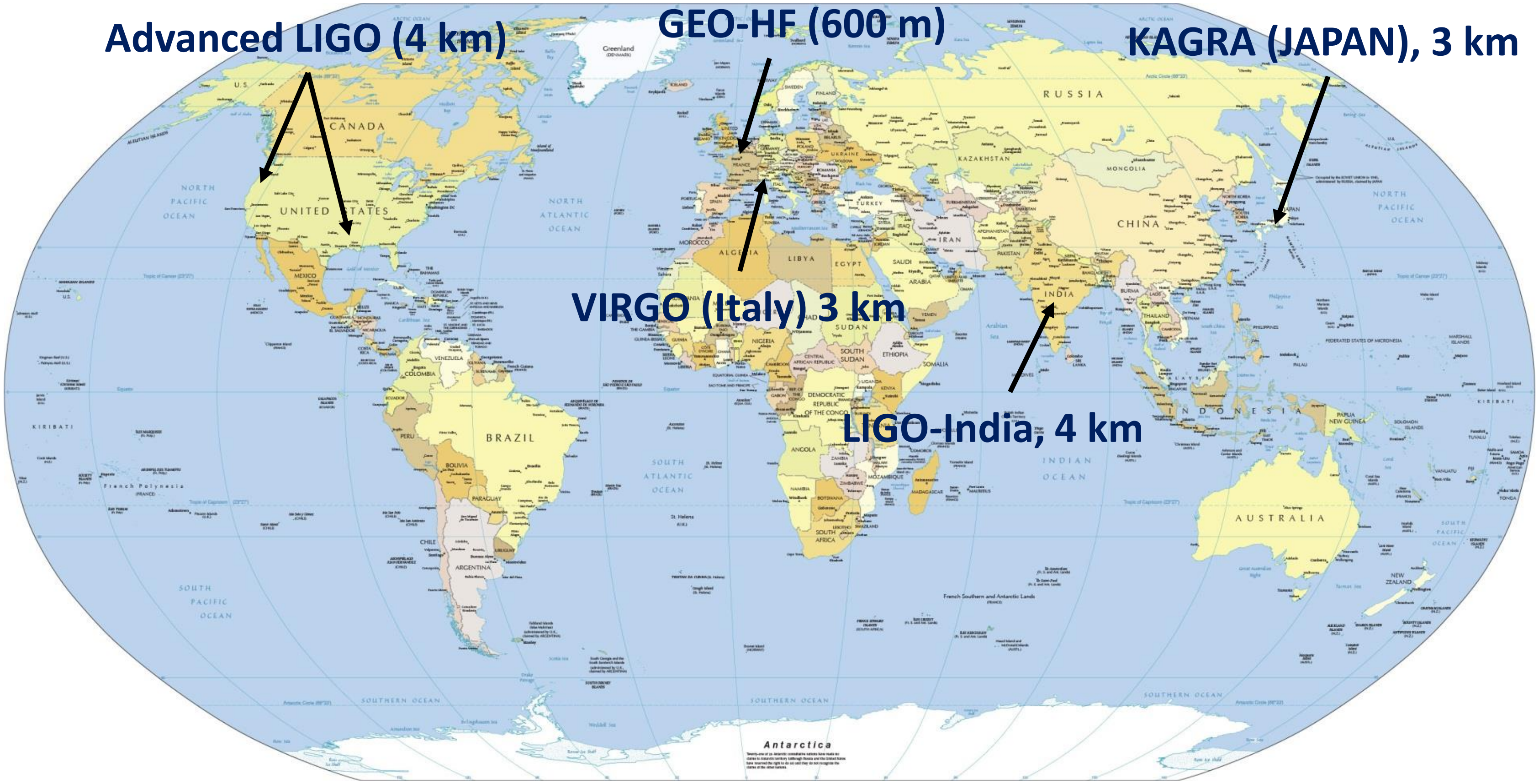


$$Q = \frac{1}{\phi(\omega_0)}$$



Use low loss materials =>
low noise off resonance

Network of detectors



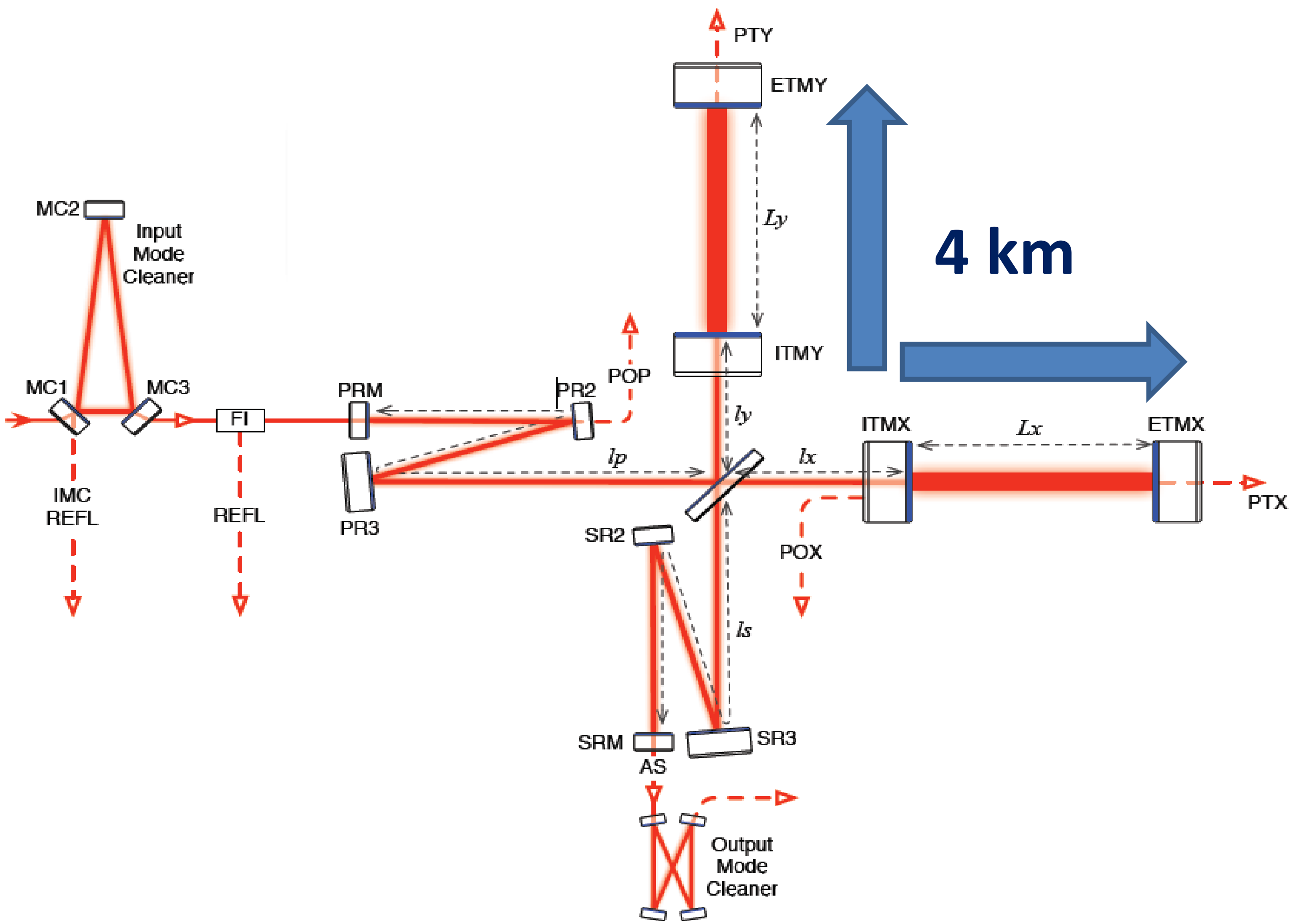
Wide network of detectors built around the world

LIGO & Advanced LIGO

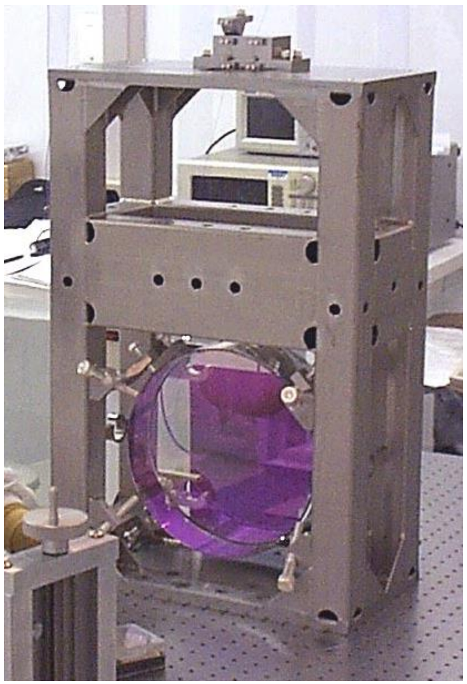
- 4 km long interferometer at 2 sites in USA
- Funded by NSF (200 million $)
- LIGO detectors are currently undergoing an upgrade to advanced LIGO
- A third detector in India (LIGO India, Indigo project)

Vacuum tanks housing the optics

Interferometer

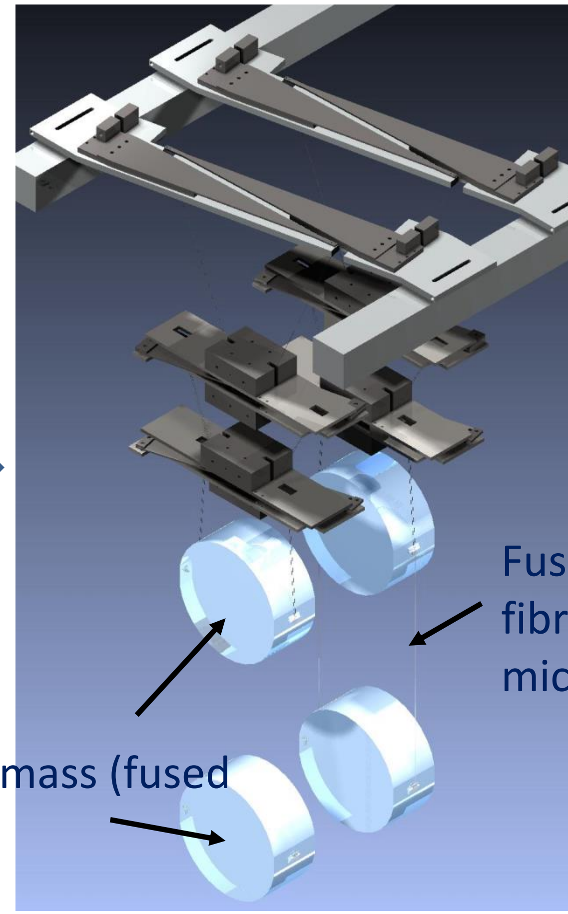


Advanced LIGO upgrades



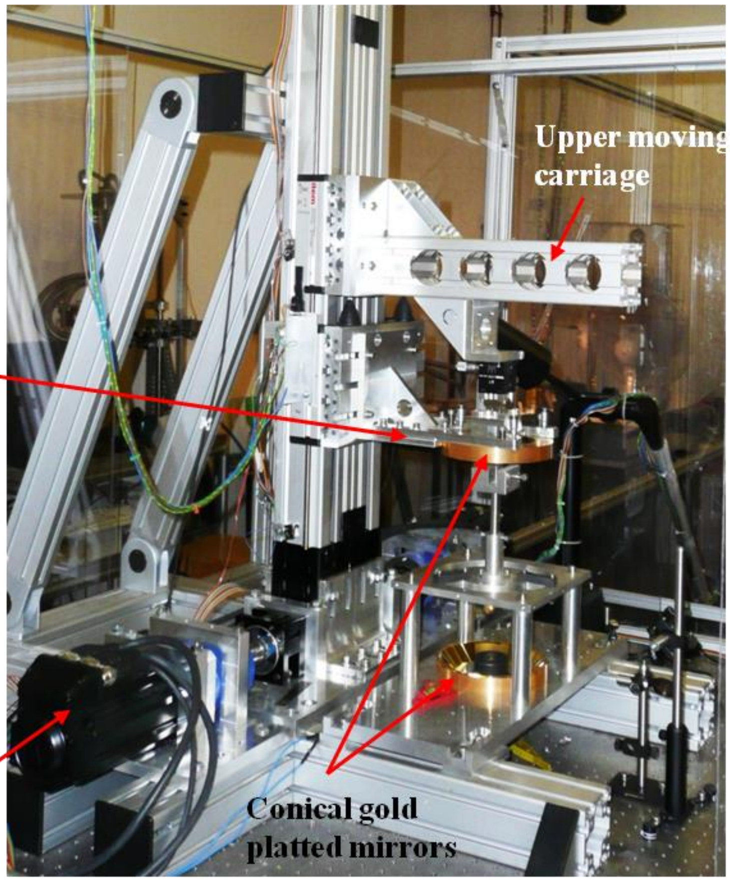
LIGO suspension

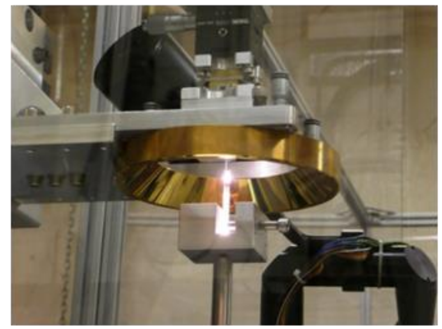
10.7 kg test mass



Advanced LIGO suspension - Quasi monolithic Quadruple pendulum

CO_2 laser - pulling machine



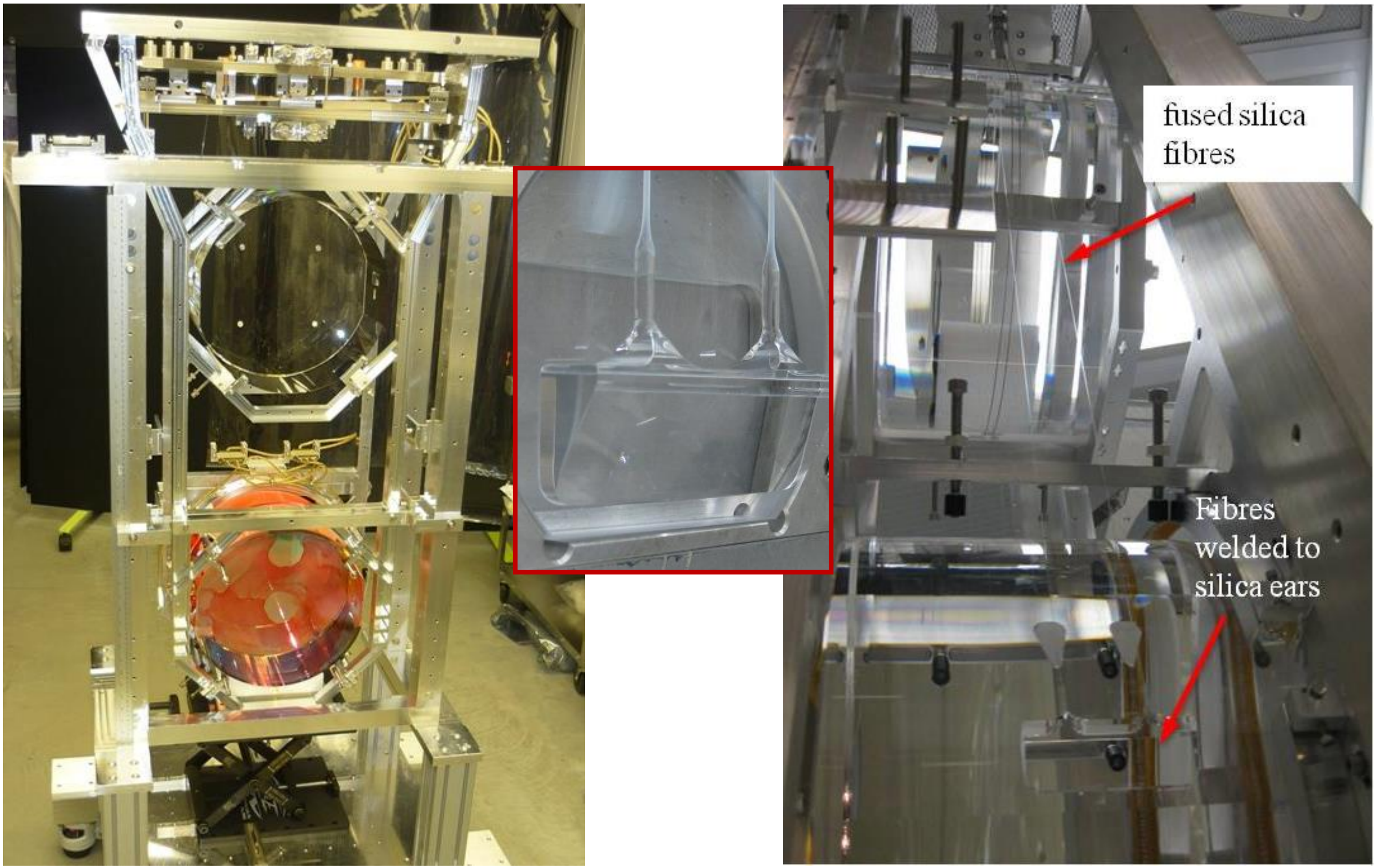


Laser beam heating the silica rod

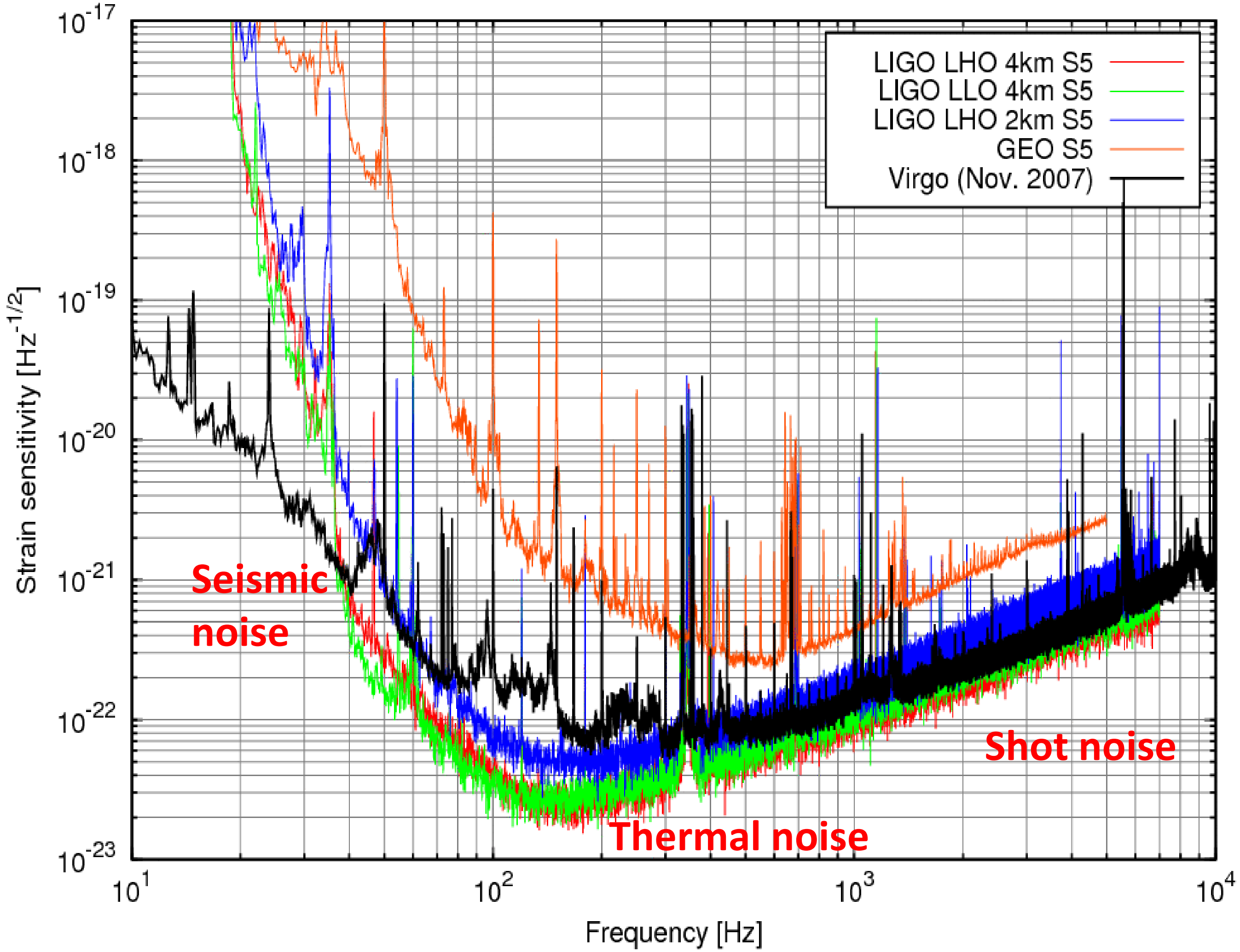
100 W Laser

For the fabrication of fused silica fibres

Advanced LIGO suspension

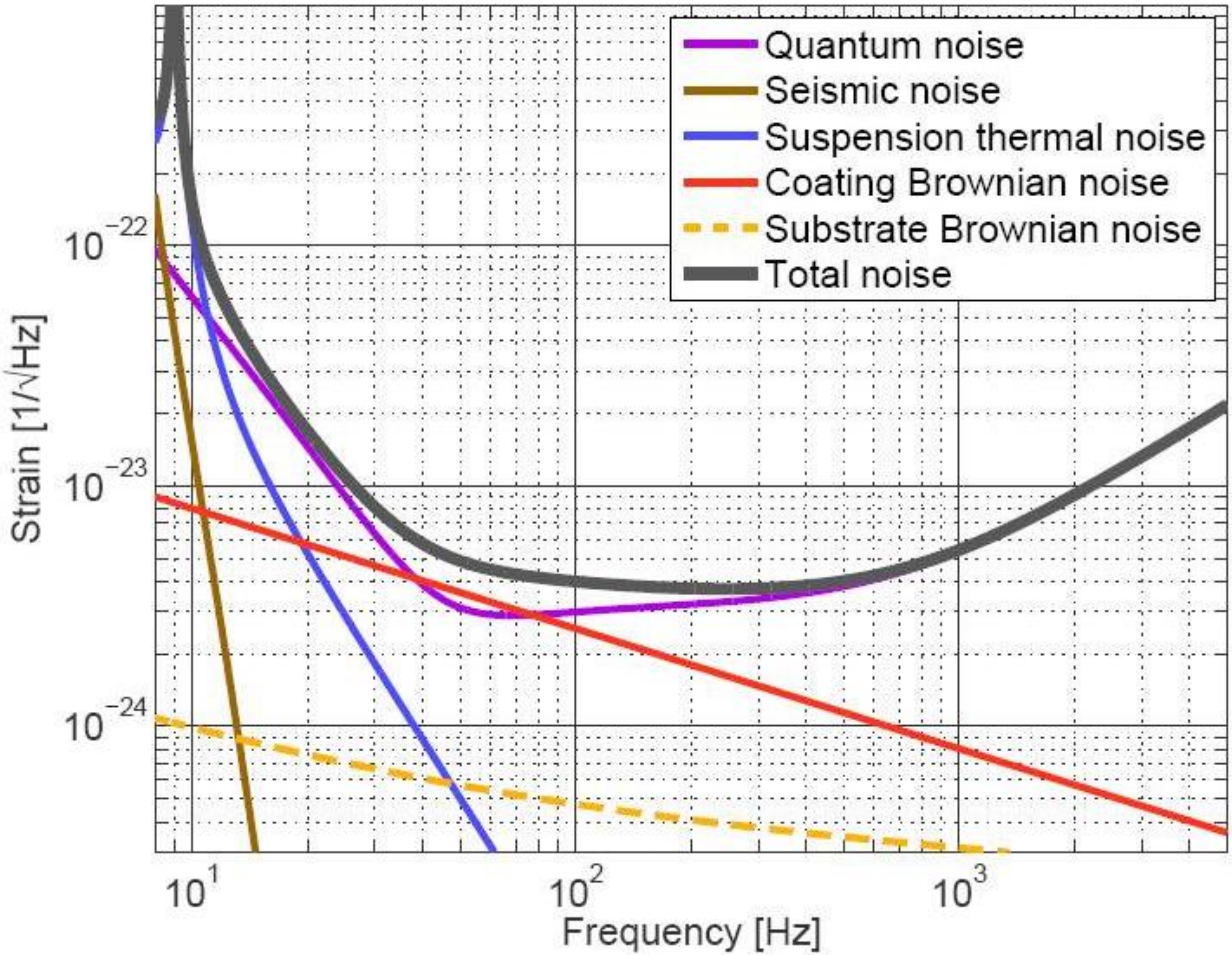


Sensitivity - LIGO



Best strain sensitivity measured: $h \approx 3 \times 10^{-23}\sqrt{Hz}$ **(100 Hz to 200 Hz)**

Sensitivity - AdLIGO



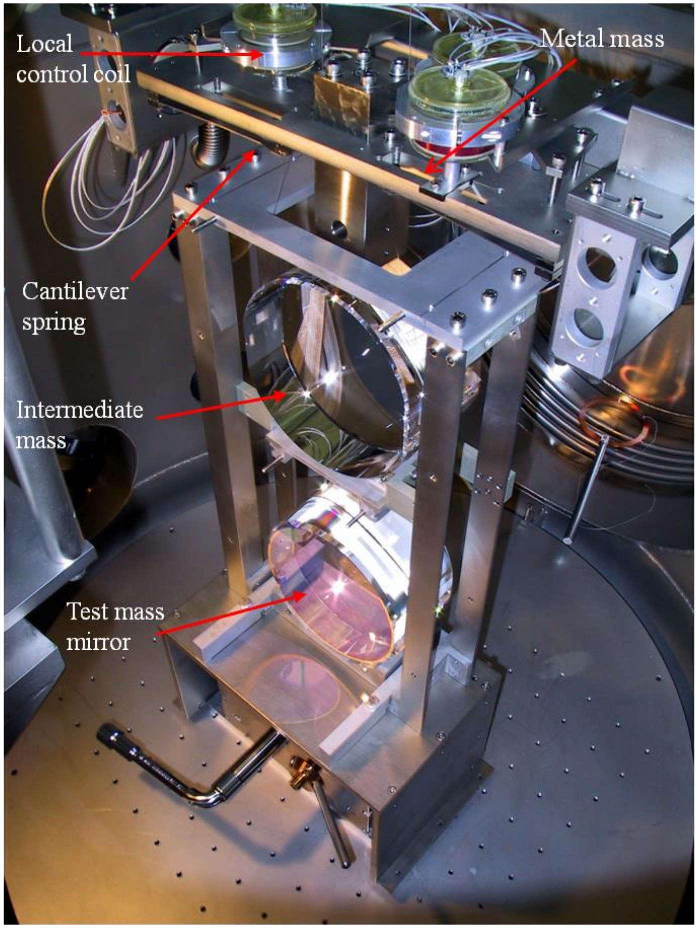
Watch out for 2015-16

- AdLIGO is currently under installation/fabrication
- Is expected to be online by 2015-16
- Increased laser power, improved optics, coating materials
- Will employ a quasi monolithic quadruple pendulum system (fused silica)
- Seismic noise below 10 Hz
- Sensitivity will be improved by a factor of 10
- Expected events – several 10’s per year

GEO-HF detector


- Earlier called GEO-600 detector
- German-British detector in Hannover
- Armlength 600 m
- Currently undergoing an upgrade to GEO-HF (high frequency)

Suspension system



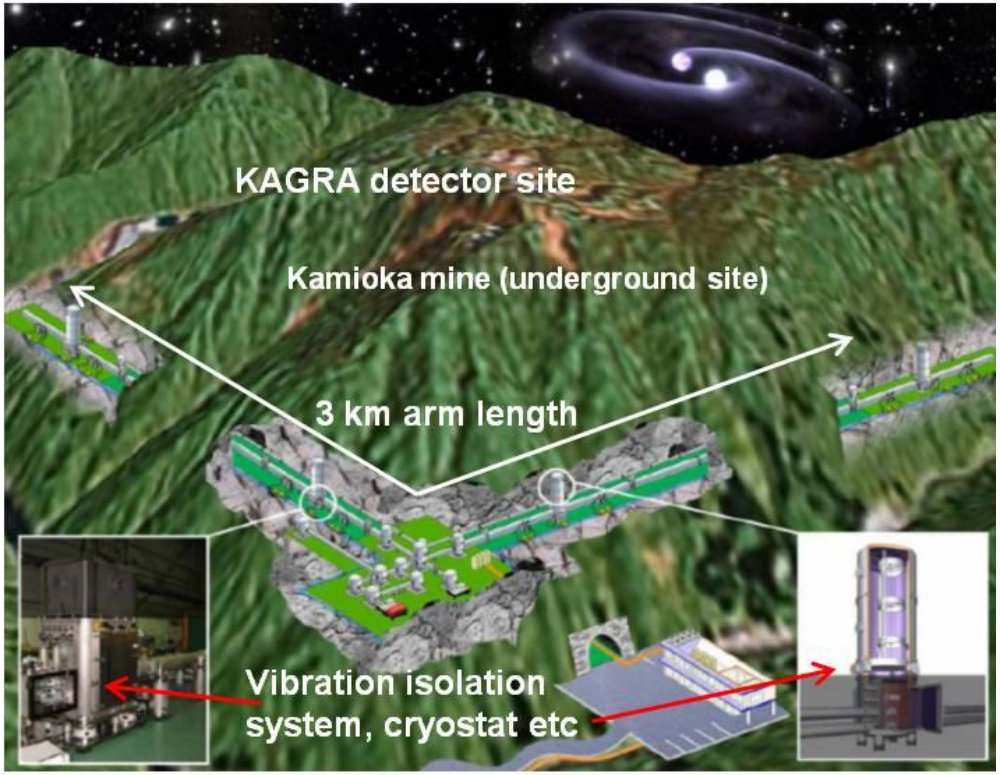
Triple pendulum system of the GEO detector

Status – GEO-HF

- GEO-HF will employ squeezed light technology
- Will install an output mode cleaner to improve it’s performance above 1 kHz
- Readout scheme from Hetrodyne (RF) to a DC read-out (Homodyne detection system)
- Increased laser power: 35 W
- Will be the only detector to be online till 2016 while other detectors are undergoing an upgrade

KAGRA detector

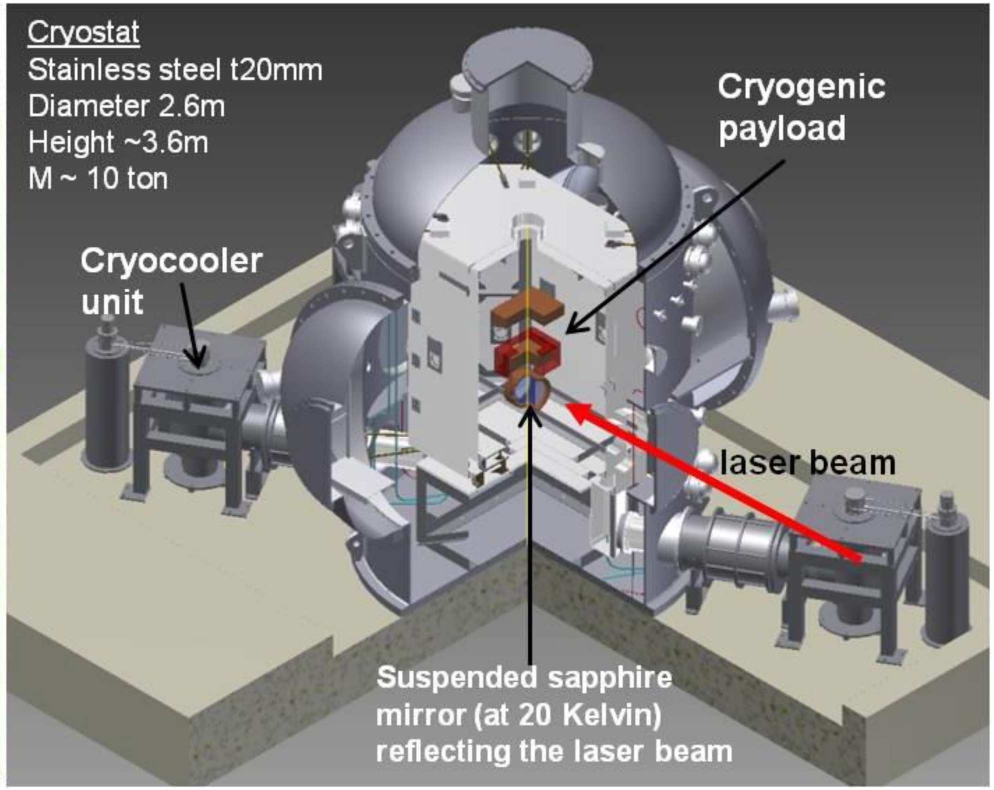
- Currently being built in Japan
- Located 200 meters underground to reduce seismic noise
- KAGRA is unique compared to other detectors since it will be the first cryogenic temperature detector
- Cryogenic temperature will reduce thermal noise and will improve the sensitivity



Cryogenic detector

Cryogenic payload

- Cryogenic payload is in the form of multiple pendulum, housed in a cryostat operating at 20 Kelvin
- Use of Sapphire as a substrate material for the suspension (mirrors and fibres) system
- Sapphire is a crystalline material.
  - Extremely low mechanical loss at 20 K
  - Good optical properties
  - High thermal conductivity



Conclusions

- A network of detectors exist around the world
- Science runs conducted by the 1st generation of detectors have placed upper limits on various sources
- 2nd generation of detectors are expected to be online by 2016
- New materials and technologies are expected to improve the sensitivity by 10 times
- Once online - may lead to 1st detection of GW
- Open new avenues in the field of GW signals
- Continued R&D is required for the 3rd gen detectors for precision GW astronomy