引力波

LIGO-G1601925-v1

Detection of gravitational waves with a laser interferometer

Koji Arai (新井宏二) – LIGO Laboratory / Caltech

GW mini-school: Beijing Normal Universuty 2016/9/15~18

Self-introduction

- **Senior Scientist @Caltech**
  - Interferometer Sensing and Control

- **Ph.D** (U of Tokyo,1995-1999)
  - TAMA300 double suspension
  - Interferometer length sensing
  - 3m prototype interferomter

- **TAMA300 interferometer** (NAOJ 1999-2009)
  - Commissioning and science runs

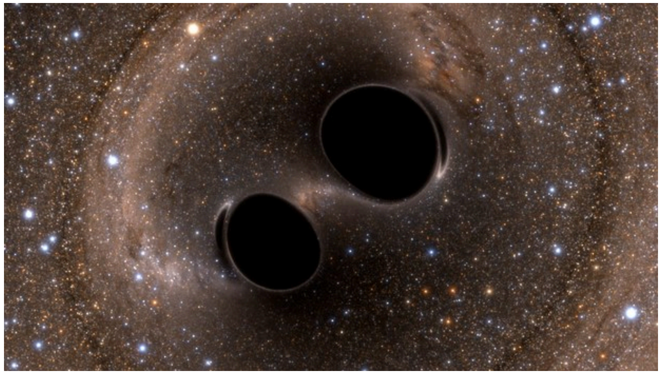
- **LIGO** (Caltech 2009-)
  - Output optics chain, eLIGO/aLIGO commissioning

Detector Topics

- **Introduction**
  - Gravitational wave detection with laser interferometers
- **Laser interferometry**
- **Noises in laser interferometer detectors**
- **Linear control system**

Interferometer GW detection

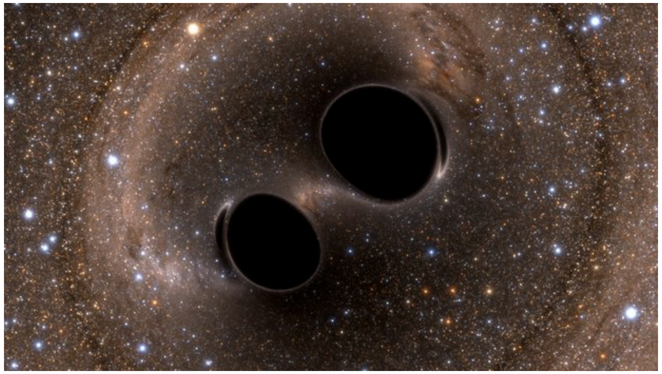
GW detection



GW Sources

GW Detectors

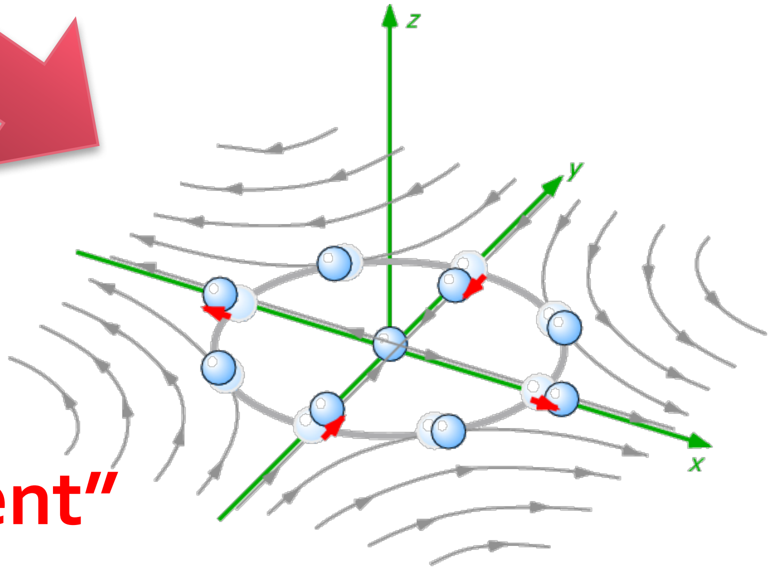
GW: Generation, Propagation, and Detection



Generation:
Change of quadrupole moment
Post-newtonian, NR

1/R

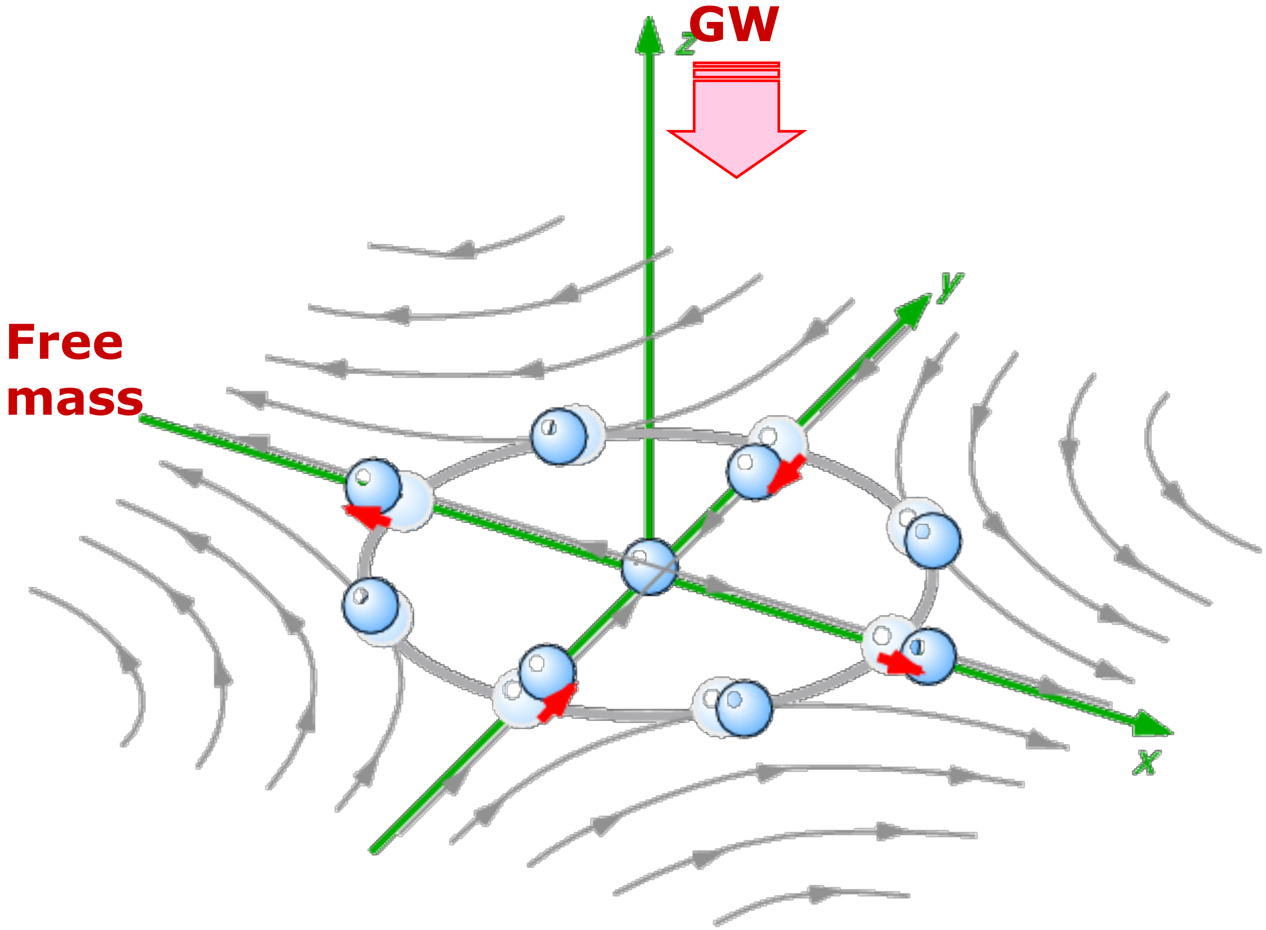
Propagation:
Wave equation of
the spacetime metric



Detection:
Quadrupolar "displacement"
of the masses

Gravitational wave

- Quadrupole deformation of the spacetime



GW Detection

- Measure strain between free masses

- Free fall = no external force
- Local measurement show no effect of GW

GW Detection

- **Measure strain between free masses**

$$\textbf{Metric}: \; g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

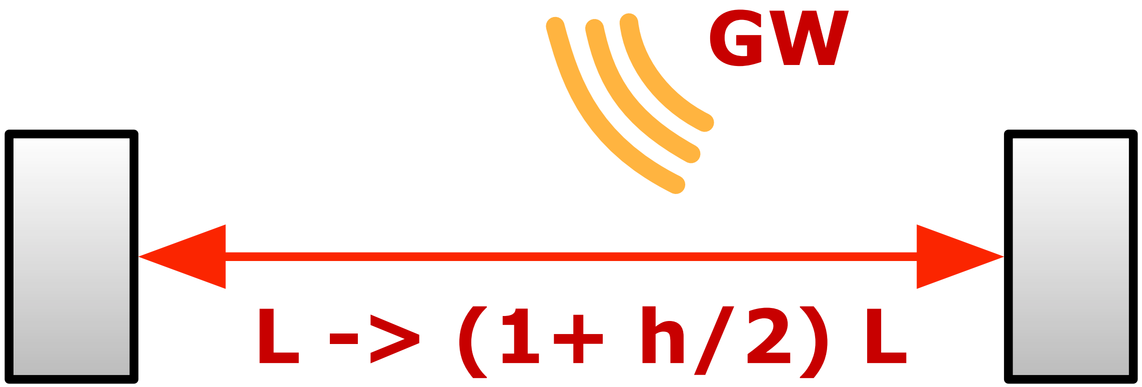
$$\eta_{\mu\nu} = \begin{pmatrix} -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}, \; g_{\mu\nu} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & h_+ & h_\times & 0 \\ 0 & h_\times & -h_+ & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

$$\textbf{Distance}: \; ds^2 = g_{\mu\nu} dx^\mu dx^\nu$$

$$ds^2 = -(c\,dt)^2 + (1 + h_+)dx^2 + dy^2 + dz^2$$

GW Detection

- Measure strain between free masses

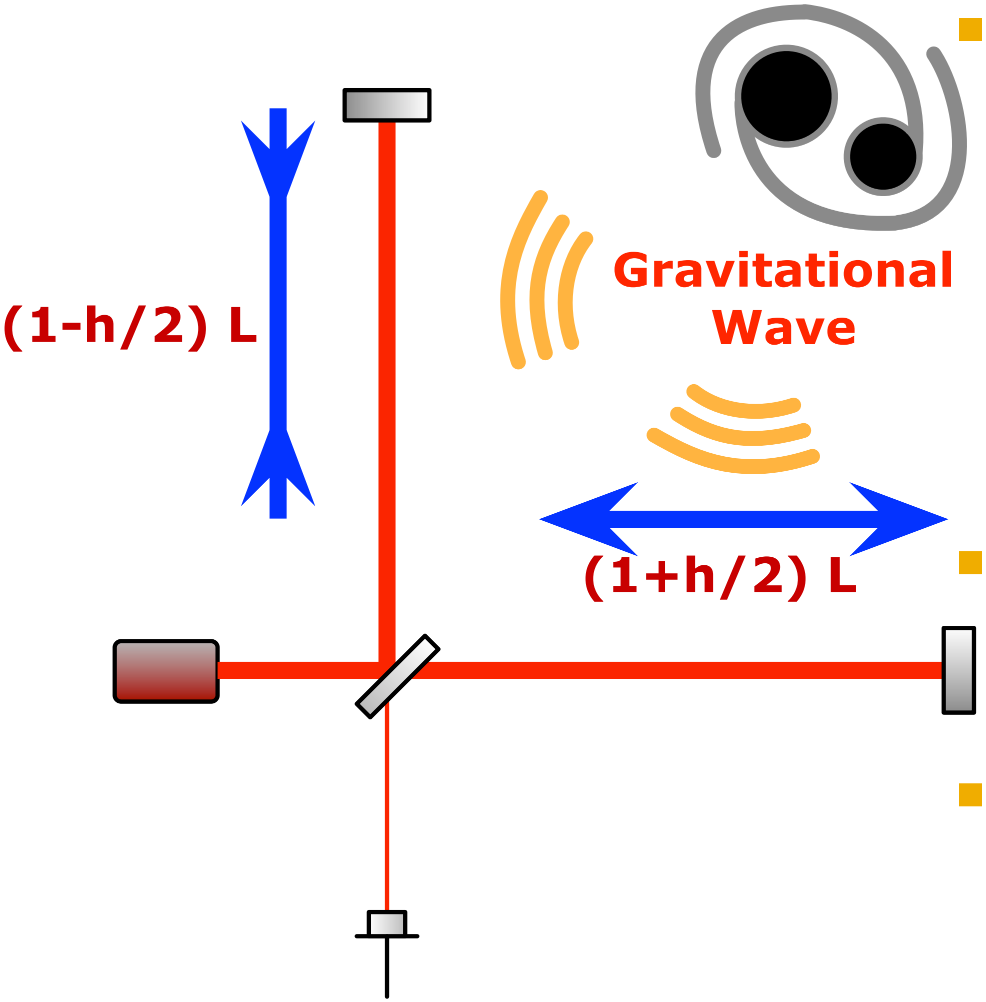


- Changes in optical distance between the masses

$$\int ds = \int_{\mathrm{M1}\rightarrow\mathrm{M2}} \sqrt{1+h_+}dx \simeq \int_{\mathrm{M1}\rightarrow\mathrm{M2}} (1+h_+/2)dx$$
$$=(1+h_+/2)L$$

Quadrupole nature of GWs

- Differential motion => Michelson interferometer

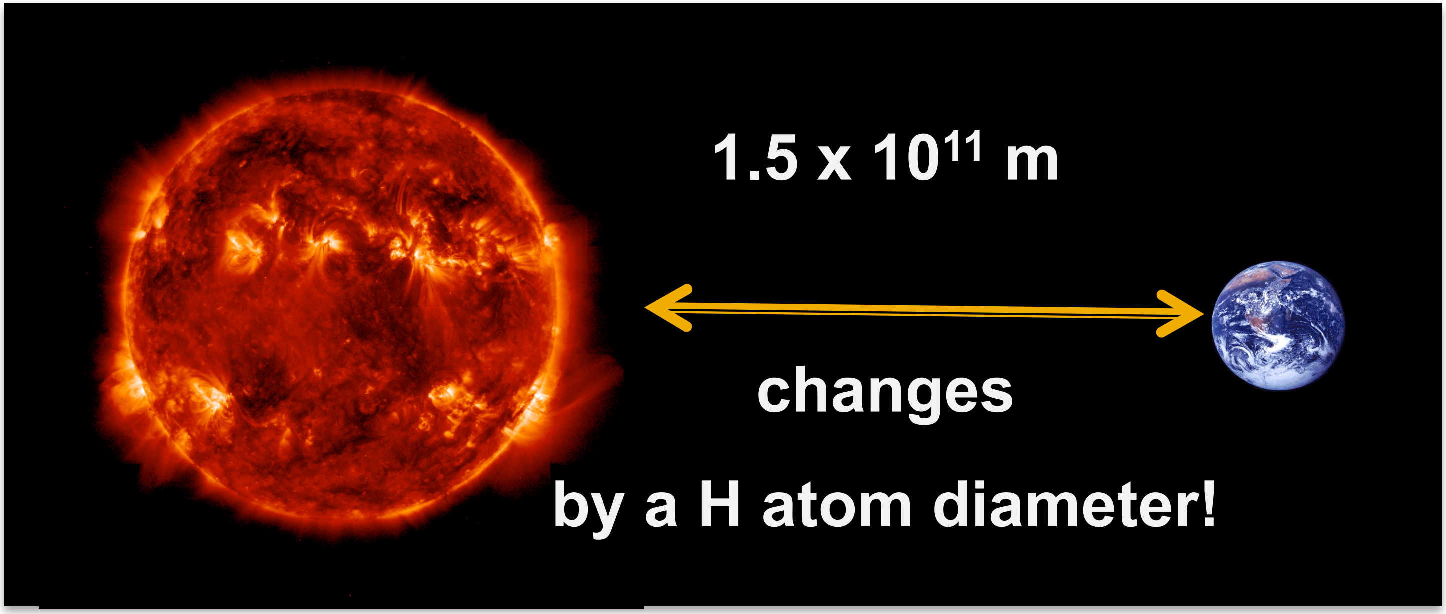


- Longer baseline
  -> bigger change
  - (displacement dx)
    = (Strain h) x (baseline L)
- GW effect is tiny
  - $h \sim 10^{-21}$, $L \sim 1$km -> $dx \sim 10^{-18}$ m
- Need to measure the phase of the laser light
  - => use "laser interferometry"

Amplitude of GWs

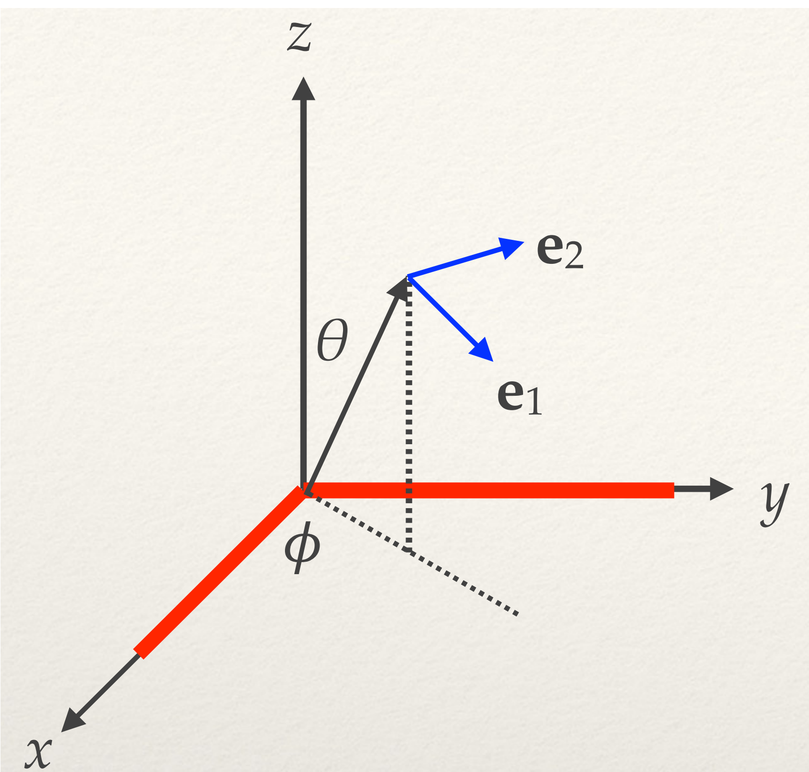
- The effect of GW is very small
- $h \sim 10^{-21}$ => distance of 1m changes 10^{-21}m

- Corresponds to:
  change by **~1 angstrom (or 100pm)**
  for distance between the sun and the earth



Antenna pattern

- Fixed on the ground, can not be directed
- Poor directivity => More like an antenna
- Antenna pattern (at low frequencies)



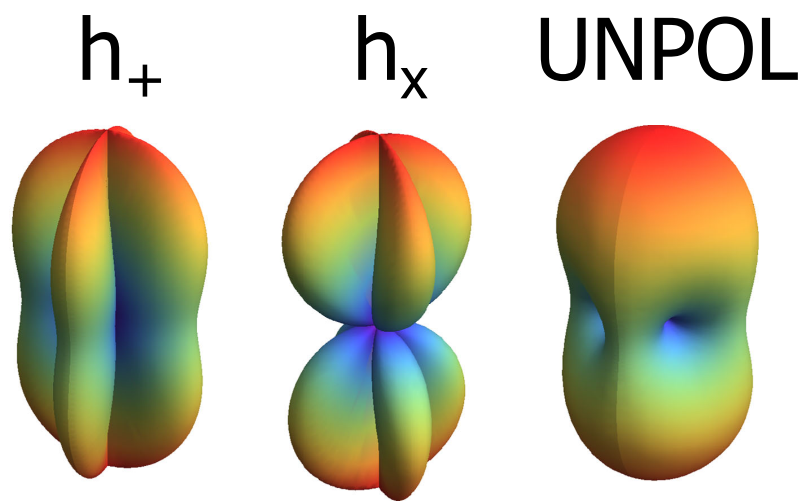


FIG. 2 (color online). Interferometer antenna response for (+) polarization (left), (×) polarization (middle), and unpolarized waves (right).

Rev. Mod. Phys. **86** (2014) 121-151
http://link.aps.org/doi/10.1103/RevModPhys.86.121
(http://arxiv.org/abs/1305.5188)

Interferometer GW Network

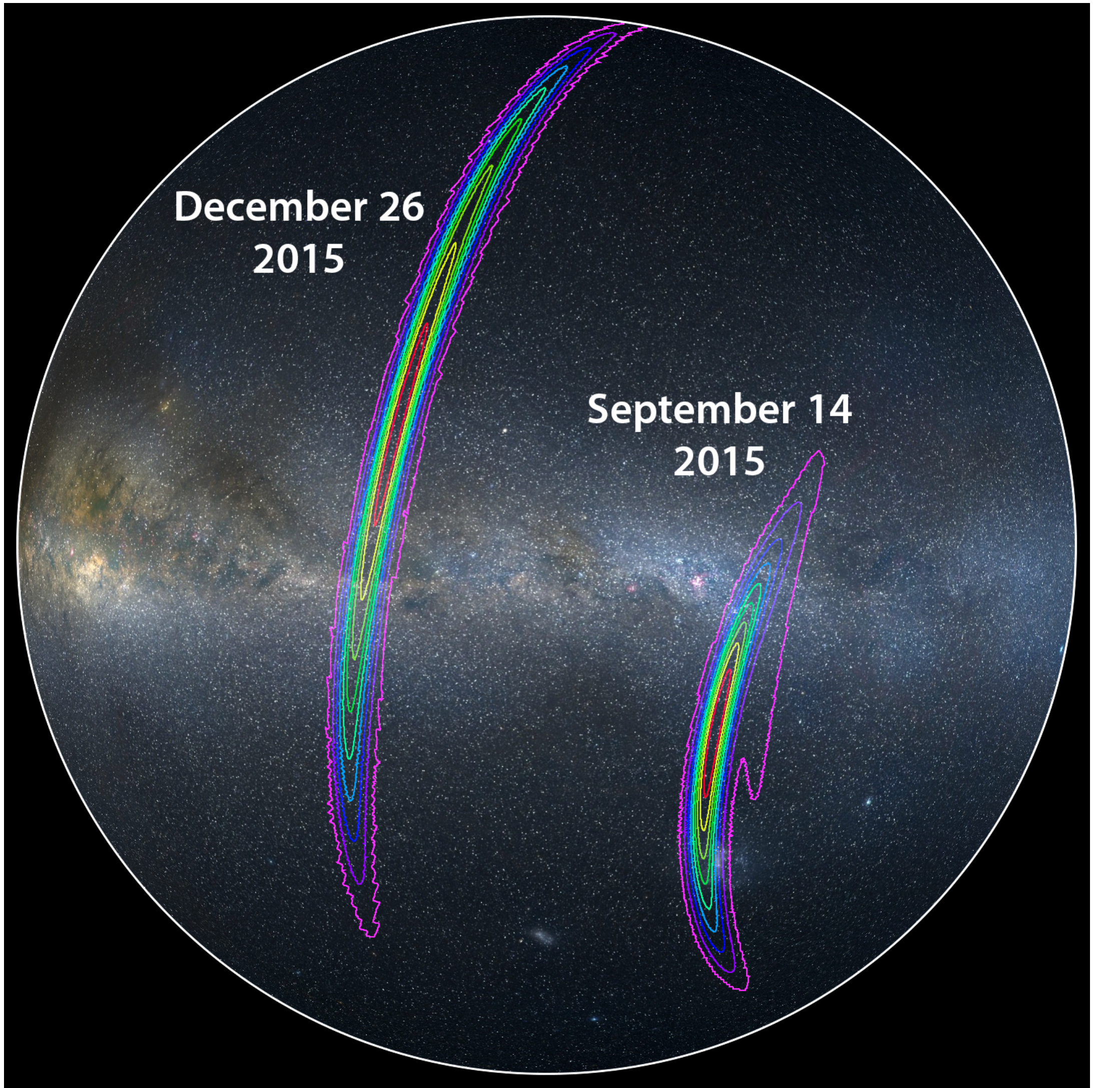
- **LIGO Observatories**
  Hanford / Livingston 4km

  Still shorter than the optimum length
  => Use optical cavity to increase life time of the photons in the arm

c.f. Virgo (FRA/ITA) 3km, KAGRA (JPN) 3km, GEO (GER/GBR) 600m

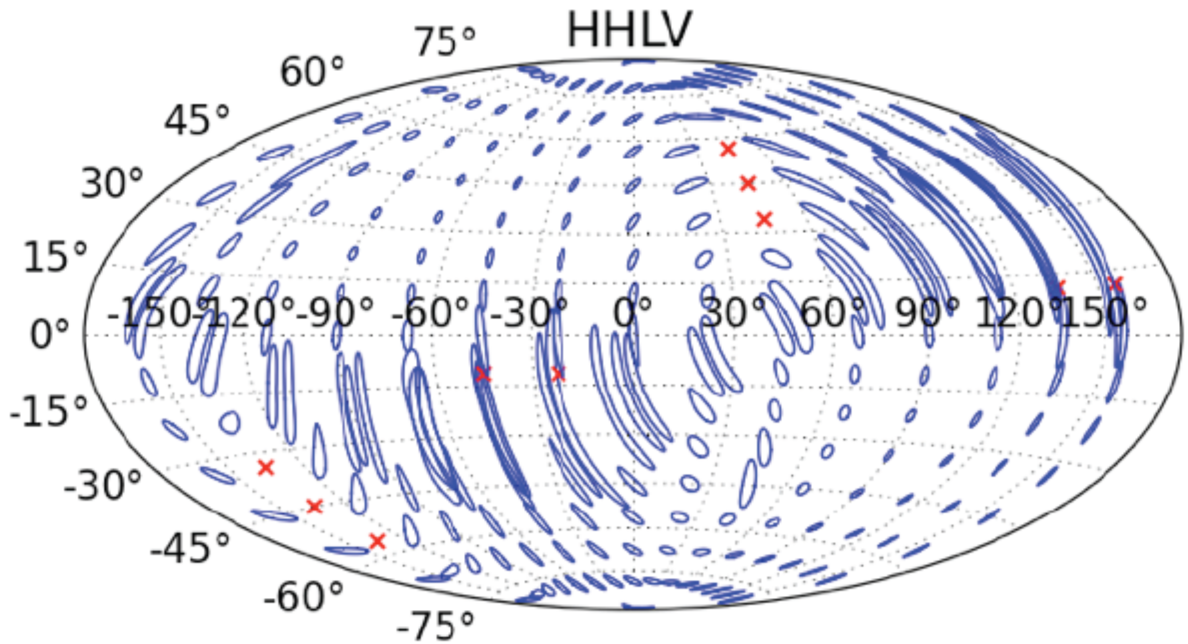
Localization capability:

- Localization of GW150914 & GW151226



Localization capability:

- LIGO-Virgo only



Fairhurst 2011

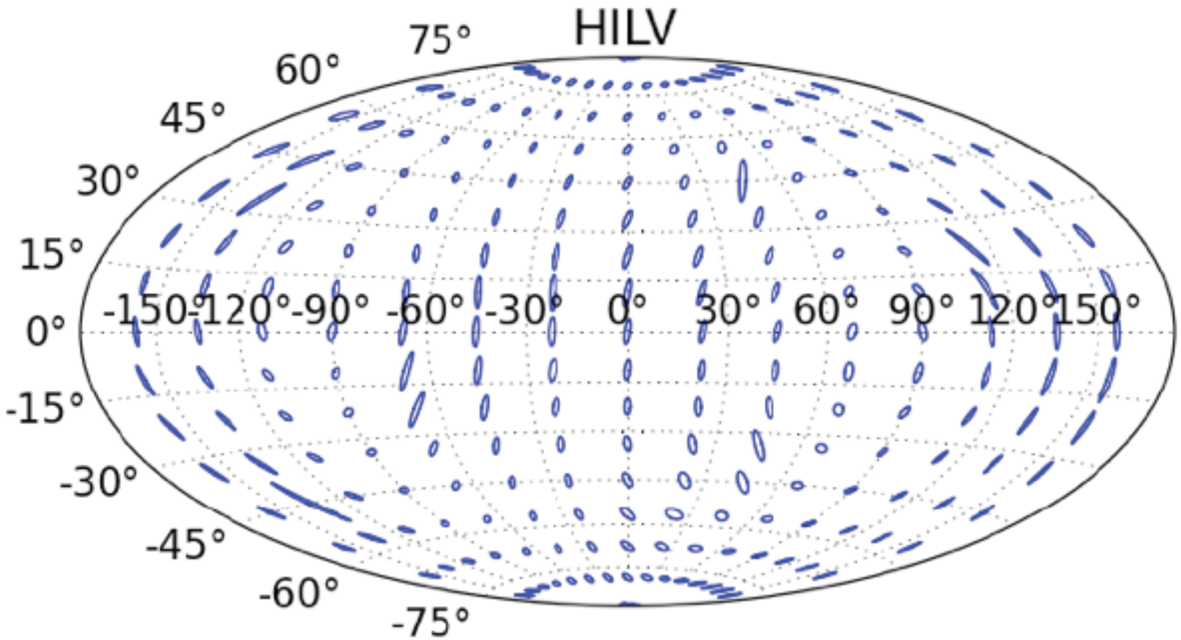
Red crosses denote regions where the network has blind spots

10

From LIGO-G1201135-v4

Localization capability:

- LIGO-Virgo plus LIGO-India

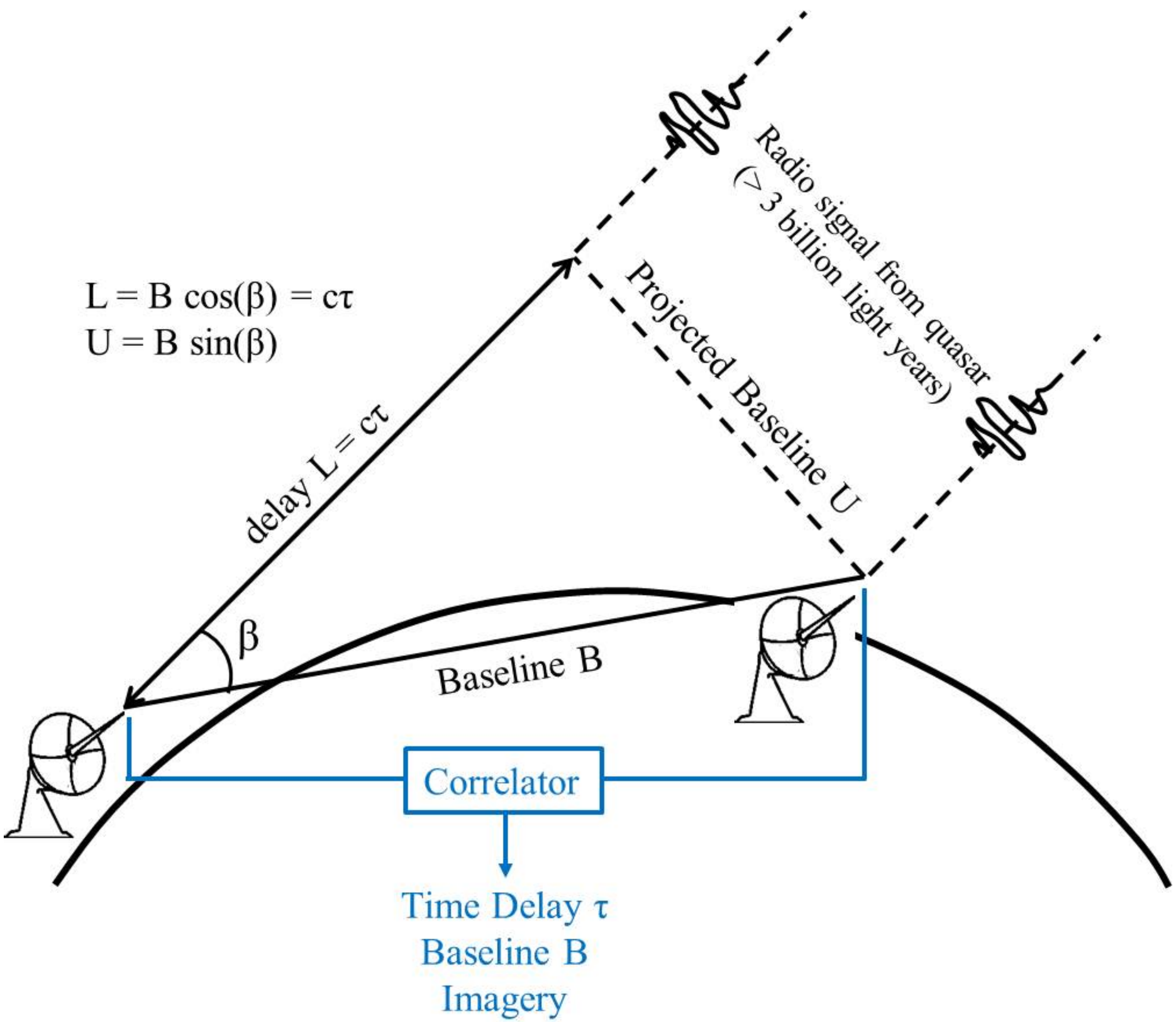


Fairhurst 2011

From LIGO-G1201135-v4

World Wide GW detector network

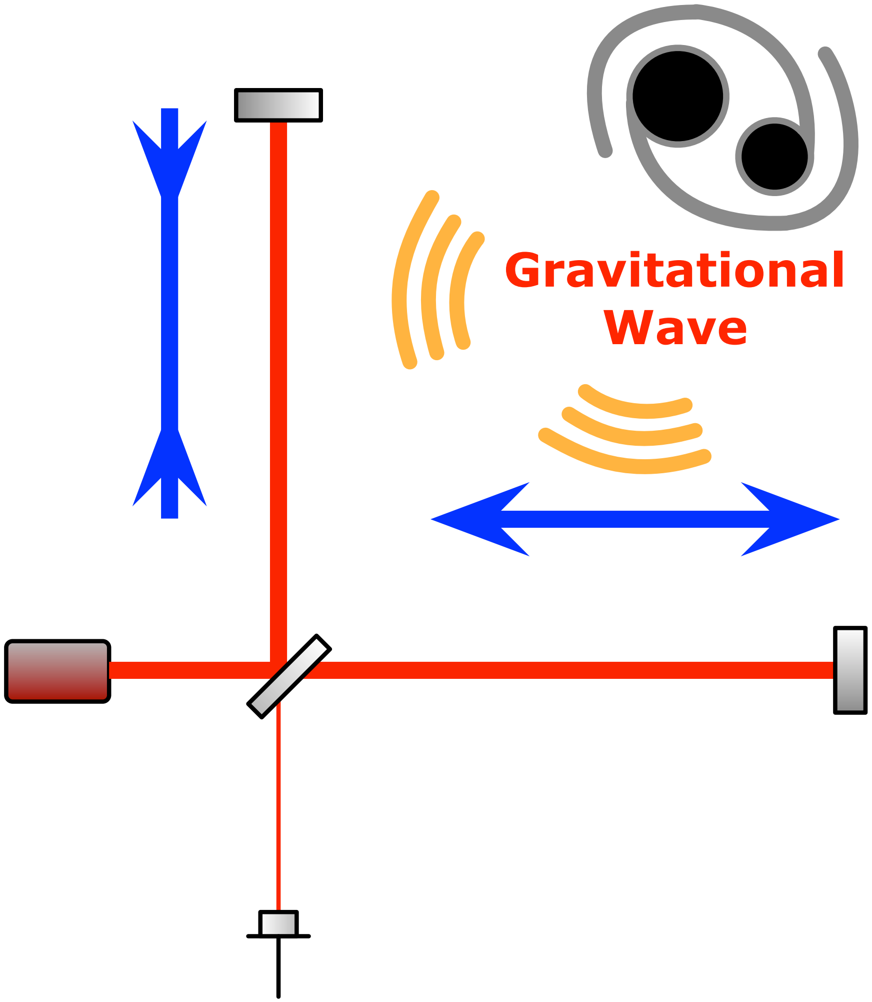
cf. Radio Telescope Interferometer ~ VLBI



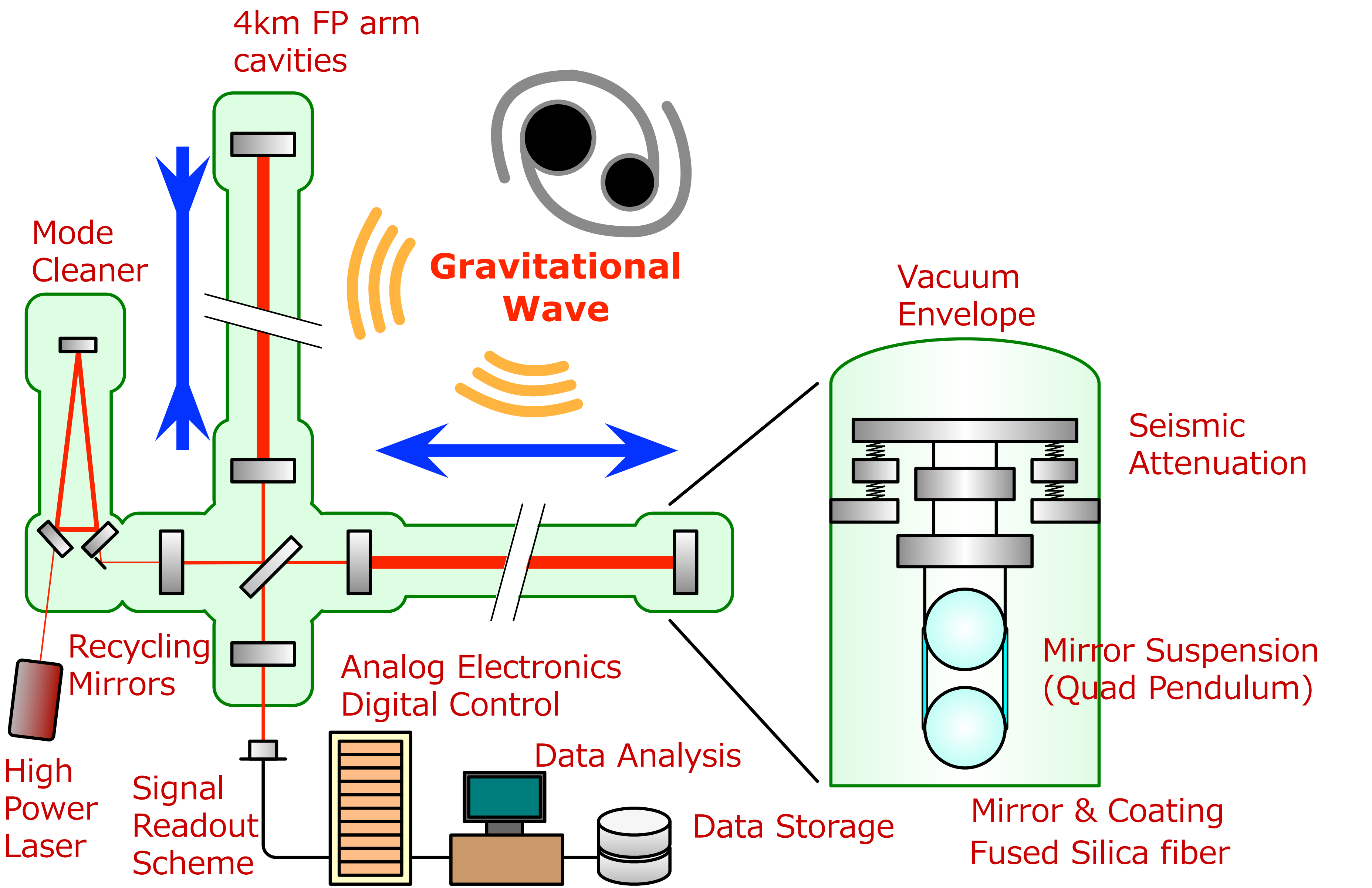
Technologies of Interferometer GW detectors

Simplified interferometer GW detector

- Differential motion => Michelson interferometer



Actual GW detector (still simplified)

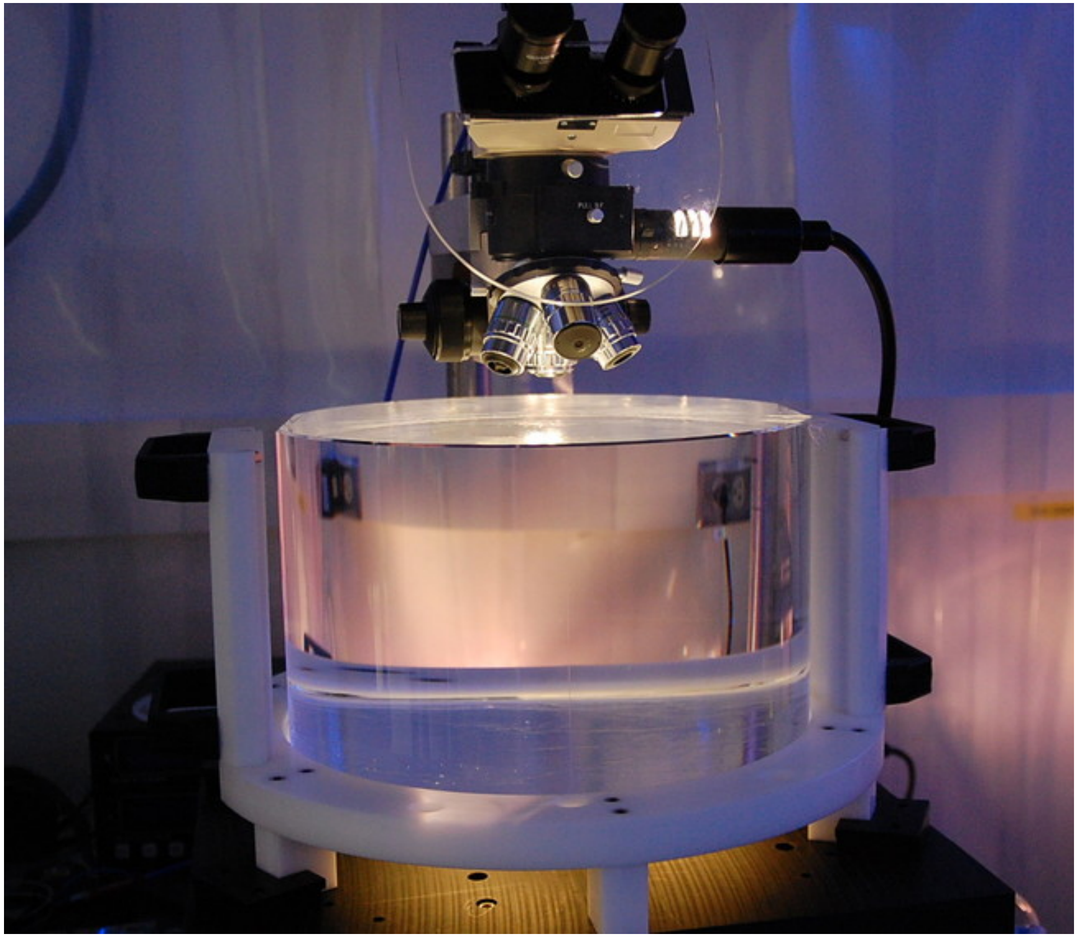


Vacuum system

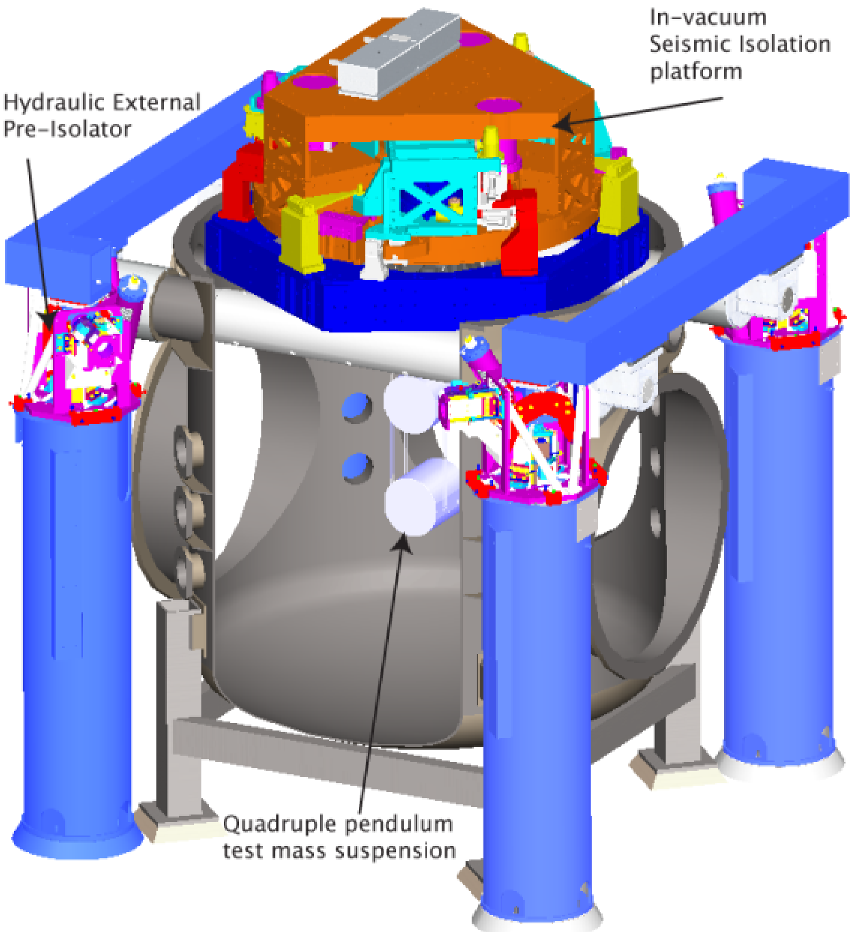
- World's biggest UHV vacuum system, straighter than earth's curvature
- Large vacuum chambers to accommodate main optics and suspensions

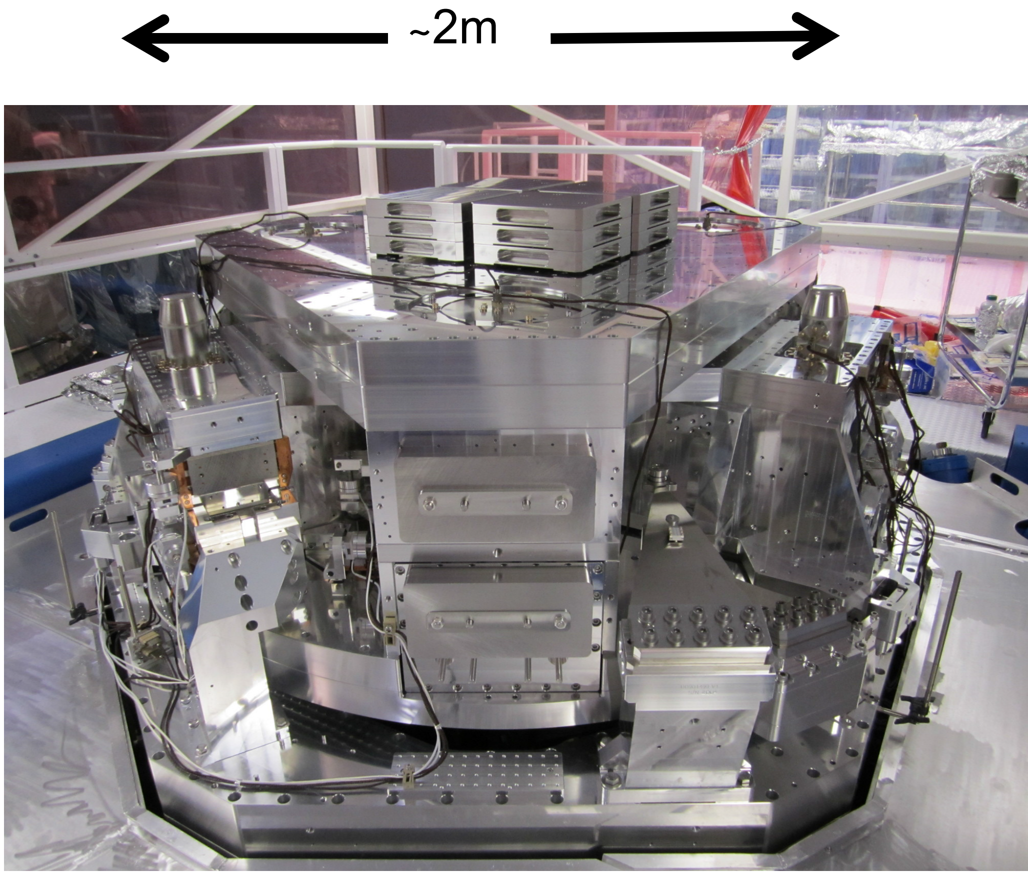
Test Masses

- **Requires the state of the art in substrates, polishing, coating**
  - Half-nm flatness over 300mm diameter
  - 0.2 ppm absorption at 1064nm
  - Coating specs for 1064 and 532 nm
  - Mechanical requirements: bulk and coating thermal noise, high resonant frequency



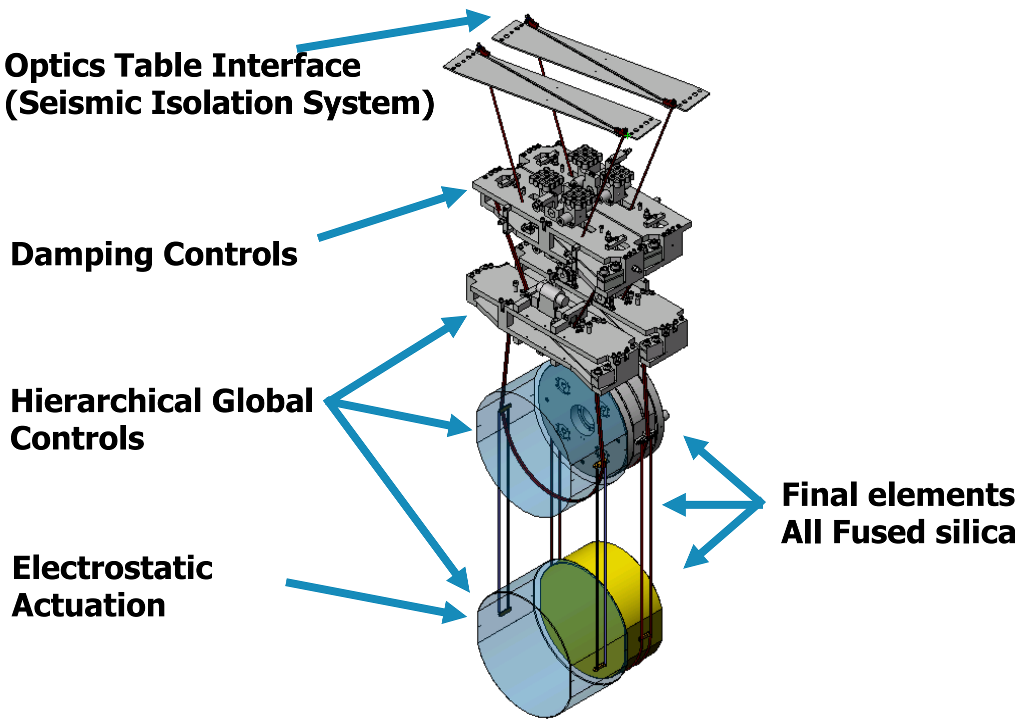
Seismic Isolation system





Quadruple monolithic suspension

- Quadruple pendulum suspensions for the test masses
- Monolithic final stage using fused silica fibers to suspend 40 kg test mass

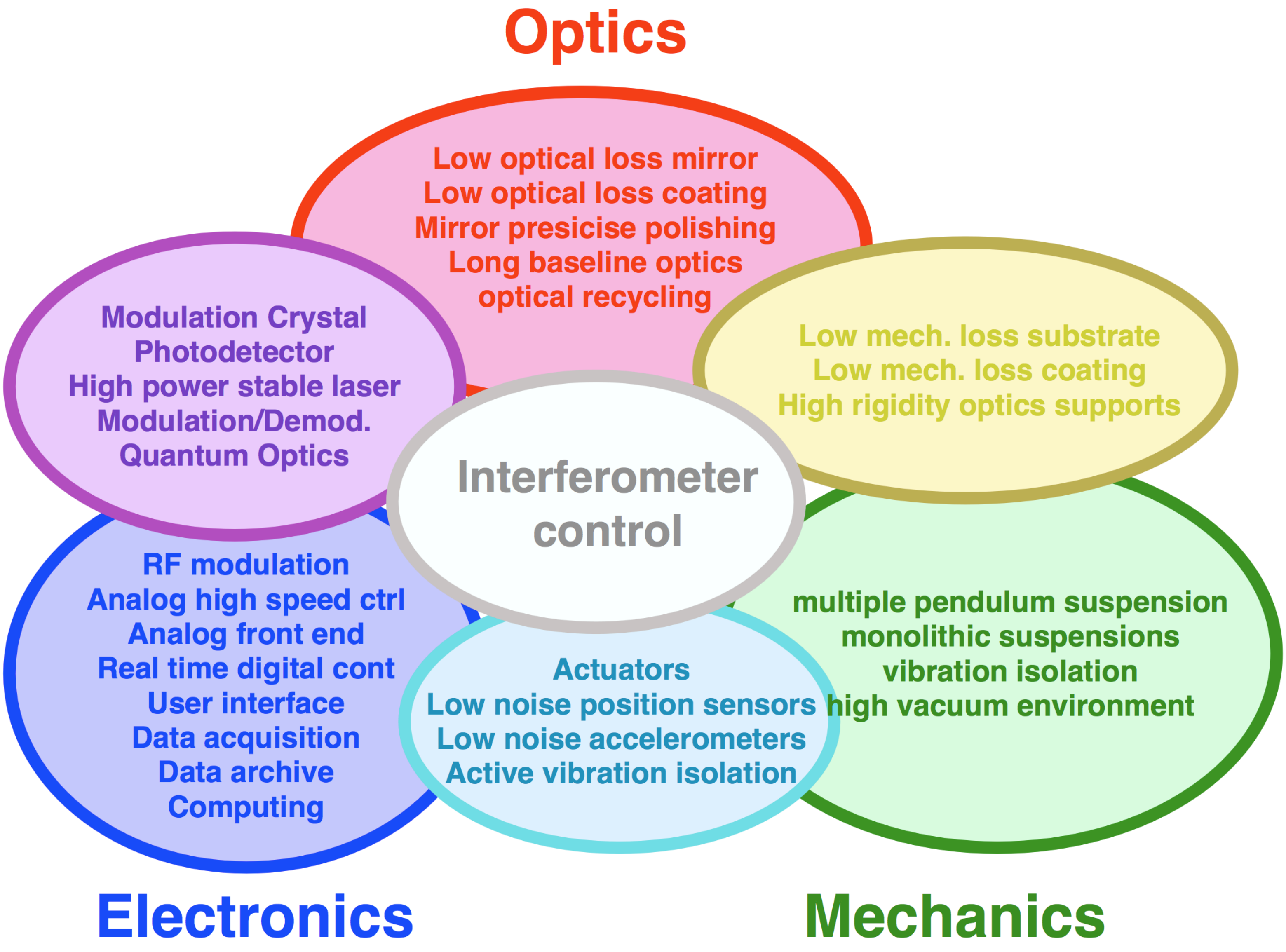


Components of the interferometer

- 3 elements of a GW detector
  - Mechanics
  - Optics
  - Electronics

Components of the interferometer

- 3

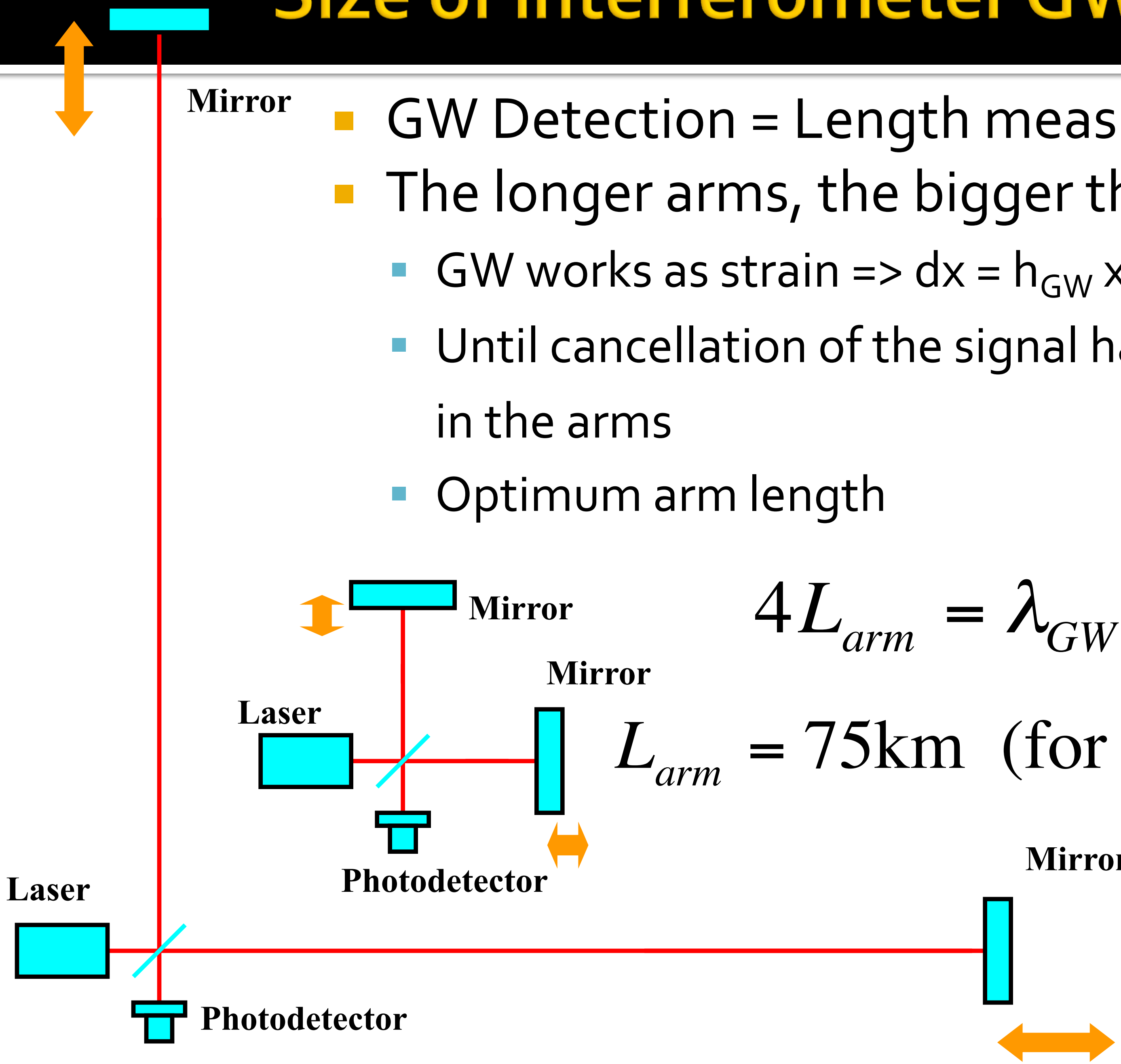


Size of interferometer GW detectors

- GW Detection = Length measurement
- The longer arms, the bigger the effect
  - GW works as strain => $dx = h_{GW} \times L_{arm}$
  - Until cancellation of the signal happens in the arms
  - Optimum arm length

$$4L_{arm} = \lambda_{GW} (= c / f_{GW})$$

$$L_{arm} = 75\text{km} \quad (\text{for } f_{GW} = 1\text{kHz})$$

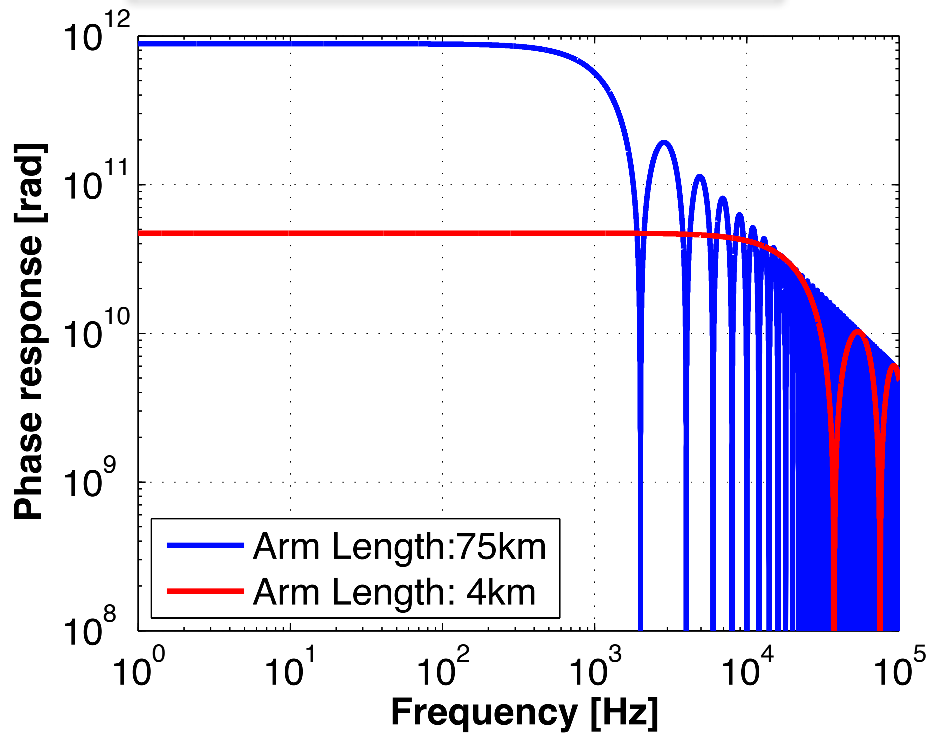


Michelson interferometer

- **Frequency response of the Michelson to GWs**

$$\Delta\phi = \boxed{\frac{2L\Omega}{c} e^{-iL\omega/c} \frac{\sin(L\omega/c)}{L\omega/c}} \cdot h_0 e^{i\omega t}$$

DC Response
longer -> larger



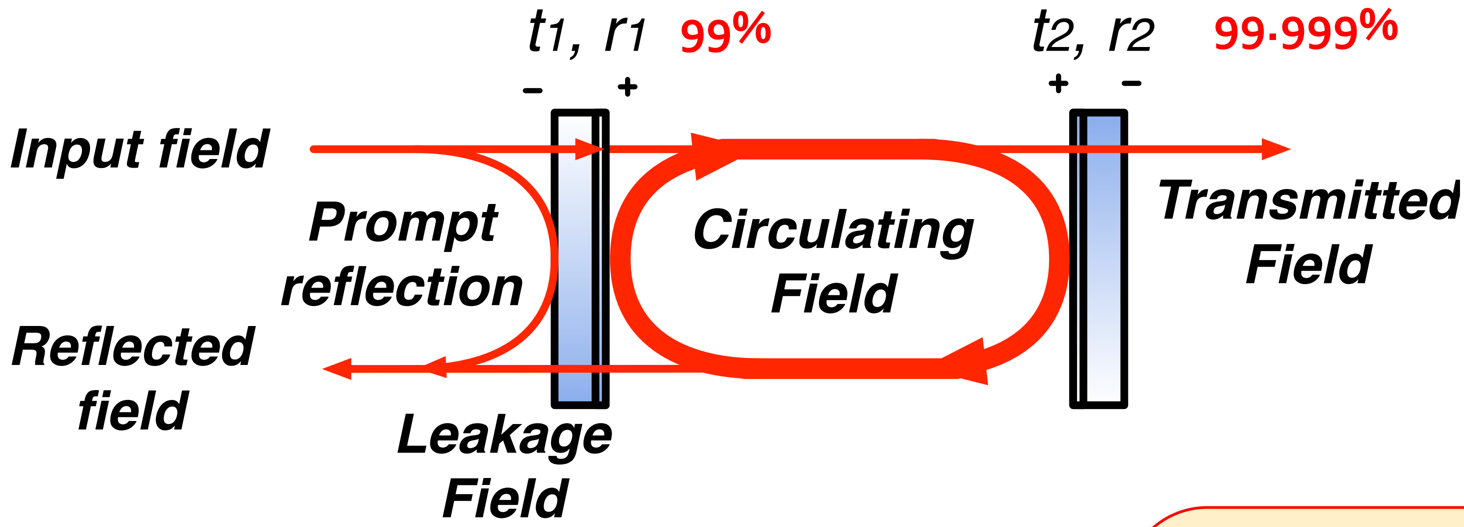
Cut off freq
longer -> lower

Notch freq
f = n c / (2 L)

Michelson arm length optimized for 1kHz GW -> 75km, too long!

Fabry-Perot optical resonator

- Storing light in an optical cavity



  - Input vs circulating: constructive
    Prompt reflection vs leakage: destructive
    => The circulating field grows up

  - N times more power
    Equivalent to have N times longer arm

Finesse

$$\mathcal{F} = \frac{\pi\sqrt{r_1 r_2}}{1 - r_1 r_2}$$

Folding Number

$$N = 2\mathcal{F}/\pi$$

Fabry-Perot optical resonator

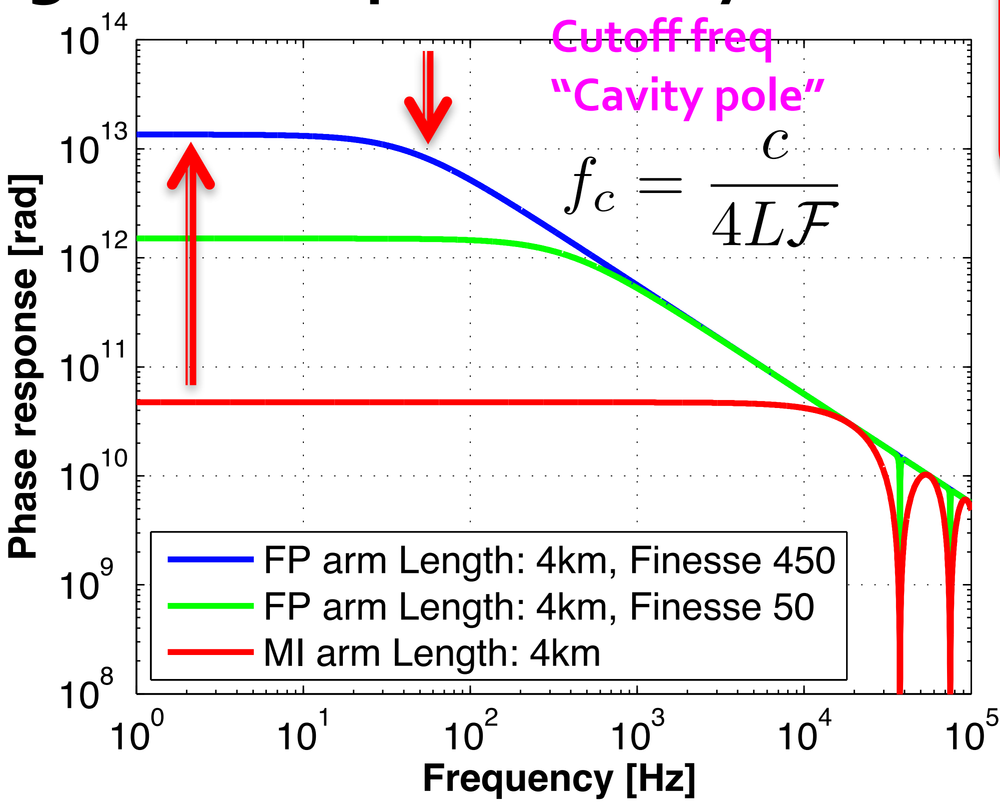
- Storing light in an optical cavity

Finesse

$$\mathcal{F} = \frac{\pi\sqrt{r_1 r_2}}{1 - r_1 r_2}$$

DC Response amplification

$$N = 2\mathcal{F}/\pi$$

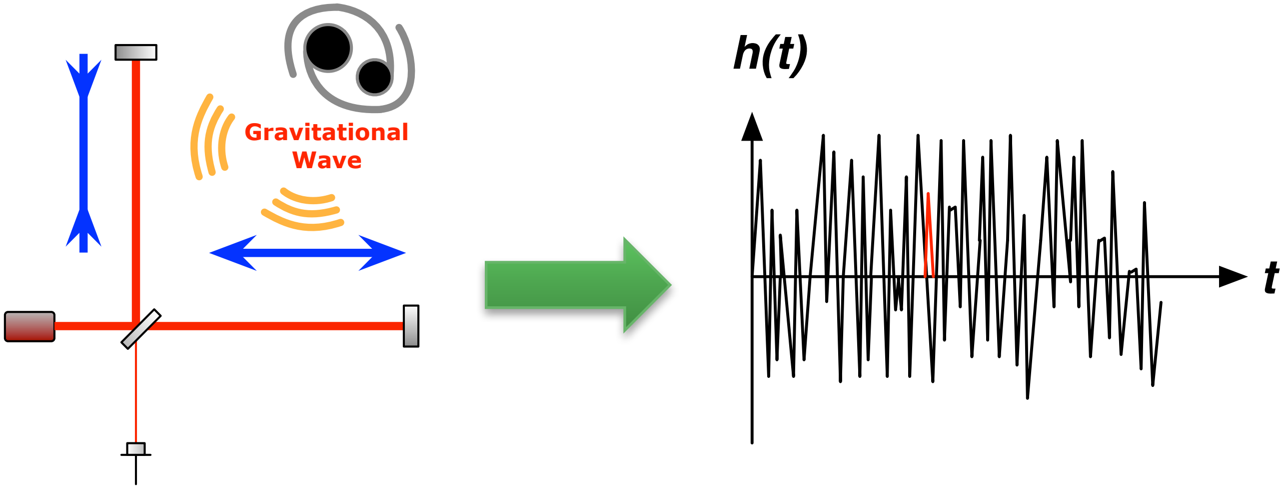


1. FP increases stored power in the arm
2. FP increases accumulation time of the signal

=> Above the roll-off, increasing F does not improve the response

GW telescope?

- A continuous signal stream from an interferometer

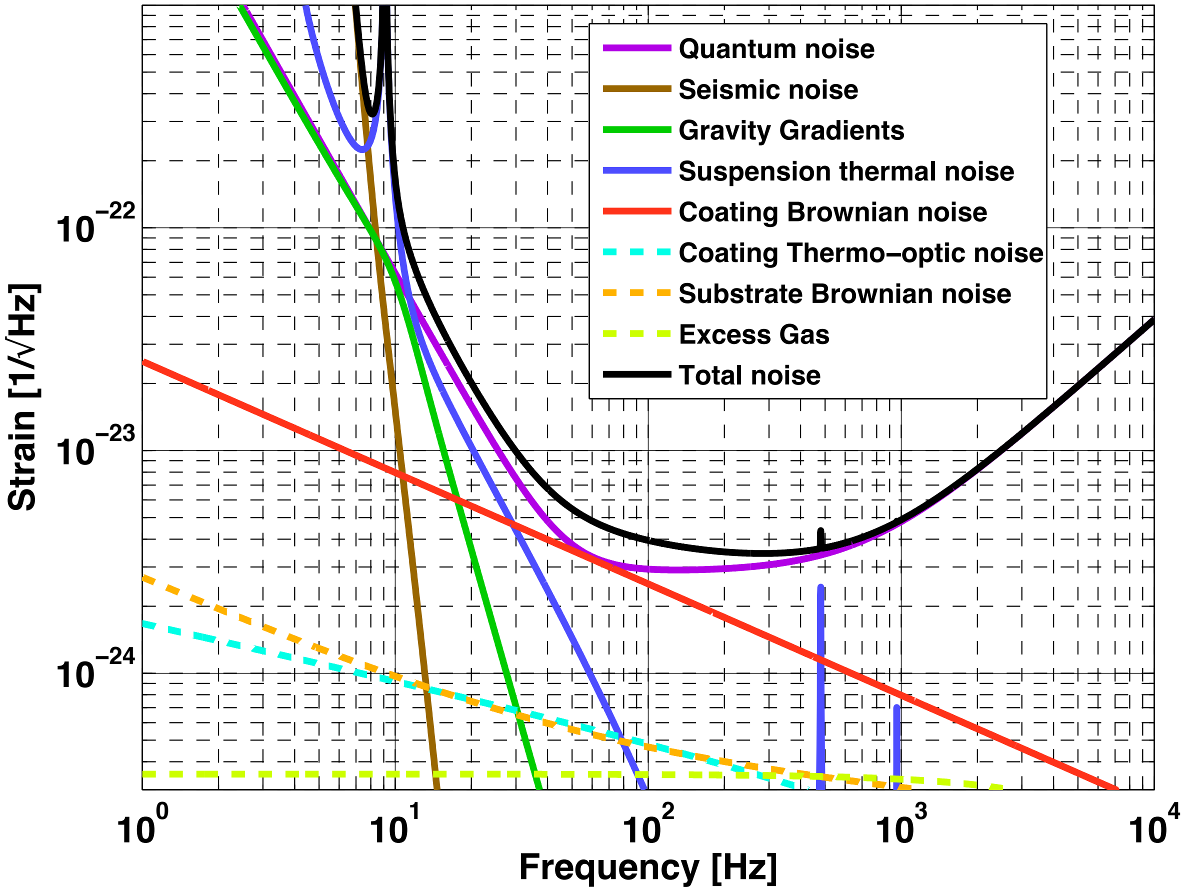


- GWs and noises: in principle, **indistinguishable** => Anything we detect is GW

- **Reduce noises!**
  - Obs. distance is inv-proportional to noise level
  - x10 better => x10 farther => x1000 more galaxies

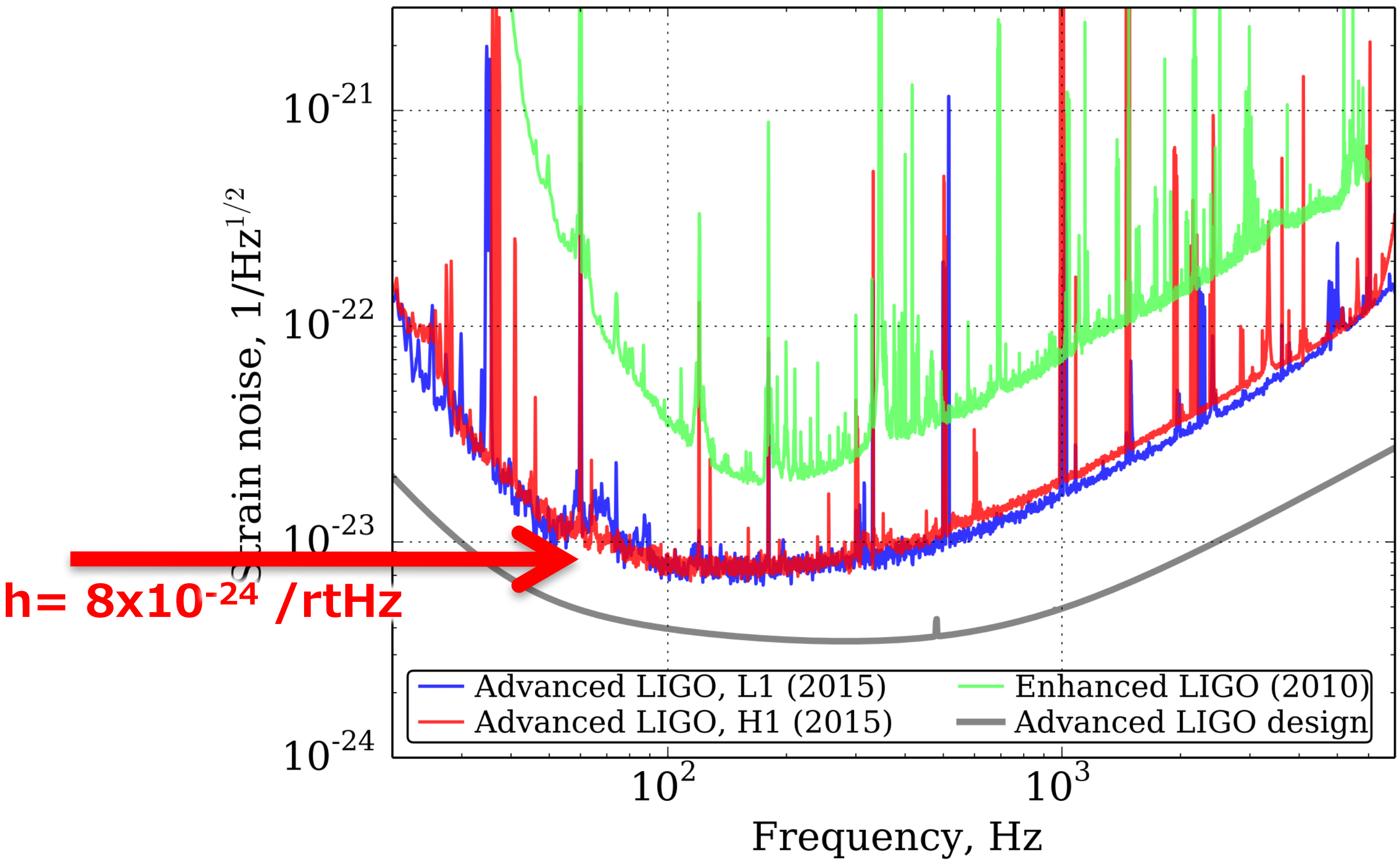
Sensitivity and noise

- Sensitivity (=noise level) of Advanced LIGO
- Design



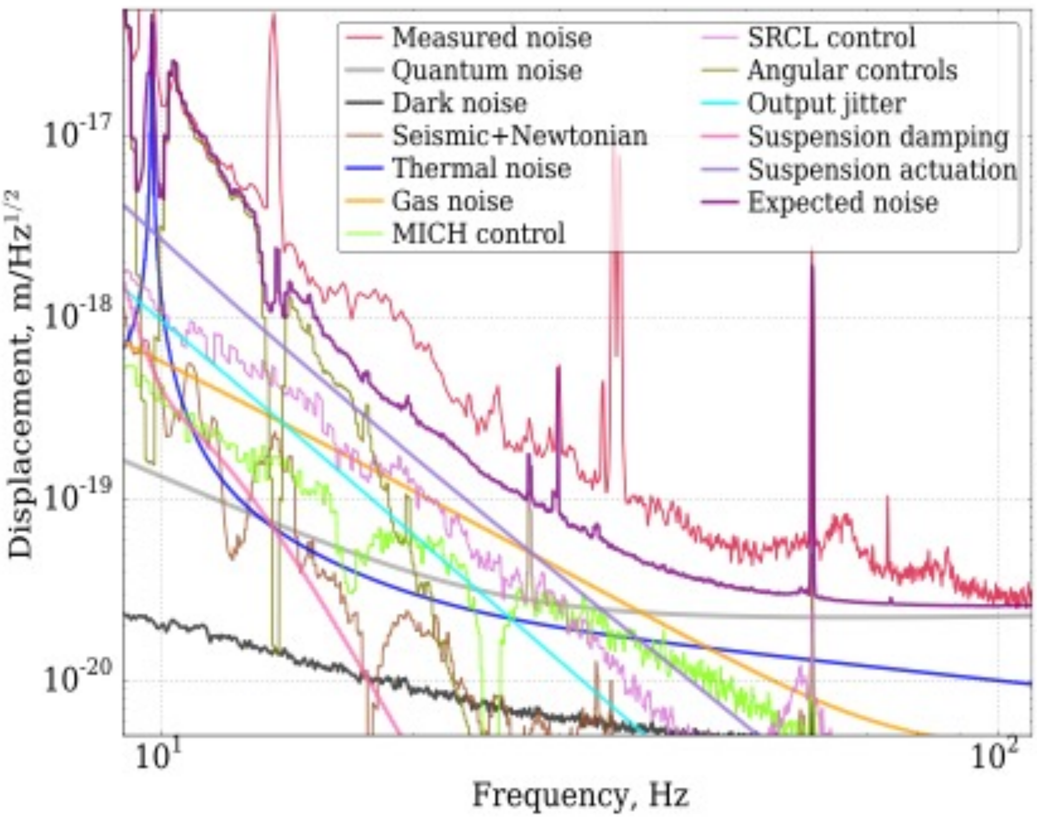
Sensitivity and noise

- Sensitivity (=noise level) of Advanced LIGO
- Current sensitivity

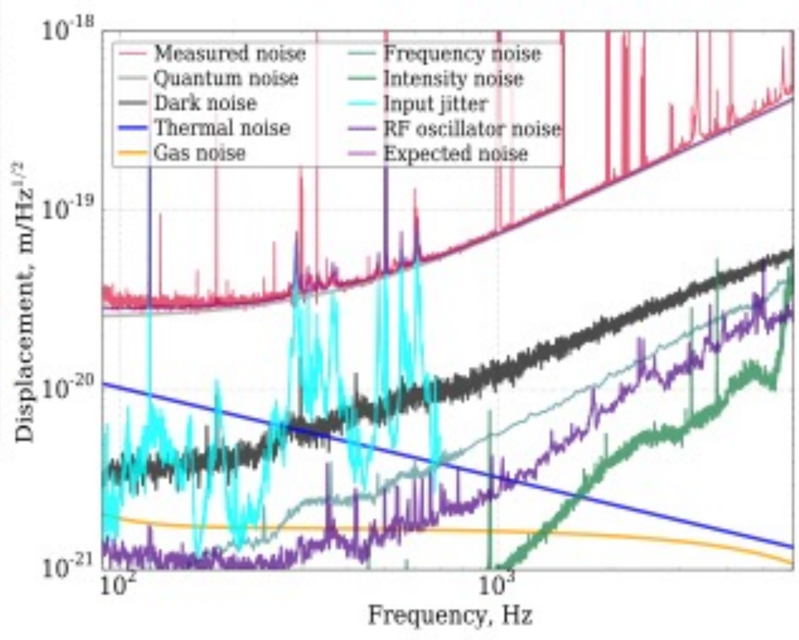


Sensitivity and noise

- Sensitivity (=noise level) of Advanced LIGO
- Noise budget



(a) LIGO Livingston Observatory



(b) LIGO Hanford Observatory

Summary

- GWs ~ ripples of the spacetime
- GW effect is very small
  ~ the effect is so small ($h<10^{-21}$)
- ~~**Not yet** directly detected~~
  Sufficiently sensitive detectors allow us to detect
- **Michelson**-type interferometers are used
- GW detection is a **precise** length (=displacement) measurement!

Summary

- Basically, **the larger, the better.**
  LIGO has two largest interferometers in the world, and multiple detector will have very important role in GW astronomy

- **IFO consists of many components**
  Optics / Mechanics / Electronics
  and their combinations (e.g. Opto-Electronics)

- Noises and signals are, in principle, indistinguishable.
  Noise reduction is essential