How to measure a distance of one thousandth of the proton diameter? The detection of gravitational waves

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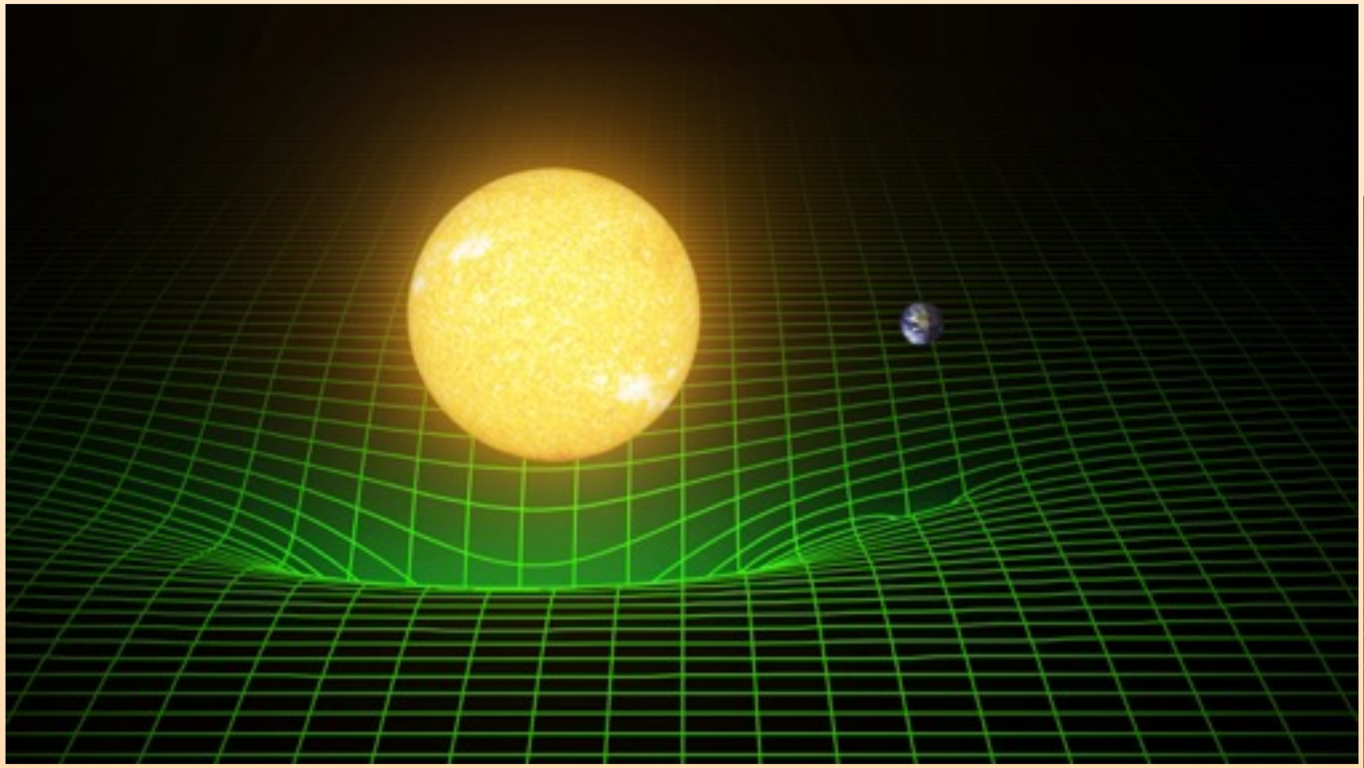
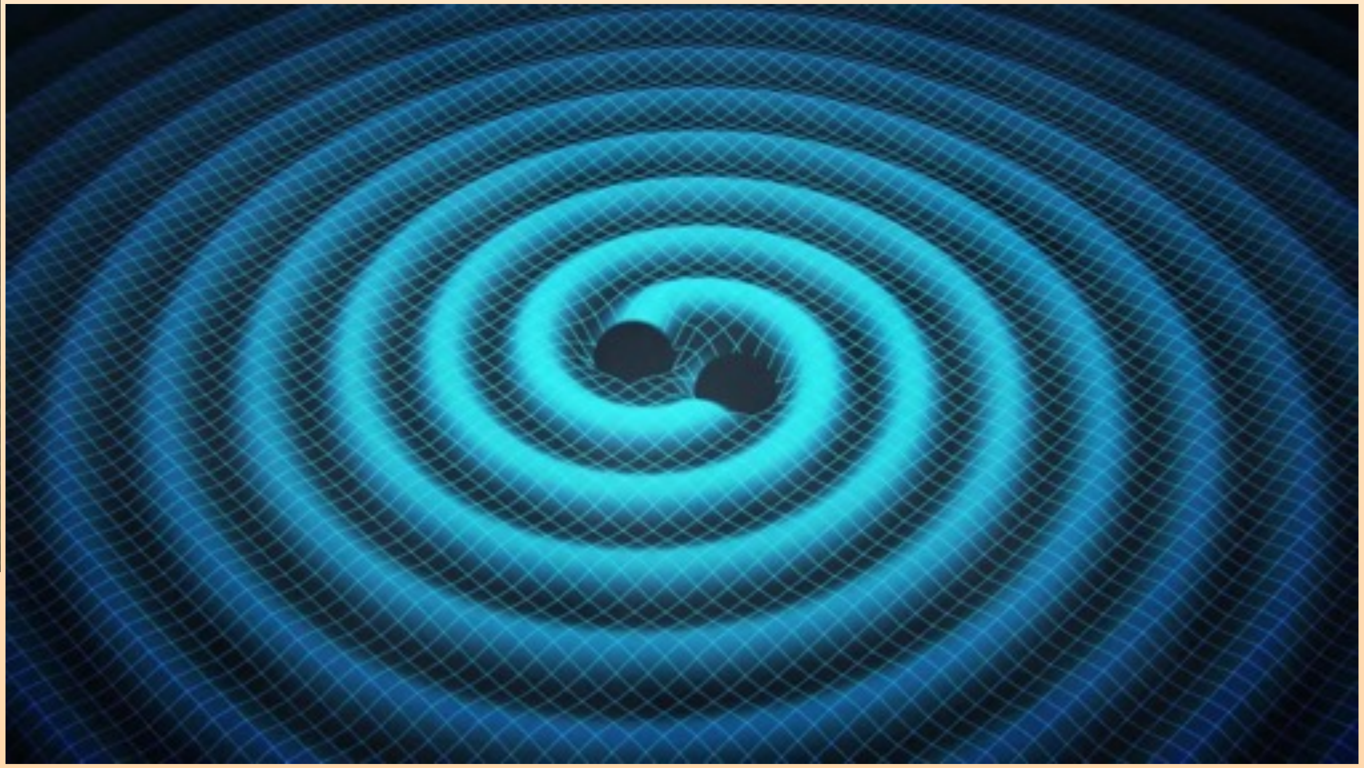
General Relativity & Gravitational Waves

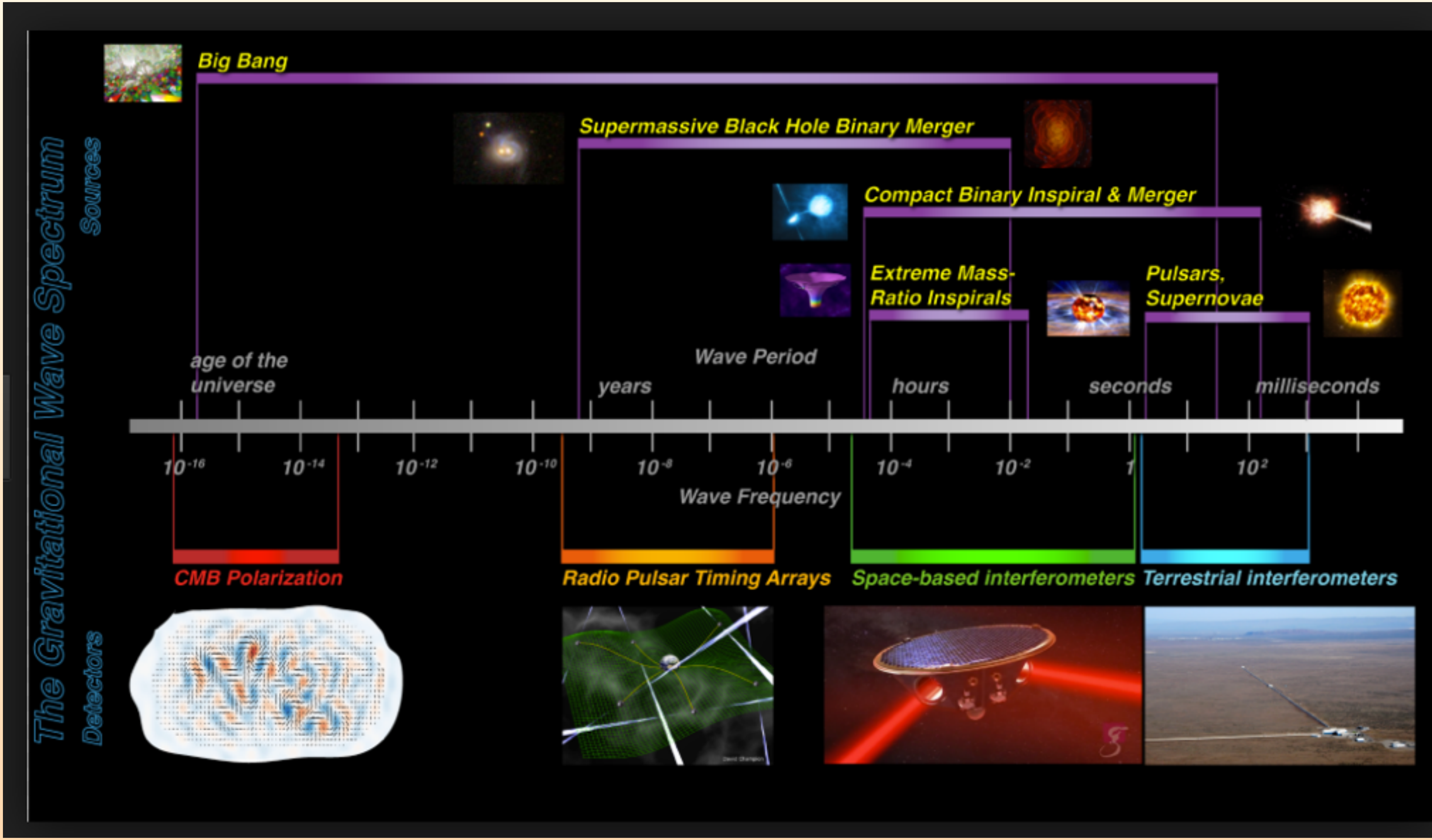
- 1915: General Relativity -> dynamic space-time
  gravity = space-time curvature

- 1916: Gravitational Waves -> ripples in space-time propagating at the speed of light

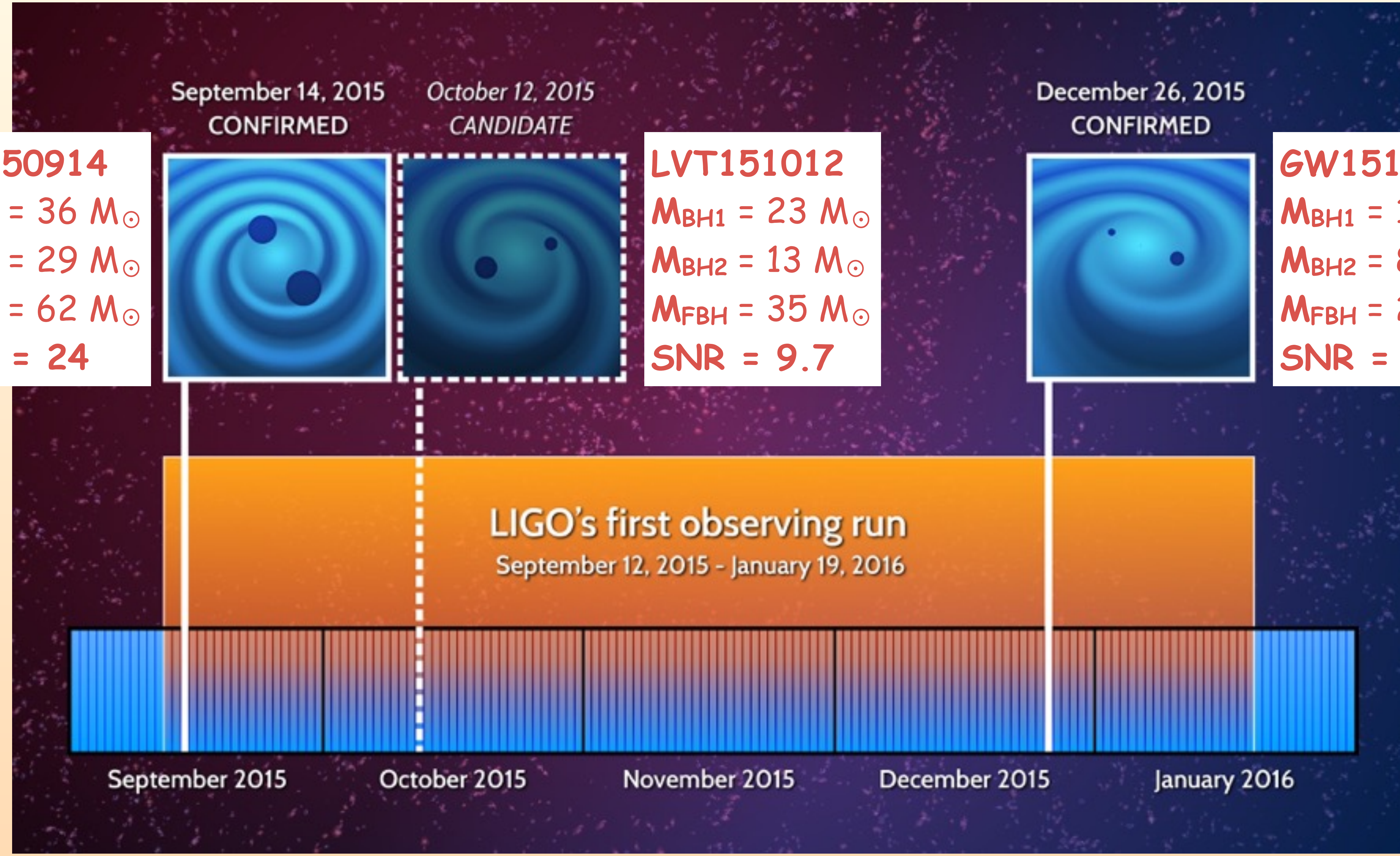




Gravitational Waves Sources & Detectors



Gravitational Waves Observations



GW150914
$M_{BH1} = 36\ M_\odot$
$M_{BH2} = 29\ M_\odot$
$M_{FBH} = 62\ M_\odot$
SNR = 24

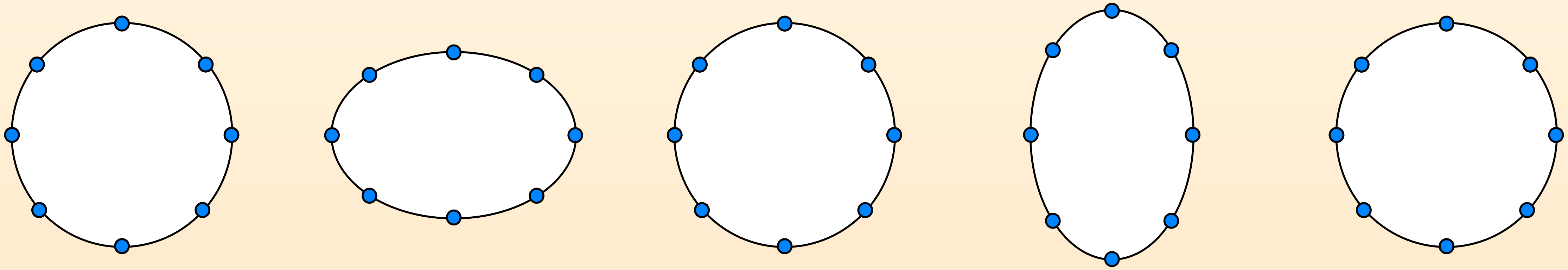
LVT151012
$M_{BH1} = 23\ M_\odot$
$M_{BH2} = 13\ M_\odot$
$M_{FBH} = 35\ M_\odot$
SNR = 9.7

GW151226
$M_{BH1} = 14\ M_\odot$
$M_{BH2} = 8\ M_\odot$
$M_{FBH} = 21\ M_\odot$
SNR = 13

The events begin to reveal a population of stellar mass black hole mergers

How to measure Gravitational Waves?

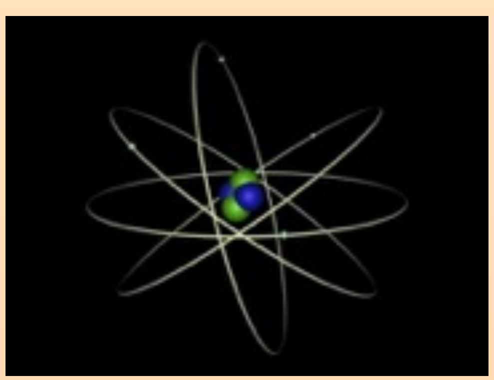
Gravitational Waves on Earth modify distances: stretch space in one direction and compress space in the other direction.



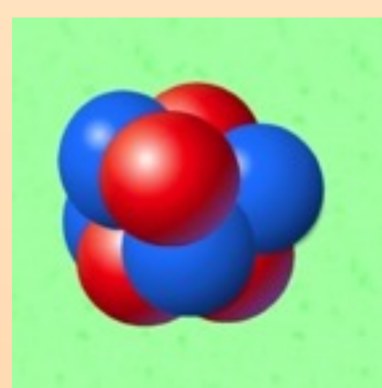
This deformation is TINY:

$d = 10^{-18}$ m = 0.000000000000000001 m

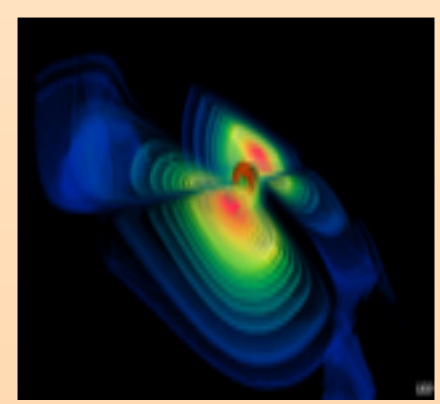
1 m



10^{-10} m



10^{-15} m

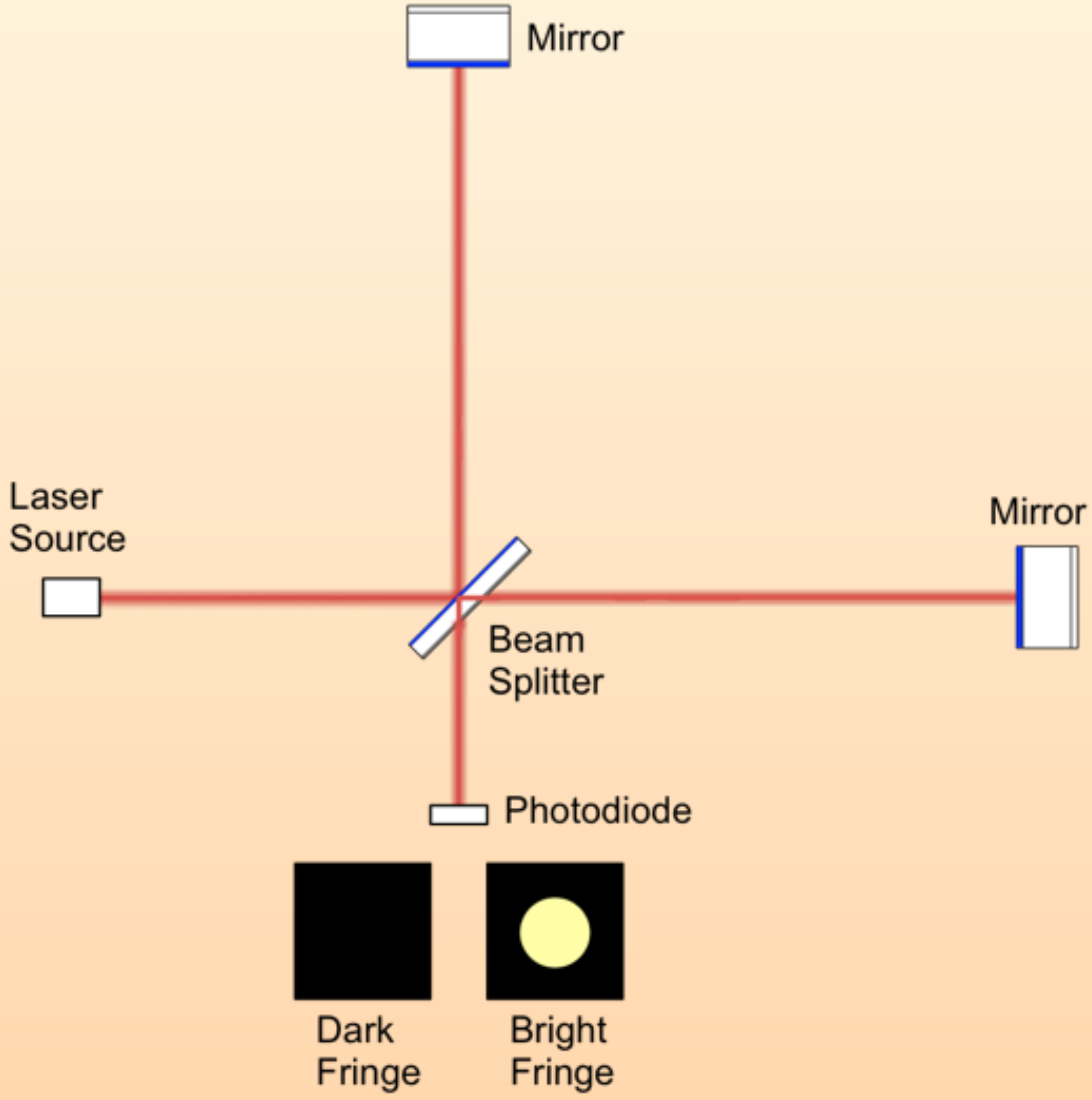


10^{-18} m

How to measure this tiny deformation?

How to measure Gravitational Waves?

The Michelson Interferometer detects differential effects in arms.

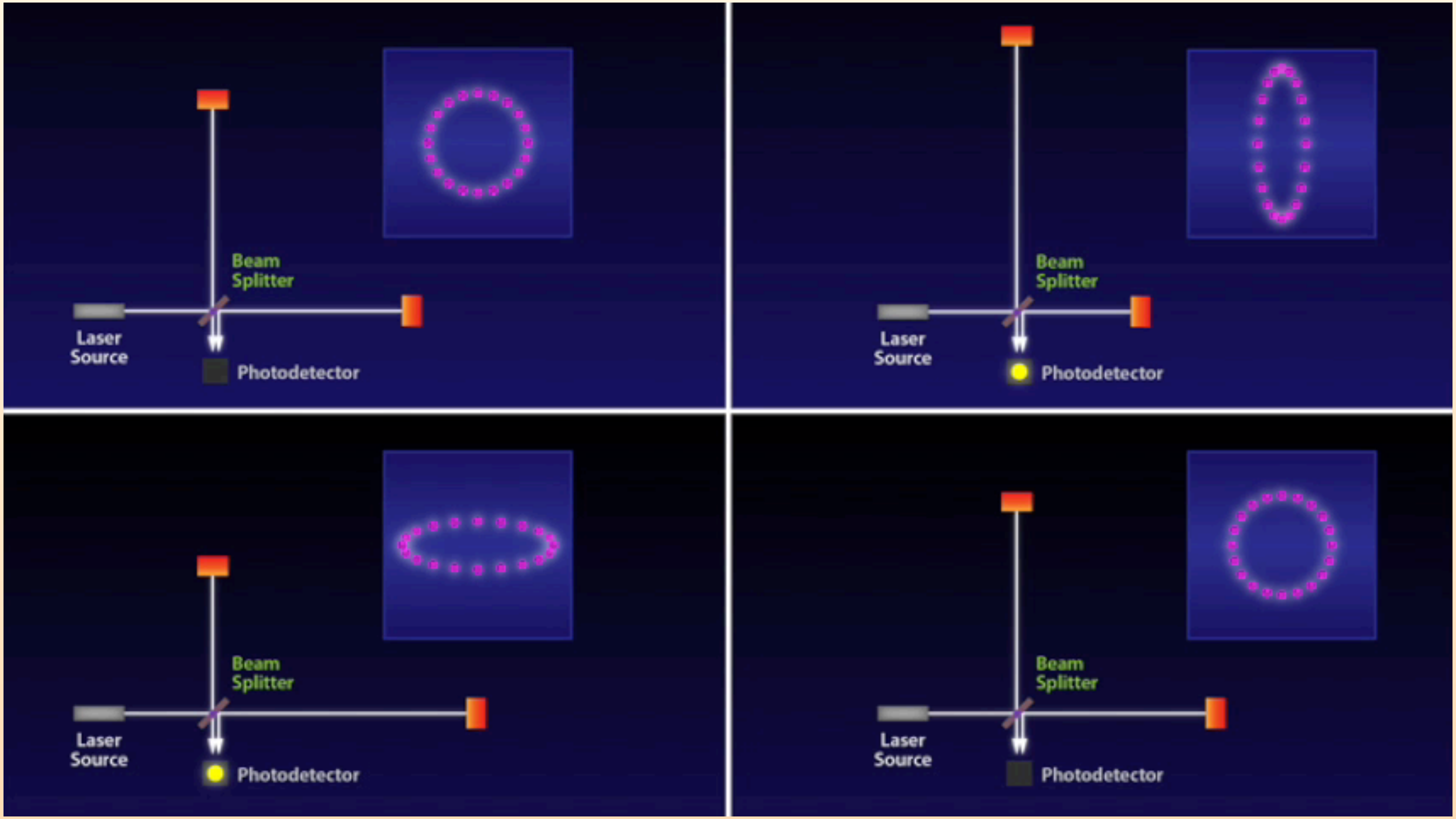


Dark Fringe: destructive field recombination.

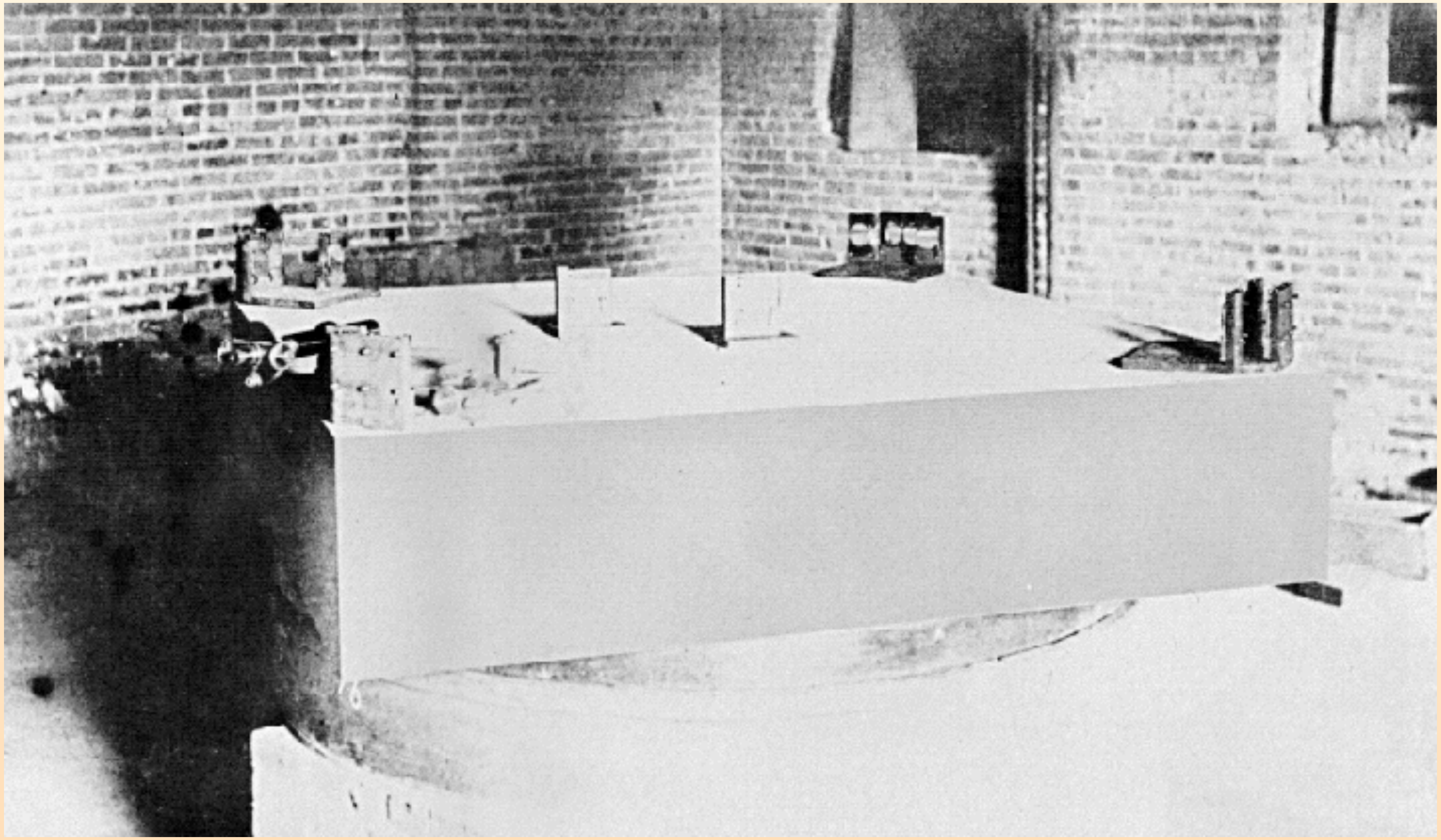
Bright Fringe: constructive field recombination.

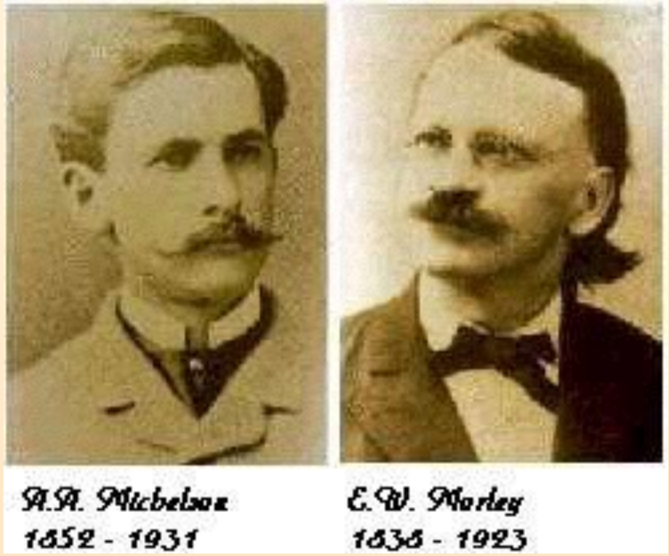
GW passage changes the working point.

Gravitational Waves & Michelson Interferometer



Gravitational Waves & Michelson Interferometer





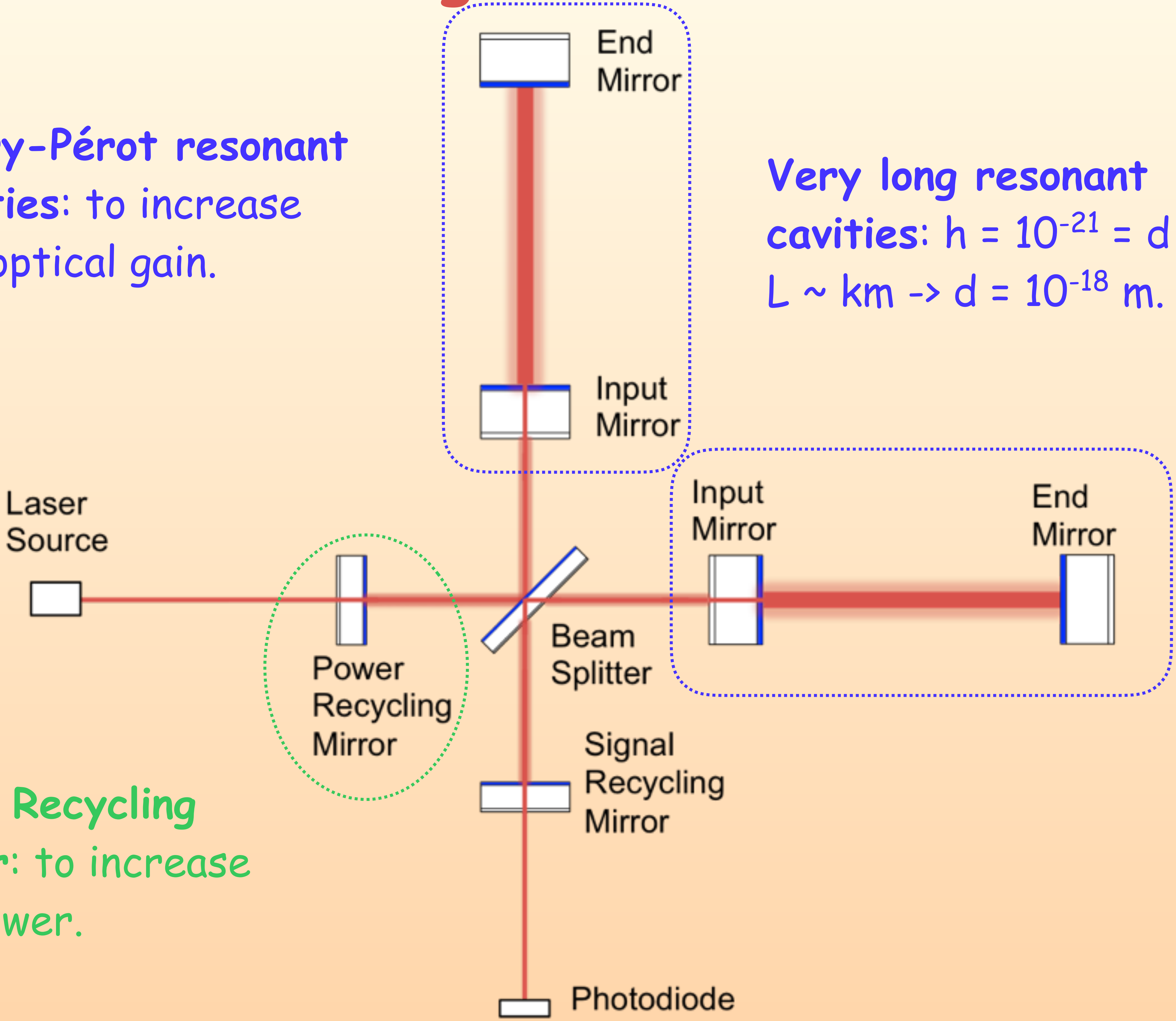
$d \sim \lambda / 50$

How to measure $d = 10^{-18}$ m $= \lambda / 10^{12}$?

LIGO & Virgo Interferometers

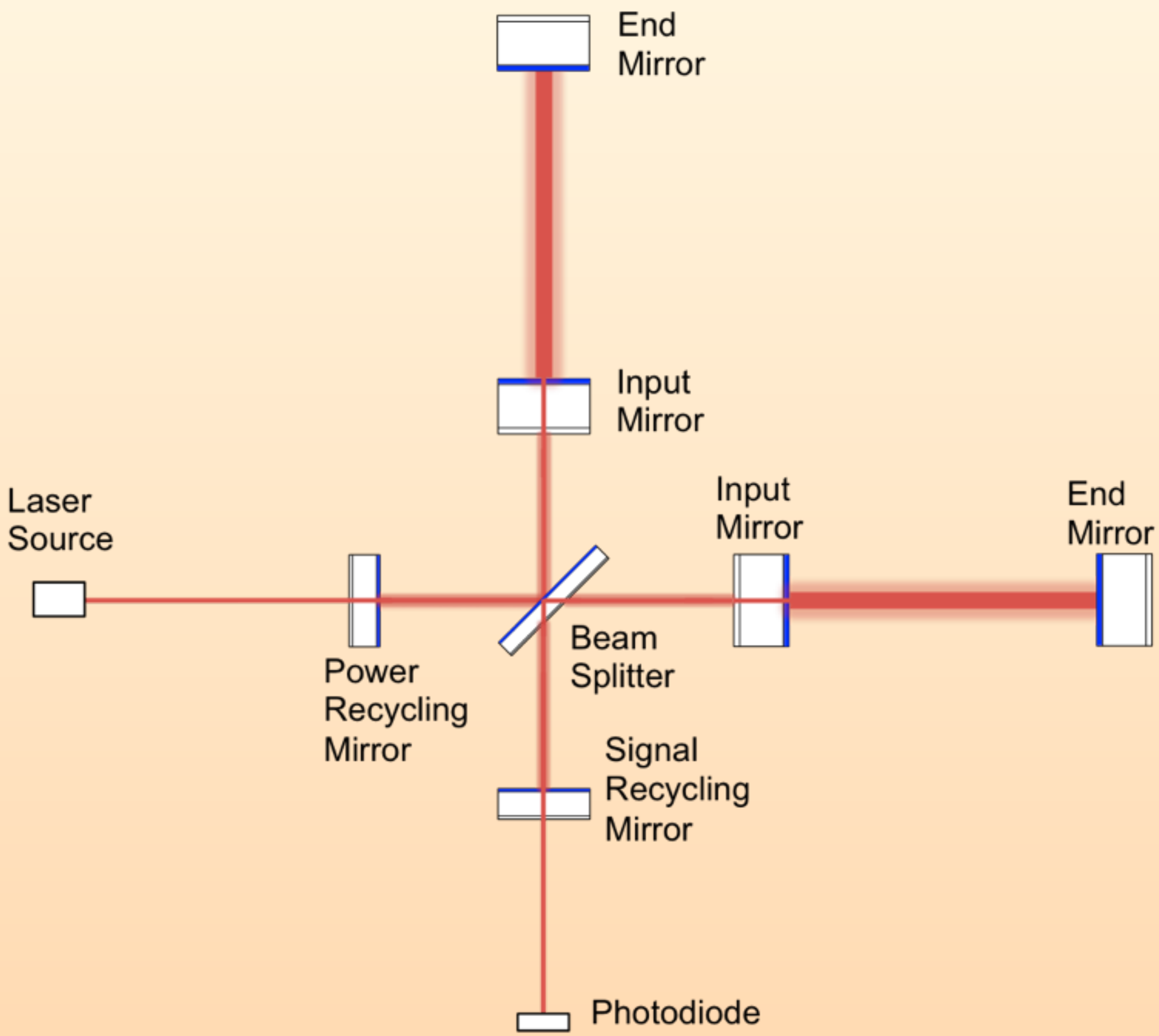
Fabry-Pérot resonant cavities: to increase the optical gain.

Very long resonant cavities: $h = 10^{-21} = d / L$; $L \sim km \rightarrow d = 10^{-18}$ m.



Power Recycling Mirror: to increase the power.

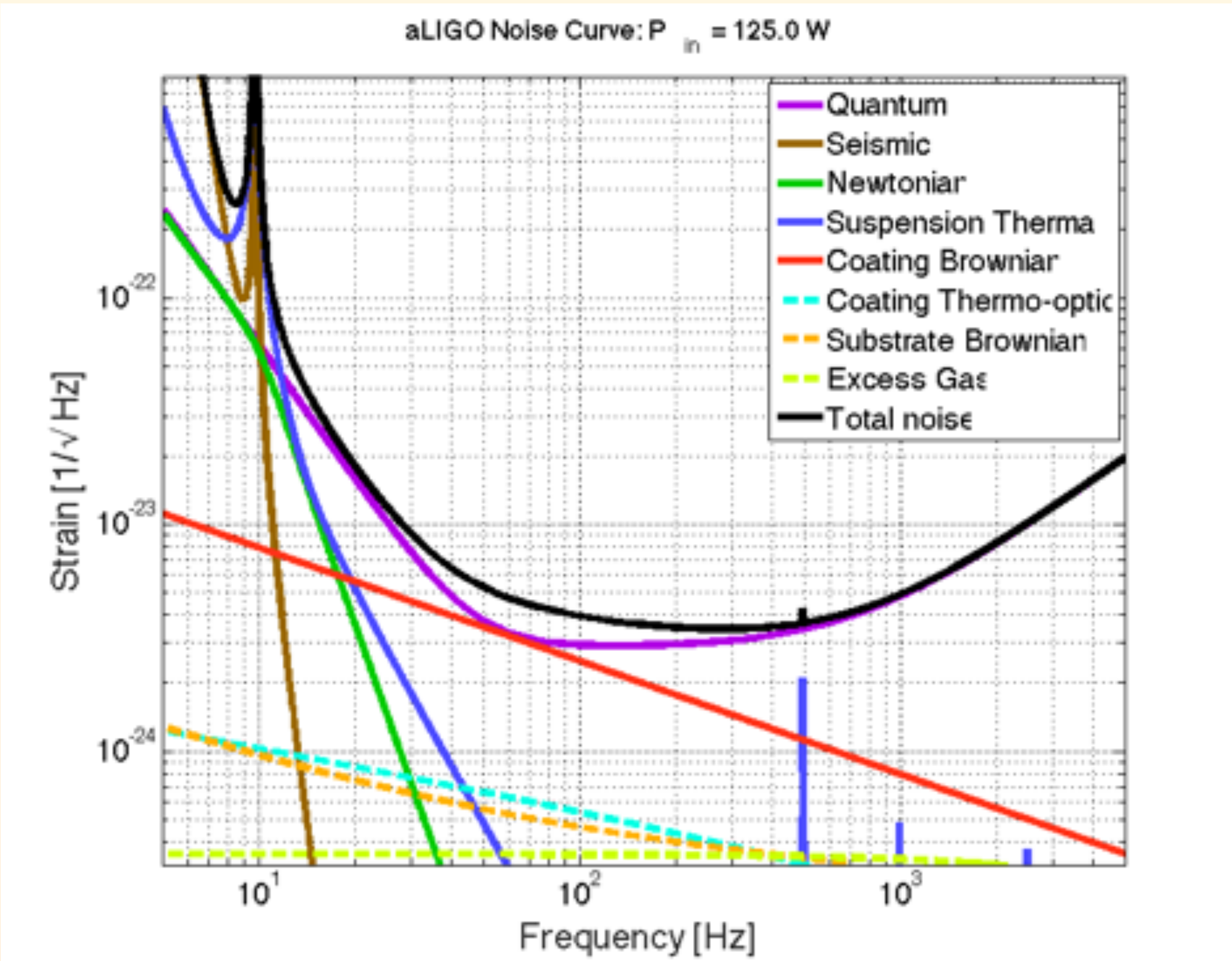
LIGO & Virgo Interferometers



Mirrors fluctuations induced by many phenomena :

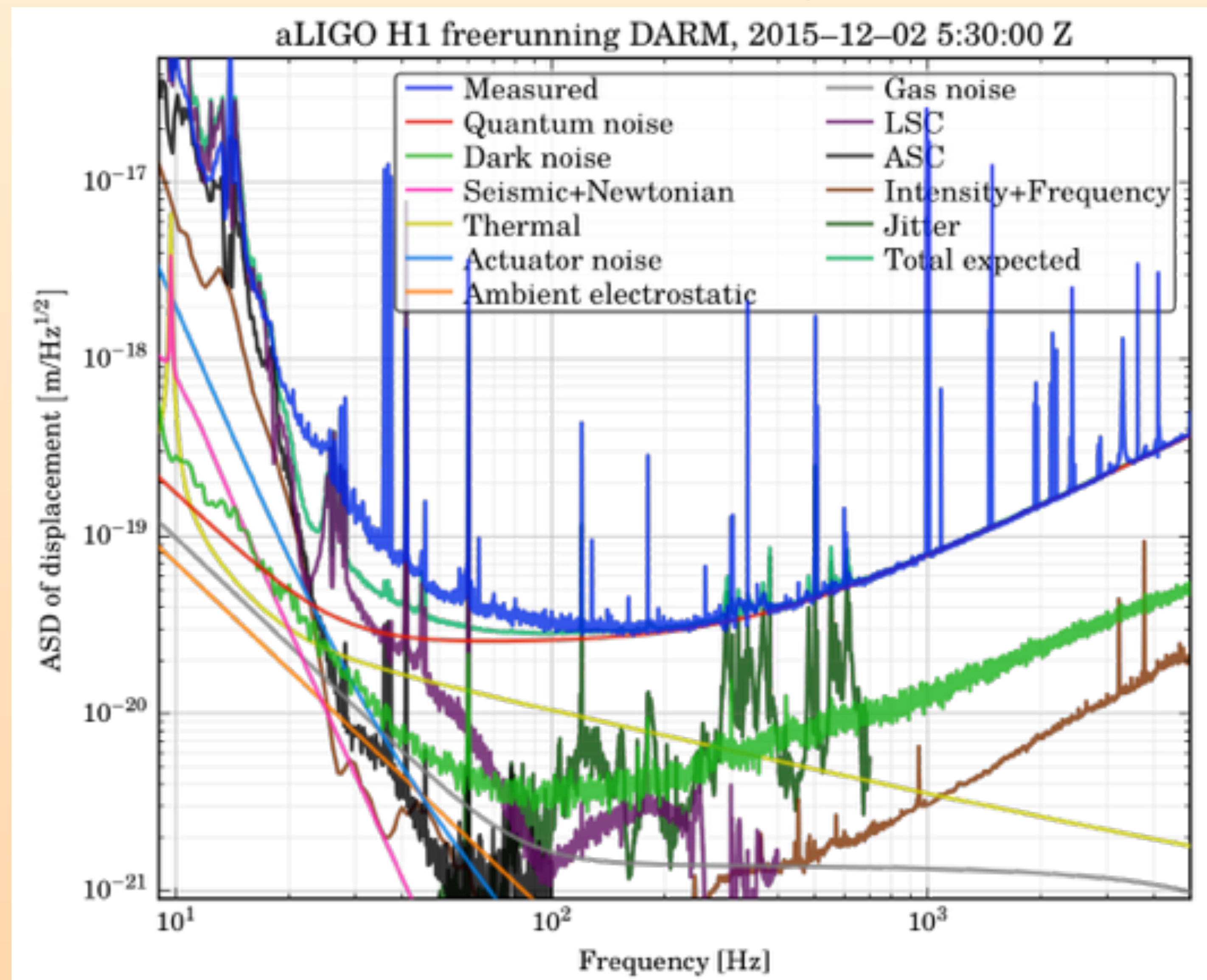
- motion of the Earth -> **seismic noise**
- molecules thermal motion -> **thermal noise**
- light quantum nature -> **quantum noise**
- laser instability -> **frequency noise**
- mirror defects -> **scattered light noise**
- environmental conditions -> **environmental noise**

LIGO & Virgo Interferometers



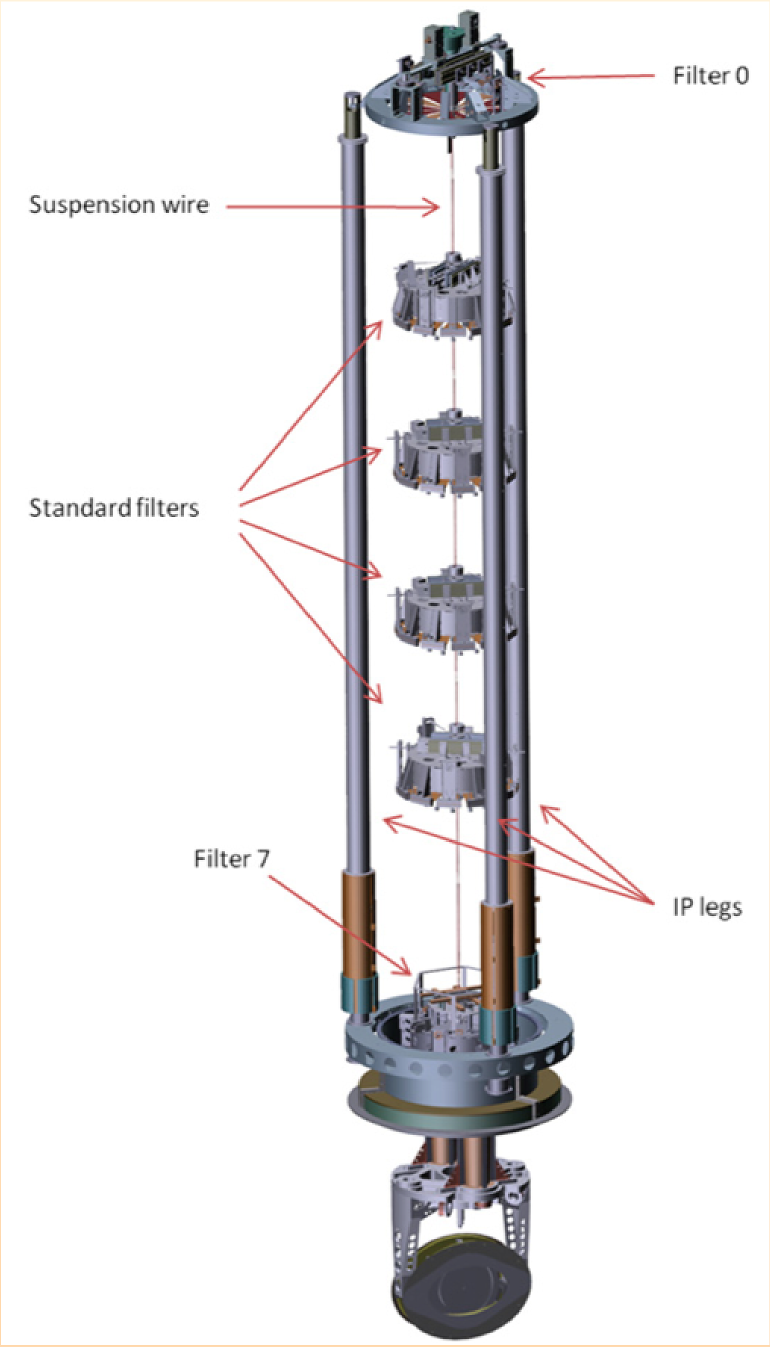
Theoretical Sensitivity

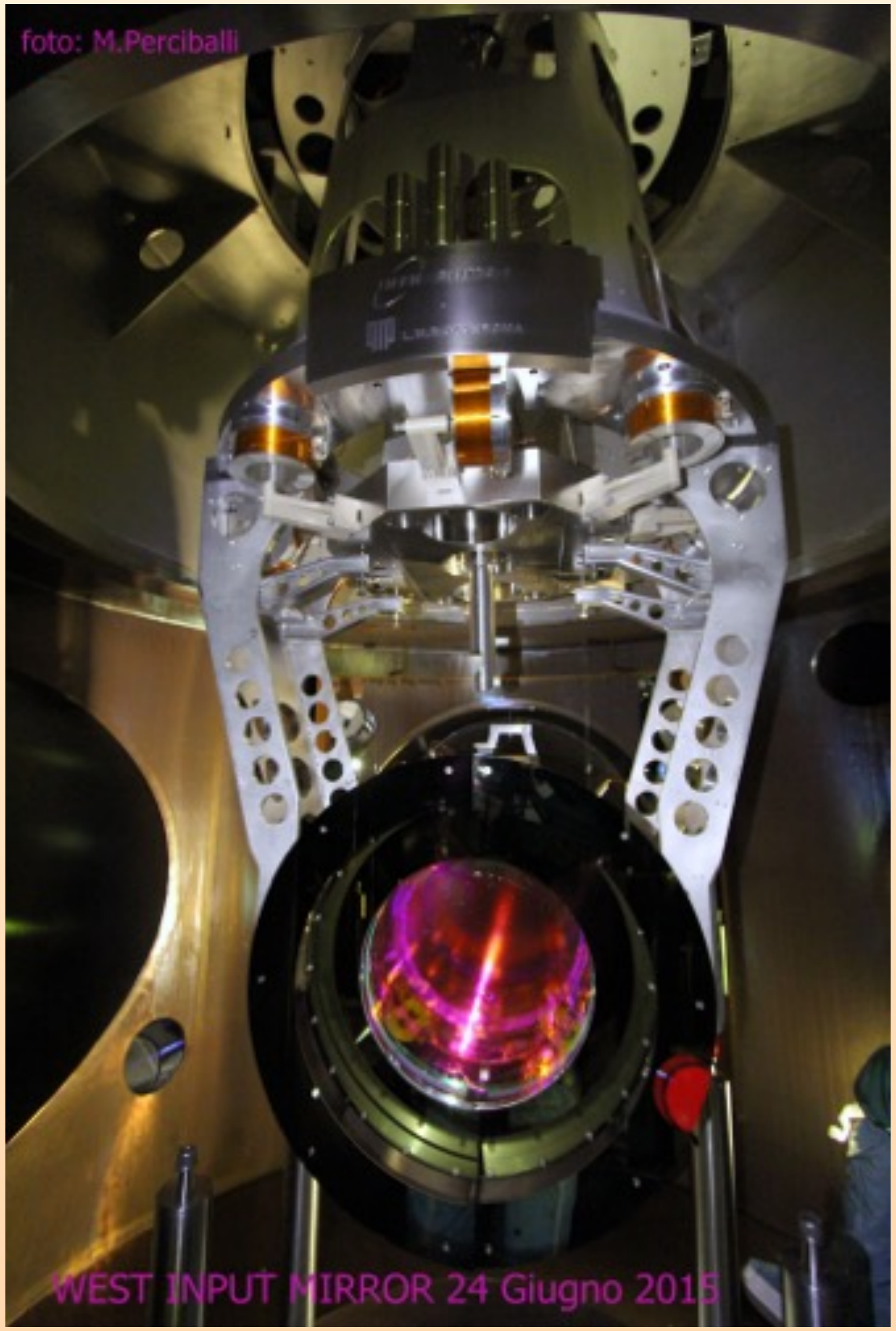
Real Noise Budget



LIGO & Virgo Interferometers

At Virgo site **Seismic noise** is ~ 10^{-9} m @ 10 Hz. It must be attenuated: mirrors are suspended -> attenuation > 10^{10} @ 10 Hz.

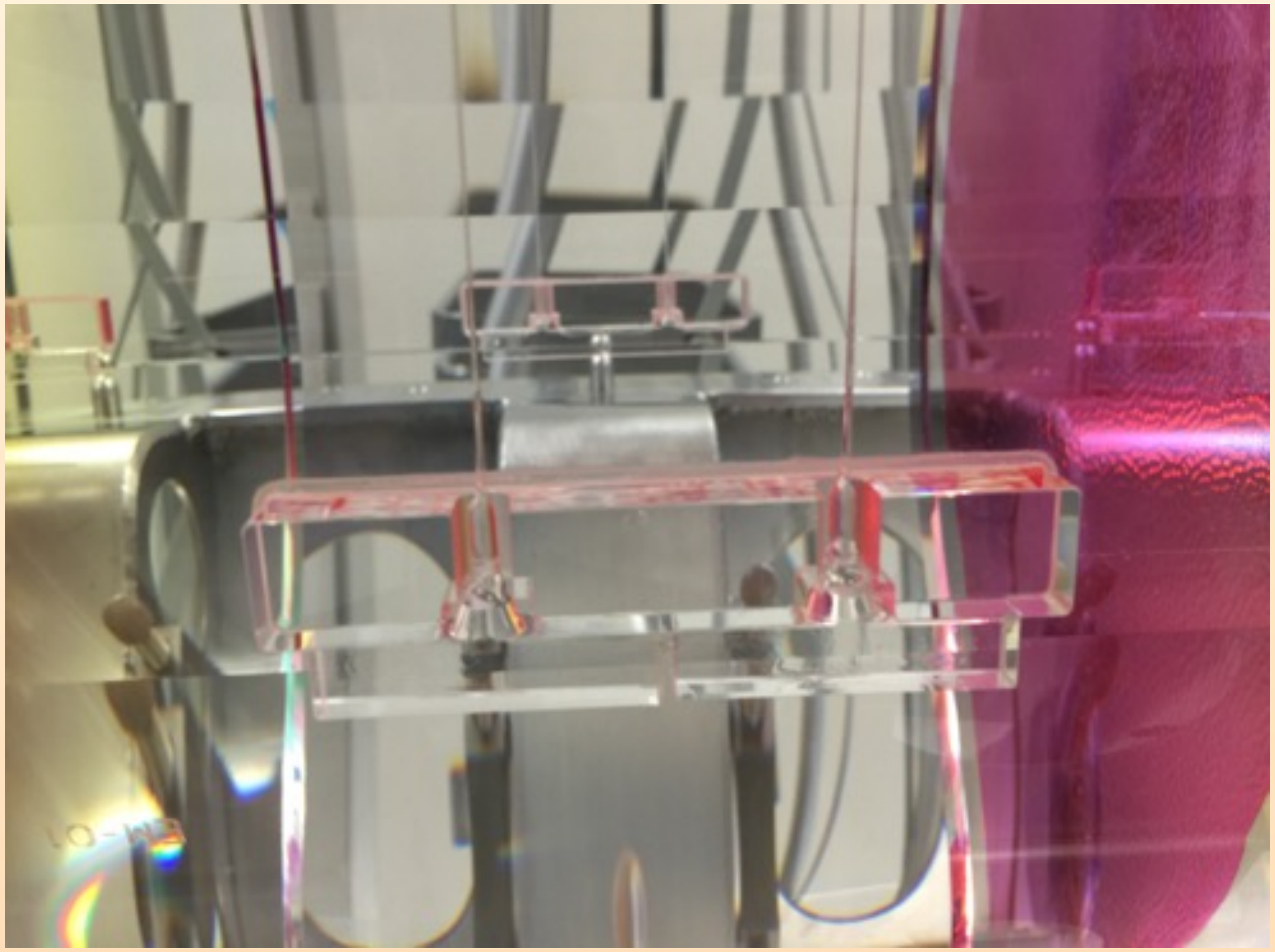




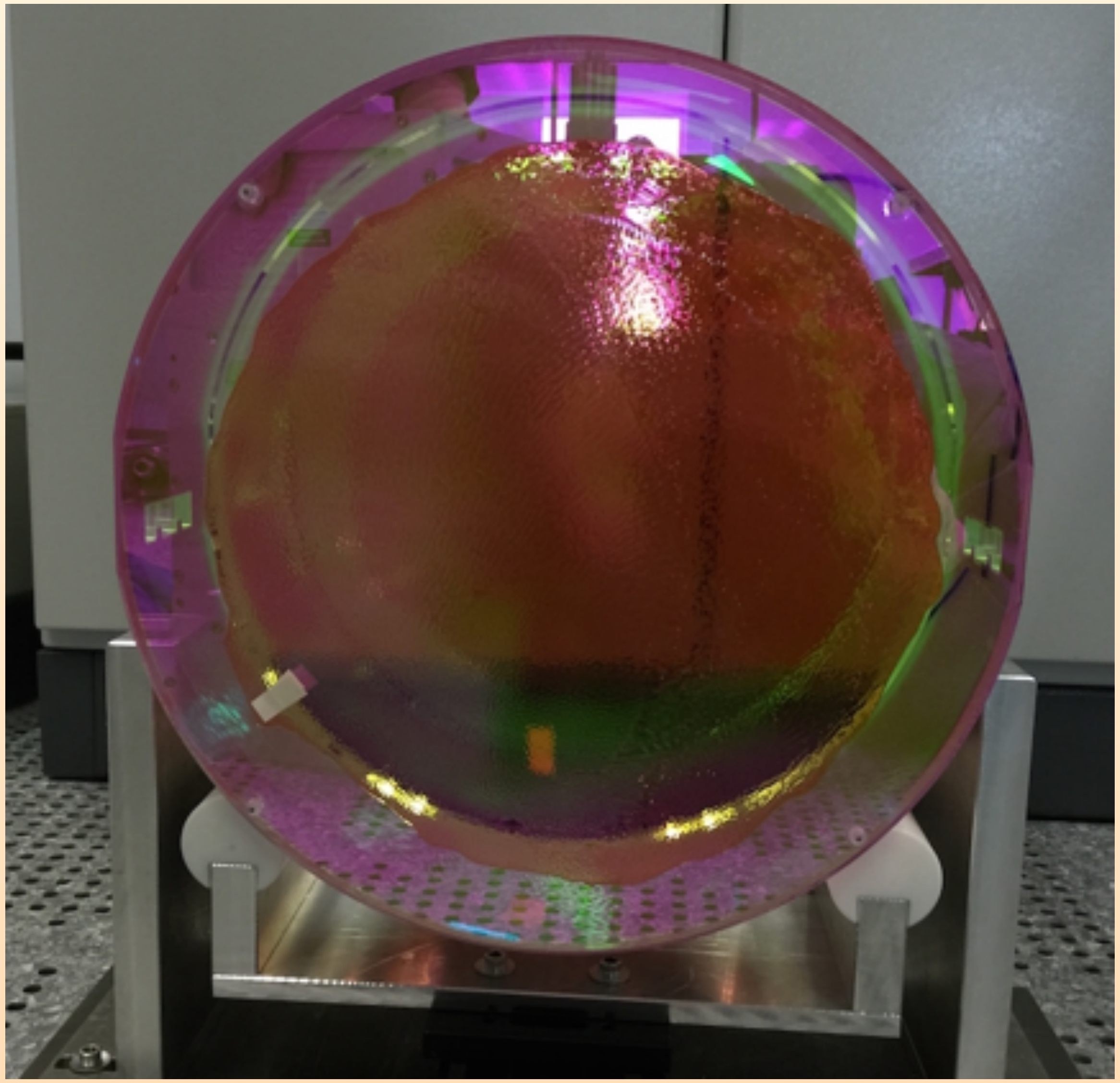
Virgo (Passive) Suspension System

LIGO & Virgo Interferometers

Thermal Noise: suspension wires (losses) and mirrors coating (losses & roughness).



Suspensions: silica wires used to create a monolithic structure between suspension and mirror (losses ~ 10^{-7}).



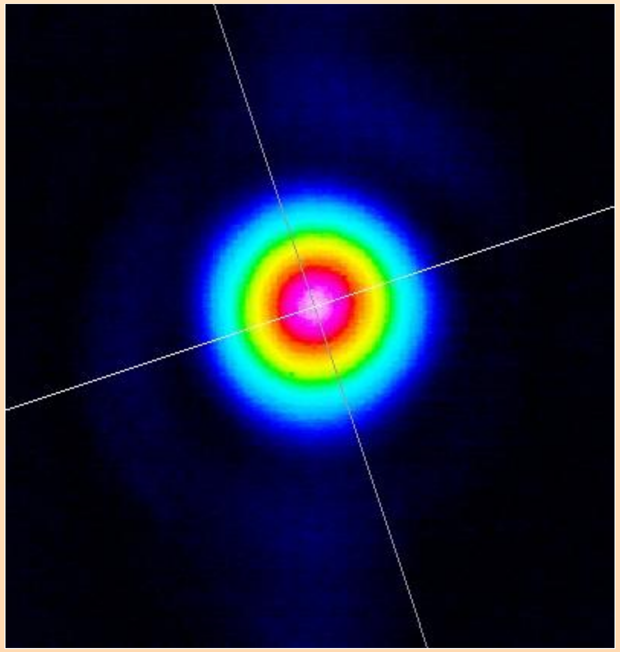
Mirrors: surface defects ~ 0.5 nn over d = 35 cm with losses ~ 10^{-4} (coating made by LMA Lyon)

LIGO & Virgo Interferometers

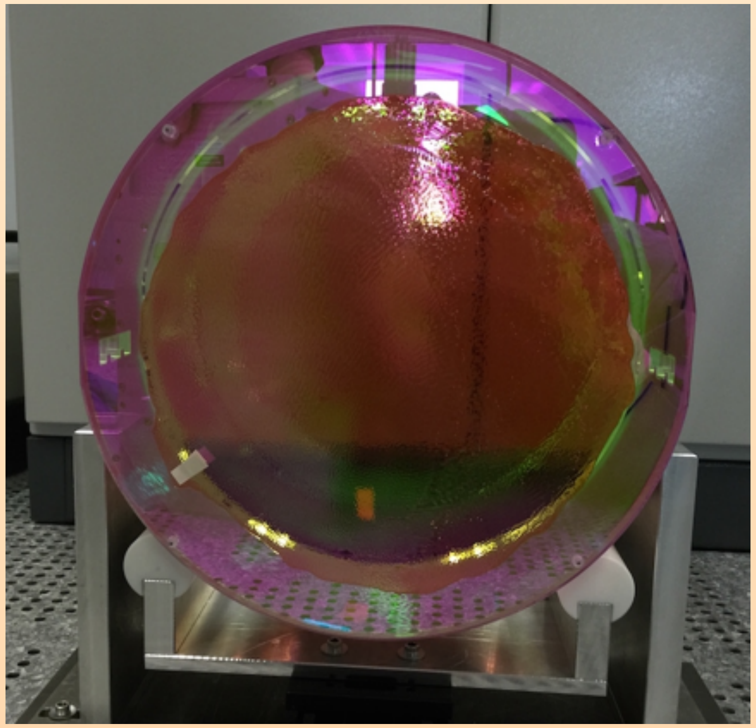
Two components of **quantum noise**: **shot noise** (at high frequency) and **radiation pressure noise** (at low frequency).

Shot noise: fluctuation oh photon number impinging on the photodetector $\propto 1 / P_{in}$. SN ~ 10^{-20} m for P_{in} = 100 W -> **high power laser.**

Radiation pressure noise: motion induced by photons impacting on the mirrors $\propto 1 / m$ -> **heavy mirrors**.



Laser beam: P ~ 200 W



Heavy Mirrors: m = 40 kg

LIGO & Virgo Interferometers

Frequency noise of a top class commercial laser ~ $10^4/f$ Hz/√Hz @ 1 Hz.

Frequency noise needed in GW detector ~ 10^{-6} Hz/√Hz @ 10 - 10k Hz.

Frequency stabilized using auxiliary cavities and the Interferometer.

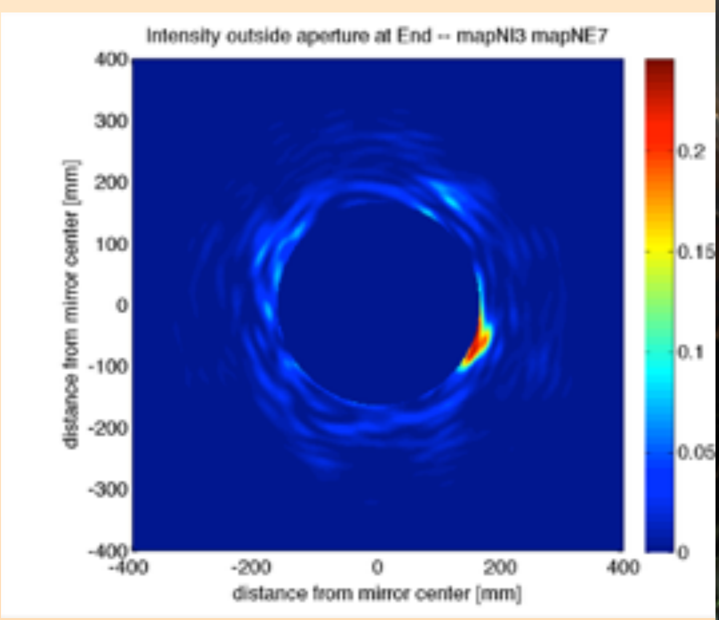
Laser bench

Laser amplifier

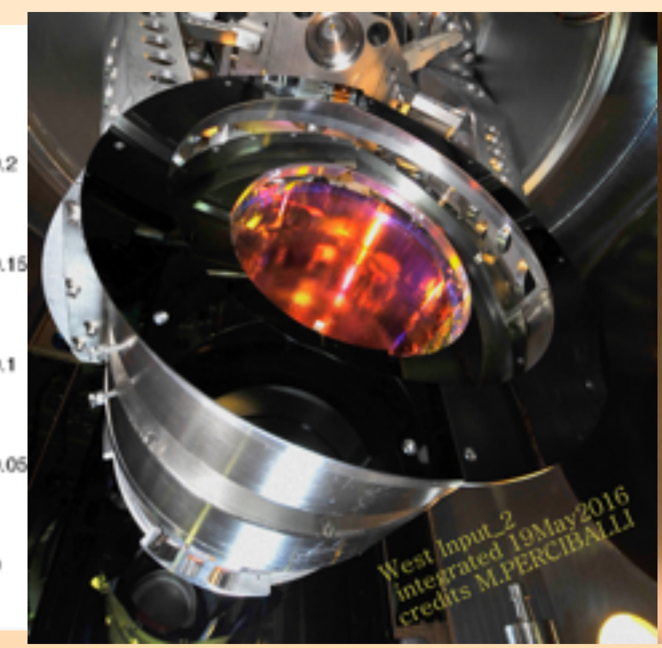
LIGO & Virgo Interferometers

Scattered light: difficult to estimate but always present -> one of the major risk towards the final sensitivity.

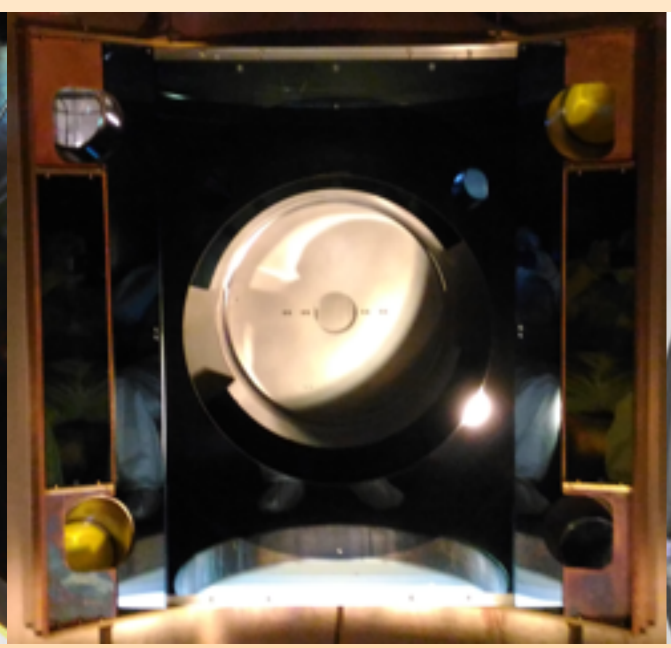
Mitigation strategy: improve the quality of the optics; baffle to shield mirrors, towers, pipes; photodiodes suspended in vacuum; control of the position of the photodiodes benches with respect to the interferometer.



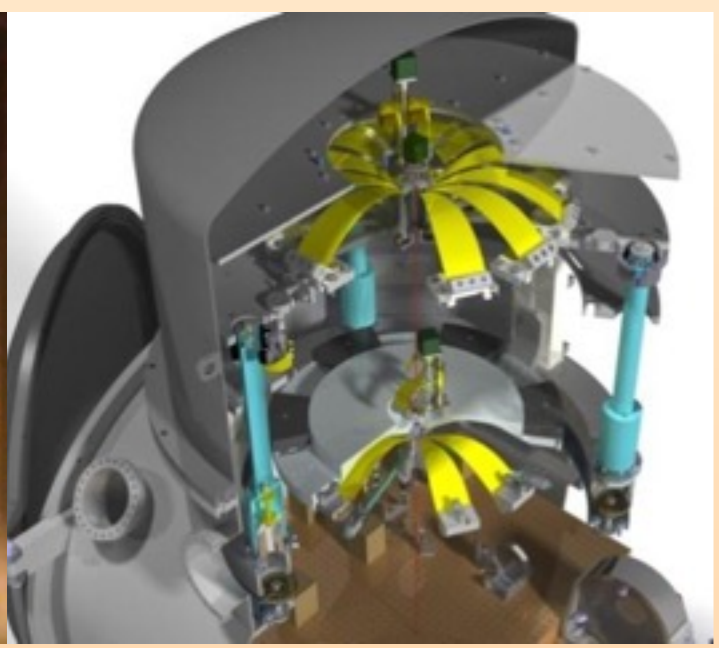
Scattered light around the mirror



Mirror baffle



Tower baffle



Photodiode Bench suspension

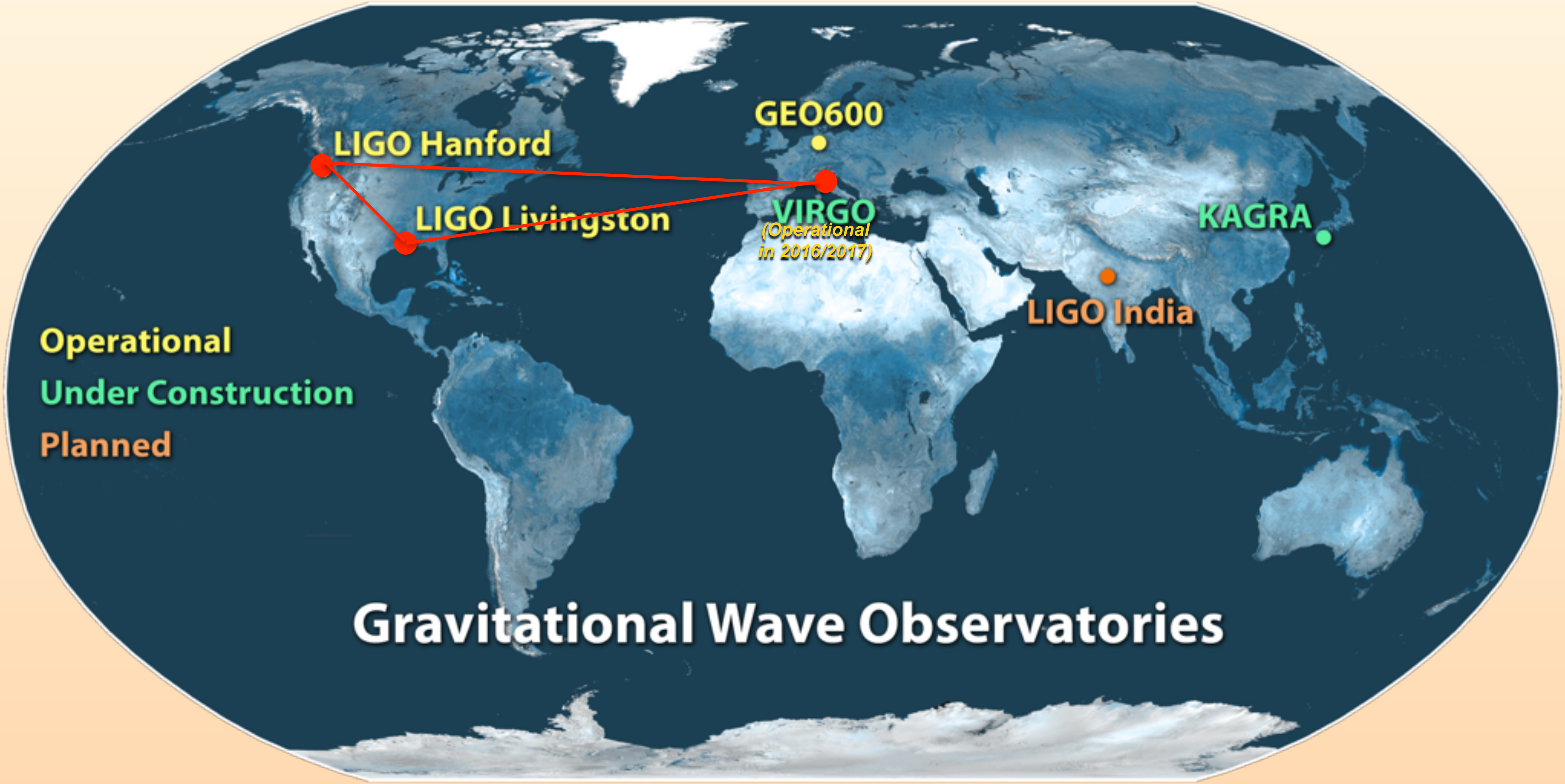
LIGO & Virgo Interferometers

To stabilize the environmental conditions -> The core of the instruments is in UH vacuum (p = 10^{-9} mbar for H_2).

Virgo (Italy)

LIGO Livingston (LA)

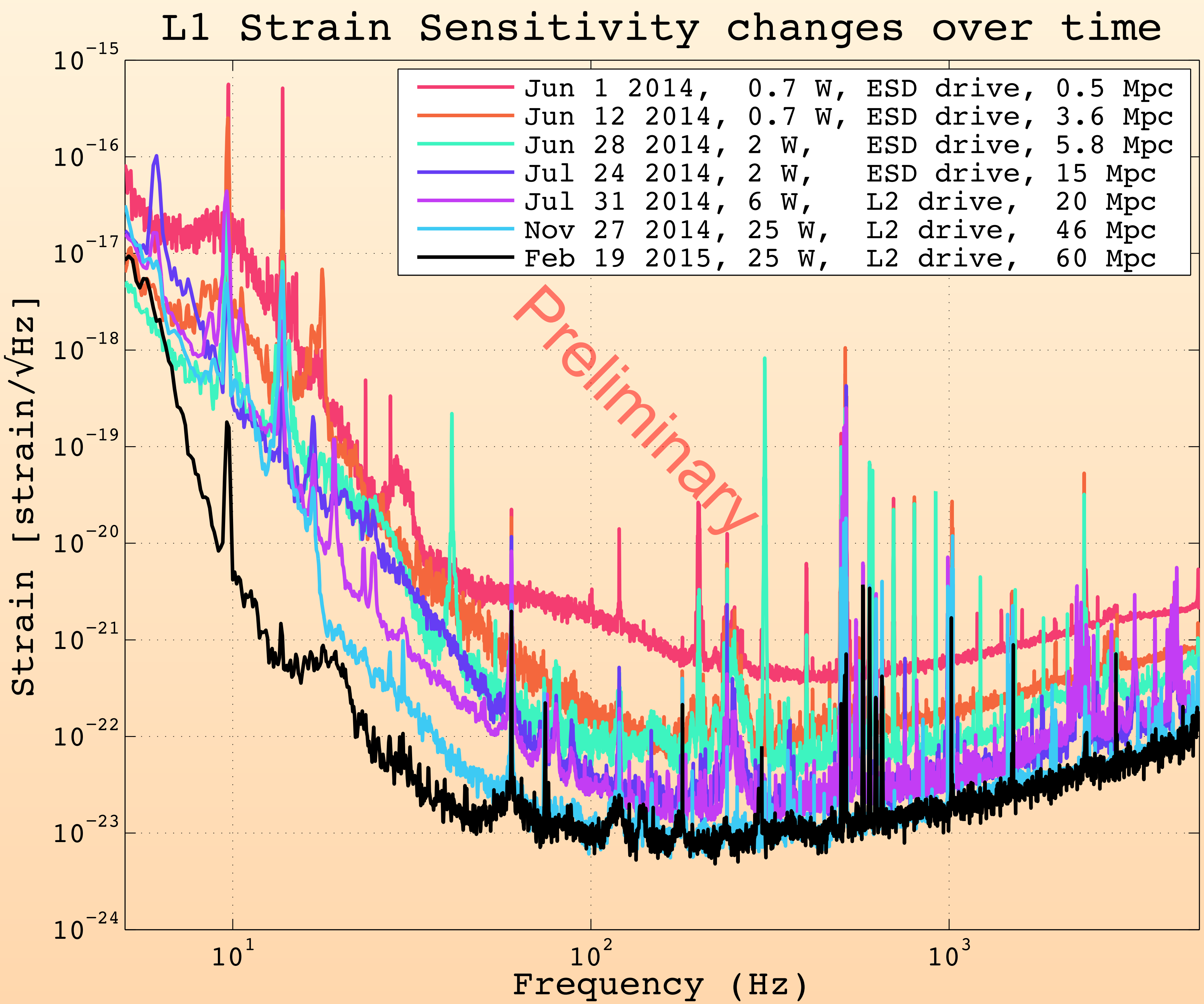
LIGO & Virgo Interferometers



LIGO & Virgo Interferometers

LIGO & Virgo Interferometers

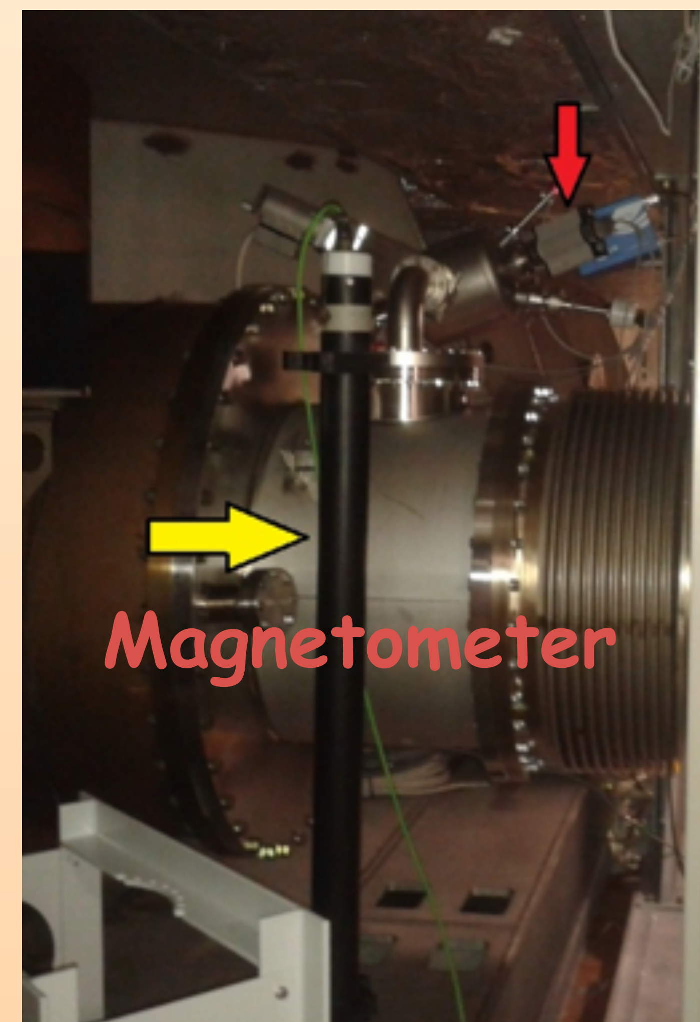
Once the interferometer is built, the commissioning work can start.



How can we be sure to have measured a GW?

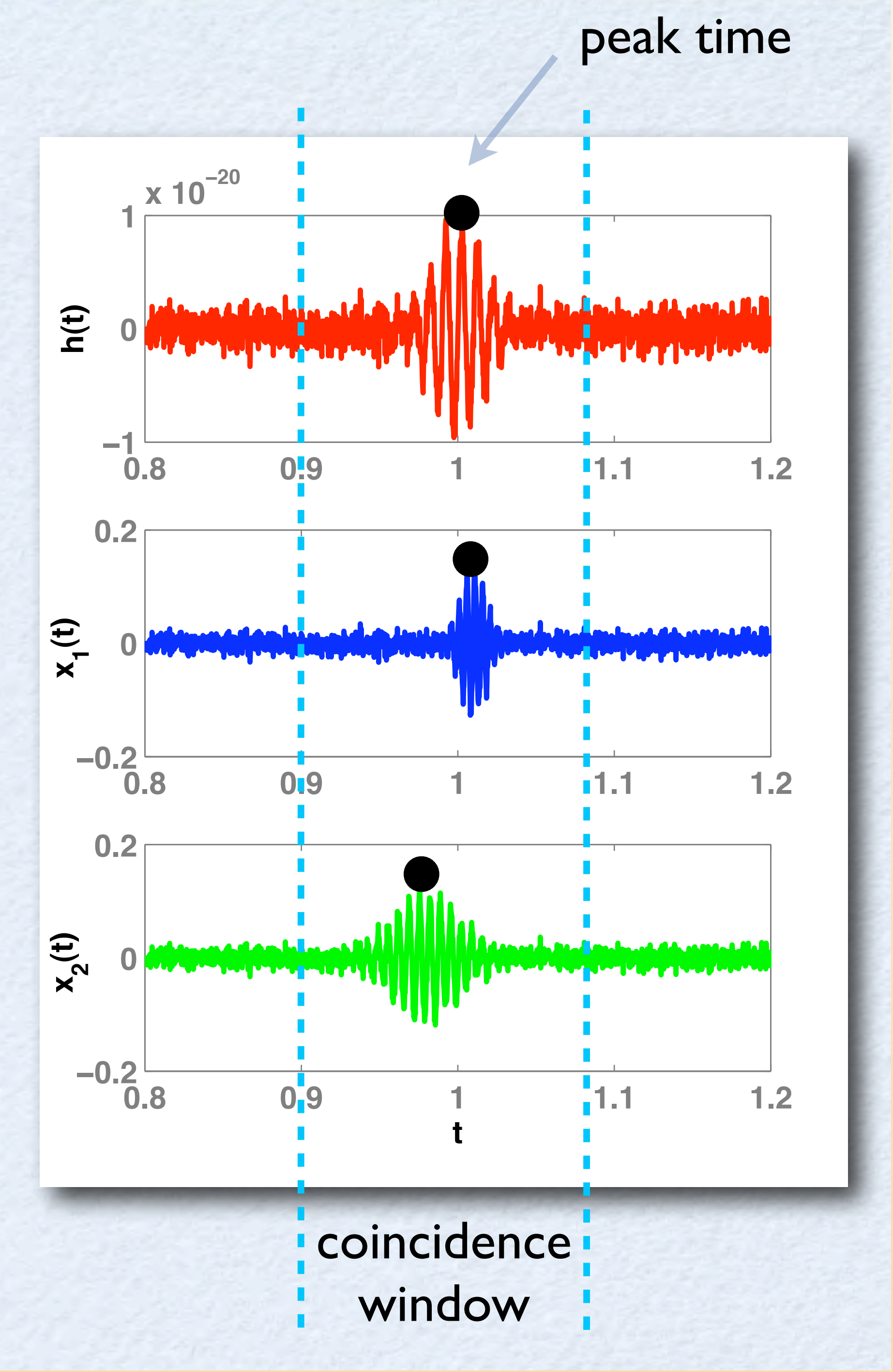
The status of the interferometer is monitored and analyzed during the data taking.

- sensors are installed everywhere around the interferometer;
- more than 200000 auxiliary channels recorded to monitor the detector behavior and the environmental conditions.

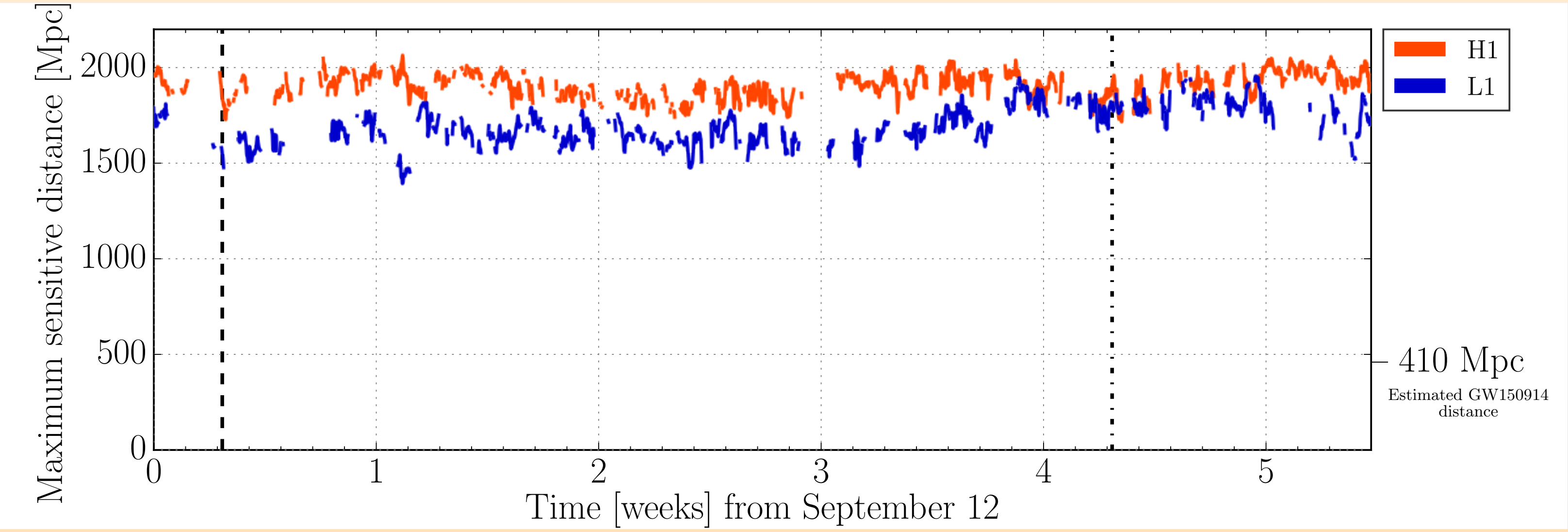


How can we be sure to have measures a GW?

VETO Method: find time coincidence between glitches in GW signal and in auxiliary channels to erase corrupted data.



Time coincidence between the two interferometers



All noise sources are excluded and only clean data are considered to search for a GW signal

Conclusions

On September 14th 2015 the two LIGO detectors observed for the first time a transient gravitational wave signal. On December 26th 2015 a second BH-BH coalescence has been observed by the two LIGO detectors.

A gravitational wave induces a tiny deformation.

Michelson Interferometer is the most appropriate instrument to measure such deformation.

BUT $d = 10^{-18}$ m challenging to be measured: many “tricks” used to improve the sensitivity of the Interferometer.

Careful detector characterization made to consider only clean data in the search for gravitational waves.