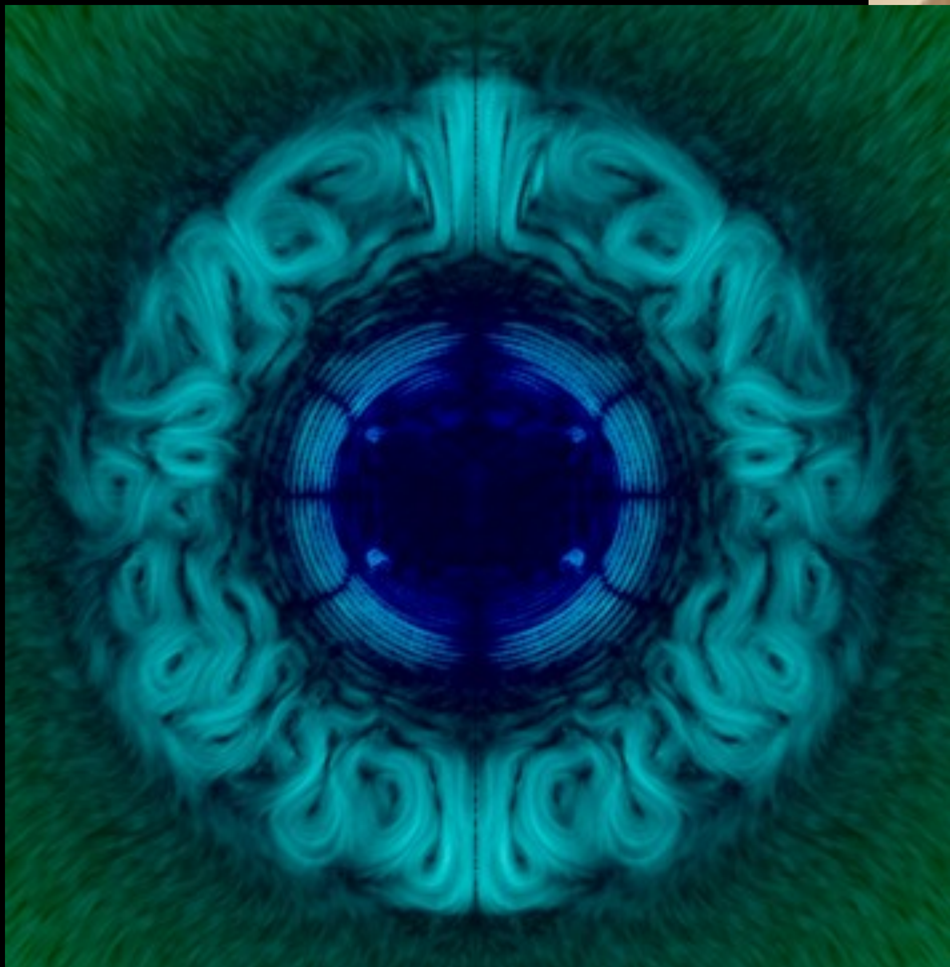
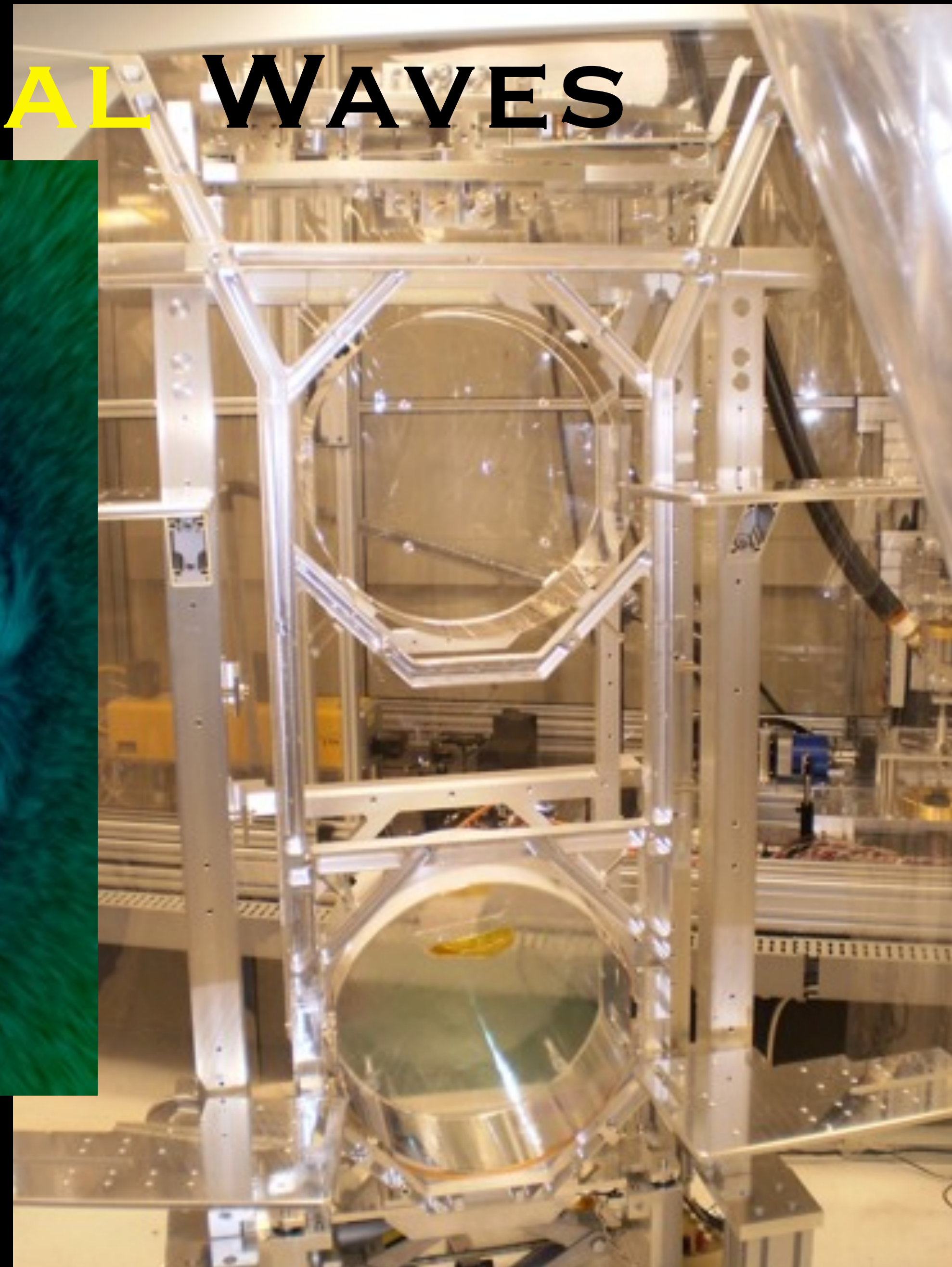
Gravitational Waves





UCSD Oct. 19, 2011

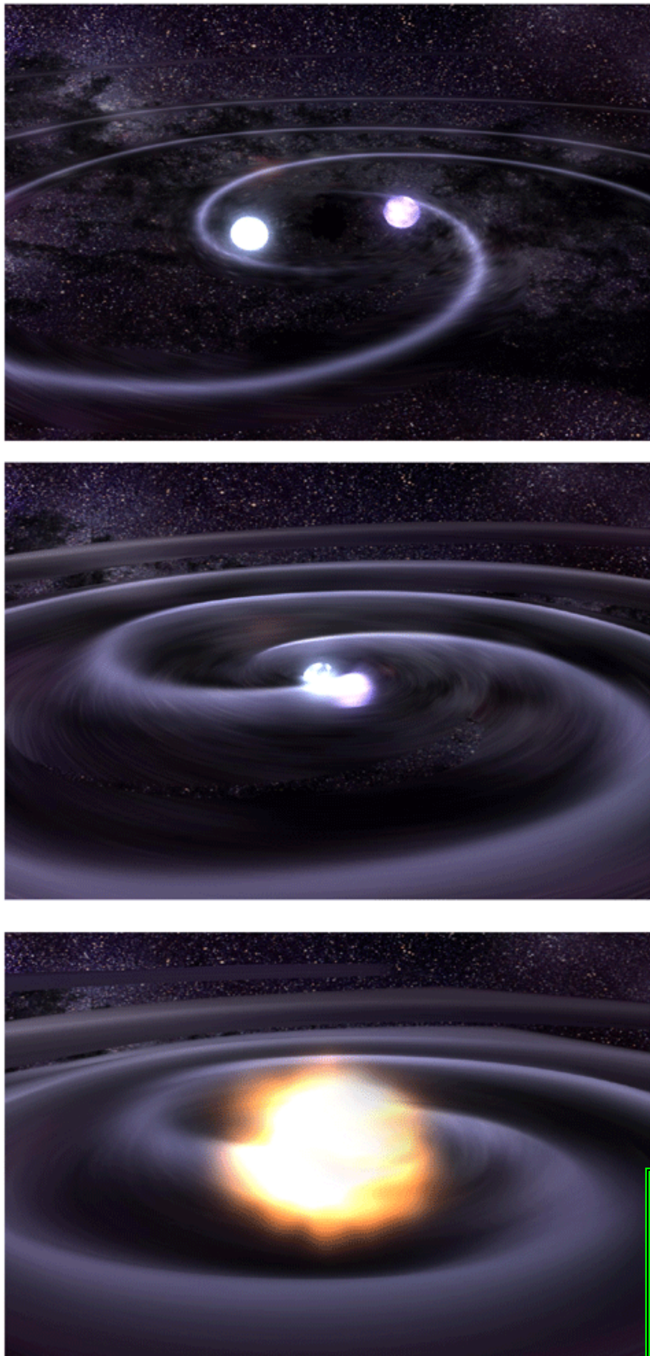
G1101173-v1

Rana Adhikari Caltech

OUTLINE

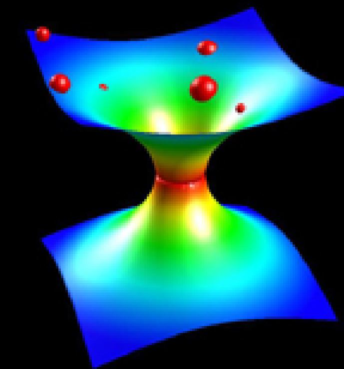
- Gravitational Waves and History
- Is it impossible to measure 10^{-20} meters?
- Isn’t it *too easy* to measure 10^{-20} meters?

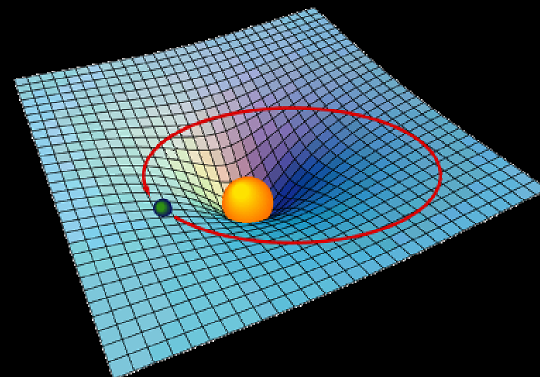
Gravitational Waves



NASA/Dana Berry, Sky Works Digital

$$G_{\mu\nu} = (8\pi G/c^4)T_{\mu\nu}$$





"Mass tells space-time how to curve,
and space-time tells mass how to move."
--- John Wheeler

Einstein's Equations:

When matter moves, or changes its configuration, its gravitational field changes. This change propagates outward as a *ripple in the curvature of space-time*: a gravitational wave.

Gravitational Waves?

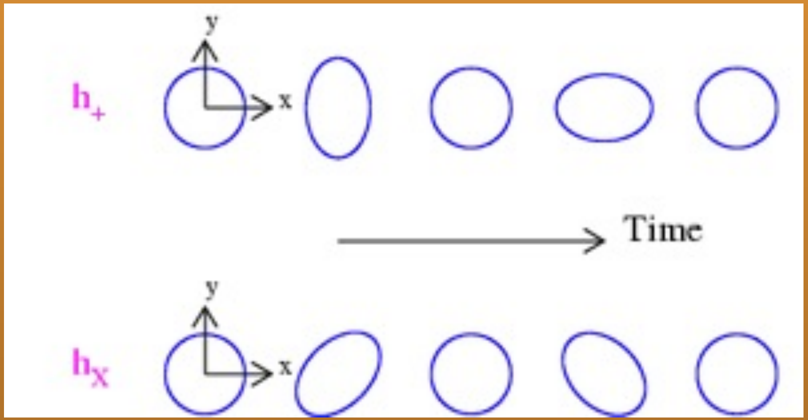
- Gravitational Waves = “Ripples in space-time”
- Two transverse polarizations - quadrupolar: + and x

Example:

Ring of test masses

responding to wave

propagating along z



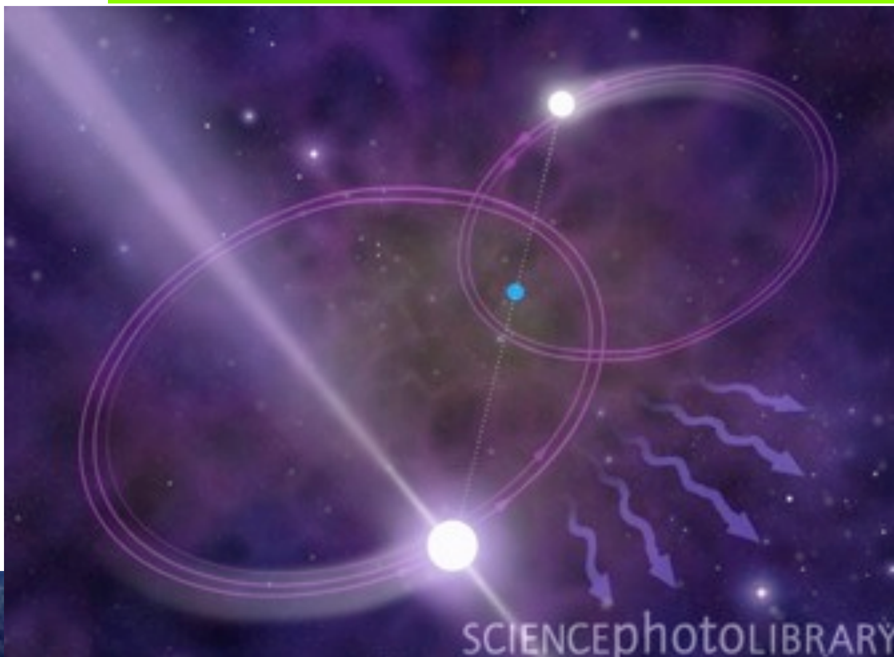
Amplitude parameterized by

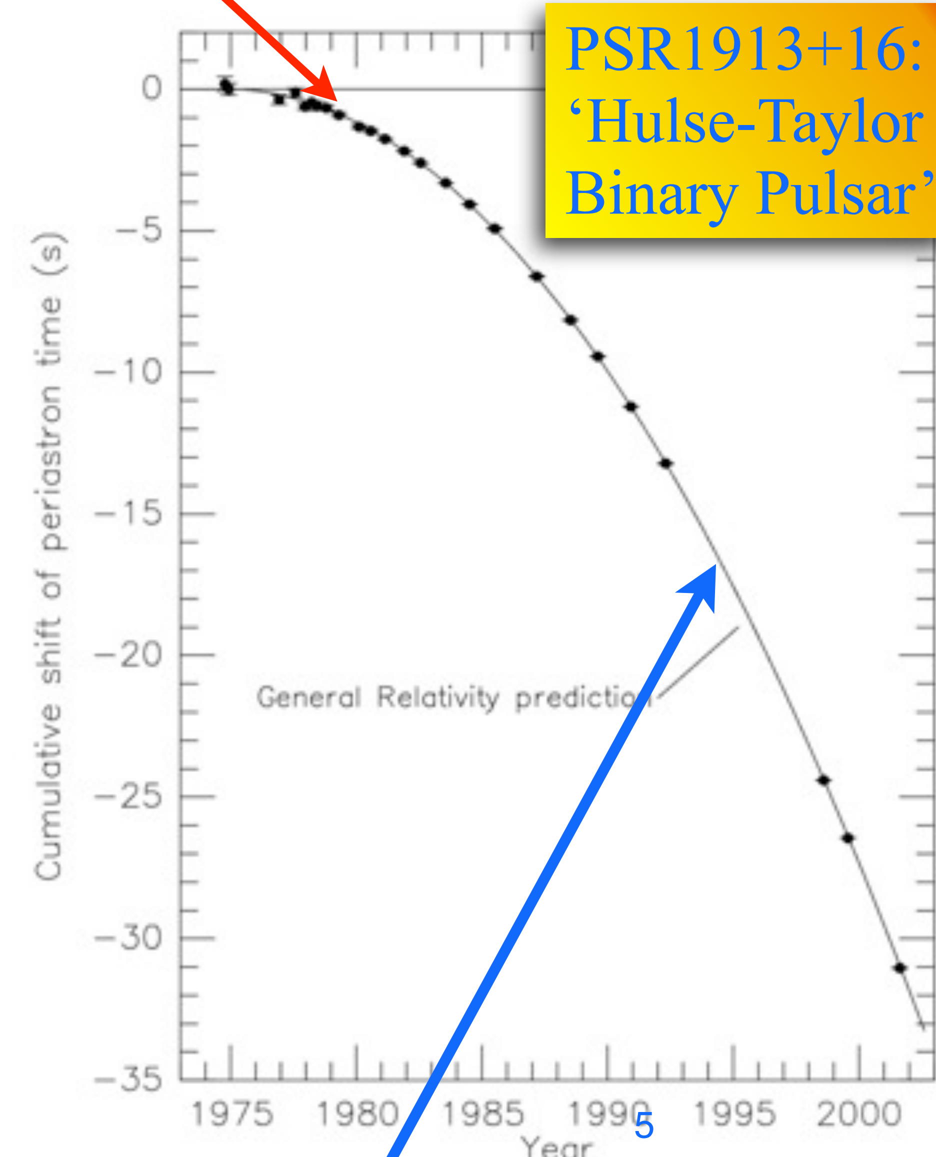
dimensionless strain h: $\Delta L \sim h(t) \times L$

Need to measure strain of ~ 10^{-21}-10^{-22}

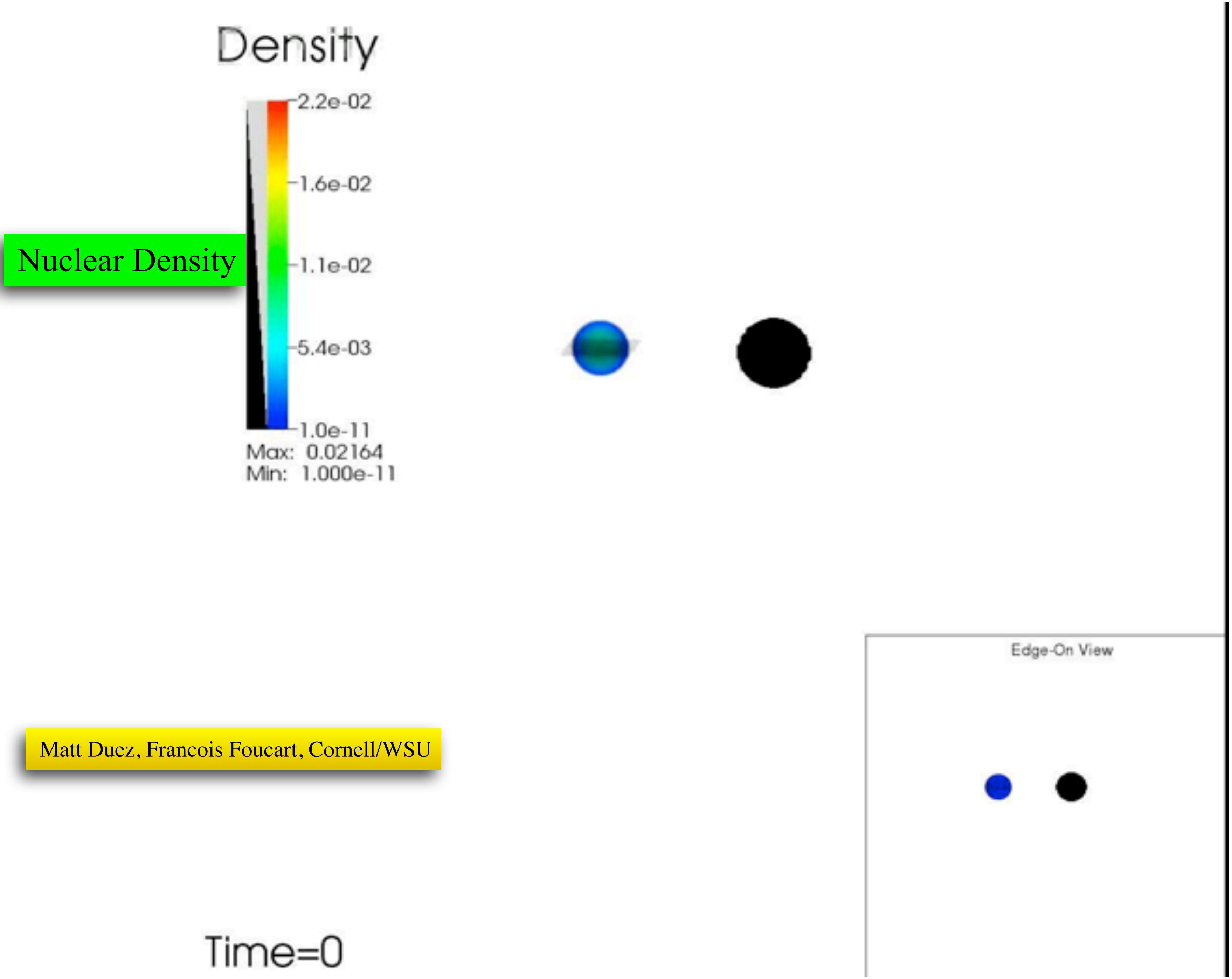
We want a very large ‘L’

1979:
Gravitational Waves Detected!



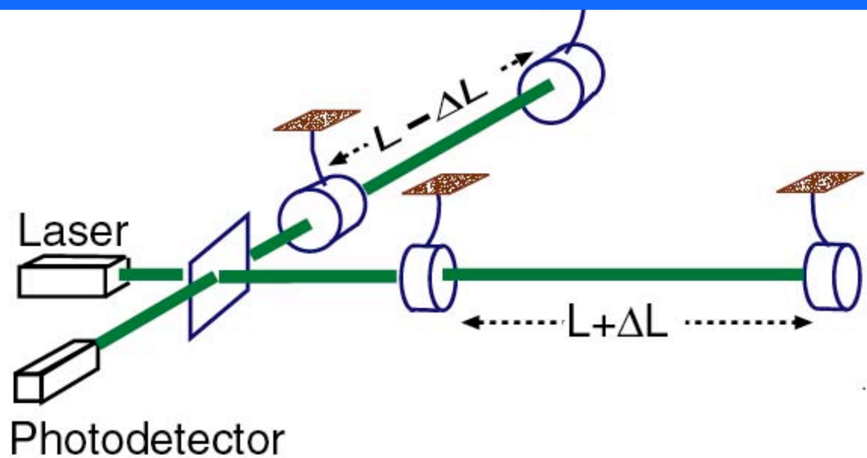


http://nobelprize.org/nobel_prizes/physics/laureates/1993/


Density
2.2e-02
1.6e-02
1.1e-02
5.4e-03
1.0e-11
Max: 0.02164
Min: 1.000e-11
Nuclear Density
Edge-On View
Matt Duez, Francois Foucart, Cornell/WSU
Time=0

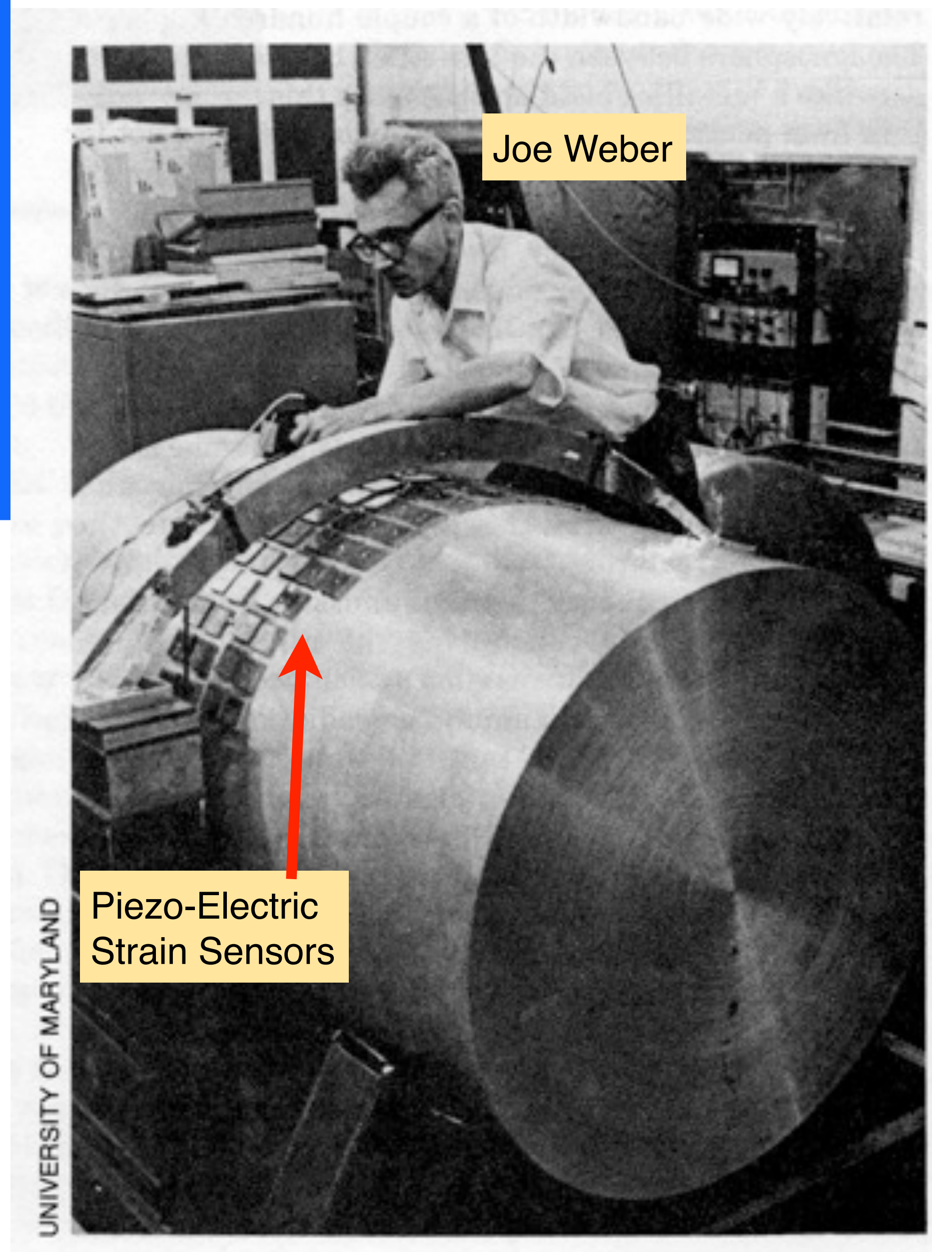
GW Detectors

- **Bar detectors**
  - Like a large bell, set ringing by Gravitational Waves
- **Michelson interferometers**
  - First table-top prototypes: *Malibu*, Munich, **Caltech**, MIT
  - **Now**: km scale, in-vacuum, several 100M$
  - Groups in U.S., Europe, Japan, Australia, India



$$\Delta L = h\,L \lesssim 4\times10^{-16}\ \text{cm}$$

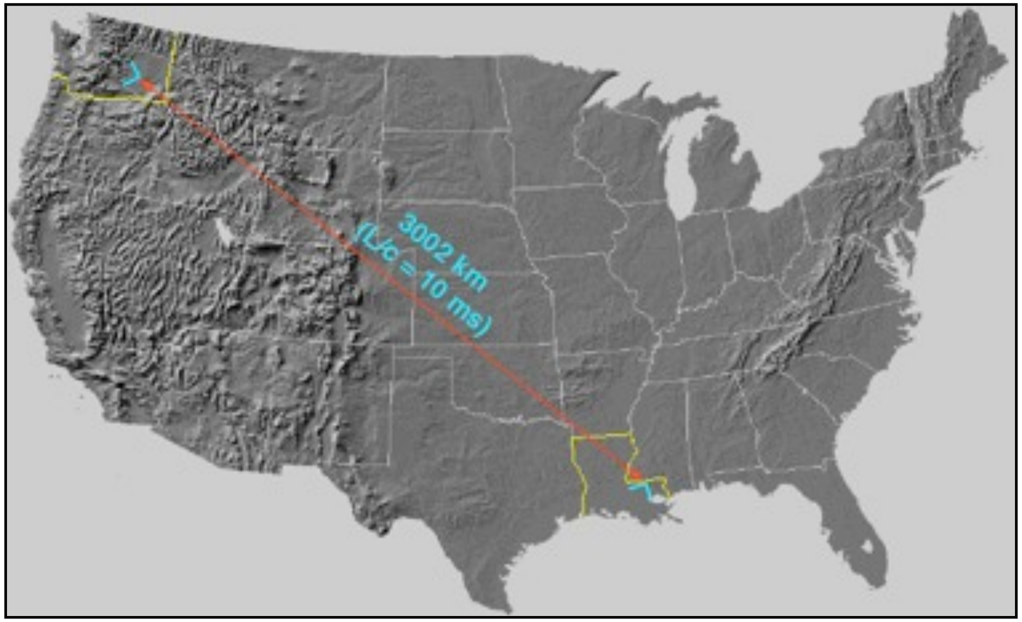
$h \lesssim 10^{-21}$, $L = 4$ km



<u>**LIGO**</u>: Big Michelson Interferometers

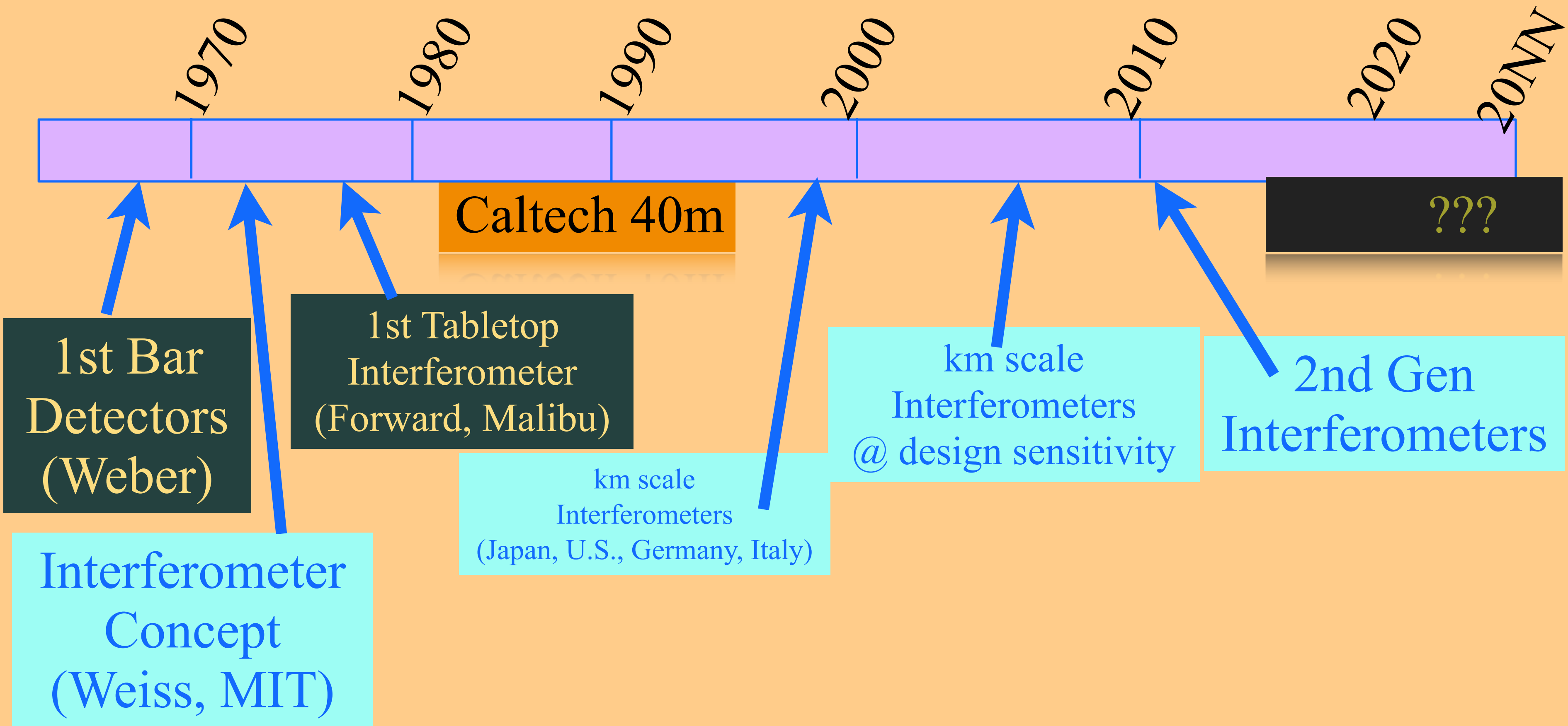
Hanford Nuclear Reservation, Eastern WA (H1 4km, H2 2km)

- *Interferometers are aligned to be as close to parallel to each other as possible*
- *Observing signals in coincidence increases the detection confidence*
- *Determine source location on the sky, propagation speed and polarization of the gravity wave*



Livingston, LA (L1 4km)

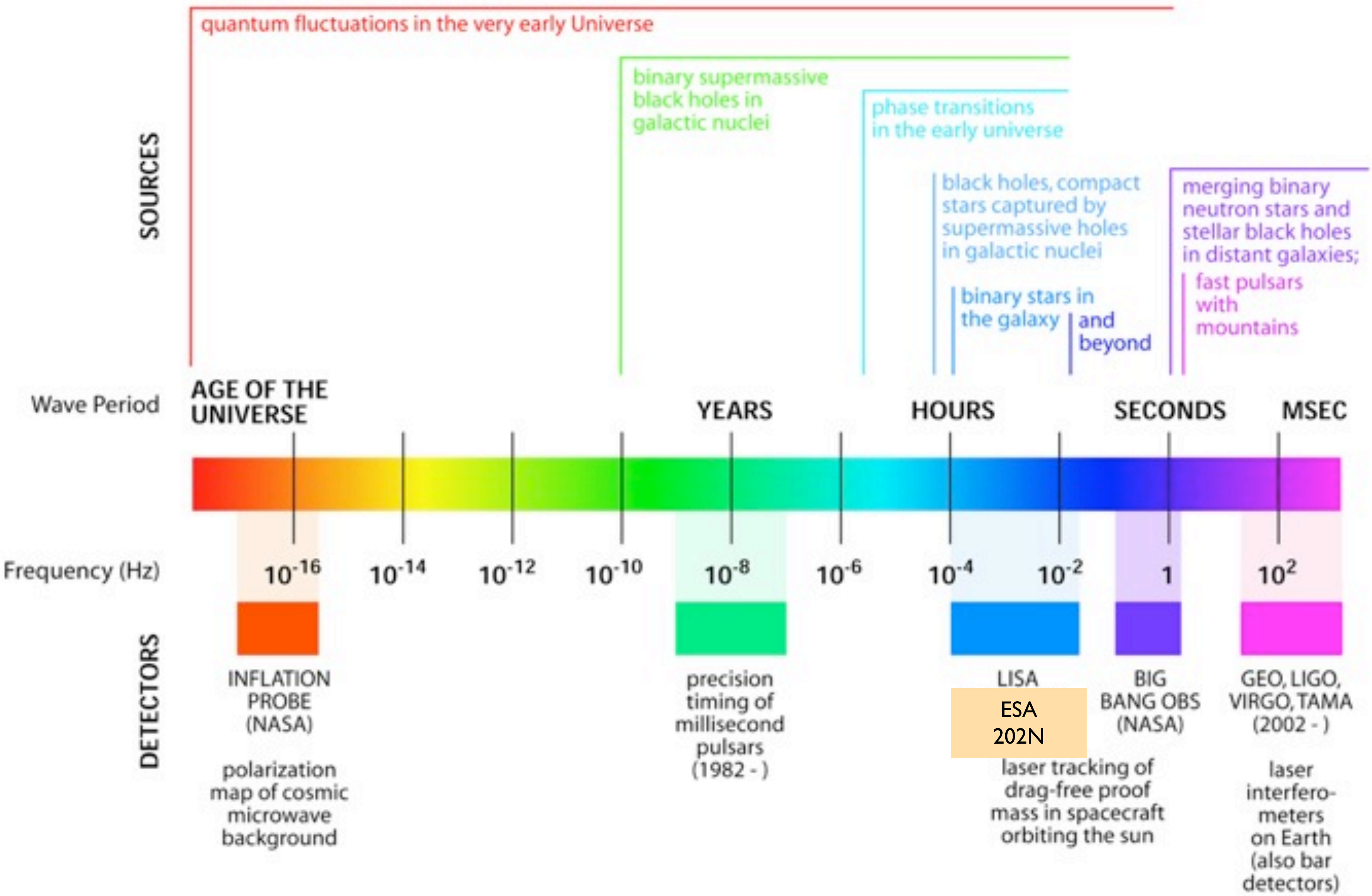
Timeline of GW Detectors




mid station

Louisiana

THE GRAVITATIONAL WAVE SPECTRUM



The Michelson Interferometer

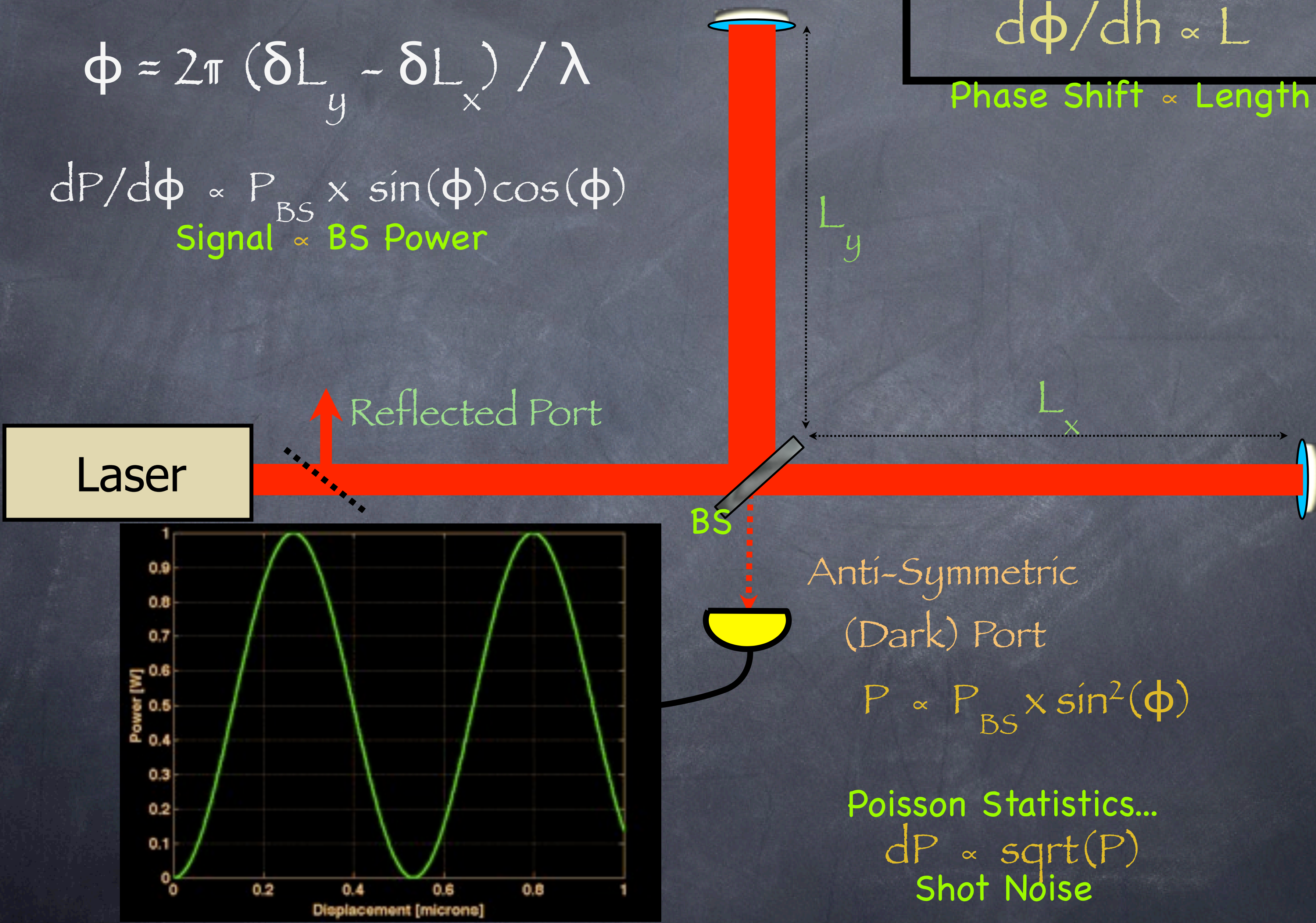
$\phi = 2\pi\,(\delta L_y - \delta L_x)\,/\,\lambda$

$d\phi/dh \propto L$

Phase Shift ∝ Length

$dP/d\phi \propto P_{BS} \times \sin(\phi)\cos(\phi)$

Signal ∝ BS Power



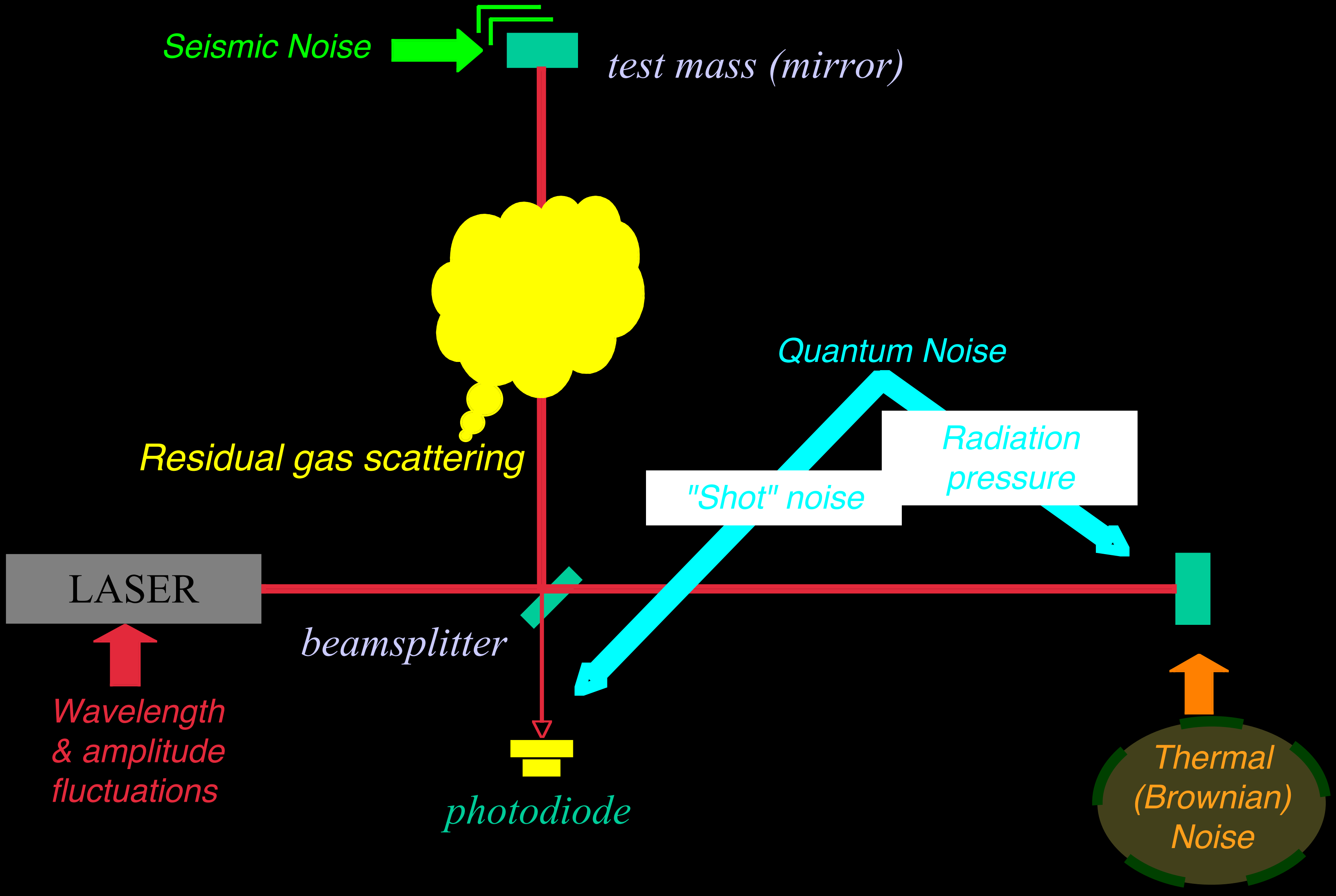
$P \propto P_{BS} \times \sin^2(\phi)$

Poisson Statistics...

$dP \propto \mathrm{sqrt}(P)$

Shot Noise

Noise Cartoon



Non-Fundamental Noise

Science Requirements Doc: The LIGO-I Sensitivity Goal

Seismic:

Natural and anthropogenic ground motions, filtered by active/passive isolation systems.
Depends strongly on in-vac seismic isolation.

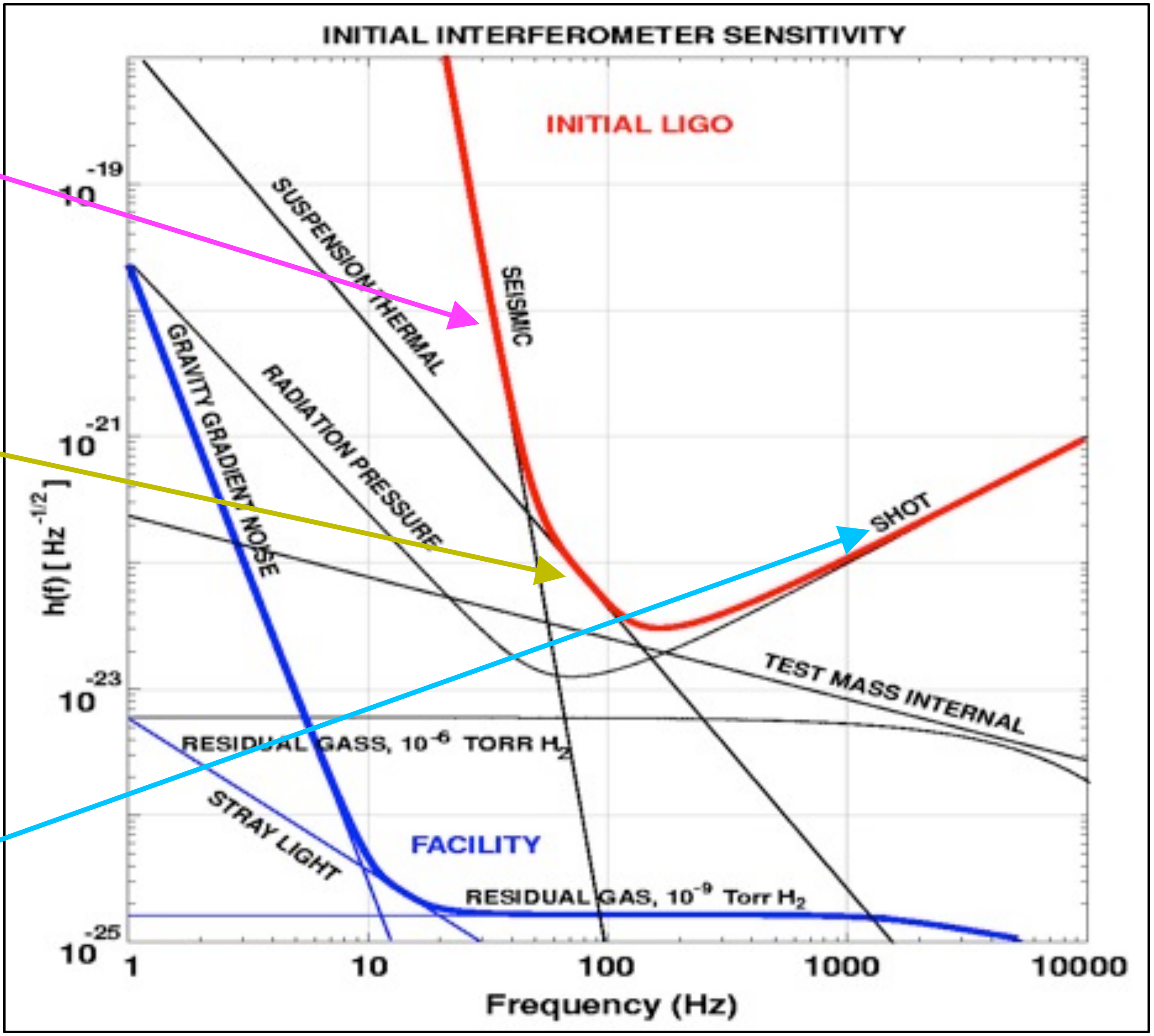
Thermal:

Brownian noise in the mirrors and in the mirrors' steel suspension wires.
Depends mostly on internal rubbing in the suspension wires.

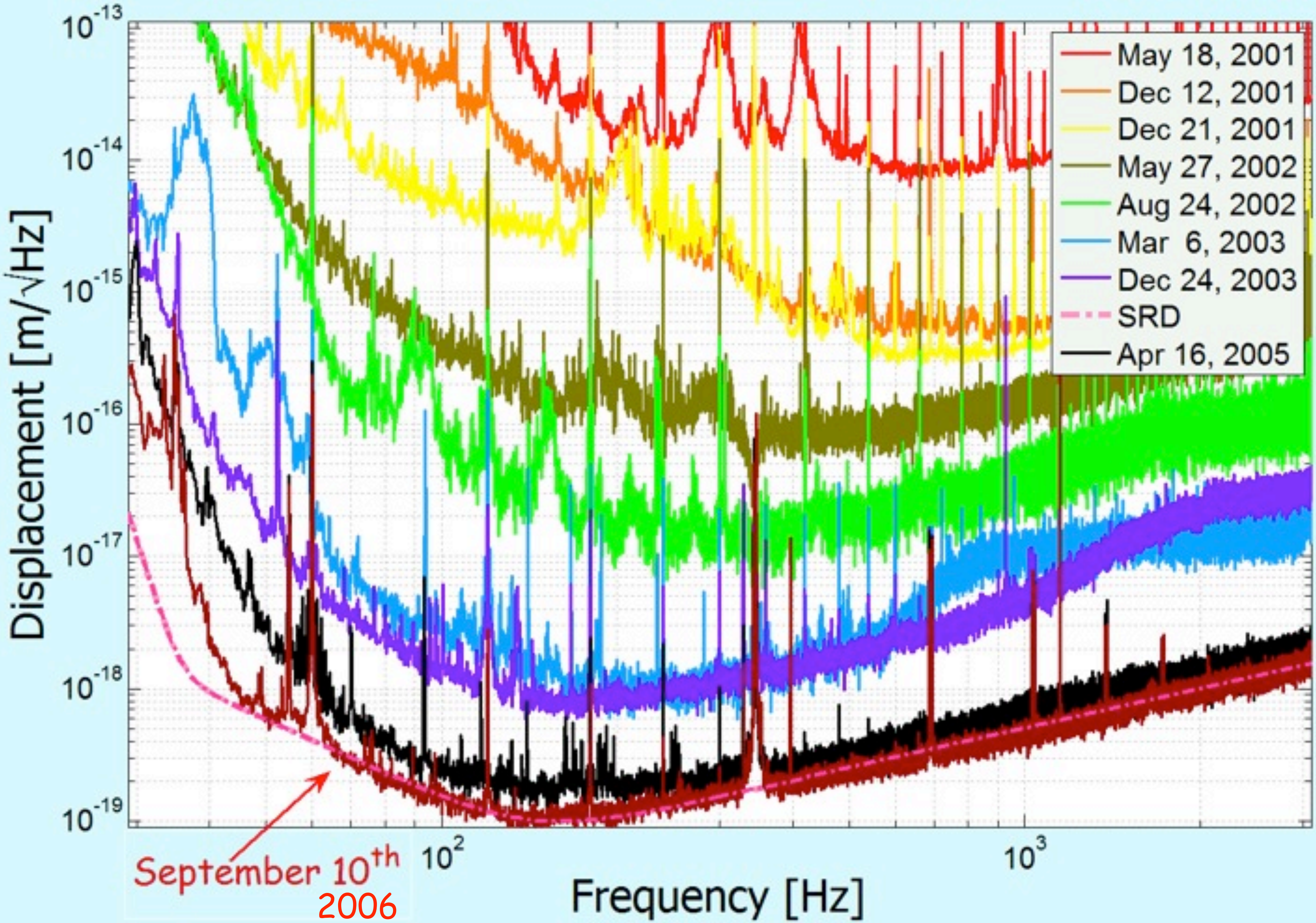
Shot Noise:

Photon counting statistics --
> 10 kW in the cavities
~ 200 mW detected power

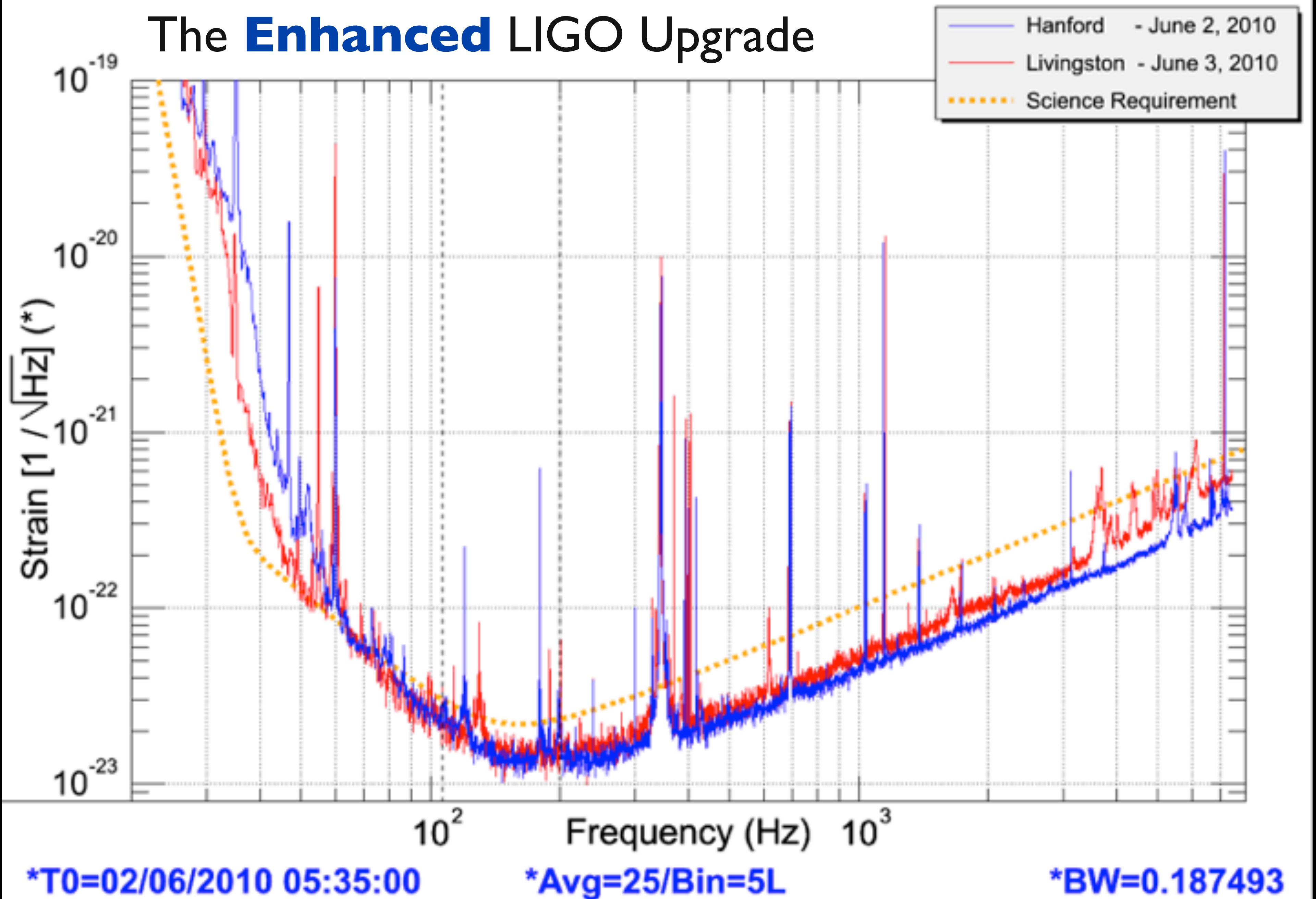
- Goes down with increased laser power and better fringe contrast



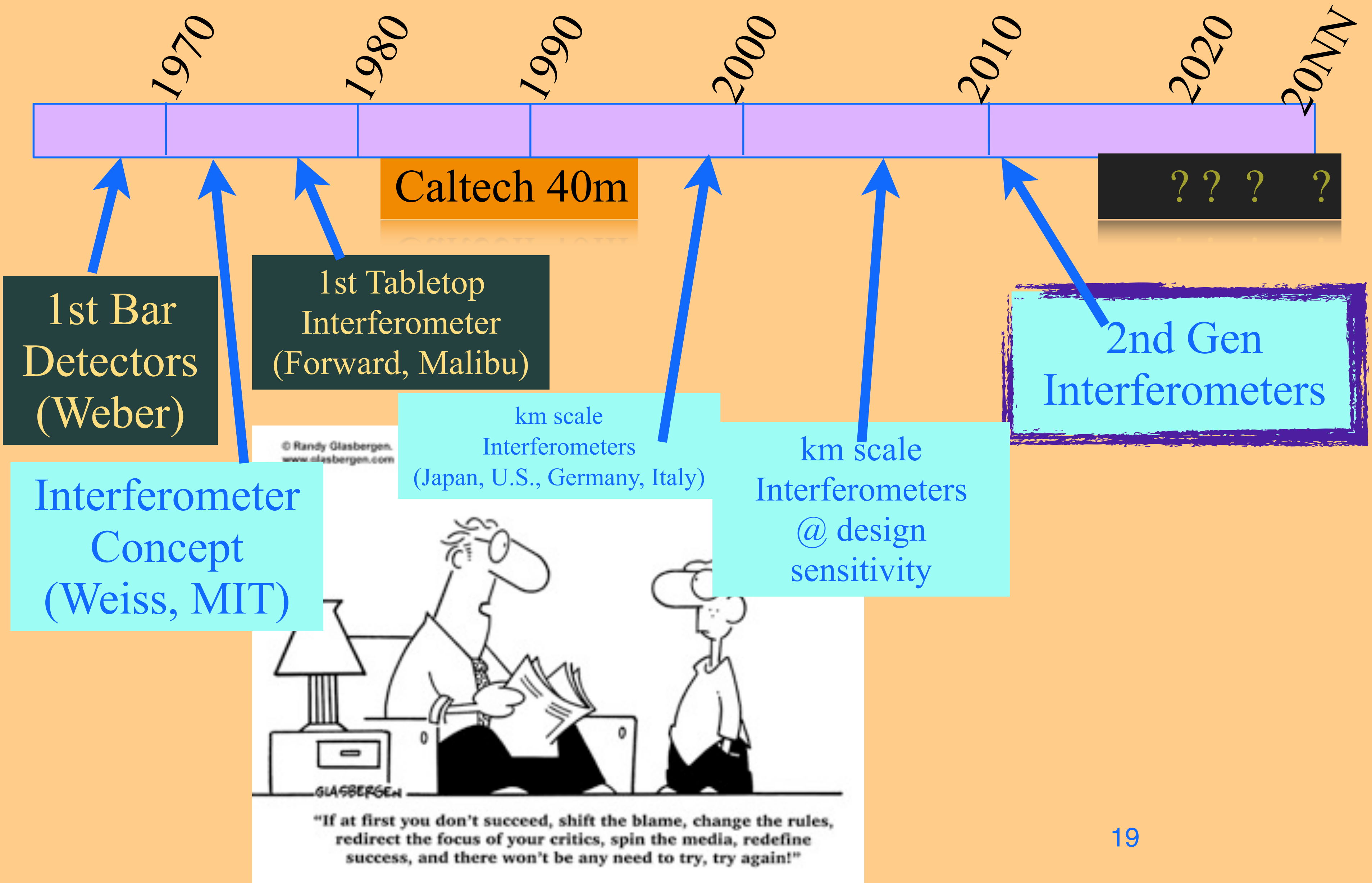
LIGO Louisiana Noise Progression



The **Enhanced** LIGO Upgrade



Timeline of GW Detectors



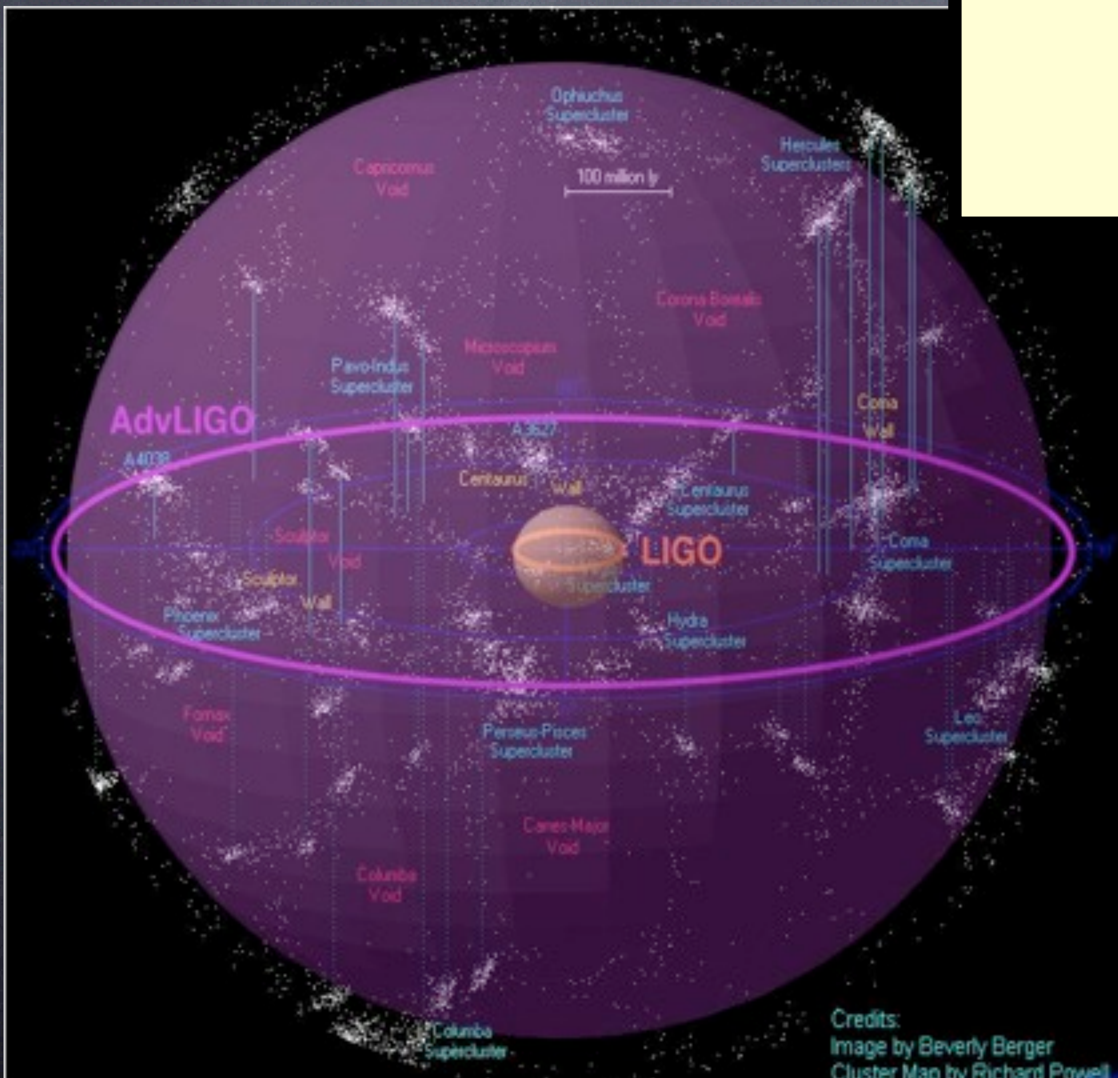
Advanced LIGO

x10 better amplitude sensitivity

⇒ x1000 rate=(reach)^3

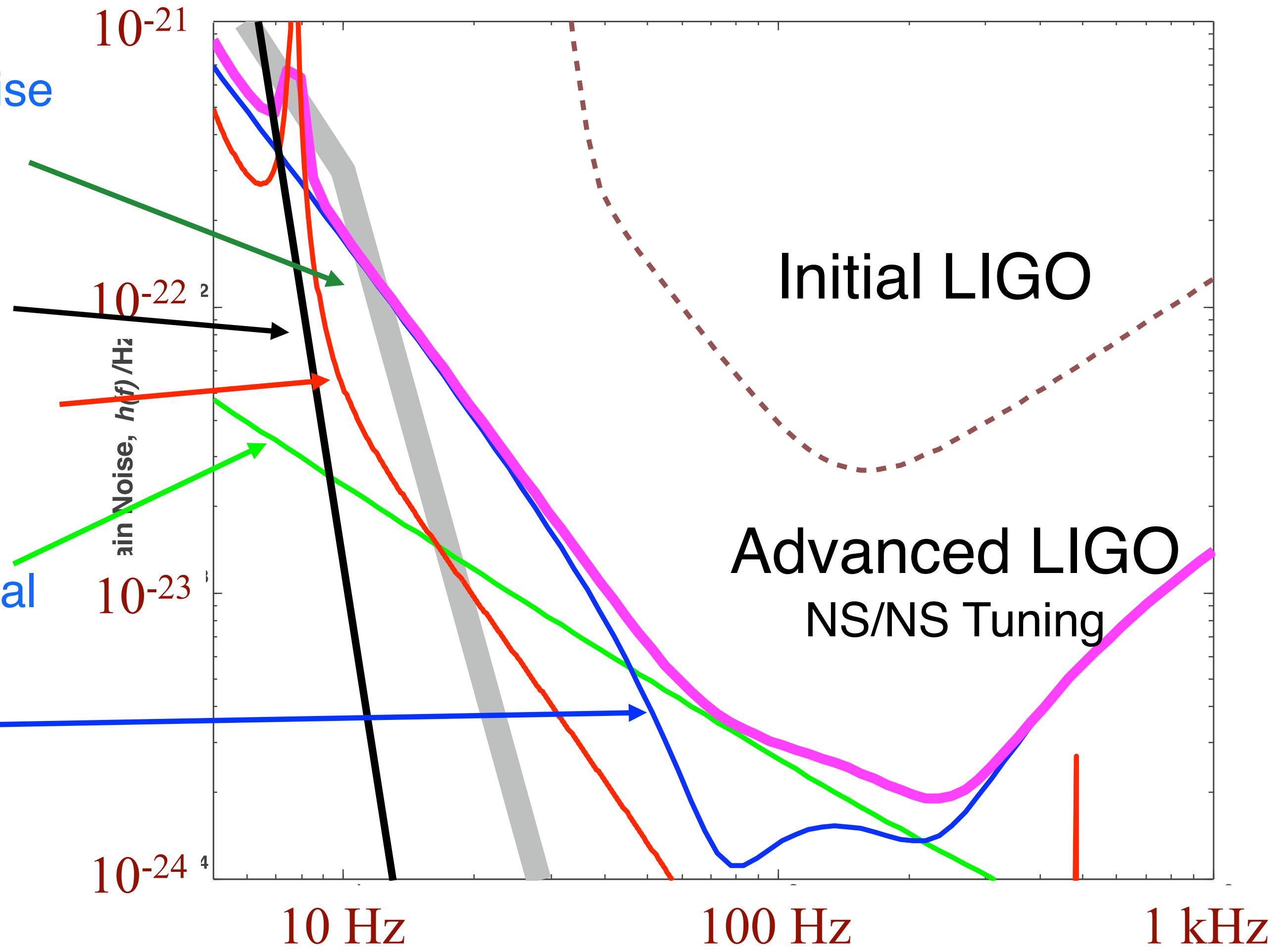
⇒ 1 day of Advanced LIGO

» 1 year of Initial LIGO

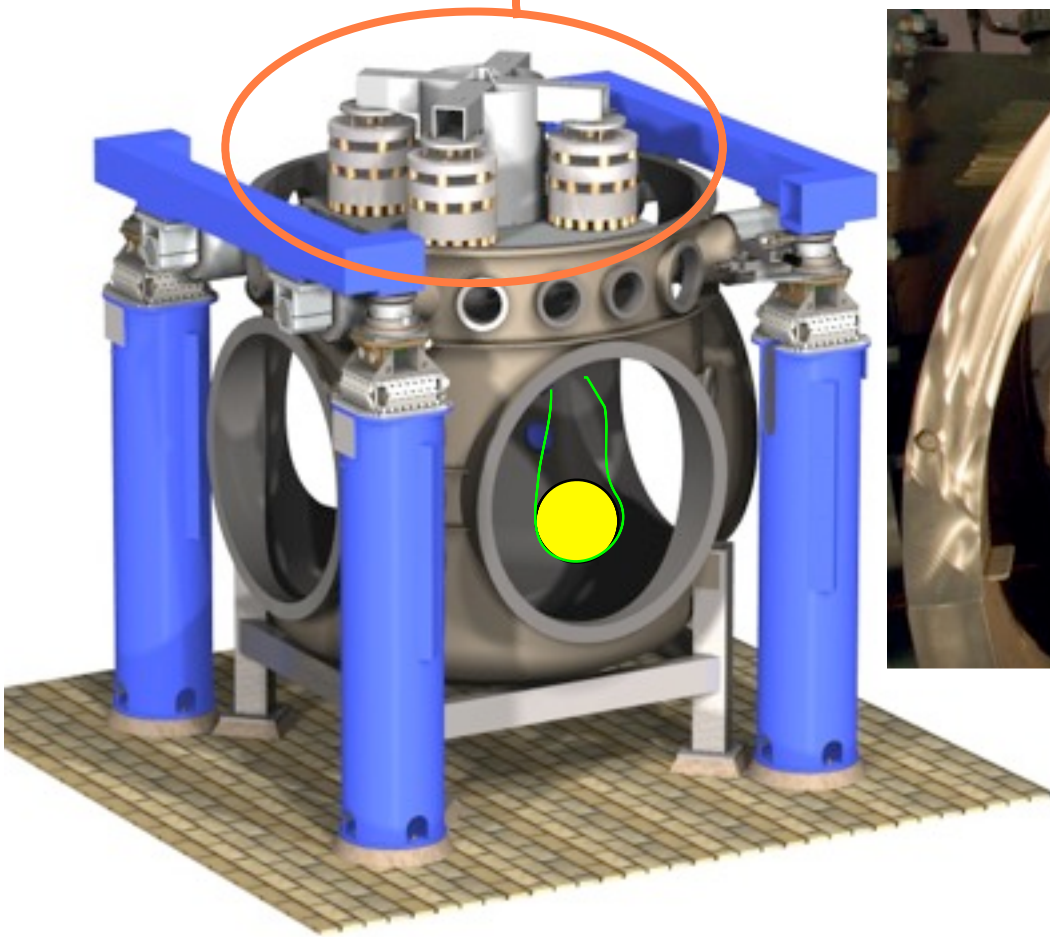


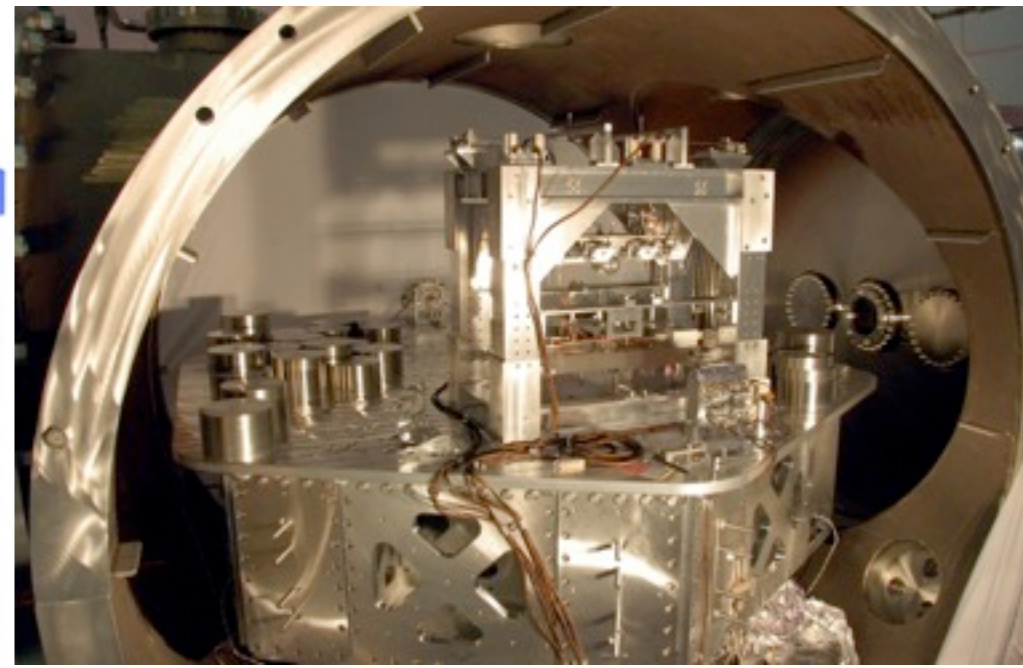
Anatomy of the interferometer performance

- Newtonian gravity noise
(aka Gravity Gradients)
- Filtered Seismic
- Silica Suspension Thermal Noise
- Mirror Coating Thermal
- Quantum Noise
  Radiation Pressure
  Shot Noise

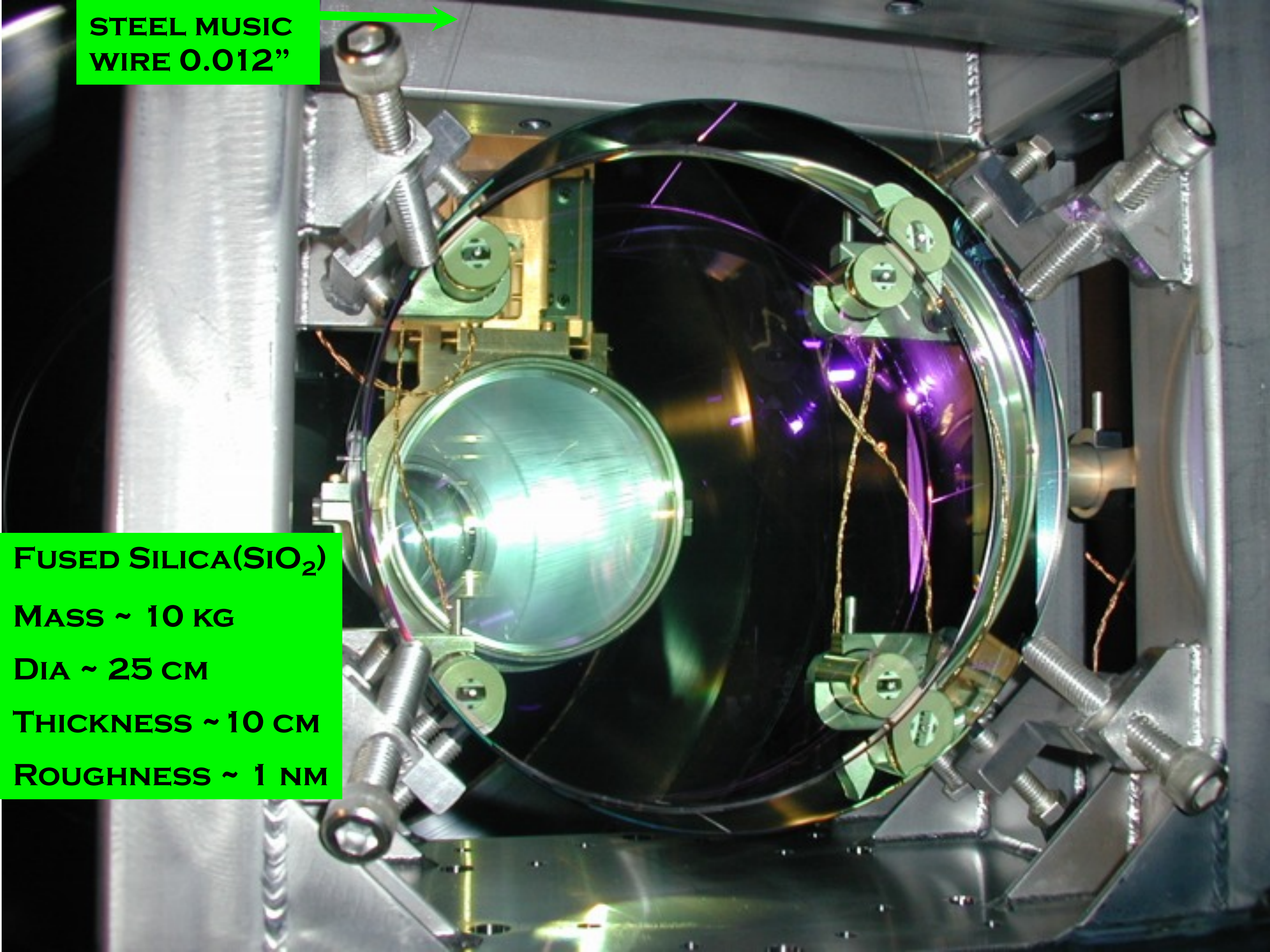


Seismic Noise



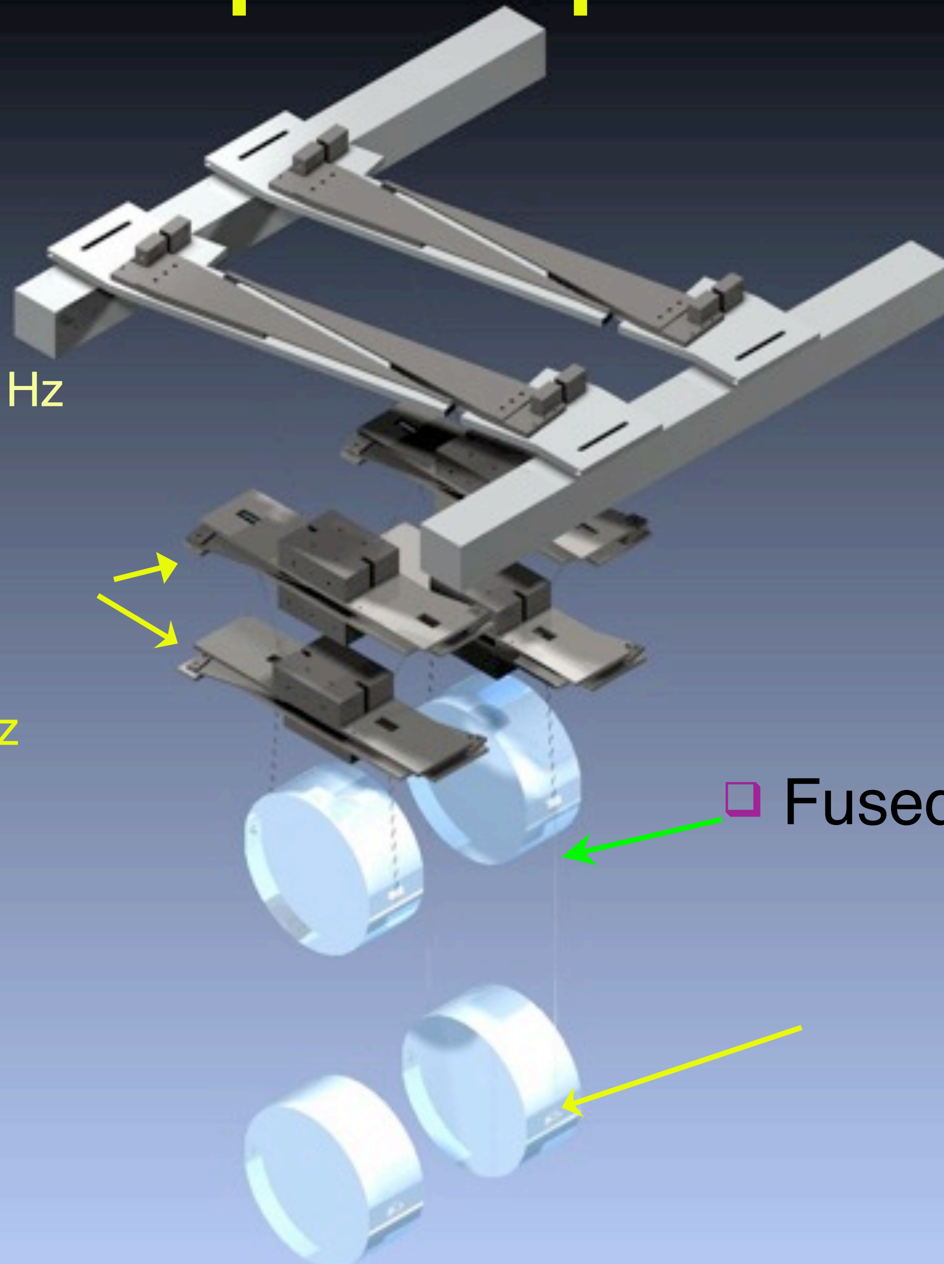


actively controlled space frame
w/ low noise inertial sensors


STEEL MUSIC
WIRE 0.012”
Fused Silica(SiO_2)
Mass ~ 10 kg
Dia ~ 25 cm
Thickness ~10 cm
Roughness ~ 1 nm

Quadruple Suspensions

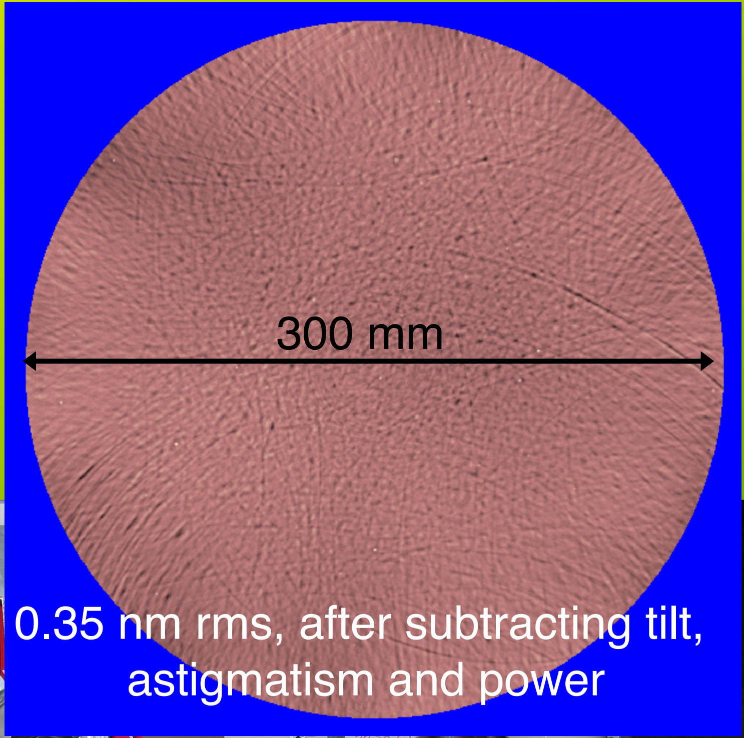
- 10^7 attenuation @ 10 Hz
- Seismic platform and suspension together:
  - » 10^{-19} m/rtHz at 10 Hz



- ❑ Fused silica fiber

Bigger Mirrors

- **Size: 34 cm wide, 20 cm thick => 40 kg**
- Material: Heraeus Suprasil Silica
- Bulk Absorption: 0.2 ppm/cm
- Coating absorption: 0.5 ppm/bounce
- **High Q (10^8) -> low thermal noise**

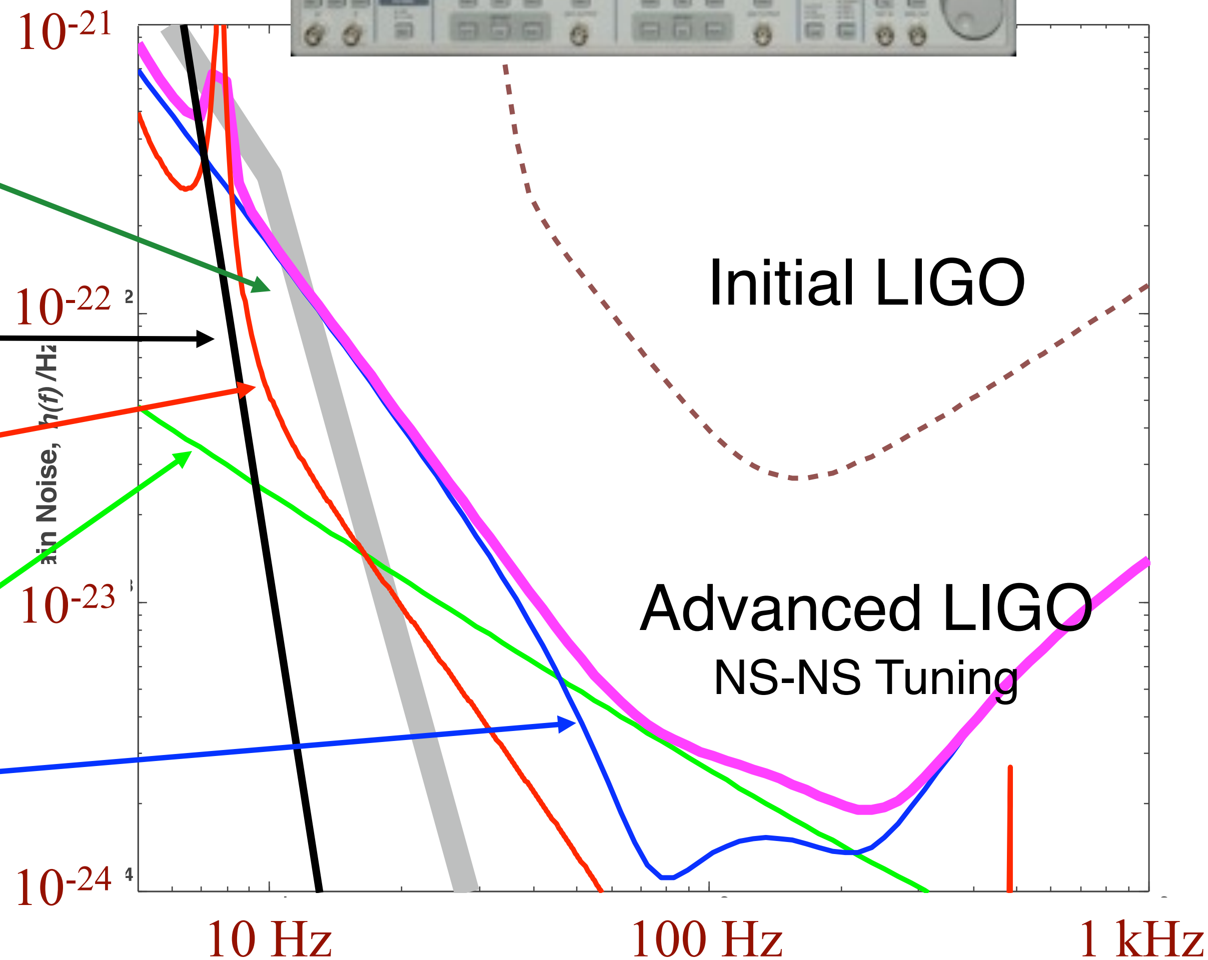


OUTLINE

- Gravitational Waves and History
- How to measure 10^{-20} m?
- How do we move into **the future**?

Trick #1: Chopping

- Newtonian gravity noise (aka Gravity Gradients)
- Filtered Seismic
- Silica Suspension Thermal Noise
- Mirror Coating Thermal
- Quantum Noise
  Radiation Pressure
  Shot Noise



LIGO has ~no sensitivity at DC

Measure @ Audio Frequencies

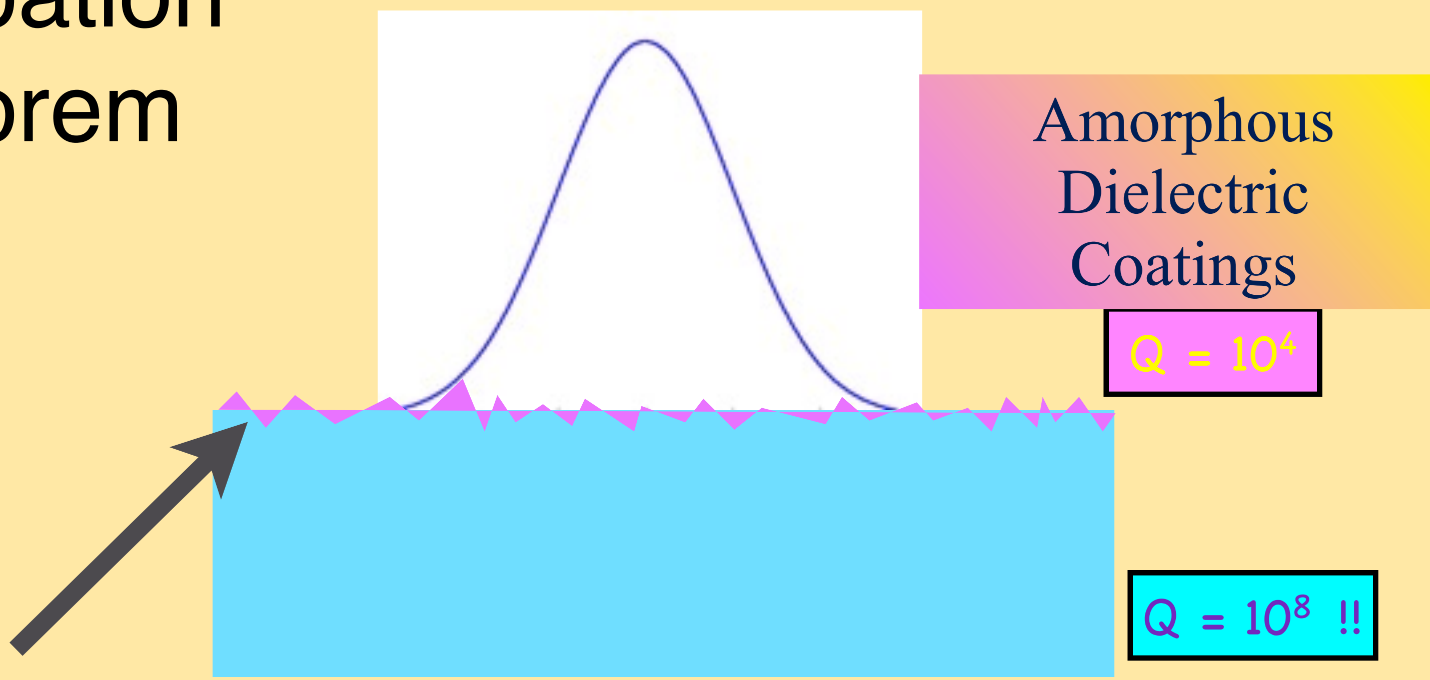
Brownian Thermal Fluctuations

$$S_x(\omega) = \frac{4k_BT}{\omega^2 Re[Z(\omega)]}$$

Simple
Harmonic
Oscillator

$$Z(\omega) = \frac{\dot{x}}{F} = \frac{K - M\omega^2}{i\omega}$$

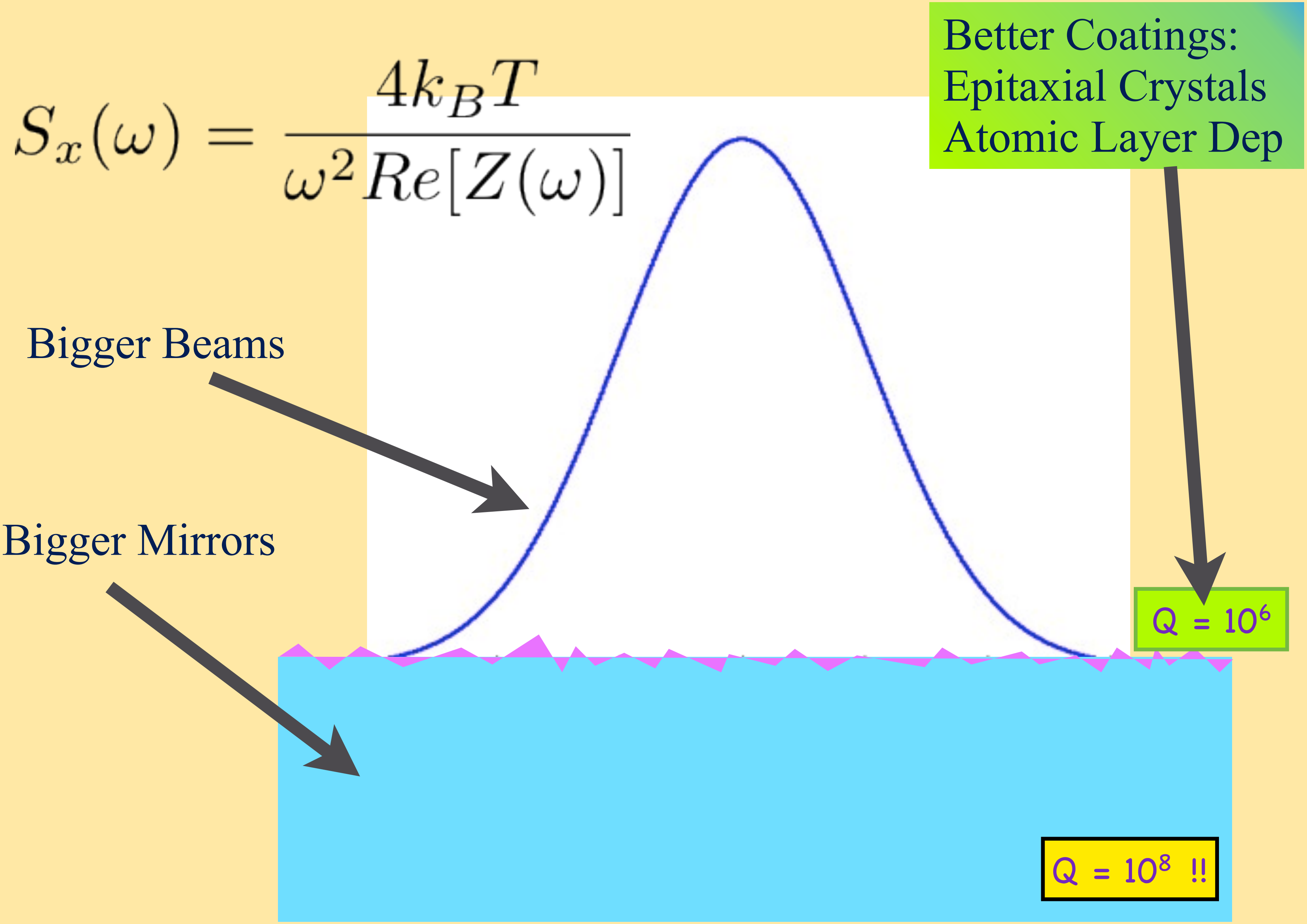
Fluctuation
Dissipation
Theorem



Mirror Surface
Thermal Fluctuations

Brownian Thermal Fluctuations

$$S_x(\omega) = \frac{4k_B T}{\omega^2 Re[Z(\omega)]}$$



Anatomy of the interferometer performance

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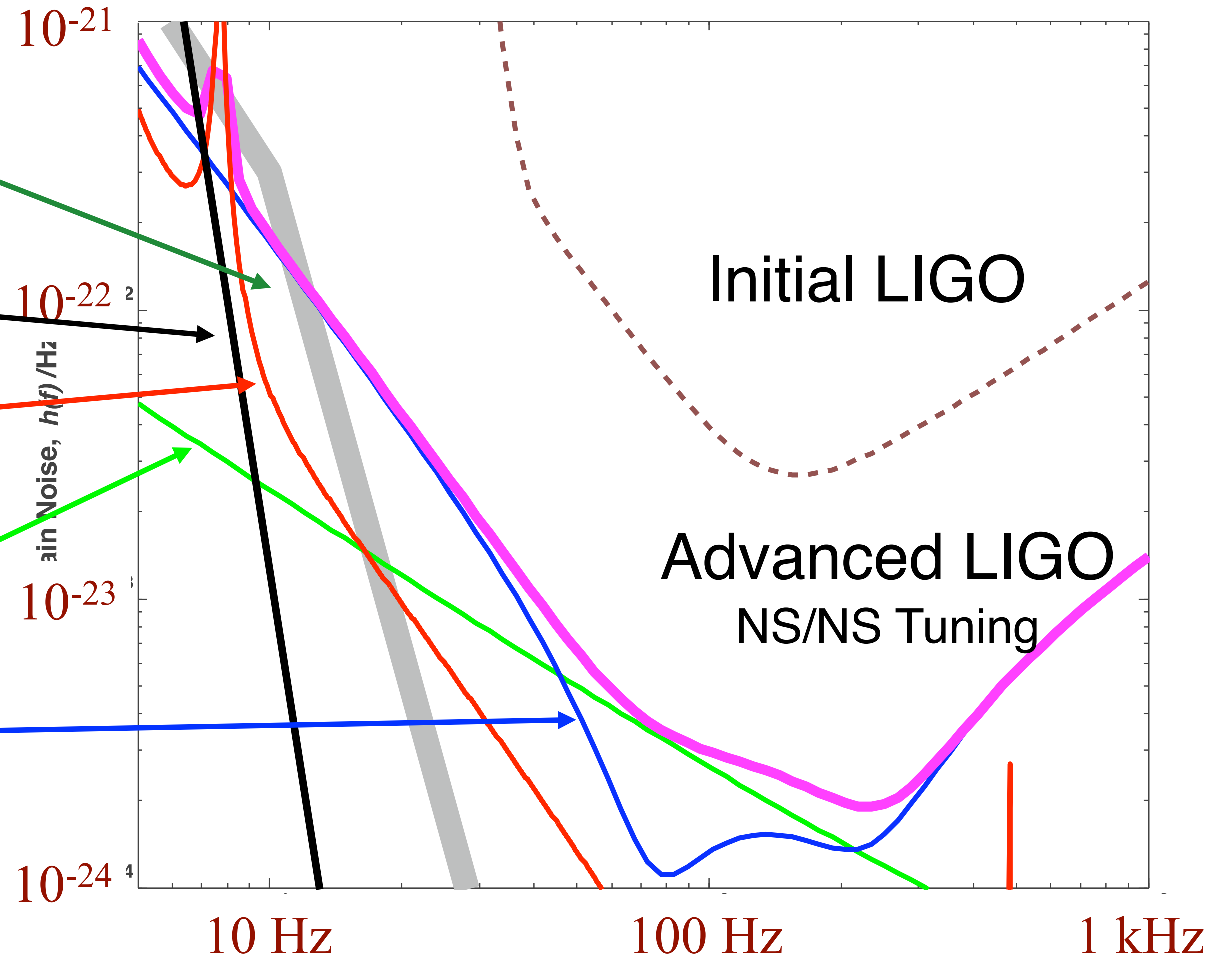
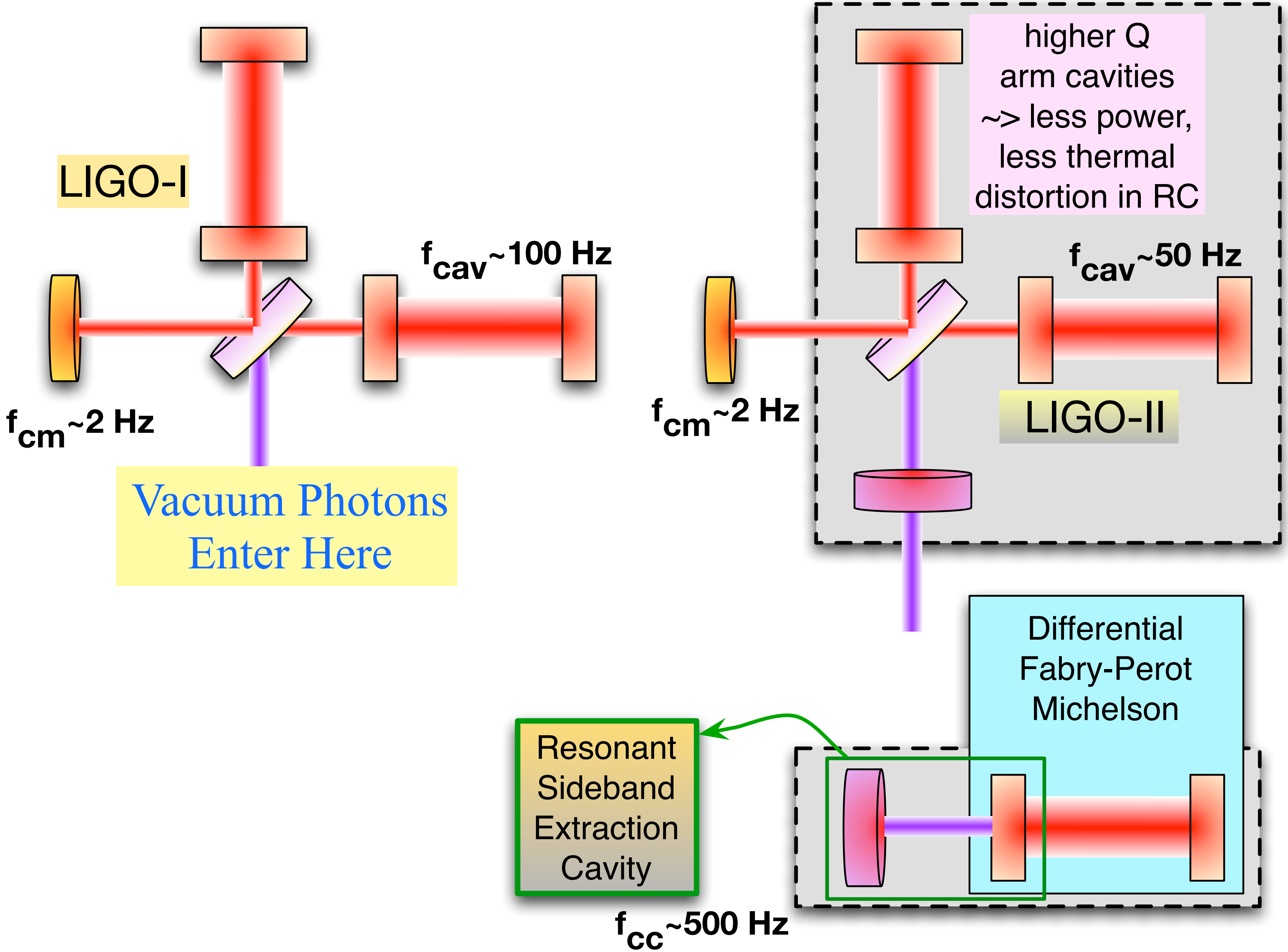
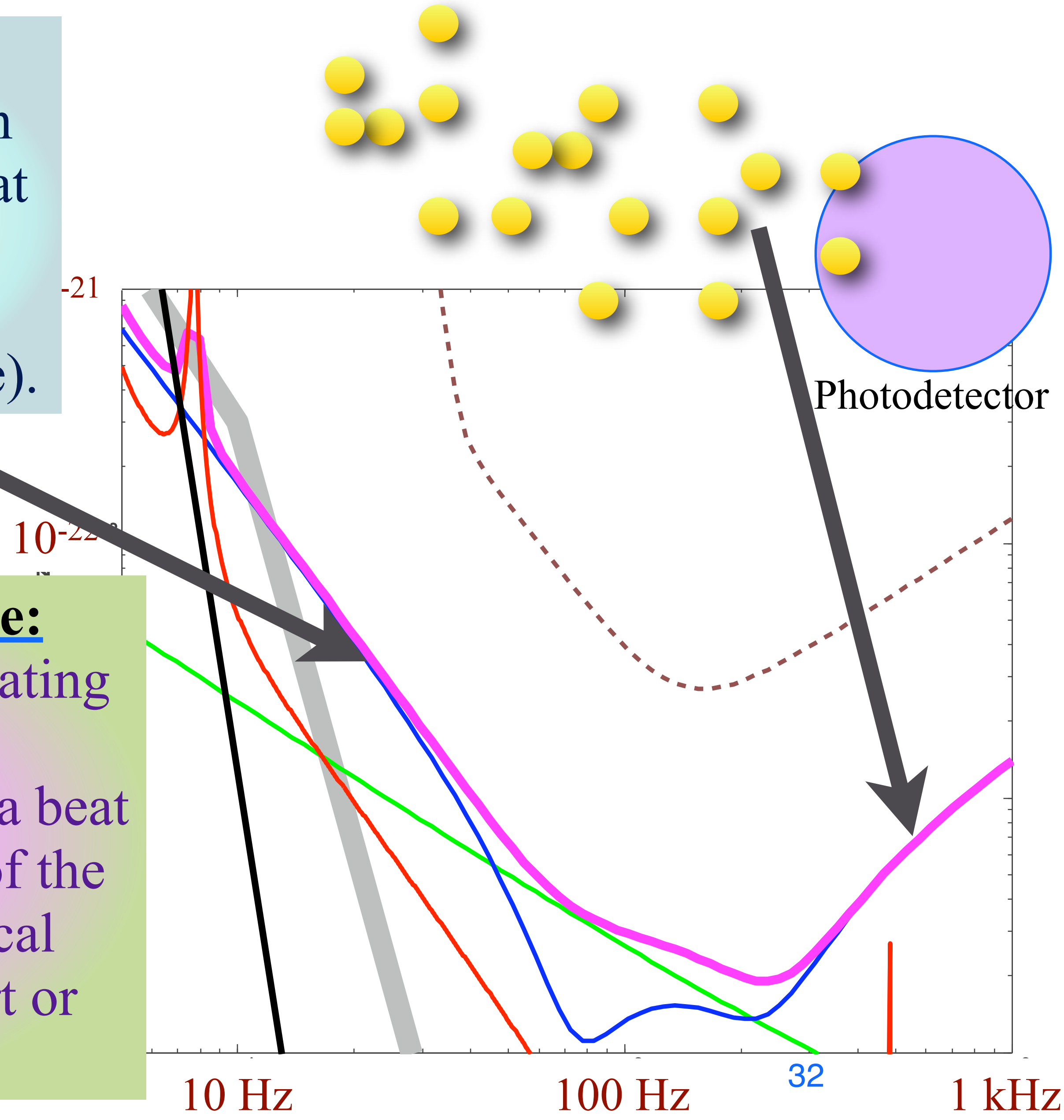




LIGO-I
f_{cav}~100 Hz
f_{cm}~2 Hz
Vacuum Photons
Enter Here
higher Q
arm cavities
~> less power,
less thermal
distortion in RC
f_{cav}~50 Hz
f_{cm}~2 Hz
LIGO-II
Differential
Fabry-Perot
Michelson
Resonant
Sideband
Extraction
Cavity
f_{cc}~500 Hz

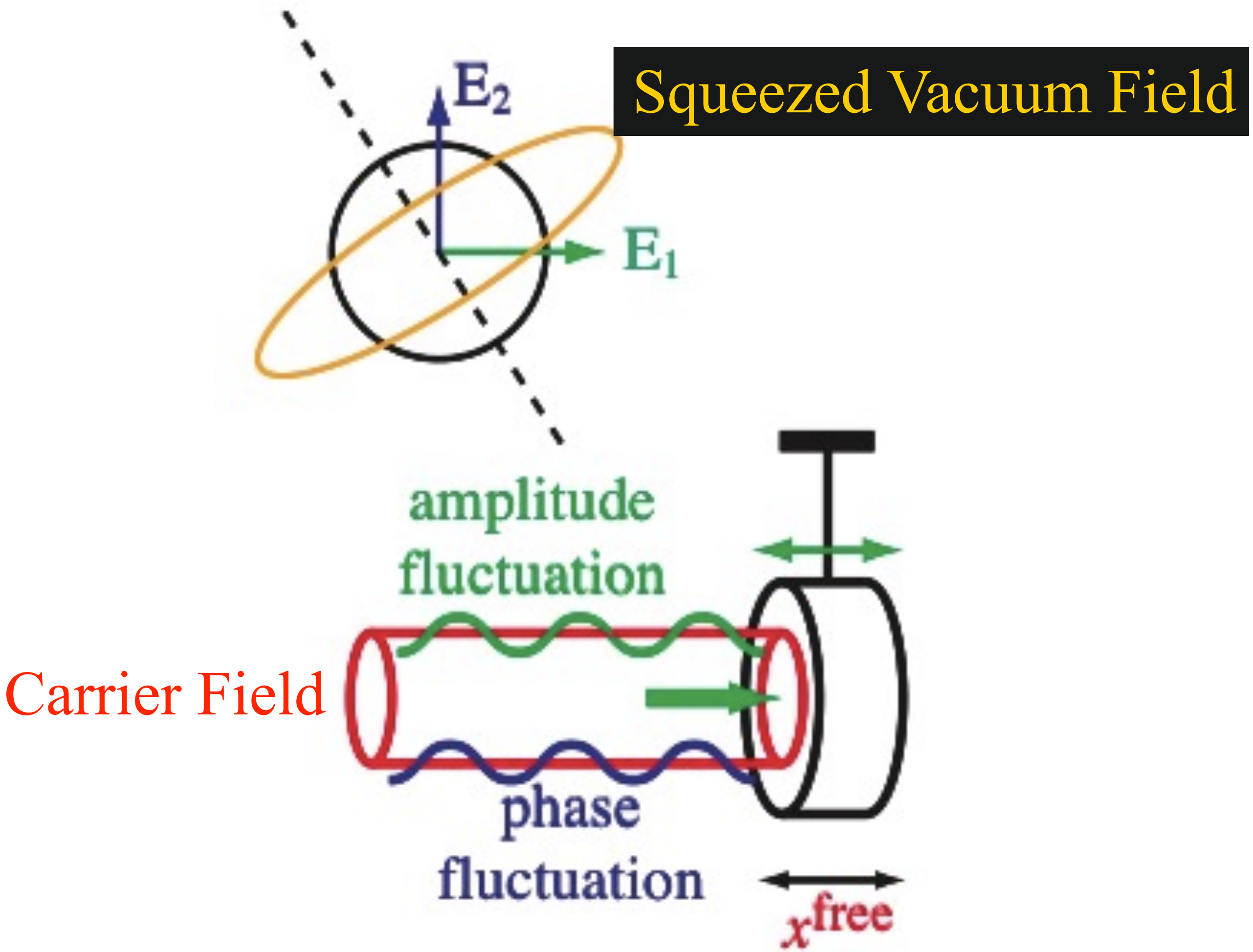
What about this Quantum noise?

Shot Noise Picture:
Poisson statistics govern arrival time of photons at the photodetector. Also arrival times at the test mass (radiation pressure).

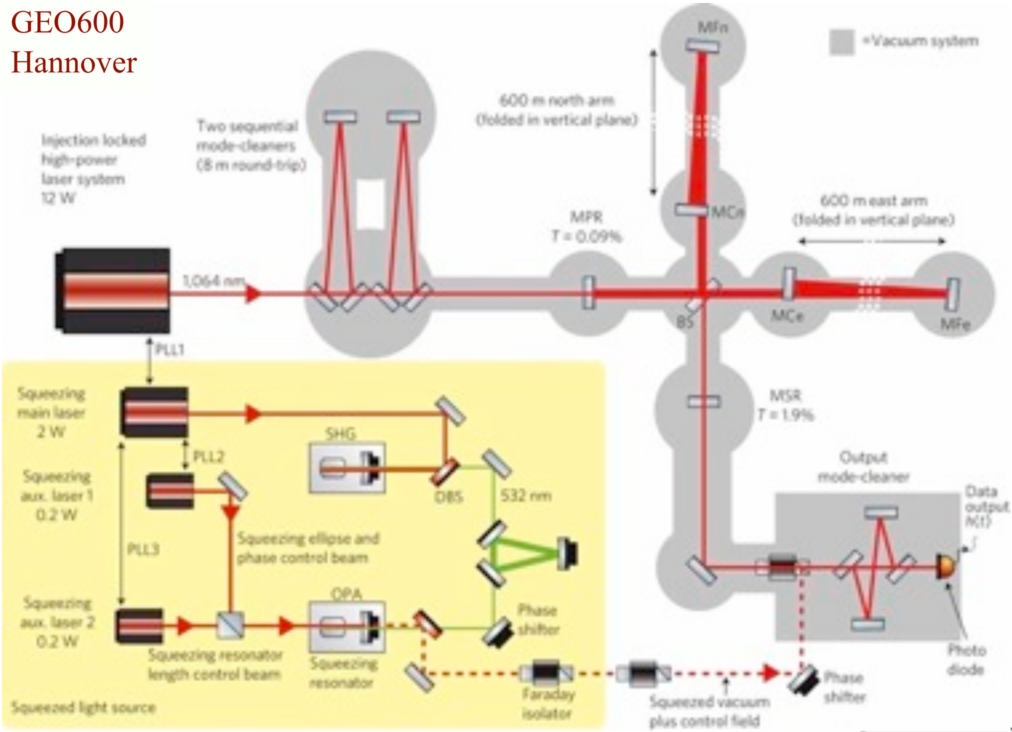


Vacuum Photon Picture:
Losses couple the fluctuating vacuum field to the interferometer. Noise is a beat between the amplitude of the ***vacuum field*** and the local field (field at the AS port or field at the test mass).

Circumventing Usual Quantum Noise

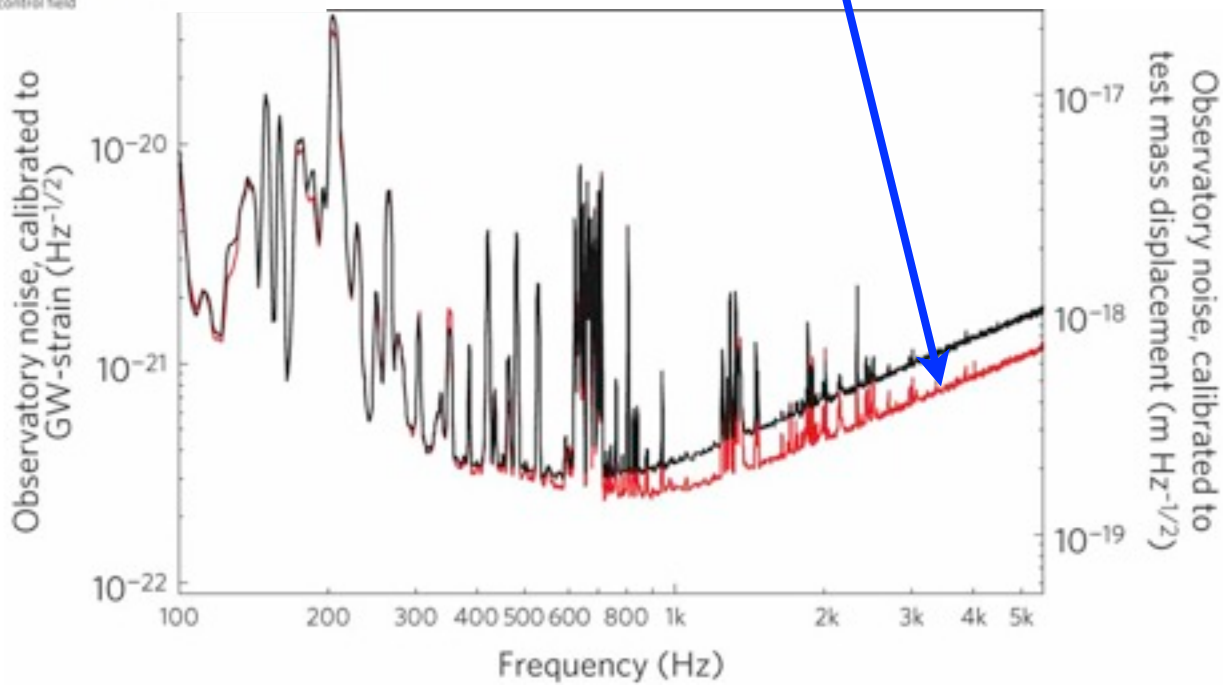


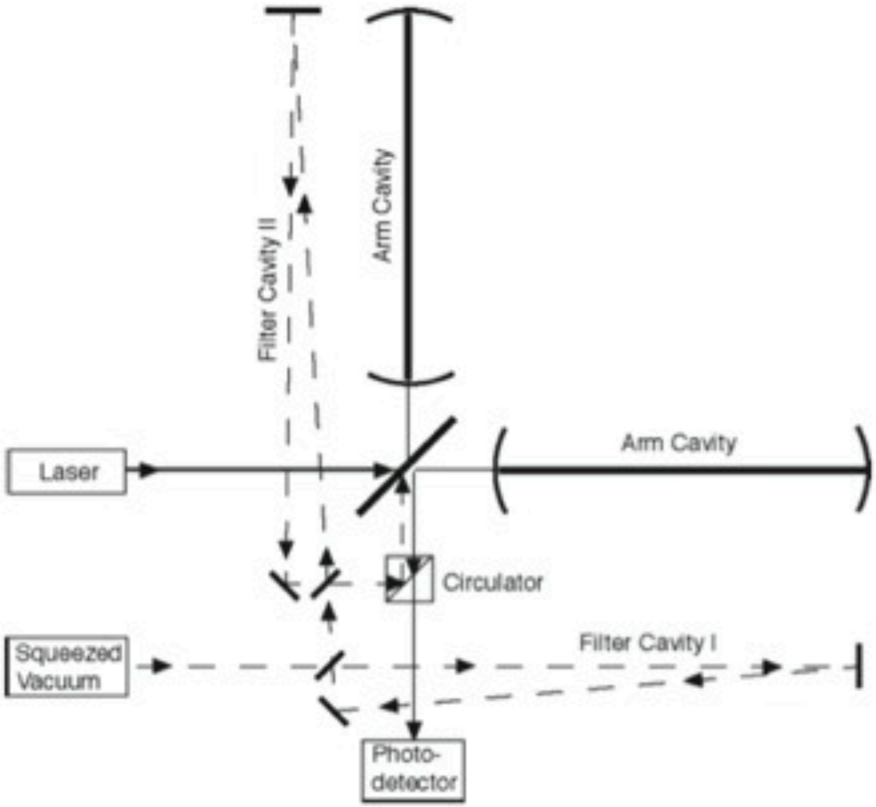
GEO600
Hannover



3.5 dB of noise reduction
~2x in laser power

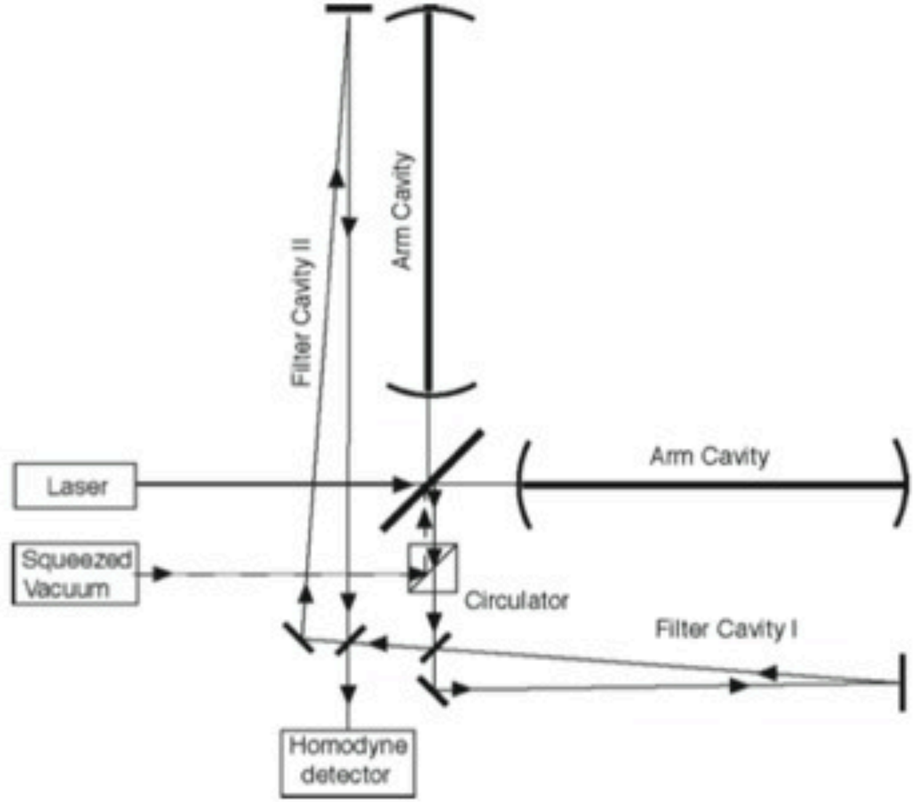
Beyond Quantum Hopes





Squeezed Input

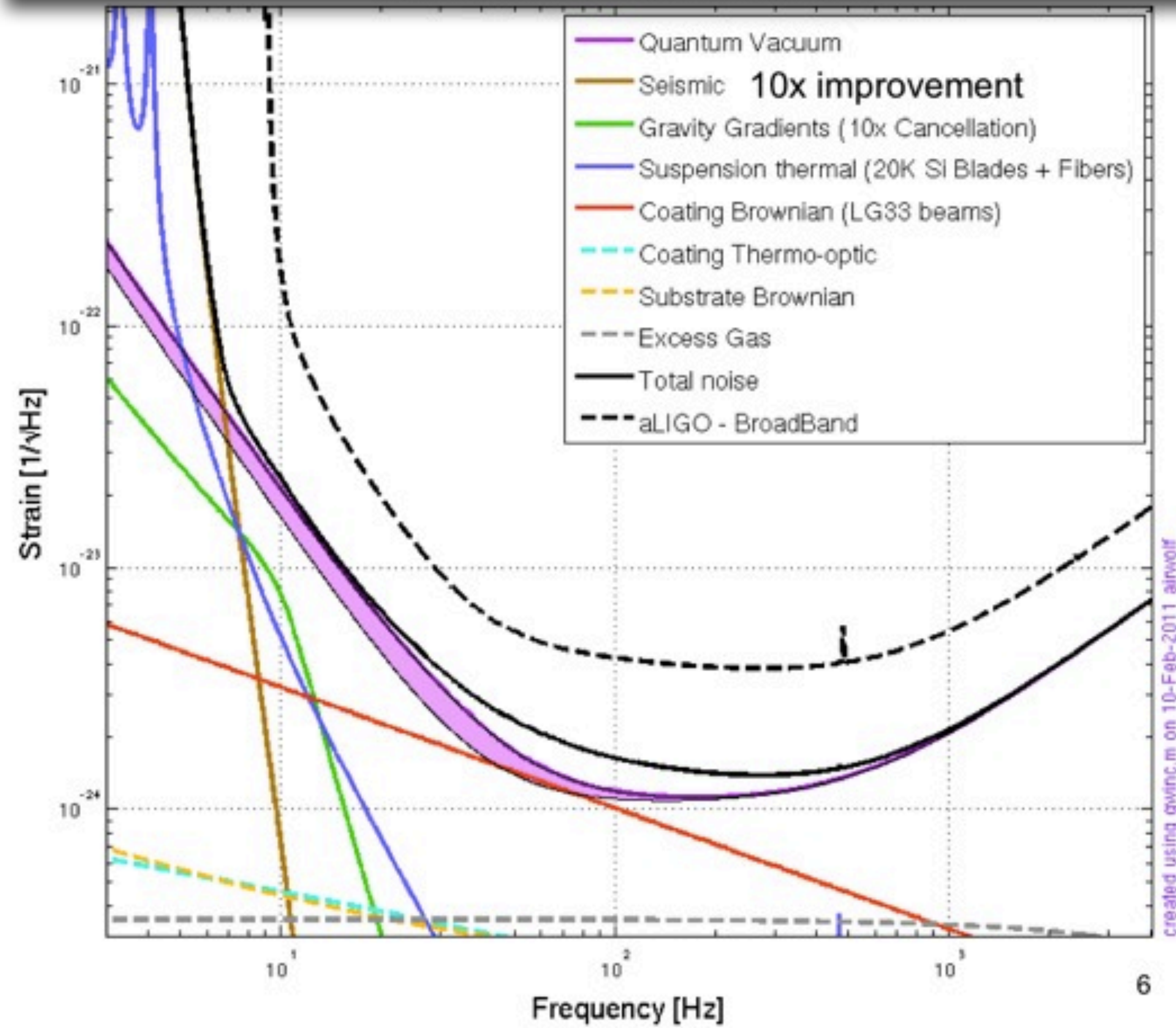
frequency dependent
input squeezing quadrature

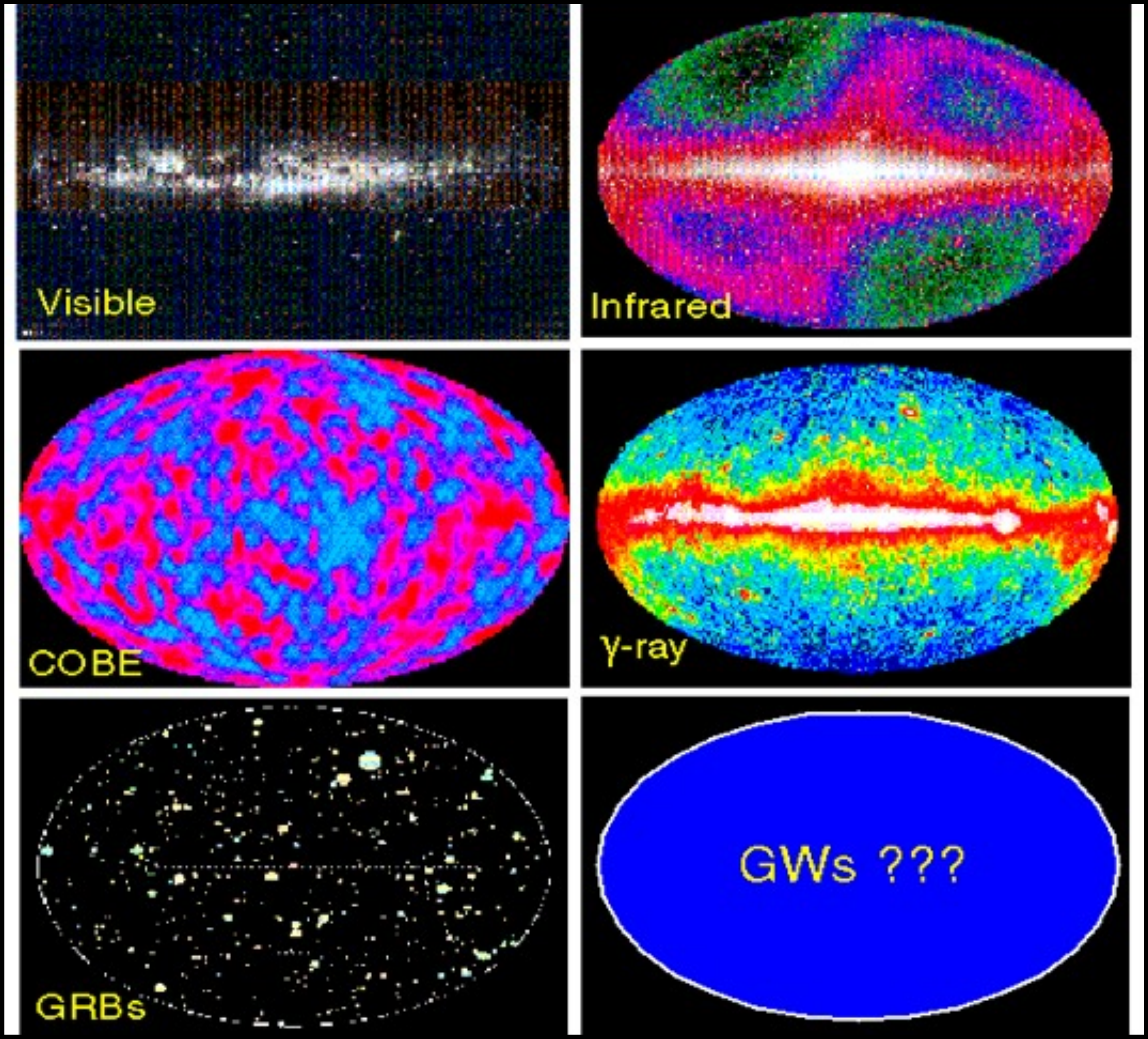


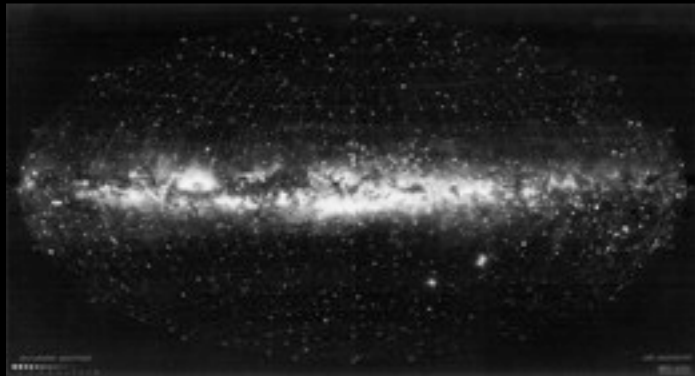
Variational Readout

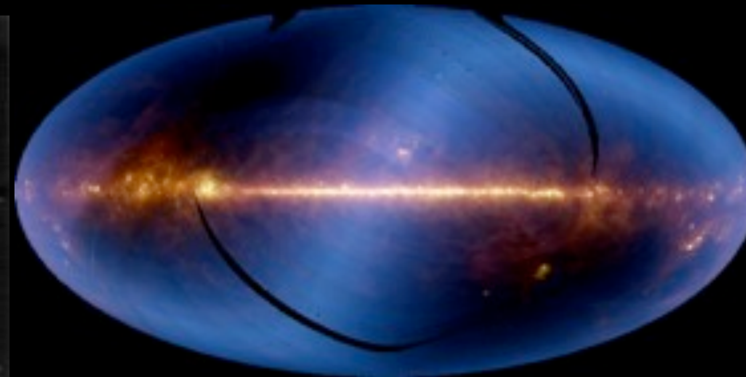
frequency dependent
readout quadrature

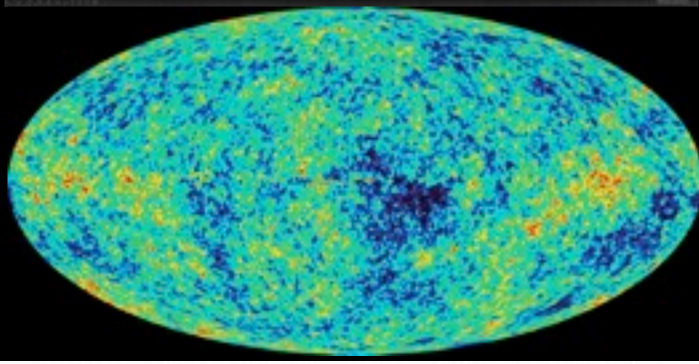
3rd Generation LIGO

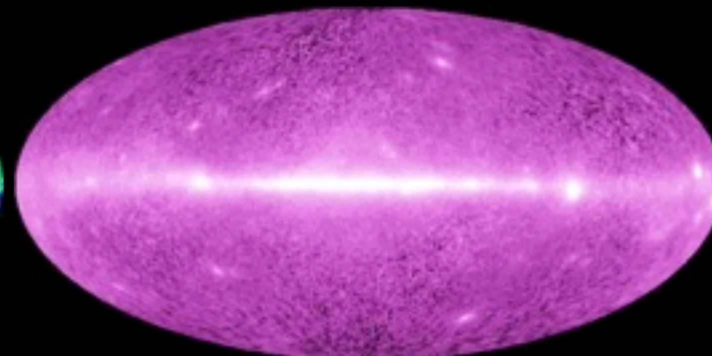


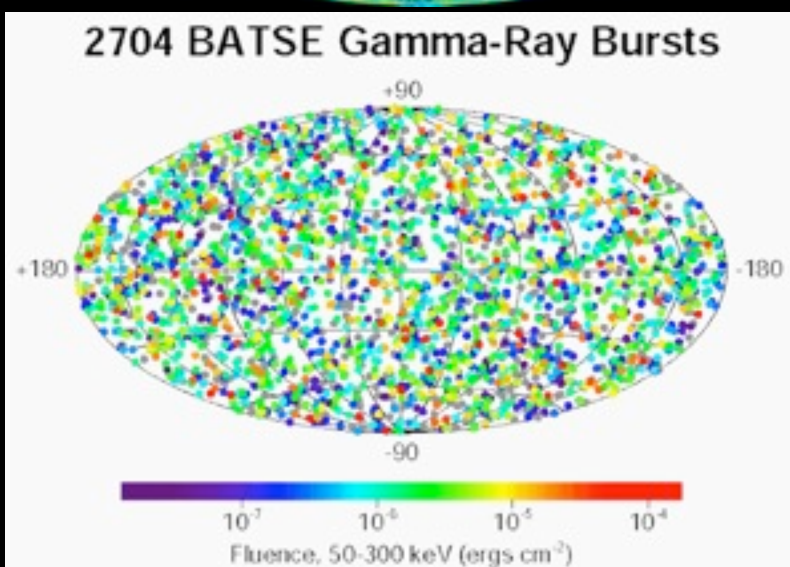

Visible
Infrared
COBE
γ-ray
GRBs
GWs ???









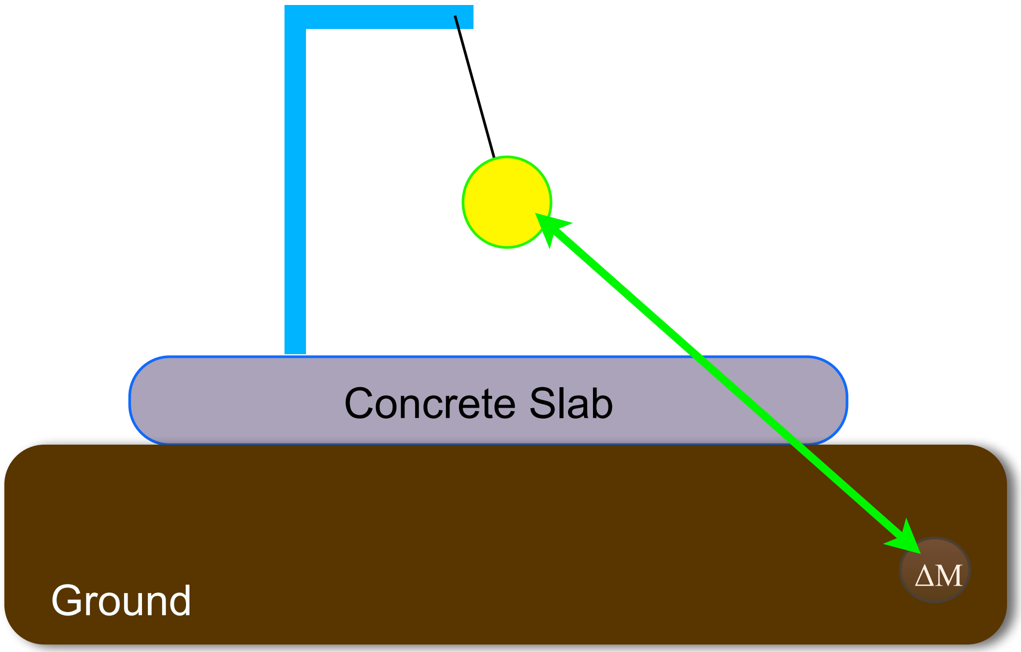

2704 BATSE Gamma-Ray Bursts
+90
+180
-180
-90
10^{-7}
10^{-6}
10^{-5}
10^{-4}
Fluence, 50-300 keV (ergs cm^{-2})

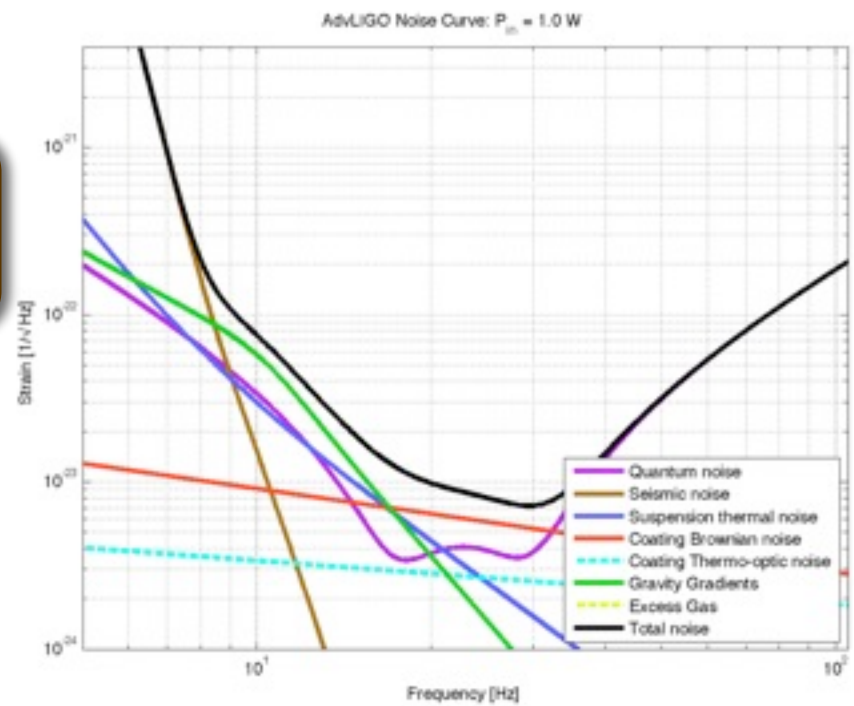
Summary

- 2nd Generation Interferometers ~ 2014
- 3rd Generation Interferometers < 2020
- Tests of NS physics, GR, discoveries of new phenomena
- Macroscopic Quantum Mechanics

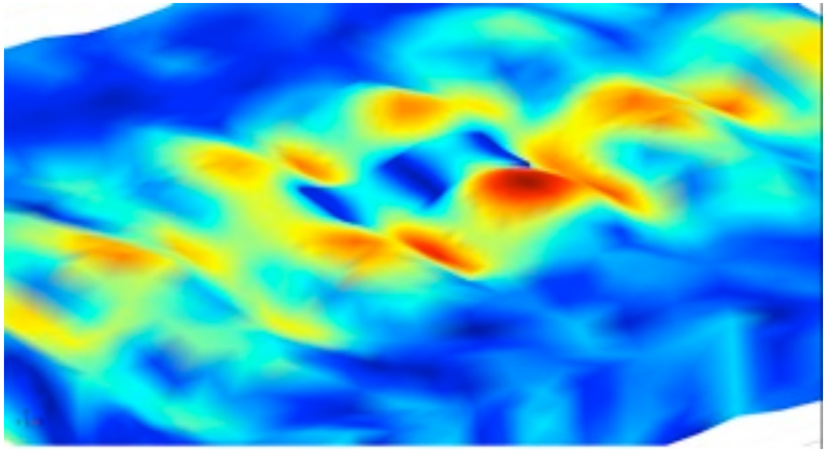
Gravity Gradient Noise

$x(f) = G\,\Delta M(f)\,/(f^2\,r^2)$

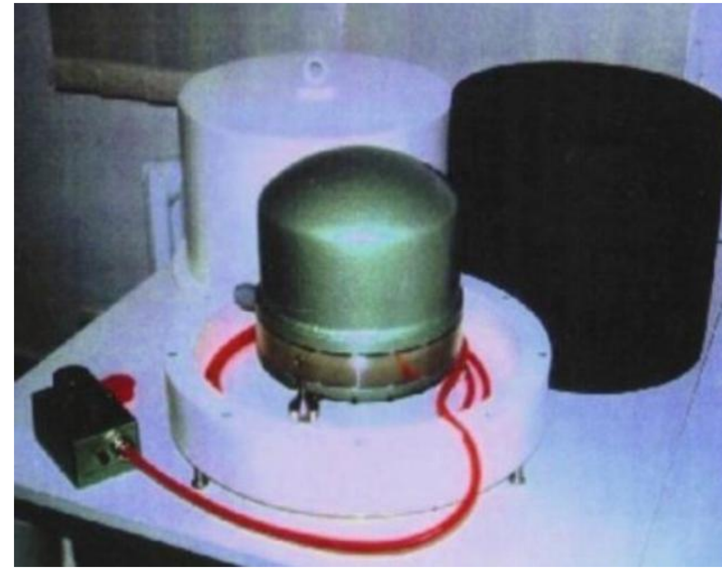


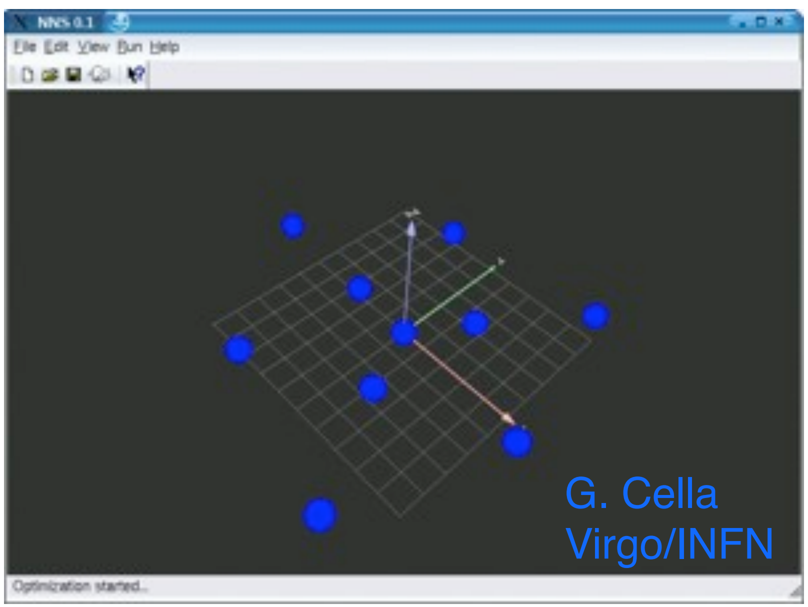


- **Noise Sources**
  - **Surface Waves**
  - **Air Pressure Fluctuations**
  - **Subsurface density**



FEA of Ground





- **Noise Cancellation**
  - Accelerometers measure ground motion
  - Adaptive algorithm estimates GG noise