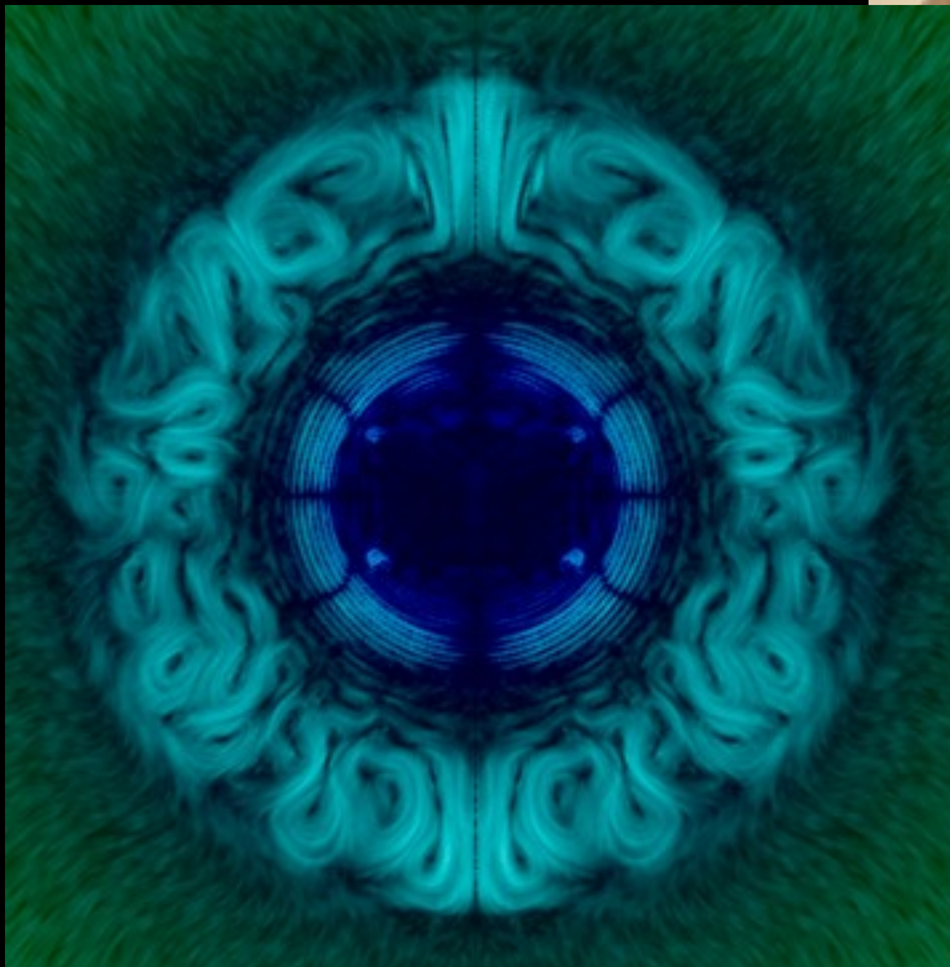
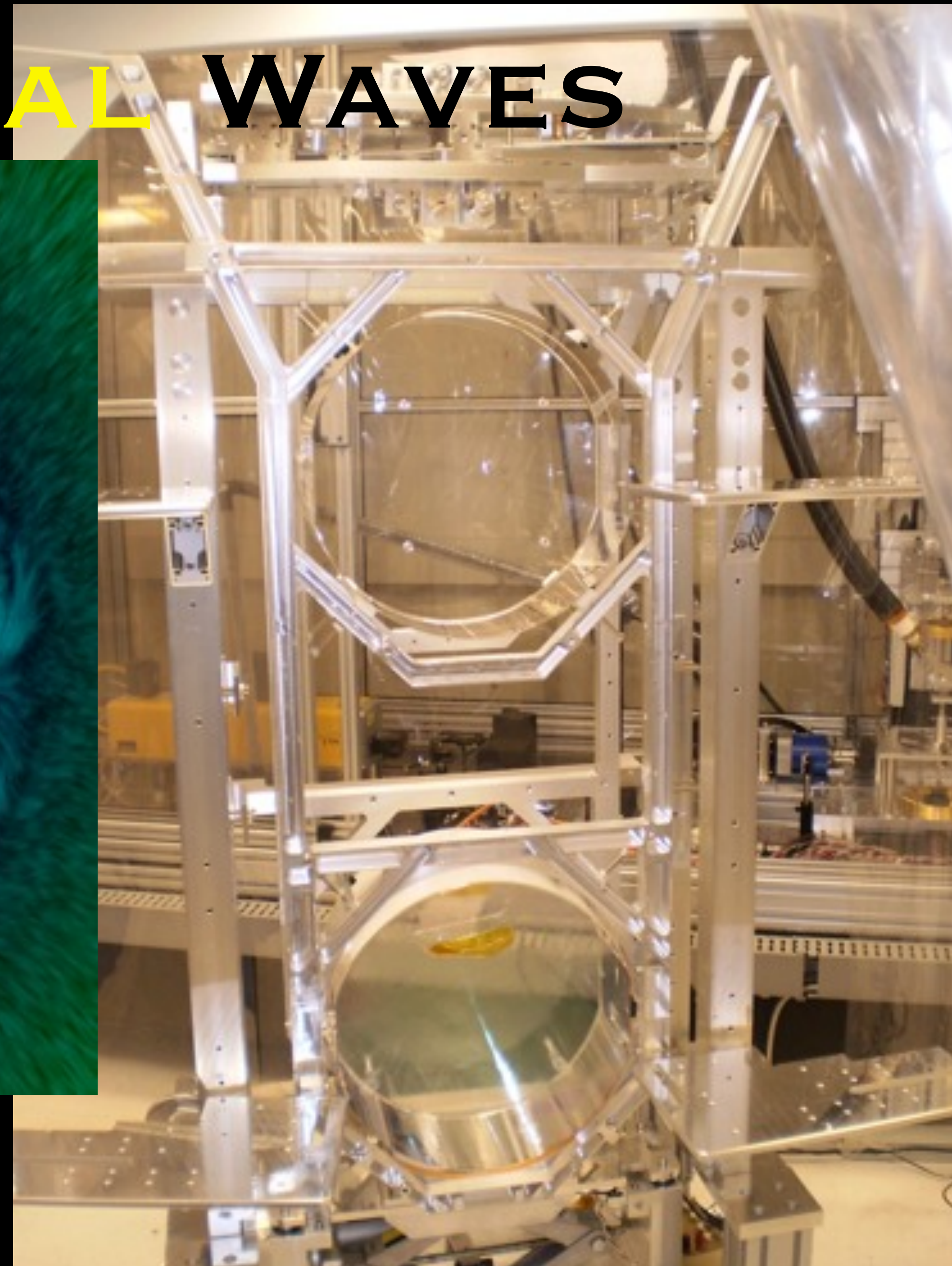
Gravitational Waves

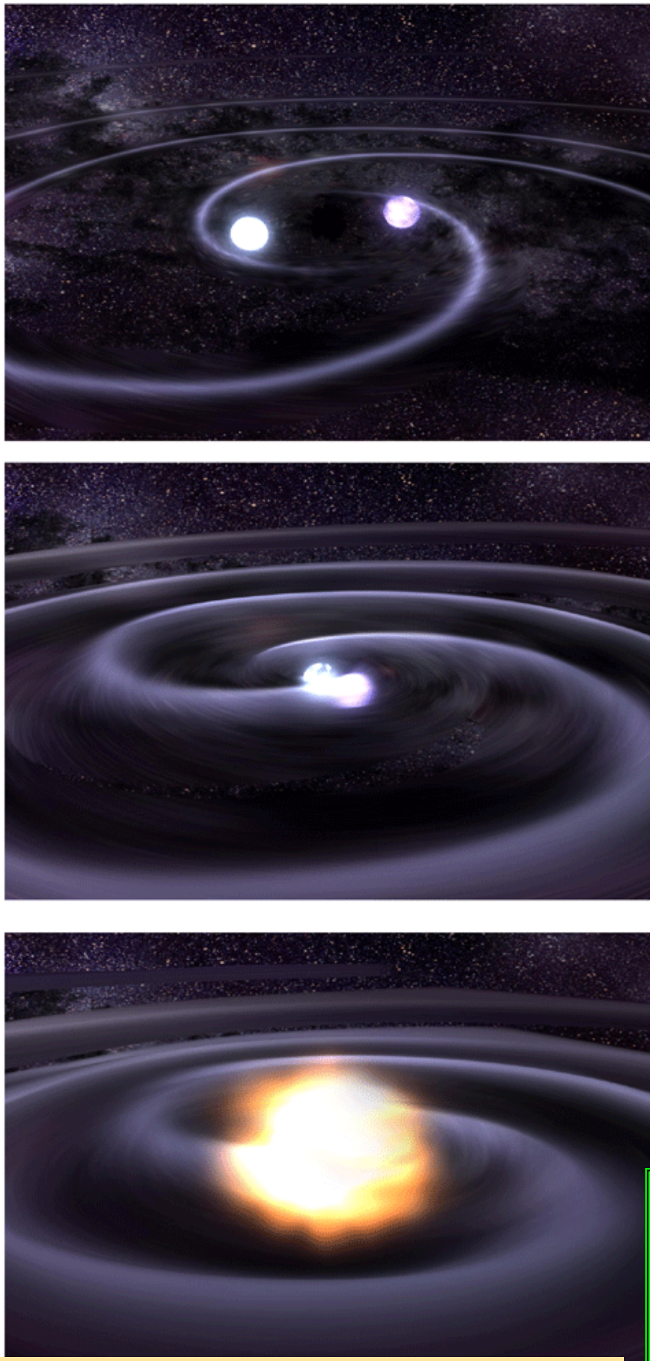




NASA QFT

Jan 18, 2012

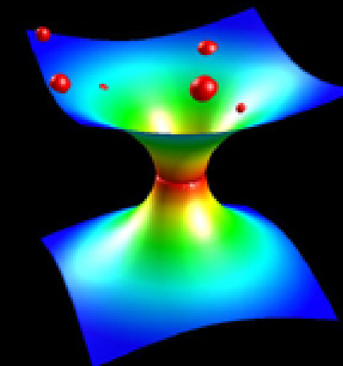
Rana Adhikari Caltech

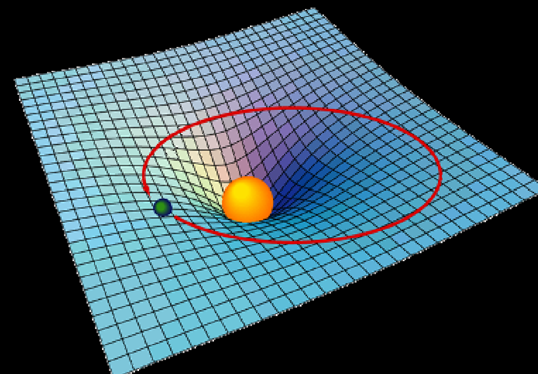


NASA/Dana Berry, Sky Works Digital

Gravitational Waves

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





"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?

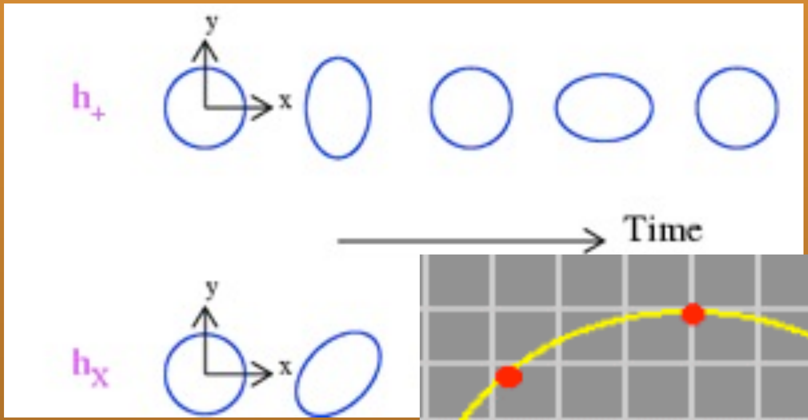
- Gravitational Waves = “Ripples in space-time”
- Two transverse polarizations - <u>quadrupolar</u>: + and x

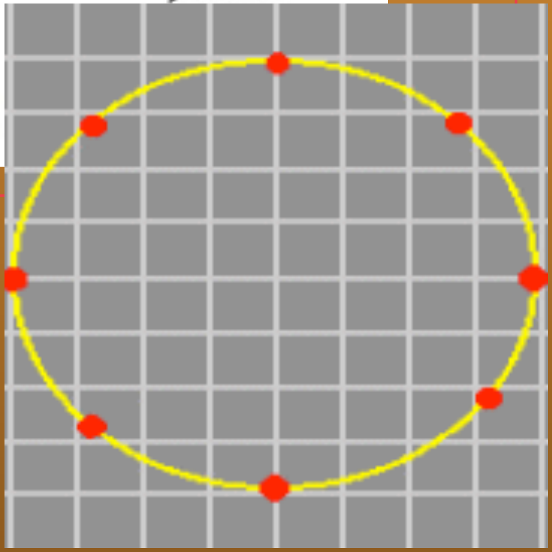
Example:

Ring of test masses

responding to wave

propagating along z





Amplitude parameterized by

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

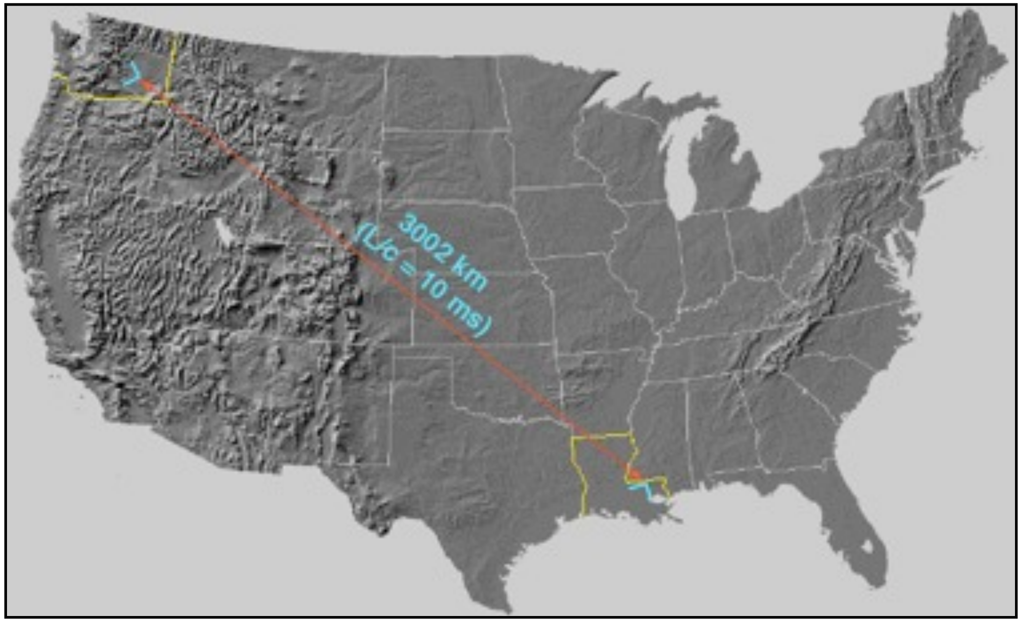
Need to measure strain of ~ 10^{-21}-10^{-22}

<u>We want a very large 'L'</u>

LIGO: Big Michelson Interferometers

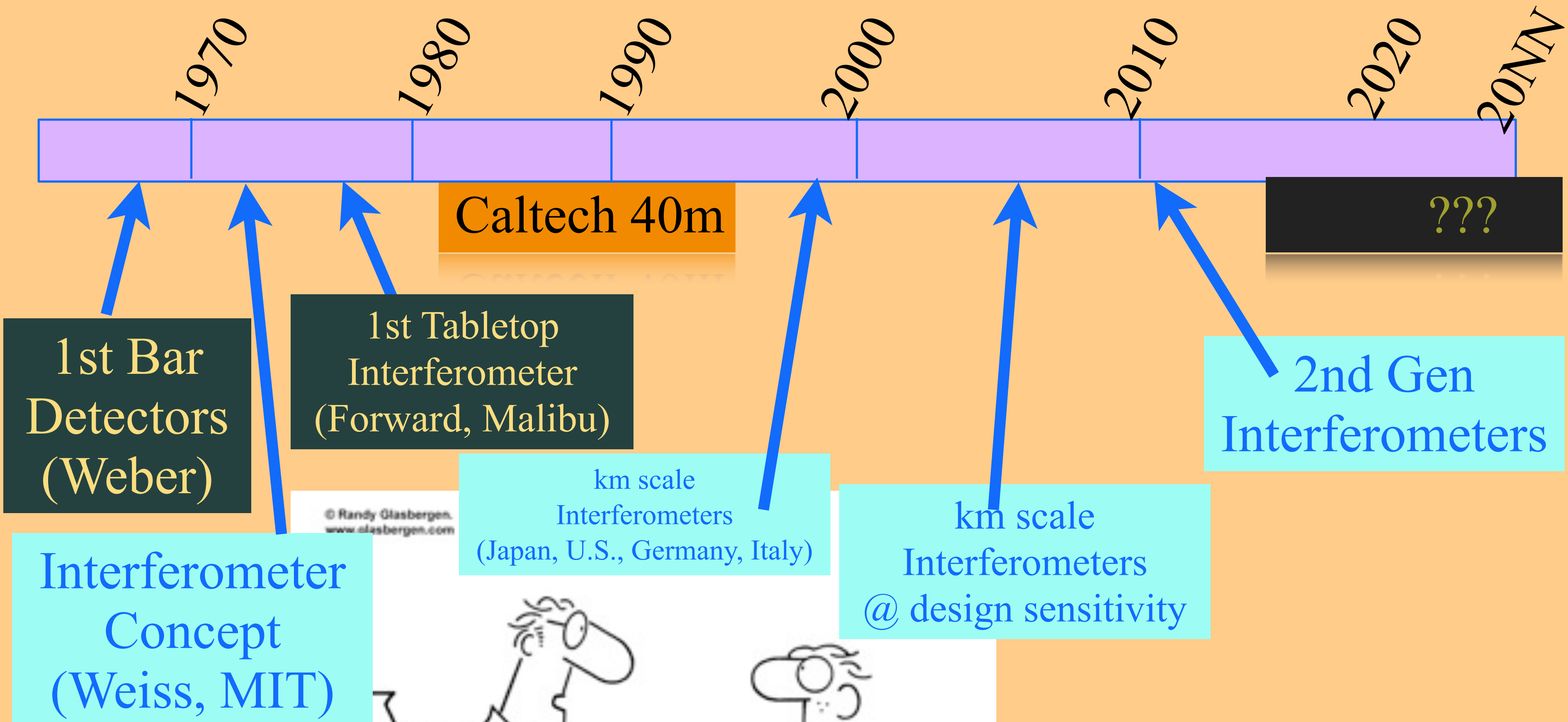
Hanford Nuclear Reservation, Eastern WA (H1 4km, H2 2km)

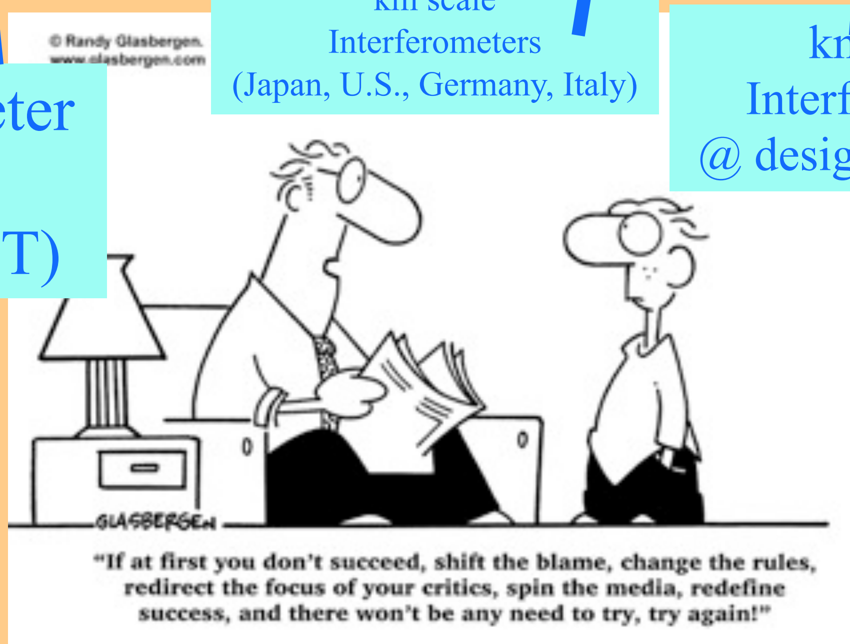
- ***Interferometers are aligned to be as close to parallel to each other as possible***
- ***Observing signals in coincidence increases the detection confidence***
- ***Determine source location on the sky, propagation speed and polarization of the gravity wave***



Livingston, LA (L1 4km)

Timeline of GW Detectors





The Michelson Interferometer

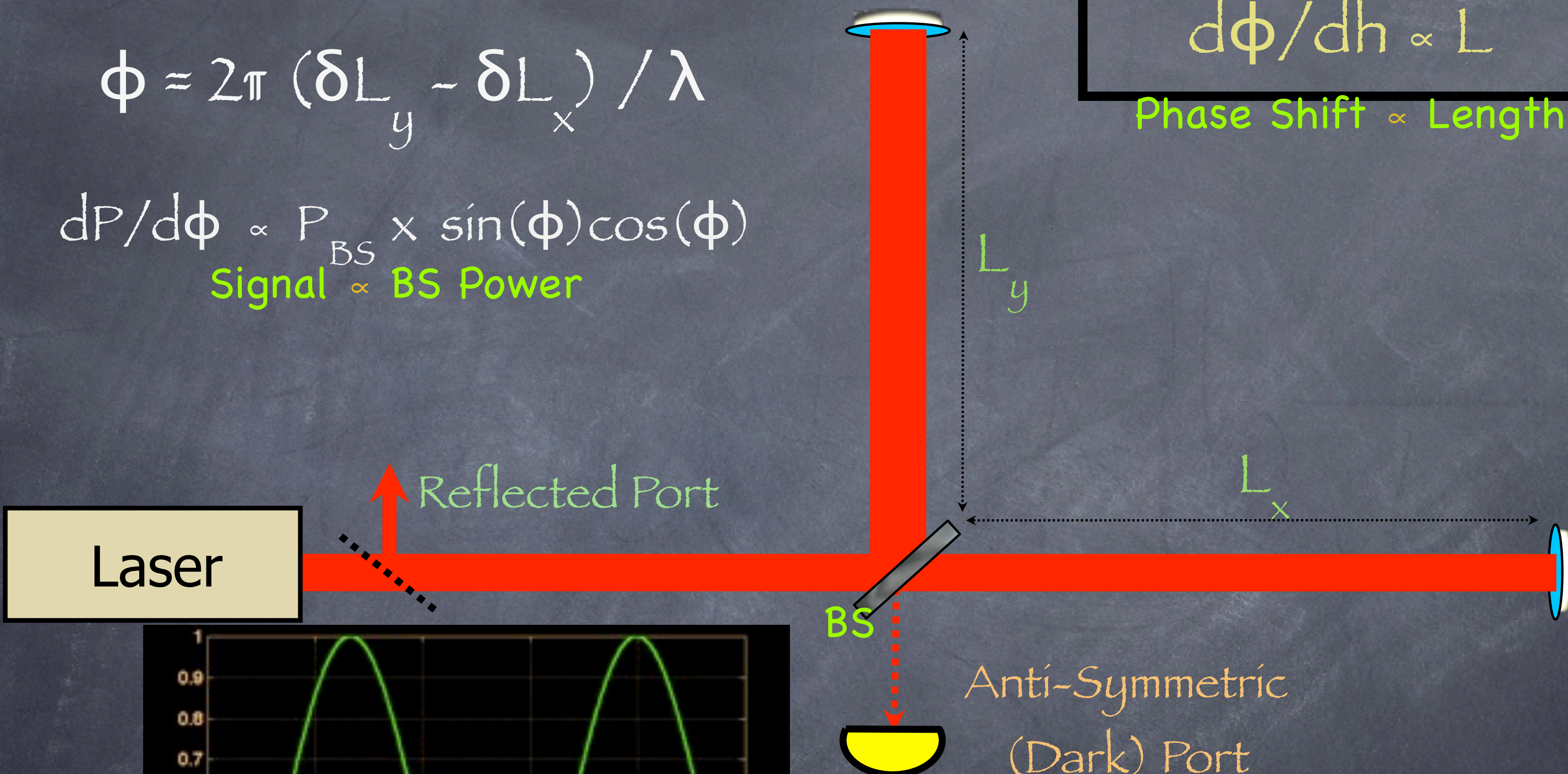
$\phi = 2\pi\,(\delta L_y - \delta L_x)\,/\,\lambda$

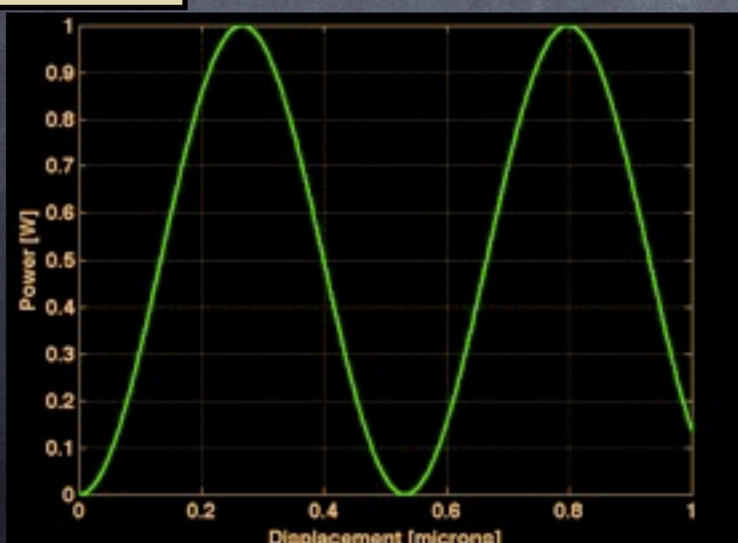
$d\phi/dh \propto L$

Phase Shift ∝ Length

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

Signal ∝ BS Power





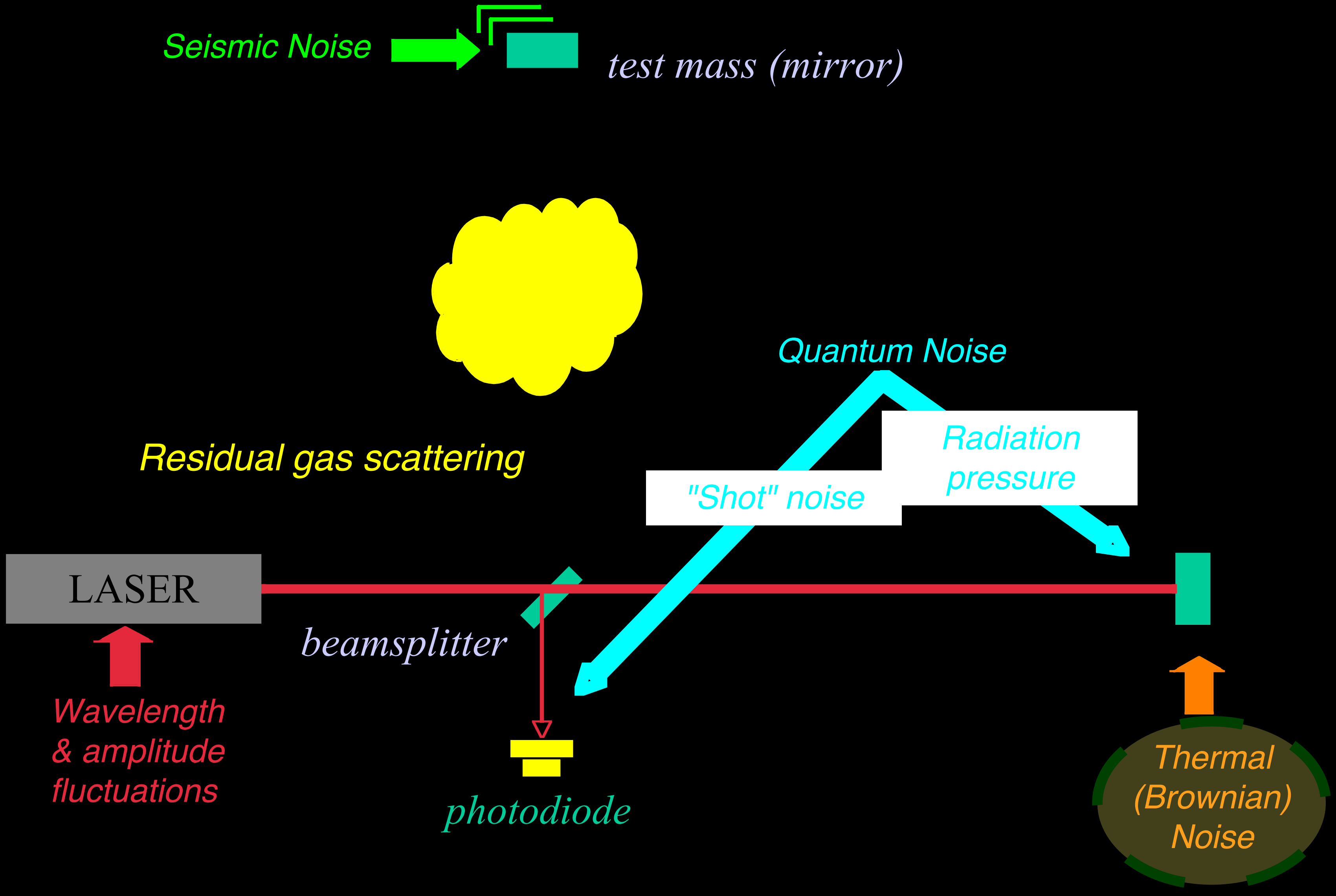
$P \propto P_{BS} \times \sin^2(\phi)$

Poisson Statistics...

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

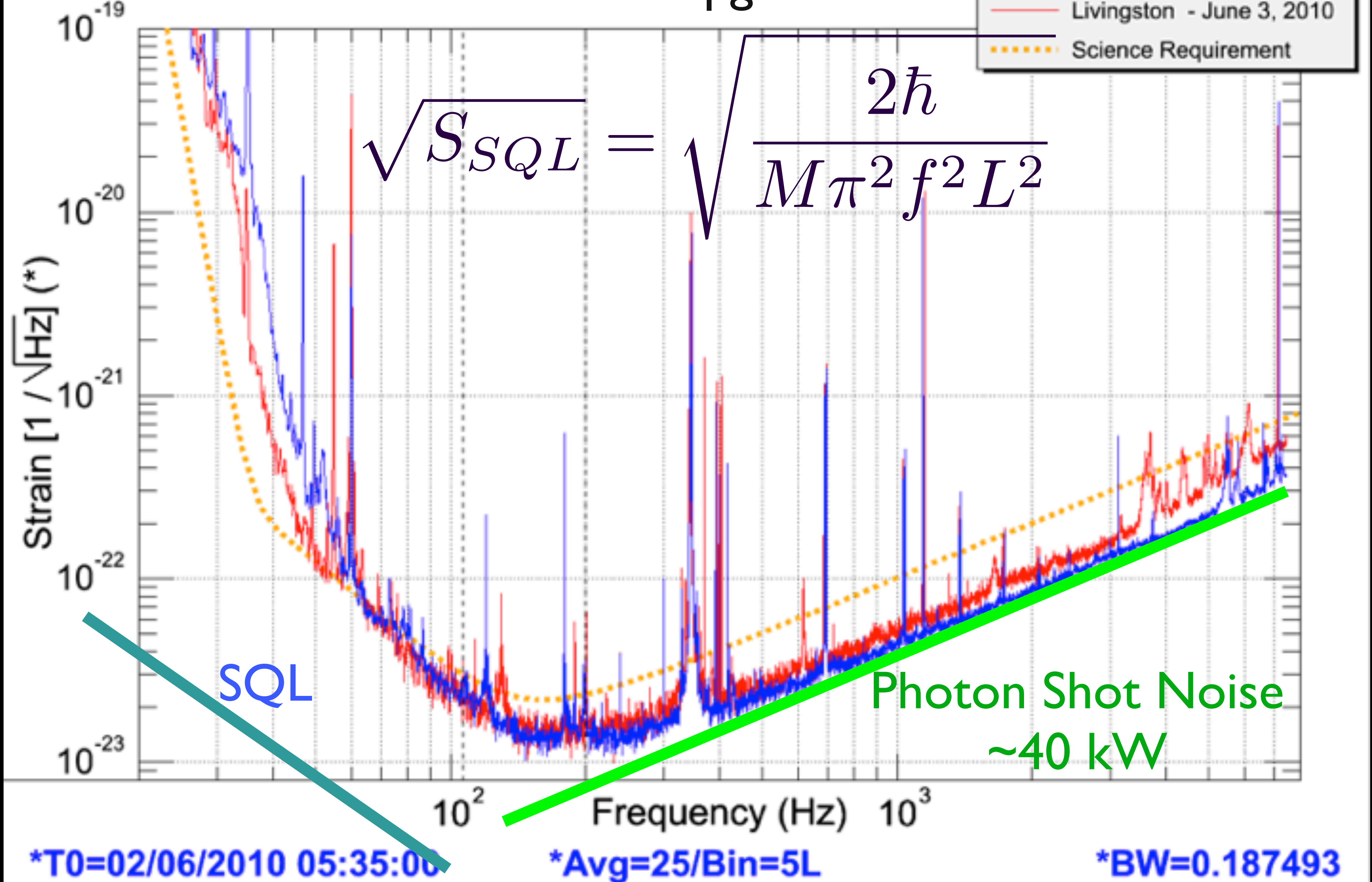
Shot Noise

Noise Cartoon



The **Enhanced** LIGO Upgrade

$$\sqrt{S_{SQL}} = \sqrt{\frac{2\hbar}{M\pi^2 f^2 L^2}}$$



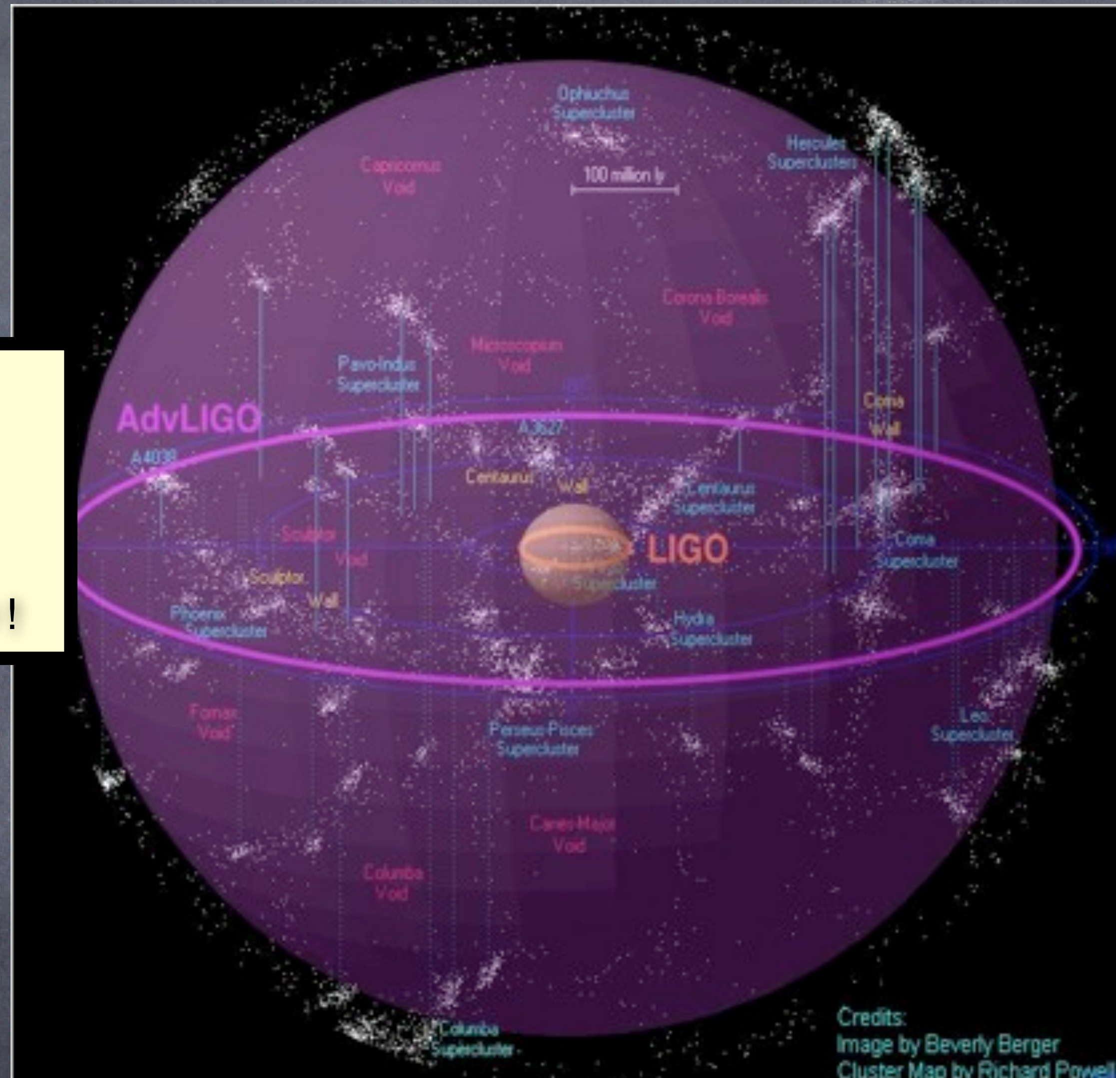
Advanced LIGO

x10 better amplitude sensitivity

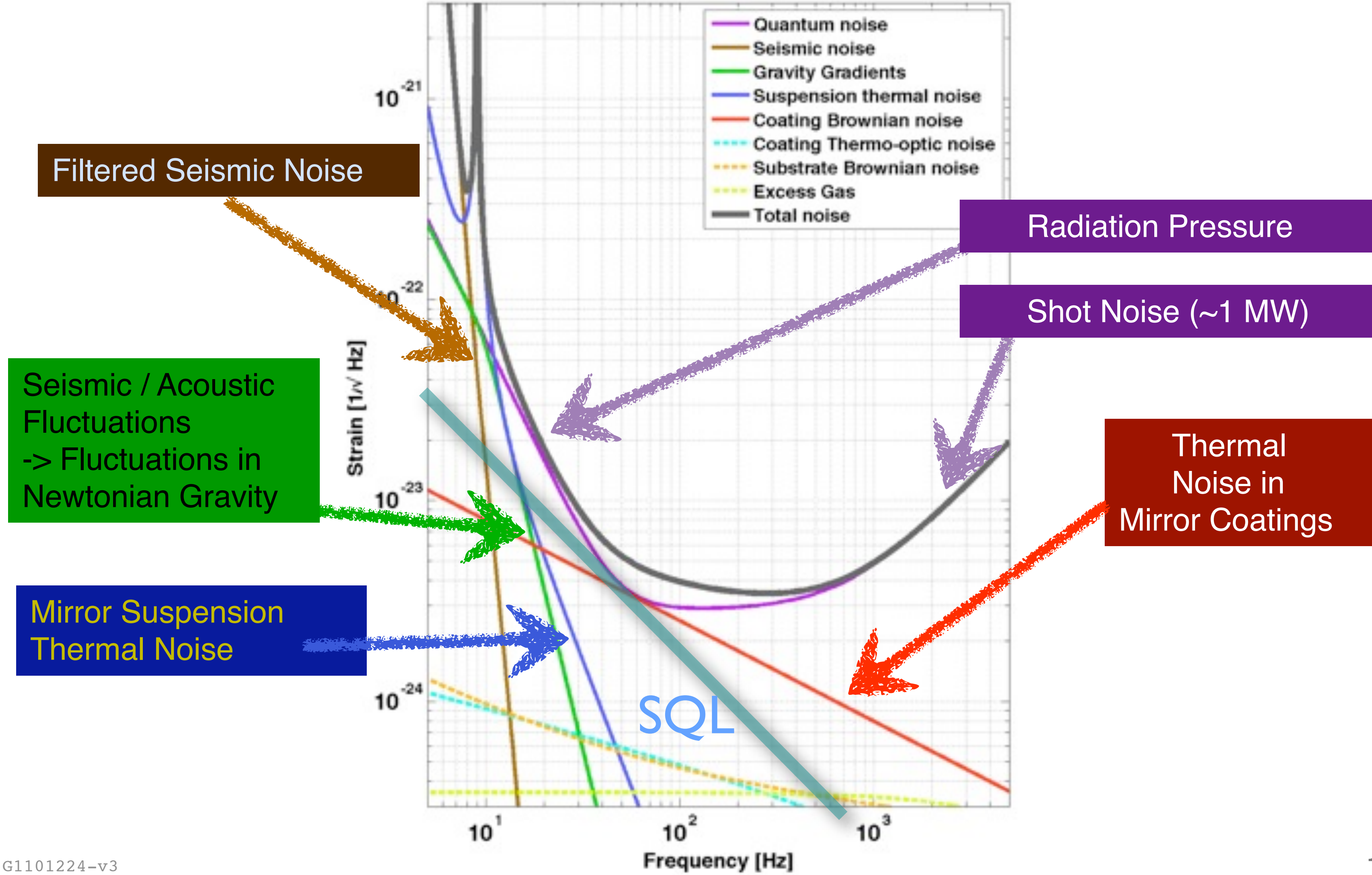
⇒ x1000 rate=(reach)³

⇒ 1 day of Advanced LIGO

» 1 year of Initial LIGO !

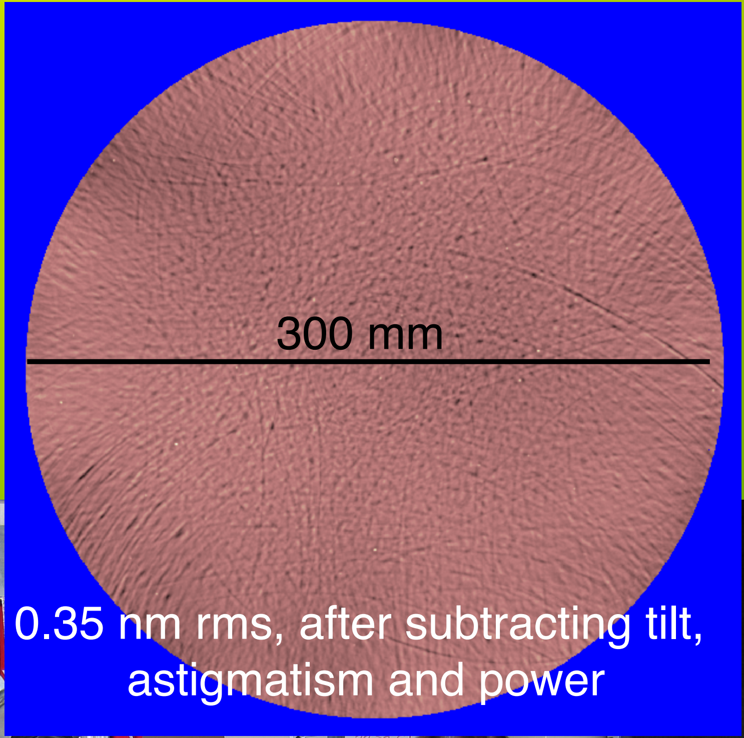


Advanced LIGO Noise Breakdown

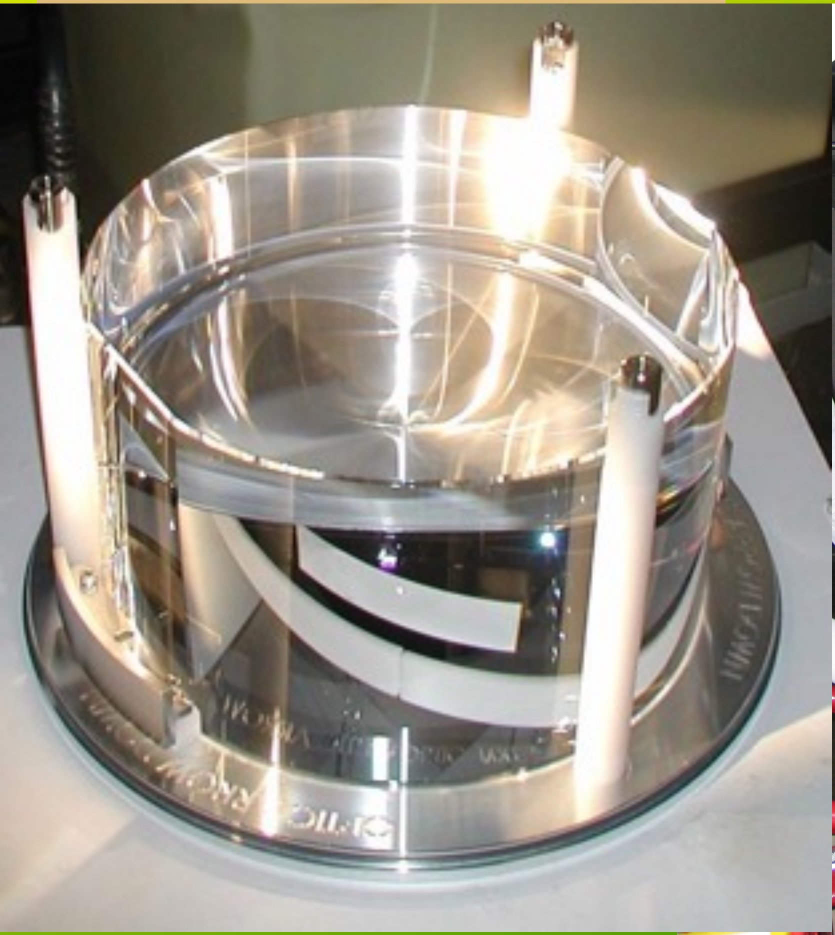


Large Optics

- 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**



0.35 nm rms, after subtracting tilt, astigmatism and power



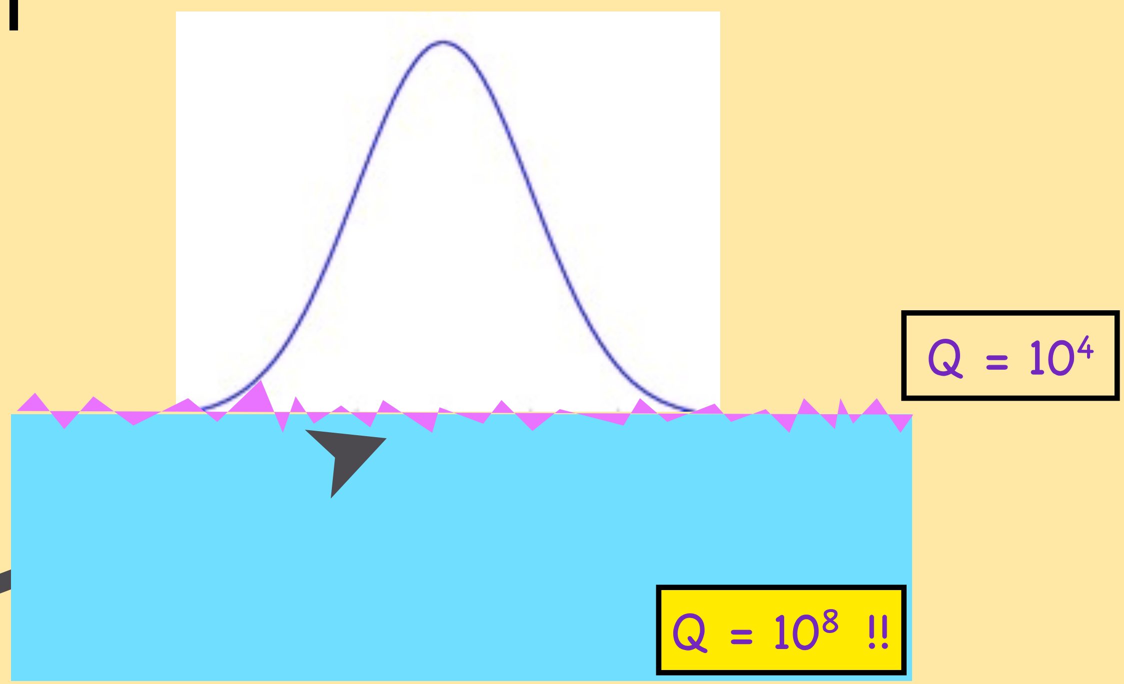
Brownian Thermal Fluctuations

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

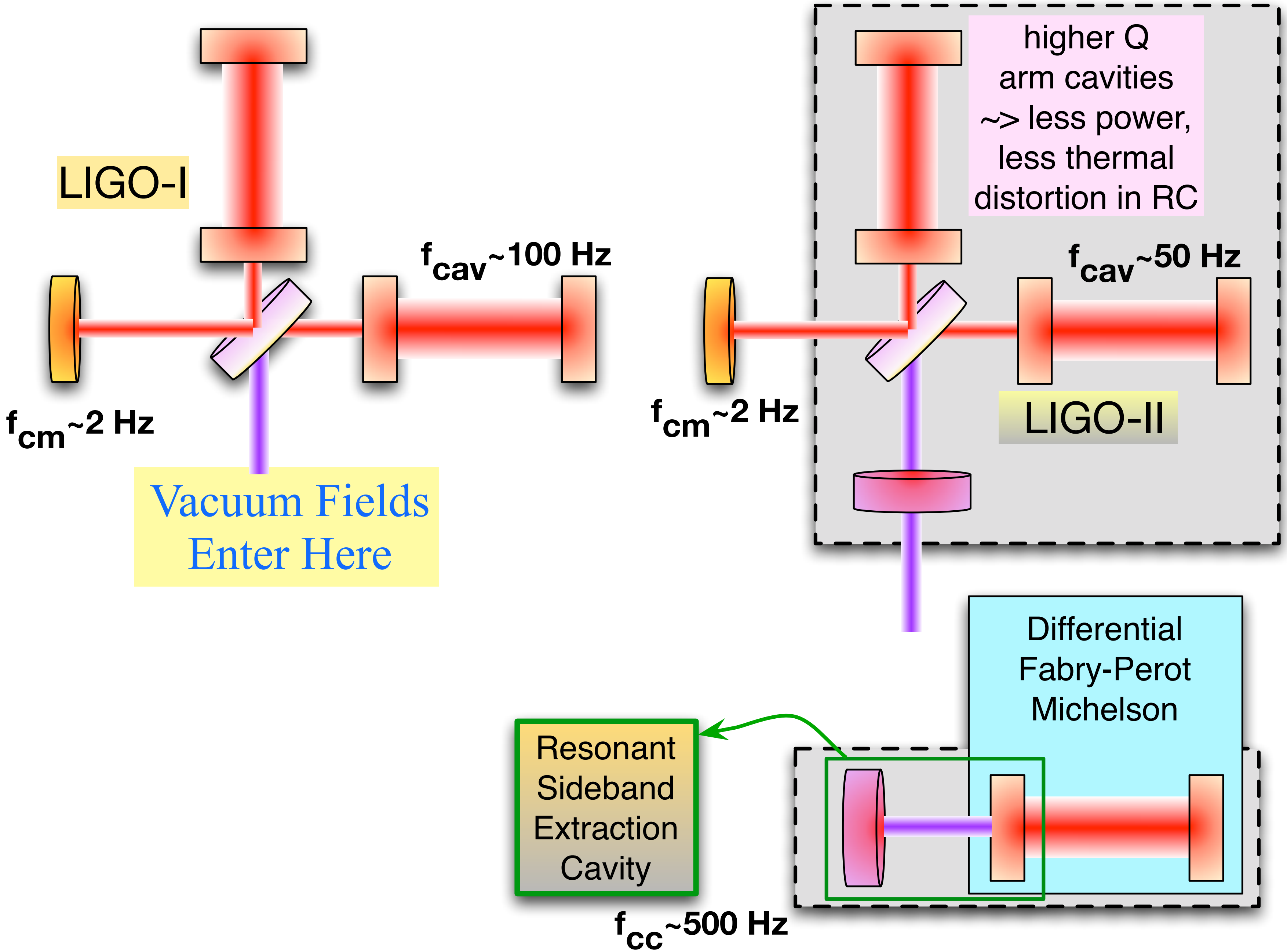
Simple Harmonic Oscillator

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

Fluctuation Dissipation Theorem

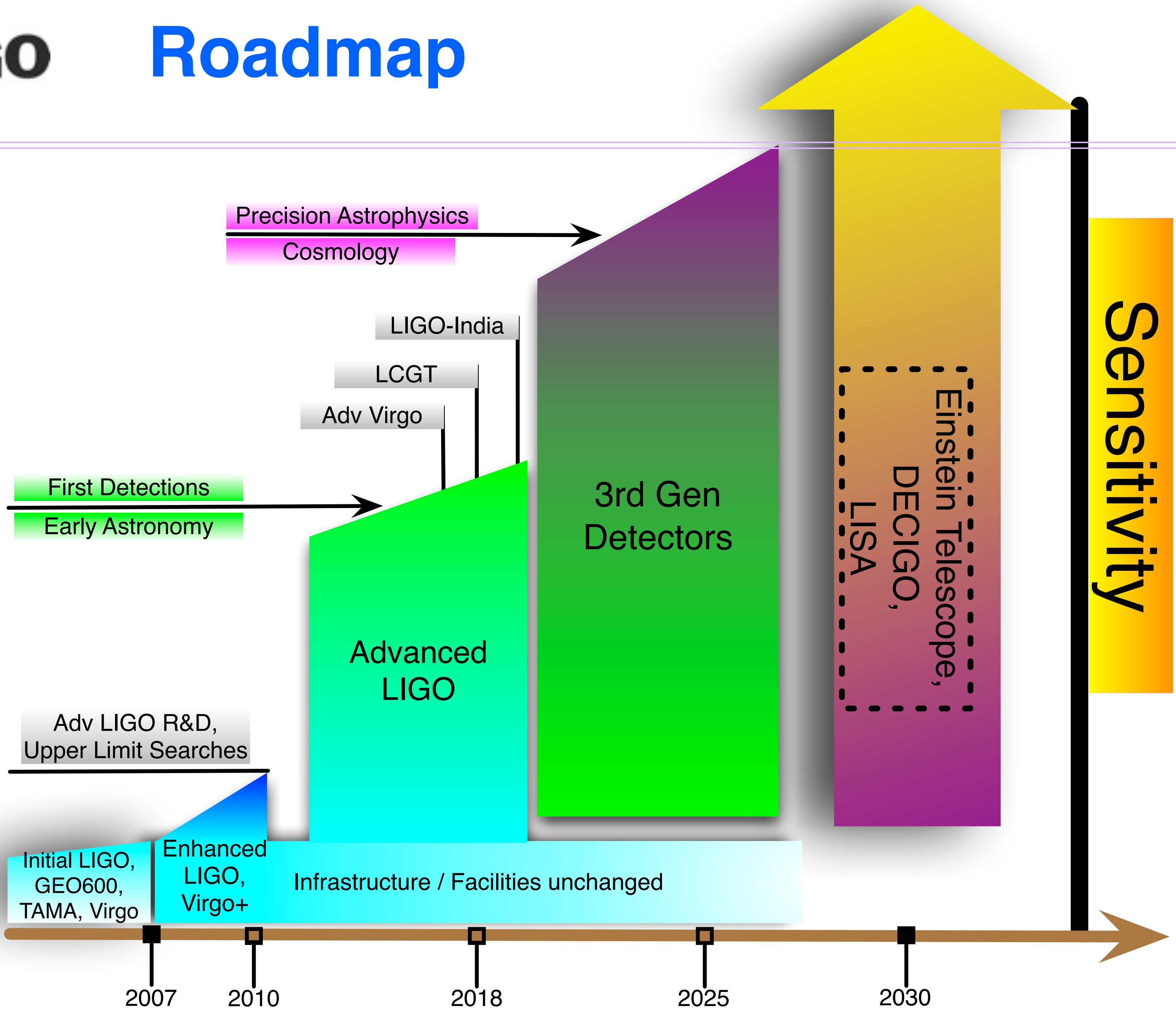


Mirror Surface Thermal Fluctuations



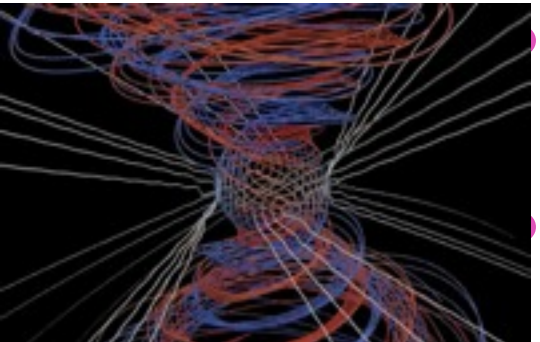
LIGO-I
f_{cav}~100 Hz
f_{cm}~2 Hz
Vacuum Fields
Enter Here
higher Q
arm cavities
~> less power,
less thermal
distortion in RC
f_{cav}~50 Hz
f_{cm}~2 Hz
LIGO-II
Differential
Fabry-Perot
Michelson
Resonant
Sideband
Extraction
Cavity
f_{cc}~500 Hz

Roadmap

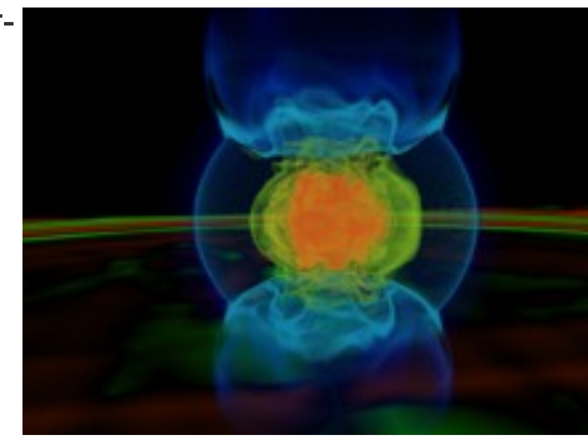


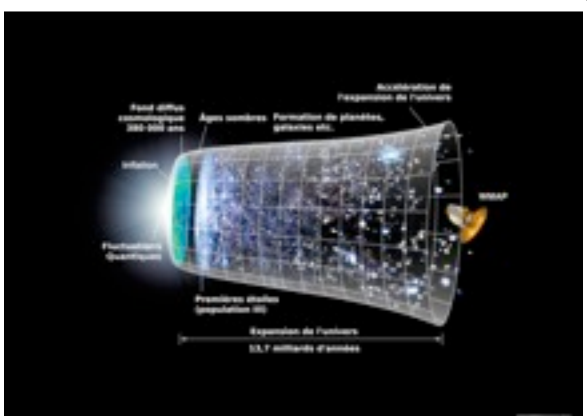
Precision Astrophysics
Cosmology
LIGO-India
LCGT
Adv Virgo
First Detections
Early Astronomy
3rd Gen Detectors
Advanced LIGO
Einstein Telescope, DECIGO, LISA
Sensitivity
Adv LIGO R&D, Upper Limit Searches
Initial LIGO, GEO600, TAMA, Virgo
Enhanced LIGO, Virgo+
Infrastructure / Facilities unchanged
2007
2010
2018
2025
2030

Motivations for 3^{rd} Gen Detectors

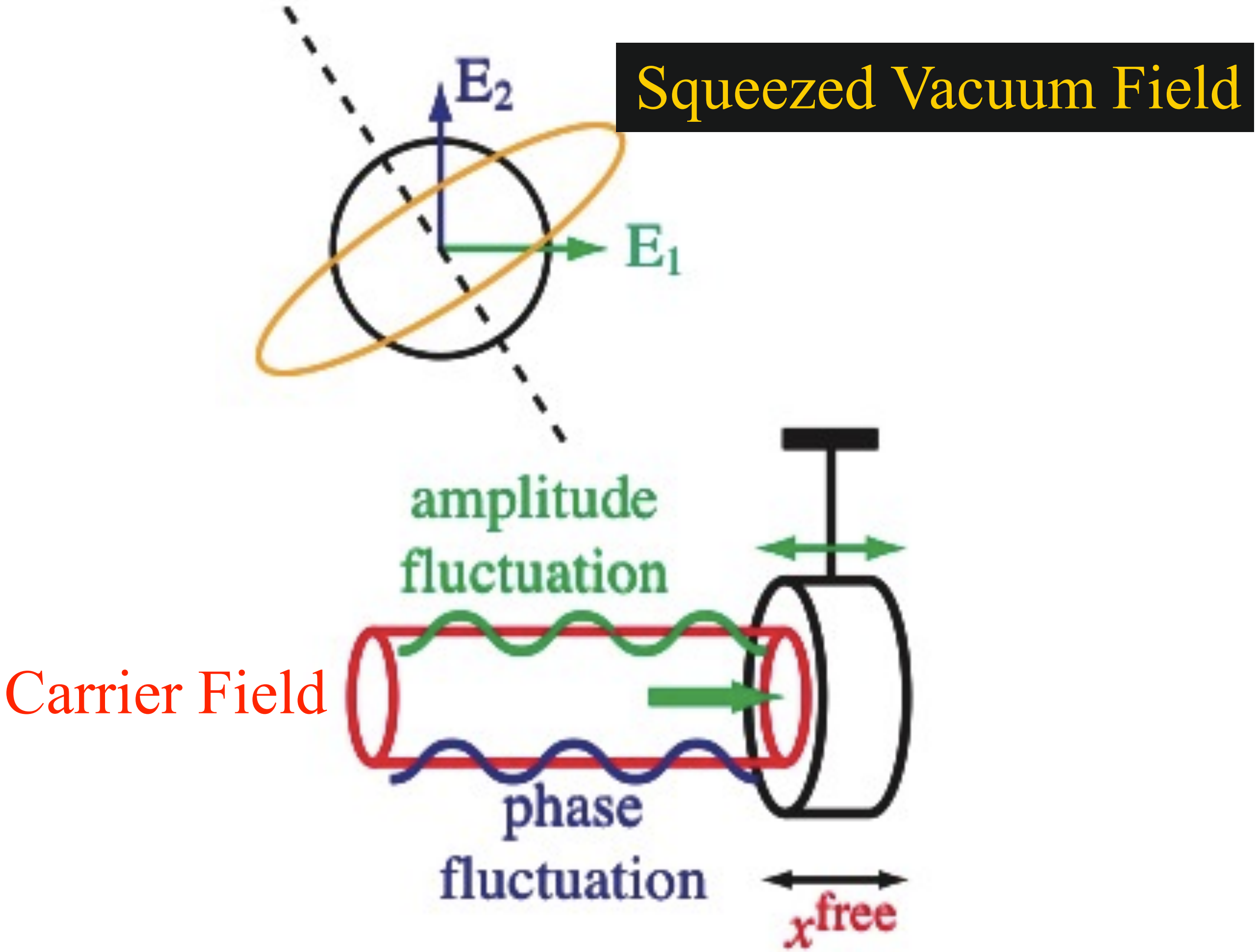


- 2^{nd} Generation Detectors will have many detections, but likely very few high SNR events
- 3G design aims for 3x higher SNR over the whole band
- Tests of Fundamental Physics
  - massive gravitons, scalar-tensor, vector-tensor, no hair theorem, higher dimensional theories
- Relativistic Astrophysics w/ EM
  - Extragalactic Supernovae, GRBs, Intermediate Mass BHs
- Cosmology
  - Standard GW ‘sirens’ for distance determination, fit to Concordance model (DM / DE densities)
  - GUT scale phase transitions, cosmic strings
  - The Unknown

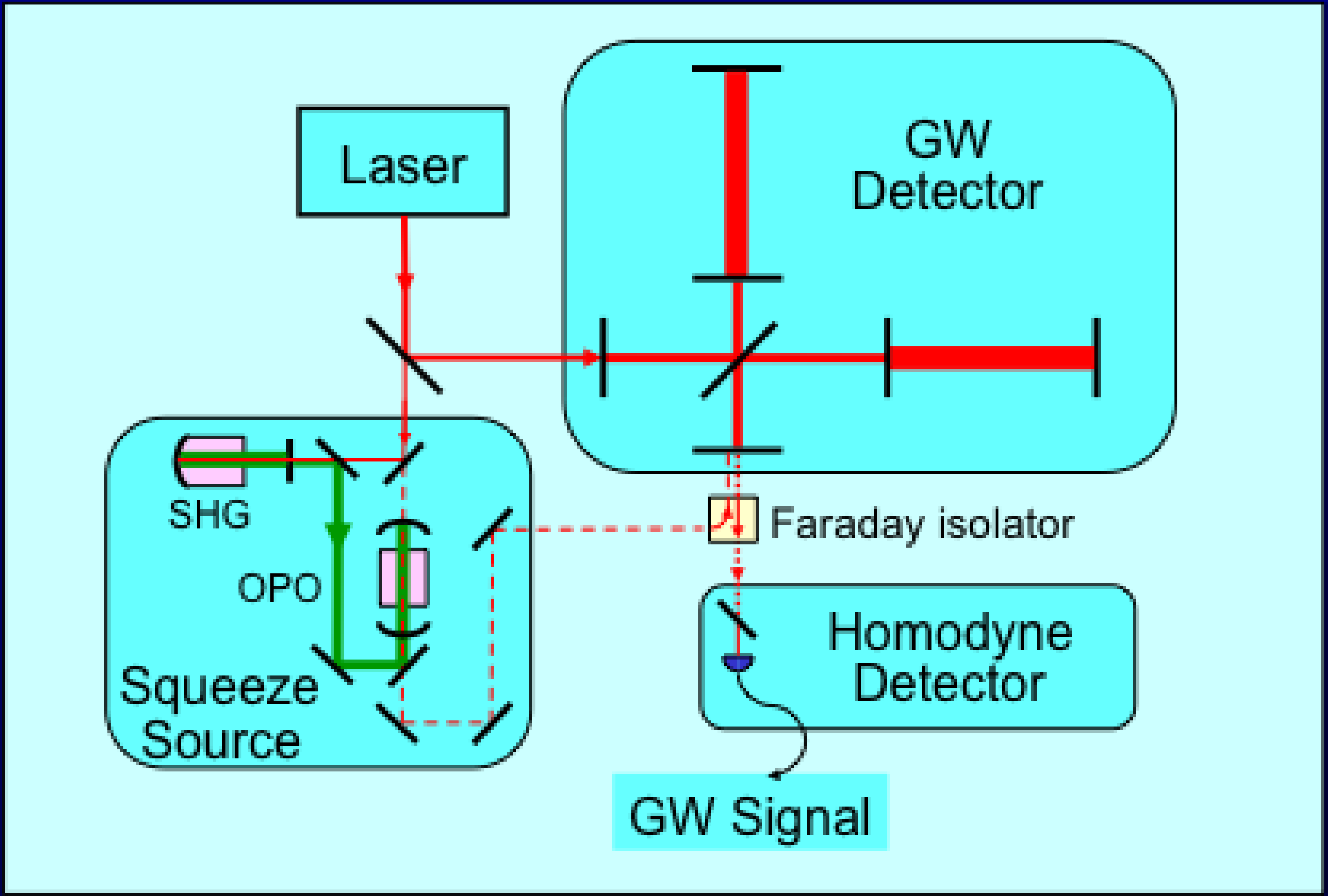




Circumventing Usual Quantum Noise

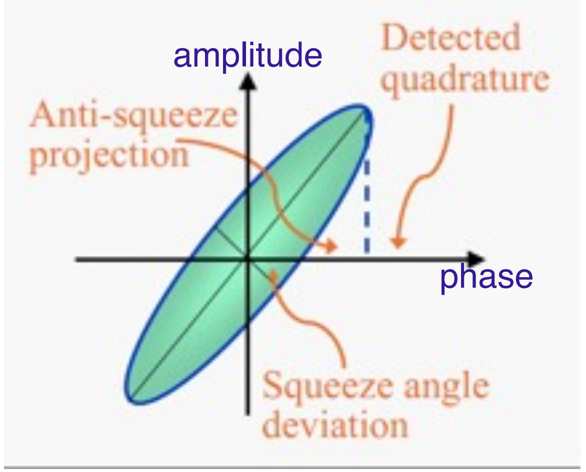


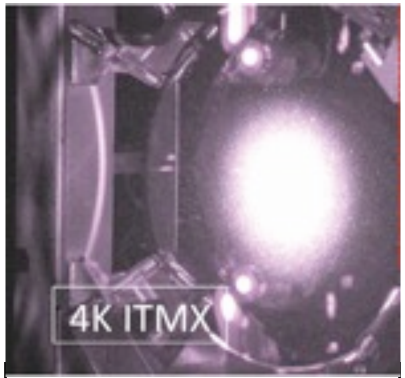
Squeezed Input Interferometer



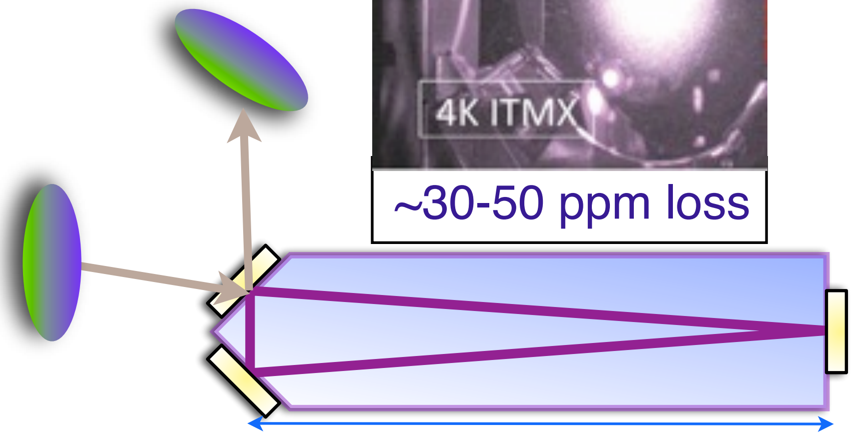
Quantum Noise Reduction

- Shot Noise limits at high frequency
- Quantum Radiation Pressure fluctuations limit at low frequencies
- Laser power 'knob' allows for a trade off; limited by interferometer thermal instability on the high power end
- **Squeezed Light Injection** can re-allocate the quantum noise (phase noise v. amplitude noise)
  - Demonstrated on IFOs at GEO600, LIGO Hanford
- ***Frequency Dependent*** Squeeze Angle
  - Long cavities act as optical phase shifters
  - **Prototyping of 10-20m cavity at MIT**
- **Needs:**
  - **Ultra-low loss optics (~10 ppm / bounce)**
  - 10 dB of squeezing *into the interferometer*
  - Low loss viewports, isolators, etc.

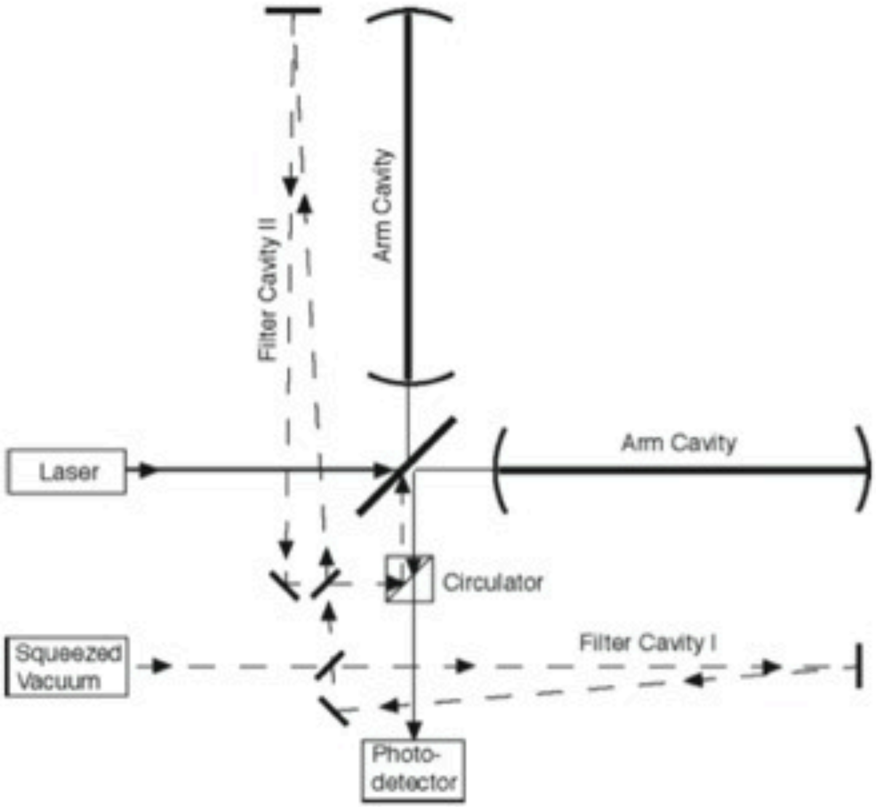




~30-50 ppm loss

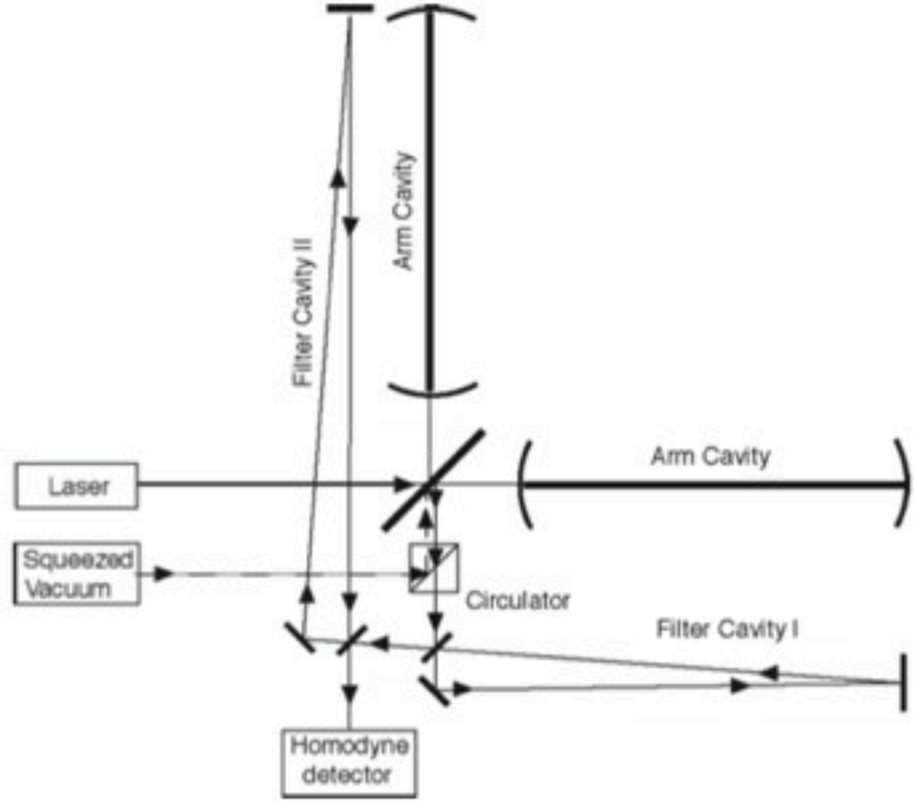


Harms, et. al., PRD (2003)



Squeezed Input

frequency dependent
input squeezing quadrature

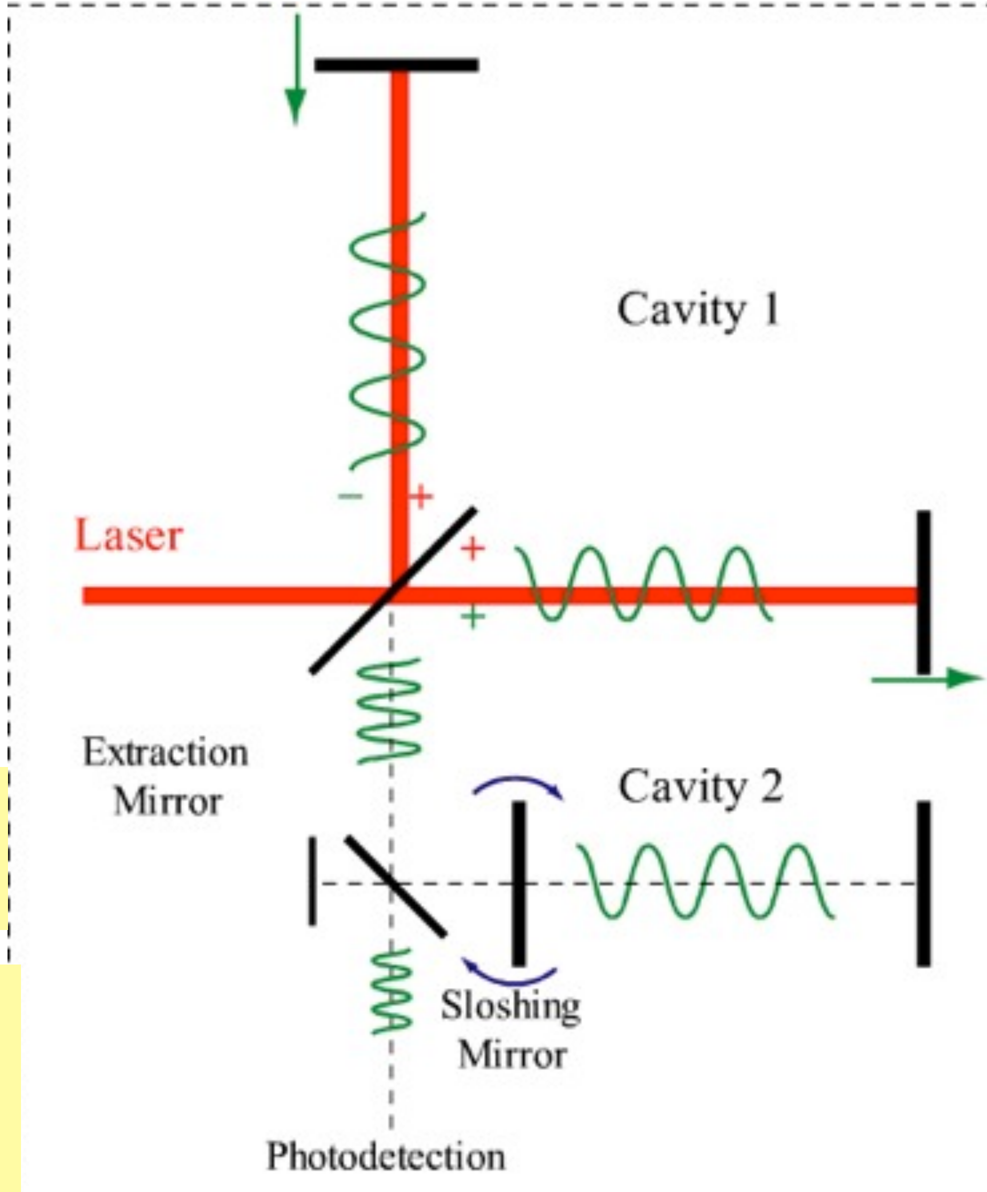


Variational Readout

frequency dependent
readout quadrature

QND via momentum

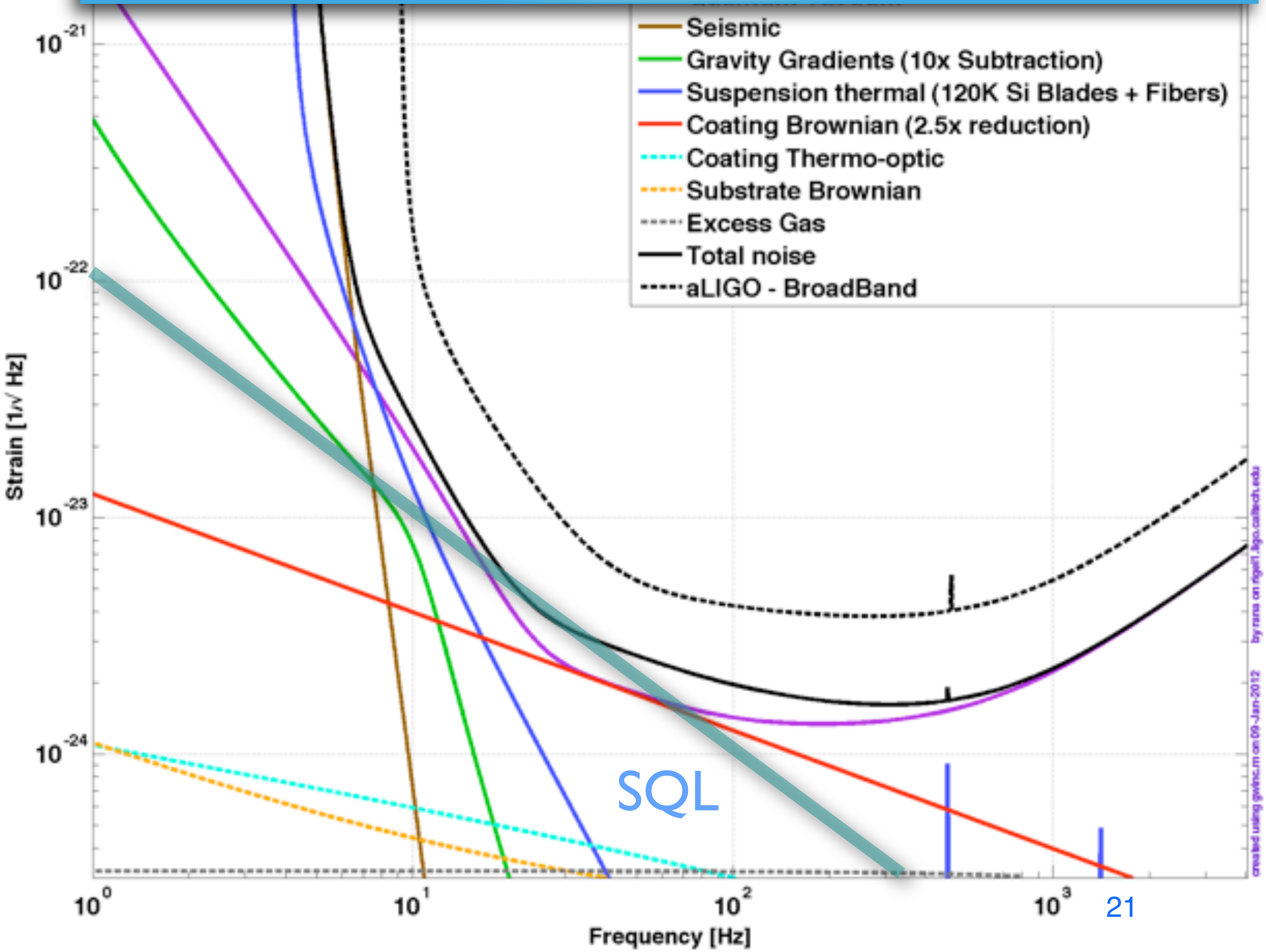
- Radiation pressure noise from dark port
- Some light experiences delay via the sloshing cavity
- Delay leads to phase flip for momentum kicks
- **Broadband Speedmeter**
  - req. low loss optics
  - **req. very long cavities**

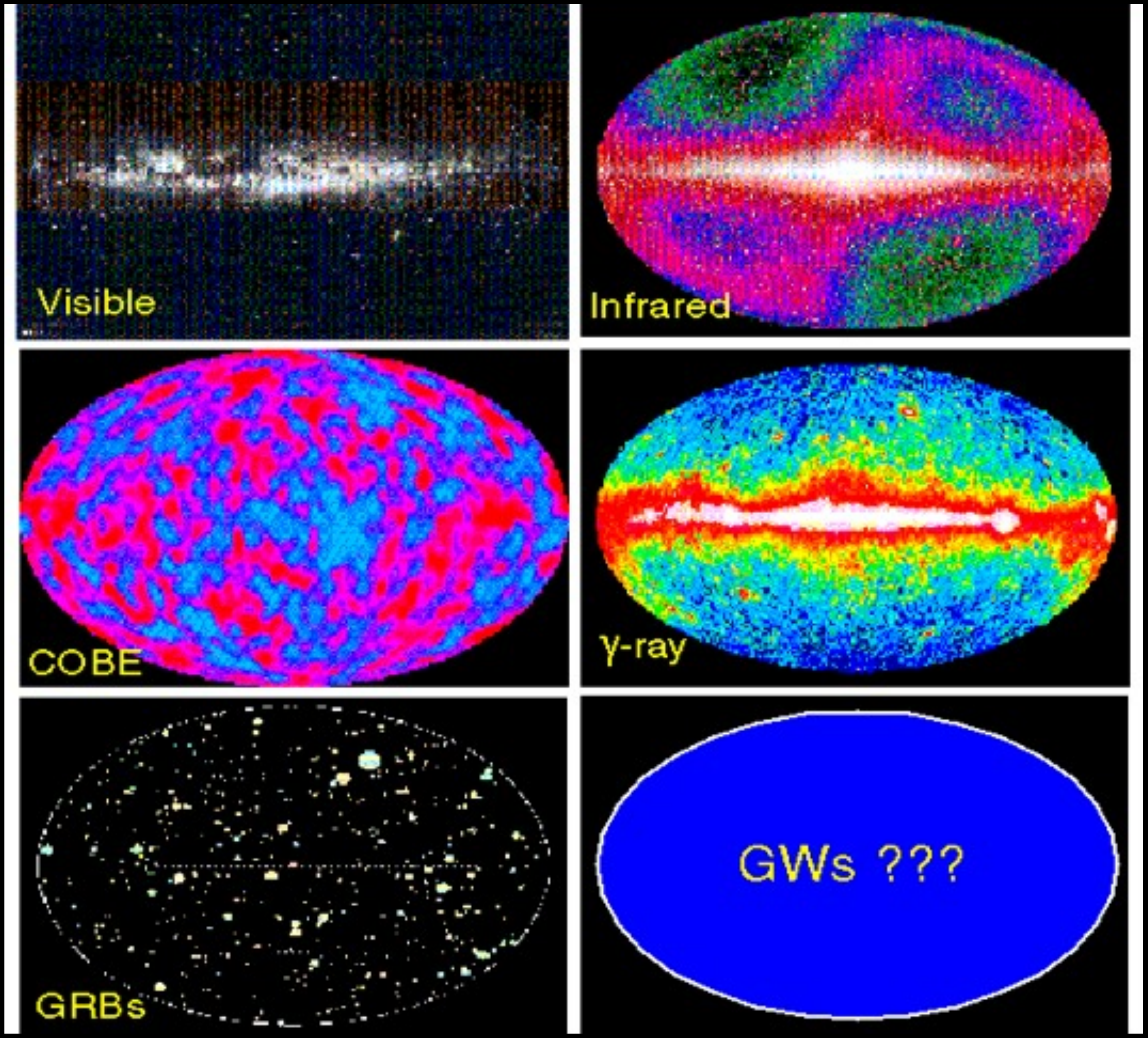


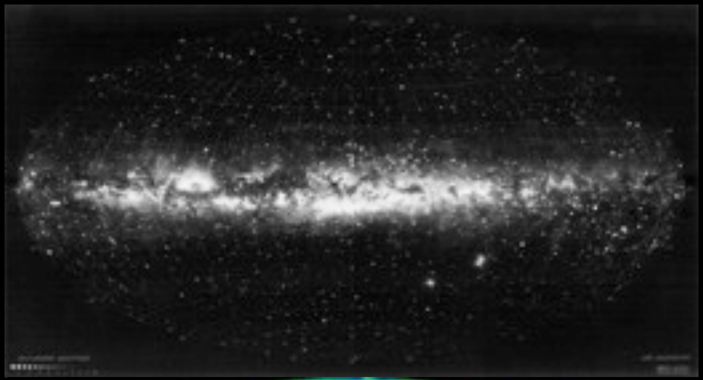
Momentum is a QND observable

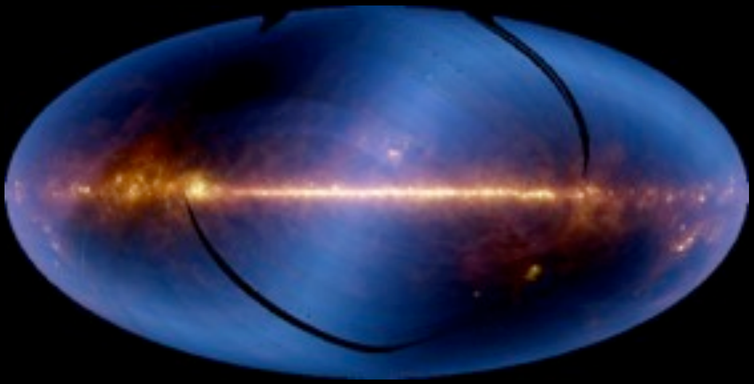
Observe momentum, perturb position. Position noise doesn't influence momentum.

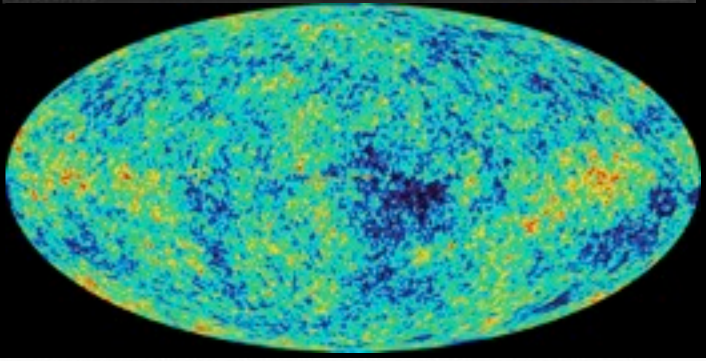
3rd Generation LIGO

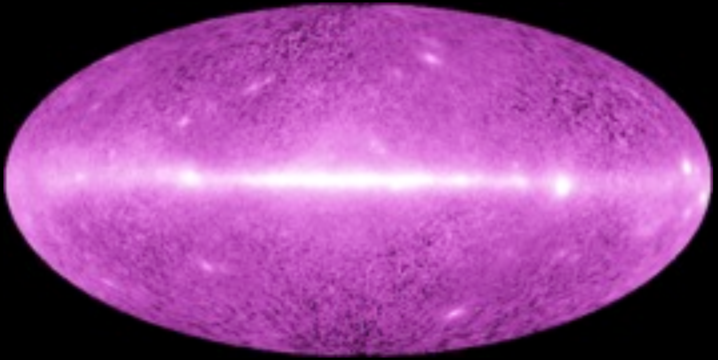


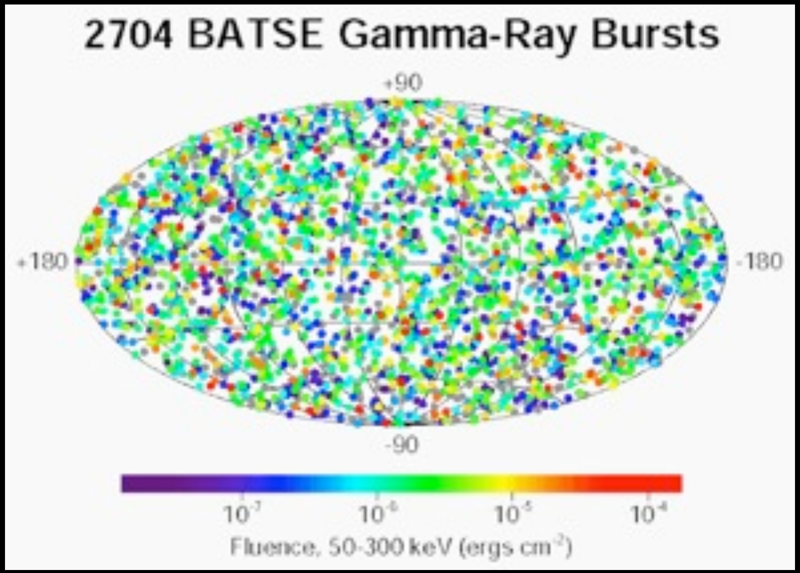

Visible
Infrared
COBE
γ-ray
GRBs
GWs ???










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