Experimental Techniques in GW Detection

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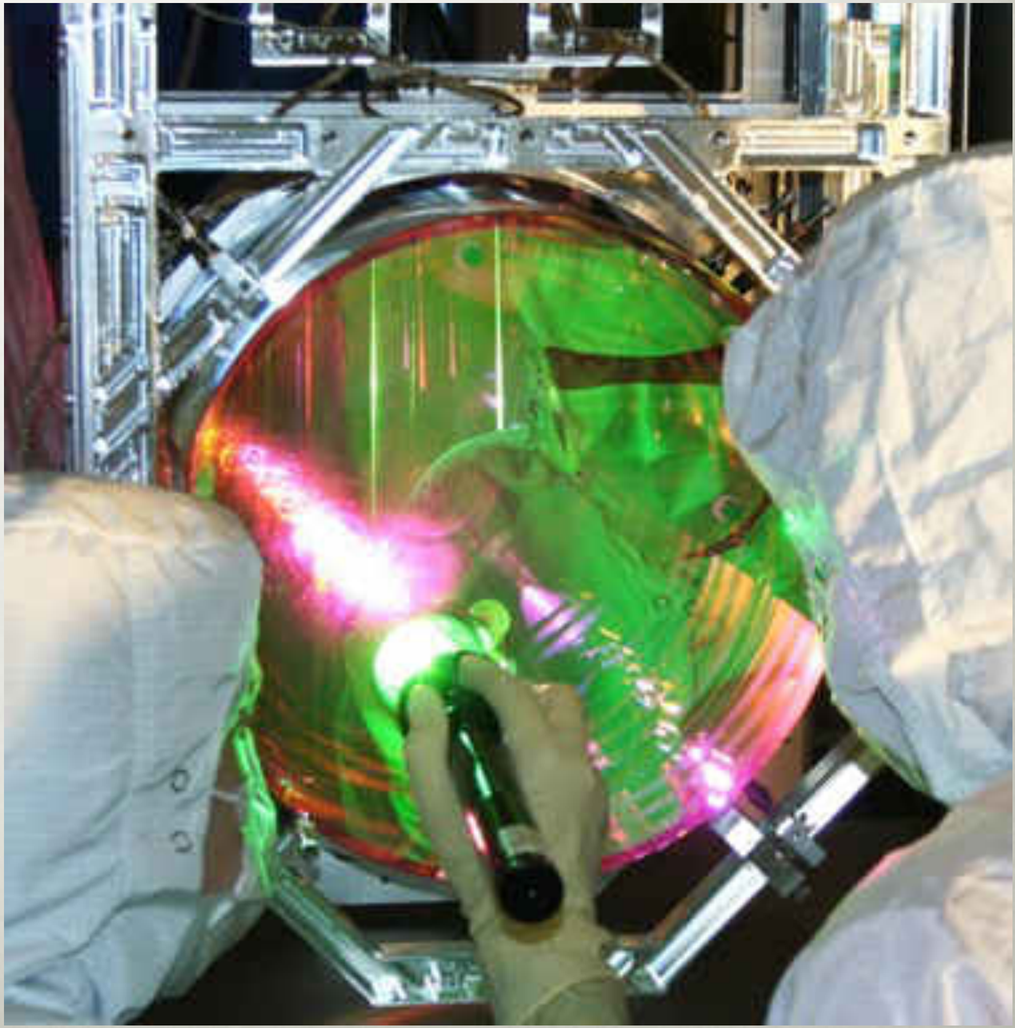
LIGO - G1500814 - v1

OUTLINE

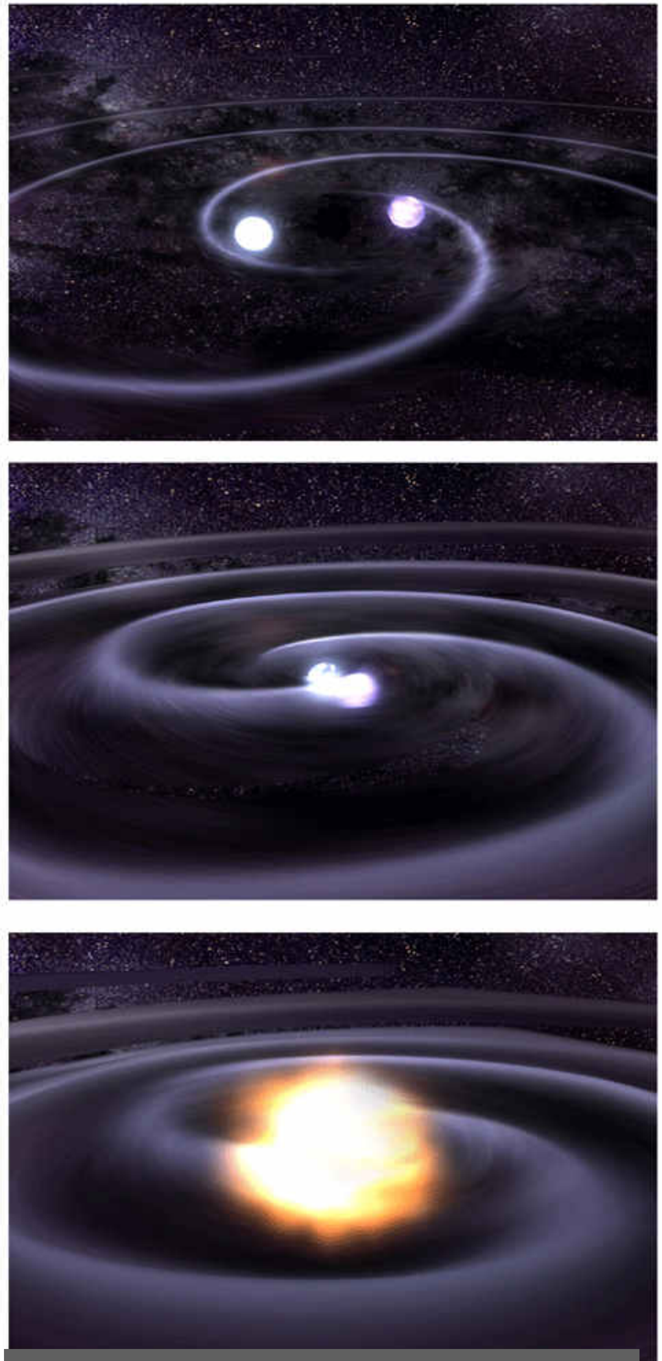
- Gravitational Waves and History
- Some Noise Lingo
- Interferometers and Noise
- Quantum Limits



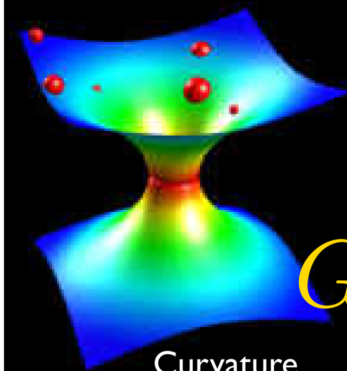
Summary

1. Optical Interferometry allows measuring 0.01 nrad of optical phase.
2. Optical cavities boost the phase shift by 200x.
3. GW measurement made only at audio frequencies where ground motion is tiny.
4. GW measurement made only away from the instrument's mechanical eigenfrequencies (avoid k_B*T noise).
5. Signal increases proportionally to the (large) detector size.

Gravitational Waves

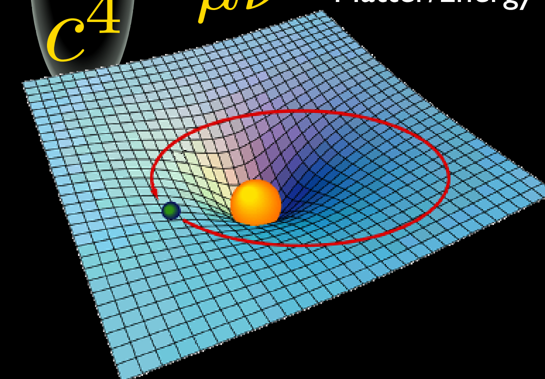


NASA/Dana Berry, Sky Works Digital



$$G_{\mu\nu} = 8\pi \frac{G}{c^4} T_{\mu\nu}$$

10^{-44}



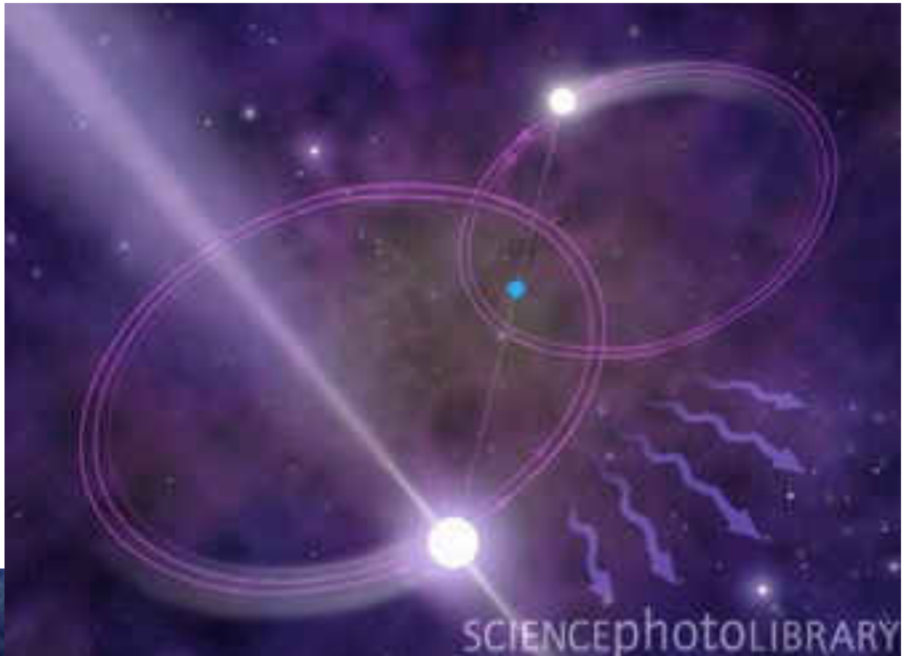
Einstein's Equations

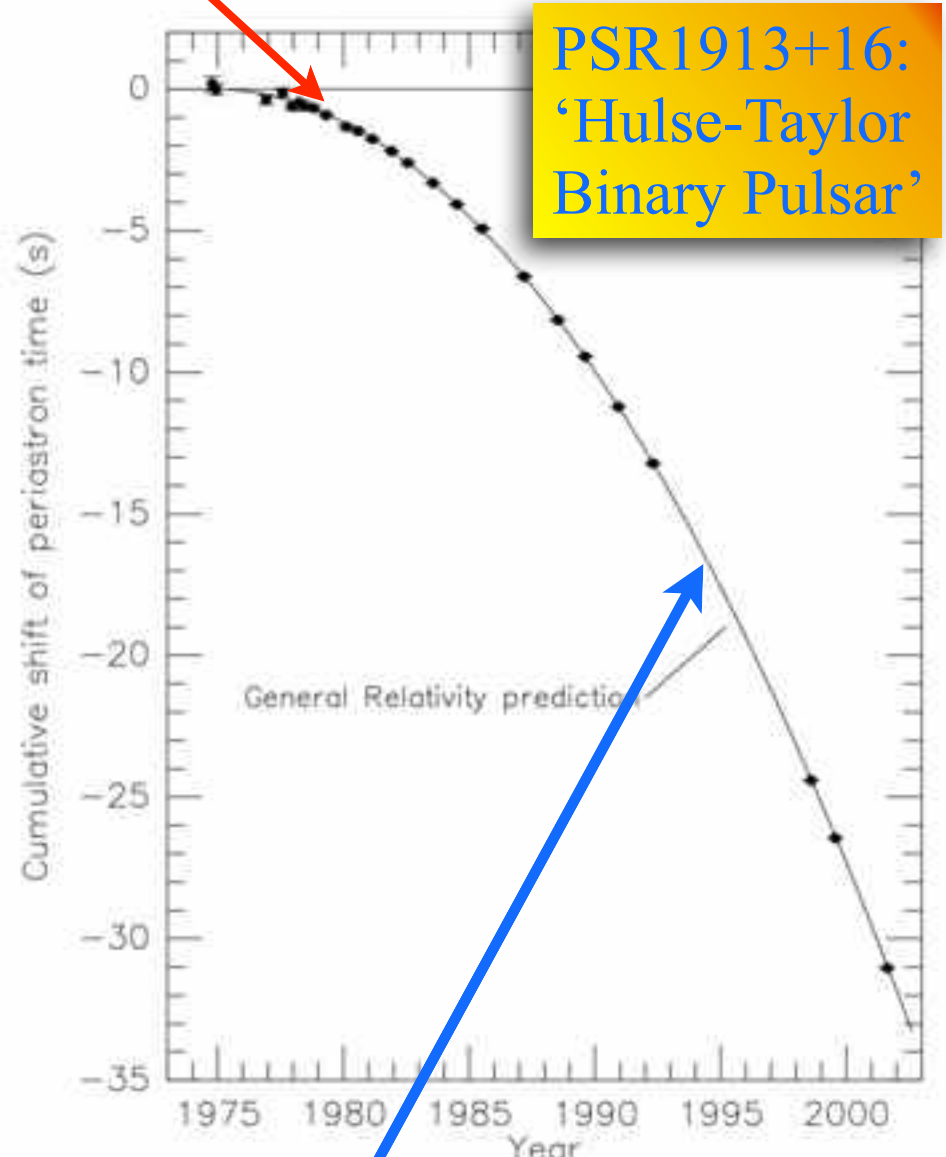
WHEN MATTER MOVES, ITS GRAVITATIONAL FIELD CHANGES. THIS CHANGE PROPAGATES AS A RIPPLE IN THE CURVATURE OF SPACE-TIME:

gravitational radiation

Wikipedia: In fluid dynamics, **gravity waves** are waves generated in a fluid medium or at the interface between two media (e.g., the atmosphere and the ocean) which has the restoring force of gravity or buoyancy.

1979:
Gravitational Waves Detected!





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

The ElectroMagnetic Spectrum

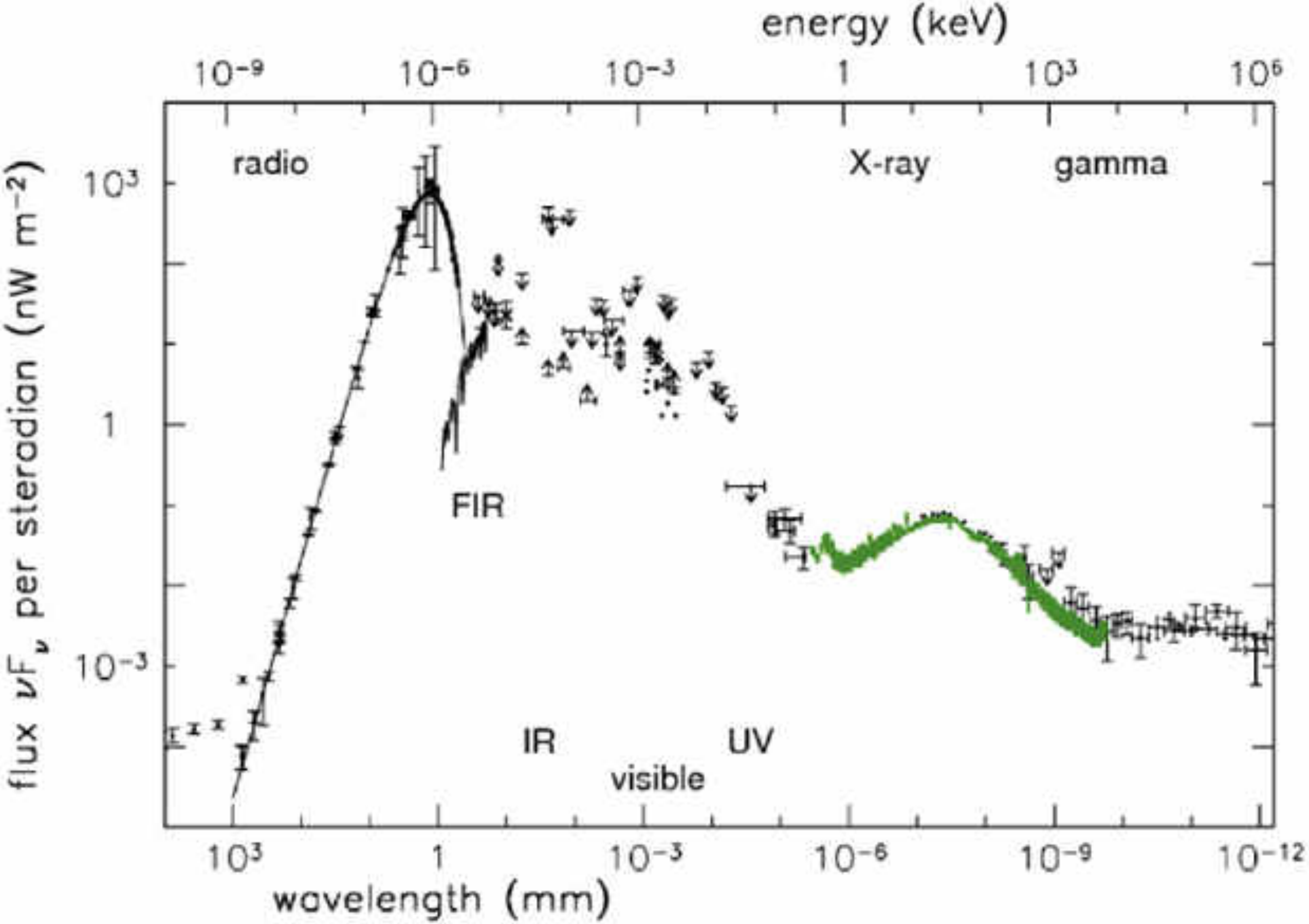
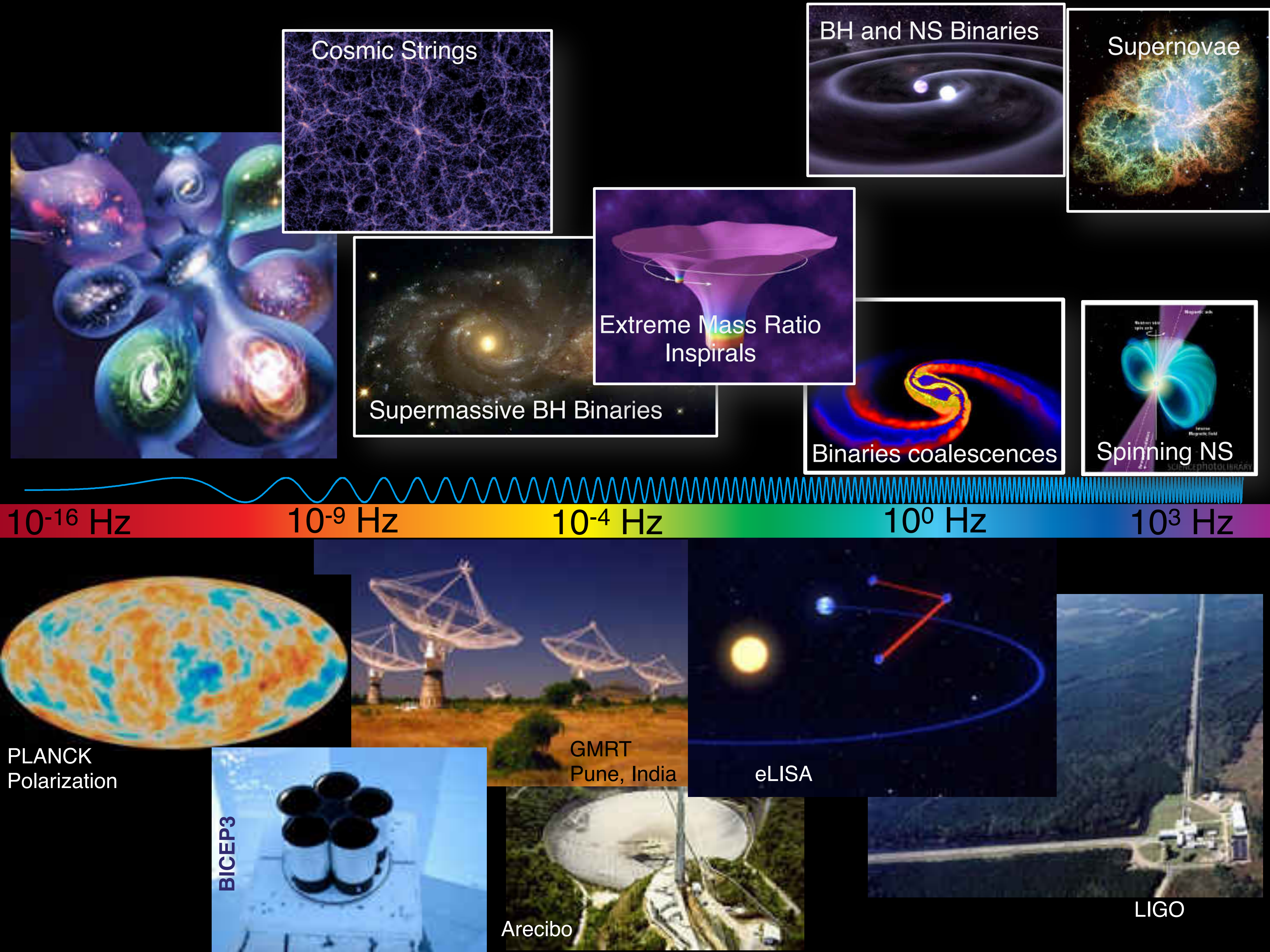


Fig 1.19 (D. Scott) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

The ElectroMagnetic Spectrum

Griffith Observatory, Los Angeles

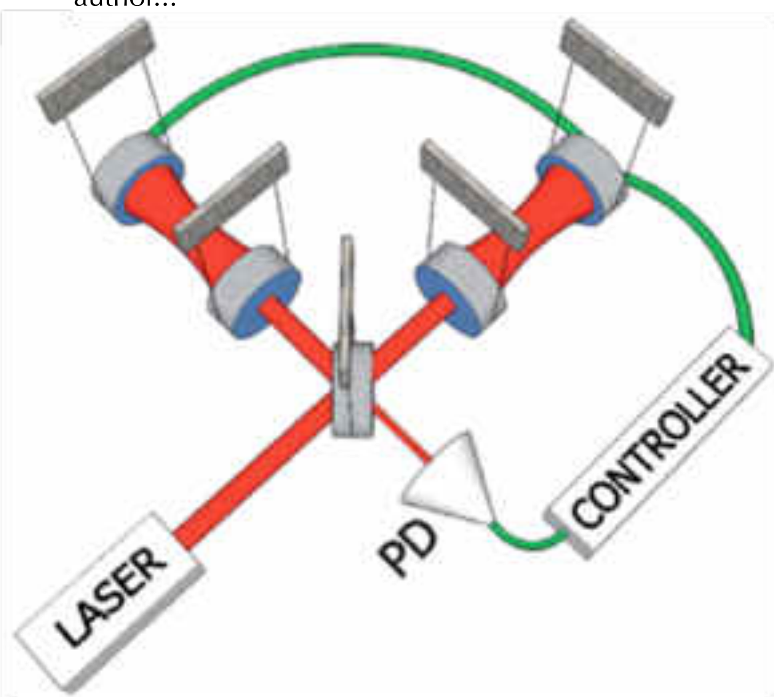

Cosmic Strings
BH and NS Binaries
Supernovae
Extreme Mass Ratio Inspirals
Supermassive BH Binaries
Binaries coalescences
Spinning NS
10^{-16} Hz
10^{-9} Hz
10^{-4} Hz
10^{0} Hz
10^{3} Hz
PLANCK Polarization
BICEP3
GMRT Pune, India
Arecibo
eLISA
LIGO

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

Robert Forward (HRL)

also a sci-fi author...

Joe Weber (UMD)



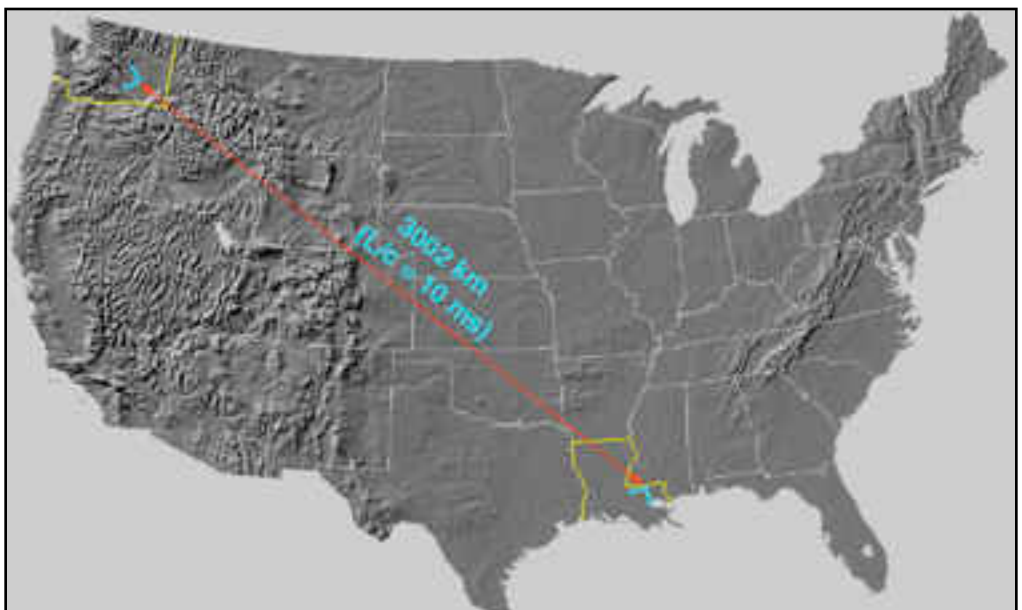
Ron Drever (Caltech)

Rai Weiss (MIT)

<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

1970 1980 1990 2000 2010 2020 20NN

1st Bar Detectors (Weber)

Interferometer Concept (Weiss, MIT)

1st Tabletop Interferometer (Forward, Malibu)

Caltech 40m

km scale Interferometers (Japan, U.S., Germany, Italy)

km scale Interferometers @ design sensitivity

2nd Gen Interferometers

???


mid station
LIGO Hanford

LIGO Louisiana

The Michelson Interferometer

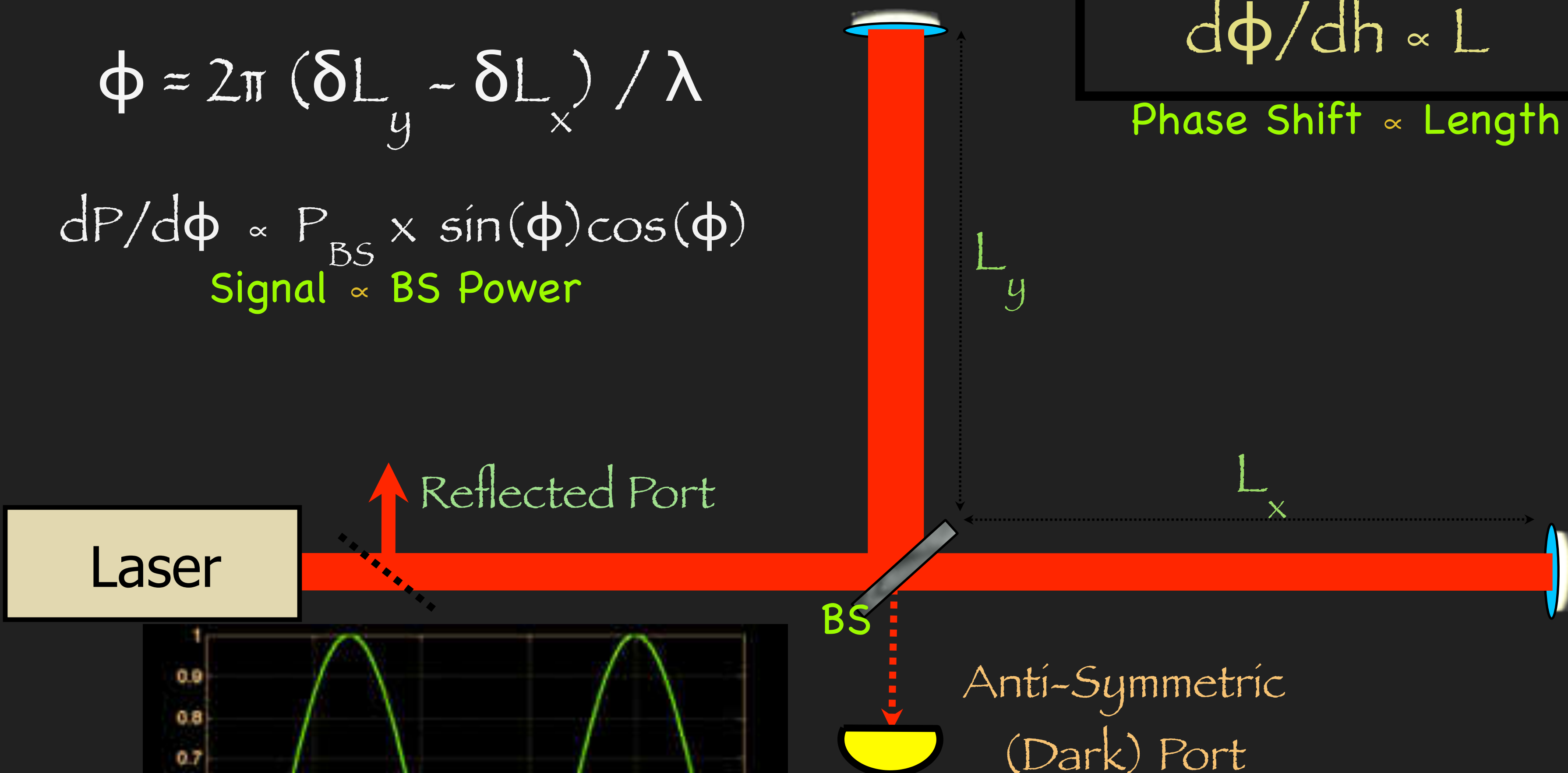
$d\phi/dh \propto L$

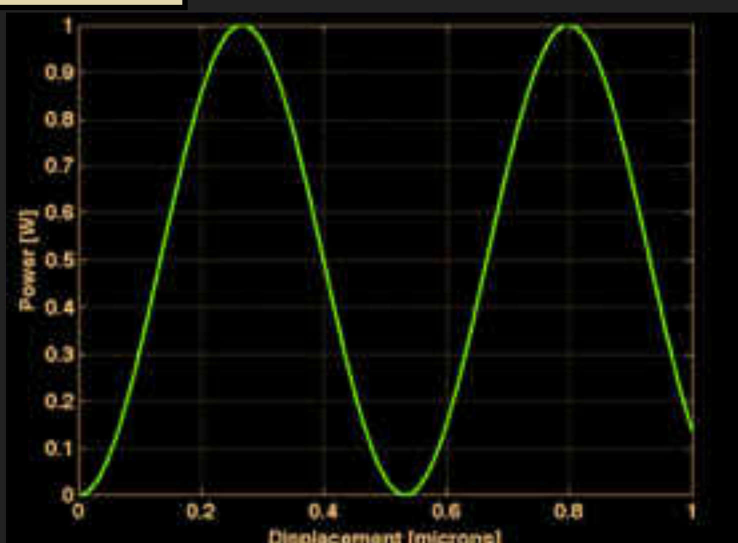
Phase Shift ∝ Length

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

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

Signal ∝ BS Power





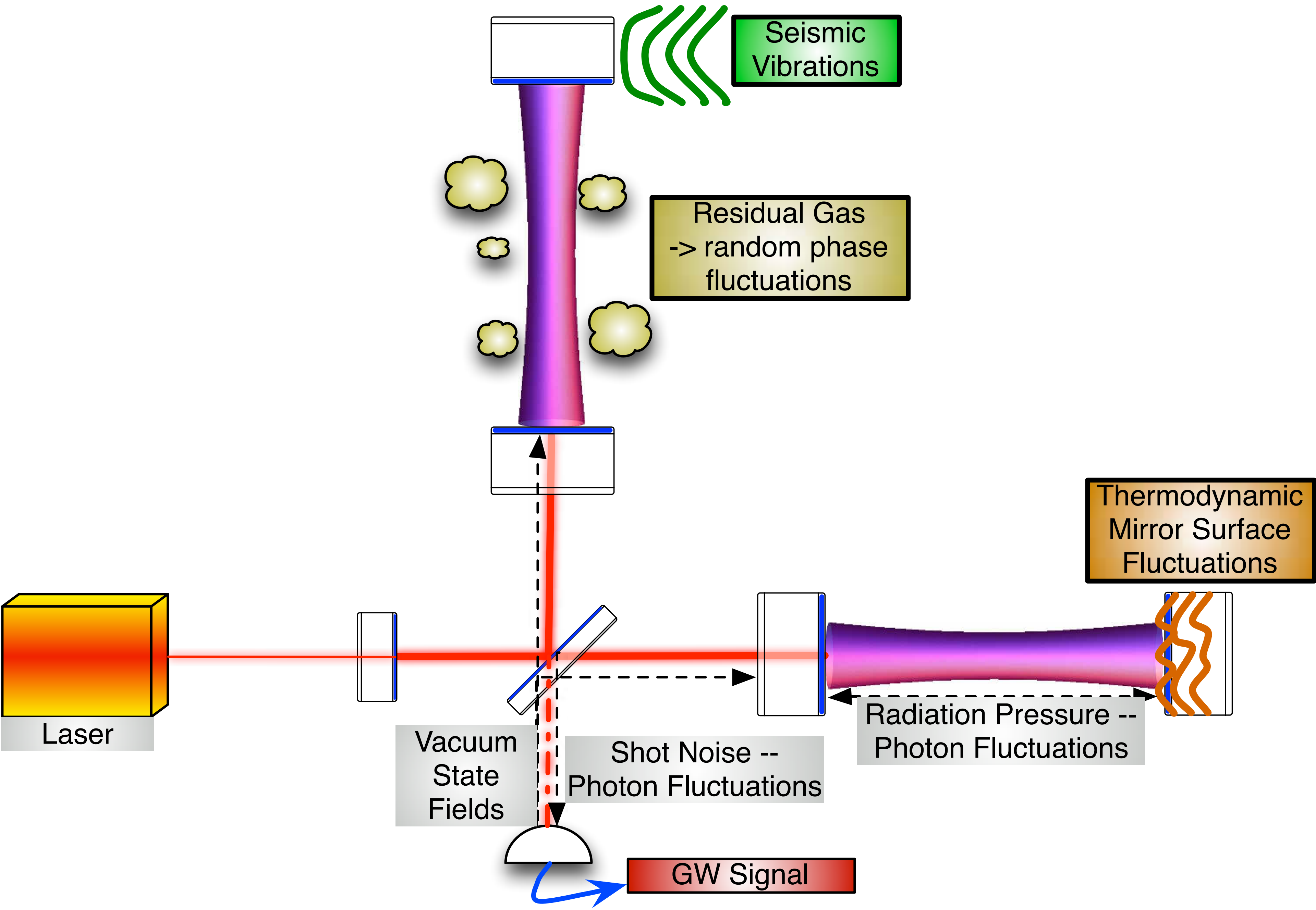
$P \propto P_{BS} \times \sin^2(\phi)$

Poisson Statistics…

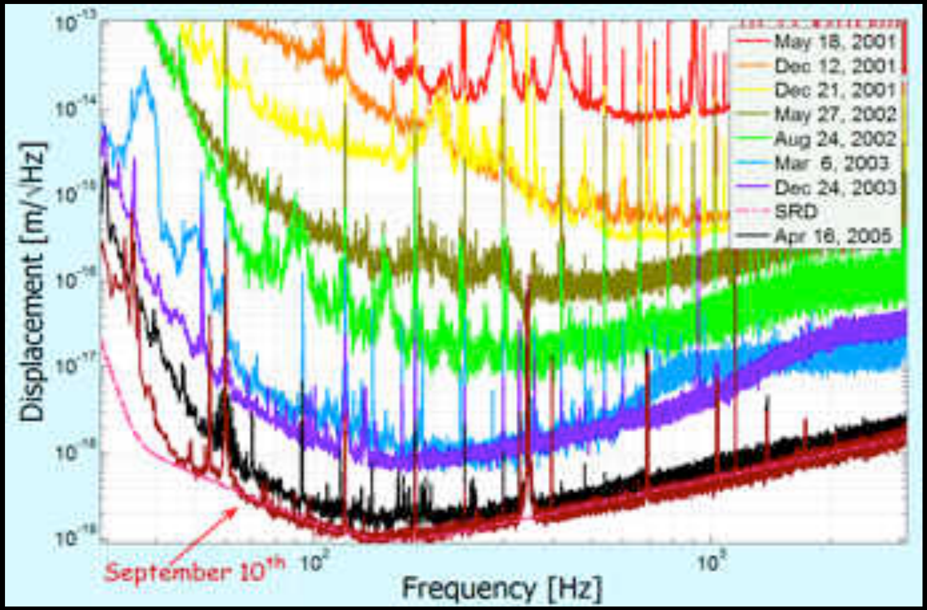
$dP \propto \mathrm{sqrt}(P)$

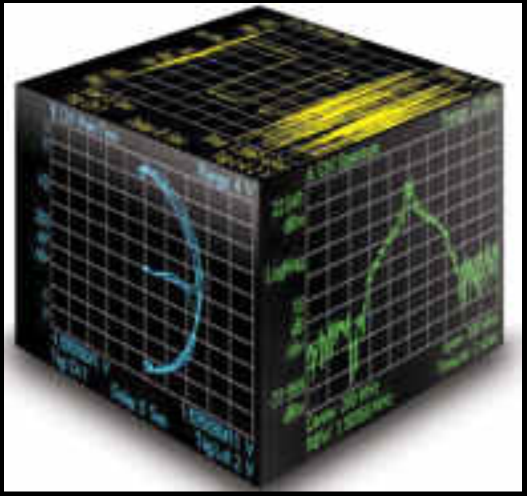
Shot Noise

LIGO: Major Sources of Noise

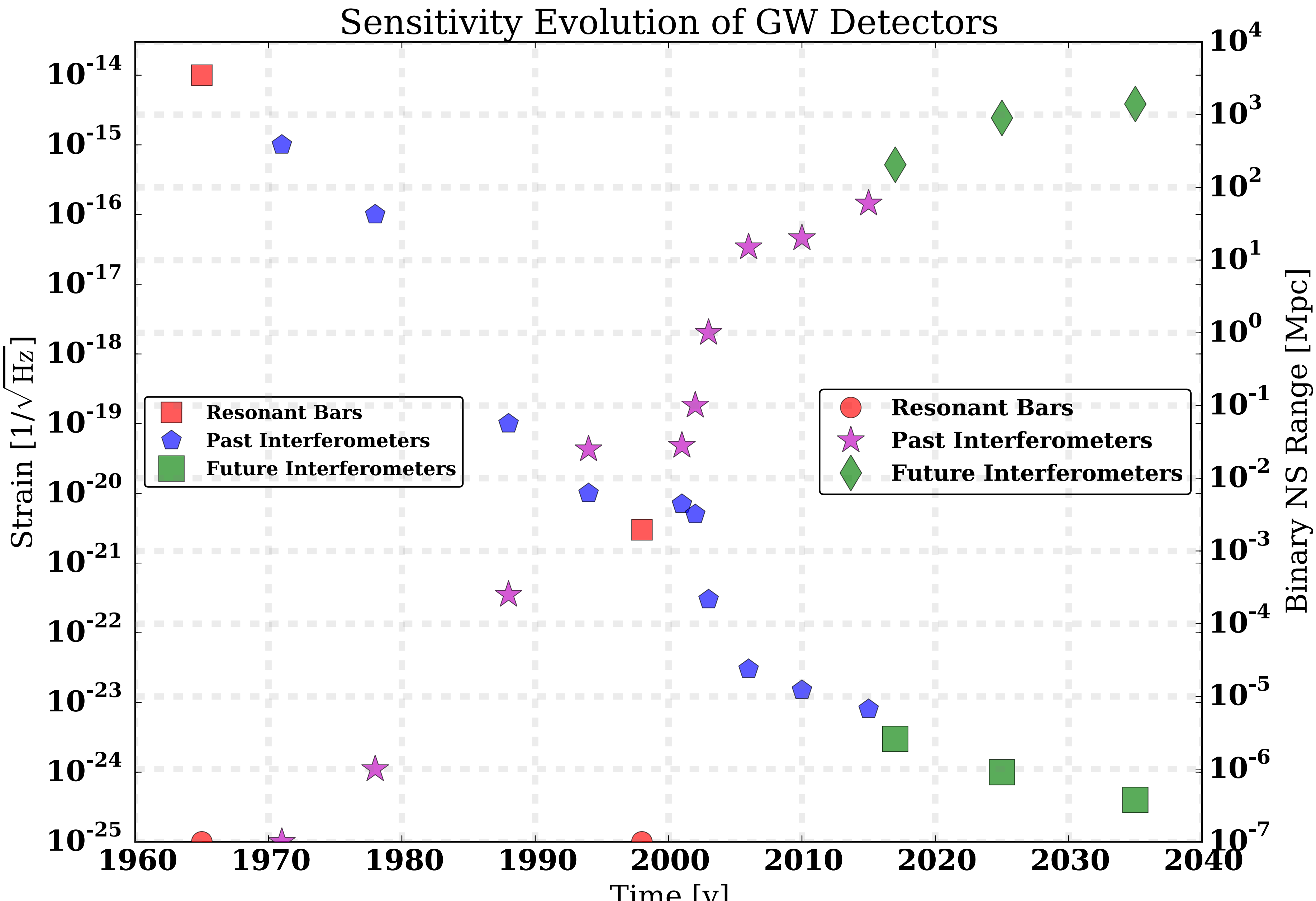


Noise Lingo





1. Spectrum Analysis Basics: Agilent App. Note 150-1
2. Fundamentals of Signal Analysis: Agilent App. Note 243
3. Wikipedia: FFT, Window Functions, Aliasing, etc.



"Gravitational radiation detection with laser interferometry",http://arxiv.org/abs/1305.5188

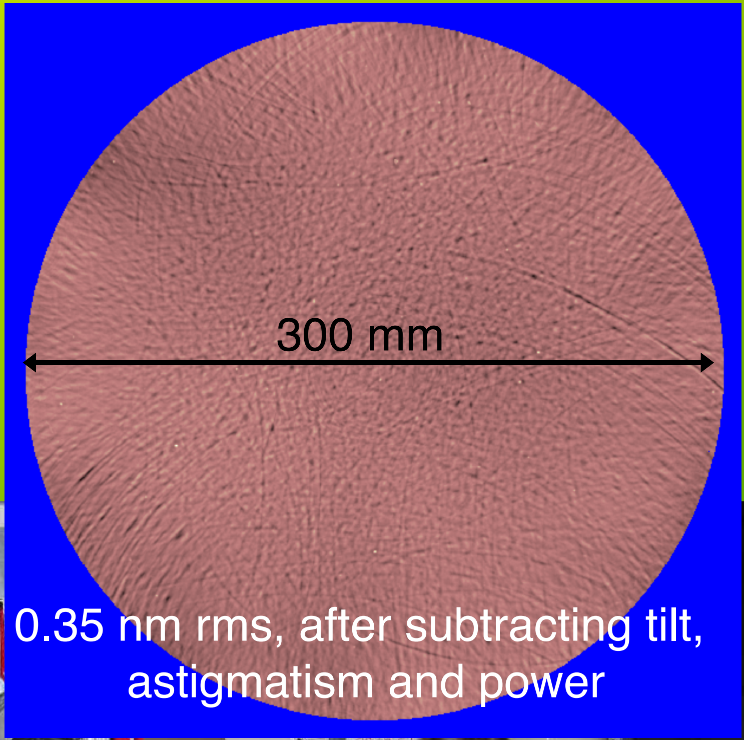
Optics and Resonators

- Optics 101 -> Ray Matrices
- Gaussian Beams, Gaussian Beam Propagation
- Fabry-Perot Cavities
- Higher Order Transverse Modes
- Simple Cavity Locking (Why PDH?)


steel music wire
(0.012″ dia.)
Fused Silica (SiO_2)
Mass ~ 10 kg
Dia ~ 25 cm
Thickness ~10 cm
Roughness ~ 1 nm
LIGO-I End Test Mass

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**



Summary

1. Optical Interferometry allows measuring 10^{-11} rad of optical phase.
2. Optical cavities boost the phase shift by ~200x.
3. GW measurement made only at **audio frequencies** where ground motion is tiny.
4. GW measurement made only away from the instrument's mechanical eigenfrequencies (avoid $k_B T$ thermal noise).
5. Signal increases ~proportionally to the (large) detector size.