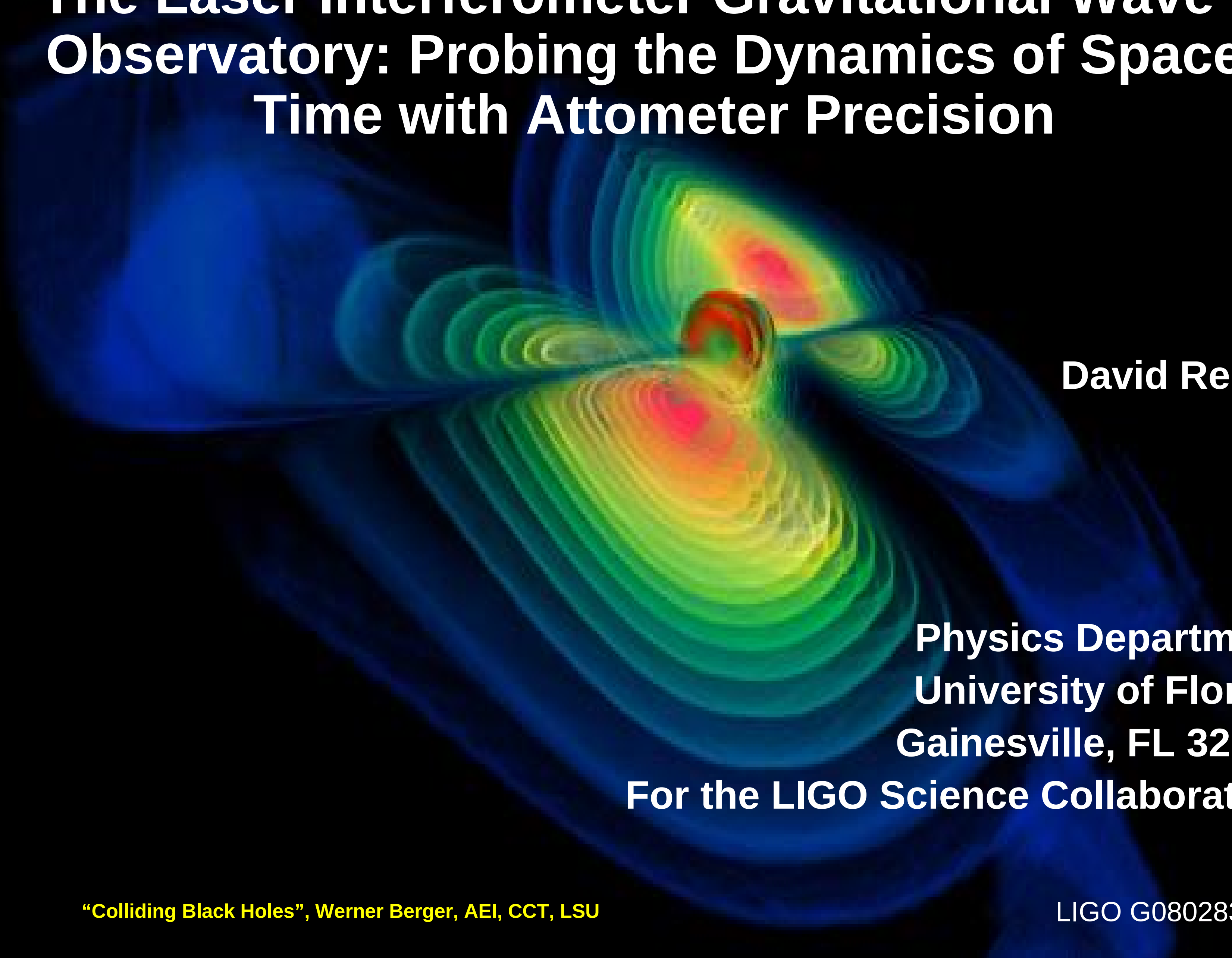
The Laser Interferometer Gravitational Wave Observatory: Probing the Dynamics of Space-Time with Attometer Precision



“Colliding Black Holes”, Werner Berger, AEI, CCT, LSU

David Reitze

Physics Department
University of Florida
Gainesville, FL 32611
For the LIGO Science Collaboration

LIGO G080283-00-Z

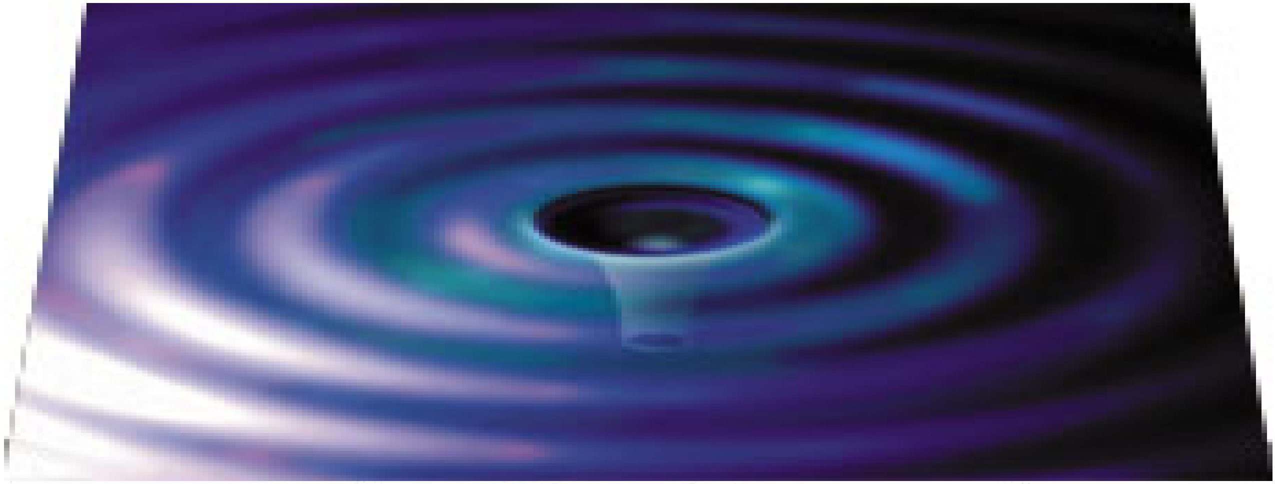
LIGO Interferometer

General relativity 101

- "Gravity is Geometry"
  - Space tells matter how to move ←→ matter tells space how to curve
- Space-time 'metric': $ds^2 = g_{\mu\nu} dx^\mu dx^\nu$
  - Weak gravity: $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$ $\quad |h_{\mu\nu}| << 1$
- Propagating gravitational waves:

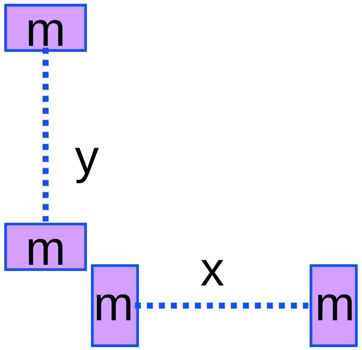
$$\left(\nabla^2 - \frac{1}{c^2} \frac{\partial^2}{\partial t^2} \right) h = 0$$

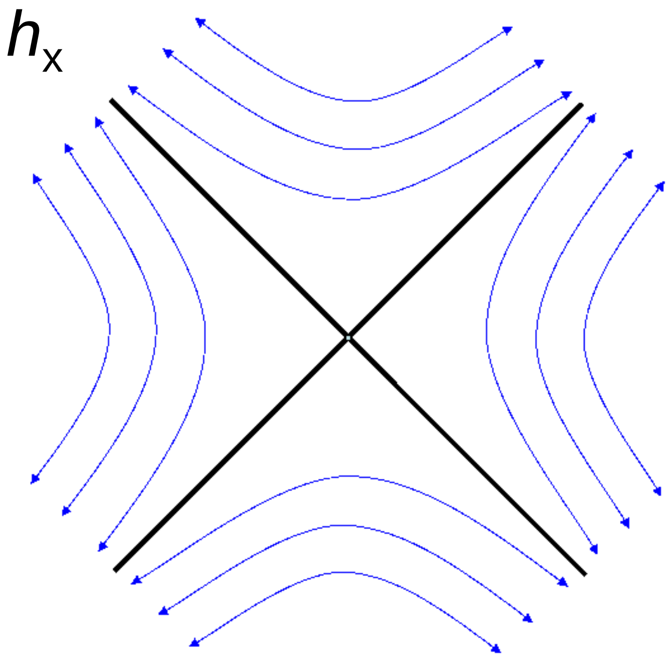
$$h(t) \sim h_{\mu\nu} e^{i(k_\alpha x^\alpha - \omega t)} + h_{\mu\nu} e^{-i(k_\alpha x^\alpha - \omega t)}$$



Advanced GR: gravitational waves

- Effect of a gravitational wave (in z) on light traveling between freely falling masses, observer fixed to near masses





***h* is a *strain*: ΔL/L**

Gravitational waves & electromagnetic waves: a comparison

Electromagnetic Waves

- Time-dependent dipole moment arising from *charge motion*

$$\vec{E}(\vec{r},t) \sim \frac{\mu_0}{4\pi r}\left[\hat{r}\times\left(\hat{r}\times\ddot{\vec{p}}\right)\right]$$

- Traveling wave solutions of Maxwell wave equation, $v = c$

- Two polarizations: σ^+, σ^-

Gravitational Waves

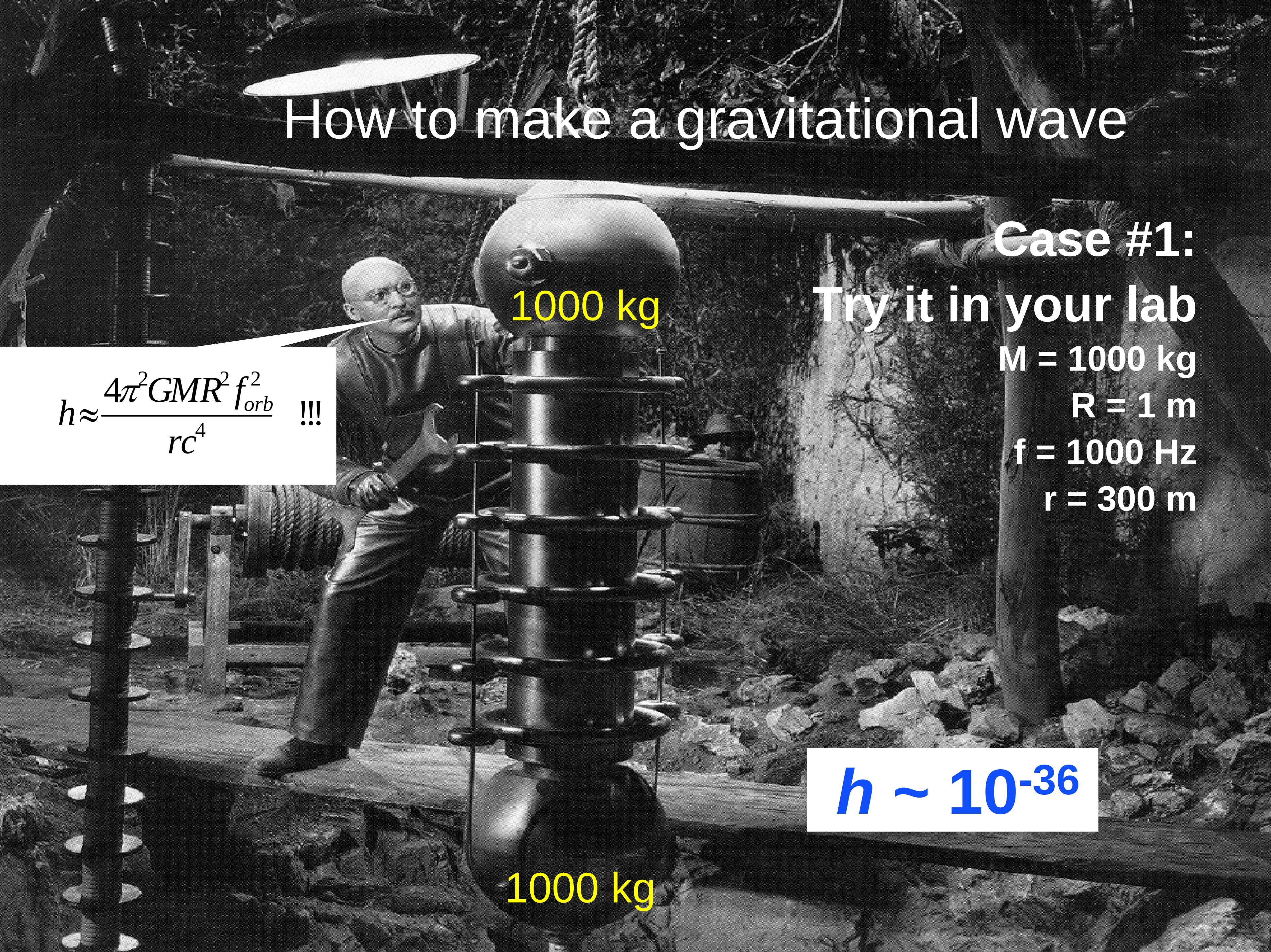
- Time-dependent quadrapole moment arising from *mass motion*

$$h_{\mu\nu}(\omega,t) = \frac{2G}{r\,c^4}\ddot{I}_{\mu\nu}(\omega,t)$$

$$h \approx \frac{4\pi^2 G M R^2 f_{orb}^2}{r c^4}$$

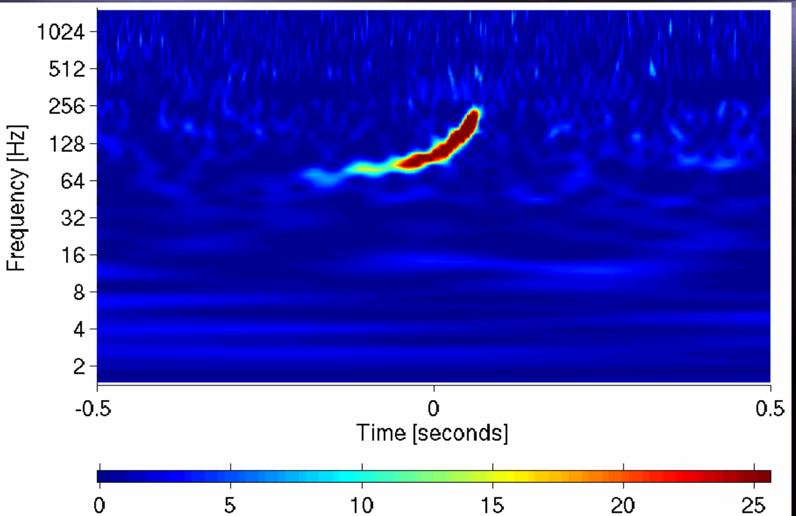
- Traveling wave solutions of Einstein's equation, $v = c$

- Two polarizations: h_+, h_x


How to make a gravitational wave
1000 kg
$h \approx \frac{4\pi^2 G M R^2 f_{orb}^2}{r c^4}$!!!
Case #1:
Try it in your lab
M = 1000 kg
R = 1 m
f = 1000 Hz
r = 300 m
$h \sim 10^{-36}$
1000 kg

How to make a larger gravitational wave

- **Case #2: A 1.4 solar mass binary pair**
  - **$M = 1.4\ M_{\odot}$**
    $R = 11$ km
    $f = 400$ Hz
    $r = 10^{23}$ m



$h \sim 10^{-21}$

What did Einstein think?

- Einstein predicts gravitational waves (1916,1918)

  A. Einstein, Sitzber. deut. Akad. Wiss. Berlin, Kl. Math. Physik u. Tech. (1916), p. 688; (1918), p. 154

- Einstein changes his mind (1936)

  Together with a young collaborator, I arrived at the interesting result that gravitational waves do not exist, though they had been assumed a certainty to the first approximation. This shows that the non-linear general relativistic field equations can tell us more or, rather, limit us more than we have believed up to now.[4]

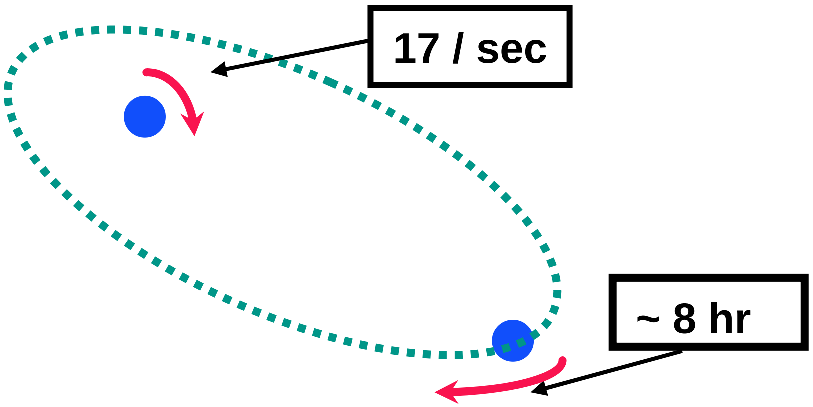
  4. A. Einstein, *The Born–Einstein Letters: Friendship, Politics, and Physics in Uncertain Times*, MacMillan, New York (2005), p. 122.

  Daniel Kennefick, Physics Today, Sept. 2005

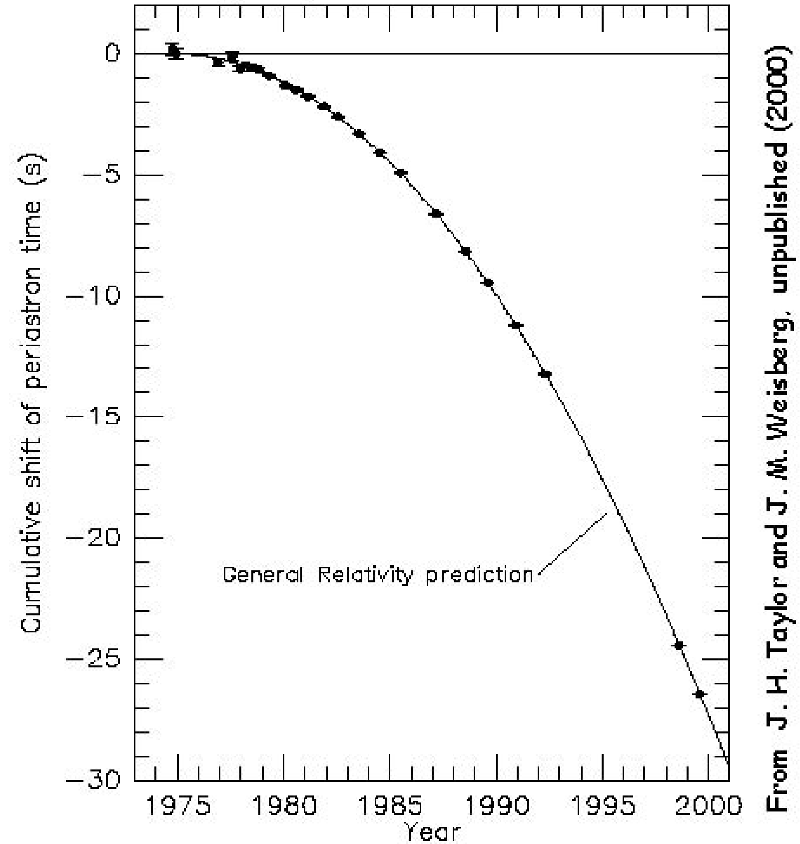
Existence proof: PSR 1913+16

Joseph Taylor

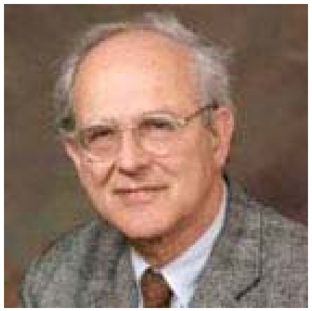
Russell Hulse



Comparison between observations of the binary pulsar PSR1913+16, and the prediction of general relativity based on loss of orbital energy via gravitational waves



How to detect a gravitational wave



Rai Weiss, MIT

Ron Drever, Caltech

ELECTROMAGNETICALLY COUPLED BROADBAND GRAVITATIONAL ANTENNA

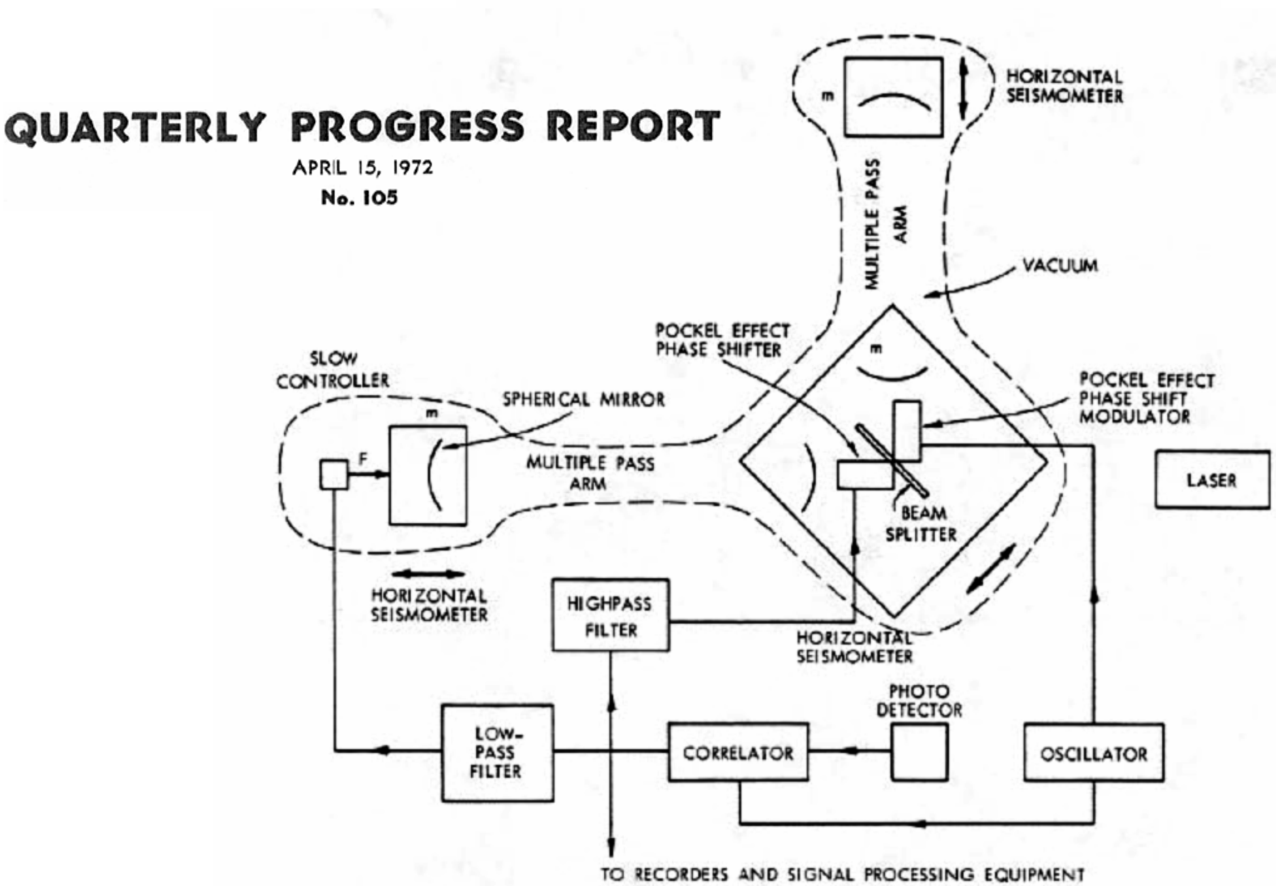


Fig. V-20. Proposed antenna.

Realistically, how sensitive can an interferometer be?

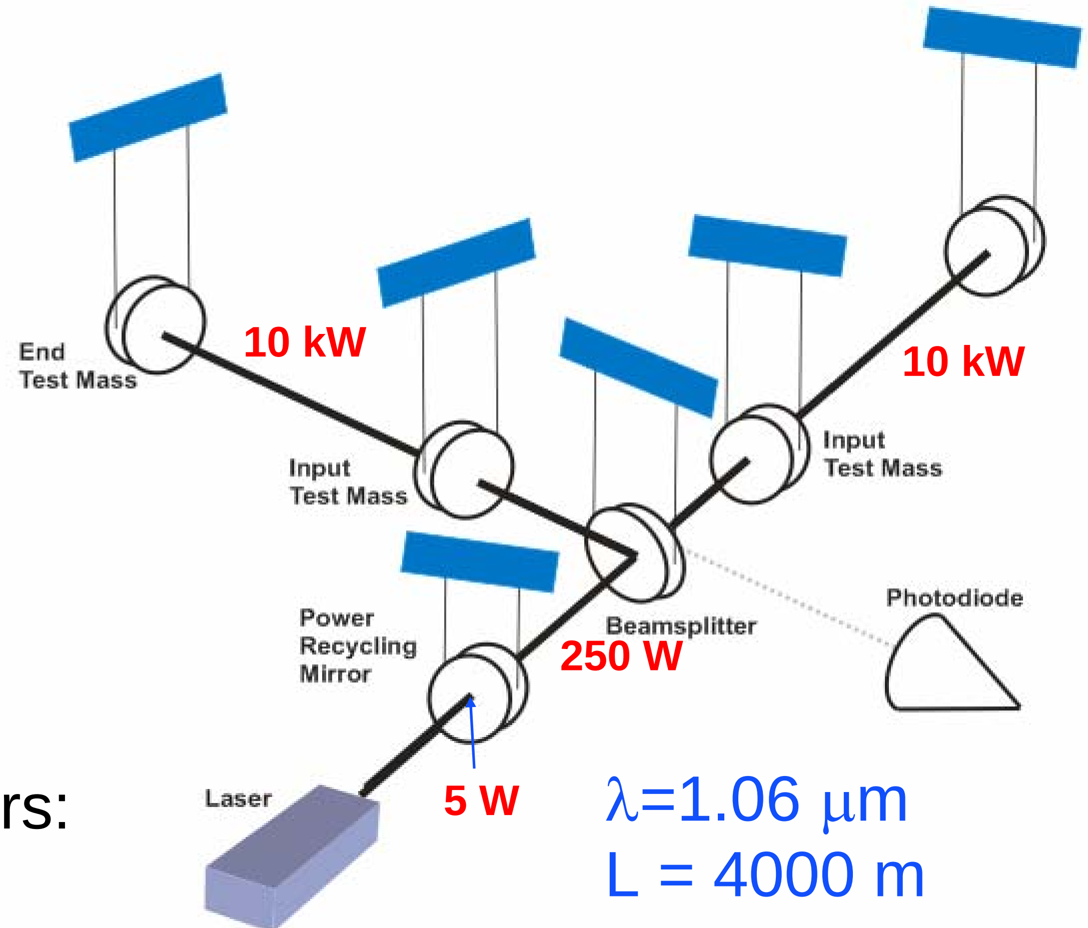
$$h \sim \frac{\lambda}{L}$$

$$\times \frac{1}{N_{roundtrip}}$$

$$\times \sqrt{\frac{1}{\dot{N}_{photon}\,\tau_{storage}}}$$

Putting in numbers:

***h* ~ 10^{-21}**



λ=1.06 μm

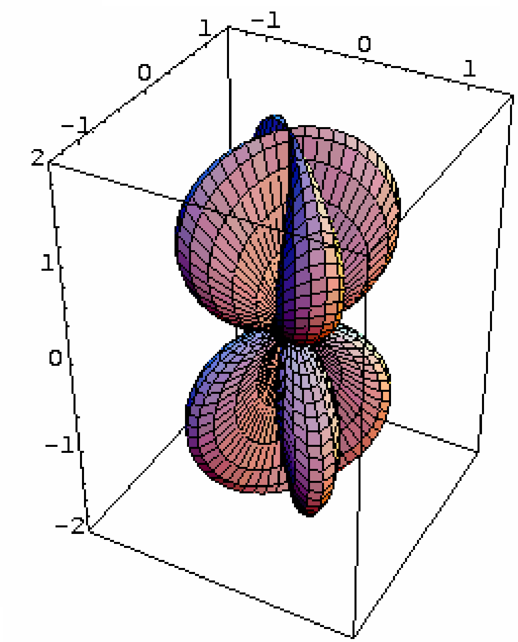
L = 4000 m

$N_{roundtrip}$ = 40

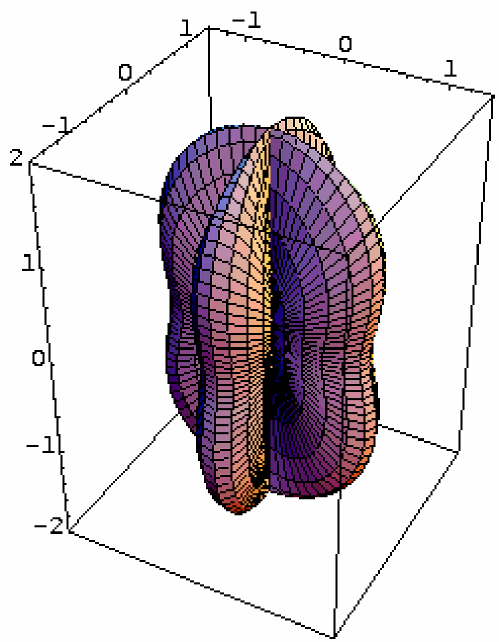
An interferometer is not a telescope

- Sensitivity depends on propagation direction, polarization

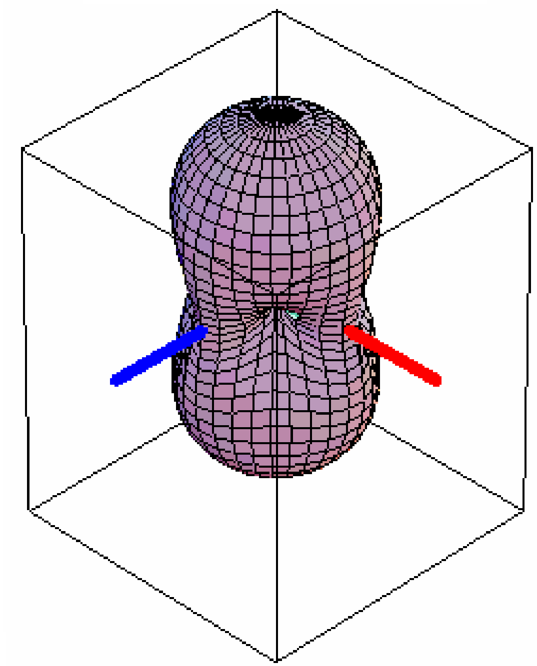
“×” polarization



“+” polarization

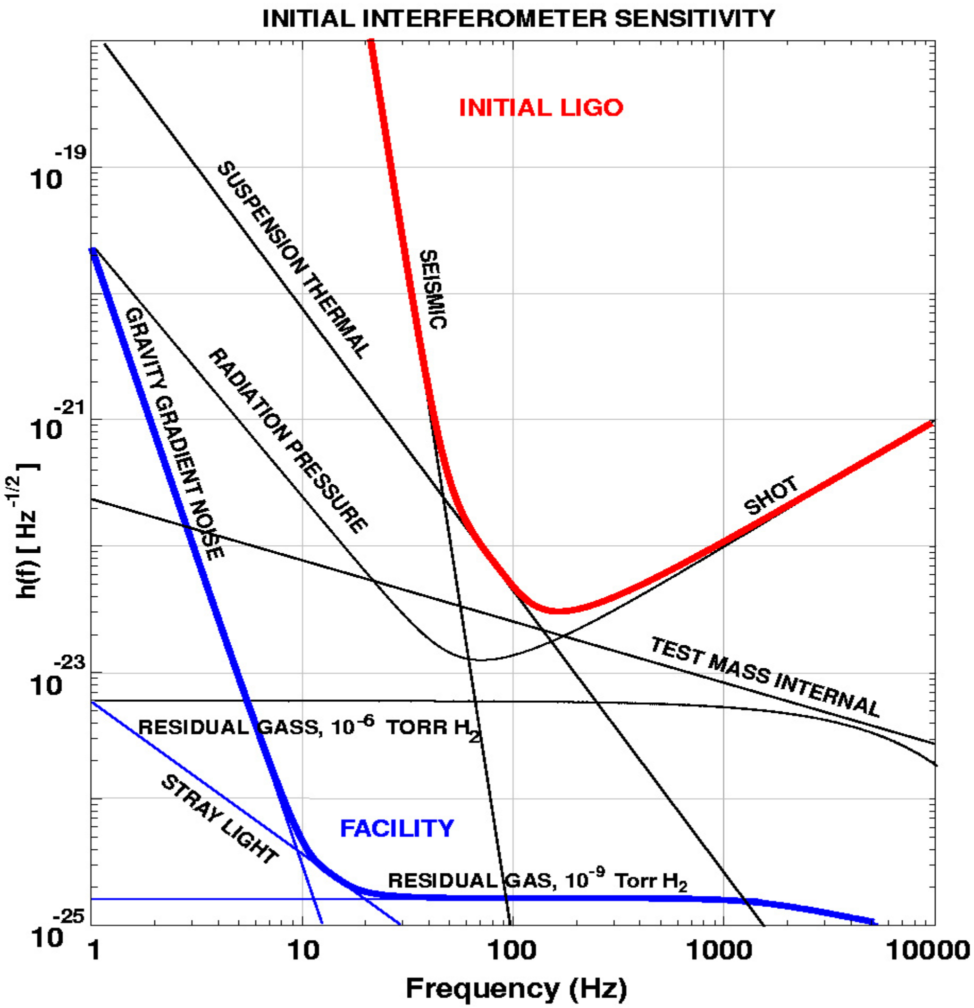


RMS sensitivity



- Really a microphone!

Fundamental noises in LIGO

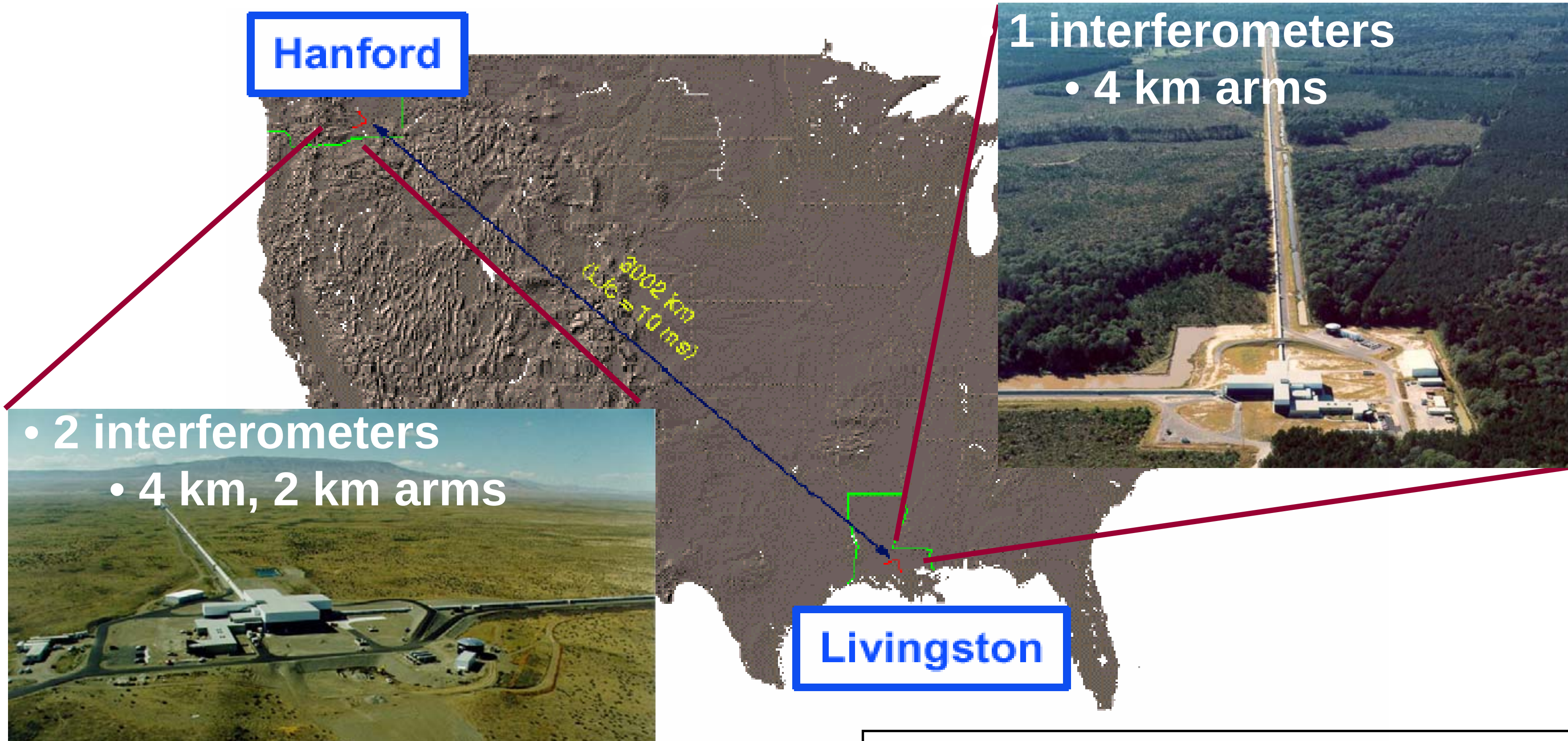


- **Displacement noises**
  - **Seismic noise**
  - **Radiation pressure**
  - **Thermal noise**
    - **Suspensions**
    - **Optics**
- **Sensing noises**
  - **Shot noise**
  - **Residual gas noise**

LIGO sites

LIGO Livingston Observatory

- 1 interferometers
  - 4 km arms

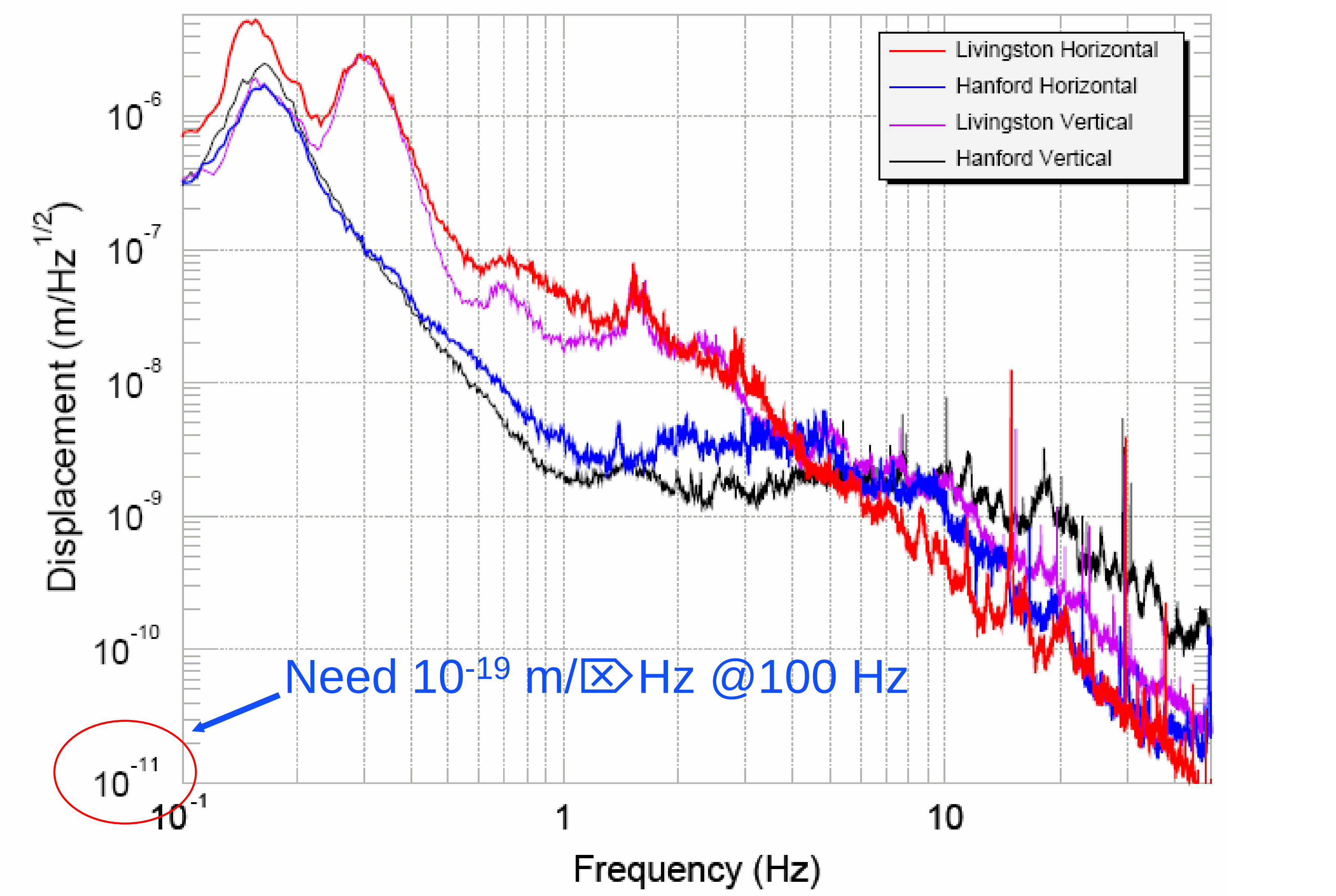


- 2 interferometers
  - 4 km, 2 km arms

LIGO Hanford Observatory

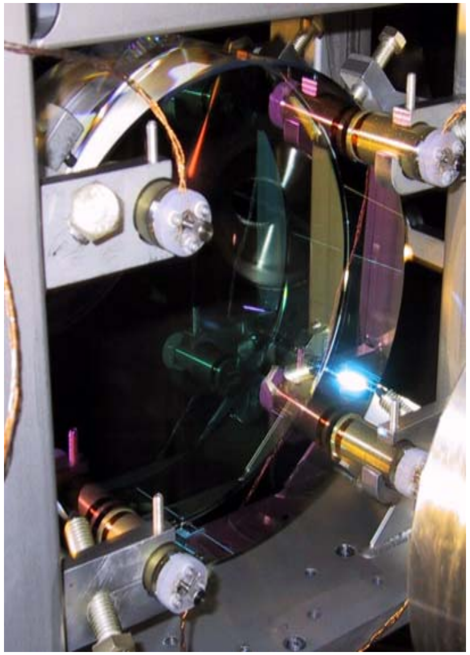
LIGO Observatories are operated by Caltech and MIT

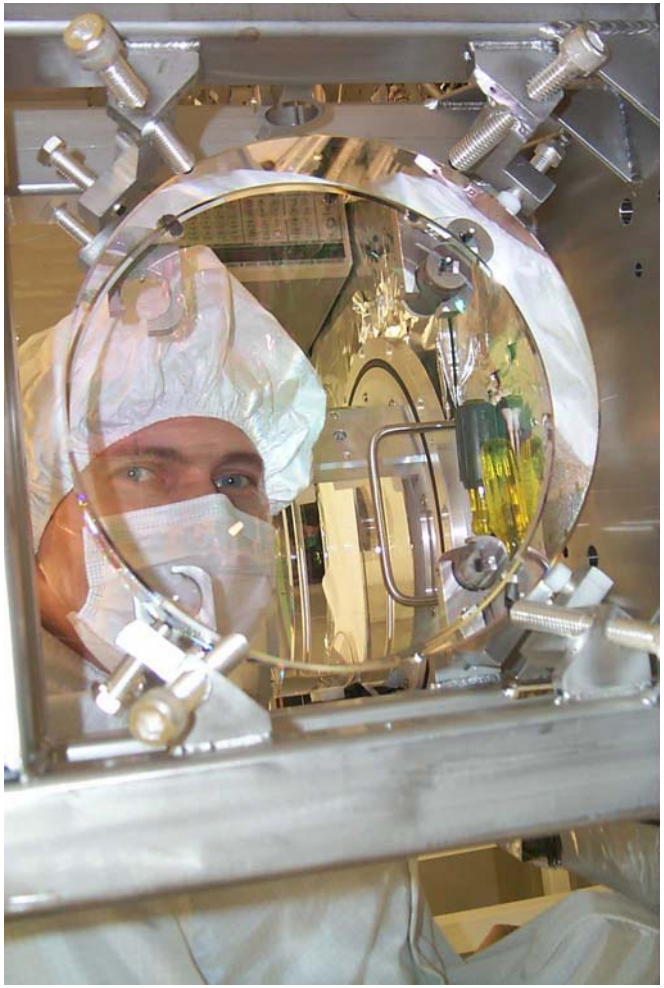
Seismic noise



Suspended Mirrors

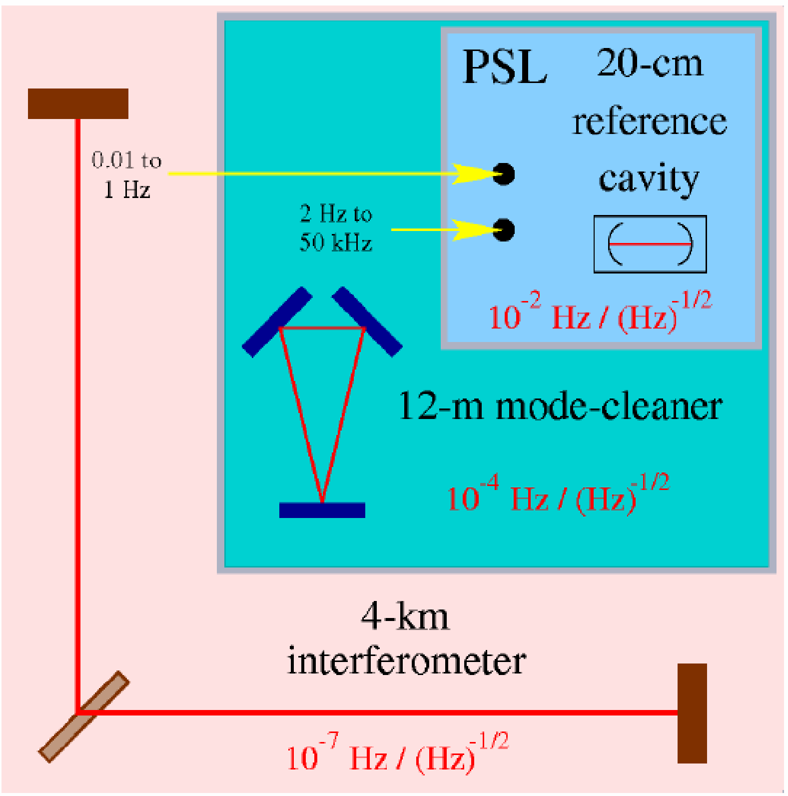
- mirrors are hung in a pendulum
  - → ‘freely falling masses’
- provide 100x suppression above 1 Hz
- provide ultraprecise control of mirror displacement (< 1 pm)

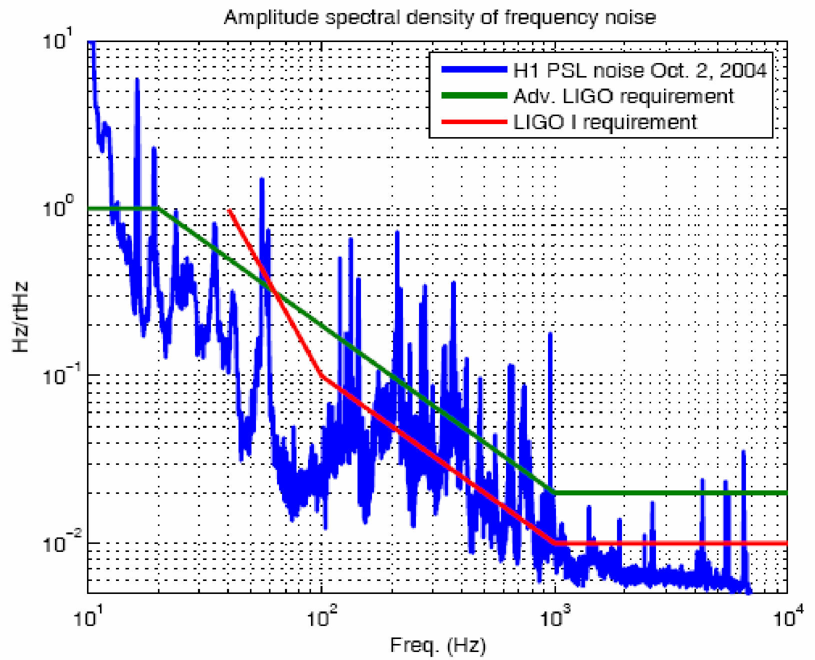




Frequency stabilization in LIGO

Hierarchical approach → use the *stability* provided by the arm cavities





Ultimately:

$\Delta f/f \sim 3 \times 10^{-22}$ @ 100 Hz

Shot noise and radiation pressure in LIGO

- Photons obey Poissonian statistics
- How to discriminate between Δn_{photon} and ΔL??

Shot noise:

$$h_{min,shot}(f) = \frac{1}{L}\sqrt{\frac{\eta c \lambda}{2\pi P_{in}}}$$

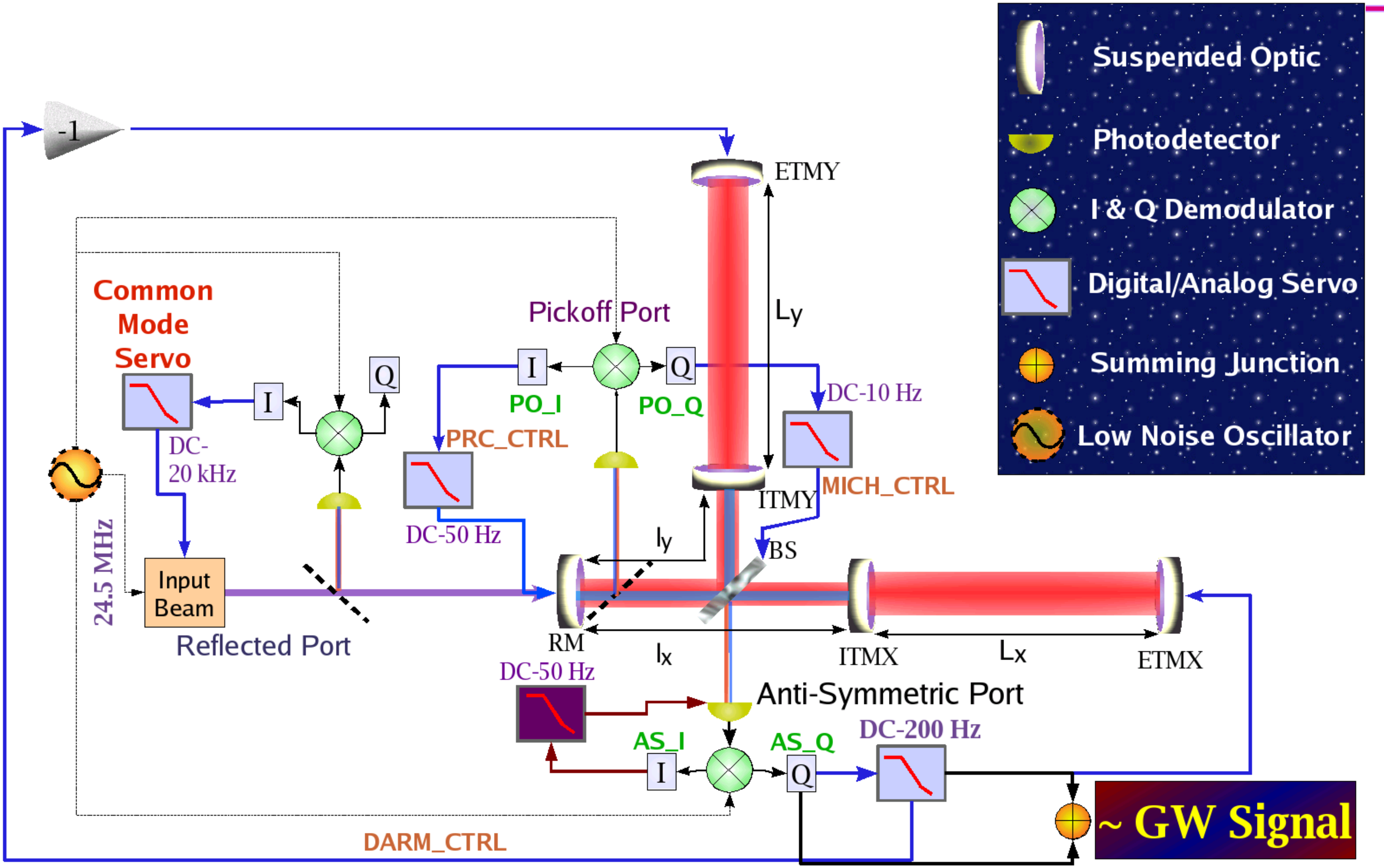
Radiation pressure noise:

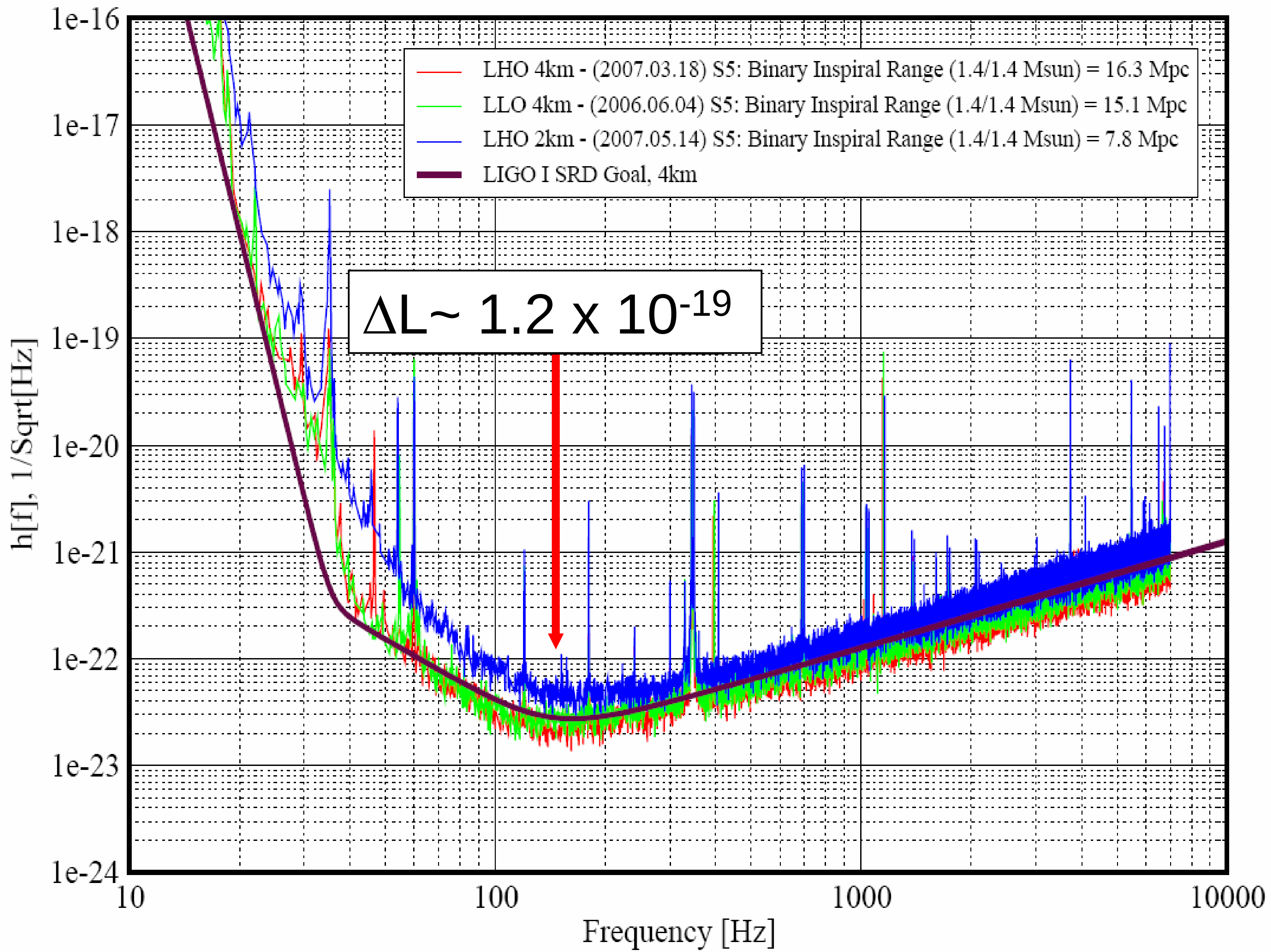
$$h_{rad}(f) = \frac{1}{m_{mirror}\pi f^2 L}\sqrt{\frac{\eta P_{in}}{2\pi c \lambda}}$$

"Standard Quantum Limit"

$$h_{SQL}(f) = \frac{1}{\pi f L}\sqrt{\frac{\eta}{m_{mirror}}}$$

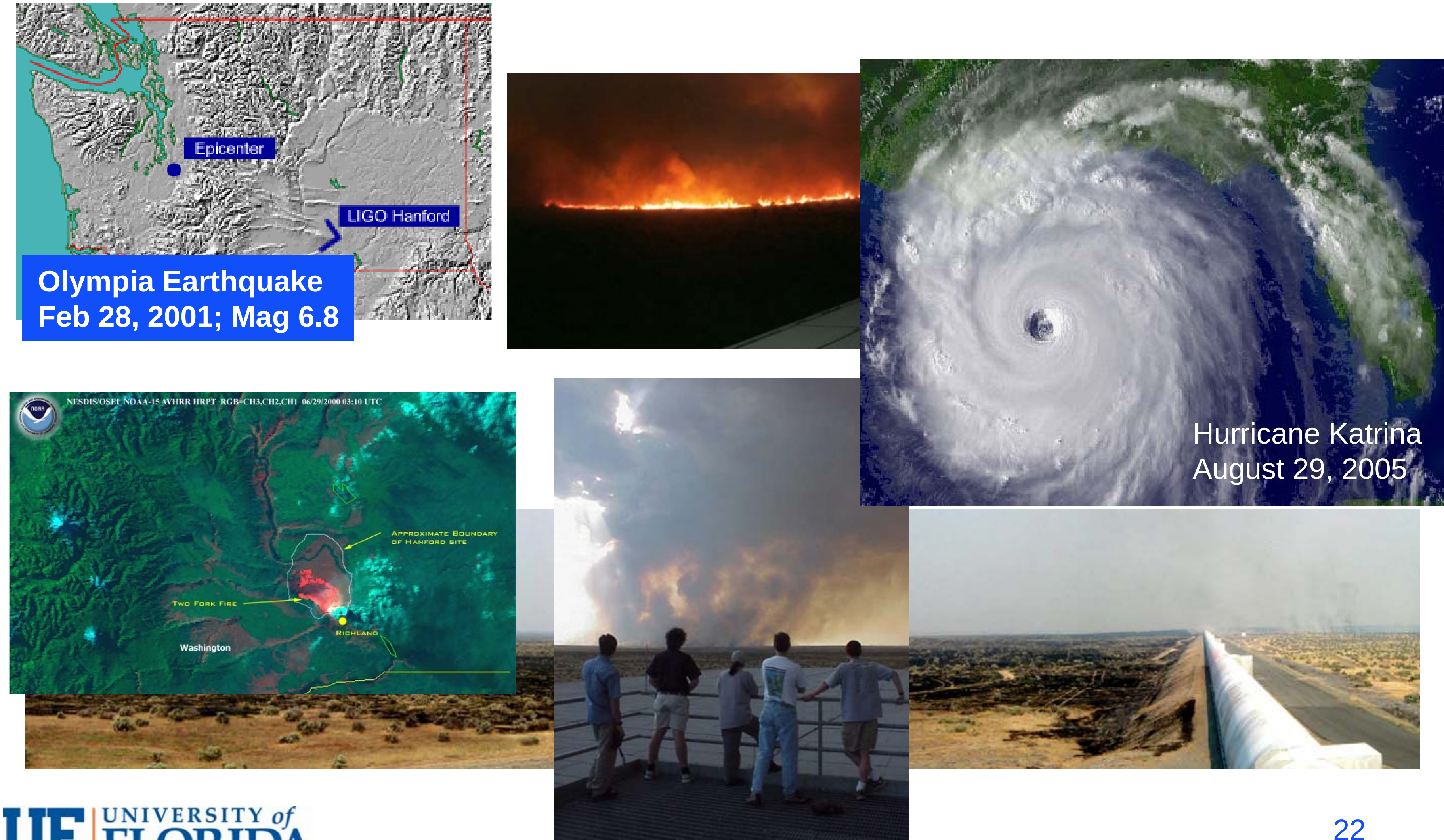
Length readout and control




LHO 4km - (2007.03.18) S5: Binary Inspiral Range (1.4/1.4 Msun) = 16.3 Mpc
LLO 4km - (2006.06.04) S5: Binary Inspiral Range (1.4/1.4 Msun) = 15.1 Mpc
LHO 2km - (2007.05.14) S5: Binary Inspiral Range (1.4/1.4 Msun) = 7.8 Mpc
LIGO I SRD Goal, 4km
ΔL~ 1.2 x 10-19
h[f], 1/Sqrt[Hz]
Frequency [Hz]
1e-16
1e-17
1e-18
1e-19
1e-20
1e-21
1e-22
1e-23
1e-24
10
100
1000
10000

Man-made noise

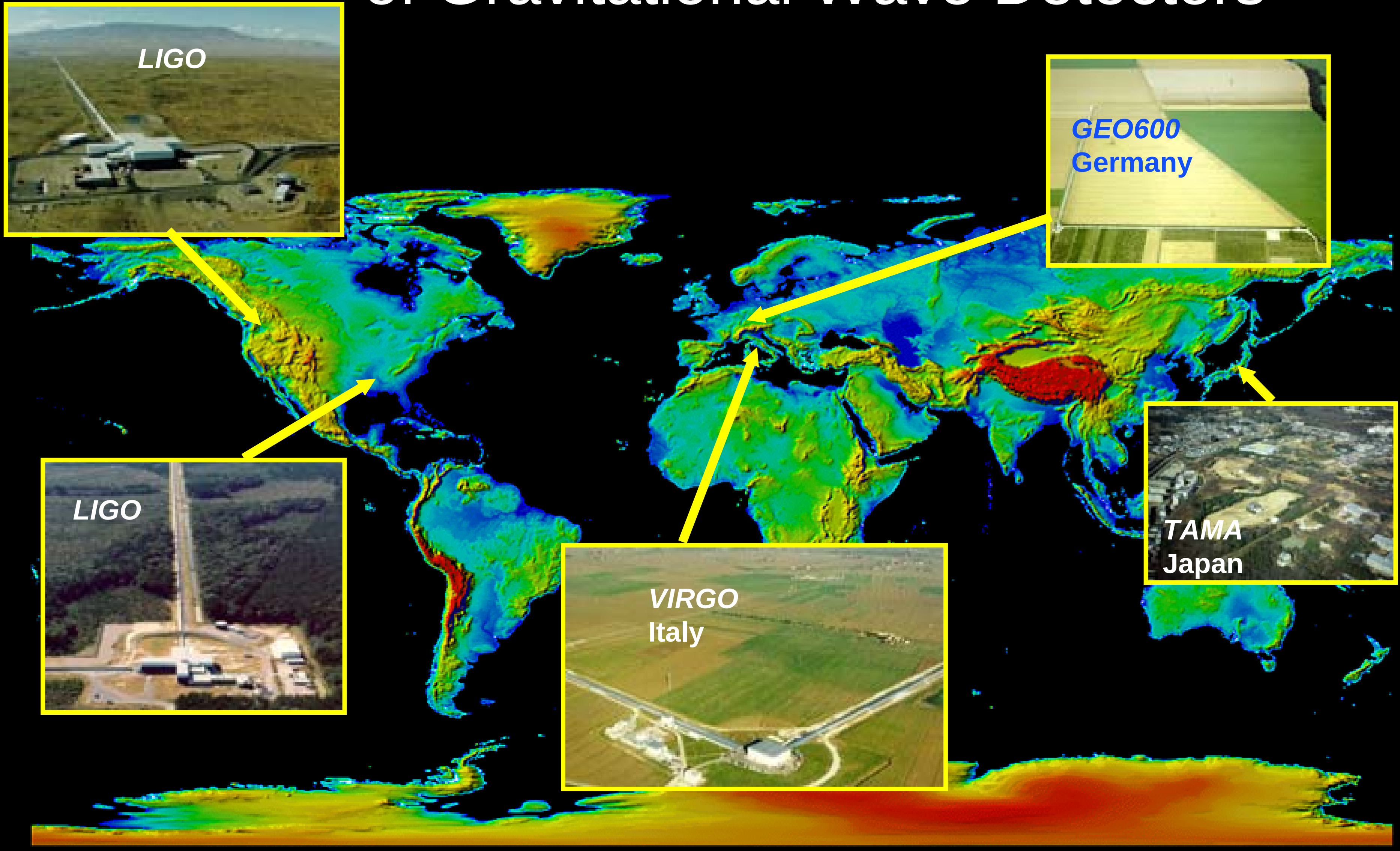
Nature can also be a problem…



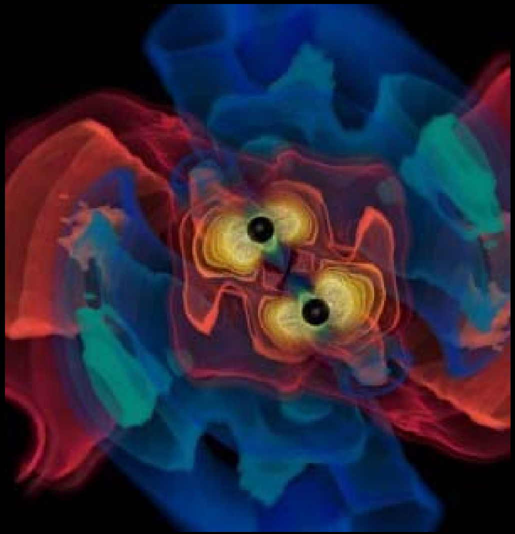
Olympia Earthquake
Feb 28, 2001; Mag 6.8

Hurricane Katrina
August 29, 2005

The Global Network of Gravitational Wave Detectors



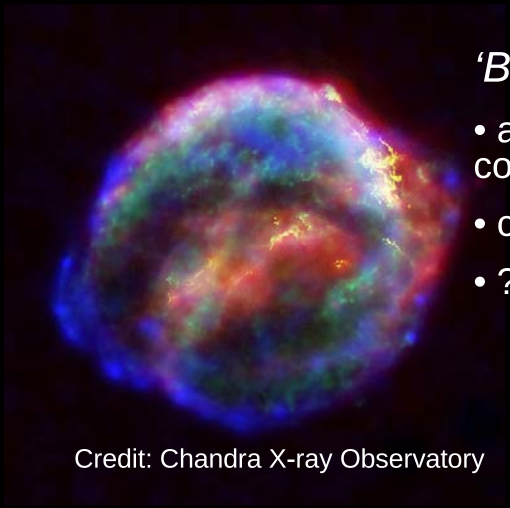
The astrophysical gravitational wave source catalog



Credit: AEI, CCT, LSU

Coalescing Binary Systems

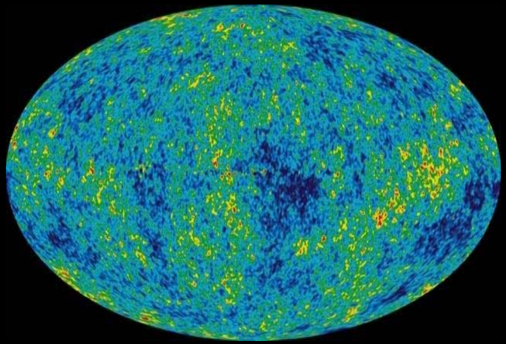
- Neutron stars, black holes
- ‘chirped’ waveform



Credit: Chandra X-ray Observatory

‘Bursts’

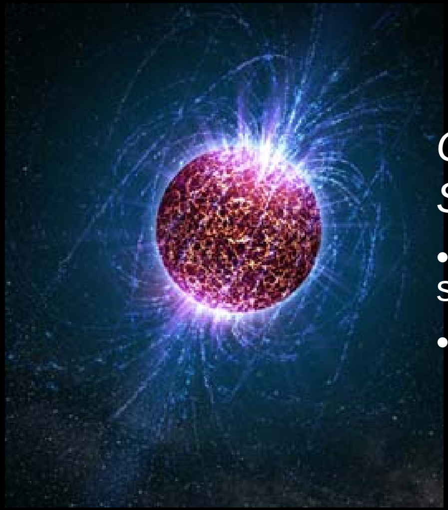
- asymmetric core collapse supernovae
- cosmic strings
- ???



NASA/WMAP Science Team

Cosmic GW background

- residue of the Big Bang
- probes back to 10^{-21} s
- stochastic, incoherent background

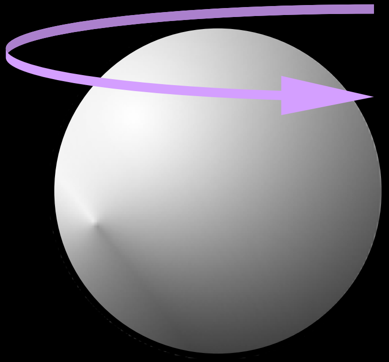


Casey Reed, Penn State

Continuous Sources

- Spinning neutron stars
- monotone waveform

The Crab Pulsar



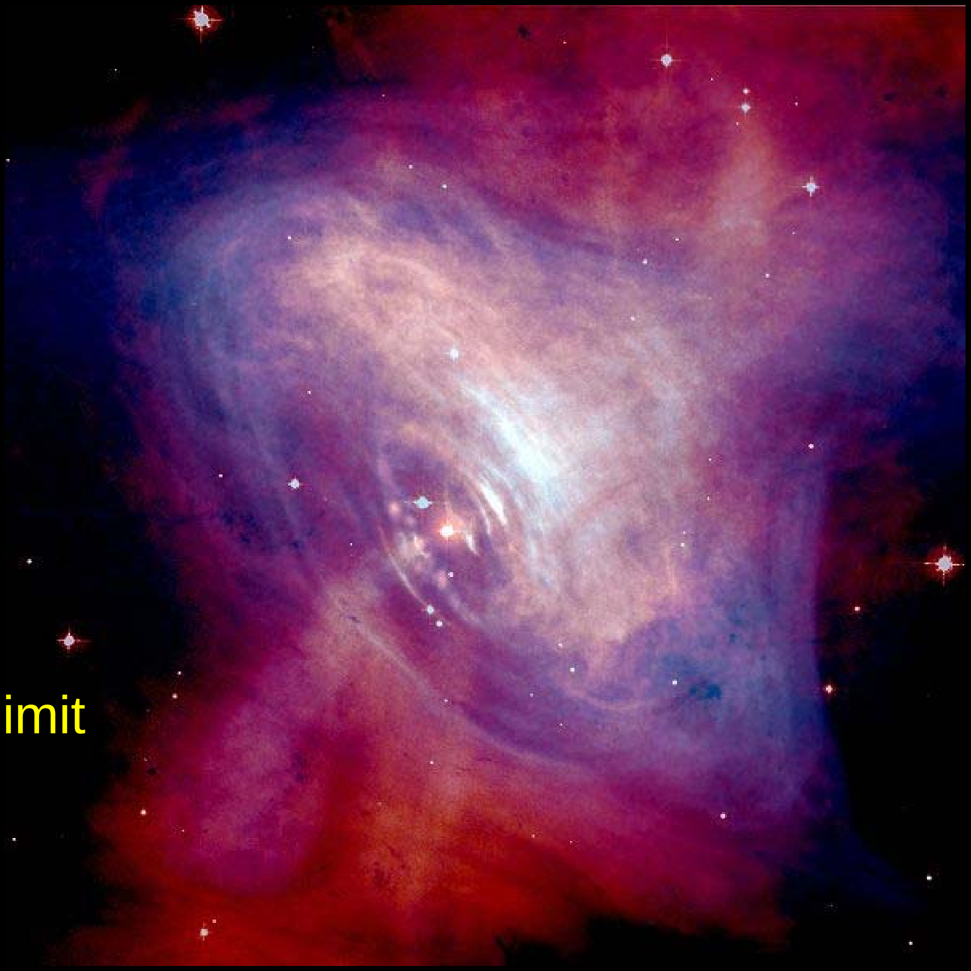
- Spinning neutron star
  - remnant from supernova in year 1054
- spin frequency ν_{EM} = 29.8 Hz

  → $\nu_{gw} = 2\,\nu_{EM}$ = 59.8 Hz
- spin down due to:
  - electromagnetic braking
  - *GW emission?*

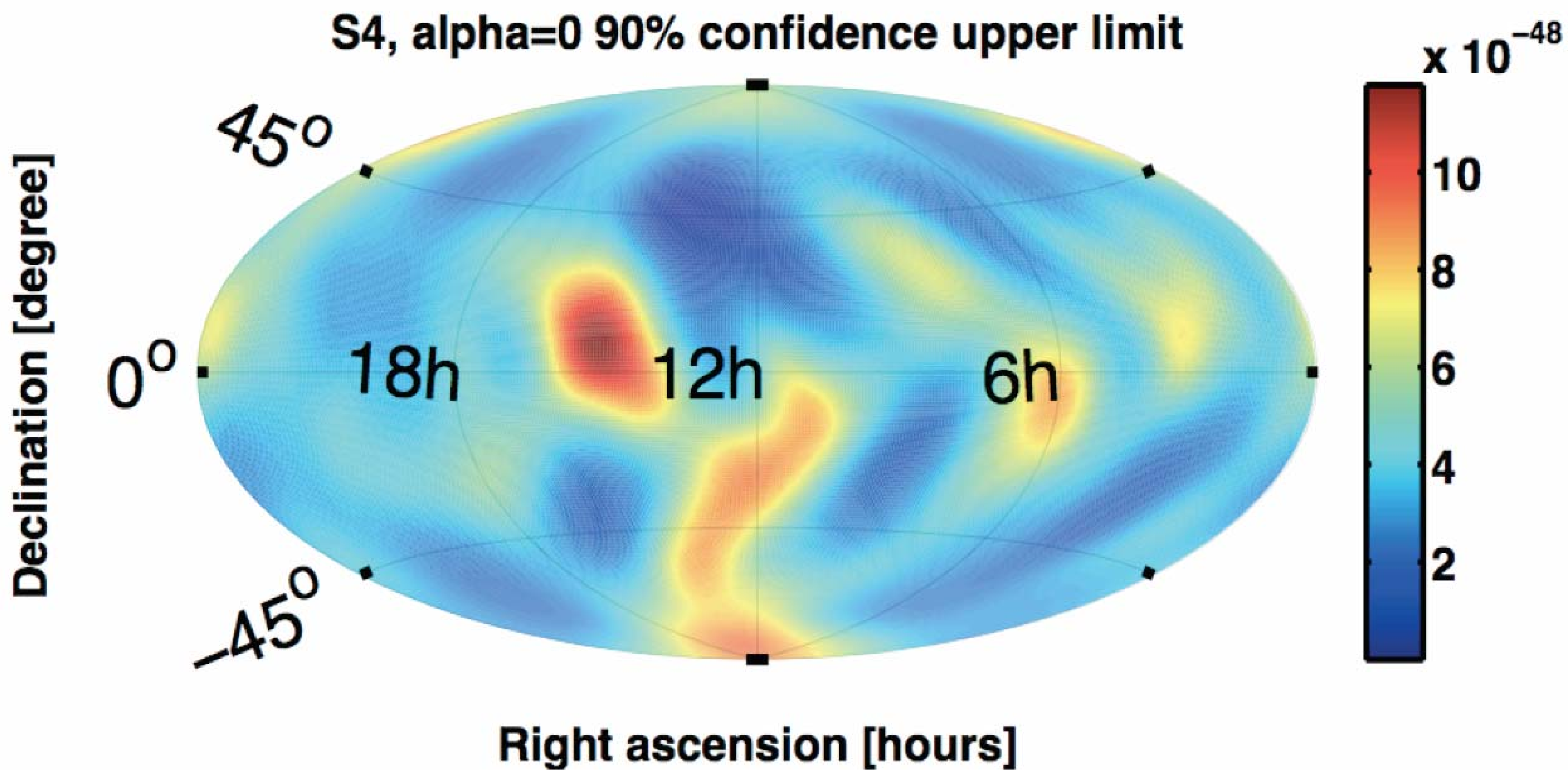
- S5 <u>preliminary</u> upper limit:

  $h < 3.4 \times 10^{-25}$ → 4.2x <u>*below*</u> the spindown limit
- S5 <u>preliminary</u> ellipticity:

  $\varepsilon < 1.8 \times 10^{-4}$

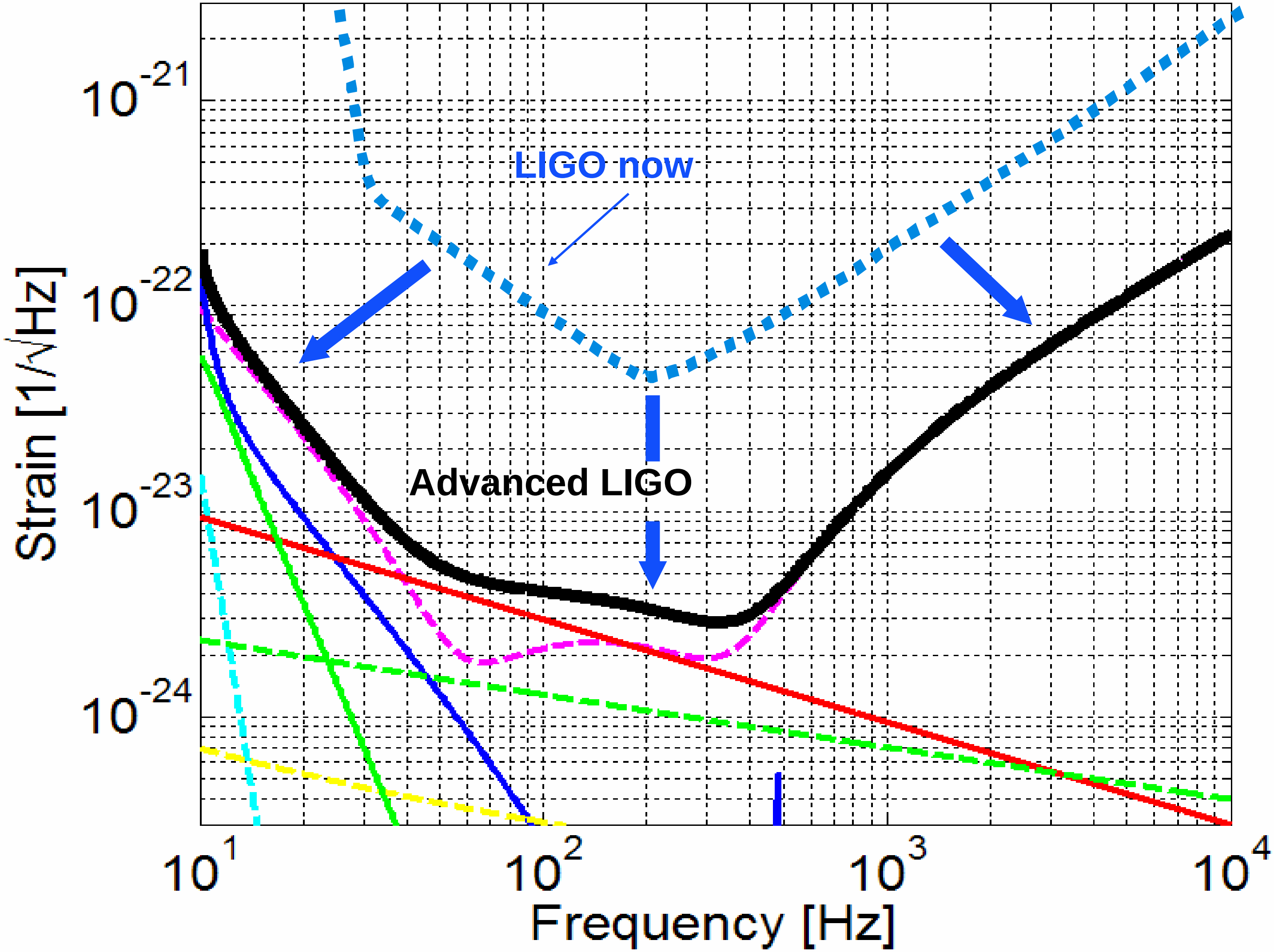


Upper limit map of gravitational wave stochastic background

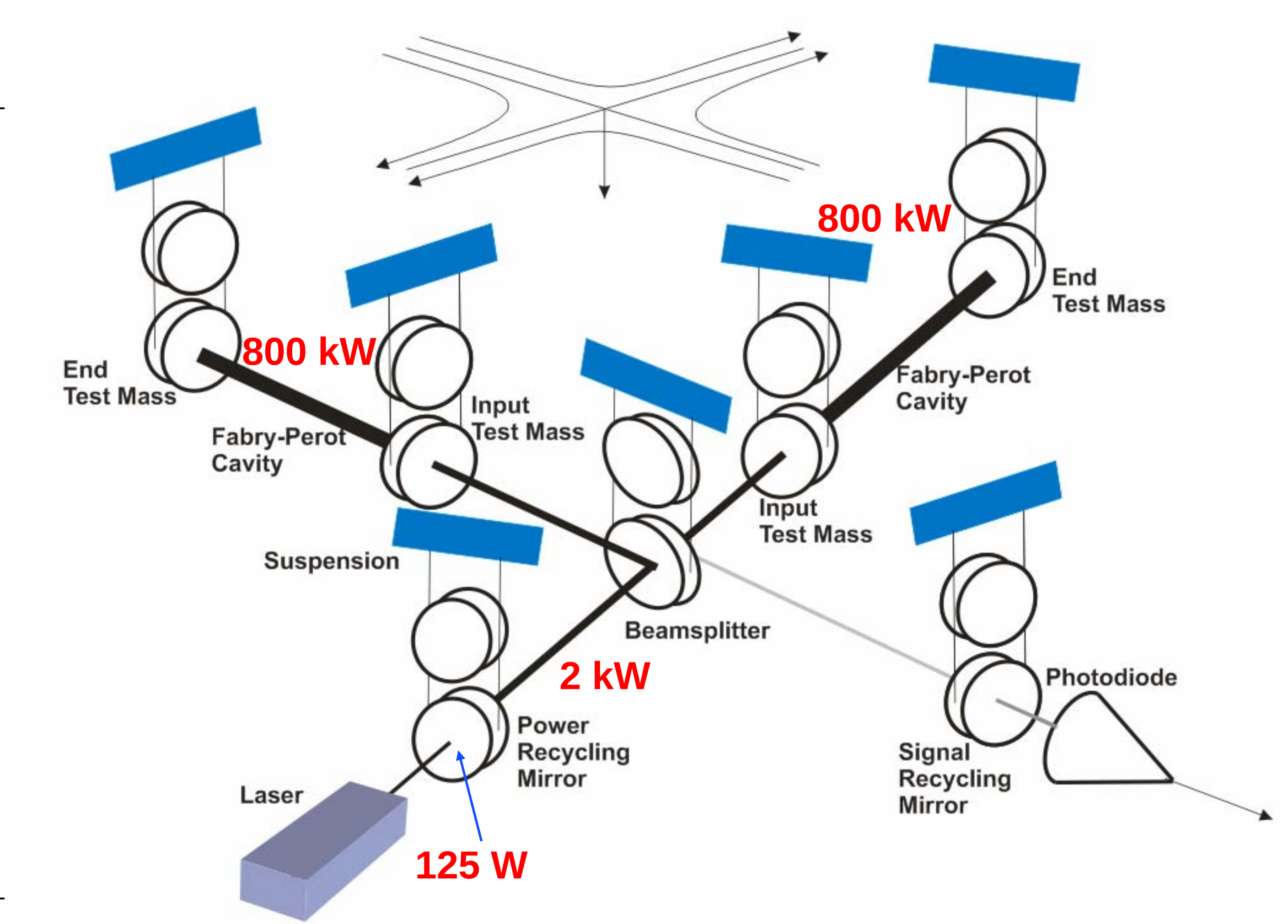


Current upper limit on gravitational wave stochastic background (preliminary): Ω_{GW} ($\equiv$ ρ/ρ_{crit}) $< 9 \times 10^{-6}$

Advanced LIGO

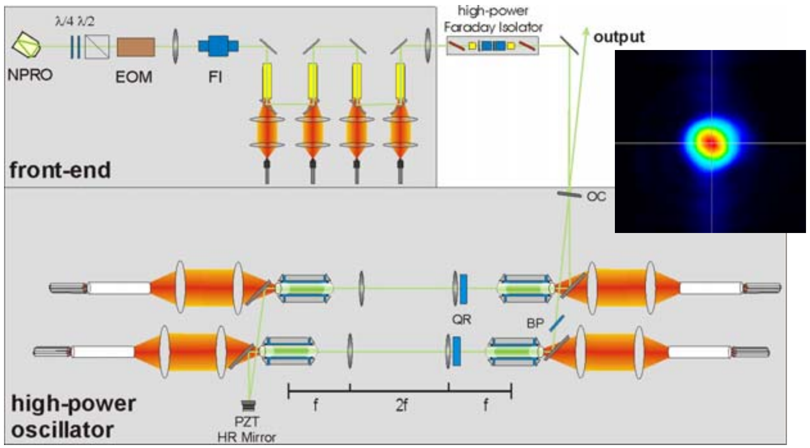


Advanced LIGO



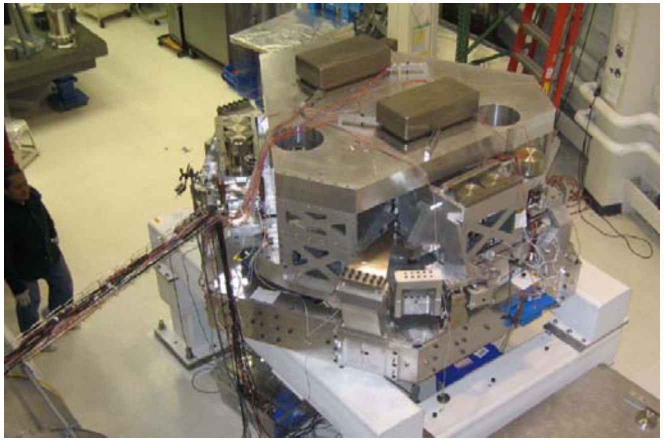
Advanced LIGO

180 W laser

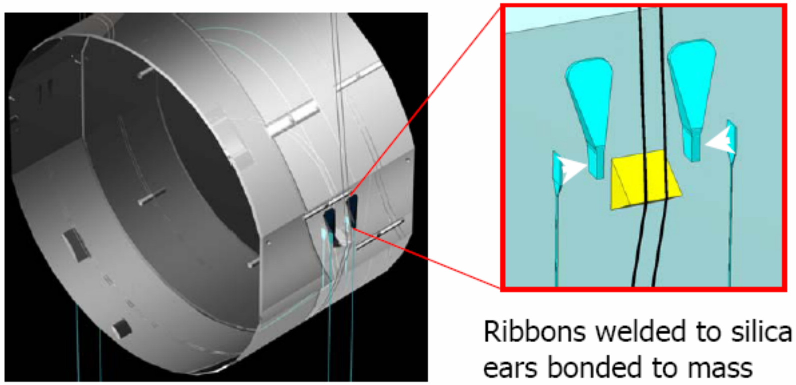


Mirror Suspensions

Seismic isolation



Mirrors



Ribbons welded to silica ears bonded to mass

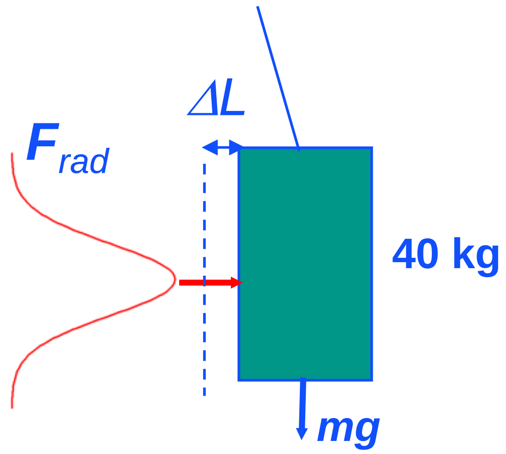
Radiation pressure effects in Advanced LIGO

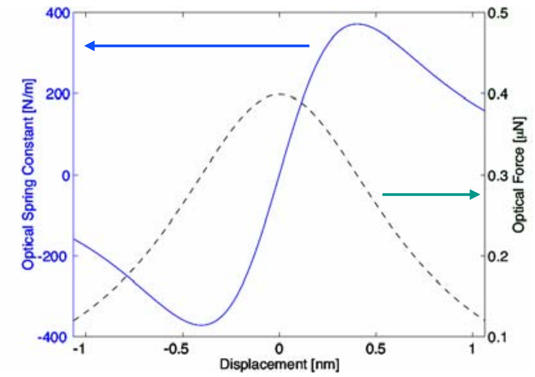
- Advanced LIGO: 600-800 kW on resonance
  - Radiation pressure on resonance:

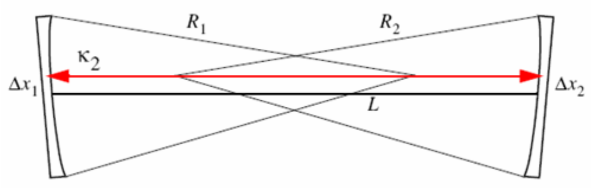
    $F_{rad} = 2P_{cav}/c \sim 5$ mN

  - Leads to (uncontrolled) **$\Delta L \sim$ 10s of μm**

- 3 types of potential instabilities
  - Optical springs
  - Angular 'tilt' instabilities
  - Parametric instabilities







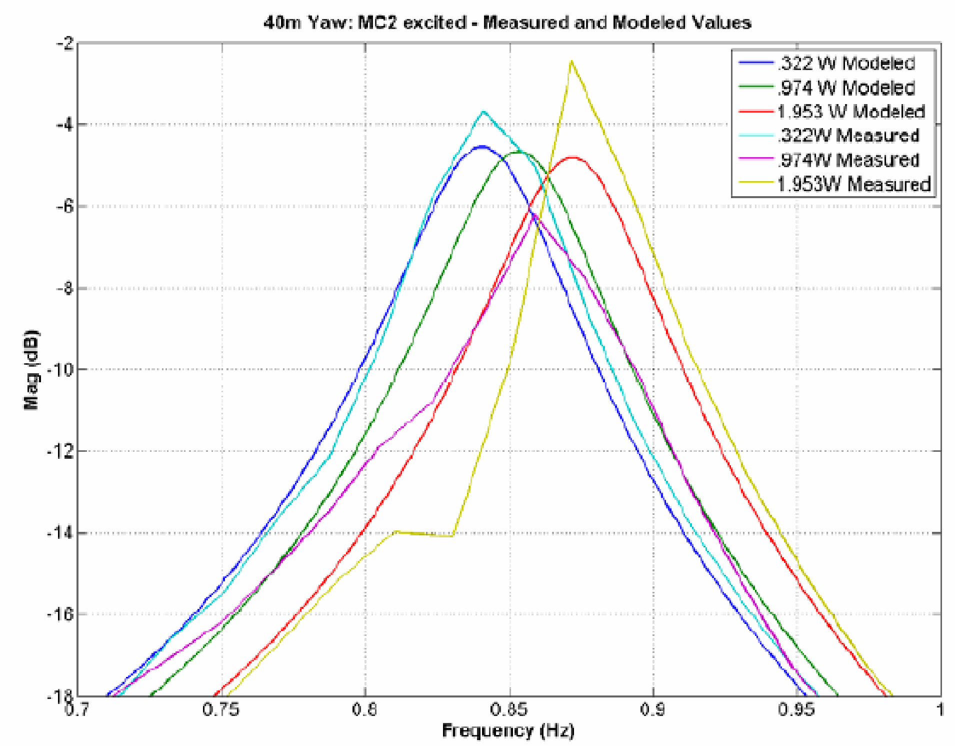
Angular instabilities

Sidles and Sigg, Phys. Lett. A **354**,167-172 (2006)

- If cavity beam is displaced off center, F_{rad} exerts torques on mirrors:

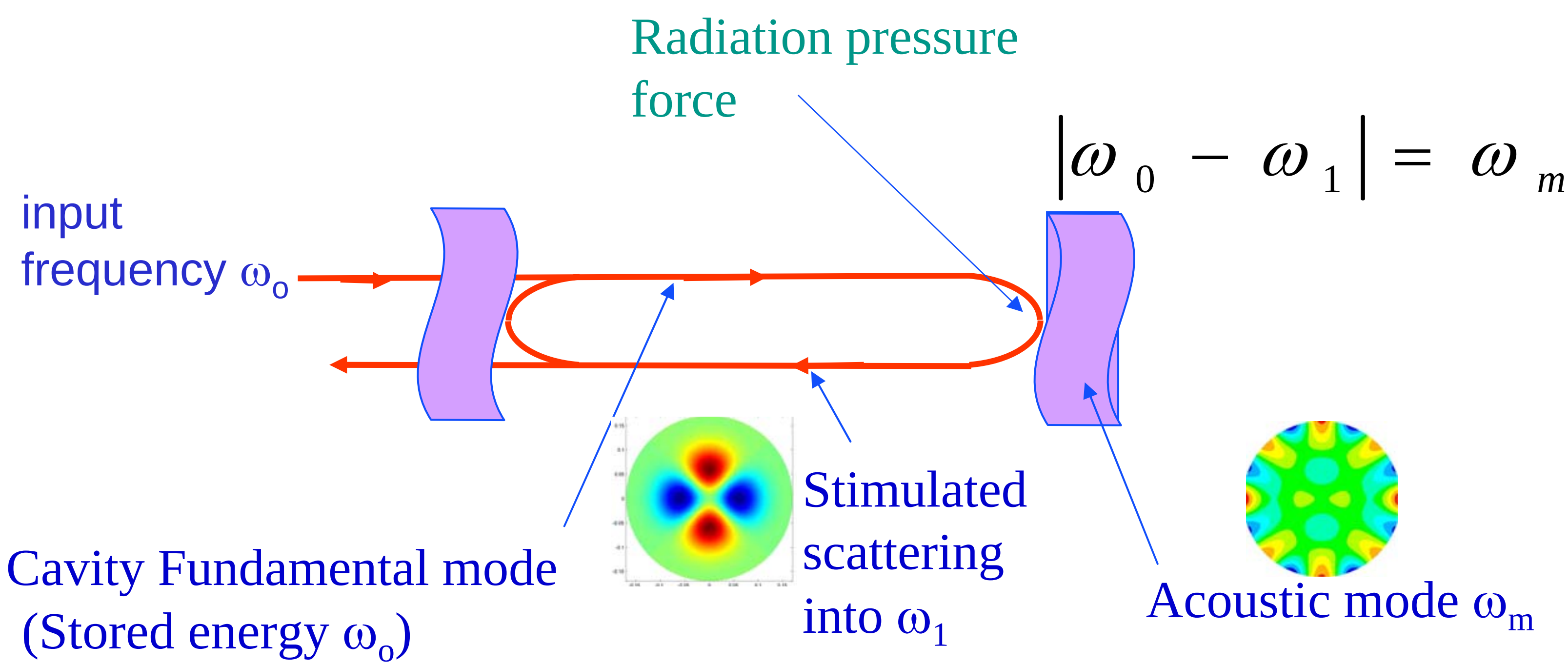
$$\tau = \frac{2P_{cav}\Delta x}{c}$$

- Mirrors act as torsional pendulum
  - » One stable mode
  - » one unstable mode



Parametric instabilities

- Light (Brillioun) scattering from higher order optical modes to mirror



Braginsky, et al., Phys. Lett. A**287**, 331 (2001)
Zhao, et al., PRL **94**, 121102 (2005)

Beyond the standard quantum limit

A. Buonanno and Y. Chen, PRD 64, 042006 (2001)

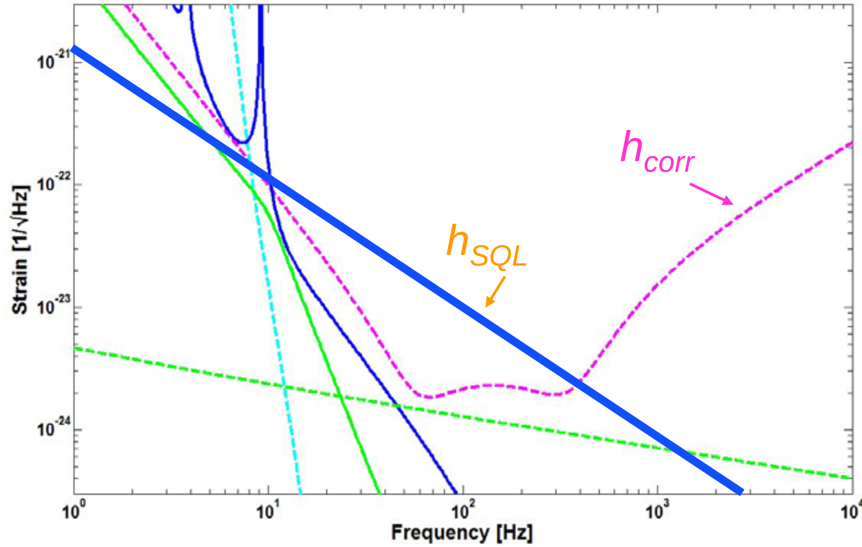
- Standard Quantum Limit
  - » assumes no correlations between SN and RP

$$h_{SQL}(f) = \frac{1}{\pi f L}\sqrt{\frac{\eta}{m_{mirror}}}$$

- Signal recycling induces photon 'back-action' on mirrors
  - » Quantum noise is *dynamically correlated*, leading to $h(f) < h_{SQL}(f)$ in a limited frequency range:

$$h_{corr} = h_{SQL}\frac{\Delta b_{\zeta}}{\sqrt{2\kappa}}$$

< 1



Stay

Tuned...

LIGO Scientific Collaboration

LIGO

LSC

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UNIVERSITY OF STRATHCLYDE

ACIGA

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LOYOLA UNIVERSITY NEW ORLEANS

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THE AUSTRALIAN NATIONAL UNIVERSITY

Università degli Studi del Sannio

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1891

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San José State UNIVERSITY

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Acknowledgments

- **Members of the LIGO Laboratory**
- **Members of the LIGO Science Collaboration**
- **National Science Foundation**

More Information

- **http://www.ligo.caltech.edu; www.ligo.org**

Thank you!