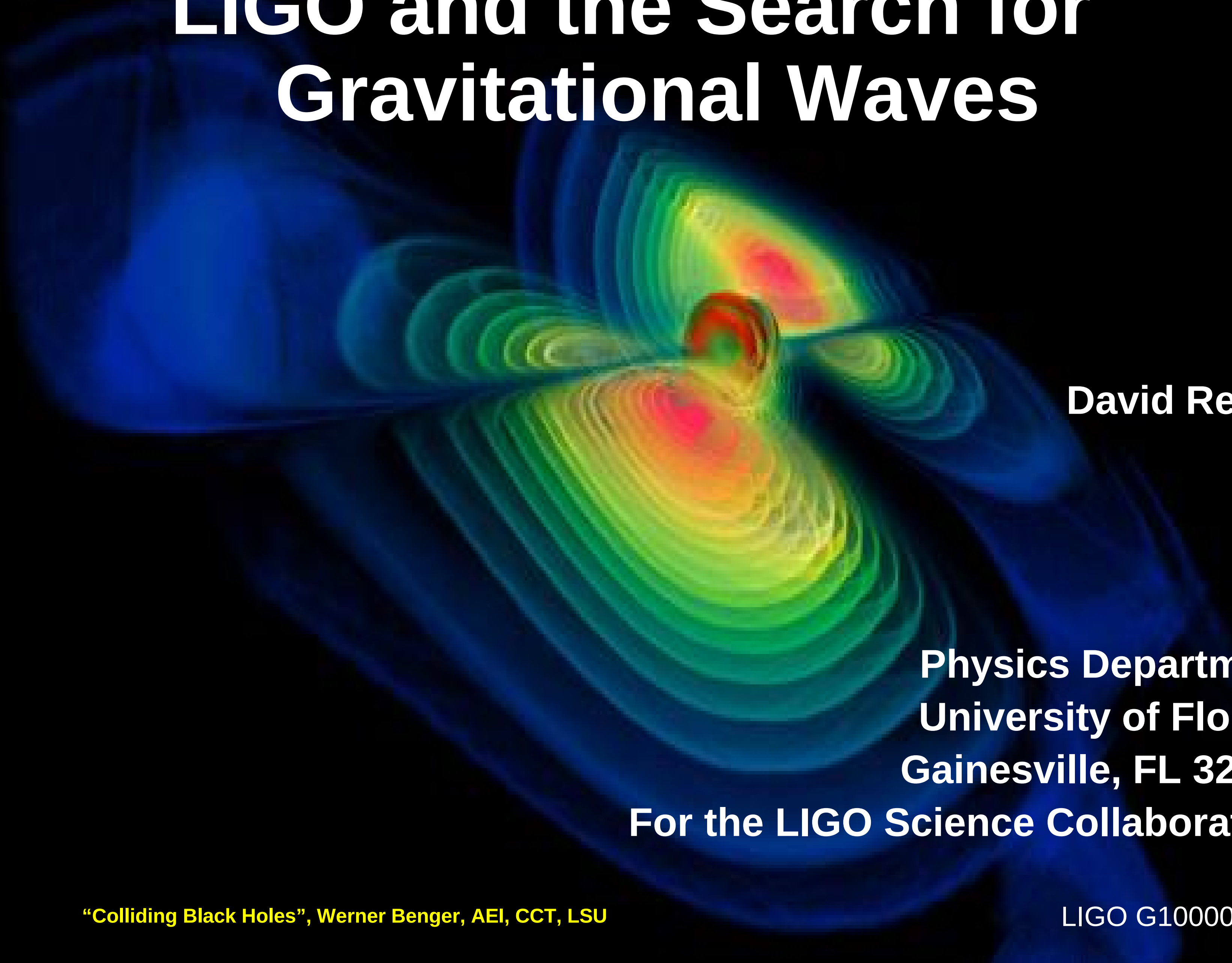
Physics Colloquium, University of North Carolina, Feb 15, 2010

LIGO and the Search for Gravitational Waves



David Reitze

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

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

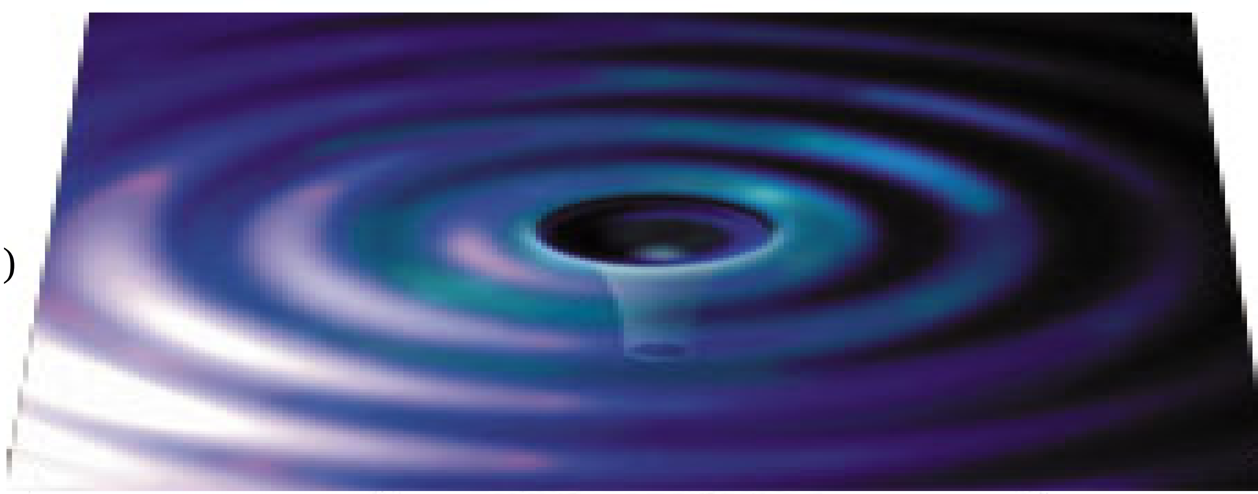
LIGO G1000096-v1


LIGO
Interferometer

General relativity simplified

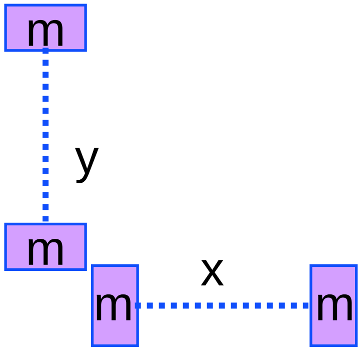
- "Gravity is Geometry"
  - Space tells matter how to move ←→ matter tells space how to curve
  - Metric ($g_{\mu\nu}$) = flat spacetime ($\eta_{\mu\nu}$) + perturbation ($h_{\mu\nu}$)
- Propagating gravitational waves: $\left(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right)h = 0$

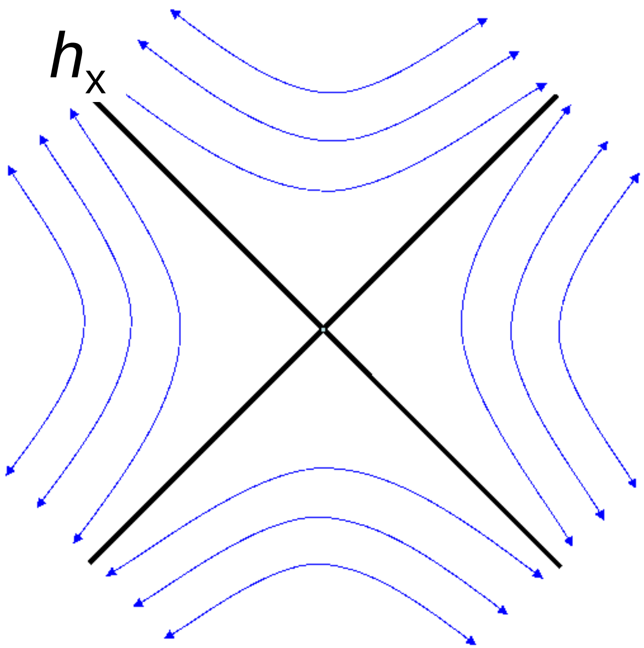
$$h(t) \sim h_{\mu\nu}\, e^{i(\vec{k}\bullet\vec{x} - \omega t)} + h_{\mu\nu} e^{-i(\vec{k}\bullet\vec{x} - \omega t)}$$



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^-

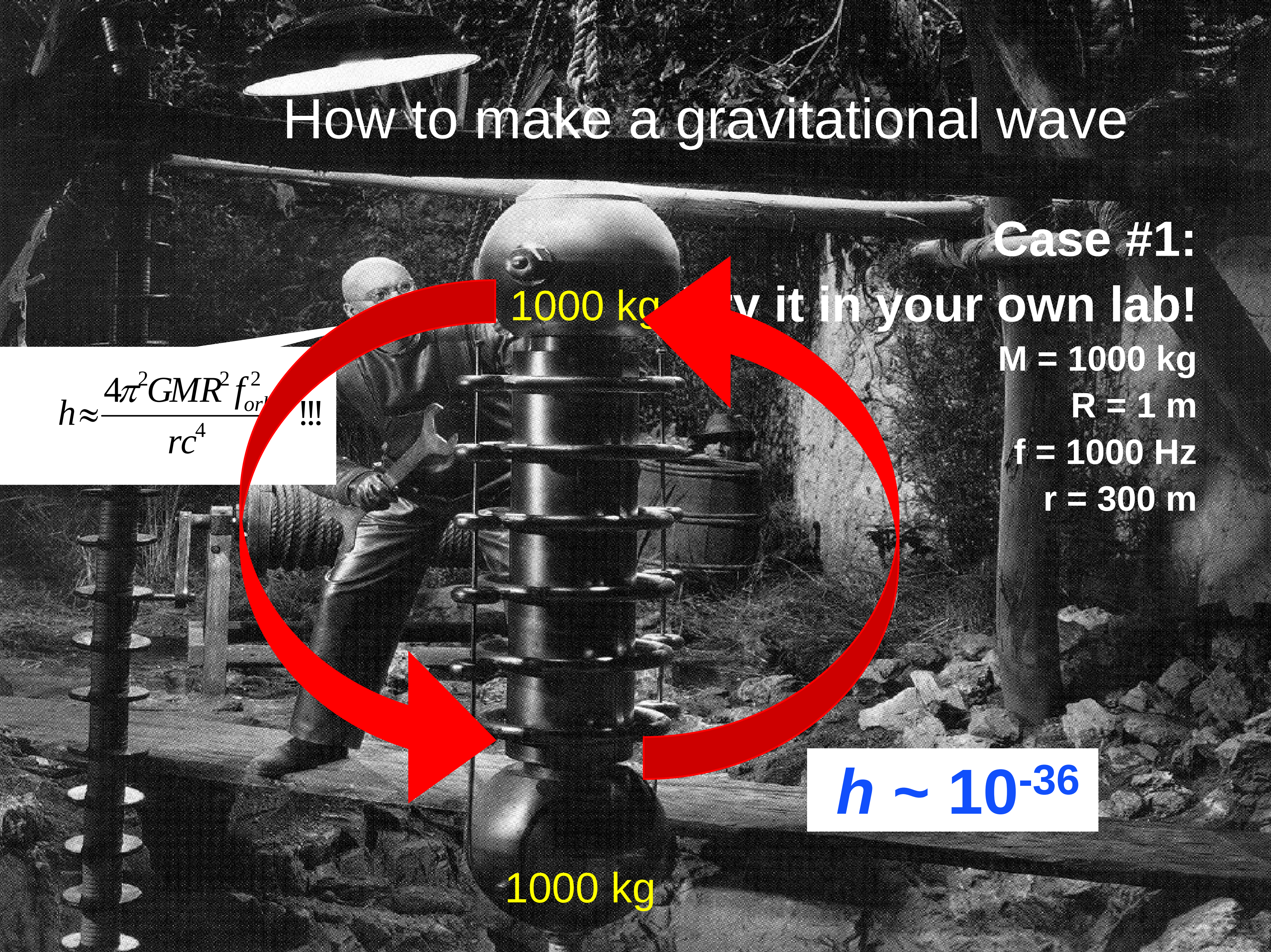
Gravitational Waves

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

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

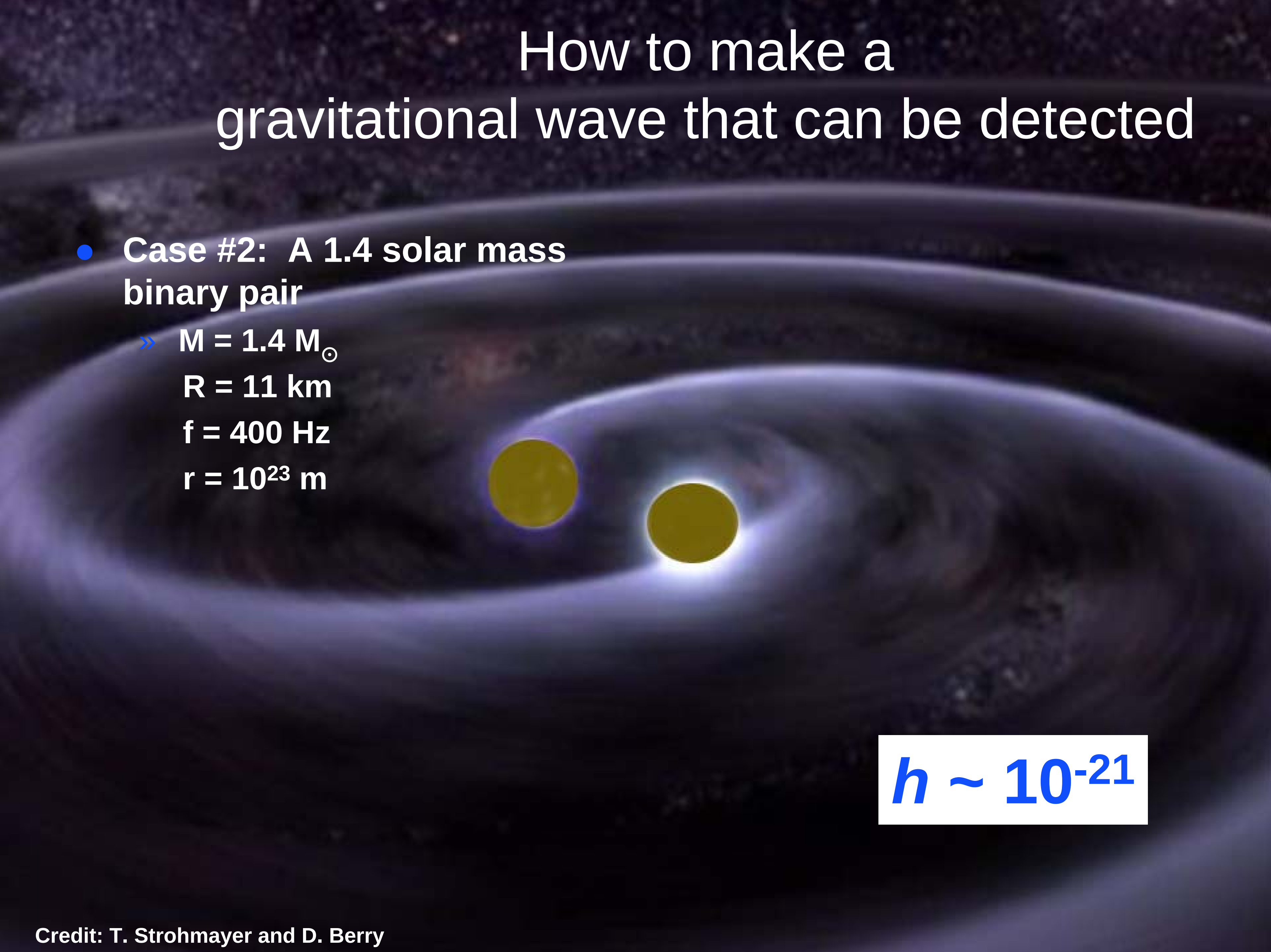
$$h \approx \frac{4\pi^2 G M R^2 f_{orb}^2}{r c^4}$$

- Traveling wave solutions of Einstein's equation, $v = c$
- Two polarizations: h_+, h_x


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

How to make a gravitational wave that can be detected

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



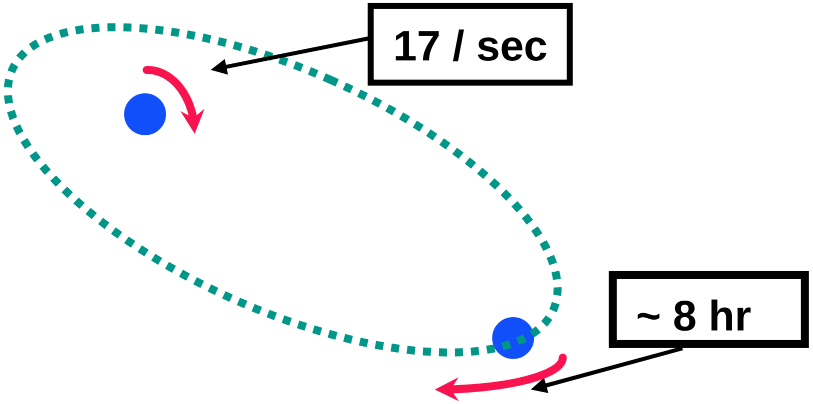
$h \sim 10^{-21}$

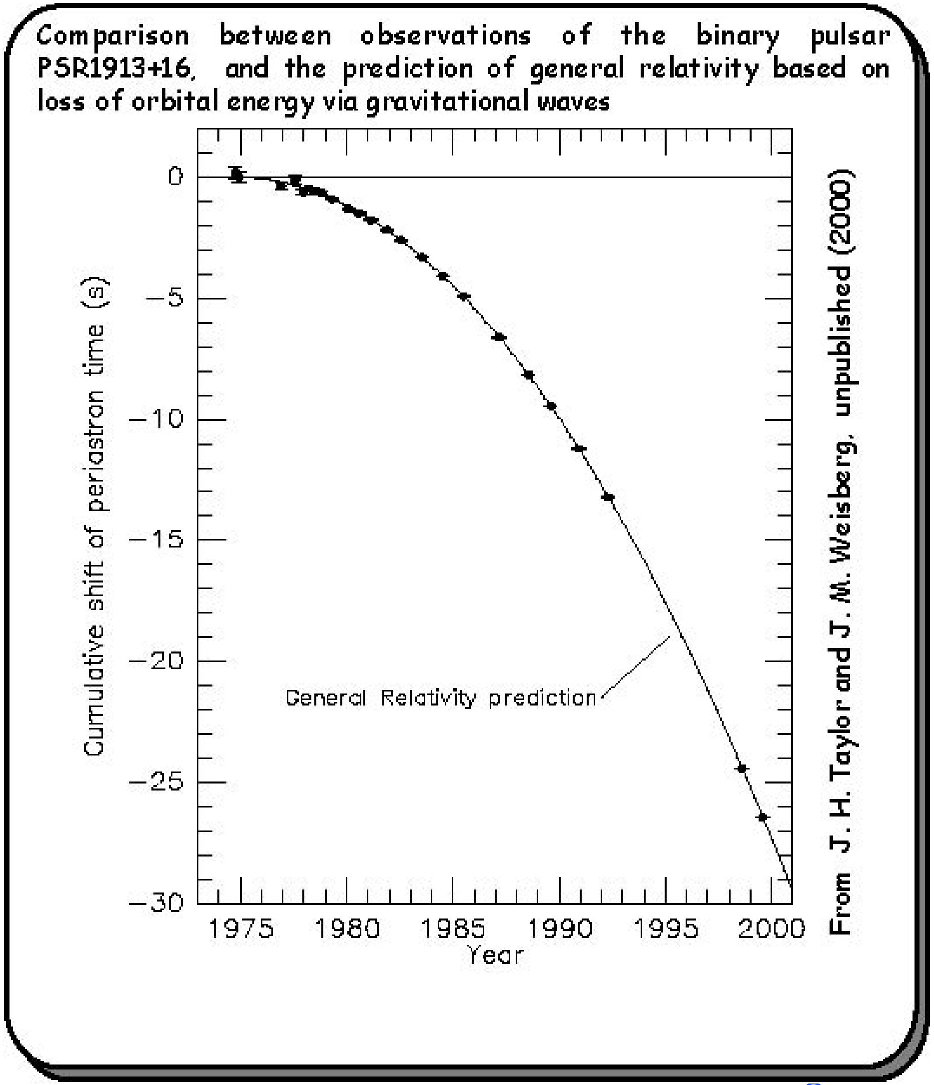
Credit: T. Strohmayer and D. Berry

Existence proof: PSR 1913+16

Joseph Taylor

Russell Hulse

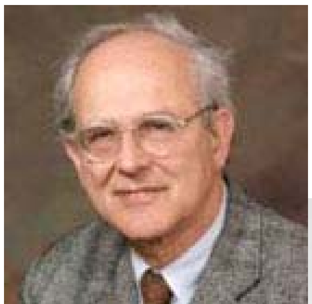




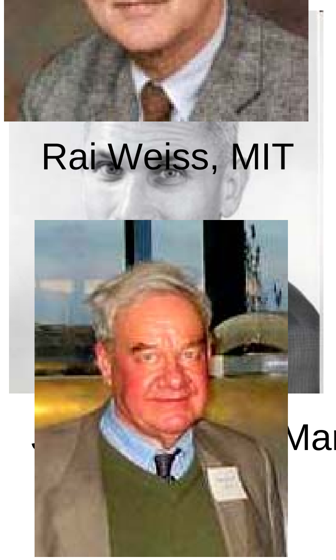
How to detect a gravitational wave

QUARTERLY PROGRESS REPORT
APRIL 15, 1972
No. 105

ELECTROMAGNETICALLY COUPLED BROADBAND GRAVITATIONAL ANTENNA



Rai Weiss, MIT



Maryland

Ron Drever, Caltech

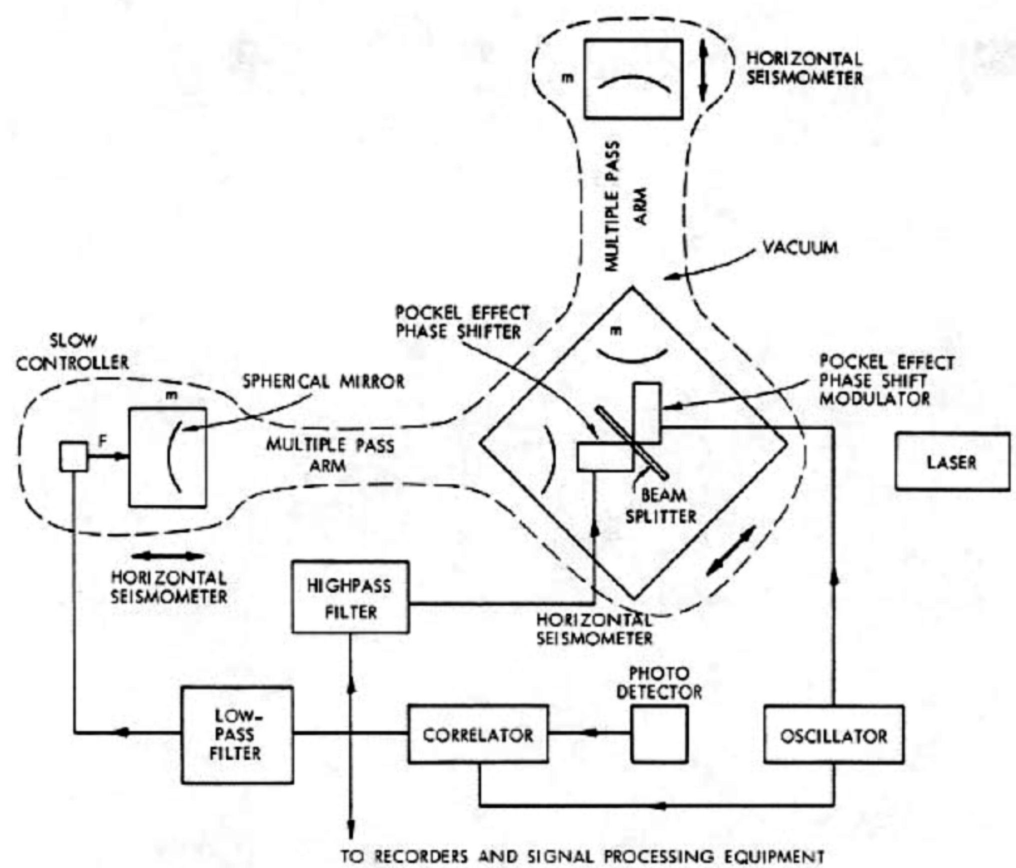


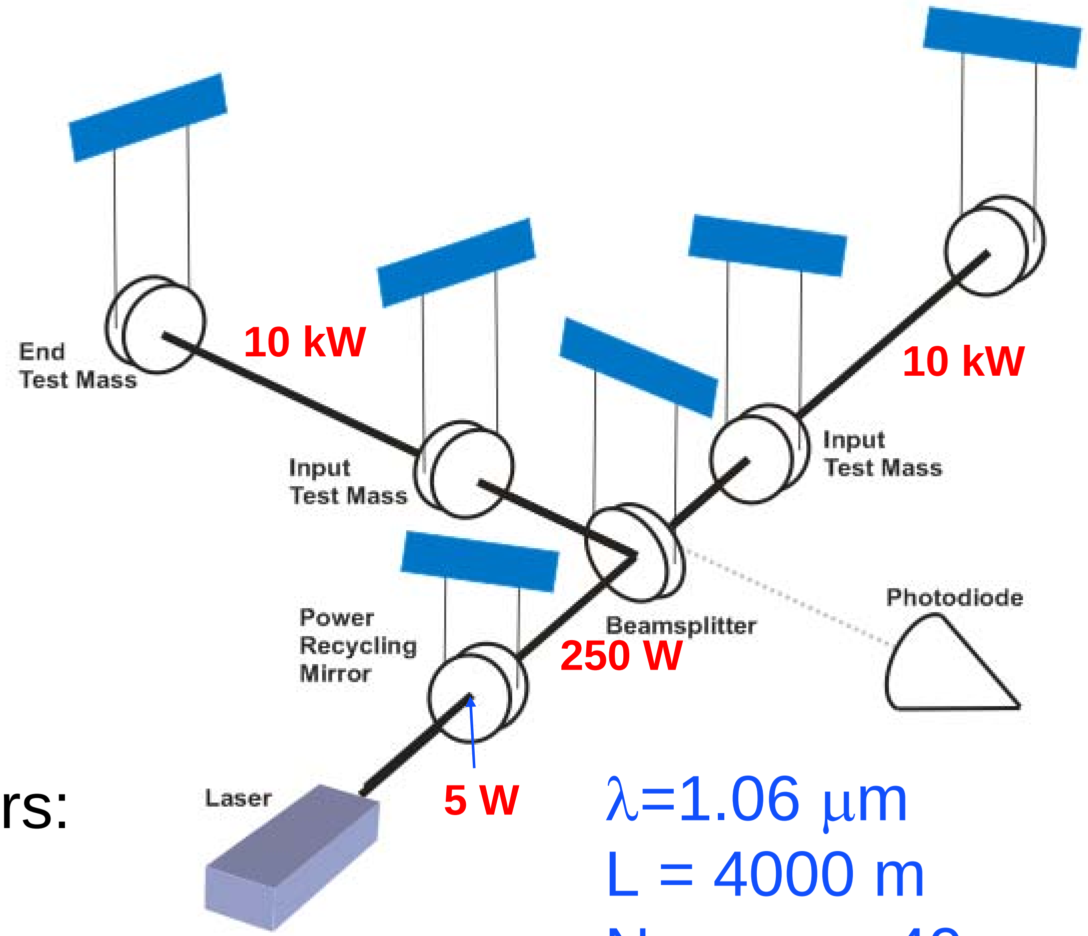
Fig. V-20. Proposed antenna.

Realistically, how sensitive can an interferometer be?

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

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

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



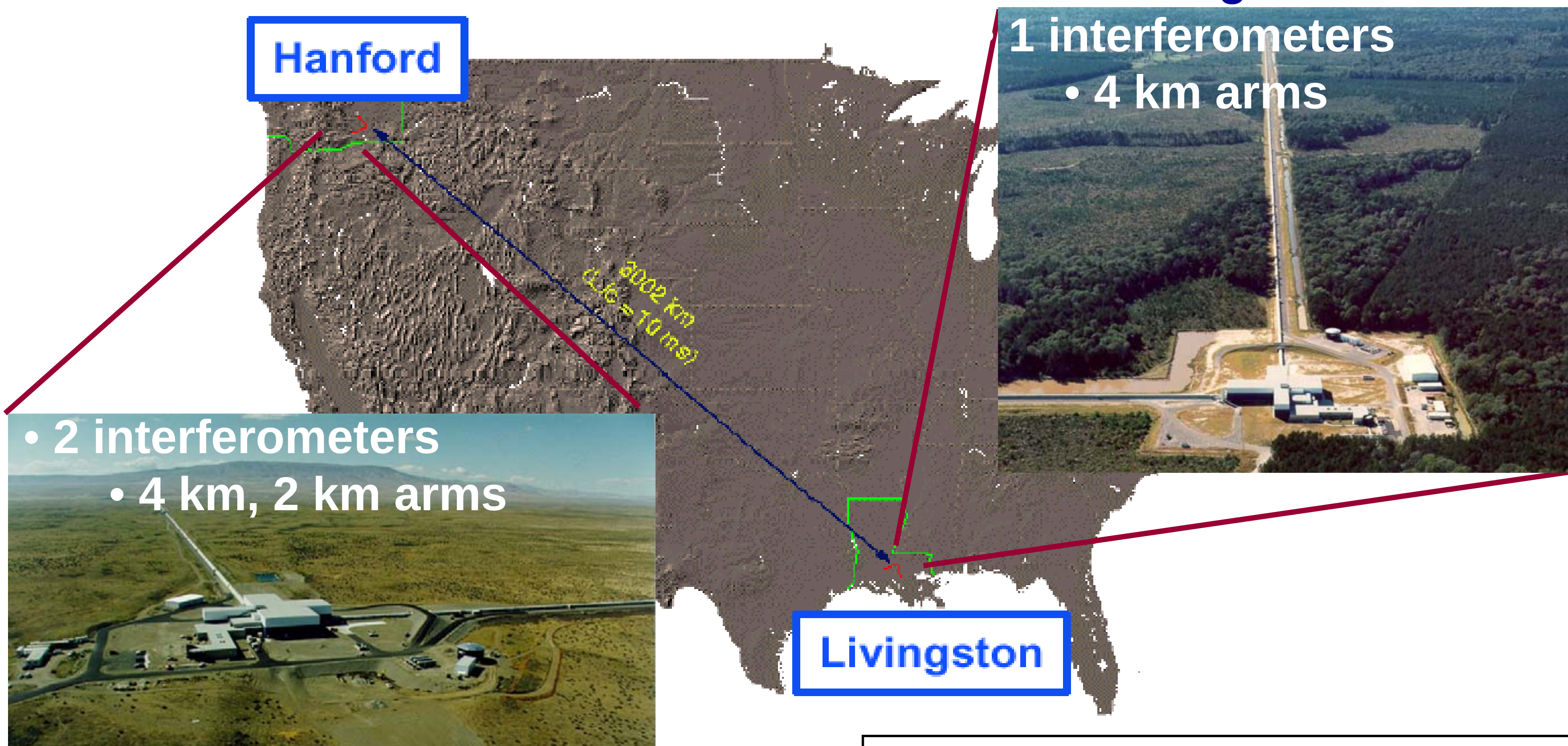
Putting in numbers:

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

λ=1.06 μm
L = 4000 m
$N_{roundtrip}$ = 40

LIGO sites

LIGO Livingston Observatory



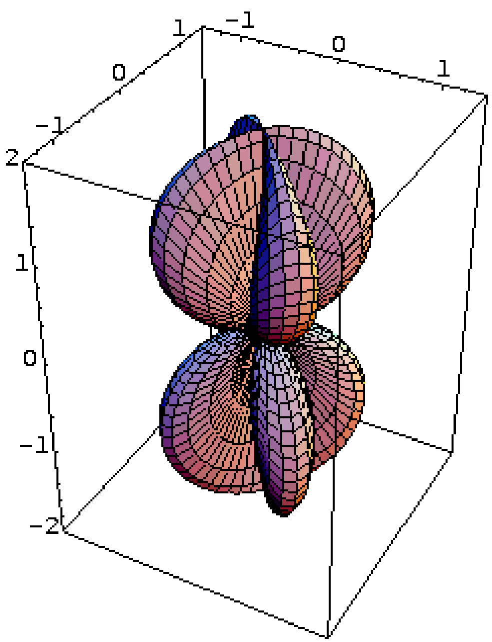
LIGO Hanford Observatory

LIGO Observatories are operated by Caltech and MIT

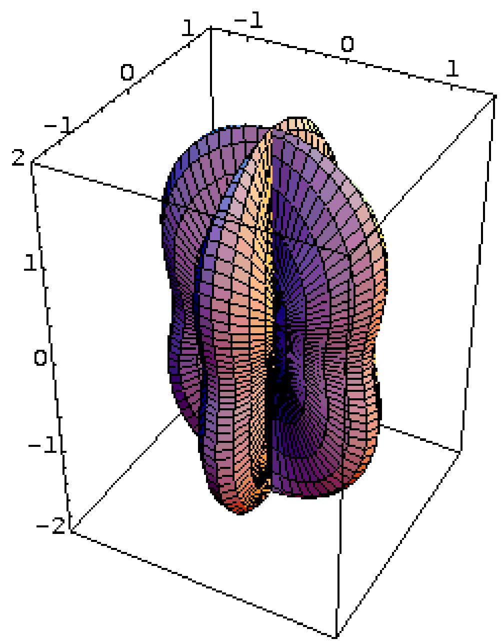
An interferometer is really a microphone

- Sensitivity depends on propagation direction, polarization

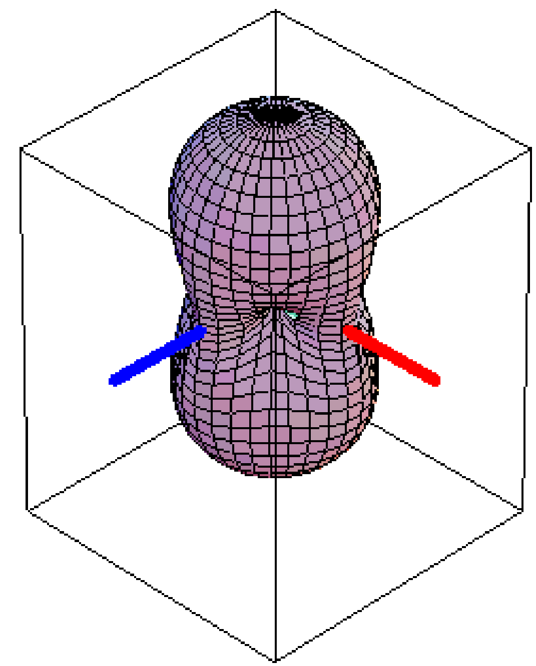
“×” polarization



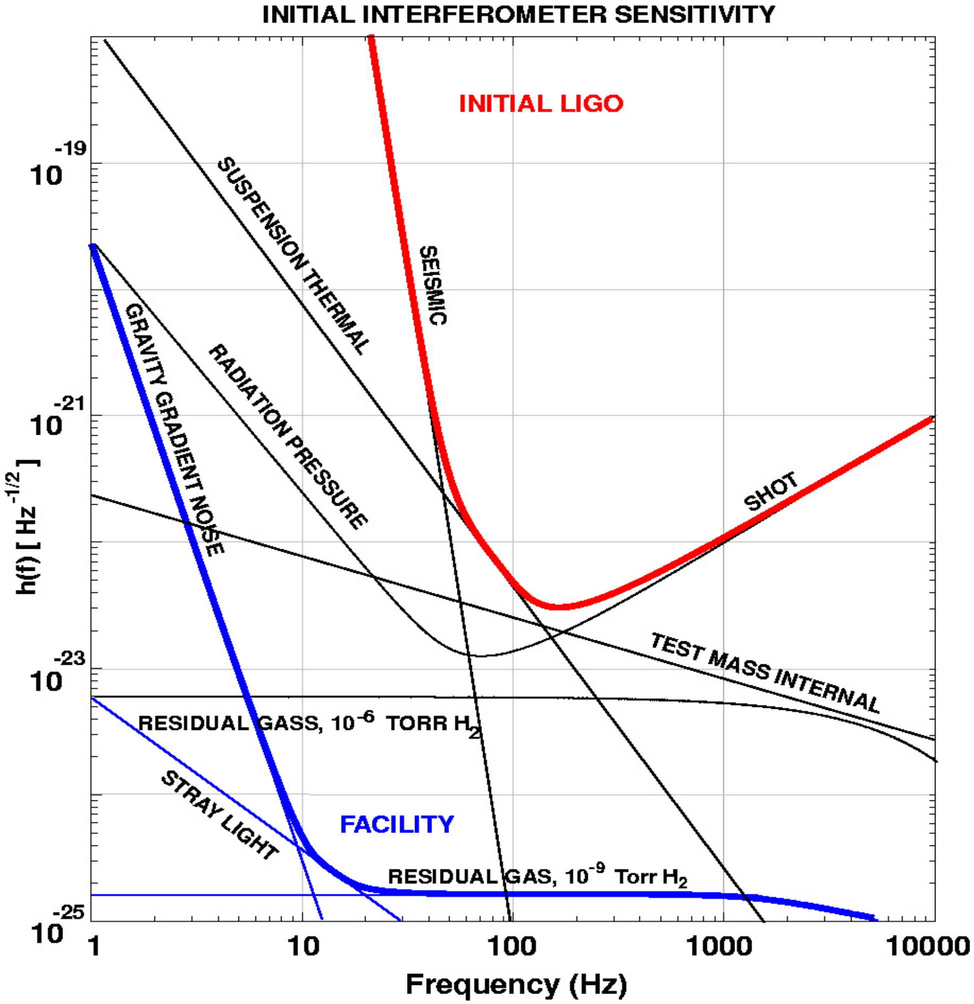
“+” polarization



RMS sensitivity

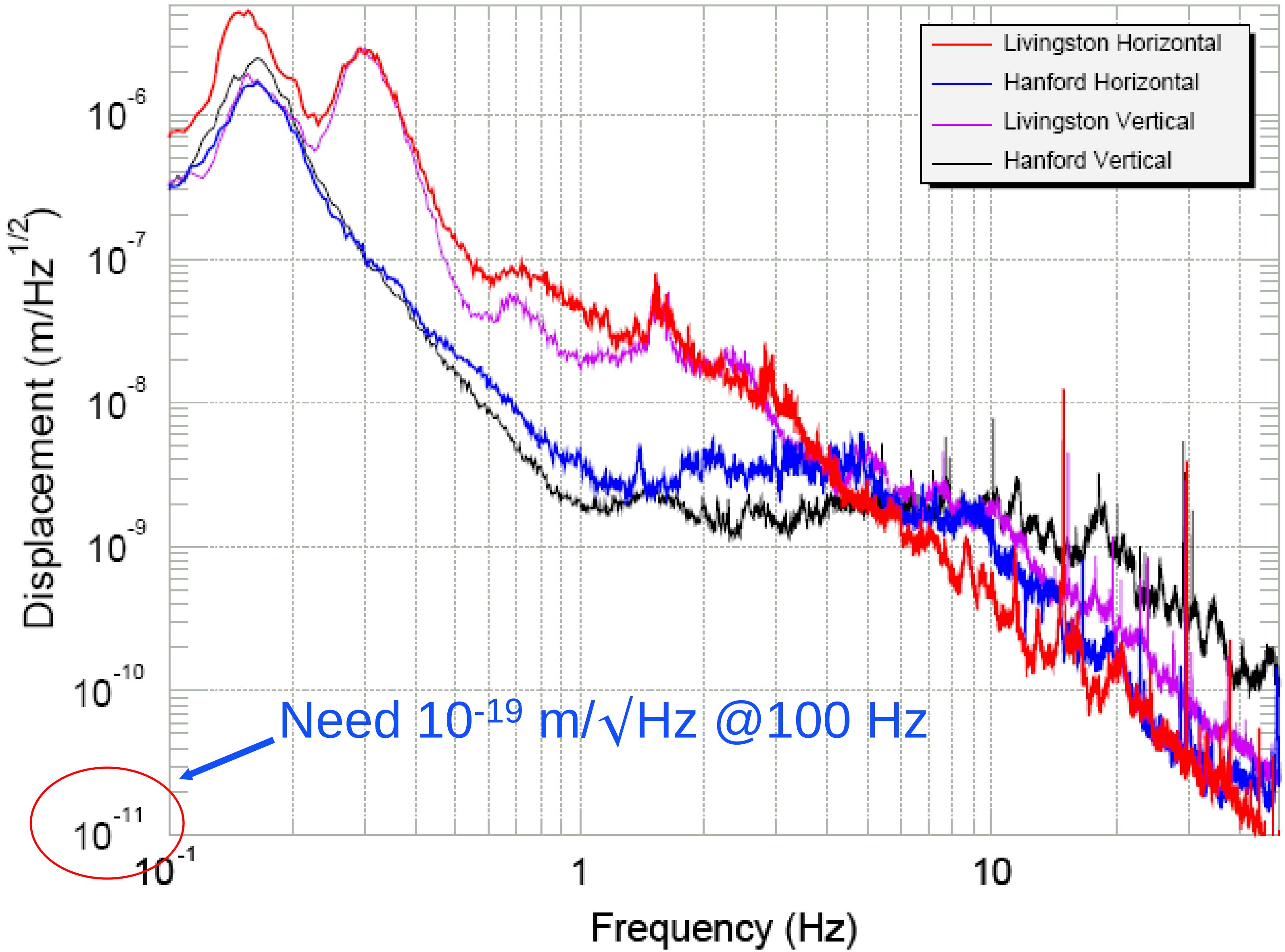


Fundamental noises in LIGO



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

Seismic noise



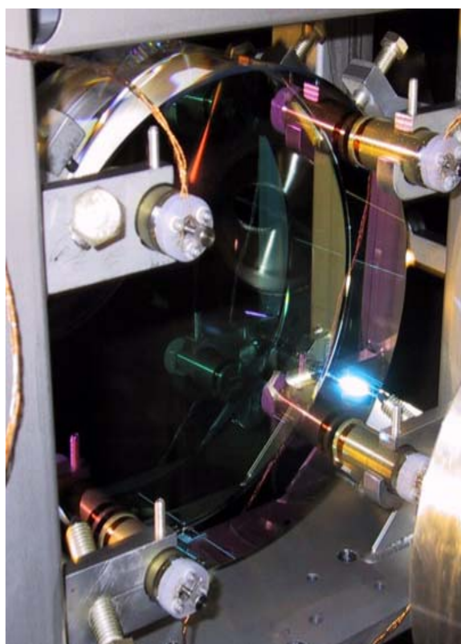
LIGO Vacuum Chambers

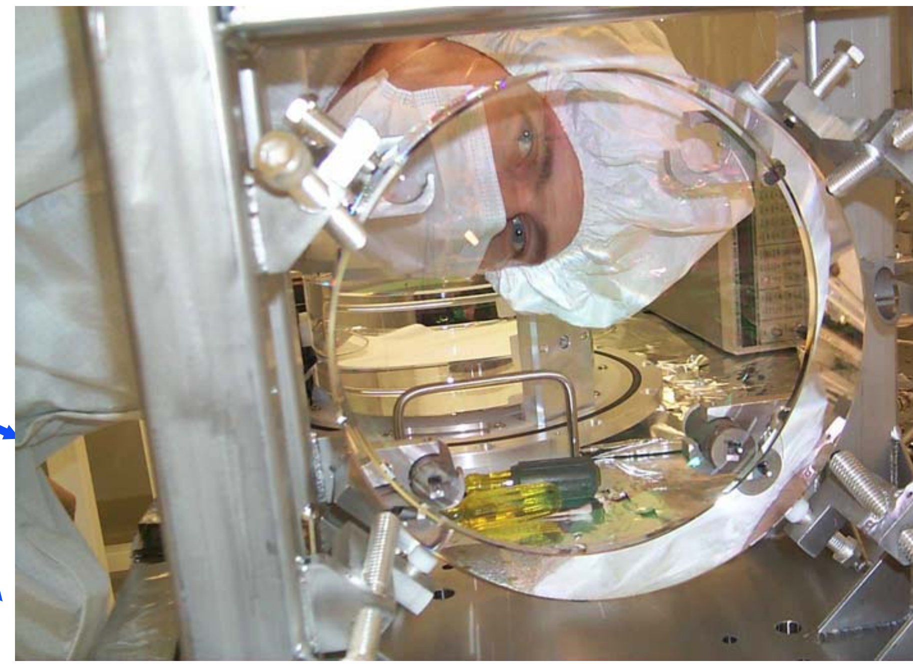
Suspended Mirrors

- mirrors are hung in a pendulum

  → ‘freely falling masses’

- provide 100x suppression above 1 Hz
- provide ultraprecise control of mirror displacement (< 1 pm)

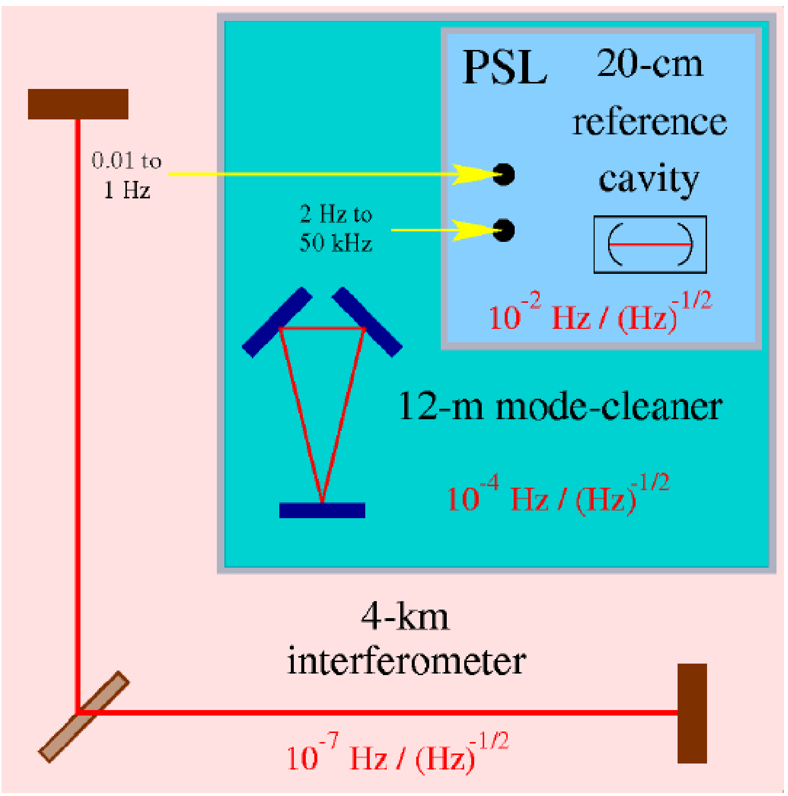


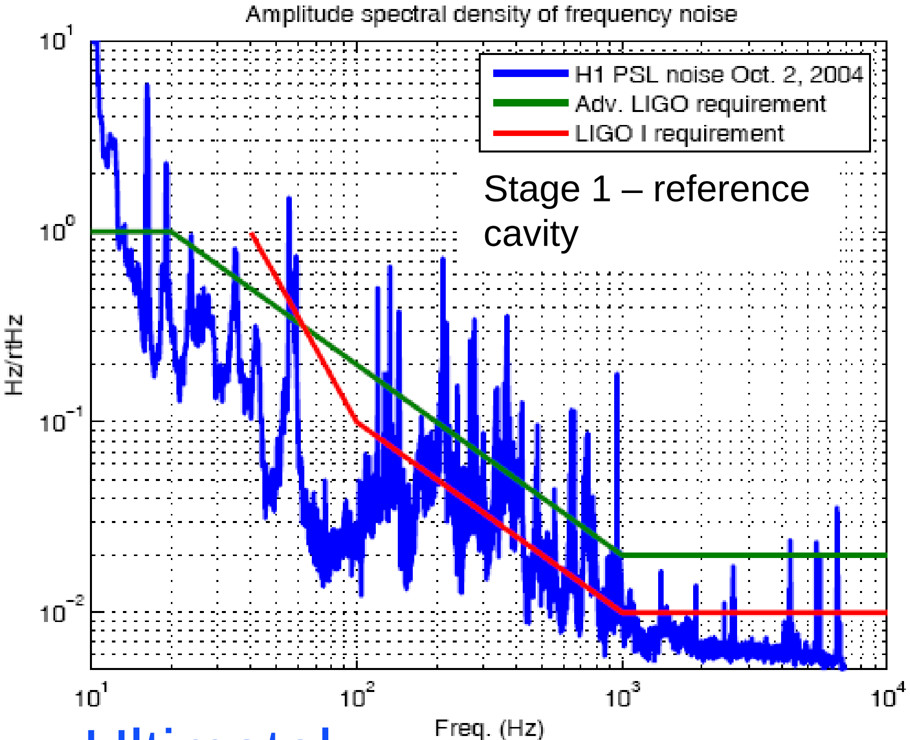


Frequency stabilization in LIGO

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

$\Delta f/f_0 = \Delta L/L_0$

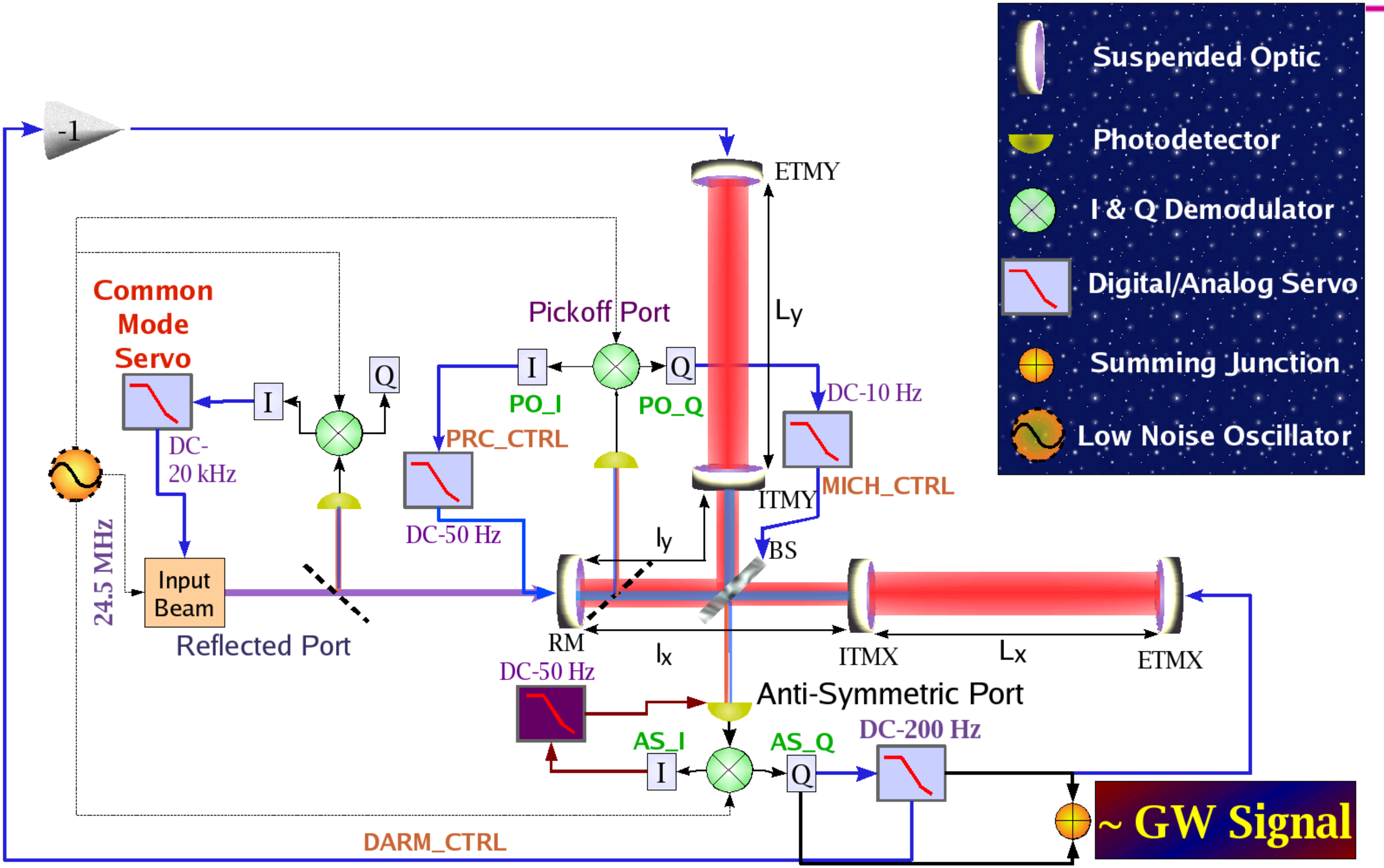




Ultimately:

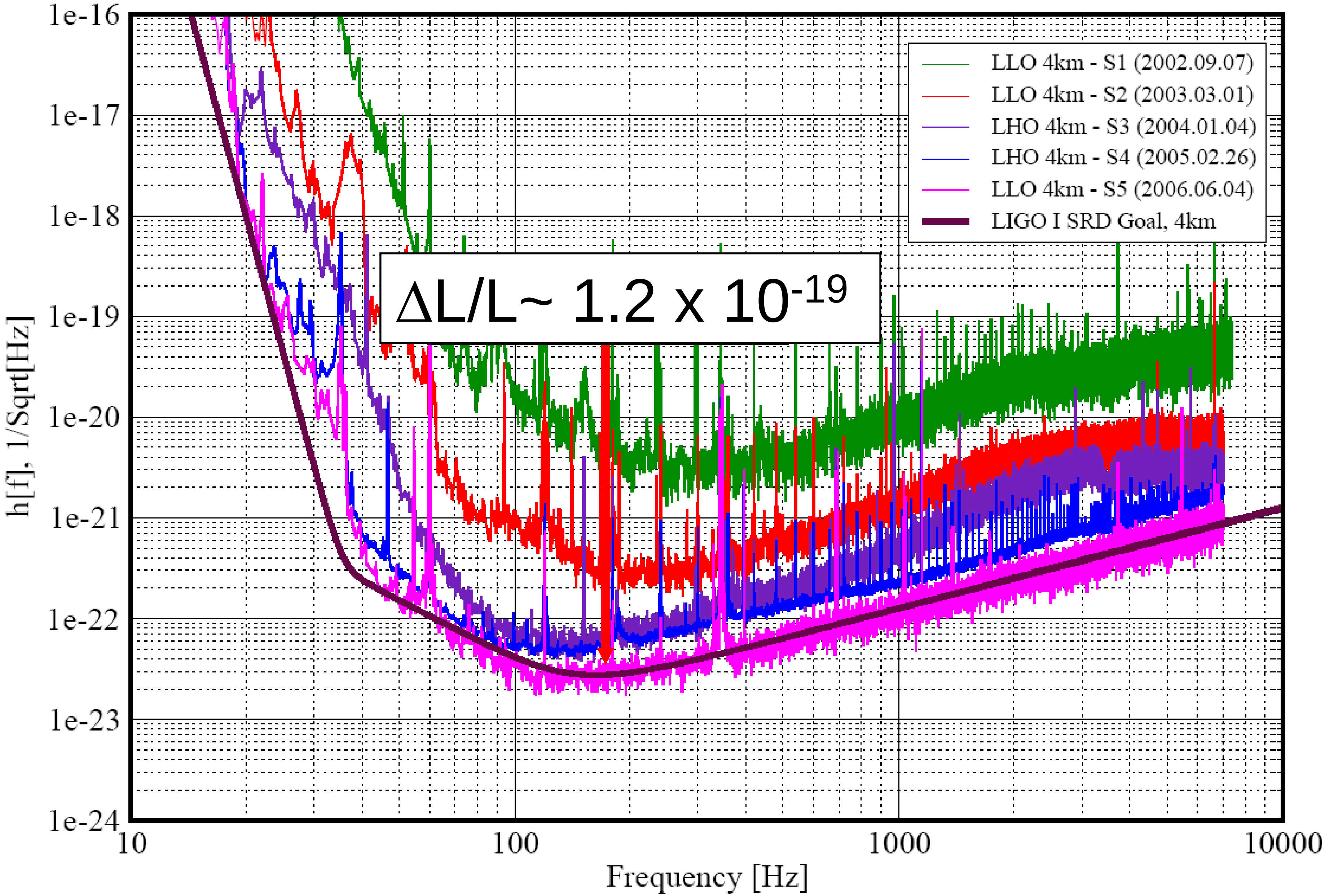
$\Delta f/f \sim 3 \times 10^{-22}$ @ 100 Hz

Length readout and control



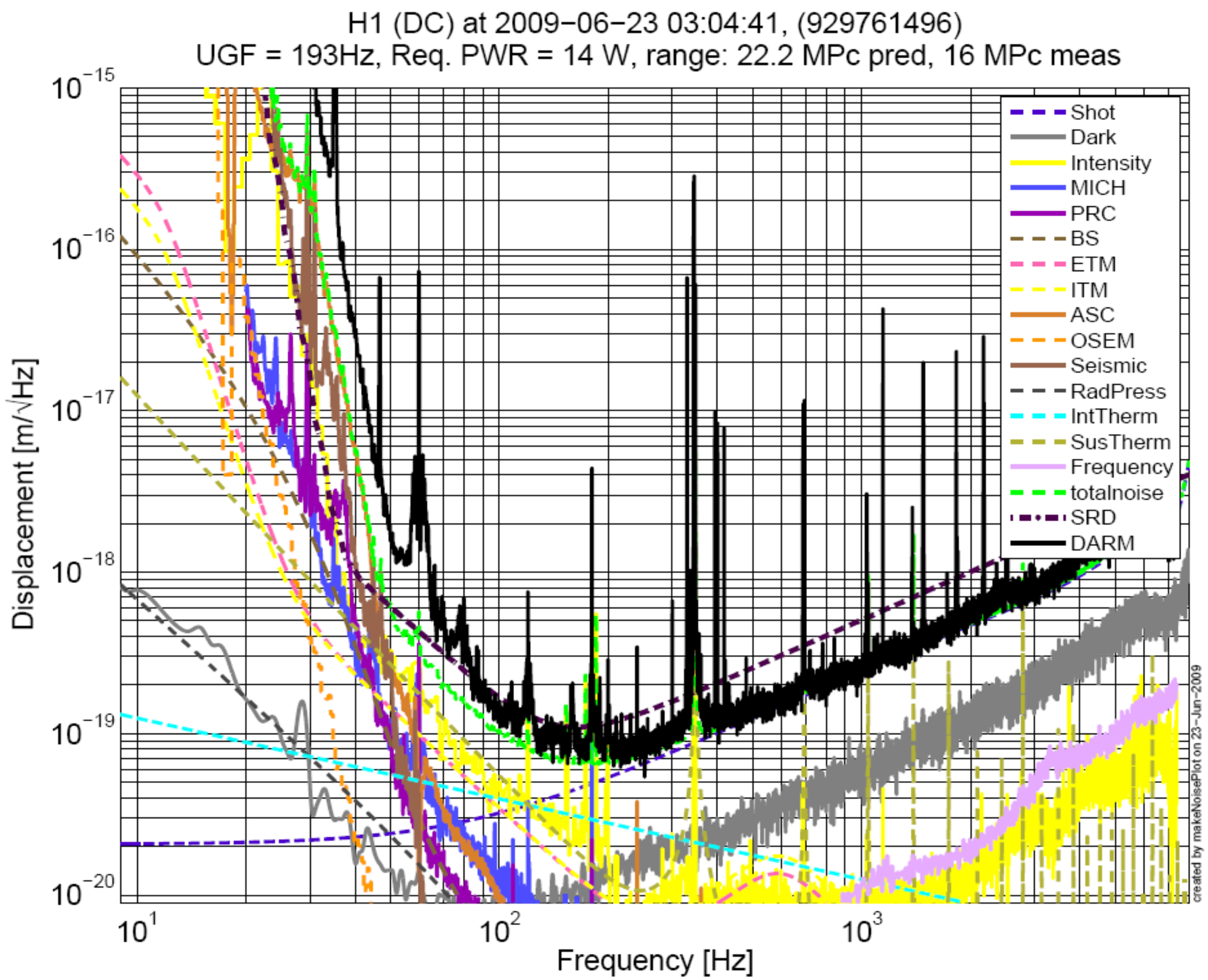
Best Strain Sensitivities for the LIGO Interferometers

Comparisons among S1 - S5 Runs   LIGO-G060009-02-Z

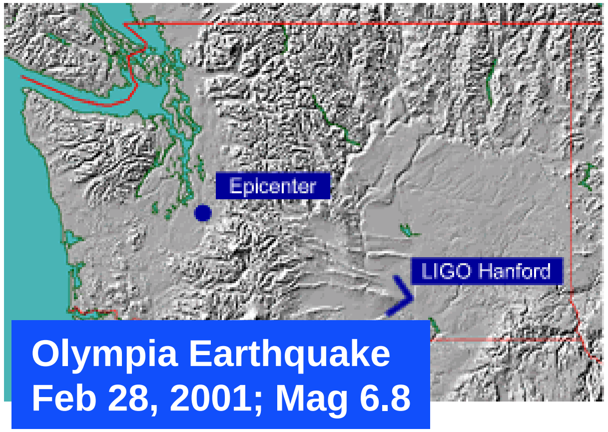


Enhanced LIGO

- Improved sensitivity over initial LIGO
- New readout scheme
  - » DC (homodyne)
  - » Suspended output mode cleaner + seismic isolation
  - » In-vacuum detection diodes
- Higher laser power → 35 W
  - » New Input Optics Upgraded thermal compensation system
- New magnets, better electronics, a few other fixes
- Science Run S6 began July 7
  - » Will go through late 2010



Nature can be a problem…

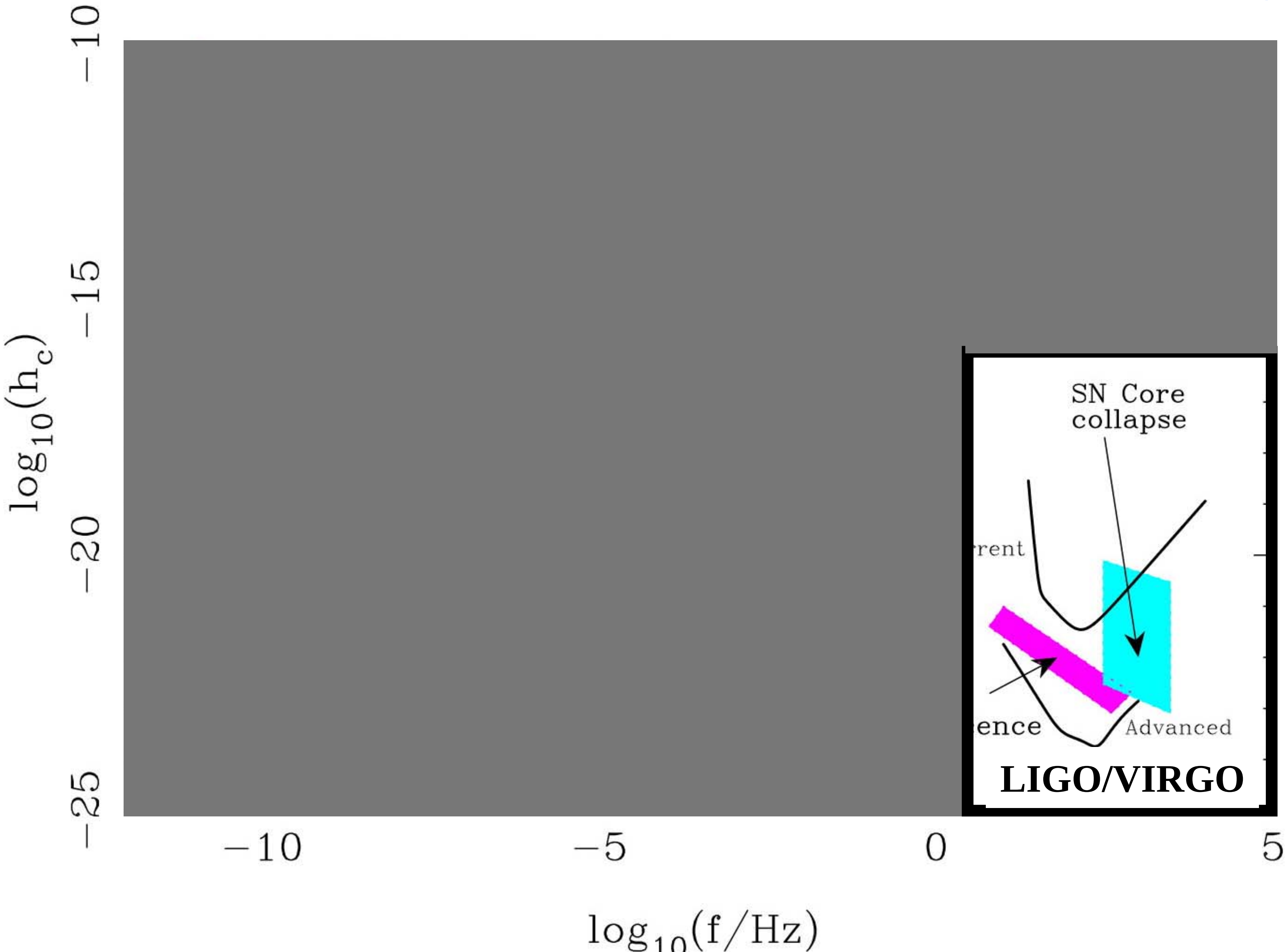


UF FLORIDA

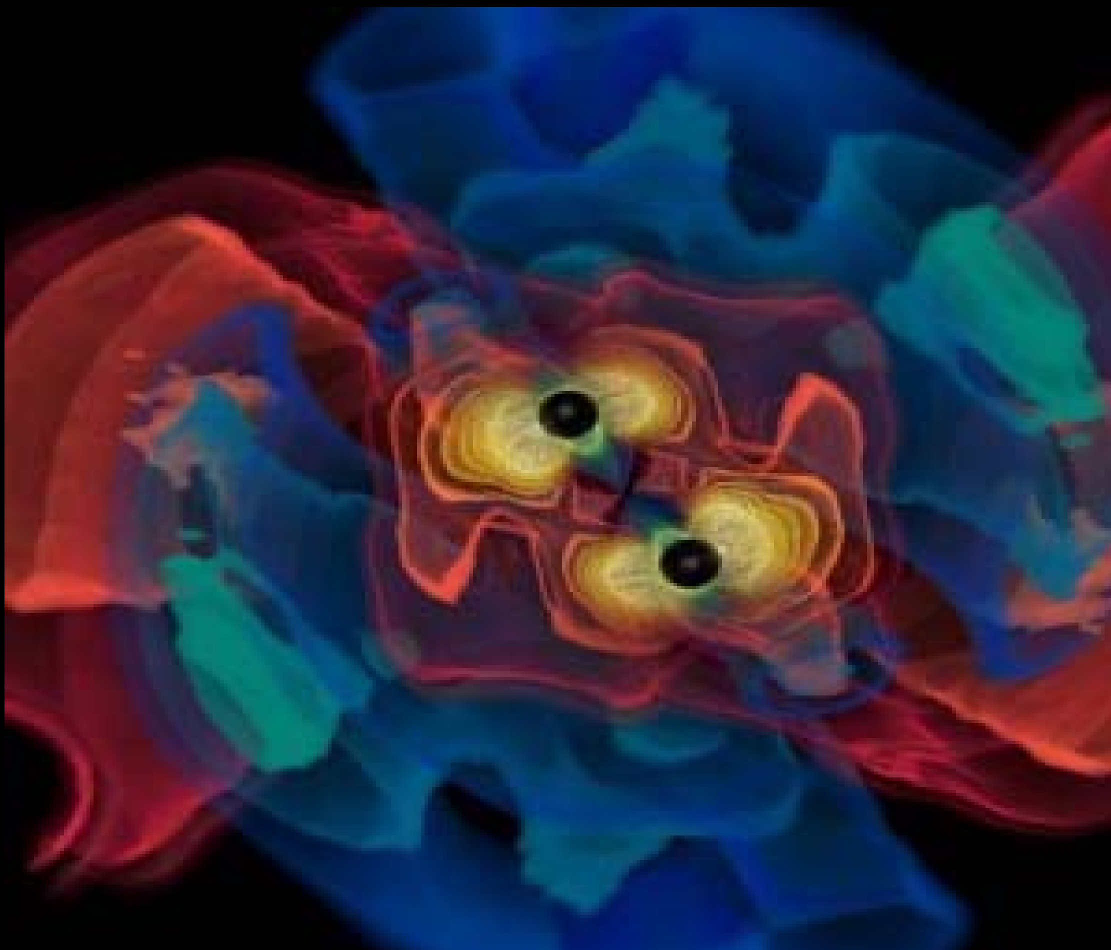
As can cars…

The Gravitational Wave Spectrum

Dick Manchester, CSIRO



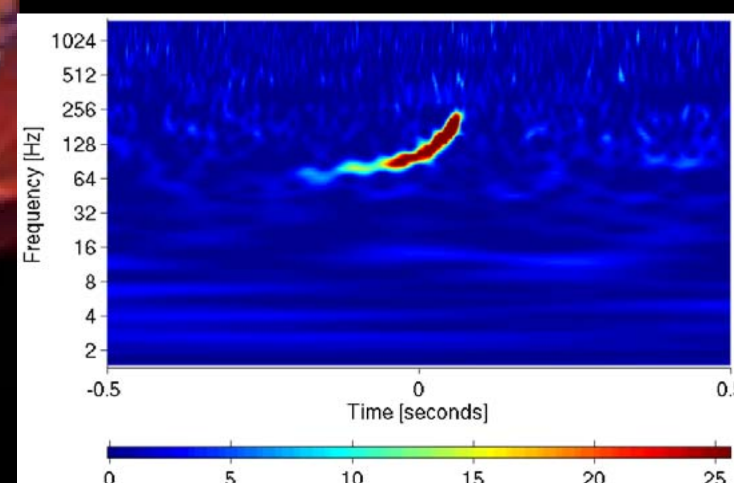
The astrophysical gravitational wave source catalog



Credit: AEI, CCT, LSU

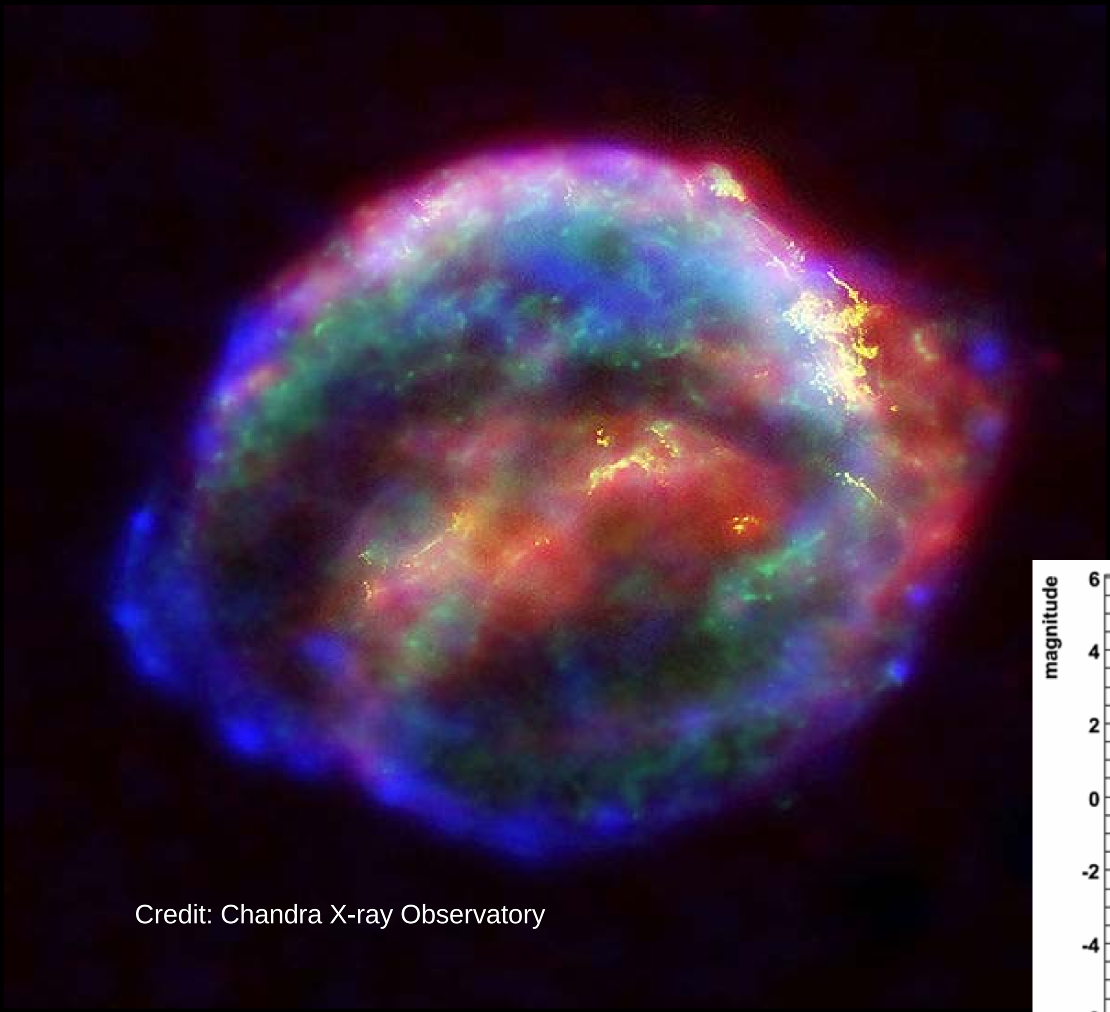
Coalescing Binary Systems

- Neutron stars, black holes
- ‘chirped’ waveform



http://www.ligo.org/science/GW-Overview/sounds/chirp40-1300Hz.wav

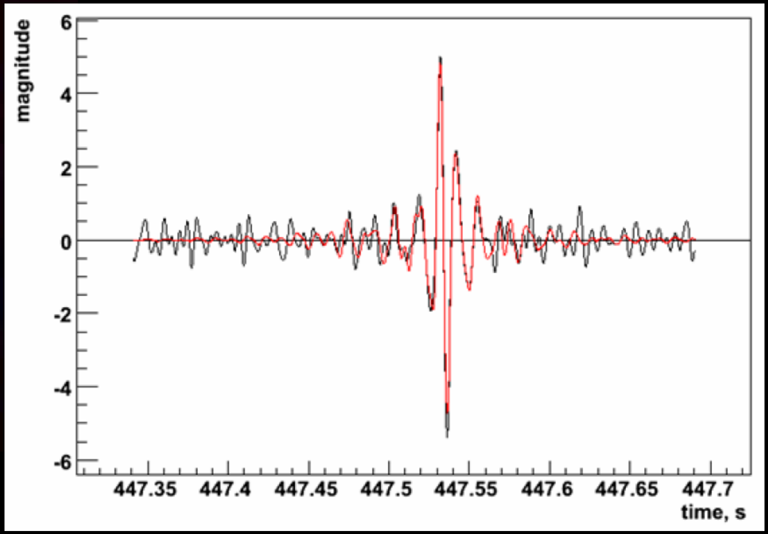
The astrophysical gravitational wave source catalog



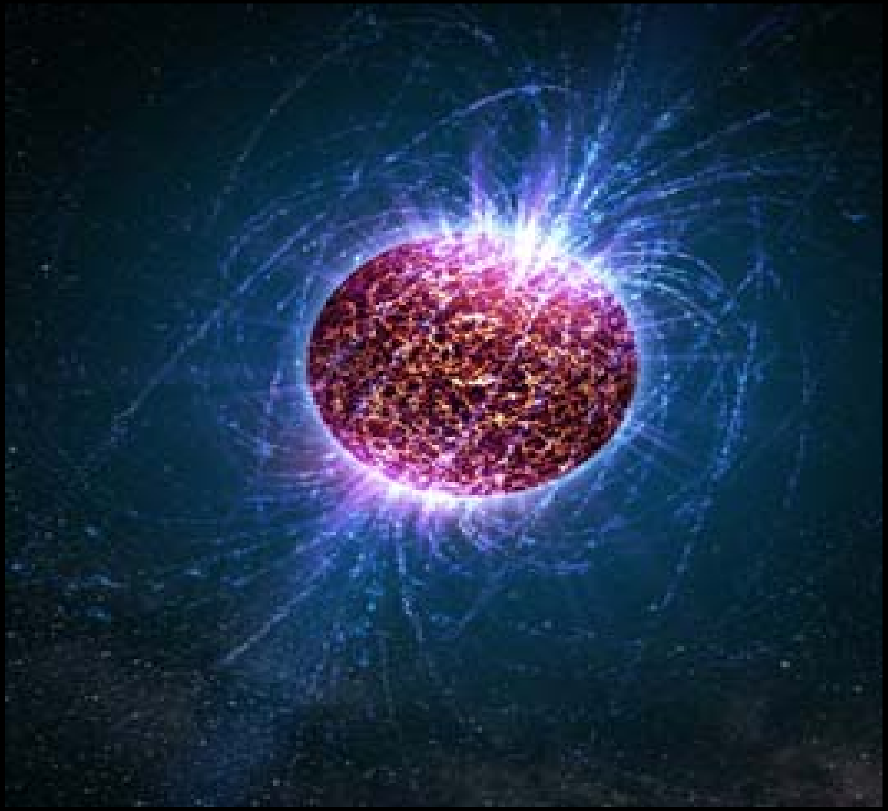
Credit: Chandra X-ray Observatory

'Bursts'

- asymmetric core collapse supernovae
- cosmic strings
- ???? (sources we haven't thought about)



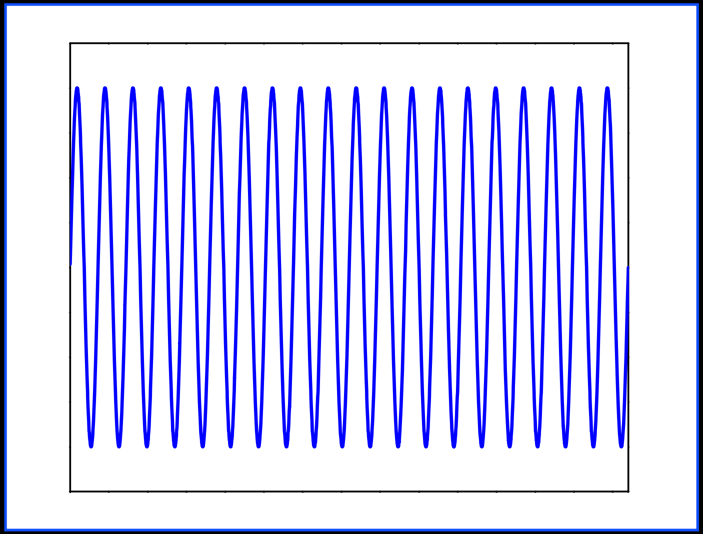
The astrophysical gravitational wave source catalog



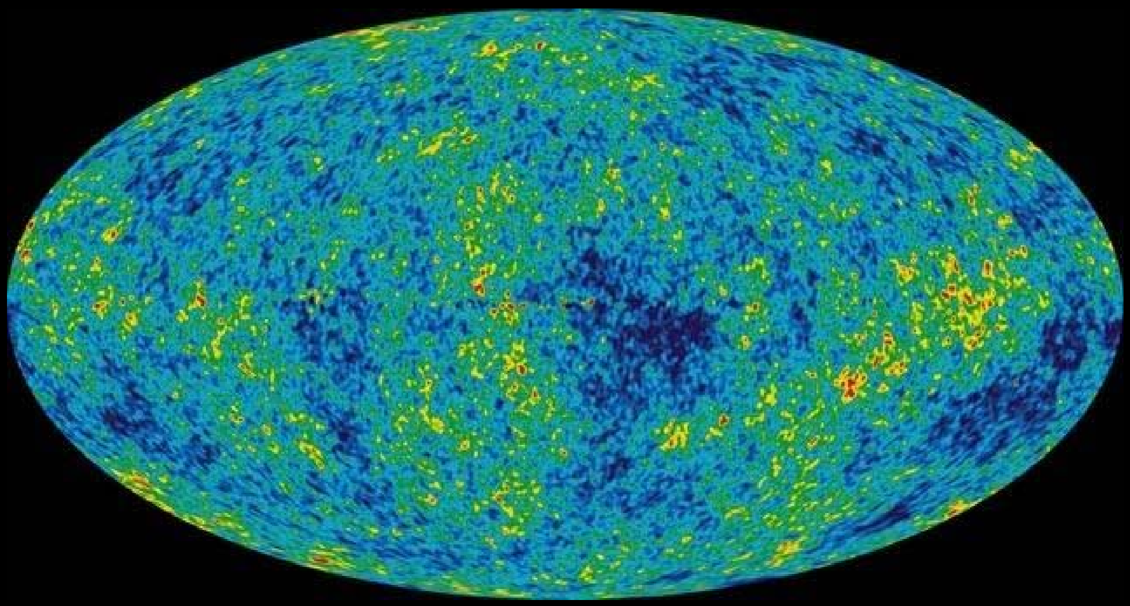
Casey Reed, Penn State

Continuous Sources

- Spinning neutron stars
- monotone waveform



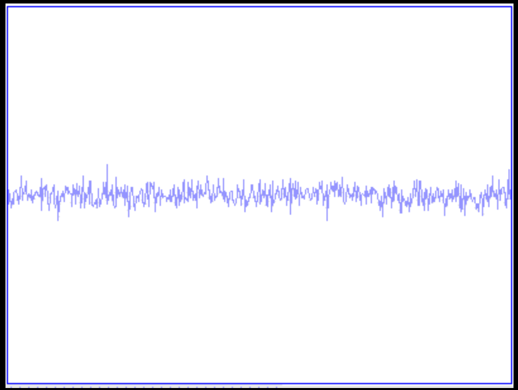
The astrophysical gravitational wave source catalog



NASA/WMAP Science Team

Cosmic GW background

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



Has LIGO detected a gravitational wave yet?

- No, not yet.
- When will LIGO detect a gravitational wave?
- "Predictions are difficult, especially about the future" (Yogi Berra)

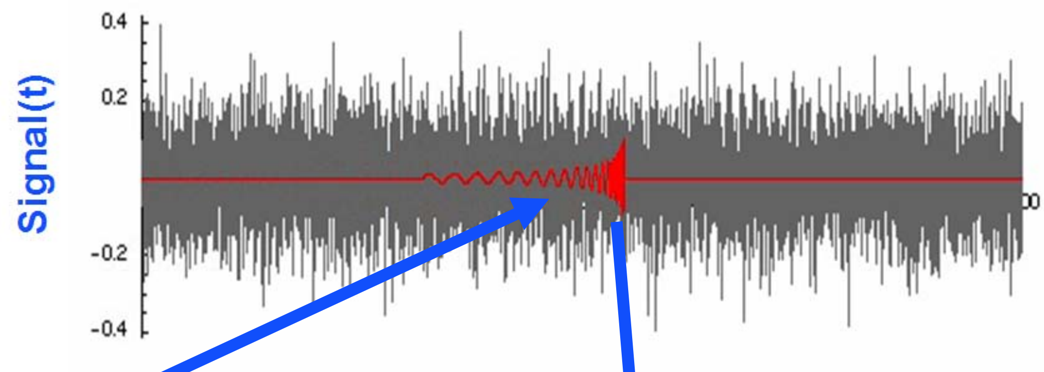
TABLE V: Detection rates for compact binary coalescence sources.

IFO	Source	$\dot{N}_{\rm low}$ yr^{-1}	$\dot{N}_{\rm re}$ yr^{-1}	$\dot{N}_{\rm pl}$ yr^{-1}	$\dot{N}_{\rm up}$ yr^{-1}
Initial	NS-NS	2×10^{-4}	0.02	0.2	0.6
	NS-BH	7×10^{-5}	0.004	0.1	
	BH-BH	2×10^{-4}	0.007	0.5	
	IMRI into IMBH			< 0.001[b]	0.01[c]
	IMBH-IMBH			10^{-4}[d]	10^{-3}[e]
Advanced	NS-NS	0.4	40	400	1000
	NS-BH	0.2	10	300	
	BH-BH	0.4	20	1000	
	IMRI into IMBH			10[b]	300[c]
	IMBH-IMBH			0.1[d]	1[e]

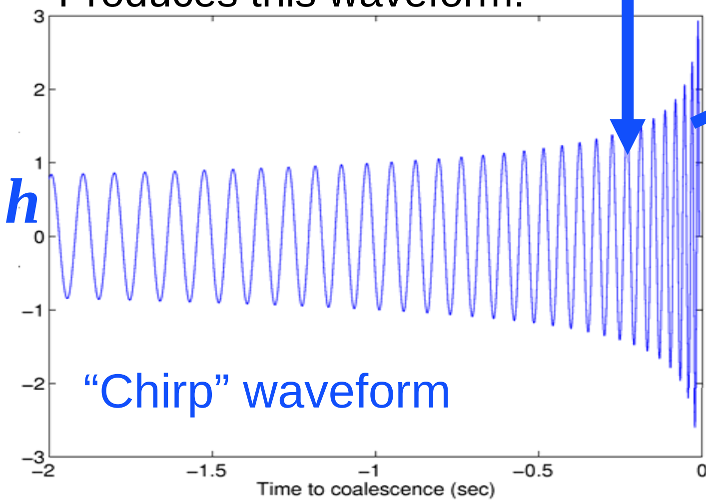
The challenge of LIGO data analysis

This source:

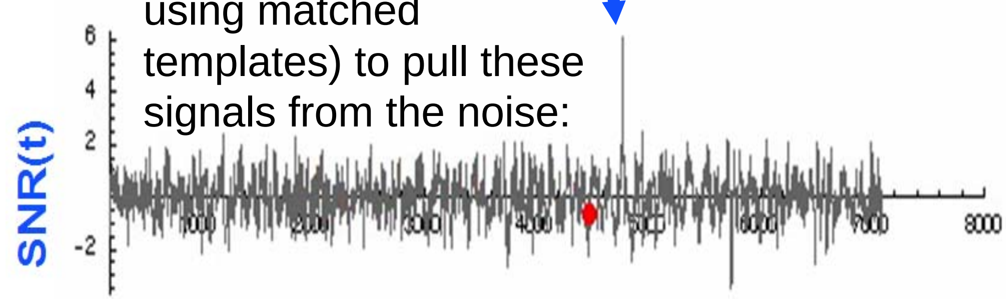
Embedded in this noise stream:



Produces this waveform:



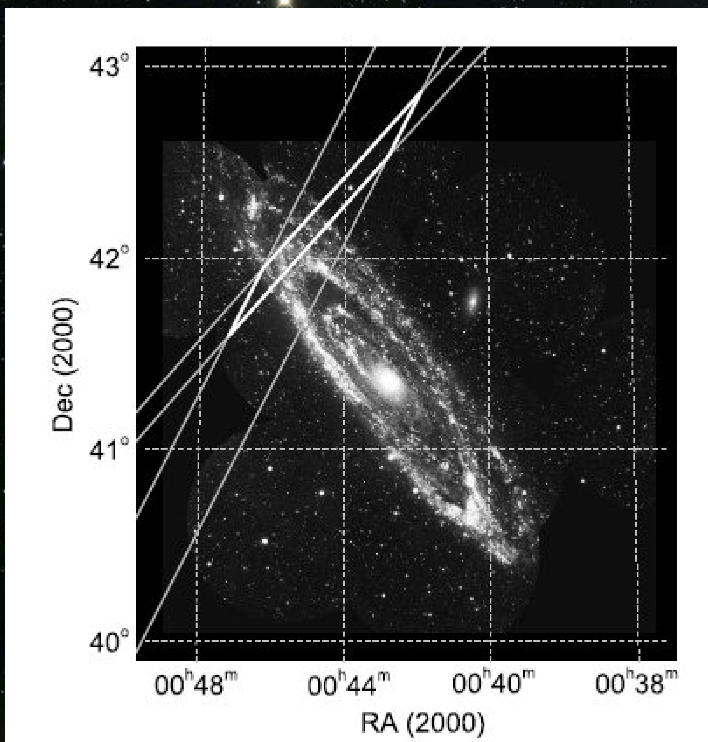
We use different methods (in this case optimal Weiner filtering using matched templates) to pull these signals from the noise:



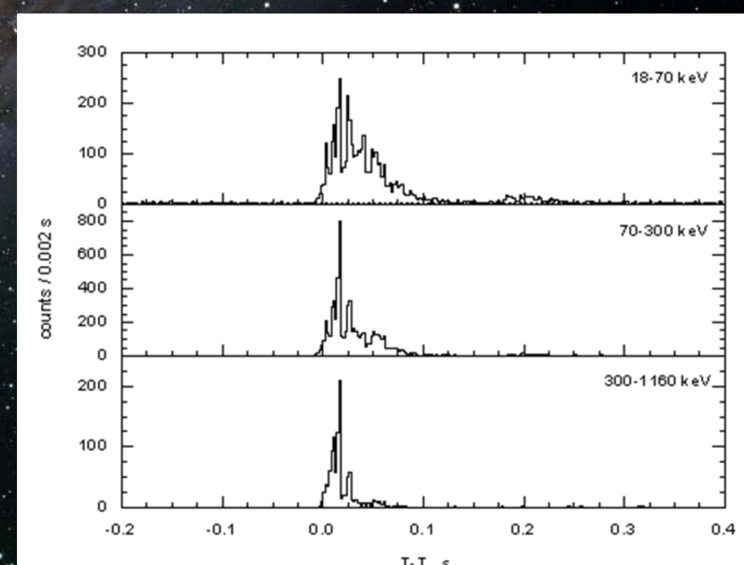
The problem is that non-astrophysical sources also produces signals (false positives)

GRB 070201

Refs:
GCN: http://gcn.gsfc.nasa.gov/gcn3/6103.gcn3



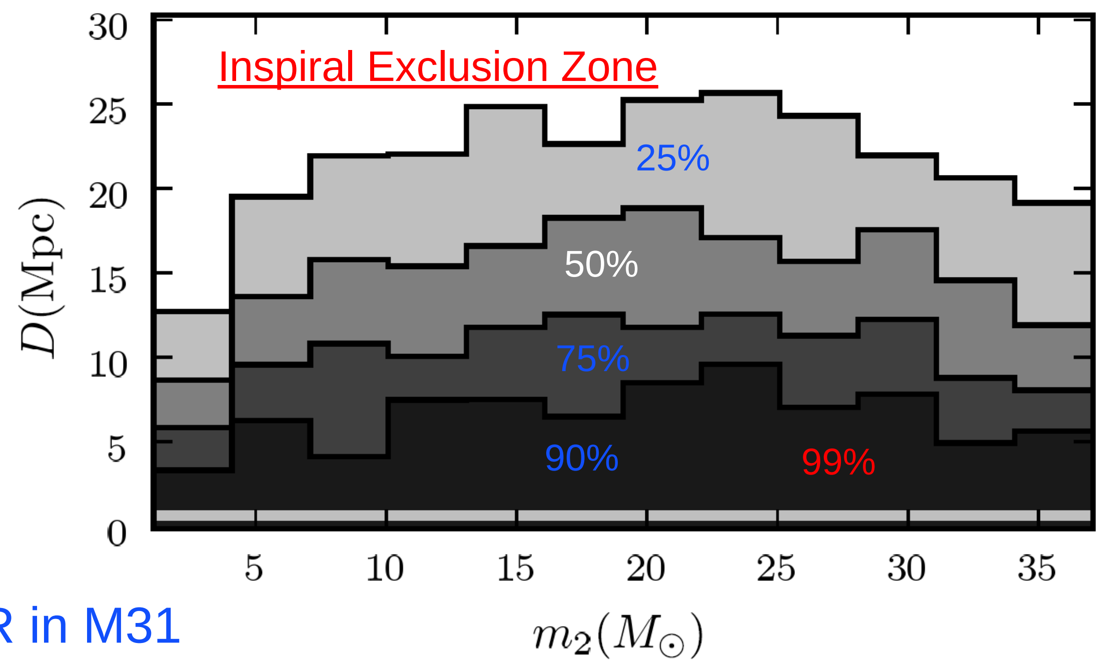
X-ray emission curves (IPN)



GRB070201:
Not a Binary Merger in M31!

Abbott, et al. "Implications for the Origin of GRB 070201 from LIGO Observations", Ap. J., 681:1419–1430 (2008).

- Inspiral (matched filter search:
  - Binary merger in M31 scenario excluded at >99% level
  - Exclusion of merger at larger distances



- Burst search:
  - Cannot exclude an SGR in M31
    - SGR in M31 is the current best explanation for this emission
  - Upper limit: 8×10^{50} ergs (4×10^{-4} $M_\odot c^2$) (emitted within 100 ms for isotropic emission of energy in GW at M31 distance)

The stochastic GW background

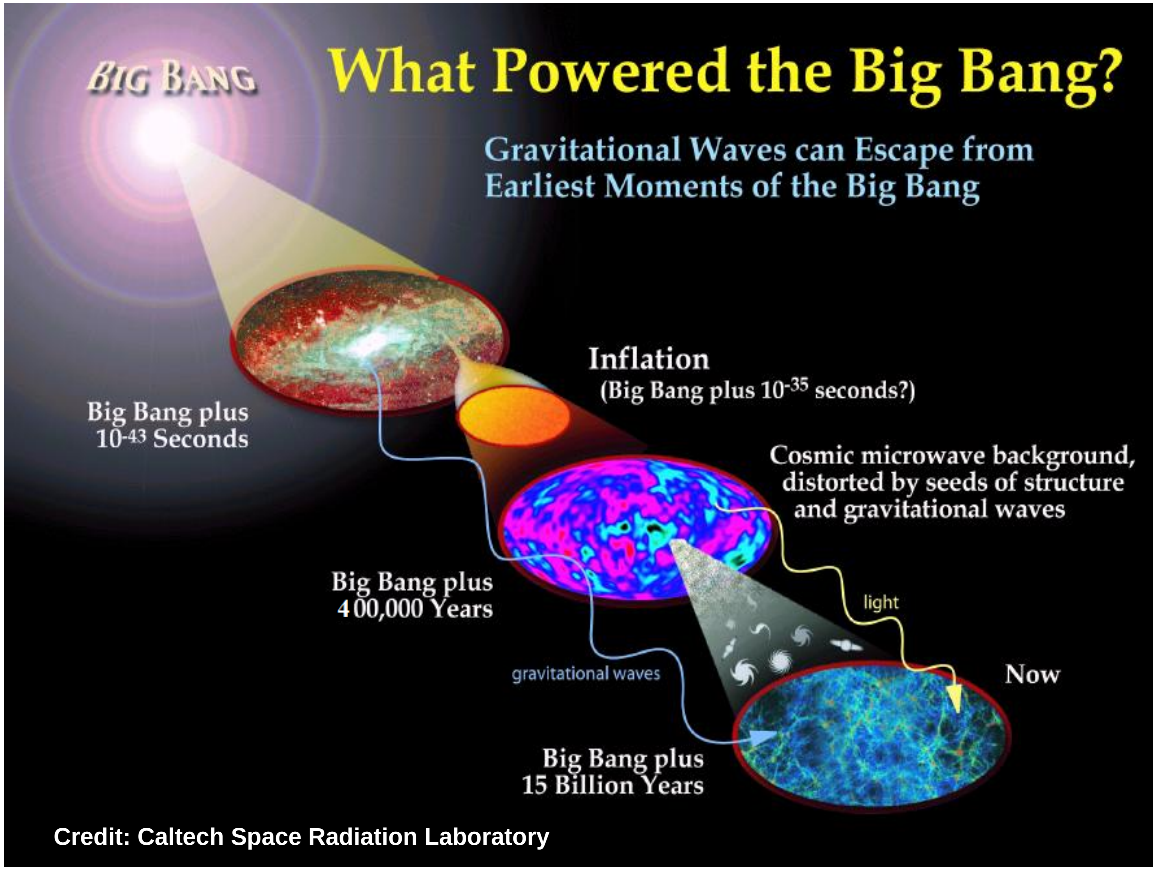
- An isotropic Stochastic GW background could come from:
  - » Primordial universe (inflation)
  - » Incoherent sum of point emitters isotropically distributed over the sky
- Expressed a fraction of closure density of the universe:

$$\Omega_{GW}(f) = \frac{1}{\rho_c} \frac{d\rho_{GW}(f)}{d\ln f}$$

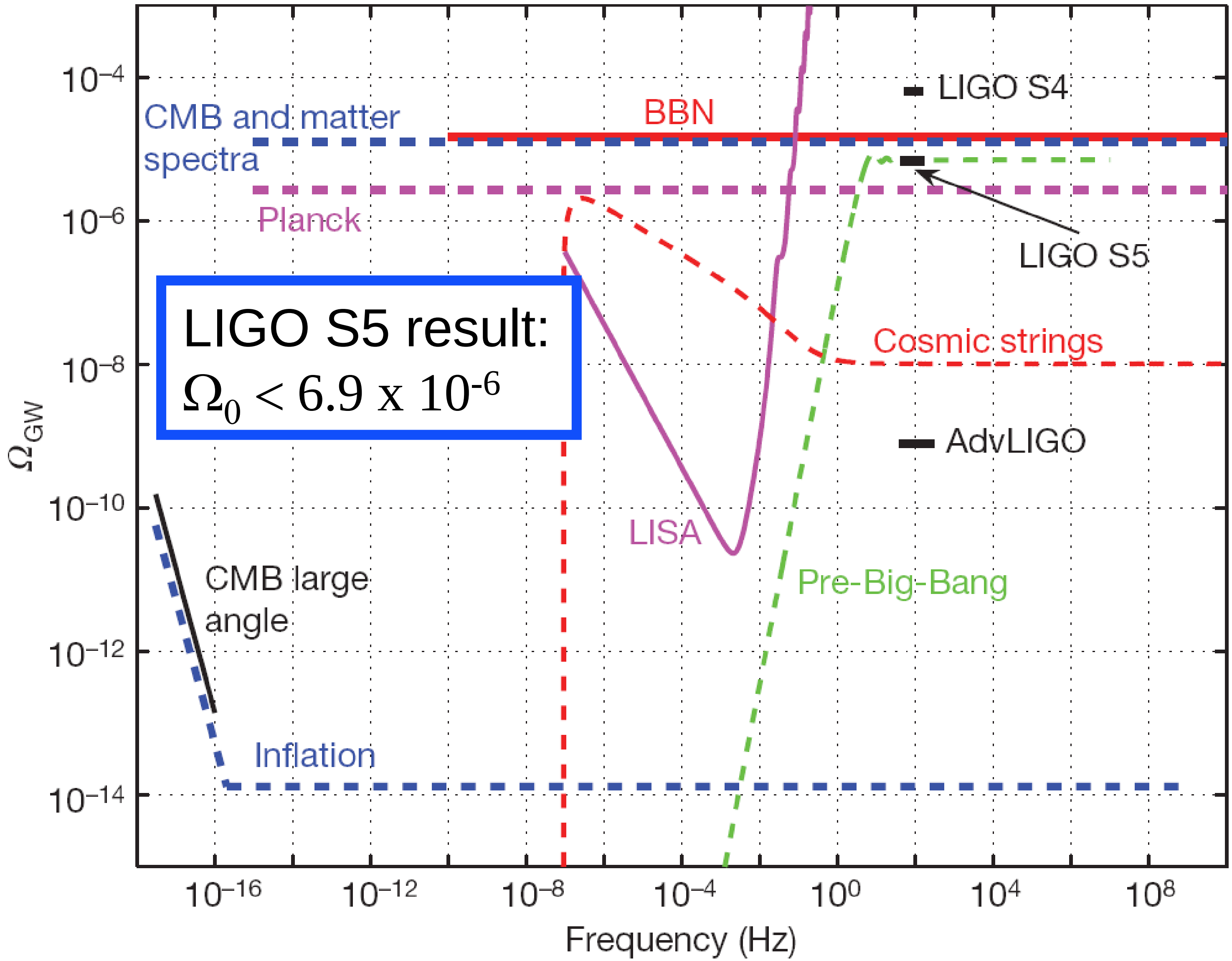
$$\int \Omega_{GW}(f)\, d(\ln f) = \frac{\rho_{GW}}{\rho_c} \equiv \Omega_0$$

- Big Bang Nucleosynthesis limit:

$$\Omega_{0,\,BBN} < 1.1 \times 10^{-5}$$



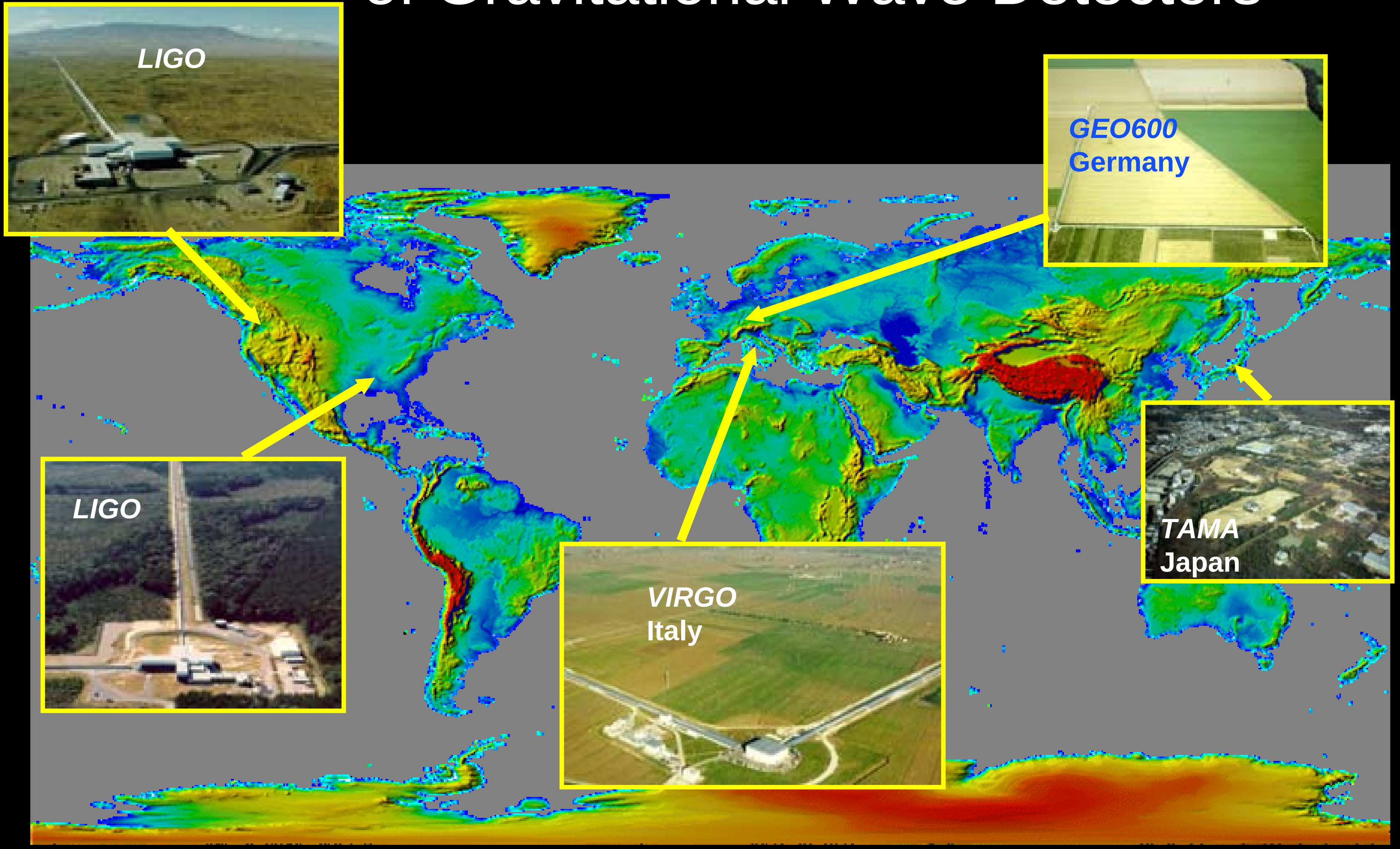
Abbott, et al. "*An upper limit on the stochastic gravitational-wave background of cosmological origin*", Nature., V460: 990 (2009).

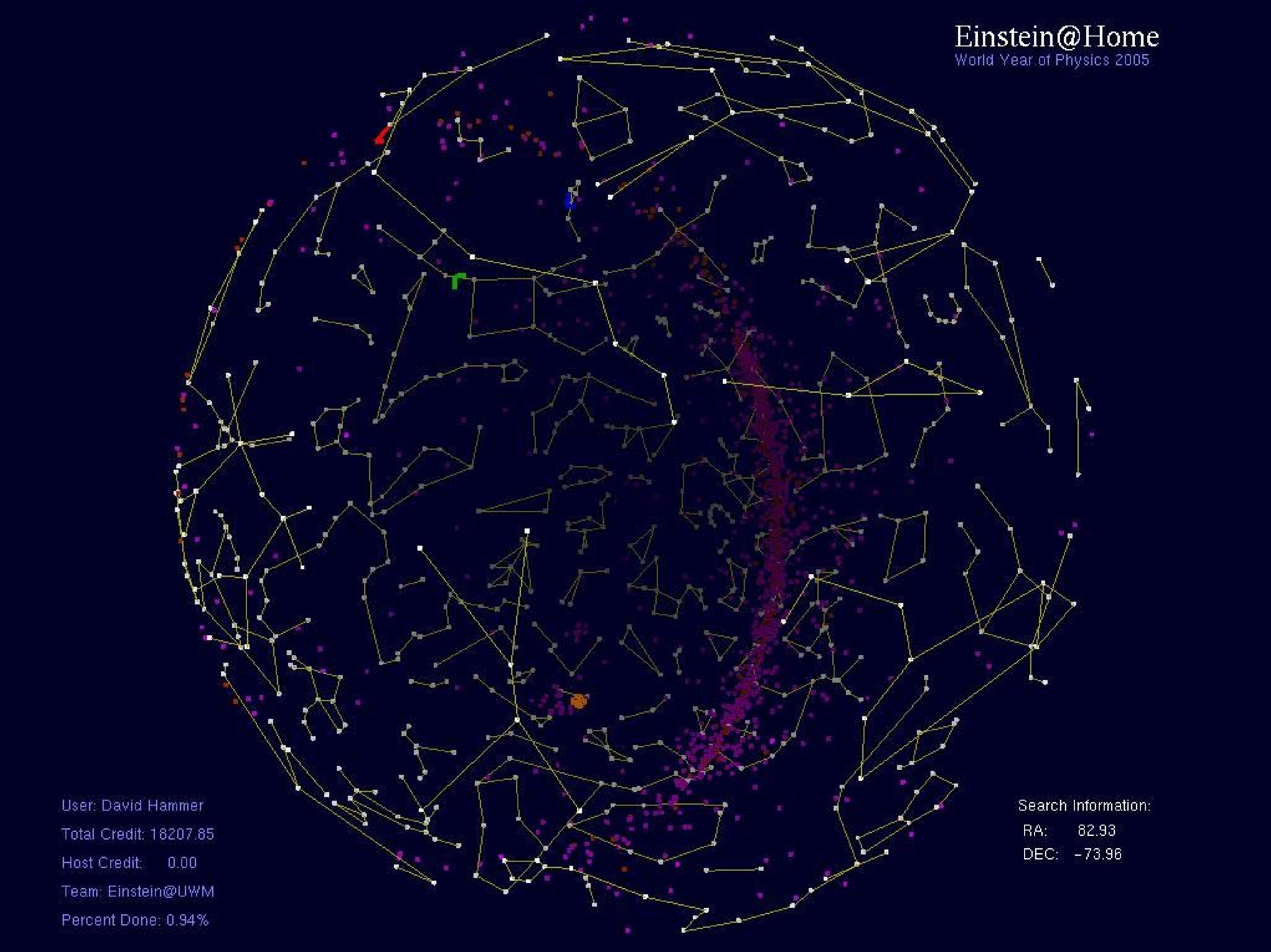


LIGO S5 result:

$\Omega_0 < 6.9 \times 10^{-6}$

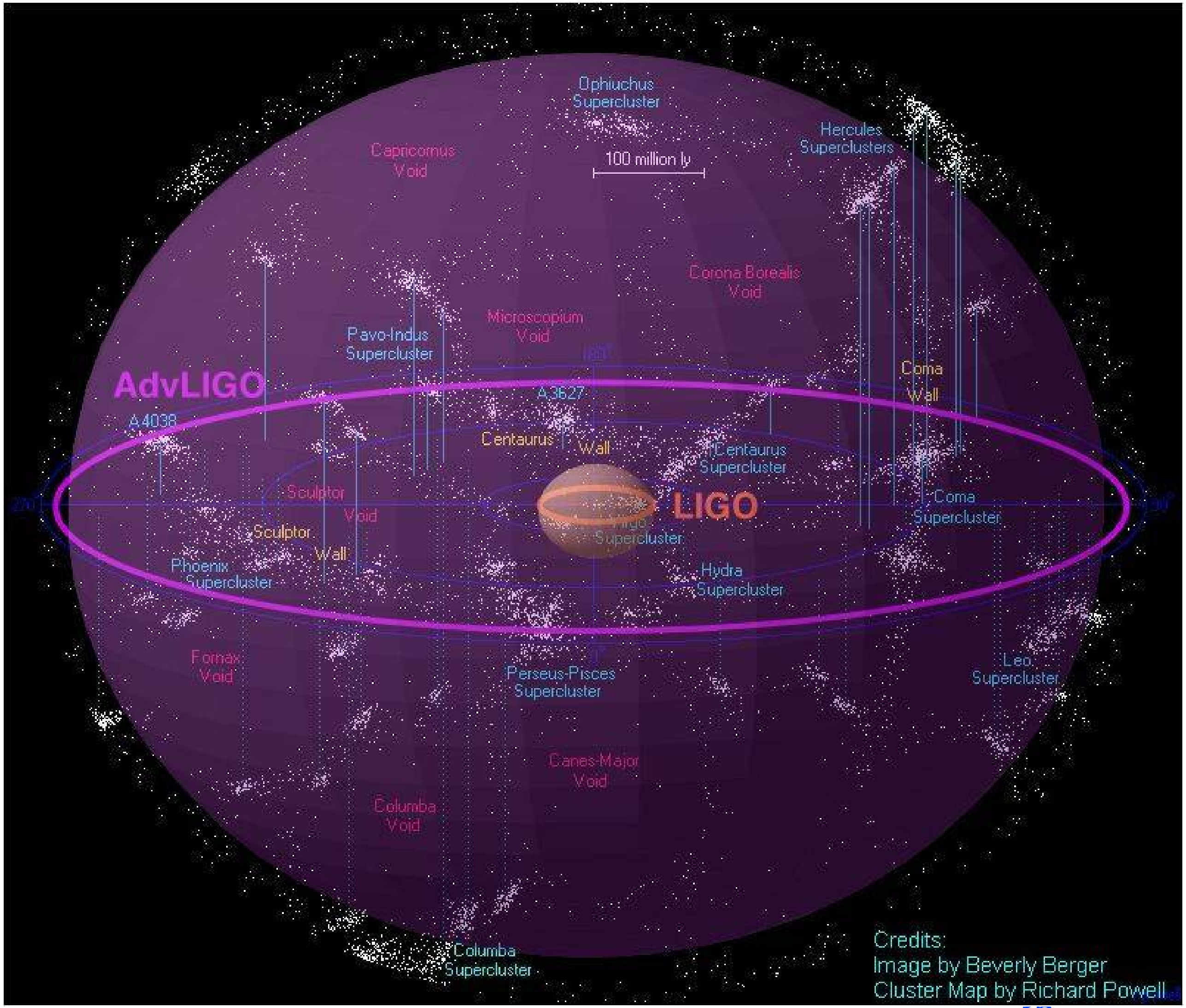
The Global Network
of Gravitational Wave Detectors



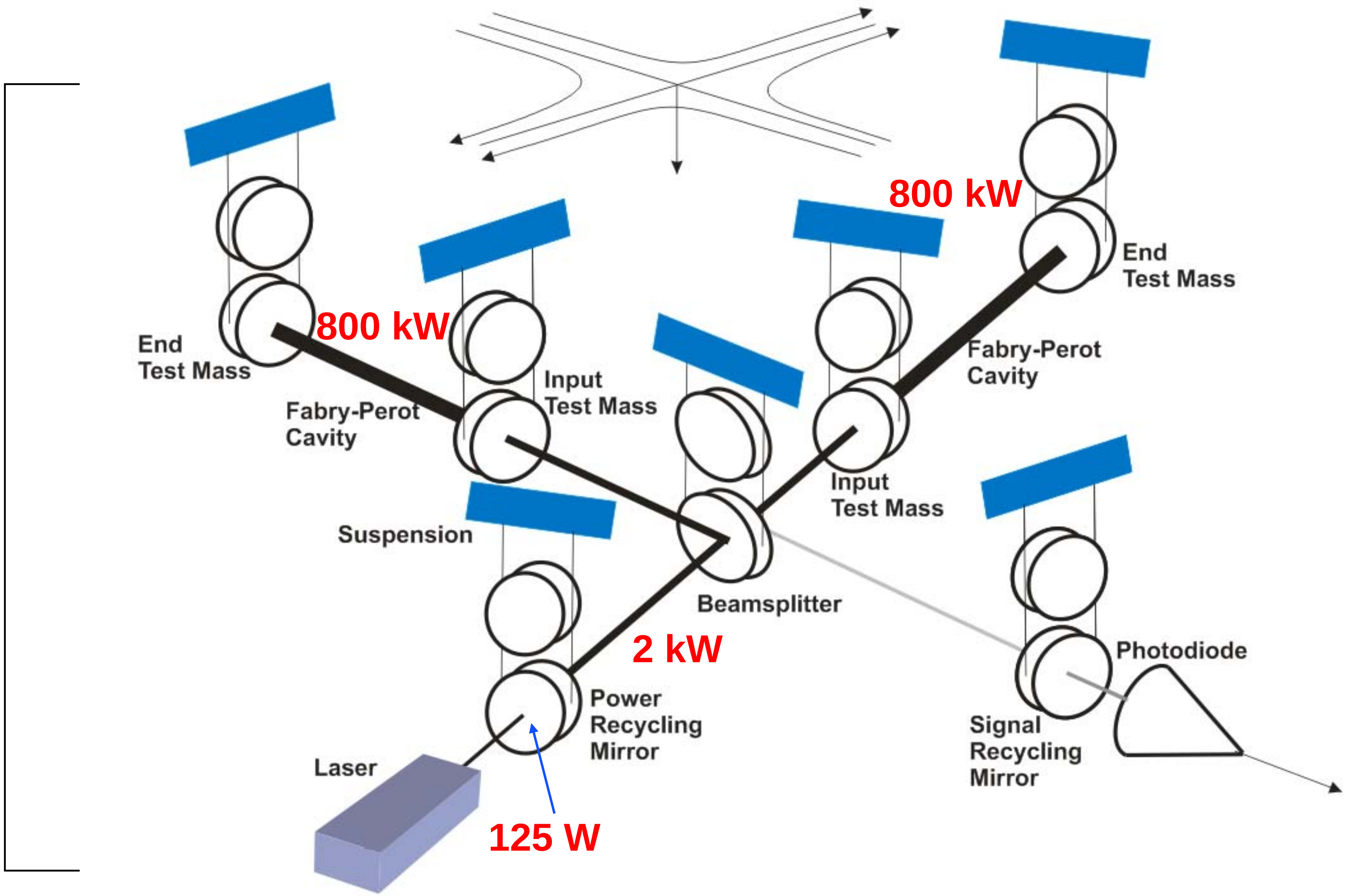

Einstein@Home
World Year of Physics 2005
User: David Hammer
Total Credit: 18207.85
Host Credit: 0.00
Team: Einstein@UWM
Percent Done: 0.94%
Search Information:
RA: 82.93
DEC: -73.96

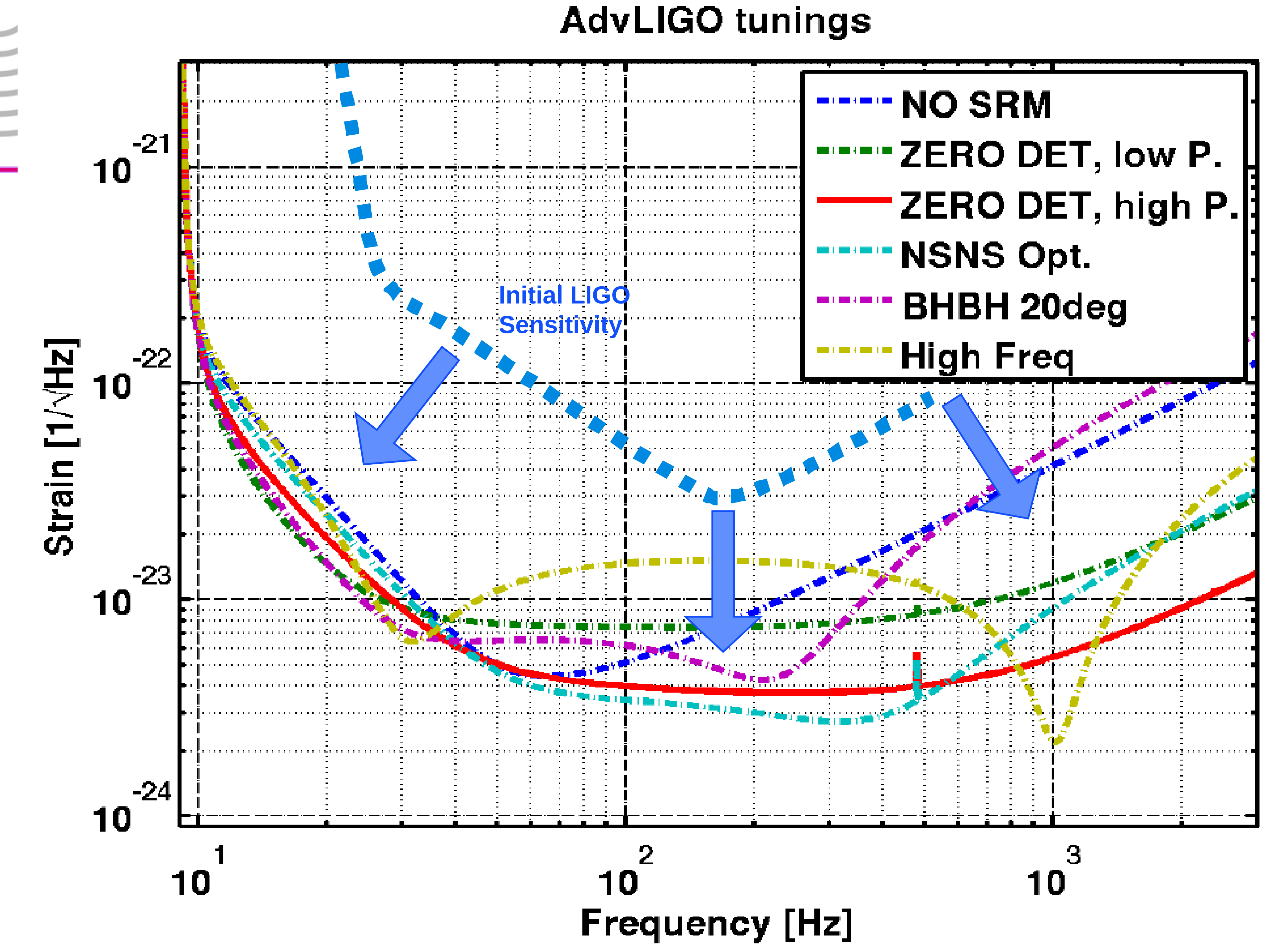
Advanced LIGO

- Current LIGO is ‘rate-limited’
  - » Detection of a gravitational wave is ‘possible’, but not ‘likely’
- Detector upgrade is planned for 2011-2015
  - » Factor of 10 increase in distance probed (‘reach’)
  - » Factor of 1000 increase in event rate



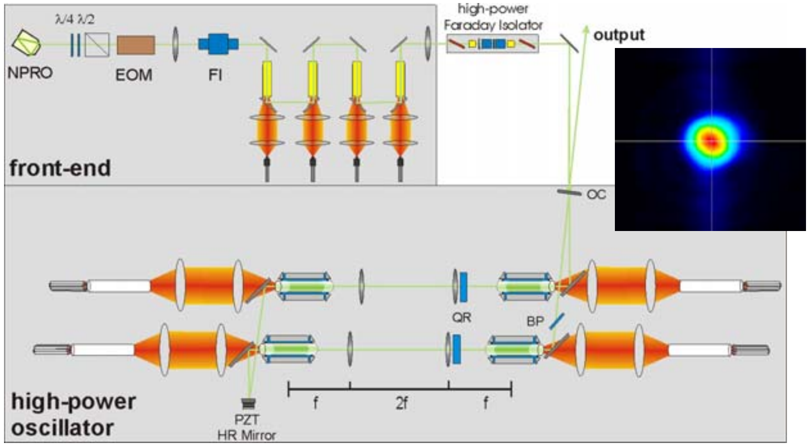
Advanced LIGO




AdvLIGO tunings
NO SRM
ZERO DET, low P.
ZERO DET, high P.
NSNS Opt.
BHBH 20deg
High Freq
Initial LIGO
Sensitivity
Strain [1/√Hz]
Frequency [Hz]
10^-21
10^-22
10^-23
10^-24
10^1
10^2
10^3

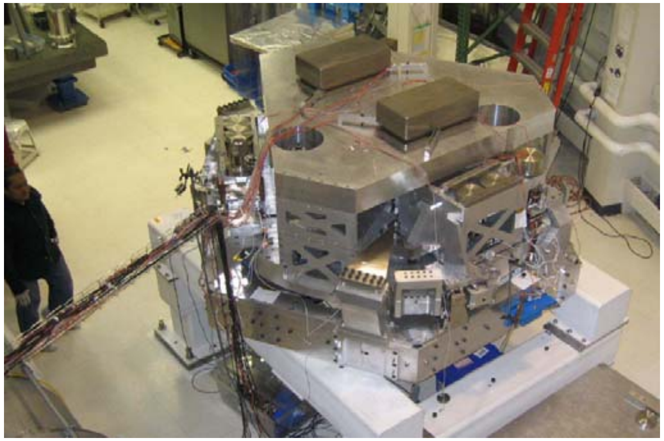
Advanced LIGO

180 W laser

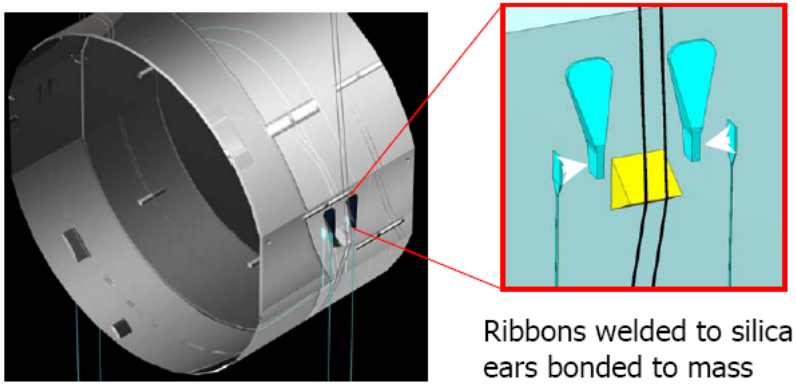


Mirror Suspensions

Seismic isolation



Mirrors



Ribbons welded to silica ears bonded to mass

Stay Tuned…

LIGO Scientific Collaboration

LIGO

LSC

University of Maryland 1856

Michigan

University of Strathclyde

Tsinghua University

ACIGA

Leland Stanford Junior University 1891

Montana State University

PAH

University of Washington

Syracuse University Suos Cultores Scientia Coronat Founded AD 1870

University of Glasgow

Università degli Studi del Sannio

Trinity University

ANU The Australian National University

University of Wisconsin UW Milwaukee

San José State University

LSU

UTB TSC

The University of Western Australia

1754

NASA Goddard Space Flight Center

California Institute of Technology 1891

Northwestern University

Andrews University

Massachusetts Institute of Technology 1861 Mens et Manus

Southeastern Louisiana University

The University of Texas at Austin

Moscow State University

R·I·T

The University of Adelaide Australia

PAN

GEO 600

Sigill. Coll. Carleton Northfield, Minn. A.D. 1866

University of Massachusetts Amherst 1863

Embry-Riddle Aeronautical University

University of Southampton

PennState 1855

Cardiff University

Washington State University

Universitat de les Illes Balears UIB

UF University of Florida

The University of Mississippi 1848

Charles Sturt University

NAOJ

University of Minnesota

Universität Hannover

Southern University Agricultural & Mechanical College

Hobart College

William Smith College 1908

Science & Technology Facilities Council Rutherford Appleton Laboratory

Acknowledgments

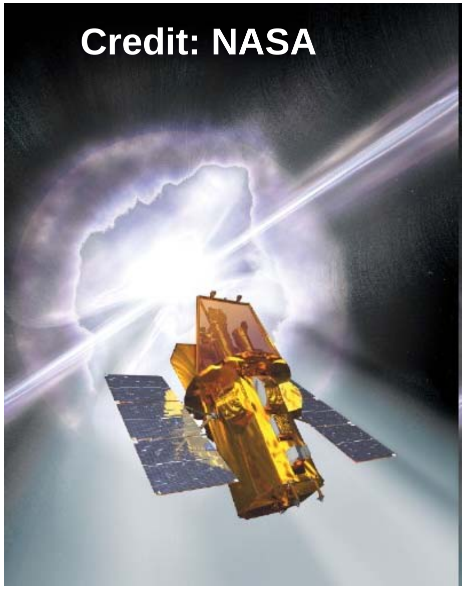
- Members of the UF LIGO group
-
- Members of the LIGO Laboratory
- Members of the LIGO Science Collaboration
- National Science Foundation

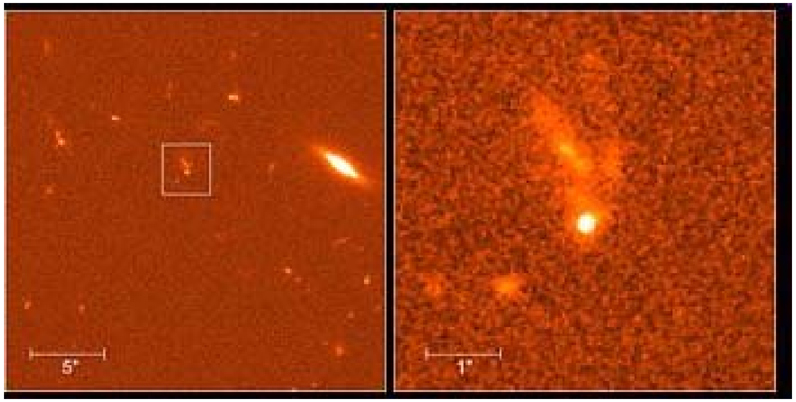
More Information

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

Gamma Ray Bursts

- Intense flashes of gamma rays from (mostly) extra-galactic sources
  - » GRBs are the most luminous events in the Universe
- Long (> 2 s) and short duration (< 2 s)
  - » Long GRBs are associated with star forming galaxies
    - – Large red shift, Z>8 reported last week
  - » Short GRBs are less well understood
    - – Progenitor is NS-BH, BH-BH binary merger!
    - – Soft gamma repeaters → magnatars





NASA Hubble Space Telescope Imaging Spectrograph (STIS)

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

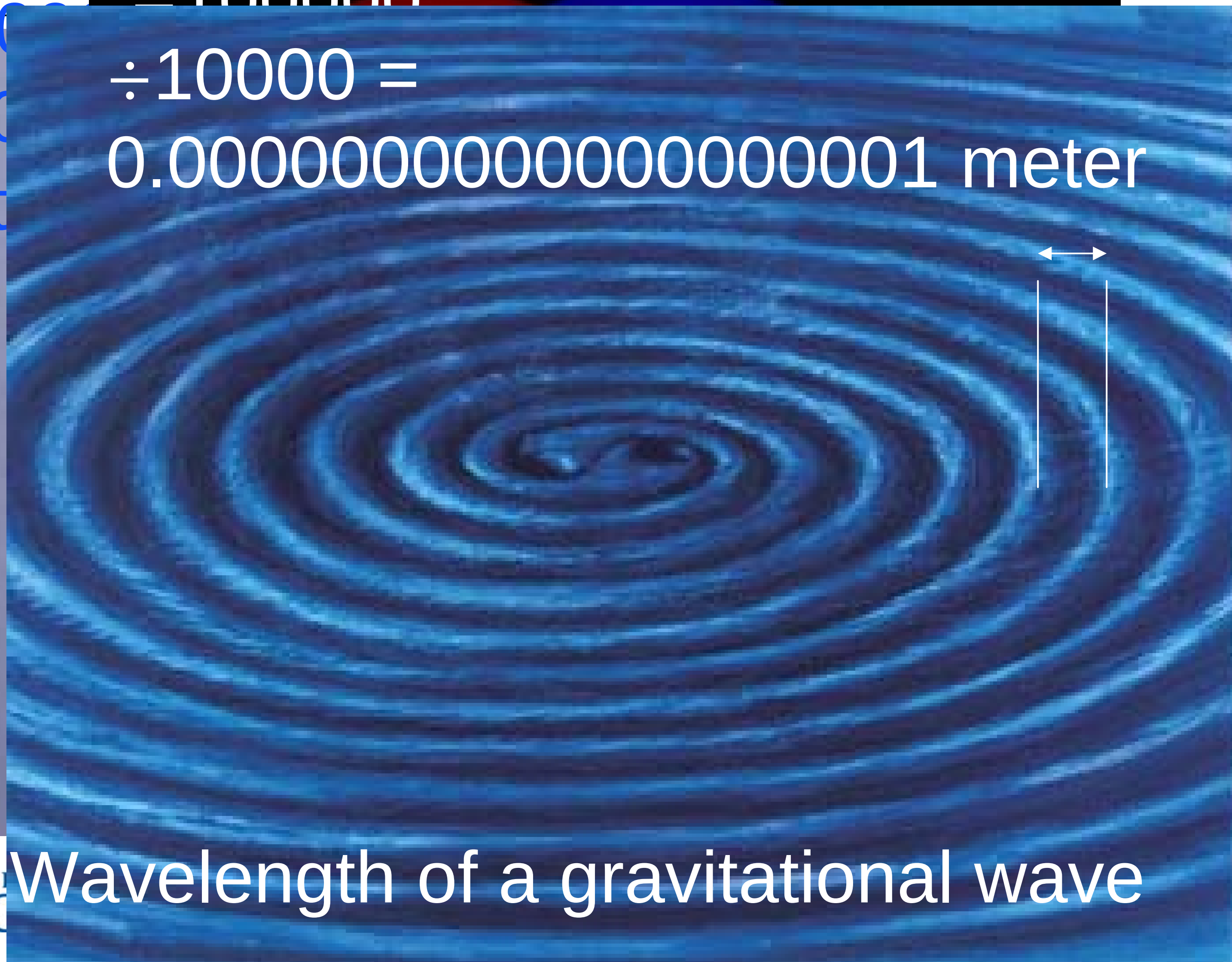
How big is a gravitational wave?

÷1,0

0.00

met

÷100000 =

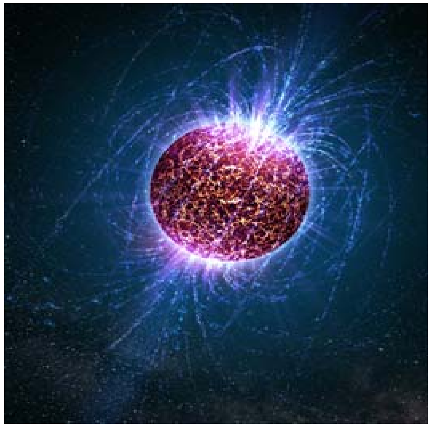


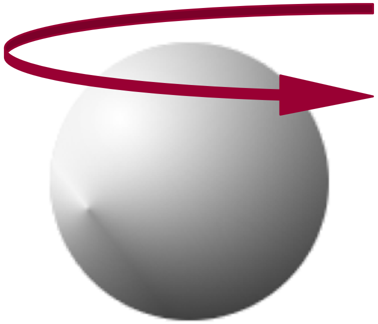
Pulsars

- Spinning neutron stars ‘brake’ due to:
  - » Symmetric particle ejection
  - » Magnetic dipole radiation
  - » Gravitational wave emission
- Neutron stars could emit gravitational waves if:
  - » They are non-axially distorted from crustal shear stresses

$$\epsilon_{\rm max} \approx 5 \times 10^{-7} \left(\frac{\sigma}{10^{-2}}\right)$$

  - » They have non-axisymmetric instabilities due to internal hydrodynamic modes
  - » they wobble about their axis
- But the emission amplitude will be very small…





The Crab Pulsar: *Beating the Spin Down Limit!*

- Remnant from supernova in year 1054
- Spin frequency ν_{EM} = 29.8 Hz

  → $\nu_{gw} = 2\ \nu_{EM}$ = 59.6 Hz

- observed luminosity of the Crab nebula

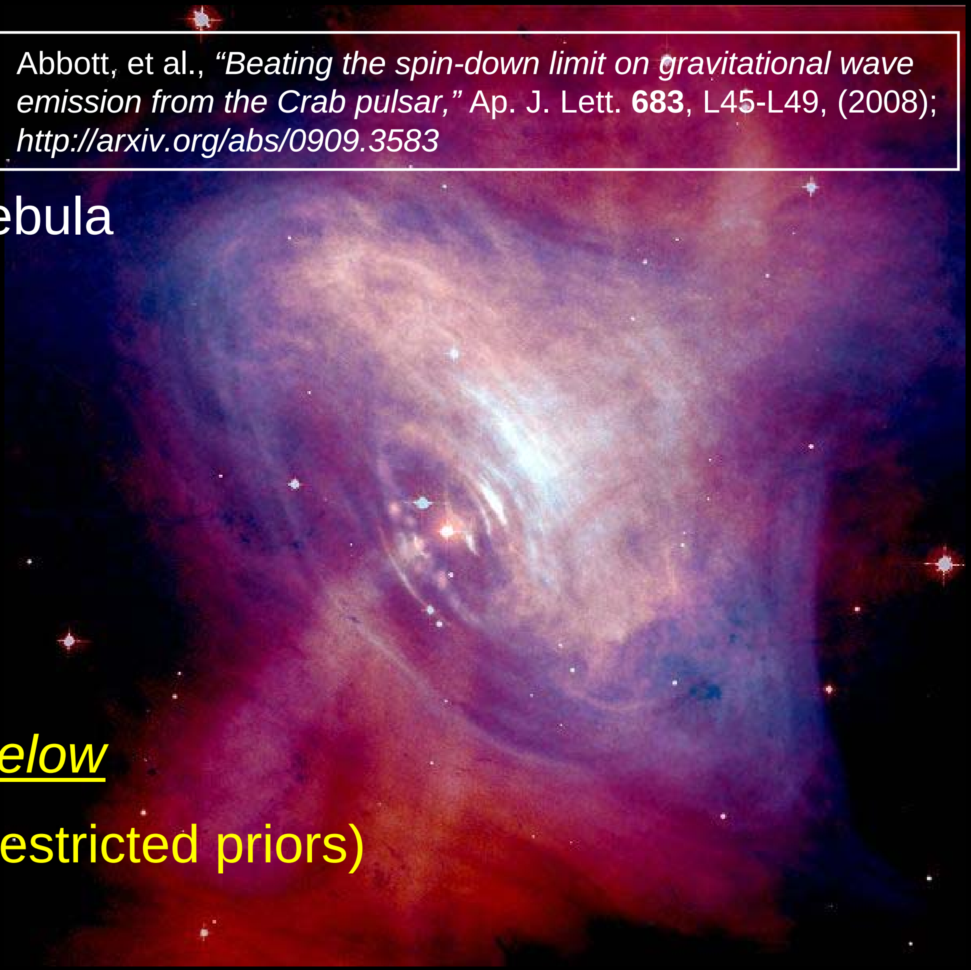
accounts for < 1/2 spin down power

- spin down due to:
  - electromagnetic braking
  - particle acceleration
  - *GW emission?*

- S5 result: $h < 2.0 \times 10^{-25}$ → < 7X <u>*below*</u>

  the spin down limit (assuming restricted priors)

- ellipticity upper limit: $\varepsilon < 1.0 \times 10^{-4}$
- GW energy upper limit < 2% of radiated energy is in GWs

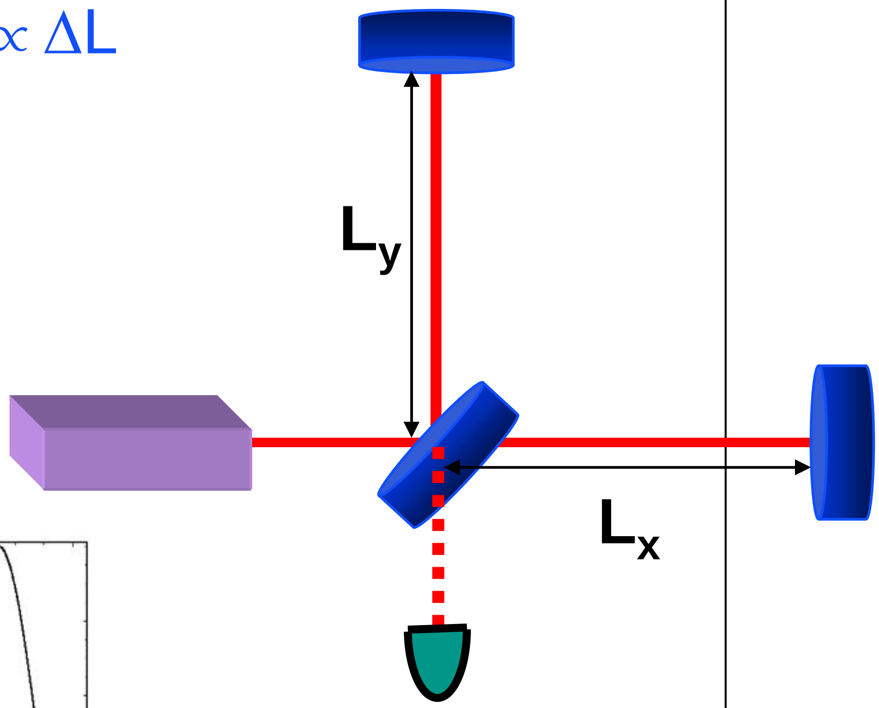


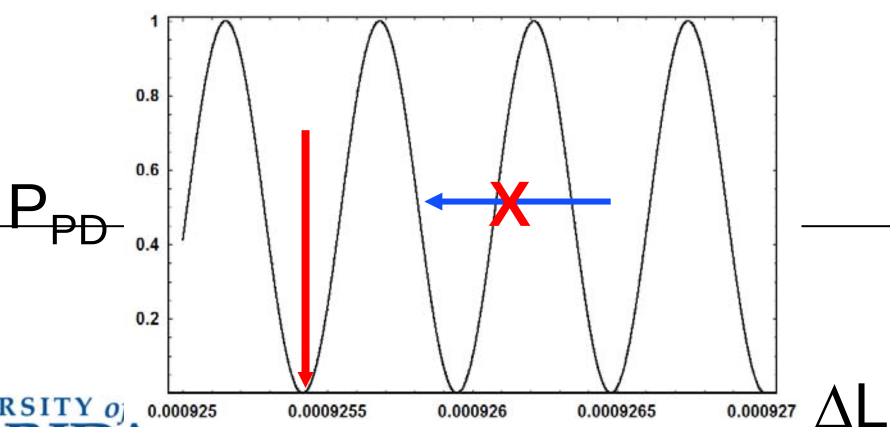
Abbott, et al., *"Beating the spin-down limit on gravitational wave emission from the Crab pulsar,"* Ap. J. Lett. **683**, L45-L49, (2008); *http://arxiv.org/abs/0909.3583*

Interferometry: the basics

- Simple Michelson
  - » Phase: $\phi = 4\pi\,(L_x - L_y)\,/\lambda \propto \Delta L$
  - » Power: $P_{PD} = P_{BS}\,\sin^2\phi$
    - – $dP/d\phi \sim\; P_{BS}\,\sin\phi\,\cos\phi$
  - » Strain: $h = 2\Delta L/L$
    - – Phase sensitivity:

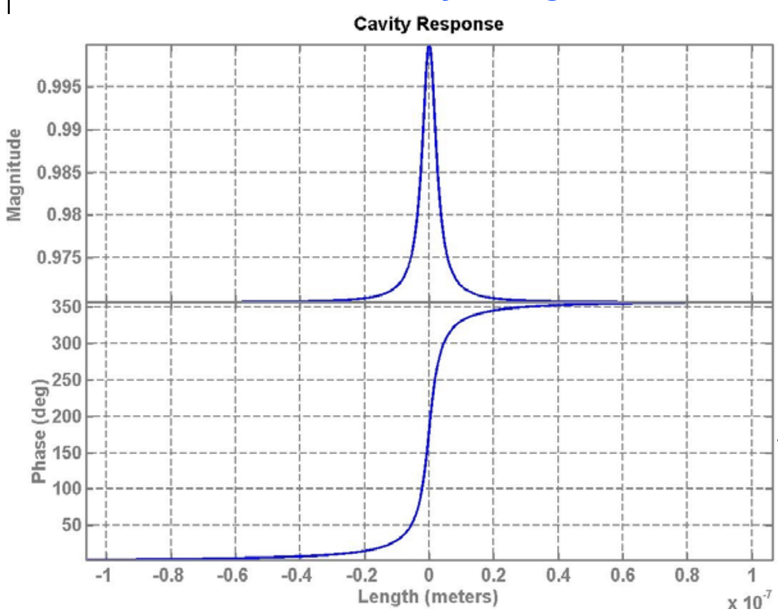
$$d\phi/dh \propto L$$

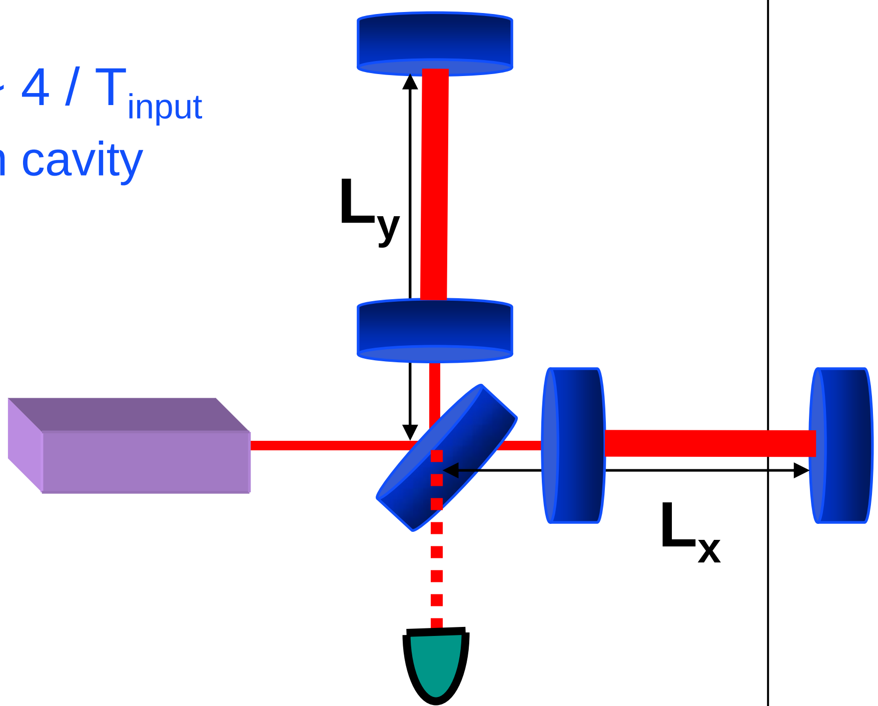




Beefed-up Interferometry: Fabry-Perot Arm Cavities

- Fabry-Perot cavity
  - » Increases power in arms
    - – Overcoupled cavity gain: $G_{FP} \sim 4 / T_{input}$
  - » Enhances storage time of light in cavity
    - – Phase shift on resonance
    - – Effectively 'lengthens' arms





$df/dh \propto G_{FP} \times L$

Advanced Interferometry II: Power Recycling

- ‘Recycle’ light coming back from beamsplitter
  - » Add a mirror which forms a resonant cavity with the rest of the interferometer

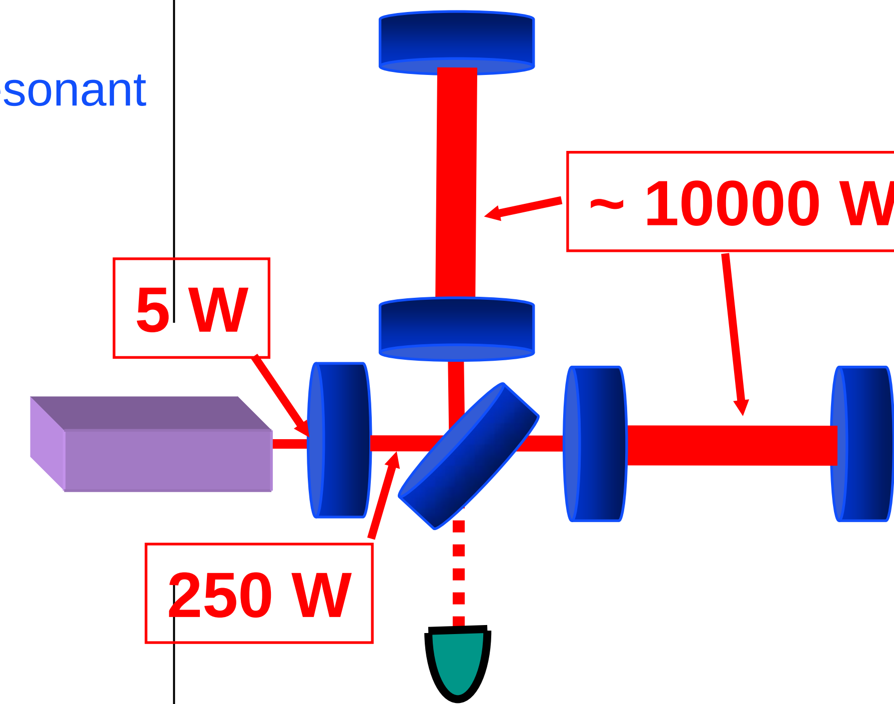
$$P_{BS} = G_{RC}\, P_{input}$$

+

$$df/dh \propto G_{FP} \times L$$

=

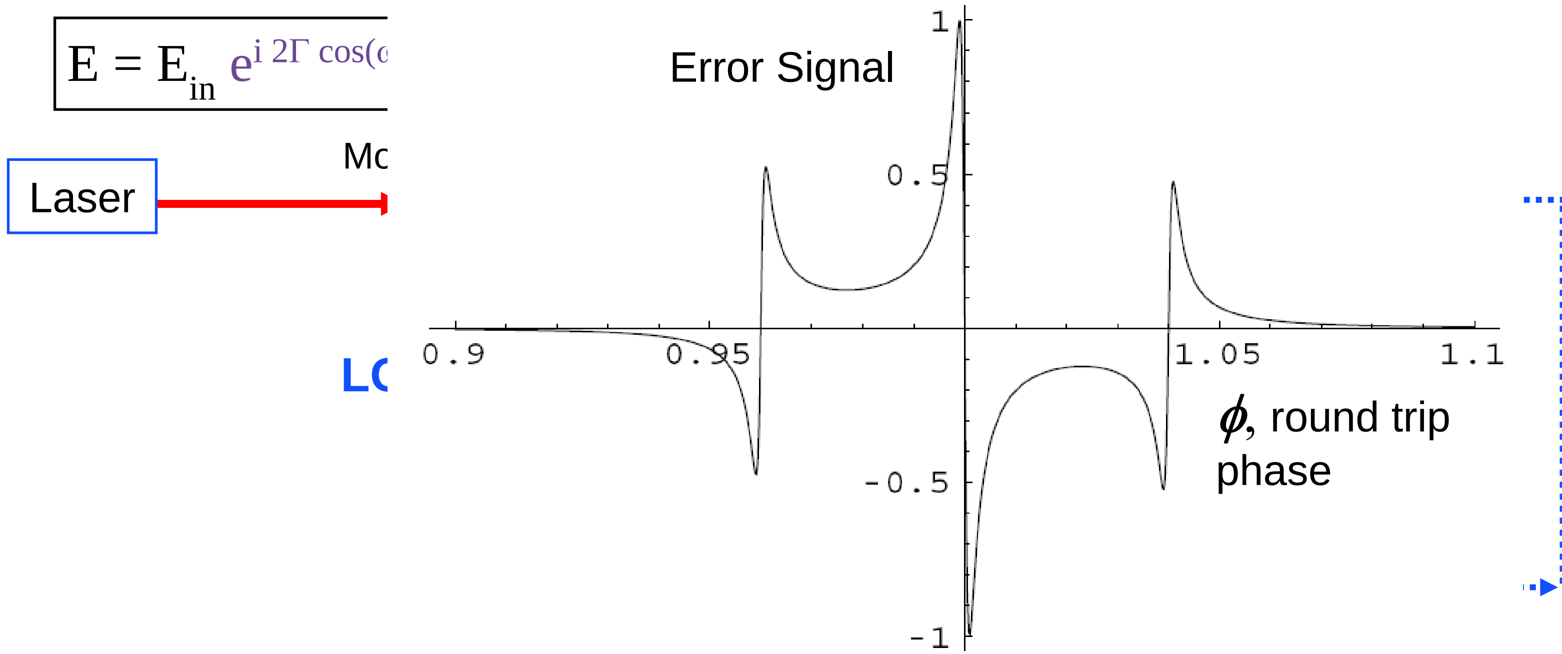
Enhanced Phase Sensitivity!



$G_{RC} \sim 50,\ G_{FP} \sim 80$

Keeping the Interferometer Together

- All length degrees of freedom must be held on resonance (ie, locked)
  - heterodyne detection → Pound-Drever-Hall Locking
    - reference field provided by electro-optic modulator



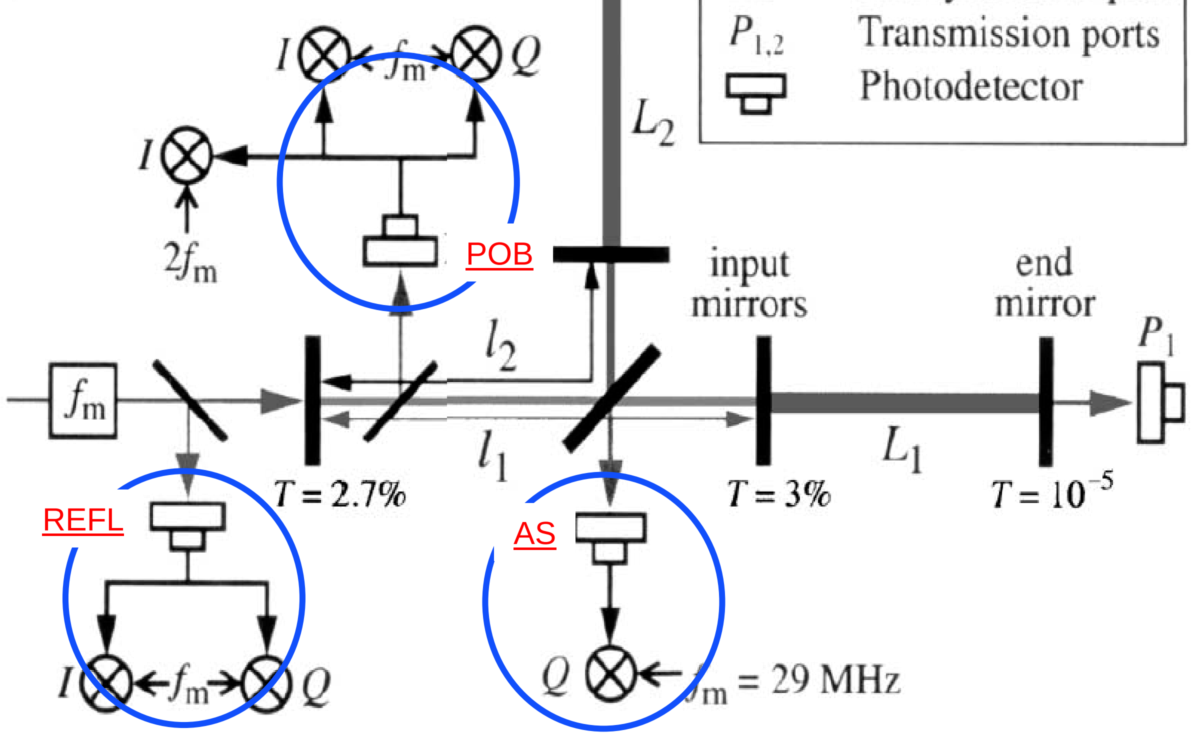
- LIGO Interferometers are very complex: 4 length + 10 alignment degrees of freedom
  - Absolute position must be held to 10^{-13} m

The LIGO Length Control Scheme

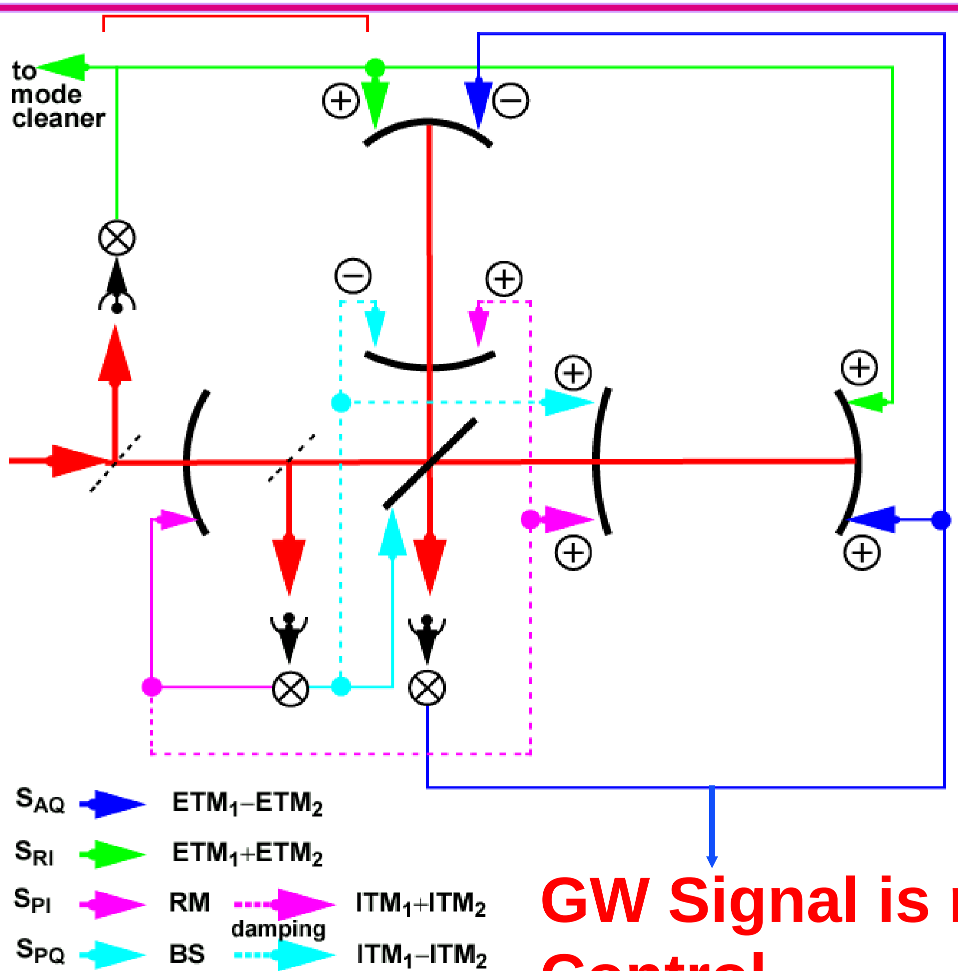
Length Degrees of freedom →

$$L_{\pm} = (L_1 \pm L_2)/2$$

$$l_{\pm} = (l_1 \pm l_2)/2$$



Locking the Interferometer



- Multiple Input / Multiple Output.
- Four tightly coupled cavities.
- Ill-conditioned (off-diagonal) plant matrix.
- Highly nonlinear response over most of phase space.
- Transition to stable, linear regime takes plant through singularity.
- Employs adaptive control system that evaluates plant evolution and reconfigures feedback paths and gains during lock acquisition.

GW Signal is measured from DARM Control

Alignment Sensing and Control

- Need to also control angular fluctuations θ_x, θ_y of the mirrors θ_x, θ_y for 5 of the 6 interferometer mirrors
- Spatially-resolved PDH locking…

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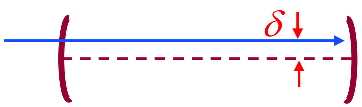
Alignment of resonant optical cavities

Dana Z. Anderson

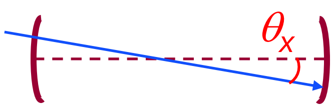
When an input Gaussian beam is improperly aligned and mode-matched to a stable optical resonator, the electric field in the resonator couples to off-axis spatial eigenmodes. We show that a translation of the input axis or a mismatch of the beam waist to the resonator waist size causes a coupling of off-axis modes which is inphase with the input field. On the other hand, a tilt of the input beam or a mismatch of the beam waist position to cavity waist position couples to these modes in quadrature phase. We also propose a method to measure these coupling coefficients and thereby provide a means to align and mode-match a resonant optical cavity in real time.

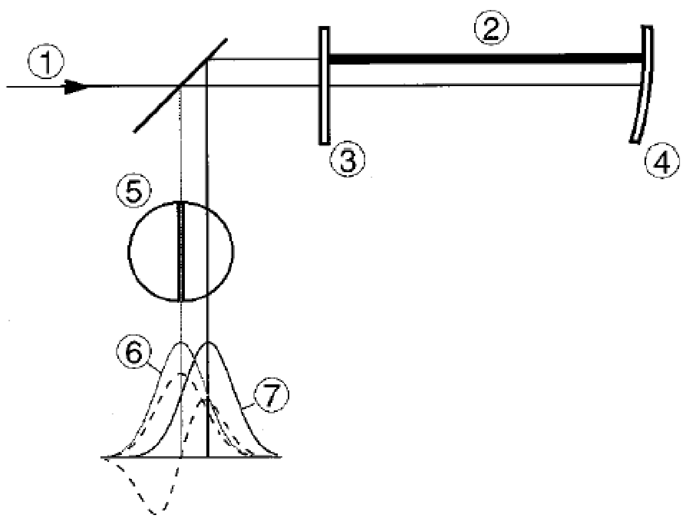
Alignment Sensing and Control

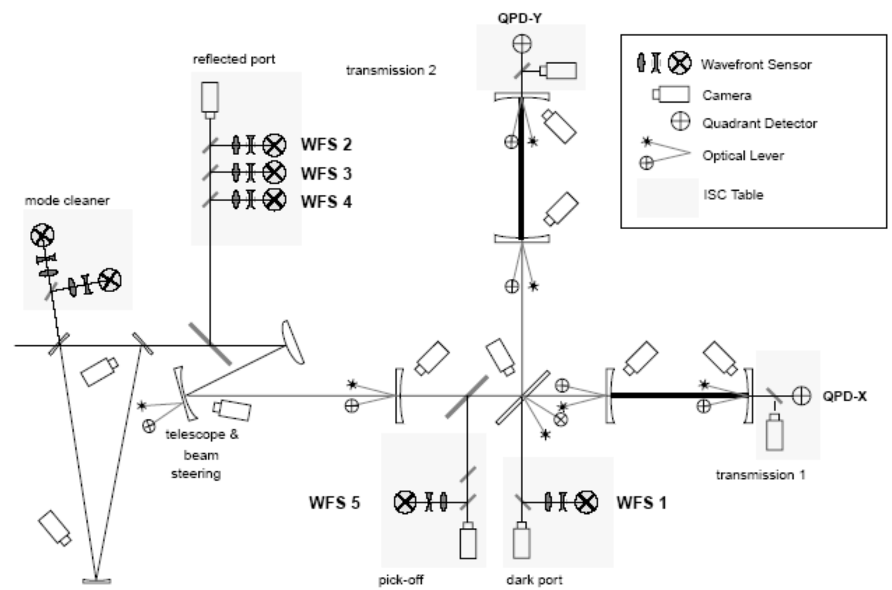
- Cavity modes U decompose into HG_0 and HG_1 modes:
  - » Displacement: $U(x) = HG_0(x-\delta) \cong HG_0(x) + (\delta/w_o)\, HG_1(x)$



  - » Tilt: $U(x) = HG_0(x')/\cos\theta_x \cong HG_0(x) + i\,\pi\,(\theta_x w_o/\lambda)\, HG_1(x)$



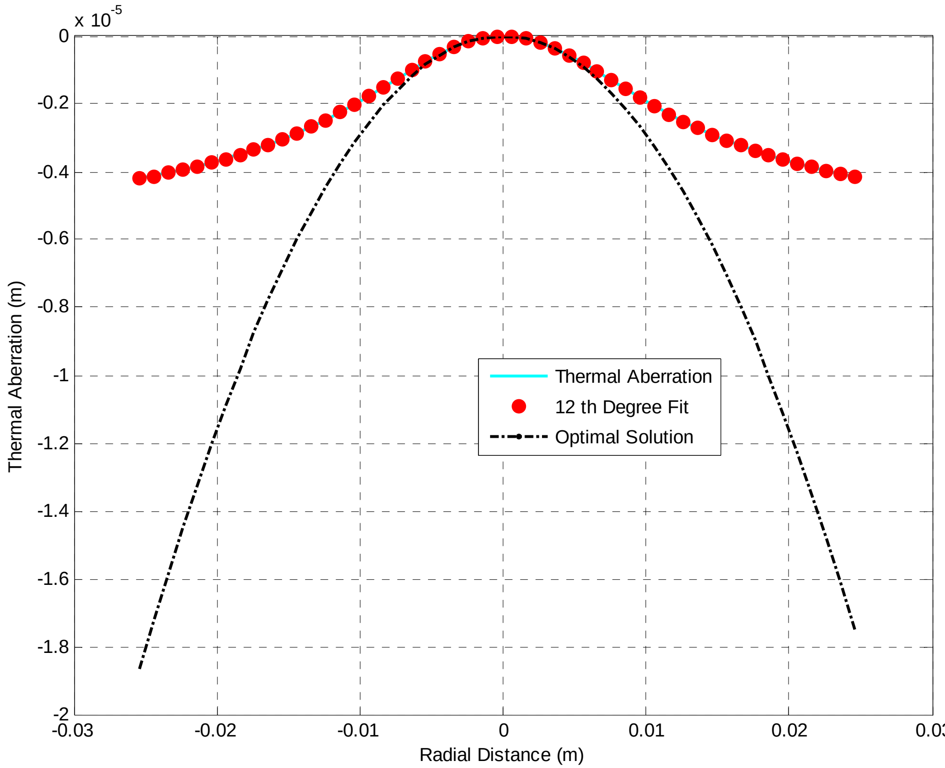




Thermal Effects in LIGO Core Optics

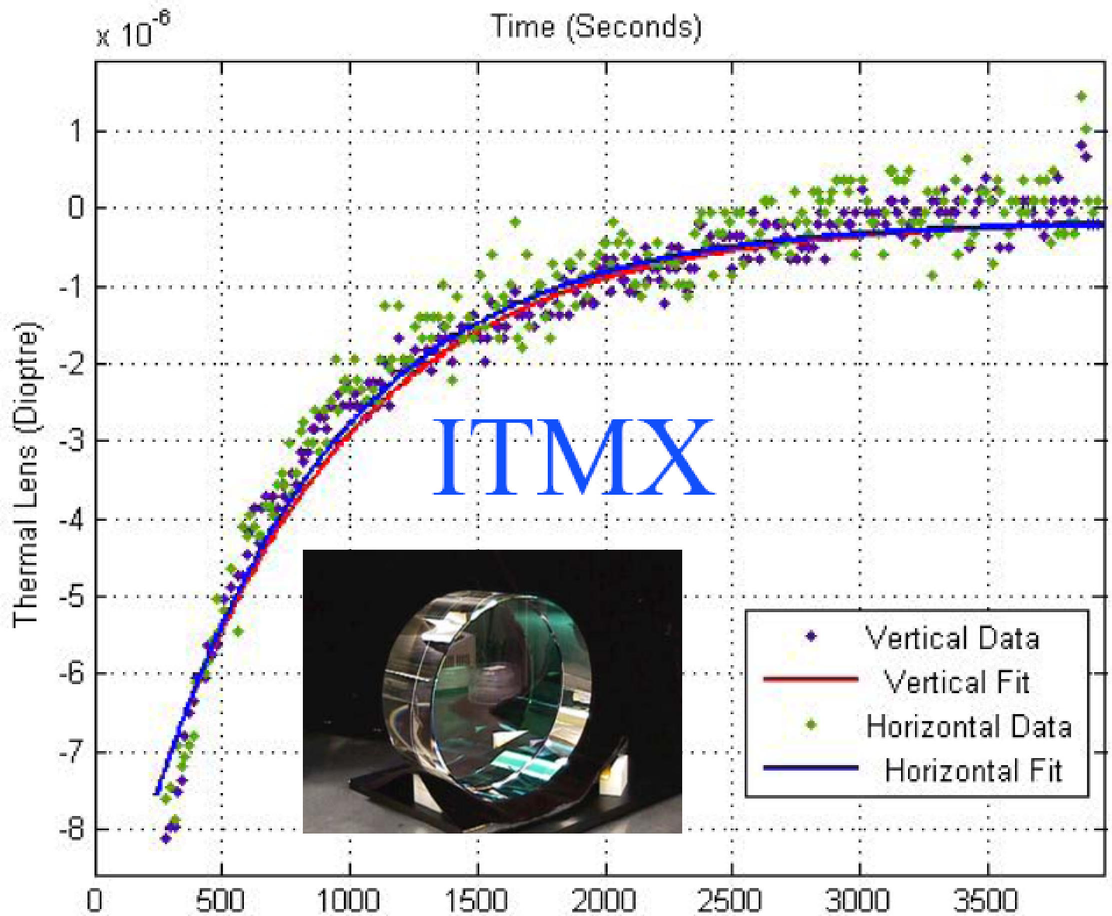
- Absorption in the mirror substrates and coatings leads to thermal aberratior in the mirrors
  - » Temperature couples to index c refraction *n*, thermal expansion and photo-elastic stress

$$OPL(r) = \left(\frac{dn}{dT} + \alpha_T (n-1) \right) \int_0^L \Delta T(r,z)$$



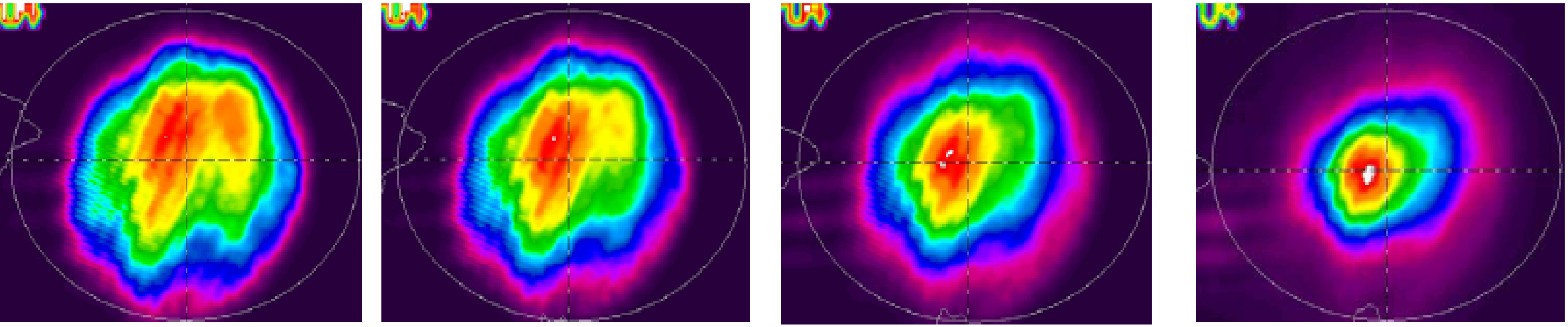
Thermal Effects in LIGO Core Optics

- High quality low absorption fused silica substrates
  - » ~ 2 -10 ppm/cm bulk absorption
  - » ~ 1-5 ppm coating absorption
    - – Different for different mirrors
    - – Can change with time
  - » All mirrors are different
  - » Unstable recycling cavity
  - → Requires adaptive control of optical wavefronts



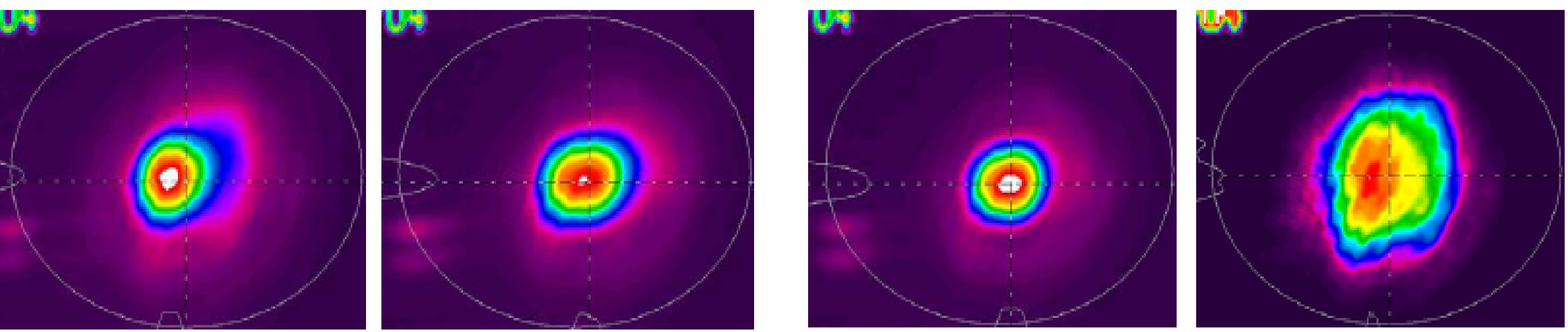
Thermal Compensation

RF sidebands-->|



no heating | 30 mW | 60 mW | 90 mW

RF sidebands--->| Carrier



120 mW | 150 mW | 180 mW | (thru unlocked IFO)