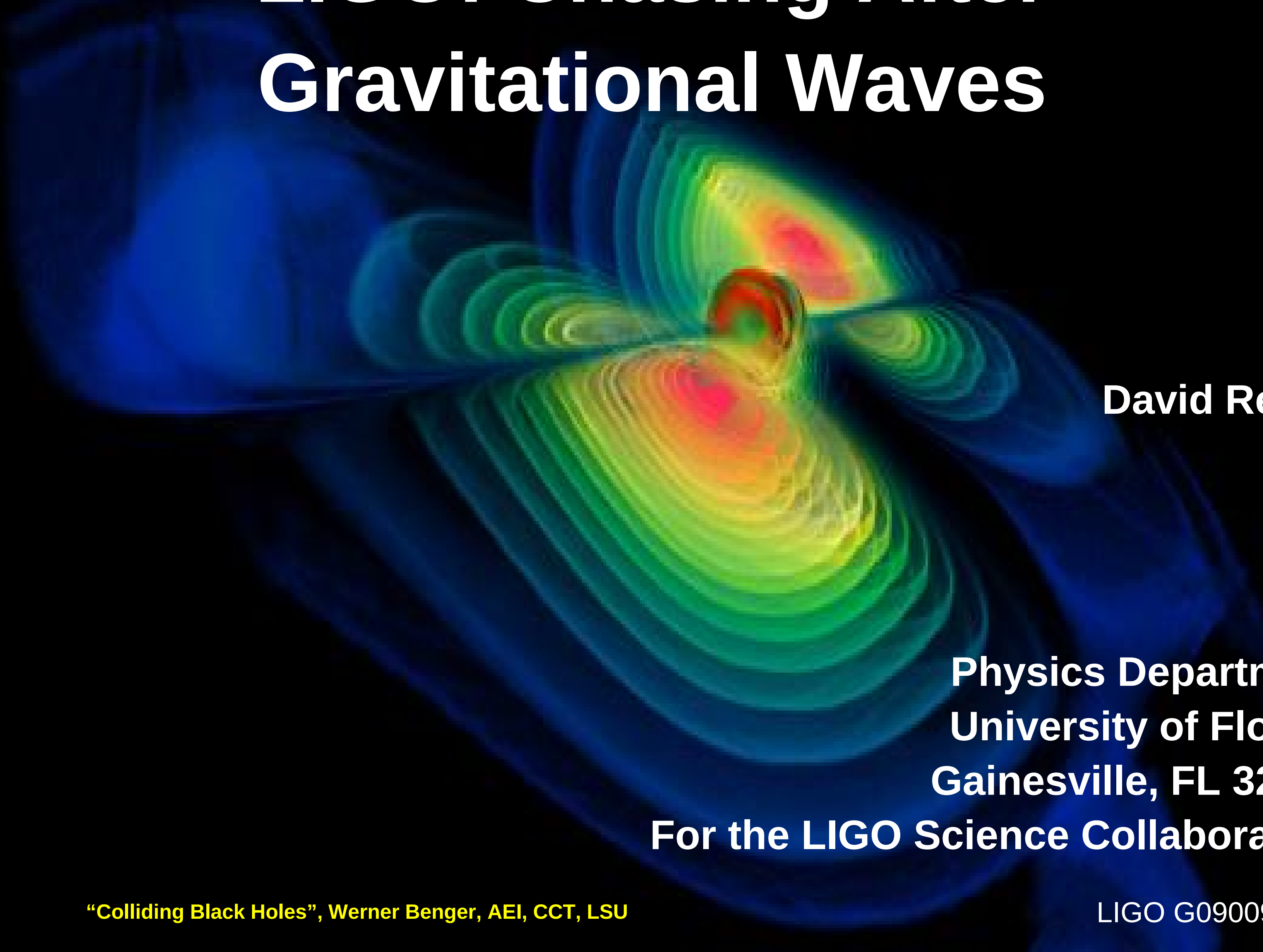
Physics Colloquium, Purdue University, Nov. 5, 2009

LIGO: Chasing After 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 G0900991-v1

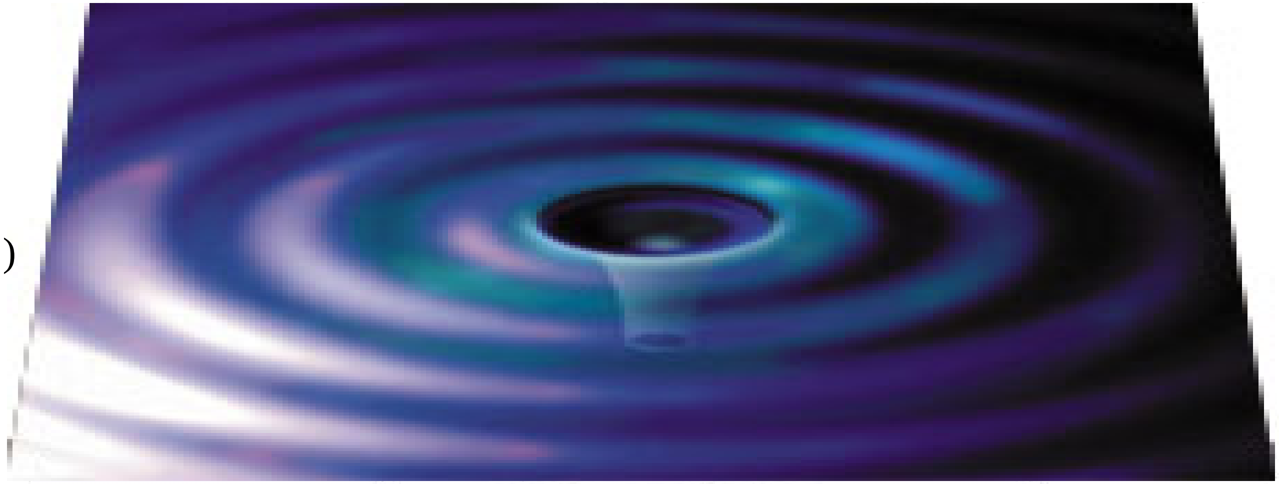
LIGO Interferometer

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:

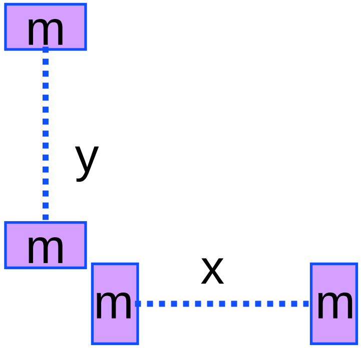
$$\left(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right)h = 0$$

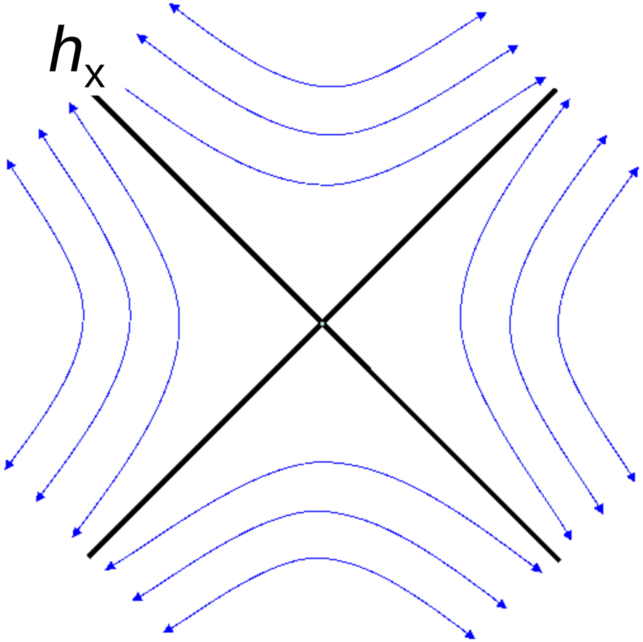
$$h(t) \sim h_{\mu\nu}\, e^{i(\vec{k}\bullet\vec{x} - \omega t)} + h_{\mu\nu} e^{-i(\vec{k}\bullet\vec{x} - \omega t)}$$



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

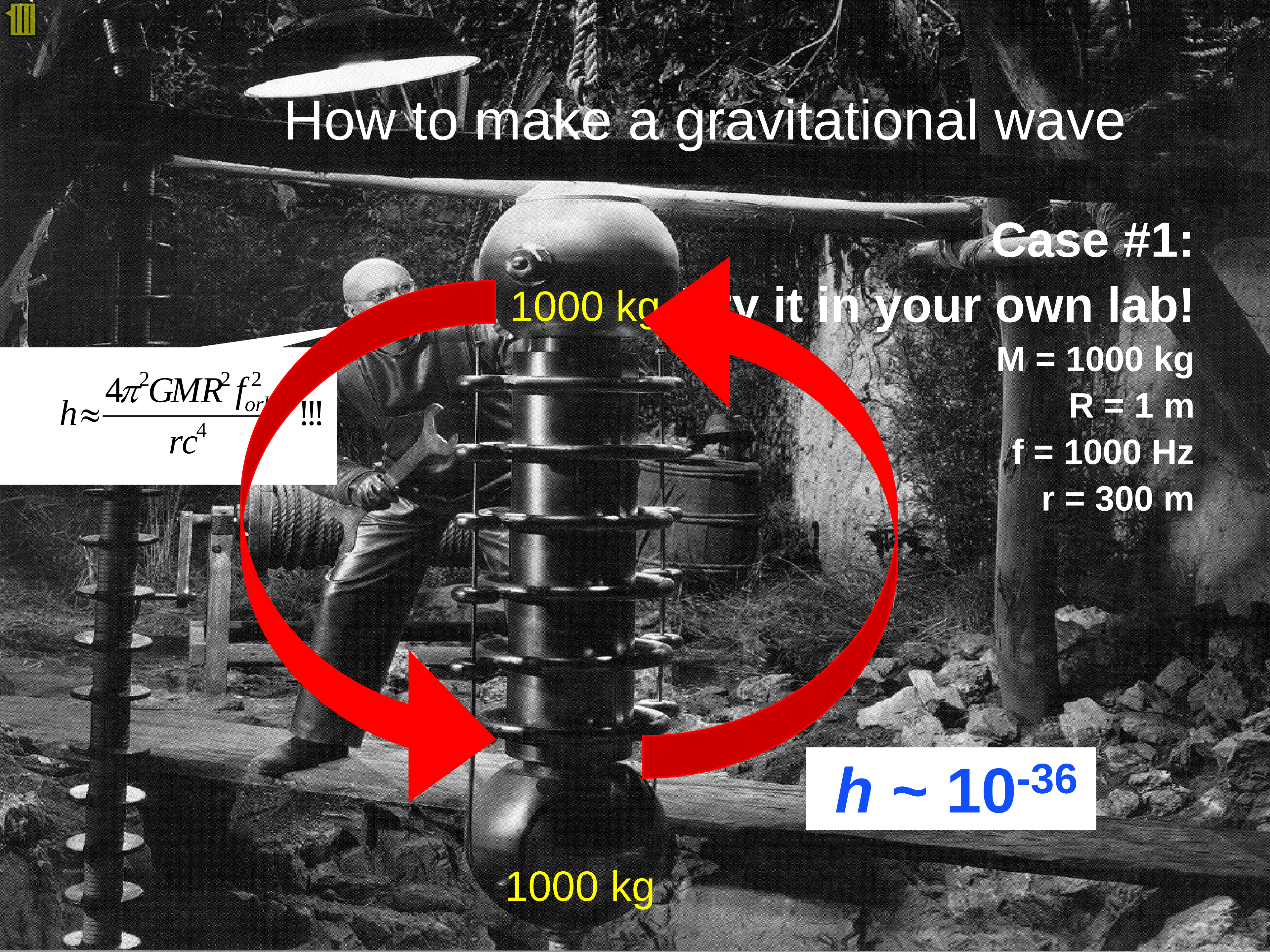
- Time-dependent quadrapole moment arising from *mass motion*

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

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

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

How to make a gravitational wave



Case #1:

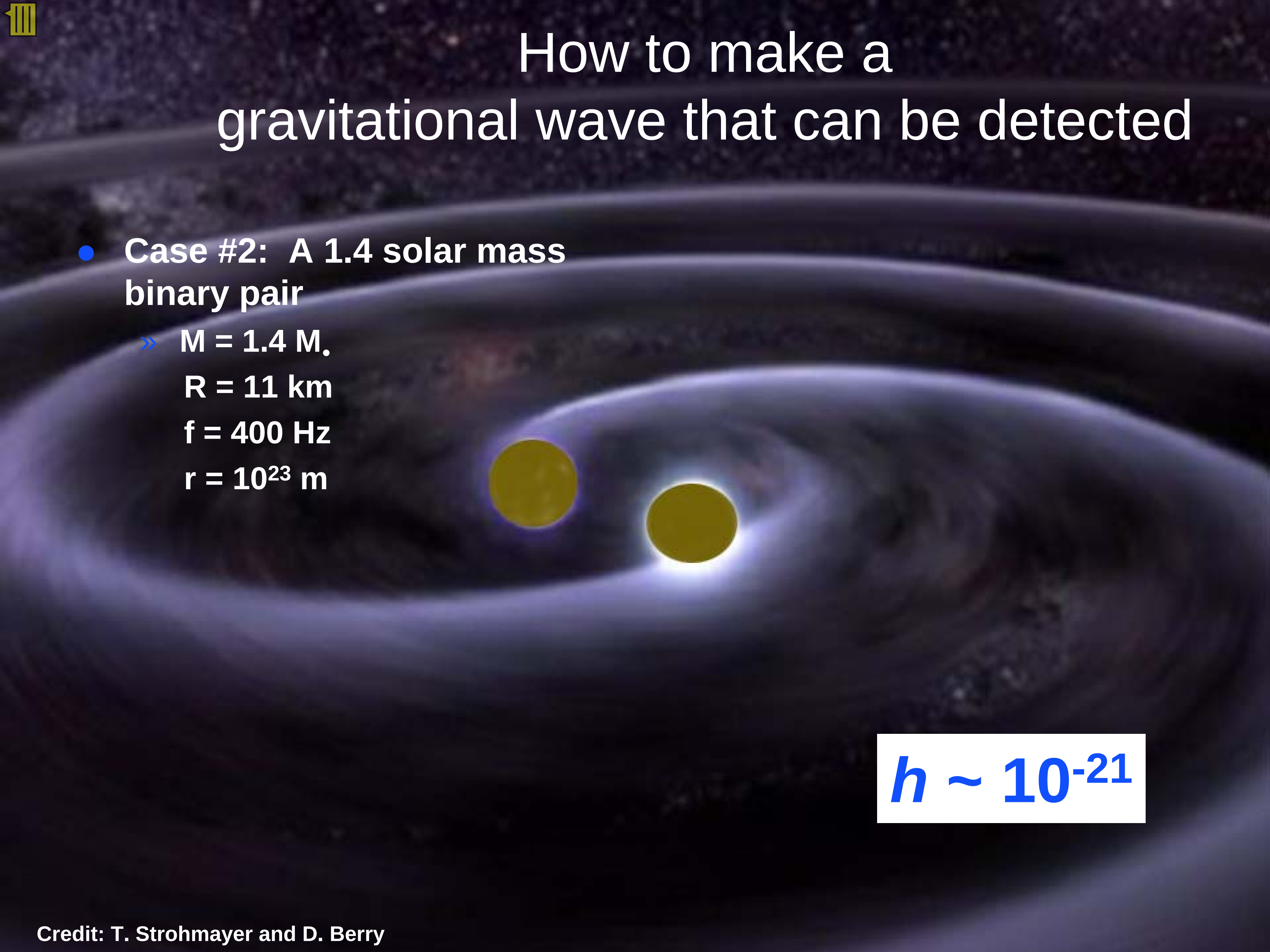
y it in your own lab!

M = 1000 kg
R = 1 m
f = 1000 Hz
r = 300 m

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

$$h \sim 10^{-36}$$

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

$h \sim 10^{-21}$

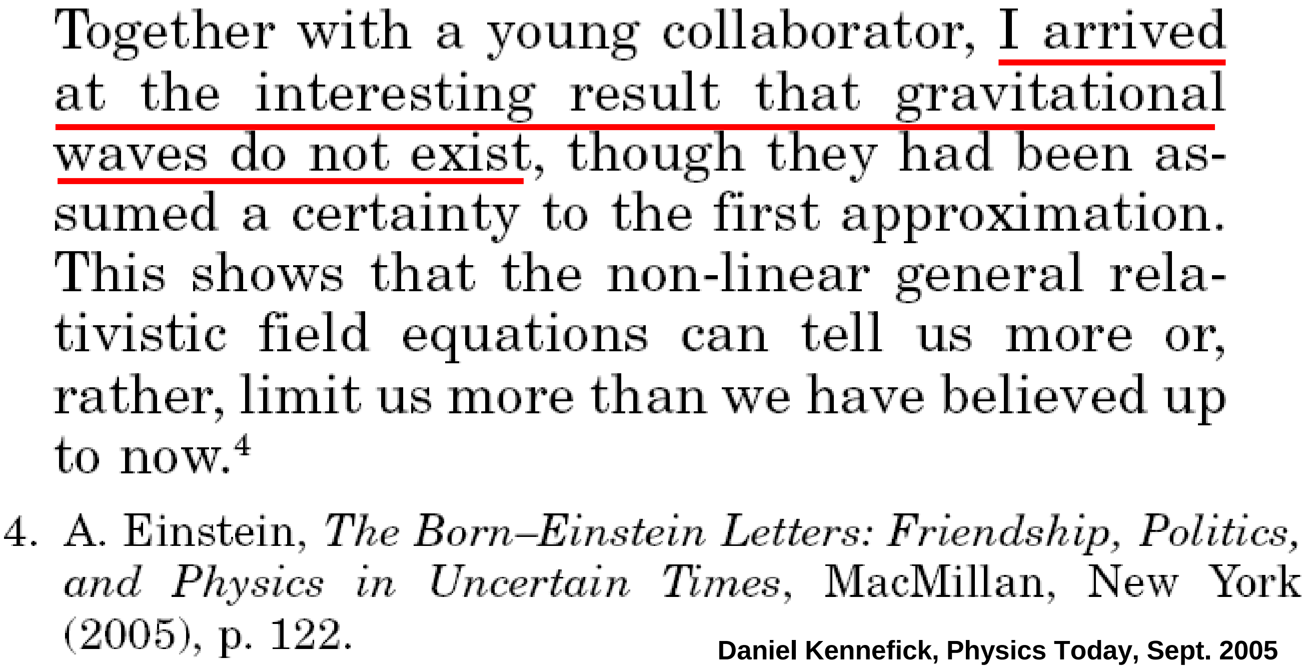
Credit: T. Strohmayer and D. Berry

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]

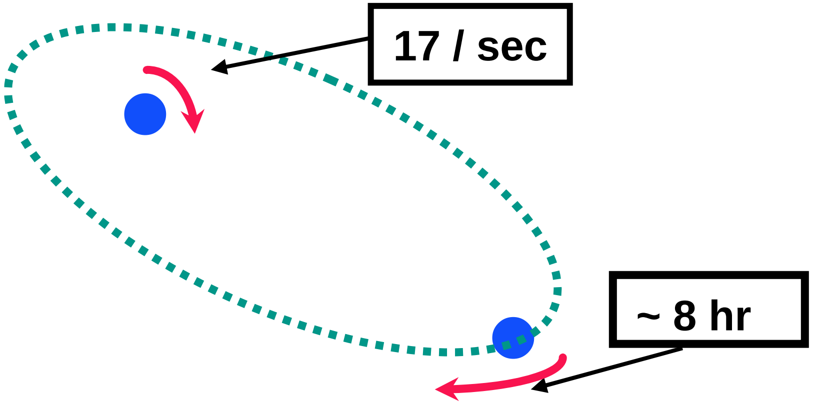
4. A. Einstein, *The Born–Einstein Letters: Friendship, Politics, and Physics in Uncertain Times*, MacMillan, New York (2005), p. 122.

Daniel Kennefick, Physics Today, Sept. 2005

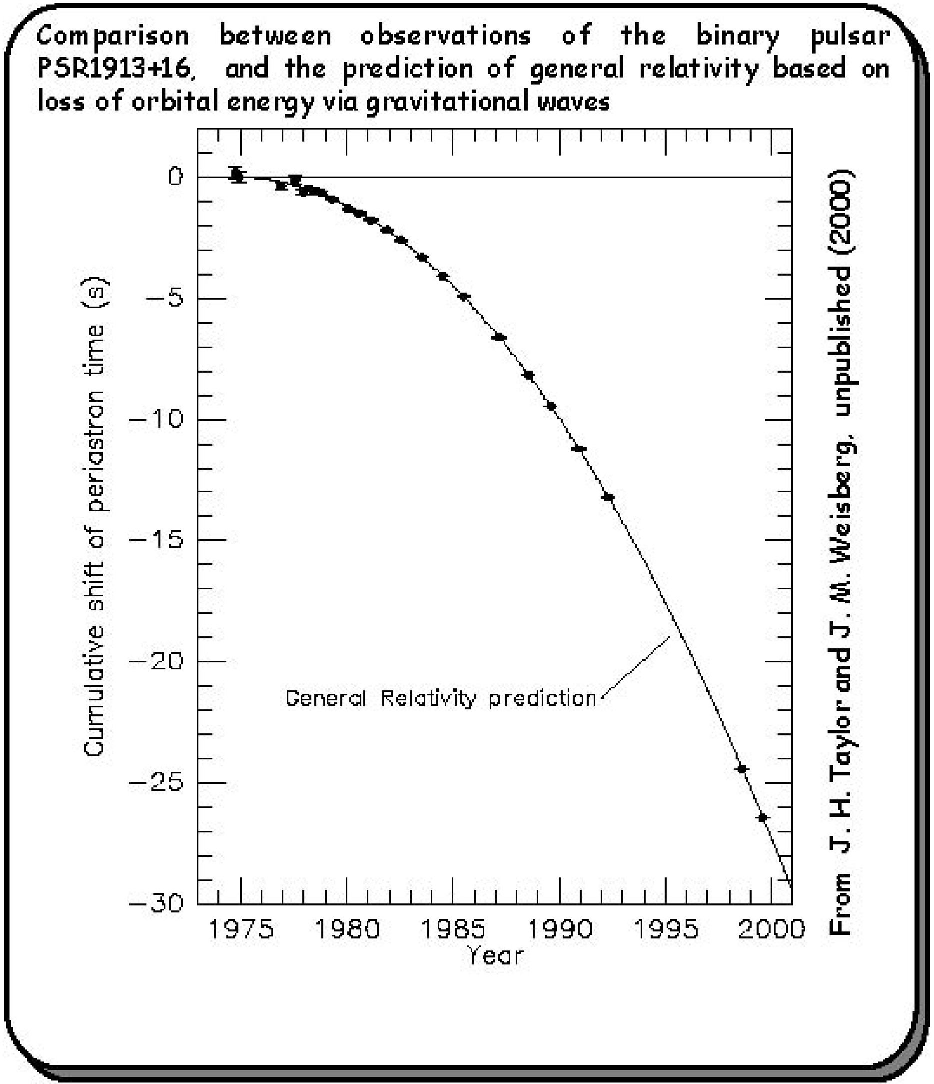
Existence proof: PSR 1913+16


Joseph Taylor

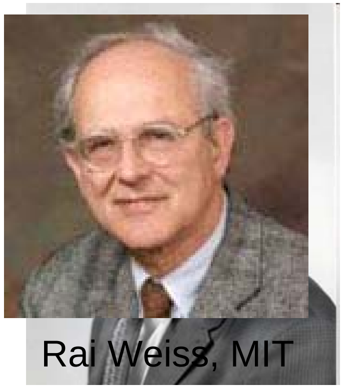

Russell Hulse


17 / sec

~ 8 hr


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

Joe Weber, U. Maryland

QUARTERLY PROGRESS REPORT

APRIL 15, 1972

No. 105

ELECTROMAGNETICALLY COUPLED BROADBAND GRAVITATIONAL ANTENNA

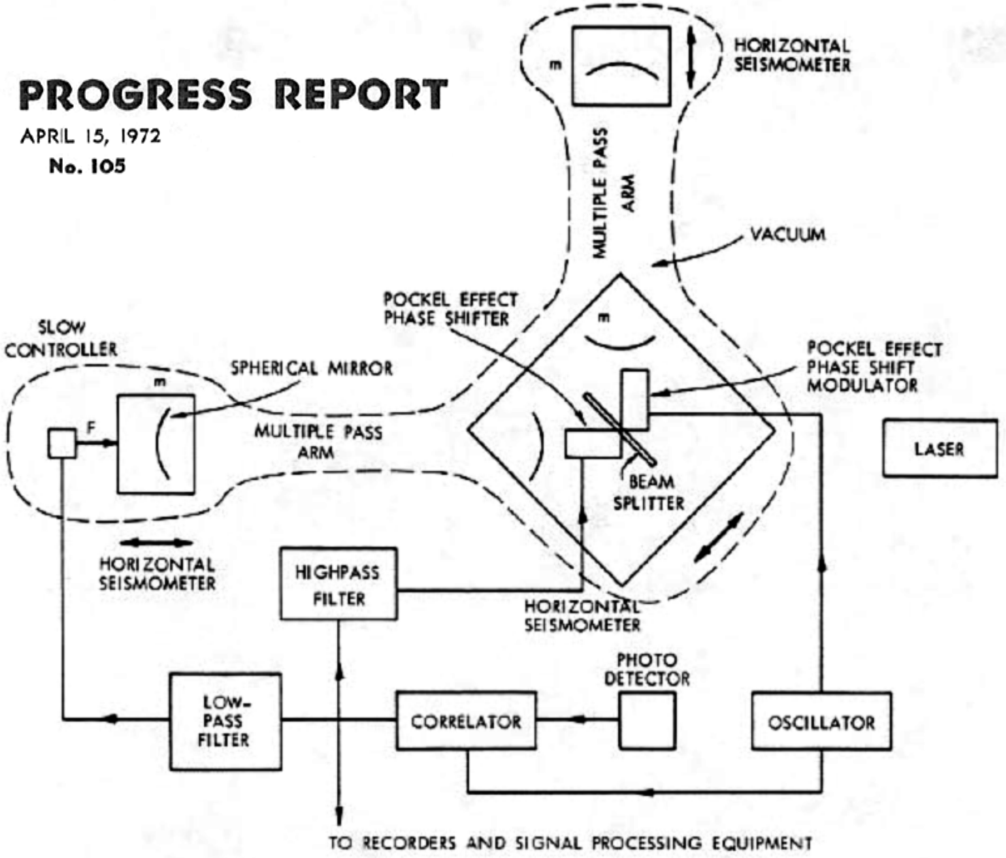


Fig. V-20. Proposed antenna.

UNIVERSITY OF MARYLAND

Realistically, how sensitive can an interferometer be?

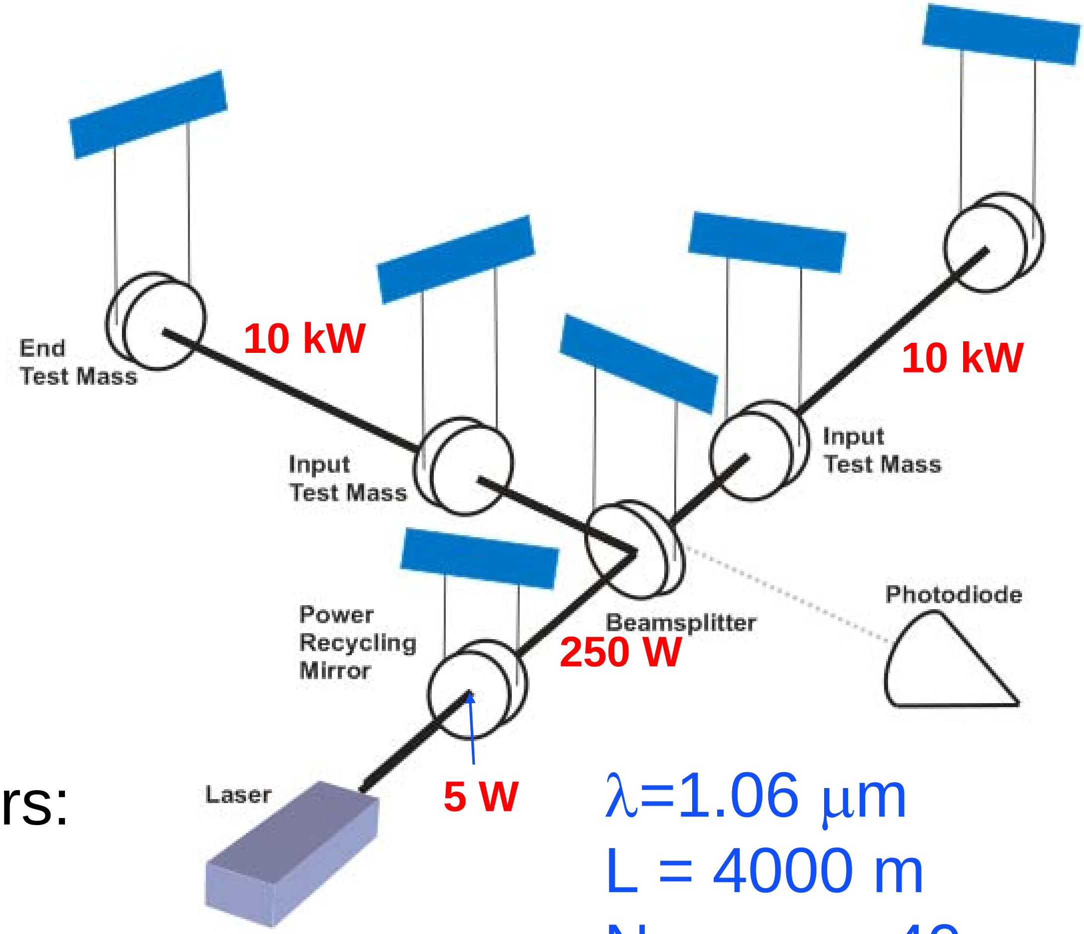
$$h \sim \frac{\lambda}{L}$$

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

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

Putting in numbers:

$$\boldsymbol{h \sim 10^{-21}}$$



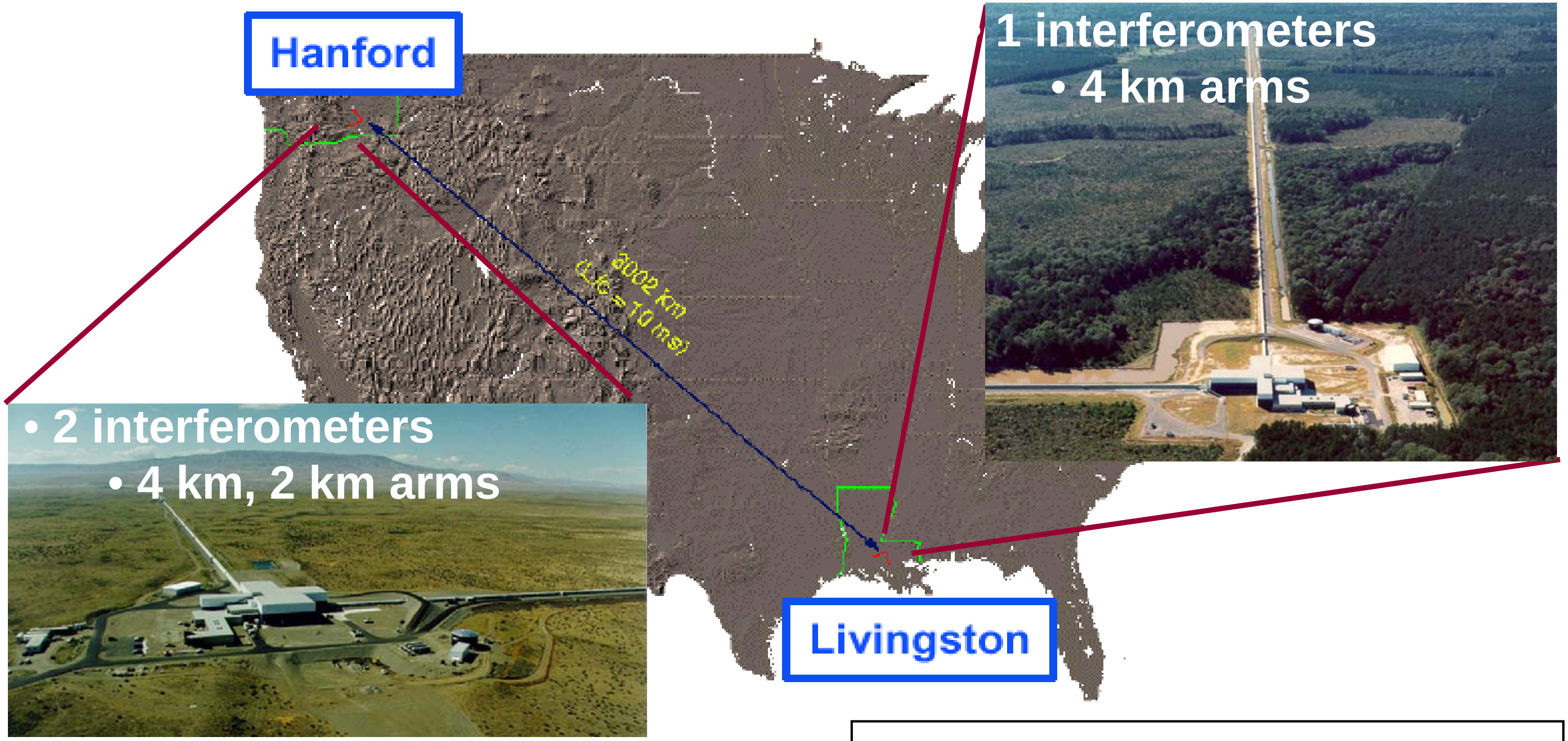
λ=1.06 μm

L = 4000 m

$N_{roundtrip}$ = 40

LIGO sites

LIGO Livingston Observatory



- 1 interferometers
  - 4 km arms

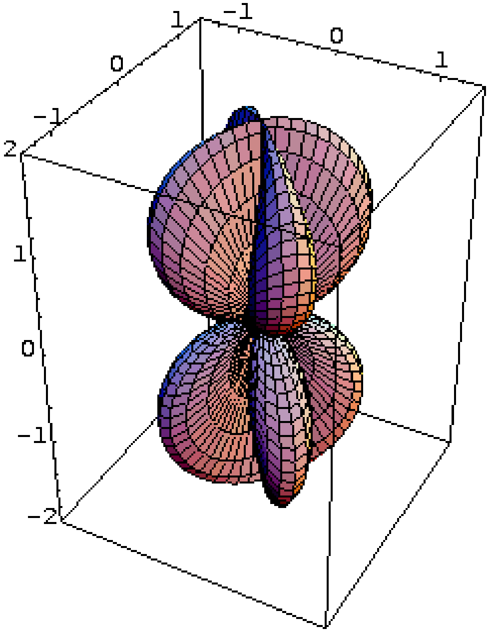
- 2 interferometers
  - 4 km, 2 km arms

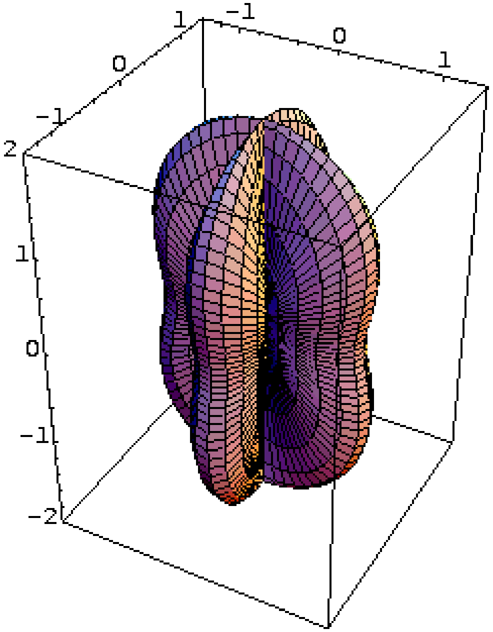
LIGO Hanford Observatory

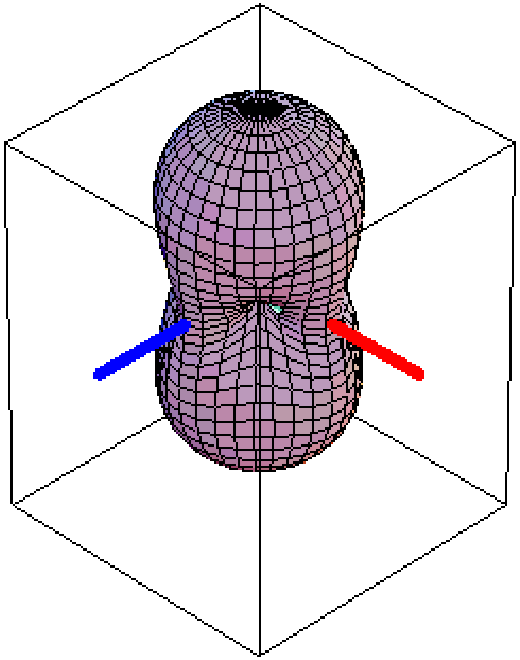
LIGO Observatories are operated by Caltech and MIT

An interferometer is really a microphone

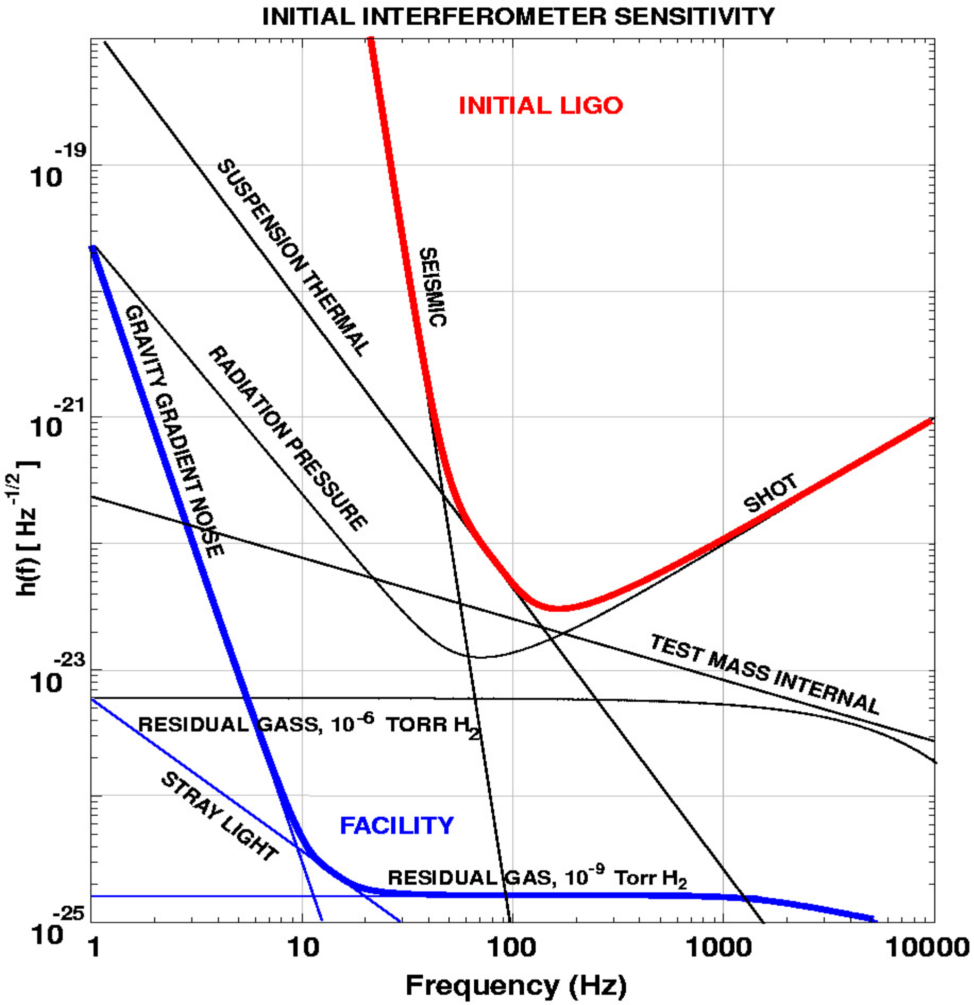
- Sensitivity depends on propagation direction, polarization


"×" polarization


"+" polarization

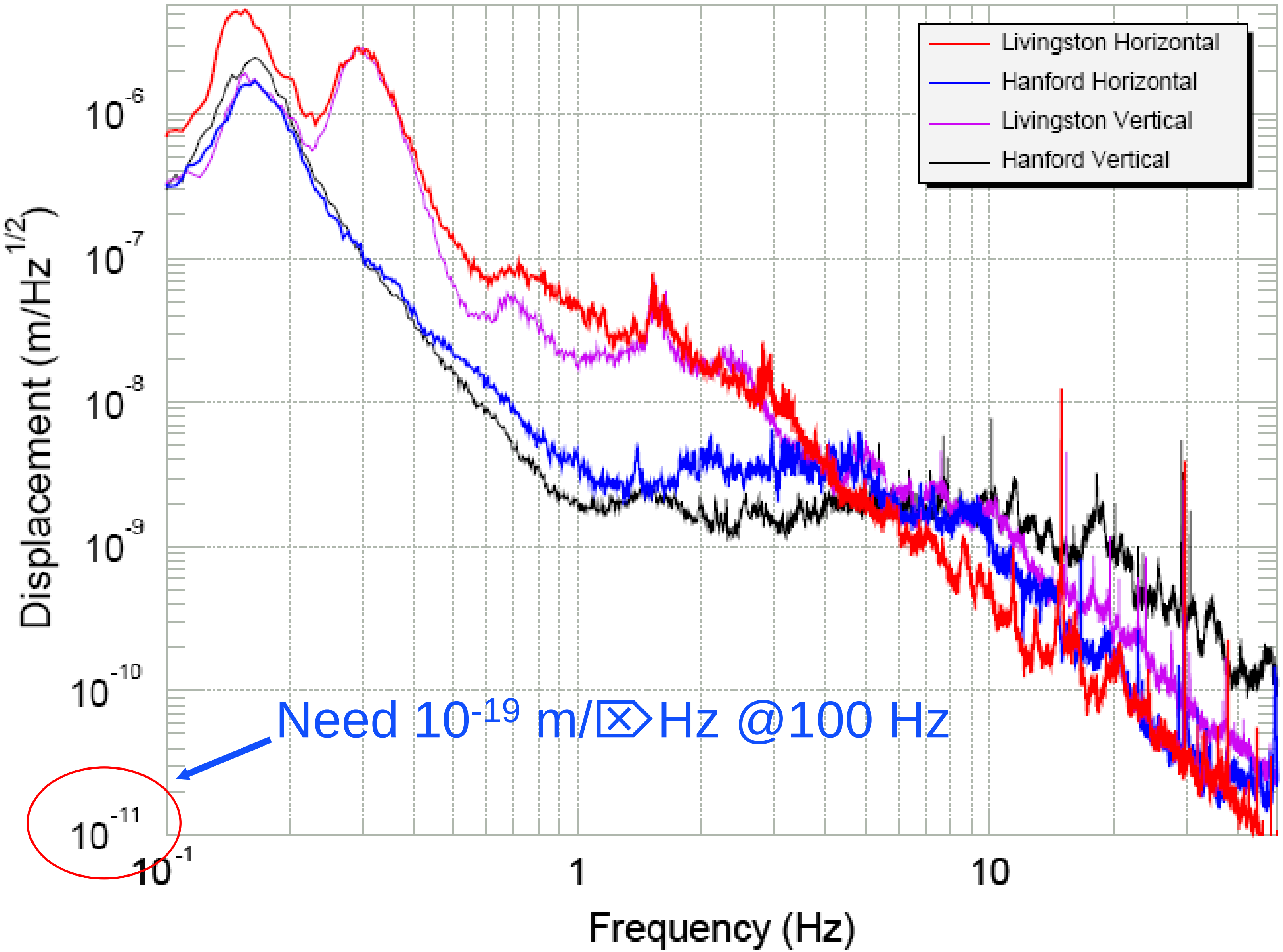

RMS sensitivity

Fundamental noises in LIGO



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

Seismic noise



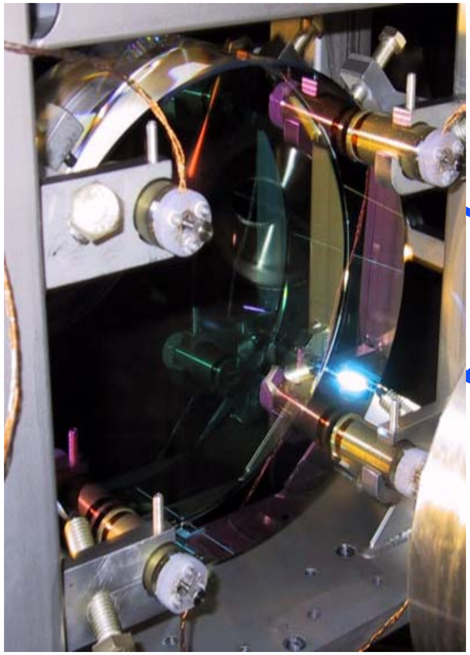
Need 10^{-19} m/⌧Hz @100 Hz

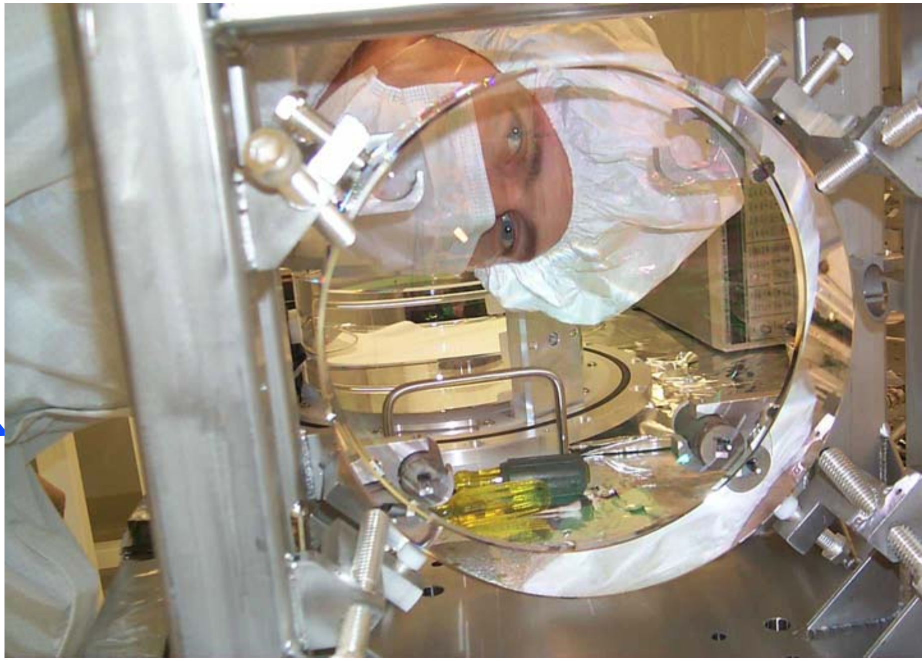
LIGO Vacuum Chambers

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)

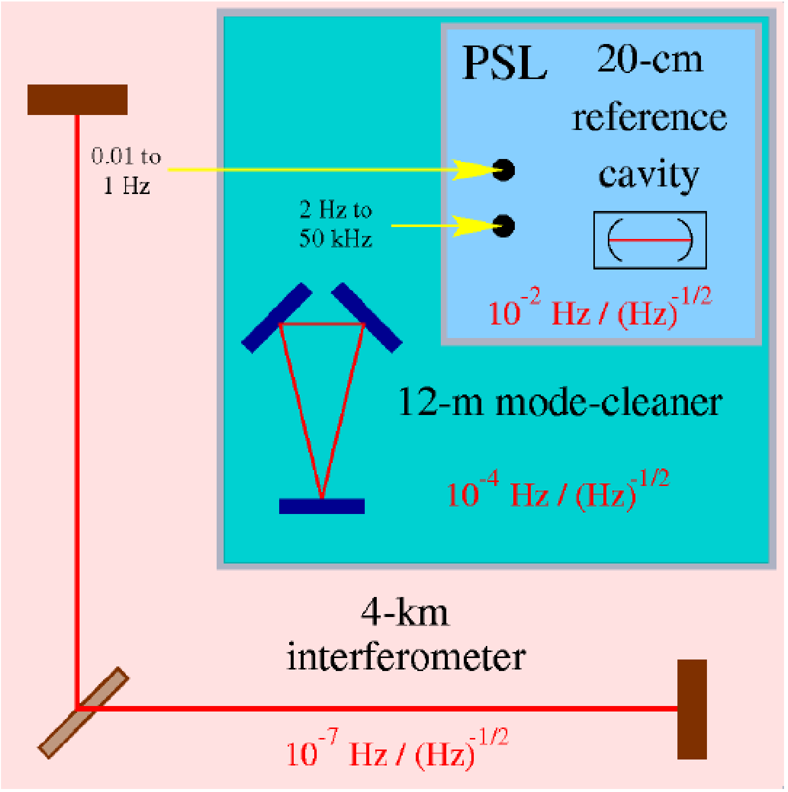
Wire standoff & magnet

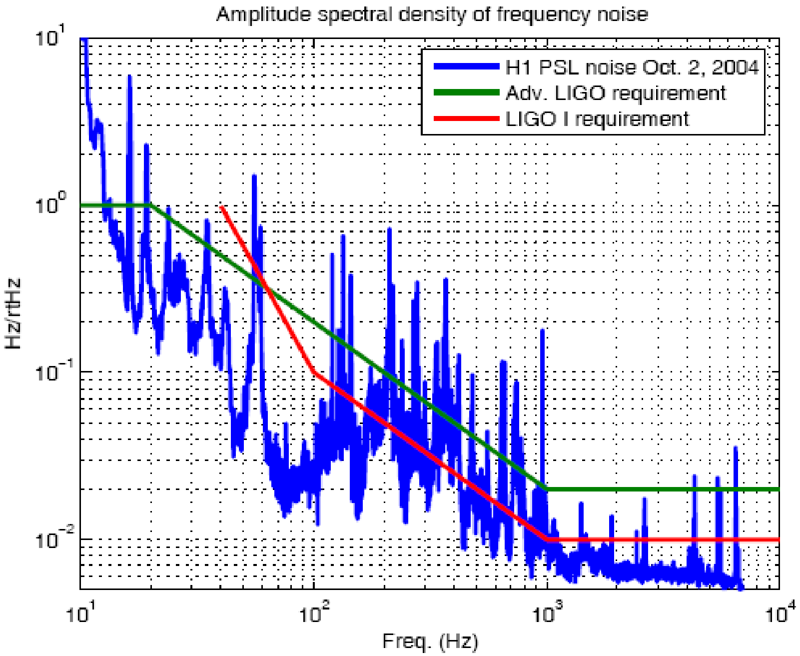




Frequency stabilization in LIGO

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

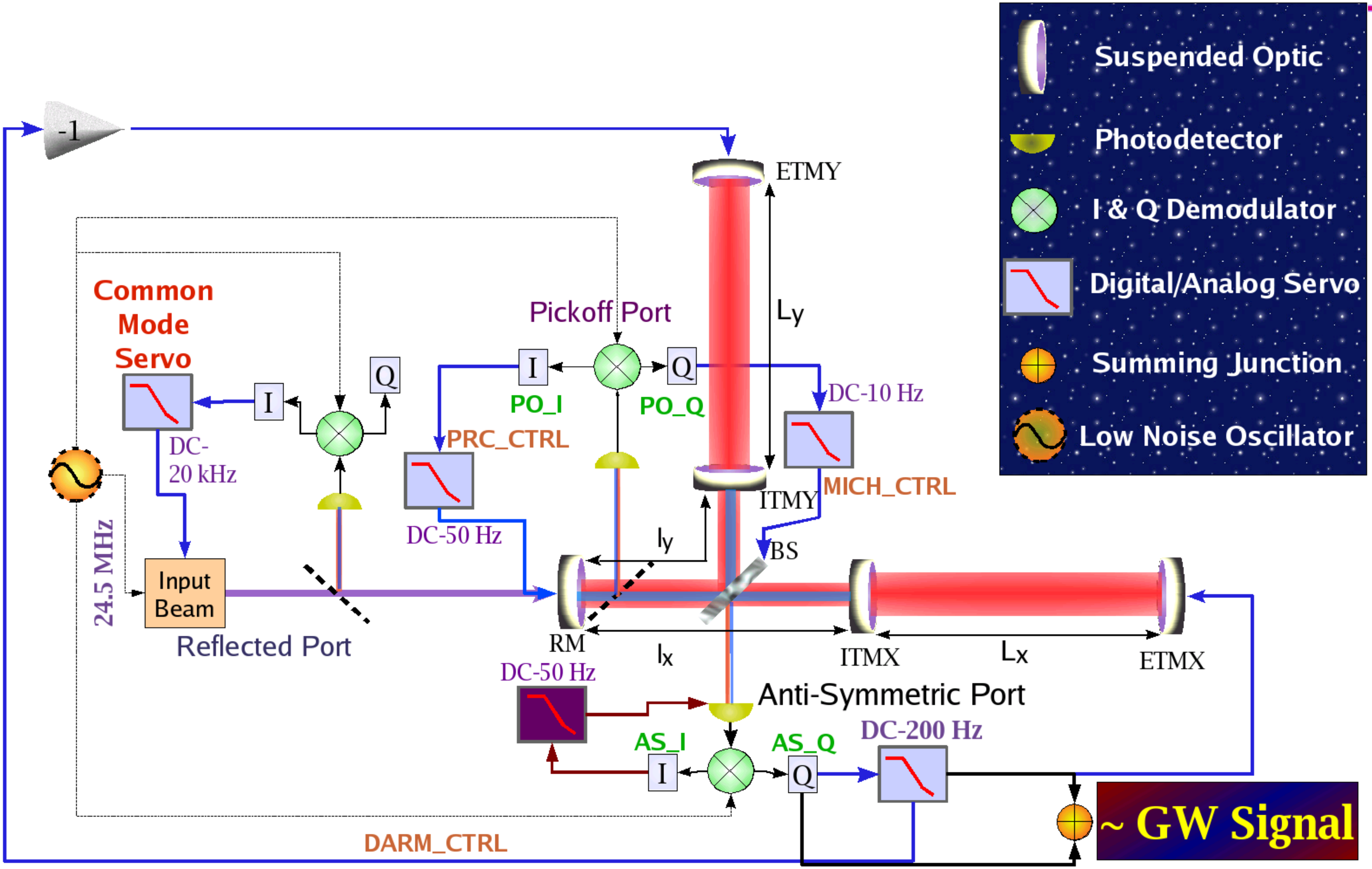




Ultimately:

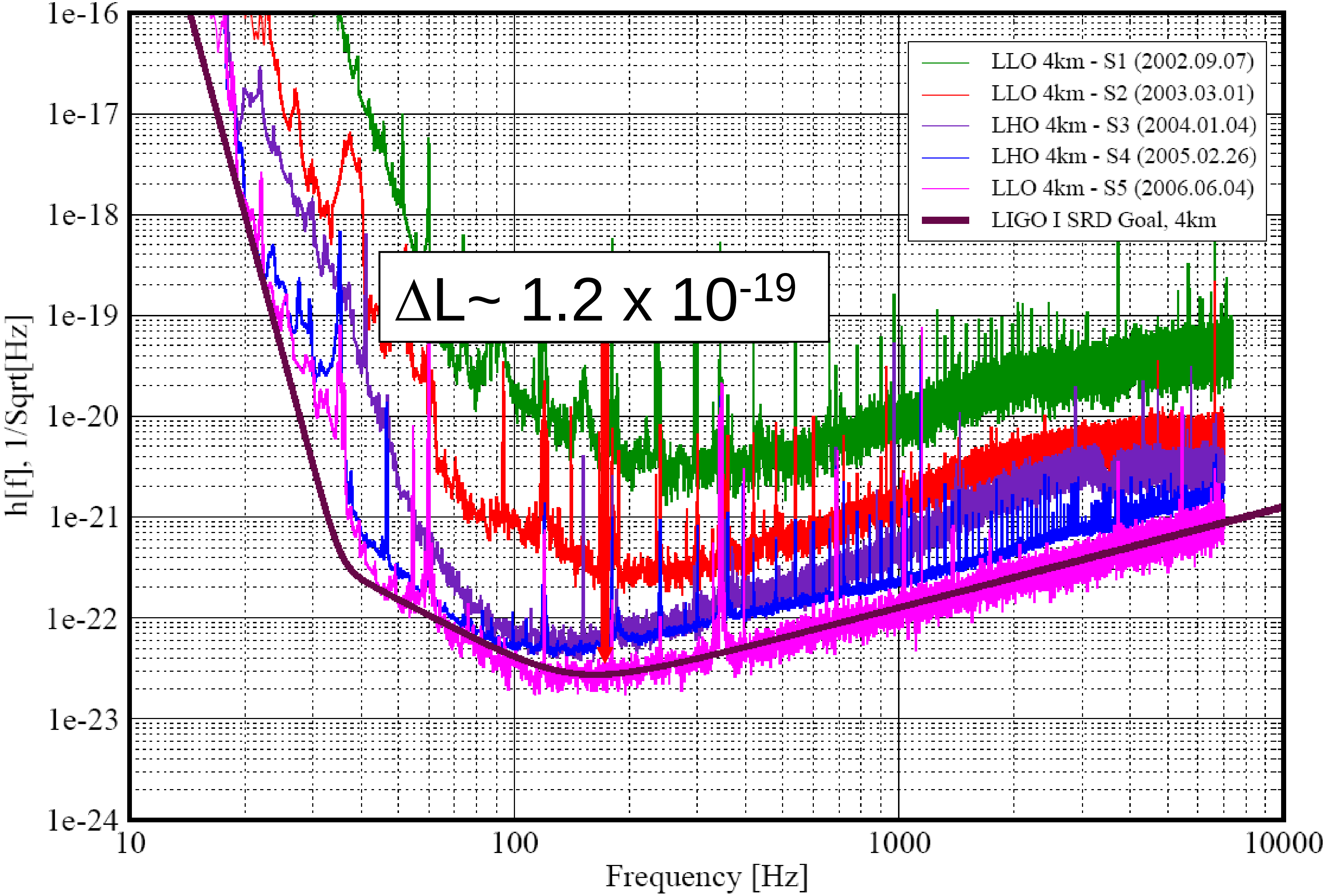
$\Delta f/f \sim 3 \times 10^{-22}$ @ 100 Hz

Length readout and control



Best Strain Sensitivities for the LIGO Interferometers

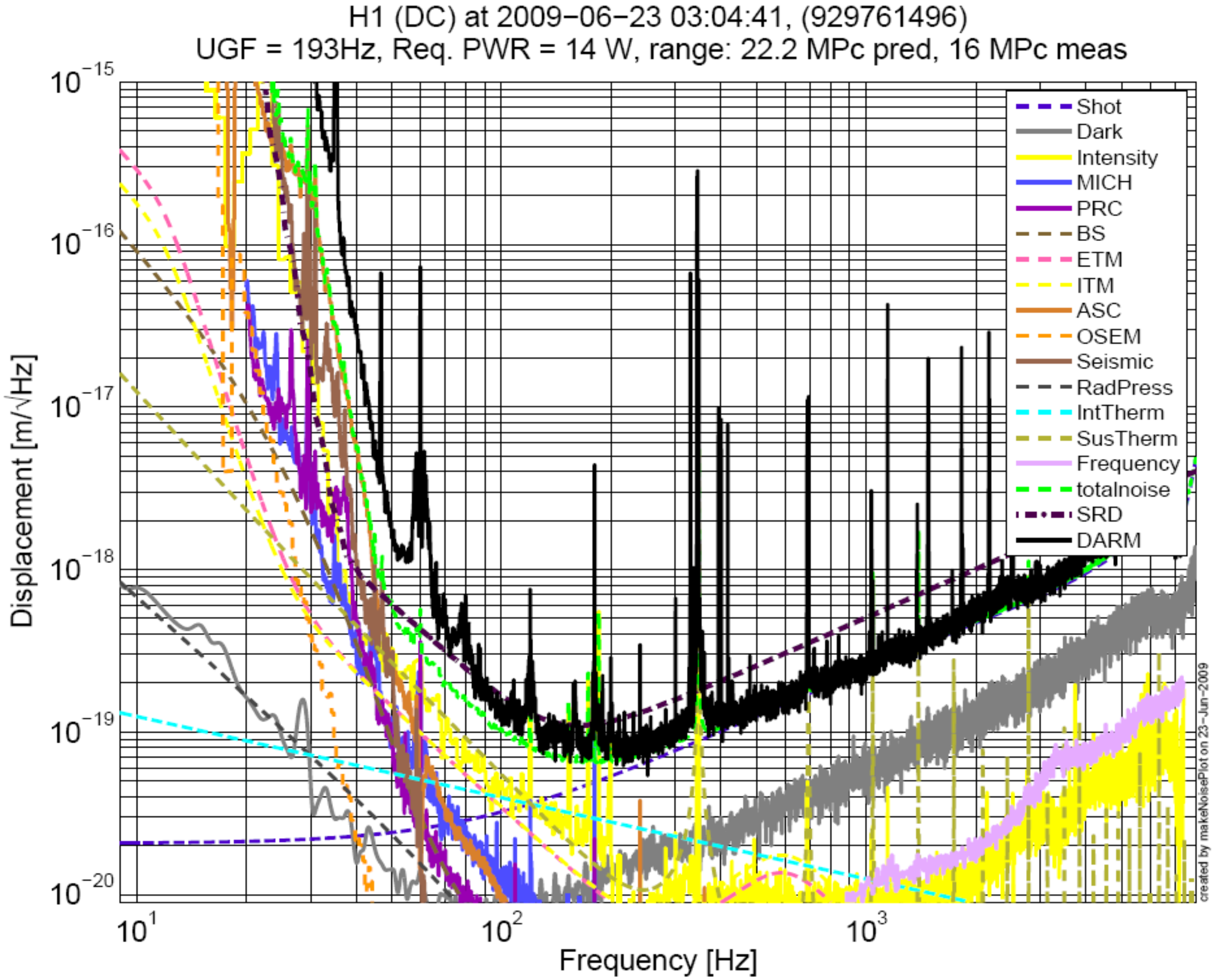
Comparisons among S1 - S5 Runs LIGO-G060009-02-Z



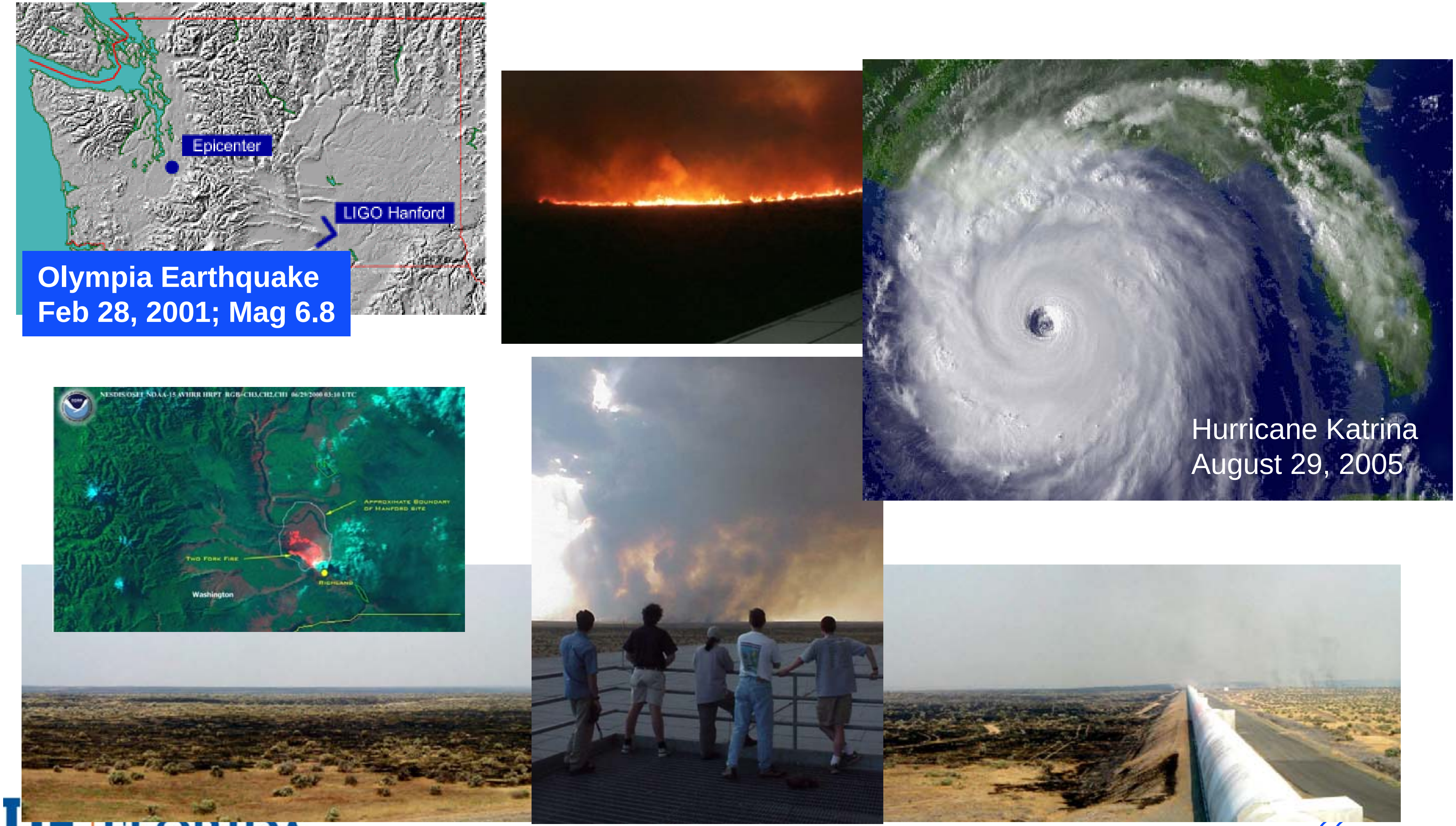
$\Delta L \sim 1.2 \times 10^{-19}$

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…



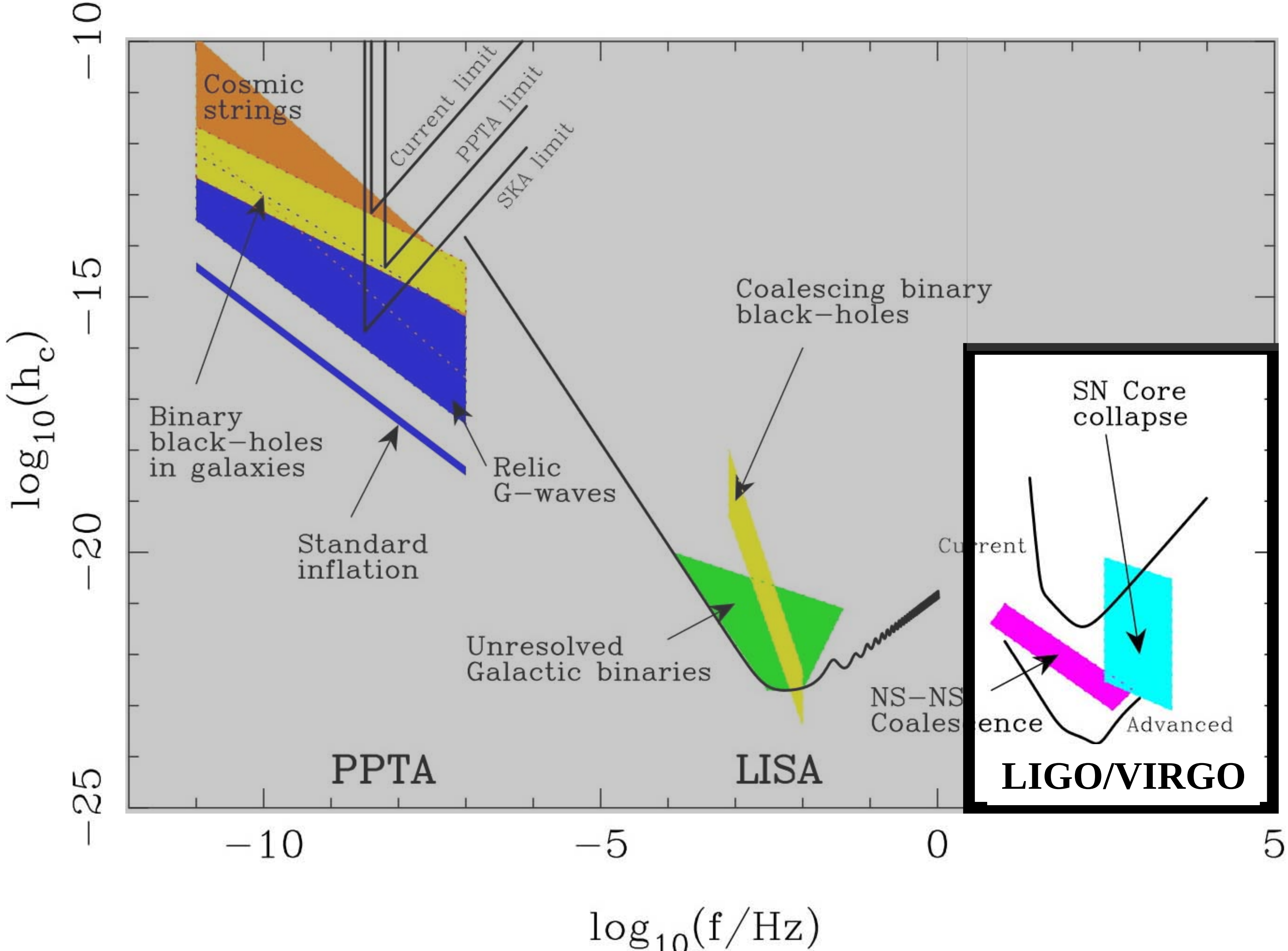
Olympia Earthquake
Feb 28, 2001; Mag 6.8

Hurricane Katrina
August 29, 2005

As can cars…

The Gravitational Wave Spectrum

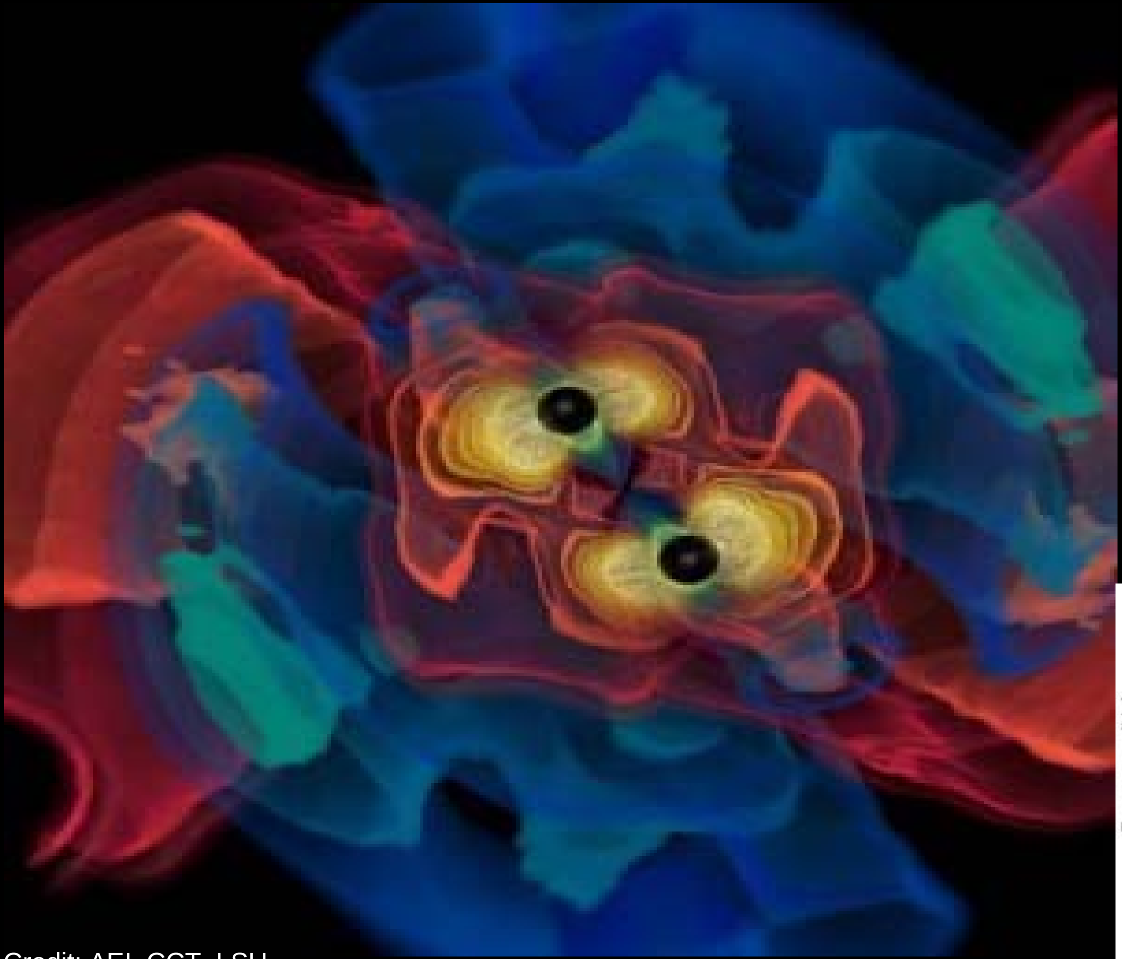
Dick Manchester, CSIRO



LIGO Astrophysics

- The LIGO Scientific Collaboration
  - 640 members, 50 institutions, 11 countries
- Five Science Runs To Date
  - S1: August 23 - September 9, 2002 (17 days)
  - S2: February 14 – April 14, 2003 (59 days)
  - S3: October 31, 2003 – January 9, 2004 (70 days)
  - S4: February 22 – March 23, 2005 (30 days)
  - **S5: November 4, 2005 – September 31, 2007**
    - > 365 days of triple coincidence, 400 days of double coincidence
    - Duty cycle: 78% for the Hanford 4k, 79% for the Hanford 2k and 66% for Livingston 4k
- LSC-Virgo started data-sharing on May 18, 2007
  - Virgo VSR1: May 18, 2007 – Oct 1, 2007
  - >75 days of 3-site coincidences with LIGO, 95 days of 2-site coincidences
  - Duty cycle: 81% for Virgo

The astrophysical gravitational wave source catalog

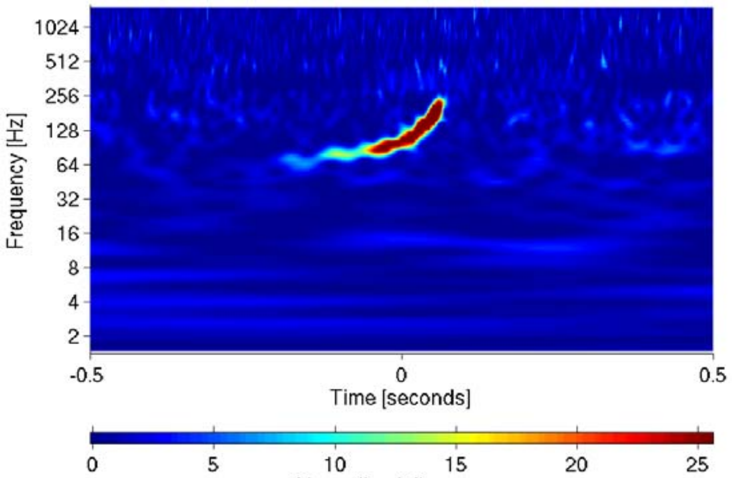


Credit: AEI, CCT, LSU

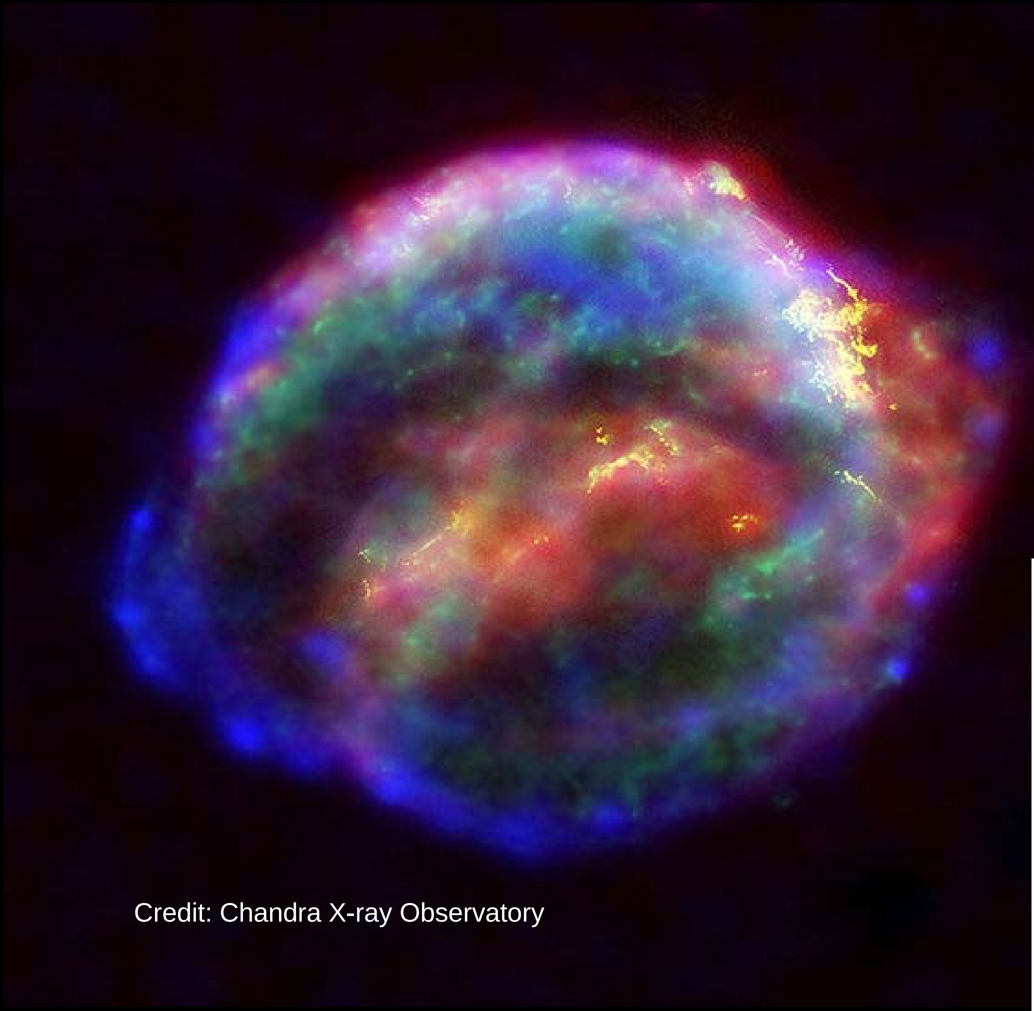
http://web.mit.edu/sahughes/www/sounds.html

Coalescing Binary Systems

- Neutron stars, black holes
- ‘chirped’ waveform



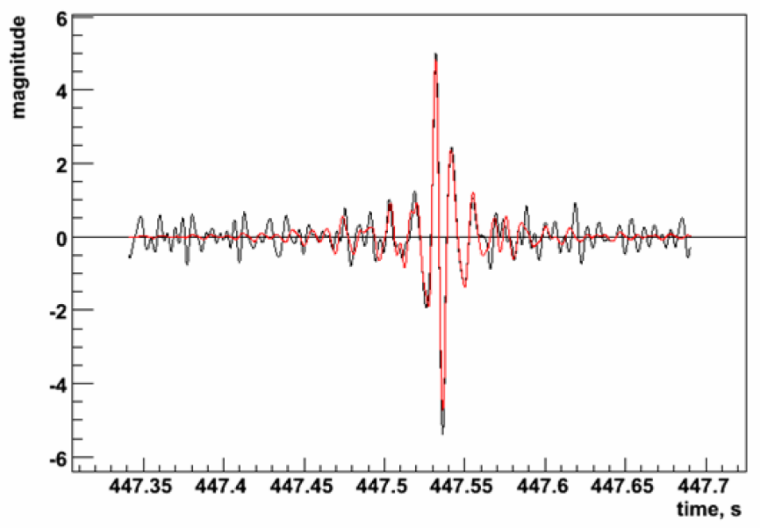
The astrophysical gravitational wave source catalog



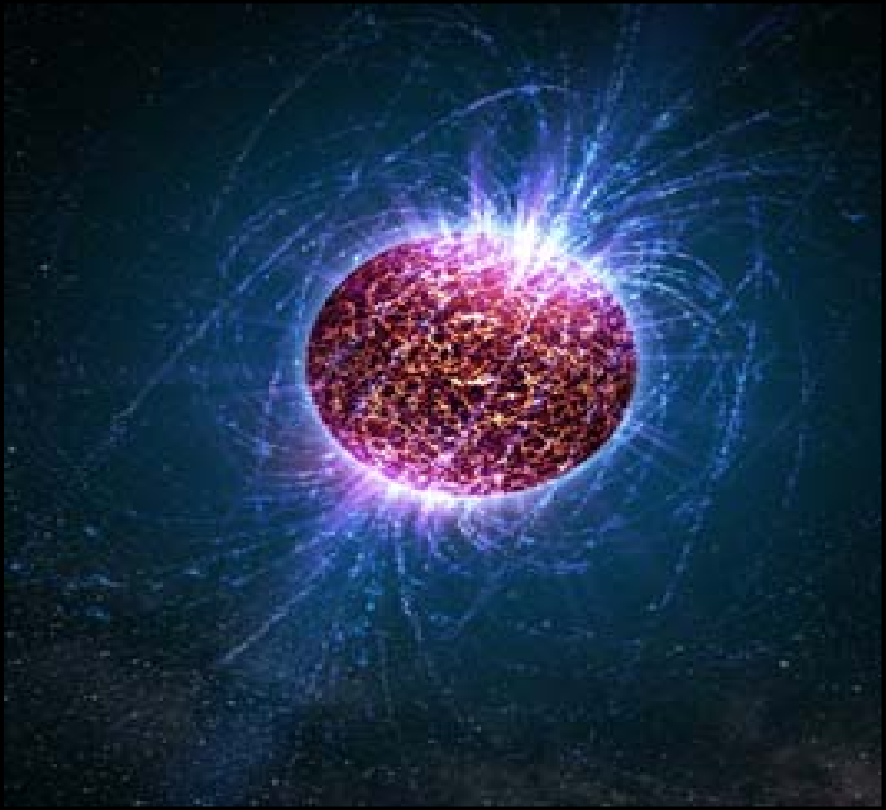
Credit: Chandra X-ray Observatory

‘Bursts’

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



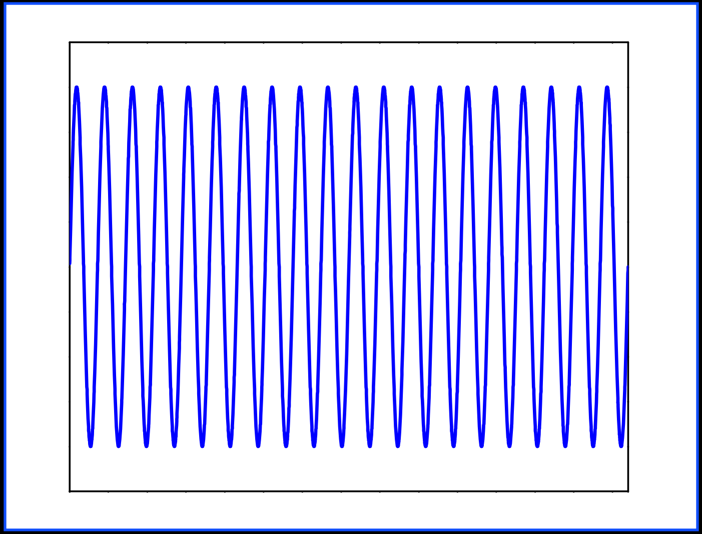
The astrophysical gravitational wave source catalog



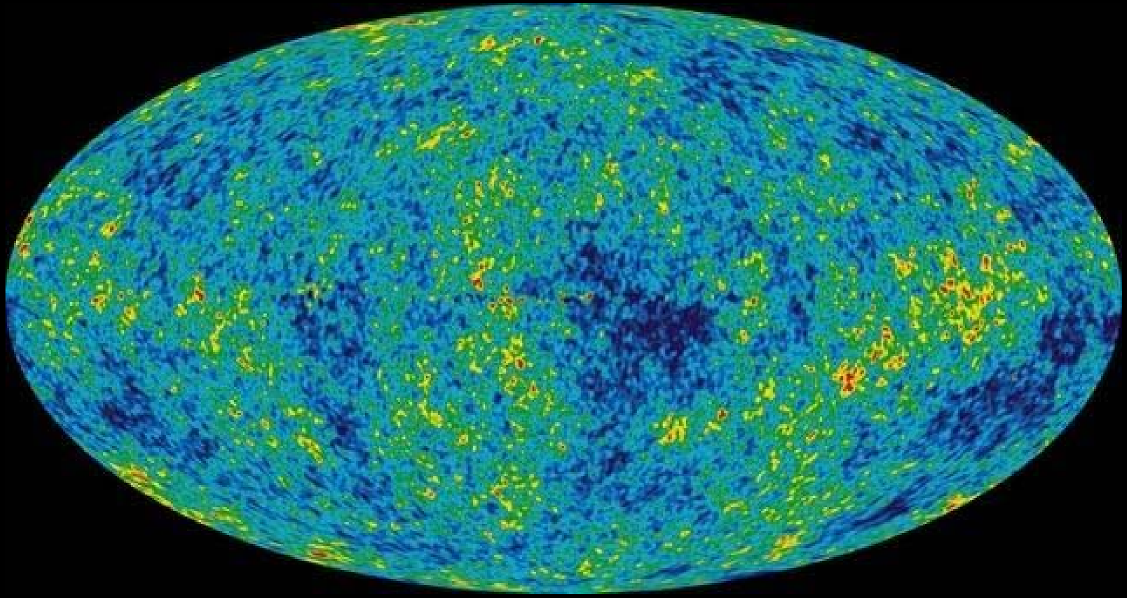
Casey Reed, Penn State

Continuous Sources

- Spinning neutron stars
- monotone waveform



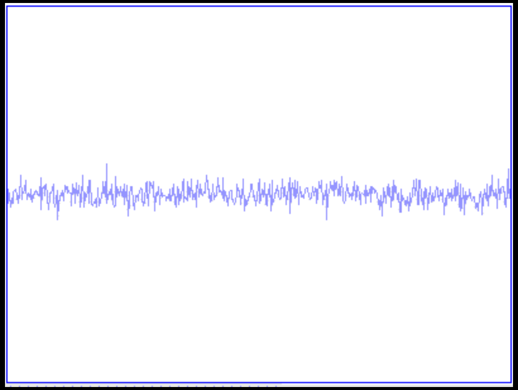
The astrophysical gravitational wave source catalog



NASA/WMAP Science Team

Cosmic GW background

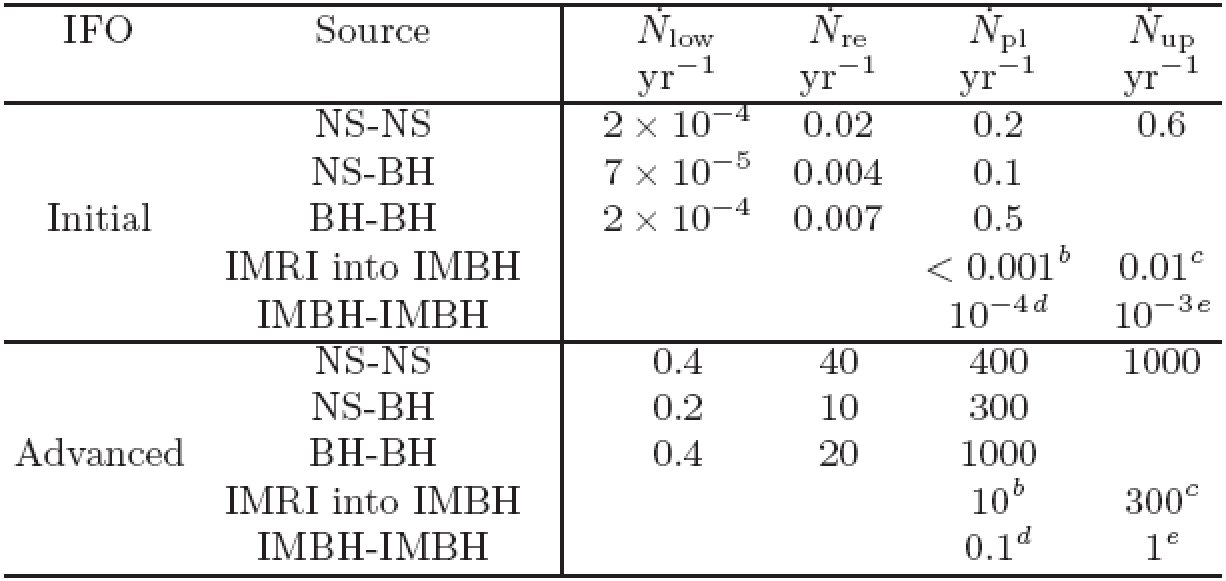
- residue of the Big Bang
- probes back to 10^{-21} s after the birth of the universe
- stochastic, incoherent background



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)

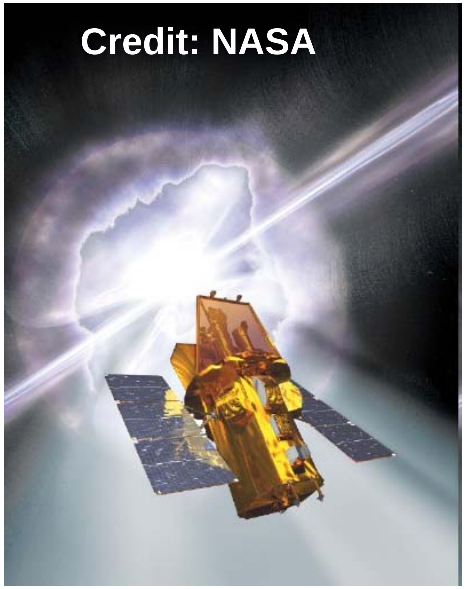
TABLE V: Detection rates for compact binary coalescence sources.



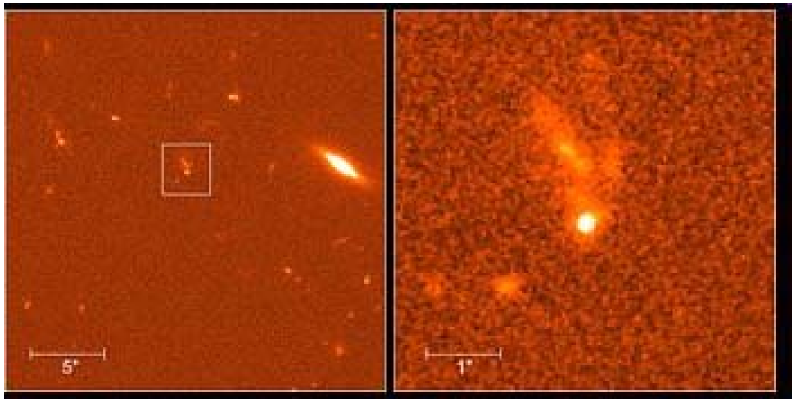
IFO	Source	$\dot N_{\rm low}$ $\rm yr^{-1}$	$\dot N_{\rm re}$ $\rm yr^{-1}$	$\dot N_{\rm pl}$ $\rm yr^{-1}$	$\dot N_{\rm up}$ $\rm yr^{-1}$
Initial	NS-NS	2×10^{-4}	0.02	0.2	0.6
	NS-BH	7×10^{-5}	0.004	0.1	
	BH-BH	2×10^{-4}	0.007	0.5	
	IMRI into IMBH			$< 0.001^{b}$	0.01^{c}
	IMBH-IMBH			$10^{-4\,d}$	$10^{-3\,e}$
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}

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=2.6
  - » Short GRBs are less well understood
    - – Soft gamma repeaters → magnatars



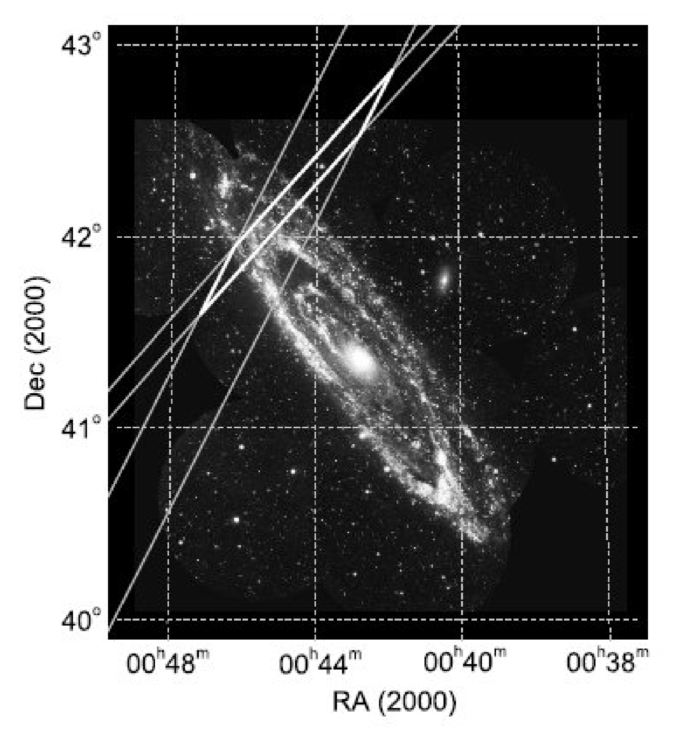
Credit: NASA



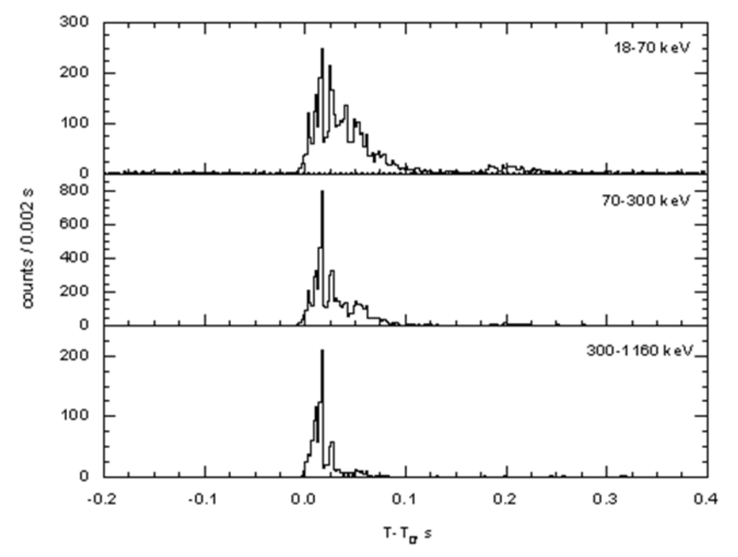
NASA Hubble Space Telescope Imaging Spectrograph (STIS)

GRB 070201

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



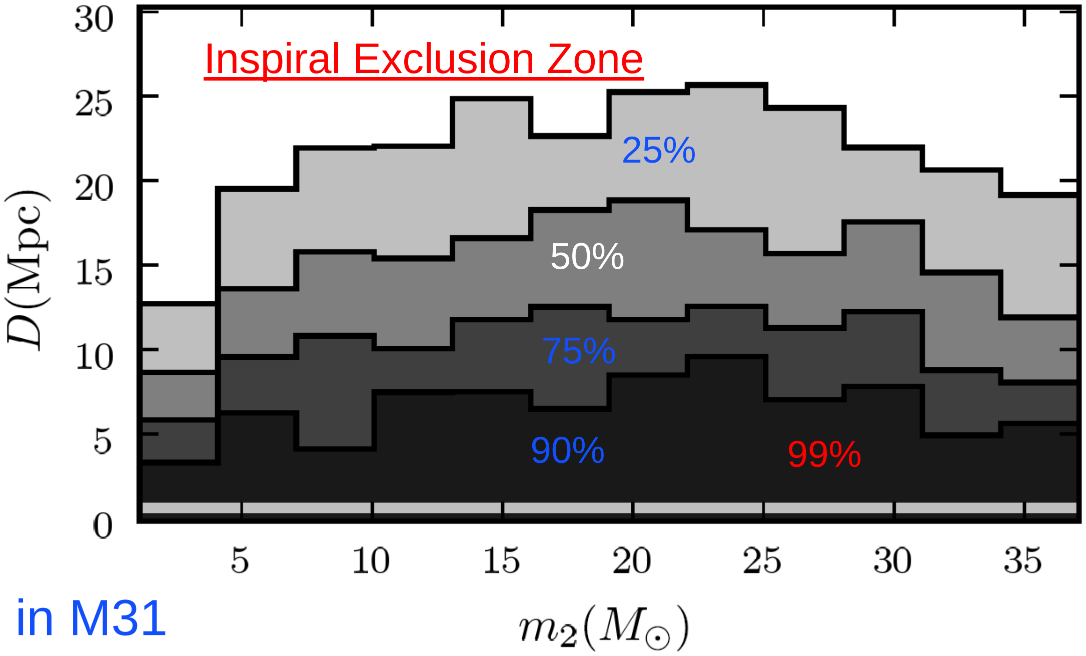
X-ray emission curves (IPN)



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



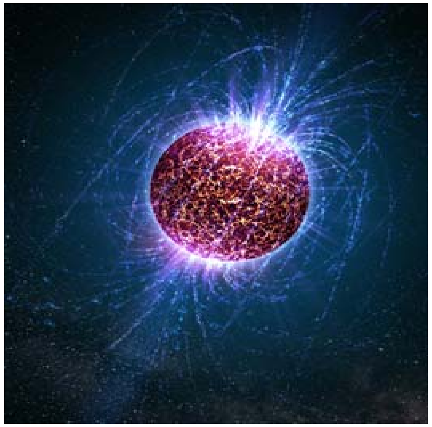
- Burst search:
  - Cannot exclude an SGR in M31
    - SGR in M31 is the current best explanation for this emission
  - Upper limit: $8\mathrm{x}10^{50}$ ergs ($4\mathrm{x}10^{-4}$ $M_\bullet c^2$) (emitted within 100 ms for isotropic emission of energy in GW at M31 distance)

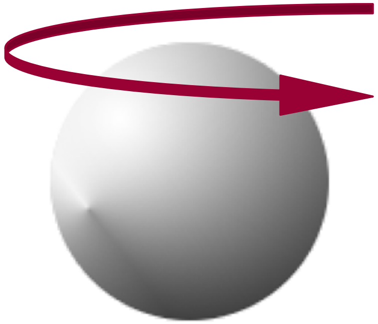
Pulsars

- 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

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

  - 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

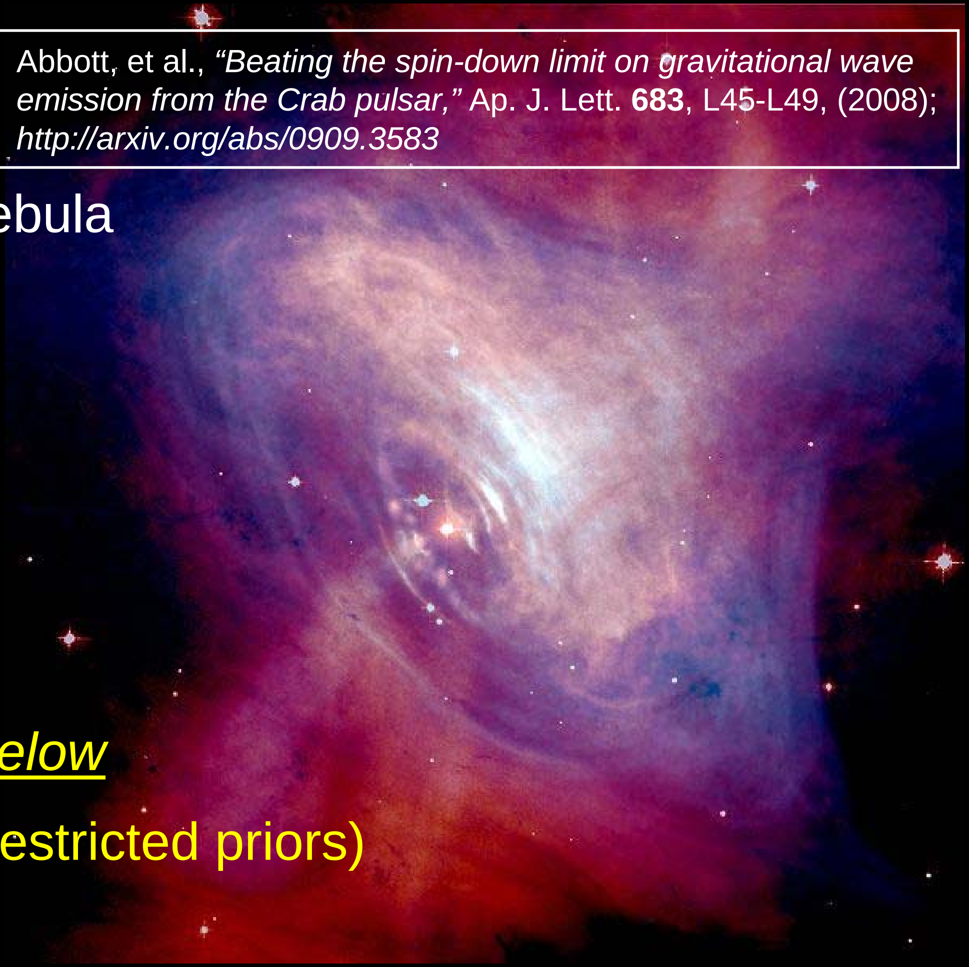
  → $\nu_{gw} = 2\ \nu_{EM}$ = 59.6 Hz
- observed luminosity of the Crab nebula

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 *below*

  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*

The stochastic GW background

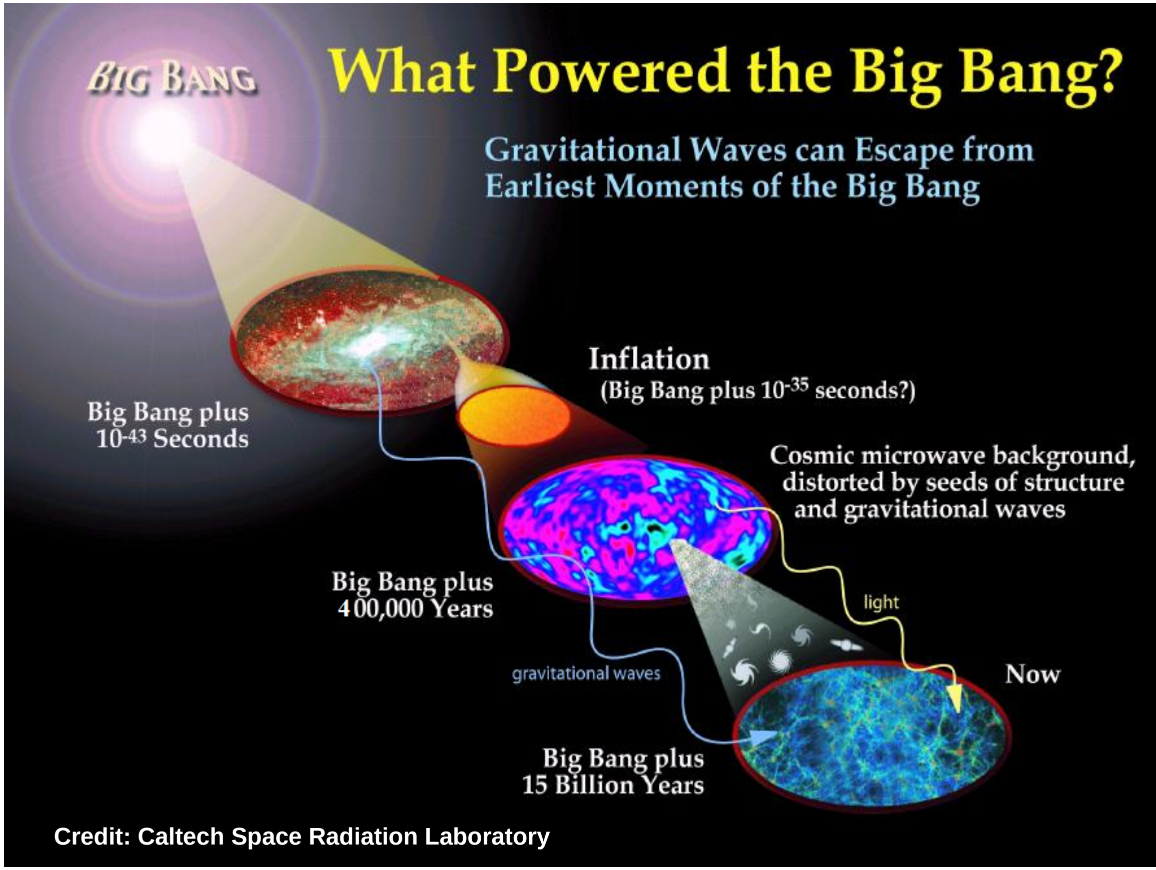
- An isotropic Stochastic GW background could come from:
  - » Primordial universe (inflation)
  - » Incoherent sum of point emitters isotropically distributed over the sky
- Expressed a fraction of closure density of the universe:

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

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

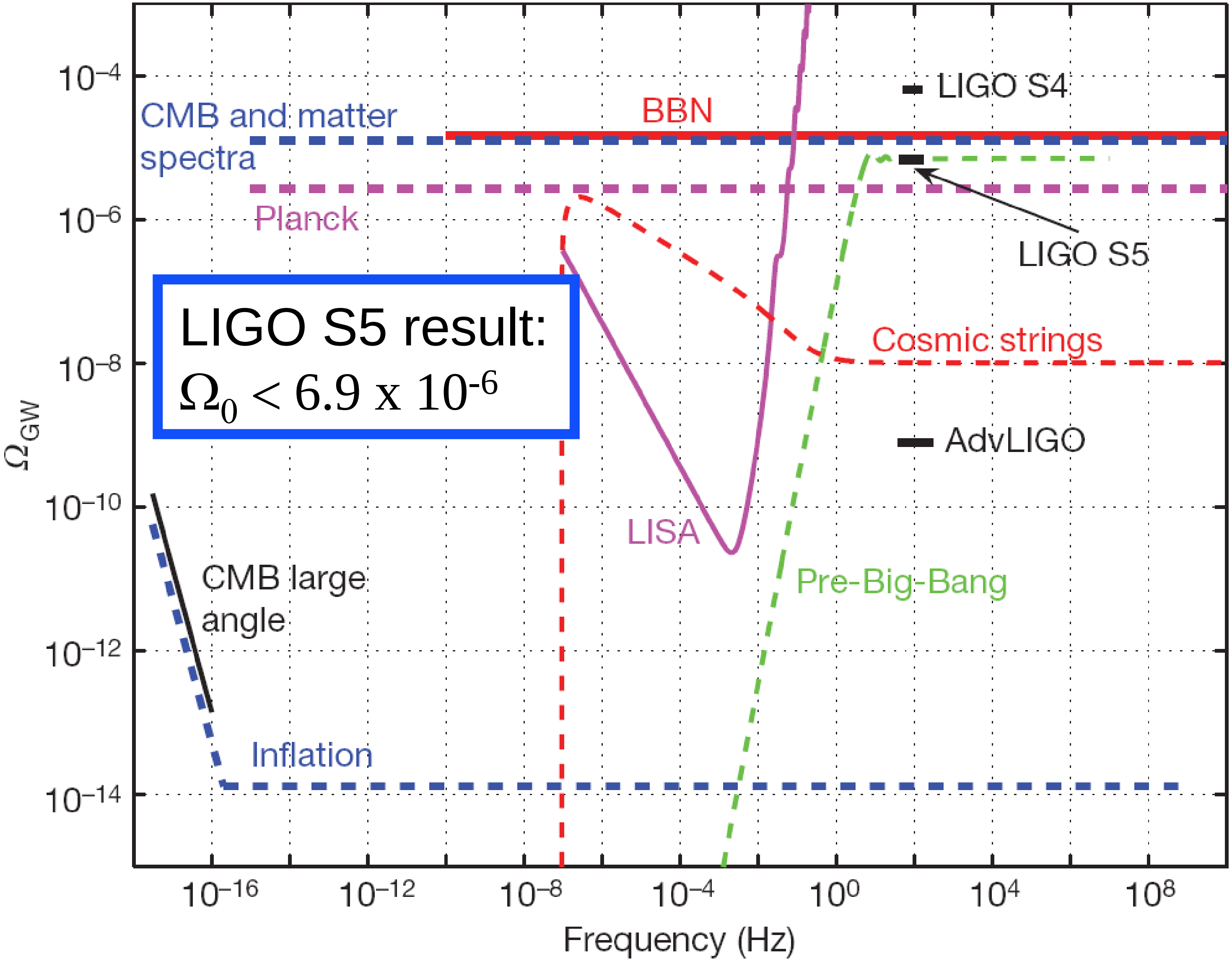
- Big Bang Nucleosynthesis limit:

$$\Omega_{0,\ \mathrm{BBN}} < 1.1 \text{ x } 10^{-5}$$



Credit: Caltech Space Radiation Laboratory

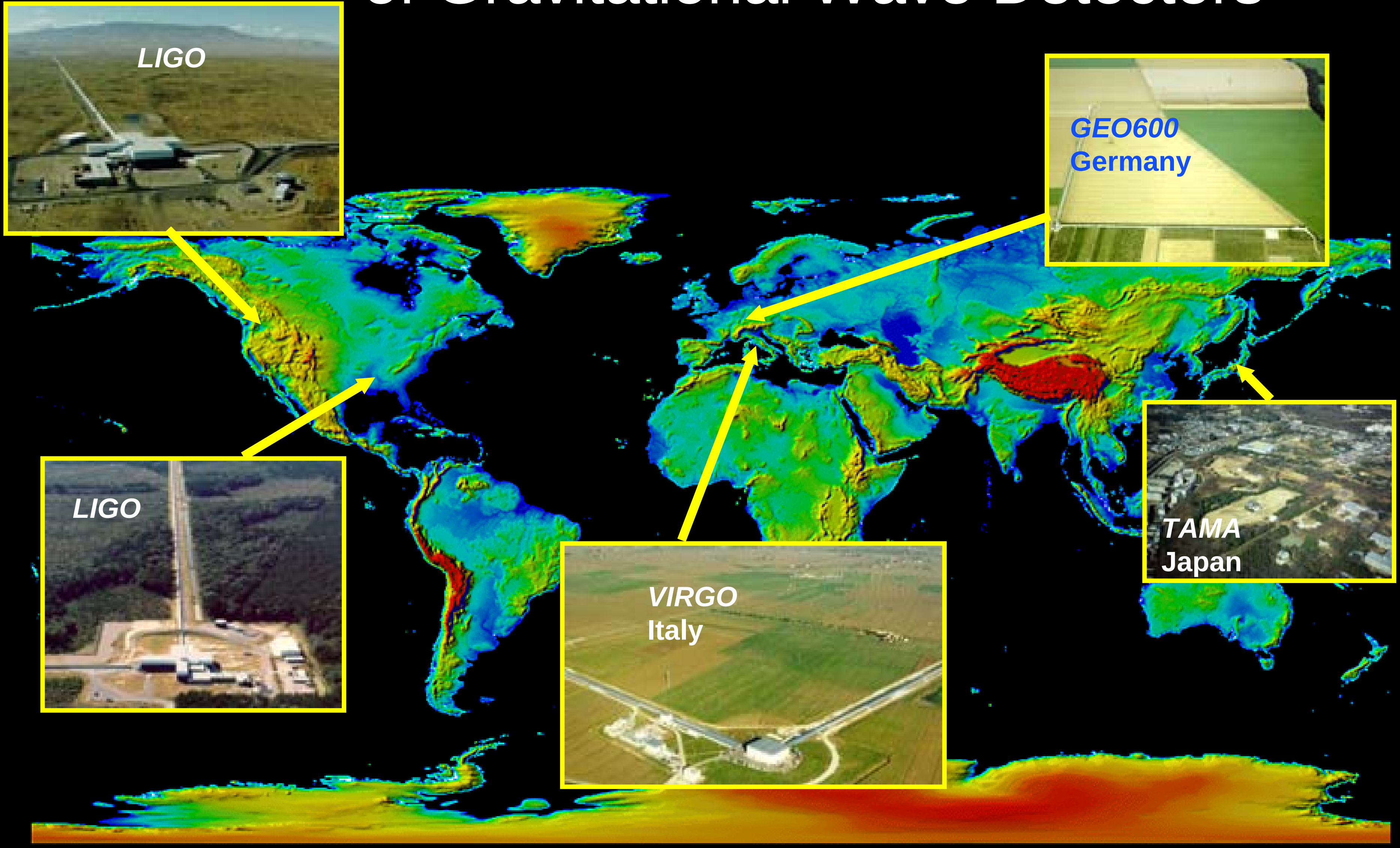
Abbott, et al. “*An upper limit on the stochastic gravitational-wave background of cosmological origin*”, Nature., V460: 990 (2009).

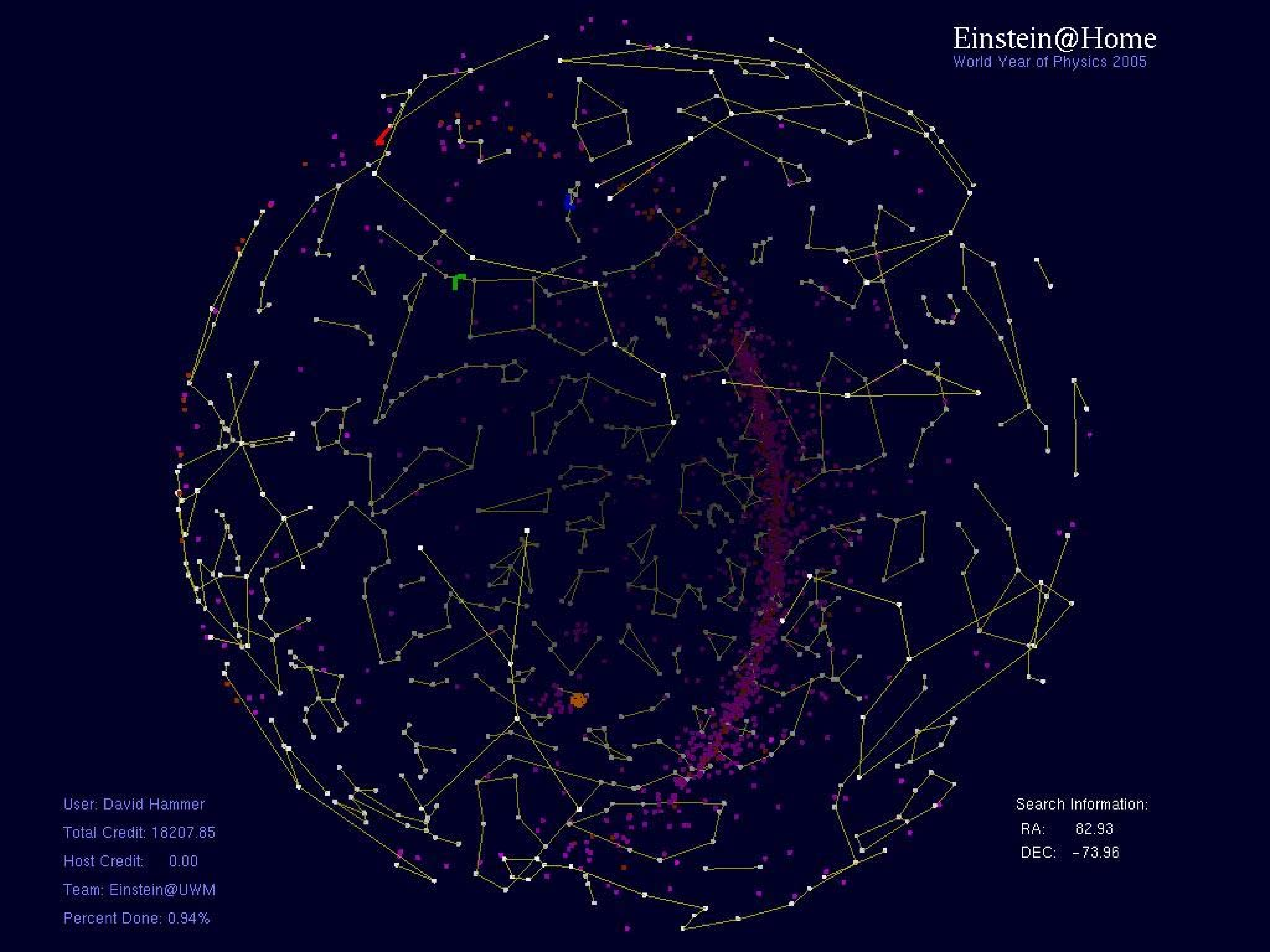


LIGO S5 result:

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

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

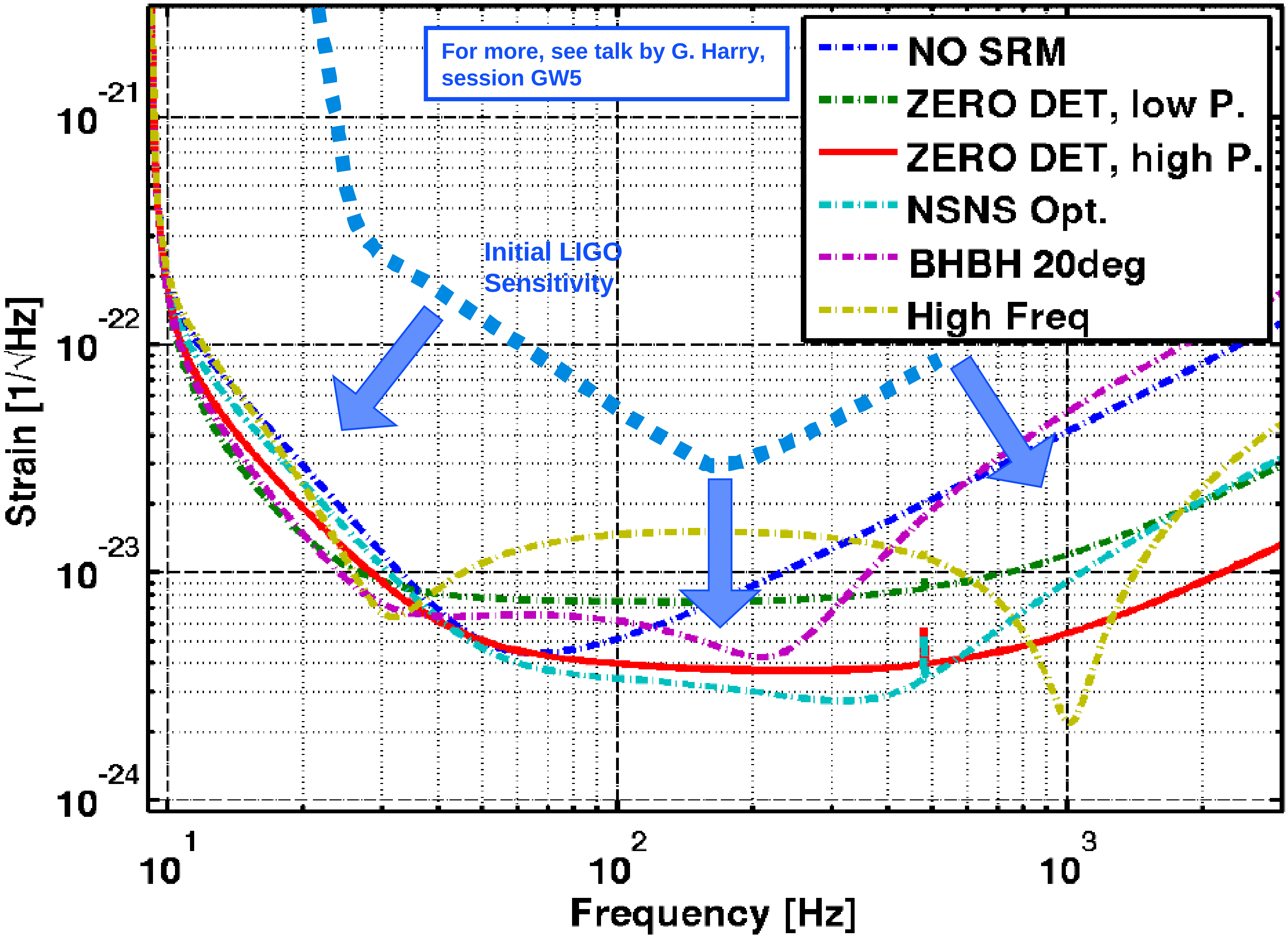
Percent Done: 0.94%

Search Information:

RA: 82.93

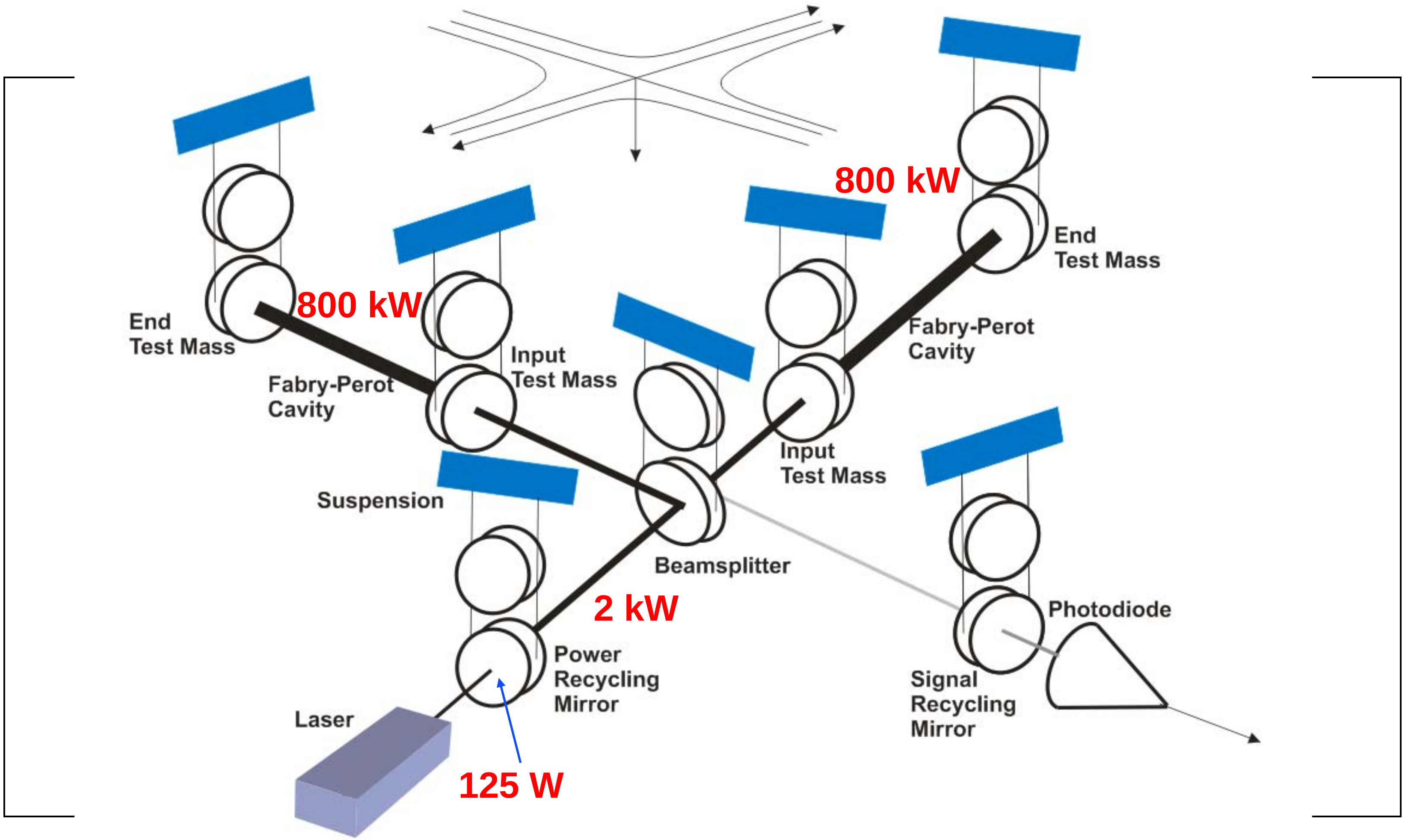
DEC: -73.96

AdvLIGO tunings



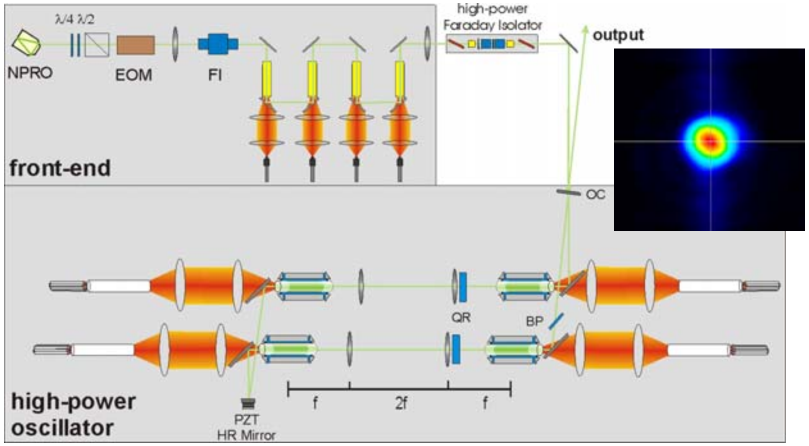
For more, see talk by G. Harry, session GW5

Advanced LIGO



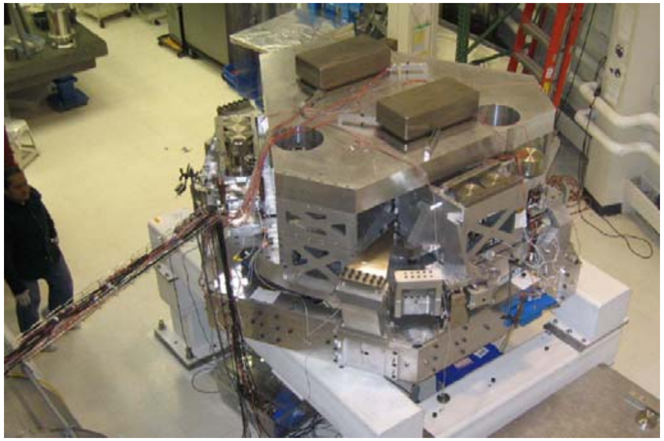
Advanced LIGO

180 W laser

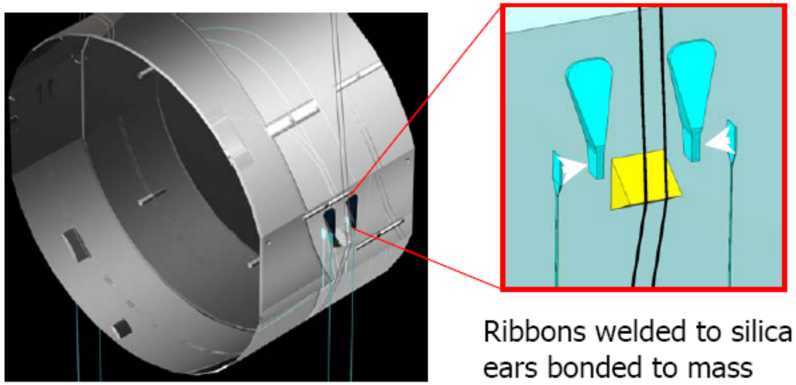


Mirror Suspensions

Seismic isolation



Mirrors



Ribbons welded to silica ears bonded to mass

The Gravitational Wave Universe

Stay Tuned...

LIGO

LIGO Scientific Collaboration

LSC

University of Maryland 1856

MICHIGAN

University of Strathclyde

Tsinghua University

ACIGA

LOYOLA UNIVERSITY NEW ORLEANS

MONTANA STATE UNIVERSITY

PAH

UNIVERSITY OF WASHINGTON

TRINITY UNIVERSITY

San José State UNIVERSITY

UNIVERSITY of WISCONSIN UWMILWAUKEE

ANU THE AUSTRALIAN NATIONAL UNIVERSITY

SYRACUSE UNIVERSITY FOUNDED AD 1870 SUOS CULTORES SCIENTIA CORONAT

UNIVERSITY of GLASGOW

Università degli Studi del Sannio

UTB TSC

THE UNIVERSITY OF WESTERN AUSTRALIA

1754

NASA GODDARD SPACE FLIGHT CENTER

LSU

CALIFORNIA INSTITUTE OF TECHNOLOGY 1891

NORTHWESTERN UNIVERSITY

Andrews University

MASSACHUSETTS INSTITUTE OF TECHNOLOGY 1861

SOUTHEASTERN

THE UNIVERSITY OF TEXAS AT AUSTIN

Moscow State University

R·I·T

THE UNIVERSITY OF ADELAIDE AUSTRALIA

PAN

GEO 600

EMBRY-RIDDLE AERONAUTICAL UNIVERSITY

UNIVERSITY OF MASSACHUSETTS AMHERST 1863

University of Southampton

PENNSTATE 1855

SIGILL: COLL: CARLETON NORTHFIELD, MINN. AD. 1866

CARDIFF UNIVERSITY

UIB Universitat de les Illes Balears

WASHINGTON STATE UNIVERSITY

UF UNIVERSITY of FLORIDA

The University of Mississippi 1848

CHARLES STURT UNIVERSITY

NAOJ

UNIVERSITY OF MINNESOTA

UNIVERSITY OF ROCHESTER

UNIVERSITY of

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