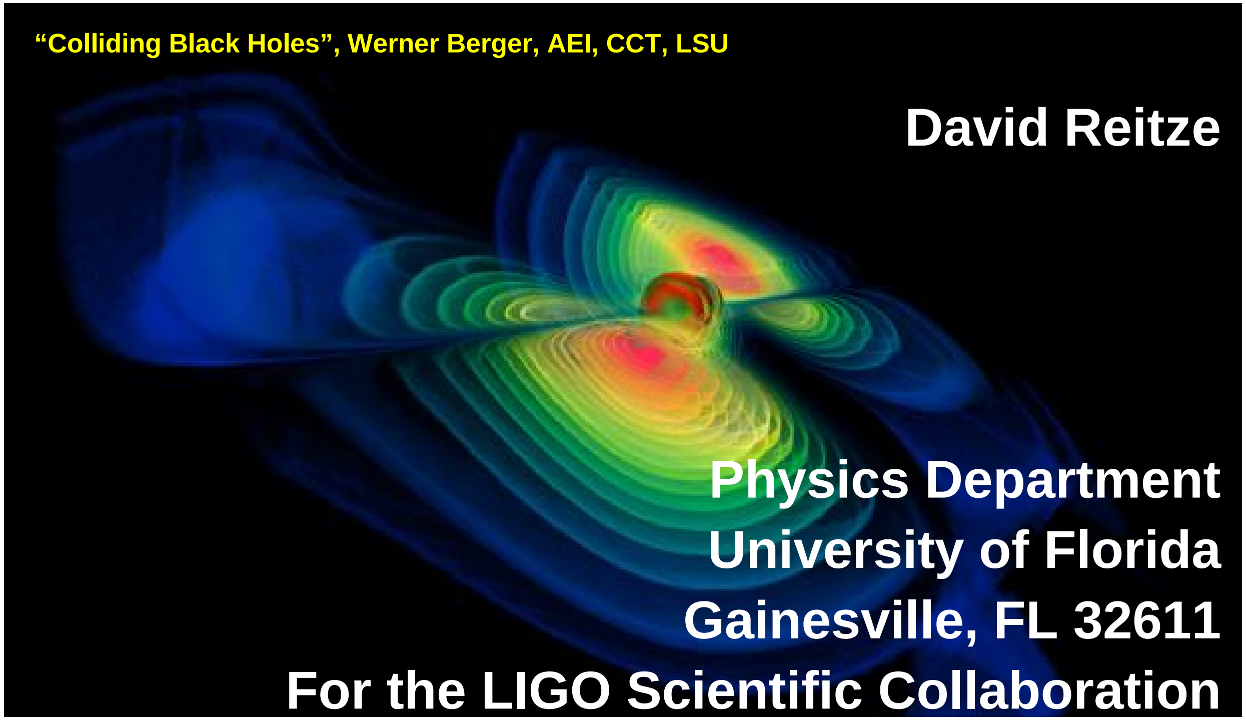
G070639-00-Z

The Laser Interferometer Gravitational Wave Observatory: Shining Light on Black Holes



"Colliding Black Holes", Werner Berger, AEI, CCT, LSU

David Reitze

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

This talk is about …

- … gravitational waves and where they come from, and what they tell us about the universe.
  - Black holes, the Big Bang, and other objects
- …laser interferometry to detect gravitational waves.
  - LIGO and other GW projects
  - The physics of gravitational wave detectors: "It's all about noise!"
- … what have we learned about gravitational waves to date with LIGO.
- … future gravitational wave detectors
  - Advanced LIGO

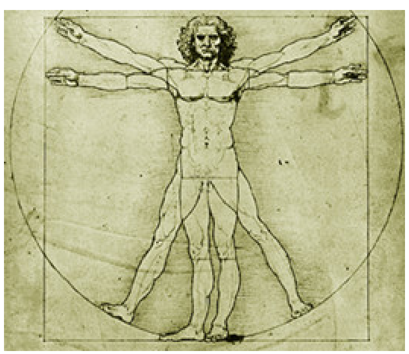
Gravitational Waves

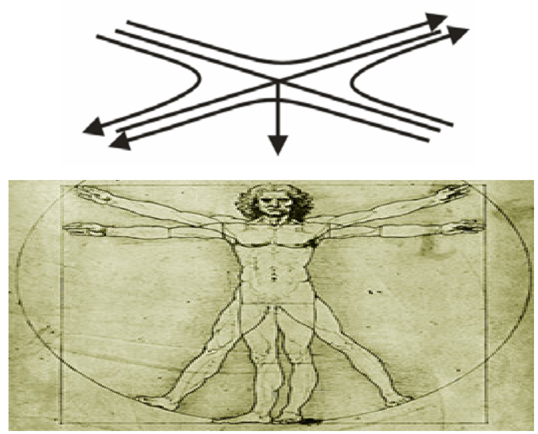
<u>Gravitational Waves:</u> **"Odd man out" in general relativity; predicted, but never *directly* observed.**

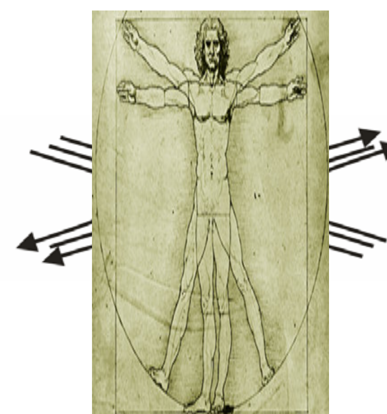
Weak Field Limit of GR:

***h* is a *strain*: $\Delta L/L$**

$$ds^2 = g_{\mu\nu}\, dx^\mu\, dx^\nu \qquad g_{\mu\nu} \approx \eta_{\mu\nu} + h_{\mu\nu} \qquad h(r,t) = h_{+,x}\, \exp[i(k \cdot r - \omega t)]$$







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
- Two polarizations: σ^+, σ^-
- Spin 1 fields → 'photons'

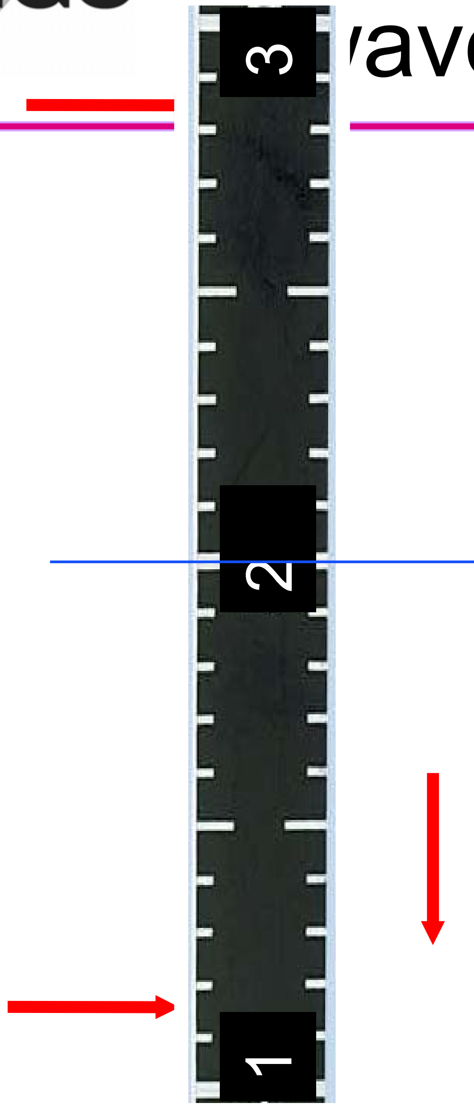
Gravitational Waves

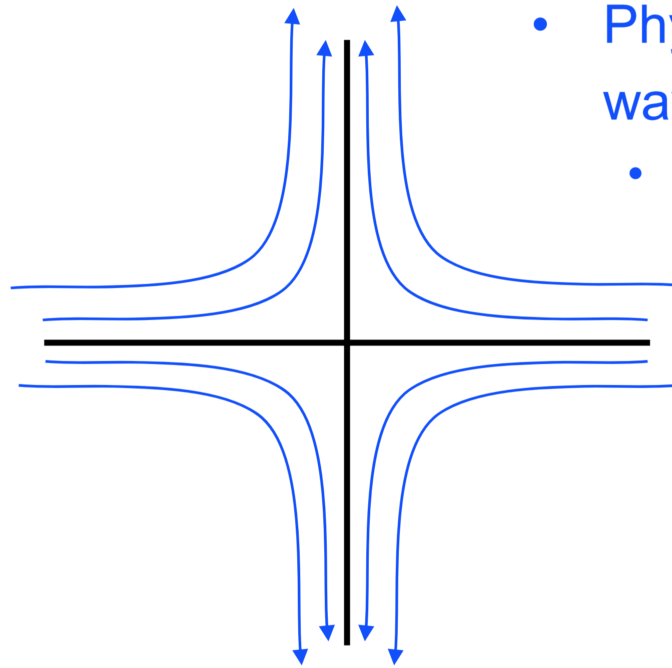
- Time-dependent quadrapole moment arising from *mass motion*

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

- Traveling wave solutions of Einstein's equation
- Two polarizations: h^+, h^x
- Spin 2 fields

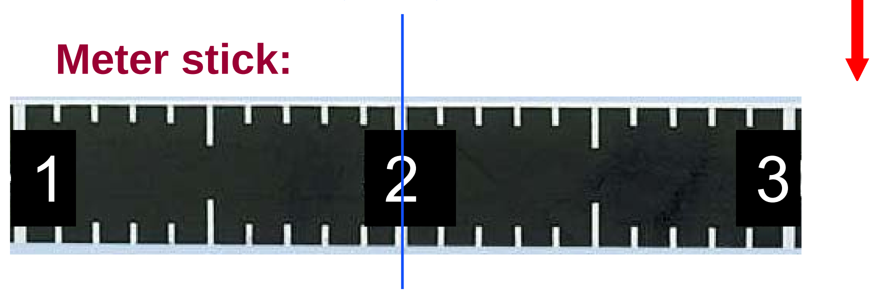
Gravitational waves: effects on space-time





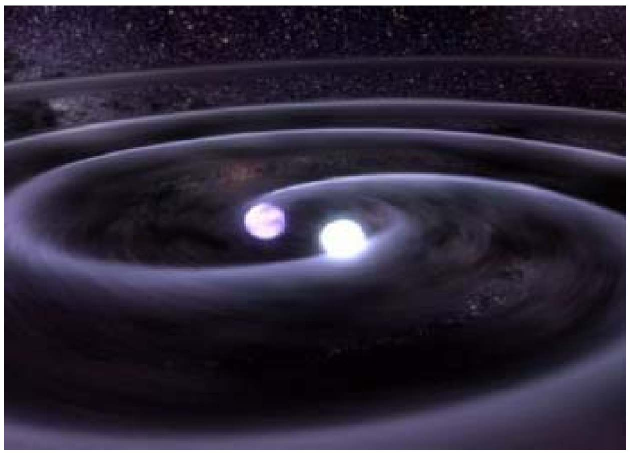
- Physically, gravitational waves are ‘strains’
  - Change in length per unit length, or $\Delta L/L$

Meter stick:

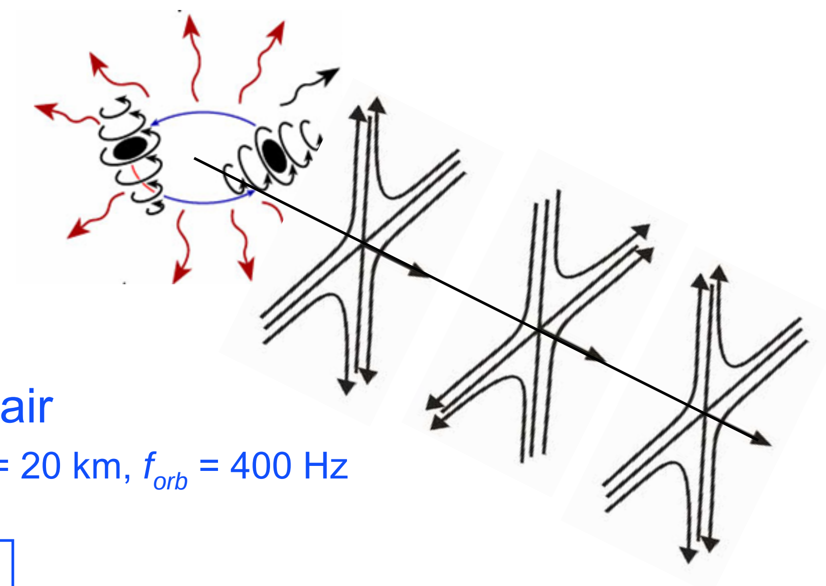


Gravitational waves and astrophysics

- Emissions from accelerating non-spherical mass distributions



$$\Rightarrow \quad h_{\mu\nu}(\omega,t) = \frac{2G}{r c^4} \ddot{I}_{\mu\nu}(\omega,t) \quad \Rightarrow \quad h \approx \frac{4\pi^2 GMR^2 f_{orb}^2}{c^4 r}$$



- Sense of scale: binary neutron star pair
  - » M = 1.4 $M_\odot$, r = 10^{23} m (15 Mpc, Virgo), R = 20 km, f_{orb} = 400 Hz

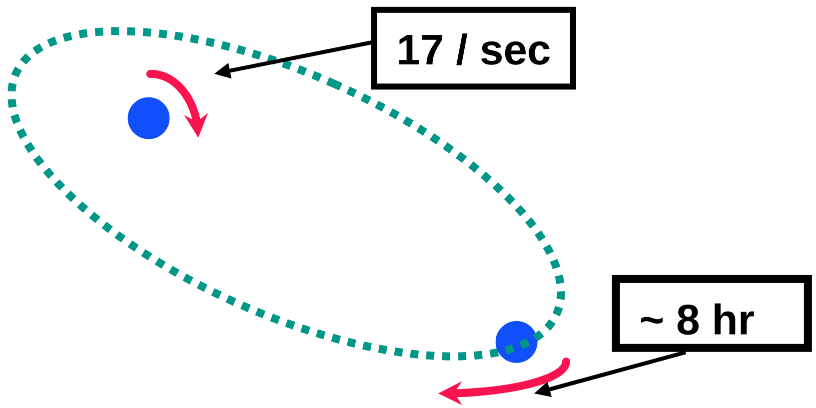
→ $h \sim 10^{-21}$

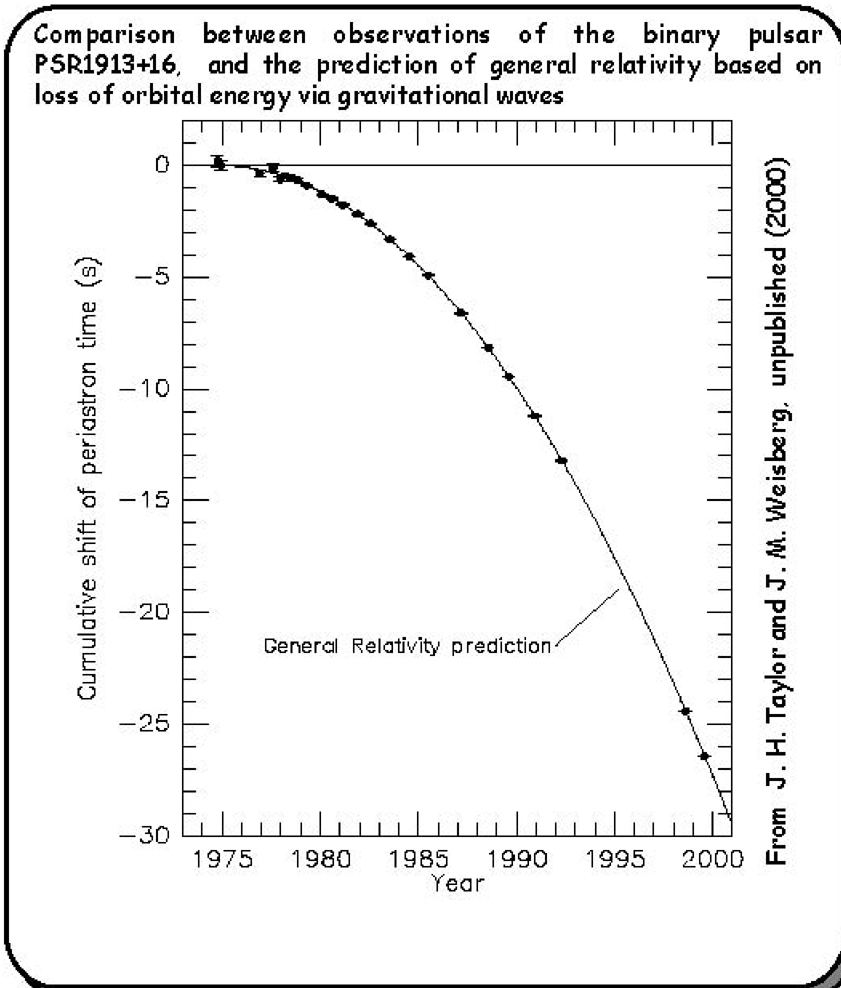
Existence proof: PSR 1913+16

Neutron Binary System – Hulse & Taylor

Pulsar Timing - Nobel prize 1993

Periastron change: 30 sec in 25 years





Neutron Binary System

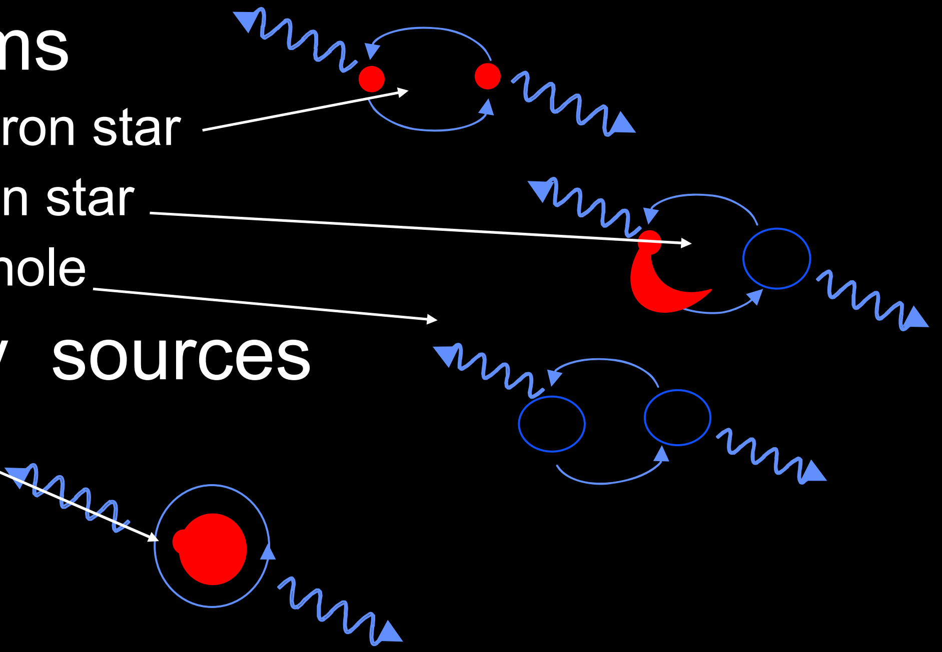
- separated by 10^6 miles
- $m_1 = 1.4 m_\odot$; $m_2 = 1.36 m_\odot$; $\varepsilon = 0.617$

Prediction from general relativity

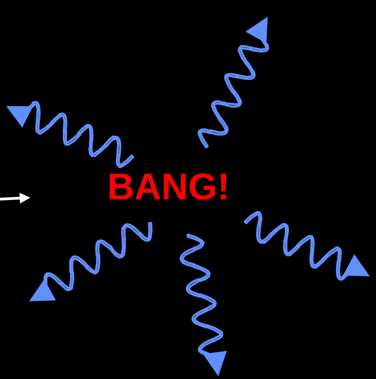
- spiral in by 3 mm/orbit

GW Sources Lurking in the Dark

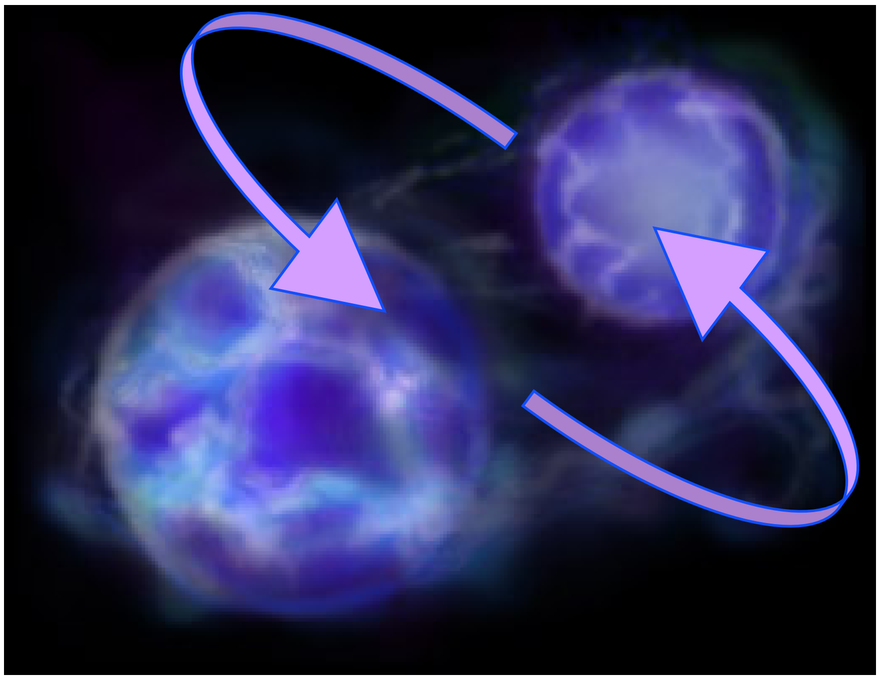
- Two body systems
  - » Neutron star – Neutron star
  - » Black hole – Neutron star
  - » Black hole – Black hole
- Single frequency sources
  - » Rotating pulsars
- “Burst” sources
  - » Supernovae
  - » Gamma ray bursts (GRBs)
  - » ?????



- the Big Bang
  - » Stochastic background
  - » Cosmic Strings

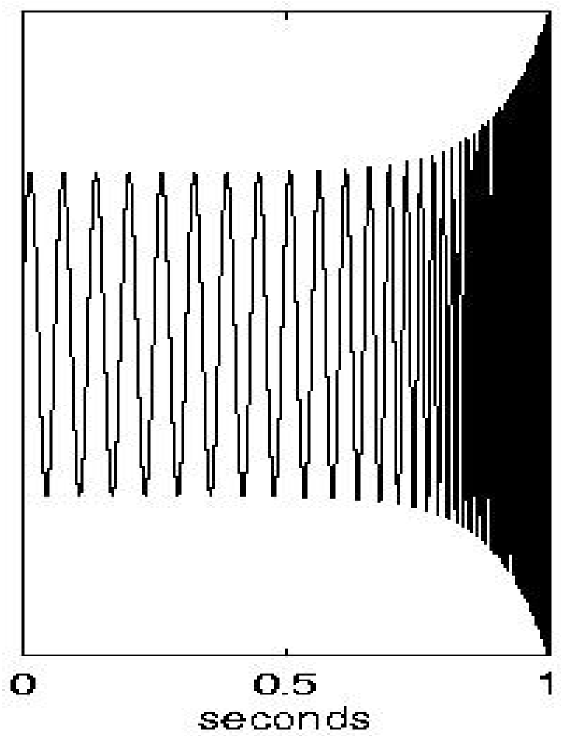


Neutron-star binary systems



Credit: Jillian Bornak

Frequency Chirp



Credit:
http://www.srl.caltech.edu/lisa/graphics/master.html

Short Duration GRBs

Oct. 6, 2005

Fox, et al., Nature 437, 845 (2005)

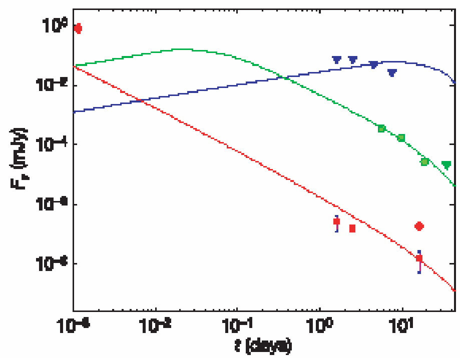


Figure 3 | Observations of the GRB 050709 afterglow and illustrative models. The X-ray (red), optical (green) and radio (blue) data taken from

Gehrels, et al., Nature 437, 851 (2005)

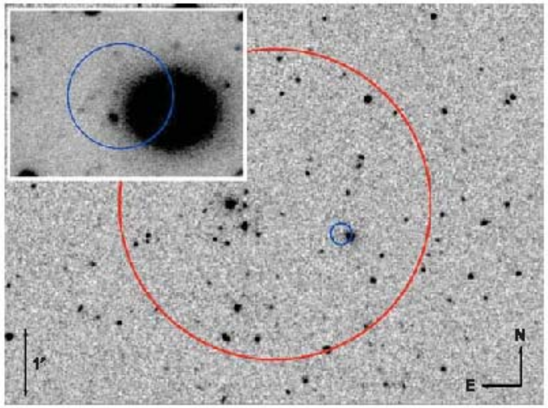


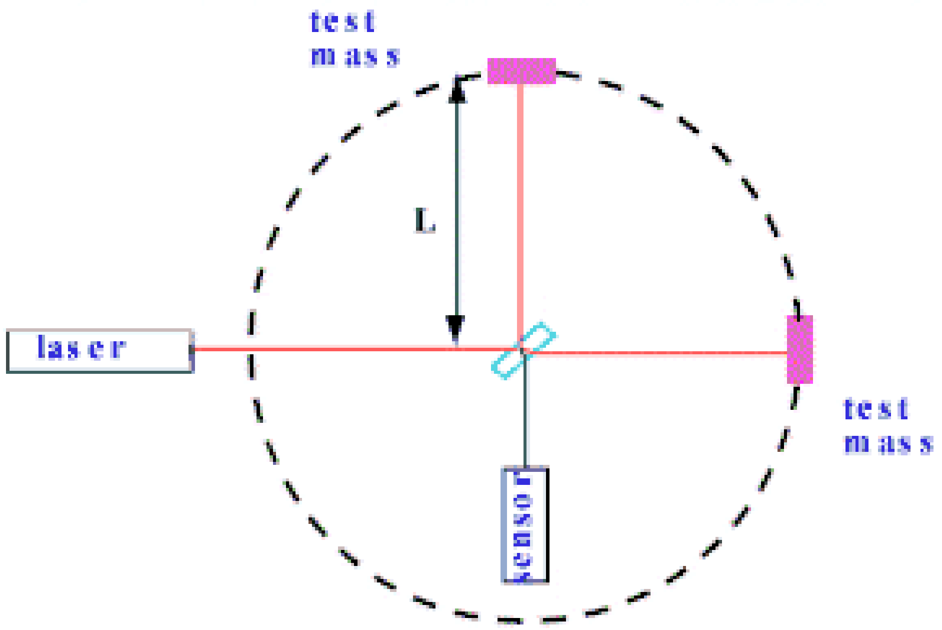
Figure 1 | Optical images of the region of GRB 050509B showing the association with a large elliptical galaxy. The Digitized Sky Survey image.

"There may be more than one origin of short GRBs, but this particular short event has a high probability of being unrelated to star formation and of being caused by a binary merger."

"In all respects, the emerging picture of SHB properties is consistent with an origin in the coalescence events of neutron star–neutron star or neutron star–black hole binary systems."

How does a gravitational wave interact with an interferometer?

- ‘Test mass’ mirrors accelerate as GW passes
- GW wave alternatively ‘stretches’ and compresses interferometer arms
- Time dependence of interference pattern on photodiode sensor records passage of GW



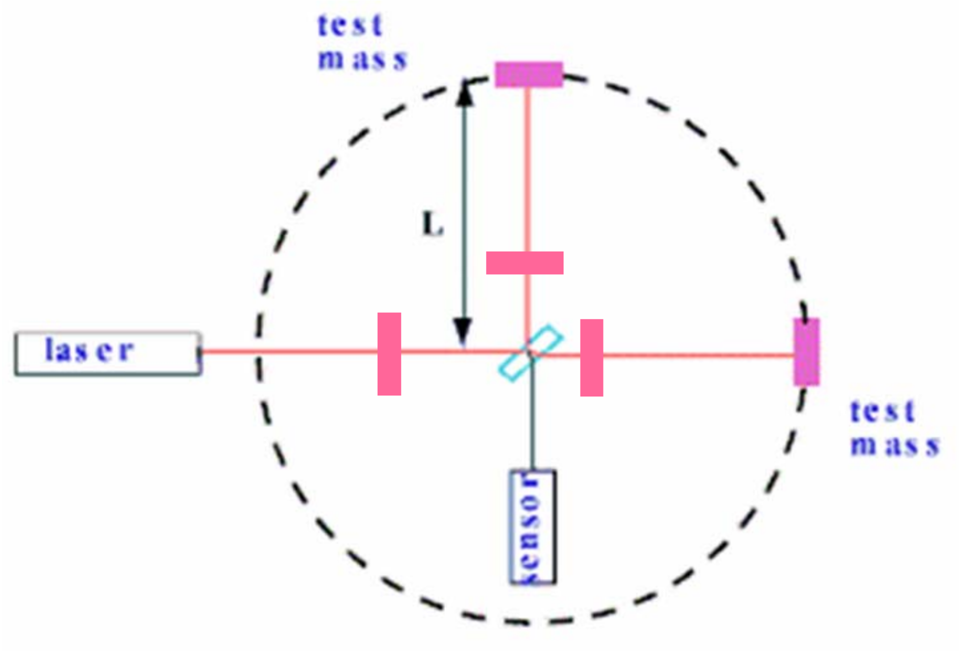
How sensitive can an interferometer be?

- Strain $h \sim \frac{\lambda}{L}$
- Now multiply the number of round-trips in the arms by adding Fabry-Perot cavities

$$h \sim \frac{\lambda}{L} \frac{1}{N_{roundtrip}}$$

- Now take into account shot noise (but recycle the photons!)

$$h \sim \frac{\lambda}{L} \frac{1}{N_{roundtrip}} \sqrt{\frac{1}{\dot{N}_{photon} \tau_{storage}}}$$

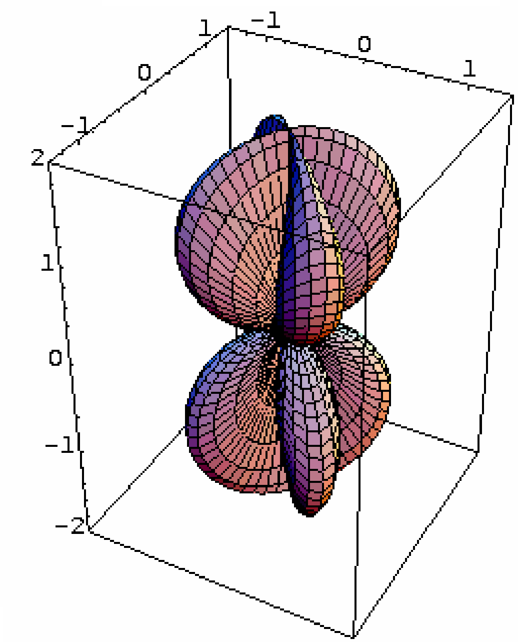


Putting in numbers: $h \sim 10^{-21}$

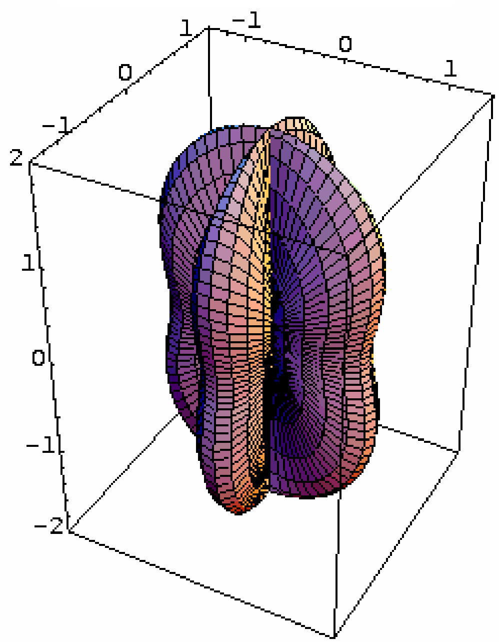
An interferometer is not a telescope

- Sensitivity depends on propagation direction, polarization

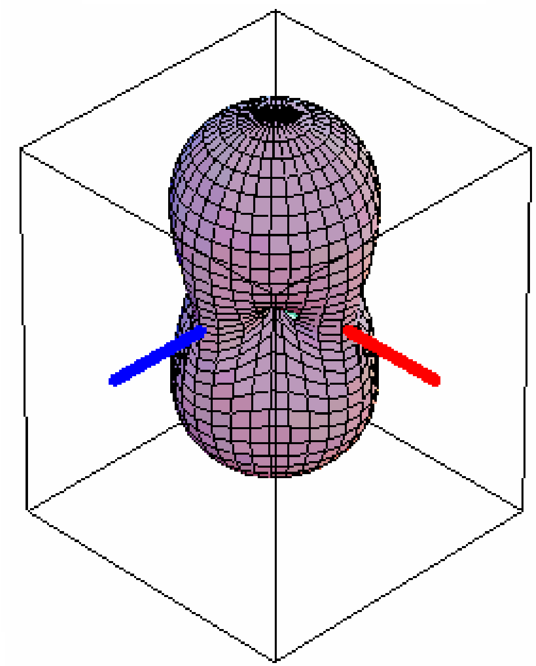
“×” polarization



“+” polarization



RMS sensitivity

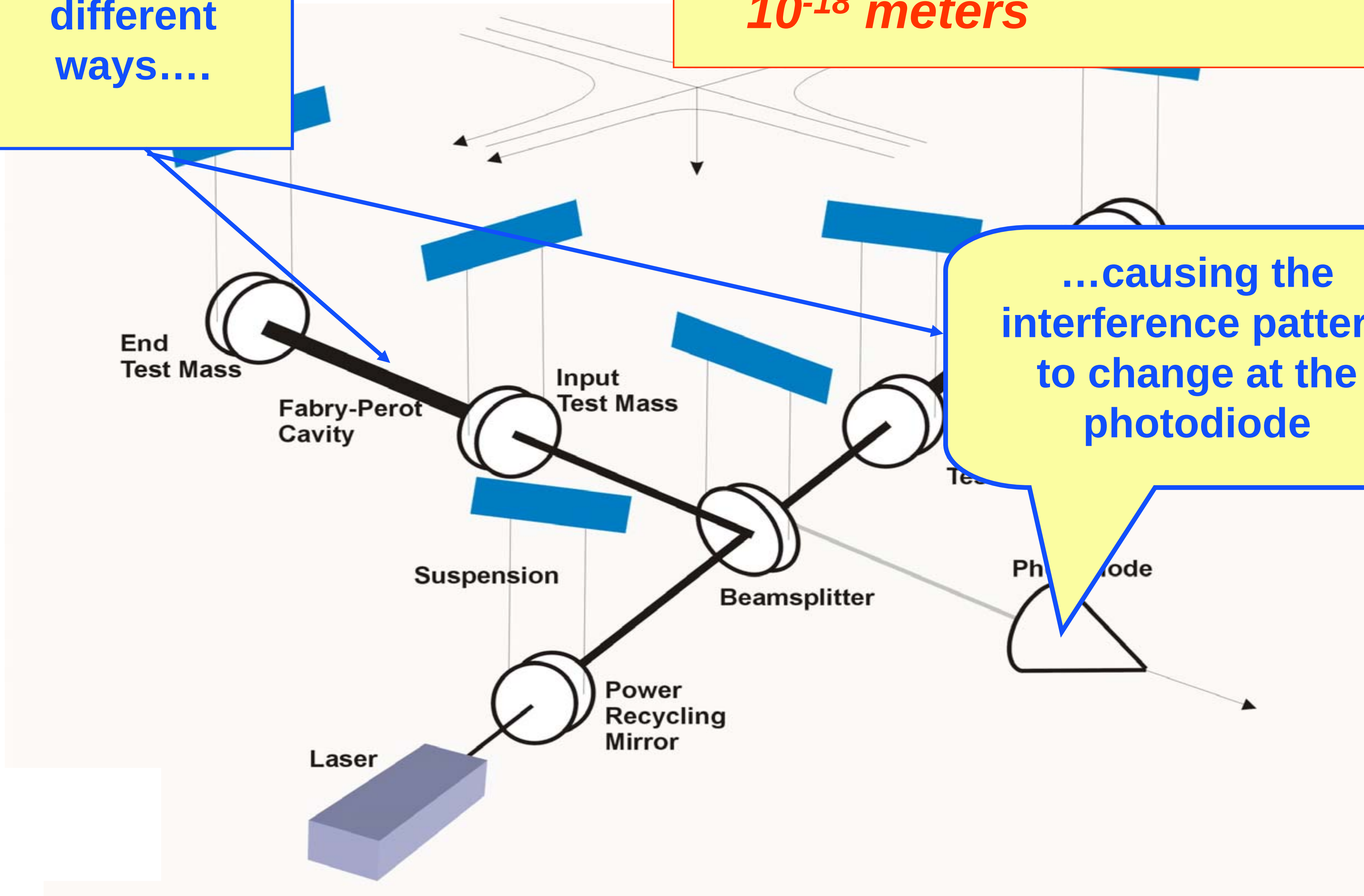


- Really a microphone!

Funda
LIGO int

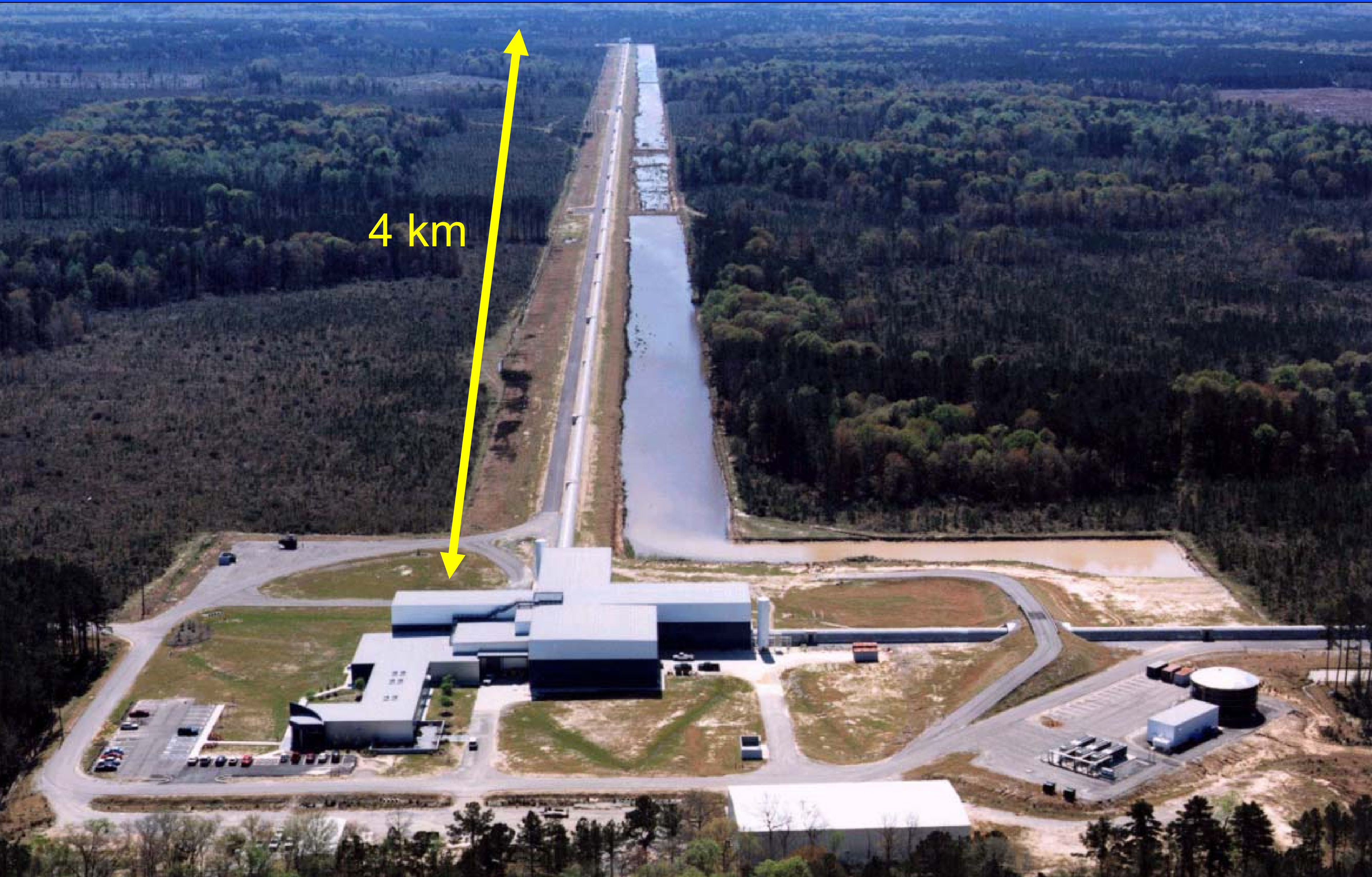
- **Arms in LIGO are 4 km long**
- **Measure *difference in length to one part in 10^{21} or 10^{-18} meters***

As a wave passes, the arm lengths change in different ways….

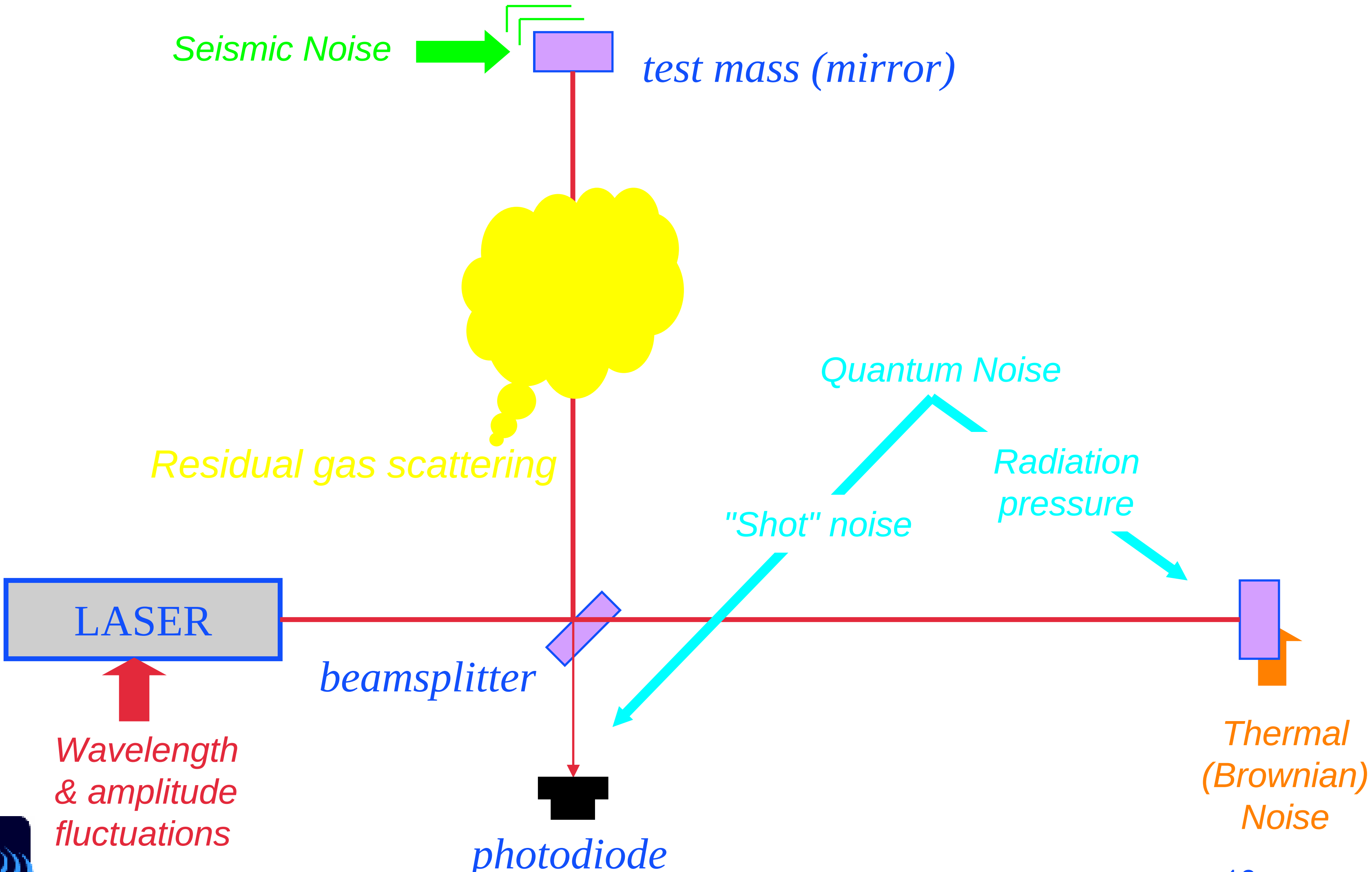


…causing the interference pattern to change at the photodiode

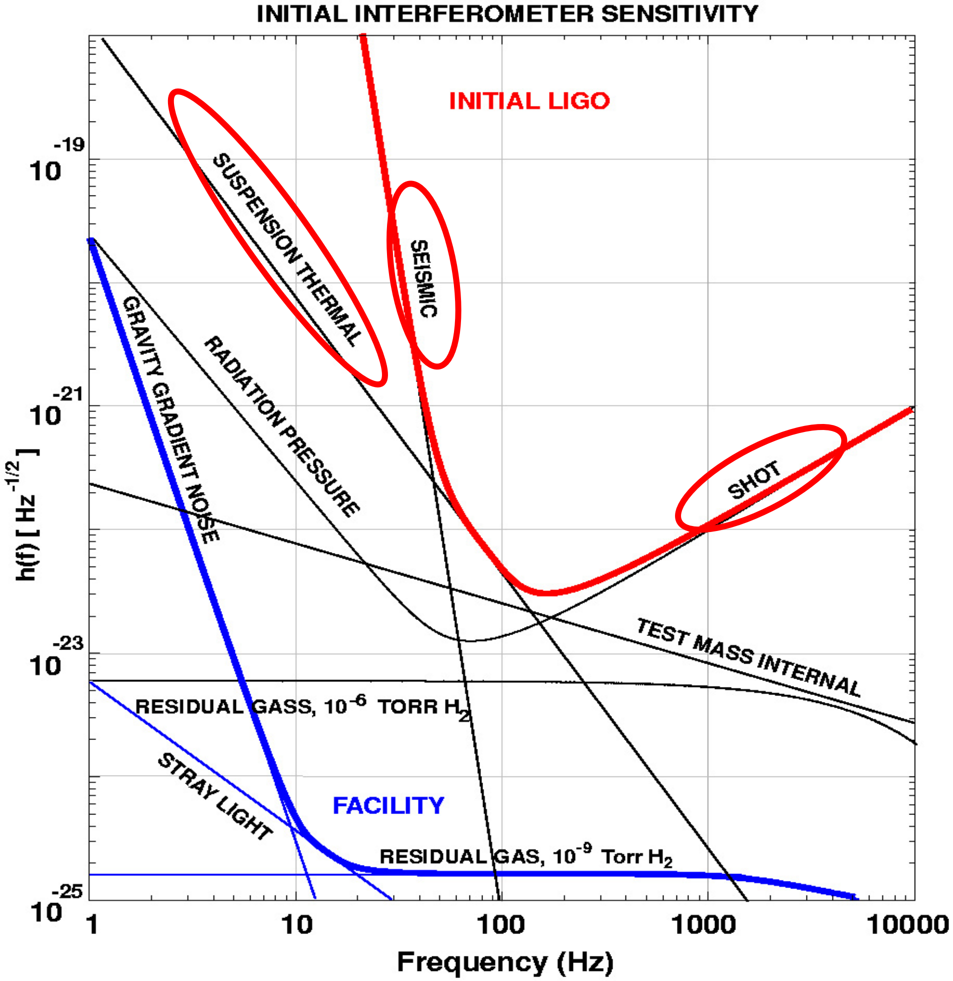
LIGO sites



The earth is a noisy place



‘Noise’ in LIGO



Noise Sources:

- **Displacement noise**
  - **Seismic noise**
  - **Radiation Pressure**
  - **Thermal noise**
    - **Suspensions**
    - **Optics**
- **Sensing Noise**
  - **Shot Noise**
  - **Residual Gas**

Coincidence Detection

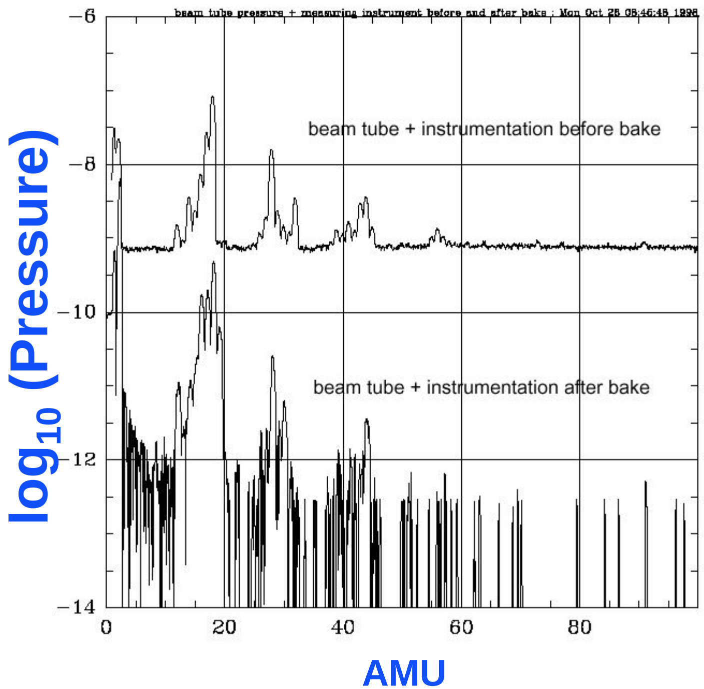
Residual Gas Noise

- Molecular polarizability → excess phase

→ Phase fluctuation

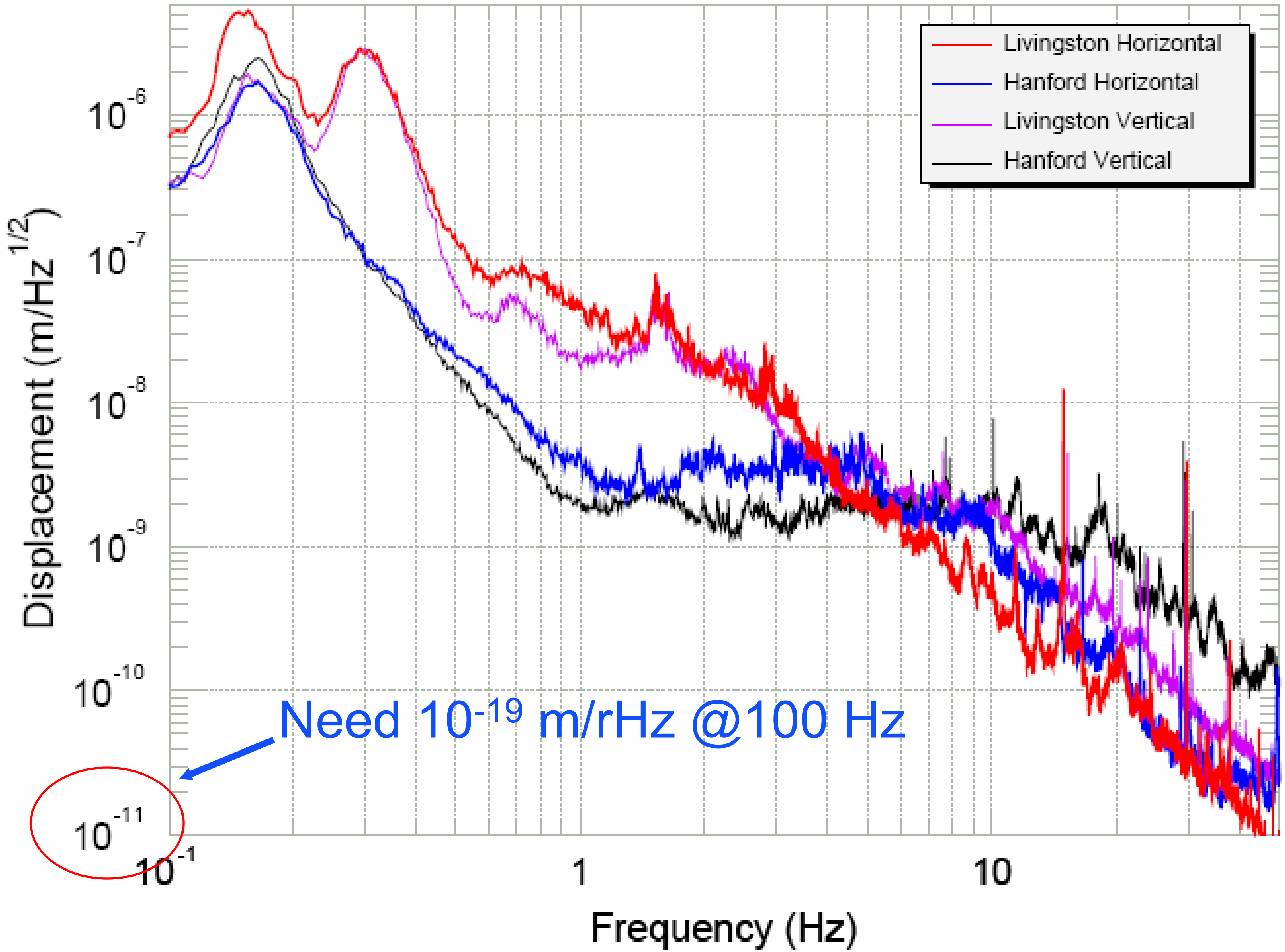
→ strain noise: $h \sim \alpha \sqrt{\dfrac{\rho}{L\, w_o \bar{v}}}$

Require Pressure < 10^{-8} torr

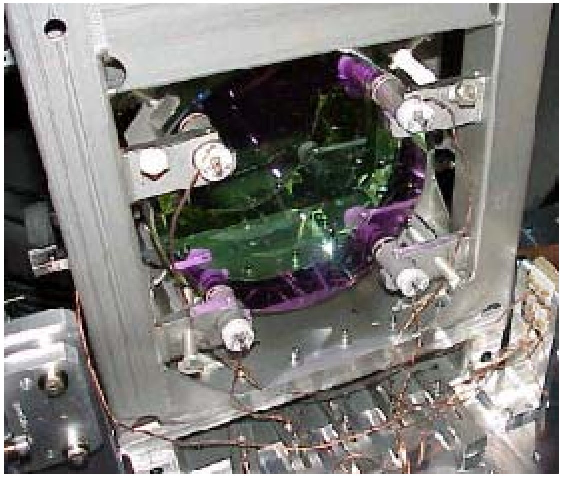


Beamtube covers are important

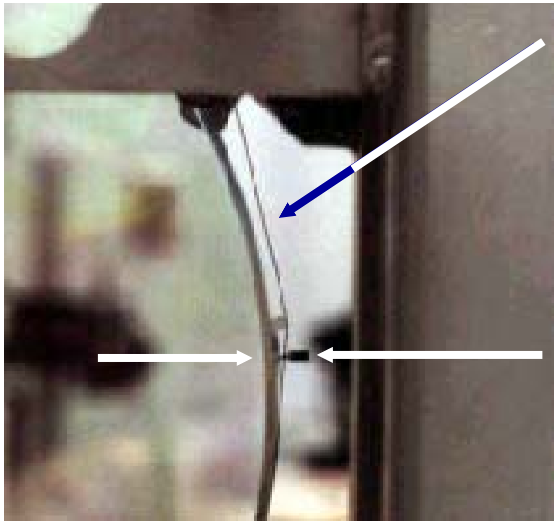
Seismic Noise

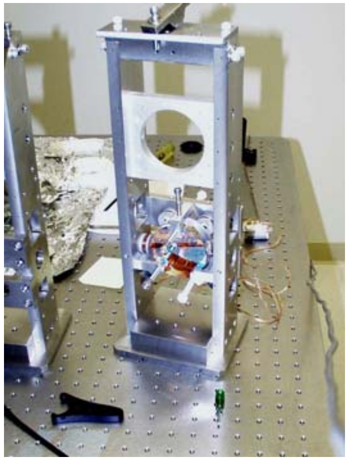


Suspensions



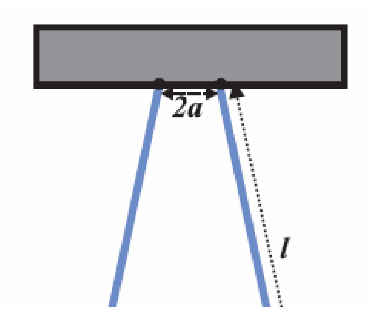
"piano wires, magnets, and glue"

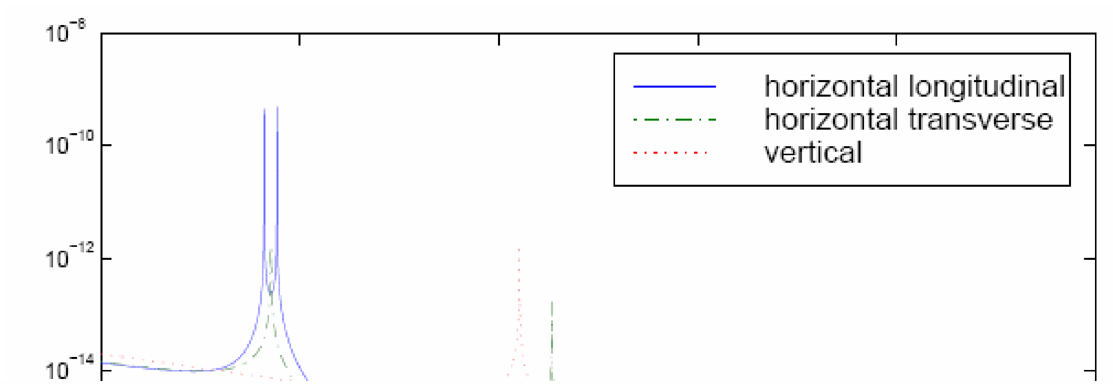


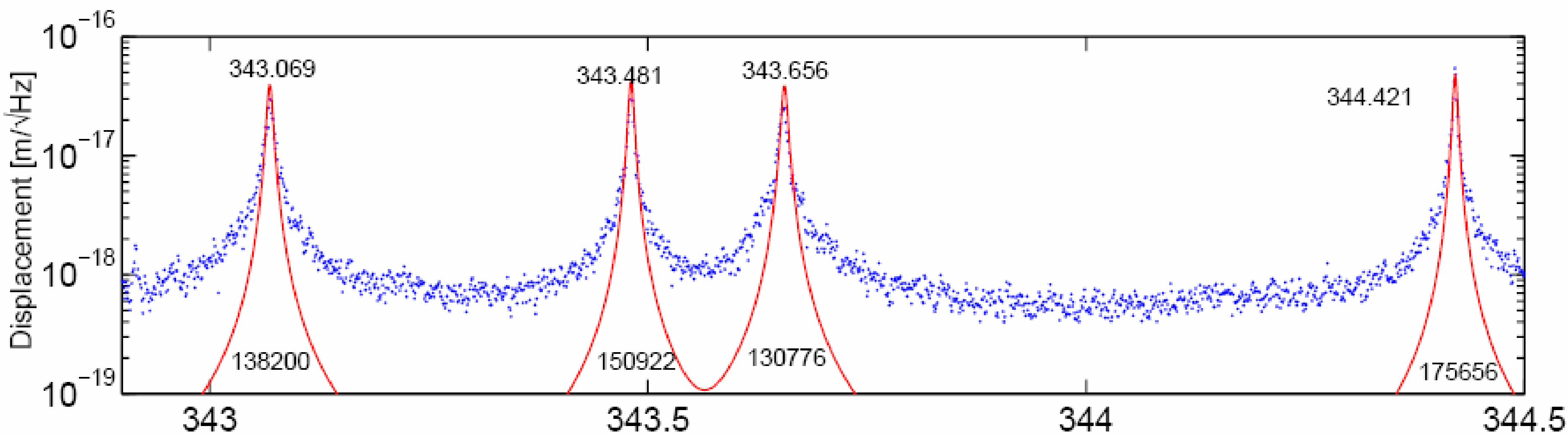


Thermal noise: Suspensions

G. Gonzalez, Class. Quantum Grav. **17**, 4409-4435 (2000)







Shot Noise and Radiation Pressure

- Photons obey Poissonian statistics: $\Delta n/n \sim 1/(n\tau)^{1/2}$ for large n
- How to discriminate between Δn and ΔL??
- Simple (back of the envelope) calculation for a Michelson interferometer operating at the ½ power point:

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

- Photons also carry momentum → radiation pressure noise

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

- Combined shot and radiation pressure noise → "Standard Quantum Limit"

$$h_{SQL}(f) = \frac{1}{\pi f L}\sqrt{\frac{\hbar}{m}}$$

LIGO Vacuum Chambers

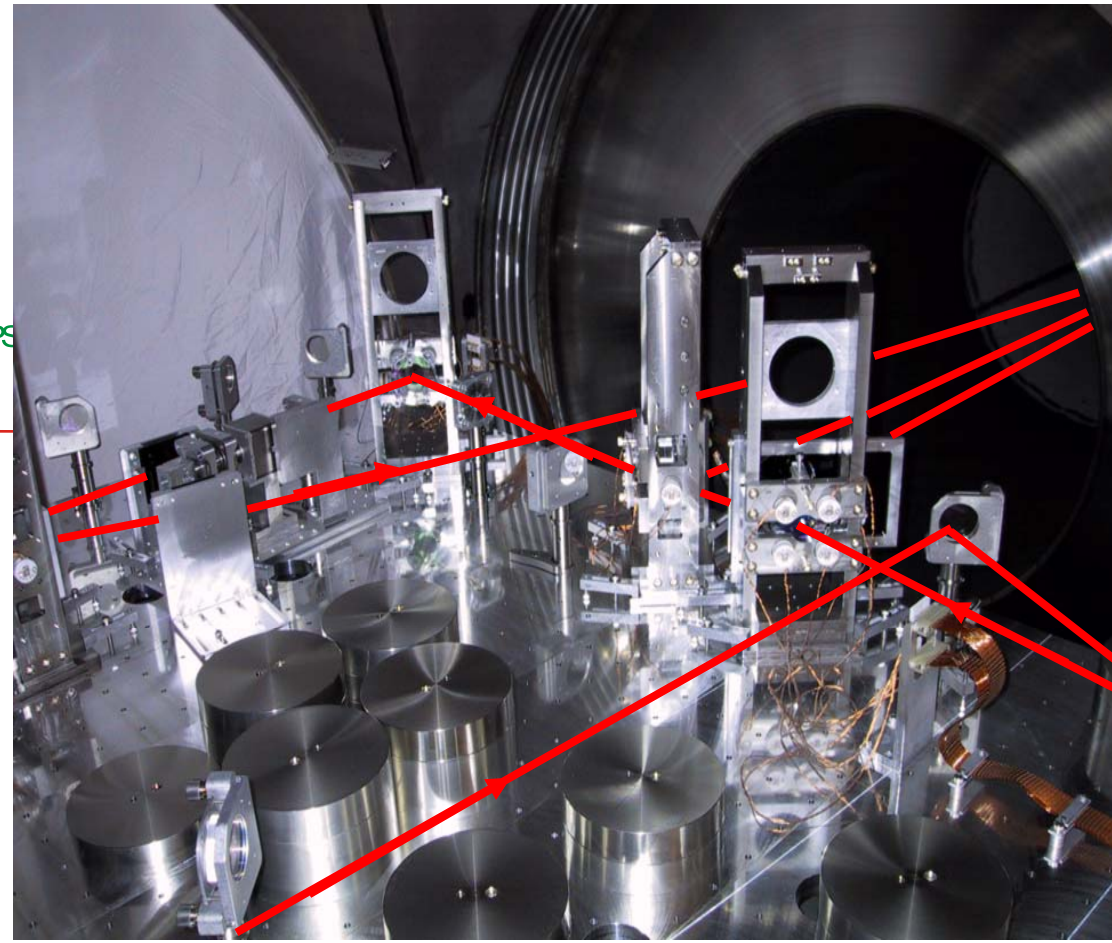
LIGO Vacuum Chambers

LIGO Laser

- Neodynium:YAG laser
  - 8 Watts
  - Wavelength 1064 nm
    - Near infrared
- Intensity-stabilized
  - $\Delta I/I_0 < 10^{-7}$/rHz
- Frequency-stabilization
  - $\Delta f/f_0 < 10^{-2}$ Hz/rHz

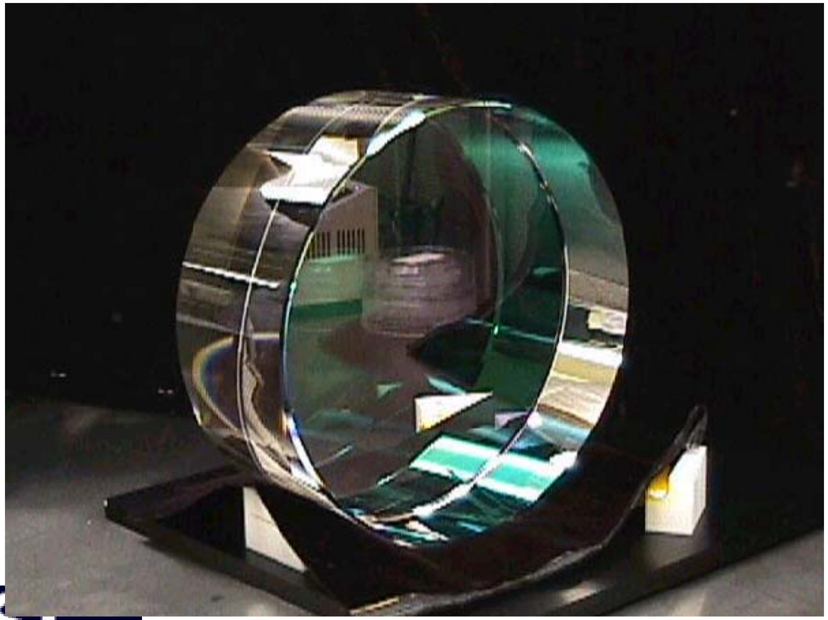
LIGO Input Optics

- **Prepares the laser for the interferometers**
- **Optically complex**

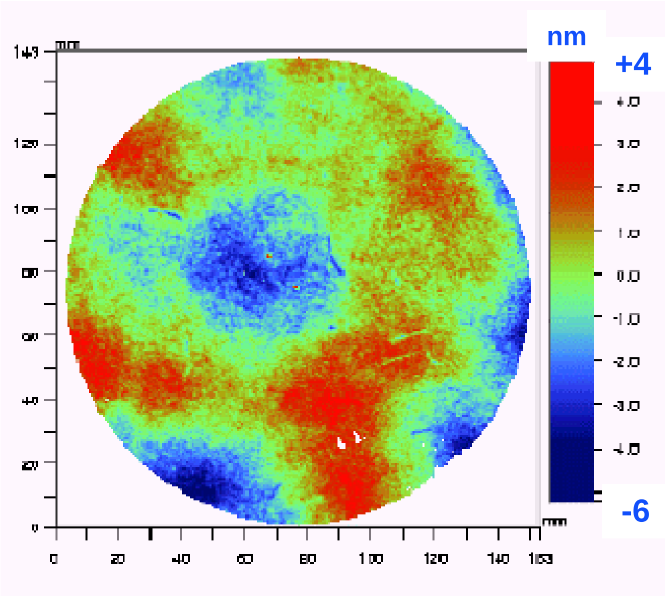


LIGO Core Optics

- Define the state of the art in optics processing and metrology
  - Better than astronomical telescopes!
  - surface deviation approaching the diameter of a hydrogen atom!
  - And therefore quite expensive…

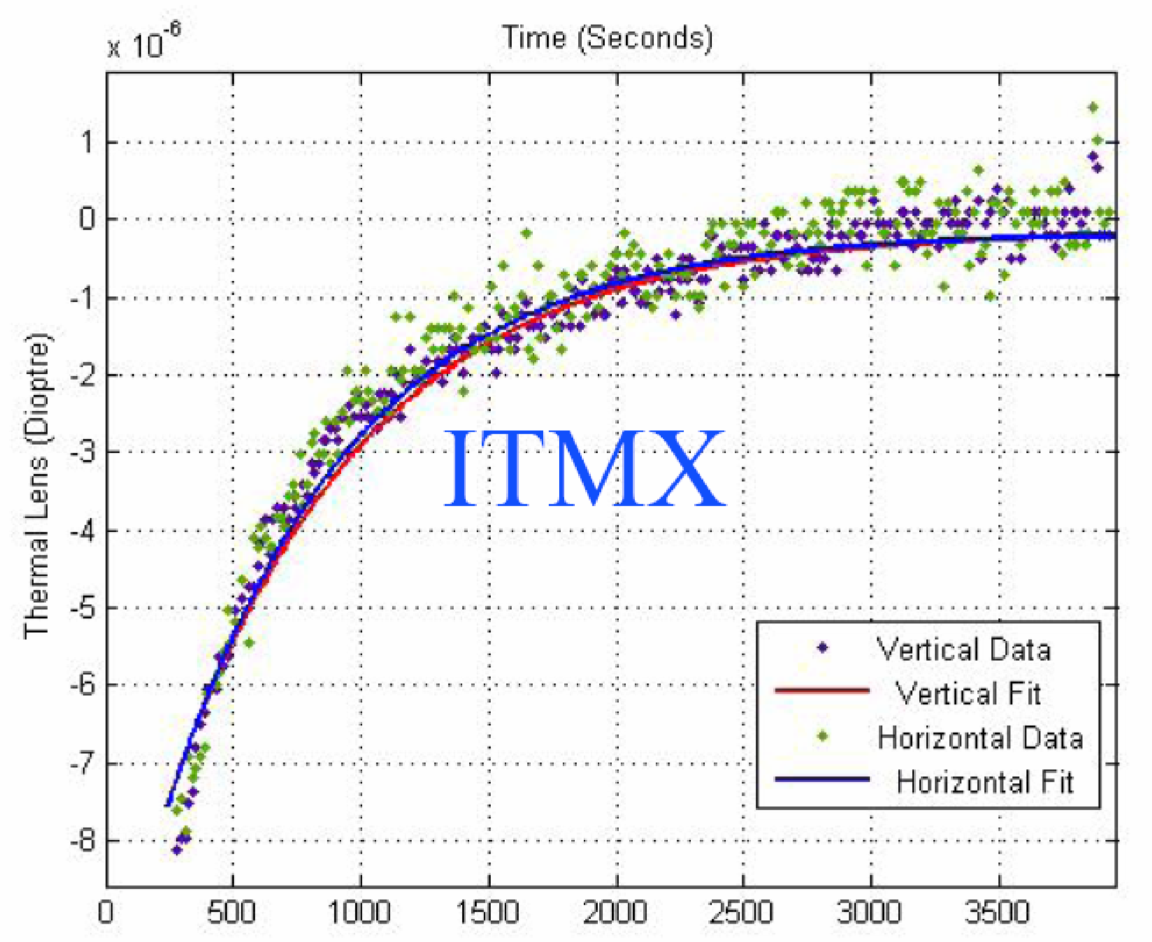


Metrology: Phase Maps

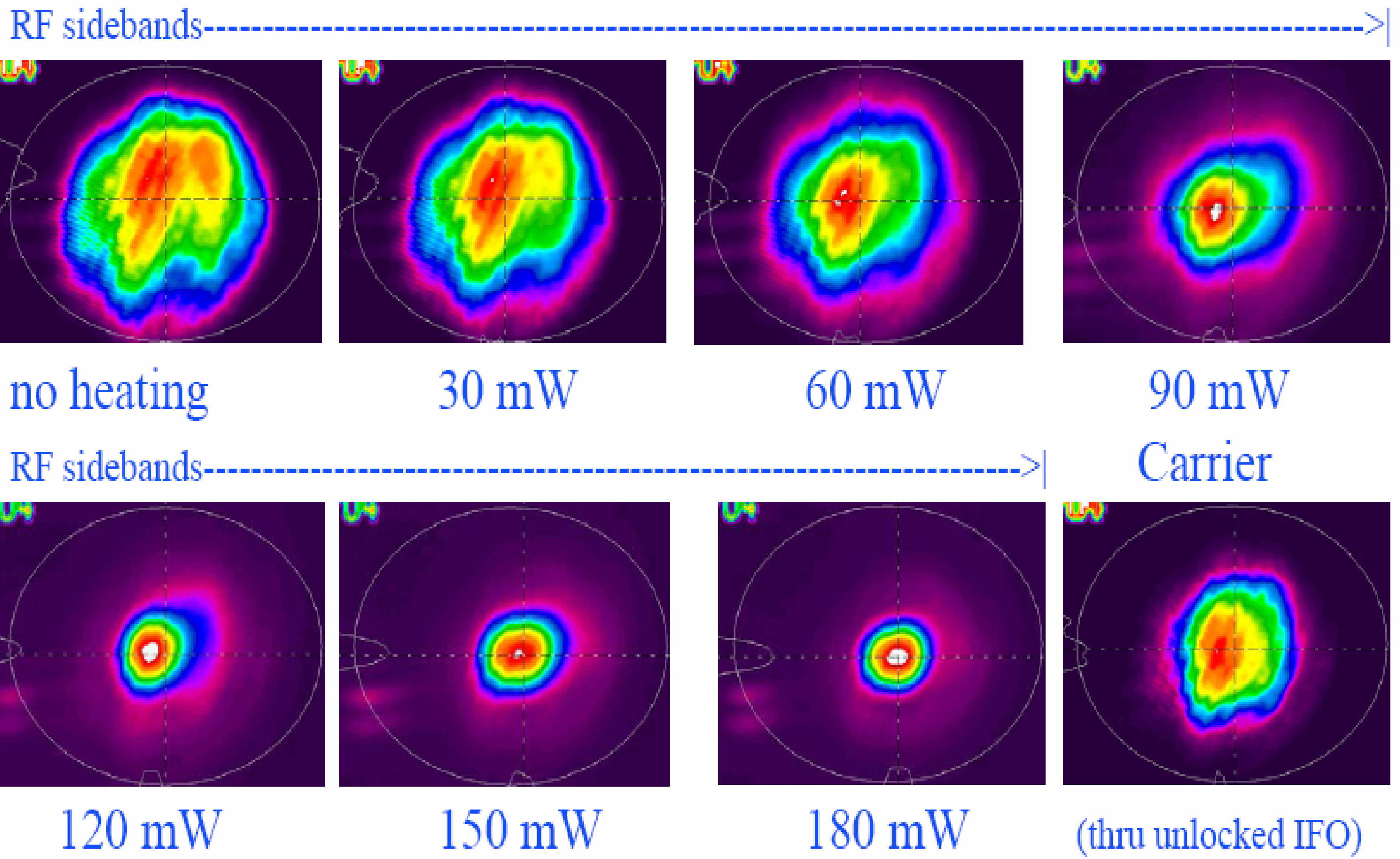


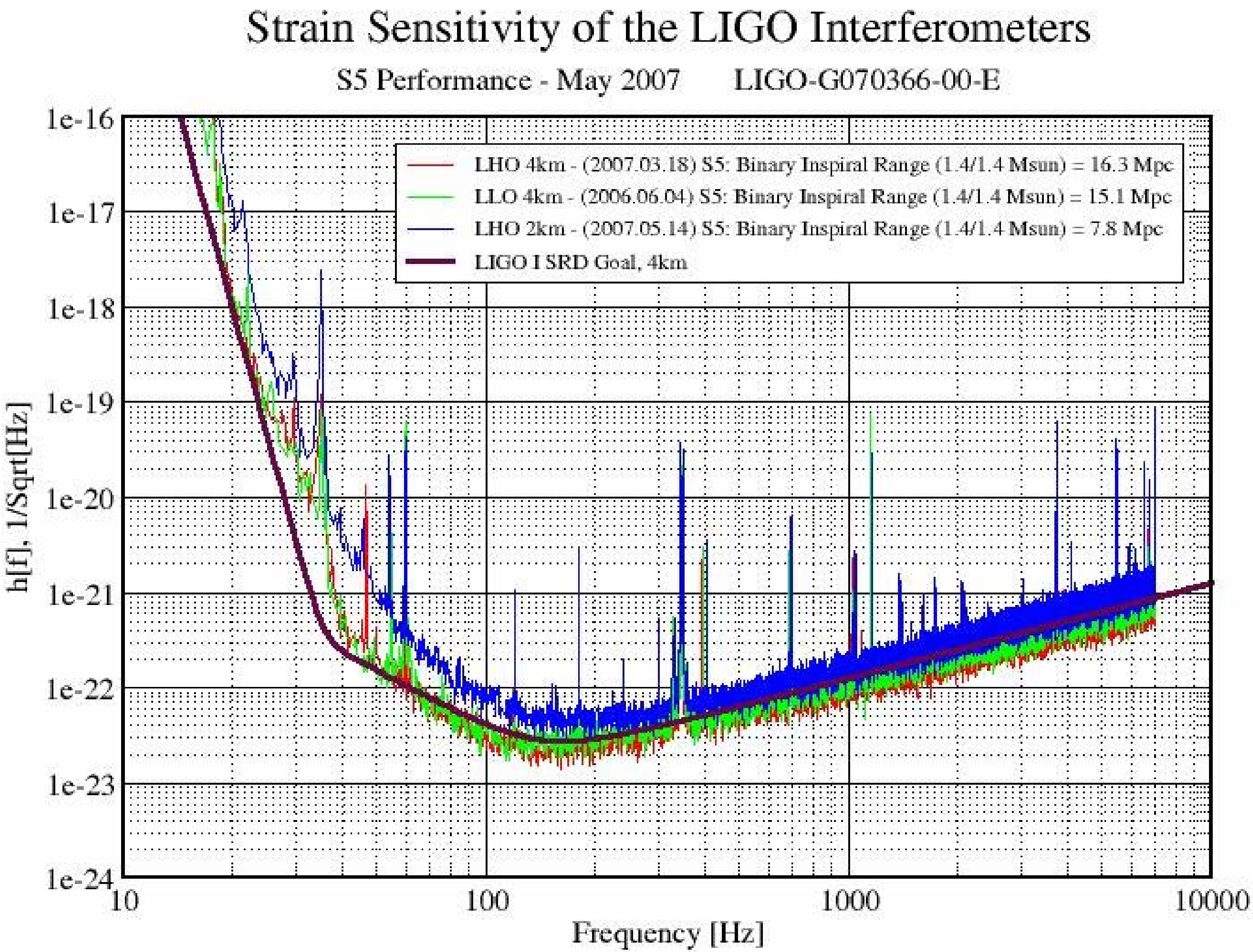
Thermal effects in LIGO optical components

- ‘High quality low absorption fused silica substrates’
  - » Heraeus 312 (ITM)
  - » All mirrors have different absorption levels
- 100s mW absorption in current LIGO interferometers
  - » Interferometer sensitivity suffers
    - – **Unstable recycling cavity causes loss of sensitivity**
- Requires *adaptive* control of optical wavefronts
  - » Thermal compensation system (TCS)



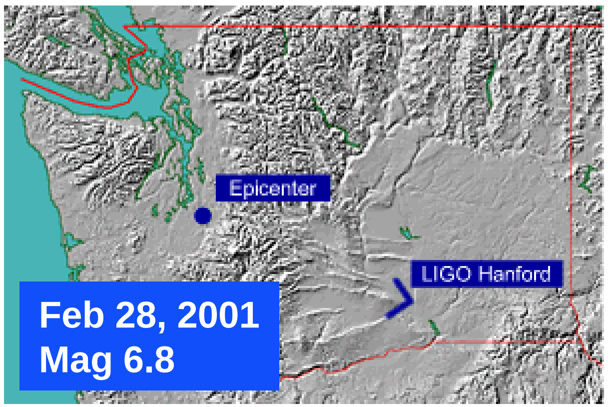
Thermal compensation in initial LIGO

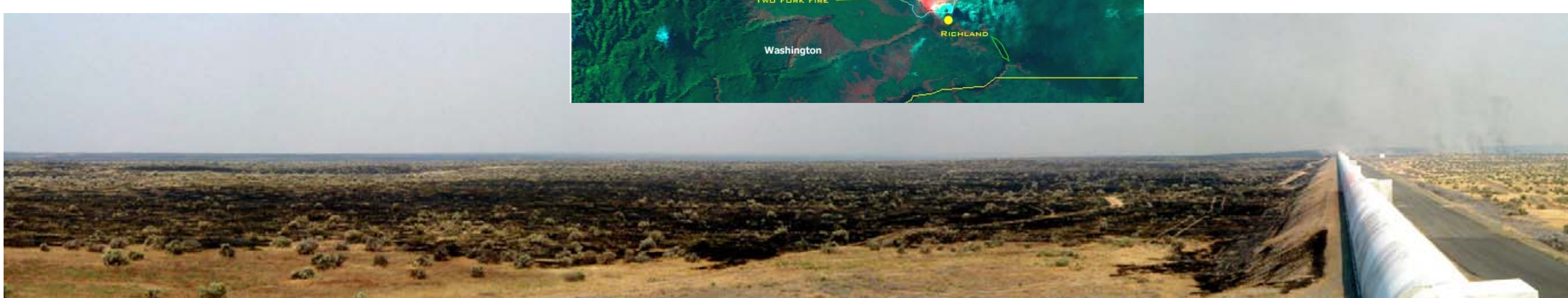




Strain Sensitivity of the LIGO Interferometers
S5 Performance - May 2007
LIGO-G070366-00-E
LHO 4km - (2007.03.18) S5: Binary Inspiral Range (1.4/1.4 Msun) = 16.3 Mpc
LLO 4km - (2006.06.04) S5: Binary Inspiral Range (1.4/1.4 Msun) = 15.1 Mpc
LHO 2km - (2007.05.14) S5: Binary Inspiral Range (1.4/1.4 Msun) = 7.8 Mpc
LIGO I SRD Goal, 4km
h[f], 1/Sqrt[Hz]
1e-16
1e-17
1e-18
1e-19
1e-20
1e-21
1e-22
1e-23
1e-24
10
100
1000
10000
Frequency [Hz]

Fires and Earthquakes…



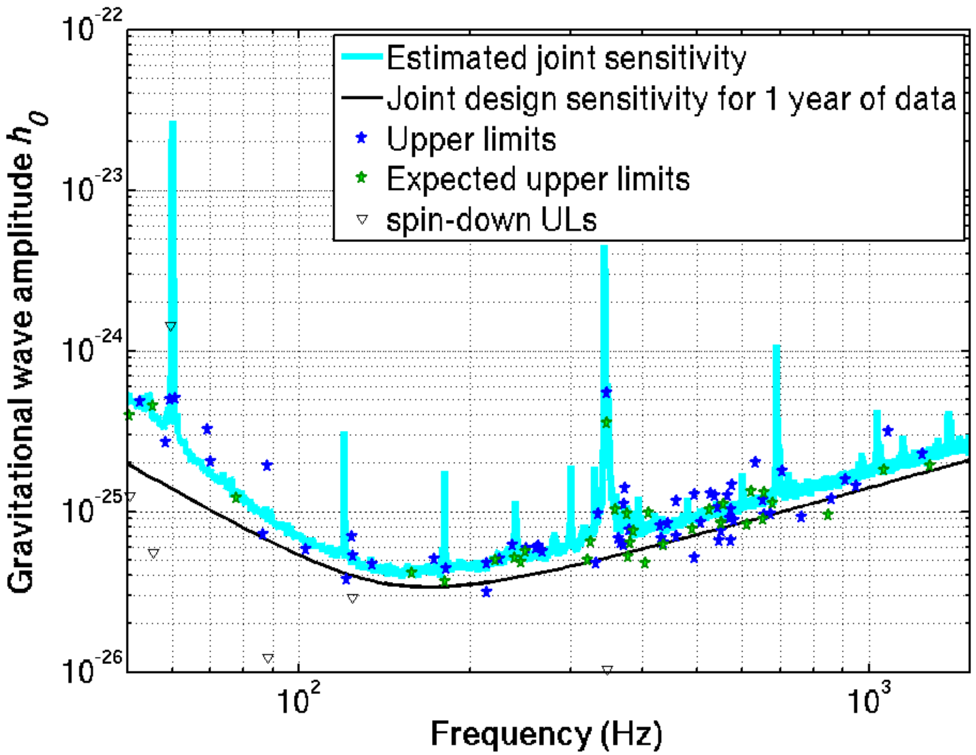


Has LIGO detected a gravitational wave yet?

- No, not yet.
- When will LIGO detect a gravitational wave?
- "Predictions are difficult, especially about the future" (Yogi Berra)
- Nonetheless…
  - » Enhanced LIGO
    - 2009-2010
    - Most probable event rate is 1 per 6 years for NS/NS inspirals
  - » Advanced LIGO
    - 2015-beyond
    - Rates are much better
- In the meantime, we set upper limits on rates from various sources

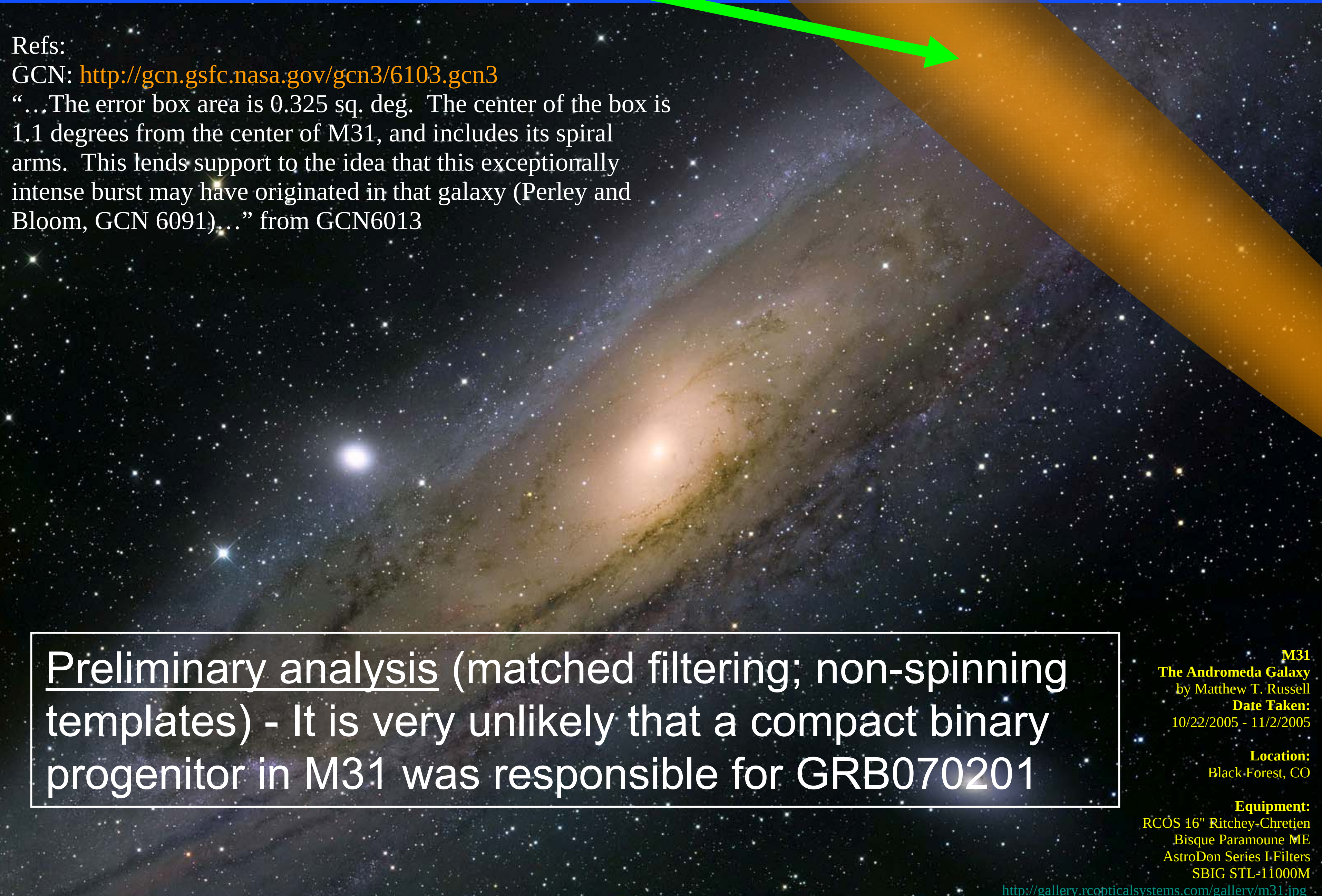
Searches for Periodic Signalsfrom Known Radio/X-ray Pulsars

- Use demodulation, correcting for motion of detector
  - » Doppler frequency shift, amplitude modulation from antenna pattern
  - » Demodulate data at twice the spin frequency
- S5 *preliminary* results (using first 13 months of data):
  - » Placed limits on strain h_0 and equatorial ellipticity ε
  - » ► ε limits as low as $\sim 10^{-7}$
  - » Crab pulsar: LIGO limit on GW emission is now below upper limit inferred from spindown rate



GRB 070201

Refs:
GCN: http://gcn.gsfc.nasa.gov/gcn3/6103.gcn3
"…The error box area is 0.325 sq. deg. The center of the box is 1.1 degrees from the center of M31, and includes its spiral arms. This lends support to the idea that this exceptionally intense burst may have originated in that galaxy (Perley and Bloom, GCN 6091)…" from GCN6013



Preliminary analysis (matched filtering; non-spinning templates) - It is very unlikely that a compact binary progenitor in M31 was responsible for GRB070201

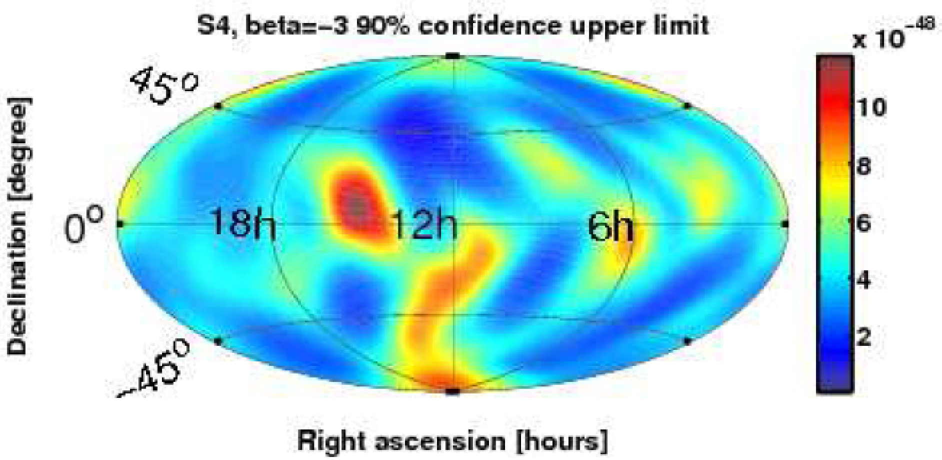
M31
The Andromeda Galaxy
by Matthew T. Russell
Date Taken:
10/22/2005 - 11/2/2005

Location:
Black Forest, CO

Equipment:
RCOS 16" Ritchey-Chretien
Bisque Paramoune ME
AstroDon Series I Filters
SBIG STL-11000M
http://gallery.rcopticalsystems.com/gallery/m31.jpg

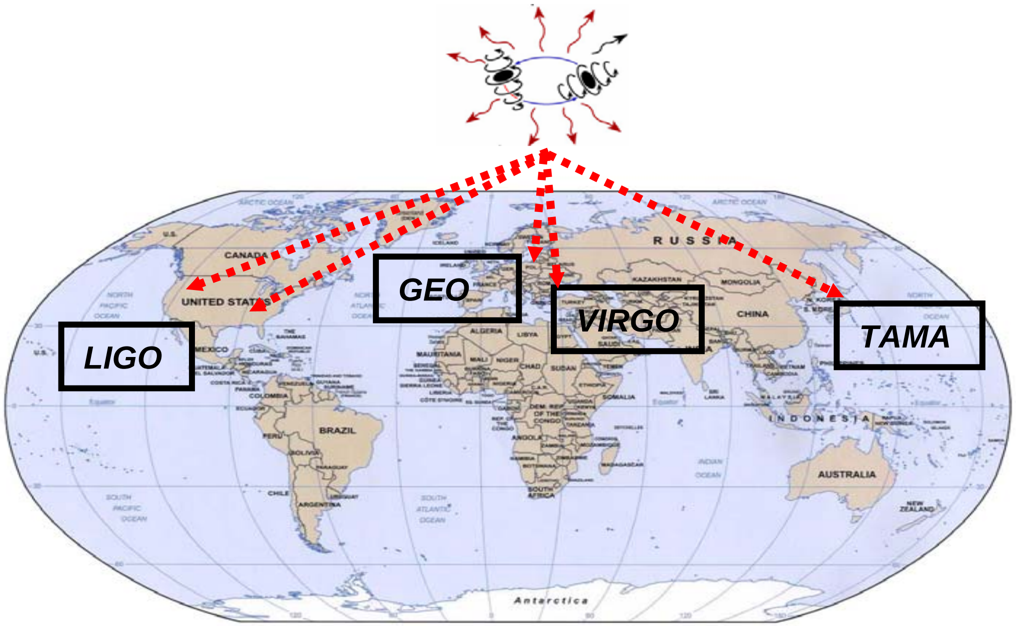
Searches for a Stochastic Signal

- Weak, random gravitational waves could be bathing the Earth
  - » Left over from the early universe, analogous to CMBR ;
    or from many overlapping signals from astrophysical objects
  - » Assume spectrum is constant in time
- Search by cross-correlating data streams
- S4 result *[**Astrophys. J.** 659, **918 (2007)**]*
  - » Searched for isotropic stochastic signal with power-law spectrum
  - » For flat spectrum, set upper limit on energy density in gravitational waves:
  - » $\Omega_0 < 6.5 \times 10^{-5}$
- Or look for anisotropic signal:
  [Phys. Rev. D]
- S5 analysis in progress



The Global Network

- *Better detections*: Coincidence through redundancy
- *Coverage*: Ability to be 'on the air' with one or more detectors
- *Source location*: Ability to triangulate and more accurately pinpoint source locations in the sky
- *Polarization*: array of oriented detectors is sensitive to two polarizations
- *Coherent analysis*: optimal waveform and coordinate reconstruction, better discrimination



GWIstat - Sep 24, 21:05 UTC			HH:MM		Help
	ALLEGRO	Http error			
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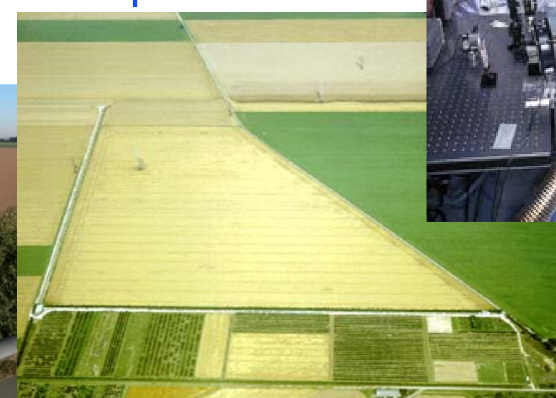
ROG	EXPLORER	Good Data	13:51		
ROG	NAUTILUS	Good Data	86:32		
	GEO 600	Science	3:16	SummaryReports	
LIGO	H1	Science	1:38	LockHistory	RangeHistory
LIGO	H2	Science	1:42	LockHistory	RangeHistory
LIGO	L1	Science	0:03	LockHistory	RangeHistory
	Virgo	Science	9:31	GeneralStatus	

GEO600

- LIGO runs in collaboration with the GEO600, the German-British interferometer in Hannover Germany
  - » Operated as one of the four LSC detectors and has been taking data since 2002.
    - – 1200 m long interferometer; employs different configuration
  - » Also a think-tank and test-bed for the technical improvements for future gravitational wave detectors.



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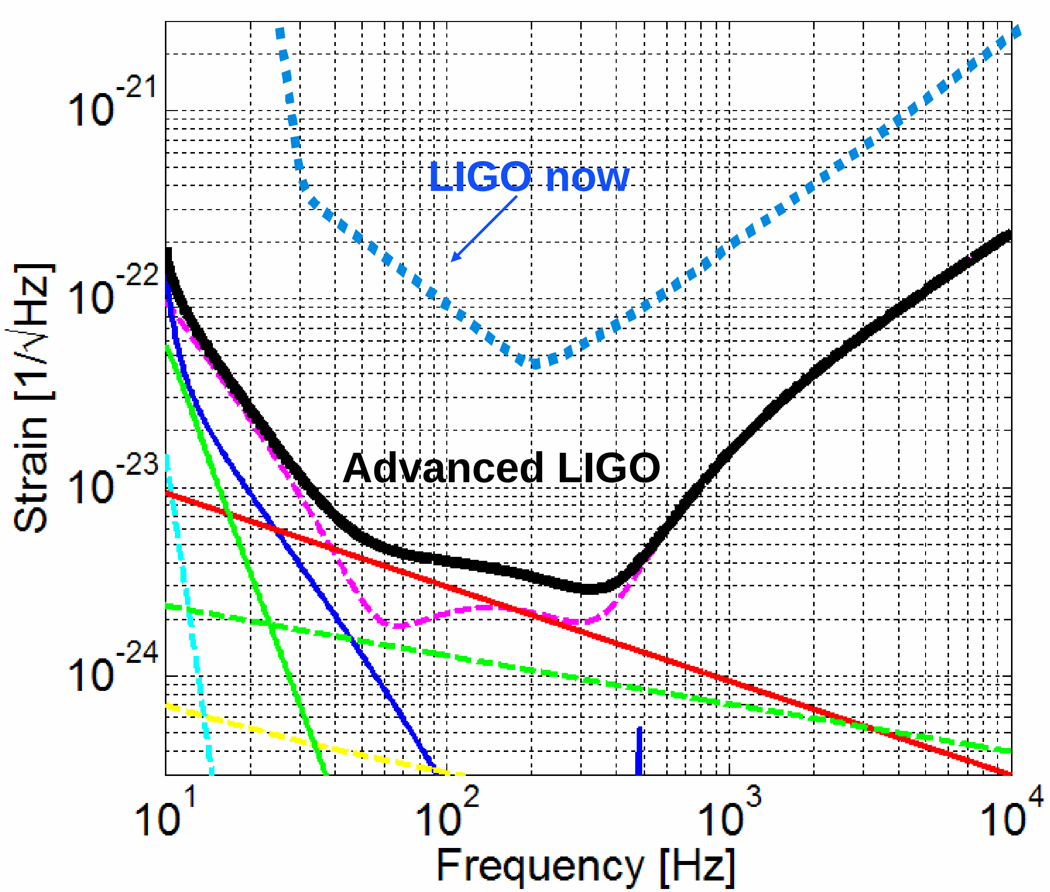
Virgo

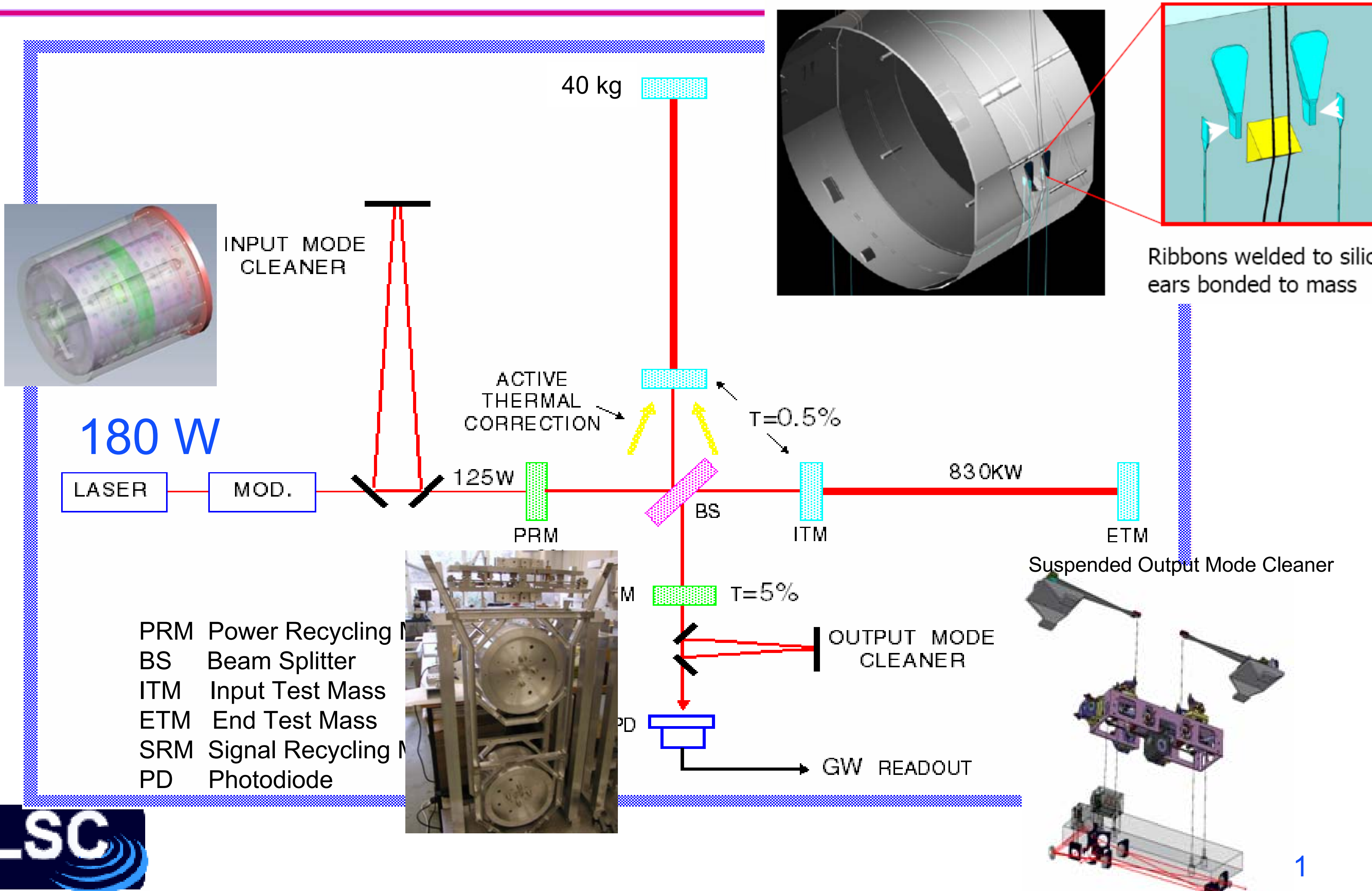
- Located near Pisa, Italy
- 3 km arms; configuration similar to LIGO
- The LSC and Virgo have recently signed a data sharing agreement

LIGO: The Next Generation

- LIGO is currently detection rate-limited at 0.01 events per year for NS/NS inspirals
- Advanced LIGO will increase sensitivity (hence rate) over initial LIGO
  - » range $r \sim h$
  - » Event rate $\sim r^3$
- Most probable NS/NS event rate in Advanced LIGO is 40/yr
- Anticipate funding to start in early 2008, construction to begin in 2011



Advanced LIGO



Ribbons welded to silica ears bonded to mass

Suspended Output Mode Cleaner

PRM Power Recycling

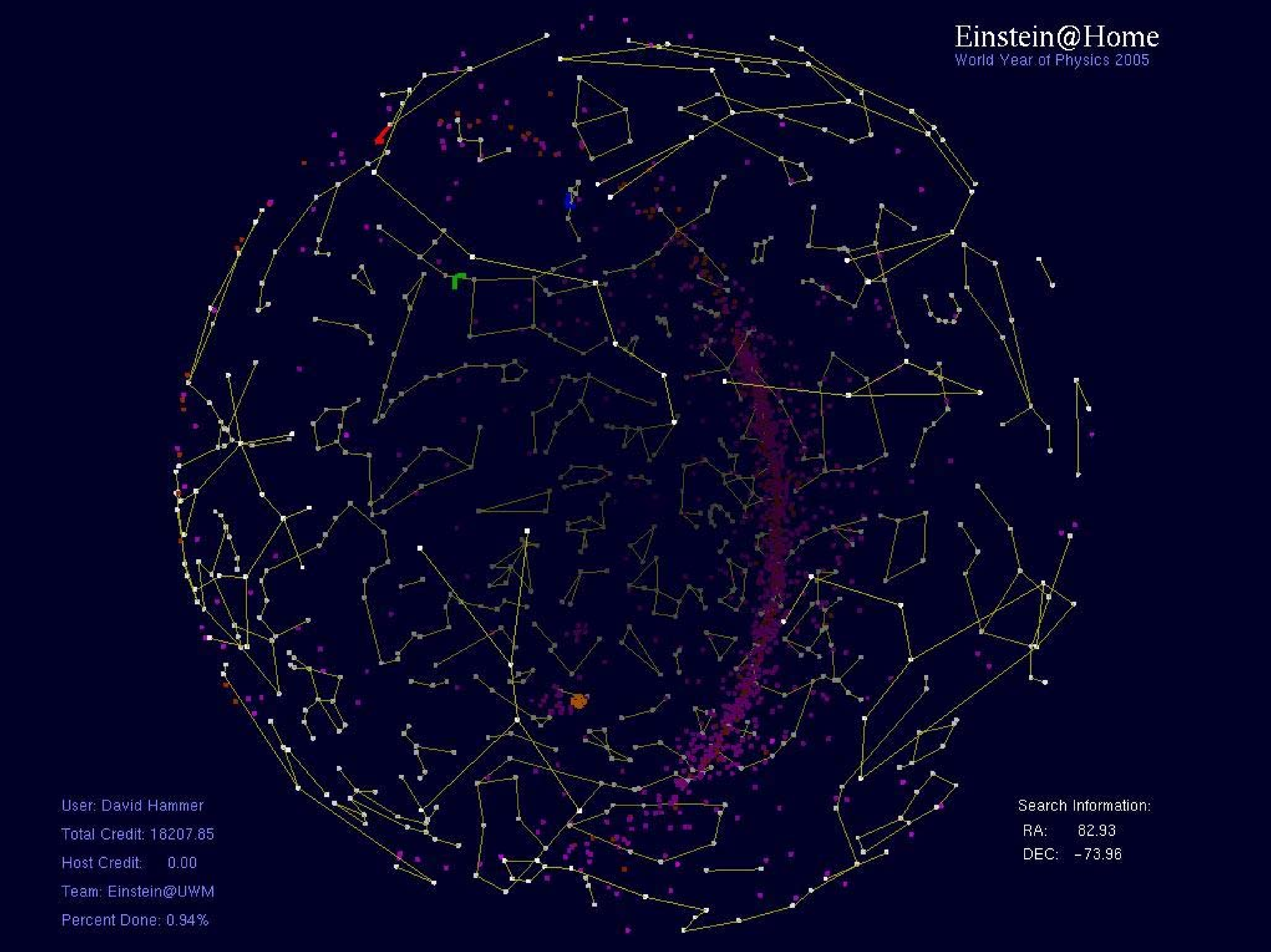
BS Beam Splitter

ITM Input Test Mass

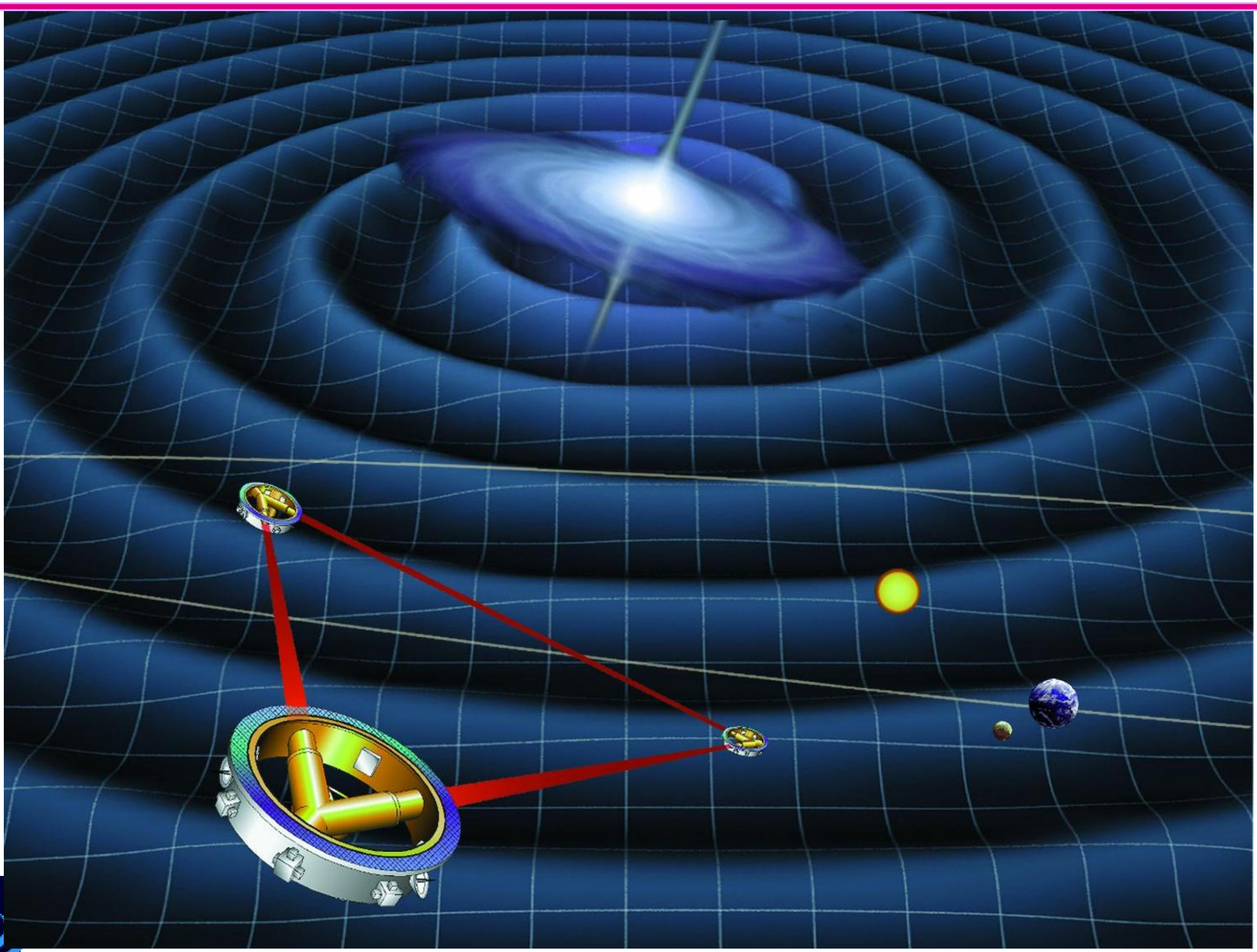
ETM End Test Mass

SRM Signal Recycling

PD Photodiode


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

LISA: LIGO's big sister



The Gravitational Wave Universe

?

Stay tuned…

LIGO Scientific Collaboration

LIGO

LSC

University of Maryland 1856

Michigan

University of Strathclyde

ACIGA

Montana State University

PAH

University of Washington

Loyola University New Orleans

California Institute of Technology 1891

University of Glasgow

Università degli Studi del Sannio

Trinity University

UW Milwaukee, University of Wisconsin

ANU, The Australian National University

San José State University

NASA Goddard Space Flight Center

LSU

UTB TSC

The University of Western Australia

1754

Syracuse University, Suos Cultores Scientia Coronat, Founded AD 1870

Northwestern University

Rochester Institute of Technology R·I·T 1829

Andrews University

Massachusetts Institute of Technology

Southeastern

Moscow State University

The University of Adelaide Australia

PAN

University of Massachusetts Amherst 1863

GEO 600

Embry-Riddle Aeronautical University

University of Southampton

PennState 1855

Sigill. Coll. Carleton, Northfield, Minn. AD 1866

Cardiff University

Universitat de les Illes Balears

Washington State University

UF University of Florida

The University of Mississippi 1848

Charles Sturt University

University of Rochester

NAOJ

University of Minnesota

Southern University Agricultural & Mechanical College

Hobart College

William Smith College

Science & Technology Facilities Council Rutherford Appleton Laboratory

Universität Hannover

Acknowledgments

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- National Science Foundation

More Information

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

http://www.physics2005.org/events/einsteinathome/index.html

References

- Web of Science, search under Abbott et al., or LIGO SCI COLLABORATION