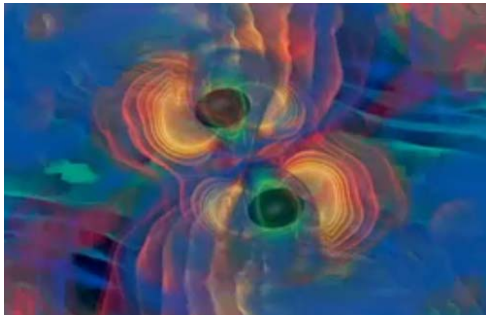


Interferometric detectors of Gravitational Waves: a new window to the Universe

Gabriela González

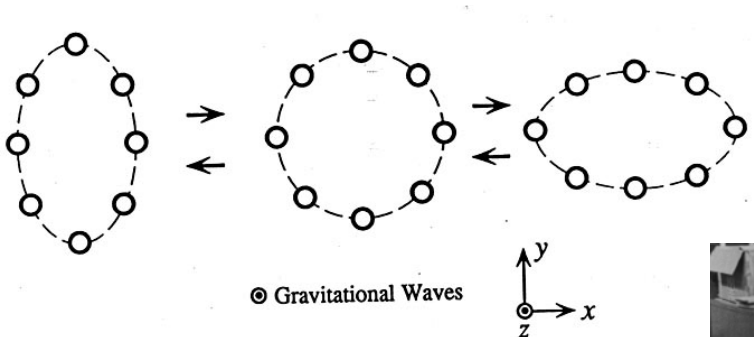
Physics and Astronomy, Louisiana State University

LIGO Scientific Collaboration

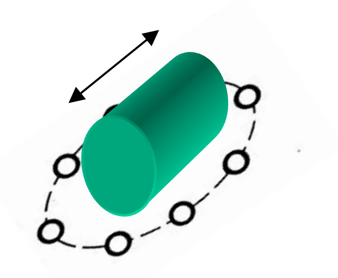
Argonne National Laboratory

February 9, 2007

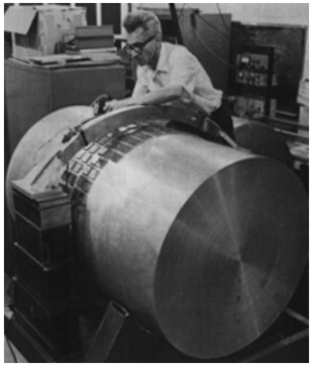
Gravitational waves

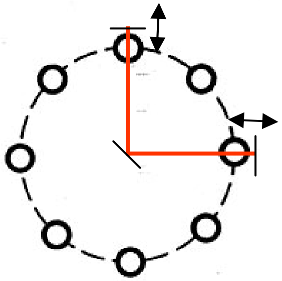


Gravitational waves are quadrupolar distortions of distances between freely falling masses. They are produced by time-varying mass quadrupoles.



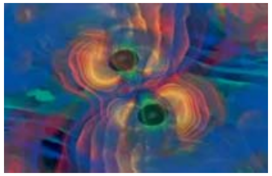
Resonant systems can measure elastic response to distance distortion: resonant bar detectors.



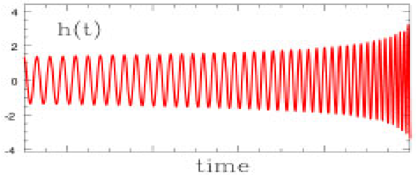


Michelson-type interferometers can detect distance changes in orthogonal directions.

In both cases, what's measured is **$\Delta L = hL$**

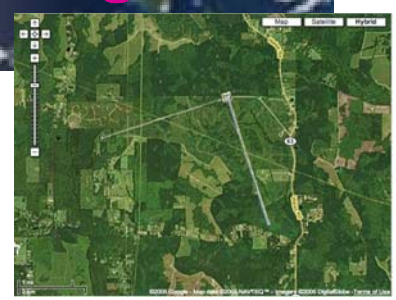


Amplitude of GWs produced by binary neutron star systems in the Virgo cluster have $h = \Delta L/L \sim 10^{-21}$ and frequencies sweeping up to ~1400 Hz.



The LIGO project

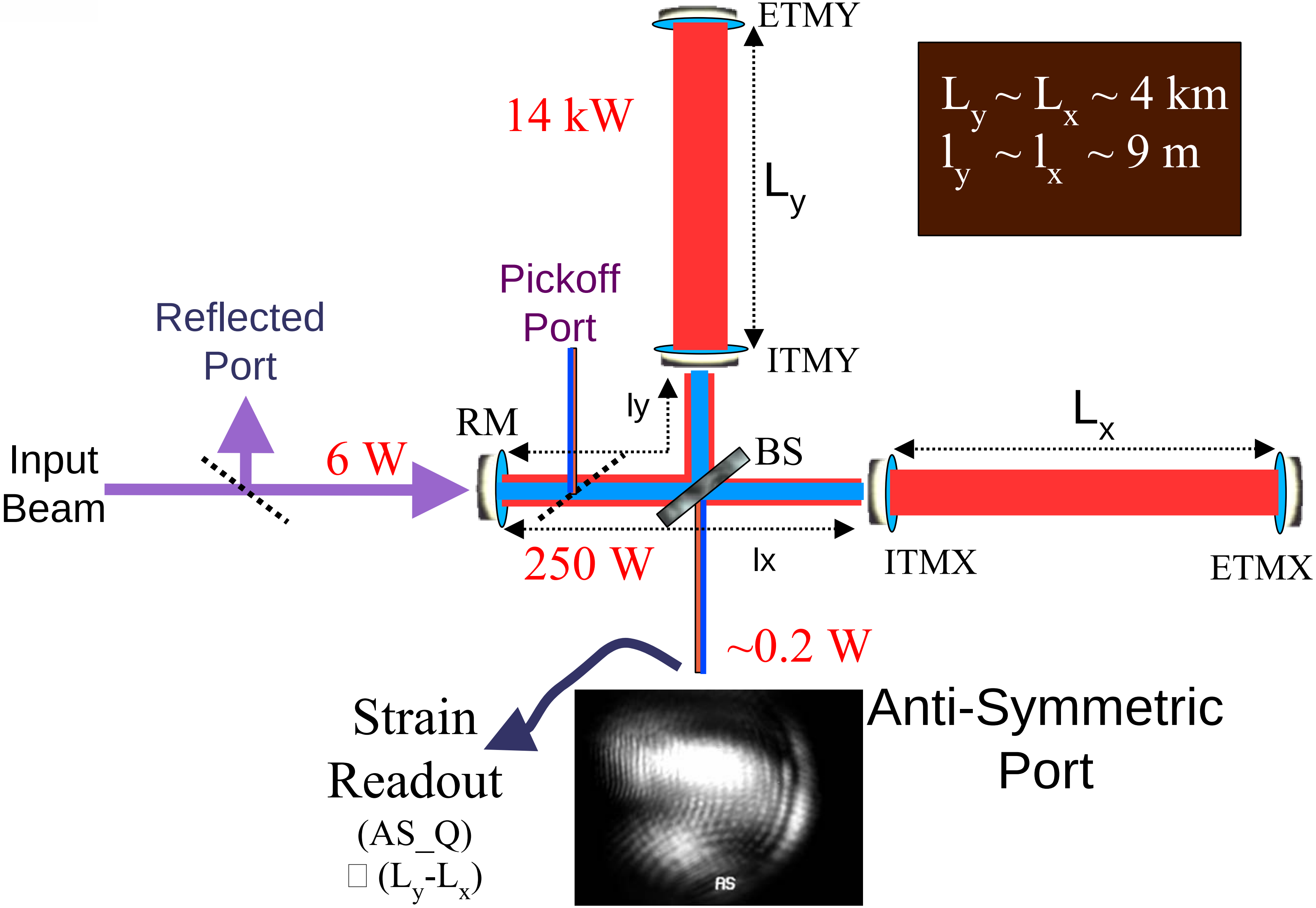
$h = \Delta L / L \sim 10^{-21}$ and $L = 4\text{km} \Rightarrow \Delta L = hL \sim 10^{-18}$ m !



Three LIGO detectors: 4km long in Livingston, LA (L1); 4km and 2km long in Hanford, WA (H1, H2).

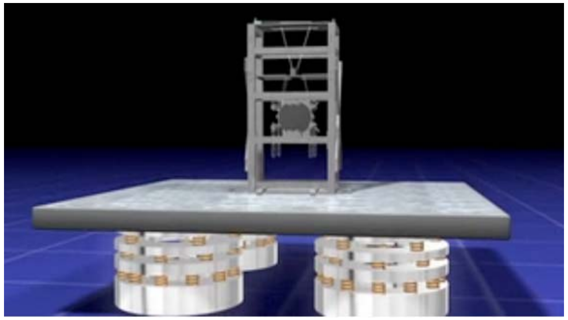
Hundreds of people working on the experiment and looking at the data: LIGO Scientific Collaboration

The INTERFEROMETER



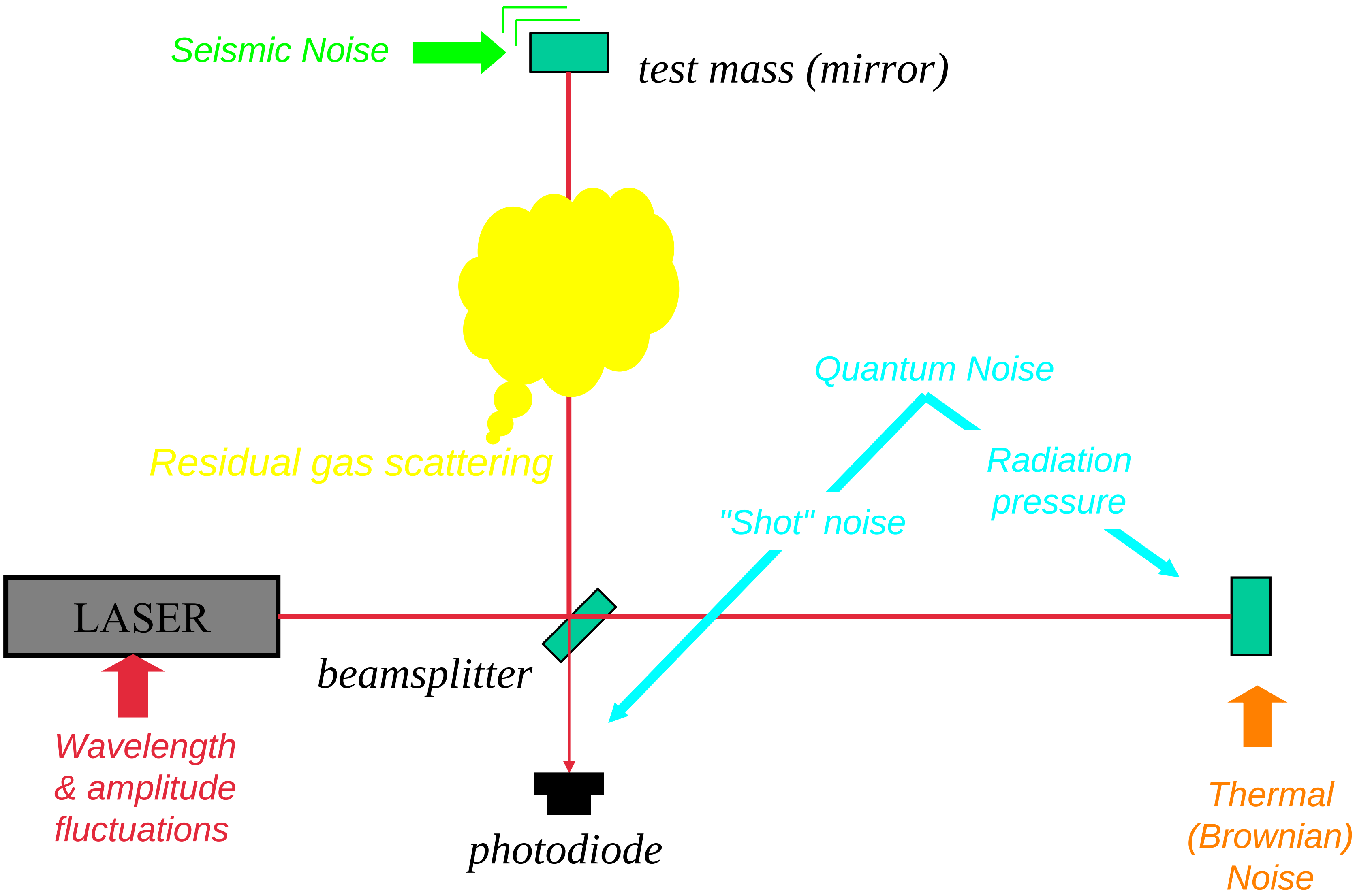
GW Detection:
a difficult and fun experiment

QuickTime™ and a
Animation decompressor
are needed to see this picture.



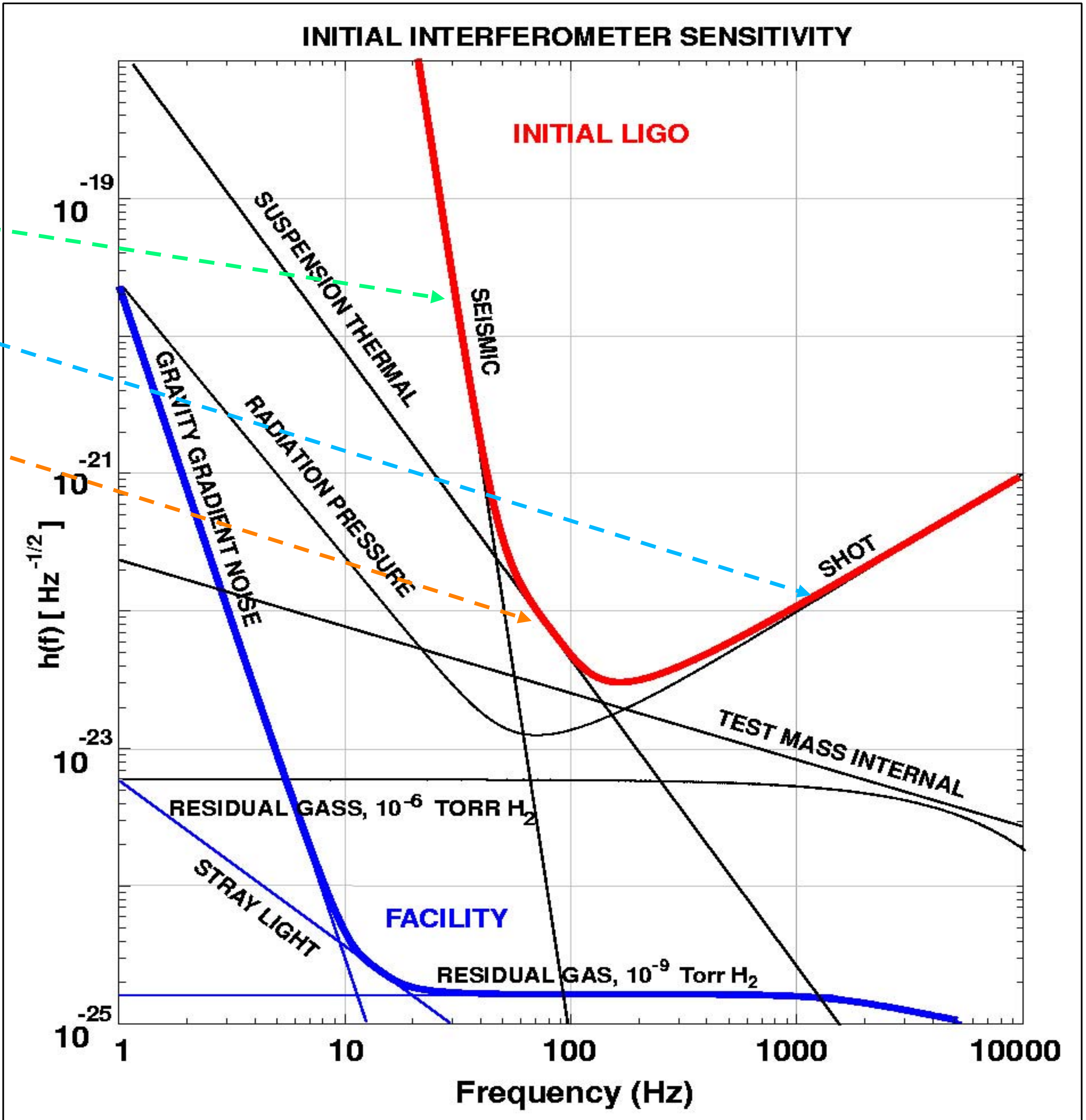
QuickTime™ and a
Animation decompressor
are needed to see this picture.

Interferometer Noise

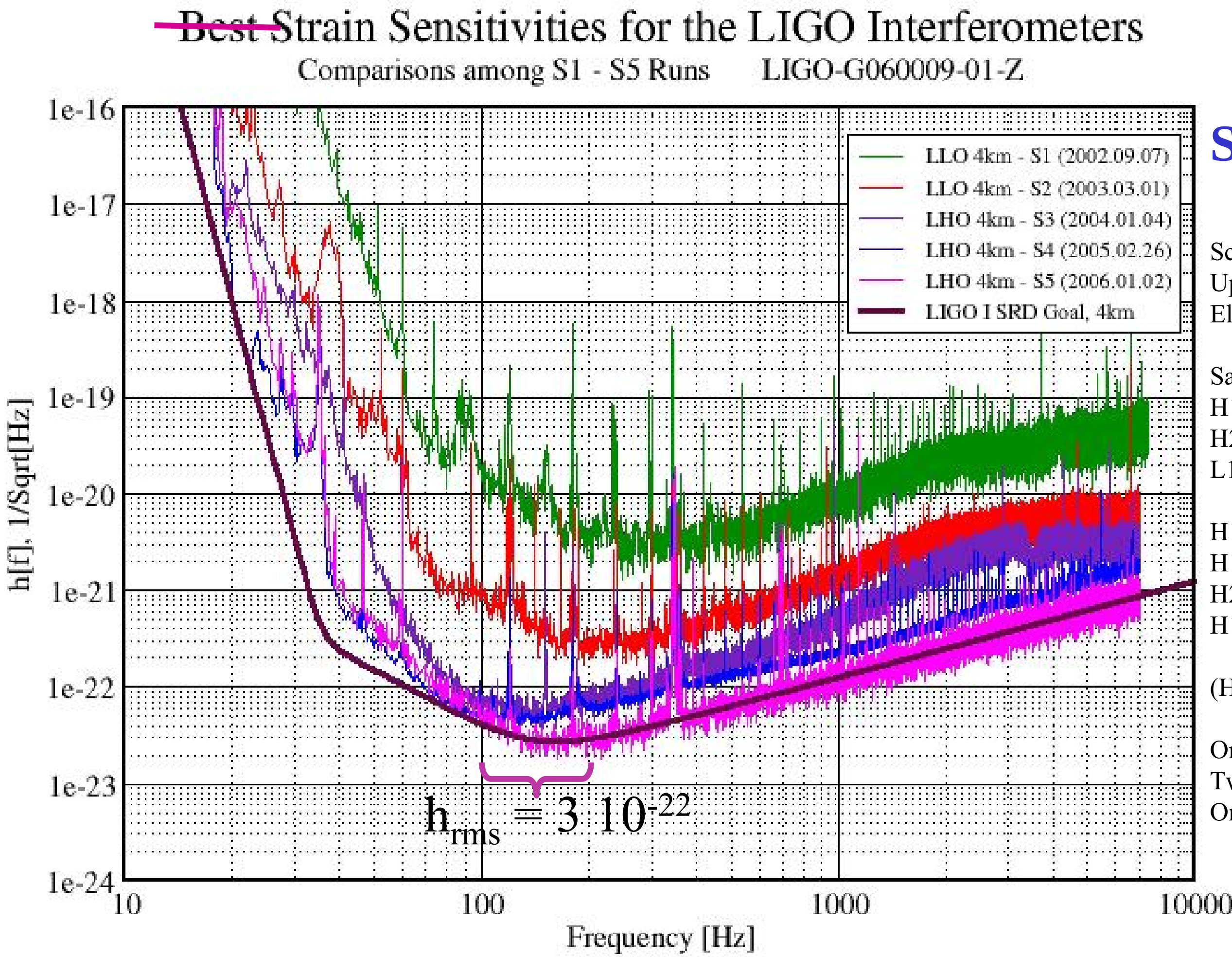


Design Noise Limits

- Initial sensitivity limits
  - **seismic noise** at the lowest frequencies
  - **shot noise** at high frequencies
  - **thermal noise** at intermediate frequencies
- Based on conservative extrapolation of prototype technologies (circa ~'97)
- Facility limits designed much lower to allow improvement as detector technology advances



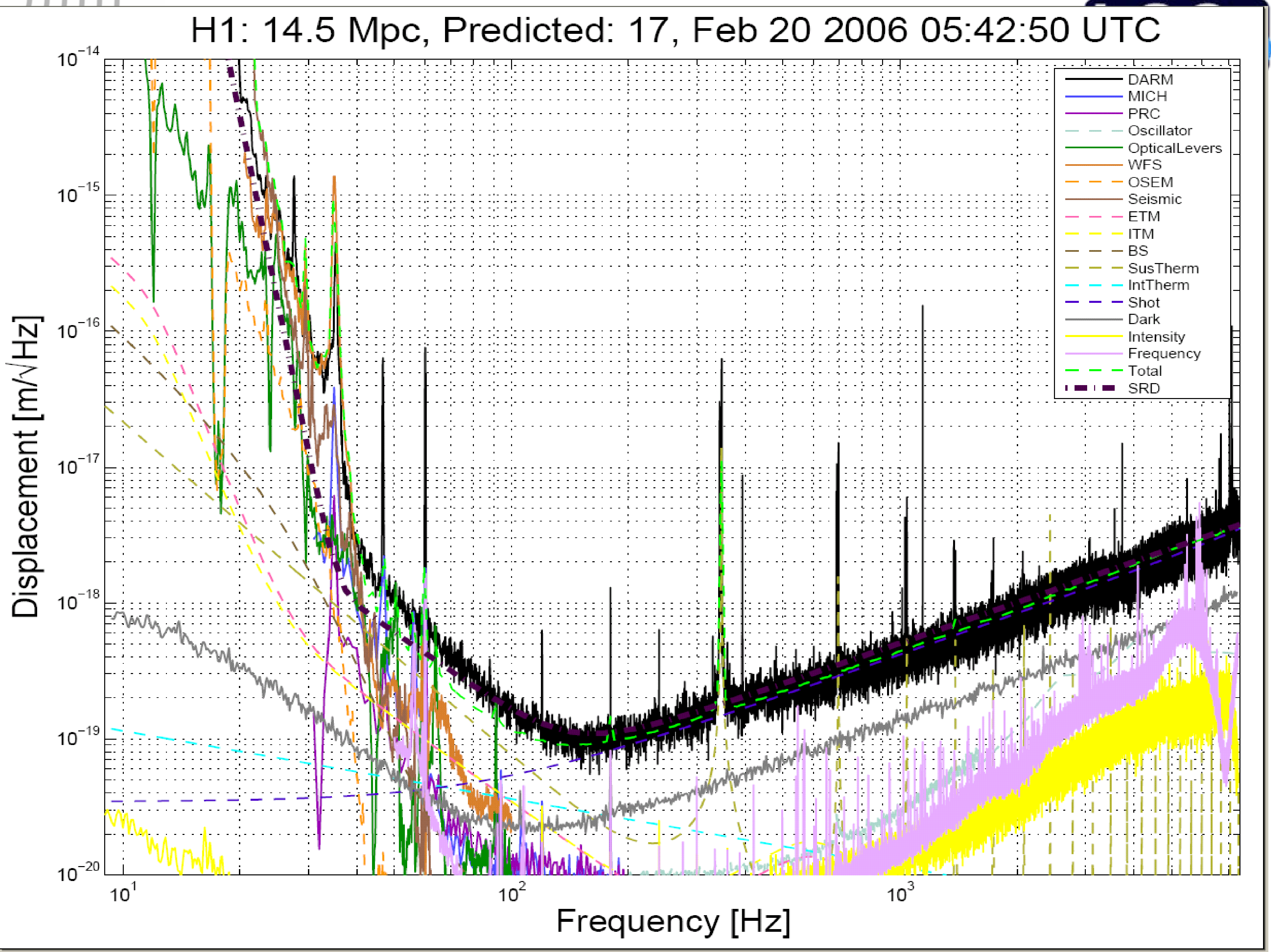
LIGO: Steady progress



S5 so far:

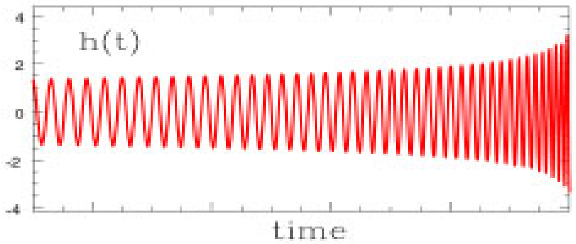
Science-mode statistics for S5 run
Up to Feb 08 2007 17:36:05 UTC
Elapsed run time = 11065.6 hours

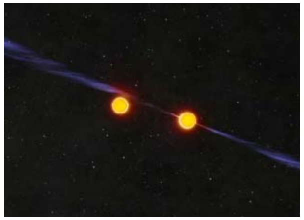
Sample	Hours	Percent	
H1	8097.8	73.2	since Nov 4, 2005
H2	8452.5	76.4	since Nov 4, 2005
L1	6658.9	61.5	since Nov 14, 2005
H1+H2	7427.3	67.1	since Nov 4, 2005
H1+L1	5545.0	51.2	since Nov 14, 2005
H2+L1	5586.9	51.6	since Nov 14, 2005
H1+H2+L1	5130.4	47.4	since Nov 14, 2005
(H1orH2)+L1	6002.2	54.2	since Nov 4, 2005
One or more LIGO	9780.4	88.4	since Nov 4, 2005
Two or more LIGO	8299.0	75.0	since Nov 4, 2005
One or more LSC	10491.8	94.8	since Nov 4, 2005



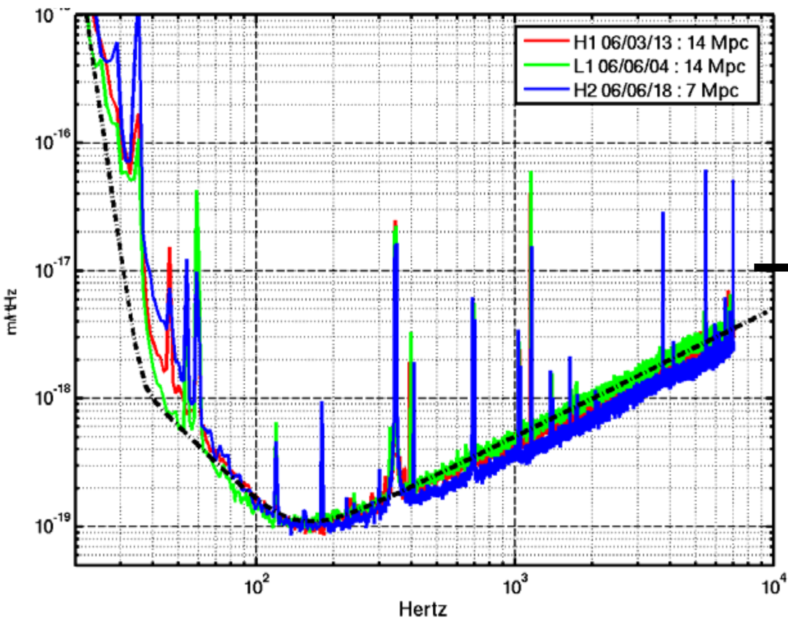
H1: 14.5 Mpc, Predicted: 17, Feb 20 2006 05:42:50 UTC
Displacement [m/√Hz]
Frequency [Hz]
DARM
MICH
PRC
Oscillator
OpticalLevers
WFS
OSEM
Seismic
ETM
ITM
BS
SusTherm
IntTherm
Shot
Dark
Intensity
Frequency
Total
SRD

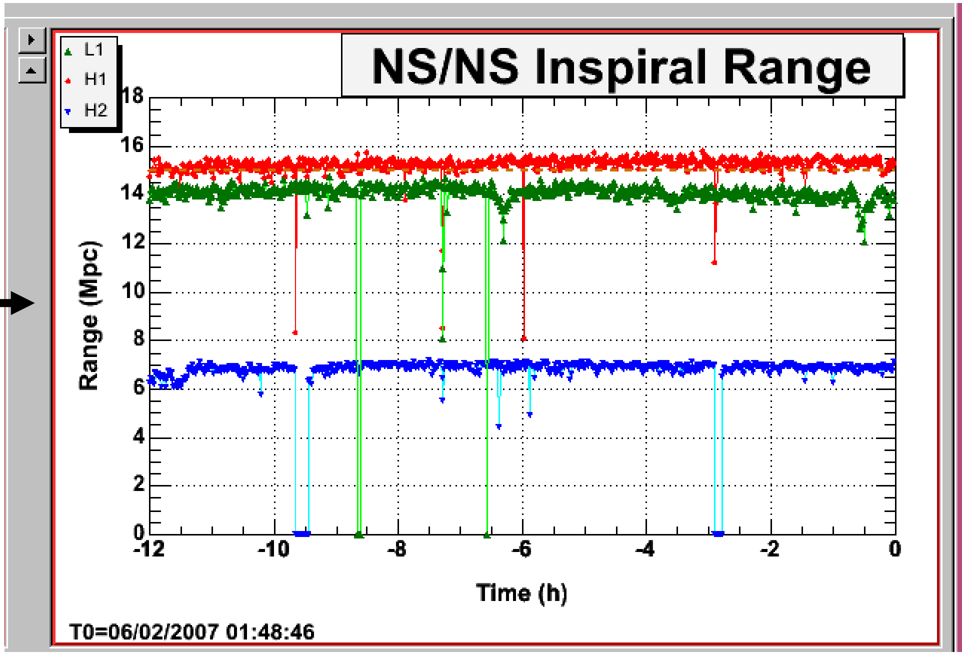
Binary systems: a measure of performance





Can translate strain amplitude into (effective) distance



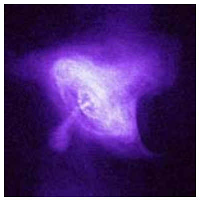


If system is optimally located and oriented, we can see even further: we are surveying hundreds of galaxies!

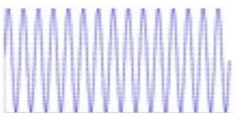
Electronic logs are public!
www.ligo.caltech.edu

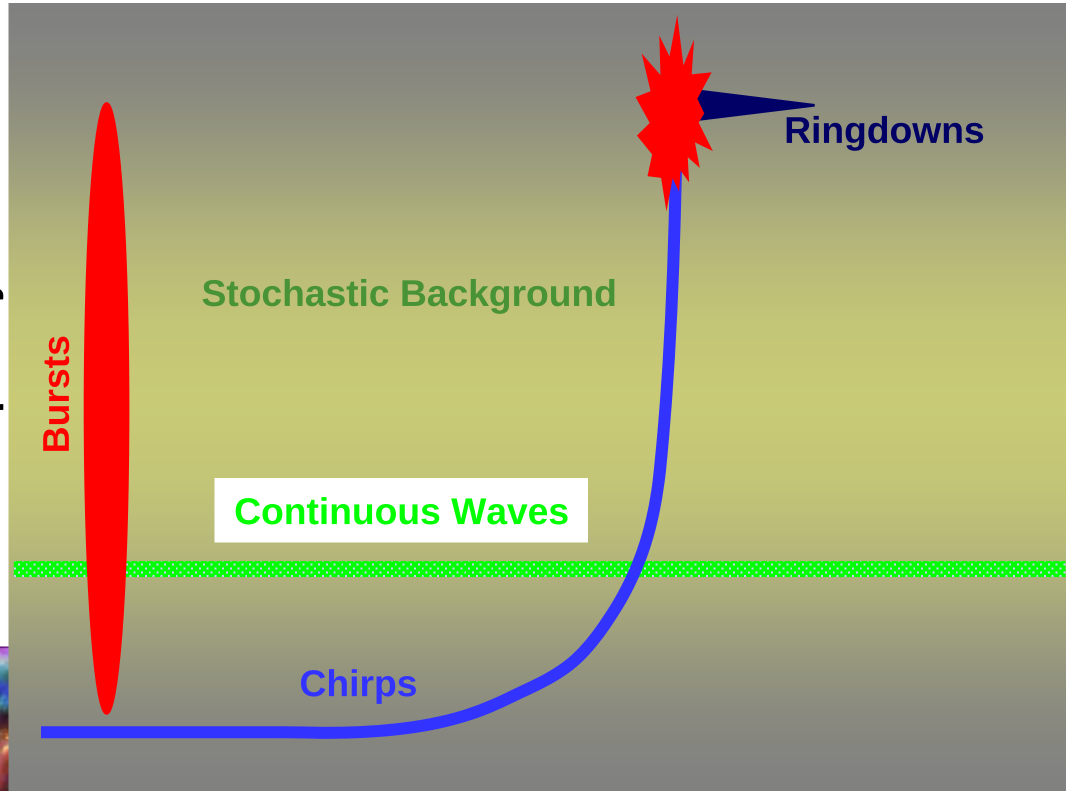
Observational Results

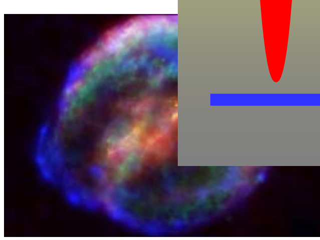
www.ligo.org



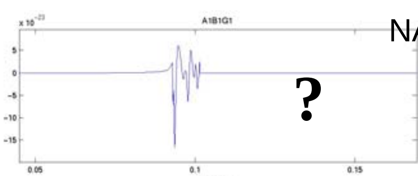
Crab pulsar (NASA, Chandra Observatory)

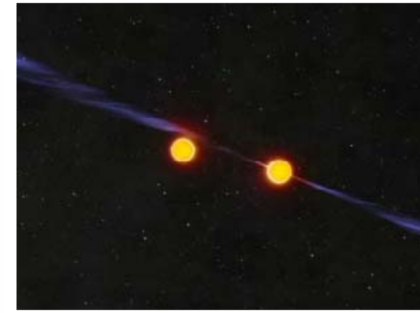




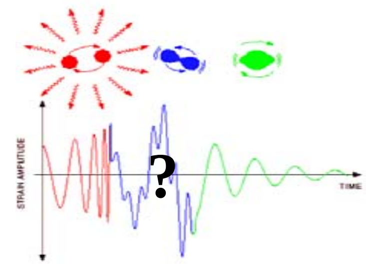


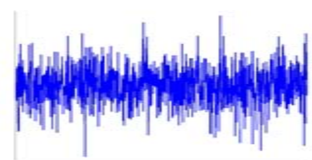
NASA, HEASARC

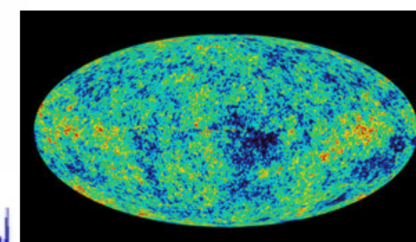




John Rowe, CSIRO



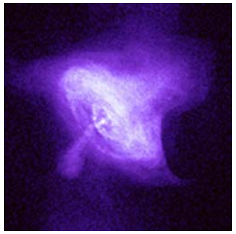


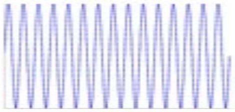


NASA, WMAP

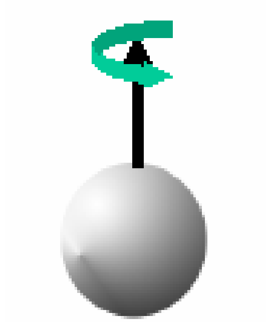
Gravitational wave searches: pulsars

Crab pulsar
(Chandra Telescope)





- Rotating stars produce GWs *if* they have asymmetries or *if* they wobble.
- *Observed* spindown can be used to set strong indirect upper limits on GWs.
- There are many known pulsars (rotating stars!) that produce GWs in the LIGO frequency band (40 Hz-2 kHz).
  - Targeted searches for 73 known (radio and x-ray) systems in S5: isolated pulsars, binary systems, pulsars in globular clusters…
- There are likely to be many non-pulsar rotating stars producing GWs.
  - All-sky, unbiased searches; wide-area searches.
- GWs (or lack thereof) can be used to measure (or set up upper limits on) the ellipticities of the stars.
- Search for a sine wave, modulated by Earth's motion, and possibly spinning down: easy, but computationally expensive!



http://www.einsteinathome.org/

Gravitational wave searches: pulsars

Lowest GW strain upper limit:

PSR J1802-2124

(f_{gw} = 158.1 Hz, r = 3.3 kpc)

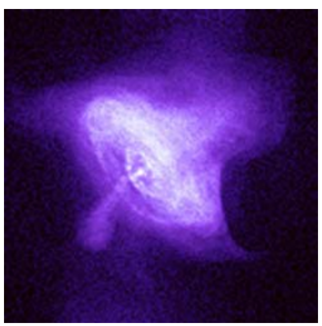
$\mathbf{h_0 < 4.9\times10^{-26}}$

Lowest ellipticity upper limit:

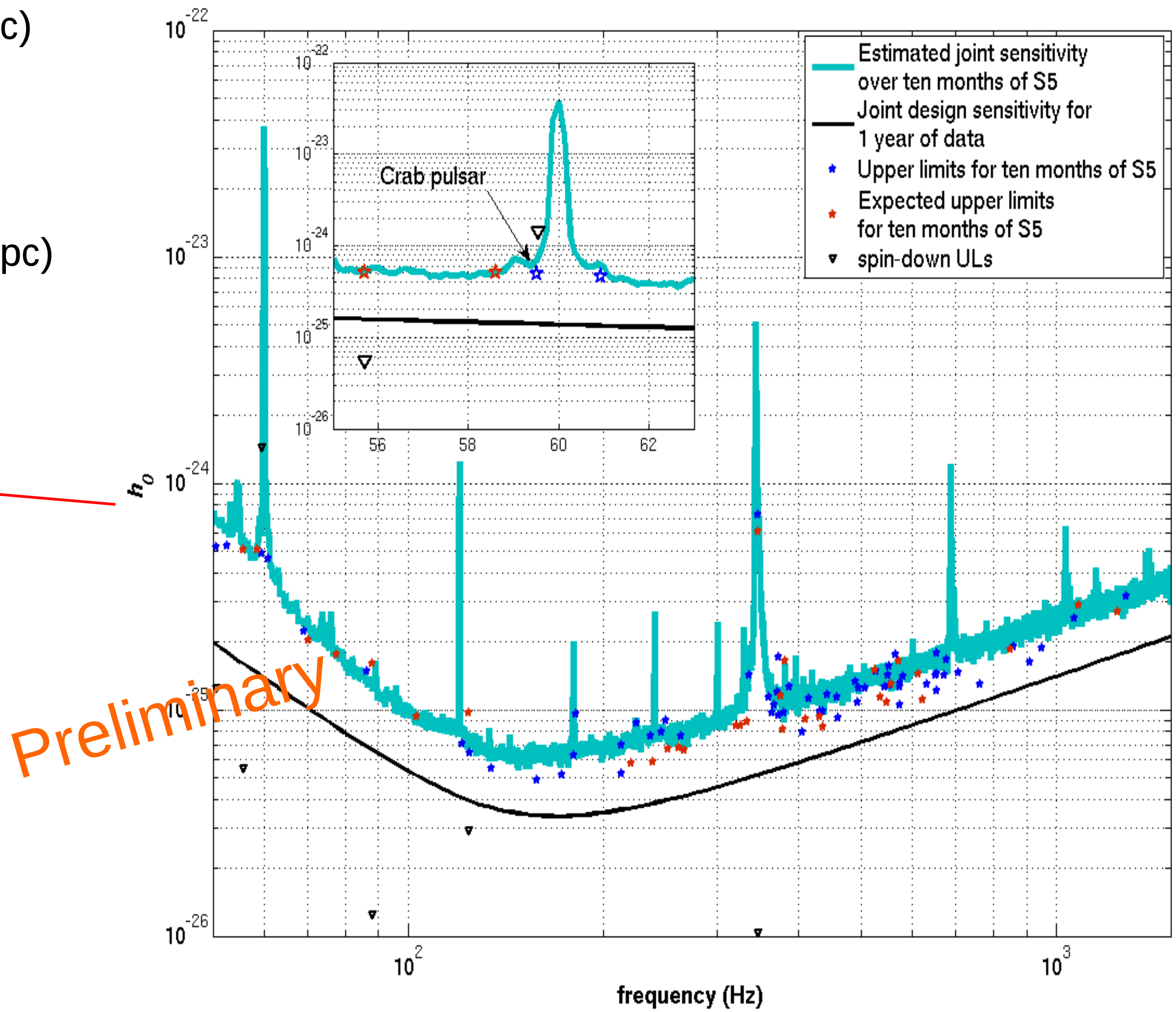
PSR J2124-3358

(f_{gw} = 405.6 Hz, r = 0.25 kpc)

$\boldsymbol{\varepsilon < 1.1\times10^{-7}}$

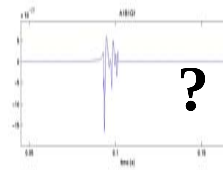


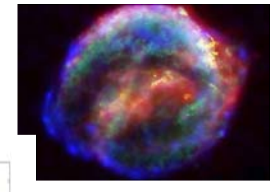
Crab pulsar

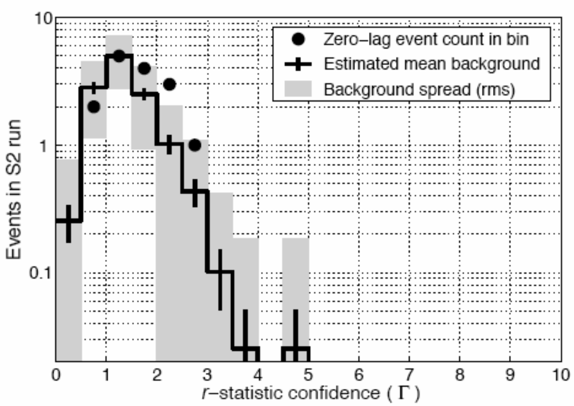


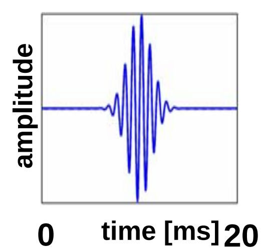
LIGO searches: “burst” sources (untriggered)

- Search for <u>triple coincident</u> triggers with a wavelet algorithm
- Measure waveform consistency
- Set a threshold for detection for <u>low false alarm probability</u>
- Compare with efficiency for detecting simple waveforms

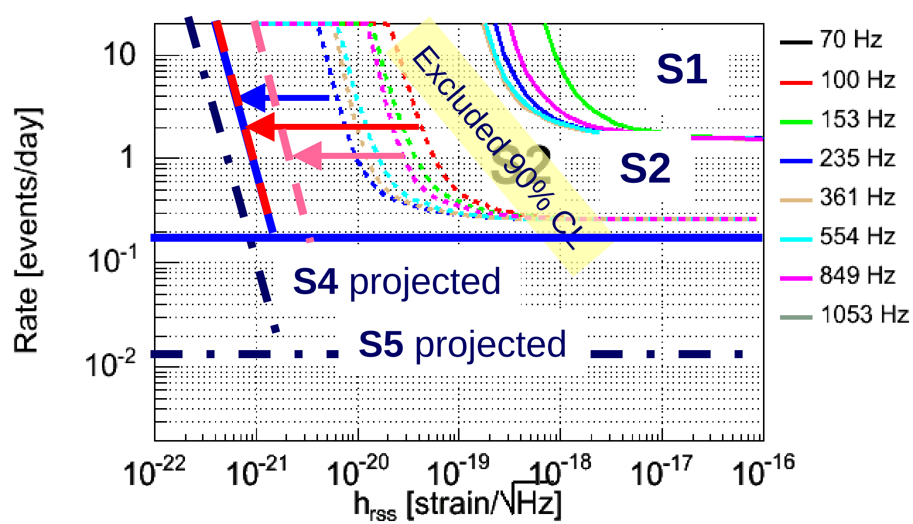






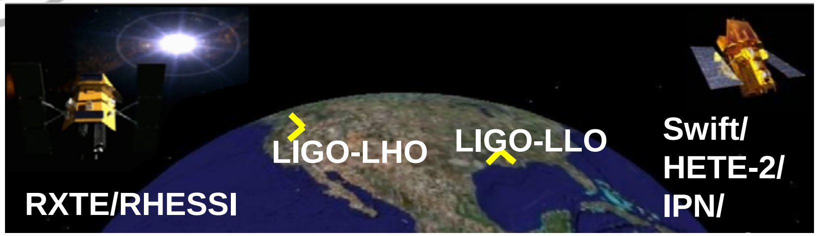


PRD 72 (2005) 042002

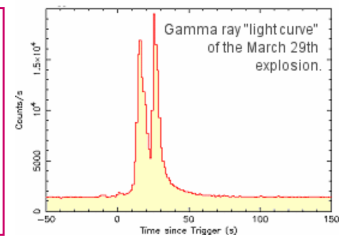


- S1: First upper limits from LIGO on gravitational wave bursts, Phys. Rev. D 69, 102001 (2004)
- S2: Upper Limits on Gravitational Wave Bursts in LIGO's Second Science Run, Phys. Rev. D 72, 062001 (2005)
- S2: Upper Limits from the LIGO and TAMA Detectors on the Rate of Gravitational-Wave Bursts, Phys. Rev. D 72, 122004 (2005)
- S3: Search for gravitational wave bursts in LIGO's third science run, Class. Quant. Grav. 23, S29-S39 (2006)
- S4: results completed, paper in progress
- S5 analysis in progress

Triggered Searches for GW Bursts



HETE GRB030329 (~800 Mpc SN): during S2, search resulted in no detection (**PRD** 72, 042002, 2005)



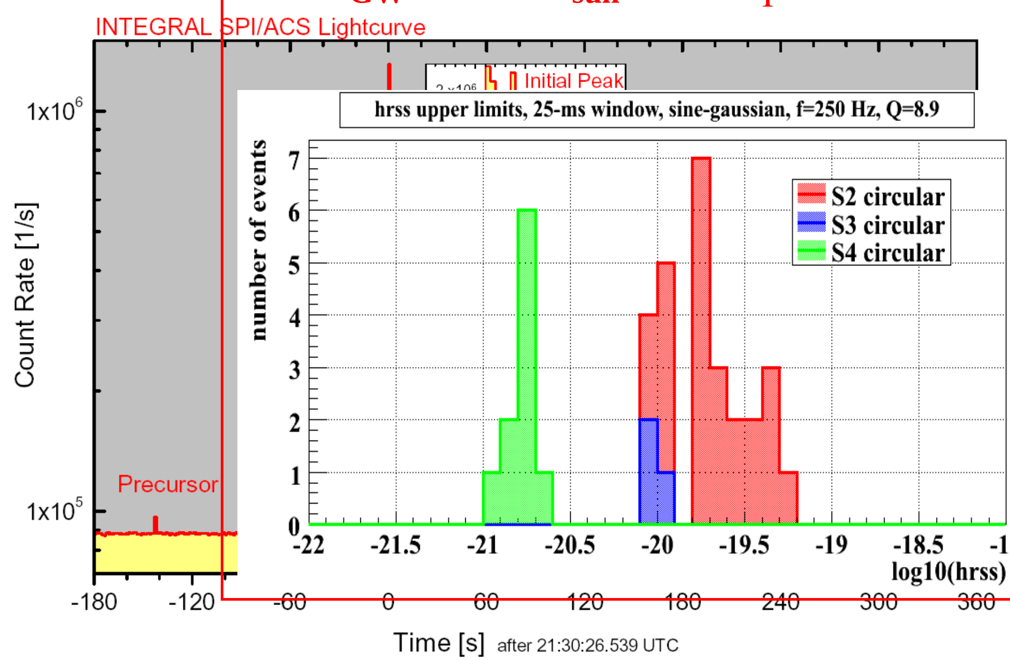
Gamma-Ray Bursts

- search LIGO data surrounding GRB trigger using cross-correlation method
- no GW signal found associated with 39 GRBs in S2, S3, S4 runs
- set limits on GW signal amplitude
- 53 GRB triggers for the first five months of LIGO S5 run
- typical S5 sensitivity at 250 Hz: $E_{GW} \sim$ **0.3 M_{sun}** at 20 Mpc

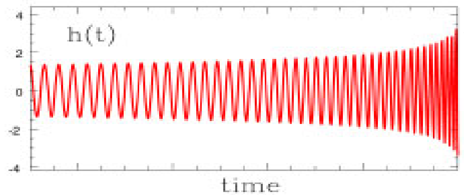
Soft Gamma Repeater 1806-20

- galactic neutron star (10-15 kpc) with intense magnetic field (~10^{15} G)
- source of record gamma-ray flare on December 27, 2004
- quasi-periodic oscillations found in RHESSI and RXTE x-ray data
- search S4 LIGO data for GW signal associated with quasi-periodic oscillations-- no GW signal found
- sensitivity: $E_{GW} \sim 10^{-7}$ to 10^{-8} Msun for the 92.5 Hz QPO
- this is the same order of magnitude as the EM energy emitted in the flare

SGR 1806-20 Outburst on December 27, 2004

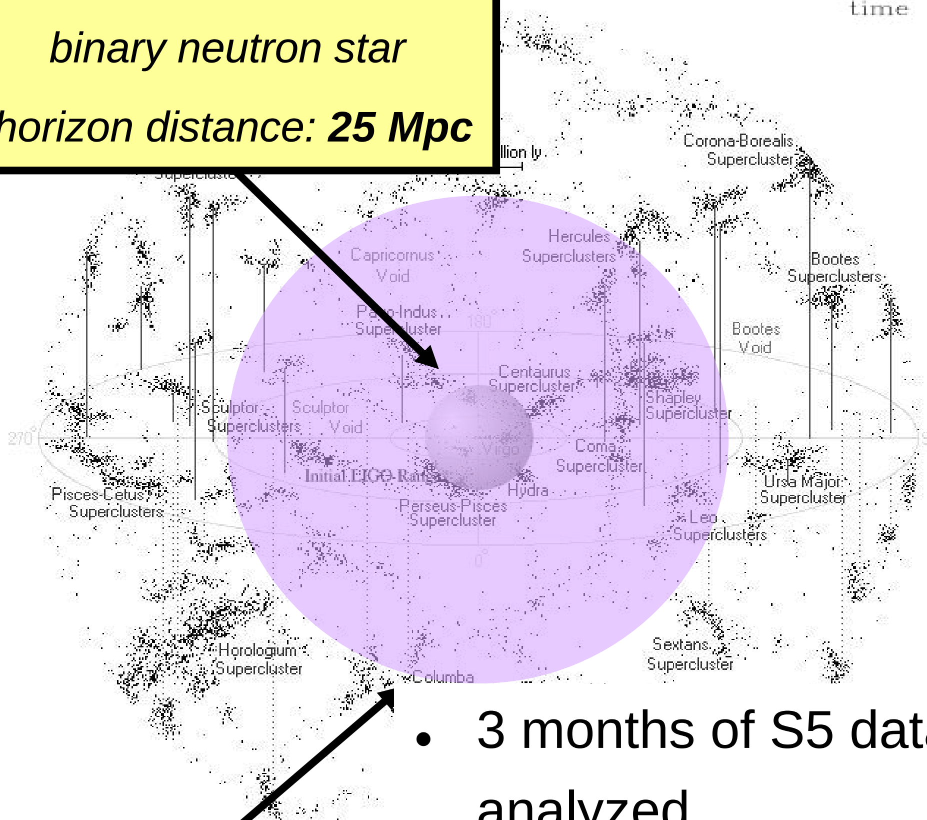


Searches for coalescing compact binary signals in S5



$f_{coal} \sim 1/M$

binary neutron star horizon distance: ***25 Mpc***



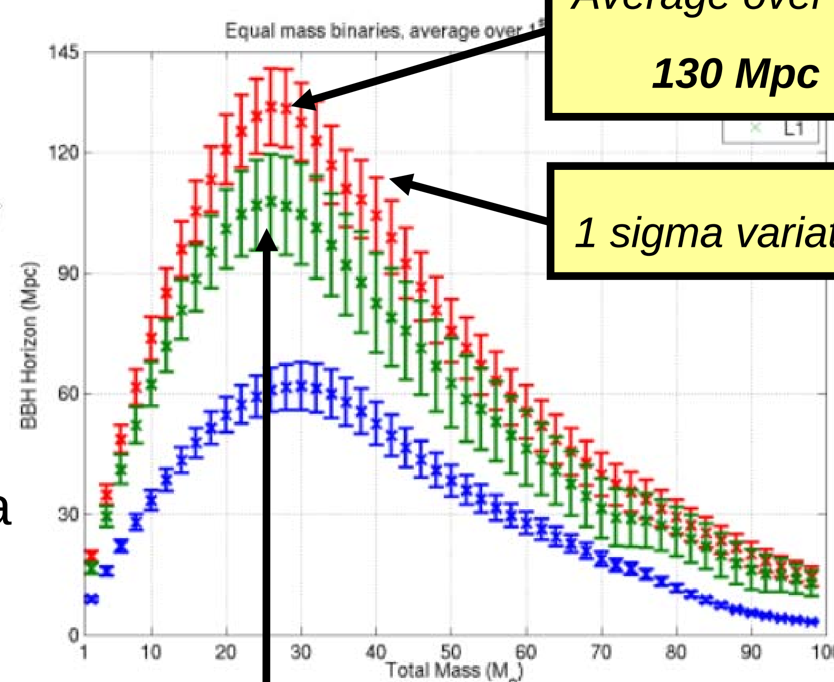
binary black hole horizon distance

- 3 months of S5 data analyzed
- 1 calendar yr in progress

Inspiral Horizon distance vs mass

Average over run ***130 Mpc***

1 sigma variation

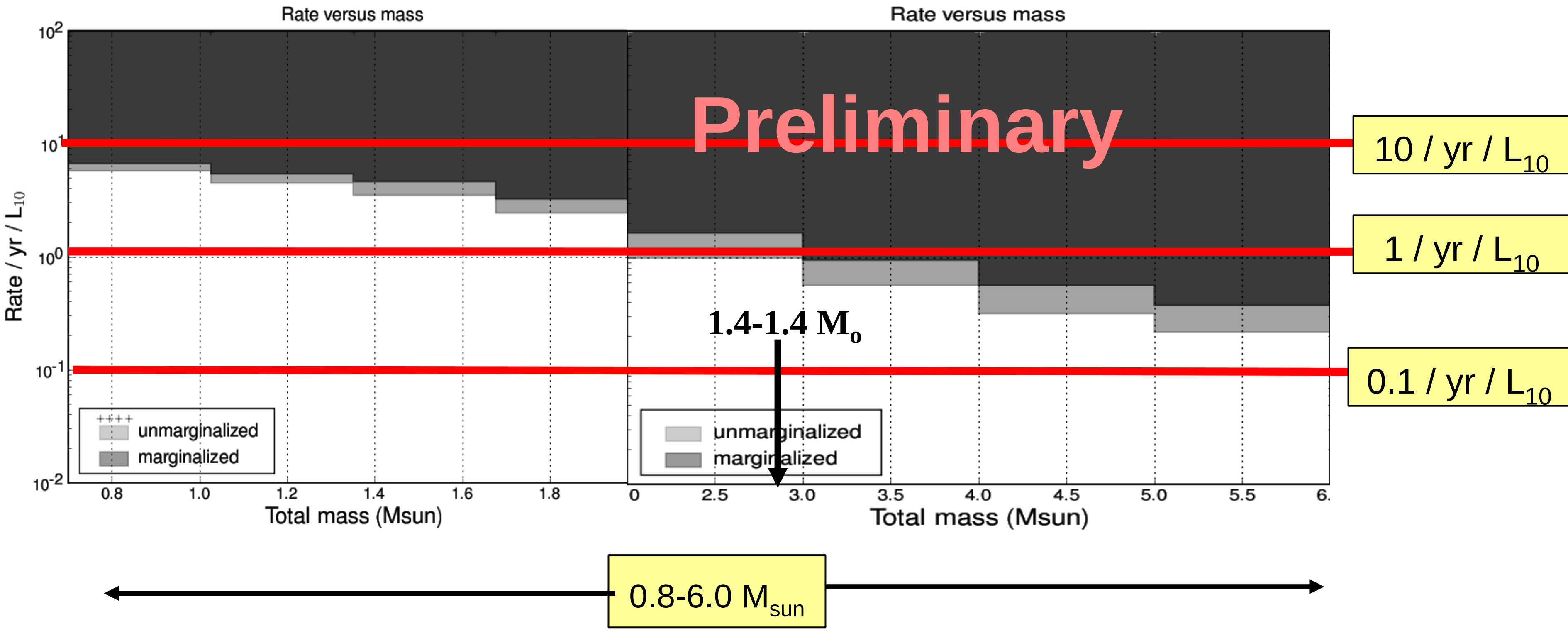


Peak at total mass ~ $25M_{sun}$

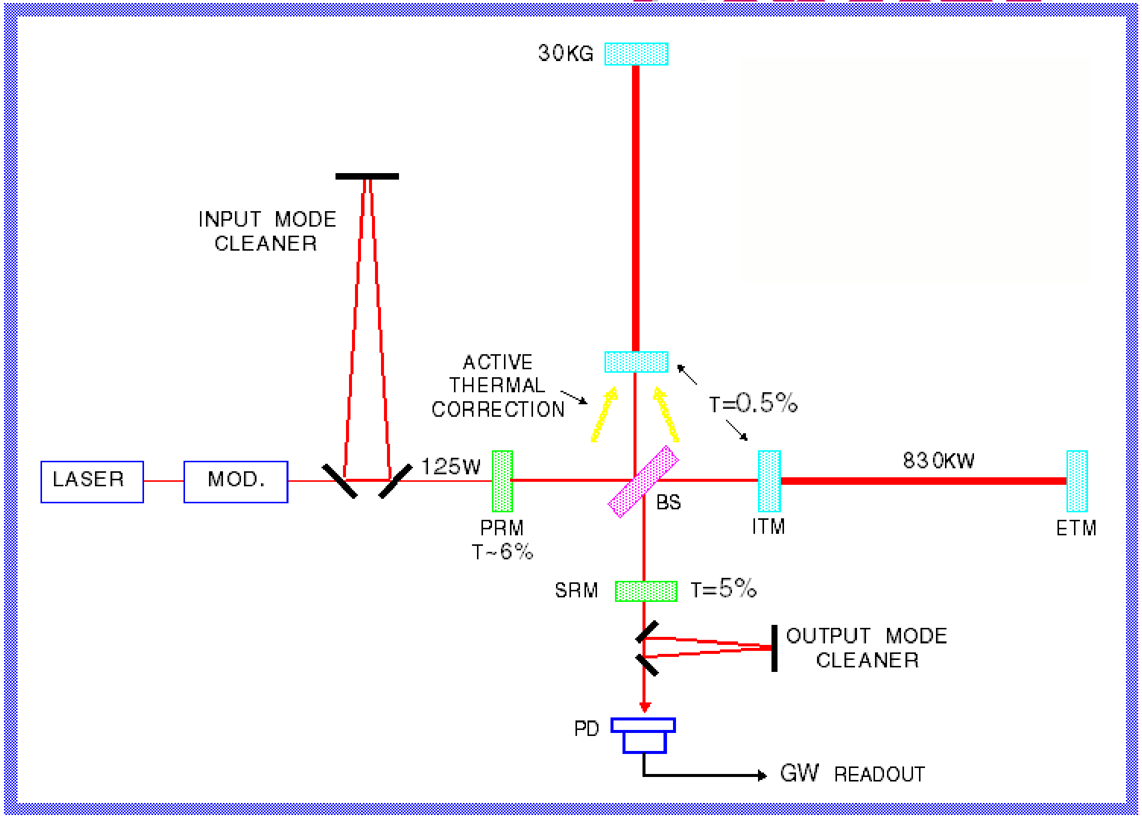
S4 upper limits-compact binary coalescence

- Rate/year/L_{10} vs. binary total mass

  $L_{10} = 10^{10} L_{sun,B}$ (1 Milky Way = 1.7 L_{10})
- Dark region excluded at 90% confidence.



Advanced Interferometer Concept



» Signal recycling

» Output mode cleaner

» 180 W laser

(800 kW in arms)

» 30 kg test masses

» Quadruple suspensions

» Active seismic isolation

» Active thermal correction

Advanced Suspensions

R. Jones, Glasgow U.

- Based on successful GEO triple pendulum design
- Quad pendula for TM, BS; Triples for input optics
- Blade springs for vertical isolation
- Indirect damping through upper stage recoil
- Electrostatic or photon drive for fast control at final stage; reaction mass for ES recoil

LIGO detectors: future

- **Neutron Star Binaries:**

  Initial LIGO: ~10-20 Mpc →

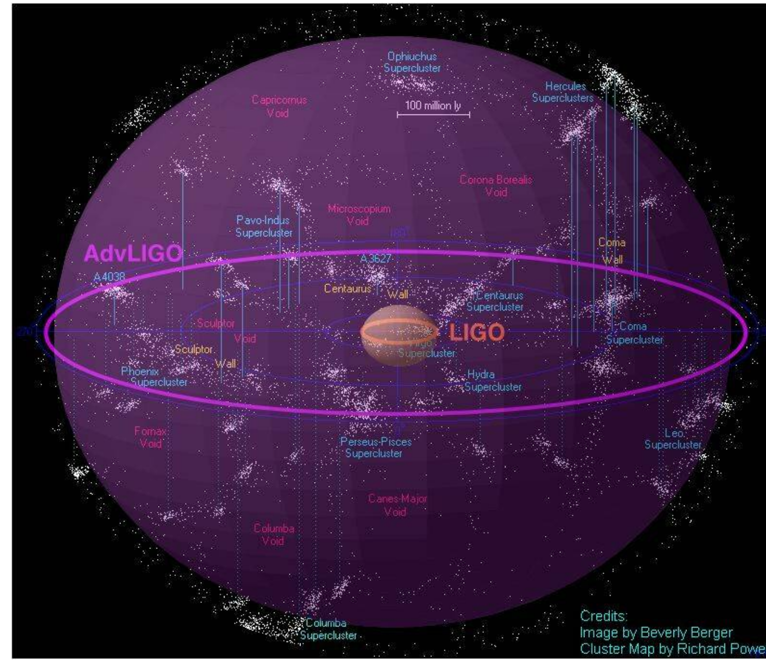
  Advanced LIGO: ~200-350 Mpc

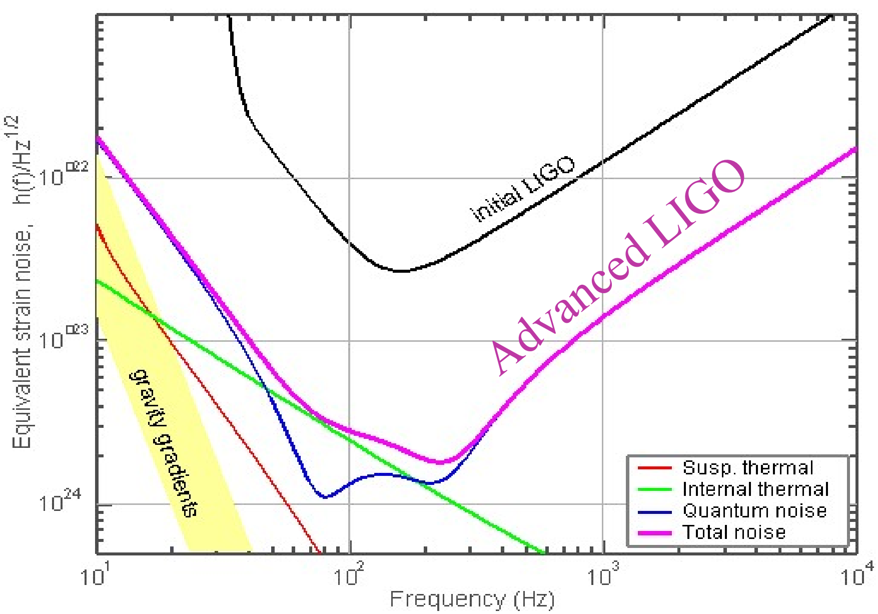
  <u>Most likely rate: 1 every 2 days !</u>

- **Black hole Binaries:**

  Up to 30 M_o, at ~ 100 Mpc

  → up to 50 M_o, in most of the observable Universe!





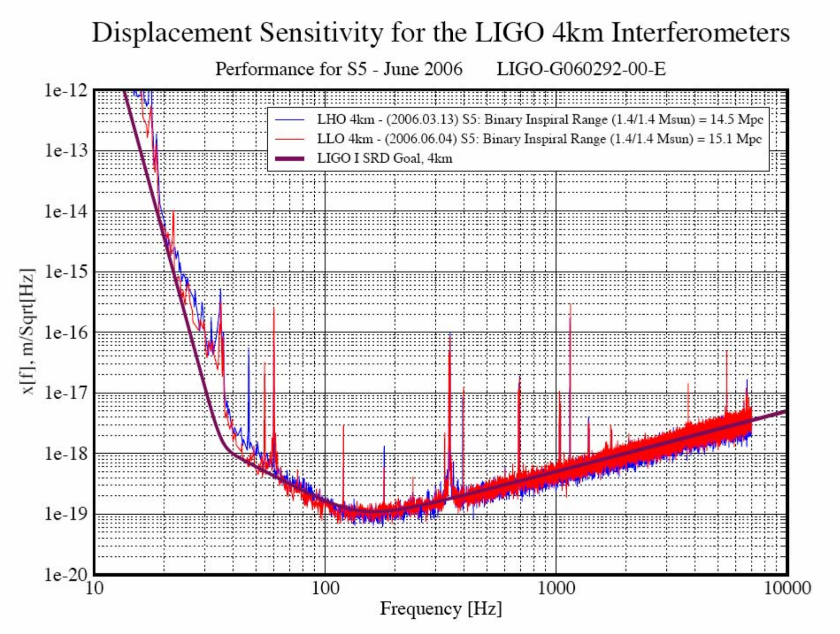
x10 better amplitude sensitivity

⇒ x1000 rate=(reach)³

⇒ 1 year of Initial LIGO < 1 day of Advanced LIGO !

Planned NSF Funding in FY'08 budget (being discussed right now!).

These are exciting times!



- We are taking data at unprecedented sensitivity, and we are searching for gravitational waves.
- We are getting ready for Advanced LIGO.

- We are preparing ourselves for a direct observation of gravitational waves:
  not if, but when!
- LIGO detectors and their siblings will open a new window to the Universe: what's out there?

Back up slides

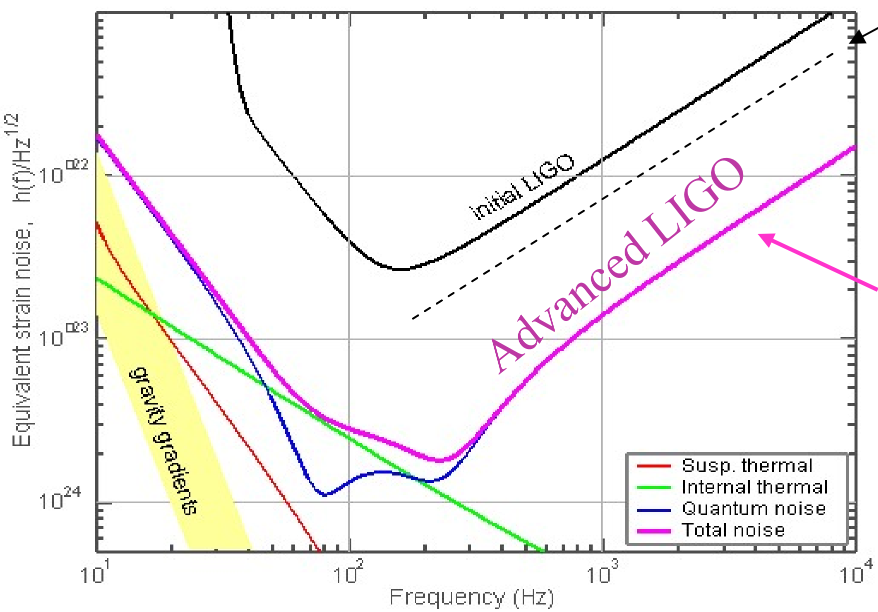
Present, future

4Q '05 | 4Q '06 | 4Q '07 | 4Q '08 | 4Q '09 | 4Q '10

S5 | ***~2 years*** | **S6?** | ***Decomm IFO1***

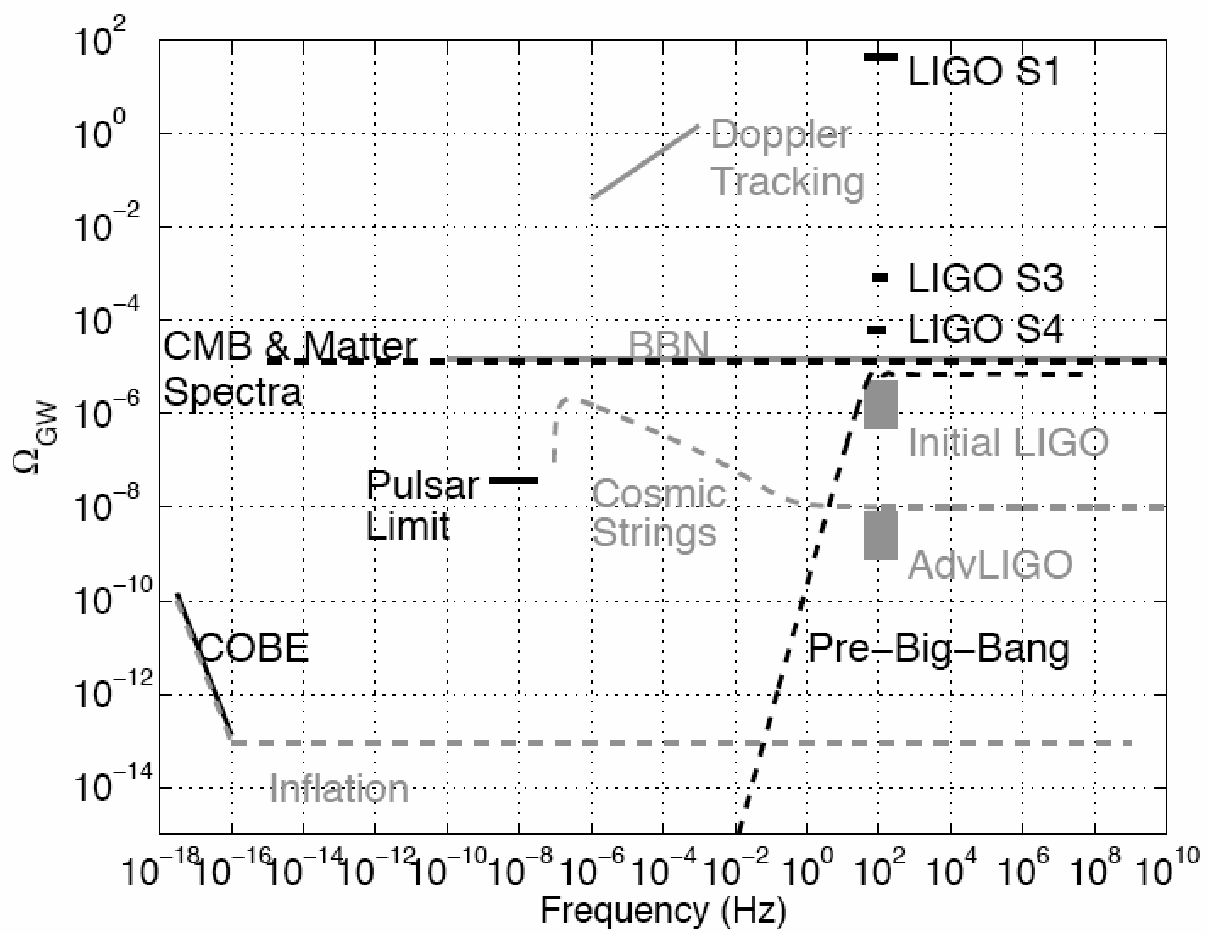
today

BNS: 1/30 yr
BBH: ??



BNS: 1/2days
BBH: we'll measure it!

Stochastic Background: the landscape



Beam Tubes a

Precast concrete enclosure: *bulletproof*

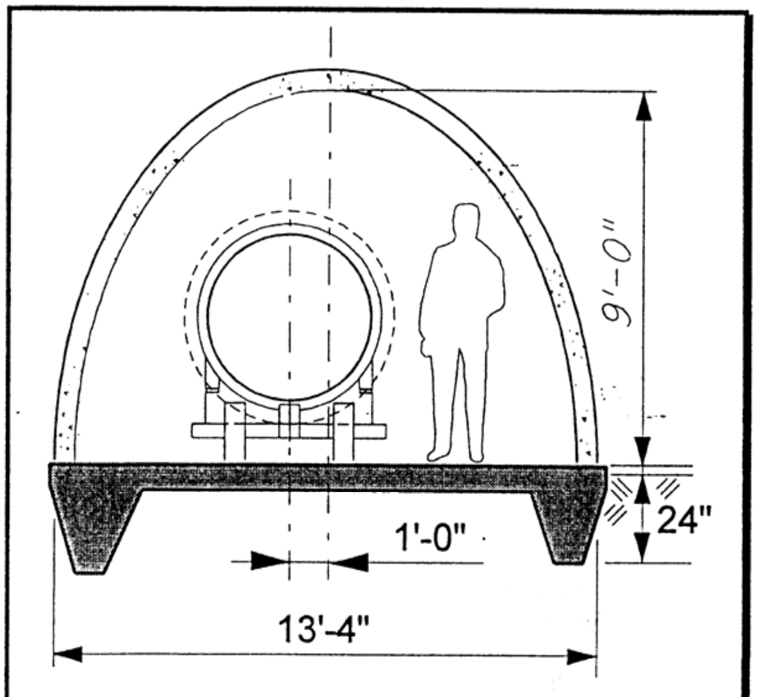
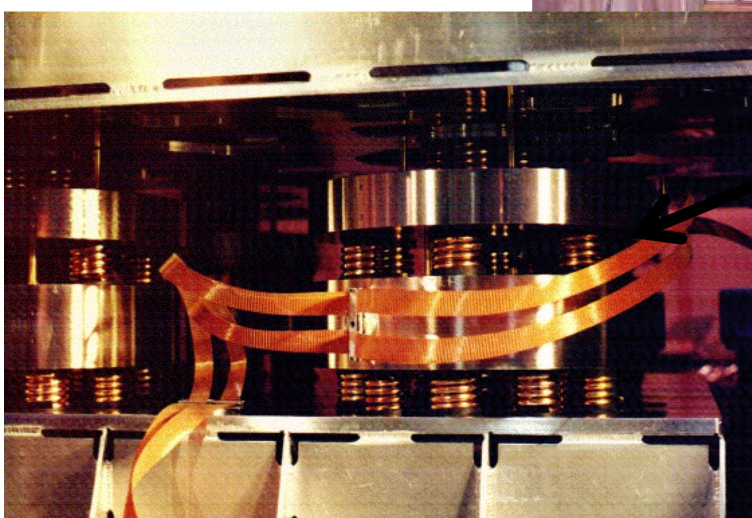


Figure 2.1-1 -- Cross Section of Design Baseline at Hanford

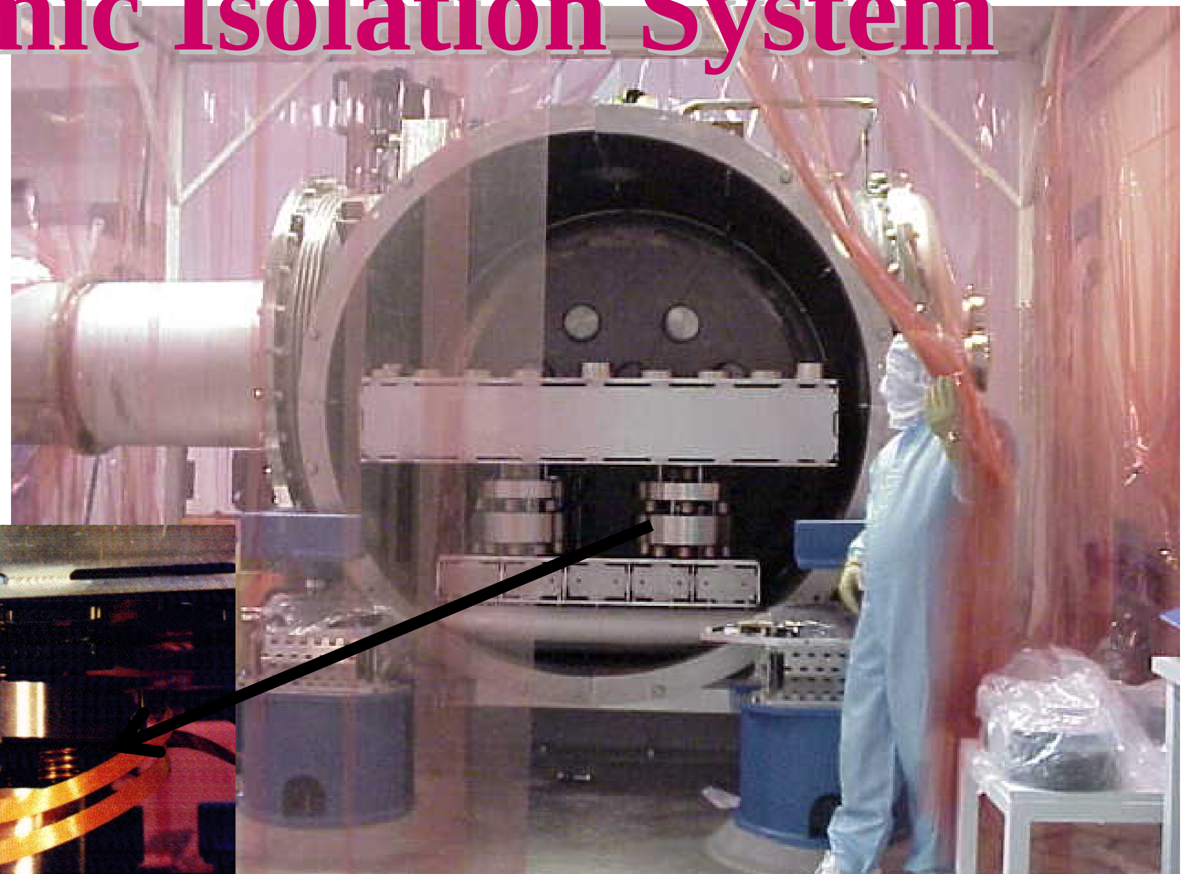
- **Beam Tube**
  - **1.2m diam; 3 mm stainless**
  - **special low-hydrogen steel process**
  - **65 ft spiral weld sections**
  - **50 km of weld (NO LEAKS!)**
  - **20,000 m^3 @ 10^{-8} torr; earth's largest high vacuum system**

Vacuum Equipment

Seismic Isolation System

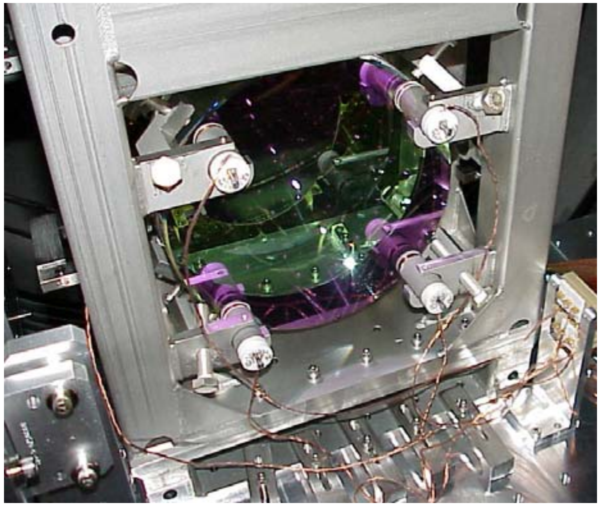


Tubular coil springs with internal constrained-layer damping, layered with reaction masses



Isolation stack in chamber

Core Optic Suspensions

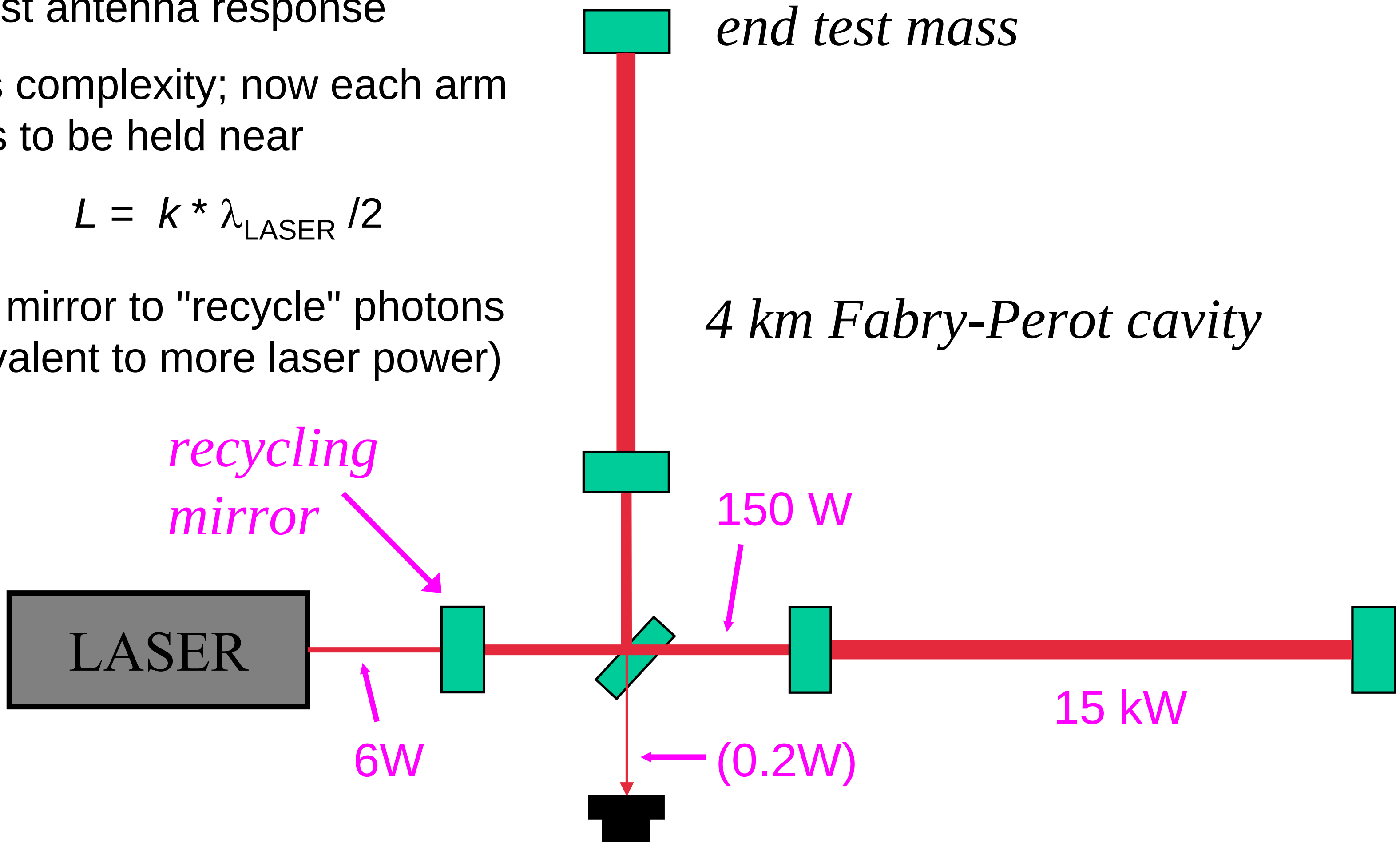


Interferometry

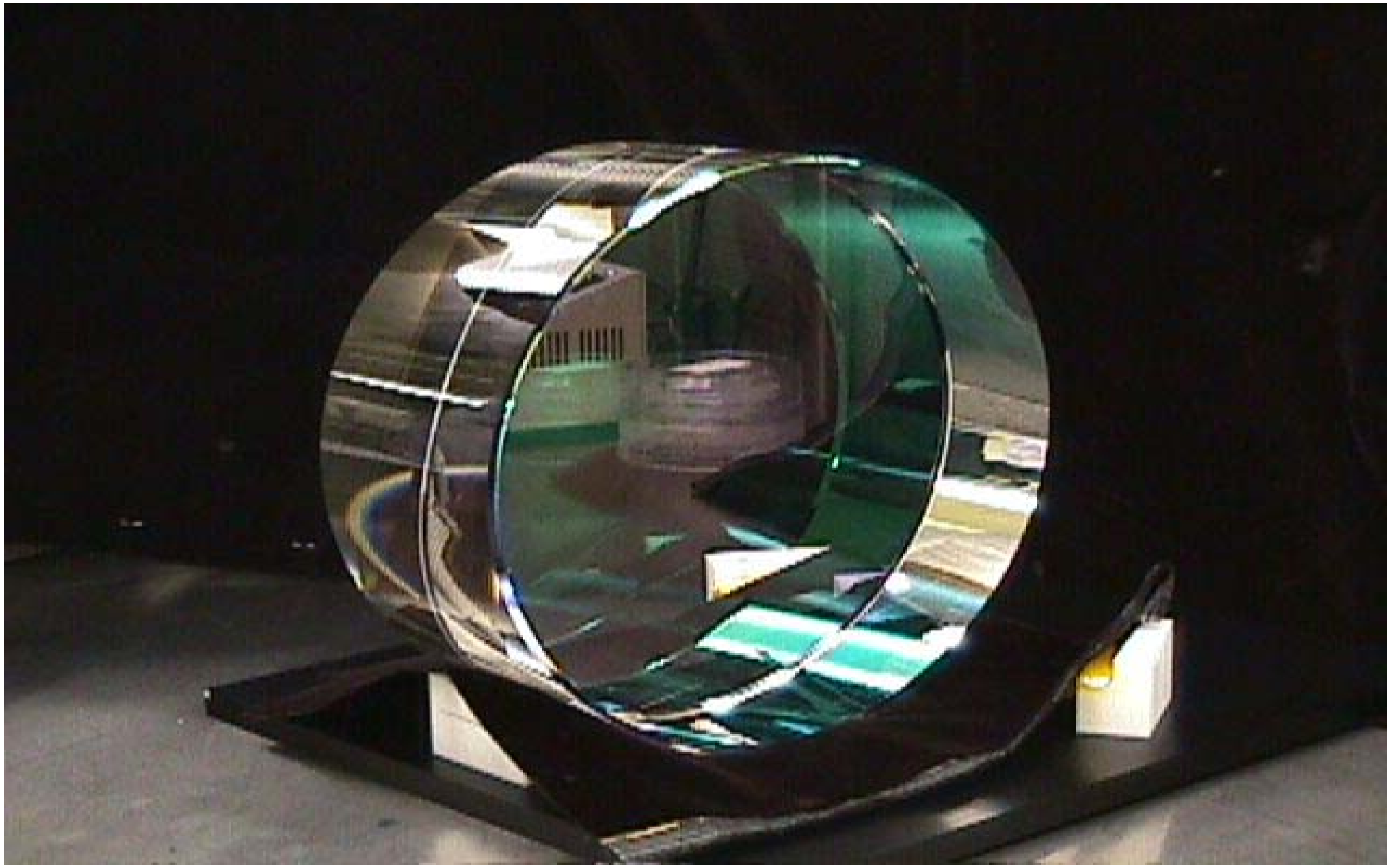
- Want "optical" arm length ~ λ_{GW} /4 for best antenna response
- Adds complexity; now each arm needs to be held near

$$L = k * \lambda_{LASER} /2$$

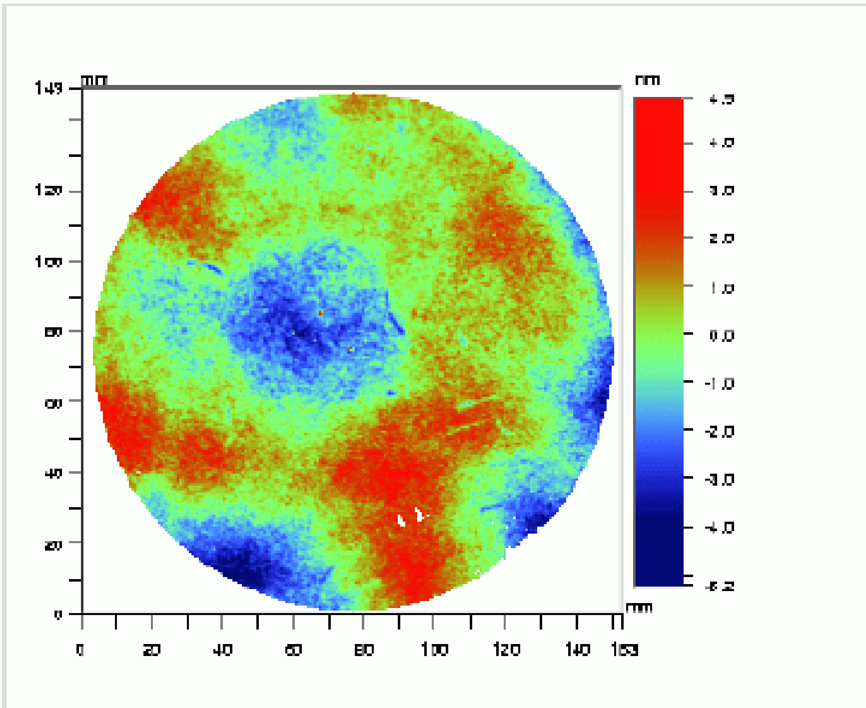
- Add mirror to "recycle" photons (equivalent to more laser power)



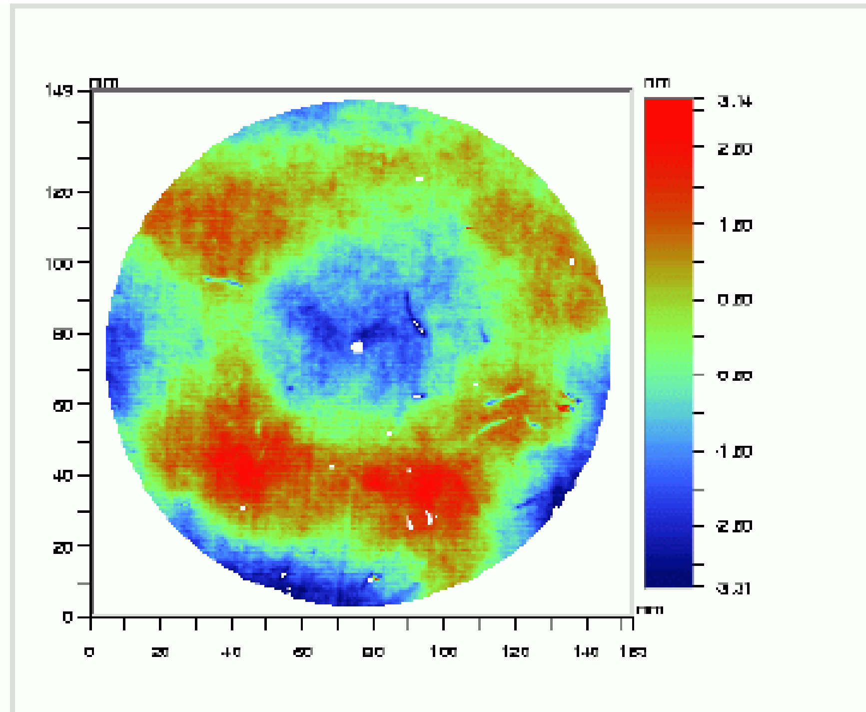
Core Optics



Core Optic Metrology



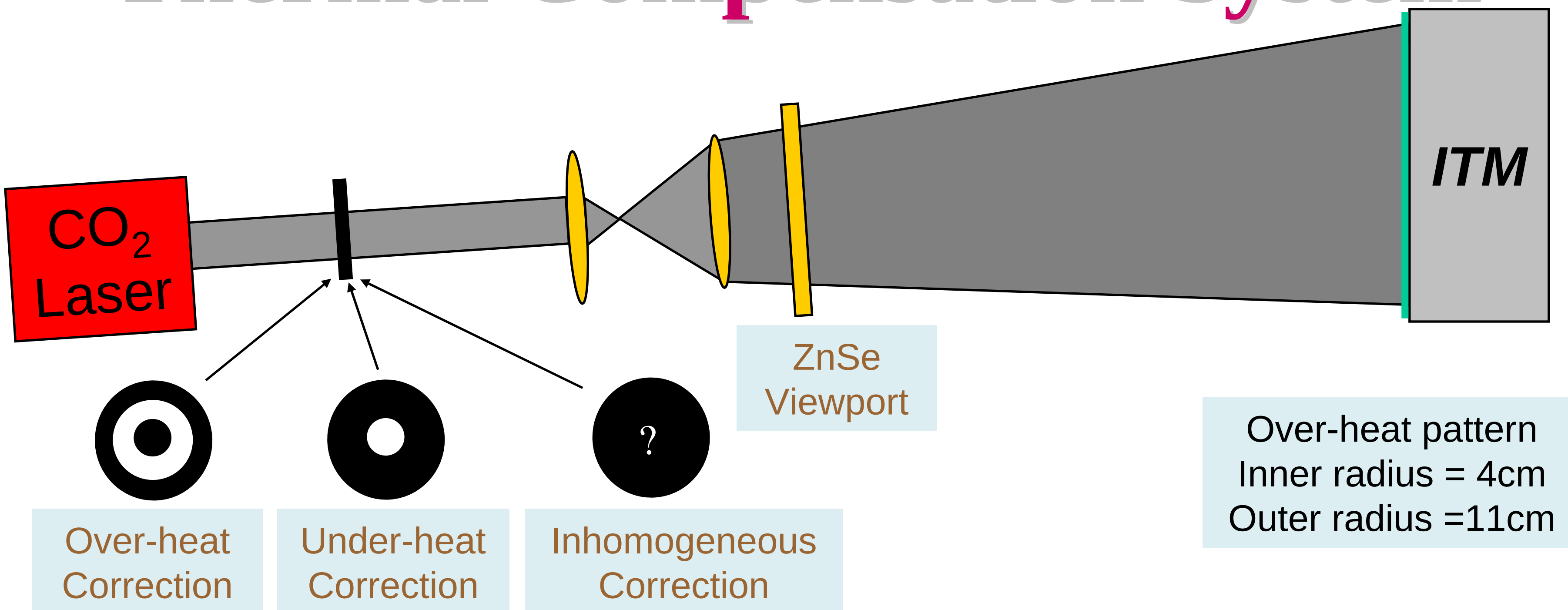
LIGO data (1.2 nm rms)



CSIRO data (1.1 nm rms)

- *Best mirrors are λ/6000 over the central 8 cm diameter*

Thermal Compensation System

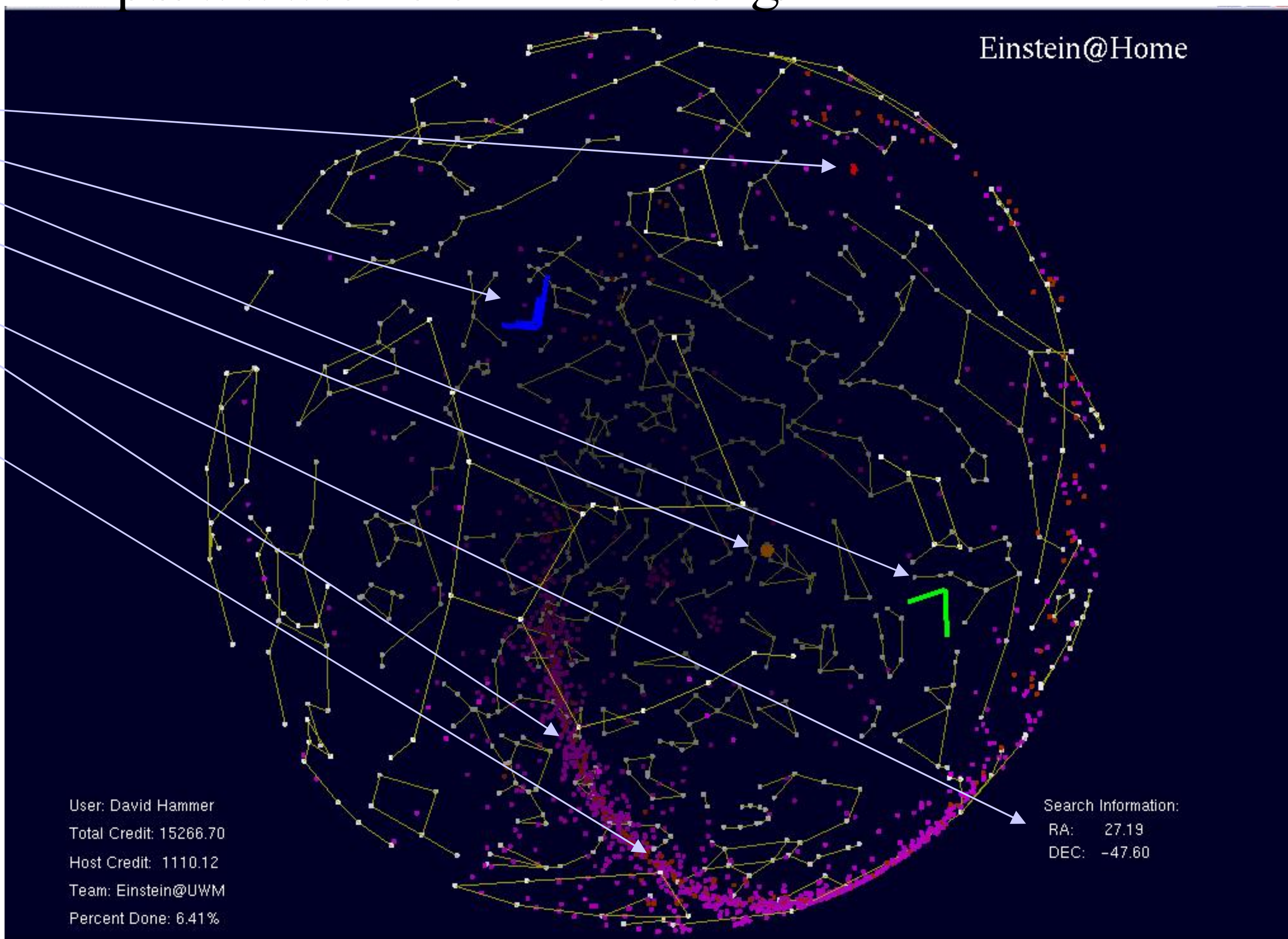


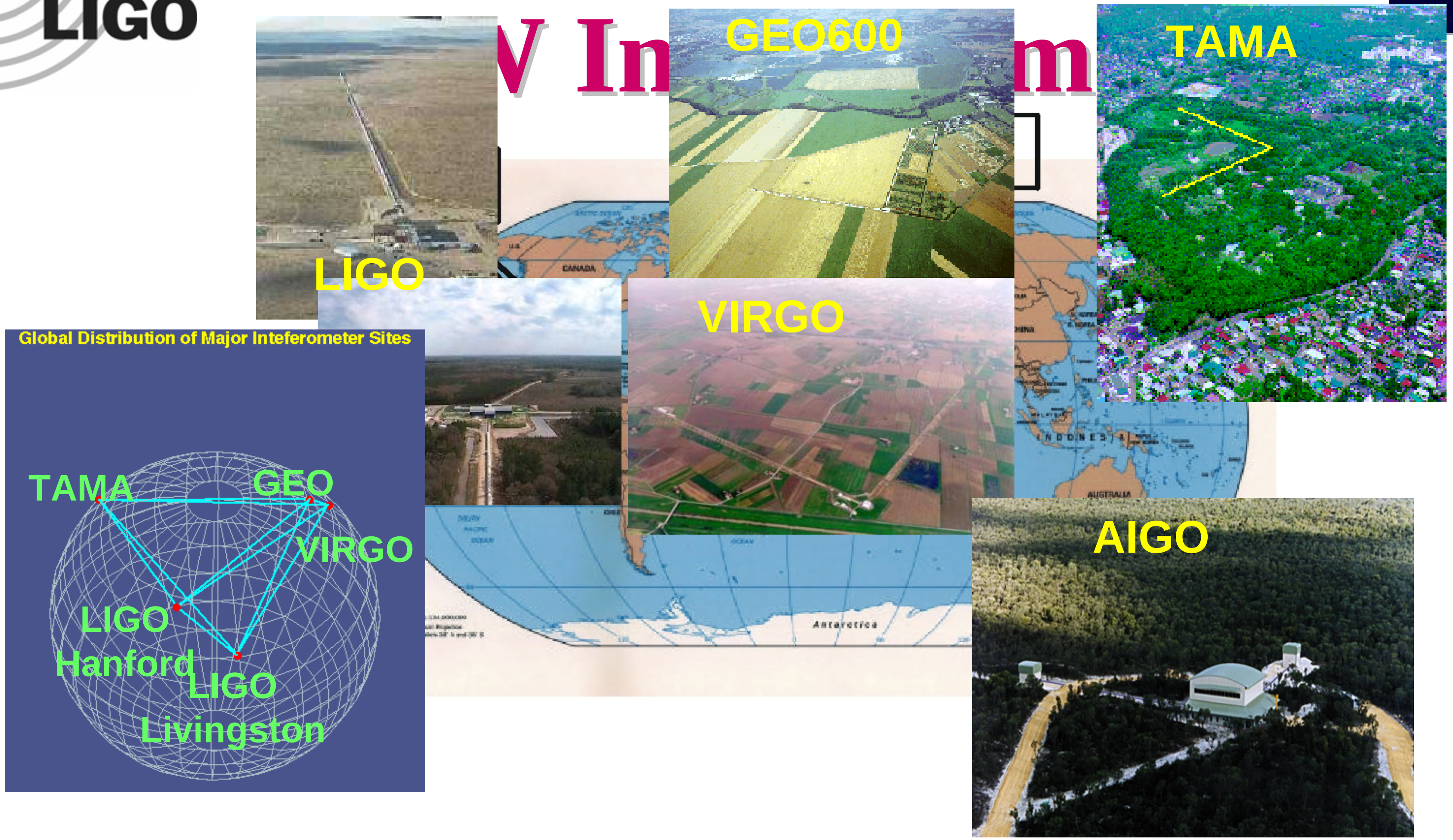
- Cold power recycling cavity is unstable: poor buildup and mode shape for the RF sidebands
- Require 10's of mW absorbed by 1µm beam

EINSTEIN@HOME
Catch a Wave From Space

http://www.einsteinathome.org/

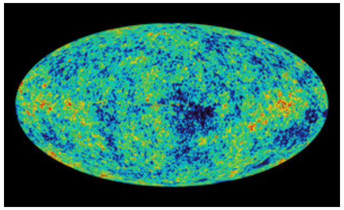
- GEO-600 Hannover
- LIGO Hanford
- LIGO Livingston
- Current search point
- Current search coordinates
- Known pulsars
- Known supernovae remnants





- Worldwide Network:
  - GEO and LIGO detectors' data analyzed by LSC
  - We have coordinated observations and shared data with TAMA
  - We just finalized agreements with VIRGO
  - AIGO is still in planning stage; AIGO personnel currently share in LIGO operation

Gravitational Wave sources: Stochastic Background



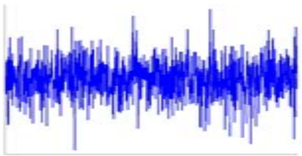
NASA, WMAP

- A primordial GW stochastic background is a prediction from most cosmological theories.
- Given an energy density spectrum $\Omega_w(f)$, there is a strain power spectrum:

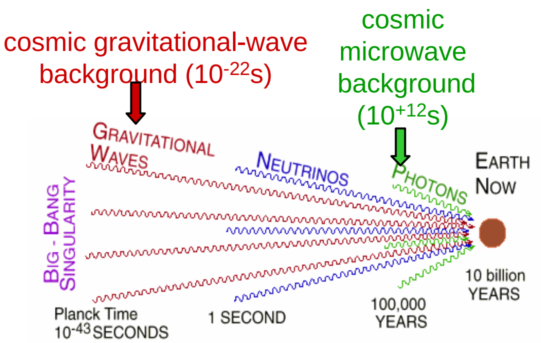
$$\Omega_{GW}(f) = \frac{1}{\rho_c}\frac{d\rho_{GW}(f)}{d\ln f}$$

$$S_{\rm gw}(f) = \frac{3H_0^2}{10\pi^2}\, f^{-3}\,\Omega_{\rm gw}(f)$$

$$h(f) = S_{\rm gw}^{1/2}(f) = 5.6\times10^{-22}\, h_{100}\sqrt{\Omega_0}\left(\frac{100\mathrm{Hz}}{f}\right)^{3/2}\ \mathrm{Hz}^{1/2}$$



- The signal can be searched from cross-correlations in different pairs of detectors: L1-H1, H1-H2, L1-ALLEGRO… the farther the detectors, the lower the frequencies that can be searched.

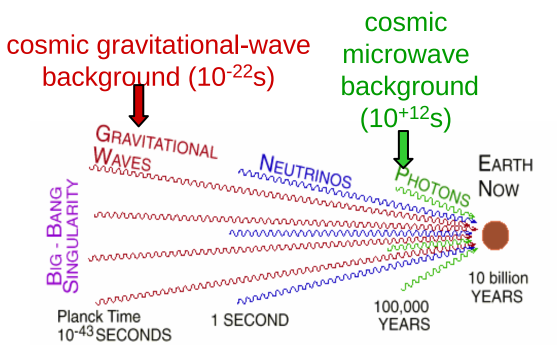


Gravitational Wave sources: Stochastic Background

- Cross-correlate signals between 2 interferometers
- LIGO S1: $\Omega_{GW} < 44$
  PRD 69 122004 (2004)

  H_0 = 72 km/s/Mpc
- LIGO S3: $\Omega_{GW} < 8.4 \times 10^{-4}$
  PRL 95 221101 (2005)
- LIGO S4: $\Omega_{GW} < 6.5 \times 10^{-5}$ (new upper limit; accepted for publication in ApJ)
  - Bandwidth: 51-150 Hz;
- Initial LIGO, 1 yr data
  Expected sensitivity ~ 4×10^{-6}
  upper limit from Big Bang nucleosynthesis 10^{-5}; interesting scientific territory
- Advanced LIGO, 1 yr data
  Expected Sensitivity ~1×10^{-9}

Cosmic strings (?) ~10^{-8}
Inflation prediction ~10^{-14}



LIGO

LSC

Collaborating Institutions

NSF

UTB TSC

Southeastern Louisiana University

Loyola University New Orleans

University of Maryland

LSU

GEO 600

Northwestern University

Universitat de les Illes Balears

Southern University Agricultural & Mechanical College

Hobart and William Smith Colleges

University of Florida

The University of Adelaide Australia

California Institute of Technology

NAOJ 国立天文台

Massachusetts Institute of Technology

University of Wisconsin Milwaukee

Carleton College

Columbia University in the City of New York

The University of Birmingham

The University of Texas at Austin

Syracuse University

IGR

Universität Hannover

Embry-Riddle Aeronautical University

Washington State University

Cardiff University

The University of Western Australia

Michigan

The Physics of the Universe PPARC

PAH

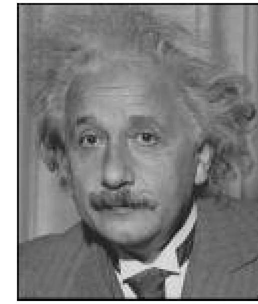
PennState 1855

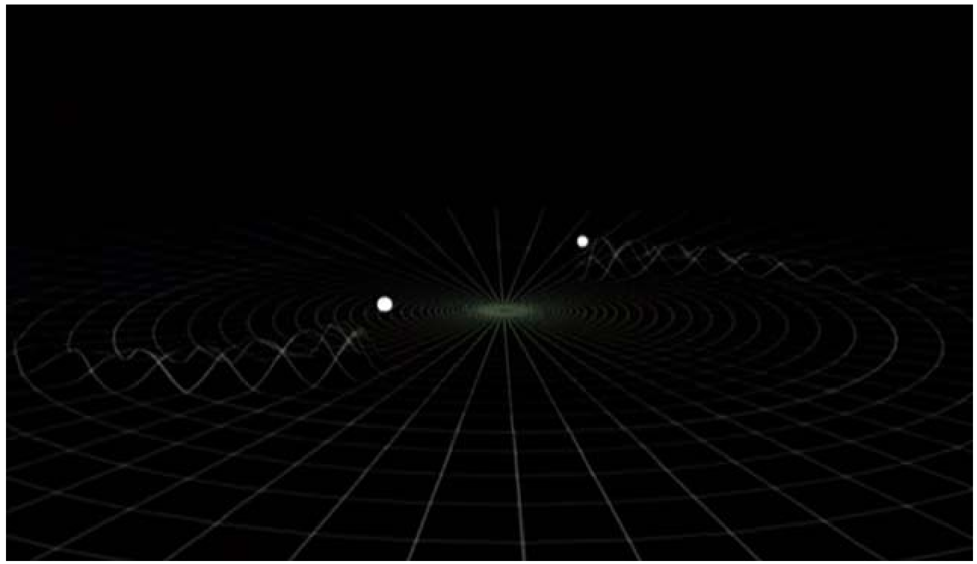
University of Glasgow

G070029-00-Z

Einstein's gravitation

When masses move, they wrinkle the space time fabric, making other masses move…



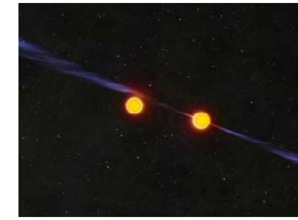


Einstein's messengers,
National Science Foundation video
www.ligo.caltech.edu

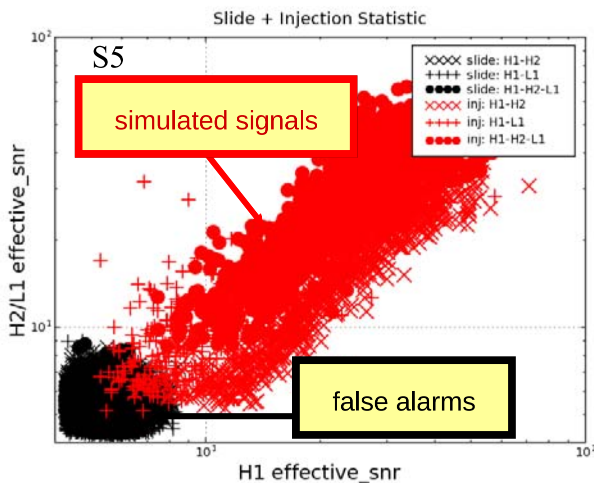
The theory predicts gravitational waves traveling away from moving masses.

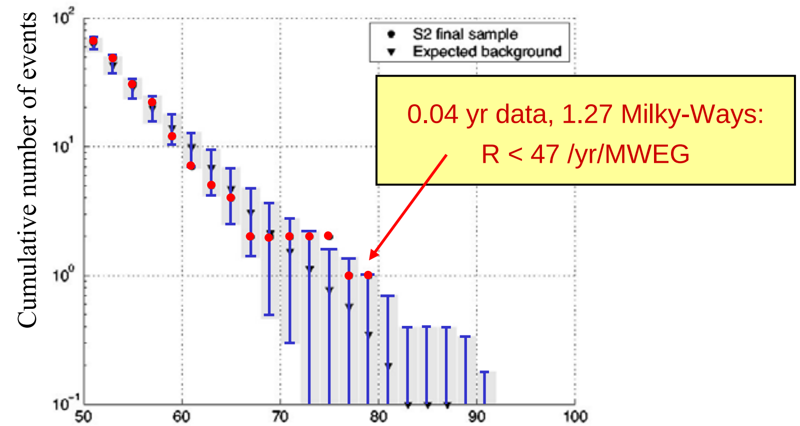
Search for binary systems

- Use two or more detectors: search for double or triple *coincident* "triggers"
- Can infer masses and "effective" distance.
- Estimate false alarm probability of resulting candidates: detection?
- Compare with expected efficiency of detection and surveyed galaxies: upper limit



John Rowe, CSIRO



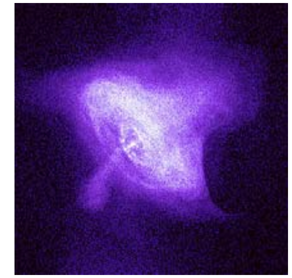


B. Abbott et al. (LIGO Scientific Collaboration):

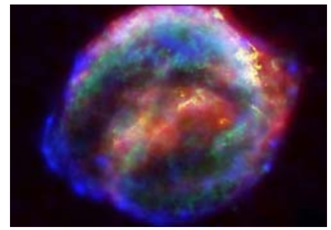
- S1: Analysis of LIGO data for gravitational waves from binary neutron stars, Phys. Rev. D 69, 122001 (2004)
- S2: Search for gravitational waves from primordial black hole binary coalescences in the galactic halo, Phys. Rev. D 72, 082002 (2005)
- S2: Search for gravitational waves from galactic and extra-galactic binary neutron stars, Phys. Rev. D 72, 082001 (2005)
- S2: Search for gravitational waves from binary black hole inspirals in LIGO data, Phys. Rev. D 73, 062001 (2006)
- S2: Joint Search for Gravitational Waves from Inspiralling Neutron Star Binaries in LIGO and TAMA300 data (LIGO, TAMA collaborations), PRD, in press
- S3, S4: finished searched for BNS, BBH, PBBH: no detection; paper in progress
- S5: analysis in progress

When will we see something?

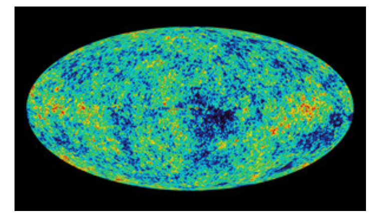
Predictions are difficult… many unknowns!



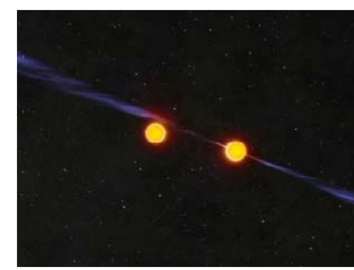
- Rotating stars: how lumpy are they?



- Supernovae, gamma ray bursts:
  how strong are the waves
  (and what do they look like)?

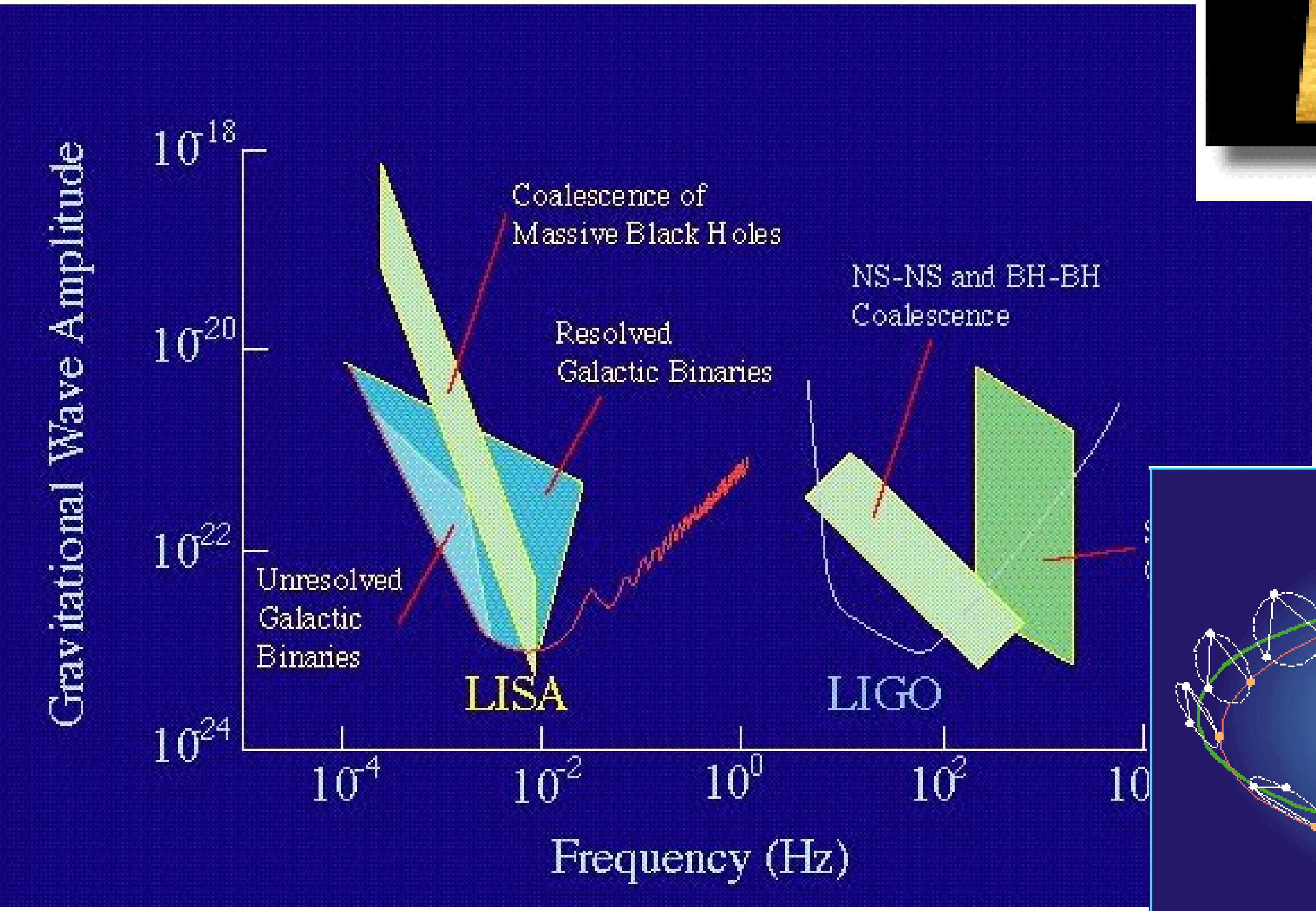


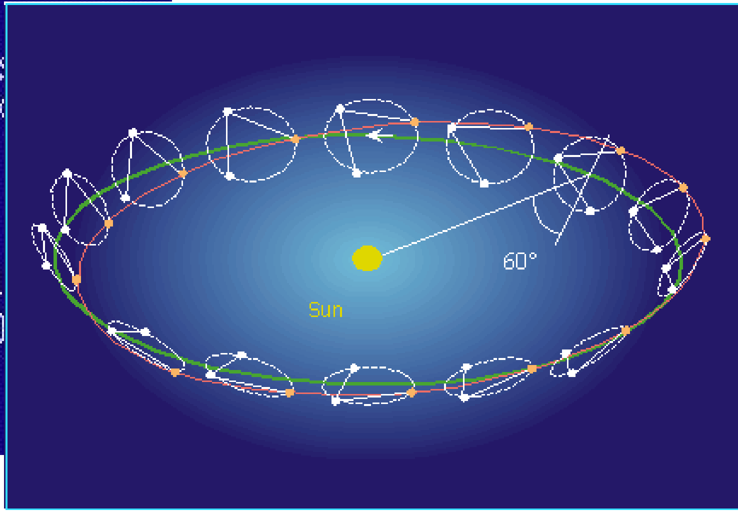
- Cosmological background:
  how did the Universe evolve?



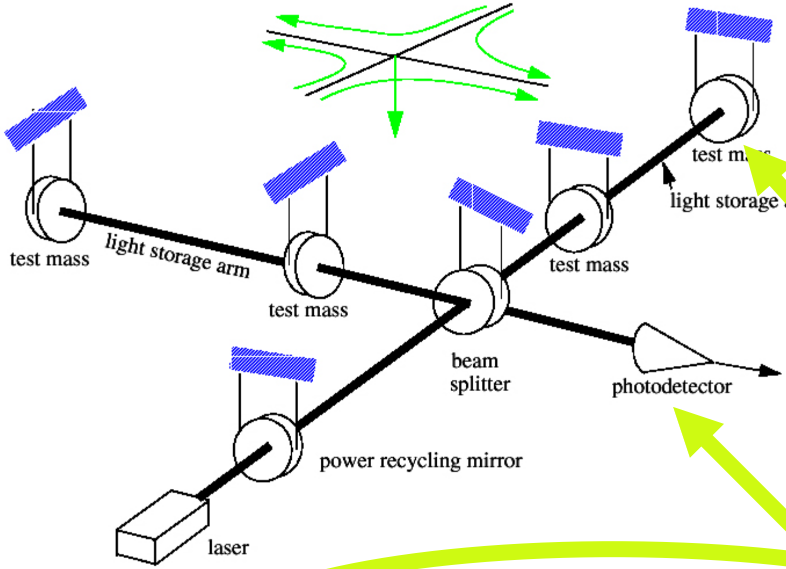
- Binary black holes: how many are there?
  What masses do they have?
- Binary neutron stars: from observed systems in our galaxy, predictions are up to 1/3yrs, but most likely one per 30 years, at LIGO's present sensitivity.
- From rate of short GRBs, much more optimistic predictions for BNS and BBH rates?□ Ready to be tested with S5!

Space interferometer: LISA





GW LIGO detectors: interferometers



QuickTime™ and a
Animation decompressor
are needed to see this picture.

**suspended test masses
("freely falling objects")**

**dark port
(RF heterodyne modulation)**