LIGO, on the threshold of Gravitational Wave Astronomy

Stan Whitcomb (for the LIGO Scientific Collaboration)

Seminar at the National Superconducting Cyclotron Lab

Michigan State University

14 February 2007

LIGO-G070022-00-D

A Series of Questions

- What is LIGO?
- Why is LIGO?
- How does LIGO work?
- Where is LIGO?
- When is LIGO?
- How well does LIGO work?
- What has LIGO seen?
- What's next for LIGO?
- Who is LIGO?

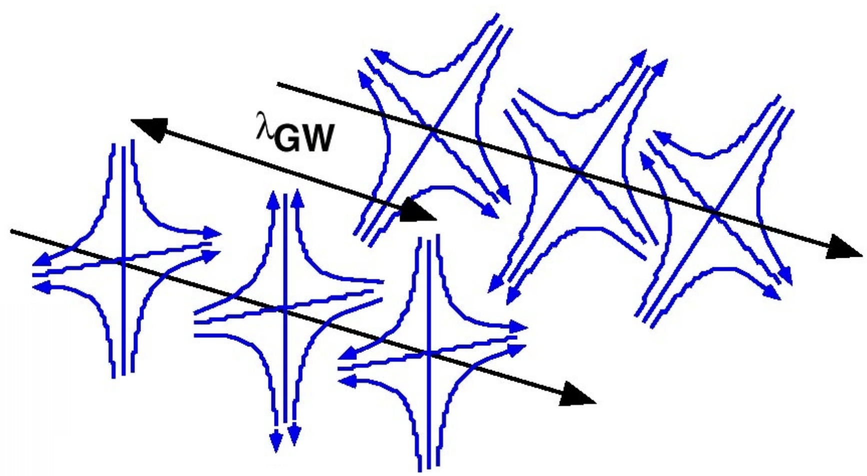
What is LIGO?

Numb3rs
"The Running Man"
February 3, 2005

- National facility operated by Caltech and MIT for NSF
- Cutting edge technology in lasers, optics, quiet mechanical systems, control systems, computational systems, …
- Tabletop experimental physics on a really BIG scale
- Rich community of researchers and educators

Gravitational Wave Physics

- Einstein (in 1916 and 1918) recognized gravitational waves in his theory of General Relativity
  - » Necessary consequence of Special Relativity with its finite speed for information transfer
  - » Most distinctive departure from Newtonian theory
- Time-dependent distortions of space-time created by the acceleration of masses
  - » Propagate away from the sources at the speed of light
  - » Pure transverse waves
  - » Two orthogonal polarizations

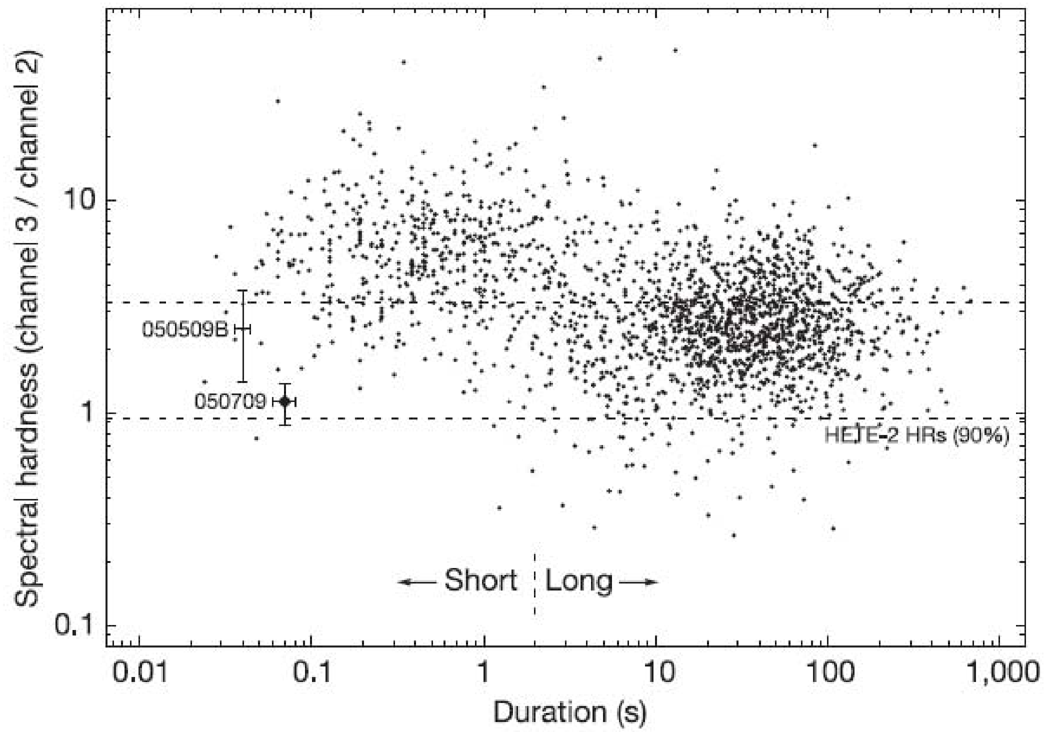


Why is LIGO?

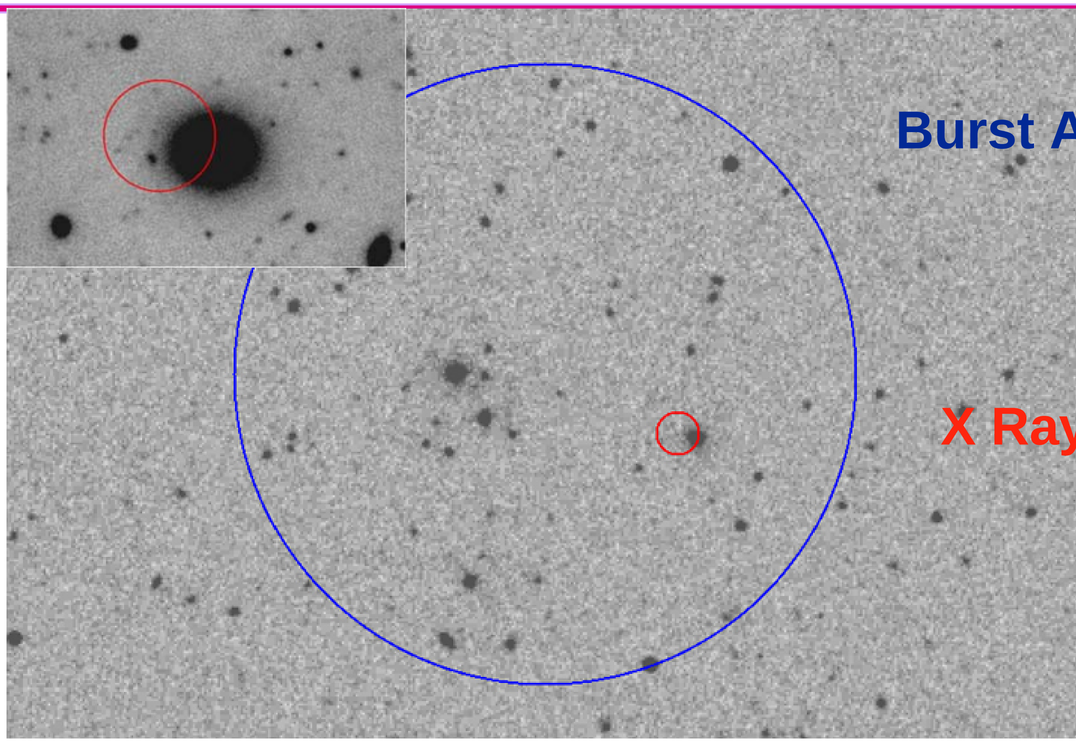
- Physics
  - »Existence of gravitational waves
  - »Dynamics of General Relativity in the strong field regime
- Astronomy
  - »Sources of strong gravitational waves hard to study using electromagnetic radiation (weak EM emission, hidden by matter)
  - »Waves carry direct information about the source which is difficult or impossible to get in other ways

Short Gamma Ray Bursts (GRBs)

- GRBs: long-standing puzzle in astrophysics
  - » Short, intense bursts of gamma rays
  - » Isotropic distribution
- "Long" GRBs identified with type II (or Ic) supernovae in 1998
- "Short" GRBs hypothesized as NS-NS or NS-BH collisions/mergers
- Inability to identify host galaxies left many questions



First Identification from SWIFT GRB050509b (May 9, 2005)

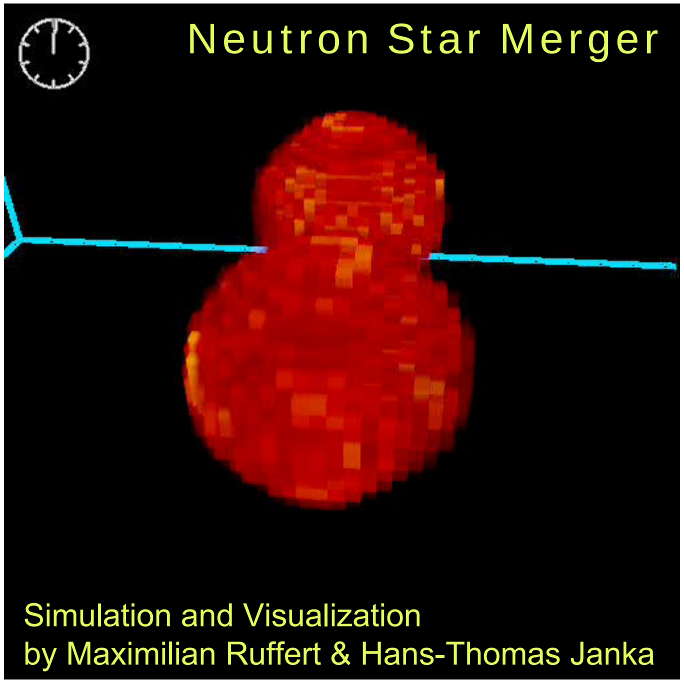


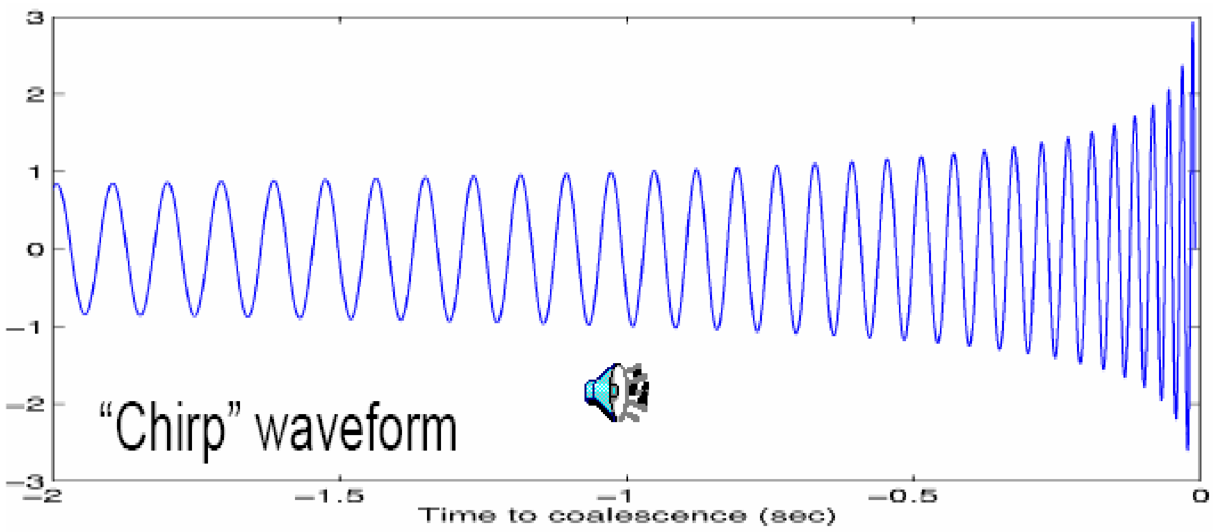
Gehrels et al., Nature, 437, 851, 2005

- Near edge of large elliptical galaxy (z = 0.225)
- Apparent distance from center of galaxy = 35 kpc
- Strong support for inspiral/merger hypothesis

Using Gravitational Waves to Learn about Short GRBs

Chirp Signal
binary inspiral

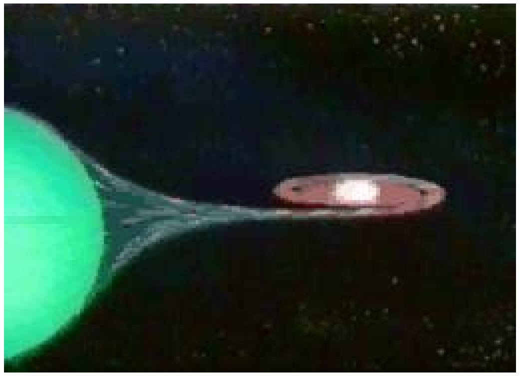




Chirp parameters give:
- **Masses of the two bodies (NS, BH)**
- **Distance from the earth**
- **Orientation of orbit**
- **Beaming of gamma rays (with enough observed systems)**

Another Potential GW Source: Low-Mass X-ray Binaries

- Binary systems consisting of a compact object (neutron star or blackhole) and a <1 $M_{\odot}$ companion star (example Sco X-1)
- Companion over-fills Roche-lobe and material transfers to the compact star (X-ray emission)
- Angular momentum transfer spins up neutron star
- Observed Quasi-Periodic Oscillations indicate maximum spin rate for neutron stars
- Mechanism for radiating angular momentum: gravitational waves?



Imagine the Universe
NASA High Energy Astrophysics Science Archive

How does LIGO work?

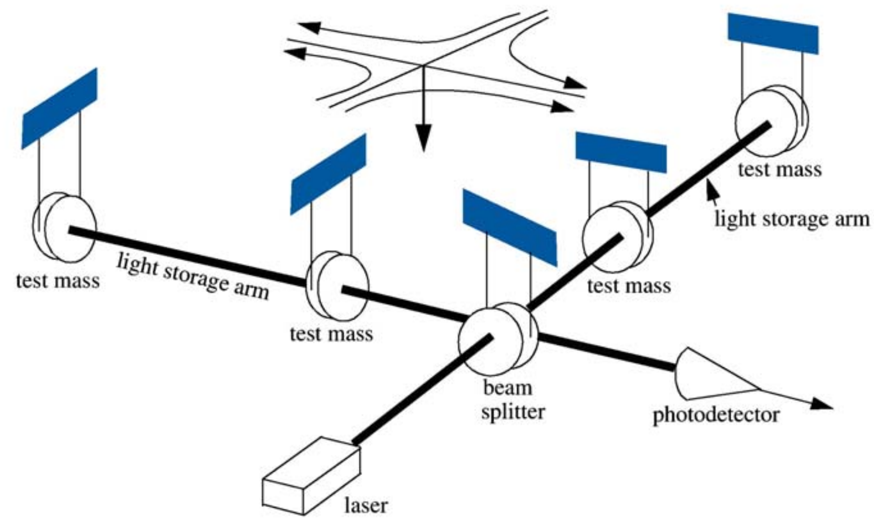
Numb3rs
"The Running Man"
February 3, 2005

- Need to do a bit more than just shoot the beams through a 4 km L-shaped vacuum pipe

Detecting GWs with Interferometry

Suspended mirrors act as "freely-falling" test masses (in horizontal plane) for frequencies f >> f_{pend}

$$h = \Delta L / L$$

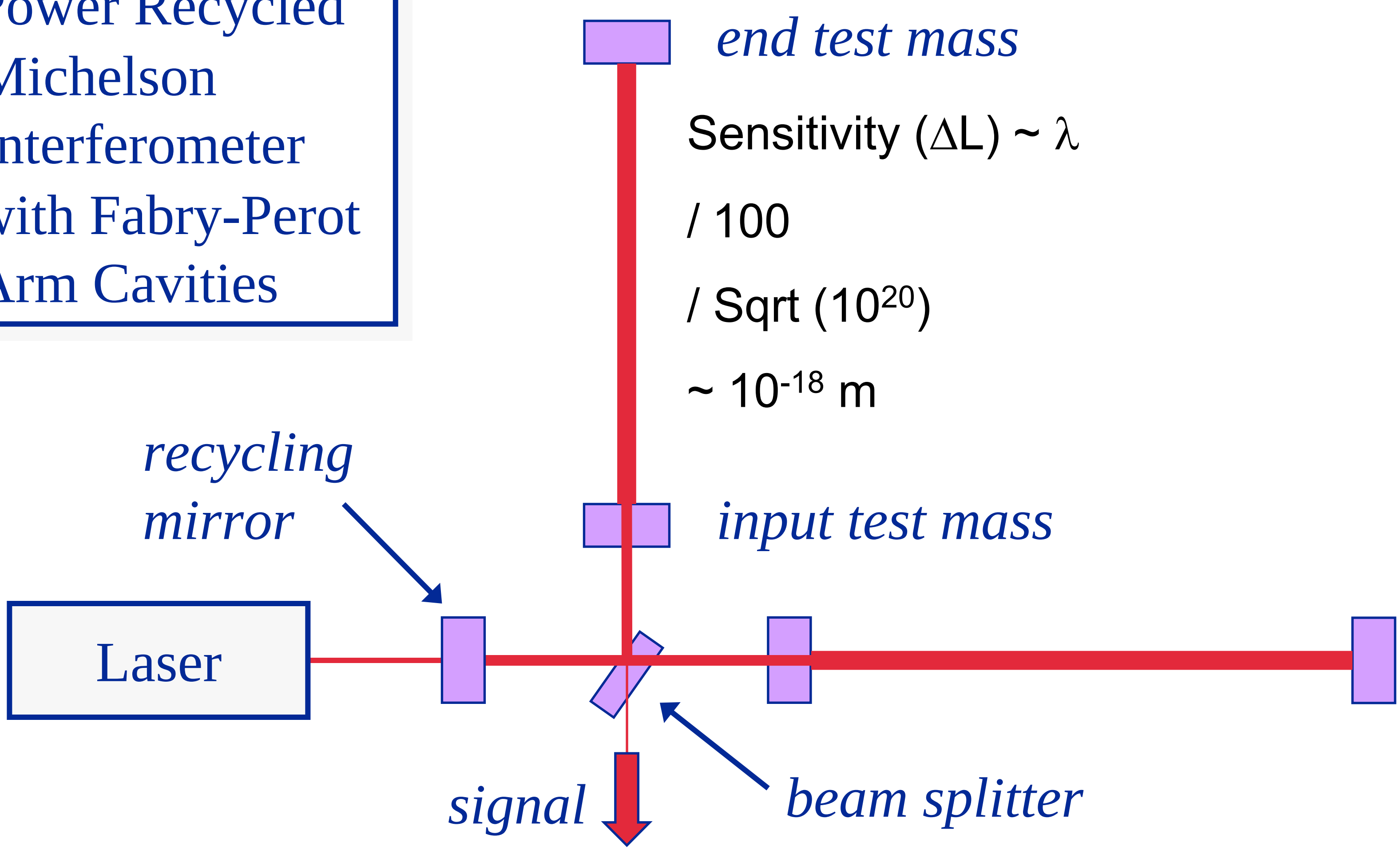


Terrestrial detector
For $h \sim 10^{-22} - 10^{-21}$
L ~ 4 km (LIGO)
$\Delta L \sim 10^{-18}$ m

Optical Configuration

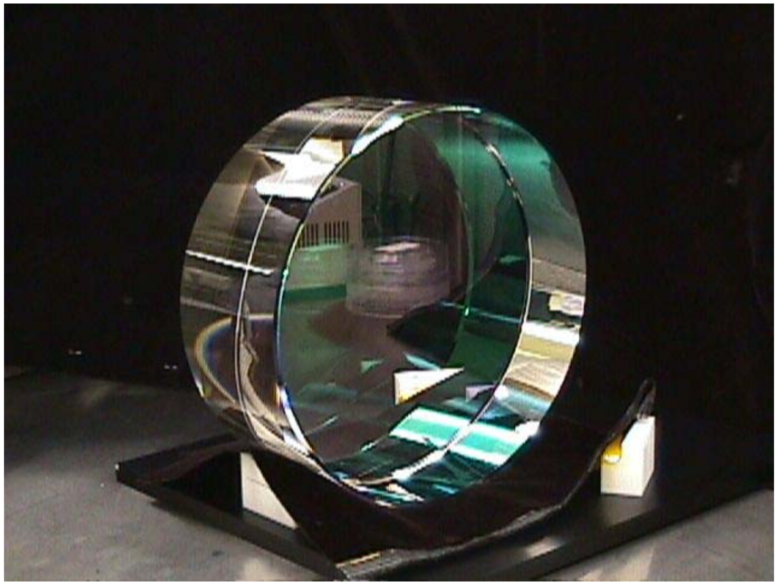
Power Recycled Michelson Interferometer with Fabry-Perot Arm Cavities

Sensitivity (ΔL) ~ λ / 100 / Sqrt (10^{20}) ~ 10^{-18} m

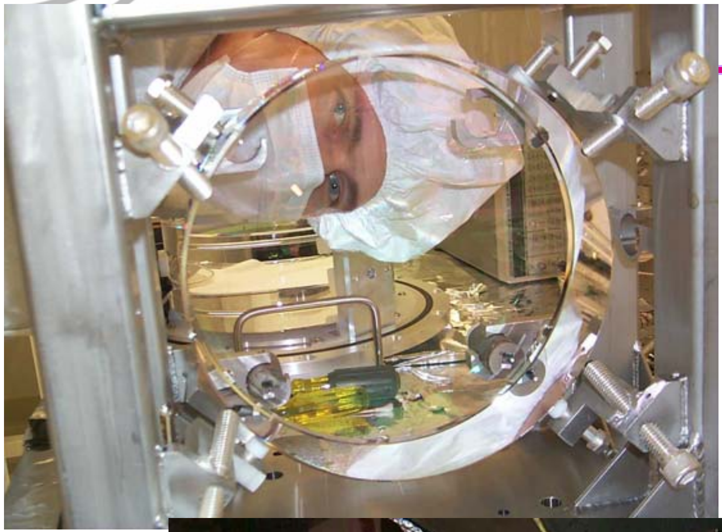


Test Mass/Mirrors

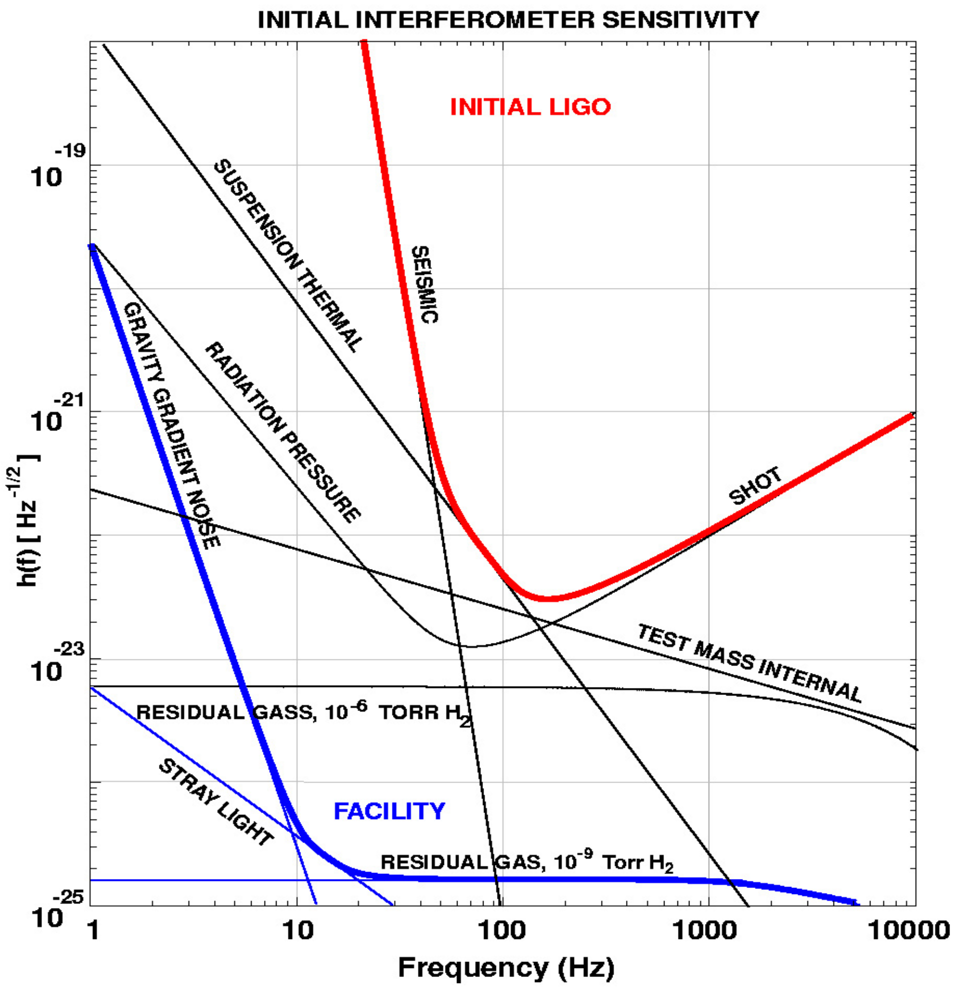
- Substrates: SiO_2
  - » 25 cm Diameter, 10 cm thick
  - » Homogeneity < 5 x 10^{-7}
  - » Internal mode Q's > 2 x 10^{6}
- Polishing
  - » Surface uniformity < 1 nm rms (λ / 1000)
  - » Radii of curvature matched < 3%
- Coating
  - » Scatter < 50 ppm
  - » Absorption < 0.5 ppm
  - » Uniformity <10^{-3}
- Production involved 6 companies, NIST, and LIGO



Test Mass Suspension and Control



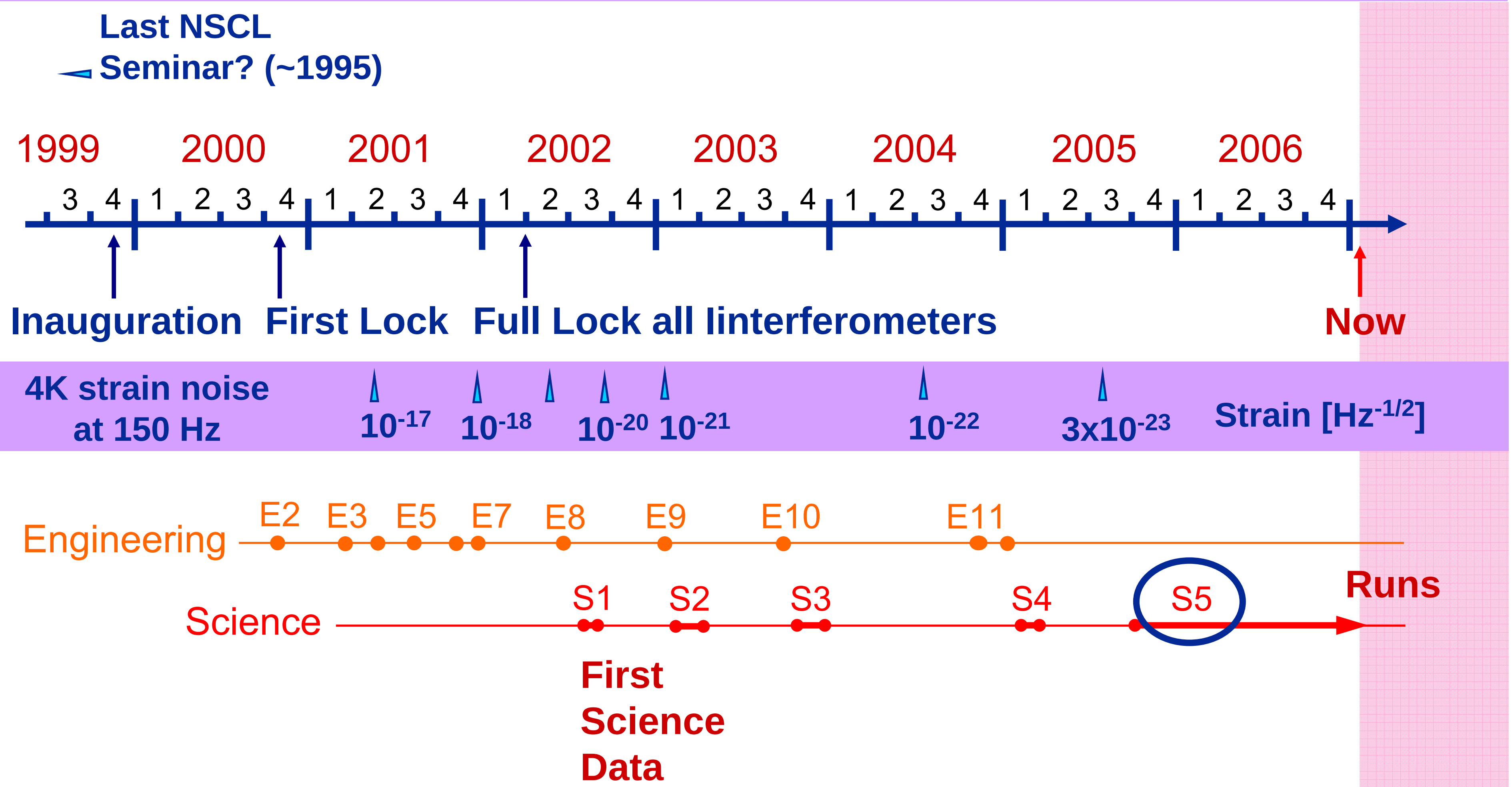
How does LIGO work?
Initial LIGO Sensitivity Goal



- Strain sensitivity $<3\times10^{-23}$ 1/Hz$^{1/2}$ at 200 Hz
- Sensing Noise
  - » Photon Shot Noise
  - » Radiation Pressure
  - » Residual Gas
- Displacement Noise
  - » Seismic motion
  - » Thermal Noise

Where is LIGO?

When is LIGO?



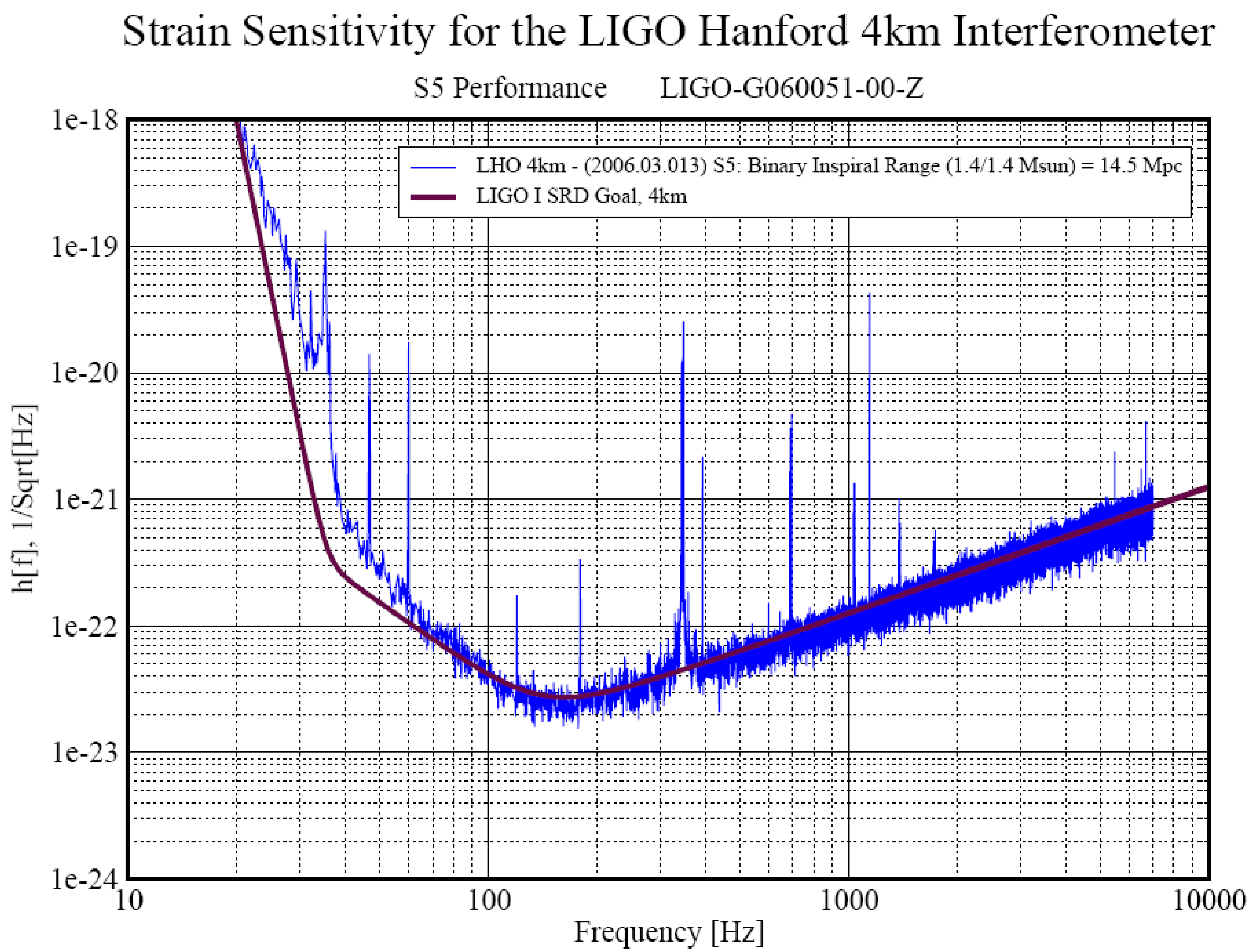
Last NSCL
Seminar? (~1995)
1999
2000
2001
2002
2003
2004
2005
2006
3 4 1 2 3 4 1 2 3 4 1 2 3 4 1 2 3 4 1 2 3 4 1 2 3 4 1 2 3 4
Inauguration
First Lock
Full Lock all Iinterferometers
Now
4K strain noise
at 150 Hz
10^-17
10^-18
10^-20
10^-21
10^-22
3x10^-23
Strain [Hz^-1/2]
Engineering
E2
E3
E5
E7
E8
E9
E10
E11
Science
S1
S2
S3
S4
S5
Runs
First
Science
Data

How well does LIGO work?

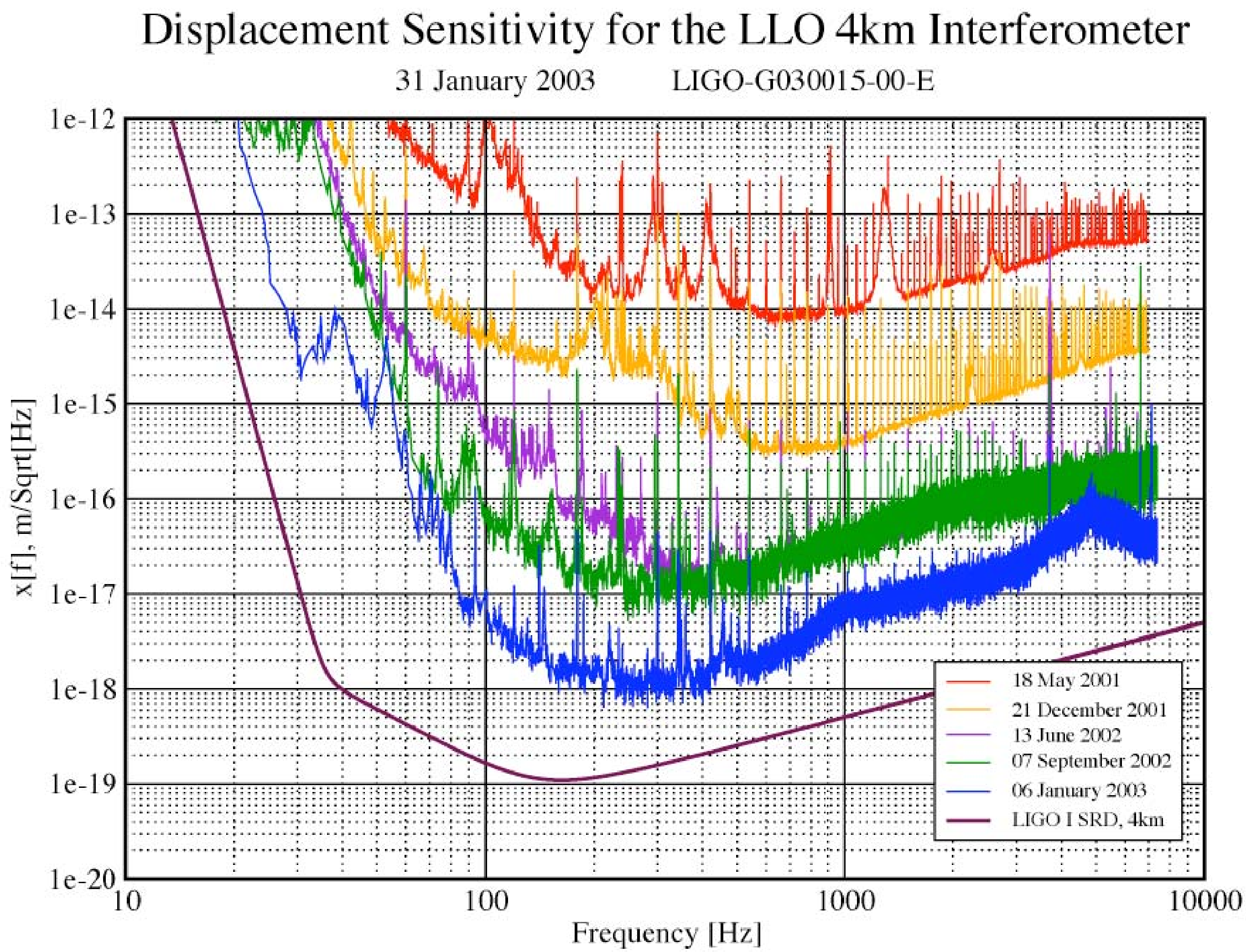
Measures of performance

- Spectral sensitivity
- Duty factor
- Non-gaussian noise

How well does LIGO work? Sensitivity

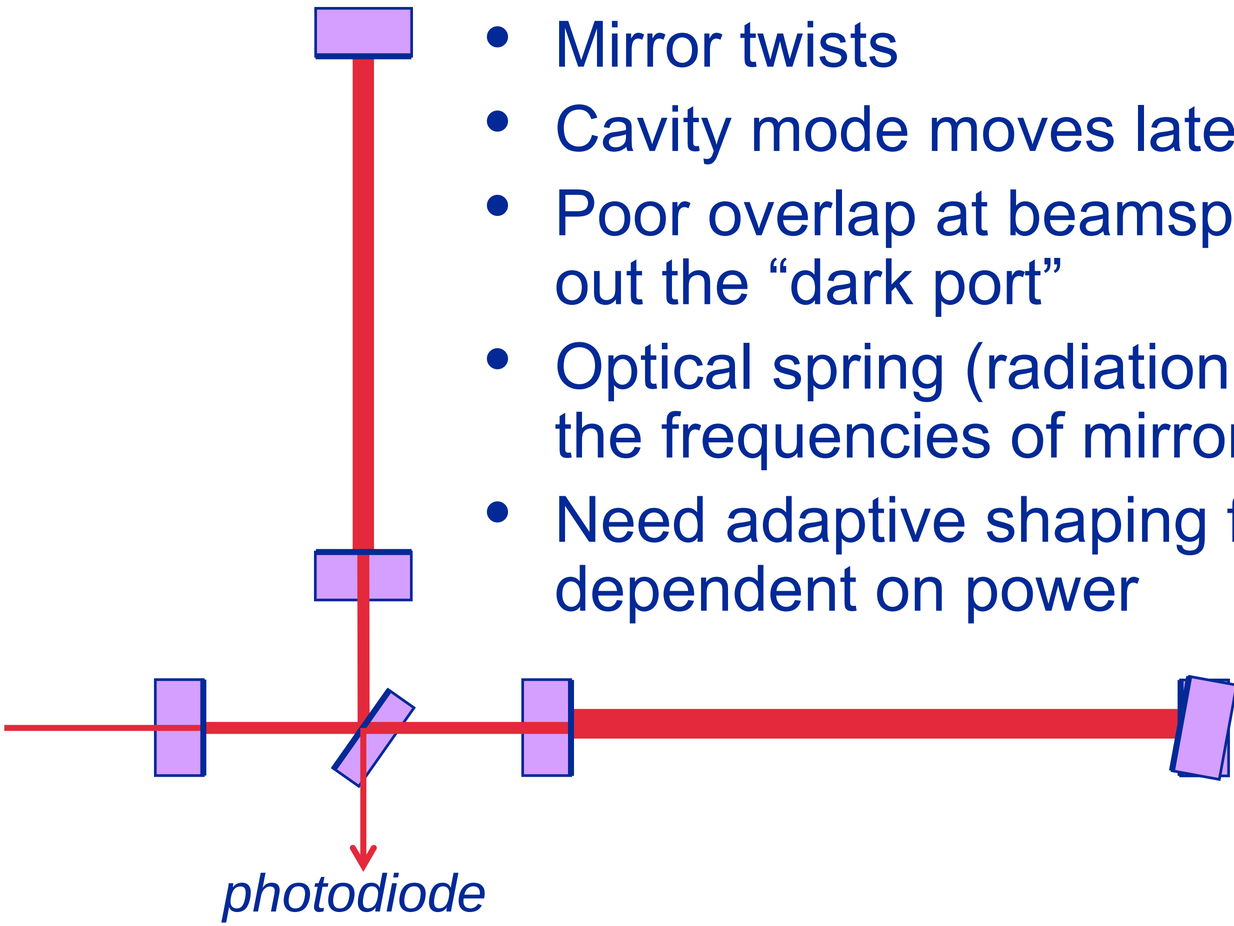


How well does LIGO work? Progress toward Design Sensitivity

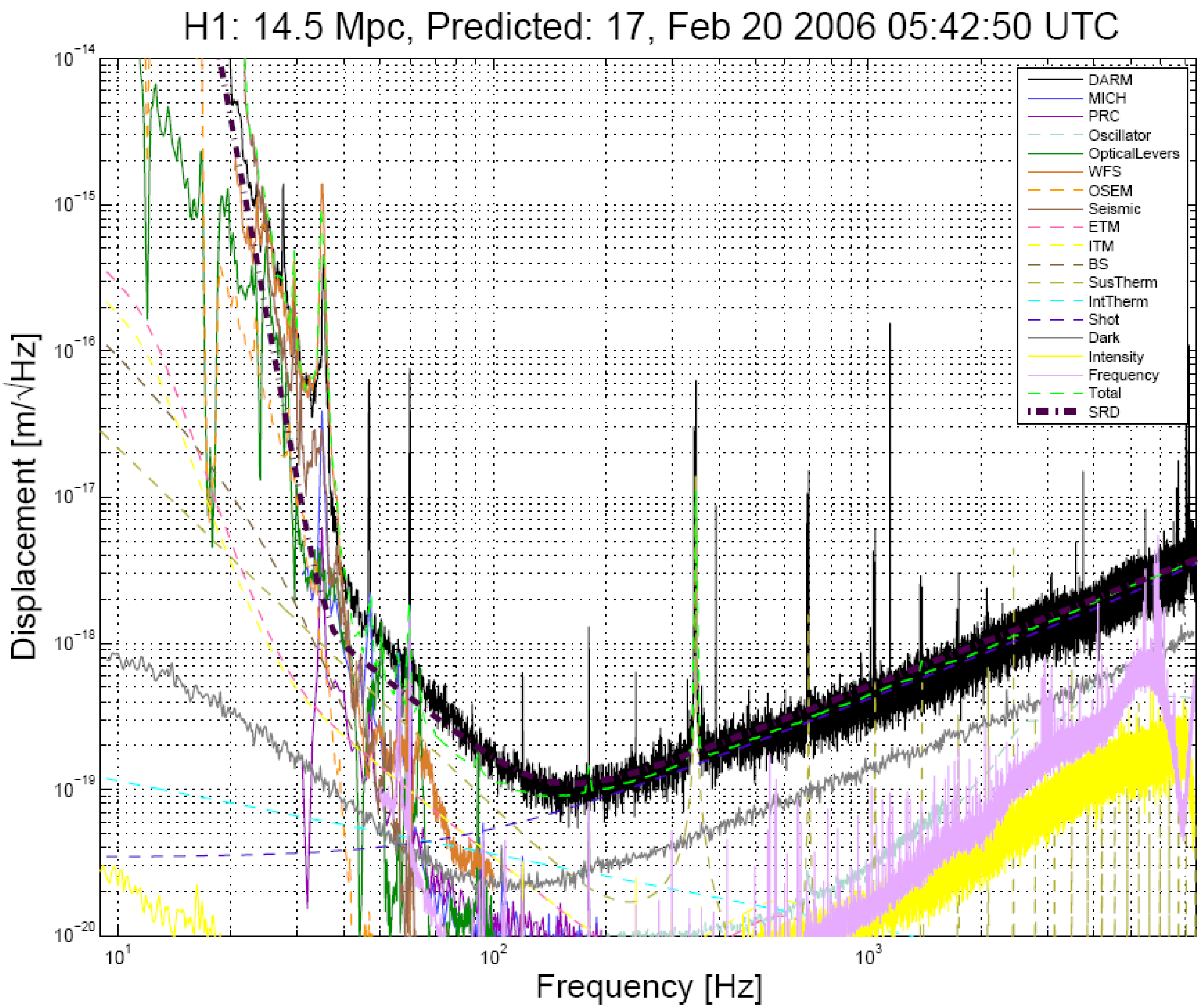


"Just" Increase the Laser Power?

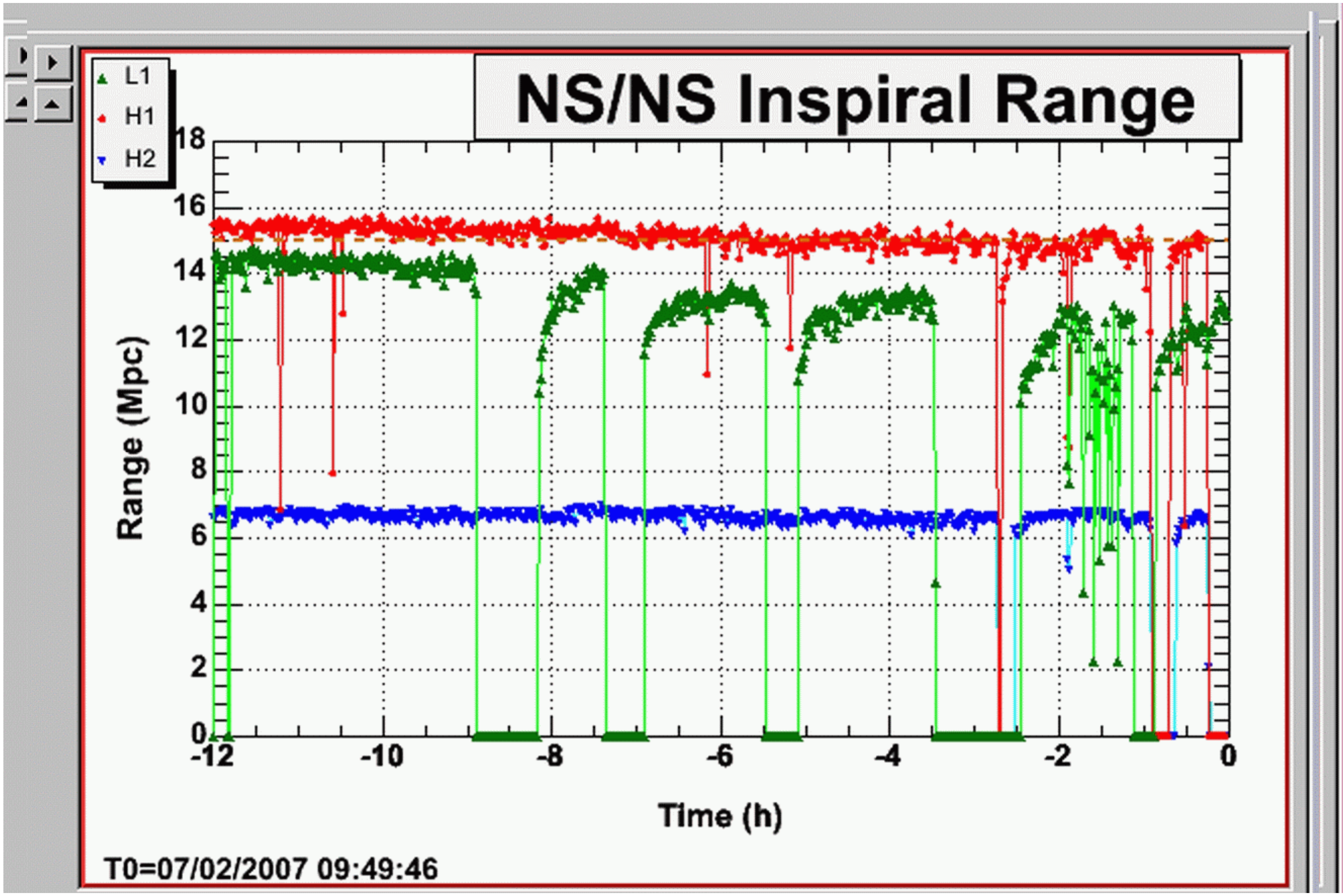
- Importance of angular control of optics
  - » Servo control at low frequencies to maintain alignment
- Mirror twists
- Cavity mode moves laterally
- Poor overlap at beamsplitter increase light out the "dark port"
- Optical spring (radiation pressure) changes the frequencies of mirror's angular mode
- Need adaptive shaping for feedback dependent on power



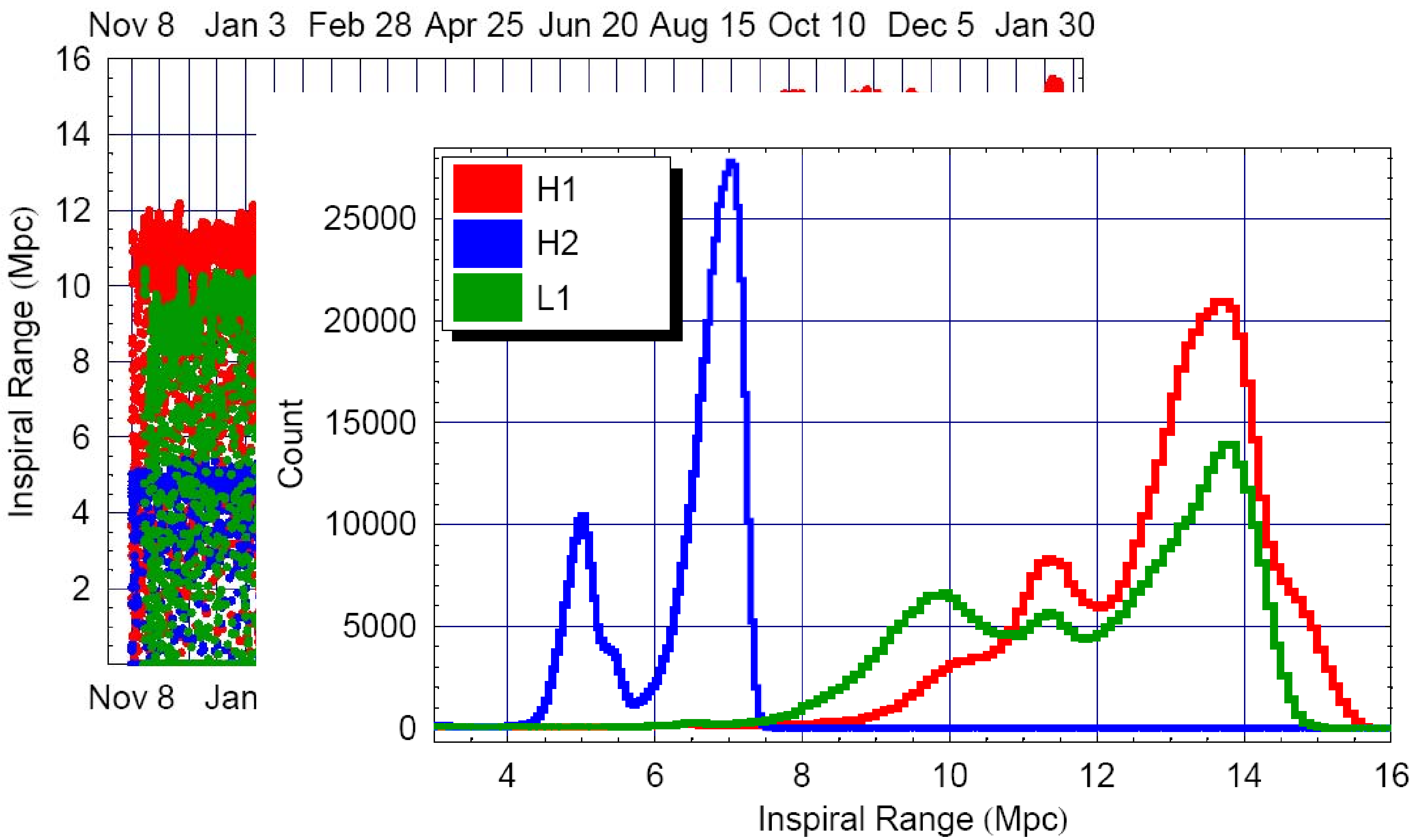
How well does LIGO work? Sensitivity



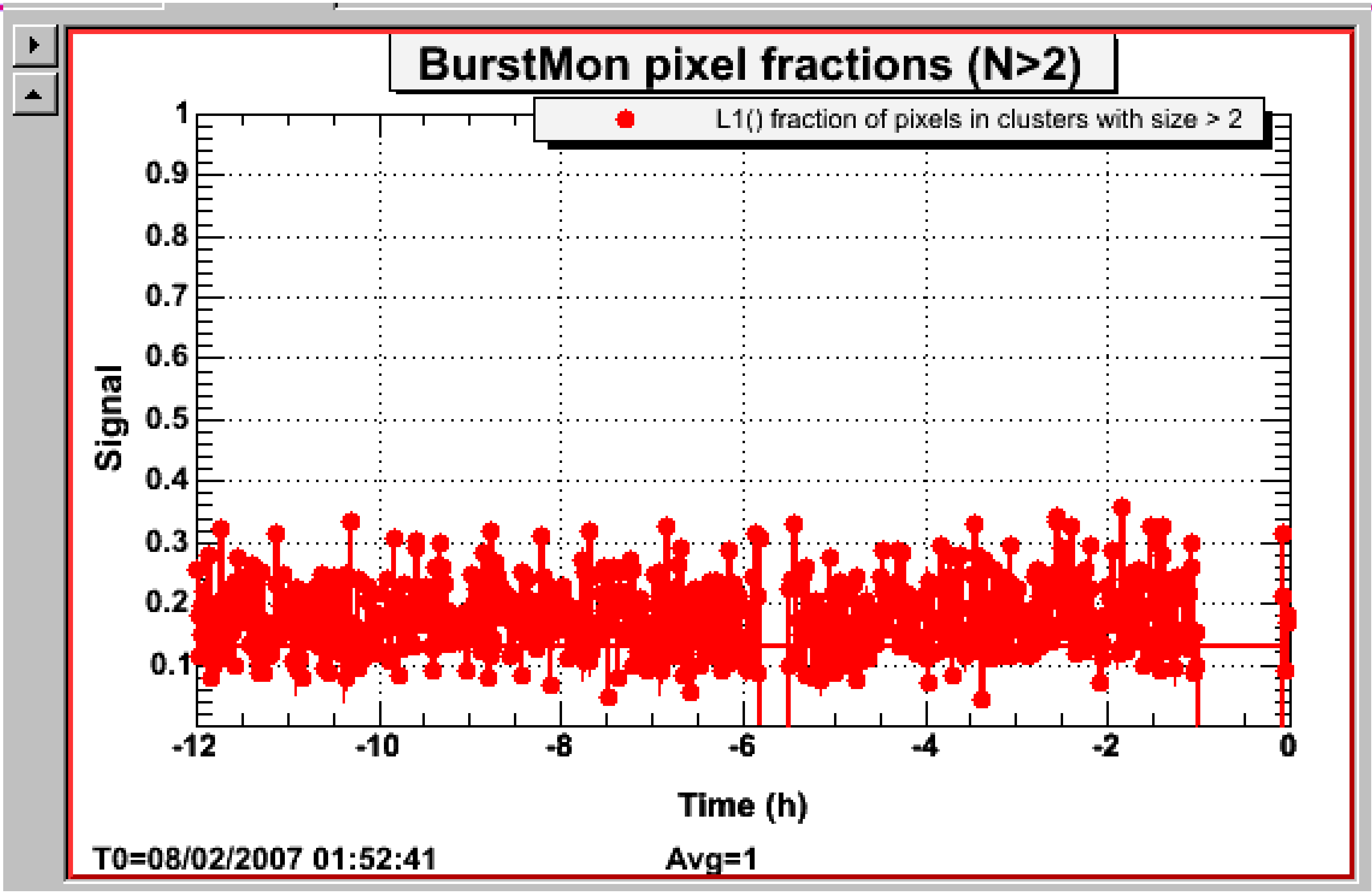
How well does LIGO work? Duty Factor



How well does LIGO work? S5 so Far



How well does LIGO work? Non-Gaussian Noise



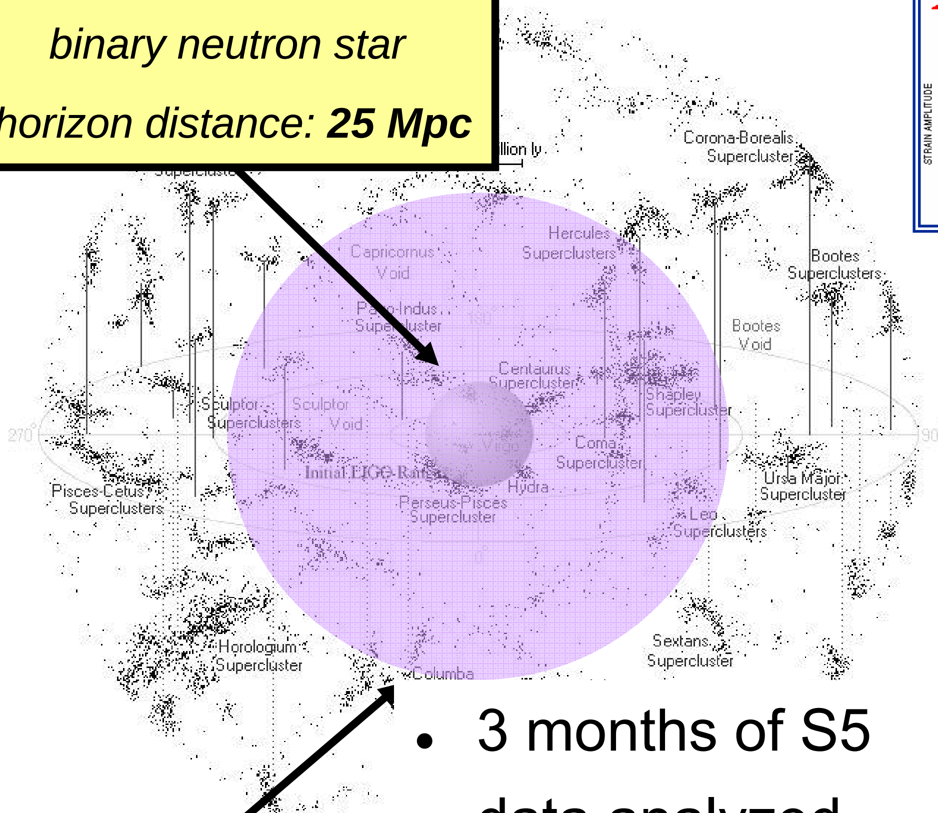
What has LIGO Seen?
LIGO Data Analysis

Data analysis by the LIGO Scientific Collaboration (LSC) is organized into four types of analysis:

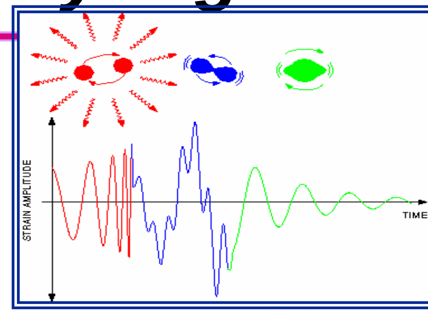
- Binary coalescences with modeled waveforms ("inspirals")
- Transients sources with unmodeled waveforms ("bursts ")
- Continuous wave sources ("GW pulsars")
- Stochastic gravitational wave background (cosmological & astrophysical foregrounds)

Searches for Coalescing Compact Binary Signals in S5

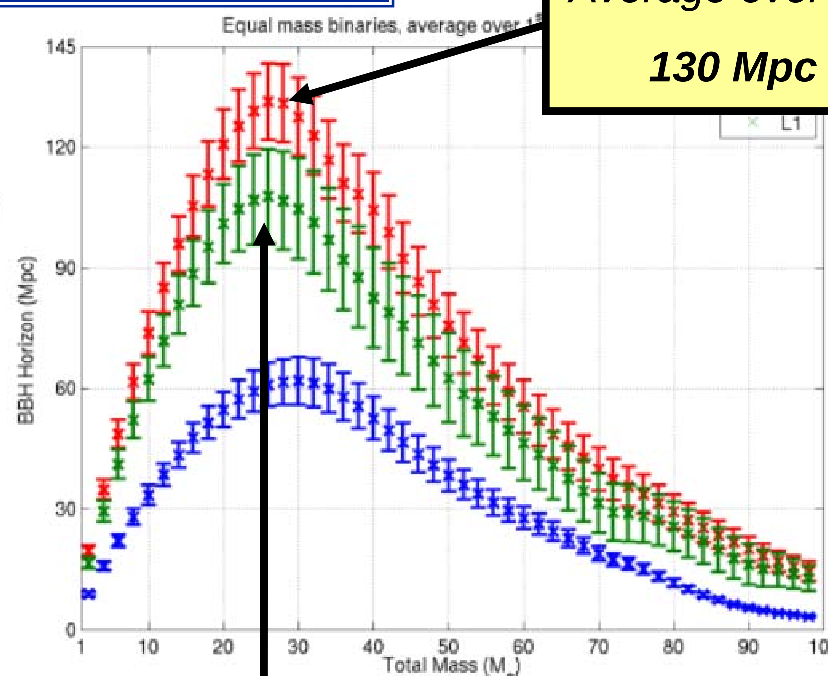
binary neutron star horizon distance: ***25 Mpc***



binary black hole horizon distance



Average over run ***130 Mpc***



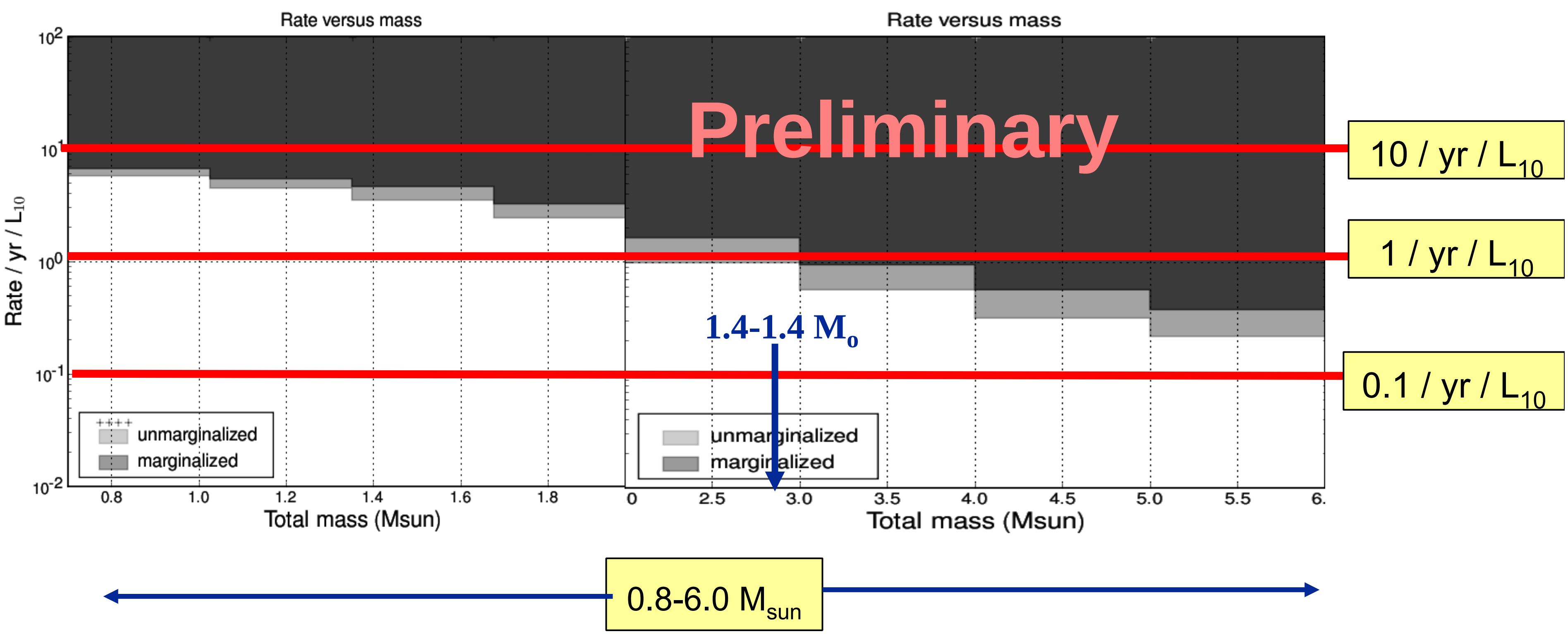
Peak at total mass ~ $25M_{sun}$

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

S4 Upper Limit: Compact Binary Coalescence

preliminary

- Rate/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

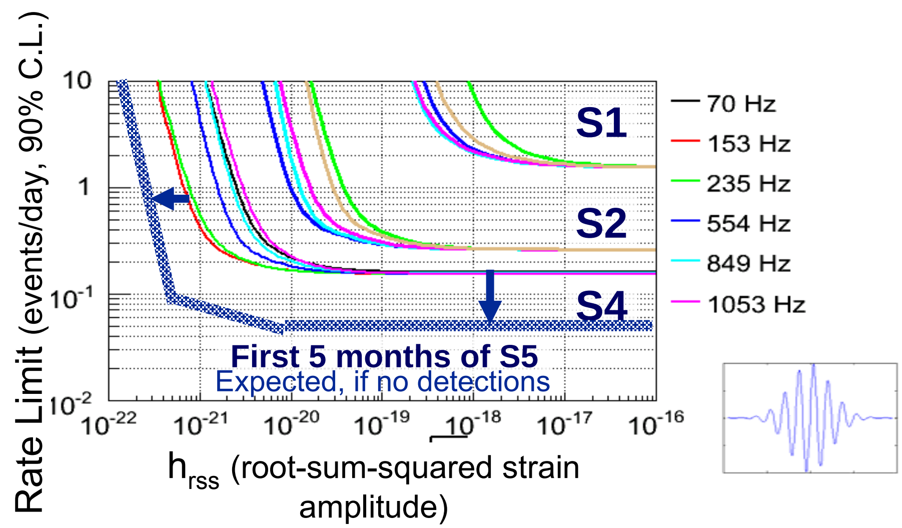


All-Sky Searches for GW Bursts

- Goal: detect short, arbitrary GW signals in LIGO frequency band
  - » Stellar core collapse, compact binary merger, etc. — or unexpected sources
- No matched filtering! Excess signal power and cross-correlation among data streams from multiple detectors

Search for GW bursts in LIGO data

- Detection algorithms tuned for 64–1600 Hz, duration << 1 sec
- Veto thresholds pre-established before looking at data
- Corresponding energy emission sensitivity **$E_{GW} \sim 10^{-1}\ M_{sun}$ at 20 Mpc** (153 Hz case)



Triggered Searches for GW Bursts

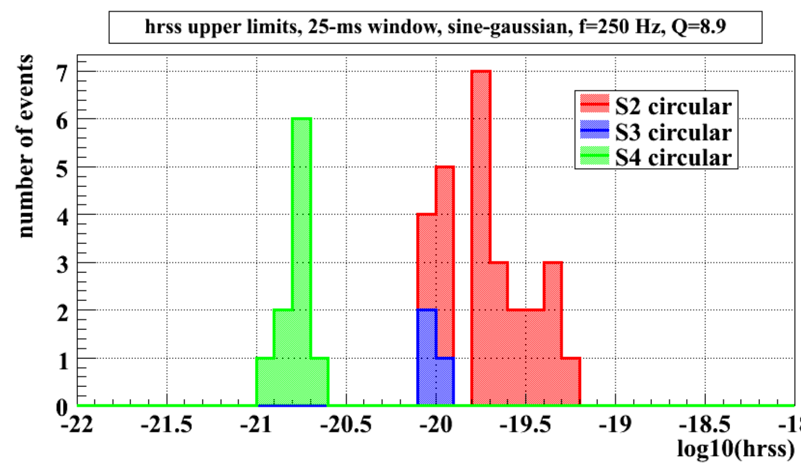
preliminary

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 LIGO data for GW signal associated with quasi-periodic oscillations ➔ no GW signal found
- sensitivity: $E_{GW} \sim 10^{-7}$ to 10^{-8} M_{sun} for the 92.5 Hz QPO
- this is the same order of magnitude as the EM energy emitted in the flare

Gamma-Ray Bursts

- search LIGO data surrounding GRB trigger using crosscorrelation 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



Search for Known Pulsars

preliminary

- Joint 95% upper limits for 97 pulsars using ~10 months of the LIGO S5 run. Results are overlaid on the estimated median sensitivity of this search.

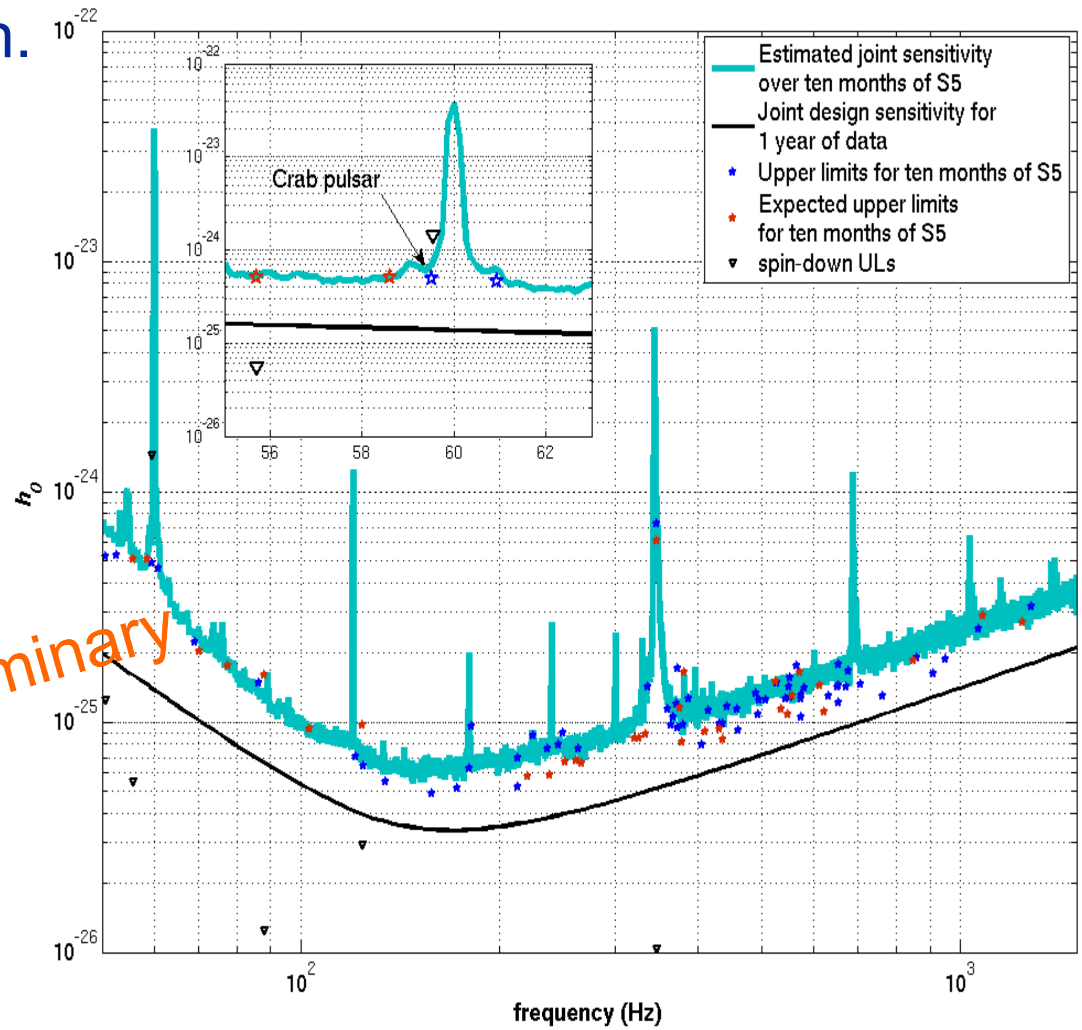
For 32 of the pulsars we give the *expected* sensitivity upper limit (red stars) due to uncertainties in the pulsar parameters

Pulsar timings provided by the Jodrell Bank pulsar group

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

Preliminary

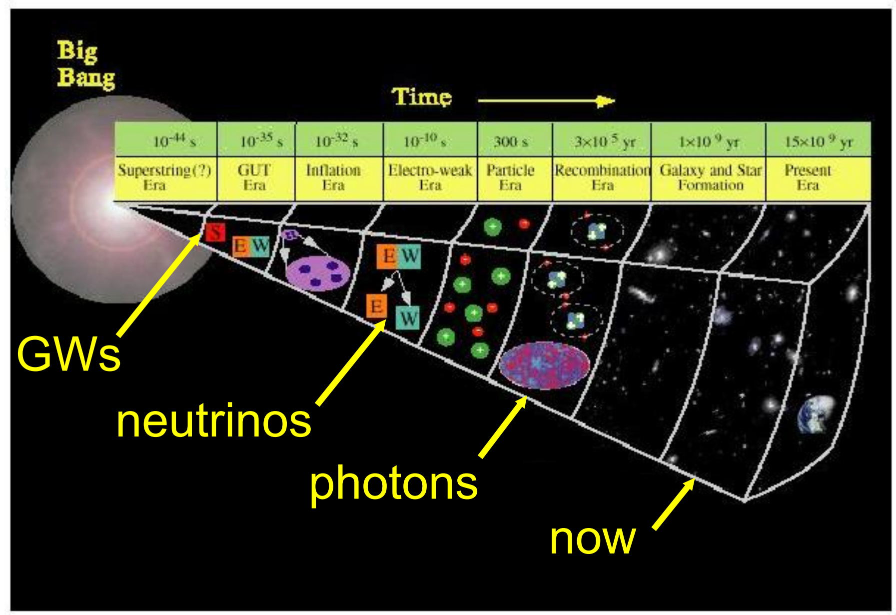


LIGO Limits on Isotropic Stochastic GW Signal

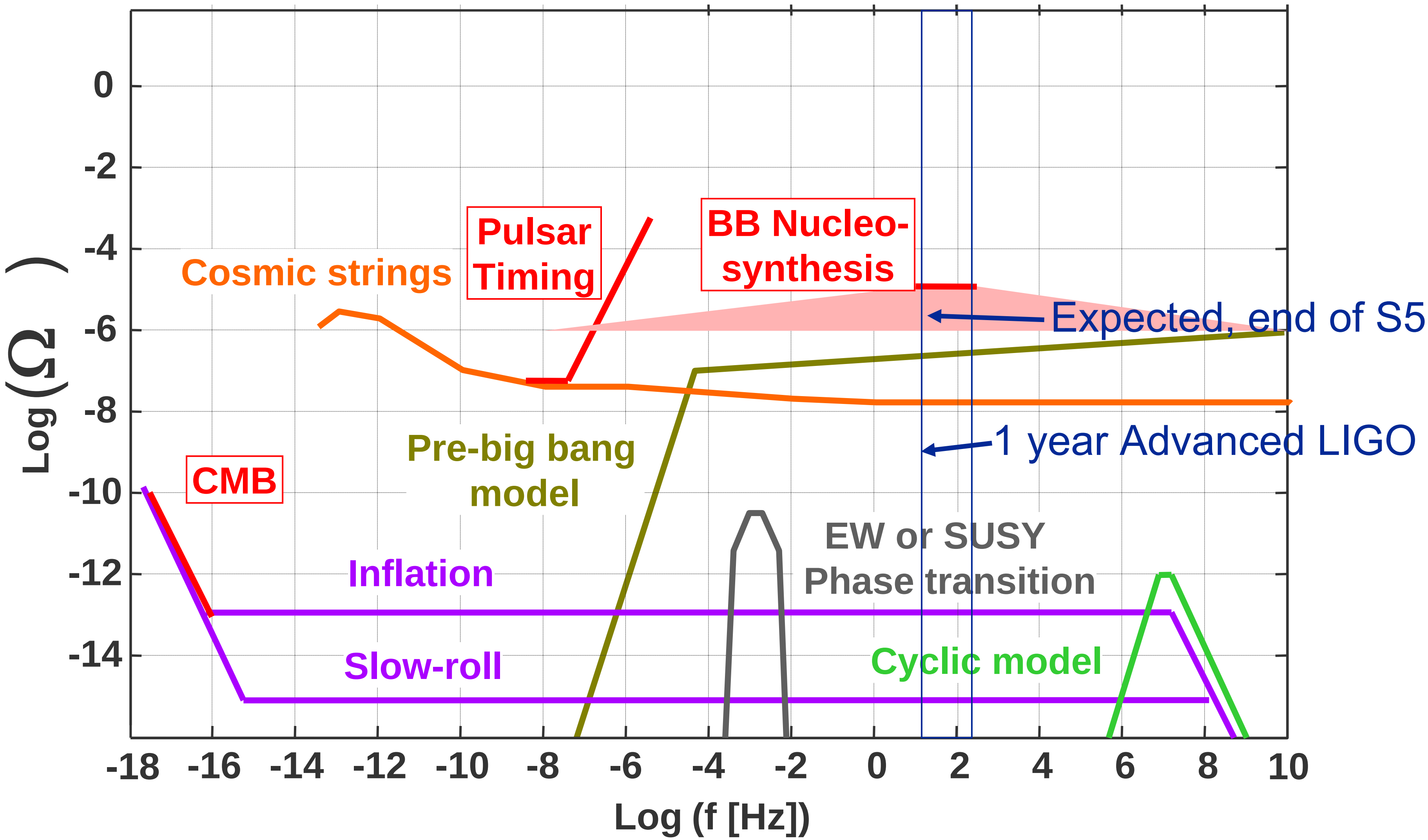
- Cross-correlate signals between 2 interferometers
- LIGO S1: $\Omega_{GW} < 44$
  PRD 69 122004 (2004)

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 ApJ)
  - Bandwidth: 51-150 Hz;
- Initial LIGO, 1 yr data
  Expected sensitivity ~ 4×10^{-6}
  Upper limit from Big Bang nucleosynthesis 10^{-5}
- Advanced LIGO, 1 yr data
  Expected Sensitivity ~1×10^{-9}



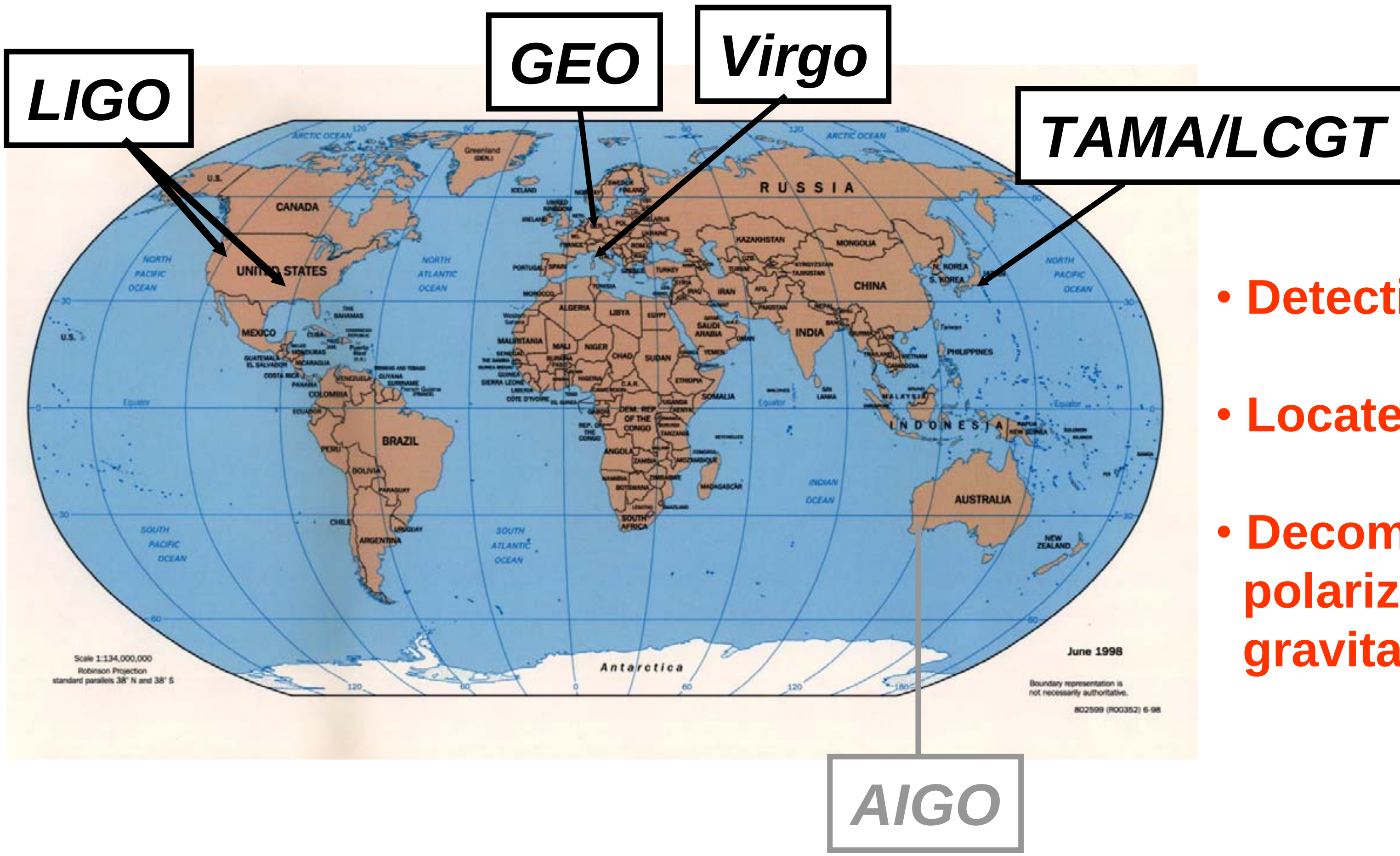
Stochastic Sources including Big Bang: Predictions and Limits



What's next for LIGO? More S5 Results?

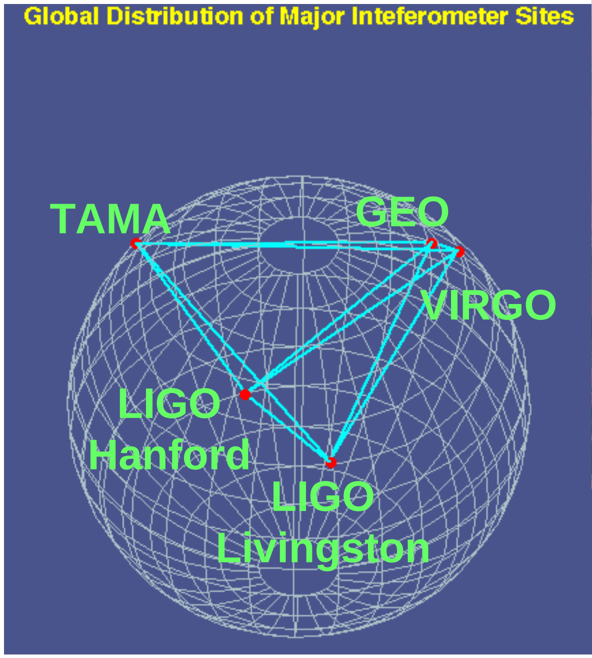
- APS meeting, Jacksonville, April 14-17, 2007

What is next for LIGO?
A Global Network of GW Detectors



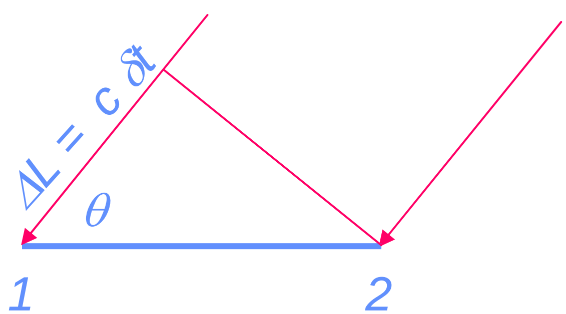
- Detection confidence
- Locate sources
- Decompose the polarization of gravitational waves

What's next for LIGO?
A Global Network of GW Detectors



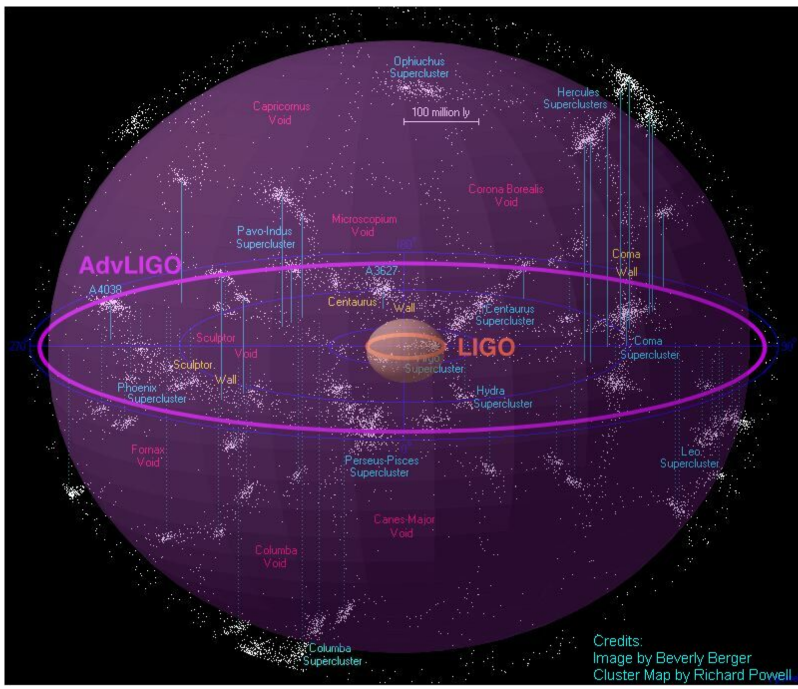
Virgo
Italy

GEO 600
Germany



What’s next for LIGO? Advanced LIGO

- Take advantage of new technologies and on-going R&D
  - » Active anti-seismic system operating to lower frequencies
  - » Lower thermal noise suspensions and optics
  - » Higher laser power
  - » More sensitive and more flexible optical configuration



x10 better amplitude sensitivity

$\Rightarrow$ x1000 rate=(reach)^3

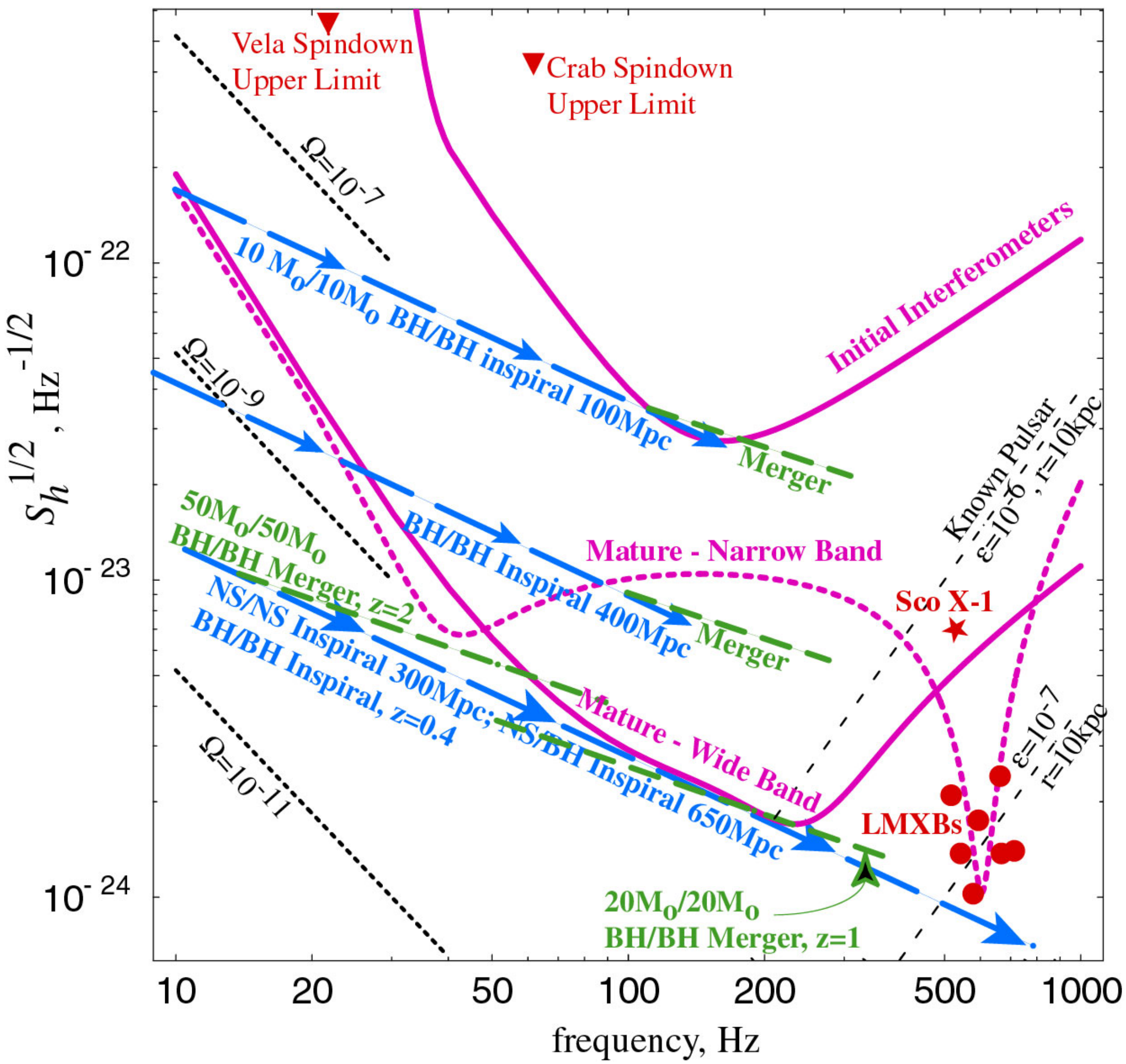
$\Rightarrow$ 1 day of Advanced LIGO

» 1 year of Initial LIGO !

Planned for FY2008 start, installation beginning 2011

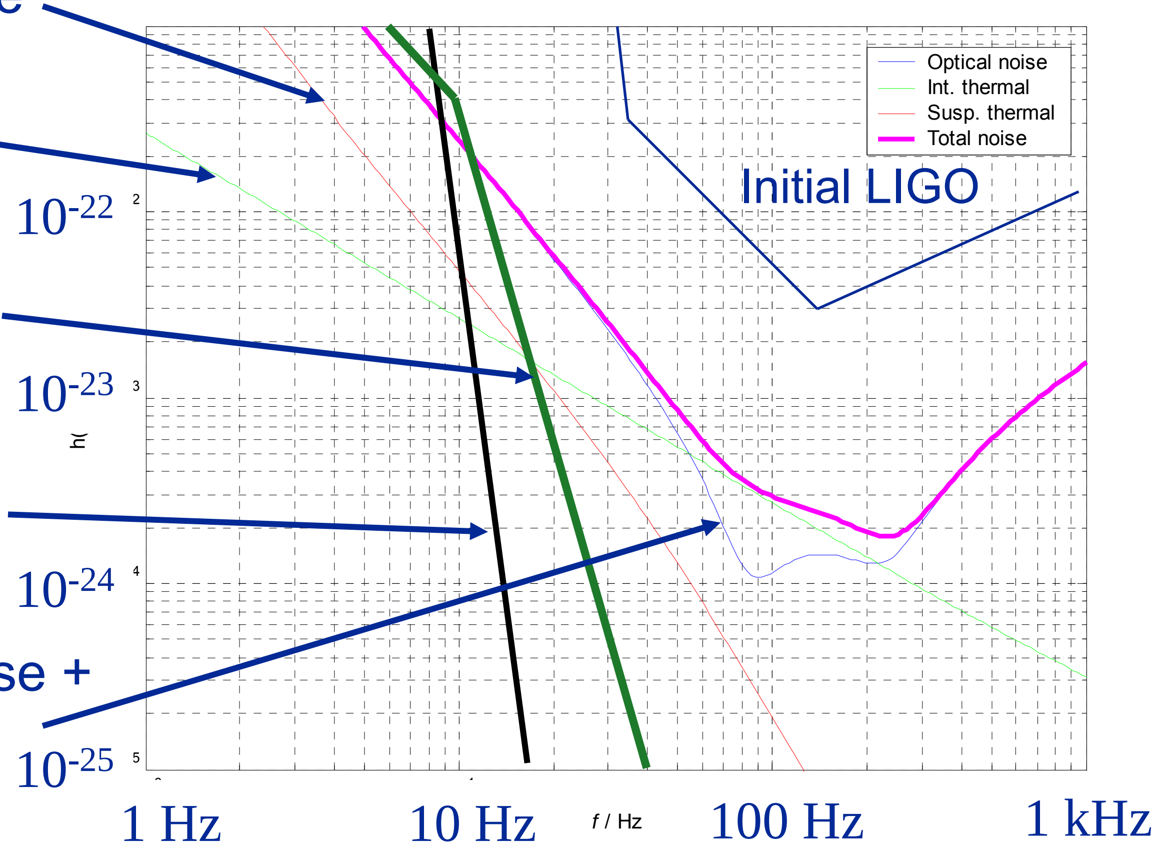
What's next for LIGO?
Targets for Advanced LIGO

- Neutron star & black hole binaries
  - » inspiral
  - » merger
- Spinning neutron stars
  - » LMXBs
  - » known pulsars
  - » previously unknown
- Supernovae
- Stochastic background
  - » Cosmological
  - » Early universe



Anatomy of the Projected Adv LIGO Detector Performance

- Suspension thermal noise
- Internal thermal noise
- Newtonian background, estimate for LIGO sites
- Seismic ‘cutoff’ at 10 Hz
- Quantum noise (shot noise + radiation pressure noise) dominates at most frequencies



What's next for LIGO? Beyond Advanced LIGO

- Third generation GW interferometers will have to confront (and beat) the uncertainty principle
- Standard Quantum Limit (early 1980's)
  - Manifestation of the "Heisenberg microscope"
  - Shot noise ~ $P^{-1/2}$
  - Radiation pressure noise ~ $P^{1/2}$
  - Together define an optimal power and a maximum sensitivity for a "conventional" interferometer
- Resurgent effort around the world to develop sub-SQL measurements ("quantum non-demolition")
  - Require non-classical states of light, special interferometer configurations, …
- Cryogenic? Underground?

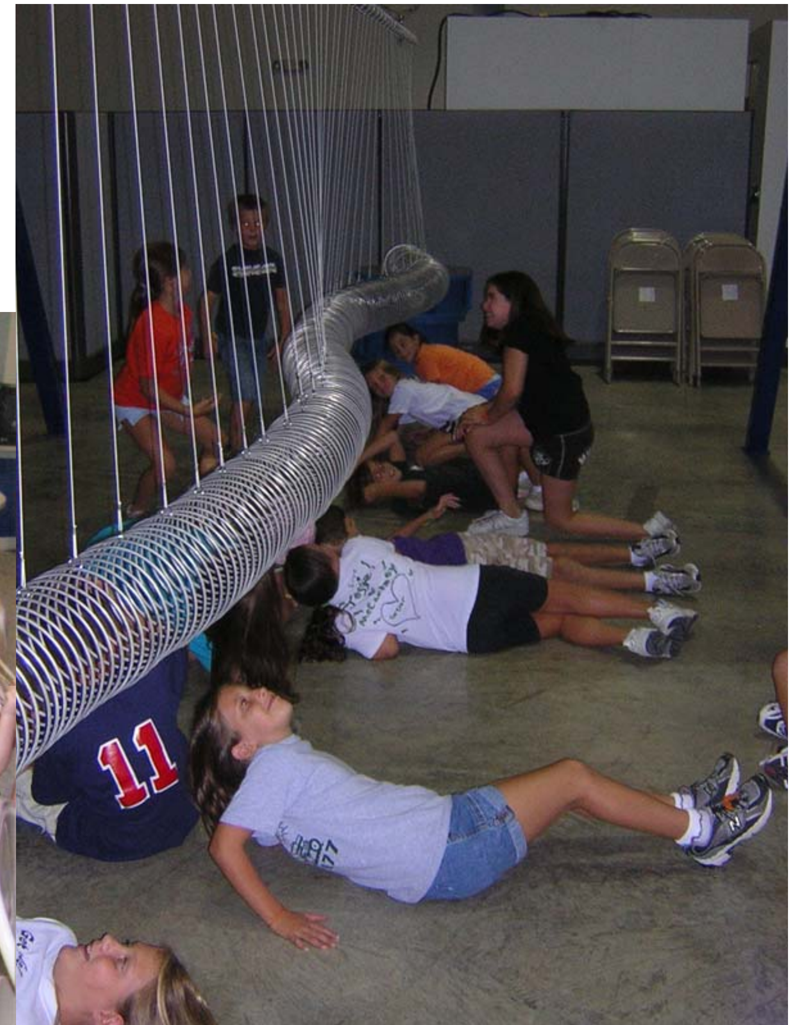
Who is LIGO?

- LIGO Laboratory
  - » Four sites (Caltech, MIT, LIGO Hanford, LIGO Livingston)
  - » ~180 scientists, students, engineers, other staff
- LIGO Scientific Collaboration
  - » Over 500 members
  - » Over 40 universities or research centers
  - » Eight countries

Who is LIGO?
The LIGO Scientific Collaboration

Who is LIGO?
Education motivated by Research

- Outreach to communities, schools, based at two LIGO sites
- 1/3 of all people at sites are visitors!



Final Thoughts

- We are on the threshold of a new era in GW detection
  - » LIGO has reached design sensitivity and is taking data
  - » First detections could come in the next year (or two, or three …)
- A worldwide network is starting to come on line
  - » Groundwork has been laid for operation as a integrated system
- Second generation detector (Advanced LIGO) is approved and ready to start fabrication
  - » Will expand the “Science” (astrophysics) by factor of 1000