LIGO, on the threshold of Gravitational Wave Astronomy

Stan Whitcomb (for the LIGO Scientific Collaboration)

Seminar at the Australian National University

16 July 2007

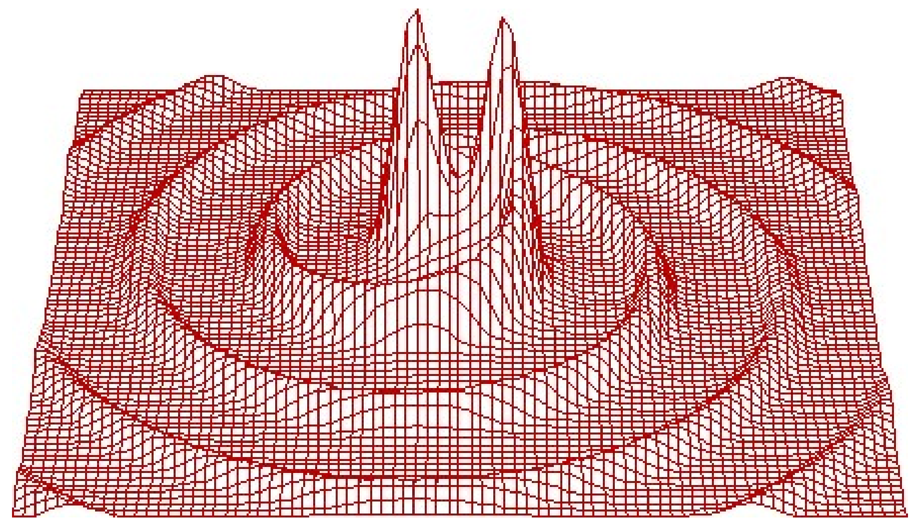
LIGO-G070418-00-D

LIGO Scientific Collaboration

- Australian Consortium for Interferometric Gravitational Astronomy
- The Univ. of Adelaide
- Andrews University
- The Australian National Univ.
- The University of Birmingham
- California Inst. of Technology
- Cardiff University
- Carleton College
- Charles Stuart Univ.
- Columbia University
- Embry Riddle Aeronautical Univ.
- Eötvös Loránd University
- University of Florida
- German/British Collaboration for the Detection of Gravitational Waves
- University of Glasgow
- Goddard Space Flight Center
- Leibniz Universität Hannover
- Hobart & William Smith Colleges
- Inst. of Applied Physics of the Russian Academy of Sciences
- Polish Academy of Sciences
- India Inter-University Centre for Astronomy and Astrophysics
- Louisiana State University
- Louisiana Tech University
- Loyola University New Orleans
- University of Maryland
- Max Planck Institute for Gravitational Physics
- University of Michigan
- Massachusetts Inst. of Technology
- Monash University
- Montana State University
- Moscow State University
- National Astronomical Observatory of Japan
- Northwestern University
- University of Oregon
- Pennsylvania State University
- Rochester Inst. of Technology
- Rutherford Appleton Lab
- University of Rochester
- San Jose State University
- Univ. of Sannio at Benevento, and Univ. of Salerno
- University of Sheffield
- University of Southampton
- Southeastern Louisiana Univ.
- Southern Univ. and A&M College
- Stanford University
- University of Strathclyde
- Syracuse University
- Univ. of Texas at Austin
- Univ. of Texas at Brownsville
- Trinity University
- Universitat de les Illes Balears
- Univ. of Massachusetts Amherst
- University of Western Australia
- Univ. of Wisconsin-Milwaukee
- Washington State University
- University of Washington

Outline of Talk

- Quick Review of GW Physics
- LIGO Detector Overview
- Early Results
- Global Network
- Advanced LIGO Detectors

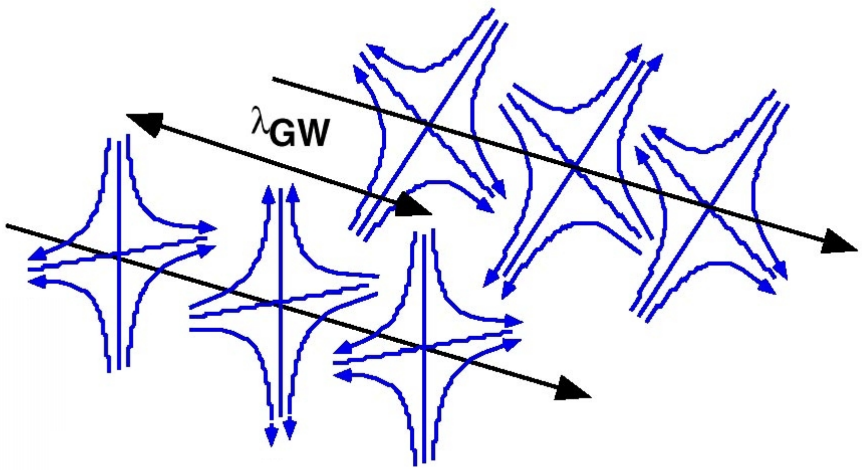


gravitational radiation
binary inspiral of compact objects
(blackholes or neutron stars)

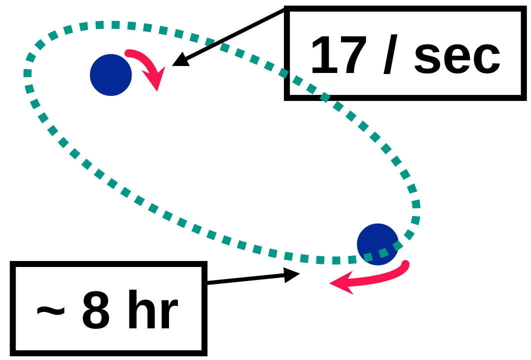
Gravitational Wave Physics

- **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**

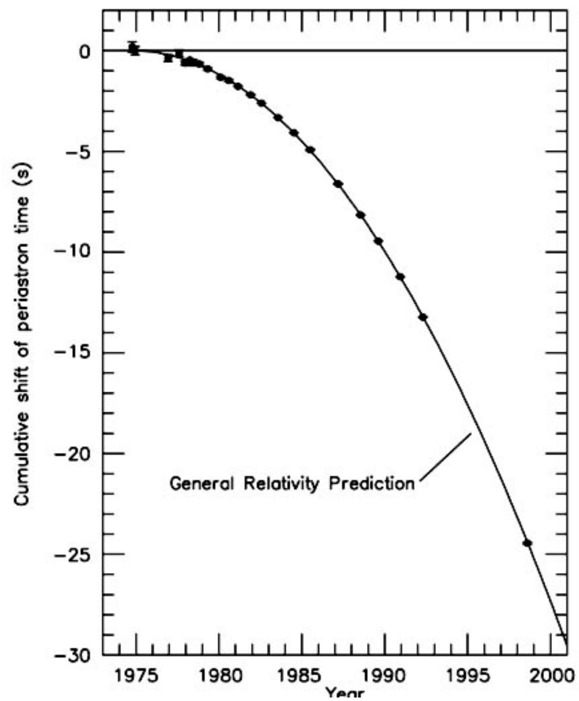
$$h = \Delta L / L$$



Evidence for Gravitational Waves:
Neutron Star Binary PSR1913+16



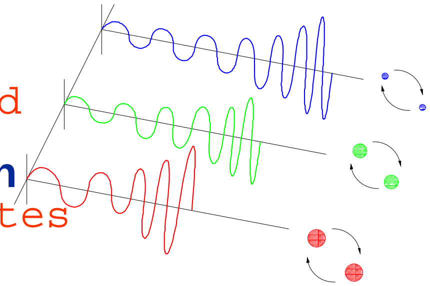
- **Discovered by Hulse and Taylor in 1975**
- **Unprecedented laboratory for studying gravity**
  - » **Extremely stable spin rate**
- **Possible to repeat classical tests of relativity (bending of “starlight”, advance of “perihelion”, etc.**



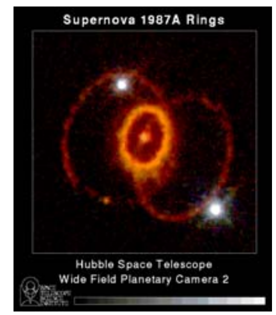
- **After correcting for all known relativistic effects, observe loss of orbital energy**
=> Emission of GWs

Astrophysical Sources of GWs

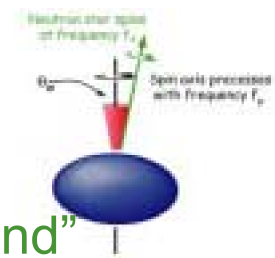
- Compact binary inspiral: “chirps”
  - » **NS-NS binaries well understood**
  - » **BH-BH binaries need further calculation, spin**
  - » **Search technique: matched templates**



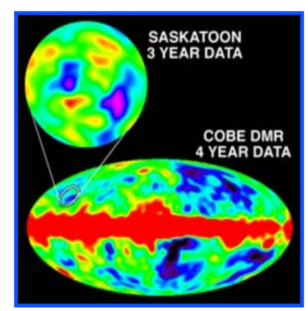
- Supernovas or GRBs: “bursts”
  - » **GW signals observed in coincidence with EM or neutrino detectors**
  - » **Prompt alarm for supernova? (~1 hour?)**



- Pulsars in our galaxy: “periodic waves”
  - » **Search for observed neutron stars (frequency, doppler shift known)**
  - » **All sky search (unknown sources) computationally challenging**
  - » **Bumps? r-modes? superfluid hyperons?**

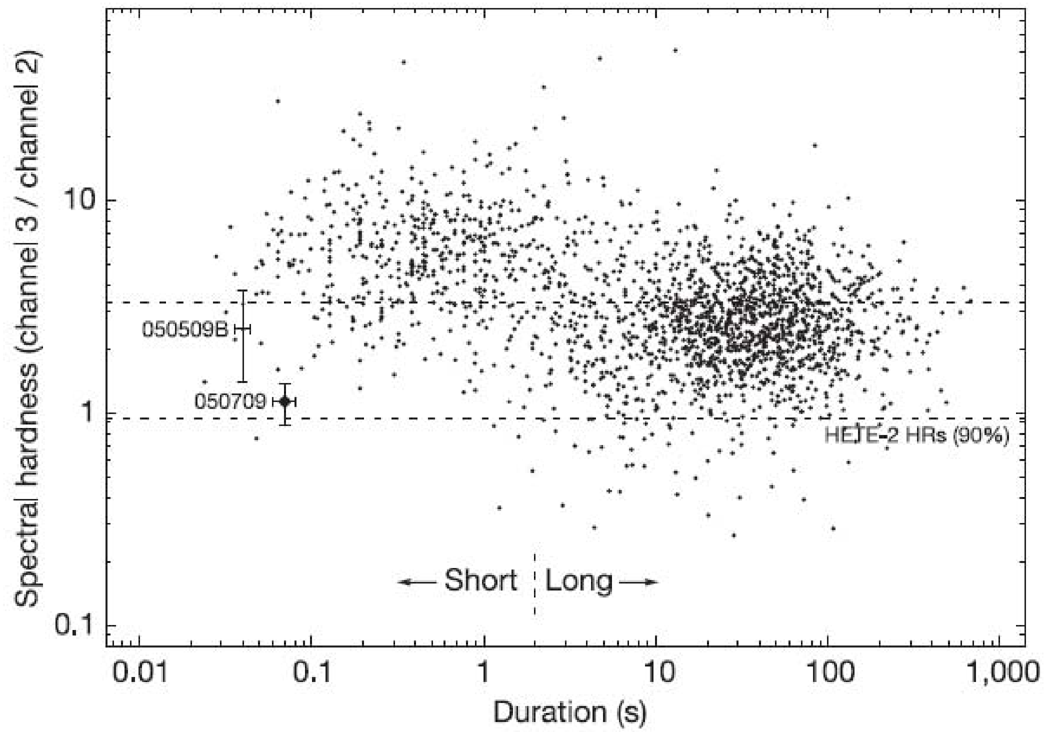


- Cosmological: “stochastic background”
  - » **Probing the universe back to the Planck time (10^{-43} s)**

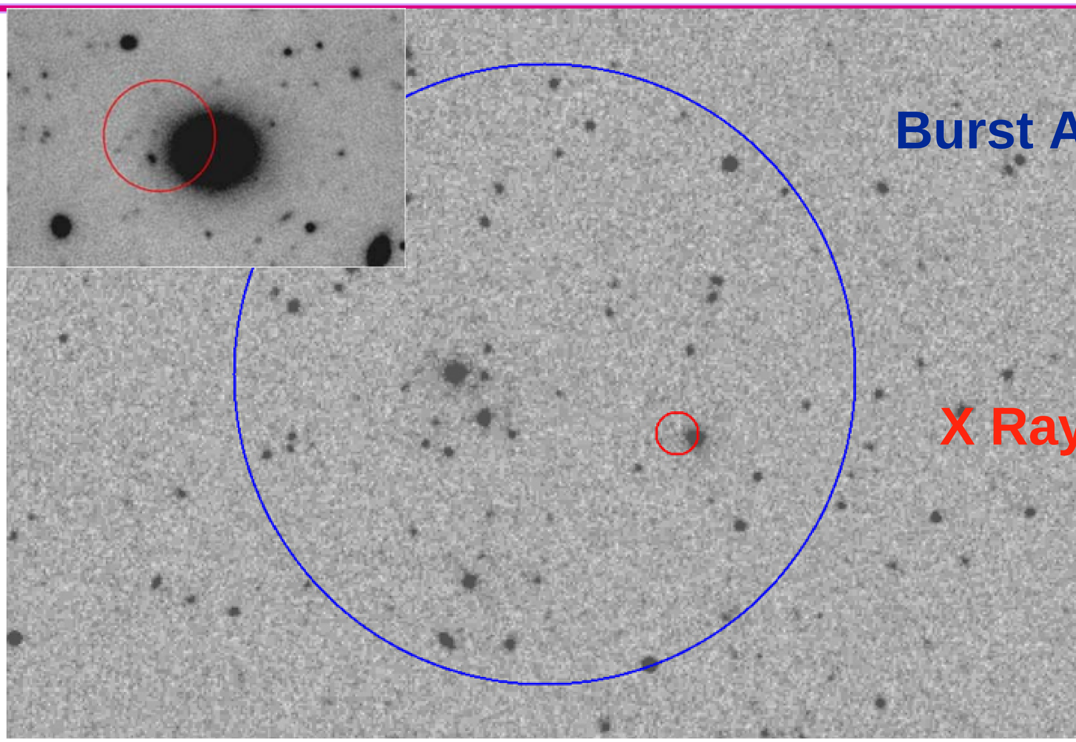


Short Gamma Ray Bursts (GRBs)

- 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)

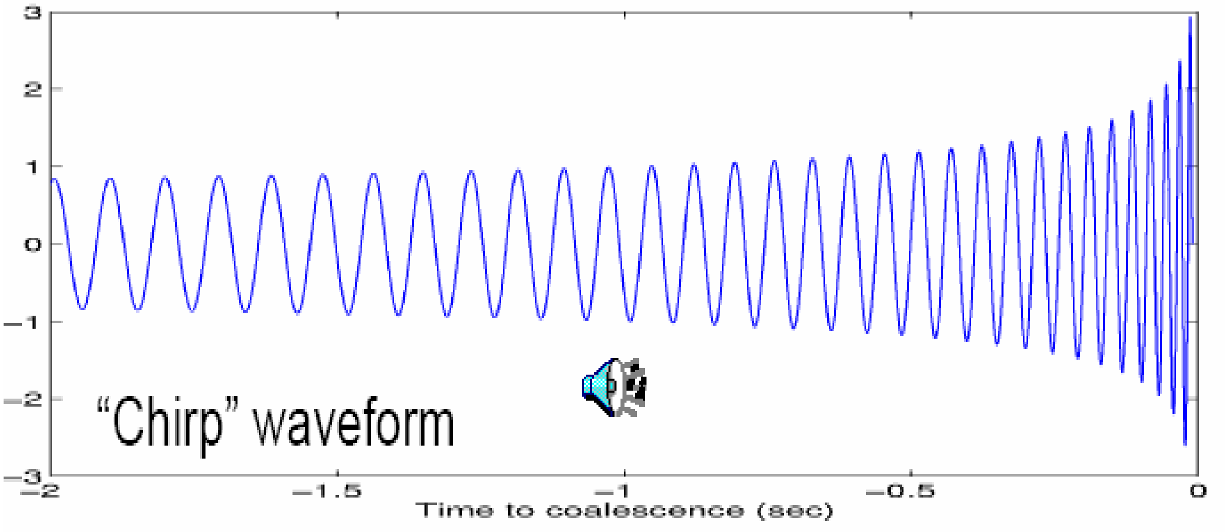


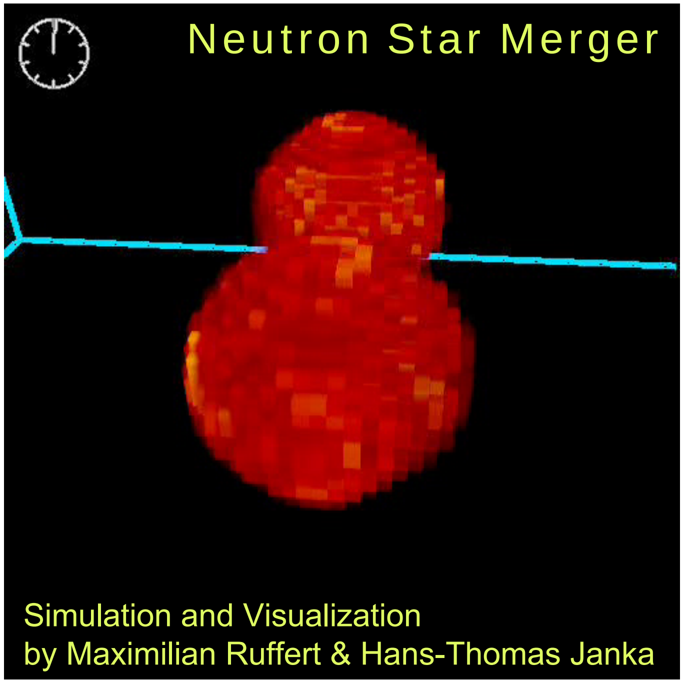
Gehrels et al., Nature, 437, 851, 2005

- 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

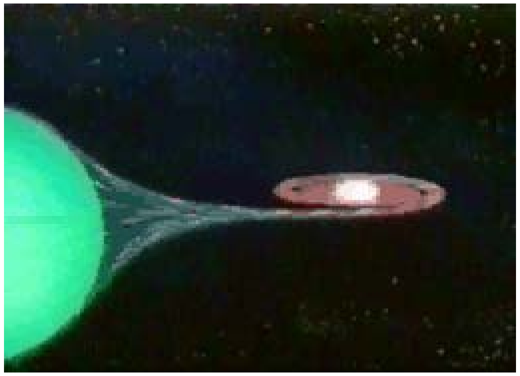




Chirp parameters give:
- **Masses of the two bodies (NS, BH)**
- **Distance from the earth**
- **Orientation of orbit**
- **Beaming of gamma rays (with enough observed systems)**

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?

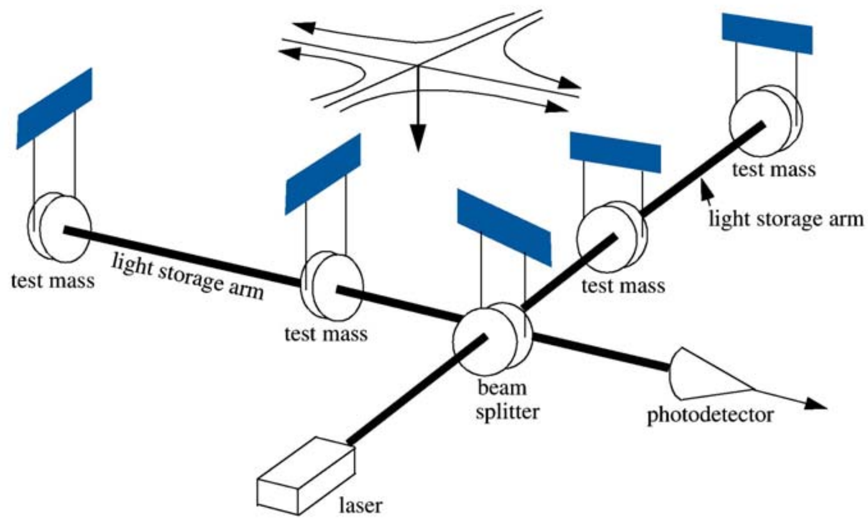


Imagine the Universe
NASA High Energy Astrophysics Science Archive

Detecting GWs with Interferometry

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

$$h = \Delta L / L$$



Terrestrial detector

For $h \sim 10^{-22} - 10^{-21}$

L ~ 4 km (LIGO)

$\Delta L \sim 10^{-18}$ m

Optical Configuration

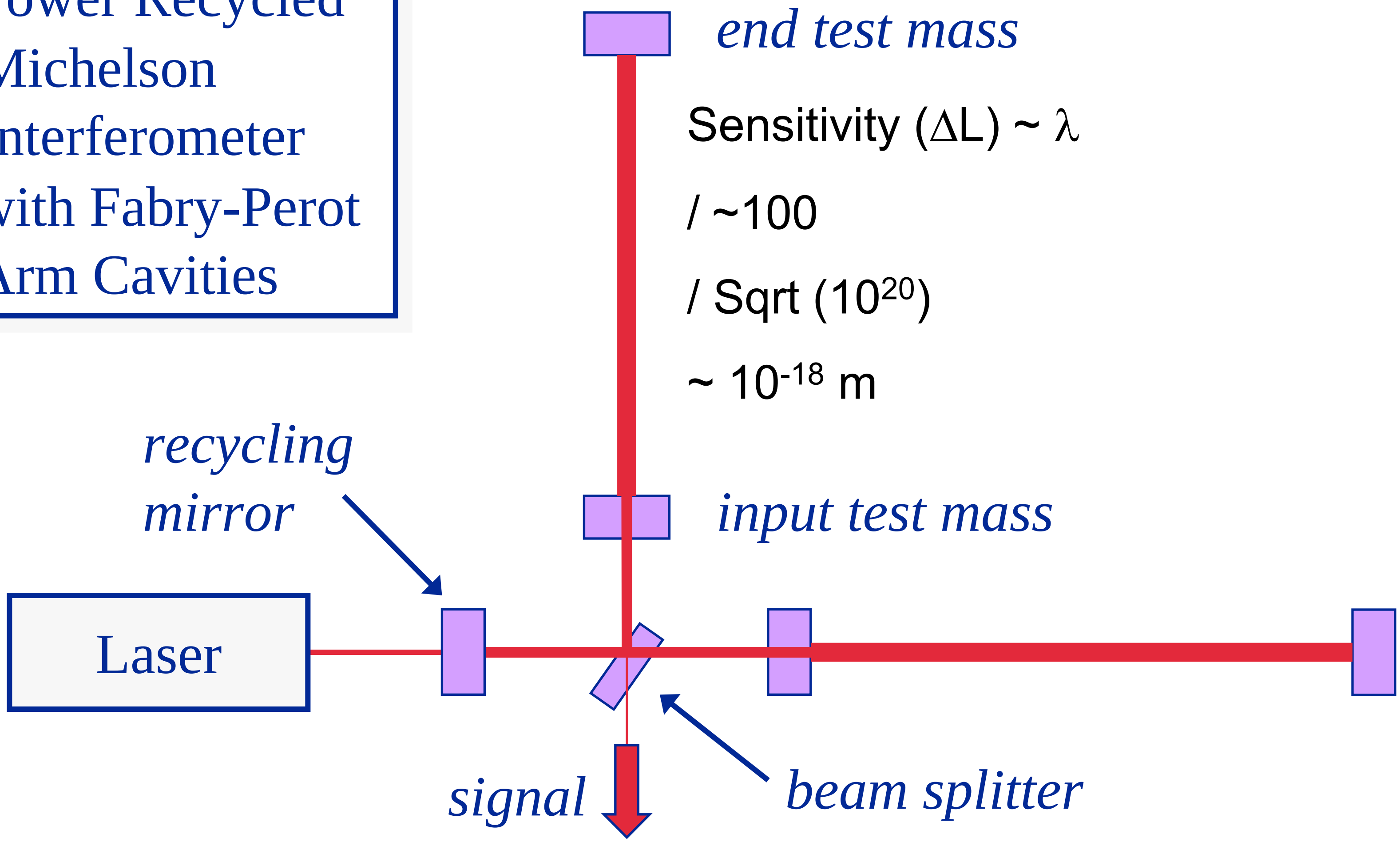
Power Recycled Michelson Interferometer with Fabry-Perot Arm Cavities

Sensitivity (ΔL) ~ λ

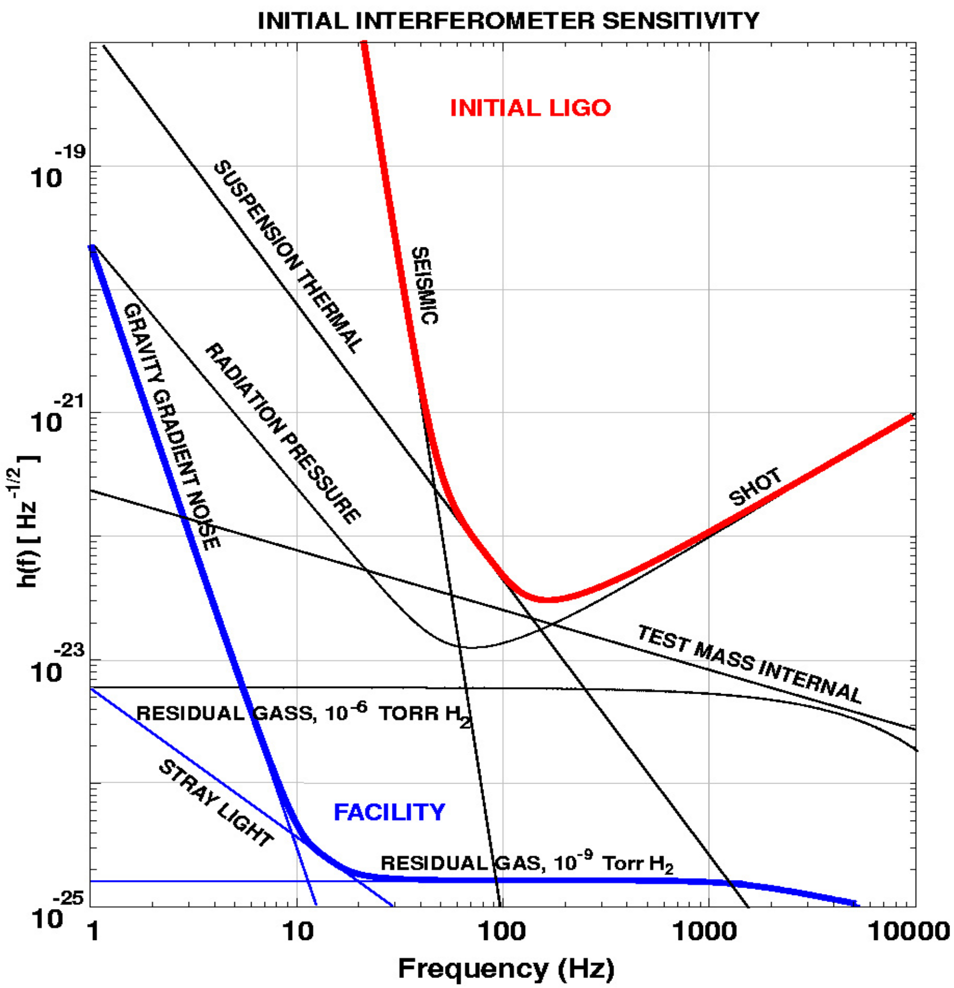
/ ~100

/ Sqrt (10^{20})

~ 10^{-18} m



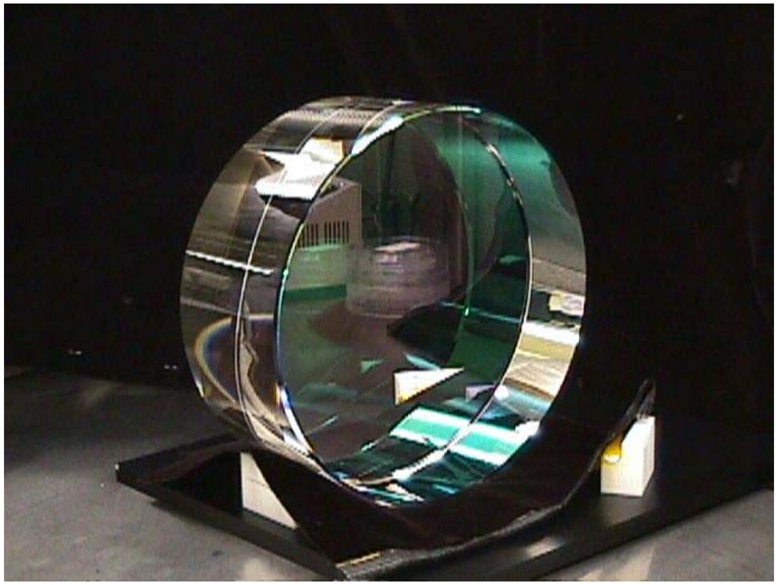
Initial LIGO Sensitivity Goal



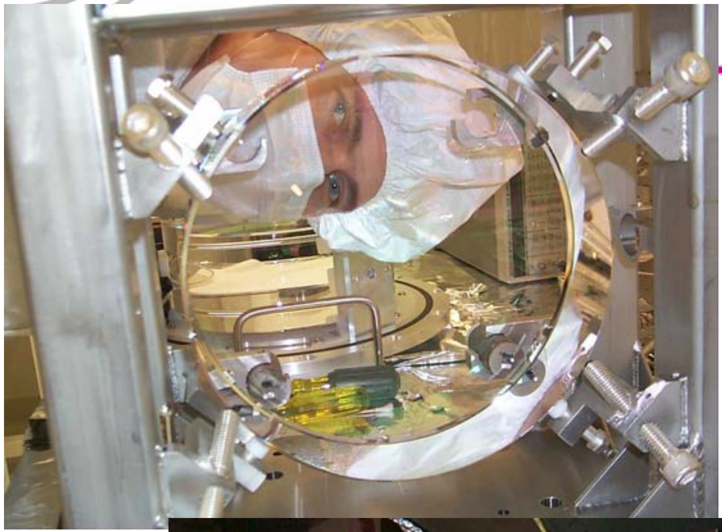
- Strain sensitivity $<3 \times 10^{-23}$ $1/Hz^{1/2}$ at 200 Hz
- Sensing Noise
  - » Photon Shot Noise
  - » Residual Gas
- Displacement Noise
  - » Seismic motion
  - » Thermal Noise
  - » Radiation Pressure

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 < 2 ppm
  - » Uniformity <10^{-3}
- Production involved 5 companies, CSIRO, NIST, and LIGO

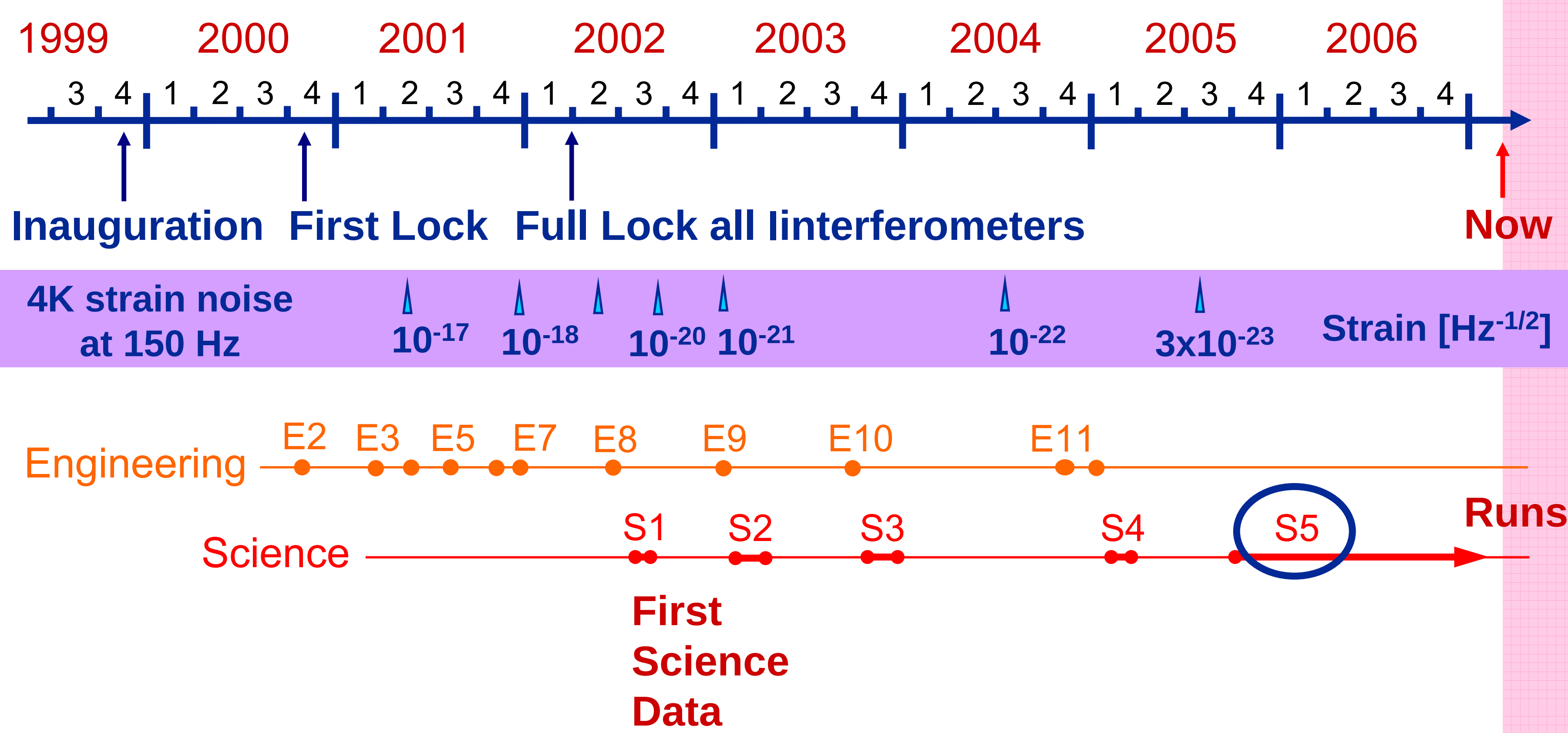


Test Mass Suspension and Control

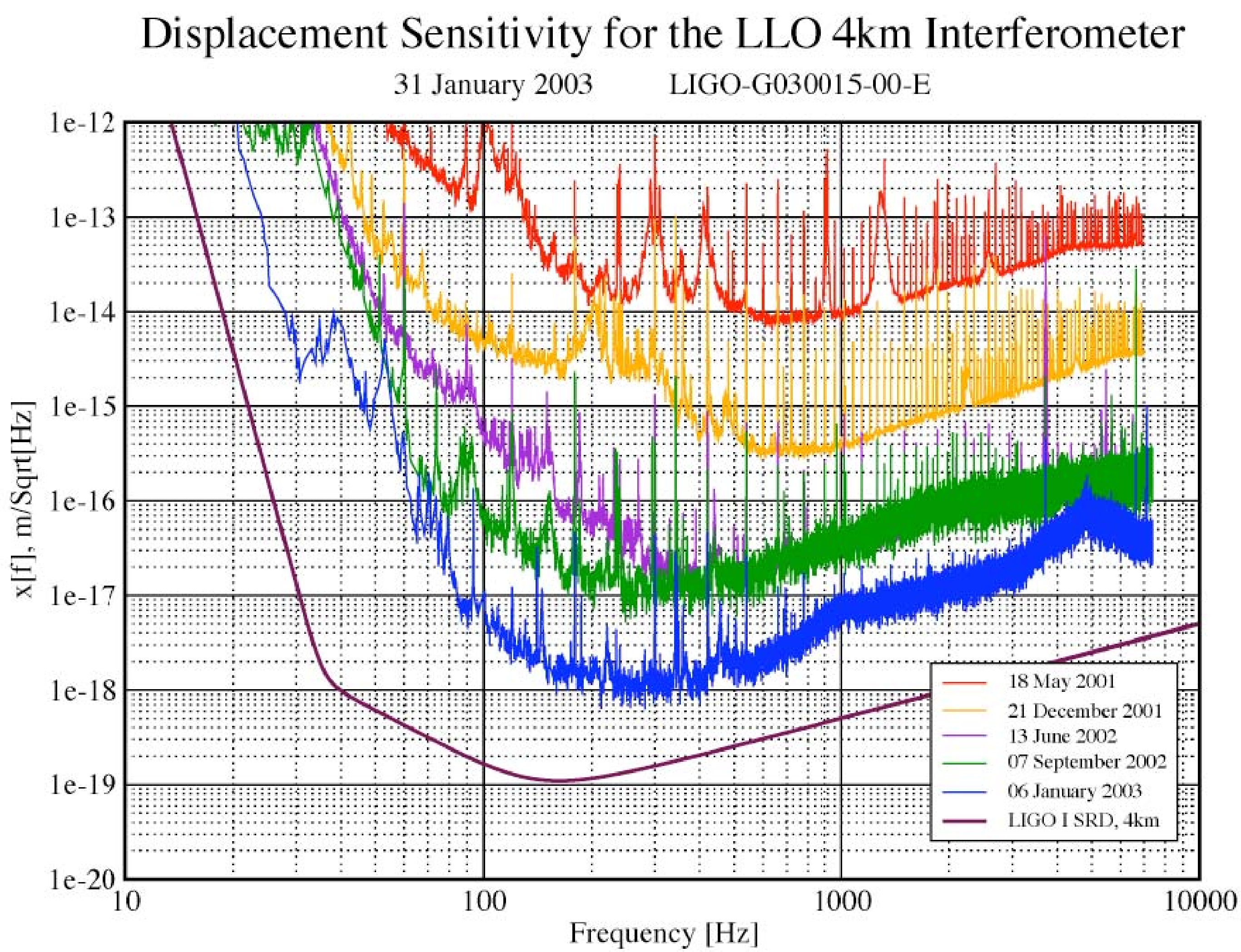


LIGO Observatories

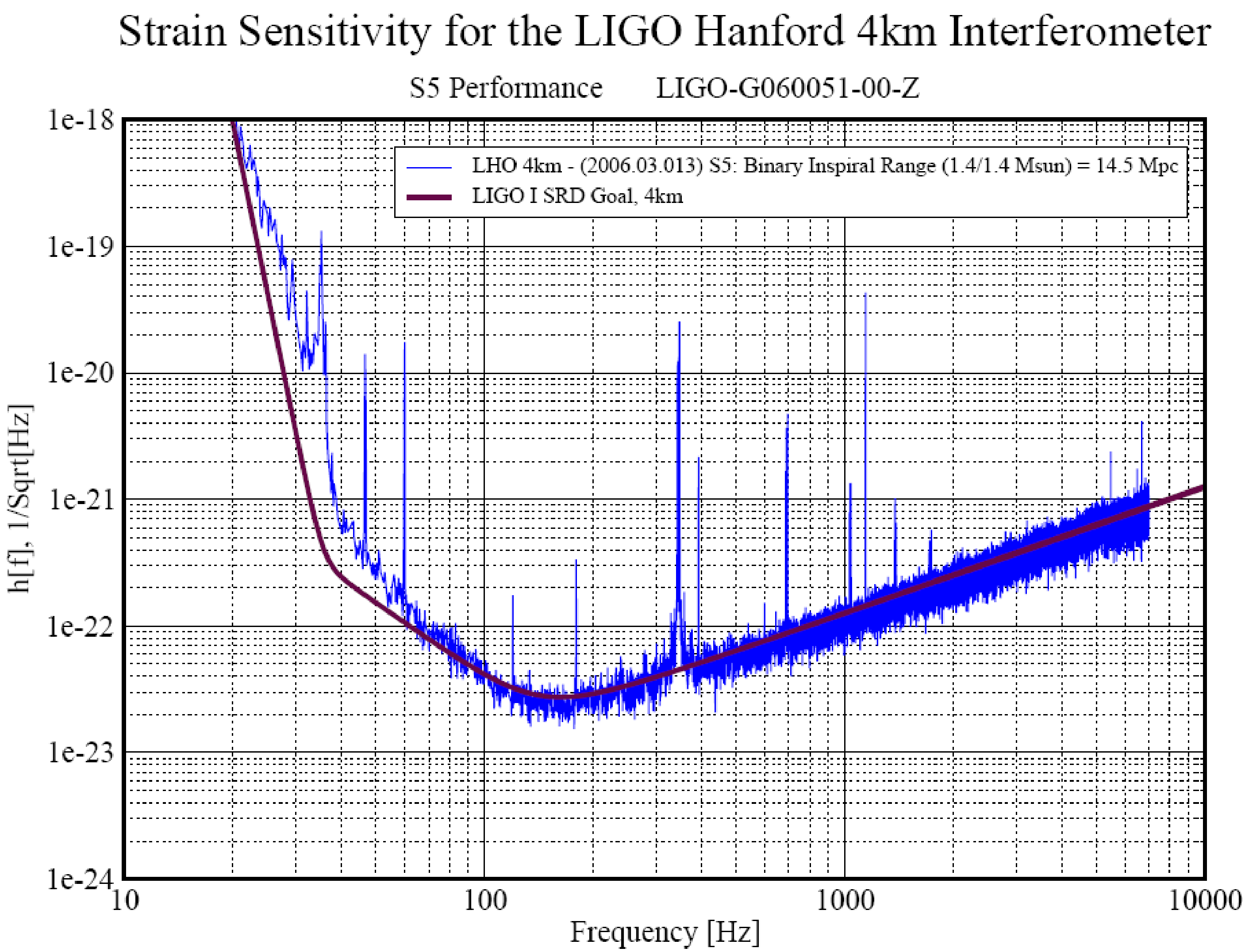
LIGO History



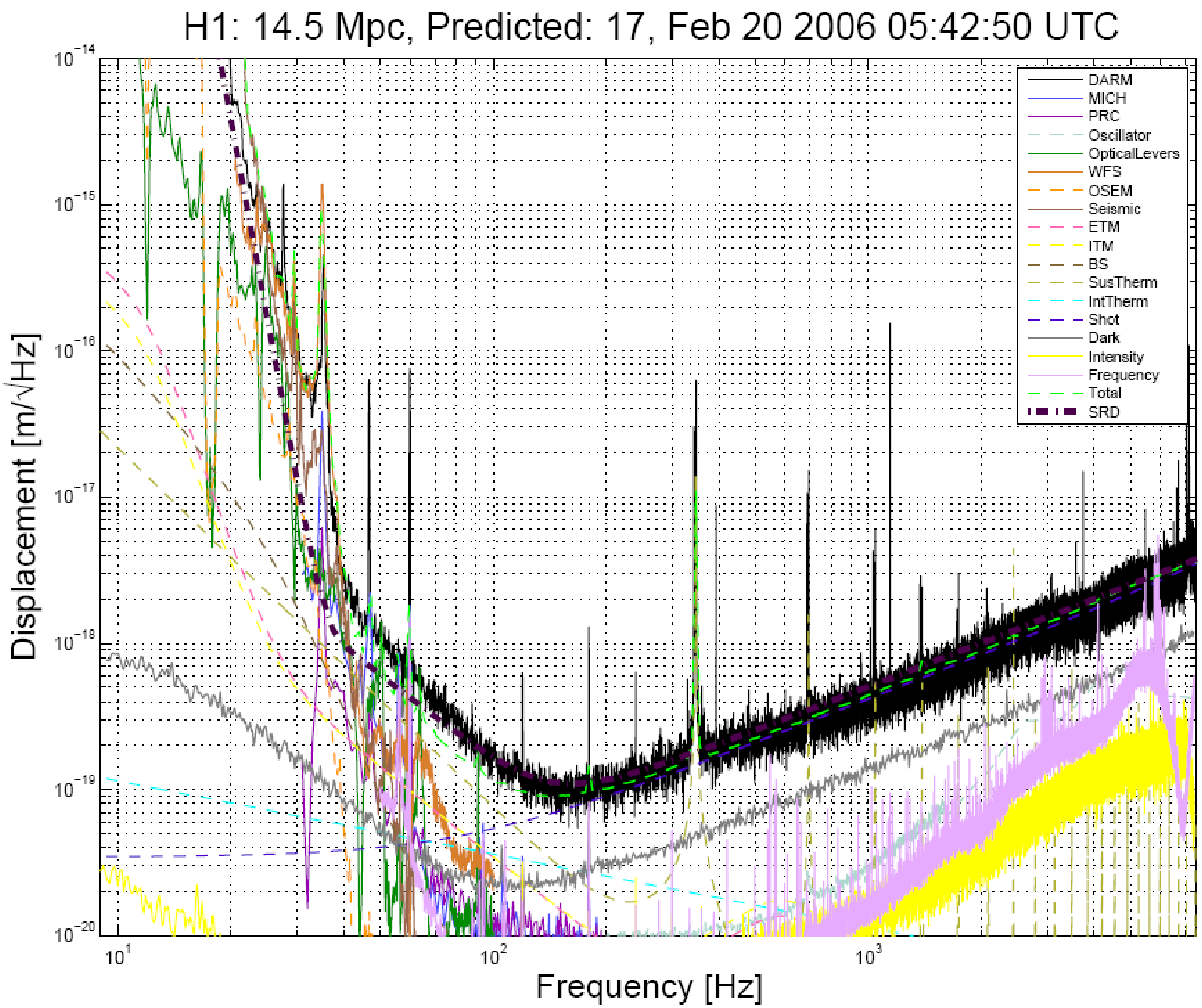
Progress toward Design Sensitivity



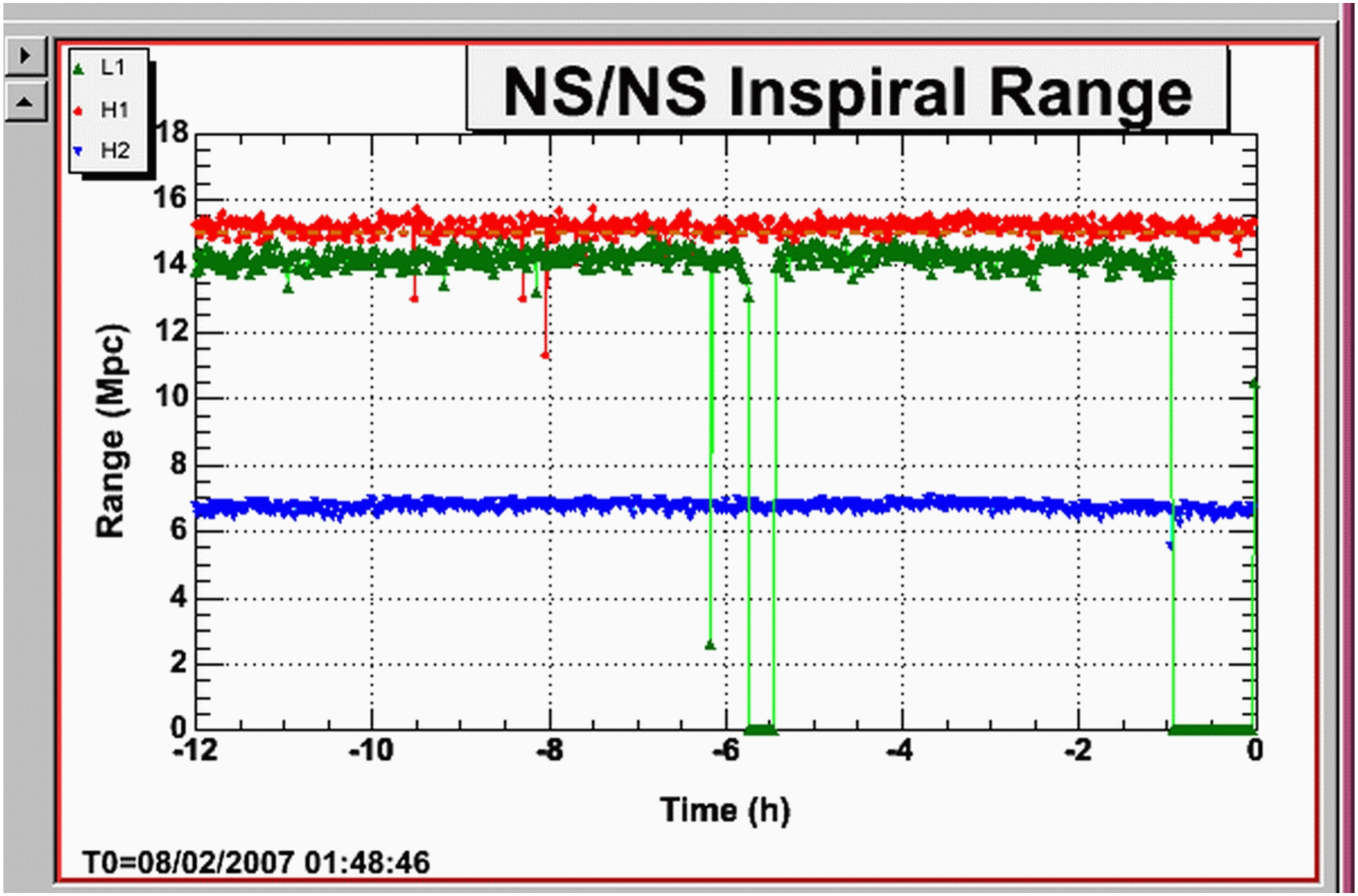
LIGO Sensitivity



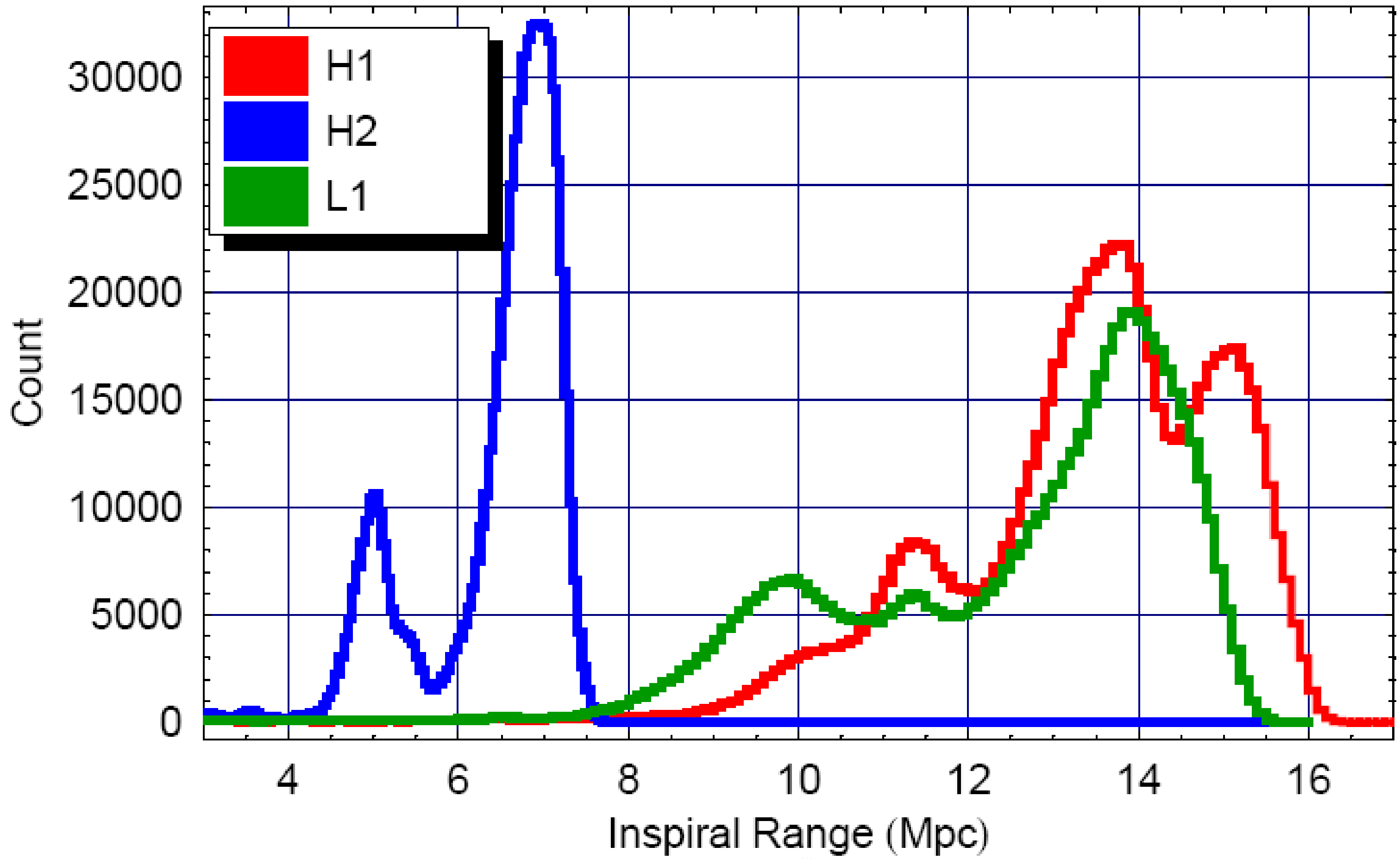
Anatomy of a Noise Curve



LIGO Duty Factor



Duty Factor for S5



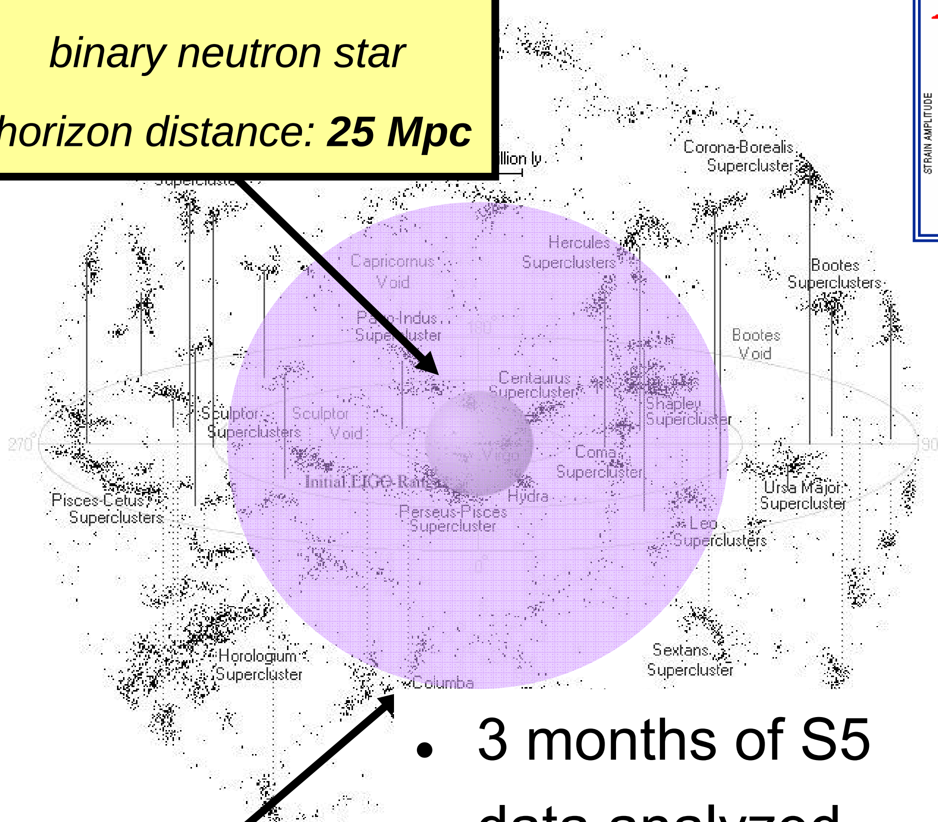
LIGO Data Analysis

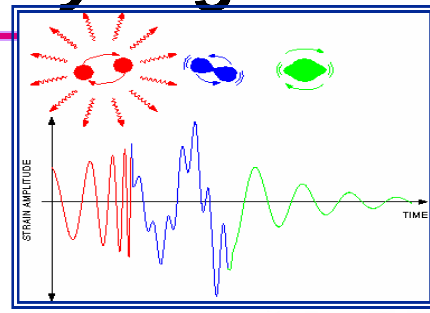
Data analysis by the LIGO Scientific Collaboration (LSC) is organized into four types of analysis:

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

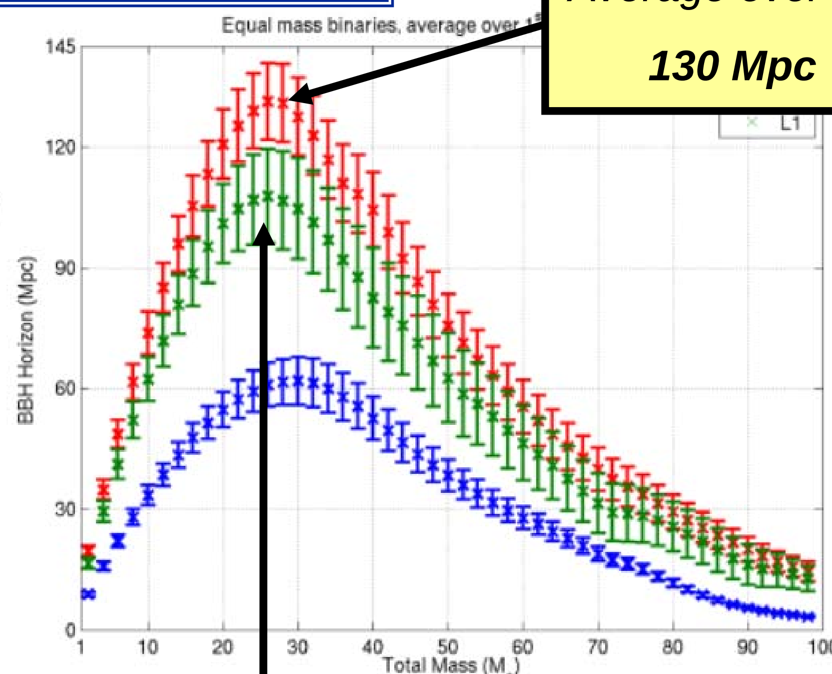
Searches for Coalescing Compact Binary Signals in S5

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





Average over run ***130 Mpc***



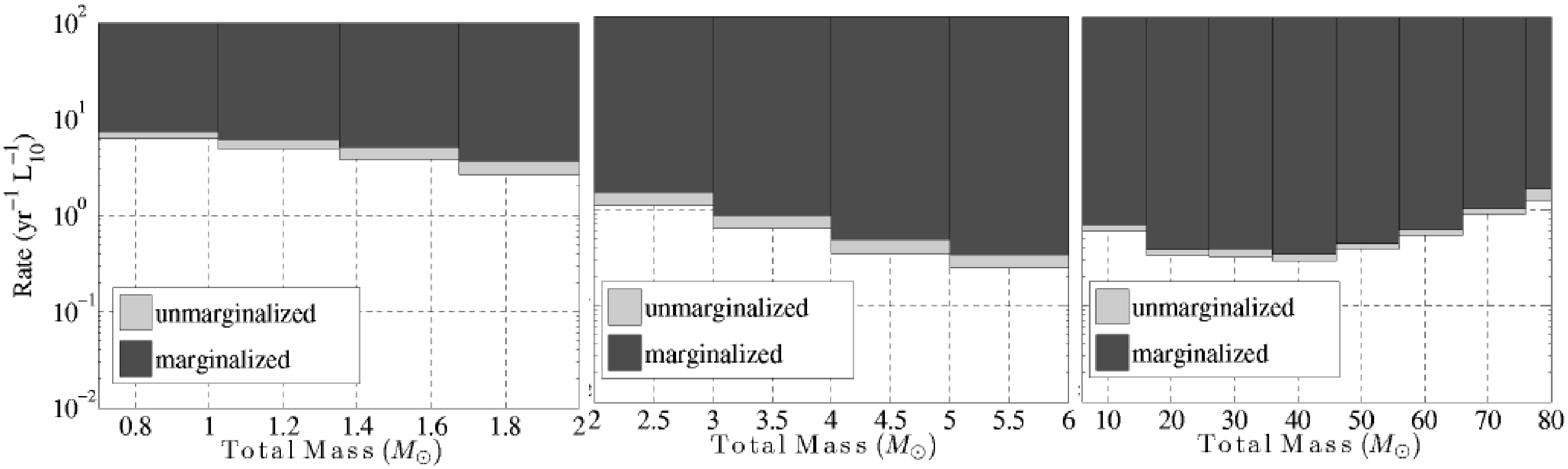
binary black hole horizon distance

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

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

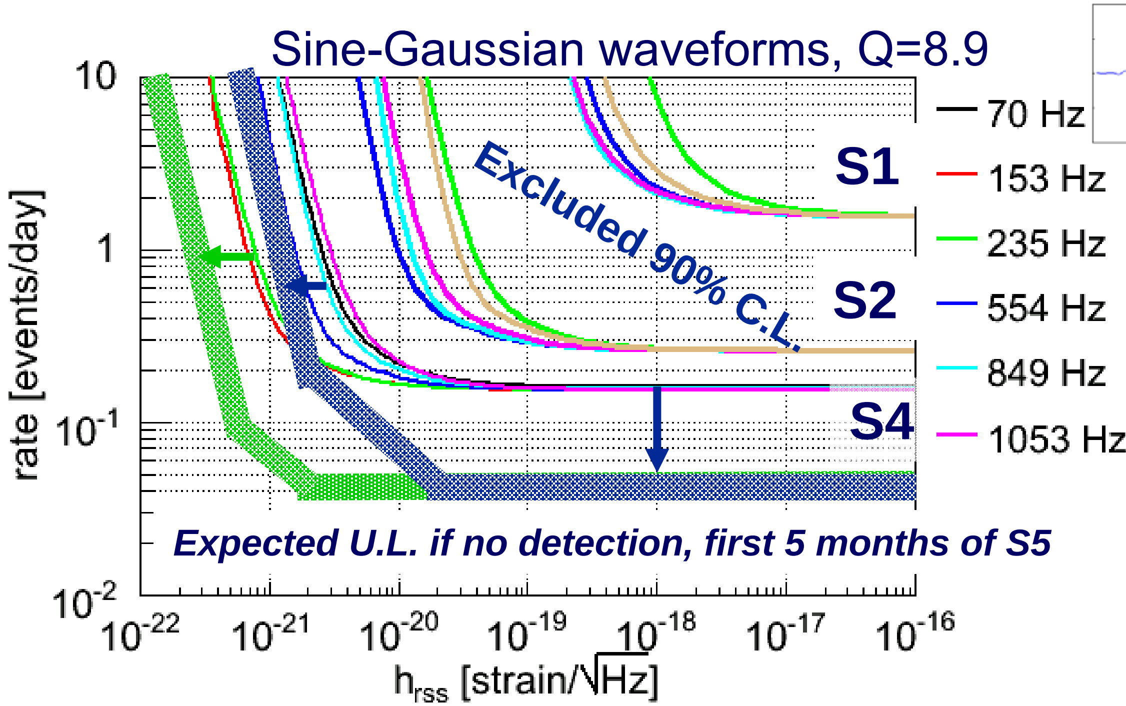
S4 Upper Limit: Compact Binary Coalescence

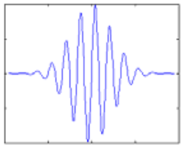
- Rate/L_{10} vs. binary total mass
  $L_{10} = 10^{10}\ L_{sun,B}$ (1 Milky Way = 1.7 L_{10})
- Dark region excluded at 90% confidence



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



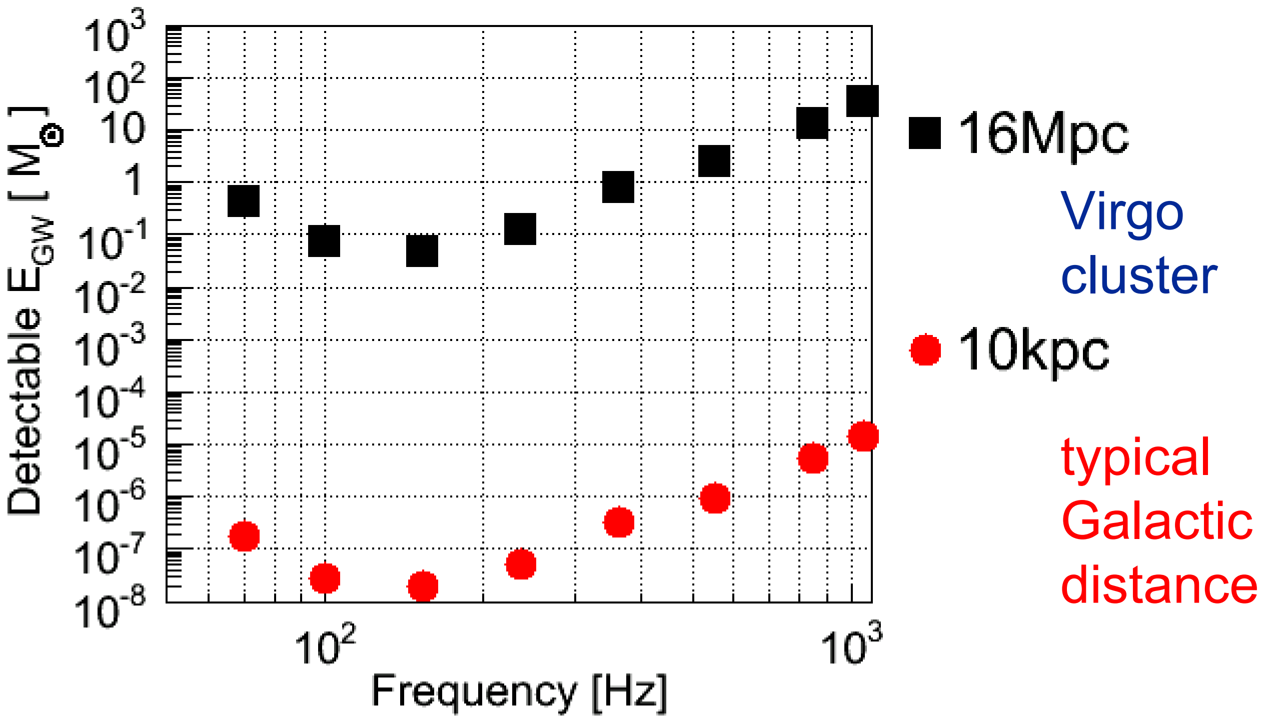


- Detection algorithms tuned for 64–1600 Hz, duration << 1 sec
- Veto thresholds pre-established before looking at data
- Corresponding energy emission **$E_{GW} \sim 10^{-1} M_{\odot}$ at 20 Mpc** (153 Hz case)

$$h_{\rm rss} \equiv \sqrt{\int \left(|h_+(t)|^2 + |h_\times(t)|^2\right) dt}$$

Burst Detection Efficiency / Range

Q =8.9 sine-Gaussians, 50% detection probability:



For a 153 Hz, *Q* =8.9 sine-Gaussian, the S5 search can see with 50% probability:

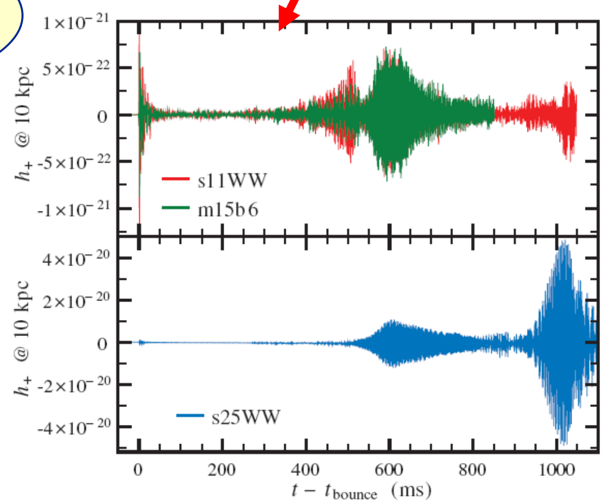
$\sim 2 \times 10^{-8}\ M_\odot c^2$ at 10 kpc (typical Galactic distance)

$\sim 0.05\ M_\odot c^2$ at 16 Mpc (Virgo cluster)

Order of Magnitude Range Estimate for Supernovae and BH Mergers

Model dependent!

Ott, Burrows, Dessart and Livne, PRL 96, 201102 (2006)



Frequency

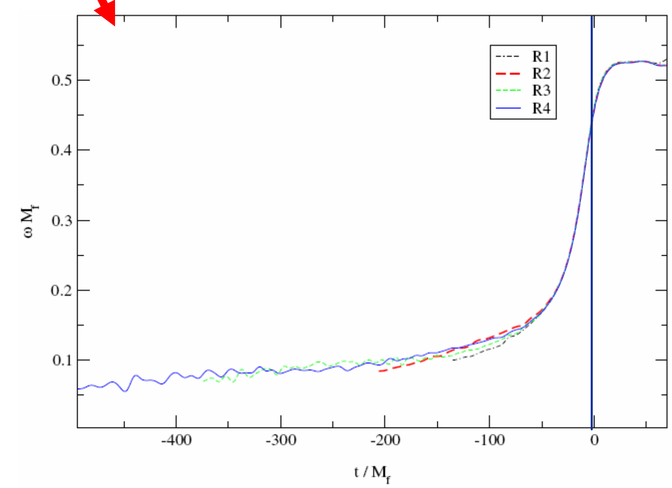


TABLE I. MODEL SUMMARY.

Model	Δt[a] (ms)	$\lvert h_{+,\max}\rvert$[b] (10^{-21})	$h_{\rm char,max}$[b,c] (10^{-21})	$f(h_{\rm char,max})$ (Hz)	$E_{\rm GW}$[d] $(10^{-7} M_\odot c^2)$
s11WW	1045	1.3	22.8	654	0.16
s25WW	1110	50.0	2514.3	937	824.28
m15b6	927.2	1.2	19.3	660	0.14

$$f_{\rm peak} \approx \frac{0.46}{2\pi M_f} \approx \frac{15\ \rm kHz}{(M_f/M_\odot)}$$

Baker et al, PRD 73, 104002 (2006)

11 $M_\odot$ progenitor (s11WW model)
$\Rightarrow$ reach ≈ 0.4 kpc
25 $M_\odot$ progenitor (s25WW model)
$\Rightarrow$ reach ≈ 16 kpc

Assuming ~3.5% mass radiates in the merger:
10+10 $M_\odot$ binary $\Rightarrow$ reach ≈ 3 Mpc
50+50 $M_\odot$ binary $\Rightarrow$ reach ≈ 100 Mpc

Search for Known Pulsars

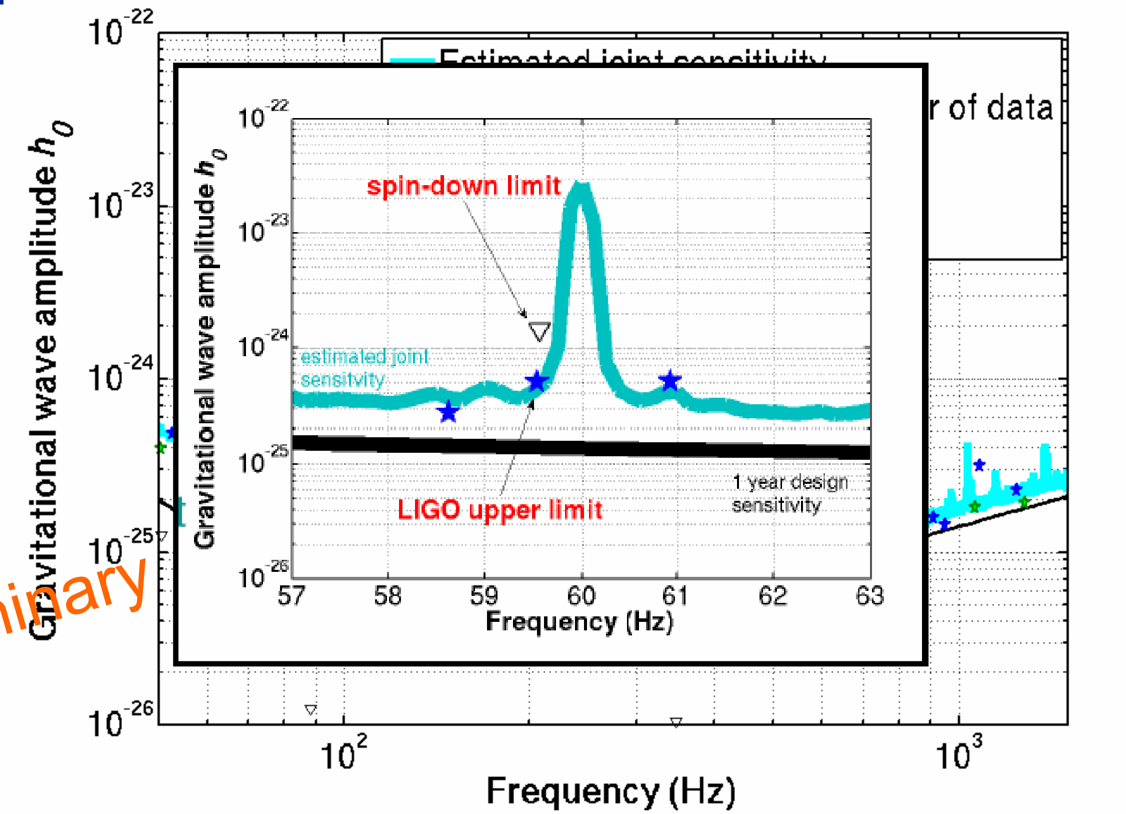
- Joint 95% upper limits for 97 pulsars using ~10 months of the LIGO S5 run. Results are overlaid on the estimated median sensitivity of this search.

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

Pulsar timings provided by the Jodrell Bank pulsar group

Lowest GW strain upper limit:
PSR J1623-2631
(f_{gw} = 180.6 Hz, r = 2.2 kpc)
$\mathbf{h_0 < 3.4 \times 10^{-26}}$

Lowest ellipticity upper limit:
PSR J2124-3358
(f_{gw} = 405.6 Hz, r = 0.25 kpc)
$\boldsymbol{\varepsilon < 7.3 \times 10^{-8}}$

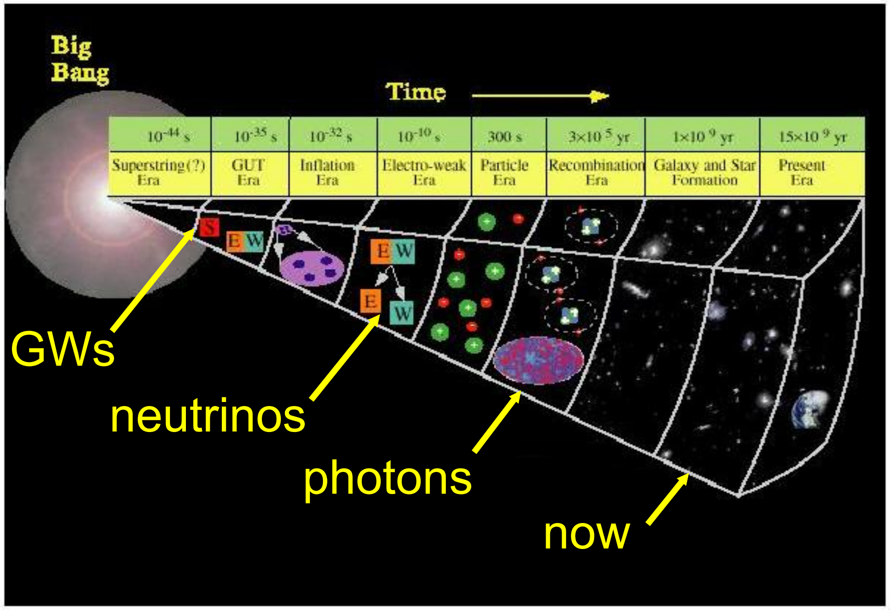


LIGO Limits on Isotropic Stochastic GW Signal

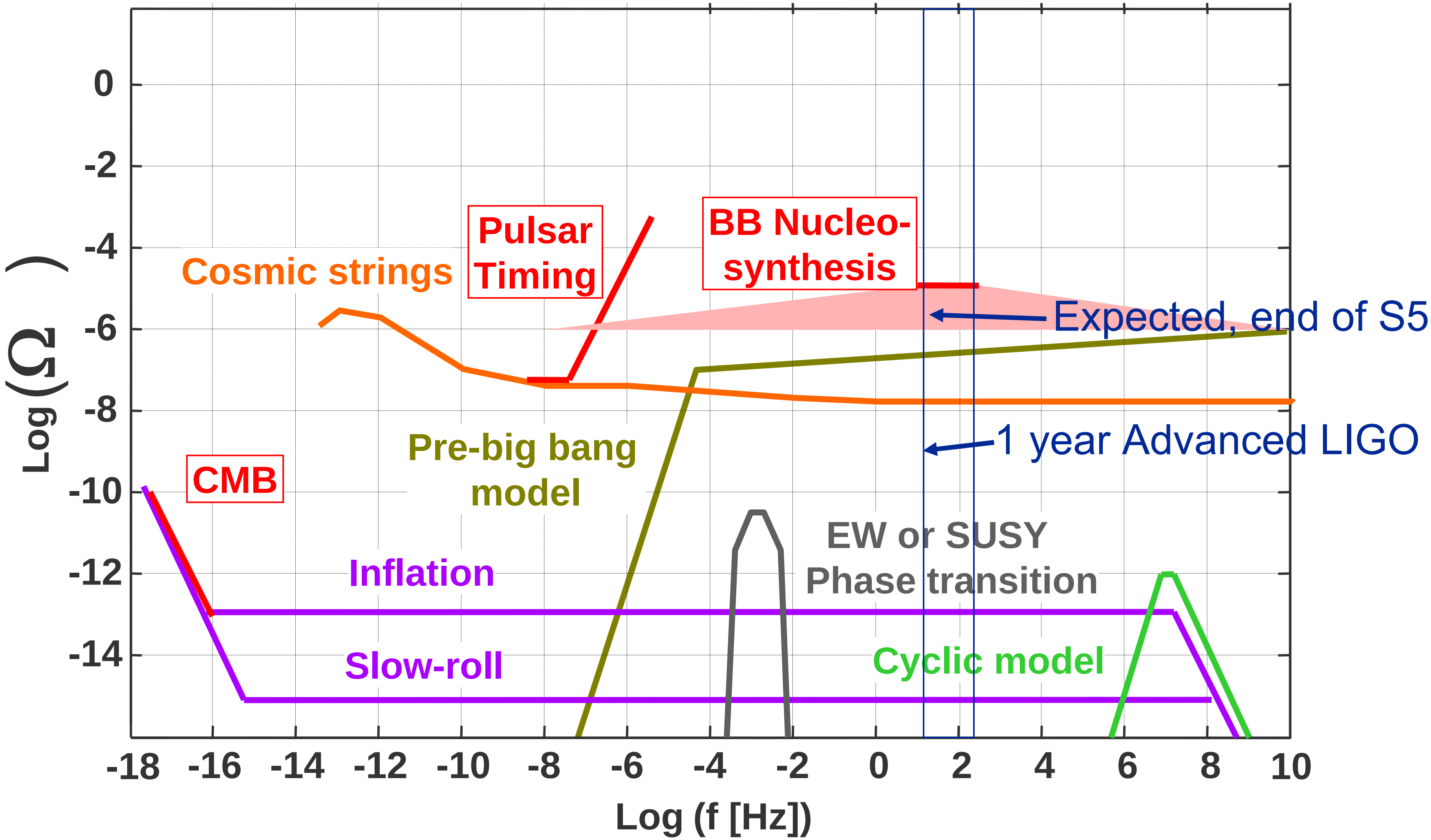
- Cross-correlate signals between 2 interferometers
- LIGO S1: $\Omega_{GW} < 44$
  - PRD 69 122004 (2004)

H_0 = 72 km/s/Mpc

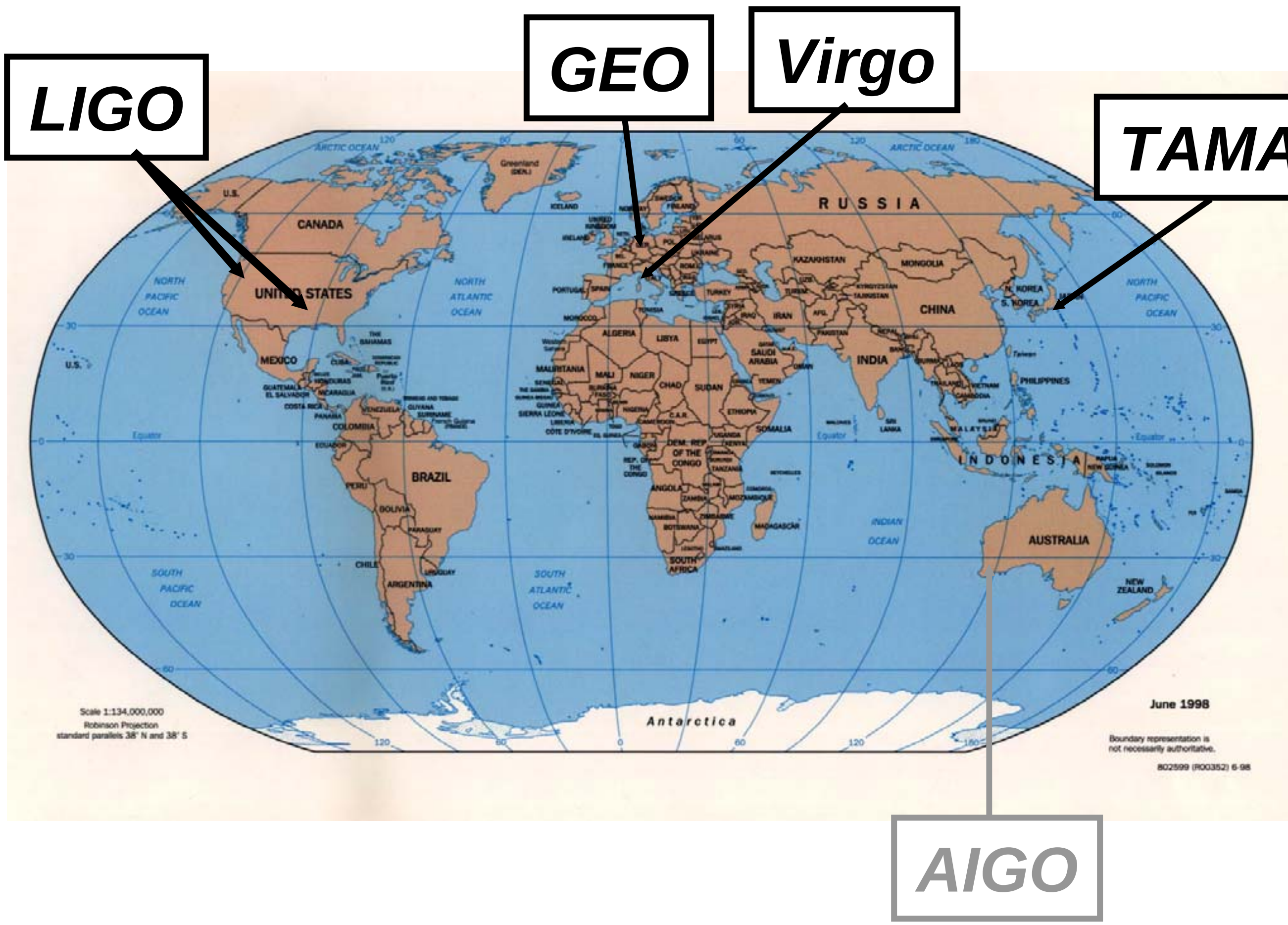
- LIGO S3: $\Omega_{GW} < 8.4 \times 10^{-4}$
  - PRL 95 221101 (2005)
- LIGO S4: $\Omega_{GW} < 6.5 \times 10^{-5}$ {new upper limit; *ApJ* **659,** 918 (2007)}
  - Bandwidth: 51-150 Hz;
- Initial LIGO, 1 yr data
  - Expected sensitivity ~ 4×10^{-6}
  - Upper limit from Big Bang nucleosynthesis 10^{-5}
- Advanced LIGO, 1 yr data
  - Expected Sensitivity ~1×10^{-9}



Stochastic Sources Predictions and Limits

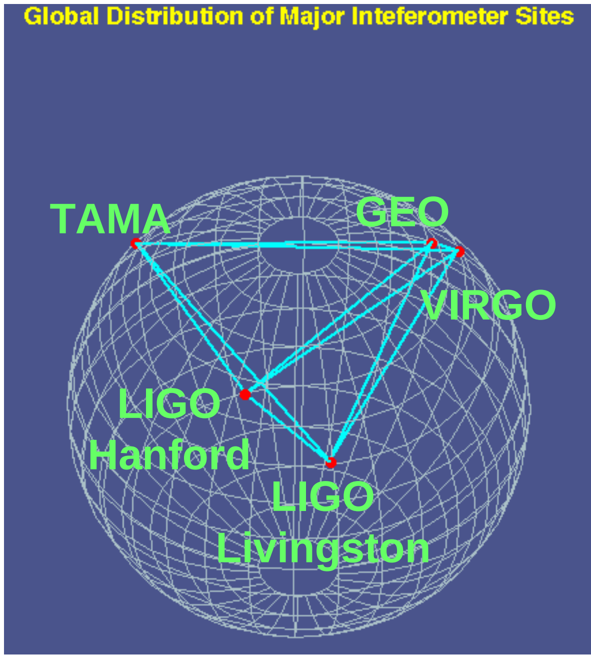


What is next for LIGO?
A Global Network of GW Detectors



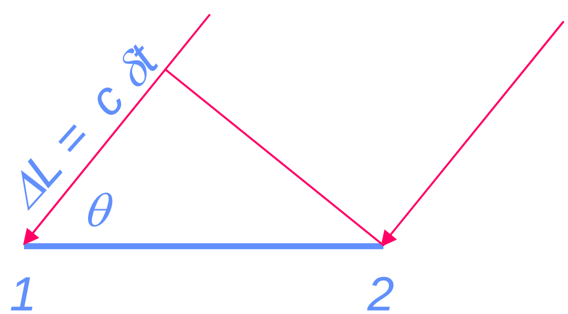
- **Detection confidence**
- **Locate sources**
- **Decompose the polarization of gravitational waves**

A Global Network of GW Detectors



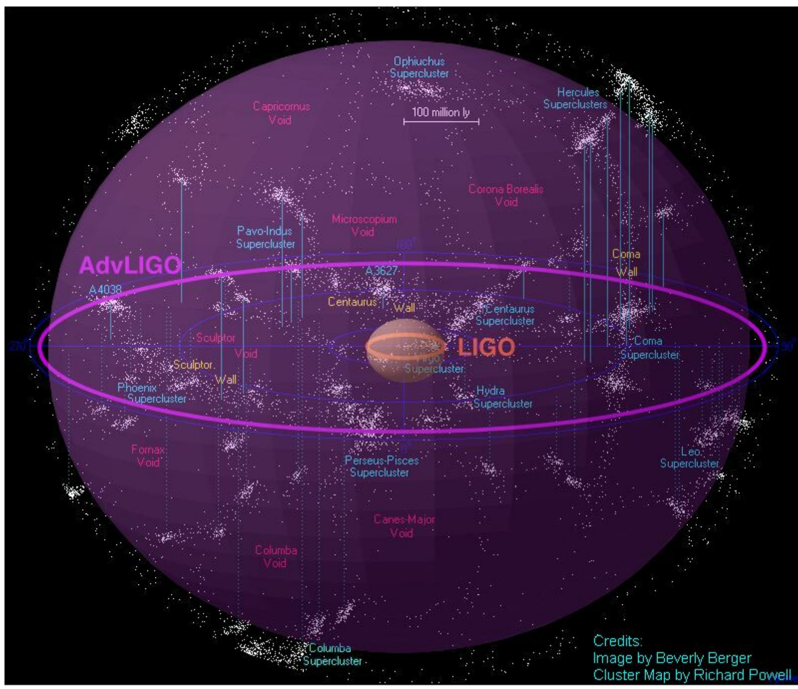
Virgo
Italy

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

⇒ x1000 rate=(reach)³

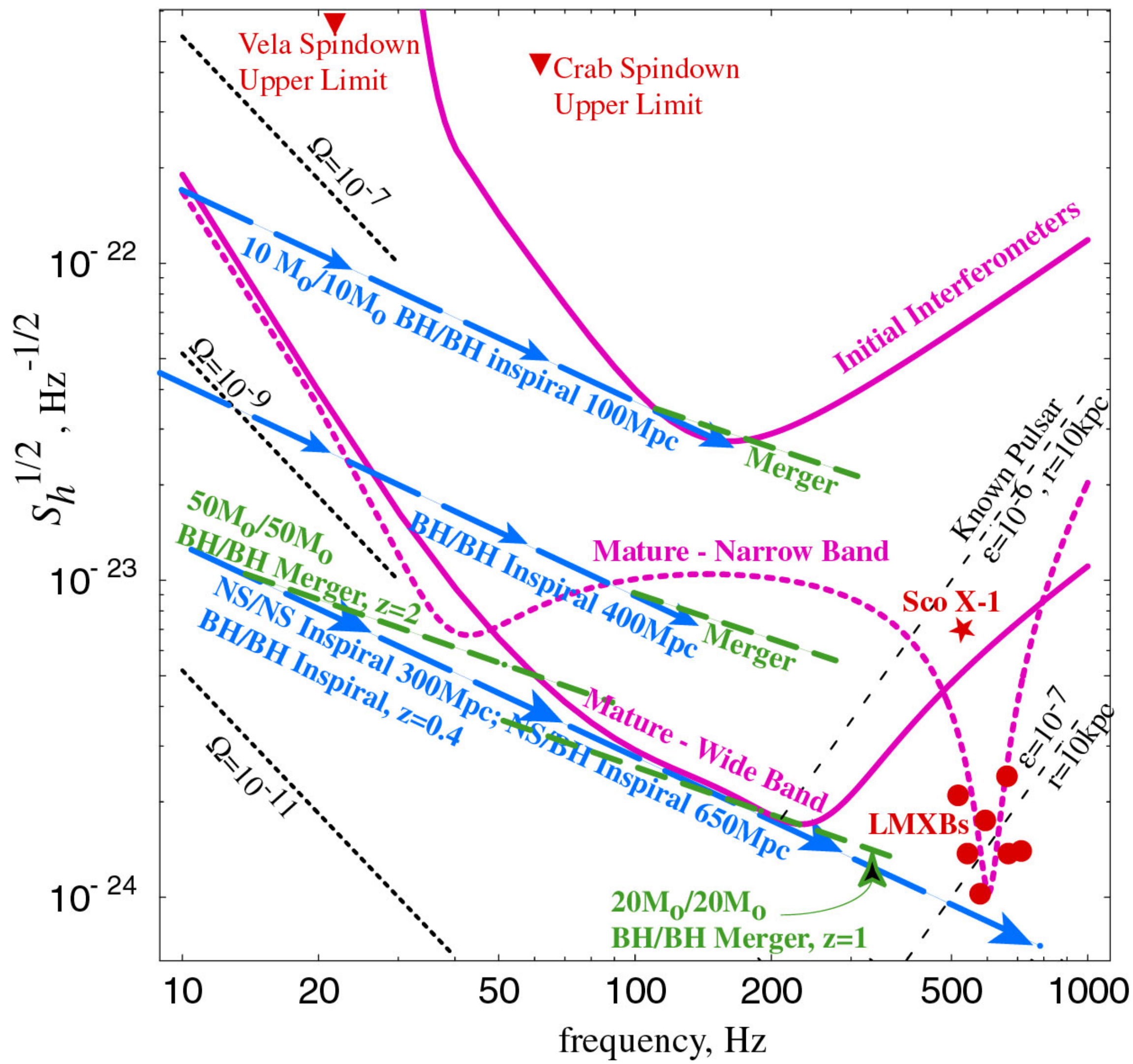
⇒ 1 day of Advanced LIGO

» 1 year of Initial LIGO !

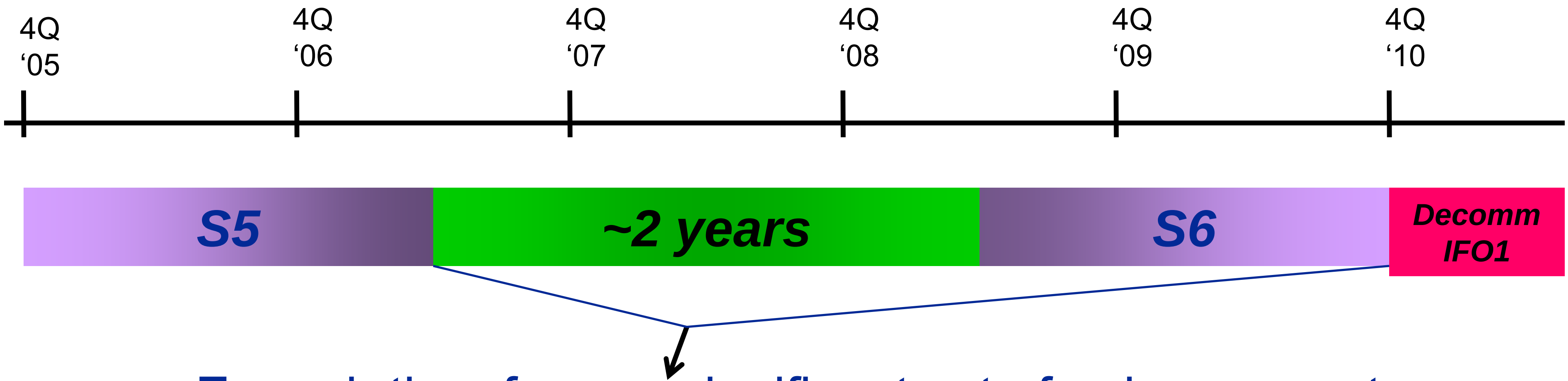
Planned for FY2008 start, installation beginning 2011

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



Enhanced LIGO



- Enough time for one significant set of enhancements
- Aim for a factor of 2 improvement in sensitivity (factor of 8 in event rate)
- Early tests of Advanced LIGO hardware and techniques
- Planning should consider contingency options for potential Advanced LIGO delays

Is There Anything 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?

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