LIGO, on the threshold of Gravitational Wave Astronomy

Stan Whitcomb (for the LIGO Scientific Collaboration)

Seminar at Notre Dame University

18 April 2007

The LIGO Scientific Collaboration

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Outline of Talk

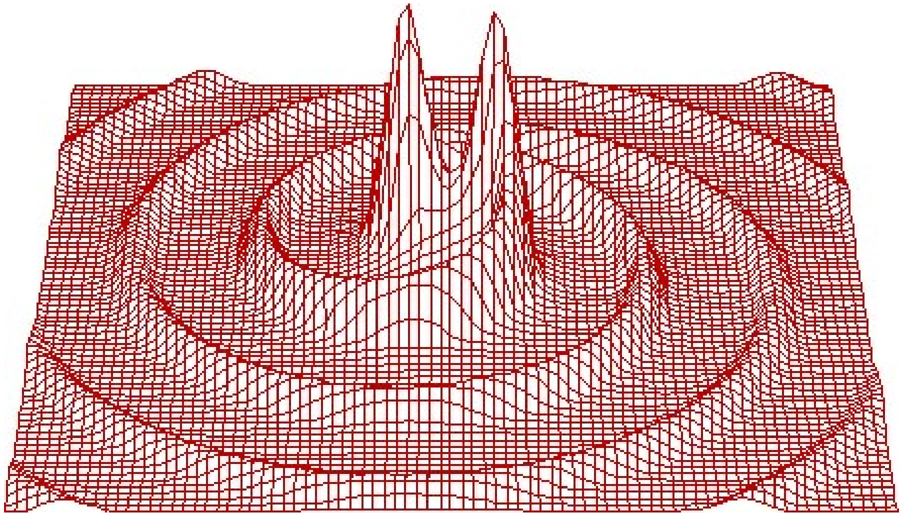
- Quick Review of GW Physics
- LIGO Detector Overview
  - » Performance Goals
  - » How do they work?
  - » What do the parts look like?
- Early Results
- Global Network
- Advanced LIGO Detectors

Gravitational Waves

- **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**

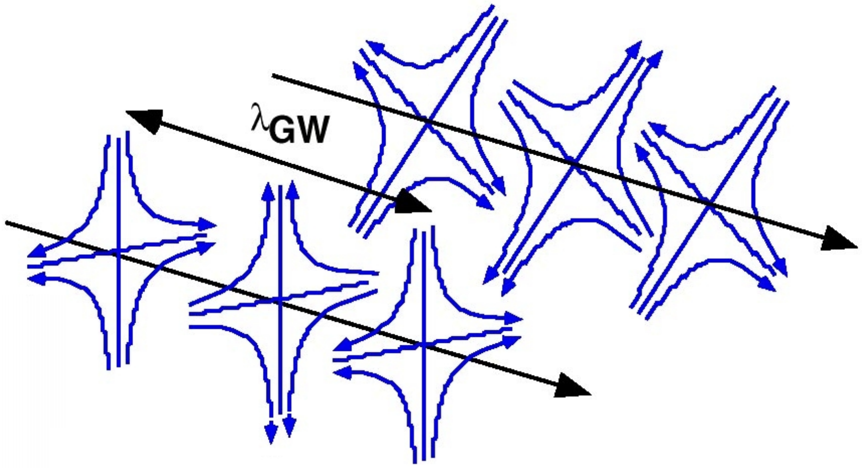
- **Time-dependent distortion of space-time created by the acceleration of masses that propagates away from the sources at the speed of light**



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

Gravitational Wave Physics

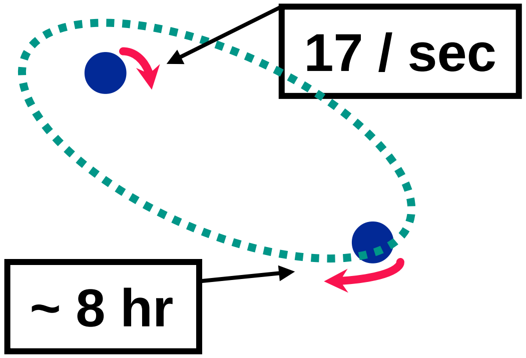
- Einstein (in 1916 and 1918) recognized gravitational waves in his theory of General Relativity
  - » Necessary consequence of Special Relativity with its finite speed for information transfer
  - » Most distinctive departure from Newtonian theory
- Time-dependent distortions of space-time created by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



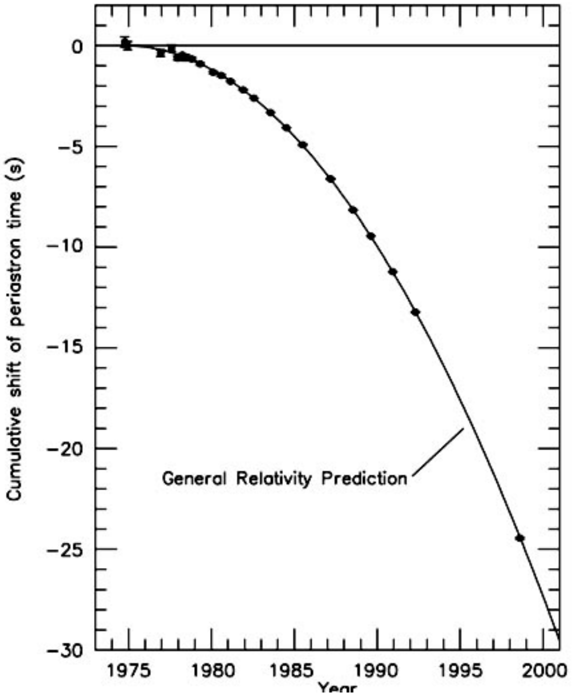
$$h = \Delta L / L$$

Evidence for Gravitational Waves:

Neutron Star Binary PSR1913+16



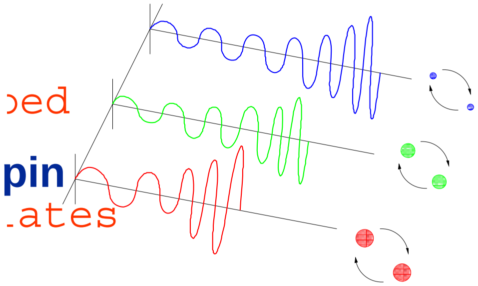
- **Discovered by Hulse and Taylor in 1975**
- **Unprecedented laboratory for studying gravity**
  - **» Extremely stable spin rate**
- **Possible to repeat classical tests of relativity (bending of “starlight”, advance of “perihelion”, etc.**



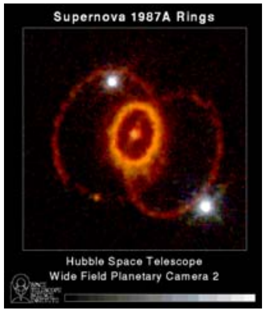
- **After correcting for all known relativistic effects, observe loss of orbital energy**
=> Emission of GWs

Astrophysical Sources of GWs

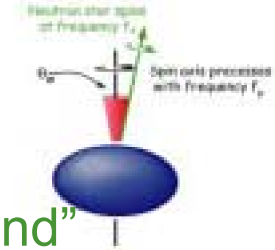
- Compact binary inspiral: “chirps”
  - NS-NS binaries well understood
  - BH-BH binaries need further calculation, spin
  - Search technique: matched templates



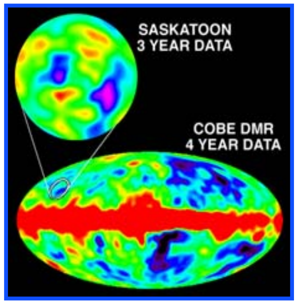
- Supernovas or GRBs: “bursts”
  - GW signals observed in coincidence with EM or neutrino detectors
  - Prompt alarm for supernova? (~1 hour?)



- 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?

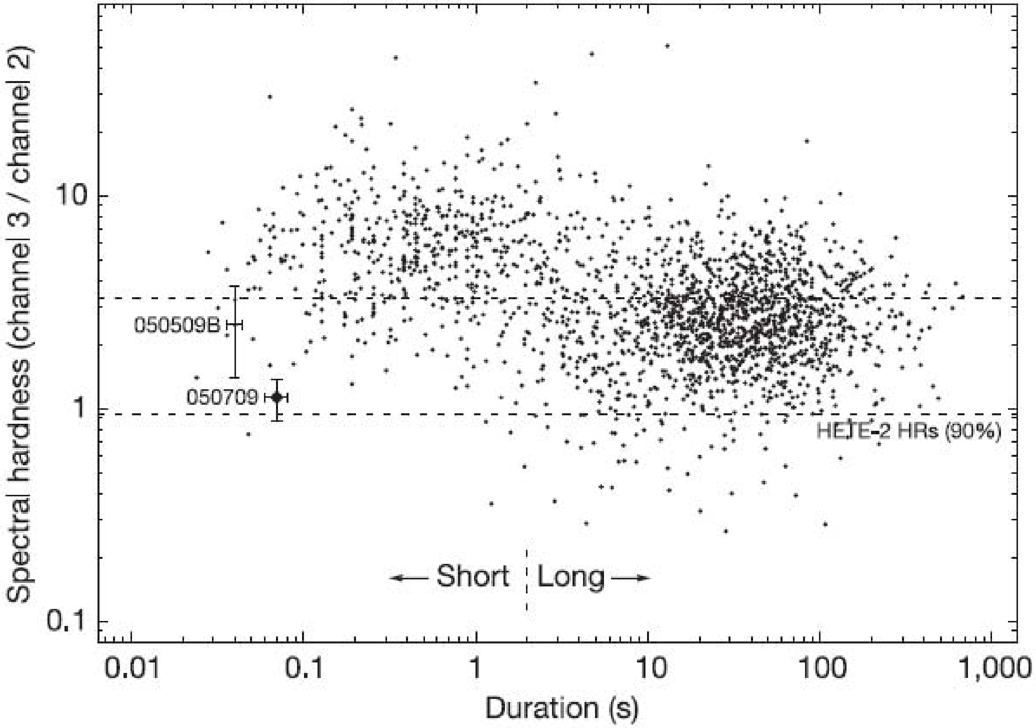


- Cosmological: “stochastic background”
  - Probing the universe back to the Planck time (10^{-43} s)

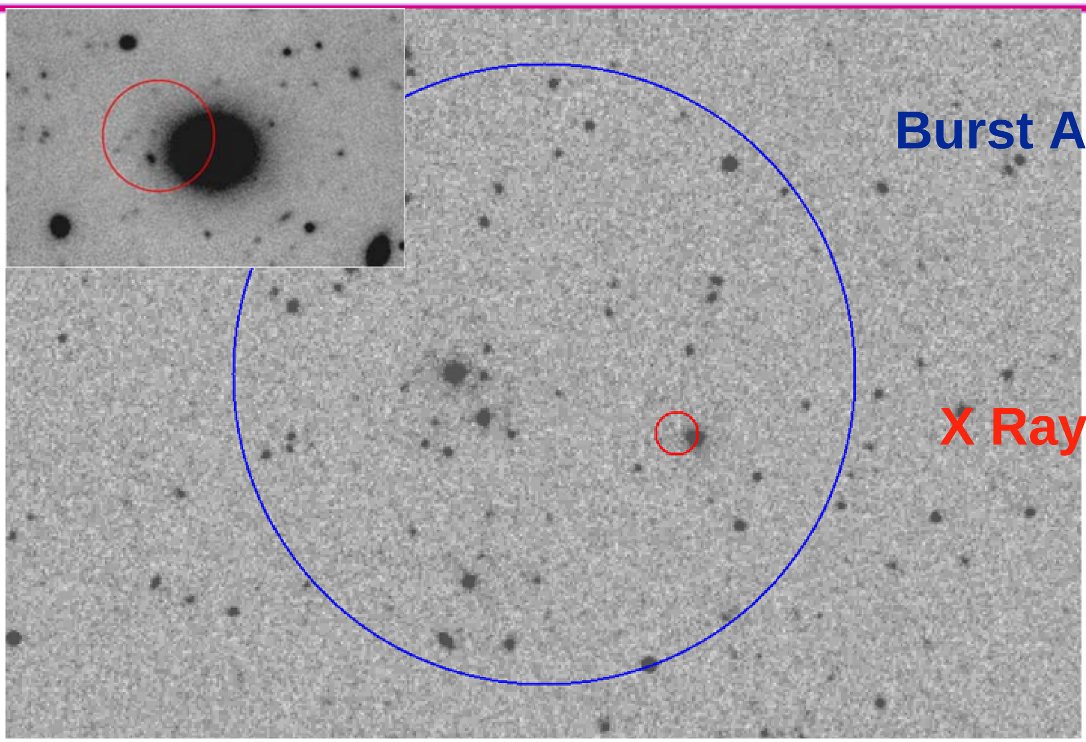


Short Gamma Ray Bursts (GRBs)

- 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)



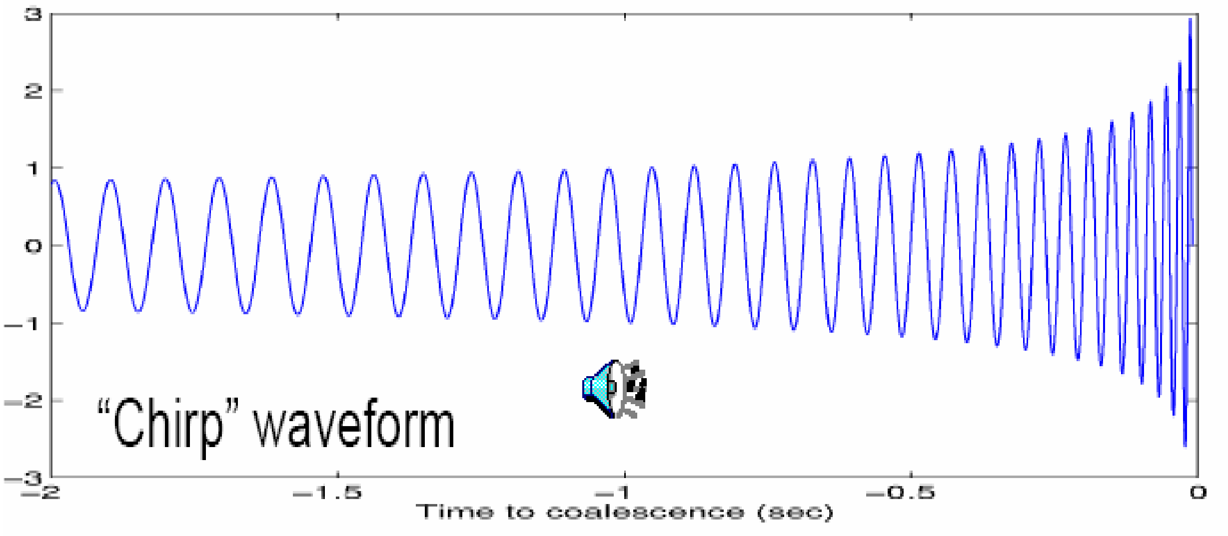
Gehrels et al., Nature, 437, 851, 2005

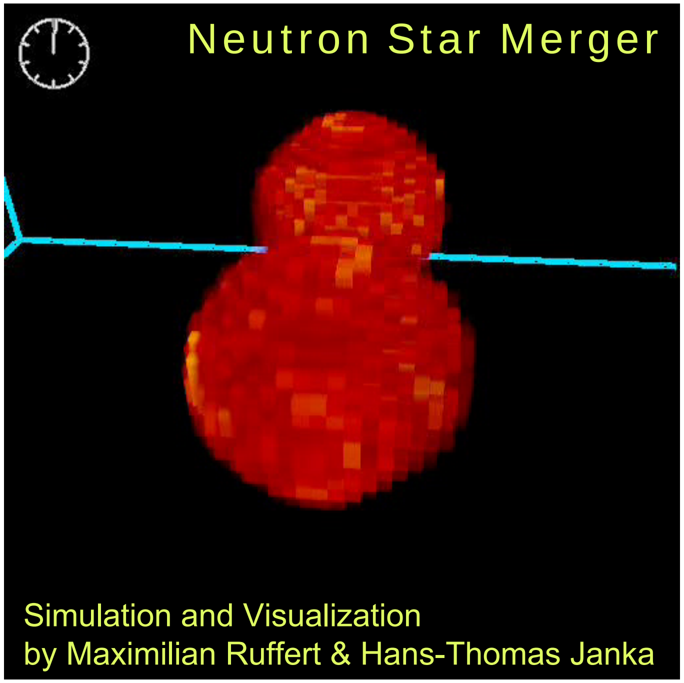
- Near edge of large elliptical galaxy (z = 0.225)
- Apparent distance from center of galaxy = 35 kpc
- Strong support for inspiral/merger hypothesis

Using Gravitational Waves to Learn about Short GRBs

Chirp Signal

binary inspiral





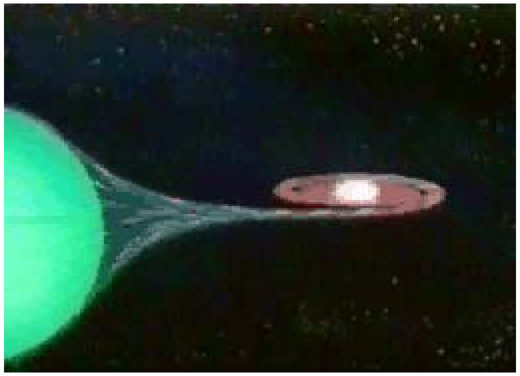
Simulation and Visualization
by Maximilian Ruffert & Hans-Thomas Janka

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?

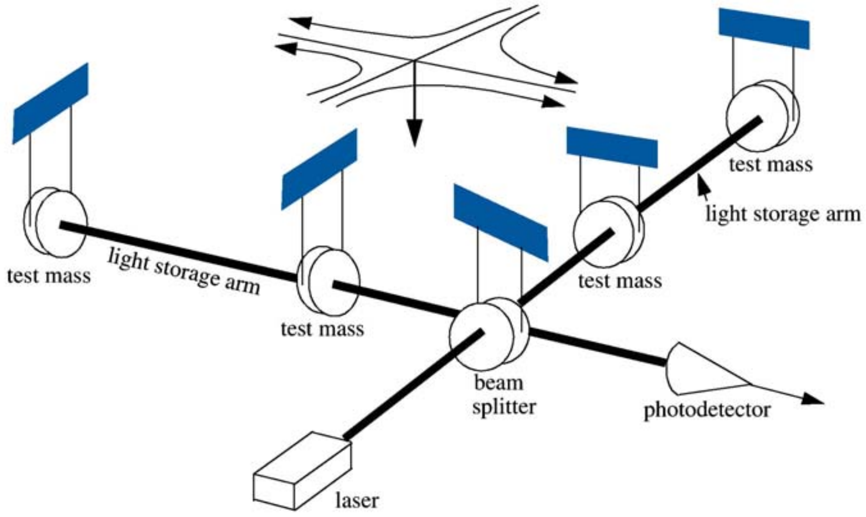


Imagine the Universe
NASA High Energy Astrophysics Science Archive

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

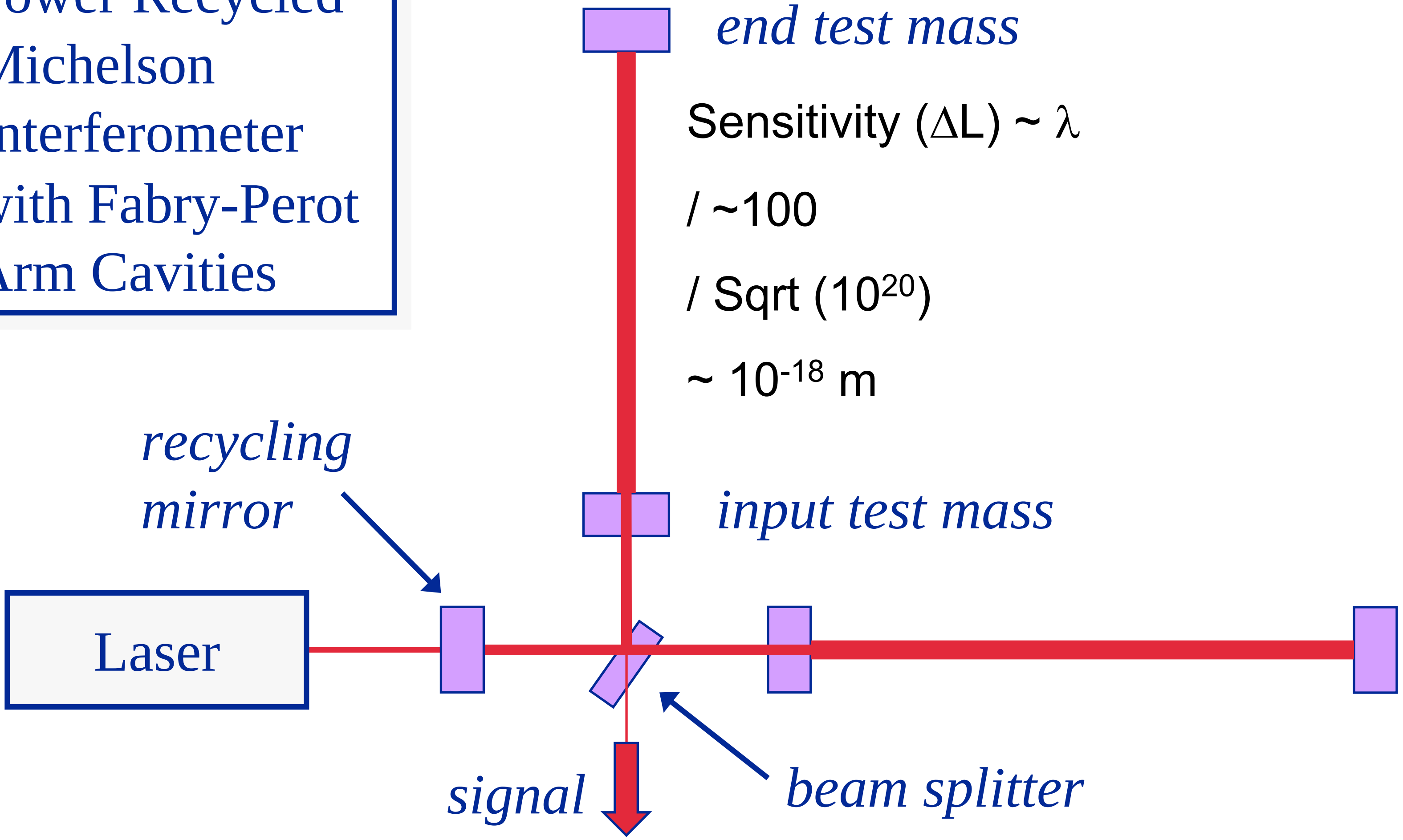
For $h \sim 10^{-22} - 10^{-21}$

L ~ 4 km (LIGO)

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

Optical Configuration

Power Recycled
Michelson
Interferometer
with Fabry-Perot
Arm Cavities



end test mass

input test mass

recycling mirror

Laser

beam splitter

signal

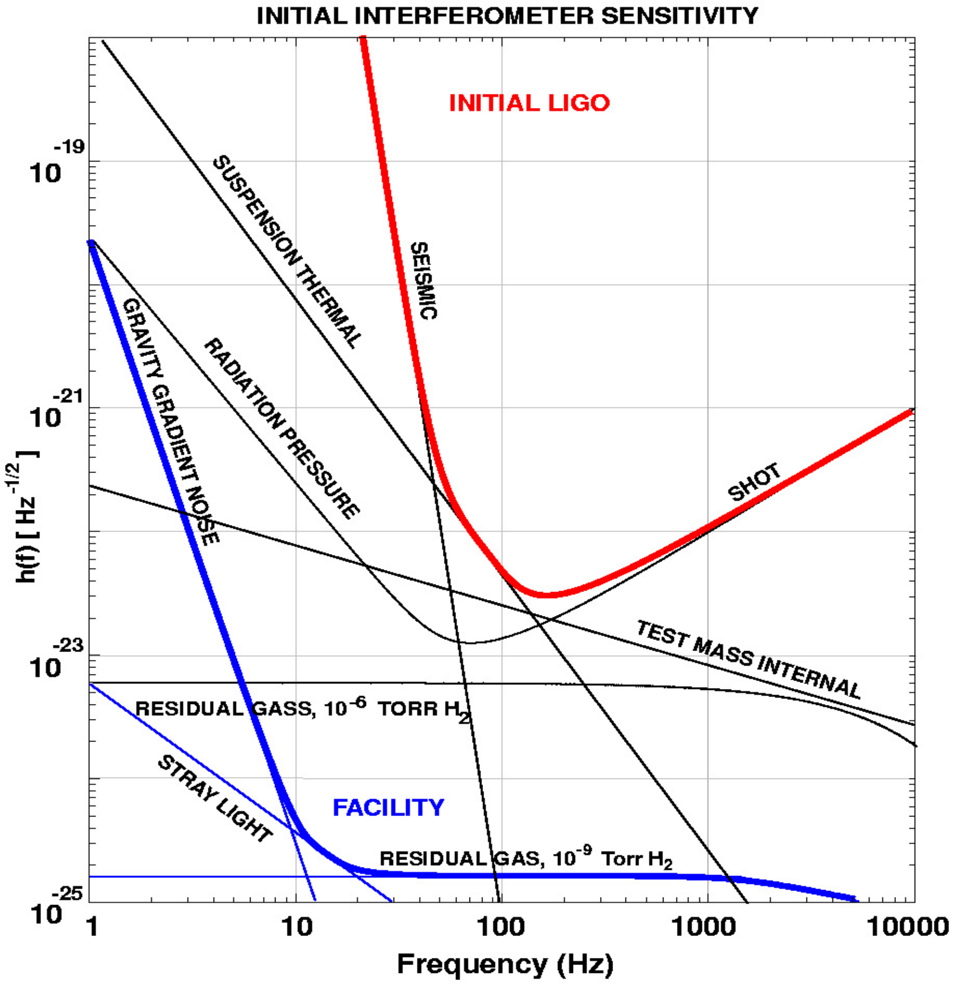
Sensitivity (ΔL) ~ λ

/ ~100

/ Sqrt (10^{20})

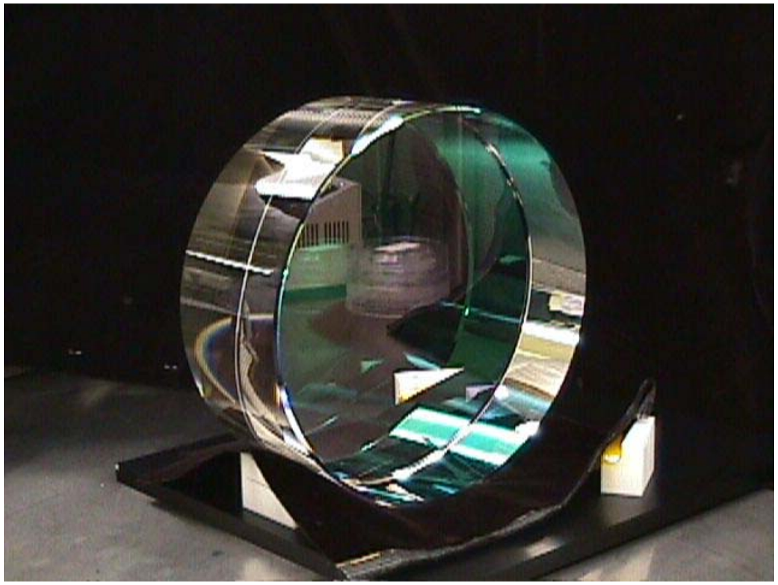
~ 10^{-18} m

Initial LIGO Sensitivity Goal



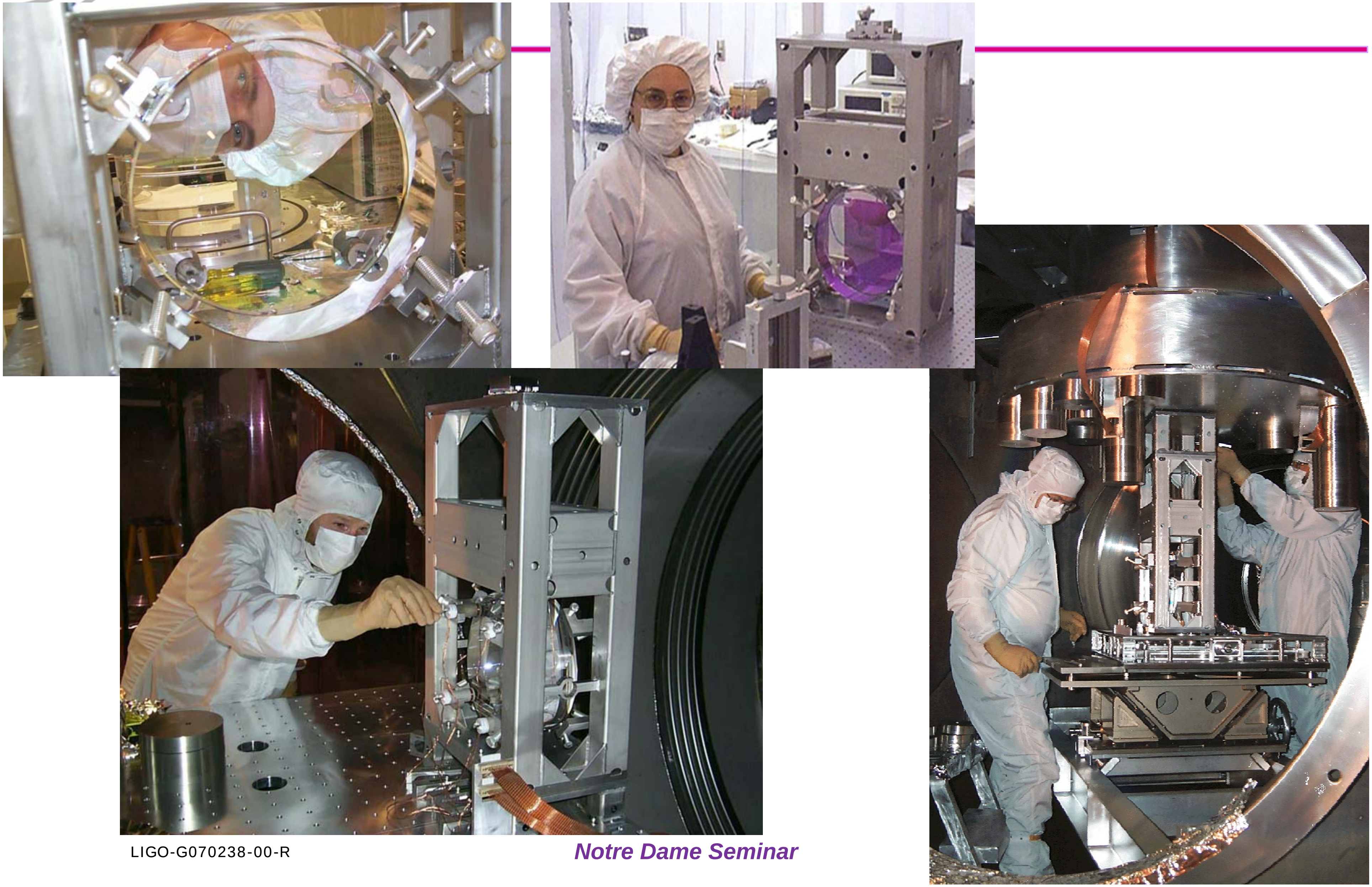
- Strain sensitivity $<3\times10^{-23}$ 1/Hz$^{1/2}$ at 200 Hz
- Sensing Noise
  - Photon Shot Noise
  - Residual Gas
- Displacement Noise
  - Seismic motion
  - Thermal Noise
  - Radiation Pressure

Test Mass/Mirrors

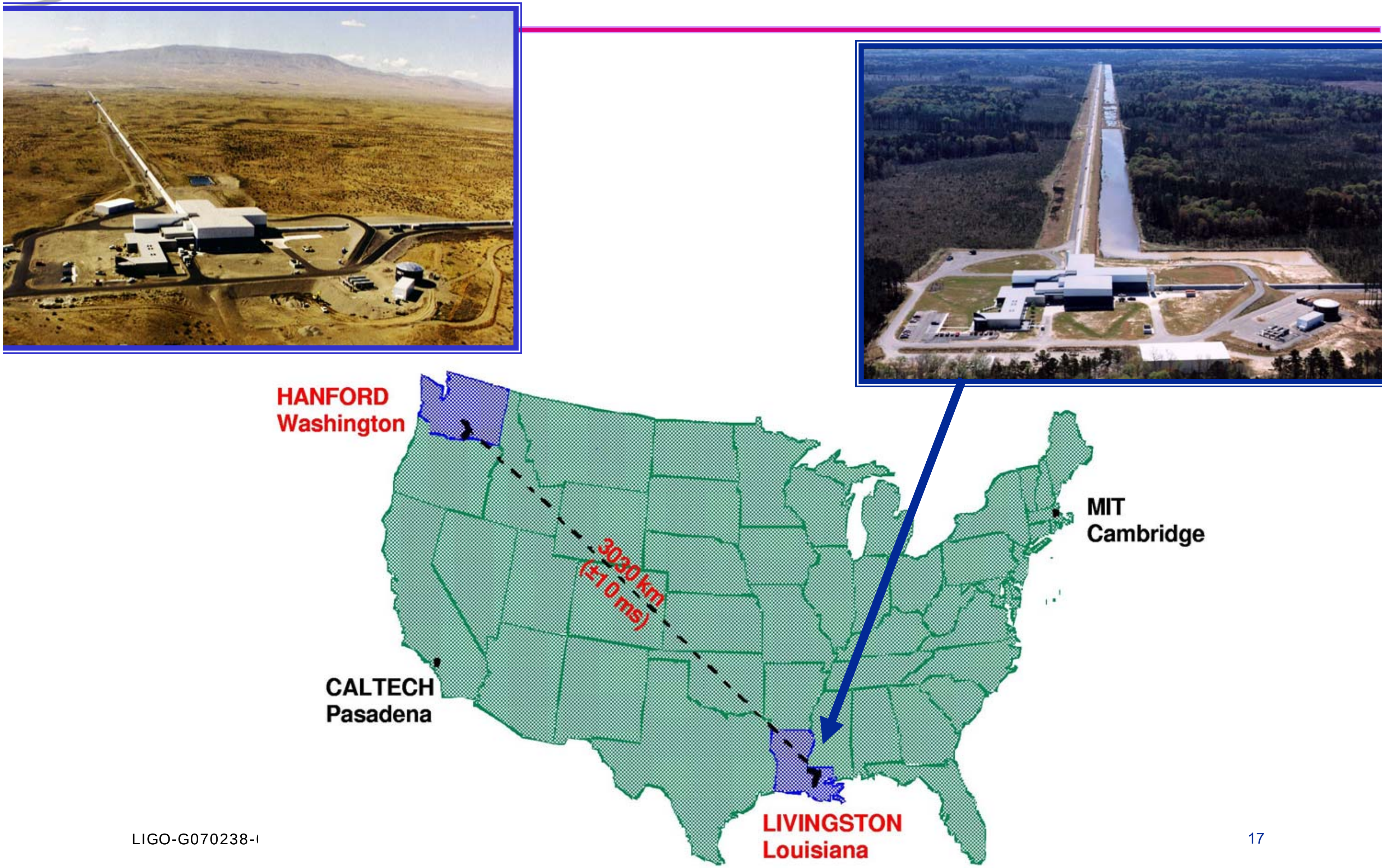


- Substrates: SiO_2
  - » 25 cm Diameter, 10 cm thick
  - » Homogeneity < 5 x 10^{-7}
  - » Internal mode Q's > 2 x 10^{6}
- Polishing
  - » Surface uniformity < 1 nm rms (λ / 1000)
  - » Radii of curvature matched < 3%
- Coating
  - » Scatter < 50 ppm
  - » Absorption < 2 ppm
  - » Uniformity <10^{-3}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

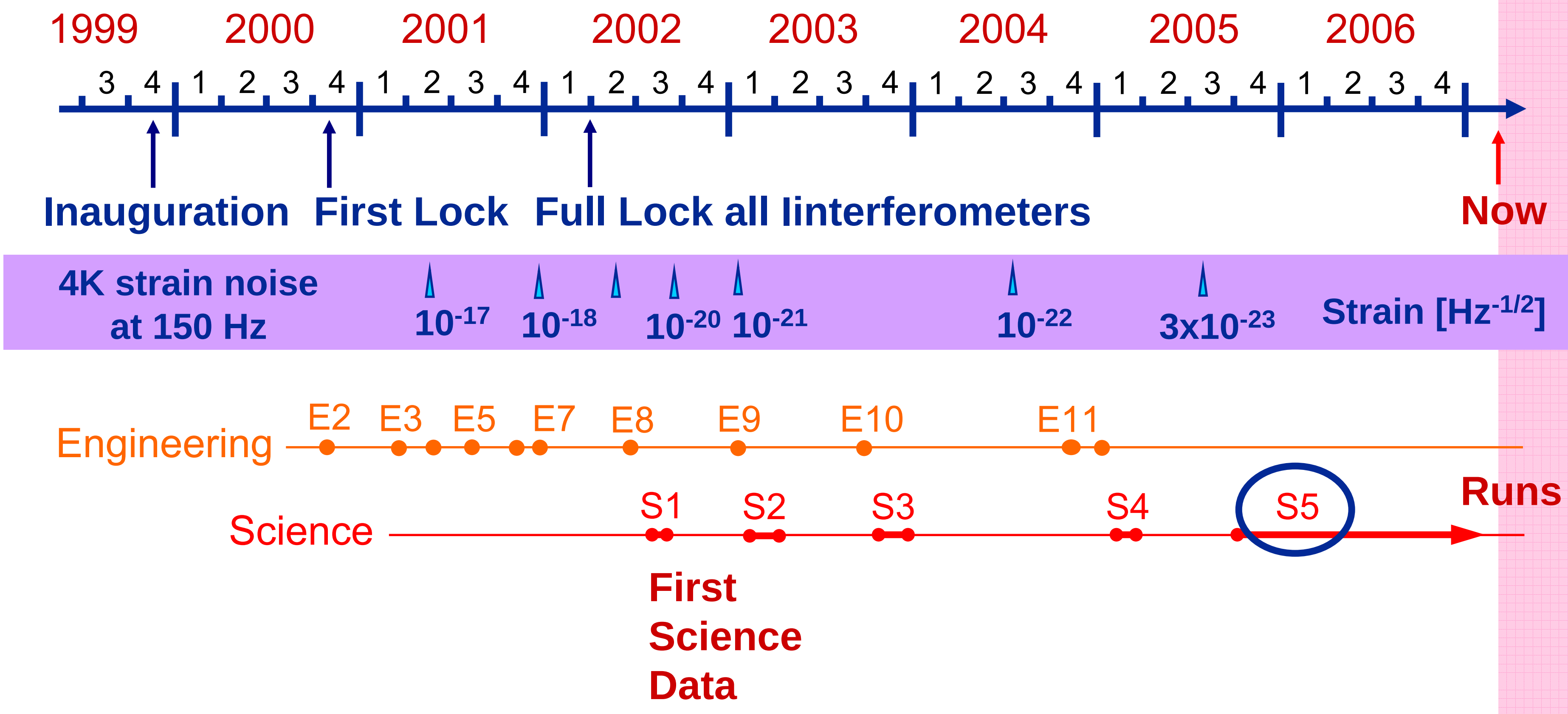
Test Mass Suspension and Control



LIGO Observatories



LIGO History



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} 3×10^{-23}

Strain [$Hz^{-1/2}$]

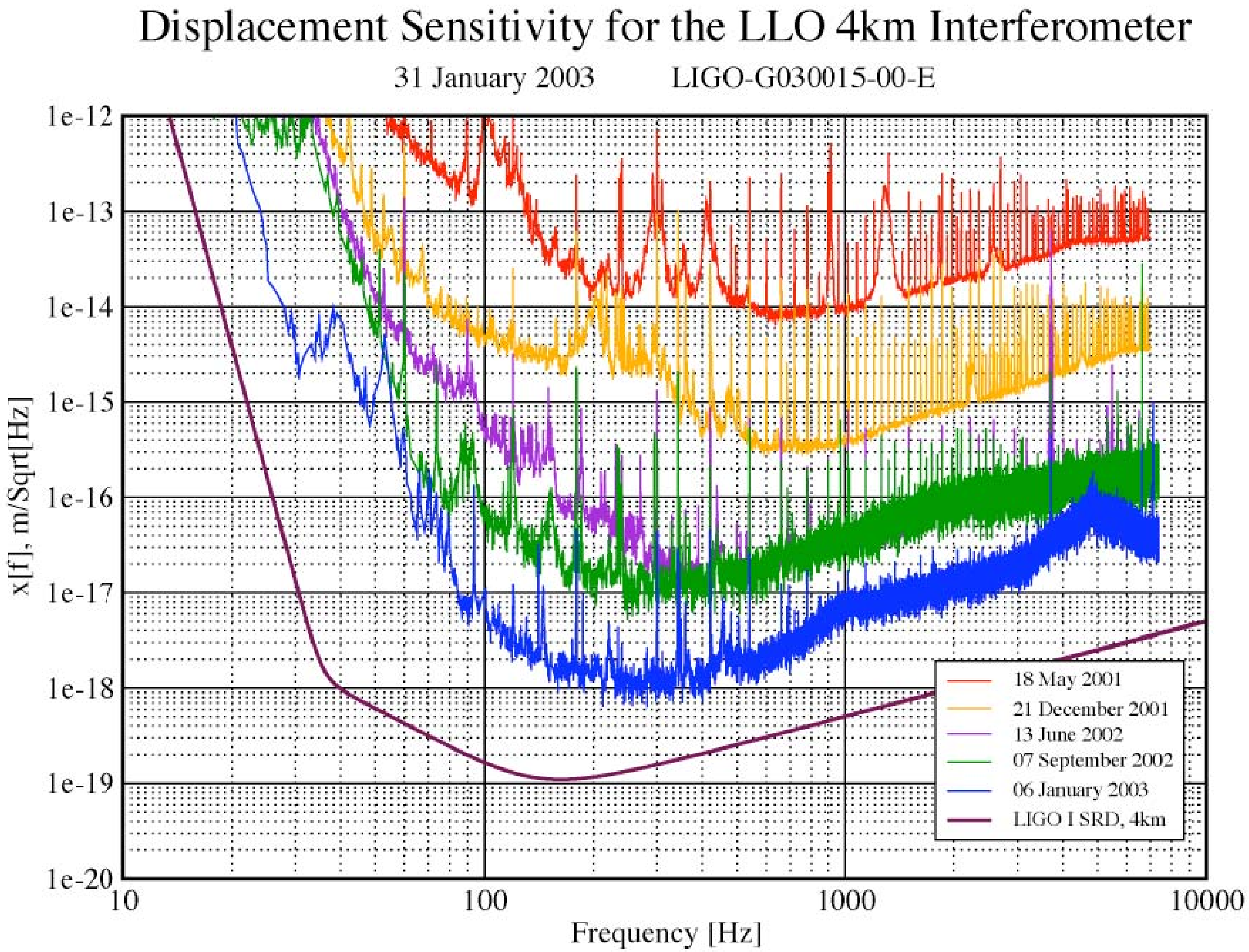
Engineering: E2 E3 E5 E7 E8 E9 E10 E11

Science: S1 S2 S3 S4 S5

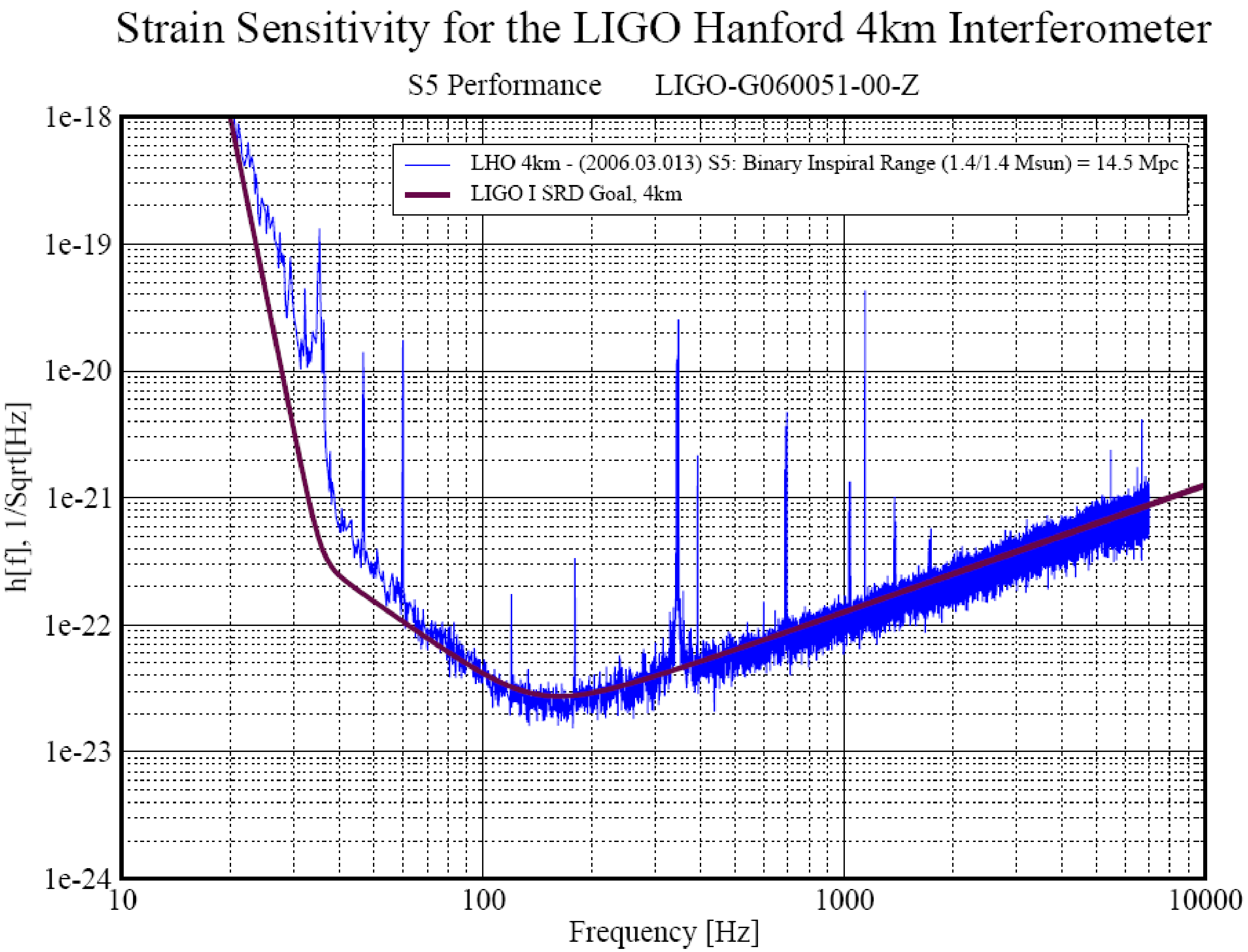
Runs

First Science Data

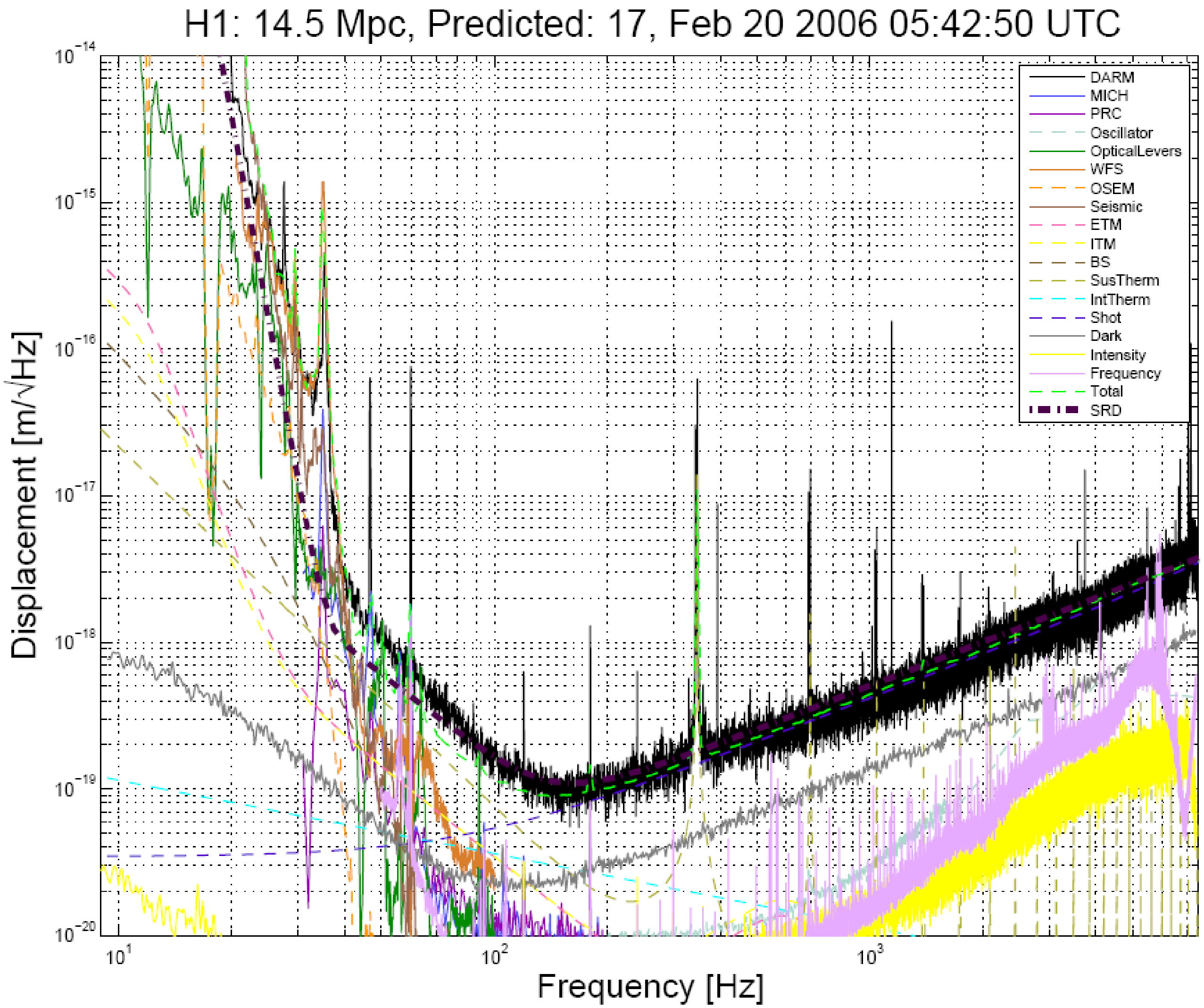
Progress toward Design Sensitivity



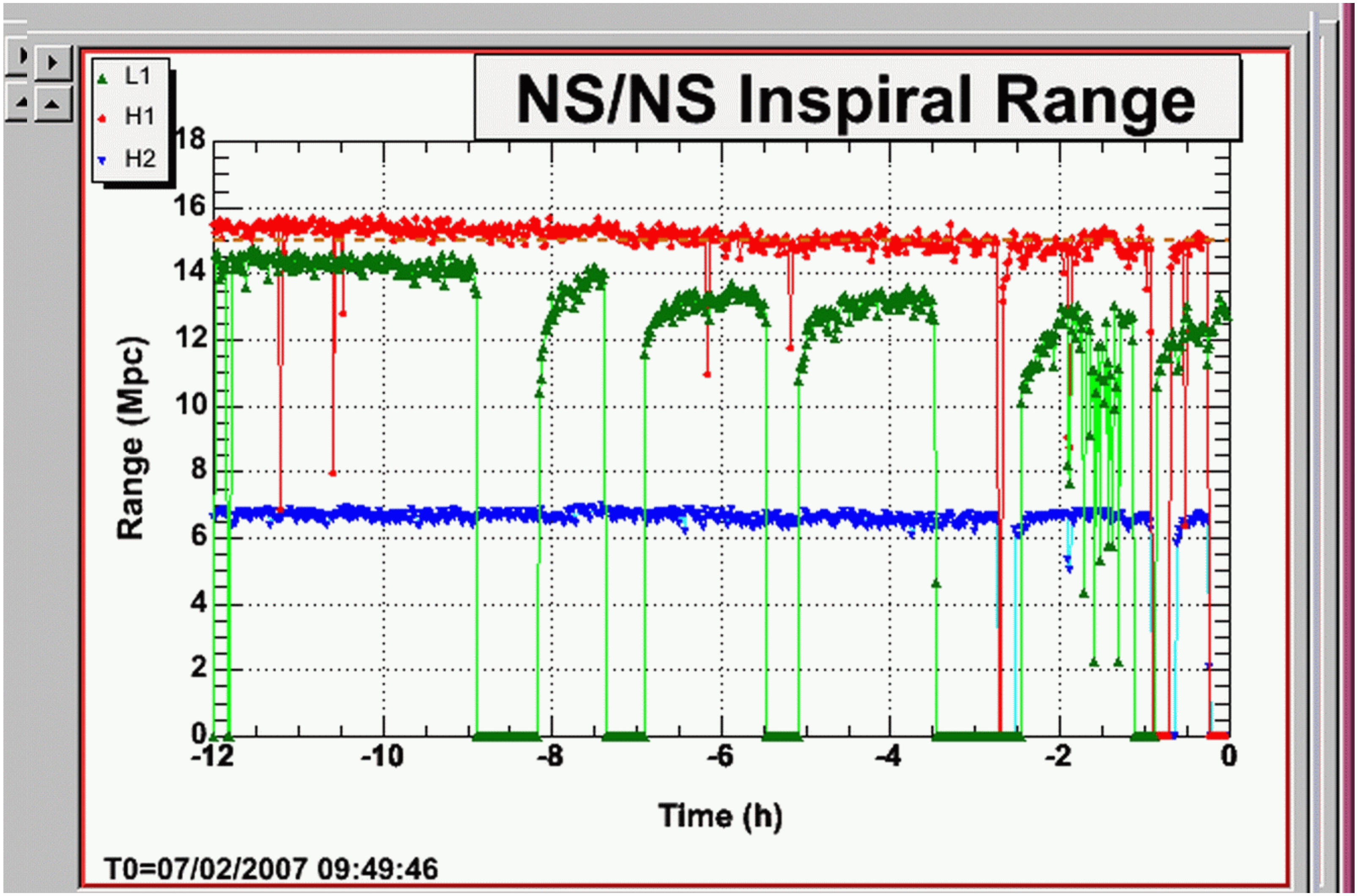
LIGO Sensitivity



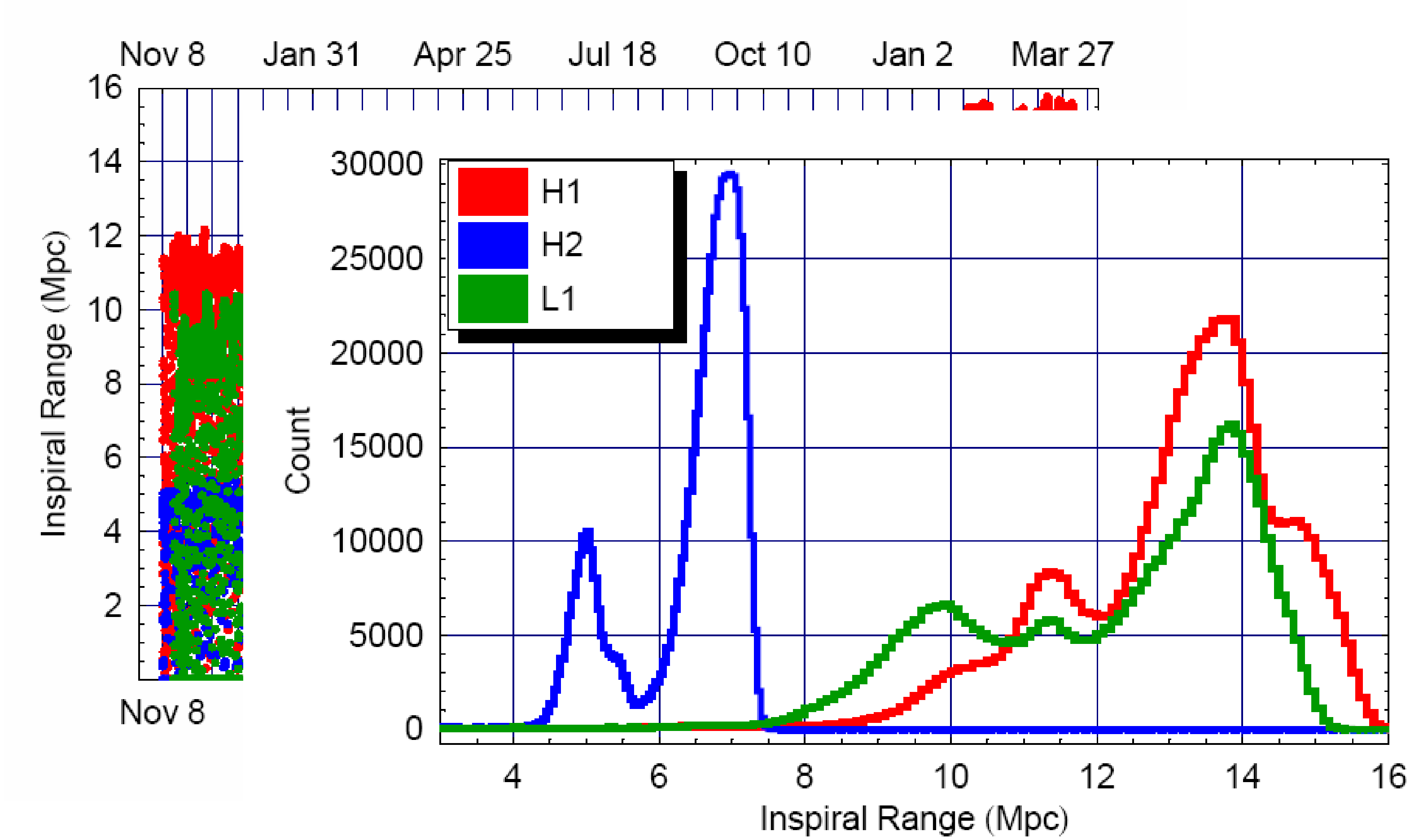
Anatomy of a Noise Curve



LIGO Duty Factor



Duty Factor for S5

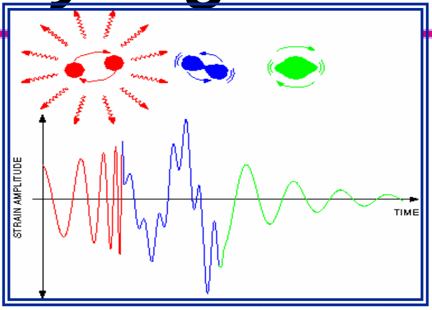


LIGO Data Analysis

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

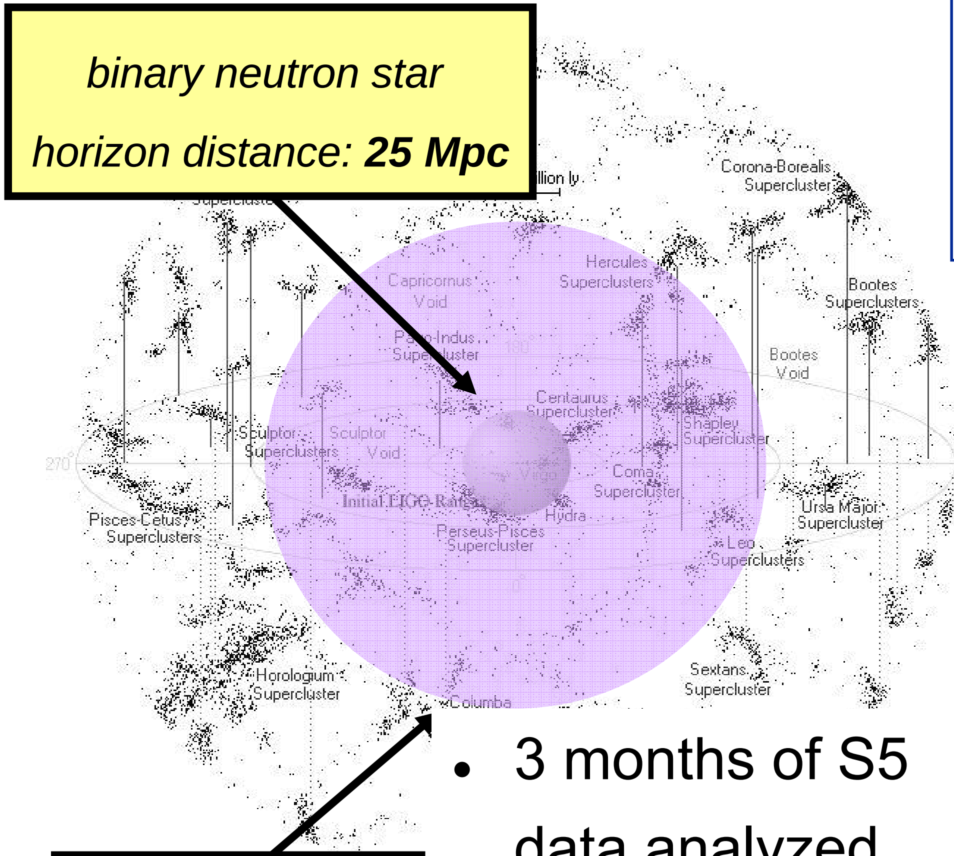
- Binary coalescences with modeled waveforms (“inspirals”)
- Transients sources with unmodeled waveforms (“bursts “)
- Continuous wave sources (“GW pulsars”)
- Stochastic gravitational wave background (cosmological & astrophysical foregrounds)

Searches for Coalescing Compact Binary Signals in S5



binary neutron star

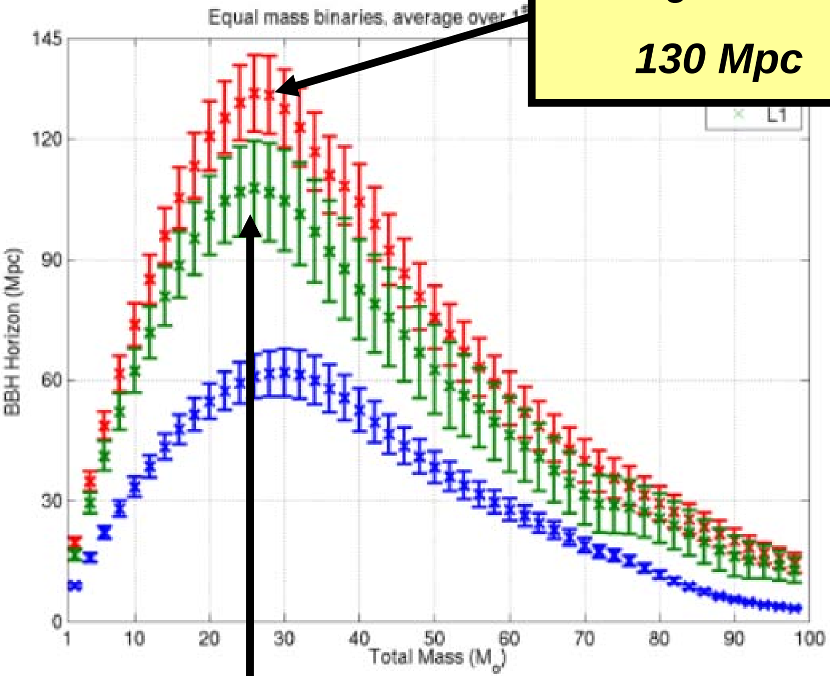
horizon distance: **25 Mpc**



binary black hole

horizon distance

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



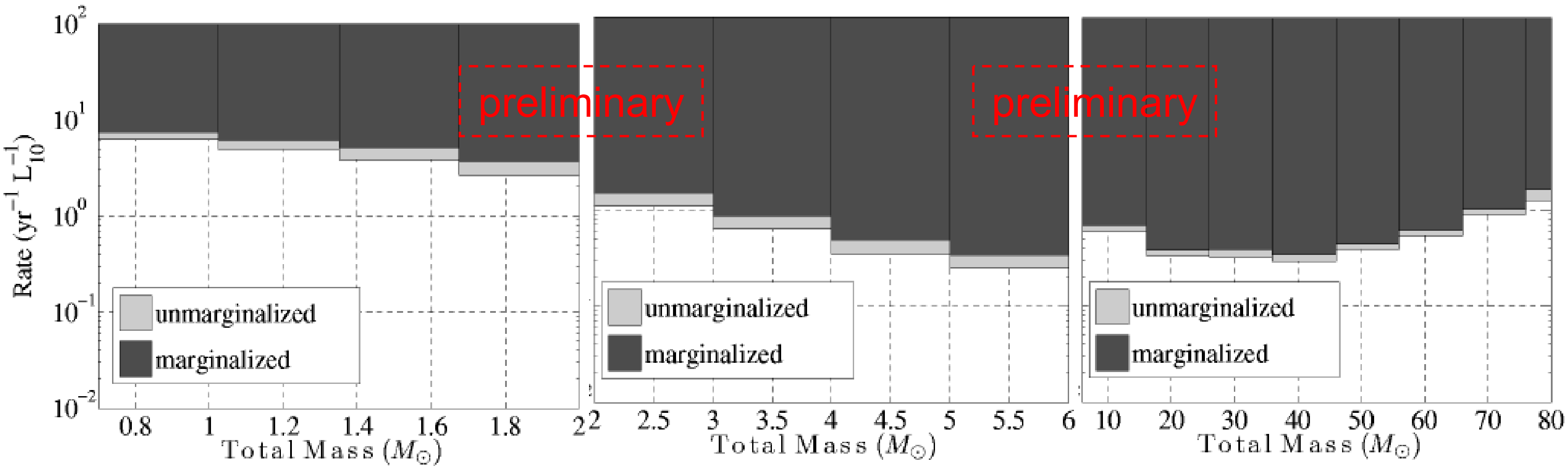
Average over run

130 Mpc

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

S4 Upper Limit: Compact Binary Coalescence

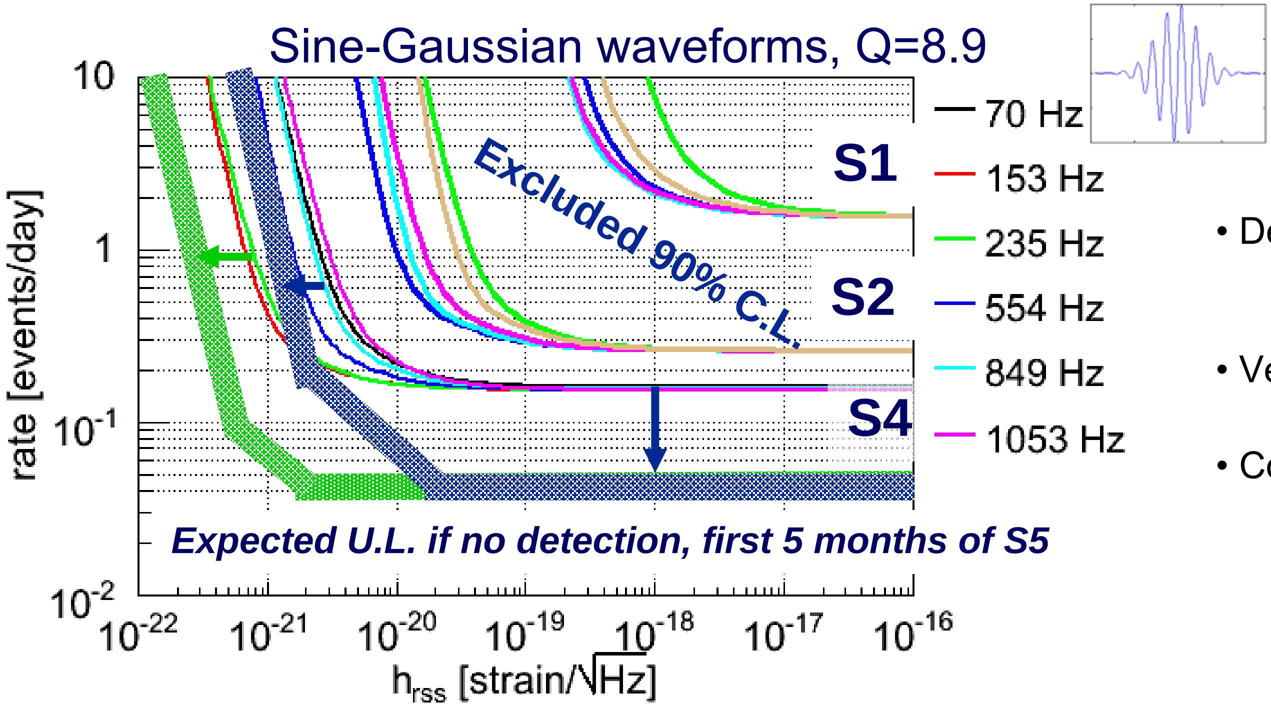
- Rate/L_{10} vs. binary total mass
  $L_{10} = 10^{10}\ L_{sun,B}$ (1 Milky Way = 1.7 L_{10})
- Dark region excluded at 90% confidence



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

Sine-Gaussian waveforms, Q=8.9



Excluded 90% C.L.

Expected U.L. if no detection, first 5 months of S5

- 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)

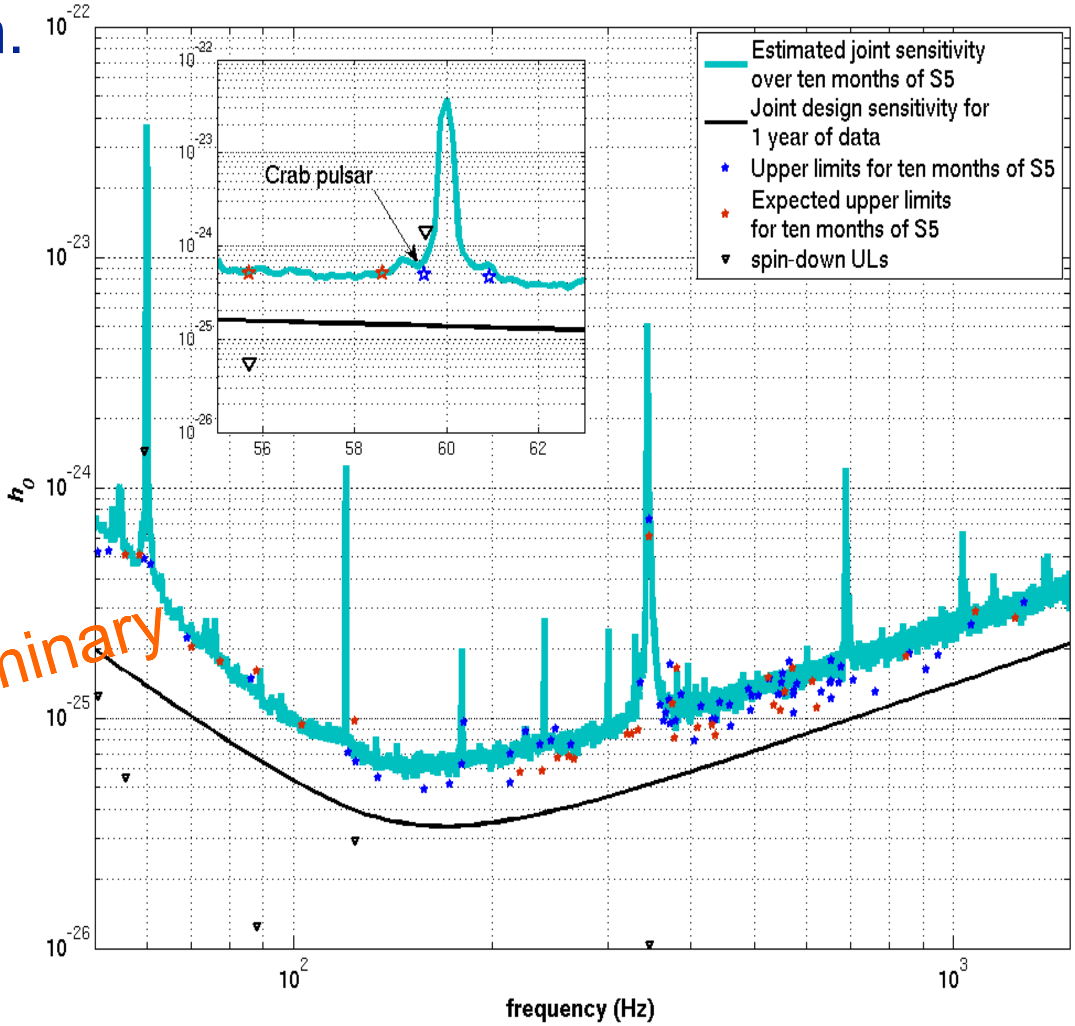
$$h_{\rm rss} \equiv \sqrt{\int \left(|h_{+}(t)|^2 + |h_{\times}(t)|^2\right) dt}$$

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 (red stars) due to uncertainties in the pulsar parameters

Pulsar timings provided by the
Jodrell Bank pulsar group



Preliminary

Lowest GW strain upper limit:
PSR J1802-2124
(f_{gw} = 158.1 Hz, r = 3.3 kpc)
$h_0 < 4.9\times10^{-26}$

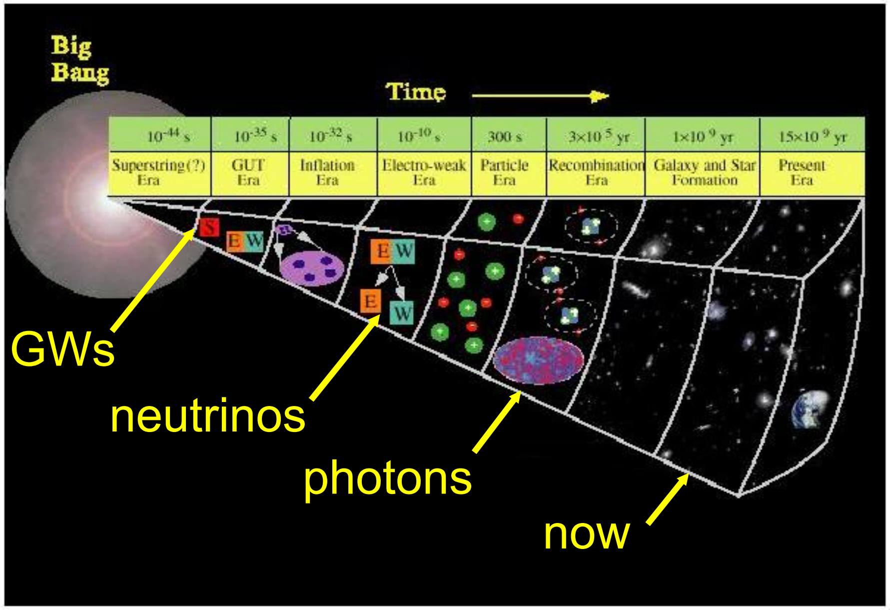
Lowest ellipticity upper limit:
PSR J2124-3358
(f_{gw} = 405.6 Hz, r = 0.25 kpc)
$\varepsilon < 1.1\times10^{-7}$

LIGO Limits on Isotropic Stochastic GW Signal

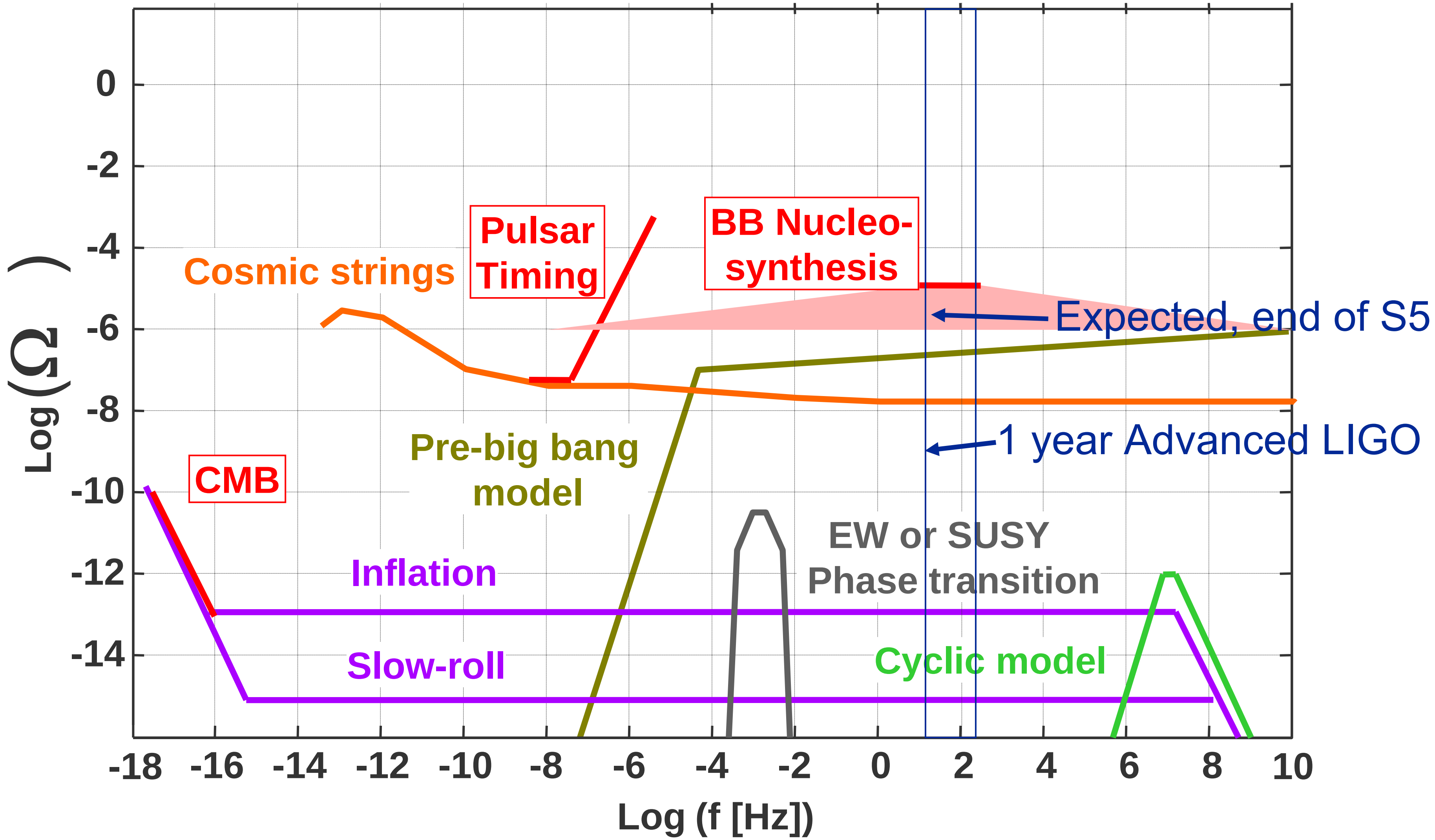
- Cross-correlate signals between 2 interferometers
- LIGO S1: $\Omega_{GW} < 44$
  PRD 69 122004 (2004)

$H_0 = 72$ km/s/Mpc

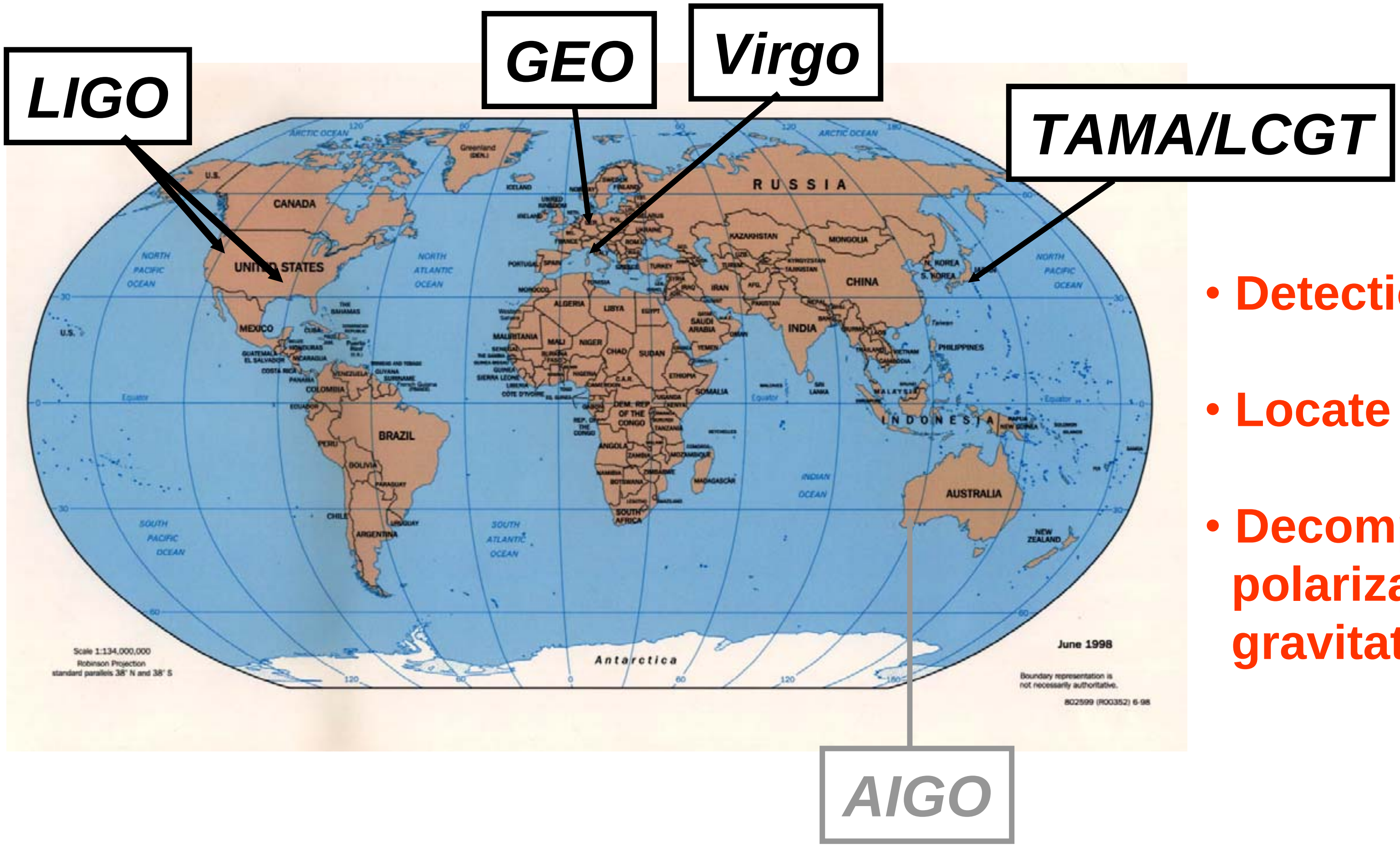
- LIGO S3: $\Omega_{GW} < 8.4\times10^{-4}$
  PRL 95 221101 (2005)
- LIGO S4: $\Omega_{GW} < 6.5\times10^{-5}$ {new upper limit; *ApJ* **659,** 918 (2007)}
  - Bandwidth: 51-150 Hz;
- Initial LIGO, 1 yr data
  Expected sensitivity ~ 4×10^{-6}
  Upper limit from Big Bang nucleosynthesis 10^{-5}
- Advanced 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

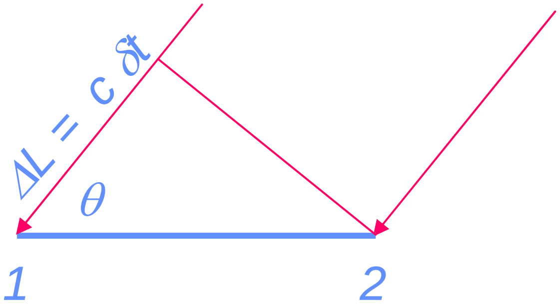


- Detection confidence
- Locate sources
- Decompose the polarization of gravitational waves

A Global Network of GW Detectors

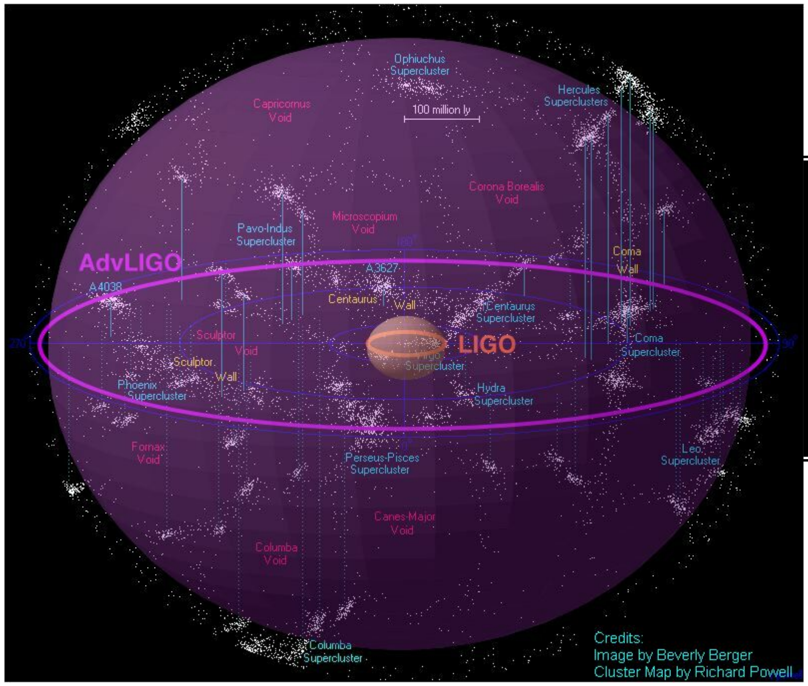
Virgo
Italy

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



Credits:
Image by Beverly Berger
Cluster Map by Richard Powell

x10 better amplitude sensitivity

⇒ x1000 rate=(reach)^3

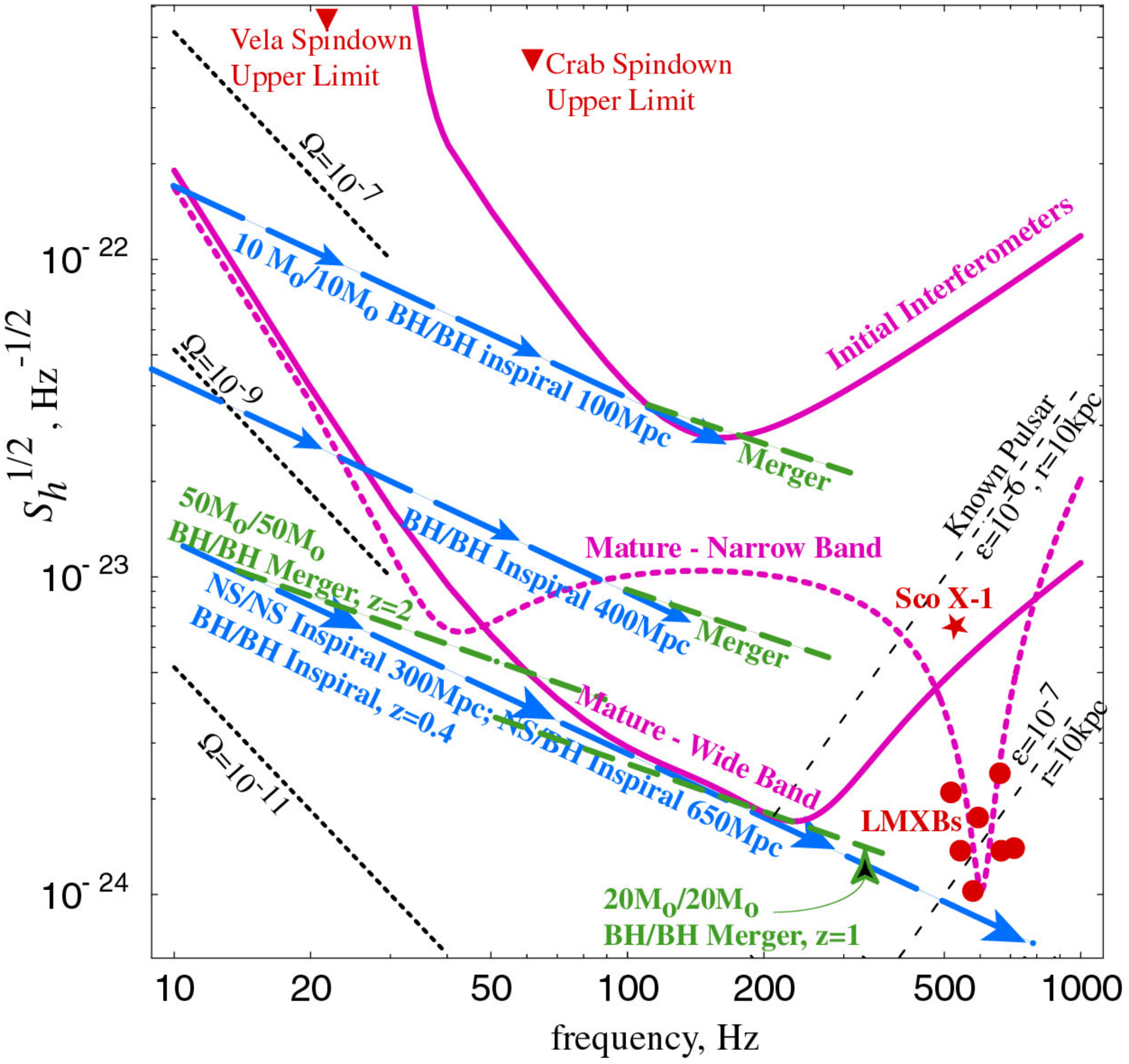
⇒ 1 day of Advanced LIGO

» 1 year of Initial LIGO !

Planned for FY2008 start, installation beginning 2011

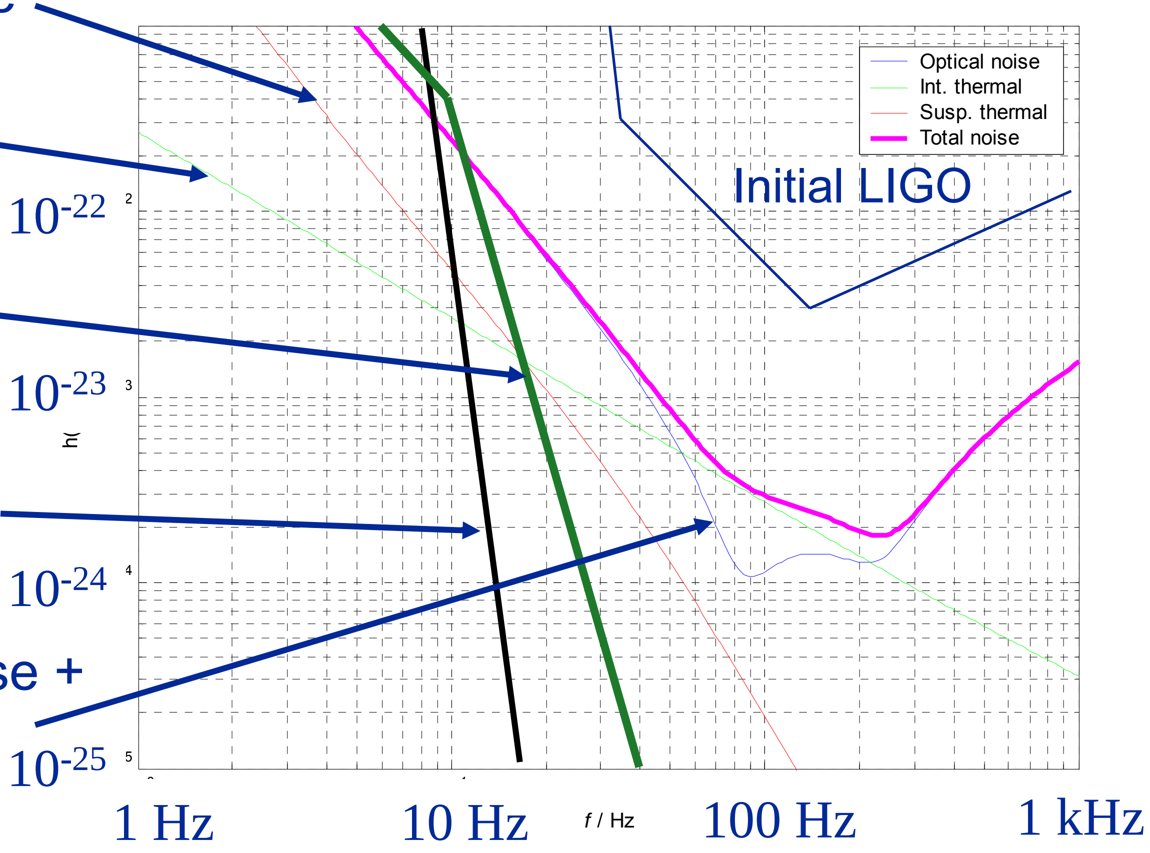
What's next for LIGO?
Targets for Advanced LIGO

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

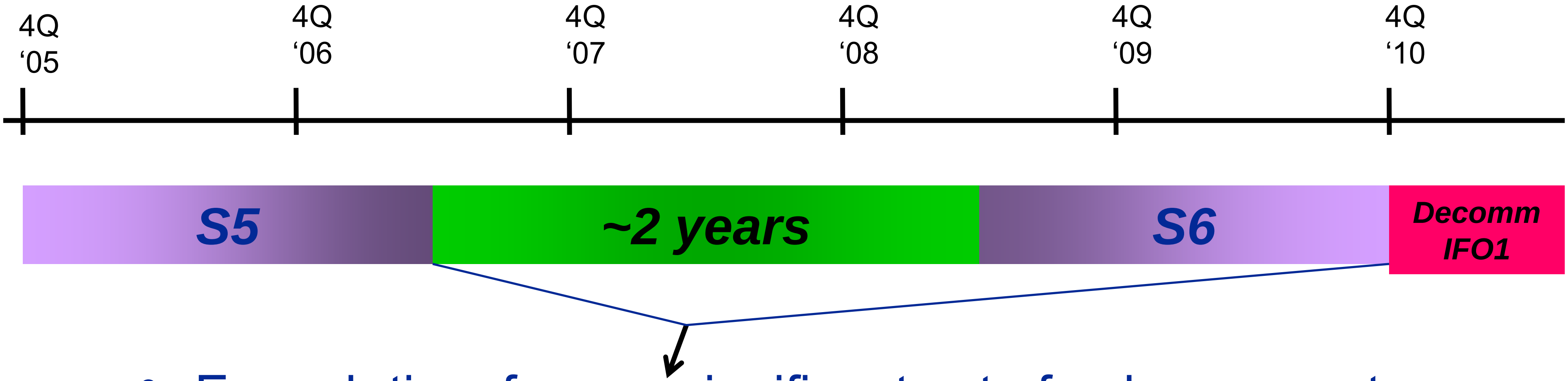


Anatomy of the Projected Adv LIGO Detector Performance

- 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



Enhanced LIGO



4Q ‘05

4Q ‘06

4Q ‘07

4Q ‘08

4Q ‘09

4Q ‘10

S5

~2 years

S6

Decomm IFO1

- 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