LIGO, on the threshold of Gravitational Wave Astronomy

Stan Whitcomb (for the LIGO Scientific Collaboration)

Seminar at CSIRO Division of Industrial Physics

Lindfield, Sydney

11 July 2007

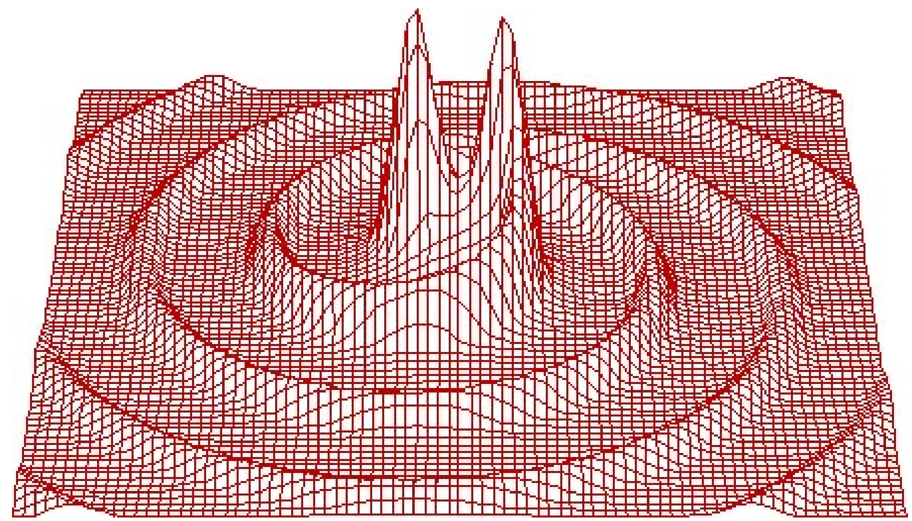
LIGO-G070417-01-D

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

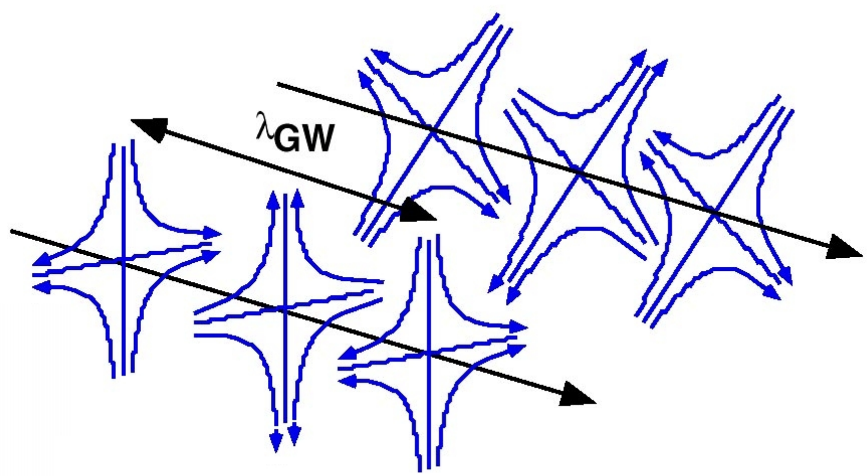
- Quick Review of GW Physics
- LIGO Detector Overview
  - » Performance Goals
  - » How do they work?
  - » What do the parts look like?
- Early Results
- Global Network
- Advanced LIGO Detectors
  - » New challenges



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

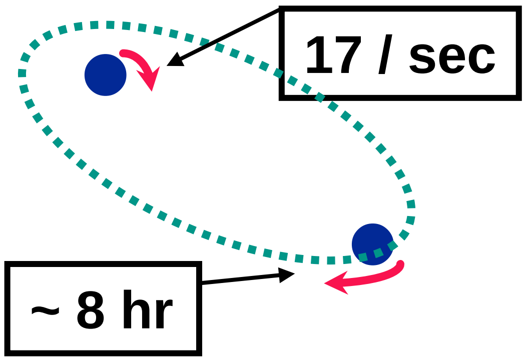
Gravitational Waves

- 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
  - » 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

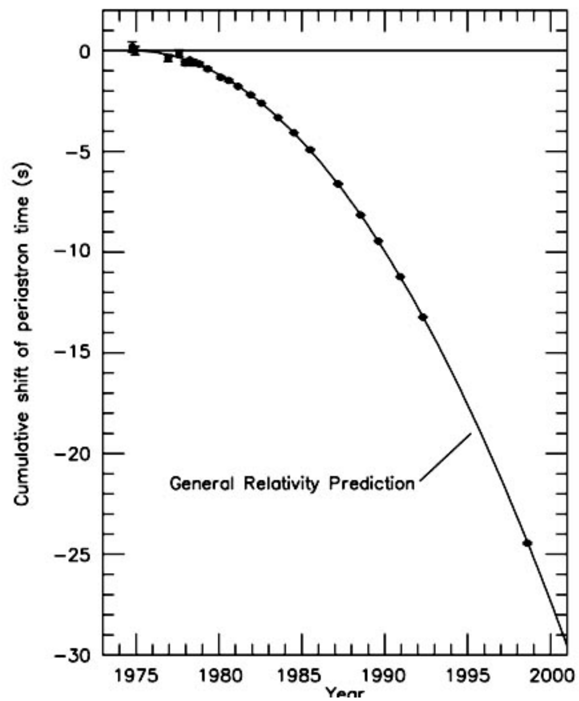


$$h = \Delta L / L$$

Evidence for Gravitational Waves:
Neutron Star Binary PSR1913+16



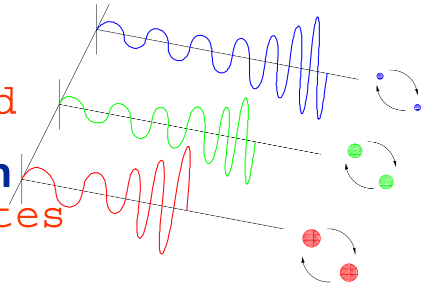
- **Discovered by Hulse and Taylor in 1975**
- **Unprecedented laboratory for studying gravity**
  - » **Extremely stable spin rate**
- **Possible to repeat classical tests of relativity (bending of "starlight", advance of "perihelion", etc.**



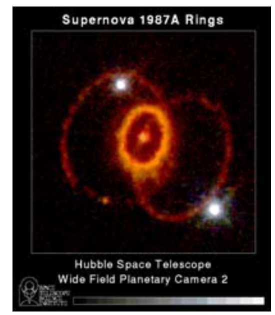
- **After correcting for all known relativistic effects, observe loss of orbital energy**
=> Emission of GWs

Astrophysical Sources of GWs

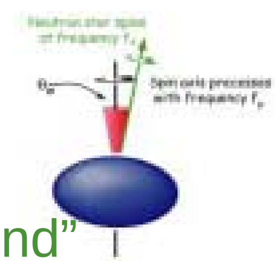
- Compact binary inspiral: "chirps"
  - » **NS-NS binaries well understood**
  - » **BH-BH binaries need further calculation, spin**
  - » **Search technique: matched templates**



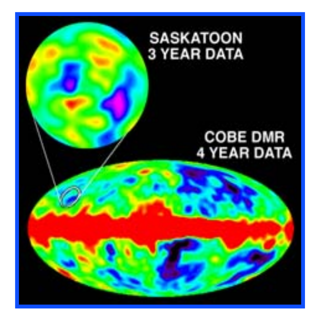
- Supernovas or GRBs: "bursts"
  - » **GW signals observed in coincidence with EM or neutrino detectors**
  - » **Prompt alarm for supernova? (~1 hour?)**



- 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?**

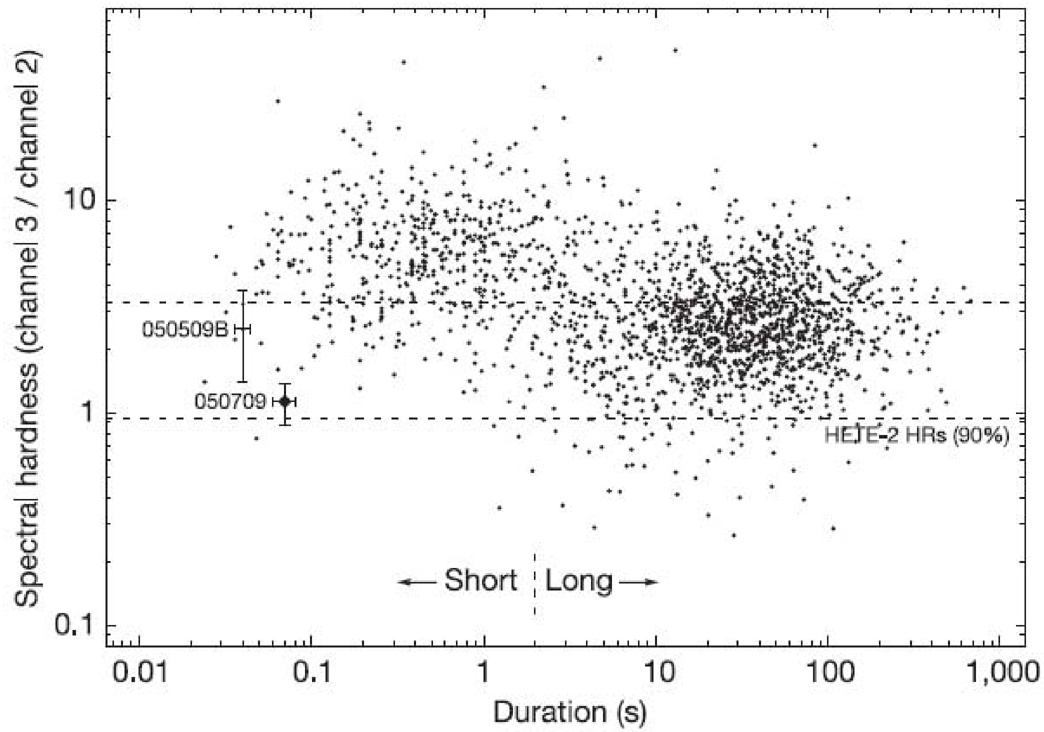


- Cosmological: "stochastic background"
  - » **Probing the universe back to the Planck time (10^{-43} s)**

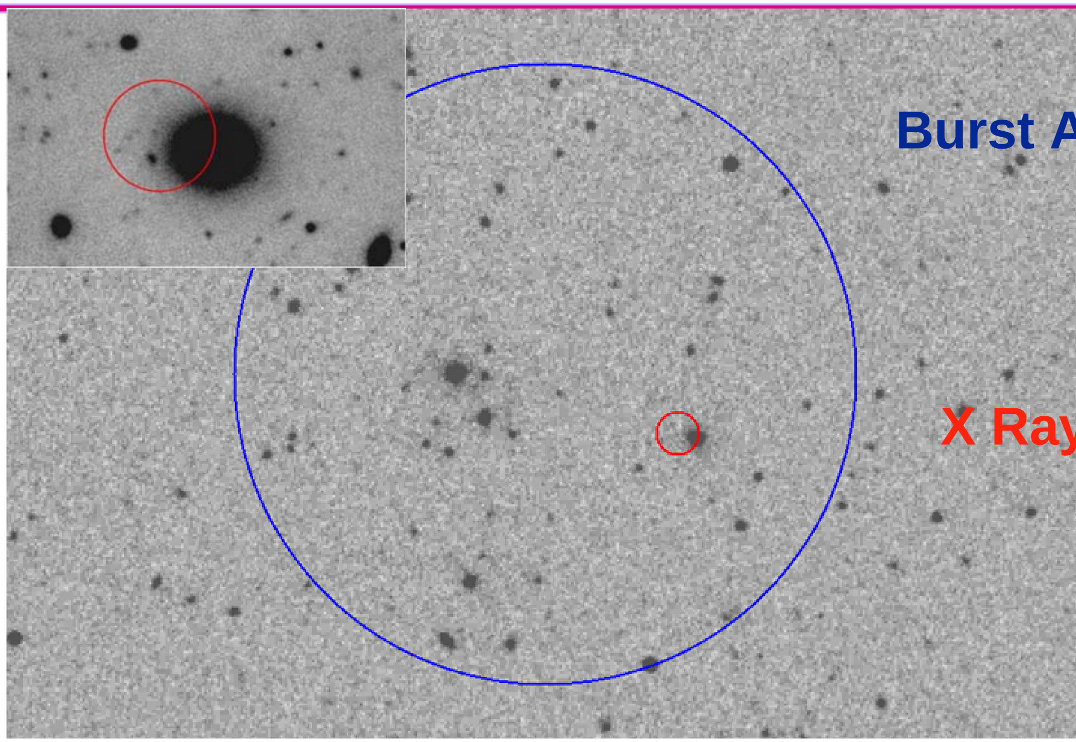


Short Gamma Ray Bursts (GRBs)

- 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)

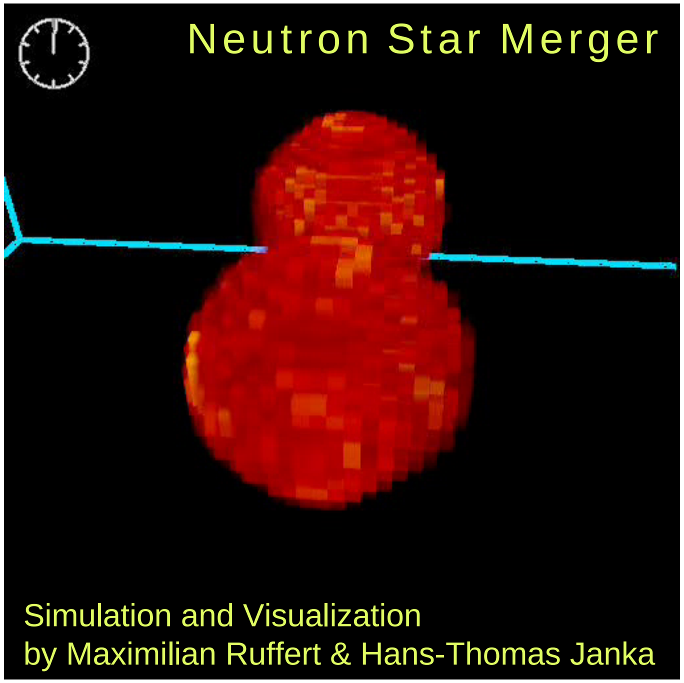


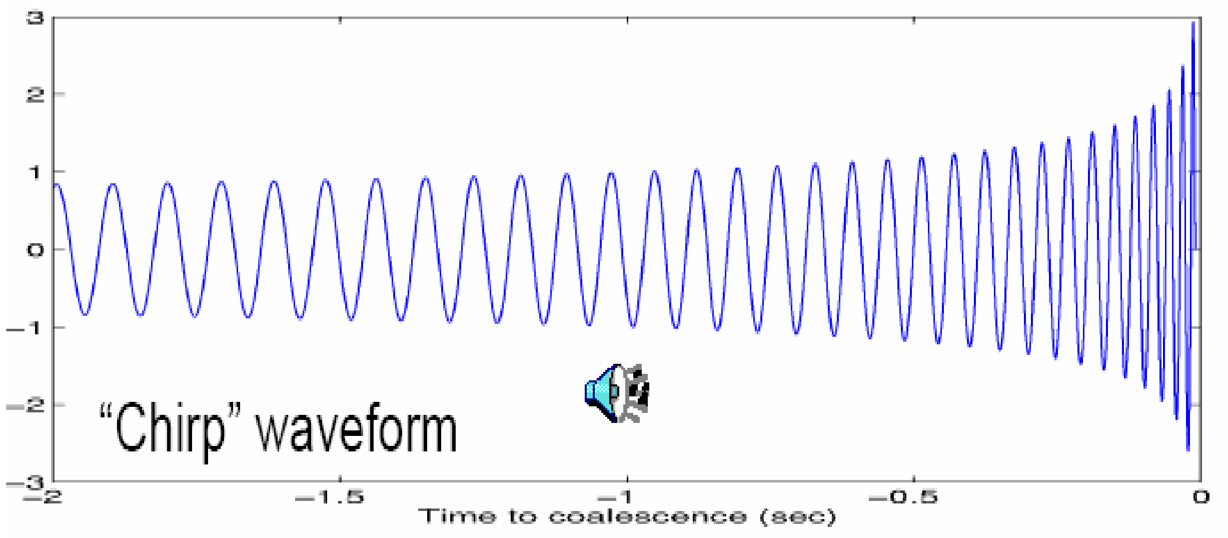
Gehrels et al., Nature, 437, 851, 2005

- 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





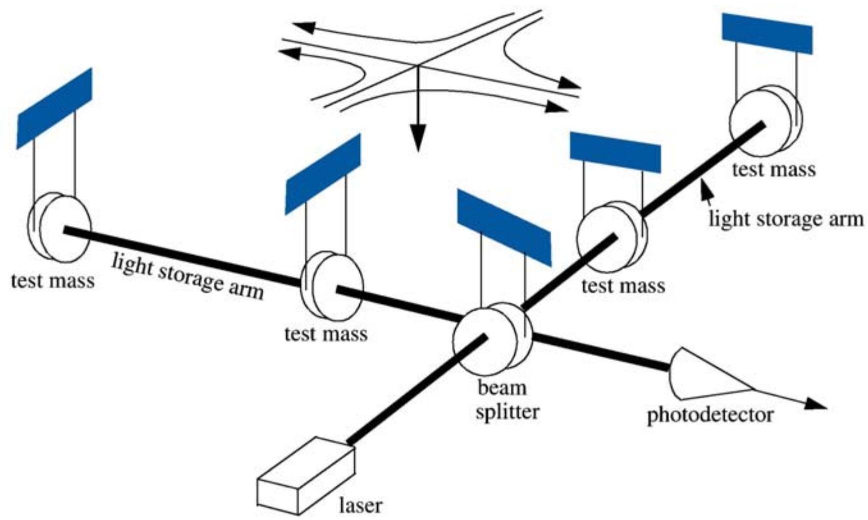
Chirp parameters give:

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

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

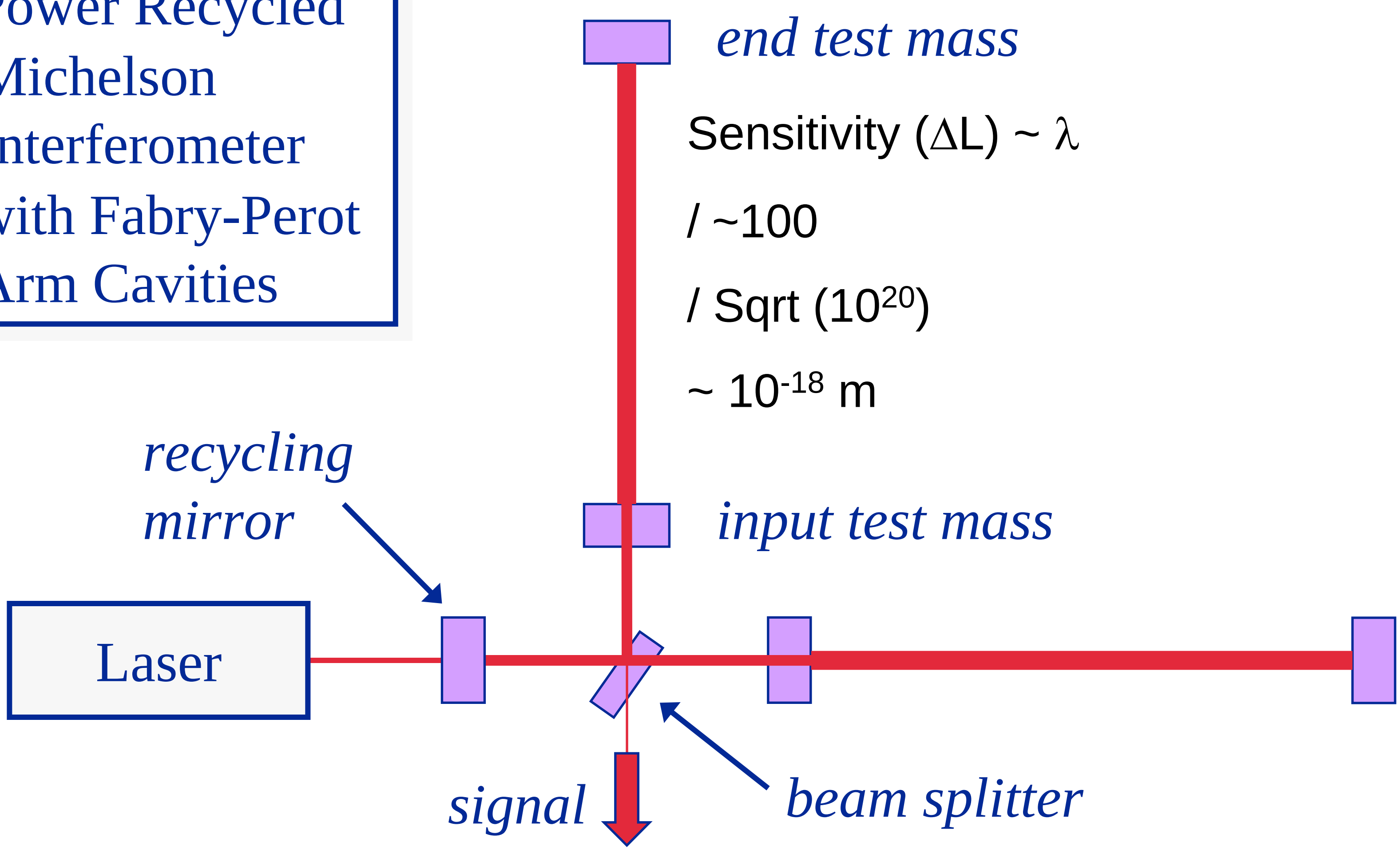
For $h \sim 10^{-22} - 10^{-21}$

L ~ 4 km (LIGO)

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

Optical Configuration

Power Recycled Michelson Interferometer with Fabry-Perot Arm Cavities



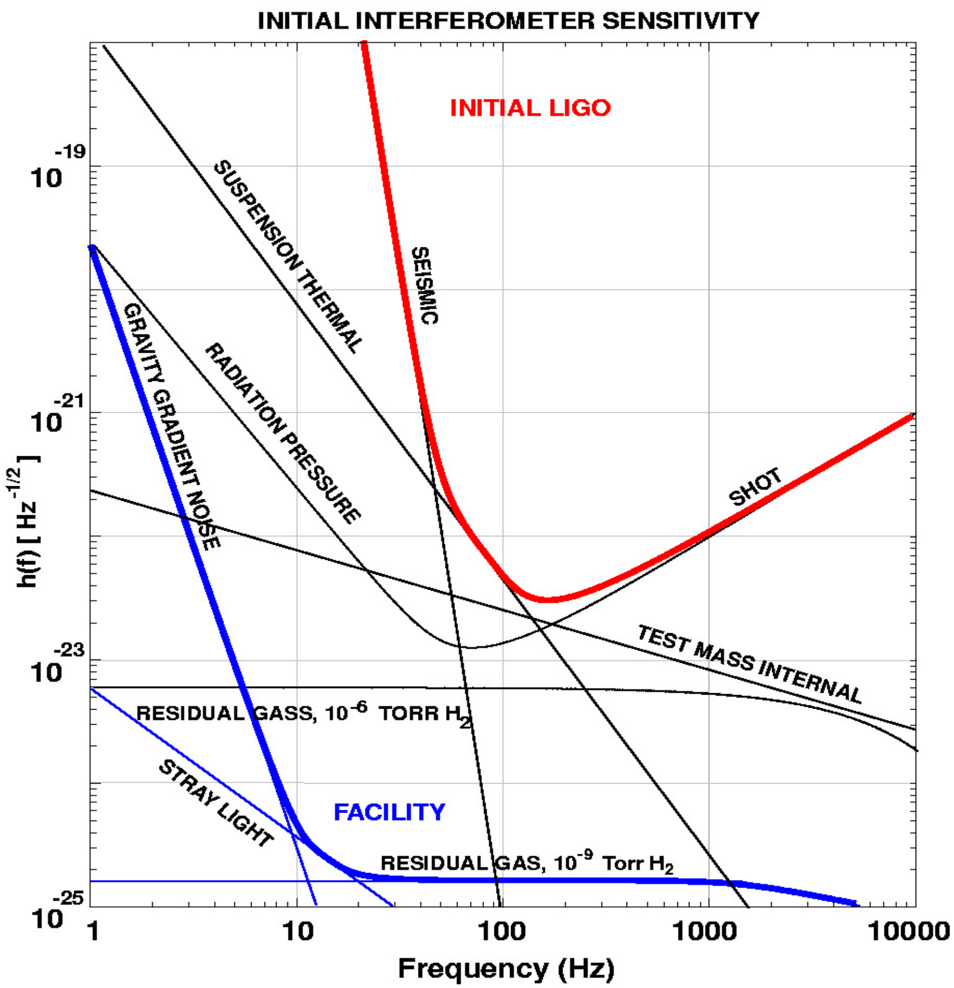
Sensitivity (ΔL) ~ λ

/ ~100

/ Sqrt (10^{20})

~ 10^{-18} m

Initial LIGO Sensitivity Goal



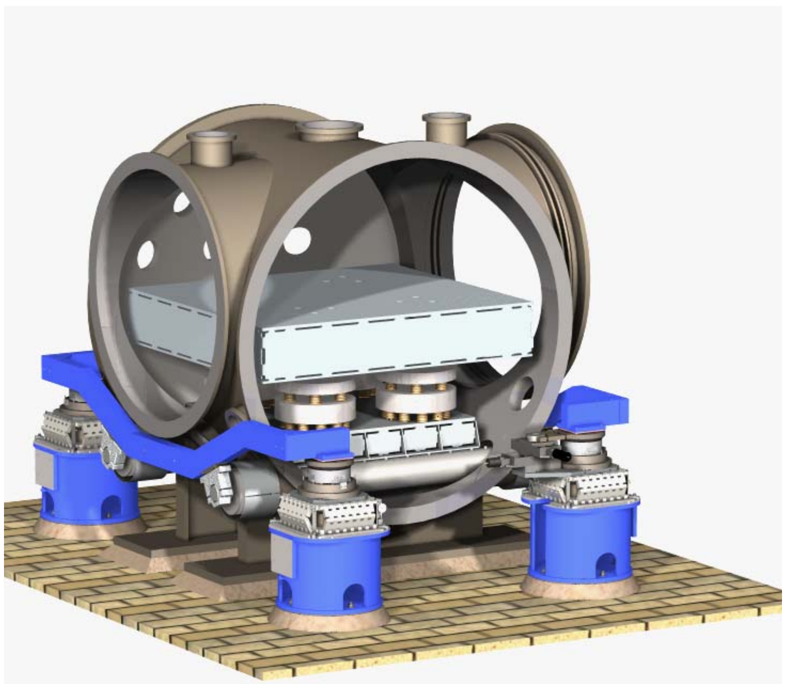
- Strain sensitivity $<3\times10^{-23}$ $1/Hz^{1/2}$ at 200 Hz
- Sensing Noise
  - » Photon Shot Noise
  - » Residual Gas
- Displacement Noise
  - » Seismic motion
  - » Thermal Noise
  - » Radiation Pressure

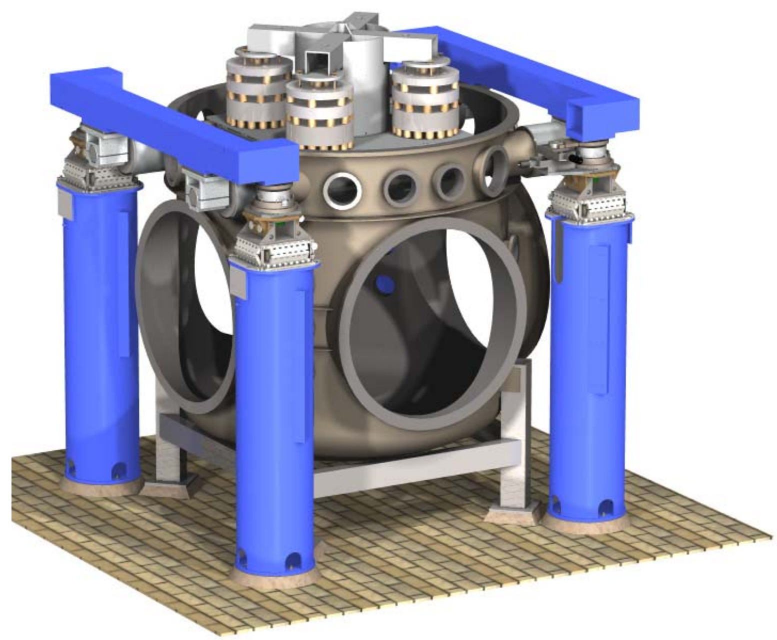
Vibration Isolation Systems

» Reduce in-band seismic motion by 4 - 6 orders of magnitude

» Large range actuation for initial alignment and drift compensation

» Quiet actuation to correct for Earth tides and microseism at 0.15 Hz during observation

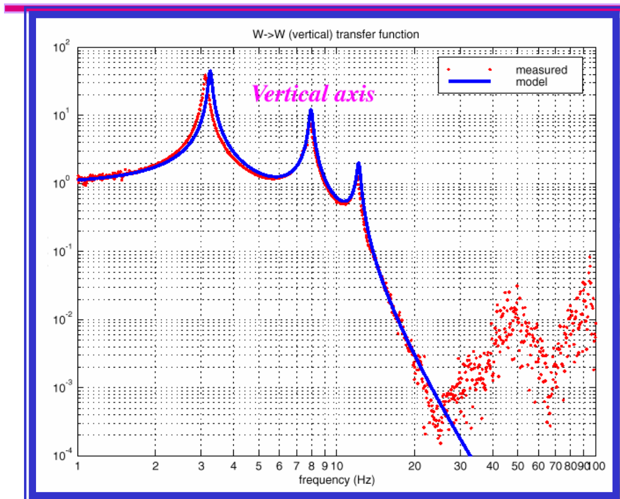


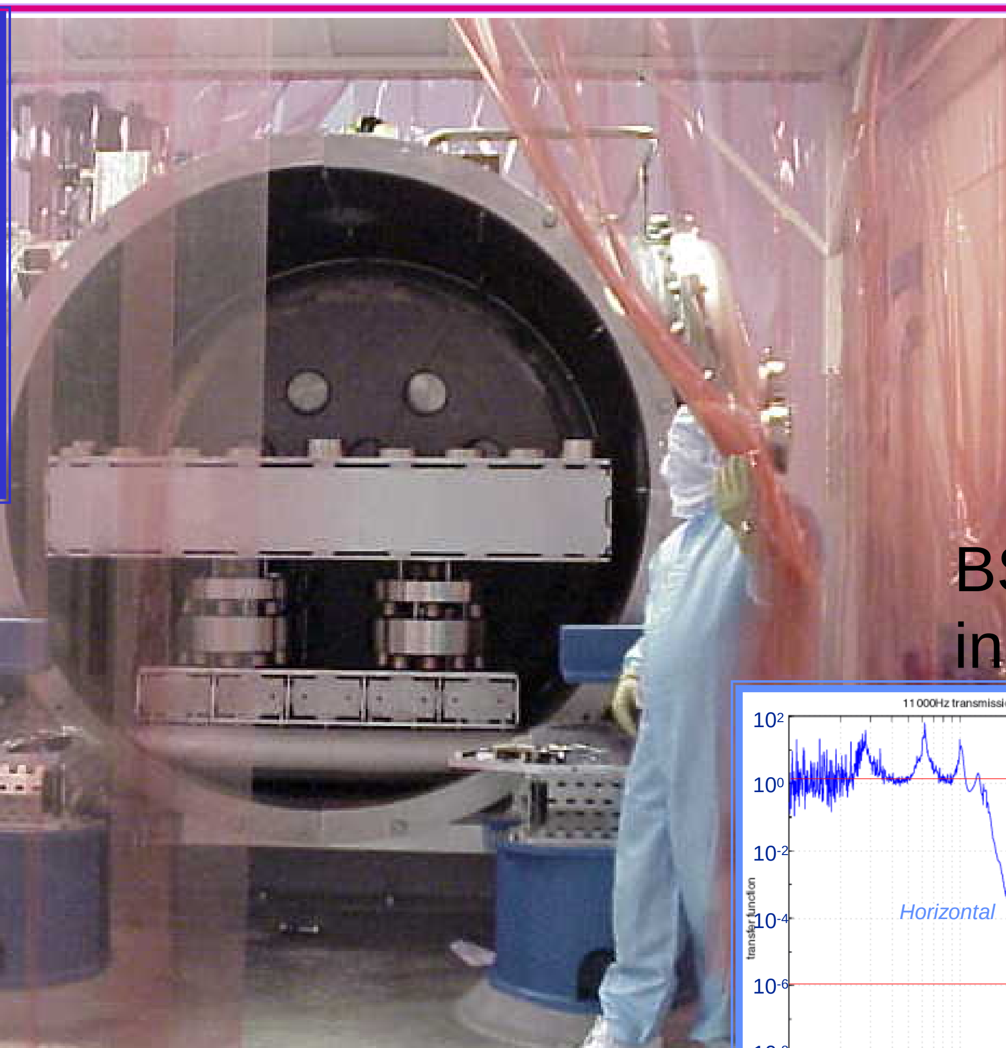


Seismic Isolation – Springs and Masses

damped spring
cross section

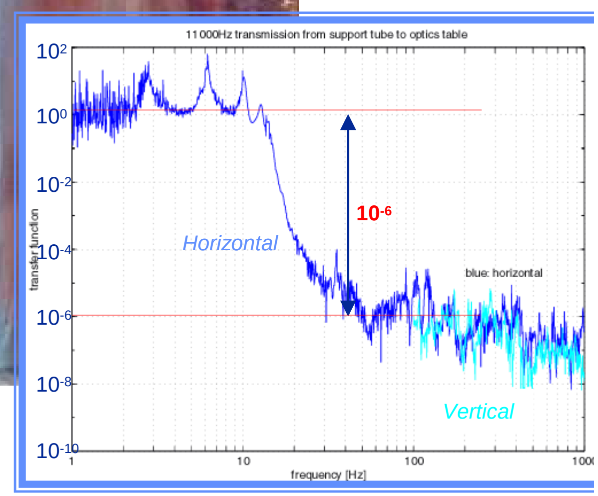
Seismic System Performance



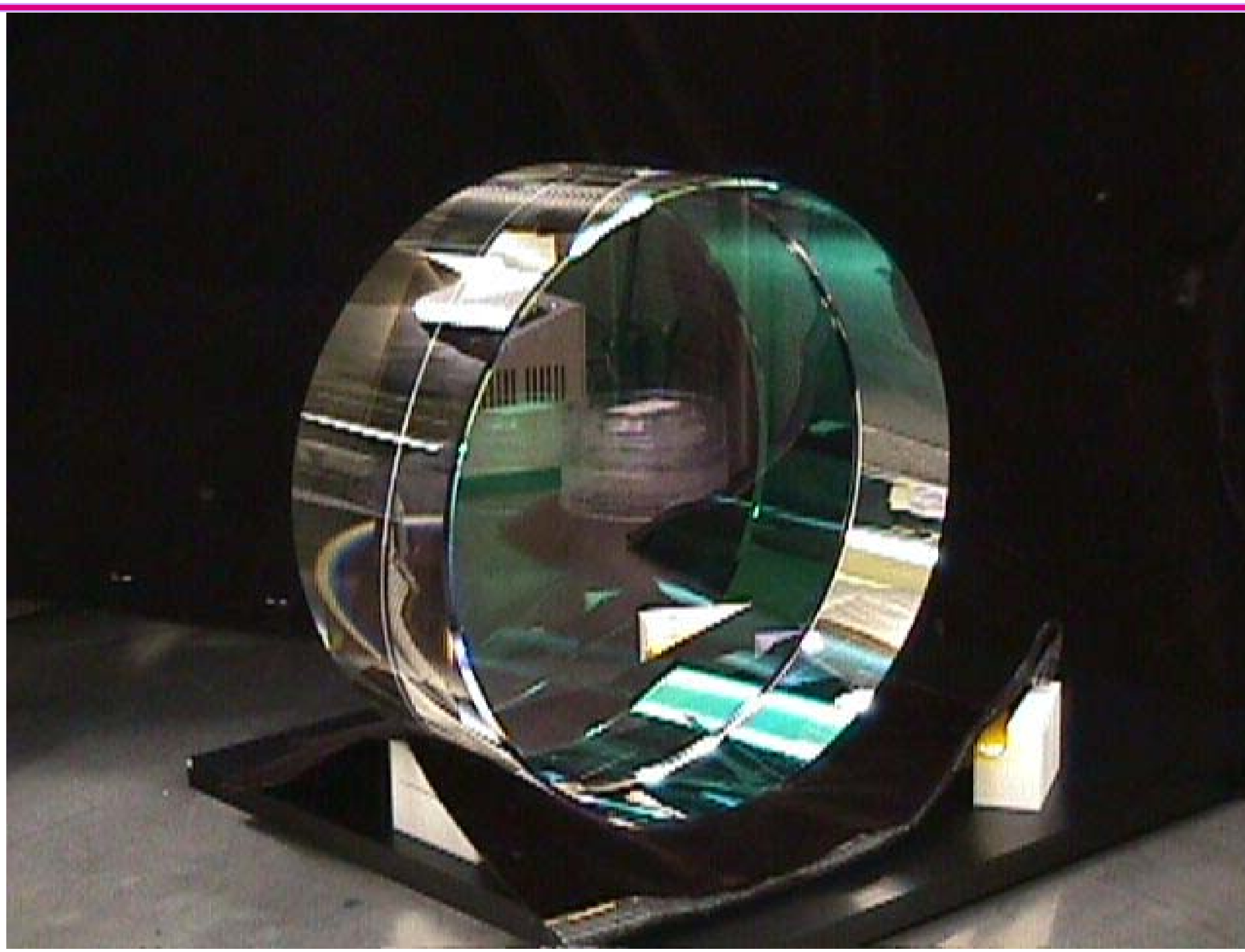


HAM stack
in air

BSC stack
in vacuum

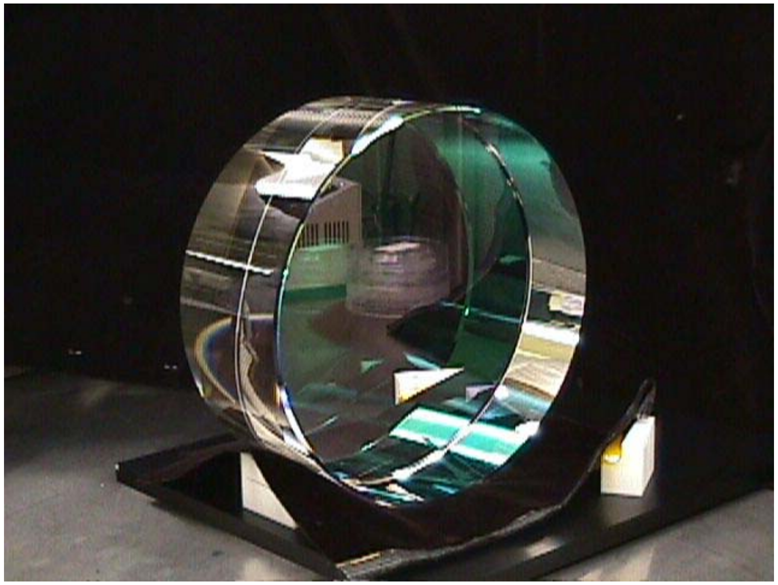


Core Optics



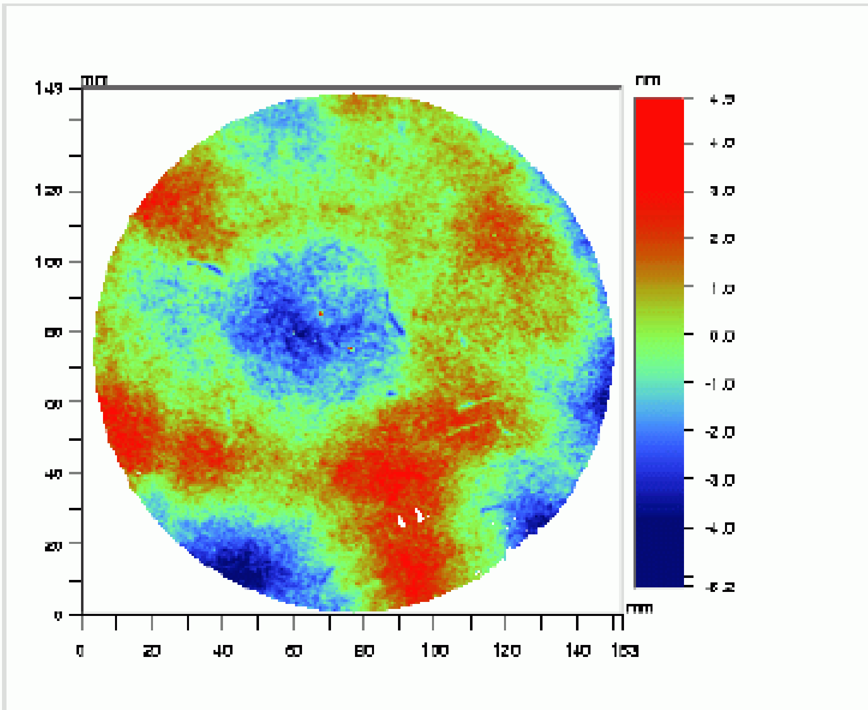
Core Optics Requirements

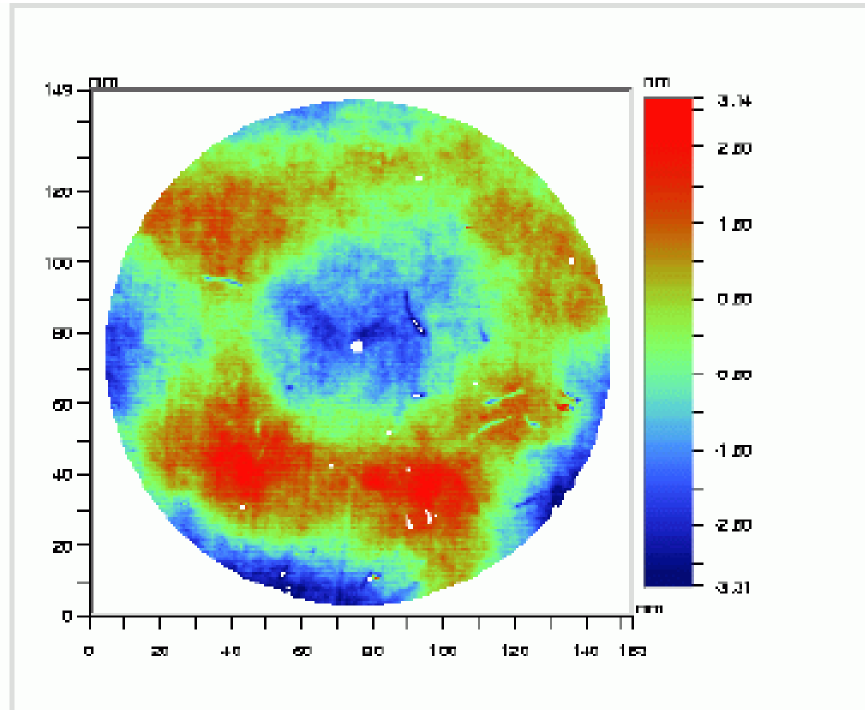
- Substrates: SiO_2
  - 25 cm Diameter, 10 cm thick
  - Homogeneity < 5 x 10^{-7}
  - Internal mode Q's > 2 x 10^6
- Polishing
  - Surface uniformity < 1 nm rms (λ / 1000)
  - Radii of curvature matched < 3%
- Coating
  - Scatter < 50 ppm
  - Absorption < 2 ppm
  - Uniformity <10^{-3}
- Production involved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



Core Optic Metrology

- Current state of the art: 0.2 nm repeatability

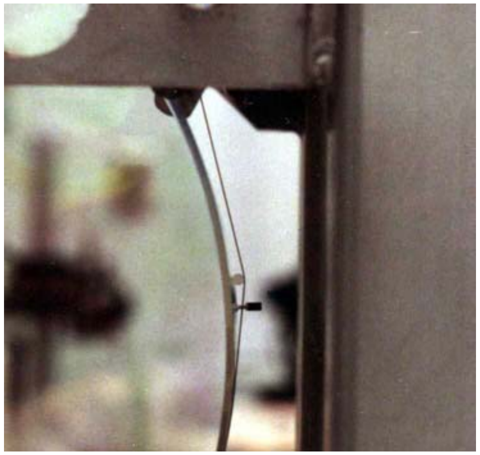


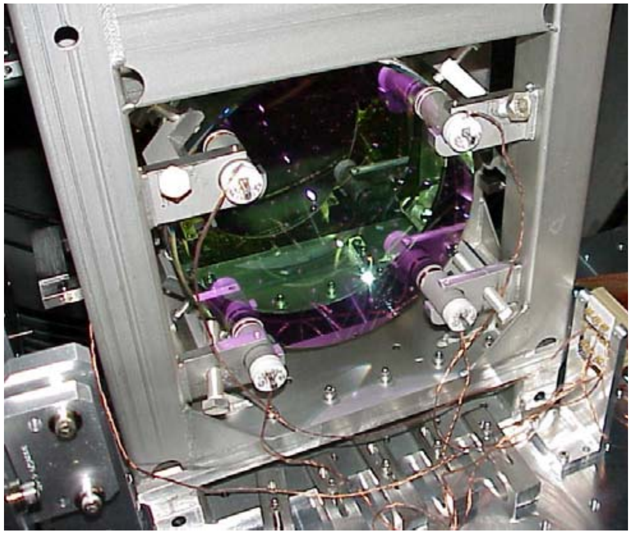


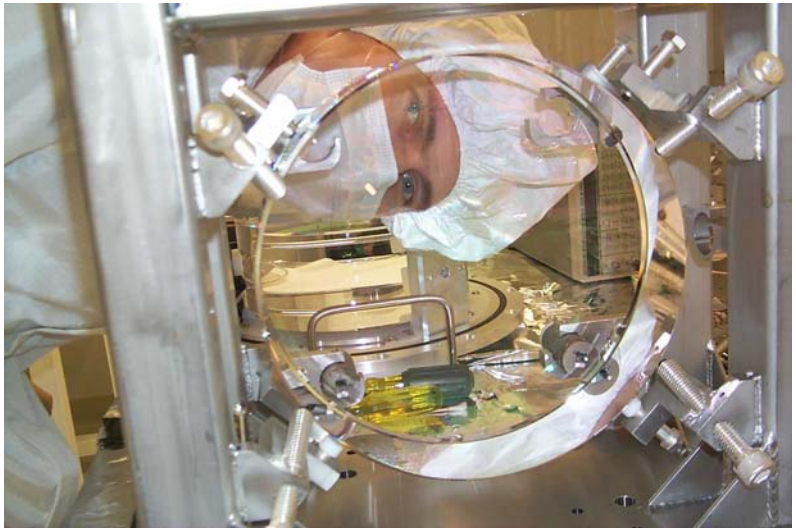
LIGO data (1.2 nm rms)

CSIRO data (1.1 nm rms)

Core Optics Suspension and Control



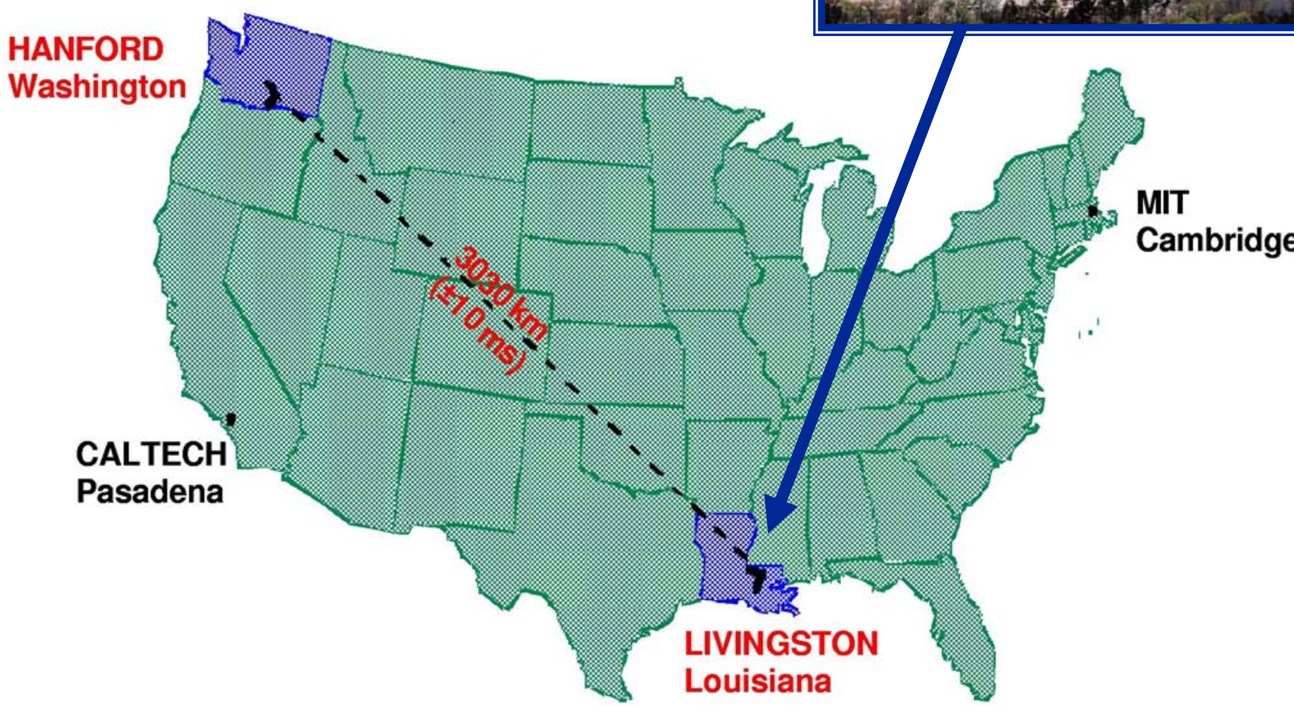




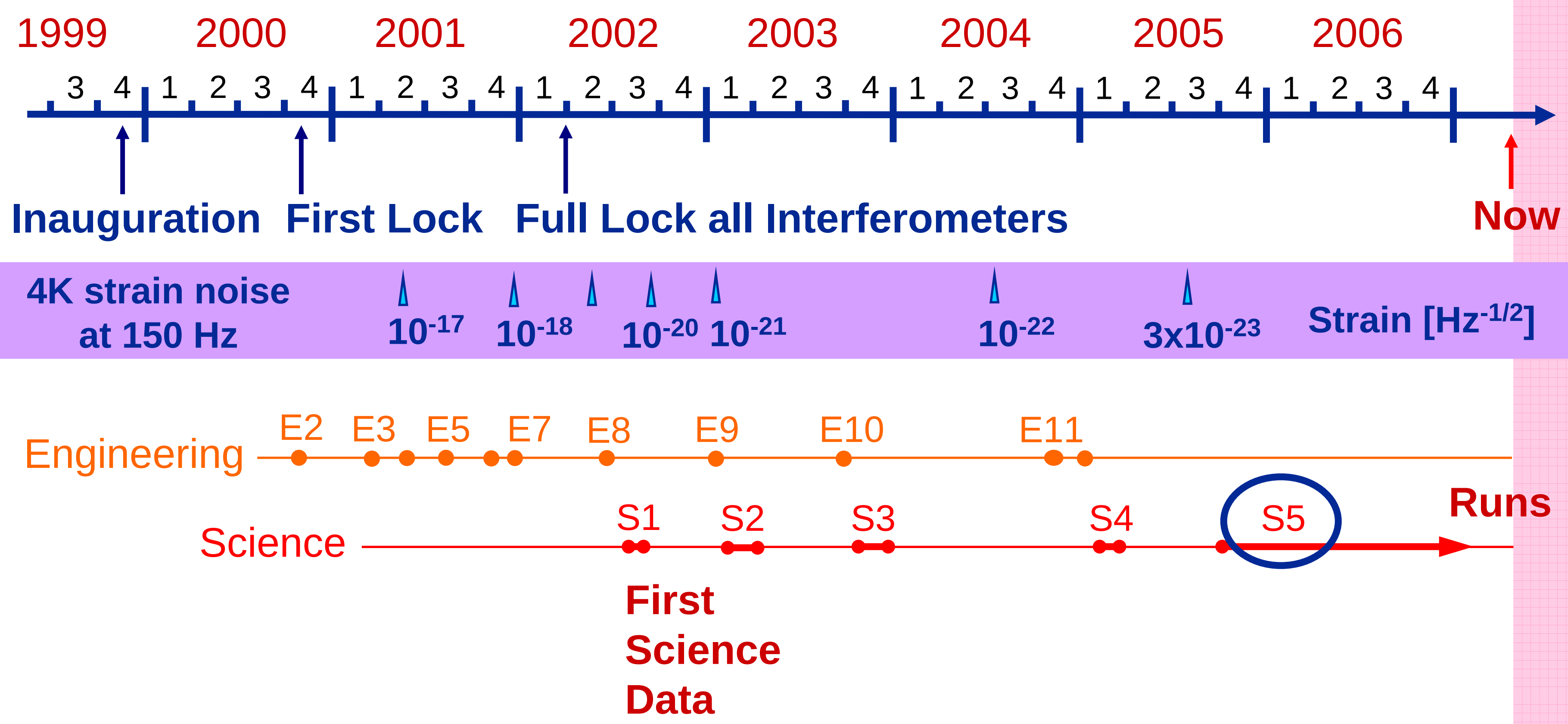
Core Optics Installation and Alignment

Initial Alignment Requirement:
100 microradians (50 goal)

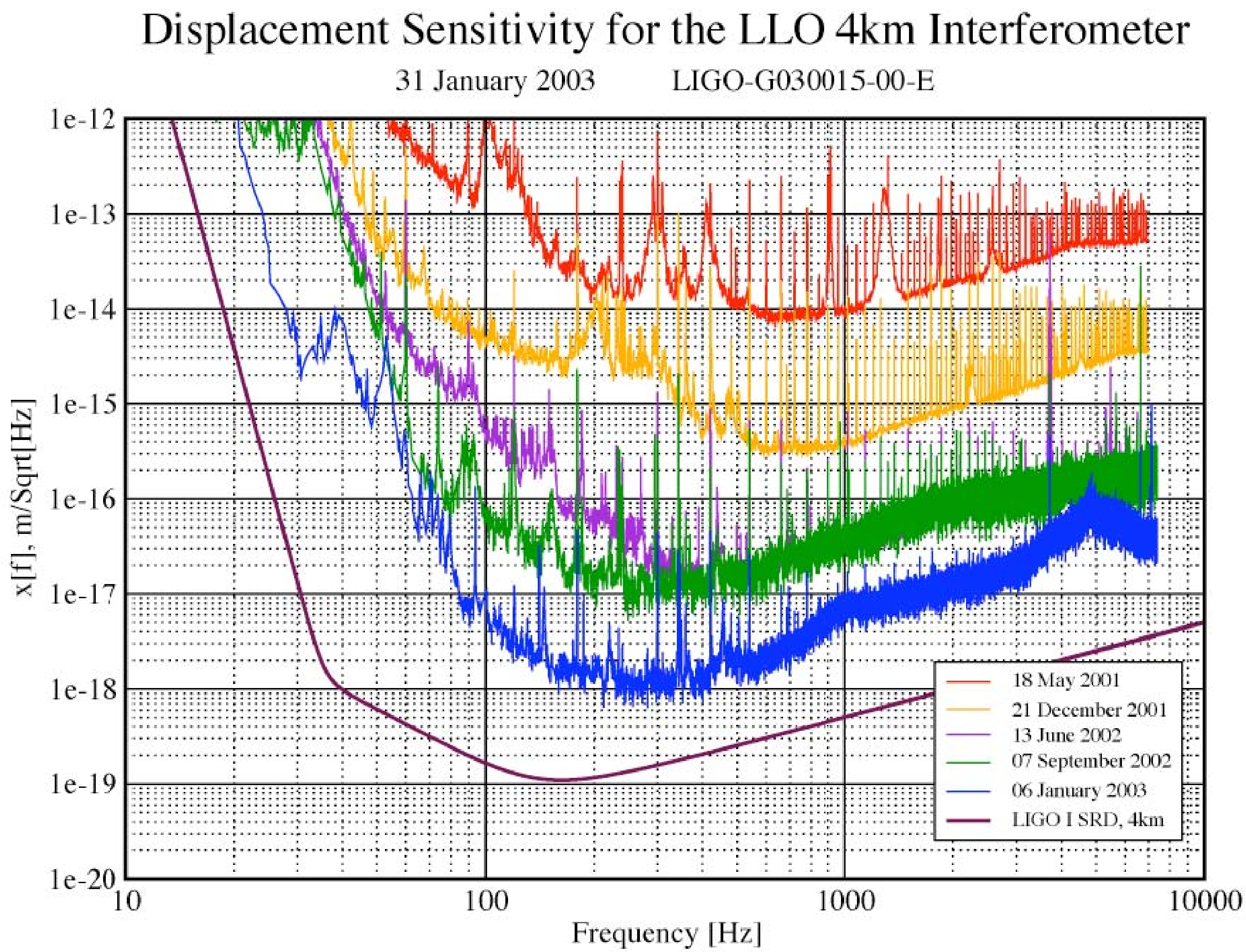
LIGO Observatories



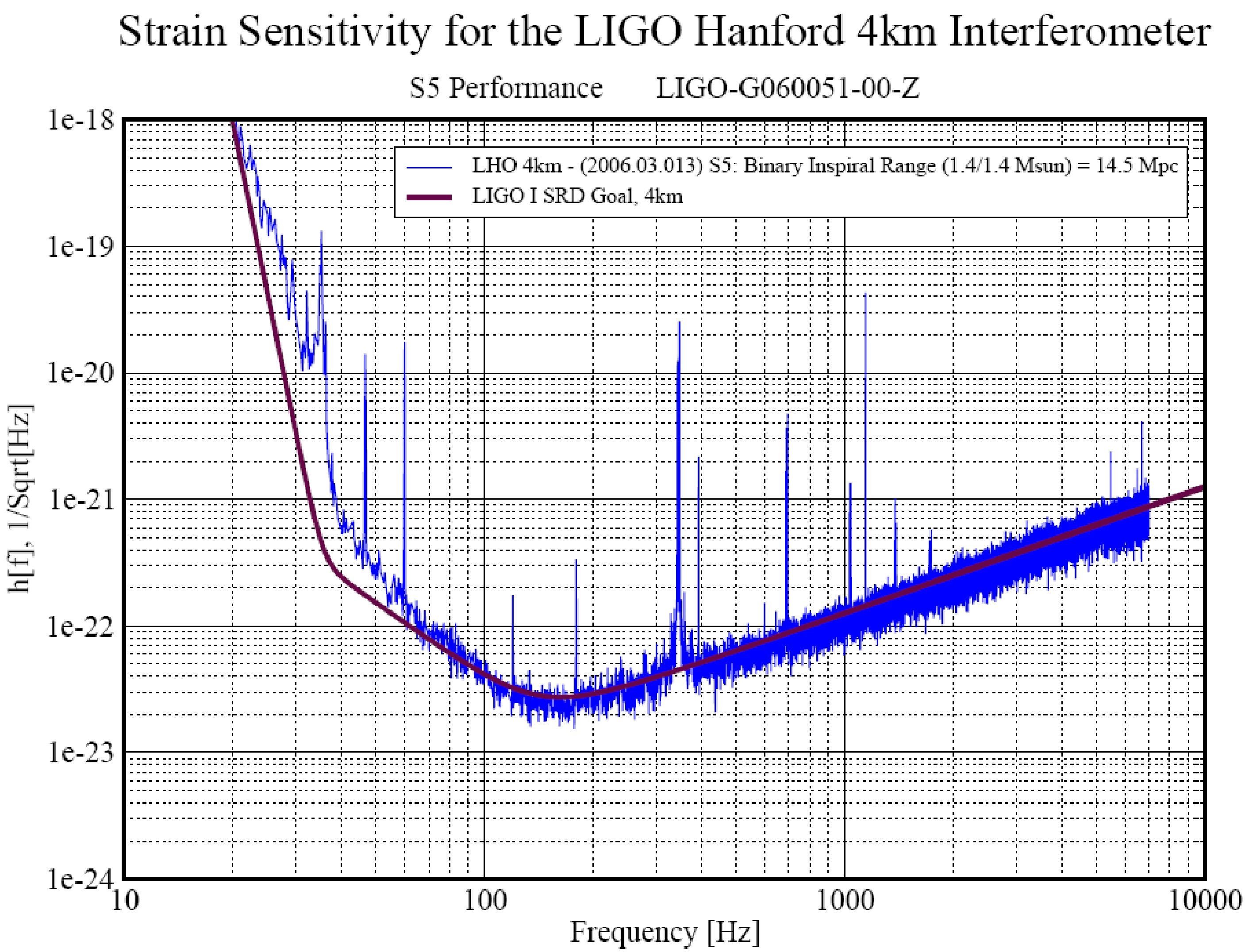
LIGO History



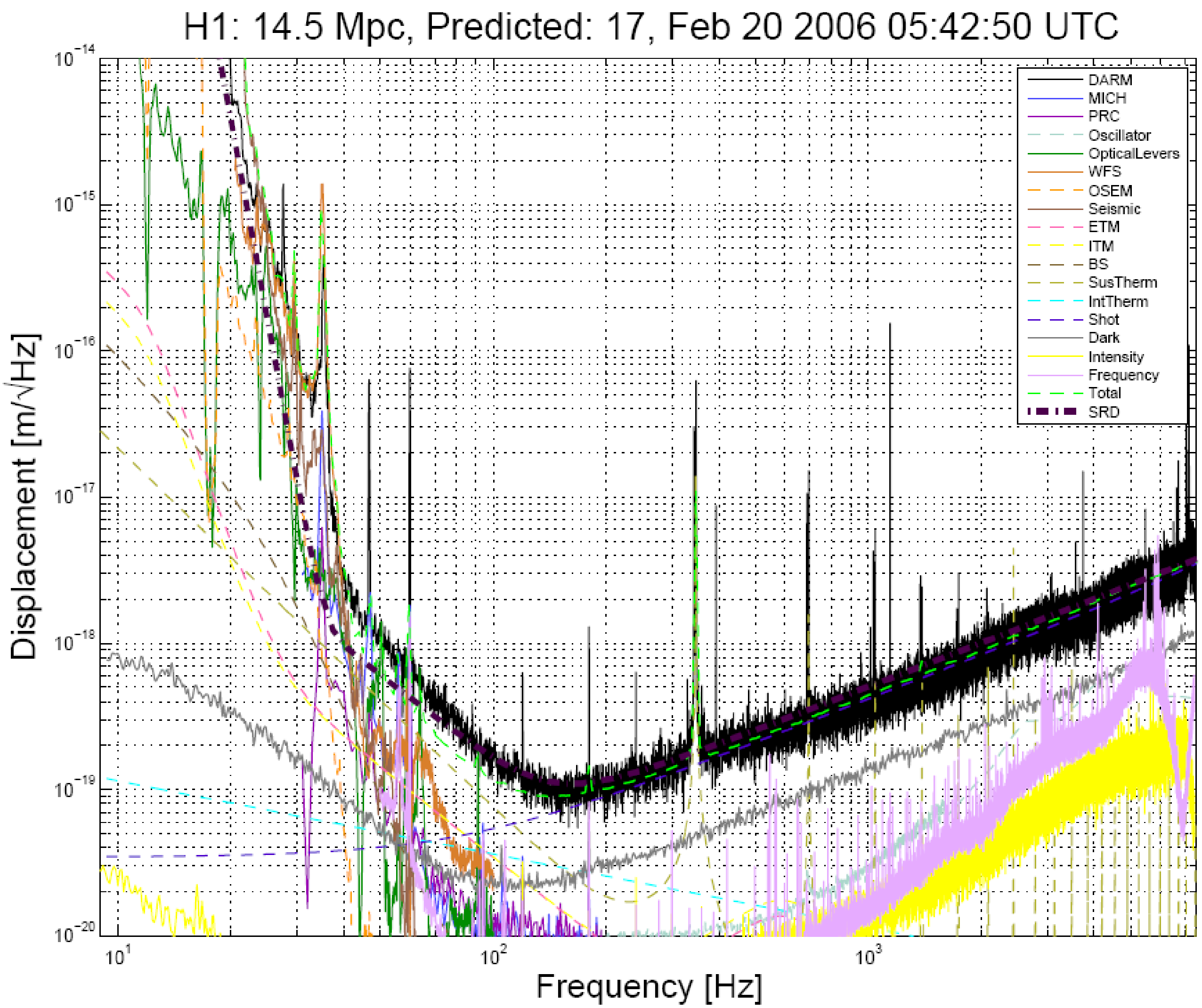
Progress toward Design Sensitivity



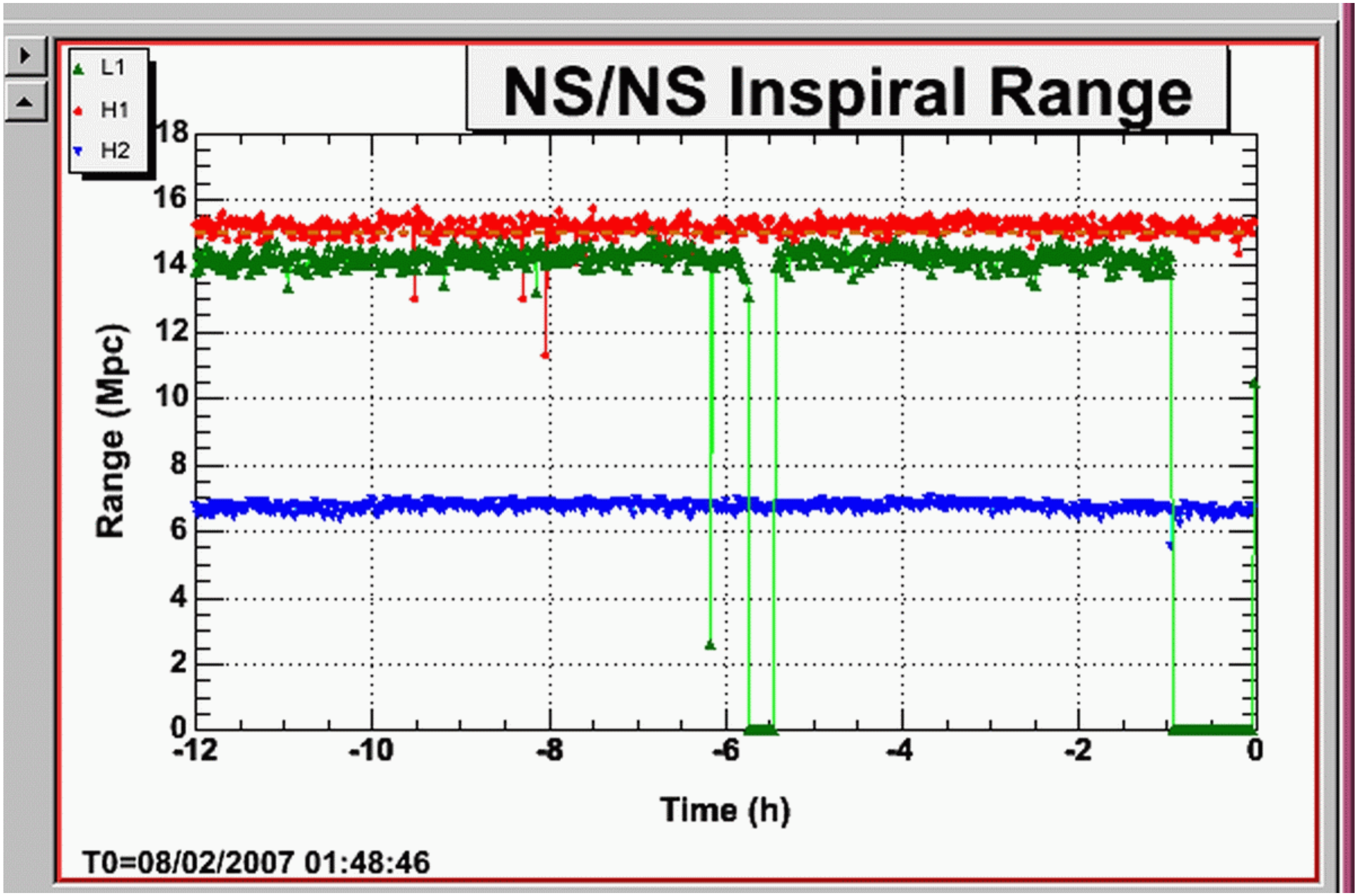
LIGO Sensitivity



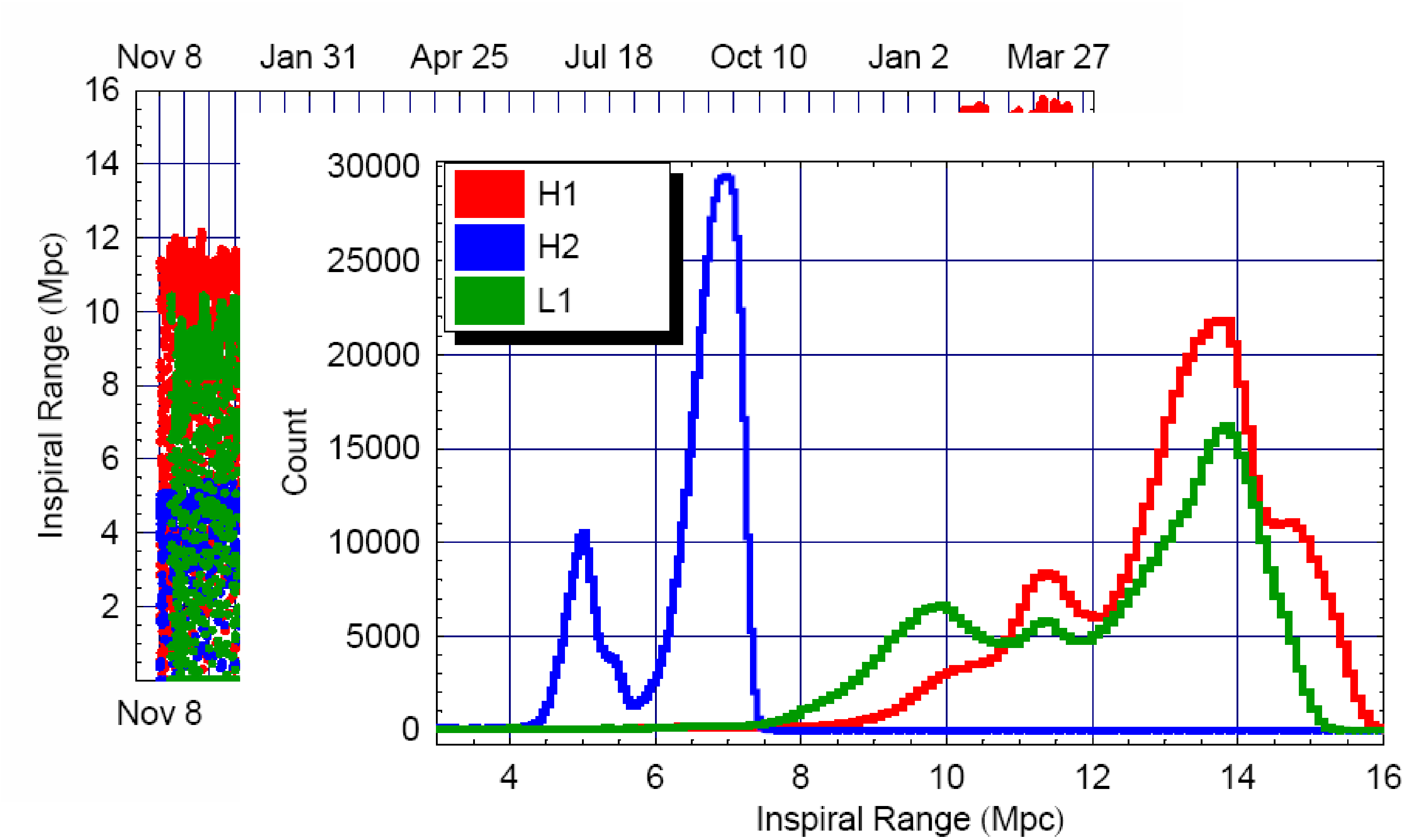
Anatomy of a Noise Curve



LIGO Duty Factor



Duty Factor for S5

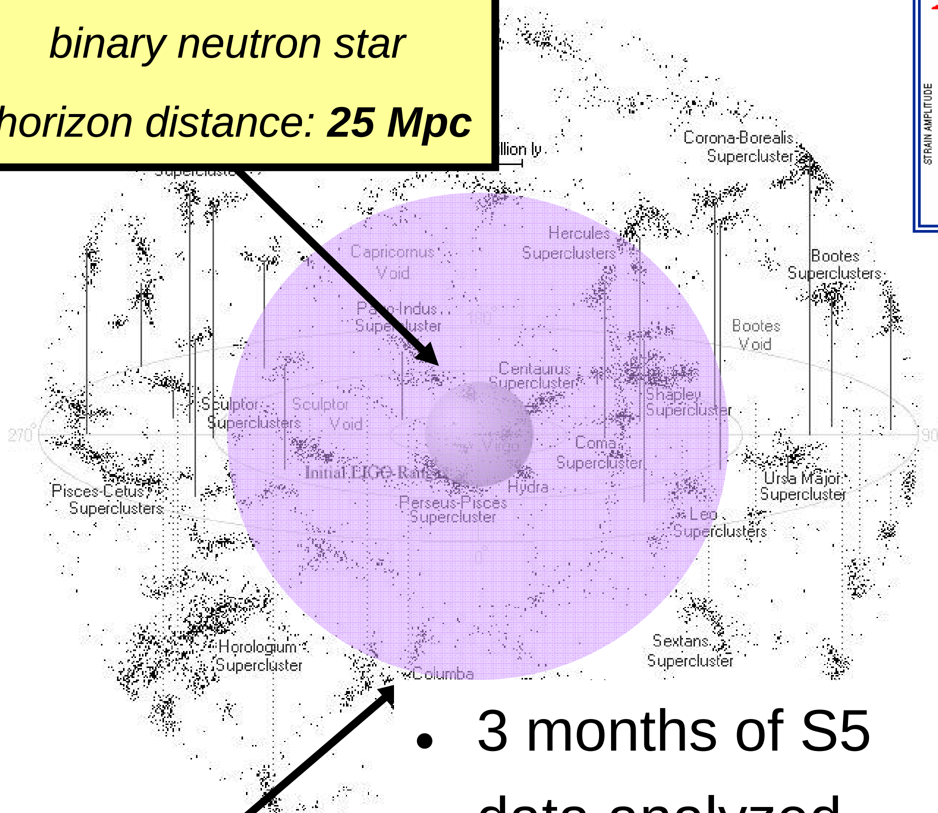


LIGO Data Analysis

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)

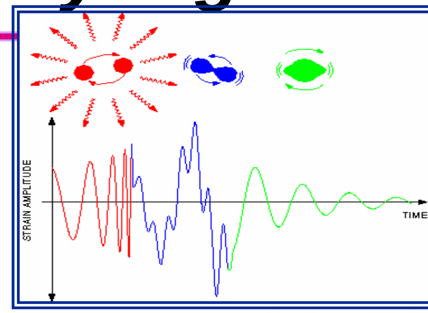
Searches for Coalescing Compact Binary Signals in S5

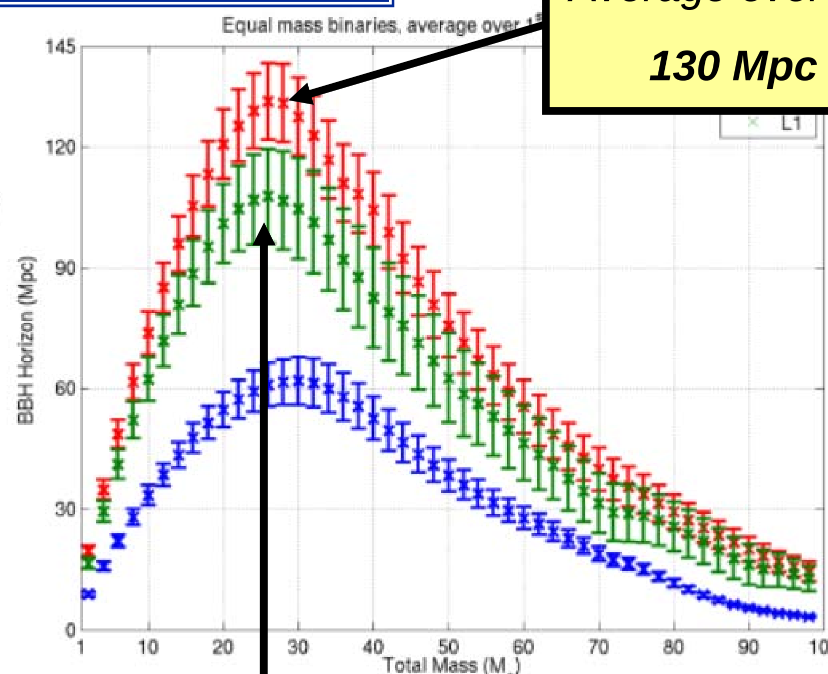


binary neutron star horizon distance: ***25 Mpc***

binary black hole horizon distance

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



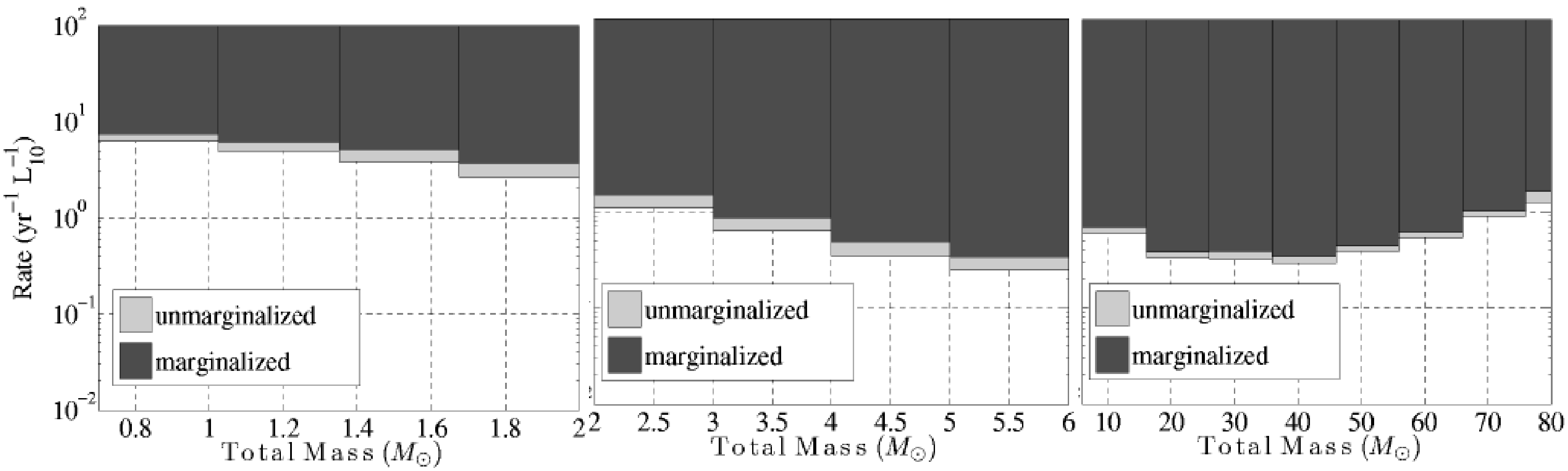


Average over run ***130 Mpc***

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

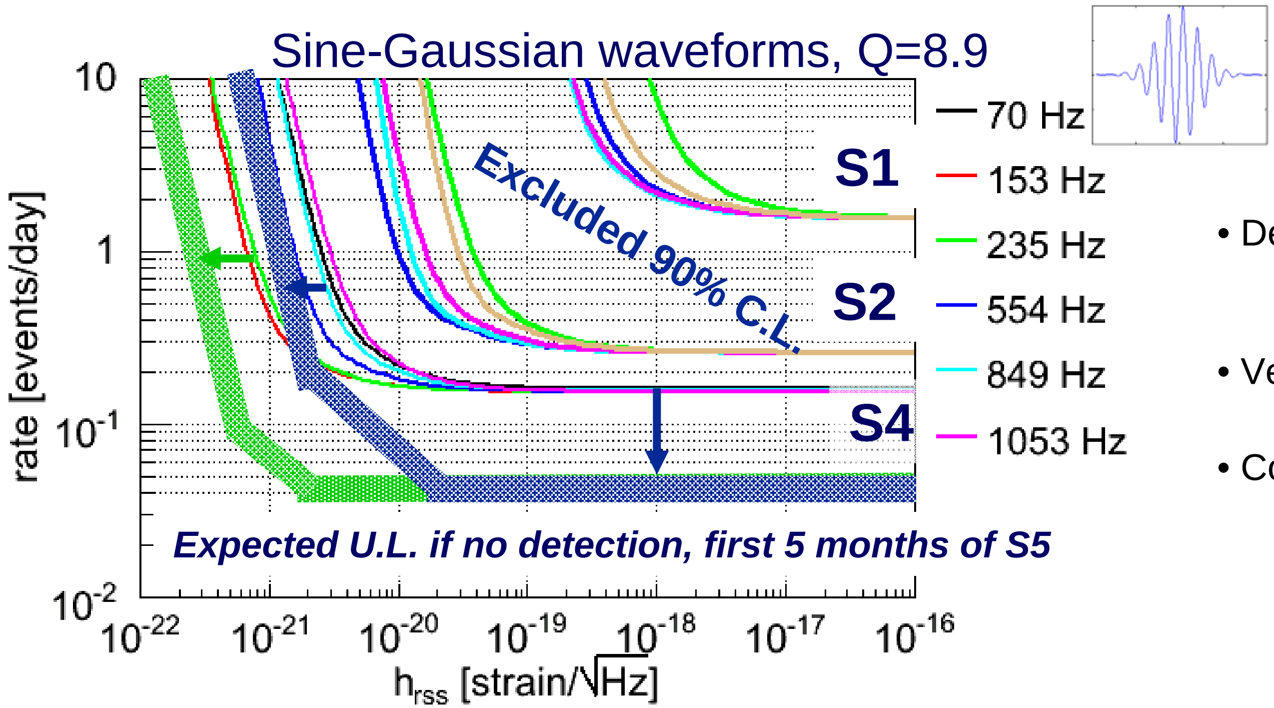
S4 Upper Limit: Compact Binary Coalescence

- 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

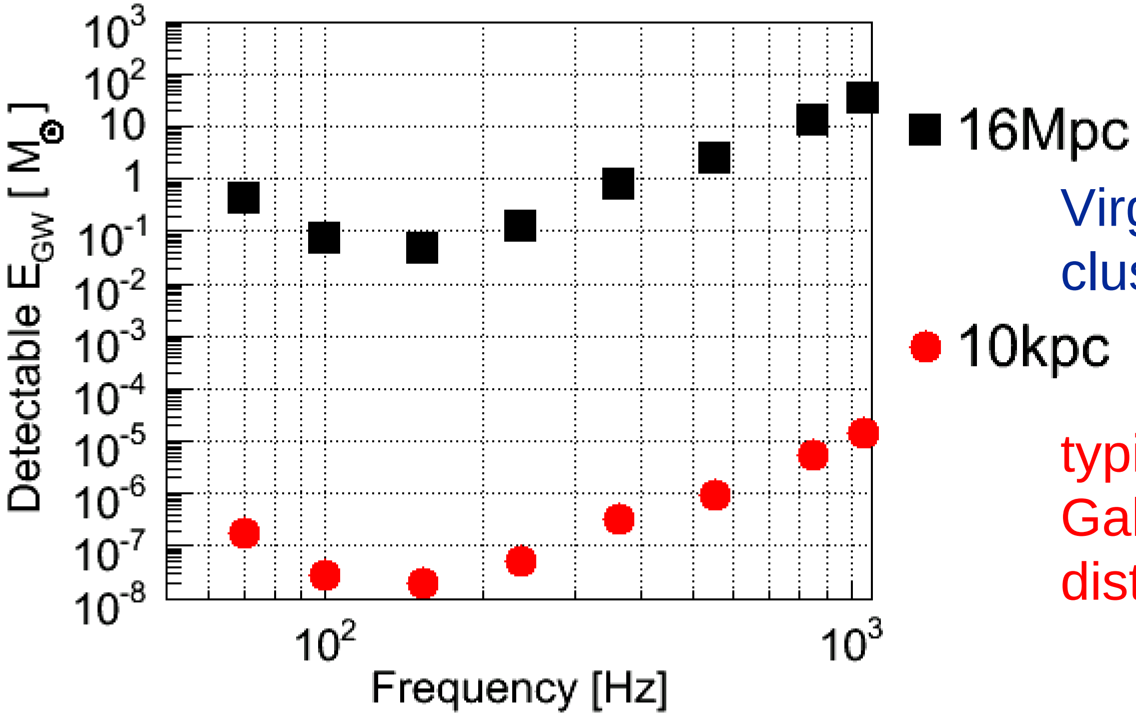


- Detection algorithms tuned for 64–1600 Hz, duration << 1 sec
- Veto thresholds pre-established before looking at data
- Corresponding energy emission **$E_{GW} \sim 10^{-1} M_\odot$ at 20 Mpc** (153 Hz case)

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

Burst Detection Efficiency / Range

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



Virgo cluster

typical Galactic distance

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

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

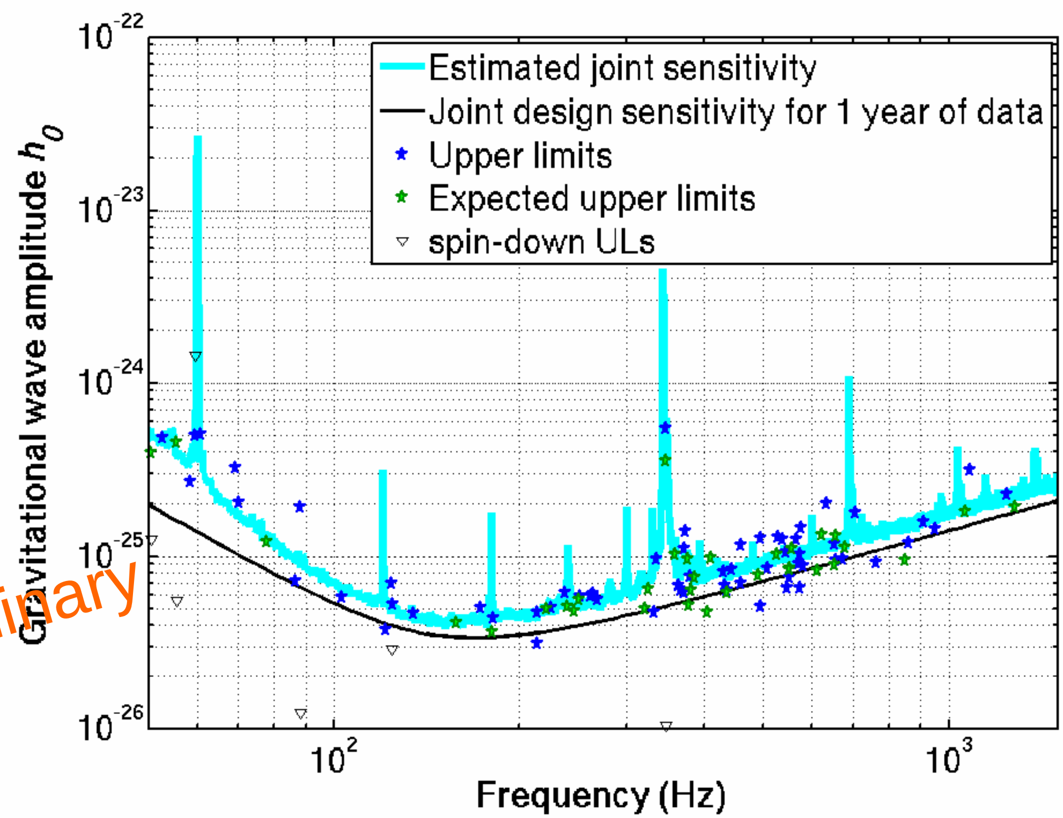
~ 0.05 $M_\odot c^2$ at 16 Mpc (Virgo cluster)

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)

$\mathbf{h_0 < 3.4\times10^{-26}}$

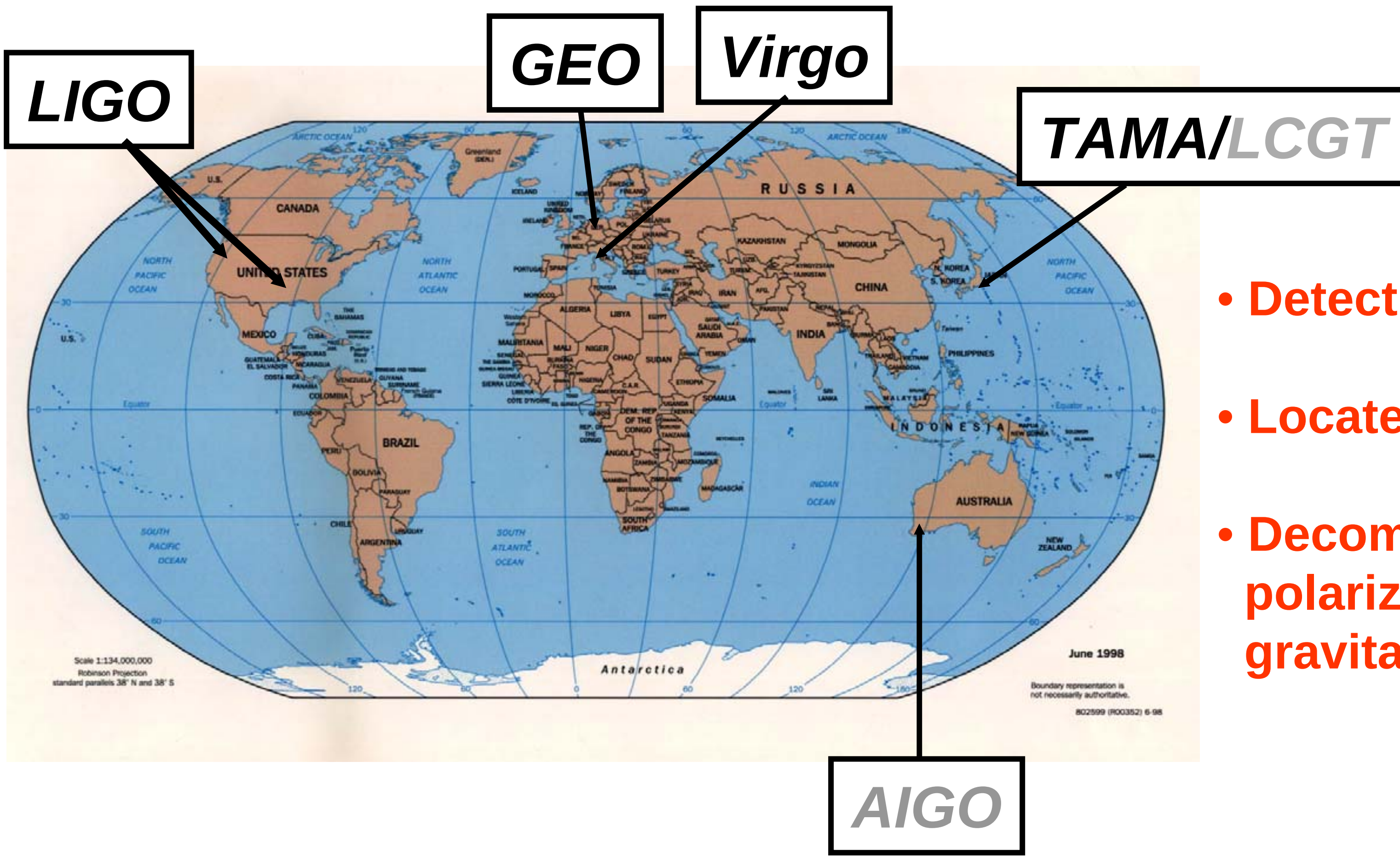
Lowest ellipticity upper limit:

PSR J2124-3358

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

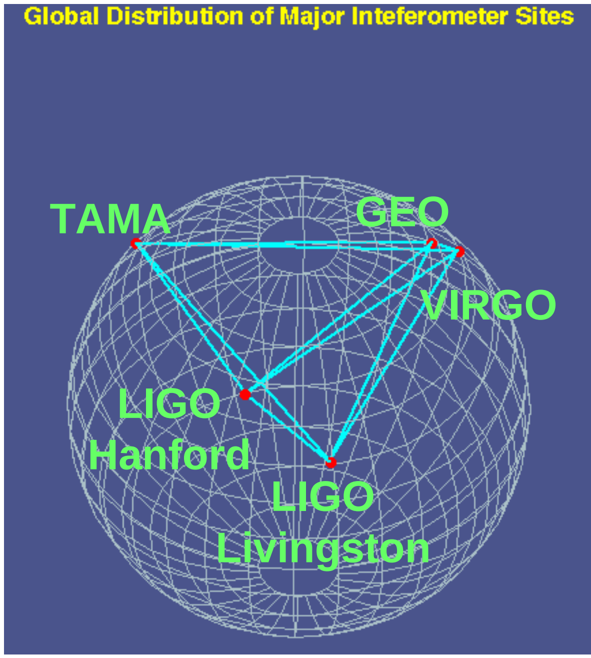
$\varepsilon < 7.3\times10^{-8}$

A Global Network of GW Detectors



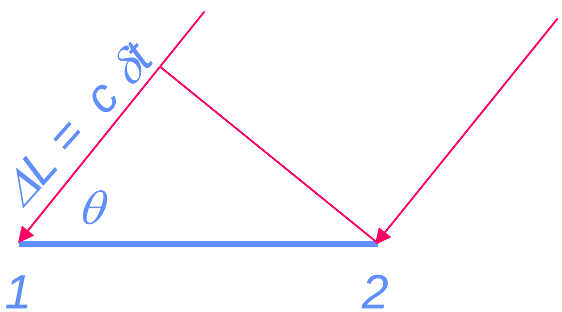
- Detection confidence
- Locate sources
- Decompose the polarization of gravitational waves

A Global Network of GW Detectors



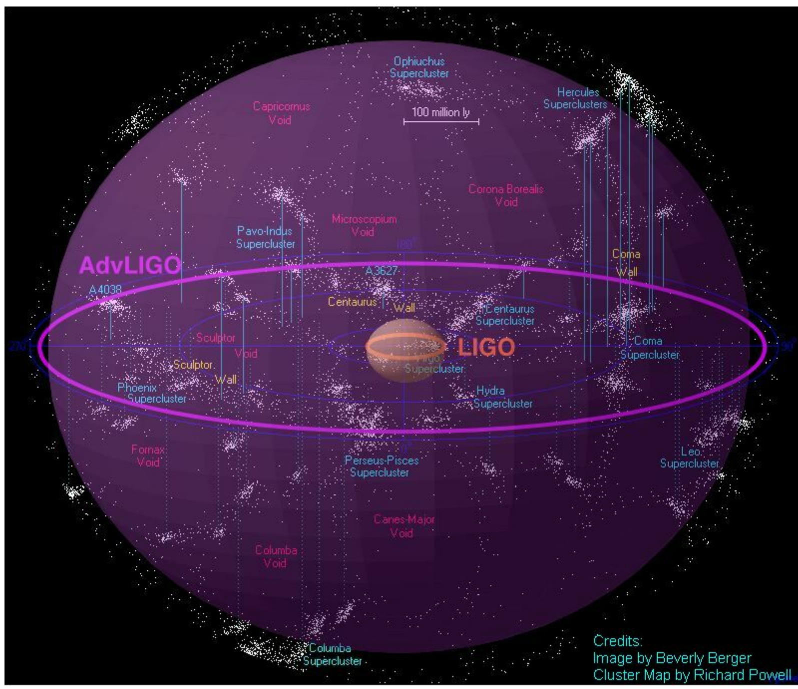
Virgo
Italy

GEO 600
Germany



What's the Future 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

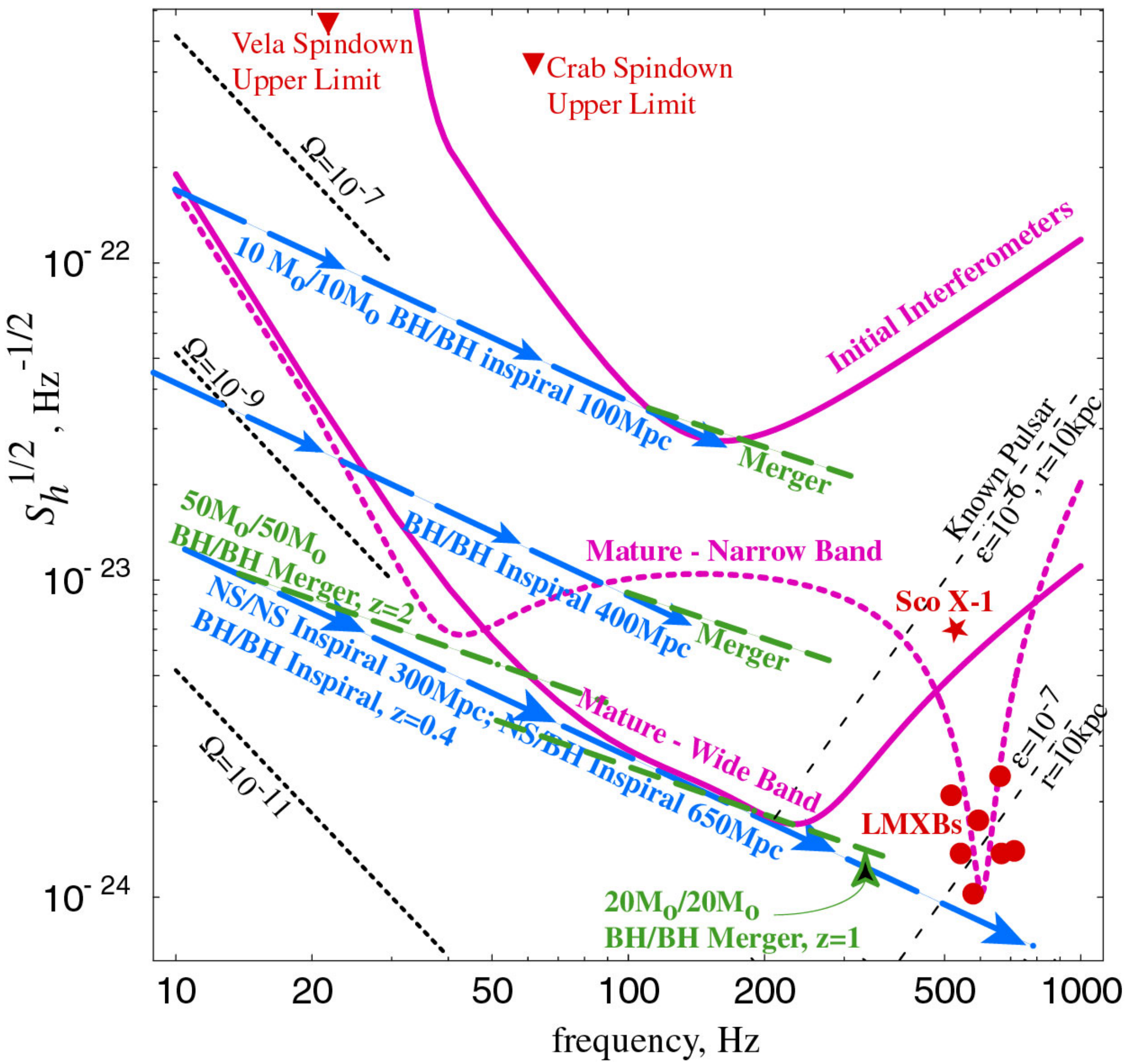
⇒ 1 day of Advanced LIGO

» 1 year of Initial LIGO !

Planned for FY2008 start, installation beginning 2011

Astrophysical 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

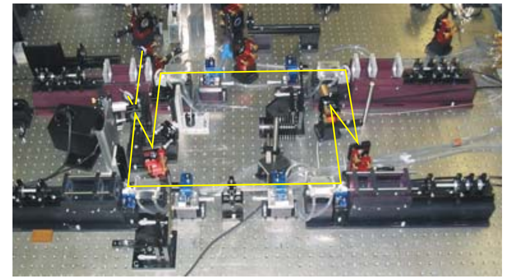


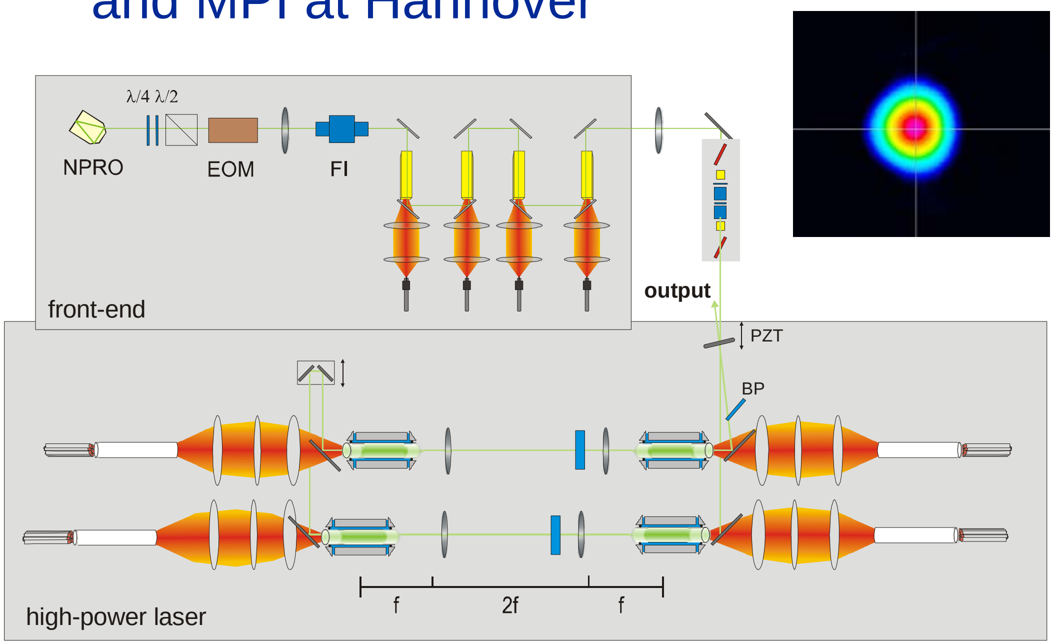
What is Advanced about Advanced LIGO?

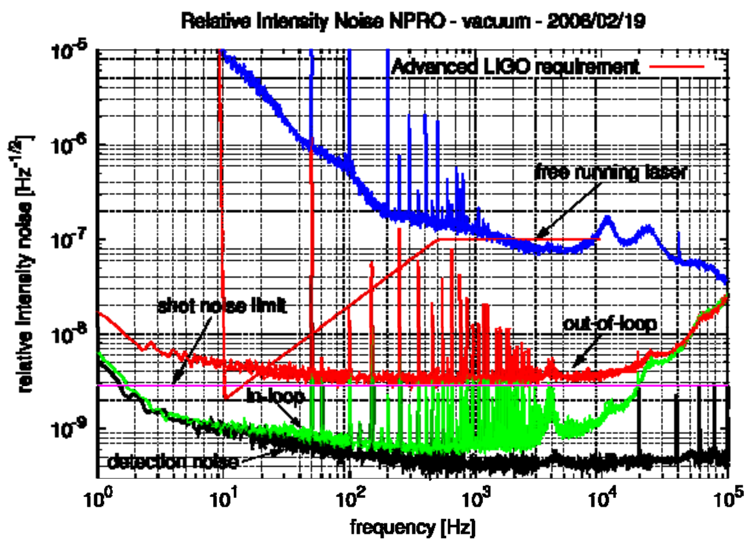
Parameter	LIGO	Advanced LIGO
Input Laser Power	10 W	180 W
Mirror Mass	10 kg	40 kg
Interferometer Topology	Power-recycled Fabry-Perot arm cavity Michelson	Dual-recycled Fabry-Perot arm cavity Michelson
GW Readout Method	RF heterodyne	DC homodyne
Optimal Strain Sensitivity	3×10^{-23} / rHz	Tunable, better than 5×10^{-24} / rHz in broadband
Seismic Isolation Performance	f_{low} ~ 50 Hz	f_{low} ~ 10 Hz
Mirror Suspensions	Single Pendulum	Quadruple pendulum

Advanced LIGO pre-stabilized laser

- 180 W amplitude and frequency stabilized Nd:YAG laser
- Two stage amplification
  - » First stage: MOPA (NPRO + single pass amplifier)
  - » Second stage: injection-locked ring cavity
- Developed by Laser Zentrum Hannover and MPI at Hannover



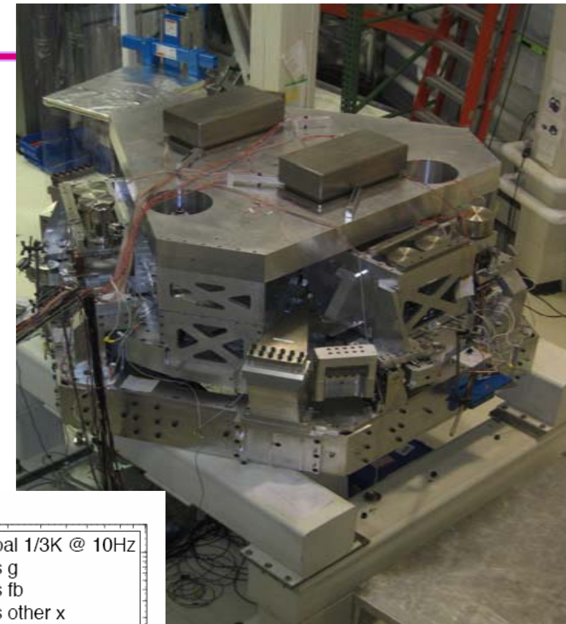


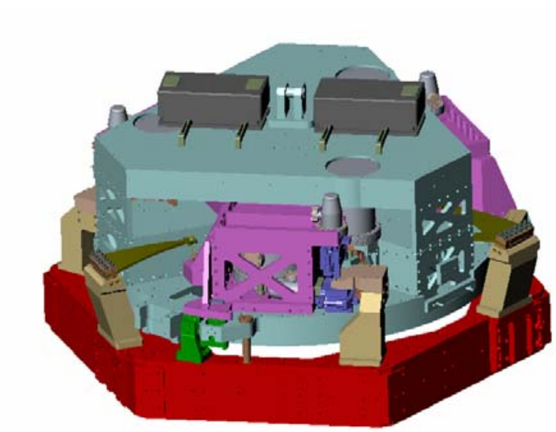


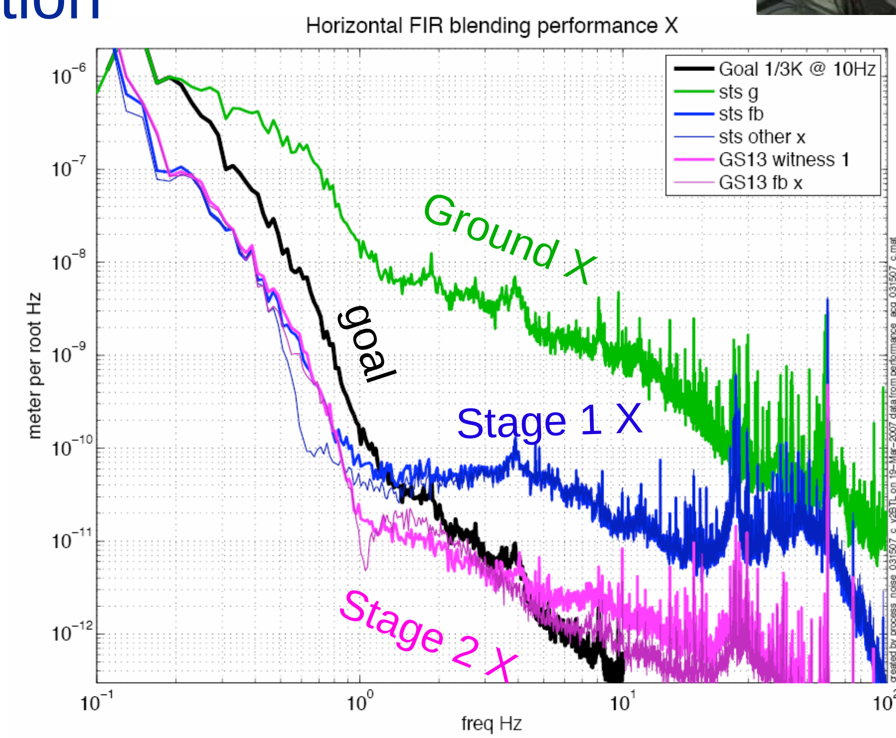
Frede et al, *Opt. Express* **22** p459 (2007)

Seismic isolation

- To open Advanced LIGO band at low frequencies, a complete redesign of the seismic isolation system is needed
- Active isolation, feed forward
- Required Isolation
  - » 10x @ 1 Hz
  - » 3000x @ 10 Hz

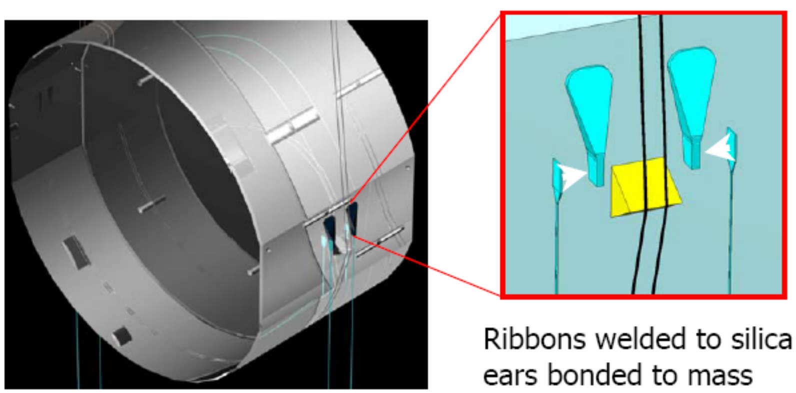






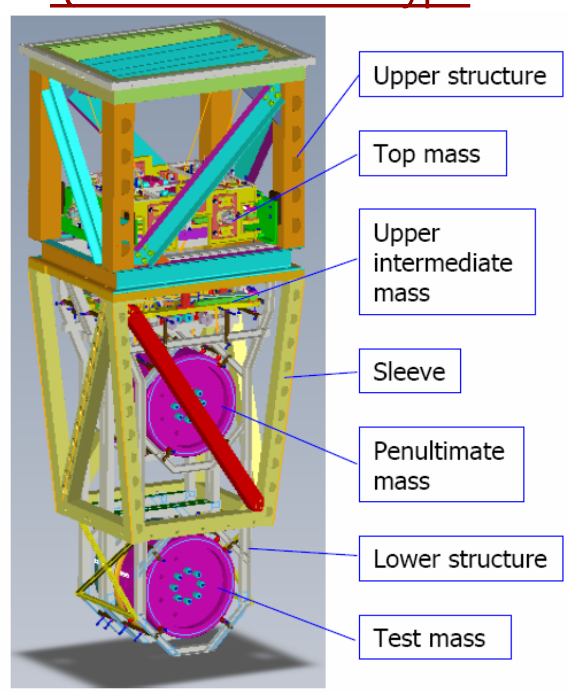
Advanced LIGO suspensions

- Quad controls prototype installed at MIT and undergoing testing
- Noise prototype in fabrication
  - » Lowest mode predicted @ 100 Hz



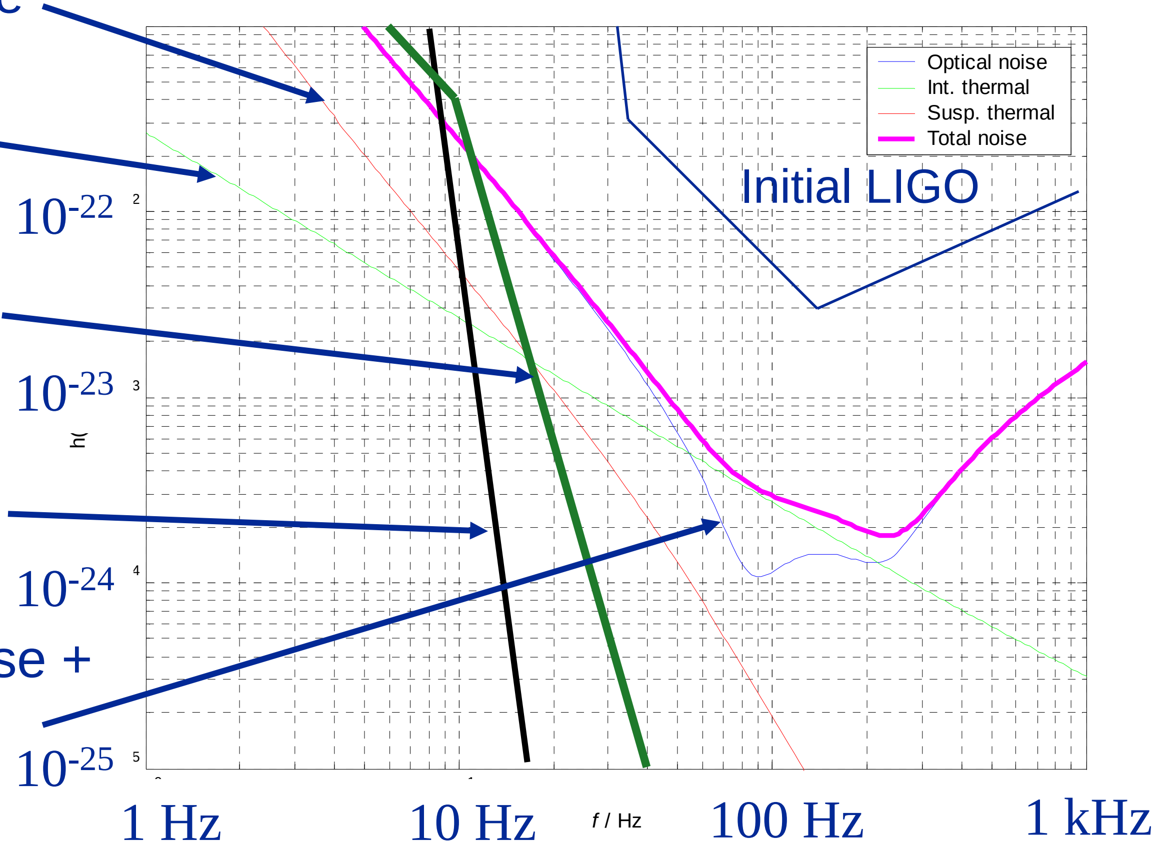
Ribbons welded to silica ears bonded to mass

Quad Noise Prototype



Anatomy of the Projected Adv LIGO Detector Performance

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



The Importance of Advanced LIGO Core Optics

- Two limiting noise sources in Advanced LIGO—both dependent on core optics properties
  - » Thermal noise due to coating-substrate interaction
  - » Quantum noise (shot noise plus radiation pressure)
- Improvements in optics lead directly to improved sensitivity
  - » Reduced scatter
  - » Tighter control on ROC
  - » Lower mechanical loss in coating
- Roles of substrate, polishing, and coating still under investigation

Added Optics Challenges

- Circulating power in LIGO arm cavities will approach 1 MW
  - » Absorption (leading to distortion) becomes even more significant
- Size increases from 11 kg to 40 kg
  - » Handling tooling required
  - » Cleaning techniques must be augmented, tested
- Beam spot size increases
  - » Metrology over larger regions than in initial LIGO
- Fabrication schedule

Final Thoughts

- We are on the threshold of a new era in GW detection
  - » The technical challenges of the first generation interferometers have been overcome
  - » LIGO has reached design sensitivity and is taking data
  - » First detections could come in the next year (or two, or three …)
- Worldwide network is forming
  - » 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
  - » Brings a new set of technological challenges