LIGO –
The Laser Interferometer Gravitational-wave Observatory

Albert Lazzarini

Technical Interchange Meeting at LLNL on Optics Contamination

Livermore, CA

11 September 2007

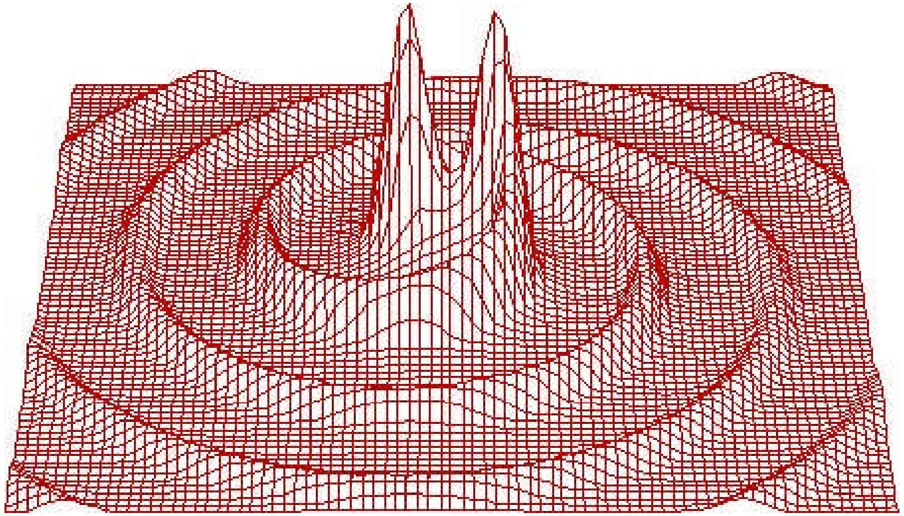
LIGO Scientific Collaboration

- 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
  - The opening of a new window on the Universe
- LIGO Detector Overview
  - Performance Goals
  - How do they work?
  - What do the parts look like?
- Recent Results
- Towards a Global Network
- Advanced LIGO Detectors
  - New challenges

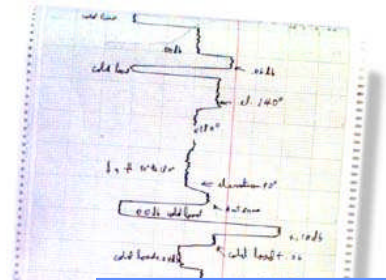


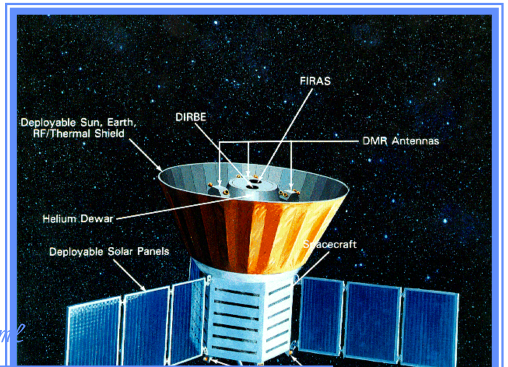
gravitational radiation
binary inspiral of compact objects
(blackholes or neutron stars)

The Opening of New Observational Windows on the Universe

New technologies bring surprises

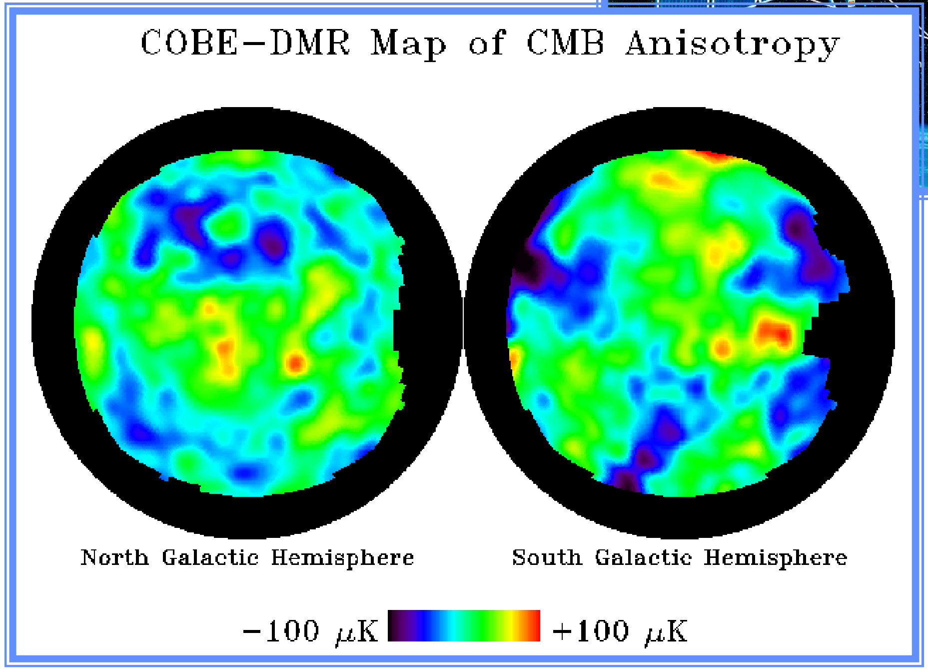
- Penzias & Wilson, 1963
  - Track down excess antenna noise
    - Discover the cosmic microwave background radiation (CMBR)





http://www.gsfc.nasa.gov/astro/cobe/cobe_home.html

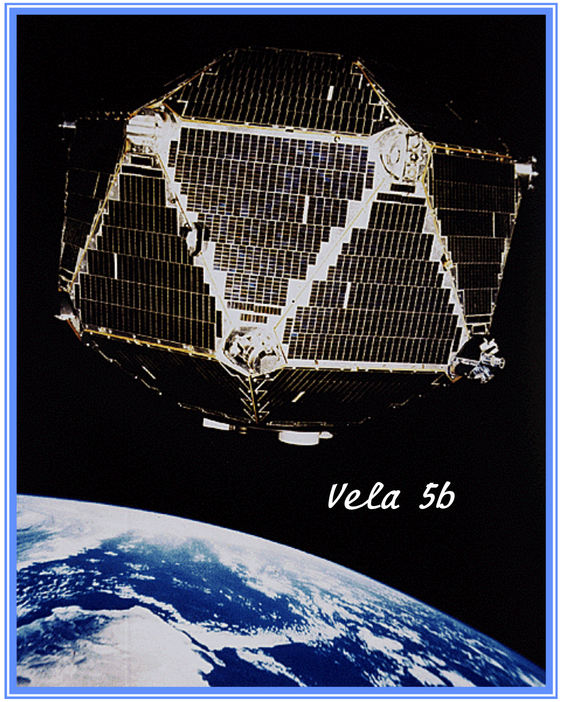
http://www.lucent.com/museum/1964bang.html



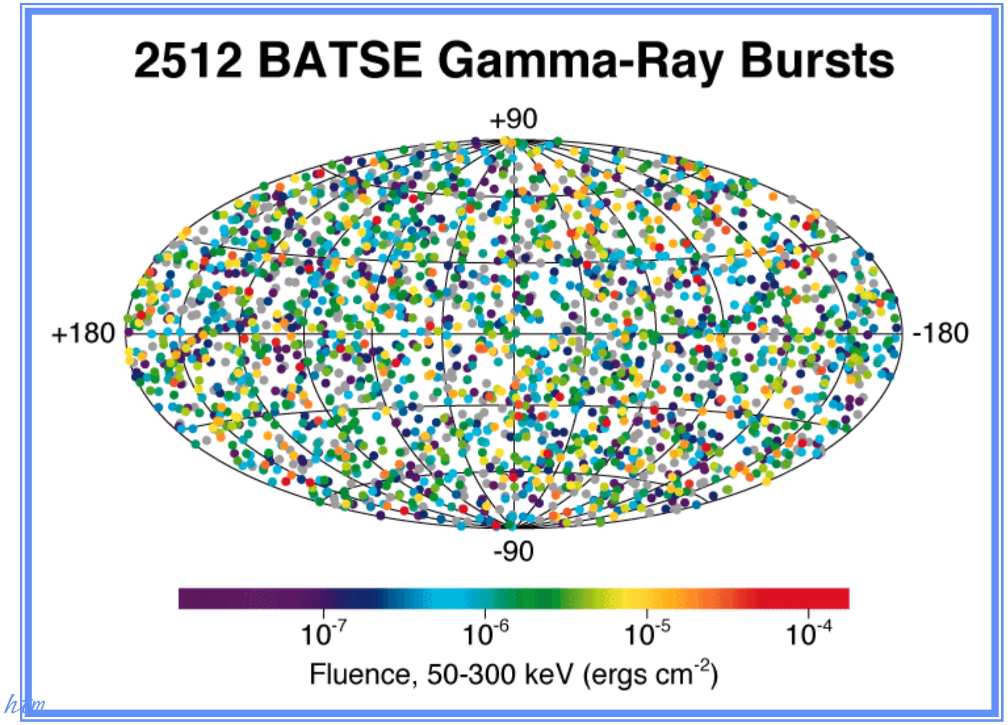
The Opening of New Observational Windows on the Universe

New technologies bring surprises

- Klebesadel, Strong & Olsen (LANL), 1969
  - » Review of Vela 5 satellite data from 1967.07.02 showed a γ event of non-terrestrial origin
    - » Discover γ–ray bursts (GRBs), X-ray sources



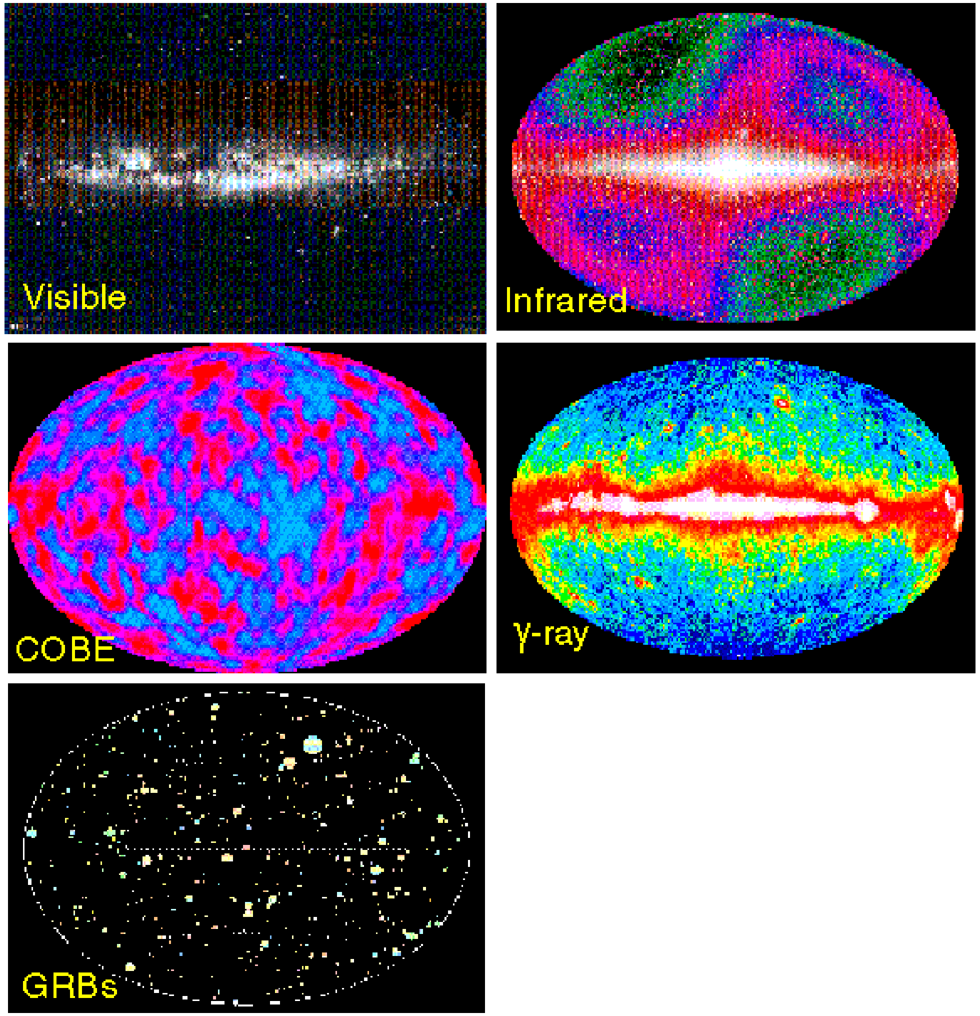
http://science.msfc.nasa.gov/newhome/headlines/ast19sep97_2.htm

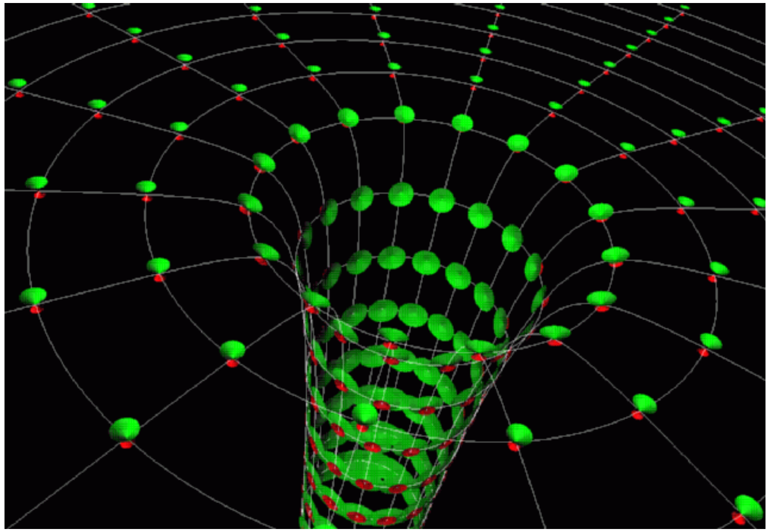


http://www.batse.com/

Opening of a New Window on Universe

New messengers may bring new surprises!



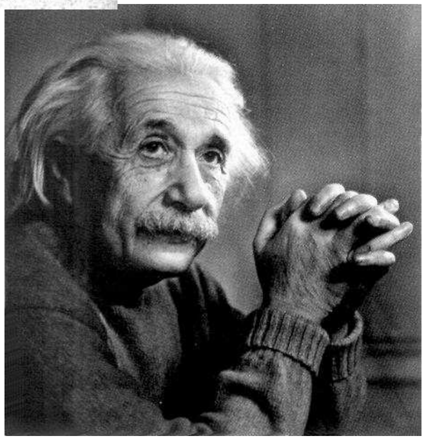


GRAVITATIONAL WAVES WILL GIVE A NEW AND UNIQUE VIEW OF THE DYNAMICS OF THE UNIVERSE.

EXPECTED **SOURCES:**
BLACK HOLES,
SUPERNOVAE, PULSARS AND
COMPACT BINARY SYSTEMS.

POSSIBILITY FOR THE UNEXPECTED IS VERY REAL!

Albert Einstein

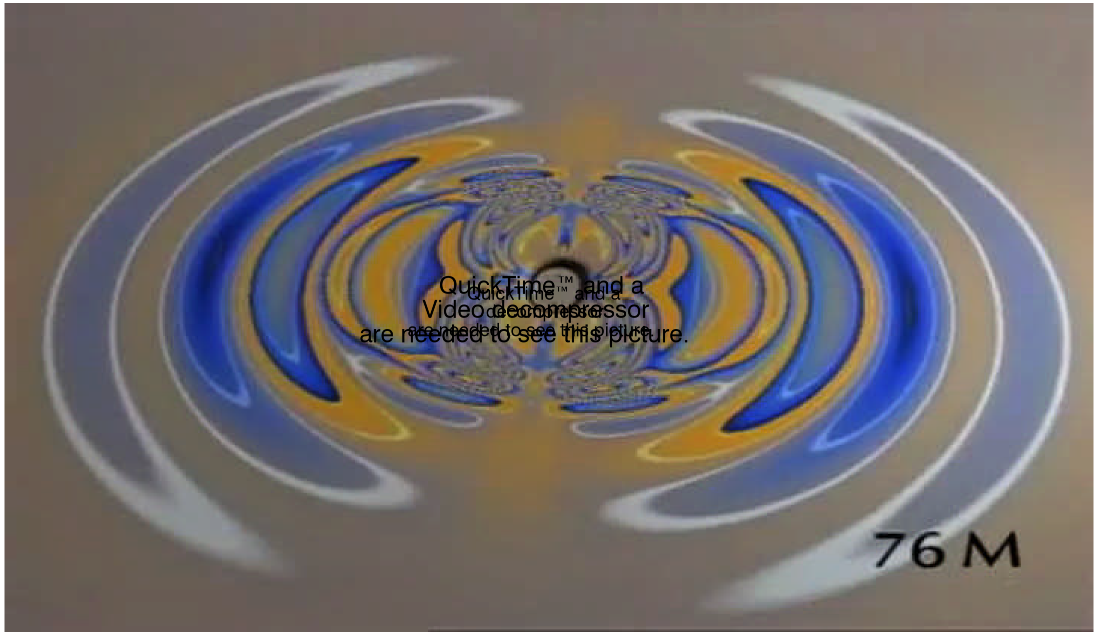


- The Special Theory of Relativity (1905) overthrew commonsense assumptions about space and time
    - » Finite propagation of information
        - ☒ Electromagnetic radiation
- The General Theory of Relativity and theory of Gravity (1916)
    - » Gravity described as a warpage of spacetime, not a force acting at a distance
    - » Finite propagation of influence of gravity
        - ☒ Gravitational radiation

Einstein's Theory of Relativistic Gravity

Newton's Theory

"instantaneous action at a distance"



Einstein's Theory

Curved spacetime

Information carried by gravitational radiation at the speed of light

$\left|\dot{E}\right| \approx \frac{G}{45c^5}\dddot{Q}^2$ radiated power

$1.4M_{sun} + 1.4M_{sun} @ D = 50km$

$f = 275Hz \; ; \; \frac{v}{c} \approx 0.15 \; (!)$

$\left|\dot{E}\right| \approx 6\times10^{46} W ; \; R_{Virgo} = 17 Mpc$

$\Phi_{Earth} \approx 200 \; mW/m^2$

Luminosity is huge

Solar luminosity: 4 x 10^{26} W

… but …

spacetime is VERY stiff …

Effect: TINY!!!

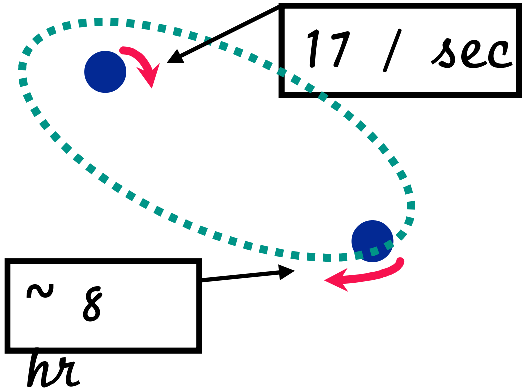
h => Gravitational wave strain: h = ΔL/L

$h \approx \frac{2G}{3c^4 r}\ddot{Q}$ amplitude of wave

$h \approx 10^{-21} @ 10Mpc$

Evidence for Gravitational Waves:

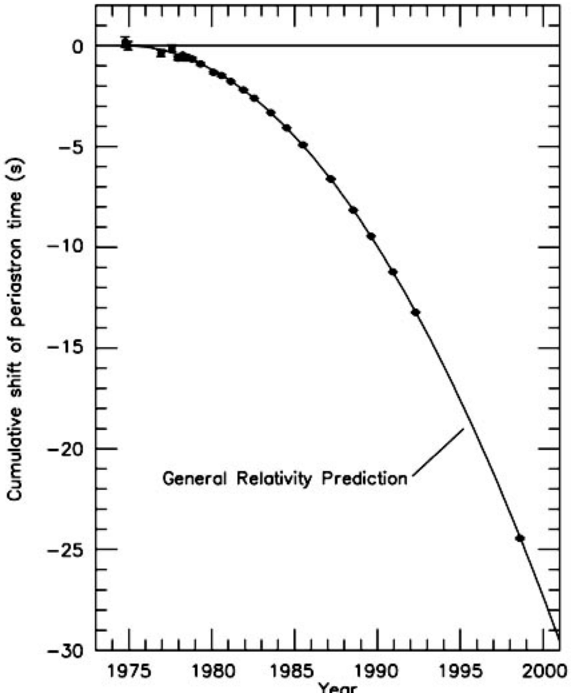
Neutron Star Binary PSR1913+16



17 / sec

~ 8 hr

- 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.

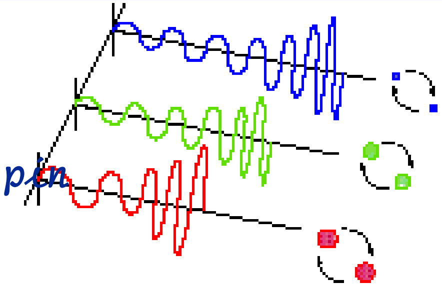


- After correcting for all known relativistic effects, observe loss of orbital energy

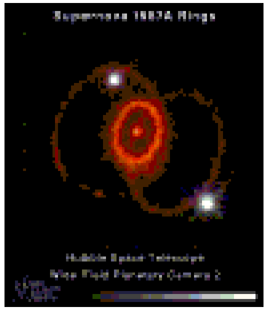
=> Emission of GWs

Astrophysical Sources of GWs

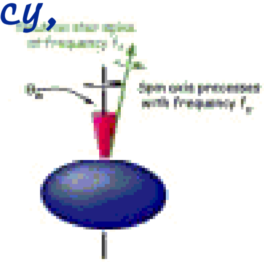
- Compact binary inspiral: "chirps"
  - NS-NS binaries well understood
  - BH-BH binaries need further calculation, spin
  - Search technique: matched templates



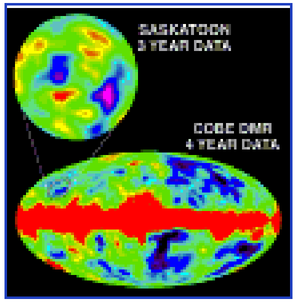
- Supernovas or GRBs: "bursts"
  - GW signals observed in coincidence with EM or neutrino detectors
  - Prompt alarm for supernova? (~1 hour?)



- 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?

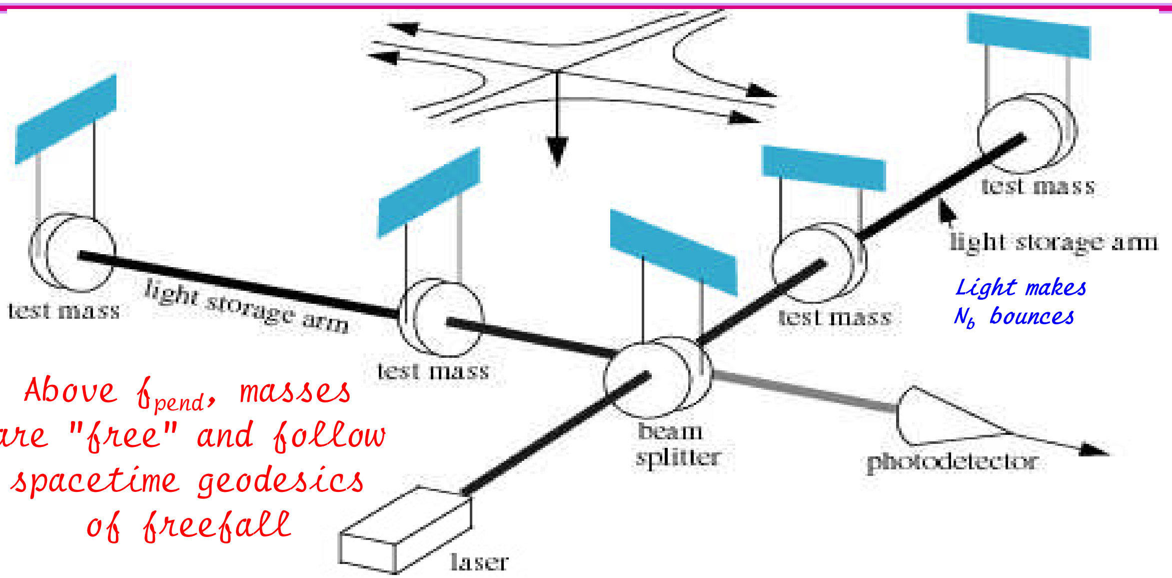


- Cosmological: "stochastic background"
  - Probing the universe back to the Planck time (10^{-43} s)



Interferometers as precision strain meters

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



Light makes N_b bounces

Above f_{pend}, masses are "free" and follow spacetime geodesics of freefall

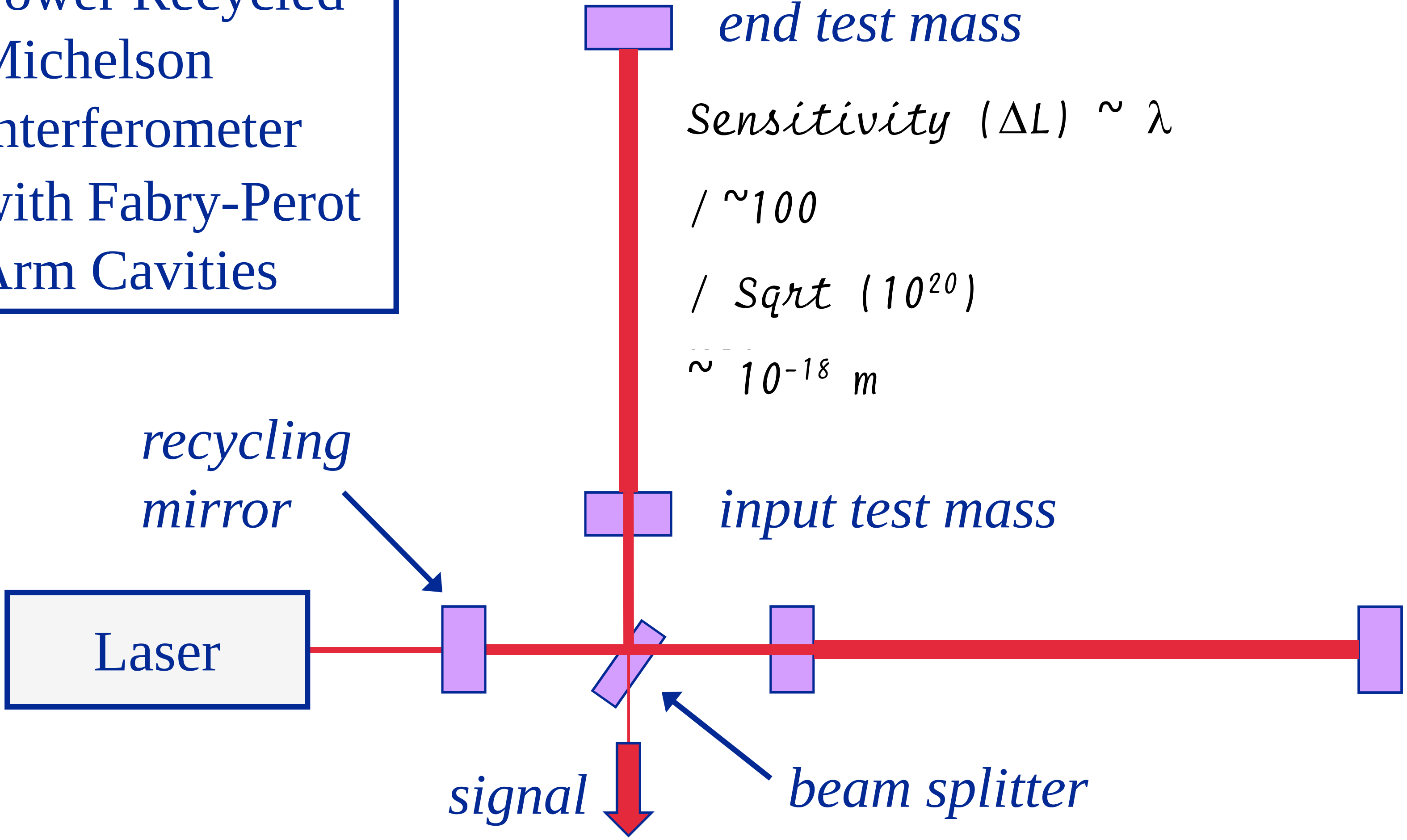
$h = 1/2\ (\Delta L_x - \Delta L_y)/L \Rightarrow \Delta\phi/2\pi = 2\ N_b\ hL/\lambda$

Detector concept

- The concept is to compare the time it takes light to travel in two orthogonal directions transverse to the gravitational waves.
- The gravitational wave causes the time difference to vary by stretching one arm and compressing the other.
- The interference pattern is measured (or the fringe is split) to one part in 10^{10}, in order to obtain the required sensitivity.

Optical Configuration

Power Recycled Michelson Interferometer with Fabry-Perot Arm Cavities



Sensitivity $(\Delta L) \sim \lambda$

$/ \sim 100$

$/ \mathrm{Sqrt}\ (10^{20})$

$\sim 10^{-18}$ m

LIGO Observatories

GEODETIC DATA (WGS84)

h: -6.574 m

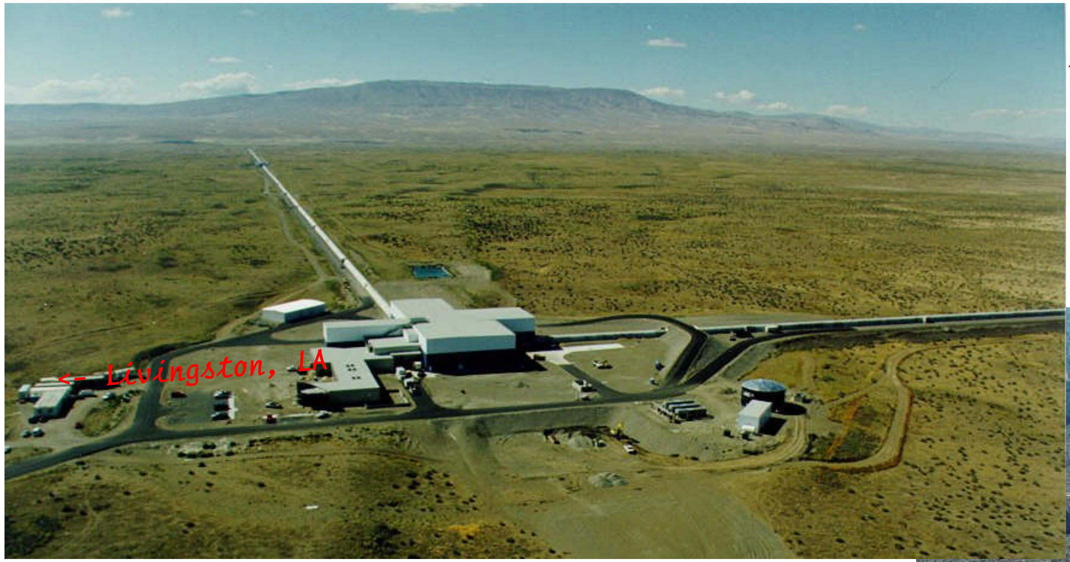
X arm: S72.283

ϕ: N30°33□46.419531□

Ψ αρμ: Σ17.7164°E

λ: Ω90°46□27.265294□

Livingston Observatory
Louisiana
One interferometer (4km)



Hanford Observatory
Washington
Two interferometers
(4 km and 2 km arms)

GEODETIC DATA (WGS84)

h: 142.555 m

X arm:

N35.9993°W

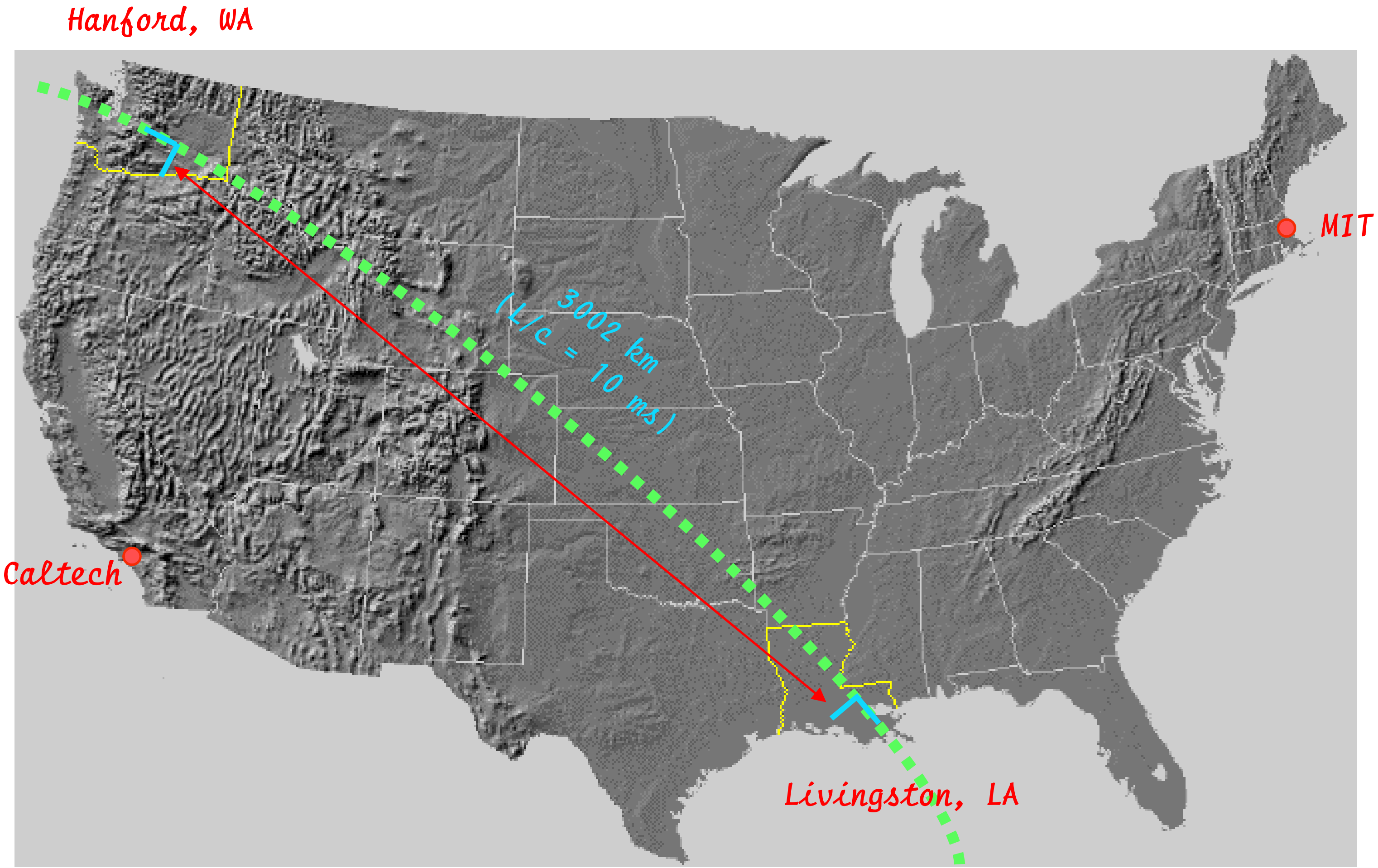
ϕ: N46°27□18.527841□

Ψ αρμ: Σ54.0007°Ω

λ: Ω119°24□27.565681□

The LIGO Laboratory Sites

Interferometers are aligned along the great circle connecting the sites

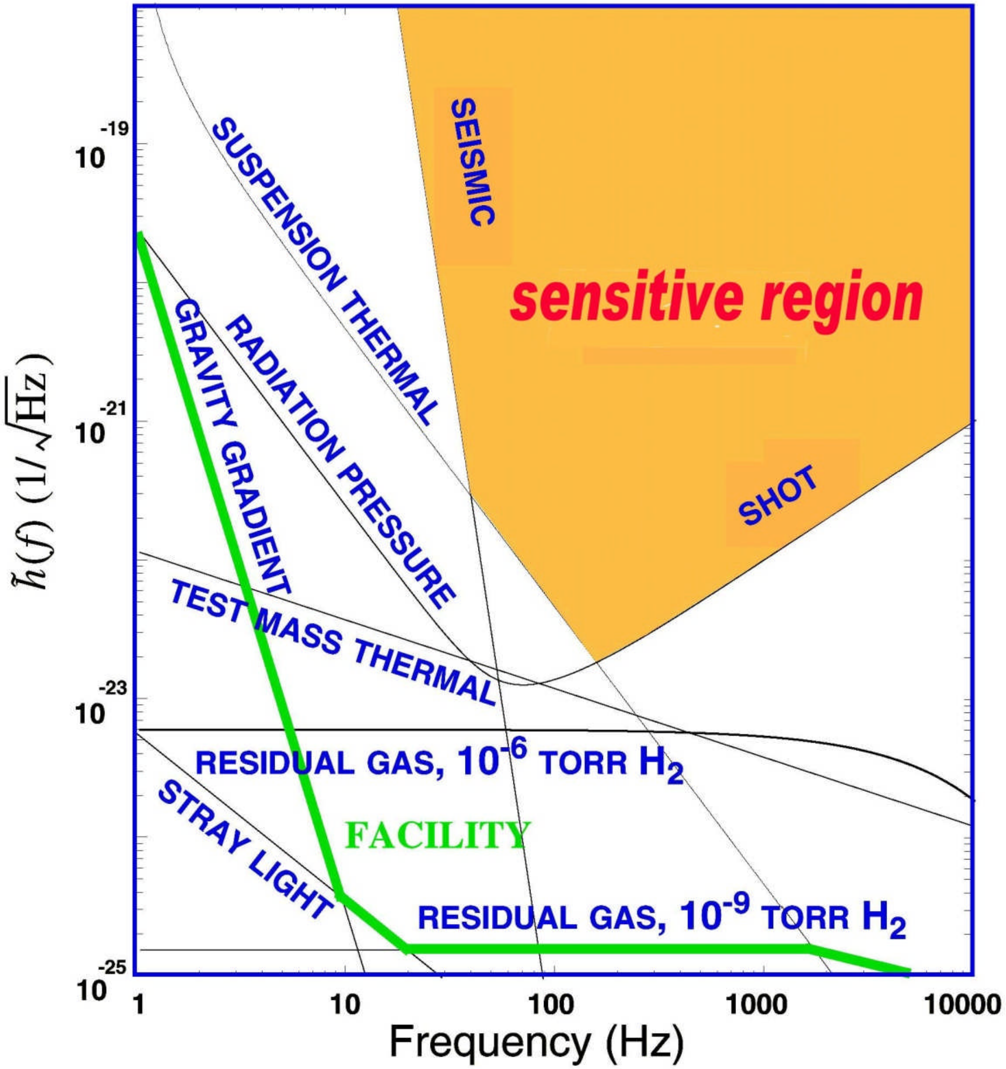


LIGO First Generation Detector

Limiting noise floor

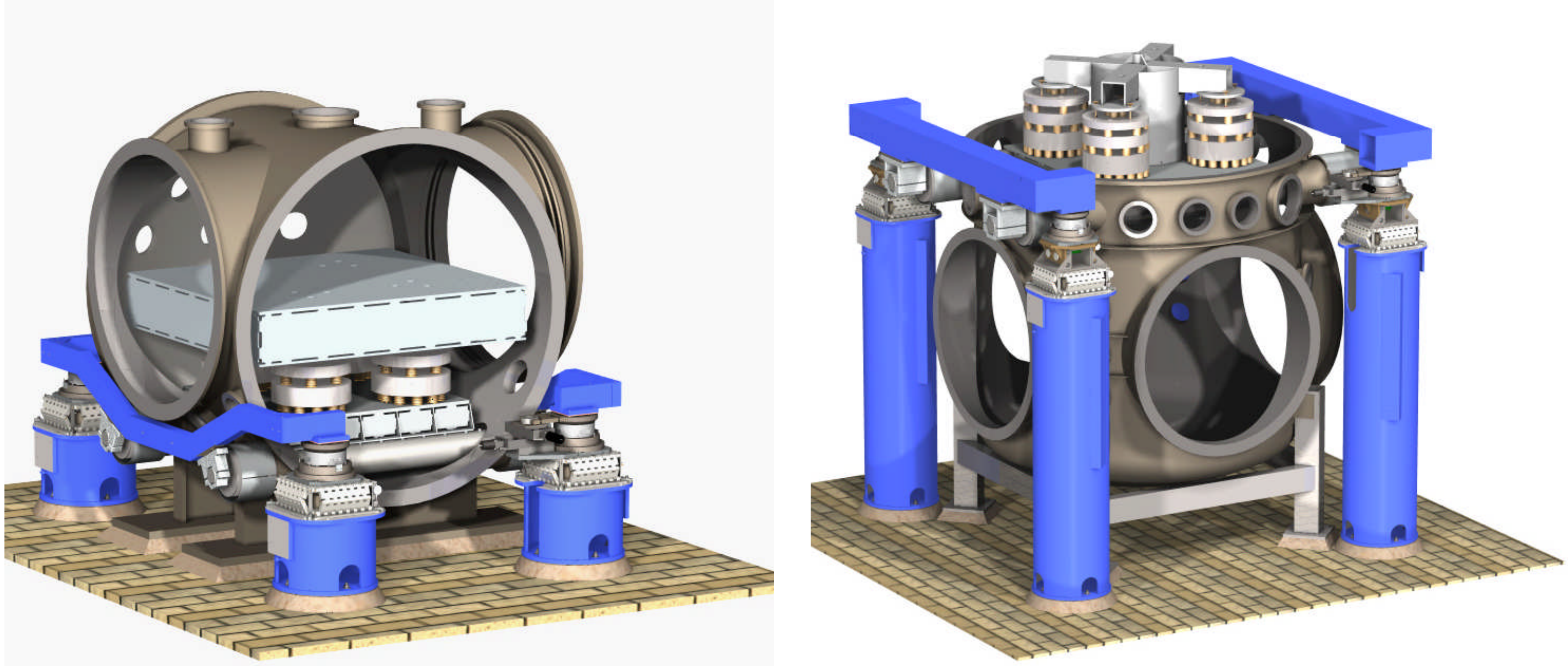
- **Interferometry is limited by three fundamental noise sources**
  - **seismic noise at the lowest frequencies**
  - **thermal noise (Brownian motion of mirror materials, suspensions) at intermediate frequencies**
  - **shot noise at high frequencies**

- **Many other noise sources lie beneath and must be controlled as the instrument is improved**

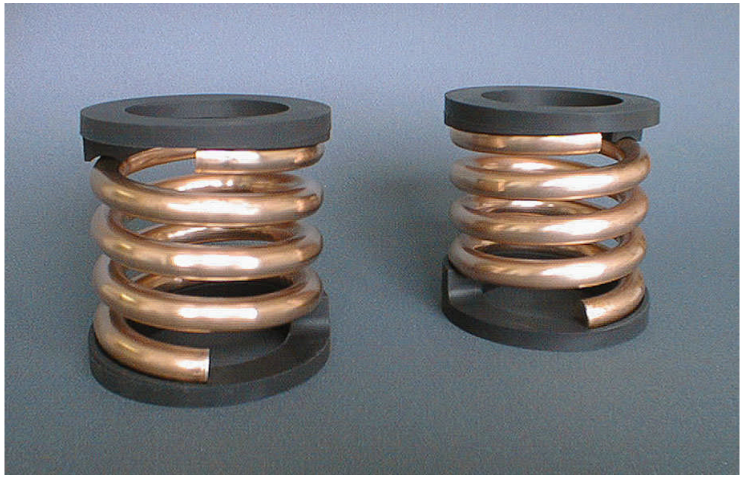


Vibration Isolation Systems

- 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

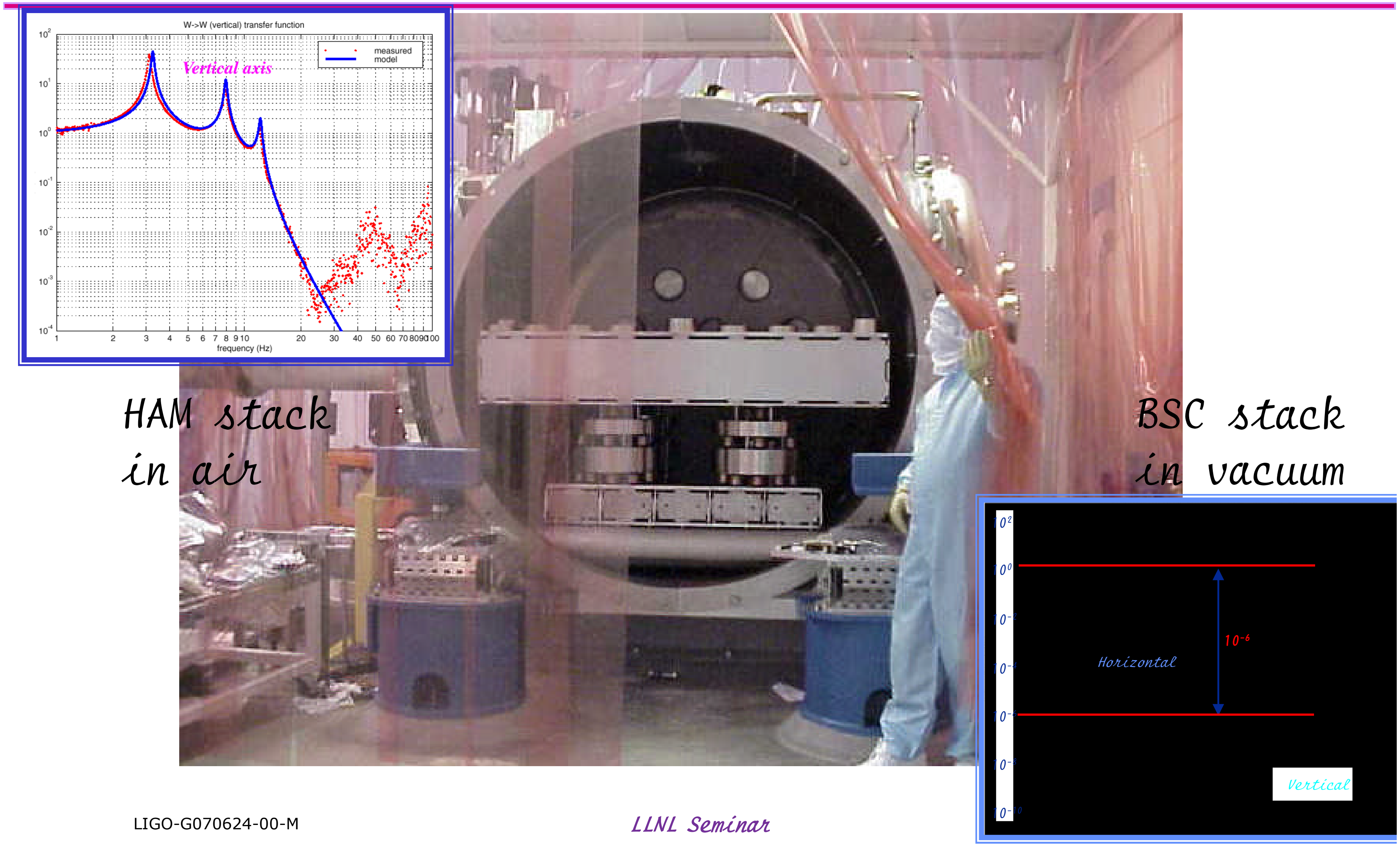


Seismic Isolation - Springs and Masses



damped spring
cross section

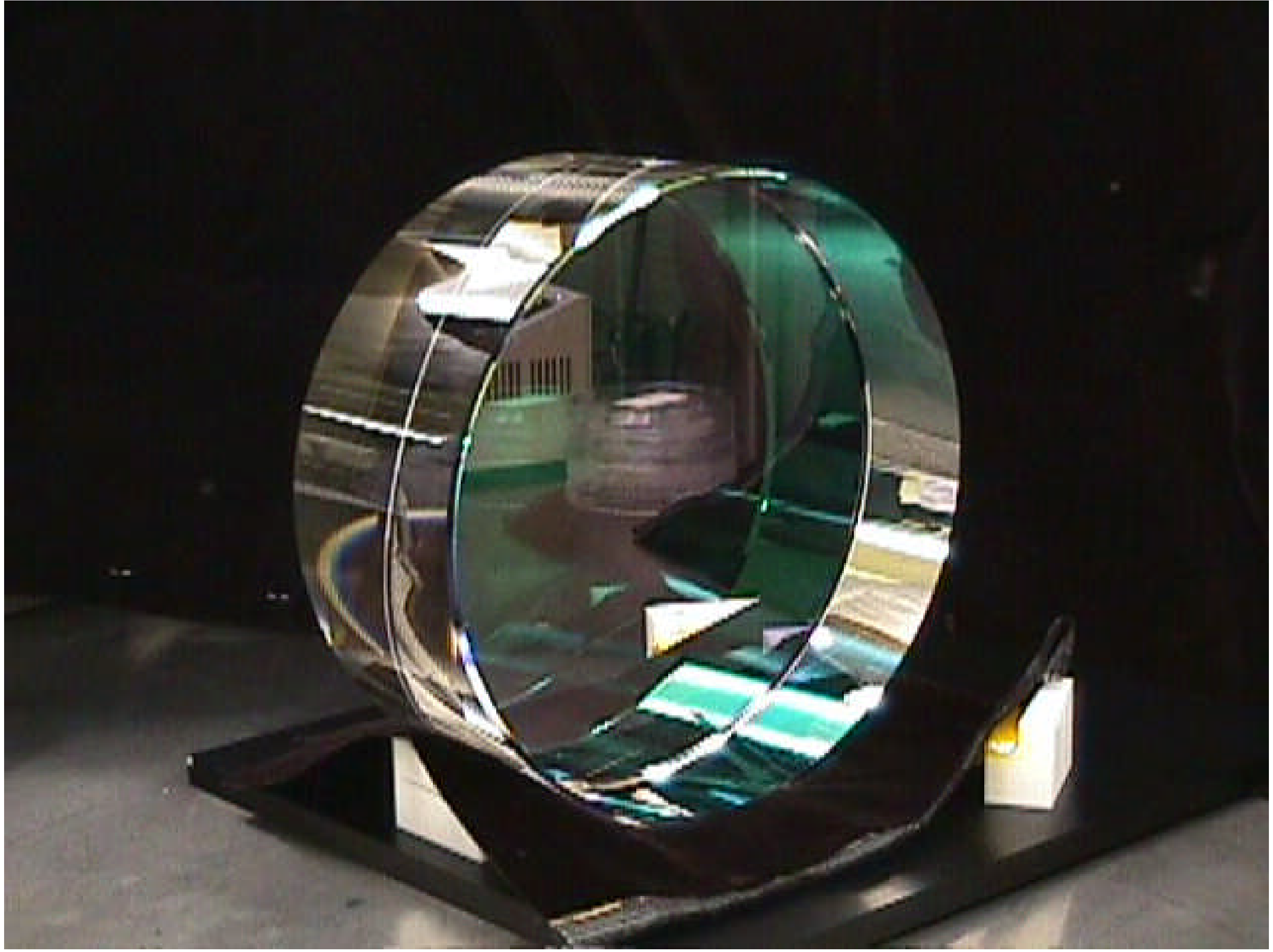
Seismic System Performance



HAM stack
in air

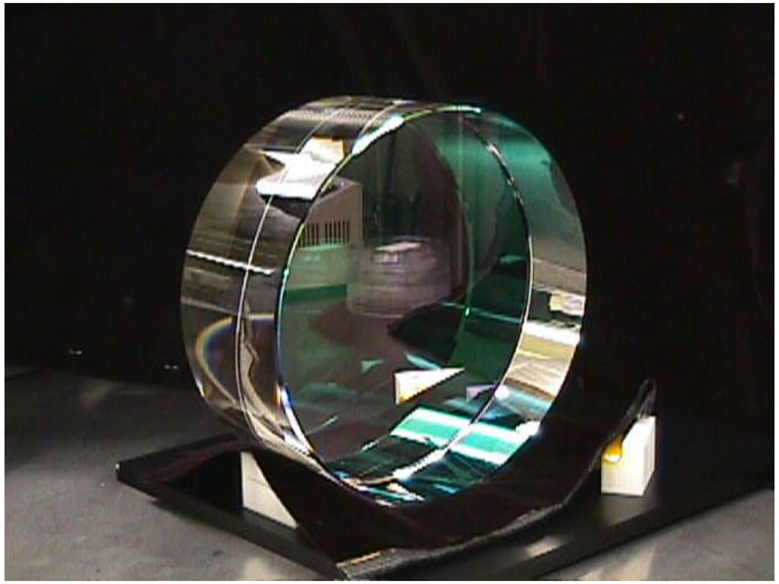
BSC stack
in vacuum

Core Optics



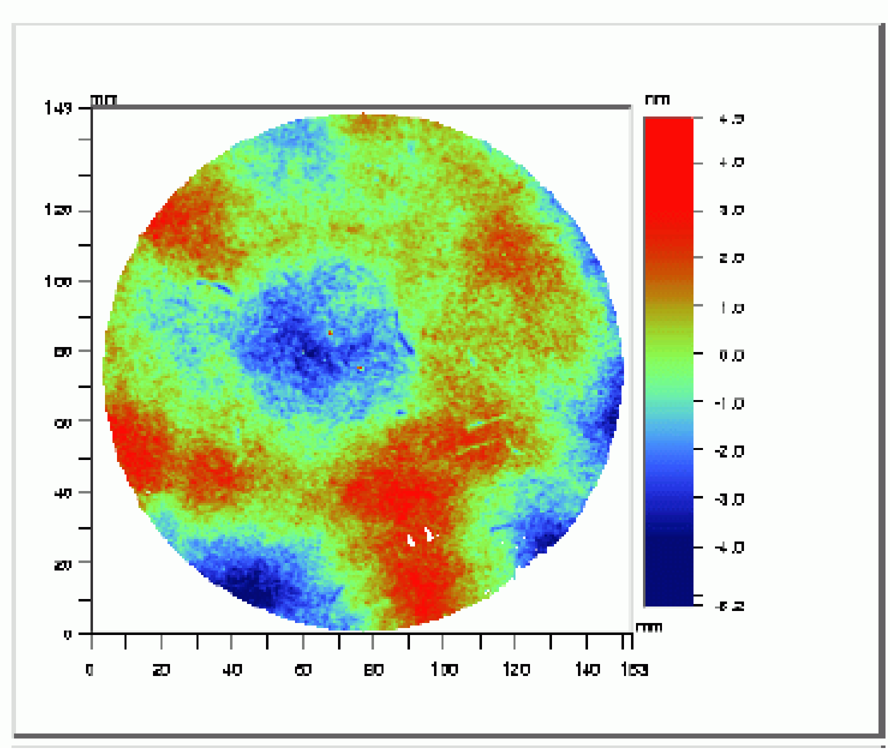
Core Optics Requirements

- Substrates: SiO_2
  - » 25 cm Diameter, 10 cm thick
  - » Homogeneity $< 5 \times 10^{-7}$
  - » Internal mode Q's $> 2 \times 10^{6}$
- 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

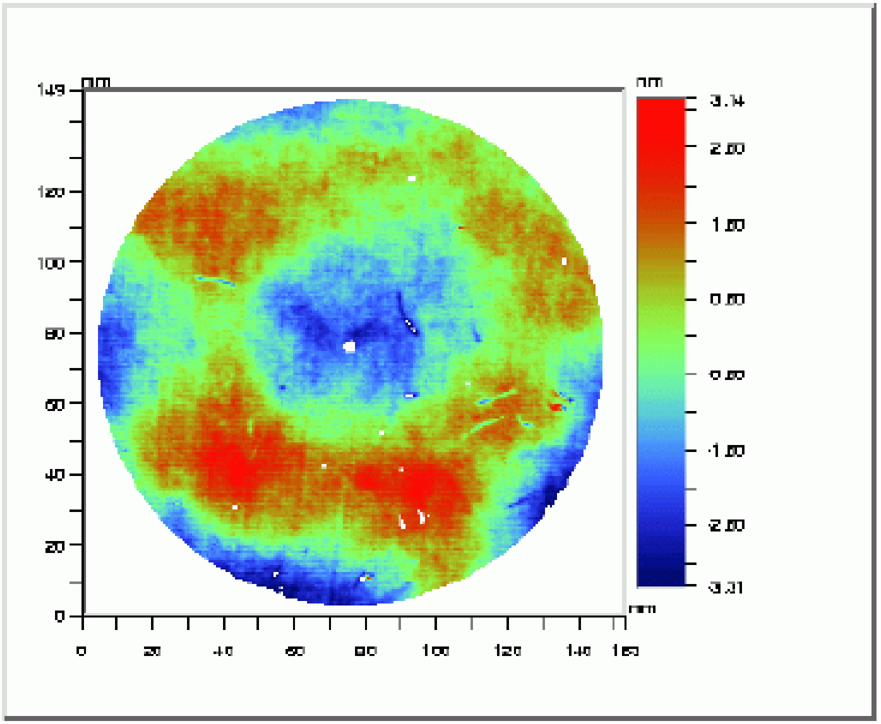


Core Optic Metrology

- Current state of the art: 0.2 nm

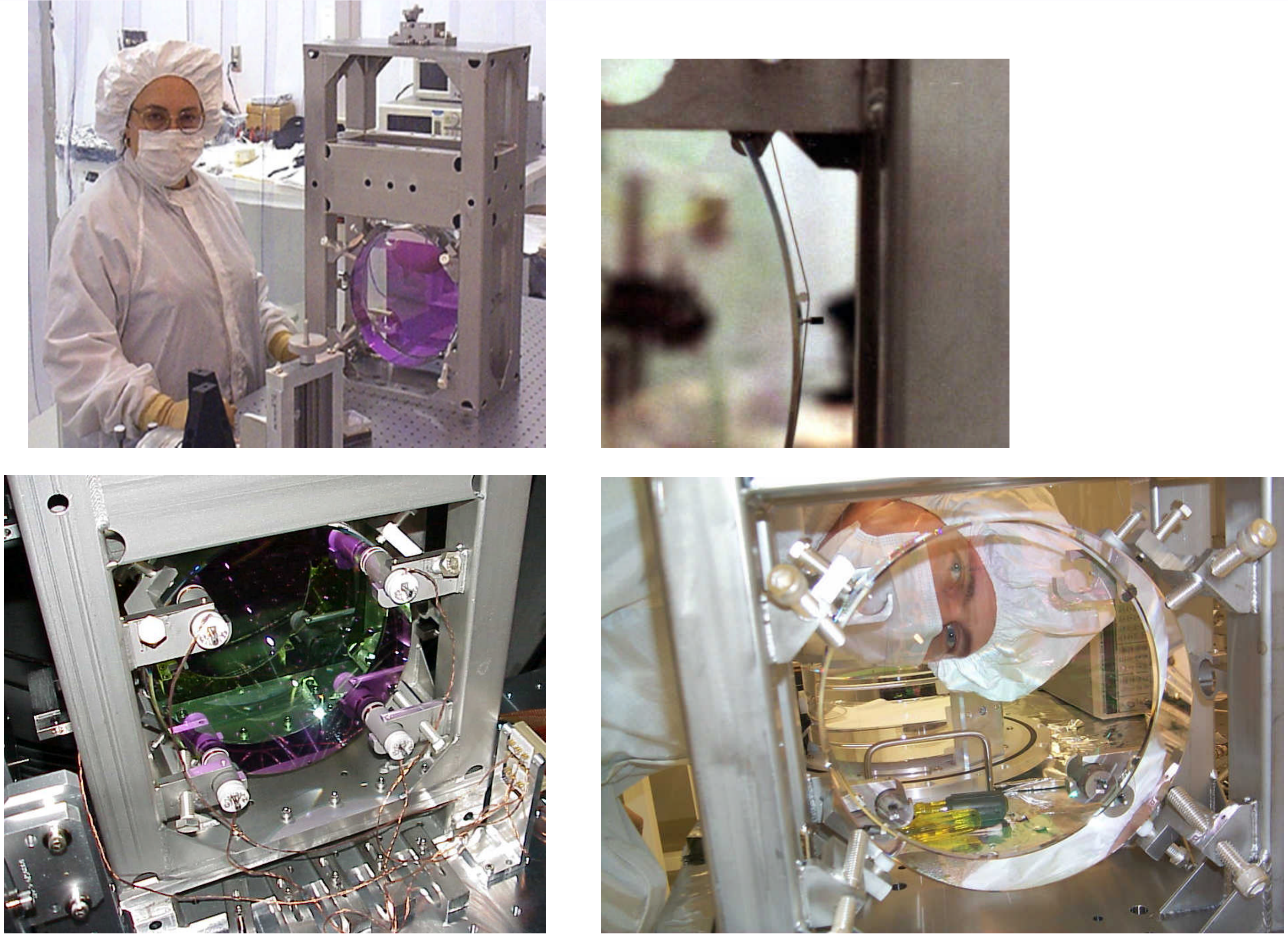


LIGO data (1.2 nm rms)



CSIRO (vendor) data (1.1 nm rms

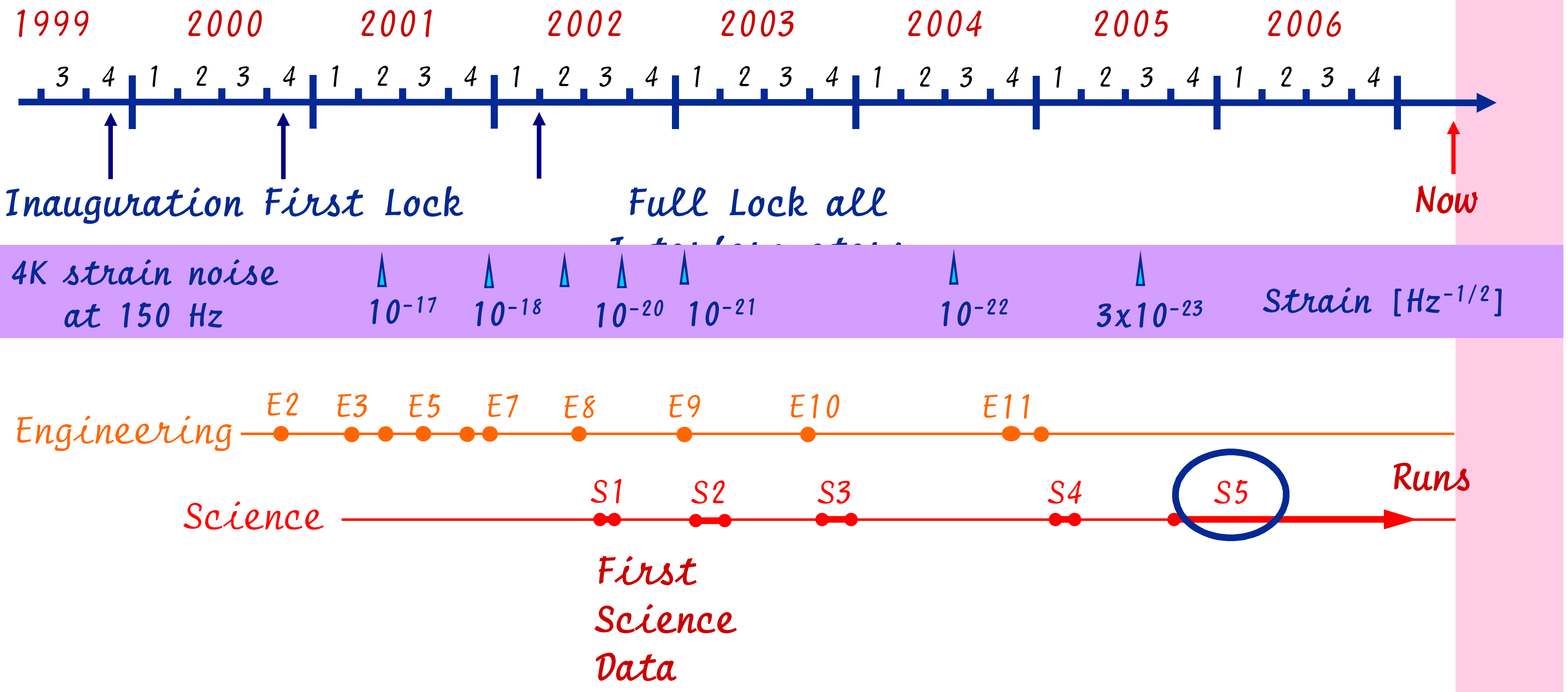
Core Optics Suspension and Control



Core Optics Installation and Alignment

Initial Alignment Requirement:
100 microradians (50 goal)

LIGO History



Inauguration

First Lock

Full Lock all

Now

4K strain noise
at 150 Hz

10^{-17} 10^{-18} 10^{-20} 10^{-21} 10^{-22} $3x10^{-23}$

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

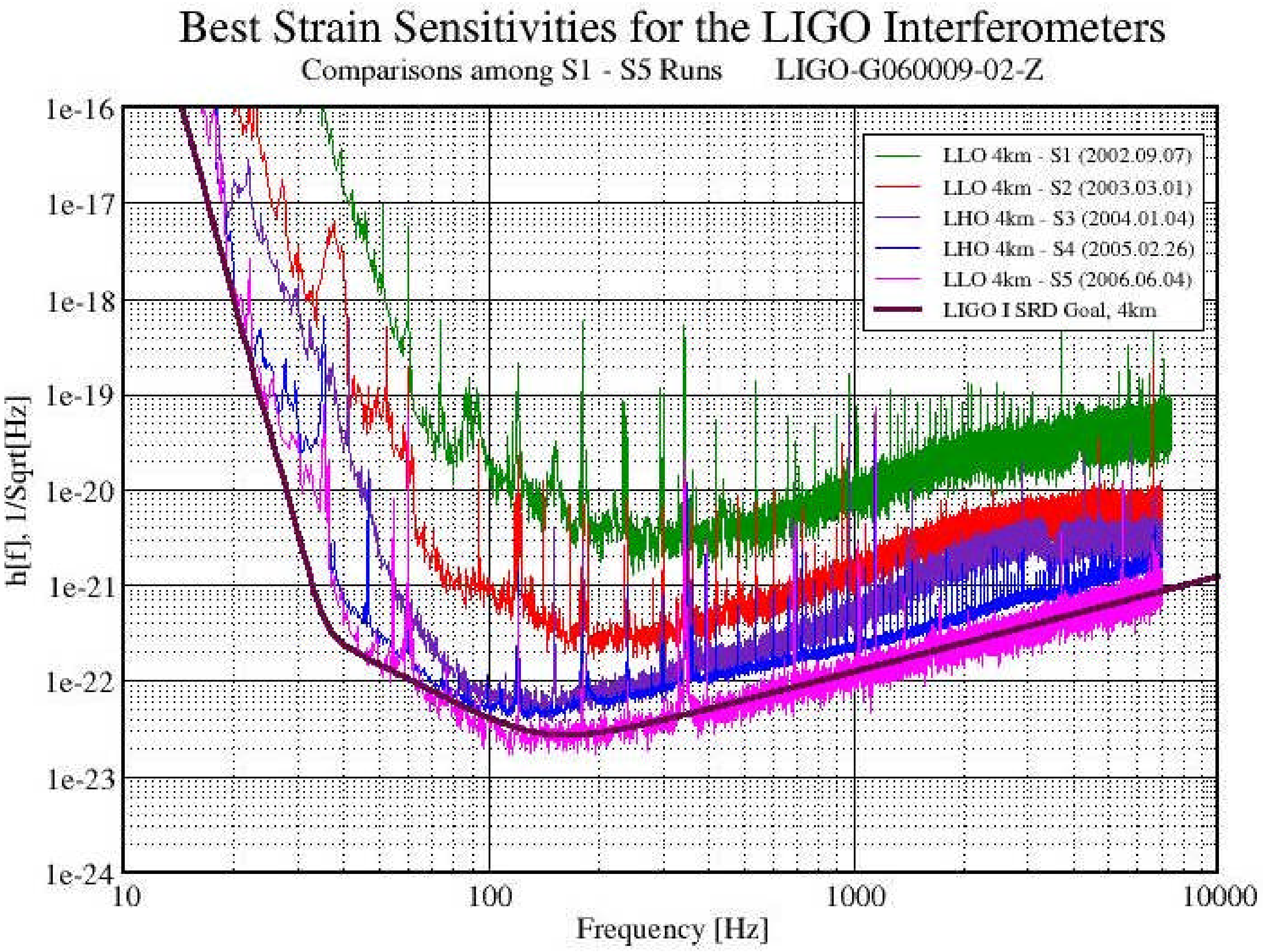
Engineering

Science

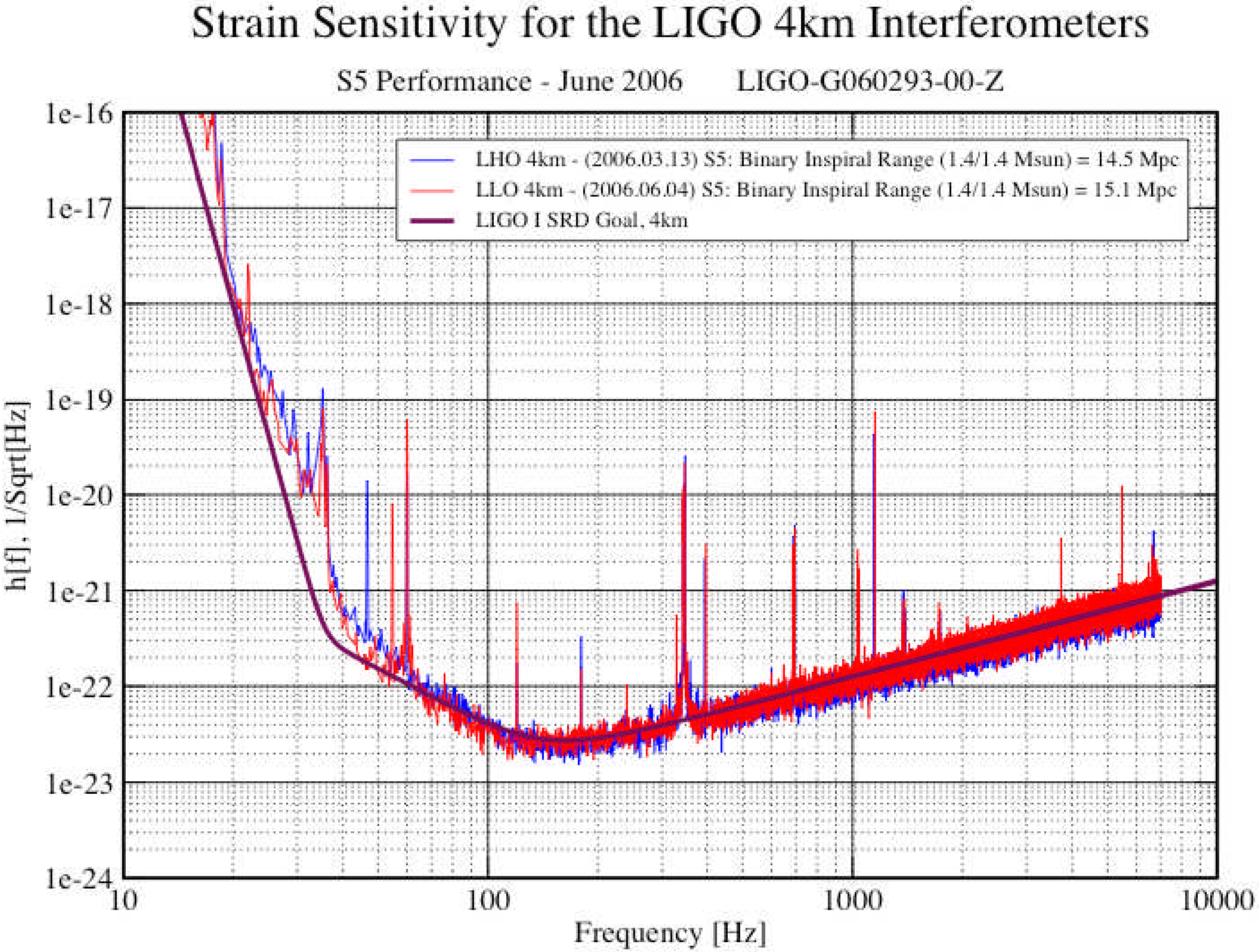
Runs

First
Science
Data

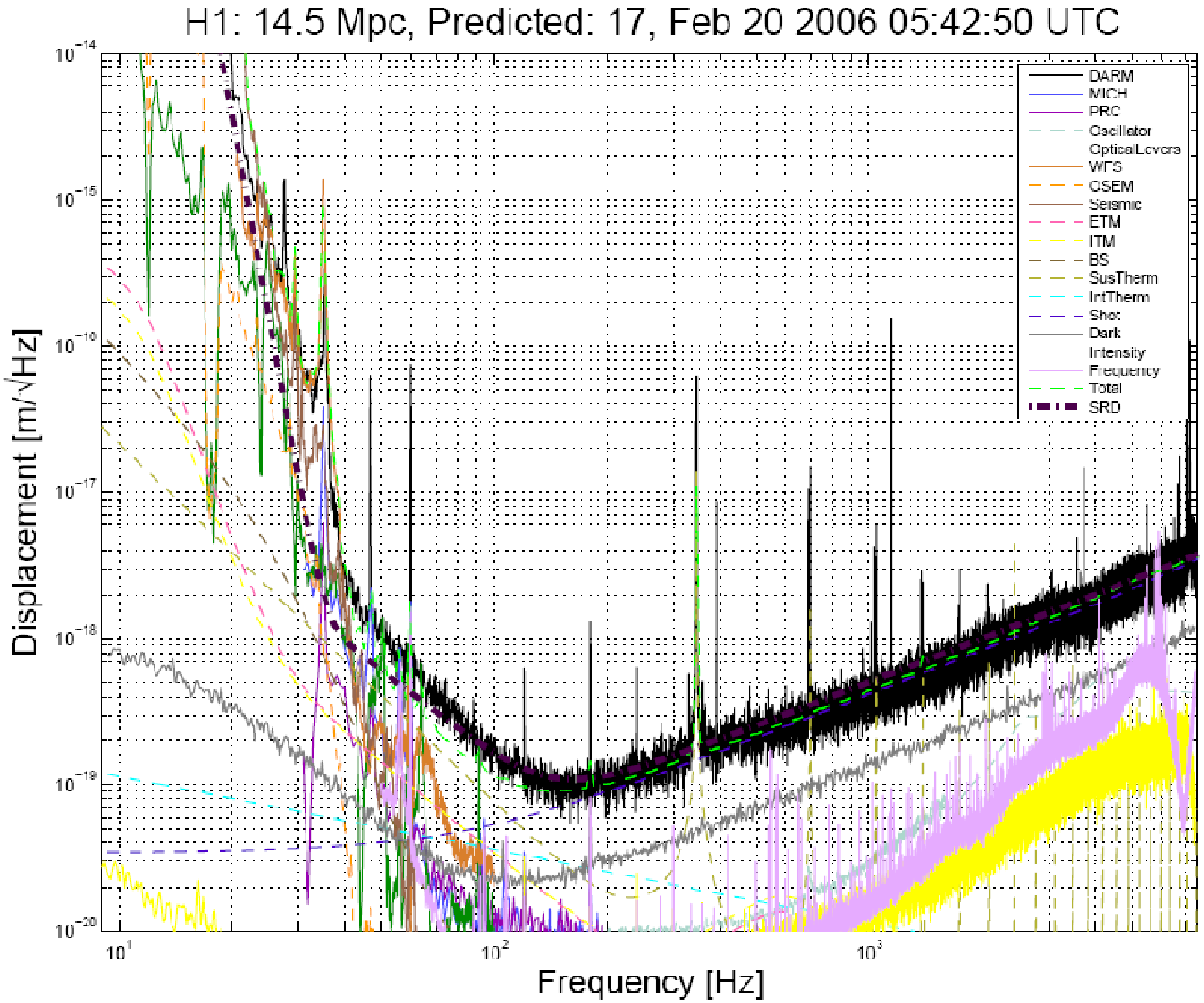
Sensitivity Progress



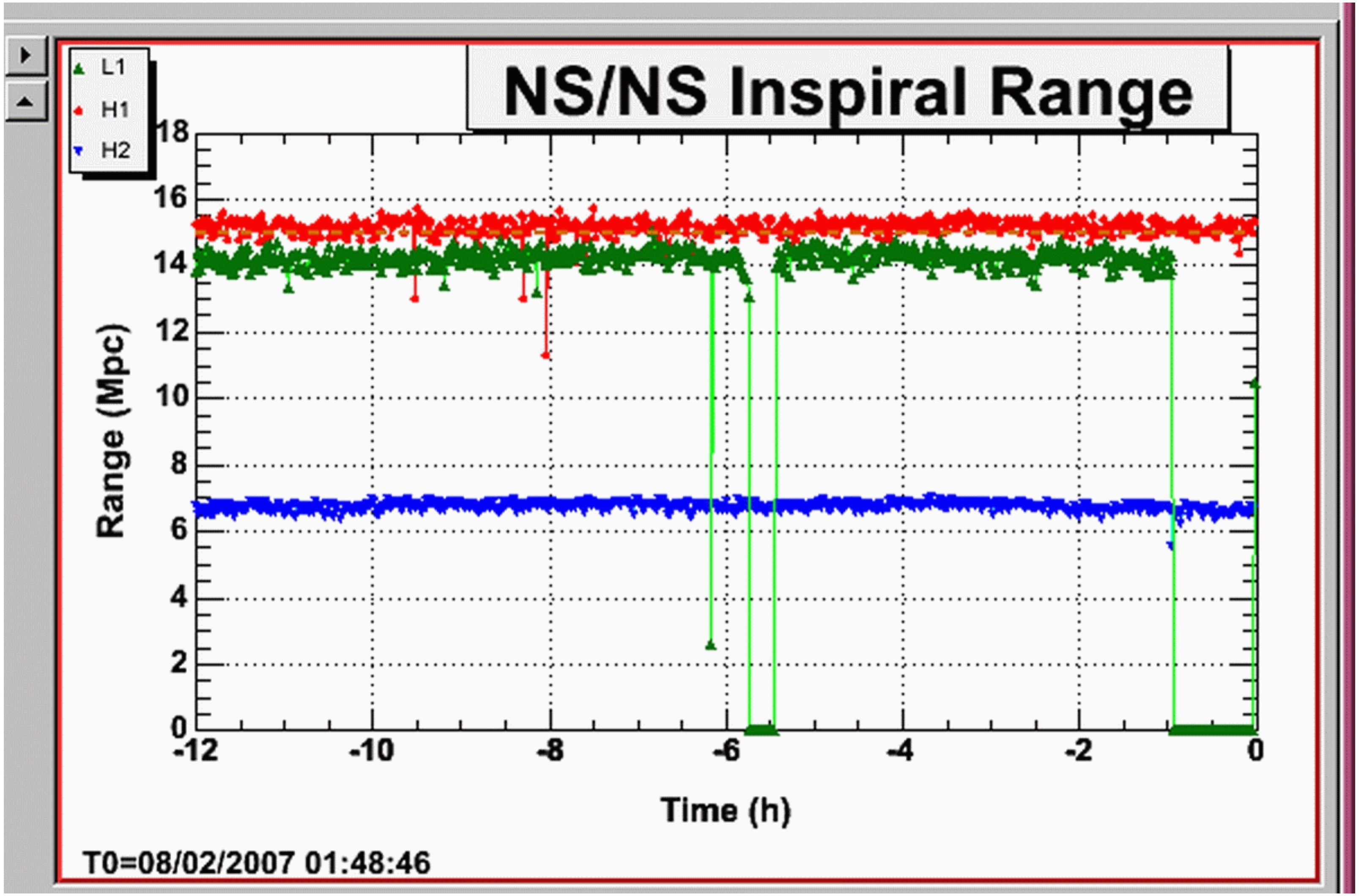
Sensitivity has reached design performance



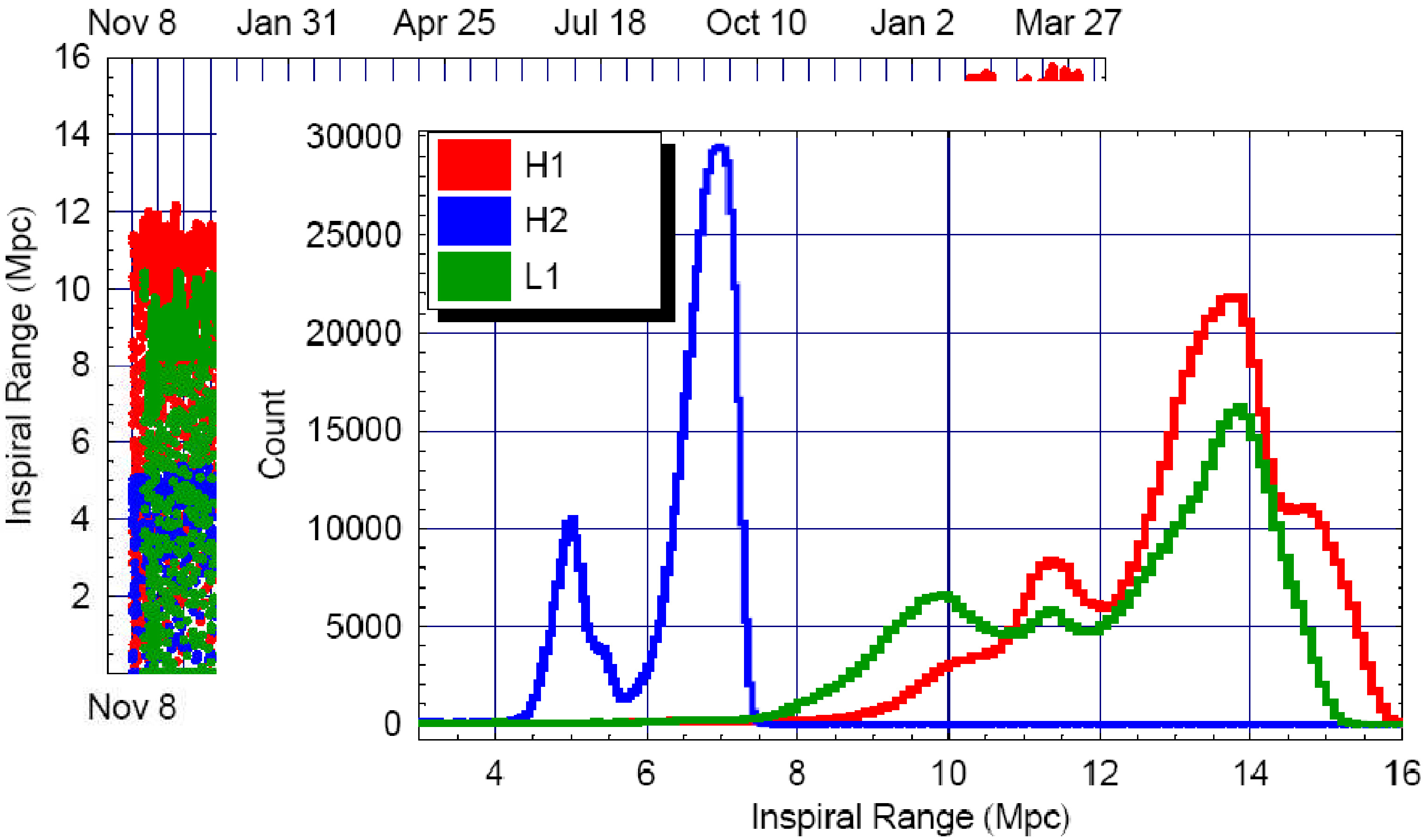
Anatomy of a Noise Curve



LIGO Duty Factor



Duty Factor for S5



The S5 Science Run observation time so far…

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

⇒ Project will complete 1y triple coincidence ~ 1 October 2007 (± few days)

LIGO Data Analysis

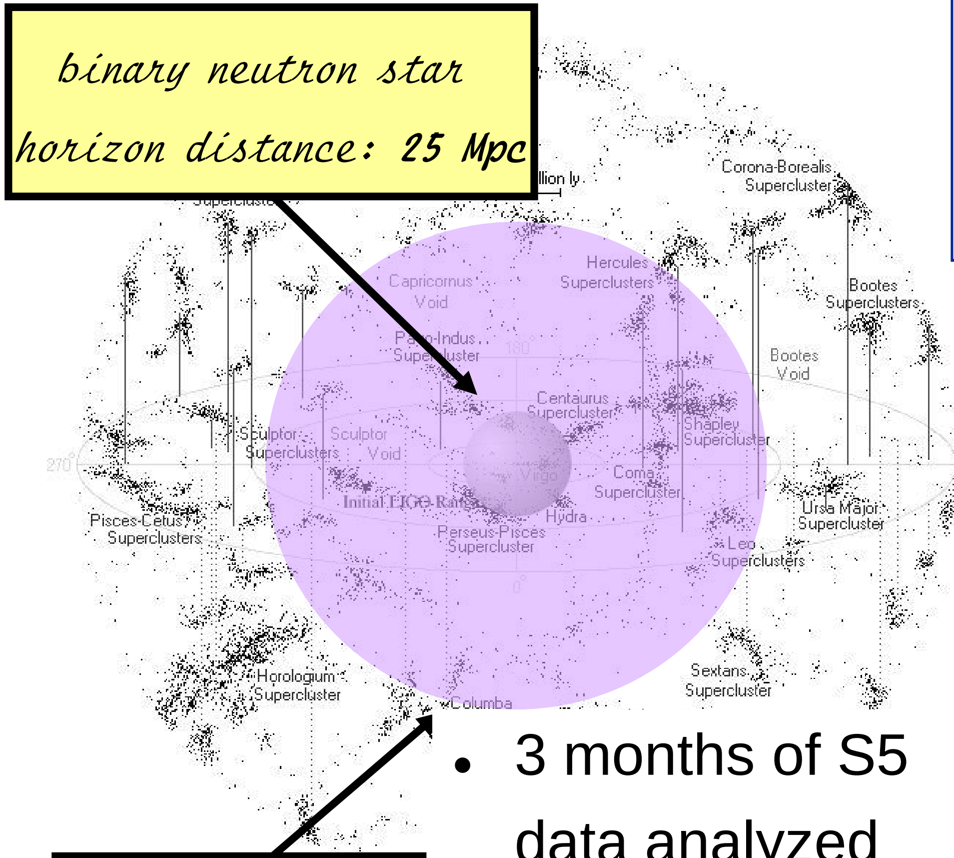
Data analysis by the LIGO Scientific Collaboration (LSC) is organized into four types of analysis:

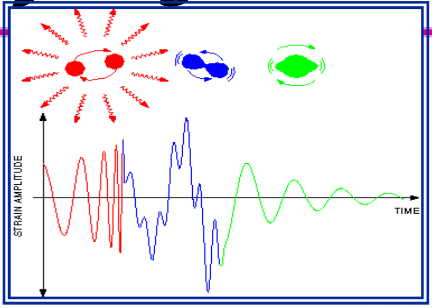
- Binary coalescences with modeled waveforms ("inspirals")
- Transients sources with unmodeled waveforms ("bursts ")
- Continuous wave sources ("GW pulsars")
- Stochastic gravitational wave background (cosmological & astrophysical foregrounds)

Searches for Coalescing Compact Binary Signals in S5

binary neutron star

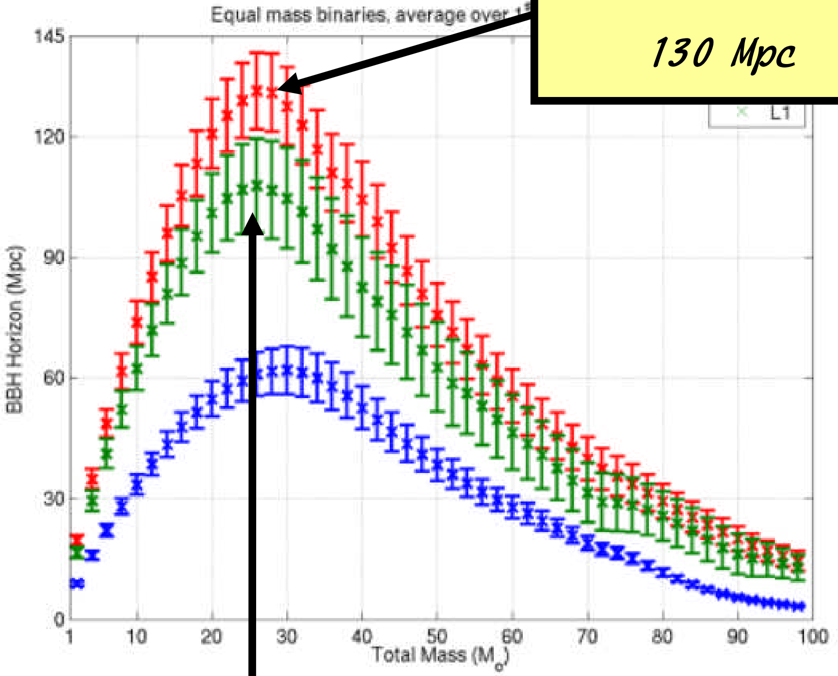
horizon distance: 25 Mpc





Average over run

130 Mpc



binary black hole

horizon distance

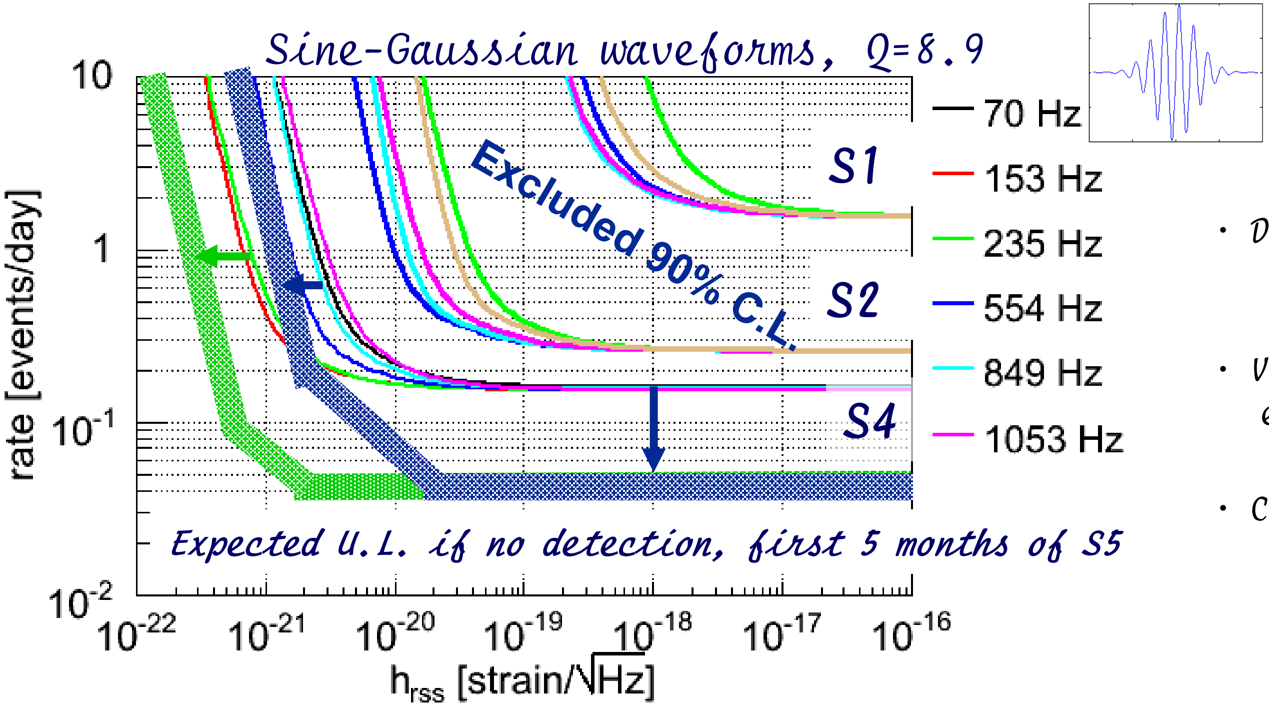
- 3 months of S5 data analyzed
- 1 calendar yr in progress

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

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

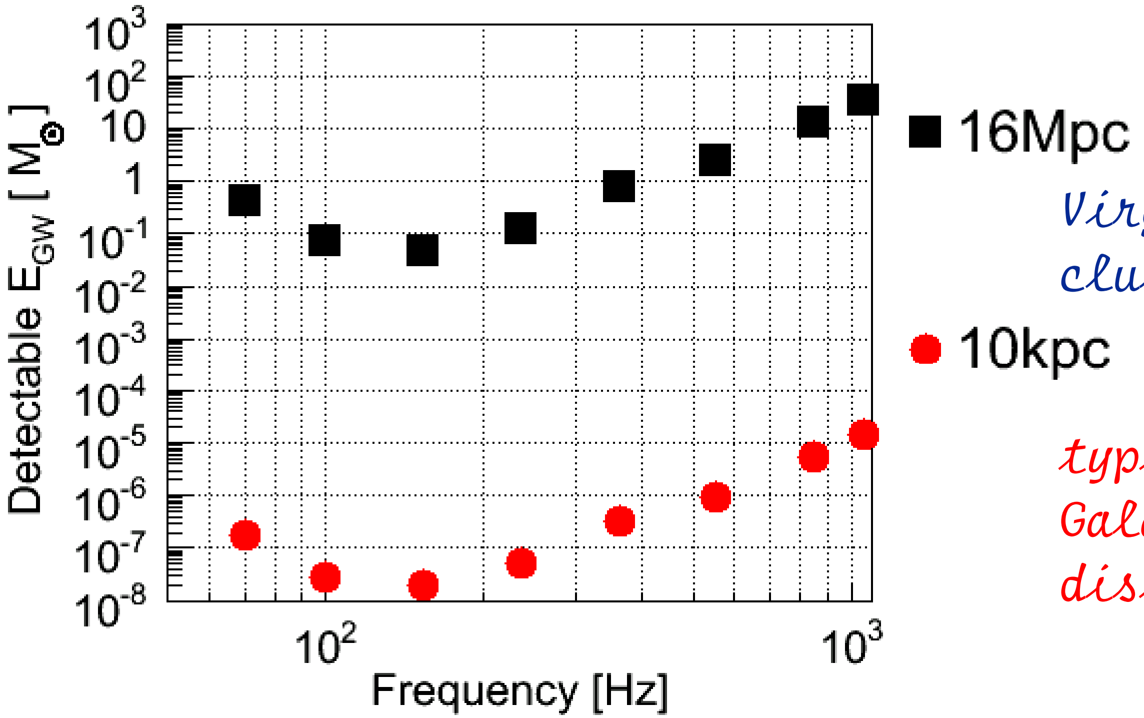


- Detection algorithms tuned for 64-1600 Hz, duration << 1 sec
- Veto thresholds pre-established before looking at data
- Corresponding energy emission $E_{GW} \sim 10^{-1}$ M. at 20 Mpc (153 Hz case)

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

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:

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

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

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)

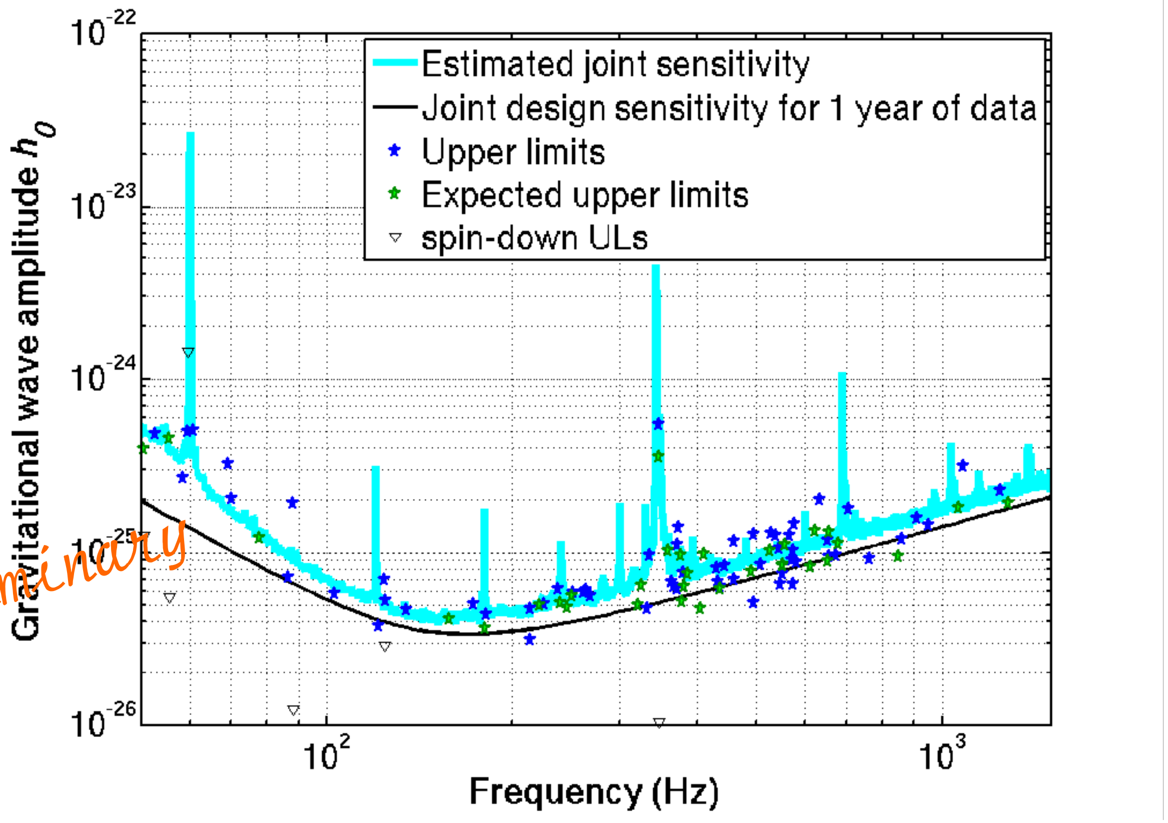
$h_0 < 3.4\times10^{-26}$

Lowest ellipticity upper limit:

PSR J2124-3358

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

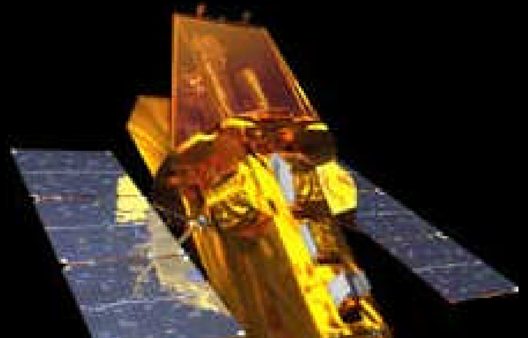
$\varepsilon < 7.3\times10^{-8}$

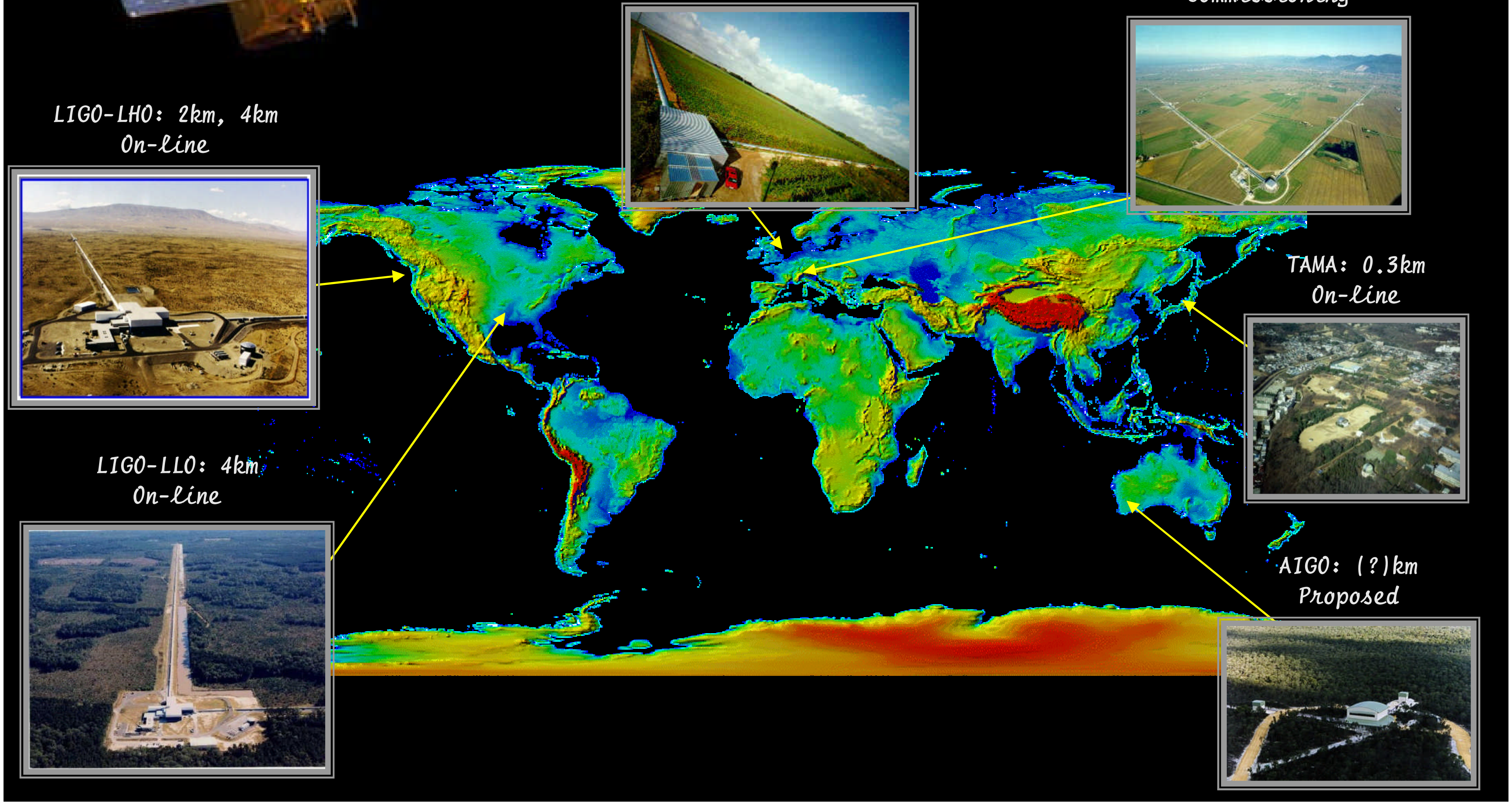


Growing International Network of GW Interferometers

Operated as a phased array:

- Enhance detection confidence
- Localize sources
- Decompose the polarization of gravitational waves
- Triggers from EM detectors





GEO: 0.6km
On-line

VIRGO: 3km
Commissioning

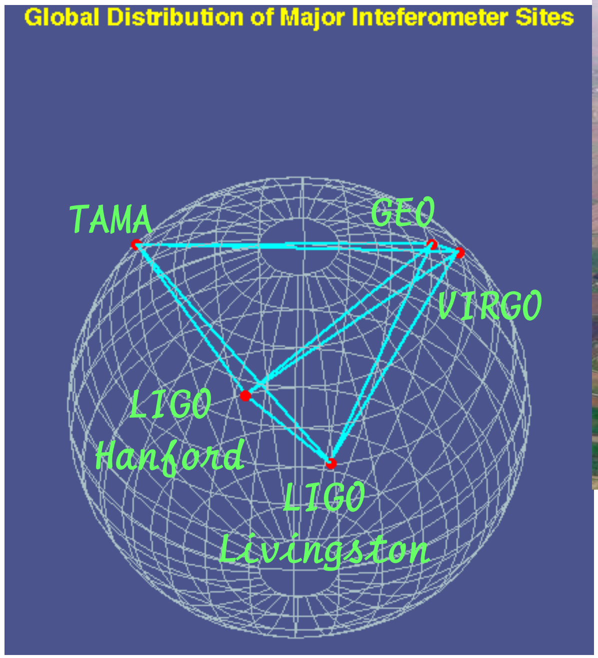
LIGO-LHO: 2km, 4km
On-line

TAMA: 0.3km
On-line

LIGO-LLO: 4km
On-line

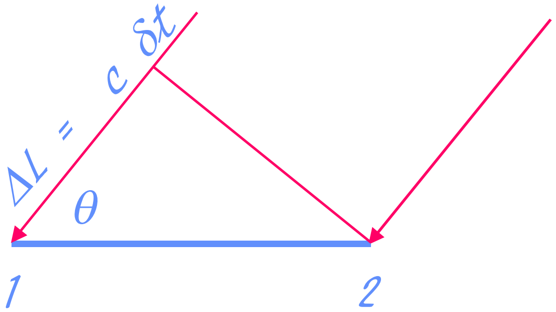
AIGO: (?)km
Proposed

A Global Network of GW Detectors



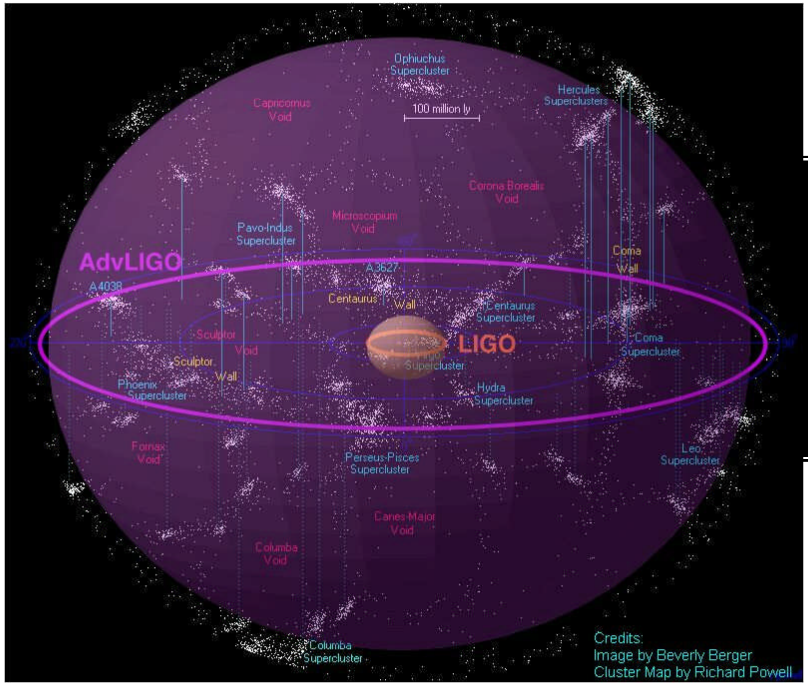
Virgo
Italy

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



Credits:
Image by Beverly Berger
Cluster Map by Richard Powell

x10 better amplitude sensitivity

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

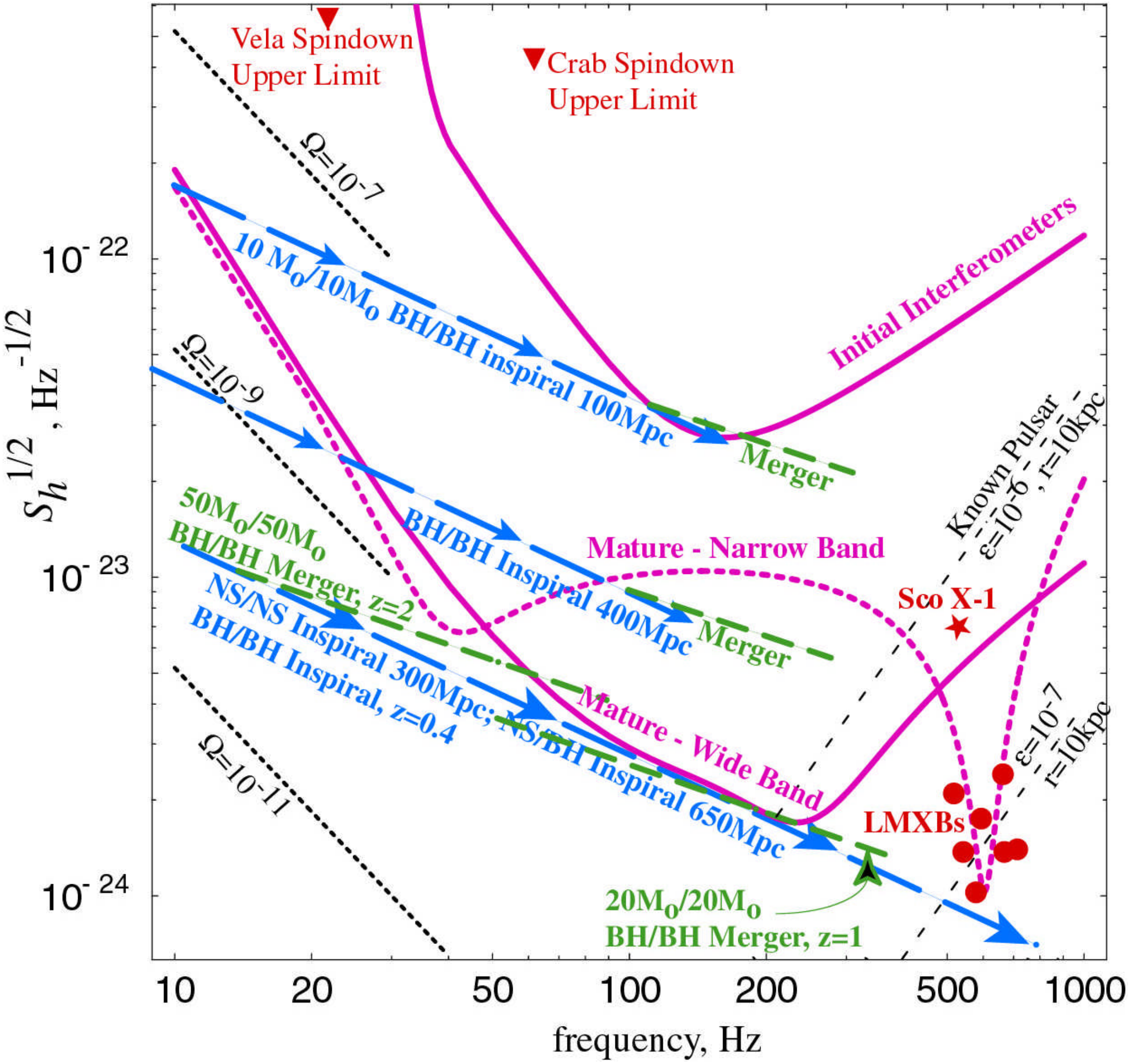
$\Rightarrow$ 1 day of Advanced LIGO

» 1 year of Initial LIGO !

Planned for FY2008 start,
installation beginning 2011

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

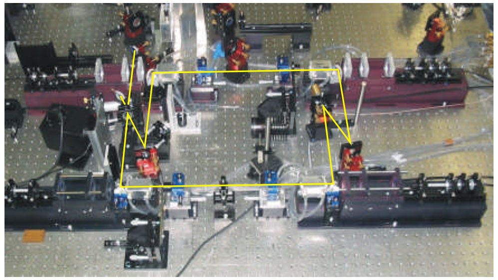


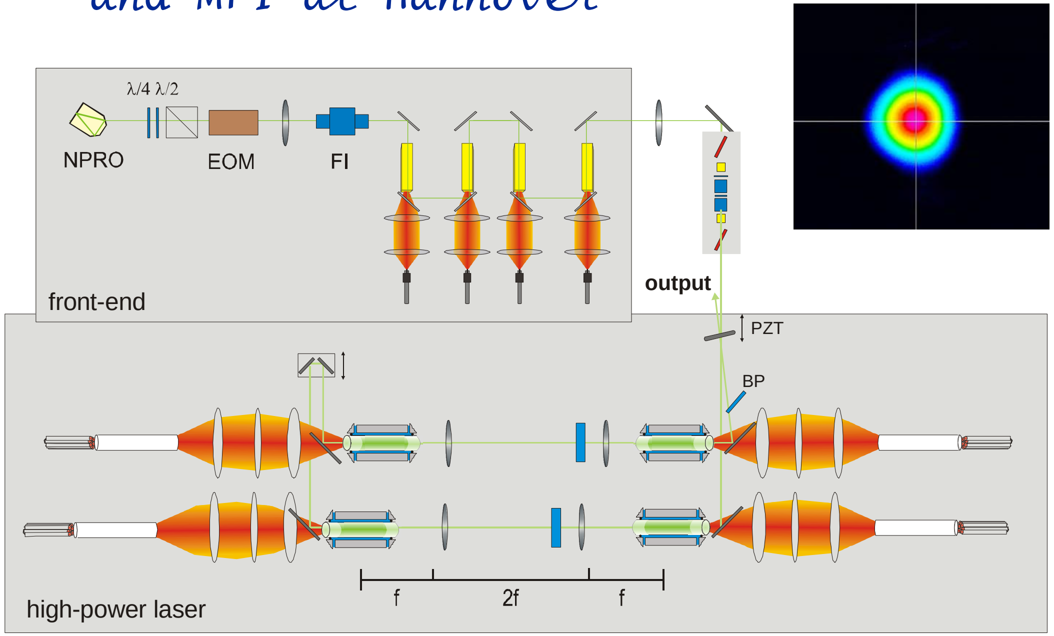
What is Advanced about Advanced LIGO?

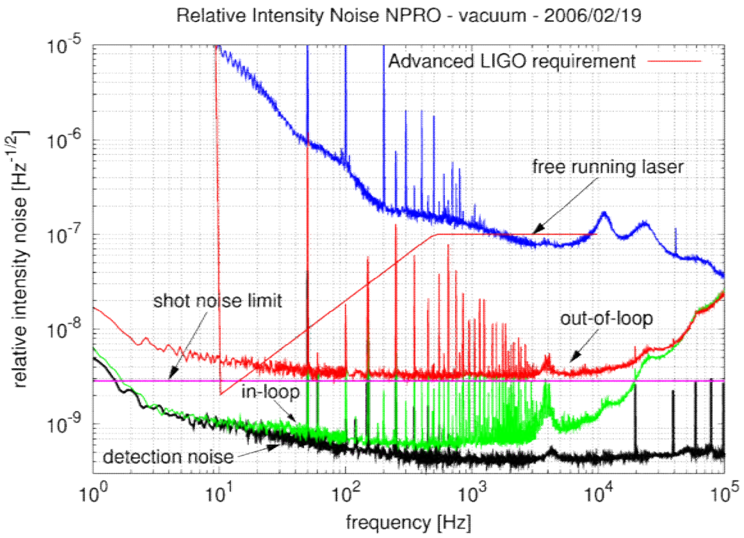
Parameter	LIGO	Advanced LIGO
Input Laser Power	10 W	180 W
Mirror Mass	10 kg	40 kg
Interferometer Topology	Power-recycled Fabry-Perot arm cavity Michelson	Dual-recycled Fabry-Perot arm cavity Michelson
GW Readout Method	RF heterodyne	DC homodyne
Optimal Strain Sensitivity	3×10^{-23} / rHz	Tunable, better 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

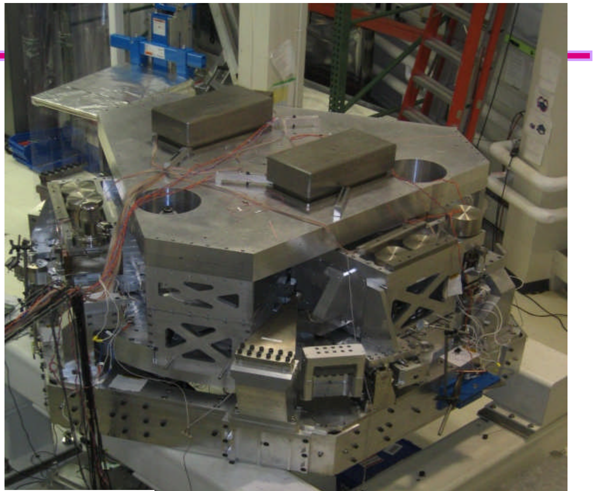




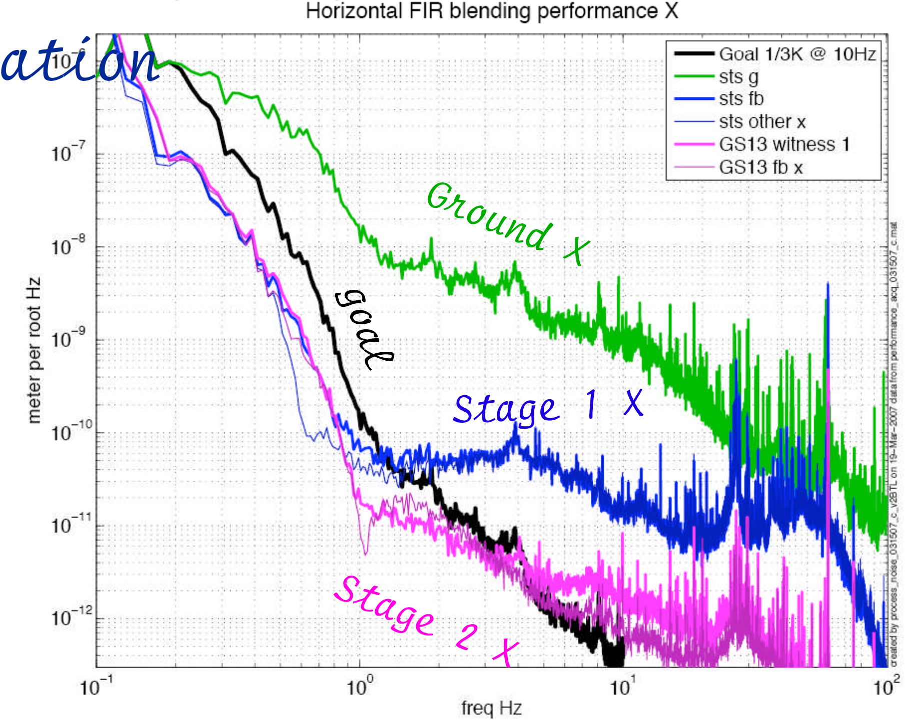


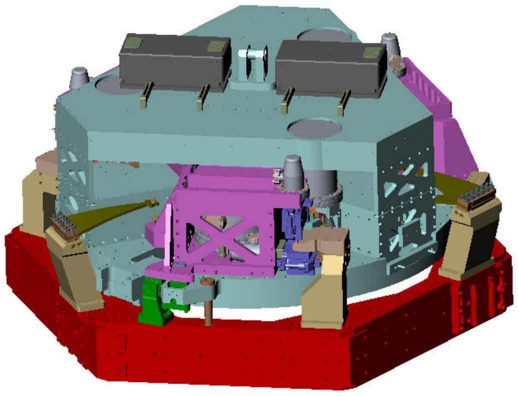
Frede et al, *Opt. Express* **22** p459 (2007)

Seismic isolation



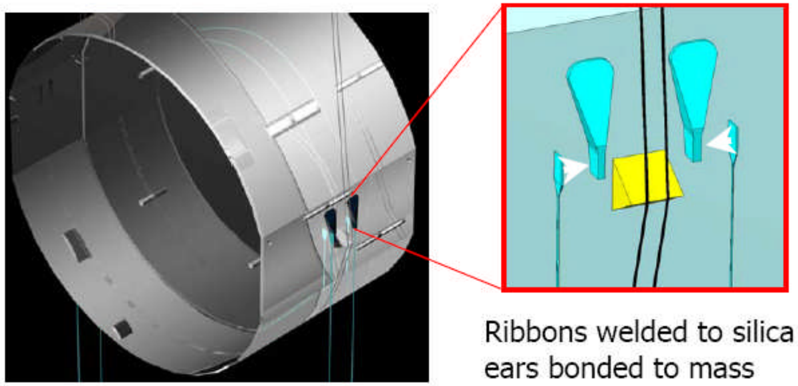
- To open Advanced LIGO band at low frequencies, a complete redesign of the seismic isolation system is needed
- Active isolation, feed forward
- Required Isolation
  - » 10x @ 1 Hz
  - » 3000x @ 10 Hz





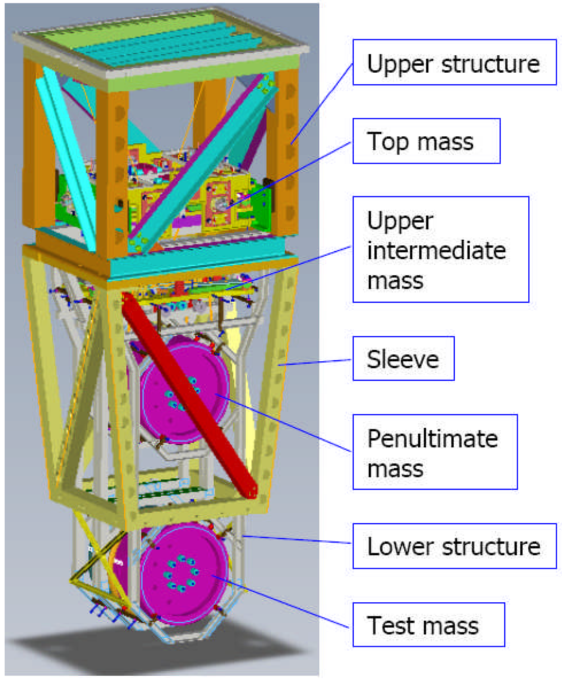
Advanced LIGO suspensions

- *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



Upper structure

Top mass

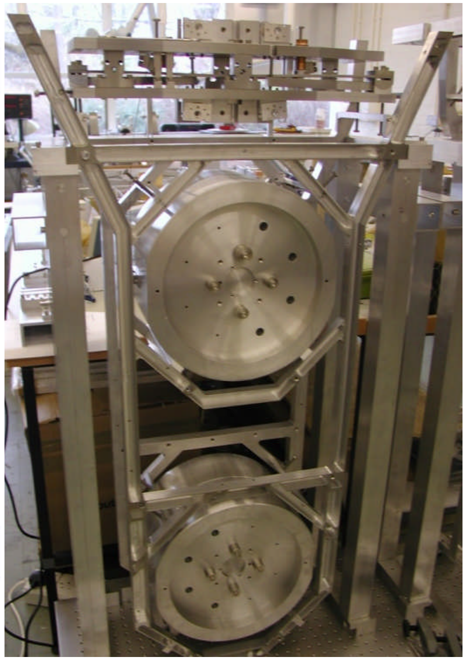
Upper intermediate mass

Sleeve

Penultimate mass

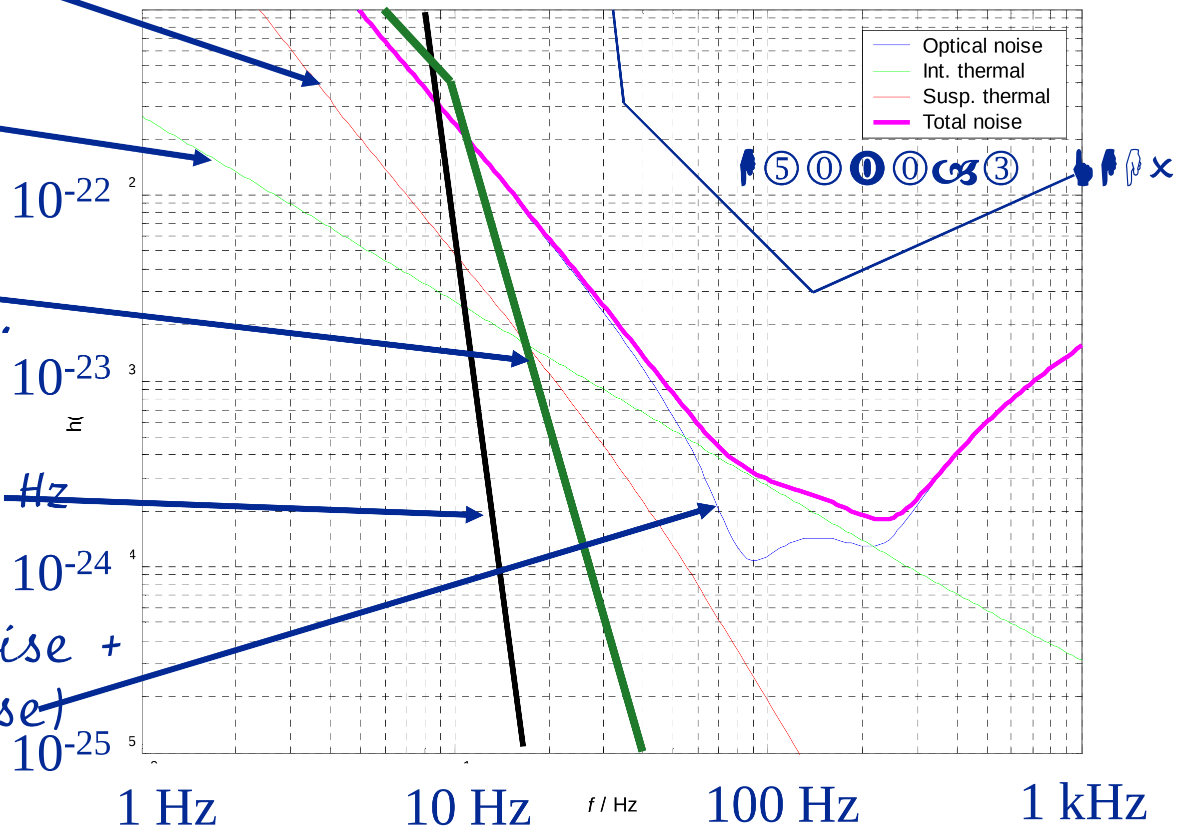
Lower structure

Test mass



Anatomy of the Projected Adv LIGO Detector Performance

- Suspension thermal noise
- Internal thermal noise (due to coating)
- Newtonian background, estimate for LIGO site
- 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 L
- Fabrication schedule

Summary

- 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