Recent Progress at LIGO

Brian O'Reilly

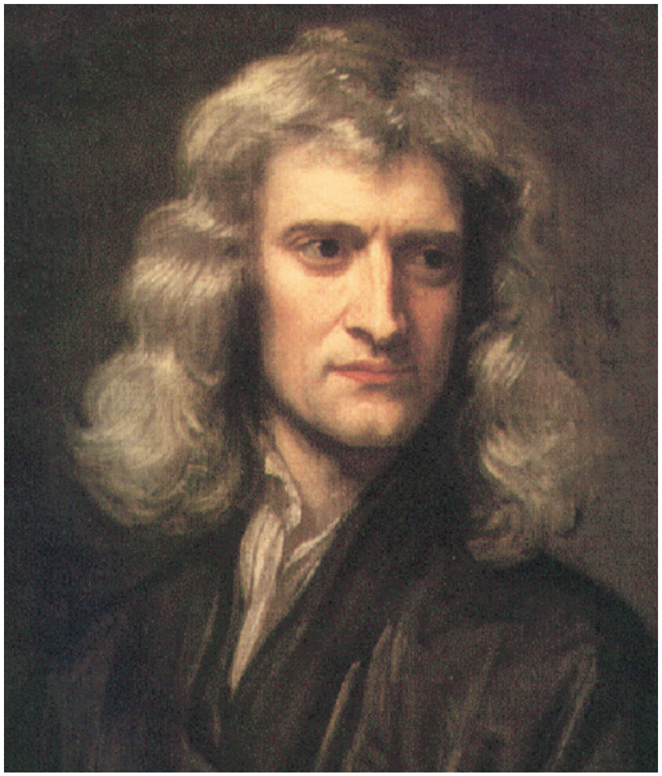
LIGO Livingston Observatory

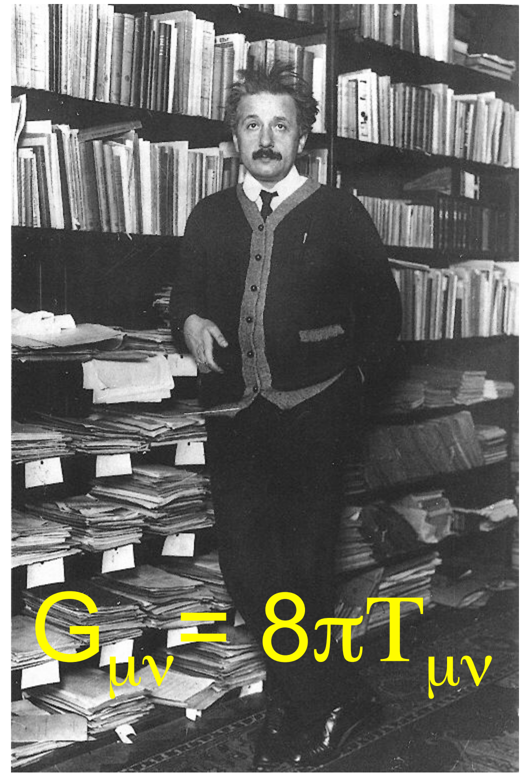
California Institute of Technology

Outline

- Gravity, gravitational waves and sources.
- Interferometer configuration.
- The LIGO Observatories.
- Sources of noise and noise mitigation.
- Example analysis, Pulsar search.
- Outlook.

What is Gravity?





Newton

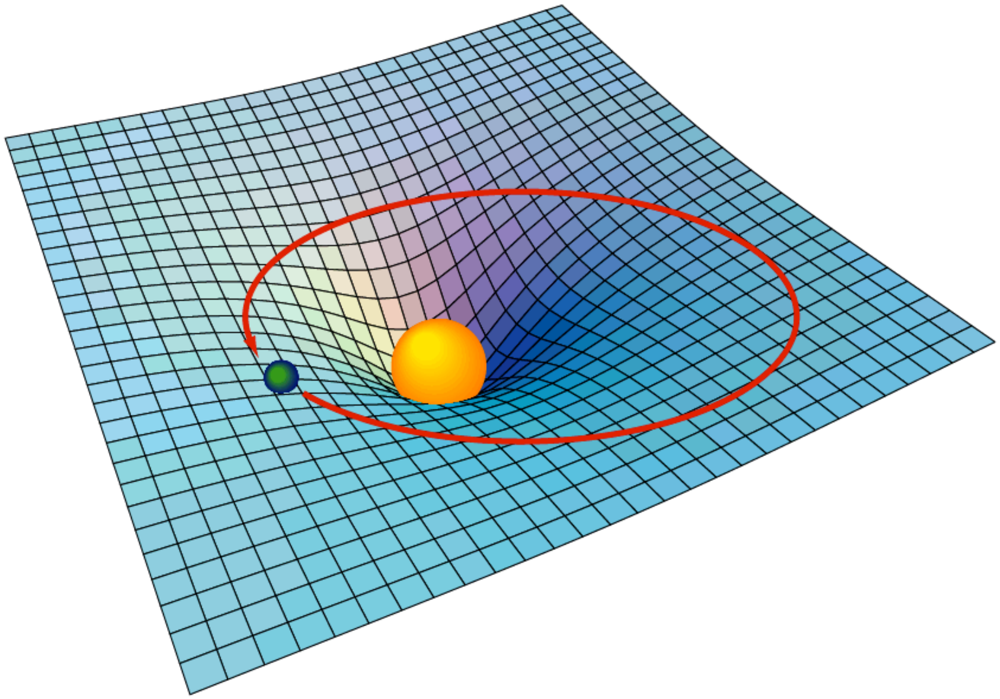
Action at a distance

Einstein

Gravitational Radiation
traveling at the speed of light

General Relativity

Einstein theorized that smaller masses travel toward larger masses, not because they are "attracted" by a mysterious force, but because the smaller objects travel through space that is warped by the larger object



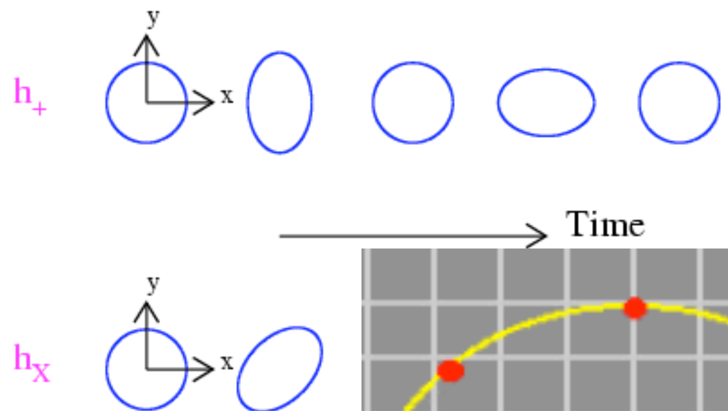
- **Imagine space as a stretched rubber sheet.**
- **A mass on the surface will cause a deformation.**
- **Another mass dropped onto the sheet will roll toward that mass.**

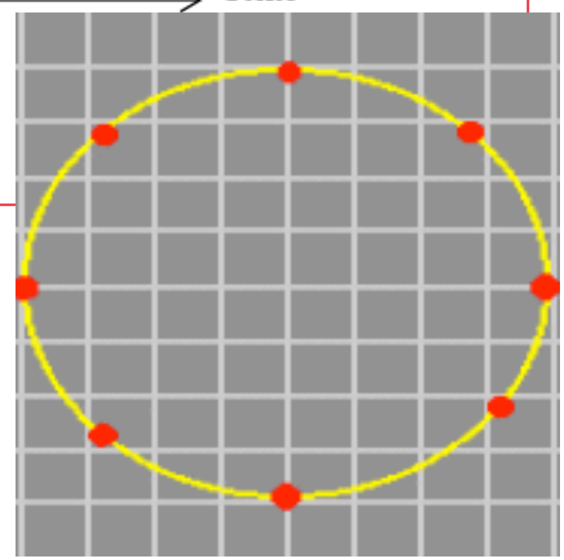
What are Gravitational Waves?

- Gravitational Waves = “Ripples in space-time”
- Two transverse polarizations - quadrupolar: + and x

Example:

Ring of test masses
responding to wave
propagating along z

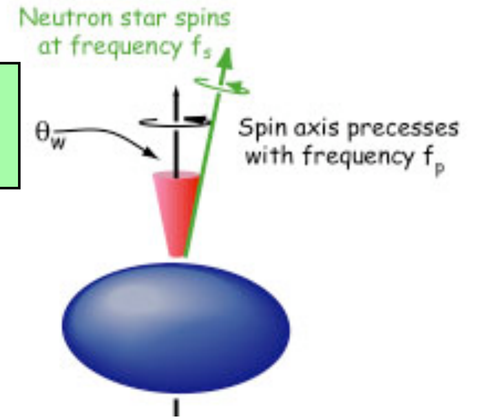




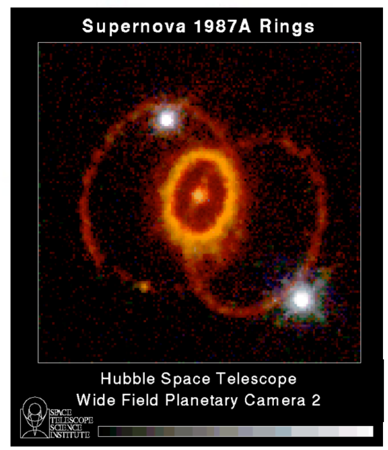
Amplitude parameterized by (tiny) dimensionless strain h: $\Delta L \sim h(t) \times L$

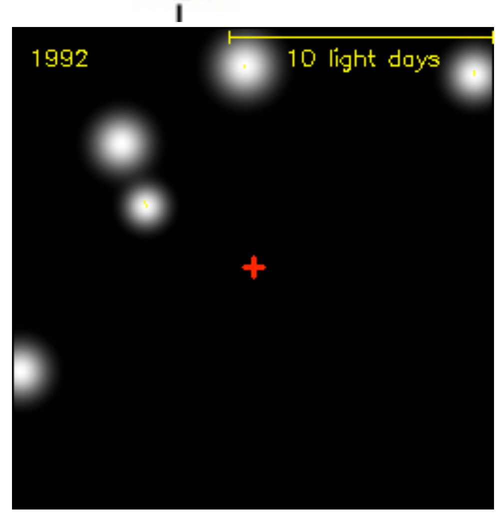
Making “detectable” gravitational waves

Spinning or wobbling neutron stars



matter





Massive Star

Giant Phases

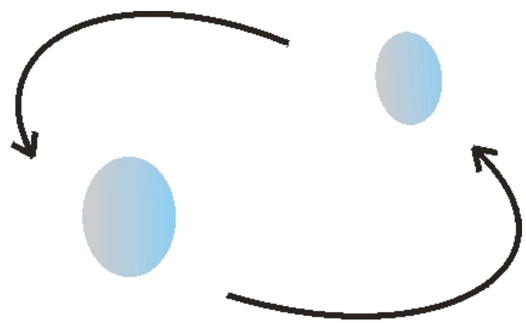
Grav

Compress into small space

GRB, Ringdowns

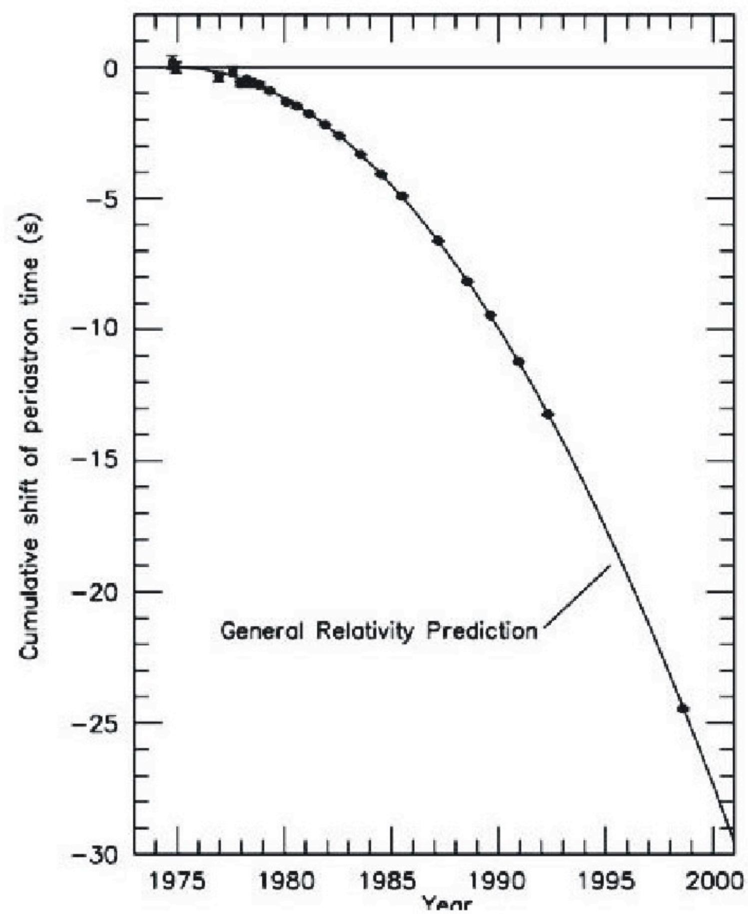
Evidence for Gravitational Waves

Taylor and Hulse
Binary Pulsar

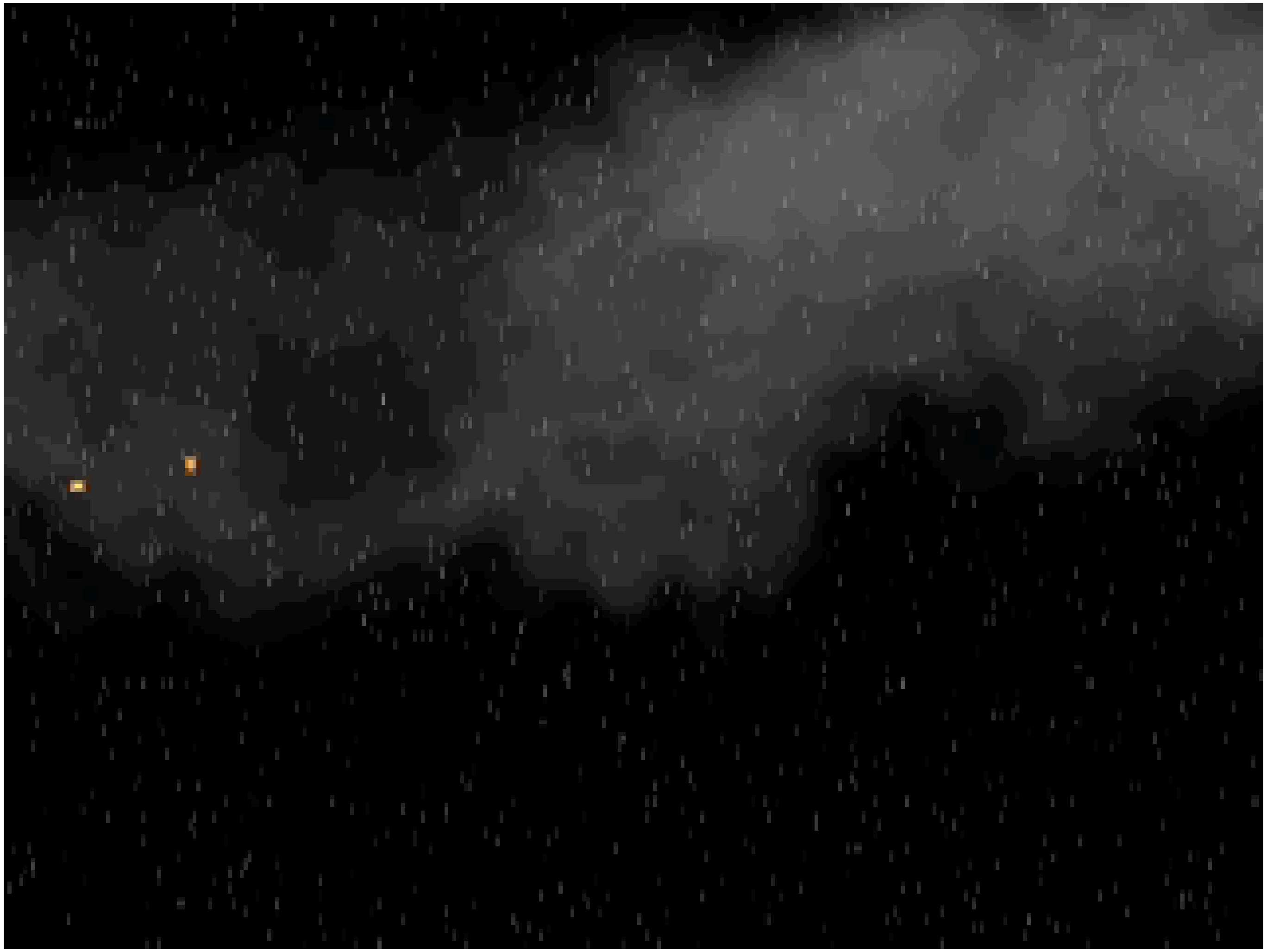


- Orbital decay of binary neutron stars through the emission of gravitational radiation.

Period change of PSR 1913+16

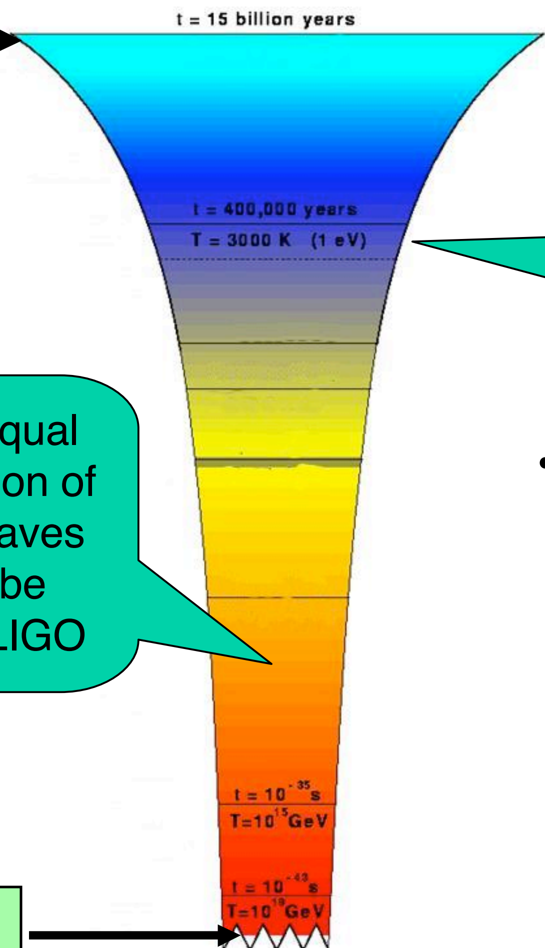


“Chirps”



Stochastic background of gravitational waves

Today



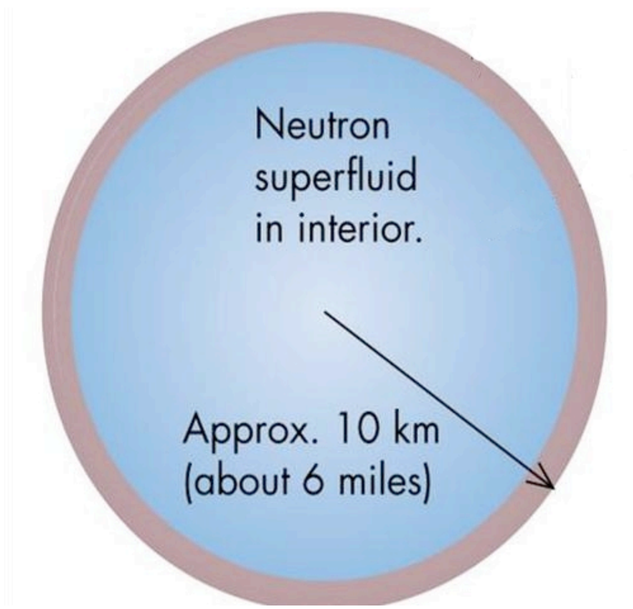
Big Bang

400,000 years after big bang: production of photons in Cosmic Microwave Background

Less than or equal 10^{-22}s: production of gravitational waves which might be detected with LIGO

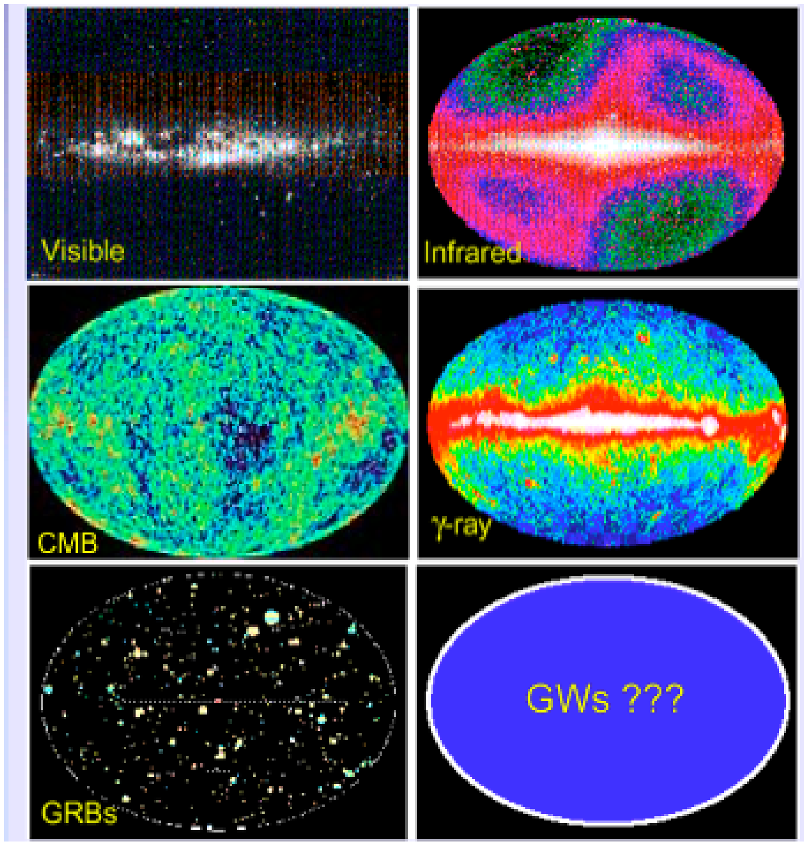
- General properties
  - Weak superposition of many incoherent sources – a hiss.
  - Only characterized statistically.

Isolated spinning neutron stars



- Isolated neutron stars
  - faults in crust.
  - Small ellipticity
  - Excited oscillation modes
- LIGO is sensitive throughout Milky Way *if* the waves are strong enough.

GW Astronomy

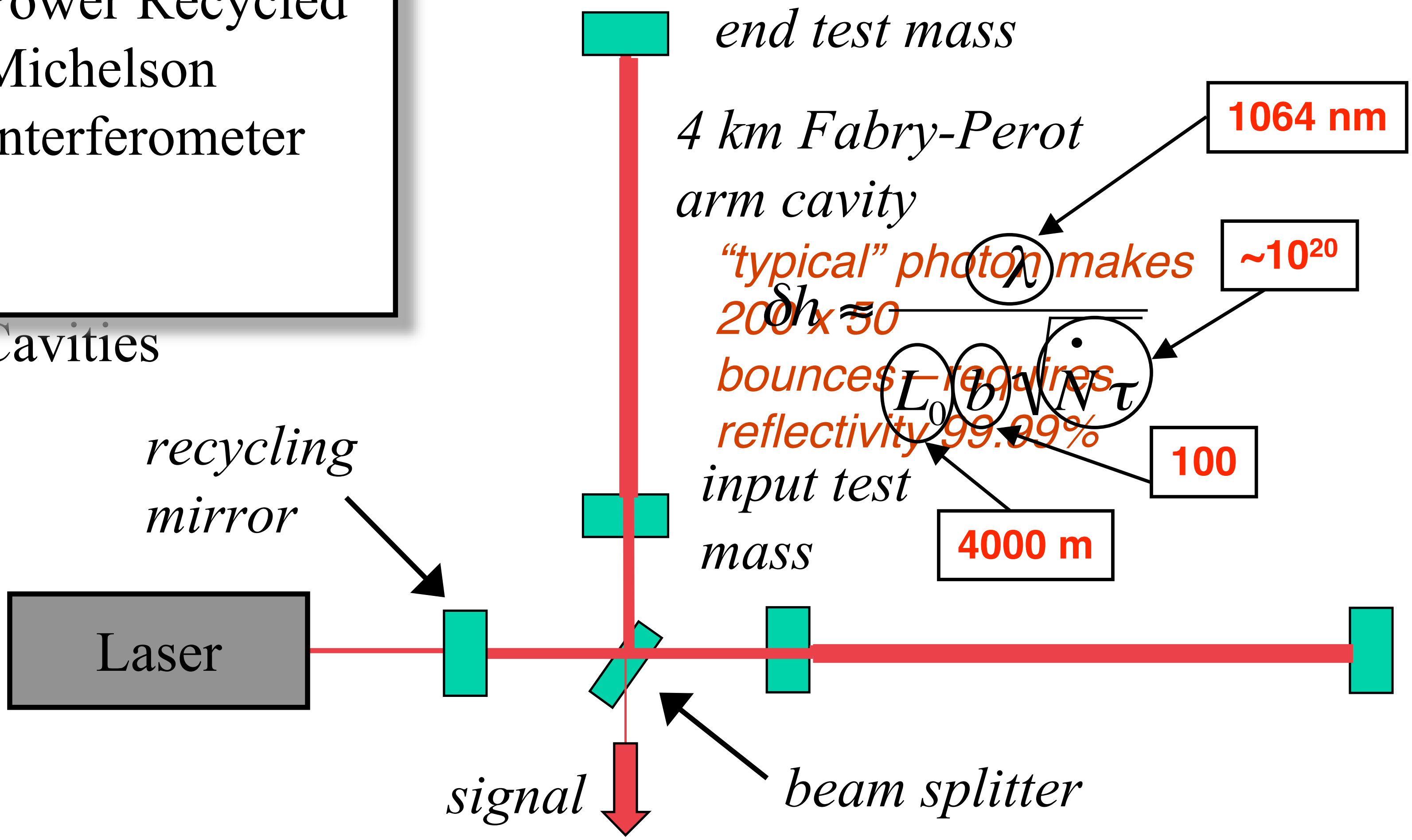


- A new way to look at the universe.
- We expect surprises.
- But gravitational radiation is very weak.
- Need to measure distance changes on the order of 10^{-18} m!

Optical Configuration

Power Recycled Michelson Interferometer

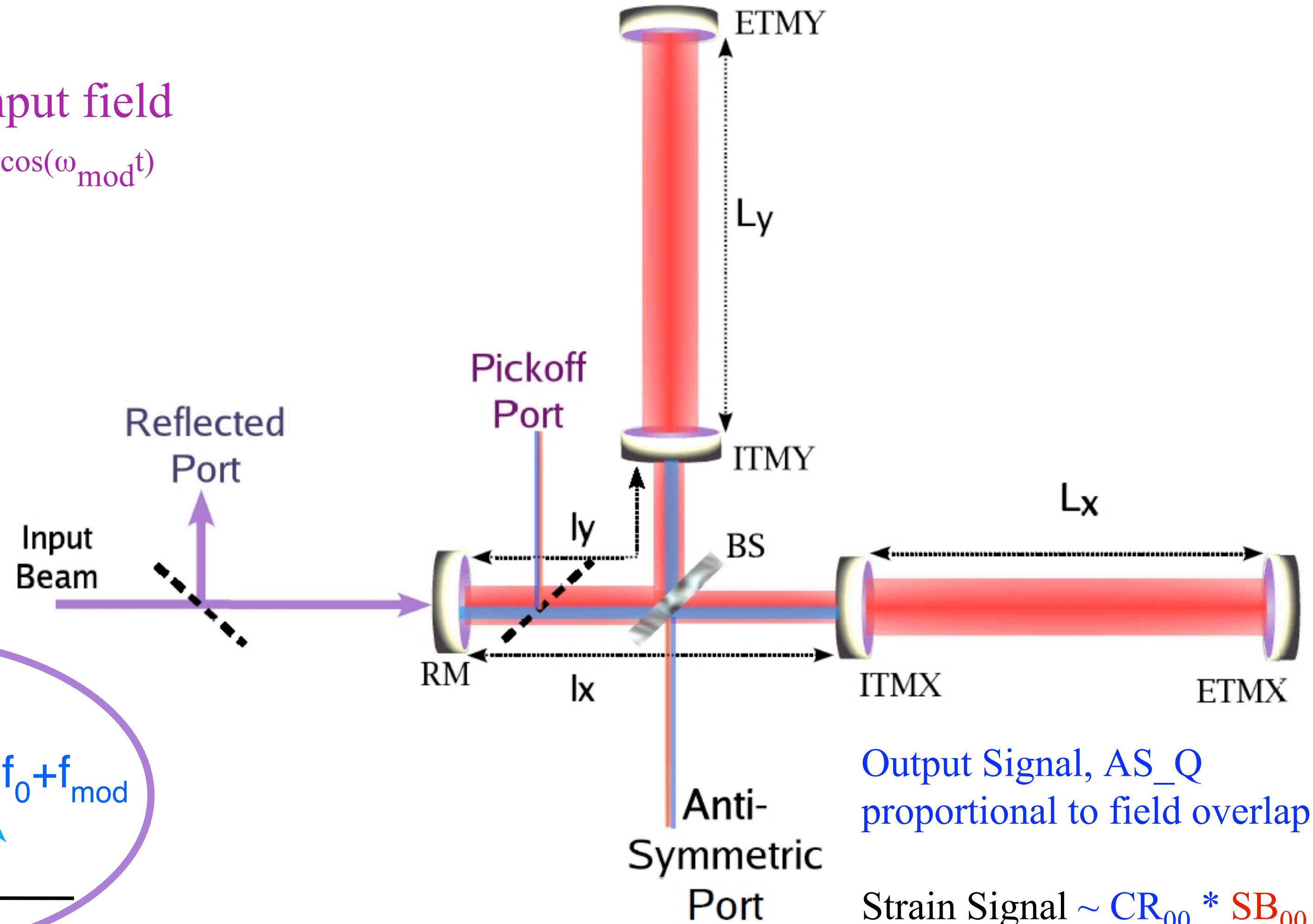
Cavities

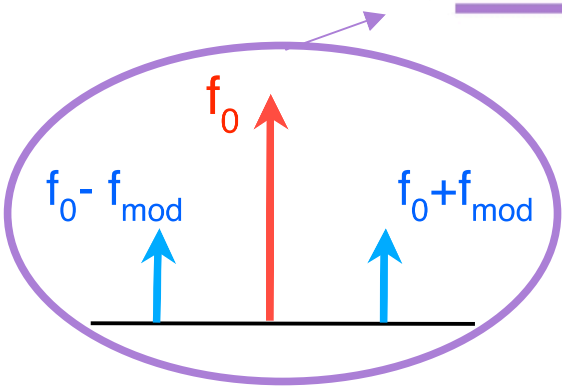


Optical Configuration

- Phase modulated input field

$$E_{in} = E_0 \text{ x } e^{i*\Gamma*\cos(\omega_{mod}t)}$$





Output Signal, AS_Q
proportional to field overlap

Strain Signal ~ CR_{00} * SB_{00}

• Three interferometers: H1, H2, L1

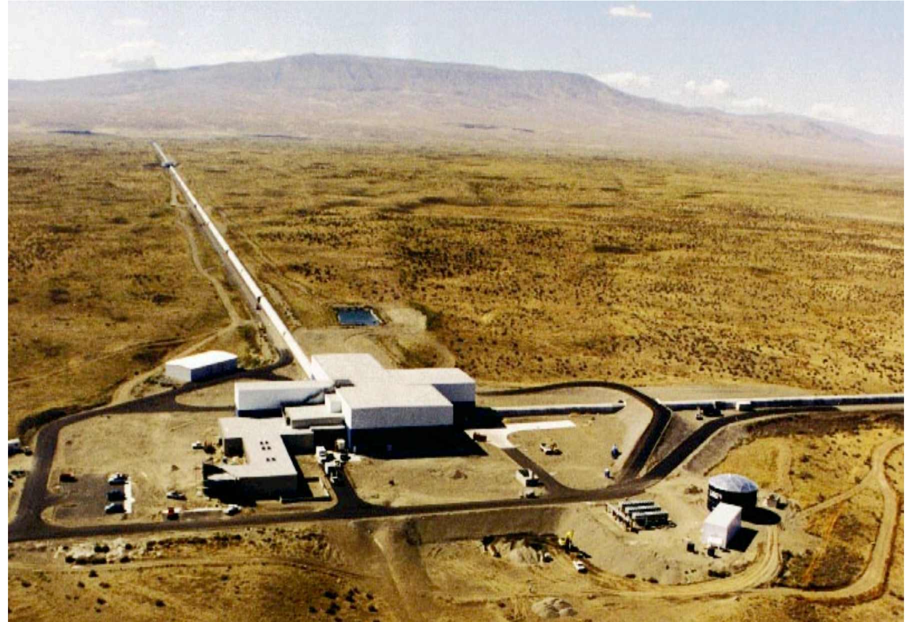
• Funded by NSF, construction began in 1995, and finished 1999.

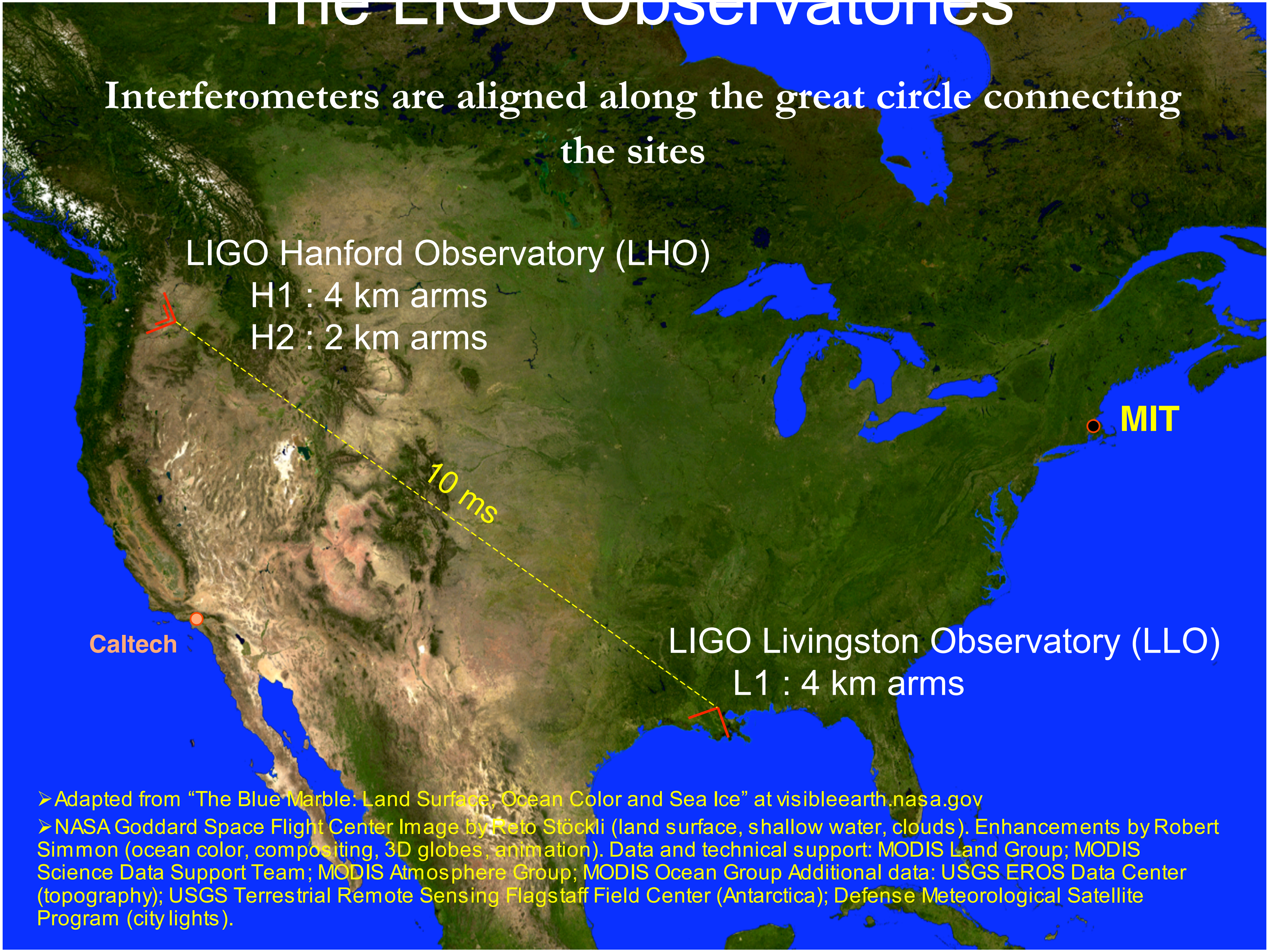
• Installation was finished in 2001.

• Many engineering runs in '01-'04.

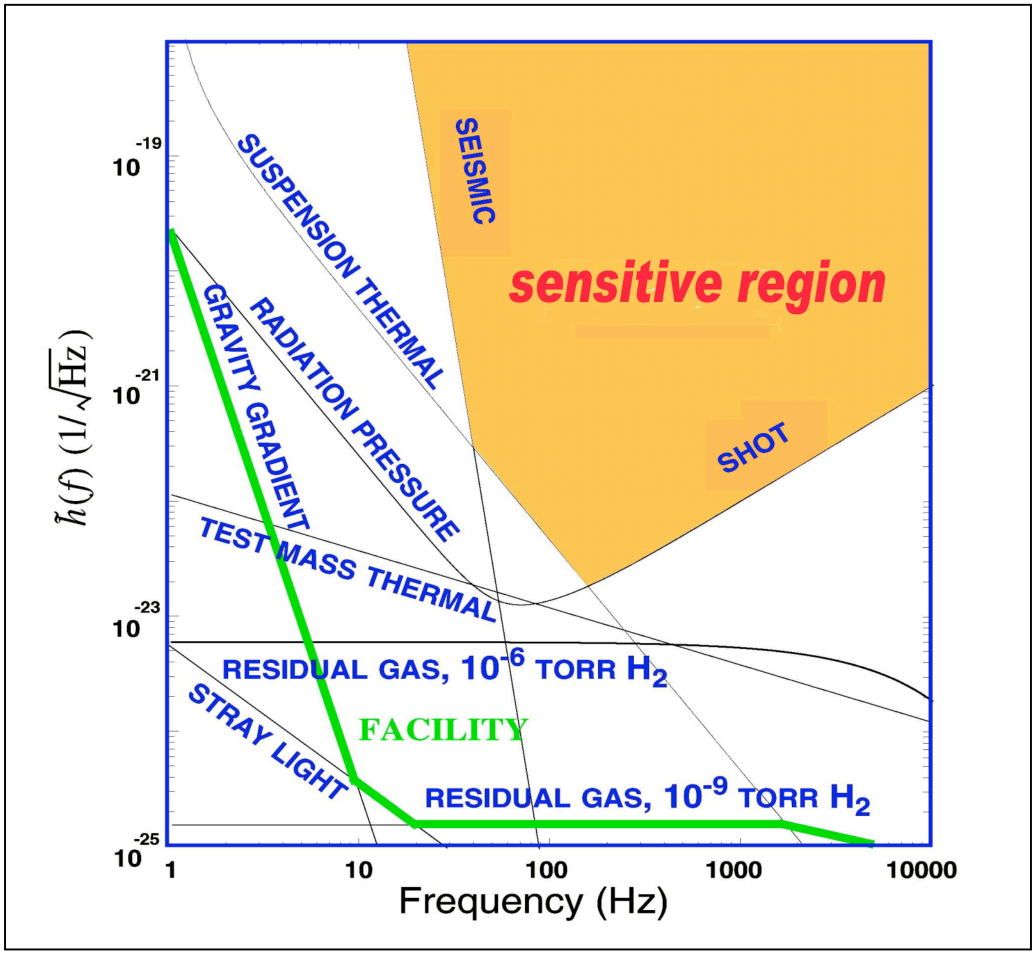
• Four scientific data runs in '02-'05.

• Commissioning is still in progress.




The LIGO Observatories
Interferometers are aligned along the great circle connecting the sites
LIGO Hanford Observatory (LHO)
H1 : 4 km arms
H2 : 2 km arms
10 ms
MIT
Caltech
LIGO Livingston Observatory (LLO)
L1 : 4 km arms
➢Adapted from "The Blue Marble: Land Surface, Ocean Color and Sea Ice" at visibleearth.nasa.gov
➢NASA Goddard Space Flight Center Image by Reto Stöckli (land surface, shallow water, clouds). Enhancements by Robert Simmon (ocean color, compositing, 3D globes, animation). Data and technical support: MODIS Land Group; MODIS Science Data Support Team; MODIS Atmosphere Group; MODIS Ocean Group Additional data: USGS EROS Data Center (topography); USGS Terrestrial Remote Sensing Flagstaff Field Center (Antarctica); Defense Meteorological Satellite Program (city lights).

Sources of Noise

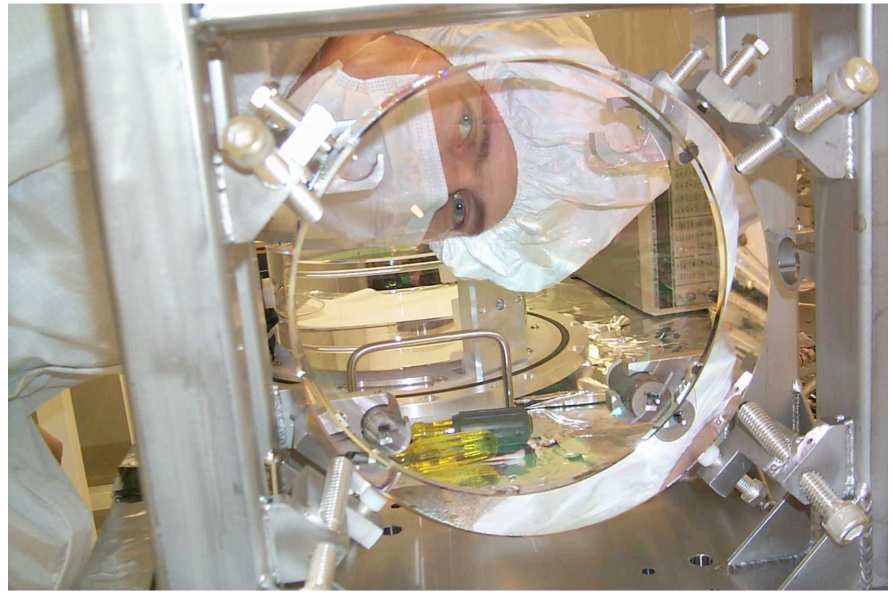


- Seismic at low frequencies.
- Thermal at mid-frequencies.
- Shot noise at high frequencies.
- Facility limits are all significantly lower; room for upgrades.

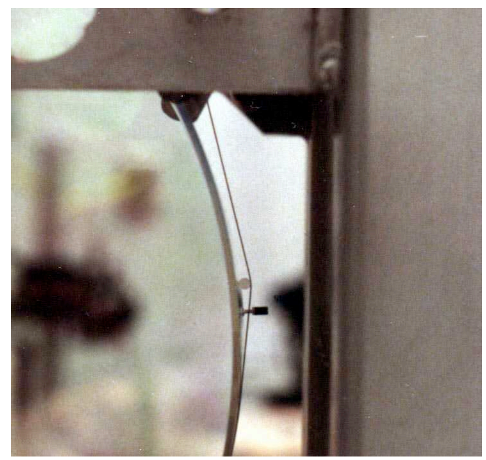
Vacuum "Envelope"

~10,000 m^3 of vacuum at 10^{-9} torr.

Optic Suspension

- Magnets and coils control position and angle of mirrors
- Suspension provides $1/f^2$ attenuation above the pendulum resonance ~0.75 Hz.
- Suspension is critical to controlling thermal noise.



LIGO Optics

Substrates: SiO_2

25 cm Diameter, 10 cm thick

Homogeneity < 5 x 10^{-7}

Internal mode Q's > 2 x 10^{6}

Polishing

Accuracy < 1 nm

Micro-roughness < 0.1 nm

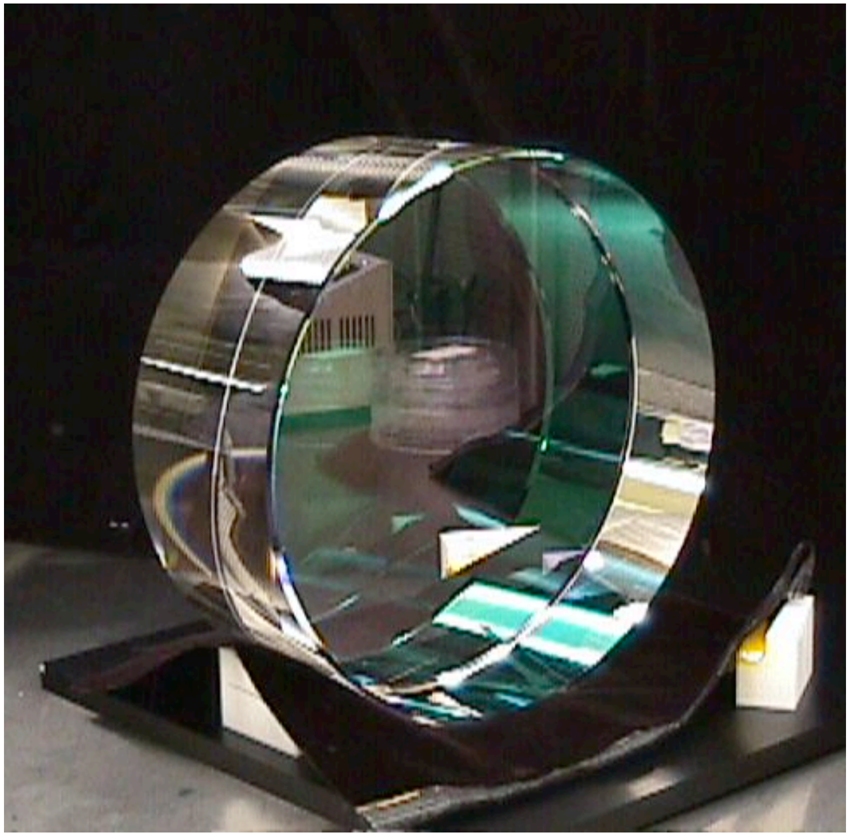
Radii of curvature matched < 3%

Coating

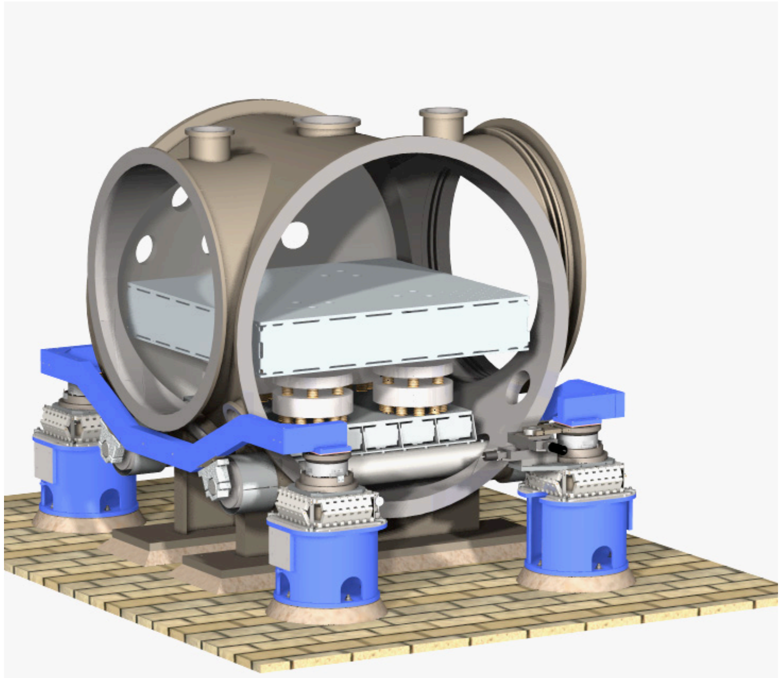
Scatter < 50 ppm

Absorption < 0.5 ppm

Uniformity <10^{-3} (~1 atom/layer)



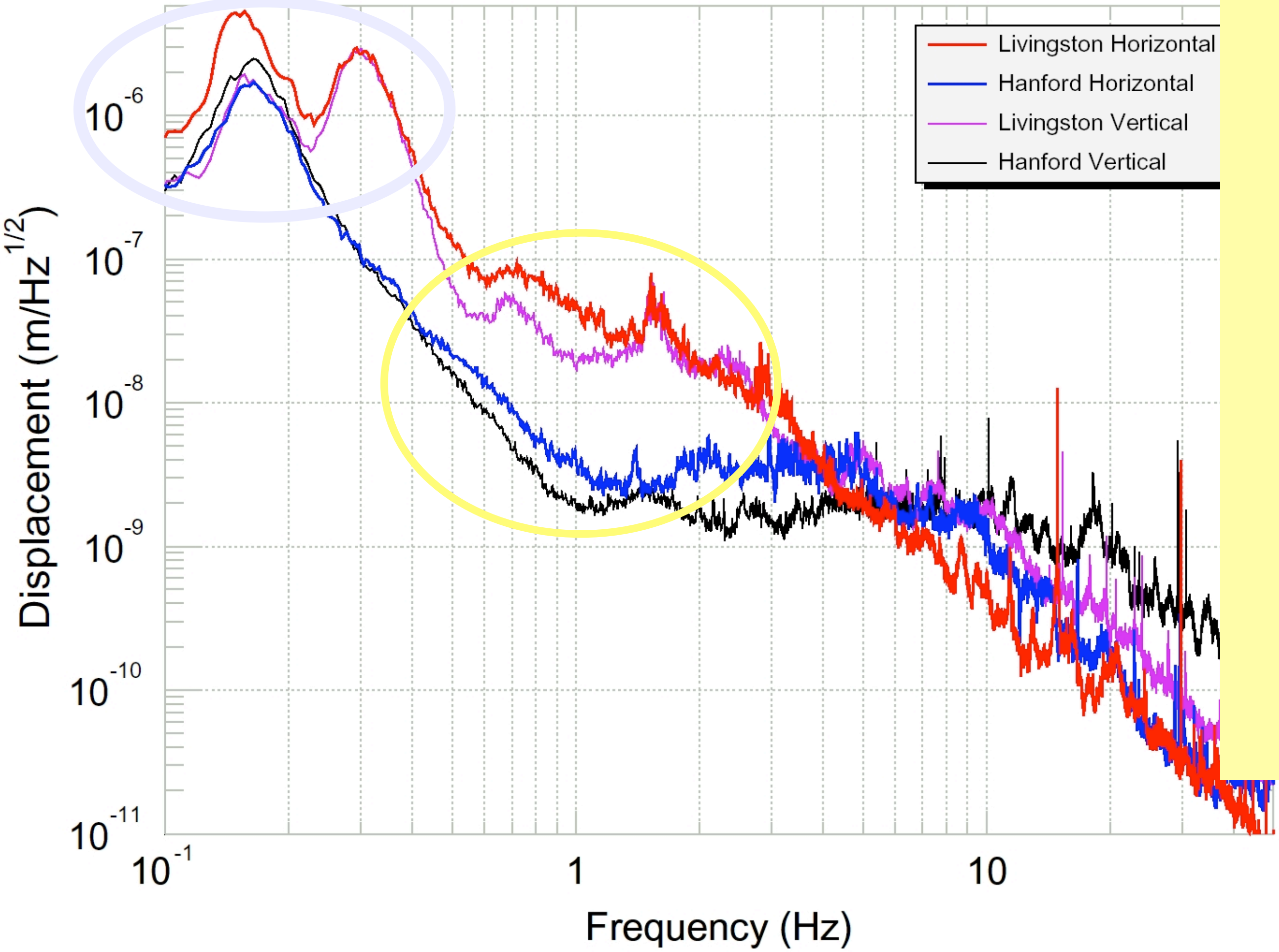
Passive Isolation



- Suppression of ~10^{-6} between support and optics table above 30 Hz.
- But resonances at low frequencies excited by ground motion.

Ground Noise

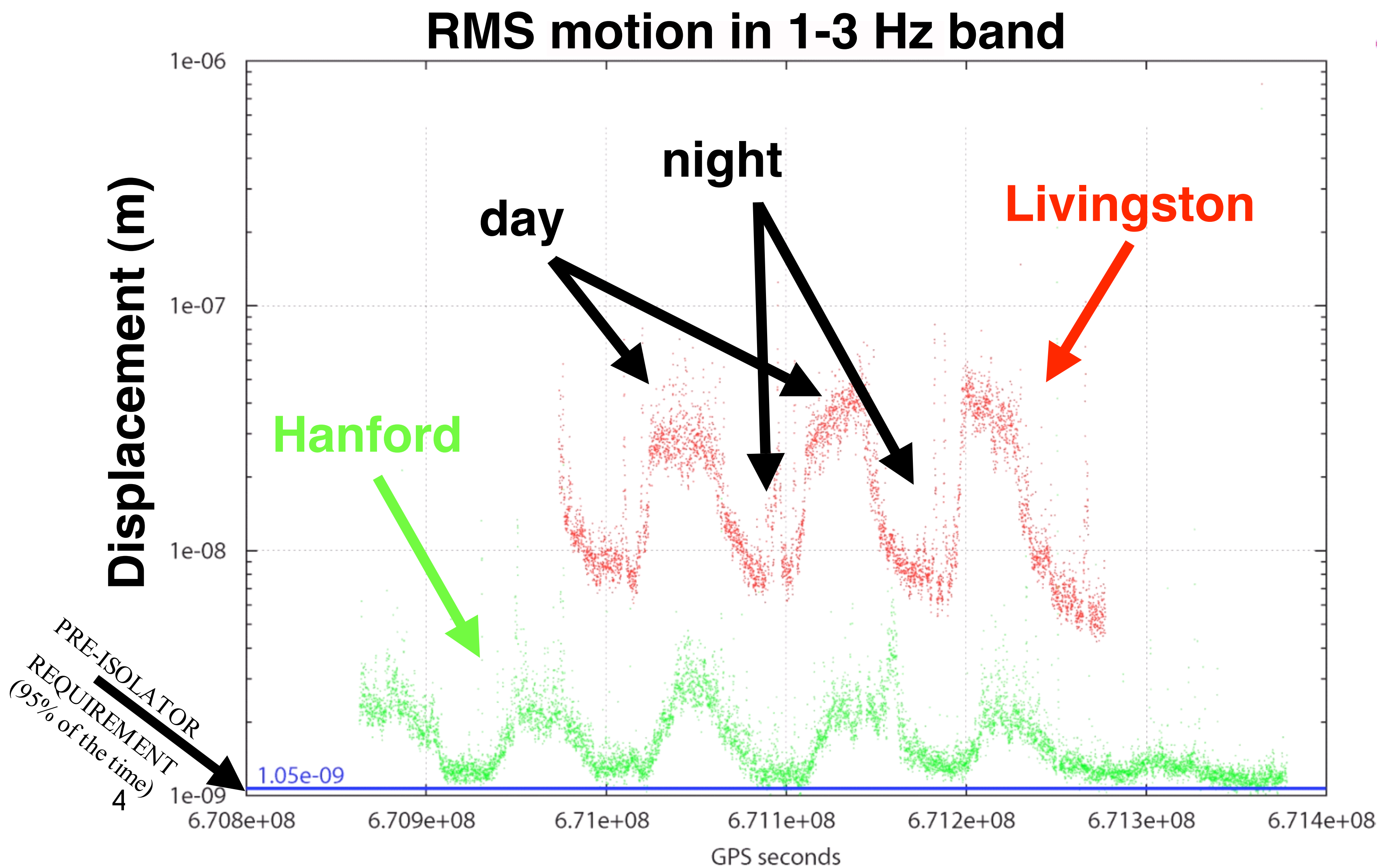
Ocean activity, hurricanes



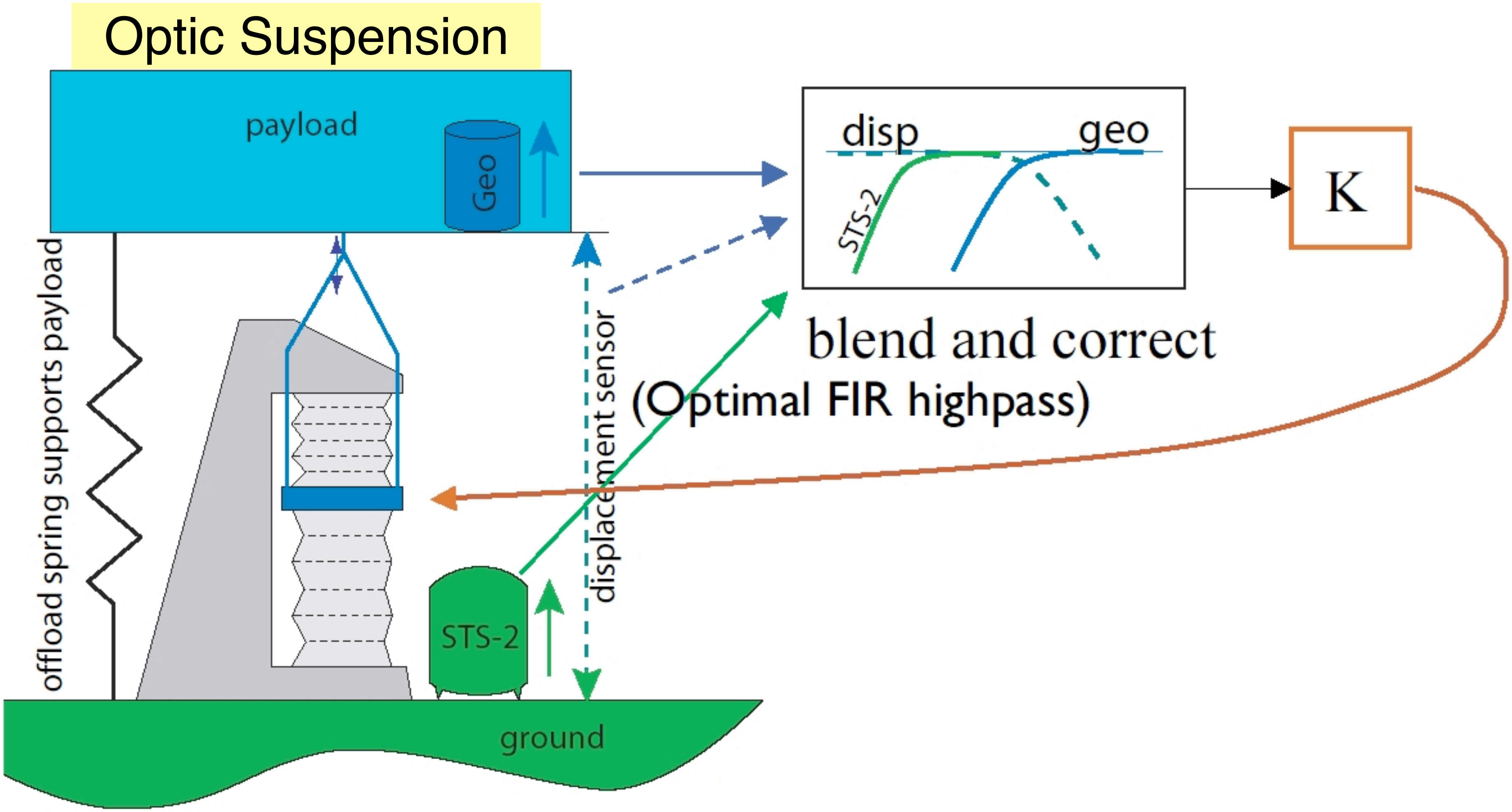
Human activity:
Cars,
Trains,
Trucks,
Logging,
Well Drilling,
Oil Pipeline

Amplified by internal isolation stack resonances

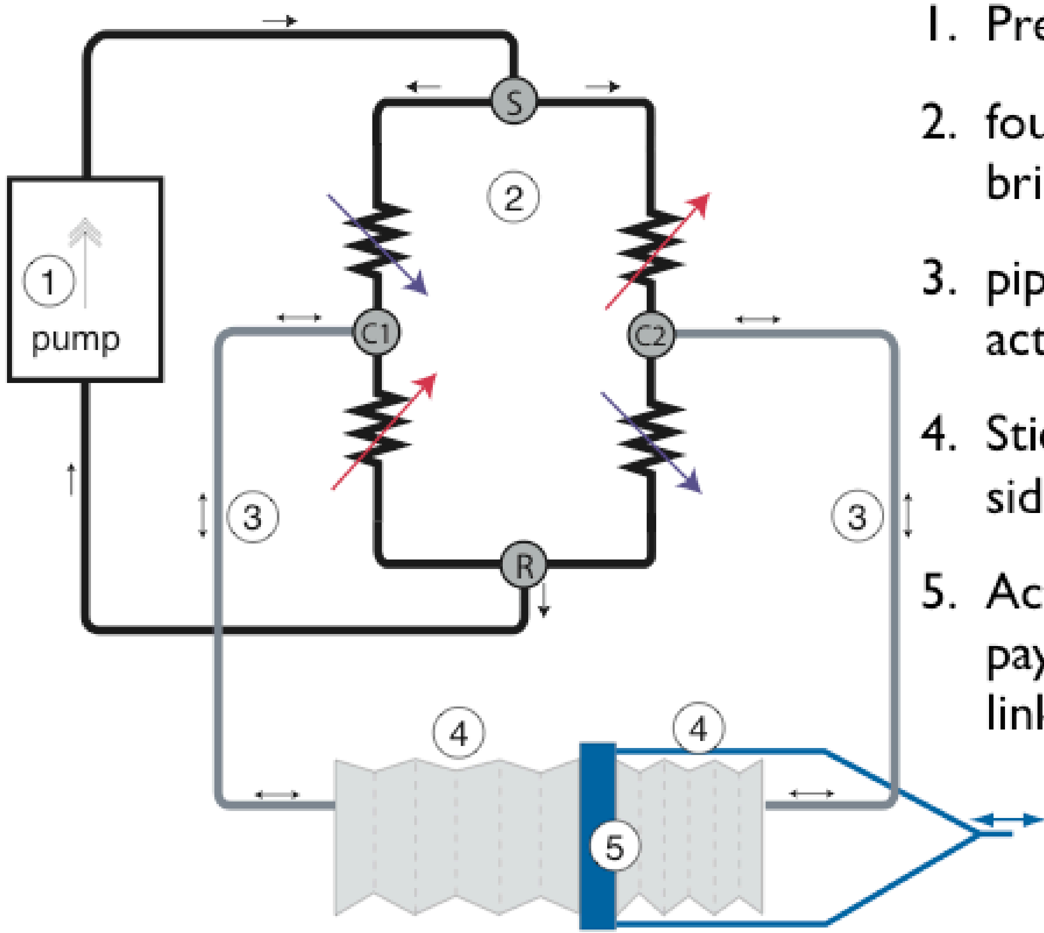
Seismic Noise



Active Seismic Isolation



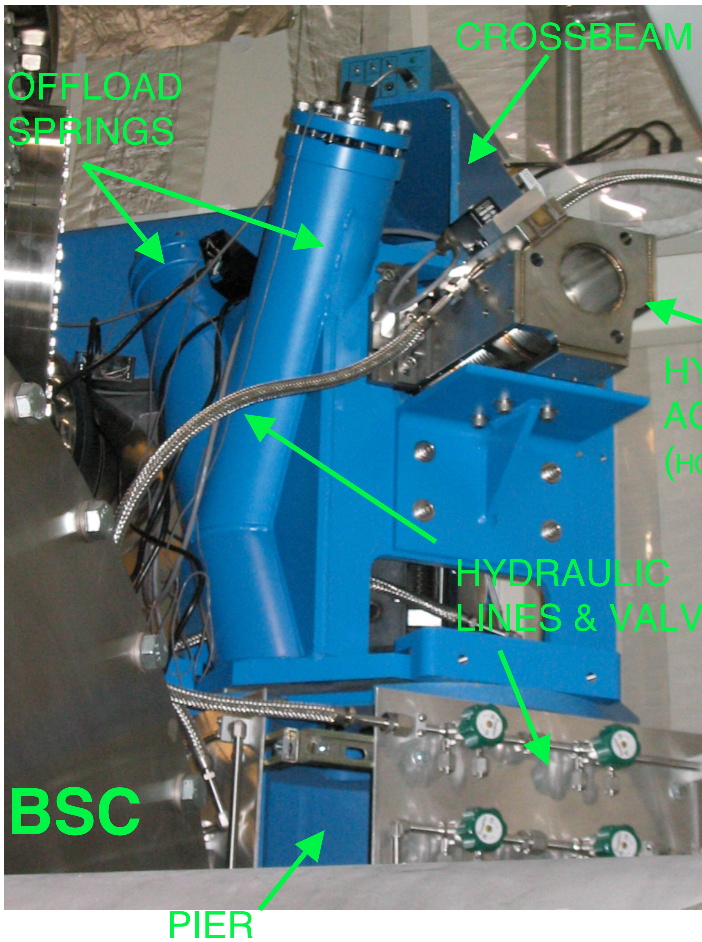
Hydraulic bridge actuation



1. Pressure-stabilized pump.
2. four-valve flow-resistance bridge.
3. pipes connect bridge to actuator.
4. Stiction-free bellows on each side of actuated plate.
5. Actuated plate connected to payload through 1-DOF linkage.

Active Seismic Isolation

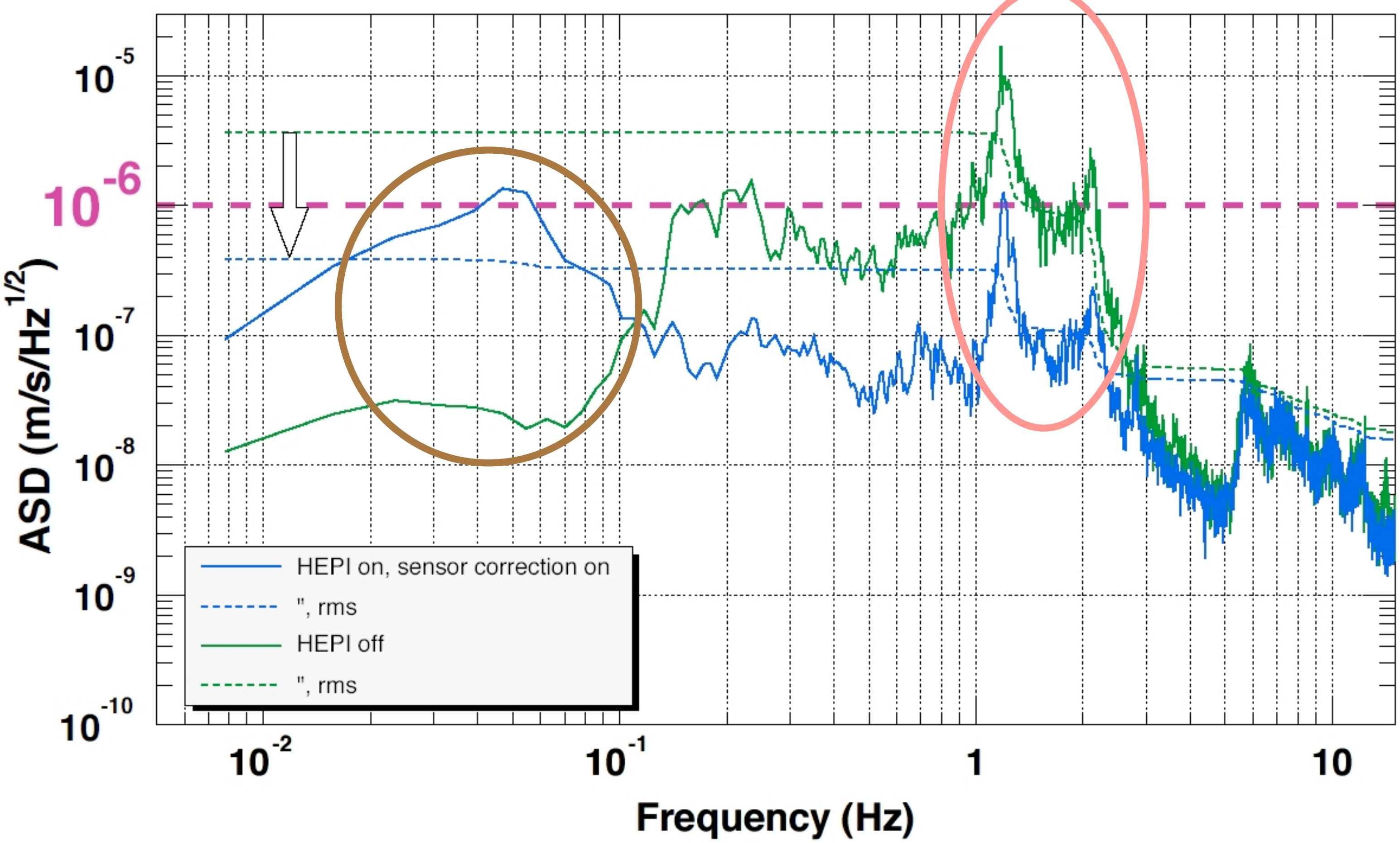
Hydraulic External Pre-Isolator (HEPI)

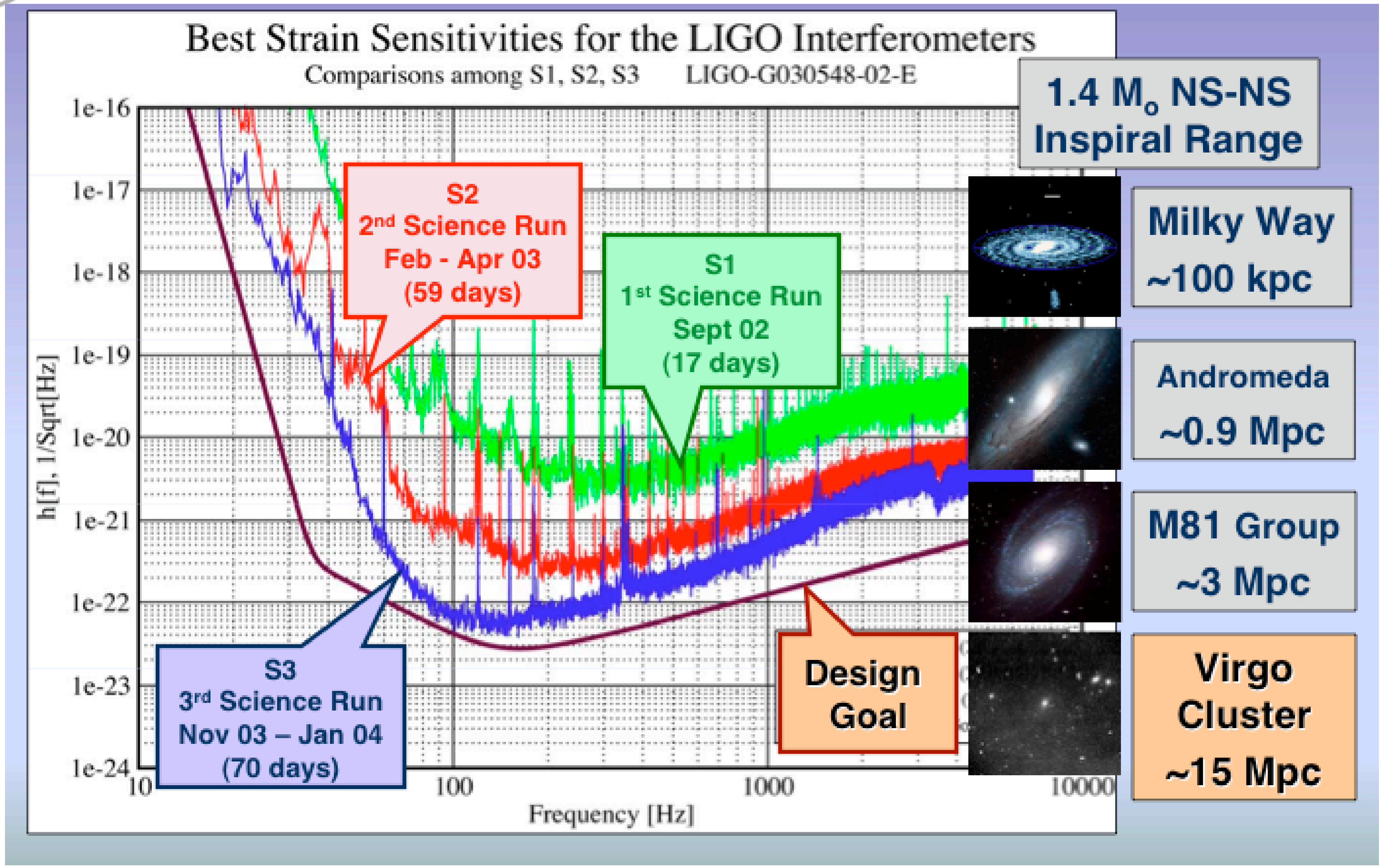


Isolation Performance for a single arm cavity

Amplification in the earthquake band: automatic fade-out during earthquakes

10x reduction in the crucial frequency band

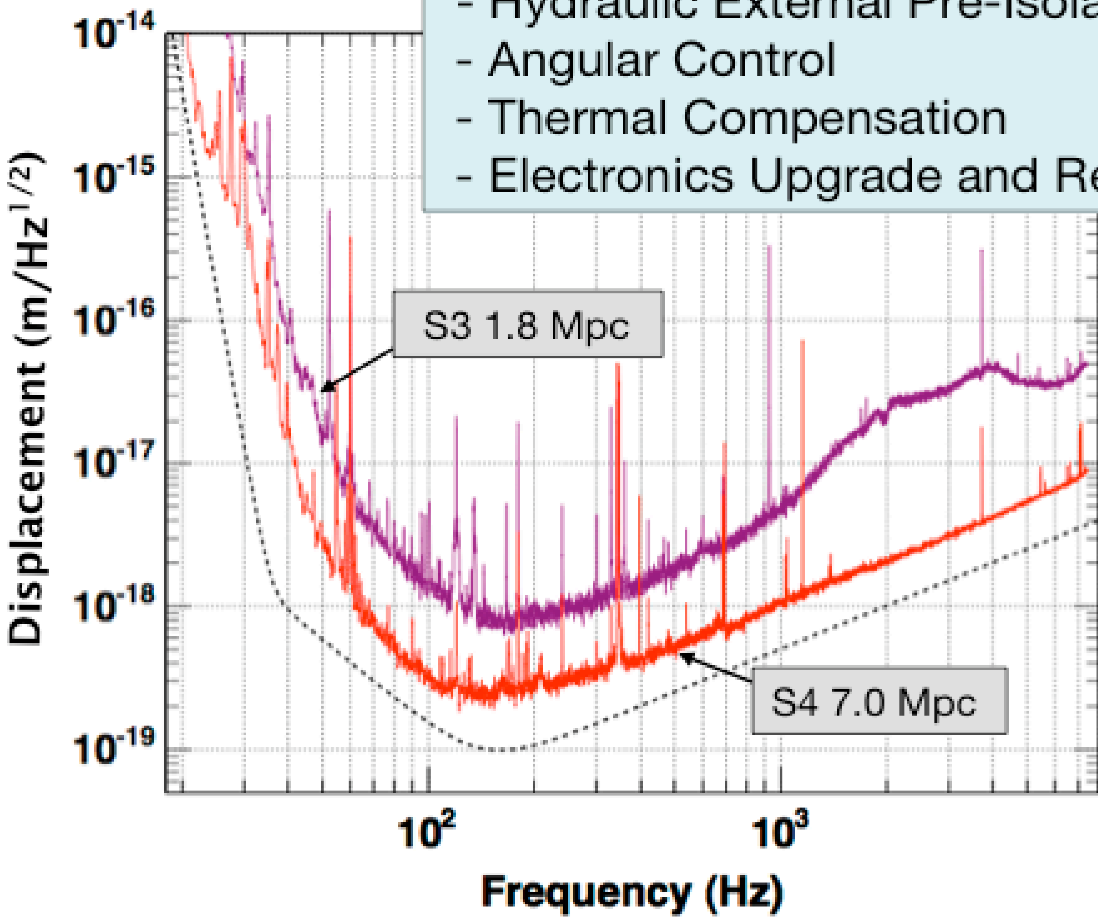


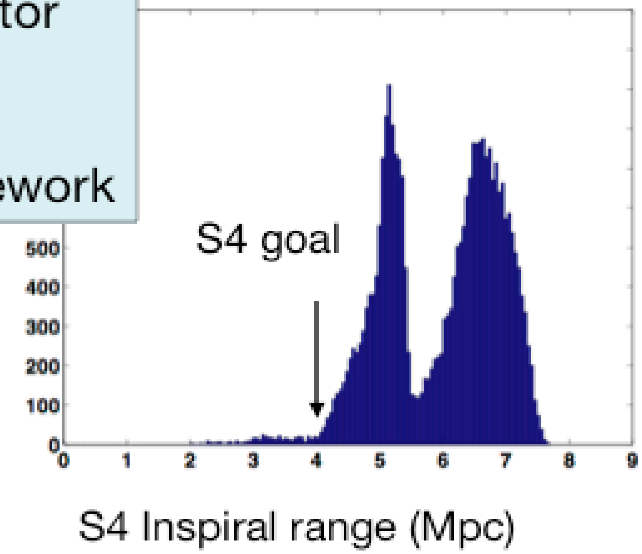

Best Strain Sensitivities for the LIGO Interferometers
Comparisons among S1, S2, S3 LIGO-G030548-02-E
1.4 M_o NS-NS Inspiral Range
S2
2nd Science Run
Feb - Apr 03
(59 days)
S1
1st Science Run
Sept 02
(17 days)
S3
3rd Science Run
Nov 03 – Jan 04
(70 days)
Design Goal
Milky Way
~100 kpc
Andromeda
~0.9 Mpc
M81 Group
~3 Mpc
Virgo Cluster
~15 Mpc
h[f], 1/Sqrt[Hz]
1e-16
1e-17
1e-18
1e-19
1e-20
1e-21
1e-22
1e-23
1e-24
10
100
1000
10000
Frequency [Hz]

L1 during S4

Preliminary

Main Efforts Since S3:
- Hydraulic External Pre-Isolator
- Angular Control
- Thermal Compensation
- Electronics Upgrade and Rework



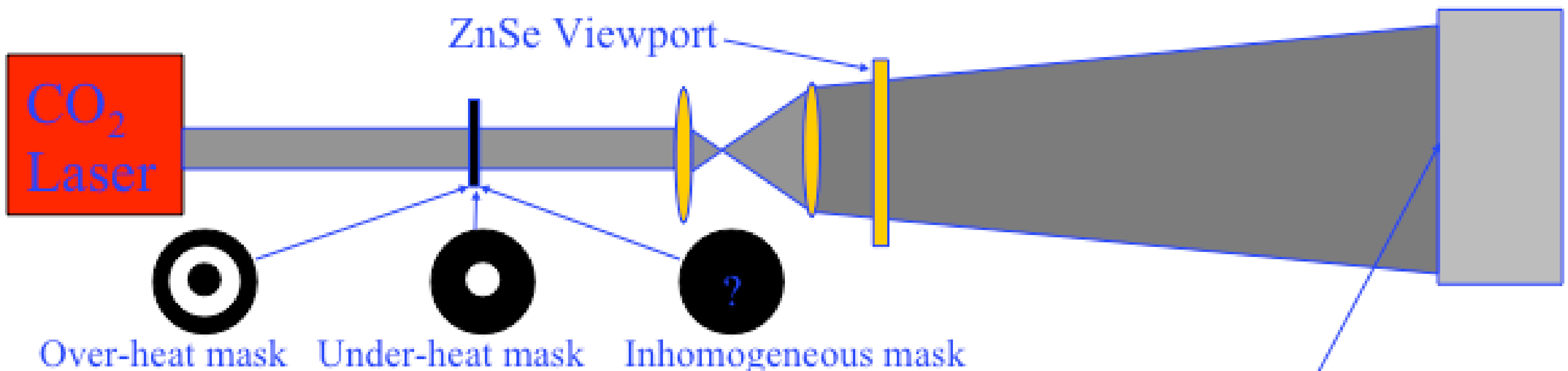


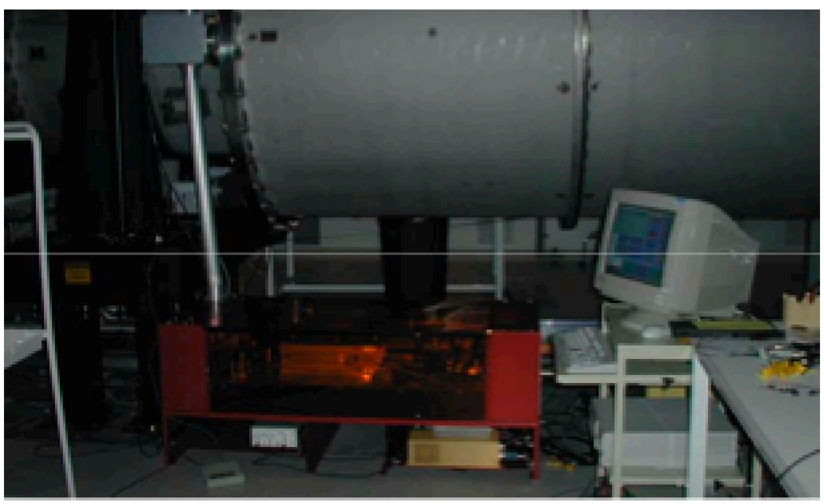
Duty cycle	
S3	22%
S4	72%
S4 goal	70%

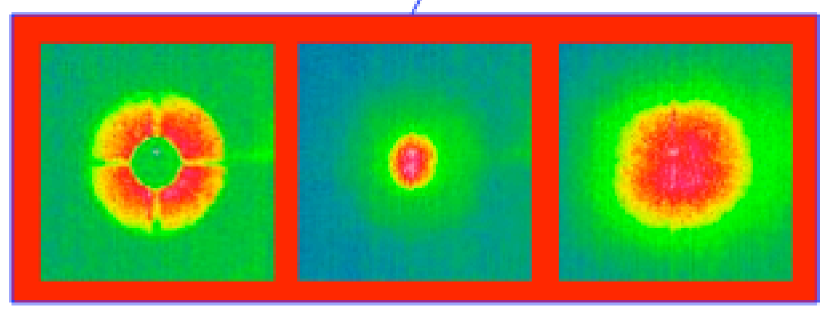
Other Improvements

- Improved coil actuation electronics
- Extra photodiodes added to the output table
- Angular control using Wave Front Sensor (WFS) system.
- Thermal Compensation System (TCS).

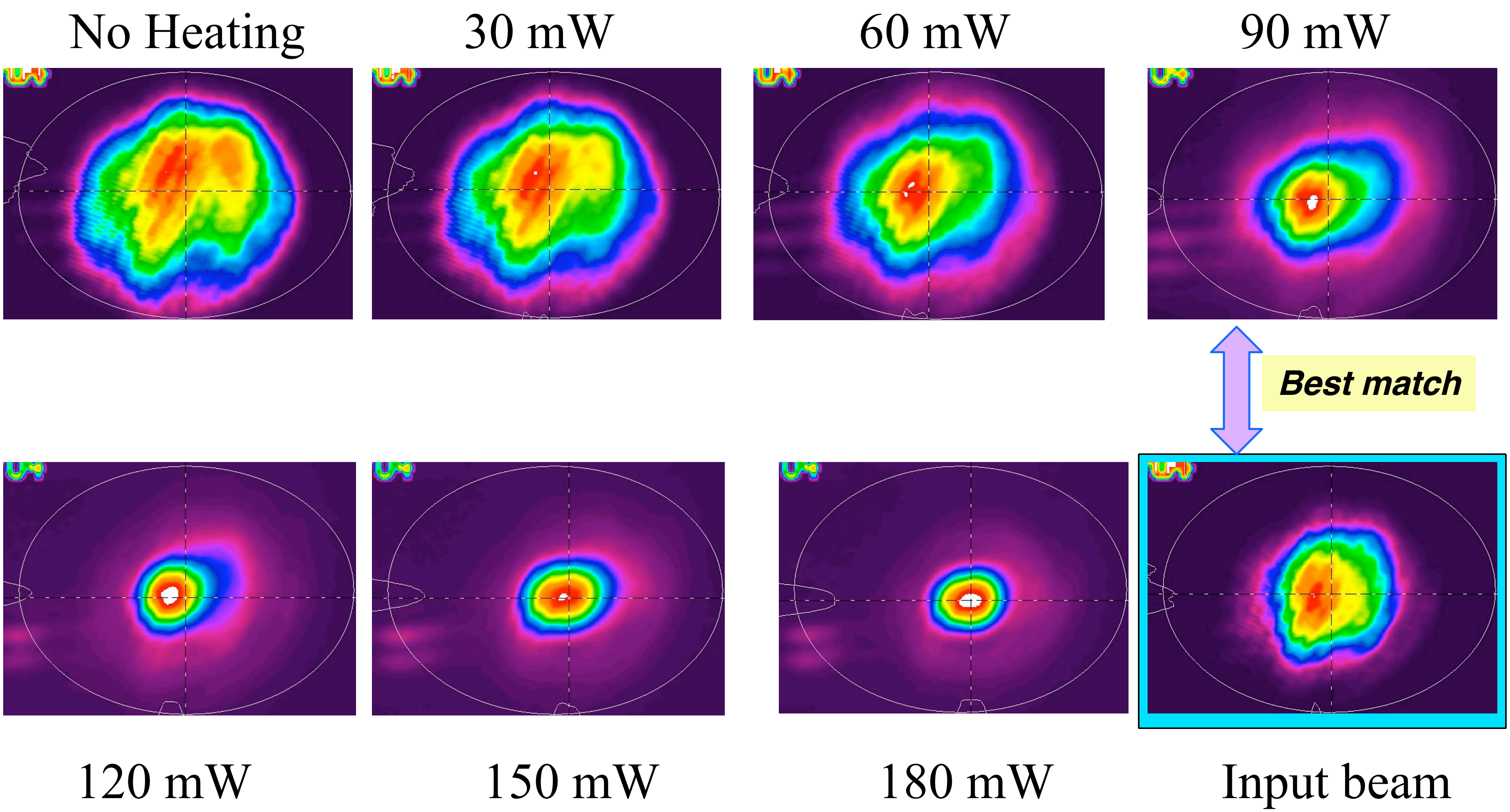
TCS


ZnSe Viewport
CO_2 Laser
?
Over-heat mask
Under-heat mask
Inhomogeneous mask

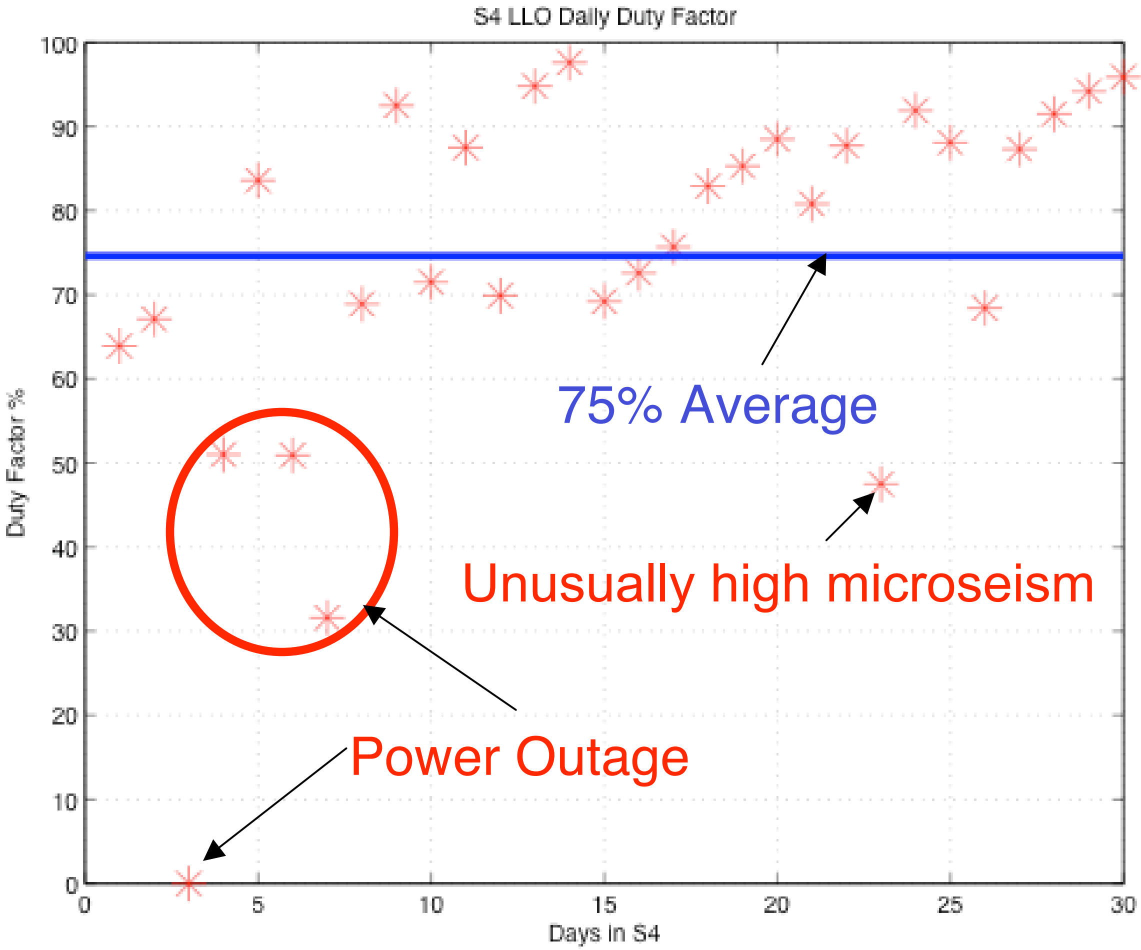



Over-heat pattern
Under-heat pattern
Raw Heating pattern

Sideband beam images at the dark port



L1 Performance for S4



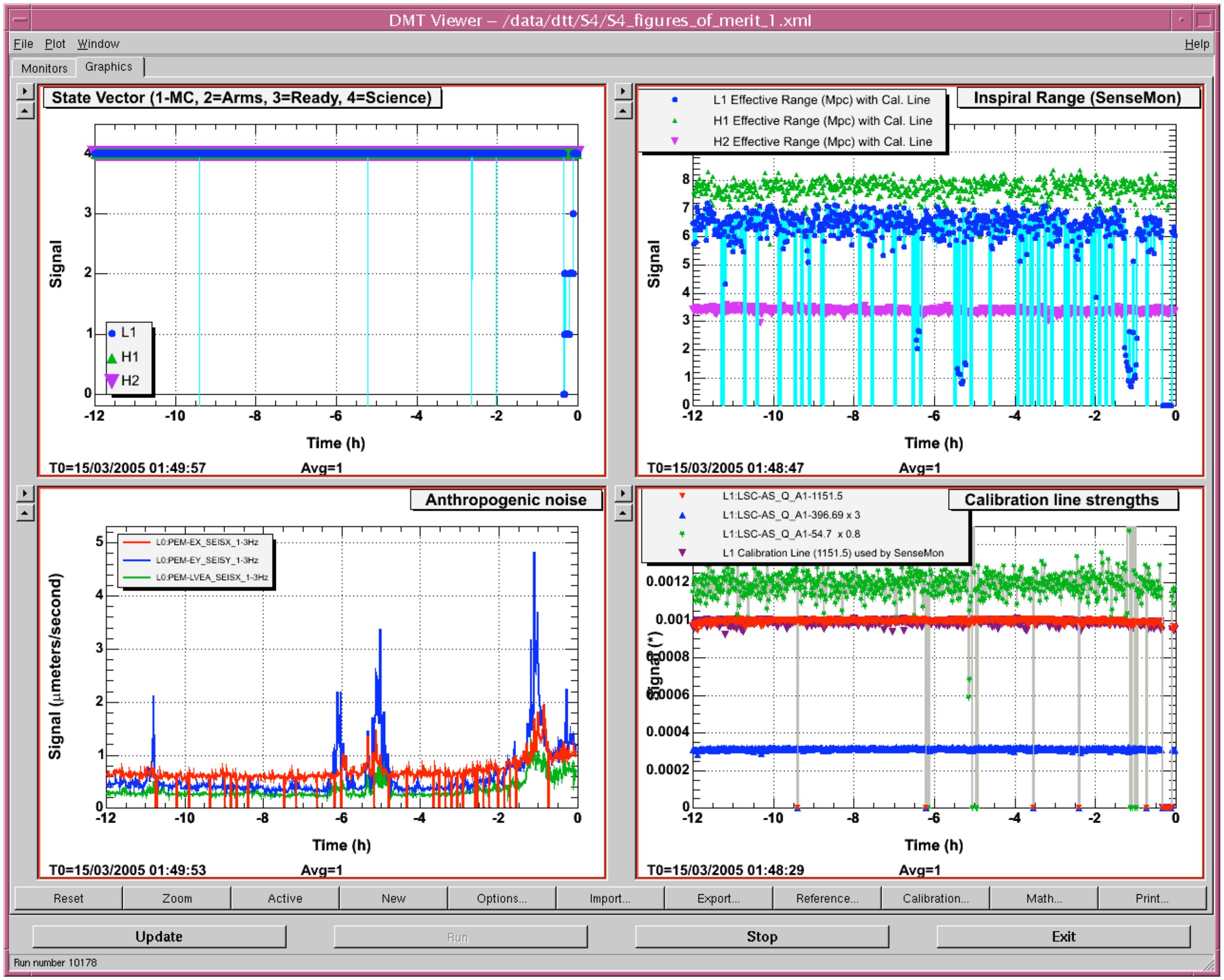
HEPI enabled very high duty Factor at Livingston.

H1 ~ 80% ~8.5 Mpc
H2 ~ 81% ~3.5 Mpc
L1 ~ 75% ~7.0 Mpc

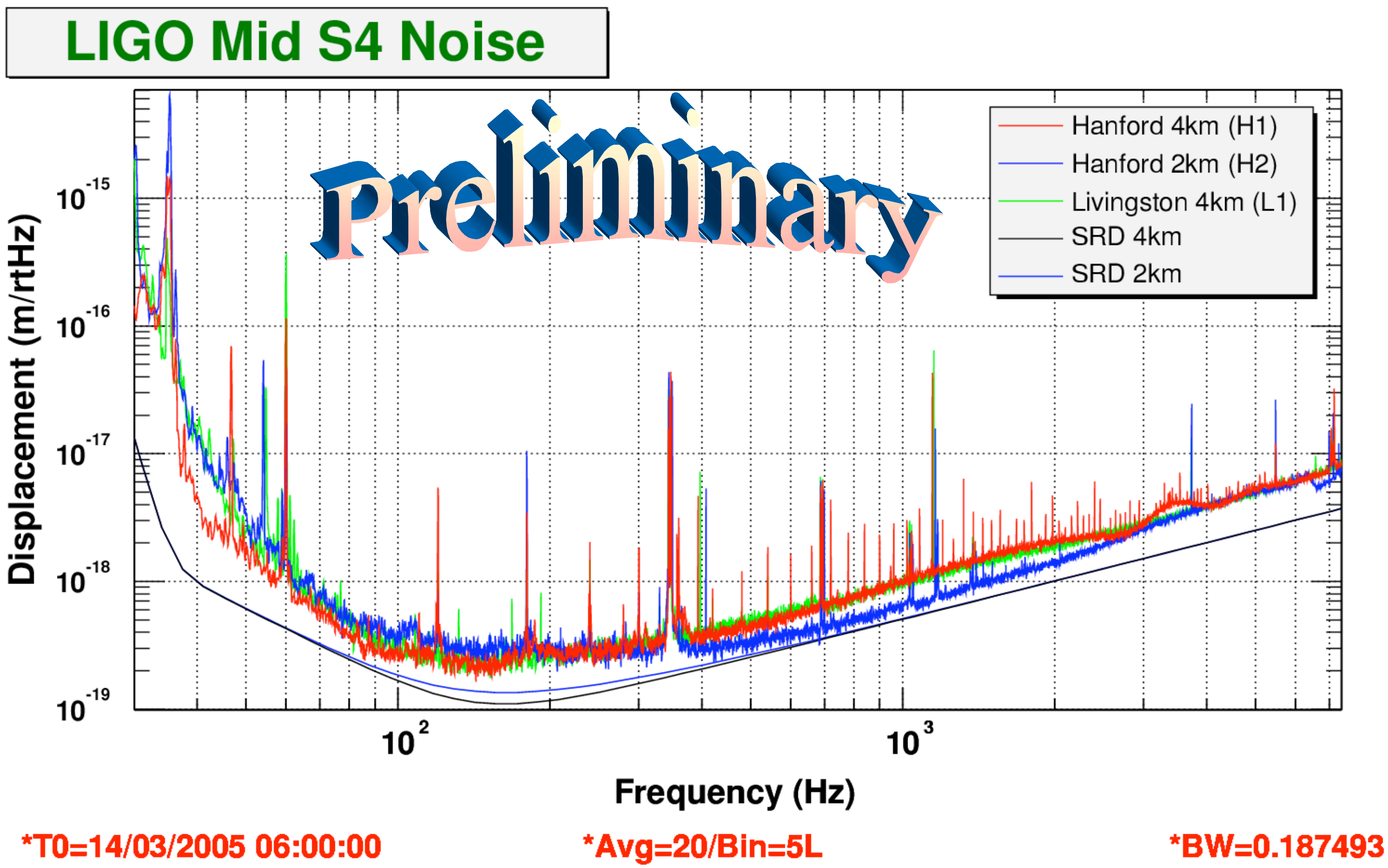
Triple Coincidence ~56%
403 hours, more than any previous science run.

Preliminary

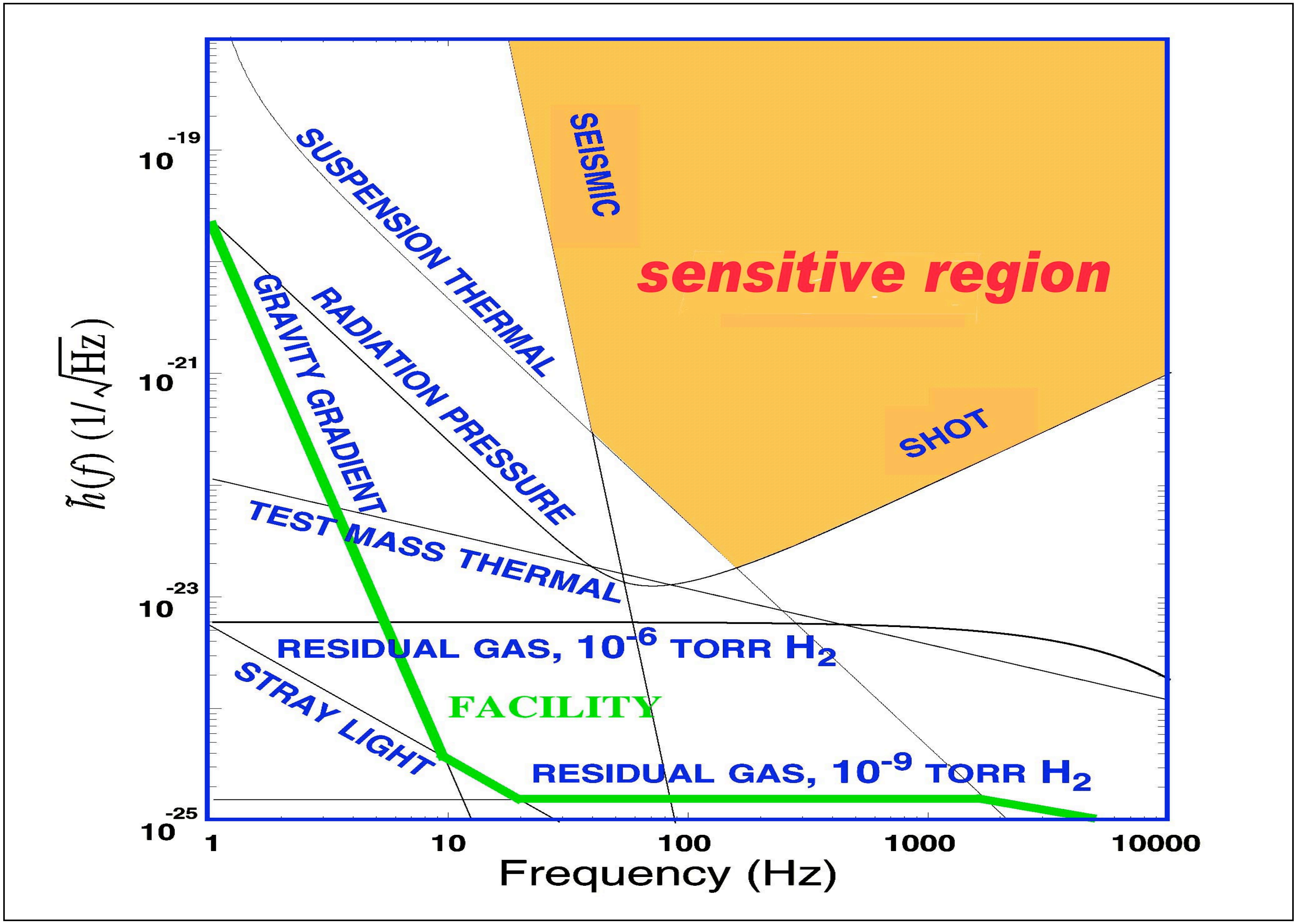
Performance of LIGO



"Typical" noise midway through S4



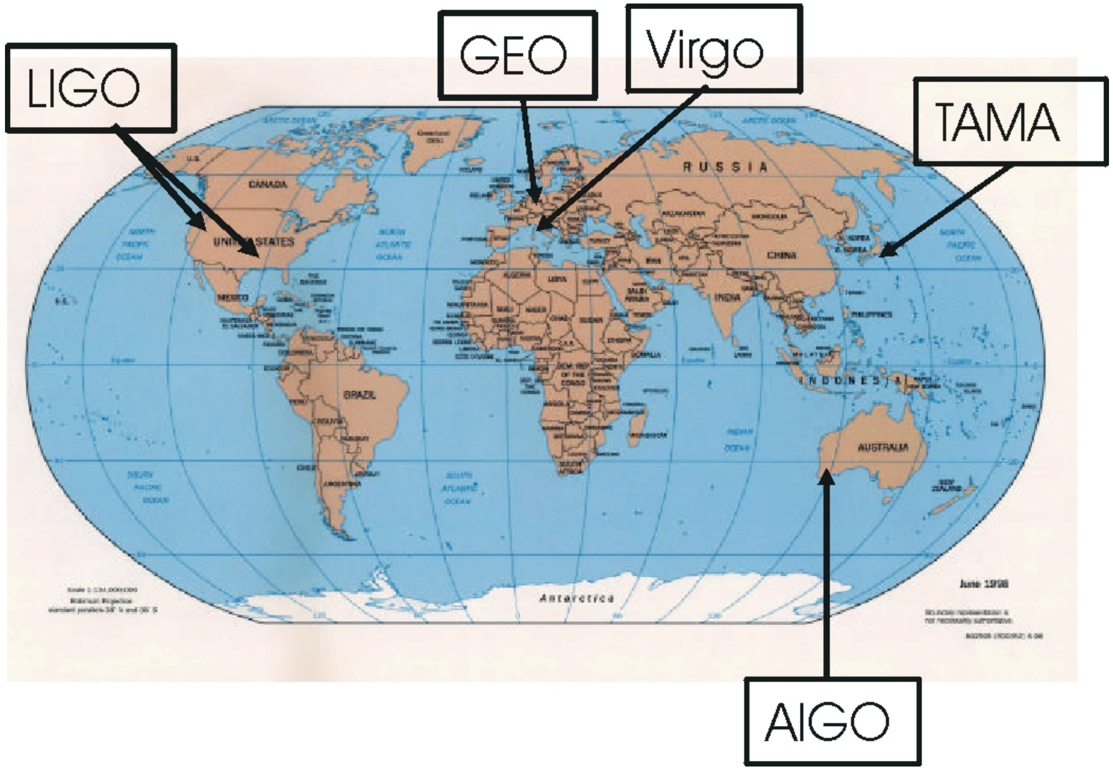
Preliminary Noise Budget



The LIGO Scientific Collaboration

- At last count 501 members
- 35 Institutions plus the LIGO laboratory.
- International participation from Australia, Germany, India, Japan, Russia, Spain and the U.K.
- Consists of technical and data analysis groups tasked with detector characterization, Advanced LIGO R&D and the search for signals.

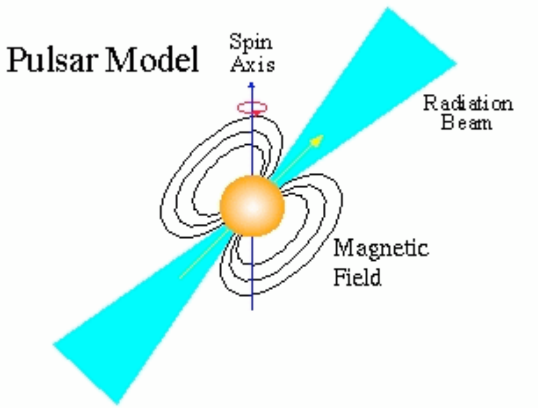
GW Interferometers



- Worldwide Network:
  - Coincidence greatly increases confidence in detection.
  - Localization of a source by triangulation.

CW sources

- Nearly-monochromatic continuous sources of gravitational waves include neutron stars with:
  - spin precession at $\sim f_{rot}$
  - excited oscillatory modes such as the r-mode at 4/3 * f_{rot}
  - non-axisymmetric distortion of crystalline structure, at $2f_{rot}$
- Limit our search to gravitational waves from a triaxial neutron star emitted at twice its rotational frequency (for the analysis presented here, only)
- Signal would be frequency modulated by relative motion of detector and source, plus amplitude modulated by the motion of the antenna pattern of the detector



Source model

The expected signal has the form:

$$h(\mathrm{t}) = \mathrm{F}_{+}(\mathrm{t};\psi)\mathrm{h}_0\left(\frac{1+\cos^2\iota}{2}\right)\cos\Phi(t) - \mathrm{F}_{\times}(\mathrm{t};\psi)\mathrm{h}_0\cos\iota\sin\Phi(t)$$

PRD **58** 063001 (1998)

- F_+ and F_x : strain antenna patterns of the detector to plus and cross polarization, bounded between -1 and 1
- Here, signal parameters are:
  - h_0 – amplitude of the gravitational wave signal
  - ψ – polarization angle of signal
  - ι – inclination angle of source with respect to line of sight
  - ϕ_0 – initial phase of pulsar; $\Phi(t=0)$, and $\Phi(t) = \phi(t) + \phi_0$

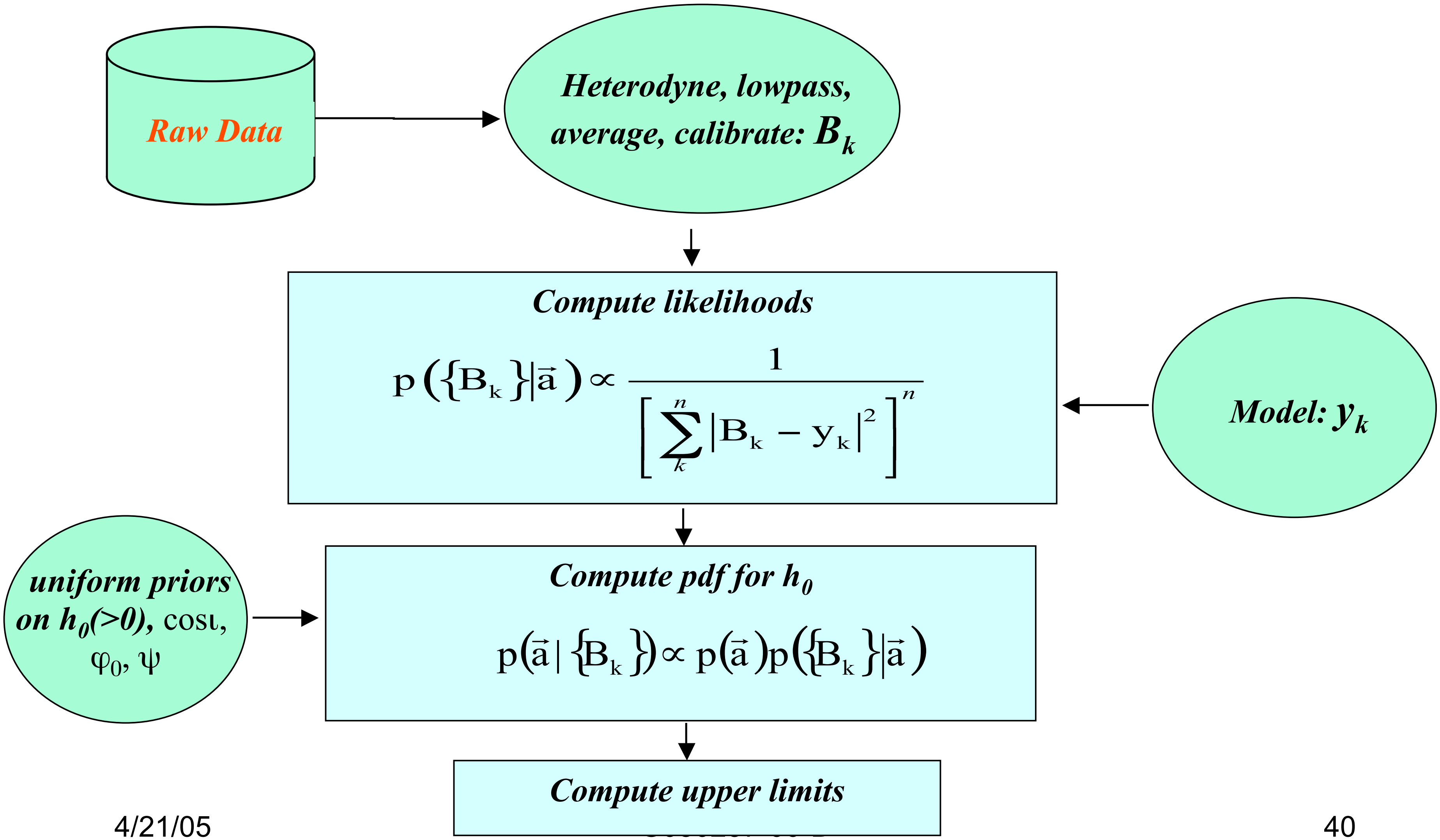
Heterodyne, i.e. multiply by: $e^{-i\phi(t)}$

so that the expected demodulated signal is then:

$$\mathrm{y}(\mathrm{t_k};\mathbf{a}) = \frac{1}{4}\mathrm{F}_{+}(\mathrm{t_k};\psi)\mathrm{h}_0(1+\cos^2\iota)e^{i\phi_0} - \frac{i}{2}\mathrm{F}_{\times}(\mathrm{t_k};\psi)\mathrm{h}_0(\cos\iota)e^{i\phi_0}$$

Here, $\mathbf{a} = \mathbf{a}(h_0, \psi, \iota, \phi_0)$, a vector of the signal parameters.

Analysis summary

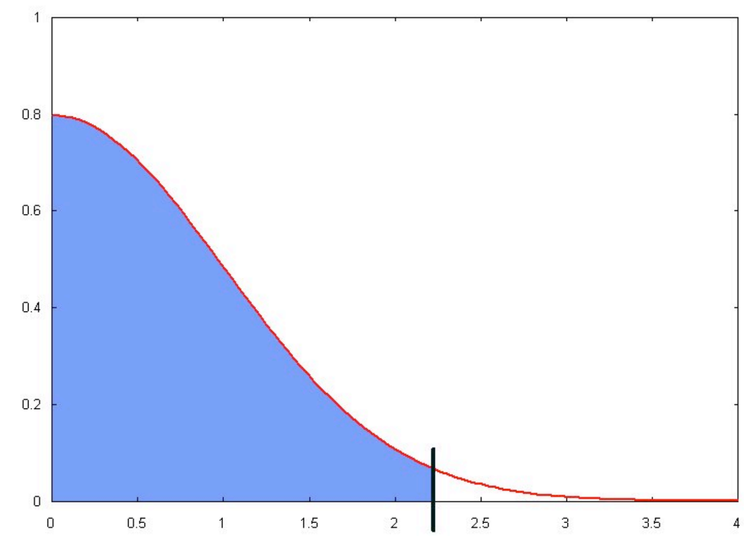


S2 known pulsar analysis

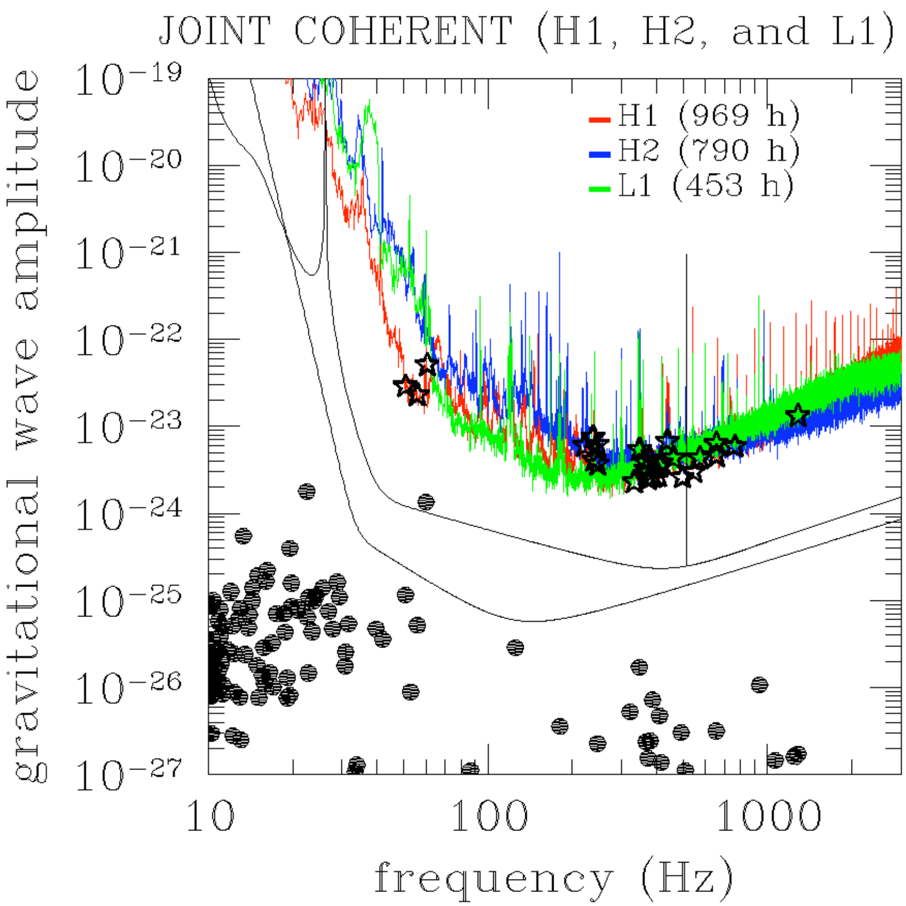
- Analyzed 28 known isolated pulsars with $2f_{rot}$ > 50 Hz.
  - Another 10 isolated pulsars are known with $2f_{rot}$ > 50 Hz but the uncertainty in their spin parameters is sufficient to warrant a search over frequency.
- Crab pulsar heterodyned to take timing noise into account.
- Total observation time:
  - 969 hours for H1 (Hanford, 4km)
  - 790 hours for H2 (Hanford, 2km)
  - 453 hours for L1 (Livingston, 4km)
- Marginalize over the nuisance parameters ($\cos\iota$, φ_0, ψ)
- We define the 95% upper limit by a value h_{95} satisfying

$$0.95 = \int_0^{h_{95}} p(h_0 \mid \{B_k\}) \mathrm{d}h_0$$

- Such an upper limit can be defined even when signal is present.



Multi-detector upper limits



☆ 95% upper limits

- Performed joint coherent analysis for 28 pulsars using data from all IFOs.

- Most stringent UL is for pulsar J1629-6902 (~333 Hz) where 95% confident that $h_0 < 2.3 \times 10^{-24}$.
- 95% upper limit for Crab pulsar (~ 60 Hz) is $h_0 < 5.1 \times 10^{-23}$.
- 95% upper limit for J1939+2134 (~ 1284 Hz) is $h_0 < 1.3 \times 10^{-23}$.

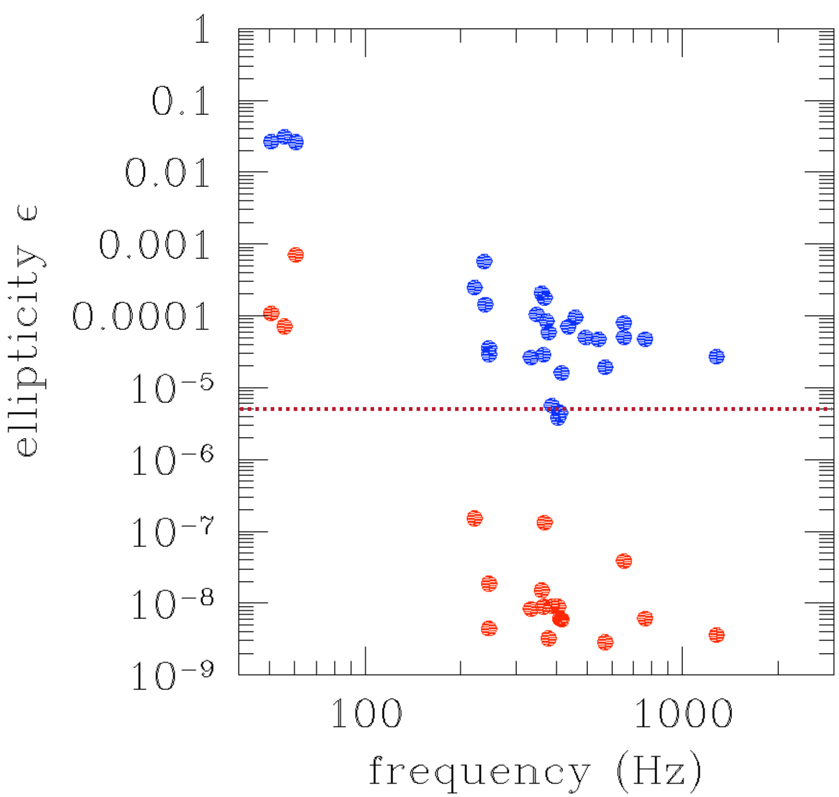
Upper limits on ellipticity

Equatorial ellipticity:

$$\varepsilon = \frac{I_{xx} - I_{yy}}{I_{zz}}$$

Pulsars J0030+0451 (230 pc), J2124-3358 (250 pc), and J1024-0719 (350 pc) are the nearest three pulsars in the set and their equatorial ellipticities are all constrained to less than 10^{-5}.

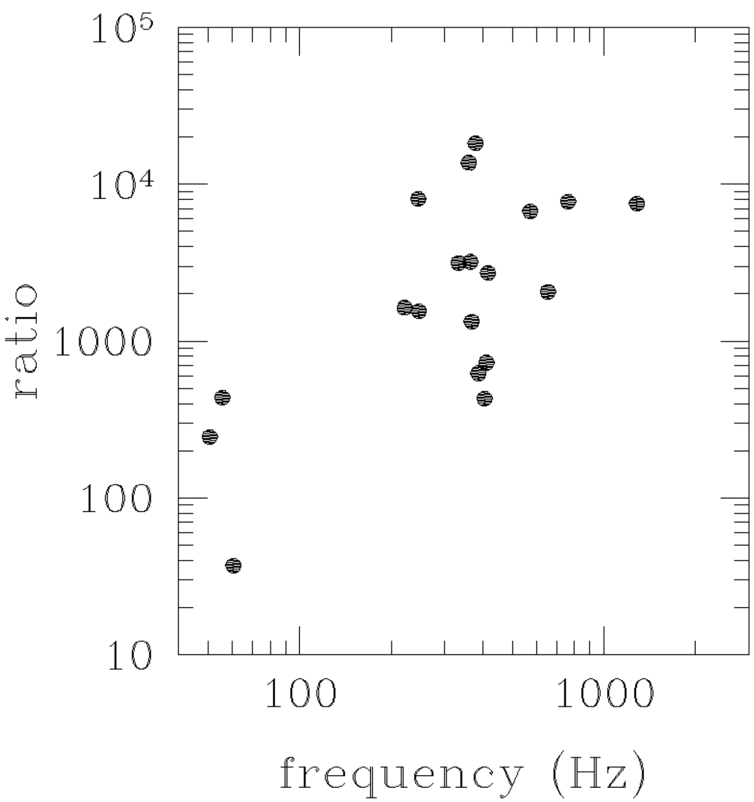
- S2 upper limits
- Spin-down based upper limits



Approaching spin-down upper limits

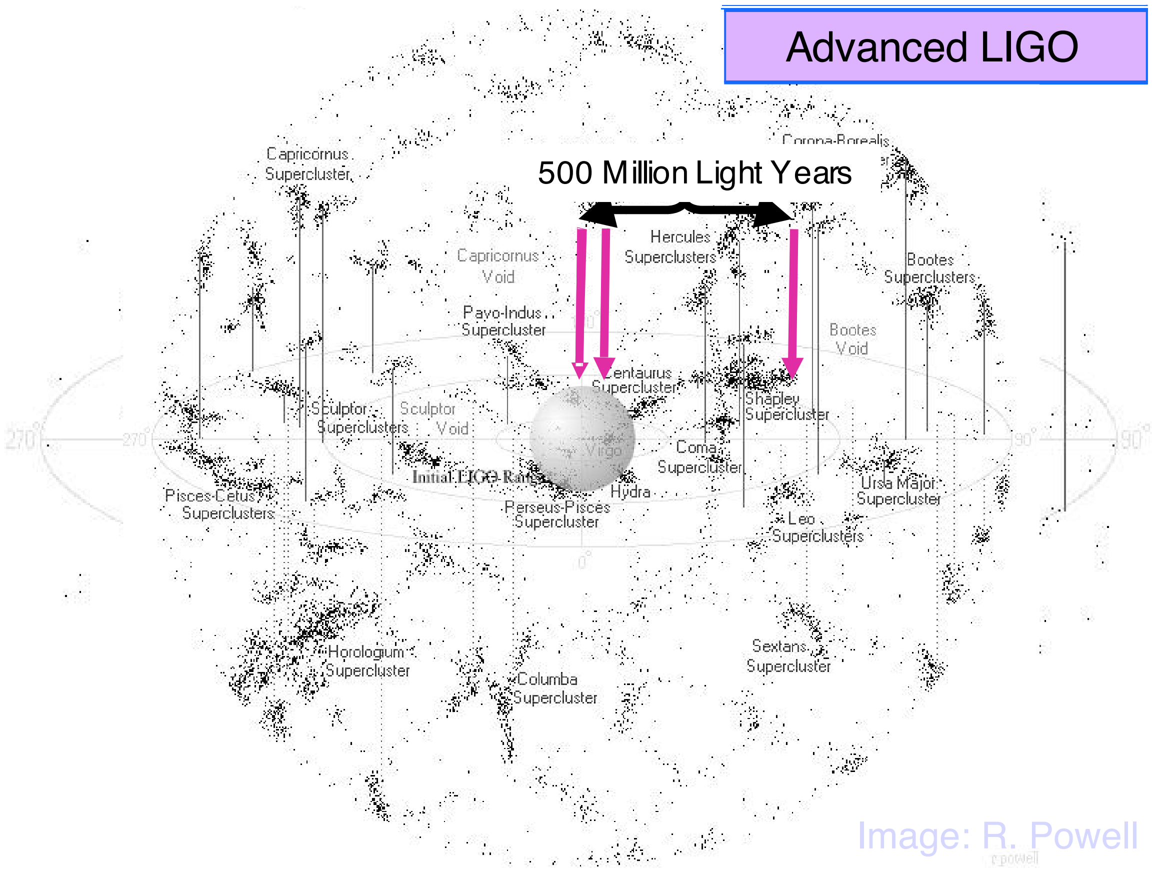
- For Crab pulsar (B0531+21) we were still a factor of ~35 above the spin-down upper limit in S2.
- Hope to reach spin-down based upper limit in S3!
- Note that not all pulsars analysed are constrained due to spin-down rates; some actually appear to be spinning-up (associated with accelerations in globular cluster).

Ratio of S2 upper limits to spin-down based upper limits



LIGO to Advanced LIGO

- Beyond the Virgo cluster we will see **~r^{3}** increase in available sources for **r** increase in range.

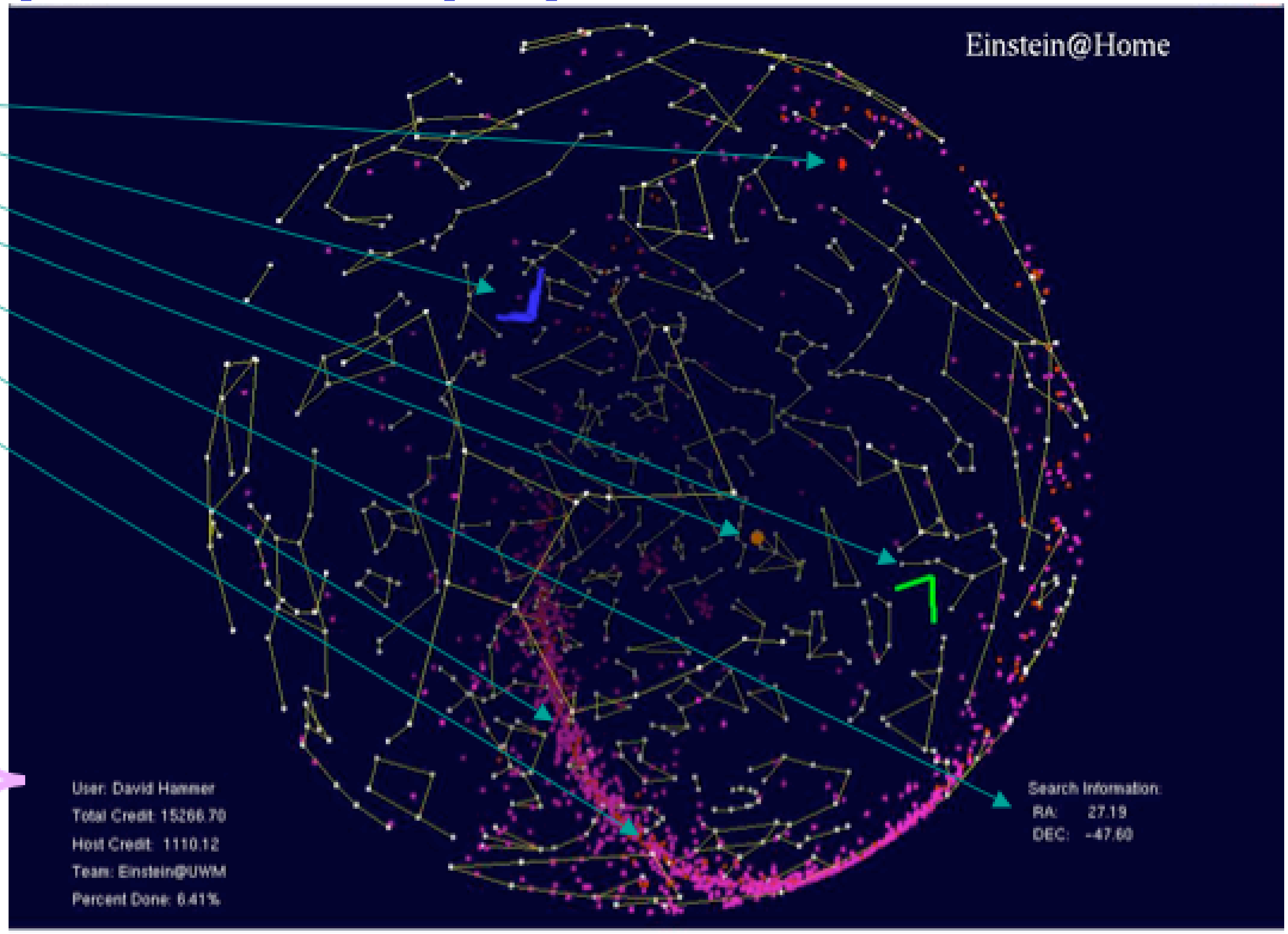


Outlook

- Initial LIGO is approaching design sensitivity.
- The just completed S4 science run acquired data of unprecedented sensitivity.
- Work is now in progress to prepare for S5 which will be a six month run.
- Many papers have appeared or are about to appear setting limits on binary neutron star inspirals, unmodelled bursts, stochastic background and continuous wave sources.
- How can you help?

http://einstein.phys.uwm.edu/

- GEO-600 Hannover
- LIGO Hanford
- LIGO Livingston
- Current search point
- Current search coordinates
- Known pulsars
- Known supernovae remenants



- User name
- User's total credits
- Machine's total credits
- Team name
- Current work % complete

Now: S3 all-sky search.

Next: S4 data, best 40 hours.

Feedback

$$y = (I+GK)^{-1}GK\,r \quad \text{command tracking}$$
$$+ (I+GK)^{-1}G_\mathrm{d}\,d \quad \text{disturbance suppression}$$
$$- (I+GK)^{-1}GK\,n. \quad \text{noise}$$

Feedforward

$K_\mathrm{ff}G_\mathrm{ff}G = G_\mathrm{d} \Rightarrow$ noise cancellation

Sensor Correction

M corrects error signal within servo loop