Recent Progress at LIGO

Brian O'Reilly

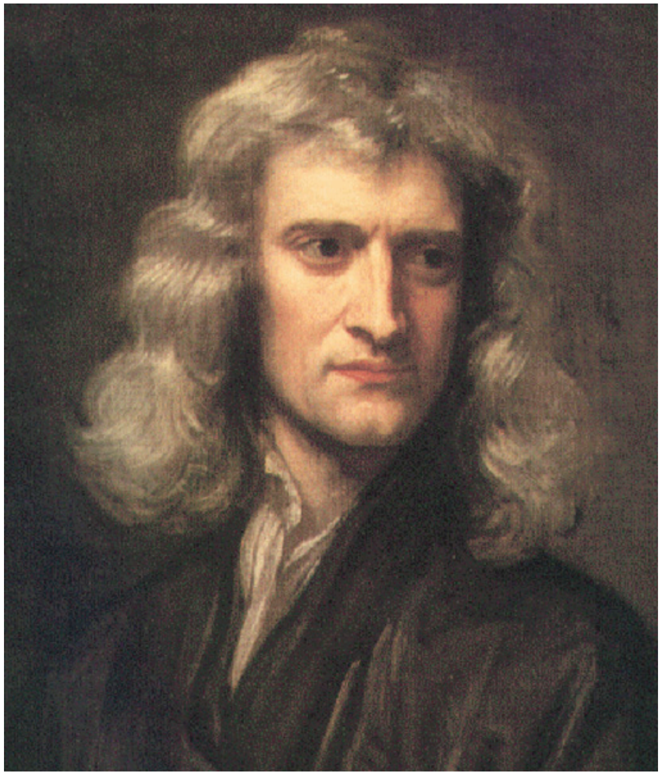
California Institute of Technology

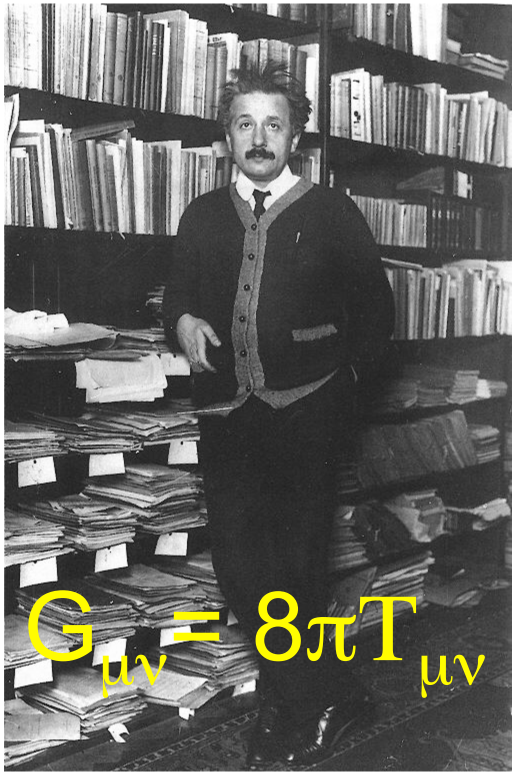
LIGO Livingston Observatory

Outline

- Gravity, gravitational waves and sources.
- Interferometer configuration.
- The LIGO Observatories.
- Sources of noise and noise mitigation.
- S2 CW time domain search.
- S2 Inspiral search
- LIGO publications.
- Advanced LIGO.
- Outlook.

What is Gravity?





Newton

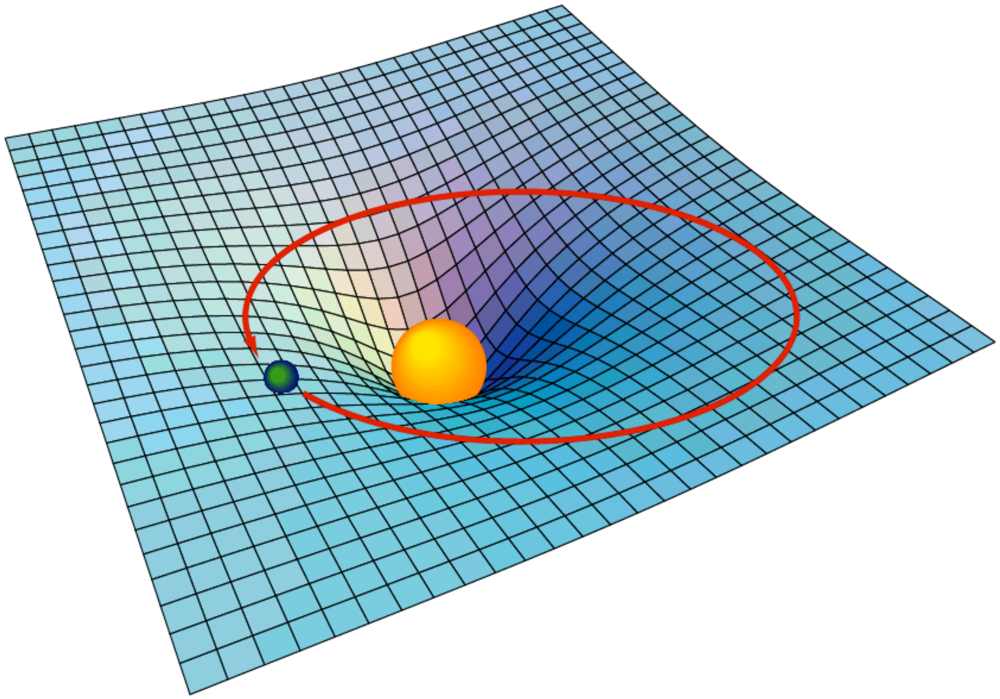
Action at a distance

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?

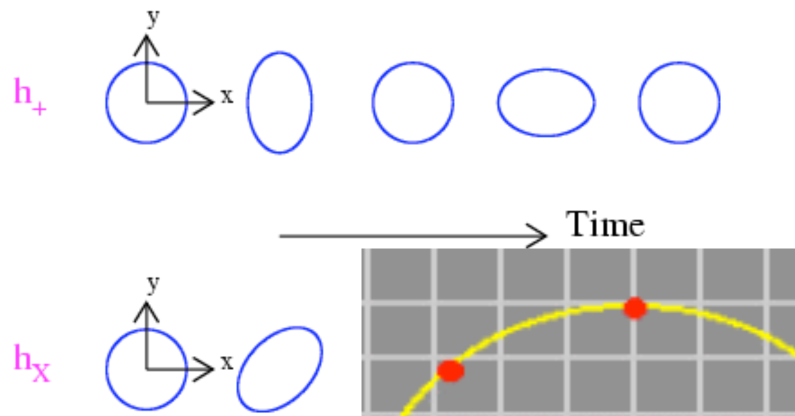
- Gravitational Waves = “Ripples in space-time”
- Two transverse polarizations - quadrupolar: + and x

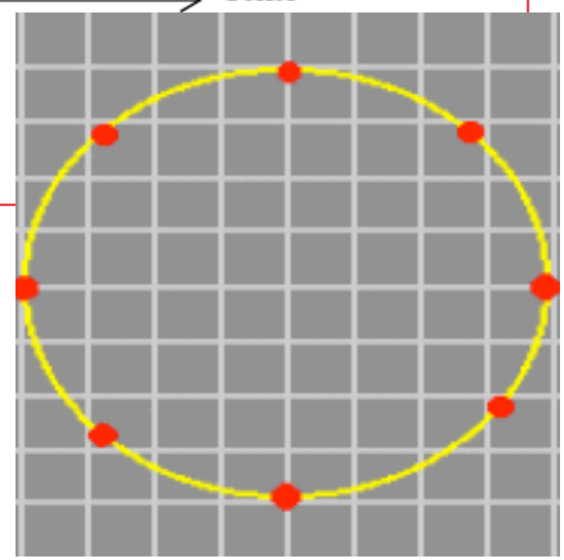
Example:

Ring of test masses

responding to wave

propagating along z

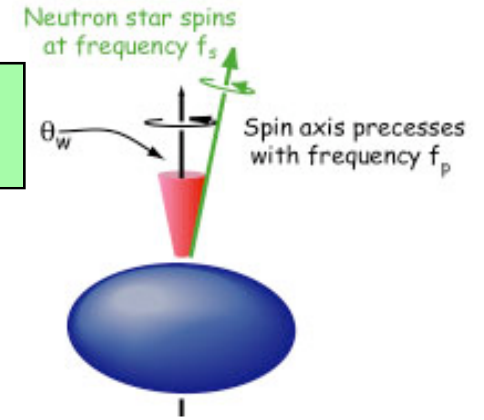




Amplitude parameterized by (tiny)
dimensionless strain h: $\Delta L \sim h(t) \times L$

Making “detectable” gravitational waves

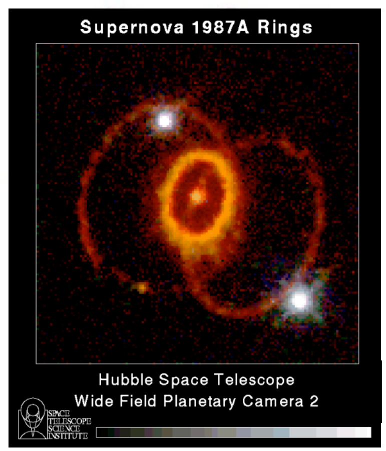
Spinning or wobbling neutron stars

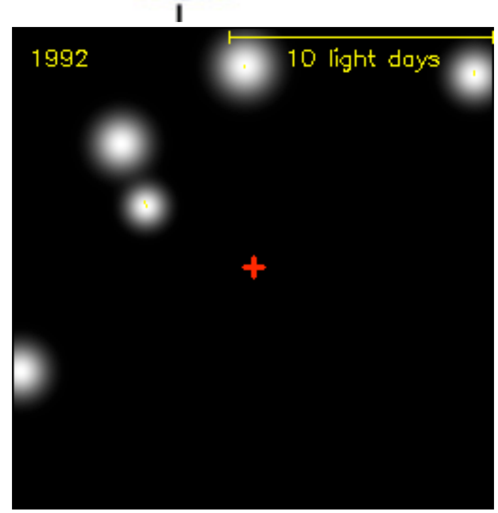


matter

Massive Star

Giant Phases





Grav

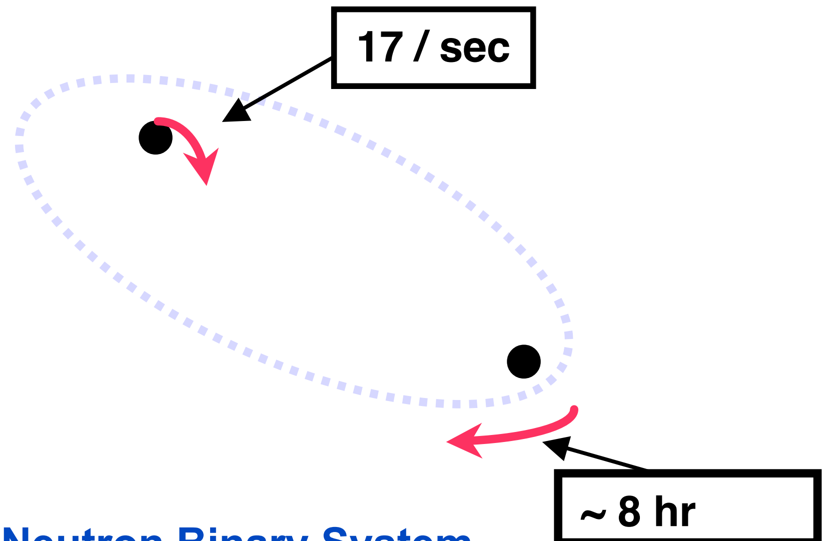
Compress into small space

GRB, Ringdowns

Strong Evidence: Orbital Decay

Neutron Binary System – Hulse & Taylor

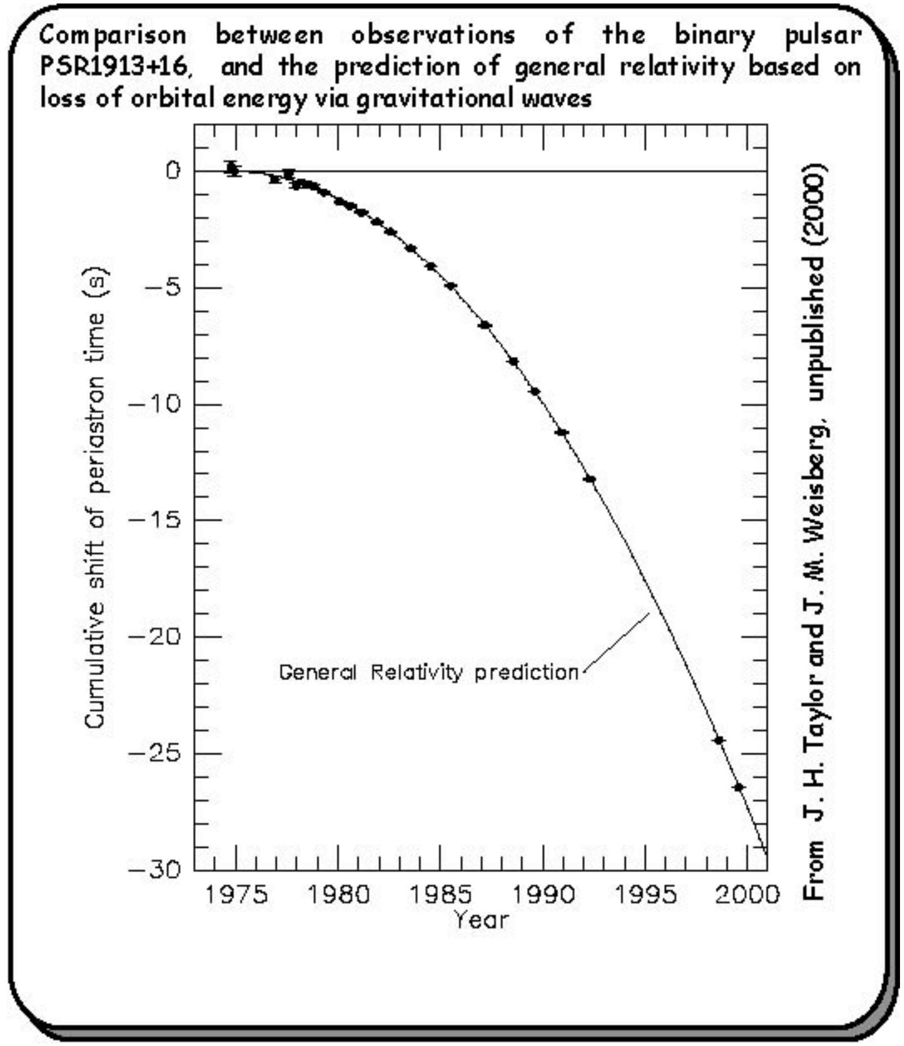
PSR 1913 + 16 -- Timing of pulsars



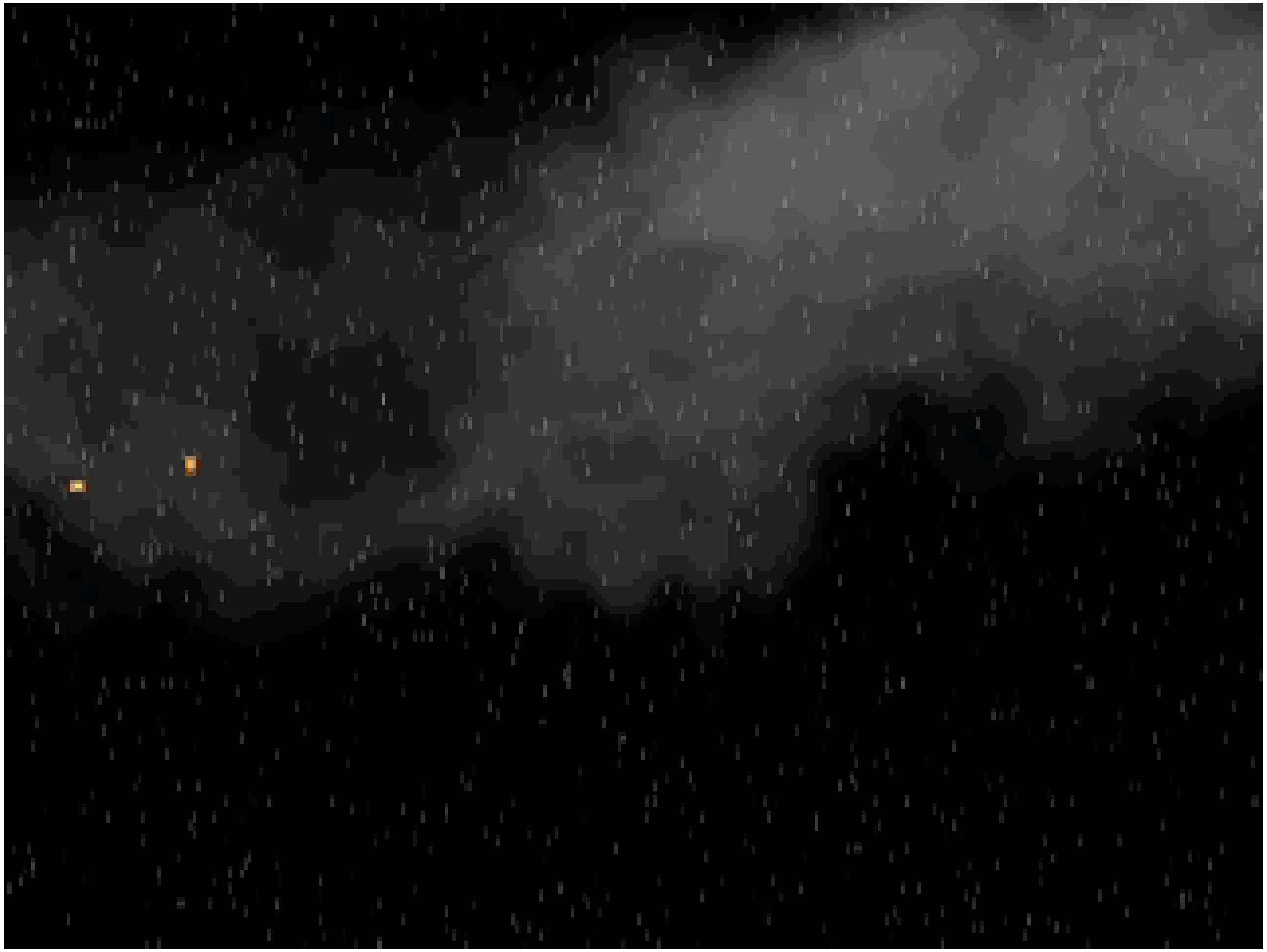
Neutron Binary System
- **separated by 10^6 miles**
- **$m_1 = 1.44 m_\odot$; $m_2 = 1.39 m_\odot$; $\varepsilon = 0.617$**

Prediction from general relativity
- **spiral in by 3 mm/orbit**
- **rate of change orbital period**

Emission of gravitational waves

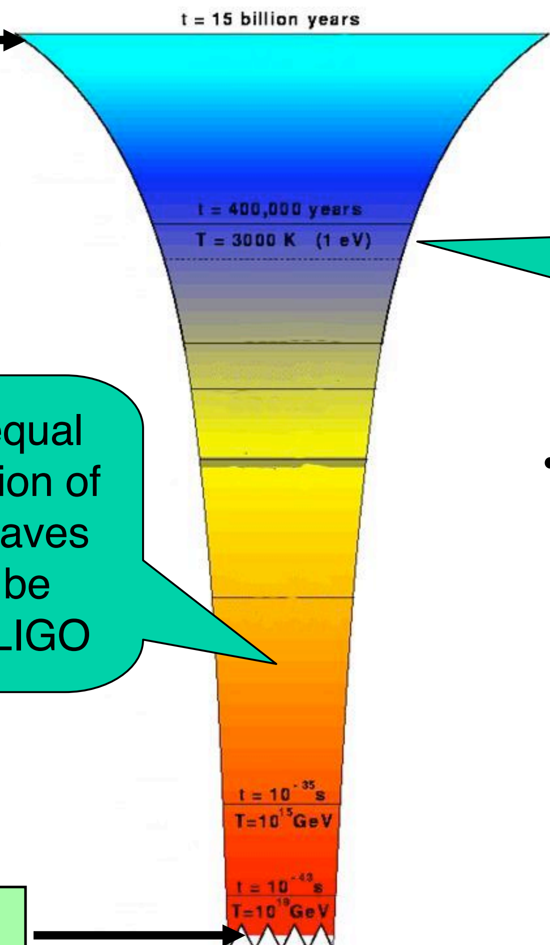


“Chirps”



Stochastic background of gravitational waves

Today



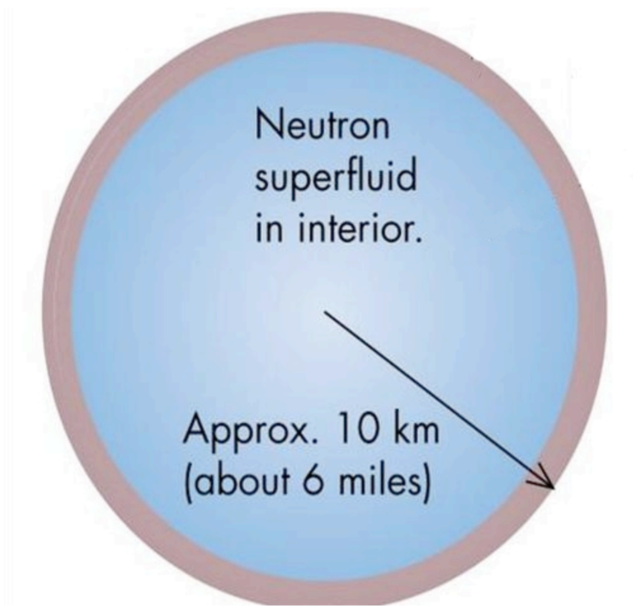
Big Bang

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

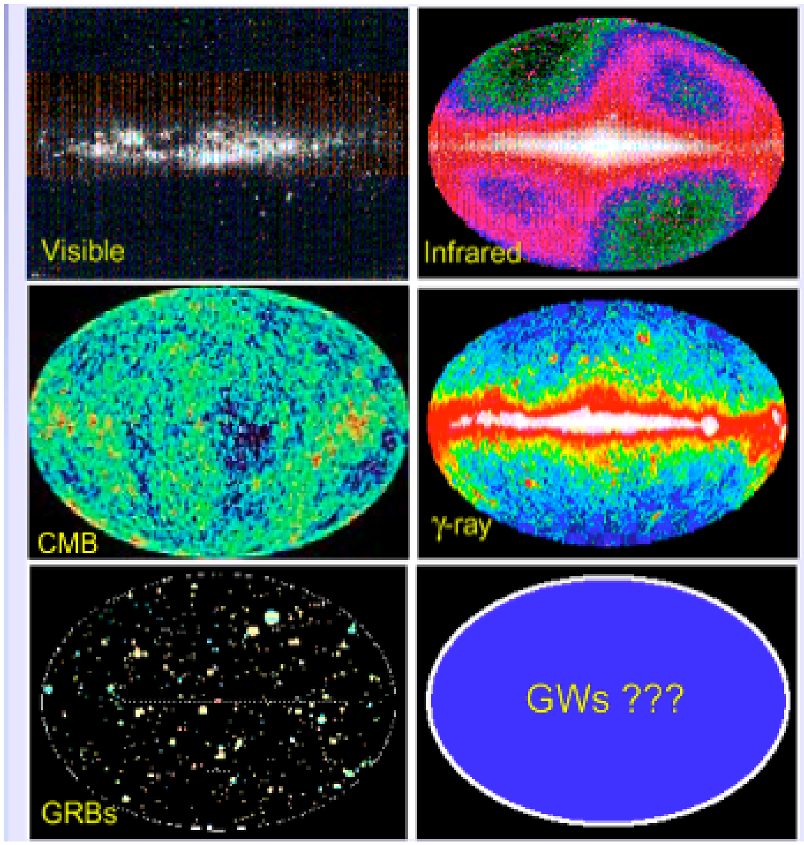
- General properties
  - Weak superposition of many incoherent sources – a hiss.
  - Only characterized statistically.

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

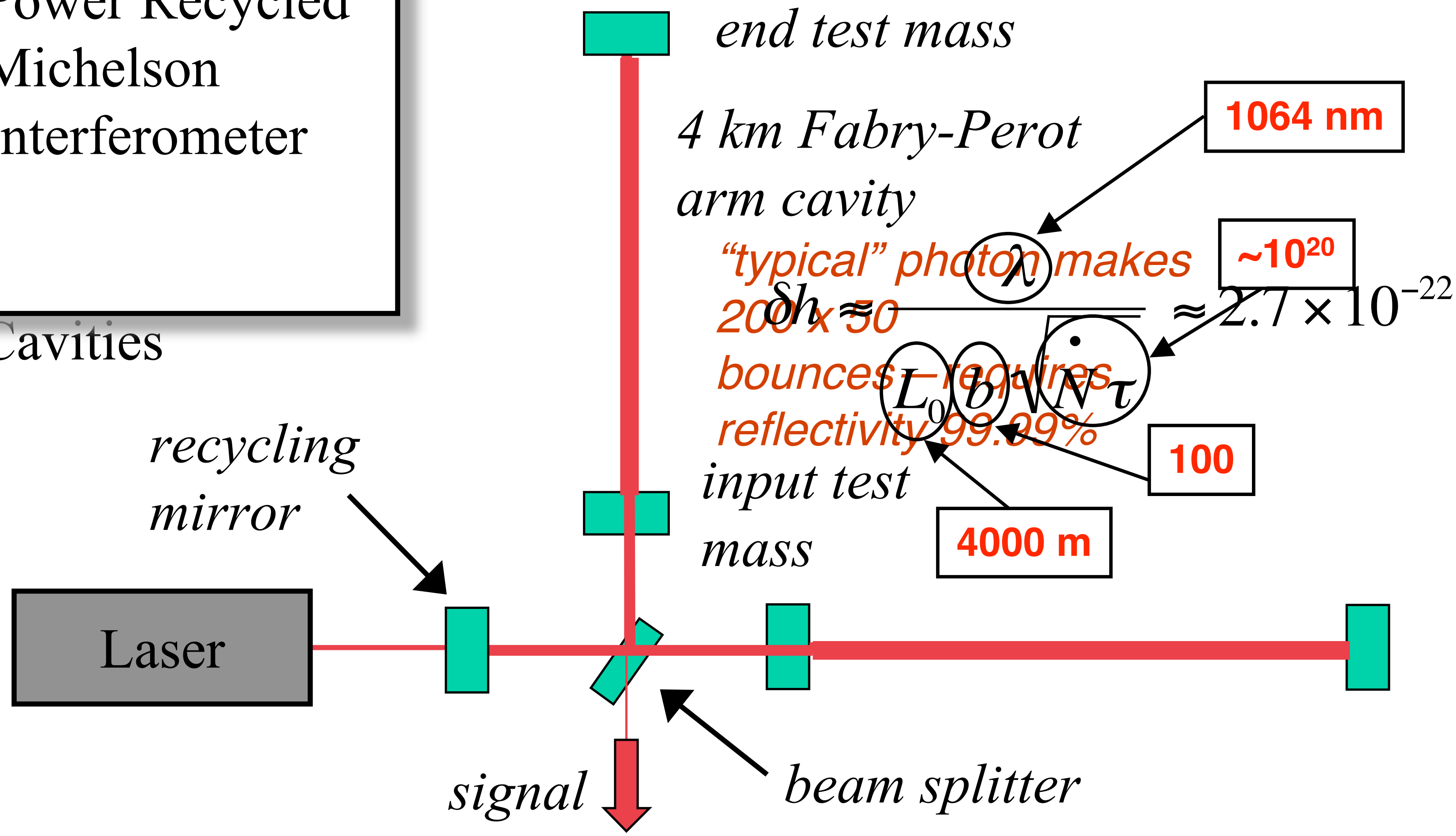


- A new way to look at the universe.
- We expect surprises.
- But gravitational radiation is very weak.
- Need to measure distance changes on the order of 10^{-18} m! for 4 km arms.

Optical Configuration

Power Recycled Michelson Interferometer

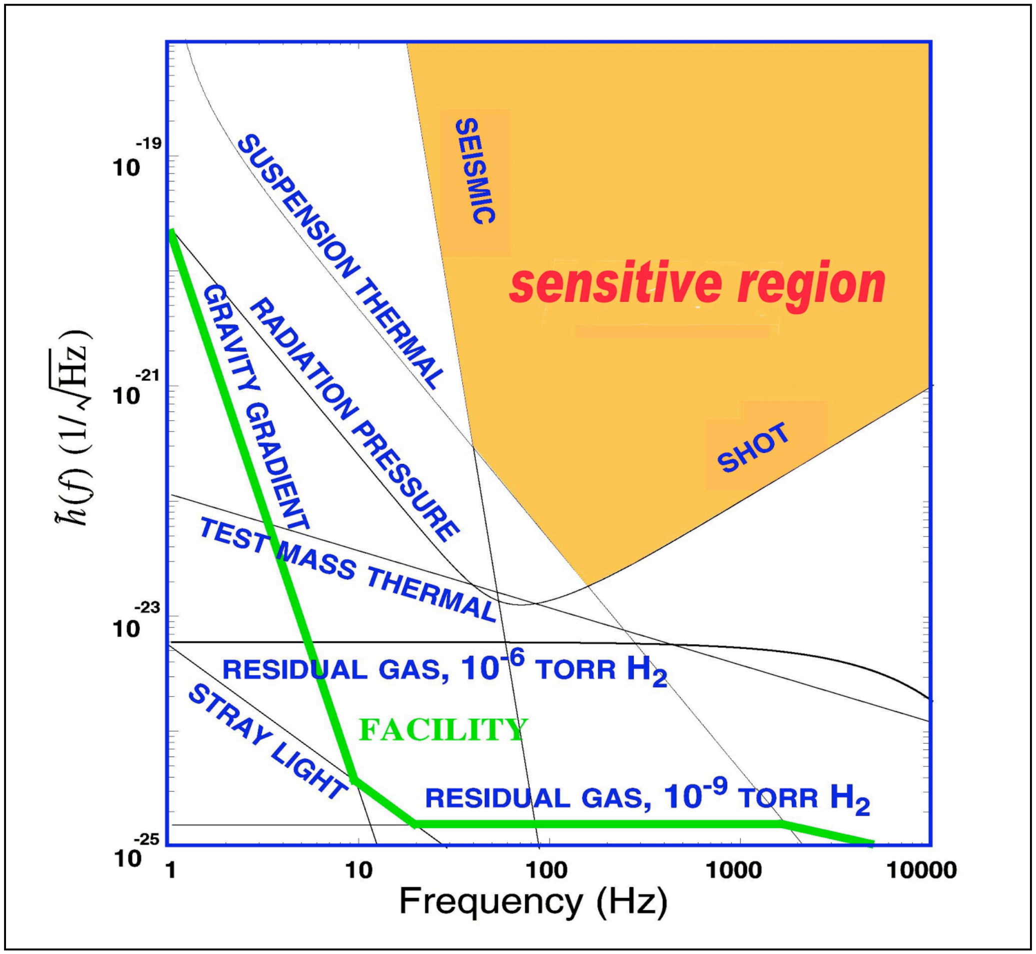
Cavities



$$\delta h \approx \frac{\lambda}{L_0 b \sqrt{\dot{N}\tau}} \approx 2.7 \times 10^{-22}$$


servatories
g the great circle connecting
es
O)
MIT
10 ms
Caltech
➢Adapted from “The Blue Marble: Land Surface, Ocean Col
➢NASA Goddard Space Flight Center Image by Reto Stöckli
Simmon (ocean color, compositing, 3D globes, animation).
Science Data Support Team; MODIS Atmosphere Group; M
(topography); USGS Terrestrial Remote Sensing Flagstaff F
Program (city lights).

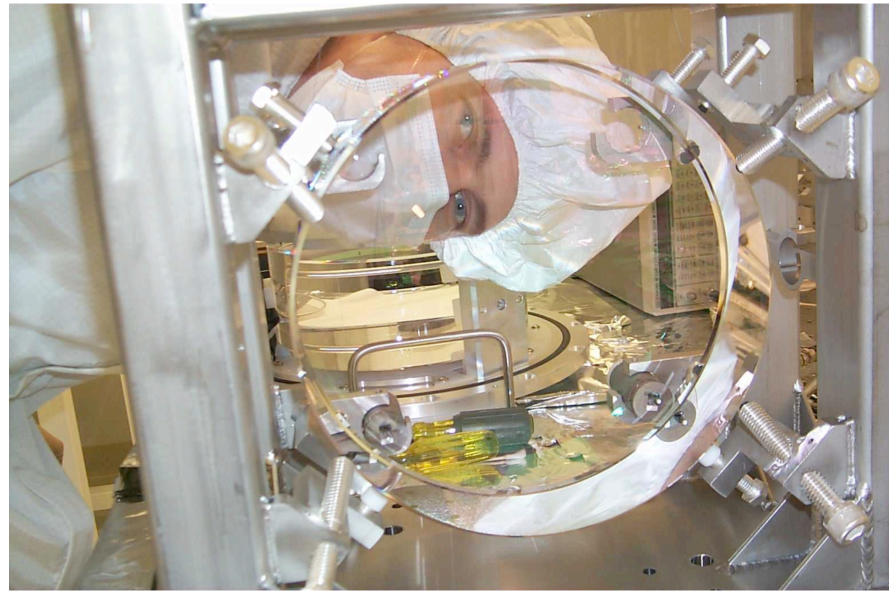
Sources of Noise



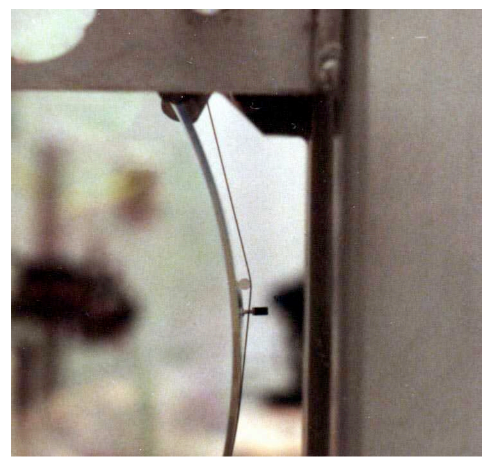
- Seismic at low frequencies.
- Thermal at mid-frequencies.
- Shot noise at high frequencies.
- Facility limits are all significantly lower; room for upgrades.

Vacuum “Envelope”

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

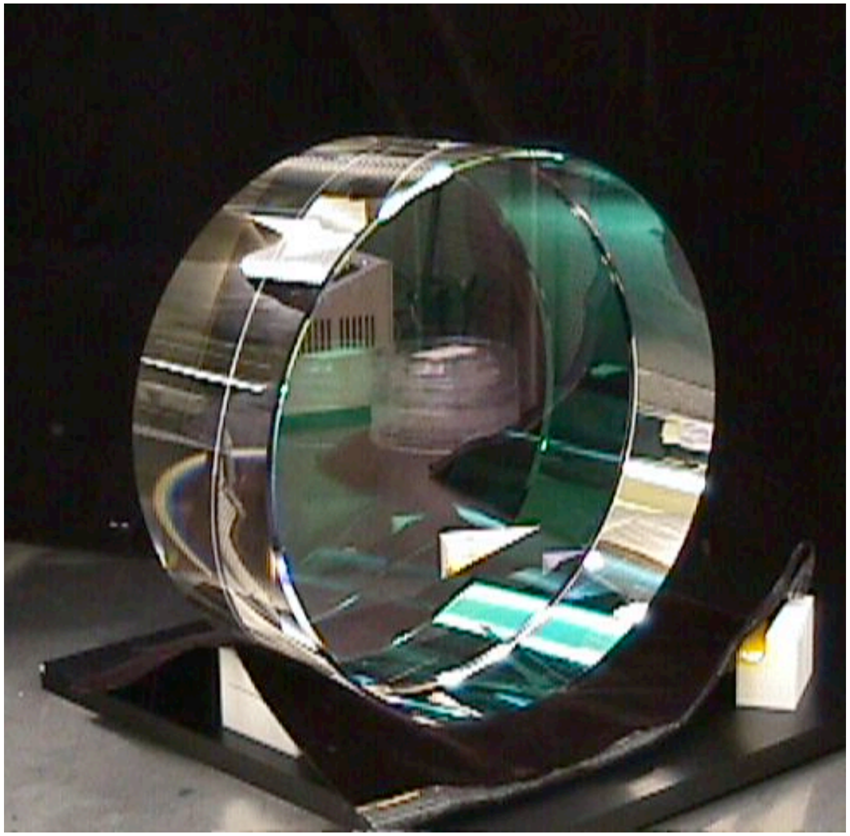
Radii of curvature matched < 3%

Coating

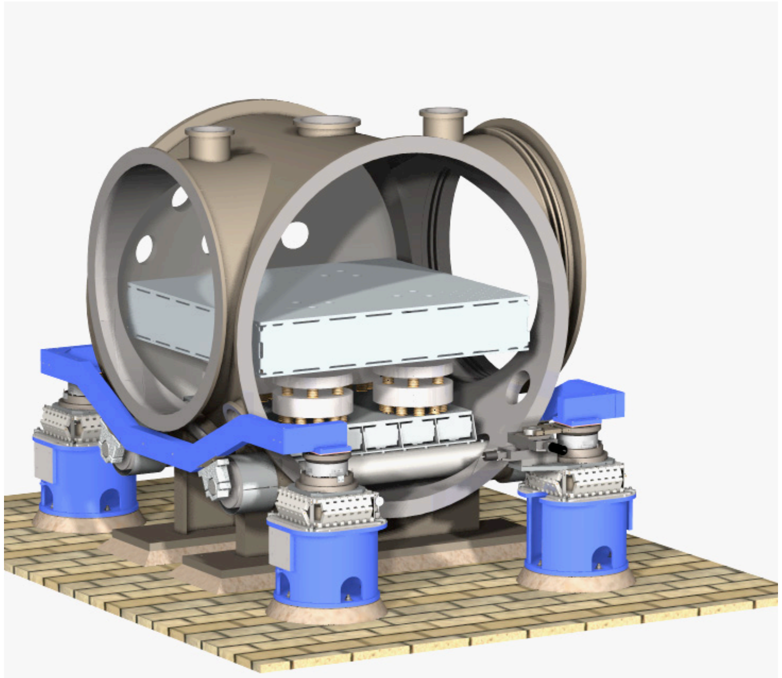
Scatter < 50 ppm

Absorption < 0.5 ppm

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



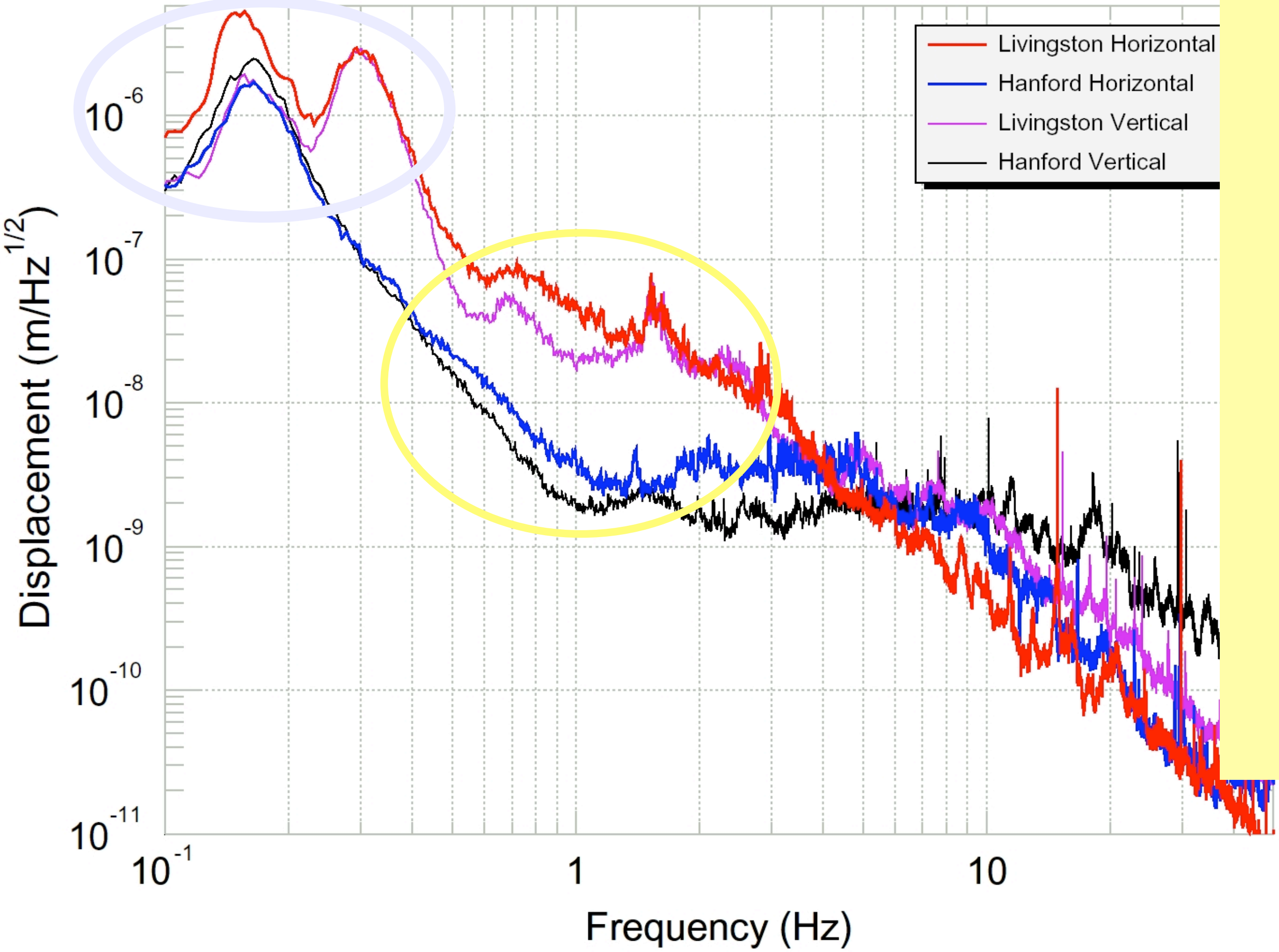
Passive Isolation



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

Ground Noise

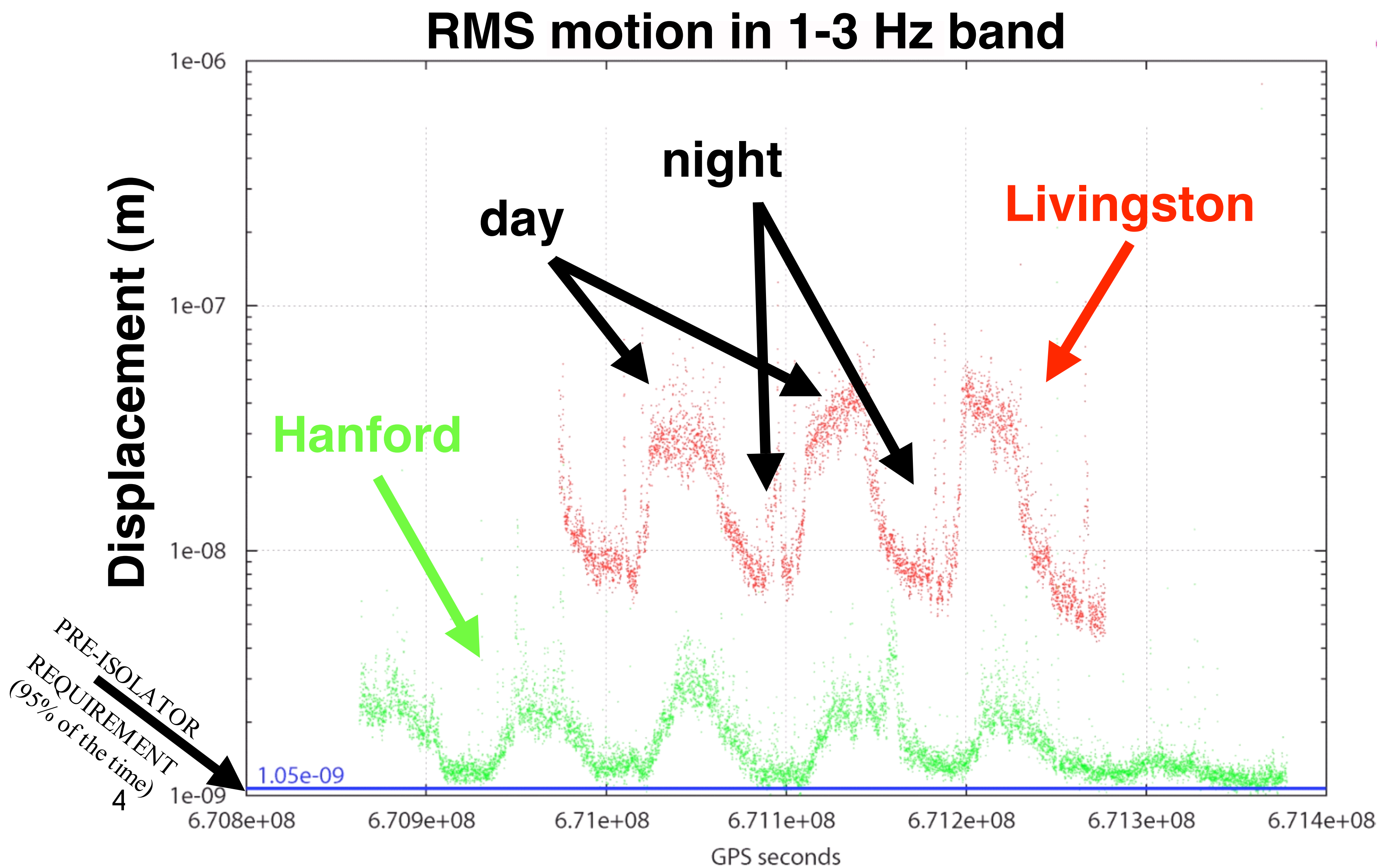
Ocean activity, hurricanes



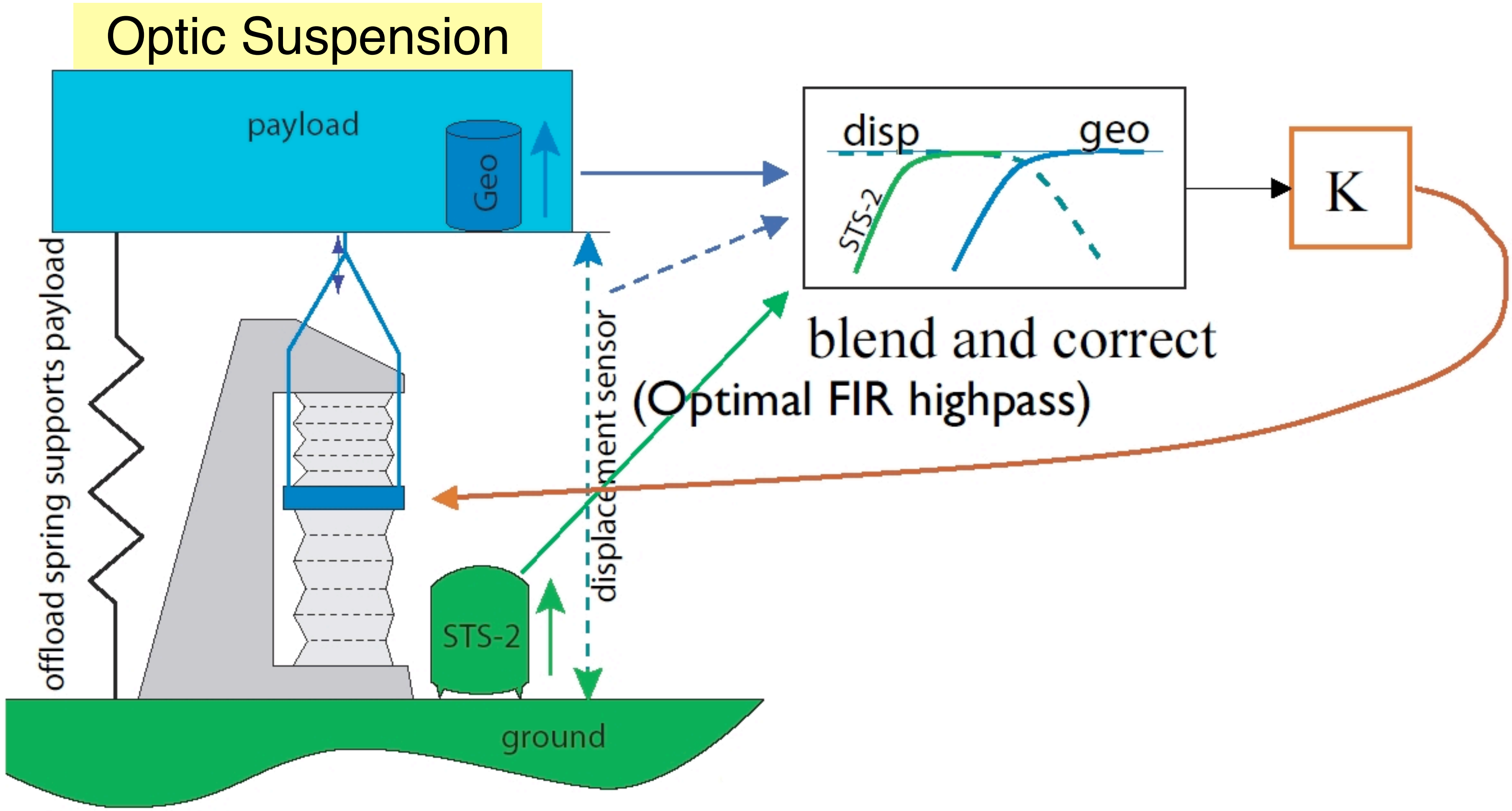
Human activity:
Cars,
Trains,
Trucks,
Logging,
Well Drilling,
Oil Pipeline

Amplified by internal isolation stack resonances

Seismic Noise

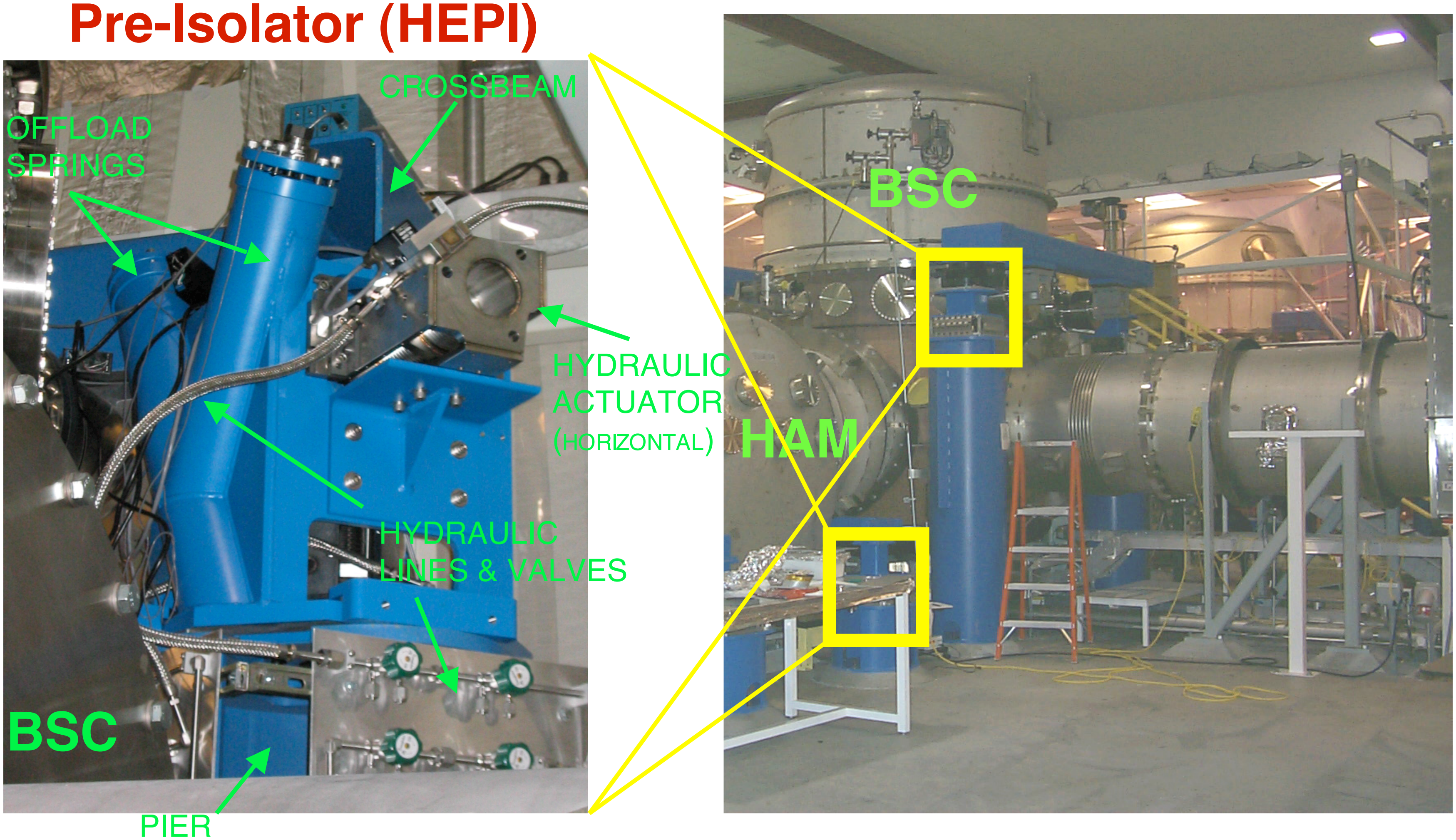


Active Seismic Isolation



Active Seismic Isolation

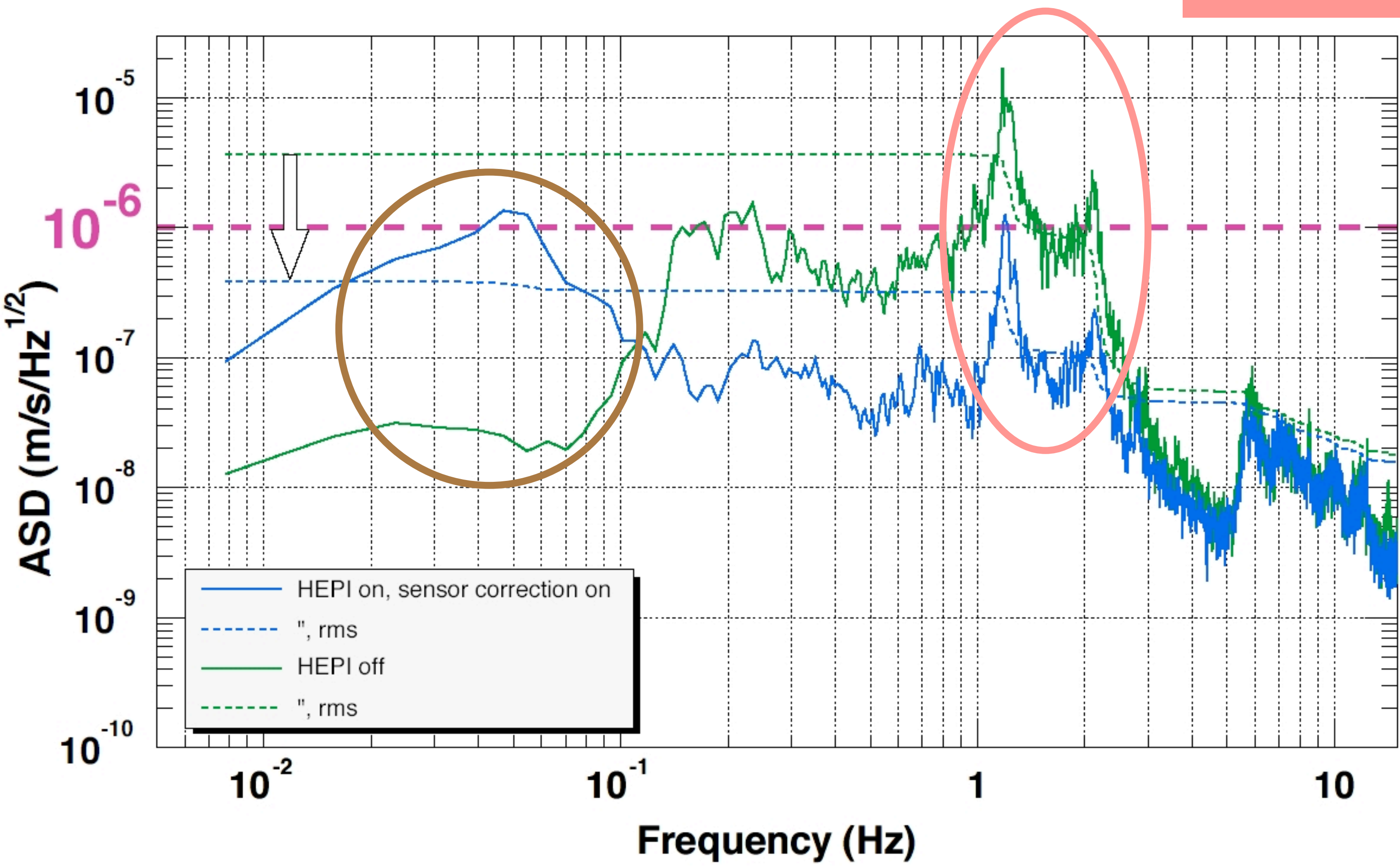
Hydraulic External Pre-Isolator (HEPI)



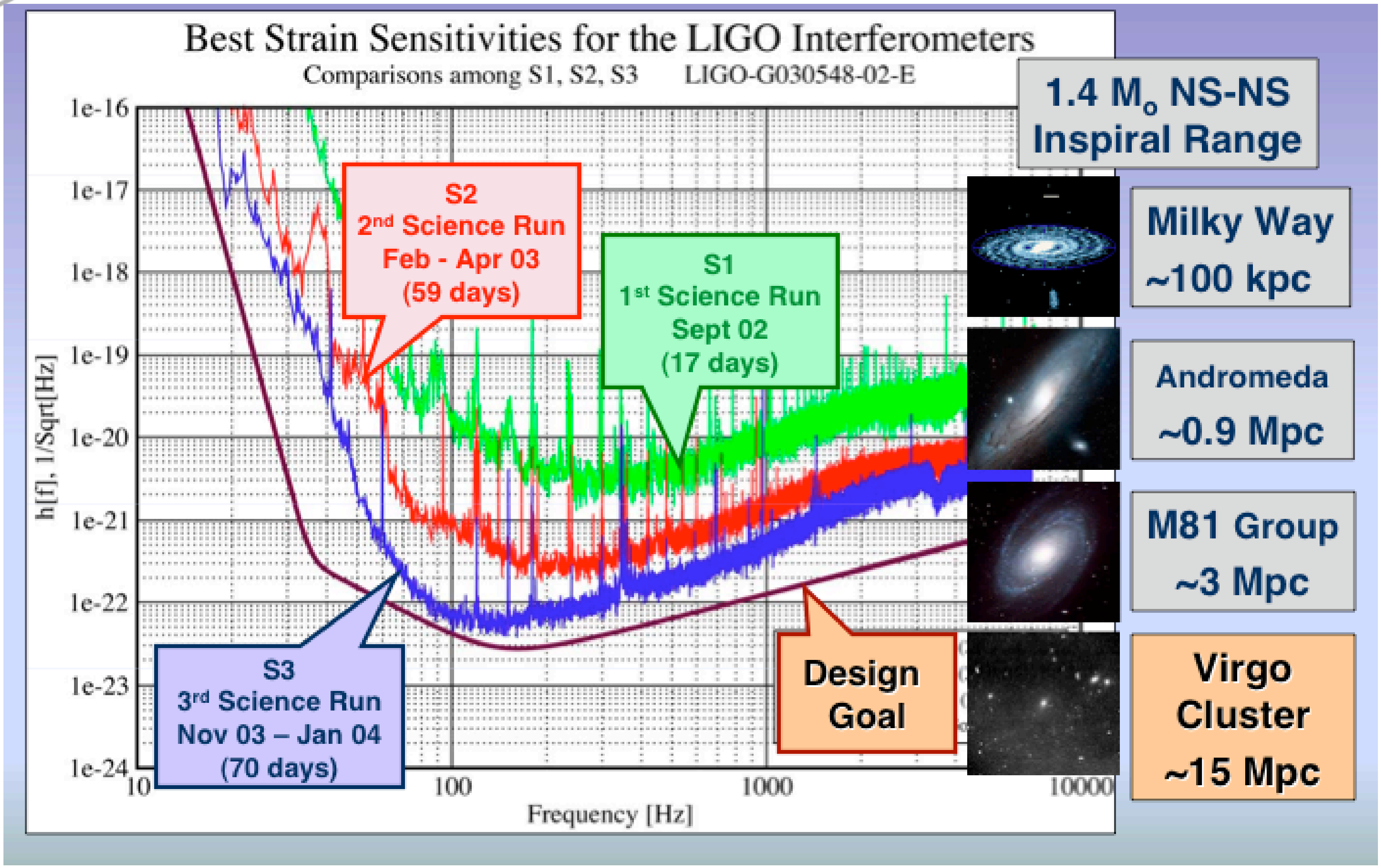
Isolation Performance for a single arm cavity

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

10x reduction in the crucial frequency band



LIGO

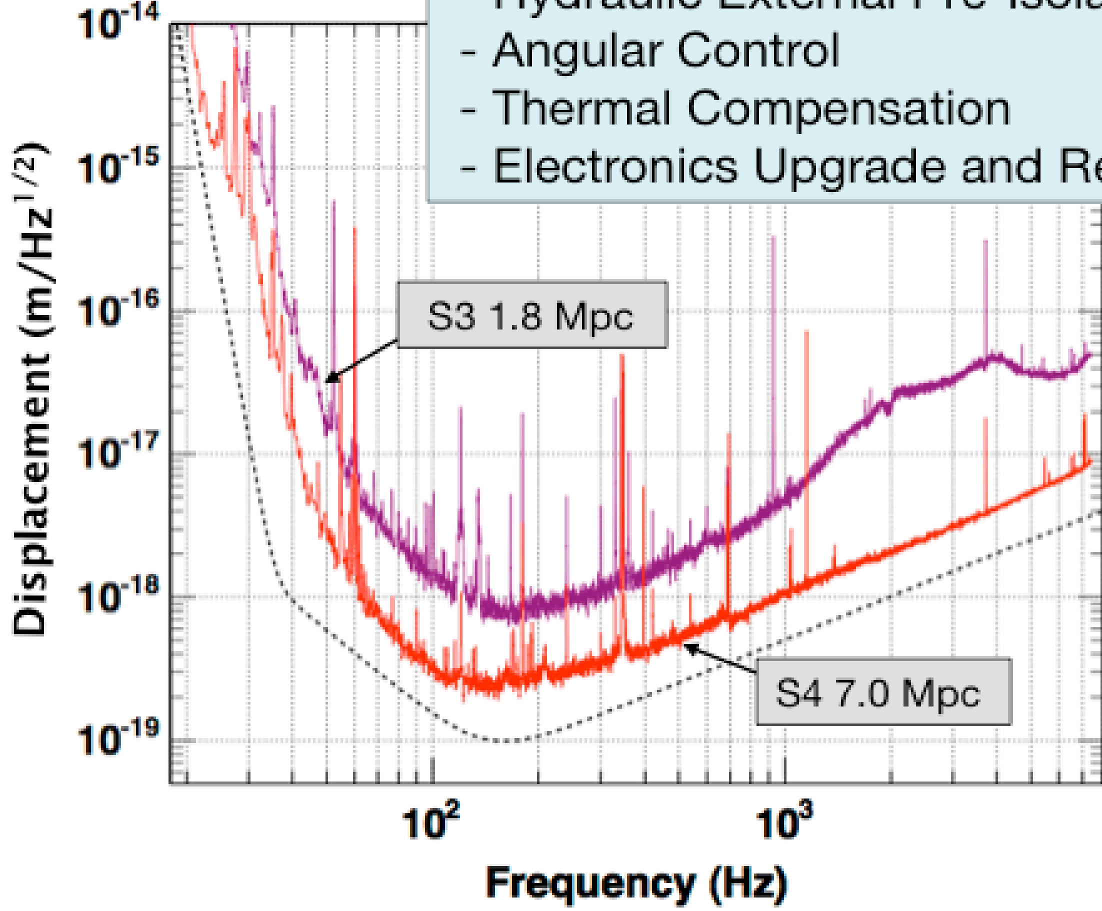


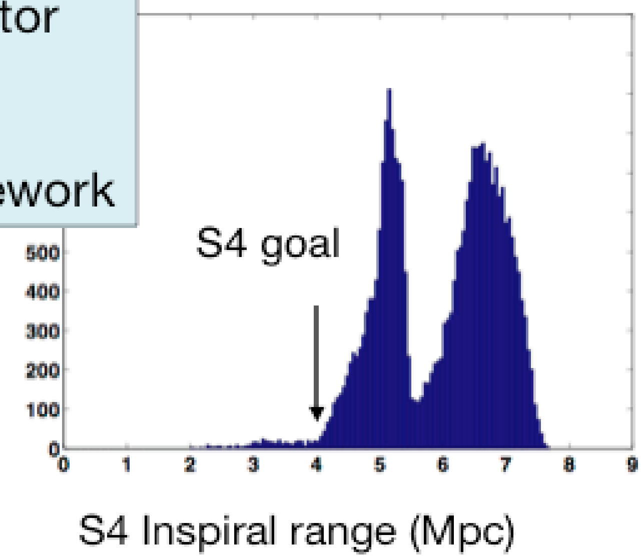
Best Strain Sensitivities for the LIGO Interferometers
Comparisons among S1, S2, S3 LIGO-G030548-02-E
h[f], 1/Sqrt[Hz]
1e-16
1e-17
1e-18
1e-19
1e-20
1e-21
1e-22
1e-23
1e-24
10
100
1000
10000
Frequency [Hz]
S2
2nd Science Run
Feb - Apr 03
(59 days)
S1
1st Science Run
Sept 02
(17 days)
S3
3rd Science Run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

L1 during S4

Preliminary

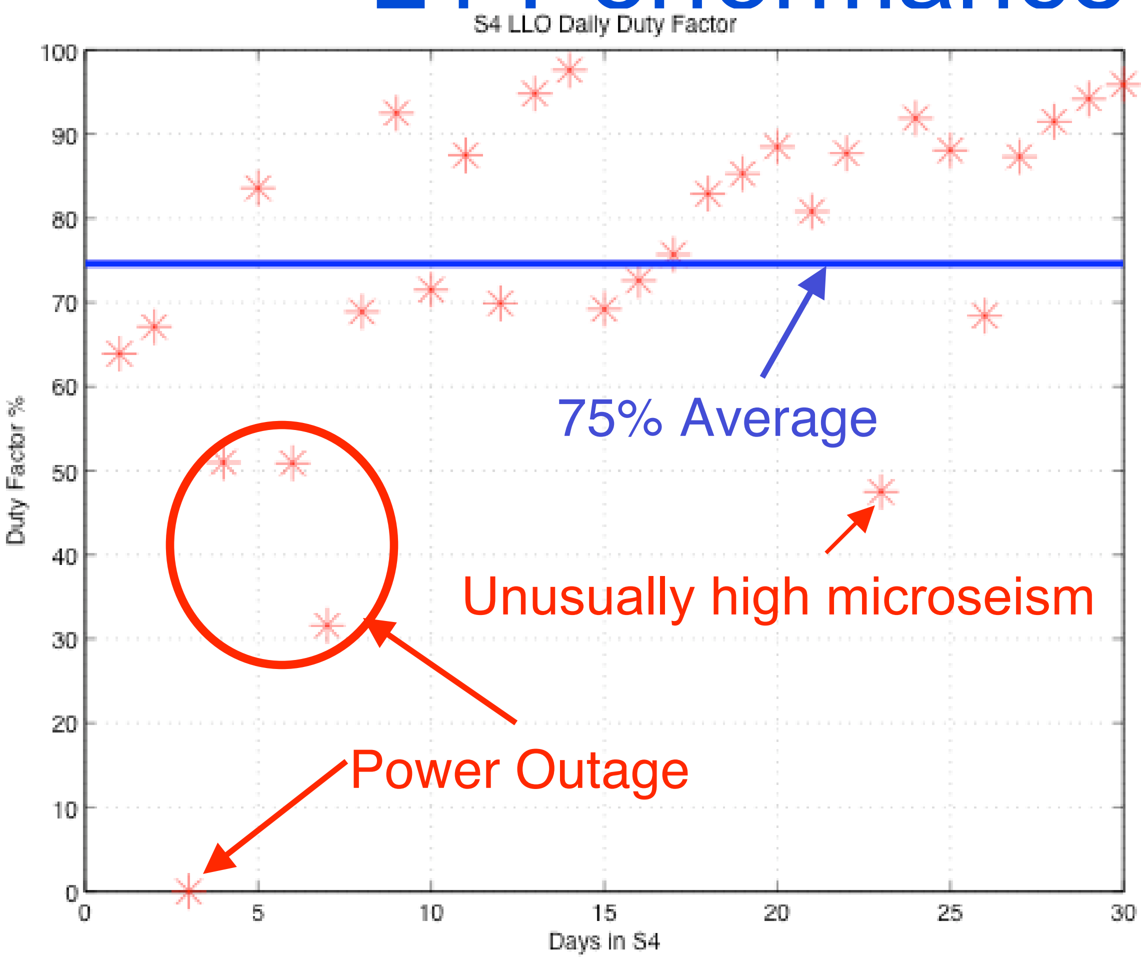
Main Efforts Since S3:
- Hydraulic External Pre-Isolator
- Angular Control
- Thermal Compensation
- Electronics Upgrade and Rework





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

L1 Performance for S4

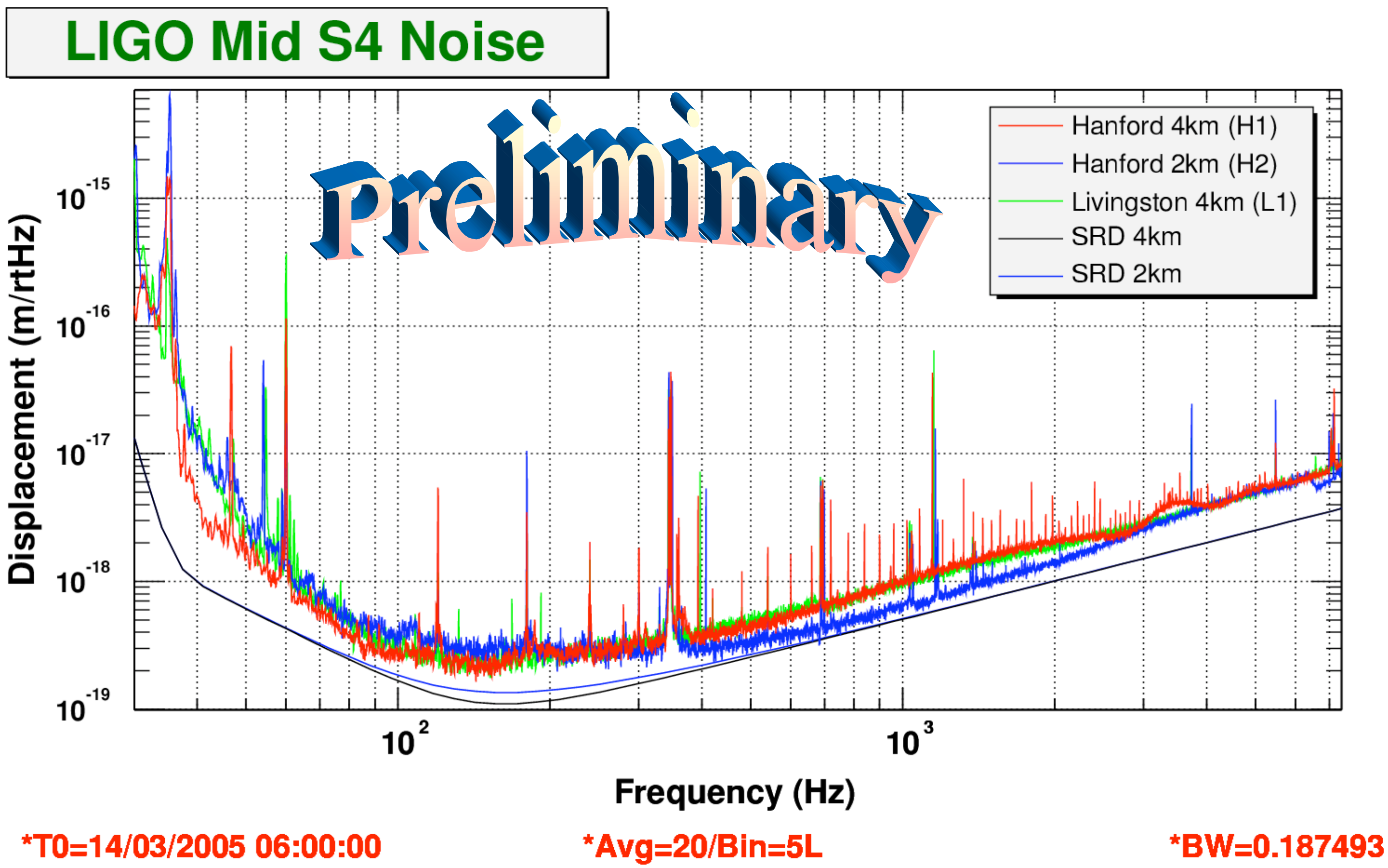


HEPI enabled very high duty Factor at Livingston.

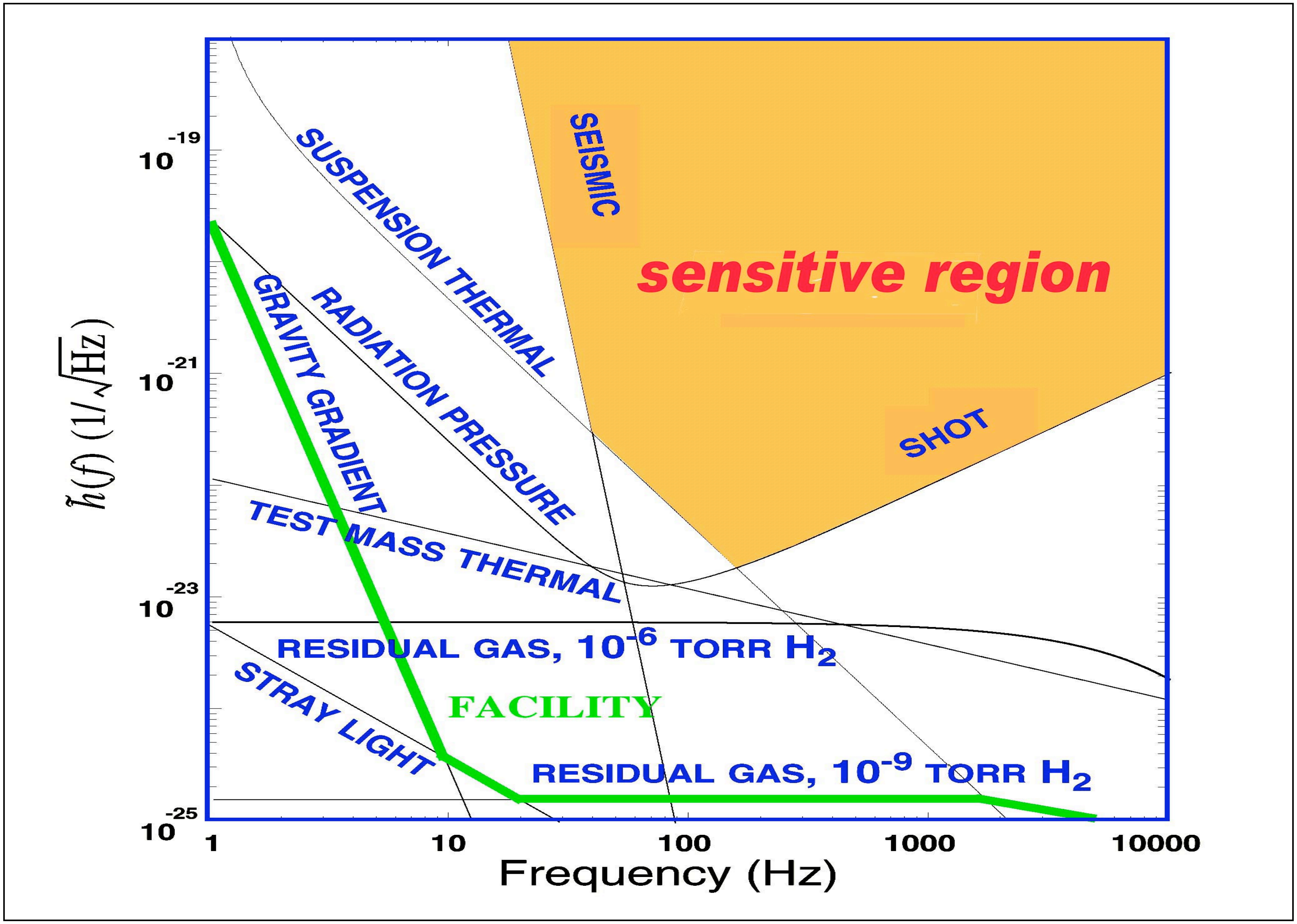
H1 ~ 80% ~8.5 Mpc
H2 ~ 81% ~3.5 Mpc
L1 ~ 75% ~7.0 Mpc

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

“Typical” noise midway through S4

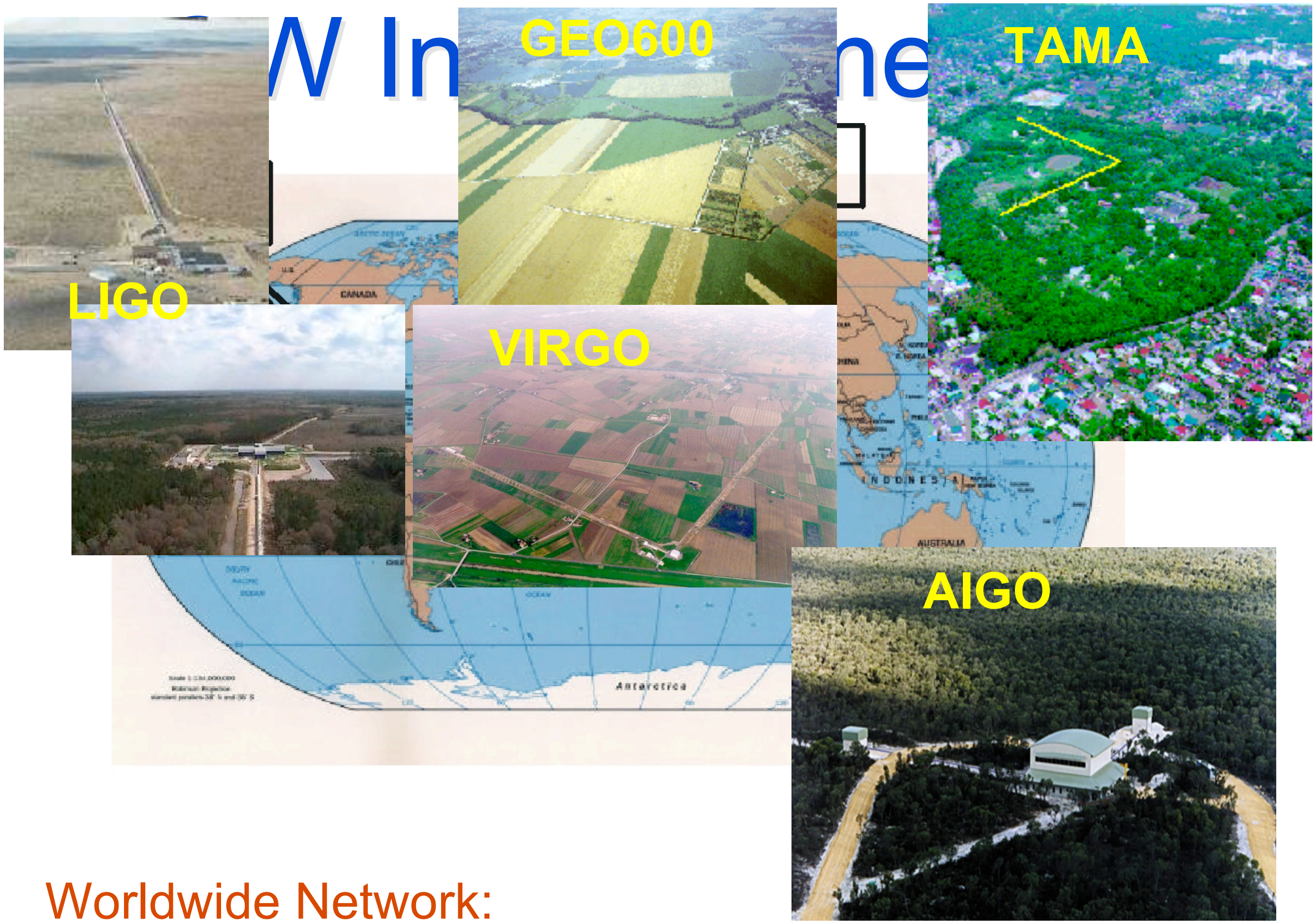


Preliminary Noise Budget



The LIGO Scientific Collaboration

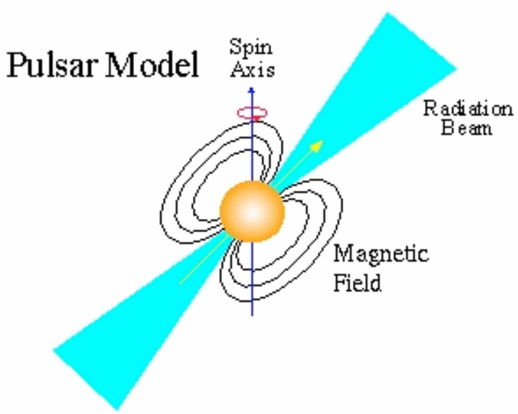
- At last count 501 members
- 35 Institutions plus the LIGO laboratory.
- International participation from Australia, Germany, India, Japan, Russia, Spain and the U.K.
- Consists of technical and data analysis groups tasked with detector characterization, Advanced LIGO R&D and the search for signals.



- 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 $\Phi(t)= \phi(t) + \phi_0$

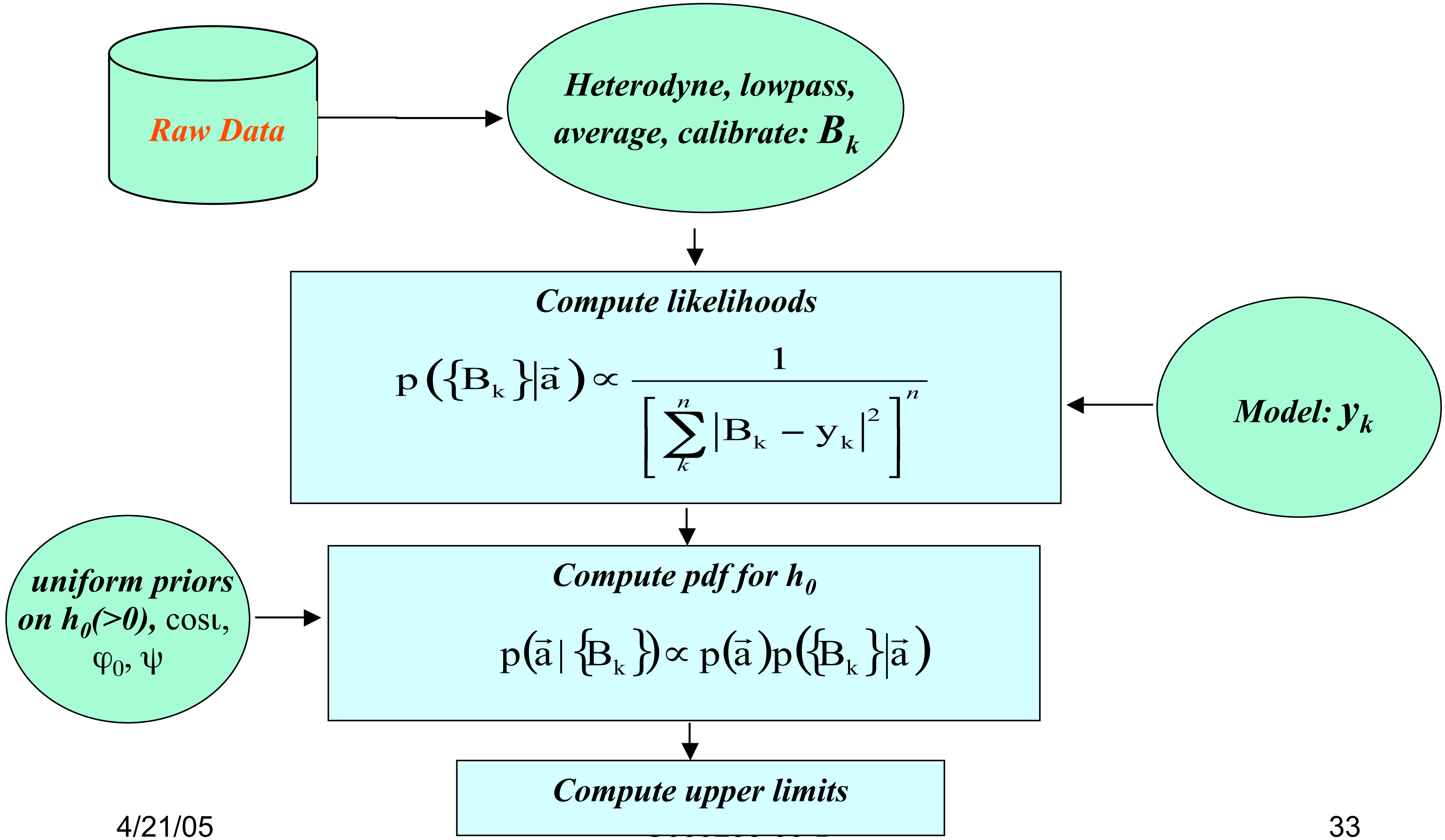
Heterodyne, i.e. multiply by: $e^{-i\phi(t)}$

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, **a** = **a**(h_0, ψ, ι, ϕ_0), a vector of the signal parameters.

Analysis summary

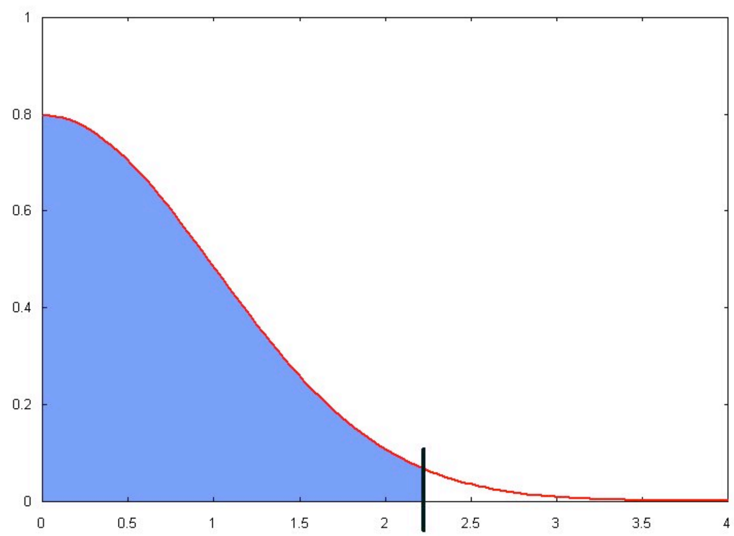


S2 known pulsar analysis

- 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.



Validation using Injections

- Injected two artificial pulsar signals into all three interferometers for 12 hours.

- Validates the analysis pipeline.

- Verifies that the relative phase of the detectors is known (from calibration), so a joint coherent analysis can be performed.

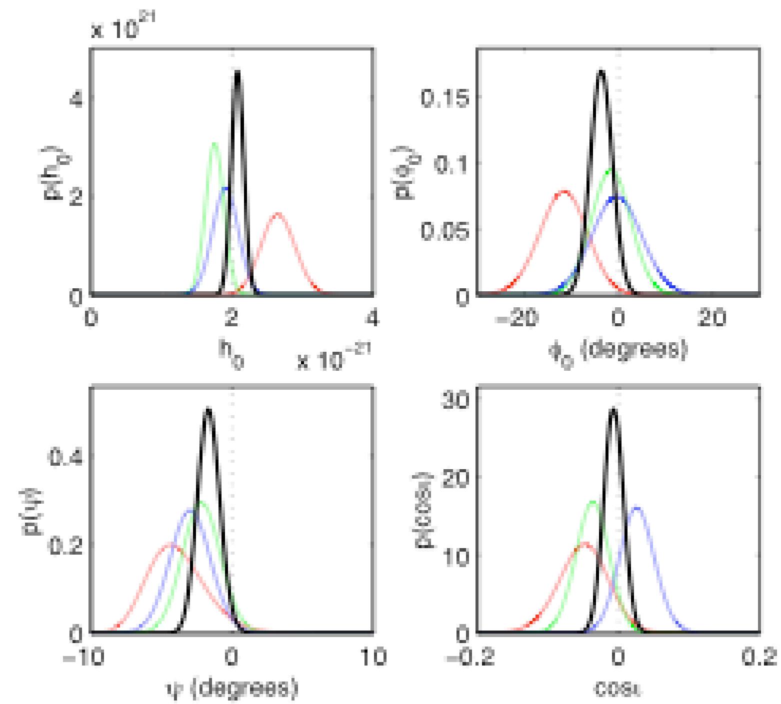
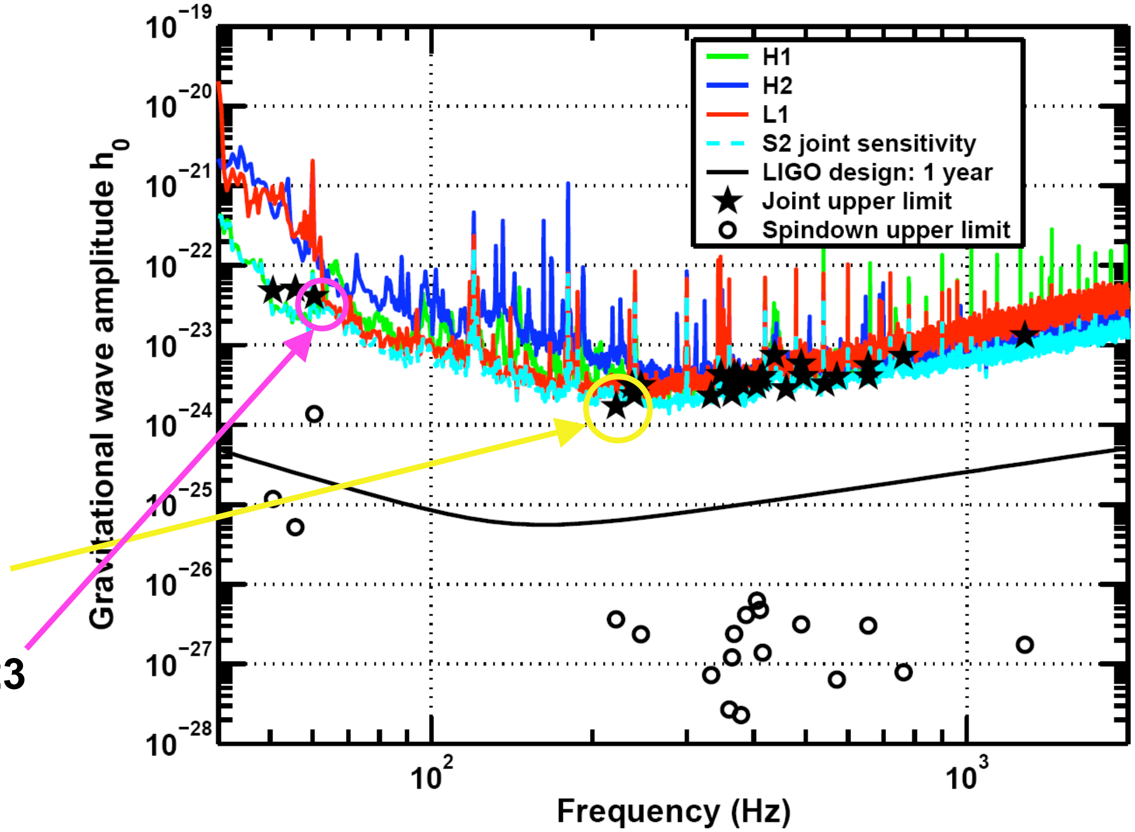


FIG. 2: Parameters of the artificial pulsar P1, recovered from 12 h of strain data from the Hanford and Livingston interferometers. The results are displayed as marginal pdfs for each of the four signal parameters. The vertical dotted lines show the values used to generate the signal, the colored lines show the results from the individual detectors (H1 green, H2 blue, L1 red), and the black lines show the joint result from combining coherently data from all three.

S2 Analysis

- No GW signal.
- First direct upper limit for 26 of 28 sources studied.
- Best UL is for J1910-5959D where 95% CL that $\mathbf{h_0 < 1.7x10^{-24}}$
- Crab $\mathbf{h_0 < 4.1x10^{-23}}$



Equatorial Ellipticity

- Results on h_0 can be interpreted as UL on equatorial ellipticity.
- Ellipticity scales with the difference in radii along x and y axes.

$$\varepsilon = \frac{I_{xx} - I_{yy}}{I_{zz}}, \quad \varepsilon = \frac{c^4}{4\pi^2 G} \cdot \frac{r}{f_{gw}^2} \cdot \frac{h_0}{I_{zz}}$$

- Distance r to pulsar is known, I_{zz} is assumed to be typical, 10^{45} g cm^2.
- Pulsars J0030+0451 (230pc), J2124-3358 (250 pc), J1744-1134 (360 pc), and J1024-0719 (350 pc); the nearest four pulsars: $\varepsilon < 10^{-5}$
- Nine of the pulsars are spinning up, so this analysis is the first upper limit on the ellipticity for these objects.

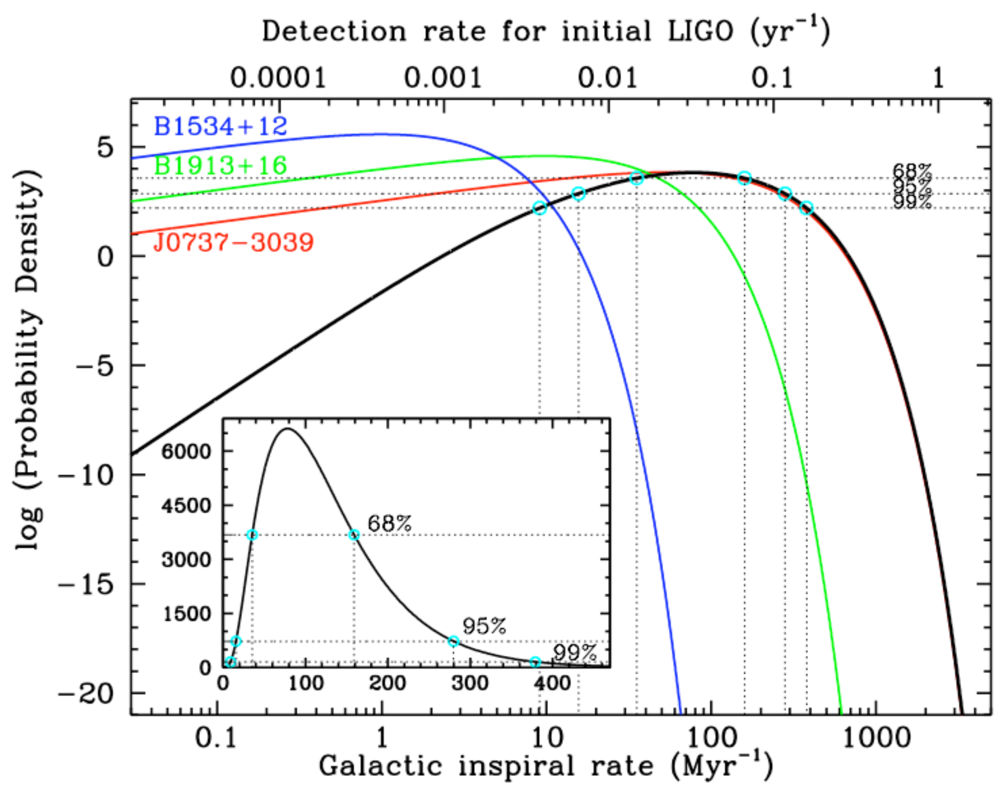
Pulsar Analyses

- Time domain search complements frequency domain search.
- S3 analysis will cover many more pulsars (~110) including binary systems.
- All sky search in progress using S3 data.

DNS Rate Predictions

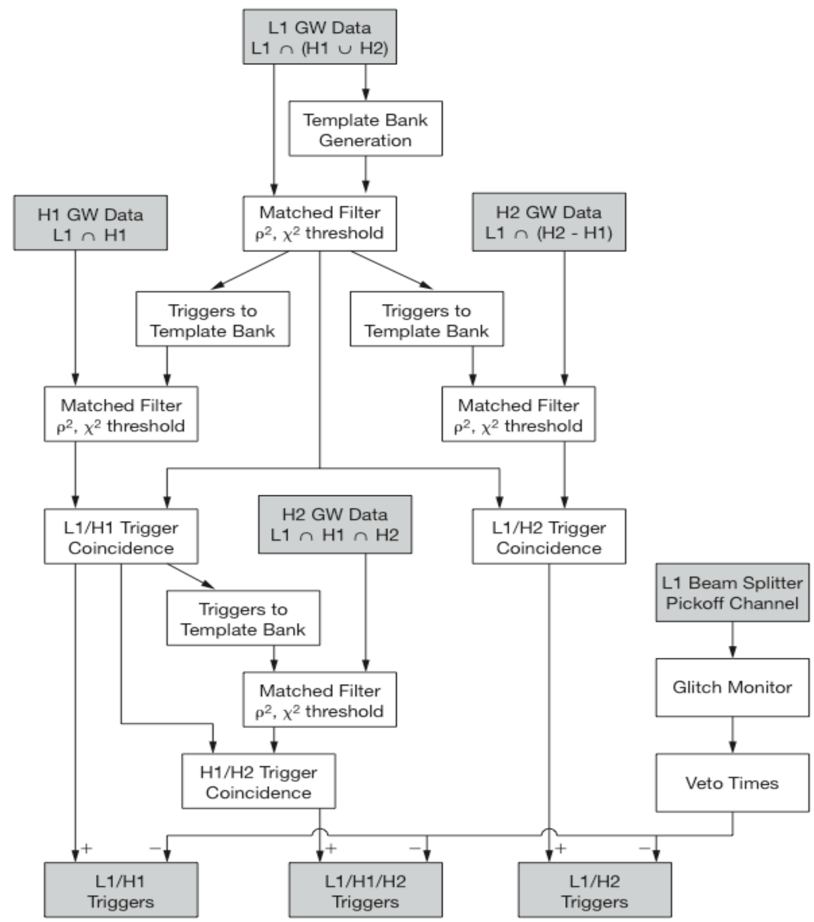
- Initial LIGO (20 Mpc):
  - Peak: 1 event /(30 yr)
  - 95% CL: 1 event/(8 yr)
  - Best Case: 1 event/(3 yr)
- Advanced LIGO (350 Mpc)
  - Peak: 1 event/day
  - 95% CL: 2 events/day
  - Best Case: 5 events/day
- But small statistics, based on relativistic binaries. Latest discovery increased rate by factor of 5-7!

V. Kalogera et al.



Inspiral Analysis Pipeline

- All coincident triggers are double-coincident candidates
- 145 candidates in the final sample:
  - 92 from L1-H1
  - 35 from triple (SNR too low for H2)
  - 18 from L1-H1
- Follow up implicates instrumental artifacts and clustering algorithm.



S2 Result

- Loudest event statistic:

$$R < R_{90\%} = \frac{2.303 + \ln P_b}{T N_G(\rho_{\max})}$$

- A frequentist upper limit. ρ_{max} is the maximum observed SNR, P_b is the probability that all background triggers have SNR > ρ^*, conservatively taken = 1, T is the total observation time (339 h) and $N_G(\rho_{max})$ is the total number of MWEG to which the search is sensitive.

$$R < 47\ y^{-1}\ \mathrm{MWEG}^{-1}$$

S1 Physics Papers

- *First Upper Limits from LIGO on GW Bursts,* B. Abbott et al. (LSC), Phys. Rev. D **69** (2004) 102001
- *Setting Upper Limits on the Strength of Periodic GW from PSR J1939 + 2134 Using the First Science Data from the GEO600 and LIGO Detectors,* B. Abbott et al. (LSC), Phys. Rev. D **69** (2004) 082004
- *Analysis of LIGO Data for GW from Binary Neutron Stars*, B. Abbott et al. (LSC), Phys. Rev. D **69** (2004) 122001
- *Analysis of LIGO Data for Stochastic GW,* B. Abbott et al. (LSC), Phys. Rev. D **69** (2004) 122004

S2 Analyses

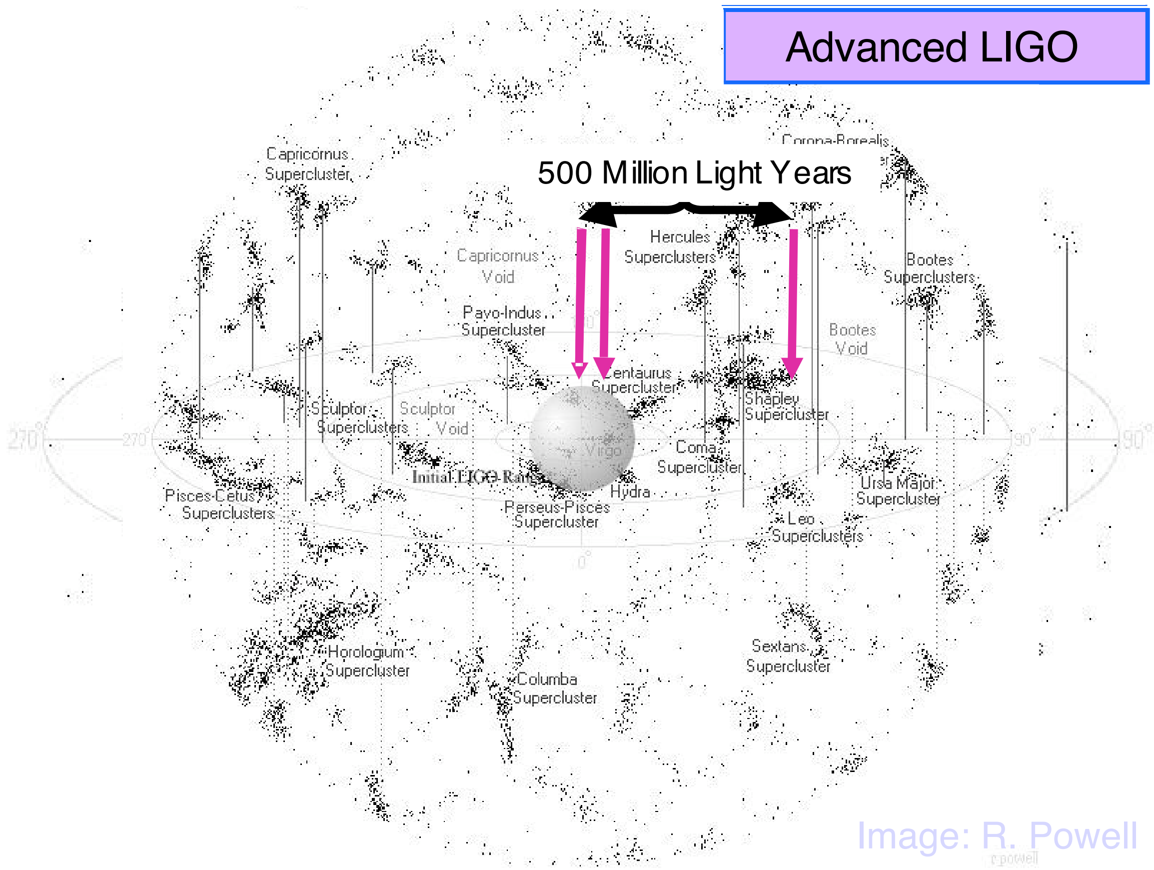
- *A Search for Gravitational Waves Associated with the Gamma Ray Burst GRB030329 Using the LIGO Detectors,*
  B. Abbott et al., **gr-qc/0501068**
- *Limits on gravitational wave emission from selected pulsars using LIGO data CW time domain paper* accepted in PRL.
- Under review:
  - S2 Binary NS Inspiral paper
  - S2 untriggered burst search
  - MACHO source search
  - BBH Inspiral search
  - LIGO-TAMA Burst search
  - LLO-ALLEGRO Stochastic search

Other Analyses

- Work on S3 analyses is following close behind the S2 work.
- Involves increased scope and sensitivity of most analyses, and the use of new algorithms.
- S4 run just completed. Had online real-time analysis efforts which should significantly speed up publication of results.

LIGO to Advanced LIGO

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

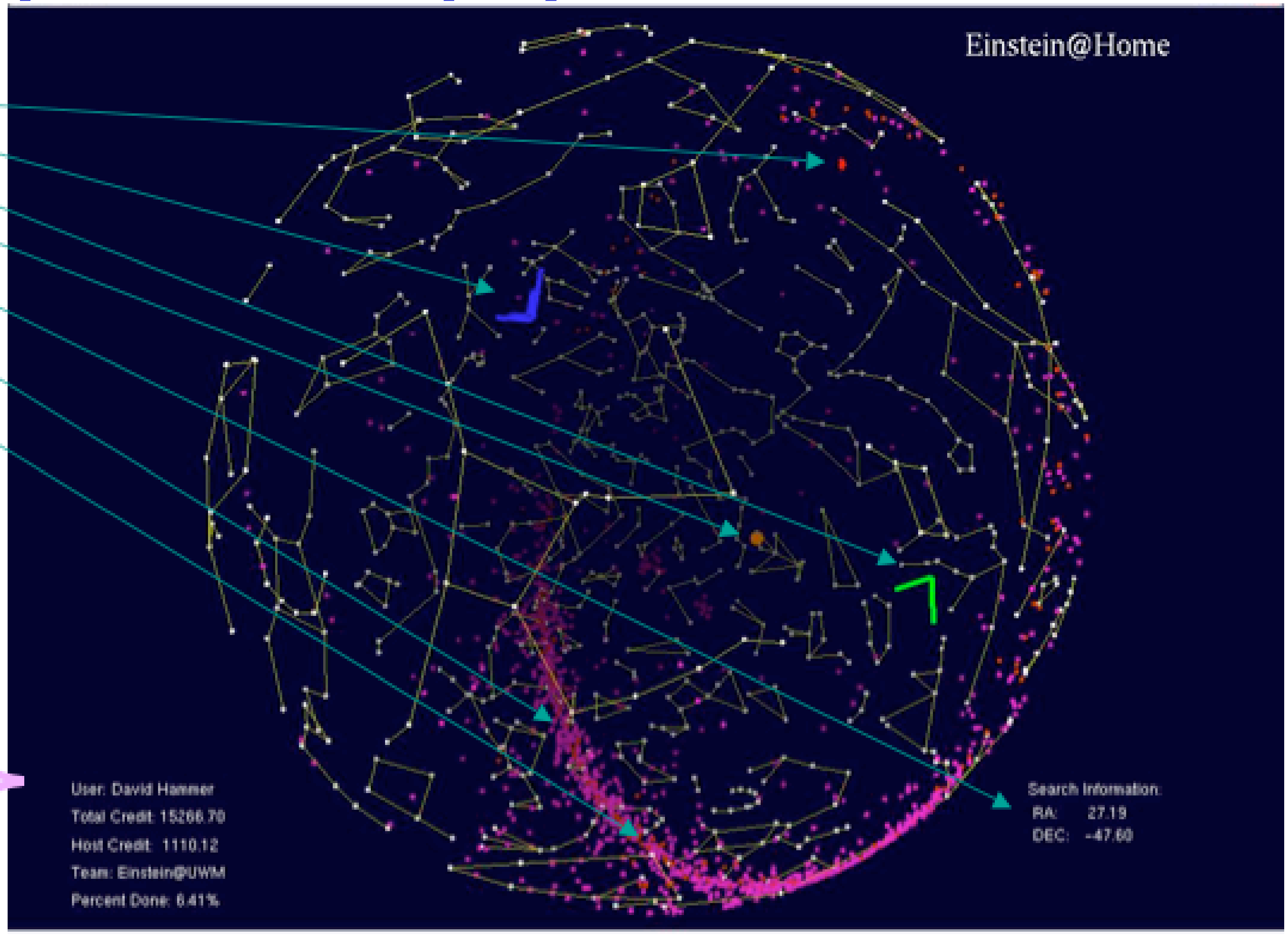


Outlook

- 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.