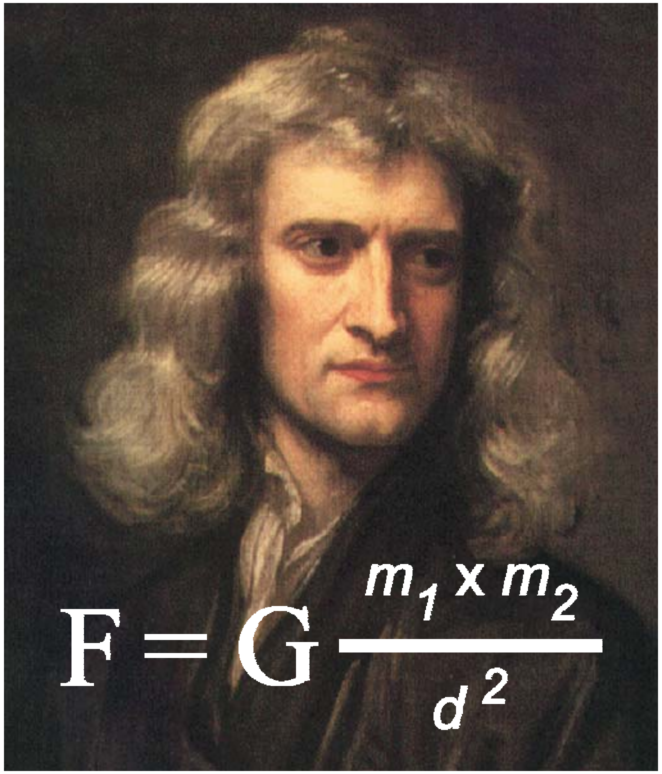
LIGO: Present Status and Initial Results

Brian O’Reilly

Outline

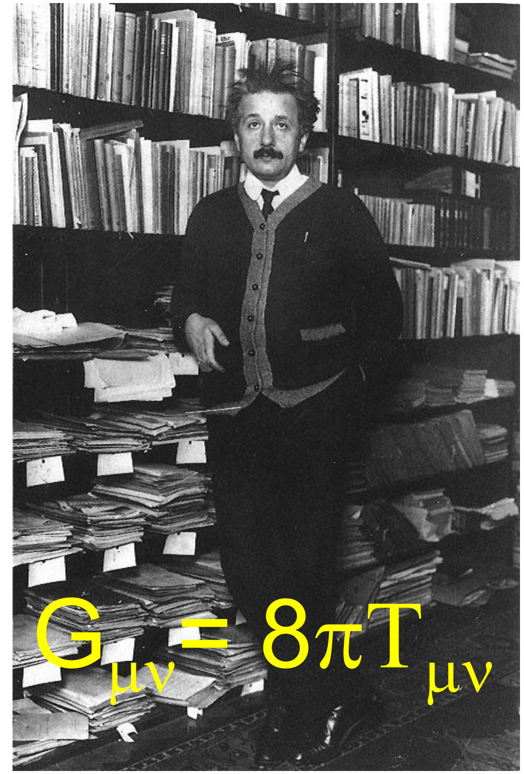
- Gravity, gravitational waves and sources.
- Basics of detection.
- The LIGO Observatories.
- Data analysis.
- Results
- Status and future prospects.

What is Gravity?



Newton

Action at a distance

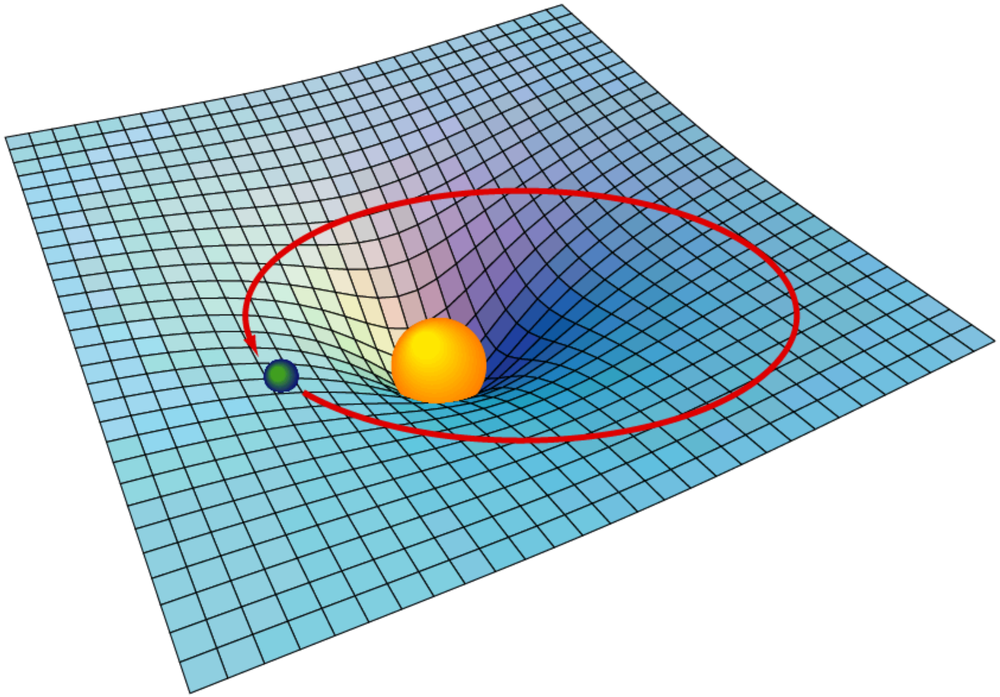


Einstein

Gravitational Radiation traveling at the speed of light

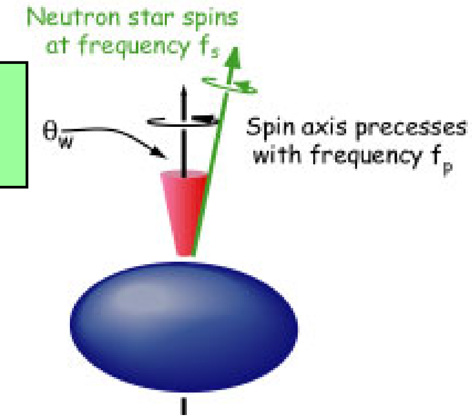
General Relativity

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



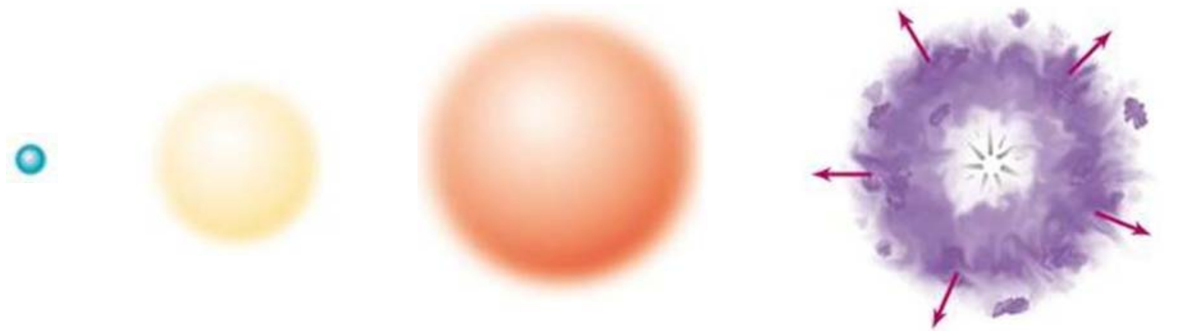
- **Imagine space as a stretched rubber sheet.**
- **A mass on the surface will cause a deformation.**
- **Another mass dropped onto the sheet will roll toward that mass.**

Making "detectable" gravitational waves



Spinning or wobbling neutron stars

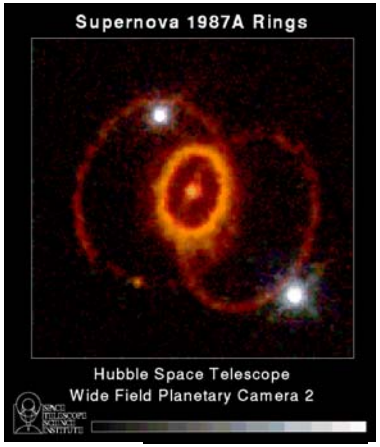
matter



Massive Star

Giant Phases

Supernova Explosion

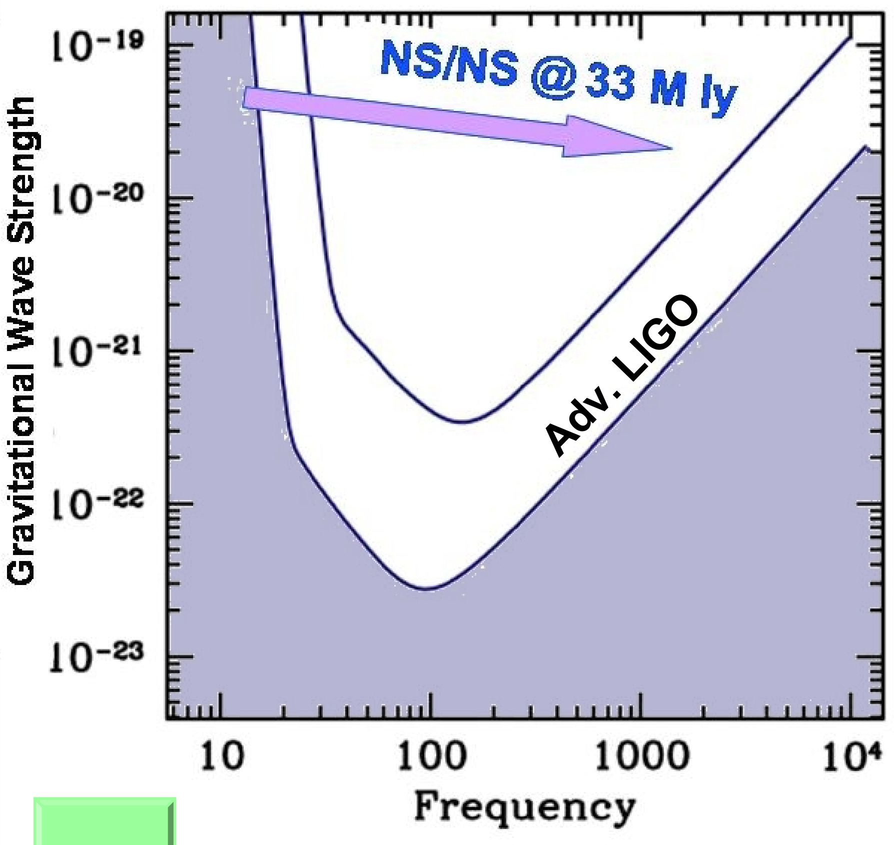


Compress into small space

al wave bursts

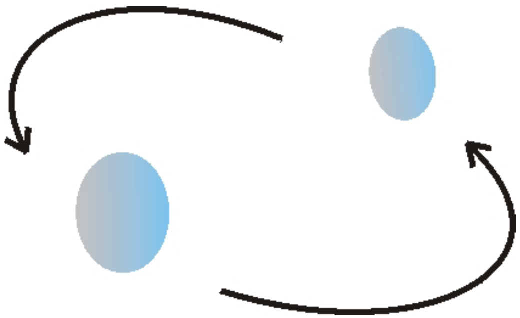
Binary Neutron Stars

- Binary systems:
  - Contain pairs of neutron stars and/or black holes orbiting each other
  - The objects spiral inward as gravitational waves are emitted
- LIGO sensitive to gravitational waves:
  - from binaries with neutron stars and/or low-mass black holes
  - emitted during the last several minutes of inspiral

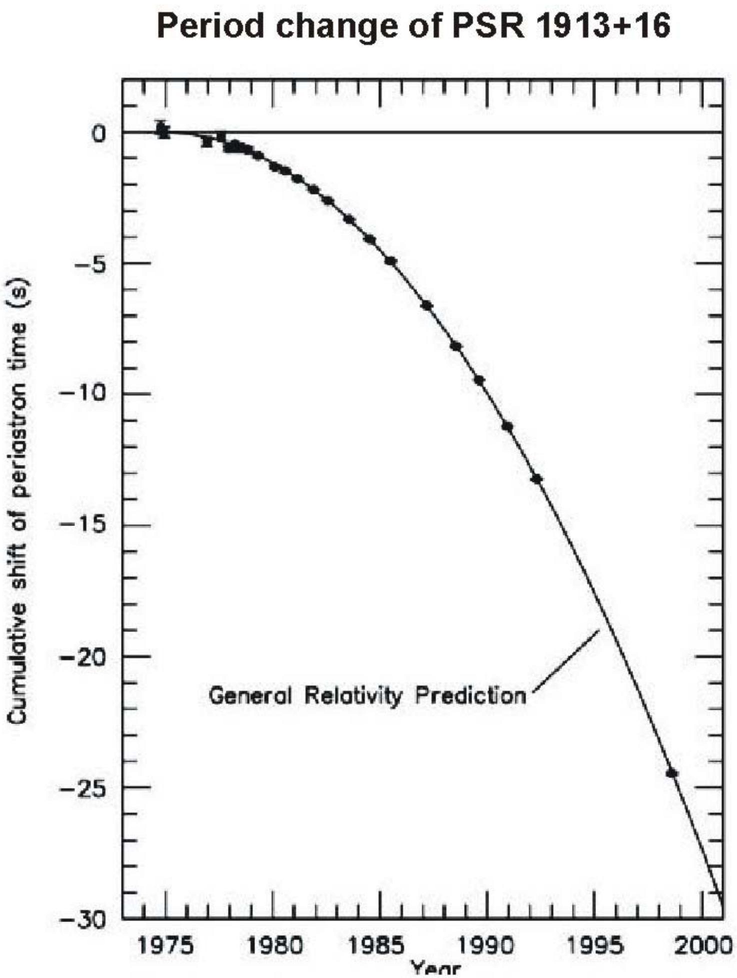


Evidence for Gravitational Waves

Taylor and Hulse Binary Pulsar

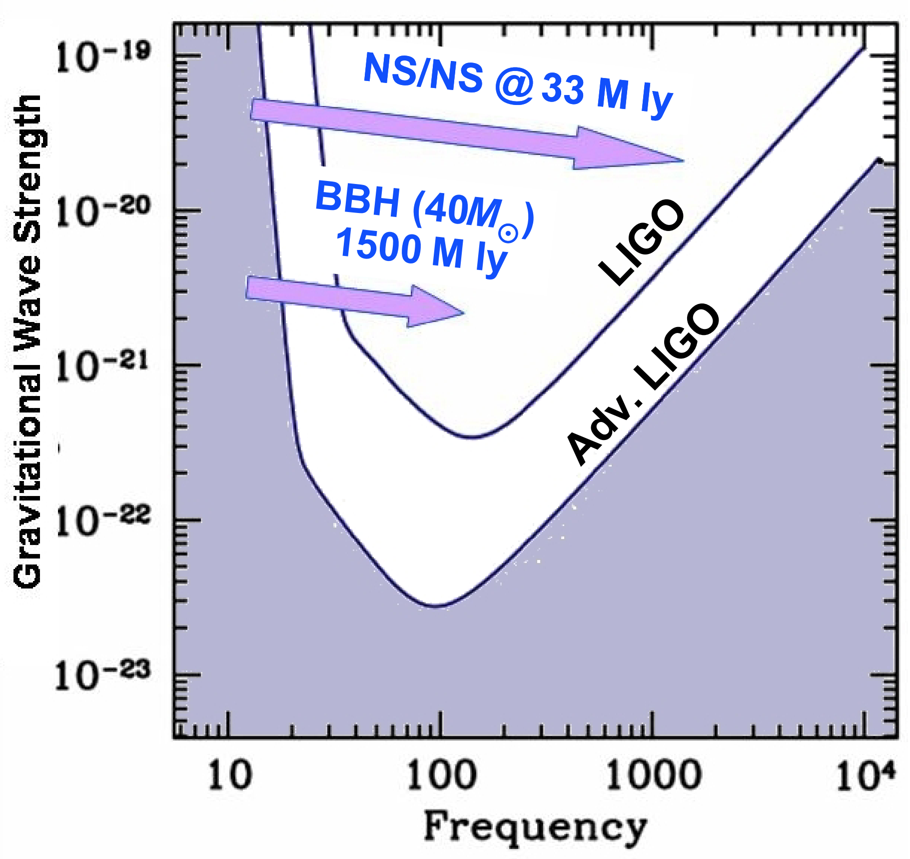


– Orbital decay of binary neutron stars through the emission of gravitational radiation.

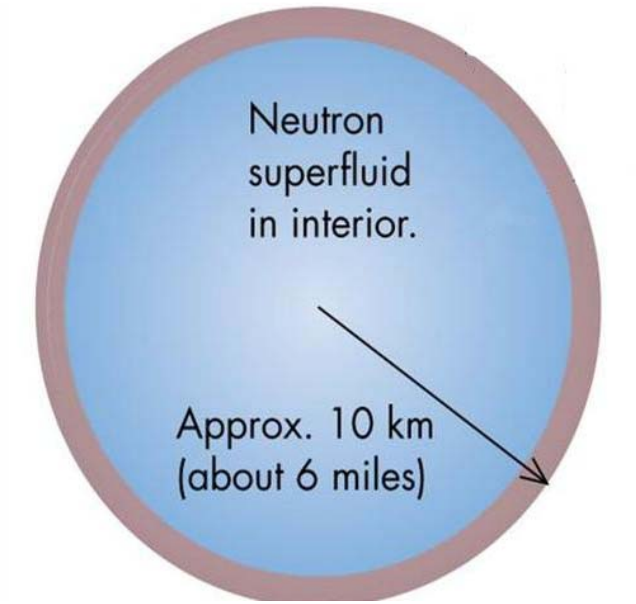


Binary Black Holes

- Black hole collisions test GR in strong field
  - About 10% of holes' mass converted to gravitational radiation
  - Nuclear explosions only convert about 0.5% of mass into energy
- Interferometers sensitive in 40-10000 Hz band
  - Excellent for low and intermediate mass objects
  - High mass → low frequency → Space Based → LISA

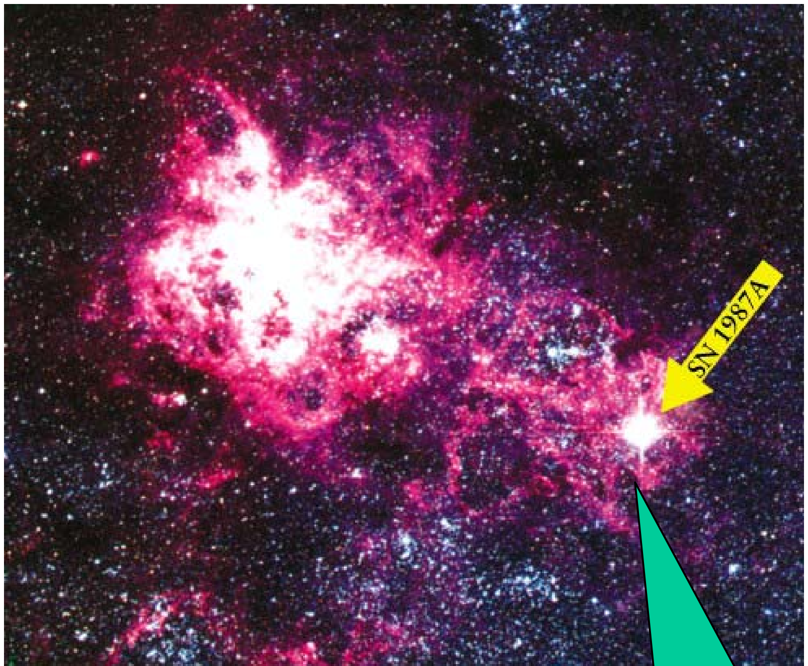


Isolated spinning neutron stars



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

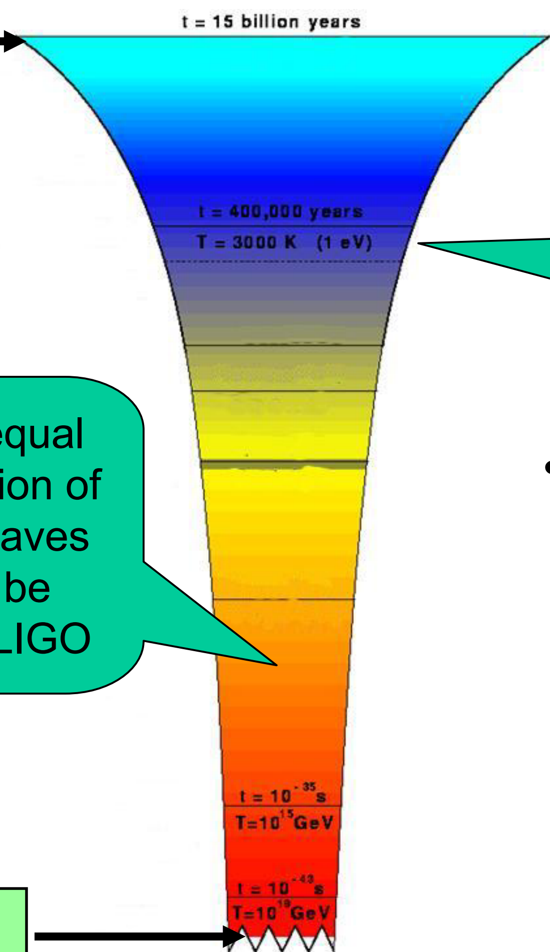
Burst Sources



- General properties.
  - Duration << observation time.
  - No accurate waveform.
- Possible Sources
  - Neutron star merger phase.
  - Supernova explosion.
- Promise
  - Unexpected sources and serendipity.
  - Detection uses minimal information.
  - Possible correlations with γ-ray or neutrino observations

Stochastic background of gravitational waves

Today



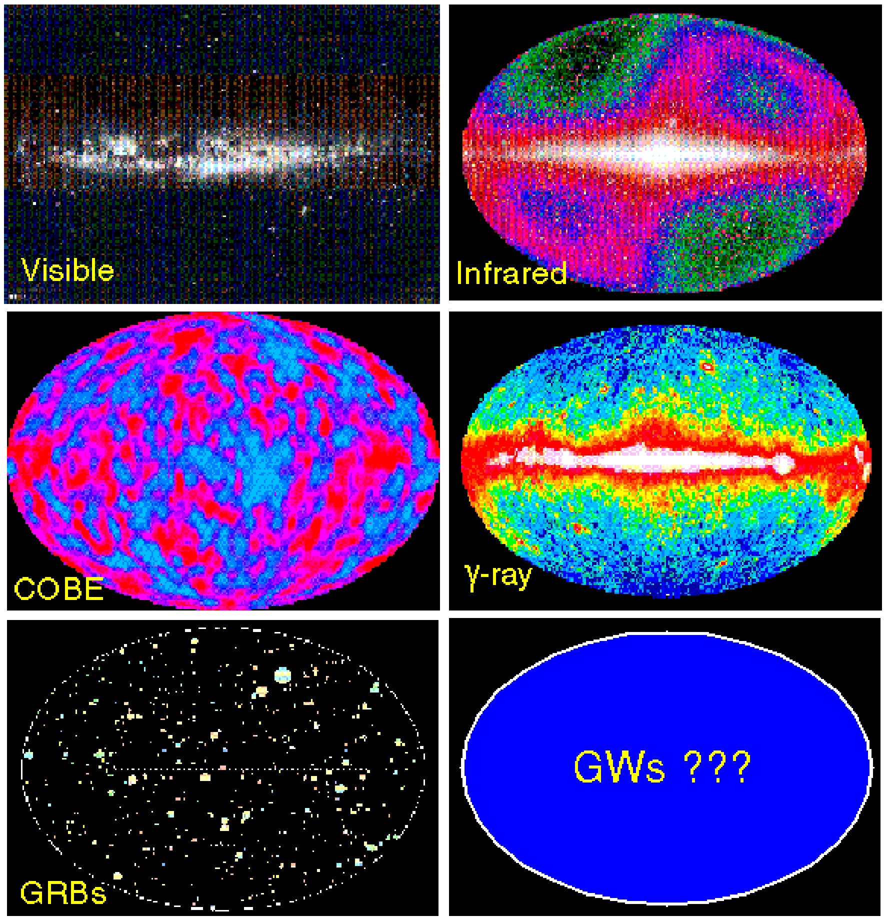
Big Bang

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

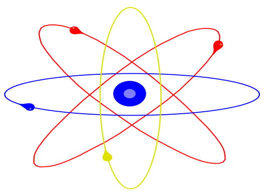
- General properties
  - » Weak superposition of many incoherent sources – a hiss.
  - » Only characterized statistically.

GW Astronomy

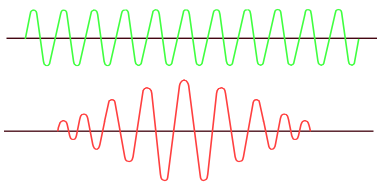


- A new way to look at the universe.
- We expect surprises.
- But gravitational radiation is very weak.
- Need to measure distance changes on the order of 10^{-18} m!

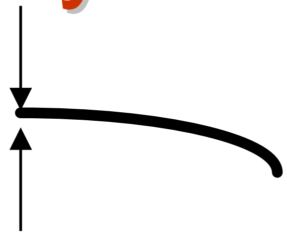
How Small is the effect of a Gravity Wave?



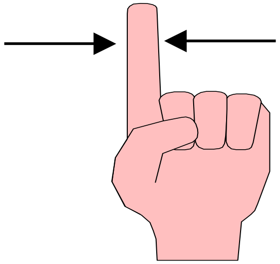
atom
10^{-10} m



wavelength of light
green ½ of 10^{-6} m
infrared 10^{-6} m



hair thickness
10^{-5} m

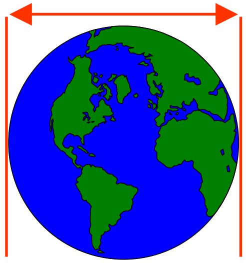


finger thickness
10^{-2} m

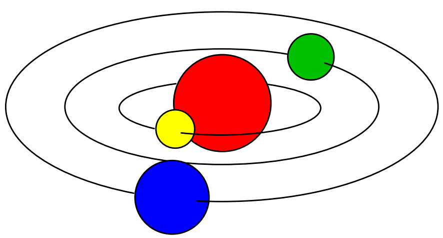
Child
1 m

Distance scale

Baton Rouge-New Orleans
10^{5} m



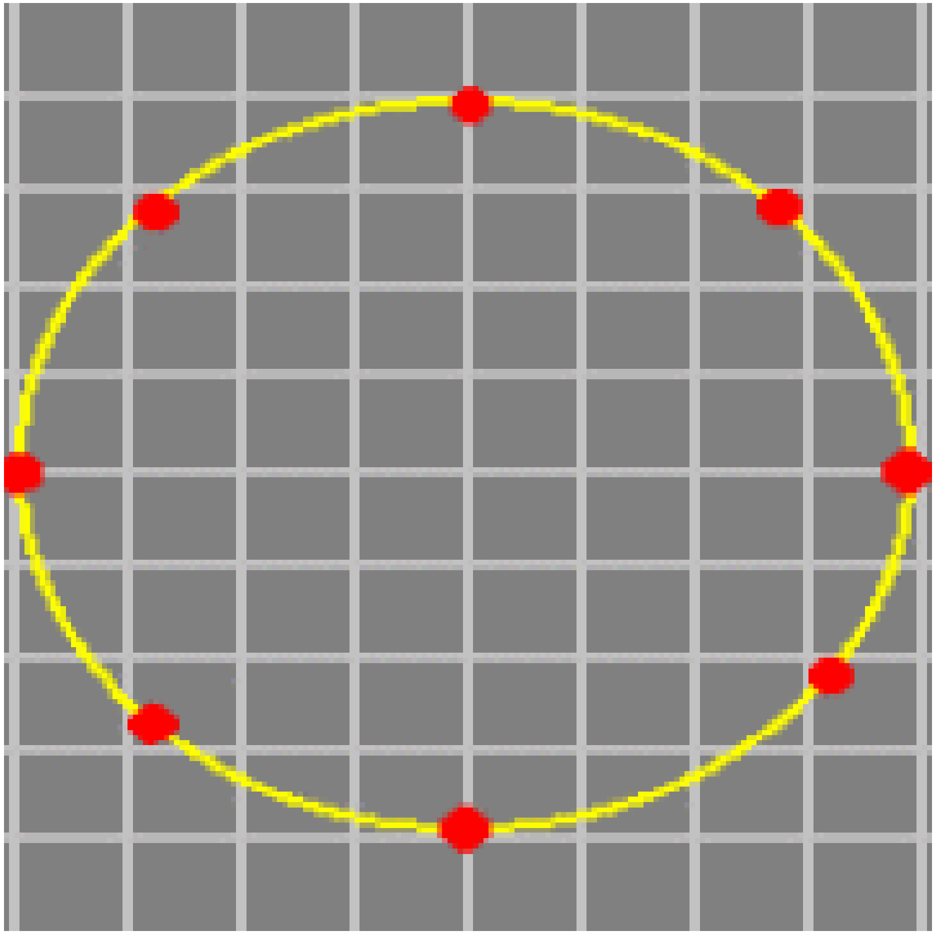
diameter of planet earth
10^{7} m



diameter of earth's orbit
10^{11} m

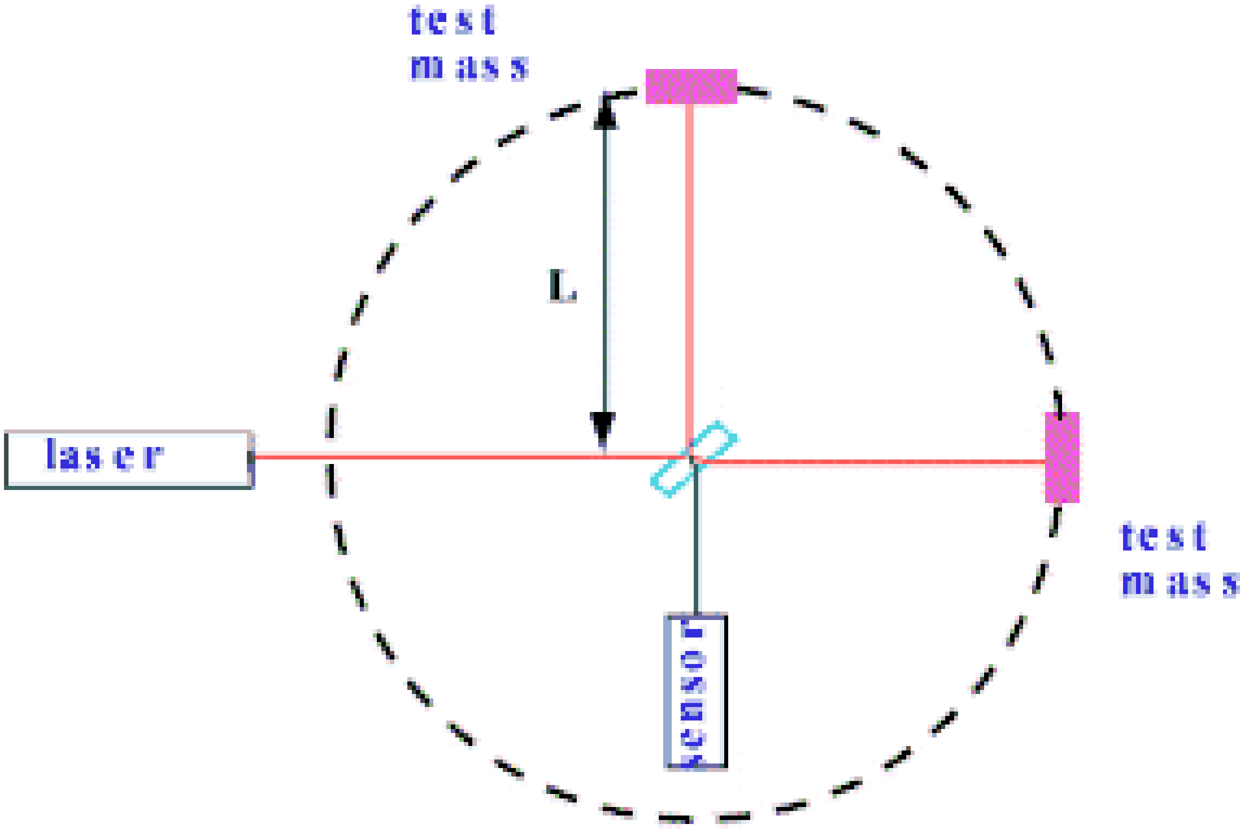
Effect of a GW

Free Test Masses in the presence of a Gravitational Wave



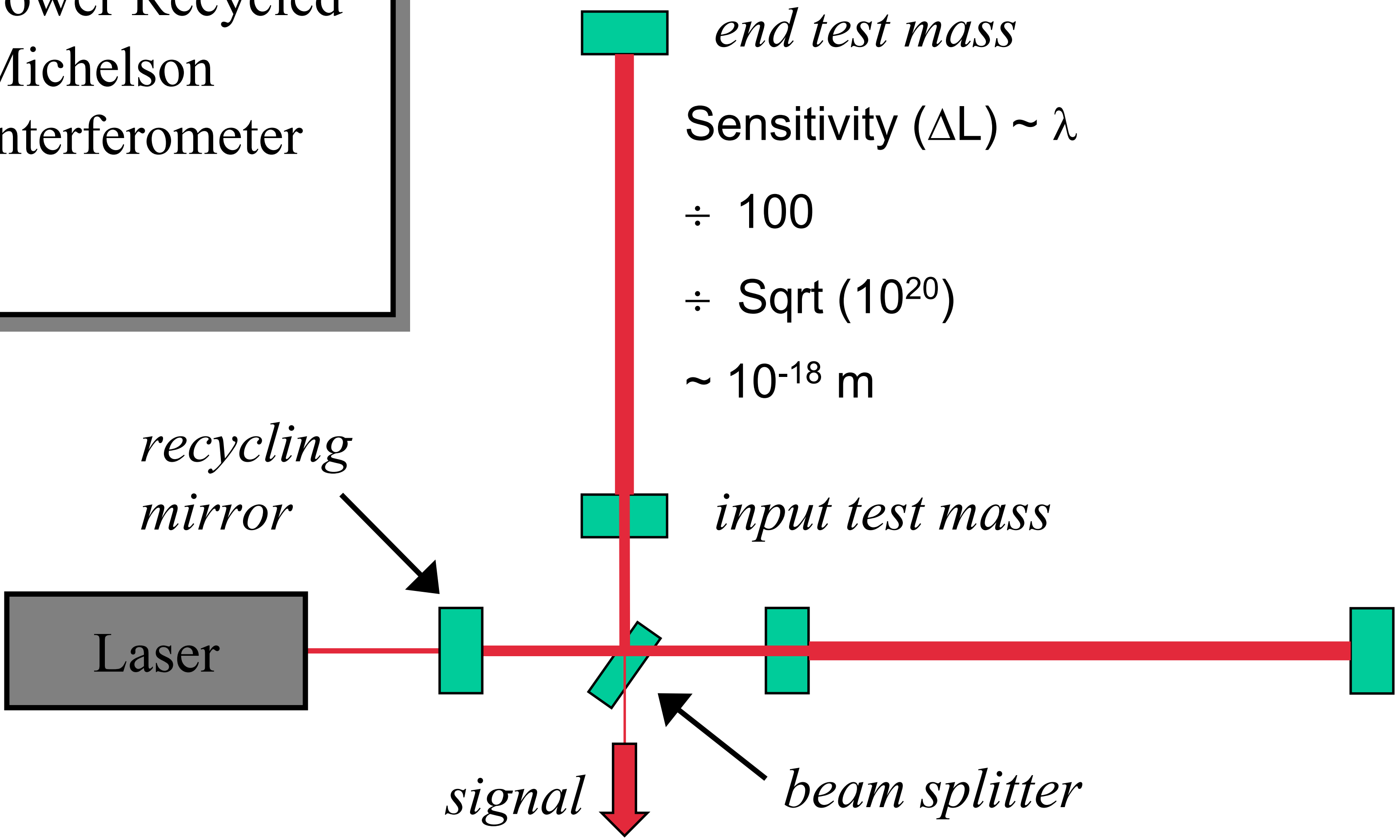
Detecting a GW

Interferometer



Optical Configuration

Power Recycled Michelson Interferometer

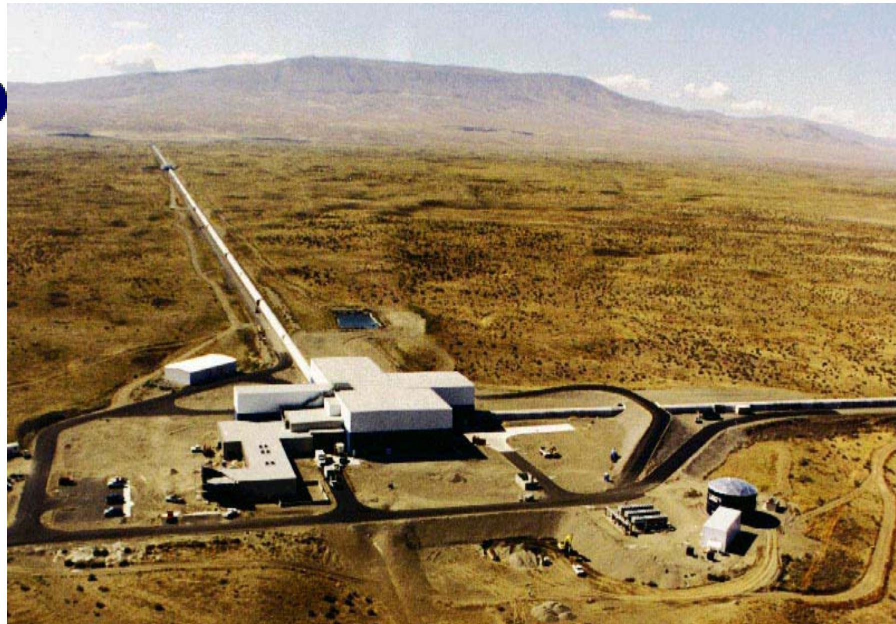


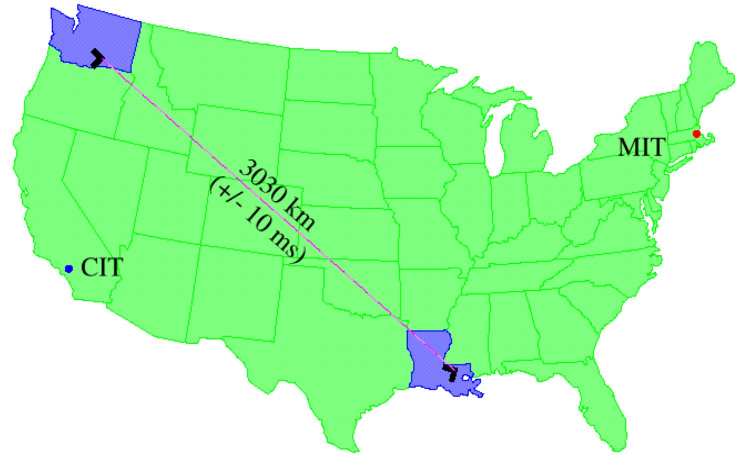
Sensitivity (ΔL) ~ λ

÷ 100

÷ Sqrt (10^{20})

~ 10^{-18} m





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-’02.

Three scientific data runs in ’02-’04,

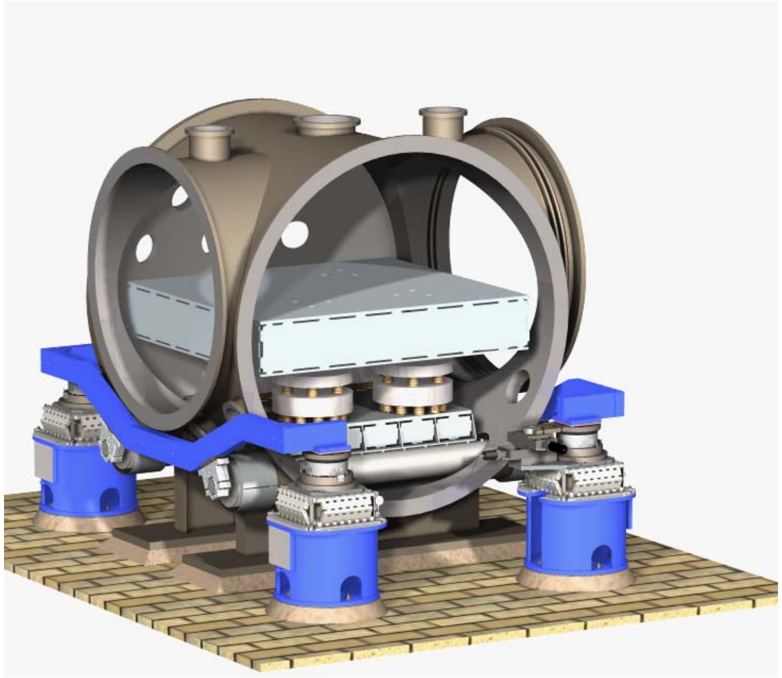
Commissioning is still in progress.

Vacuum “Envelope”

Passive seismic isolation.

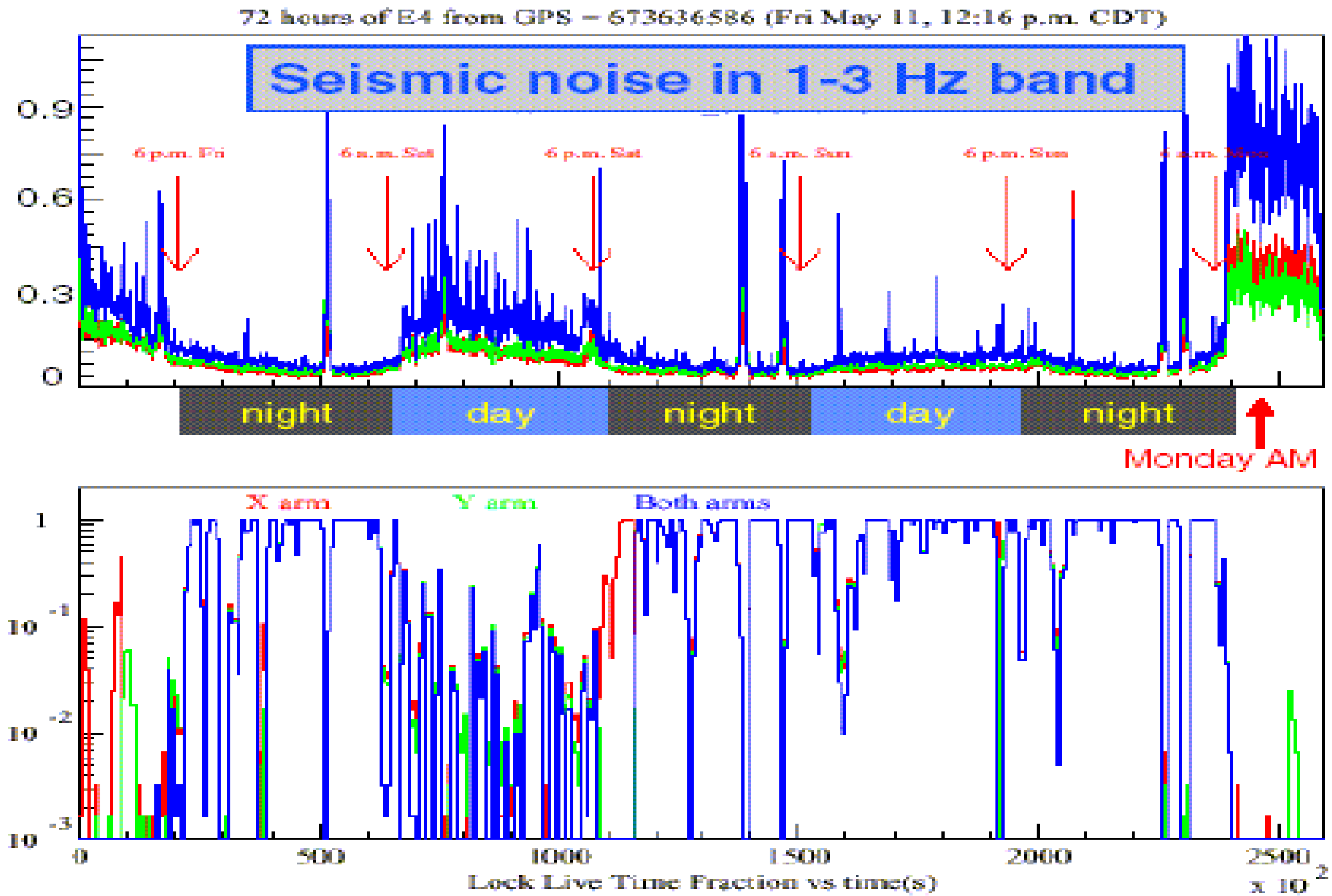
~10,000 m^3 of vacuum at 10^{-9} torr.

Vacuum "Envelope"

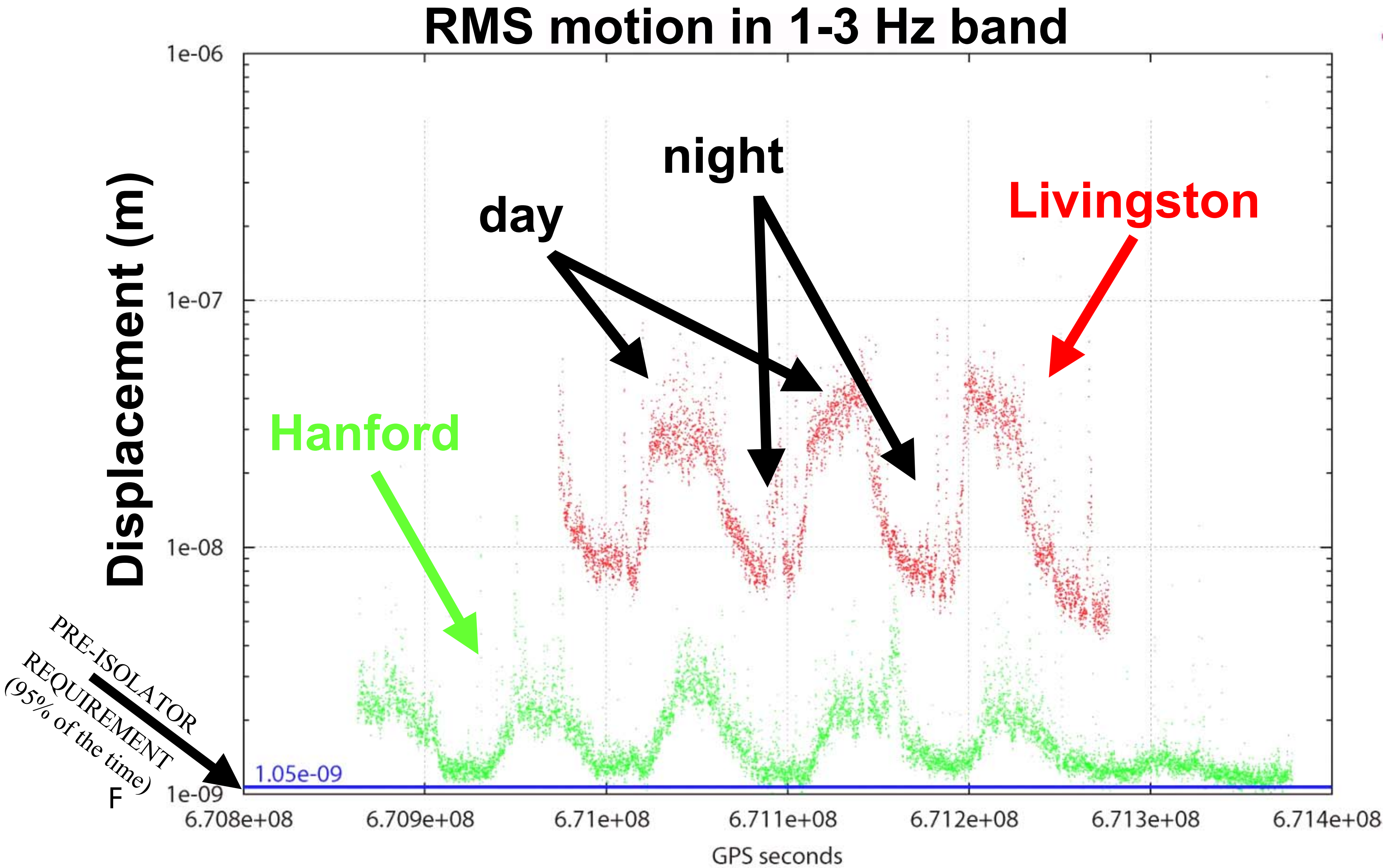


- Suppression of ~10^{-6} between support and optics table above 30 Hz.
- But resonances at low frequencies excited by ground motion.

Ground Noise

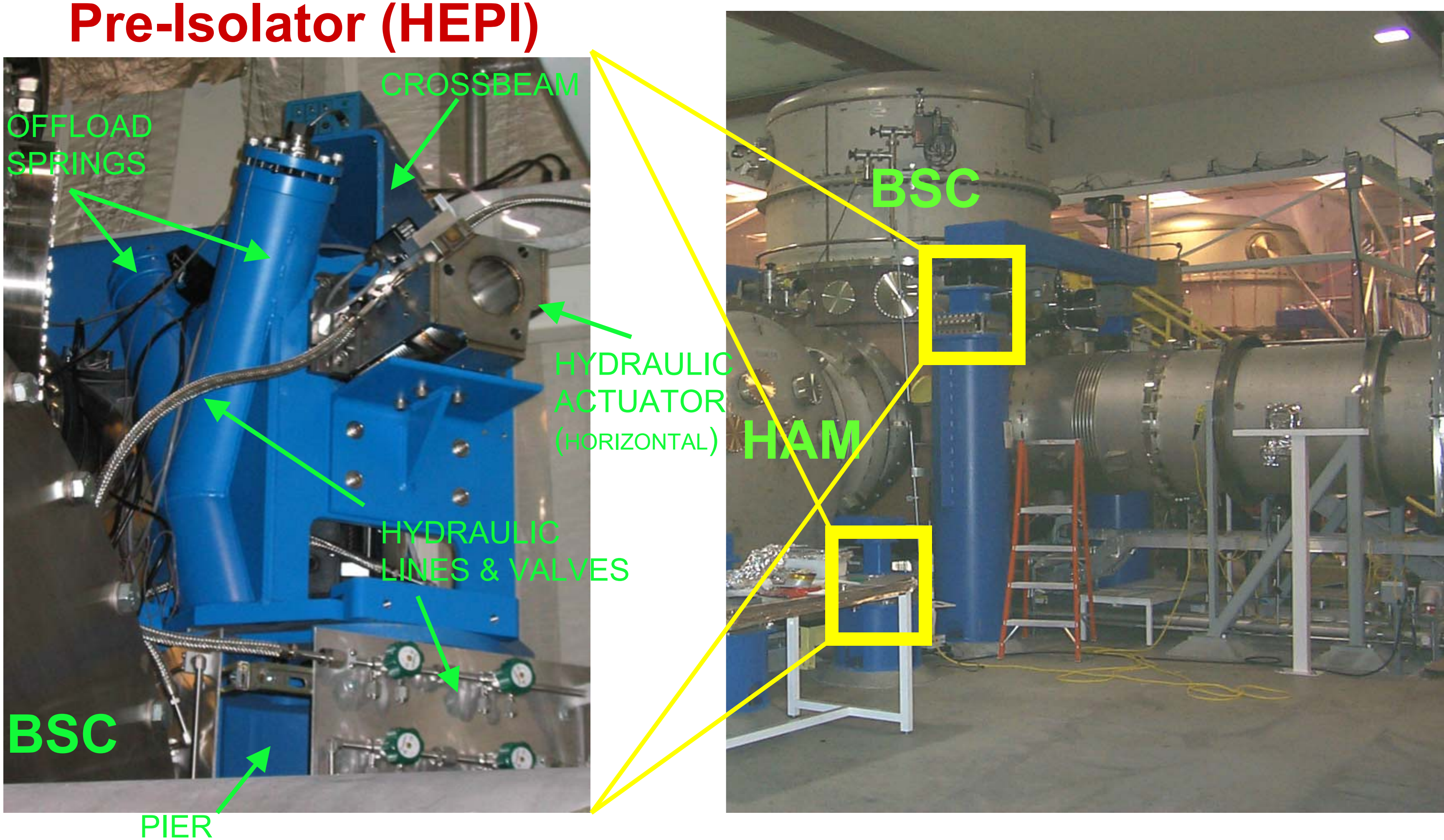


Seismic Noise

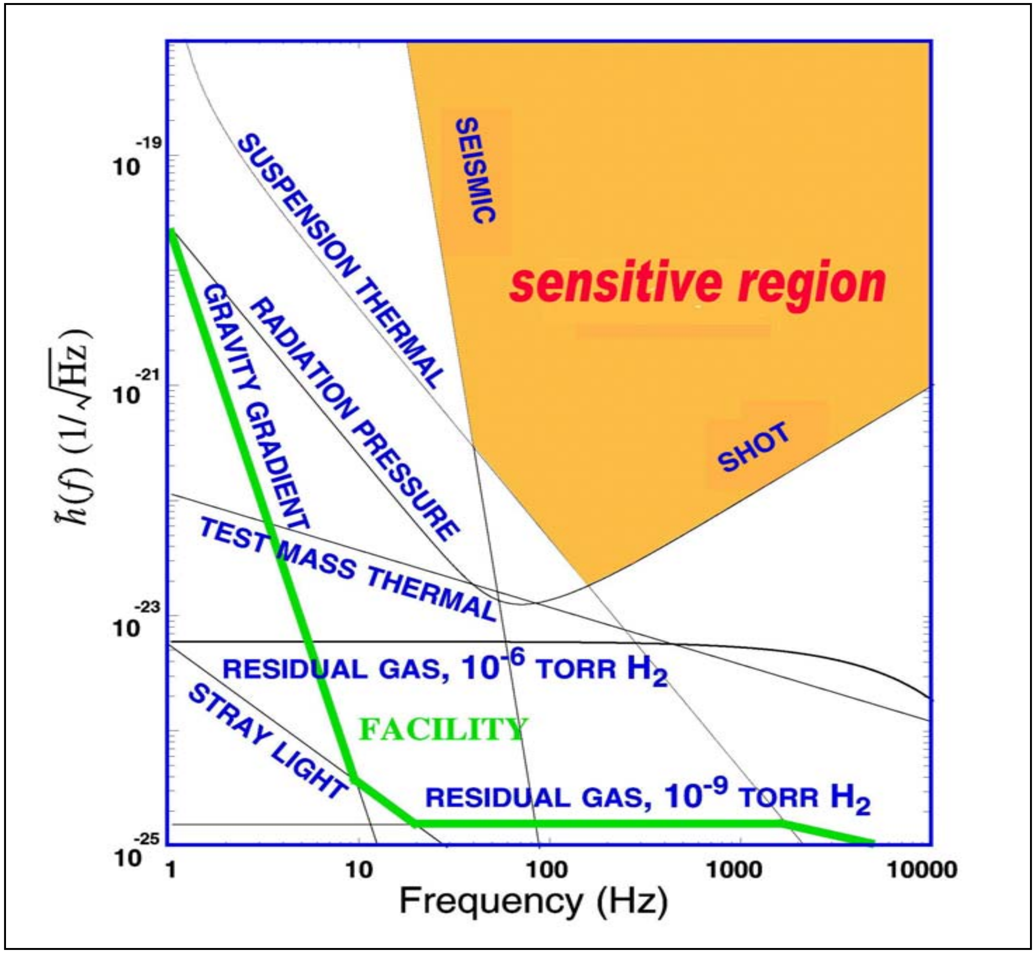


Active Seismic Isolation

Hydraulic External Pre-Isolator (HEPI)

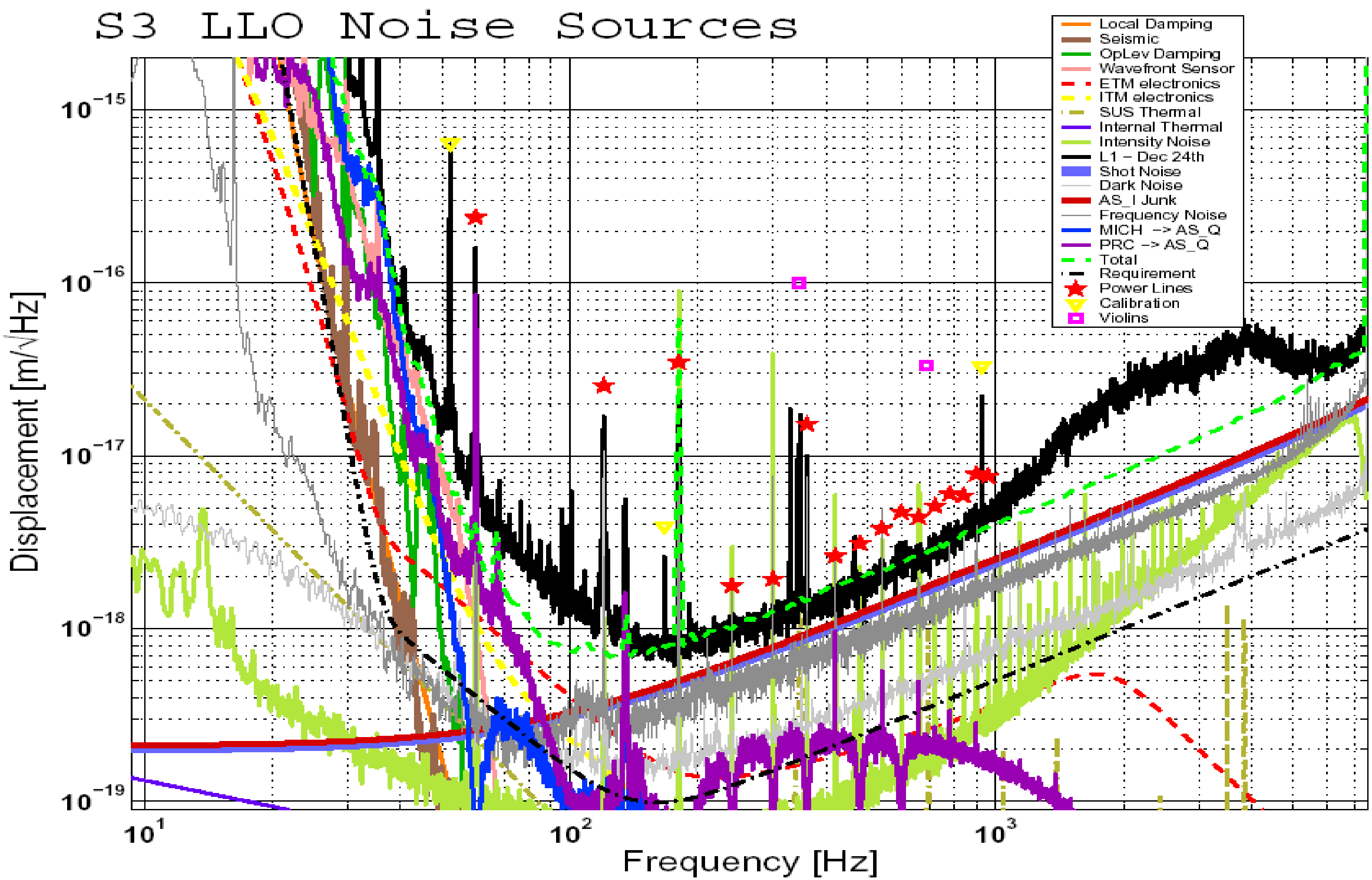


Sources of Noise



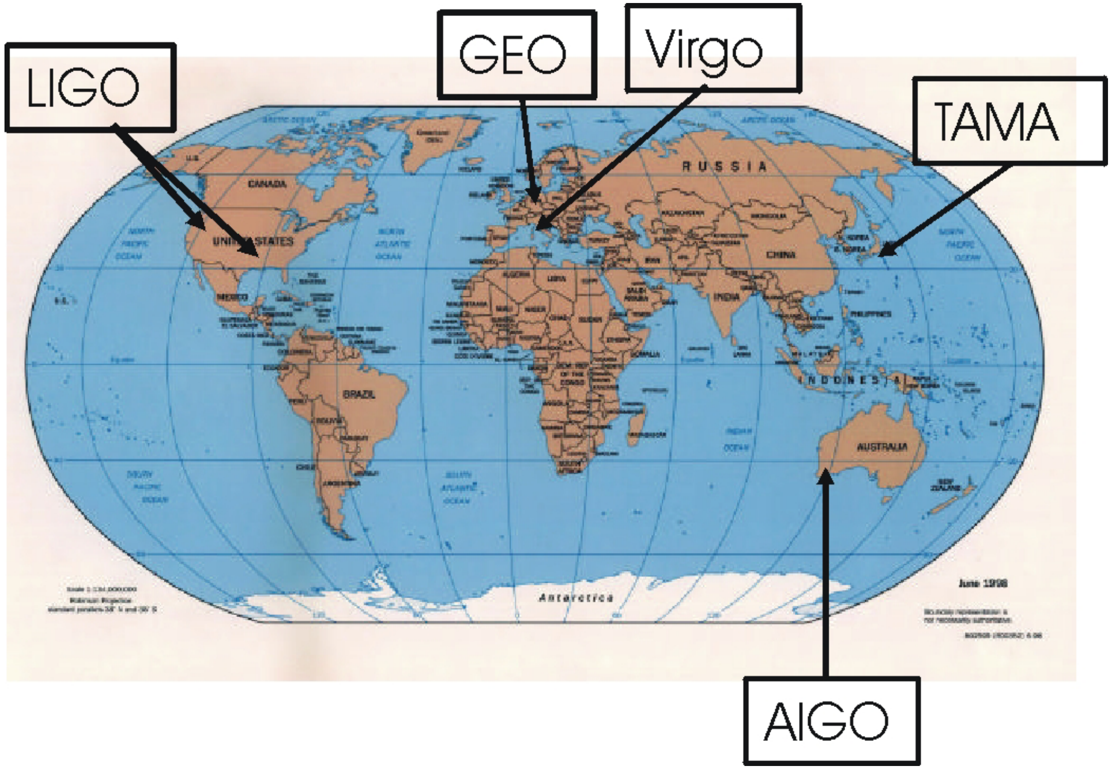
- Seismic at low frequencies.
- Thermal at mid-frequencies.
- Shot noise at high frequencies.
- Facility limits are all significantly lower; room for upgrades.

"Real" Noise



S3 LLO Noise Sources
Local Damping
Seismic
OpLev Damping
Wavefront Sensor
ETM electronics
ITM electronics
SUS Thermal
Internal Thermal
Intensity Noise
L1 – Dec 24th
Shot Noise
Dark Noise
AS_I Junk
Frequency Noise
MICH -> AS_Q
PRC -> AS_Q
Total
Requirement
Power Lines
Calibration
Violins
Displacement [m/√Hz]
Frequency [Hz]

GW Interferometers



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

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.

Data Analysis Groups

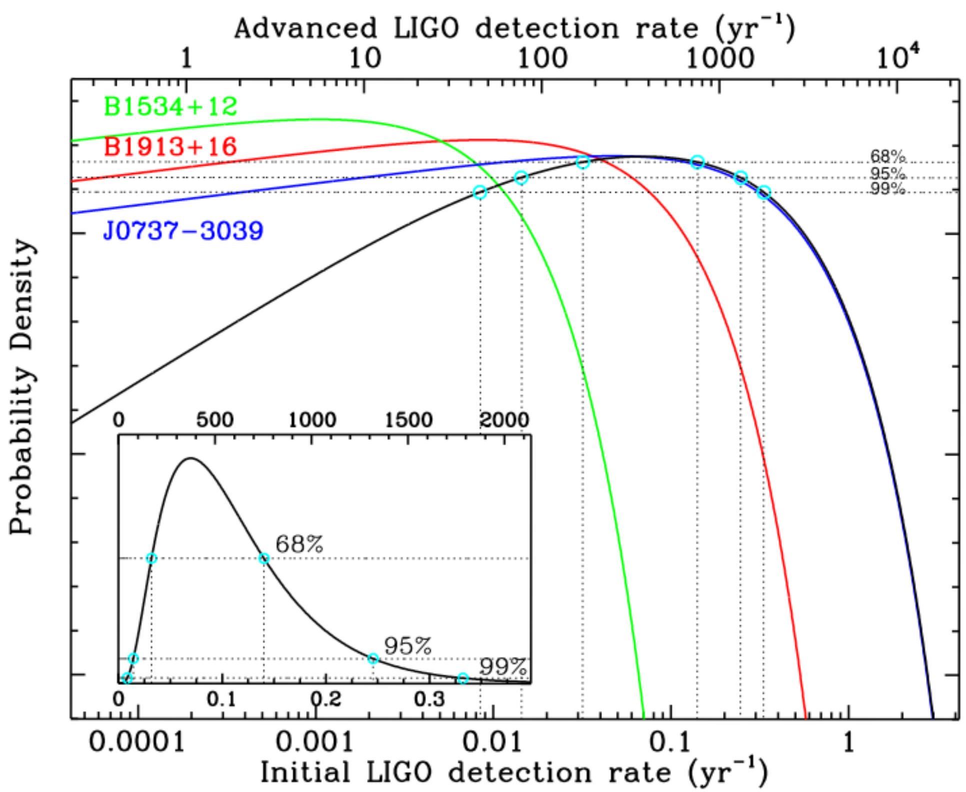
- Inspiral Analysis.
- Periodic Sources.
- Stochastic Background.
- Burst Sources.

Binary Neutron Star Inspiral Rates

- PSR population is dominated by faint objects.
- Estimate was dominated by PSR 1913+16.
- The recent discovery of a new BNS system PSR J0737-3039 has increased the predicted merger rate by a factor of 6-7.
- Increase mainly due to shorter lifetime and lower luminosity.
- Assumes observed binary systems are representative of galactic population.

Current Predictions

Burgay et al. 2003, Nature, 426, 531
VK et al. 2003, ApJ Letters, submitted



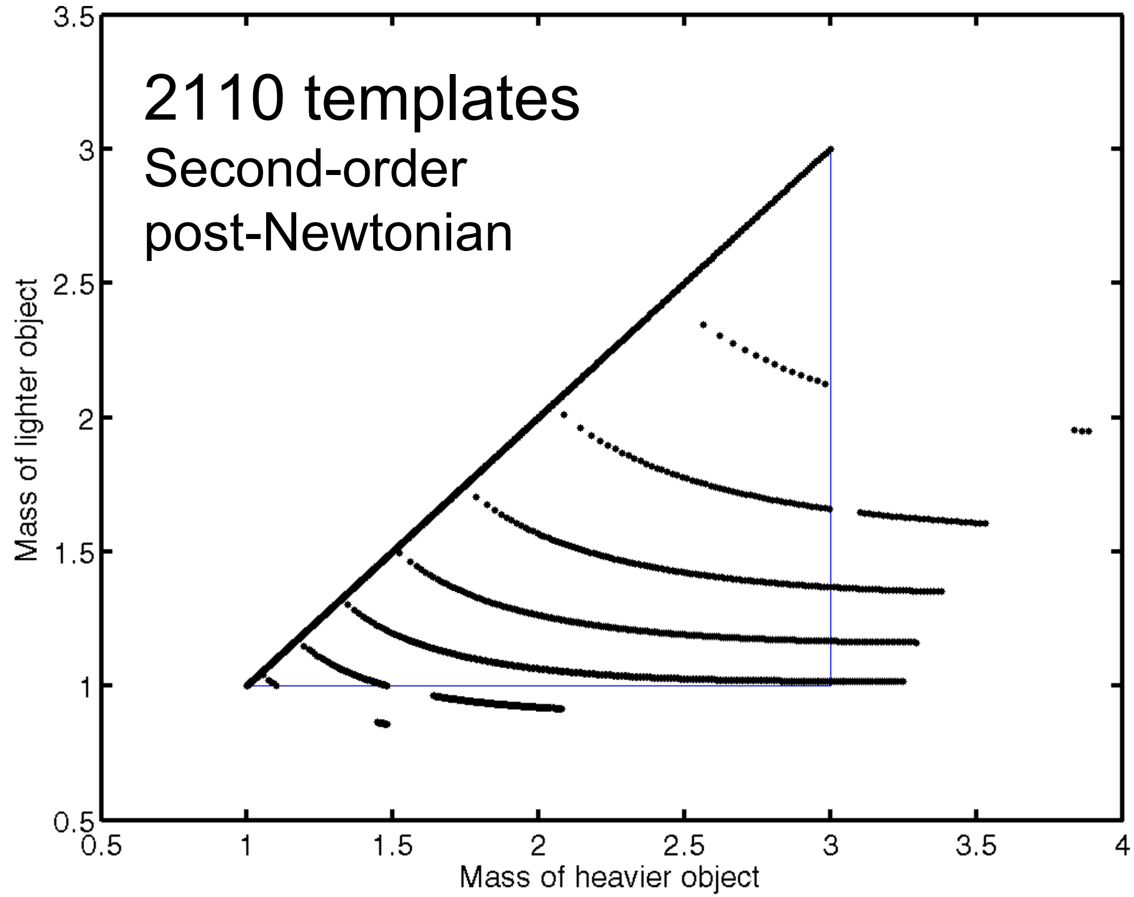
- Initial LIGO:
  - Peak ~75 kyr^{-1}
  - 95% 15-275 kyr^{-1}
- Adv. LIGO:
  - Peak ~400 kyr^{-1}
  - 95% 80-1500 kyr^{1}
- Optimal Model increases these values by a factor of 2-3.

Inspiral Search

- Waveforms are calculable. However, we must accommodate different orientations and masses.
- Construct a “template bank” of waveforms to cover the parameter space of interest.
- Use matched filtering in the frequency domain.
  - Frequencies weighted according to the noise spectrum.
- Test that the signal has the right distribution in frequency.

Inspiral Search

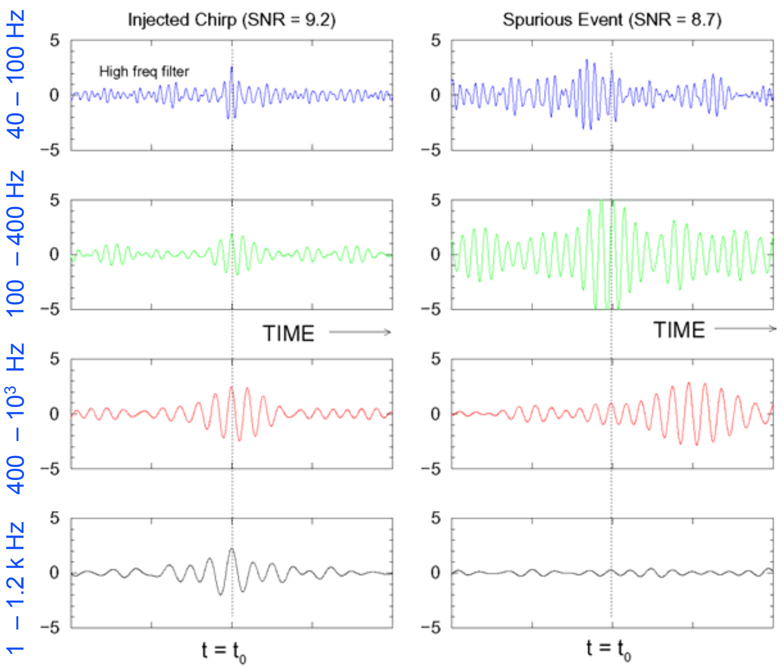
- Calculated using L1 noise curve.
- Mass of each binary component between $M_\odot$ and $3M_\odot$.
- Designed so that maximum loss of SNR due to a parameter mismatch < 3%.



The χ^2 Veto

- Loud transients often "ring" many template waveforms.
- Eliminate spurious events with a χ^2 test.
- Split the signal into p frequency bins with approx. equal power in each band.
- For Gaussian noise get a χ^2 distribution with 2p-2 d.o.f.

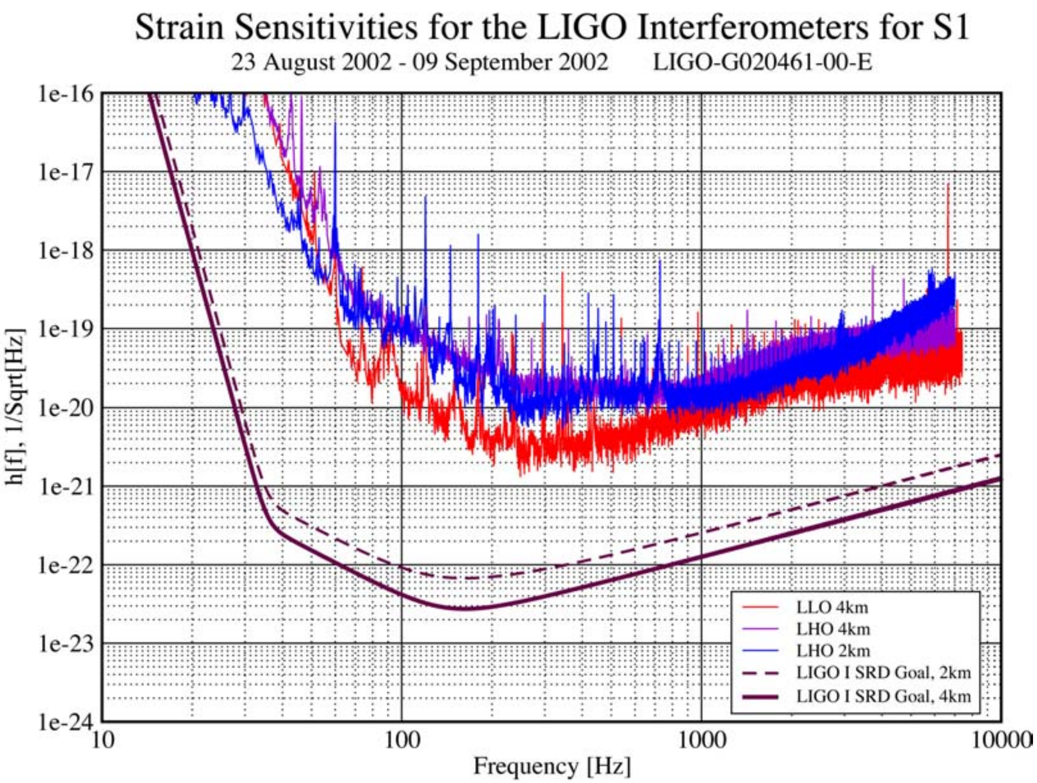
- For S1 used p=8.
- Veto events with high χ^2



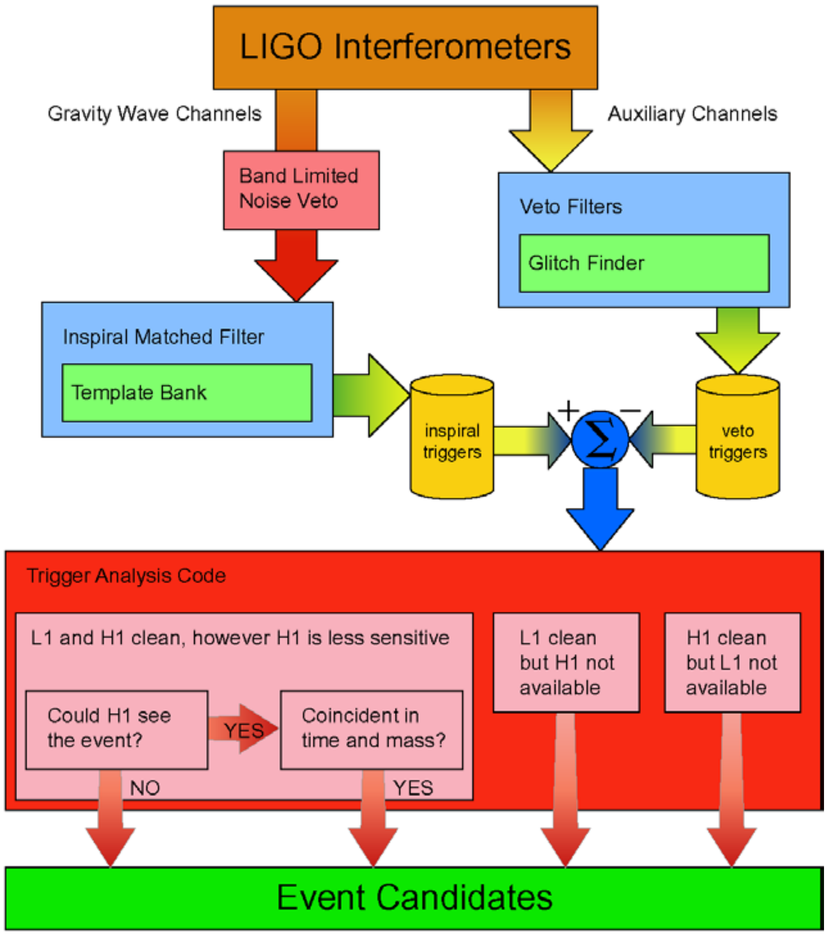
S1 Inspiral Sensitivity

- Average sensitivity to optimally oriented $2 \times 1.4\ M_{sun}$ neutron star binary at SNR = 8:
  - LLO 4k: 176 kpc
  - LHO 4k: 36 kpc

- During S1 LIGO was sensitive to inspirals in
  - Milky Way
  - Magellanic Clouds



S1 Inspiral Pipeline

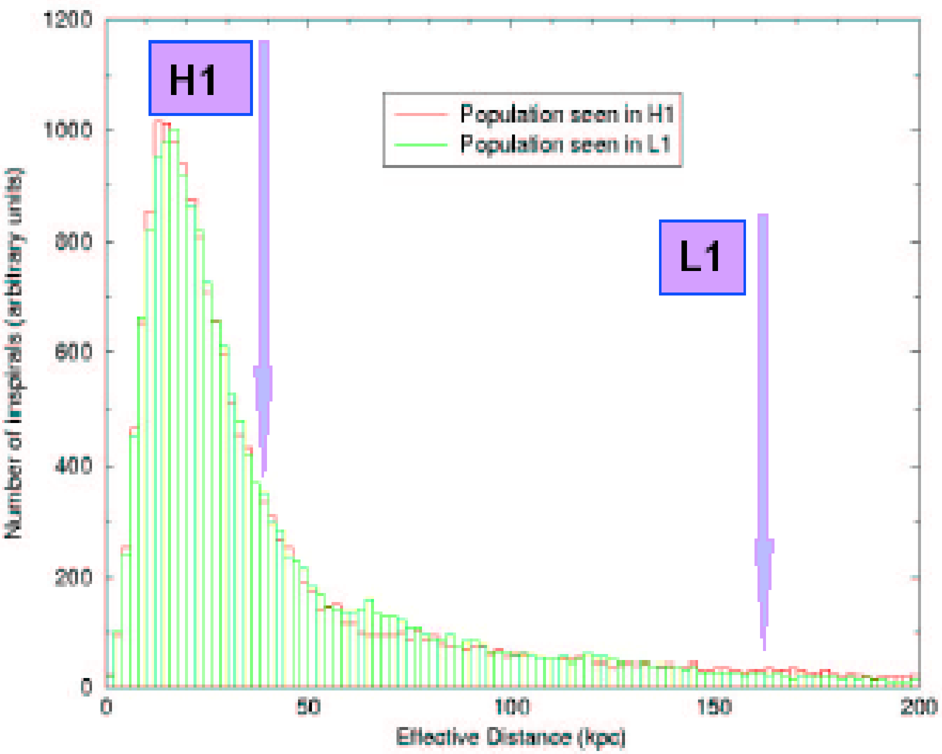


- Used a band limited RMS on GW channel to remove bad data
- Filtered L1 and H1 interferometer separately
- Used coincident or single interferometer data
  - Only demanded coincidence if both interferometers were available

S1 Inspiral Results

B. Abbott et. al. “Analysis of LIGO Data for Gravitational Waves from Binary Neutron Stars” **gr-qc/0308069**, submitted to PRD

Mass distribution and effective distance



Blind analysis, cuts were tuned on a playground data set. Upper Limit set using Loudest Event Statistic.

R< 170/yr/MWEG BNS coalescence.
58 hrs L1&H1, 76 hrs L1, 102 hrs H1

Previous searches:

- LIGO 40m (’94, 25 hrs) 0.5/hr, 25 kpc
- TAMA300 ’99 (6 hrs) 0.6/hr, ~ 1kpc
- Glasgow-Garching ’89 (100 hrs)
  no events, ~1kpc
- IGEC ’00-’01 (2yrs):
  no events, ~10 kpc

Results of CW Search

- **No evidence** of continuous wave emission from **PSR J1939+2134**.
- LLO upper limit on $h_o < 1.4\times10^{-22}$ constrain **ellipticity < 2.7×10^{-4}** (assuming $M=1.4M_{sun}$, r=10km, R=3.6kpc)

Setting upper limits on the strength of periodic gravitational waves using the first science data from the GEO600 and LIGO detectors **gr-qc/0308050** submitted to PRD.

Burst Results

- **Generic search** (no templates).
- **End result** of analysis pipeline: **number of triple coincidence events.**
- Use **time-shift** experiments to establish number of **background events.**
- Use **Feldman-Cousins** to set **90%** confidence upper limits on rate of foreground events. result:

Upper Limit of < 1.6 Events/Day

First upper limits from LIGO on gravitational wave bursts, LIGO Scientific Collaboration: B. Abbott, et al, **gr-qc/0312056**, accepted by PRD.

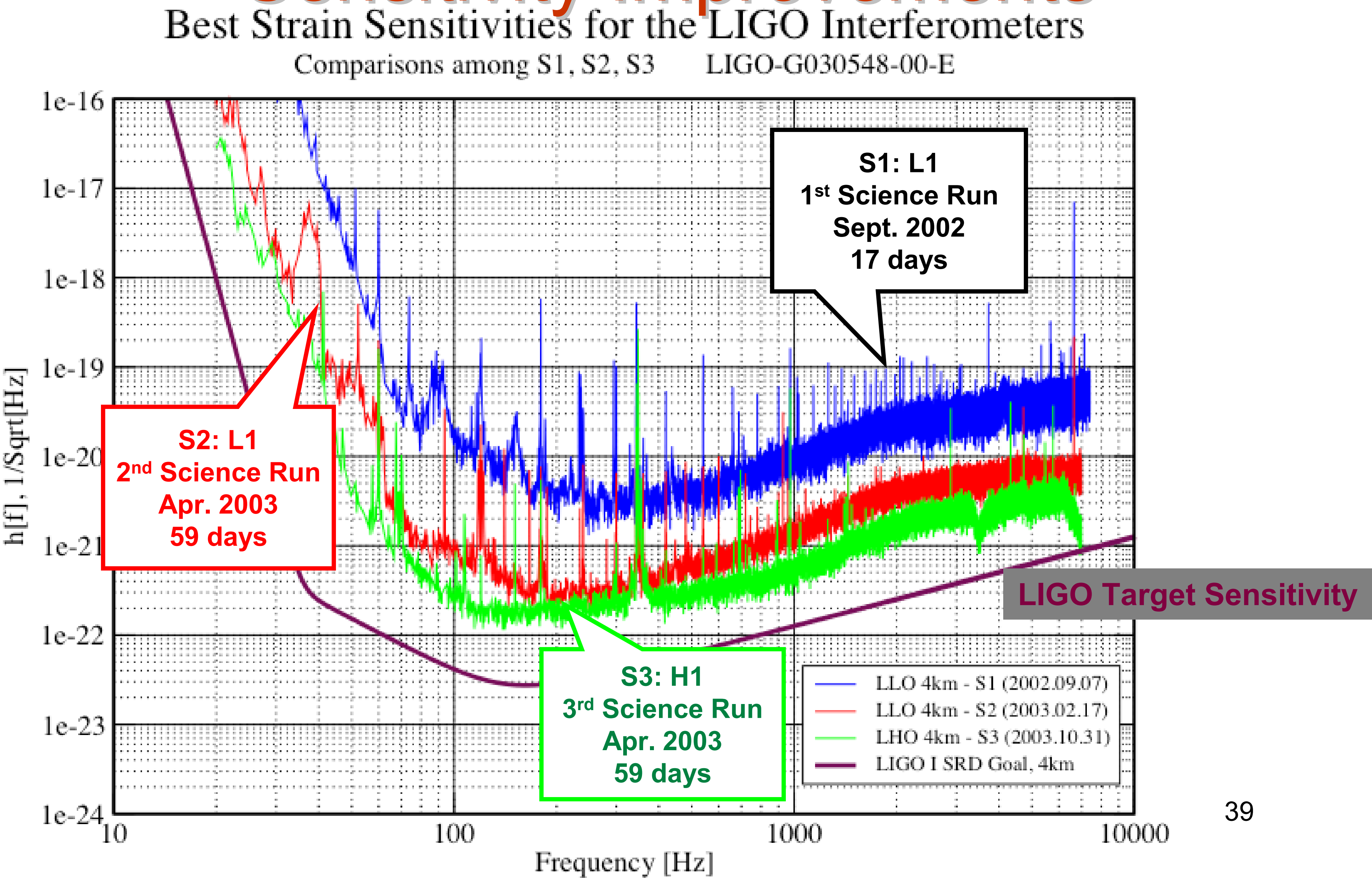
Stochastic Background Results

- **Method:** optimally filtered **cross-correlation** of detector pairs.

Interferometer pair	$\widehat{\Omega}_{\rm eff}\, h_{100}^2$	$\widehat{\Omega}_{\rm eff}\, h_{100}^2/\widehat{\sigma}_{\Omega,{\rm tot}}$	90% confidence interval on $\Omega_{\rm eff}\, h_{100}^2$	90% confidence upper limit	$\chi^2_{\rm min}$ (per dof)	Frequency range	Observation time
H1-H2	-8.3	-8.8	$[-9.9 \pm 2.0\,,\ -6.8 \pm 1.4]$	–	4.9	40 – 300 Hz	100.25 hr
H1-L1	32	1.8	$[2.1 \pm .42\,,\ 61 \pm 12]$	$\Omega_0\, h_{100}^2 < 55 \pm 11$	0.96	40 – 314 Hz	64 hr
H2-L1	0.16	0.0094	$[-30 \pm 6.0\,,\ 30 \pm 6.0]$	$\Omega_0\, h_{100}^2 \leq 23 \pm 4.6$	1.0	40 – 314 Hz	51.25 hr

Analysis of First LIGO Science Data for Stochastic Gravitational Waves, LIGO Scientific Collaboration: B. Abbott, et al., **gr-qc/0312088**, submitted to PRD

Sensitivity Improvements



LIGO to Advanced LIGO

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

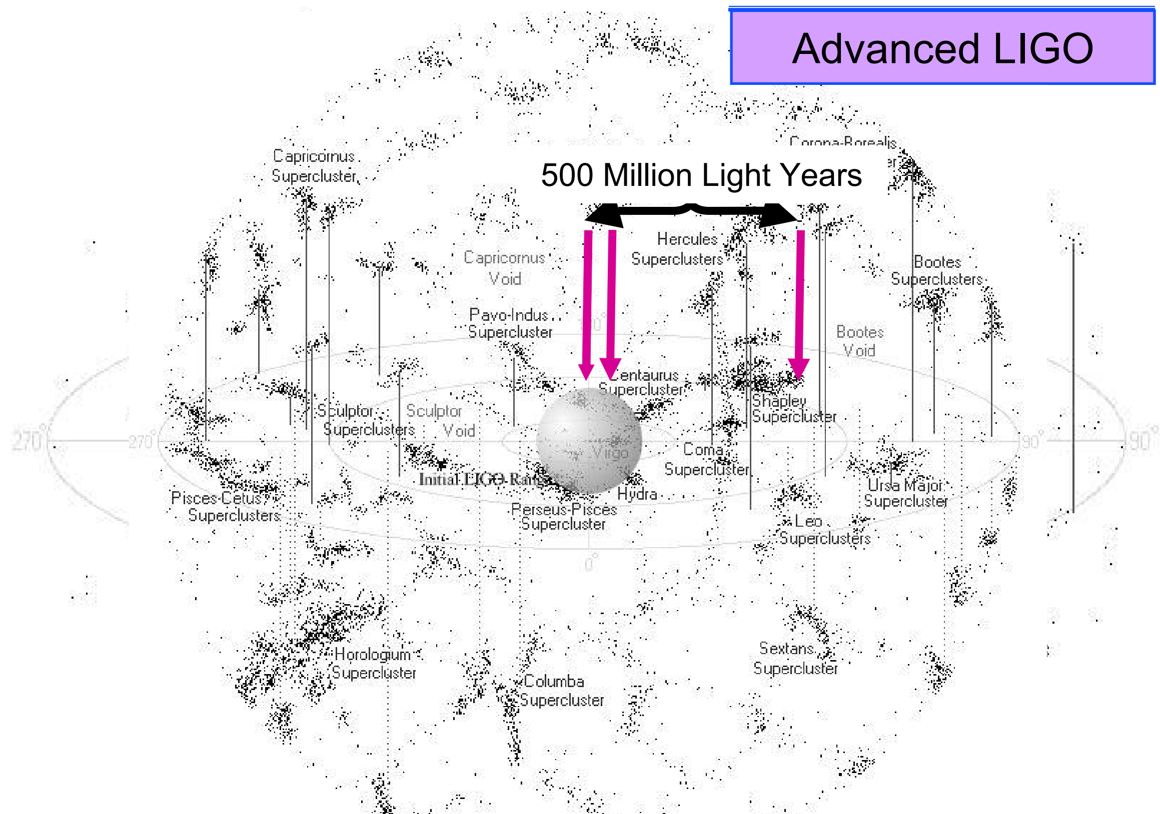


Image: R. Powell

- Initial LIGO continues to make good progress towards design sensitivity.
- S2 and S3 analyses will use all three interferometers at a much higher sensitivity.
- We hope that with active isolation, and other improvements, S4 will be at or close to the SRD.
- With the addition of new international instruments and LISA the future looks bright for GW astronomy.

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)