The Search for GRAVITATIONAL WAVES using the LIGO INTERFEROMETERS

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On behalf of the LIGO Scientific Collaboration

In honor of Professor Piyare Lal Jain
University of Buffalo, October 21, 2006

LIGO-G060620-00-Z

GRAVITATIONAL WAVES

What are gravitational waves? A change in the space-time metric (in the weak field approximation)

$$g_{\mu\nu} = \eta_{\mu\nu} - h_{\mu\nu} \qquad h_{\mu\nu} << 1$$

Where

$$\Box\, h_{\mu\nu} = -(16\pi G/c^4)\, T_{\mu\nu}$$

$$= 0 \qquad \text{(in free space)}$$

Generated by catastrophic events such as SN collapse, binary star or black hole mergers; should be emitted by rotating astrophysical bodies (i.e. pulsars with $Q \neq 0$).

Possibly produced in the early universe and manifested today as a stochastic background.

Estimates of the amplitude density of gravitational waves at the earth (strain density)

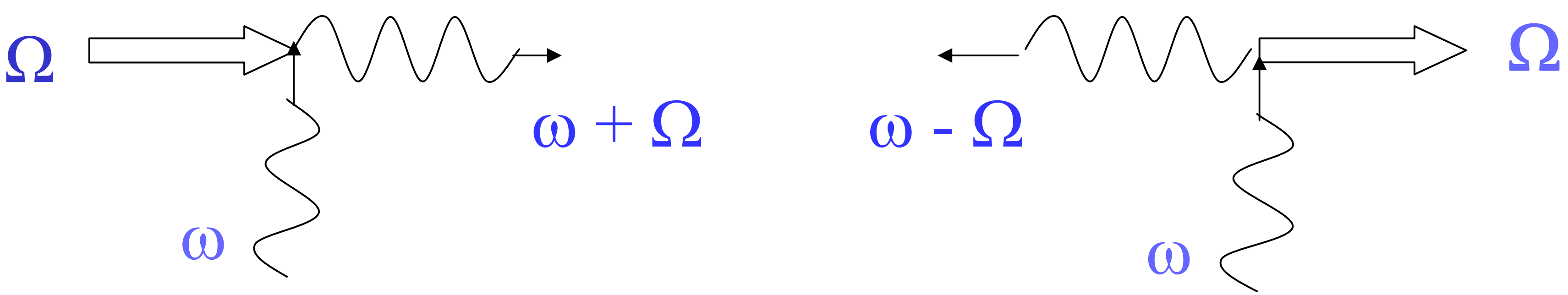
$$h(f) \sim 10^{-23}/\sqrt{\text{Hz}}$$

DETECTION OF a G.W.

1. **Direct coupling to matter:** J.Weber's resonant cylinders absorb energy from the wave and "ring". They are narrow band devices and of limited sensitivity even when cooled to mK temeperatures.

2. **Direct coupling to photons:** In R.L.Forward's and R.Weiss' interferometers the GW interacts "elastically" with the optical field.

SIDEBANDS AT ±Ω ARE DUE TO ABSORPTION **AND** STIMULATED EMISSION OF A GRAVITON FROM/INTO THE FIELD



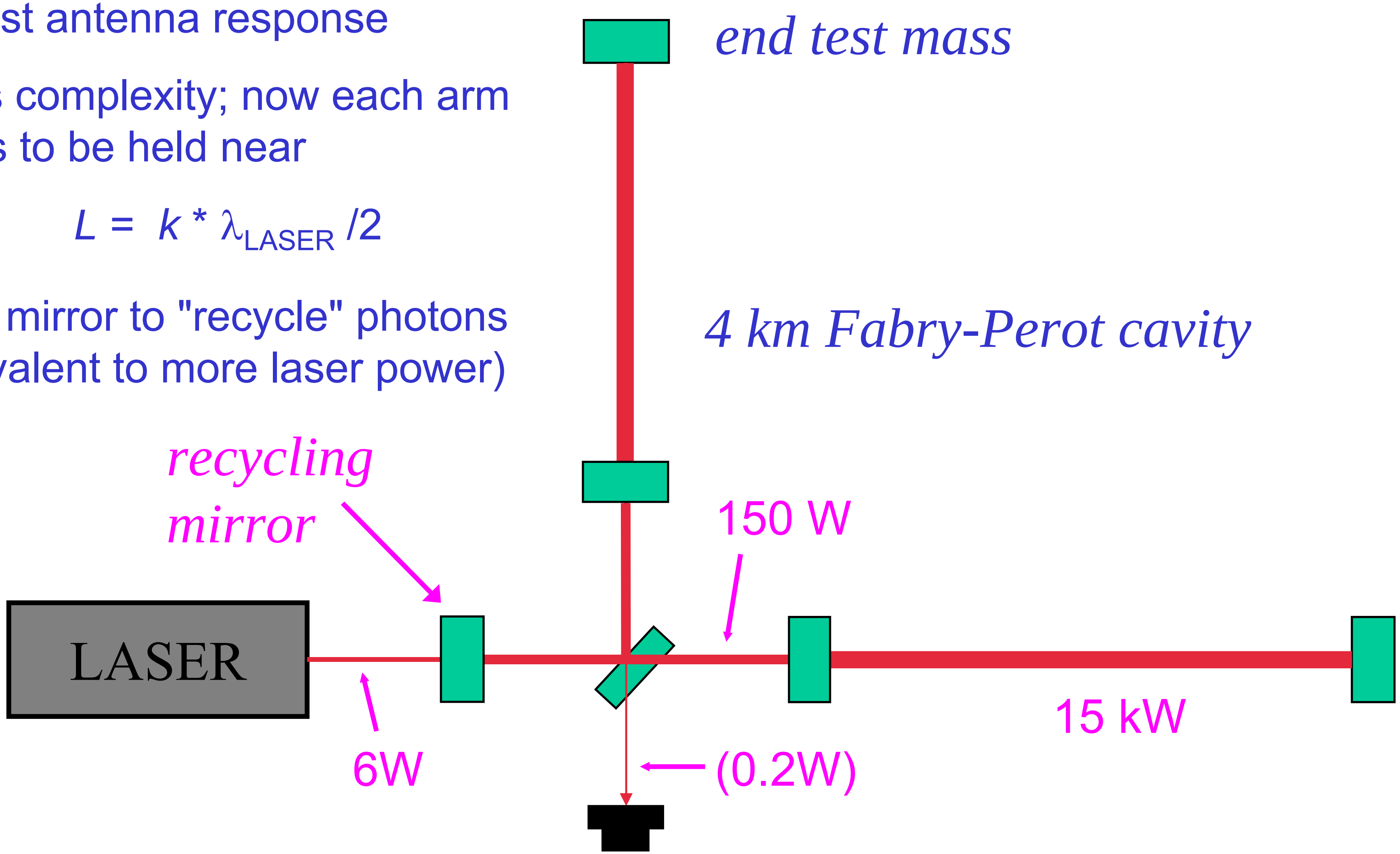
Usual interpretation: the distance between **free-falling** mirrors is modified resulting in a phase shift of the stored optical field.

Recycled Michelson Interferometer with Fabry-Perot arms

- Want "optical" arm length ~ λ_{GW} /4 for best antenna response
- Adds complexity; now each arm needs to be held near

$$L = k * \lambda_{LASER} /2$$

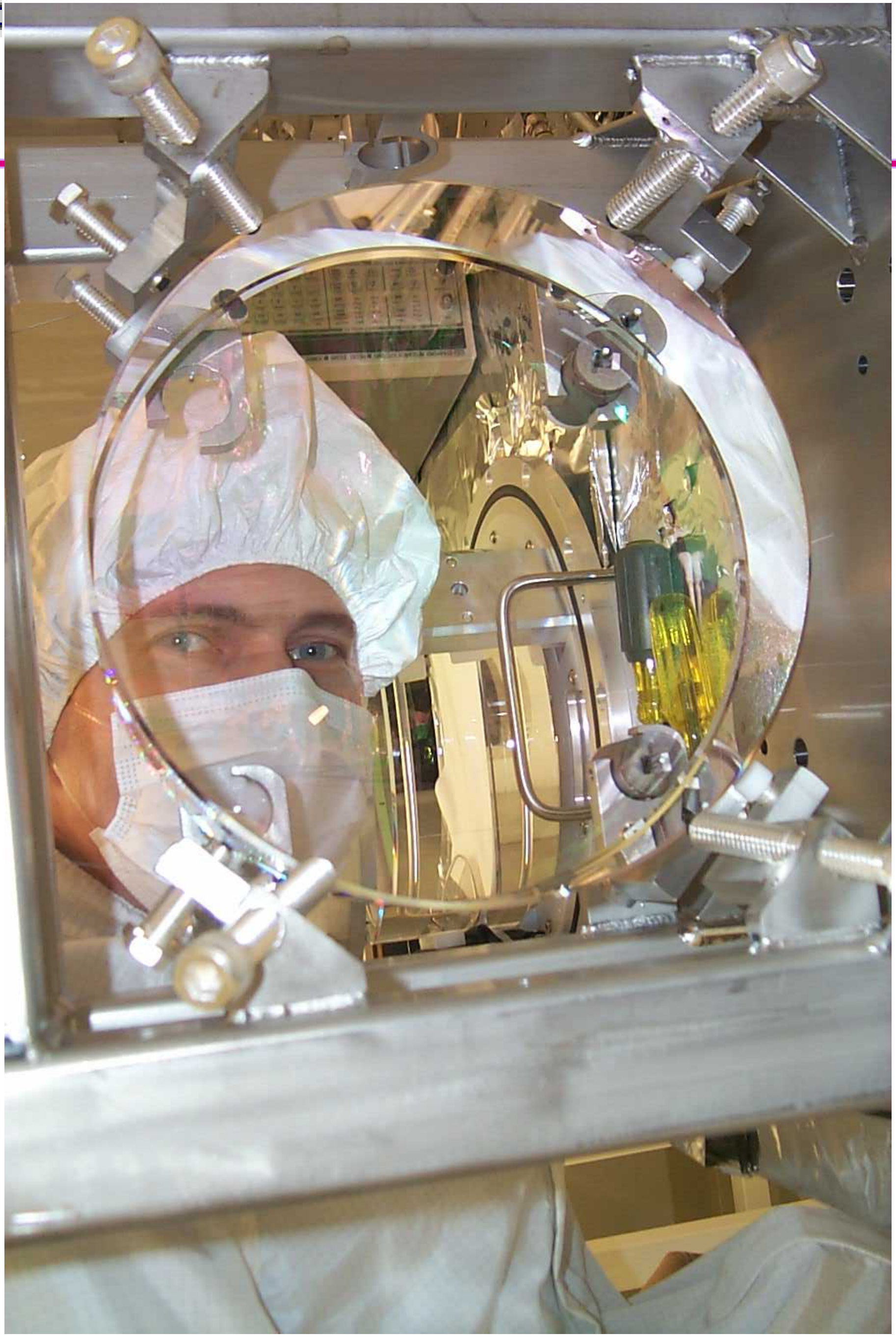
- Add mirror to "recycle" photons (equivalent to more laser power)



THE HANFORD AND LIVINGSTON LIGO INTERFEROMETERS

LIGO Beam Tube

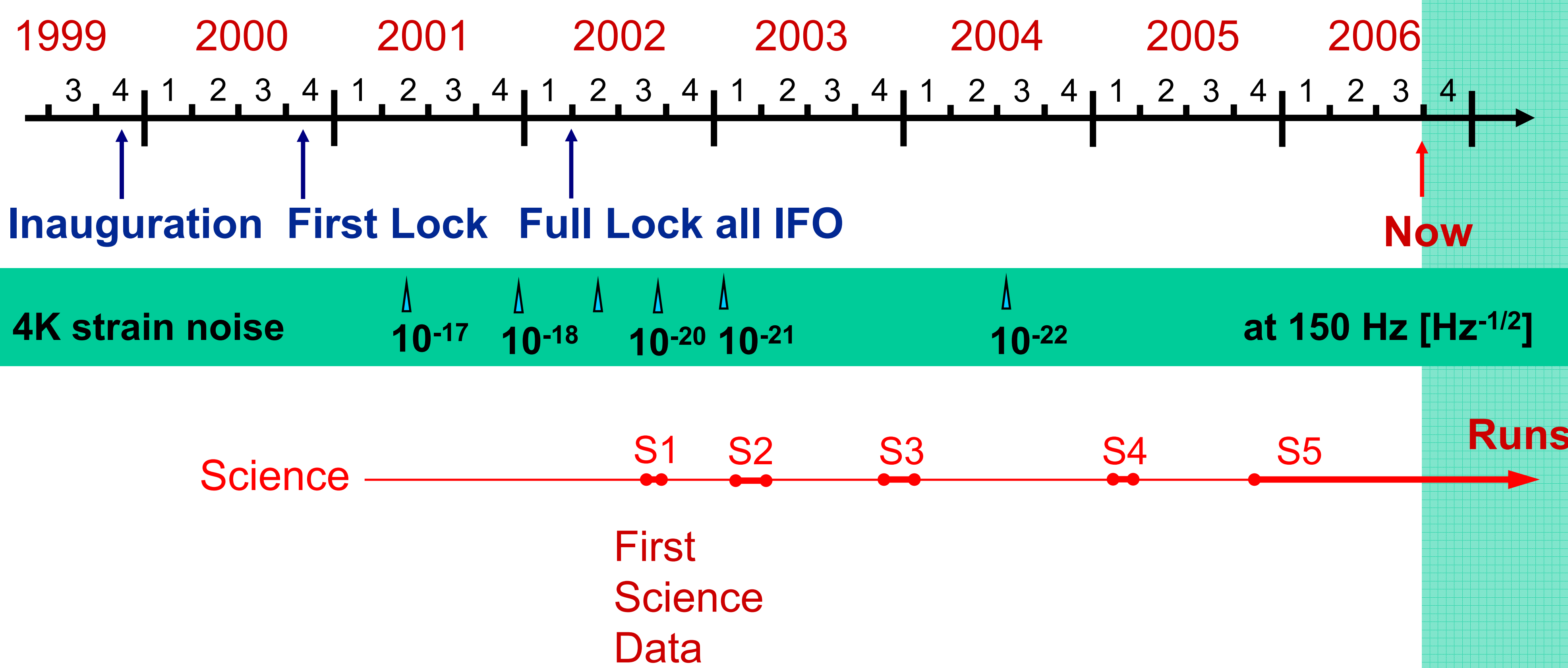
LIGO Vacuum Equipment



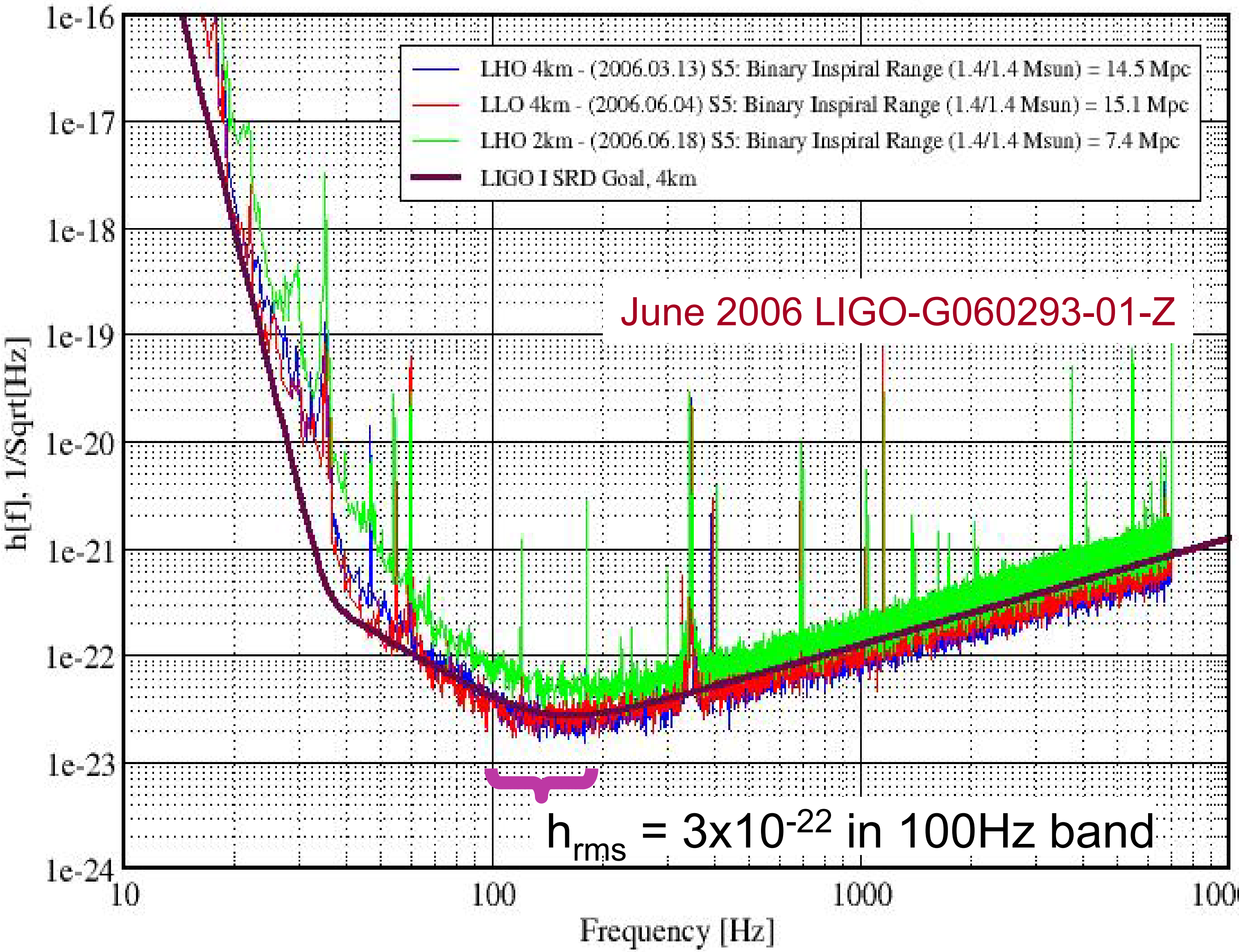
CORE OPTICS

10 kg Fused Silica,
25 cm diameter
10 cm thick

LIGO TIME LINE

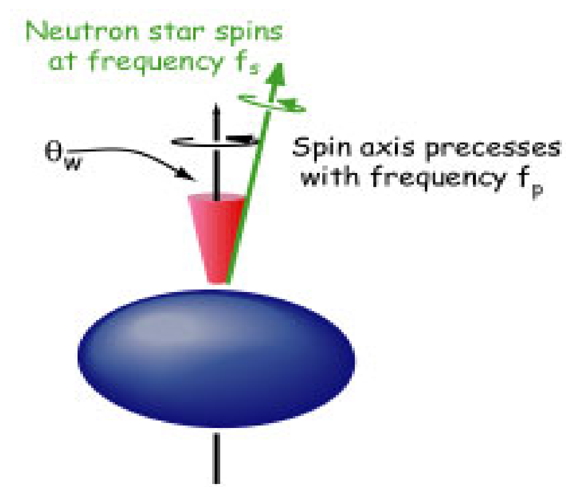


S5 Science Run: Nov '05 -…



Astrophysical Sources of Gravitational Waves

- Compact binaries
  - Black holes & neutron stars
  - Inspiral and merger
  - Probe internal structure, populations, and spacetime geometry
- Spinning neutron stars
  - Isolated neutron stars with mountains or wobbles
  - Low-mass x-ray binaries
  - Probe internal structure and populations



LIGO

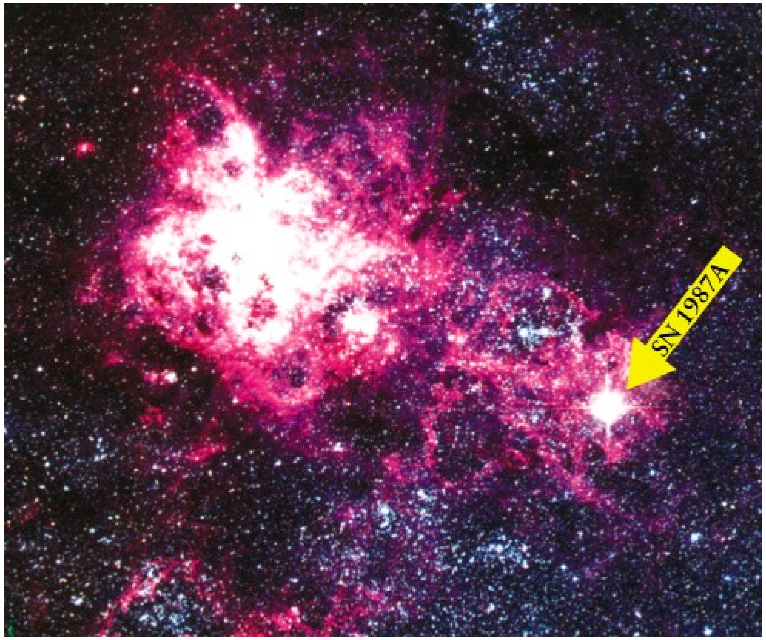
Gravitational-Wave Bursts

LSC

- Catastrophic events involving solar-mass (1-100 M_o) compact objects.
  - » core-collapse supernovae
  - » accreting/merging black holes
  - » gamma-ray burst engines
  - » other … ???

- Sources typically not well understood, involving complicated (and interesting!) physics.
  - » Dynamical gravity with event horizons
  - » Behavior of matter at supra-nuclear densities

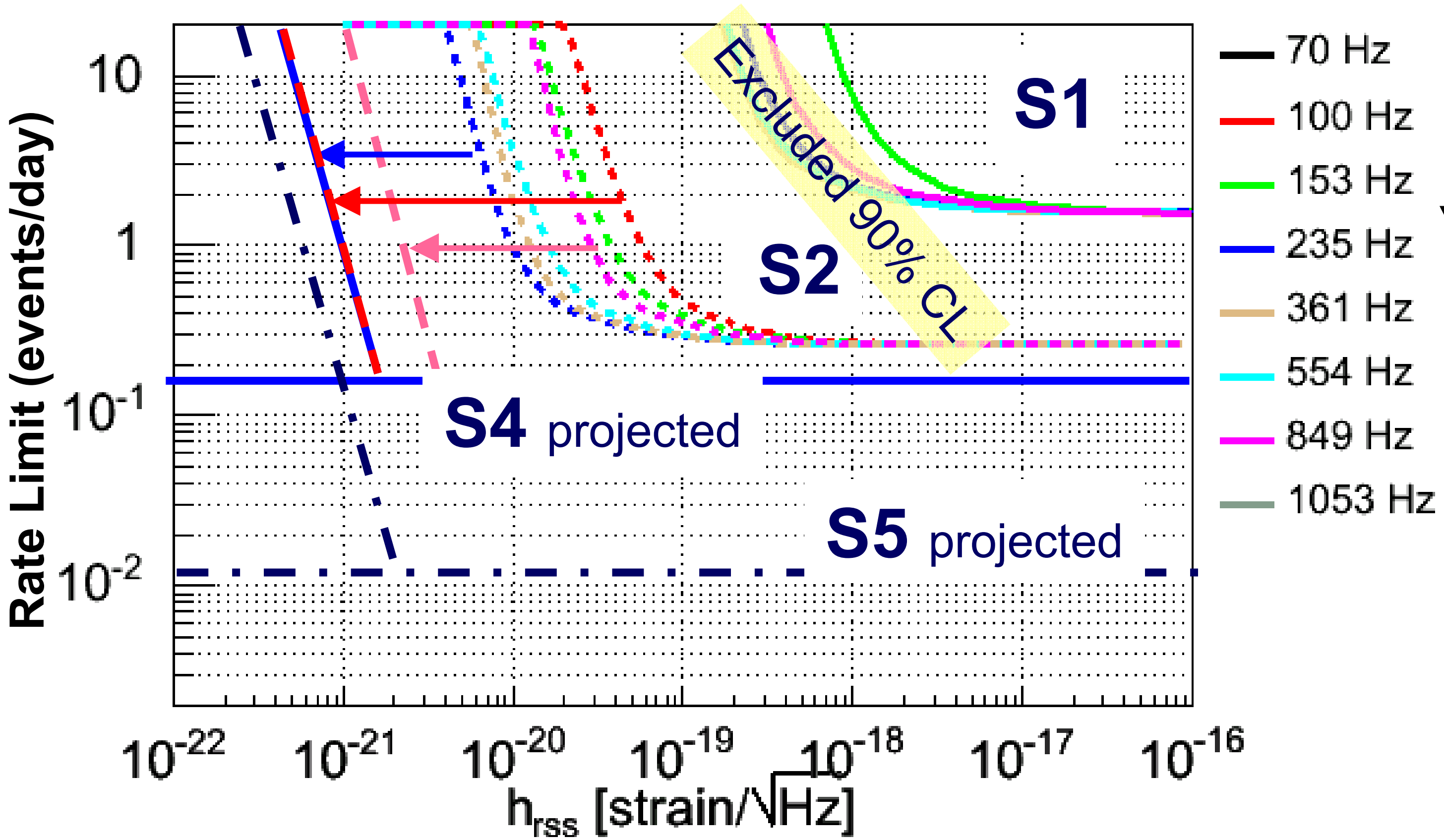
- Lack of signal models makes GWBs more difficult to detect.



SN 1987 A

Progress in Upper Limits

- No GWBs detected through S4.
- Set limits on GWB rate as a function of amplitude.

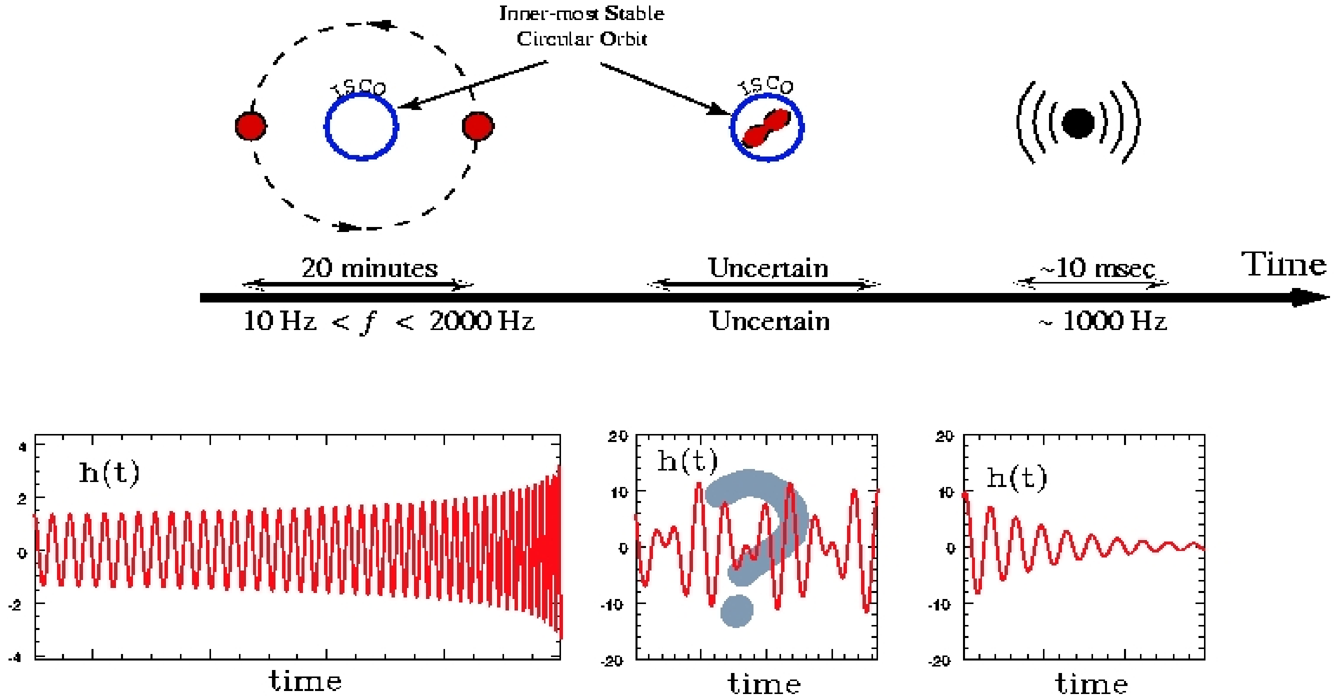


Lower rate limits from longer observation times

Lower amplitude limits from lower detector noise

Gravitational waves from compact binaries

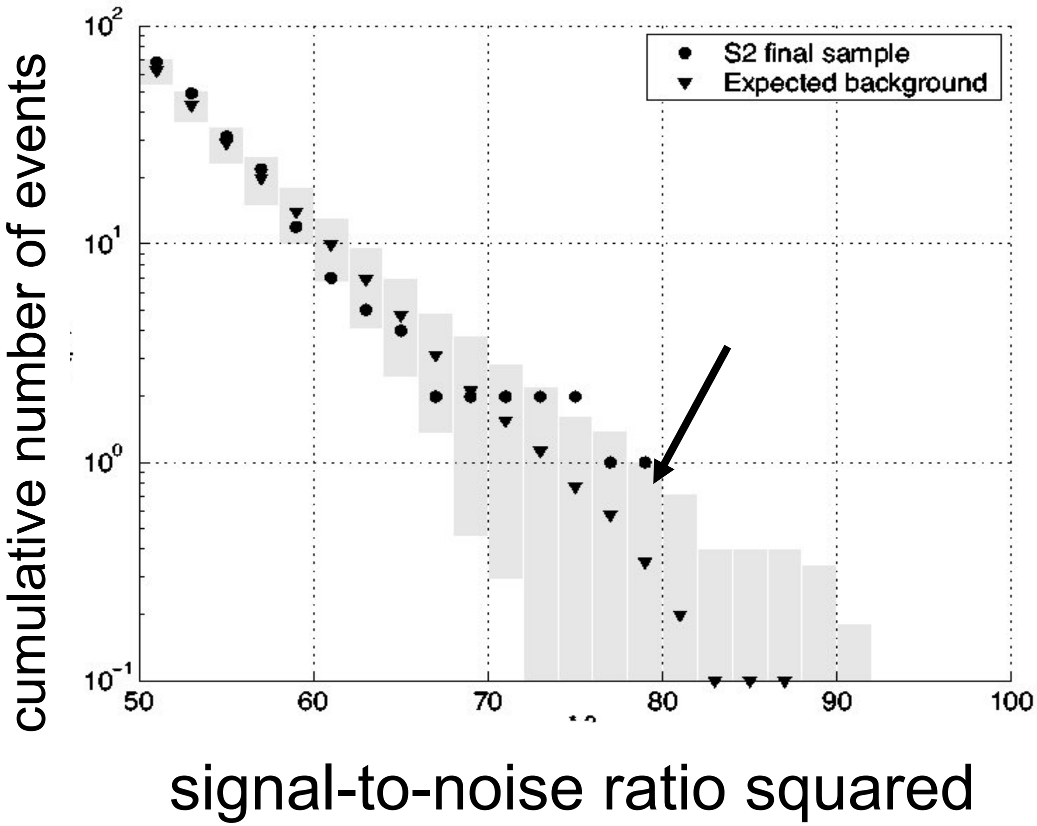
- LIGO is sensitive to gravitational waves from binary systems with neutron stars & black holes
  - Waveforms depend on masses and spins.
- Binary neutron stars
  - Estimates give upper bound of 1/3 yr in LIGO S5
- Binary black holes
  - Estimates give upper bound of 1/yr in LIGO S5



Binary Neutron Stars

S2 Observational Result

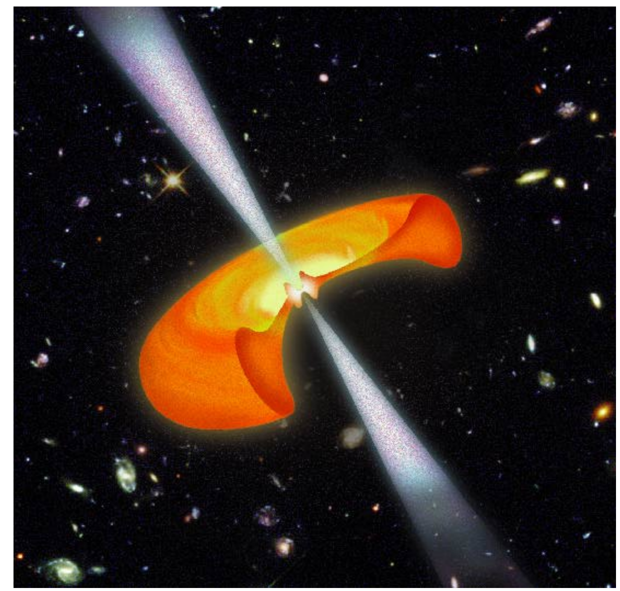
Phys. Rev. D. 72, 082001 (2005)



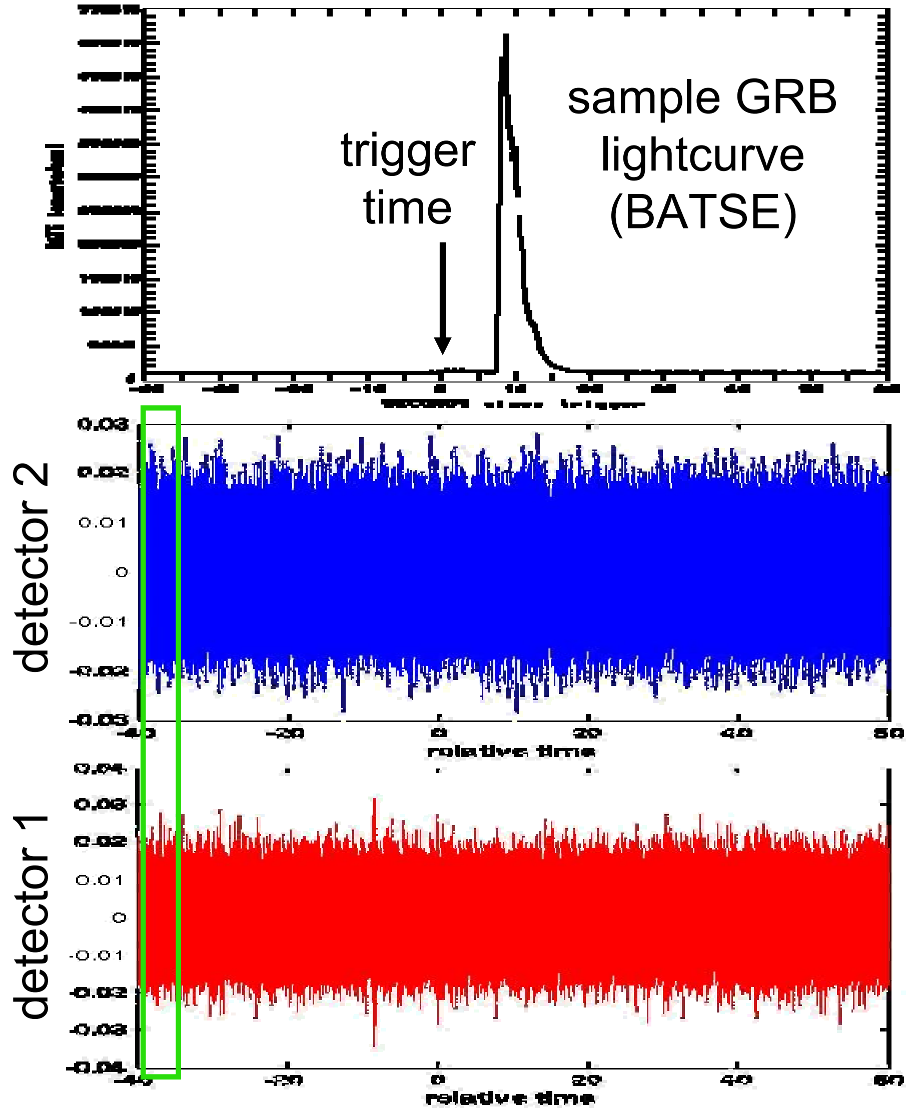
- S3 search
- Under internal review
  - 0.09 yr of data
  - ~3 Milky-Way like galaxies

  - S4 search complete
  - Under internal review
  - 0.05 yr of data
  - ~24 Milky-Way like galaxies

- Bright bursts of gamma rays
  - occur at cosmological distances
  - seen at rate ~1/day.
- Long duration > 2s
  - associated with "hypernovae" (core collapse to black hole)
  - Hjorth et al, Nature **423** 847 (2003).
  - Leonor/Sannibale,

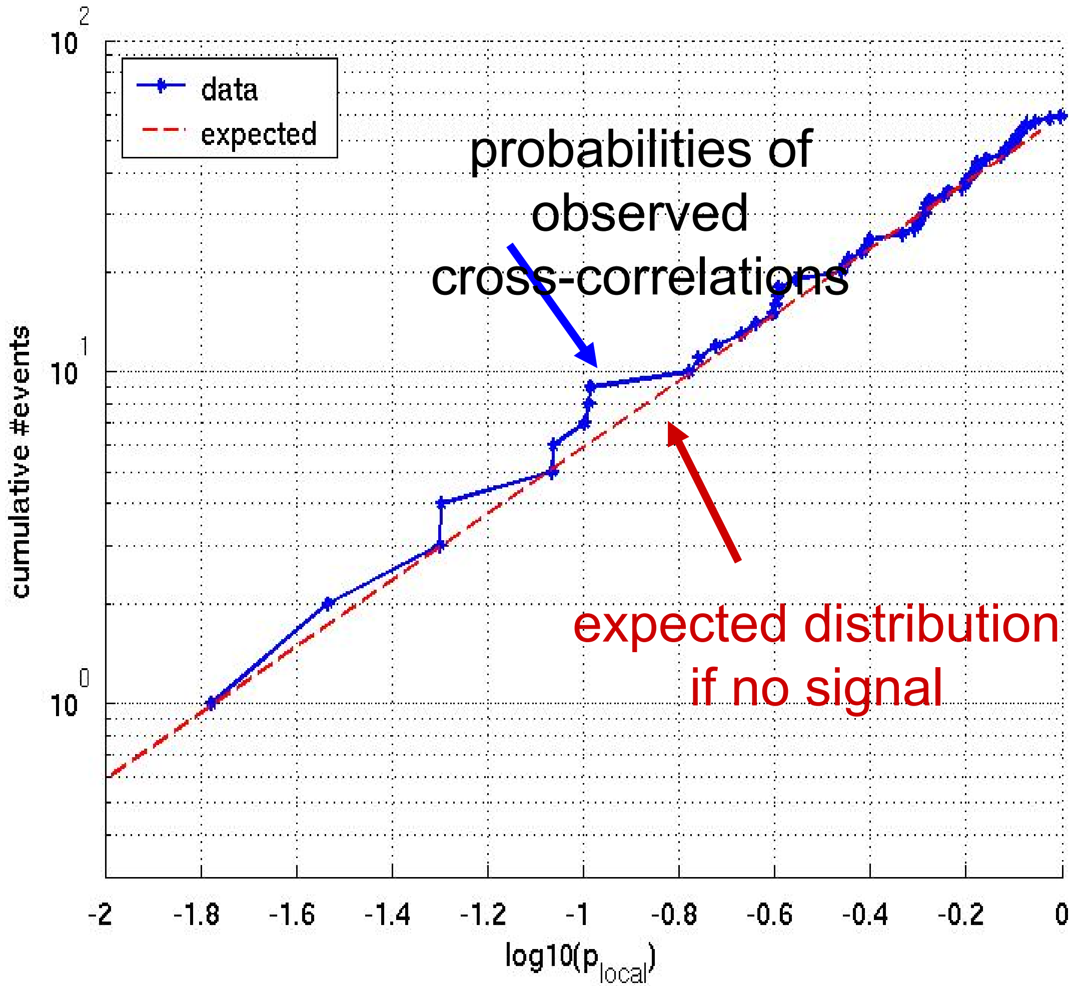


Strongly relativistic -
Interesting targets for LIGO!



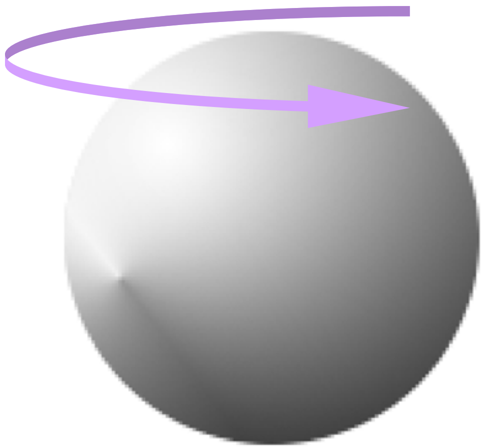
- Use triggers from satellites
  - Swift, HETE-2, INTEGRAL, IPN, Konus-Wind
  - Include both “short” and “long” GRBs
- Cross correlate data between pairs of detectors around time of event
  - 25 – 100 ms target signal duration
  - [-2,+1] min around GRB

- No loud signals seen so far.
- Look also for weak cumulative effect from population of GRBs.
  - Use binomial test to compare to uniform distribution.
- No significant deviation from



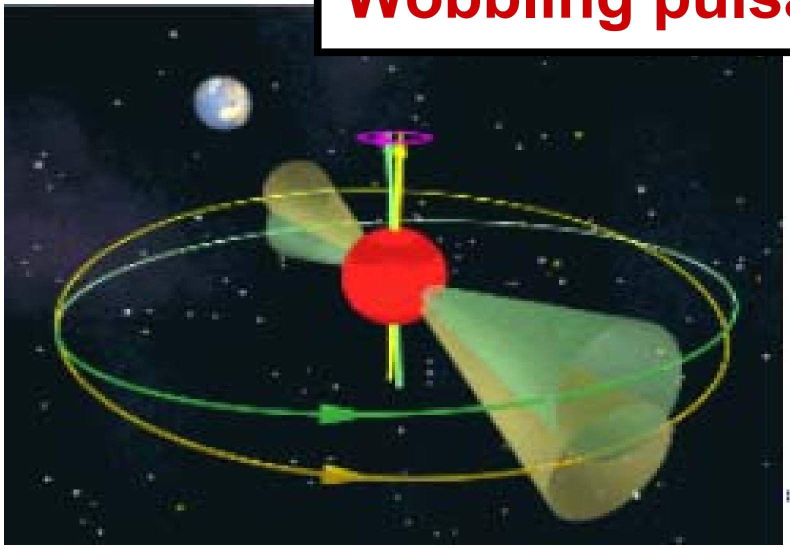
Leonor / Sannibale, Session W11

Continuous waves



Bumpy Neutron Star

Low-mass x-ray binary

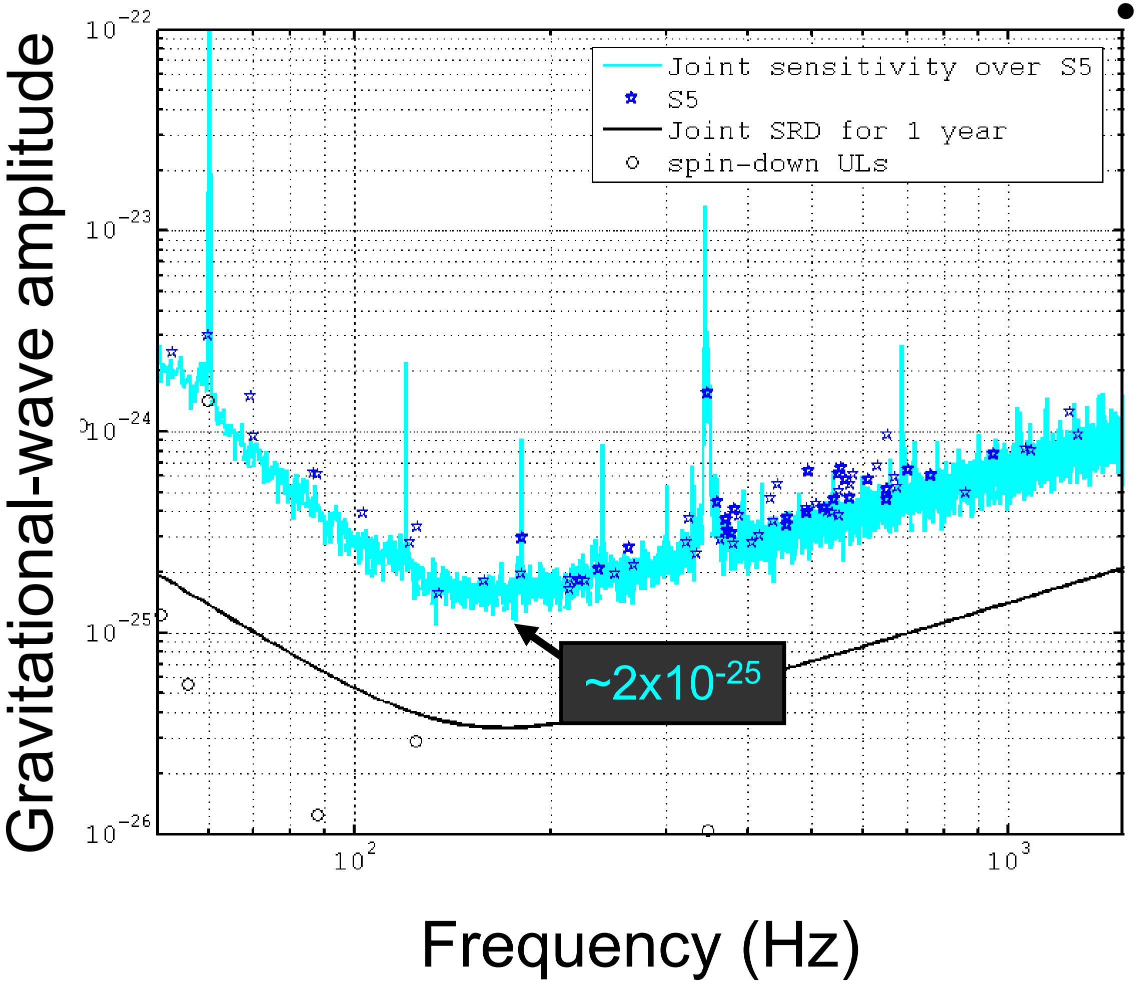


Wobbling pulsars

Credit: Dana Berry/NASA

Credit: M. Kramer

Known pulsars S5 preliminary

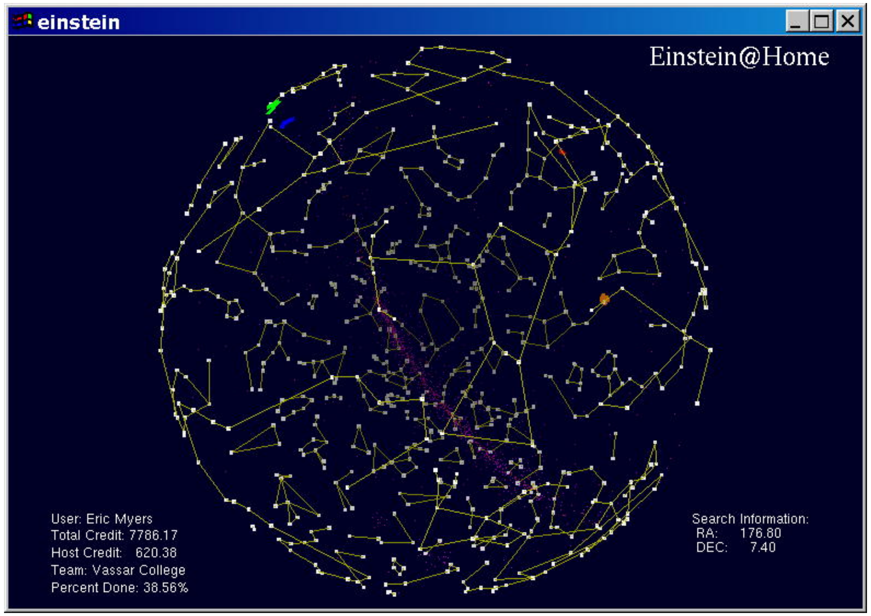


- 32 known isolated, 44 in binaries, 30 in globular clusters

Lowest ellipticity upper limit:
PSR J2124-3358
(f_{gw} = 405.6Hz, r = 0.25kpc)
ellipticity = 4.0×10^{-7}

Einstein@Home

To participate, sign up at
http://www.physics2005.org



- S3 results:
  - No evidence of pulsars
- S4 search
  - Underway

- Matched-filtering for continuous GWs
- All-sky, all-frequency search
  - computationally limited
- Aiming at detection, not upper limits
- Public outreach distributed computing

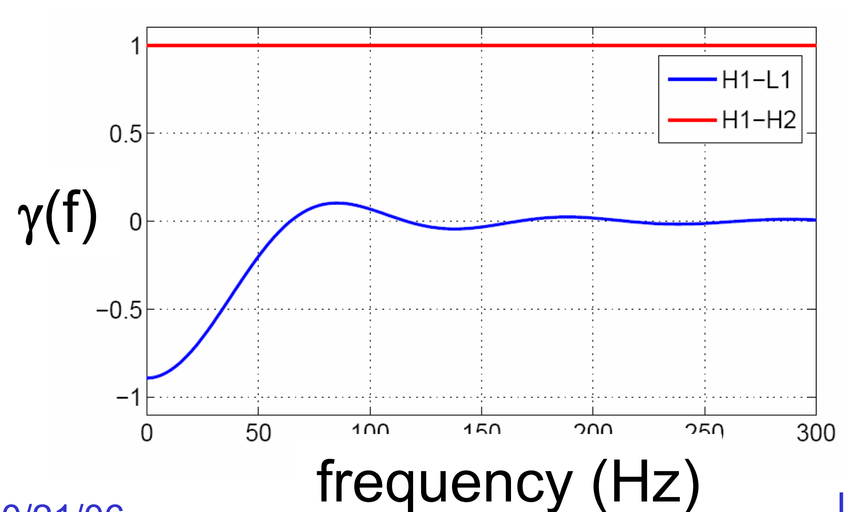
Stochastic Background

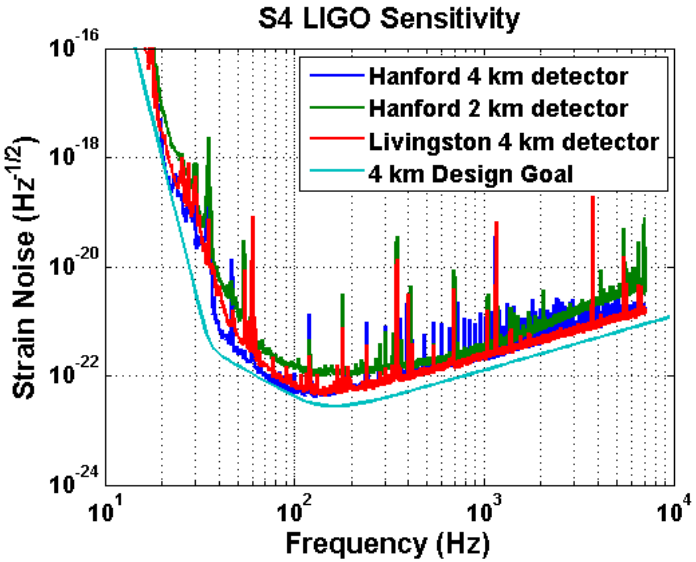
- Cross-correlate two data streams x_1 and x_2
- For isotropic search optimal statistic is

$$Y = \int_{-\infty}^{\infty} df \, \tilde{x}_1^*(f) \frac{\gamma(f)\,\Omega_{GW}(f)}{N f^3 \, P_1(f)\, P_2(f)} \tilde{x}_2(f)$$

"Overlap Reduction Function"
(determined by network geometry)

Detector noise spectra

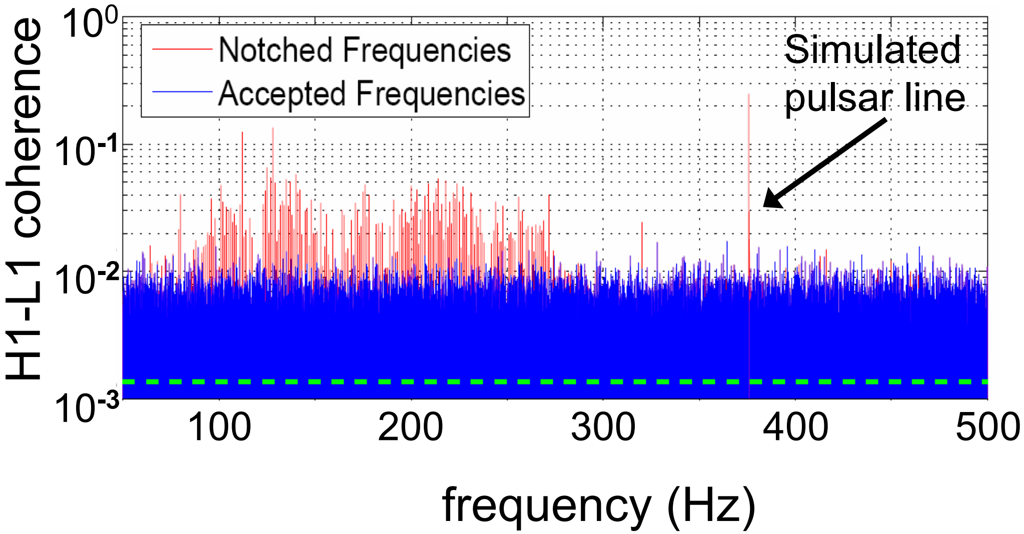




Technical Challenges

- Digging deep into instrumental noise looking for small correlations.
- Need to be mindful of possible non-GW correlations
  - » common environment (two Hanford detectors)
  - » common equipment (could affect any detector pair!)

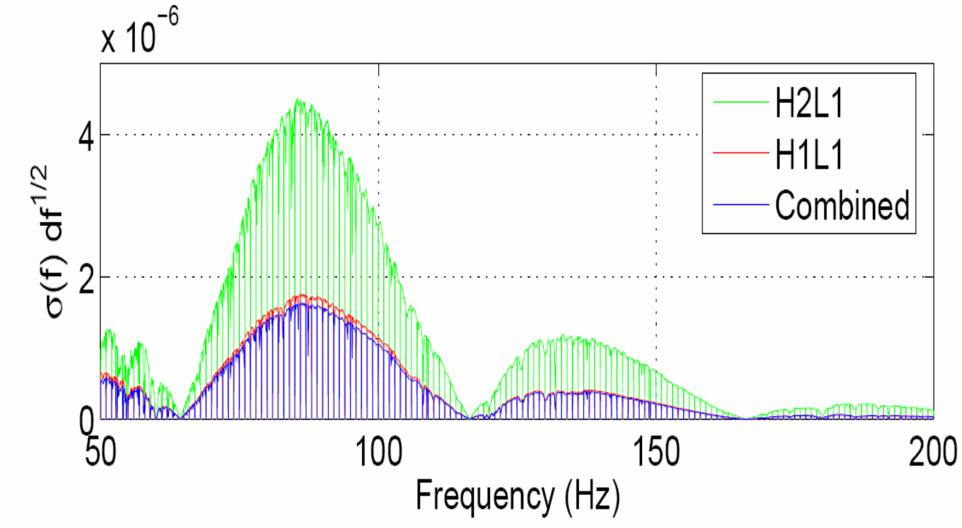
- Example:
  - » Correlations at harmonics of 1 Hz.
  - » Due to GPS timing system.
  - » Lose ~3% of the total bandwidth (1/32 Hz resolution).



S4 Analysis Details

- Cross-correlate Hanford-Livingston
  - » Hanford 4km – Livingston
  - » Hanford 2km – Livingston
  - » Weighted average of two cross-correlations (new in S4).
  - » Do not cross-correlate the Hanford detectors.

S4: Sensitivity vs Frequency

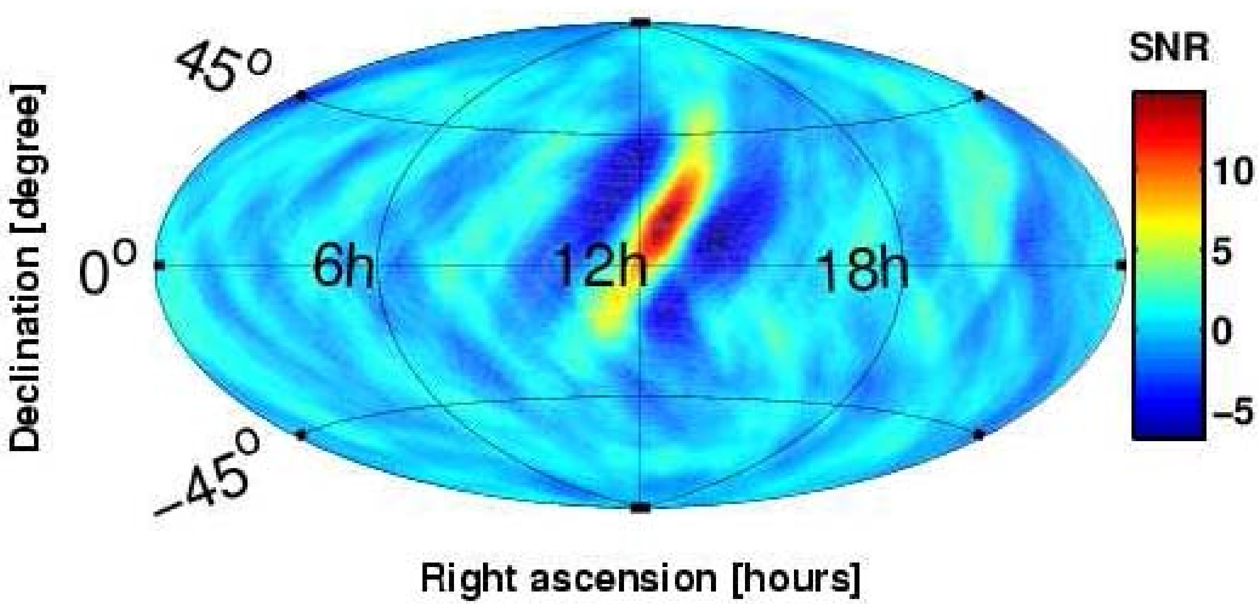


- Data quality:
  - » Drop segments when noise changes quickly (non-stationary).
  - » Drop frequency bins showing instrumental correlations (harmonics of 1 Hz, bins with pulsar injections).

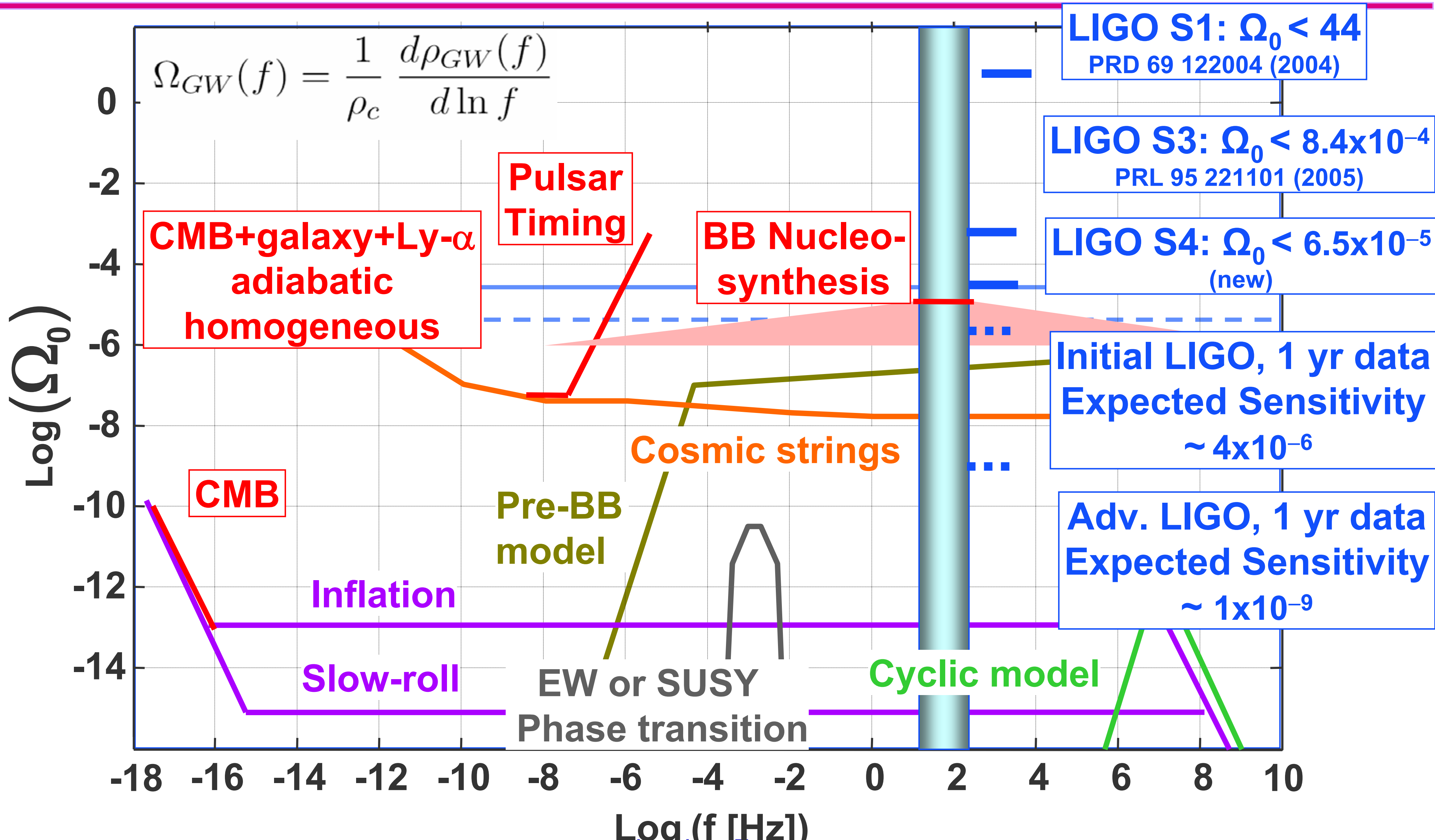
- Bayesian UL: $\Omega_{90\%} = 6.5 \times 10^{-5}$
  - » Use S3 posterior distribution for S4 prior.
  - » Marginalized over calibration uncertainty with Gaussian prior (5% for L1, 8% for H1 and H2).

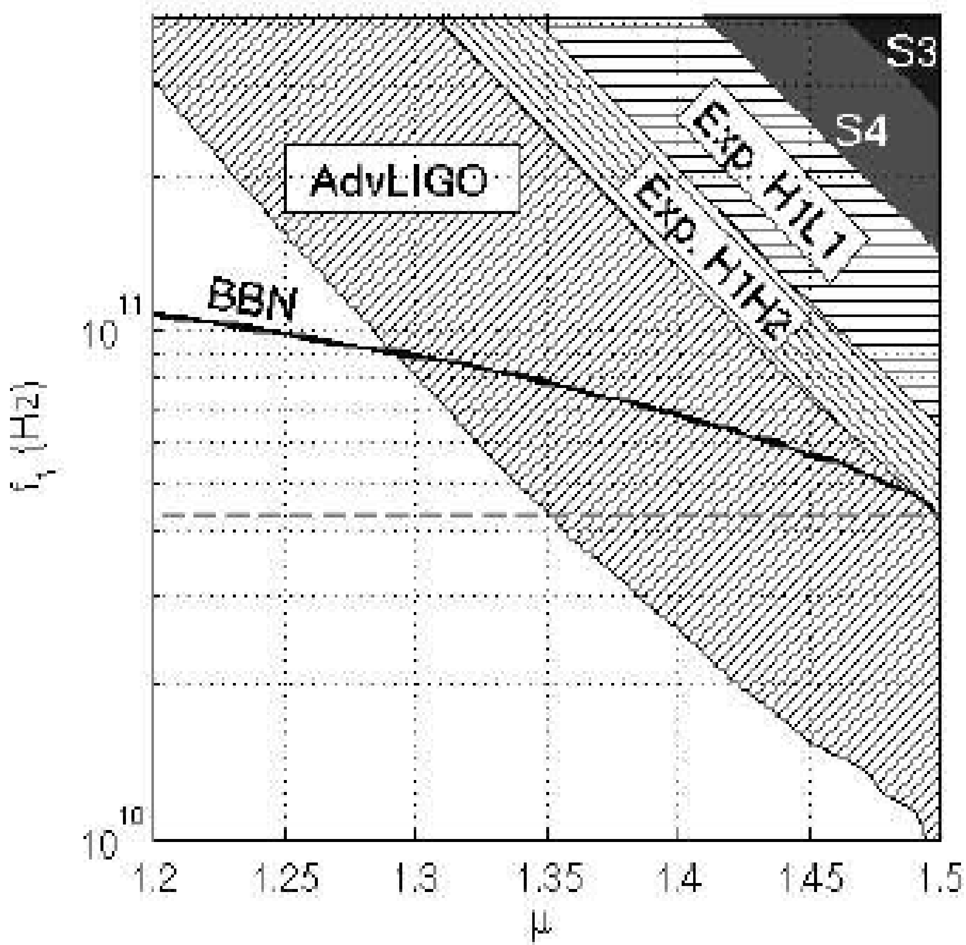
Radiometer: Proof-of-Principle

- Analysis of a simulated point source at the position of the Virgo galaxy cluster (12.5h,12.7⌖).
  - » simulated H1-L1 data

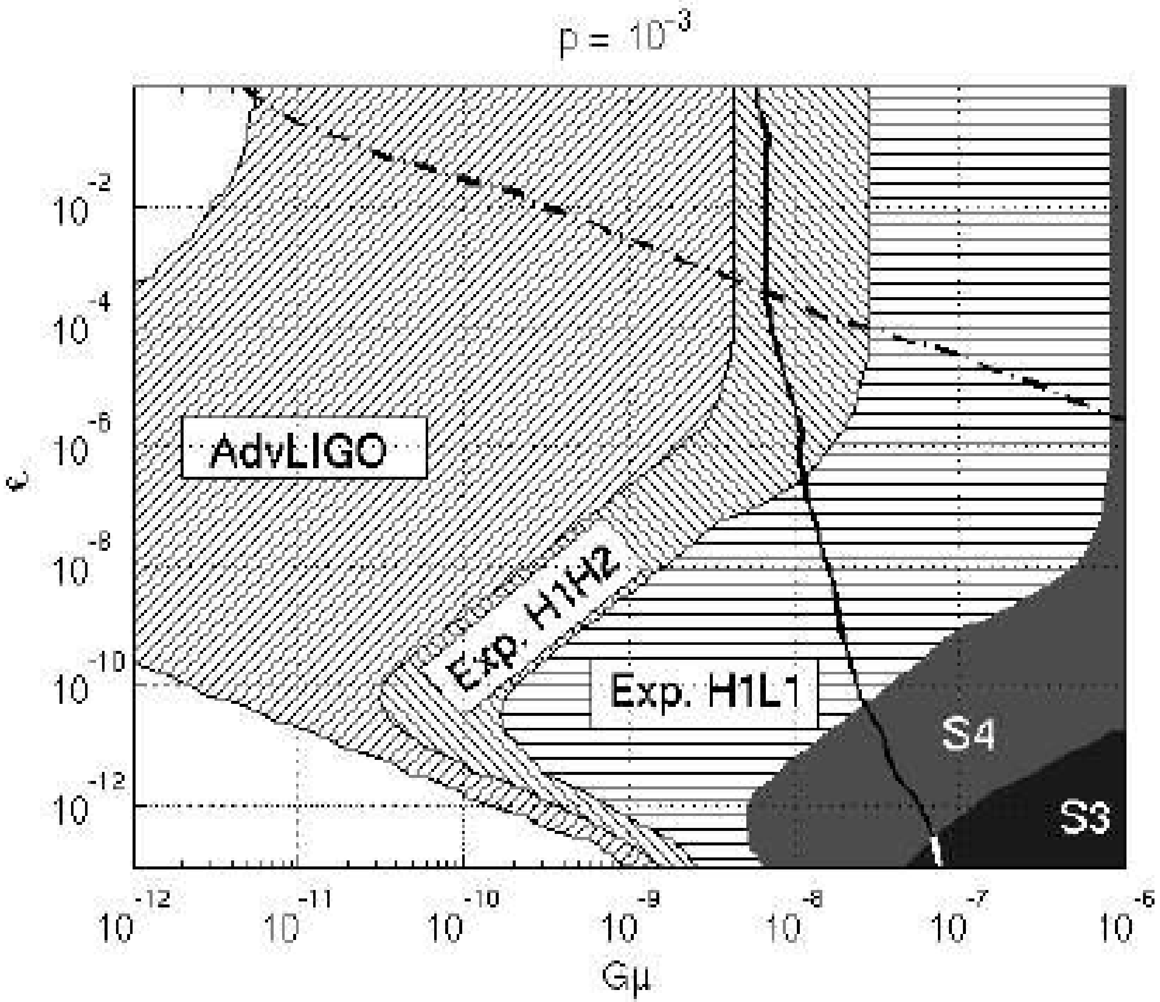


Predictions and Limits

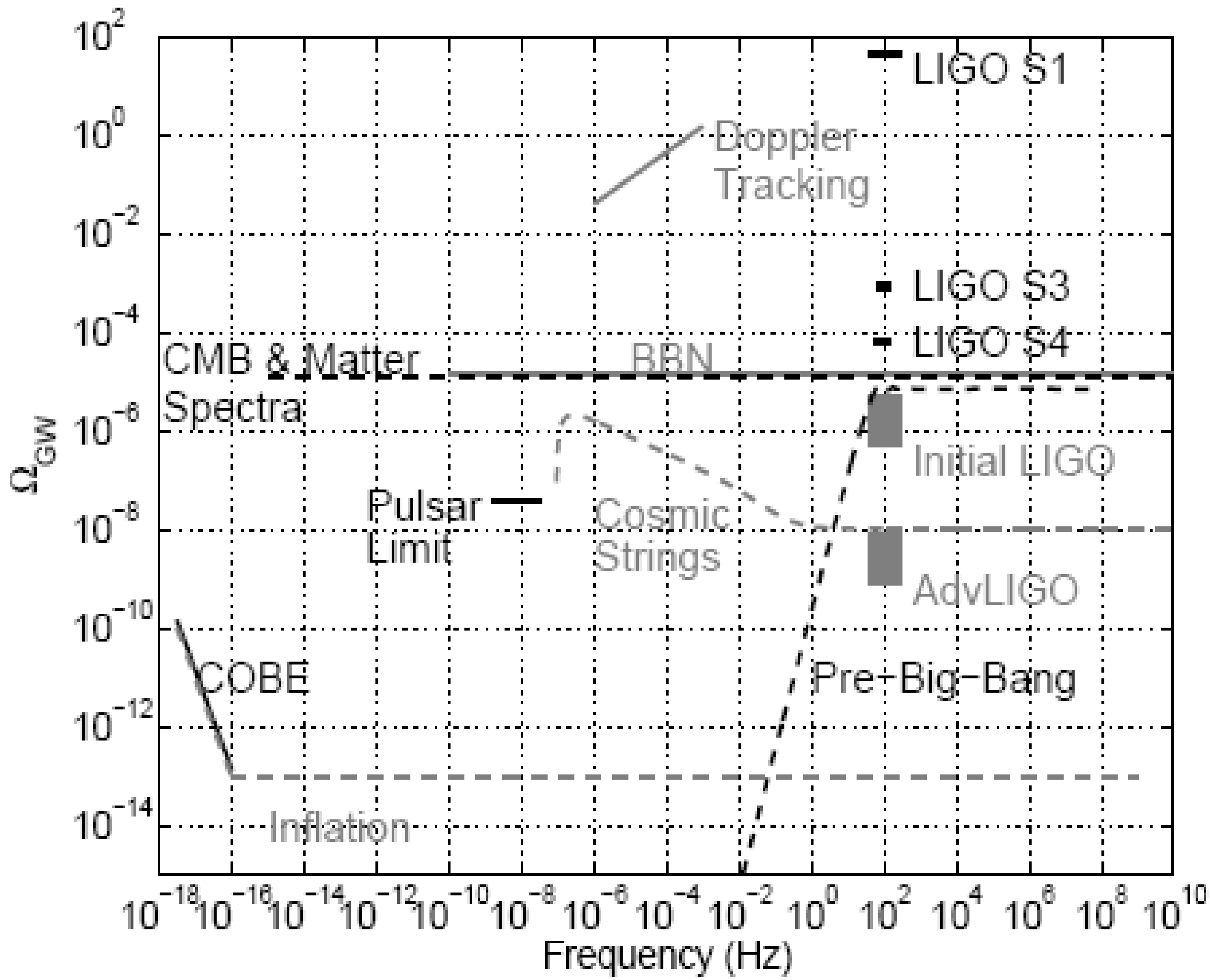




S3
S4
Exp. H1L1
Exp. H1H2
AdvLIGO
BBN
f_1 (Hz)
10^{11}
10^{10}
1.2
1.25
1.3
1.35
1.4
1.45
1.5
μ



p = 10^-3
AdvLIGO
Exp. H1H2
Exp. H1L1
S4
S3
ε
Gμ



LIGO S1
Doppler Tracking
LIGO S3
LIGO S4
CMB & Matter Spectra
BBN
Initial LIGO
Pulsar Limit
Cosmic Strings
AdvLIGO
COBE
Pre-Big-Bang
Inflation
Ω_{GW}
Frequency (Hz)