The Laser Interferometer Gravitational Wave Observatory

LIGO: Status of operation at design sensitivity and future prospects

Albert Lazzarini

Deputy Director, LIGO Laboratory
Representing the LIGO Scientific Collaboration

Physics Colloquium
University of Mississippi, Oxford, MS

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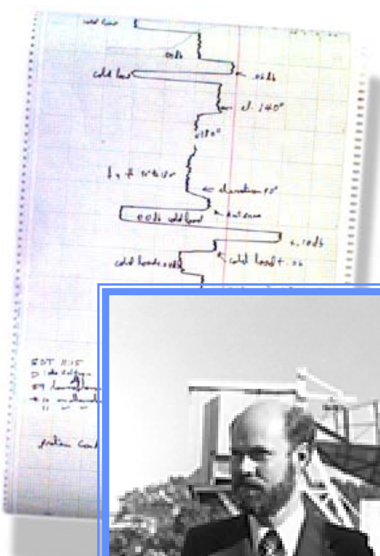
Outline of this talk

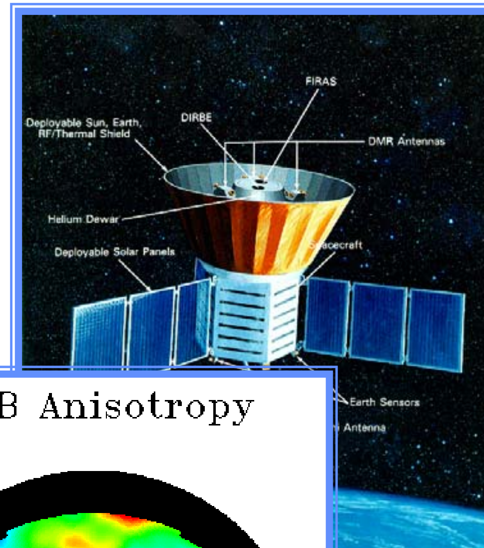
- Background
  - Relativity and gravitational waves
  - Sources of gravitational waves
  - Interferometers as detectors of gravitational waves
- Current Status
  - LIGO performance
  - Science results from recent science runs
- Prospects
  - Enhancements (2008 - 2010)
  - Advanced LIGO (2014+)
  - Outreach

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)





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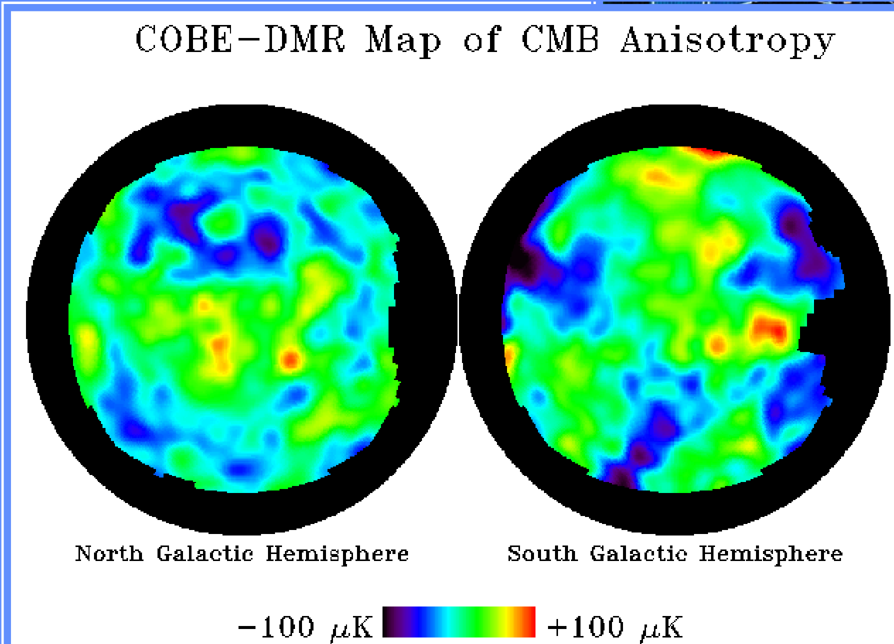
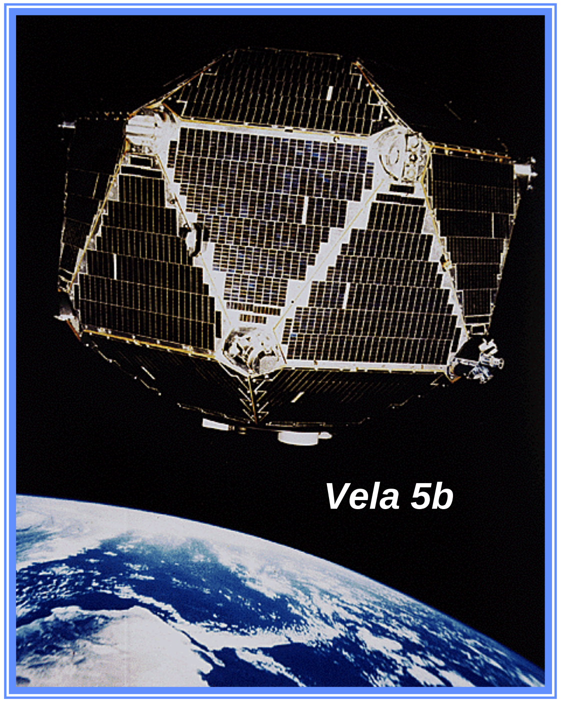
http://www.lucent.com/museum/1964bang.html



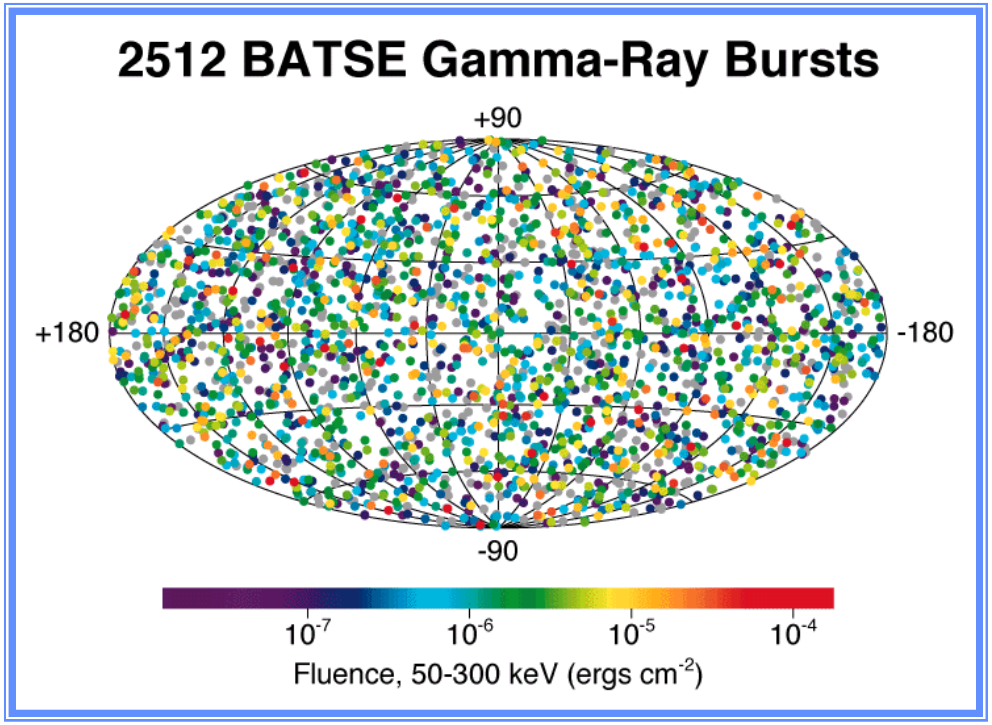
The Opening of New Observational Windows on the Universe

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



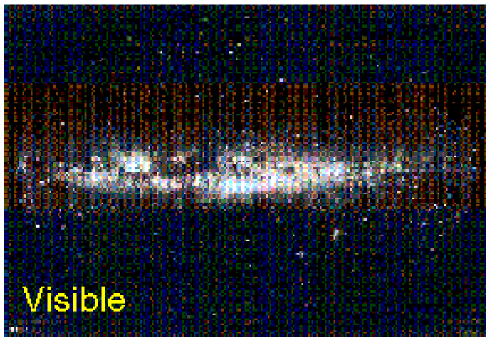
http://science.msfc.nasa.gov/newhome/headlines/ast19sep97_2.htm

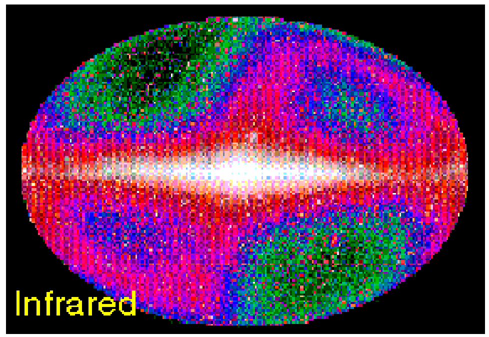


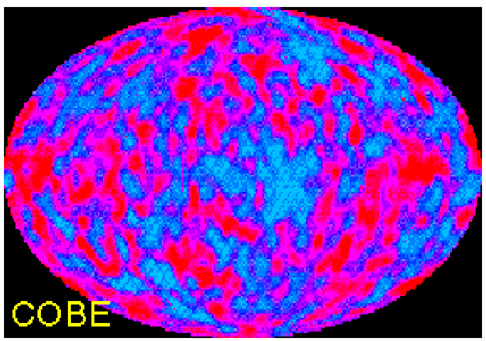
http://www.batse.com/

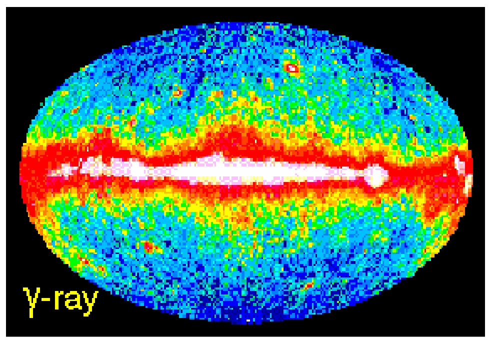
Opening of a New Window on Universe

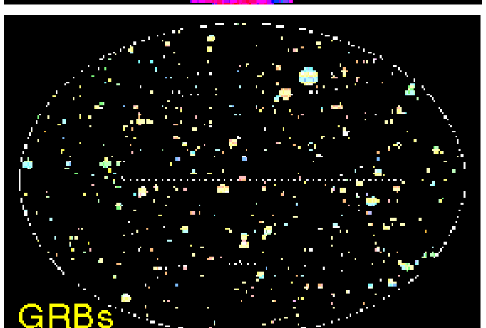
New messengers may bring new surprises!

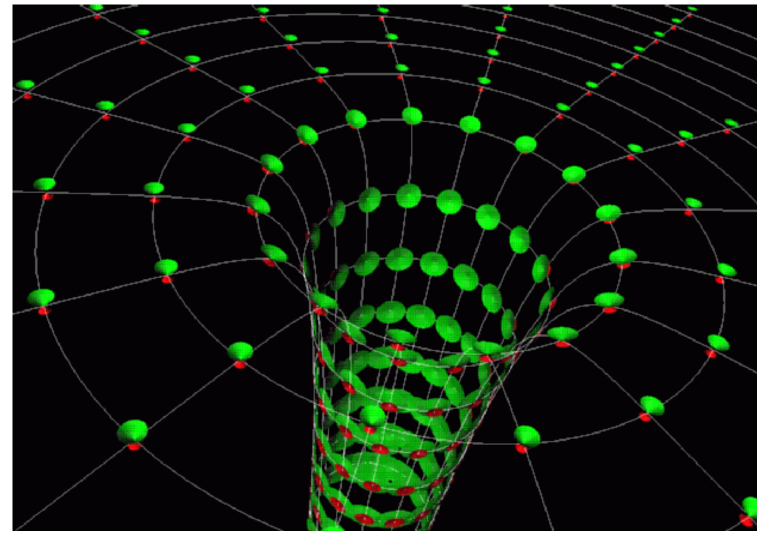










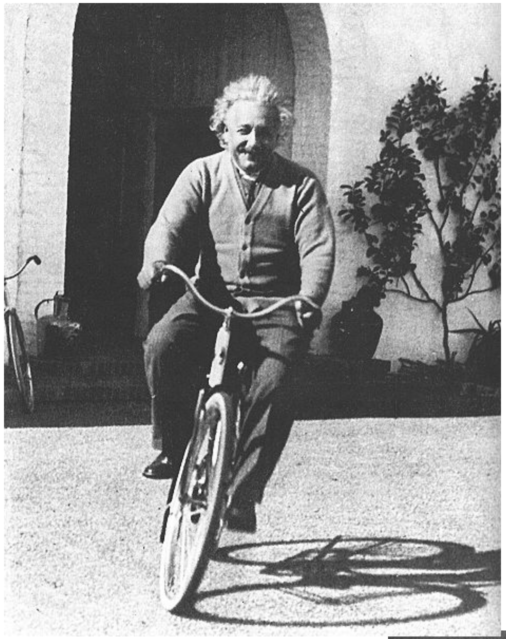


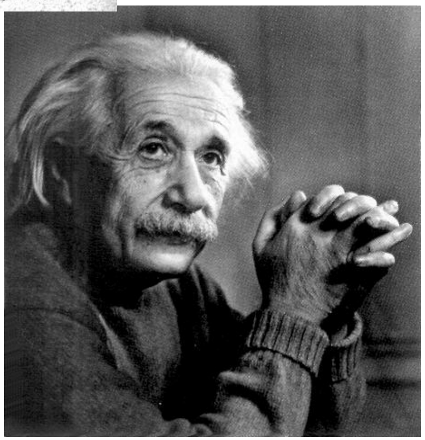
GRAVITATIONAL WAVES WILL GIVE A NEW AND UNIQUE VIEW OF THE DYNAMICS OF THE UNIVERSE.

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*

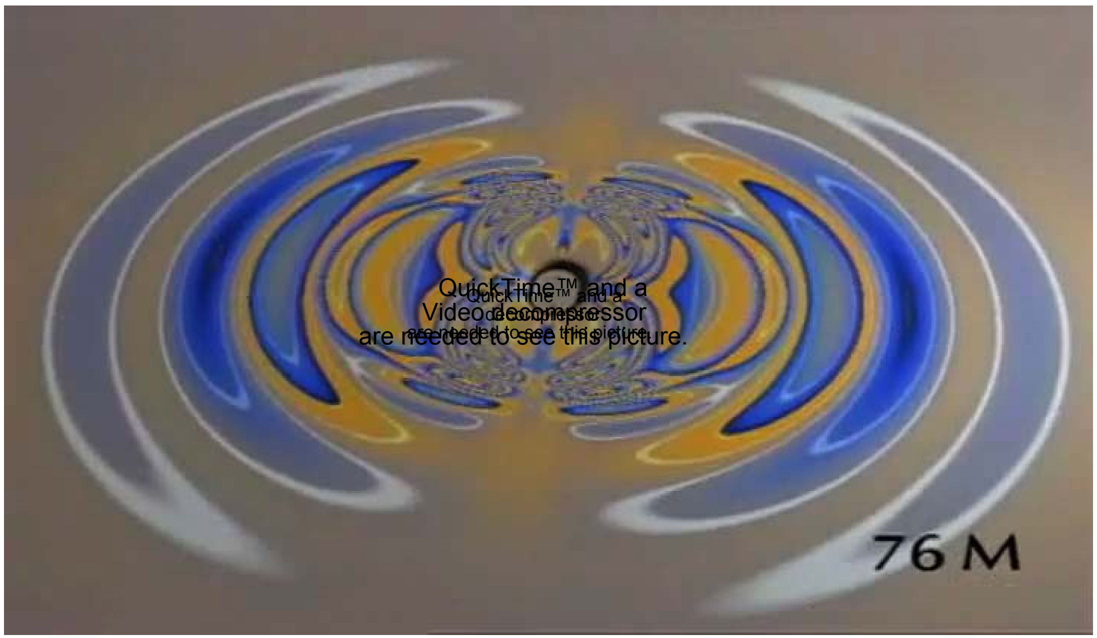
- The General Theory of Relativity and theory of Gravity (1916)
  - Gravity described as a warpage of spacetime, not a force acting at a distance
  - Finite propagation of influence of gravity
    - *Gravitational radiation*

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



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

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

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

$$|\dot{E}| \approx 6 \times 10^{46} W; \; R_{Virgo} = 17Mpc$$

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

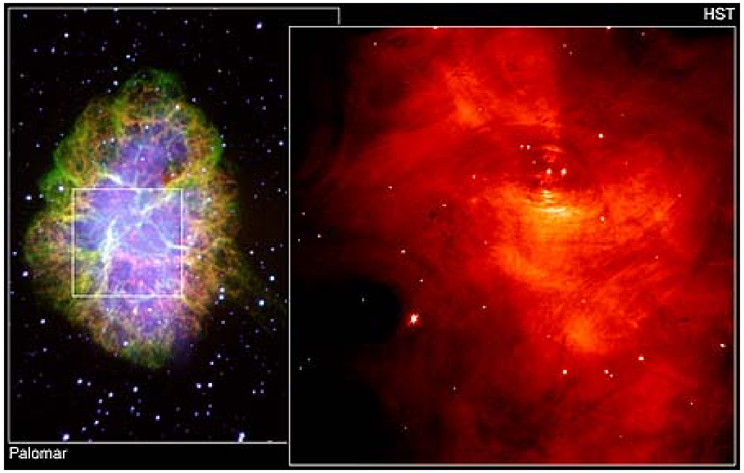
Luminosity is huge…
Solar luminosity: 4 x 10^{26} W
… but …
spacetime is VERY stiff …
***Effect:** __TINY__!!!*

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

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

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

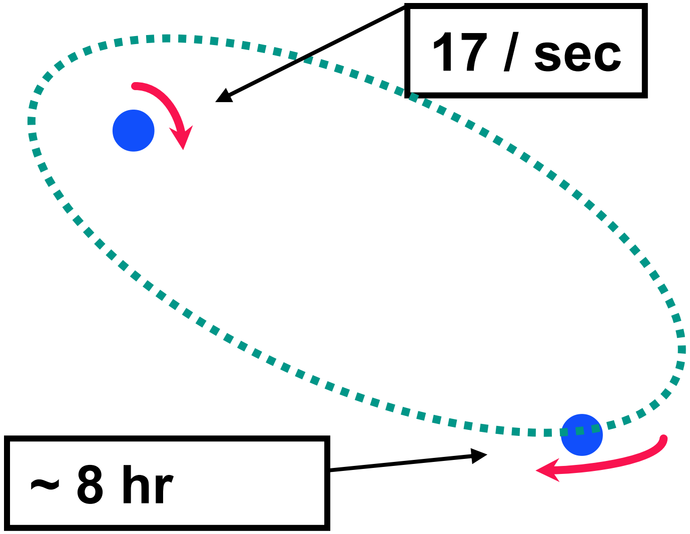
Indirect Evidence



Neutron Binary System

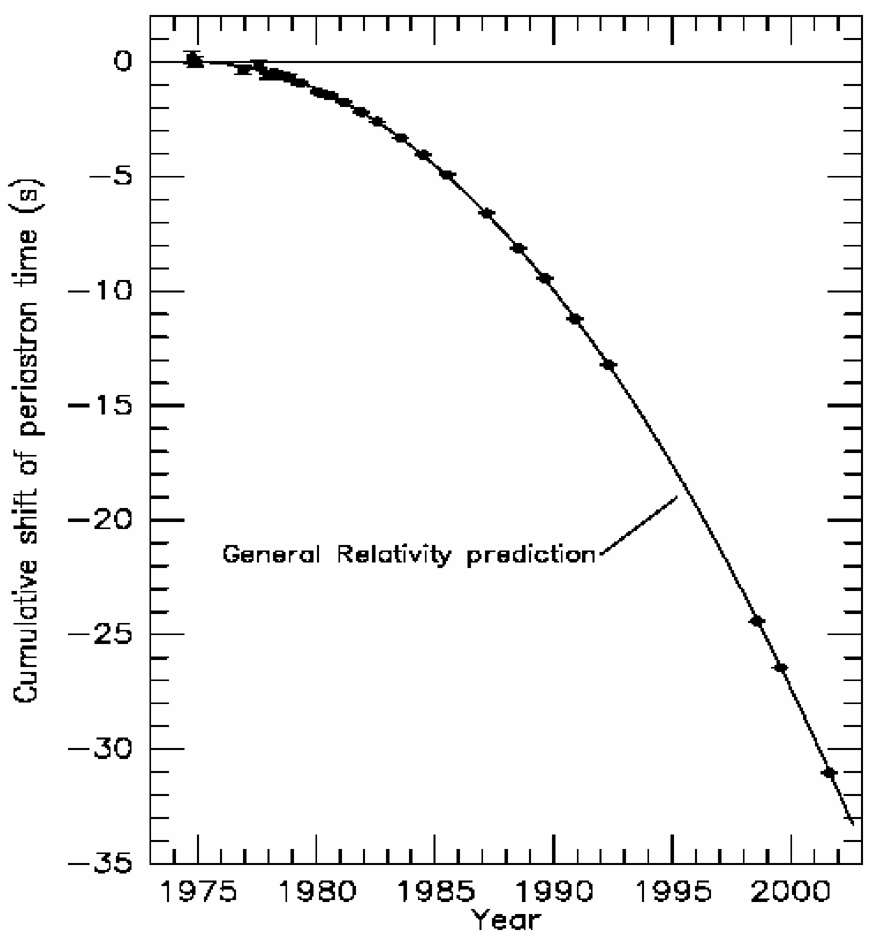
PSR 1913 + 16 -- Timing of pulsars

ref: *Weisberg & Taylor gr-qc/0407149*



Notable Binary Neutron Star Systems

- PSR B1913+16
  - Hulse and Taylor, 1974 *ApJ* ***195***, *L51*
  - Masses: 1.44 $M_\odot$, 1.39 $M_\odot$
  - Orbital decay exactly matches prediction from gravitational wave emission
  - Will coalesce in ~300 Myr



Weisberg & Taylor, astro-ph/0211217

- ***PSR J0737-3039*** NEW!
  - Burgay *et al.*, 2003 *Nature* ***426***, *531*
  - Orbital period = 2.4 hours
  - Will coalesce in ~85 Myr
  - Will yield improved tests of G.R.

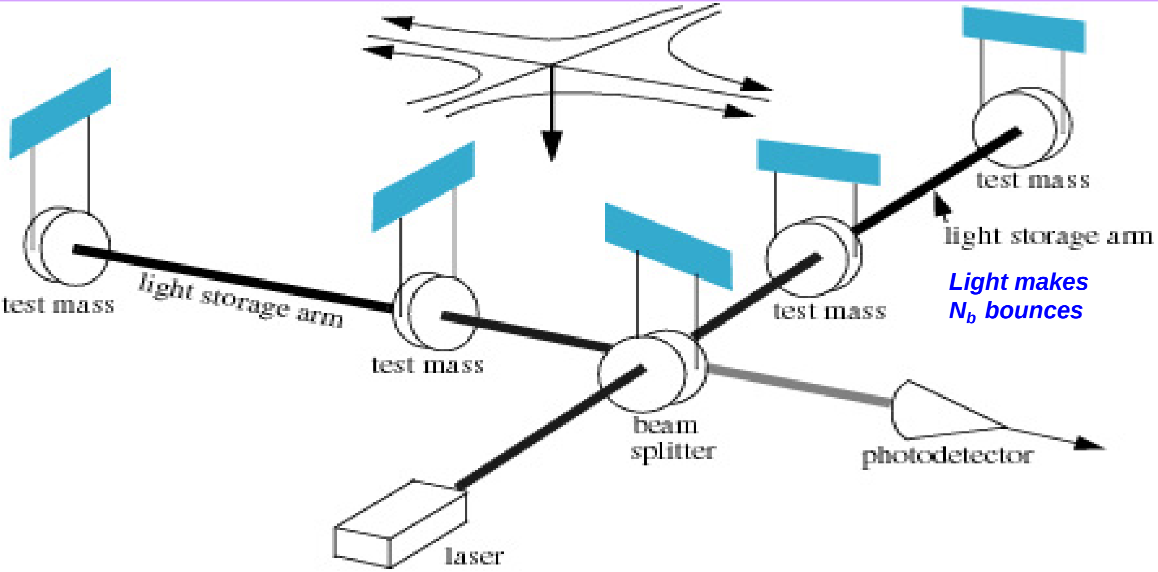
Ultimate Goals for the Detection of Gravitational Waves

- Tests of Physics & Relativity
  - Black holes & strong-field gravity (ring down of excited BH)
  - Spin character of the radiation field (polarization of radiation from CW sources)
  - Wave propagation speed (delays in arrival time of bursts)
  - Merger of neutron stars provides insight into the physics of matter at nuclear densities

- Gravitational Wave Astronomy
  - Compact binary inspirals
  - Gravitational waves and gamma ray burst associations
  - Black hole formation
  - Supernovae in our galaxy
  - Newly formed neutron stars - spin down in the first year
  - Pulsars and rapidly rotating neutron stars
  - Low-Mass X-Ray Binaries (LMXBs)
  - Stochastic GW background

Interferometers as precision strain meters

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



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

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.

LIGO Observatories

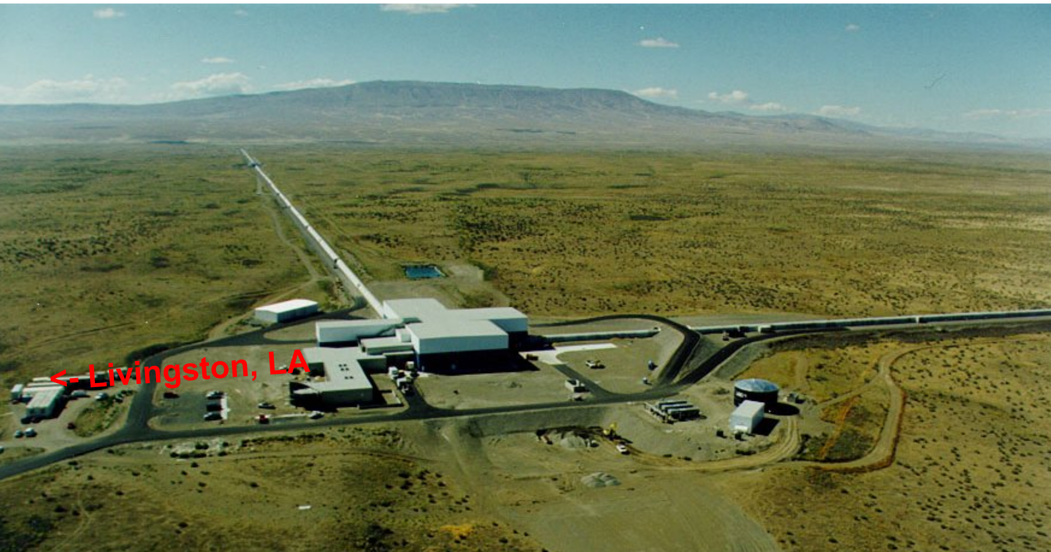
GEODETIC DATA (WGS84)

h: -6.574 m ***X arm: S72.2836°W***

ϕ: N30°33'46.419531" ***Y arm: S17.7164°E***

λ: W90°46'27.265294"

Livingston Observatory
Louisiana
One interferometer (4km)



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

GEODETIC DATA (WGS84)

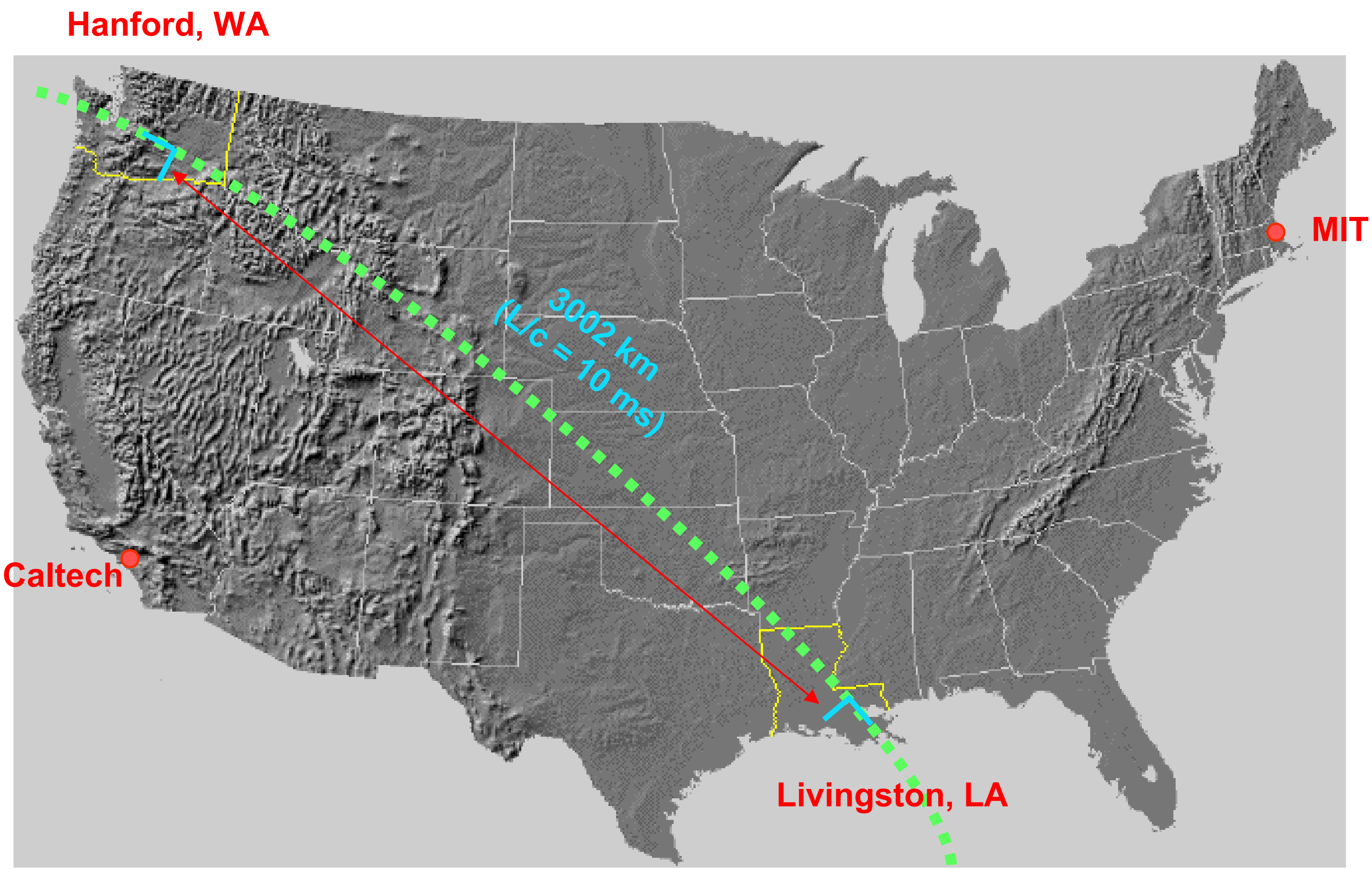
h: 142.555 m ***X arm: N35.9993°W***

ϕ: N46°27'18.527841" ***Y arm: S54.0007°W***

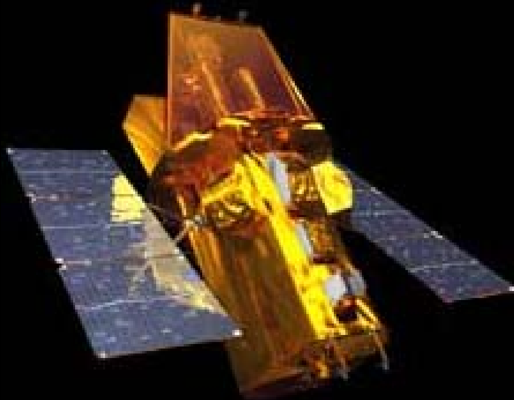
λ: W119°24'27.565681"

The LIGO Laboratory Sites

Interferometers are aligned along the great circle connecting the sites

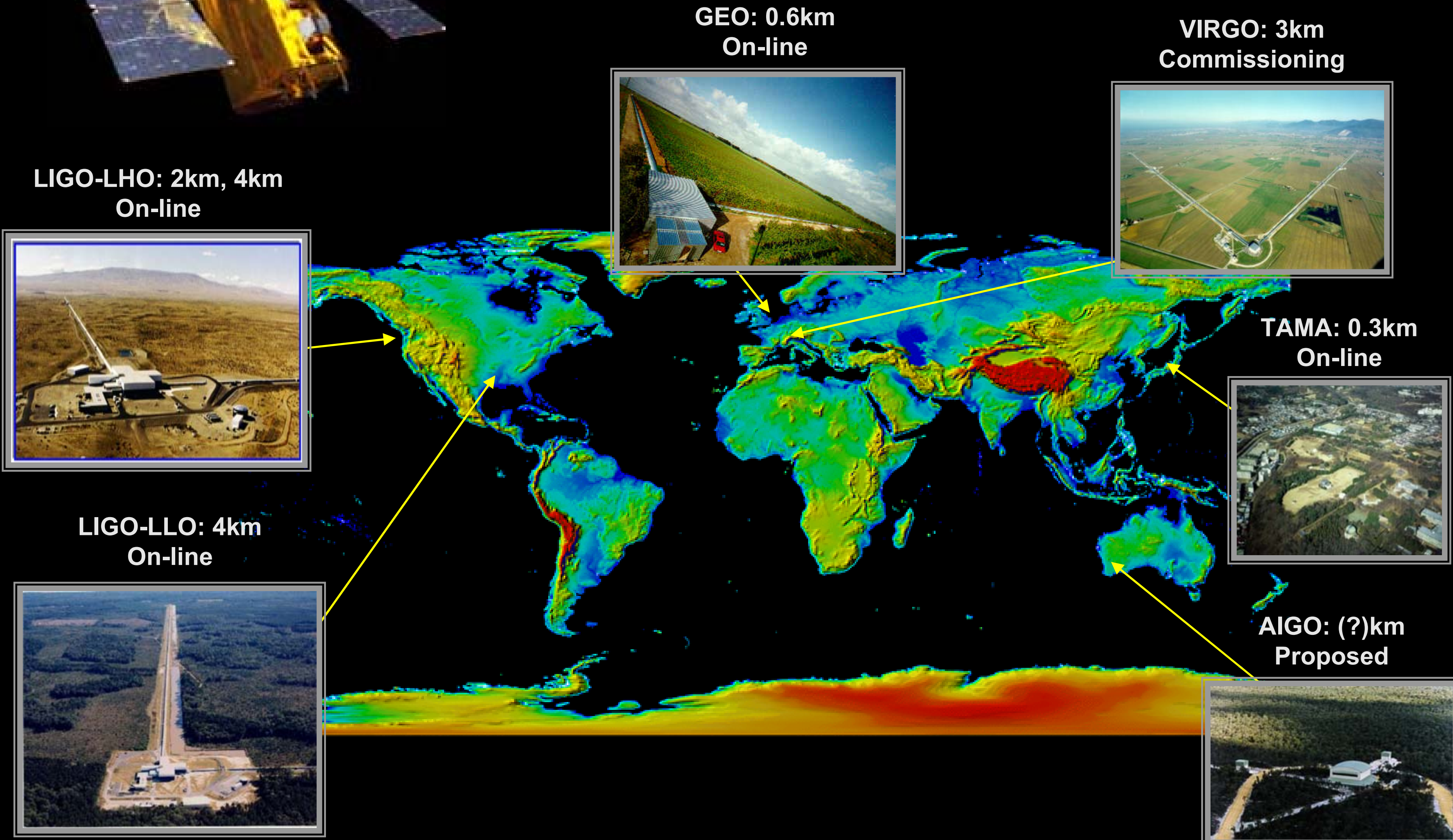


Growing International Network of GW Interferometers



Operated as a phased array:

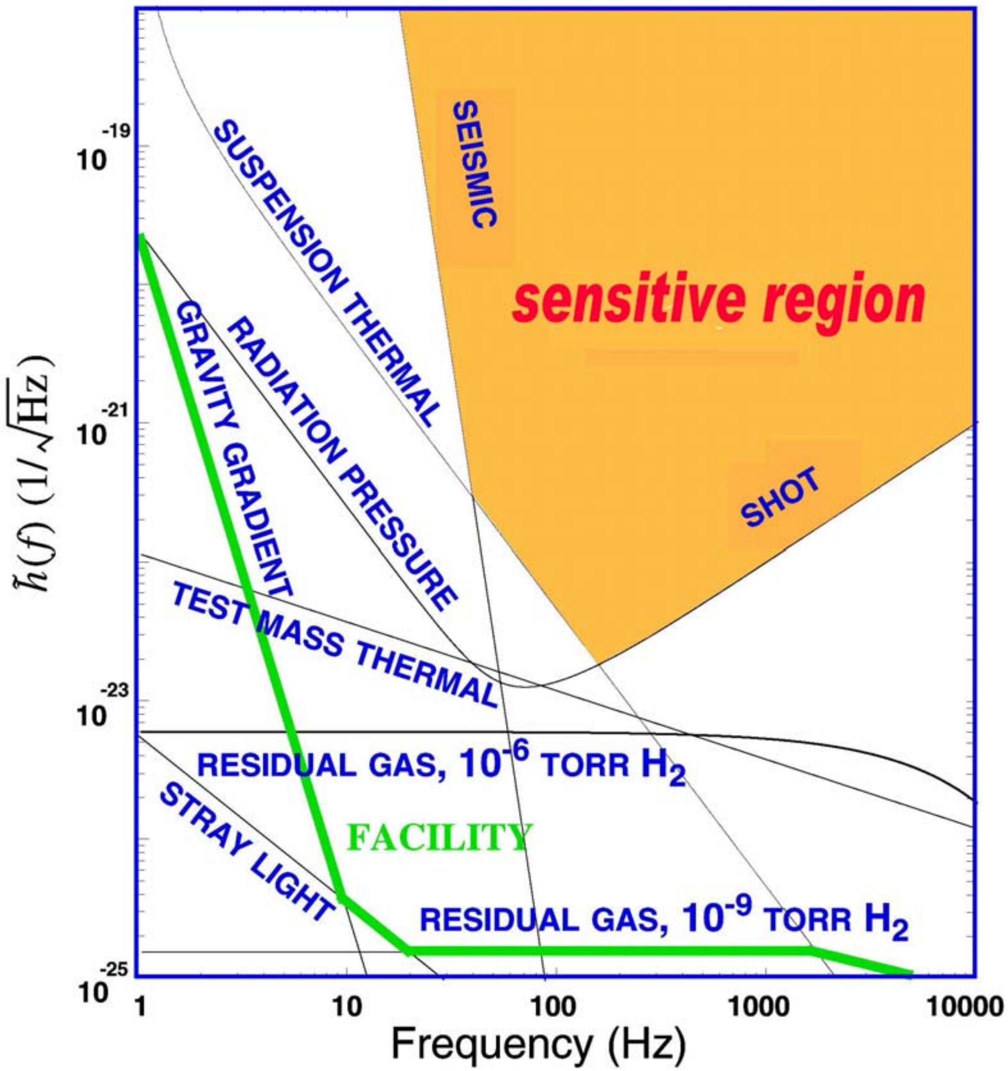
- Enhance detection confidence
- Localize sources
- Decompose the polarization of gravitational waves
- Triggers from EM detectors



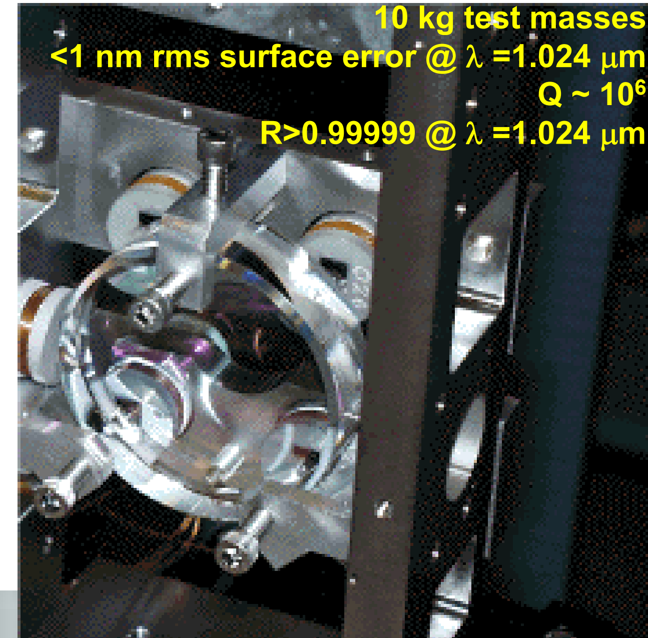
LIGO First Generation Detector

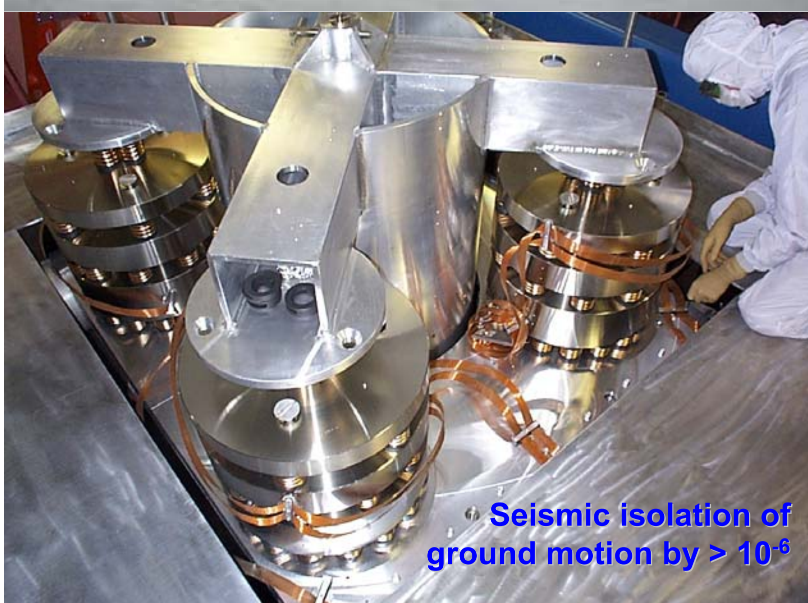
Limiting noise floor

- **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**

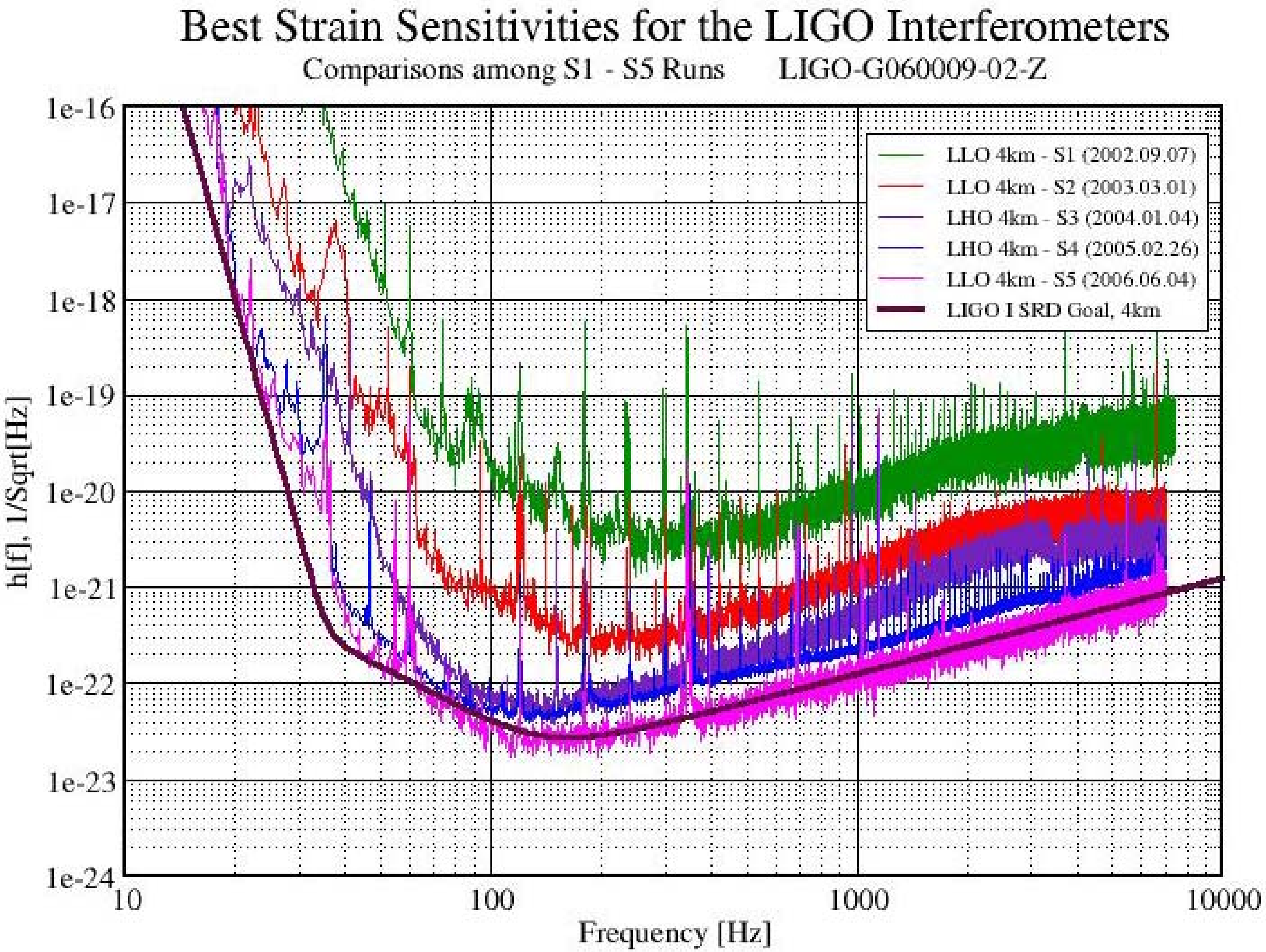


Interferometric GW Detectors

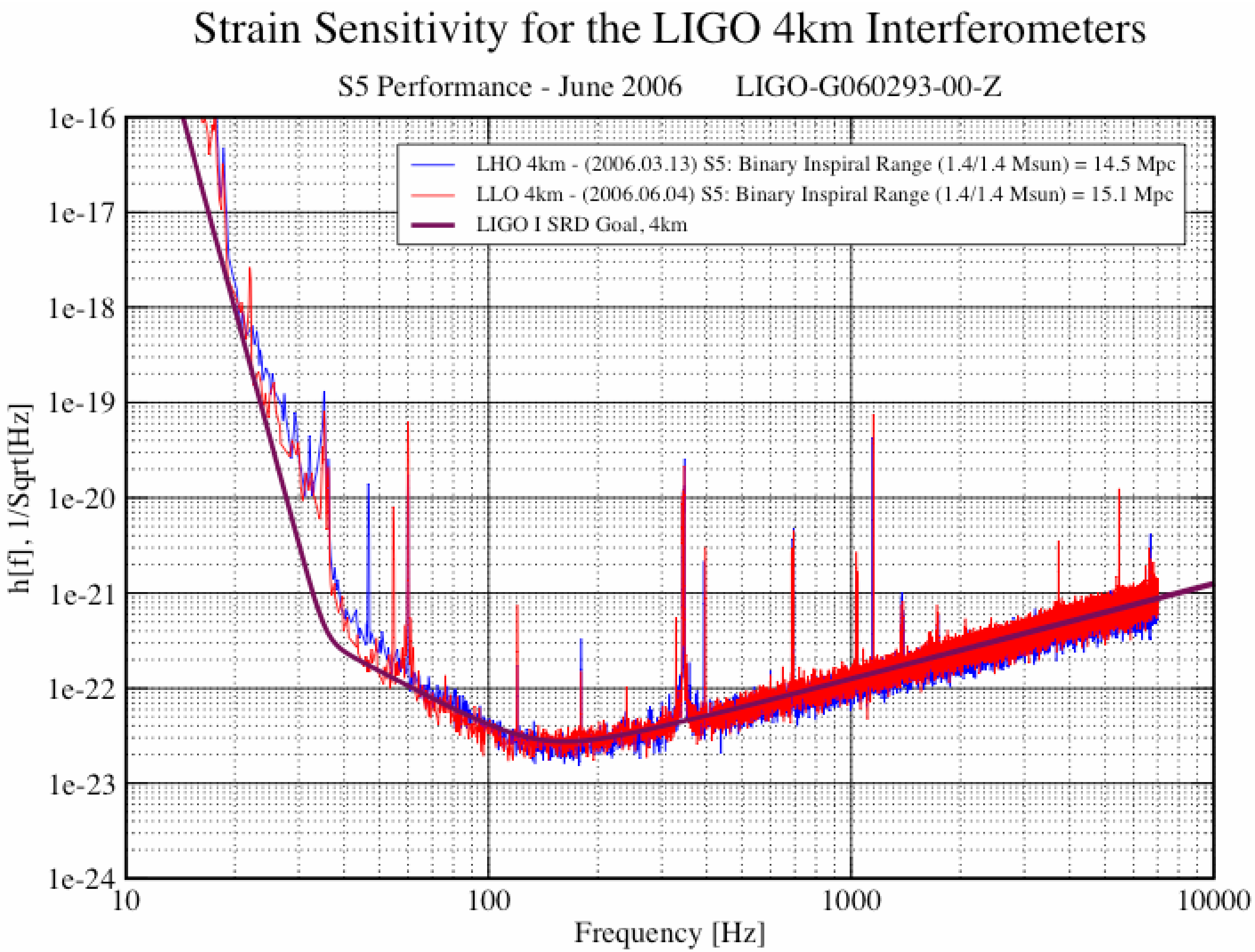


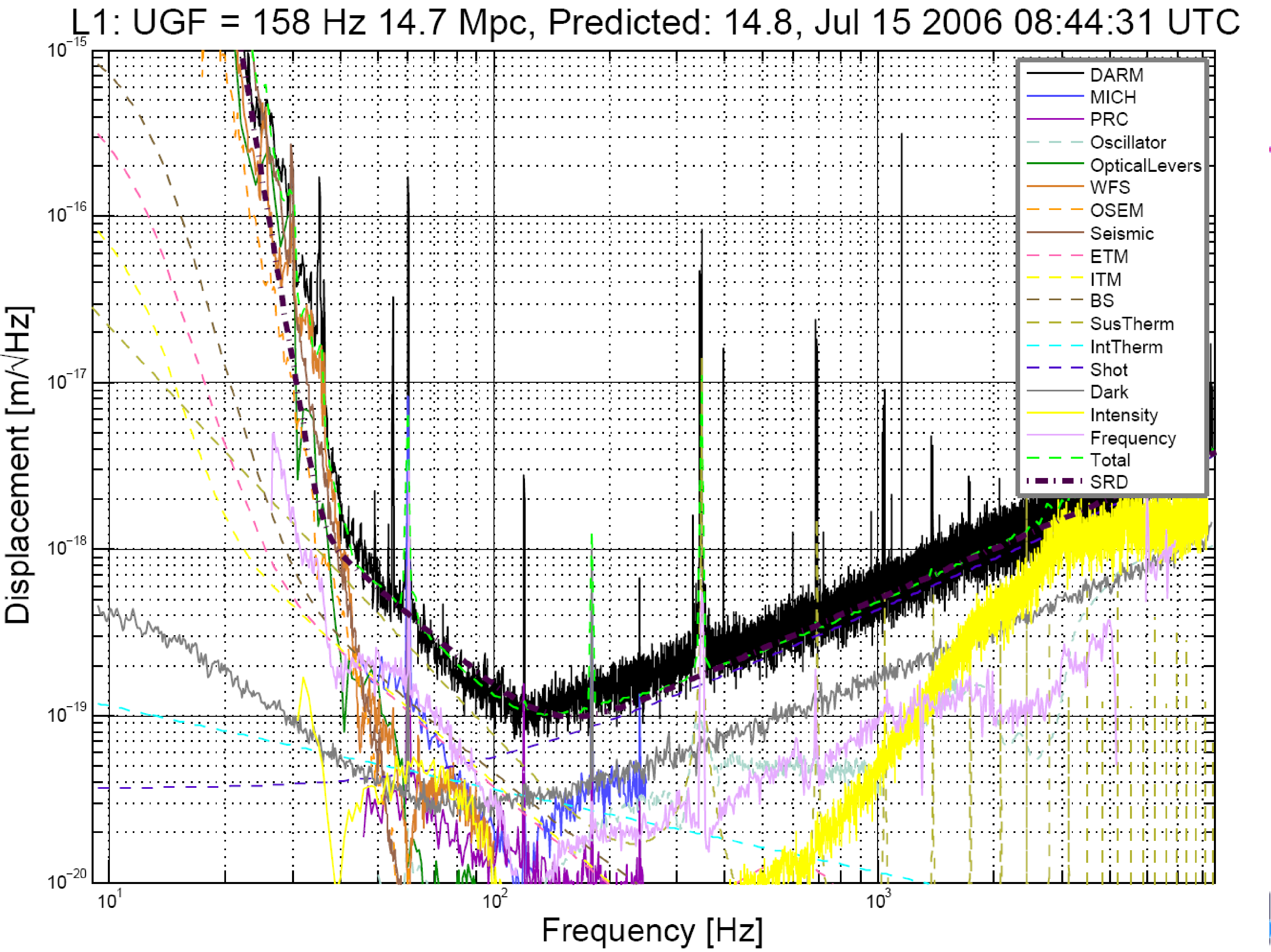


Sensitivity Progress

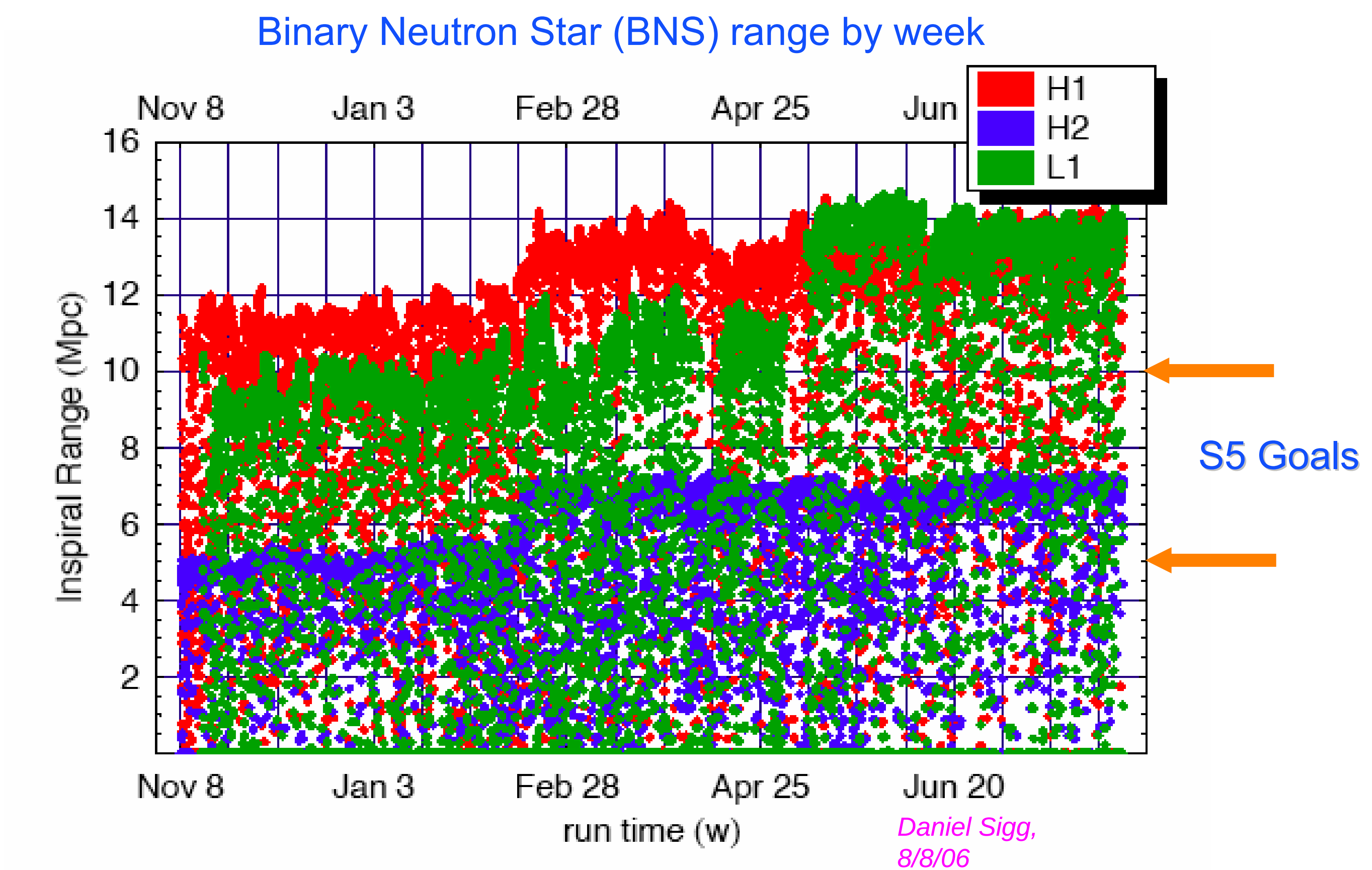


Sensitivity has reached design performance



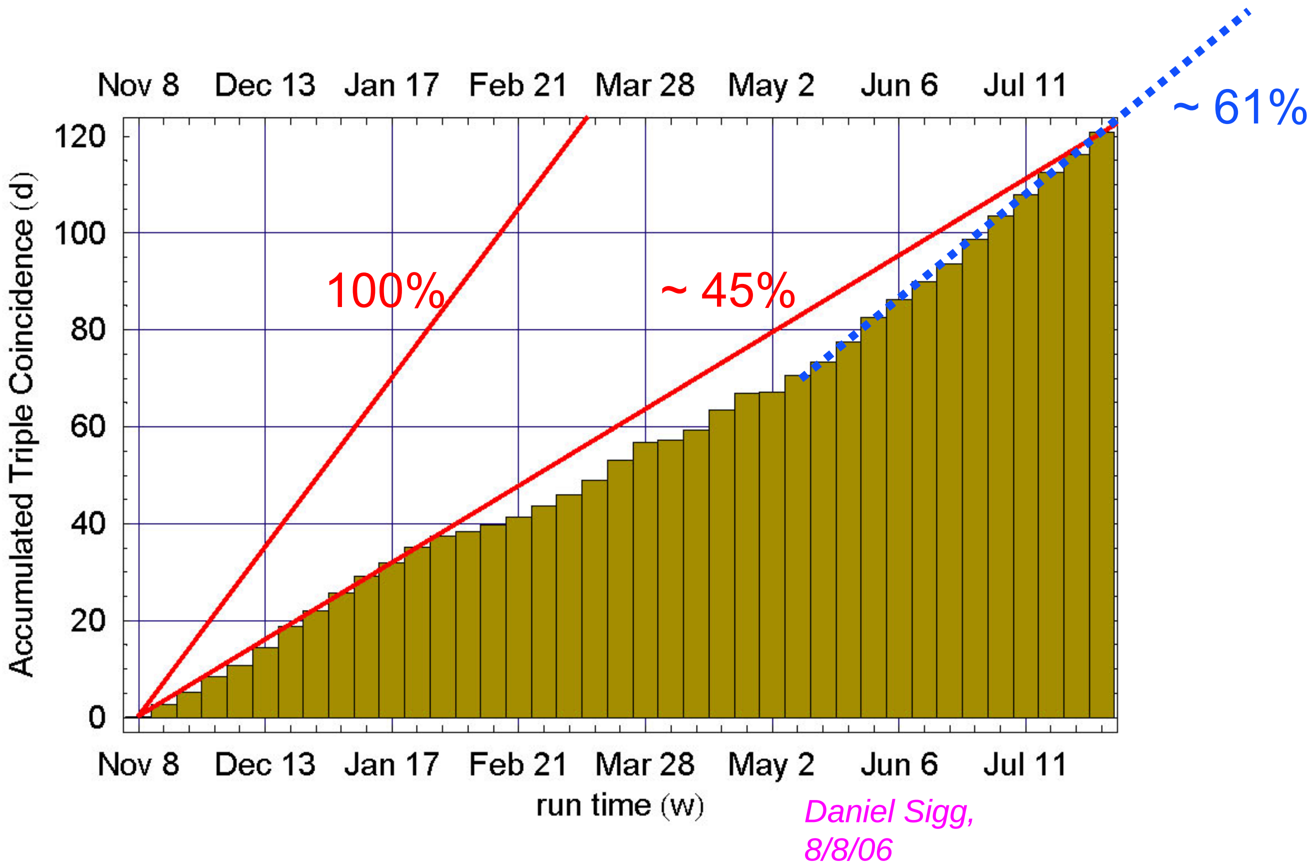

L1: UGF = 158 Hz 14.7 Mpc, Predicted: 14.8, Jul 15 2006 08:44:31 UTC
Displacement [m/√Hz]
Frequency [Hz]
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{1}
10^{2}
10^{3}
DARM
MICH
PRC
Oscillator
OpticalLevers
WFS
OSEM
Seismic
ETM
ITM
BS
SusTherm
IntTherm
Shot
Dark
Intensity
Frequency
Total
SRD

The Improvement in (sky-averaged) Detectable Range for 1.4 + 1.4 M_{sun} binaries



The S5 Science Run observation time so far…

Triple coincidence accumulation



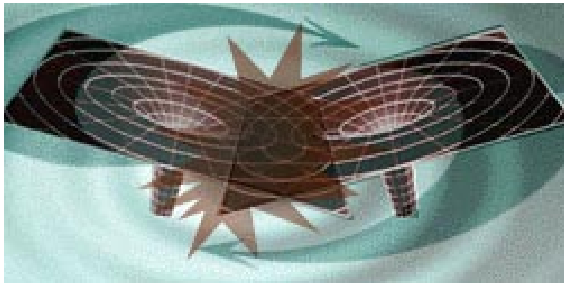
⇒ Project bagging 1y triple coincidence @ **September 2007 (±)**

LIGO Science

- The LIGO Scientific Collaboration (LSC) is organized around LIGO Laboratory and carries out the mission of observation & analysis of LIGO data. LIGO Laboratory scientific & technical staff are members of the LSC.
- Presently the LSC is composed of 35+ groups (US and international) and 400+ members.
  - The collaboration is open to new groups wishing to support the science operations & observations and join the analysis working groups.
  - Scientific observation is organized into 4 working groups:
    1. Binary coalescences with modeled waveforms (“inspirals”);
    2. Transients sources with unmodeled waveforms (“bursts “)
    3. Continuous wave sources (“GW pulsars”)
    4. Stochastic gravitational wave background (cosmological & astrophysics foregrounds)
- We have carried out four Science Runs (S1--S4) interspersed with commissioning periods.
- Presently nearing end of 1st year of continuous observation (S5)
  - S1 - S4 have produced over 30 publications documenting observational results, including
    - 2 Physical Review Letters
    - 11 Physical Review D articles (and 1 to be submitted)
      - *available from http://xxx.lanl.gov/find/gr-qc and http://xxx.lanl.gov/find/astro-ph*
    - 1 Astrophysical Journal (to be submitted)
    - Numerous other papers from more recent runs, including the current run, are in preparation and under review within the collaboration

1. Searches for signals from compact binaries

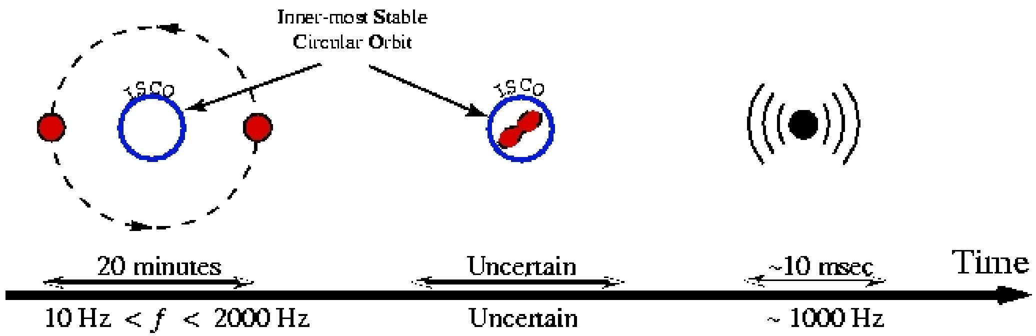
- LIGO is sensitive to gravitational waves from binary systems with neutron stars & black holes
  - Waveforms depend on masses and spins.



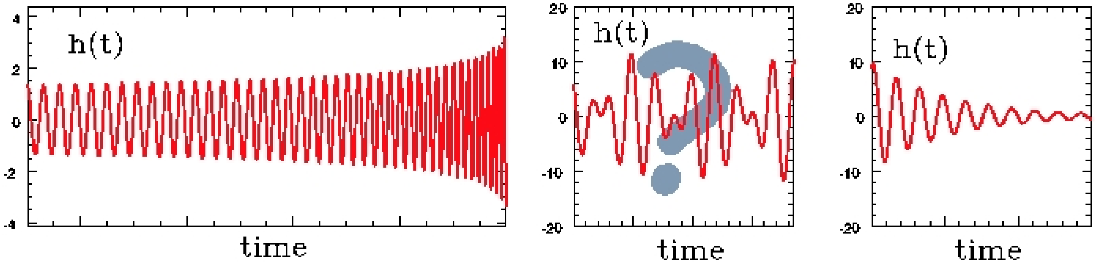
- Binary neutron stars
  - THEORETICAL estimates give upper bound of 1/3 yr in LIGO S5

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

$$h \approx 10^{-21} @ R_{Virgo}$$



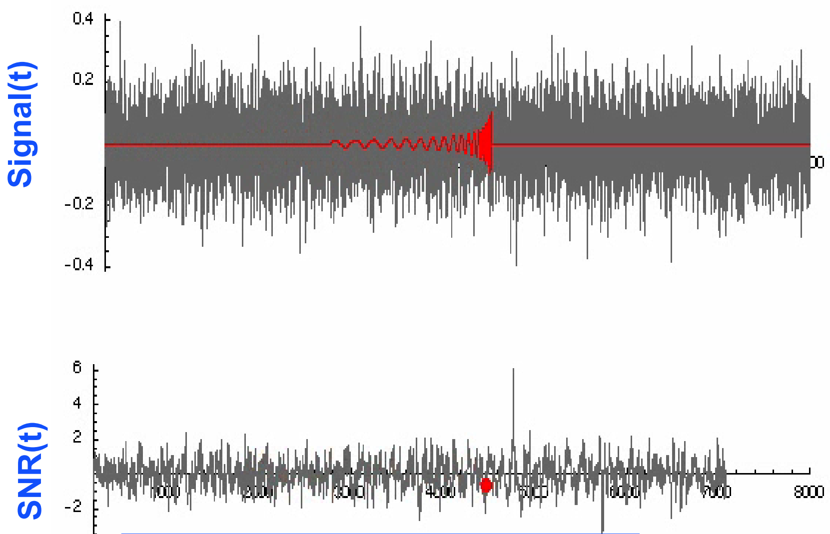
- Binary black holes
  - THEORETICAL estimates give upper bound of 1/yr in LIGO S5



Matched filtering

Optimal Wiener Filter

GW strain signal
+
simulated chirp



SNR vs. coalescence time

– Thresholds on

- Signal-to-noise (SNR) : $\rho(t) == |z(t)|/\sigma_z > 6.5$

$$z(t) = x(t) + iy(t) = 4\int_0^\infty \frac{\tilde{h}_c^I(f)\tilde{s}^*(f)}{S_n(f)}\, e^{2\pi i f t} df$$

$$\sigma^2 = 4\int_0^\infty \frac{|\tilde{h}(f)|^2}{S(f)} df$$

- Distribution

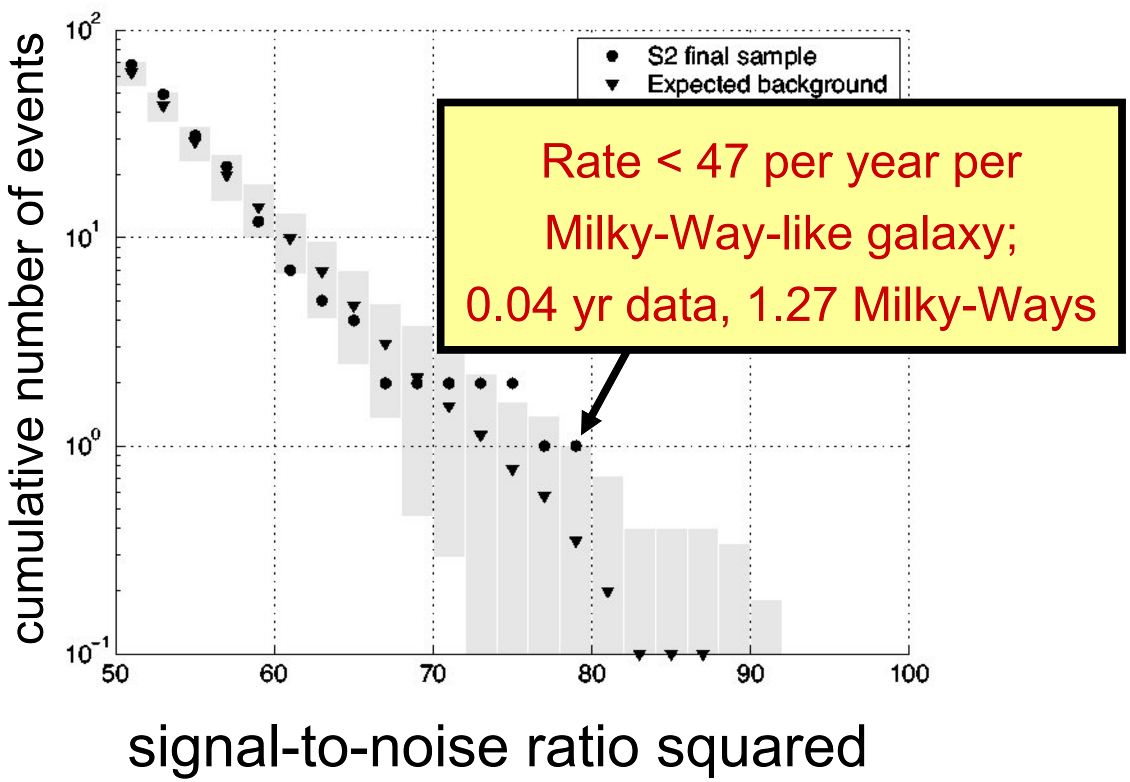
$$\chi^2(t) = \frac{p}{\sigma^2}\sum_{l=1}^{p} |z_l(t) - z(t)/p|^2$$

p = 8 frequency bins, each containing 1/8 of total SNR

Binary Neutron Stars

S2 Observational Result

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



- S3 search complete
  - 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

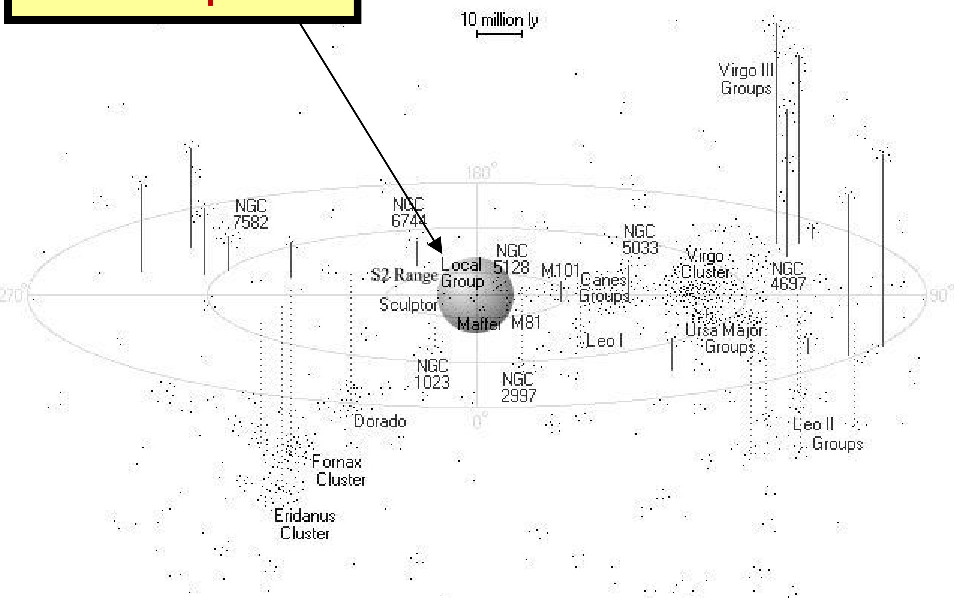
Binary Neutron Stars
S5 Search

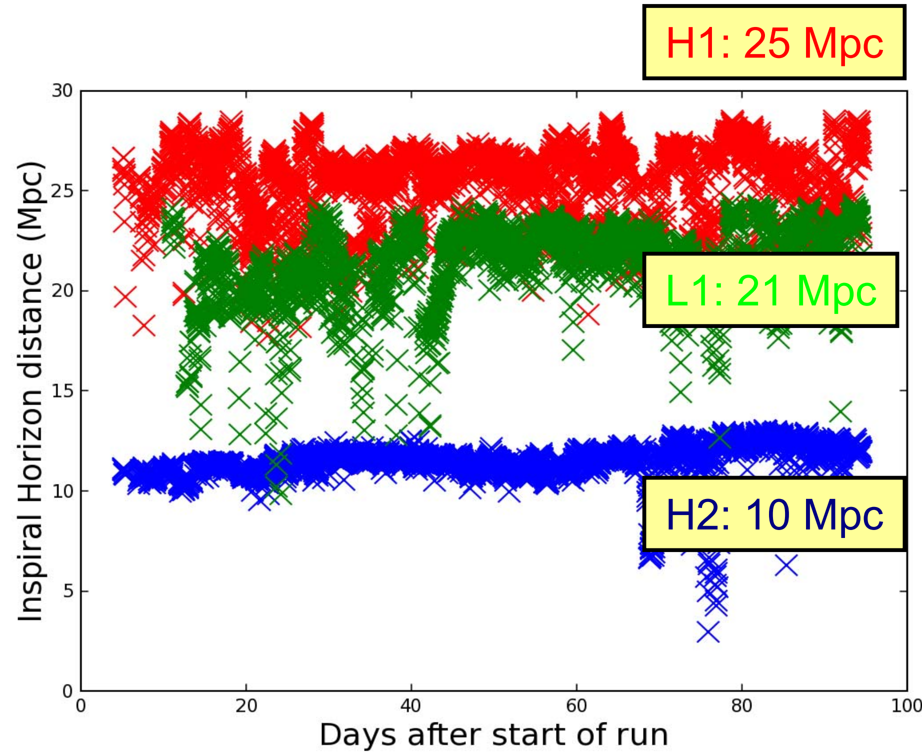
- First three months of S5 data is analyzed

- Horizon distance
  - Distance to 1.4+1.4 Msun optimally oriented & located binary at SNR=8

S2 Horizon Distance

1.5 Mpc

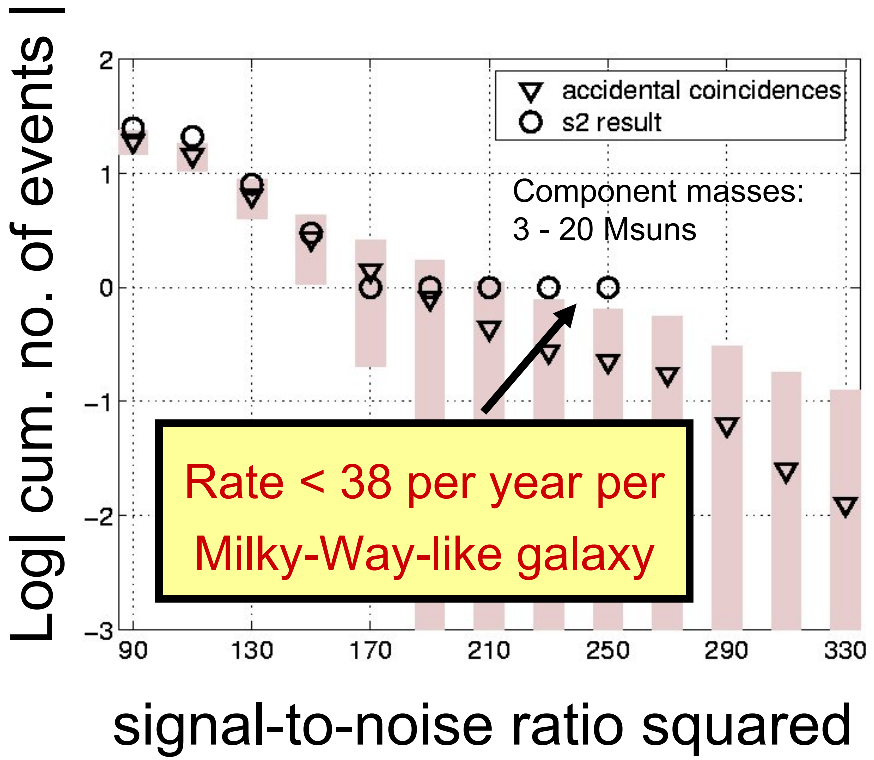




Binary Black Holes

S2 Observational Result

Phys. Rev. D. 73, 062001 (2006)



- S3 search complete
  - Under internal review
  - 0.09 yr of data
  - 5 Milky-Way like galaxies for 5+5 Msuns
- S4 search complete
  - Under internal review
  - 0.05 yr of data
  - 150 Milky-Way like galaxies for 5+5 Msuns

Binary Black Holes
S5 Search

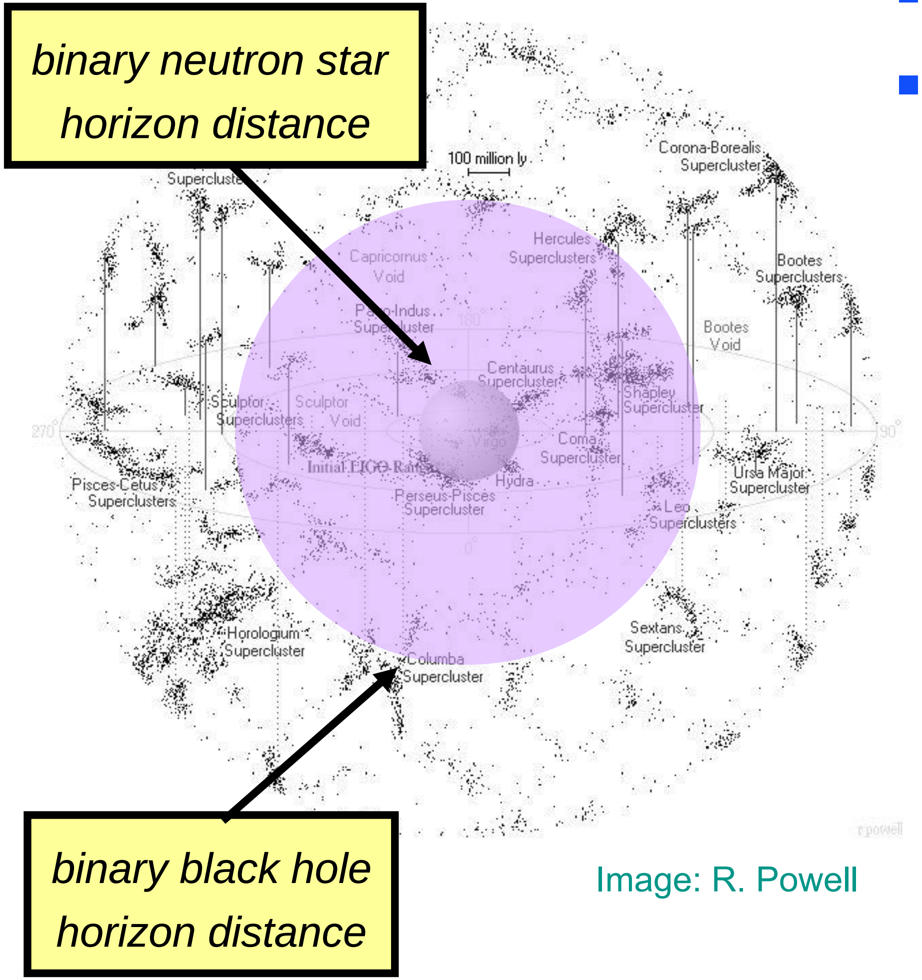
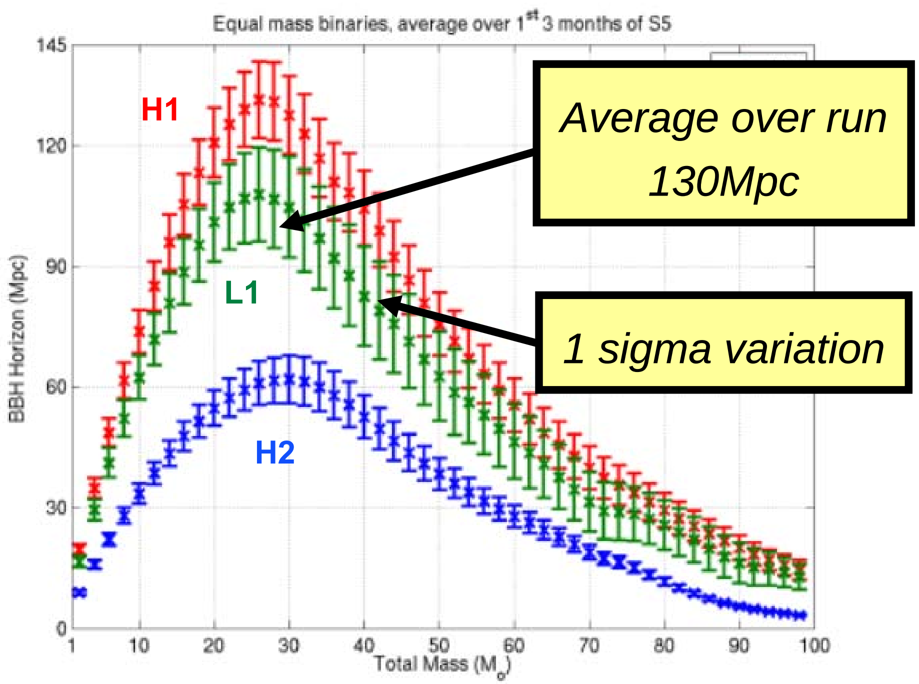


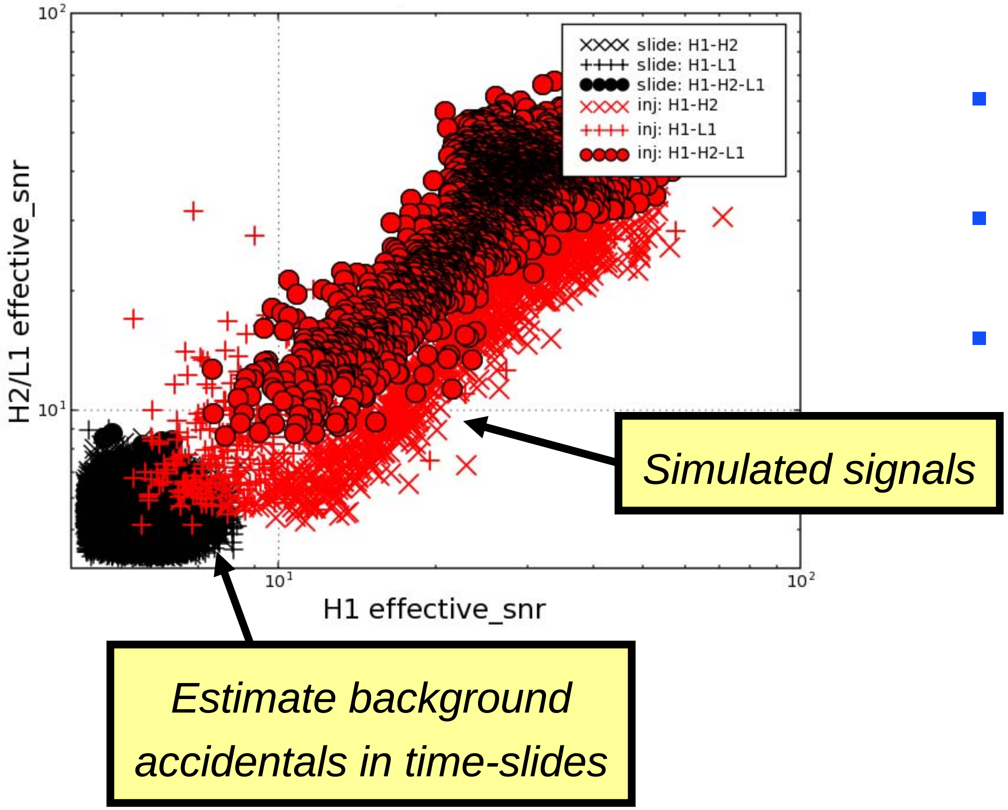
Image: R. Powell

- 3 months of S5 analyzed
- Horizon distance versus mass for BBH



Are we capable of detection?

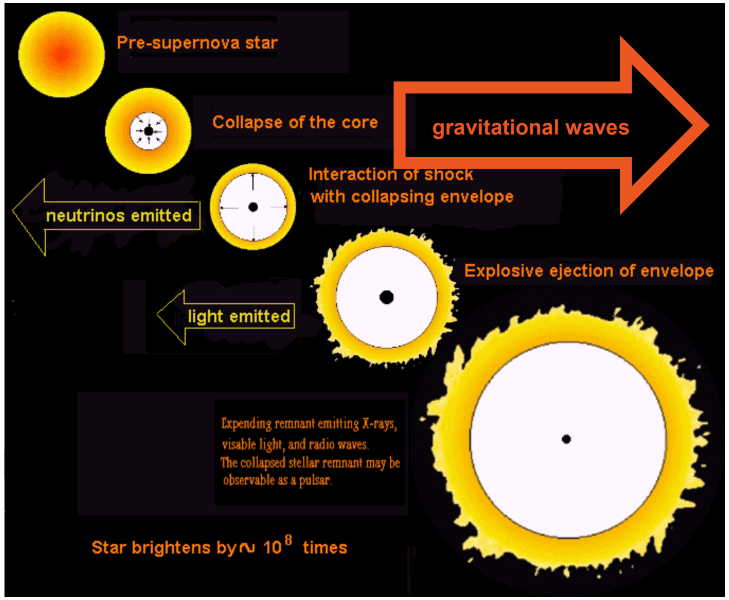
Sample of S5 Data



- Yes! we're getting ready
  - Lower masses, accurate waveforms, gives better discrimination than
  - BBH, waveforms are not accurately known means less discrimination power
  - Instrumental vetoes available; signal based vetoes available
  - Follow-ups on loudest triggers at end of each search as "fire drill"

2. Burst search overview and goals

- Sources emitting short transients of gravitational radiation (supernovae, black holes, Gamma Ray Bursts engines, cosmic string cusps, the unknown!)
- Untriggered:
  - Only basic assumptions on the signal morphology/origin
  - establish a bound on their rate at the instruments
  - interpret bound on a rate vs. strength exclusion
  - interpret in terms of source and population models
  - perform analysis of energy spectrum of burst events
  - compare with gravitational wave bar antenna results
- Triggered:
  - look at times around astronomical events: GRBs, neutrino candidates
  - concentrate on inter-detector cross-correlation search
  - bound gravitational wave transient strengths coincident with other astronomical events
- Operate as part of an international network of detectors
- Search to establish a detection

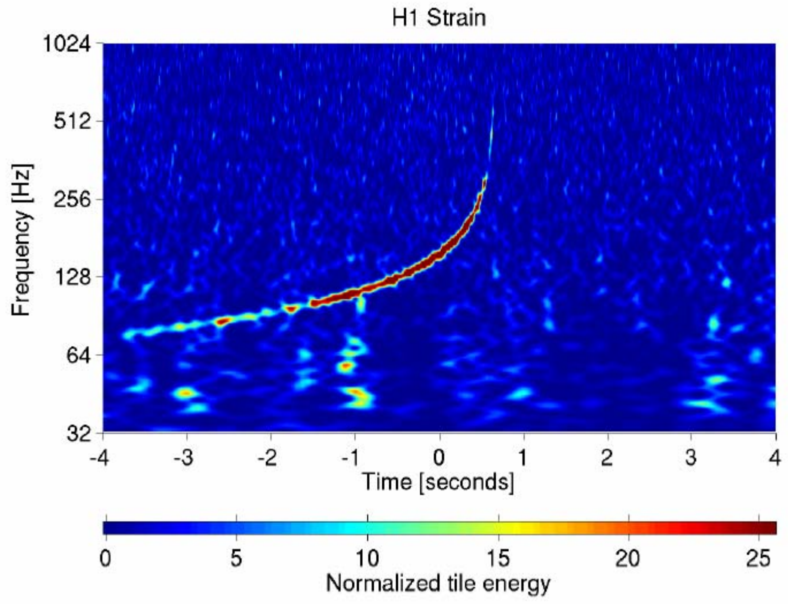


SNe Rate	*Strengths*
•*1/50 yr - our galaxy*	• $h \sim 1/R\ 4G/c^2(\Delta E_{kin\text{-}asym}/c^2)$
•*3/yr - out to Virgo cluster*	•$\Delta E_{kin\text{-}asym} \sim 10^{-7}\ M_{sun}$ $h \sim 3 \times 10^{-21}\ (30\ kpc/R)$

Search Technique for Untriggered Bursts: Excess-Power Detection

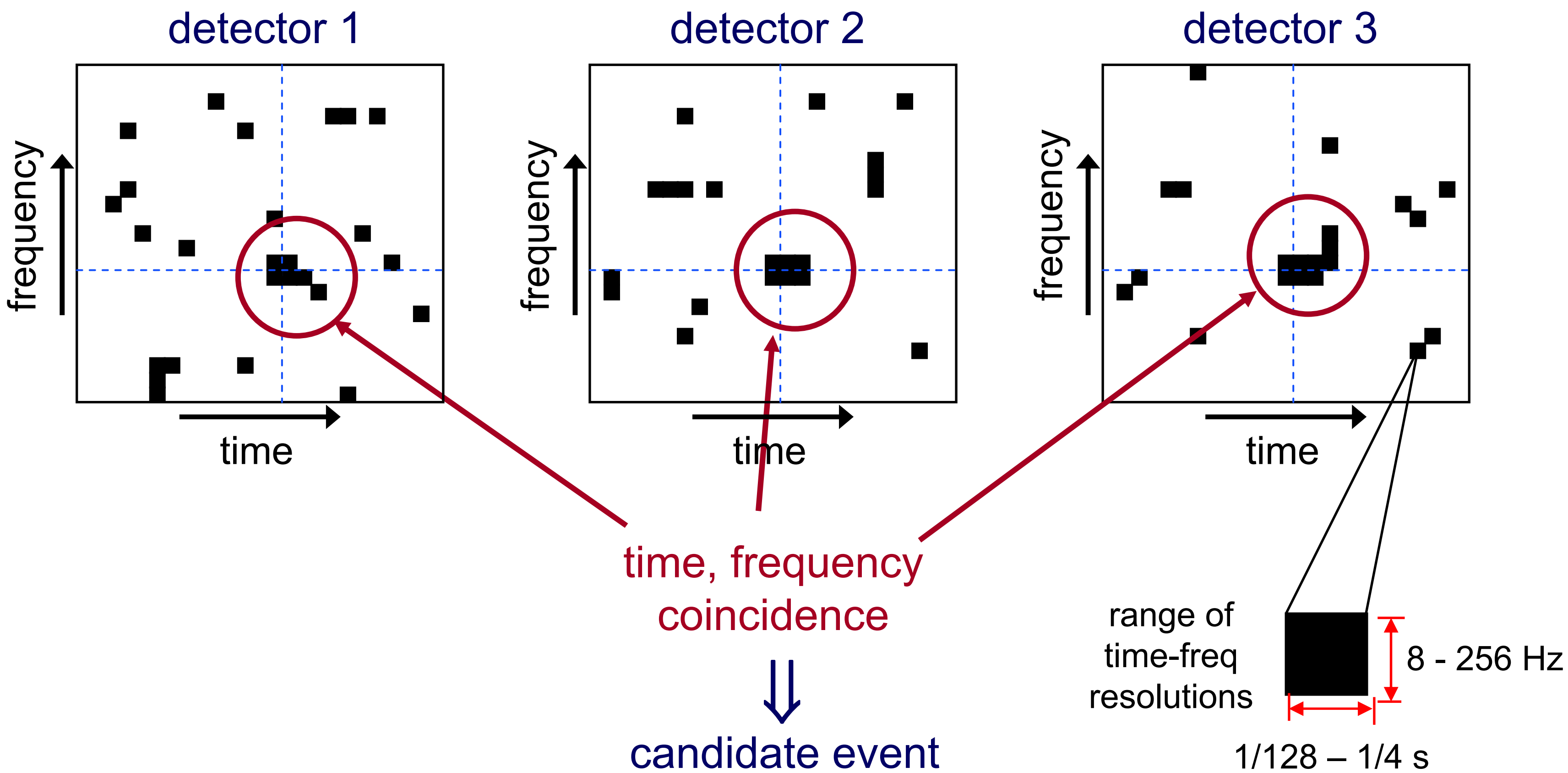
- Look for transient jump in power in some time-frequency region:
  - frequency ~ [60,2000] Hz (determined by noise curves of instruments)
  - duration ~ [1,100] ms (time scale associated with solar-mass COs)
  - Anderson et al. PRD **63** 042003 (2001).
- Many different implementations in LIGO:
  - Fourier modes, wavelets, Gaussian-modulated sinusoids.
  - Multiple time-frequency resolutions.
  - Provide redundancy & robustness.
  - Also time-domain & optimal filter searches.

Simulated binary inspiral signal in S5 data



LIGO Schematic - Coincidence Requirement

Typically require coincident detection in all 3 LIGO interferometers:



Progress in Upper Limits

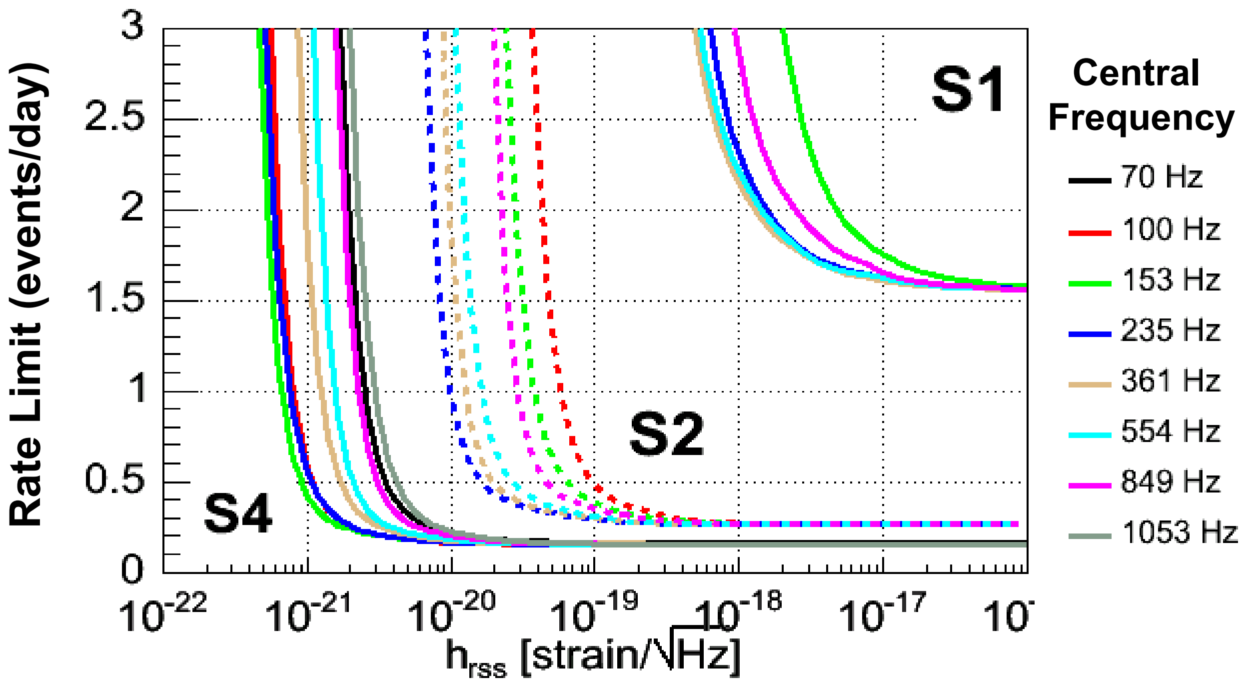
<u>No GWBs detected</u> **<u>through S4</u>**.

So, we set limit on GWB rate vs. signal strength:

$$R(h_{rss}) = \frac{N}{\varepsilon(h_{rss}) \times T}$$

□ = upper limit on event number
T = observation time
$\varepsilon(h_{rss})$ = efficiency vs strength

S5: Run & analysis still in progress



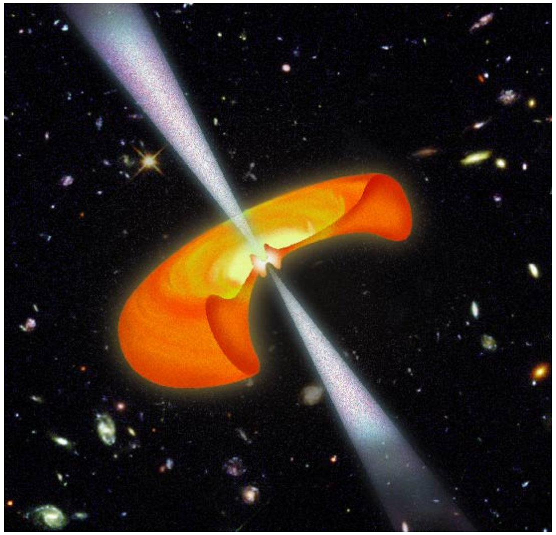
Progress:

Lower rate limits from <u>longer</u> observation times

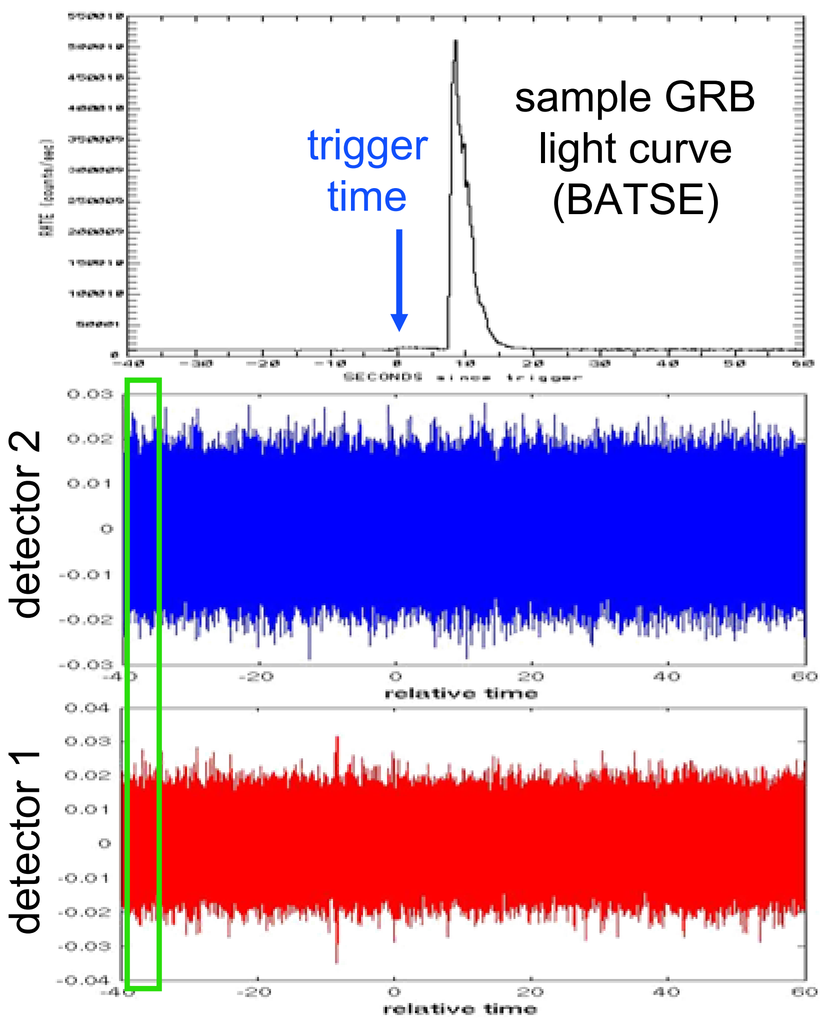
Lower amplitude limits from <u>lower</u> detector noise

Gamma-Ray Bursts

- Bright bursts of gamma rays
  - occur at cosmological distances
  - seen at rate ~1/day.
  - duration ~1 ms – ~100 sec, with ms structure.
- Long duration > 2s
  - in beam few degrees wide (see only 1/500)
  - ~1/yr within 100Mpc
  - associated with "hypernovae" (core collapse to black hole) - Hjorth et al, Nature **423** 847 (2003).
- Short duration < 2 s
  - Binary NS-NS or NS-BH coalescence?
  - Gehrels et al., Nature **437**, 851–854 (2005).
- Strongly relativistic – likely to produce GWBs.
  - Spectrum & polarization of GWB tell about progenitor (e.g., non-axisymmetry).



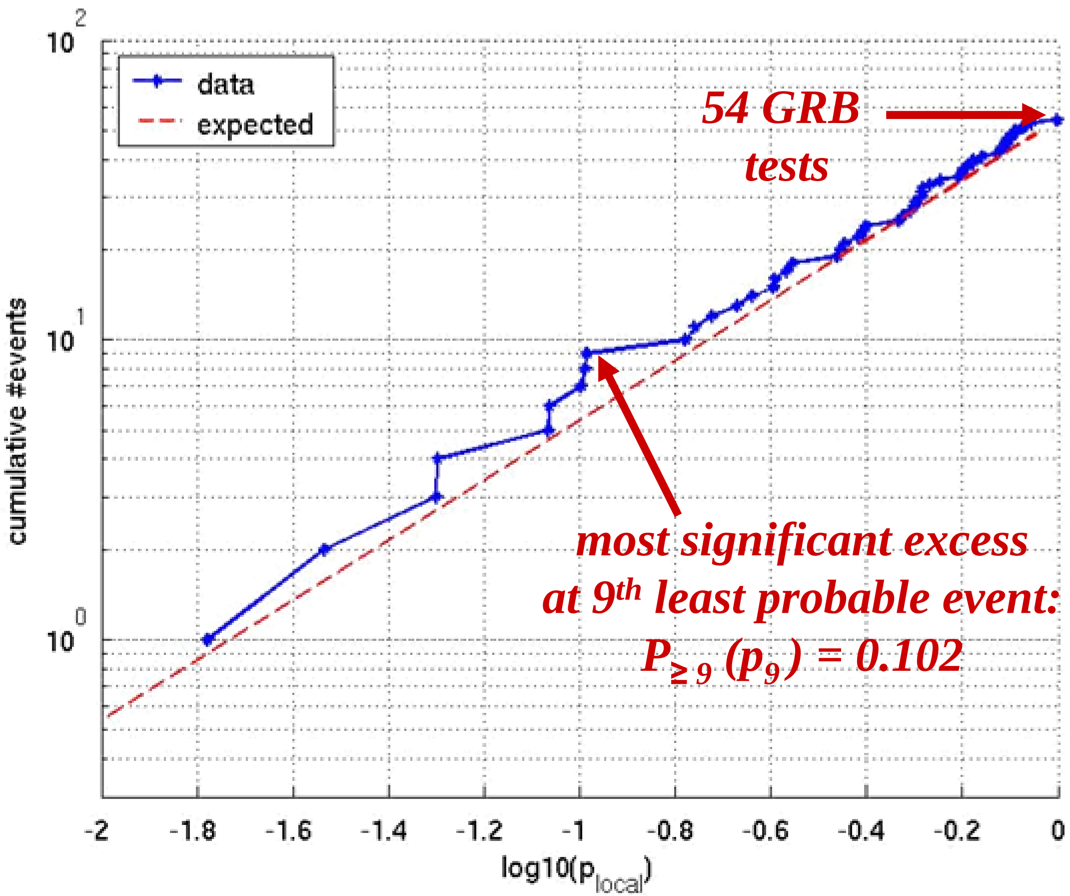
Procedure: GRBs



- **Know time of event**
  - Can concentrate efforts to probe sensitively small amount of data around the event time.
- **Often know sky position**
  - Can account for time delay, antenna response of instrument in consistency tests
- **Sensitivity improvement**
  - variable, often a factor of ~2 in amplitude
- **Cross correlate data between pairs of detectors around time of event**
  - 25 – 100 ms target signal duration
  - [-2,+1] min around GRB
- **Compute probability of largest measured CC using distribution of CCs from neighboring times (no GRB, with time shifts).**
  - Improbably large CC equals candidate GWB

Statistical Tests

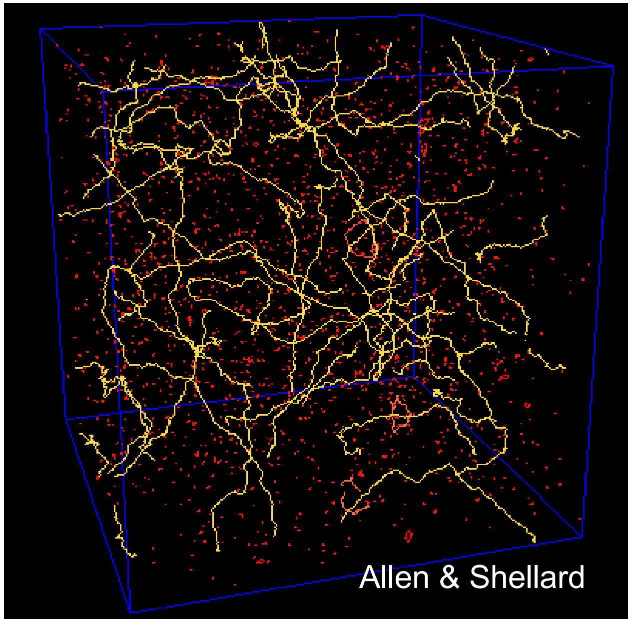
- No loud signals seen.
- Look also for weak cumulative effect from population of GRBs.
  - Use binomial test to compare to uniform distribution.
- No significant deviation from expected distribution.
- Max-likelihood test also used.
  - Mohanty, CQG 22 S1349 (2005)



Leonor / Sannibale, Session W11

Other Efforts

- GWBs from cosmic string cusps
  - Siemens, session S11: *Search Techniques for GWBs from cosmic strings* (Monday 3:30pm Cumberland E).



Simulation of a network of cosmic strings.

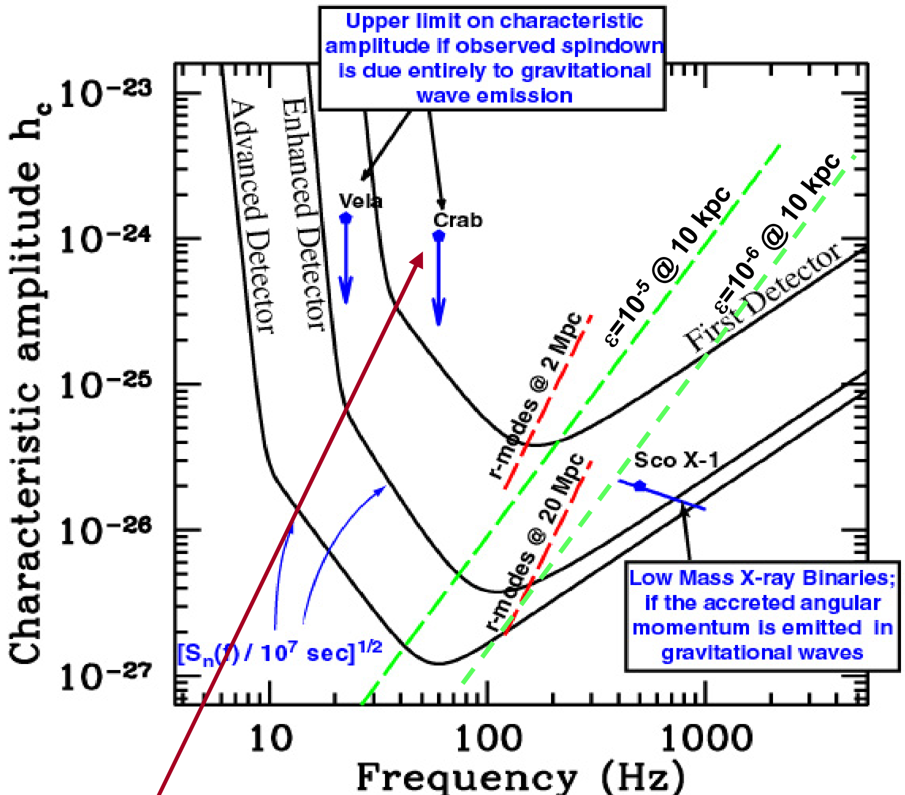
- “Online” analysis
  - quick look for loud GWBs
  - rapid feedback on detector performance.

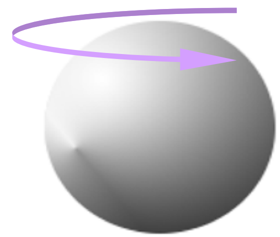
3. Periodic Sources

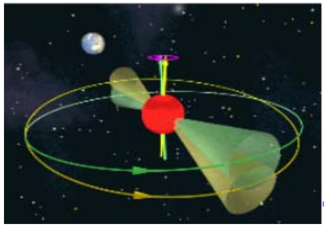
Target signals: slowly varying instantaneous frequency, e.g. rapidly rotating neutron stars in different moments of their evolution.

Sensitivity of LIGO to continuous wave sources

** Graphs from Brady, Creighton, Cutler, and Schutz, gr-qc/9702050*

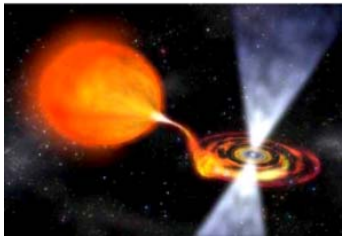


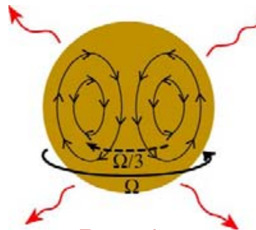




"Mountain" on neutron star

Wobbling neutron star





Accreting neutron star

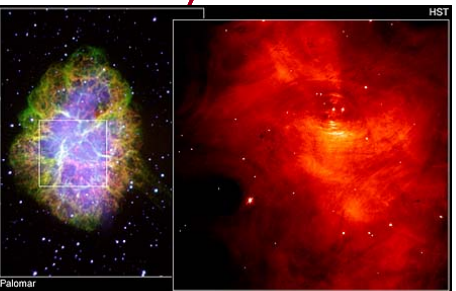
R-modes

h_c: the amplitude of the weakest signal detectable with 99% confidence with 4 months of integration, *<u>if the phase evolution were known.</u>*

$$h_c = 2.3\times10^{-25}\,\frac{\varepsilon}{10^{-5}}\,\frac{I_{zz}}{10^{45}\,g\,cm^2}\,\frac{8.5\,kpc}{R}\left(\frac{f_0}{500Hz}\right)^2$$

$$\langle h_c\rangle = 11.4\sqrt{S_n(f_s)/T}$$

<u>Data must be corrected for each source position on the sky</u>



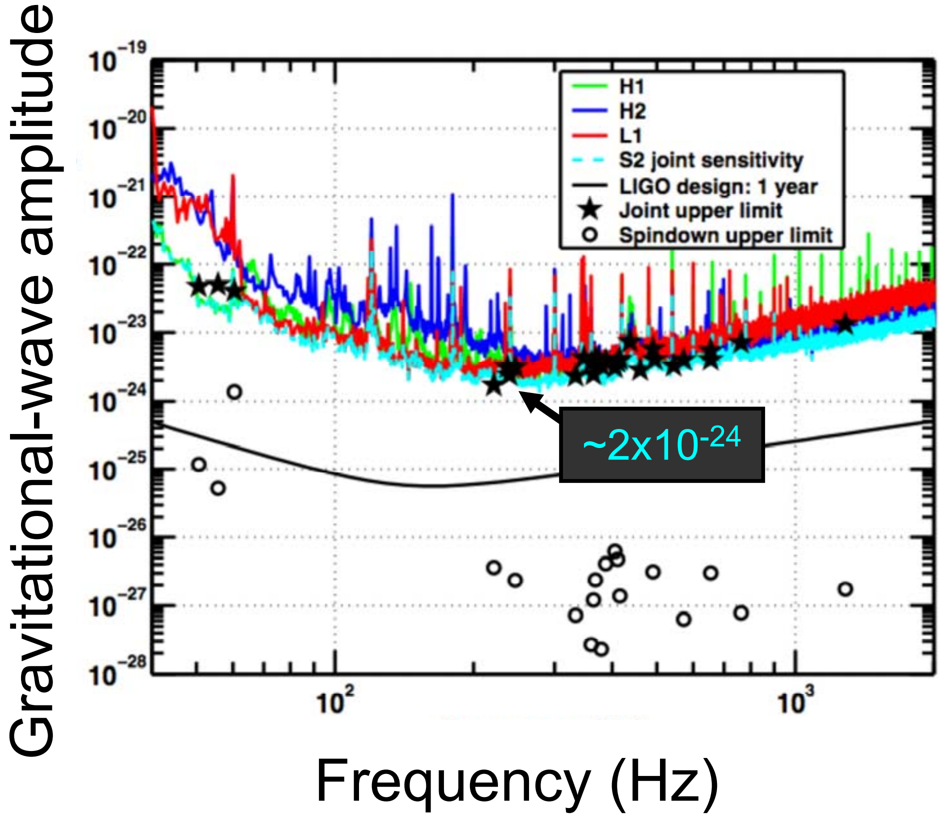
Continuous-wave searches

- Known pulsar searches
  - Catalogue of known pulsars
  - Narrow-band folding data using pulsar ephemeris
- All sky incoherent searches
  - Sum many short spectra
- Wide area search
  - Doppler correction followed by Fourier transform
  - Computationally very costly
  - Hierarchical search under development

Search for waves from known pulsars

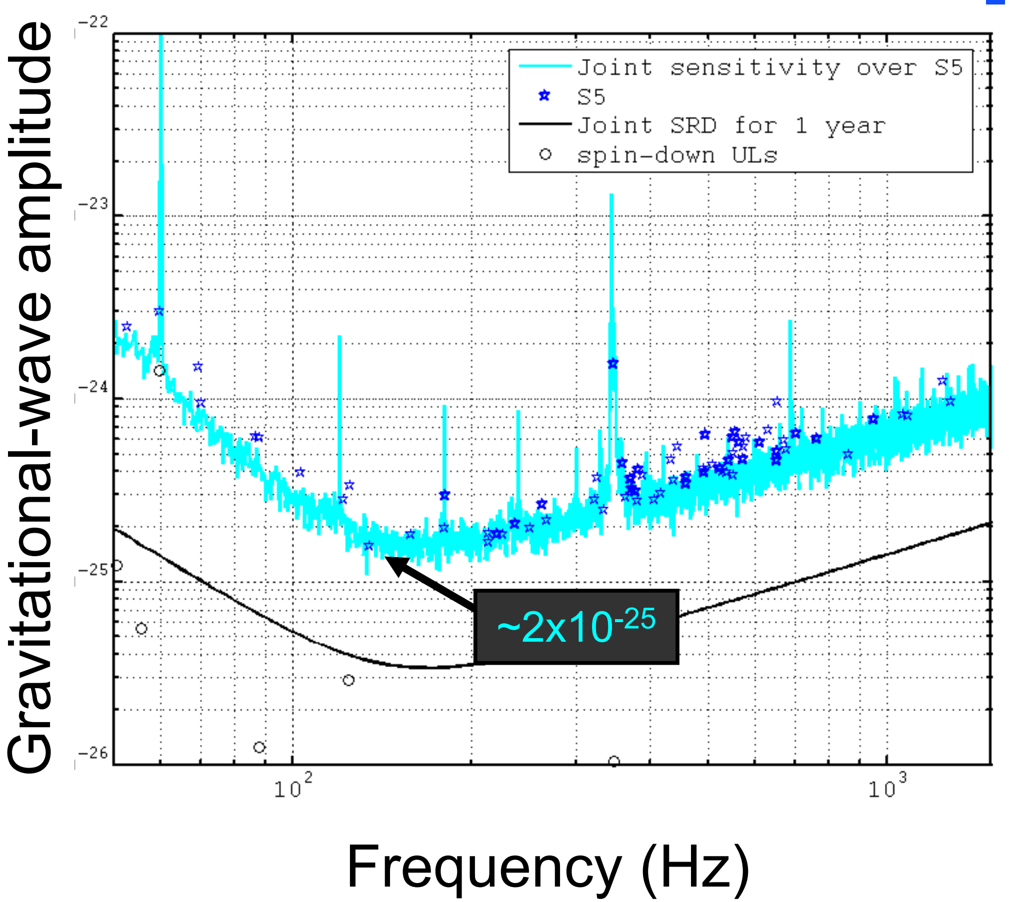
S2 Results reported in

*Physical Review Letters **94** 181103 (2005)*



- Pulsars for which the ephemeris is known from EM observations
- In S2
  - 28 known isolated pulsars targeted
- Spindown limit
  - assumes all angular momentum radiated to GW

Known pulsars S5 preliminary

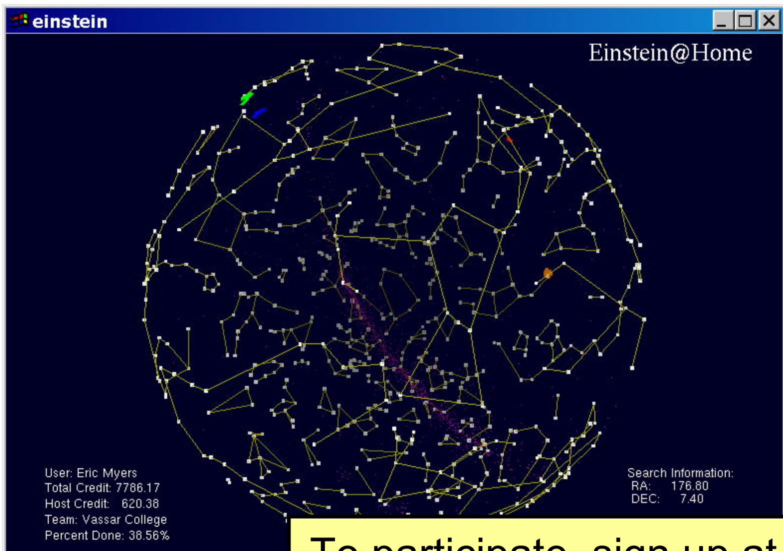


- 32 known isolated, 44 in binaries, 30 in globular clusters

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

Einstein@Home

(http://www.physics2005.org)

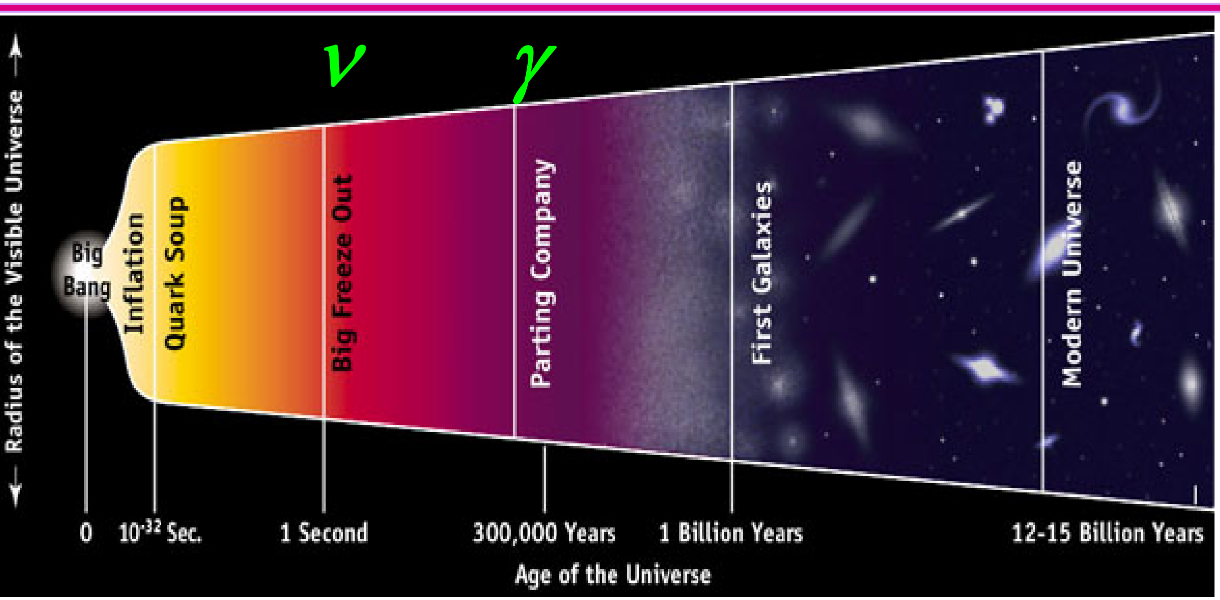


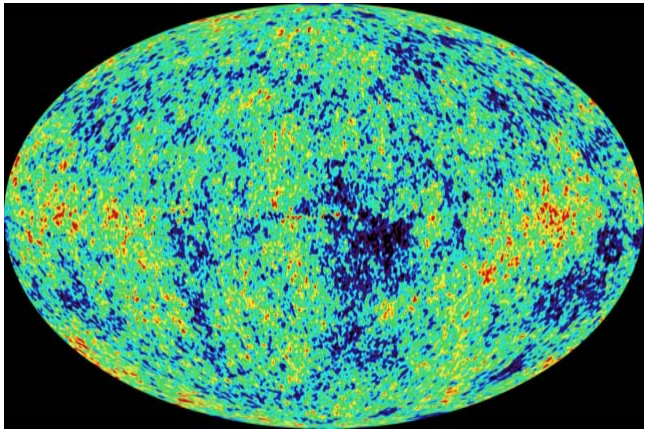
To participate, sign up at
http://www.physics2005.org

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

- Matched filtering for continuous GWs
- All-sky, all-frequency search
  - computationally limited
- Goal: detection, not upper limits
- Public outreach
  - Distributed computing via a screensaver interface

4. Stochastic gravitational wave background





Analog from cosmic microwave background -- WMAP 2003

GWs can probe the very early universe

- Detect by cross-correlating interferometer outputs in pairs:

  Hanford - Livingston, Hanford - Hanford

- Good sensitivity requires:
  - $\bullet_{GW} \geq 2D$ (detector baseline)
  - $f \leq 40$ Hz for LIGO pair over 3000 km baseline

- Initial LIGO limiting sensitivity (1 year search): $\phi_{GW} < 10^{-6}$

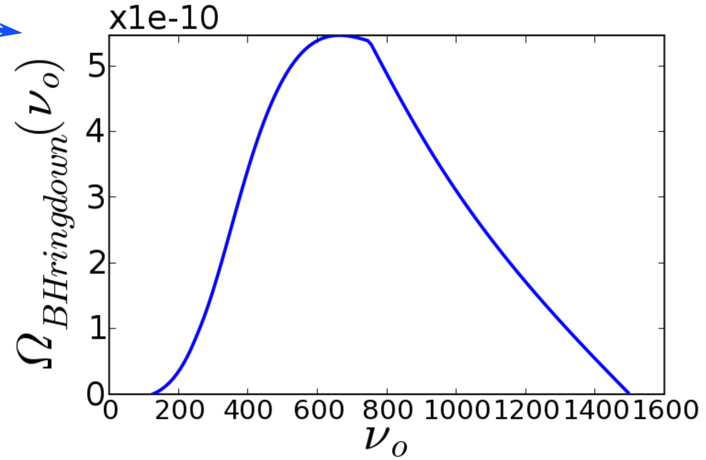
$$\int_0^\infty d(\ln f)\ \Omega_{GW}(f) = \frac{\rho_{GW}}{\rho_{critical}}$$

The integral of $[1/f \bullet \Omega_{GW}(f)]$ over all frequencies corresponds to the fractional energy density in gravitational waves in the Universe

Stochastic signals

Stochastic backgrounds can arise either from

- *Cosmological processes*, such as inflation, phase transitions, or cosmic strings, or from
- *Astrophysical processes*, as the superposition of many signals from the other signal classes already described earlier in talk.
  - e.g., GW spectrum due to cosmological BH ring downs (Regimbau & Fotopoulos

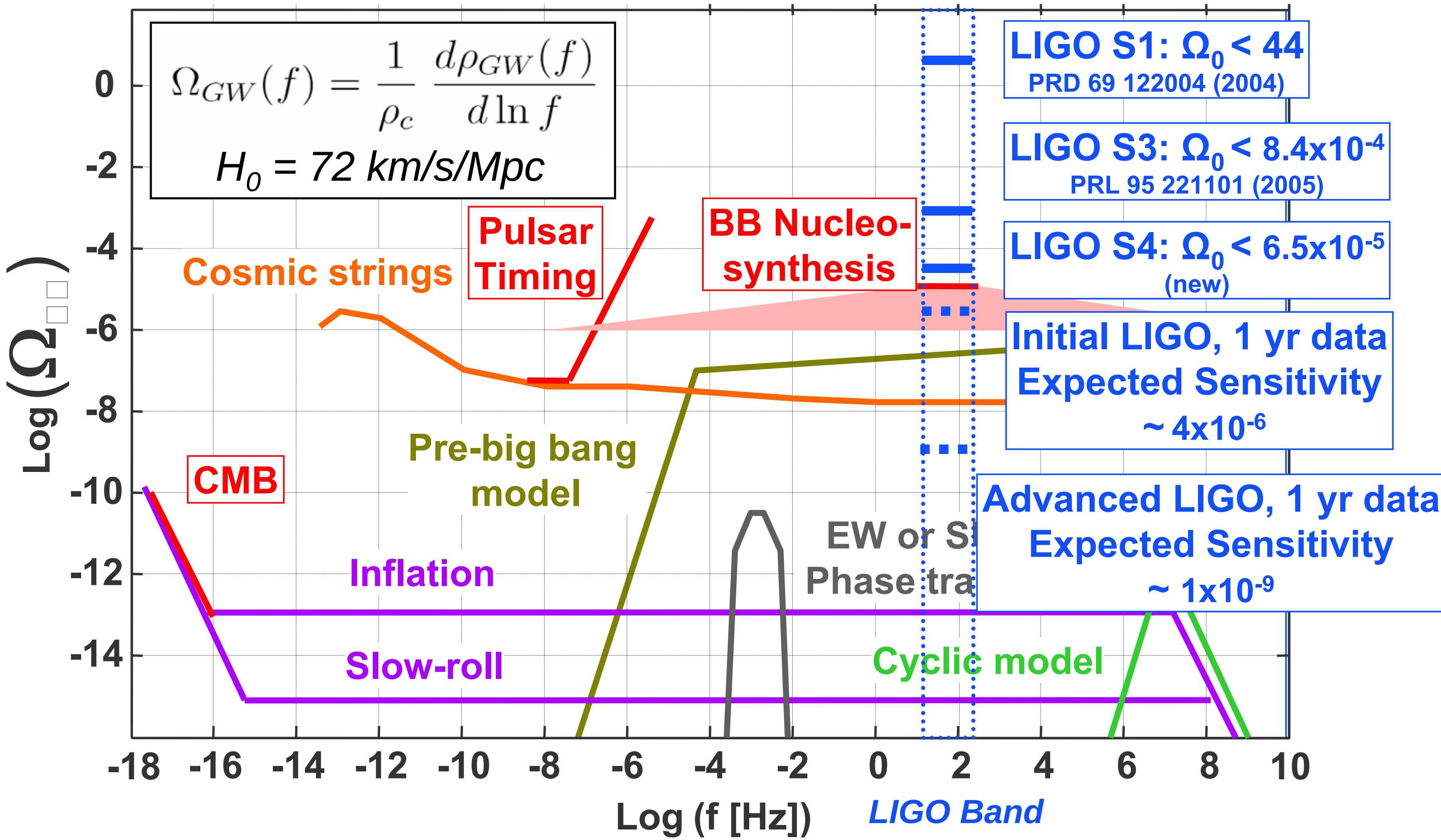


)

Characterize the strength by

$\Omega_{GW}(f)$, defined as the fraction of cosmic closure density in the background, in a logarithmic frequency interval near frequency *f*.

The “Big-picture Landscape”
-- Predictions & Limits --



Search Procedure

Cross-correlate data streams $x_1(t)$, $x_2(t)$.

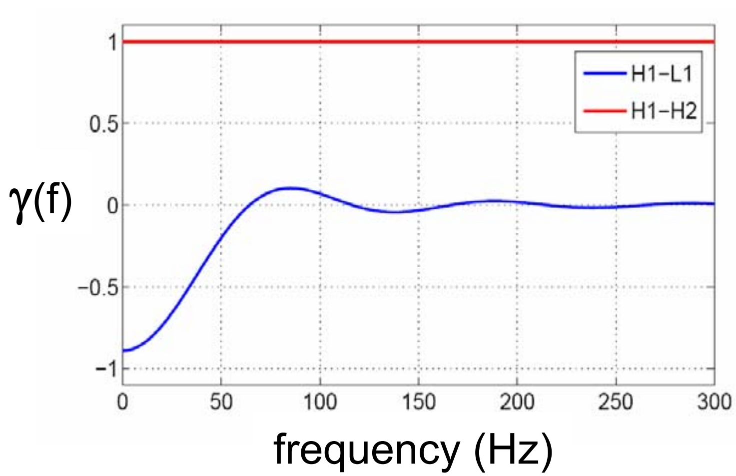
Optimal statistic Y for all-sky search is:

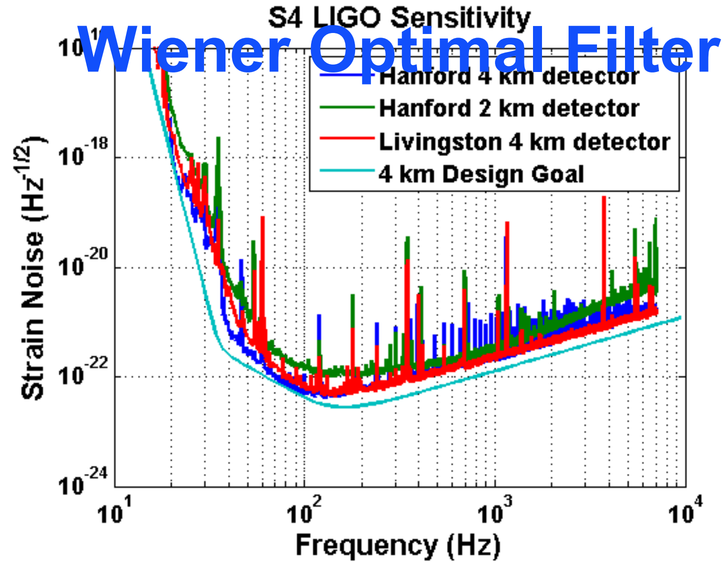
$$Y = \int_{-\infty}^{\infty} df \, \tilde{x}_1^*(f) \left[\frac{\gamma(f)\Omega_{GW}^{mod}(f)}{N f^3 P_1(f) P_2(f)} \right] \tilde{x}_2(f)$$

"Overlap Reduction Function"
(determined by network geometry)

detector noise spectra

Wiener Optimal Filter

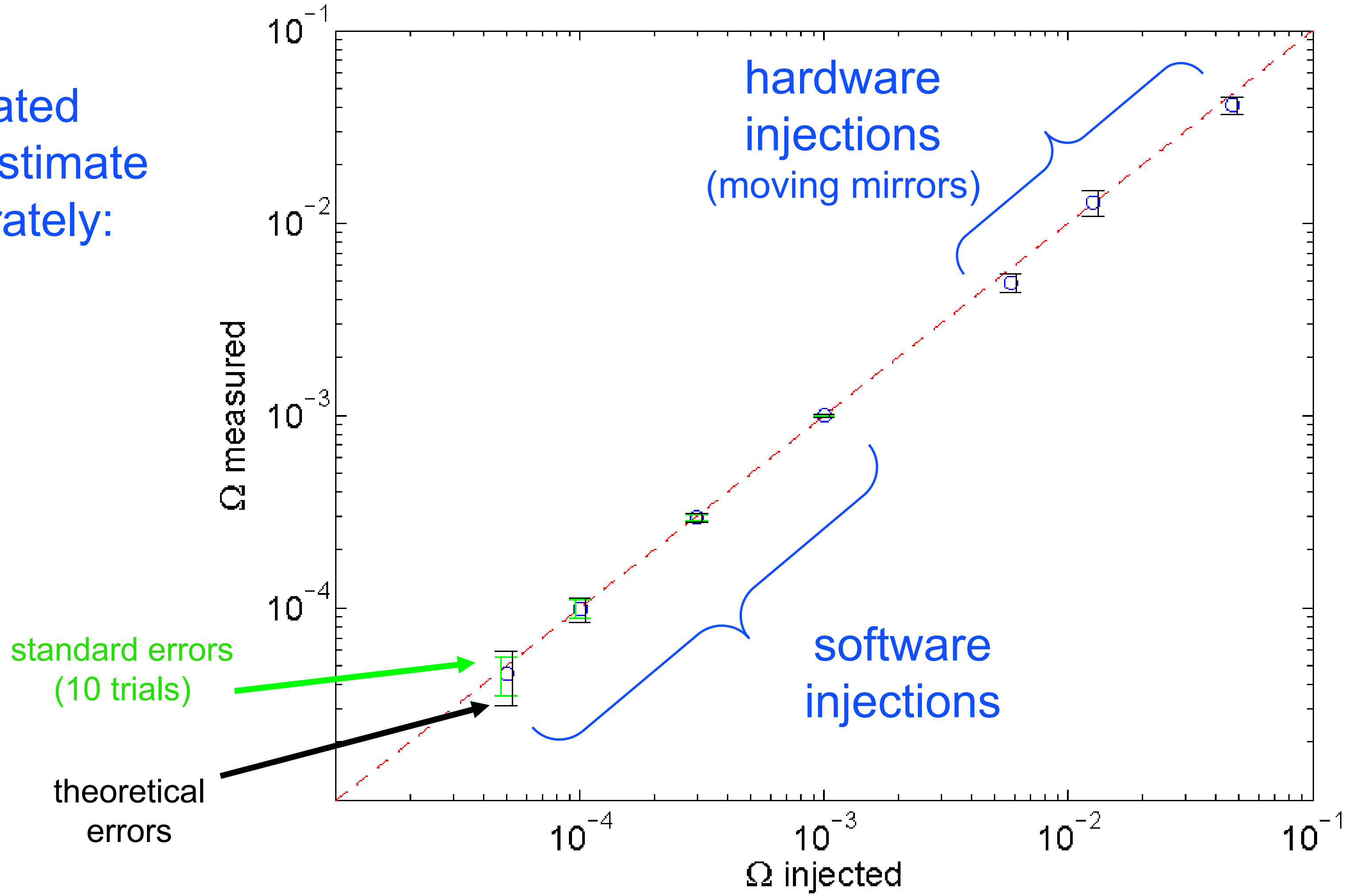




- Test: $\Omega^{\square\square\square}_{GW}(f) = \Omega_\alpha (f/100Hz)^\alpha$.
- Most sensitive in the 50-150 Hz band (due to LHO-LLO baseline).

Signal Recovery

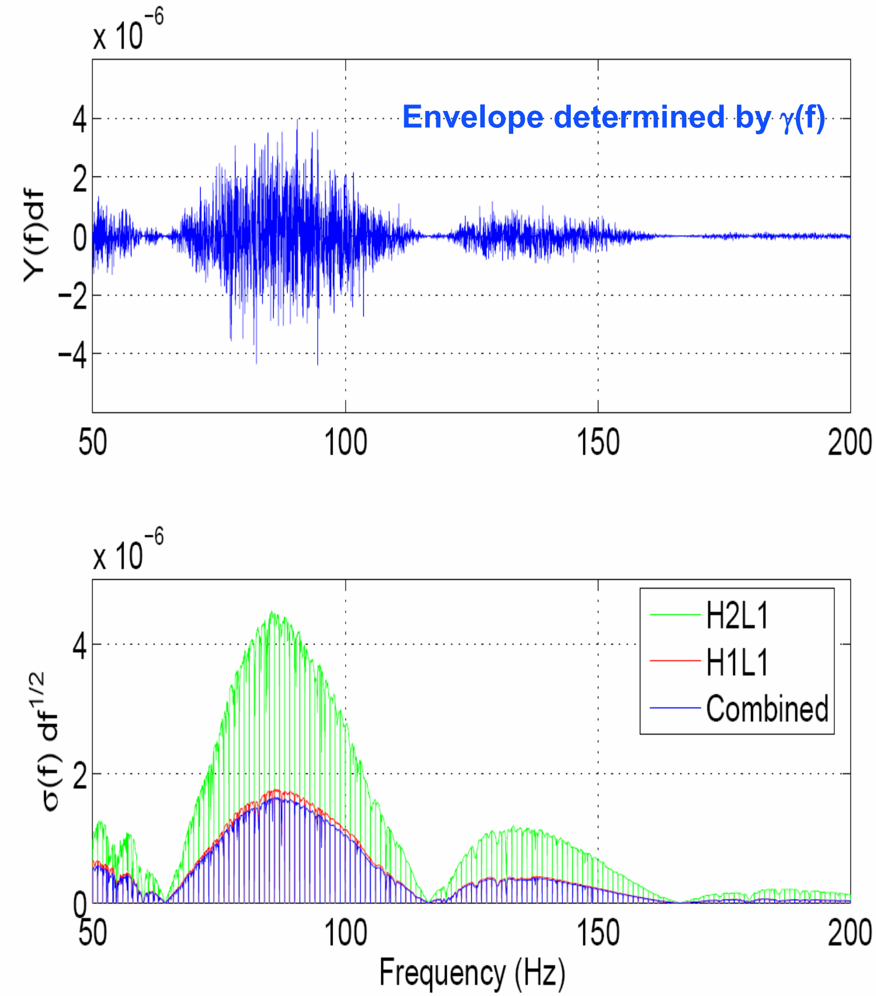
Demonstrated ability to estimate Ω_{GW} accurately:



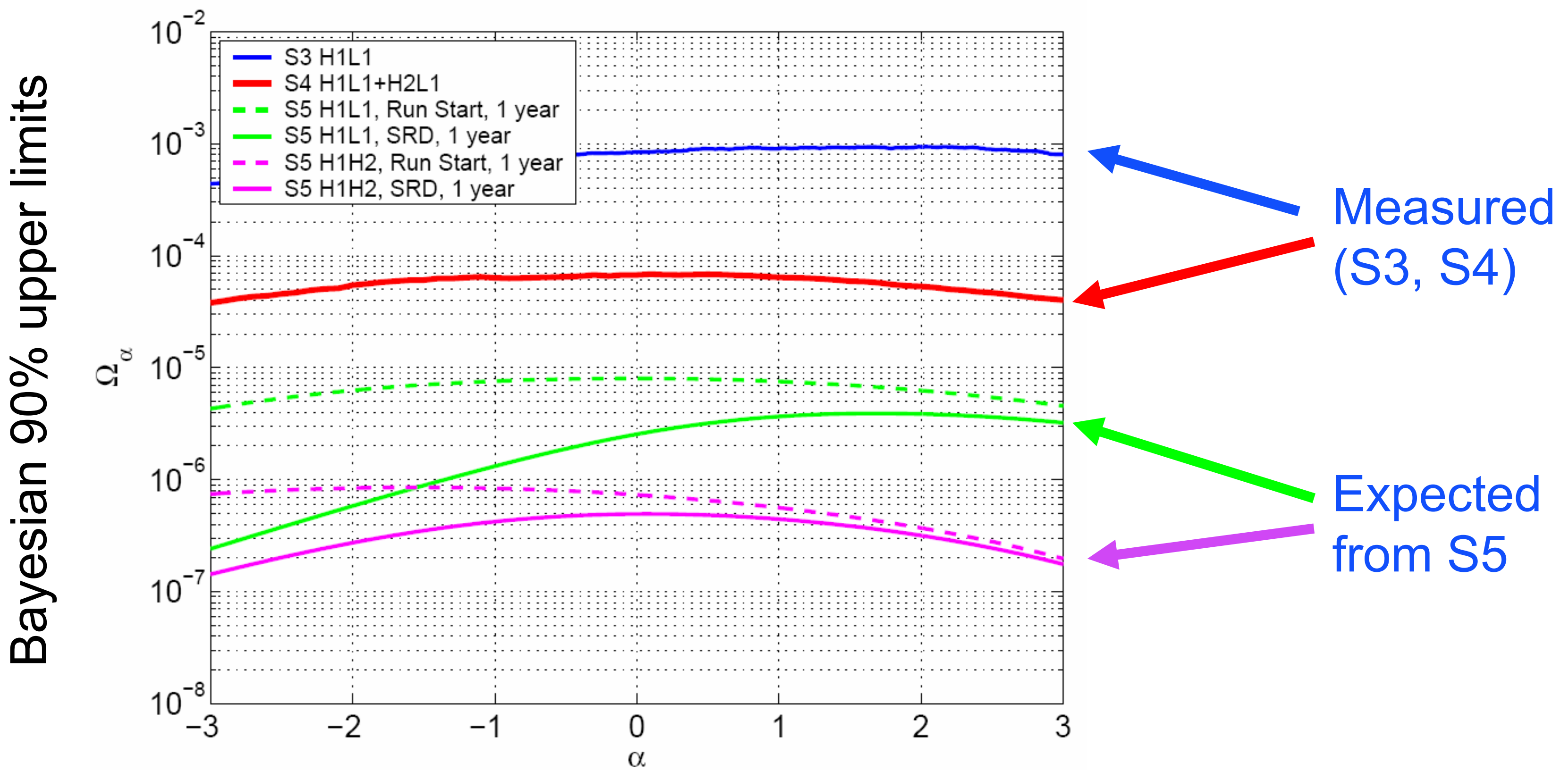
Combined Results

- Weighted average of H1-L1 and H2-L1 measurements (new in S4).
  - Weights: 1/variance(f).
  - $\Omega \pm \sigma_\Omega = (-0.8 \pm 4.3) \times 10^{-5}$
  - h = 72 km/s/Mpc
  - 51-150 Hz (includes 99% of inverse variance)
- Bayesian 90% UL:
  - Use S3 posterior distribution for S4 prior.
  - Marginalized over calibration uncertainty with Gaussian prior (5% for L1, 8% for H1 and H2).

$\Omega_{90\%} = 6.5 \times 10^{-5}$



Results for Other $\Omega_\alpha(f)$



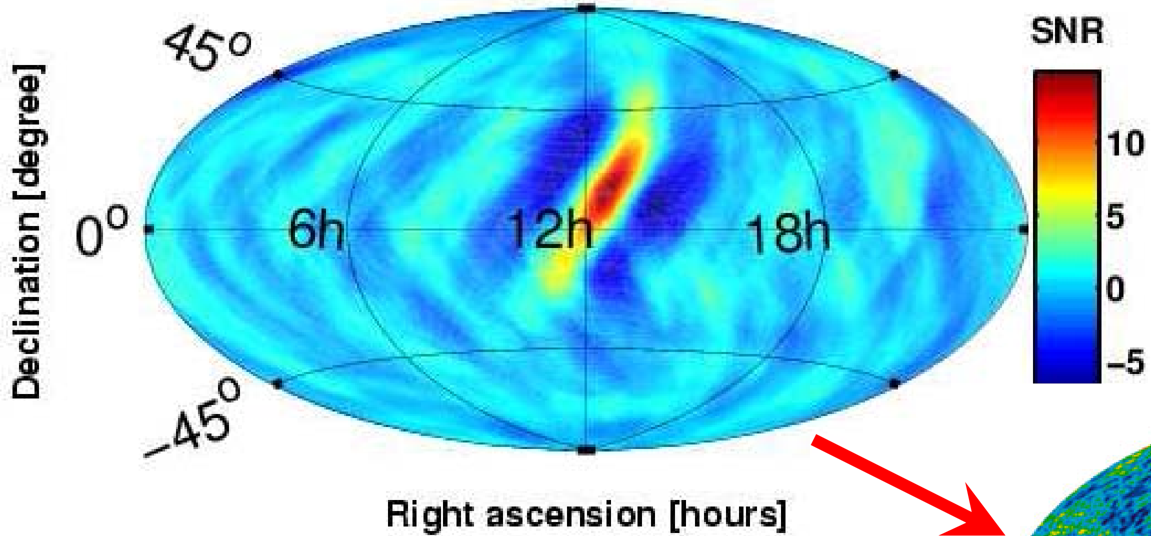
$$\Omega_t(f) = \Omega_\alpha(f/100\ \mathrm{Hz})^\alpha$$

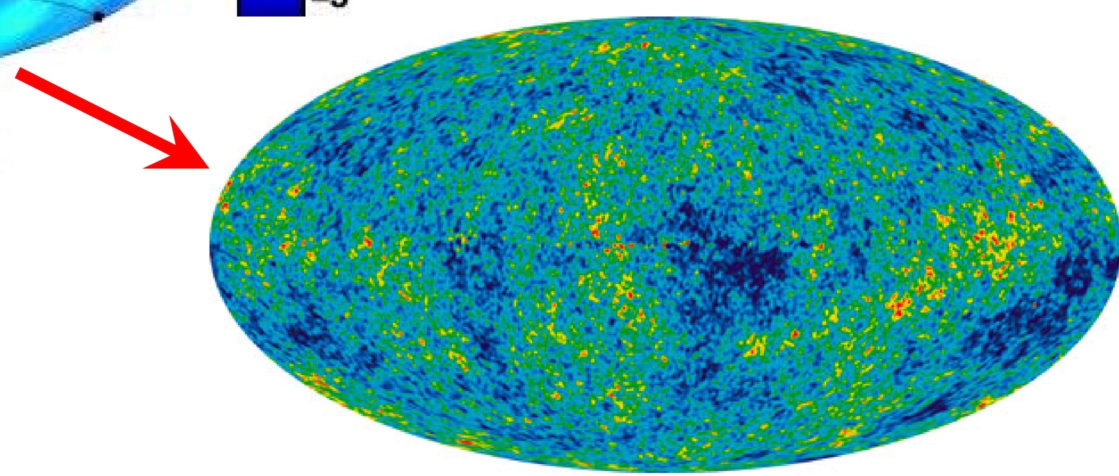
Other Activities

- Directional search ("GW Radiometer")
  - Use cross-correlation kernel optimized for unpolarized point source
  - Ballmer, gr-qc/0510096
- Suppressing correlated noise for H1-H2 pair.
  - Fotopoulos, to be published in Class. & Quant. Grav.
- S4 L1-ALLEGRO (bar detector) search
  - Paper under internal review
- Search at LIGO Free Spectral Range (37.5 kHz).
  - Search for "*very high f*" stochastic GWs @ 2nd harmonic of interferometer free spectral range
  - S4 & S5 analysis in progress

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

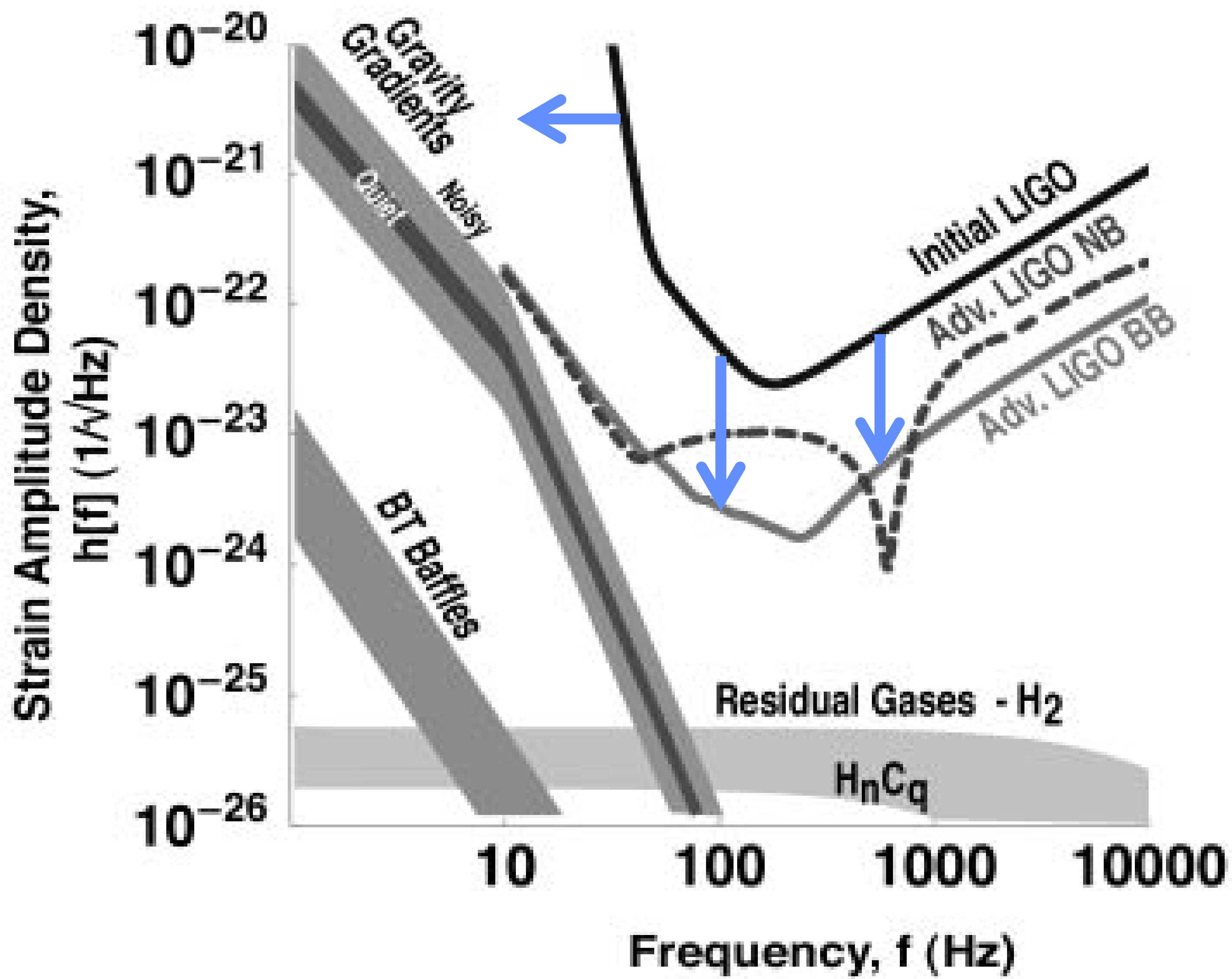




Prospects 2006 - 2010

- The LIGO interferometers are all operating at design sensitivity during S5 run
  - Commissioning has improved both sensitivity, and duty cycle
  - Current S5 will run for 18+ months with goal to accumulate ~ 1year of coincident data at or slightly above design sensitivity
- *At current LIGO-I design sensitivity, we might see*
  - a NS binary inspiral, if rates are at top of allowed range,
  - a burst from a cosmic string cusp, for some plausible parameters from string theory,
  - CW signals from the Crab pulsar, if a large portion of its spin-down is due to emission of gravitational waves
  - a cosmological stochastic background, if it is not far below present upper limits
  - or, a surprise!
- After S5, enhanced upgrade is planned to improve sensitivity in “sweet spot” of the 4 km instruments by factor ~2X
  - 1 - 1.5 year upgrade
- **Conduct a final ~ 2-year LIGO I science run, S6, at better sensitivity -> 6-8X event rate!**

A Look to the Future:
The Era of Advanced LIGO

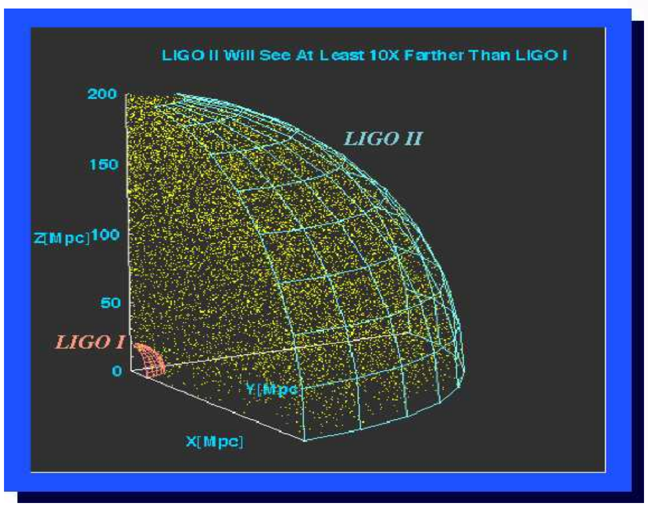


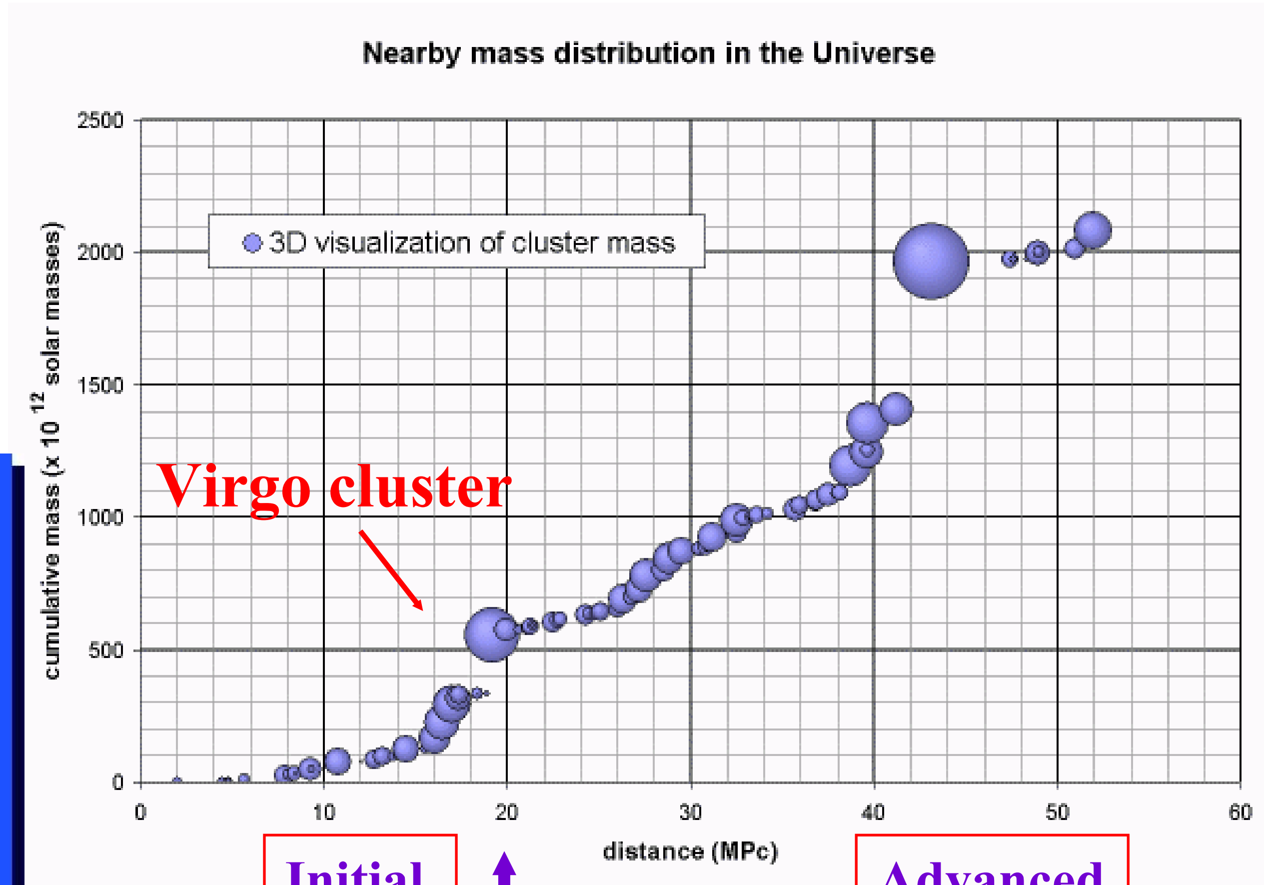
Advanced LIGO:

Cubic Law for "*Window*" on the Universe

Improve amplitude sensitivity by a factor of <u>10x</u>…

…number of sources goes up <u>1000x</u>!





Initial LIGO

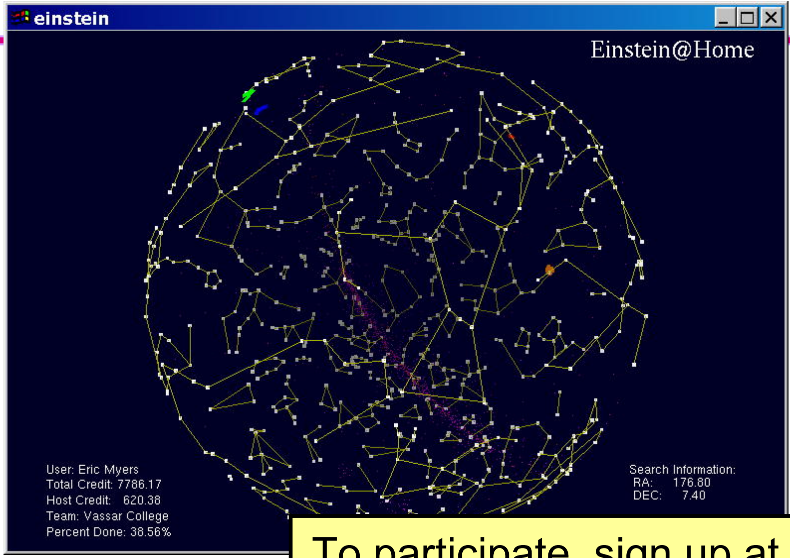
Advanced LIGO

LIGO Science Education Center at Livingston Observatory

- 8000 ft^2 facility with ~50 hands-on exhibits illustrating LIGO science themes
  - Developed in collaboration with S.F. Exploratorium
- School group, family, club visits
- K-12 teacher professional development
- *OPENING IN NOVEMBER!!*

Exploring LIGO Science at Home

- LIGO developed a screensaver application in collaboration with the APS for the 2005 World Year of Physics in celebration of the centennial of Einstein's *Annus Mirabilis*
  - *Analyzes LIGO science data to search for GW pulsars*
  - ***~70,000 CPUs helping LIGO worldwide (> 70 TFLOPS !!!)***



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

- *NSF has produced a NOVA-quality documentary on LIGO*
  - *Einstein's Messengers*
  - *Streamed by LIGO Laboratory:*
    - http://www.ligo.caltech.edu/einstein.ram
- Also available on CD

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

Come on down, y'all

FINIS