LIGO:
Status, Results from the First Science Run, and Plans

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(On behalf of the LIGO Scientific Collaboration)

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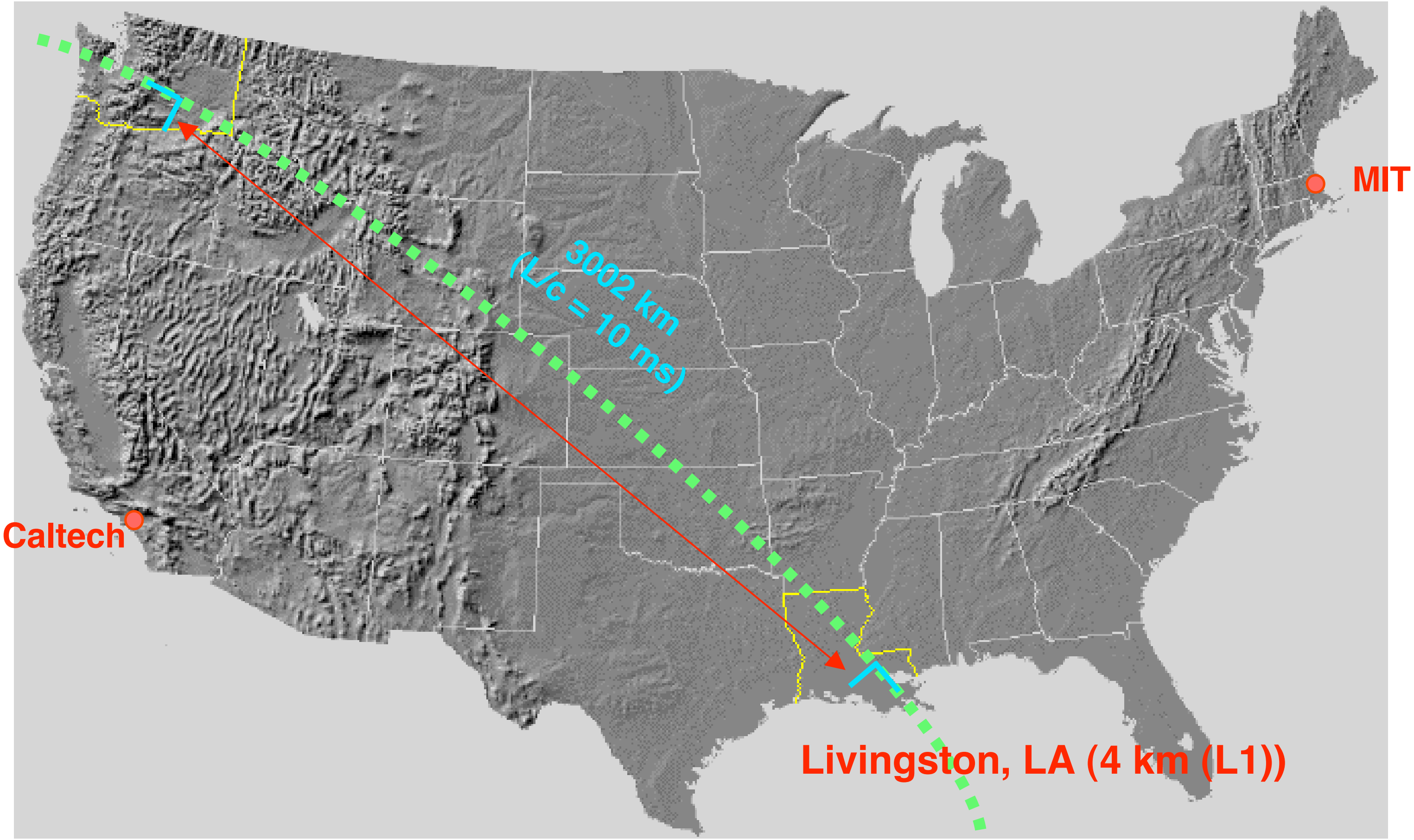
LIGO-G030662-00-E

The LIGO Laboratory Sites

Interferometers are aligned along the great circle connecting the sites

Hanford, WA (4 km (H1) + 2 km (H2))



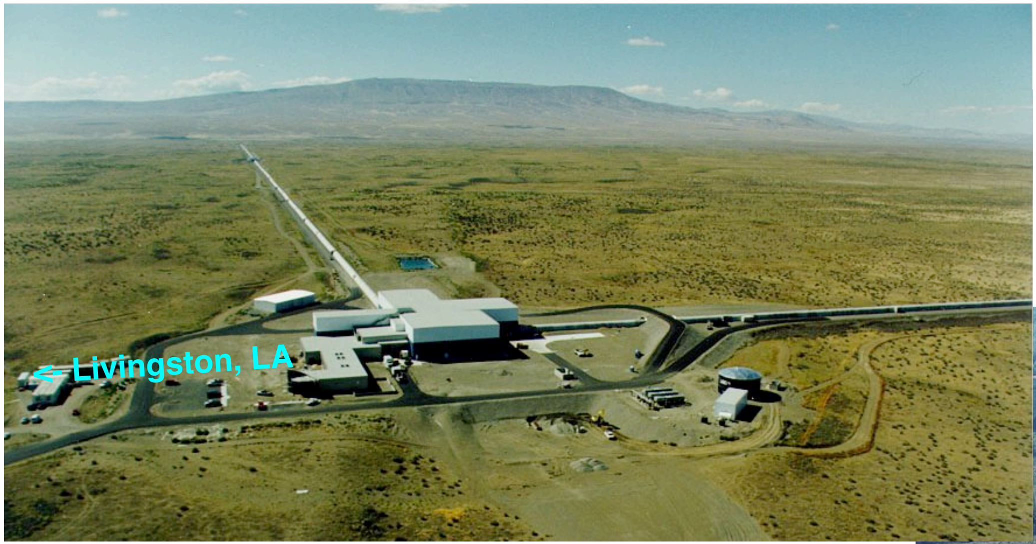
LIGO-G030662-00-E

LIGO Observatories

GEODETIC DATA (WGS84)

h: -6.574 m
ϕ: N30°33'46.419531"
λ: W90°46'27.265294"
X arm: S72.2836°W
Y arm: S17.7164°E

Livingston Observatory
Louisiana
One interferometer (4km)

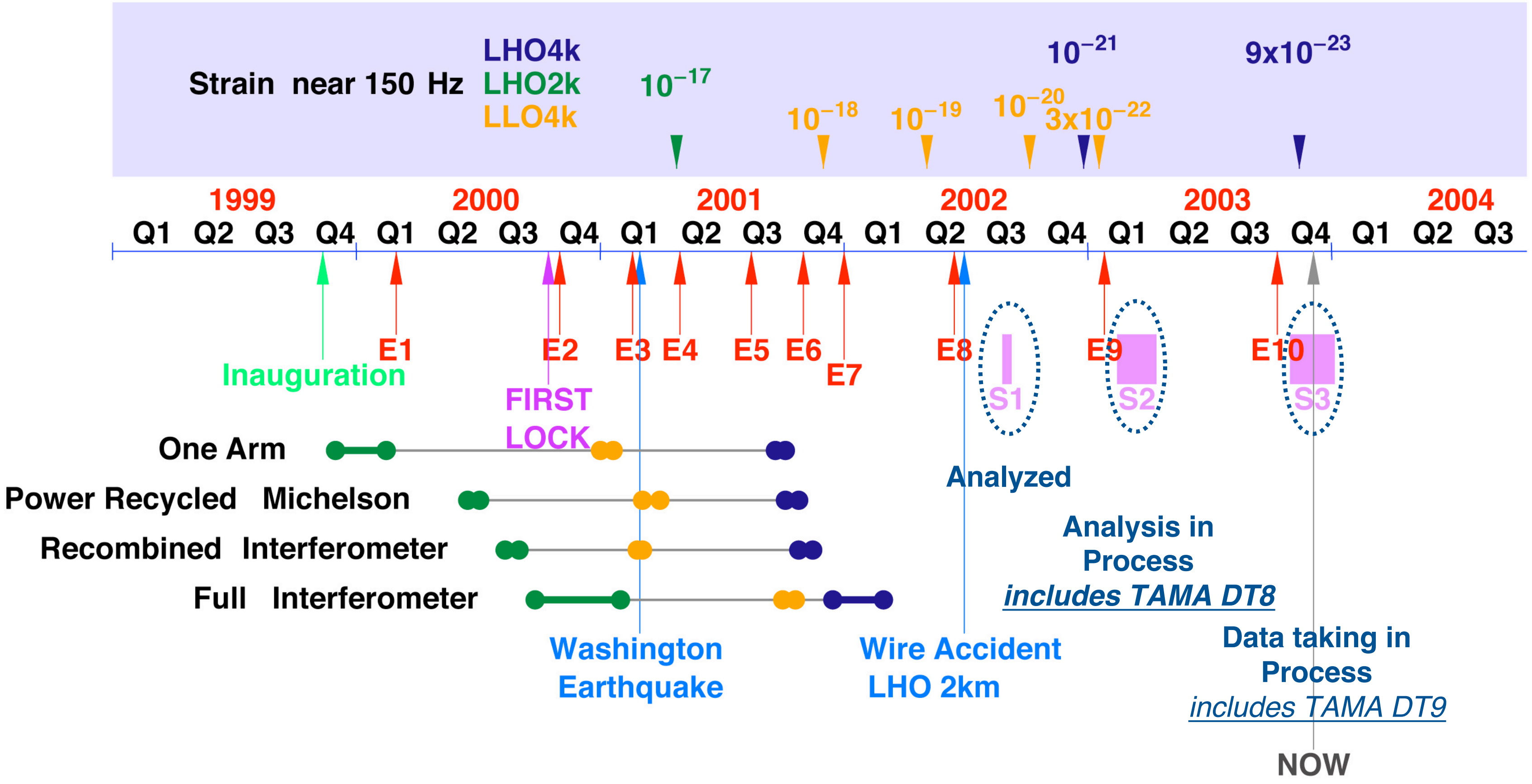


Hanford Observatory
Washington
Two interferometers
(4 km and 2 km arms)

GEODETIC DATA (WGS84)

h: 142.555 m
ϕ: N46°27'18.527841"
λ: W119°24'27.565681"
X arm: N35.9993°W
Y arm: S54.0007°W

LIGO Commissioning and Science Timeline



Strain near 150 Hz

LHO4k
LHO2k
LLO4k

10^{-17} 10^{-18} 10^{-19} 10^{-20} 10^{-21} 3×10^{-22} 9×10^{-23}

1999 2000 2001 2002 2003 2004

Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3

Inauguration

E1 E2 E3 E4 E5 E6 E7 E8 E9 E10

FIRST LOCK

S1 S2 S3

One Arm

Power Recycled Michelson

Recombined Interferometer

Full Interferometer

Washington Earthquake

Wire Accident LHO 2km

Analyzed

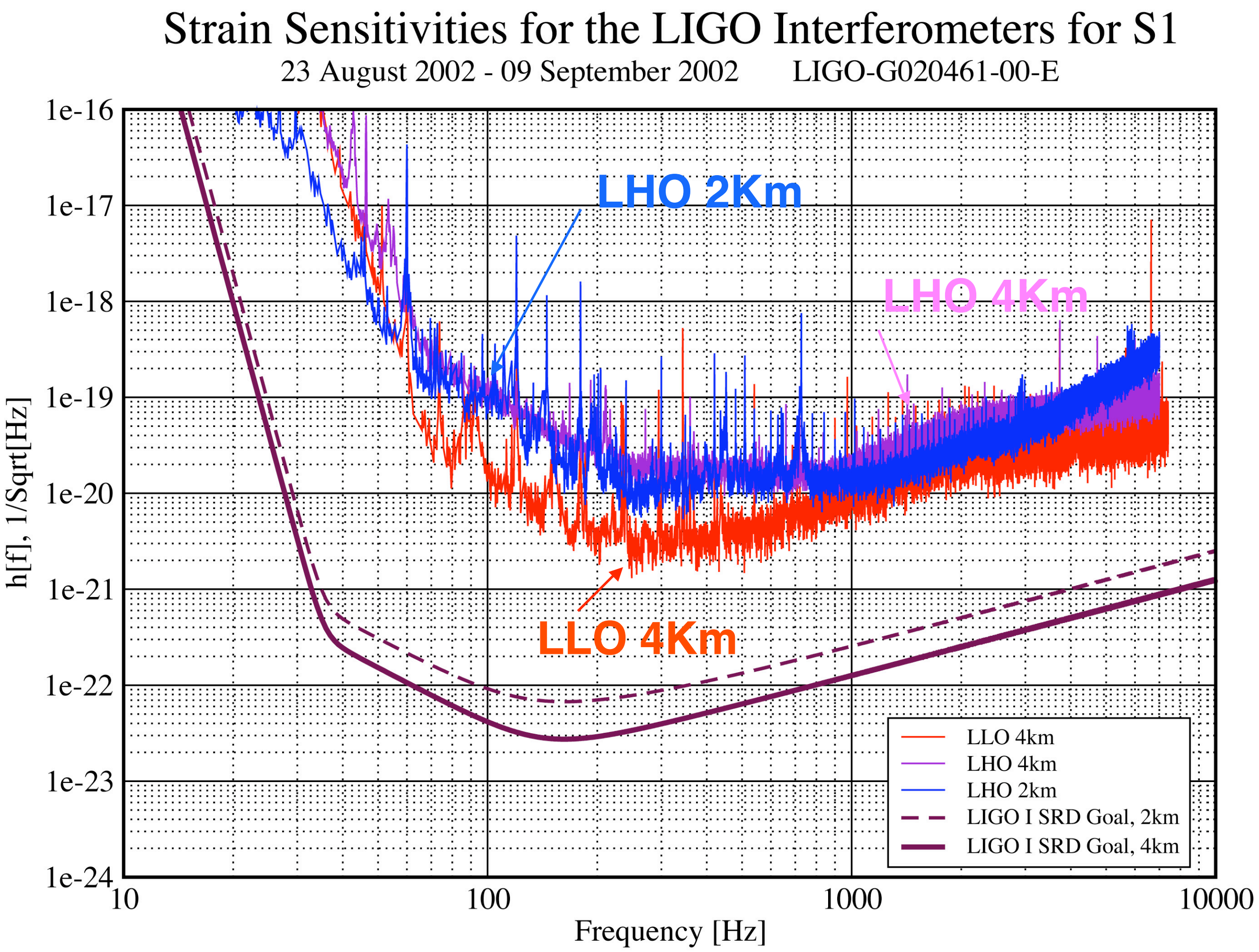
Analysis in Process
includes TAMA DT8

Data taking in Process
includes TAMA DT9

NOW

Sensitivity during S1

- During S1 the 3 LIGO interferometers offered the opportunity for the most sensitive ***coincidence*** observations ever made in the low frequency band around a few hundred Hertz



Summary Science Run Metrics

RUN⇒	**GOAL ("SRD")**		**S1**		**S2** **(results not yet available)**	
IFO **⇓**	*BNS RANGE (kpc)*	*DUTY FACTOR*	*BNS RANGE (kpc)*	*DUTY FACTOR*	*BNS RANGE (kpc)*	*DUTY FACTOR*
L1 (4km)	14,000	90%	~150	43%	900	37%
H1 (4km)	14,000	90%	~30	59%	350	74%
H2 (2km)	7,000	90%	~40	73%	200	58%
3X conic.		75%		24%		22%

Data analysis organization
LIGO Scientific Collaboration (LSC)

Data analysis is organized in **four** working groups organized by source type

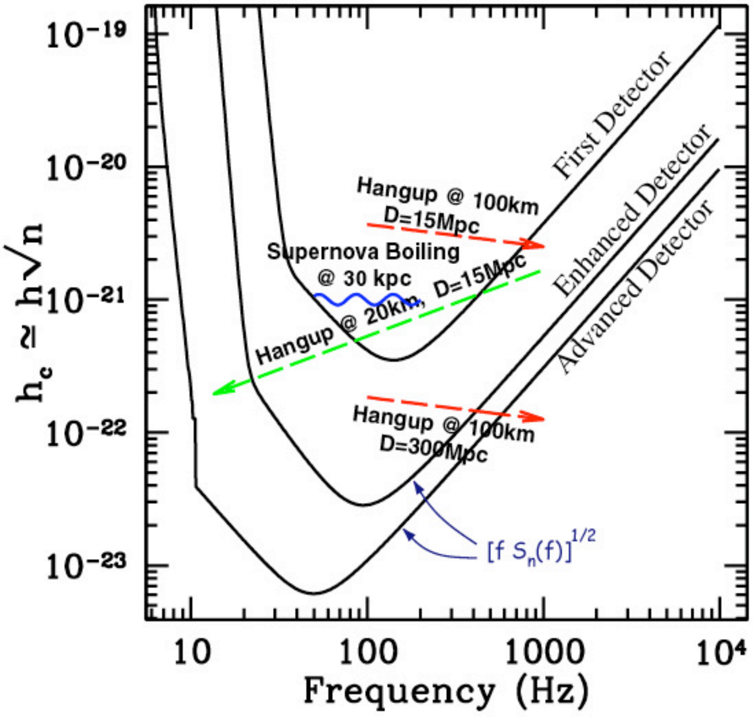
- **Unmodeled Signals -- SNe, GRBs, …**
  - **1. Burst Group**:
    - Non-parametric techniques
      - Excess power in frequency-time domain
      - Excess amplitude change, rise-time in time domain
- **Deterministic Signals:**
  - **2. Binary Inspiral Group**
  - **3. Pulsars/CW Group**
    - Amplitude and frequency evolution parameterized
    - Set of templates covering parameter space matched to data
- **Statistical Signals**
  - **4. Stochastic BG Group**
    - Cross-correlation of detector pairs, look for correlations above statistical variations

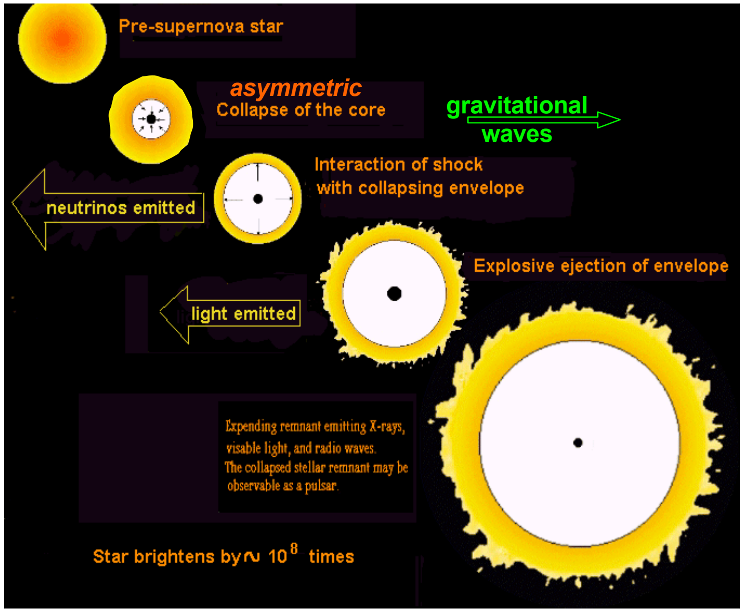
- LIGO S1 author list includes more than 300 scientists and representing more than 30 institutions from the USA, Europe, and Asia.

1. Burst Sources

- Sources:
  Phenomena emitting short transients of gravitational radiation of unknown waveform (supernovae, hypernovae, black hole mergers).
  - »Expected SNe Rate:
    - *1/50 yr - our galaxy*
    - *3/yr - Integrated to distance of Virgo cluster*
- Analysis goals:
  - »Do not bias search in favor of particular signal model(s)
  - »Search in a broad frequency band
  - »Establish bound on rate of instrumental events using [3X] coincidence techniques
  - »Interpret these bounds in terms of source/population models in rate versus strength plots

Sensitivity of LIGO to burst sources





Expending remnant emitting X-rays, visable light, and radio waves. The collapsed stellar remnant may be observable as a pulsar.

Star brightens by ~ 10^8 times

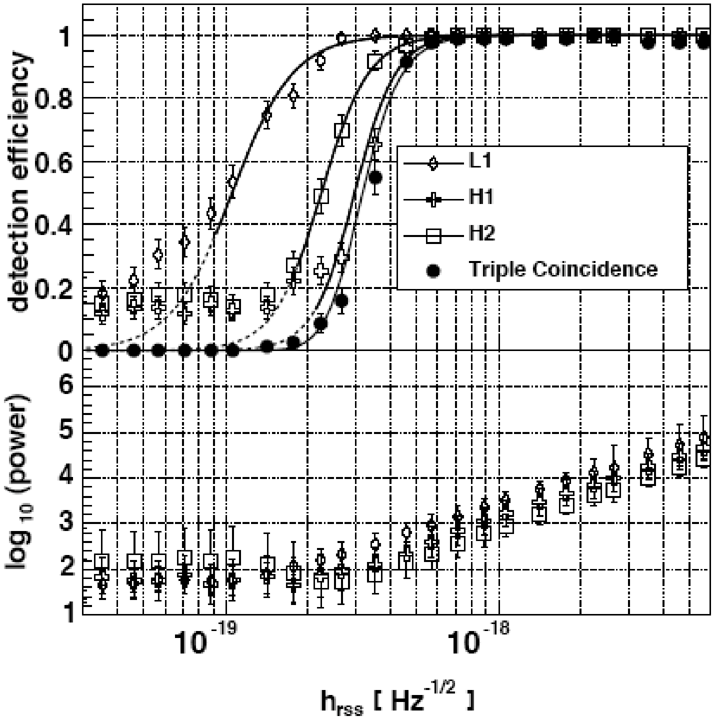
Burst Sources

- S1 Search methods:
  - Create database of ***potential GW*** events with a parallel pipeline analysis
    - "TF-Clusters" algorithm identifies regions in the time-frequency plane with excess power (threshold on pixel power and cluster size) <- ***REST OF THIS DISCUSSION***
    - "SLOPE" algorithm (time domain) is an optimal filter for a linear function of time with a 610 μsec rise-time.
  - ***Veto*** potential GW events by using instrumental, environtmental monitors
    - Tune thresholds using a 10% test dataset from run
  - Use Monte-Carlo studies to determine detection ***efficiency*** as a function of signal strength and model - *Gaussians* (τ), *sine-Gaussians*($f_0, Q := \sqrt{2}\pi\tau f_0$)
  - Use ***time-shift analysis*** to estimate ***background*** rates, and Feldman-Cousins to set upper limits or confidence belts
  - Upper bound: $R(h) \propto N / (\varepsilon(h)\, T)$ <- depends on h
    - N: number observed events
    - $\varepsilon(h)$: detection efficiency for amplitude h
    - T: observation time -- *livetime*
    - Proportionality constant depends on confidence level (CL) -- of order 1 for 90%

Efficiency determination using Monte Carlo

TFCLUSTERS -- Single and triple coincidences

Optimal Wave & Polarization Orientation



$$h_{rss} \equiv \sqrt{\int |h|^2 dt}$$

$$\sqrt{\sqrt{\pi/2}\tau h_0} \text{ (Gaussians)}$$

$$= \sqrt{Q/(4\sqrt{\pi} f_0)} h_0 \text{ (sine-Gaussians)}$$

Detection threshold vs. frequency

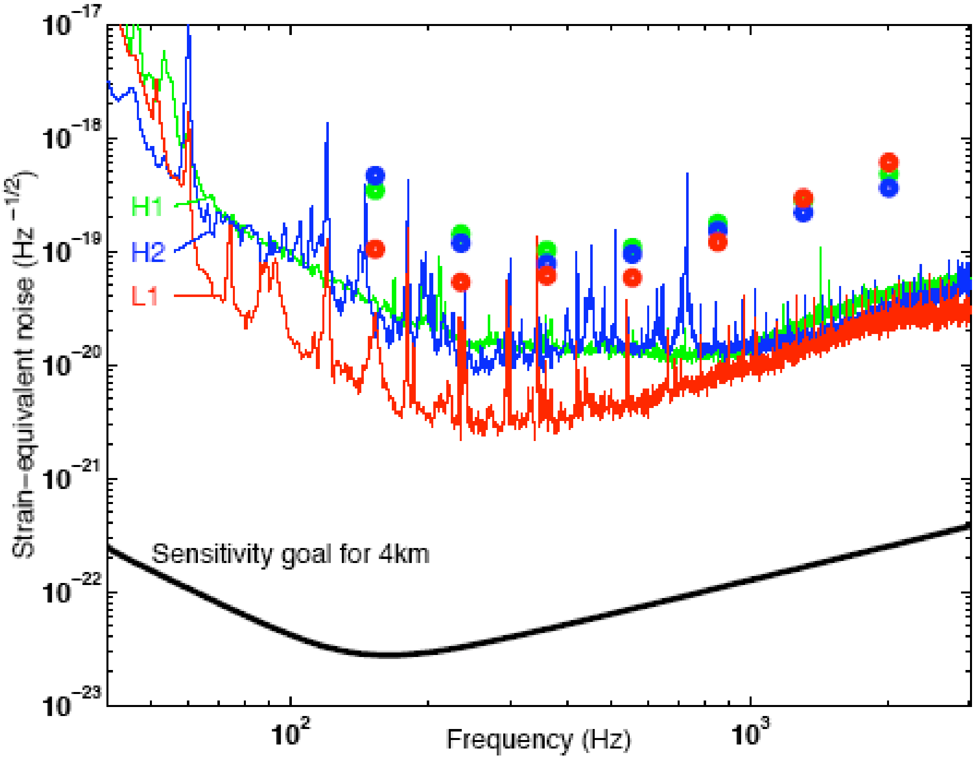


FIG. 1: Typical sensitivities of the three LIGO detectors during the S1 data run, in terms of equivalent strain noise amplitude density. The points are the root-sum-square strain (h_{rss}) of sine-Gaussian bursts for which our TFCLUSTERS analysis pipeline is 50% efficient, as reported in section V B.

Background Estimation and Upper Limits Analysis
TFCLUSTERS algorithm

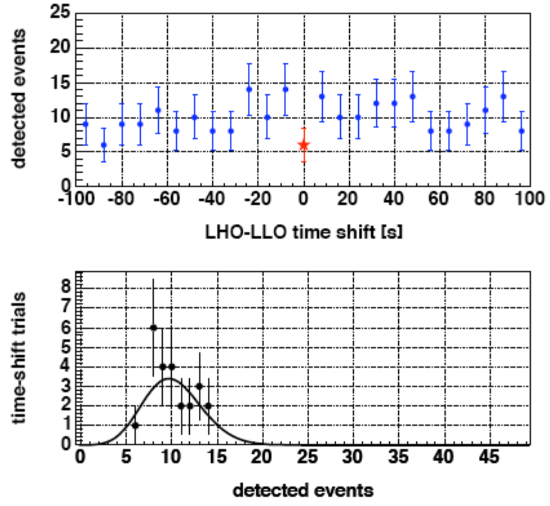


FIG. 6: Time-shifted triple coincident events from TFCLUSTERS event triggers, as a function of an artificial time shift introduced between the Hanford (LHO) and Livingston (LLO) sites. Top: Number of events versus time shift, in 8 second steps; the point at zero time shift is the number of true triple coincident events. Bottom: Histogram of the number of time-shifted coincident events, with the Poisson fit overlaid (the zero time shift point is excluded). In both plots, the error bars are Poissonian.

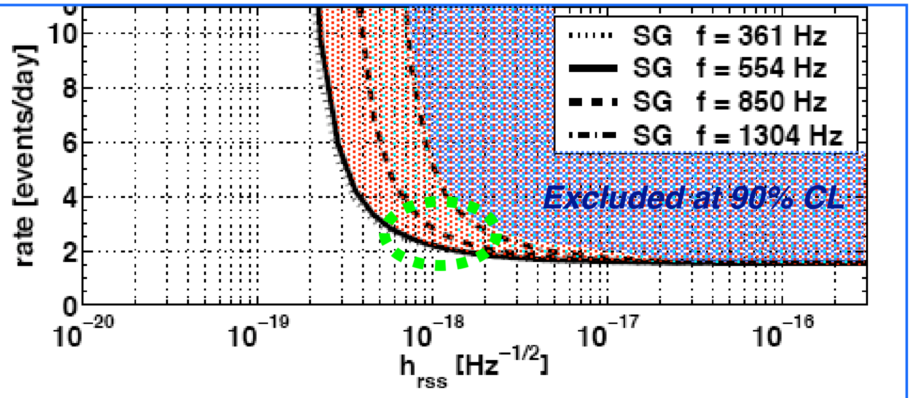


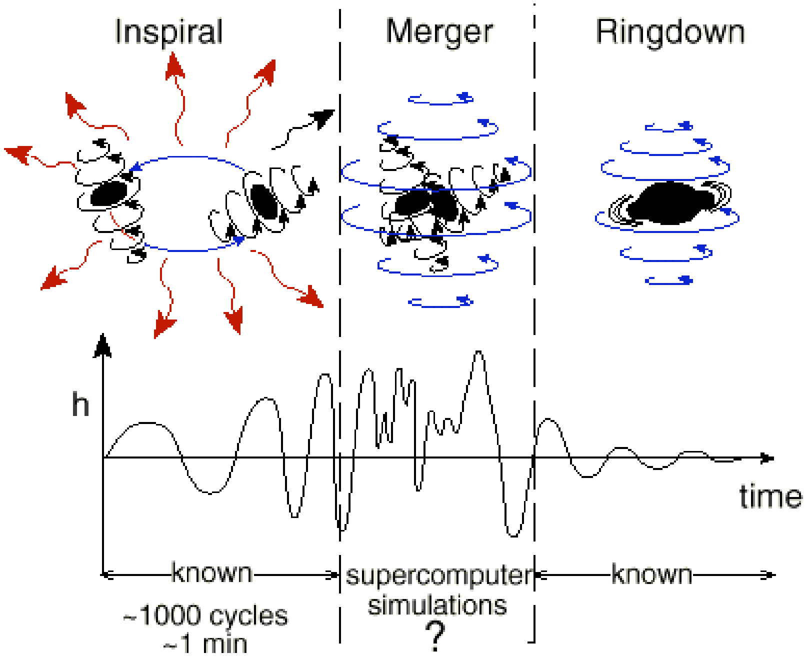
FIG. 15: Rate versus h_{rss} for detection of specific waveforms using the TFCLUSTERS event trigger generator. The region above and to the right of the curves is excluded at 90% confidence level or greater. The effect of the 20% uncertainty in the detector response is included. Top: For Gaussians with $\tau = 1.0$ ms and $\tau = 2.5$ ms. Bottom: For sine-Gaussians with $Q = 9$ and central frequency $f_0 =$ 361, 554, 850 and 1304 Hz.

TABLE I: Confidence bands on the number of excess events in the S1 run (35.5 hours of observation time) from the TFCLUSTERS pipeline.

Coincident events	6
Background	10.1 ± 0.6
90% confidence band	$0 - 2.3$
95% confidence band	$0 - 3.5$
99% confidence band	$0 - 5.9$

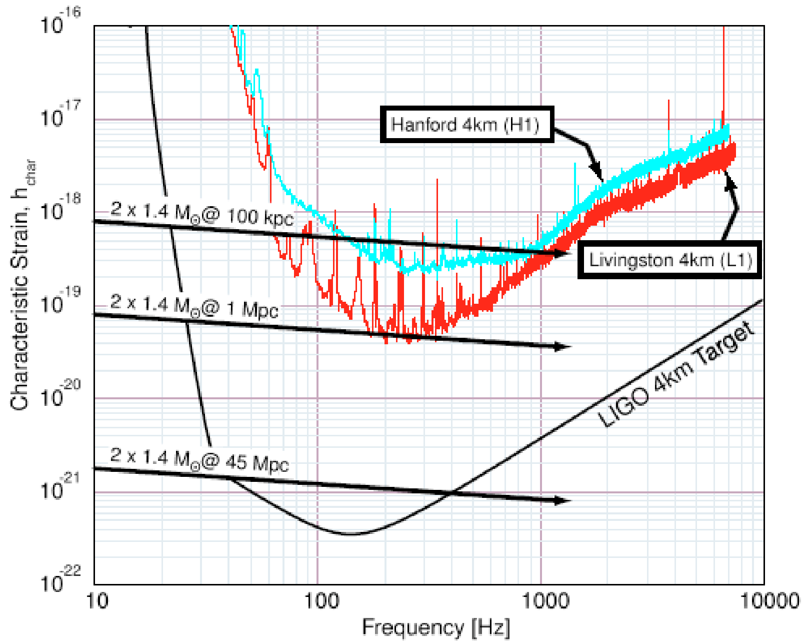
2. Search for compact binary sources

- Sources:
  Compact neutron star binaries undergoing orbital decay and coalescence.
  - Masses, positions, orbital parameters, distances: ***unknown***



Detectability of coalescing binary sources during S1

(for optimal location & orientation relative to antenna pattern)



- Analysis goals:
  - » Develop and test an inspiral detection pipeline incorporating instrumental vetos and multi-instrument coincidence
  - » Obtain upper limit on the NS-NS inspiral rate
    - For setting upper limits, need a source distribution model:
      - ***S1 range included Milky Way (our Galaxy) and LMC and SMC***
      - ***S2 range includes Andromeda***

Search for compact binary sources

- S1 Search method:
  - » Optimal Filtering used to generate GW candidates -- “triggers”
    - – Used only most sensitive two interferometers: H1 and L1. Distance to an optimally located & oriented SNR=8 source is ***L1: 176 kpc, H1: 46 kpc***.
    - – Bank of 2110 second post-Newtonian stationary-phase templates for $1 < m_1 \leq m_2 < 3\ M_{sun}$ with 3% maximum mismatch for $(m_1 + m_2) < 4\ M_{sun}$
    - – Thresholds on
      - •Signal-to-noise (SNR) : $\rho(t) == |z(t)|/\sigma_z > 6.5$ $\quad z(t) = x(t) + iy(t) = 4 \int_0^\infty \frac{\tilde{h}_c^I(f)\tilde{s}^*(f)}{S_n(f)} e^{2\pi i f t} df$
      - •Distribution of SNR : $\chi^2(t) = \frac{p}{\sigma^2} \sum_{l=1}^{p} |z_l(t) - z(t)/p|^2$

        p = 8 frequency bins, each containing 1/8 of total SNR
    - – Process ancillary channels to generate “vetoes” and cull data. Criteria established with playground dataset:
      - •Eliminate 360s of contiguous science-mode intervals having large band-limited strain noise (3σ -- lowest band; 10σ -- higher bands) compared to run averages.
      - •H1: vetoed ±1 second windows from reflected port PD (*laser freq. noise*), eliminating 0.2% of data.
  - » ***Detection :*** require coincidence in time (<11 ms) and chirp mass (<1%) for triggers which are strong enough to be seen in both detectors
  - » ***Upper limit:*** set by measured detection efficiency at highest SNR event

- Compact Binaries - Diurnal variation of interferometer range during S1

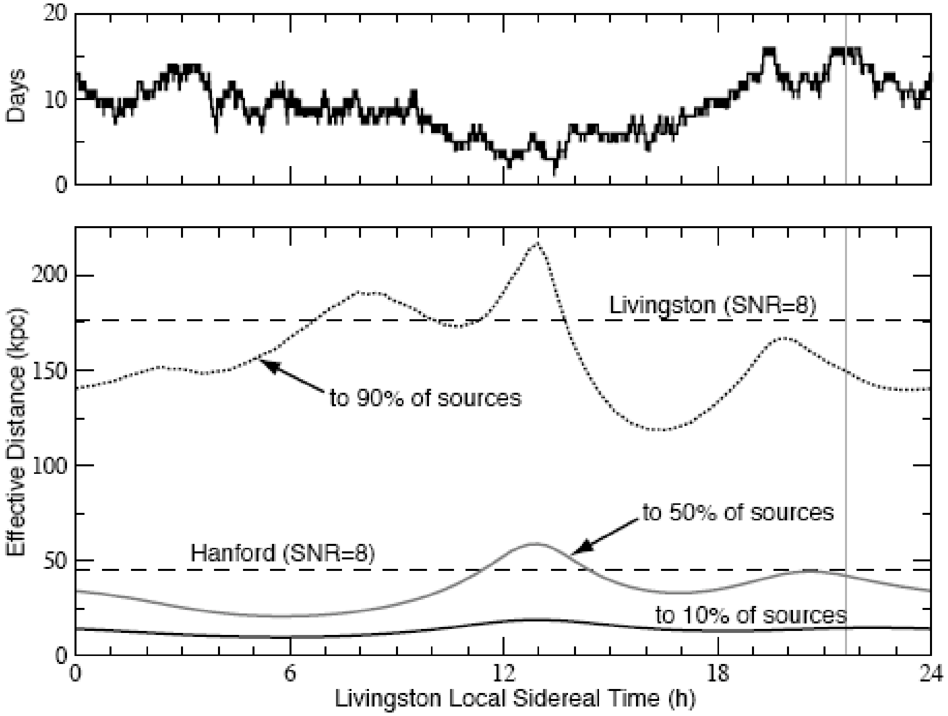


FIG. 2: Summary of detector status and sensitivity to the population of neutron stars described in Sec.   as a function of sidereal time. For a given sidereal time, the upper panel shows the number of days during the run when at least one of the interferometers (H1 or L1) was collecting scientific data. For reference, the vertical dotted line indicates 05:00 UTC (corresponding to midnight at Livingston) on September 01, 2002. The lower panel shows the effective distance as measured in Livingston [and defined by Eq. ( )] to 10%, 50%, and 90% of the binary neutron star population described in Sec. . The horizontal dashed lines show the average distance at which an inspiral of $2 \times 1.4 M_\odot$ neutron stars, in the optimal direction and orientation with respect to each detector, would produce a signal-to-noise ratio of 8, *i.e.* 176 kpc for L1 and 46 kpc for H1.

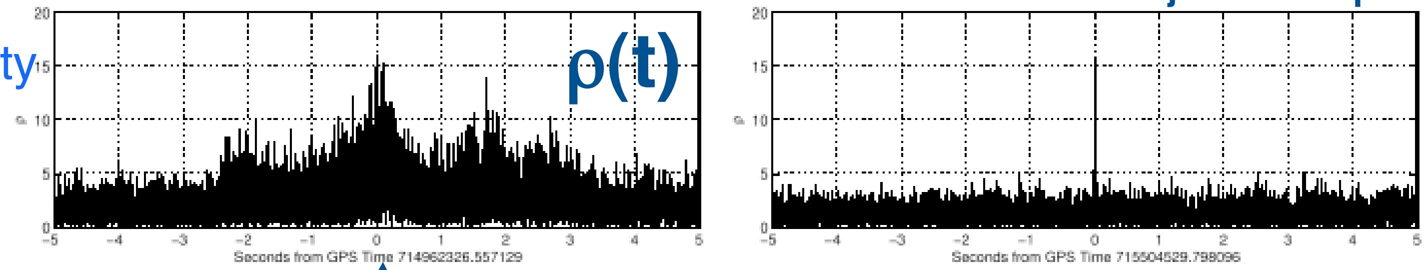
Compact binary sources

Setting an upper limit on coalescence rate during S1

Catalog of largest SNR events after pipeline analysis

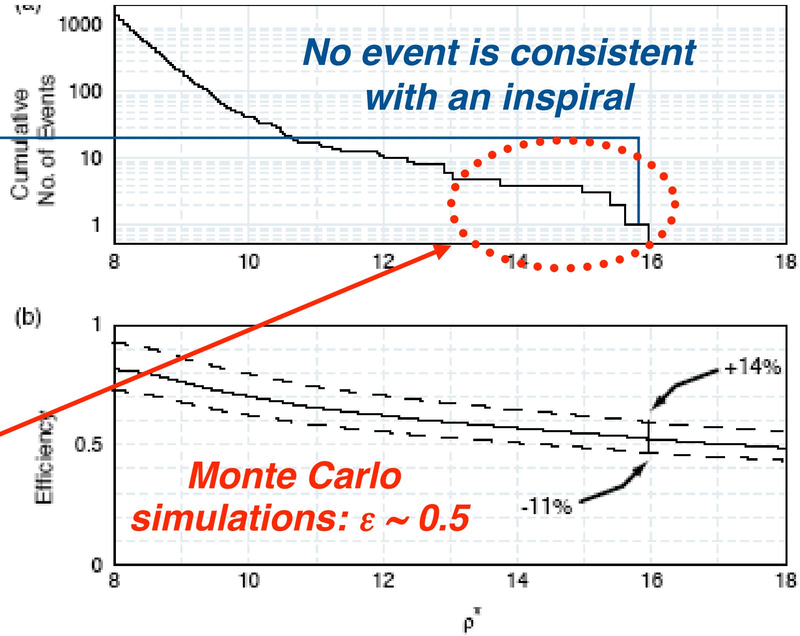
- Due to the sensitivity mismatch and low duty cycles during S1, highest SNR events were *only seen* in the Livingston interferometer

S1 data -- details of SNR = 15.9 event … vs … M.C. simulation: Injected chirp



5 highest SNR events

Date 2002	Time (UTC)	Detector(s)	SNR	χ^2/DOF	D_{eff} (kpc)	m_1 (M_{sun})	m_1 (M_{sun})
9/2	00:38:33.56	L1 only	15.9	4.3	95	1.31	1.07
9/8	12:31:38.28	L1 only (H1 on)	15.6	4.1	68	1.95	0.92
8/25	13:33:31.00	L1 only	15.3	4.9	101	3.28	1.16
8/25	13:29:24.25	L1 only	14.9	4.6	89	1.99	1.99
9/2	13:06:56.73	L1 only	13.7	2.2	96	1.38	1.38



No event is consistent with an inspiral

Monte Carlo simulations: ε ~ 0.5

FIG. 6: Panel (a) shows the number of events in the data with SNR > ρ^* as a function of ρ^*. The largest event has SNR = 15.9. Panel (b) shows the detection efficiency $\epsilon(\rho^*)$ for sources in the target population (Milky Way and Magellanic Clouds) as a function of ρ^*. The dashed lines indicate boundaries of our estimated systematic errors on the efficiency.

Compact binary sources
Upper limit on coalescence rate during S1

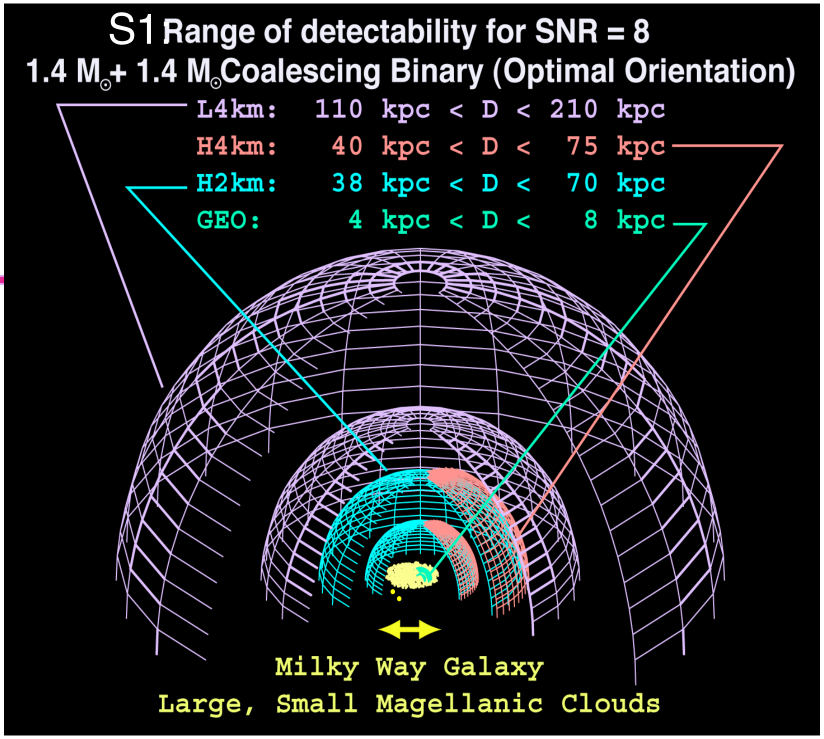
- ***FULL GALACTIC COVERAGE*** - limit on binary neutron star coalescence rate:
  - »Observation time: T = 236 h = 0.027 y
  - »Observed population: (ε = detection eff.)

N_G = 0.6 (= ε 1.13 MWEG*) $^{+\,0.12}_{-\,0.10}$ (systematic)

= 0.5 (min)

$$\mathcal{R}_{90\%} = 2.303 \times \left(\frac{1\text{ y}}{T}\right)\left(\frac{1}{N_G}\right)\ \text{y}^{-1}\ \text{MWEG}^{-1}\,{}^{*}$$

$$\mathcal{R} < 1.7 \times 10^{2}\ \text{y}^{-1}\ \text{MWEG}^{-1}$$



MWEG = "Milky Way Equivalent Galaxy"

Sensitive to Milky Way + SMC + LMC = 1.13 Milky Way Equivalent Galaxies

No event candidates found in coincidence

90% confidence upper limit in the (m_1, m_2) range of 1 to 3 M_{sun}

- *26X lower than best previous LIGO observational limit -- 40m prototype at Caltech[1]:*
  - *»$R_{90\%}$ (Milky Way) < 4400 /yr*
- *Recent TAMA analysis (1000 hr run)[2] gave a slightly better result:*
  - *»R < 123 /yr for MW Galaxy*

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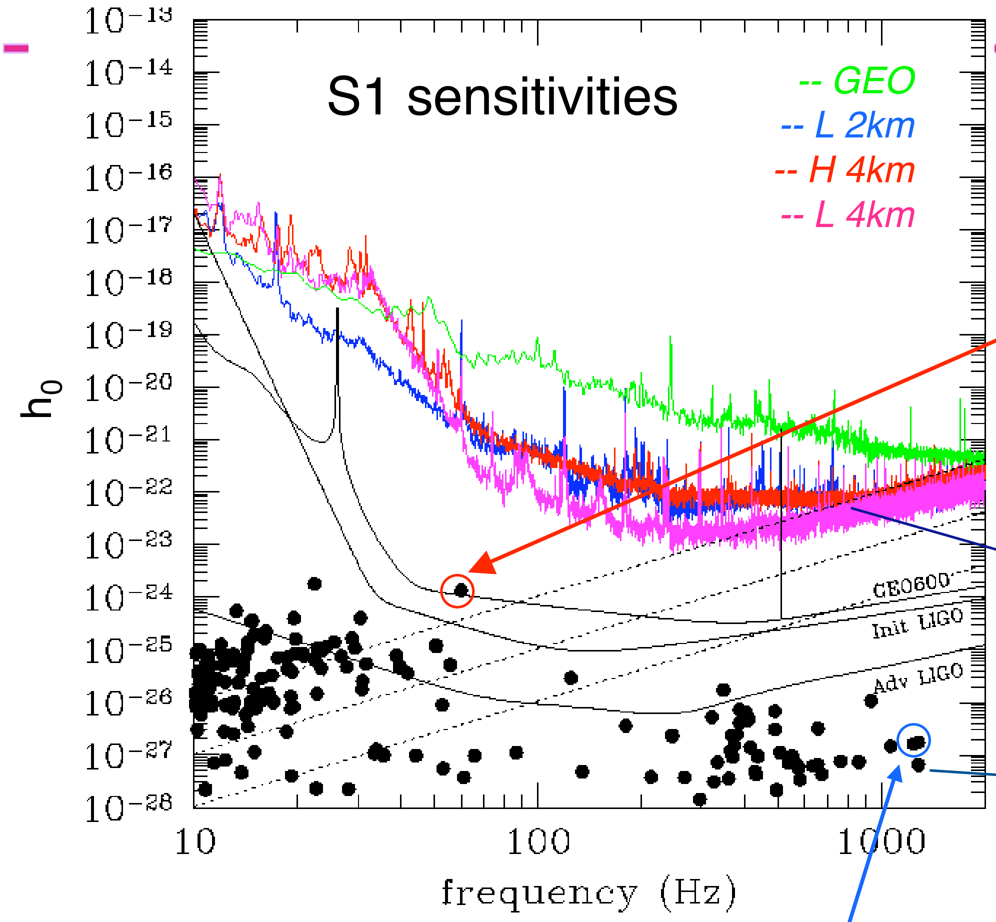
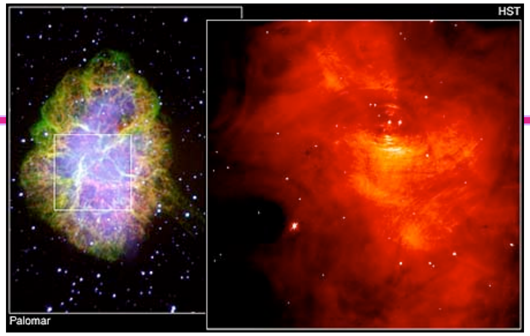
[1] *1994 data, Allen et al., Phys.Rev.Lett. 83 (1999) 1498*

[2] *TAMA Collaboration, 28th International Cosmic Ray Conference Proc, p3059*

3. Periodic sources



Crab pulsar



- h_0: Amplitude detectable with 99% confidence during observation time T

$$\langle h_0 \rangle = 11.4\sqrt{S_n(f_s)/T}$$

- *Limit of detectability for rotating NS with equatorial ellipticity, $\varepsilon = \delta I/I_{zz}$:*

  10^{-3} , 10^{-4} , 10^{-5} @ 10 kpc

- ***Known** EM pulsars*
  - *Values of h_0 derived from measured spin-down*
    - *IF spin-down were entirely attributable to GW emissions*
    - *Rigorous astrophysical upper limit from energy conservation arguments*

PSR J1939+2134
P = 0.00155781 s
f_{GW} = *1283.86 Hz*
$\dot{P}$ = 1.0519 10^{-19} s/s
D = 3.6 kpc

Search for Continuous Waves

- Source:
  PSR J1939+2134 (fastest known rotating neutron star) located 3.6 kpc from Earth
  - Known quantities:
    - Frequency of source
    - Rate of change of frequency (spindown)
    - Sky coordinates (α, δ) of source
  - Unknown quantities for search:
    - Amplitude h_0 (though spindown implies $h_0 < 10^{-27}$)
    - Orientation ι
    - Phase, polarization φ, ψ
- S1 Analysis goals:
  - Search for emission at 1283.86 Hz (2 f_{EM}). Set upper limits on strain amplitude h_0.
  - Develop and test an analysis pipeline optimized for efficient "known target parameter" searches (*time domain method*)
  - Develop and test an efficient analysis pipeline that can be used for blind searches (*frequency domain method*)

Search for Continuous Waves

- S1 Search Methods:
  - »Performed for four interferometers: L1, H1, H2, GEO
  - »No joint interferometer result (timing problems, L1 best anyway)
  - »Time-domain method (sets Bayesian upper limit): <- ***REST OF THIS DISCUSSION***
    - – Heterodyne data (with fixed freq) to 4 samples/second
    - – Heterodyne data (with doppler/spindown) to 1 sample/minute -- time series, $B(t_k)$
    - – Calculate $\chi^2(h_0, \iota, \varphi, \psi)$ for source model, antenna pattern
      - Easily related to probability distribution function (for noise Gaussian)
    - – Marginalize over ι, φ, ψ to get PDF for (and upper limit on) h_0
    - – Well suited for searches targeting pulsars with known EM counterparts
  - »Frequency-domain method (optimal for blind detection, frequentist upper limit):
    - – Take short-time FTs of (high-pass filtered) 1-minute stretches of GW channel
    - – Calibrate in the frequency domain, weight by average noise in narrow band
    - – Compute $\mathcal{F}$ == likelihood ratio (analytically maximized over ι, φ, ψ)
    - – Obtain upper limit using Monte-Carlo simulations, by injecting large numbers of simulated signals at nearby frequencies

Power spectra near pulsar f_{GW}

Narrowband noise obeys Gaussian statistics

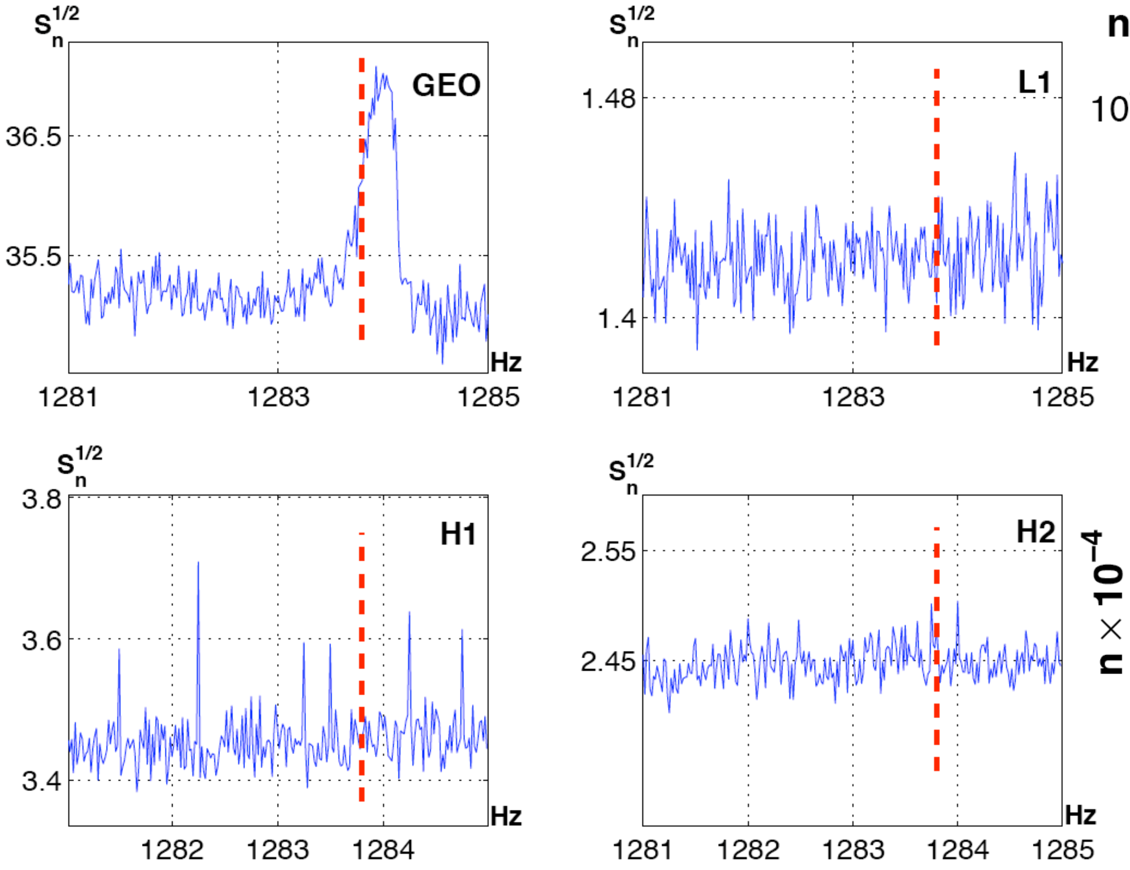
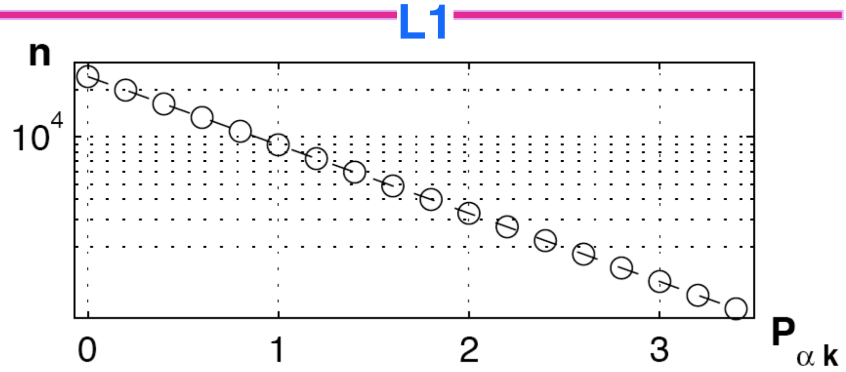
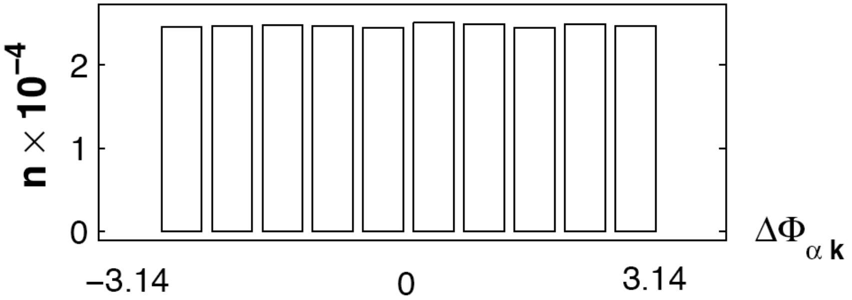


FIG. 5: $\sqrt{S_n}$ in a band of 4 Hz (starting at 1 281 Hz) using the entire S1 data set analyzed from the four interferometers. The noise $\sqrt{S_n}$ is shown in units of $10^{-20}\ \mathrm{Hz}^{-1/2}$. The dashed vertical line indicates the expected frequency of the signal received from J1939+2134.



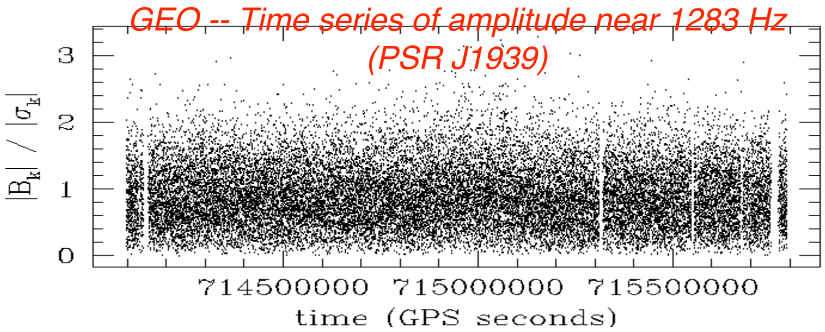
$$P_{\alpha k} = \frac{|\tilde{x}_{\alpha k}|^2}{\sum_k^M |\tilde{x}_{\alpha k}|^2 / M}$$



$$\Delta\Phi_{\alpha k} = \Phi_{\alpha k} - \Phi_{\alpha k-1}$$

For Gaussian amplitude noise:
- *exponential (Rayleigh) power dist.*
- *uniform phase dist.*

Time domain behavior of data follow ideal behavior for Gaussian noise at pulsar f_{GW}


GEO -- Time series of amplitude near 1283 Hz (PSR J1939)

- *$B_k(t_k)$ are the down-sampled & heterodyned data series*
  - ✓Residuals are normal deviates with N[0,1] -> χ^2 per DOF ~ 1

- *$y(t_k;$ **a**$)$* is source model
  - ***a** = $\{h,I,\psi,\phi_0\}$* - parameters

$$y(t_k;\mathbf{a}) = \frac{1}{4}F_+(t_k;\psi)h_0(1+\cos^2\iota)e^{i2\phi_0} - \frac{i}{2}F_\times(t_k;\psi)h_0\cos\iota\, e^{i2\phi_0}.$$

- Probability distribution function of data given model:

$$p(\mathbf{a}|\{B_k\}) \propto p(\mathbf{a})\exp\left[-\sum_k \frac{\Re\{B_k - y(t_k;\mathbf{a})\}^2}{2\sigma^2_{\Re\{B_k\}}}\right] \times \exp\left[-\sum_k \frac{\Im\{B_k - y(t_k;\mathbf{a})\}^2}{2\sigma^2_{\Im\{B_k\}}}\right]$$

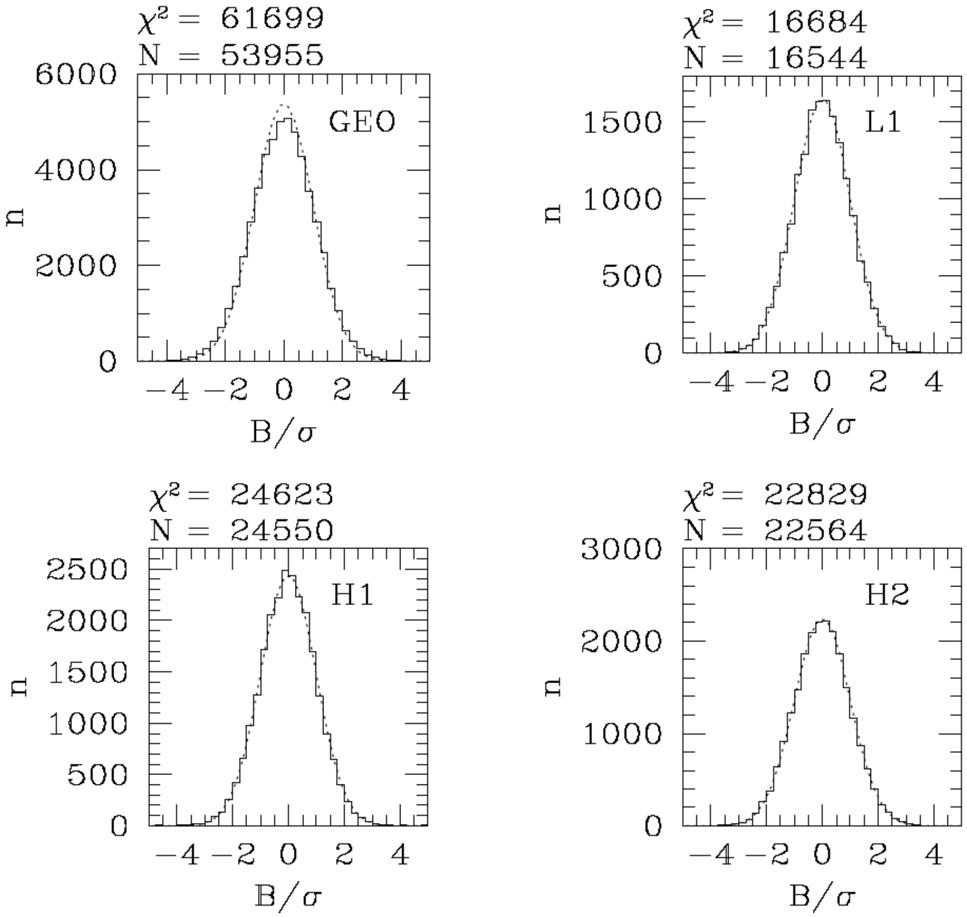


FIG. 7: Histograms of $B/\sigma = \Re(B_k)/\sigma_{\Re\{B_k\}} + \Im(B_k)/\sigma_{\Im\{B_k\}}$ for each interferometer. The dotted lines represent the expected Gaussian distribution, with $\mu = 0$ and $\sigma = 1$.

Bayesian upper limits from time domain analysis

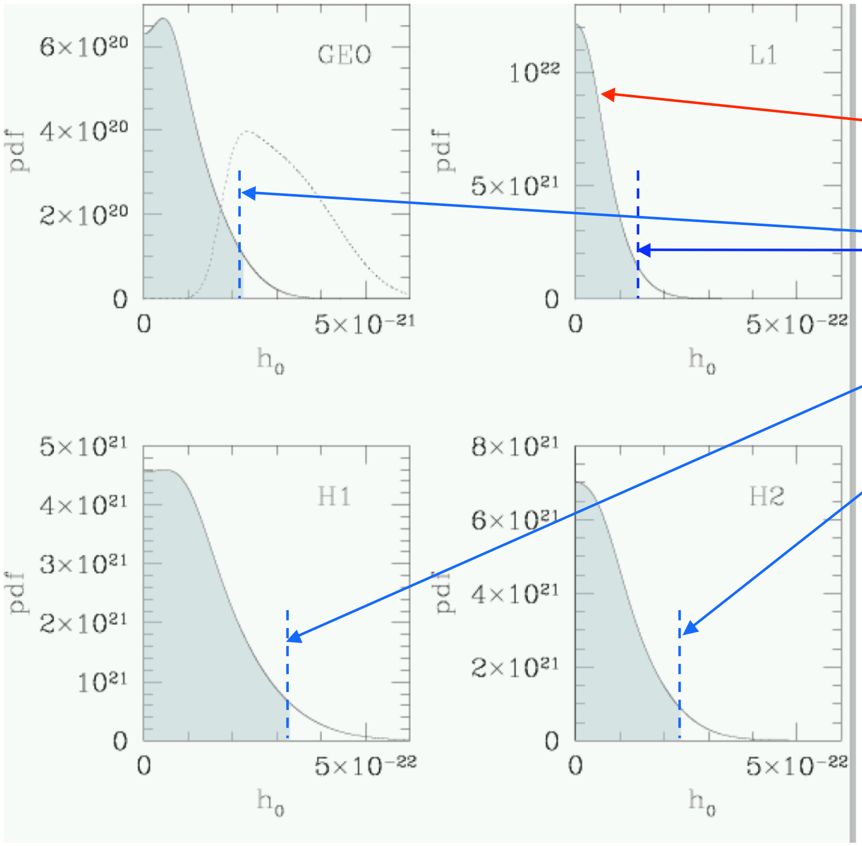


FIG. 8: For each interferometer, the solid line represents the marginalized posterior pdf for h_0 (PSR J1939+2134) resulting from the S1 data. The 95% upper limits (extent of the shaded region) are 2.2×10^{-21} for GEO, 1.4×10^{-22} for L1, 3.3×10^{-22} for H1 and 2.4×10^{-22} for H2. The dotted line in the GEO plot shows the posterior pdf of h_0 in the presence of a simulated signal injected into the GEO S1 data stream using $h_0 = 2.2 \times 10^{-21}$, $\phi_0 = 0°$, $\psi = 0°$ and $\iota = 0°$.

$$p(h_0|\{B_k\}) \propto \iiint p(\mathbf{a}|\{B_k\})\, d\iota\, d\psi\, d\phi_0$$

$$0.95 = \int_0^{h_0^{95\%}} p(h_0|\{B_k\})\, dh_0$$

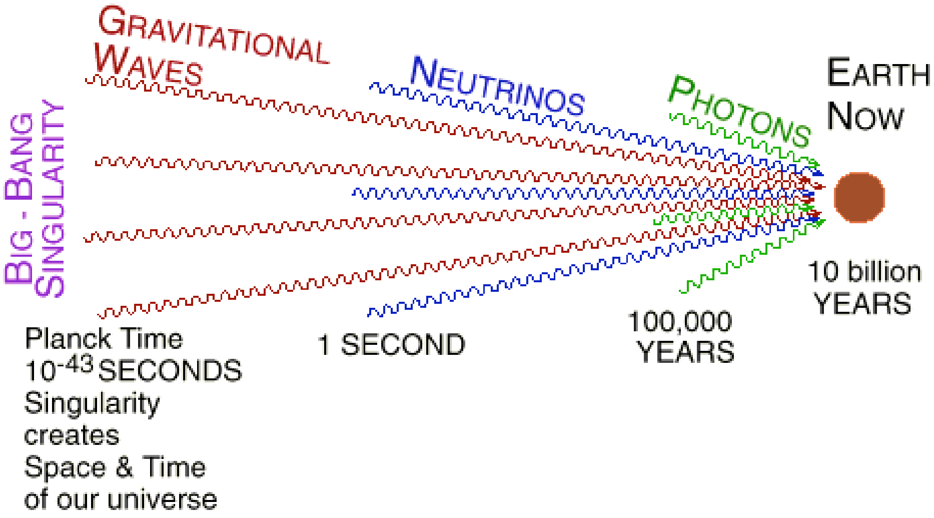
IFO	Frequentist FDS	Bayesian TDS
GEO	$(1.9 \pm 0.1) \times 10^{-21}$	$(2.2 \pm 0.1) \times 10^{-21}$
L1	$(2.7 \pm 0.3) \times 10^{-22}$	$(1.4 \pm 0.1) \times 10^{-22}$
H1	$(5.4 \pm 0.6) \times 10^{-22}$	$(3.3 \pm 0.3) \times 10^{-22}$
H2	$(4.0 \pm 0.5) \times 10^{-22}$	$(2.4 \pm 0.2) \times 10^{-22}$

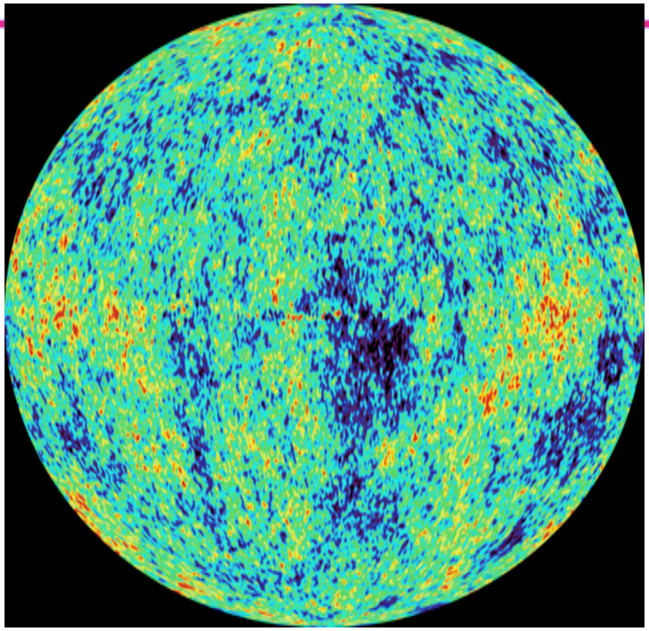
TABLE IV: Summary of the 95% upper limit values of h_0 for PSR J1939+2134. The frequency domain search (FDS) quotes a conservative frequentist upper limit and the time domain search (TDS) a Bayesian upper limit after marginalizing over the unknown ι, ψ and ϕ_0 parameters.

Upper limit on h_0 implies upper limit on ε:

$$\boxed{\epsilon^{95\%} = 2.9 \times 10^{-4} \left(\frac{10^{45}\ \mathrm{g\ cm}^2}{I_{zz}}\right)}$$

4. Stochastic gravitational wave background





Analog from cosmic microwave background -- WMAP 2003

- Detect by cross-correlating interferometer outputs in pairs

$$Y \equiv \int_{-T/2}^{T/2} dt_1 \int_{-T/2}^{T/2} dt_2\, s_1(t_1)\, Q(t_1 - t_2)\, s_2(t_2)$$

  - Hanford - Livingston, Hanford - Hanford

- Good sensitivity requires:
  - $\lambda_{GW} \geq 2D$ (detector baseline)
  - $f \leq 40$ Hz for L - H pair
- Initial LIGO limiting sensitivity: $\Omega < 10^{-6}$

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

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

Stochastic background radiation

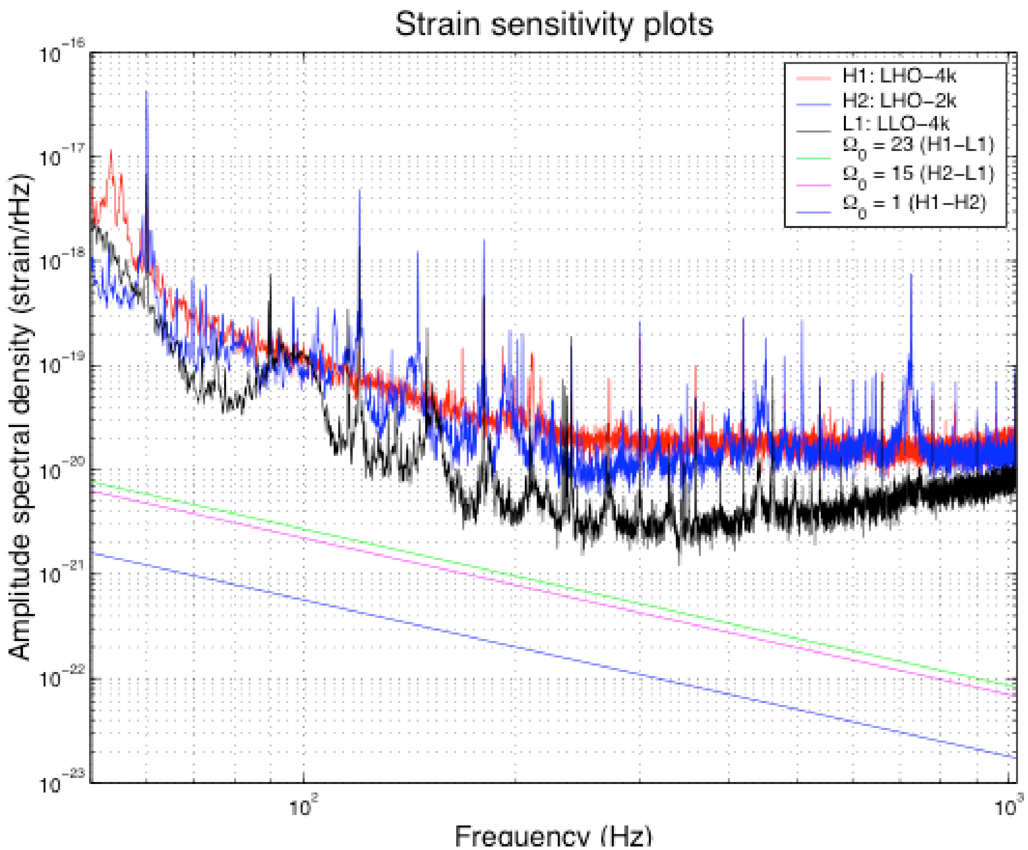
- Sources
  - » Early universe sources (inflation, cosmic strings, etc) produce very weak, non-thermal unpolarized, isotropic, incoherent background spectrum
  - » Contemporary sources (unresolved SN & inspiral sources) produce power-law spectrum
  - » Indirect constraints on fractional energy density $\Omega_{GW}(f) < 10^{-5}$
- Analysis goals:
  - » Directly constrain $\Omega_{GW}(f)$ for $40\ \text{Hz} \leq f \leq 300\ \text{Hz}$
  - » Investigate instrumental correlations

LIGO Stochastic background radiation

- S1 search method
  - Look for correlations between pairs of detectors
  - Analyze data in (2-detector coincident) 900-second stretches
  - Condition data
    - Partition each of these into 90-second stretches to characterize statistics
    - Window, zero pad, FFT, estimate power spectrum for 900 sec
    - Notch out frequencies containing instrumental artifacts
      - Very narrow features - 0.25 Hz bins
      - n × 16 Hz, n × 60 Hz, 168.25 Hz, 168.5 Hz, 250 Hz
  - Find cross-correlation with filter optimal for $\Omega_{GW}(f) \propto f^0$ (constant)
  - Extensive statistical analysis to set 90% confidence upper limit

Stochastic background radiation

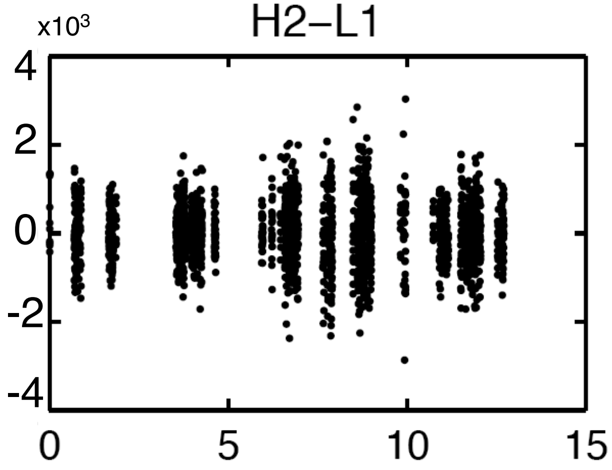
Cross-correlation technique enables one to “dig” signal below individual interferometer noise floors



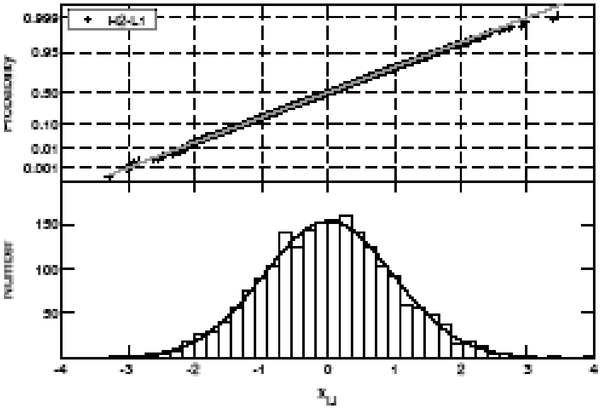
- Current best upper limits in 100Hz - 1kHz region:
  - Inferred: From Big Bang nucleosynthesis: (Kolb et al., 1990) $\int \Omega_{GW}(f)\ d\ln f < 1\times 10^{-5}$
  - *Measured:* Garching-Glasgow interferometers (Compton et al. 1994): $\Omega_{GW}(f) < 3\times 10^{5}$
  - *Measured*: EXPLORER-NAUTILUS (cryogenic bars -- Astone et al., 1999): $\Omega_{GW}(907Hz) < 60$

Stochastic background radiation

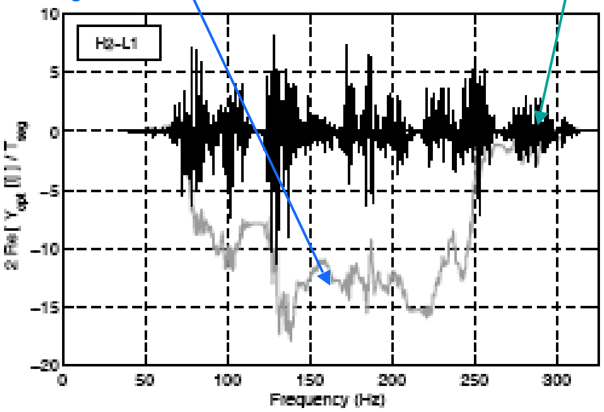
Best upper limit on Ω_{GW} provided by H2-L1



Days of observation during S1
2010 Measurements over S1



Normalized residuals over S1 run



$\int_0^f df'\, d\Omega_{CC}(f')$ $d\Omega_{CC}(f)/df$

Run-averaged spectrum of cross correlation (CC)

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	$[2.1 \pm .42\,,\ 61 \pm 12]$	$\Omega_0\, h_{100}^2 \le 55 \pm 11$	0.96	40 – 314 Hz	64 hr
H2-L1	0.16	0.0094	$[-30 \pm 6.0\,,\ 30 \pm 6.0]$	$\Omega_0\, h_{100}^2 \le 23 \pm 4.6$	1.0	40 – 314 Hz	51.25 hr

- During S1 run, Hanford - Hanford correlations exhibited an unphysical (negative !) ***9σ*** correlation due to local environment --
    - Power mains, acoustics outside vacuum chambers

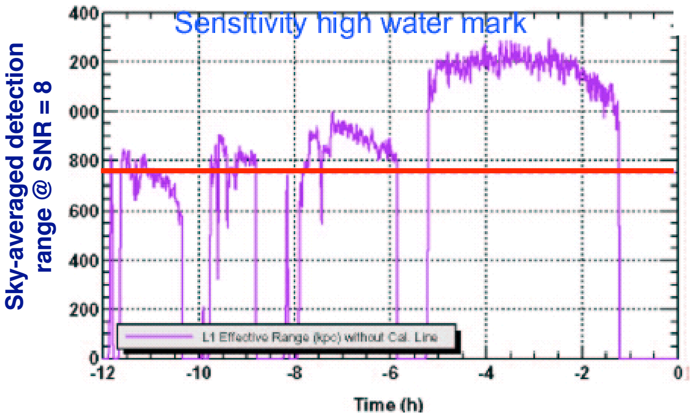
Plans for S2 and beyond

Inspirals

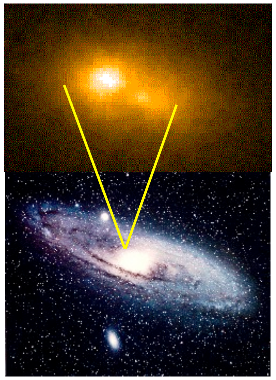
- (If no detections) get better upper limit, making use of longer observation time, **additional sources in Andromeda**
- Improved data quality cuts and statistical testing; coherent analysis
- Search for non-spinning BHs up to ~20 solar masses (or UL)
- Search for MACHO binaries (low mass BHs) in Galactic Halo

Bursts

- "Eyes wide open" search for signals in the 1-100 msec duration
- Triggered search for correlations with GRBs
- Modeled search for
  - Black hole ringdown
  - Supernovae waveform catalog
- ***Four-way coincidence with TAMA***
- Introduce amplitude constraints, tighter time coincidence windows, cross-correlation of time-series data from multiple interferometers near event candidates for better discrimination



M31 in Andromeda



Periodic Sources

Time domain method:

- Upper limits on all known pulsars > 50 Hz
- Search for Crab
- Develop specialized statistical methods (Metropolis-Hastings Markov Chain) to characterize PDF in parameter space

Frequency domain method

- Search parameter space (nearby all-sky broadband + deeper small-area)
- Specialized search for SCO-X1 (pulsar in binary)
- Incoherent searches: Hough, unbiased, stack-slide

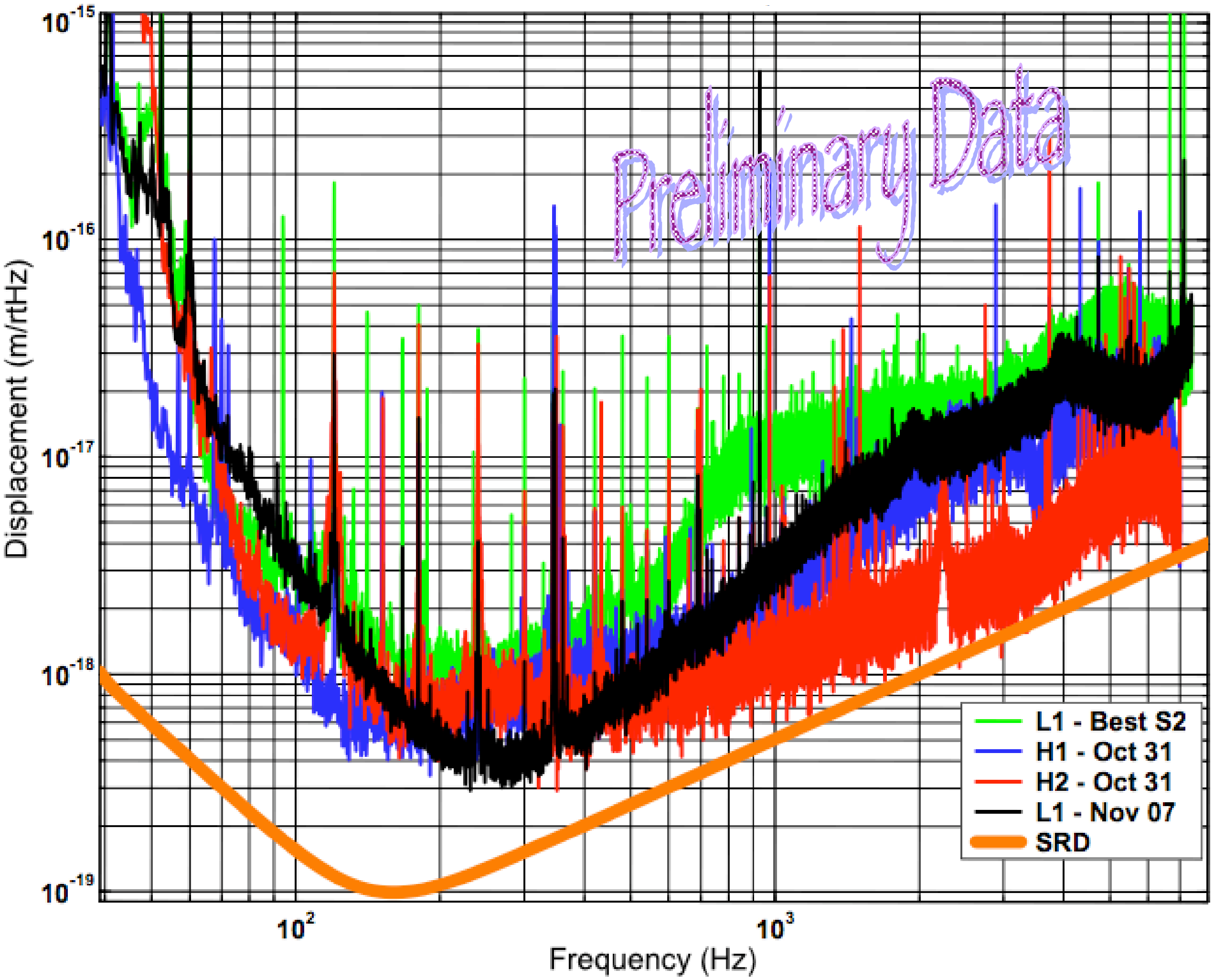
Stochastic

- May optimally filter for power-law spectra: $\Omega_{GW}(f) \propto f^{\beta}$
- Correlate ALLEGRO-LLO
- Technical improvements: apply calibration data once/minute, overlapping lower-leakage windows, study H1-H2 correlations in more detail.

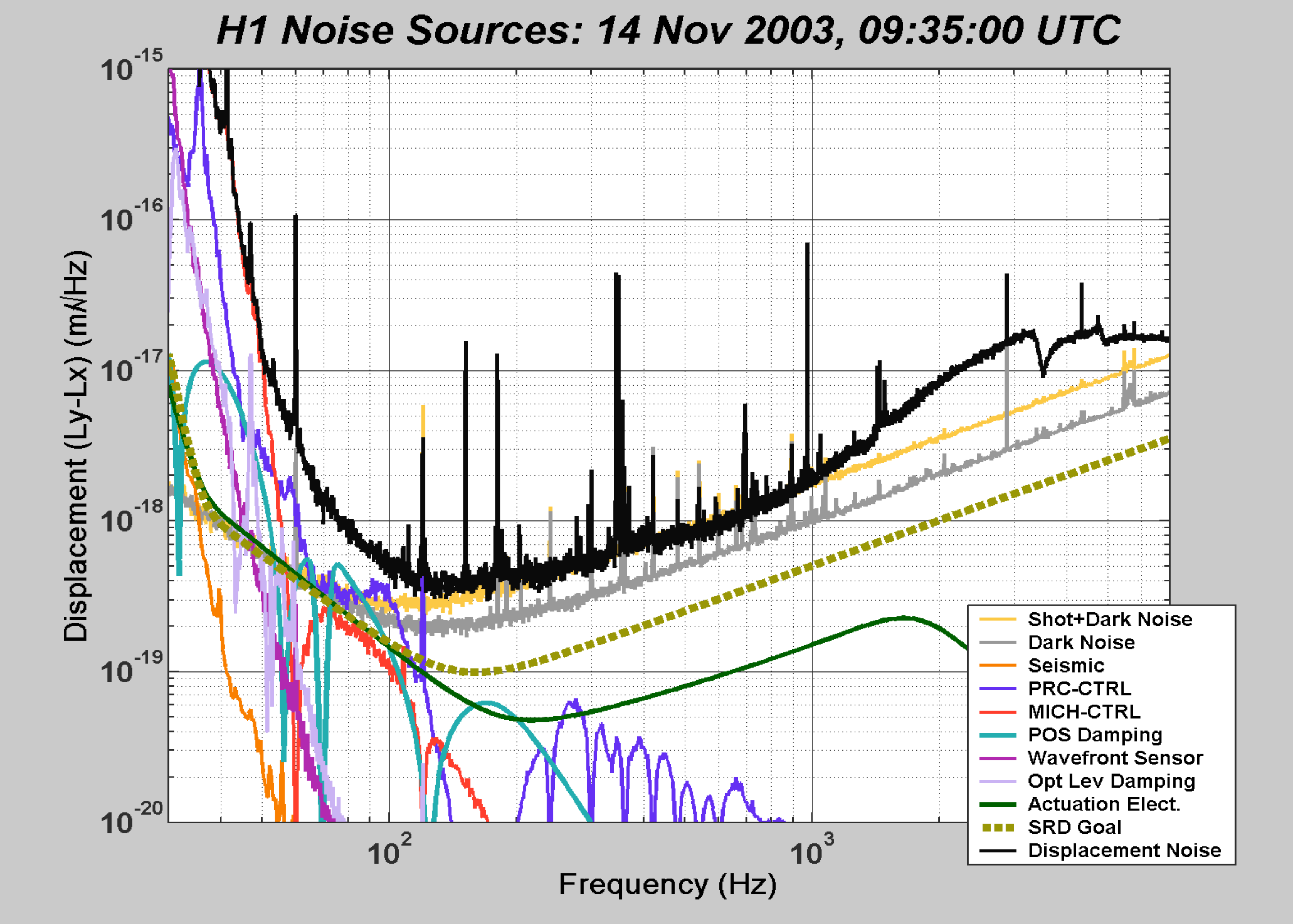
Start of S3: All 3 LIGO Interferometers at Extragalactic Sensitivity

- ***S3 range sensitivity for Hanford 4km interferometer has occasionally exceeded 4 Mpc***

Displacement spectral density



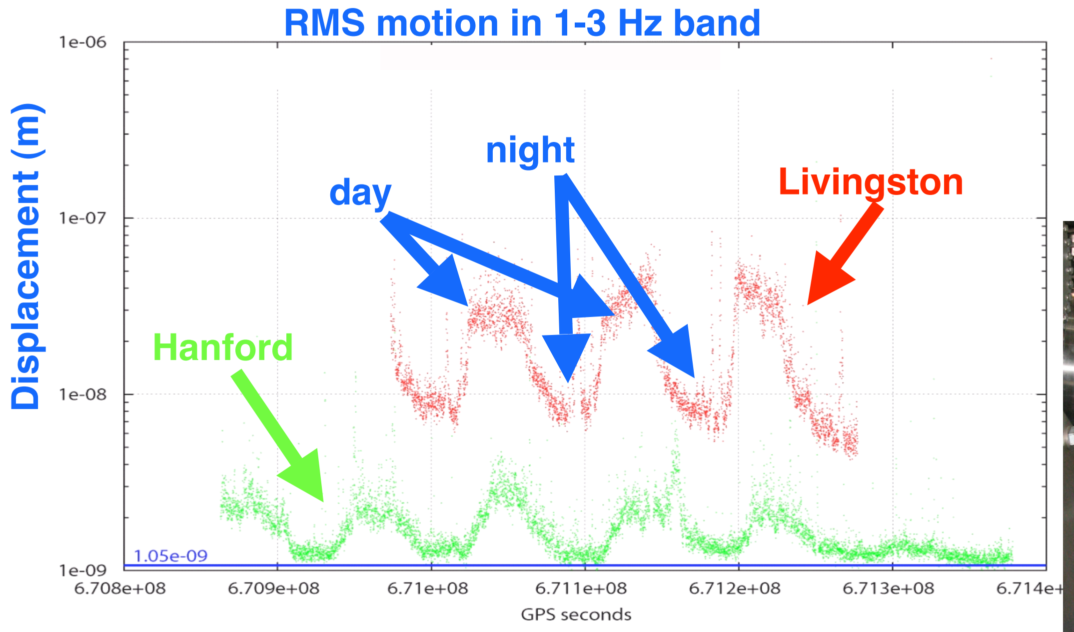
Details of S3 sensitivity...



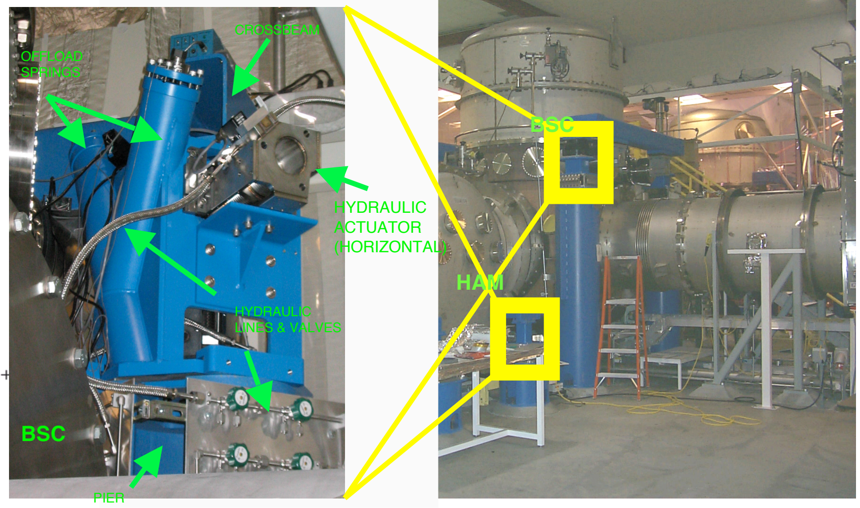
Plans: From S3 to S4 + …

1. Accommodate Variability of Seismic Noise

- Human activity limits observational duty cycle at Livingston, LA observatory
  - Introduce active seismic isolation subsystem
  - Similar to TAMA experience !
- Add hydraulic actuator systems on piers of existing seismic isolation systems
  - HEPI:
    - ***H***ydraulic ***E***xternal ***P***re-***I***solator



Hydraulic External Pre-Isolator (HEPI)

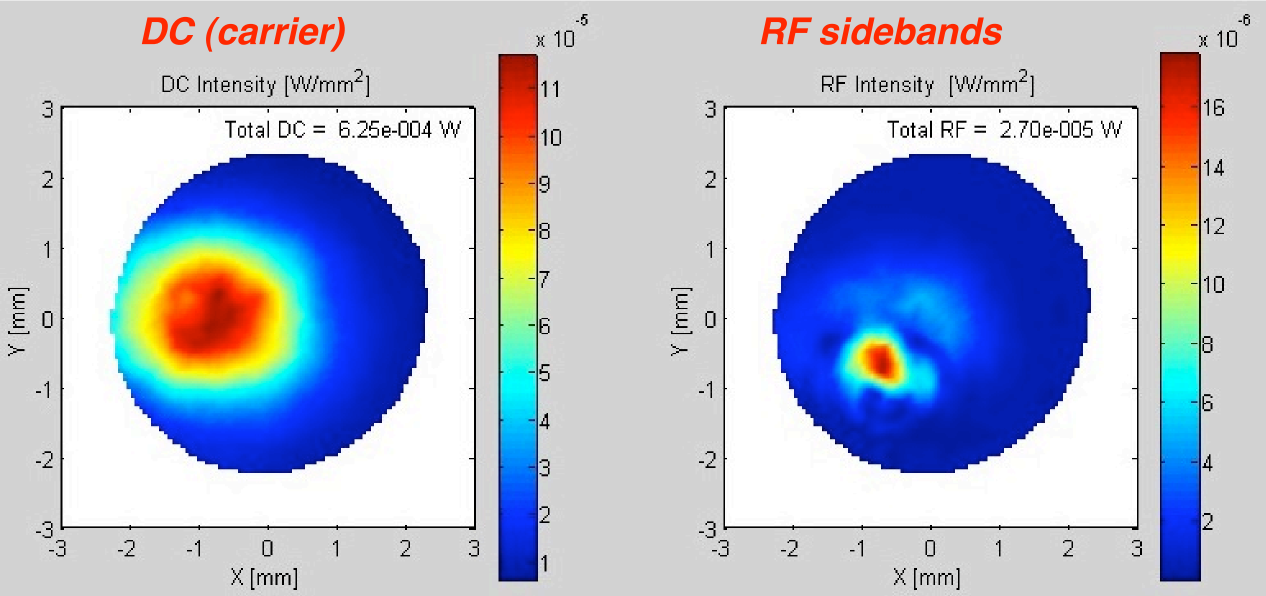


Plans: From S3 to S4 + …

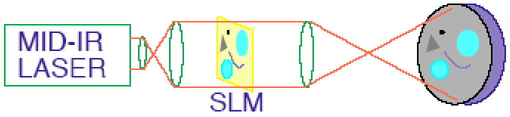
2. Full Power Operation -- Remove Recycling Cavity Degeneracy

- ❑ Achieving LIGO design shot noise limit requires optimal cavity - laser matching
  - ➢ Local heating by absorbed laser light produces a ***thermal lens*** that must be ***compensated*** to achieve design performance
    - ▪ Original "point design" assumed a specific level of balanced **thermal lensing**
  - ➢ As-built mirrors absorb ***less*** power -> mirror curvatures not optimal
  - ➢ ***Insufficient*** input mirror thermal lens makes $g_1 \cdot g_2 > 1$ (unstable resonator)
- ❑ Plan
  - ➢ Use CO_2 + mask to create artificial thermal lens for compensation

⇒Bad mode overlap!



'Staring' shaped-beam heating

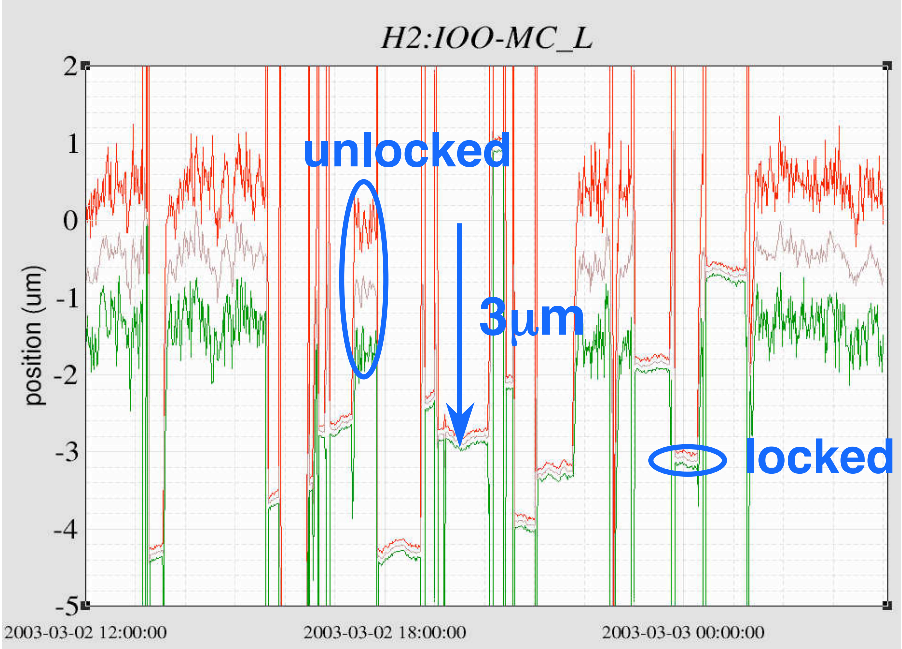


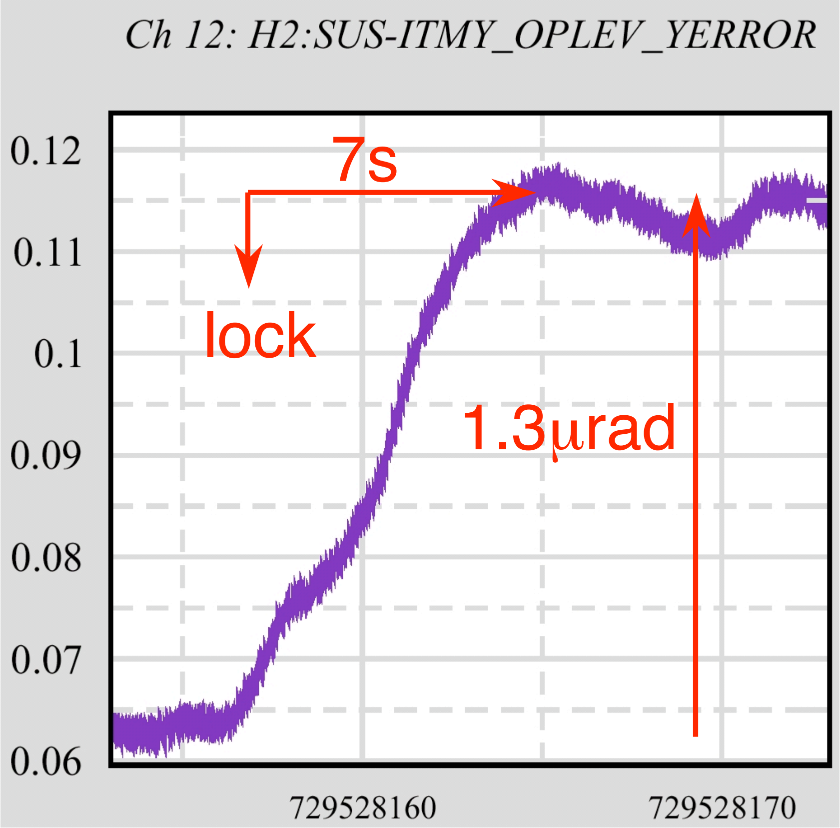
Plans: From S3 to S4 + …

3. Accommodate effects of radiation pressure on alignment, shot noise

- Misaligned cavities & de-centered beams
  - Torque depends on alignment, build-up of radiation pressure within cavities
- Strategy: modify controls
  - Powers and beam centroids already sensed
  - Enhanced alignment "Plant model " to include light as a dynamic mechanical component
  - Design calculations, code prototype under development

Mode cleaner length shift (2kW)





Arm cavity angular shift
2cm de-centering at 5kW

Summary

LIGO Science has begun

Over 4 decades sensitivity improvement since "first light"

Now within a decade of design sensitivity at 150 Hz

(of course, that's the longest mile!)

Commissioning strategy has helped to use 3 concurrent machines to continuously improve sensitivity

Astrophysically interesting sensitivity ***ON ALL 3 INSTRUMENTS***

Livingtson seismic retrofit is crucial for improving uptime

Thermal compensation, other high power upgrades to reduce noise

S4 run: longer duration, better uptime, and lower noise