Introduction to LIGO, Overview and Status

Peter R. Saulson
Spokesperson, LIGO Scientific Collaboration

Outline

- Introduction to today’s talks
- Synopsis of gravitational wave detection and LIGO
- Brief highlights of progress on
  - » Commissioning of LIGO I
  - » Preparation for Advanced LIGO
- Status of the LSC
- Results of analysis of LIGO data
- Some responses to last year’s review

Today’s presentations

09:00 LIGO Overview and Status -- Peter Saulson

09:45 LIGO commissioning -- Rana Adhikari

11:00 Advanced LIGO R&D progress -- David Shoemaker

13:30 Cyber security -- Albert Lazzarini

14:15 Management and operation plans/budget -- Stan Whitcomb

Science Goals

- Physics
  - Direct verification of the most "relativistic" prediction of general relativity
  - Detailed tests of properties of gravitational waves: speed, strength, polarization, …
  - Probe of strong-field gravity – black holes
  - Early universe physics
- Astronomy and astrophysics
  - Abundance & properties of supernovae, neutron star binaries, black holes
  - Tests of gamma-ray burst models
  - Neutron star equation of state
  - *A new window on the universe*

LIGO Observatories

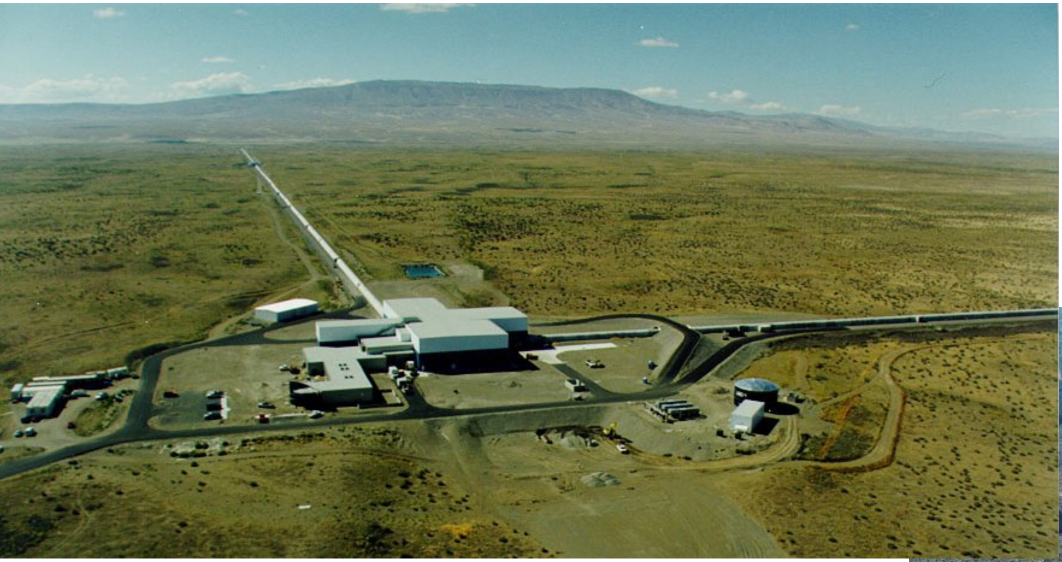
GEODETIC DATA (WGS84)

h: -6.574 m ***X arm: S72.2836***

ϕ: N30°33’46.419531” ***Y arm: S17.7164***

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***

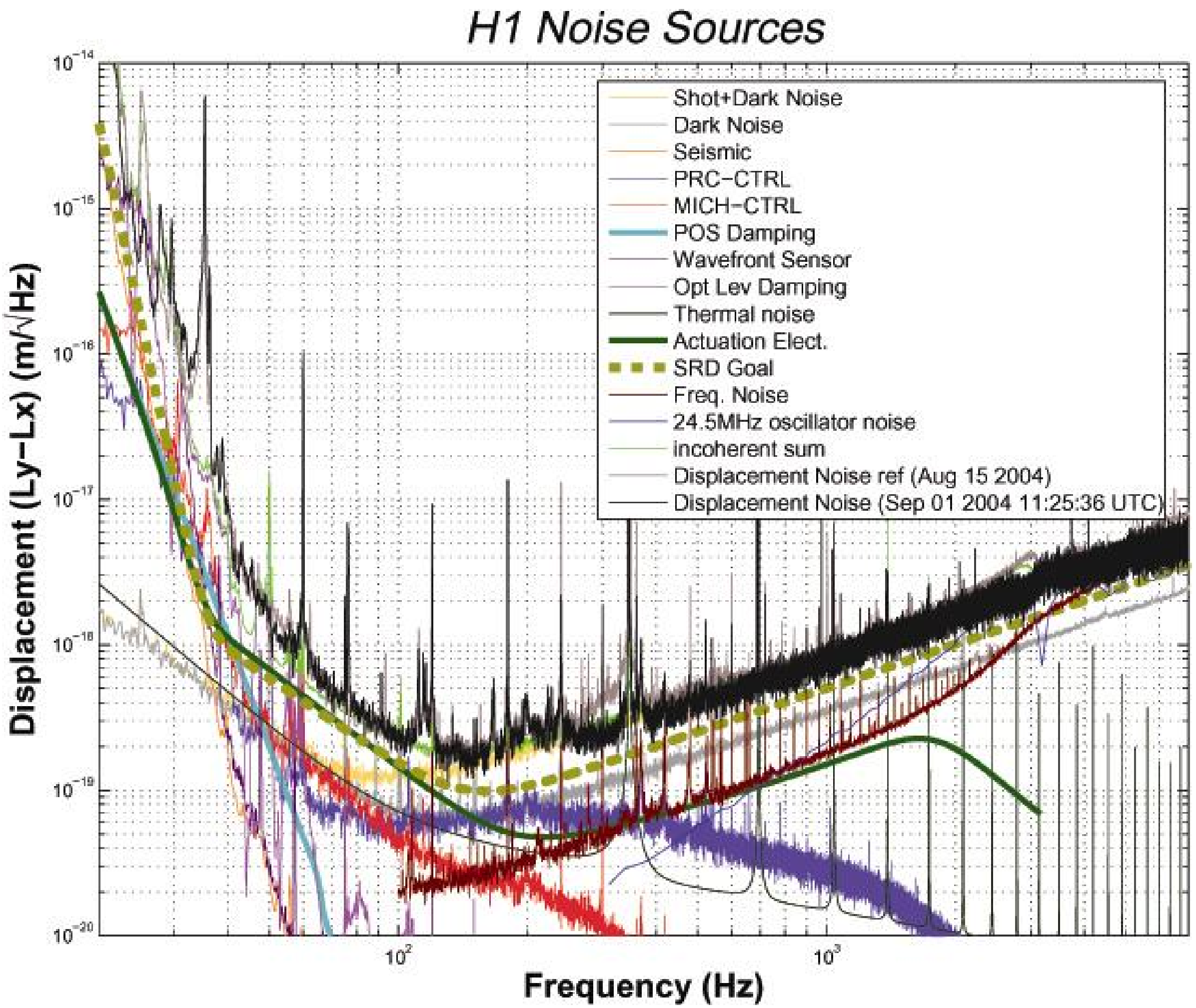
ϕ: N46°27’18.527841” ***Y arm: S54.0007°W***

λ: W119°24’27.565681”

GEO 600

Hanford 4 km ifo approaches design sensitivity

Details in
Rana Adhikari's talk.

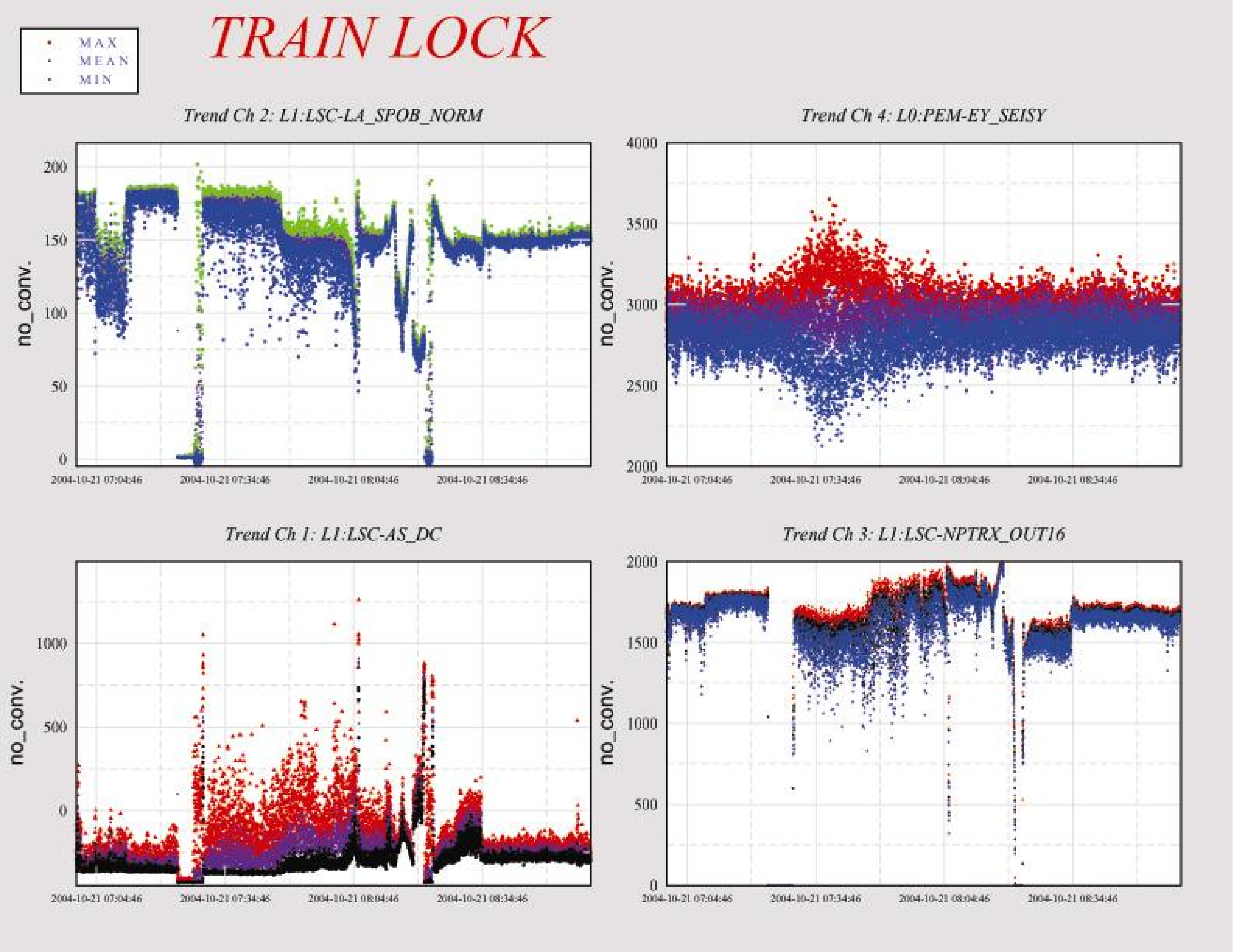


HEPI Installation

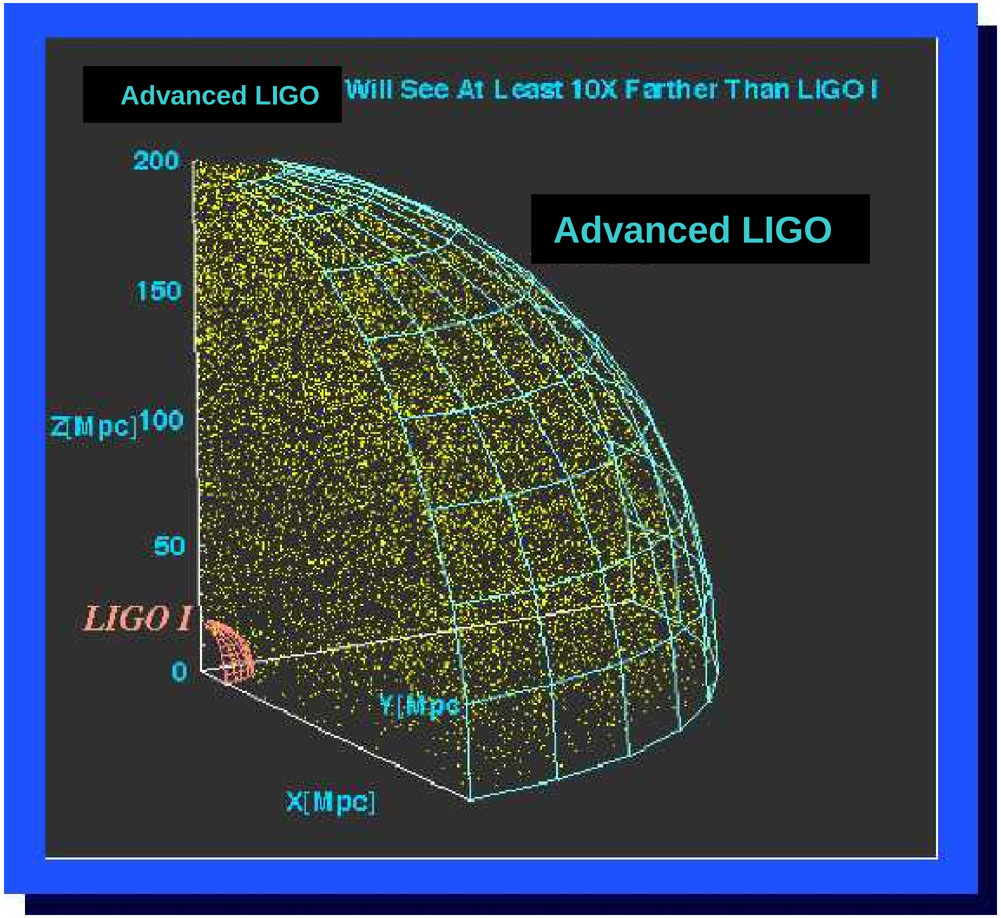
Commissioning procedure

1. Manual sensor & actuator check-out, platform alignment.
2. Automated system identification of 8 input, 16 output, plant.
3. Feedback servo design and implementation for x, y, z, rx, ry, rz and two overconstrained DOFs.
4. Sensor correction sys-id, using portable witness geophones.
5. Sens. correction filter design and implementation for x, y, z.

LLO ifo holds lock while train goes by



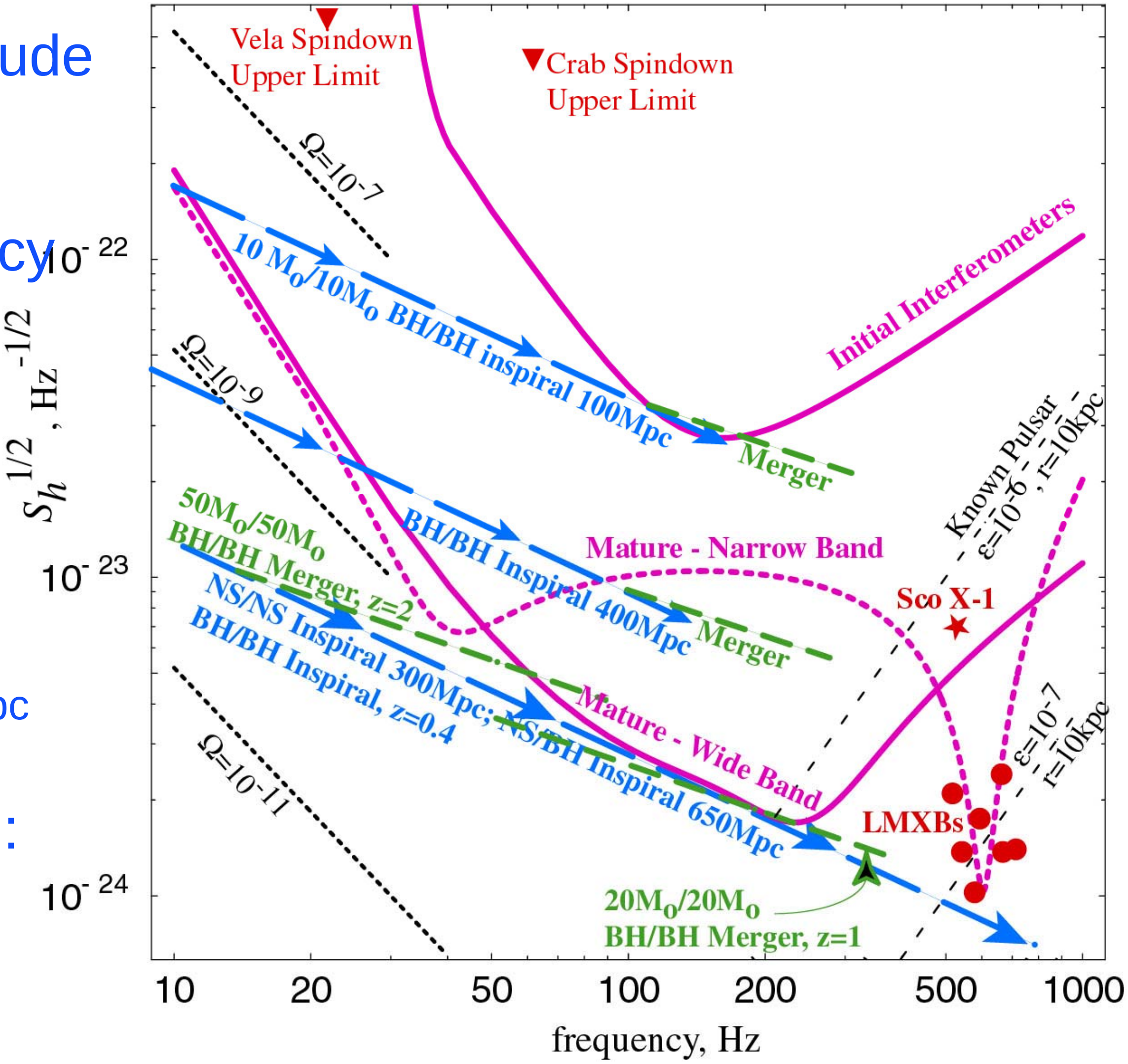
Advanced LIGO will dramatically extend our reach



Science from a few hours of Advanced LIGO observing should be comparable to 1 year of initial LIGO!

Advanced LIGO

- Factor 10 better amplitude sensitivity
  - (Reach)^3 = rate
- Factor 4 lower frequency bound
- NS Binaries: for three interferometers,
  - Initial LIGO: ~20 Mpc
  - Adv LIGO: ~350 Mpc
- BH Binaries:
  - Initial LIGO: 10 M_o, 100 Mpc
  - Adv LIGO : 50 M_o, z=2
- Stochastic background:
  - Initial LIGO: ~3e-6
  - Adv LIGO ~3e-9



Advanced LIGO status

David Shoemaker will give details, including:

- National Science Board approval
- Progress on R&D, design
  - » Laser
  - » Mirror substrate
  - » Coatings
  - » Suspensions
  - » Vibration isolation

LIGO

LIGO Scientific Collaboration

LSC

NSF

UTB TSC

Southeastern Louisiana University

Loyola University New Orleans

California State University Dominguez Hills

Leland Stanford Junior University Organized 1891

Northwestern University

GEO 600

LSU

Universitat de les Illes Balears

Southern University Agricultural & Mechanical College

Hobart and William Smith Colleges

The University of Adelaide Australia

California Institute of Technology 1891

University of Florida

NAOJ 国立天文台

SKC

University of Wisconsin UW Milwaukee

Carleton College Northfield, Minn. A.D. 1866

Cornell University

The University of Birmingham

IGR

Syracuse University Founded AD 1870 Suos Cultores Scientia Coronat

Universität Hannover

Washington State University

Cardiff University

The Physics of the Universe PPARC

PAH

The University of Western Australia

Michigan

Penn State 1855

Massachusetts Institute of Technology

University of Glasgow

LIGO-G040472-00-Z

LSC status

- Membership: 500 people at 42 institutions
  - 15 Foreign groups (11 in GEO), 27 US groups
  - 403 authors on most recent papers
- 5 hardware working groups, 3 software working groups, 4 data analysis groups
- 4 meetings per year
  - 2 full 4-day meetings and 2 weekend Observational Results meetings
    - Most recent one ended yesterday.

The LSC has taken the lead on:

- » R&D for Advanced LIGO
- » Analysis of LIGO data

LSC governance changes in the works

Aiming for better integration with LIGO Lab to support

- Data analysis
- Advanced LIGO
- Interferometer operations

Revisions are now under way to the LSC and Lab Charters.

Key changes being planned:

- » LSC Spokesperson will join the LIGO Directorate.
- » LSC will report to LIGO Directorate, and thus its work will be reviewed by the existing review structure.
- » LSC members will be able to take on responsibility and authority for operational functions or as part of Advanced LIGO project organization.
- » LSC institutions (besides Caltech and MIT) will be represented on the LIGO Oversight Committee.

Also, we are working to cement our tight integration with GEO.

- » GEO members are members of the LSC.
- » LIGO and GEO data to be analyzed together as a single set, by the LSC.

(More details in Stan Whitcomb’s talk.)

Collaborative data analysis

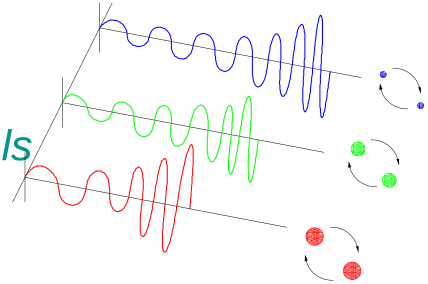
In addition to our intimate collaboration with GEO, we are in various stages of organizing collaborations with other gravitational wave detectors.

- With TAMA 300 m interferometer in Japan, we have carried out joint searches for bursts and for inspirals in S2 data. Papers written and in review.
- With ALLEGRO bar at LSU, we are carrying out stochastic background search. Unique features: measure at high freq, can “chop” signal by rotating bar.
- With AURIGA bar in Italy, we have commenced joint burst search in S3 data.
- With Virgo, have negotiated a data exchange MOU, and set up joint working group on data analysis. First exercises are focused on inspiral and burst searches, cross-calibrating algorithms on simulated data.

We search for four classes of signals

- Chirps

  “sweeping sinusoids” from compact binary inspirals

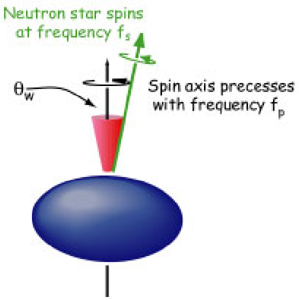


- Bursts

  transients, usually without good waveform models

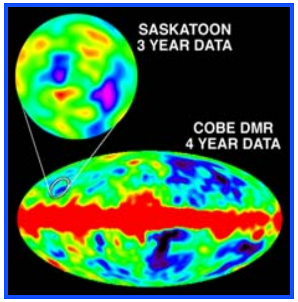
- Periodic, or “CW”

  from pulsars in our galaxy

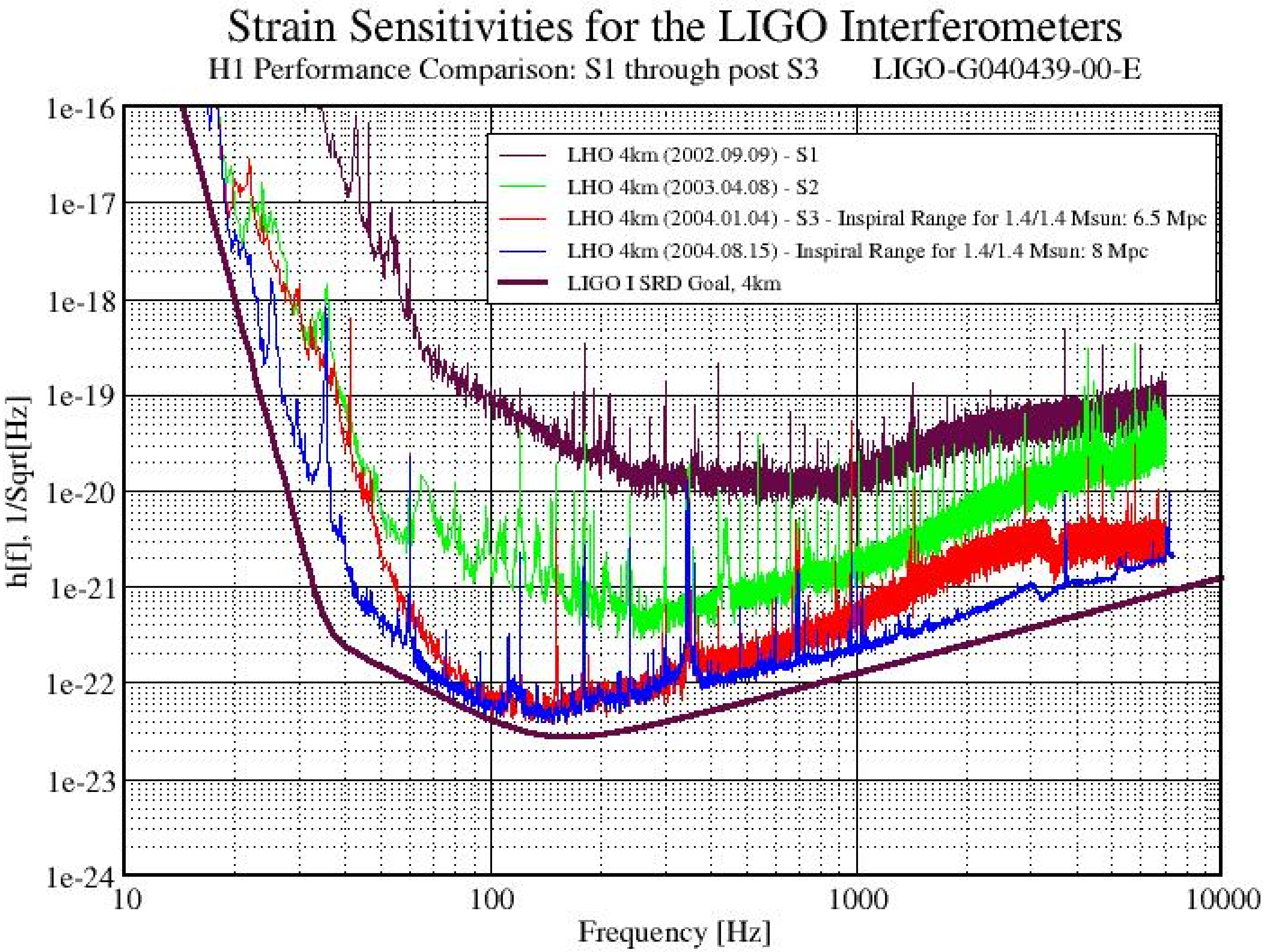


- Stochastic background

  cosmological background, or superposition of other signals



Sensitivity



Data Runs

We have carried out three Science Runs (S1--S3) interspersed with commissioning.

S1 run:

17 days (August / September 2002)

Four detectors operating: LIGO (L1, H1, H2) and GEO600

Triple-LIGO-coincidence (96 hours)

Four S1 astrophysical searches published (*Phys. Rev. D* *69*, 2004):

» **Inspiraling neutron stars 122001**

» **Bursts 102001**

» **Known pulsar (J1939+2134) with GEO 082004**

» **Stochastic background 122004**

Data Runs

S2 run:

59 days (February—April 2003)

Four interferometers operating: LIGO (L1, H1, H2) and TAMA300 plus Allegro bar detector at LSU

Triple-LIGO-coincidence (318 hours)

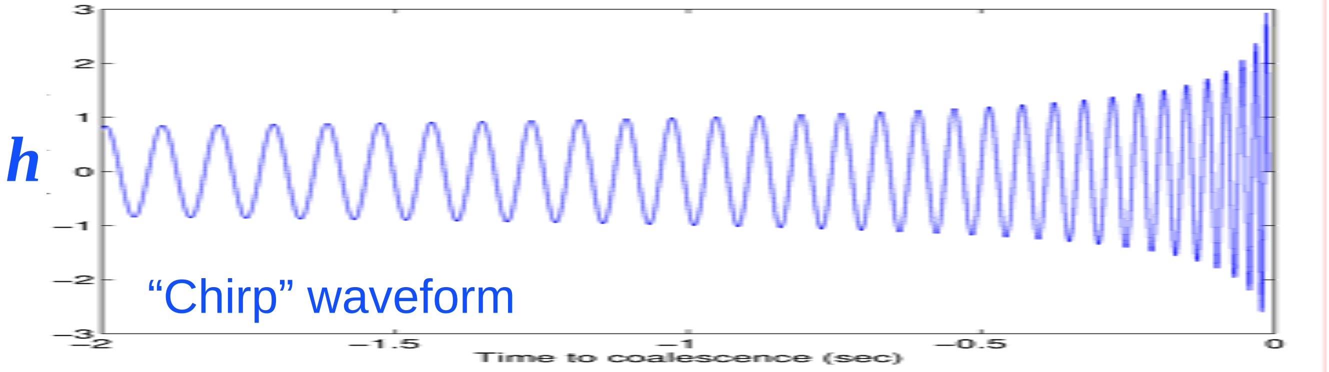
S2 searches are mostly complete, some results here

S3 run:

70 days (October 2003 – January 2004) – Analysis is in full swing

Inspiral Gravitational Waves

Compact-object binary systems lose energy due to gravitational waves. Waveform traces history.



“Chirp” waveform

In LIGO frequency band (40–2000 Hz) for a short time just before merging:
anywhere from a few minutes to <<1 second, depending on mass.

Waveform is known accurately for objects up to ~3 $M_\odot$

“Post-Newtonian expansion” in powers of (Gm/rc^2) is adequate

➔ Use *matched filtering.*

Preliminary
S2 Binary Neutron Star Result

- Observation time (T_{obs}) : 355 hours
- Conservative lower bound on N_G = 1.14
  - » Take the “worst case” for all systematic uncertainties to obtain this value
- Conservative upper limit:

Preliminary S2 Upper Limit:
$R_{90\%} < 50$
per year per MWEG

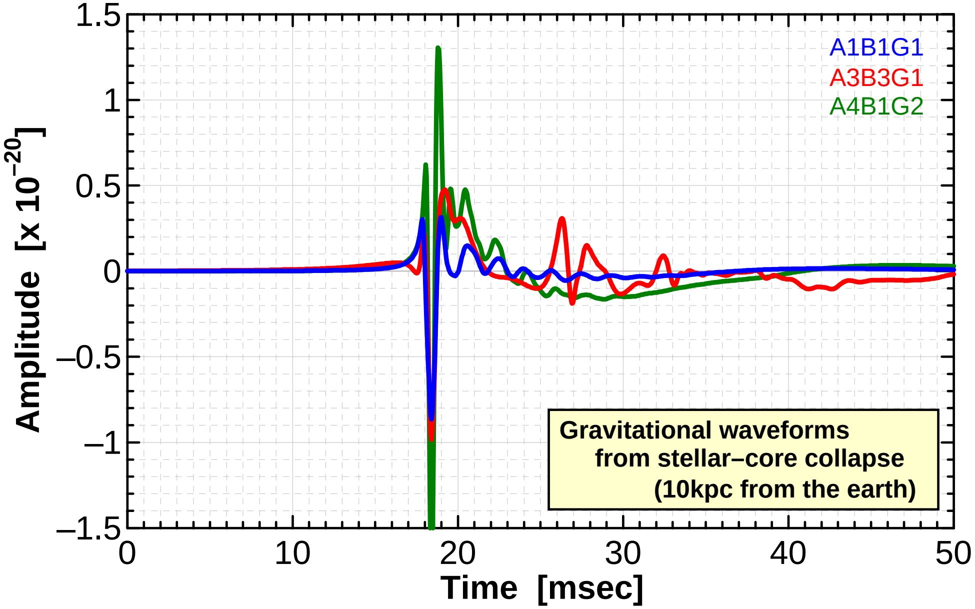
Burst Analysis

Catastrophic events involving solar-mass compact objects can produce transient “bursts” of gravitational radiation in the LIGO frequency band:

- core-collapse supernovae
- merging, perturbed, or accreting black holes
- gamma-ray burst engines
- cosmic strings
- others?

Precise nature of gravitational-wave burst (GWB) signals typically unknown or poorly modeled.

- Can’t base such a broad search on having precise waveforms.
- Search for generic GWBs of duration ~1ms-1s, frequency ~100-4000Hz.



possible supernova waveforms
T. Zwerger & E. Muller, Astron. Astrophys. *320* 209 (1997)

S1 Burst Search Results

S1 rate-strength exclusion plots,
for various Gaussian and
Sine-Gaussian pulses.

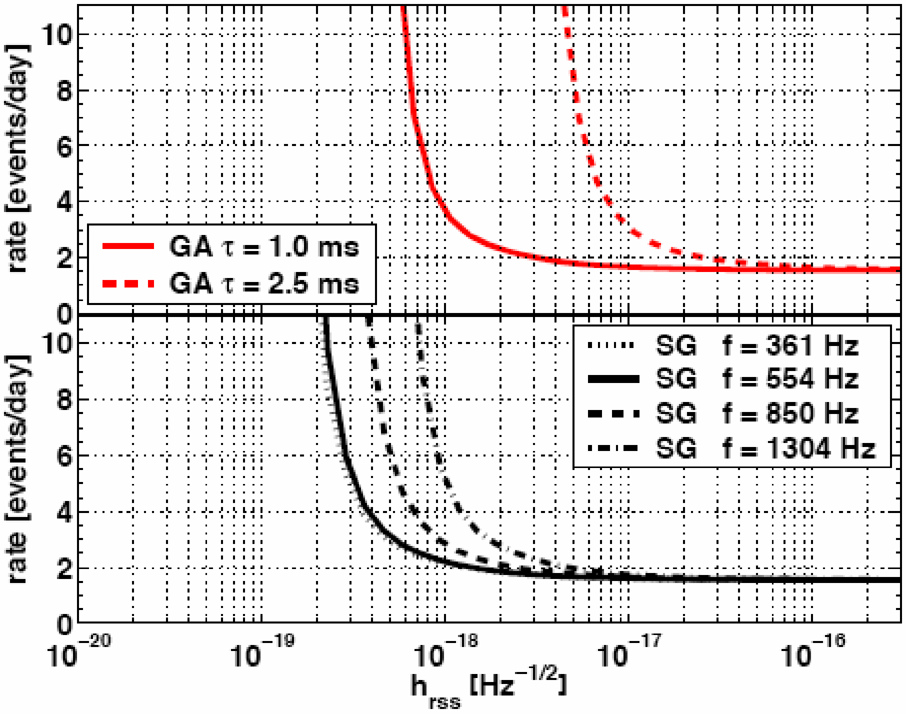
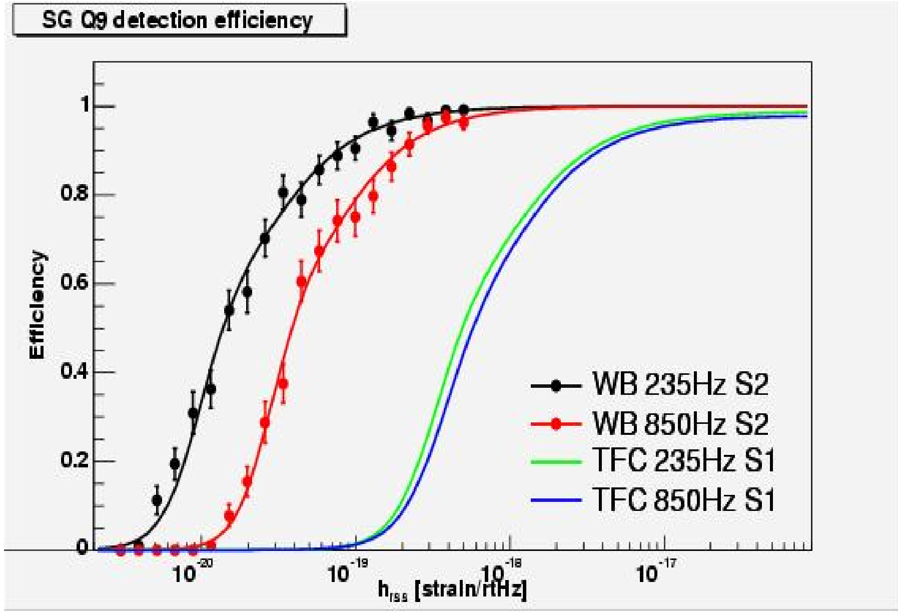


FIG. 15: Rate versus h_{rss} for detection of specific waveforms using the TFCLUSTERS event trigger generator. The region above and to the right of the curves is excluded at 90% confidence level or greater. The effect of the 20% uncertainty in the detector response is included. Top: For Gaussians with $\tau = 1.0$ ms and $\tau = 2.5$ ms

Comparison of efficiency of
S1 and S2 searches,
for two Sine-Gaussian waveforms.



Triggered searches: γ-ray bursts & gravitational waves

During S2, GRB 030329 occurred.

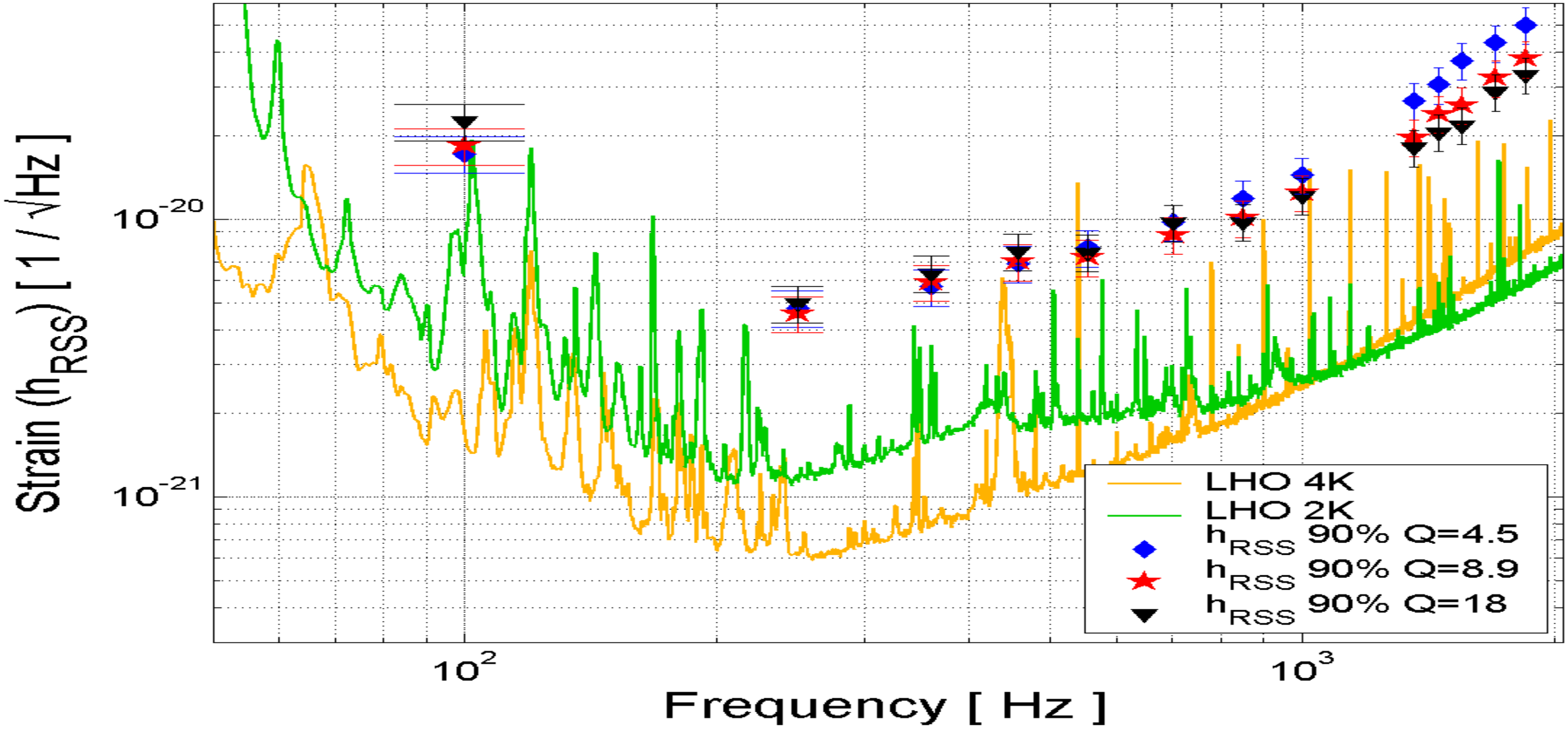
- Detected by HETE-2, Konus-Wind, Helicon/KoronasF
- “Close”: $z = 0.1685$; d_L=800Mpc (WMAP params)
- Strong evidence for *supernova origin of long GRBs*.
- H1, H2 operating before, during, after burst

Radiation from a broadband burst at this distance?

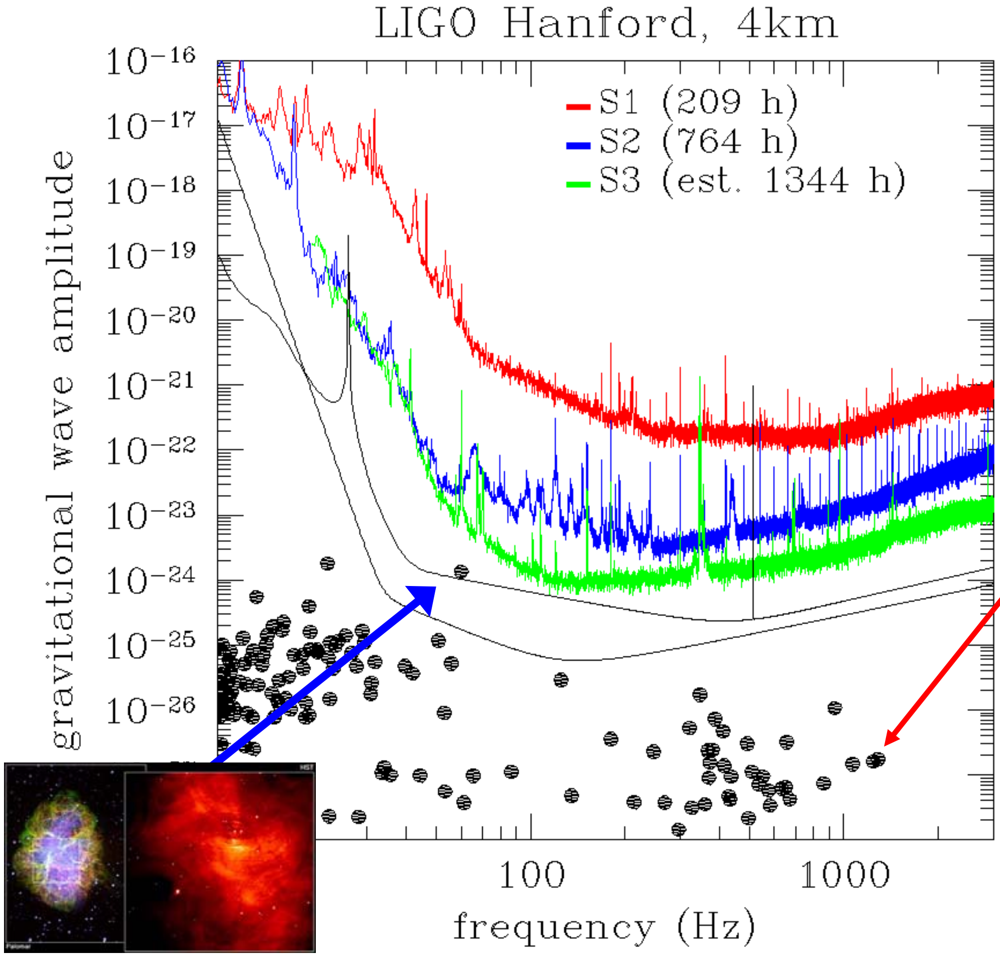
We searched, using cross-correlation between H1 and H2 as a measure of possible signal strength.

GRB030329 approved for posting to gr-qc

- No event exceeded analysis threshold
- Using simulations an upper limit on the associated gravitational wave strength at the detector at the level of $h_{RSS} \sim 6 \times 10^{-20}\ \mathrm{Hz}^{-1/2}$ was set
- Radiation from a broadband burst at this distance? $E_{GW} > 10^5 M_\odot$

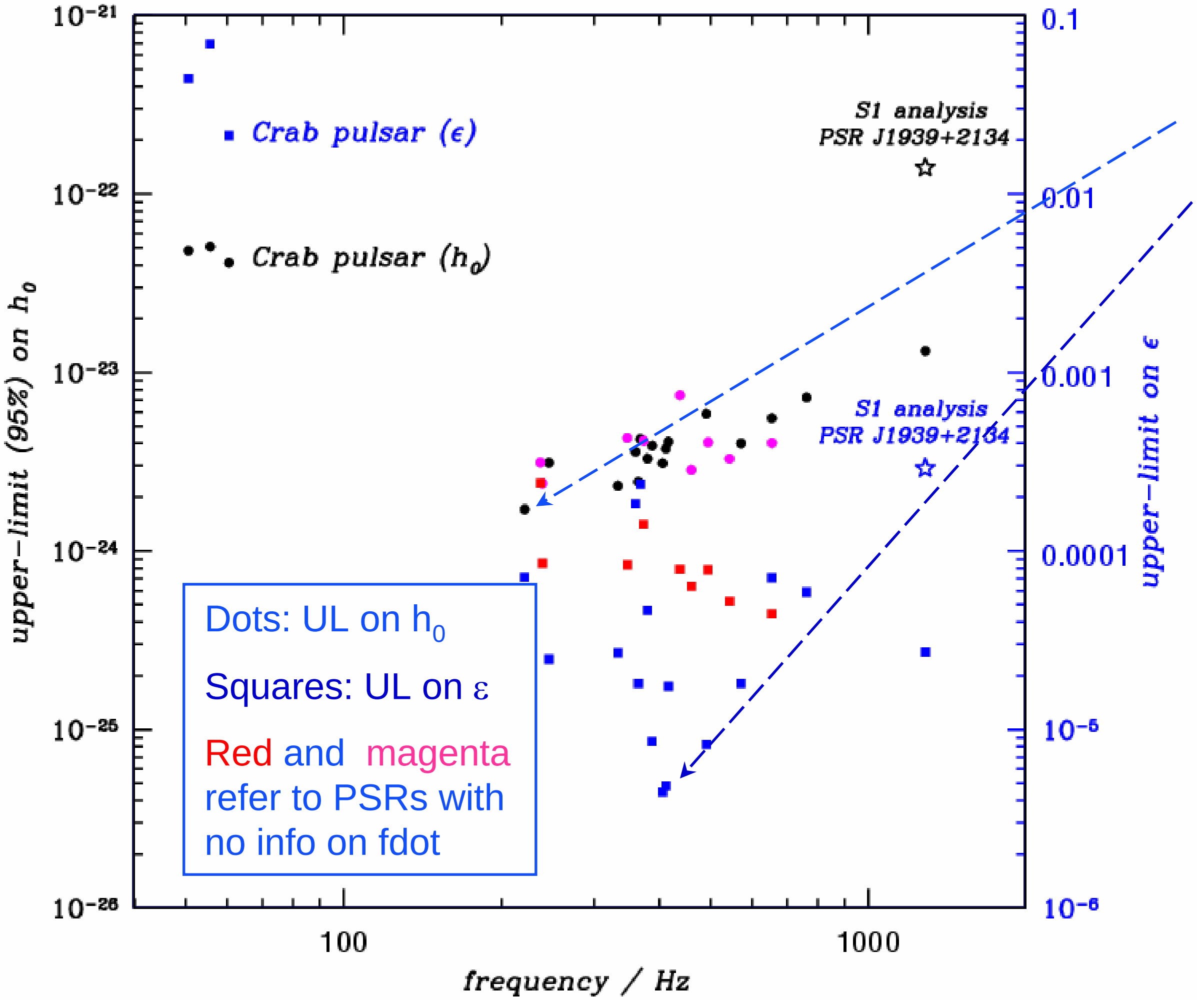


Pointing at known neutron stars



- Targeted search of GWs from known isolated radio pulsars
- S1analysis: upper-limit (95% confidence) on PSR J1939+2134: $h_0 < 1.4 \times 10^{-22}$ ($\varepsilon < 2.9 \times 10^{-4}$) Phys Rev D **69**, 082004 (2004)
- **S2 analysis**: 28 pulsars (all the one above 50 Hz for which search parameters are “exactly” known)

Summary of S2 results submitted to *PRL*



Dots: UL on h_0

Squares: UL on ε

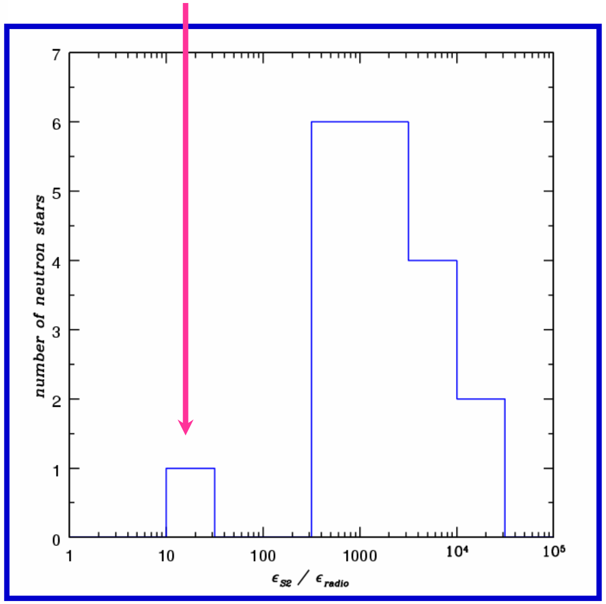
Red and magenta refer to PSRs with no info on fdot

Best upper-limits:

- J1910 – 5959D: $h_0 = 1.7 \times 10^{-24}$
- J2124 – 3358: $\varepsilon = 4.5 \times 10^{-6}$

How far are S2 results from spin-down limit?

- ➢**Crab: a factor ~ 30**



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 in this talk.

In a single detector, a stochastic signal is indistinguishable from noise. To detect it, we *cross-correlate* the outputs of multiple detectors.

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.

Current and expected results on $\Omega_{gw} h_{100}^2$

	H-L	H1-H2	Freq range	Observation Time
S1 (upper limit) **PRD 69, 122004, 2004**	< 23 +/- 4.6 (H2-L1)	seen instrumental noise	64-265 Hz	64 hours (08/23/03 – 09/09/04)
S2 (upper limit) Preliminary	< 0.018 +0.007- 0.003 (H1-L1)	seen instrumental noise	50-300 Hz	387 hours (02/14/03 – 04/14/04)
S3 (sensitivity) **Expected from noise curves**	$\sim 5 \times 10^{-4}$ (H1-L1)	potentially ~10x lower than S3 H1-L1	50-300 Hz	~240 hours (10/31/04 – 01/09/04)
Design sensitivities				
LIGO I	$\sim 1 \times 10^{-6}$	$\sim 1.5 \times 10^{-7}$	50-300 Hz	1 year
LIGO Advanced **nominal tuning** **low-freq tuning**	$\sim 1.5 \times 10^{-9}$ $\sim 3.5 \times 10^{-10}$	$\sim 3 \times 10^{-10}$ $\sim 2.5 \times 10^{-10}$	10-200 Hz 10-50 Hz	1 year 1 year

Science Run Metrics

RUN ⇒	**S1**		**S2**		**S3**	
IFO ⇓	*BNS RANGE (kpc)*	*DUTY FACTOR*	*BNS RANGE (kpc)*	*DUTY FACTOR*	*BNS RANGE (kpc)*	*DUTY FACTOR*
L1	~150	43%	900	37%	1,000 (up to 2,000)	22%
H1	~30	59%	350	74%	2,500 (up to 6,500)	69%
H2	~40	73%	200	58%	1,000	63%
3-way		24%		22%		11%*

Plans for running and commissioning

Commissioning progress has been very good.

H1 is almost at design sensitivity now.

We need to propagate changes to H2 and L1, learn how to improve duty cycle, and then to run for long duration.

Overall picture:

- S4, a 1 month run in early 2005, to produce new data at improved sensitivity.
- Period of commissioning to propagate changes to other interferometers, and to improve duty cycle.
- S5, a long run beginning in latter part of 2005, at design sensitivity in all interferometers.

S4 plan

- Science run S4, with a duration of 4 weeks, to begin around 22 Feb 2005.
- The run is intended to meet the following performance goals:
  - Sensitivity goals (inspiral range):
    - H1: 7.5 Mpc
    - L1: 4 Mpc
    - H2: 2 Mpc
  - Duty cycle goal:
    - 70% individual ifos, 40% triple

Response to observations of last year’s Review Panel

Observations 1 – 3 remarked on good progress in commissioning. Rana Adhikari’s talk will show progress since last year.

Observations 4 – 7 referred to Advanced LIGO R&D. David Shoemaker will give detailed responses.

Observations 8 – 11 were related to the LSC’s activities. Responses given on the next few slides.

Responses to LSC issues in last year's review

8. The LIGO lab and the LSC have made remarkable progress on the organization of data analysis efforts. The S1 analyses have established a firm foundation for the analysis of future datasets and have fed back important information for further commissioning of the system. Each analysis group should come up with its own simple figure of merit for instrument performance so as not to lose priority relative to the binary neutron star inspiral group.
9. Software flexibility has already led to data management improvements that should improve analysis efficiency, and will allow responses to continued developments in distributed computing.
10. LIGO/LSC should continue streamlining their publication review process to improve timeliness of publication.
11. The panel urges the LIGO lab and the LSC to participate more actively in the efforts of the Penn State PFC to bridge the astrophysics and experimental relativity communities. Regular presentations at the semi-annual American Astronomical Society meetings would make the astronomical community generally aware of LIGO's remarkable experimental progress

New figures of merit

Up to now, we quoted a single scalar figure of merit, the distance to which we could see a neutron star binary with SNR = 8.

We are now testing software for three new FOMs, which will be in operation during S4.

- BurstMon
  - Measures h_{rss} sensitivity for injected waveforms vs. time; also reports a measure of non-stationarity.
- PulsarMon
  - Measures time needed to reach Crab spin-down limit at present noise.
  - Measures ellipticity sensitivity vs. frequency for a pulsar at 1 kpc.
- StochMon
  - Measures sensitivity in 1 minute integration for one ifo’s present data combined with another’s typical data.

Software flexibility

- Data Analysis Software Working Group founded in early 2004. (Chair: Patrick Brady, Milwaukee)
- It adopted the “multiple flowers” approach to analysis software as official LSC policy.
- Worked out standards and procedures for
  - Quality assurance and software review
  - Data formats
  - CVS repositories

Streamlining of publication review process

Since S1, we added members to review committees.

  Named a chair for each group, and an “embedded reviewer.”

Engaged reviewers early in the process of producing results.

  Often, review committee chairs attend telecons of their analysis group.

Promoted frequent communication, and especially a “heads up” when intensive review will be needed.

On the other hand,

- » We now require careful reviews of all software used to produce results. This is an extra reviewing burden, but we don’t want to make mistakes.
- » We post papers for three weeks on gr-qc before submitting to a journal, and invite comment from our colleagues.

Connection to astronomical community

In the past year:

- Two LIGO/LSC members attended Penn State CGWP workshop on intermediate mass black holes, 20-22 May 2004.
- 11 LIGO/LSC members attended Penn State CGWP workshop “Imagining the Future: Gravitational Wave Astronomy,” 27-30 October 2004.

Upcoming:

- AAS Special Session on Gravitational Wave Astronomy, 13 Jan 2005: 2 LIGO/LSC speakers
- GravStat: Statistical Challenges of Gravitational Wave Data Analysis (with applications to answering astrophysical questions using gravitational wave date), at Penn State, 19-21 May 2005, organized by LIGO/LSC committee.

In general, we expect to start speaking more often at astronomical meetings.