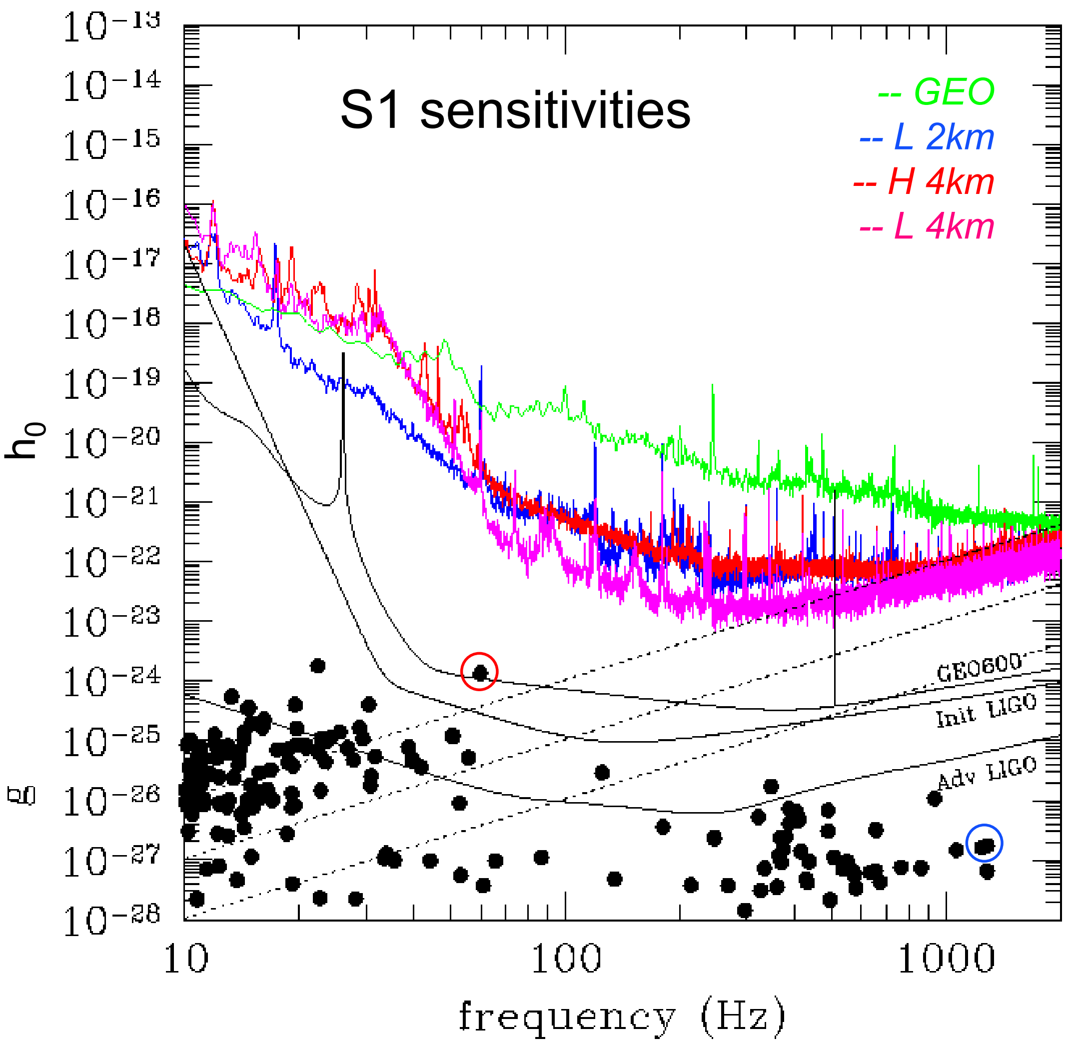


State of LIGO

Barry Barish

LSC Meeting

LLO Hanford, WA

10-Nov-03

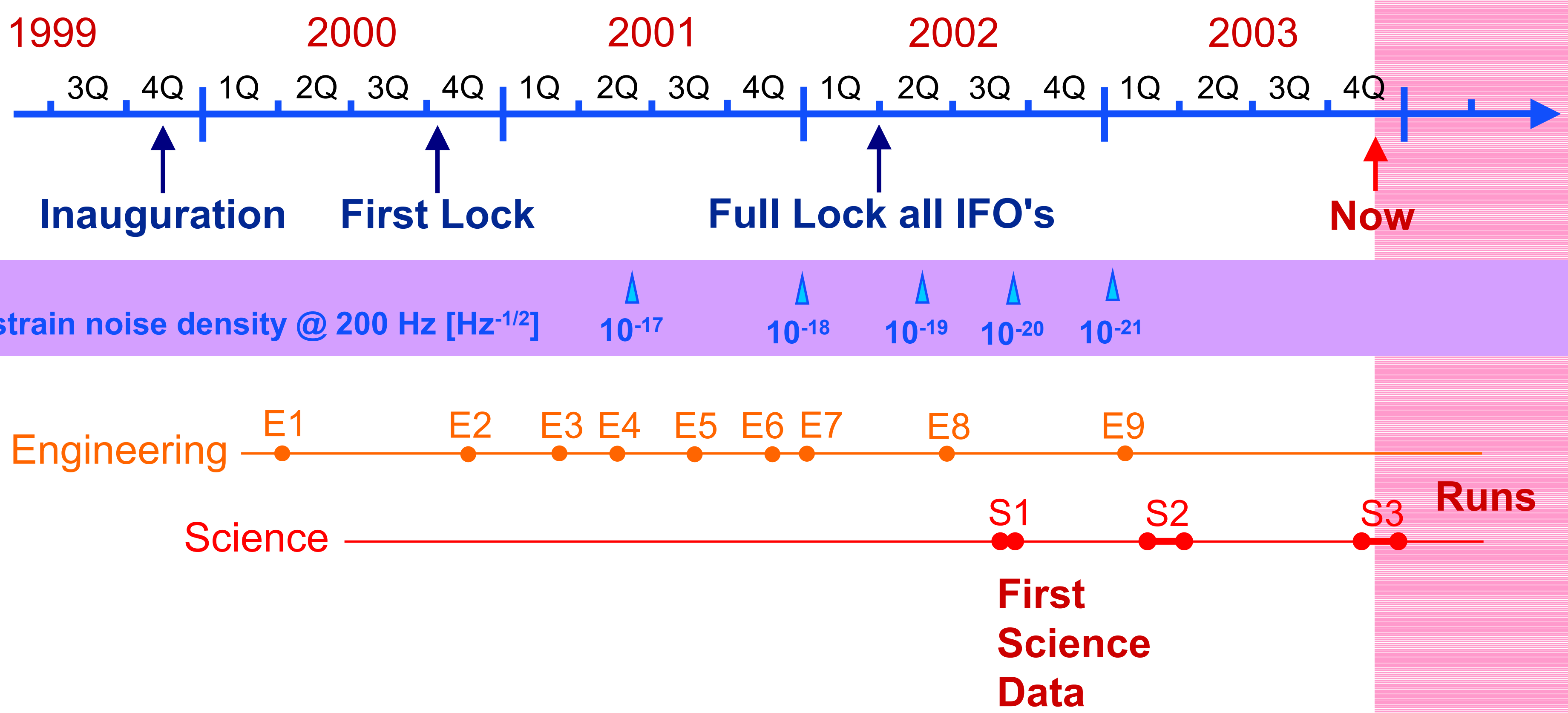
LIGO-G030557-00-M

Goals and Priorities

LSC -Aug 02

- Interferometer performance
  - » Integrate commissioning and data taking consistent with obtaining one year of integrated data at $h = 10^{-21}$ by end of 2006
- Physics results from LIGO I
  - » Initial upper limit results by early 2003
  - » First search results in 2004
  - » Reach LIGO I goals by 2007
- Advanced LIGO
  - » Prepare advanced LIGO proposal this fall
  - » International collaboration and broad LSC participation
  - » Advanced LIGO installation beginning by 2007

Commissioning / Science Timeline



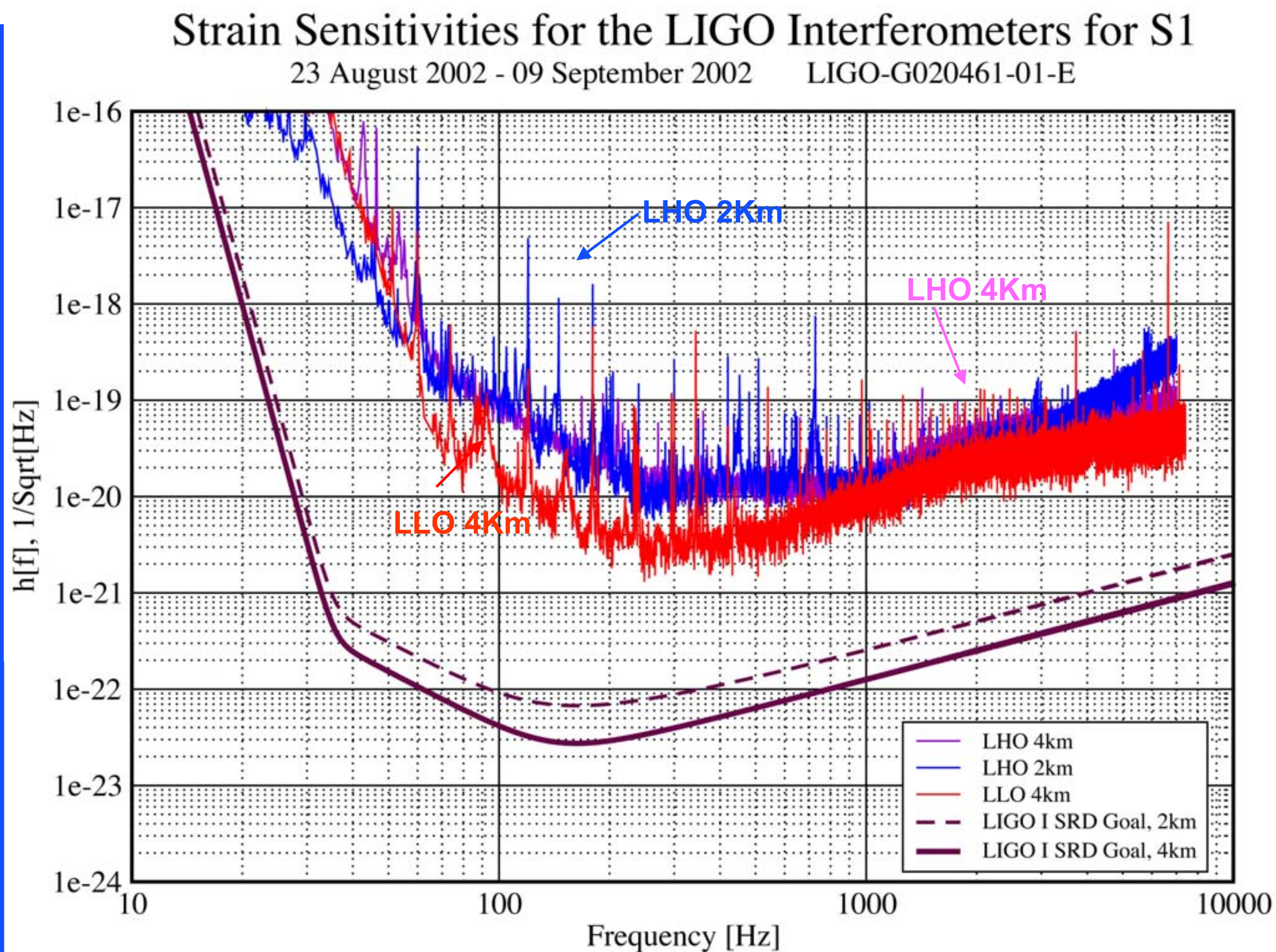
Sensitivity during S1

LIGO S1 Run

"First Upper Limit Run"

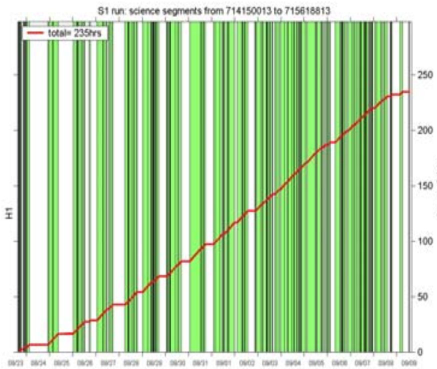
- 23 Aug–9 Sept 2002
- 17 days
- All interferometers in power recycling configuration

GEO data exchange for S1 RUN

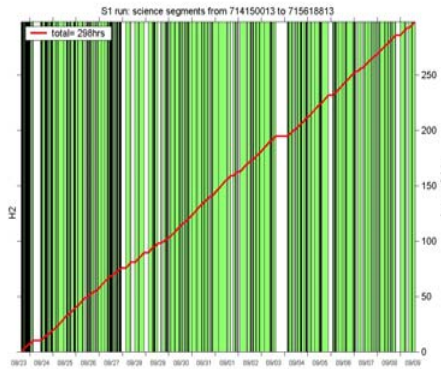


In-Lock Data Summary from S1

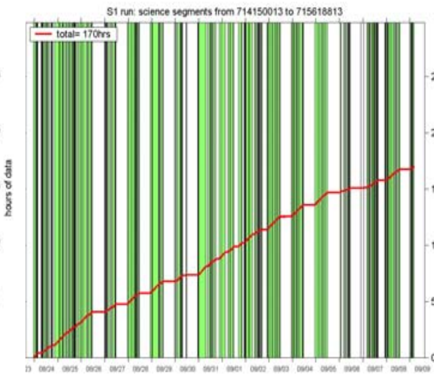
H1: 235 hrs



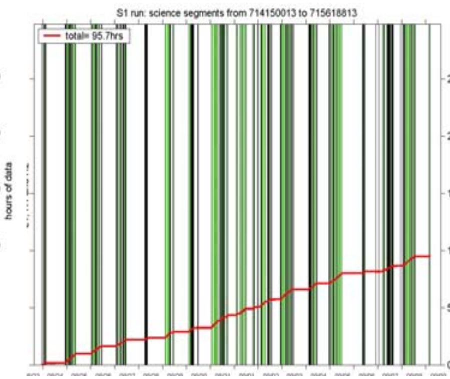
H2: 298 hrs



L1: 170 hrs



3X: 95.7 hrs



Red lines: integrated up time Green bands (w/ black borders): epochs of lock

- August 23 – September 9, 2002: 408 hrs (17 days).
  - H1 (4km): duty cycle 57.6% ; Total Locked time: 235 hrs
  - H2 (2km): duty cycle 73.1% ; Total Locked time: 298 hrs
  - L1 (4km): duty cycle 41.7% ; Total Locked time: 170 hrs

- Double coincidences:
  - L1 && H1 : duty cycle 28.4%; Total coincident time: 116 hrs
  - L1 && H2 : duty cycle 32.1%; Total coincident time: 131 hrs
  - H1 && H2 : duty cycle 46.1%; Total coincident time: 188 hrs

Triple Coincidence: L1, H1, and H2 : duty cycle 23.4% ; total 95.7 hours

S1 "Methodology" Papers

- **Detector Paper** (gr-qc/0308043 v1 14 Aug 2003) **ACCEPTED**

  "Detector Description and Performance for the First Coincidence Observations between LIGO and GEO"

- **Periodic Sources** (gr-qc/0308050 v1 14 Aug 2003)

  "Setting upper limits on the strength of periodic gravitational waves using the first science data from the GEO600 and LIGO detectors"

- **Inspiral Sources** (gr-qc/0308069 v1 21 Aug 2003)

  "Analysis of LIGO data for gravitational waves from binary neutron stars"

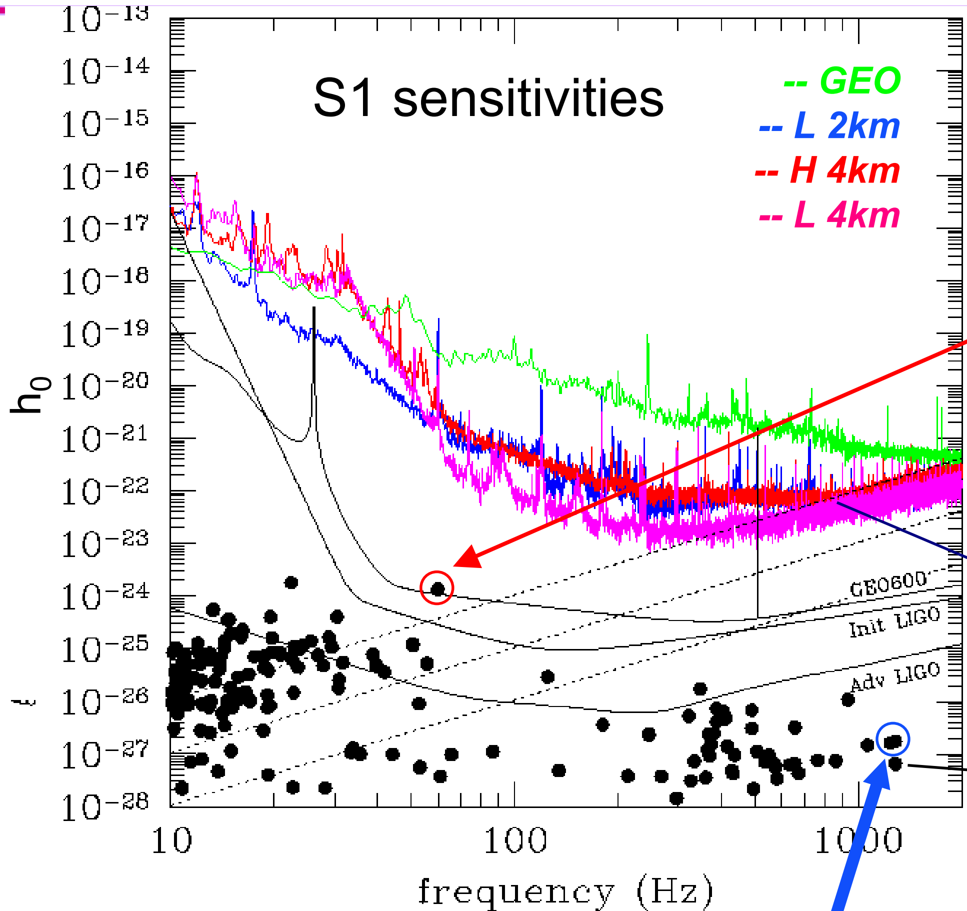
- **Stochastic Sources**

  "Analysis of First LIGO Science Data for Stochastic Gravitational Waves"

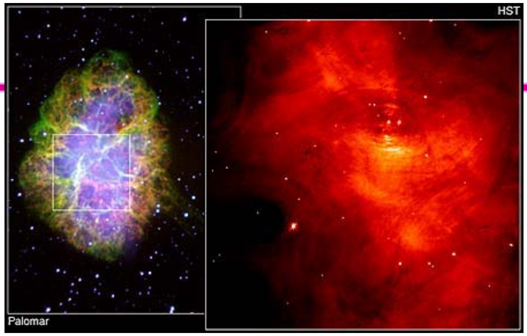
- **Burst Sources**

  "First upper limits on gravitational wave bursts from LIGO"

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*
P = 1.0519 10^{-19} s/s
D = 3.6 kpc

Bayesian Time Domain Analysis

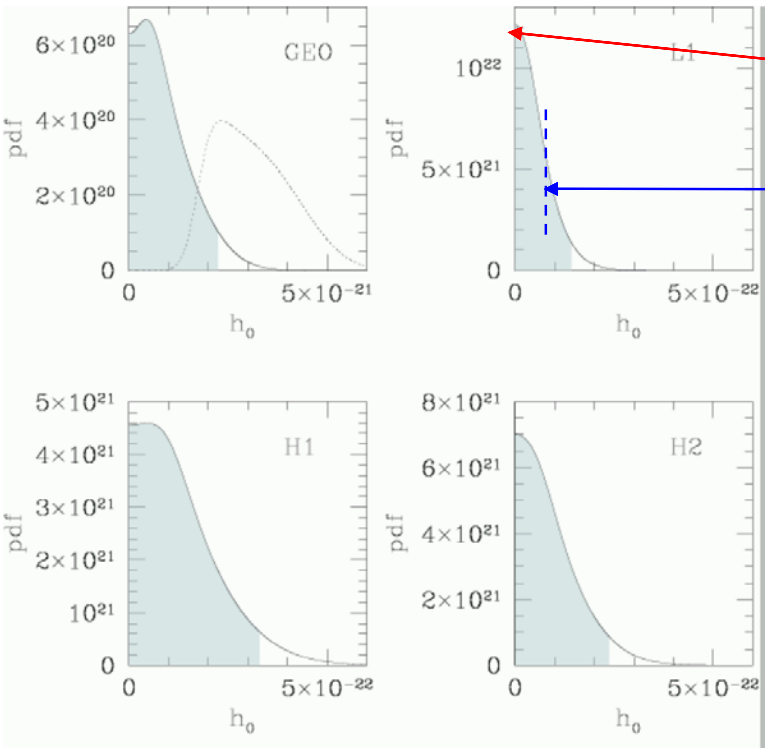


FIG. 8: For each interferometer, the solid line represents the marginalized posterior pdf for h_0 (PSR J1939+2134) resulting from the S1 data. The 95% upper limits (extent of the shaded region) are 2.2×10^{-21} for GEO, 1.4×10^{-22} for L1, 3.3×10^{-22} for H1 and 2.4×10^{-22} for H2. The dotted line 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	$(4.0 \pm 0.5) \times 10^{-22}$	$(2.4 \pm 0.2) \times 10^{-22}$

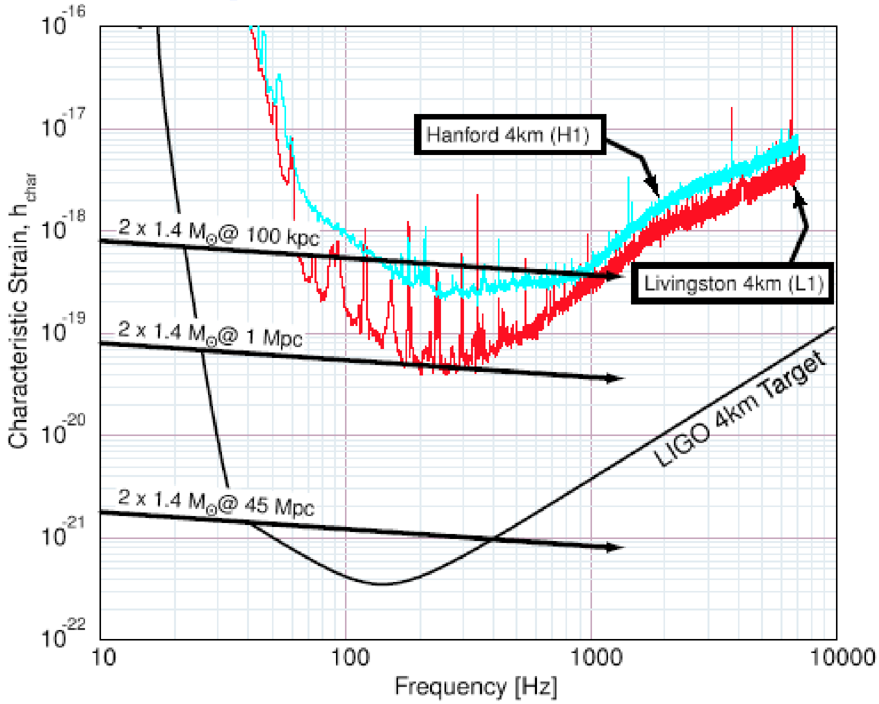
TABLE IV: Summary of the 95% upper limit values of h_0 for PSR J1939+2134. The frequency domain search (FDS) quotes a conservative frequentist upper limit and the time domain search (TDS) a Bayesian upper limit after marginalizing over the unknown ι, ψ and ϕ_0 parameters.

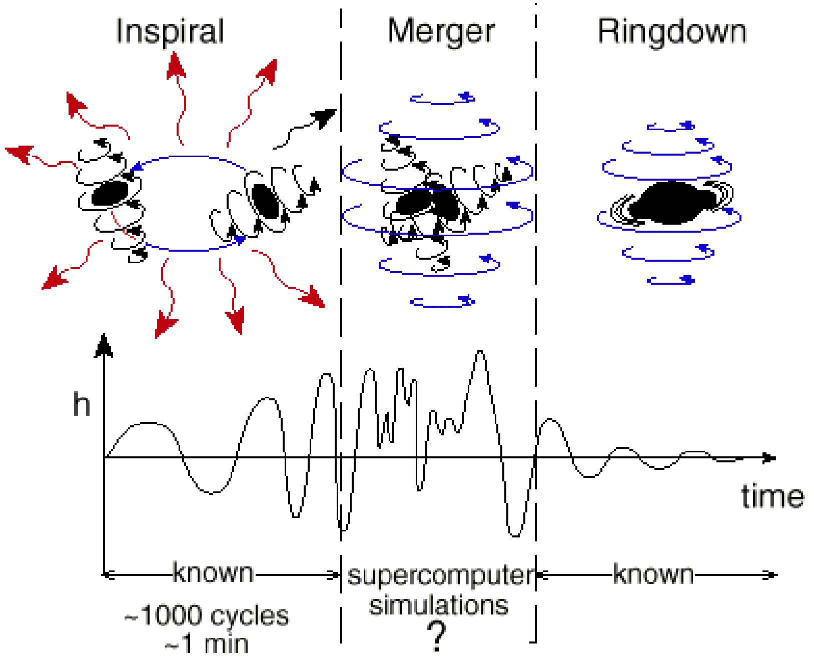
Upper limit on h_0 implies upper limit on ε:

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

S1 Binary Inspiral Analysis

Detectability
optimal orientation

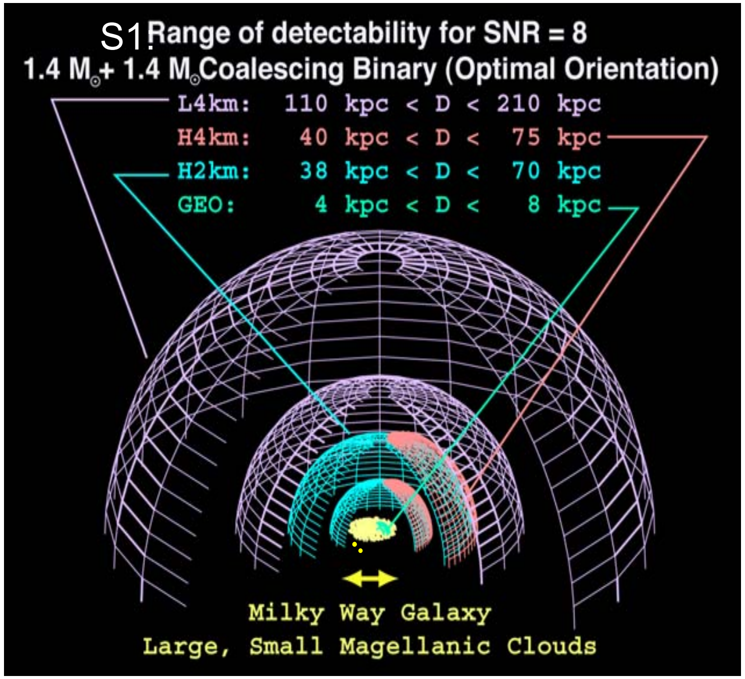




V. Kalogera (population synthesis)

Search for NS-NS Inspirals

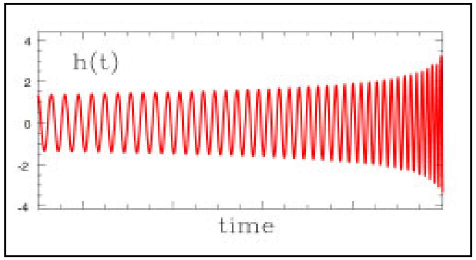
- **Sources:**
  - » Compact neutron star binary inspiral is in our frequency band.
  - » Waveforms calculable
  - » Masses, positions, orbital parameters, distances: unknown
- **S1 Analysis goals:**
  - » Develop and demonstrate the analysis methodology
  - » Obtain UL on the NS-NS inspiral rate
    - – source distribution model:
      - S1 range included Milky Way (our Galaxy) and LMC and SMC
      - *S2 range includes Andromeda*



LIGO-G030557-00-M

Compact binary sources search

- Approach - Optimal Wiener filtering with chirp templates
  - Implemented for 40m data, TAMA data



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

  - Additionally require signal strength distributed in frequency-time plane according to a chirp

$$\rho(t) = \frac{|z(t)|}{\sigma}$$

    - **Select p = 8 frequency bands containing *equal signal strength***
    - **Form χ^2 statistic to discriminate on integrated SNR -- z(t)/σ**

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

Average SNR per band

    - **Require:** $\chi^2 < 5(p + 0.03\rho^2)$

Compact binary sources

Discrimination - non-stationary noise artifacts

- **Time dependence of signal strengths**
  - » **SNR - ρ**
  - » χ^2
- **Can distinguish true events vs. noise with same ρ and χ^2**

S1 data | **injected chirp**

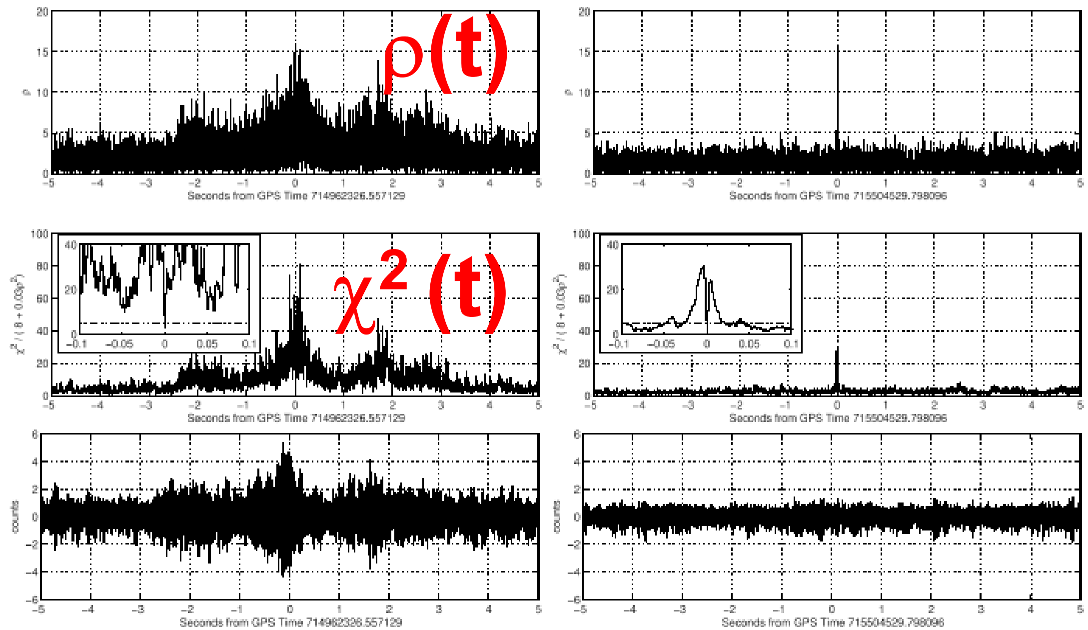


FIG. 5: Left Panels: The largest SNR candidate event seen during our search of the LIGO data. This candidate event occurred at a time when only L1 was in stable operation. The top panel shows the signal-to-noise time series, $\rho(t)$. Notice that $\rho(t) > 6.5$ many times in a ~ 5 second interval around the candidate event. The center panel shows $\chi^2/(p + 0.03\rho^2)$ as a function of time; notice $\chi^2/(p + 0.03\rho^2) > 5$ for ~ 5 seconds around the candidate event, but drops below this threshold right at the time of maximum ρ. The inset shows this more clearly for ± 0.1 second around the event where the threshold is indicated by a dot-dashed horizontal line. The bottom panel shows the time series for this candidate event after applying a high-pass filter with a knee frequency of 200 Hz. Notice the bursting behavior which does not look like an inspiral chirp signal. Right Panels: A simulated injection into the L1 data. This example was chosen for comparison with the largest SNR event shown in the left panels since it similar in mass parameters, detected signal to noise and χ^2. The instrument was behaving well at the time around the simulated injection. The top panel shows that $\rho(t) < 6.5$ except in close proximity to the signal detection time. The center panel shows $\chi^2/(p + 0.03\rho^2)$ as a function of time. Notice that it is much closer to threshold at all times around the simulated injection; this contrasts dramatically with the case of the candidate event shown in the left panels. The inset shows this more clearly for ± 0.1 seconds around the injection. The bottom panel shows the time series for this simulated injection after applying a high-pass filter with a knee frequency of 200 Hz. The inspiral chirp signal is not visible in the noisy detector output.

S1 Upper Limit

- **Limit on rate:**
  - » **T = 236 h = 0.027 y**
  - » **N_G = 0.6 (= ε 1.13 L_G/L_G) $^{+0.12}_{-0.10}$ (systematic)**
    = 0.5 (min)

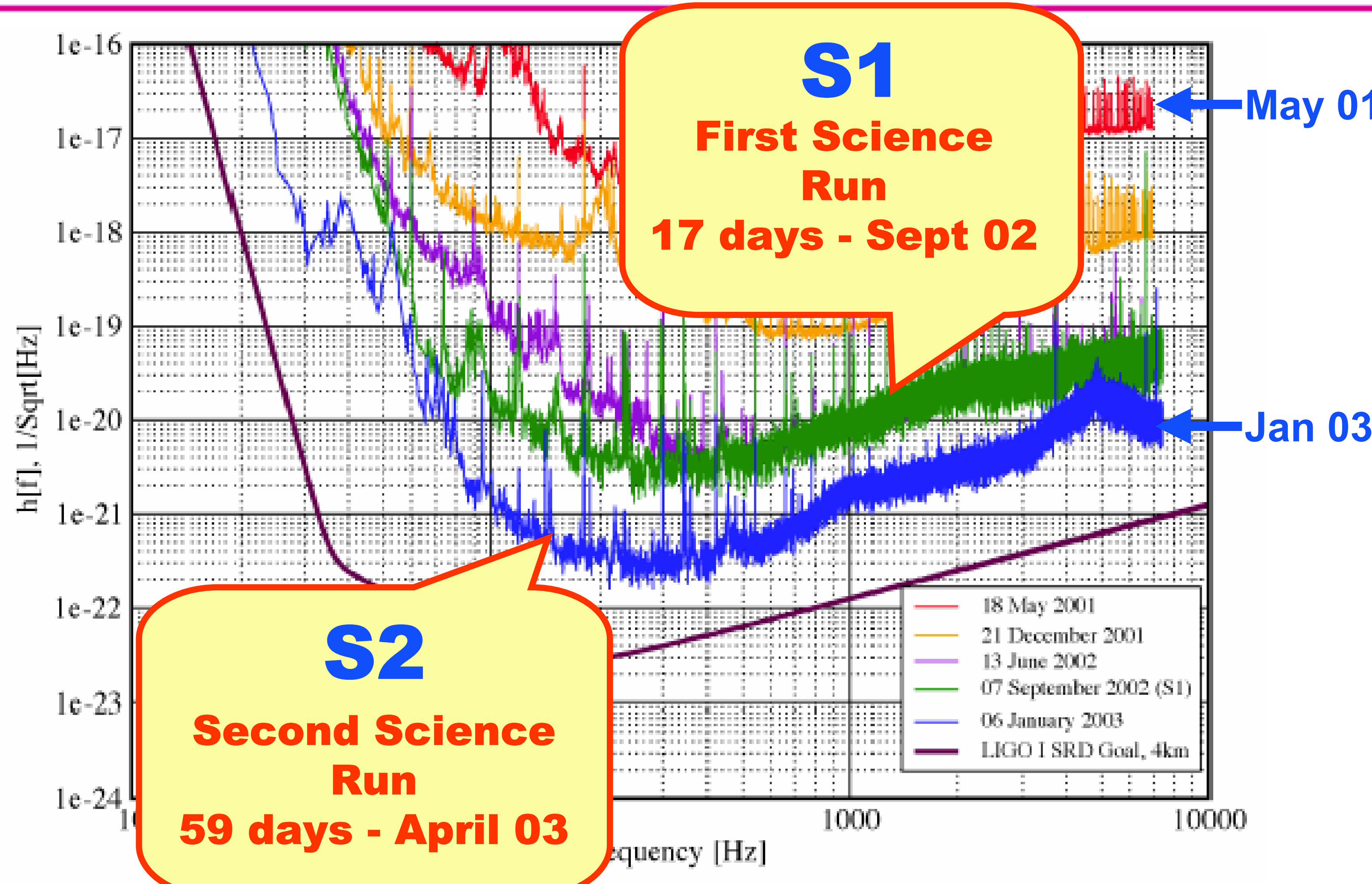
$$\mathcal{R}_{90\%} = 2.303 \times \left(\frac{1\ \mathrm{y}}{T}\right)\left(\frac{1}{N_G}\right)\ \mathrm{y}^{-1}\ \mathrm{MWEG}^{-1}$$

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

- ***26X lower than best published observational limit -- 40m prototype at Caltech:***
  - » ***$R_{90\%}$ (Milky Way) < 4400 /yr***

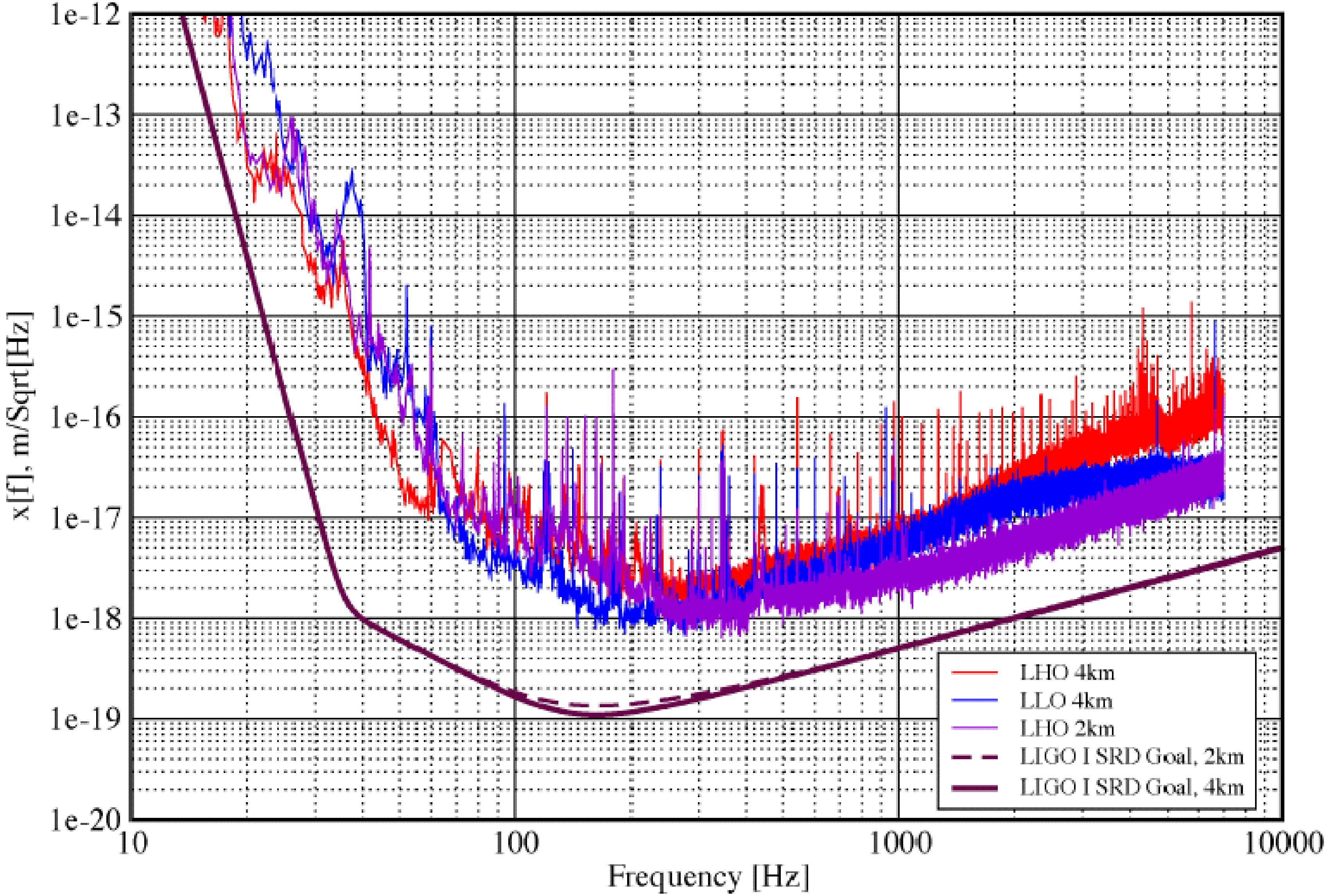
- ***Comparable to recent TAMA analysis (1000 hr run) :***
  - » ***R < 123 /yr for MW Galaxy***

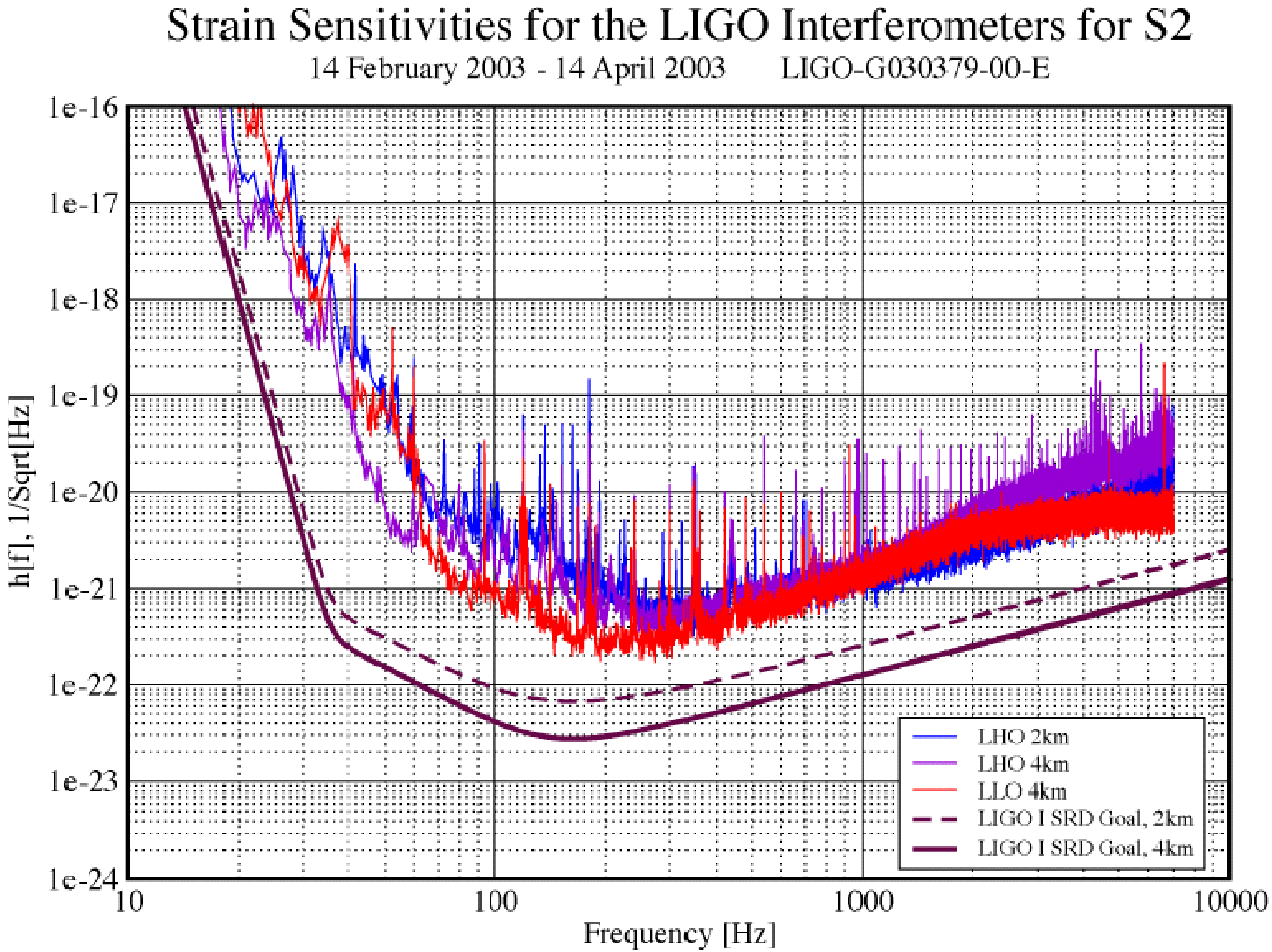
LIGO Sensitivity -- L1



Displacement Sensitivities for the LIGO Interferometers for S2

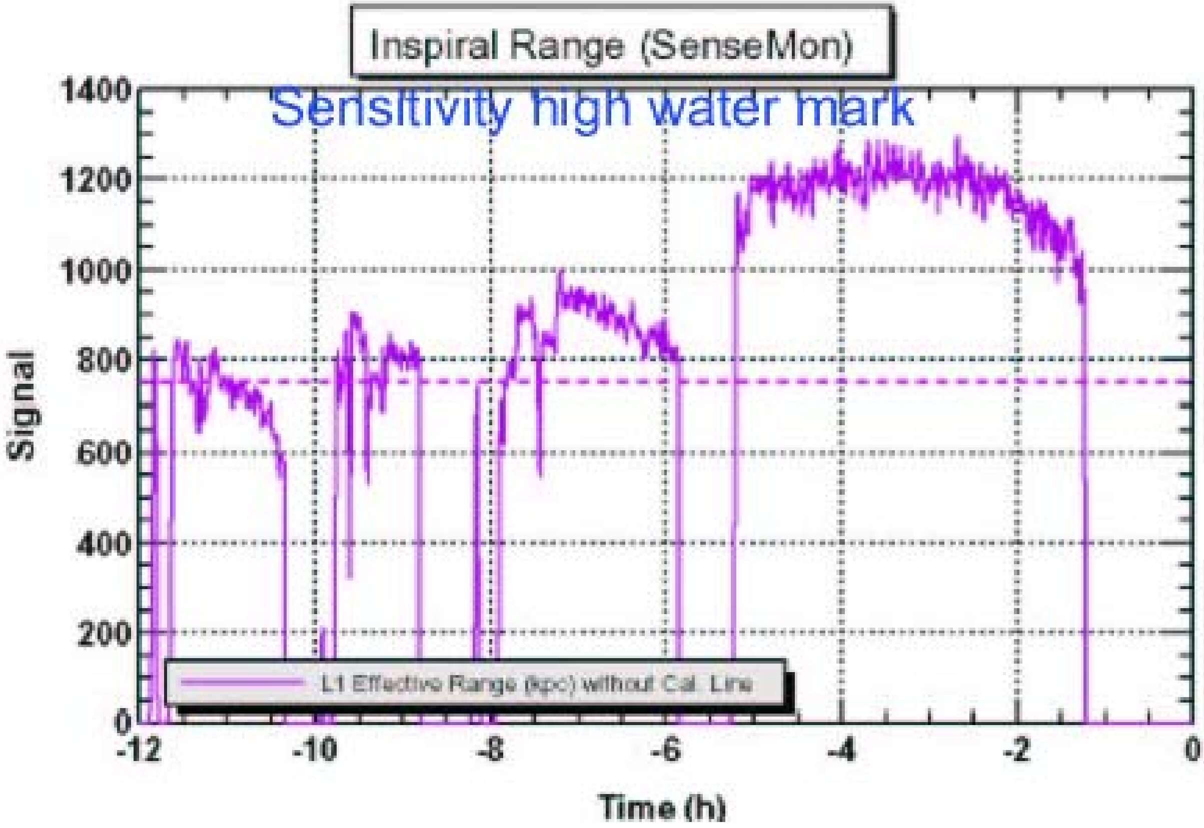
14 February 2003 - 14 April 2003 LIGO-G030378-00-E



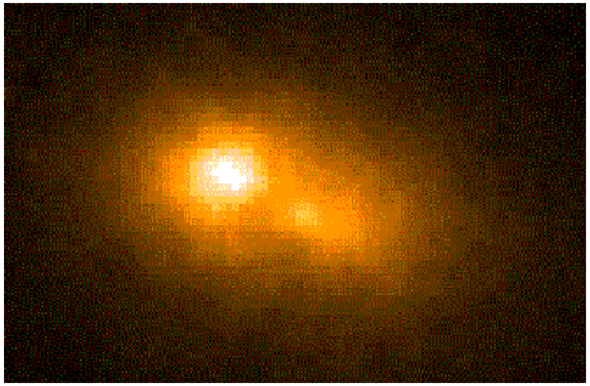


LIGO-G030557-00-M

S2 -- L1 reaches Andromeda



M31 in Andromeda



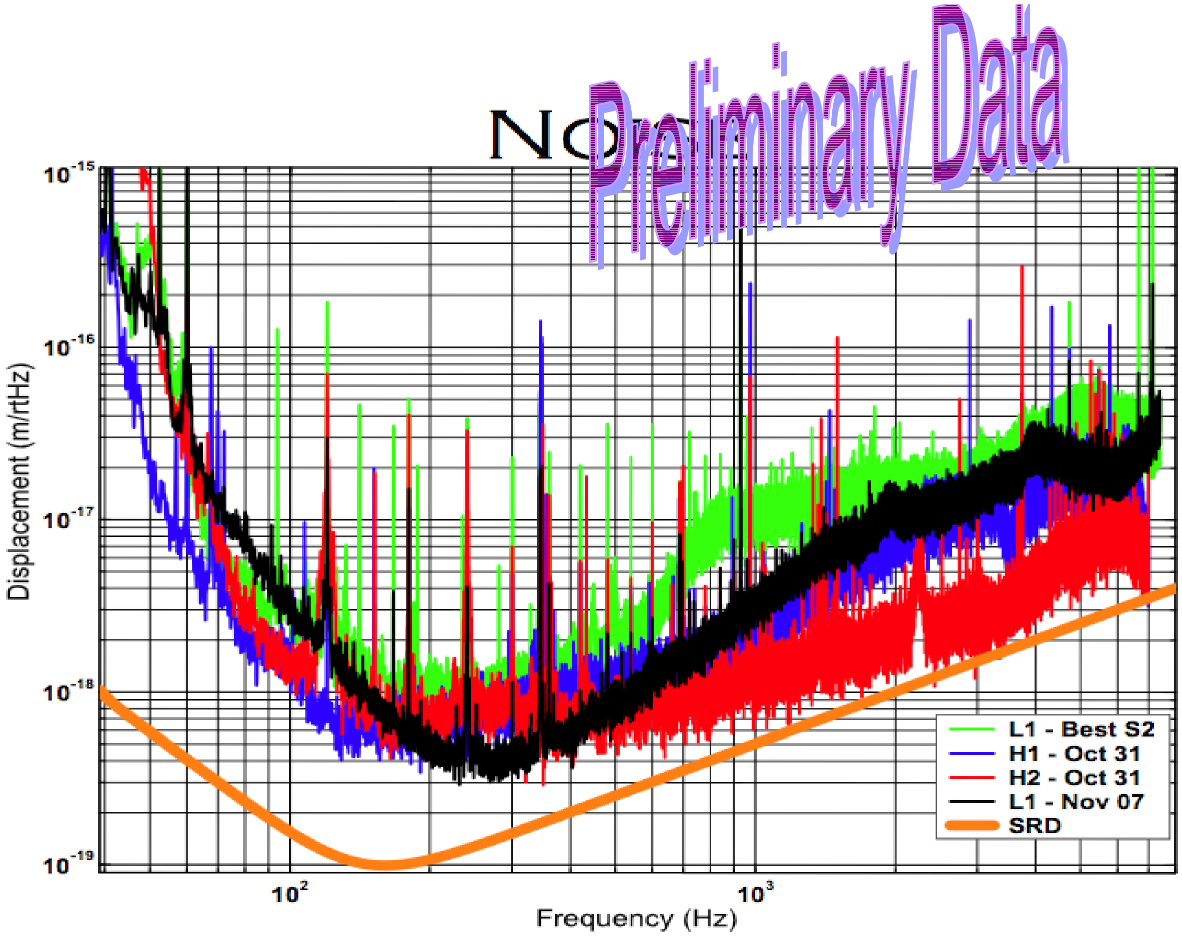
Future Data Analysis

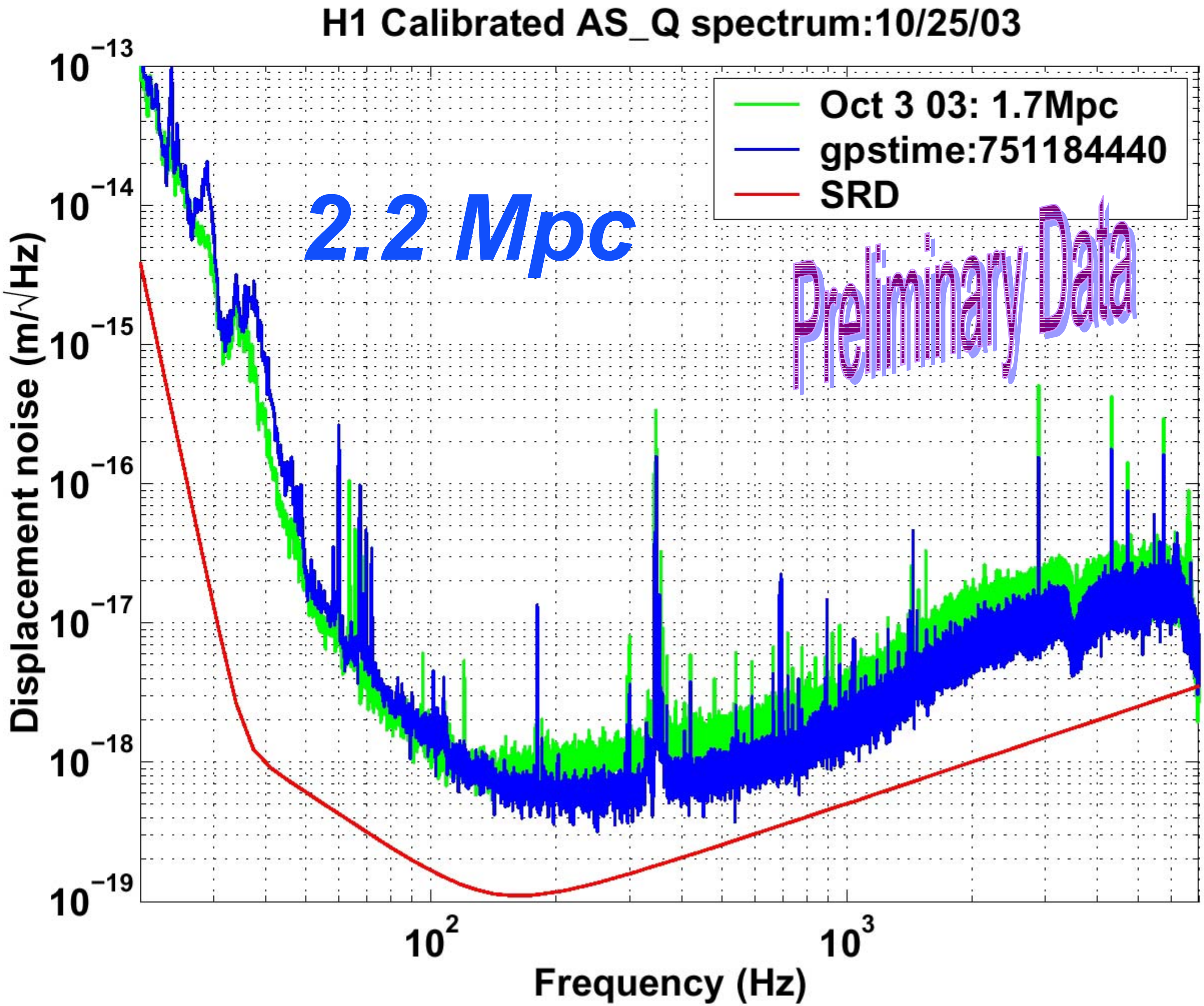
- **S2 Data Analysis:**
  - » Data sample has 4 x S1 running time and 10 x better sensitivity
  - » Many lessons learned from S1 data analysis.
  - » There are expanded goals of the analysis working groups for S2
  - » One of the main tasks at this meeting is to fully transition to S2 data analysis, define goals for S2 analysis and determine presentations at GWDAW.

- **S3 Data Analysis Prospects:**
  - » Improved performance in for H1 and H2; L1 problems have been solved
  - » Run is underway and could be modestly extended into January
  - » For S3, three interferometers with sensitivity beyond our own galaxy. We can now begin to speak in units of Mpc range.

S3: Extragalactic Sensitivity !!

Displacement spectral density





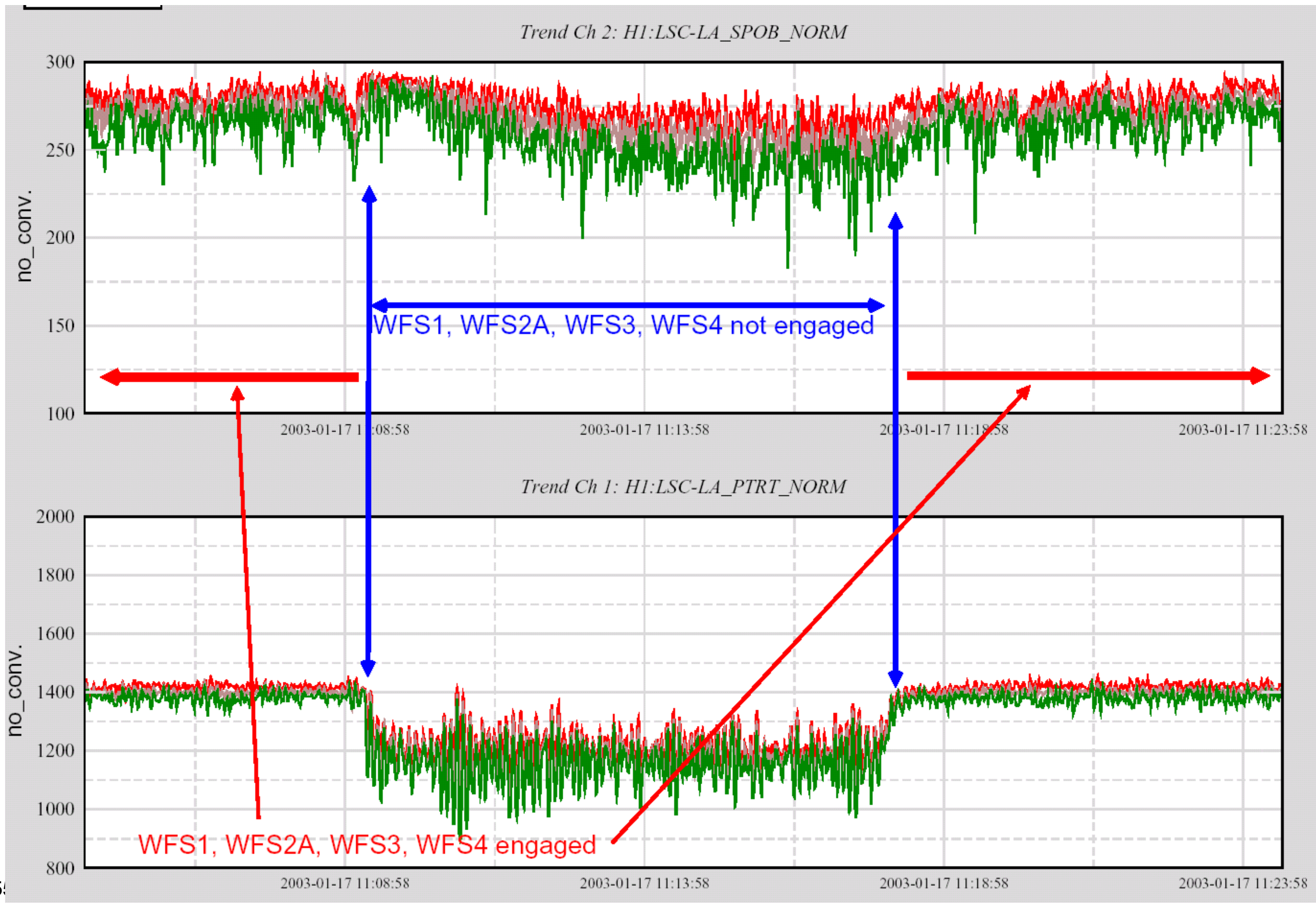
H1 Calibrated AS_Q spectrum:10/25/03
Oct 3 03: 1.7Mpc
gpstime:751184440
SRD
2.2 Mpc
Preliminary Data
Displacement noise (m/√Hz)
Frequency (Hz)
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{2}
10^{3}

Summary 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%	1700	16%*
H1	~30	59%	350	74%	2200	74%*
H2	~40	73%	200	58%	1000	63%*
3-way		24%		22%		7%*

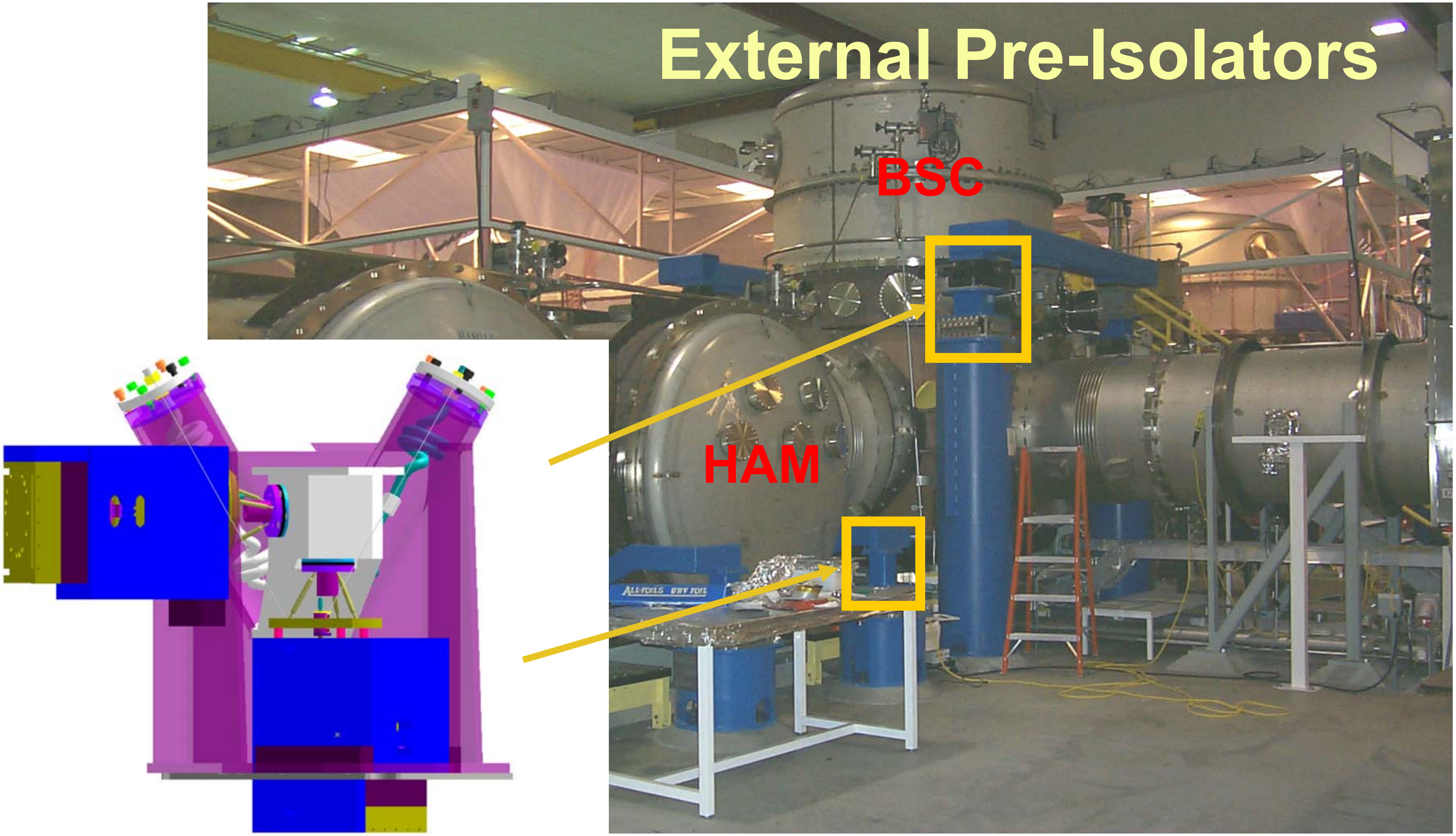
***PRELIMINARY**--*RUN IN PROGRESS*

Controlling angular degrees of freedom



Post S3 at LLO

active external seismic



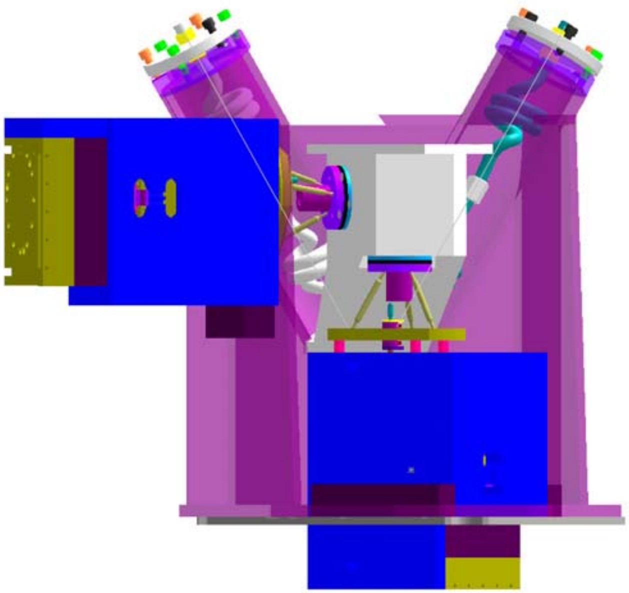
Advanced LIGO

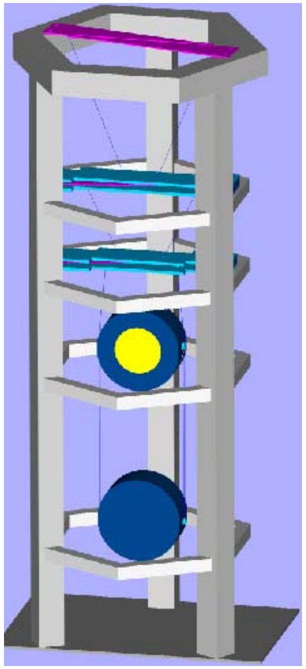
proposed in early 2003

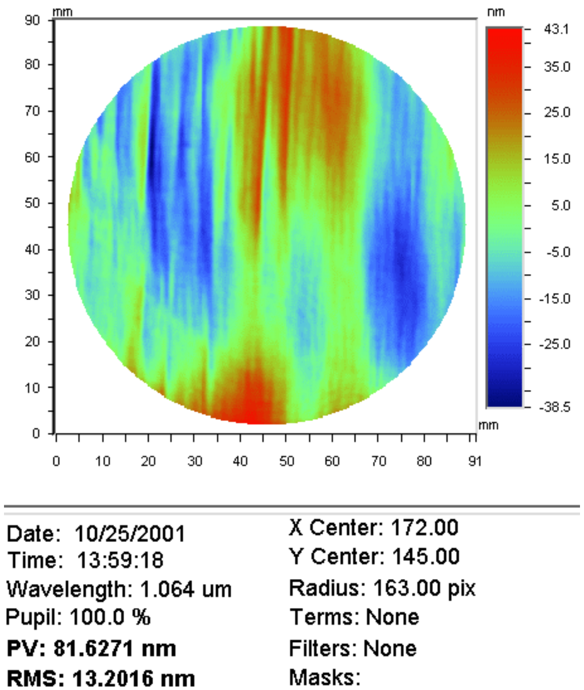
Multiple Suspensions

Active Seismic

Sapphire Optics







Higher Power Laser

AdLIGO Status as a Project

- Large Projects at NSF are funded through MREF account (projects with total cost of more than ~10% of the annual division budget)
- A long list of possible MREF projects (23) are under discussion by all the directorates and the list changes with time.
- A shorter list of reviewed projects (11) are discussed annually with the NSB annually (a more stable list, but <u>not</u> prioritized)

- The Assistant Directors advise the Directorate (who decides) what and when to bring projects forward to NSB for consideration and approval
- **Next big step is to obtain NSB approval and then inclusion in future MREF budgets to OMB (FY06?)**

LIGO Outreach

$5M for 5 years

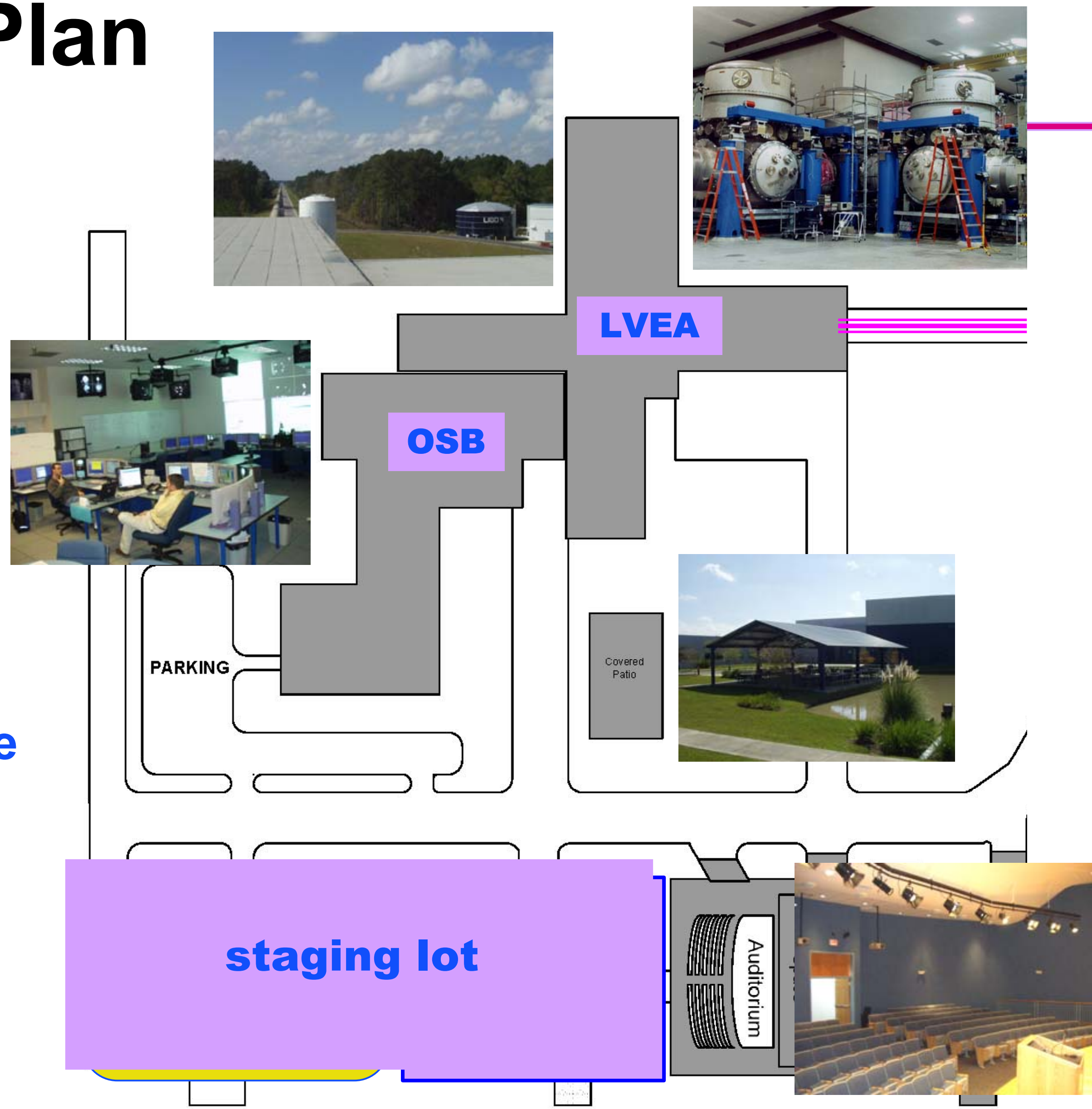
Proposal Reviewed 03-Nov-03

LSC Collaborating Groups are invited to participate in the LIGO Laboratory Outreach Activities

LIGO Outreach Collaboration

- **LIGO provides the science and facilities**
- **Exploratorium exhibits the science**
- **Southern University brings LIGO science to science education**
- **Louisiana Board of Regents extends our program through public education**

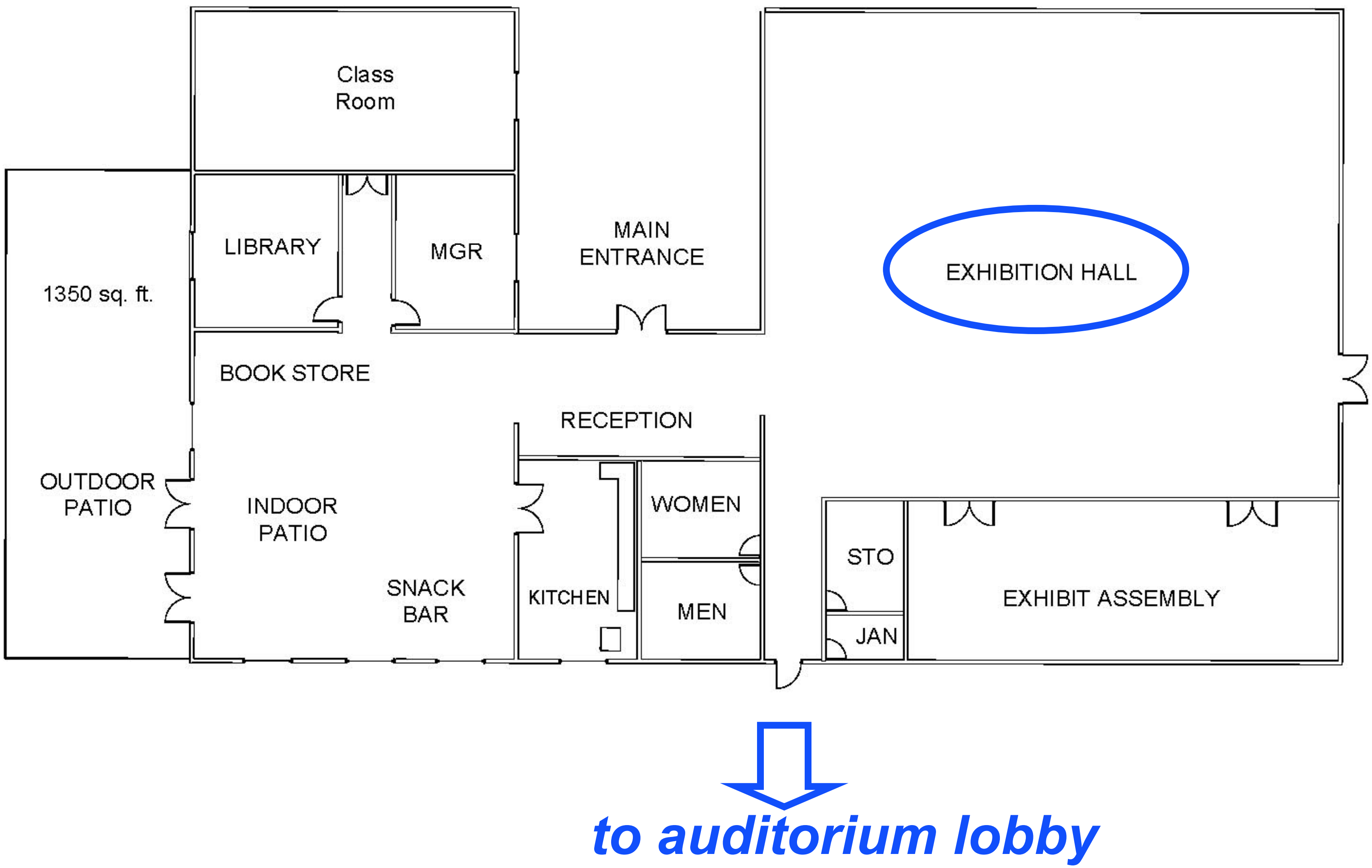
Site Plan



Existing unpaved site adjacent to LLO conference facility & temporary exhibit space

Erect new building with direct access to auditorium foyer

Outreach Center Design



LIGO-G030557-00-M

Exploratorium LIGO Exhibits

WAVES
Bells
Echo Tube
Theremin
Turn Off the Sky (giant polarizer)
Vibrating String
Water Waves
Wave Machine (suspended type)
Wave Propagation Device
Wave Upon Wave
WAVE PROPAGATION
Doppler Effect
Sound Spectrogram
Walking Beats
Watch Dog
RESONANCE
Pendulum Snake
Pendulum Table
Resonant Pendulum
Resonant Rings
Resonator
Ultraviolet Greenhouse

INTERFERENCE
Bridge Light
Interference Patterns
Long Path Diffraction
Michelson Interferometer
Soap Film Painting
Soap Films
GRAVITY
Balancing Stick
Bouncing Ball
Center of Gravity
Falling Feather
Gravity Well
Gravity's Rainbow
Satellite Orbit Simulator
LASER AND LIGHT
C – The Light
Hologram Stuff
Inverse Square Law Model
LASER Demonstration
Spectra
Zeemann Effect

Conclusions

- **S1 Analysis Complete. Five Papers being submitted for publication.**
- **S2 Data Run was ~x10 better sensitivity and ~x4 more running time. Data analysis is getting underway and we can look forward to much more significant results.**
- **S3 Data Run: Steady progress in commissioning (e.g. wave front sensing). Three interferometers with extragalactic sensitivity**
- **LIGO will shutdown to install L1 seismic mitigation - early 2004**
- **Advanced LIGO was proposed in Jan 03 and was well reviewed. It is now progressing through NSF/NSB toward funding.**
- **S4 Goal: Improve sensitivity and reliability to the point that our extended LIGO I searches can begin.**

Some Final Thoughts …

- The S1 data run was completed in September 02. No analysis paper is yet accepted for publication. **Where did fourteen months go??**
- How close do we need to get to design sensitivity/duty cycle to start a long search run? **Can we accomplish this by S4??**
- As our sensitivity improves the analysis must evolve into "searching". **Will we be capable of making the discoveries that lie in the data??**