Initial LIGO Commissioning and First Observations

Stan Whitcomb

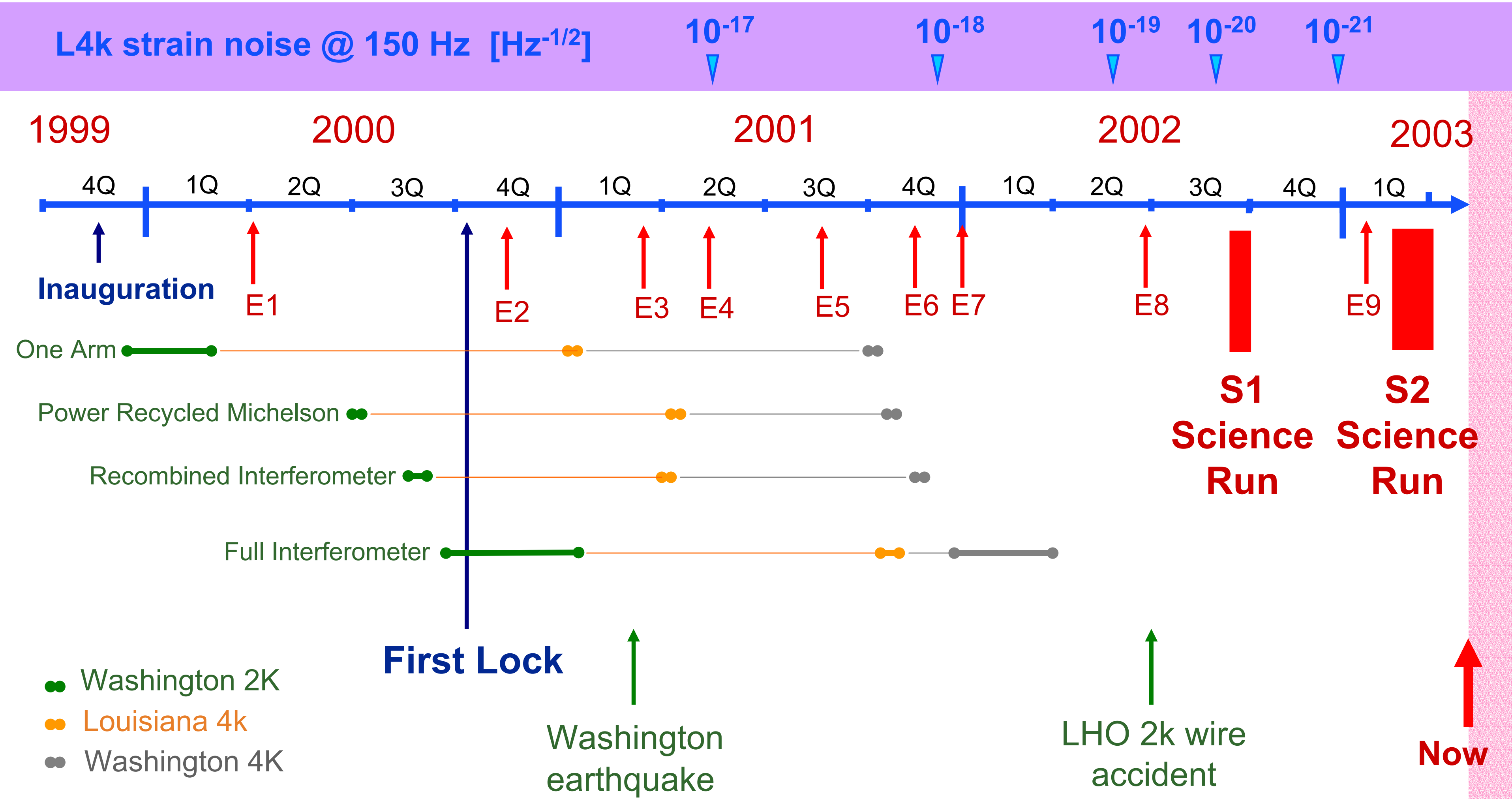
NSF AdvLIGO Review

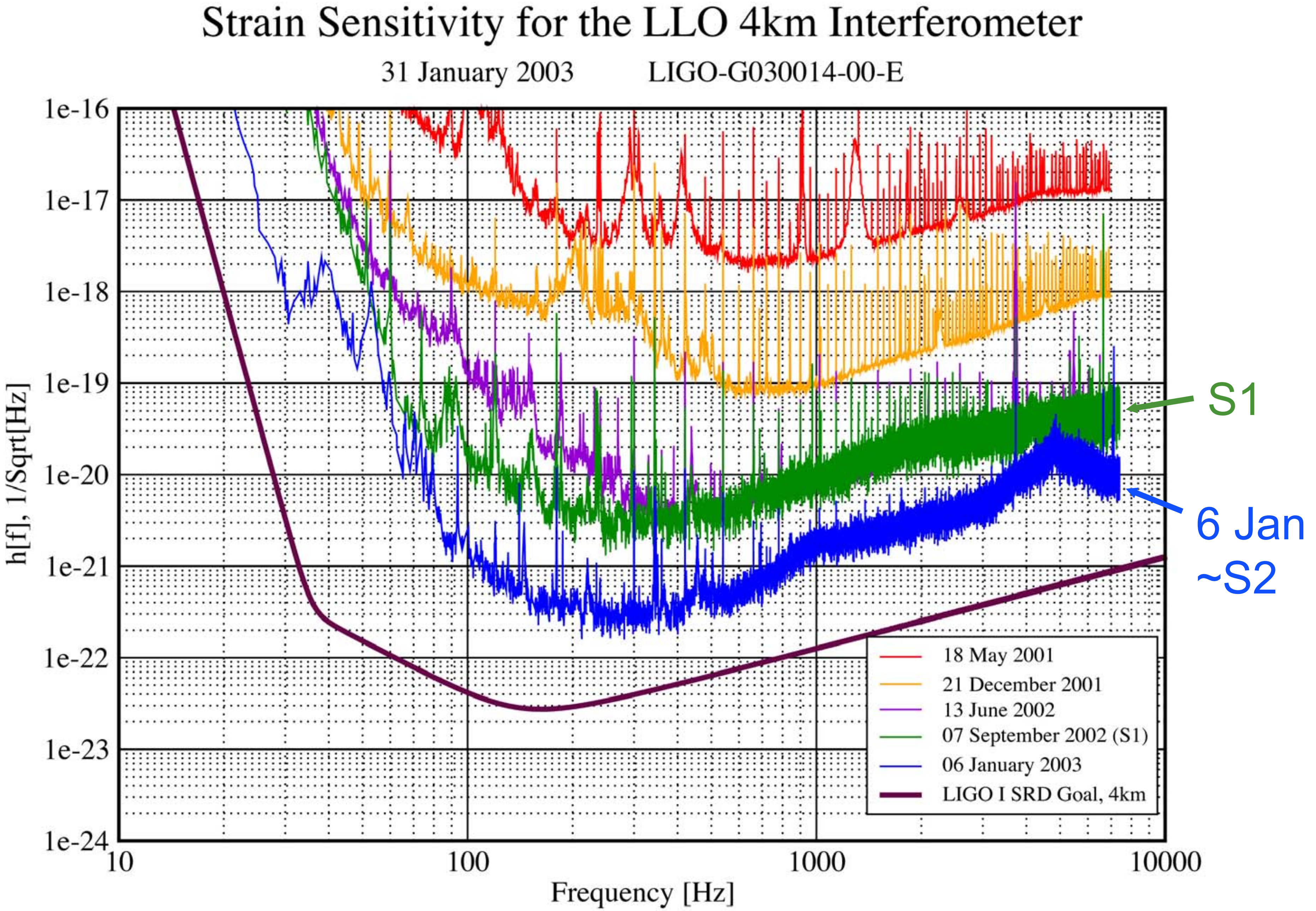
Caltech

11 June 2003

LIGO-G030280-00-D

Commissioning History

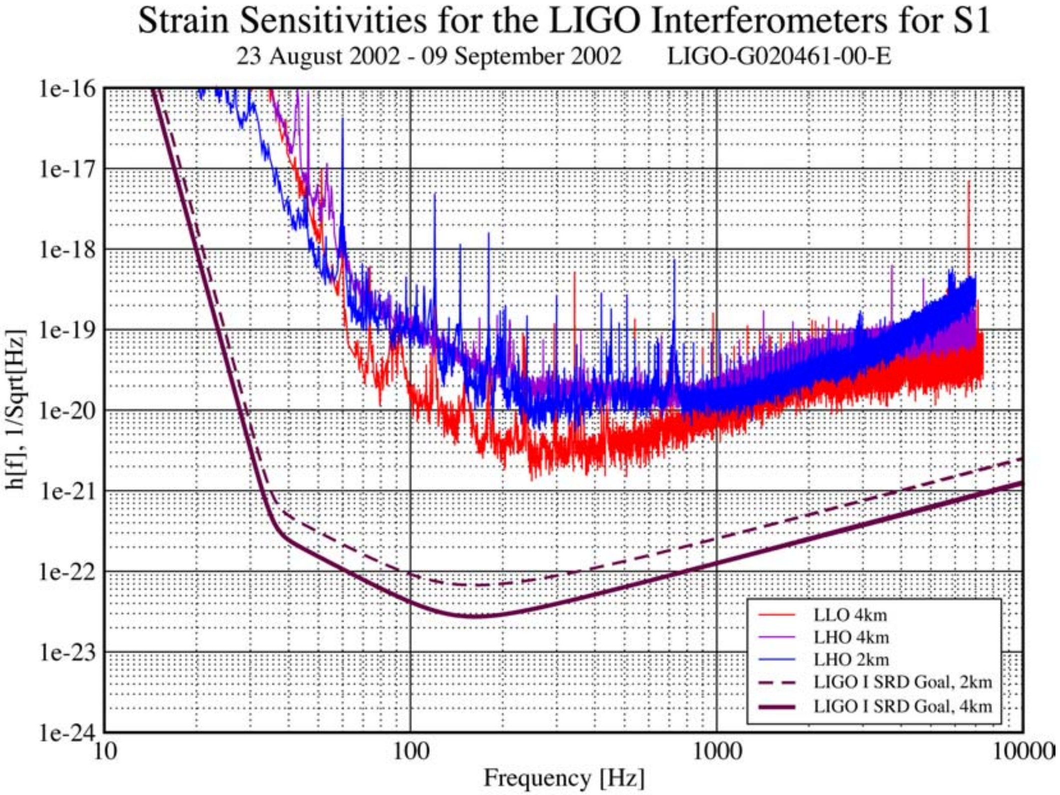




Strain Sensitivity for the LLO 4km Interferometer
31 January 2003
LIGO-G030014-00-E
1e-16
1e-17
1e-18
1e-19
1e-20
1e-21
1e-22
1e-23
1e-24
h[f], 1/Sqrt[Hz]
10
100
1000
10000
Frequency [Hz]
18 May 2001
21 December 2001
13 June 2002
07 September 2002 (S1)
06 January 2003
LIGO I SRD Goal, 4km
S1
6 Jan
~S2

First Science Run (S1)

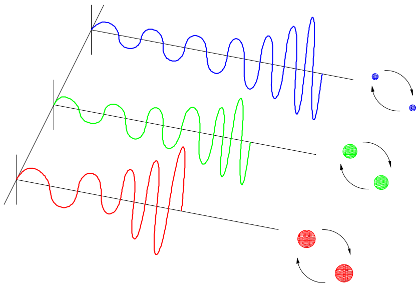
- August 23 - September 9
 (~400 hours)
- Three LIGO interferometers, plus GEO (Europe) and TAMA (Japan)
- Hardware reliability good for this stage in the commissioning
  - » Longest locked section for individual interferometer: 21 hrs



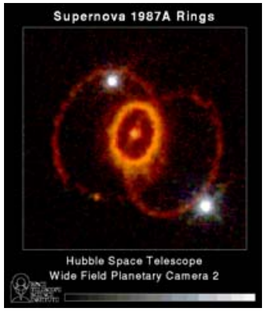
	LLO-4K	LHO-4K	LHO-2K	3x Coinc.
Duty cycle	42%	58%	73%	24%

Astrophysical Searches with S1 Data

- Compact binary inspiral: *"chirps"*
  - » NS-NS waveforms are well described
  - » BH-BH need better waveforms
  - » search technique: matched templates

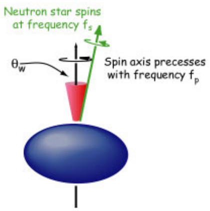


- Supernovae / GRBs: *"bursts"*
  - » burst signals in coincidence with signals in electromagn
  - » prompt alarm

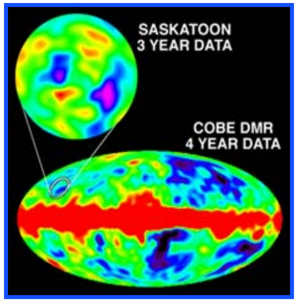


Four papers describing results in final stages of preparation

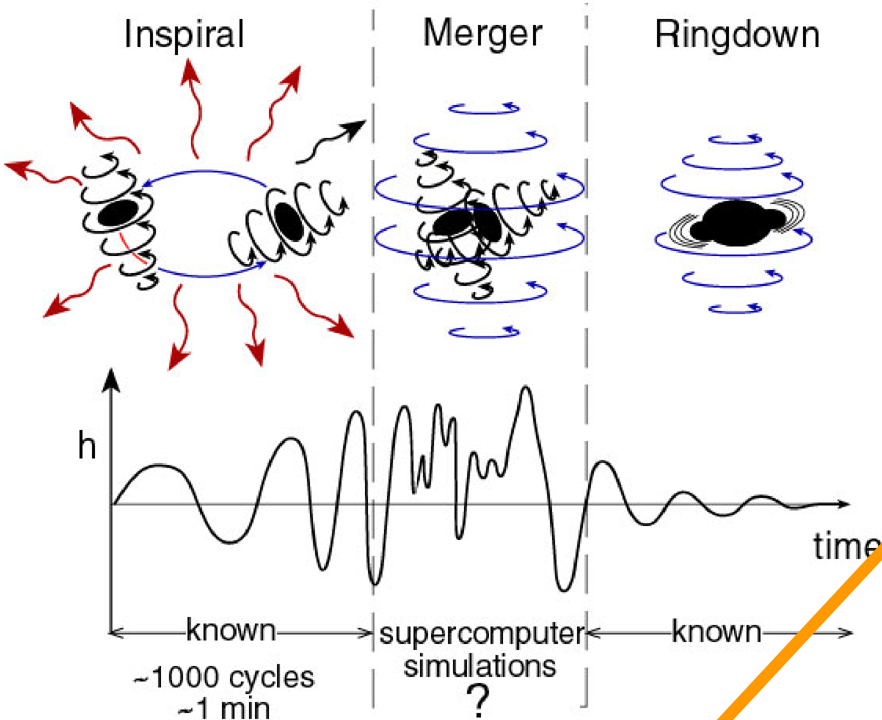
- Pulsars in our
  - » search for observed neutron stars (frequency, doppler shift)
  - » all sky search (computing challenge)
  - » r-modes



- Cosmological Signals *"stochastic background"*



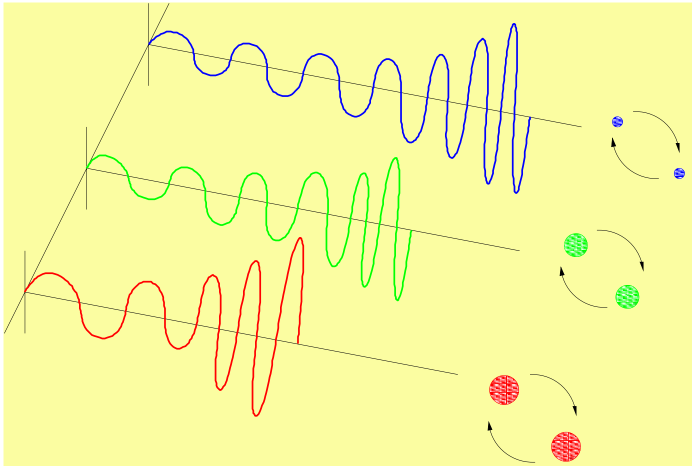
Compact Binary Coalescence



» Search: *matched templates*

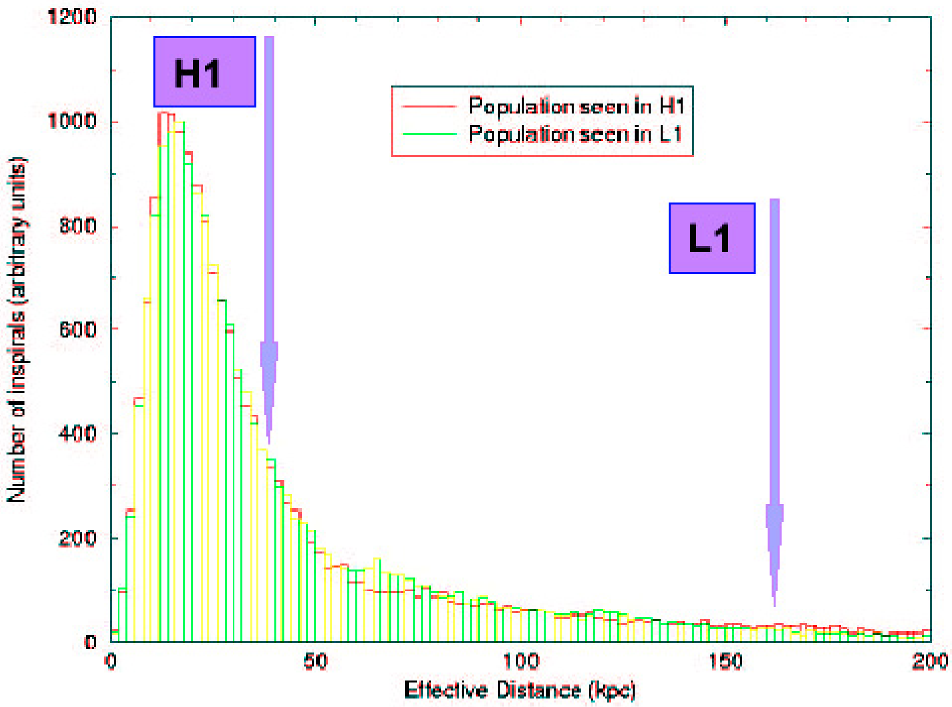
» Neutron Star – Neutron Star
  – **waveforms are well described**

» Black Hole – Black Hole
  – **need better waveforms**



- Discrete set of templates labeled by (m1, m2)
  - » 1.0 Msun < m1, m2 < 3.0 Msun
  - » 2110 templates
  - » At most 3% loss in SNR

Results of S1 Inspiral Search



Simulated Galactic Population

- Population includes Milky Way, LMC and SMC
- LMC and SMC contribute ~12% of Milky Way

LIGO S1 Upper Limit

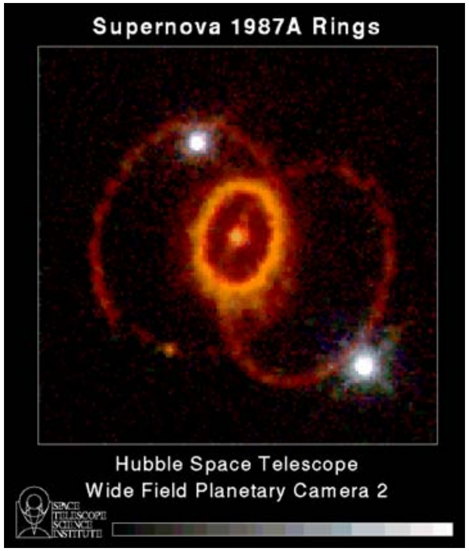
R < 160 / yr / MWEG

- » Japanese TAMA → R < 30,000 / yr / MWEG
- » Caltech 40m → R < 4,000 / yr / MWEG

- Theoretical prediction R < 2×10^{-5} / yr / MWEG

Detectable Range for S2 data will reach Andromeda!

Burst Sources



- **Known sources -- Supernovae & GRBs**
  - » **Coincidence with observed electromagnetic observations.**
    - » **No close supernovae occurred during the first science run**
    - » **Second science run – We are analyzing the recent very bright and close GRB030329**
      NO RESULT YET
- **Unknown phenomena**
  - » **Emission of short transients of gravitational radiation of unknown waveform (e.g. black hole mergers).**

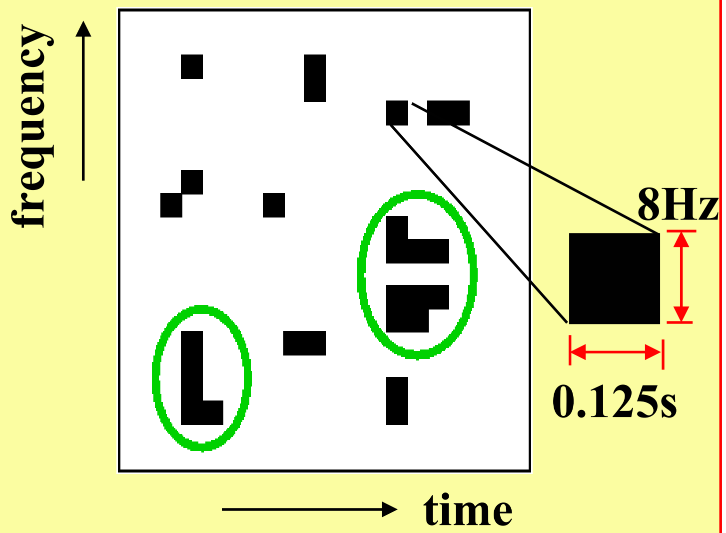
S1

‘Unmodelled’ Burst Search

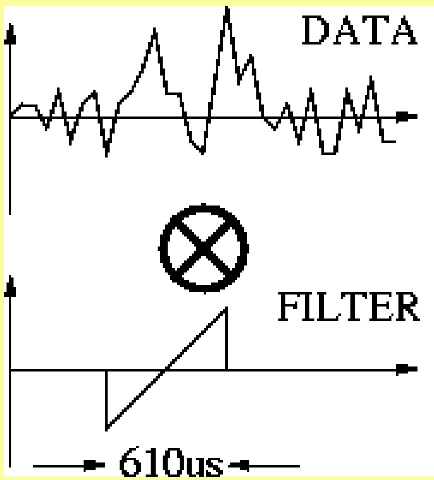
GOAL search for waveforms from sources for which we cannot currently make an accurate prediction of the waveform shape.

METHODS ‘Raw Data’ → Time-domain high pass filter

Time-Frequency Plane Search
‘TFCLUSTERS’



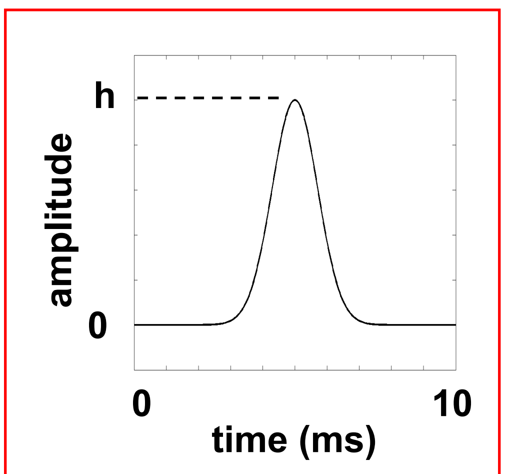
Pure Time-Domain Search
‘SLOPE’



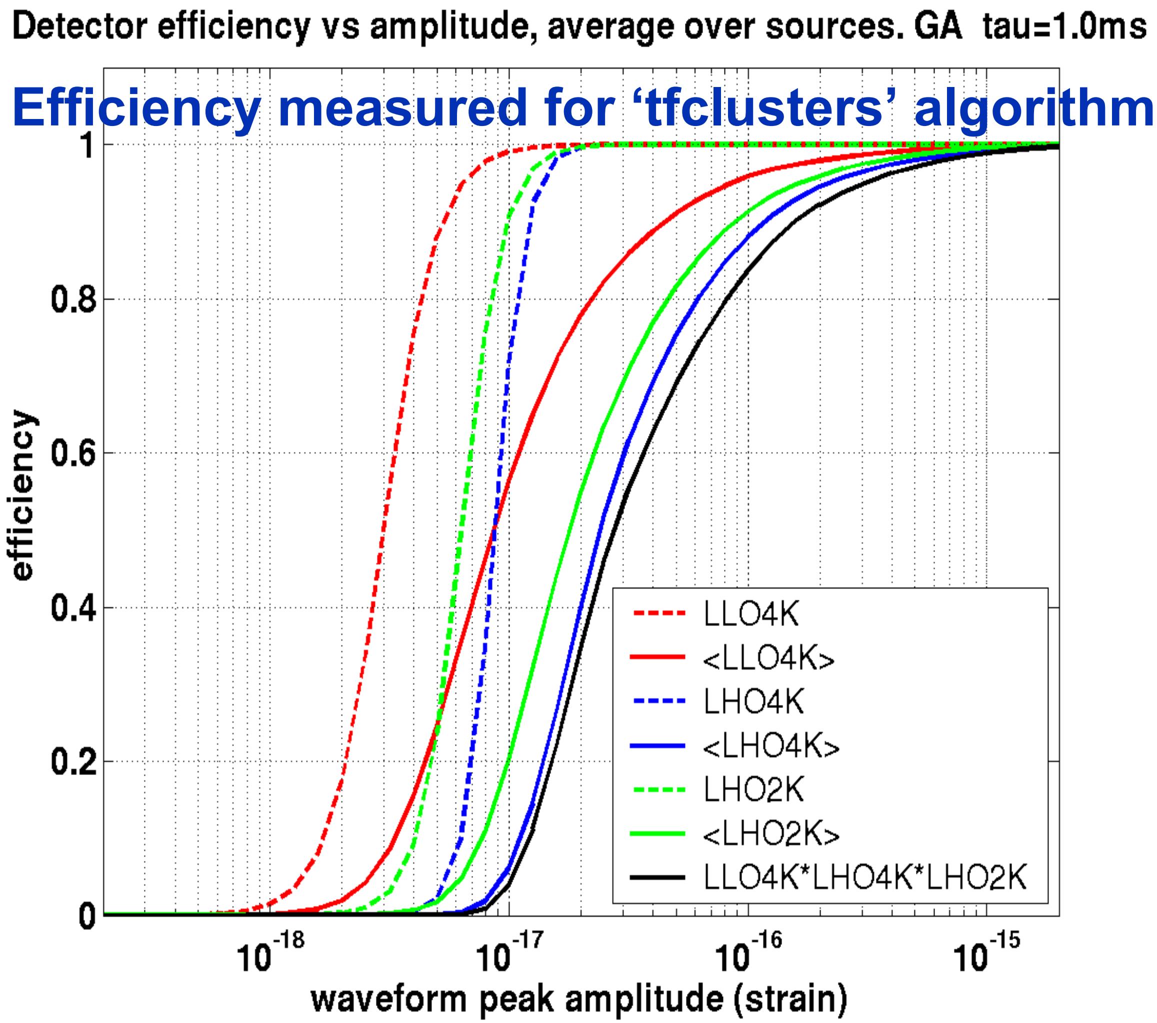
Determination of Efficiency

To measure our efficiency, we must pick a waveform.

1ms Gaussian burst

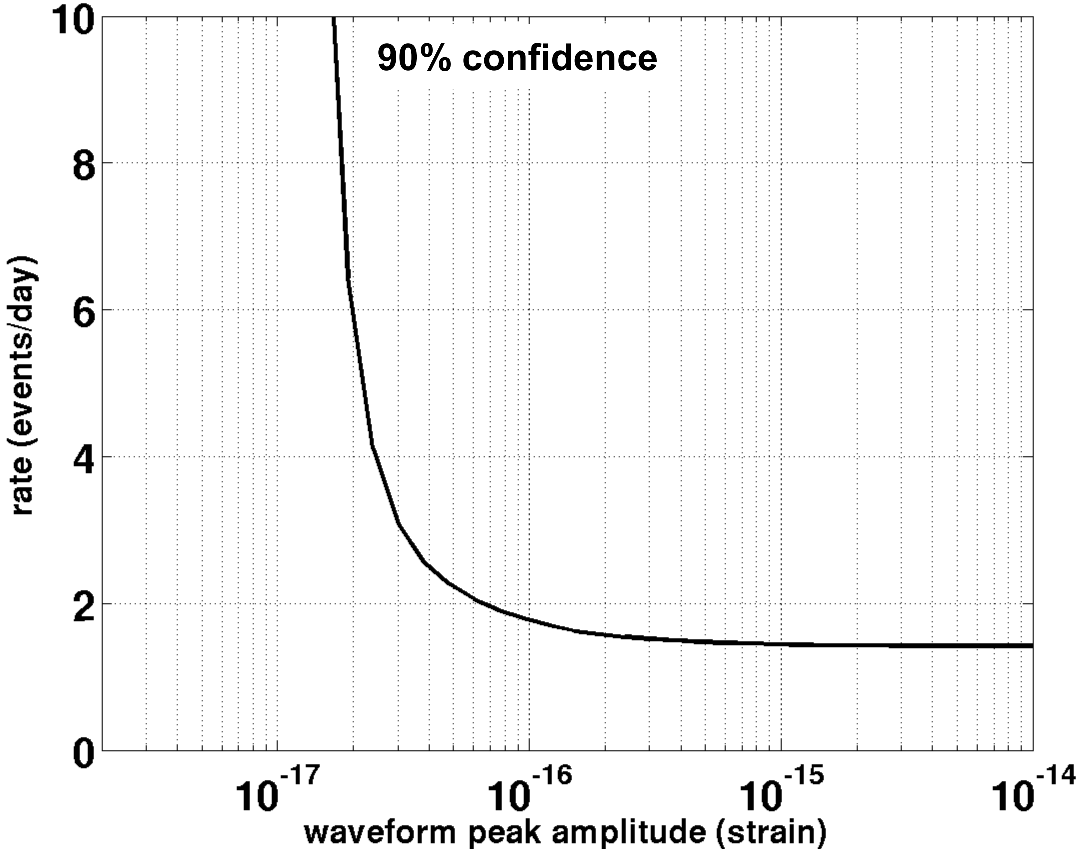


Efficiency measured for 'tfclusters' algorithm



Upper Limit
1ms gaussian bursts

Result is derived using 'TFCLUSTERS' algorithm

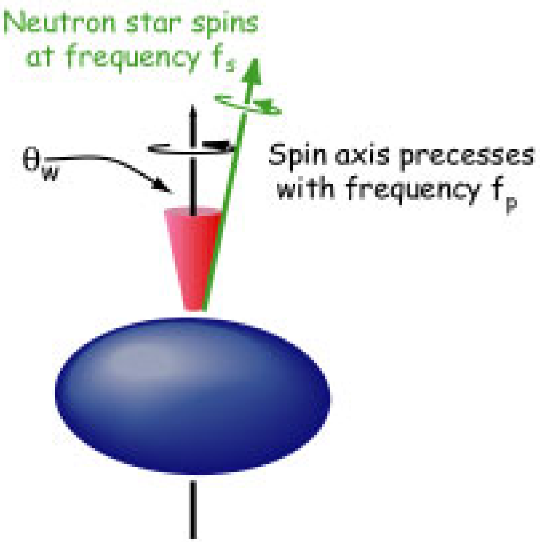


Upper limit in *strain* compared to earlier (cryogenic bar) results:

- **IGEC 2001 combined bar upper limit: < 2 events per day having $h=1\times10^{-20}$ per Hz of burst bandwidth. For a 1kHz bandwidth, limit is < 2 events/day at $h=1\times10^{-17}$**
- **Astone *et al.* (2002), report a one sigma excess of one event per day at strain level of $h \sim 2\times10^{-18}$**

Periodic Sources

- Pulsars in our galaxy:
  - » search for observed neutron stars
  - » all sky search (computing challenge)
  - » r-modes

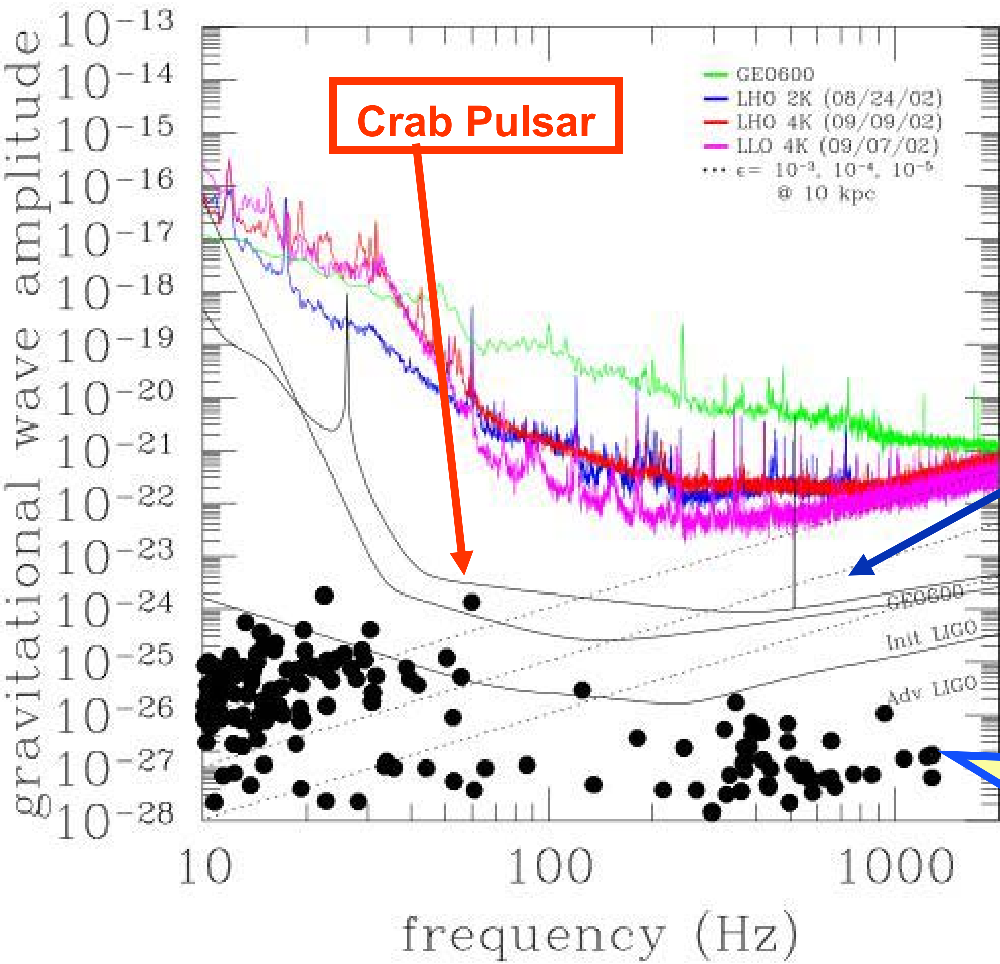


- **Frequency modulation of signal due to Earth's motion**
- **Amplitude modulation due to the detector's antenna pattern.**

Directed Search in S1

NO DETECTION EXPECTED

at present sensitivities



Predicted signal for rotating neutron star with equatorial ellipticity $\varepsilon = \delta I/I$ ***: 10^{-3} , 10^{-4} , 10^{-5} @ 8.5 kpc.***

PSR J1939+2134

1283.86 Hz

Two Search Methods

Frequency domain

- Best suited for large parameter space searches
- Maximum likelihood detection method + frequentist approach

Time domain

- Best suited to target known objects, even if phase evolution is complicated
- Bayesian approach

First science run --- use both pipelines for the same search for cross-checking and validation

Results: PSR J1939+2134

- No evidence of continuous wave emission from PSR J1939+2134.
- Summary of 95% upper limits on h:

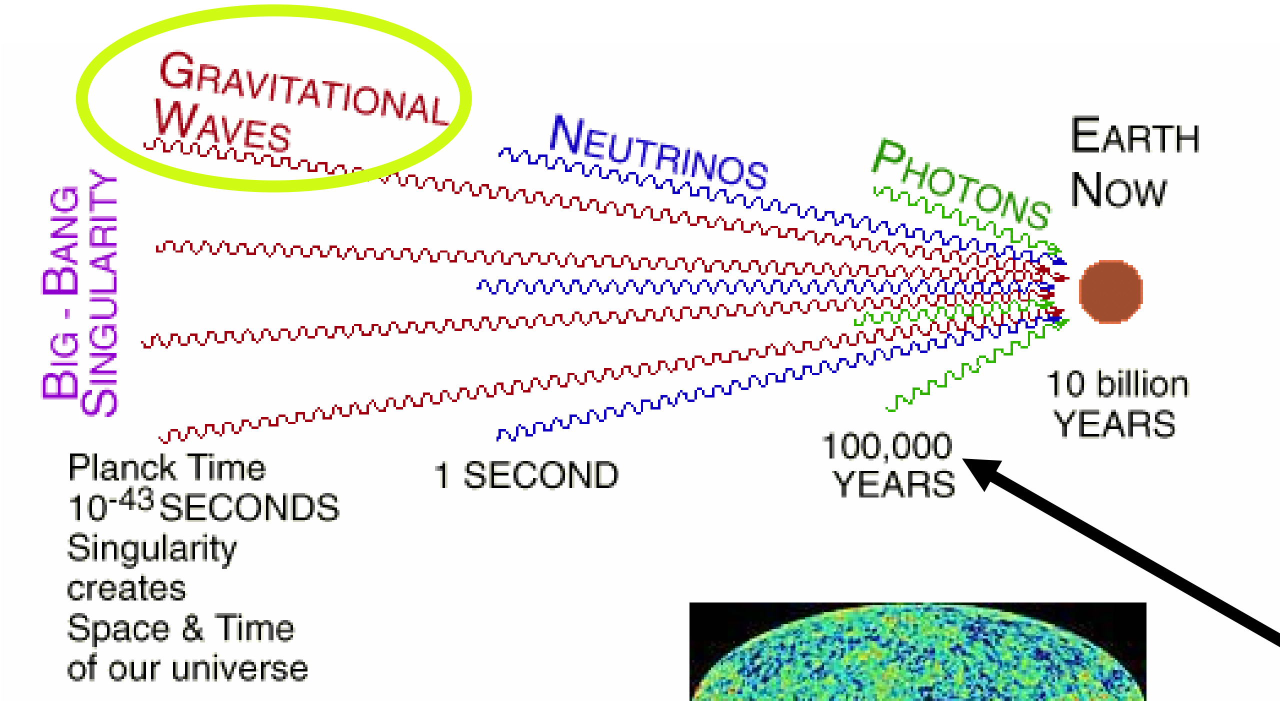
IFO	Frequentist FDS	Bayesian TDS
GEO	$(1.94\pm0.12) \times 10^{-21}$	$(2.1 \pm0.1) \times 10^{-21}$
LLO	$(2.83\pm0.31) \times 10^{-22}$	$(1.4 \pm0.1) \times 10^{-22}$
LHO-2K	$(4.71\pm0.50) \times 10^{-22}$	$(2.2 \pm0.2) \times 10^{-22}$
LHO-4K	$(6.42\pm0.72) \times 10^{-22}$	$(2.7 \pm0.3) \times 10^{-22}$

- **Best previous results for PSR J1939+2134:**

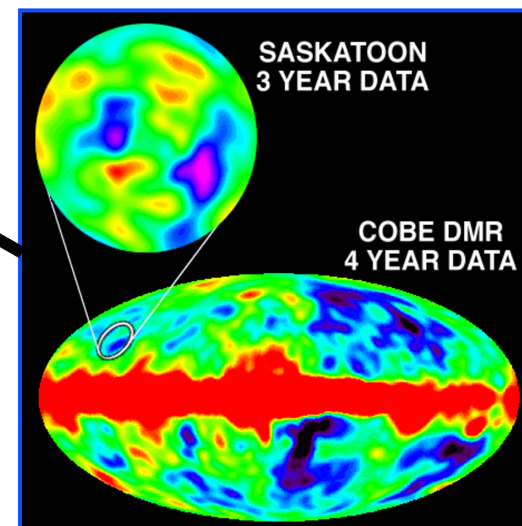
  $h_o < 10^{-20}$ (Glasgow, Hough et al., 1983)

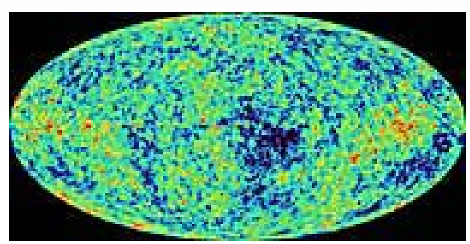
Early Universe
stochastic background

‘Murmurs’ from the Big Bang



Cosmic Microwave background





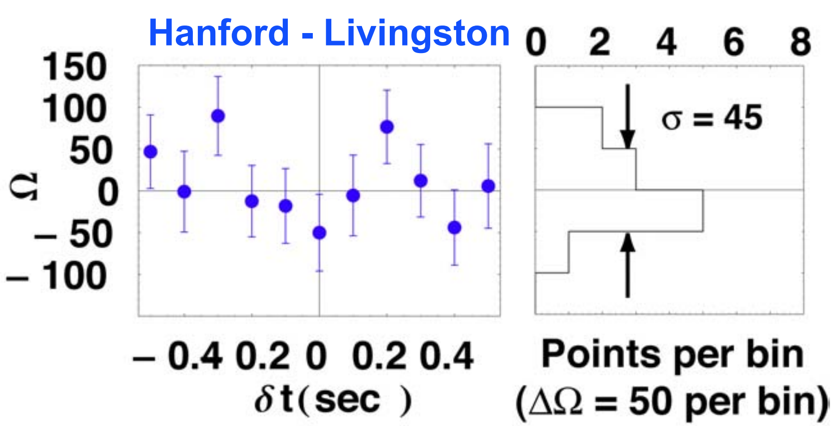
WMAP 2003

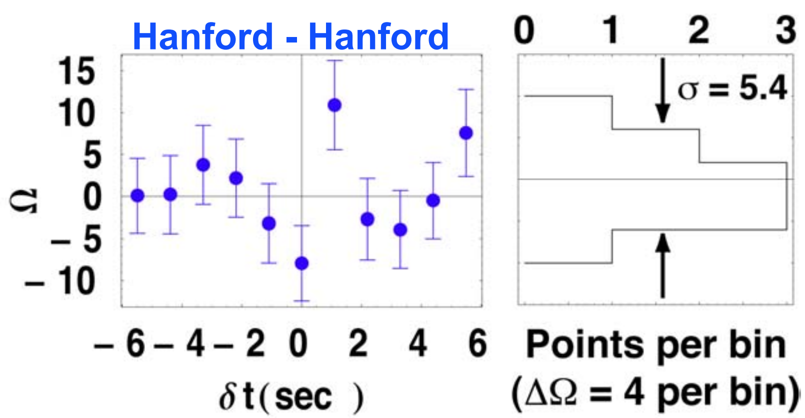
Stochastic Background

- Strength specified by *ratio of energy density in GWs to total energy density* needed to close the universe:

$$\Omega_{GW}(f) = \frac{1}{\rho_{critical}} \frac{d\rho_{GW}}{d(\ln f)}$$

- Detect by *cross-correlating* output of two GW detectors:



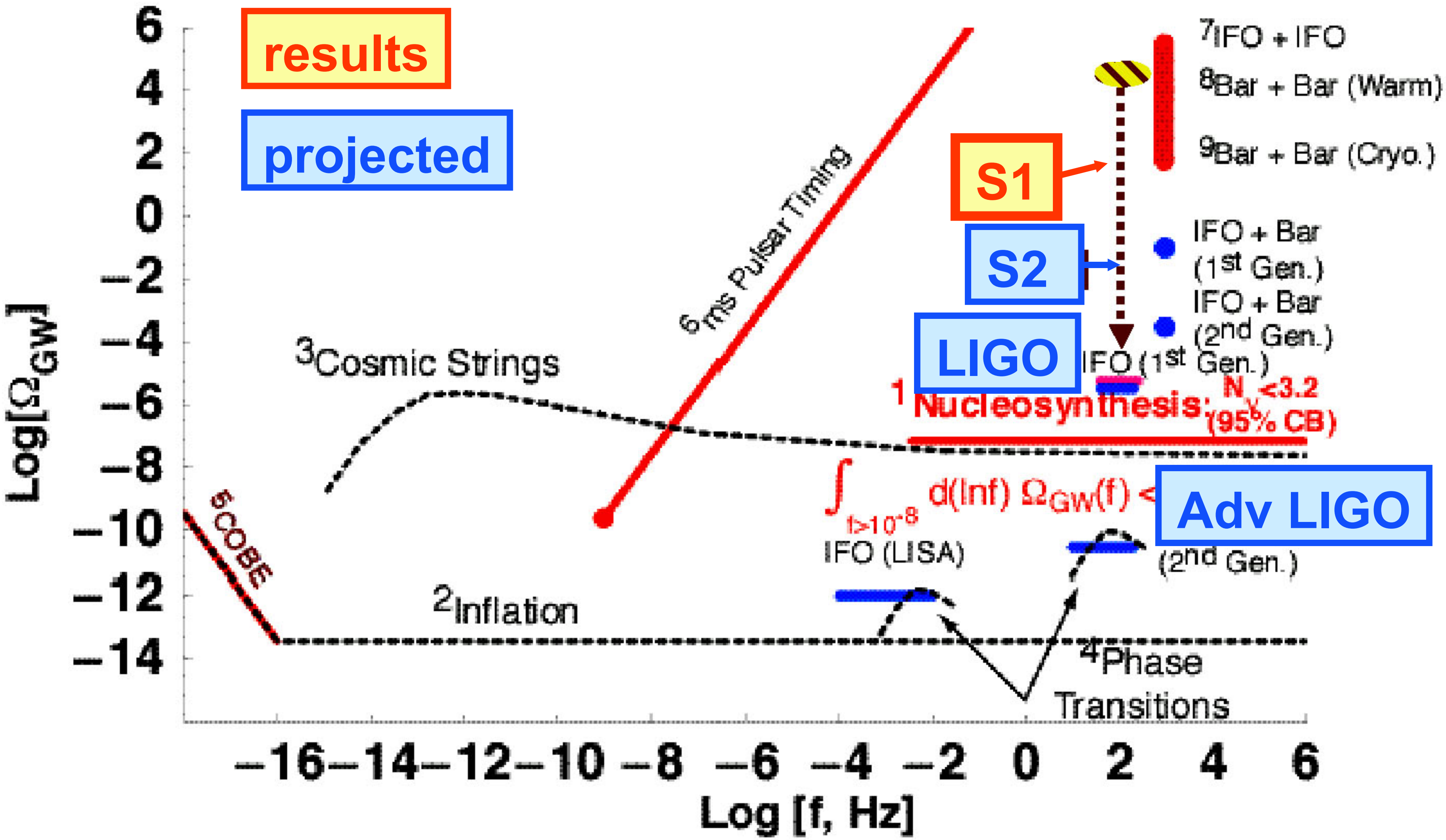


Preliminary Limits: Stochastic Search

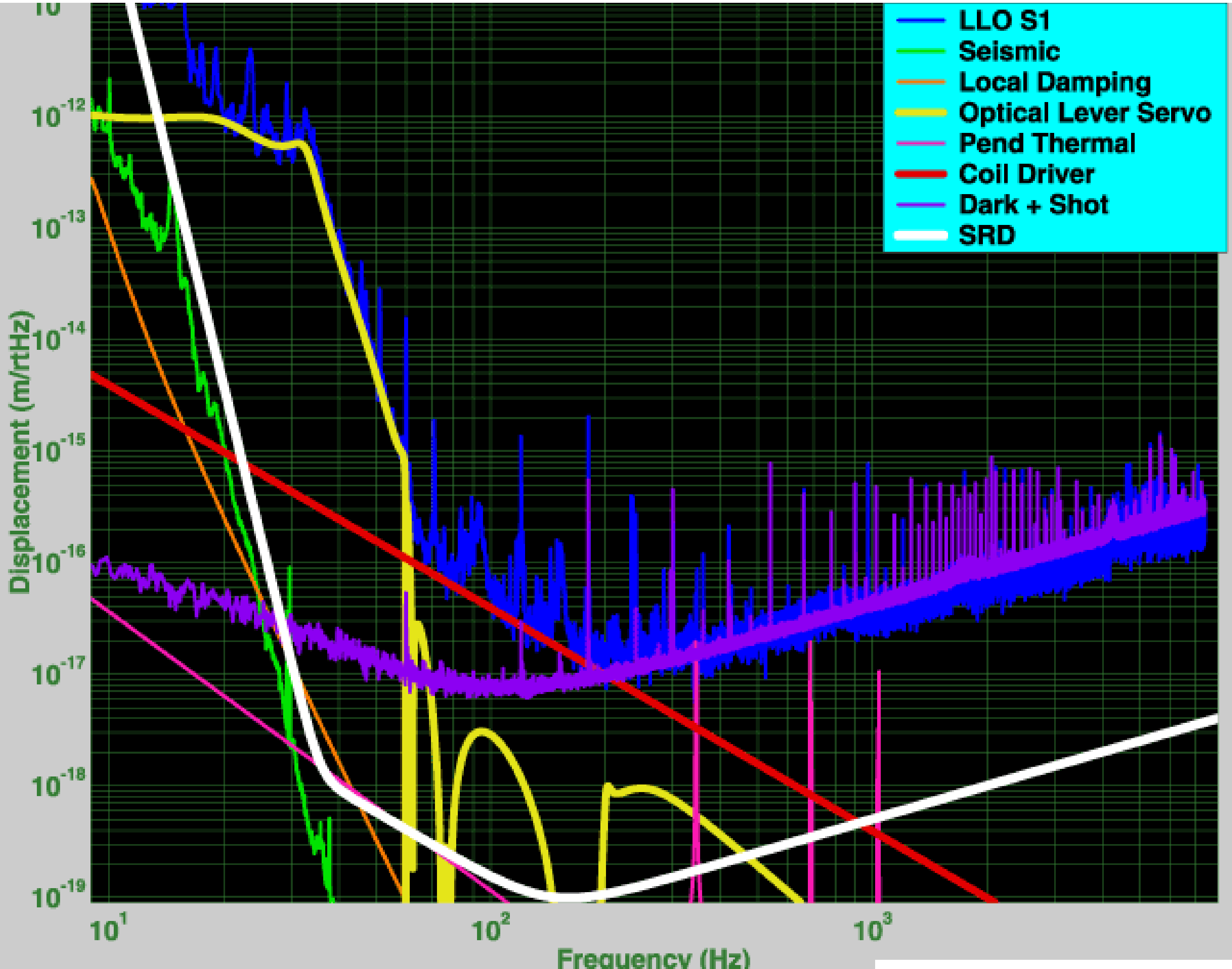
Interferometer Pair	90% CL Upper Limit	T_{obs}
LHO 4km-LLO 4km	Ω_{GW} (40Hz - 314 Hz) < 72.4	62.3 hrs
LHO 2km-LLO 4km	Ω_{GW} (40Hz - 314 Hz) < 23	61.0 hrs

- Non-negligible LHO 4km-2km (H1-H2) instrumental cross-correlation; currently being investigated.
- Previous best upper limits:
  - » *Measured:* Garching-Glasgow interferometers : $\Omega_{GW}(f) < 3\times10^5$
  - » *Measured*: EXPLORER-NAUTILUS (cryogenic bars): $\Omega_{GW}(907 Hz) < 60$

Stochastic Background
sensitivities and theory

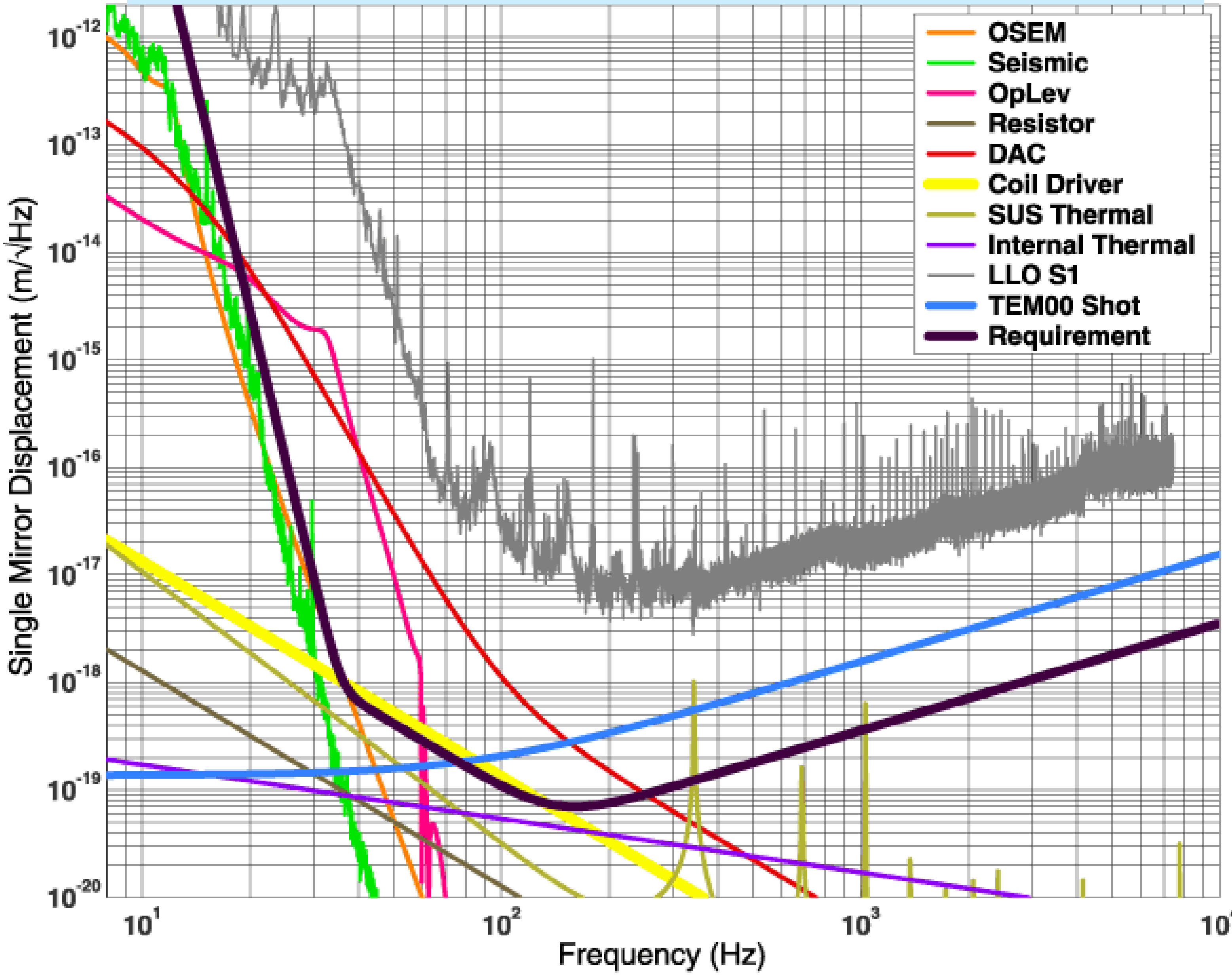


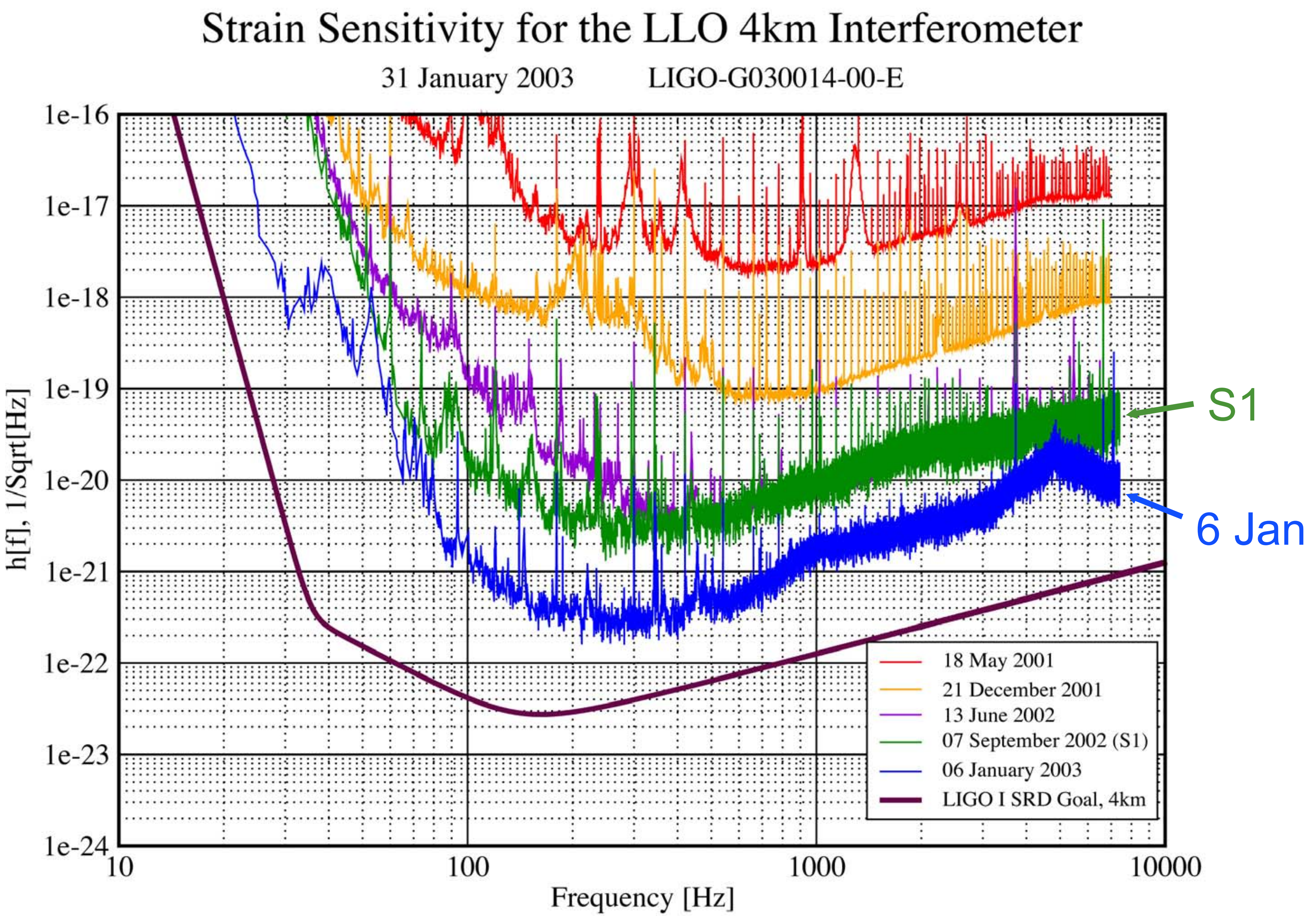
S1 Noise Component Analysis, LLO 4k



Rana Adhikari noise analysis

Estimated Noise Limits for S2 (as planned in October 2002)





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LIGO I SRD Goal, 4km
S1
6 Jan

Changes Between S1 and S2

- Digital Suspensions installed on LHO-2K and LLO-4K
  - » New coil drivers & realtime control code for suspensions
  - » Lower noise, switchable dynamic range (200 mA acquisition, 5 mA running)
  - » Separate DC biases for alignment
  - » Better filtering, diagonalization and control/sequencing features
- Optical lever improvements
  - » Structural stiffening (designed for thermal/kinematic stability, not low vibration)
  - » Improved filtering to take advantage of reduced resonances
  - » Pre-ADC "whitening" for improved dynamic reserve
- More Power
  - » Enabled by better alignment stability
  - » Also required control of "I-phase" photocurrent (overload)
  - » Now ~ 1.5 W into mode cleaners, ~ 40 W at beamsplitter (*R*~40)
  - » Only 10-20 mA average DC photocurrent at dark ports !! (optics very good)

Second Science Run (S2)

- February 14 – April 14, 2002 (~ 1400 hours)
- Three LIGO interferometers and TAMA (Japan)
- Steady improvement in sensitivity continues
  - » Approximately 10x improvement over S1
- Duty cycle similar to S1
  - » Increased sensitivity did not degrade operation
  - » Longest locked stretch ~ 66 hours (LHO-4K)

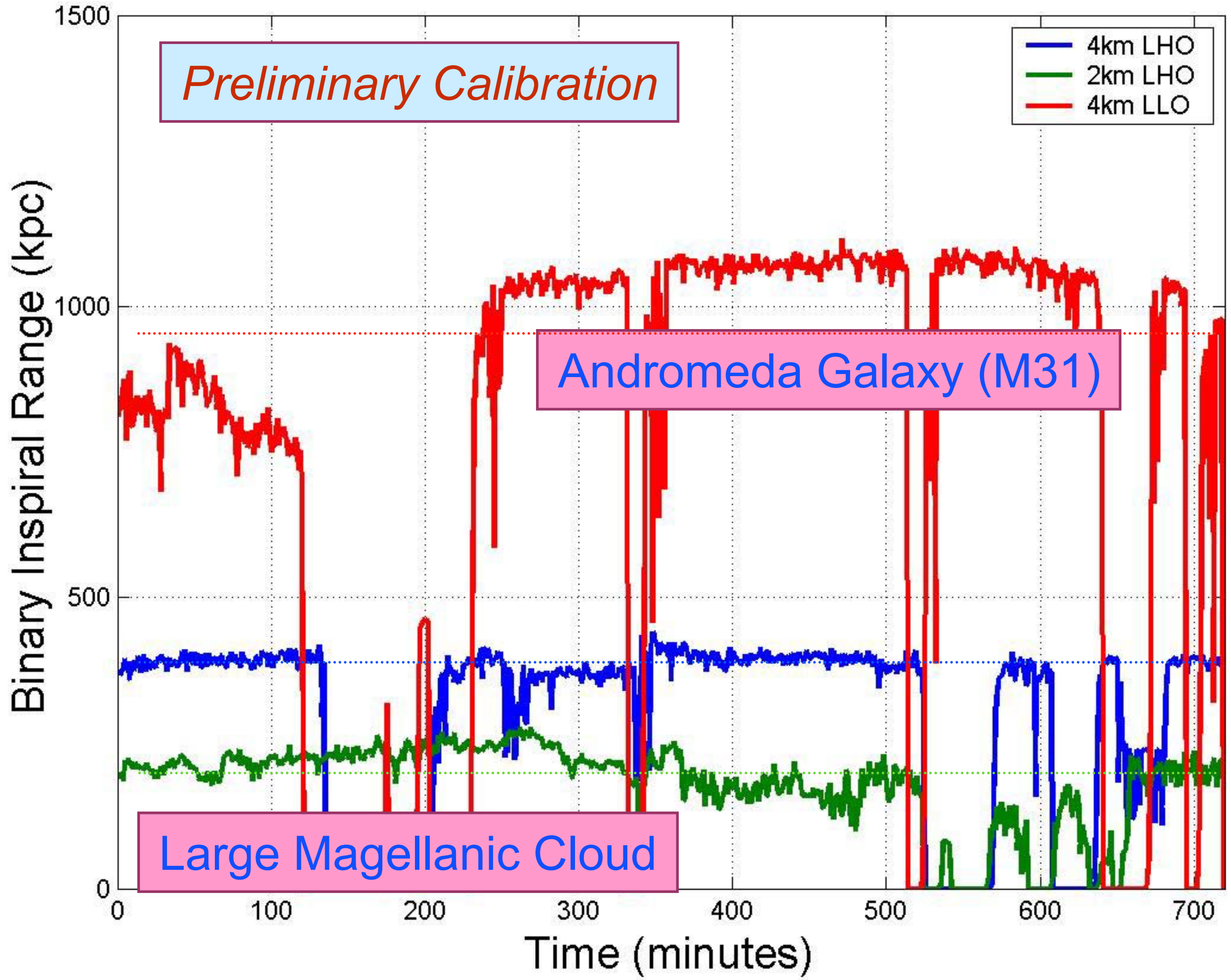
	LLO-4K	LHO-4K	LHO-2K	3x Coinc.
Duty cycle (cf. S1)	37% (42%)	74% (58%)	58% (73%)	22% (24%)

Stability improvements for S2

- Wavefront sensing (WFS) for alignment control
  - » Uses the main laser beam to sense the proper alignment for the suspended optics
  - » Complex! 10 coupled degrees of freedom,
    - – Sensing degrees-of-freedom different from control degrees-of-freedom
- S1:
  - » All interferometers had 2 degrees-of-freedom controlled by WFS
- S2:
  - » LHO-4K: 8 of 10 alignment degrees-of-freedom under feedback control
- Now:
  - »All 10 degrees-of-freedom controlled by WFS

Virgo Cluster

S2 Sensitivity and Stability



Major On-going Commissioning Activities

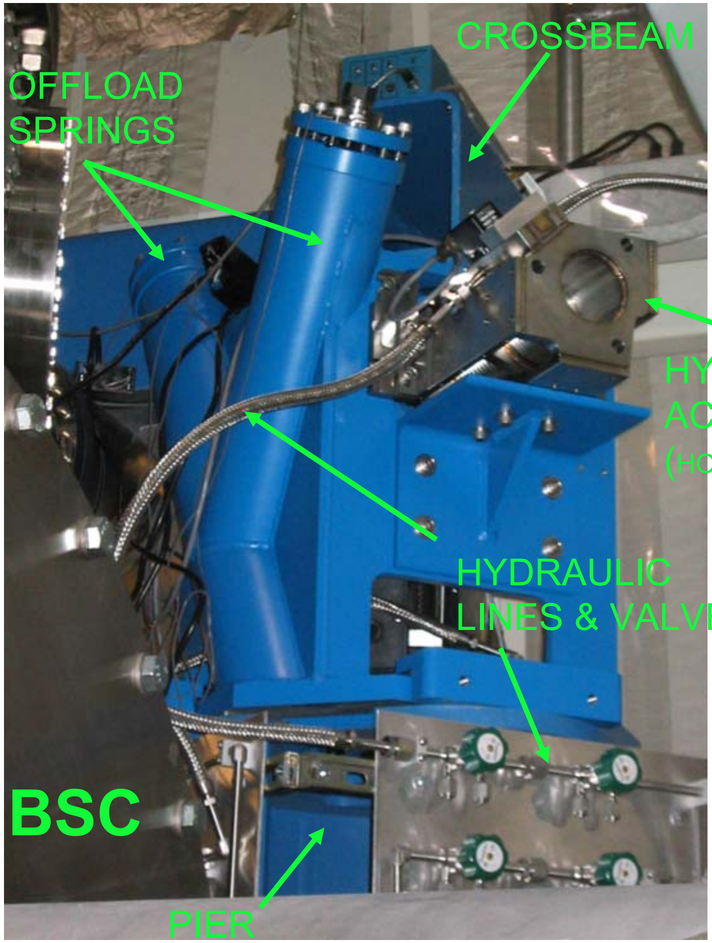
- Seismic retrofit at LLO
- Finish wavefront sensing alignment system
- RFI cleanup, linear power supplies
- Shot noise sensitivity
  - » Thermal lensing
  - » Increase of number of photodiodes
- Acoustic coupling
- Numerous smaller tasks

Seismic Isolation Upgrade

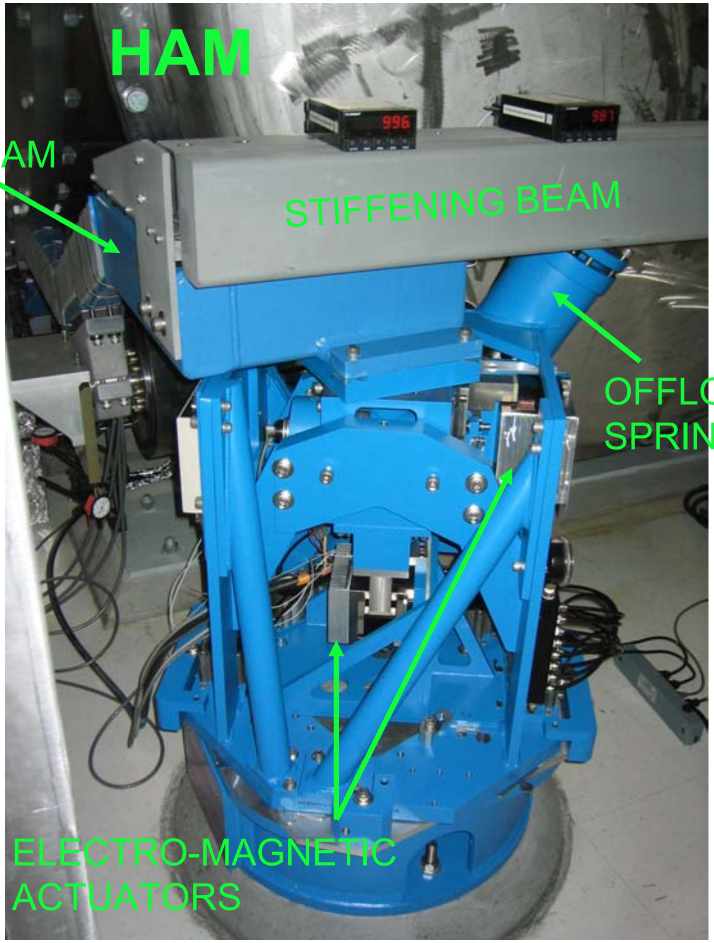
- The Seismic Isolation System at LLO needs to be upgraded
  - » Seismic noise environment much worse below 10 Hz than originally planned (logging largest factor, but also train, other anthropogenic noise)
  - » Plan is to add an active, external pre-isolation (EPI) stage without disturbing the alignment of the installed optics
- Current Plan:
  - » Continue prototype testing at MIT, including testing VME based controls
  - » Review held for 4/18; management decision on how to proceed pending
  - » Order components, fabricate and assemble; fabrication/assembly phase lasts ~5.5 months
  - » Installation starts ~Jan '04 and should complete ~Apr '04

Seismic Isolation Testing at MIT

Hydraulic External Pre-Isolator (HEPI)



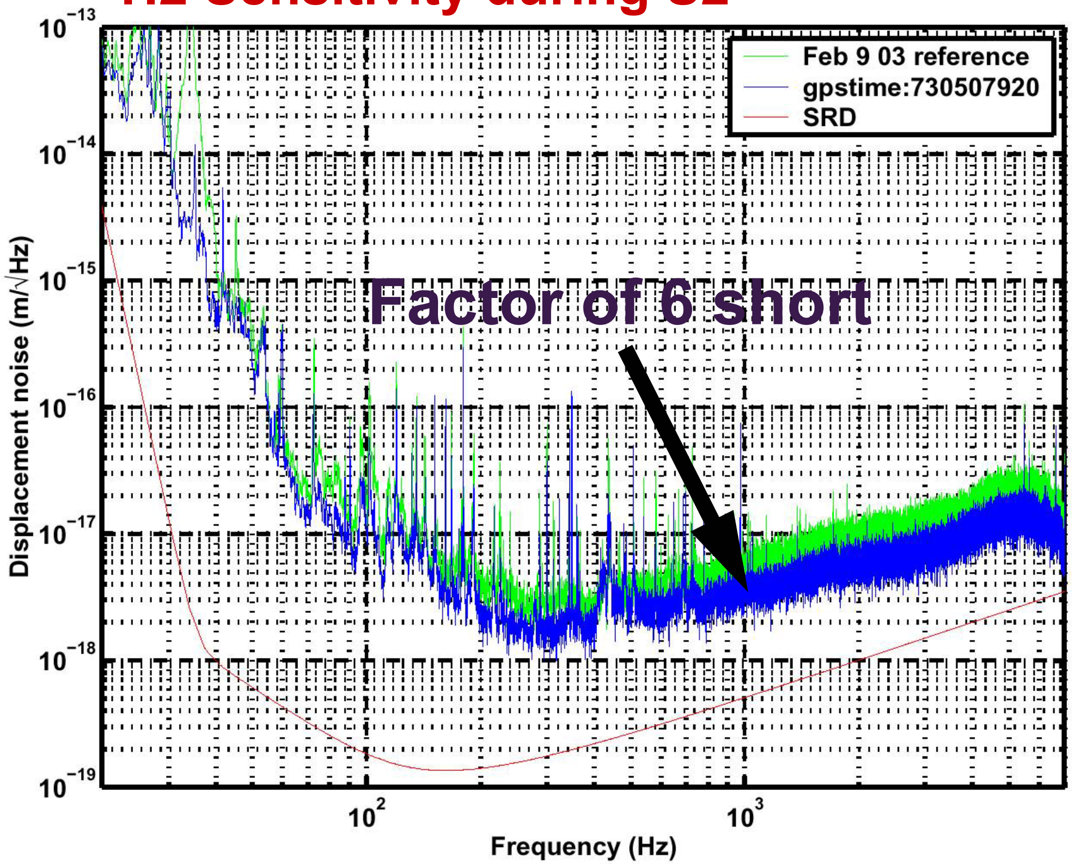
electro-Magnetic External Pre-Isolator (MEPI)



Shot Noise Sensitivity

- Simplistic power calculations suggests factor of ~2 shortfall
  - » 10x increase in laser power would give factor ~3 improvement
- Does not take improved sideband efficiency into account

H2 Sensitivity during S2

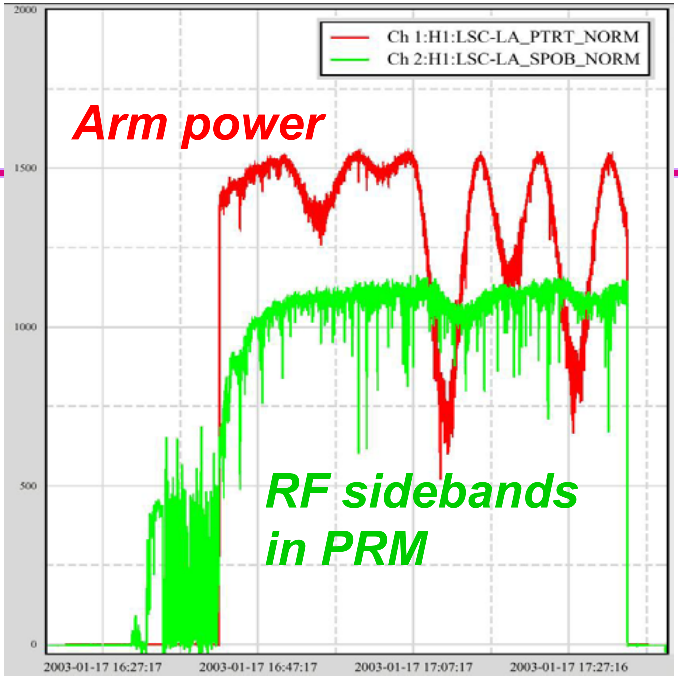


Optical characterization

- Good news: optics quality is (almost all) good
  - » Recycling gain meets or exceeds goals (design was >30)
    - – LLO-4K: Gain of nearly 50 seen, more usually about 45
    - – LHO-4K : Gain of 40-45
  - » Contrast defect meets or exceeds goals (design was < 10^{-3})
    - – LLO-4K : $P_{as}/ P_{bs} = 3 \times 10^{-5}$
    - – LHO-4K : $P_{as}/ P_{bs} = 6 \times 10^{-4}$
  - » LHO-2K: Cause of low recycling gain (20) discovered
    - – Bad AR coating on ITMX, ~~must be~~ has been replaced
- Low RF sideband gain/efficiency
  - » LHO-4K : Sideband power efficiency to AS port: ~6%
  - » Cause: thermal lensing in the ITMs isn't at the design level
  - » Achieving shot noise goal requires that this be fixed

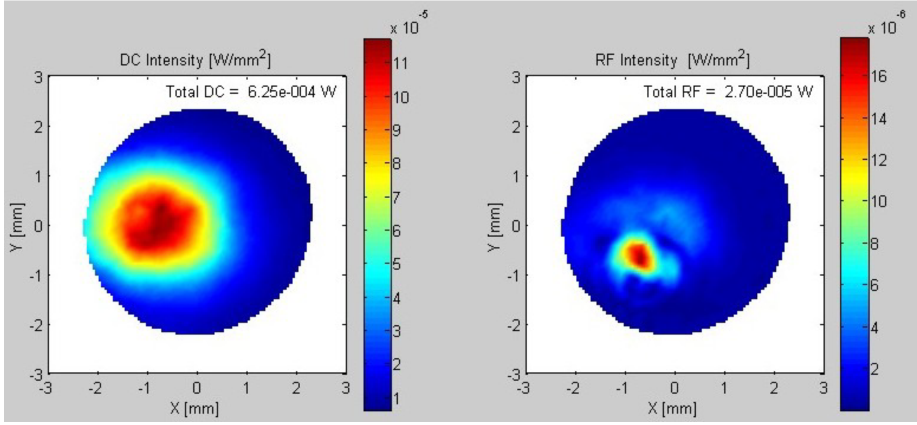
Thermal Lensing

- RF sideband efficiency is low
  - » Power recycling cavity slightly unstable: lack of Input Test Mass (ITM) thermal lens makes $g_1 \cdot g_2 > 1$
  - » Recycling Mirror (RM) curvature relies on point design for thermal lensing
  - » Heating differs from design value
- Possible solutions
  - » Change RM (w/ new radius of curvature); 6 month lead time
  - » Add the missing heat to ITMs with another source (AdvLIGO or GEO technique)
  - » Pursued in parallel with other commissioning activities



ITM Heating

Bad mode overlap

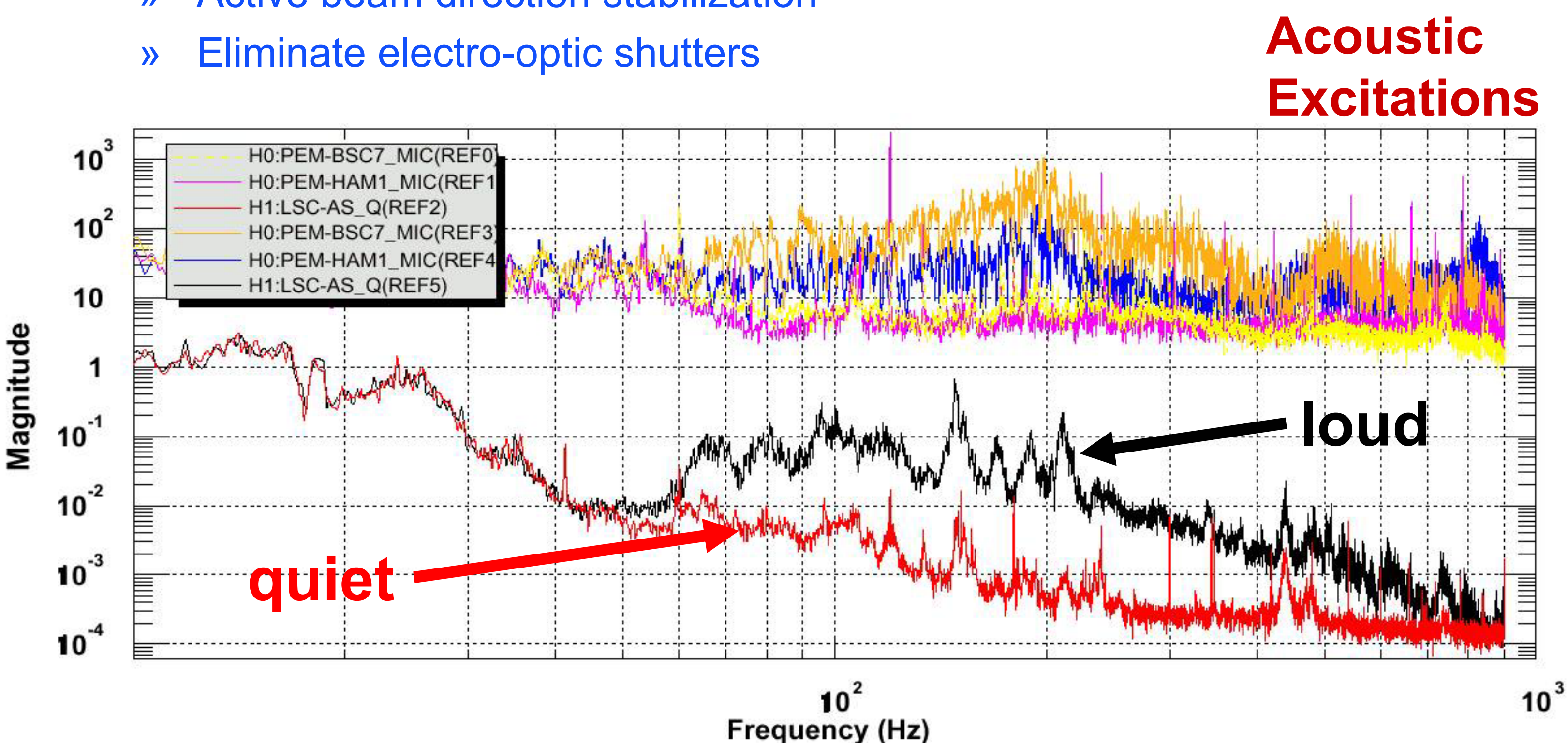


DC (carrier)

RF sidebands

Acoustic Peaks: Scattering/clipping

- Peaks occur in 80-1000 Hz band, at 10-100x required level
- Source for LHO correlated noise (stochastic search)
- Investigating:
  - » Acoustic isolation improvements
  - » Modify output periscopes/mirror mounts: stiffer, damped
  - » Active beam direction stabilization
  - » Eliminate electro-optic shutters



Summary

- Commissioning of detectors progressing well
  - » Steady progression on all fronts: sensitivity, duty cycle, stability, …
  - » Next Science Run: Nov 2003 – Jan 2004
- First Science analyses underway
  - » S1 results demonstrate analysis techniques, S2 data (and beyond) offer a real possibility to detect gravitational waves
  - » Developing synergy between detector commissioning and data analysis efforts
  - » Four analysis papers (and one instrumental one…) in final stages of preparation
- Design performance (both sensitivity and duty cycle) should be achieved next year
  - » Still a lot to do, but no showstoppers