LIGO Is ON!

Philip Lindquist, Caltech

XXXVIII Moriond Conference

Gravitational Waves and Experimental Gravity

March 23, 2003

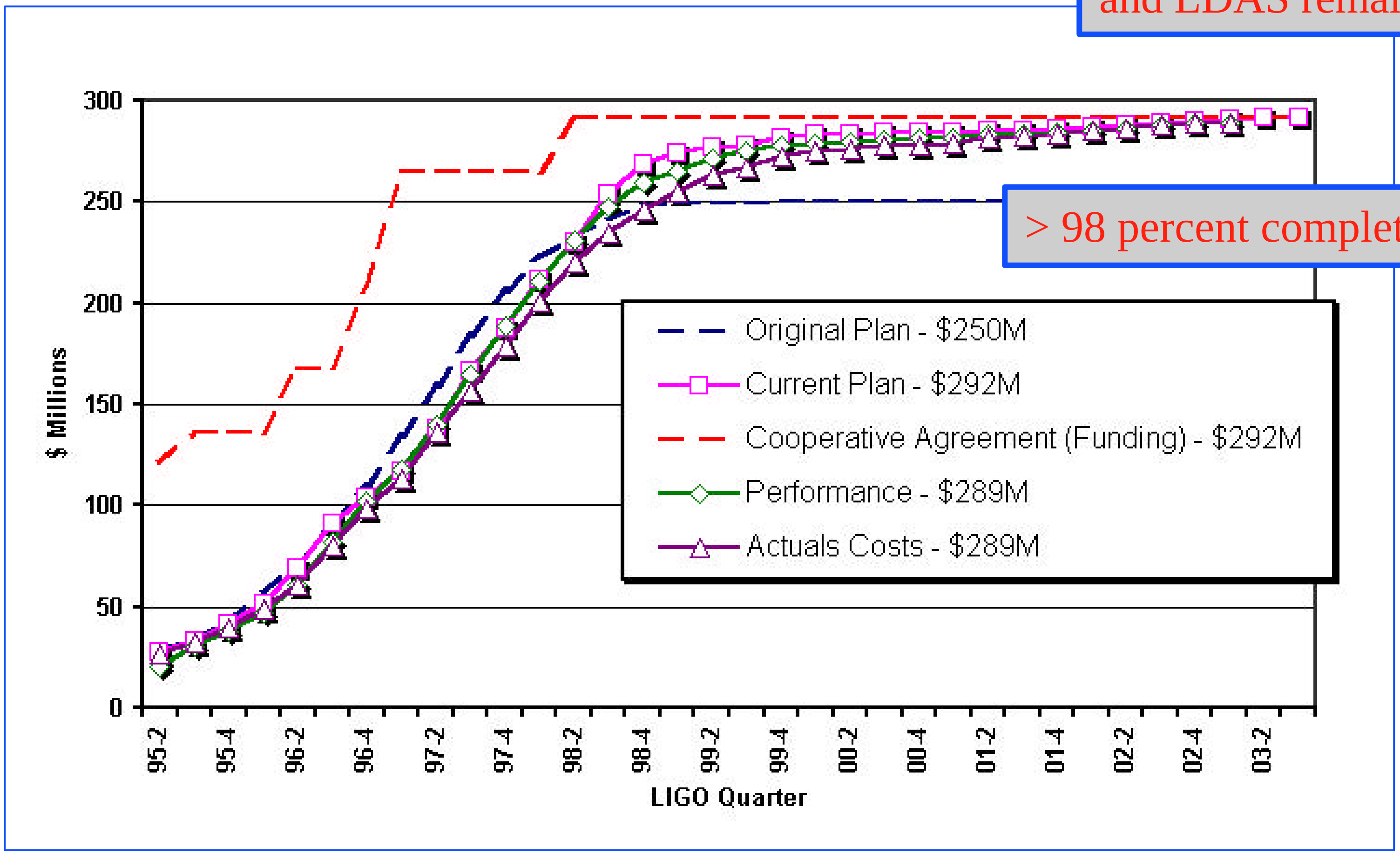
Cost Status

List of Major Awards and Costs-to-date

	Funded Amount	Amount Expended
Construction (NSF PHY-9210038)	$272M	$269M
Construction Related R&D (NSF PHY-9210038)	$20M	$20M
Initial Operations (NSF PHY-9210038)	$69M	$69M
Advanced R&D (NSF PHY-9700601, NSF PHY-9801158)	$10M	$10M
Current Operations 2002 (NSF PHY-0107417, includes Advanced R&D)	$28M	$28M
Current Operations 2003 (NSF PHY-0107417, includes Advanced R&D)	$33M	

Cost Performance

Support buildings and LDAS remain



> 98 percent complete

Schedule and Plan

Primary Activities

- 1996 Construction Underway (mostly civil construction)
- 1997 Facility Construction (vacuum system)
- 1998 Interferometer Construction (complete facilities)
- 1999 Construction Complete (interferometers in vacuum)
- 2000 Detector Installation (commissioning subsystems)
- 2001 Commission Interferometers (first coincidences)
- 2002 Sensitivity studies (first Science Run, S1)
- 2003+ LIGO I data run (one year integrated data at $h \sim 10^{-21}$)

- 2007+ Begin Advanced LIGO Installation

This is still the working plan

Hanford Observatory

LIGO Hanford Observatory

26 km north of Richland, WA

2 km + 4 km interferometers in same vacuum envelope

LIGO Livingston Observatory

42 km east of Baton Rouge, LA

Single 4 km interferometer

Beam Tube and Enclosure

1.2 m diameter - 3mm stainless

50 km of weld

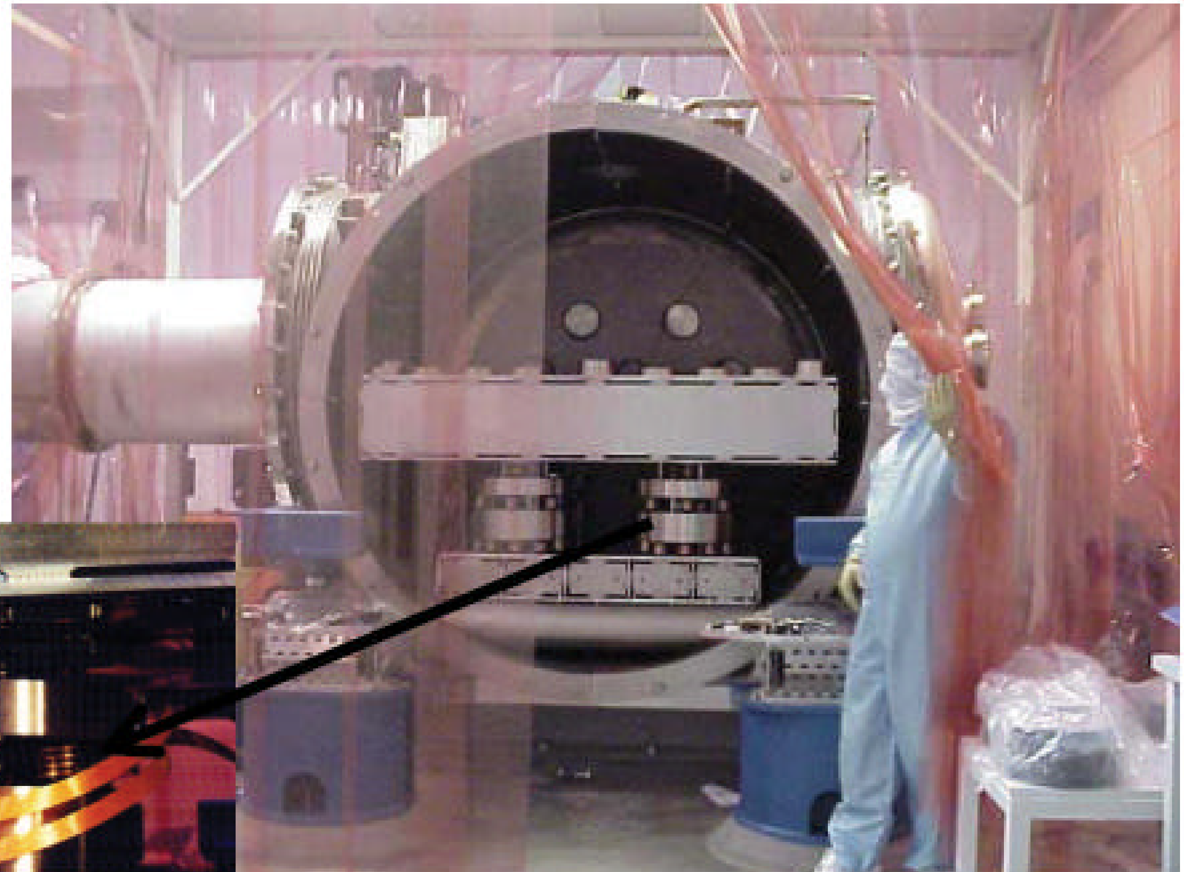
NO LEAKS !!

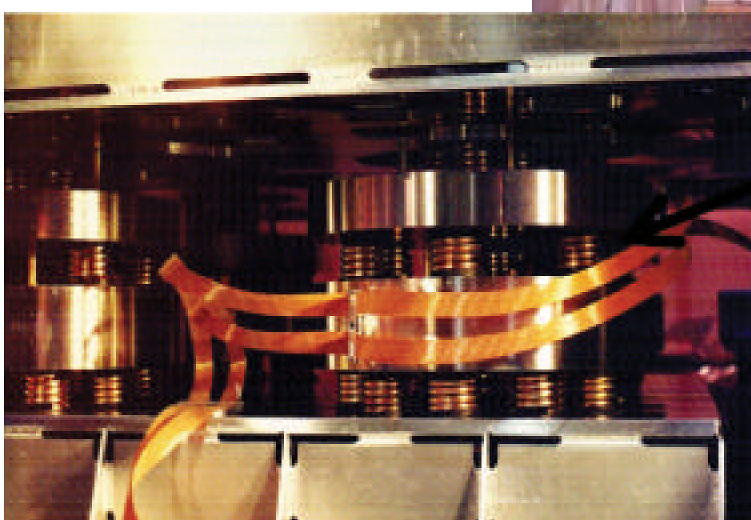
- LIGO beam tube under construction in January 1998
- 65 ft spiral welded sections
- Girth welded in portable clean room
- In situ 160 C bake
- 20,000 m^3 10^{-8} to 10^{-9} torr

Vacuum Equipment

Seismic Isolation System

Tubular coil springs with internal constrained-layer damping, layered with reaction masses





Isolation stack in chamber

LIGO Optic

Substrates: SiO_2

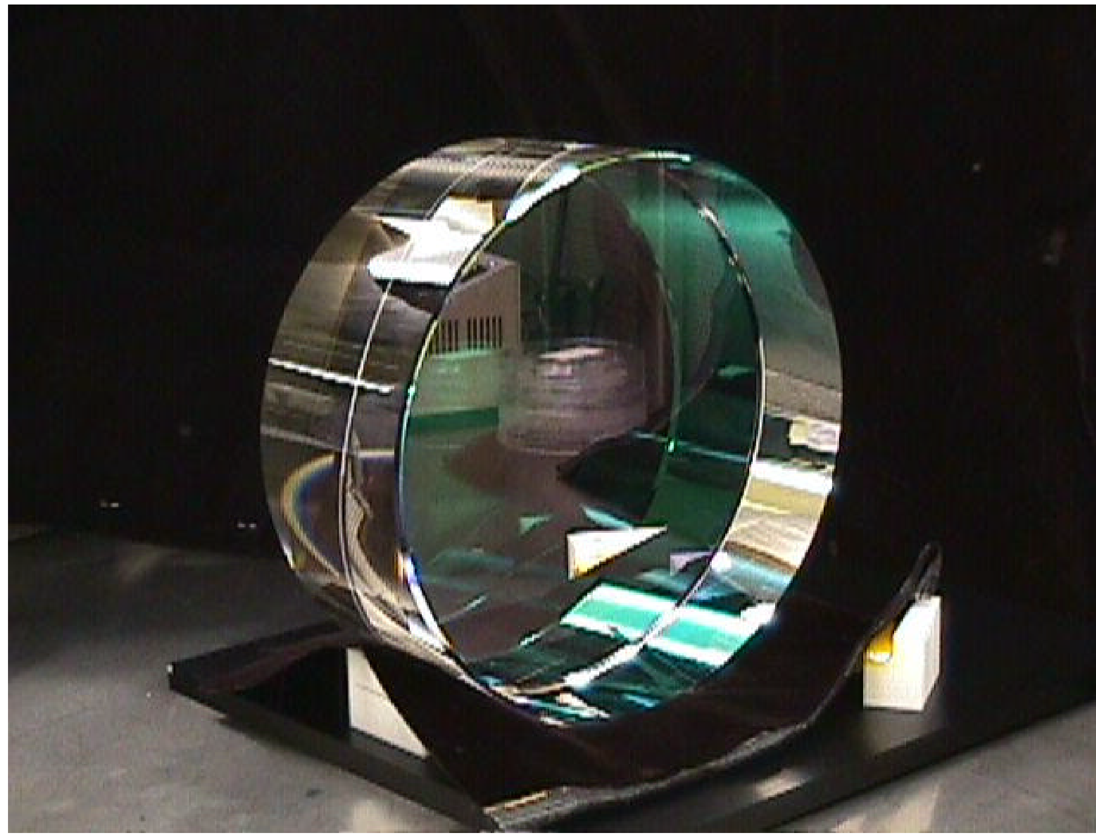
- 25 cm Diameter, 10 cm thick
- Homogeneity < 5 x 10^{-7}
- Internal mode Q's > 2 x 10^{6}

Polishing

- Surface uniformity < 1 nm rms
- Radii of curvature matched < 3%

Coating

- Scatter < 50 ppm
- Absorption < 2 ppm
- Uniformity <10^{-3}



Installation and Alignment

E7 Engineering Run

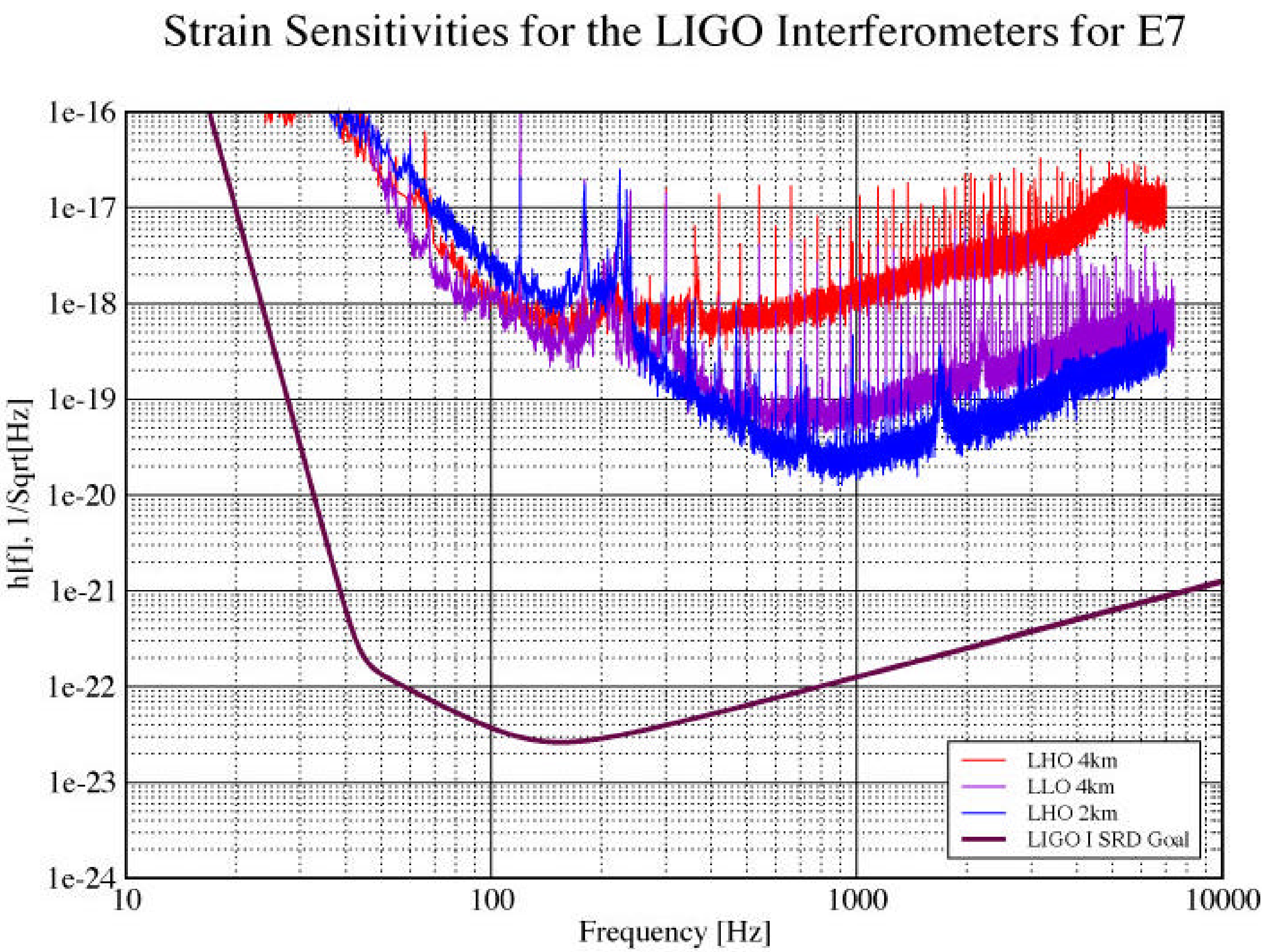
- Started December 28, 2001
- Goal
  - » Establish coincidence operation between sites
  - » Obtain first data sample for testing data analysis
  - » Last LIGO Construction Project Milestone
- LIGO + GEO Interferometers

E7—Sensitivity Curves

Final LIGO Milestone

"Coincidences Between the Sites in 2001"

Engineering Run
28 Dec 01
to
14 Jan 02



E7—Run Statistics

28 Dec 2001 - 14 Jan 2002 (402 hr)

Singles data

	All segments	Segments >15min
L1 locked	284hrs (71%)	249hrs (62%)
L1 clean	265hrs (61%)	231hrs (53%)
L1 longest clean segment: 3:58		
H1 locked	294hrs (72%)	231hrs (57%)
H1 clean	267hrs (62%)	206hrs (48%)
H1 longest clean segment: 4:04		
H2 locked	214hrs (53%)	157hrs (39%)
H2 clean	162hrs (38%)	125hrs (28%)
H2 longest clean segment: 7:24		

Coincidence Data

	All segments	Segments >15min
2X: H2, L1		
locked	160hrs (39%)	99hrs (24%)
clean	113hrs (26%)	70hrs (16%)
H2, L1 longest clean segment: 1:50		
3X : L1+H1+ H2		
locked	140hrs (35%)	72hrs (18%)
clean	93hrs (21%)	46hrs (11%)
L1+H1+ H2 : longest clean segment: 1:18		
4X: L1+H1+ H2 +GEO:	77 hrs (23 %)	26.1 hrs (7.81 %)
5X: ALLEGRO + ...		

Conclusion: Large Duty Cycle is Attainable

S1 First Science Run

August—September 2002 (17 days)

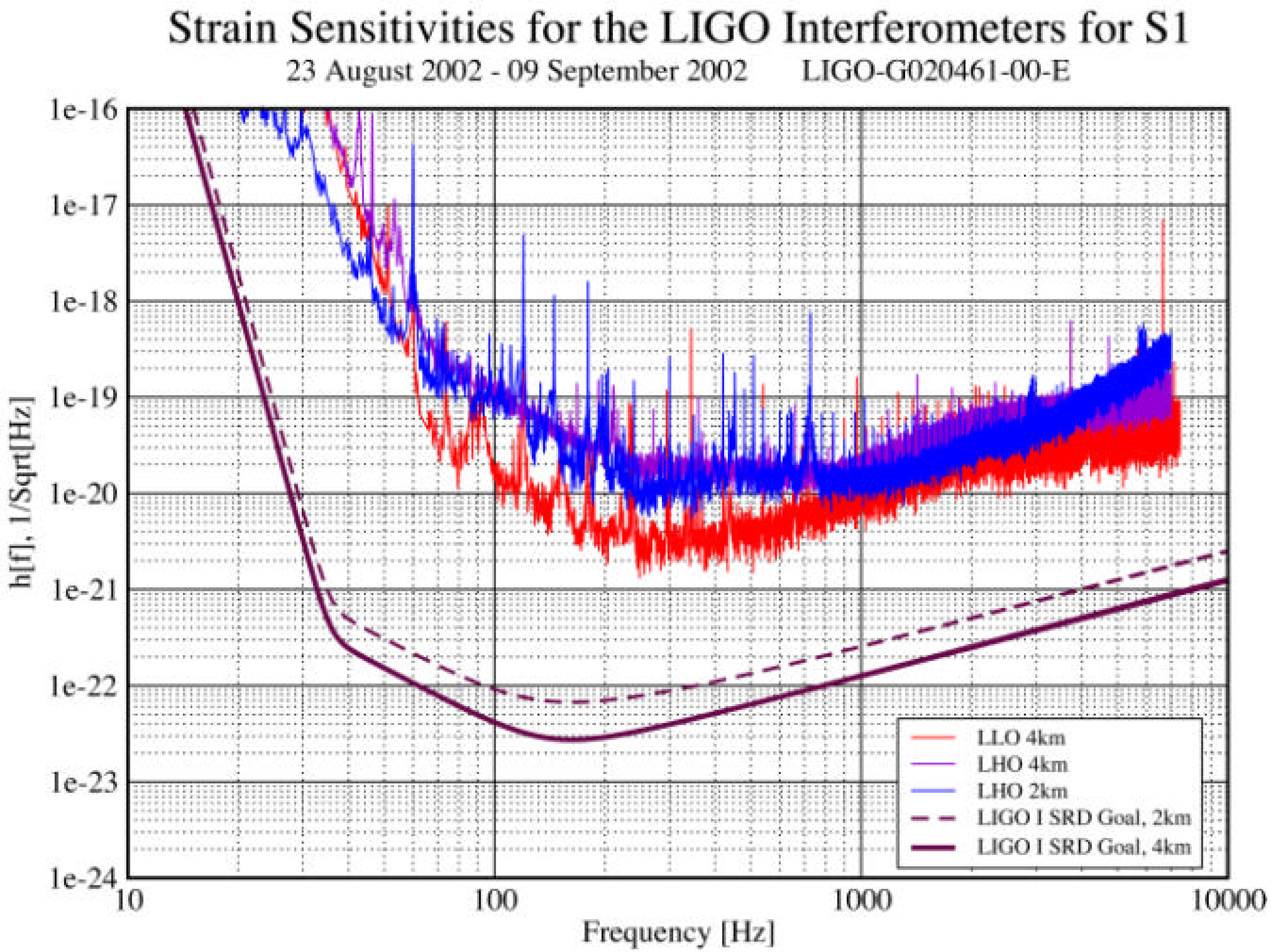
- **Stable data taking for 17 days**
- **Coincidence data with GEO**
- **“Upper Limit” sensitivities explore new regimes**
- **Results presented first quarter 2003 (AAAS) to be followed by publications**

S1 Sensitivity

LIGO S1

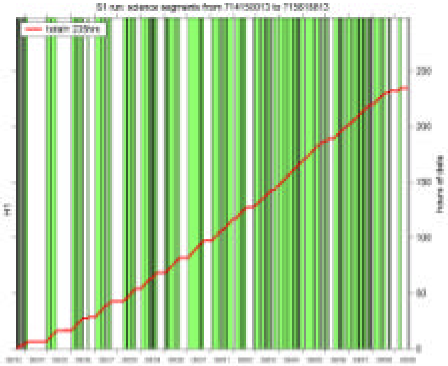
"First Upper Limit Run"

- **Aug – Sept 2002**
- **17 days**

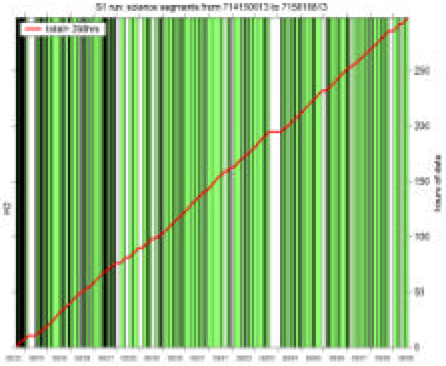


S1 'In-lock" Summary

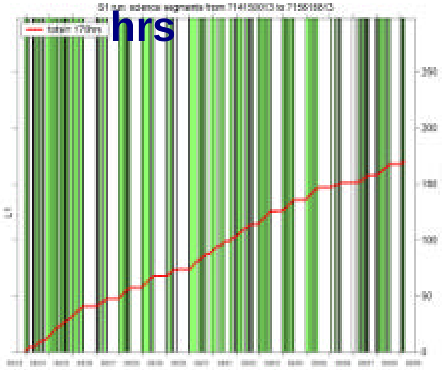
H1: 235 hrs



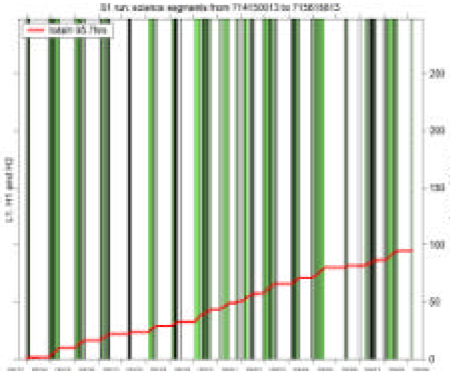
H2: 298 hrs



L1: 170 hrs



3X: 95.7 hrs



- **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 coincident time: 95.7 hrs**

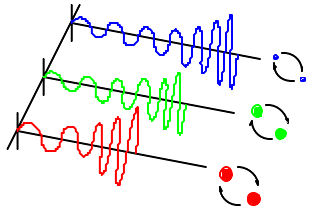
Red lines: integrated up time

Green bands (w/ black borders): epochs of lock

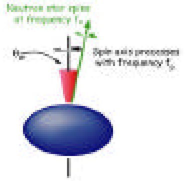
"Upper Limits"--S1 (and S2) Data Analysis

LIGO Scientific Collaboration (LSC) Upper Limits Analysis Groups

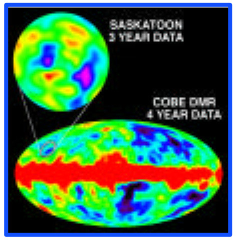
- Typically ~25 physicists
- One experimentalist and one theorist co-lead each group



- **Compact binary inspiral:** ***"chirps"***
  - » **Inspiral Sources Working Group**
- **Supernovae / GRBs:** ***"bursts"***
  - » **Burst Working Group**



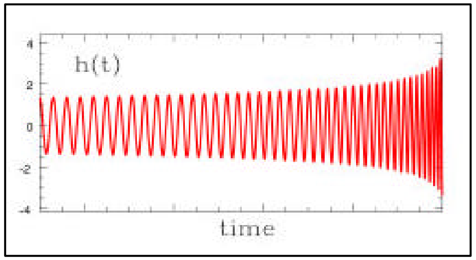
- **Pulsars in our galaxy:** ***"periodic"***
  - » **Periodic Sources Working Group**



- **Cosmological Signal:** ***"stochastic background"***

Coalescing Binaries

- **Three source targets**
  - » Neutron star binaries (1-3 M_{sun})
    - ✓ Neutron star search complete
  - » Black hole binaries (> 3 M_{sun})
    - – Black hole search will be done in next science run, S2
  - » MACHO binaries (0.5-1 M_{sun})
    - – MACHO search under way
- **Search method**
  - » **Template-based matched filtering**



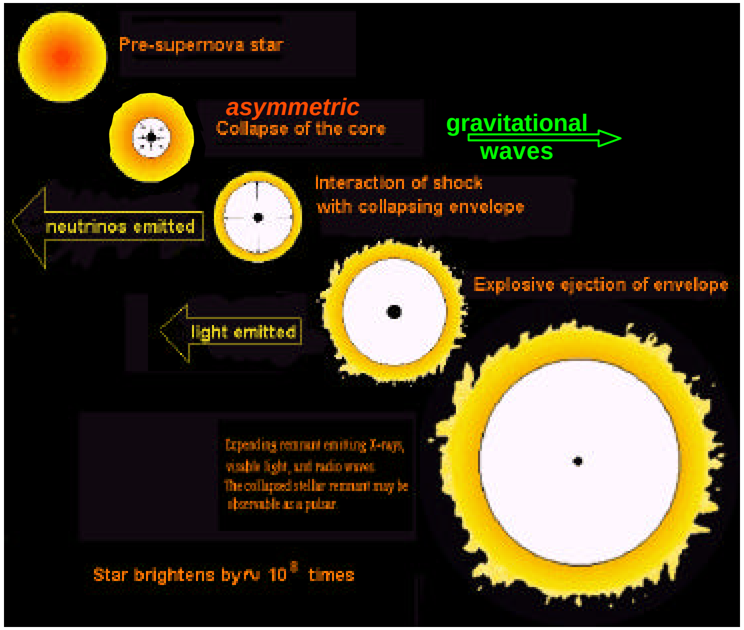
- **Limit on binary neutron star coalescence rate:**
  - » *$R_{90\%}$ (Milky Way) < 2.3 / (0.35 x 295.3 hr) =* ***170 /yr***
- **Use triggers from H 4km and L 4km interferometers: *T = 295.3 hours***
  - » Monte Carlo simulation efficiency: *e = 35%*
  - » 90% confidence limit = *2.3 / (e T)*
- *26 x lower than best published observational limit -- 40m prototype at Caltech*[1]
  - » *$R_{90\%}$ (Milky Way) < 4400 /yr*

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

Gravitational Wave Burst Search

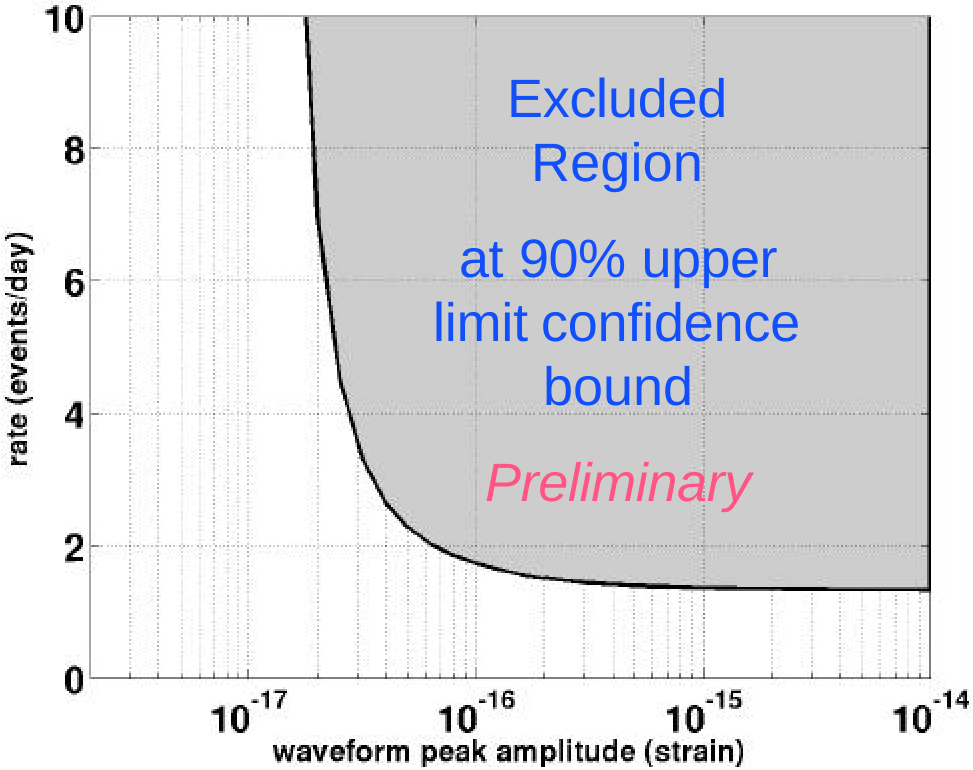
- Transient—no model for waveform
- Supernova rate: 1/50 yr – Milky Way, 3/yr out to Virgo cluster
- Event Triggers used to identify candidate events
- Determine detection efficiency via simulations
- Require coincidence between all three interferometers

  (+/- 10ms)



- Upper Bound $\propto$ N / (ε(h) T)
  - »N: number observed events
  - ≈ε(h): detection efficiency for amplitude
  - »T: observation time
  - »Proportionality constant depends on confidence level—of order 1 for 90 percent

Burst Searches—Preliminary Results

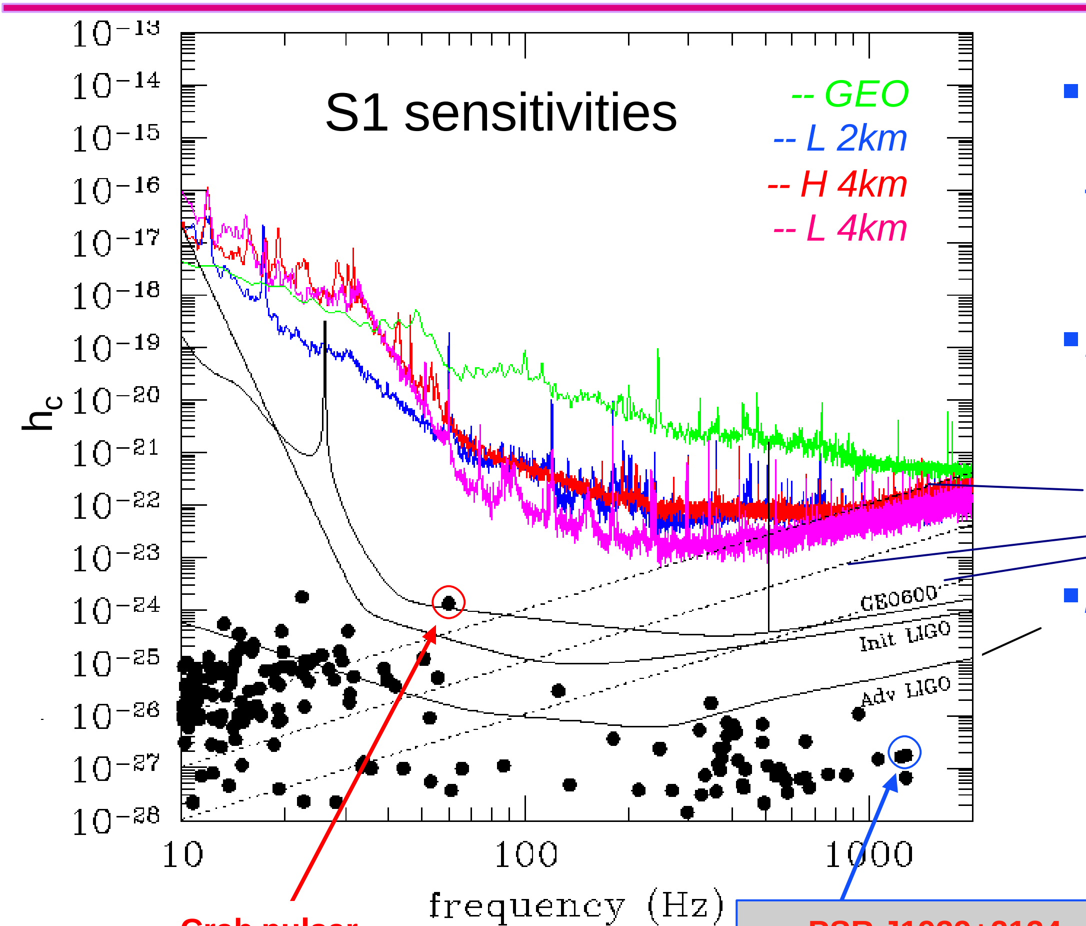


- *Able to exclude gravitational wave bursts* of peak strength ***h*** above rate ***r***
- Upper limit in *strain* compared to prior (cryogenic bar) results:
  - » S1: $h < 5 \times 10^{-17}$ - **this result**
  - » IGEC 2000[1]: $h < 1 \times 10^{-17}$
  - » Astone et al.[2] 2001: $h \sim 2 \times 10^{-18}$
- Upper limit in *rate* constrained by observation time:
  - » S1: 17d - **this result**
  - » IGEC - 90d (2X coinc.), 260d (3X coinc.)
  - » Astone - 90d

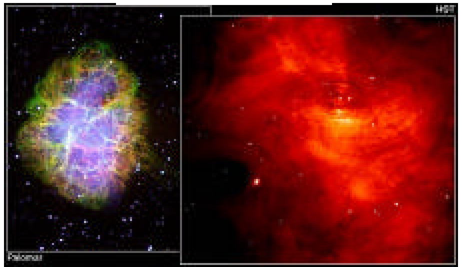
[1]Int.J.Mod.Phys. D9 (2000) 237

[2]Class.Quant.Grav. 19 (2002) 5449

Periodic Sources



Crab pulsar



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

$$h_c = 4.2\,[S_h(f)/T]^{1/2}$$

- *Limit of detectability for rotating NS with equatorial ellipticity, $e = dI/I_{zz}$: 10^{-3}, 10^{-4}, 10^{-5} @ 10 kpc*

- ***Known** EM pulsars*
  - *Values of h_c 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*
dP/dt = 1.0519 10^{-19} s/s
D = 3.6 kpc

Graphic by R. Dupuis, Glasgow

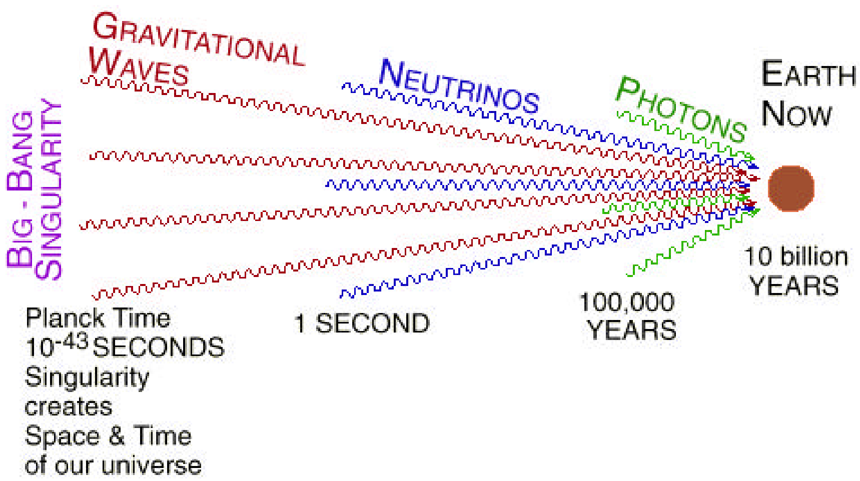
Periodic Sources

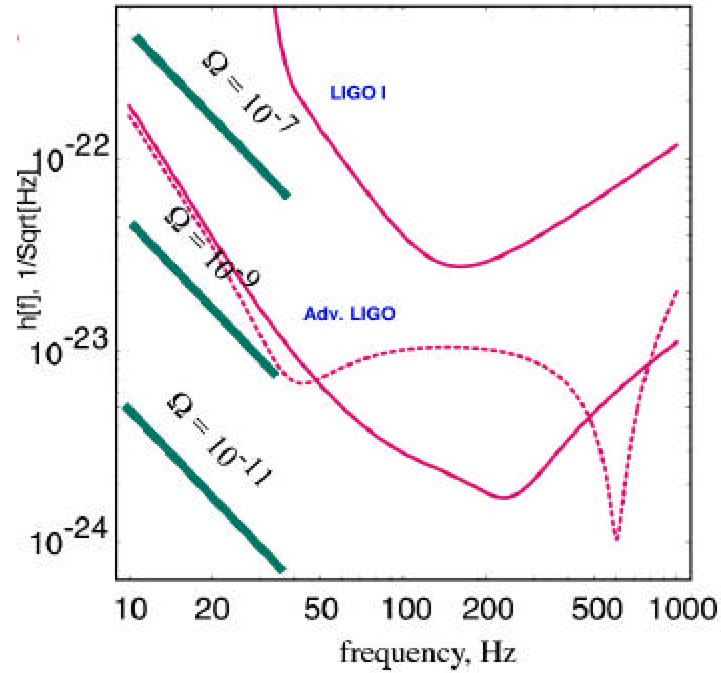
- Two complementary analysis approaches
  - » Time domain search—signal processed to remove frequency variations due to earth's motion
  - » Frequency-time domain search—can search over large parameter space when signal characteristics uncertain
    - – Analysis still in process
- Preliminary Results--***Time domain analysis:***

No evidence of signal from PSR J1939 at f = 1283.86 Hz

- 95% of the probability lies below:
  - GEO: $h_{max} < 3 \times 10^{-21}$
  - H 2km: $h_{max} < 5 \times 10^{-22}$
  - H 4km: $h_{max} < 3 \times 10^{-22}$
  - ***L 4km: $h_{max} < 2 \times 10^{-22}$ ($e < 7 \times 10^{-5}$ @ 3.6 kpc)***

Stochastic Background Sensitivity





- **Detection**
  - » **Cross correlate Hanford and Livingston Interferometers**
- **Good Sensitivity**
  - » **GW wavelength ³ 2x detector baseline Þ *f* £ 40 Hz**
- **Initial LIGO Sensitivity** W ³ **10^{-5}**
- **Advanced LIGO Sensitivity** W ³ **$5\ 10^{-9}$**

Stochastic Background

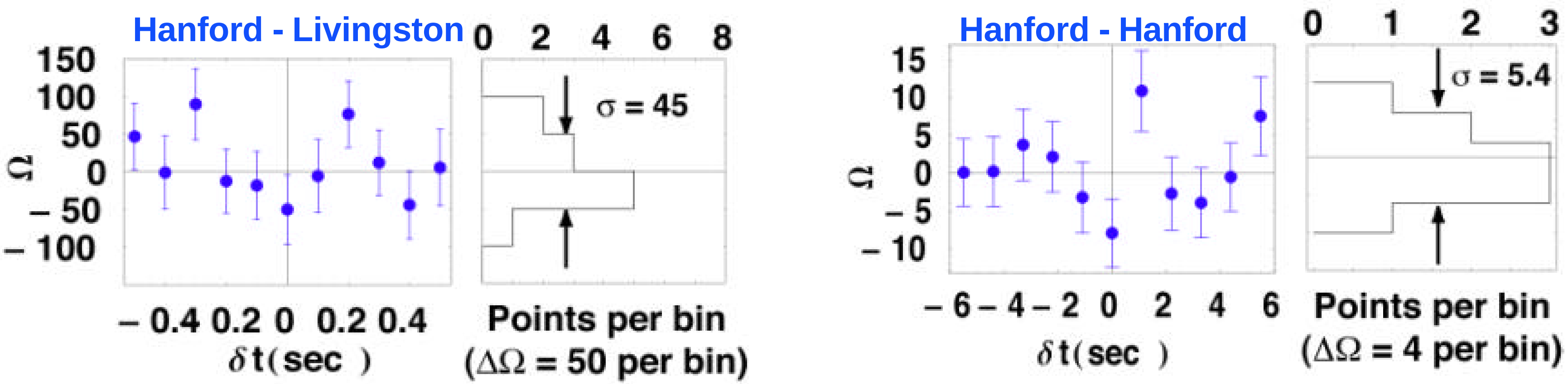
No observed correlations

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

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

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

First LIGO Science Data (Lazzarini)



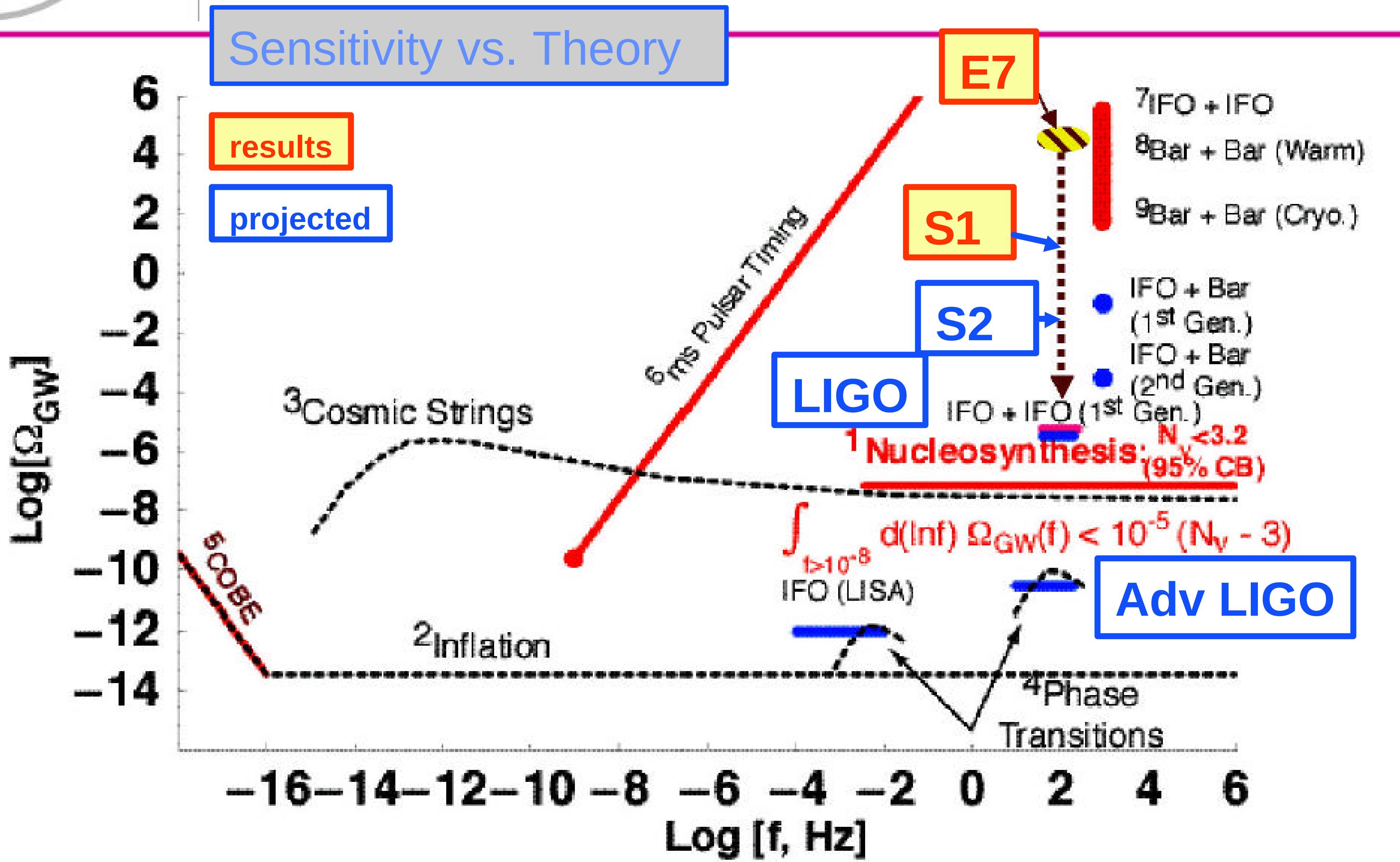
Preliminary limits from 7.5 hr of data

Stochastic Background

Results and Projections

- Best previously published limits
  - » Garching-Glasgow interferometers (1994) $\Omega_{GW}(f) \leq 3\times10^{5}$
  - » EXPLORER-NAUTILUS resonant bars (1999) $\Omega_{GW}(f) \leq 60$
- LIGO Initial Results
  - » Test data (Dec 2001) $\Omega_{GW}(f) \leq 50$
  - » First data (September 2002) **NEW RESULT** $\Omega_{GW}(f) \leq 5$
- **LIGO Projections**
  - » **Second data run (underway)** $\Omega_{GW}(f) \leq 3\times10^{-3}$
  - » **Initial LIGO sensitivity** $\Omega_{GW}(f) \leq 10^{-5}$
  - » **Advanced LIGO sensitivity** $\Omega_{GW}(f) \leq 5\times10^{-9}$

Stochastic Background

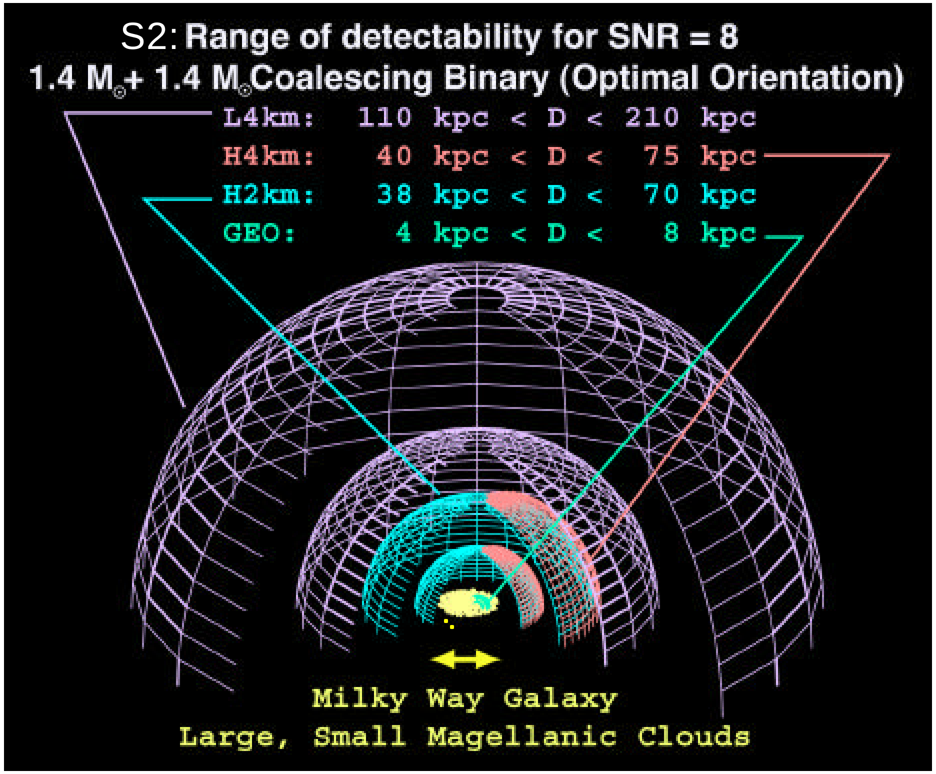


LSC Procedures for S1 Data

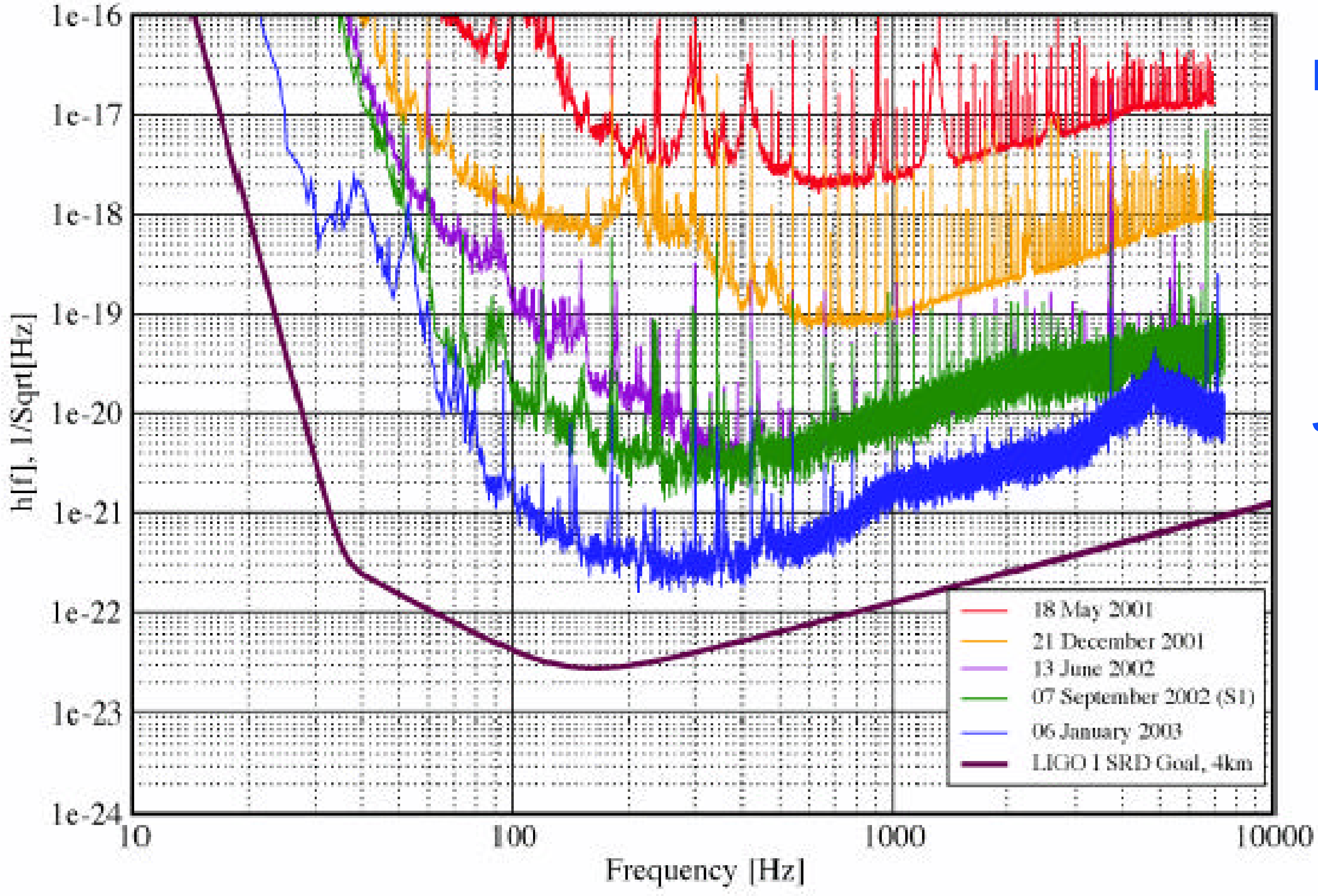
- Draft pre-prints sent to collaboration (January 2, 2003)
- Iteration by review committees and authors
- Revised pre-prints sent to collaboration (January 21)
- Release of pre-prints for general comment and for selected presentations (March 2003)
- Discussion at March LSC meeting (March 17-20)
- Iterate for publication

S2 Second Science Run

- **S2 Data expected to provide at least 10x more "Science Reach" than S1**
  - » **Better sensitivity and longer run**
  - » **Coincidence with GEO and TAMA**



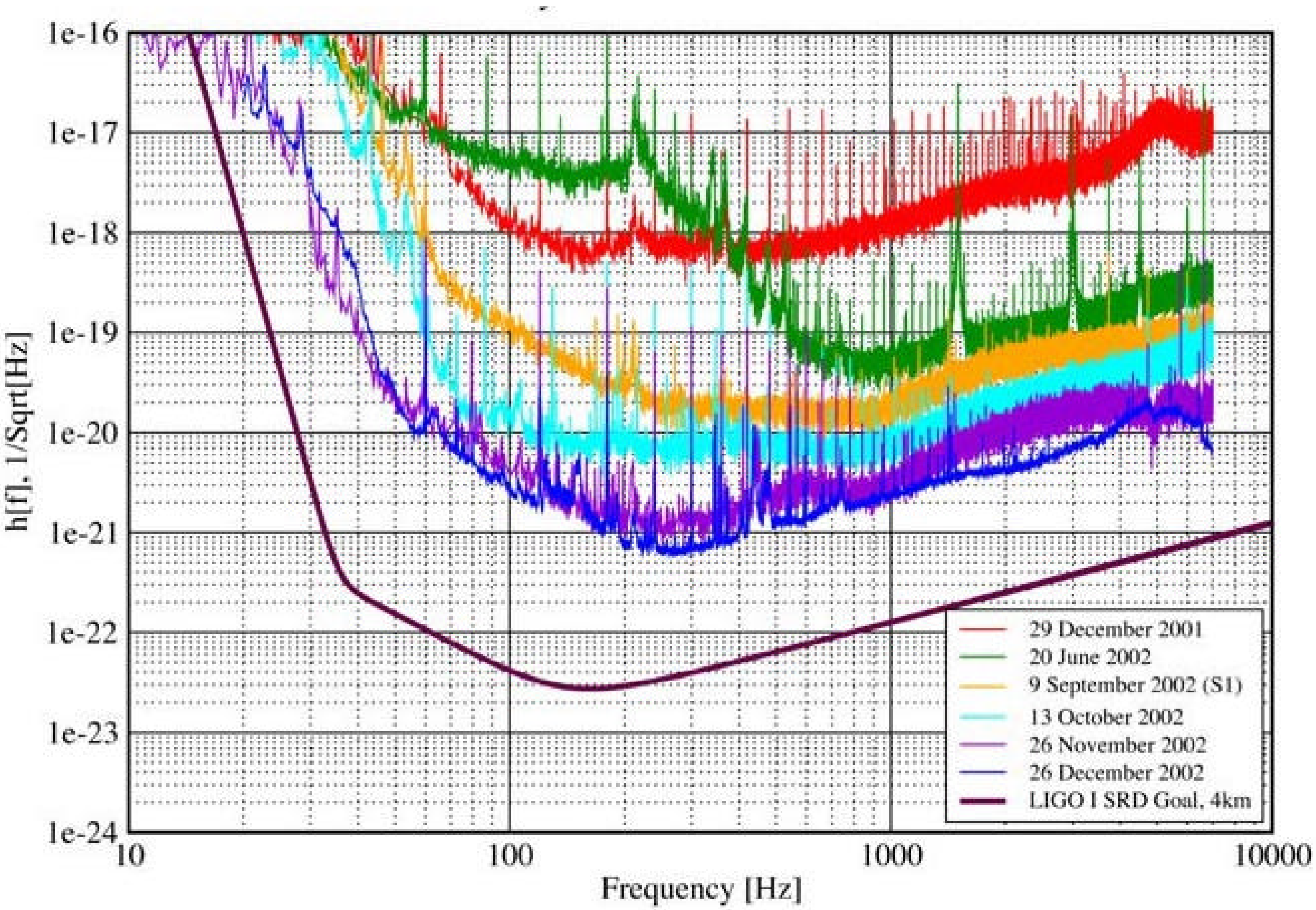
Livingston 4km Sensitivity History



May 01

Jan 03

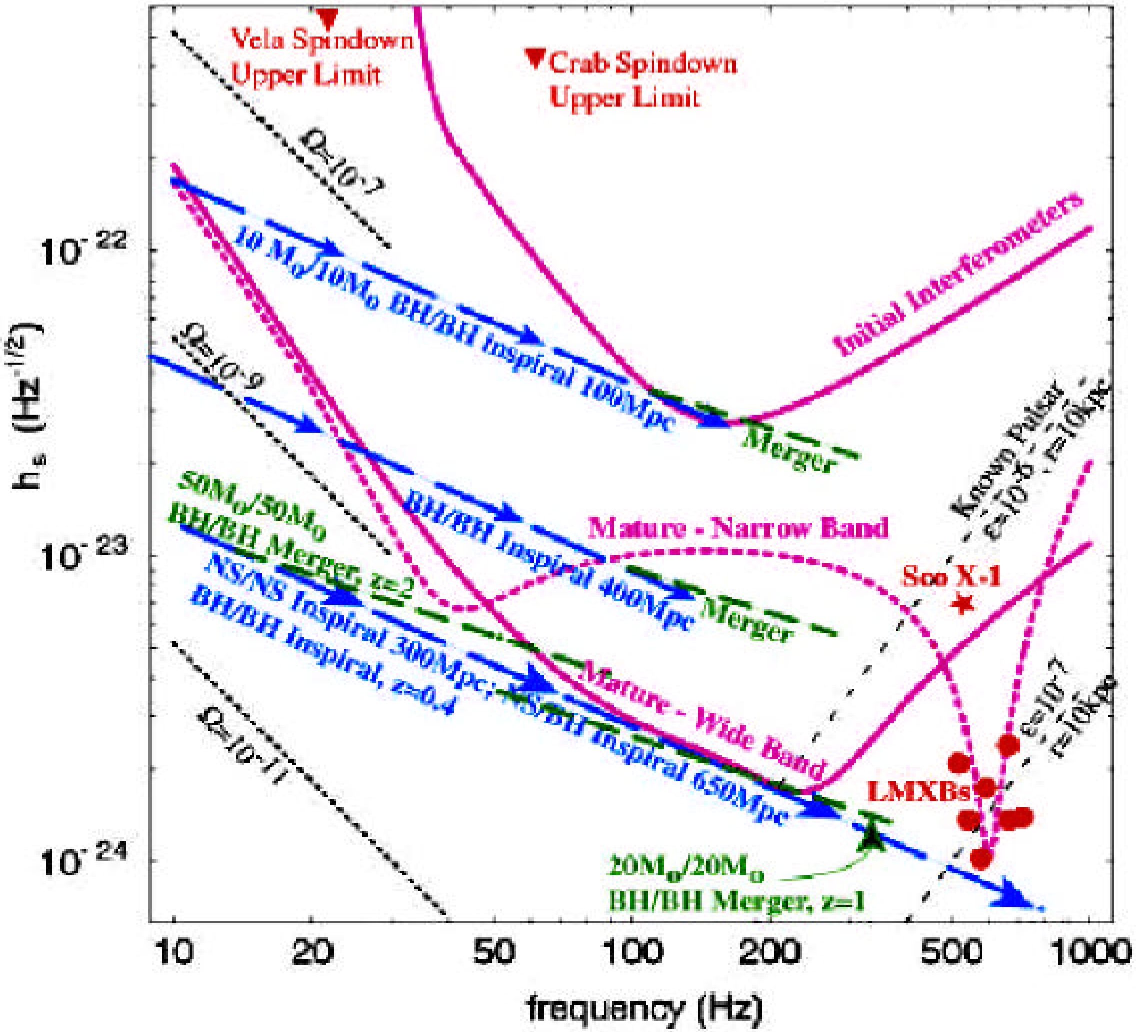
Hanford 4km Sensitivity History



S2 Has Started

- Began February 14, 2003, will last through April 14, 2003
- Duty cycles comparable to S1
  - » 67 percent H1, 60 percent H2, 40 percent L1
- Longest “science” segment is record 66 hours (H1)
- 8 of 10 alignment degrees of freedom under wave front sensing control on H1
- Livingston duty factor limited by daytime man-made seismic noise—approximately 40 percent operation in science mode
- Livingston sensitivity has varied between **0.8 and 1.2** Mpc for inspirals
- Control room tools and operational procedures starting to gel
- Five interferometers collaborating internationally
  - » GEO (UK/Germany) and TAMA (Japan) observing jointly with LIGO

Advanced LIGO (2007 +)



Enhanced Systems

- 180 W laser
- quad suspension
- active isolation
- sapphire core optics
- signal recycled

Rate improvement factor: ~ 10^4

+ narrow band optical configuration

Conclusions

- **LIGO Commissioning underway**
  » **Excellent progress towards design sensitivity**
- **Science Running beginning**
  » **Initial results about to be published**
  » **Improved data run in progress**
- **Plan**
  » **Goal is to obtain > one year of integrated data at design sensitivity before the end of 2006**
  » **Advanced interferometer will provide dramatically improved sensitivity**

Acknowledgements

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  - » NSF PHY-9210038 (Construction)
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- David Shoemaker, Advanced LIGO Project Lead
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- Barry Barish, LIGO Laboratory Director