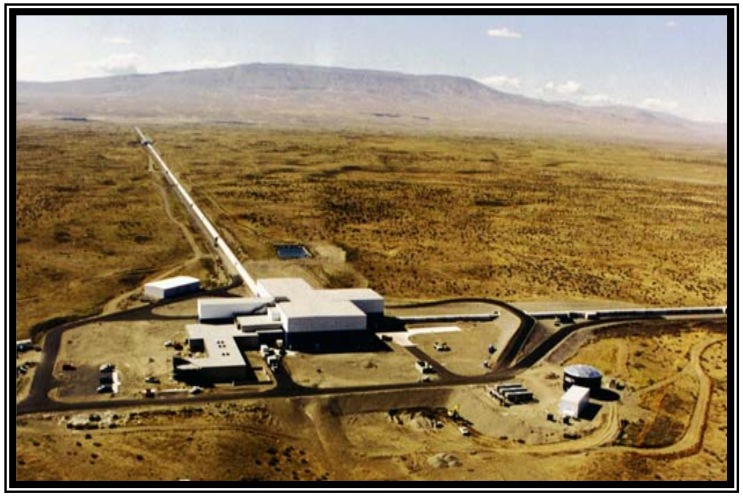
The LIGO Project: a Status Report

LIGO Hanford Observatory



LIGO Livingston Observatory

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for the LIGO Scientific Collaboration

Conference on Gravitational Wave Sources

Trieste, Italy - September 23, 2003

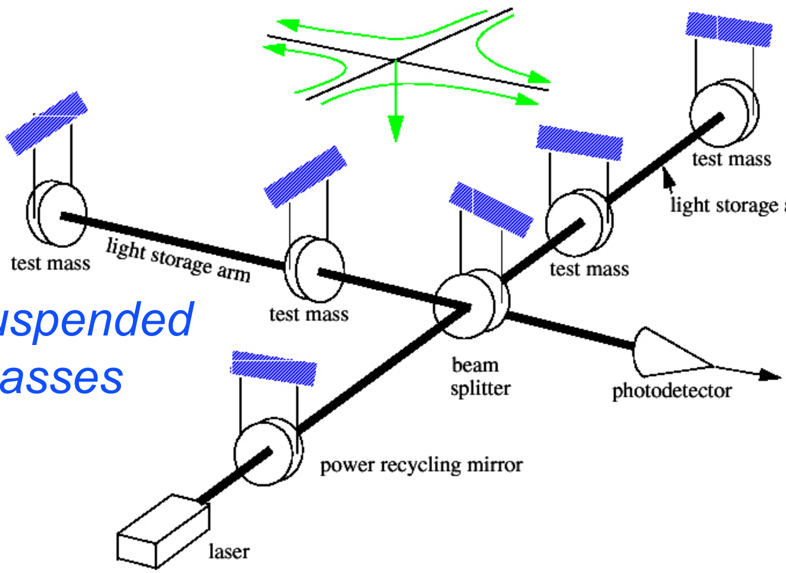
Outline

- The LIGO Project
- Initial LIGO sensitivity curve
- S1 science run
  - » Sensitivity
  - » Data Analysis Results
- S2 science run
- Advanced LIGO

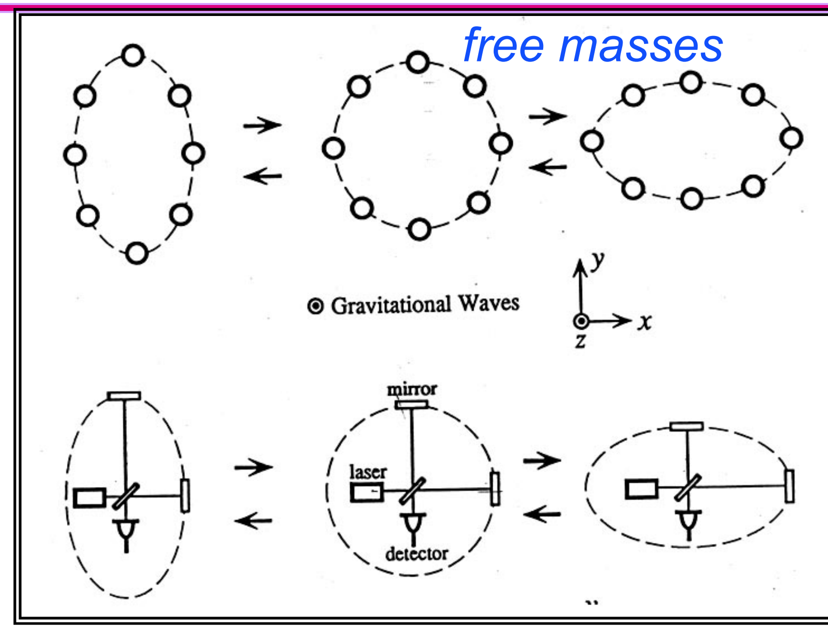
Suspended Mass Interferometer

Laser used to measure relative lengths of two orthogonal arms

As a gravitational wave passes, the arm lengths change in different ways….



suspended masses

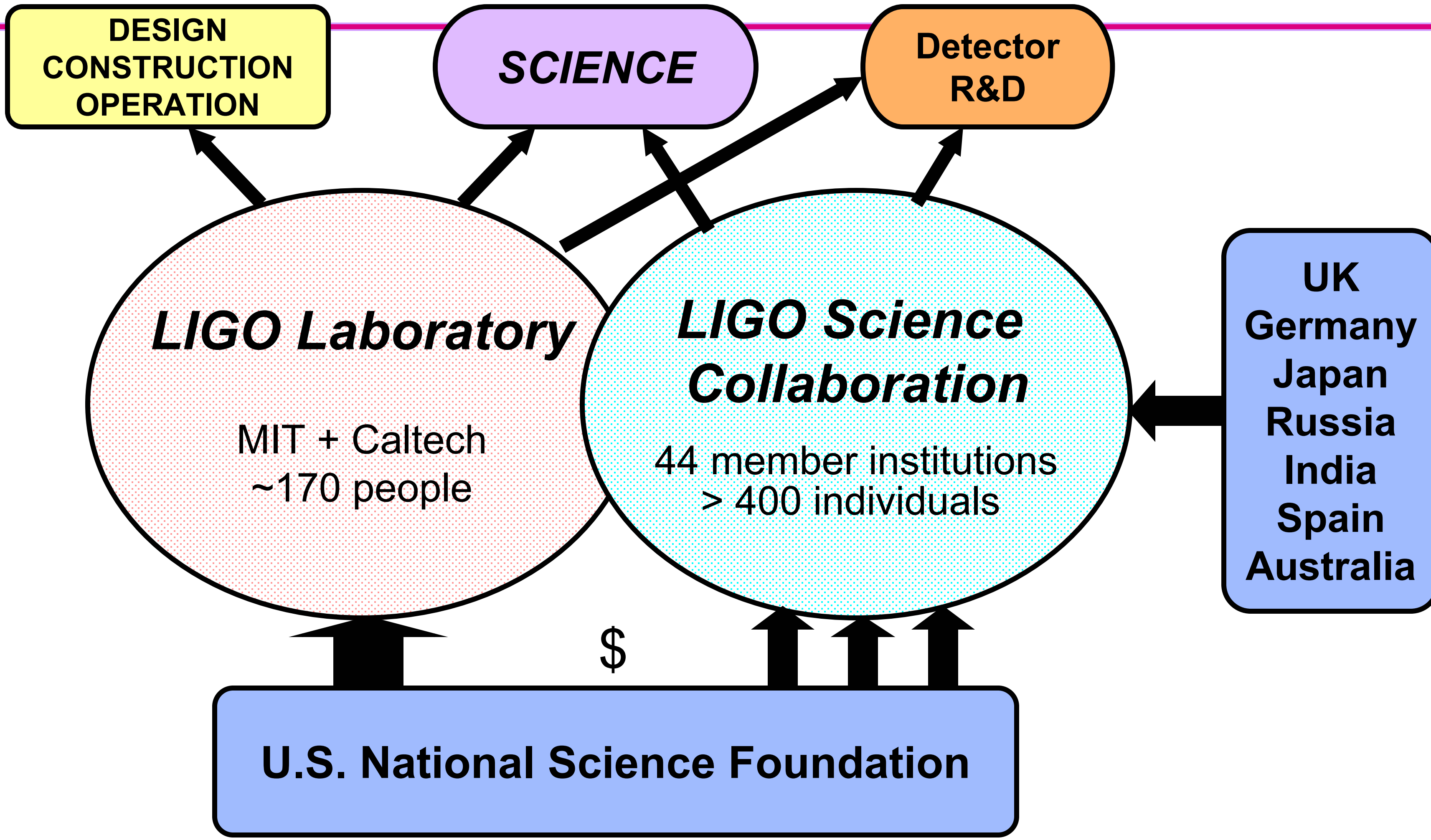


…causing the interference pattern to change at the photodiode

Arms in LIGO are 4km

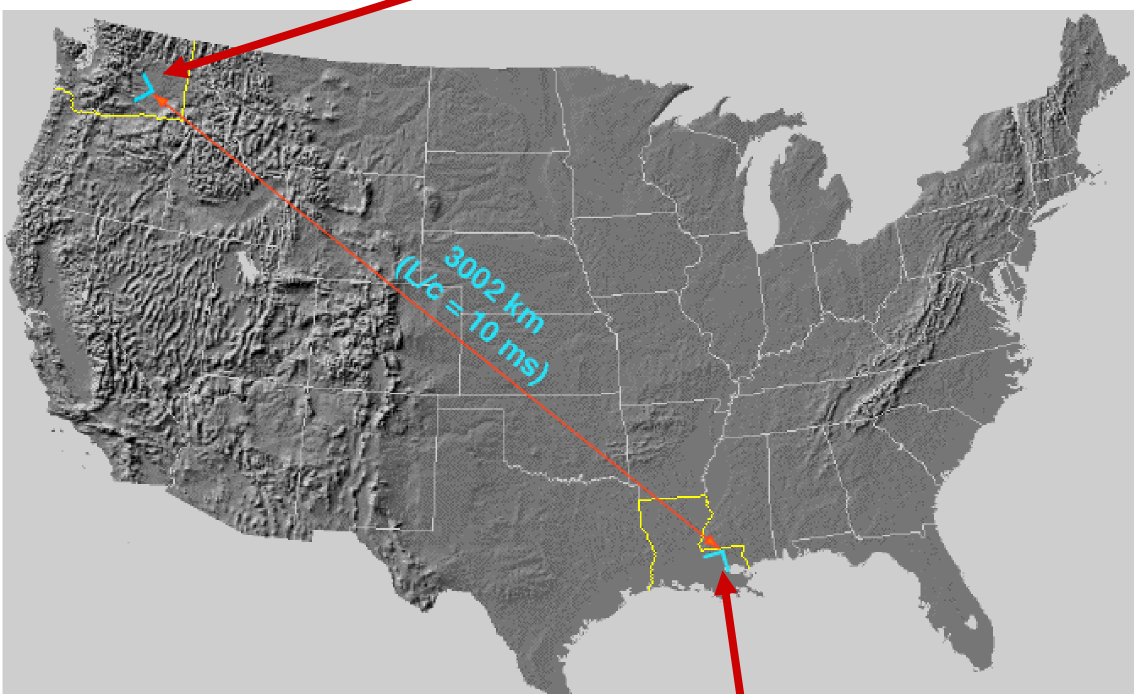
Goal: measure difference in length to one part in 10^{21}, or 10^{-18} meters

LIGO Organization & Support



The LIGO Observatory

Hanford Observatory
4 km + 2 km interferometers

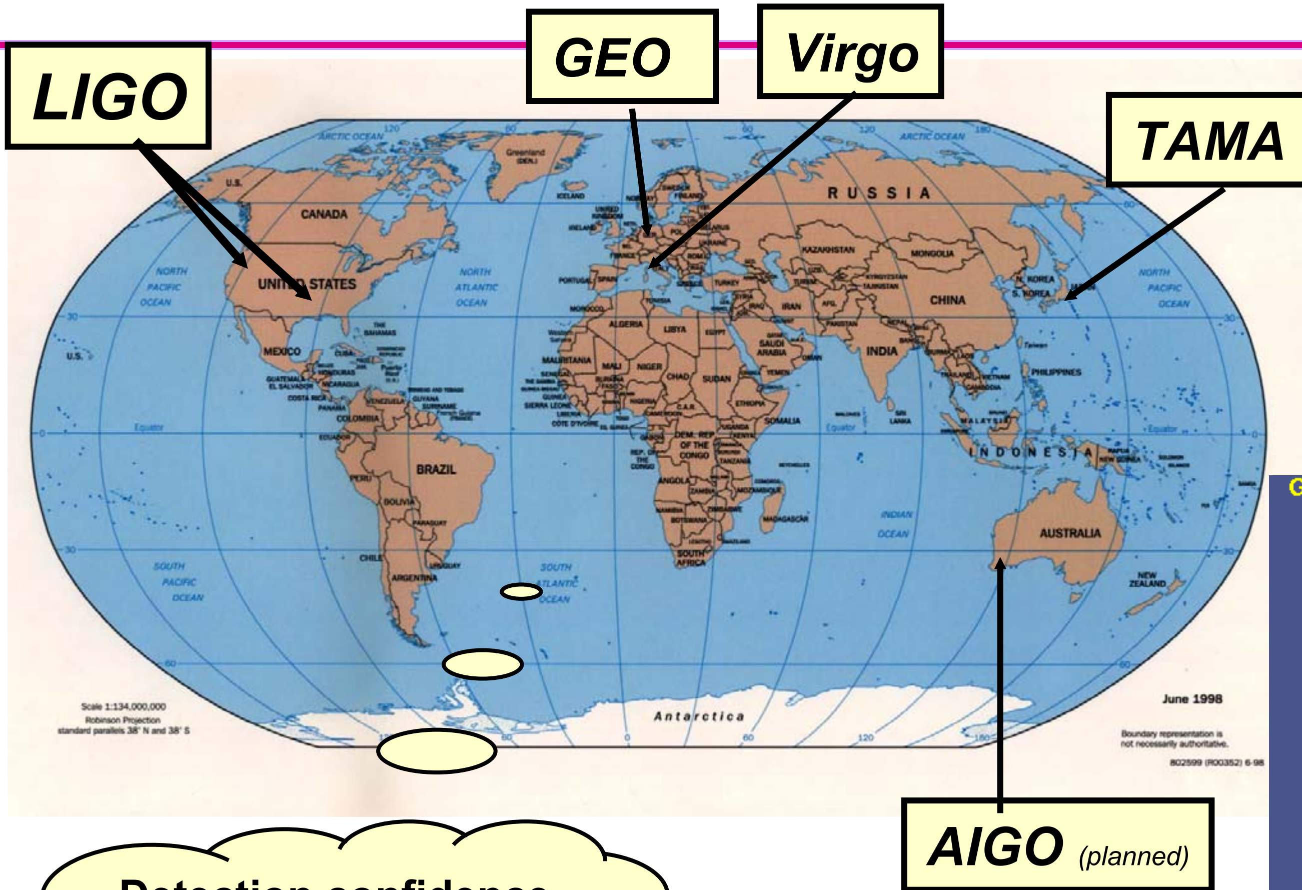


Livingston Observatory
4 km interferometer

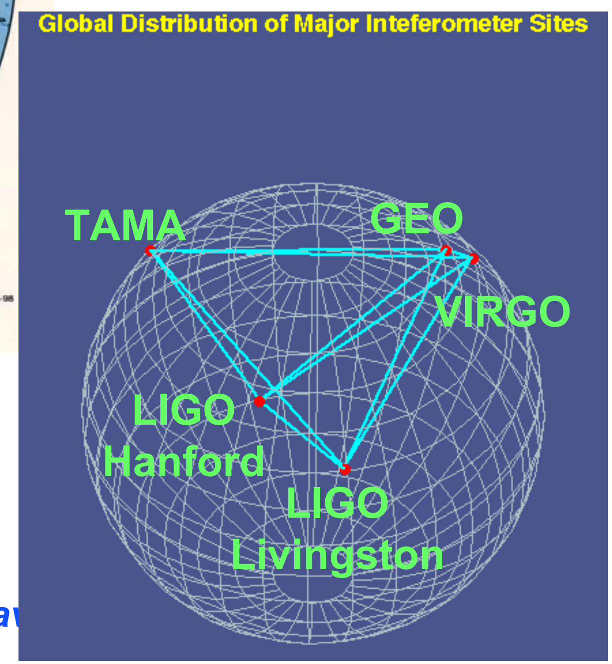
- Coincidence
- Source triangulation*

**only on an anulus, need other worldwide sites!*

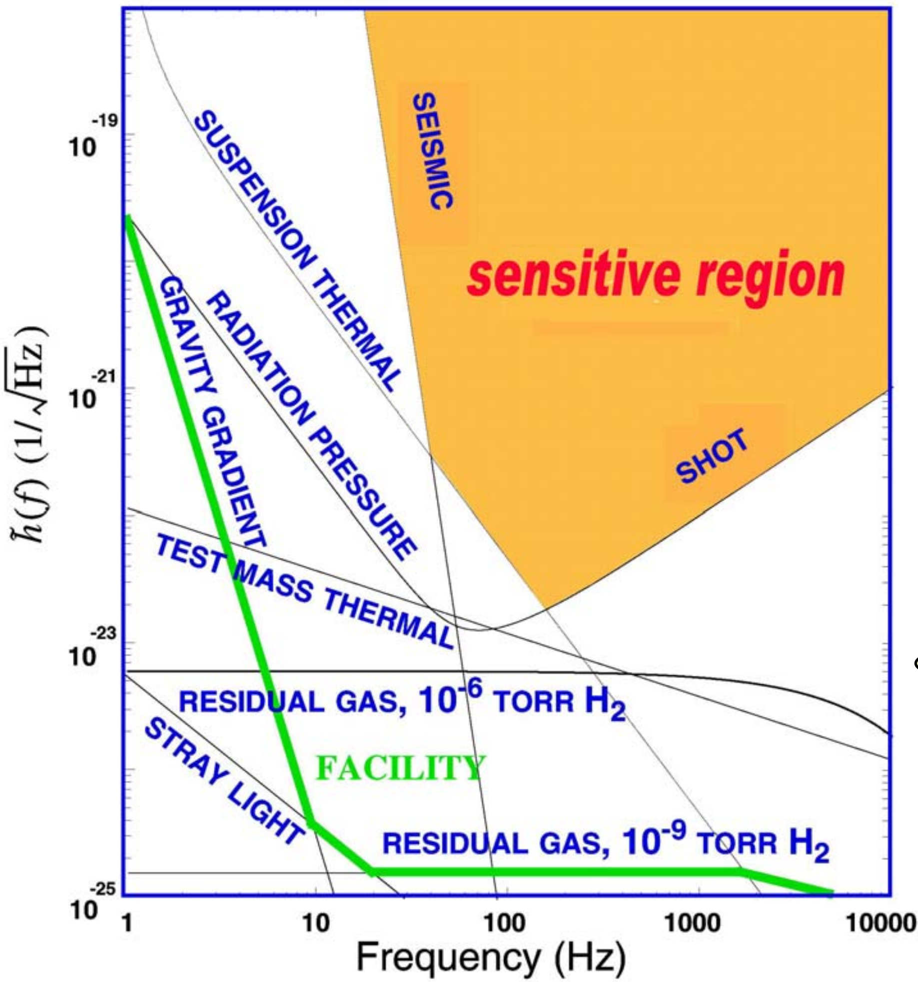
International Interferometer Network



- Detection confidence
- Source polarization
- Sky location



Initial LIGO Sensitivity Goal



Strain sensitivity
< 3x10^{-23} Hz$^{-1/2}$ at 150 Hz

Displacement Noise

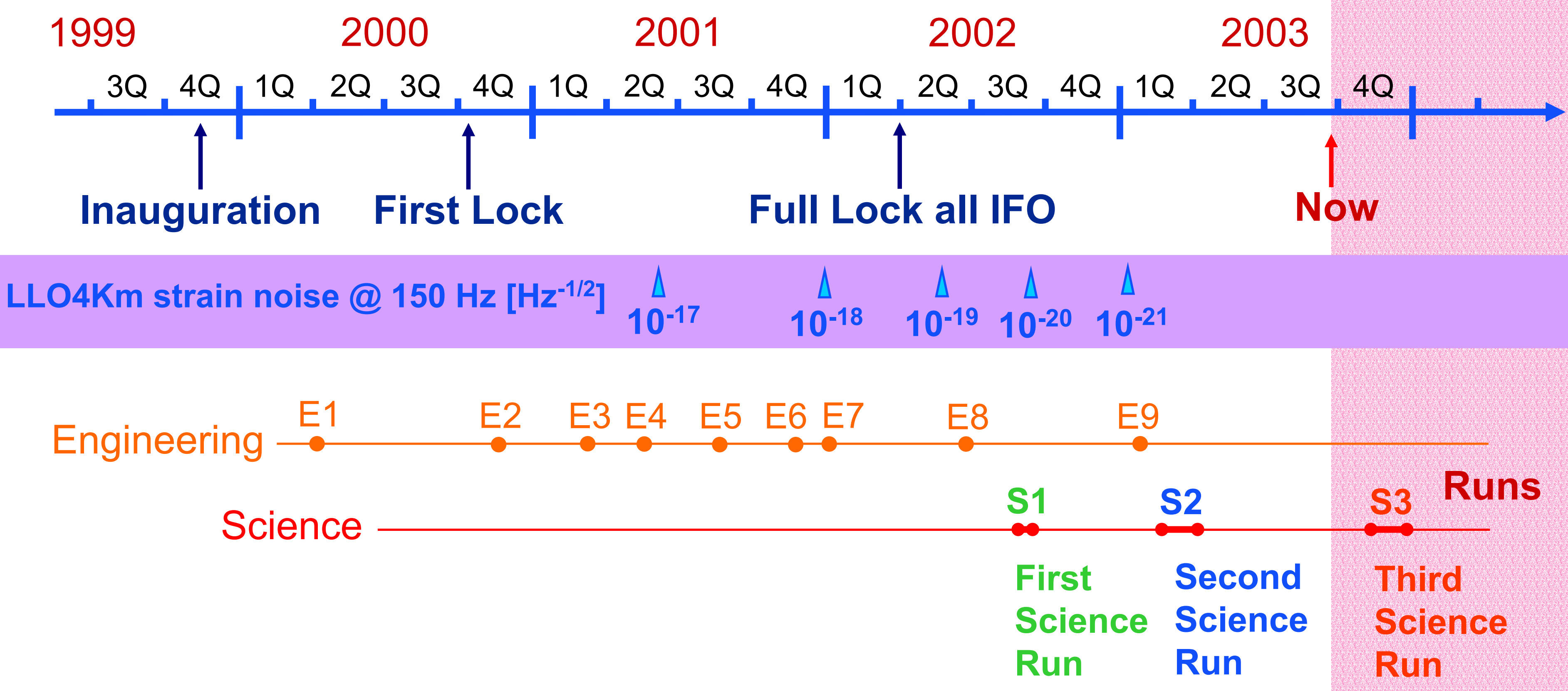
» Seismic motion (limits low frequency)
» Thermal Noise (limits intermediate freq)
» Radiation Pressure

Sensing Noise

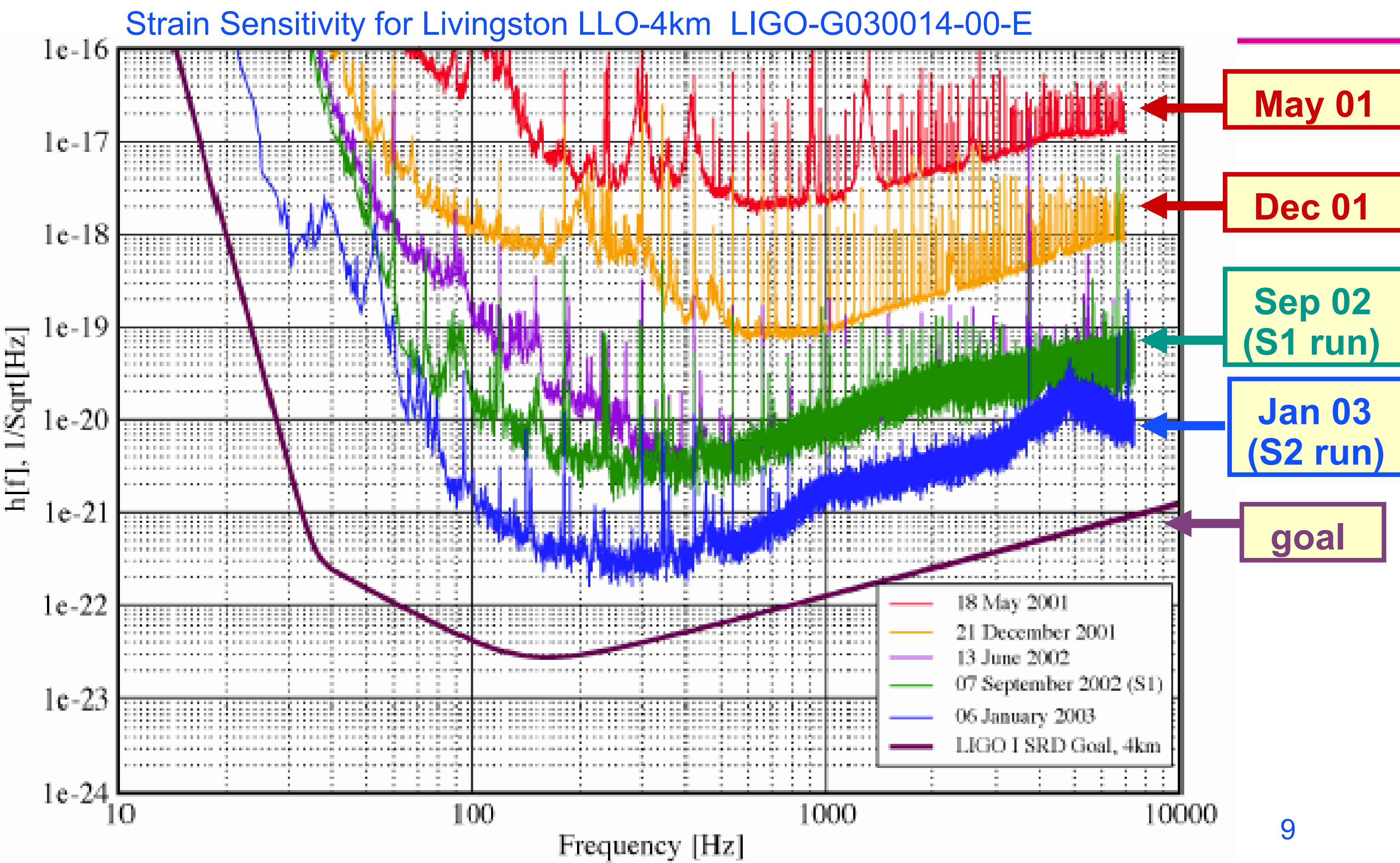
» Photon Shot Noise (limits high frequency)
» Residual Gas

Technical issues - alignment, electronics, acoustics, etc limit us before we reach these design goals

Commissioning Timeline



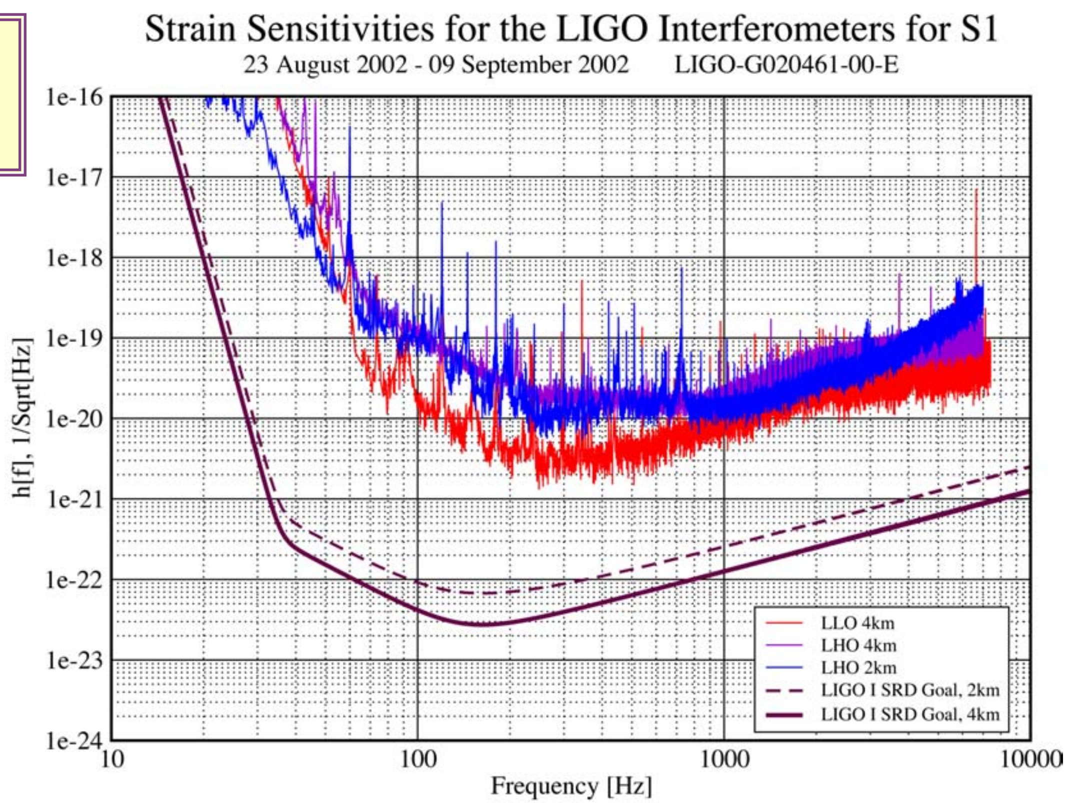
Approaching the Sensitivity Goal



First Science Run (S1)

August 23 – September 9 2002
(~400 hours)

Detector description and performance: preprint gr-qc/0308043



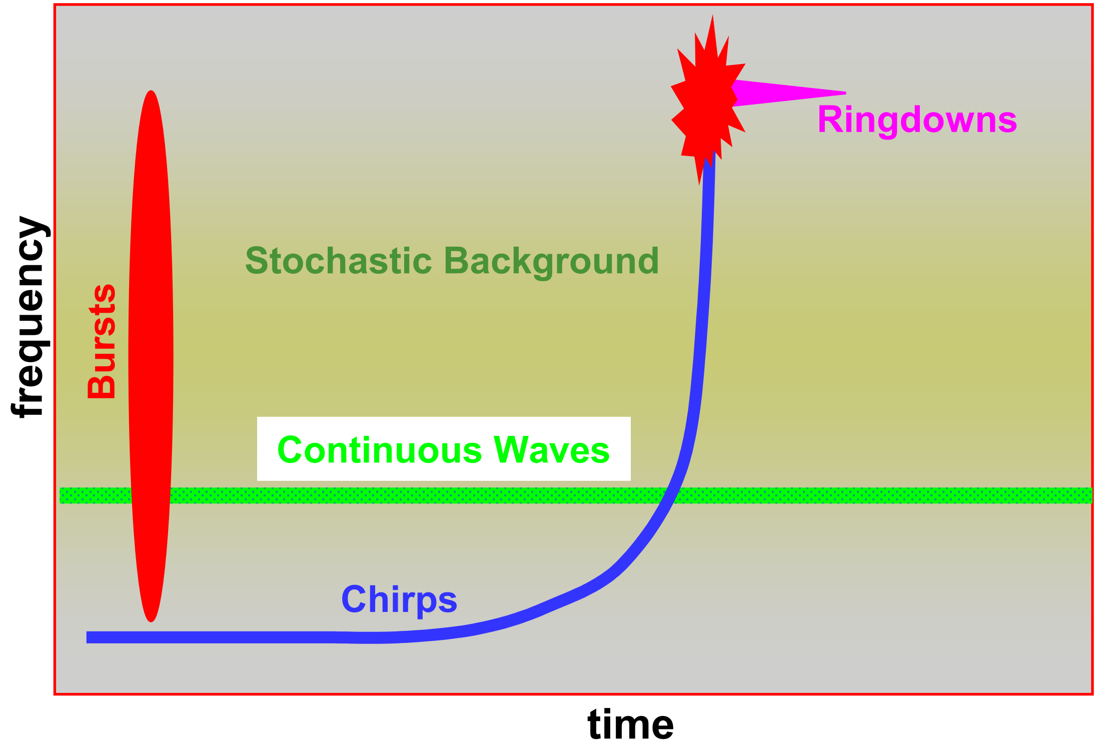
Three LIGO interferometers, plus GEO (Europe) and TAMA (Japan)

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

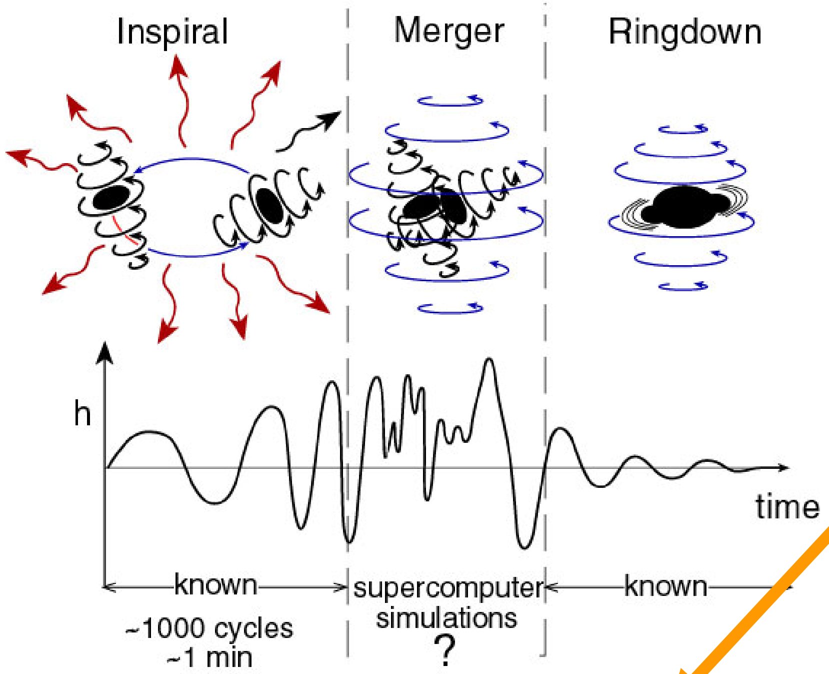
- Compact binary inspiral:
  "chirps"
- Supernovae / GRBs:
  "bursts"
- Pulsars in our galaxy:
  "periodic"
- Cosmological Signals
  "stochastic background"



Four papers describing analysis and results in final stages of preparation

In preprint archives: Inspiral: gr-qc/0308069 Periodic: gr-qc/0308050

Compact Binary Coalescence

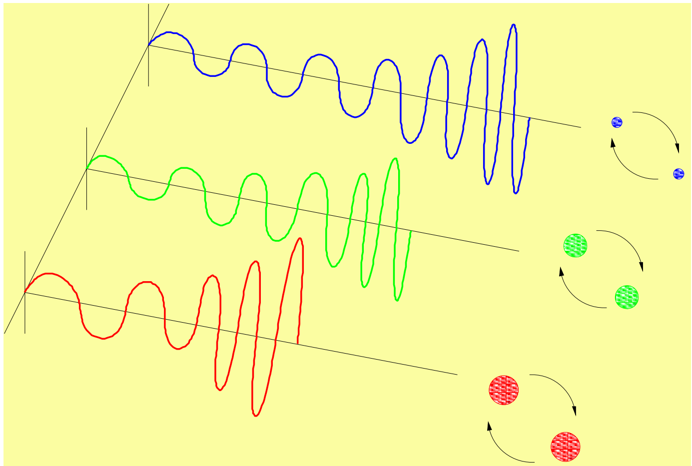


» Search: *matched templates*

» 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

Milky Way + Large and Small Magellanic Cloud (contribute ~12% of Milky Way)

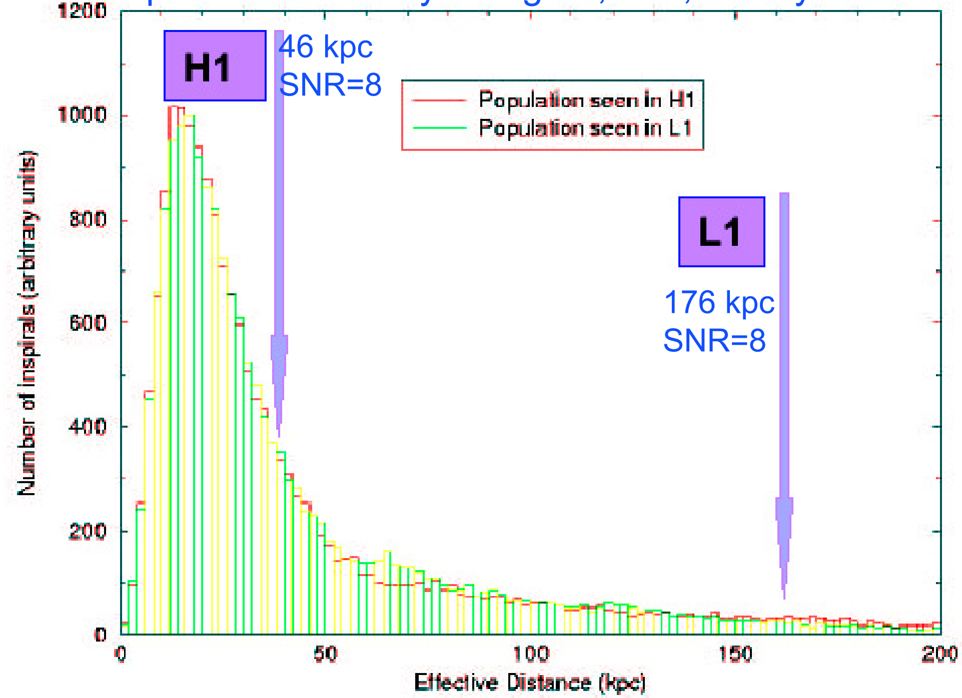
LIGO S1 Upper Limit on the rate of binary neutron star coalescence:

R < 170 / yr / MWEG

Less than 170 binary neutron star collisions per year per Milky Way Equivalent Galaxy (90% CL)

gr-qc/0308069

Population model by Kalogera, Kim, Belczynski et al



- Previous observational limits:
  - Japanese TAMA → R < 30,000 / yr / MWEG
  - Caltech 40m → R < 4,000 / yr / MWEG
- Theoretical prediction R < 2×10^{-5} / yr / MWEG

LIGO

Burst Sources

Unknown phenomena

Broadband search (150-3000Hz) for short transients (< 1 sec) of gravitational radiation of unknown waveform (e.g. black hole mergers).

Method: *excess power* or *excess amplitude* techniques

Uninterpreted limit

Bound on the rate of measured events

Interpreted limit

For specific classes of waveforms, bound on the rate of detected gravitational wave bursts, viewed as originating from fixed strength sources on a fixed distance sphere centered about Earth, expressed as a region in a rate v. strength diagram.

Known sources -- Supernovae & Gamma Ray Bursts

Exploit coincidence with electromagnetic observations.

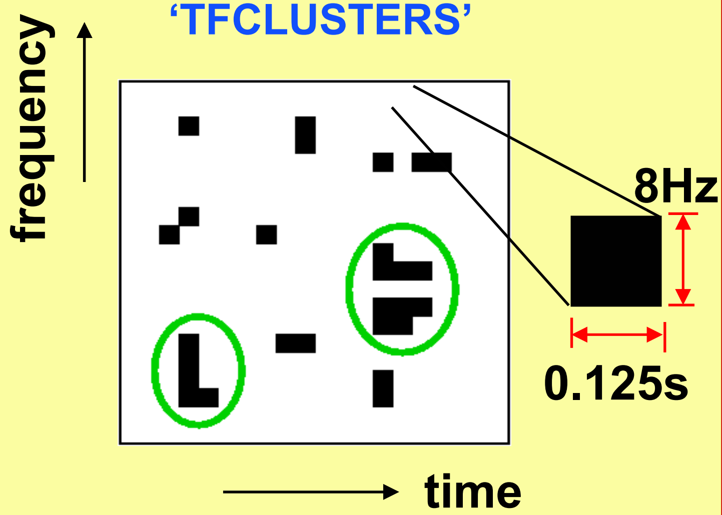
No close supernovae occurred during the first science run (Second science run – We are analyzing the recent very bright and close GRB030329 NO RESULT YET)

Techniques in Burst Search

'Raw Data' → Time-domain high pass filter

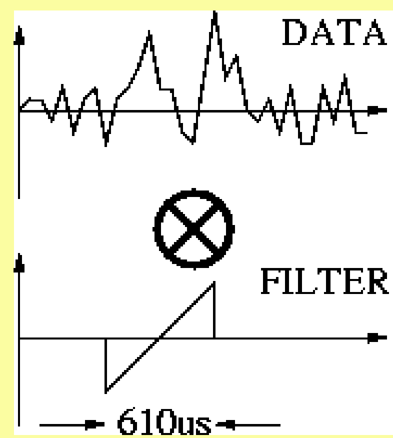
Time-Frequency Plane Search

'TFCLUSTERS'



Pure Time-Domain Search

'SLOPE'



Event-based analysis (event=instance of excess power/oscillation)

In S1: required time-frequency coincidence between 3 interferometers

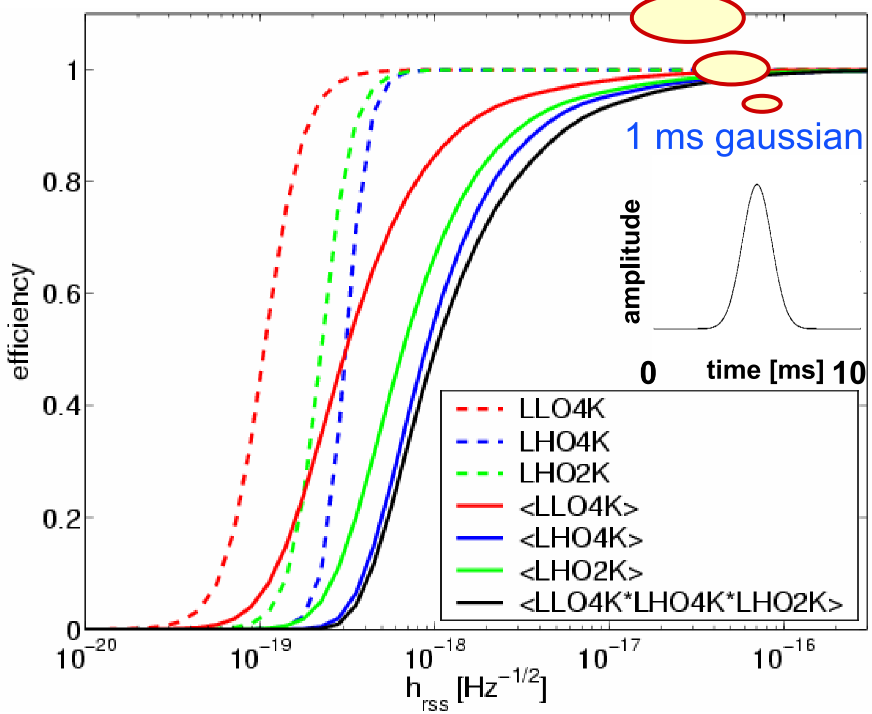
Amplitude and waveform consistency will be implemented in future science runs

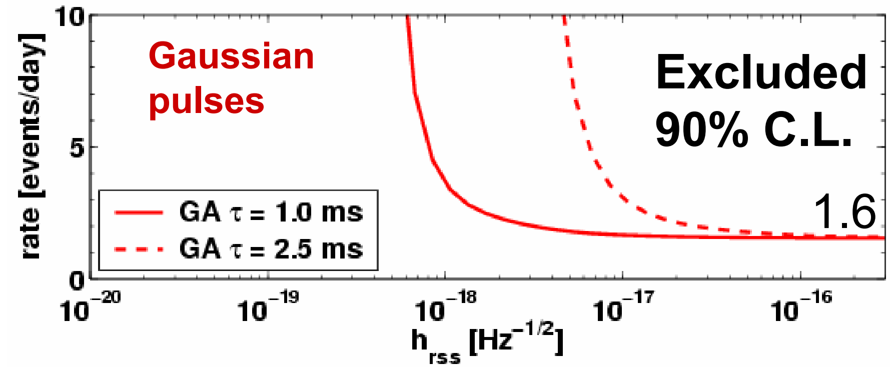
Background estimated with time-shift analysis

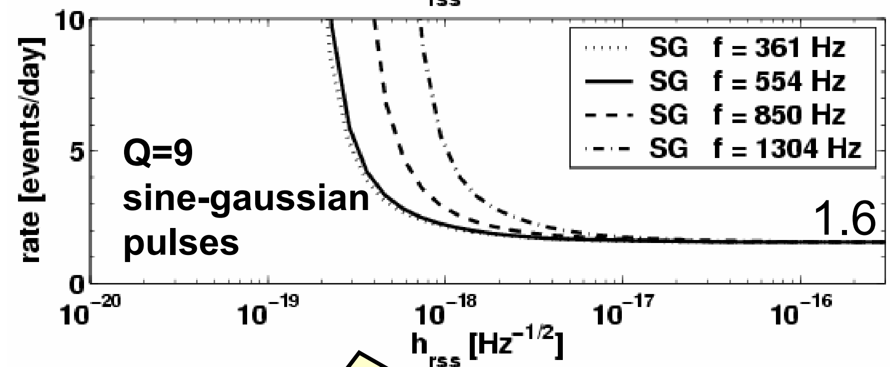
LIGO

Efficiency and Upper Limit

To measure our efficiency, we must pick a waveform.







$$\left\langle \mathcal{E} \right\rangle(h) = \int d\cos\theta \, d\phi \, d\psi \; \mathcal{E}\left(R(\theta,\phi,\psi)h\right)$$

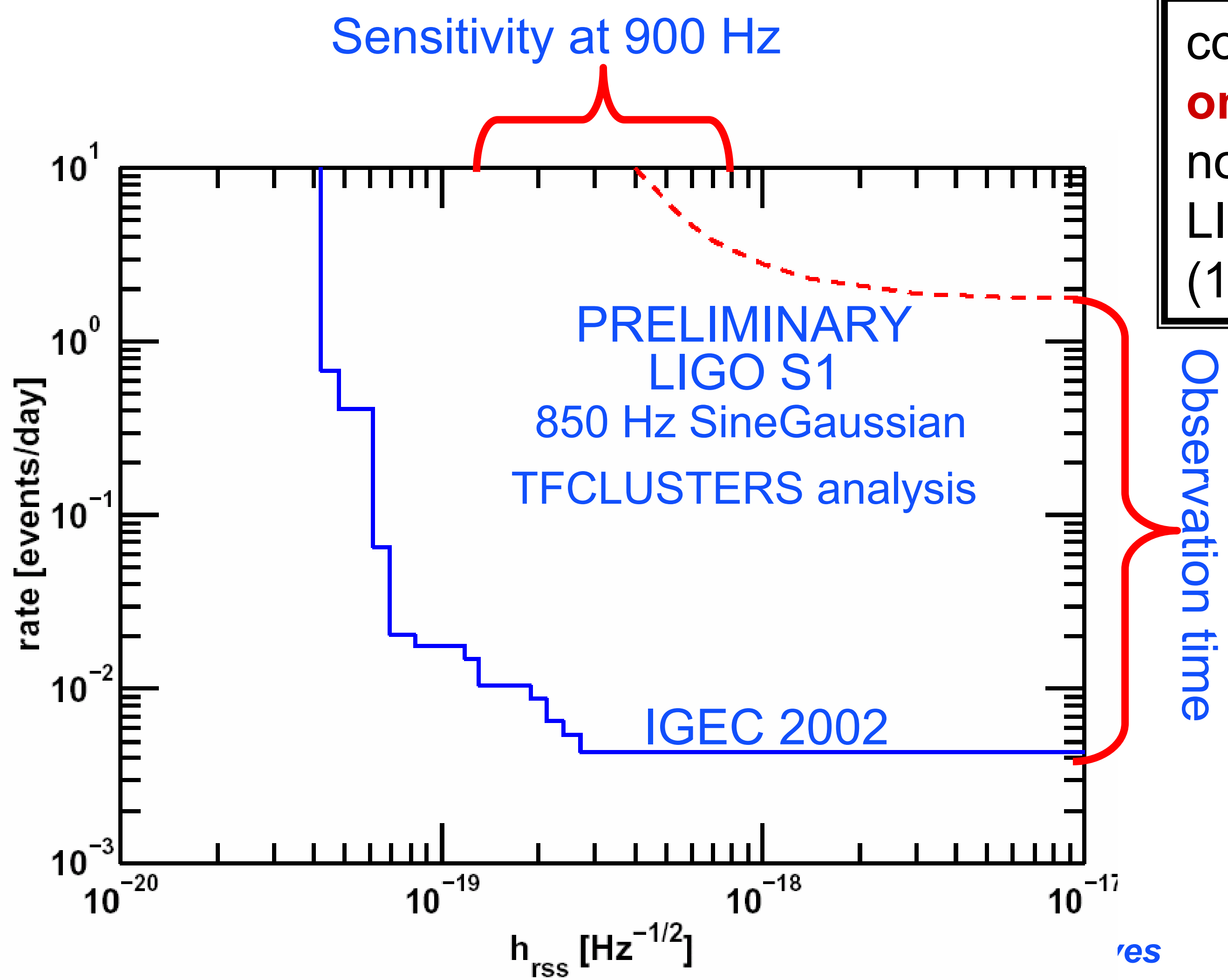
$$h_{rss} = \sqrt{\int \left|h(t)\right|^2 dt}$$

PRELIMINARY

rate vs strength curves from the TFCLUSTERS analysis

Comparison with IGEC results

comparison **only at 900 Hz**, not over full LIGO band (150-3000Hz)



Periodic Sources

No detection expected at present sensitivity

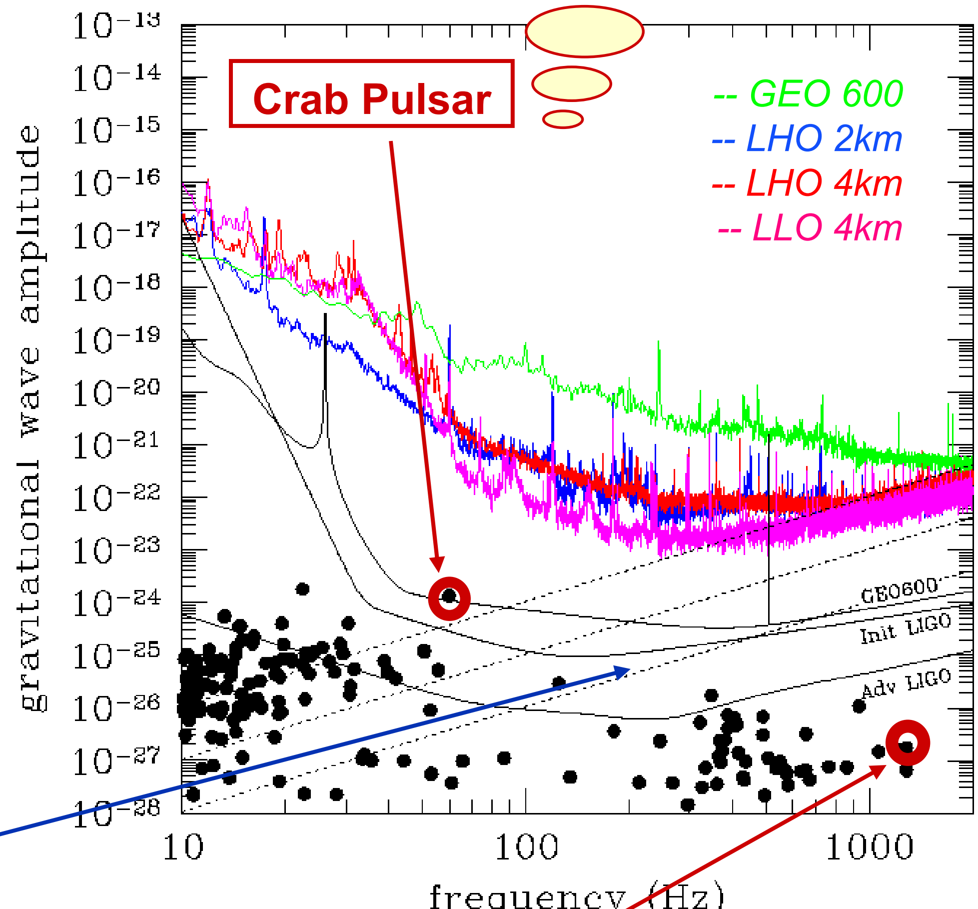
All sky and targeted survey of known and unknown pulsars

Targeted search of low mass X-ray binaries

- Colored curves: S1 sensitivity for actual observation time @1% false alarm, 10% false dismissal

$$\langle h_0 \rangle = 11.4 \sqrt{S_h(f) / T_{obs}}$$

- Solid curves : Expected instr. sensitivites for **One Year of Data**
- Dots: Upper limits on $\mathbf{h_0}$ if observed spindown all due to GW emission



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 D=3.6kpc

Two Search Methods

More details in A.Sintes talk on Friday morning

Frequency domain

- Best suited for large parameter space searches
- Maximum likelihood detection method + **frequentist approach**
- Take SFTs of (high-pass filtered) 1-minute stretches of GW channel
- Calibrate in the frequency domain, weight by average noise in narrow band
- Compute F = likelihood ratio for source model SFT (analytically maximized over ι, φ, ψ)
- Obtain upper limit using Monte-Carlo simulations, by injecting large numbers of simulated signals at nearby frequencies

Time domain

- Best suited to target known objects, even if phase evolution is complicated
- **Bayesian approach**
- Reduce the time dependence of the signal to that of the strain antenna pattern by **heterodyning** (model expected phase to account for intrinsic frequency and spin-down rate)
- Calculate $\chi^2(h_0, \iota, \varphi, \psi)$ for source model
- Marginalize over ι, φ, ψ to get PDF for (and upper limit on) h_0

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

Focused on pulsar PSR J1939+2134

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	$(6.42\pm0.72) \times 10^{-22}$	$(2.7 \pm0.3) \times 10^{-22}$

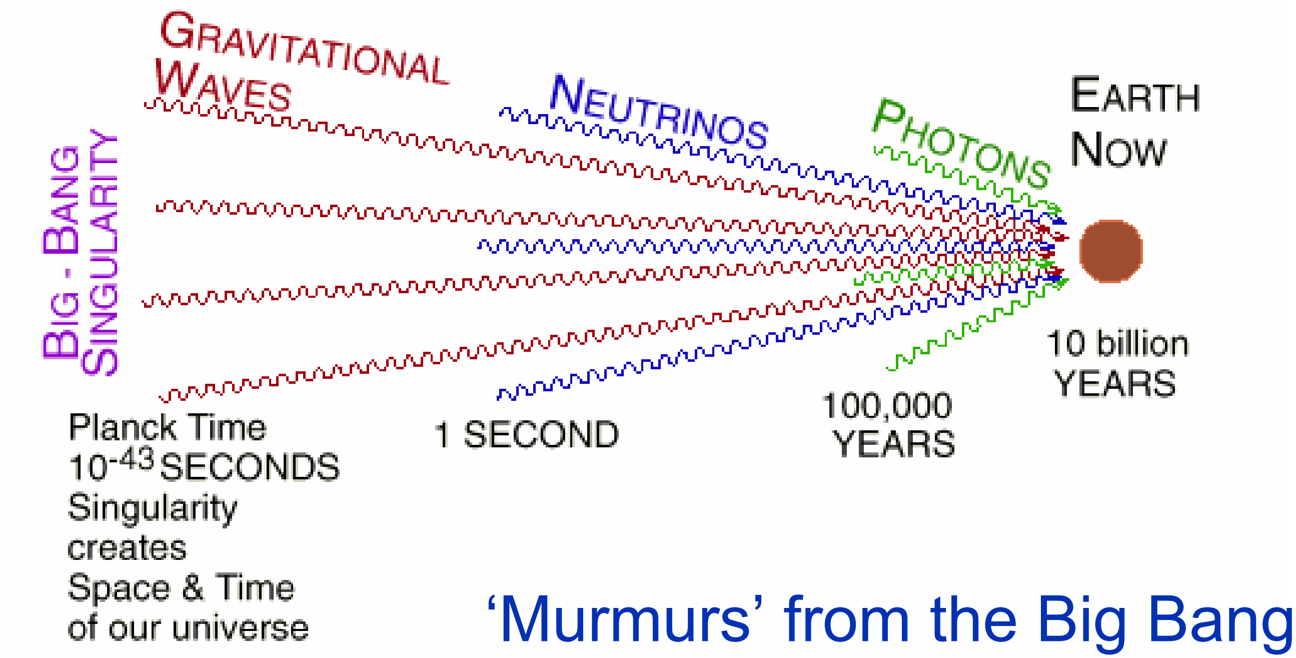
gr-qc/0308050

$h_o<1.4\times10^{-22}$ (from L1) constrains ellipticity $< 2.7\times10^{-4}$

Best previous results for PSR J1939+2134:

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

Stochastic Background



'Murmurs' from the Big Bang

Goals:

- Improved energy limit on stochastic background
- Search for background of unresolved gravitational wave bursts

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:
  - » Break data into (2-detector coincident) 900-second stretches
  - » Break each of these into 90-second stretches
  - » Window, zero pad, FFT, estimate power spectrum for 900 sec
  - » Remove ¼ Hz bins at n•16 Hz, n•60 Hz, 168.25 Hz, 168.5 Hz, 250 Hz
  - » Compute cross-correlation statistics with filter optimal for $\Omega_{GW}(f) = \Omega_0$
  - » Extensive statistical analysis to set 90% confidence upper limit

Preliminary Limits from the 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 (bars): $\Omega_{GW}(907Hz) < 60$

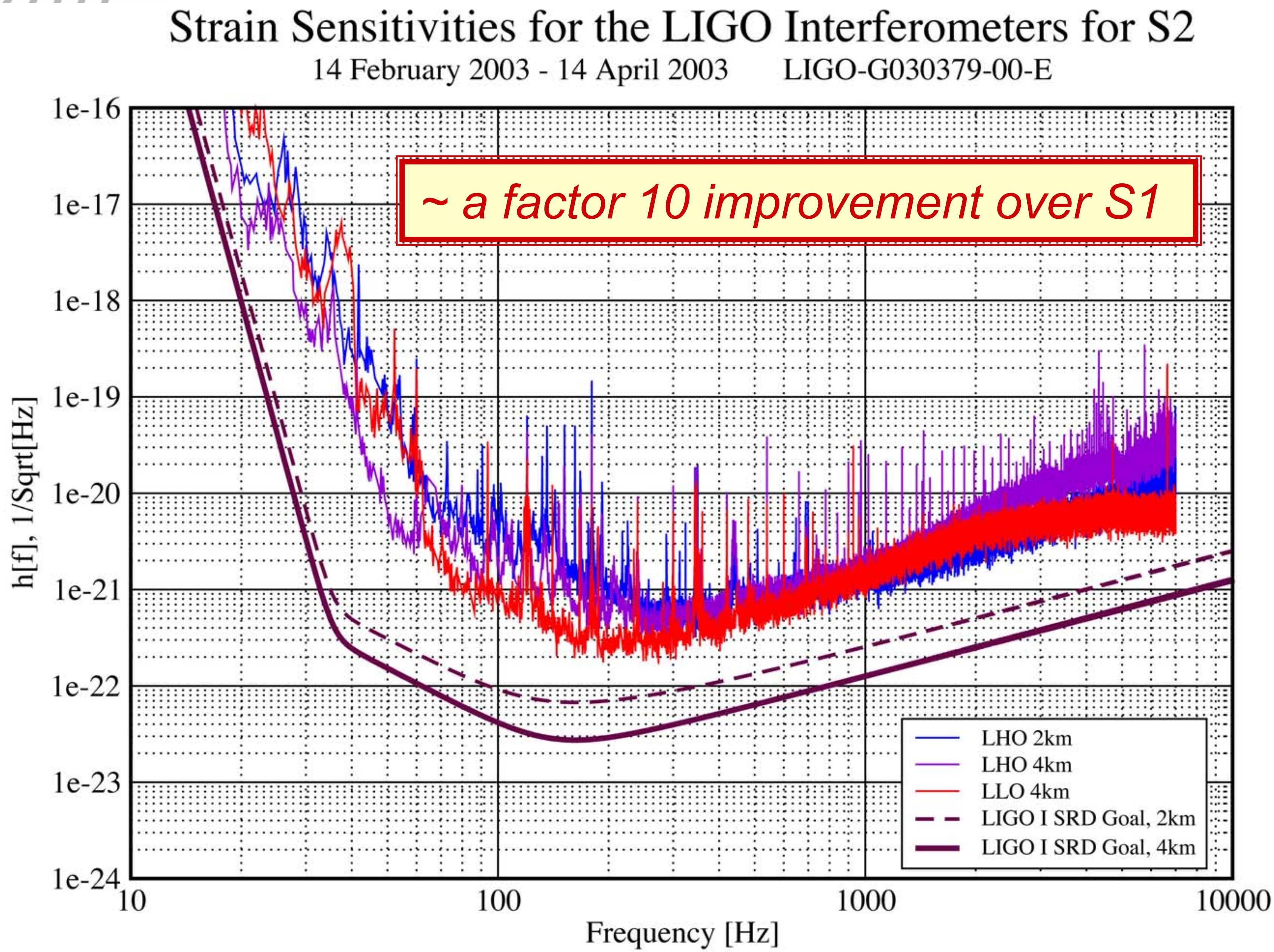
Second Science Run (S2)

February 14 – April 14 2003 (~1400 hours)

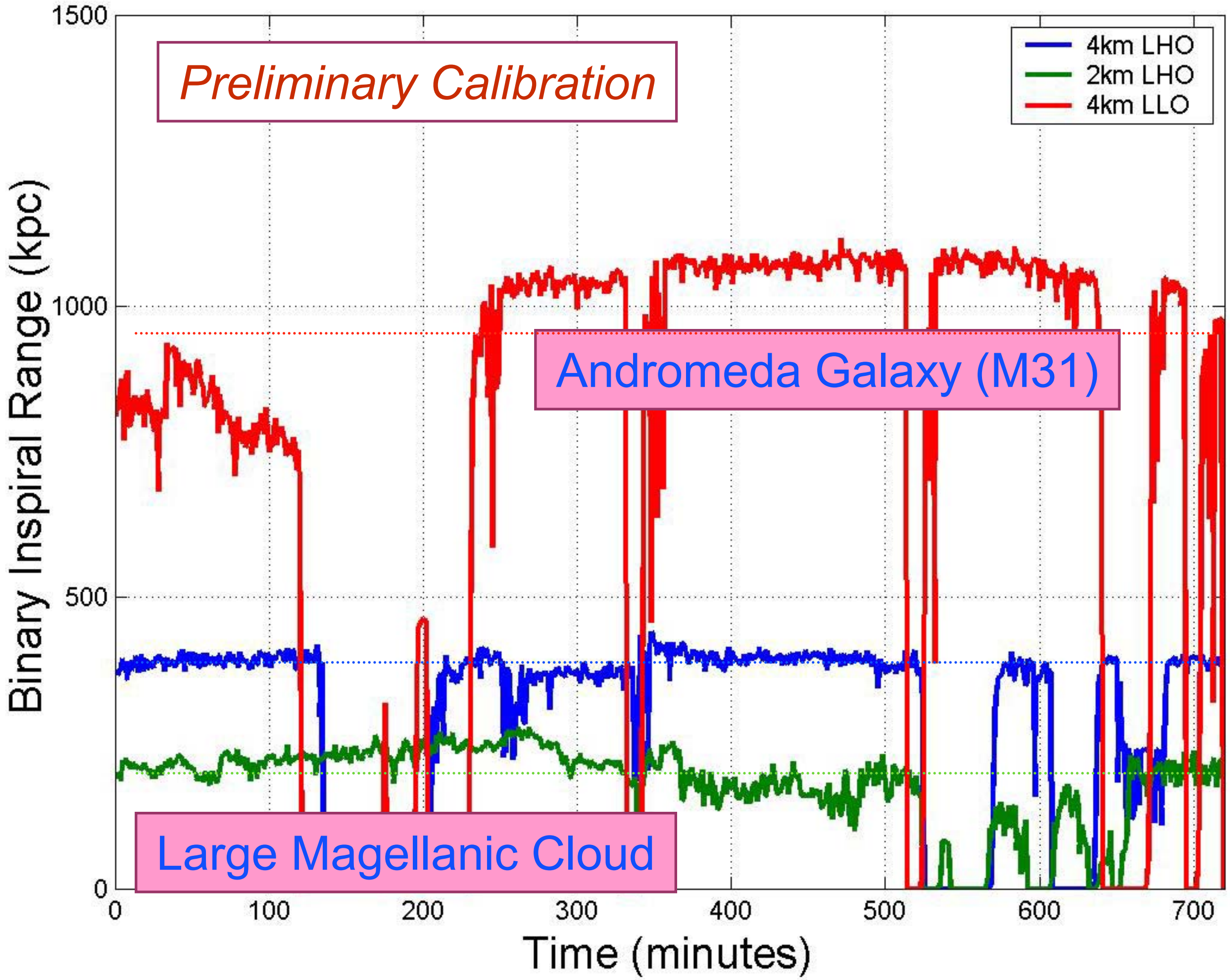
- Three LIGO interferometers and TAMA (Japan)
- Duty cycle similar to S1
  - » Increased sensitivity did not degrade operation
  - » Longest locked stretch ~ 66 hours (LHO-4K)

Improvements since S1:

- Digital suspensions installed on LHO-2K and LLO-4K
- Optical path improvements (structural stiffening, filters)
- More power (better alignment stability)
- Better monitor of suspended optics alignment using the main laser beam (wavefront sensing)


Strain Sensitivities for the LIGO Interferometers for S2
14 February 2003 - 14 April 2003
LIGO-G030379-00-E
~ a factor 10 improvement over S1
h[f], 1/Sqrt[Hz]
1e-16
1e-17
1e-18
1e-19
1e-20
1e-21
1e-22
1e-23
1e-24
10
100
1000
10000
Frequency [Hz]
LHO 2km
LHO 4km
LLO 4km
LIGO I SRD Goal, 2km
LIGO I SRD Goal, 4km

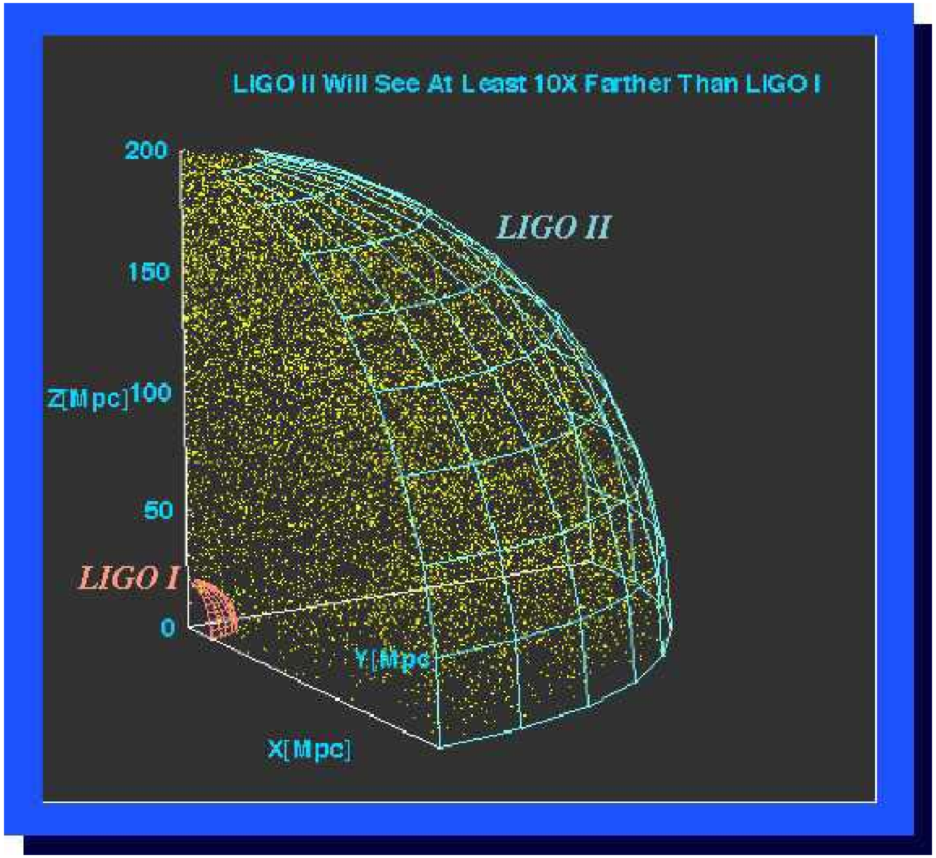
S2 Sensitivity and Stability



What's next? Advanced LIGO

- **Goals:**
  - » Quantum-noise-limited interferometer
  - » Factor of ~ 10 increase in strain sensitivity => ~ 1,000 x increase in event rates
- **Schedule:**
  - » Begin installation: 2007
  - » Begin observing: 2010

(Unconfirmed until funding requests are approved)

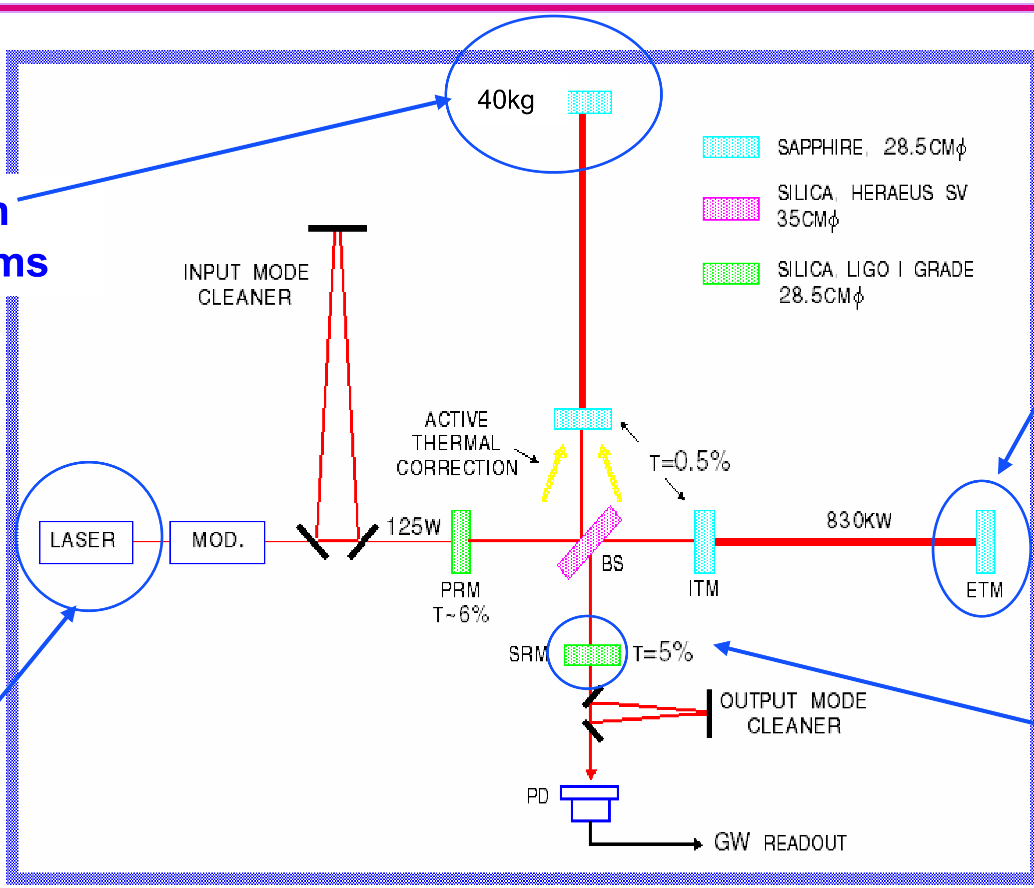


Science from the first 3 hours of Advanced LIGO observing should be comparable to 1 year of initial LIGO

Design Features of Advanced LIGO

Active vibration isolation systems

Higher power laser (10W→180W)



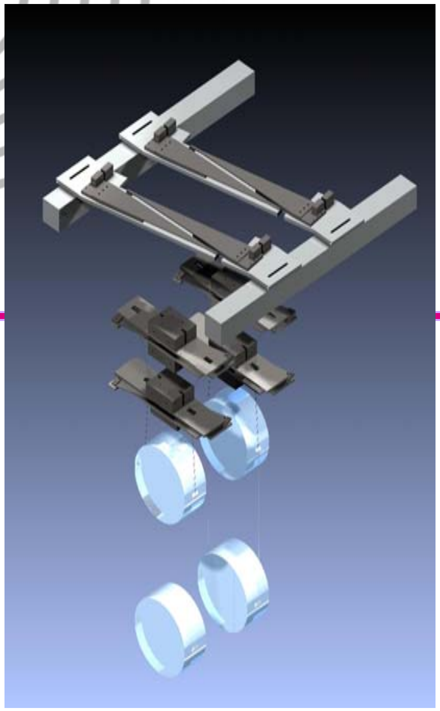
Quadruple pendulum

Sapphire optics

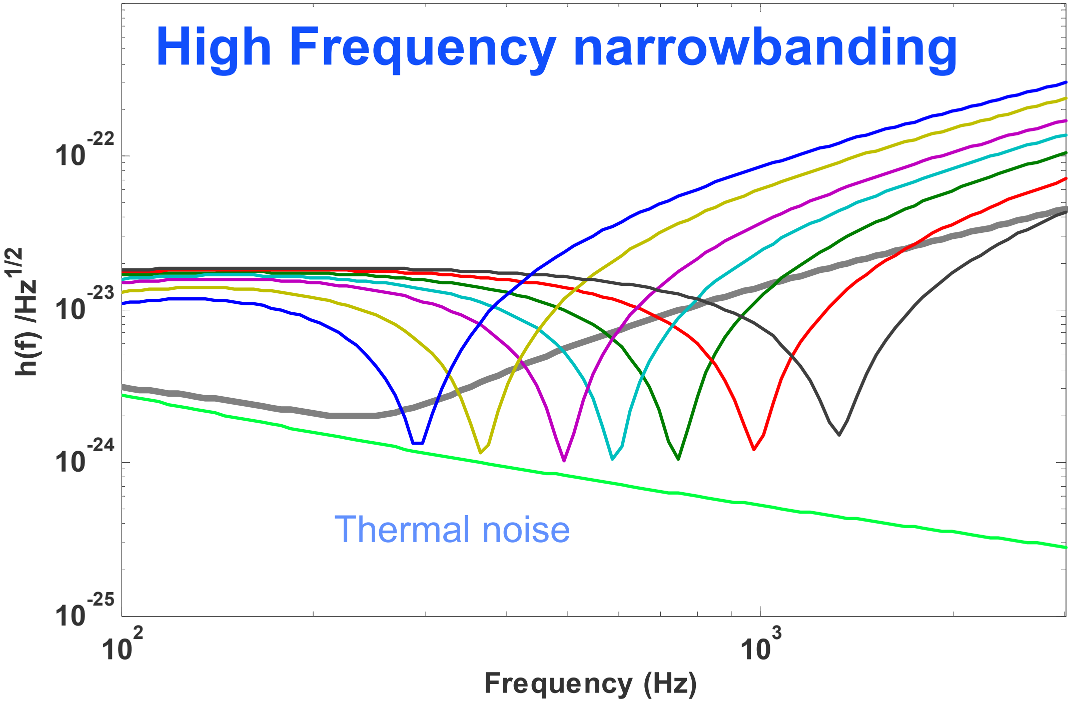
Silica suspension fibers

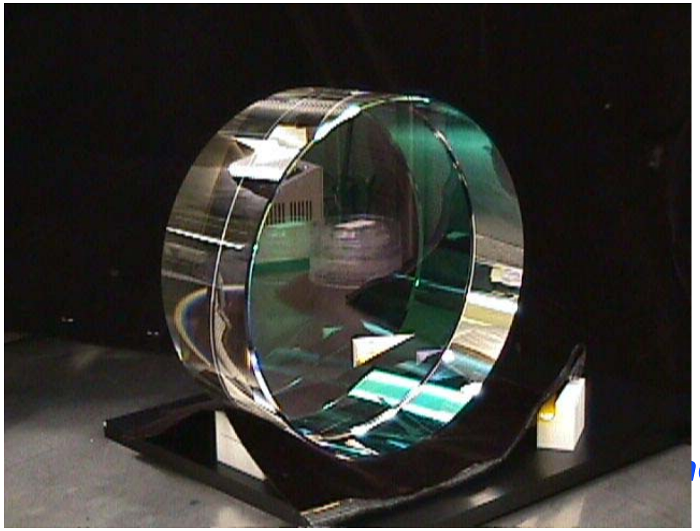
Signal recycling

Advanced LIGO



Quadruple suspensions (GEO)





40 kg sapphire test mass

Advanced vs Initial LIGO

x10 better amplitude sensitivity

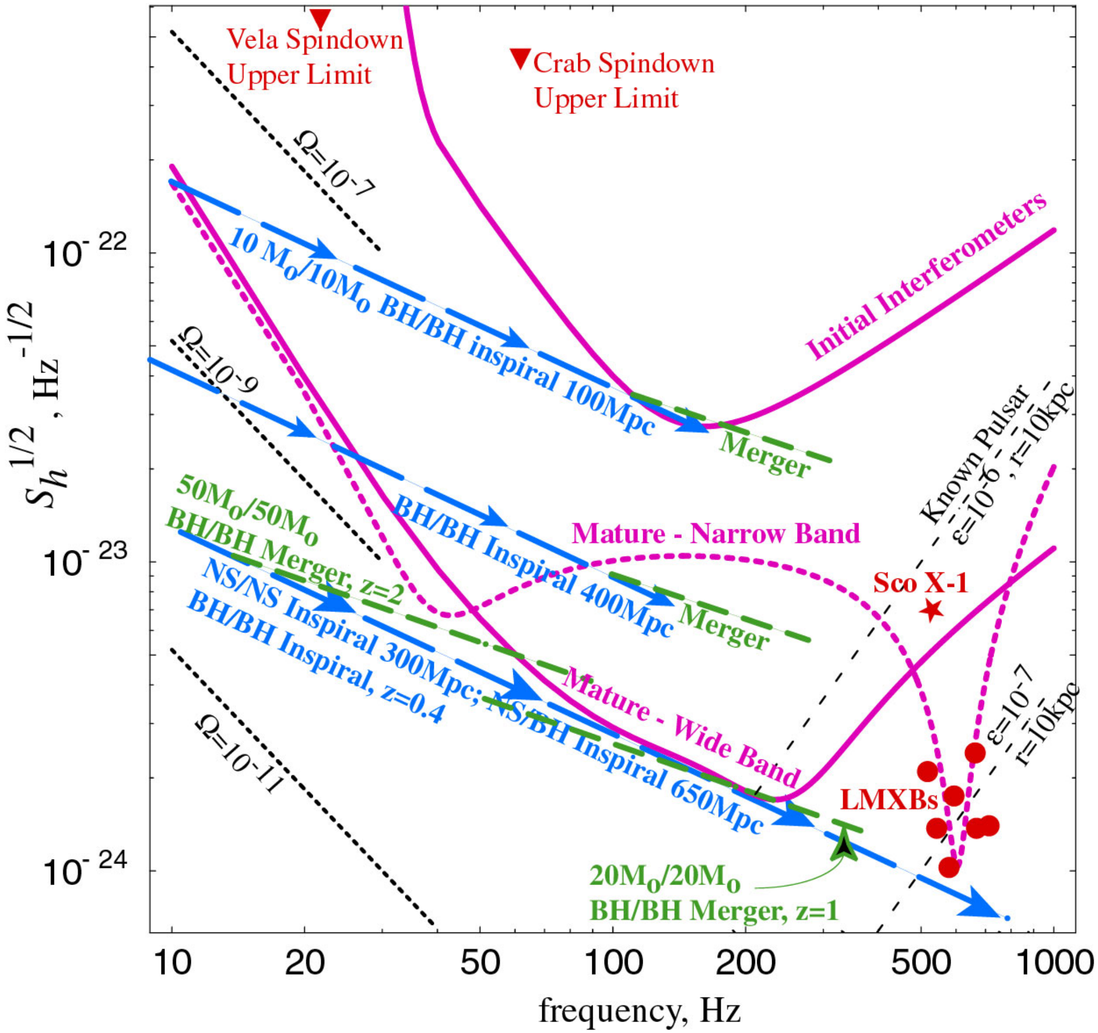
⇒ x1000 rate=(Reach)^3

x4 lower frequency bound

⇒ 40Hz → 10Hz

x100 better narrow-band at high frequencies

- **NS-NS Binaries:** ~20 Mpc → ~350 Mpc
- **BH-BH Binaries:** 10 M_o, 100 Mpc → 50 M_o, z=2
- **Known Pulsars:** ε = 3x10^{-6} → ε = 2x10^{-8}
- **Stochastic background:** Ω~3x10^{-6} → Ω~ 3x10^{-9}



Summary

- Commissioning of LIGO detectors is progressing well
  - Third Science Run (S3) will be Nov 2003 – Jan 2004
- Science analyses have begun
  - S1 results demonstrate analysis techniques, paper publications are imminent
  - S2 data (already 'in the can') x10 more sensitive and analyses currently underway
- Aiming at design performance by next year
  - Initial LIGO observation through 2006
- Advanced LIGO
  - Dramatically improves sensitivity
  - Substantial R&D effort across the LIGO Scientific Collaboration (LSC)