LIGO: Status and Prospects

Erik Katsavounidis
LIGO Laboratory
MIT
On behalf of the LIGO Scientific Collaboration

28th ICRC, August 2003, Tsukuba-Japan

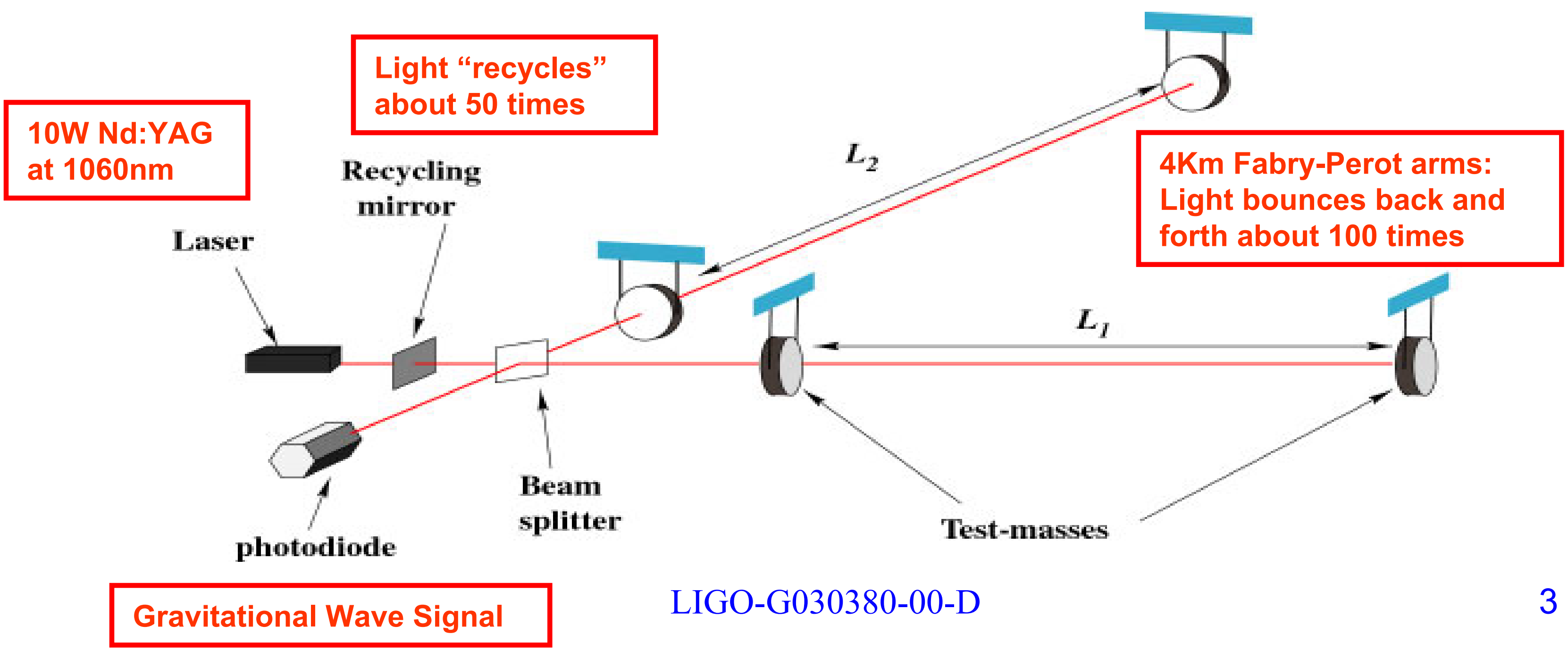
Aerial View of the LIGO Sites

LIGO Hanford Observatory

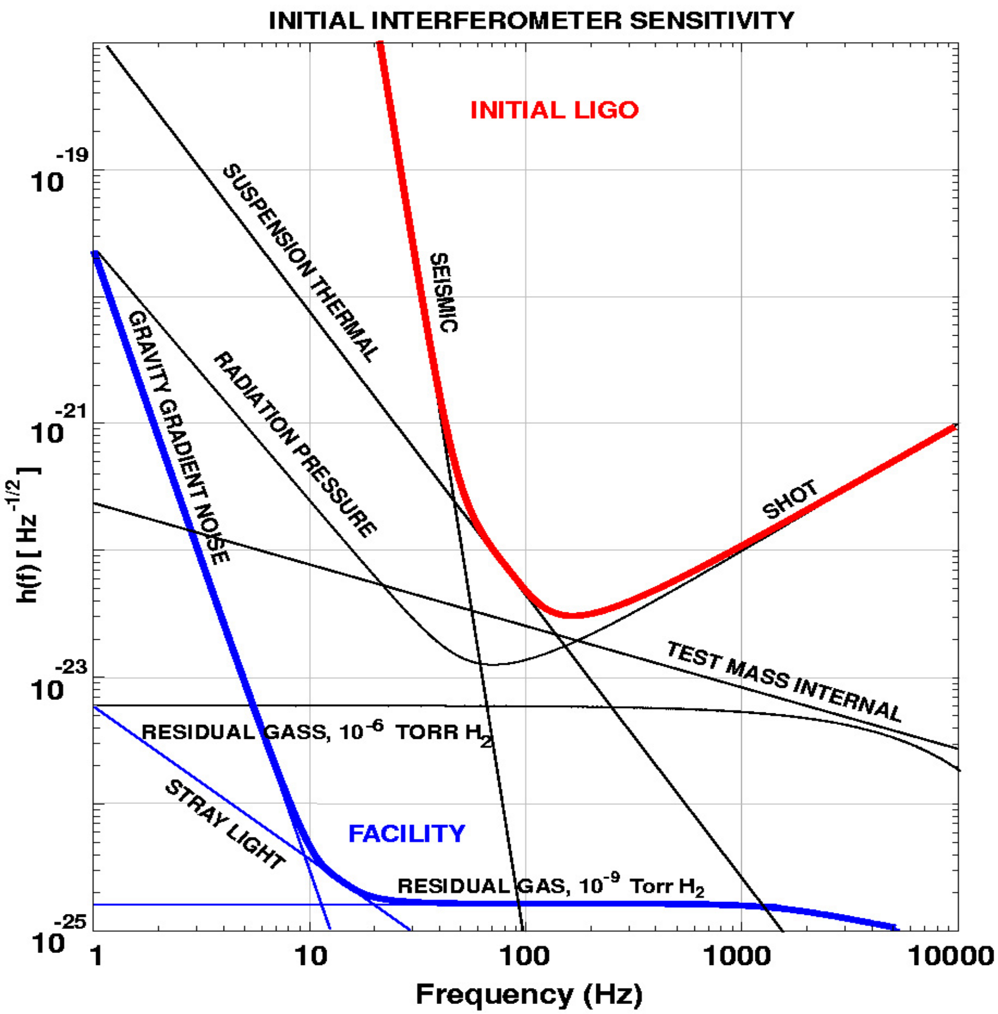
LIGO Livingston Observatory

Interferometer Concept

- Orthogonal arm lengths change in different ways as they interact with a gravitational wave
- Use Laser to measure relative lengths ΔL/L by observing the changes in interference pattern at the anti-symmetric port
- Power-recycled Michelson interferometer with Fabry-Perot arm cavities

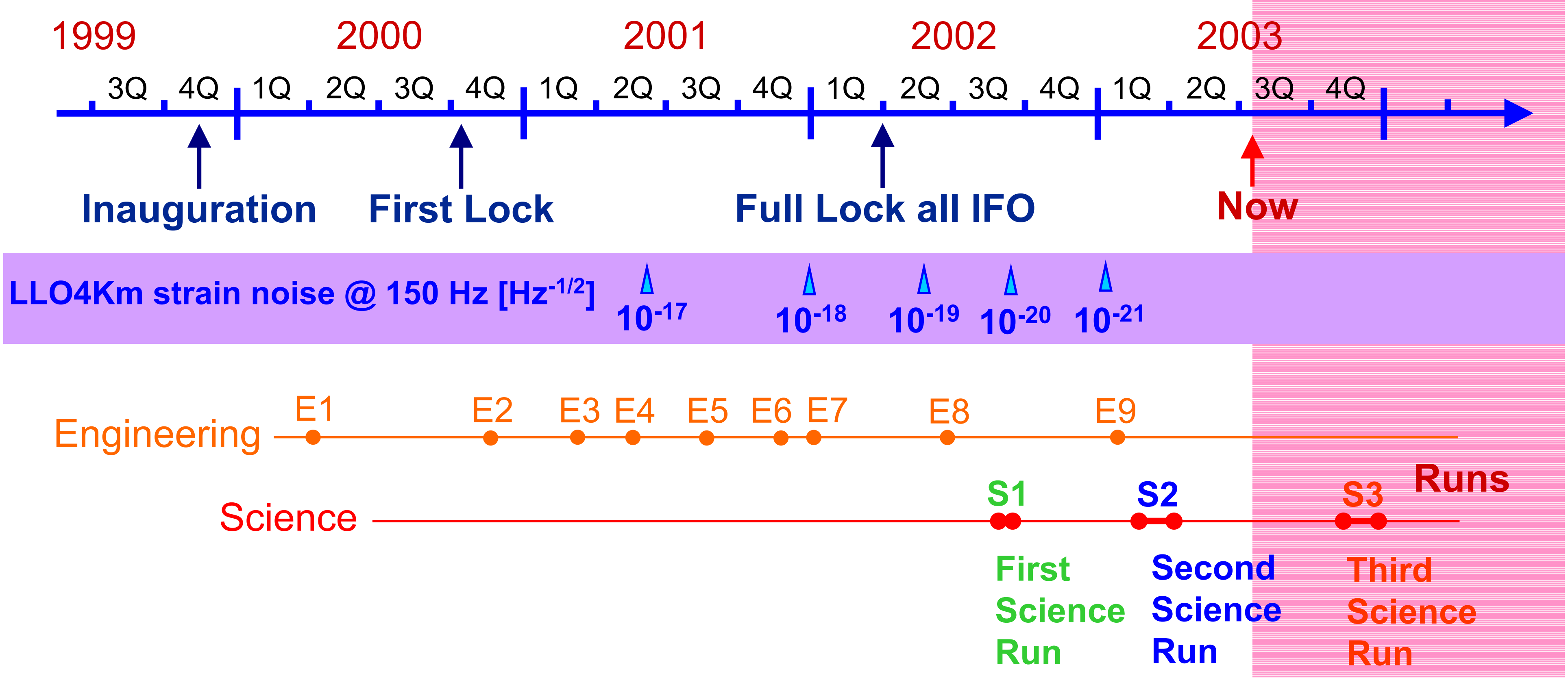


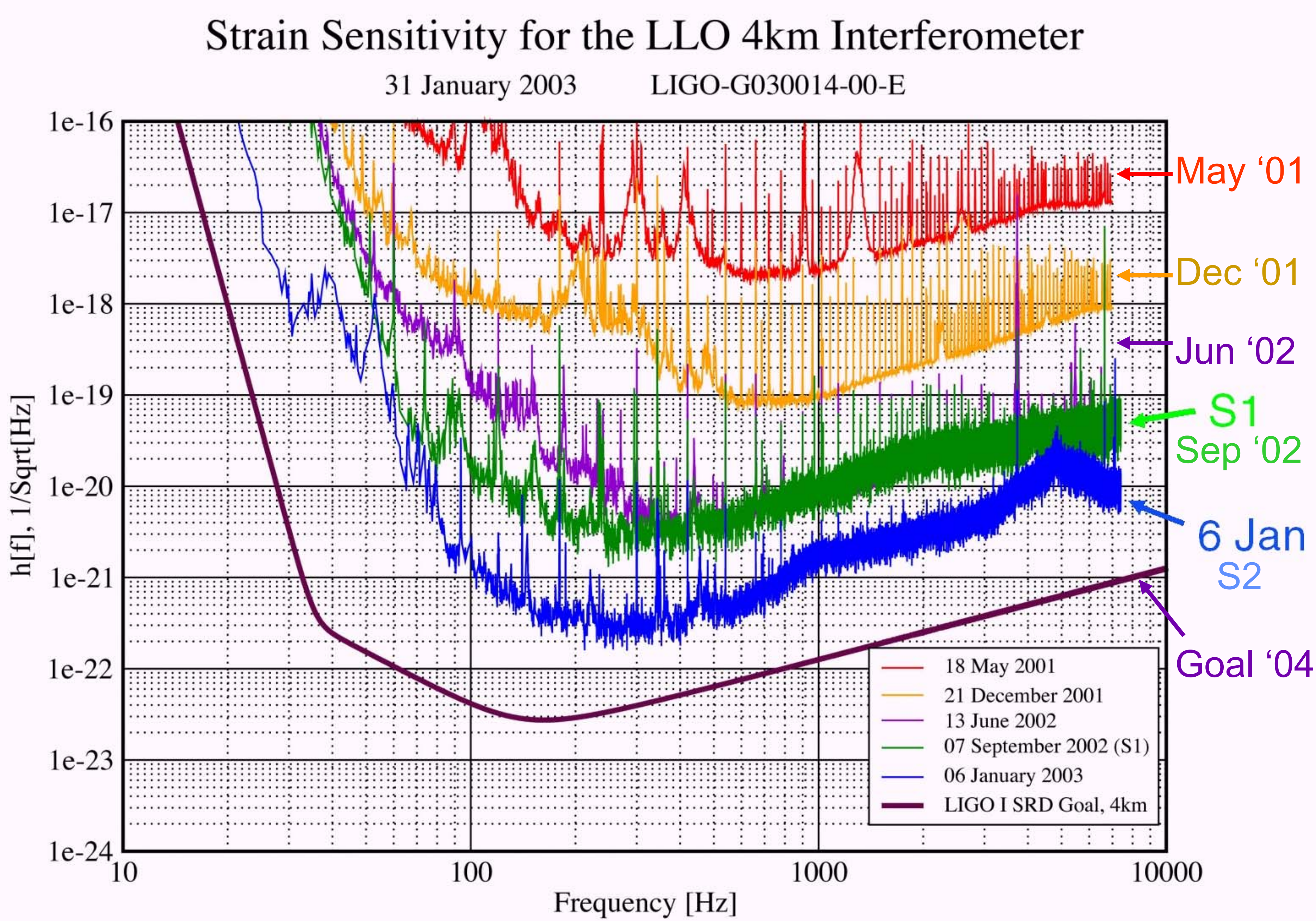
Initial LIGO Sensitivity Goal



- Strain sensitivity
  ~ $3\text{x}10^{-23}$ $1/\text{Hz}^{1/2}$
  at 150 Hz
- Displacement Noise
  - » Seismic motion
  - » Thermal Noise
  - » Radiation Pressure
- Sensing Noise
  - » Photon Shot Noise
  - » Residual Gas
- Facilities limits much lower

Commissioning Timeline





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
May '01
Dec '01
Jun '02
S1
Sep '02
6 Jan
S2
Goal '04

Commissioning Achievements

- Since last ICRC, sensitivity (at 150Hz) improved by four orders of magnitude
- All three interferometers lock routinely in power-recycled mode achieving factors of ~50 and lock durations up to 66 hours
- Great improvements in digital controls
  - >> Development of digital suspension controllers
- Partial implementation of wave-front sensing & alignment control stabilizes sensitivity to within several % over 1/2-day time scales
- Tidal and microseism compensation systems work
- First science runs (S1, S2)

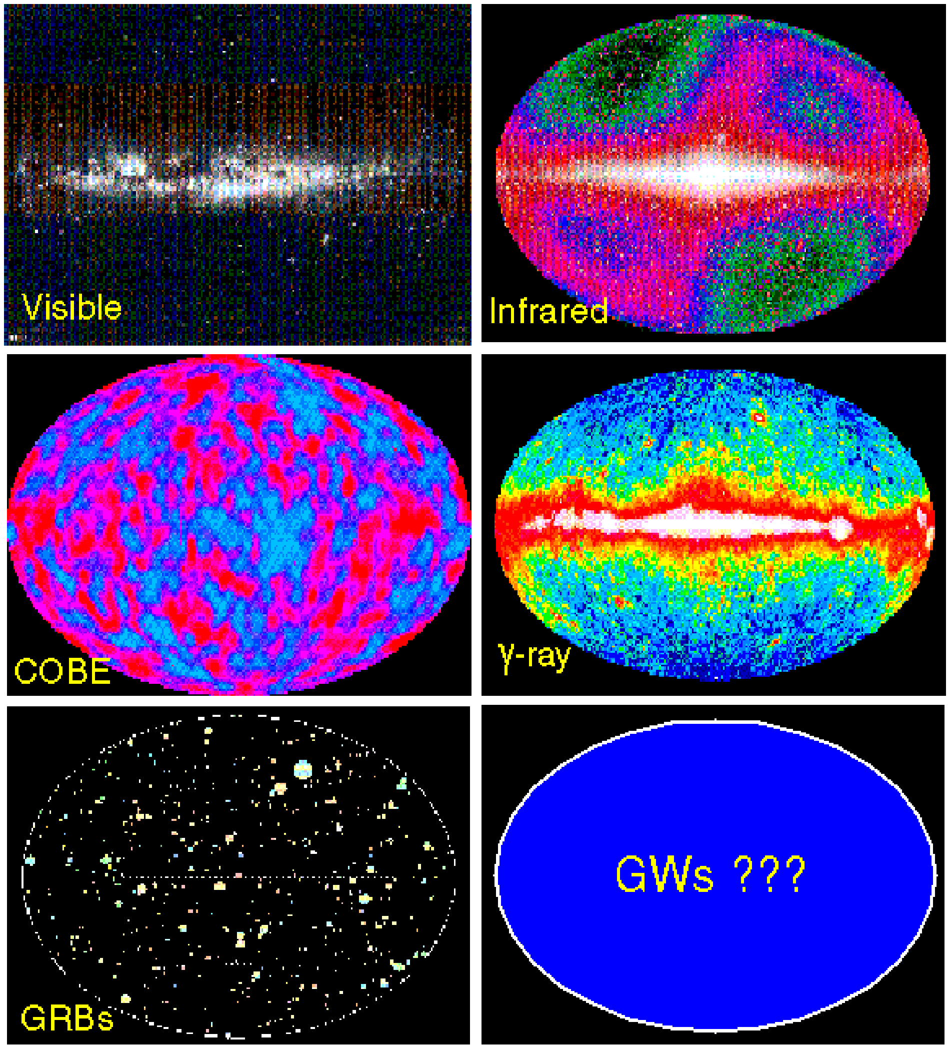
Lock Summaries for S1 and S2

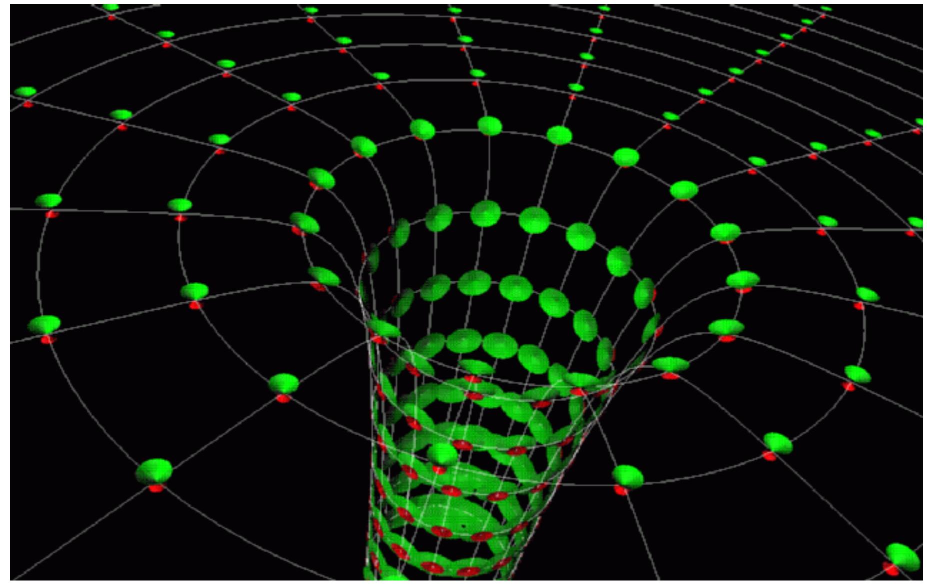
	S1 (23/8-9/9/02, 408 hours)			S2 (14/2-14/4/03,1415 hours)		
	Locked	**%**	**Longest**	**Locked**	**%**	**Longest**
H1 (2km)	235	58%	11	1040	74%	66
H2 (4km)	298	73%	8	818	58%	12
L1 (4km)	170	42%	8	523	37%	7
H1 & H2	188	46%	5	699	42%	12
H1 & L1	116	28%	6	431	31%	7
H2 & L1	131	32%	4	351	25%	5
H1 & H2 & L1	96	23%	3	312	22%	5

S1 Sensitivities: H2 < H1 < L1 (~ 3×10^{-21} $1/Hz^{1/2}$ @300Hz)

S1 Data Analyses completed – Publications in final stage of preparations

Astrophysics with LIGO: New Window on Universe





GRAVITATIONAL WAVES PROVIDE A NEW AND UNIQUE VIEW OF THE DYNAMICS OF THE UNIVERSE.

EXPECTED SOURCES:

1. **BURST & TRANSIENT SOURCES - *SUPERNOVAE***
2. **COMPACT BINARY SYSTEMS - *INSPIRALS***
3. **STOCHASTIC GRAVITATIONAL WAVE BACKGROUND**
4. **ROTATING COMPACT STARS – *“GW”PULSARS***

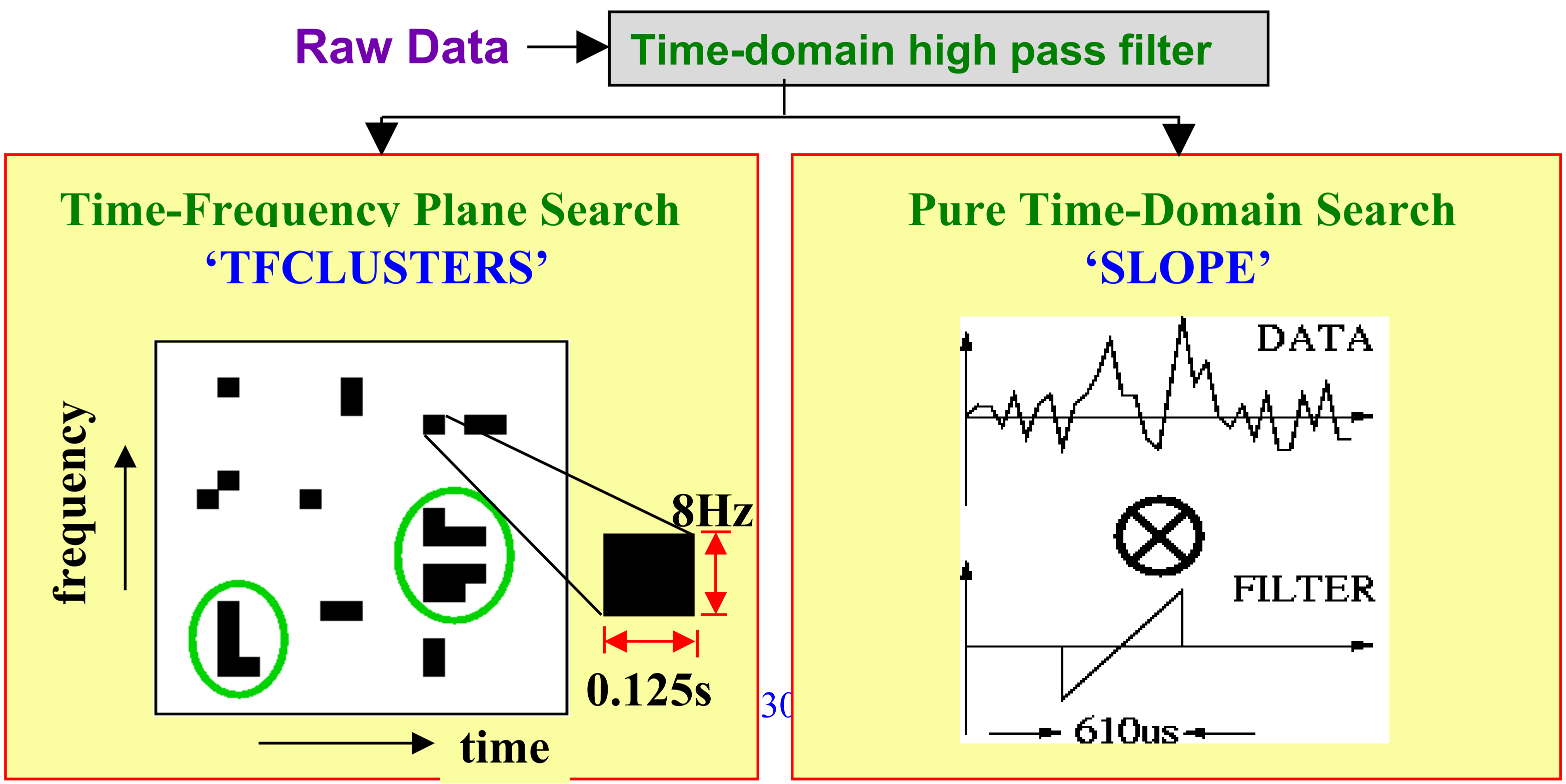
POSSIBILITY FOR THE UNEXPECTED IS VERY REAL!

Issues in Data Analysis

- Interferometric data: continuous time series (16KHz) of anti-symmetric port measures the strain of a gravitational wave.
- Additional auxiliary channels report on servo systems and instruments' environment.
- Instrument calibration at the 10% level:
  - » Response tracking: continuous fixed sinusoidals.
  - » Transfer function mapping: complete sweep sine calibration.
- S1 Analysis emphasis:
  - » Establish methodology, no sources expected.
  - » End-to-end check and validation via software and hardware injections mimicking passage of a gravitational wave.

Search for Bursts

- Sources: known and unknown phenomena emitting short transients of gravitational radiation of unknown waveform (supernovae, black hole mergers)
- Analysis goals: broad frequency band search to (a) establish a bound on their rate at the instruments, (b) interpret bound in terms of a source and population model on a rate vs. strength exclusion plot

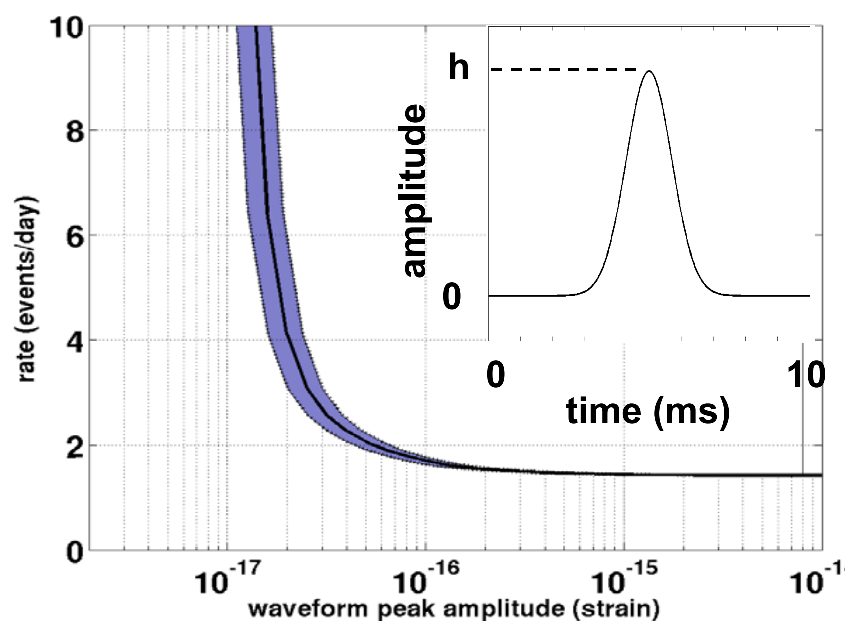


Burst Search Results

- End result of analysis pipeline: number of triple coincidence events.
- Use time-shift experiments to establish number of background events.
- Use Feldman-Cousins to set 90% confidence upper limits on rate of foreground events:
  - » TFCLUSTERS: <1.6 events/day
  - » SLOPE: <5.7 events/day
- Determine detection efficiency of the end-to-end analysis pipeline via signal injection of various morphologies.
- Assume a population of such sources uniformly distributed on a sphere around us: establish upper limit on rate of bursts as a function of their strength
- Obtain rate vs. strength plots

PRELIMINARY

Burst model: 1ms Gaussian impulses



Search for inspirals

- Sources: compact 1-3M_{sun} neutron star binaries undergoing orbital decay and coalescence
- Method: matched filtering
- S1 data used: from the two 4km interferometers
- Distance to an optimally-oriented SNR=8 source is L1: 176 kpc, H1: 46 kpc
- Analysis checked for coincidence (in time, mass) for triggers strong enough, but otherwise accepted single-interferometer events
  - » Total observation time after data selection cuts: 236 hours
- Used Monte Carlo to determine efficiency of pipeline
  - » For a model of sources in the Milky Way and Magellanic Clouds
- Upper limit set by measured detection efficiency at highest SNR event
- S1 search results:
  - » No event candidates found in coincidence
  - » 90% confidence upper limit: inspiral rate < 170/year per Milky Way equivalent galaxy

LIGO

Search for Stochastic Radiation

- Sources: early universe, many weak unresolved sources emitting gravitational waves independently so that a random type of radiation described by its spectrum (isotropic, unpolarized, stationary and Gaussian) impacts on the detectors.
- Analysis goals: constrain contribution of stochastic radiation's energy ρ_{GW} to the total energy required to close the universe $\rho_{critical}$:

$$\int_0^\infty (1/f)\,\Omega_{GW}(f)df = \frac{\rho_{GW}}{\rho_{critical}}$$

- Method: optimally filtered cross-correlation of detector pairs: L1-H1, L1-H2 and H1-H2.
- S1 search results:
  - » H1-H2 cross-correlation contaminated by environmental noise (corresponding to $\Omega_{GW} < 0$)
  - » Limit from H2-L1 (with 90% confidence): Ω_{GW} (40Hz - 314 Hz) < 23±4.6

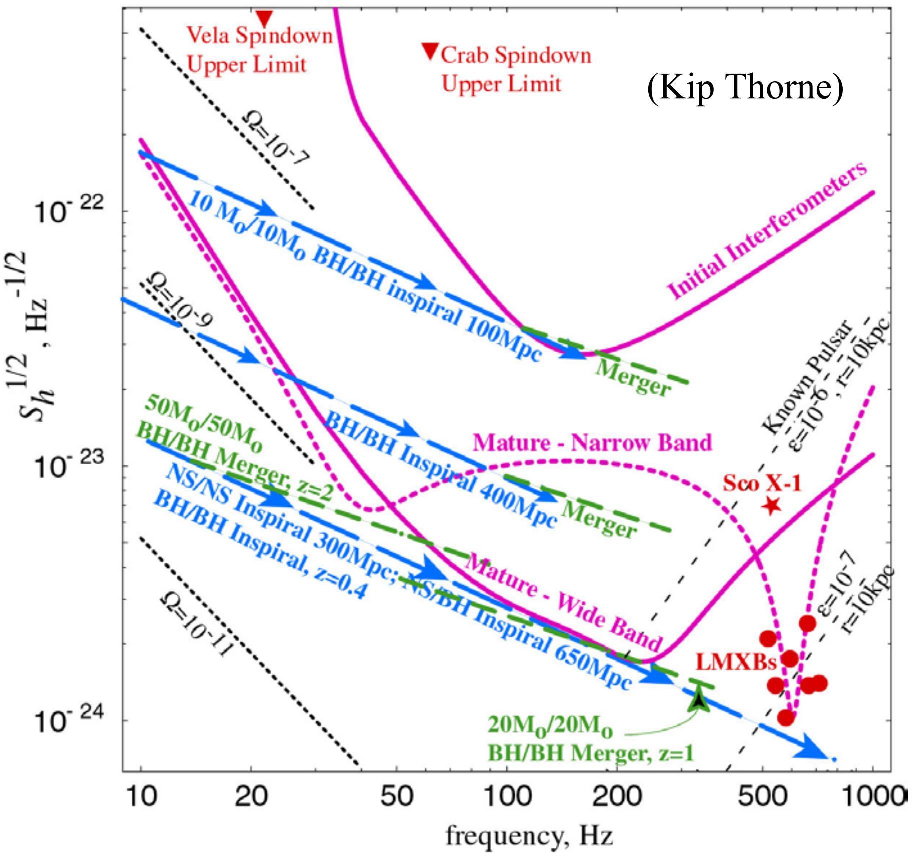
Search for Continuous Waves

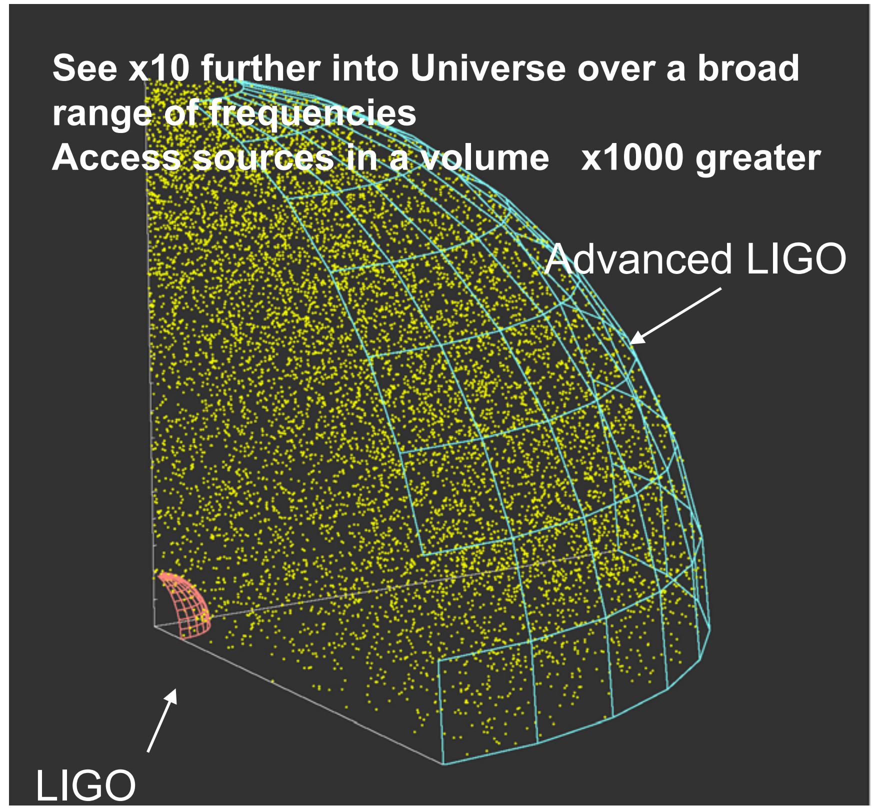
- Sources: known rotating neutron stars emitting gravitational waves due to small distortions of their shape (small ellipticity)
- Analysis goals:
  - » given the position, frequency and spin-down parameter of a known pulsar establish an upper limit on the amplitude of its continuous wave emission
- Methods:
  - » develop and test an efficient analysis pipeline that can be used for blind searches (frequency domain method)
  - » develop and test an analysis pipeline optimized for efficient "known target parameter" searches (time domain method)
  - » illustrate methods with PSR J1939+2134
- S1 search result:
  - » $h_o < 1.4 \times 10^{-22}$ (from LLO-4Km). Constrains ellipticity $< 2.7 \times 10^{-4}$

LIGO Science Has Started

- LIGO's plan of interleaved science and engineering runs is bringing the instruments to their design sensitivity while giving the opportunity for first science results
- Results close to expected, confidence that our design sensitivity is imminent and producing the targeted science results.
- Second science run ("S2") 14 Feb - 14 Apr:
  - » Sensitivity is ~10x better than S1
  - » Duration is ~ 4x longer
    - – Bursts: rate limits: 4X lower rate & 10X lower strain limit
    - – Inspirals: reach will exceed 1Mpc -- includes M31 (Andromeda)
    - – Stochastic background: limits on $W_{GW} < 10^{-2}$
    - – Periodic sources: limits on $h_{max} \sim$ few x 10^{-23} (e ~ few x 10^{-6} @ 3.6 kpc)
- Ground based interferometers are collaborating internationally:
  - » LIGO and GEO (UK/Germany) during "S1"
  - » LIGO and TAMA (Japan) during "S2"

What's next? Advanced LIGO

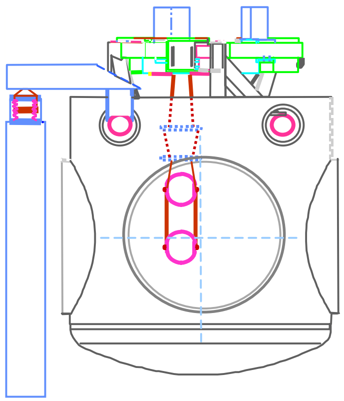




- Initial LIGO observation 2002 – 2003, at design sensitivity 2004-2006
  - » One complete year of data by 2006
  - » A few hours of observing with Advanced LIGO equivalent to 1 year observation with initial LIGO
- Start installation in 2007 with coincident observations expected in 2010

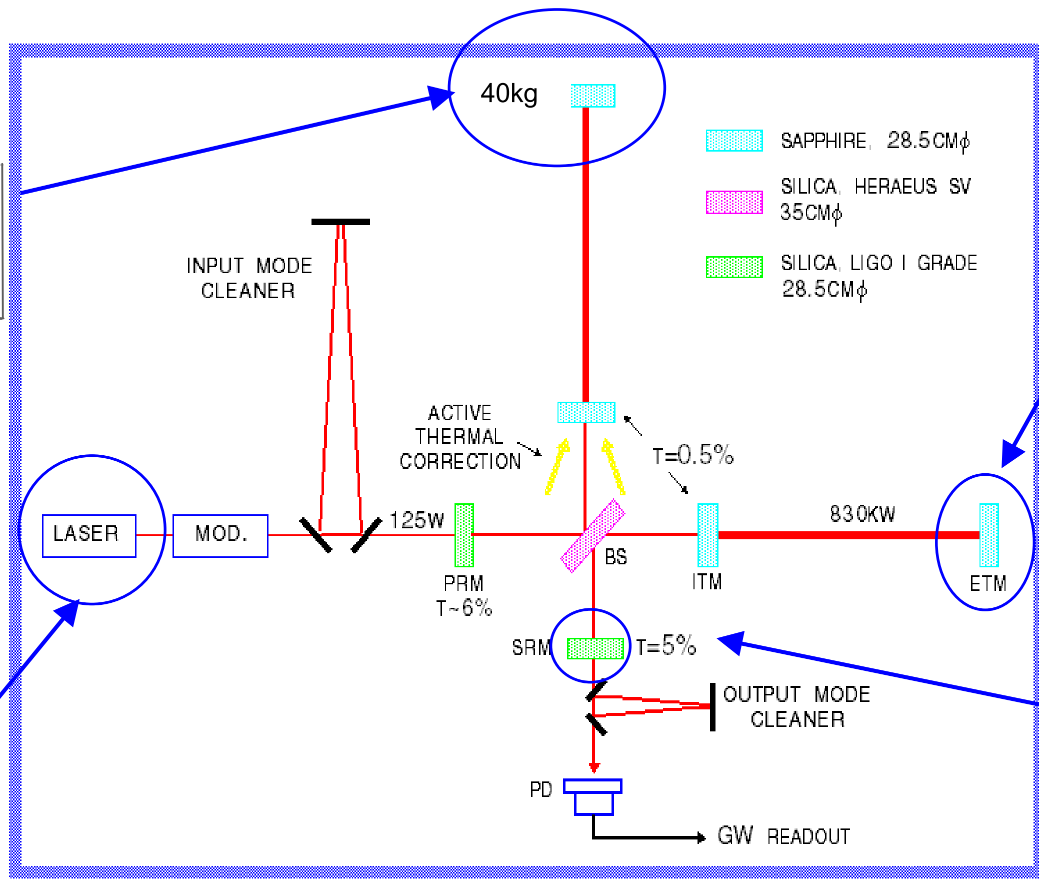
Design Features of Advanced LIGO

Enhanced Systems: **test masses, suspensions, seismic isolation, laser**

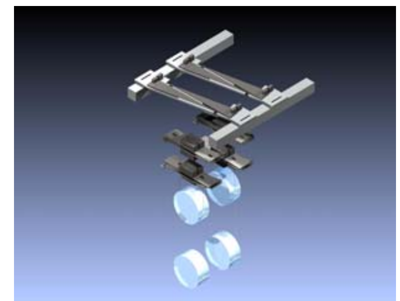


Active vibration isolation systems

High power laser (180W)



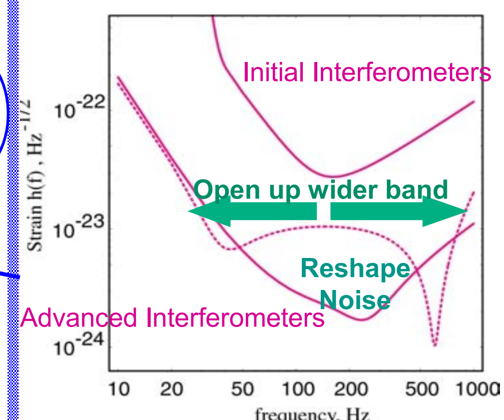
LIGO-G030380-00-D



Quadruple pendulum

Sapphire optics

Silica suspension fibers



Advanced interferometry

Signal recycling

Summary

- Commissioning of LIGO detectors is progressing well
  - » Third Science run 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' are x10 more sensitive and analyses currently underway
- Design performance both in terms of sensitivity and duty cycle should be achieved within 2004
  - » observation at design sensitivity through 2006
- Advanced LIGO
  - » Dramatically improves sensitivity
  - » Substantial progress in R&D across the LIGO Scientific Collaboration (LSC)
  - » Move from gravitational wave detection to gravitational wave astronomy