



Laser Interferometer Gravitational Wave Observatory

LIGO Commissioning and Initial Science Runs: Current Status

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on behalf of the LIGO Scientific Collaboration

<http://www.ligo.org>



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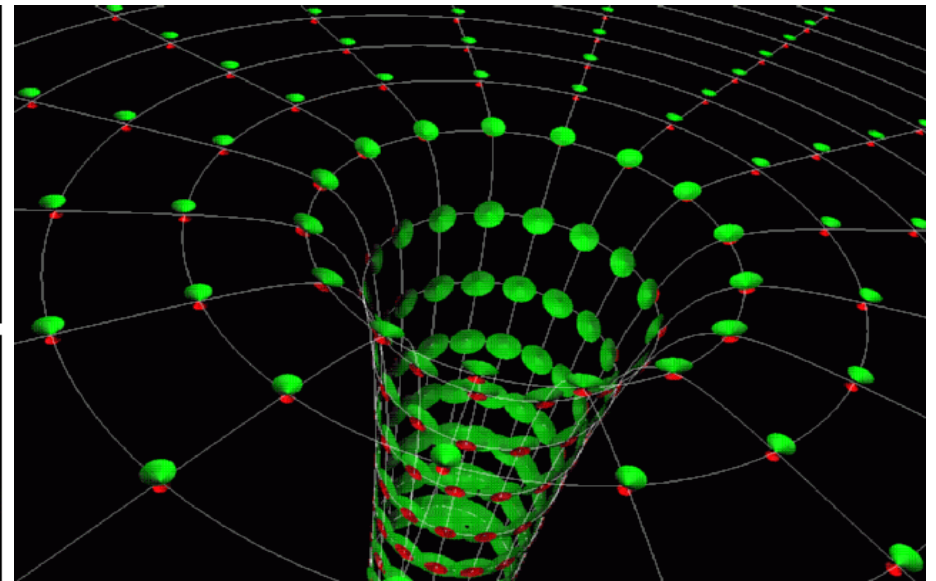
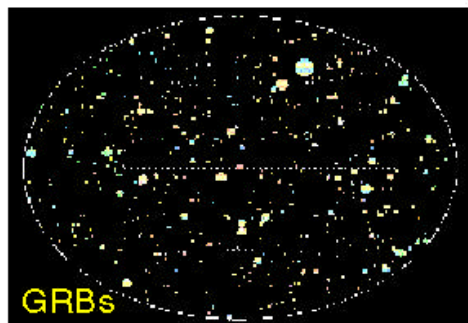
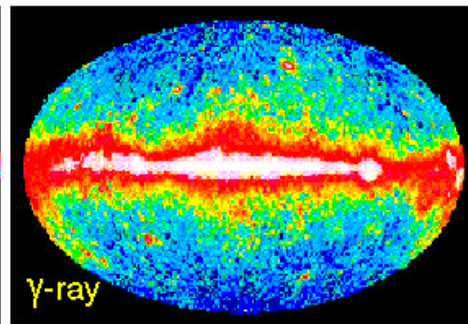
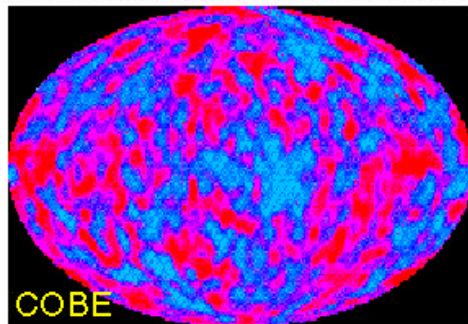
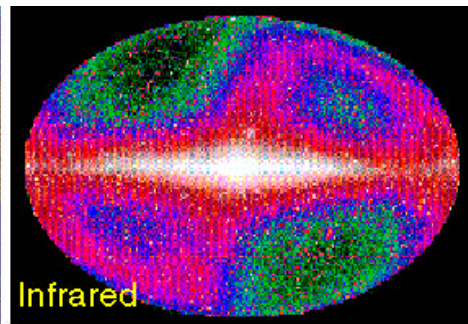
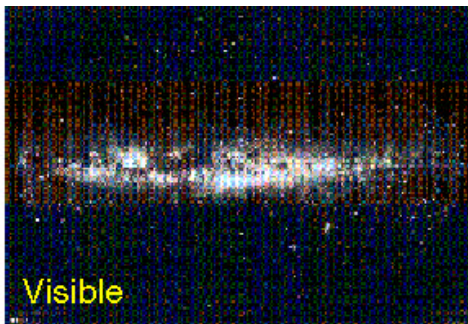


Outline

- **Background:** gravity waves and interferometers
- **Commissioning:** some commissioning benchmarks, three specific commissioning examples
- **S1 science results:** science results from searches for different gravity wave sources



New Window on Universe



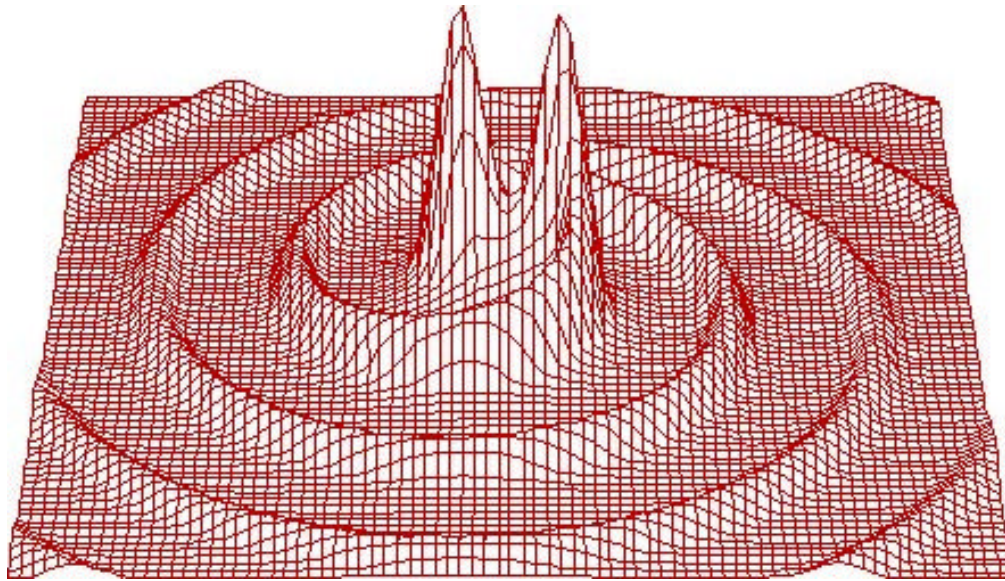
GRAVITATIONAL WAVES PROVIDE A NEW AND UNIQUE VIEW OF THE DYNAMICS OF THE UNIVERSE.

EXPECTED SOURCES:

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

POSSIBILITY FOR THE UNEXPECTED IS VERY REAL!

Einstein's Theory of Gravitation

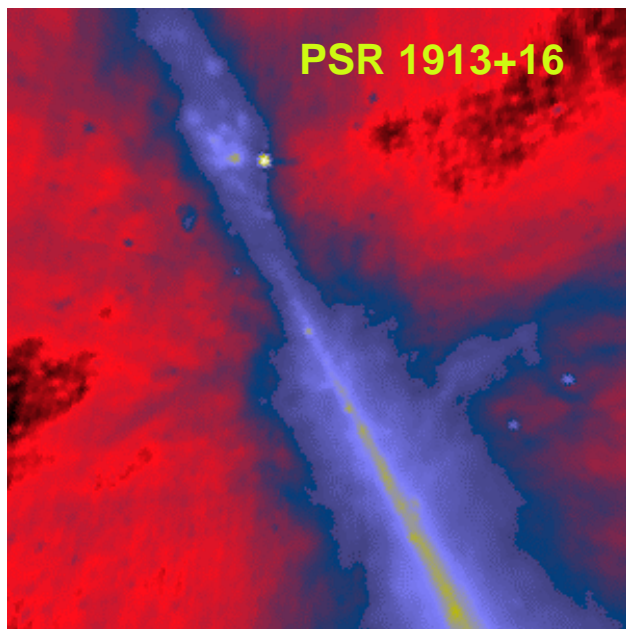


*gravitational radiation
binary inspiral
of
compact objects*

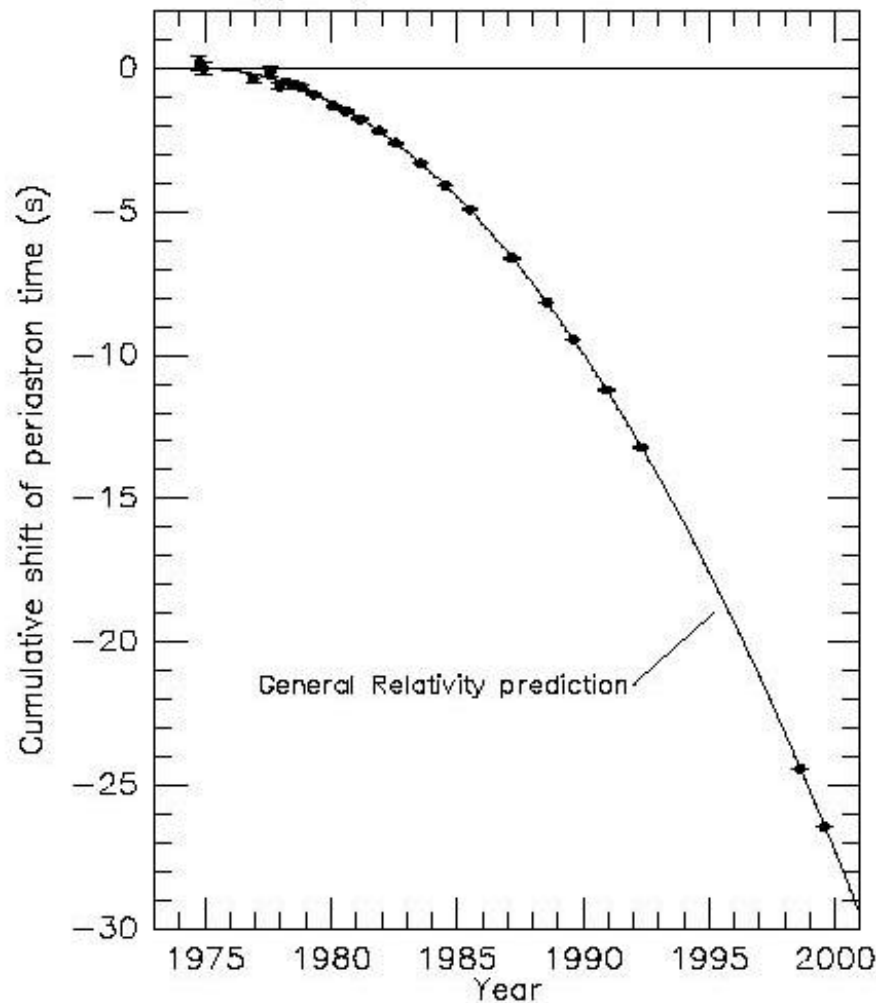
- a necessary consequence of Special Relativity with its finite speed for information transfer
- gravitational waves come from the acceleration of masses and propagate away from their sources as a space-time warpage at the speed of light
- gravitational wave strain:

$$h = \frac{\Delta L}{L}$$

“Indirect” detection of gravitational waves

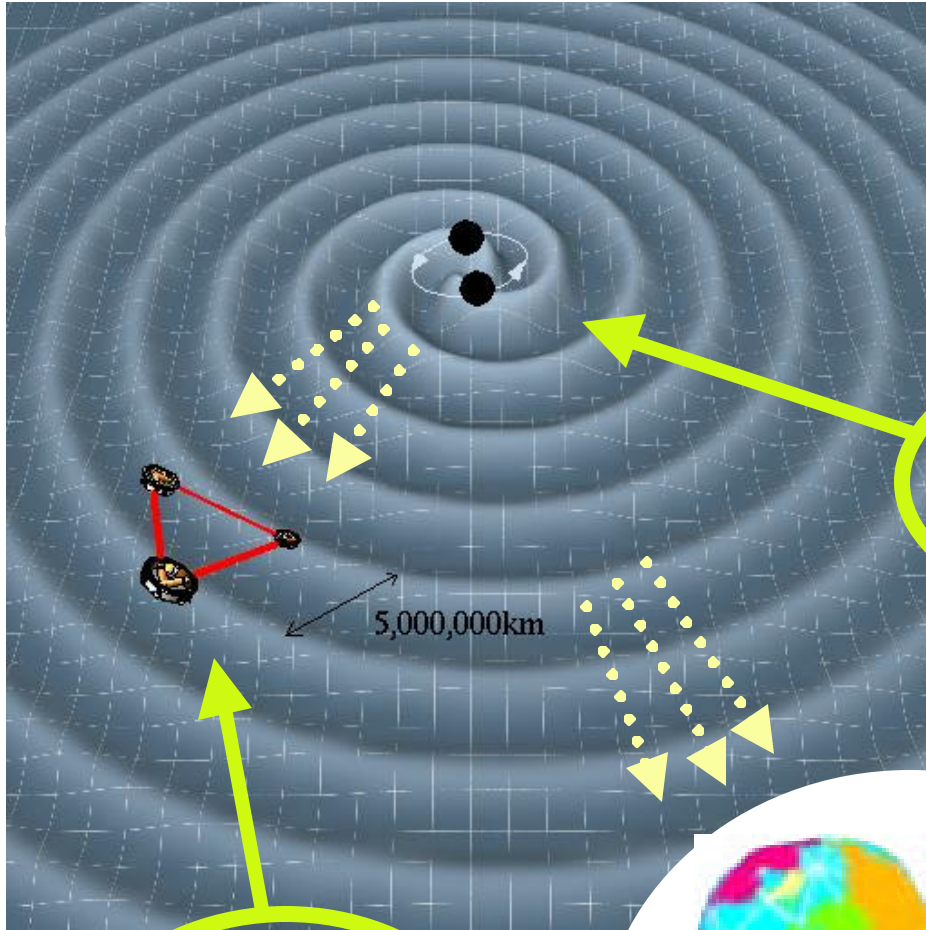


Comparison between observations of the binary pulsar PSR1913+16, and the prediction of general relativity based on loss of orbital energy via gravitational waves



From J. H. Taylor and J. M. Weisberg, unpublished (2000)

Direct Detection

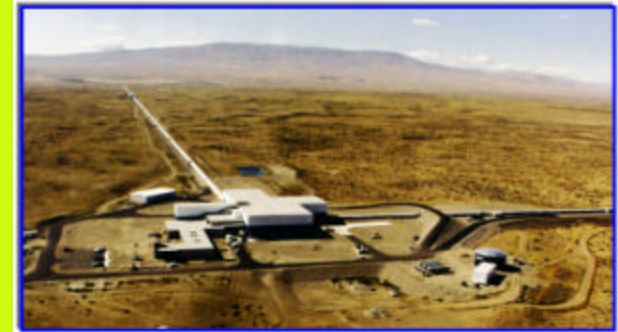


**Gravitational Wave
Astrophysical Source**

**Detectors
in space
LISA**



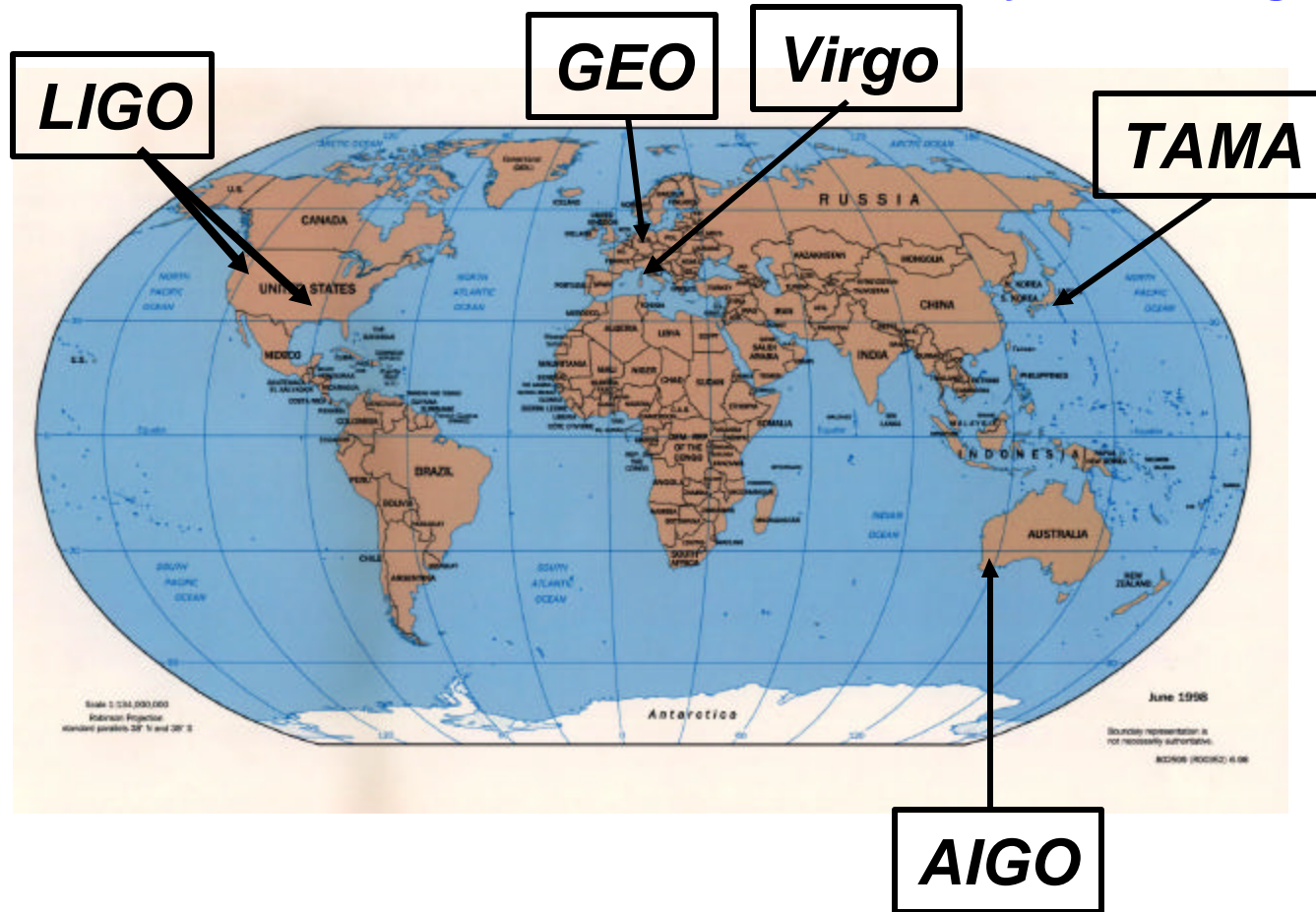
**Terrestrial detectors
LIGO, GEO, TAMA, Virgo, ALIGO**





An International Network of Interferometers

Simultaneously detect signal (within msec)



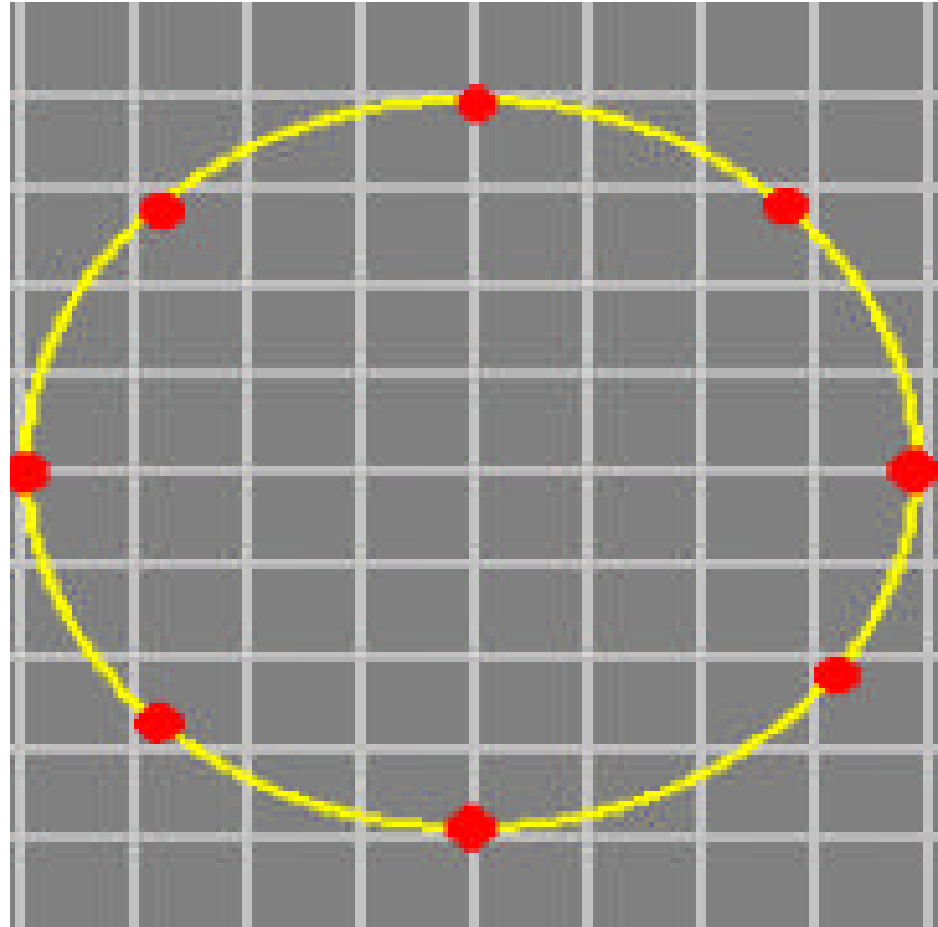
detection
confidence

locate the
sources

decompose the
polarization of
gravitational
waves

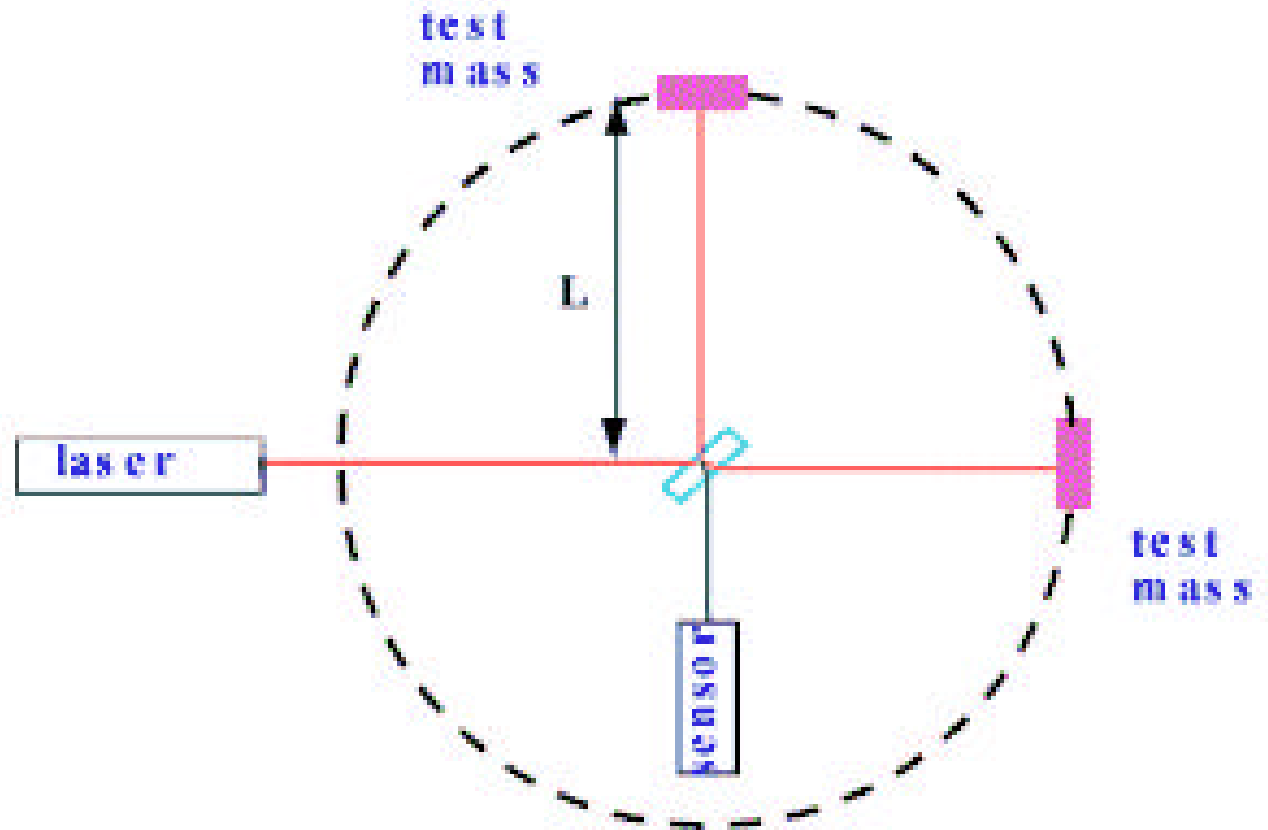
Detecting a passing wave

Free masses



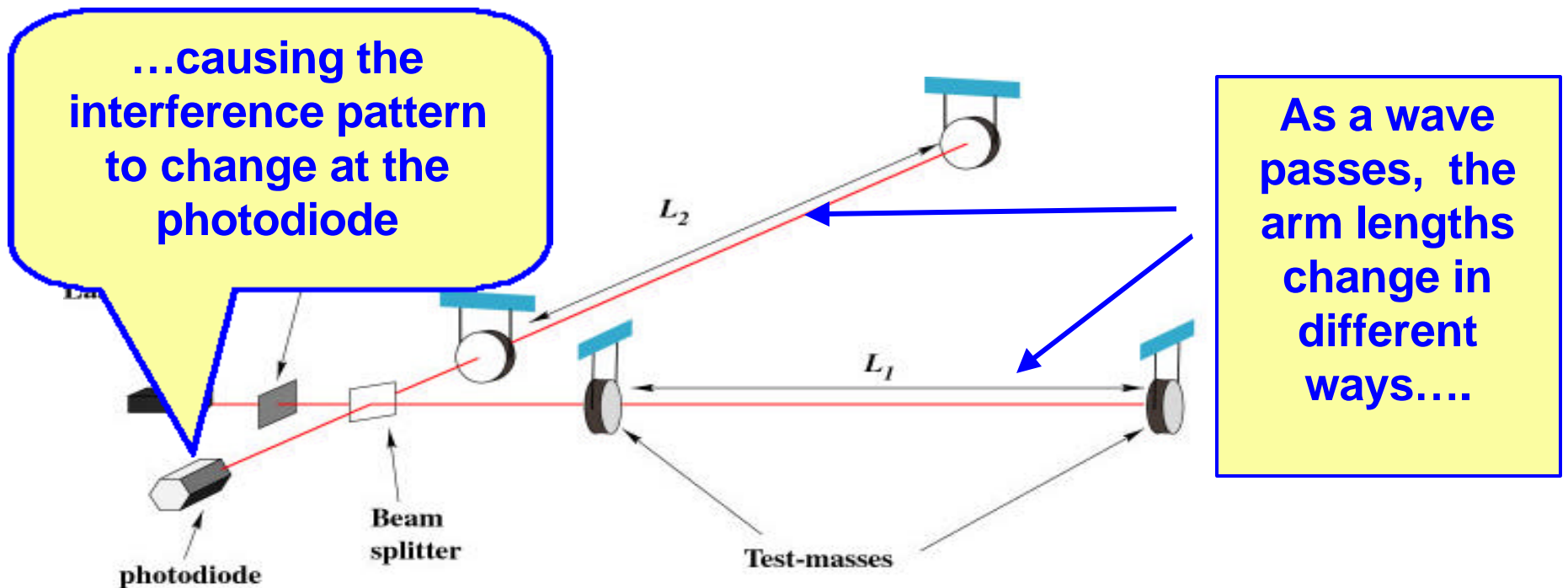
Detecting a passing wave

Interferometer



Interferometer Concept

- Laser used to measure relative lengths of two orthogonal arms
 - Arms in LIGO are 4km
 - Measure *difference in length to one part in 10^{21} or 10^{-18} meters*



LIGO sites

LIGO (Washington)

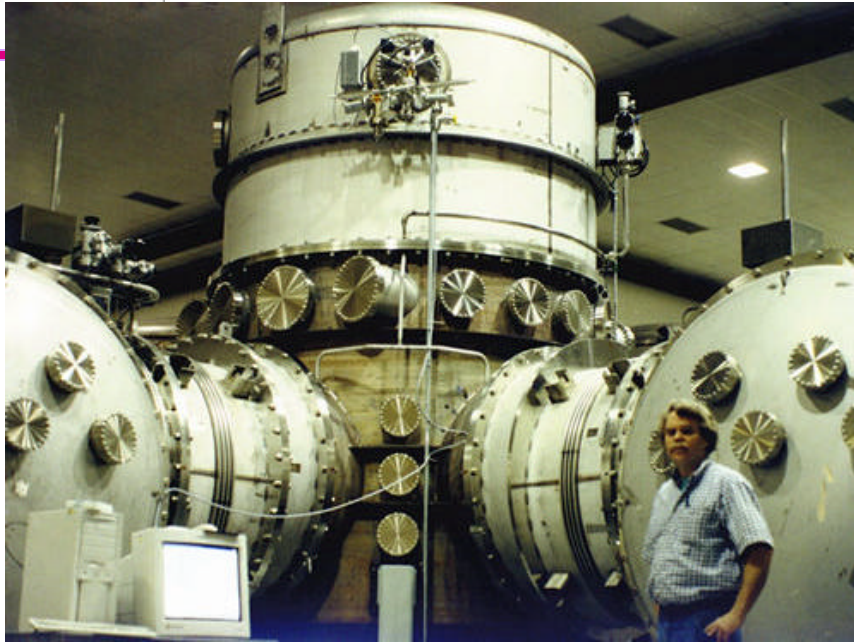


(“The evergreen state”)

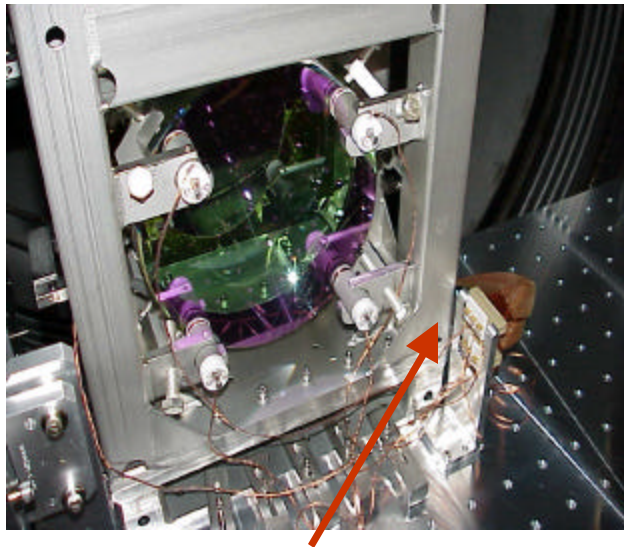
LIGO (Louisiana)



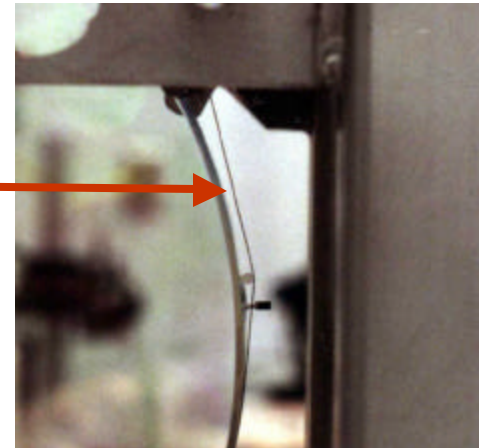
Some site details



Core Optics Suspension and Control



*Optics
suspended as
simple
pendulums*



*Shadow sensors & coil actuators
provide
damping and control forces*

*Mirror is balanced on 30 micron
diameter wire to 1/100th degree of arc*



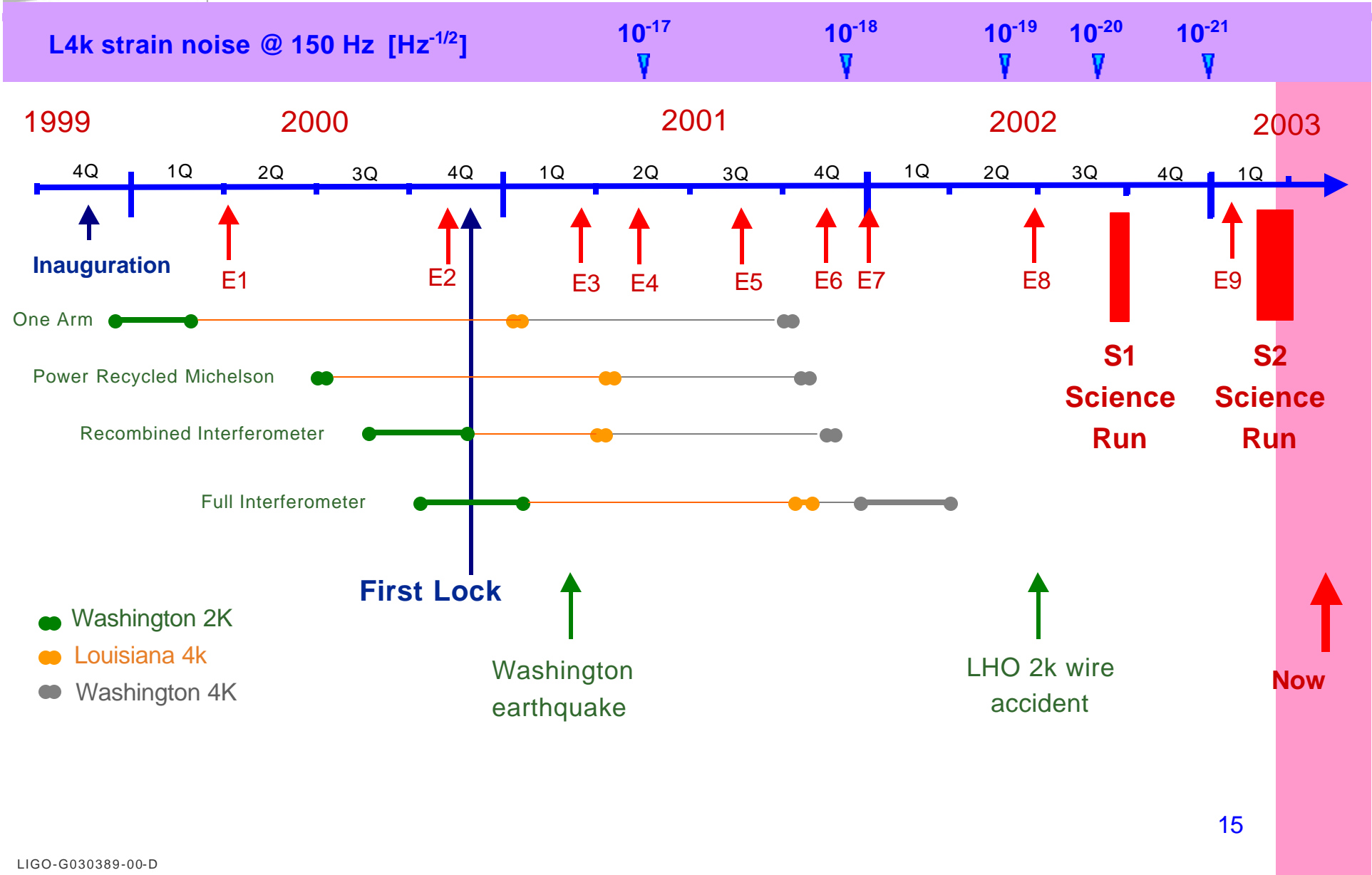


Some Commissioning Challenges

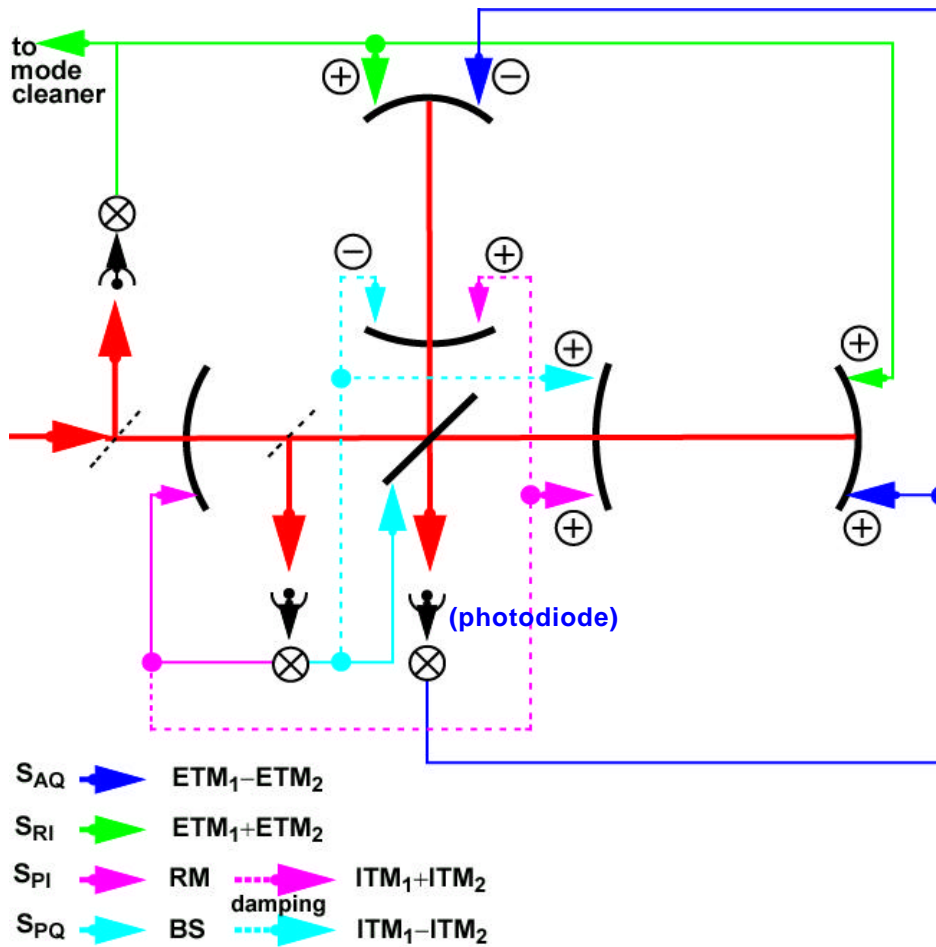
- Understand displacement fluctuations of 4-km arms at the millifermi level ($1/1000^{\text{th}}$ of a proton diameter)
- Control arm lengths to 10^{-13} meters RMS
- Detect optical phase changes of $\sim 10^{-10}$ radians
- Hold mirror alignments to 10^{-8} radians



Commissioning History



Interferometer Length Control System



- Multiple Input / Multiple Output
- Three tightly coupled cavities
- Ill-conditioned (off-diagonal) plant matrix
- Highly nonlinear response over most of phase space
- Transition to stable, linear regime takes plant through singularity
- Employs adaptive control system that evaluates plant evolution and reconfigures feedback paths and gains during lock acquisition



Tidal Compensation Data

common mode

differential mode

Tidal evaluation
on 21-hour locked
section of S1 data

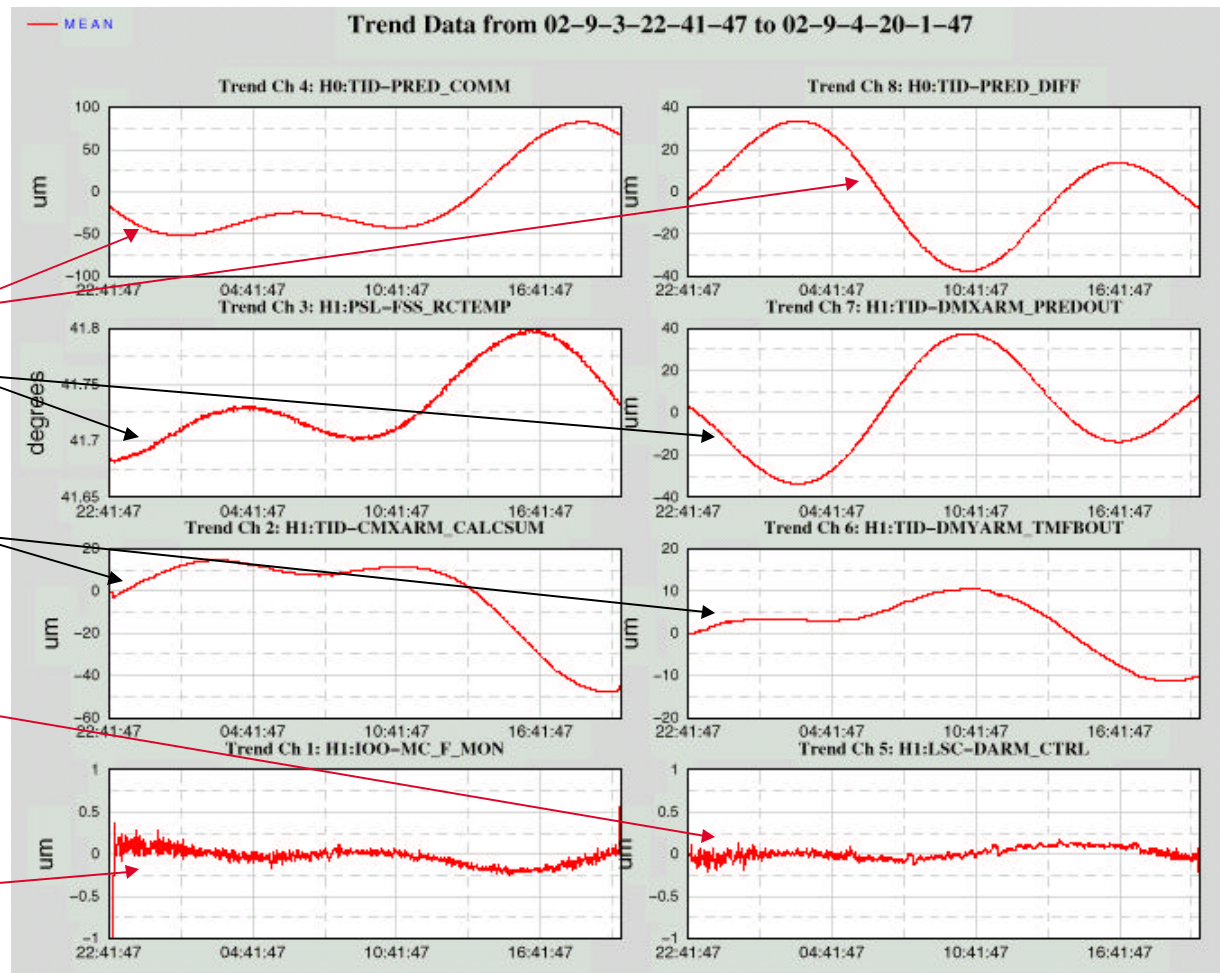
Predicted tides

Feedforward

Feedback

Residual signal
on coils

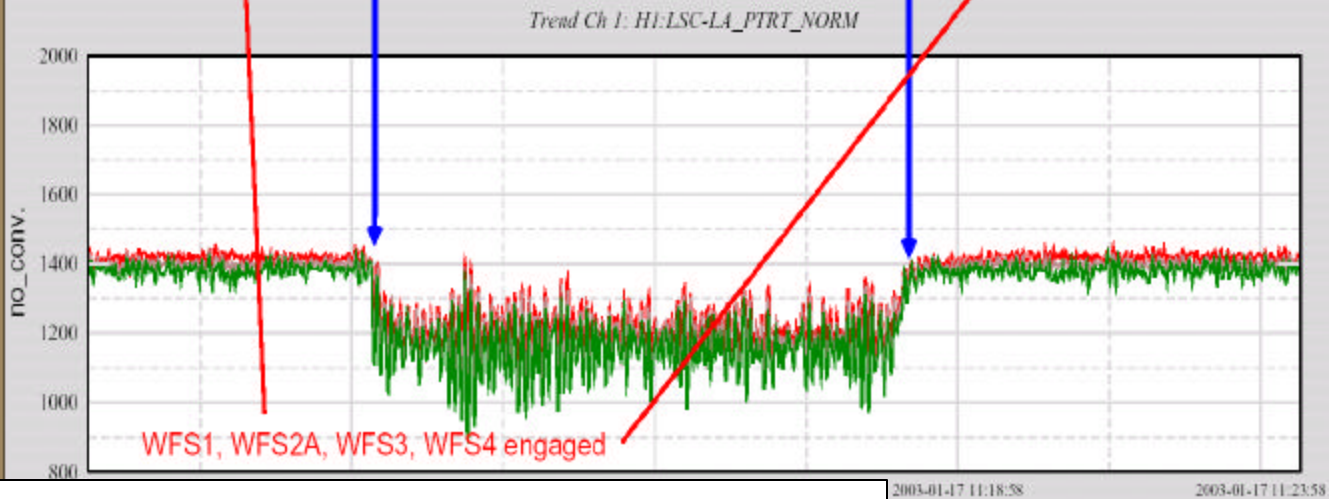
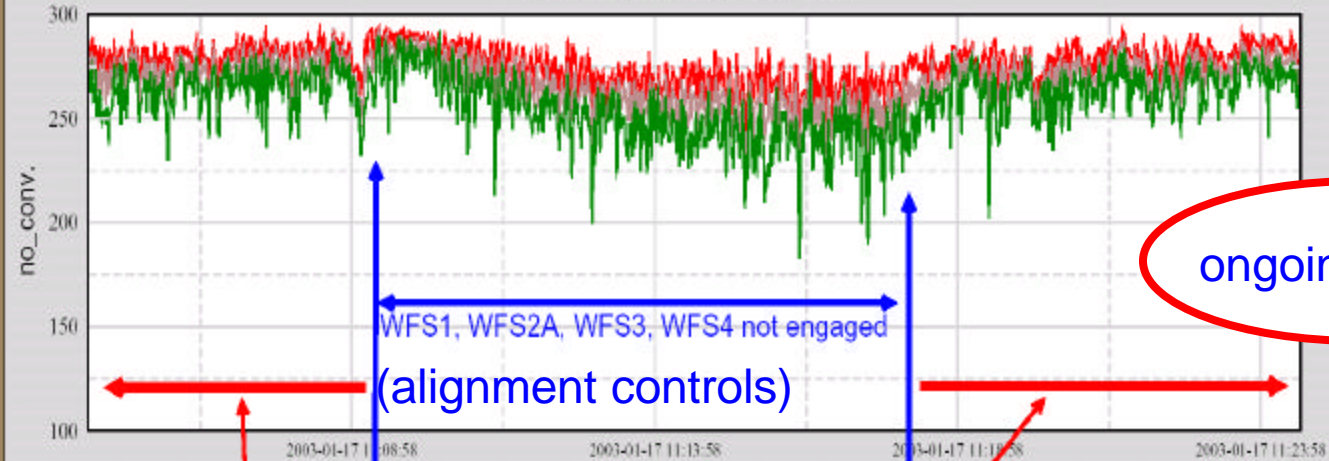
Residual signal
on laser





Controlling angular degrees of freedom

DC light level in recycling cavity



DC light level in long arms



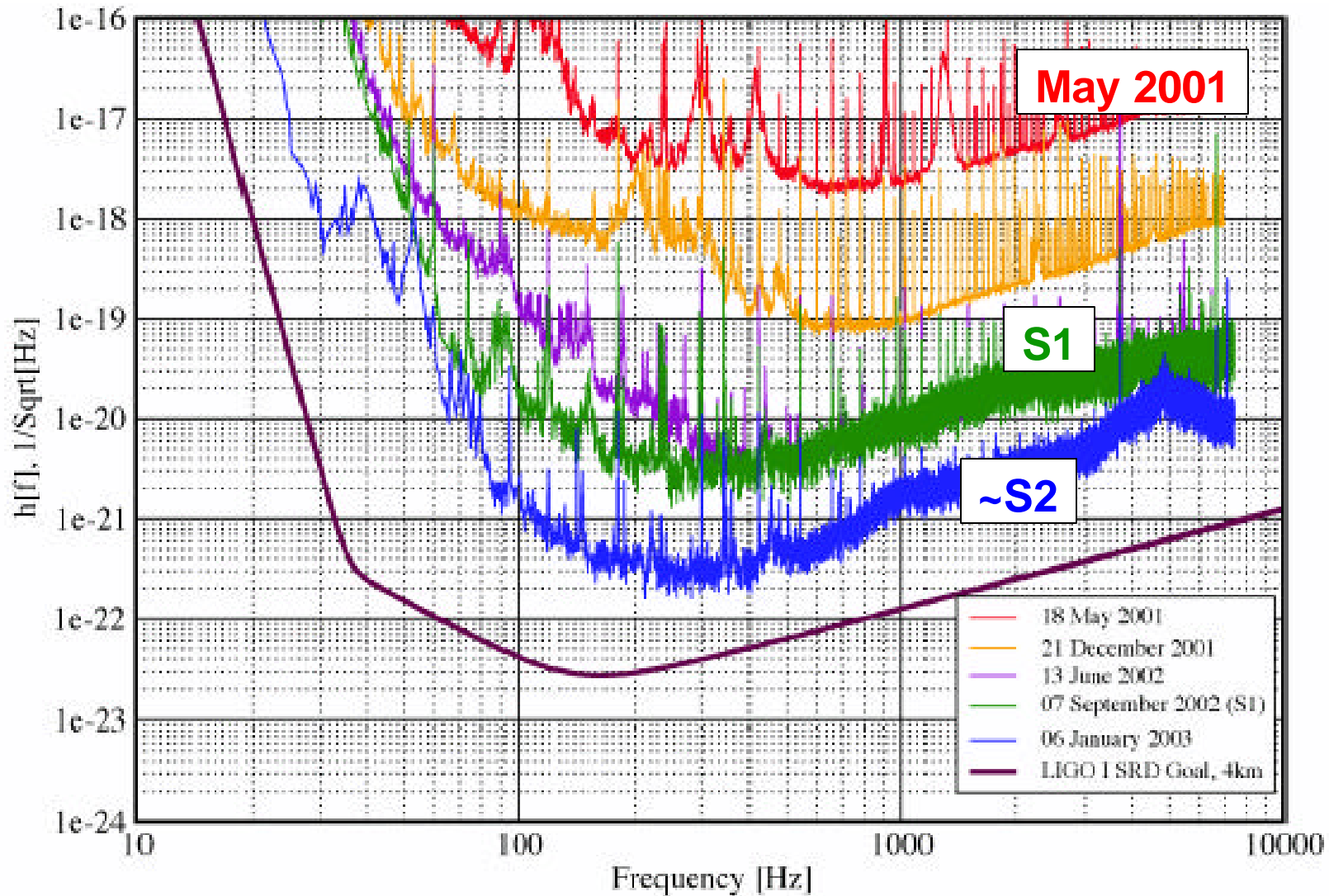
Calibration of the Detectors

- Combination of DC (calibrates voice coil actuation of suspended mirror) and Swept-Sine methods (accounts for gain vs. frequency) calibrate meters of mirror motion per count at digital suspension controllers across the frequency spectrum
- DC calibration methods
 - » fringe counting (precision to few %)
 - » fringe stepping (precision to few %)
 - » fine actuator drive, readout by dial indicator (accuracy to ~10%)
 - » comparison with predicted earth tides (sanity check to ~25%)
- AC calibration measures transfer functions of digital suspension controllers periodically under operating conditions (also inject test wave forms to test data analysis pipelines)
- CW Calibration lines injected during running to monitor optical gain changes due to drift



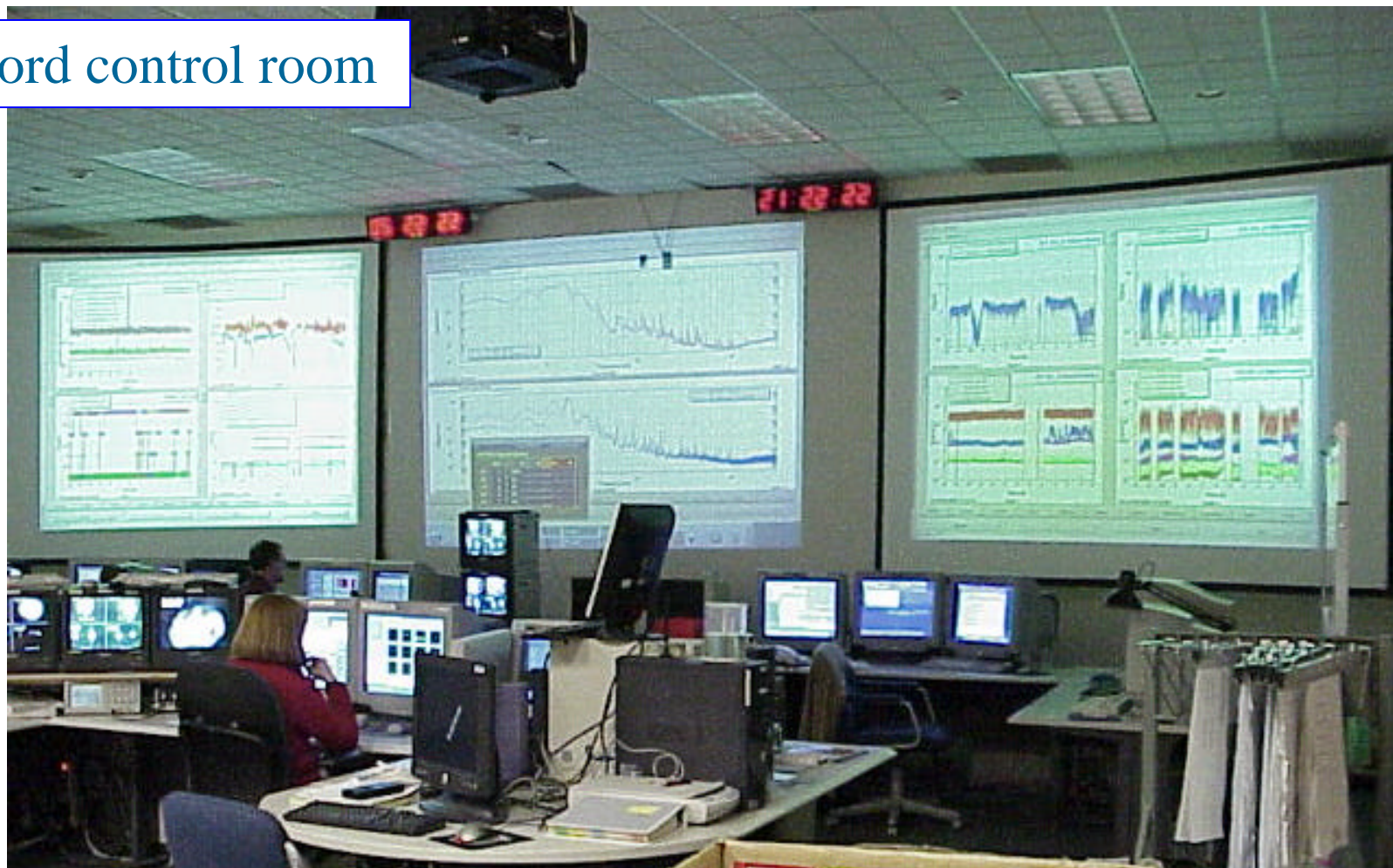
LIGO Sensitivity Over Time

Livingston 4km Interferometer



The S1 Run

Hanford control room

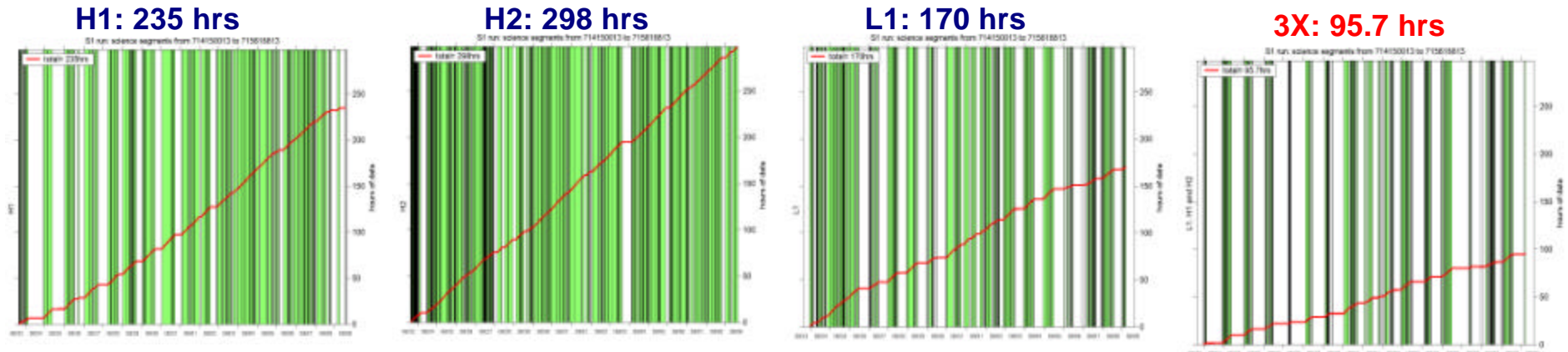




The S1 run: In-Lock Data Summary

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 coincident time: 95.7 hrs



Sensitivity during S1

LIGO S1 Run

“First
Upper Limit
Run”

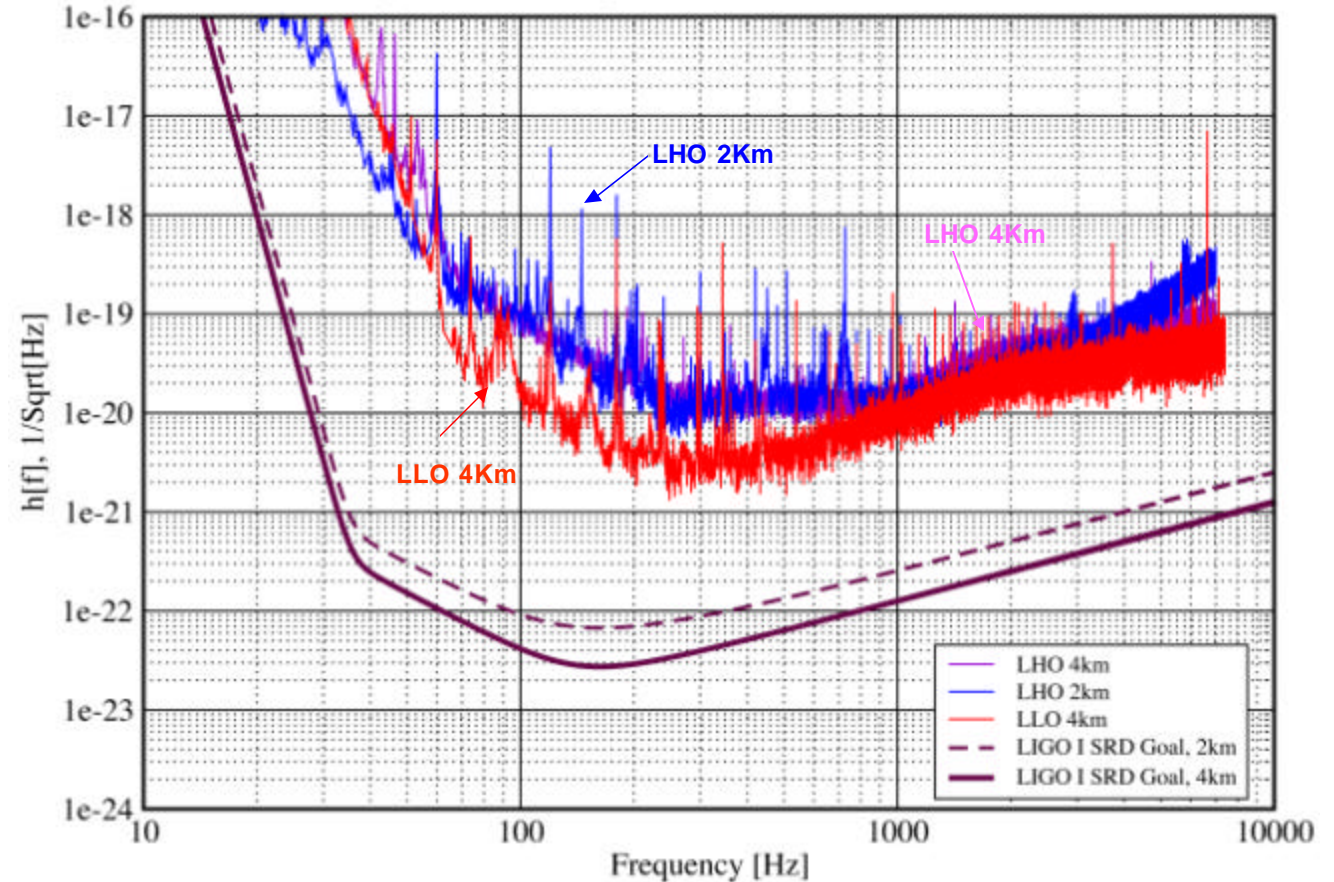
- 23 Aug–9 Sept 2002
- 17 days
- All interferometers in power recycling configuration

GEO in S1 RUN

Ran simultaneously
In power recycling
Lesser sensitivity

Strain Sensivities for the LIGO Interferometers for S1

23 August 2002 - 09 September 2002 LIGO-G020461-01-E





Potential gravity wave sources

- **Bursts:** supernovae, black hole mergers, unknown, {triggered burst search}
- **Binary inspirals:** NS-NS, {BH-BH, NS-BH, Macho}
- **Stochastic background:** big bang, weak incoherent source from more recent epoch
- **Continuous waves:** known EM pulsars, {all-sky search for unknown CW sources, LMXRB (e.g. Sco-X1)}
- **Analysis emphasis:**
 - » Establish **methodology**, no sources expected.
 - » End-to-end **check and validation** via software and hardware **injections** mimicking passage of a gravitational wave.



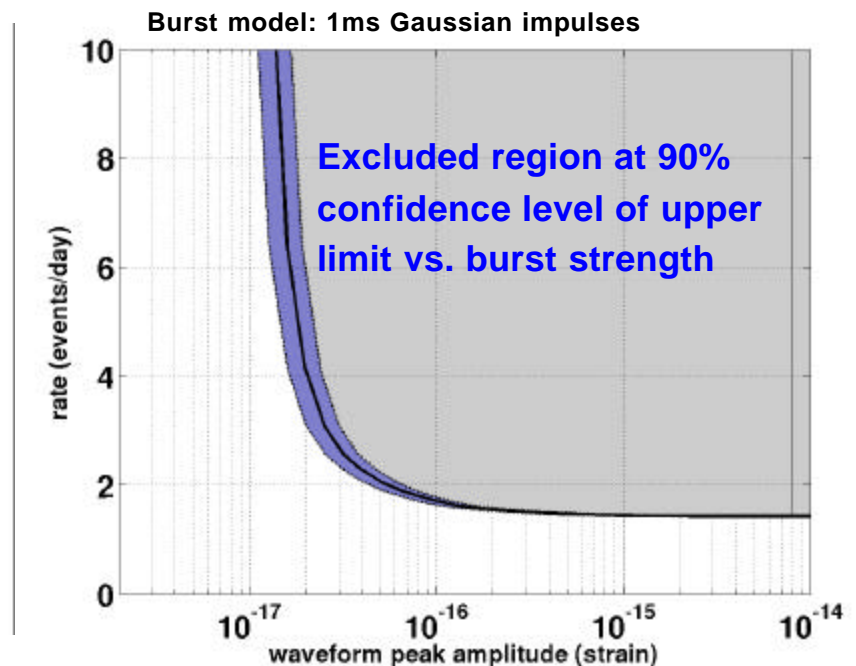
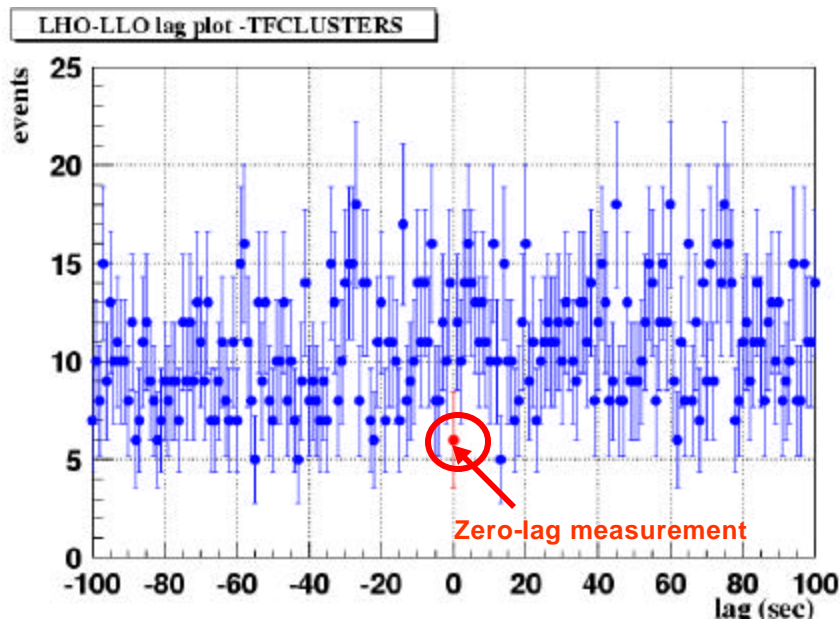
Search for Gravitational Wave Bursts

- **Search methods (generic, no templates):**
 - » **Time domain** algorithm identifies rapid increase in amplitude of a filtered time series (threshold on 'slope').
 - » **Time-Frequency domain** algorithm : identifies regions in the time-frequency plane with excess power (threshold on pixel power and cluster size).
- **Pipeline:**
 - » **Single interferometer:** noisy data epochs were excluded
 - » **essential:** use **temporal coincidence** of the 3 interferometers
 - » **correlate frequency** features of candidates (time-frequency domain analysis).



PRELIMINARY results of the Burst Search

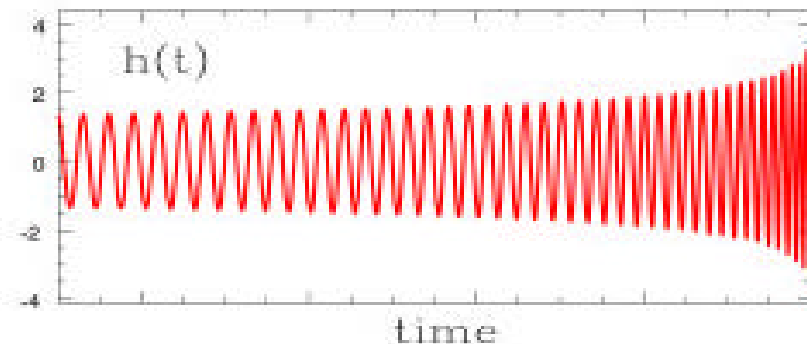
- End result of analysis pipeline: number of triple coincidence events.
- Use time-shift experiments to establish number of background events.
- Use Feldman-Cousins to set 90% confidence upper limits on rate of foreground events (preliminary results):
 - » Time domain: <5.7 events/day
 - » Time frequency domain: <1.6 events/day



Search for Inspirals

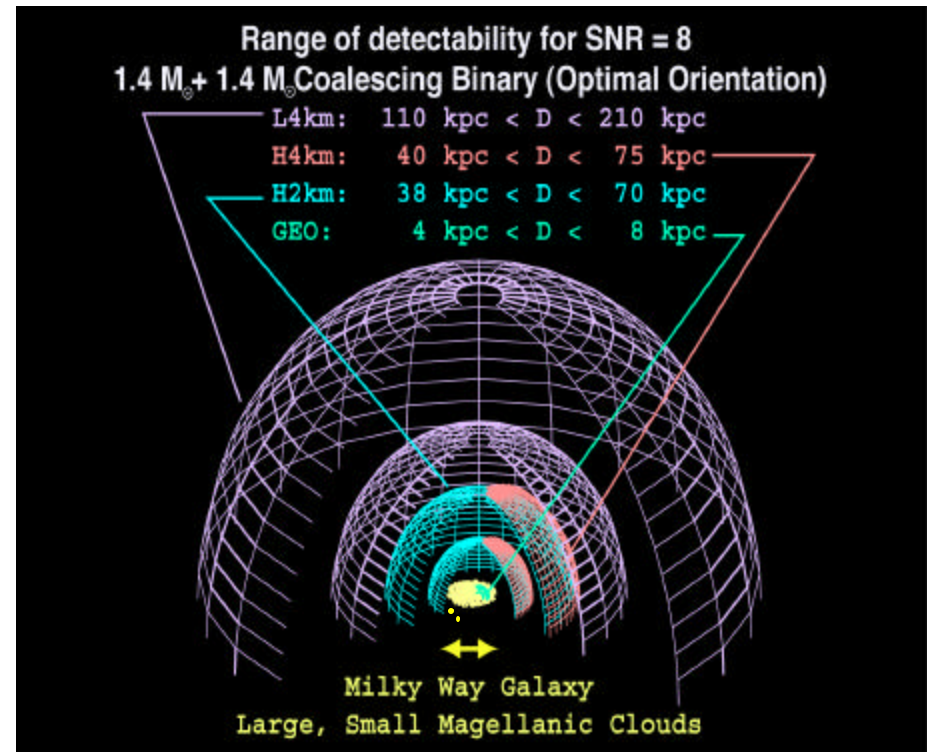
- **Sources:** orbital-decaying **compact binaries:** neutron star known to exist and emitting gravitational waves (Hulse&Taylor).
- **Search method:** system can be **modeled**, waveform is calculable:

» use optimal **matched filtering**: correlate detector's output with template waveform



Inspiral algorithm

- Use LLO 4k and LHO 4k
- Matched filter trigger:
 - » Threshold on SNR, and compute c^2
 - » Threshold on c^2 , record trigger
 - » Triggers are **clustered** within duration of each template
- Auxiliary data triggers
 - **Veto**s eliminate noisy data
- Event Candidates
 - » Coincident in time, binary mass, and distance when H1, L1 clean
 - » Single IFO trigger when only H1 or L1 operate
- Use **Monte Carlo** simulations to calculate efficiency of the analysis
 - » Model of sources in the Milky Way, LMC, SMC





Results of the Inspiral Search

- Upper limit on binary neutron star coalescence rate
- Use all triggers from Hanford and Livingston: 236 hours
 - » Cannot accurately assess **background** (be conservative, **assume zero**).
 - » Monte Carlo simulation **efficiency** $\epsilon = 0.53$
 - » Effective no. MWEG: $N_G = \epsilon(L_{\text{pop}}/L_G) = 0.53 \times 1.13 = 0.60$
 - » 90% confidence limit = **2.3/ (time * N_G)**.
 - » Express the rate as a rate per **Milky Way Equivalent Galaxies (MWEG)**.

$$N_G = 0.60^{+0.12}_{-0.10}$$

$$R < 2.3 / (0.5 \times 236 \text{ hr}) = 170 / \text{yr} / (\text{MWEG})$$

- Previous experimental results:
 - » LIGO 40m '94: 0.5/hr (25hrs, $D < 25 \text{ kpc}$, Allen et al., PRD 1998)
 - » TAMA300 '99: 0.6/hr (6 hr, $D < 6 \text{ kpc}$, Tagoshi et al., PRD 2001)
 - » TAMA300 DT6: 82/yr (1,038 hr, $D < 33 \text{ kpc}$, GWDAW 2002)
- Expected Galactic rate: $\sim 10^{-6} - 5 \times 10^{-4} / \text{yr}$ (Kalogera et al)



Search for Stochastic Radiation

- **Analysis goals:** constrain contribution of stochastic radiation's energy \mathbf{r}_{GW} to the total energy required to close the universe $\mathbf{r}_{critical}$:

$$\int_0^{\infty} (1/f) \Omega_{GW}(f) df = \frac{\mathbf{r}_{GW}}{\mathbf{r}_{critical}}$$

- Optimally filtered **cross-correlation** of detector pairs: L1-H1, L1-H2 and H1-H2.
- Detector **separation** and **orientation** reduces correlations at high frequencies ($\lambda_{GW} \geq 2 \times \text{BaseLine}$): **overlap reduction function**
 - » H1-H2 best suited
 - » L1-H1(H2) significant <50Hz



Results of Stochastic Search

| Interferometer Pair | 90% CL Upper Limit | T_{obs} |
|---------------------|--|------------------|
| LHO 4km-LLO 4km | $\mathbf{W}_{\text{GW}} (40\text{Hz} - 314 \text{ Hz}) < 55$ | 64.0 hrs |
| LHO 2km-LLO 4km | $\mathbf{W}_{\text{GW}} (40\text{Hz} - 314 \text{ Hz}) < 23$ | 51.3 hrs |

- Non-negligible LHO 4km-2km (H1-H2) cross-correlation; currently being investigated.
- Previous best upper limits:

» *Measured:* Garching-Glasgow interferometers :

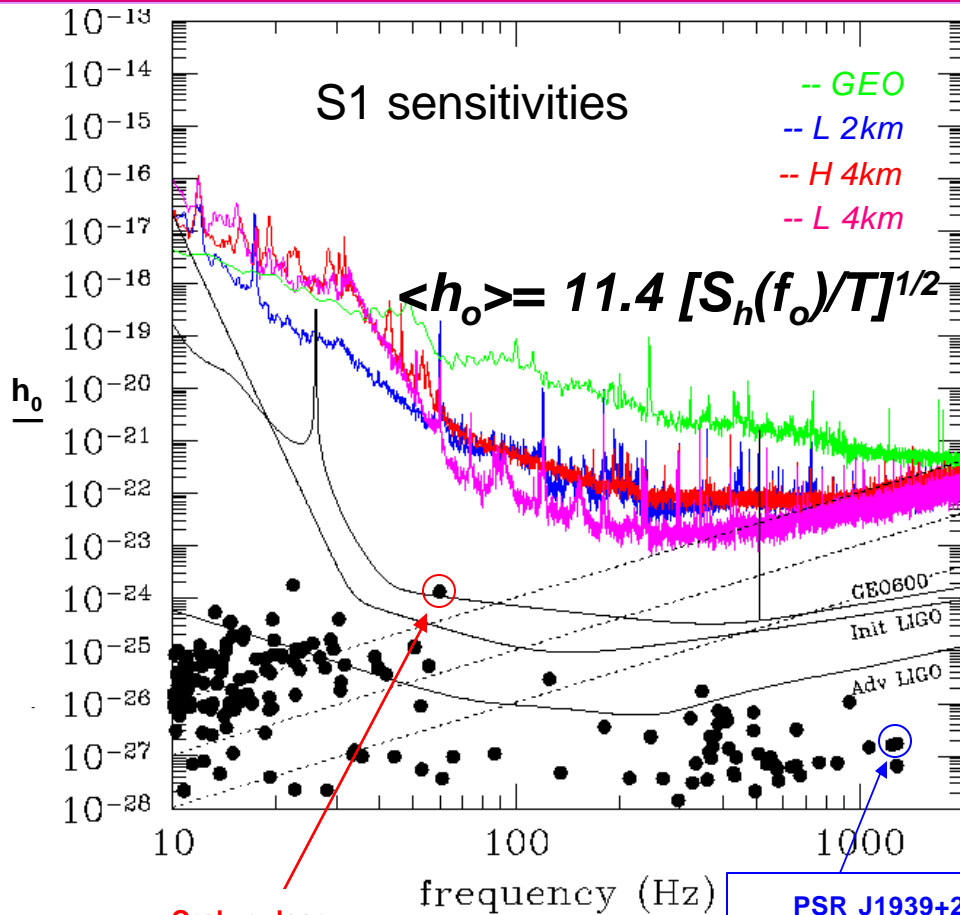
» *Measured:* EXPLORER-NAUTILUS (cryogenic bars):

$$\Omega_{\text{GW}}(f) < 3 \times 10^5$$

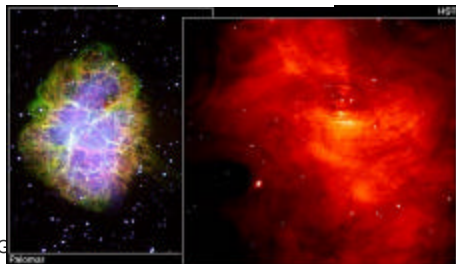
$$\Omega_{\text{GW}}(907\text{Hz}) < 60$$



Expectations for Continuous Waves



Crab pulsar



PSR J1939+2134
 P = 0.00155781 s
 $f_{GW} = 1283.86$ Hz
 $P = 1.0511 \cdot 10^{-19}$ s/s
 D = 3.6 kpc

- Detectable amplitudes with a 1% false alarm rate and 10% false dismissal rate by the interferometers during S1 (colored curves) and at design sensitivities (black curves).
- Limits of detectability for rotating NS with equatorial ellipticity $e = d/I_{zz}$: 10^{-3} , 10^{-4} , 10^{-5} @ 8.5 kpc.
- Upper limits on $\langle h_o \rangle$ from spin-down measurements of known radio pulsars (filled circles) if observed spindown all due to GW emission.

S1: NO DETECTION EXPECTED



Algorithms for CW Search

- Search for **known pulsars** dramatically reduces the parameter space: computationally feasible.
- Central parameters in detection algorithms:
 - » **frequency modulation** of signal due to Earth's motion relative to the Solar System Barycenter, intrinsic frequency changes.
 - » **amplitude modulation** due to the detector's antenna pattern.
- Two search methods used:
 - » **Frequency-domain (best for "blind" searches)** based: fourier transform data, form max. likelihood ratio ("F-statistic"), frequentist approach to derive upper limit
 - » **Time-domain (best for known target parameter searches)** based: time series heterodyned, noise is estimated. Bayesian approach in parameter estimation: result expressed in terms of posterior pdf for parameters of interest



Results of Search for CW

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

| <u>IFO</u> | <u>Frequentist FDS</u> | <u>Bayesian TDS</u> |
|---------------|---------------------------------|---------------------------------|
| GEO | $(1.9 \pm 0.1) \times 10^{-21}$ | $(2.2 \pm 0.1) \times 10^{-21}$ |
| LLO | $(2.7 \pm 0.3) \times 10^{-22}$ | $(1.4 \pm 0.1) \times 10^{-22}$ |
| LHO-2K | $(5.4 \pm 0.6) \times 10^{-22}$ | $(3.3 \pm 0.3) \times 10^{-22}$ |
| LHO-4K | $(4.0 \pm 0.5) \times 10^{-22}$ | $(2.4 \pm 0.2) \times 10^{-22}$ |

- LLO upper limit on $h_o < 1.4 \times 10^{-22}$ constrain **ellipticity** $< 2.7 \times 10^{-4}$ (assuming $M=1.4M_{\text{sun}}$, $r=10\text{km}$, $R=3.6\text{kpc}$)
- Previous results for PSR J1939+2134: $h_o < 10^{-20}$ (Glasgow, Hough et al., 1983), $h_o < 3.1(1.5) \times 10^{-17}$ (Caltech, Hereld, 1983).



LIGO science has started

- LIGO has started taking data, completing a **first science run** (“S1”) last summer
- **Second science run** (“S2”) 14 February - 14 April:
 - » Sensitivity was ~10x better than S1
 - » Duration was ~ 4x longer
 - Bursts: rate limits: 4X lower rate & 10X lower strain limit
 - Inspirals: reach will exceed 1Mpc -- includes M31 (Andromeda)
 - Stochastic background: limits on $\Omega_{\text{GW}} < 10^{-2}$
 - Periodic sources: limits on $h_{\text{max}} \sim \text{few} \times 10^{-23}$ ($\epsilon \sim \text{few} \times 10^{-6}$ @ 3.6 kpc)
- Commissioning continues, interleaved with science runs
- Ground based interferometers are **collaborating internationally**:
 - » LIGO and GEO (UK/Germany) during “S1”
 - » LIGO and TAMA (Japan) during “S2”