LIGO Commissioning and Initial Science Runs: Current Status

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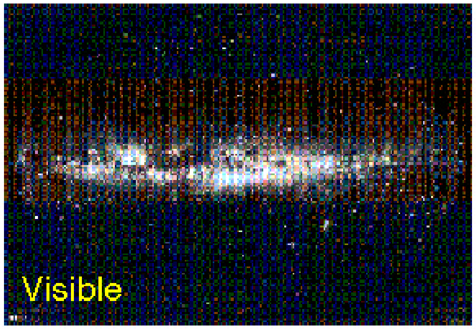
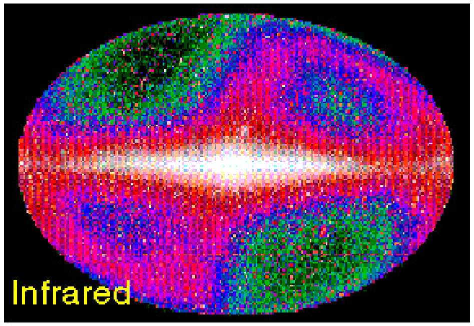
on behalf of the LIGO Scientific Collaboration

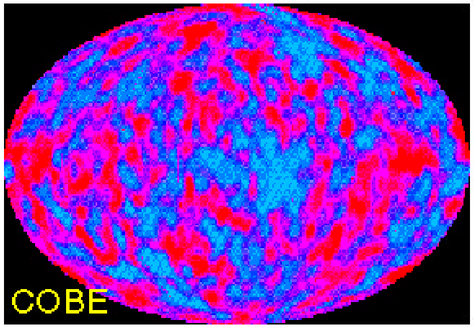
http://www.ligo.org

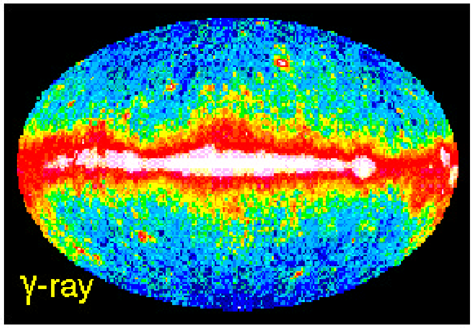
LIGO APS NW Section Meeting, May 30, 2003

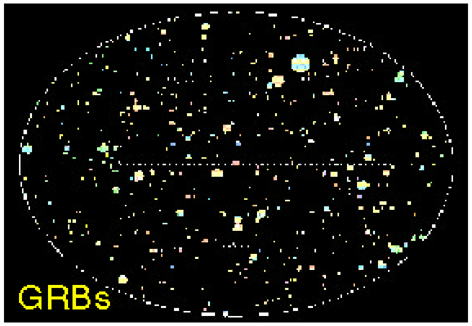
New Window on Universe

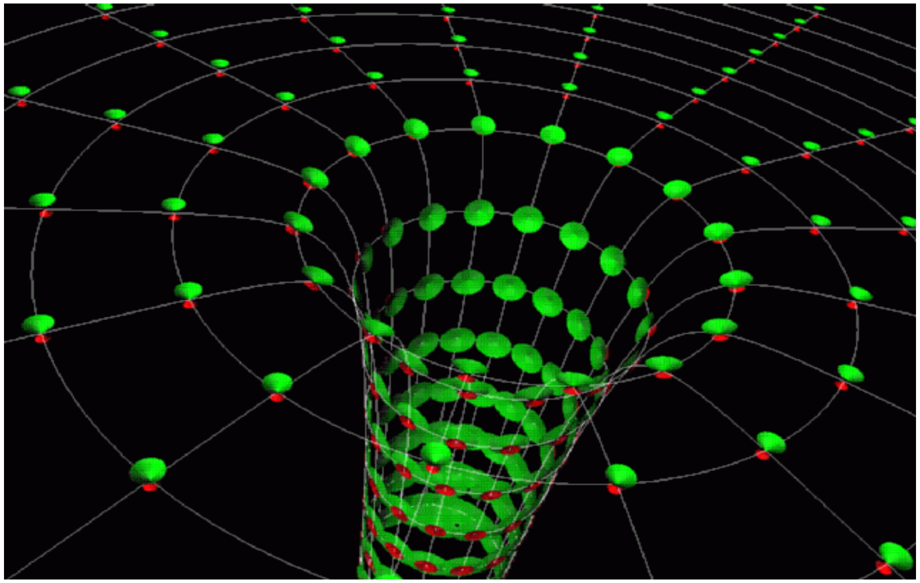












GRAVITATIONAL WAVES PROVIDE A NEW AND UNIQUE VIEW OF THE DYNAMICS OF THE UNIVERSE.

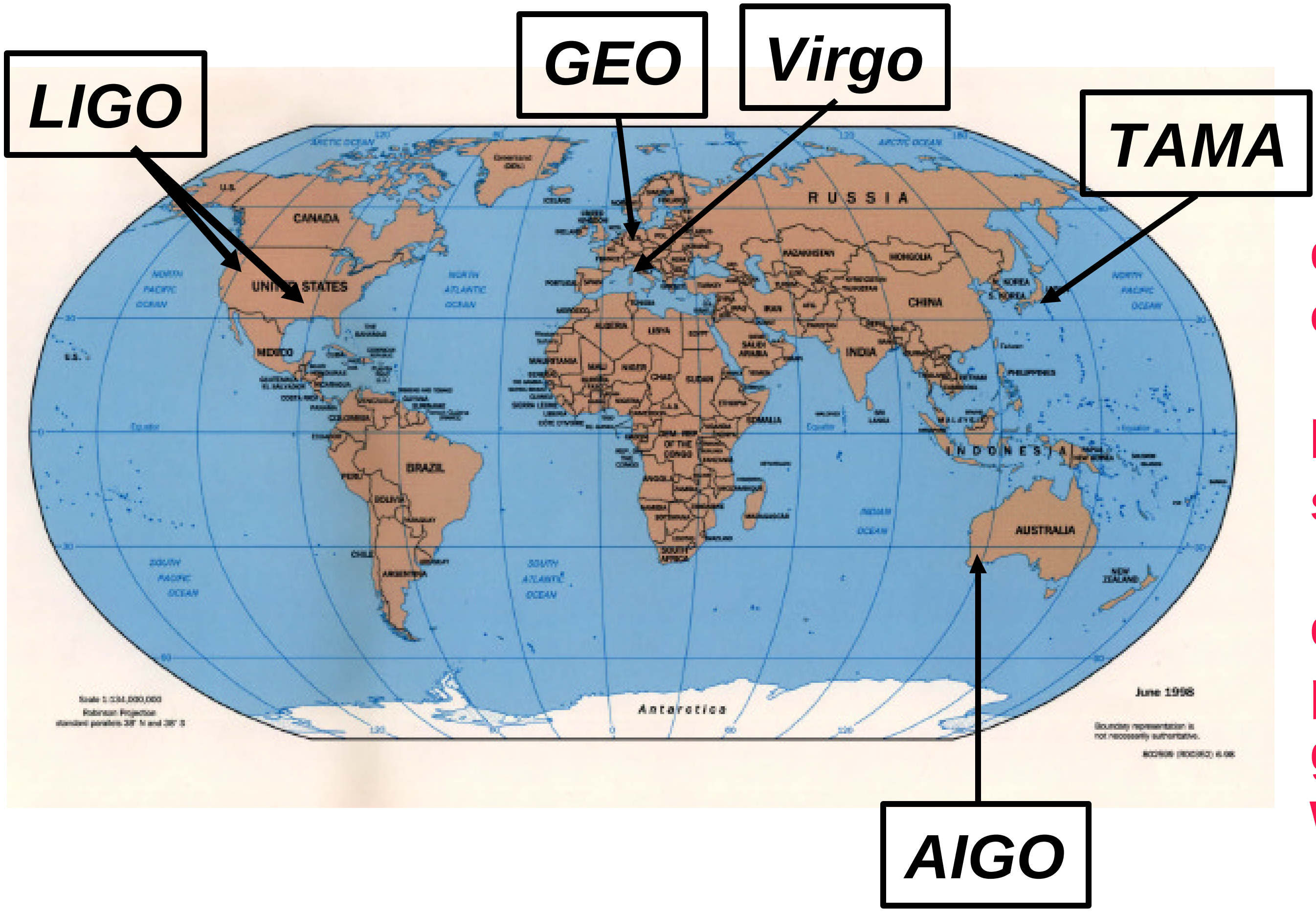
EXPECTED SOURCES:

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!

An International Network of Interferometers

Simultaneously detect signal (within msec)



LIGO

GEO

Virgo

TAMA

AIGO

detection confidence

locate the sources

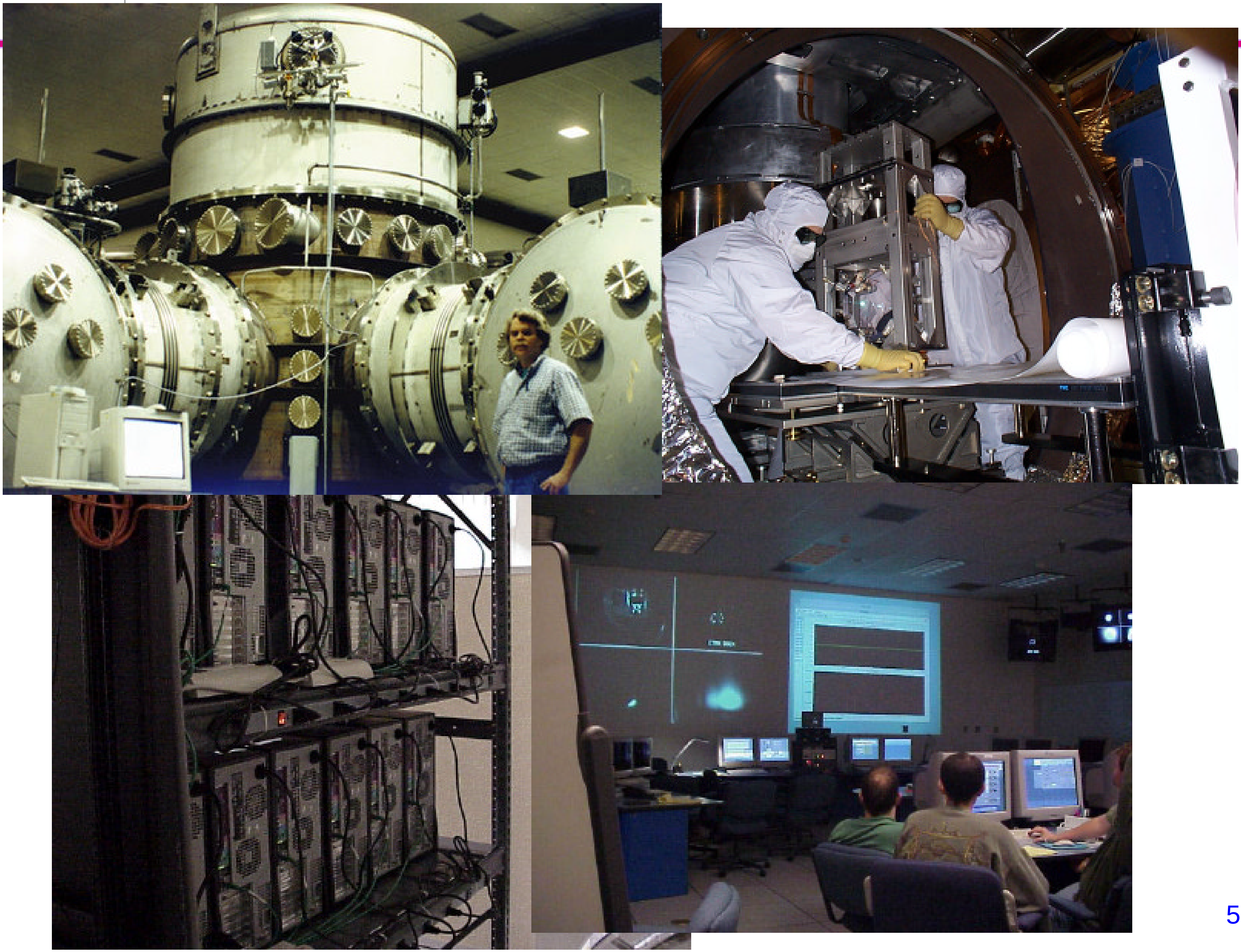
decompose the polarization of gravitational waves

LIGO sites

LIGO (Washington)

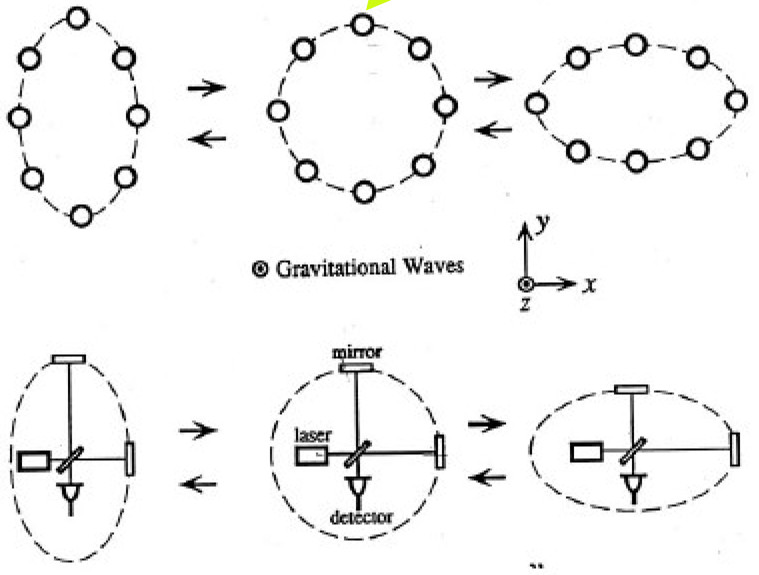
LIGO (Louisiana)

A closer look

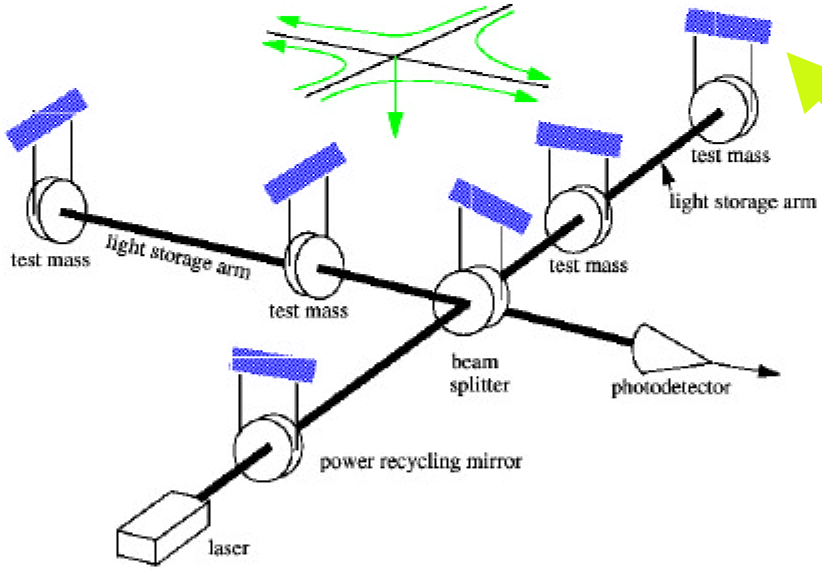


Terrestrial Interferometers

free masses

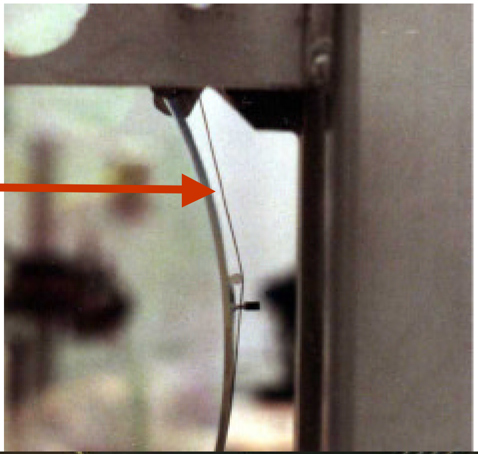


International network (LIGO, Virgo, GEO, TAMA) of suspended mass Michelson-type interferometers on earth's surface detect distant astrophysical sources

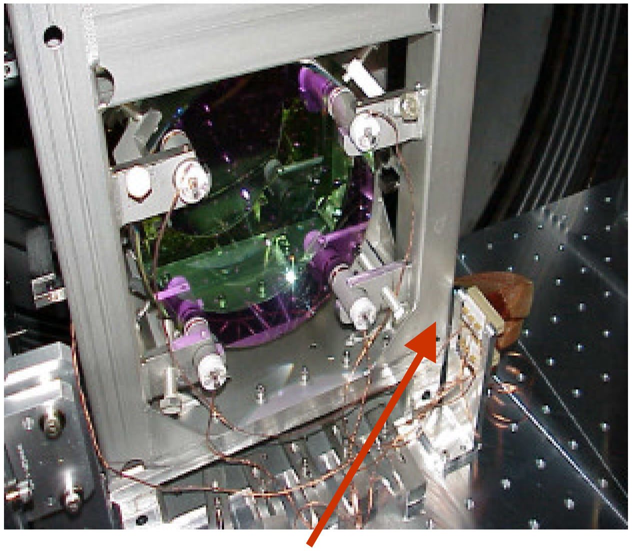


suspended test masses

Core Optics Suspension and Control



Optics suspended as simple pendulums



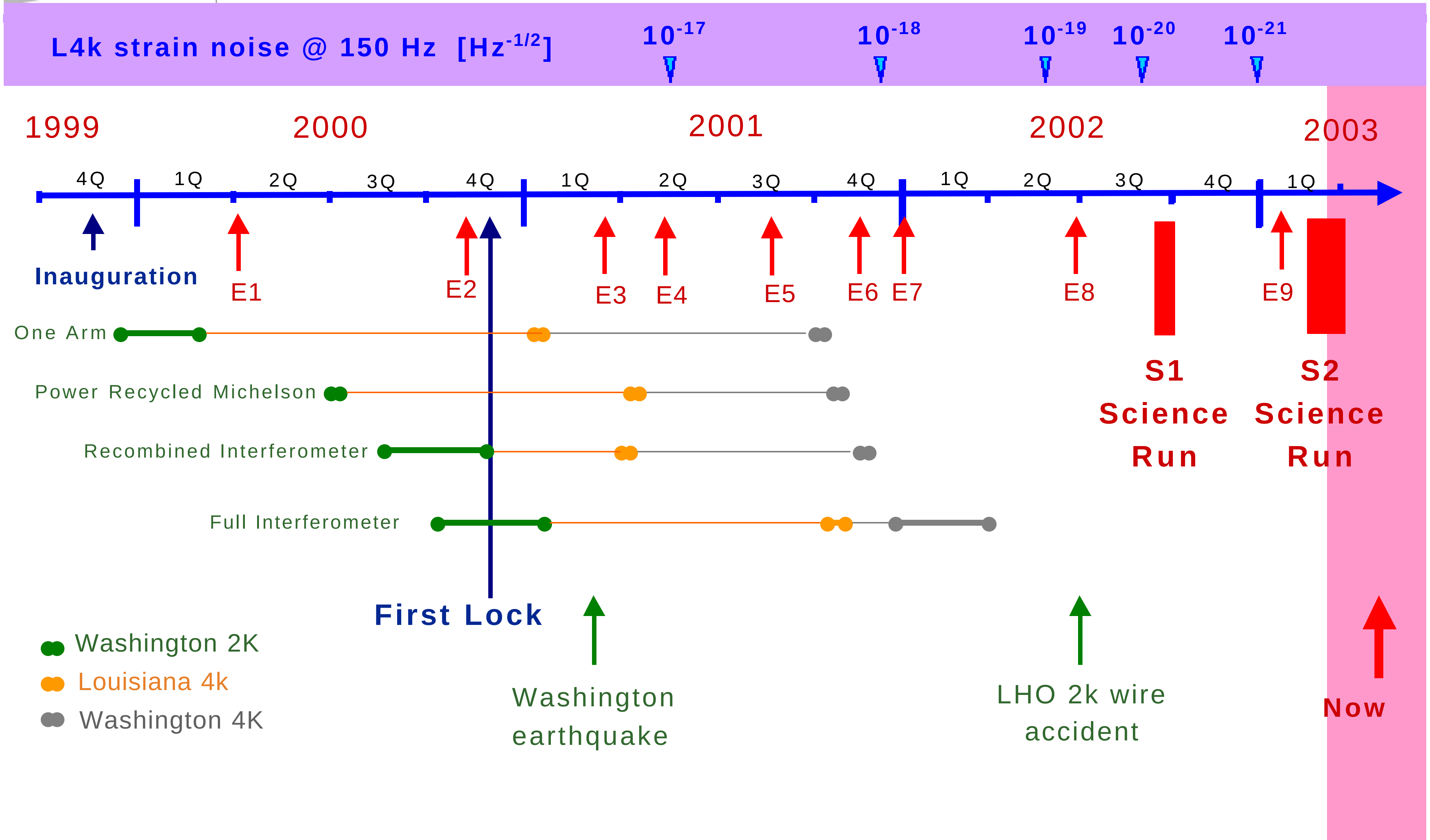
Shadow sensors & coil actuators provide damping and control forces

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 (1/1000th of a proton diameter)
- Control arm lengths to 10^{-13} meters RMS
- Detect optical phase changes of ~ 10^{-10} radians
- Hold mirror alignments to 10^{-8} radians

Commissioning History



L4k strain noise @ 150 Hz [$Hz^{-1/2}$]

10^{-17} 10^{-18} 10^{-19} 10^{-20} 10^{-21}

1999 2000 2001 2002 2003

4Q 1Q 2Q 3Q 4Q 1Q 2Q 3Q 4Q 1Q 2Q 3Q 4Q 1Q

Inauguration

E1 E2 E3 E4 E5 E6 E7 E8 E9

One Arm

Power Recycled Michelson

Recombined Interferometer

Full Interferometer

S1 Science Run

S2 Science Run

First Lock

Washington earthquake

LHO 2k wire accident

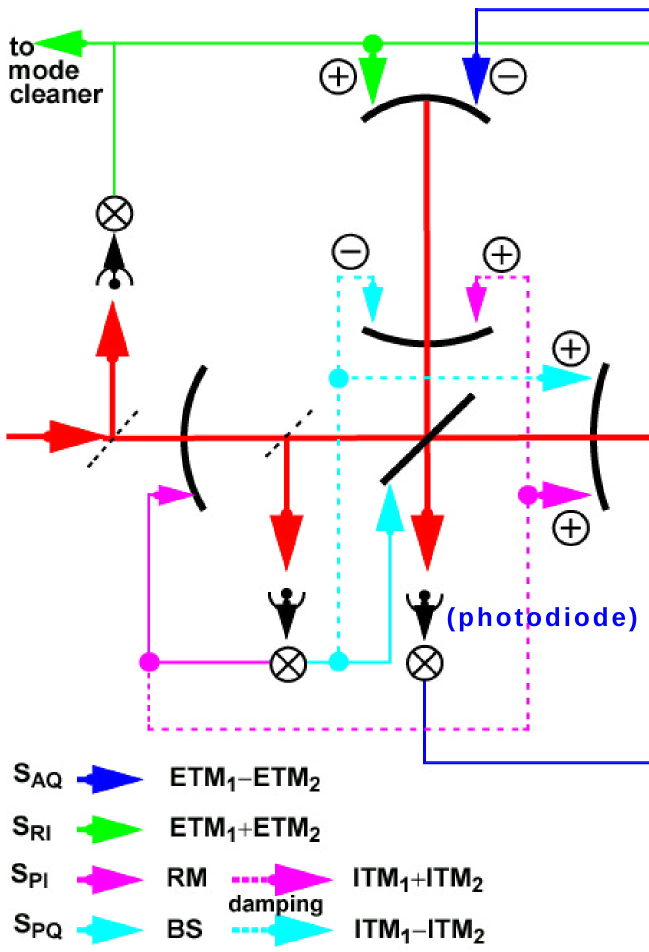
Now

●● Washington 2K

●● Louisiana 4k

●● Washington 4K

Interferometer Length Control System

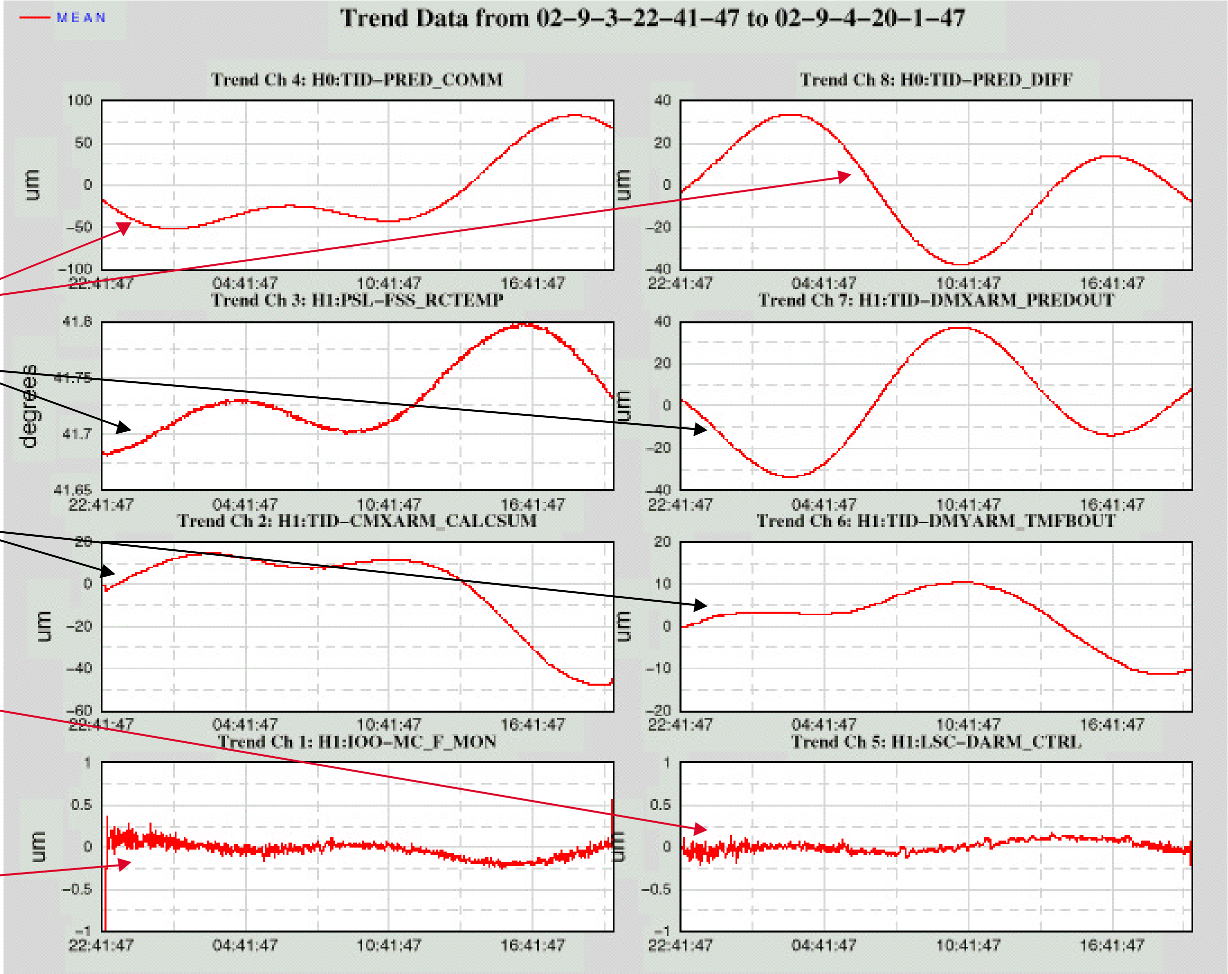


- •Multiple Input / Multiple Output
- •Three tightly coupled cavities
- •Ill-conditioned (off-diagonal) plant matrix
- •Highly nonlinear response over most of phase space
- •Transition to stable, linear regime takes plant through singularity
- •Employs adaptive control system that evaluates plant evolution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

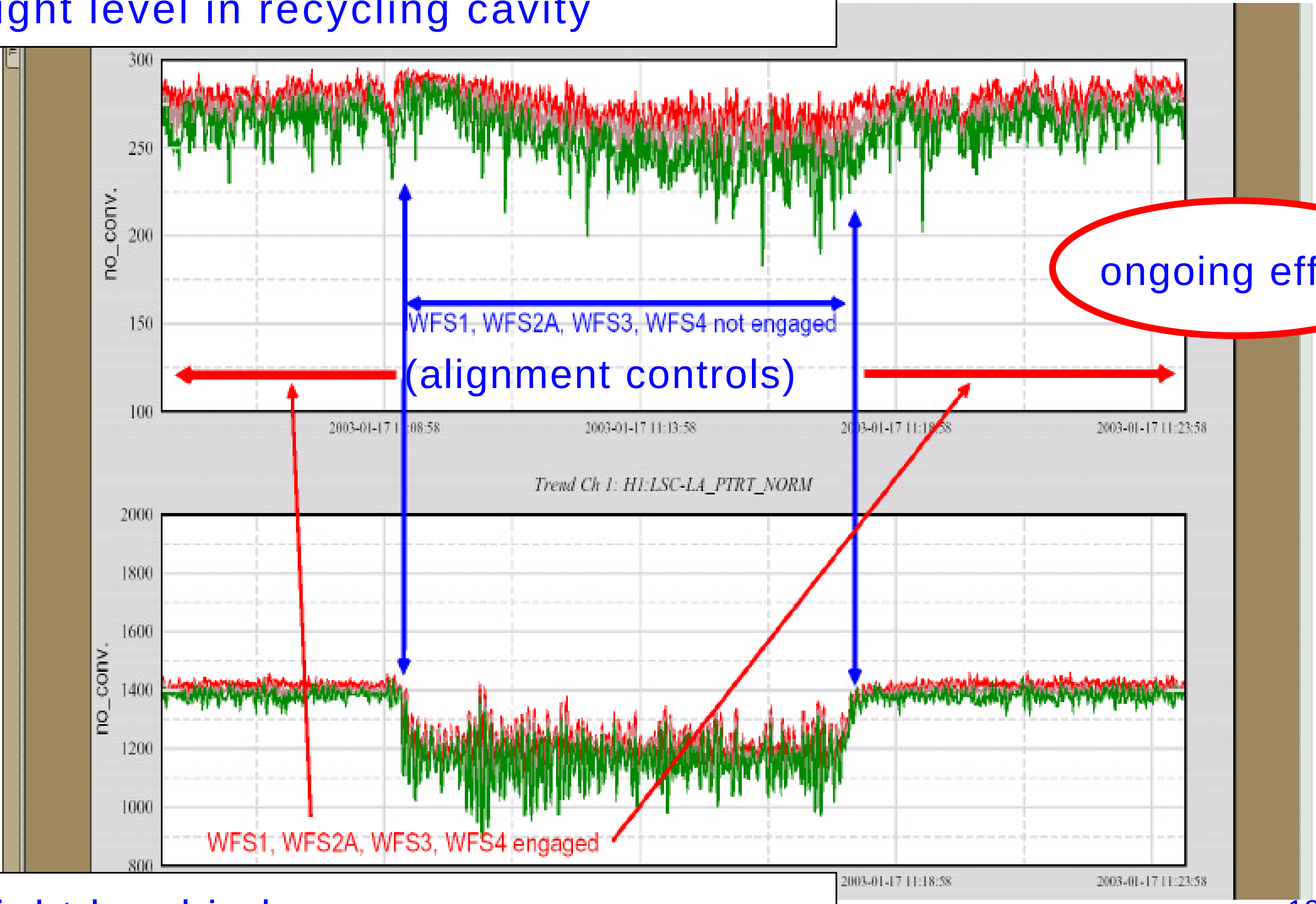
Feedback

Residual signal
on coils

Residual signal
on laser

Controlling angular degrees of freedom

DC light level in recycling cavity



WFS1, WFS2A, WFS3, WFS4 not engaged

(alignment controls)

ongoing effort!

WFS1, WFS2A, WFS3, WFS4 engaged

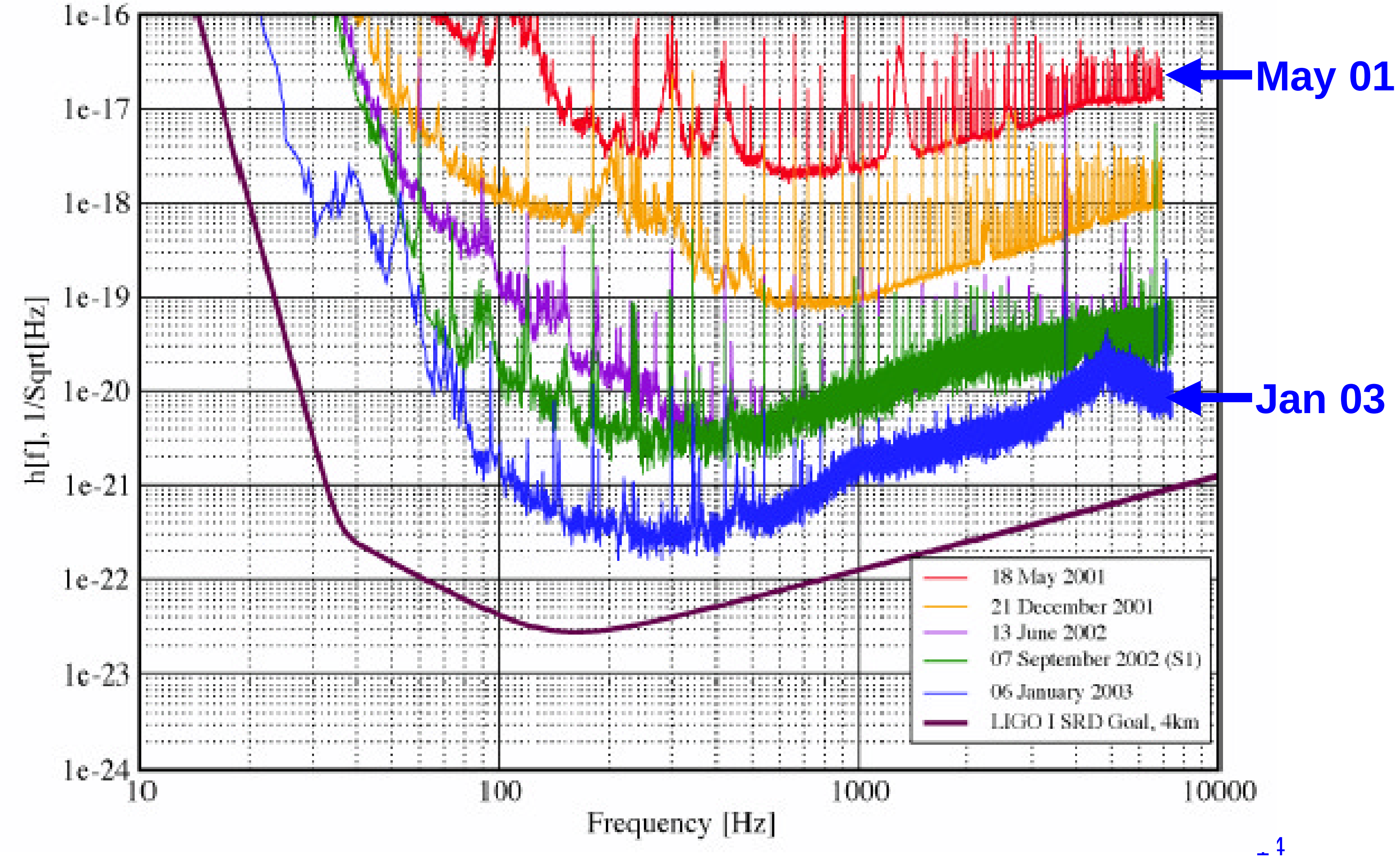
DC light level in long arms

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



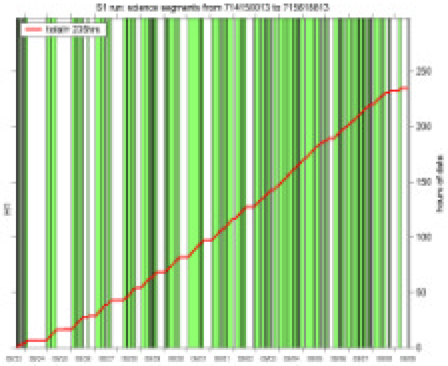
May 01

Jan 03

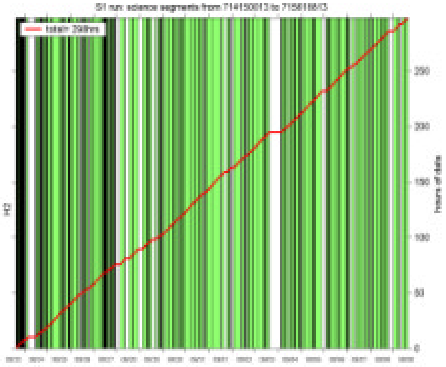
The S1 run: In-Lock Data Summary

Red lines: integrated up time   Green bands (w/ black borders): epochs of lock

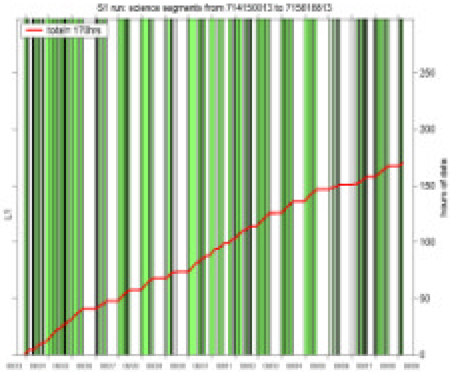
H1: 235 hrs



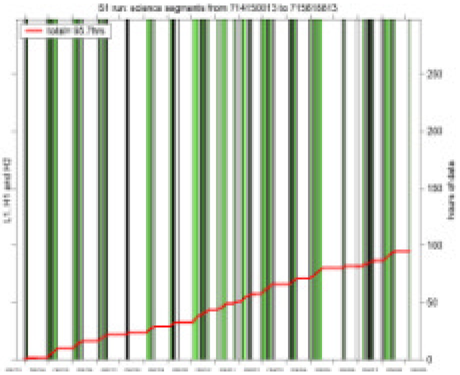
H2: 298 hrs



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

Sensitivity during S1

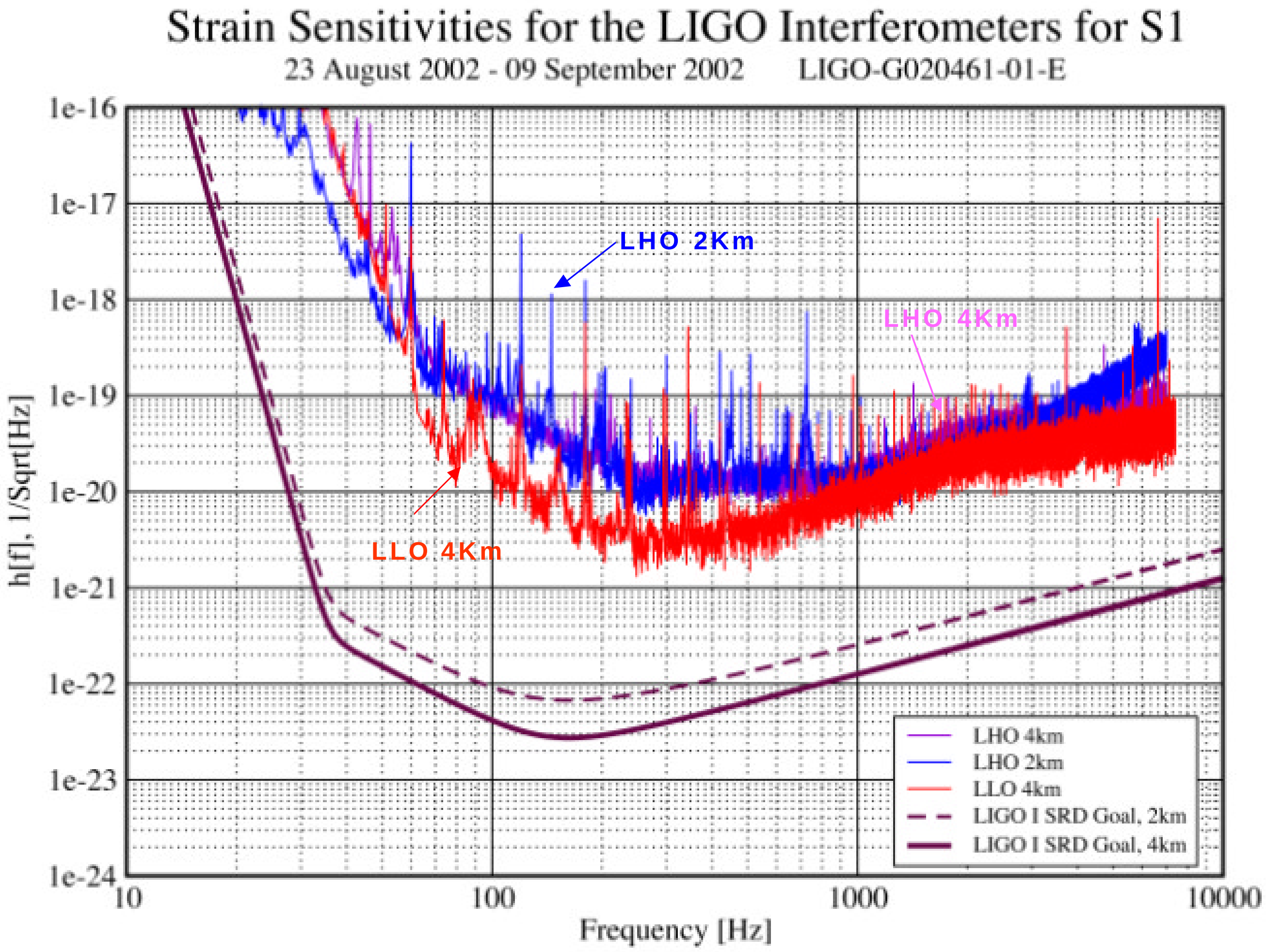
LIGO S1 Run

“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



Potential gravity wave sources

- **Bursts:** supernovae, black hole mergers, unknown, {triggered burst search – next talk by R. Rahkola}
- **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).

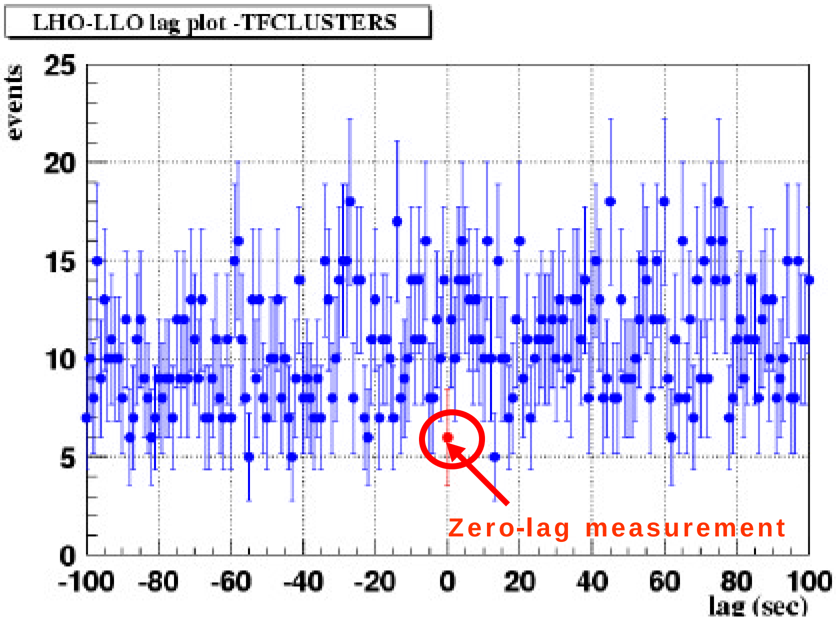
•**Single interferometer: veto** events based on data quality

•essential: use **temporal coincidence** of the 3 interferometers

•**correlate frequency** features of candidates (time-frequency domain analysis).

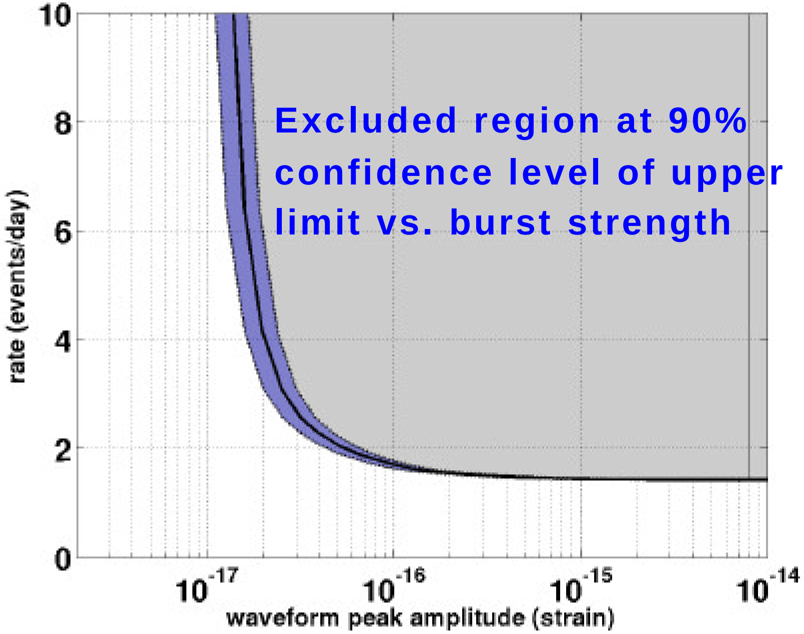
Rate vs. Strength Plots for a Burst Model

- **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: <**5.2** events/day
  - » Time frequency domain: <**1.4** events/day


LHO-LLO lag plot -TFCLUSTERS

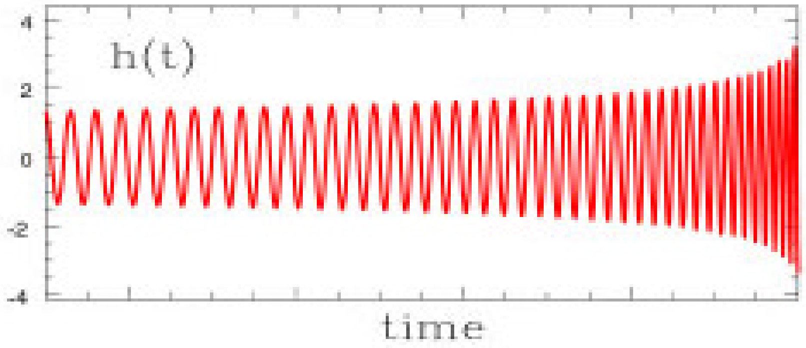
Zero-lag measurement

Burst model: 1ms Gaussian impulses


Excluded region at 90% confidence level of upper limit vs. burst strength

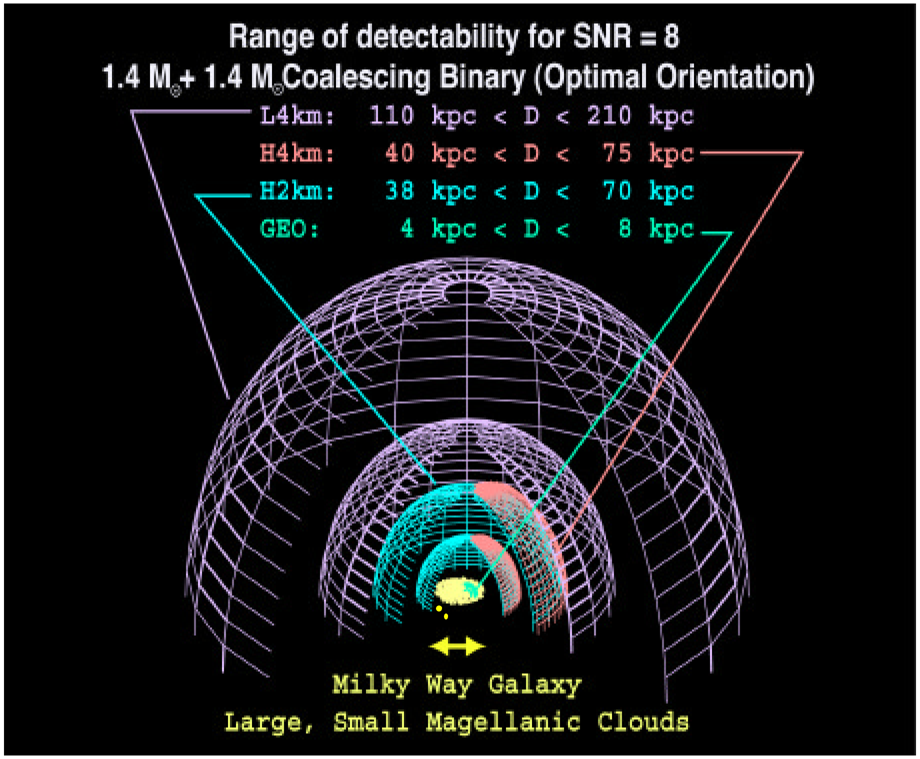
Search for Inspirals

- **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
  - **Vetoes** 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



Preliminary results of the Inspiral Search

- Upper limit on binary neutron star coalescence rate
- Use all triggers from Hanford and Livingston: 214 hours
  - » Cannot accurately assess **background** (be conservative, **assume zero**).
  - » Monte Carlo simulation **efficiency** = 0.51
  - » 90% confidence limit = **2.3/ (efficiency * time).**
  - » Express the rate as a rate per **Milky Way Equivalent Galaxies** (MWEG).

$$R < 2.3 / (0.51 \times 214\ \text{hr}) = 1.64 \times 10^{2}\ /\text{yr}/(\text{MWEG})$$

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

Search for Stochastic Radiation

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

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

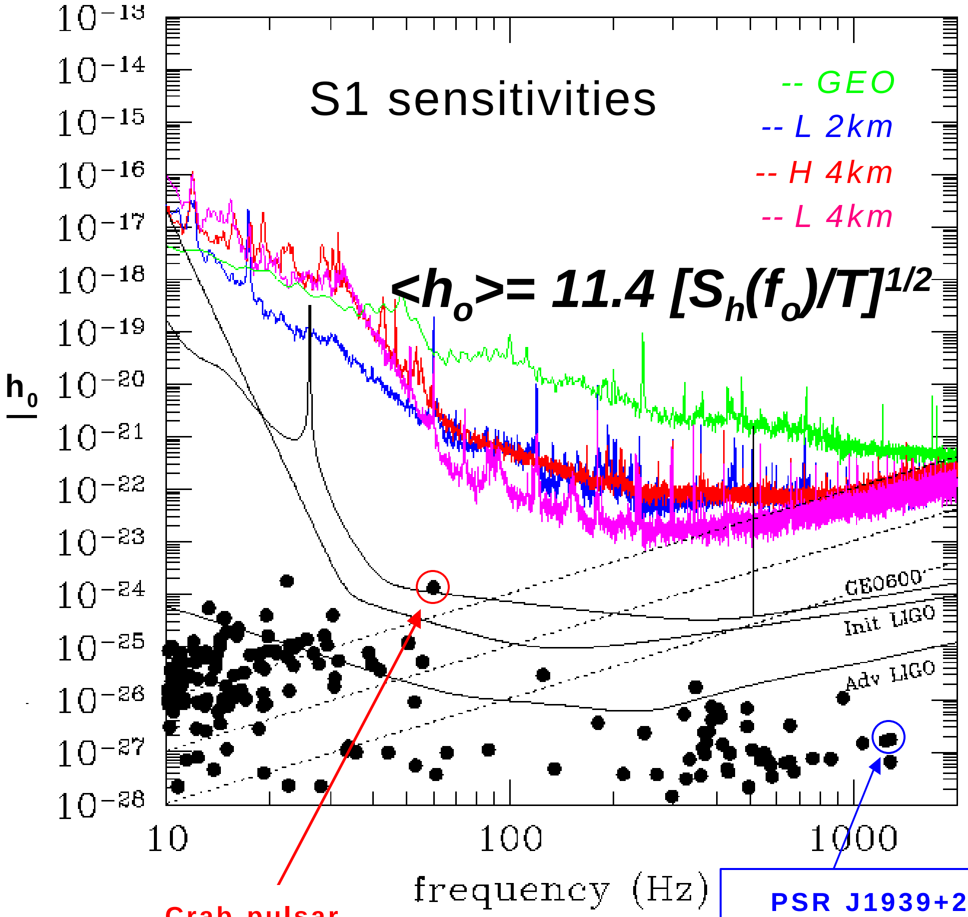
- Optimally filtered **cross-correlation** of detector pairs: L1-H1, L1-H2 and H1-H2.
- Detector **separation** and **orientation** reduces correlations at high frequencies ($\lambda_{GW} \geq$ 2xBaseLine): **overlap reduction function**
  - » H1-H2 best suited
  - » L1-H1(H2) significant <50Hz

Preliminary Results of Stochastic Search

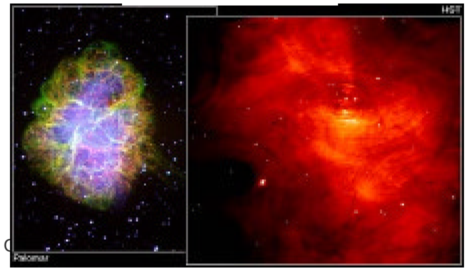
Interferometer Pair	90% CL Upper Limit	T_{obs}
LHO 4km-LLO 4km	W_{GW} (40Hz - 314 Hz) < 72.4	62.3 hrs
LHO 2km-LLO 4km	W_{GW} (40Hz - 314 Hz) < 23	61.0 hrs

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

Expectations for Continuous Waves



Crab pulsar



PSR J1939+2134
P = 0.00155781 s
f_{GW} = *1283.86 Hz*
$\dot{P}$ = 1.0511 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 ***$e = dI/I_{zz}$: 10^{-3} , 10^{-4} , 10^{-5} @ 8.5 kpc.***
- **Upper limits** on **$<h_o>$** from spin-down measurements of known radio pulsars (filled circles).

S1: NO DETECTION EXPECTED

Graphic by R. Dupuis, Glasgow

Algorithms for CW Search

- 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.
- Search for **known pulsars** dramatically reduces the parameter space: computationally feasible.
- **Two** search **methods** used:
  - » **Frequency-domain** based: fourier transform data, form max. likelihood ratio ("F-statistic"), frequentist approach to derive upper limit
  - » **Time-domain** 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:

IFO	Frequentist FDS	Bayesian TDS
GEO	$(1.94\pm0.12)\times10^{-21}$	$(2.1\pm0.1)\times10^{-21}$
LLO	$(2.83\pm0.31)\times10^{-22}$	$(1.4\pm0.1)\times10^{-22}$
LHO-2K	$(4.71\pm0.50)\times10^{-22}$	$(2.2\pm0.2)\times10^{-22}$
LHO-4K	$(6.42\pm0.72)\times10^{-22}$	$(2.7\pm0.3)\times10^{-22}$

- Final upper limits on h_o constrain **ellipticity** (assuming $M=1.4M_{sun}$, $r=10\text{km}$, $R=3.6\text{kpc}$)
- Previous results for PSR J1939+2134: $h_o < 10^{-20}$ (Glasgow, Hough et al., 1983), $h_o < 3.1(1.5)\times10^{-17}$ (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 $\Omega_{GW} < 10^{-2}$
    - Periodic sources: limits on $h_{max} \sim$ few x 10^{-23} ($\varepsilon \sim$ few x 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”