LIGO Commissioning and Initial Science Runs: Current Status

Michael Landry

LIGO Hanford Observatory/Caltech
on behalf of the LIGO Scientific Collaboration
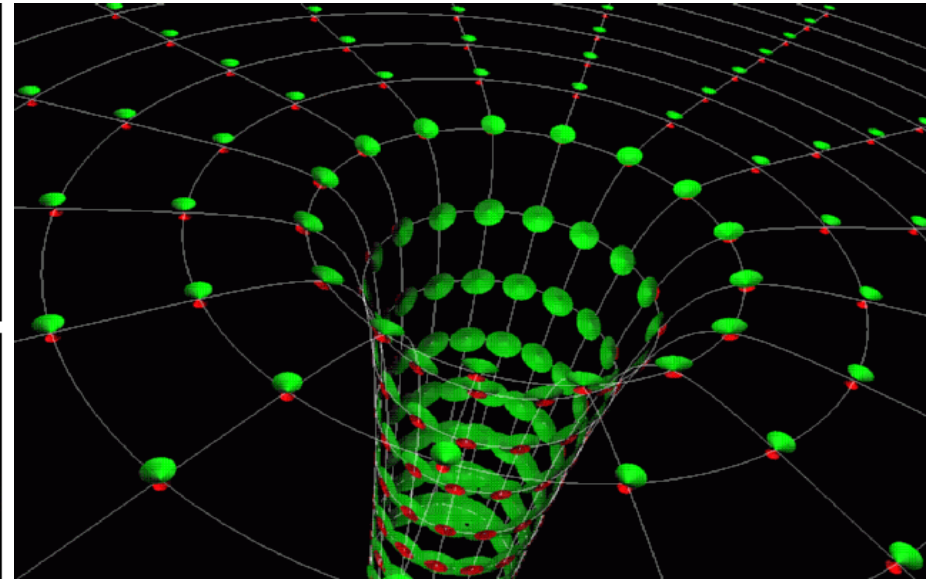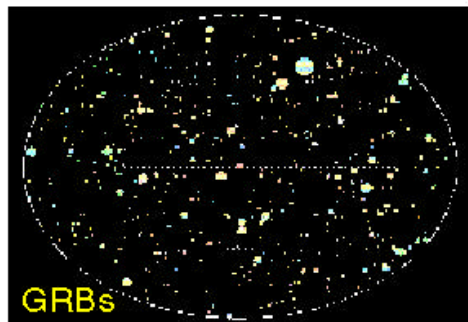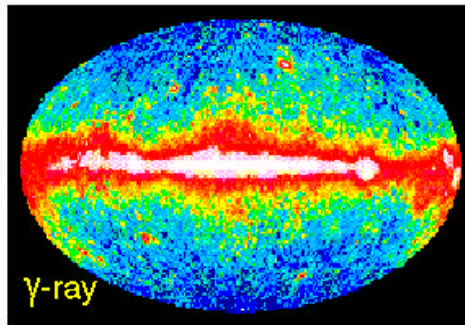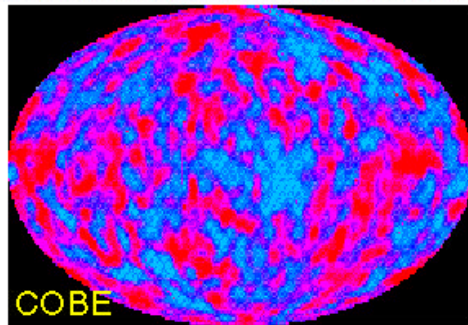*http://www.ligo.org*

COSMIC CONNECTIONS

XXXI SLAC Summer Institute SSI2003 July 28 - August 8, 2003

New Window on Universe
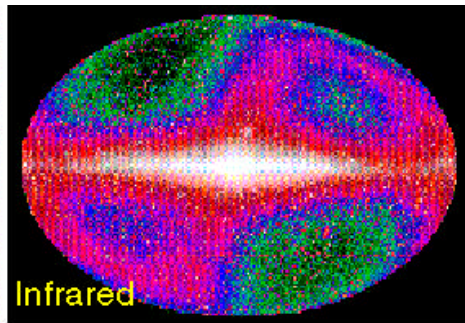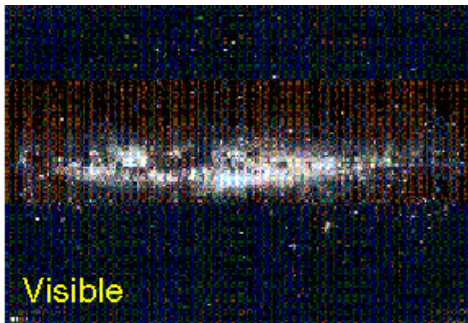
GRAVITATIONAL WAVES PROVIDE A NEW AND UNIQUE VIEW OF THE DYNAMICS OF THE UNIVERSE.

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!

Einstein's Theory of Gravitation
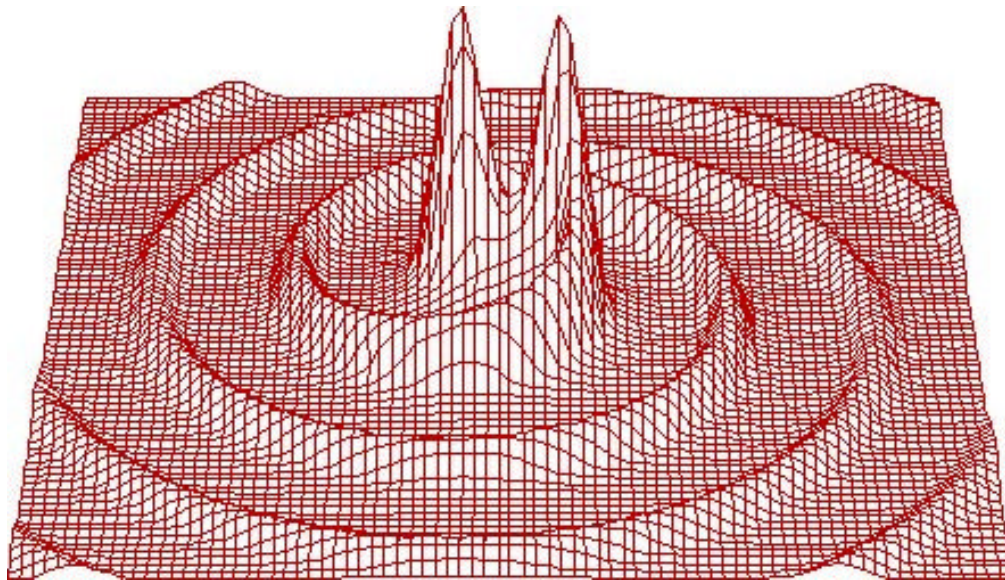
gravitational radiation
binary inspiral
of
compact objects

■ **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**

"Indirect" detection of gravitational waves
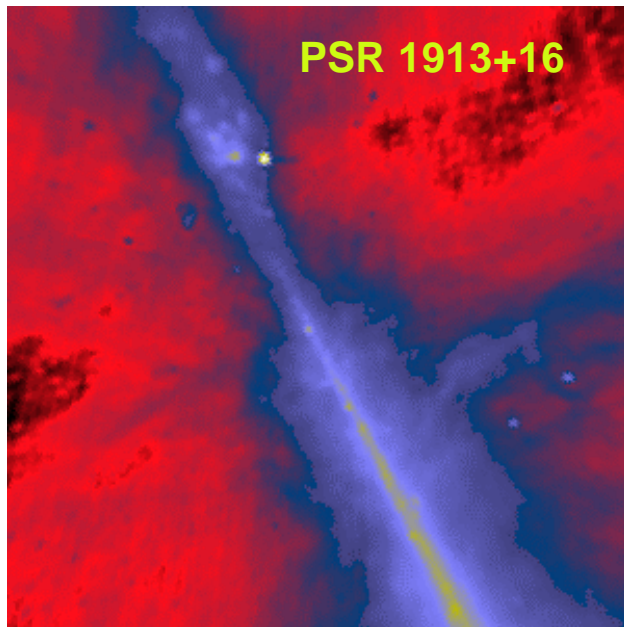
PSR 1913+16

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

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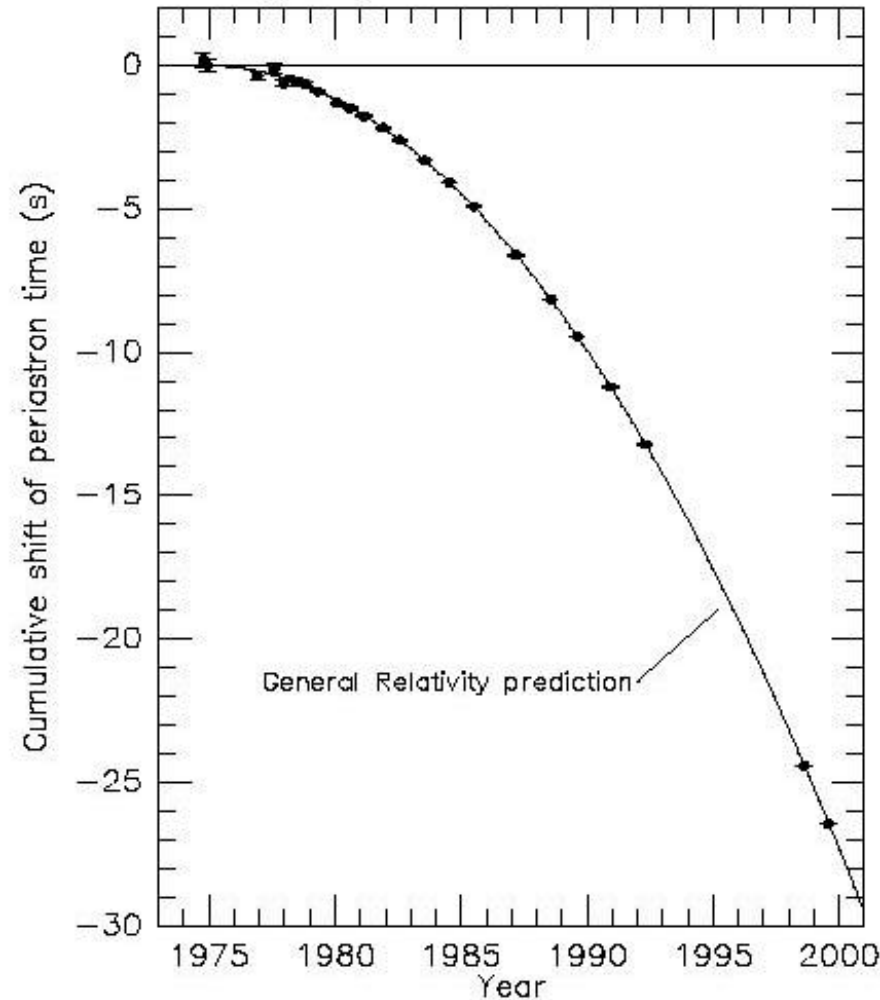
From J. H. Taylor and J. M. Weisberg, unpublished (2000)

Direct Detection
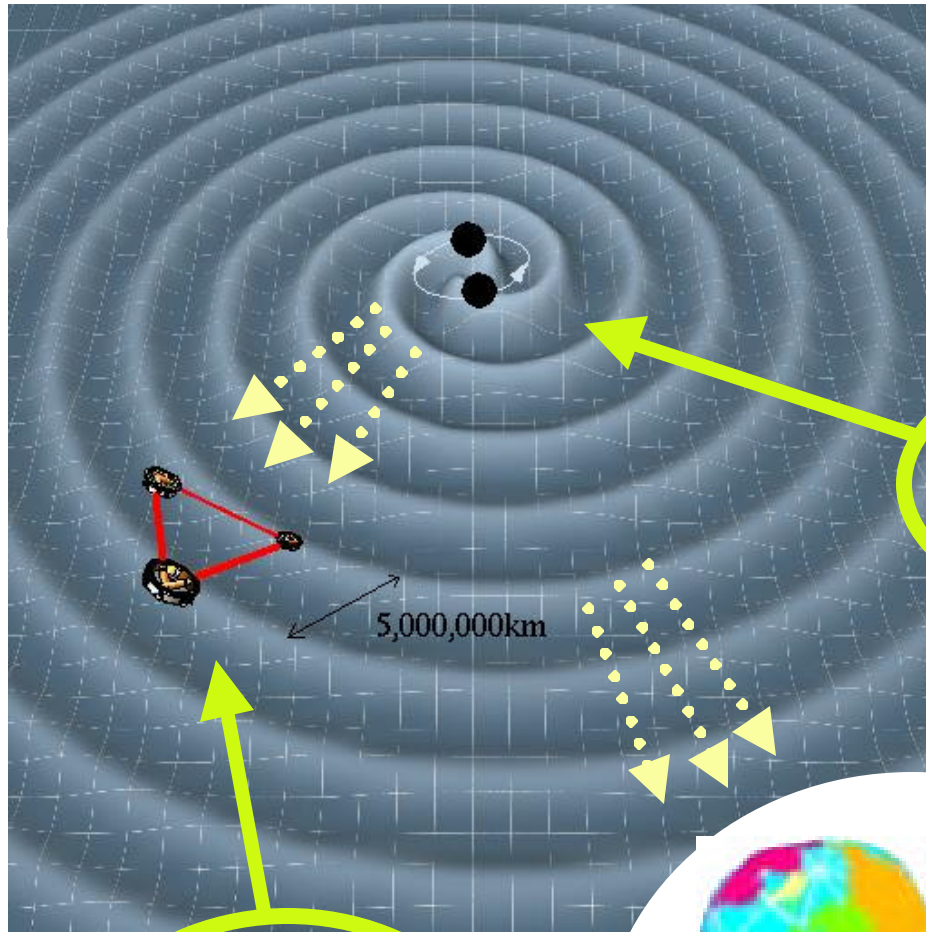
Gravitational Wave Astrophysical Source

Detectors in space LISA
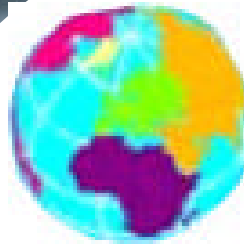
Terrestrial detectors LIGO,GEO,TAMA,Virgo,AIGO

5,000,000km
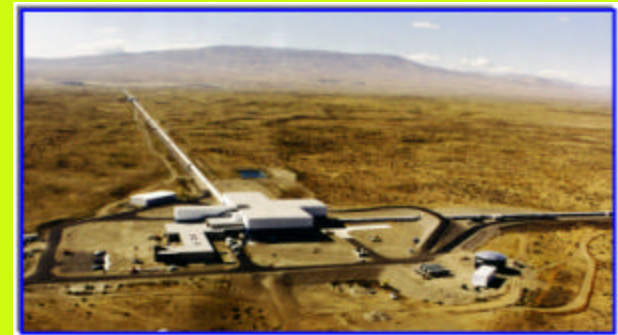
An International Network of Interferometers

Simultaneously detect signal (within msec)

GEO **Virgo**

LIGO

TAMA

AIGO
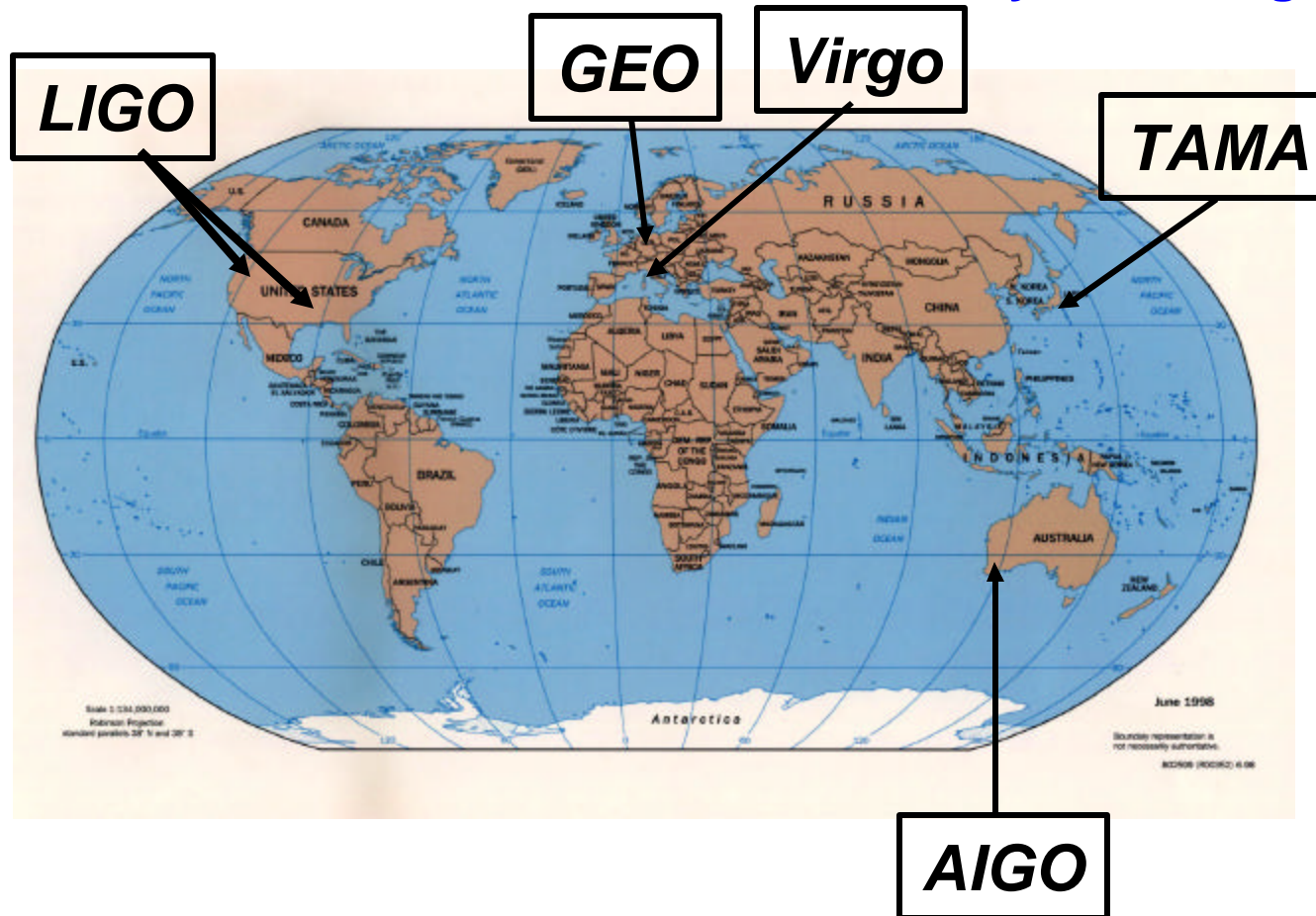
detection confidence

locate the sources

decompose the polarization of gravitational waves

Detecting a passing wave ….

Free masses
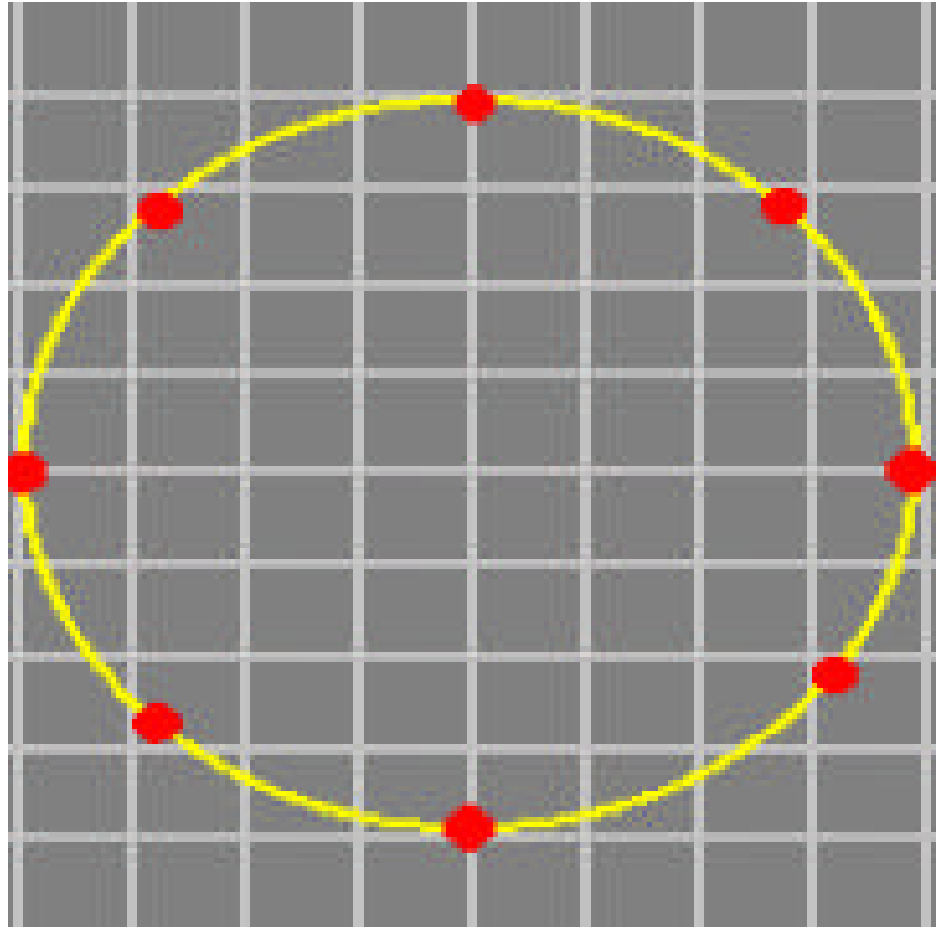
Detecting a passing wave ….

Interferometer
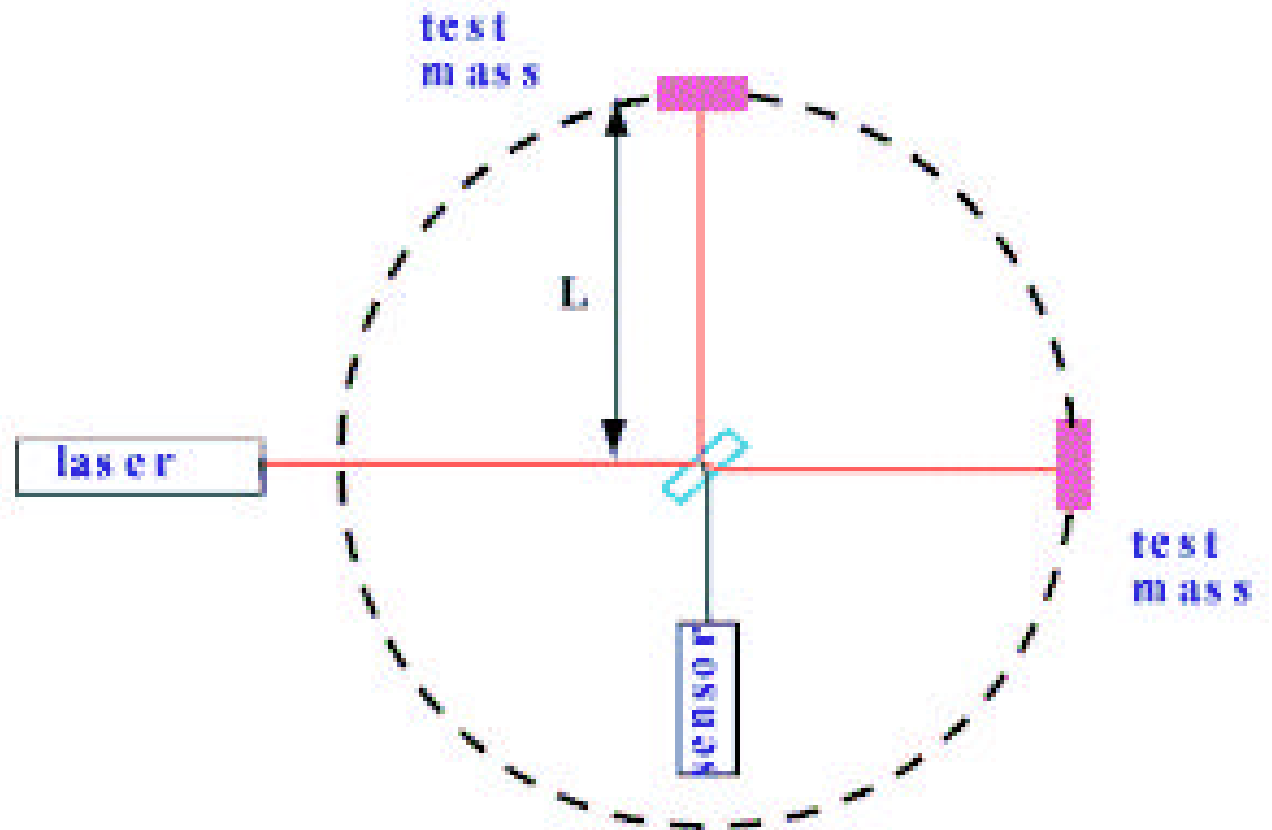
Interferometer Concept

- 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***

…causing the interference pattern to change at the photodiode

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

L_2

L_1

Beam splitter

photodiode

Test-masses

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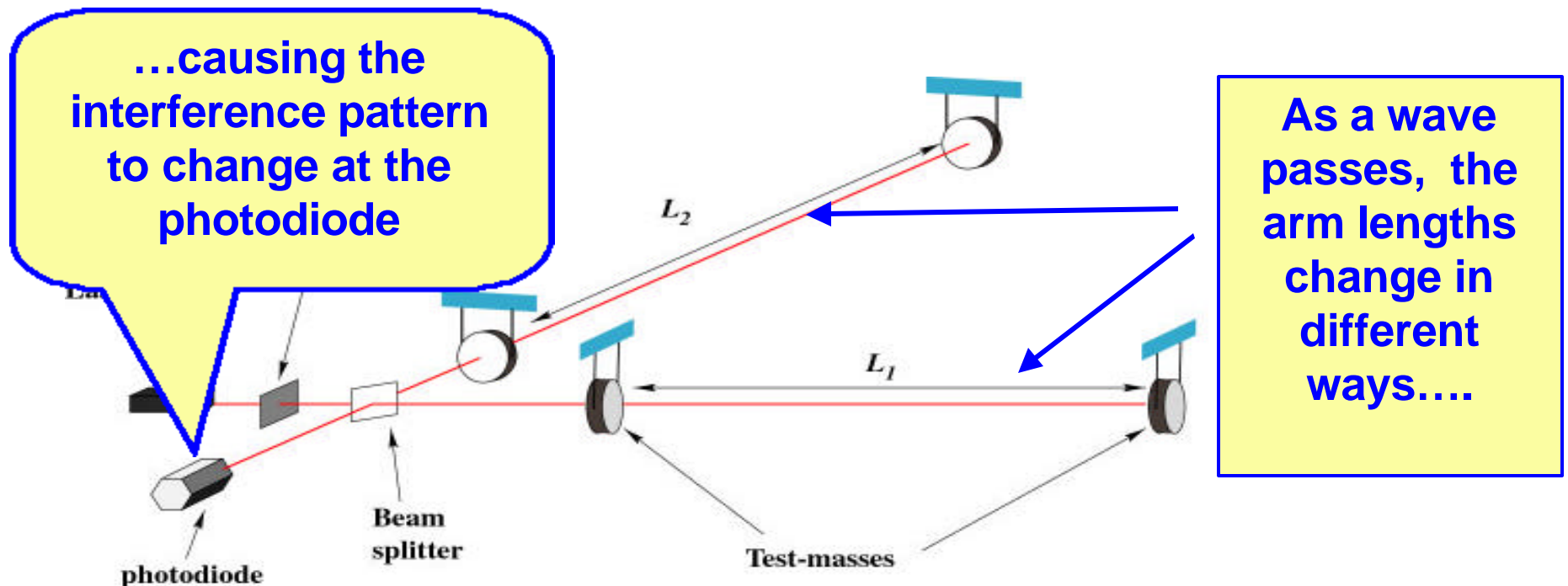
LIGO sites

LIGO (Washington)

("The evergreen state")

LIGO (Louisiana)

Some site details

LIGO-G030389-00-D
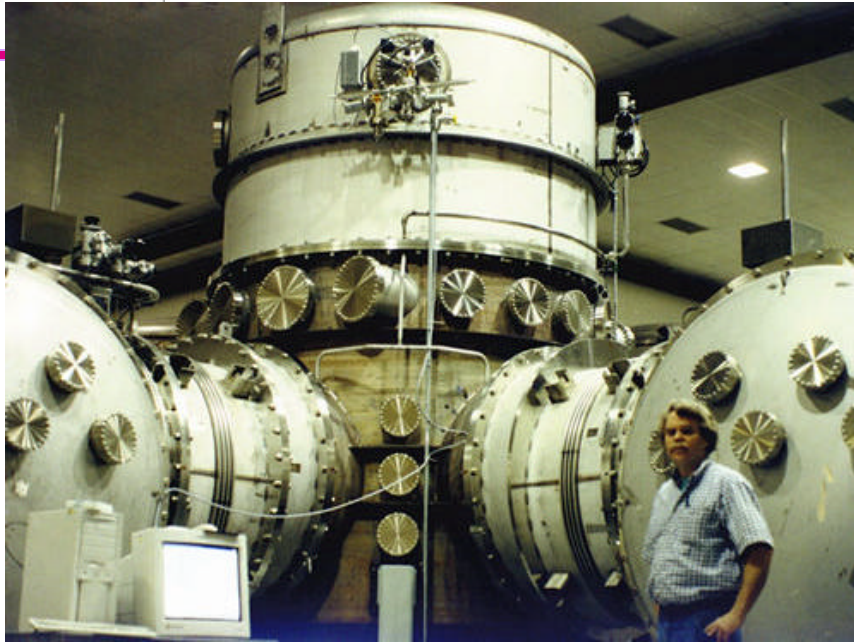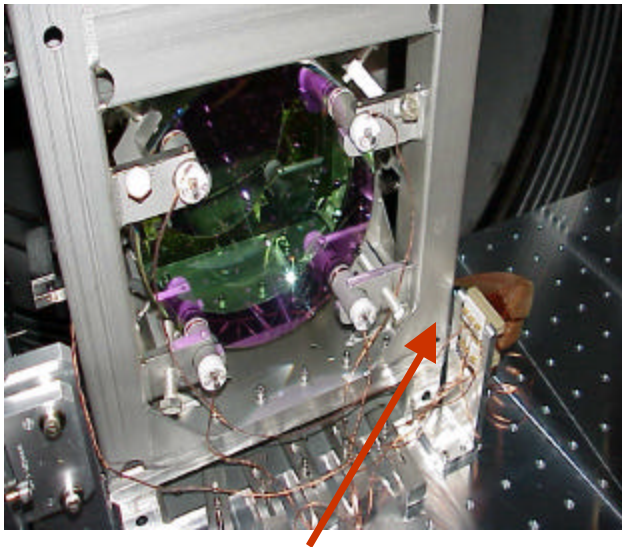
Optics suspended as simple pendulums
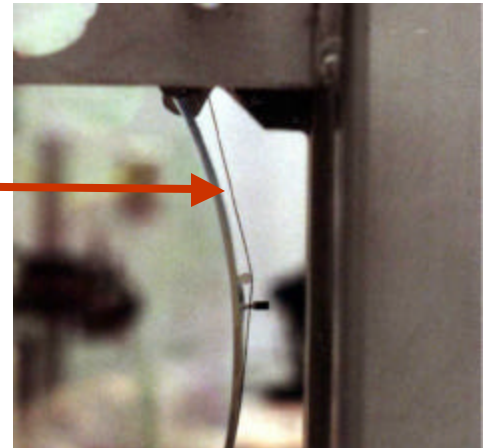
Shadow sensors & coil actuators provide damping and control forces

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

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LIGO-G030389-00-D

Some Commissioning Challenges

- Understand displacement fluctuations of 4-km arms at the millifermi level ($1/1000^{th}$ 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

LIGO

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

First Lock

S1 Science Run

S2 Science Run

● Washington 2K
● Louisiana 4k
● Washington 4K

Washington earthquake

LHO 2k wire accident

Now

Interferometer Length Control System

to mode cleaner

$(+)$ $(-)$

$(-)$ $(+)$

$(+)$

$(+)$

$(+)$ $(+)$

(photodiode)

S_{AQ} → $ETM_1 - ETM_2$

S_{RI} → $ETM_1 + ETM_2$

S_{PI} → RM ---→ $ITM_1 + ITM_2$
damping

S_{PQ} → BS ---→ $ITM_1 - ITM_2$
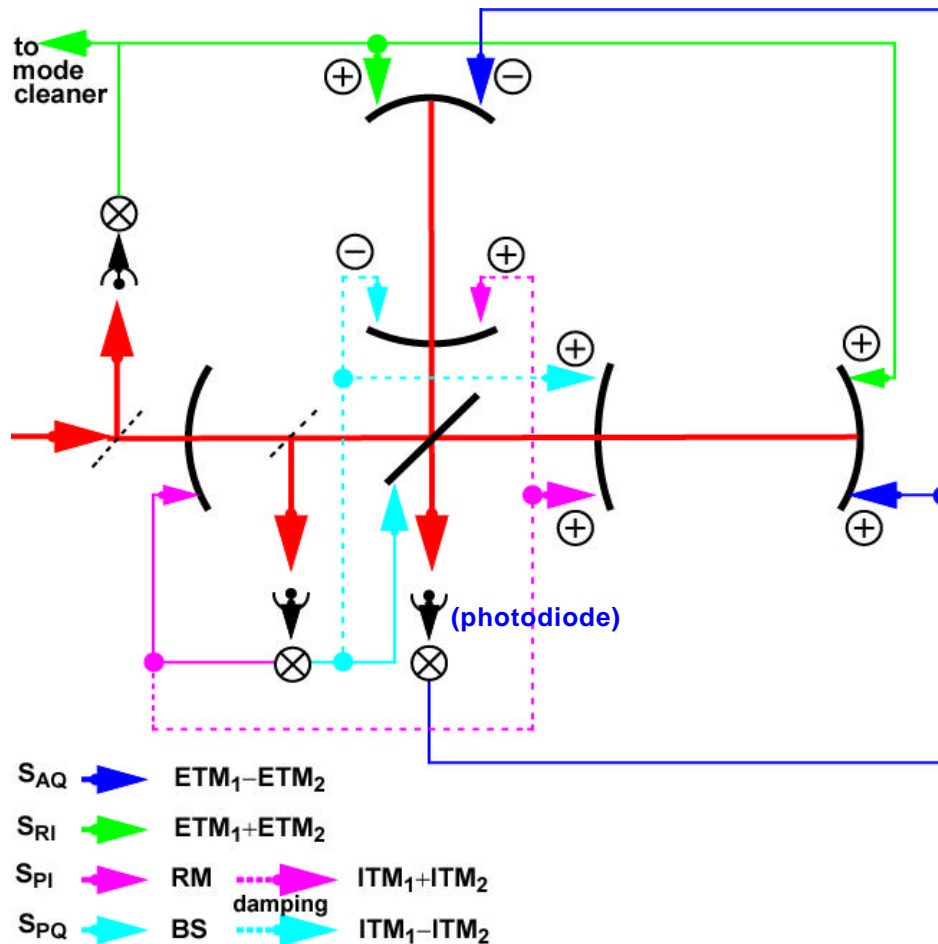
- Multiple Input / Multiple Output

- 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

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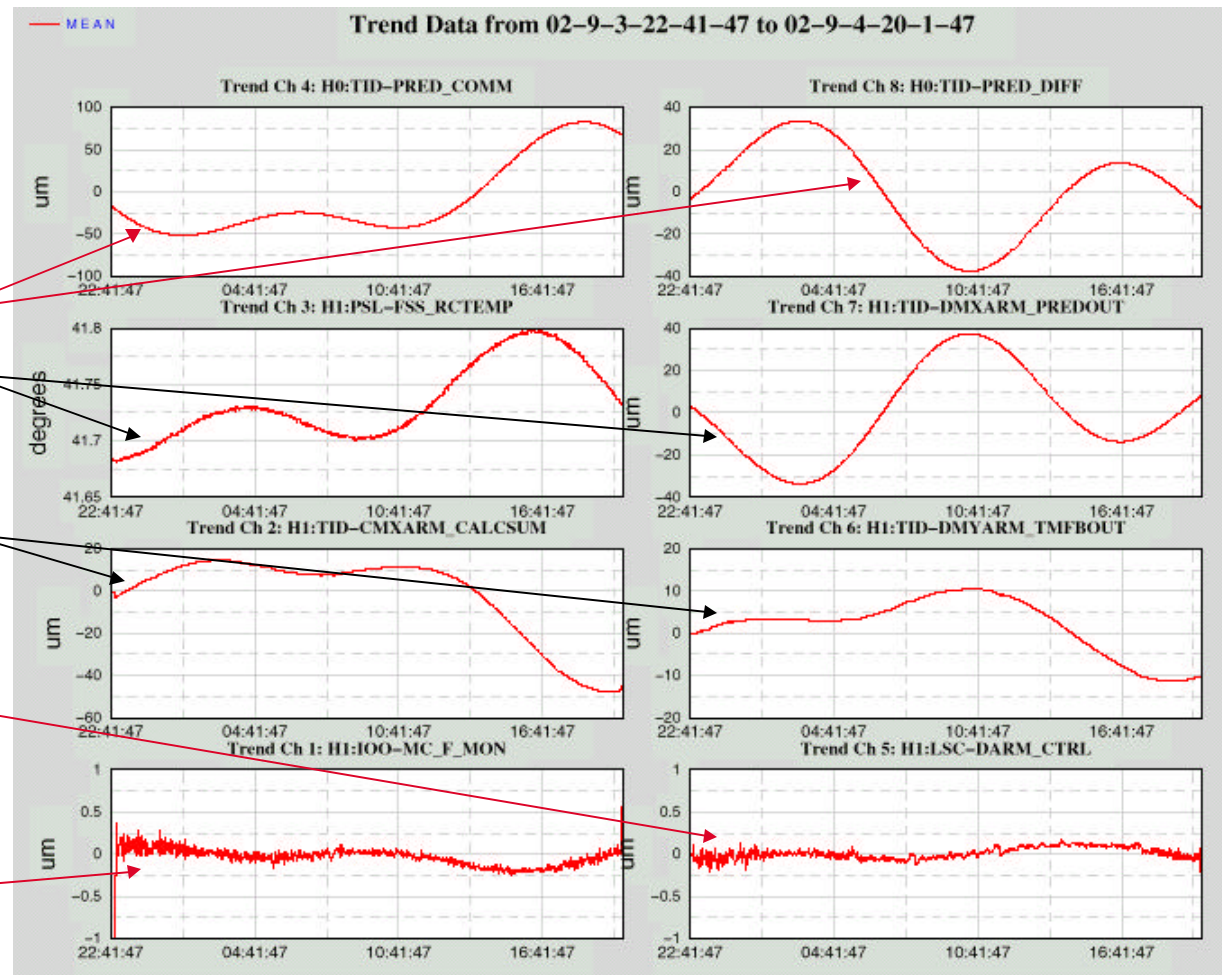
DC light level in recycling cavity

ongoing effort!

WFS1, WFS2A, WFS3, WFS4 not engaged

(alignment controls)

WFS1, WFS2A, WFS3, WFS4 engaged

Trend Ch 1: H1:LSC-LA_PTRT_NORM

DC light level in long arms

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LIGO-G030389-00-D

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
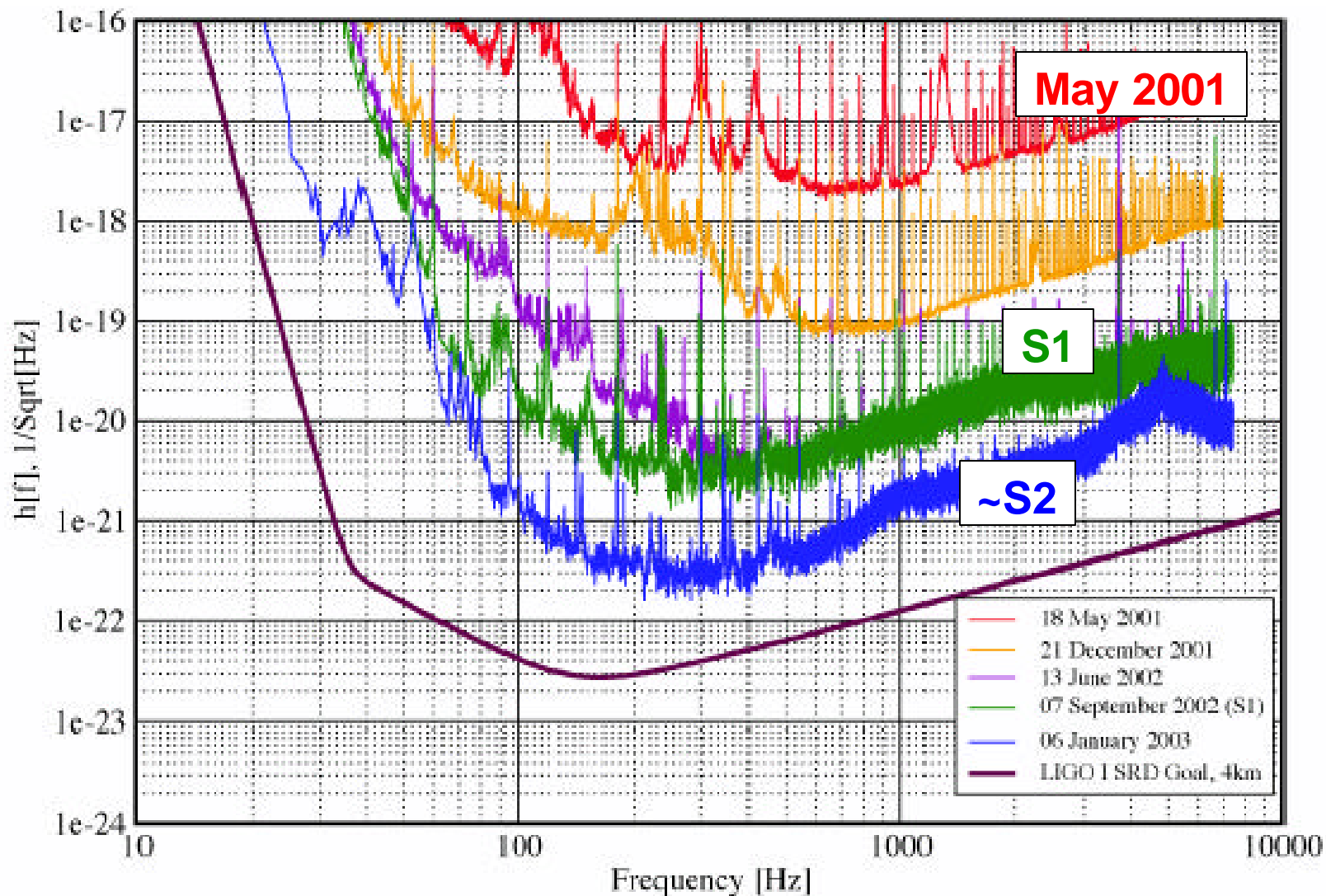
Hanford control room
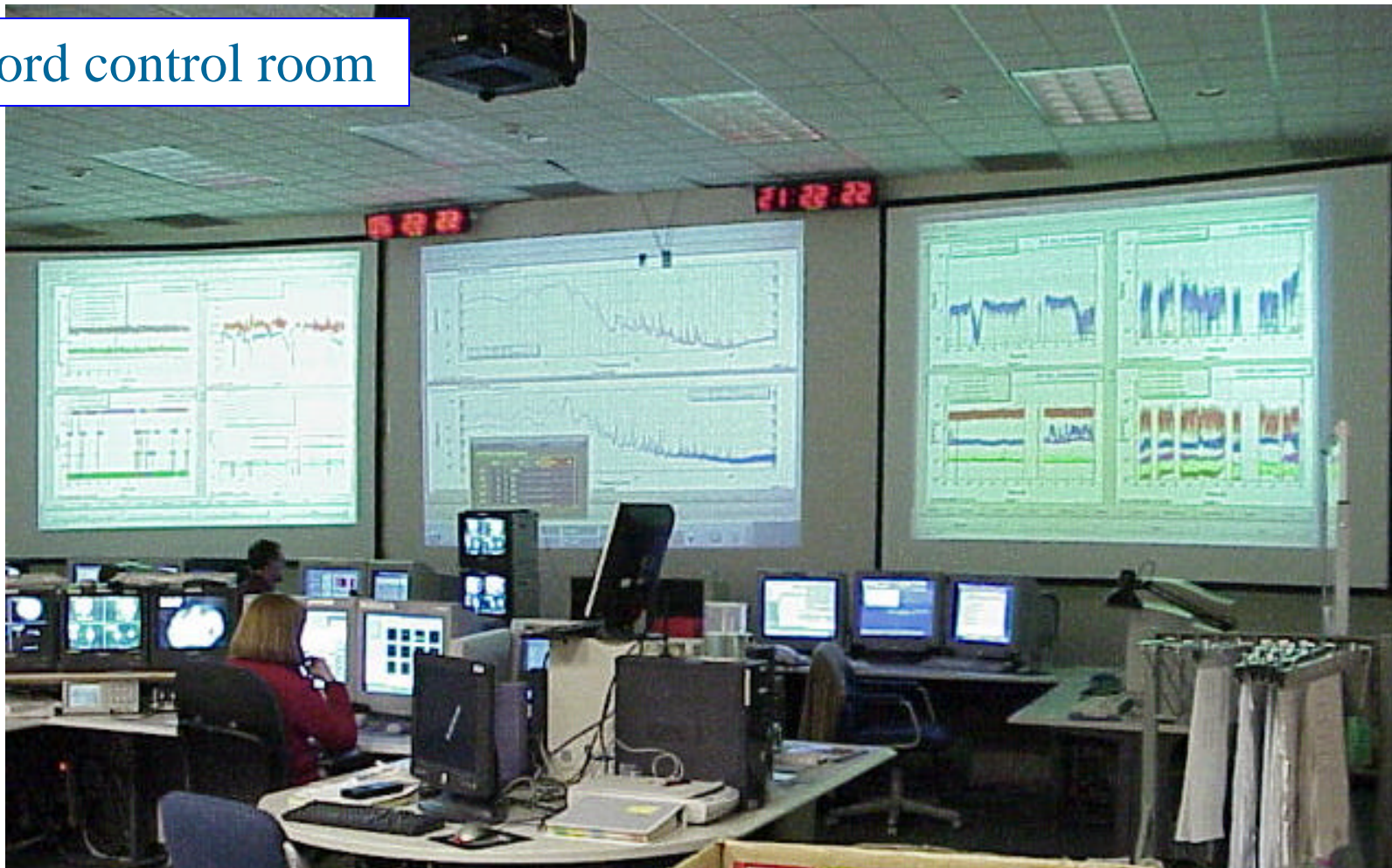
The S1 run: In-Lock Data Summary

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**
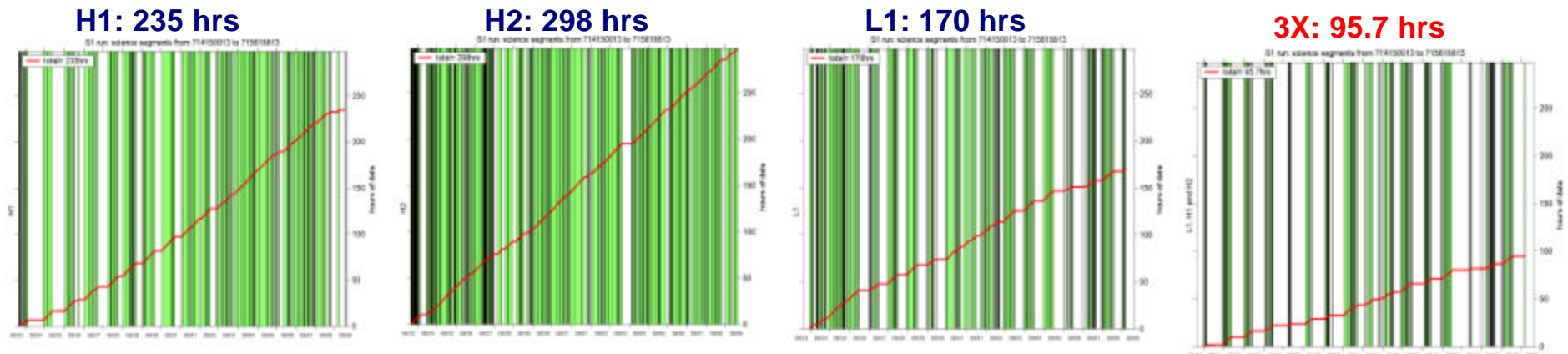
- **August 23 – September 9, 2002: 408 hrs (17 days).**
  - H1 (4km): duty cycle 57.6% ; Total Locked time: 235 hrs
  - H2 (2km): duty cycle 73.1% ; Total Locked time: 298 hrs
  - L1 (4km): duty cycle 41.7% ; Total Locked time: 170 hrs

- 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

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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 Sensitivities for the LIGO Interferometers for S1

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

LHO 2Km

LHO 4Km

LLO 4Km

Legend:
- LHO 4km
- LHO 2km
- LLO 4km
- LIGO I SRD Goal, 2km
- LIGO I SRD Goal, 4km

Axis label: h[f], 1/Sqrt[Hz]

Axis label: Frequency [Hz]

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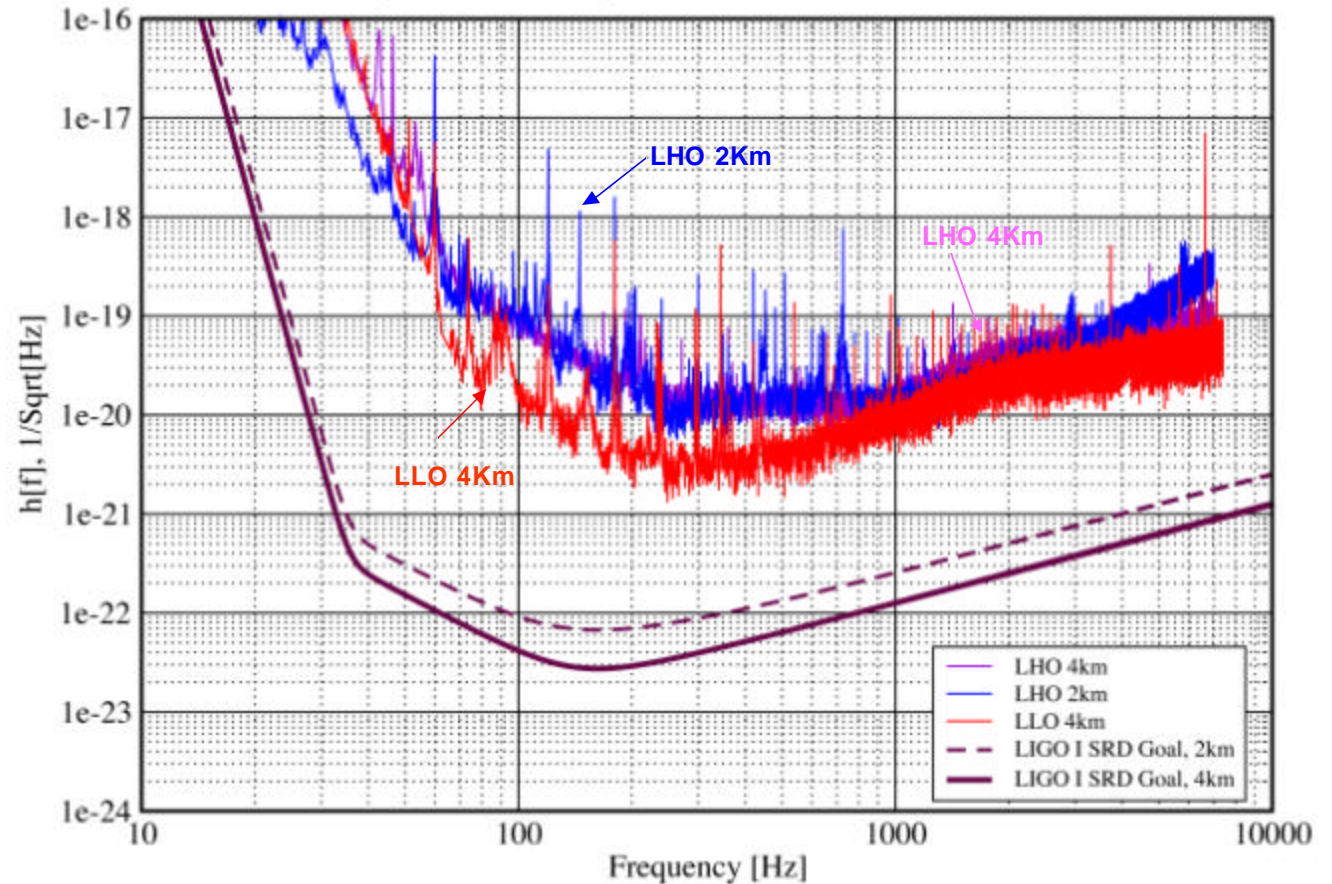
Potential gravity wave sources

- **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).

  - **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

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
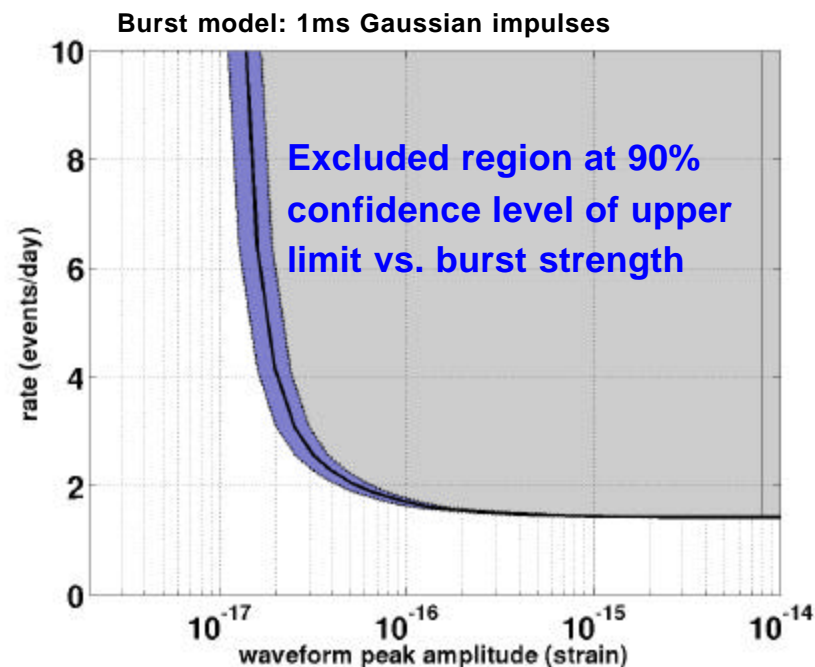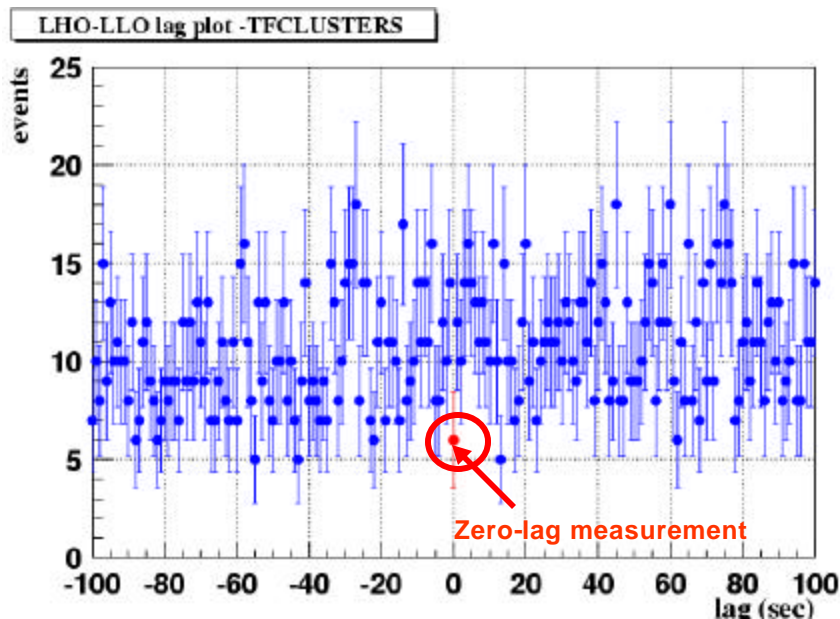
Search for Inspirals

- **Sources:** orbital-decaying **compact binaries: neutron star** known to exist and emitting gravitational waves (Hulse&Taylor).

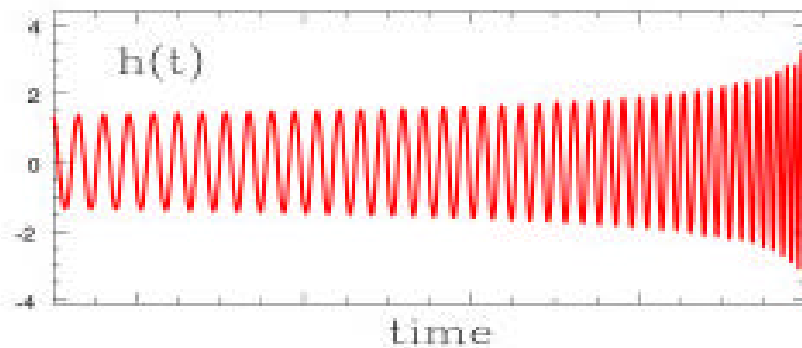- **Search method:** system can be **modeled**, waveform is calculable:

  - » 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

Range of detectability for SNR = 8
1.4 M$_\odot$ + 1.4 M$_\odot$ Coalescing Binary (Optimal Orientation)
L4km: 110 kpc < D < 210 kpc
H4km: 40 kpc < D < 75 kpc
H2km: 38 kpc < D < 70 kpc
GEO: 4 kpc < D <   8 kpc

Milky Way Galaxy
Large, Small Magellanic Clouds
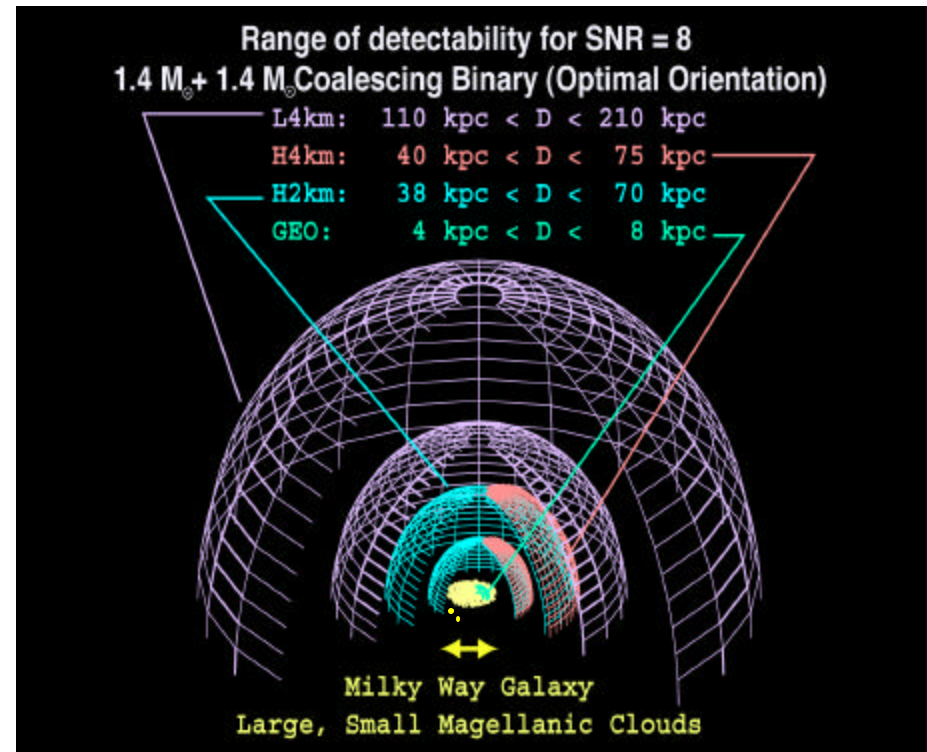
Results of the Inspiral Search

LIGO

- 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** $\varepsilon = 0.53$

  » Effective no. MWEG: $\mathbf{N_G} = \varepsilon(L_{pop}/L_G)=0.53 \times 1.13=0.60$

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

  » 90% confidence limit = **2.3/ (time * N_G).**

  » Express the rate as a rate per **Milky Way Equivalent Galaxies** (MWEG).

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

- Compare with:

  ➤ Previous experimental results:

    – LIGO 40m '94: 0.5/hr (25hrs, D<25kpc, Allen et al., PRD 1998)

    – TAMA300 '99: 0.6/hr (6 hr, D<6kpc, Tagoshi et al., PRD 2001)

    – TAMA300 DT6: 82/yr (1,038 hr, D<33 kpc, GWDAW 2002)

  ➤ Expected Galactic rate: ~10^{-6} - 5×10^{-4} /yr (Kalogera et al)

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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

Results of Stochastic Search

Interferometer Pair	90% CL Upper Limit	T_{obs}
LHO 4km-LLO 4km	W_{GW} (40Hz - 314 Hz) < 55	64.0 hrs
LHO 2km-LLO 4km	W_{GW} (40Hz - 314 Hz) < 23	51.3 hrs

- Non-negligible LHO 4km-2km (H1-H2) cross-correlation; currently being investigated.

- Previous best upper limits:

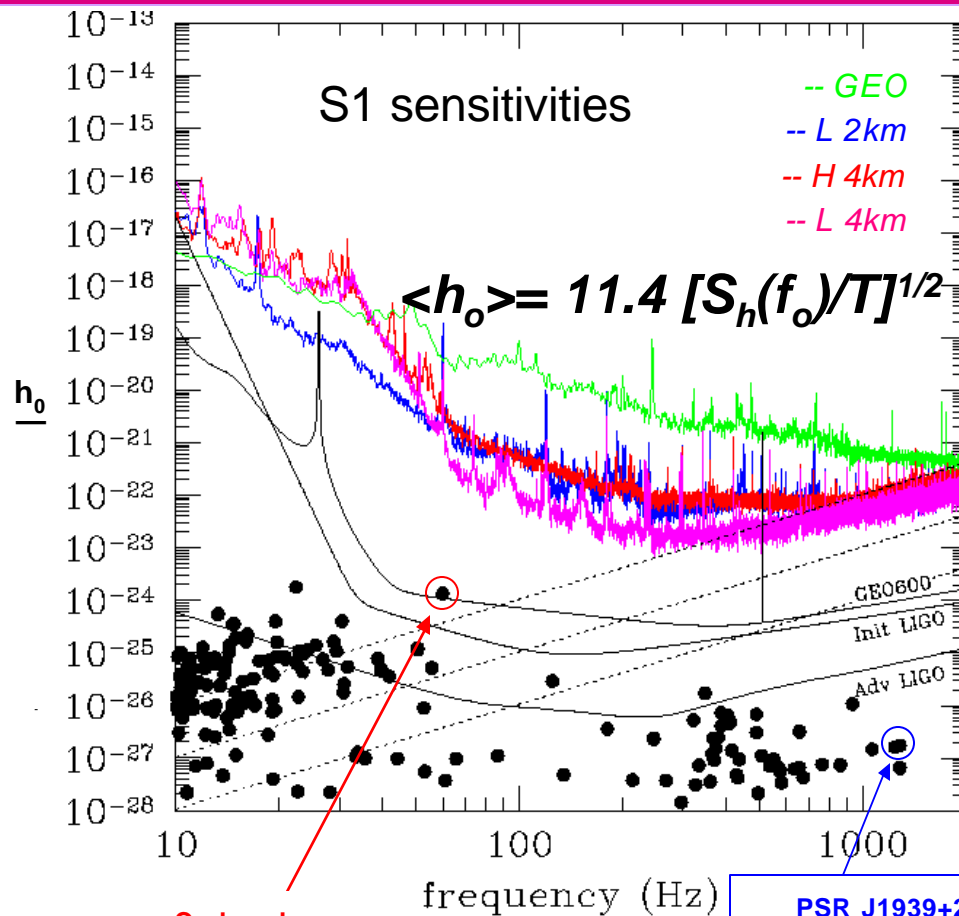   » *Measured:* Garching-Glasgow interferometers :

    » *Measured*: EXPLORER-NAUTILUS (cryogenic bars): $\Omega_{GW}(f) < 3 \times 10^5$

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

Expectations for Continuous Waves

LIGO

S1 sensitivities

-- GEO
-- L 2km
-- H 4km
-- L 4km

$$\langle h_o \rangle = 11.4 \, [S_h(f_o)/T]^{1/2}$$

h_o

GEO600
Init LIGO
Adv LIGO

frequency (Hz)

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 $e = d/I_{zz}$: 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

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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	$(1.9\pm0.1)\times10^{-21}$	$(2.2\pm0.1)\times10^{-21}$
LLO	$(2.7\pm0.3)\times10^{-22}$	$(1.4\pm0.1)\times10^{-22}$
LHO-2K	$(5.4\pm0.6)\times10^{-22}$	$(3.3\pm0.3)\times10^{-22}$
LHO-4K	$(4.0\pm0.5)\times10^{-22}$	$(2.4\pm0.2)\times10^{-22}$

- LLO upper limit on $h_o < 1.4\times10^{-22}$ constrain **ellipticity < 2.7×10^{-4}** (assuming $M=1.4M_{sun}$, r=10km, R=3.6kpc)

- 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"