LIGO Status

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on behalf of the LIGO Scientific Collaboration
http://www.ligo.org

University of Calgary
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Challenges for a young field

- First direct detection of gravitational waves
  - » Detection possible with existing detectors
  - » Probable with upgrades to existing facilities, and/or near-future new ones
- Transition to a field of observational astronomy
  - » EM emission – incoherent superposition of many emitters
  - » Gravitational wave (GW) emission – coherently produced by bulk motions of matter
  - » Matter is largely transparent to gravitational waves
    - – Makes them hard to detect
    - – Makes them a good probe of previously undetectable phenomena, e.g. dynamics of supernovae, black hole and neutron star mergers
  - » Gravitational wave detectors are naturally all-sky devices; “pointing” can be done later in software

Overview

- Introduction
  - » What are gravitational waves, and what is the observable effect?
  - » Sources
  - » Hulse-Taylor binary pulsar
- LIGO interferometers
  - » Interferometric detectors. LIGO sites and installations.
  - » Some topics in commissioning: the path to design sensitivity
  - » Science mode running with LIGO, GEO and TAMA
- Data analysis
  - » Analyses from science runs for continuous wave sources, mostly. Inspiral, burst, stochastic if we have time.
    - – Search for gravitational waves from known pulsars
    - – Hierarchical search for unknown objects
      - Incoherent method
      - Coherent method

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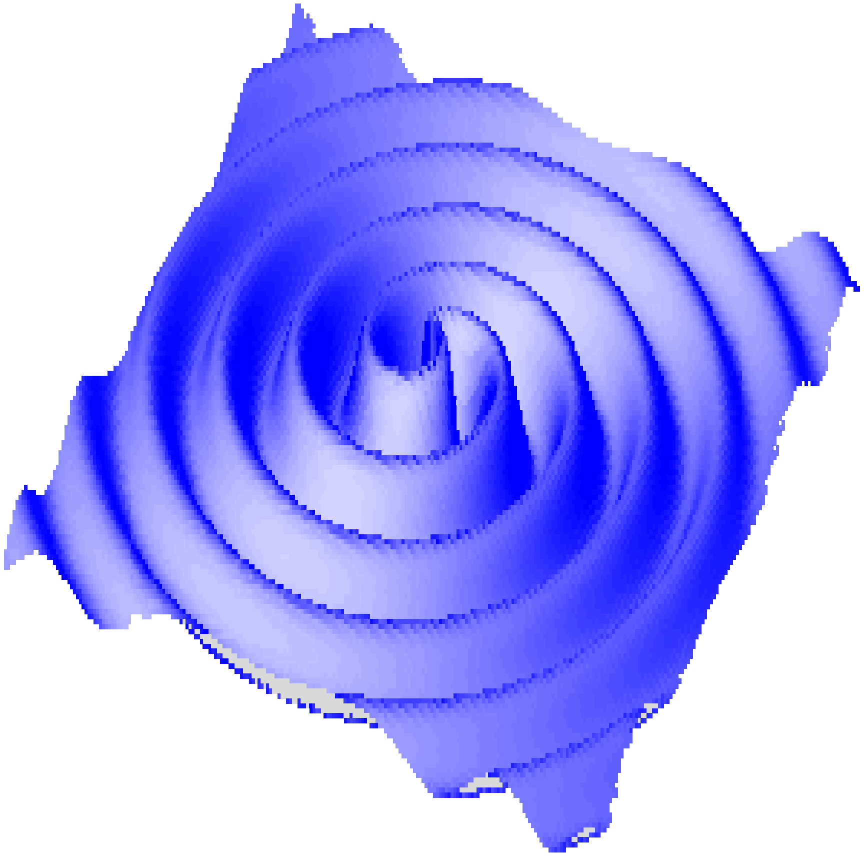
Gravitational waves

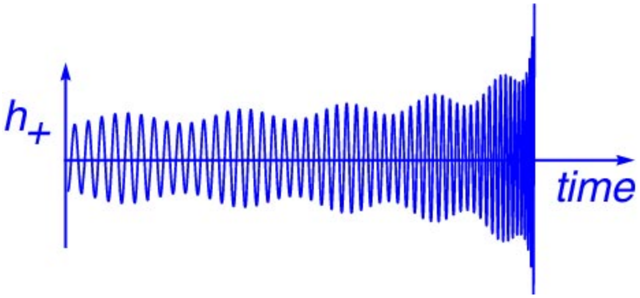
- GWs are "ripples in spacetime": rapidly moving masses generate fluctuations in spacetime curvature:
  - They are expected to propagate at the speed of light
  - They stretch and squeeze space

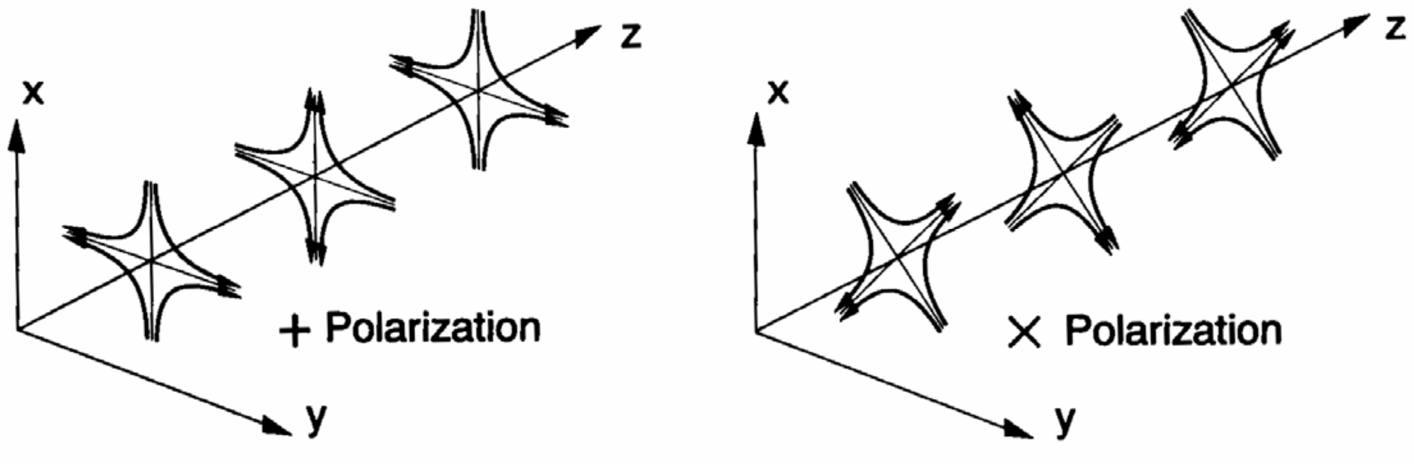
$$g_{\mu\nu} = \eta_{\mu\nu} + \boxed{h_{\mu\nu}}$$



The two polarizations: the gravitational waveforms

- The fields are described by **2** independent polarizations: $h_+(t)$ and $h_x(t)$
- The waveforms carry detailed information about astrophysical sources
- With gravitational wave detectors one observes (a combination of) $h_+(t)$ and $h_x(t)$)





LIGO-G070039-00-Z

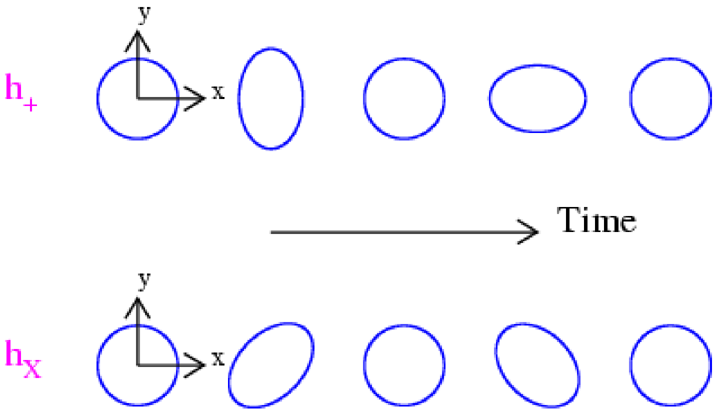
What is the observable effect?

Example:

Ring of test masses

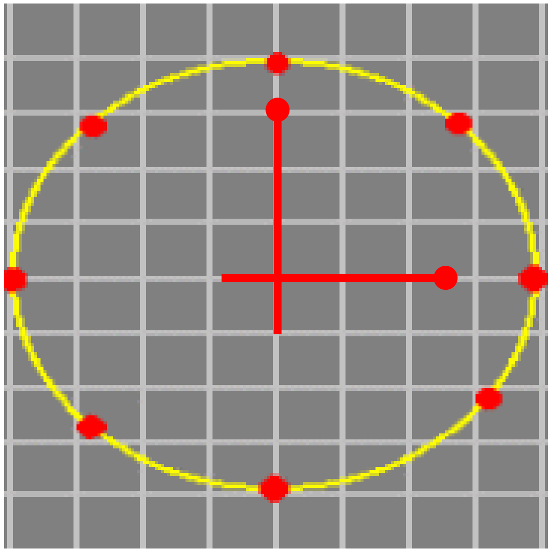
responding to wave

propagating along z



Amplitude parameterized by (tiny) dimensionless strain h:

$$h(t) = \frac{\delta L(t)}{L}$$

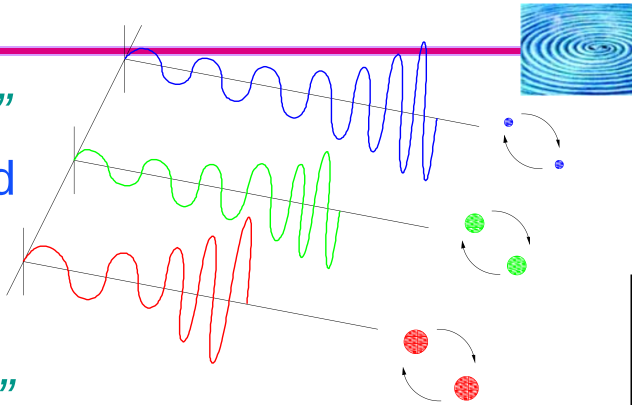


Why look for gravitational radiation?

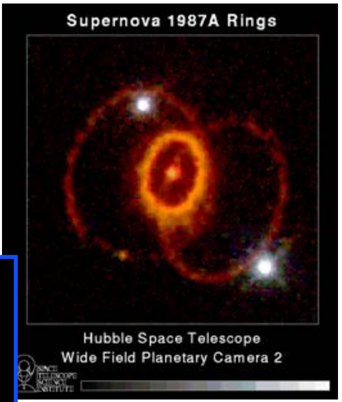
- “Because it’s there!”
  - » (George Mallory upon being asked, “why climb Everest?”)
- Test General Relativity:
  - » Quadrupolar radiation? Travels at speed of light?
  - » Unique probe of strong-field gravity
- Gain different view of Universe:
  - » Sources cannot be obscured by dust / stellar envelopes
  - » Detectable sources some of the most interesting, least understood in the Universe
  - » **Opens up entirely new non-electromagnetic spectrum.**
  - » **May find something unexpected**

What makes gravitational waves?

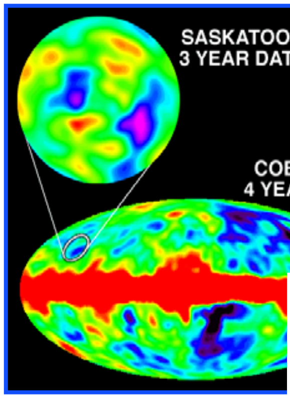
- Compact binary inspiral: *“chirps”*
  - NS-NS waveforms are well described
  - BH-BH need better waveforms



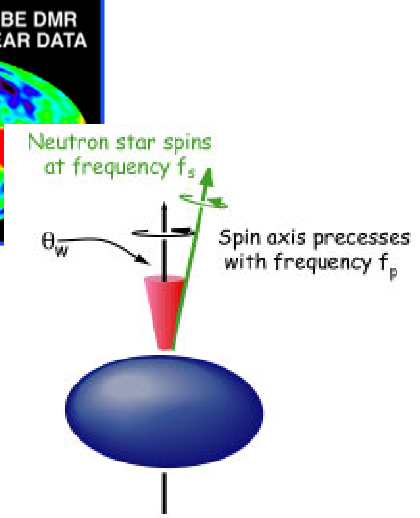
- Supernovae / GRBs: *“bursts”*
  - burst signals in coincidence with signals in electromagnetic radiation / neutrinos
  - all-sky untriggered searches too



- Cosmological Signal: *“stochastic background”*



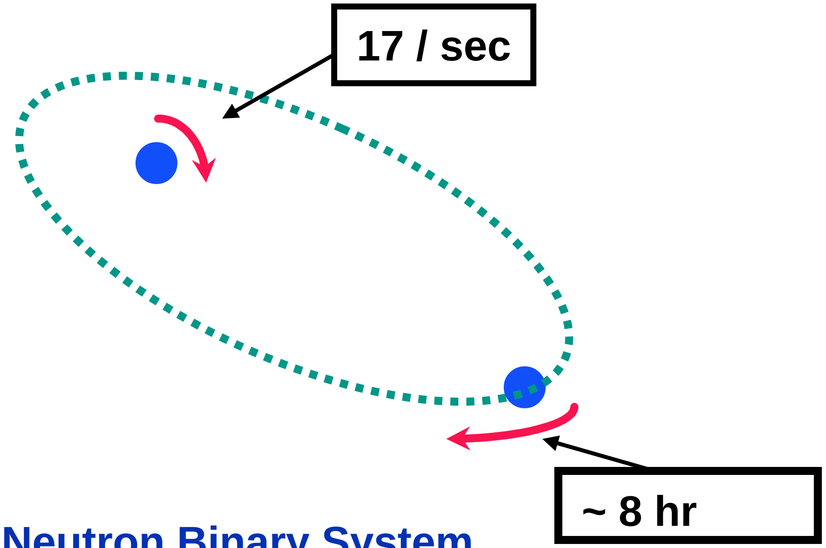
- Pulsars in our galaxy: *“continuous waves”*
  - search for observed neutron stars
  - all-sky search (computing challenge)



Orbital decay : strong indirect evidence

Neutron Binary System – Hulse & Taylor

PSR 1913 + 16 -- Timing of pulsars



Neutron Binary System

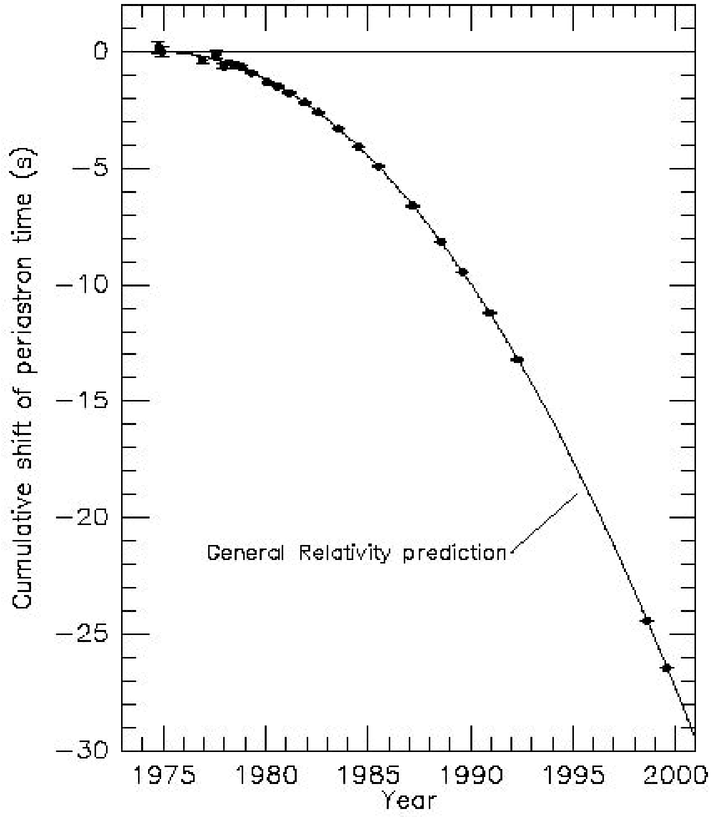
- **separated by ~2x10^6 km**
- **$m_1 = 1.44m_\odot$; $m_2 = 1.39m_\odot$; $\varepsilon = 0.617$**

Prediction from general relativity

- **spiral in by 3 mm/orbit**
- **rate of change orbital period**

Emission 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)

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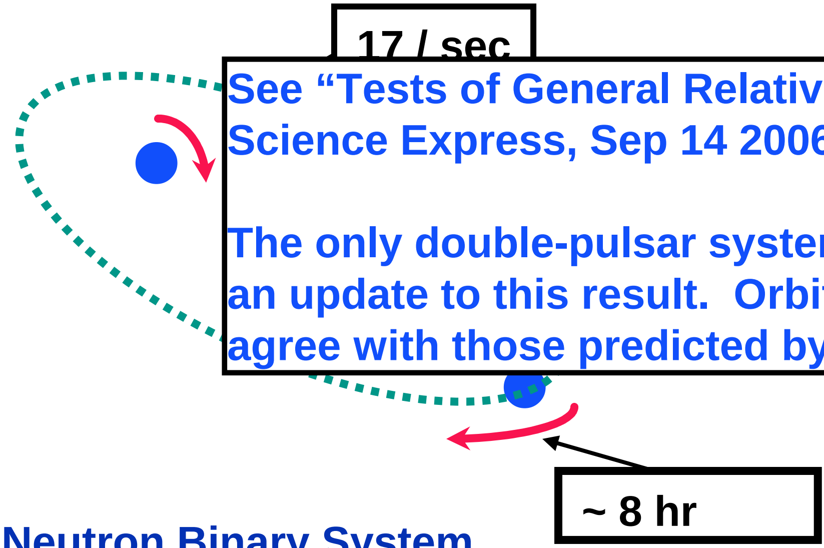
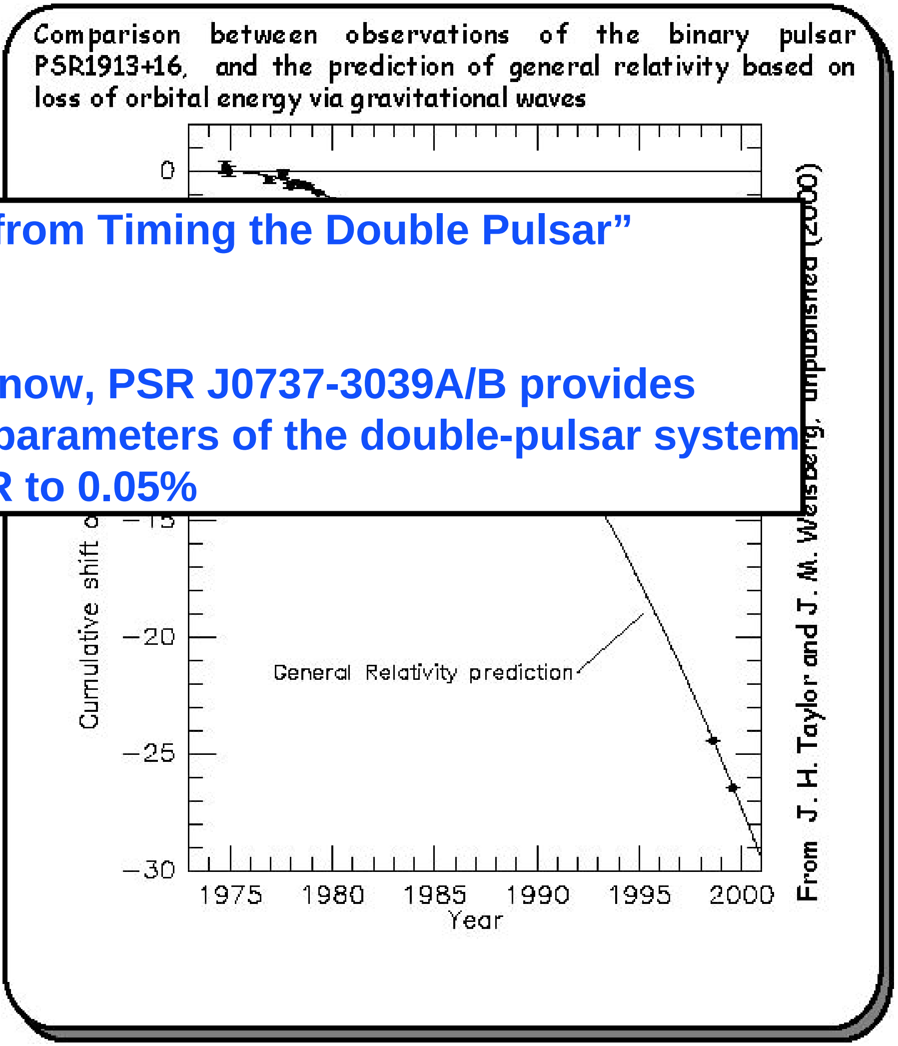


See "Tests of General Relativity from Timing the Double Pulsar" Science Express, Sep 14 2006

The only double-pulsar system know, PSR J0737-3039A/B provides an update to this result. Orbital parameters of the double-pulsar system agree with those predicted by GR to 0.05%

Emission of gravitational waves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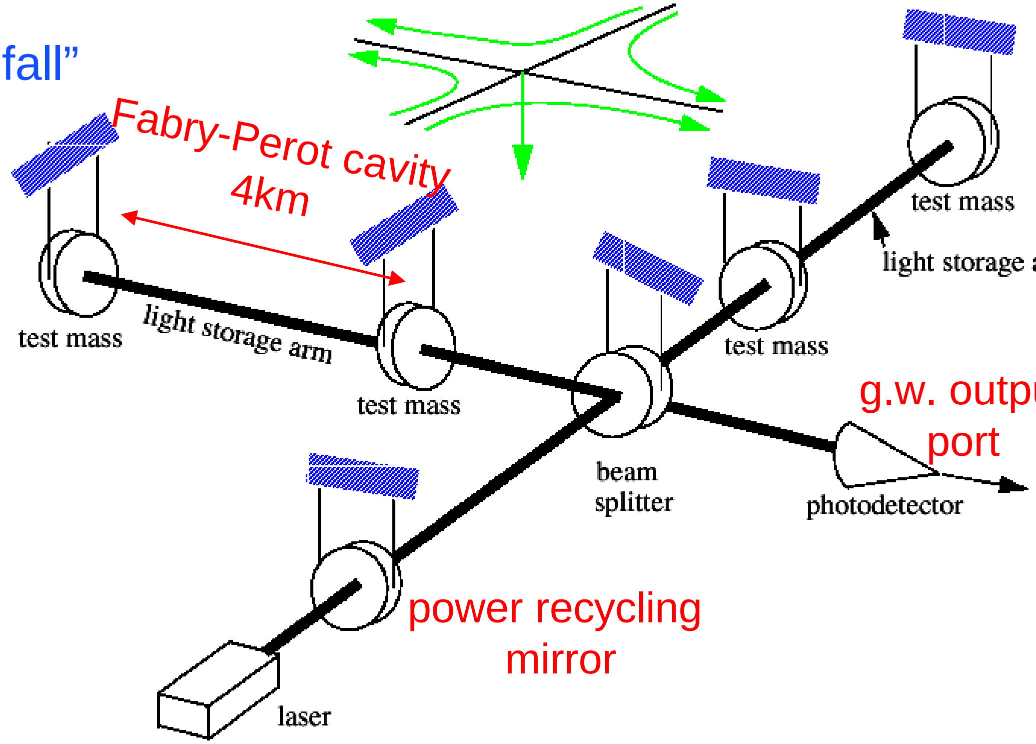
Gravitational wave detection

- Suspended Interferometers
  - » Suspended mirrors in “free-fall”
  - » Michelson IFO is “natural” GW detector
  - » Broad-band response (~50 Hz to few kHz)
  - » Waveform information (e.g., chirp reconstruction)



LIGO design length sensitivity: 10^{-18}m

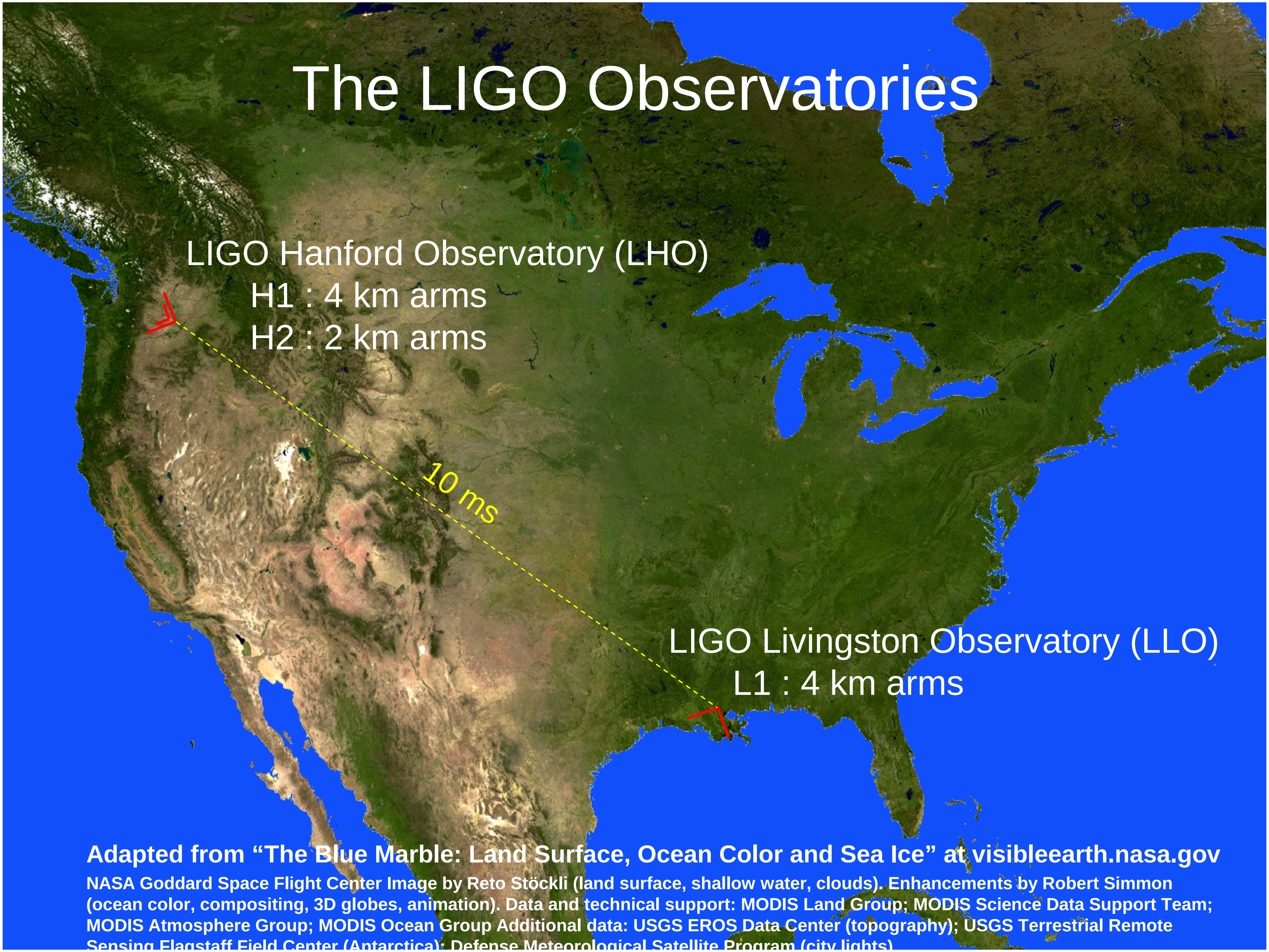
LIGO sites

LIGO (Washington)
(4km and 2km)

LIGO (Louisiana)
(4km)

Funded by the National Science Foundation; operated by Caltech and MIT; the research focus for more than 500 LIGO Scientific Collaboration members worldwide.

The LIGO Observatories



LIGO Hanford Observatory (LHO)
H1 : 4 km arms
H2 : 2 km arms

LIGO Livingston Observatory (LLO)
L1 : 4 km arms

Adapted from “The Blue Marble: Land Surface, Ocean Color and Sea Ice” at visibleearth.nasa.gov

NASA Goddard Space Flight Center Image by Reto Stöckli (land surface, shallow water, clouds). Enhancements by Robert Simmon (ocean color, compositing, 3D globes, animation). Data and technical support: MODIS Land Group; MODIS Science Data Support Team; MODIS Atmosphere Group; MODIS Ocean Group Additional data: USGS EROS Data Center (topography); USGS Terrestrial Remote Sensing Flagstaff Field Center (Antarctica); Defense Meteorological Satellite Program (city lights)

Evacuated Beam Tubes Provide Clear Path for Light

Vacuum required:
$<10^{-9}$ Torr

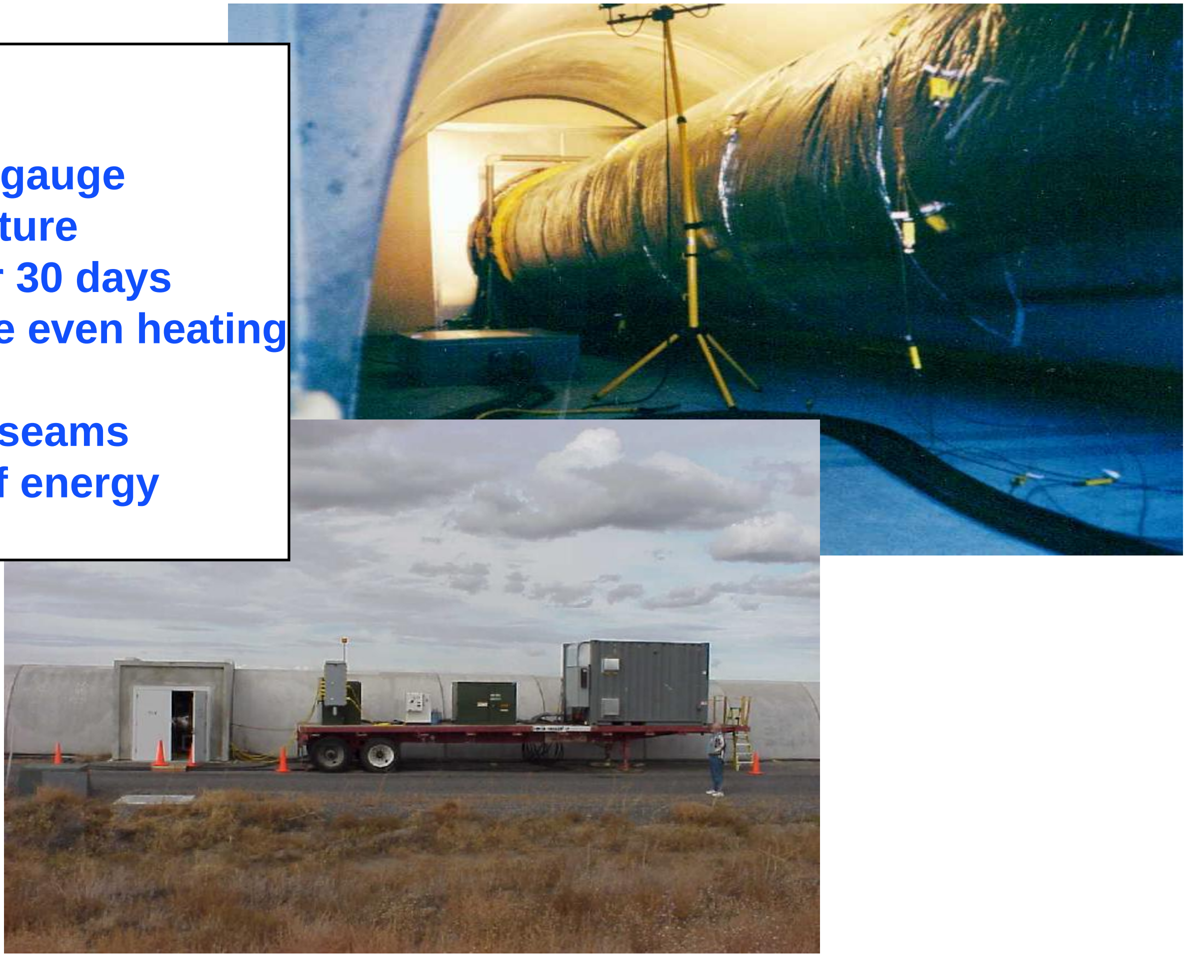
Evacuated Beam Tubes Provide Clear Path for Light

Bakeout facts:

- 4 loops to return current, 1” gauge
- 1700 amps to reach temperature
- bake temp 140 degrees C for 30 days
- 400 thermocouples to ensure even heating

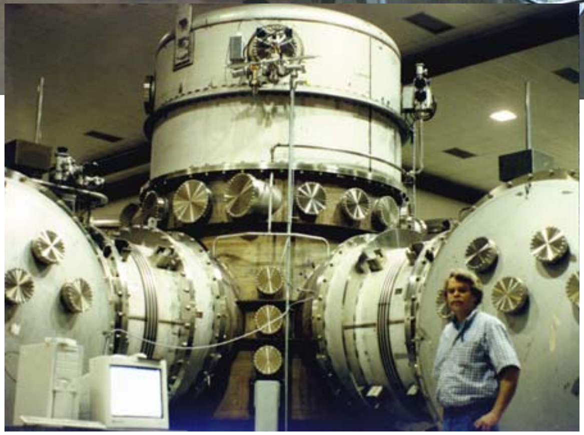
- each site has 4.8km of weld seams
- full vent of vacuum: ~ 1GJ of energy

Vacuum required:
$<10^{-9}$ Torr



Vacuum chambers provide quiet homes for mirrors

The view inside the Corner Station



Standing at the 4k vertex: beam splitter

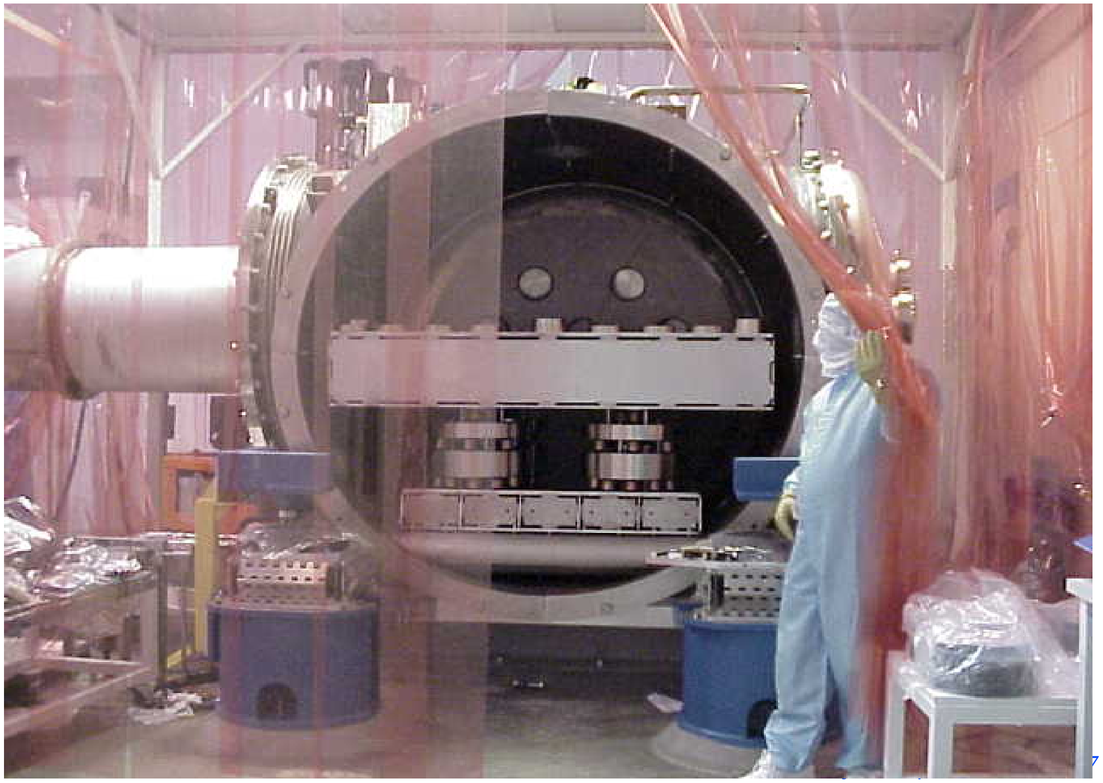
Seismic Isolation – Springs and Masses

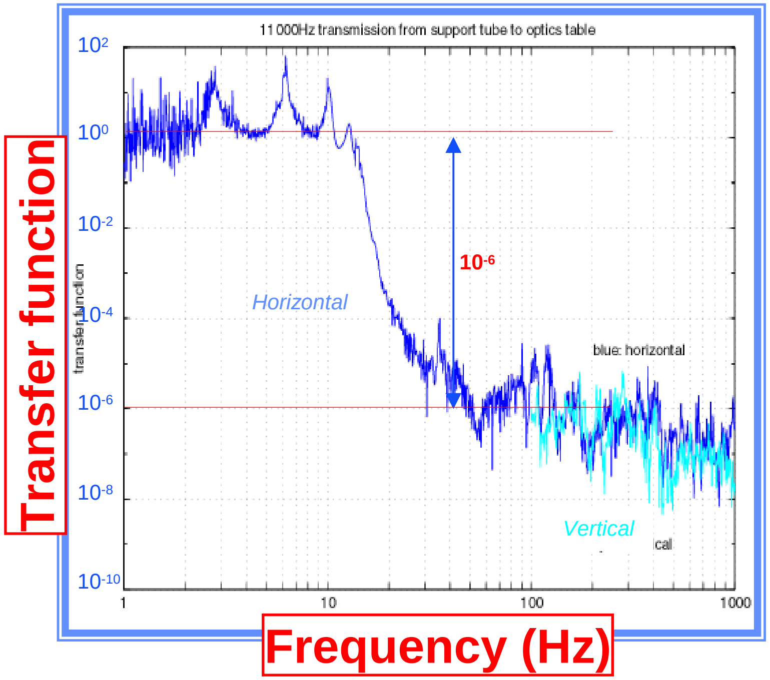
damped spring
cross section

LIGO detector facilities

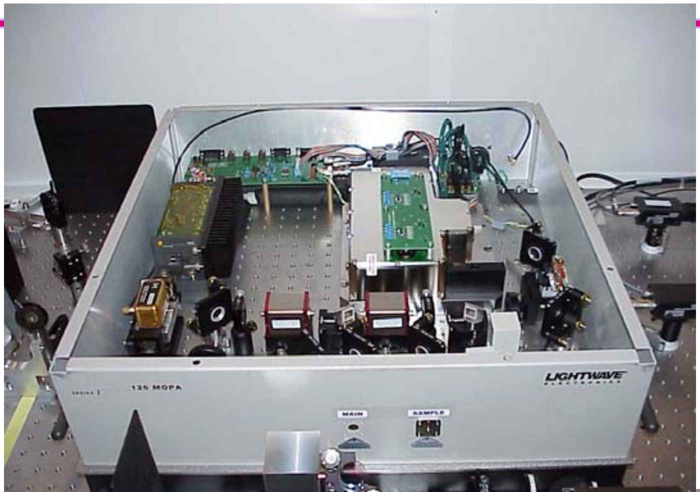
Seismic Isolation

- Multi-stage (mass & springs) optical table support gives 10^6 suppression
- Pendulum suspension gives additional $1 / f^2$ suppression above ~1 Hz

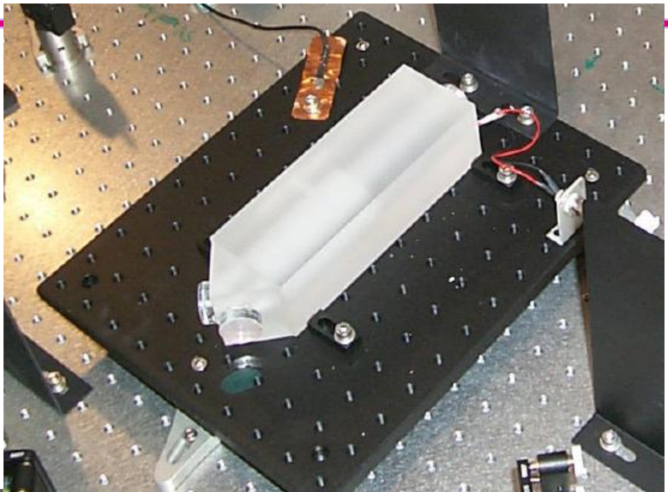




All-Solid-State Nd:YAG Laser



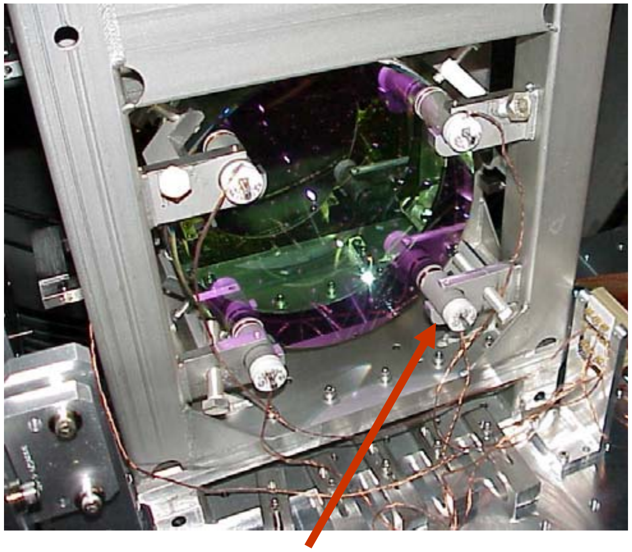
Custom-built
10 W Nd:YAG Laser,
joint development with
Lightwave Electronics
(now commercial product)



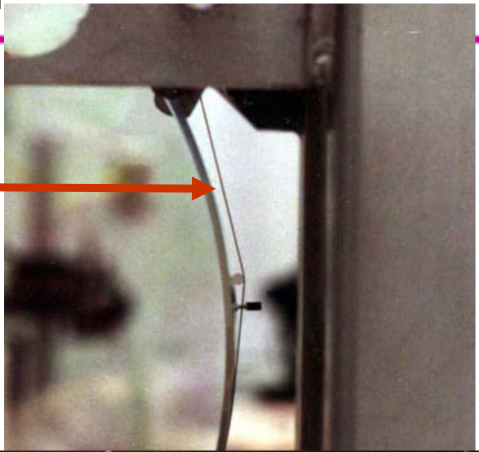
Cavity for
defining beam geometry,
joint development with
Stanford

Frequency reference
cavity (inside oven)

Core optics suspension and control



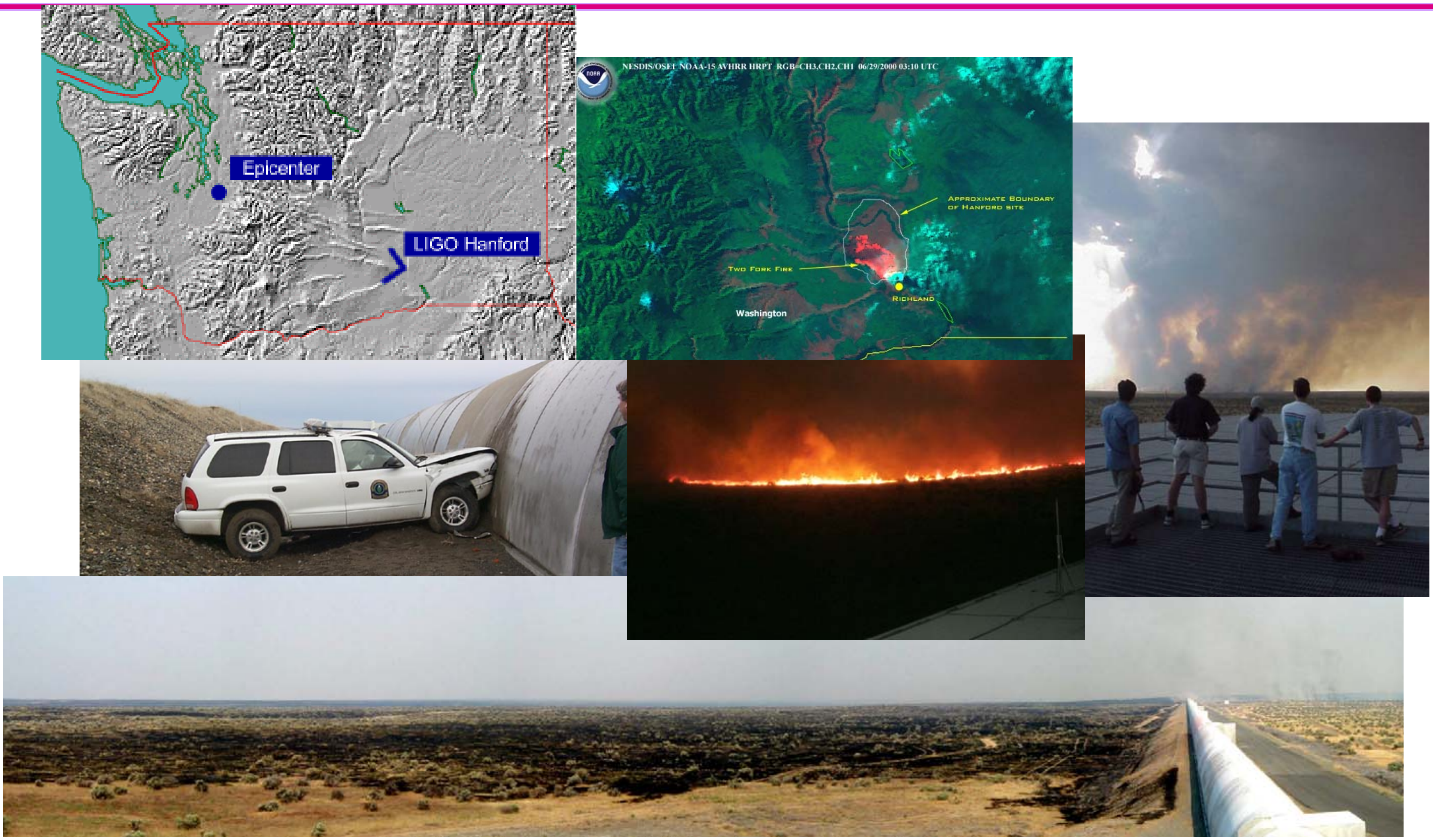
Optics suspended as simple pendulums



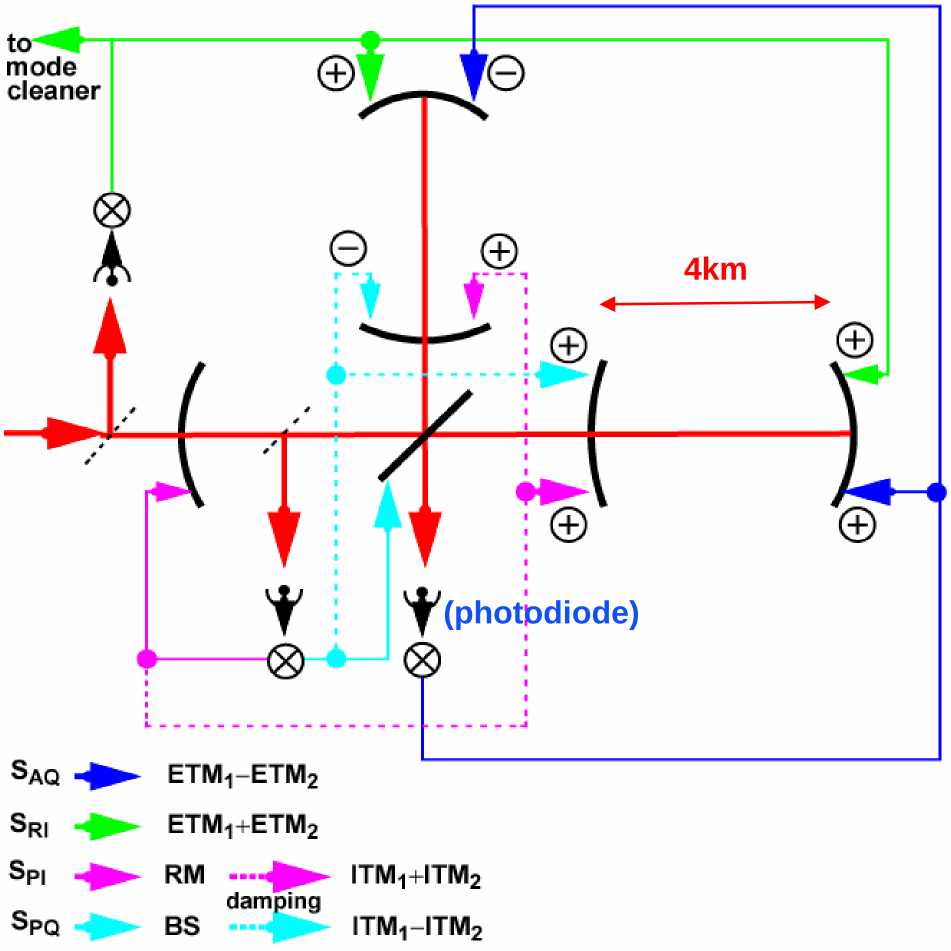
Shadow sensors & voice-coil actuators provide damping and control forces

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

The road to design sensitivity…



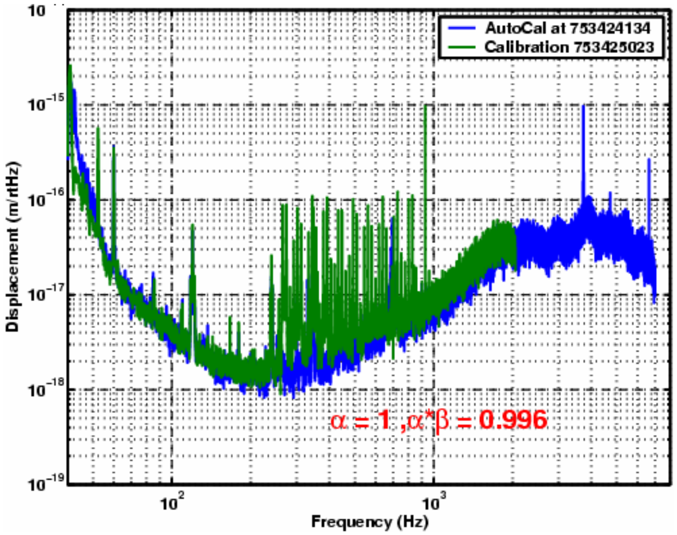
Interferometer length control system

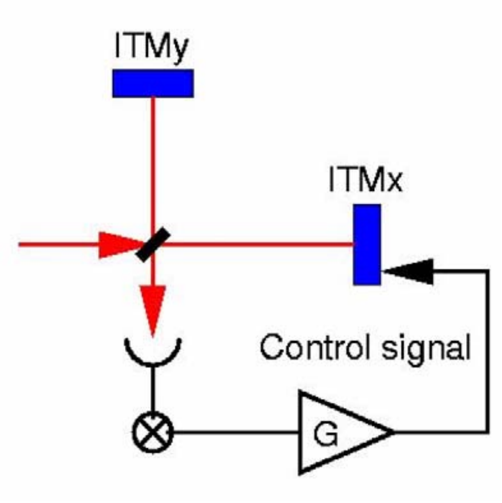


- Multiple Input / Multiple Output
- Three tightly coupled cavities
- Employs adaptive control system that evaluates plant evolution and reconfigures feedback paths and gains during lock acquisition

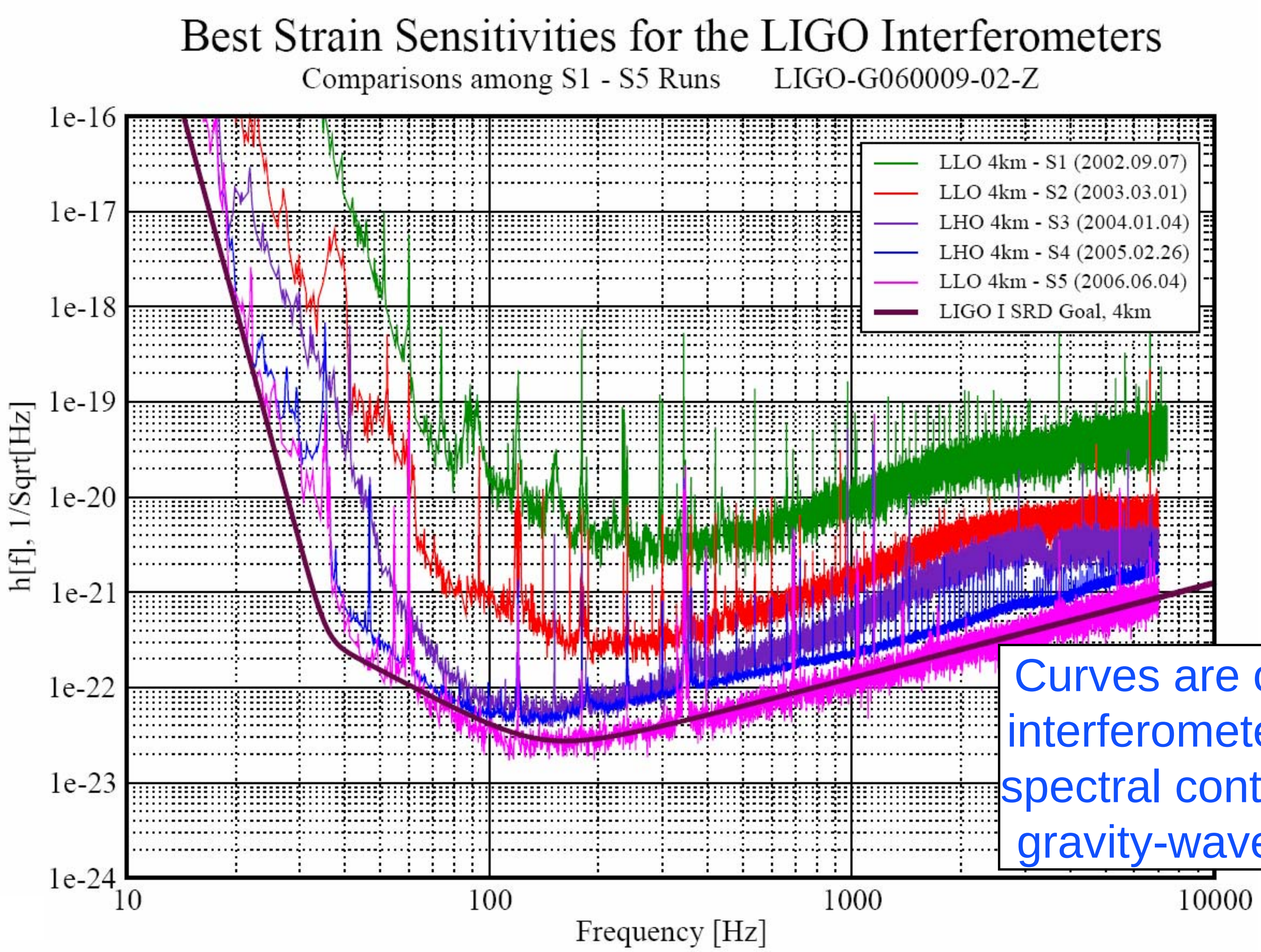
Calibration of interferometer output

- Combination of
  - Swept-Sine methods (accounts for gain vs. frequency) calibrate meters of mirror motion per count at digital suspension controllers across the frequency spectrum
  - DC measurements to set length scale (calibrates voice coil actuation of suspended mirror)
- Calibration lines injected during running to monitor optical gain changes due to drift



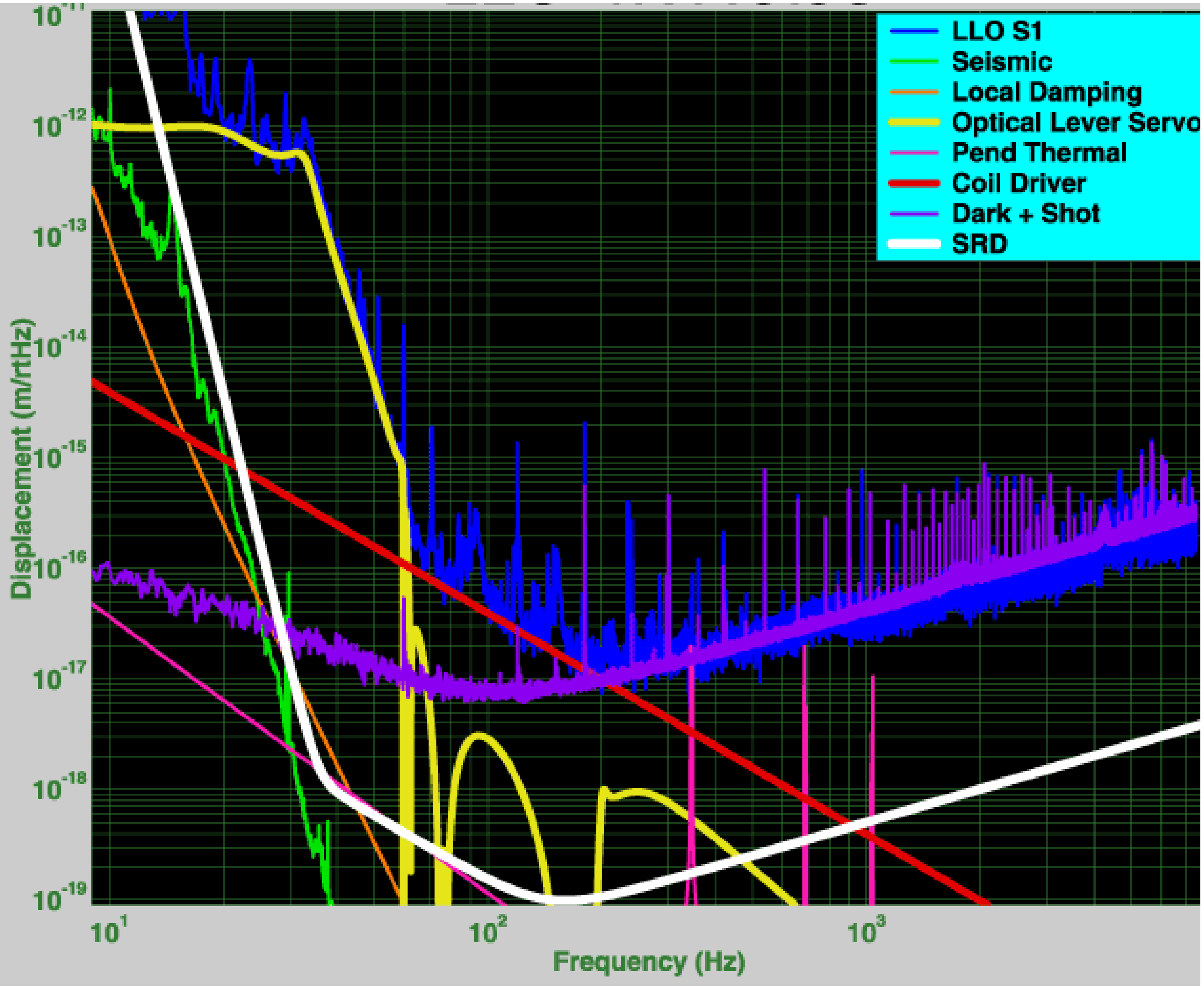


Calibrated output: LIGO noise history



Curves are calibrated interferometer output: spectral content of the gravity-wave channel

Noise component analysis from first science run (S1)



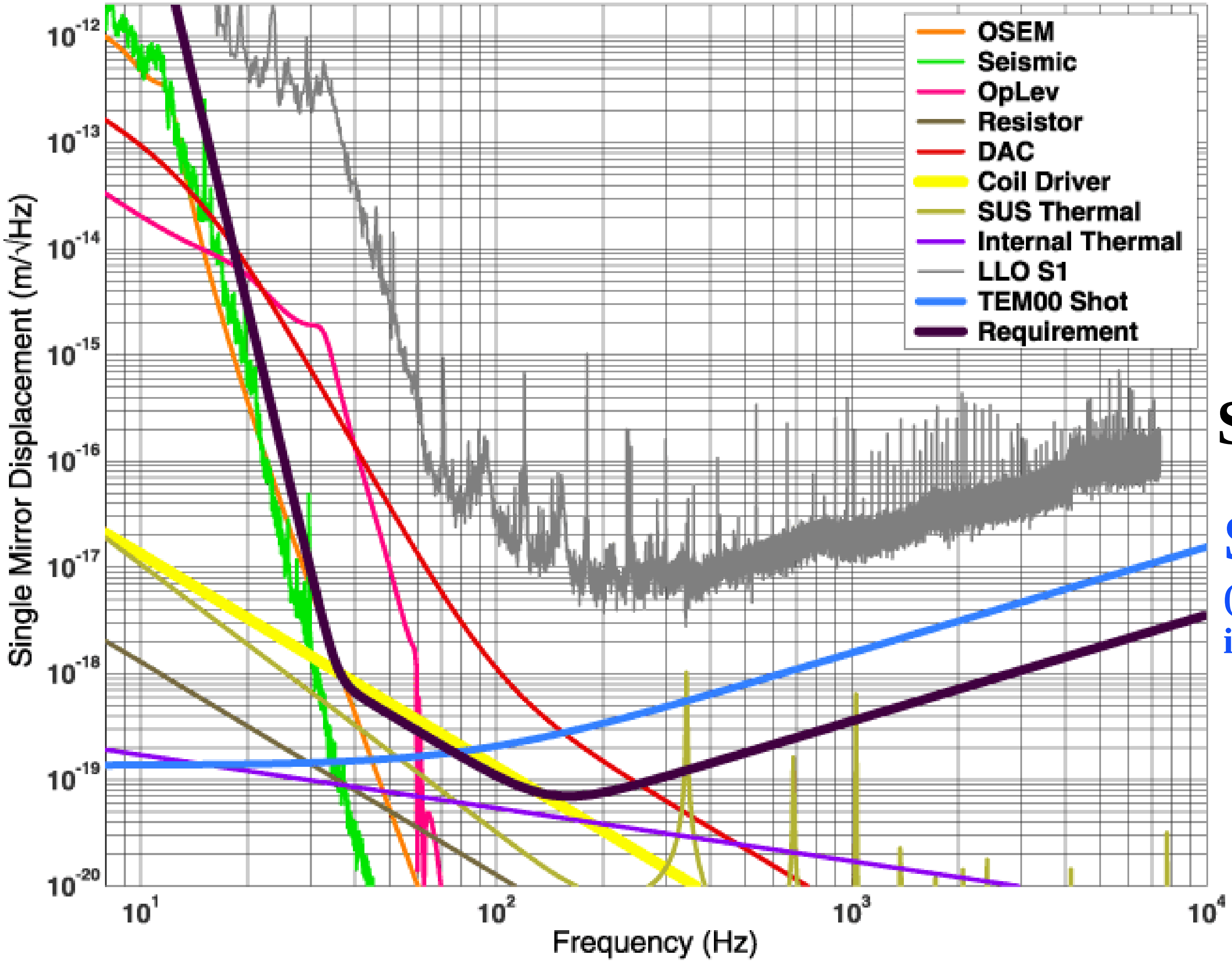
S1

LLO 4k

Blue curve is calibrated interferometer output: spectral content of the gravity-wave channel

Measure and model noise contributions of various subsytems – understand your noise

Estimated noise limits for S2
(as planned in October 2002)

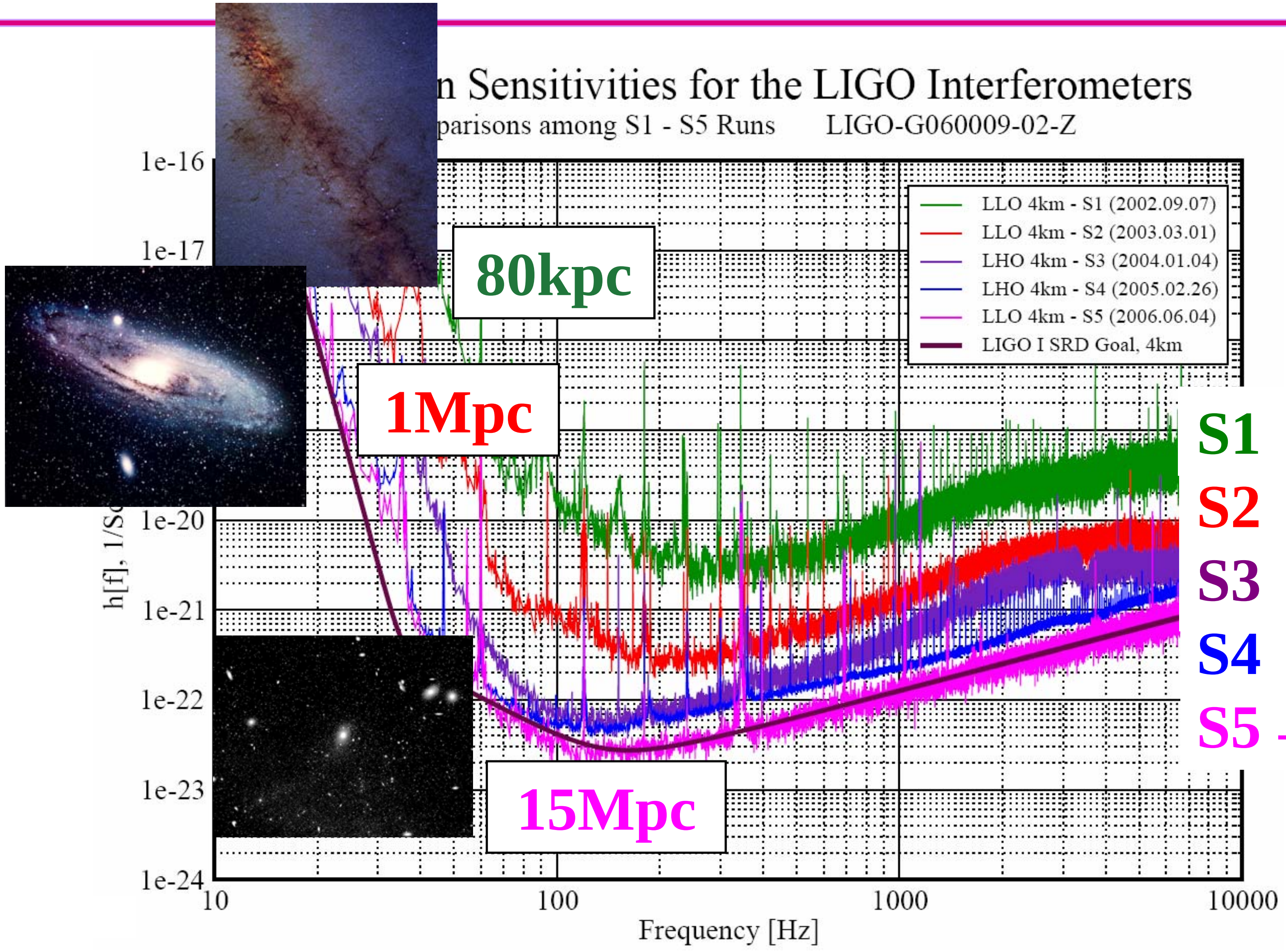


S1

S2

(expected from targeted improvements)

Calibrated output: LIGO noise history



80kpc

1Mpc

15Mpc

S1

S2

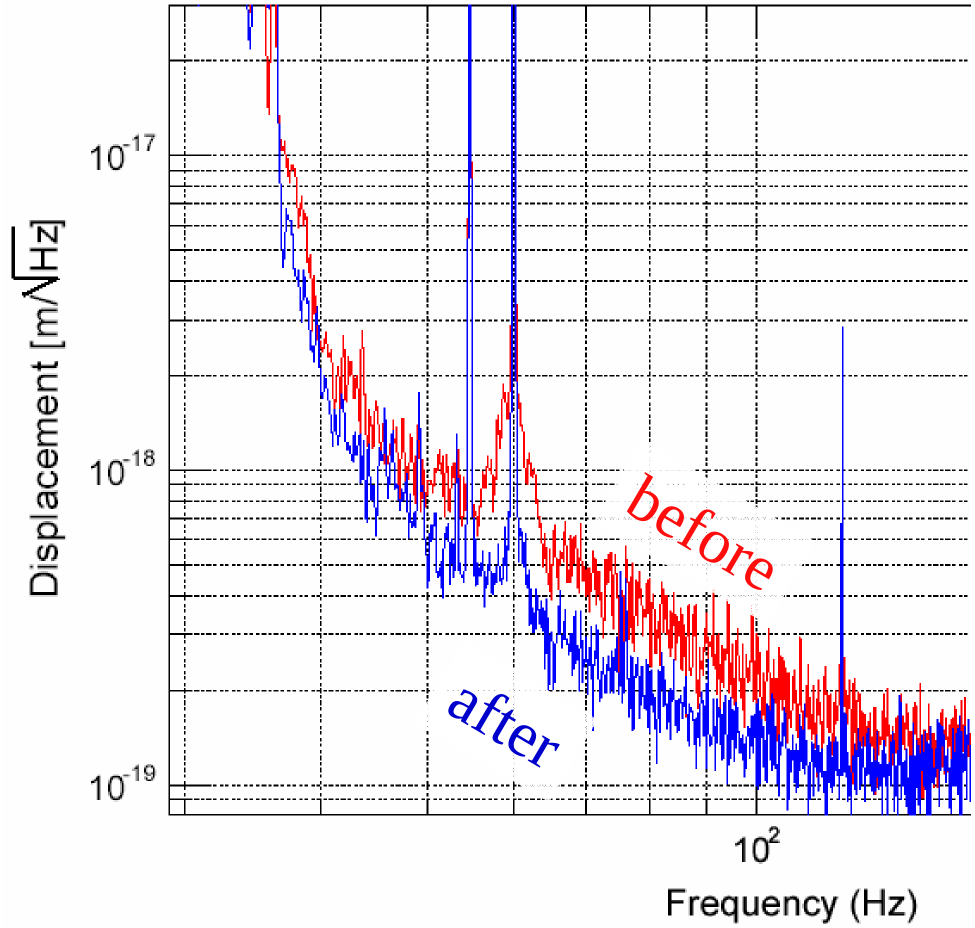
S3

S4

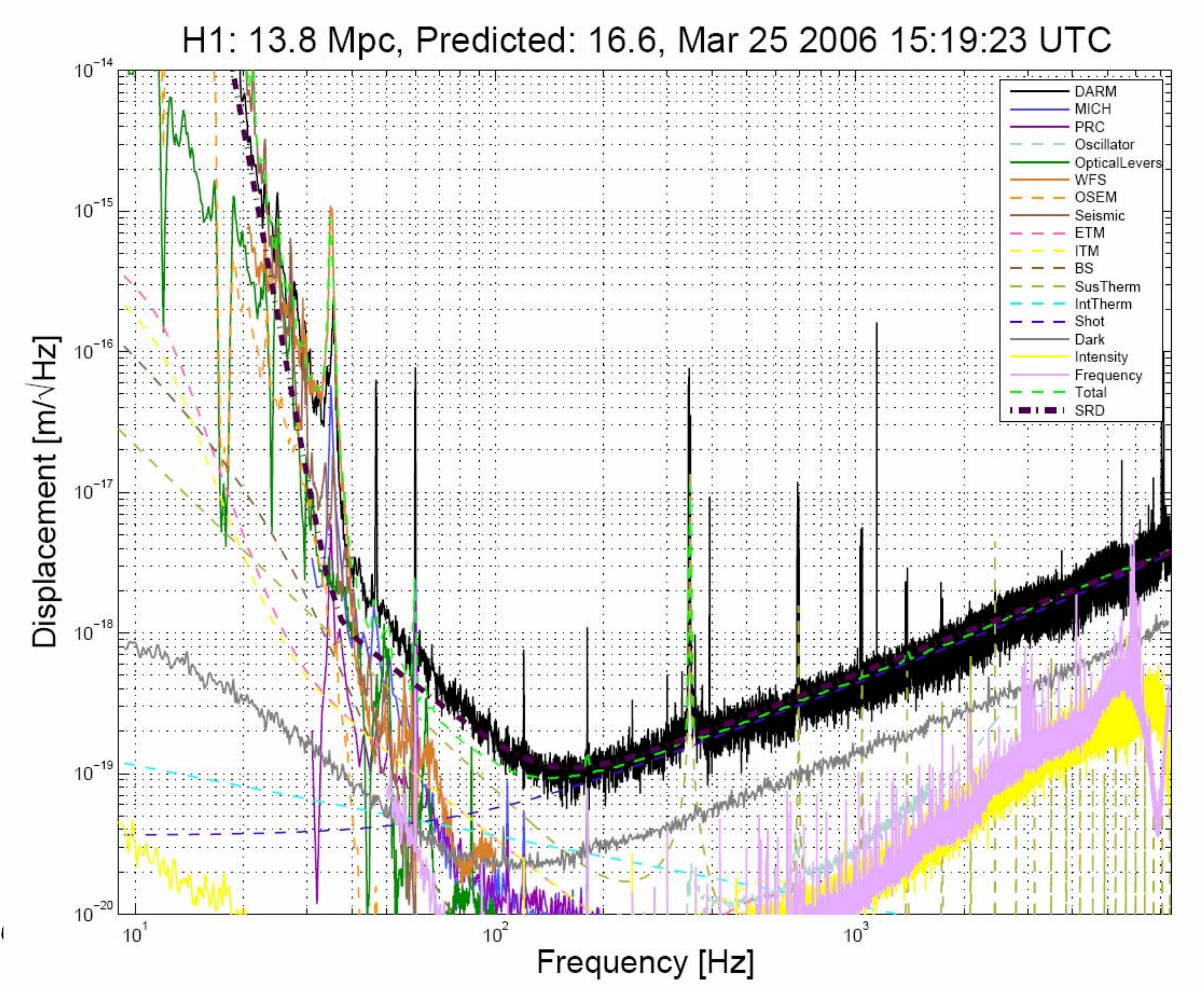
S5 - current

Now and then you get lucky

- Near disaster: L1 ITMy got stuck-
- Vented and fixed it: Noise got better!!!



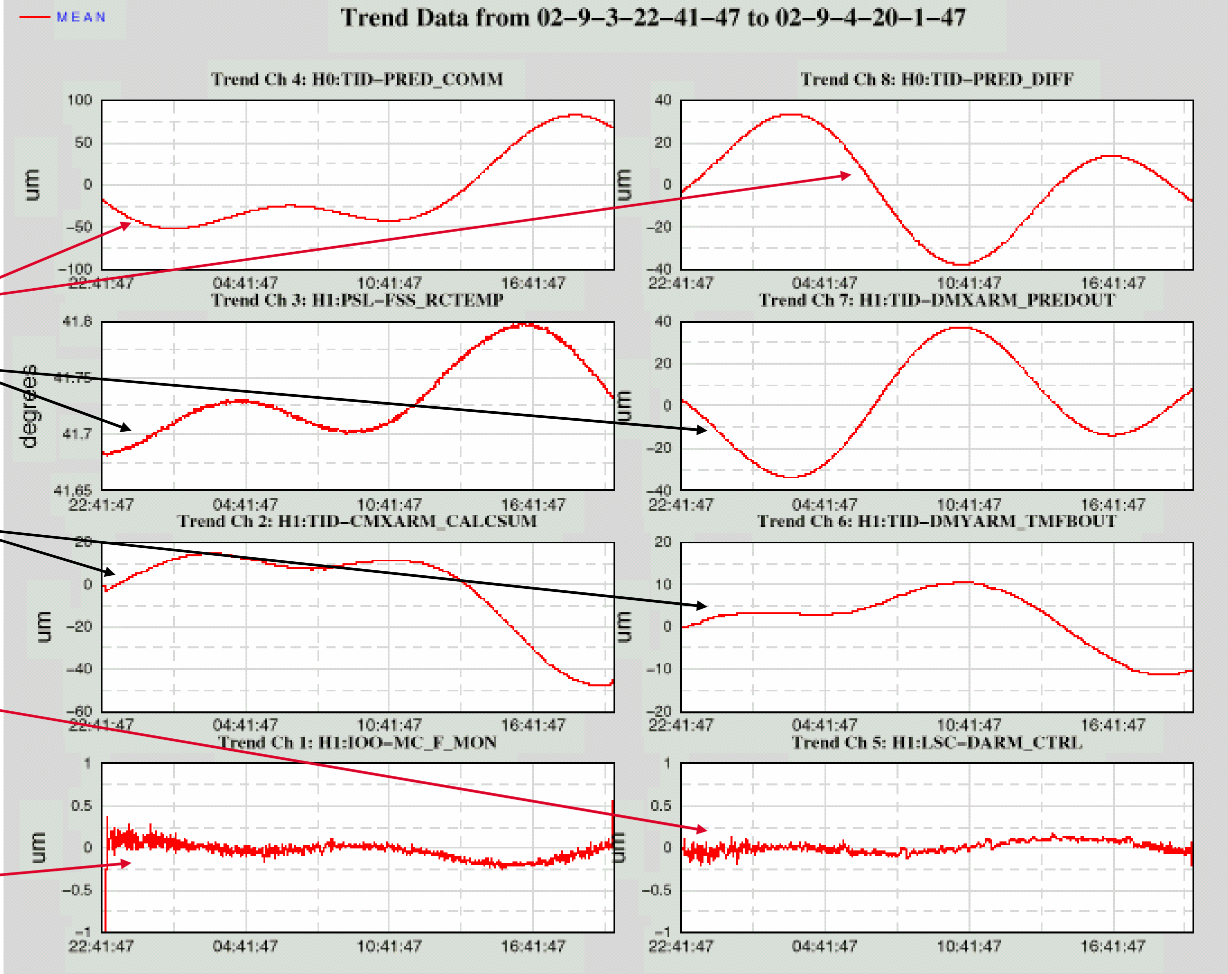
Recent noise budgets more complicated



Tidal compensation data

common mode differential mode

Tidal evaluation on 21-hour locked section of S1 data



Predicted tides

Feedforward

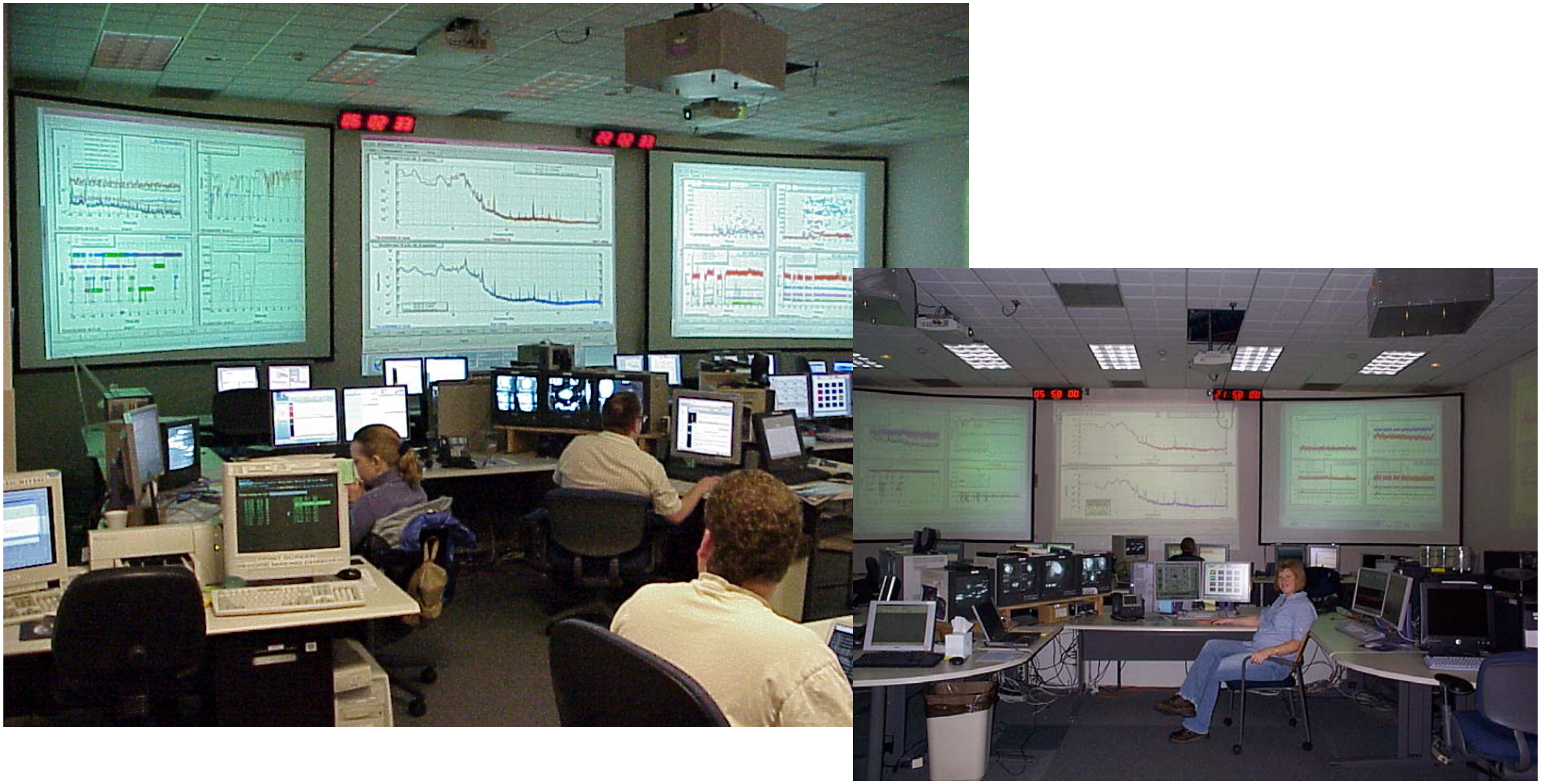
Feedback

Residual signal on coils

Residual signal on laser

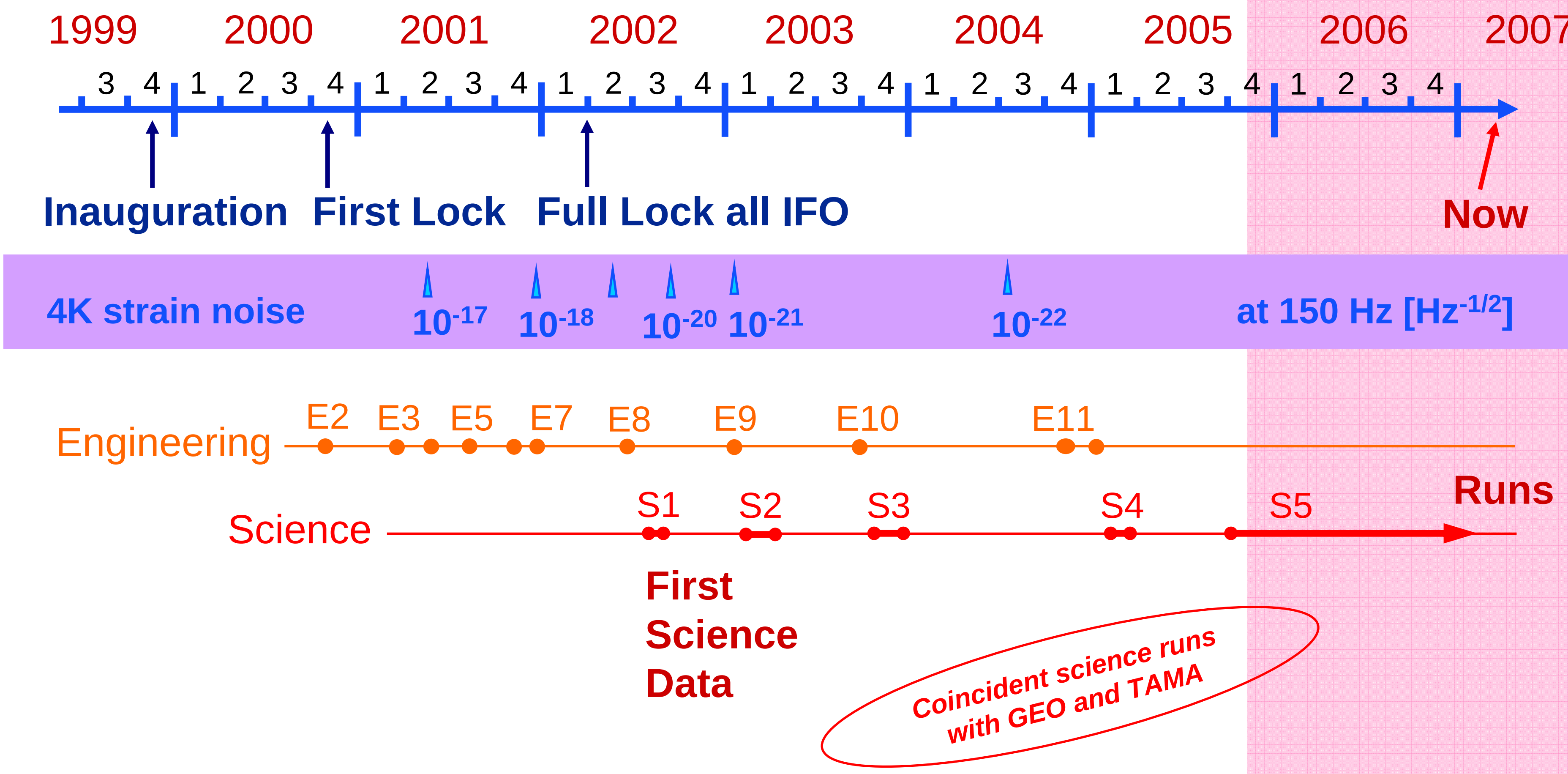
LIGO-G070039-00-Z

LIGO/GEO/TAMA Science runs



LIGO Hanford control room
31 Mar 2006 – S5

Time line



Inauguration **First Lock** **Full Lock all IFO** **Now**

4K strain noise **10^{-17}** **10^{-18}** **10^{-20}** **10^{-21}** **10^{-22}** **at 150 Hz [$Hz^{-1/2}$]**

Engineering E2 E3 E5 E7 E8 E9 E10 E11

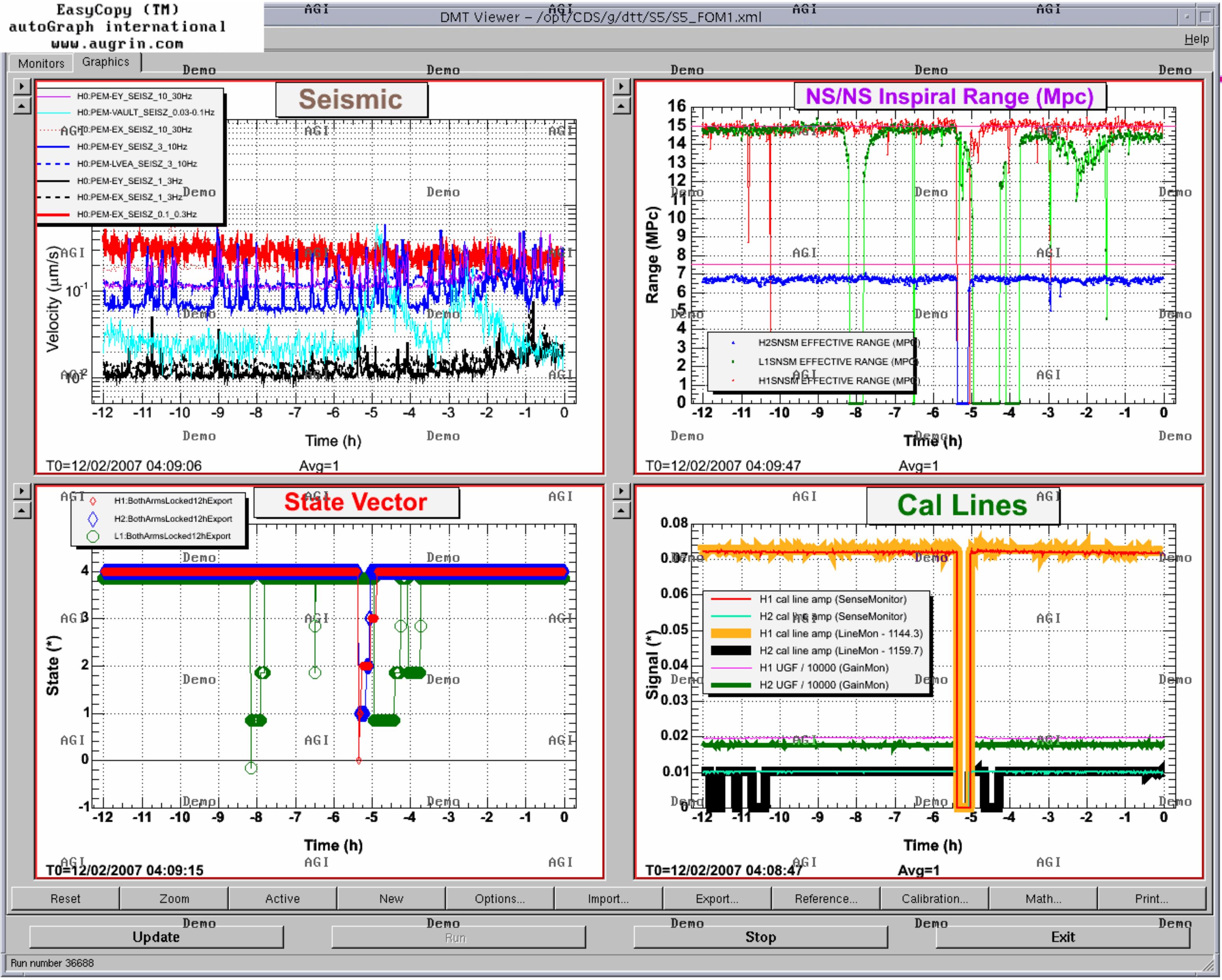
Science S1 S2 S3 S4 S5

Runs

First Science Data

Coincident science runs with GEO and TAMA

Recent S5 running

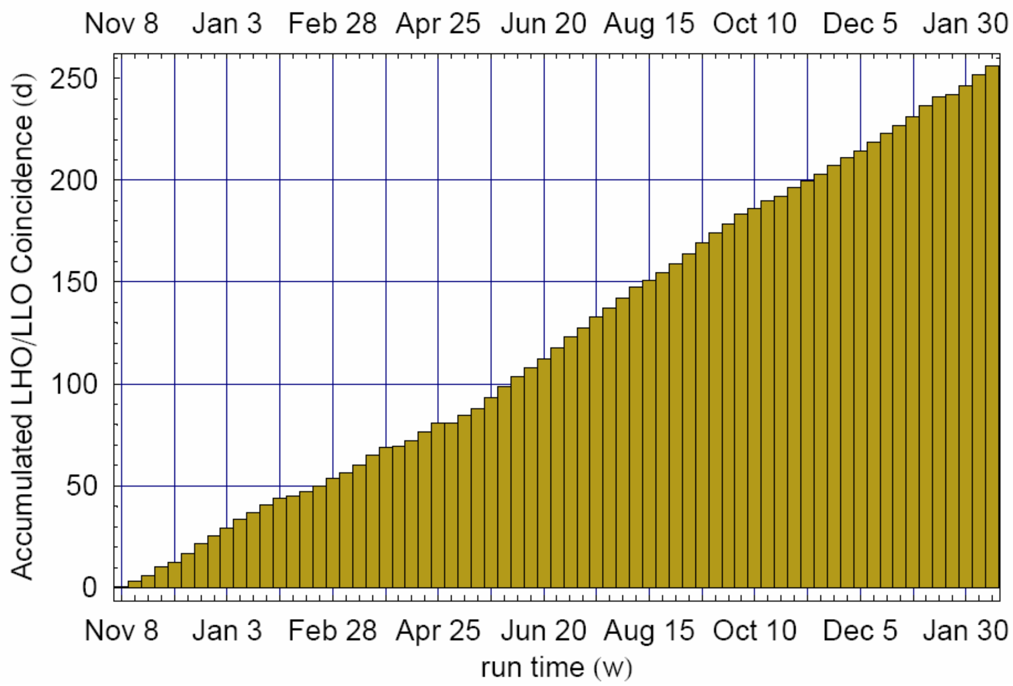


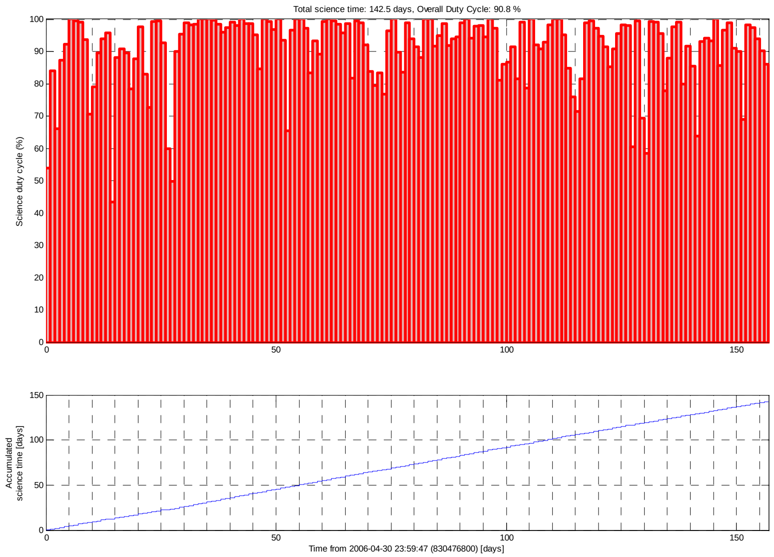
LIGO, GEO S5 duty cycle

S5 overall duty cycles:
H1: 74%
H2: 79%
L1: 59%

GEO: since May06 full attendance of S5: 91% duty cycle (143 days of total science time)

Percentage of 1-year LHO-LLO coincidence: 70%





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Search for continuous waves

Searches for g.w. :

- I. Known pulsars
- II. S4 all-sky (incoherent)
- III. S3 all-sky (coherent)

Analysis goal for S5: hierarchical search

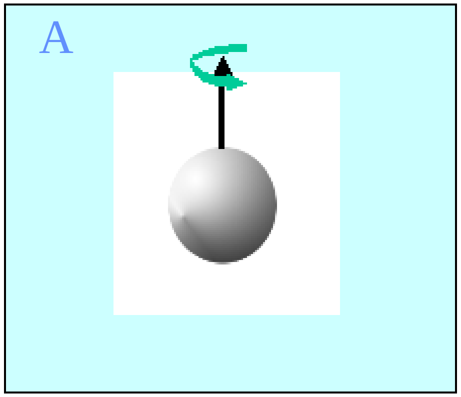
Credits:

A. image by Jolien Creighton; LIGO Lab Document G030163-03-Z.

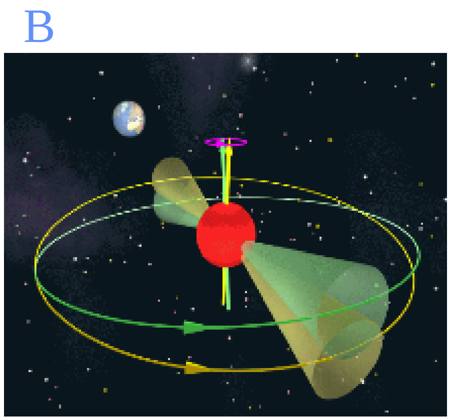
B. image by M. Kramer; Press Release PR0003, University of Manchester - Jodrell Bank Observatory, 2 August 2000.

C. image by Dana Berry/NASA; NASA News Release posted July 2, 2003 on Spaceflight Now.

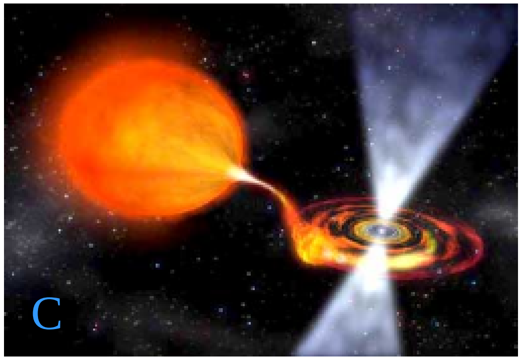
D. image from a simulation by Chad Hanna and Benjamin Owen; B. J. Owen's research page, Penn State University.



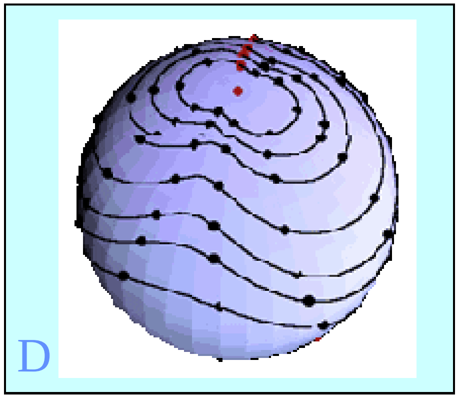
Mountain on neutron star



Precessing neutron star



Accreting neutron star



Oscillating neutron star

Analyses for continuous gravitational waves I

- S5 Time domain analysis
  - Targeted search of known objects: 97 pulsars with rotational frequencies > 25 Hz at known locations with phase inferred from radio data (knowledge of some parameters simplifies analysis) from the Jodrell Bank Pulsar Group (JBPG) and/or ATNF catalogue
  - Limit this search to gravitational waves from a neutron star (with asymmetry about its rotational axis) emitted at twice its rotational frequency, $2*f_{rot}$
  - Signal would be frequency modulated by relative motion of detector and source, plus amplitude modulated by the motion of the antenna pattern of the detector
  - Analyzed from 4 Nov 2005 - 17 Sep 2006 using data from the three LIGO observatories Hanford 4k and 2k (H1, H2) and Livingston 4k (L1)
  - Upper limits defined in terms of Bayesian posterior probability distributions for the pulsar parameters
  - Validation by hardware injection of fake pulsars
  - Results

S5 data: first
10 months

CW source model

The expected signal has the form:

$$h(\mathrm{t}) = \mathrm{F}_{+}(\mathrm{t};\psi)\mathrm{h}_0\left(\frac{1+\cos^2\iota}{2}\right)\cos\Phi(t) - \mathrm{F}_{\times}(\mathrm{t};\psi)\mathrm{h}_0\cos\iota\sin\Phi(t)$$

- F_+ and F_x : strain antenna patterns of the detector to plus and cross polarization, bounded between -1 and 1
- Here, signal parameters are:
  - » h_0 – amplitude of the gravitational wave signal
  - » ψ – polarization angle of signal
  - » ι – inclination angle of source with respect to line of sight
  - » ϕ_0 – initial phase of pulsar; $\Phi(t=0)$, and $\Phi(t) = \phi(t) + \phi_0$

Heterodyne, i.e. multiply by: $e^{-i\phi(t)}$

so that the expected demodulated signal is then:

$$\mathrm{y}(\mathrm{t_k};\mathbf{a}) = \frac{1}{4}\mathrm{F}_{+}(\mathrm{t_k};\psi)\mathrm{h}_0(1+\cos^2\iota)e^{i\phi_0} - \frac{i}{2}\mathrm{F}_{\times}(\mathrm{t_k};\psi)\mathrm{h}_0(\cos\iota)e^{i\phi_0}$$

Here, **a** = **a**(h_0, ψ, ι, ϕ_0), a vector of the signal parameters.

Aside: Injection of fake pulsars during S2

Two simulated pulsars, P1 and P2, were injected in the LIGO interferometers for a period of ~ 12 hours during S2

Parameters of P1:

P1: Constant Intrinsic Frequency

Sky position: **0.3766960246** latitude (radians)
5.1471621319 longitude (radians)

Signal parameters are defined at SSB GPS time **733967667.026112310** which corresponds to a wavefront passing:

LHO at GPS time **733967713.000000000**

LLO at GPS time **733967713.007730720**

In the SSB the signal is defined by

f = 1279.123456789012 Hz

fdot = 0

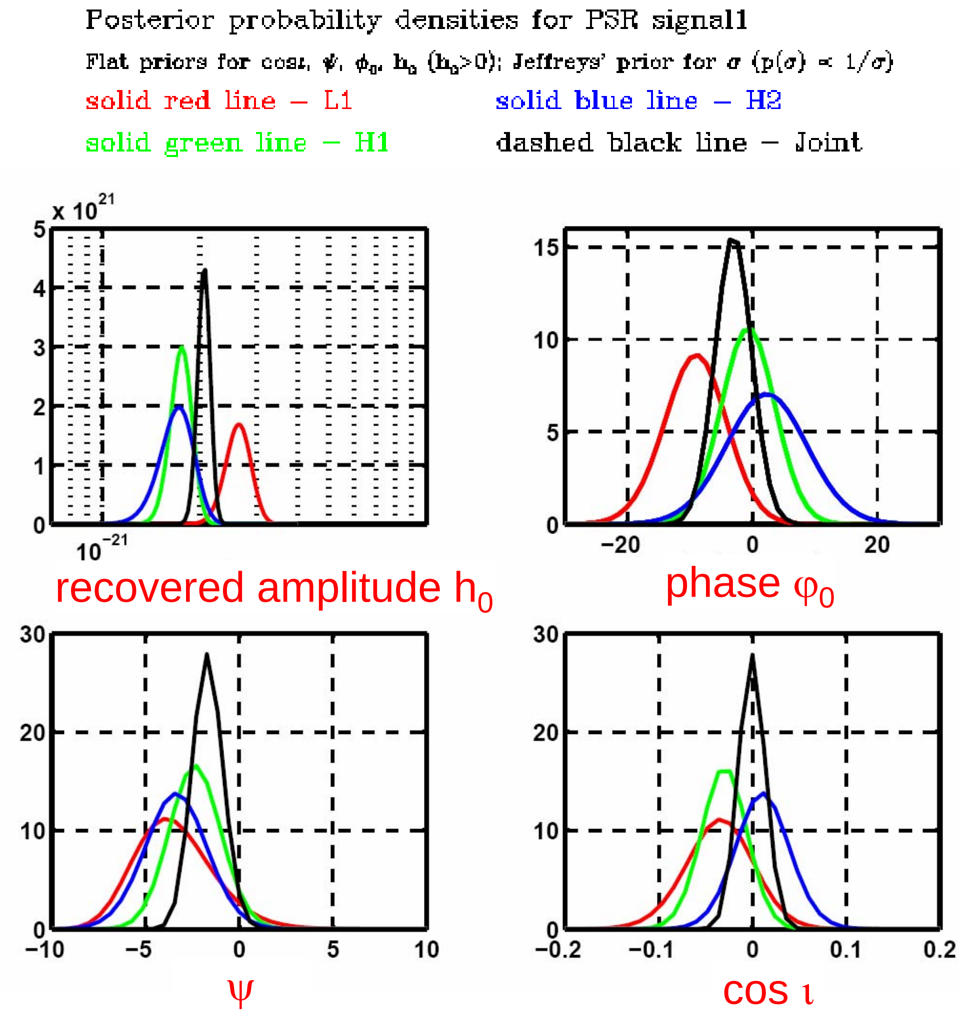
phi = 0

psi = 0

iota = $\pi/2$

$h_0 = 2.0 \times 10^{-21}$

injected amplitude h_0



S5 Results, 95% upper limits

PRELIMINARY

h_0	Pulsars
$h_0 < 10^{-25}$	35
$10^{-25} < h_0 < 5\times10^{-25}$	56
$h_0 > 5\times10^{-25}$	6

Lowest h_0 upper limit:

PSR J1802-2124 (f_{gw} = 158.1 Hz, r = 3.3kpc) $h_0 = 4.9\times10^{-26}$

Lowest ellipticity upper limit:

PSR J2124-3358 (f_{gw} = 405.6Hz, r = 0.25kpc) $\varepsilon = 1.1\times10^{-7}$

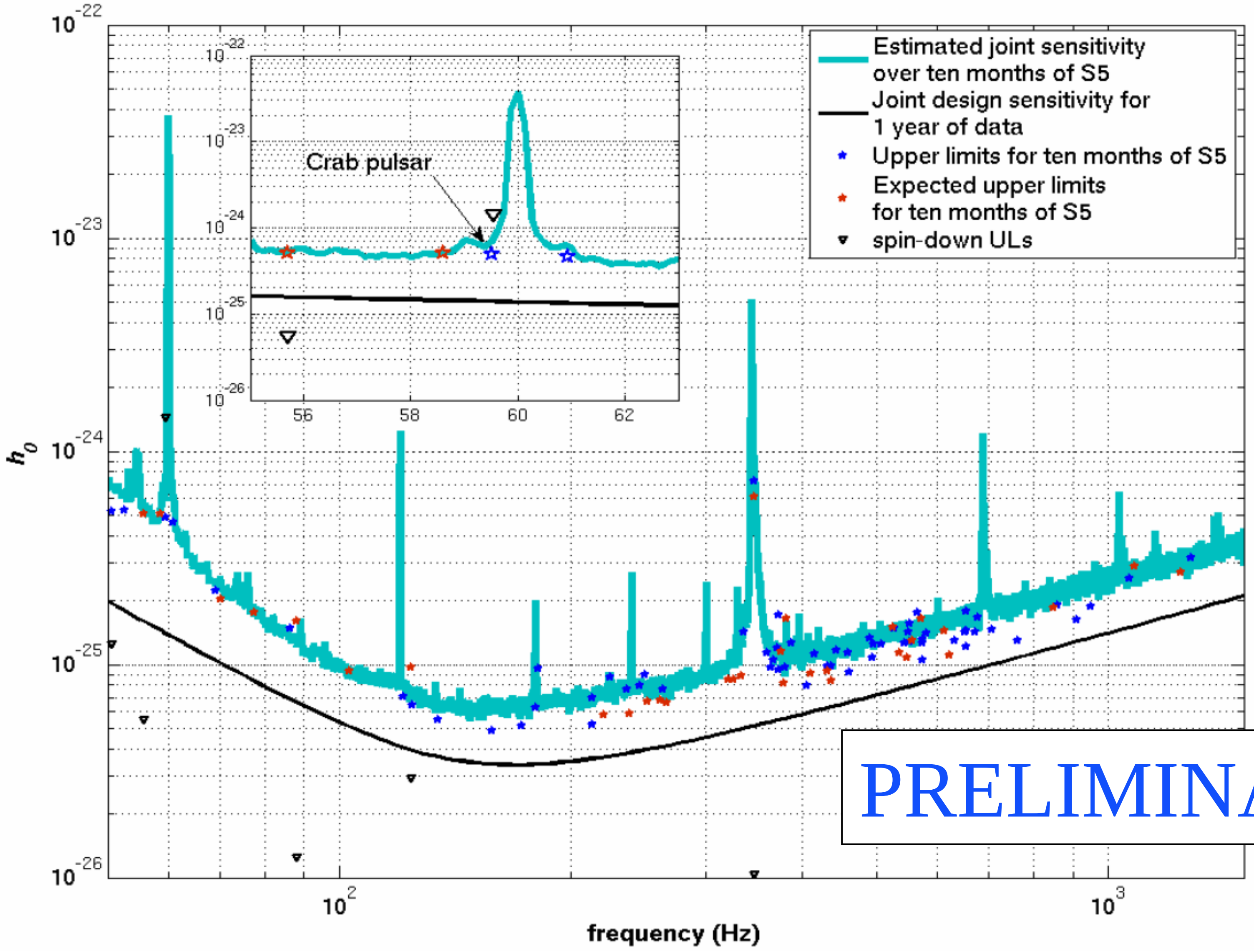
All values assume I = 10^{38} kgm^2 and no error on distance

$$\varepsilon = 0.237 \frac{h_0}{10^{-24}} \frac{r}{1\mathrm{kpc}} \frac{1\mathrm{Hz}^2}{\nu^2} \frac{10^{38}\,\mathrm{kgm}^2}{I_{zz}}$$

Ellipticity	Pulsars
$10^{-7} < \varepsilon < 5\times10^{-7}$	14
$5\times10^{-7} < \varepsilon < 10^{-6}$	20
$10^{-6} < \varepsilon < 5\times10^{-6}$	38
$\varepsilon > 5\times10^{-6}$	25

Our most stringent ellipticities (~10^{-7}) are starting to reach into the range of neutron star structures for some neutron-proton-electron models (B. Owen, **PRL**, 2005).

Preliminary S5 result: known pulsars and 10 months of data

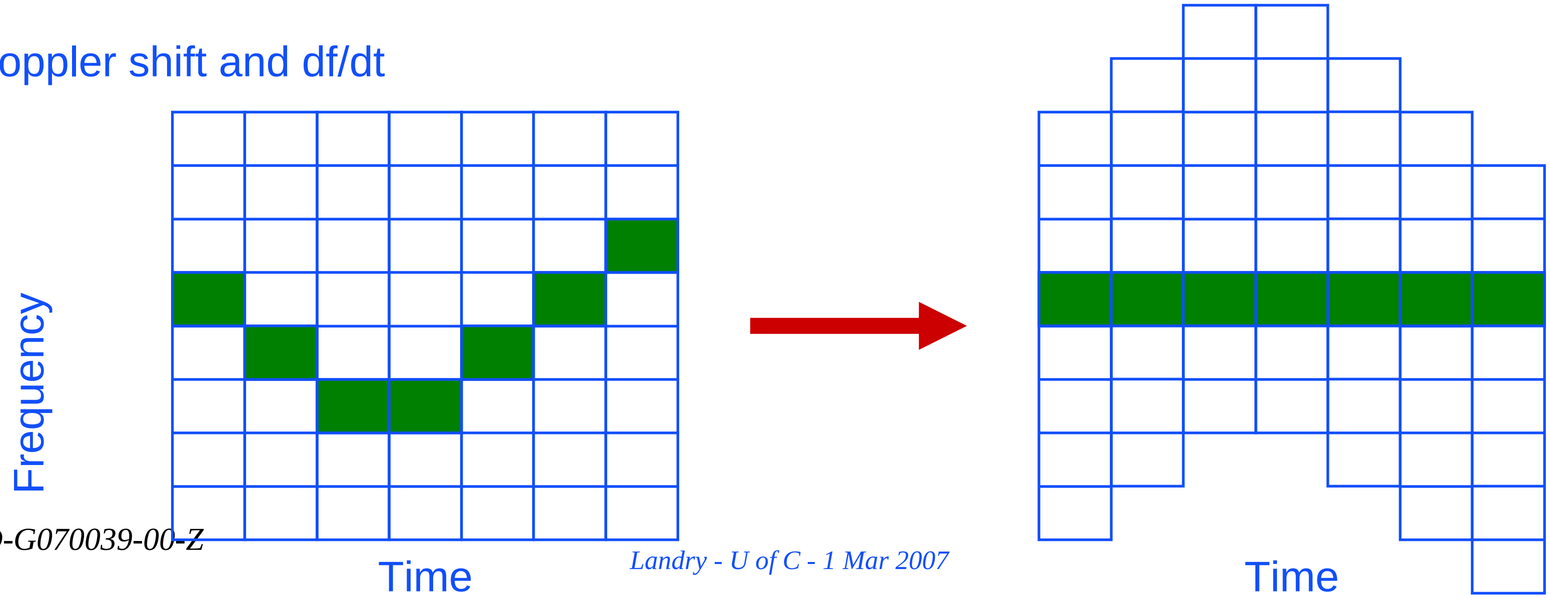


PRELIMINARY

Analyses for continuous gravitational waves II

- “Stack Slide Method”: break up data into segments; FFT each, producing Short (30 min) Fourier Transforms (SFTs) = coherent step.
- StackSlide: stack SFTs, track frequency, slide to line up & add the power weighted by noise inverse = incoherent step.
- Other semi-coherent methods:
  - » Hough Transform: Phys. Rev. D72 (2005) 102004; gr-qc/0508065.
  - » PowerFlux
- Fully coherent methods:
  - » Frequency domain match filtering/maximum likelihood estimation

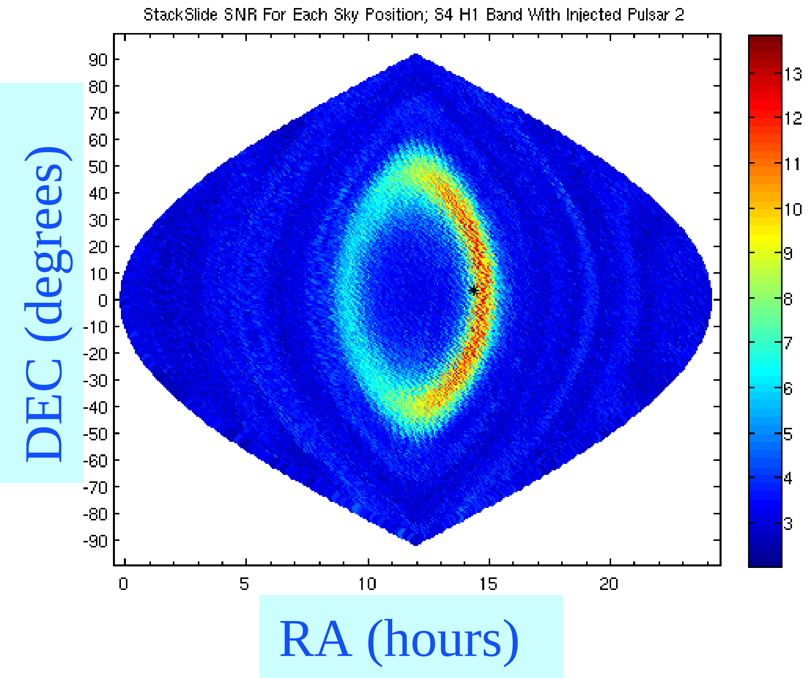
Track Doppler shift and df/dt

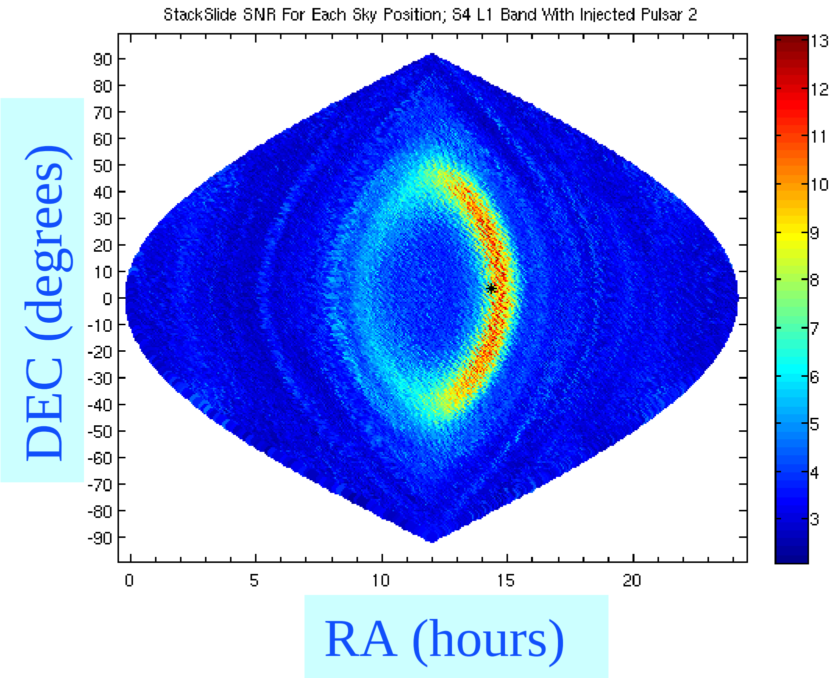


PRELIMINARY

Analysis of Hardware Injections

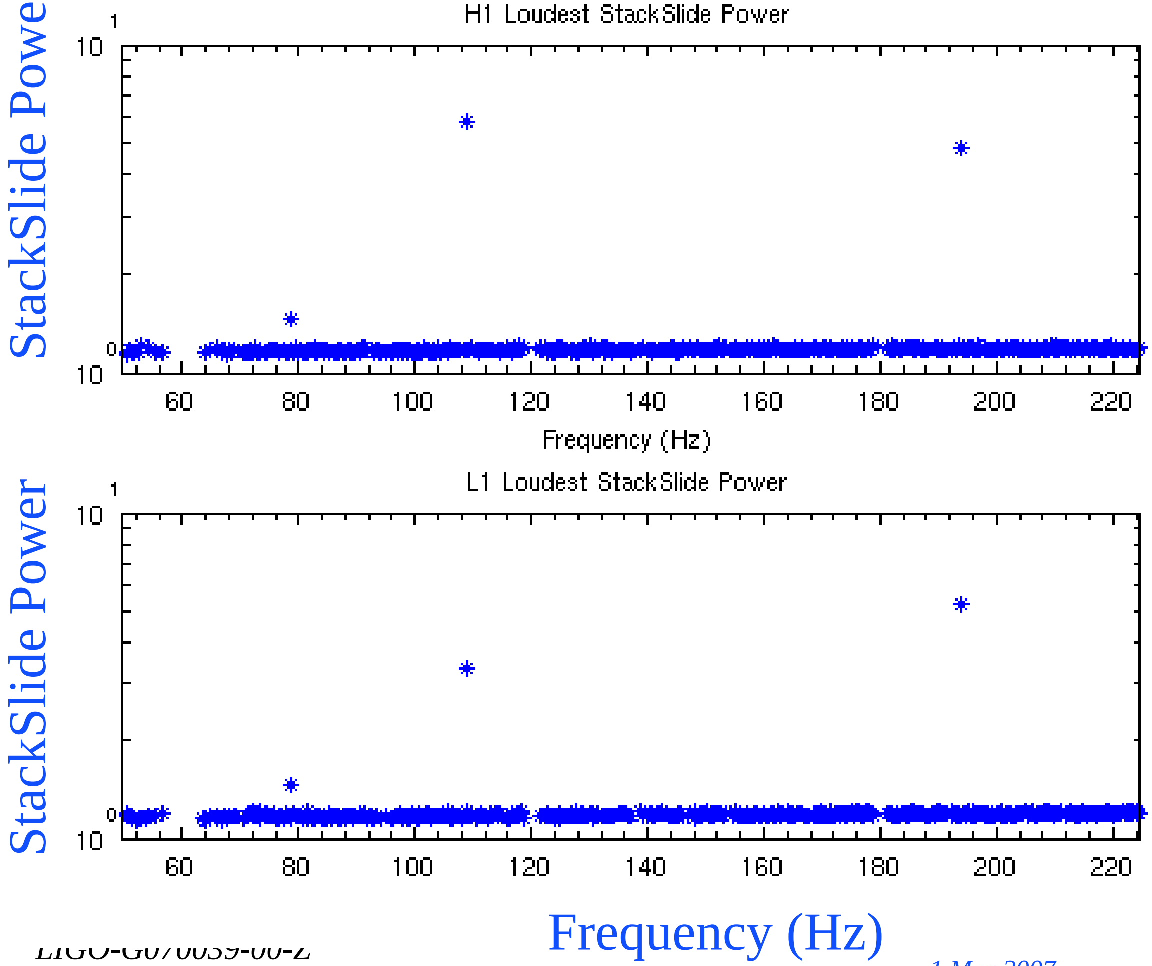
Fake gravitational-wave signals corresponding to rotating neutron stars with varying degrees of asymmetry were injected for parts of the S4 run by actuating on one end mirror. Sky maps for the search for an injected signal with h_0 ~ 7.5e-24 are below. Black stars show the fake signal's sky position.


StackSlide SNR For Each Sky Position; S4 H1 Band With Injected Pulsar 2


StackSlide SNR For Each Sky Position; S4 L1 Band With Injected Pulsar 2

S4 StackSlide “Loudest Events” 50-225 Hz

PRELIMINARY



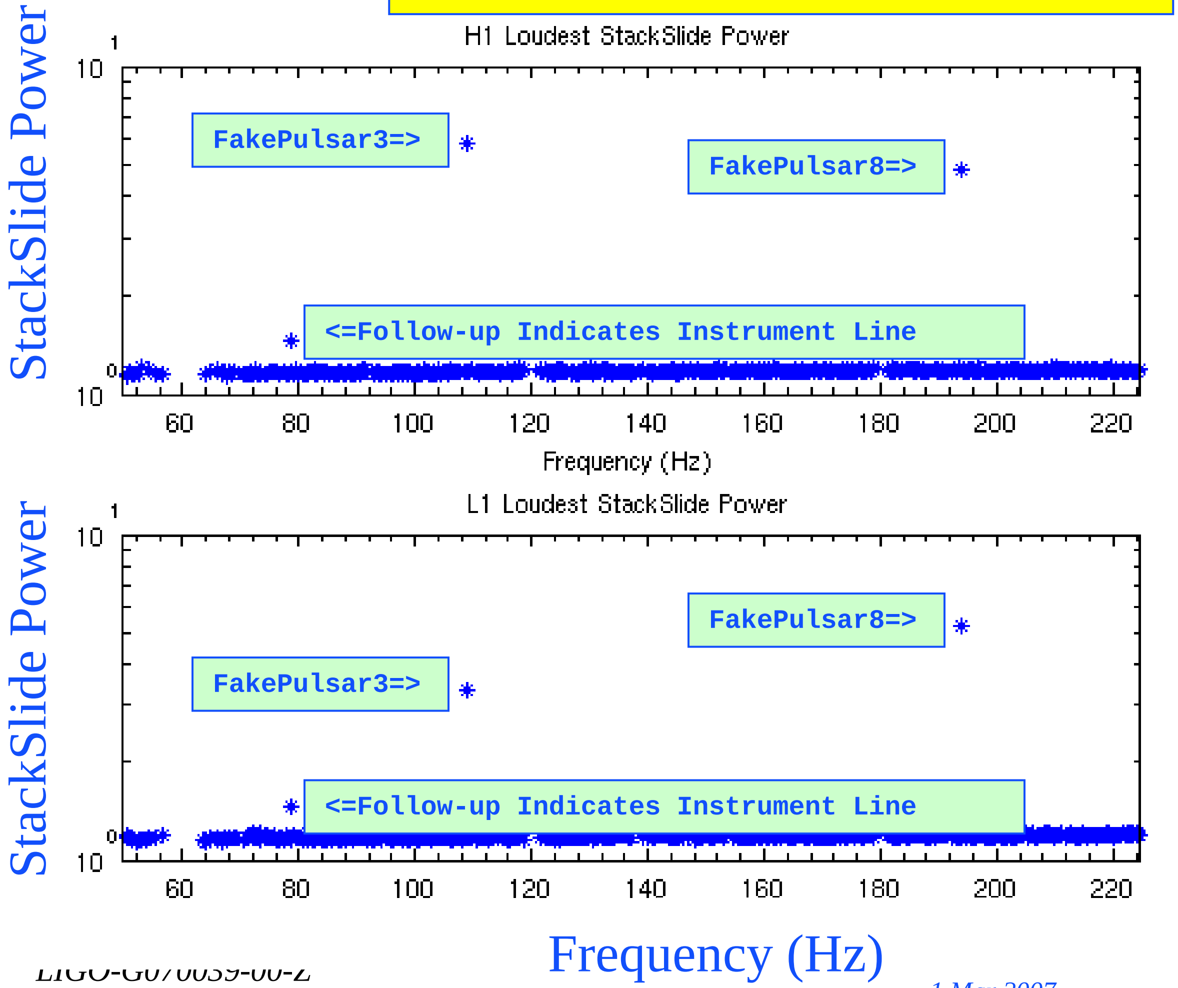
- Searched 450 freq. per .25 Hz band, 51 values of df/dt, between 0 & -1e-8 Hz/s, up to 82,120 sky positions (up to 2e9 templates). The expected loudest StackSlide Power was ~ 1.22 (SNR ~ 7)

- Veto bands affected by harmonics of 60 Hz.

- Simple cut: if SNR > 7 in only one IFO veto; if in both IFOs, veto if abs(f_{H1}-f_{L1}) > 1.1e-4*f0

S4 StackSlide “Loudest Events” 50-225 Hz

PRELIMINARY



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- •Veto bands affected by harmonics of 60 Hz.
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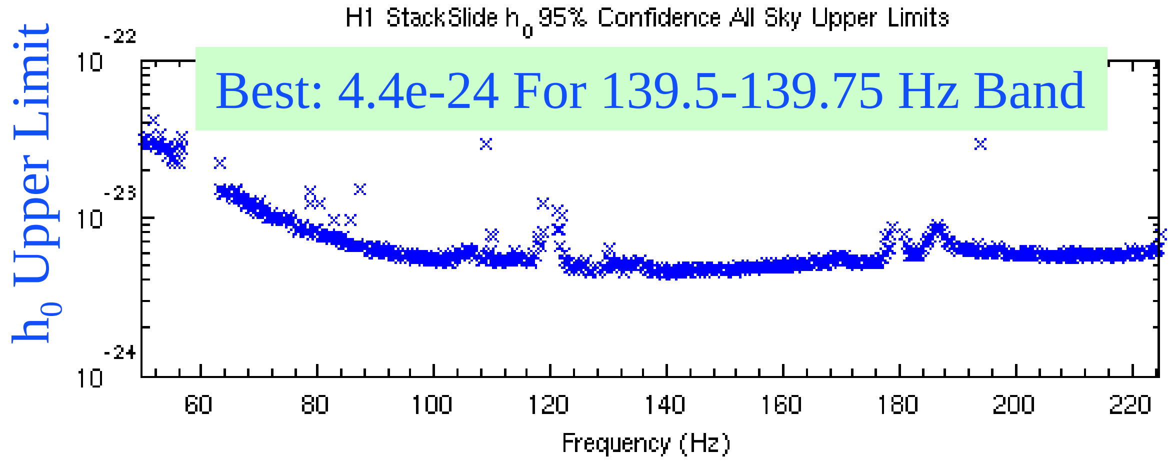
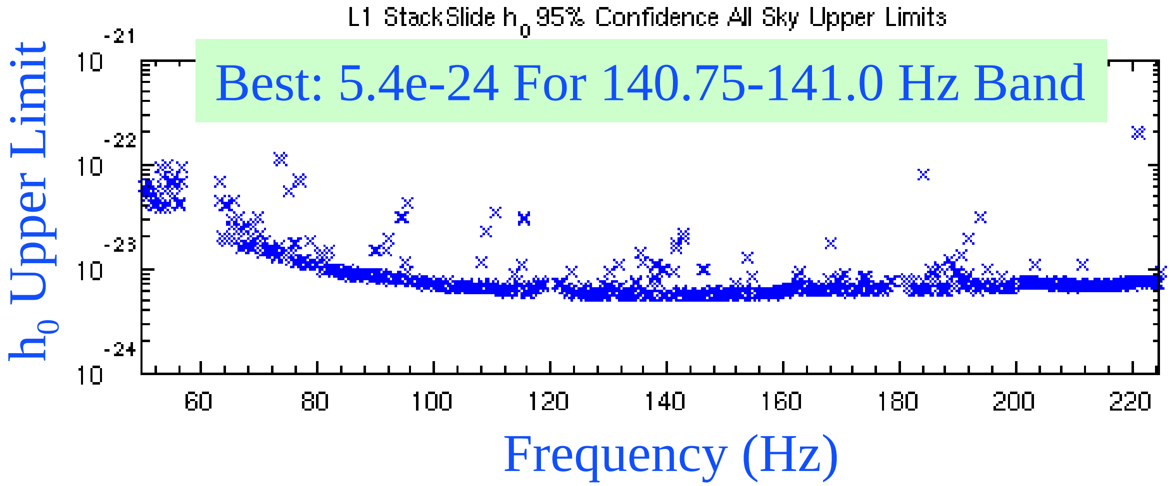
S4 StackSlide h_0 95% Confidence All Sky Upper Limits 50-225 Hz

PRELIMINARY



Best: 4.4e-24 For 139.5-139.75 Hz Band



Best: 5.4e-24 For 140.75-141.0 Hz Band

S5: ~ 2x better sensitivity, 12x or more data

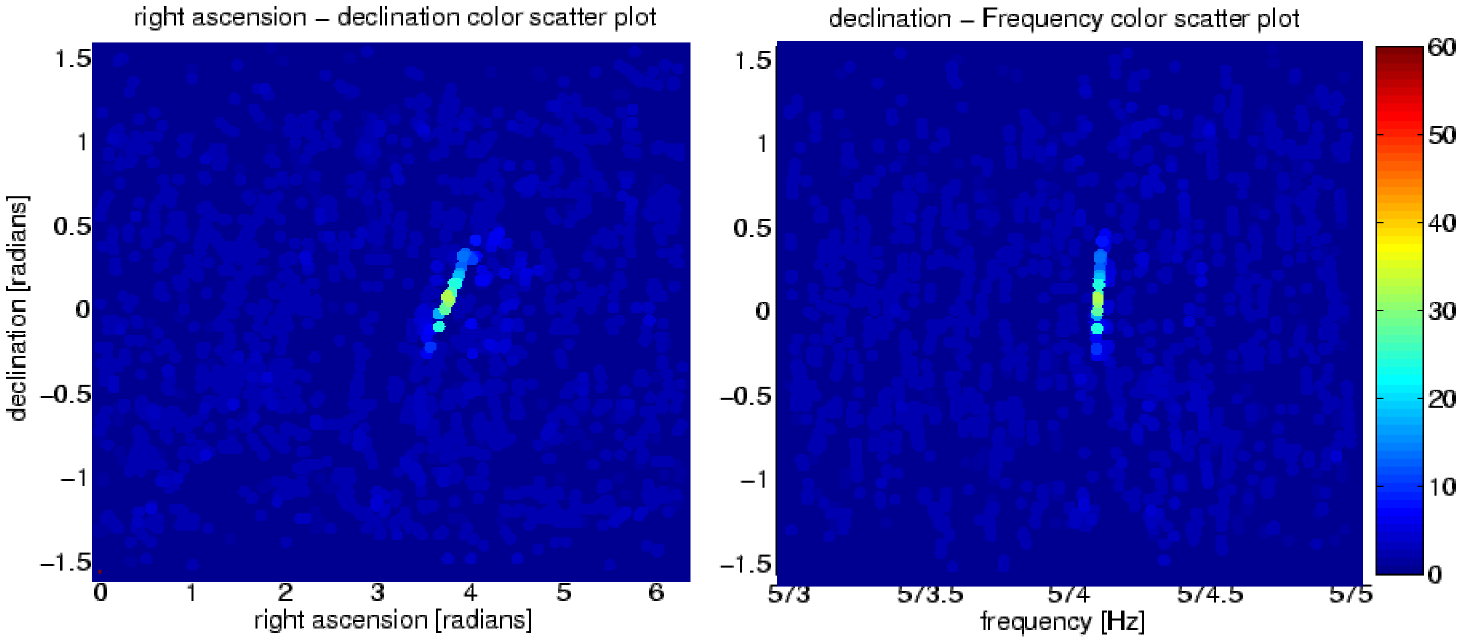
This incoherent method (and other examples, Hough and Powerflux techniques) is one piece of hierarchical pipeline

Analyses for continuous gravitational waves III

- All-sky search is computationally intensive, e.g.
  - searching 1 year of data, you have 3 billion frequencies in a 1000Hz band
  - For each frequency we need to search 100 million million independent sky positions
  - pulsars spin down, so you have to consider approximately one billion times more templates
  - Number of templates for each frequency: ~10^{23}
- S3 Frequency-domain (“F-statistic”) all-sky search
  - The F-Statistic uses a matched filter technique, minimizing chisquare (maximizing likelihood) when comparing a template to the data
  - ~10^{15} templates search over frequency (50Hz-1500Hz) and sky position
  - For S3 we are using the 600 most sensitive hours of data
  - We are combining the results of multiple stages of the search incoherently using a coincidence scheme

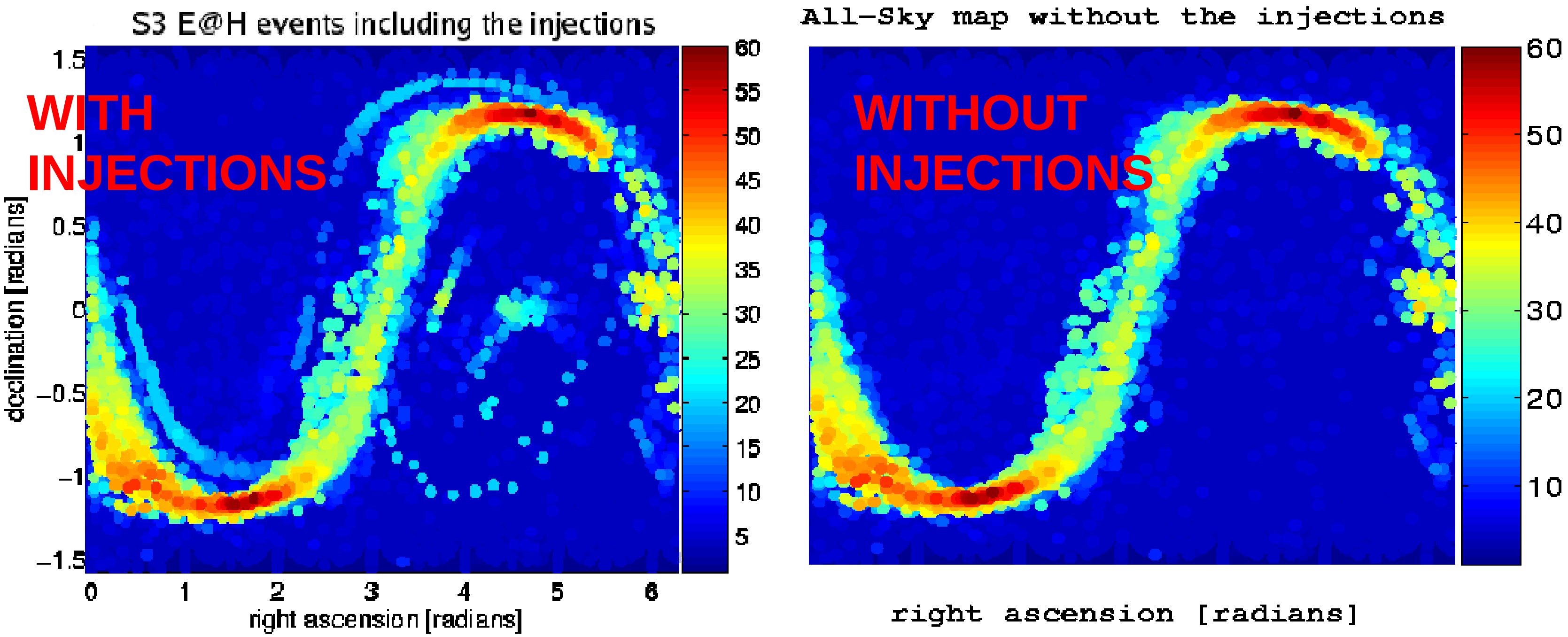
What would a pulsar look like?

- Post-processing step: find points on the sky and in frequency that exceeded threshold in many of the sixty ten-hour segments
- Software-injected fake pulsar signal is recovered below



Simulated (software) pulsar signal in S3 data

Final S3 analysis results

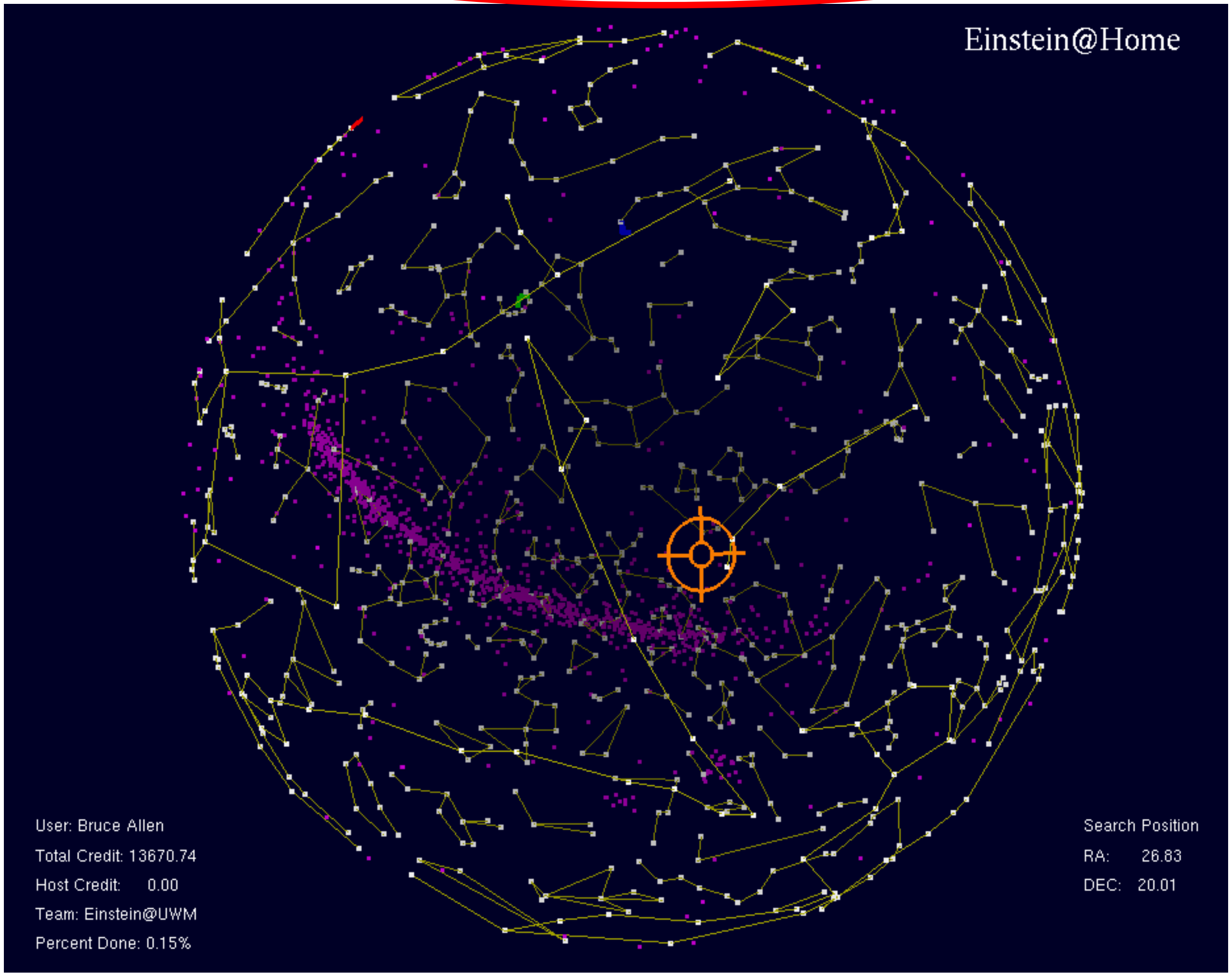


- Data: 60 10-hour stretches of the best H1 data
- Post-processing step on centralized server: find points in sky and frequency that exceed threshold in many of the sixty ten-hour segments analyzed
- 50-1500 Hz band shows no evidence of strong pulsar signals in sensitive part of the sky, apart from the hardware and software injections. There is nothing "in our backyard".
- Outliers are consistent with instrumental lines. All significant artifacts away from r.n=0 are ruled out by follow-up studies.

Einstein@home

- Like SETI@home, but for LIGO/GEO data
- American Physical Society (APS) publicized as part of World Year of Physics (WYP) 2005 activities
- Use infrastructure/help from SETI@home developers for the distributed computing parts (BOINC)
- Goal: pulsar searches using ~1 million clients. Support for Windows, Mac OSX, Linux clients
- From our own clusters we can get ~ thousands of CPUs. From Einstein@home hope to get order(s) of magnitude more at low cost
- Great outreach and science education tool
- Currently : ~160,000 active users corresponding to about 85Tflops, about 200 new users/day

http://einstein.phys.uwm.edu/



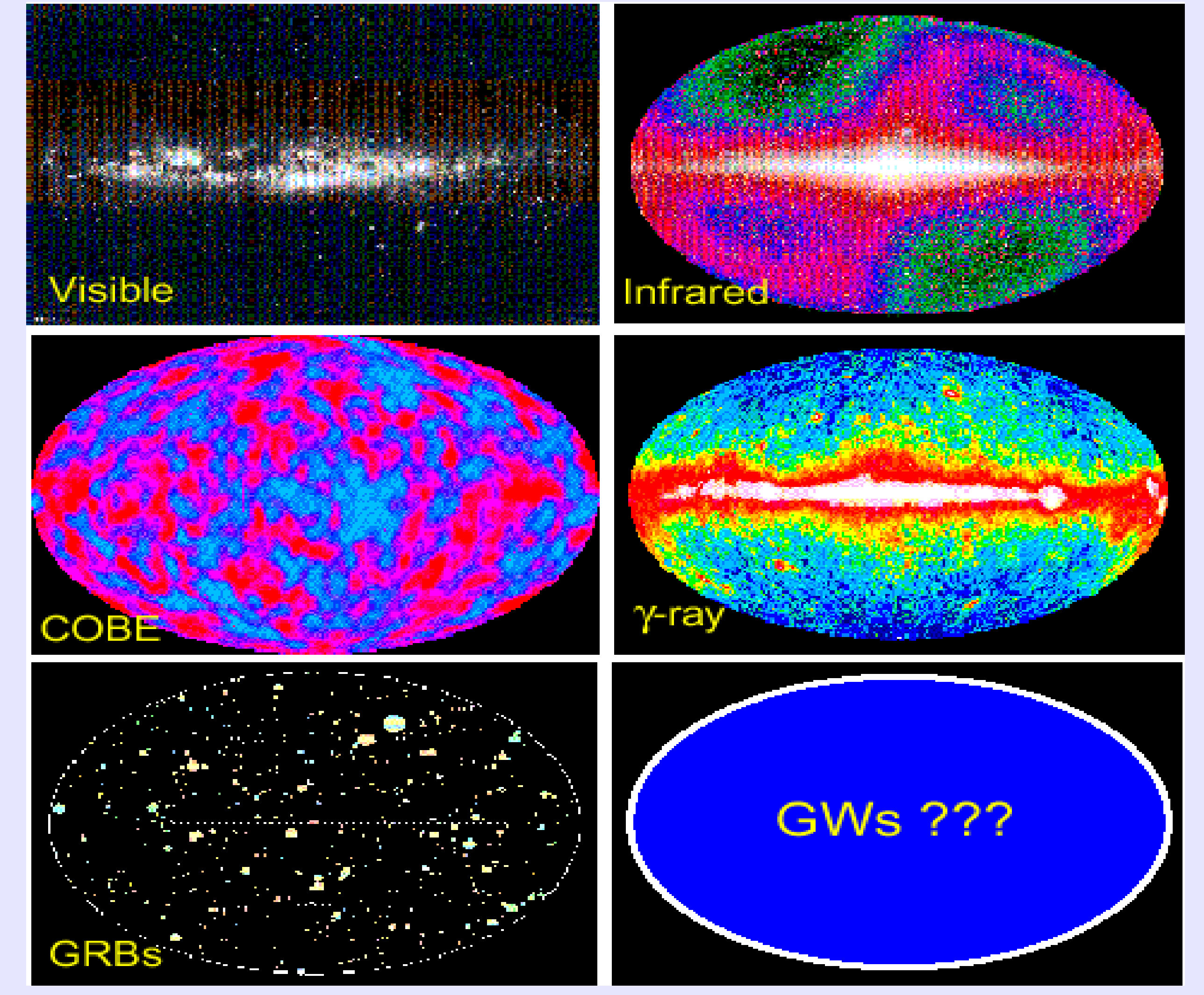
User: Bruce Allen
Total Credit: 13670.74
Host Credit: 0.00
Team: Einstein@UWM
Percent Done: 0.15%

Search Position
RA: 26.83
DEC: 20.01

Summary remarks

- LIGO achieved design sensitivity in Nov 05, a major milestone
- LIGO/GEO launched coincident S5 science run, which is to run until fall 2007
- Host of searches underway: analyses ongoing of S3, S4, and S5 data – no detections yet!
- Enhanced LIGO upgrade slated for 2008/09, factor of 2-3 in sensitivity improvement
- Advanced LIGO upgrade slated for ~2011 to dramatically improve sensitivity

We should be detecting gravitational waves regularly within the next 10 years!


Visible
Infrared
COBE
γ-ray
GRBs
GWs ???