Searching for gravitational waves with new interferometers

Michael Landry
LIGO Hanford Observatory
California Institute of Technology

on behalf of the LIGO Scientific Collaboration
Continuous Waves Search Group
http://www.ligo.org

NS/LSC meeting
MIT Nov 2, 2006

LIGO-G060546-00-Z

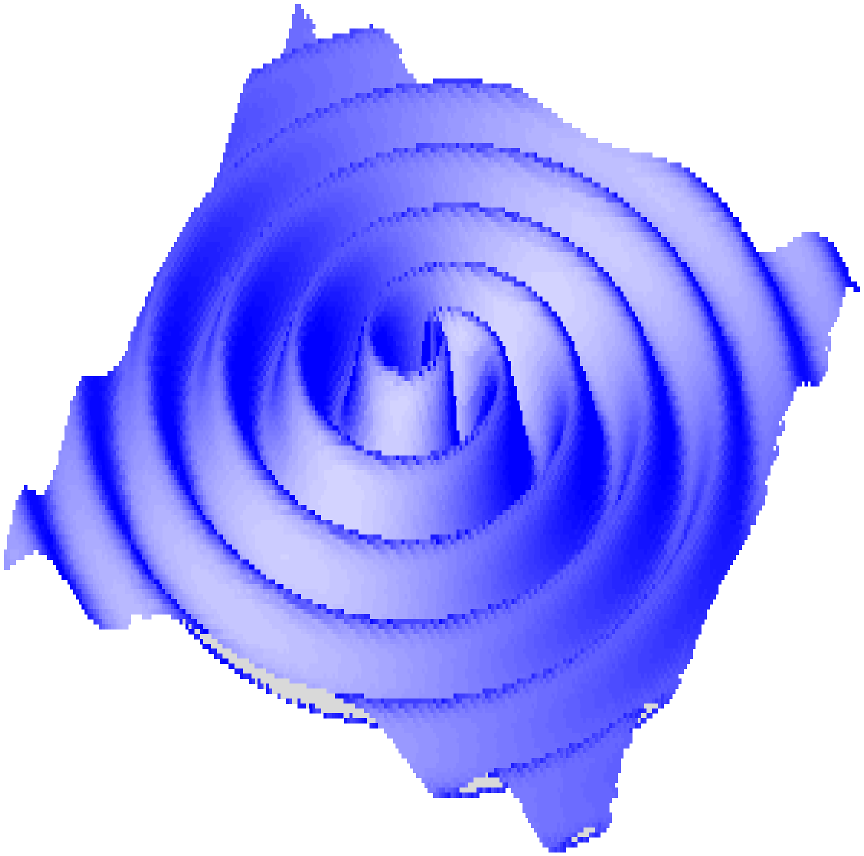
Talk overview

- Everything up to analysis
  - » Gravitational waves – what are they and what is the observable
  - » A look at LIGO and GEO interferometers
    - – some installations
    - – noise curves
  - » Observational ("Science") runs
- Analysis
  - » A one-slide introduction to the LIGO Scientific Collaboration (LSC) Continuous Waves (CW) search group and the work that they do
  - » M. Alessandra will overview the group's search efforts
  - » Ben will discuss astrophysical input

Gravitational waves

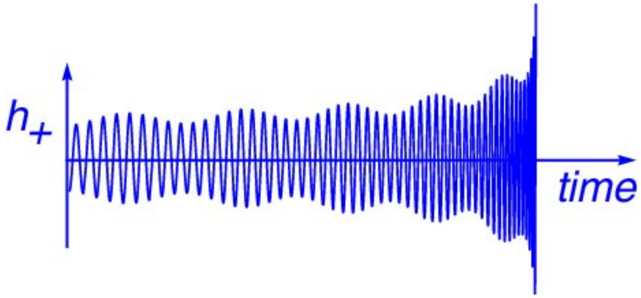
- GWs are “ripples in spacetime”: rapidly moving masses generate fluctuations in spacetime curvature:
  - » They are expected to propagate at the speed of light
  - » They stretch and squeeze space

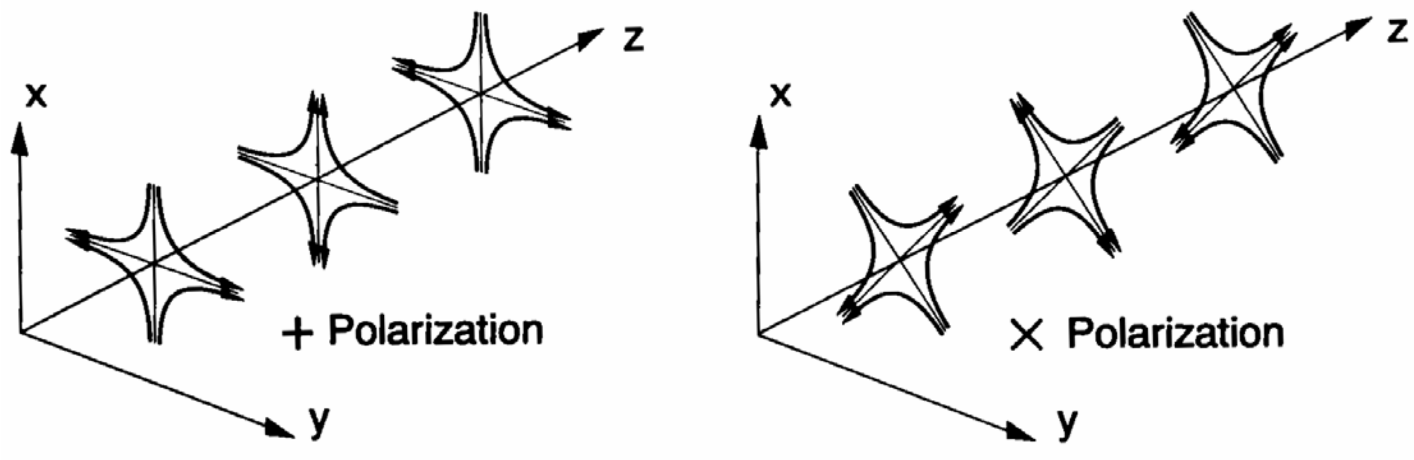
$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$



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 $h_x(t)$)





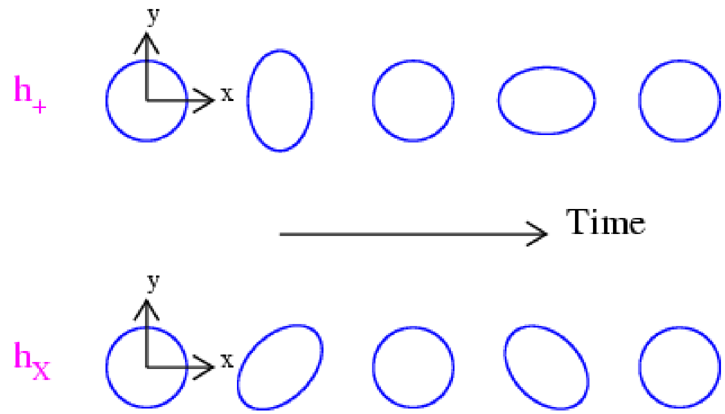
What is the observable effect?

Example:

Ring of test masses

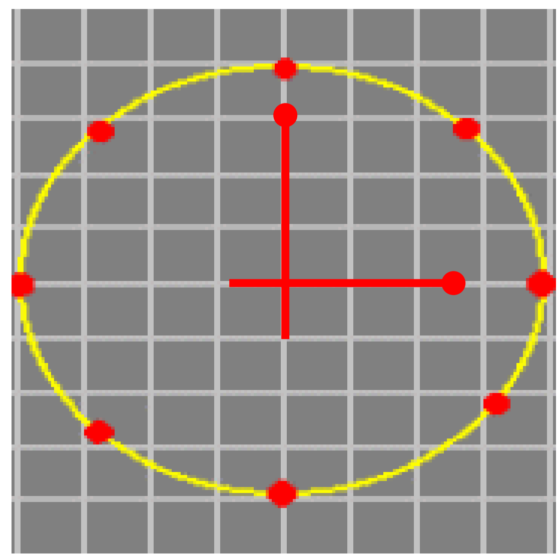
responding to wave

propagating along z

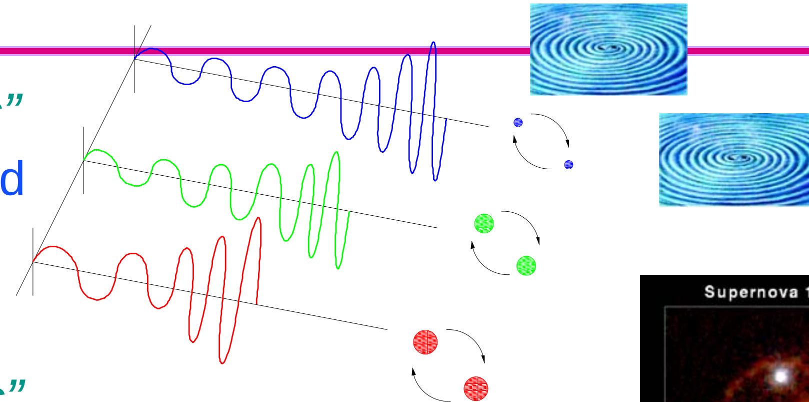


Amplitude parameterized by (tiny) dimensionless strain h:

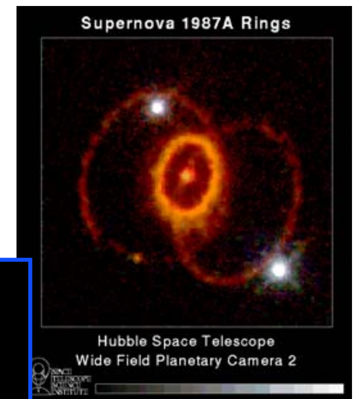
$$h(t) = \frac{\delta L(t)}{L}$$



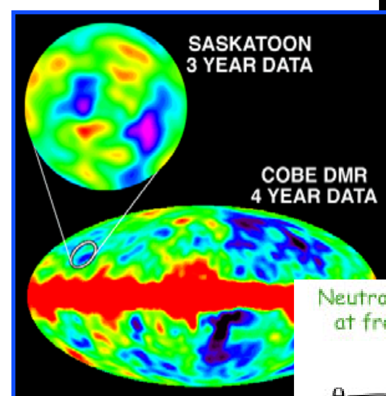
What makes gravitational waves?



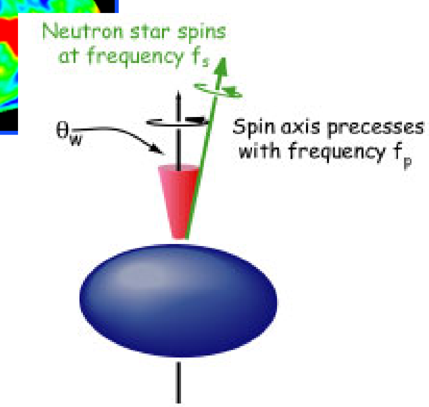
- Compact binary inspiral: *"chirps"*
  - » NS-NS waveforms are well described
  - » BH-BH need better waveforms



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



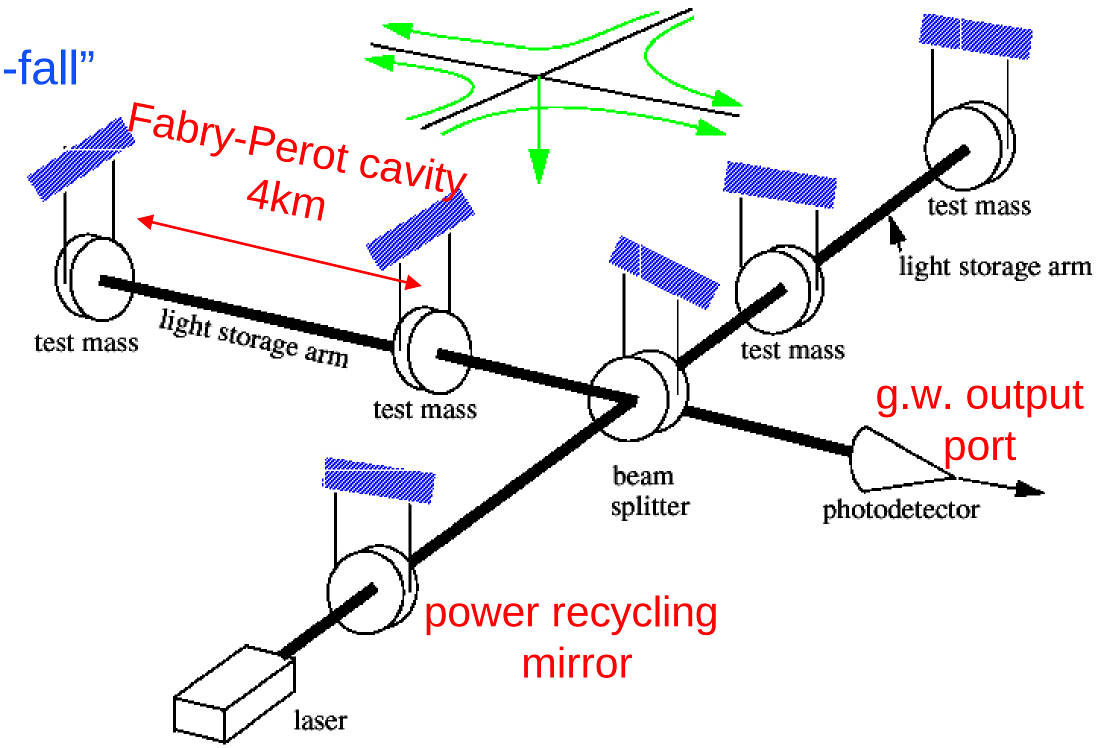
- Cosmological Signal: *"stochastic background"*



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

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.

GEO600

Work with the GEO600 Experiment (Germany / UK / Spain):

- **Arrange coincidence data runs when commissioning schedules permit**
- **GEO members are full members of the LIGO Scientific Collaboration**
- **Data exchange and strong collaboration in analysis now routine**
- **Major partners in proposed Advanced LIGO upgrade**

600-meter Michelson Interferometer just outside Hannover, Germany

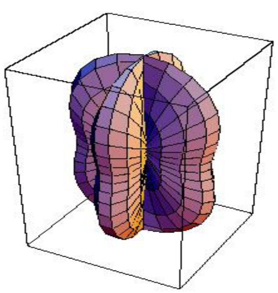
Aside: some terminology

Beam patterns

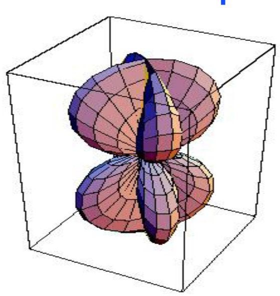
$$\frac{\delta L(t)}{L} = h(t) = F^{+}h_{+}(t) + F^{\times}h_{\times}(t)$$

- $F^{+}, F^{\times}$: [-1, 1]
- $F = F(t; \alpha, \delta)$

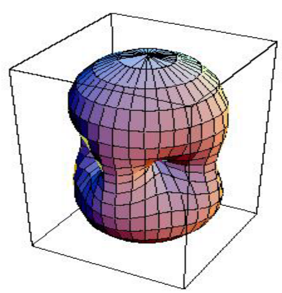
LIGO example:



F^{+}

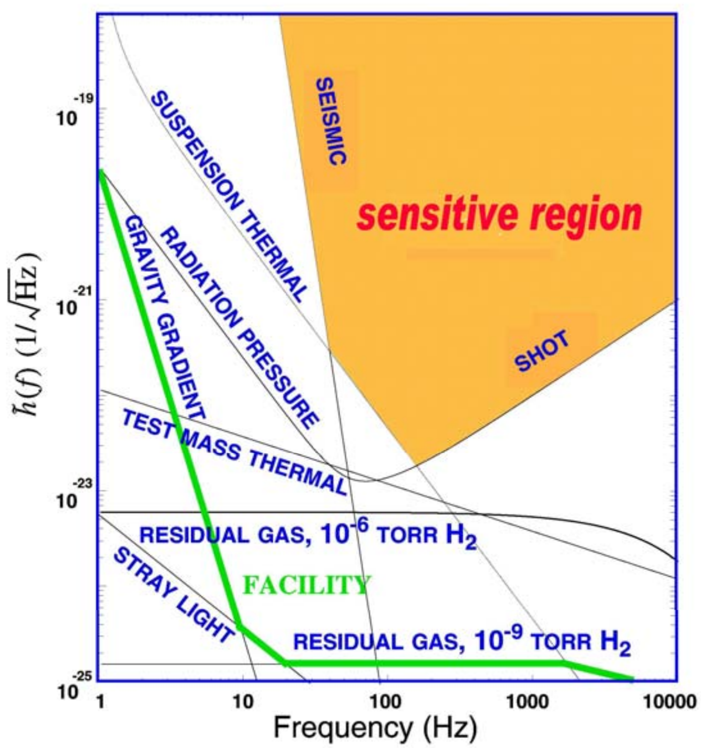


$F^{\times}$



average

Strain noise curves



Aside: some terminology

Beam patterns

$$\frac{\delta L(t)}{L} = h(t) = F^{+} h_{+}(t) + F^{\times} h_{\times}(t)$$

- F^{+}, F^{x} : [-1, 1]
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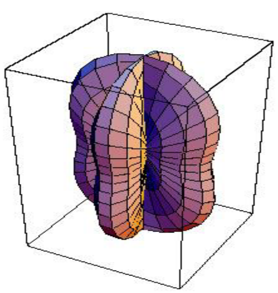
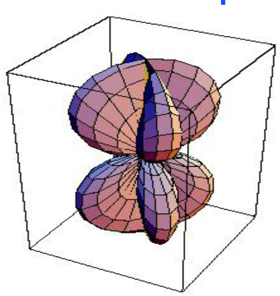
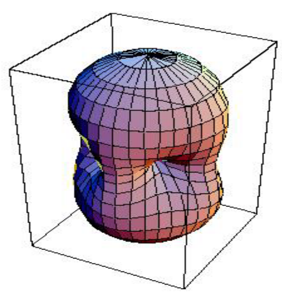
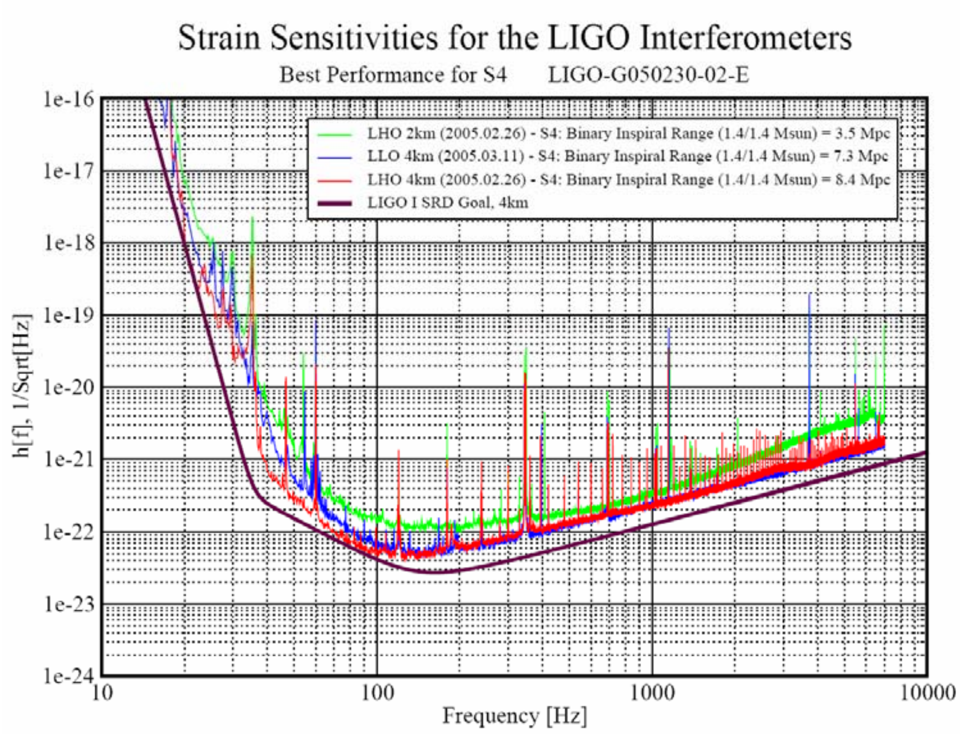
LIGO example:


F^{+}


F^{x}

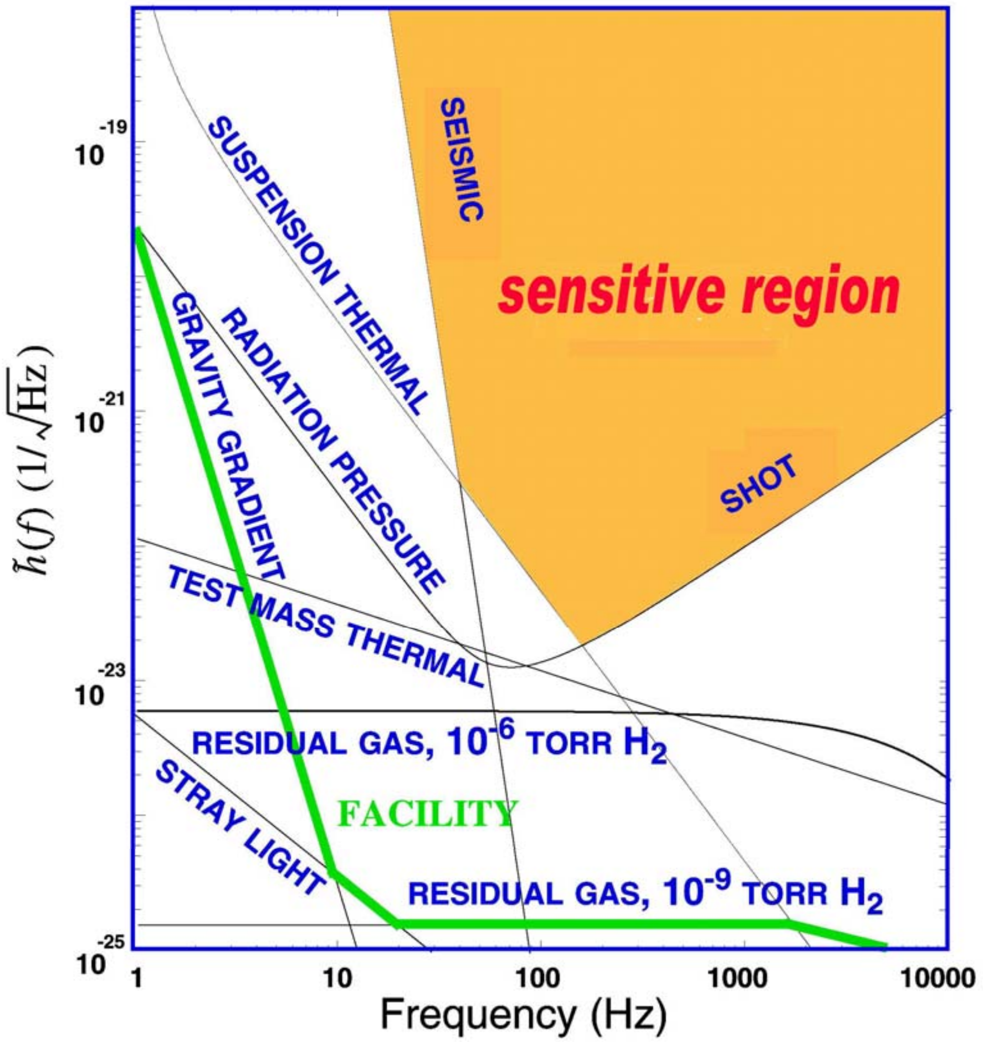

average

Strain noise curves



What Limits Sensitivity of Interferometers?

- Seismic noise & vibration limit at low frequencies
- Atomic vibrations (Thermal Noise) inside components limit at mid frequencies
- Quantum nature of light (Shot Noise) limits at high frequencies
- Myriad details of the lasers, electronics, etc., can make problems above these levels



Evacuated Beam Tubes Provide Clear Path for Light

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

Evacuated Beam Tubes Provide Clear Path for Light

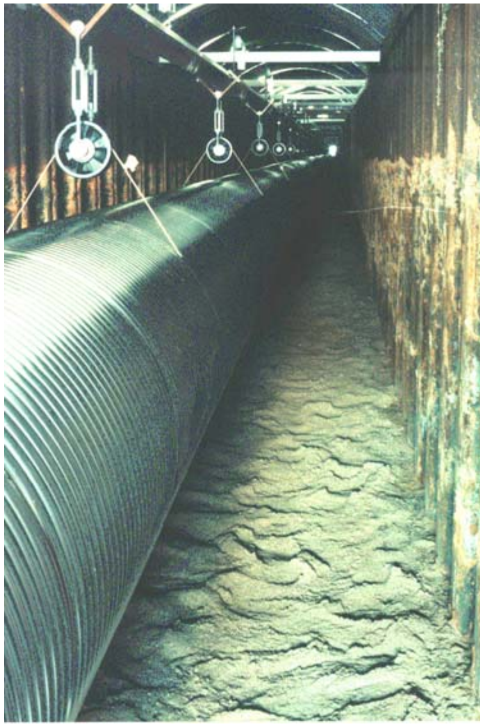
Bakeout facts:

- **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

GEO, Virgo vacuum

Virgo

GEO

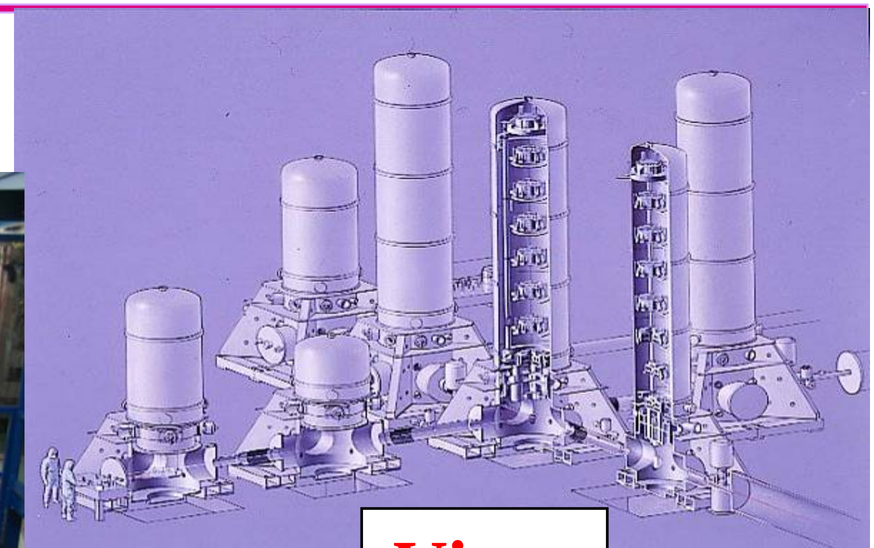
Vacuum chambers provide quiet homes for mirrors

The view inside the Corner Station

Standing at the 4k vertex: beam splitter

GEO, Virgo corner stations

GEO



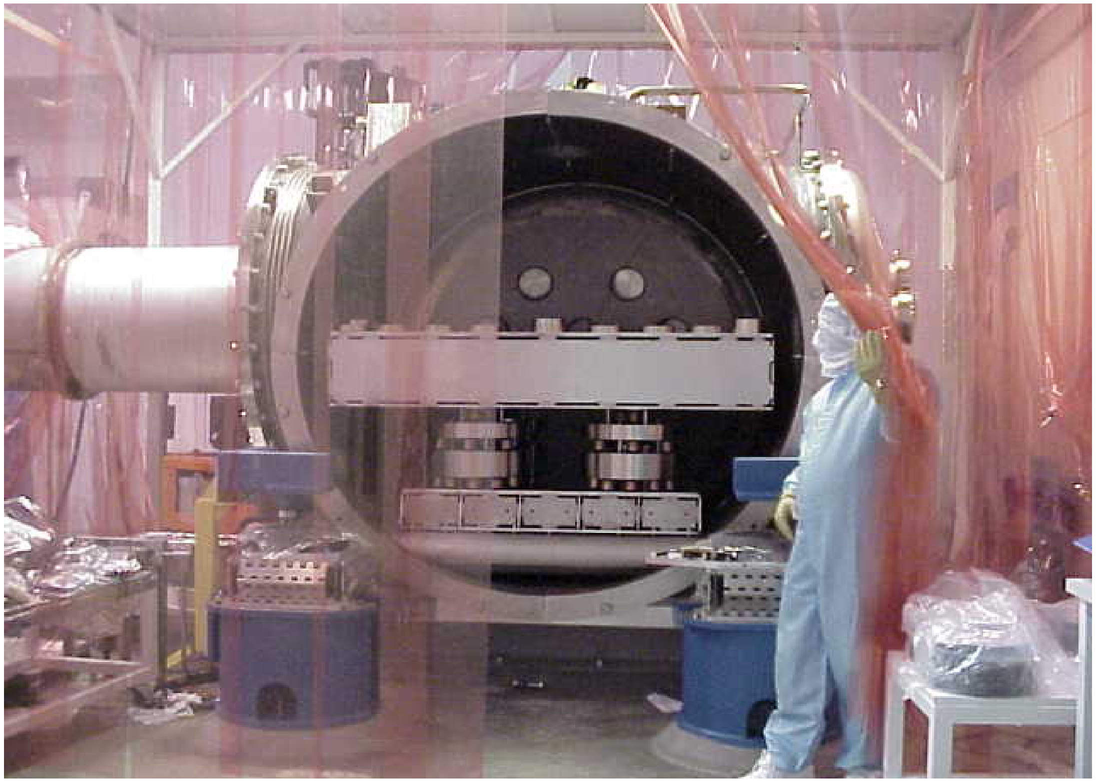
Virgo

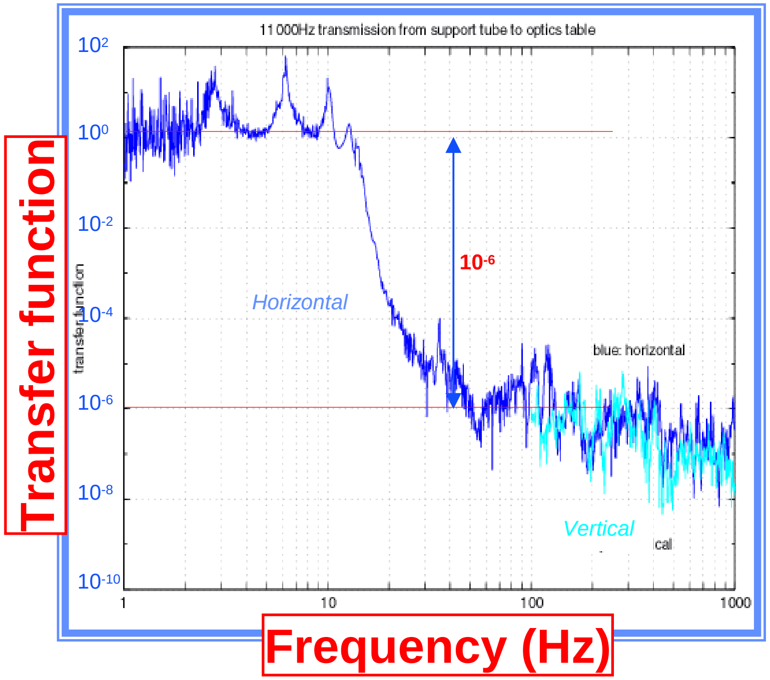
Seismic Isolation – Springs and Masses

LIGO detector facilities

Seismic Isolation

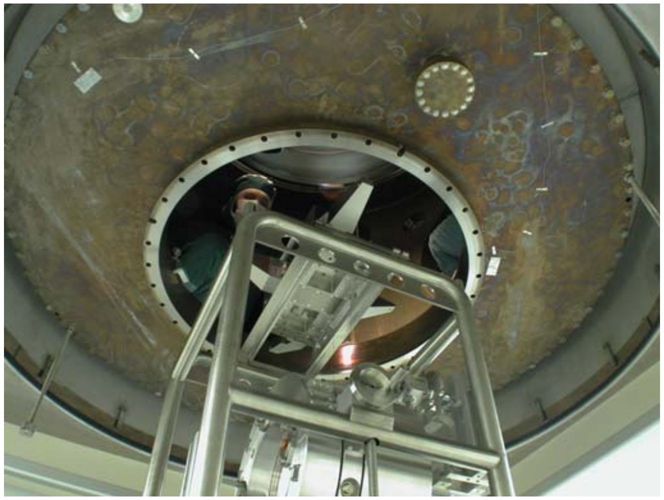
- Multi-stage (mass & springs) optical table support gives 10^6 suppression
- Pendulum suspension gives additional $1 / f^2$ suppression above ~1 Hz

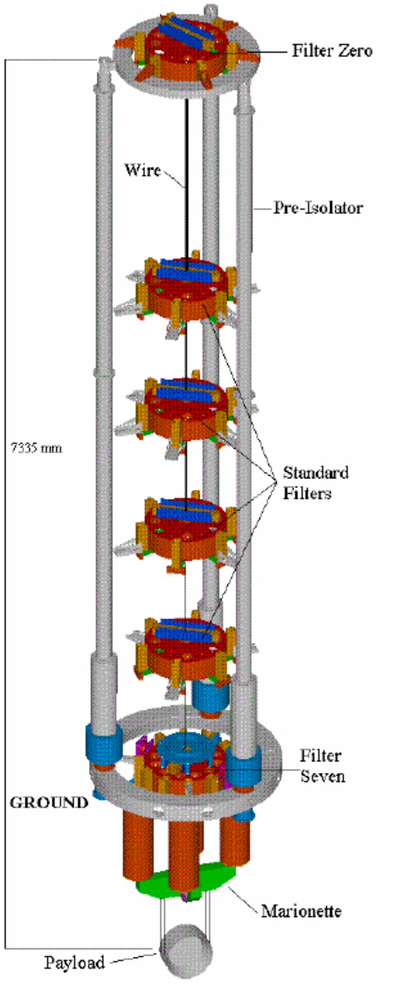


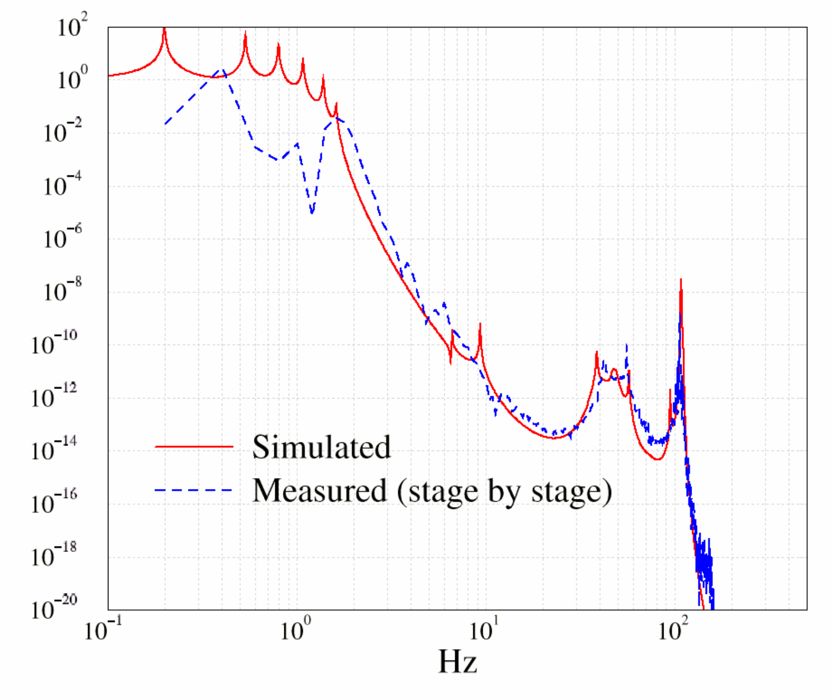


VIRGO Seismic Isolation and Suspensions

"Long Suspensions"
- **inverted pendulum**
- **five intermediate filters**



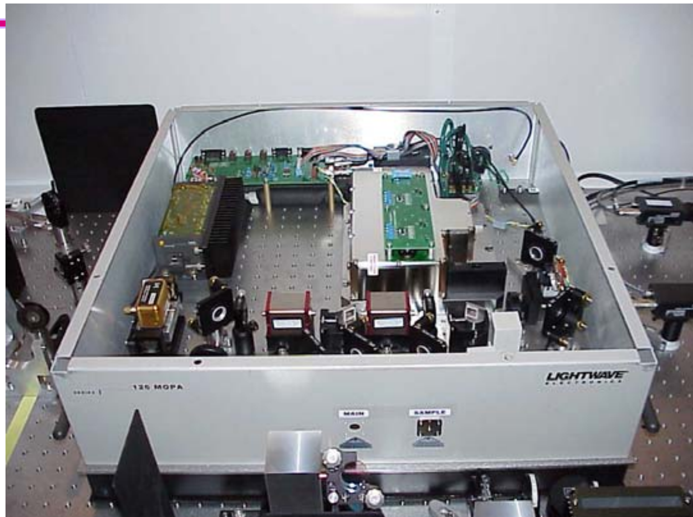




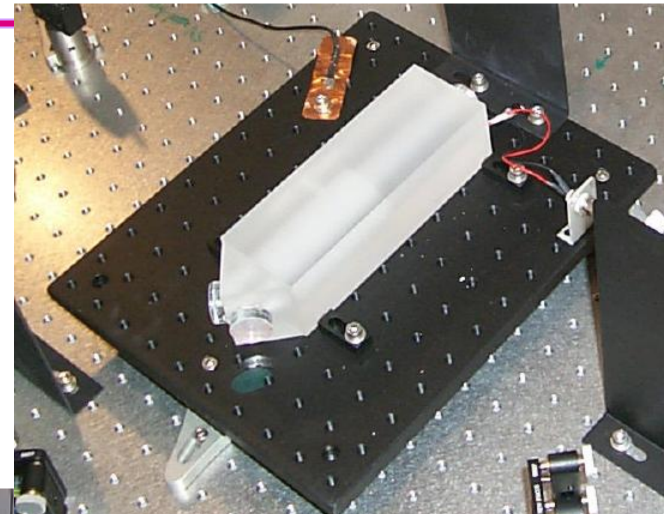
Suspension vertical transfer function measured and simulated (prototype)

LIGO-G060546-00-Z

All-Solid-State Nd:YAG Laser



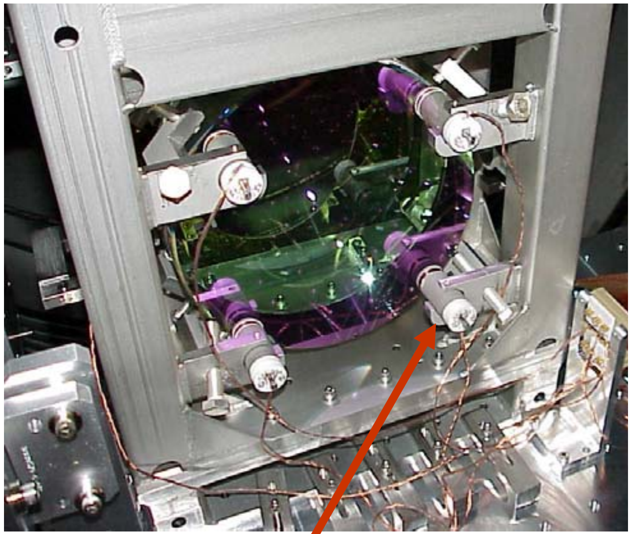
Custom-built
10 W Nd:YAG Laser,
joint development with
Lightwave Electronics
(now commercial product)



Cavity for
defining beam geometry,
joint development with
Stanford

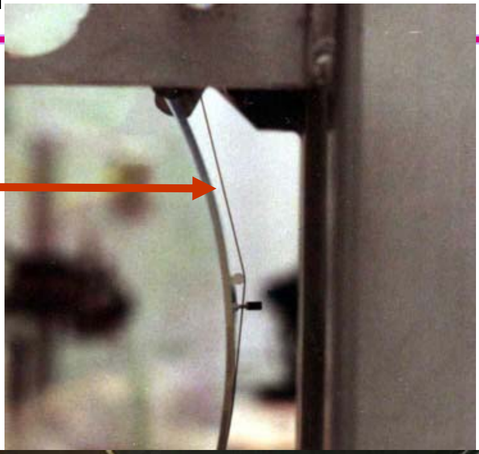
Frequency reference
cavity (inside oven)

Core optics suspension and control



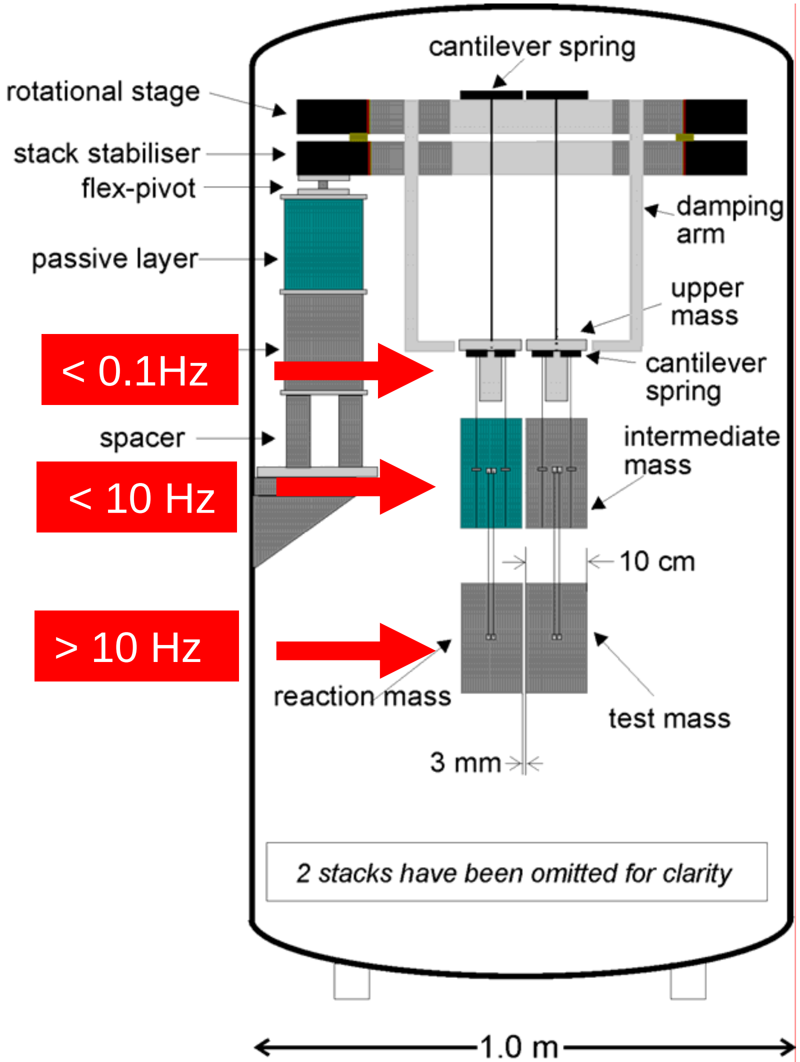
Shadow sensors & voice-coil actuators provide damping and control forces

Optics suspended as simple pendulums



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

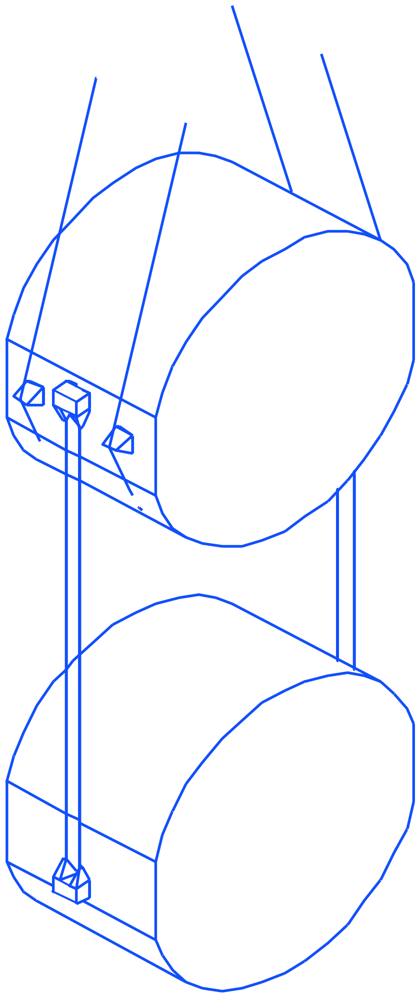
GEO Michelson length control

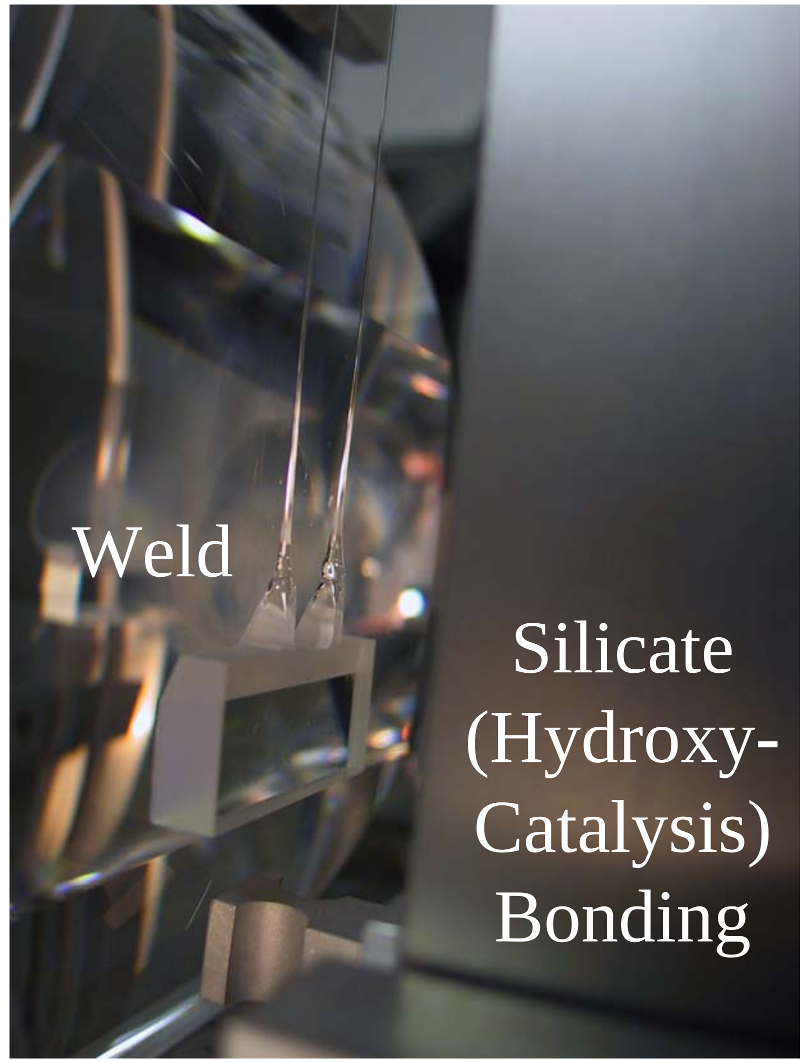


Reaction Pendulum:

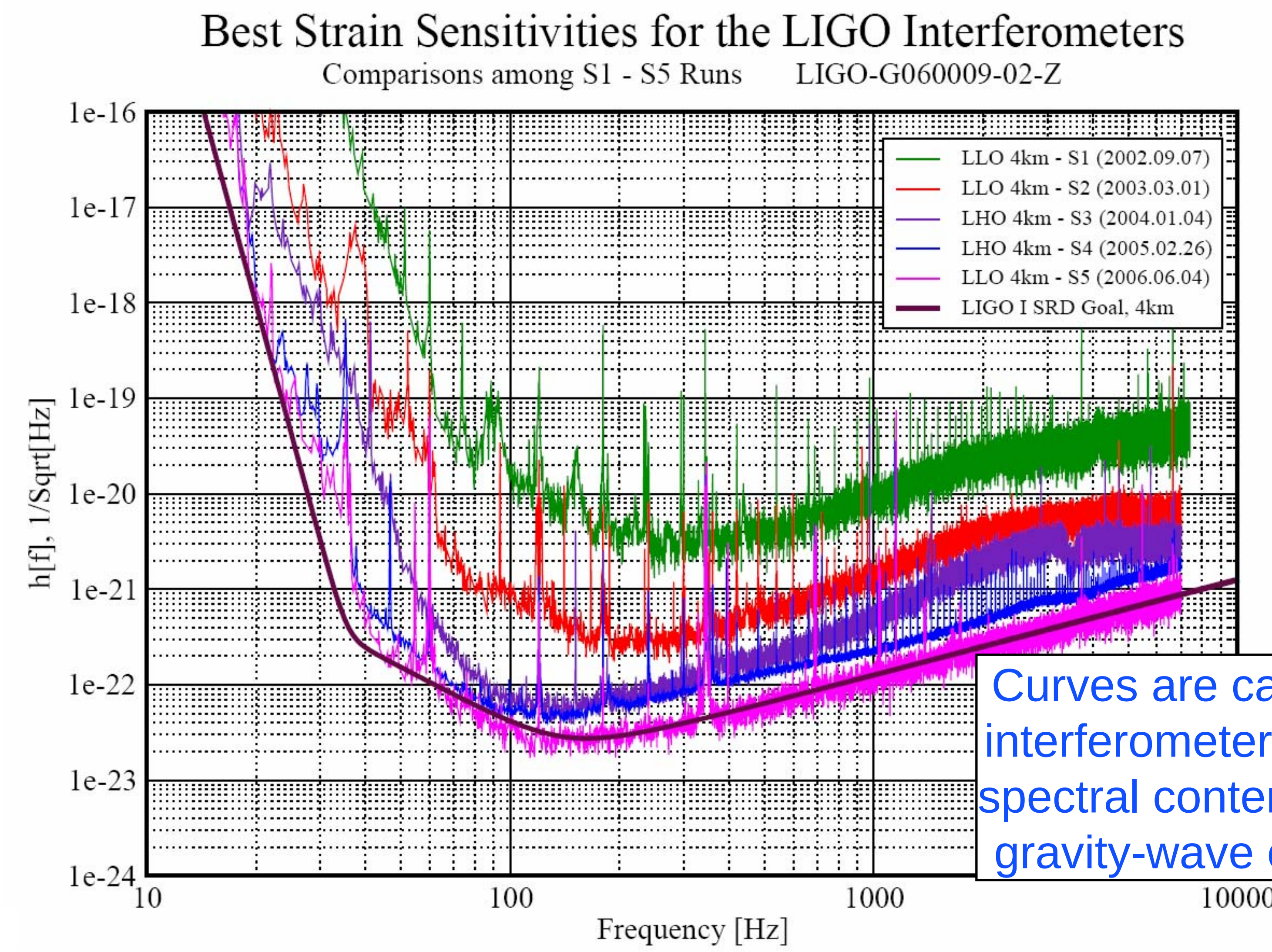
- 3 coil-magnet actuators at intermediate mass, range ~ 100µm
- Electrostatic actuation on test mass bias 630V, range 0-900V= 3.5µm

GEO Thermal Noise / Monolithic Suspension



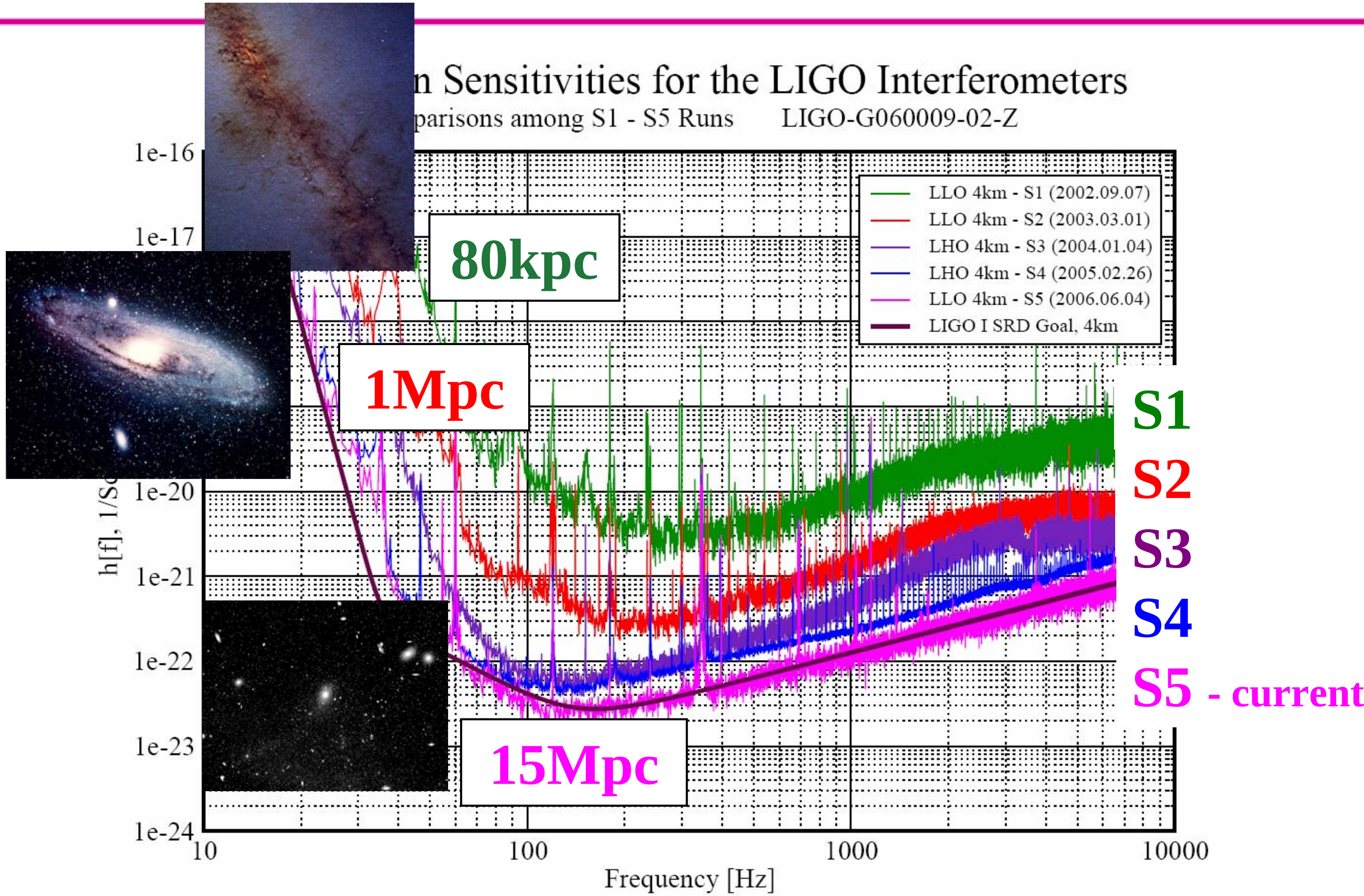


Calibrated output: LIGO noise history



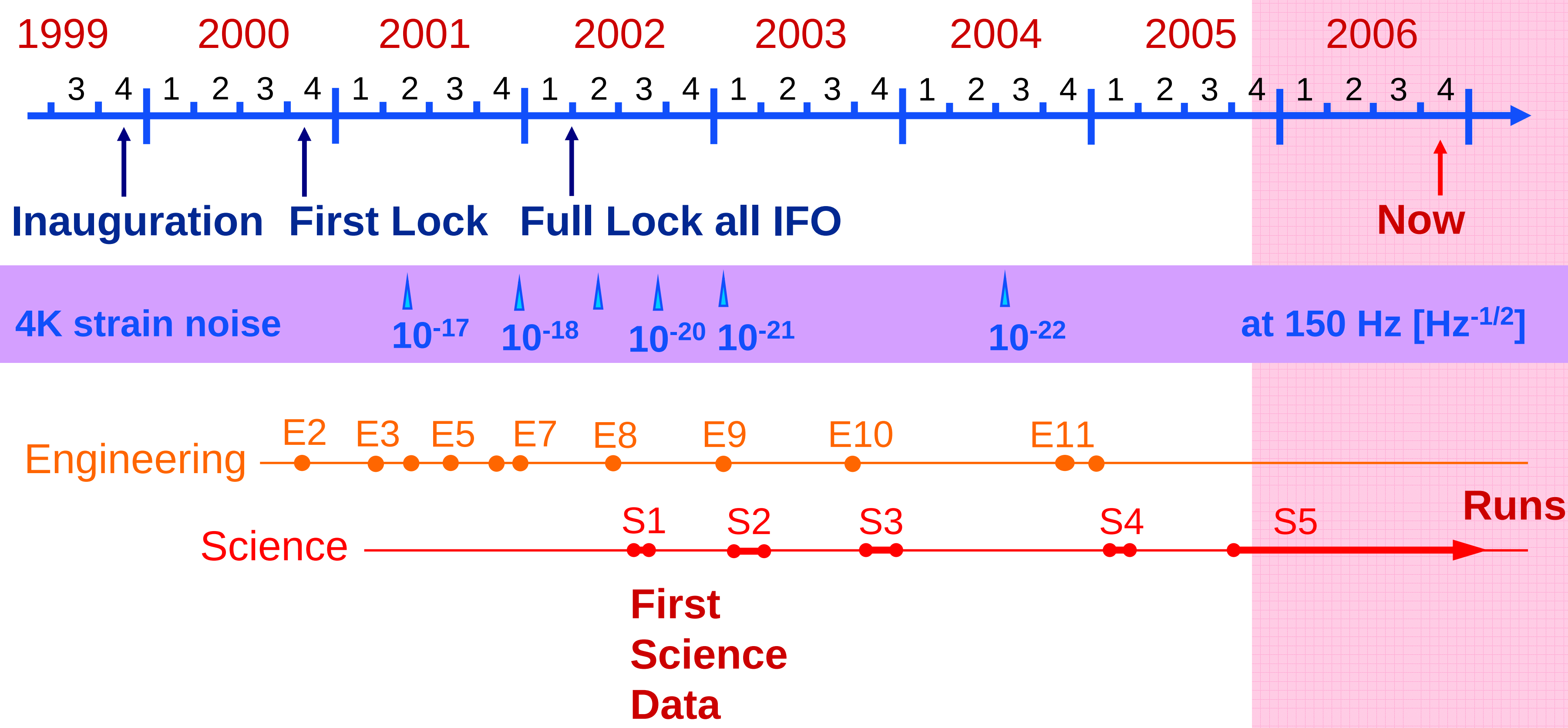
Curves are calibrated interferometer output: spectral content of the gravity-wave channel

Calibrated output: LIGO noise history

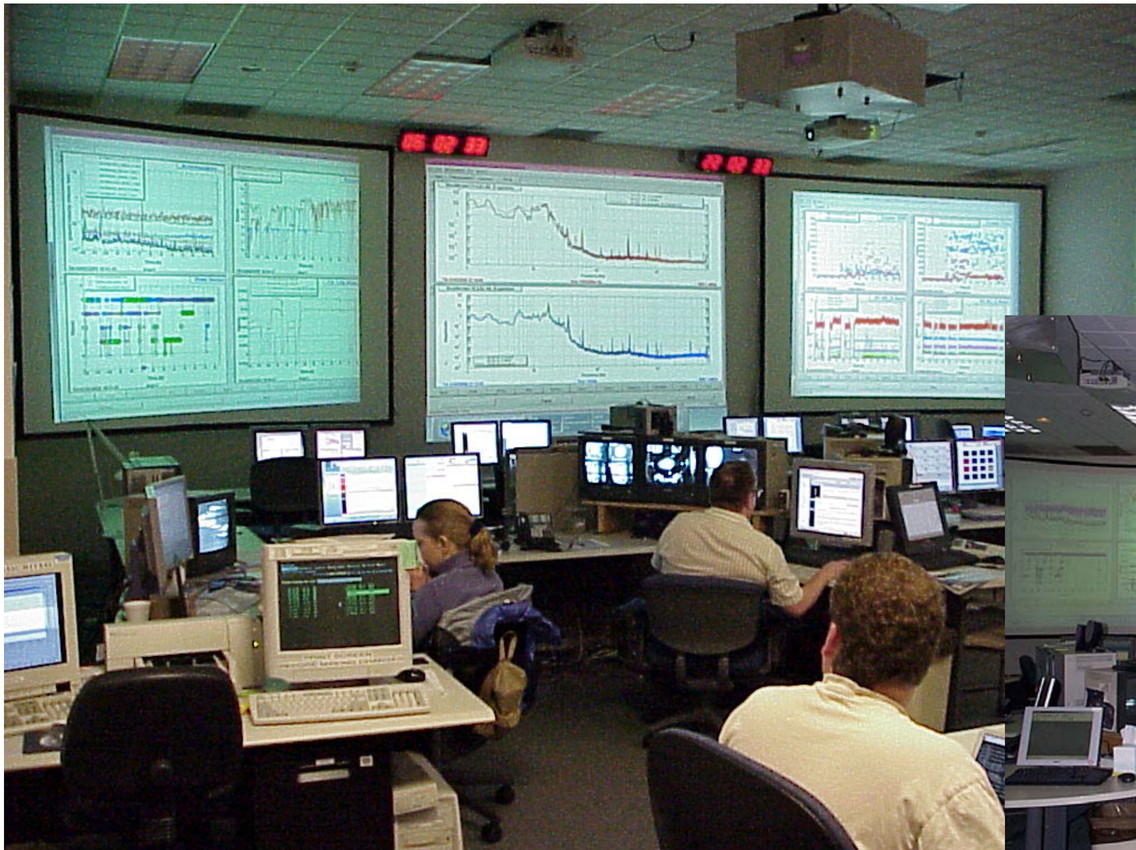


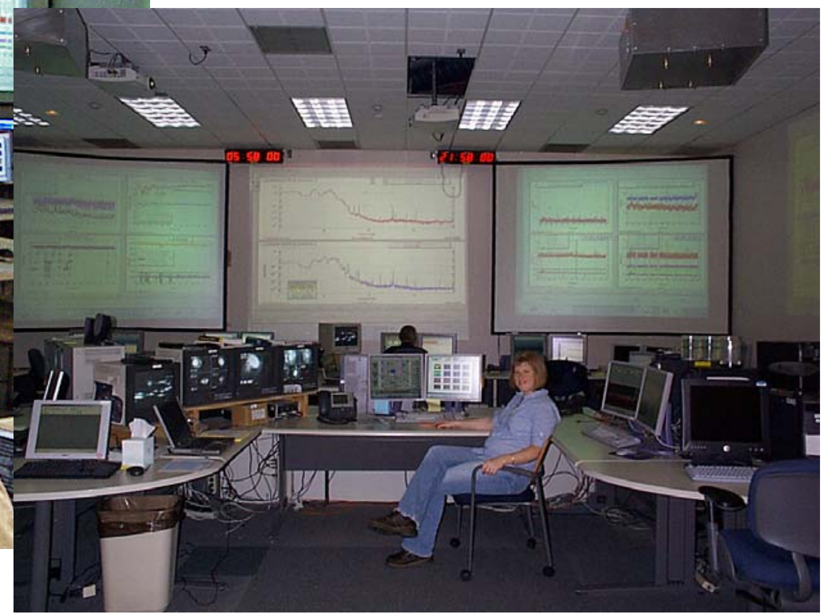
Calibrated output: GEO noise history

Time line


1999 2000 2001 2002 2003 2004 2005 2006
3 4 1 2 3 4 1 2 3 4 1 2 3 4 1 2 3 4 1 2 3 4 1 2 3 4 1 2 3 4 1 2 3 4
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

Science runs and analyses





LIGO Hanford control room
31 Mar 2006 – S5

Searches for Continuous Waves

Coherent searches:

Employs JBO timing data (Kramer/Lyne)

- Bayesian time-domain (TDS)
  - Isolated and binary pulsars
  - Markov chain Monte Carlo

Finely tuned searches over a narrow parameter space (known pulsars, parameter estimation)

- F-statistic frequency domain
  - Isolated all-sky over wide frequency range
  - Einstein@home
  - Binary x-ray with some unknown orbital parameters
  - Directed for known x-ray sources

Deep searches over a broad parameter space

Incoherent searches:

- Hough transform
- Stack-slide
- Powerflux

Fast, robust, wide-parameter searches

LSC CW publications

Summary of LIGO publications for periodic GWs:

1. Setting Upper Limits on the Strength of Periodic GW from PSR J1939+2134 Using the First Science Data from the GEO600 and LIGO Detectors, PRD 69, 082004 (2004) .
2. Limits on Gravitational-Wave Emission from Selected Pulsars Using LIGO Data, PRL 94, 181103 (2005).
3. First All-sky Upper Limits from LIGO on the Strength of Periodic Gravitational Waves Using the Hough Transform, PRD 72, 102004 (2005).
4. Coherent searches for periodic gravitational waves from unknown isolated sources and Scorpius X-1: results from the second LIGO science run, gr-qc/0605028, submitted to PRD
5. Einstein@home online report for S3 search: http://einstein.phys.uwm.edu/PartialS3Results
6. Upper limits on gravitational wave emission from 76 radio pulsars, Still in internal review process
7. All-sky LIGO (incoherent) search for periodic gravitational waves in the S4 data run, Still in internal review process

S1 (1)

S2 (2–4)

S3 (5–6)

S4 (6–7)