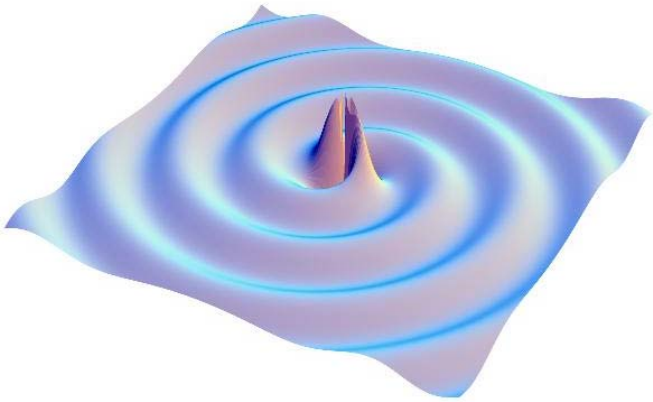
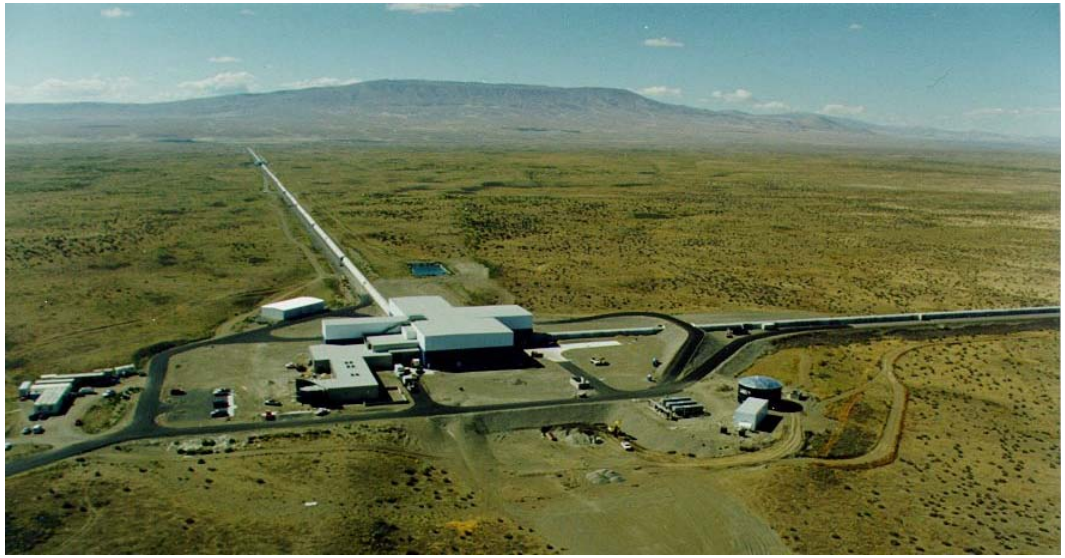
The LIGO Experiment
Present and Future



Keith Riles
University of Michigan

For the LIGO Scientific Collaboration



APS Meeting
Denver – May 1–4 , 2004

LIGO-G040239-00-Z

What are Gravitational Waves?

- **Gravitational Waves = "Ripples in space-time"**

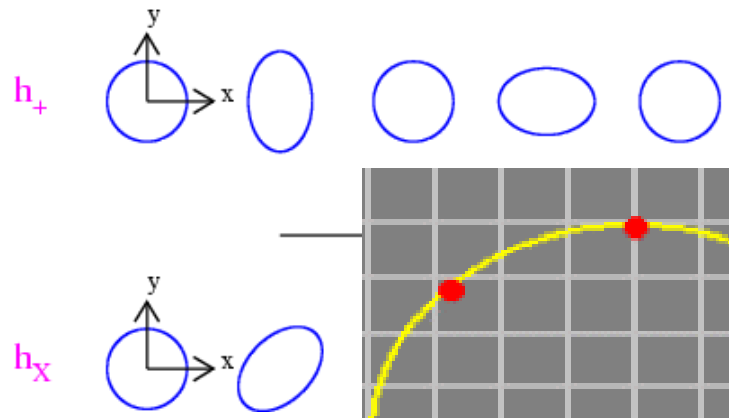
- **Perturbation propagation similar to light (obeys same wave equation!)**
  - » **Propagation speed = c**
  - » **Two transverse polarizations - quadrupolar: + and x**

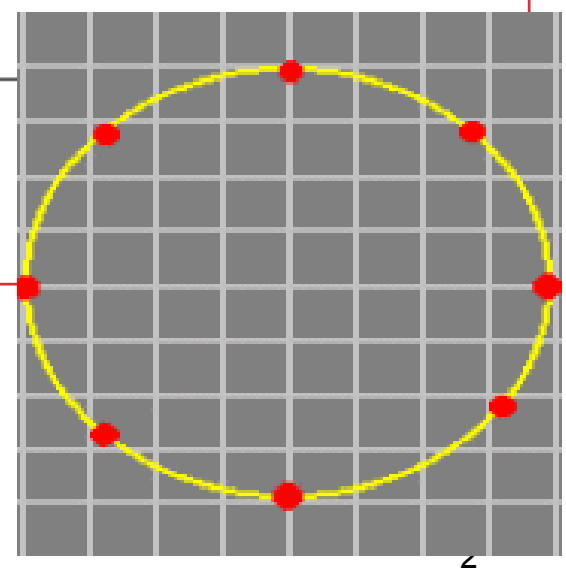
Example:

Ring of test masses

responding to wave

propagating along z





Amplitude parameterized by (tiny)

dimensionless strain h: $\Delta L \sim h(t) \times L$

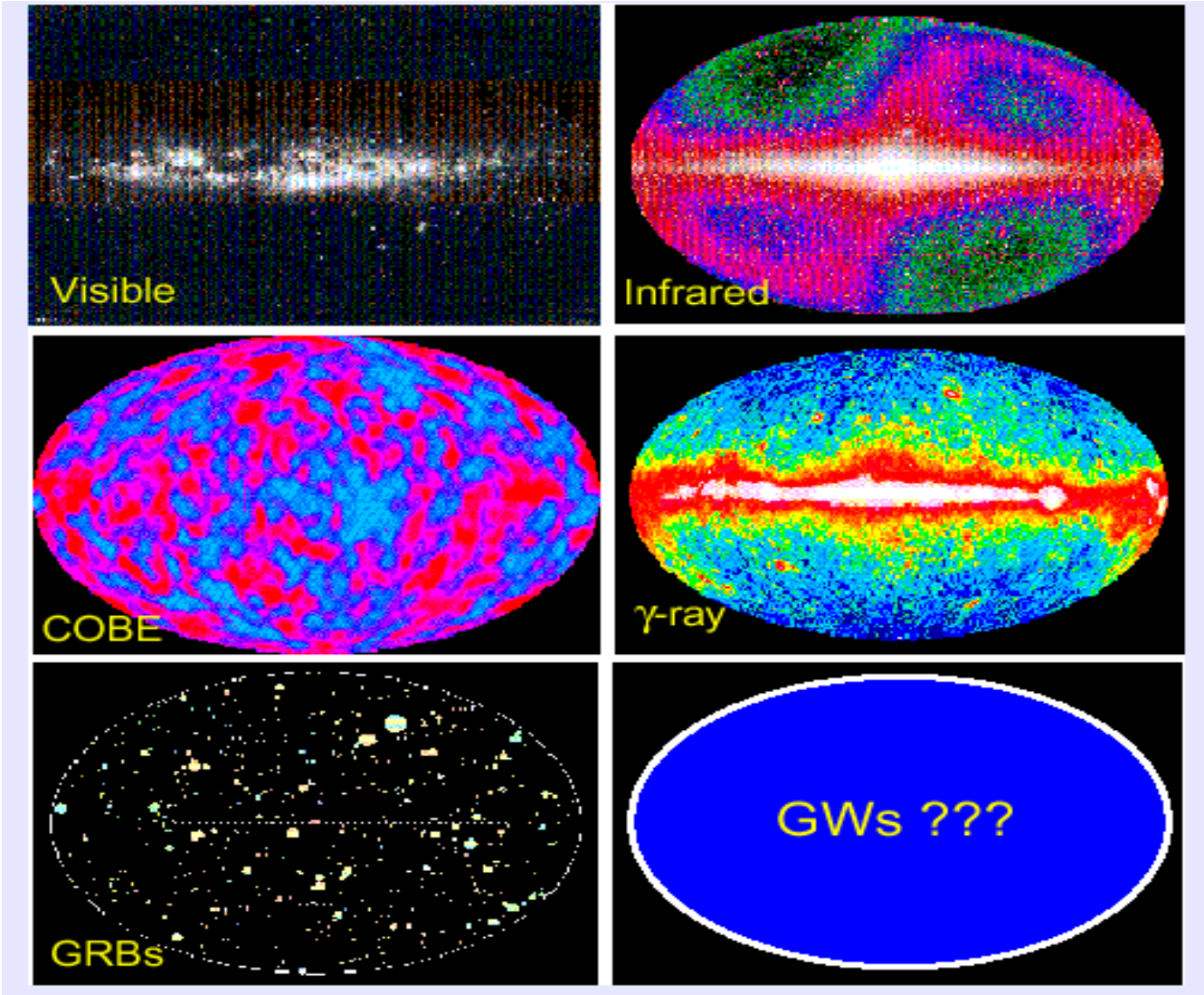
Why look for Gravitational Radiation?

- **Because it's there! (presumably)**

- **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

What might the sky look like?



What makes Gravitational Waves?

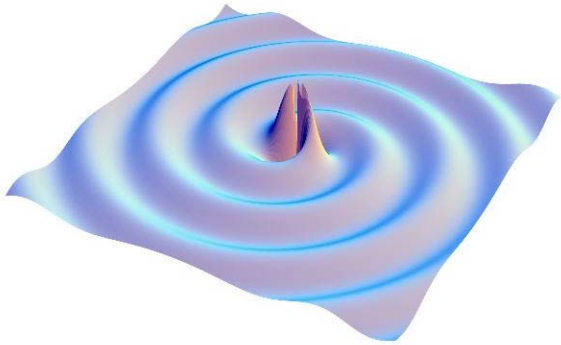
- **Radiation generated by quadrupolar mass movements:**

$$h_{\mu\nu} = \frac{2G}{rc^4}\frac{d^2}{dt^2}(I_{\mu\nu})$$

(with $I_{\mu\nu}$ = quadrupole tensor, r = source distance)

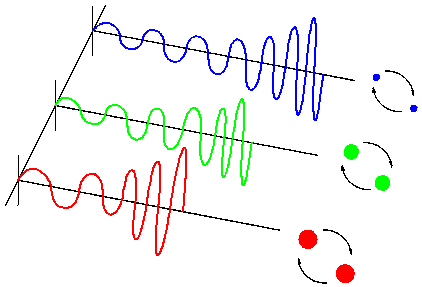
- **Example: Pair of 1.4 M_{solar} neutron stars in circular orbit of radius 20 km (imminent coalescence) at orbital frequency 400 Hz gives 800 Hz radiation of amplitude:**

$$h \approx \frac{10^{-21}}{(r/15\mathrm{Mpc})}$$



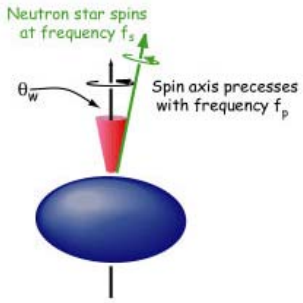
What makes Gravitational Waves?

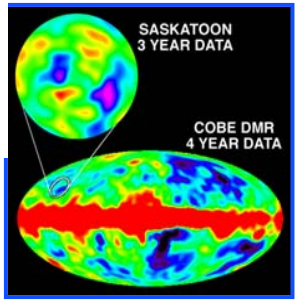
- **Compact binary inspiral:** *"chirps"*
  - » NS-NS waveforms are well described
  - » BH-BH need better waveforms



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

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



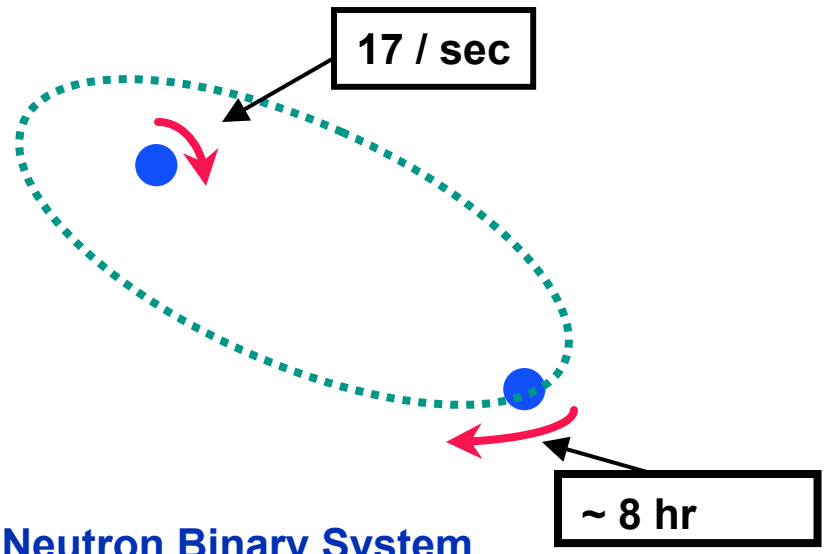


- **Cosmological Signals** *"stochastic background"*

Strong Indirect Evidence: Orbital Decay

Neutron Binary System – Hulse & Taylor

PSR 1913 + 16 -- Timing of pulsars



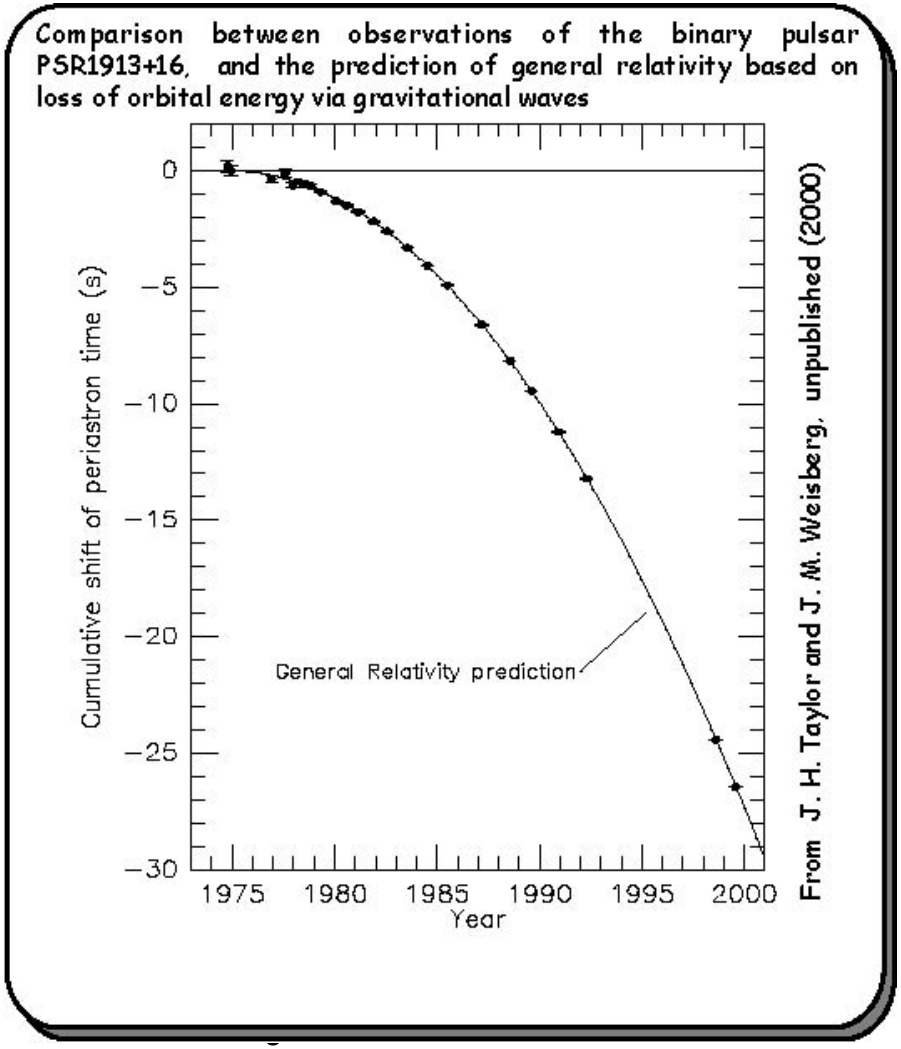
Neutron Binary System

- separated by 10^6 miles
- $m_1 = 1.44 m_\odot$; $m_2 = 1.39 m_\odot$; $\varepsilon = 0.617$

Prediction from general relativity

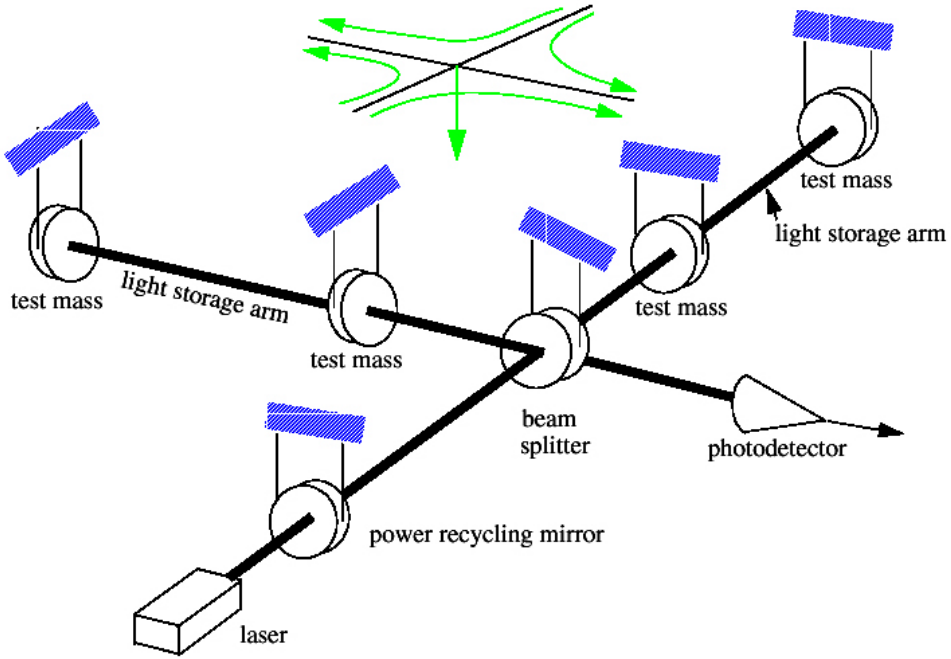
- spiral in by 3 mm/orbit
- rate of change orbital period

Emission of gravitational waves

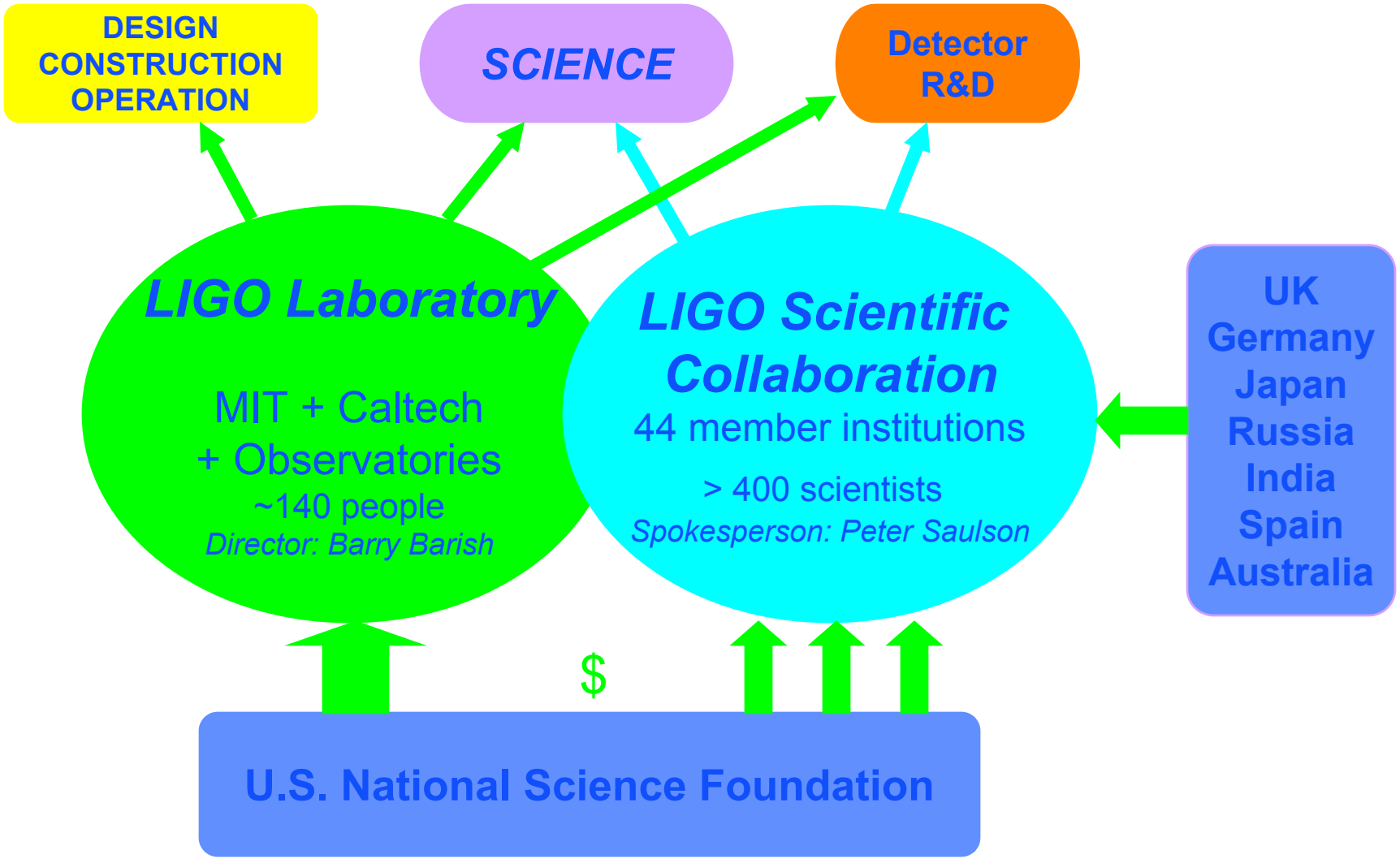


Gravitational Wave Detection

- **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 Organization & Support



LIGO Scientific Collaboration
The Logo's

GEO600

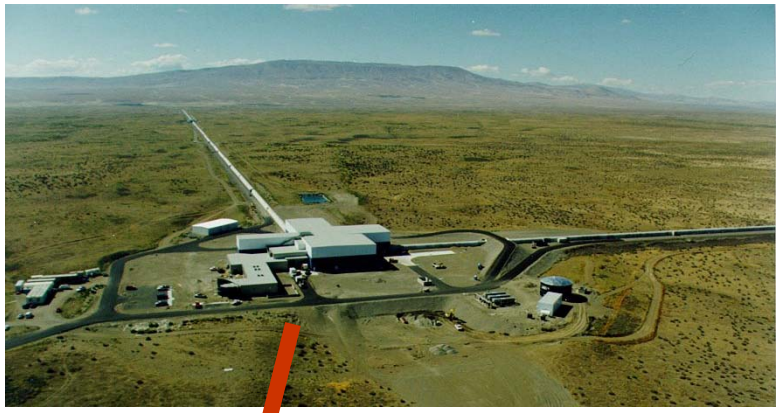
Work closely with the GEO600 Experiment (Germany / UK / Spain)

- **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**

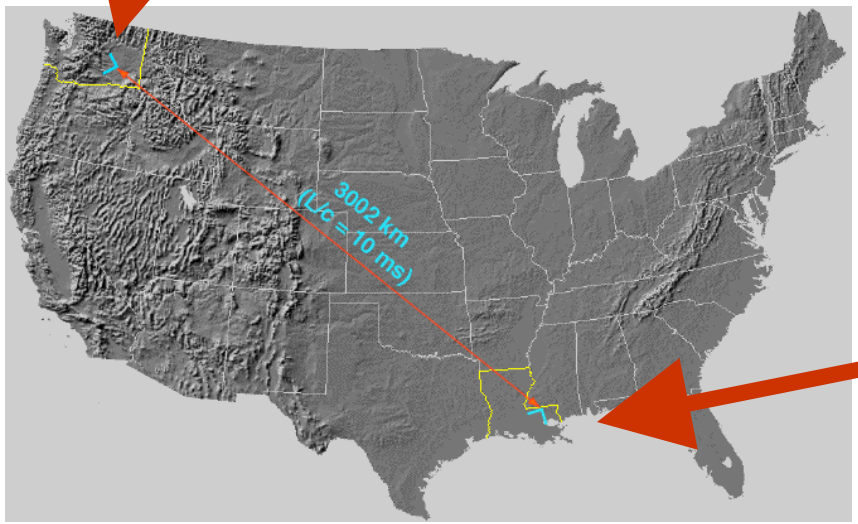
600-meter Michelson Interferometer just outside Hannover, Germany

LIGO Observatories

Hanford (H1=4km, H2=2km)

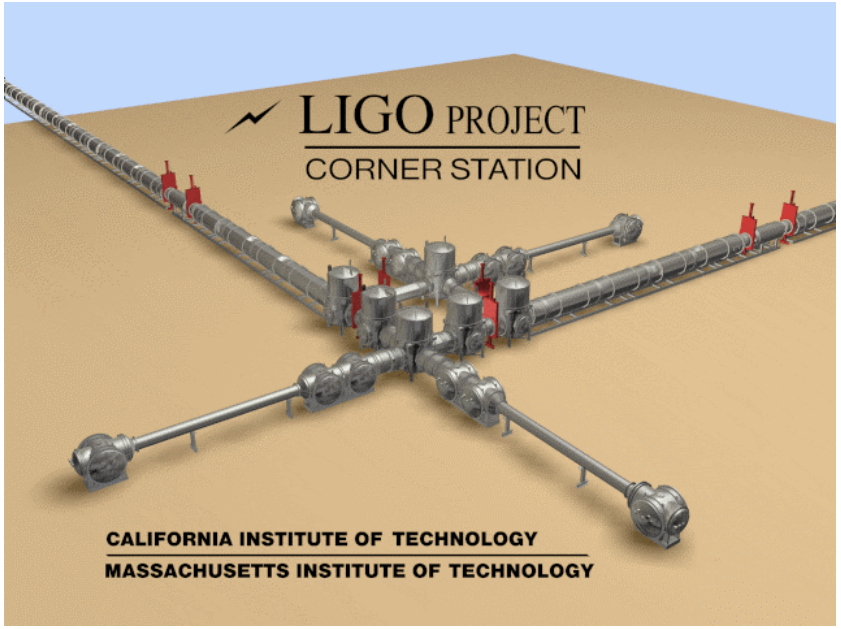


Observation of nearly simultaneous signals 3000 km apart rules out terrestrial artifacts



Livingston (L1=4km)

LIGO Detector Facilities



Vacuum System

- **Stainless-steel tubes**
  (1.24 m diameter, ~10^{-8} torr)
- **Gate valves for optics isolation**
- **Protected by concrete enclosure**

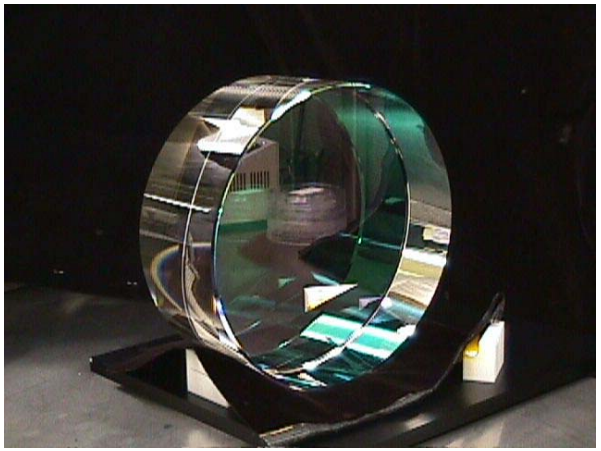
LIGO Detector Facilities

LASER

- Infrared (1064 nm, 10-W) Nd-YAG laser from Lightwave (now commercial product!)
- Elaborate intensity & frequency stabilization system, including feedback from main interferometer

Optics

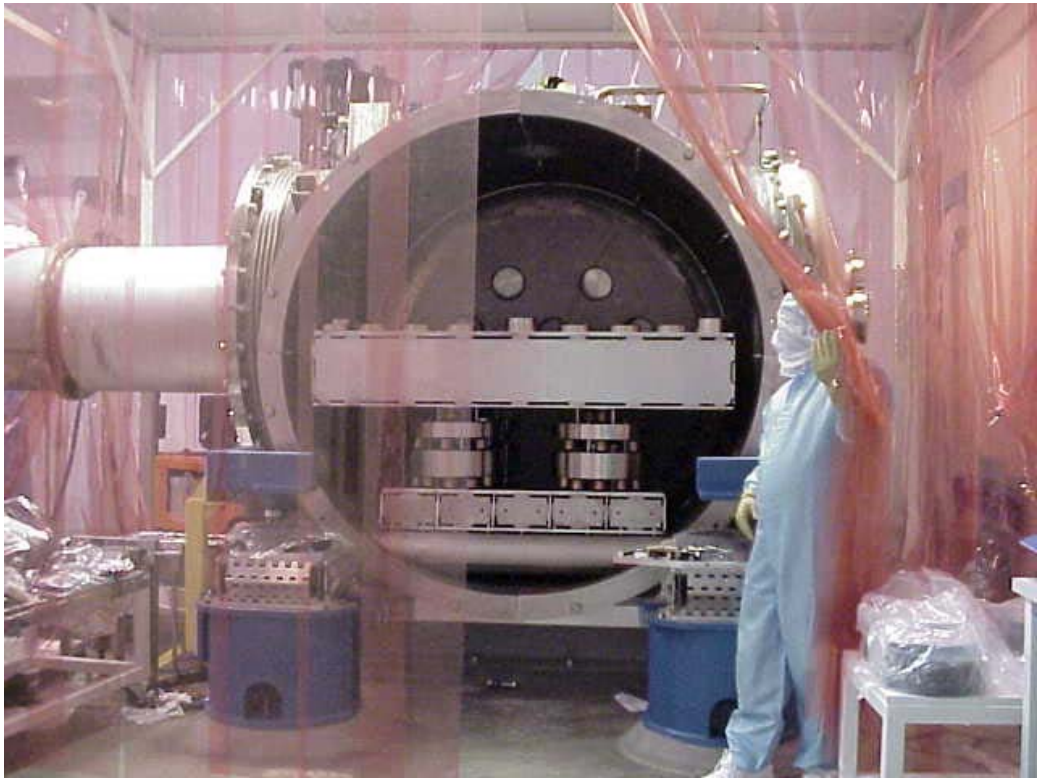
- Fused silica (high-Q, low-absorption, 1 nm surface rms, 25-cm diameter)
- Suspended by single steel wire
- Actuation of alignment / position via magnets & coils

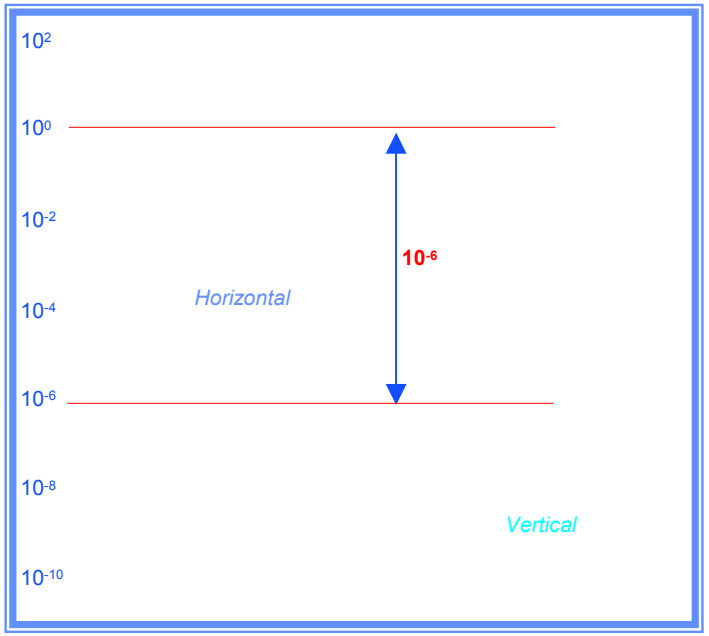


LIGO Detector Facilities

Seismic Isolation

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



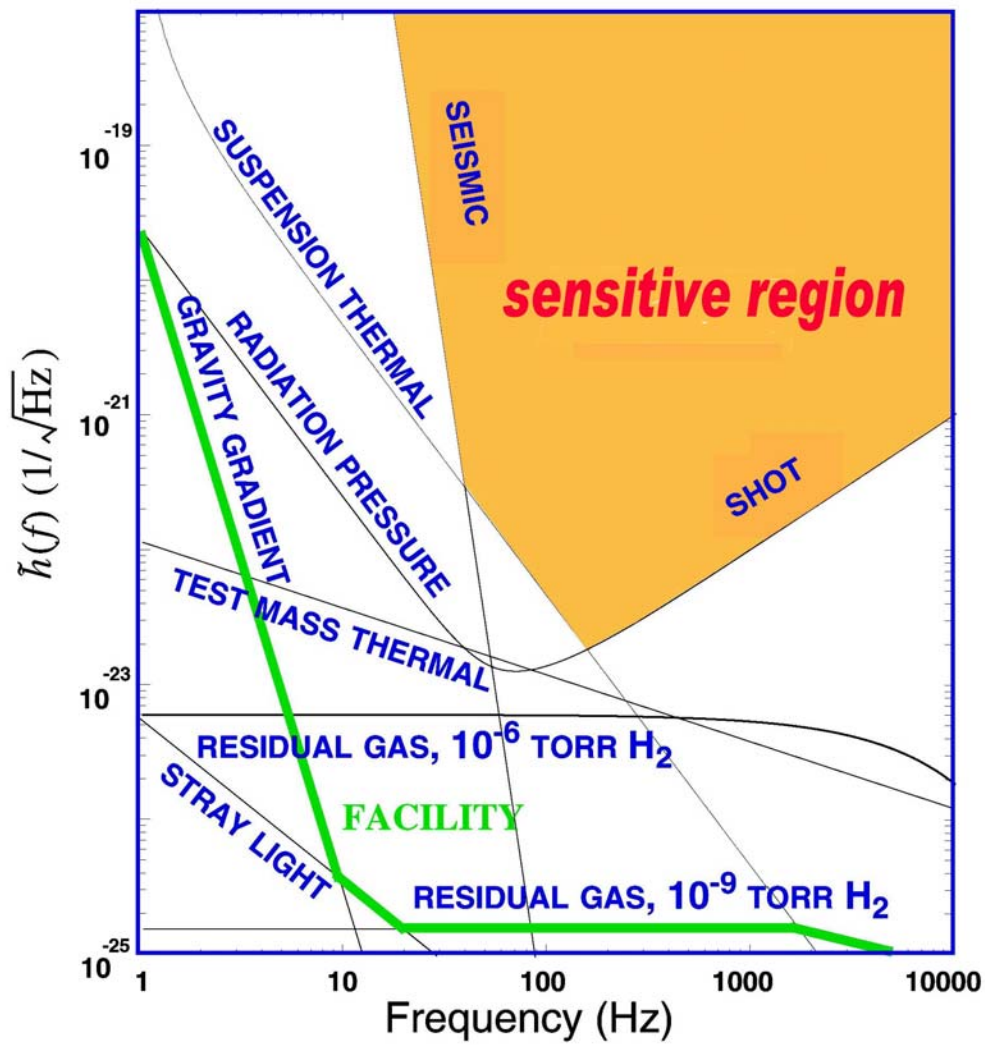


What Limits the Sensitivity of the Interferometers?

- 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

Best design sensitivity:

~ 3 x 10^{-23} $Hz^{-1/2}$ @ 150 Hz



Special Livingston Problem -- Logging

Livingston Observatory located in pine forest popular with pulp wood cutters

Spiky noise (e.g. falling trees) in 1-3 Hz band creates dynamic range problem for arm cavity control

→ ~ 40% livetime at best

Solution: Retrofit with active feed-forward isolation system (using Advanced LIGO technology)

→ Work well underway – complete summer 2004

Data Runs

Have carried out a series of Engineering Runs (E1--E10) and Science Runs (S1--S3) interspersed with commissioning

S1 run:

17 days (August / September 2002)

Four detectors operating: LIGO (L1, H1, H2) and GEO600

H1 (235 hours) H2(298 hours) L1(170 hours)

Triple-LIGO-coincidence (96 hours)

Four S1 astrophysical searches in press (Physical Review D):

» Inspiraling neutron stars -- gr-qc/0308069

» Bursts -- gr-qc/0312056

» Known pulsar (J1939+2134) with GEO -- gr-qc/0308050

» Stochastic background -- gr-qc/0312088

Data Runs

S2 run:

59 days (February—April 2003)

Four interferometers operating: LIGO (L1, H1, H2) and TAMA300 plus Allegro bar detector at LSU

H1 (1044 hours) H2 (822 hours) L1 (536 hours)

Triple-LIGO-coincidence (318 hours)

Many S2 searches underway – some preliminary results for today:

» Inspiraling neutron stars (Shawhan talk)

» Coincidence with gamma ray burst GRB030329 (Sutton talk)

» 28 known pulsars (Landry talk)

» Stochastic background (Fritschel talk)

S3 run:

70 days (October 2003 – January 2004) – Analysis ramping up…

S2 Sensitivities

Livingston (L1) Interferometer most sensitive in “sweet spot”

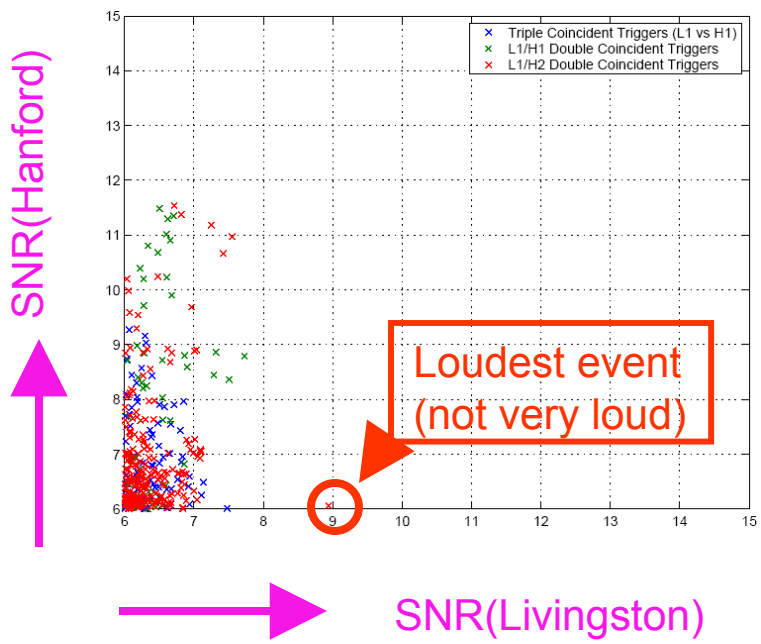
Overview of S2 Results
Inspiraling Neutron Stars

S2 sensitivity permitted seeing the Andromeda Galaxy with L1 whenever live, with H1 seeing it at times

Search based on matched filtering in Fourier domain

Hanford-Livingston coincidence required

Observed events



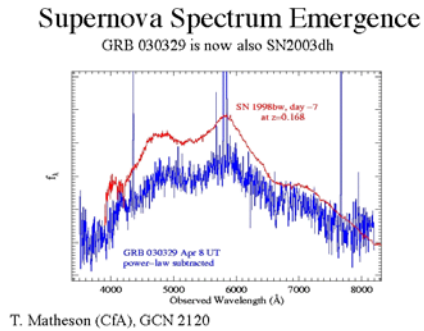
No evidence for excess events

→ Obtain preliminary rate:

$R_{90\%}$ < 50 inspirals per year per "milky-way-equivalent-galaxy"

Overview of S2 Results
Gamma Ray Burst 030329

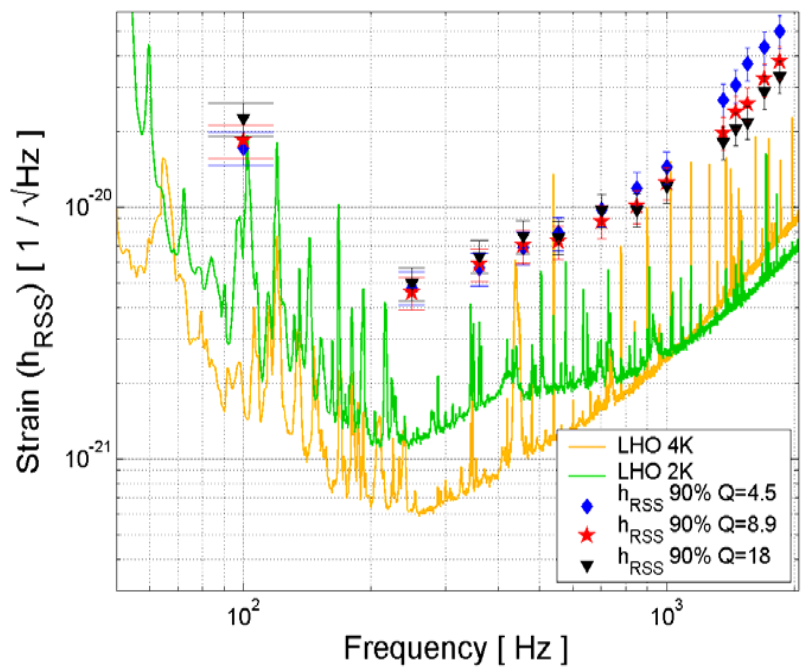
GRB030329 was a powerful burst (likely supernova) during the S2 run, seen in gammas, x-rays and optical



Distance (800 Mpc!) made it unlikely to be detectable by LIGO, but event provides interesting "practice run" for GRB detection (L1 off at time ☹)

Searched for excess cross-correlation events between Hanford Interferometers

No candidates above (or even near) threshold
→ Set upper limits:



Overview of S2 Results
Known Pulsars

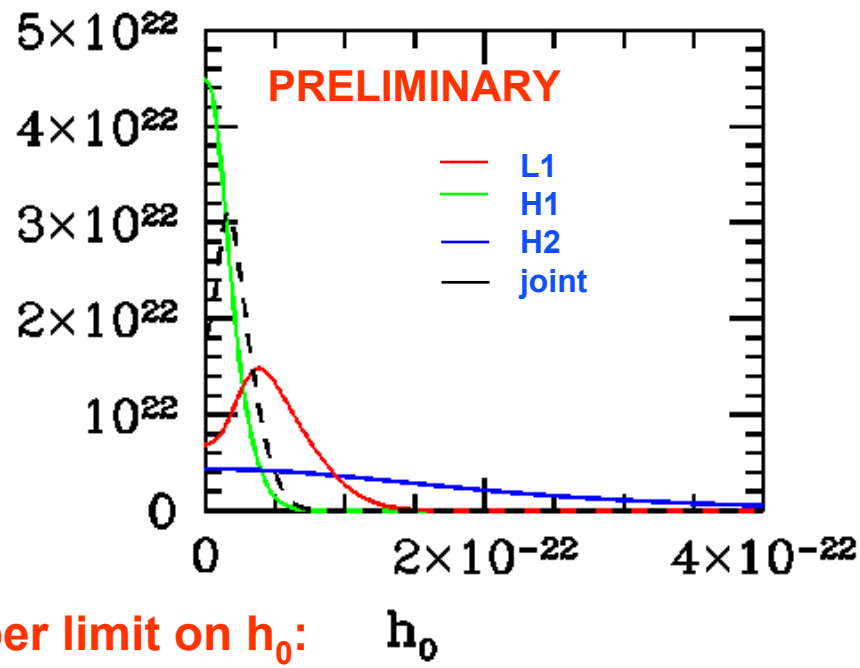
Searched for 28 known isolated pulsars for which precise timing information is available from radio astronomers

Search based on coherent time-domain heterodyne, accounting for Doppler shifts due to Earth's spin and orbital motion; and accounting for antenna pattern amplitude modulations

No signals detected

Sample Bayesian probability density function for the Crab pulsar

→ 95% CL upper limit on h_0 ~ 10^{-22}



Best 95% CL preliminary upper limit on h_0:

few x 10^{-24} (B0021-72L)

Overview of S2 Results
Stochastic Background

Random radiation described by its spectrum

(assumed isotropic, unpolarized, stationary and Gaussian)

Parametrize strength as fractional contribution to critical energy density of the Universe:

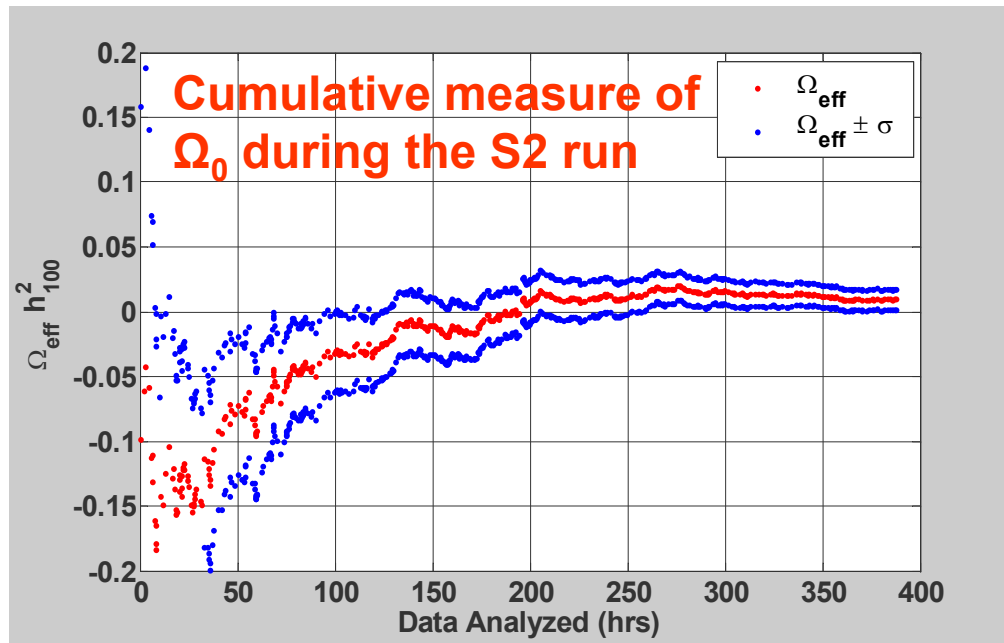
$$\int_0^\infty (1/f)\,\Omega_{GW}(f)\,df = \frac{\rho_{GW}}{\rho_{critical}}$$

(Assume $\Omega_{GW}(f)$ = constant Ω_0)

Measure cross-correlation of detector pairs:

L1-H1, L1-H2 and H1-H2

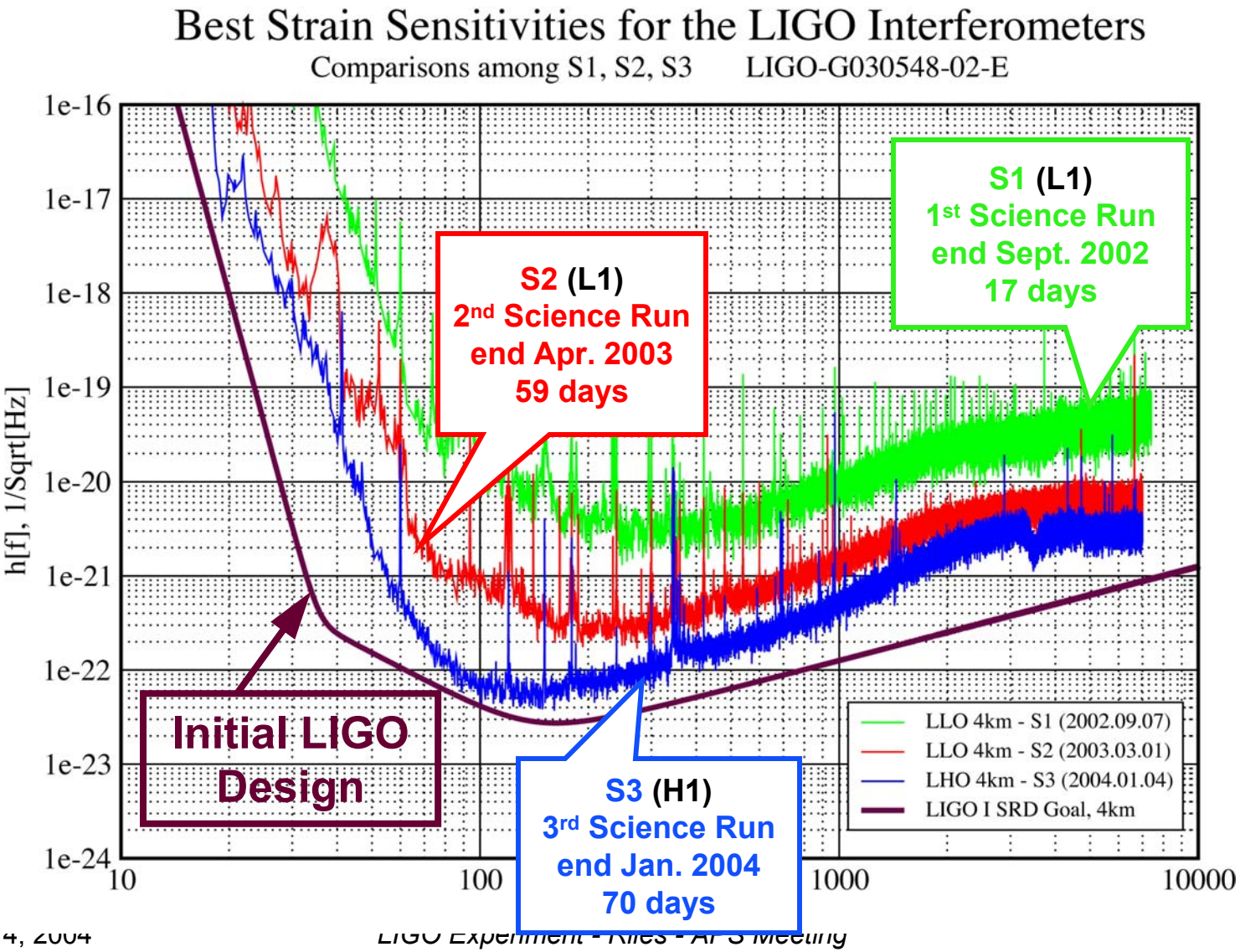
→ Report L1-H1 results today



Preliminary 90% CL limit:

$$\Omega_0\ (h_{100})^2 < 0.017$$

Looking Ahead



Looking Ahead

Resume operations in fall 2004:

- **Verify success of Livingston seismic retrofit**
- **Verify success of sensitivity improvements**

First true "Search Run" in 2005

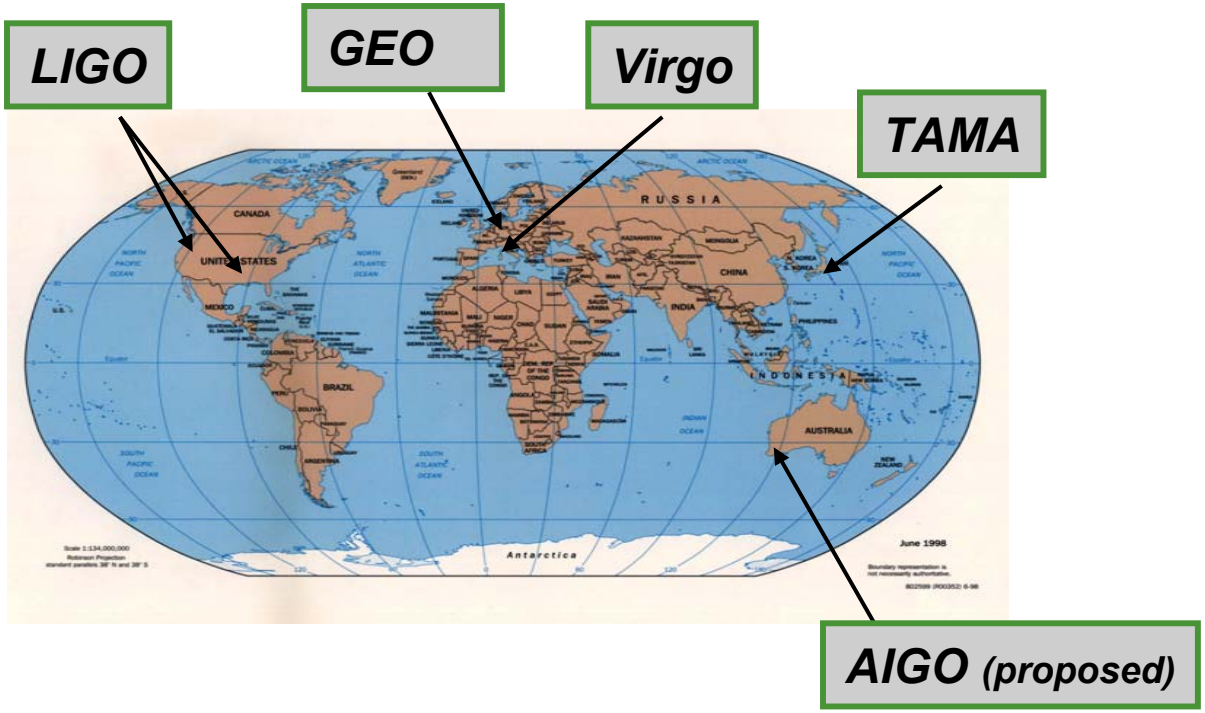
Plan before shutdown for Advanced LIGO upgrade:

$\geq$ 1 year of running at Initial LIGO design sensitivity

Looking Ahead

The three LIGO and the GEO interferometers are part of a forming Global Network.

Multiple signal detections will increase detection confidence and provide better precision on source locations and wave polarizations

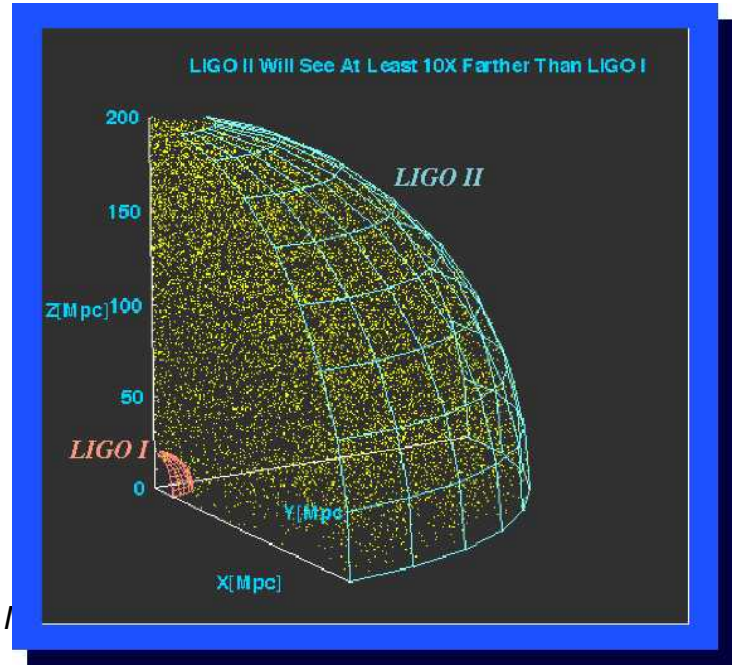


Looking Further Ahead

Despite their immense technical challenges, the initial LIGO IFO's were designed conservatively, based on "tabletop" prototypes, but with expected sensitivity gain of ~1000.

Given the expected low rate of detectable GW events, it was always planned that in engineering, building and commissioning initial LIGO, one would learn how reliably to build Advanced LIGO with another factor of ~10 improved sensitivity.

Because LIGO measures GW amplitude, an increase in sensitivity by 10 gives an increase in sampling volume, i.e, rate by ~1000

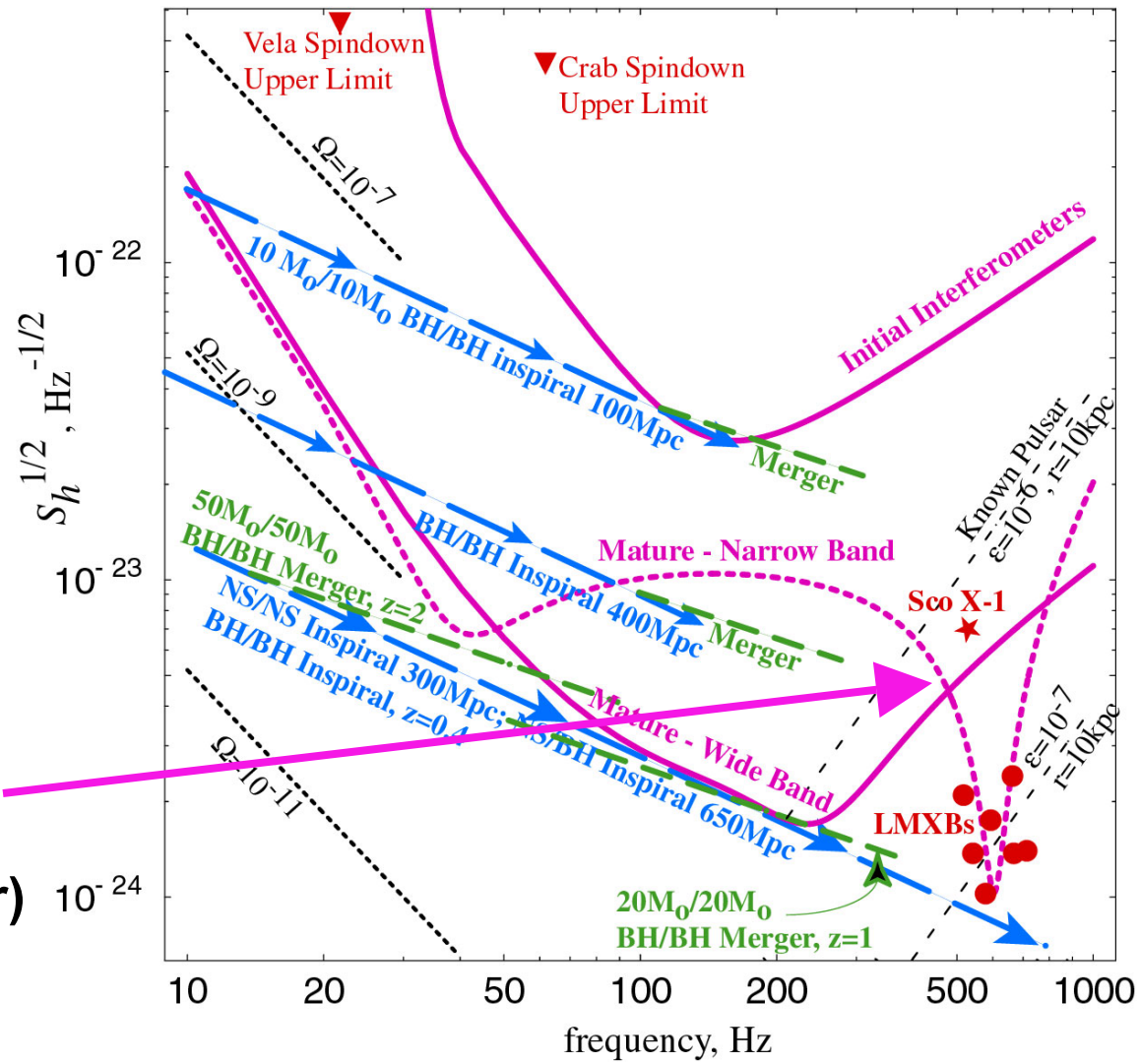


Advanced LIGO

Sampling of source strengths vis a vis Initial LIGO and Advanced LIGO

Lower h_{rms} and wider bandwidth both important

"Signal recycling" offers potential for tuning shape of noise curve to improve sensitivity in target band (e.g., known pulsar cluster)



Advanced LIGO

Increased laser power:

10 W → 180 W

Improved shot noise (high freq)

Potential new test mass material:

Fused silica → Sapphire

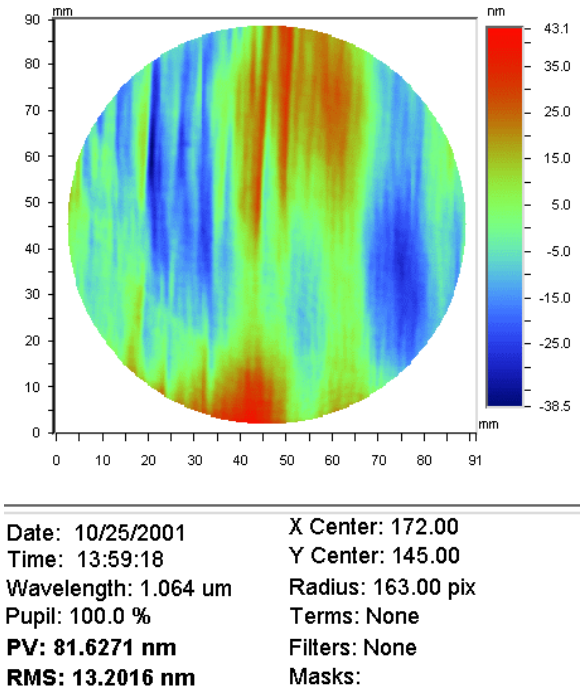
Lower internal thermal noise in bandwidth

Increased test mass:

10 kg → 40 kg

Compensates increased radiation pressure noise

Sapphire Optics



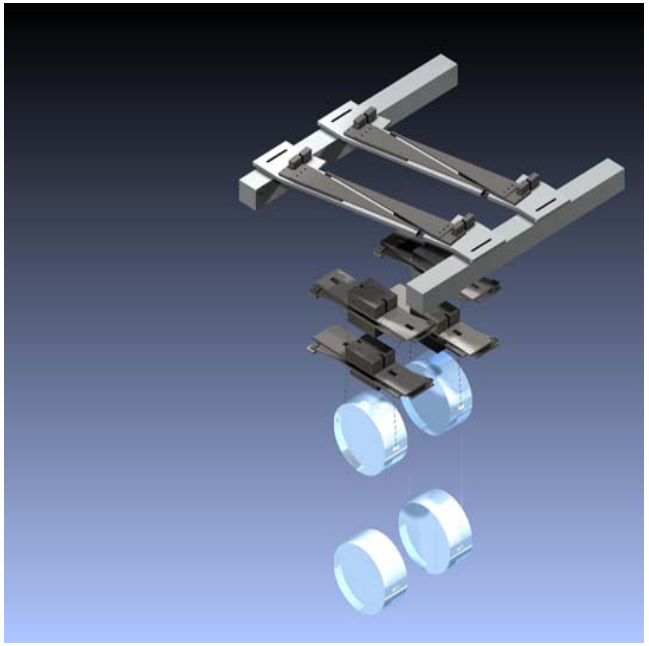
Advanced LIGO

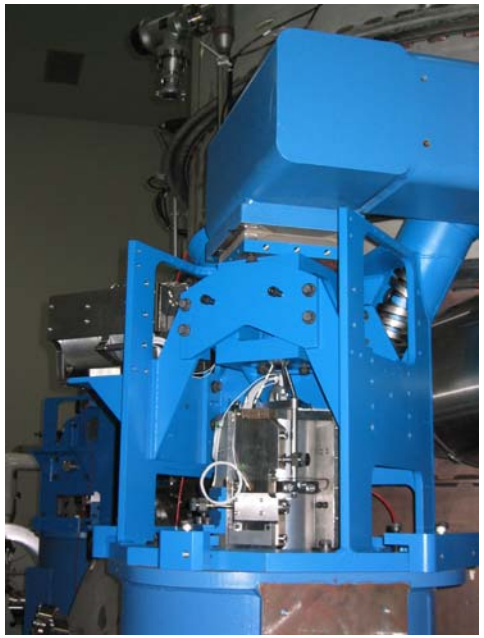
Detector Improvements:

New suspensions:

Single → Quadruple pendulum

Lower suspensions thermal noise in bandwidth





Improved seismic isolation:

Passive → Active

Lowers seismic "wall" to ~10 Hz

Conclusions

LIGO commissioning is well underway

- Good progress toward design sensitivity
- GEO, other instruments worldwide advancing as well

Science Running is beginning

- Initial results from our first two data runs

Our Plan:

- Continue commissioning and data runs with GEO & others
- Collect $\geq$ one year of data at design sensitivity before starting upgrade
- Advanced interferometer with dramatically improved sensitivity – 2008+
  (MRE proposal under review at NSF)

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