LIGO- towards detection of gravitational waves

Talk at Lawrence Berkeley National Laboratory

April 3, 2007

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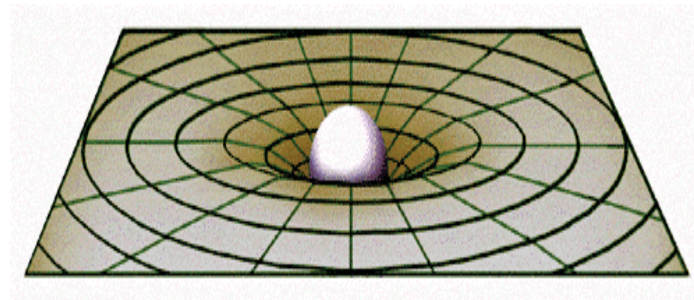
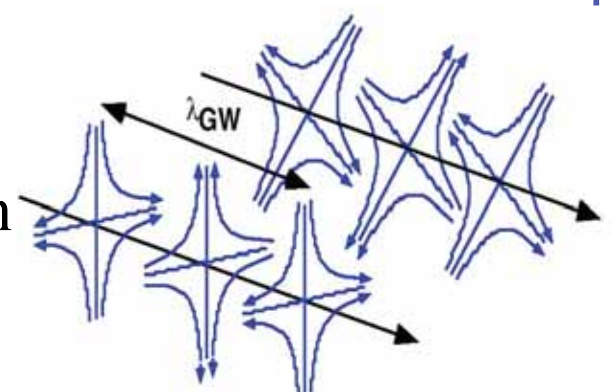
- Introduction
  - Gravitational waves and their characteristics
  - Astrophysical sources of detectable gravitational waves
- LIGO
  - How LIGO works
  - The experimental challenges and limitations
- The current status of LIGO
  - The current science run
  - LIGO's evolution over the next decade
- Some LIGO astrophysics results
- Towards a world-wide network of ground-based detectors for gravitational waves
- Education and Outreach (if time)

Introduction

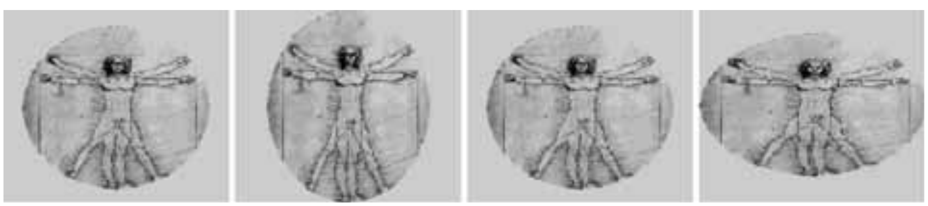
Gravitational waves



- Ripples of space-time curvature that propagate at the speed of light



- Transverse, quadrupole waves with 2 polarizations that stretch and squeeze space transverse to direction of propagation

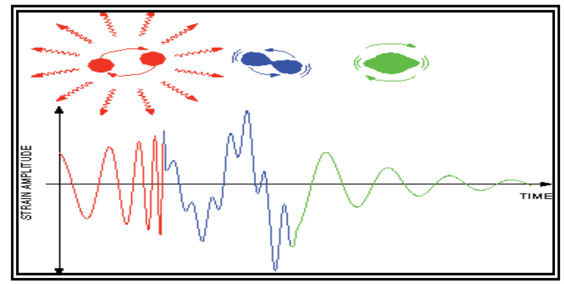


- Emitted by accelerating aspherical mass distributions
- Matter is transparent to gravitational waves-- waves travel unimpeded to us from their source

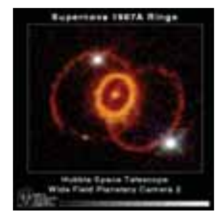
Astrophysical sources of GWs sought by LIGO

- Periodic sources in our galaxy- pulsars
  - e.g. spinning neutron stars

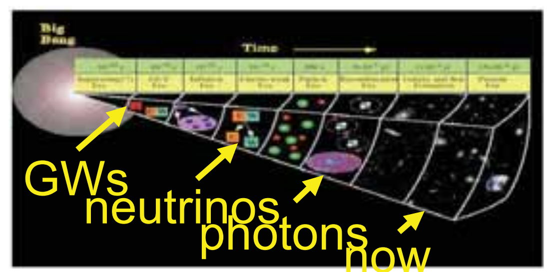
- Coalescing compact binaries
  - Classes of objects: NS-NS, NS-BH, BH-BH
  - Physics regimes: Inspiral, merger, ringdown
  - Numerical relativity will be essential to interpret GW waveforms



- Burst events (triggered: e.g. GRB or untriggered)
  - e.g. Supernovae with asymmetric collapse



- Stochastic background
  - Primordial Big Bang (t = 10^{-22} sec)
  - Continuum of sources
- The Unexpected



Strength of Gravitational Waves

e.g. Neutron Star Binary in the Virgo cluster

~ 50 million light years away

- Gravitational wave amplitude (strain)

$$h_{\mu\nu} = \frac{2G}{c^4 r}\ddot{I}_{\mu\nu} \Rightarrow h \approx \frac{4\pi^2 GMR^2 f_{orb}^2}{c^4 r}$$

I = quadrupole mass distribution of source

- For a binary neutron star

~1.4 M_o pair in Virgo cluster

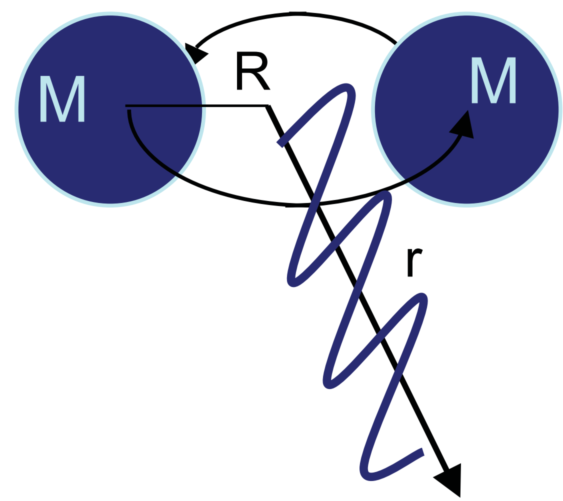
$M \approx 10^{30}$ kg

$R \approx 20$ km

$f \approx 400$ Hz

$r \approx 10^{23}$ m

⇨ $h \sim 10^{-21}$



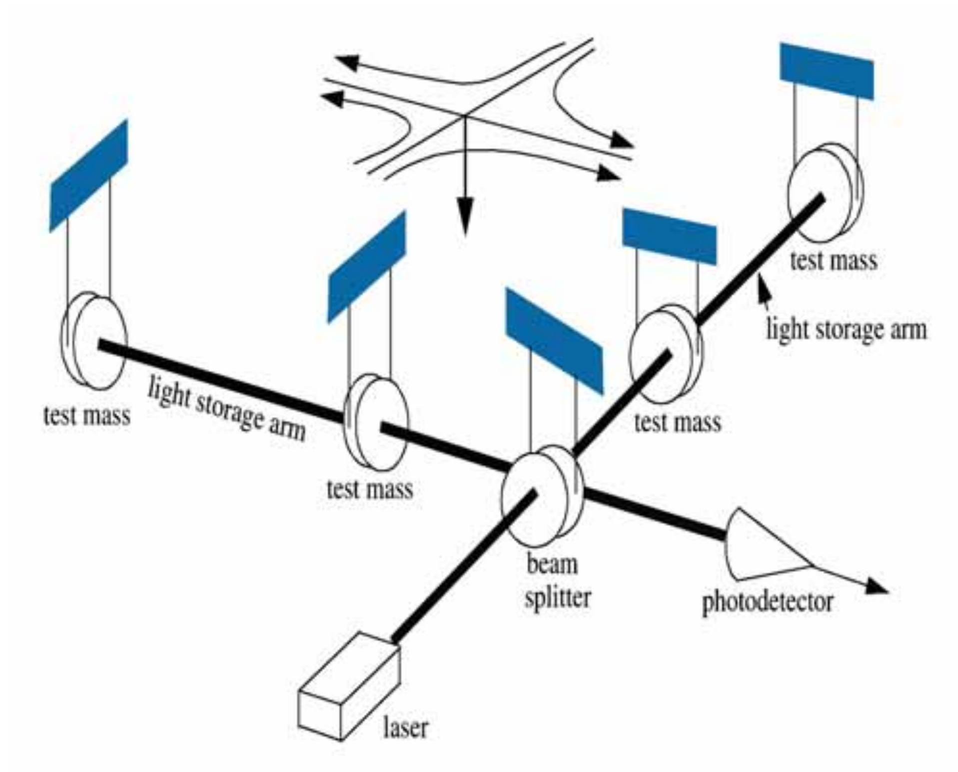
Detecting GWs with Precision Interferometry

• Suspended test masses act as "freely-falling" objects tied to their space-time coordinates

• A passing gravitational wave alternately stretches (compresses) space-time and thus the arms.

• Interferometery is used to determine relative distance between test masses (mirrors) in L-shaped arms

• Due to interference, a differential stretch/compress gives a time varying signal at the photo-detector



Experimental challenges and limitations

Amplitude of gravitational wave= strain (h)

$$h = \Delta L / L$$

For $h \sim 10^{-21}$ and L ~ 4 km

$\Delta L \sim 10^{-18}$ m

Challenge--to measure relative distance of test masses in interferometers arms to ~ 10^{-18} m --1/1000 the size of a proton!

(or distance to nearby stars to width of a human hair!)

What makes it hard?

- –Gravitational wave amplitude is very small
- –External forces also push the mirrors around
- –Laser light has fluctuations in its phase and amplitude
- –Measurement noise

How can the needed sensitivity be reached

Intrinsic resolution of interferometers- how accurately can a fringe be split?

It's counting statistics-- sqrt of number of photons during measurement

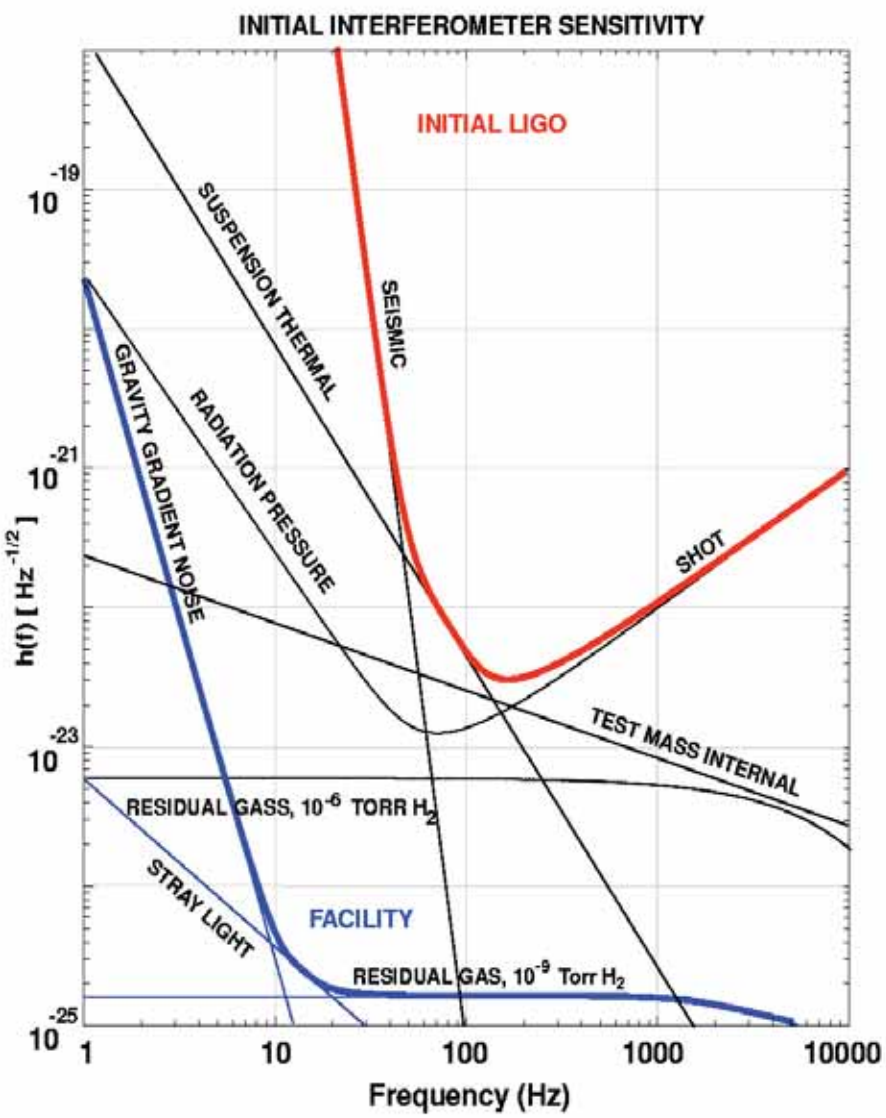
- 10^{21} photons/second at beam splitter where interference occurs
- Measurement time ~10^{-2} seconds (at 100 Hz)
- Effective arm length = 4 km * average number passes for each photon (b~50)

1 x 10^{-6} cm

$$h = \frac{x}{L} \sim \frac{\lambda}{Lb\sqrt{\dot{N}\tau}}$$

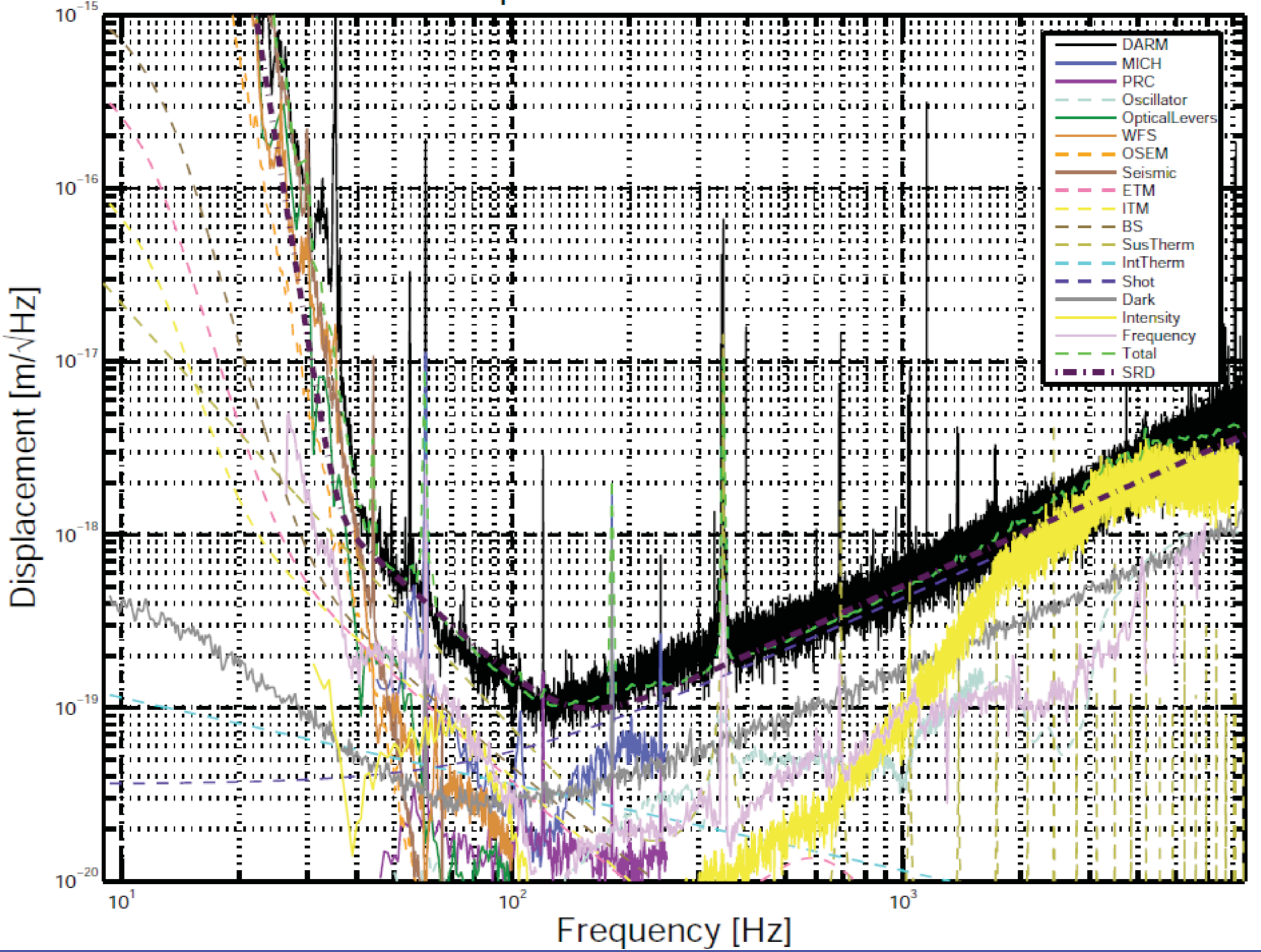
h = 6×10^{-22} at 100 Hz

Major noise sources are under control



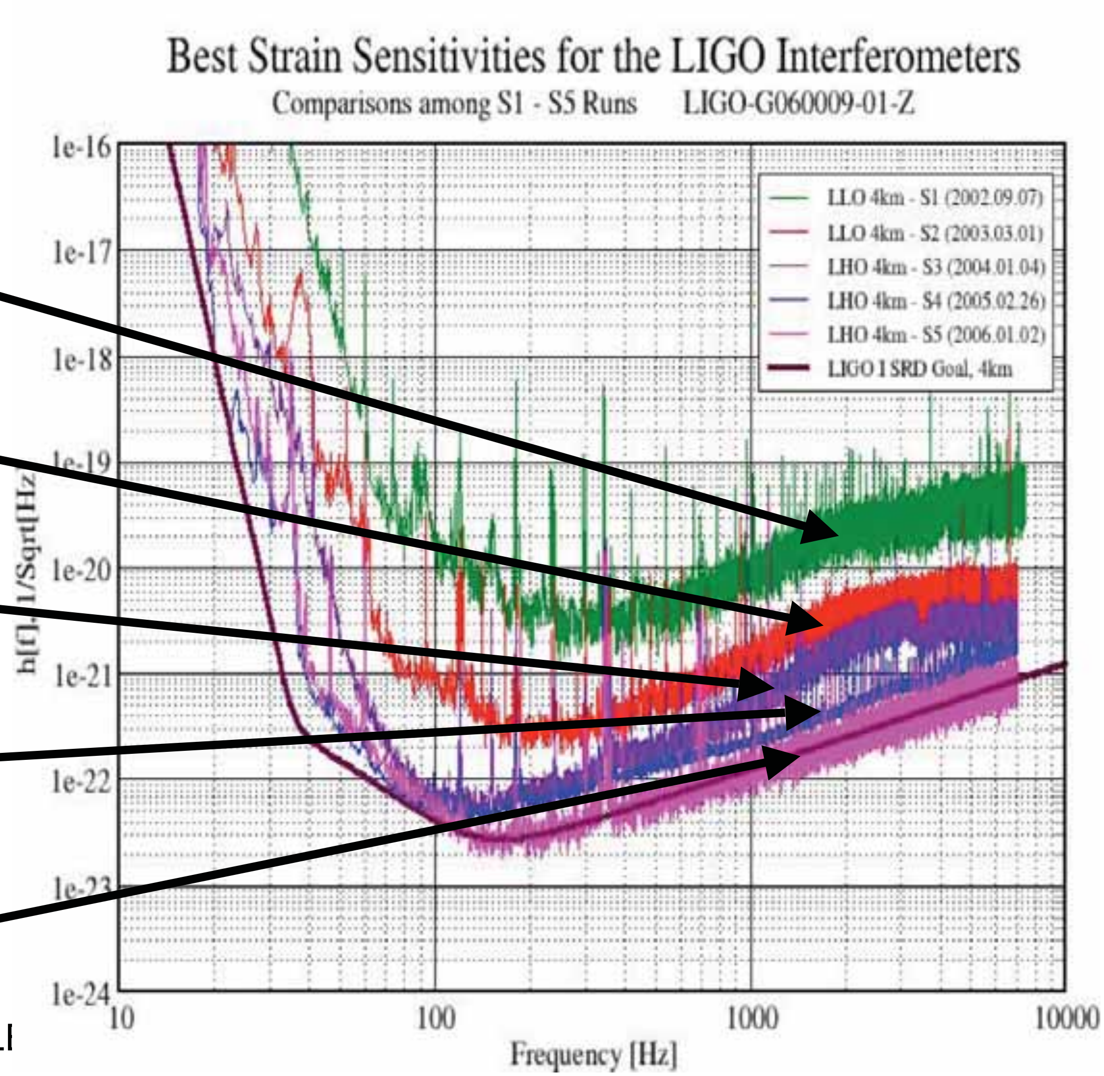
- Displacement Noise
  - Seismic motion (limit at low frequencies)
    - Ground motion from natural and anthropogenic sources
  - Thermal Noise (limit at mid-frequencies)
    - vibrations due to finite temperature
  - Radiation Pressure
- Sensing Noise (limit at high frequency)
  - Photon Shot Noise
    - quantum fluctuations in the number of photons detected
- Facilities limits
  - Residual Gas (scattering)
- Inherent limit on ground
  - Gravity gradient noise
- Technical noise-
  - laser, control, electronics, etc

L1: UGF = 159 Hz 15.1 Mpc, Predicted: 14.4, Jul 05 2006 07:20:33 UTC



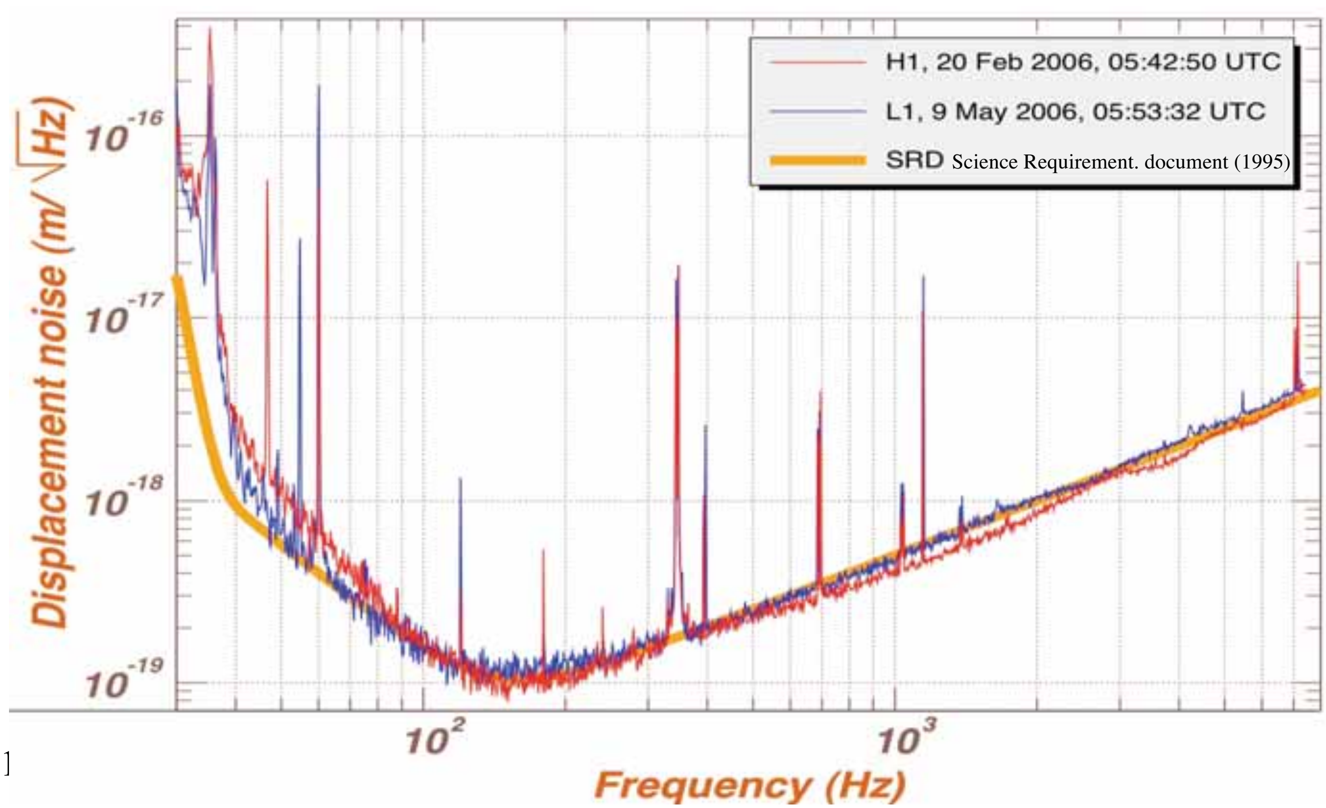
Science runs and sensitivity

Run	# days
S1 Sept '02	17
S2 Feb 02-Apr 03	59
S3 Nov 03-Jan 04	70
S4 Feb- March 05	30
S5 Nov 05------	Over 500 so far



Meeting the experimental challenge

- After 5 years of intense effort to reduce noise by ~ 3 orders of magnitude, the design sensitivity predicted in the 1995 LIGO Science Requirements Document was reached in 2005--a great achievement



How do we avoid fooling ourselves?

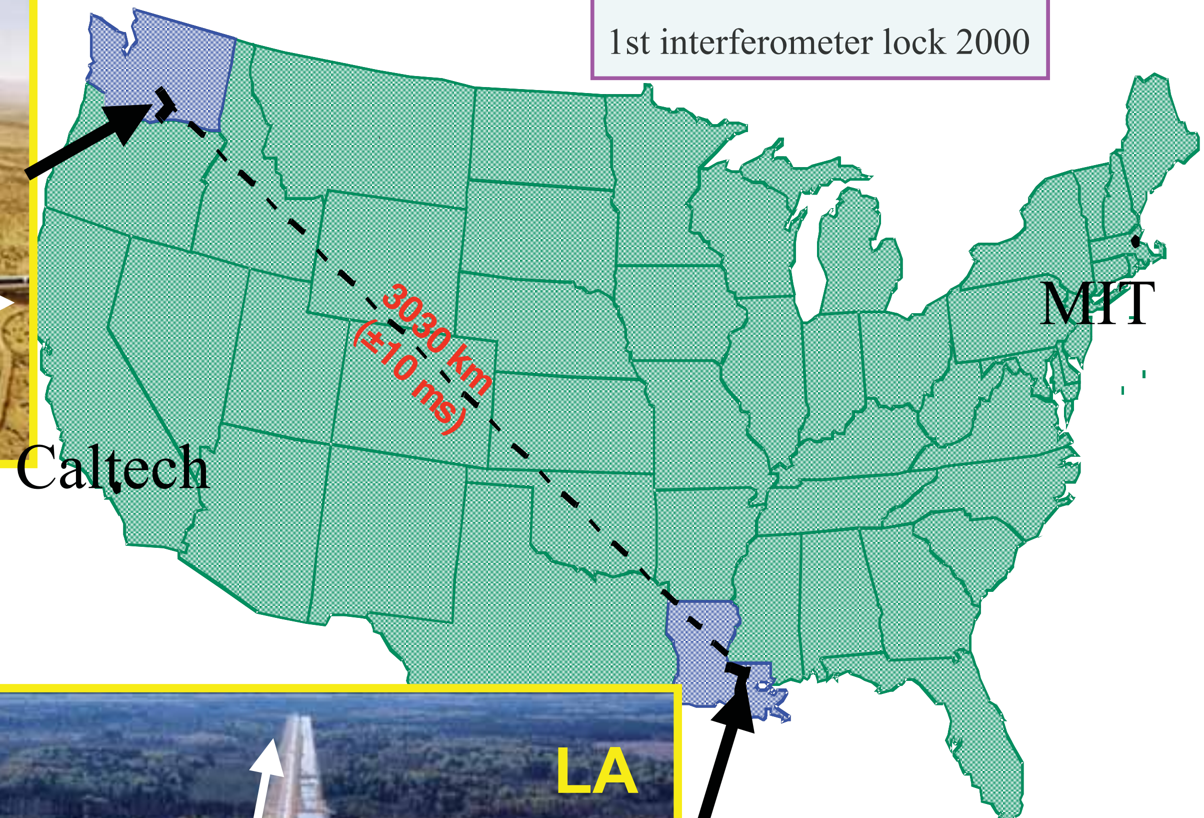
Seeing a false signal or missing a real one

- At least 2 independent signals--e.g.
  - coincidence between interferometers at 2 sites for inspiral and burst searches;
  - external trigger for GRB or nearby supernova.
- Constraints-
  - e.g. pulsar ephemeris; ~ inspiral waveform; time difference between sites.
- Environmental monitor as vetos-
  - Seismic/wind-- seismometers, accelerometers, wind-monitors
  - Sonic/accoustic- microphones
  - Magnetic fields- magnetometers
  - Line voltage fluctuations-- volt meters
- Hardware injections of pseudo signals (actually move mirrors with actuators)
- Software signal injections

LIGO Laser Interferometer Gravitational-wave Observatory

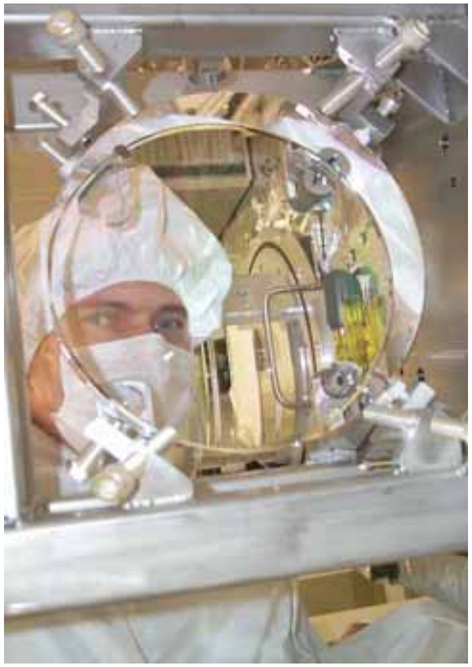
Ground breaking 1995

1st interferometer lock 2000

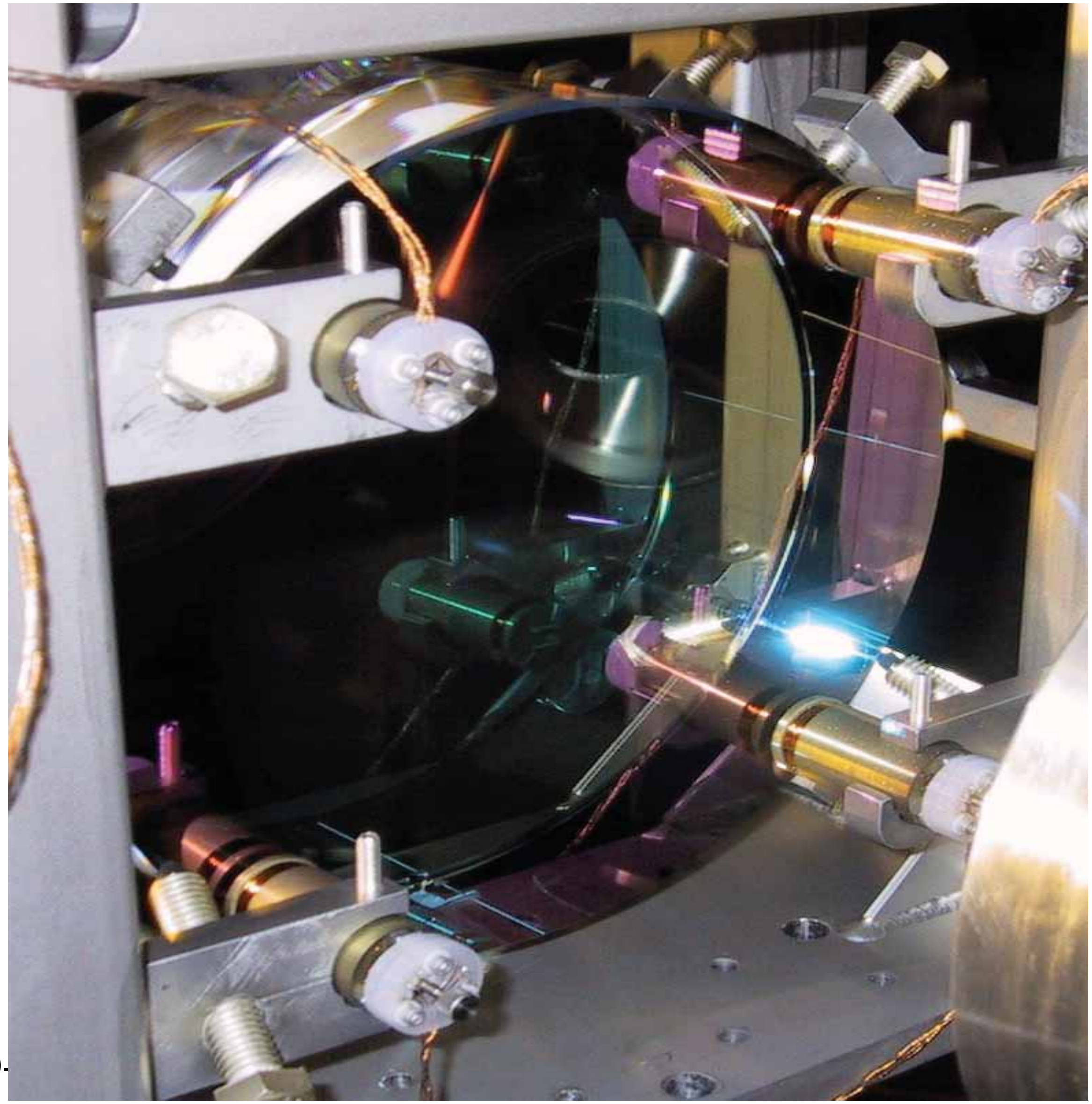


- **Managed and operated by Caltech & MIT with funding from NSF**
- **LIGO Scientific collaboration- 45 institutions, world-wide**

Some LIGO hardware



Core optics and control actuators



LIGO---
The current science run
The next steps for LIGO

The current search for gravitational waves

A science run (S5) at design sensitivity began in November 2005 and is ongoing

- Will end ~September 2007
- With 1 year live-time of 2-site coincident data

Searching for signals in audio band (~50 Hz to few kHz)

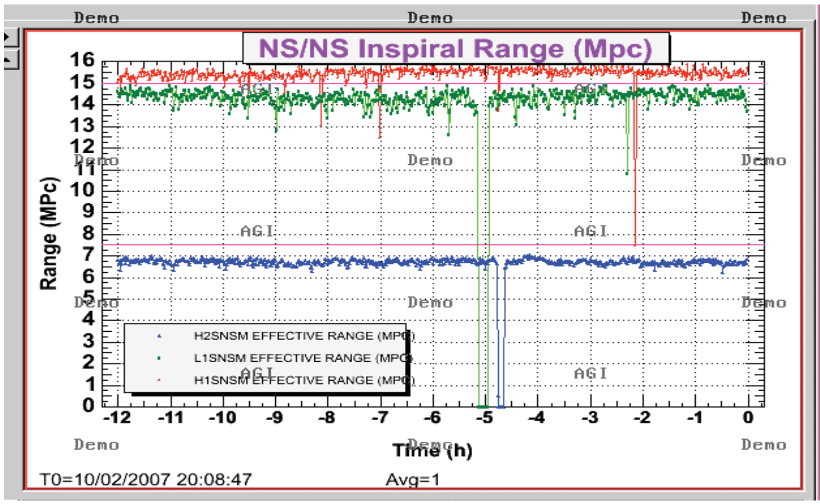
Run is going extremely well

- Range at beginning of run meets our goal (for 1.4 M_o neutron star pairs; S/N=8)
  - –for 4 km interferometers-- 10 Mpc
  - –for 2 km interferometers--- 5 Mpc
- Range is now >50% greater than beginning of run.
  - – # potential extragalactic sources goes as $(\text{range})^3$
  - – estimate ~5-10% probability to see signal in this run

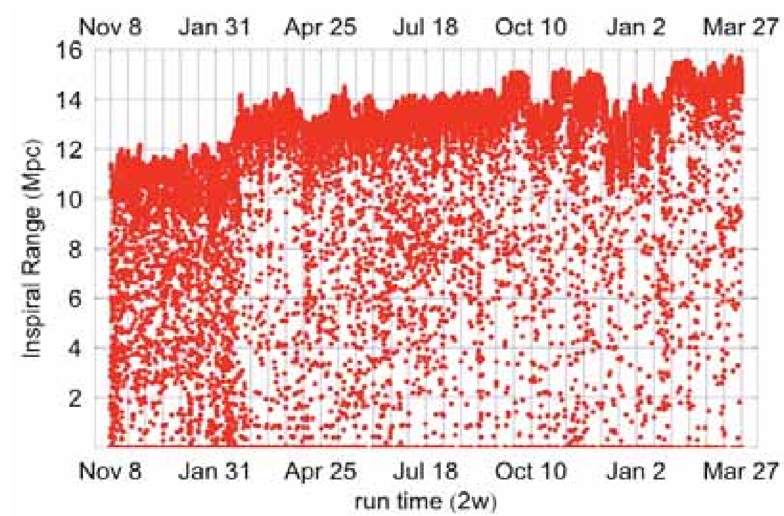
Range (Mpc)- November 2006 to present

for 1.4 M_O NS-NS (S/N=8)

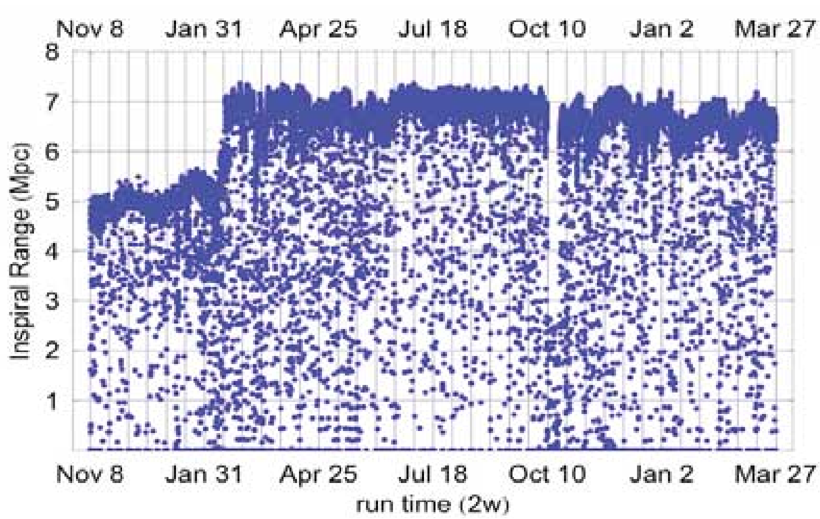
"typical" 12 hours



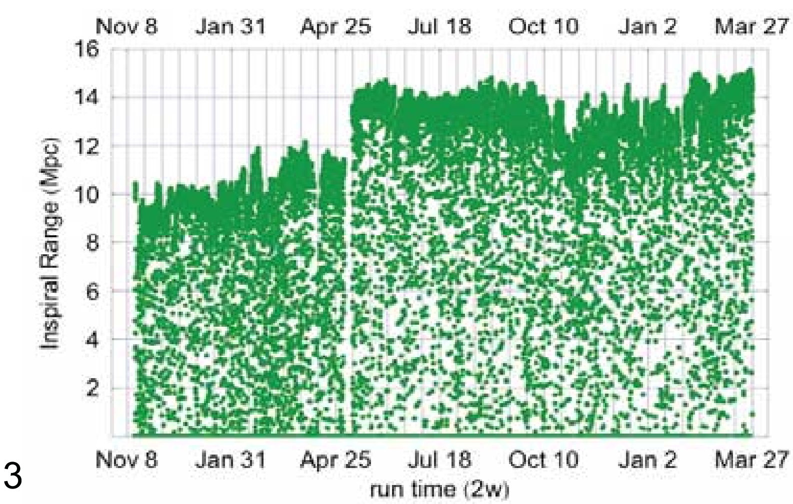
Hanford 4 km



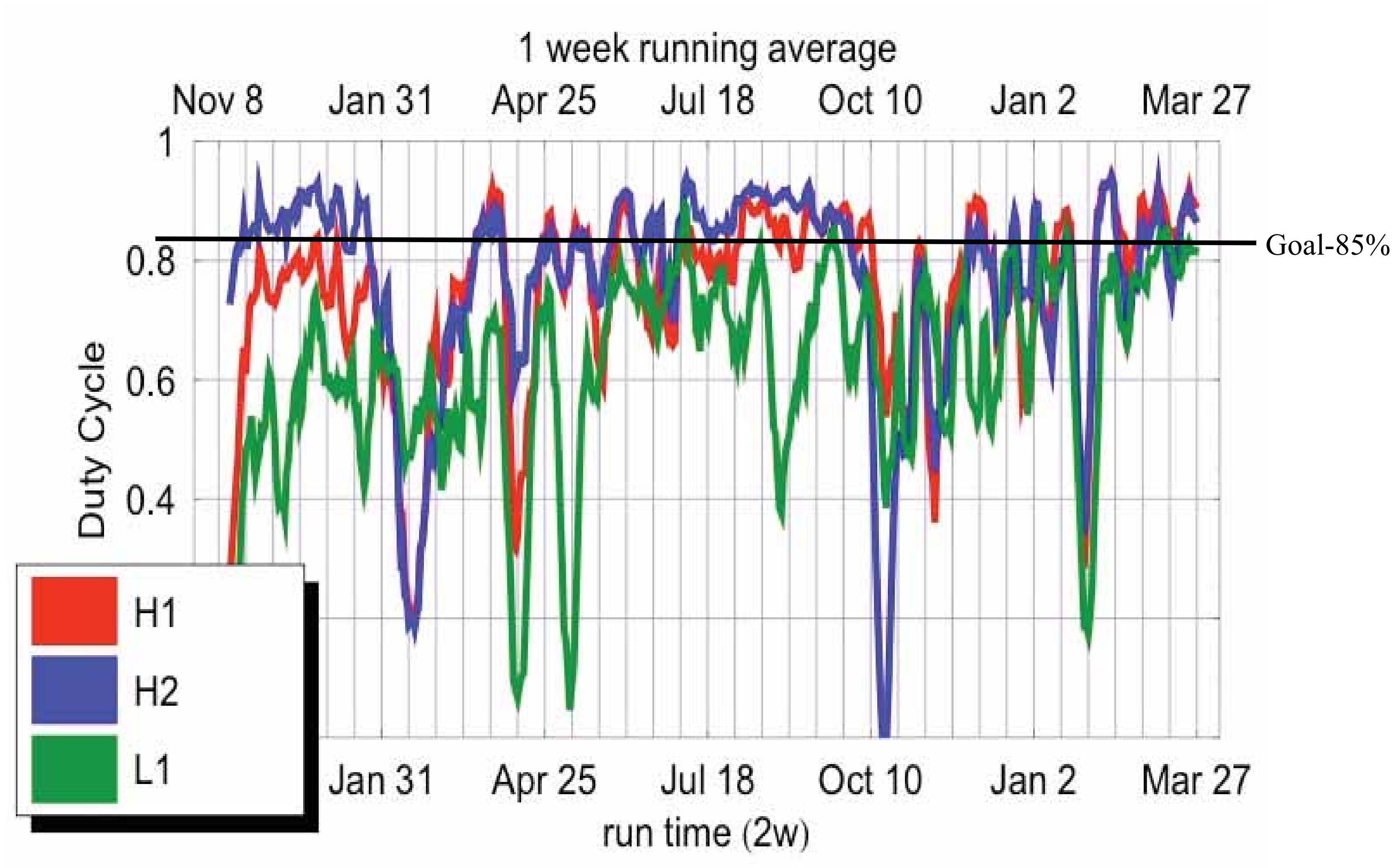
Hanford 2 km



Livingston 4 km

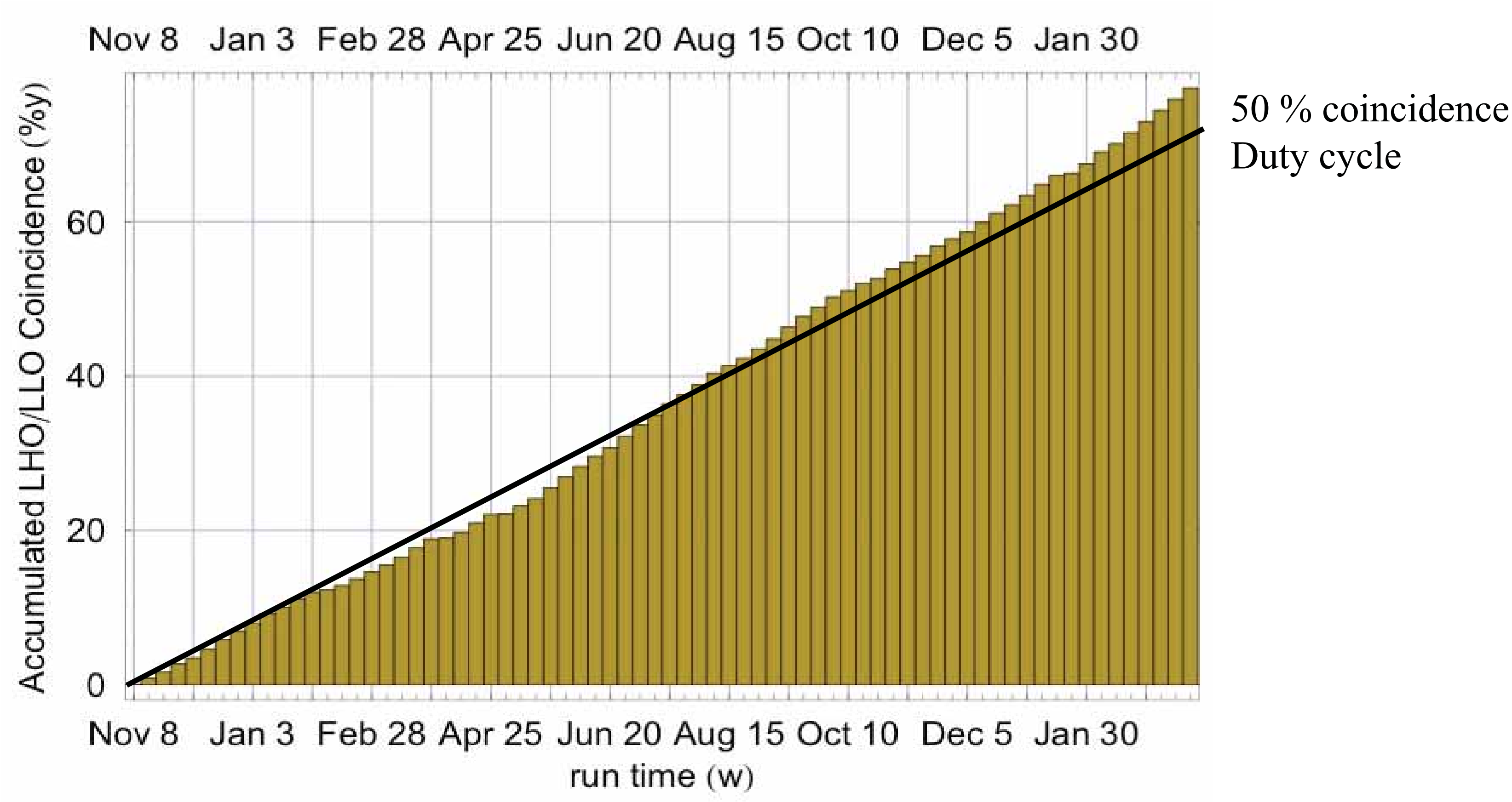


Duty cycle since beginning of run



Progress towards completion of S5

Accumulated LHO-LLO coincidence: goal 1 year



Run is 78% complete; predict run to end early September 2007

Next step-"Enhancements" to initial LIGO

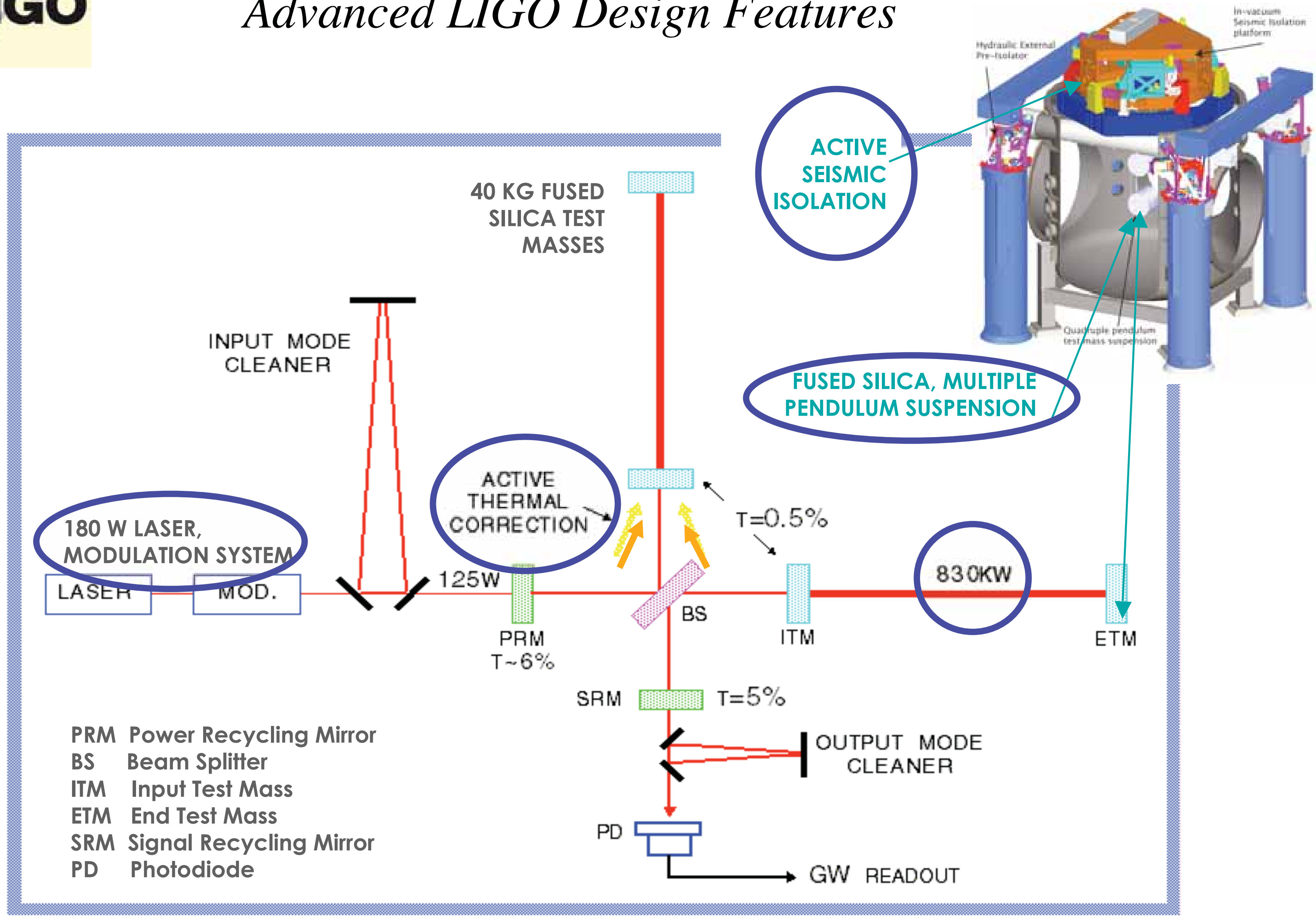
- After current run, make modest changes to 4 km interferometers at both sites to increase range by ~2
  - Reduce several known noise sources, especially at readout
    - Readout- add mode filter cavity, move into vacuum, seismically isolate

    Increase laser power by ~3
    - Modify things like thermal compensation to handle power
- Increase number of sources in range by factor ~8
- Goal- next science run with enhanced range in 2009
  - Estimate ~ 50% probability/year to see a signal with enhanced LIGO.

Advanced LIGO- the big step towards GW astrophysics

- Project to improve the sensitivity and range of LIGO by a factor of 10
  - 20x higher power laser, improved seismic suspension and isolation, signal recycling, low-noise readout (like enhancements), larger mirrors (to handle increased thermal load), etc.
- Increase detection bandwidth
  - move seismic wall from ~50 Hz to 10 Hz
- Increase the number of sources in range by ~1000
  - Expect signals at few/day to few/week rate!!!
- Go beyond discovery of GW; do astrophysics with GWs

Advanced LIGO Design Features



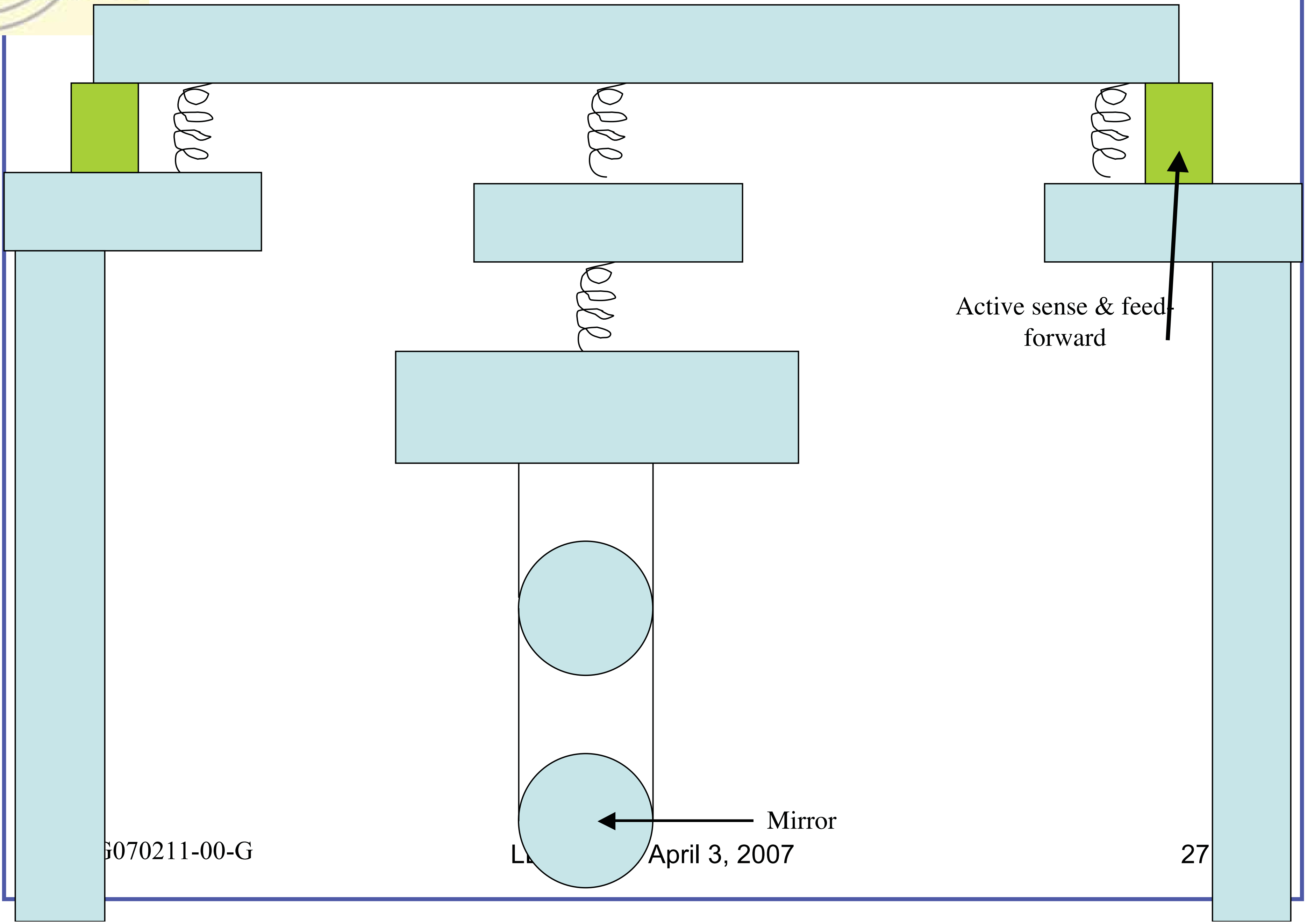
Damping seismic and other vibrations

A layered system to reduce motion at 10 Hz and up

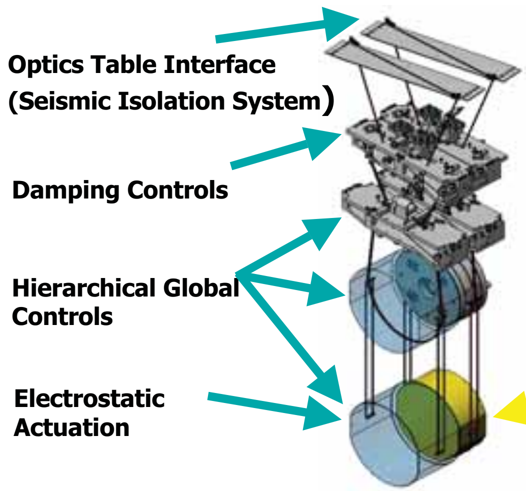
1. External sensors (accelerometers) feed forward to low frequency (a few Hz) actuators that compensate for motions by pushing the support structure
2. Test mass assemblies hang from that structure which sits on several layers of springs that further damp motions that gets through. Response of spring layer is ~1/f, so get damping at high frequencies.
3. Test masses hang from the support structure on thin fused silica wires-- pendulums with low (<< 1 Hz) natural frequency. Disturbances at higher frequency drop off at ~1/f.

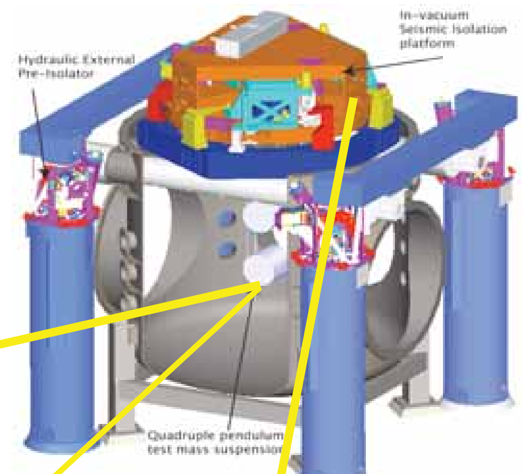
Net results is damping of factor $\sim 10^{-7}$ between 1 Hz and 100 Hz

LIGO seismic isolation concept

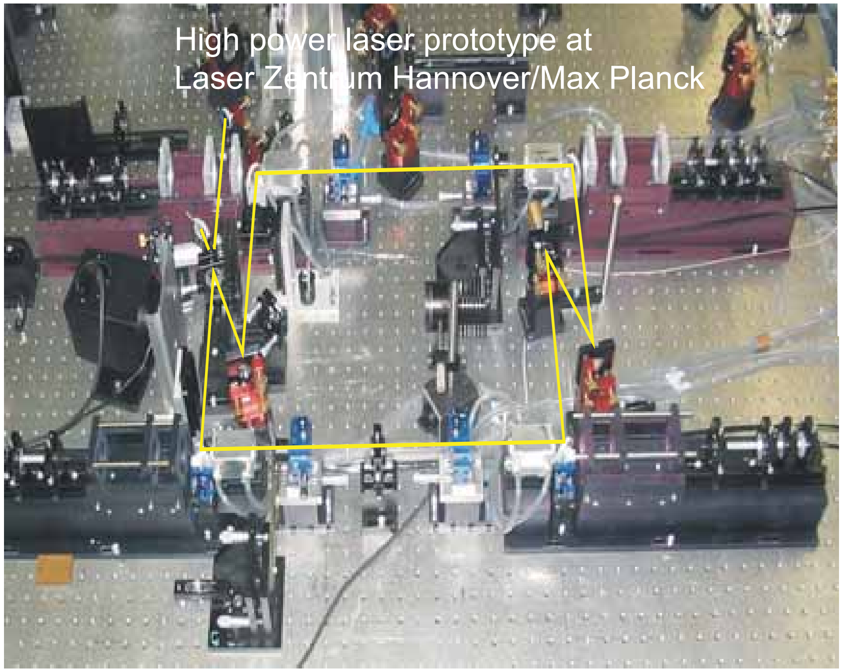


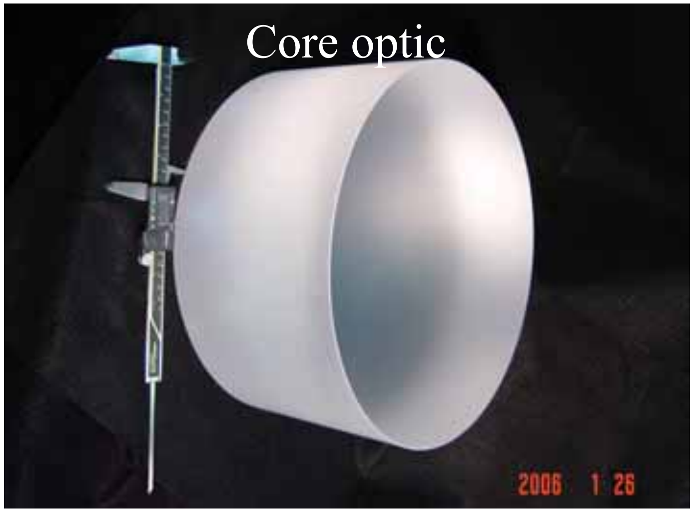
Advanced LIGO suspensions prototype





Advanced LIGO prototype hardware



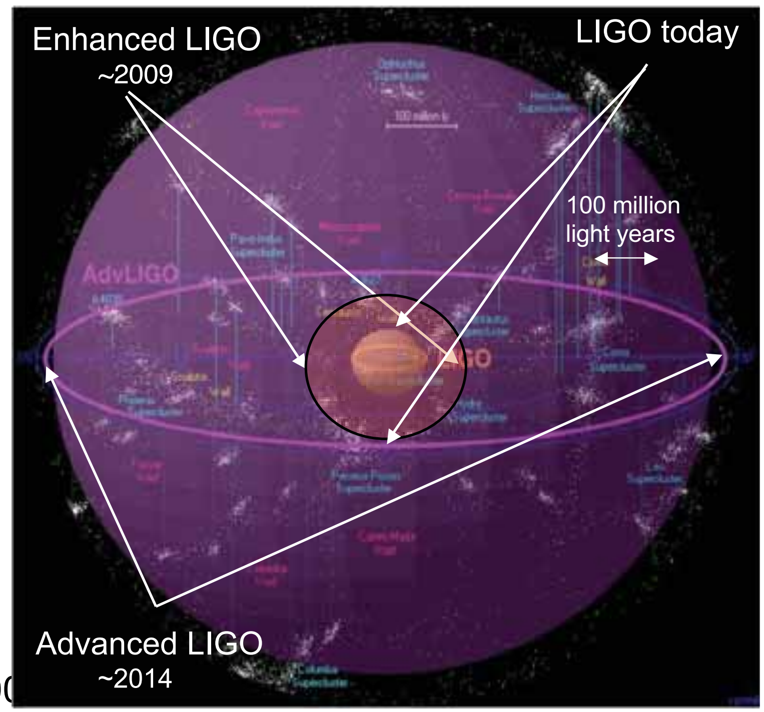


Advanced LIGO construction start in FY08

- In FY08 President's Budget--construction start in October 2007
- Schedule-
  – October 2007--August 2014 including 11 months schedule contingency
- Total NSF cost (then-year $)--
  – $205M including inflation and 27% contingency
  – $24M equivalent contributions by UK and Germany: each worth equivalent of ~$6M for development and $6M for fabrication of hardware

The scientific evolution of LIGO

- 1st full science run of LIGO at design sensitivity in progress
  - Began November 2005; ~80% complete
  - Hundreds of galaxies now in range for 1.4 M_o NS-NS binaries
  - Discovery possible but not likely (5-10%)
- Enhancement program
  - In 2009 ~8 times more galaxies (thousands) in range
  - Moderate discovery possibility (~50%)
- Advanced LIGO
  - 1000 times more galaxies in range (millions)
  - Expect ~1 signal/day -- 1/week in ~2014
  - Will usher in era of gravitational wave Astrophysics



Recent astrophysics results from LIGO

--no discovery to report--

Data analysis

Data analysis by the LIGO Scientific Collaboration (LSC) is organized into four types of search analyses:

1. Binary coalescences ("inspiraling" NS-NS or NS-BH pairs)

   - Signal shape matched to modeled chirped waveforms

2. Transients sources with unmodeled waveforms ("bursts ")

   - High S/N in coincidence with external trigger or between LIGO sites

3. Continuous wave sources ("GW pulsars")-

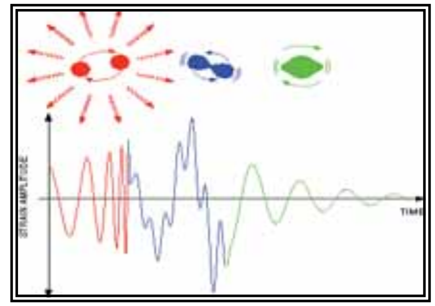
   - GW signal phased to known ephemeris after Doppler correction

4. Stochastic gravitational wave background (cosmological & astrophysical foregrounds)

   - Stochastic signal correlated between two interferometers

Searches for coalescing compact binaries- S3 & S4

- Use modeled waveforms to filter data



- Sensitive to binaries with masses:

  $0.35\ M_{sun} < m_1, m_2 < 1\ M_{sun}$

  $1\ M_{sun} < m_1, m_2 < 3\ M_{sun}$

  $3\ M_{sun} < m_1, m_2 < 80\ M_{sun}$

- No detections
- Sensitivity:
  - S3: 0.09 yr of data;

    ~3 Milky Way equivalent galaxies for 1.4 – 1.4 M_{sun} (NS-NS)
  - S4: 0.05 yr of data;

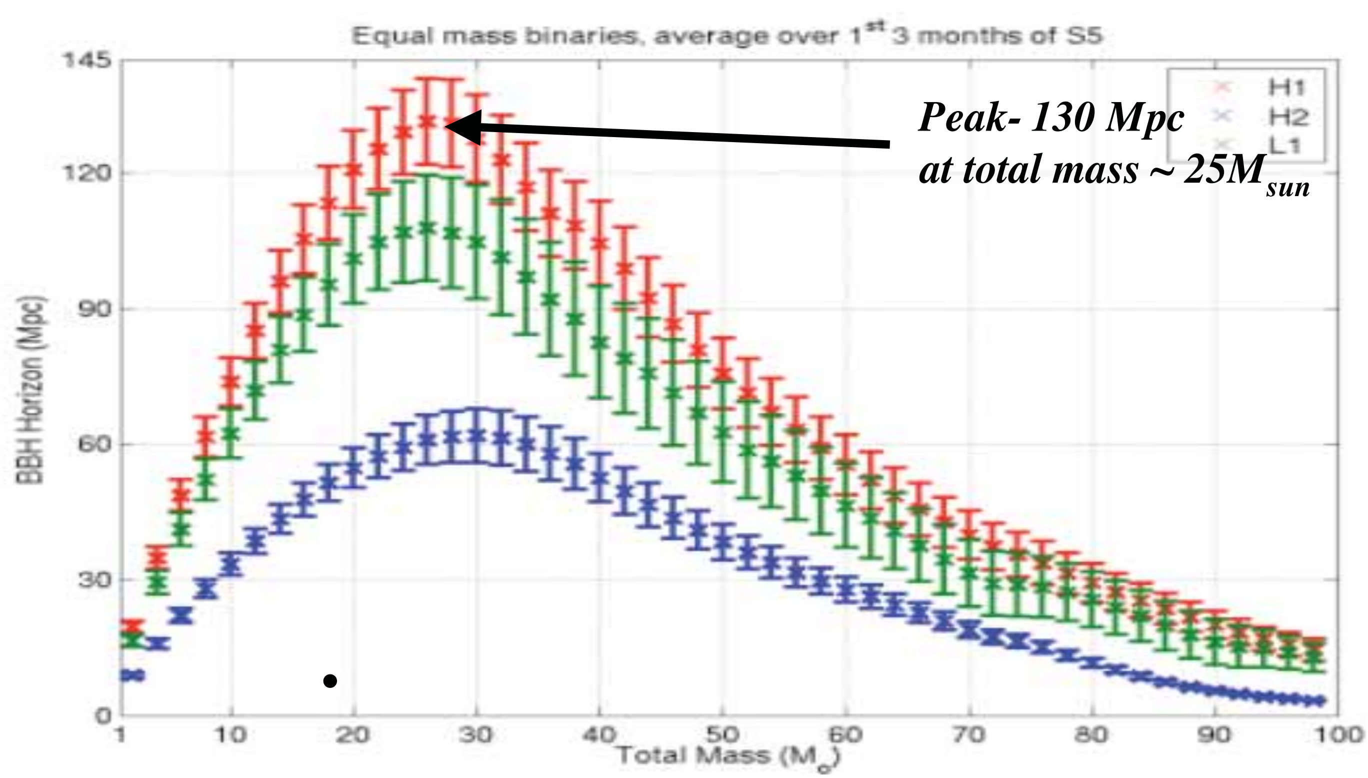
    ~24 Milky Way equivalent galaxies for 1.4 – 1.4 M_{sun} (NS-NS)

    ~150 Milky Way equivalent galaxies for 5.0 – 5.0 M_{sun} (BH-BH)

S5 search for compact binary signals

- 3 months of data analyzed- no signals seen
- For 1.4-1.4 M_o binaries, ~ 200 MWEGs in range
- For 5-5 M_o binaries, ~ 1000 MWEGs in range
- Plot- Inspiral horizon for equal mass binaries vs. total mass

(horizon=range at peak of antenna pattern; ~2.3 x antenna pattern average)



Untriggered GW burst search

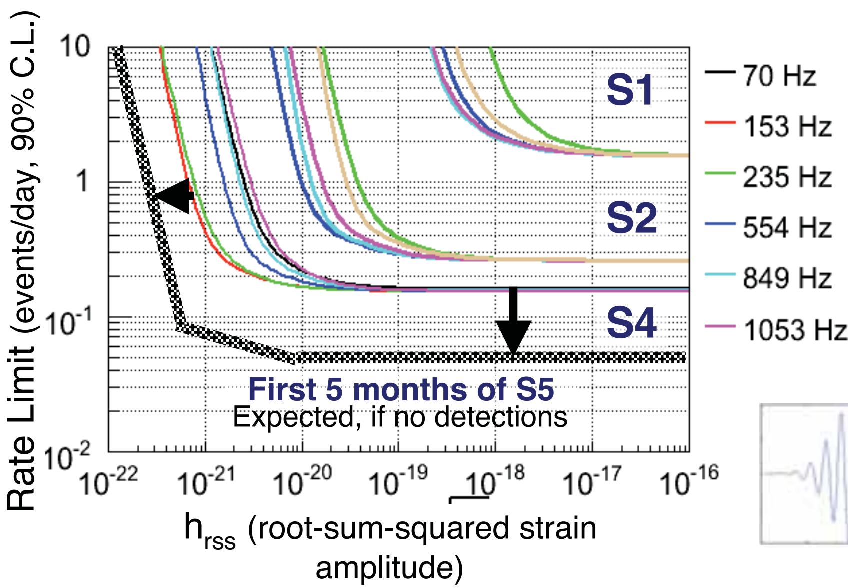
- Look for short (<< 1 sec), unmodeled GW signals in LIGO's frequency band
  - –From stellar core collapse, compact binary merger, etc. — or unexpected source
- Look for excess signal power and/or cross-correlation among data streams from different detectors

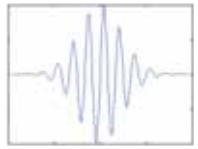
- No GW bursts detected in S1/S2/S3/S4

Limit on GRB rate vs. GW signal strength sensitivity- note S5 improvement

- Detection algorithms tuned for 64–1600 Hz, duration << 1 sec
- Veto thresholds pre-established before looking at data
- Representative S5 energy emission sensitivity:

$E_{GW} \sim 10^{-1}$ M_{sun} at 20 Mpc (@153 Hz)





Examples of triggered Searches for GW Bursts

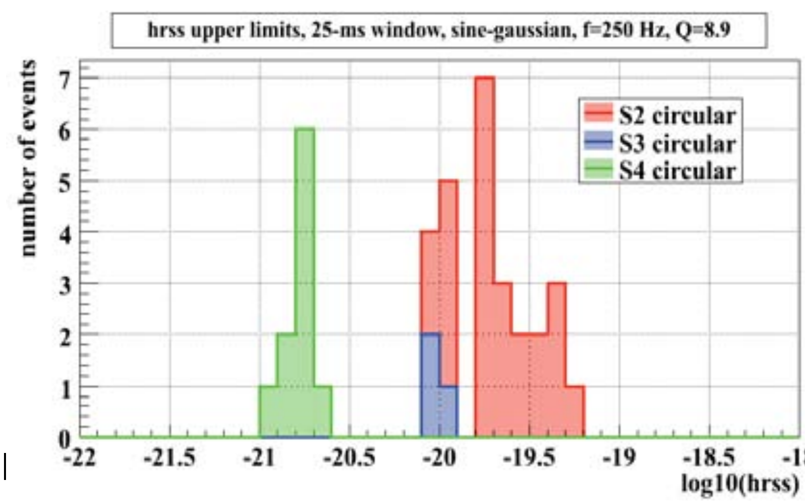
preliminary

Soft Gamma Repeater 1806-20

- galactic neutron star (close-10-15 kpc) with intense magnetic field (~1015 G)
- source of record gamma-ray flare on December 27, 2004
- quasi-periodic oscillations found in RHESSI and RXTE x-ray data
- search LIGO data for GW signal associated with quasi-periodic oscillations-- no GW signal found
- sensitivity: $E_{GW} \sim 10^{-7}$ to 10^{-8} M_{sun} for the 92.5 Hz QPO
- this is the same order of magnitude as the EM energy emitted in the flare

Gamma-Ray Bursts

- search LIGO data surrounding GRB trigger using cross-correlation method
- no GW signal found associated with 39 GRBs in S2, S3, S4 runs
- set limits on GW signal amplitude
- 53 GRB triggers for the first five months of LIGO S5 run
- typical S5 sensitivity at 250 Hz: $\mathbf{E_{GW} \sim 0.3\ M_{sun}}$ at 20 Mpc



Search for known pulsars- preliminary

- Joint 95% upper limits for 97 pulsars using ~10 months of the LIGO S5 run. Results are overlaid on the estimated median sensitivity of this search.

Crab at 60% spin-down UL!

Not all energy loss into GW

Lowest GW strain upper limit:

PSR J1802-2124

(f_{gw} = 158.1 Hz, r = 3.3 kpc)

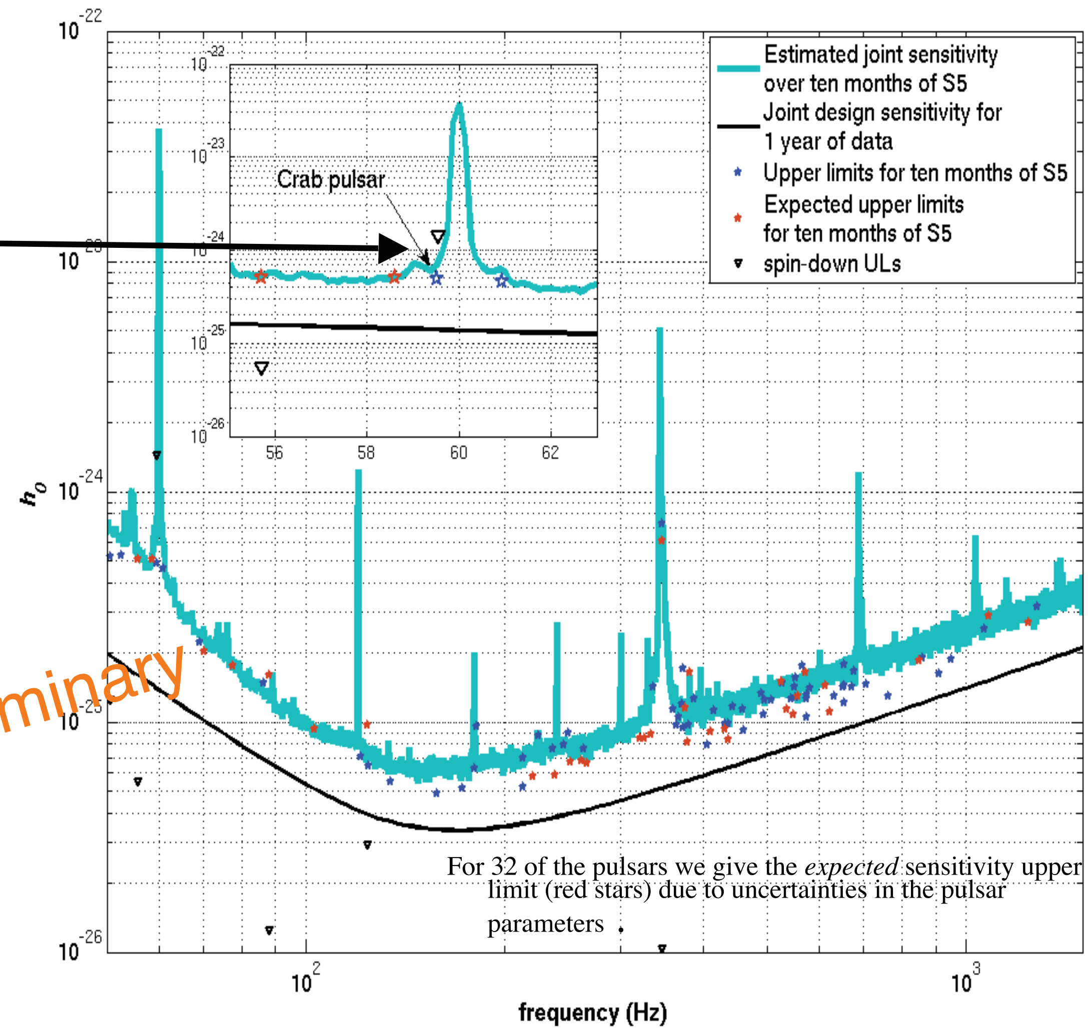
$\mathbf{h_0 < 4.9\times10^{-26}}$

Lowest ellipticity upper limit:

PSR J2124-3358

(f_{gw} = 405.6 Hz, r = 0.25 kpc)

$\boldsymbol{\varepsilon < 1.1\times10^{-7}}$

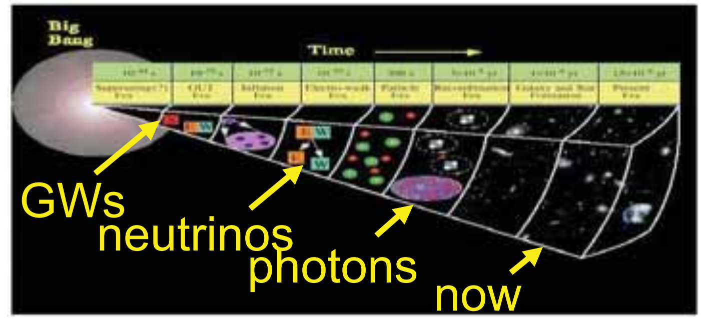


Pulsar timings provided by the Jodrell Bank pulsar group

*LIGO **limits** on isotropic stochastic GW signal*

--from big bang or stochastic background of sources--

- Cross-correlate signals between 2 interferometers



- LIGO S1: $\Omega_{GW} < 44$

  PRD 69 122004 (2004)

- LIGO S3: $\Omega_{GW} < 8.4\times10^{-4}$

  PRL 95 221101 (2005)

- LIGO S4: $\Omega_{GW} < 6.5\times10^{-5}$ (new upper limit; accepted for publication in ApJ))

  Bandwidth: 51-150 Hz

- S5 with 1 yr data---expected sensitivity ~ 4×10^{-6}
  - upper limit from Big Bang nucleosynthesis 10^{-5}; interesting scientific territory

- Advanced LIGO, 1 yr data

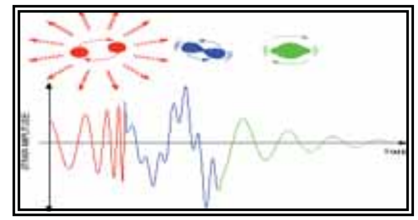
  Expected Sensitivity ~1×10^{-9}

Cosmic strings (?) ~10^{-8}
Inflation prediction ~10^{-14}

$H_0 = 72$ *km/s/Mpc*

Summary of recent science results from LIGO

- No GW observed yet--set scientifically meaningful limits on numbers or strength of cosmic sources



- Binary neutron stars or black holes coalescing
  - In Milky Way sized galaxy
    - for 1.4 M_o NS-NS happens less often than about once every 50 years
    - for 5.0 M_o BH-BH happens less often than about once every 250 years

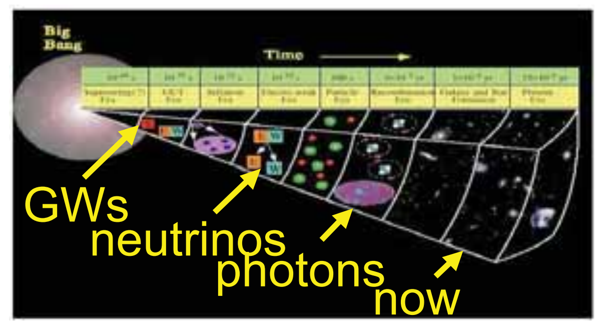
- Gamma ray burst (spotted by satellites)
  - Looked for GWs from ~50 bursts nothing seen
    - would see something if burst 65 million light years away

      has ~0.3 M_o in GW energy

Summary of recent science results from LIGO

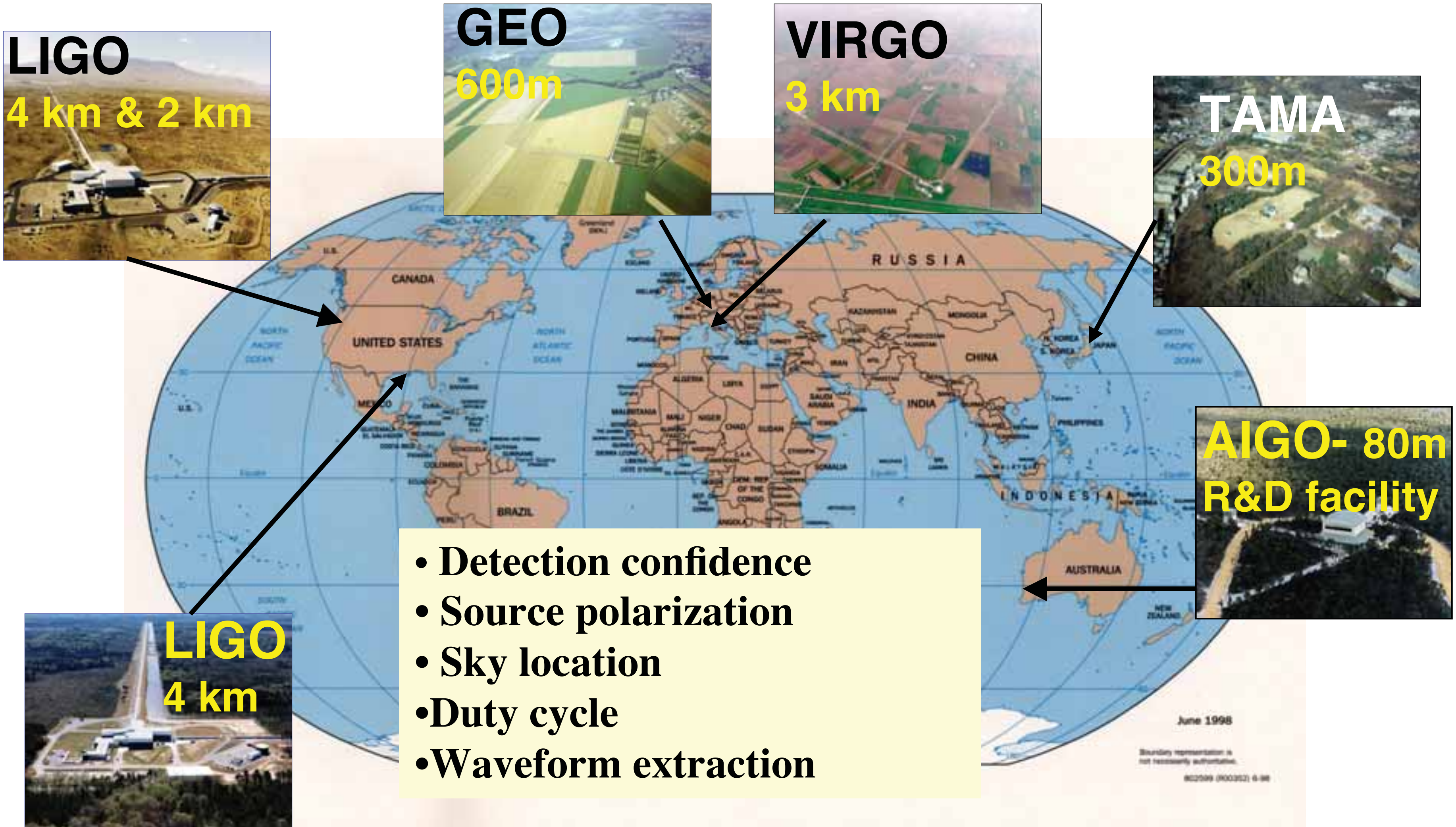
- Pulsars
  - Look for GW signal from ~100 known pulsars
    - Limits on pulsar ellipticity ~ 10^{-6} (1 cm bump on 10 km size object)
    - For Crab pulsar determine that < 60% of energy lost in spindown goes into GWs

- GWs from the Big Bang
  - Fraction of the energy density (in our frequency band) in the universe in GW is less than 65 parts per million



Towards an international network of gravitational wave observatories

Global network of interferometers



- Detection confidence
- Source polarization
- Sky location
- Duty cycle
- Waveform extraction

Status of the global network

- GEO and LIGO carry out all observing and data analysis as one team, the LIGO Scientific Collaboration (LSC).
- LIGO also carries out a few joint searches with the network of resonant bar detectors.
- LSC and Virgo have just agreed to begin joint data analysis and joint run planning.
  - Data analysis will be carried out and results published by LIGO and Virgo together beginning with data taken May18
  - Shutdowns, upgrades, etc. will be coordinated to maximize science output (e.g 2 sites up as often as possible)
  - *This collaboration will be open to other interferometers when they reach the appropriate sensitivity levels.*

The future for ground-based GW interferometers--middle next decade and beyond

- Advanced LIGO will be operating in ~2014
- Advanced Virgo will be built on the same time scale as Advanced LIGO, and will achieve comparable sensitivity.
- GEO HF will improve the sensitivity beyond GEO600, mainly at high frequencies
- The Japanese GW community is proposing LCGT, a 3 km cryogenic interferometer in the Kamioka mine.
- The Australian GW community is working towards AIGO, a 5 km interferometer at the Gingin site near Perth
- There is ongoing technology development, world-wide, towards the third generation-- even better sensitivity and lower frequency

Education and Public Outreach

Public Education and Outreach- LIGO Livingston

- Science Education Center at Livingston LIGO site
  - Funded through an NSF grant
  - 8000 ft^2 facility on the LIGO Livingston site
  - The Center features 50 hands-on exhibits
  - Enable students and the public to understand important scientific principles using concepts from LIGO
  - Serve as an important regional resource for teacher training and development.
- LIGO's partners-- Southern University (teacher training program), the San Francisco Exploratorium (developed hands-on exhibits), LA GEAR UP (state educational reform agency under the Louisiana Board of Regents).
- Opened for business on November 13, 2006

LIGO Science Education Center

Received Award of Honor from the American institute of Architects- New Orleans Chapter
"From and function come together in an exciting and unexpected way in the building, which has a dynamic exterior wall that suggests its purpose: a science education center"

LIGO Science Education Center
Livingston, Louisiana

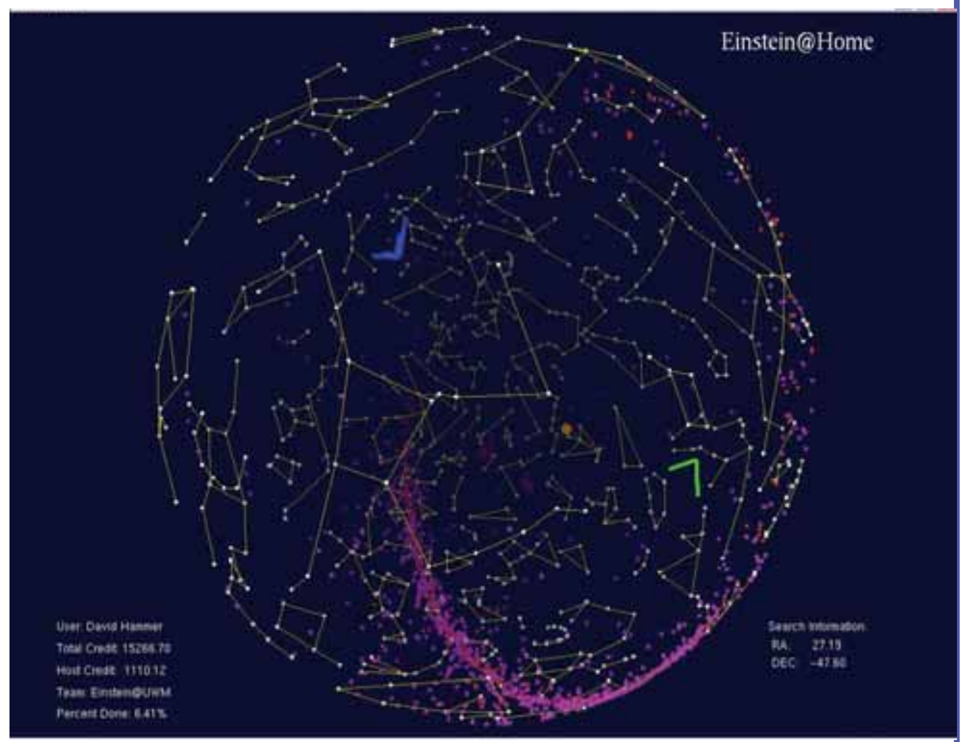
More Public Education and Outreach

- Hanford Observatory- very active education and outreach program
- Mission:
  - Bring public out to “touch and see” science in the making
  - Help schools with teacher training, internships and school tours
  - Help integrate science research into science teaching
  - Help the public to value the richness of science
- In 2005-06--- 3000 visitors to site including 900 K-12 students
- Public lectures, astronomy nights, student workshops, etc.

Einstein@Home

Public participation in LIGO data analysis

- One of the world's three largest distributed computing projects.
- LIGO All sky search for continous-wave sources (pulsars).
- 150,000 users.
- 334,000 host machines (Windows, Mac, Linux).
- More than 80 Tflops CPU 24 x 7.
- Currently searching S5 data.



Summary

- LIGO is operating in a science mode at design sensitivity
  - 1st long science run is ~80% complete
  - No detection yet
  - Results of astrophysics interest are being published
- Sensitivity/range will be increased by ~ 2 with enhanced LIGO and a factor of 10 with Advanced LIGO
  - Thousands of galaxies in range in 2009 and millions in 2014
  - Discovery reasonably possible in 2009-2010 run
  - Will be doing GW astrophysics with Advanced LIGO
- Efforts towards an international network of ground-based GW detectors are gaining momentum-- joint data analysis with Virgo begins May 18
- LIGO has a 1st-class education and outreach program anchored by the LIGO Science Education Center