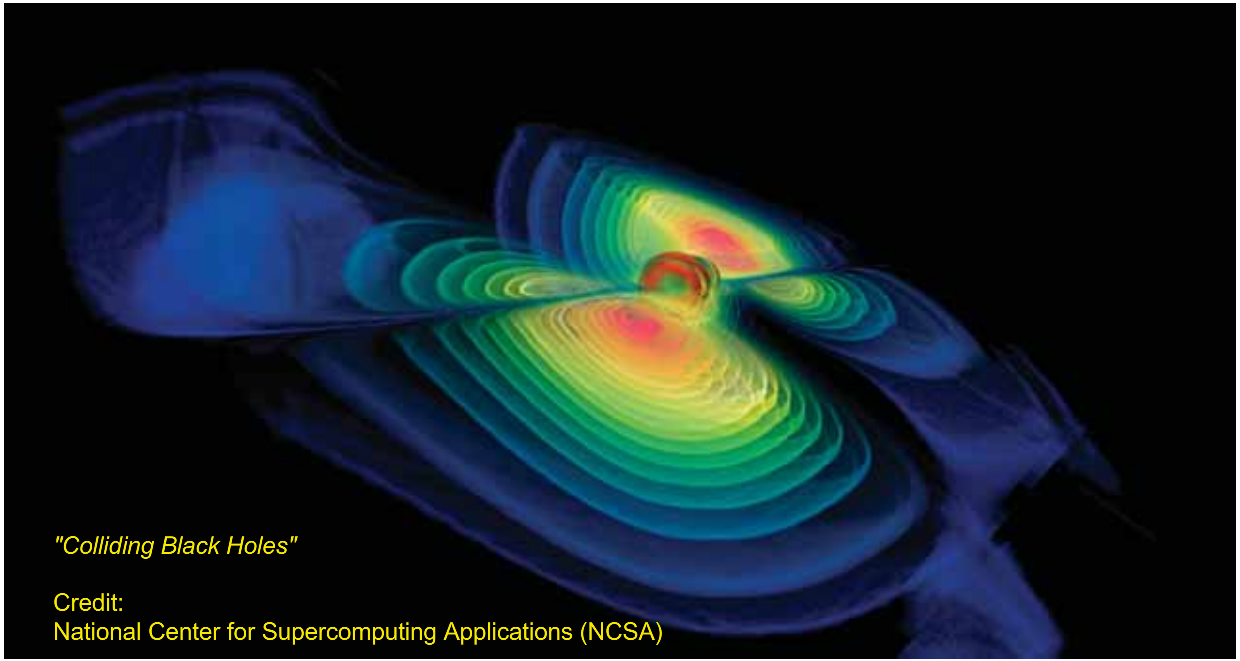
Listening for Ripples in Space-Time with LIGO

APS California Section

October 17, 2008

Jay Marx, Executive Director, LIGO



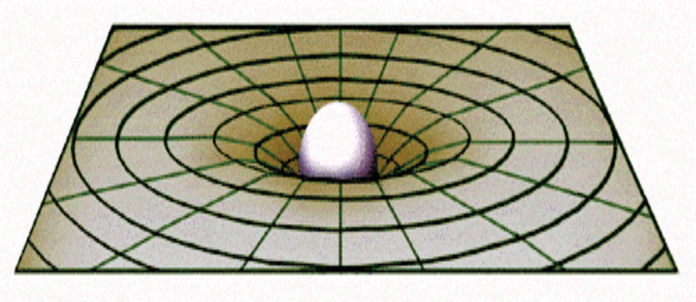
"Colliding Black Holes"

Credit:
National Center for Supercomputing Applications (NCSA)

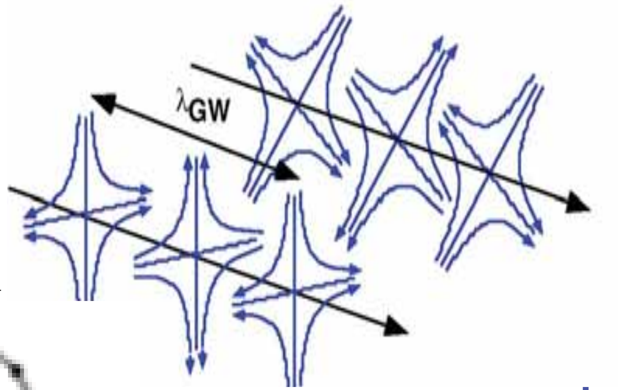
G080567-00-G

- 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

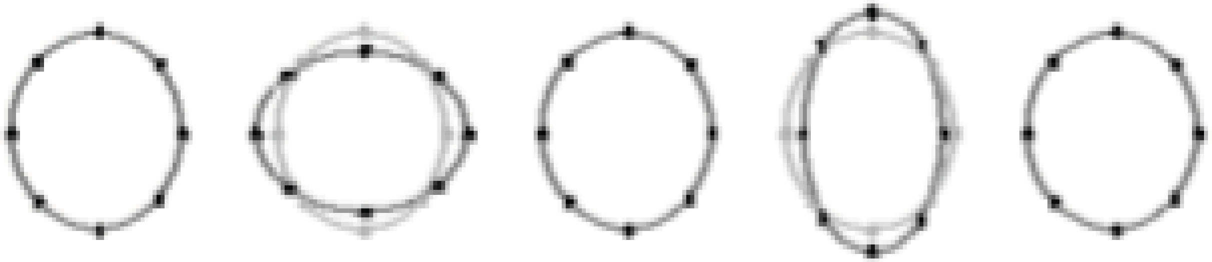
Gravitational waves



- Ripples of space-time curvature that propagate at the speed of light Emitted by accelerating aspherical mass distributions



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

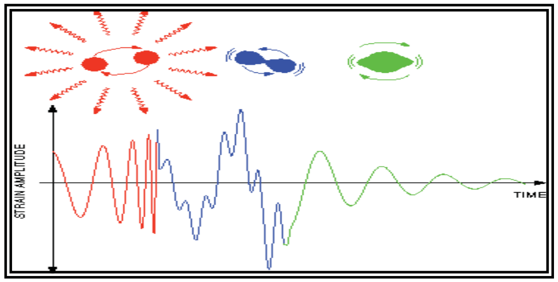


- Matter is almost transparent to gravitational waves-- waves travel unimpeded to us from their source
- Source characteristics are encoded on GW waveform

Astrophysical sources of GWs sought by LIGO

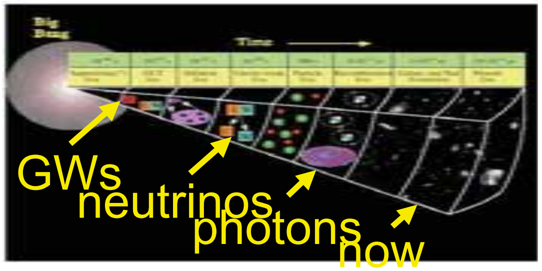
- Periodic sources in our galaxy- pulsars
  - e.g. spinning neutron stars

- Coalescing compact binaries
  - Classes of objects: NS-NS, NS-BH, BH-BH
  - Masses, spins, orientation encoded on waveform



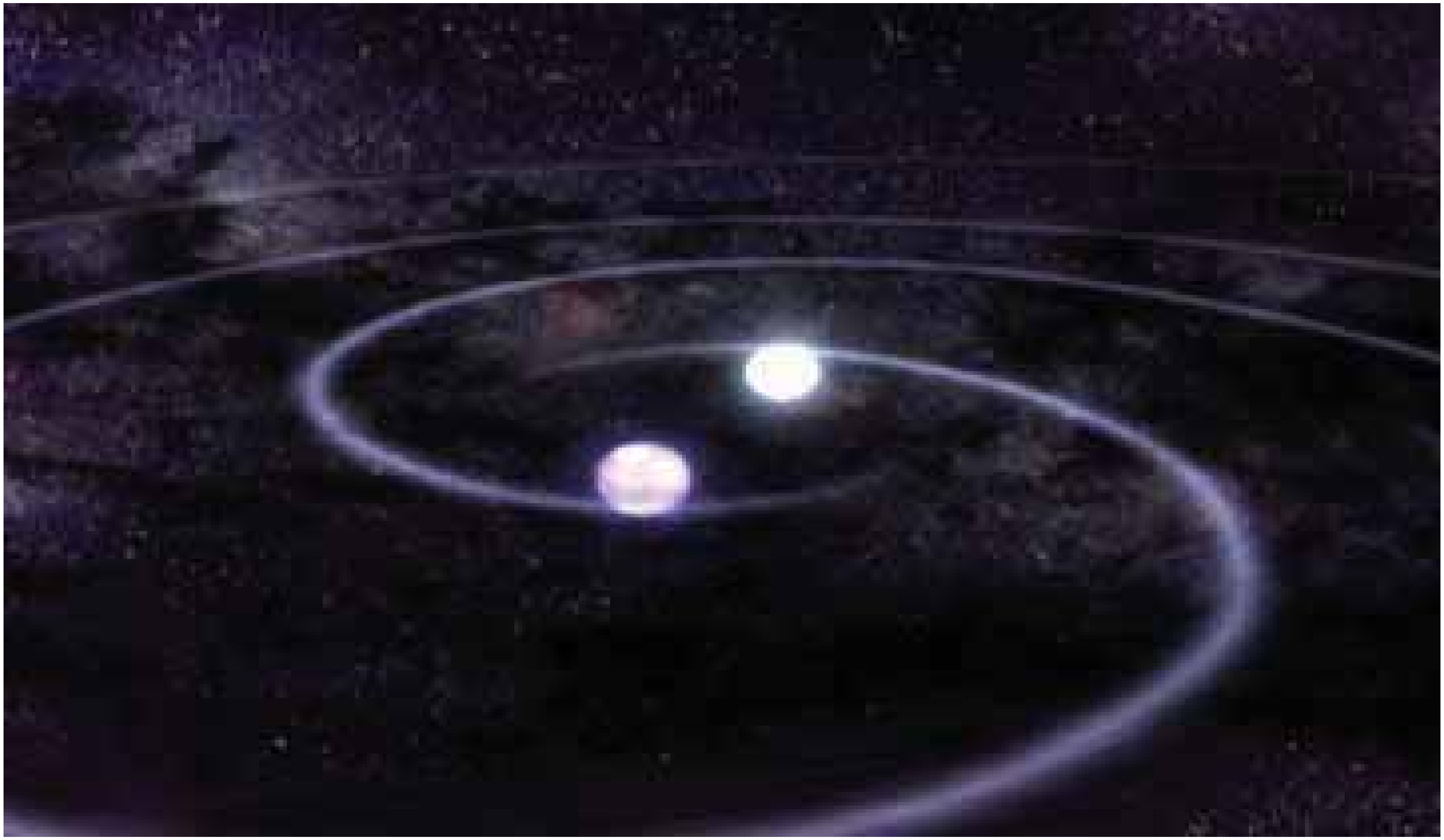
- Stellar-scale explosions
  - e.g. GRBs, supernovae with asymmetric collapse

- Stochastic background
  - From Big Bang (t = 10^{-22} sec; earliest signal)



- The Unexpected

GWs from NS-NS insprial & merger



Strength of Gravitational Waves

e.g. Neutron Star Binary in the Virgo cluster

- Gravitational wave amplitude (strain h= $\triangle$L/L)

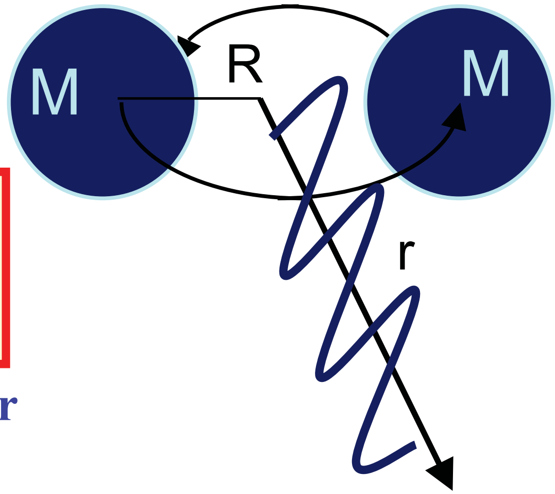
$$h_{\mu\nu} = \frac{2G}{c^4 r}\ddot{I}_{\mu\nu} \Rightarrow h \approx \frac{4\pi^2 GMR^2 f_{orb}^2}{c^4 r}$$

I = quadrupole mass distribution of source

- For a binary neutron star

~1.4 M_o pair in Virgo cluster

~ 50 million light years away



$M \approx 10^{30}$ kg

$R \approx 20$ km

$f \approx 400$ Hz

$r \approx 10^{23}$ m

$h \sim 10^{-21}$

Remember this for later

Laser Interferometer Gravitational Wave Observatory (LIGO)

- Decades-long effort to directly observe gravitational waves predicted by General Relativity and pioneer the new field of gravitational wave astronomy

- Uses laser interferometry to observe effects of GWs in ~40 Hz to few KHz bandwidth
  - Audio band-- "listen" for ripples in space-time

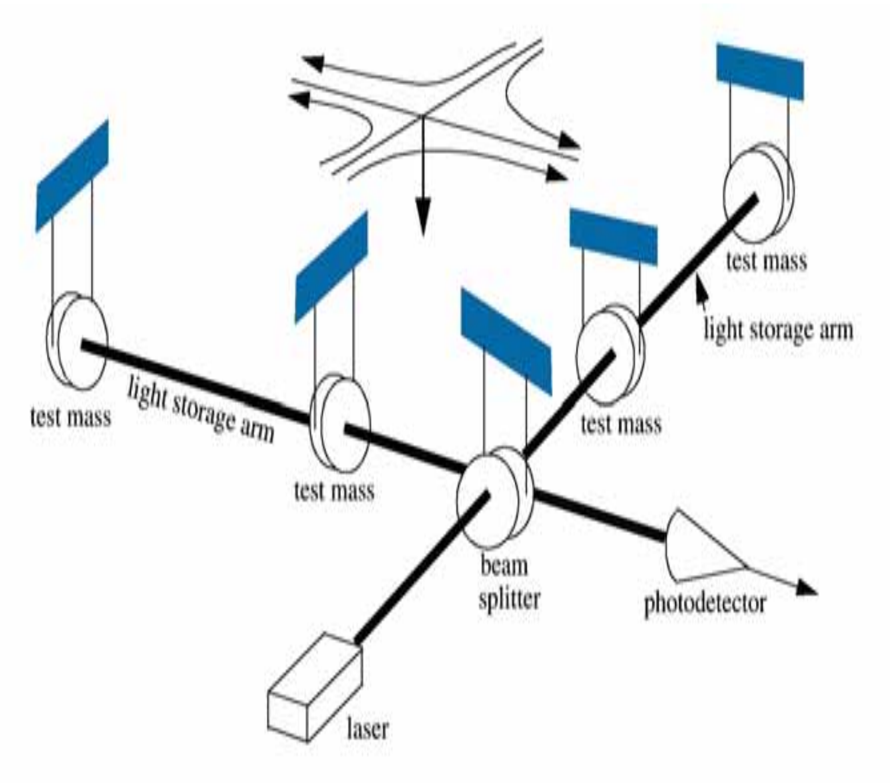
- Big science-- high precision measurement techniques on a kilometer scale

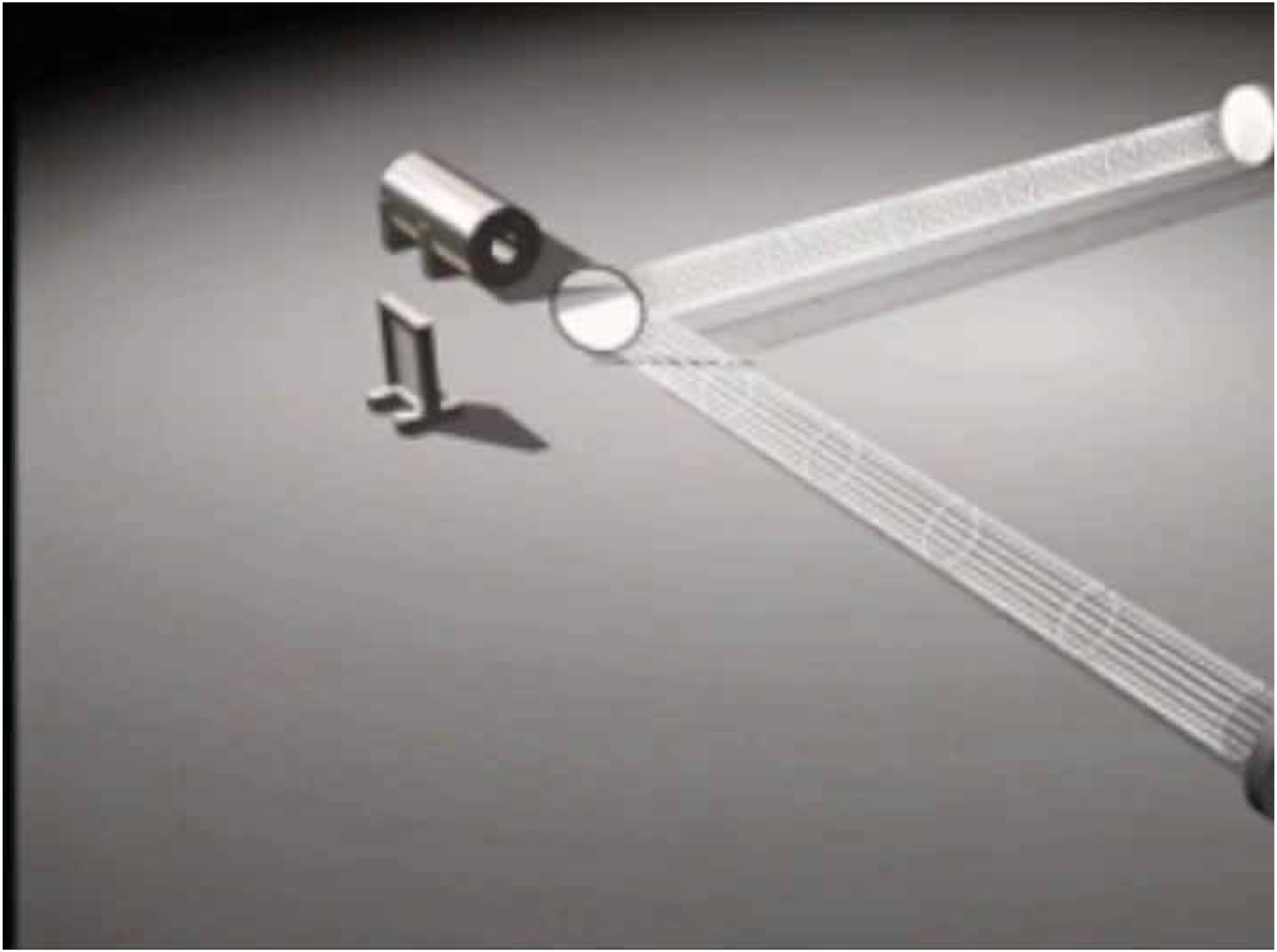
Detecting GWs with Precision Interferometry

- Suspended test masses (mirrors) act as “freely-falling” objects tied to their space-time coordinates--markers of points in the fabric of space/time

- A passing gravitational wave alternately stretches (compresses) space-time and thus the arms--changing the relative separation of the mirrors in each arm

- Optical interferometery is used to measure relative separation between mirrors in each arm

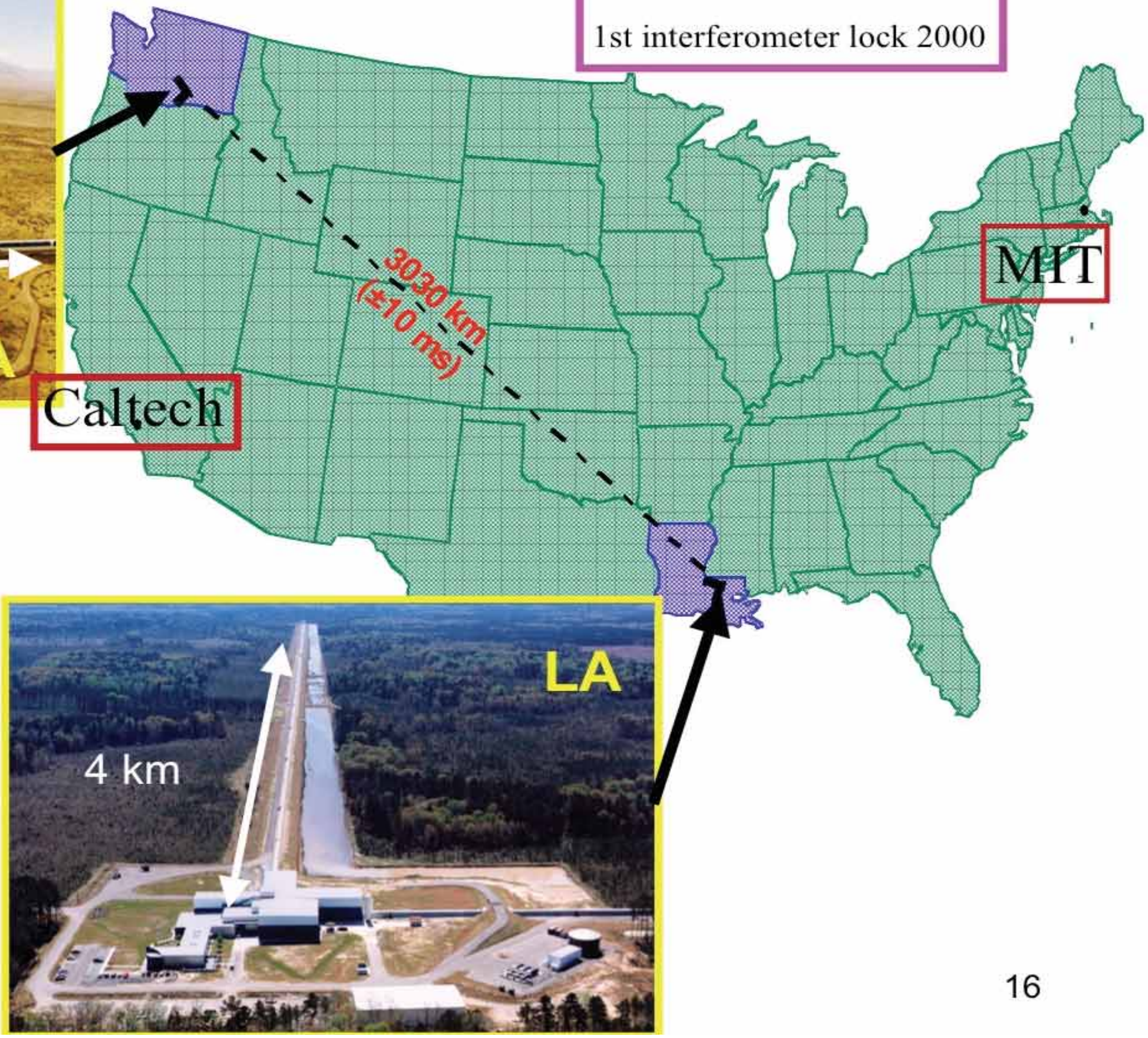




LIGO Laser Interferometer Gravitational-wave Observatory

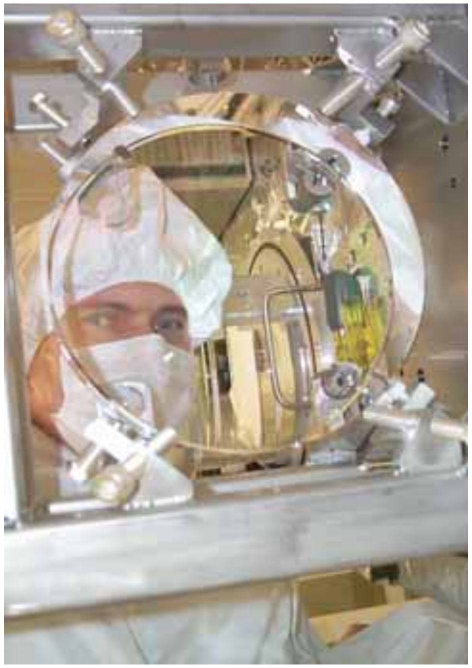
Ground breaking 1995

1st interferometer lock 2000



- Managed and operated by Caltech & MIT with funding from NSF
- LIGO Scientific collaboration- ~500 members & 45 institutions, world-wide

Some LIGO hardware



Experimental challenges and limitations

Amplitude of gravitational wave= strain (h)

$$h = \Delta L / L$$

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

$$\boxed{\Delta L \sim 4 \times 10^{-18}\ \text{m}}$$

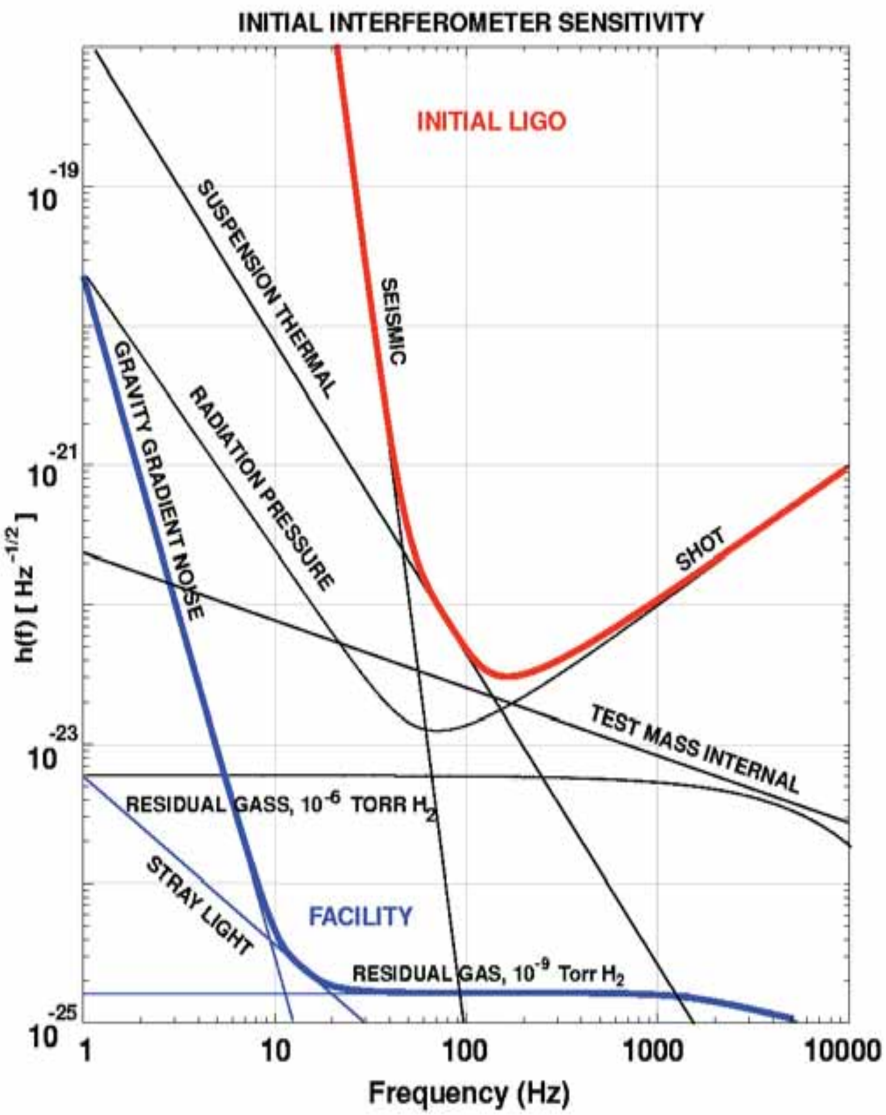
Challenge--to measure relative distance of test masses in interferometers arms to ~ 10^{-18} m --1/1000 the size of a proton!

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

What makes it hard?

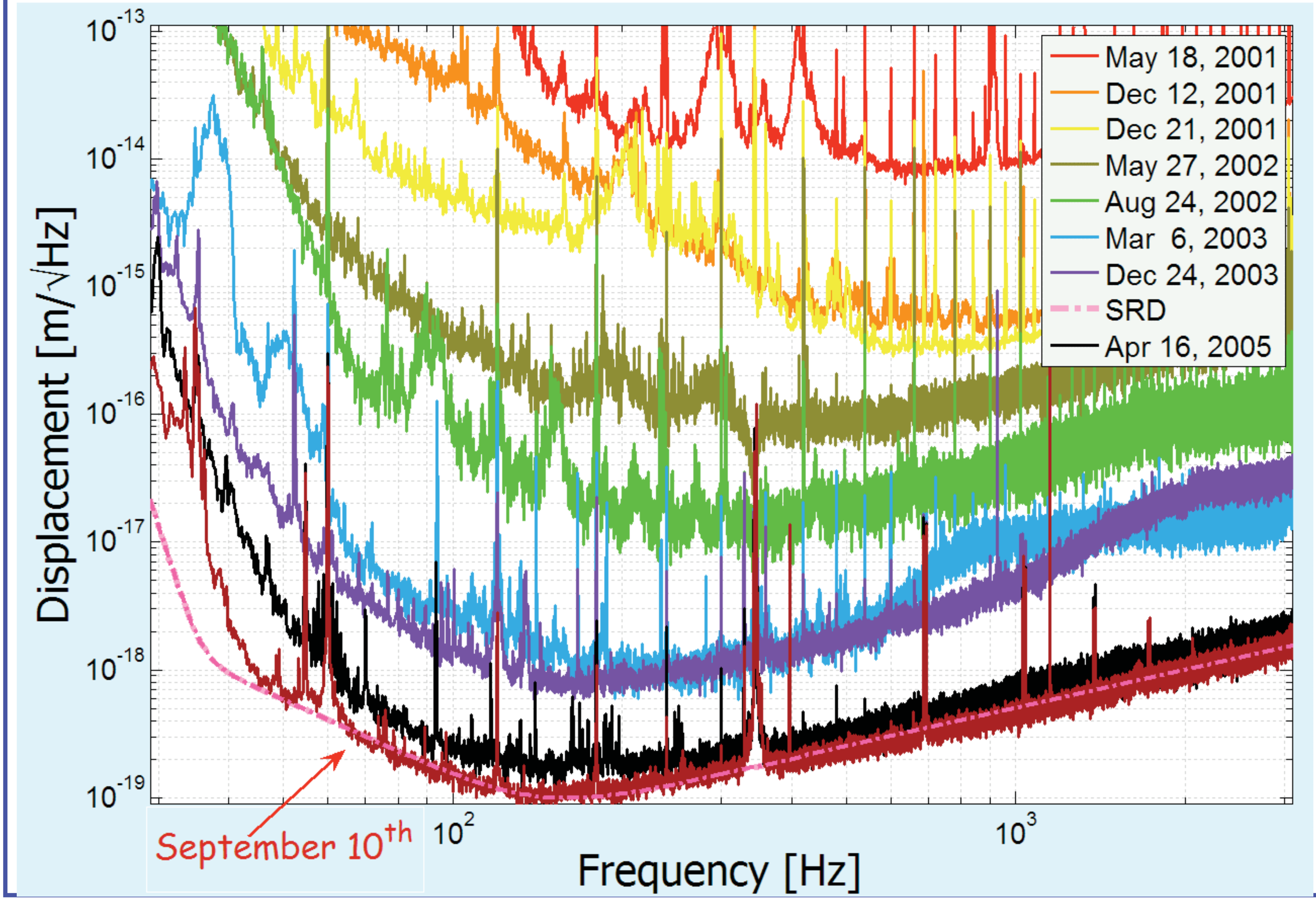
- Gravitational wave amplitude is very small
- External forces also push the mirrors around
- Laser light has fluctuations in its phase and amplitude
- Measurement noise is a challenge to control at this level

Relevant noise sources in LIGO



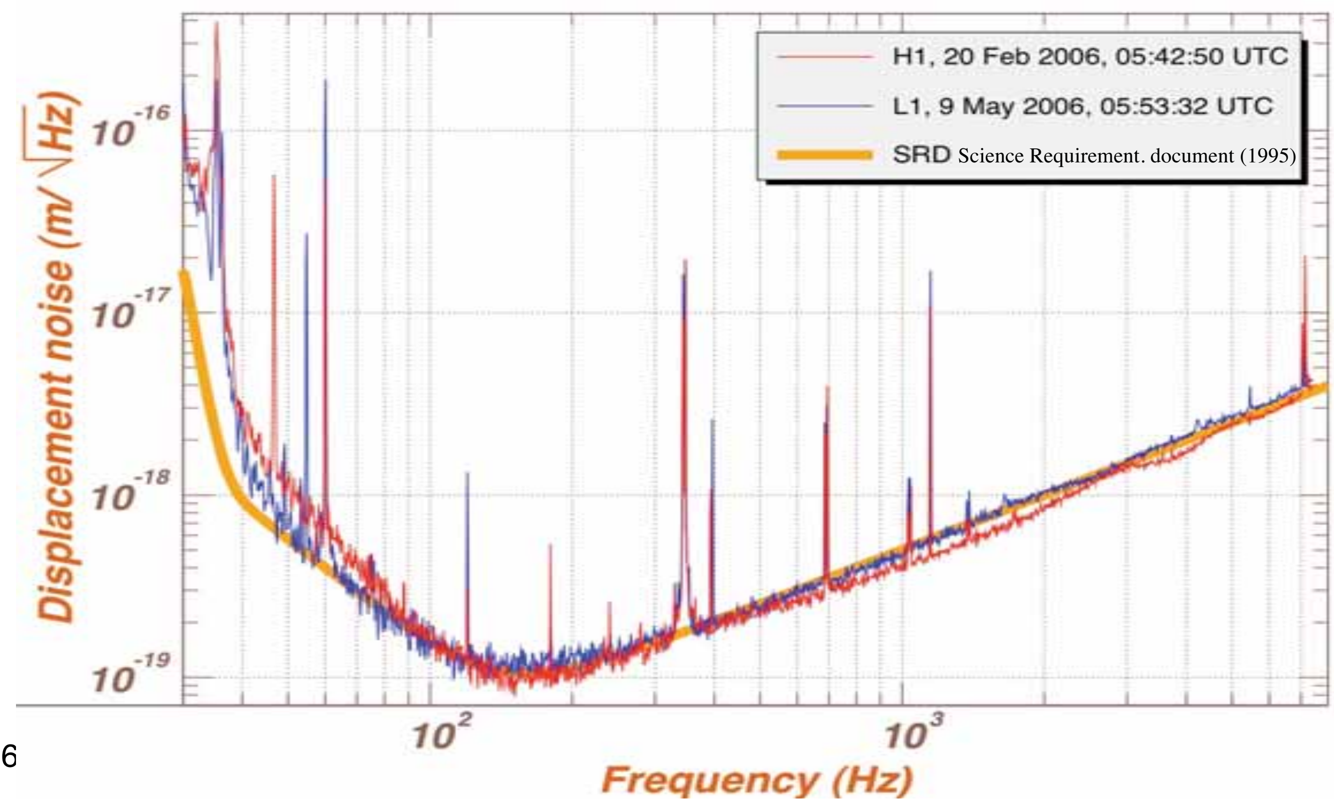
- Displacement Noise
  - Seismic motion (limit at low frequencies)
    - Ground motion from natural and anthropogenic sources
  - Thermal Noise (limit at mid-frequencies)
    - vibrations due to finite temperature
  - Radiation pressure fluctuations
- Sensing Noise (limit at high frequency)
  - Photon 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

Improving the sensitivity- 2001 to 2005



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 significant achievement



The current search for gravitational waves

A LIGO science run (S5) at design sensitivity began in November 2005 and ended October 2007

- 1 year live-time of 2-site coincident data

Searching for signals in audio band (~40 Hz to few kHz)
Note- estimate ~few % probability to see signal in this run

Run was extremely productive--reliable instruments and lots of high quality data- some results in later slides

- Sky-average range achieved (for 1.4 M_o neutron star pairs; S/N=8)
  - –for 4 km interferometers-- ~15 Mpc (~50 million light years)
  - –for 2 km interferometers--- ~7 Mpc (~25 million light years)

Note-- # potential extragalactic sources goes as $(\text{range})^3$

Next step-"Enhancements" to initial LIGO

- Now making modest changes to 4 km interferometers at both sites to increase range by ~2
  - Reduce several known noise sources
    - especially in signal readout
  - Increase laser power
- Result will be increase number of sources in range by factor ~8 (i.e. 2^3).
- Next science run with enhanced range in spring 2009
  - Estimate ~ 20% probability/year to see a signal with enhanced LIGO.

Then--Advanced LIGO-
the big step towards GW astrophysics

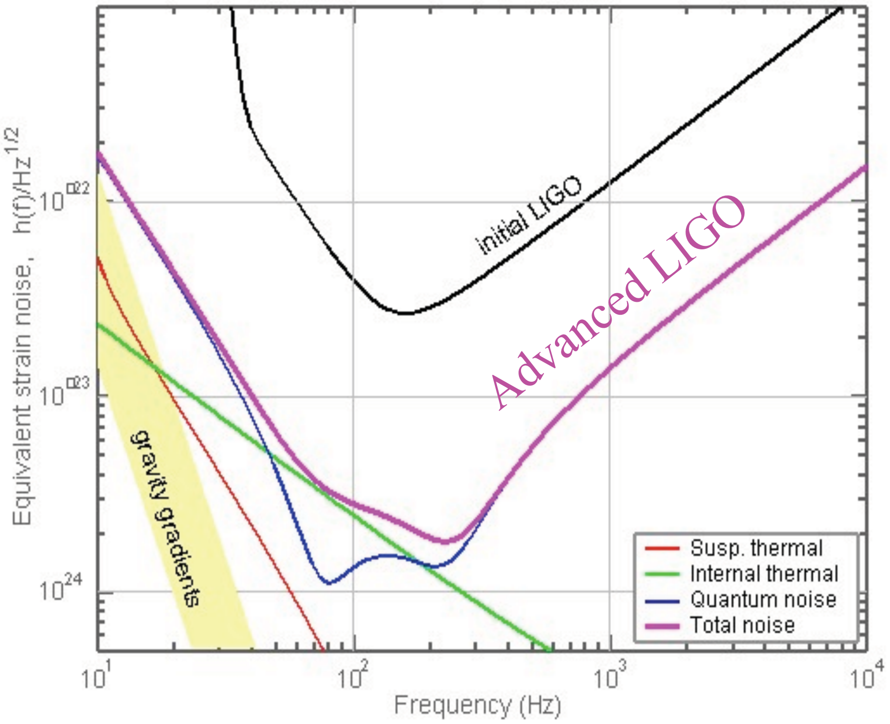
- Project to improve the sensitivity and range of LIGO by a factor of 10
- Increase the number of extragalactic sources in range by ~1000
- Increase detection bandwidth to see more pulsars and higher mass BH-BH mergers
  - move seismic wall from ~50 Hz to 10 Hz
- Go beyond discovery of GW
  - Expect signals at few/day to few/week rate!!!
- Era of astronomy & astrophysics with GWs
  - Use numerical relativity to decode GW signal to extract source characteristics

Reach of Advanced LIGO

x10 better amplitude sensitivity

⇒ x1000 rate=(reach)^3

⇒ 1 year of Initial LIGO
< 1 day of Advanced LIGO !



Neutron Star Binaries:

- Initial LIGO: ~15 Mpc
- Advanced LIGO: ~200-300 Mpc

Black hole Binaries:

- Initial LIGO: Up to 10 M_o, at ~100 Mpc
- Advanced LIGO: Up to 50 M_o in most of the observable Universe

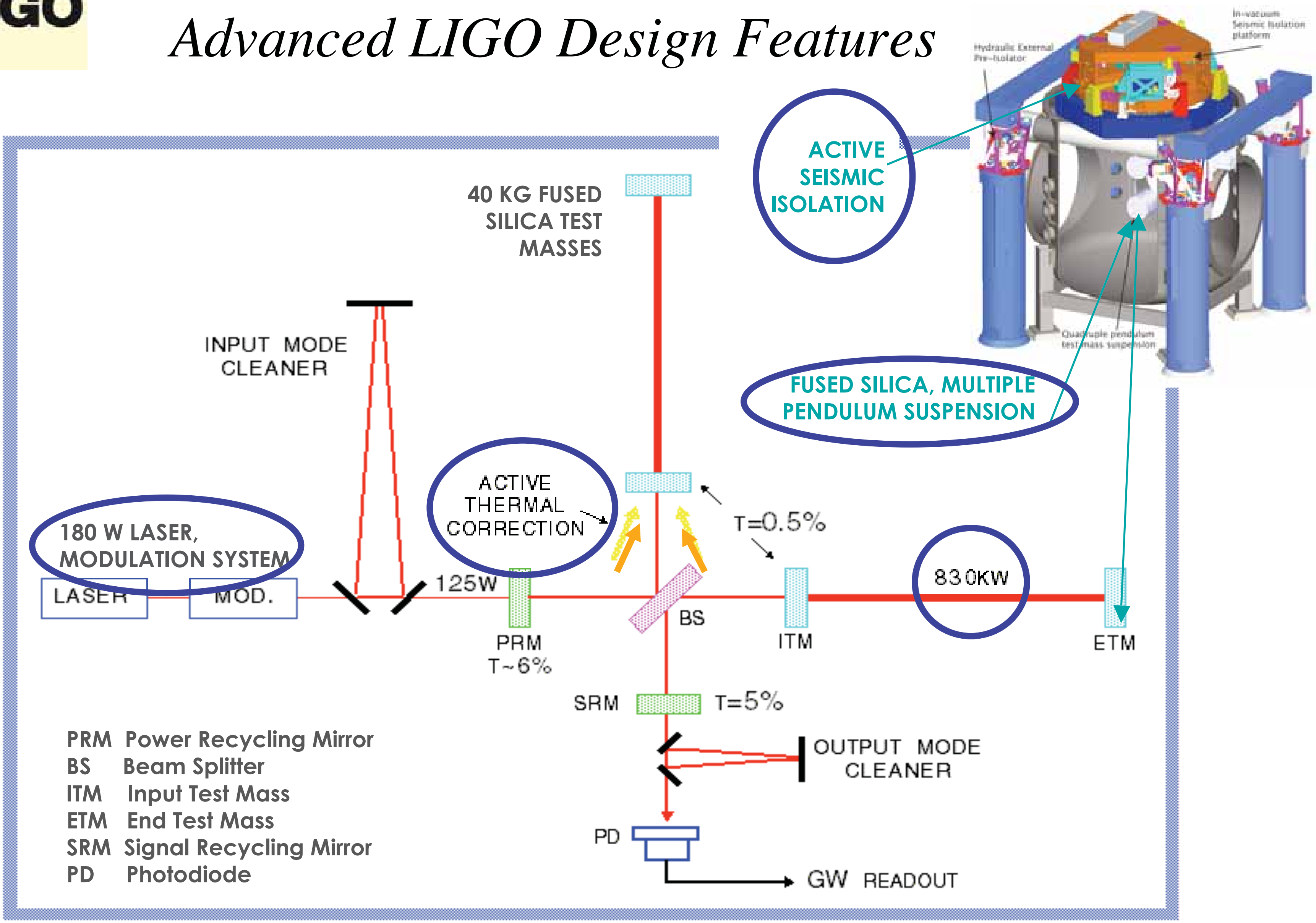
Advanced LIGO- a big project

- Construction started in April 2008
- Scheduled completion in 2014
- Total cost
  - From NSF $205M
  - Contributions by UK and Germany ~$24M
    - each ~$6M for development and $6M for fabrication of hardware

Advanced LIGO-
improvements from current LIGO

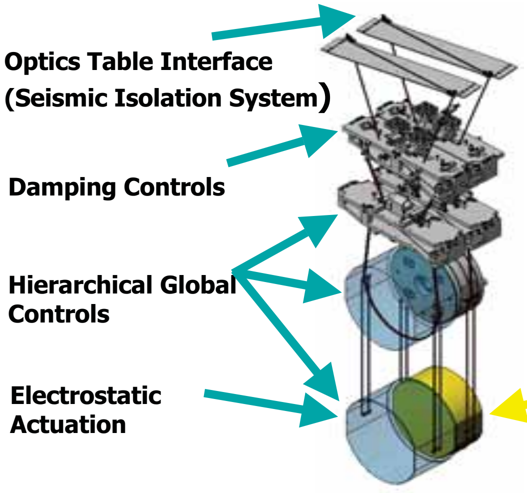
- Keep initial LIGO “infrastructure” and sites
  - Vacuum system (4 km arms), building, roads, etc.
- Will have three 4 km interferometers
- Replace technical components with---
  - 20x higher power laser (180 watts CW)
  - Much improved seismic suspension and isolation for mirrors,
  - Larger, better mirrors (to handle increased thermal load)
  - Lower-noise readout
  - New feedback & control system
- Many of these proven as part of enhanced LIGO

Advanced LIGO Design Features



PRM	Power Recycling Mirror
BS	Beam Splitter
ITM	Input Test Mass
ETM	End Test Mass
SRM	Signal Recycling Mirror
PD	Photodiode

Advanced LIGO suspensions prototype

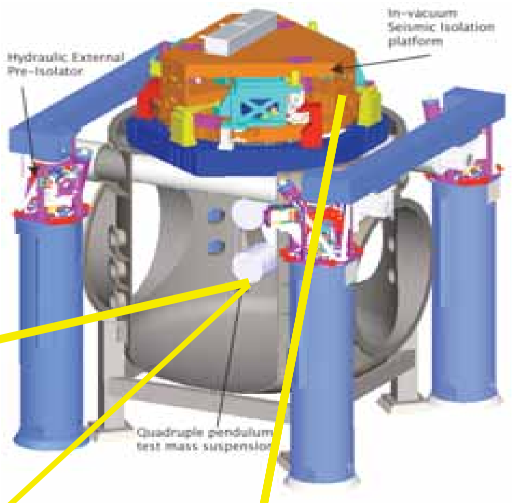


Optics Table Interface (Seismic Isolation System)

Damping Controls

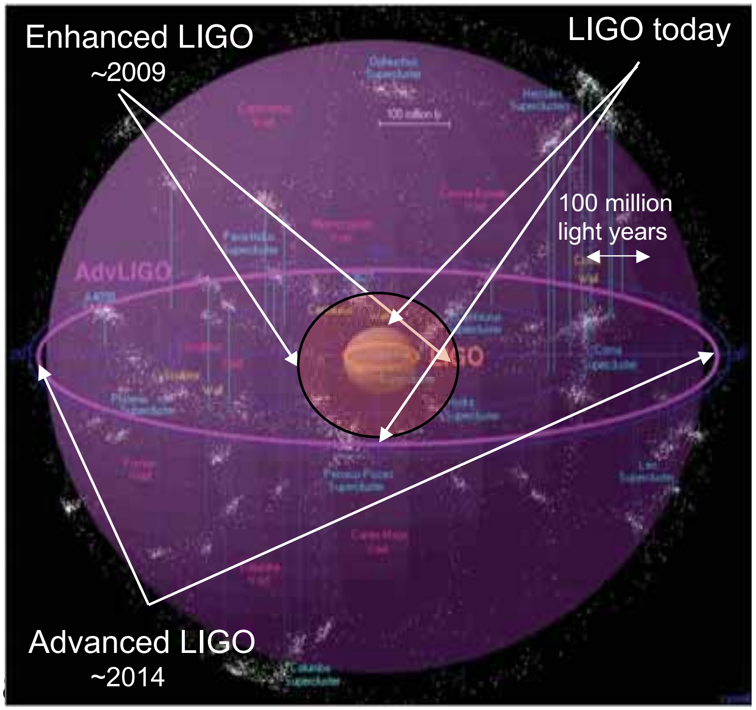
Hierarchical Global Controls

Electrostatic Actuation



The scientific evolution of LIGO

- 2 year long science run of LIGO at design sensitivity
  - Began November 2005; completed 1 year ago
  - Hundreds of galaxies in range for 1.4 M_o NS-NS binaries
  - Data still being analyzed. Discovery possible but not likely (few%)
- Enhanced LIGO
  - In 2009 ~8 times more galaxies (thousands) in range
  - Moderate discovery possibility (~20%)
- Advanced LIGO
  - 1000 times more galaxies in range (millions)
  - Expect ~1 signal/day to 1/week in ~2014
  - Will usher in era of gravitational wave astronomy & astrophysics



Some recent astrophysics results from LIGO

Data analysis

Data analysis by the LIGO Scientific Collaboration (LSC)

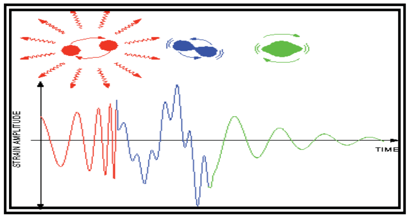
~ 650 members, 50 institutions world-wide

organized into four types of search analyses:

1. Binary coalescences ("inspiraling" NS-NS or BS-BH pairs)
   - Signal shape matched to modeled chirped waveform templates
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

Summary of recent science results from LIGO

- No GW observed yet--setting 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 ~150 bursts-- nothing seen
    - Scale-if a GRB resulted from an binary NS merger 65 million light years away with ~0.3 M_o in GW energy, it would detected in LIGO

The story of GRB 020107

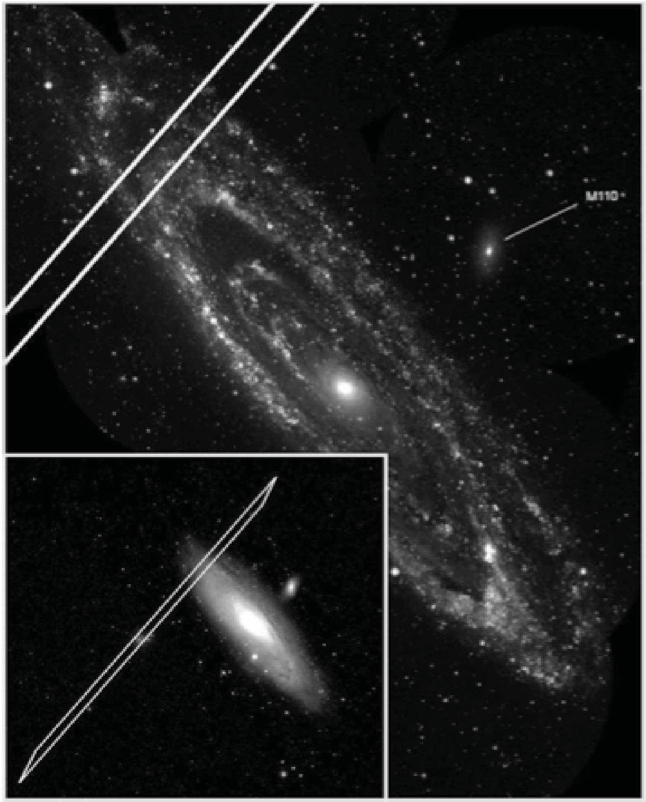
Published- The Astrophysical Journal, 681:1419–1430, 2008 July 10

- Possible progenitor of short, hard GRBs--

mergers of neutron stars or a neutron star and a black hole accompanied by gravitational-wave emission

- Analyzed LIGO data coincident with GRB 070201, a short-duration, hard-spectrum -ray burst (GRB) seen in direction of M31 (Andromeda)
- No plausible gravitational-wave candidates were found around the time of GRB 070201.
- Implies that a compact binary progenitor* located in M31 is excluded at >99% confidence.
- If the GRB 070201 progenitor was not in M31, then we can exclude a binary neutron star merger progenitor with distance D < 35 Mpc, assuming random inclination, at 90% confidence.

(* $1 M_o < m_1 < 3 M_o$ and $1 M_o < m_2 < 40 M_o$)



detected and localized by three IPN spacecraft (Konus-Wind, INTEGRAL, and MESSENGER); it was also ob- served by Swift (BAT)

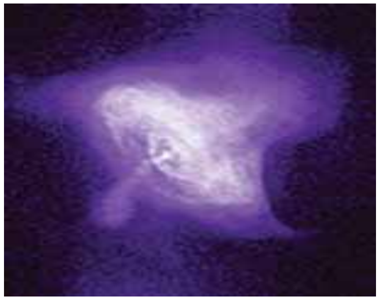
Summary of recent science results from LIGO

- Pulsars
  - Look for GW signal from ~100 known pulsars
    - Only get GW emission if source is aspherical
    - Limits on pulsar ellipticity < 10^{-6}

      (1 cm bump on 10 km size object)

  - For Crab pulsar determine strong limit on energy lost to GWs in spindown

Crab pulsar spindown limit



- Remnant of supernova explosion
  - In our galaxy, ~6500 light years distant
  - Neutron star spinning at ~30 Hz
- Slows down by ~38 ns per day
- How much of energy loss is into gravitational waves?
- Look for GW signal from Crab in phase with pulsar radio signal correcting for Doppler shift due to earth's rotation and solar orbit
- Result from S5 LIGO data--
  - < 4% of energy loss in spindown goes into GWs

Limits on isotropic stochastic GW signal

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

- Cross-correlate signals between 2 interferometers
- Determine fraction of the energy density in the universe in GW
  (in LIGO frequency band- 51-150 Hz)

- LIGO S4: $\Omega_{GW} < 6.5 \times 10^{-5}$ (published)

$H_0 = 72$ km/s/Mpc

- S5 with 1 yr data---
  - expected sensitivity well below best upper limit of 10^{-5}--from Big Bang nucleosynthesis; interesting scientific territory
    (Results to be submitted for publication soon)
- Advanced LIGO, 1 yr data
  Expected Sensitivity $\sim 1 \times 10^{-9}$

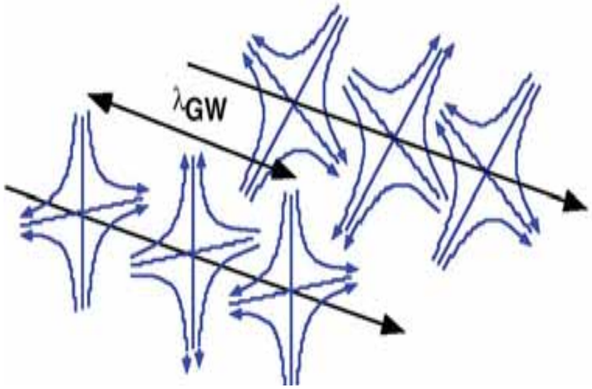
Cosmic strings (?) $\sim 10^{-8}$
Inflation prediction $\sim 10^{-14}$

Towards an international network of gravitational wave observatories

Charcteristics of GWs drive need for global network

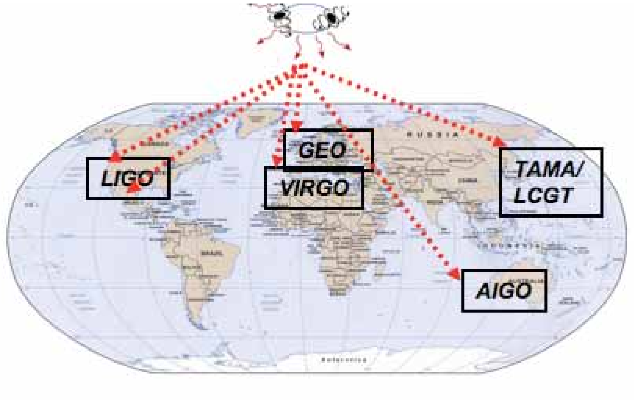
- To do GW astronomy and astrophysics need---
  - to know where source on sky to correlate with other observations (e.g. E-M, neutrino signals)
  - To know polarization to extract source characteristics

- Extraction of signal polarization
  - Requires multiple detectors oriented differently to project out the two polarizations



Charcteristics of GWs drive need for global network

- Angular resolution of source
  - Source location in sky found by triangulation using relative time-of-arrival of signal at different detectors



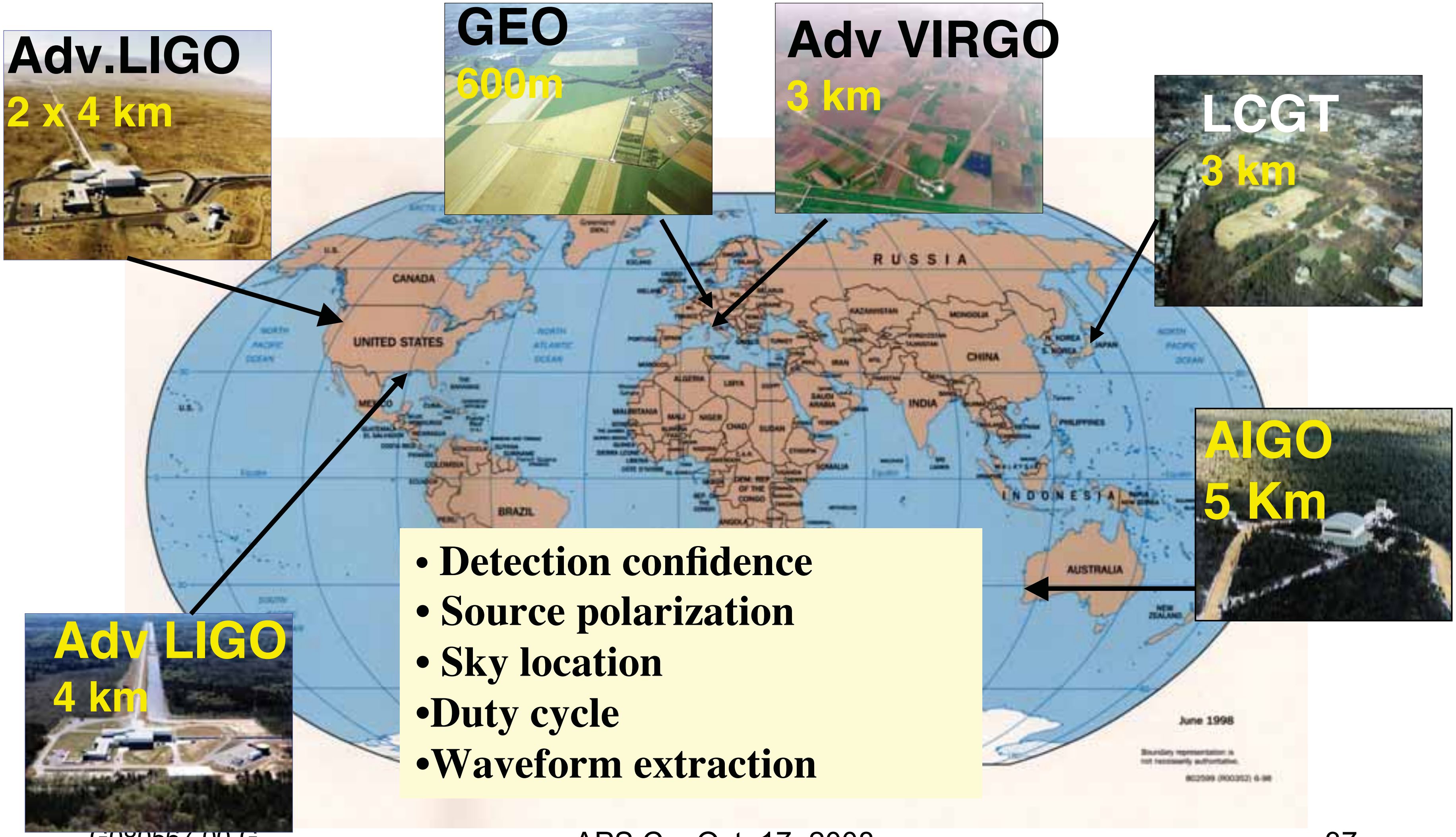
  - Angular resolution ~projected area of triangle as seen by source
    - For good full sky resolution need a tetrahedron of detectors with intercontinental baseline

Status of the global network- now

- LIGO, GEO-600 (Germany), Virgo (Italy) carry out all observing and data analysis as one team
  - *This collaboration is open to other interferometers when they reach the appropriate sensitivity levels.*

- Possible new elements of the network
  - LCGT- proposed 3 km cryogenic detector in Kamioka mine (Japan)
  - AIGO- to be proposed 5 km detector at Gingin (Australia)
  - Also nascent interest in China, Russia, India

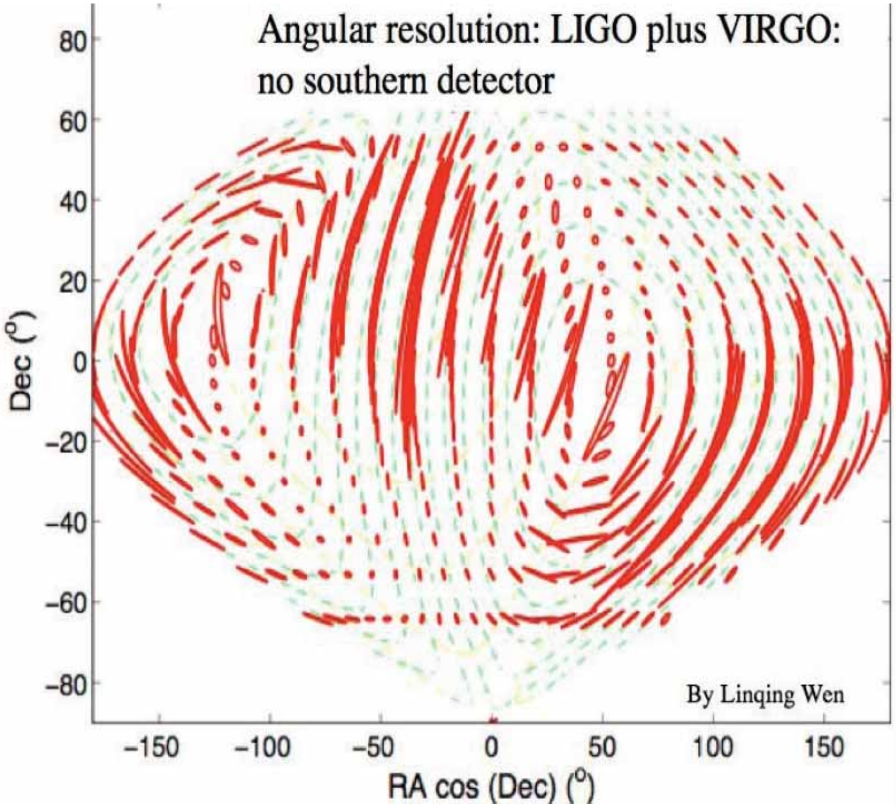
A global network of interferometers doing coherent observation-- *next decade and beyond*



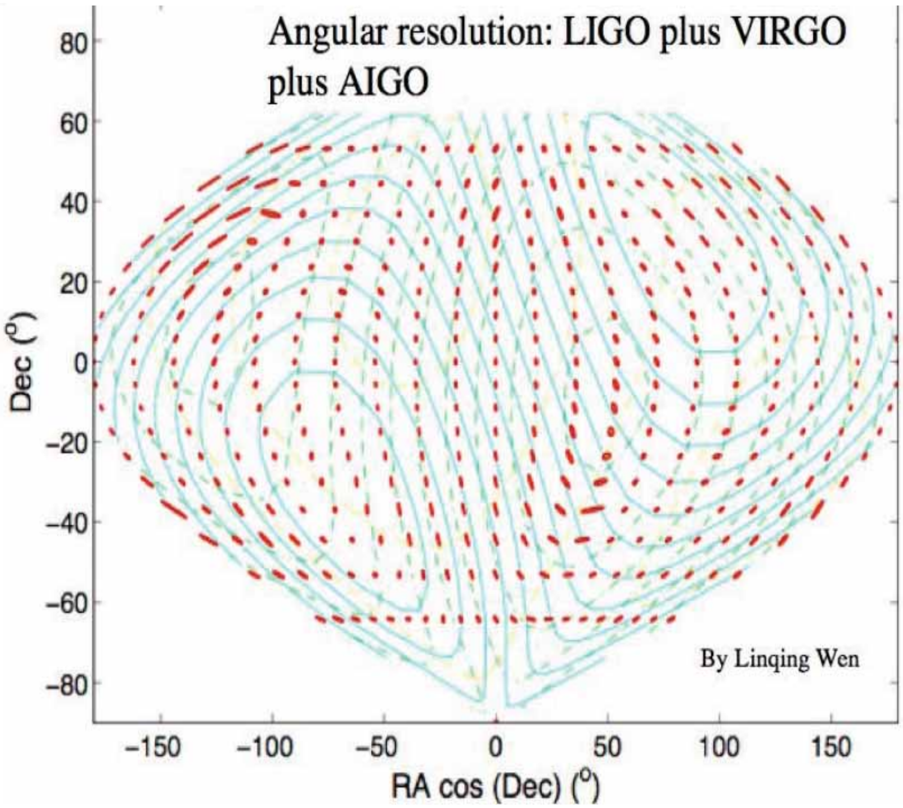
- **Detection confidence**
- **Source polarization**
- **Sky location**
- **Duty cycle**
- **Waveform extraction**

A detector in Australia comparable to LIGO and Virgo would significantly improve network's angular sensitivity

LIGO and Virgo only



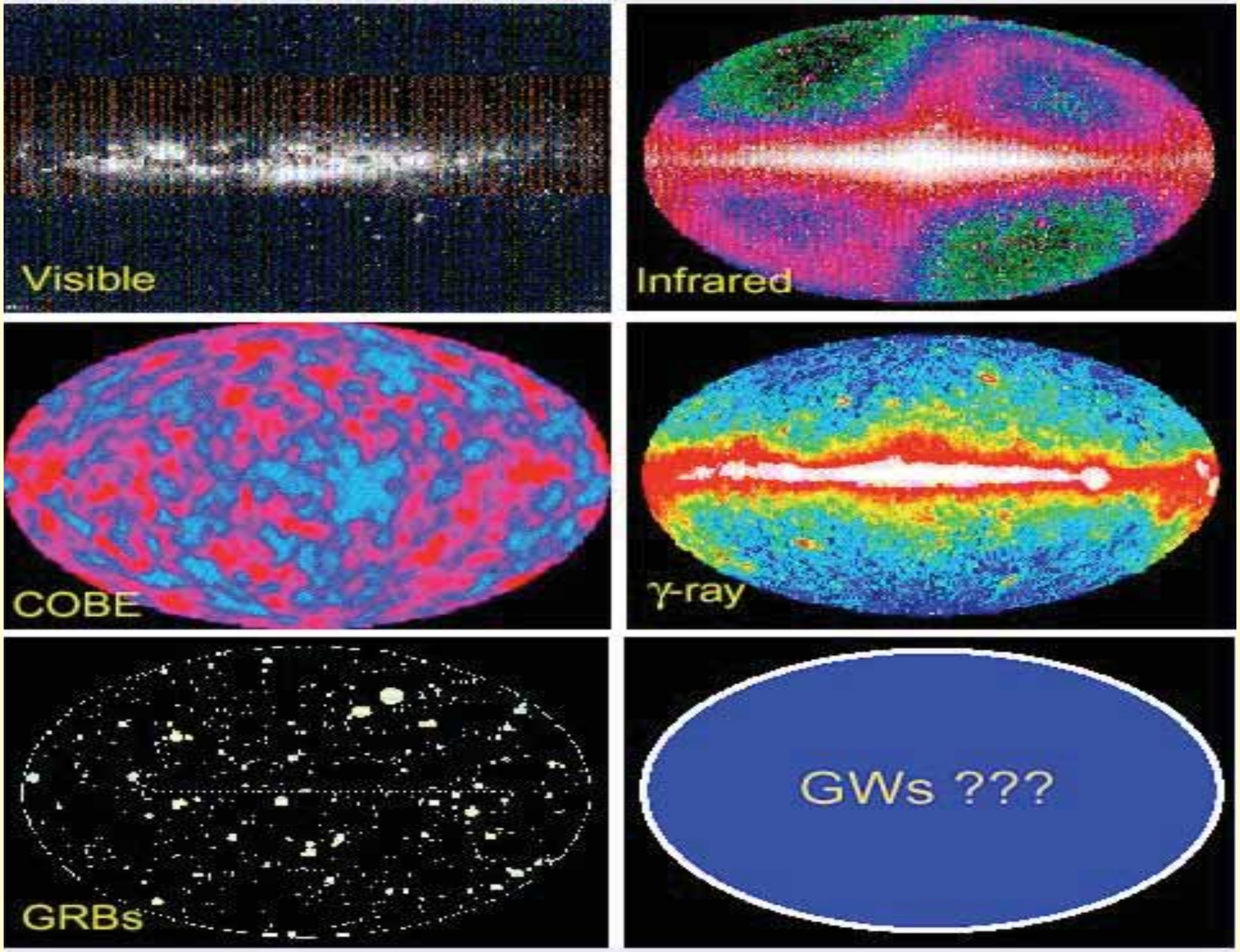
LIGO, VIRGO and AIGO (Australia)



Summary

- Gravitational waves will open a new window on the universe
- LIGO operates in science mode at design sensitivity- it works!
  - 1st long science run was a success; data being analyzed
  - 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 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--now joint data analysis by five interferometers
  - LIGO (3) (in US), Virgo (in Italy), GEO (in Germany)
  - And hope for others (e.g in Japan and Australia)

Ultimate scientific success…
New Instruments, New Field, the Unexpected…



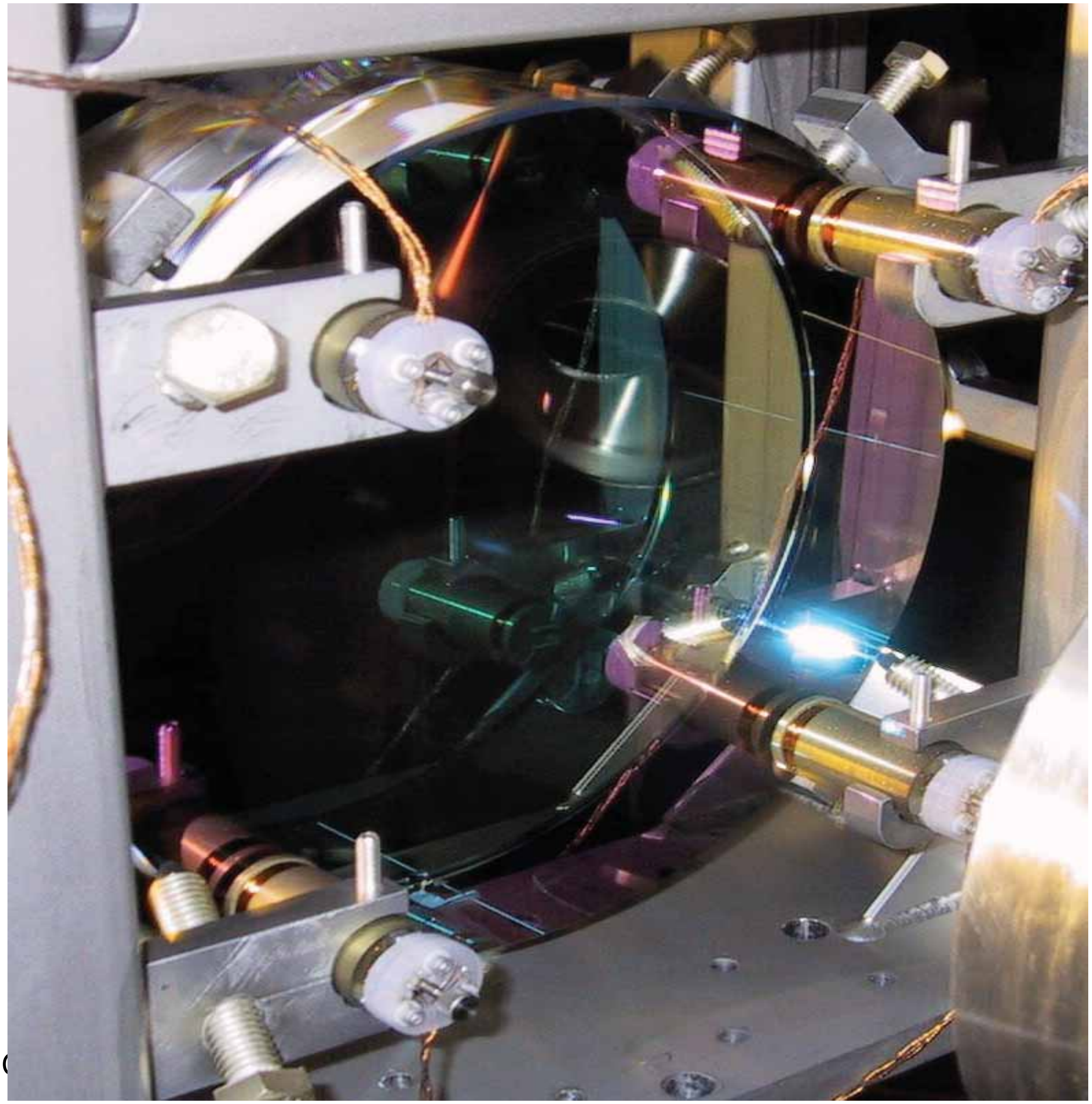
Backup slides

- Peter Saulson (Univ. of Syracuse)

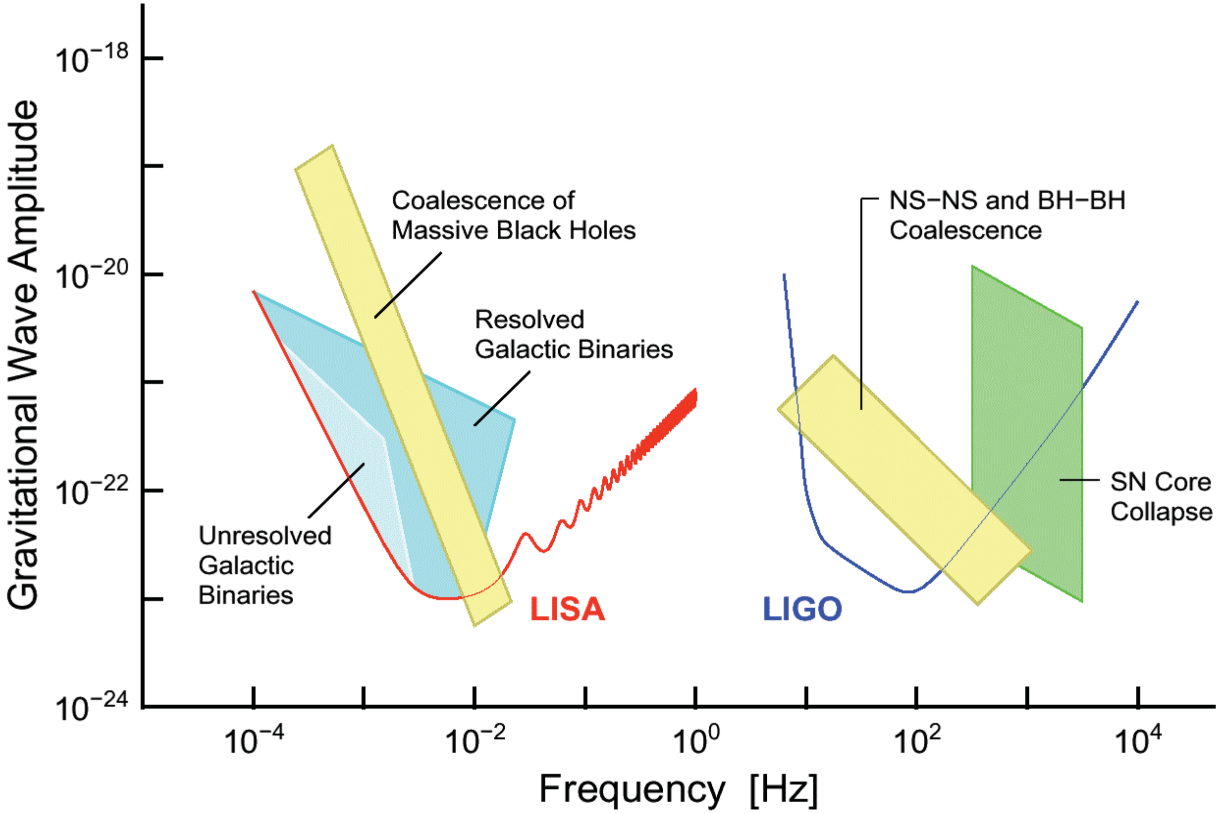
  If light waves are stretched by gravitational waves, how can we use light as a ruler to detect gravitational waves?

  Am. J. Phys. 65 (6), June 1997

Core optics and control actuators

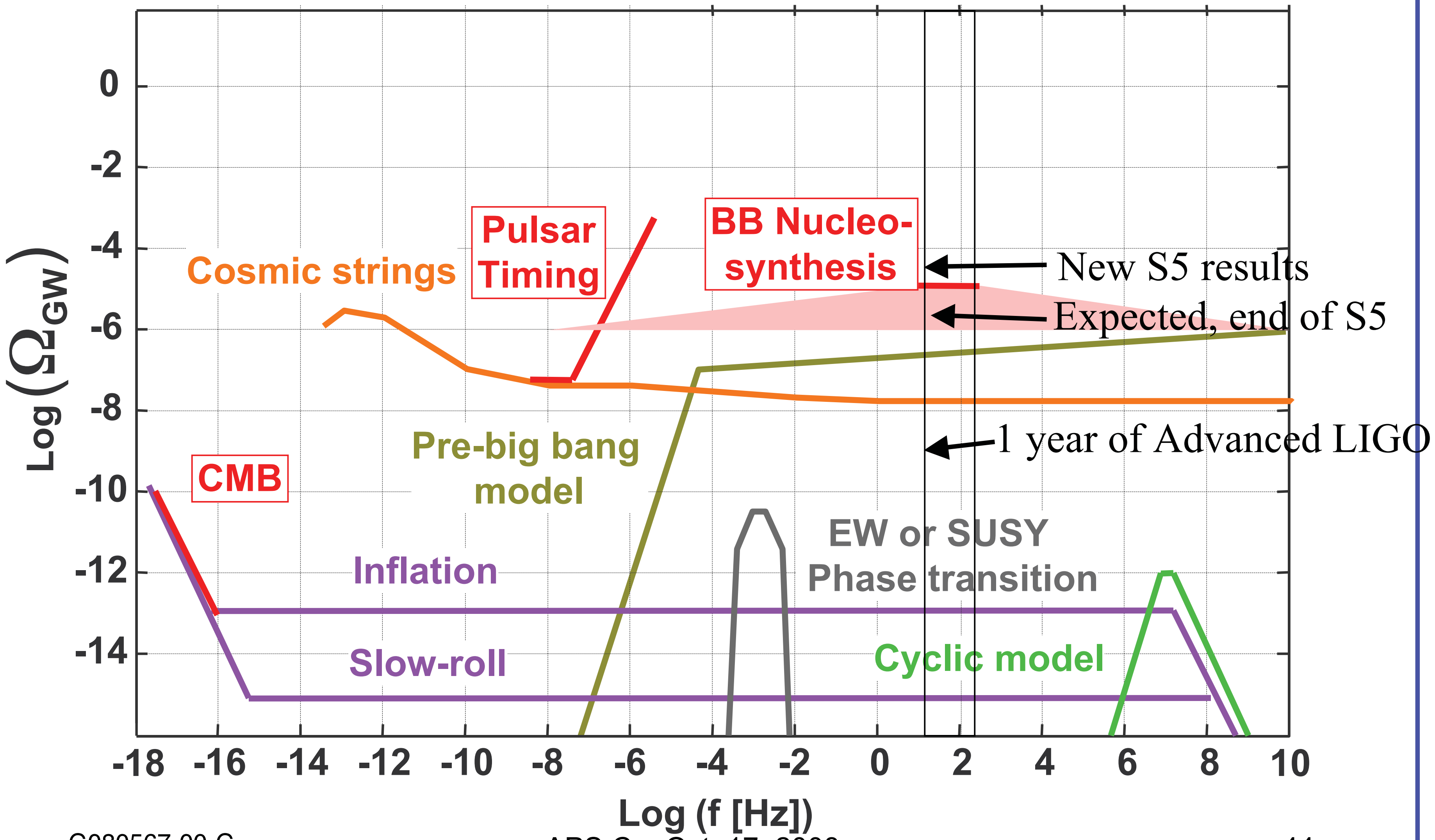


LIGO



10^{-18}
10^{-20}
10^{-22}
10^{-24}
Gravitational Wave Amplitude
10^{-4}
10^{-2}
10^{0}
10^{2}
10^{4}
Frequency [Hz]
Coalescence of Massive Black Holes
Resolved Galactic Binaries
Unresolved Galactic Binaries
LISA
LIGO
NS–NS and BH–BH Coalescence
SN Core Collapse

Stochastic sources including Big Bang
-- Predictions --



How can the needed sensitivity be reached

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

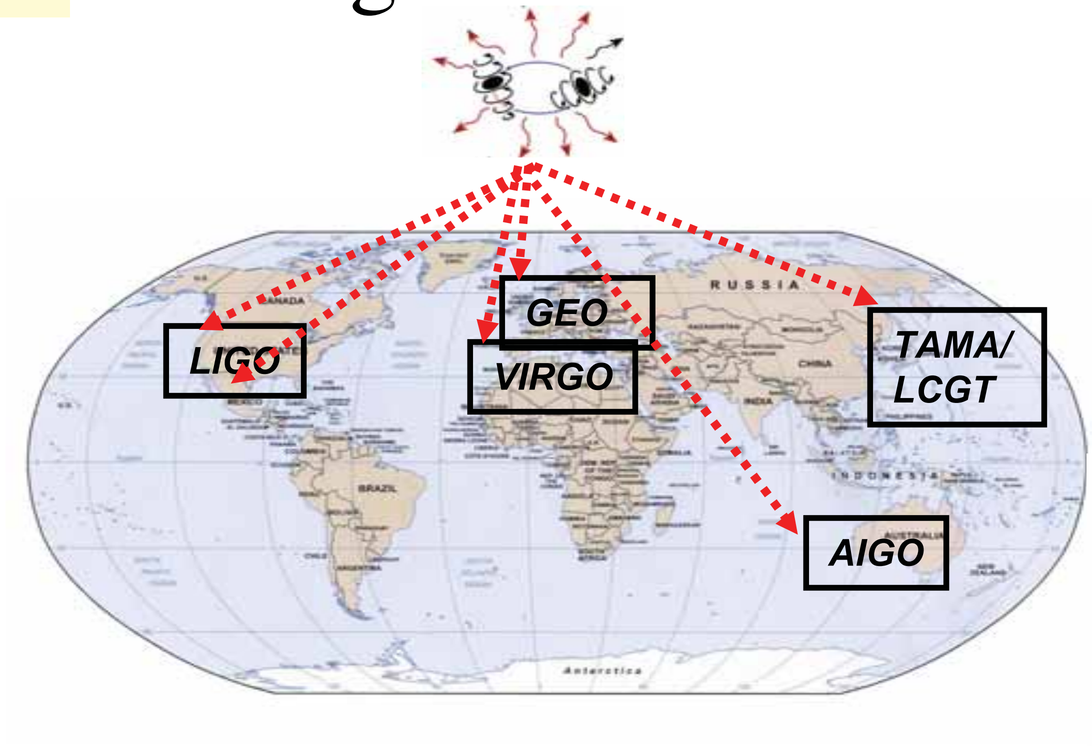
It’s counting statistics-- sqrt of number of photons during measurement

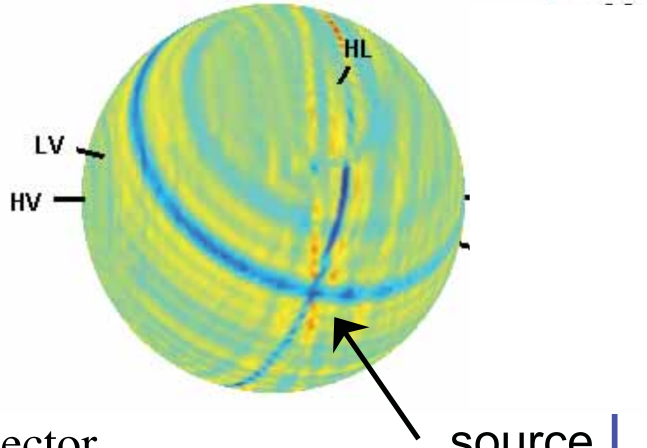
- 10^{21} photons/second at beam splitter where interference occurs
- Measurement time ~10^{-2} seconds (at 100 Hz)
- Effective arm length = 4 km * average number passes for each photon (b~50)

$$h = \frac{x}{L} \sim \frac{\overset{1 \times 10^{-6}\ \text{cm}}{\lambda}}{Lb\sqrt{\dot{N}\tau}}$$

h = 6x10^{-22} at 100 Hz

Triangulate to locate source on the sky



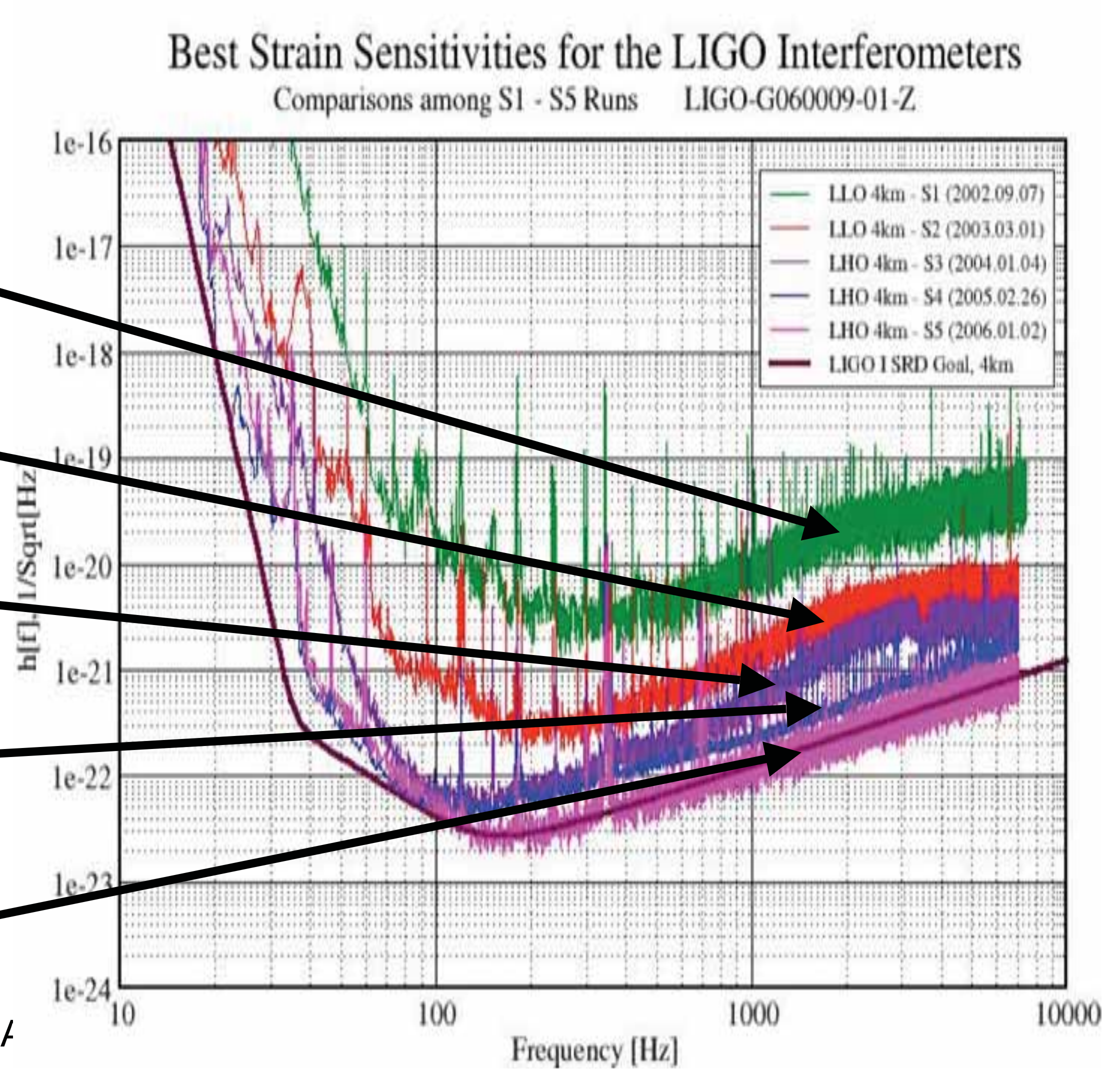


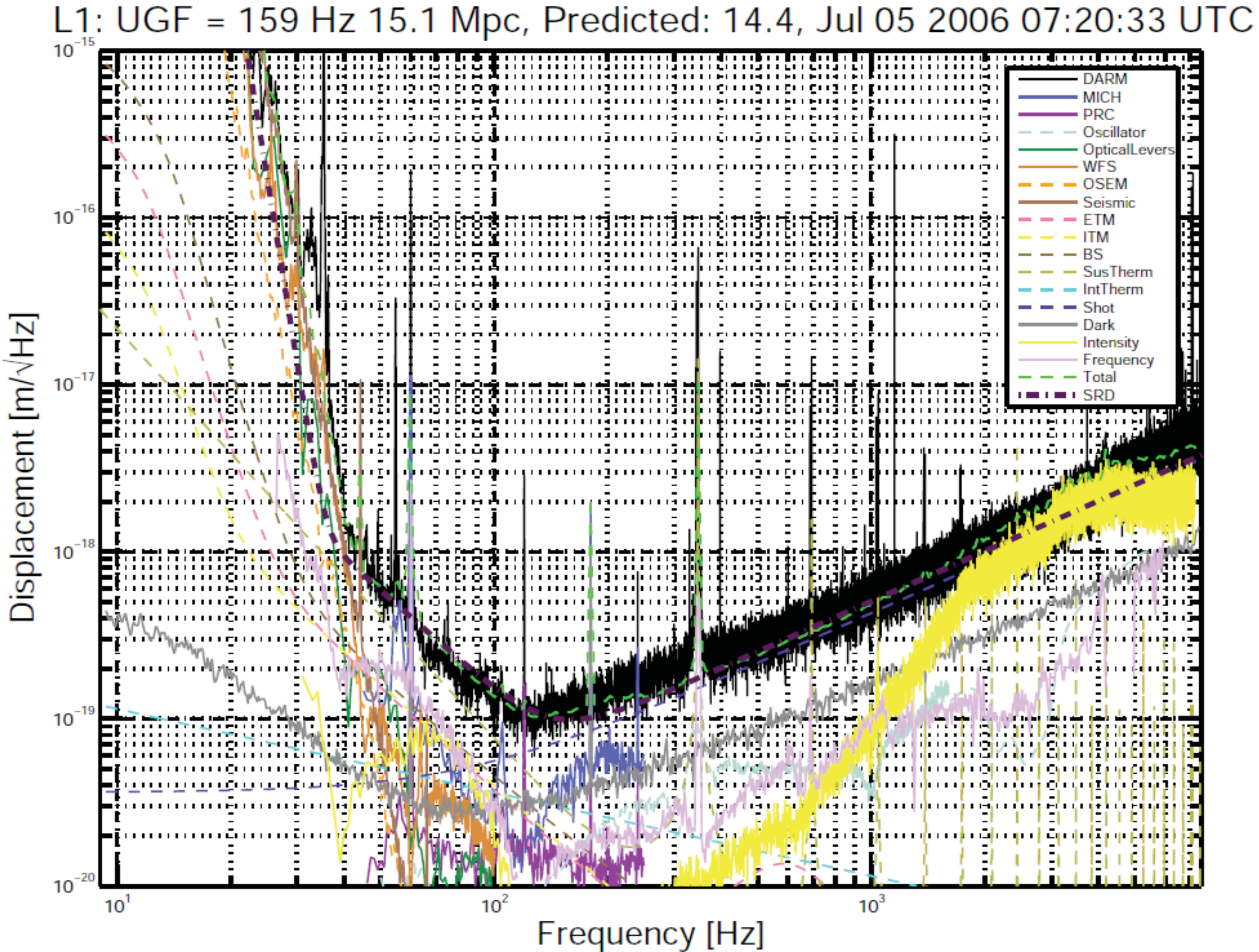
source location

- Measure relative time of arrival (TOA) of signal at each detector
- Any pair of detectors defines a circle on sky consistent it relative TOA
- 3 detectors define intersecting circles on the sky → source point on sky

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-Oct 07	2 years




L1: UGF = 159 Hz 15.1 Mpc, Predicted: 14.4, Jul 05 2006 07:20:33 UTC
Displacement [m/√Hz]
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
Frequency [Hz]
10^{1}
10^{2}
10^{3}
DARM
MICH
PRC
Oscillator
OpticalLevers
WFS
OSEM
Seismic
ETM
ITM
BS
SusTherm
IntTherm
Shot
Dark
Intensity
Frequency
Total
SRD

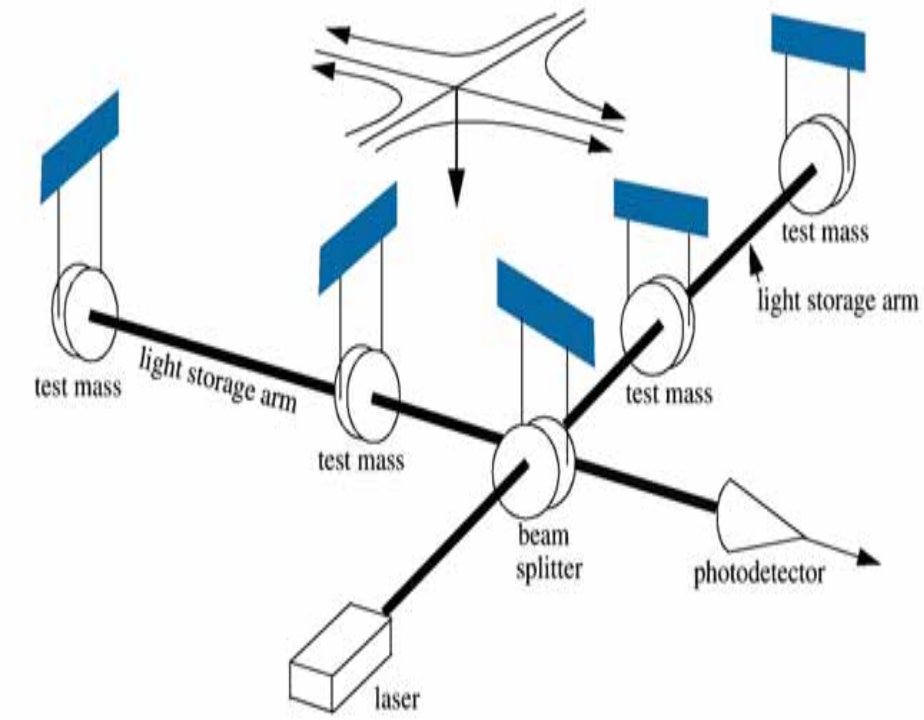
Detecting GWs with Precision Interferometry

- Suspended test masses (mirrors) act as “freely-falling” objects (at GW frequency) tied to their space-time coordinates

- A passing gravitational wave alternately stretches (compresses) space-time and thus the distance between mirrors.

- Interferometery is used to determine relative optical phase and thus relative distance between mirrors in the arms

- The differential stretch/compress of GW gives a time varying signal at the photo-detector

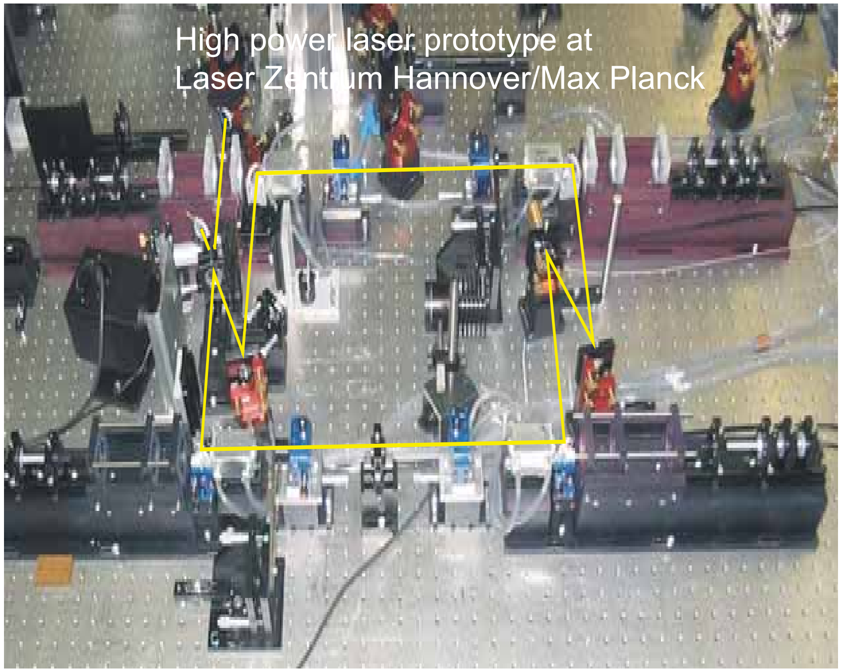


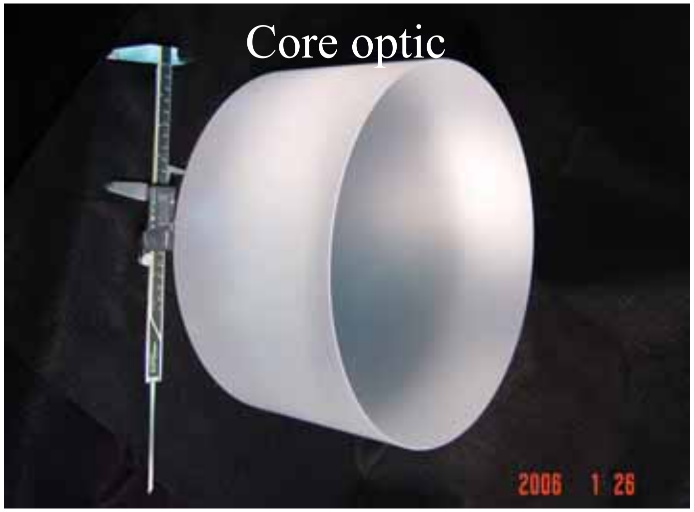
How do we avoid fooling ourselves?

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

Advanced LIGO prototype hardware


High power laser prototype at
Laser Zentrum Hannover/Max Planck


Core optic


Sensing & control @ 40m

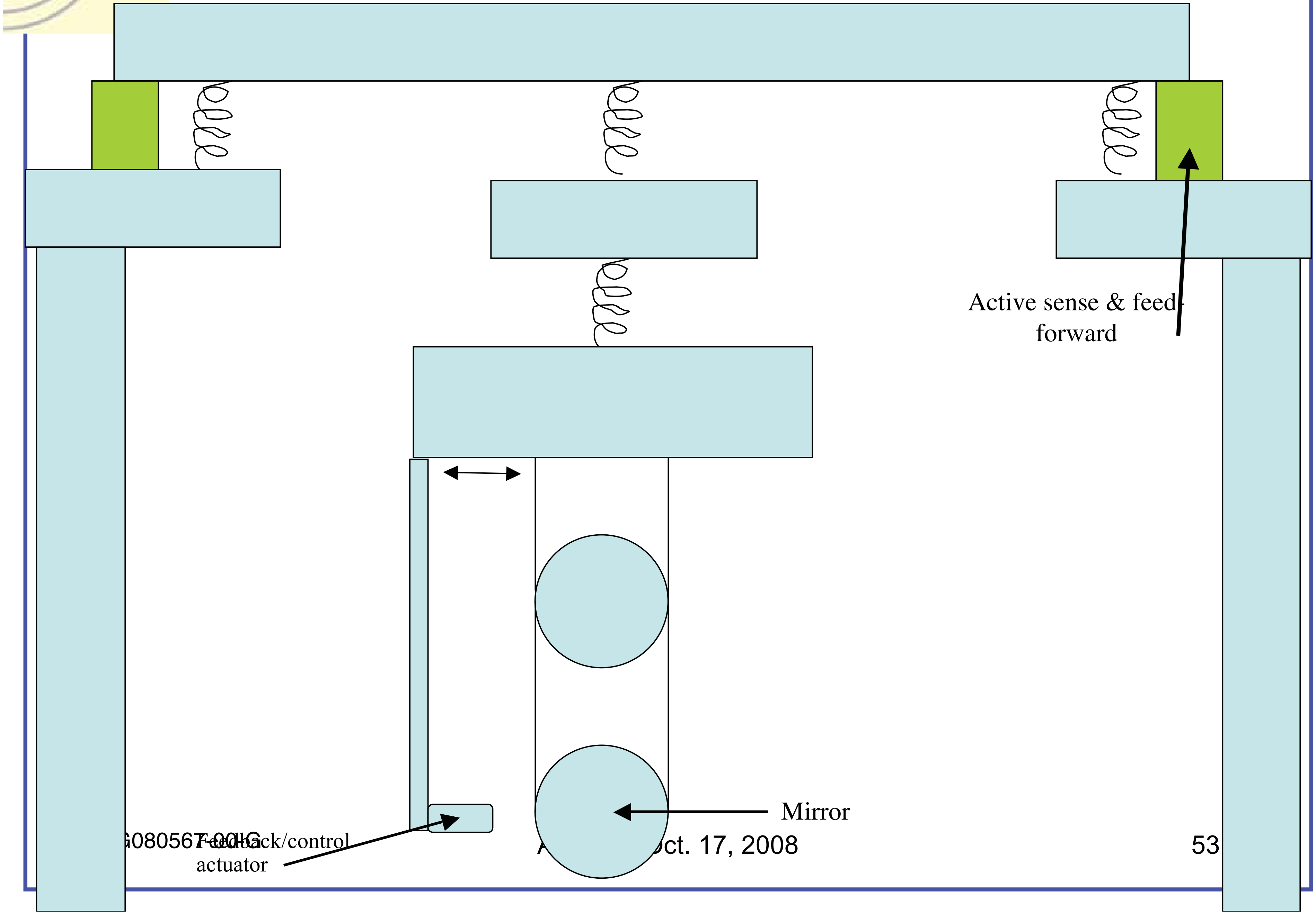
Damping seismic and other vibrations

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 ~10^{-7} between 1 Hz and 100 Hz

LIGO seismic isolation concept



The secret to damping thermal noise

- Test mass with enough mass (25kg) and large enough surface area to distribute thermal loading
- Construct test mass out of material (fused silica) with very high Q-factor at low frequency
  - Vibrations due to thermal energy cluster at this resonant frequency
  - And fall away in frequency as ~1/f

And many layers of feedback control of test masses

- Control common mode degrees of freedom; e.g. am lengths
- Control mirror motions at a few hertz (permanent magnets glued to mirrors and coils to actuate
- Control beam geometry in cavities (wavefront sensing)
- Control thermal compensation of thermal lensing (distortion due to heating)
- Etc, etc, etc

How can such accuracy be achieved with macroscopic objects?

- Large surface area -- can average over the motions of a huge numbers of atoms
- As long as surface is probed many times over a scale large compared to atomic sizes, and a huge numbers of times during each “measurement” to give a good average, extreme accuracies can be obtained.
- Each test mass (mirror) is probed by $\sim 10^{21}$ photons during each measurement period (~1/100 second) and each photon has a wavelength of ~1 micron; $\sim 10^{4}$ atomic diameters

A common question--why isn't the laser light also stretched and compressed by the gravitational wave so there's no net effect?

- Why is this different than the cosmic redshift where the wavelength of light is stretched as the universe expands?
  - In this case the propagation time of the photon is long compared to a measure of the stretching time of space
- Heuristic answers for gravitational waves

1. In LIGO a photon bounces between mirrors about 50 times before leaving the arm ⟶ path length of 200 km

   Wavelength of GW (@ 100 Hz) is 3 x 10^3 km

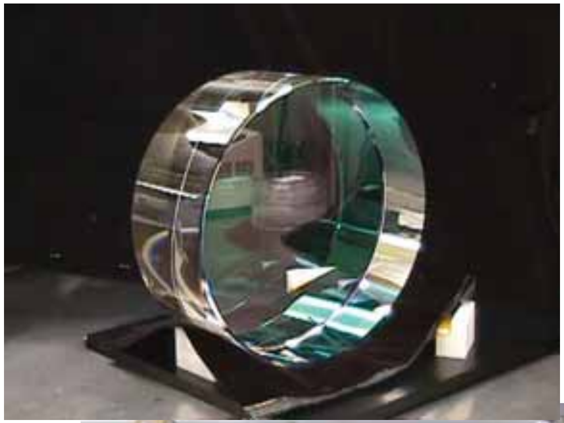
   So the travel time of a photon is only 1/15 of a GW cycle;

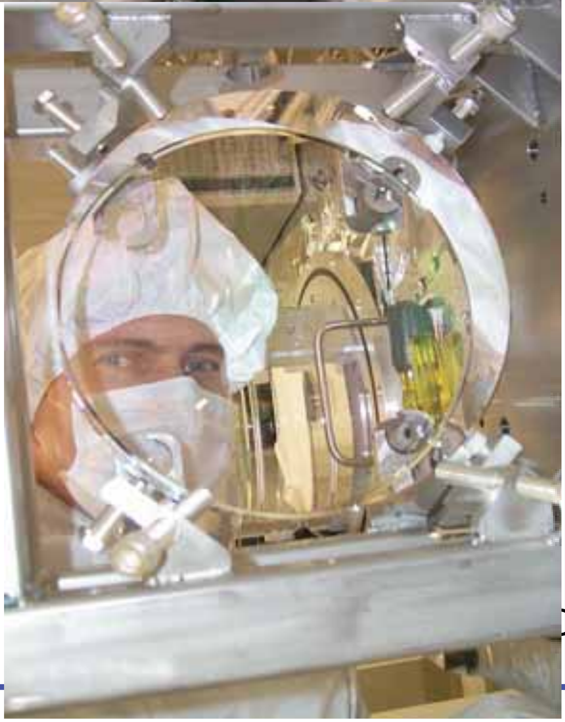
   Space doesn't stretch/compress much during the photon propagation time.

   (Another way to look at it-- c is constant, so transit time by photon between mirrors is measure of distance. Transit time difference between arms gives interference phase at beam splitter.-- photon is clock, not ruler)

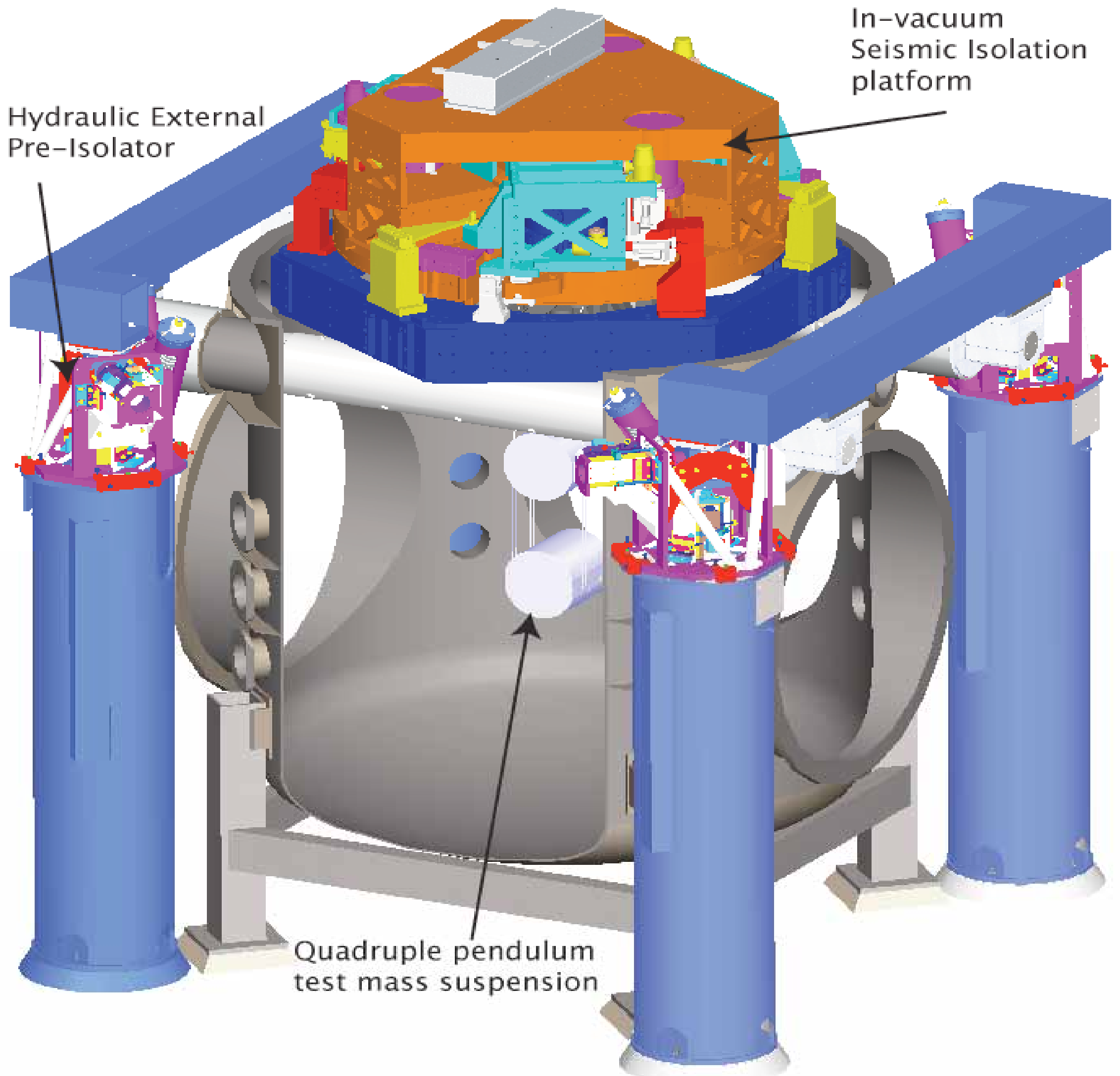
- More rigorous answer-- see P. Saulson, "If light waves are stretched by gravitational waves, how can we use light as a ruler to detect gravitational waves?," Am. J. Phys. 65, 501–505 (1997).

Some more LIGO Hardware





Advanced LIGO seismic isolation system



preliminary

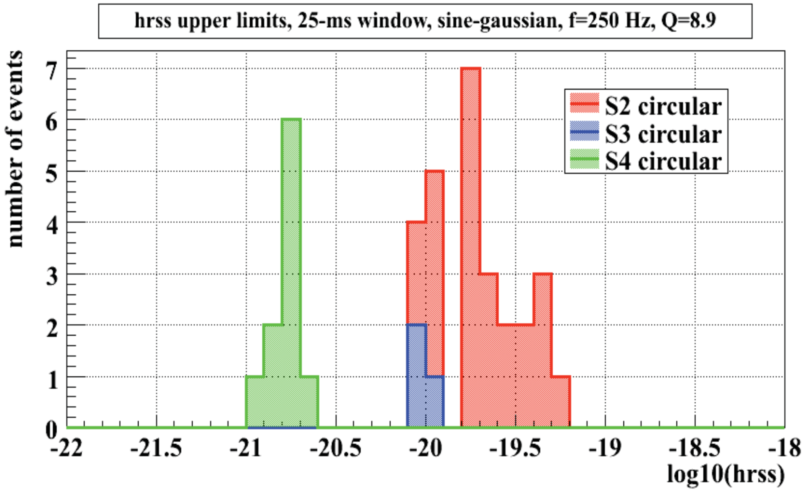
Examples of triggered Searches for GW Bursts

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: **$E_{GW} \sim 0.3\ M_{sun}$** at 20 Mpc

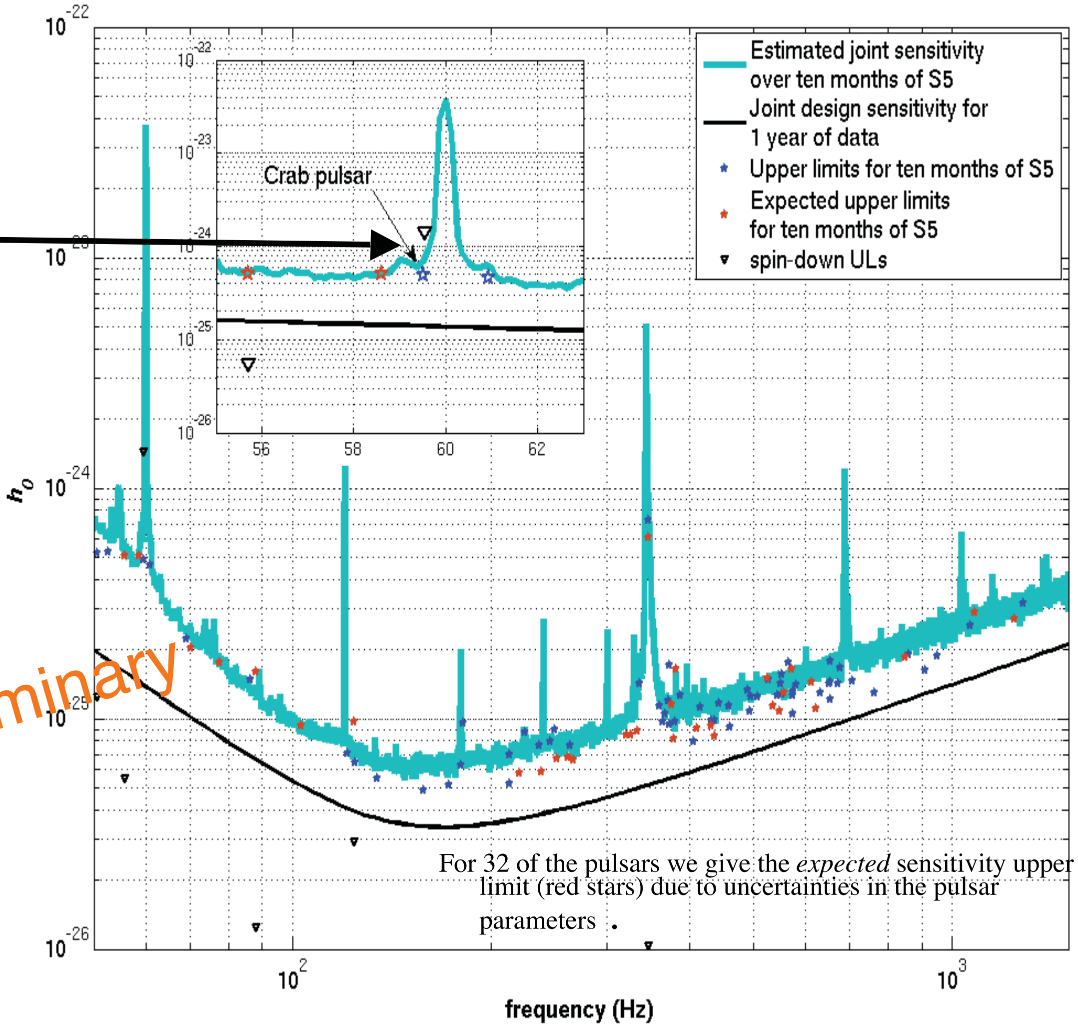


Search for known pulsars- preliminary

- 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



For 32 of the pulsars we give the *expected* sensitivity upper limit (red stars) due to uncertainties in the pulsar parameters .

Lowest GW strain upper limit:

PSR J1802-2124

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

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

Lowest ellipticity upper limit:

PSR J2124-3358

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

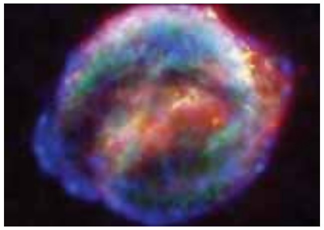
$\varepsilon < 1.1\times10^{-7}$

Pulsar timings provided by the Jodrell Bank pulsar group

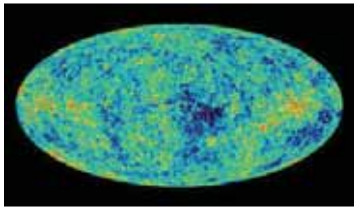
When will we see something?

Predictions are difficult… especially about the future (Y. Berra)

- Rotating stars: we know the rates,
  but not the amplitudes: how lumpy are they?



- Supernovae, gamma ray bursts:
  again rates known, but not amplitudes…



- Cosmological background:
  model dependent, but predicted strengths are low…

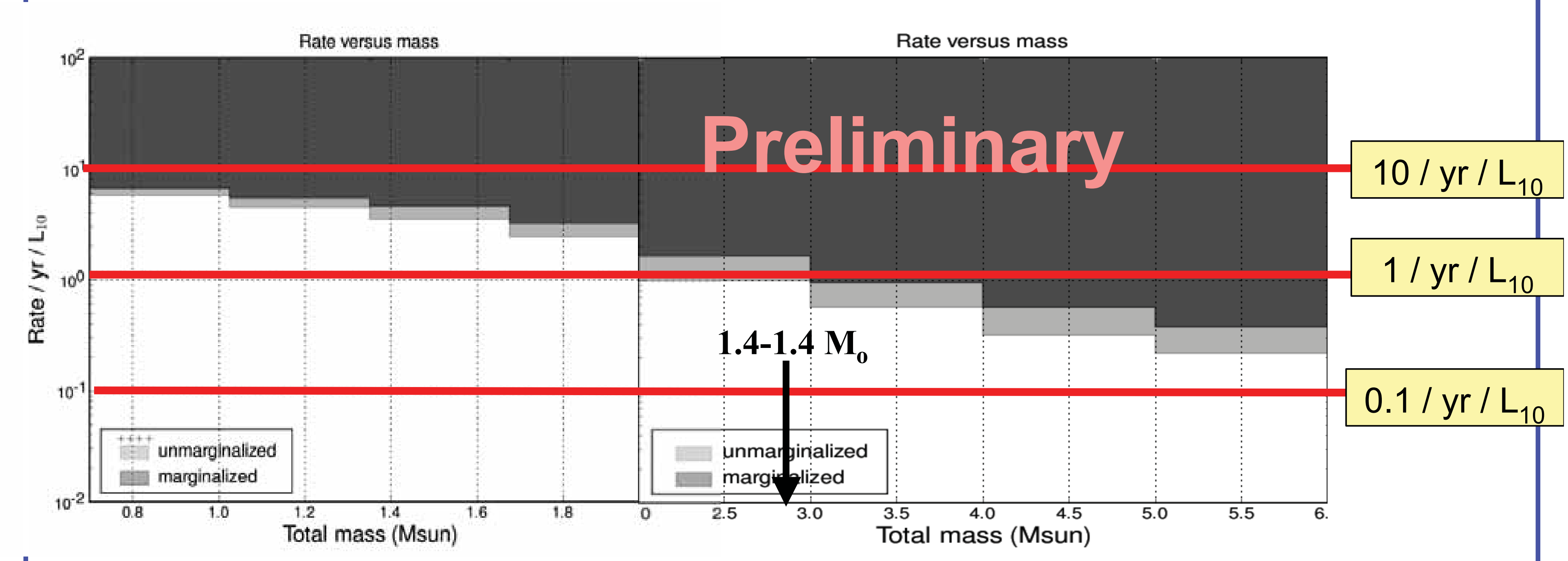
- Binary black holes:
  amplitude is known, but rates and populations
  highly unknown… Some estimates from GRBs promise
  S5 results will be interesting!
- Binary neutron stars:
  amplitude is known, and galactic rates and population can be estimated!
  Initial LIGO most likely rate: ~1/100 yrs.

Slide with inspiral limits vs mass of pair

S4 upper limits-compact binary coalescence

- Rate/year/L_{10} vs. binary total mass

  $L_{10} = 10^{10}\ L_{\mathrm{sun,B}}$ (1 Milky Way = 1.7 L_{10})
- Dark region excluded at 90% confidence.



10 / yr / L_{10}

1 / yr / L_{10}

0.1 / yr / L_{10}

1.4-1.4 M_o

0.8-6.0 M_{sun}