LIGO: Status of instruments and observations

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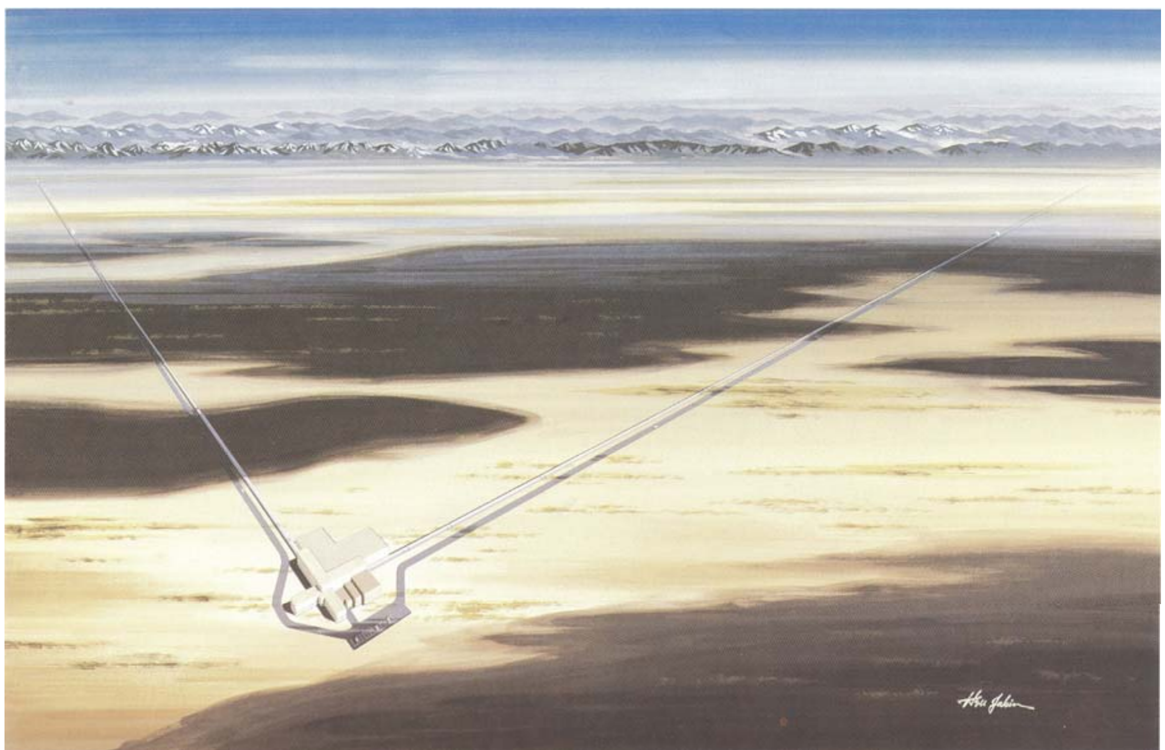
For the LIGO Scientific Collaboration

LIGO:
1989 Proposal to the US NSF

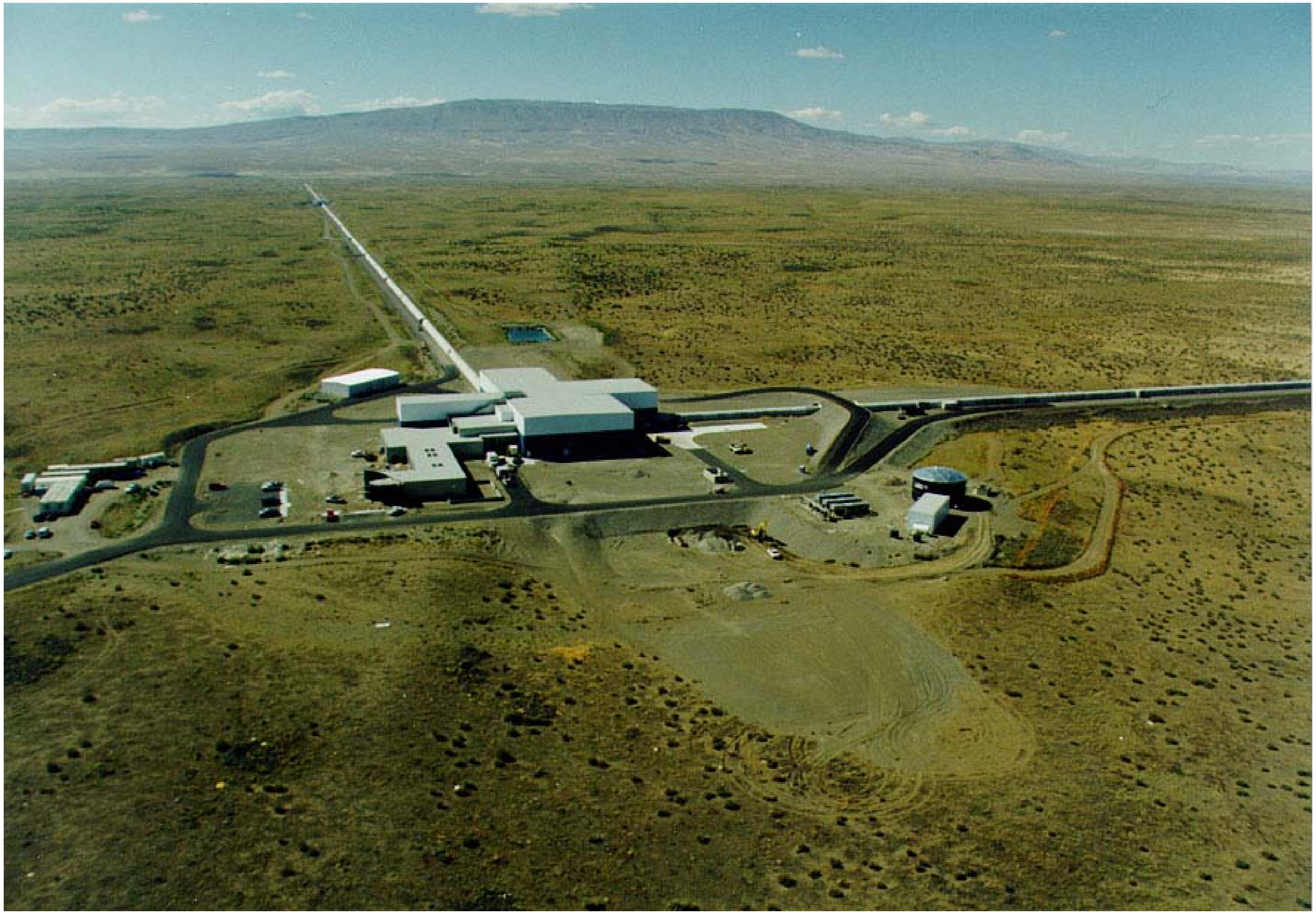
PREFACE

This proposal requests support for the design and construction of a novel scientific facility—a gravitational-wave observatory—that will open a new observational window on the universe.

The scale of this endeavor is indicated by the frontispiece illustration, which shows a perspective of one of the two proposed detector installations. Each installation includes two arms, and each arm is 4 km in length.

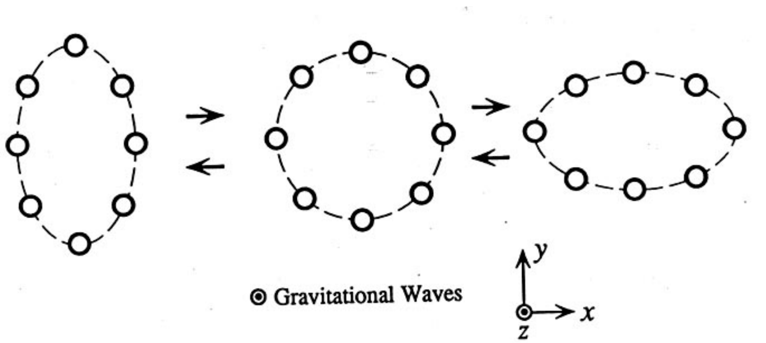


LIGO:
Today, Washington state…

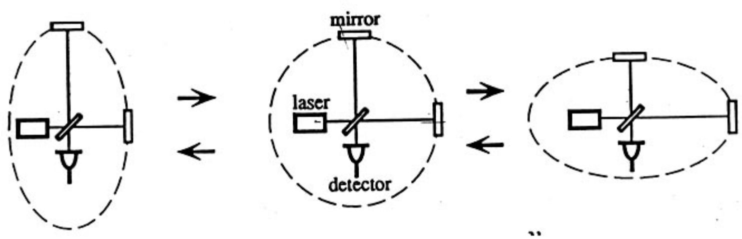


…LIGO in Louisiana

Gravitational Waves



Gravitational waves are quadrupolar distortions of distances between freely falling masses: “ripples in space-time”

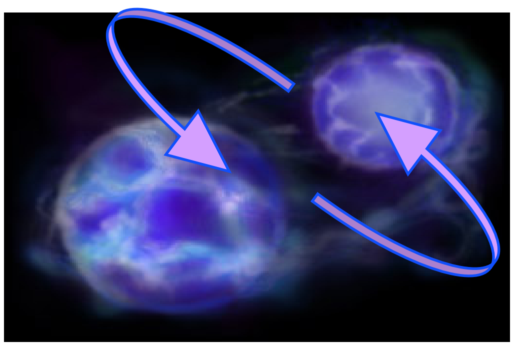


Michelson-type interferometers can detect space-time distortions, measured in “strain” $h=\Delta L/L$.

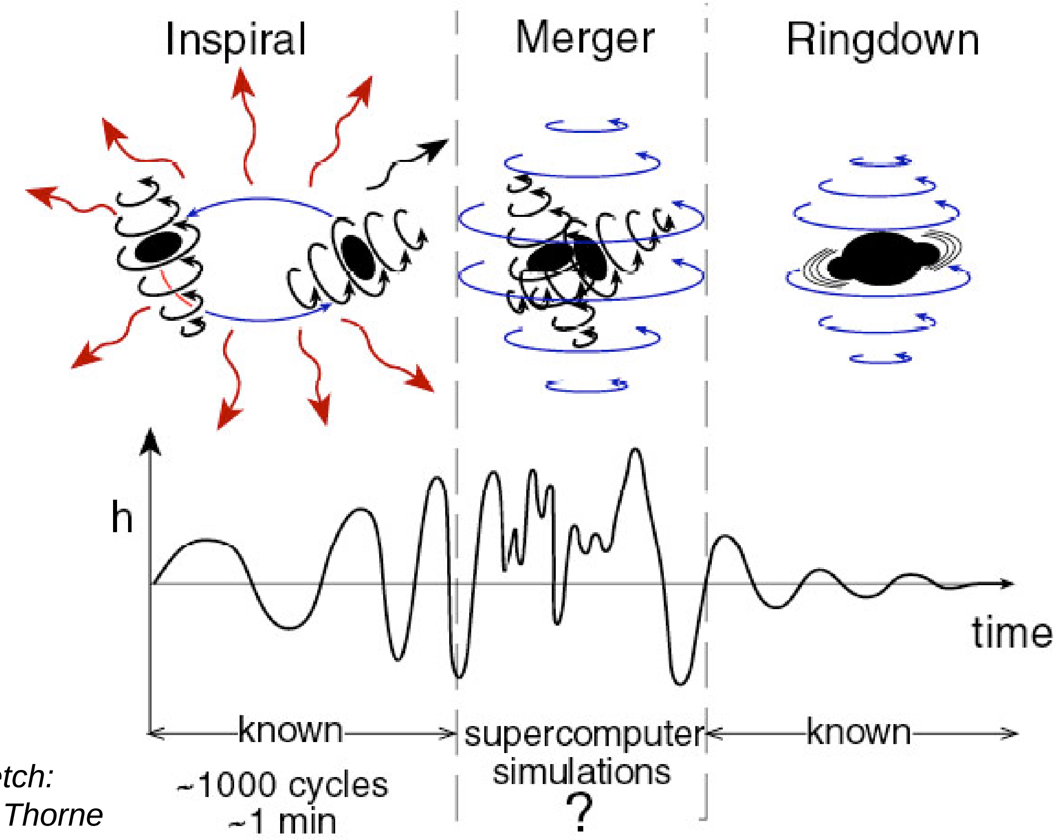
Amplitude of GWs produced by binary neutron star systems in the Virgo cluster have $h=\sim L/L\sim 10^{-21}$

What kinds of signals?

- E.g., inspiral and merger of neutron stars or black holes
- Early ‘chirp’ and resulting black hole ‘ringing’ are well known and a good source for templates
- Can learn about the complicated GR in the middle…



Credit: Jillian Bornak

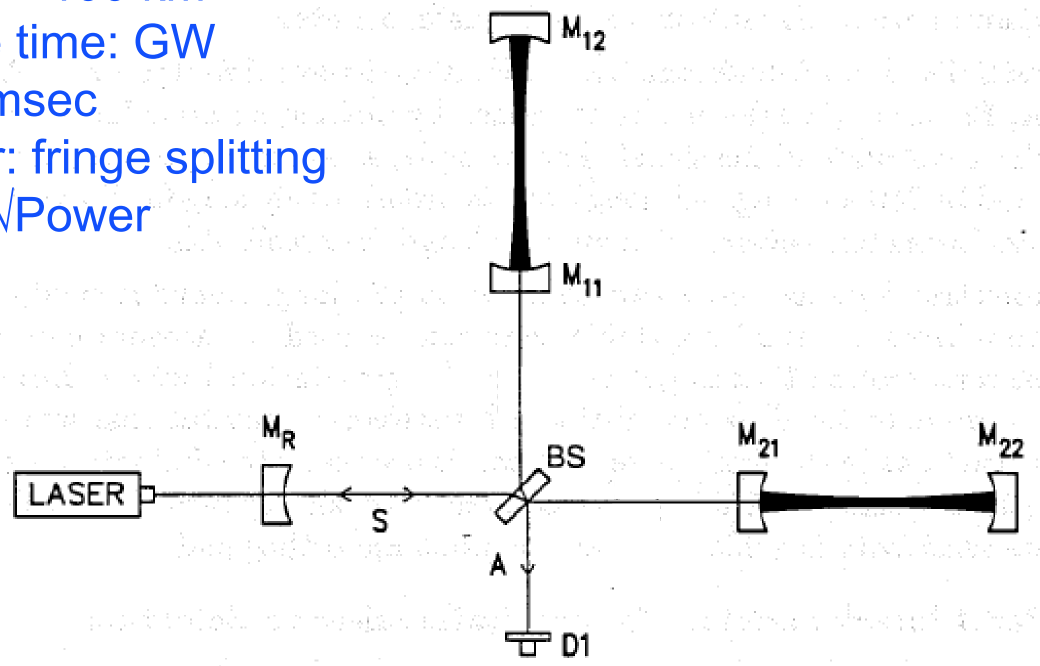


Sketch: Kip Thorne

A LIGO Detector, 1989 Proposal

Important scaling laws:

1) Length: λ_{GW} ~ 100 km
2) Arm storage time: GW period ~10 msec
3) Laser power: fringe splitting precision ~ √Power



The LIGO Detectors: a bit more detail

$h = \Delta L/L$

L ~ 4 km

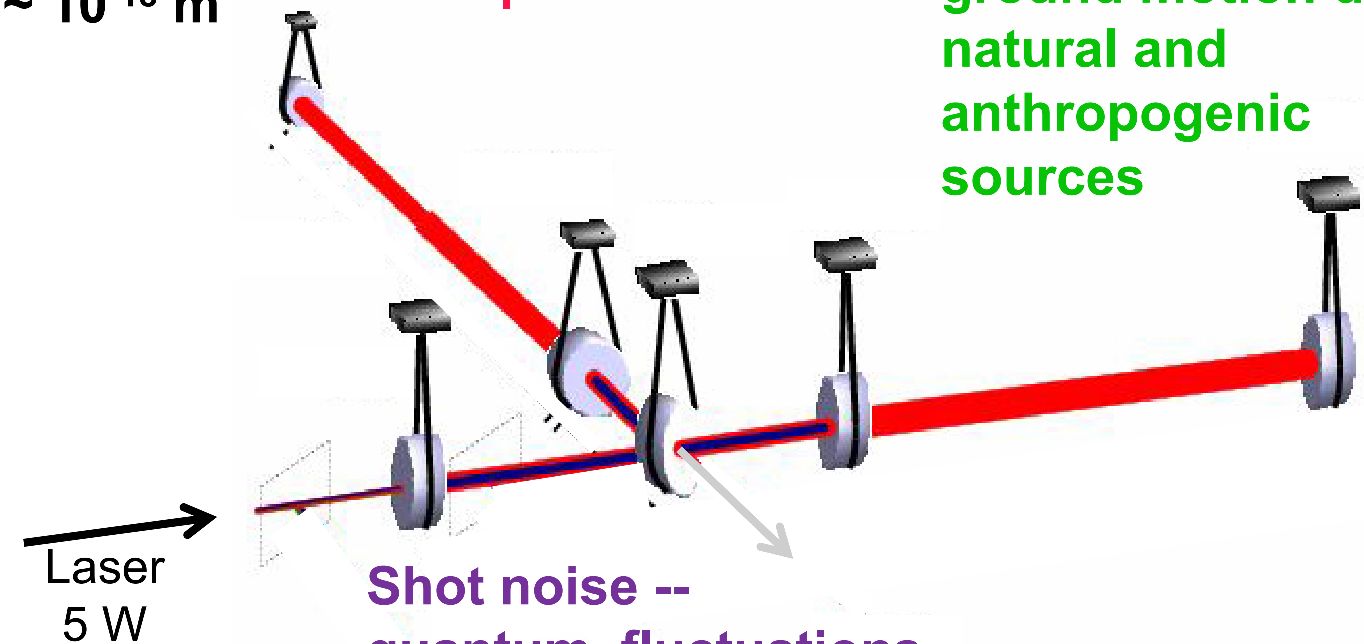
We need $h \sim 10^{-21}$

We have L ~ 4 km

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

Thermal noise -- vibrations due to finite temperature

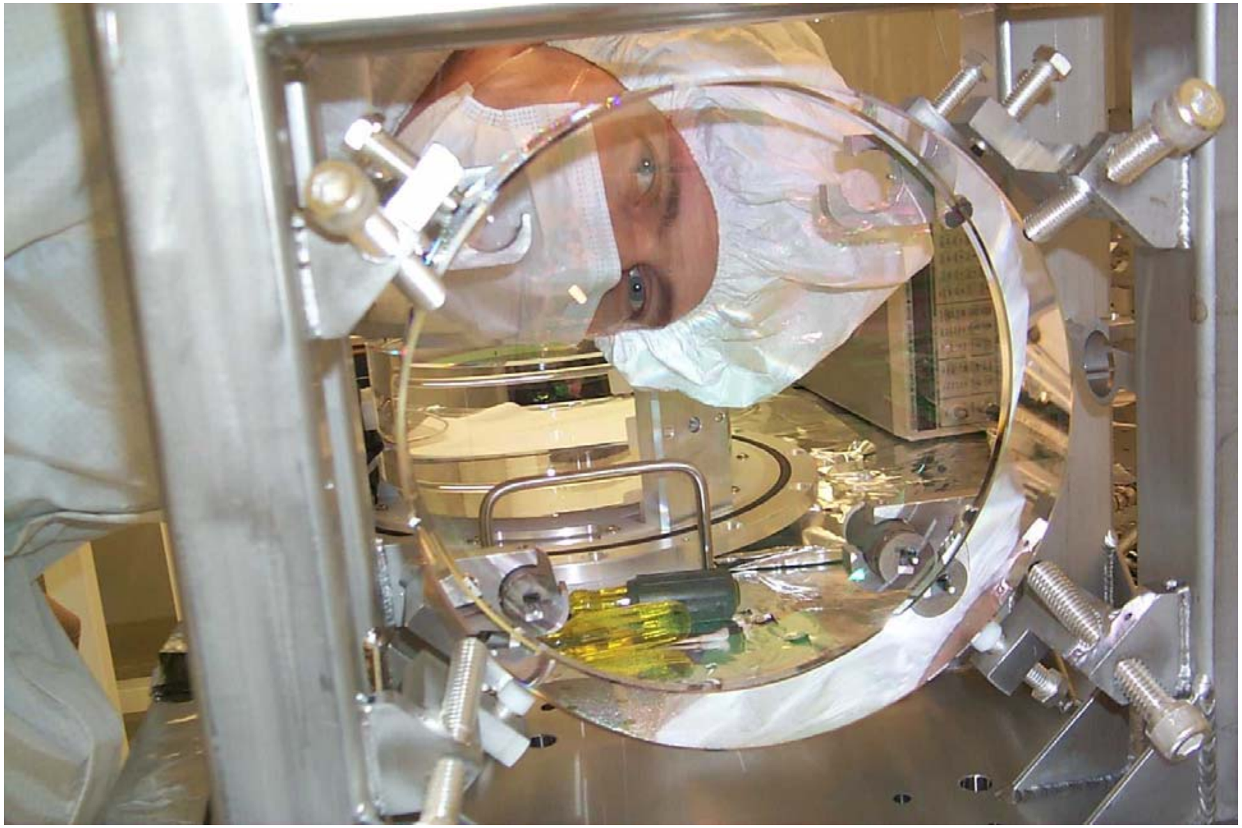
Seismic motion -- ground motion due to natural and anthropogenic sources



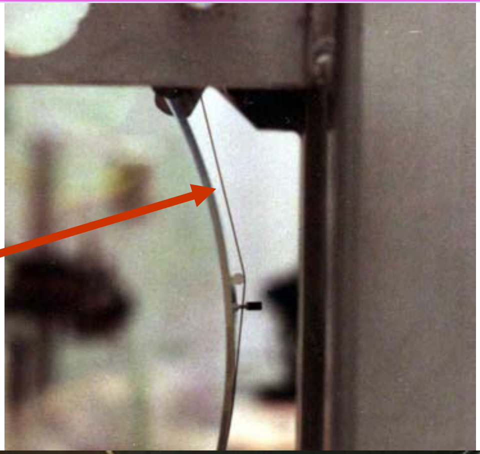
Shot noise -- quantum fluctuations in the number of photons detected

Test Masses

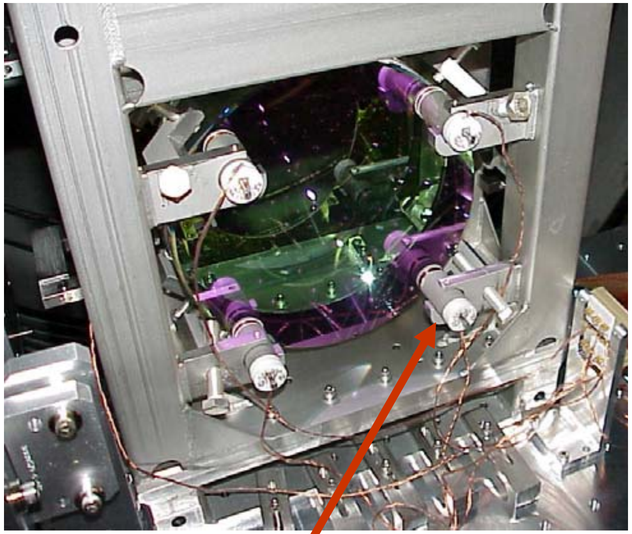
Fused Silica, 10 kg, 25 cm diameter and 10 cm thick
Polished to $\lambda/1000$ (1 nm)



Test mass suspensions



Optics suspended as simple pendulums

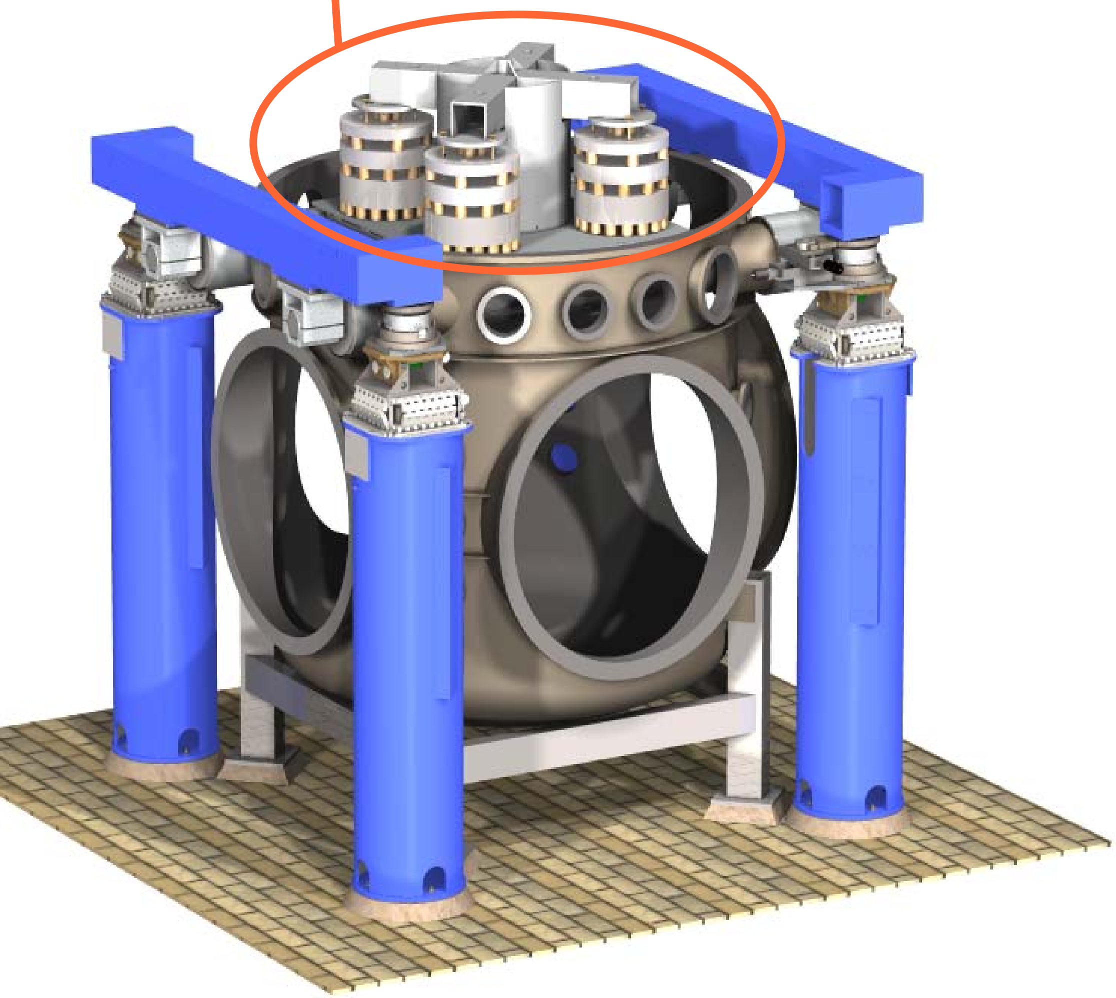


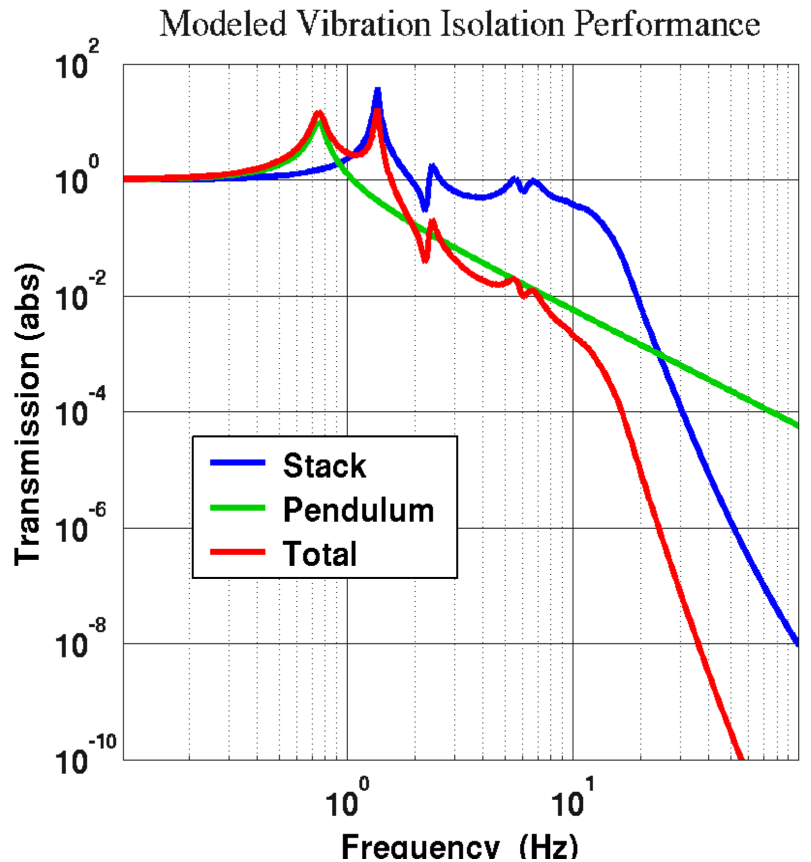
Shadow sensors & voice-coil actuators provide damping and control forces

LIGO

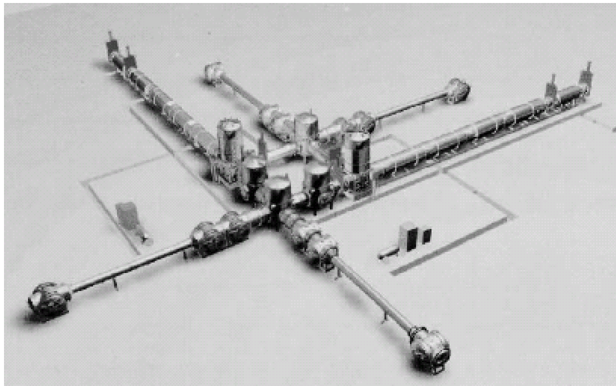
Seismic Isolation

stack of
mass-springs





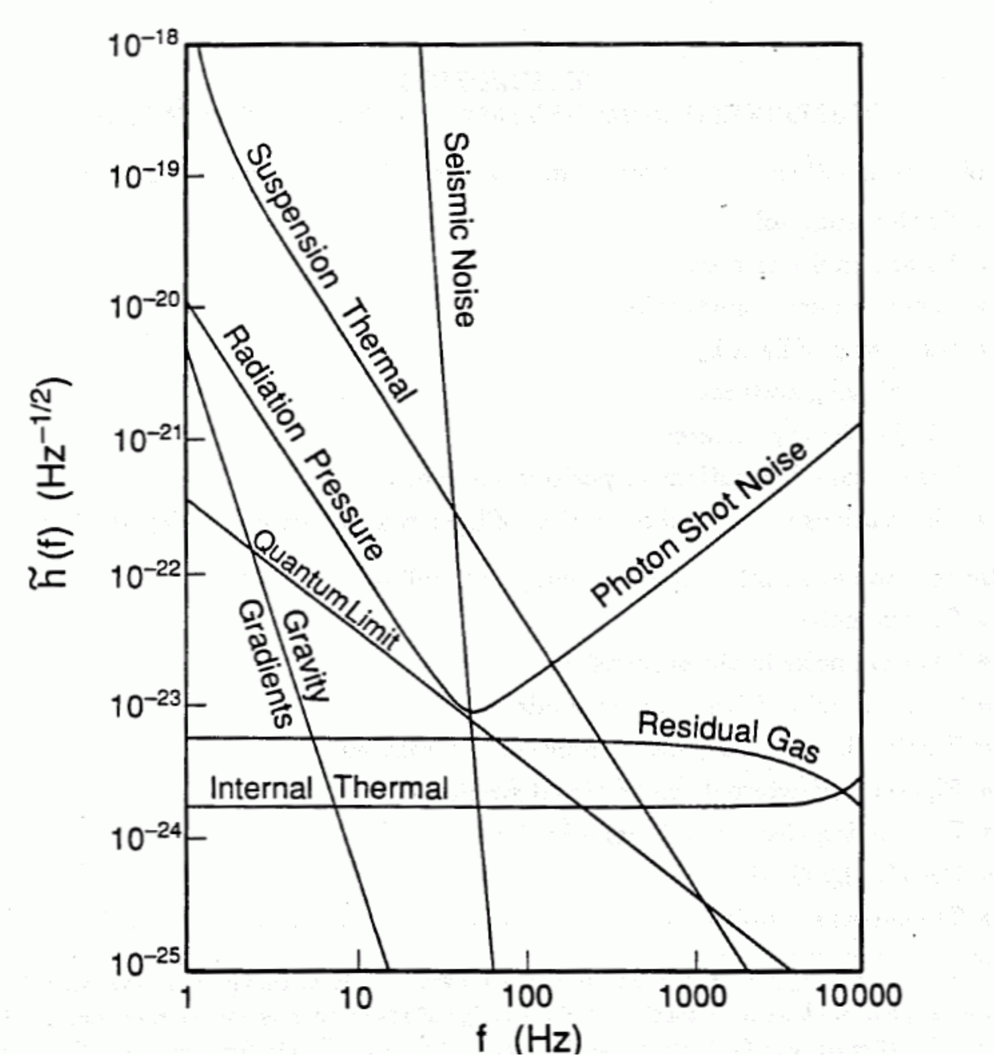
LIGO Vacuum Equipment



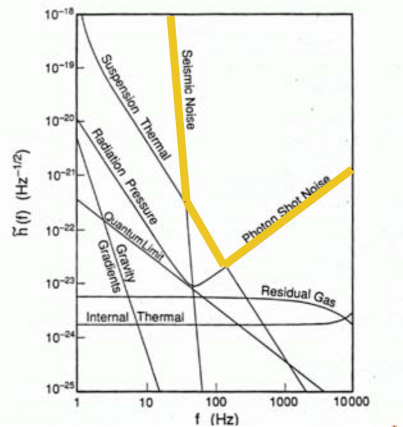
LIGO Beam Tube

- 1.2 m diameter
  - Multiple beams can be accommodated
  - Optimum also for cost considering pumping
- Aligned to within mm over km (correcting for curvature of the earth)
- Total of 16km fabricated with no leaks
- Cover needed (hunters…)

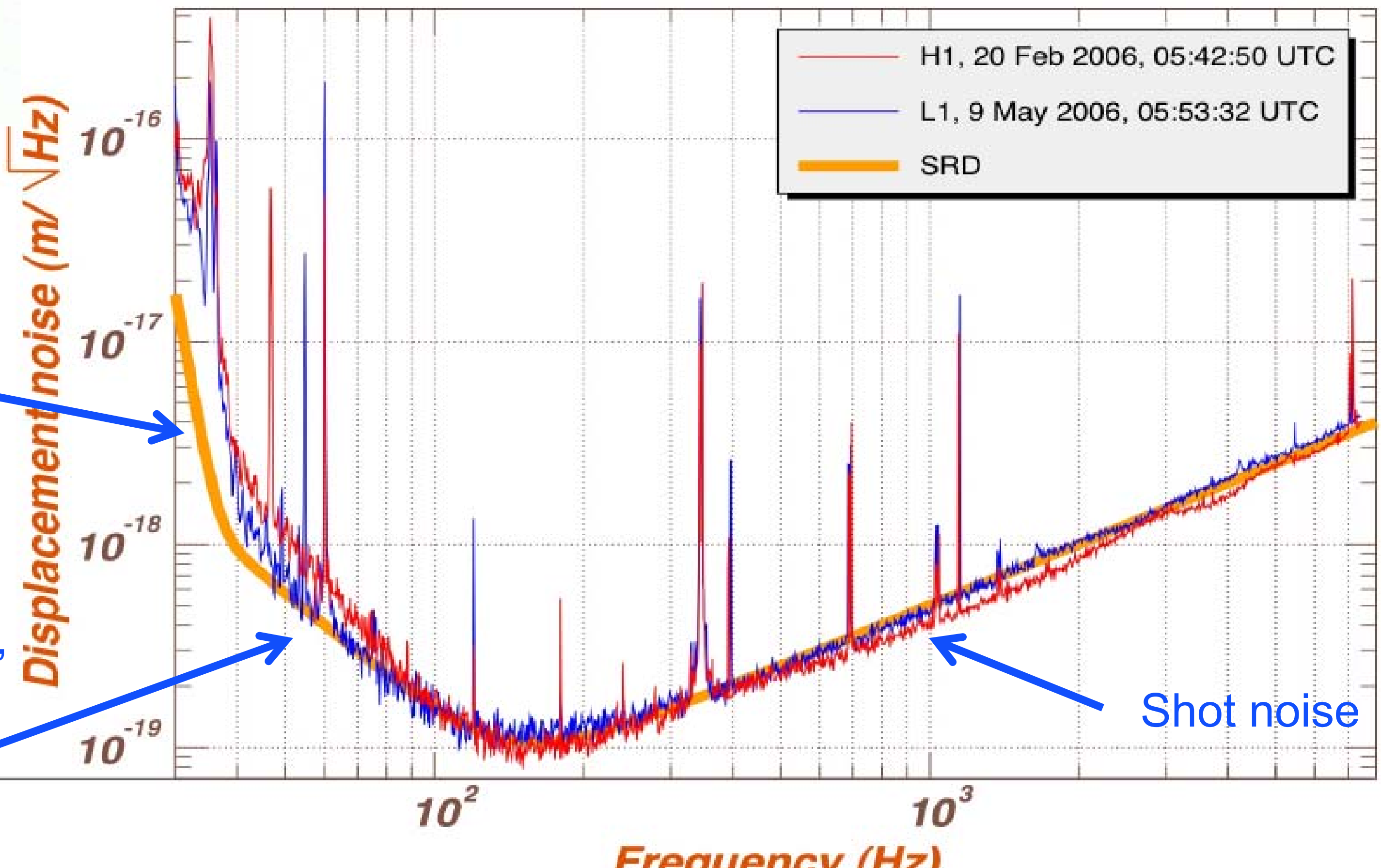
The planned sensitivity of LIGO, 1989 Proposal



The current sensitivity of LIGO



- SRD: Science Requirements Document target
- Initial LIGO performance requirement: $h_{RMS} \leq 10^{-21}$ over 100Hz Bandwidth
- Current performance ~ $h_{RMS} \approx 4 \times 10^{-22}$
- **Success!**



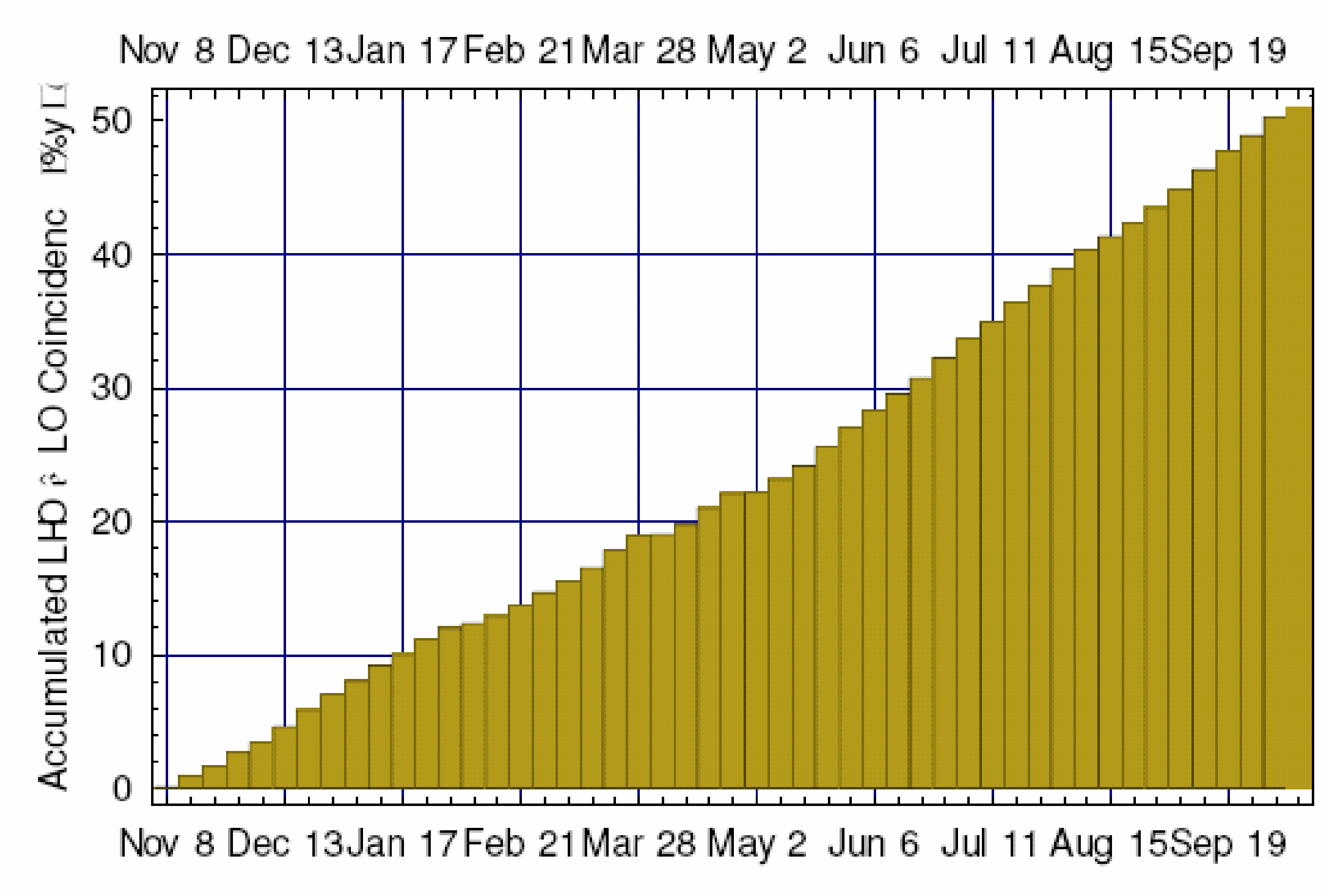
Seismic noise

Many contributors, maybe including thermal noise

Shot noise

LIGO is observing

- Present S5 Science Run to collect one integrated year of data
- Roughly 70% duty cycle; more than 50% complete!



LIGO in the larger context, 1989 Proposal

B. National Context

We envision the LIGO as an initial quasi-experimental project, focused upon the invention, development, verification, and first use of technologies for laser interferometer gravitational-wave astronomy, with a gradual transition to a mature facility. The early stages of evolution will be conducted primarily by the Caltech/MIT LIGO team, followed by a gradual transition to broader-based national and international participation.

Caltech and MIT, with the principal support of the National Science Foundation (NSF), have invested close to two decades of effort in developing a laser interferometer for gravitational-wave astronomy. The two institutions are committed to continuing a vigorous program leading to the establishment of the LIGO and gravitational-wave astronomy, and subsequently developing, operating, and maintaining LIGO under NSF sponsorship in the interest of the scientific community.

Completion of the LIGO, bringing it to operational readiness in the course of the early search for gravitational waves and, ultimately, conversion to a broadly accessible facility, will require the full commitment and expertise of the Caltech/MIT team. It is expected that once a firm NSF commitment towards construction and operation of the LIGO exists, a broader-based national scientific community will be interested in participation.

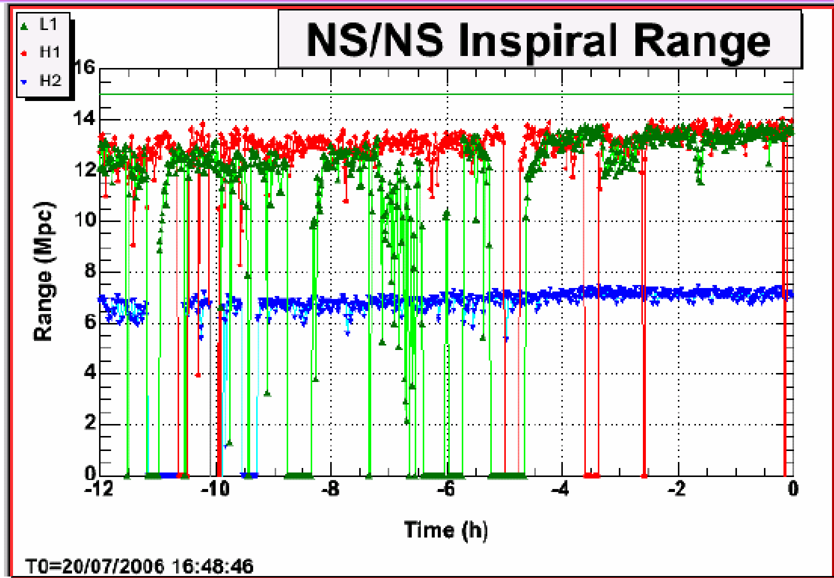
LIGO today is the Lab plus The LIGO Scientific Collaboration (LSC)

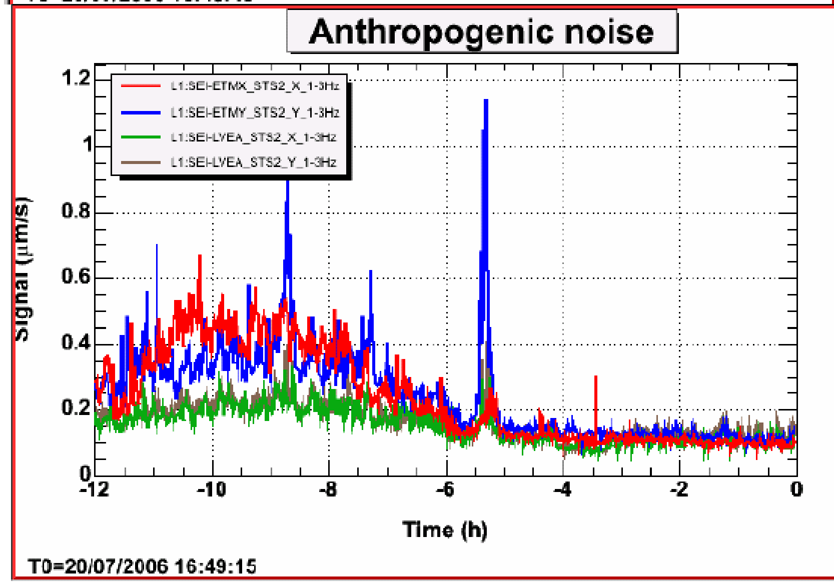
- The LSC carries out the scientific program of LIGO – instrument science, data analysis.
- US Support from the NSF – THANKS!
- The 3 LIGO interferometers and the GEO600 instrument are analyzed as one data set
- Approximately 540 members
- ~ 35 institutions plus the LIGO Laboratory.
- Participation from Australia, Germany, India, Italy, Japan, Russia, Spain, the U.K. and the U.S.A.

….Let's look at what the LSC is doing

Astrophysical interpretation of data

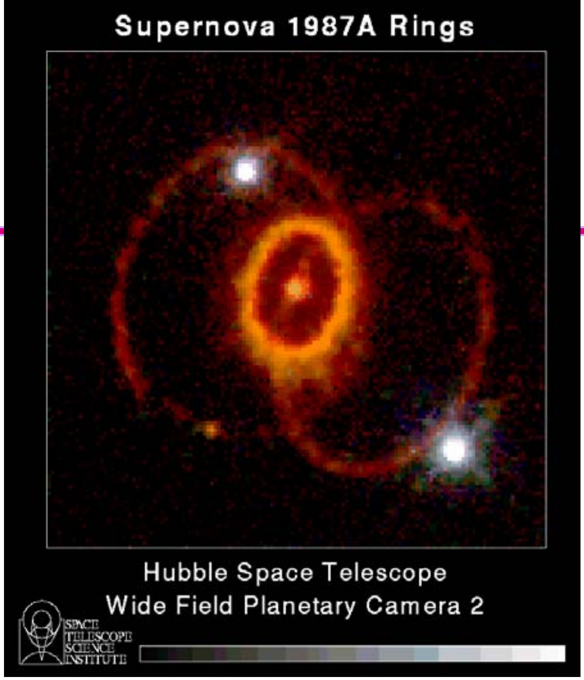
- First effort is to understand instrument and deviations from ideal behavior
  - » Extensive 'Detector Characterization' tools and intelligence
- Working groups formed by instrument scientists and analysts, from entire LSC, addressing LIGO and GEO data
  - » Intensive data analysis exercises between the LSC and Virgo -- Preparation for joint data analysis to commence in the near future
- Concentrating on classes of sources:
  - » Bursts, with or without triggers from other observations
  - » Binary inspirals, of various objects
  - » Periodic sources of GWs
  - » Stochastic backgrounds



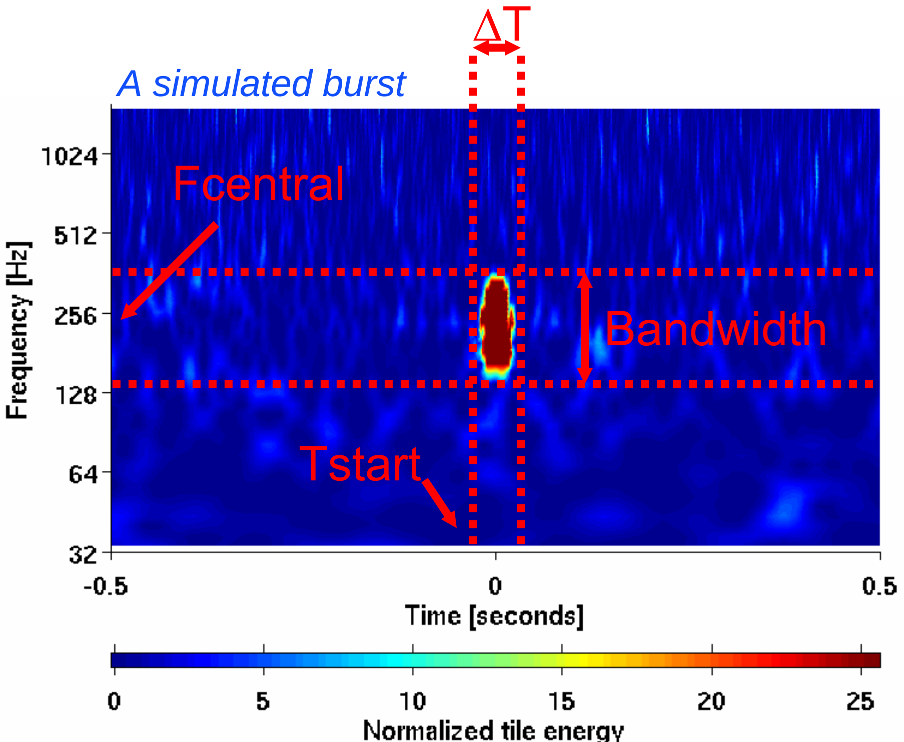


Burst sources

- General un- and ill-defined waveform search
  - » Core-collapse supernovae
  - » Accreting/merging black holes
  - » Gamma-ray burst engines
  - » Kinks/cusps in cosmic strings
  - » …or things we have not yet imagined
- No certain template a priori possible; thus, look for excess of power in instrument
- Require detection in widely separated instruments, time delay consistent with position in sky, and no recognizable instrumental vetoes
- Requires intimate knowledge of instrument behavior!
- Nice also to have a trigger (GRB, neutrino, etc.)



A simulated burst

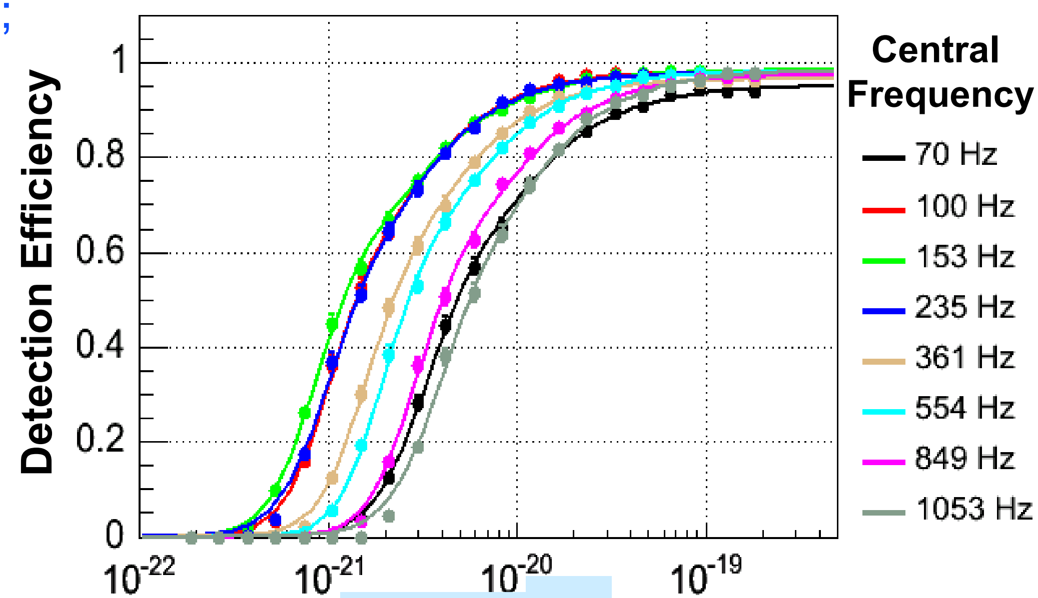


LIGO

Burst sources

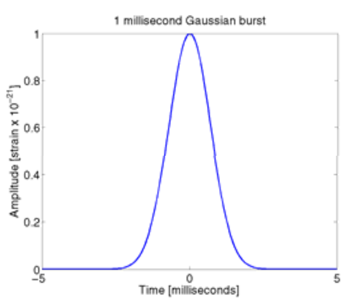
- No gravitational wave bursts detected during S1, S2, S3, and S4; upper limits set through injection of trial waveforms
- S5 anticipated sensitivity, determined using injected generic waveforms to determine minimum detectable in-band energy in GWs
- Current sensitivity:
  E_{GW} > 1 Msun @ 75 Mpc,
  E_{GW} > 0.05 Msun @ 15 Mpc
  (Virgo cluster)

Science Run 4

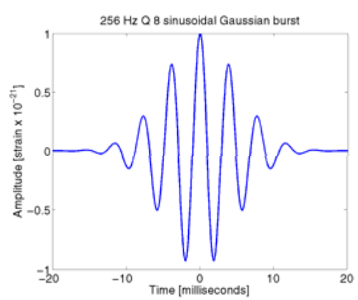


$$h_{rss} = \sqrt{\int |h(t)|^2 dt}$$

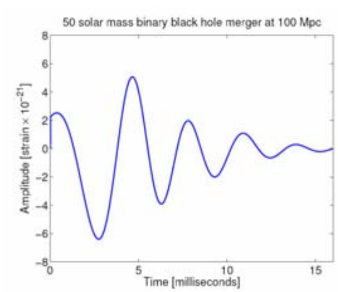
Gaussian pulse



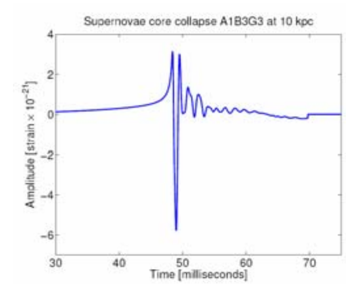
235Hz Sine Gaussian



50Mo BBH merger

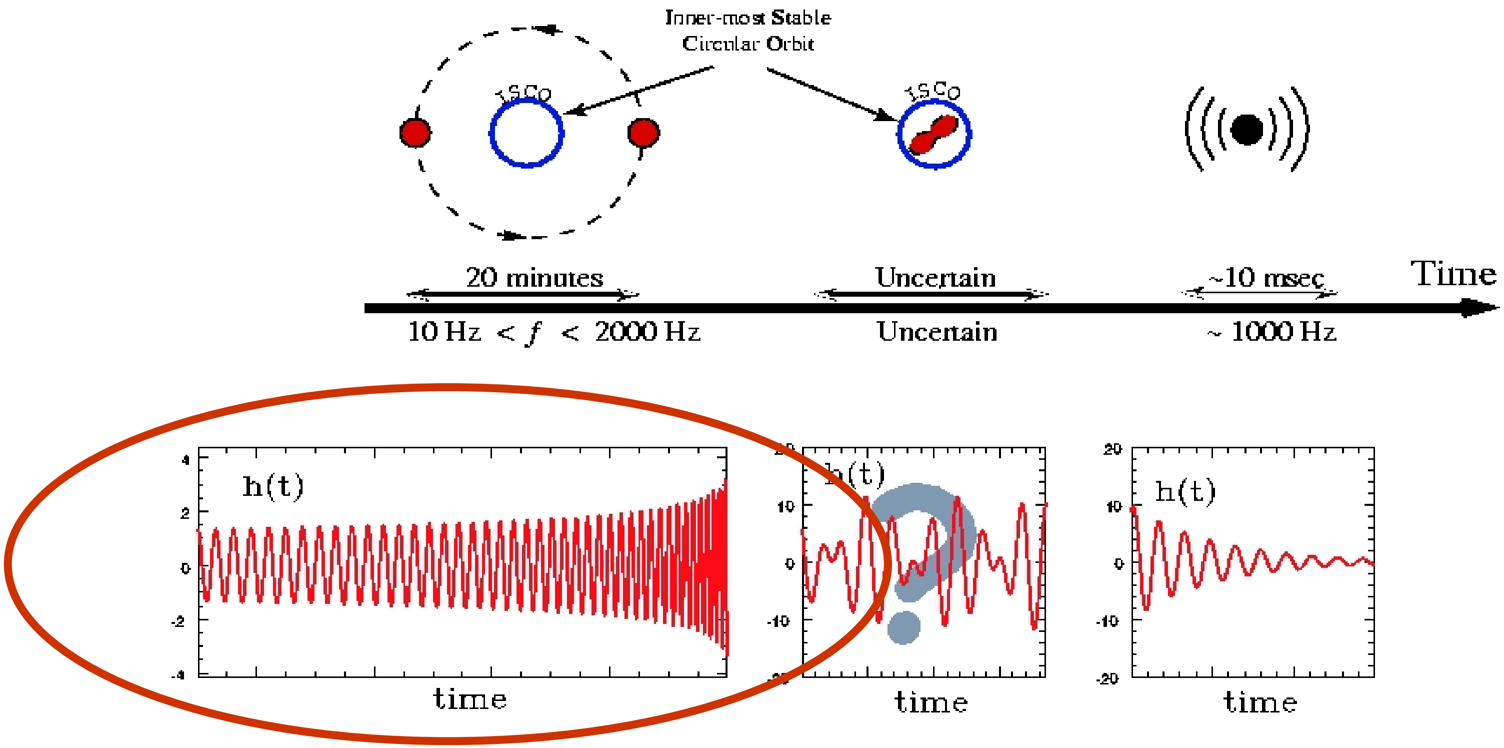


Supernova (from ZM catalog)



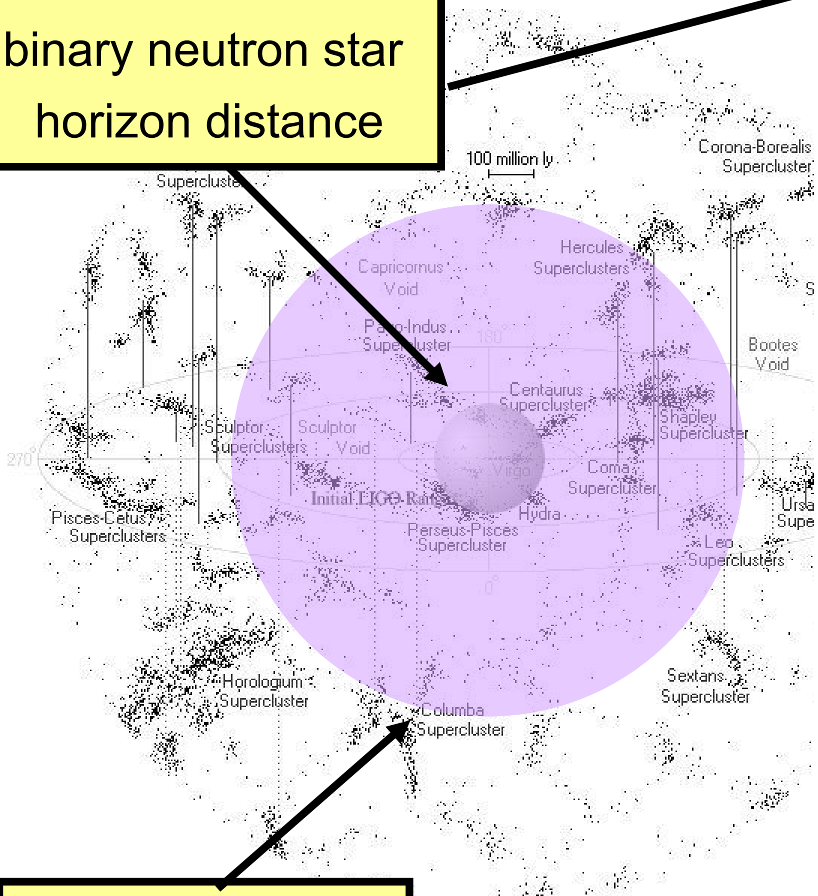
Binary Inspirals

- Neutron star or Black hole binary up to ~70 solar masses
- Template search over best-understood ‘chirp’ section of waveform, gives very good rejection of spuria;
- Can also use GRB as trigger with recent identification with inspirals
- Becomes more complicated with spins….many more templates!

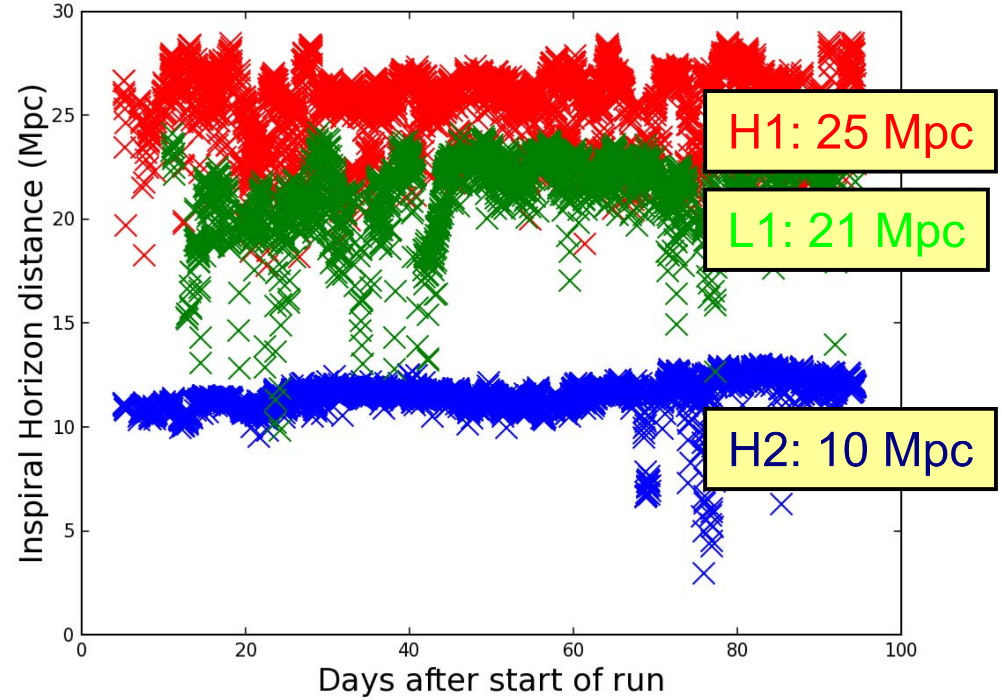


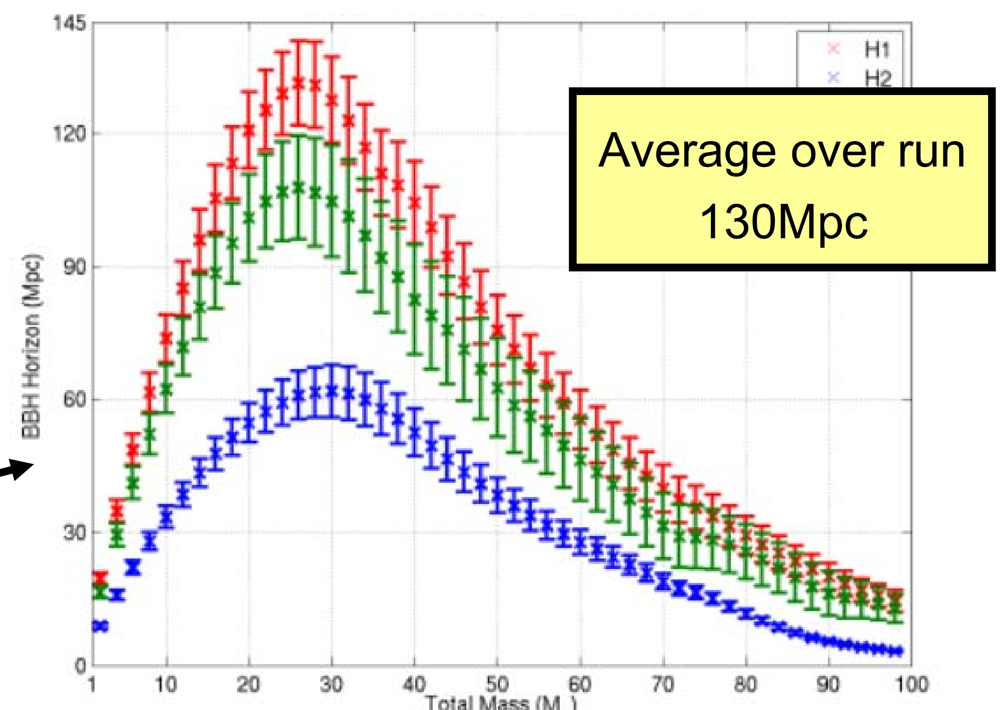
Binary Inspirals

binary neutron star horizon distance



binary black hole horizon distance





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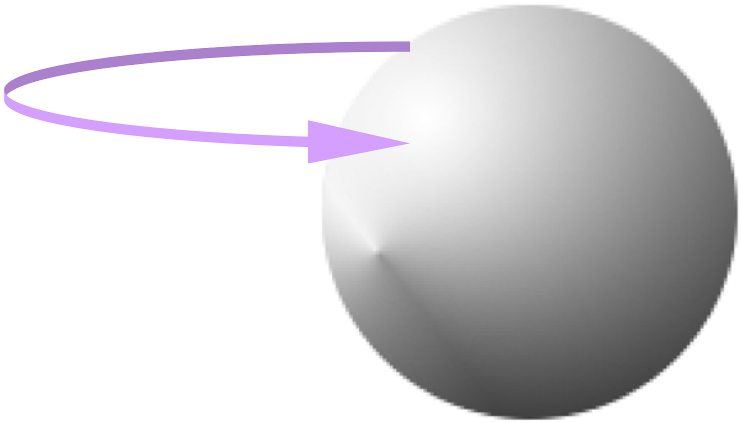
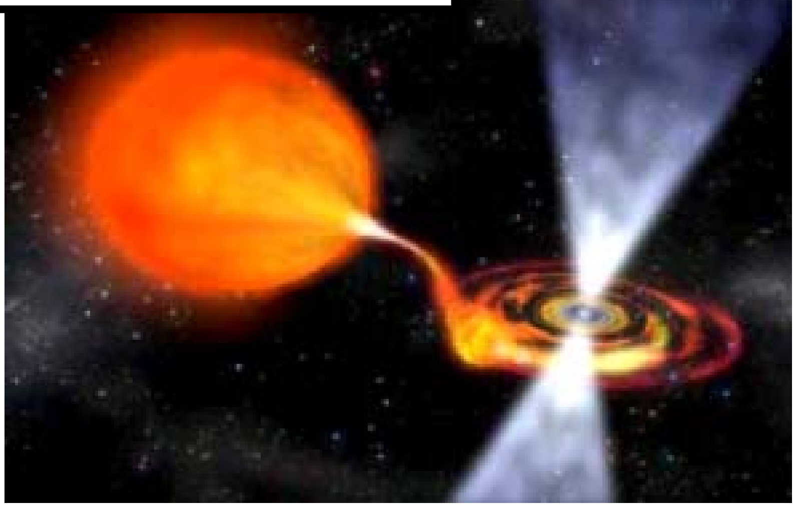
Periodic sources

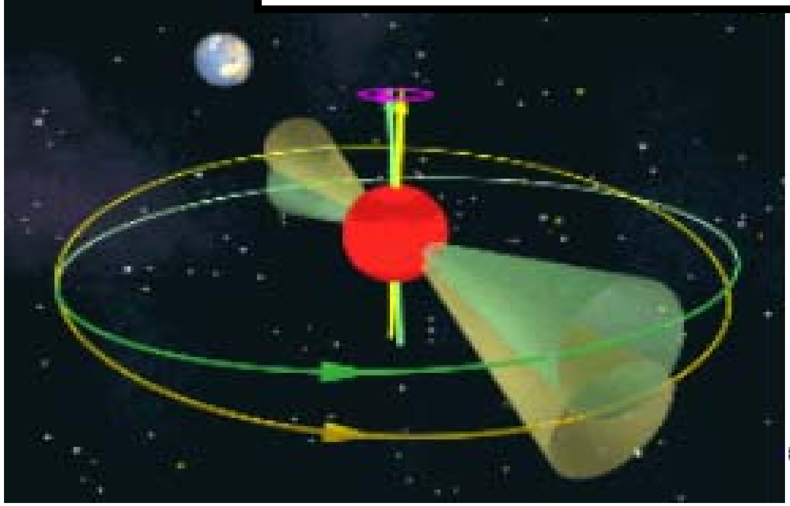


Bumpy Neutron Star

Low-mass x-ray binary

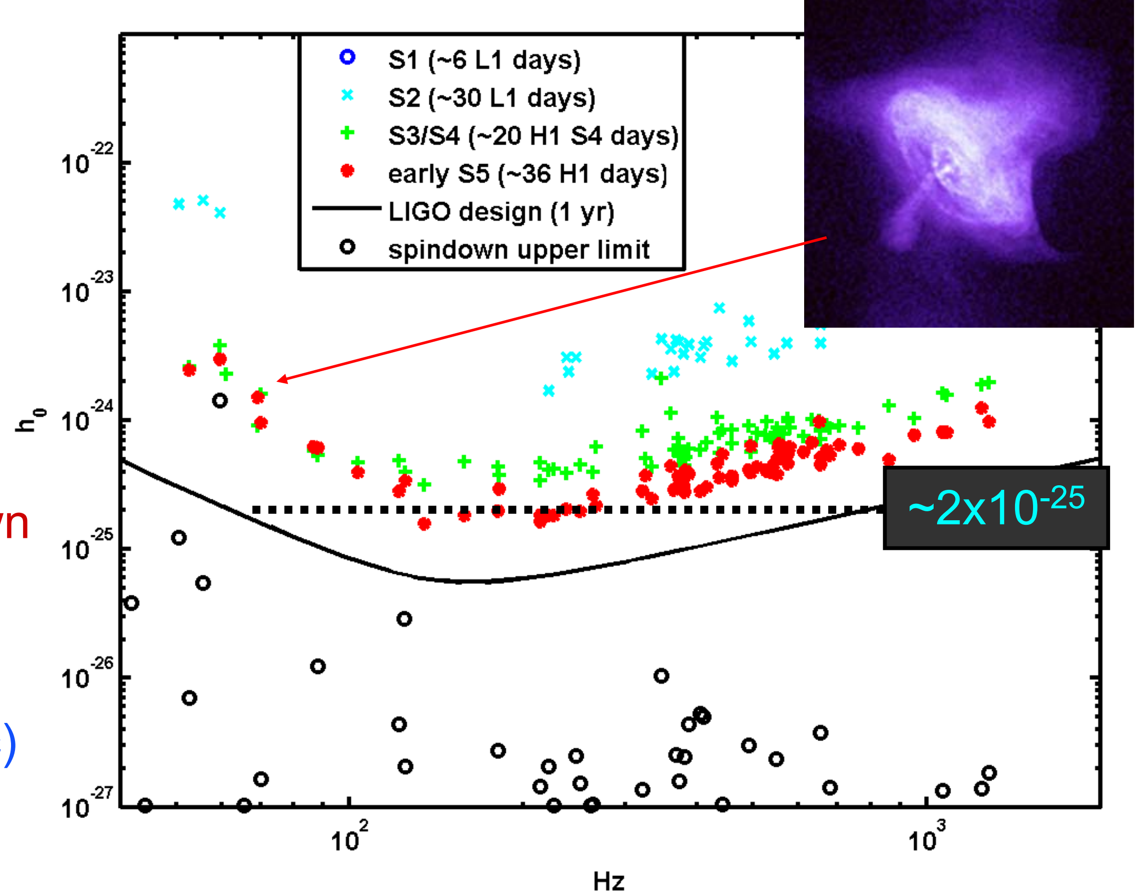


Wobbling pulsars

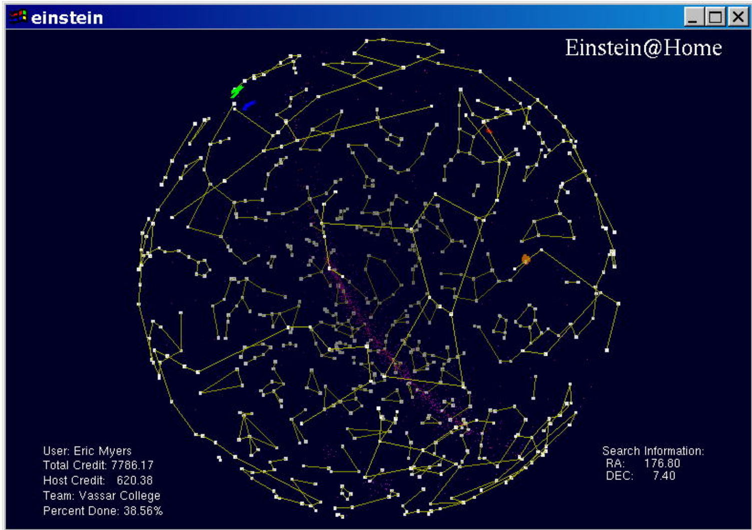


Periodic Sources

- Known pulsar searches
  - » Catalog of known pulsars
  - » Narrow-band folding data using pulsar ephemeris
  - » Approaching Crab spin-down upper limit
  - » Lowest ellipticity limit so far: PSR J2124-3358, (fgw = 405.6Hz, r = 0.25kpc) ellipticity = 4.0×10^{-7}



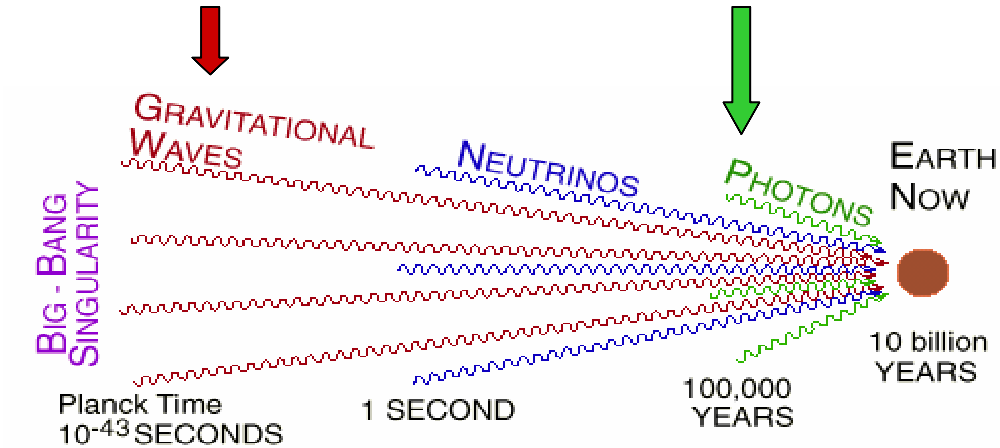
- Wide area search
  - » Doppler correction followed by Fourier transform for each 'pixel'
  - » Computationally very costly
  - » Einstein@Home – 'SETI' model of home computation
  - » ~25 Teraflops

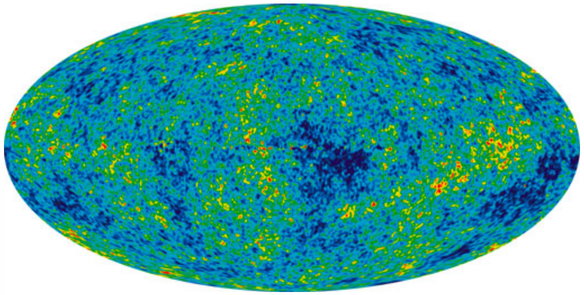


Stochastic sources

cosmic gravitational-wave background (10^{-22}s)

cosmic microwave background (10^{+12}s)

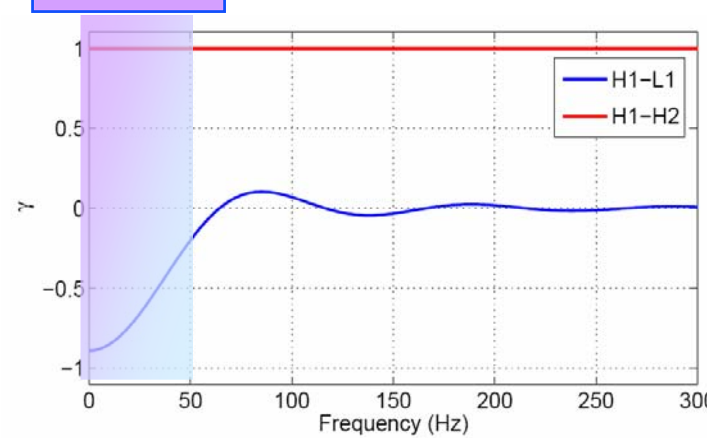




- Cosmological background from Big Bang (analog of CMB) most exciting potential origin, but not likely at a detectable level
- …or, Astrophysical backgrounds due to unresolved individual sources
- All-sky technique: cross-correlate data streams; observatory separation and instrument response imposes constraints

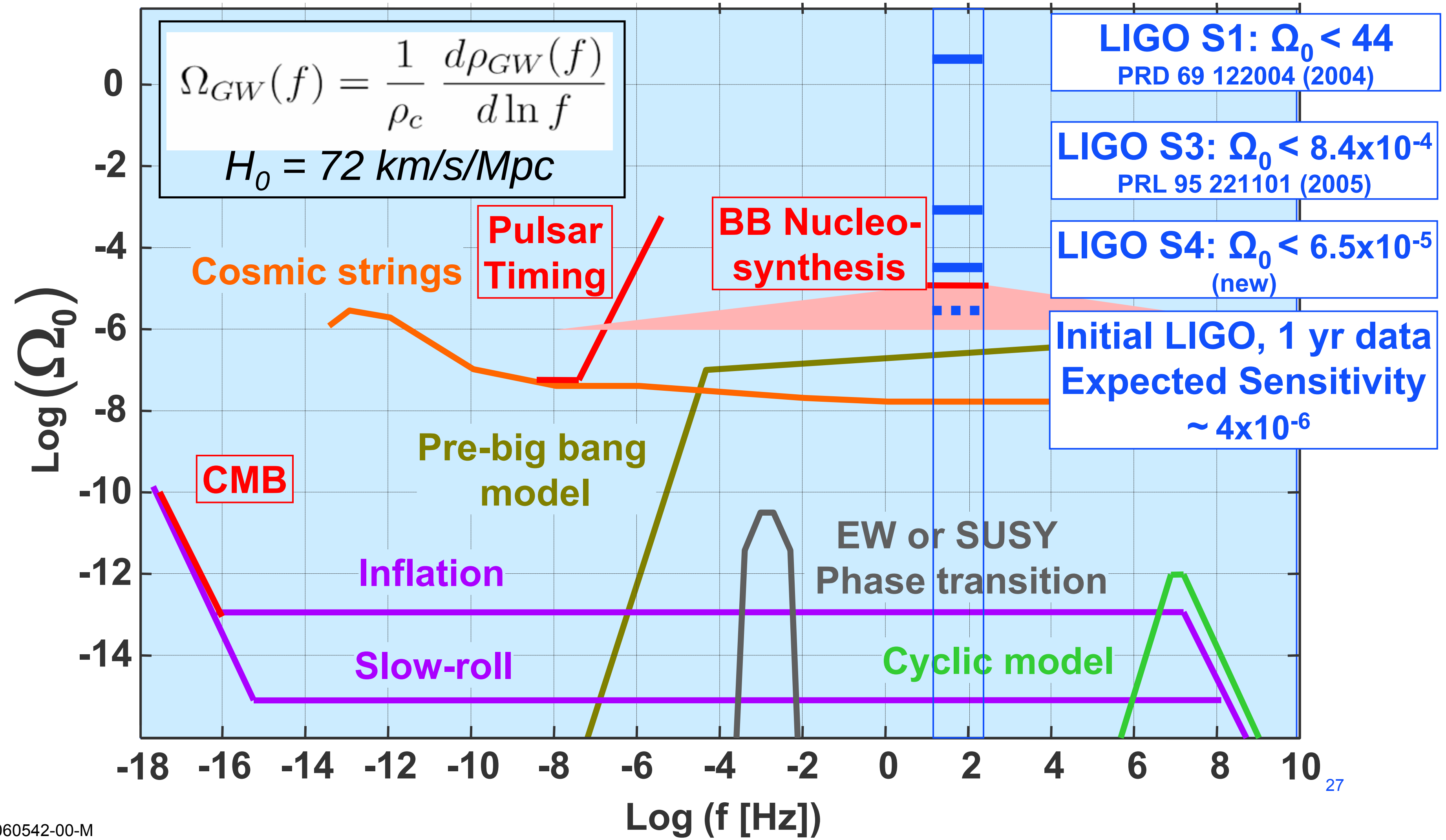
Seismic wall

"Overlap Reduction Function"
(determined by network geometry)



Stochastic sources

- Best result to date: $\Omega_{90\%} = 6.5 \times 10^{-5}$



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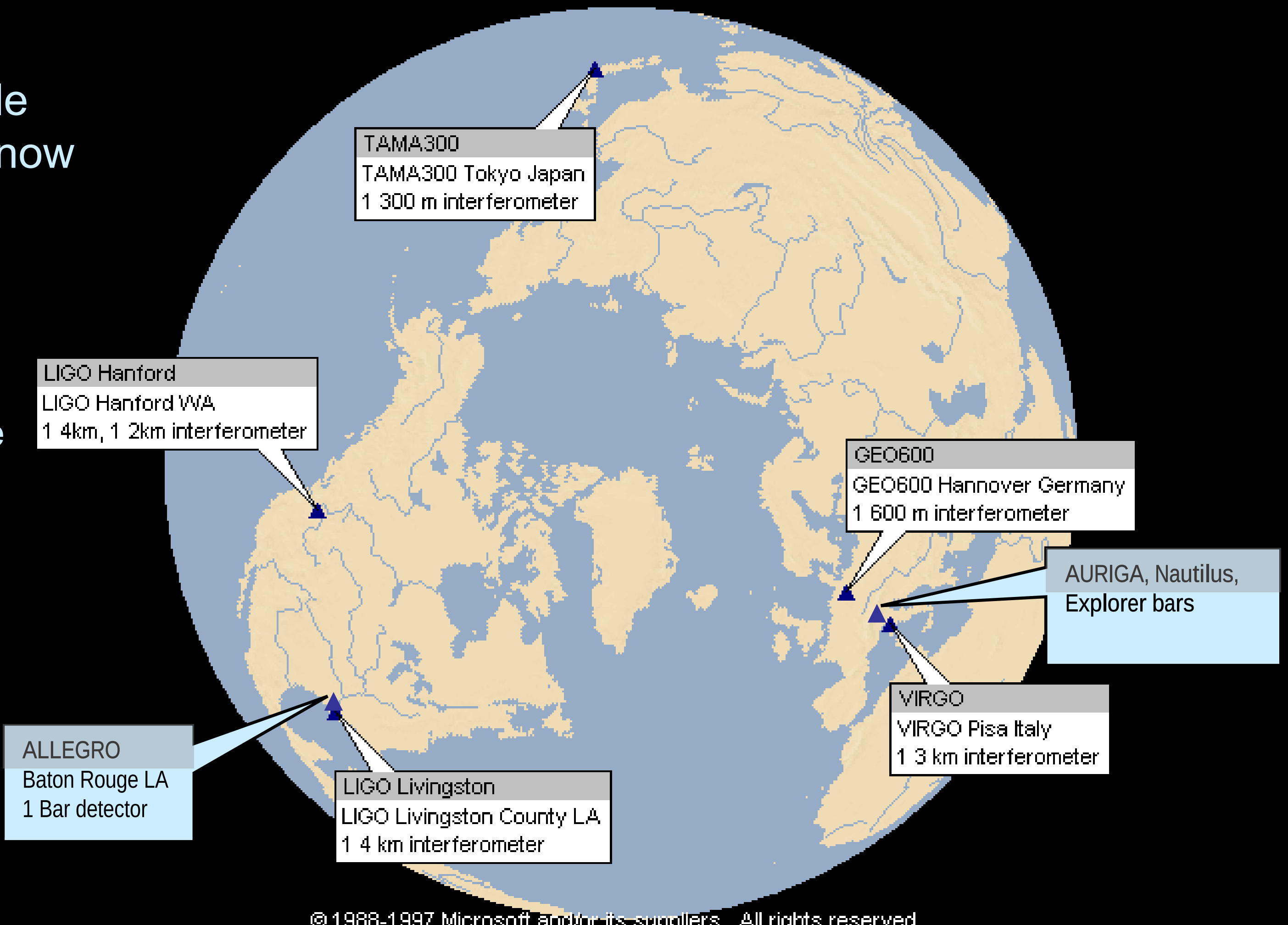
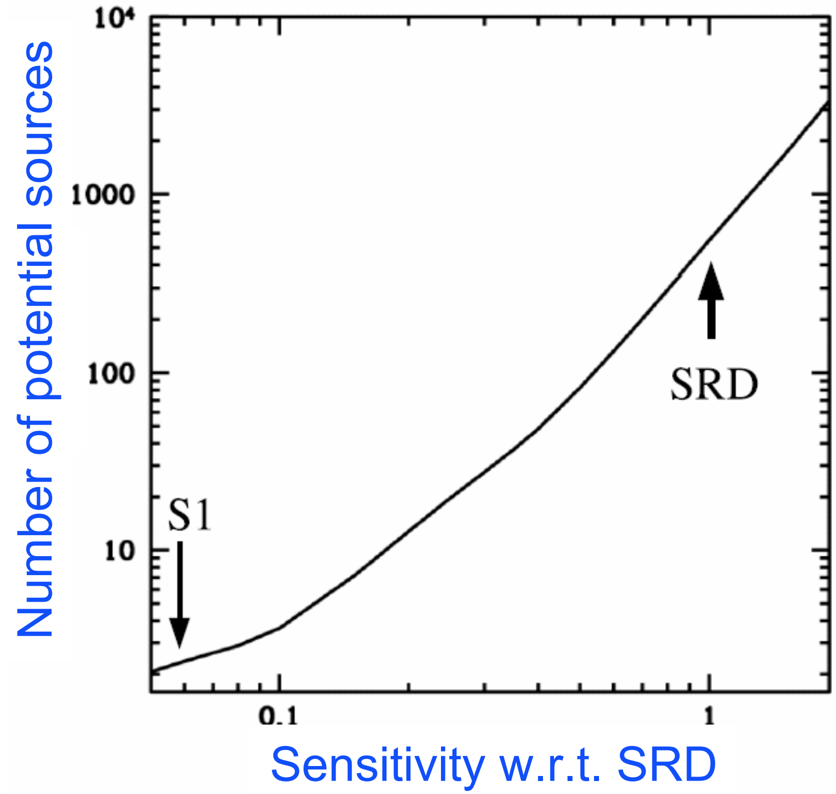
Observation with the Global Network

- Several km-scale detectors, bars now in operation
- Network gives:
  - » Detection confidence
  - » Sky coverage
  - » Duty cycle
  - » Direction by triangulation
  - » Waveform extraction

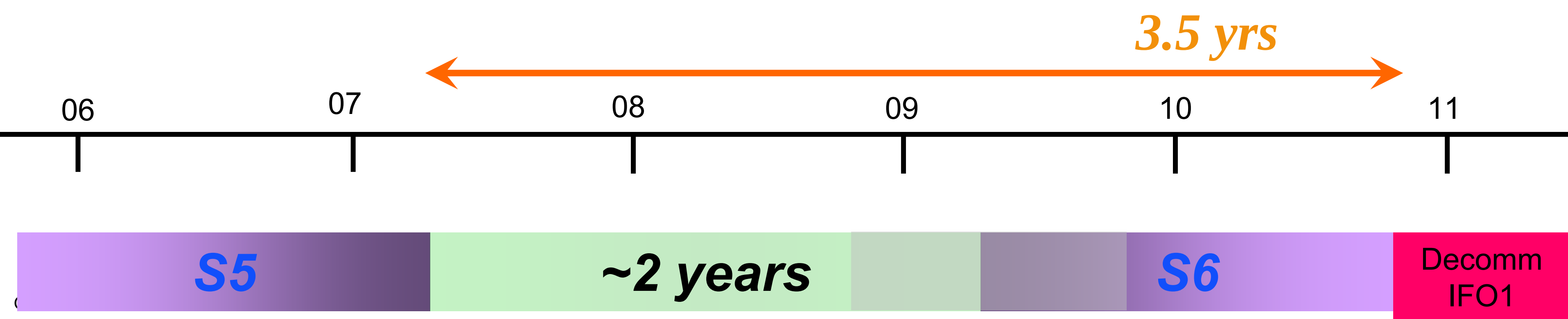


What happens next?

- Increases in sensitivity lead to (Increases)[3] in rate, so…
- Some enhancements to initial LIGO in planning
- Increased laser power, associated technical changes
- ~factor 2 in sensitivity, ~8 in ‘rate’



- Start to prepare now, be ready for end of present S5 science run
- Install, commission during 2 years, then observe for ~1.5 years
- Be ready to decommission for start of Advanced LIGO installation



Advanced LIGO: 1989 Proposal

B. Evolution of LIGO Interferometers

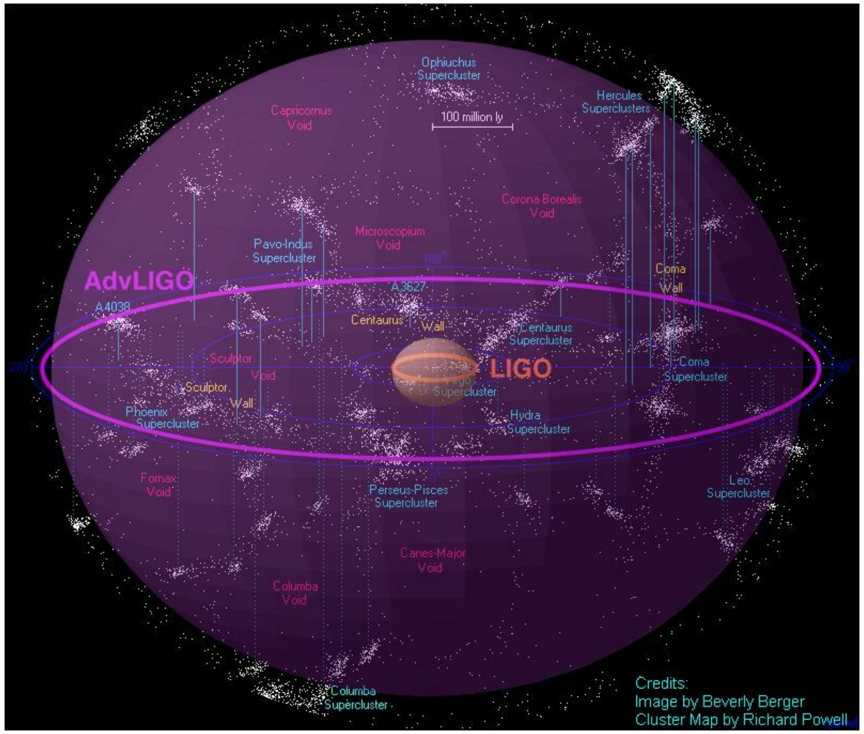
To detect gravitational waves, the use of high performance detectors in extended observational runs is necessary. Development of better detectors that enhance our ability to make new discoveries is also vital. A continuing detector development program is planned to improve LIGO capabilities. The design of the first LIGO interferometer emphasizes simplicity, so that we may place a detector in service as rapidly as possible; succeeding generations of interferometers will more fully exploit the unique capabilities of the LIGO.

2. Development of the second-generation LIGO detector

While the Mark I detector is going into operation, campus development of the second-generation LIGO detector, Mark II, will be proceeding. The Mark II design will include options not incorporated in Mark I and improvements based on the experience gained from operating Mark I. The advantages of new technology, made available after the Mark I design freeze, will be evaluated.

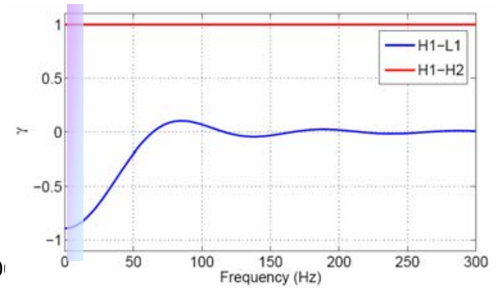
Advanced LIGO

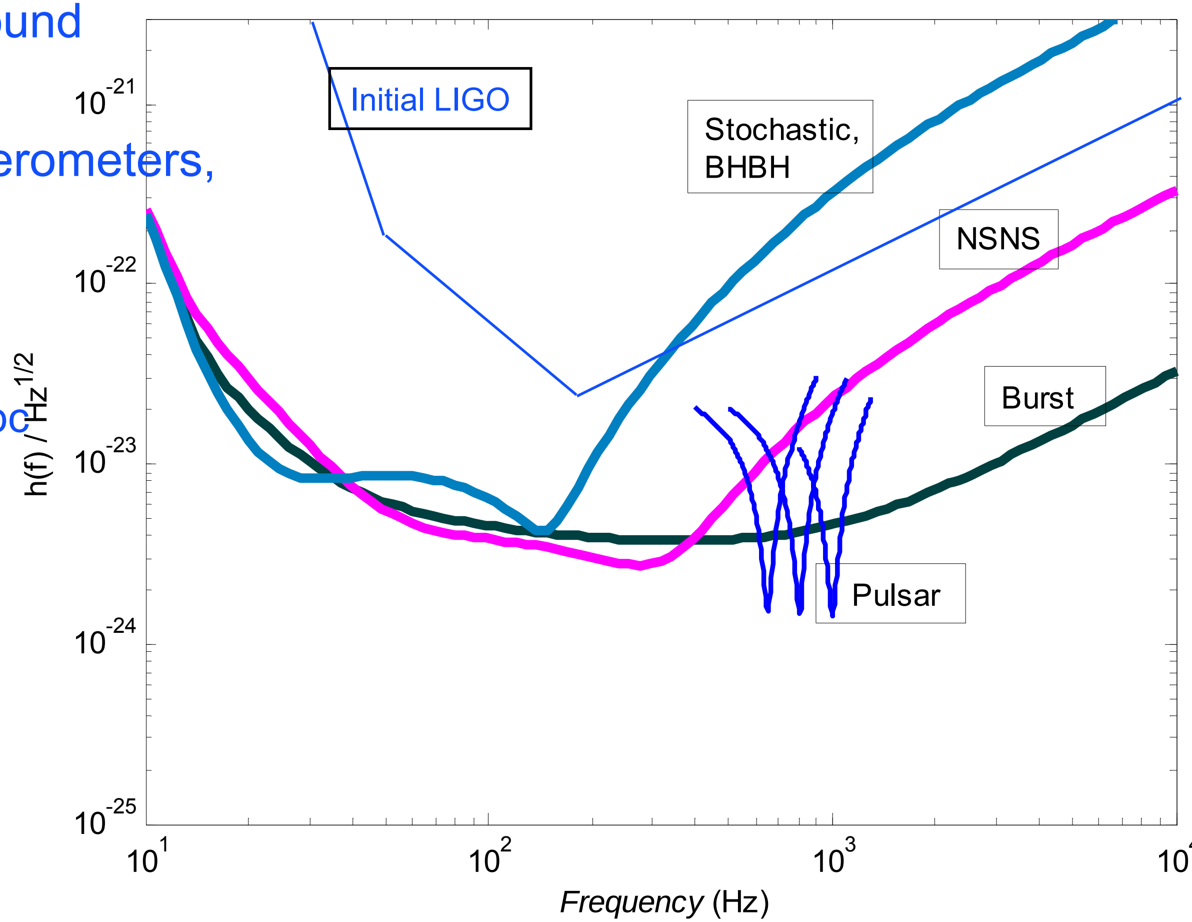
- A significant step forward toward an astronomy of gravitational wave sources
- A factor of 10 in sensitivity, thus a factor of 1000 in rate
- …a year of observation with initial LIGO is equivalent to just several hours of observation with Advanced LIGO



Advanced LIGO sensitivity

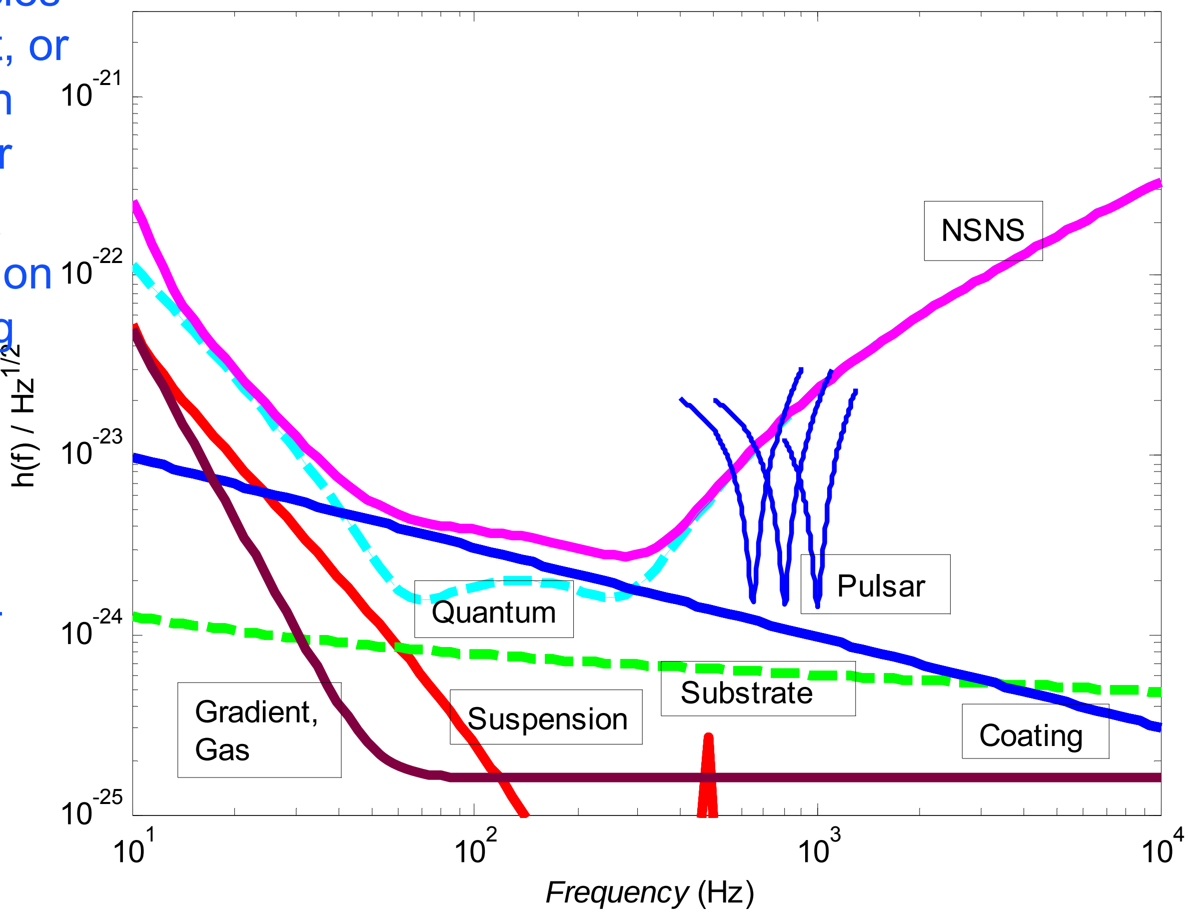
- Factor 10 better amplitude sensitivity
  - » (Reach)^3 = rate
- Factor 4 lower frequency bound
- Tunable for various sources
- NS Binaries: for three interferometers,
  - » Initial LIGO: ~20 Mpc
  - » Adv LIGO: ~300 Mpc
- BH Binaries:
  - » Initial LIGO: 10 M_o, 100 Mpc
  - » Adv LIGO : 50 M_o, z=2
- Stochastic background:
  - » Initial LIGO: ~3e-6
  - » Adv LIGO ~3e-9 (due to improved overlap)



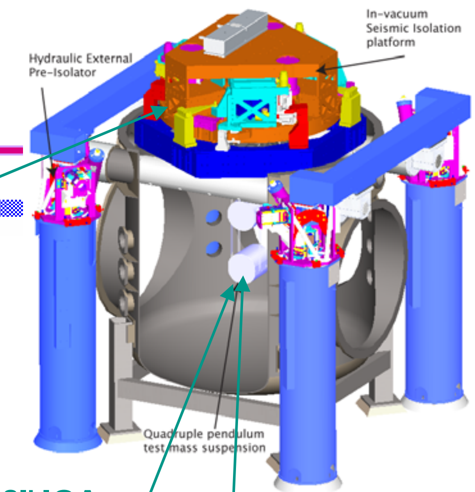


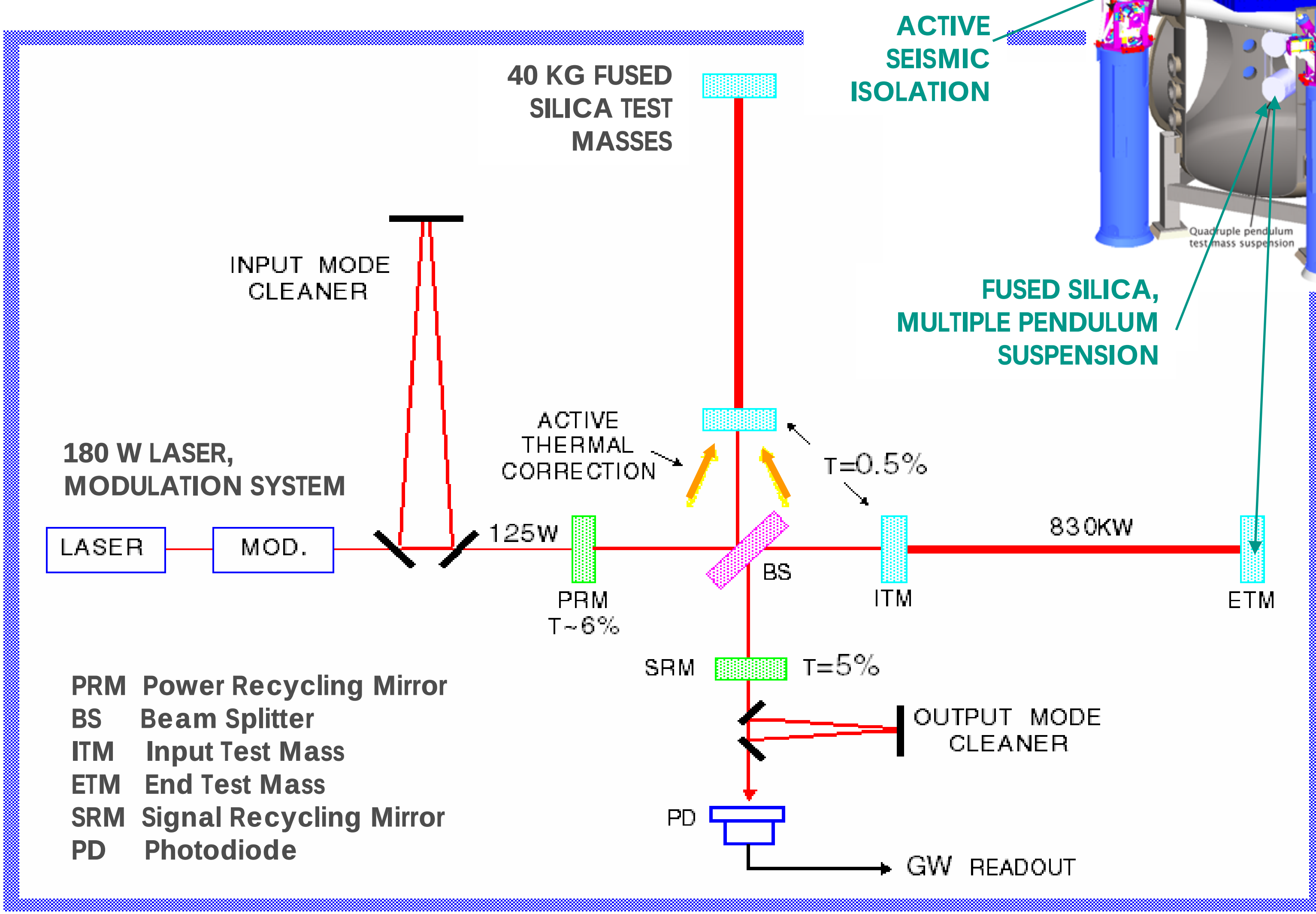
More on sensitivity

- Mid-band performance limited by Coating thermal noise – a clear opportunity for further development, but present coating satisfactory
- Low-frequency performance limited by suspension thermal noise, gravity gradients
- Performance at other frequencies limited by quantum noise (shot, or photon pressure); have chosen maximum practical laser power
- Most curves available on short time scale through a combination of signal recycling mirror tuning (sub-wavelength motions) and changes in laser power
- To change to 'Pulsar' tuning requires a change in signal recycling mirror transmission – several weeks to several days (practice) of reconfiguration (but then seconds to change center frequency)

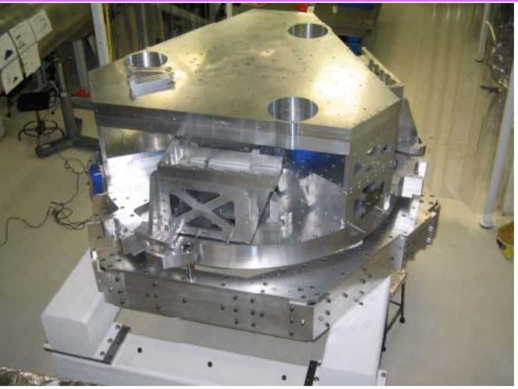


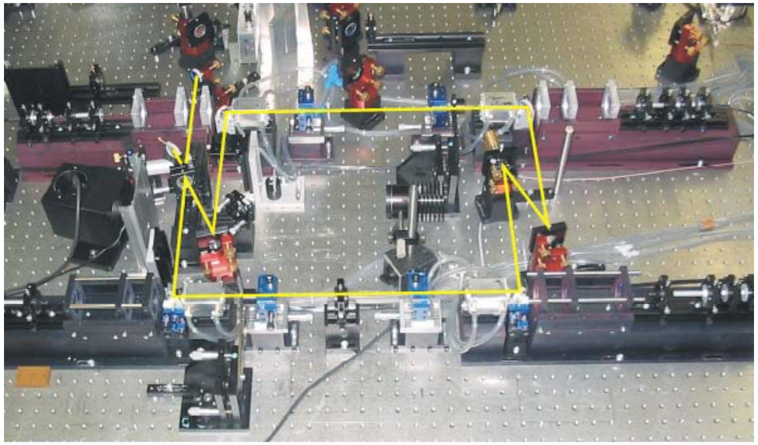
Advanced LIGO Design Features

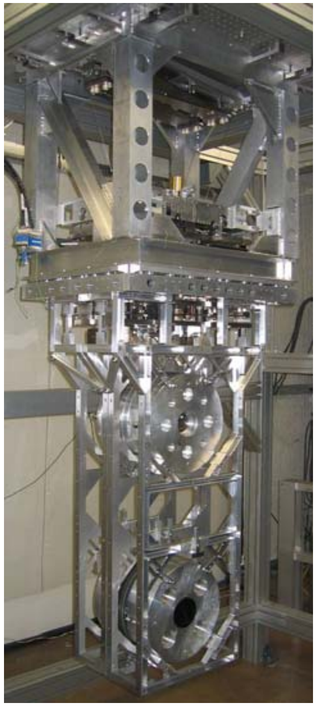


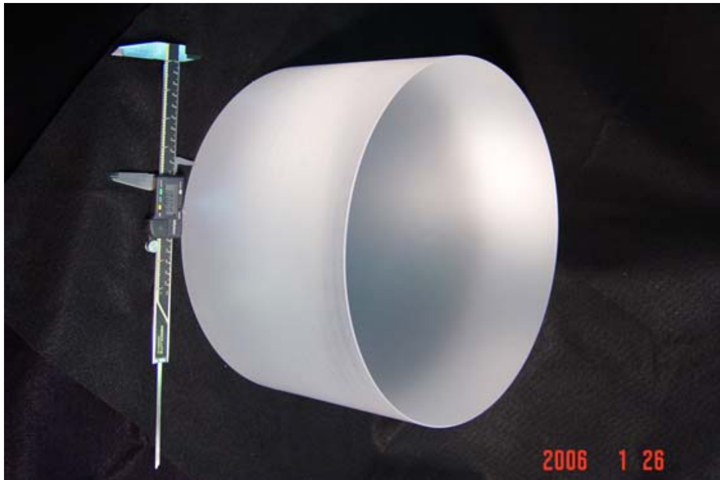


Advanced LIGO Prototypes



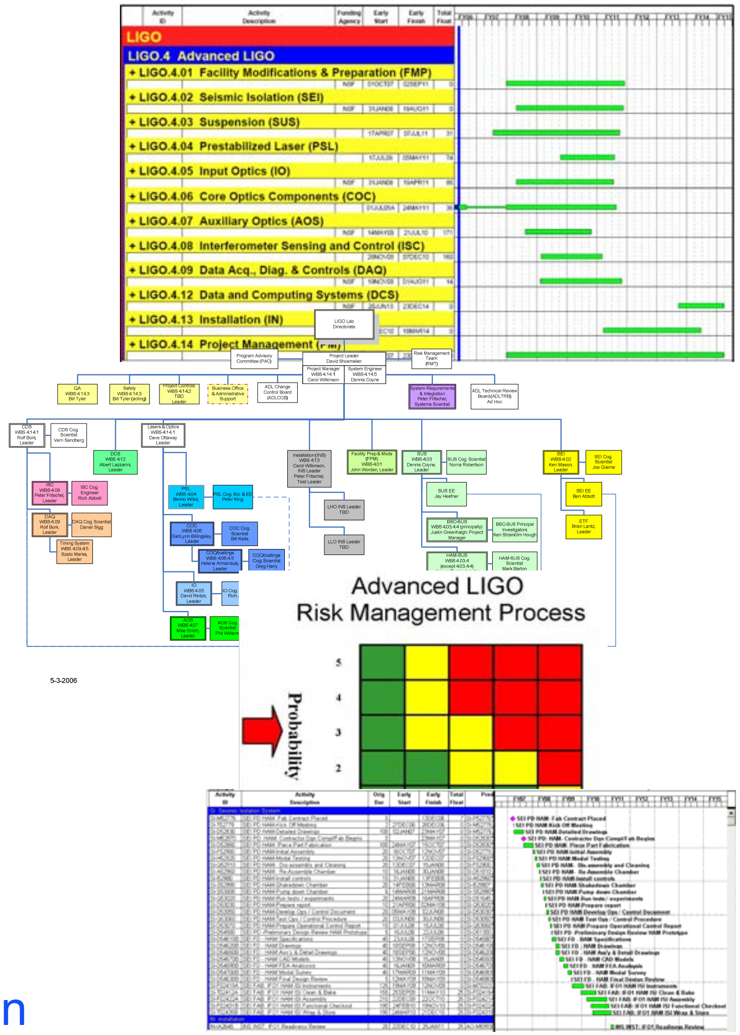






LIGO Advanced LIGO status and timing

- International team of LIGO Laboratory, Scientific Collaboration scientists
- Columbia part of the enterprise, via Szabi Marka
- Supported by the US National Science Foundation, with additional contributions by UK PPARC and German Max Planck Society
- Technical and organizational reviews completed successfully, with National Science Board approval
- Appears in budget planning of NSF and US Government
- Next step: President's budget in February 2007
- On track for a Project start in early 2008
- Decommissioning of initial LIGO in early 2011
- First Advanced LIGO instruments starting up in 2013
- Hoping, and planning, on parallel developments in other 'advanced' instruments to help form the second generation Network



LIGO

- LIGO – the Lab, the Collaboration, and the instruments – are in full swing
- Sensitivity (along with data quality, duty cycle, and duration) is such that detections are plausible – some reasonable hope that a LIGO presentation soon will be able to include this 'little step forward'
- A network of instruments is growing, allowing broad physics to be extracted from the detectors, and LIGO is pleased to be a central element
- Steps forward in sensitivity are planned which should move us from novelty detection to astrophysical tool