Pre-tour Introduction to LIGO (technical edition)

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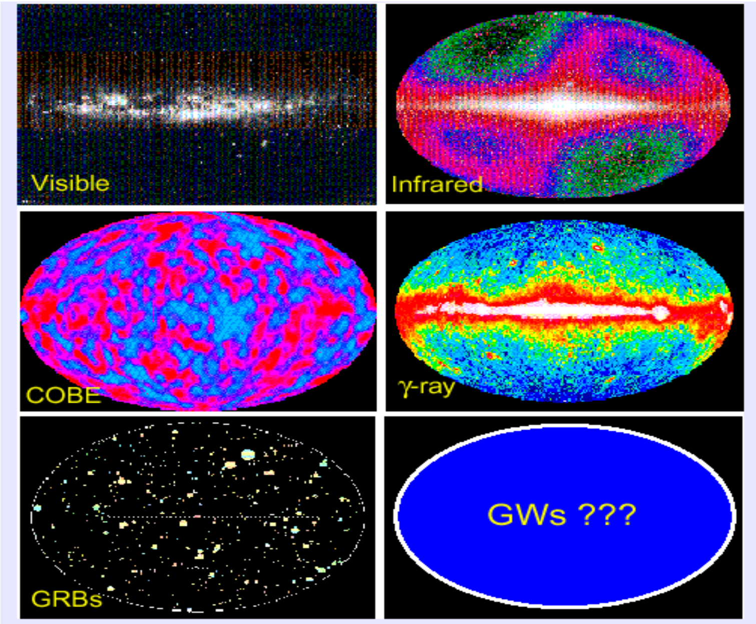
on behalf of the LIGO Scientific Collaboration

19 Jun 2012

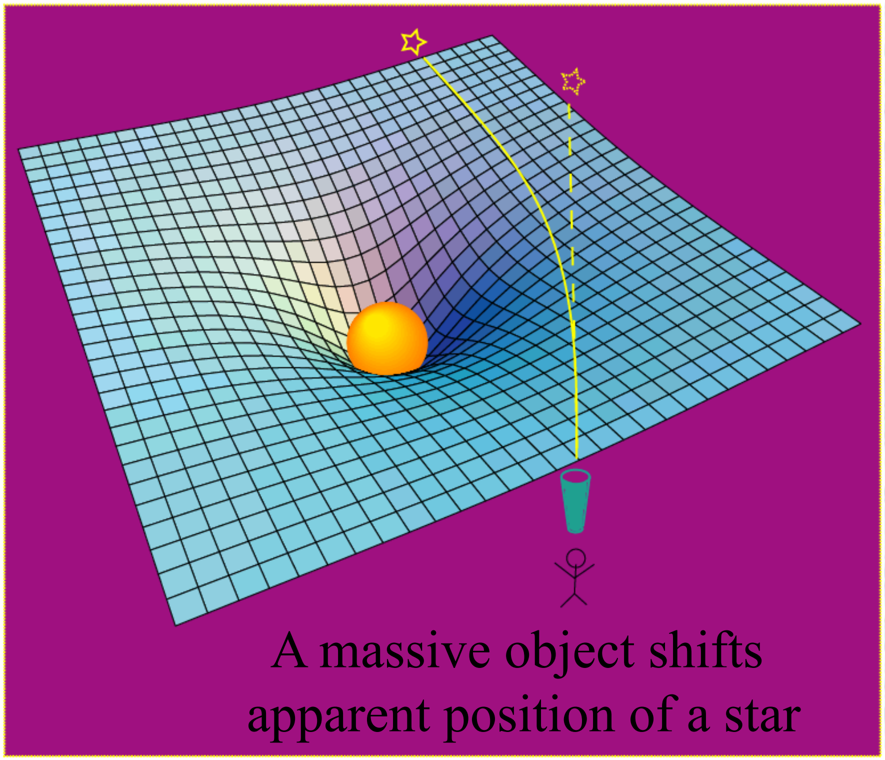


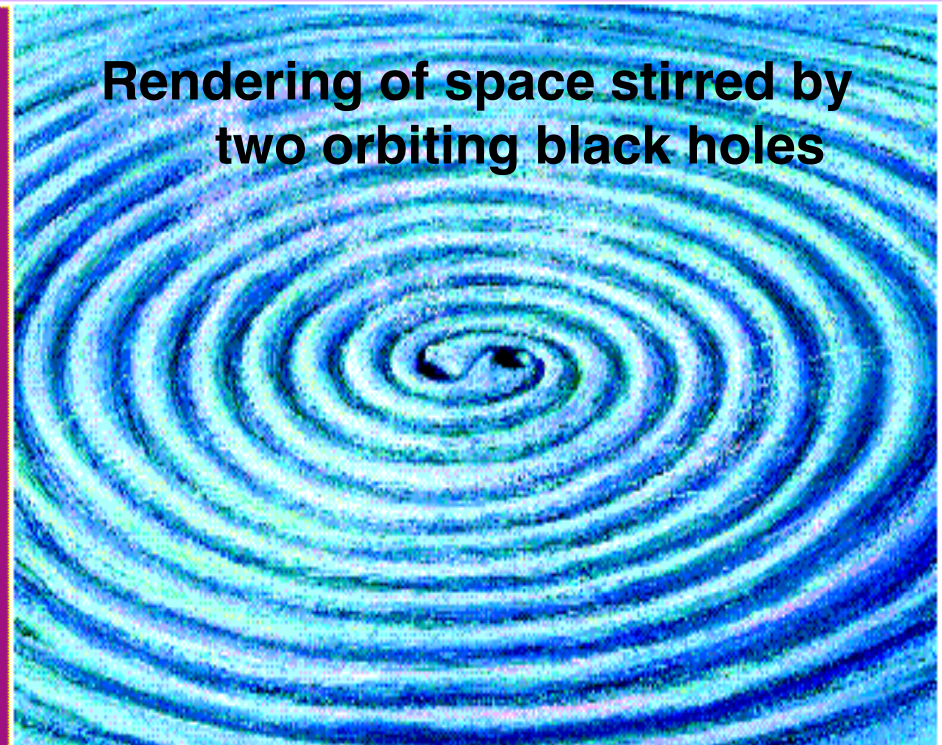
LIGO-G1200695

Big questions

- When we look out into the universe, do we see what is really there or do we see how we look at it?
- What is the nature of space and time?
- How did the universe come into being?
- What gives rise to the structure of our our universe?
- How did the universe evolve from origins to the present day?

Einstein's General Relativity re-wrote the rules of space and time





Empty space and time are things, with real physical properties. Space has a shape, a stiffness and a maximum speed for information transfer.

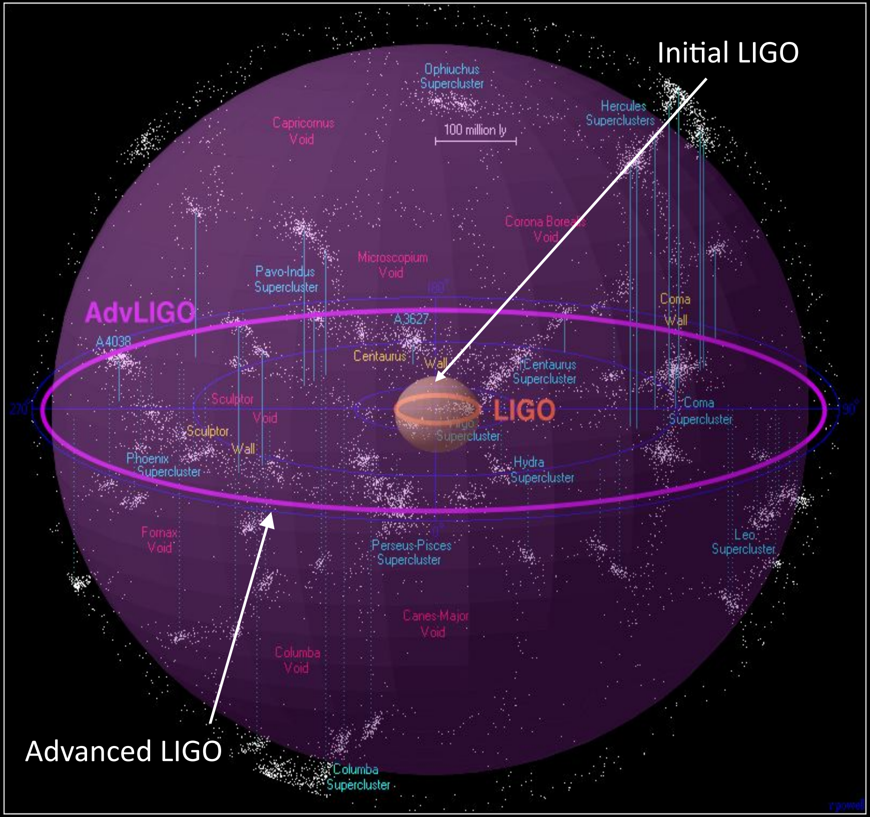
LIGO's Mission

- To establish the routine detection of gravitational waves from cosmic cataclysms and to exploit these detections for fundamental studies in physics and astrophysics

2-Step Approach, From Discovery to Astronomy

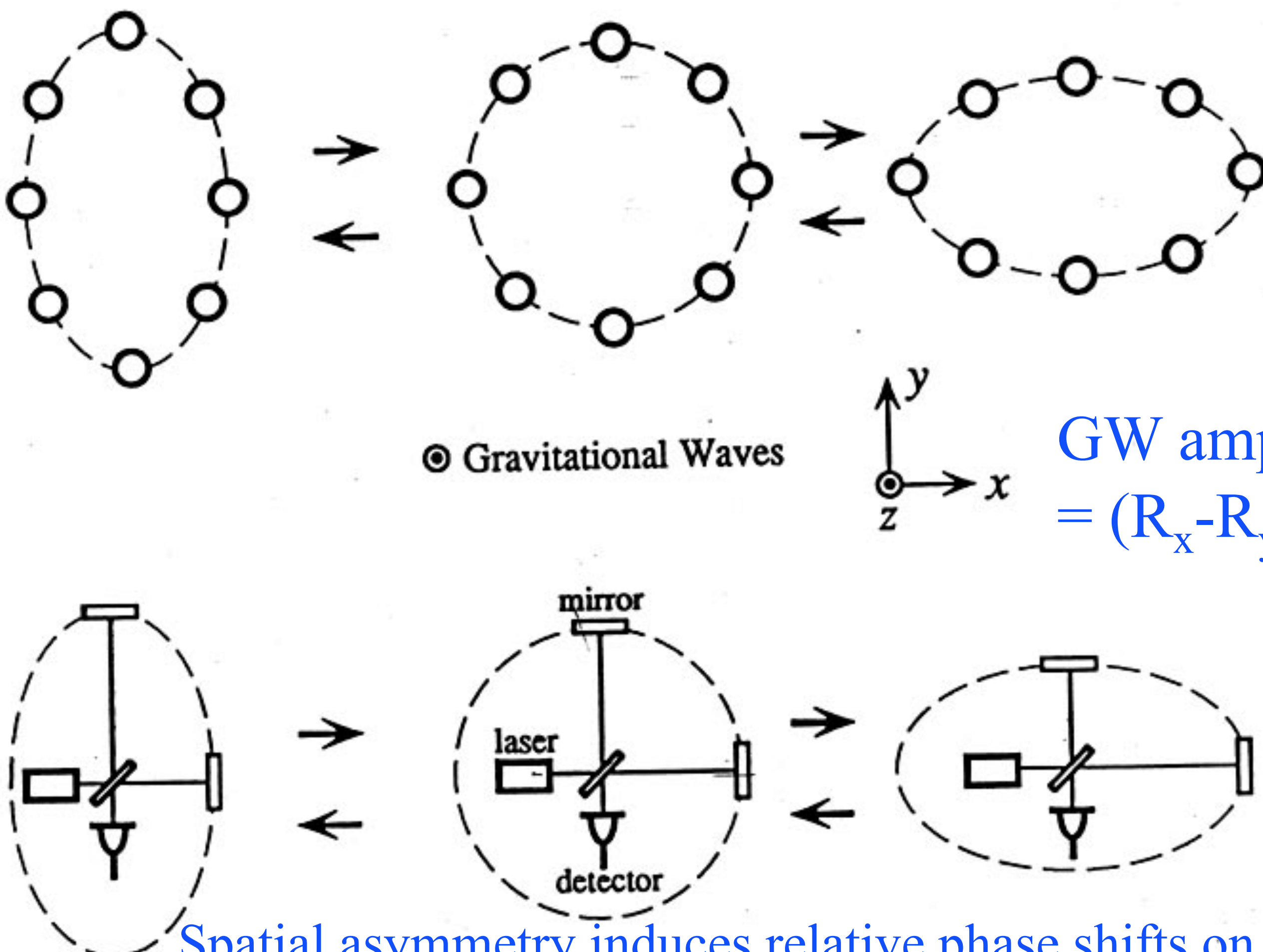
1st generation: iLIGO, pathfinder that pays the billion-fold cost of admission; no guarantee of a home run

2^{nd} generation: aLIGO, the trillion-fold home-run king



Credit: R.Powell, B.Berger

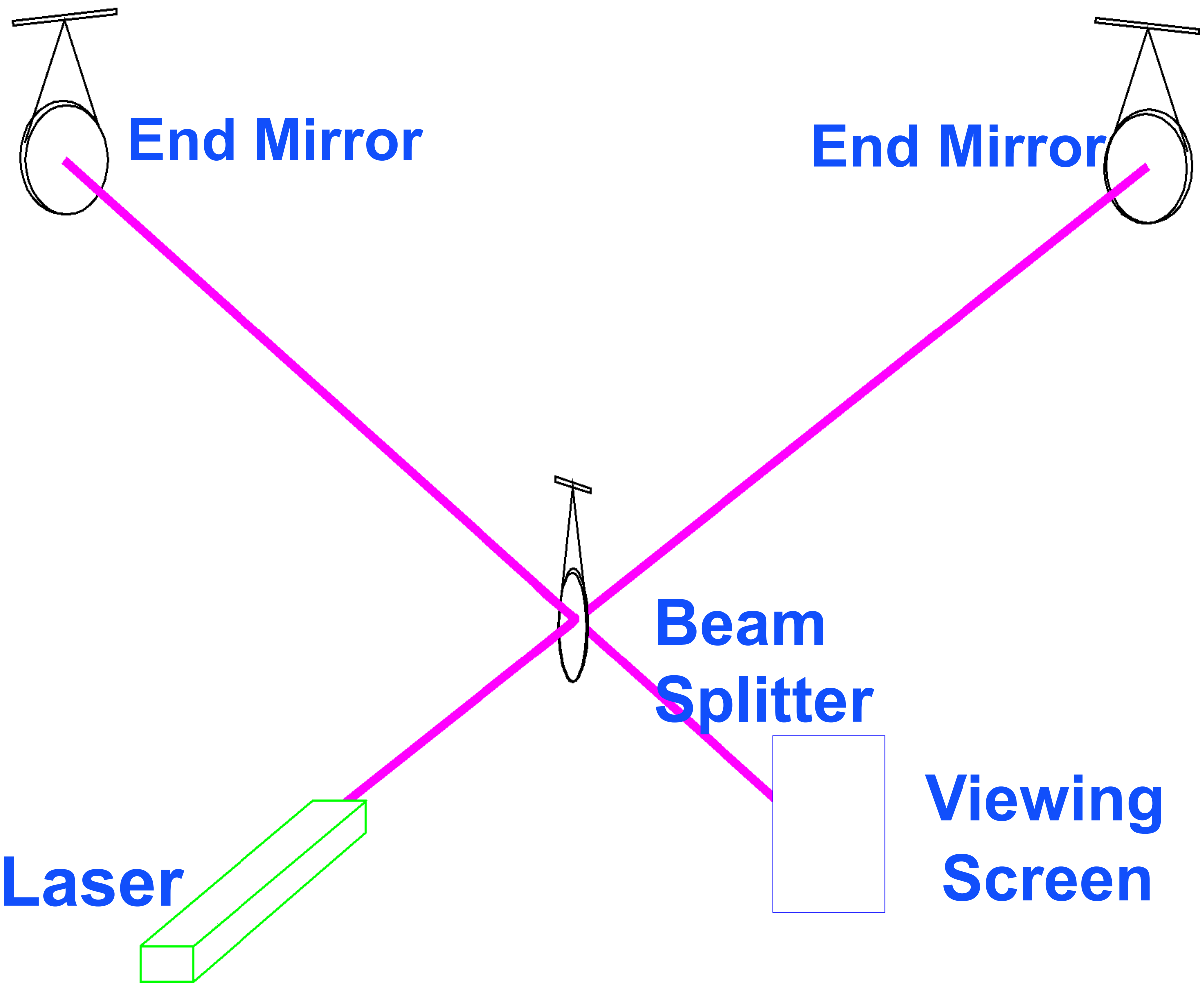
Basic idea is simple



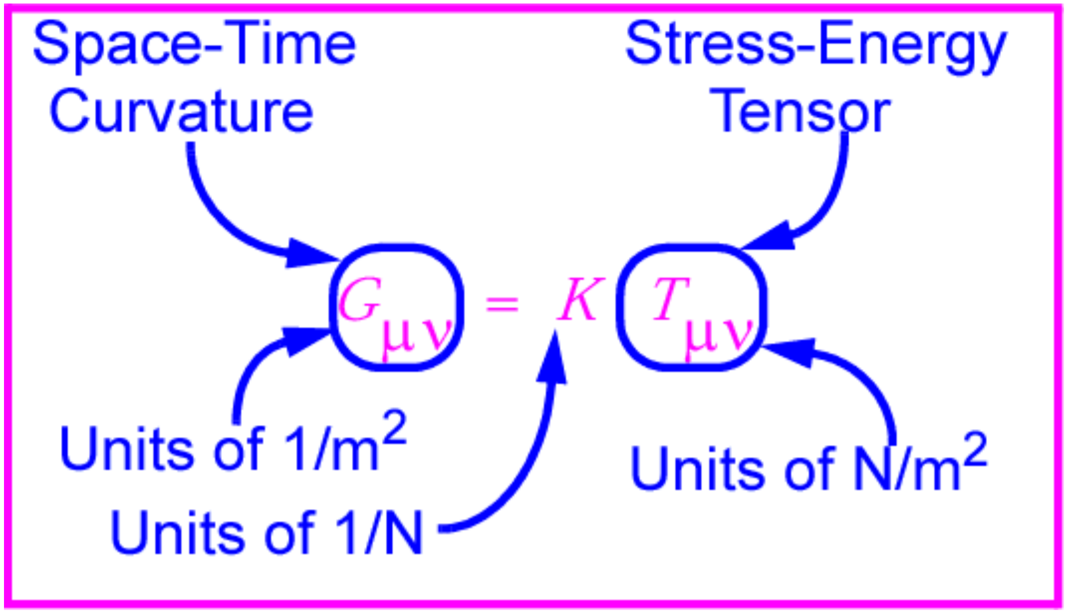
GW amplitude h
= $(R_x - R_y)/R$

Spatial asymmetry induces relative phase shifts on light in arms

Terrestrial interferometers need to counter Earth's gravity



Gravitational waves: hard to find because space-time is stiff!



- K~[G/c^4] is lowest order combination of G, c with units of 1/N

$$K \sim 10^{-44}\ N^{-1}$$

⇒ Wave can carry huge energy with miniscule amplitude!

Execution is hard

- Expected strains are below 10^{-21}, the width of a hair at 4 light years
- For a 4-km interferometer, need differential resolution of 1-10 billionths of the size of atom (near or at quantum limit)
- Need to resolve differential phase shifts of the laser light below nanoradian scale
- Need to isolate the mirrors from all background forces in signal band
- Need coincident detections over a worldwide network of detectors separated by continent-sized distances
- Need unified multinational science collaboration and protocols
- Need to work like a beehive, not like a wolf pack

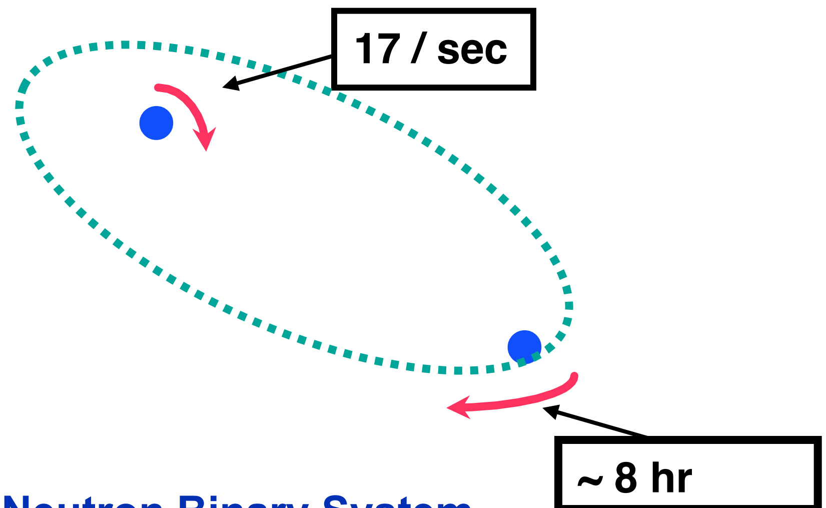
Gravitational Waves

known to exist, just hard to find

Emission of gravitational waves

Neutron Binary System – Hulse & Taylor

PSR 1913 + 16 -- Timing of pulsars

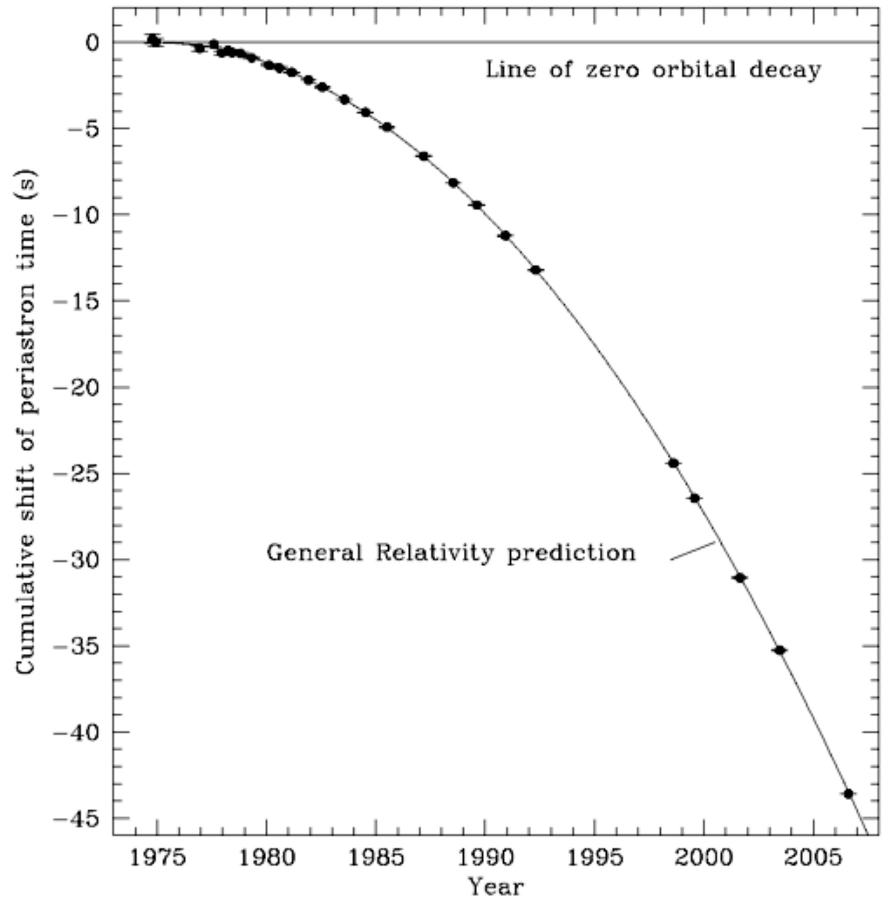


Neutron Binary System

- **separated by 10^6 miles**
- **$m_1 = 1.4 m_\odot$; $m_2 = 1.36 m_\odot$; $\varepsilon = 0.617$**

Prediction from general relativity

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



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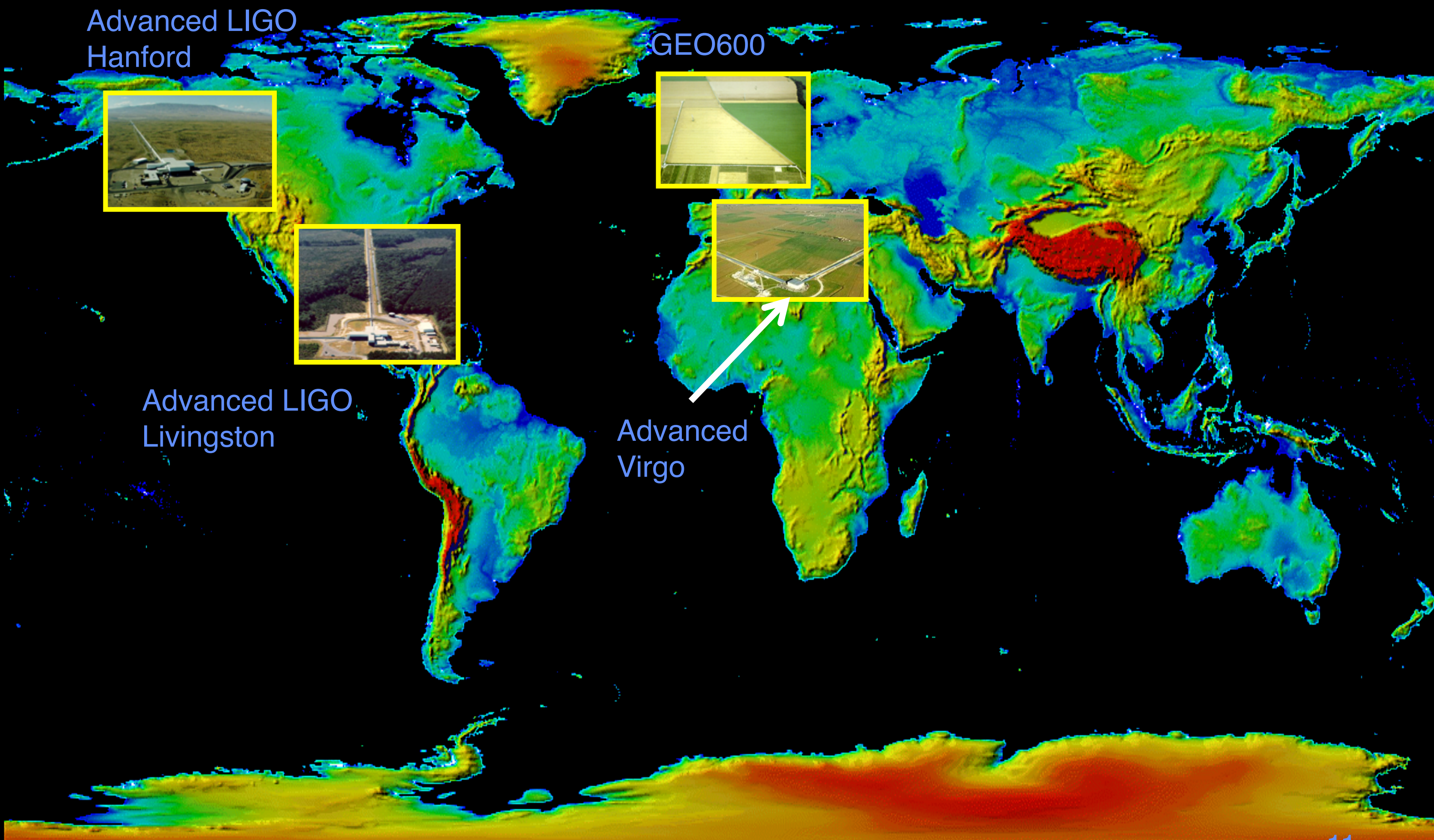
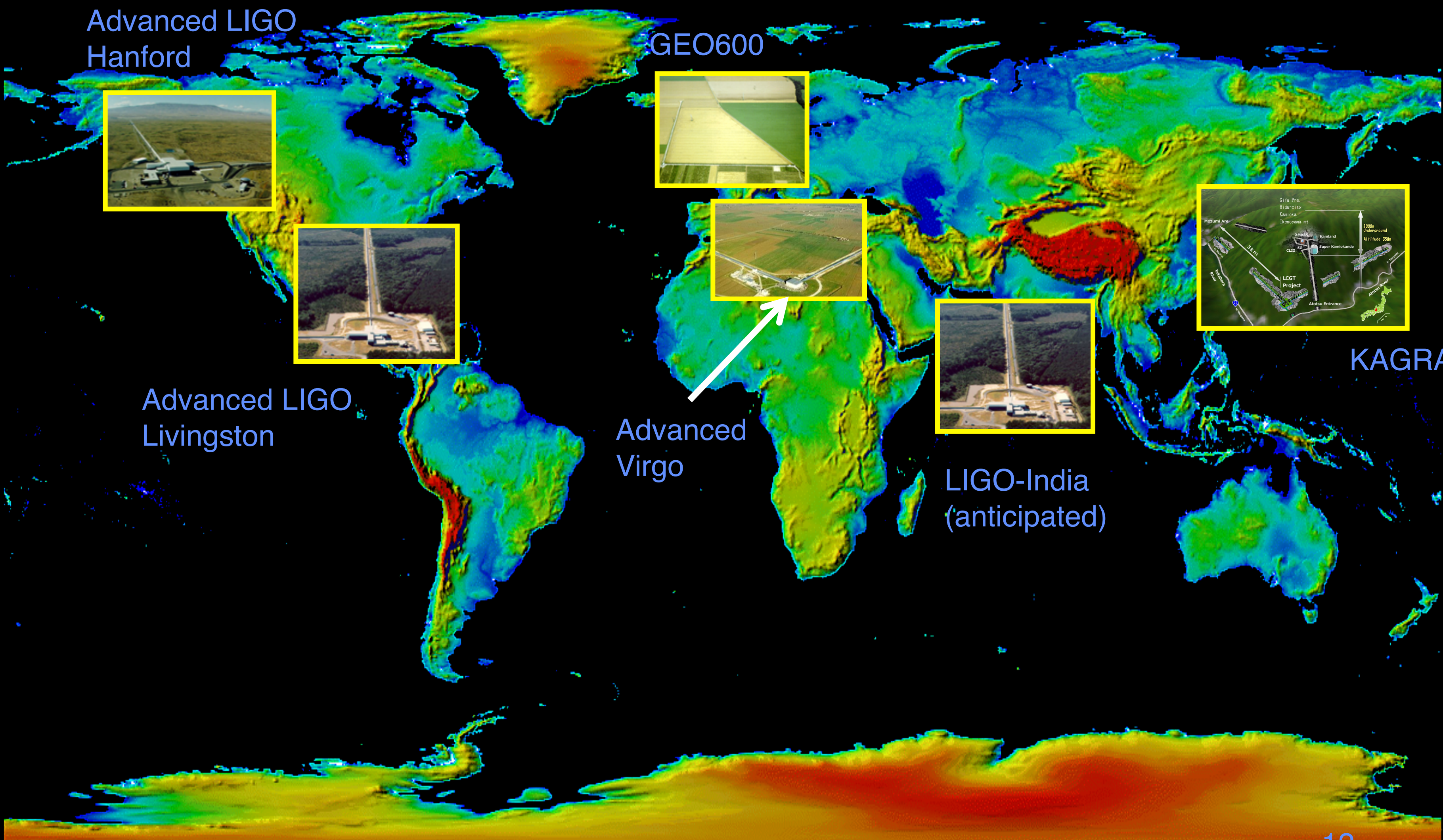
The Advanced Ground-based GW Detector Network in 2015



The Advanced Ground-based GW Detector Network in 2020



The Laser Interferometer Gravitational-Wave Observatory

LIGO (Washington)

LIGO (Louisiana)

Owned by the National Science Foundation; operated by Caltech and MIT; the research focus for 890 LIGO Scientific Collaboration members covering 5 continents. Now engaged in joint operations with Virgo Collaboration.

Interferometers in Europe

GEO 600 (Germany)
600-m

Operated by GEO, member of LIGO Scientific Collaboration

Virgo (Italy)
3-km

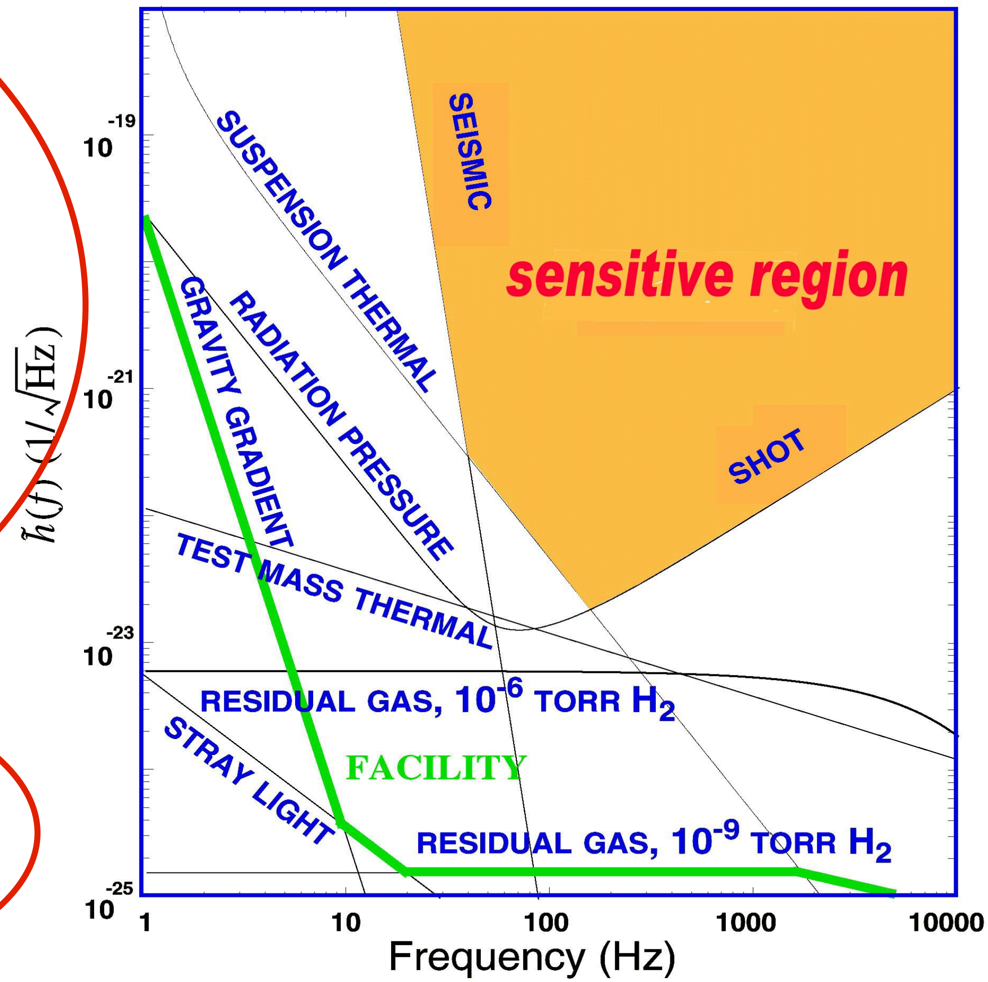
CNRS/INFN collaboration; has joint operating agreement w/ LIGO

What Limits Sensitivity of Interferometers?

DESIGN

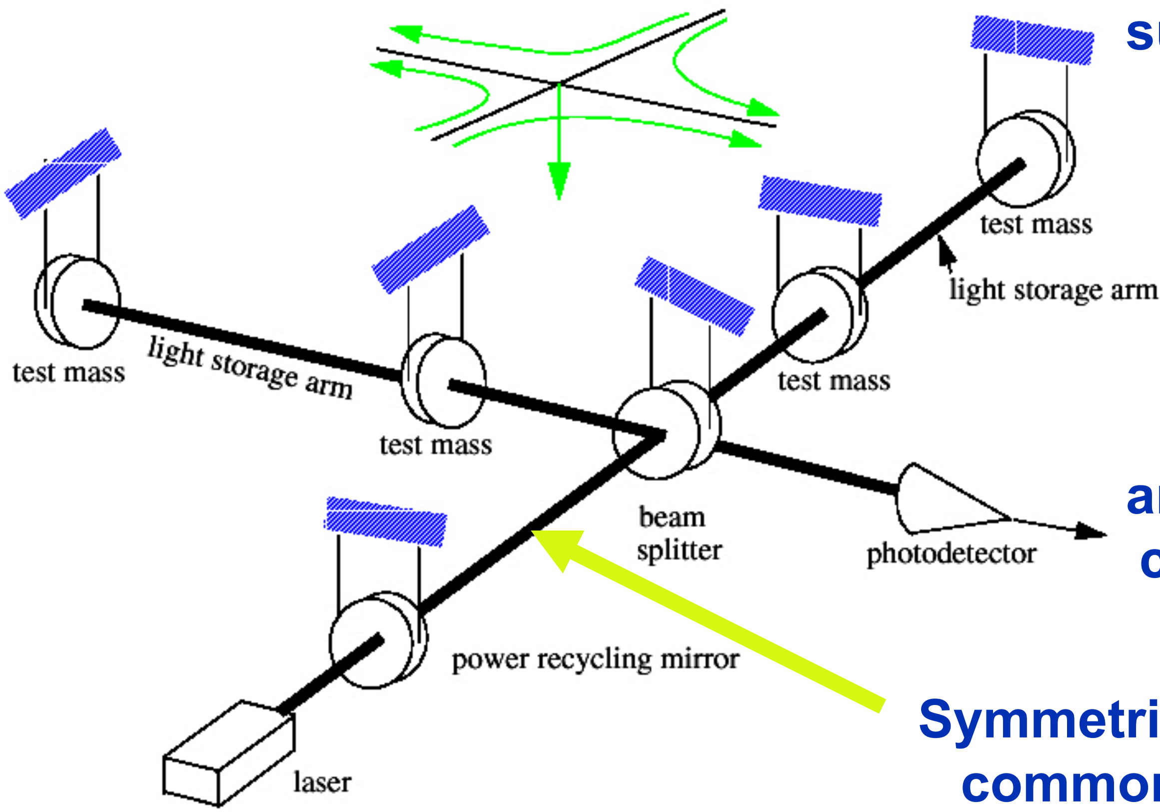
- Seismic noise & vibration limit at low frequencies
- Atomic vibrations (Thermal Noise) inside components limit at mid frequencies
- Quantum nature of light (Shot Noise) limits at high frequencies
- Myriad details of the lasers, electronics, etc., can make problems above these levels

COMMISSIONING



Raab: Pre-tour (technical edition)

Initial LIGO: Power-recycled Fabry-Perot-Michelson



suspended mirrors mark inertial frames

antisymmetric port carries GW signal

Symmetric port carries common-mode info

Intrinsically broad band and size-limited by speed of light.

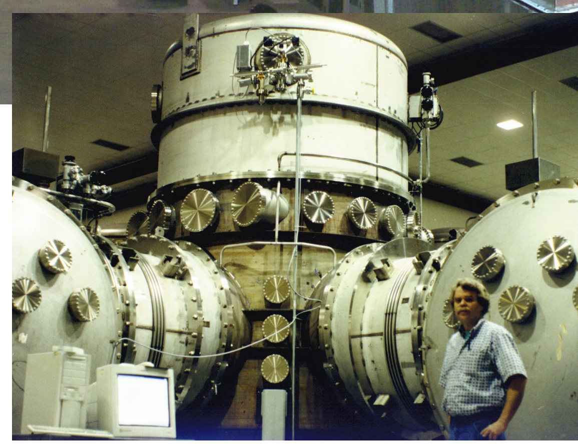
Evacuated Beam Tubes Provide Clear Path for Light

$P < 10^{-9}$ Torr

Portable power supply for bakeout

Vacuum Chambers Provide Quiet Homes for Mirrors

View inside Corner Station



Standing at vertex beam splitter

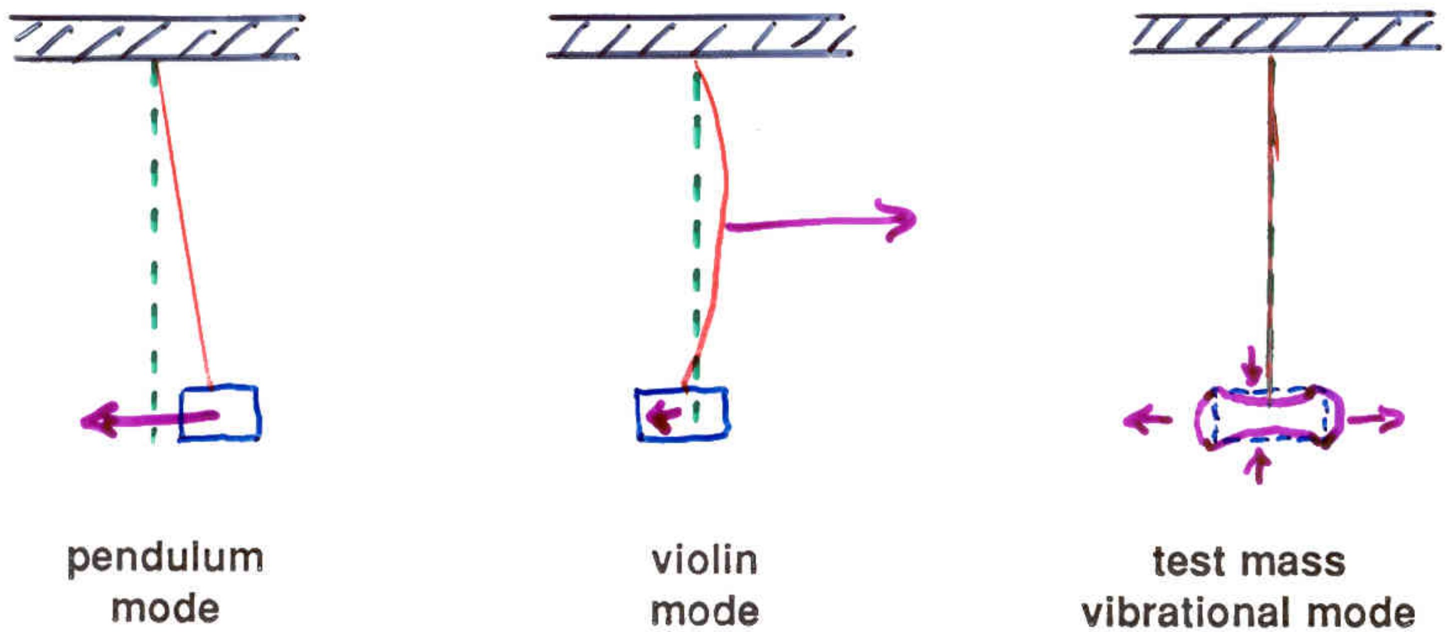
Seismic Isolation

- Strategy is to use cascades of passive springs, pendula, and active controls to approximate a “brick-wall” mechanical filter
- There is some effective frequency, f_{low}, below which seismic and other vibrations will dominate and above which external vibrations have little or no effect
  - » ~ 40 Hz for iLIGO; ~10 Hz for Virgo
  - » ~ 10 Hz for Advanced LIGO and Virgo
- Below f_{low} a control system must actively “zig” the mirrors just enough to cancel any “zag” of the lab, so the mirror remains motionless in space
- Strength of controls is limited to prevent injection of electronic noise above f_{low}
- Saturation of the control signal will occur above some threshold level of external vibration

Thermal noise

- Atom in a solid at room temperature moves of order a tenth of an atomic diameter, whereas required mirror resolution is of order a billionth of an atomic diameter
- Strategy is not to measure where a particular atom is, but to average over as many atoms as possible; variance of this average over the the mirror surface is known at thermal noise
- To reduce thermal noise:
  - » Design mechanical resonances out of the “signal band “ of the detector
  - » Maximize Q to draw as much of kT of energy into a narrow resonance, thus depleting energy in the wings of the resonances
- Major contributors are due to motions of atoms in the mirrors, atoms in the suspension wires, possibly residual gas atoms

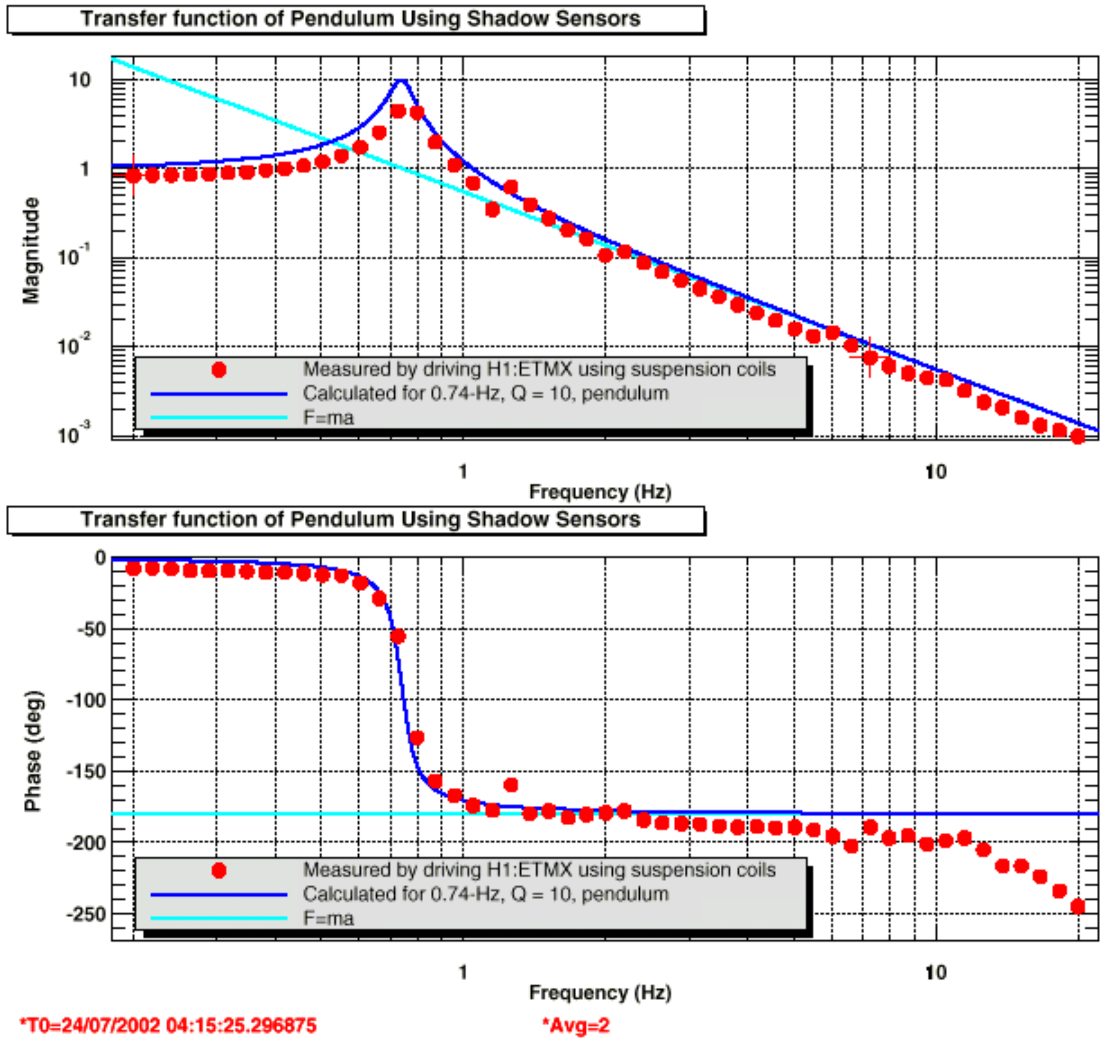
Background Forces in GW Band = Thermal Noise ~ $k_B T$/mode



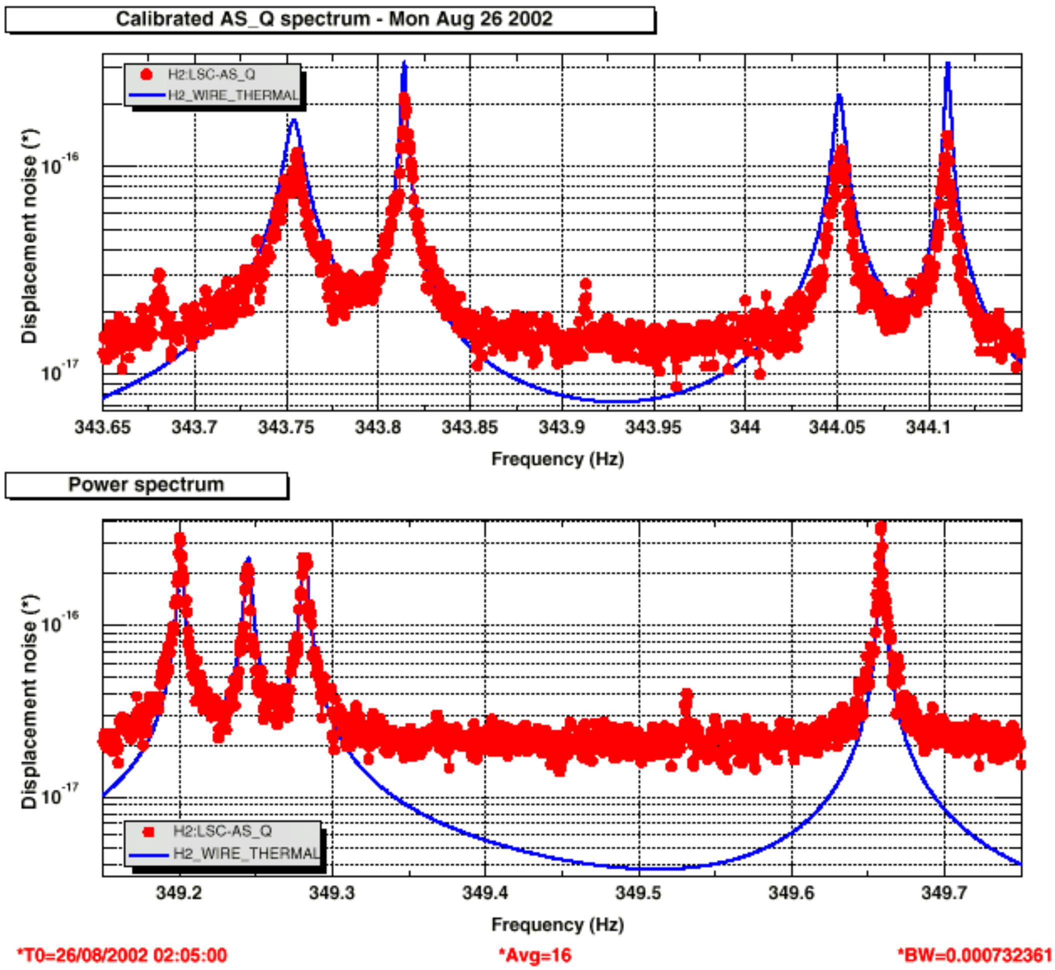
pendulum mode	violin mode	test mass vibrational mode
$x_{rms} \approx 10^{-11}$ m	$x_{rms} \approx 2\times10^{-17}$ m	$x_{rms} \approx 5\times10^{-16}$ m
$f < 1$ Hz	$f \sim 350$ Hz	$f \geq 10$ kHz

Strategy: Compress energy into narrow resonance outside band of interest ⇒ require high mechanical Q, low friction

Suspended Mirror Approximates a Free Mass Above Resonance

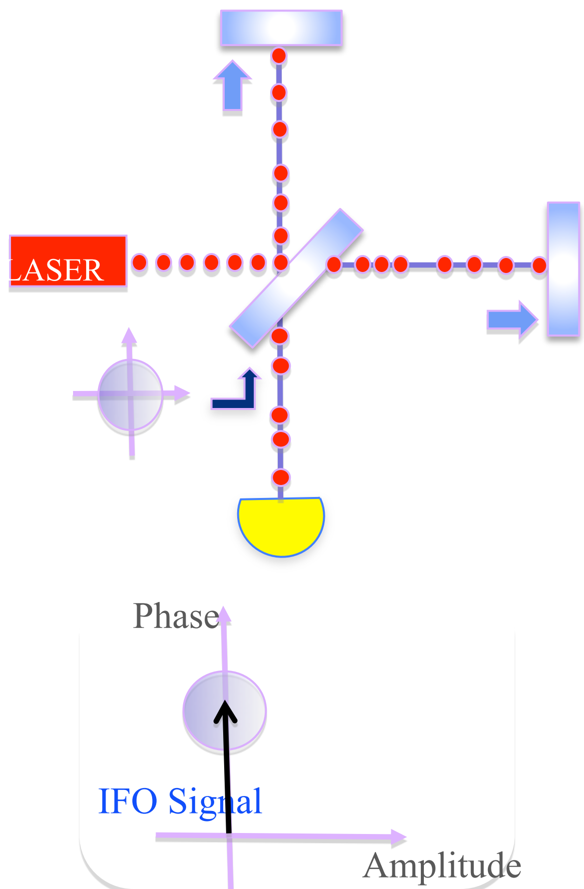


Thermal Noise Observed in 1st Violins on H2, L1 During S1



Almost good enough for tracking calibration.

Quantum Noise and Vacuum



- ✧ Quantum noise is produced by vacuum fluctuations entering the open ports
- ✧ Vacuum fluctuations have equal uncertainty in phase and amplitude:
  - ❖ Phase: Shot-Noise (photon counting noise)
  - ❖ Amplitude: Radiation Pressure Noise (back-action)

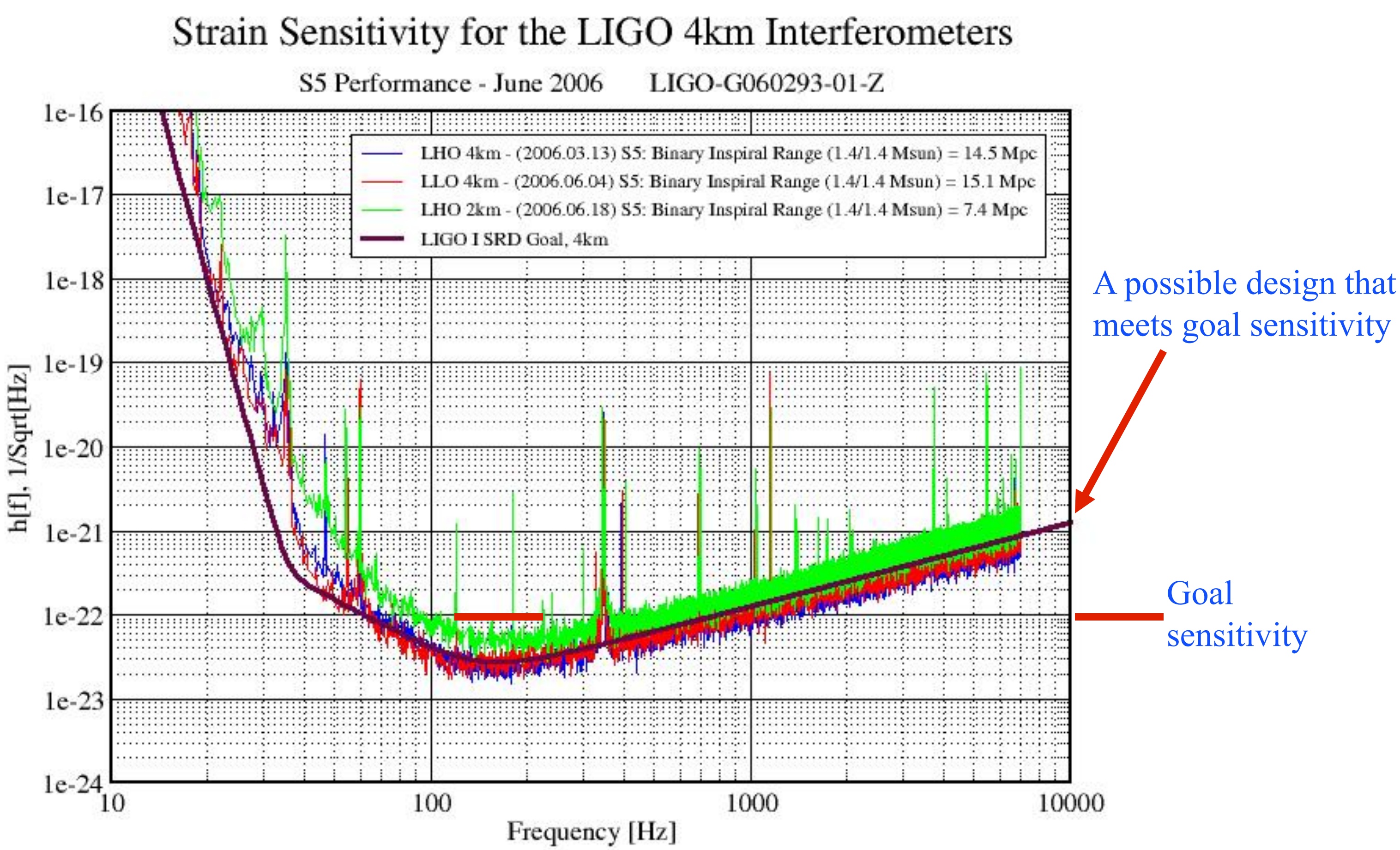
iLIGO was the most sensitive machine on Earth

- ✓ Typical Strains < 10^{-21} at Earth ~ 1 hair's width at 4 light years
- ✓ Resolve displacement fluctuations of 4-km arms at the milli-fermi level (1/1000th of a proton diameter)
- ✓ Control km-scale arm lengths to 1/1000th of atomic diameter
- ✓ Detect optical phase changes of billionths of a degree
- ✓ Hold mirror alignments to millionth of a degree in angle
- ✓ Engineer structures to mitigate recoil from atomic vibrations in suspended mirrors
- Do all of the above 7x24x365

✓ S5 science run 14Nov05 to 30Sep07

✓ S6 science run 08Jul09 to 20Oct10

Initial LIGO (iLIGO) detectors were working to 1989 design goals



Science to date

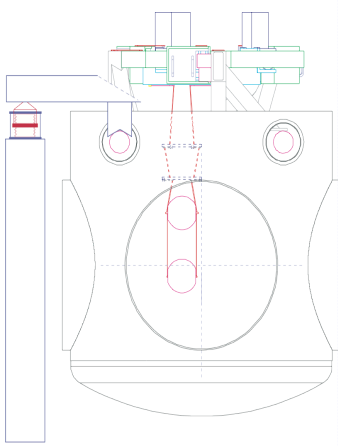
- No published detection yet, but ~68 papers based on search data interpretation, such as
  - » Limit on %-age of energy emitted by Crab Pulsar going into GWs
  - » Limits on the ellipticities of known pulsars
  - » Limit on GW background from early universe
  - » Limits on GW waves emitted by GRBs and SGRs
  - » Limits on rates of mergers of black holes and neutron stars
  - » Determined that the short GRB 070201, possibly in M31, was either a compact binary merger at much greater distance or a different source in M31, such as an SGR
  - » Developed and tested protocols for electromagnetic-observatory follow-ups of gravitational-wave triggers

Moving on to aLIGO

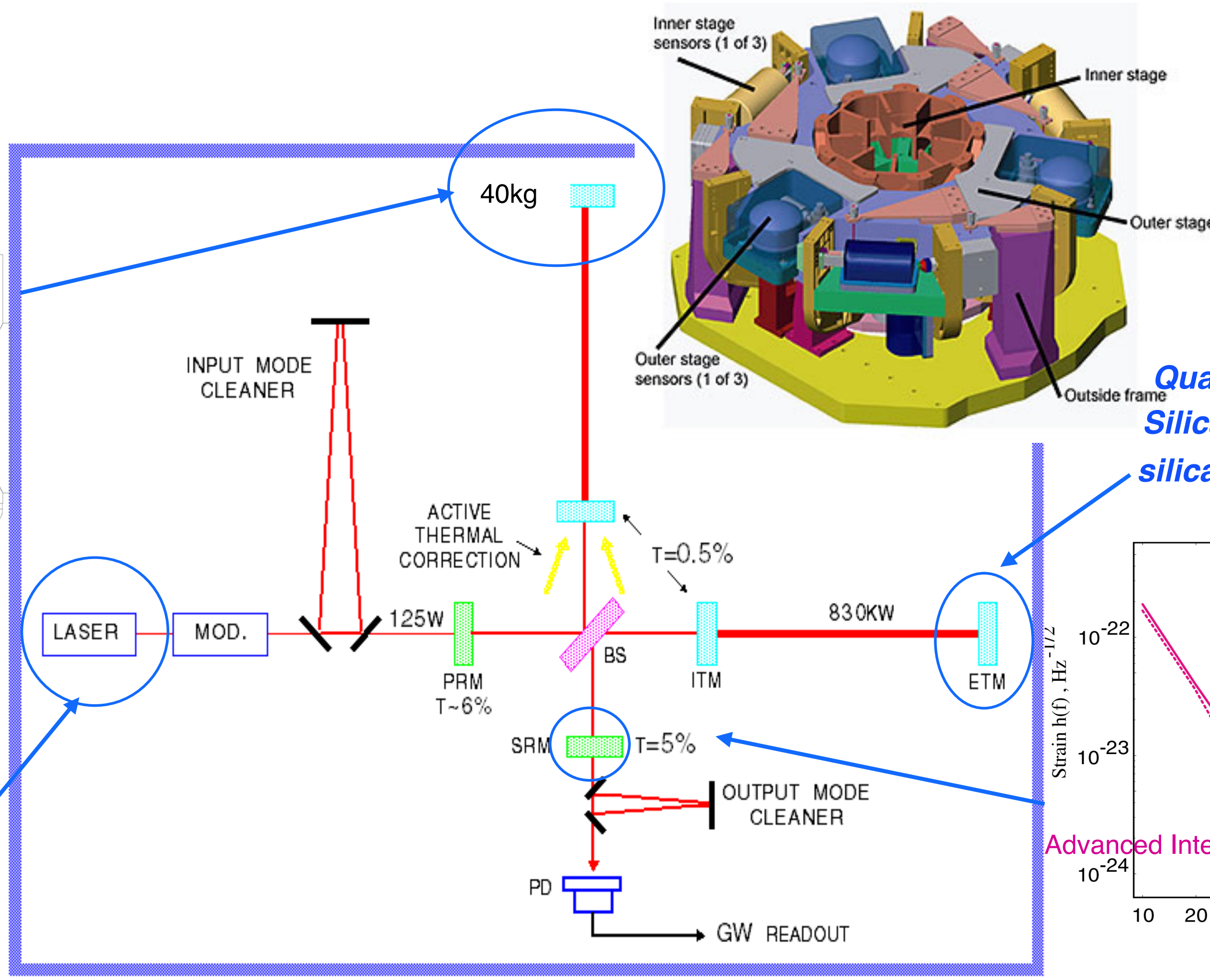
- Two decades of LIGO-driven R&D and lessons learned from Initial LIGO have resulted in:
  - » Superior laser, mirror and optical technology
  - » Superior vibration isolation technology
  - » Superior control-system technologies
  - » Refinements in understanding and reducing manifestations of atomic motion
- Funding for Advanced LIGO construction began in 2008
- 2011 is peak year of construction and beginning of installation
- 2014 delivery for operational detectors, followed by commissioning to design sensitivity
- At design sensitivity, expect monthly to weekly detections of black hole formations

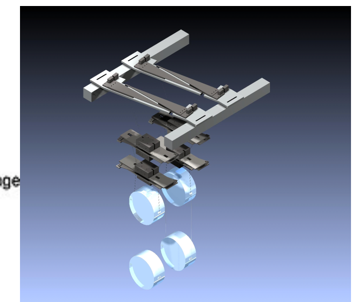
Advanced LIGO construction (aLIGO) started 1Apr2008

Major technological differences between LIGO and Advanced LIGO

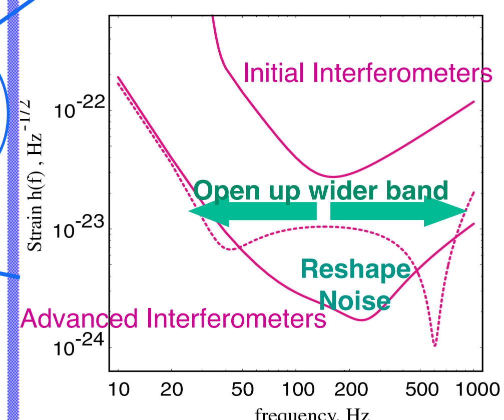


Active vibration isolation systems





Quadruple pendulum: Silica optics, welded to silica suspension fibers

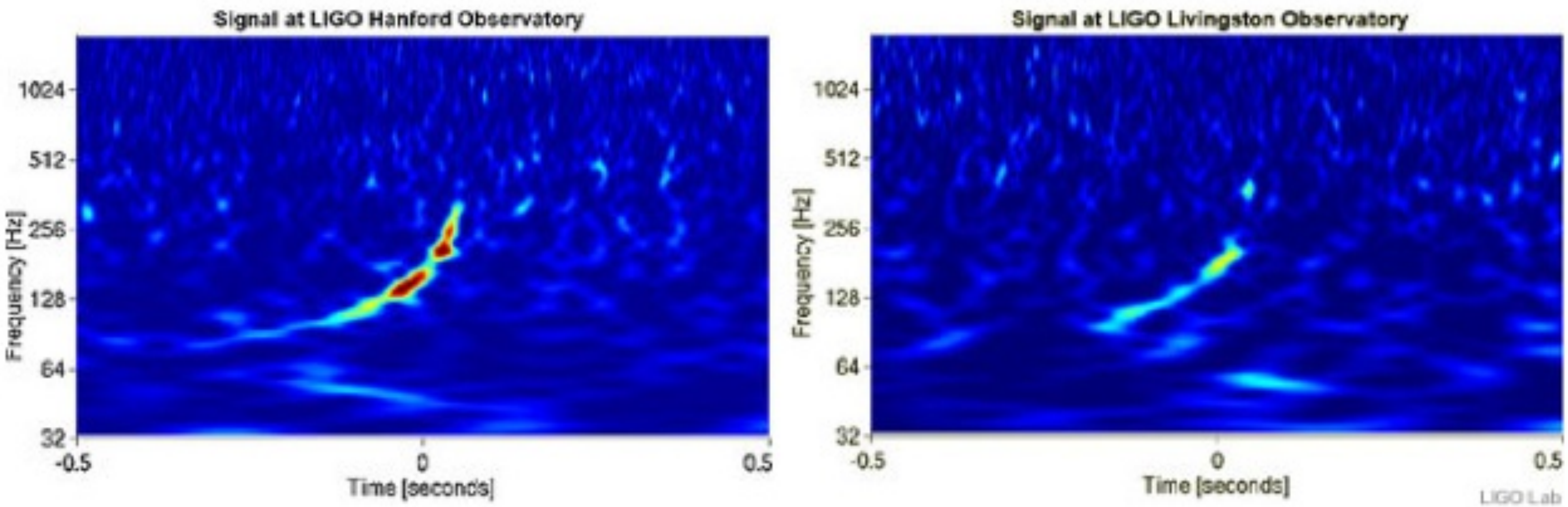


High power laser (180W)

Advanced interferometry Signal recycling

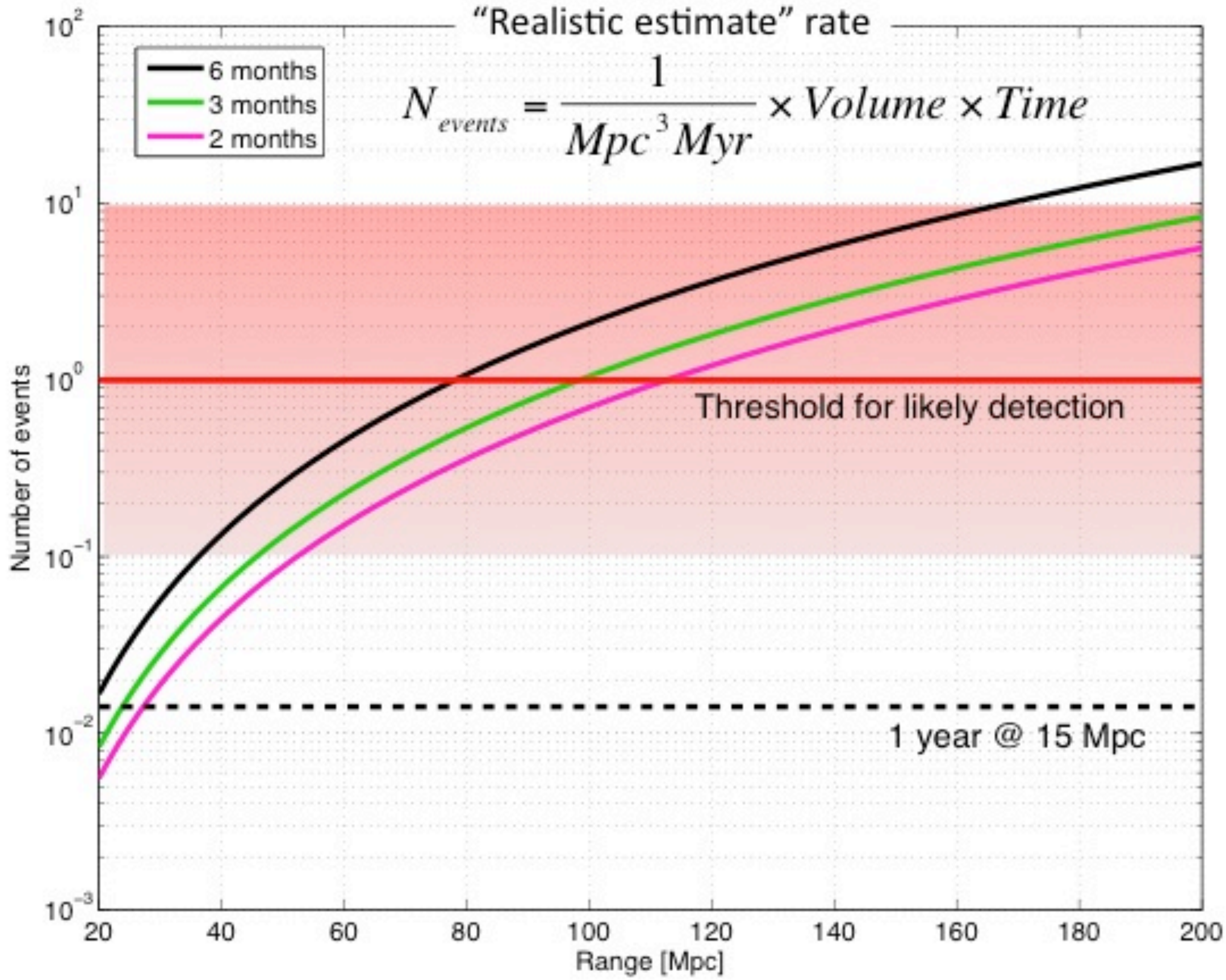
aLIGO installation in progress

What a real detection looks like (almost)



http://www.ligo.org/news/blind-injection.php
http://news.discovery.com/space/ligos-little-black-box-110317.html
http://blogs.discovermagazine.com/cosmicvariance/2011/03/15/ligo-to-collaboration-members-there-is-no-santa-claus/

Criteria for early science runs



But it's never as easy as it looks in the lecture hall…