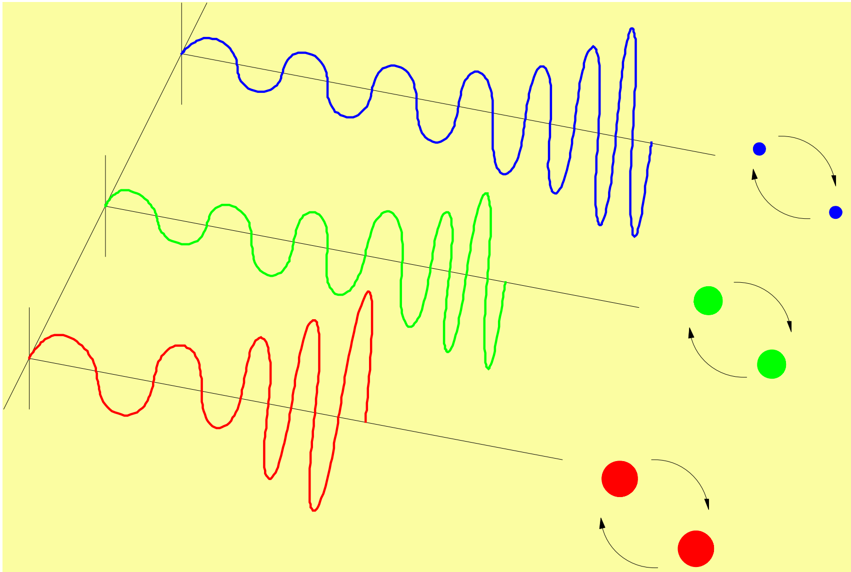
LIGO: Seeing the Cosmos with New Eyes

How does LIGO see?
What has LIGO seen?
What could LIGO see?



Alan Wiseman

University of Wisconsin– Milwaukee

(for the LIGO Scientific Collaboration)

La Thuile

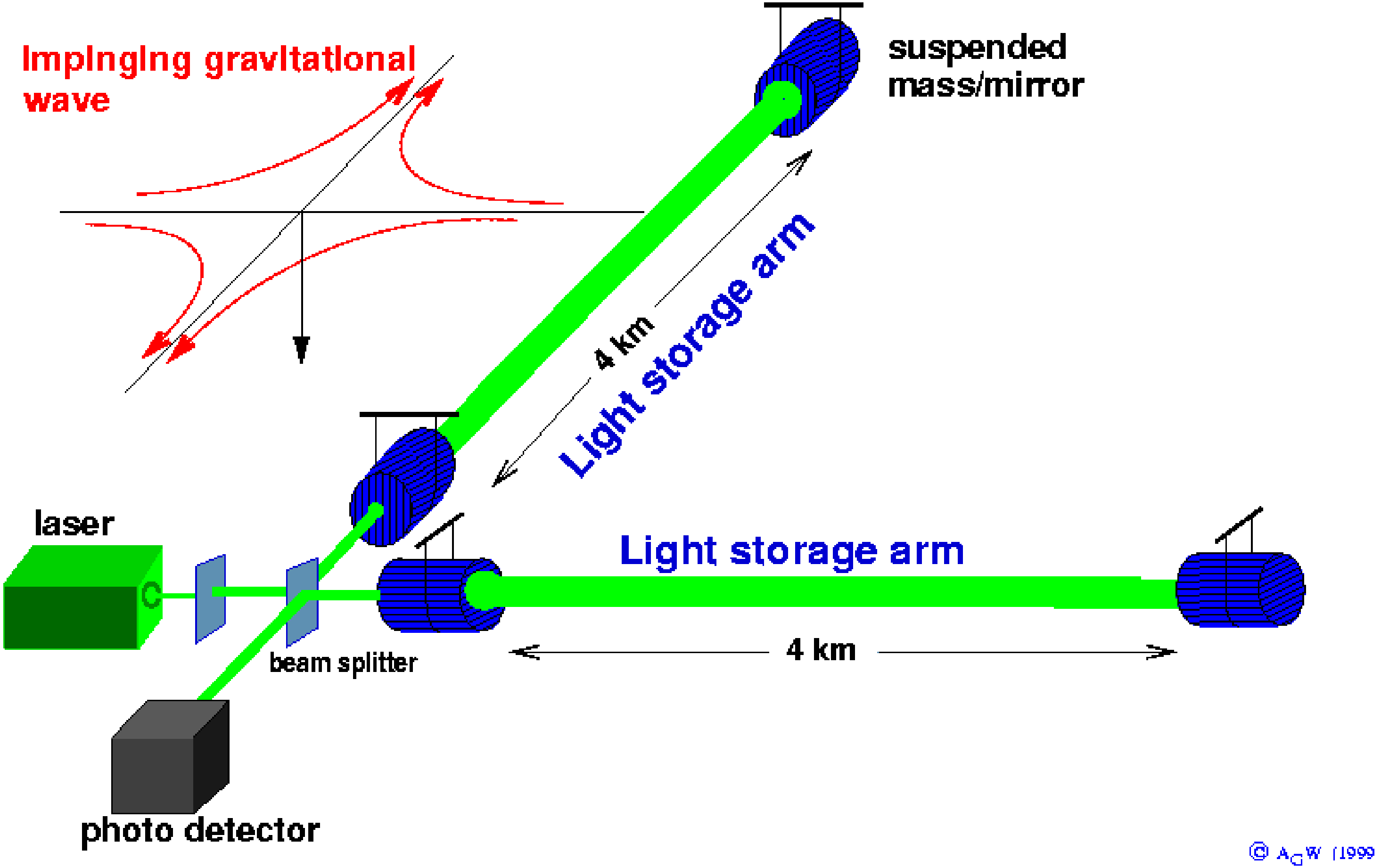
28-February-05

Seeing LIGO

- **The New Eyes:**
  - » What Does LIGO See? Gravitational waves
  - » How Does LIGO See?

- **Seeing the Universe**
  - **What has LIGO Seen?**
    - **Recent results**
  - What could LIGO see?
    - The prospects for the future

The basic layout



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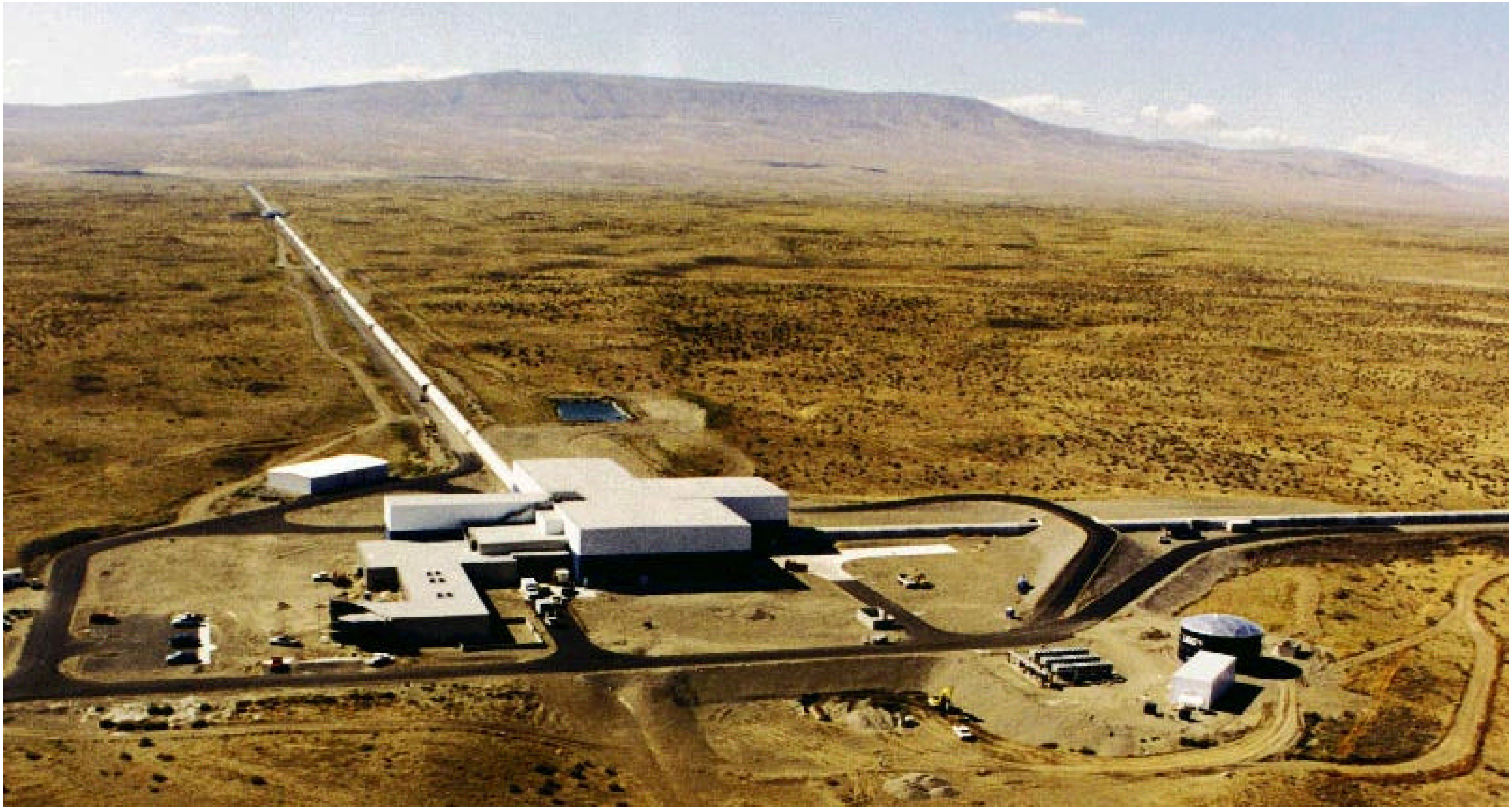
LIGO Hanford Observatory



LIGO Livingston Observatory

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LIGO Facilities

beam tube enclosure

- **minimal enclosure**
- **reinforced concrete**
- **no services**

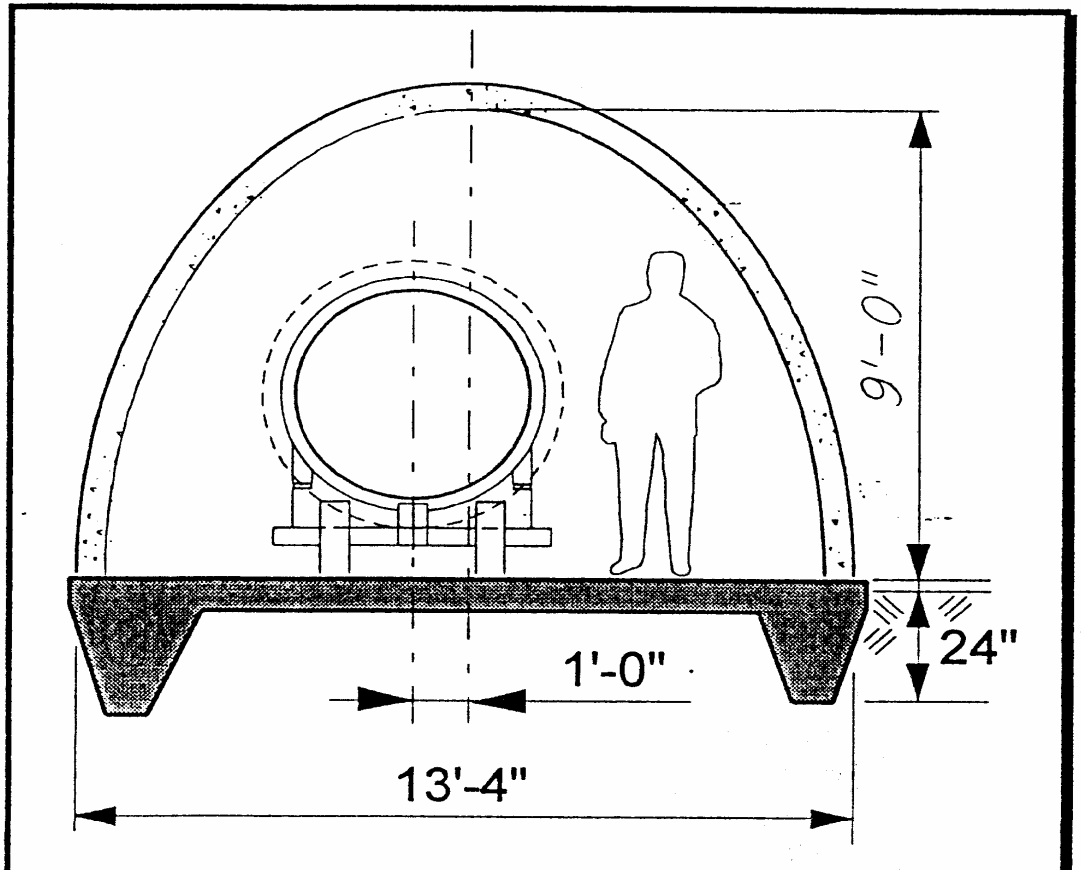


Figure 2.1-1 -- Cross Section of Design Baseline at Hanford

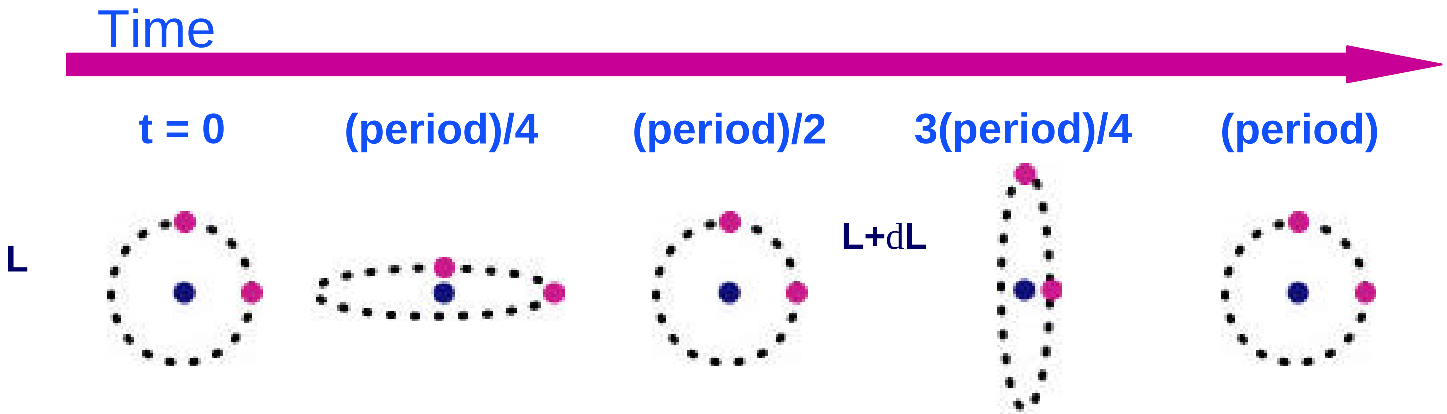
LIGO
beam tube

- LIGO beam tube under construction in January 1998
- 65 ft spiral welded sections
- girth welded in portable clean room in the field

1.2 m diameter - 3mm stainless
50 km of weld

Physical Effects of the Waves

- As gravitational waves pass, they change the distance between neighboring bodies



Time

t = 0 **(period)/4** **(period)/2** **3(period)/4** **(period)**

L

L+dL

- Fractional change in distance is the strain given by

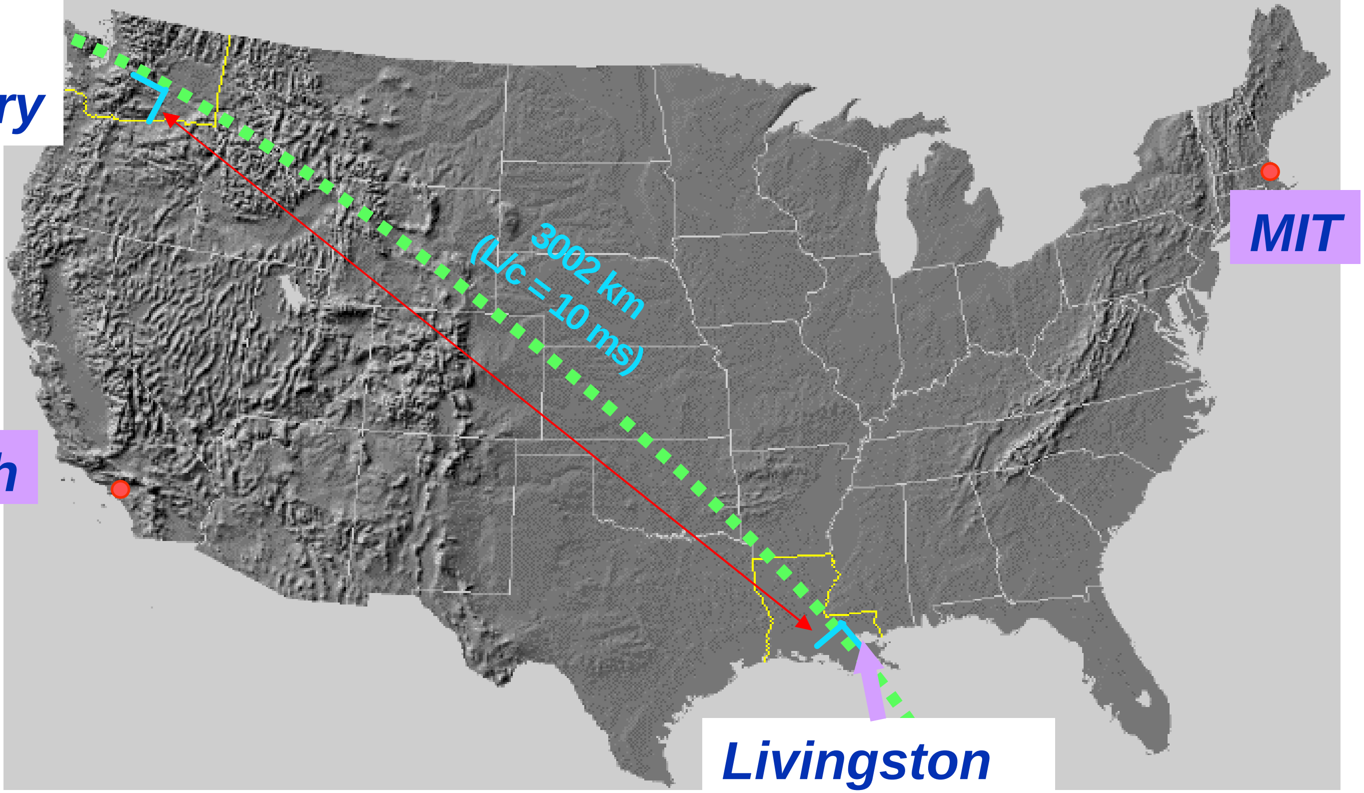
$$h = \delta L / L$$

- Technical Points:
  - **Radiation is transverse:no distortion along the line of motion**
  - **Radiation field is traceless: Area of the loop stays constant**

Second Technical Point:

- **Spin-2 massless field: two polarizations**
- **Second polarization: rotate the diagram 45degress**

Note the orientation



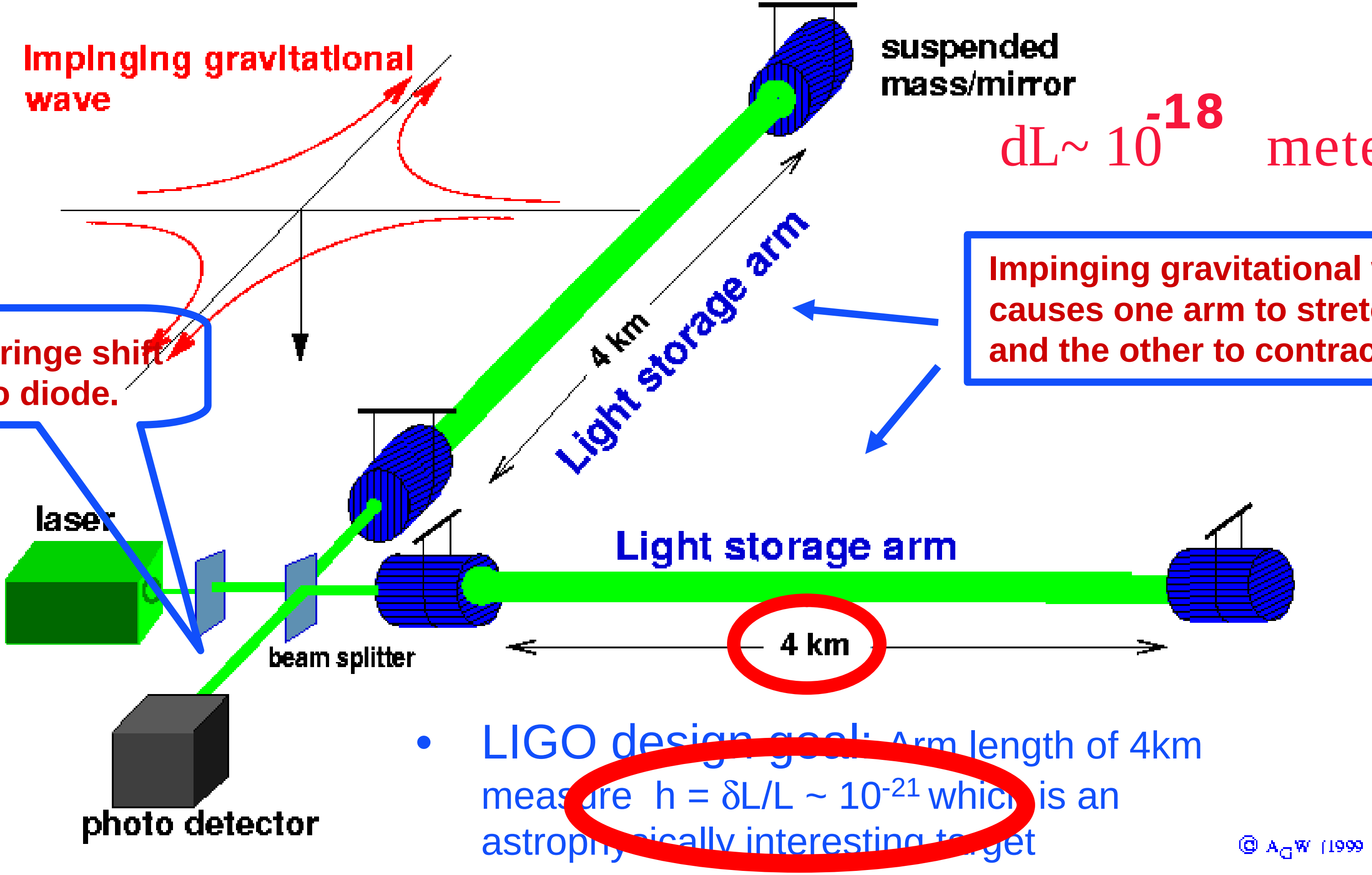
Hanford Observatory

MIT

Caltech

Livingston Observatory

How does LIGO See?



$dL \sim 10^{-18}$ meters

Impinging gravitational wave causes one arm to stretch and the other to contract.

Causing a fringe shift at the photo diode.

- LIGO design goal: Arm length of 4km measure $h = \delta L/L \sim 10^{-21}$ which is an astrophysically interesting target

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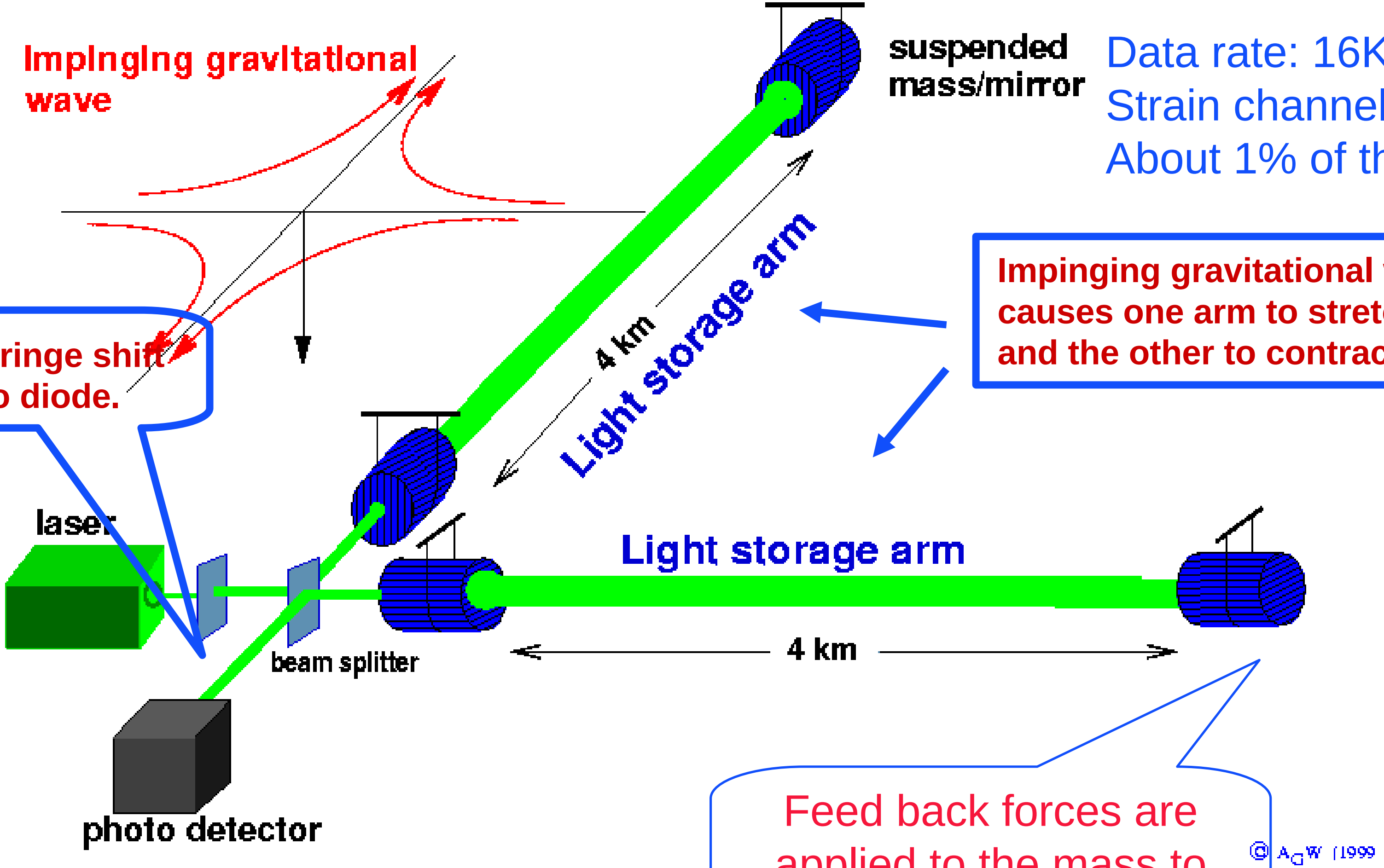
How does LIGO See?

Data rate: 16KHz
Strain channels onl
About 1% of the da



Impinging gravitational wave causes one arm to stretch and the other to contract.

Causing a fringe shift at the photo diode.

Feed back forces are applied to the mass to keep the PD near dark

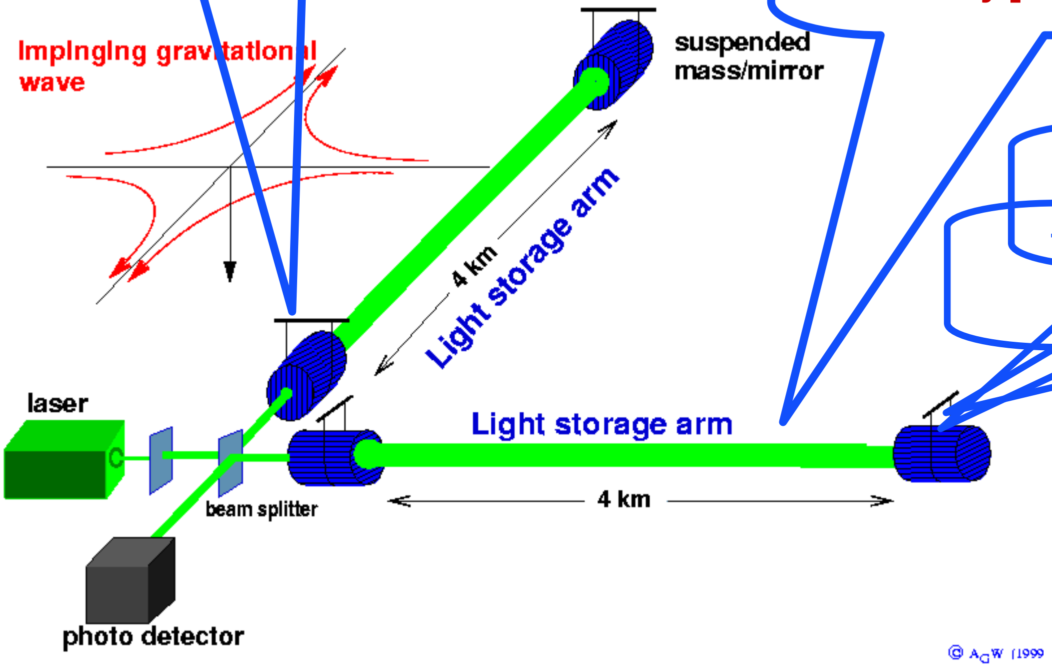
What Limits The Vision?

Seismic noise

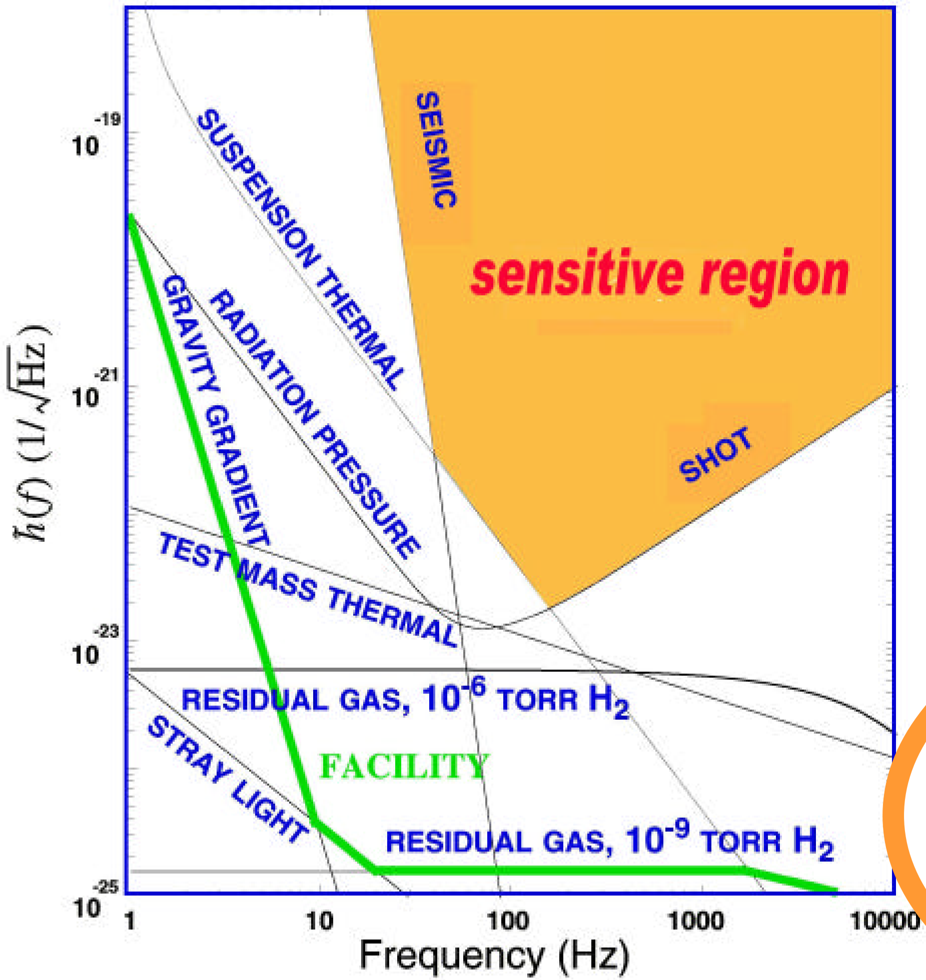
Photon Counting Statisitics [Shot noise, photons arrive “randomly’]

Thermal noise (kT) in the suspension wires

Thermal noise. Laser heats the mirror



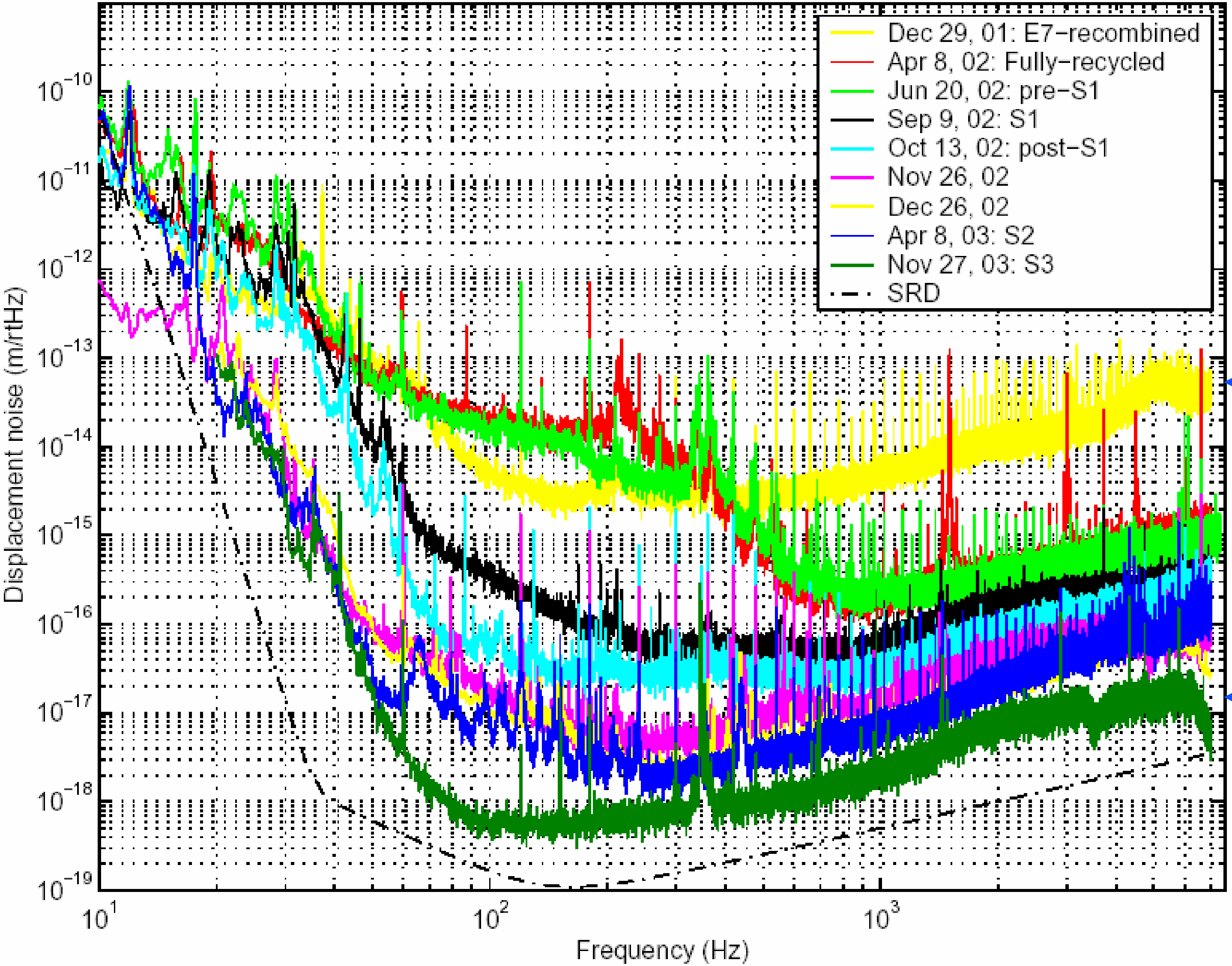
What Limits LIGO Sensitivity?



- Seismic noise limits low frequencies
- Thermal Noise limits middle frequencies
- Quantum nature of light (Shot Noise) limits high frequencies
- Technical issues - alignment, electronics, acoustics, etc limit us befor we reach these design goal

LIGO Sensitivity Evolution

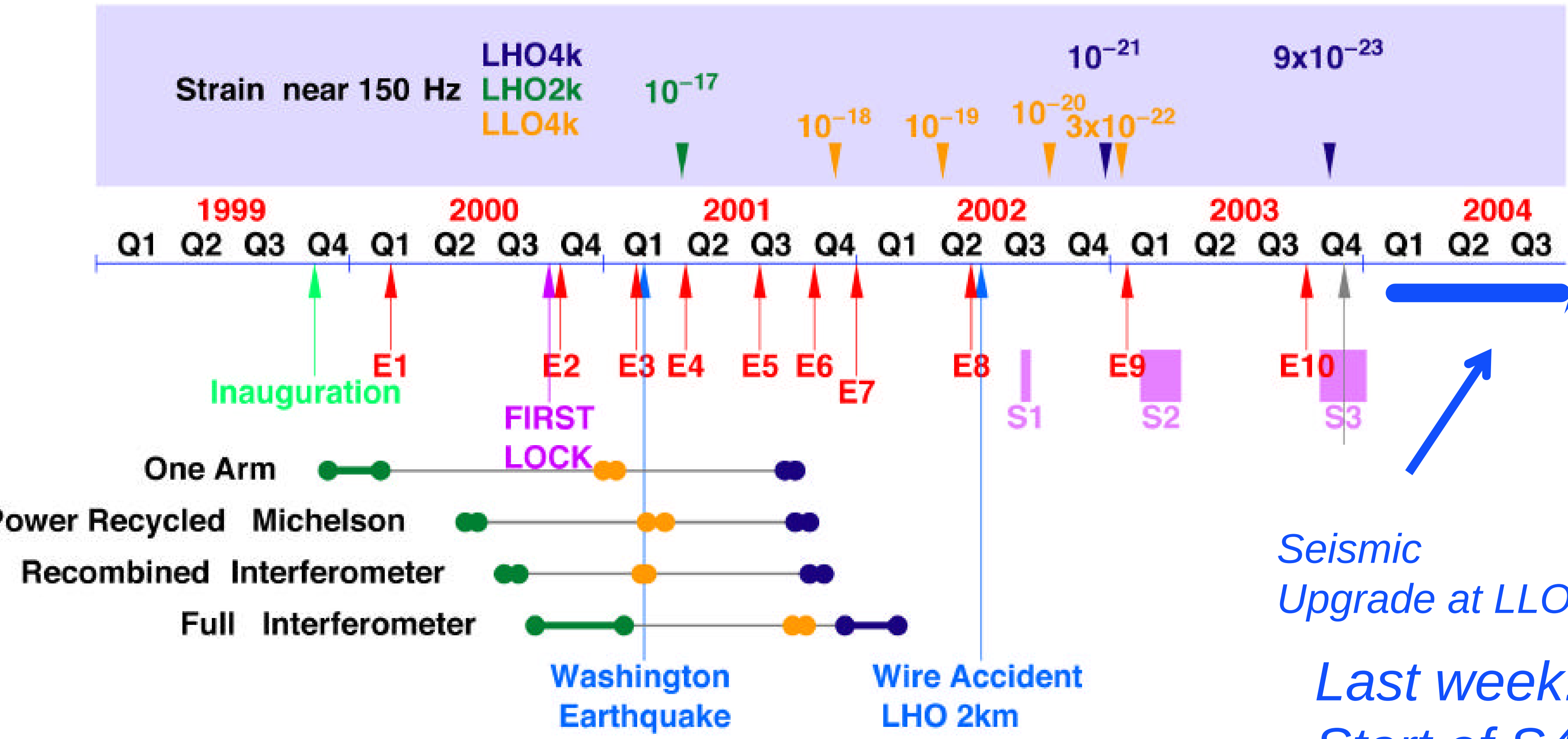
Hanford 4km Interferometer



Dec 01

Nov 03

LIGO Commissioning and Science Timeline



Seismic Upgrade at LLO

Last week
Start of S4

LIGO Livingston Observatory

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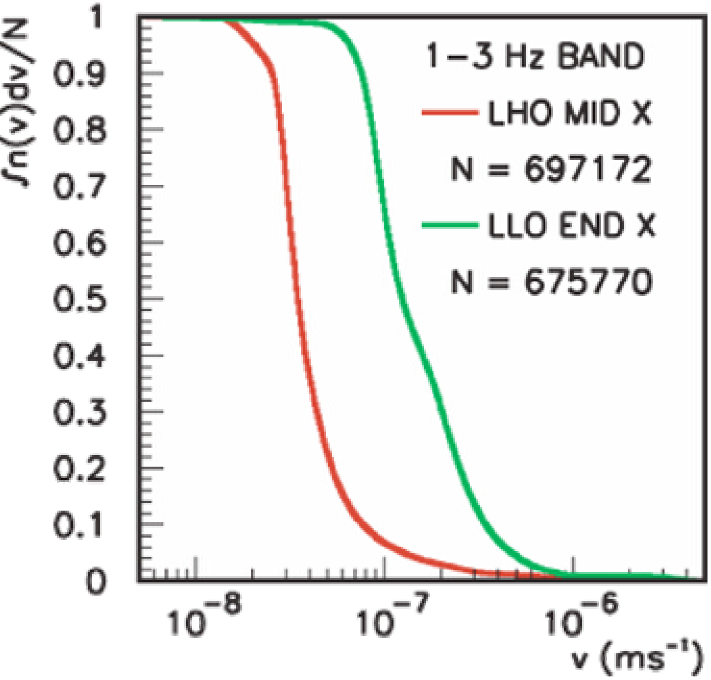
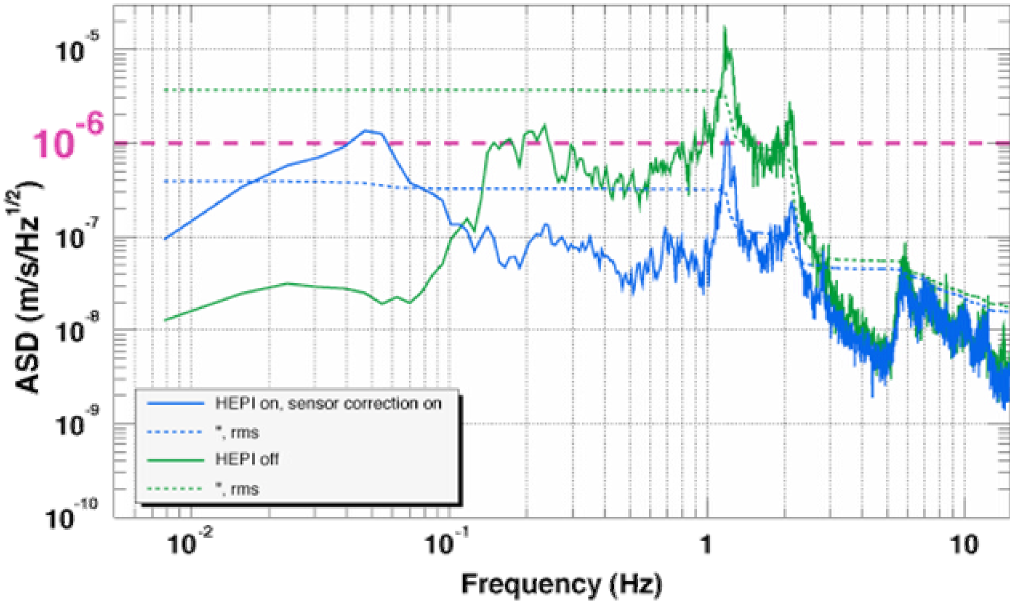
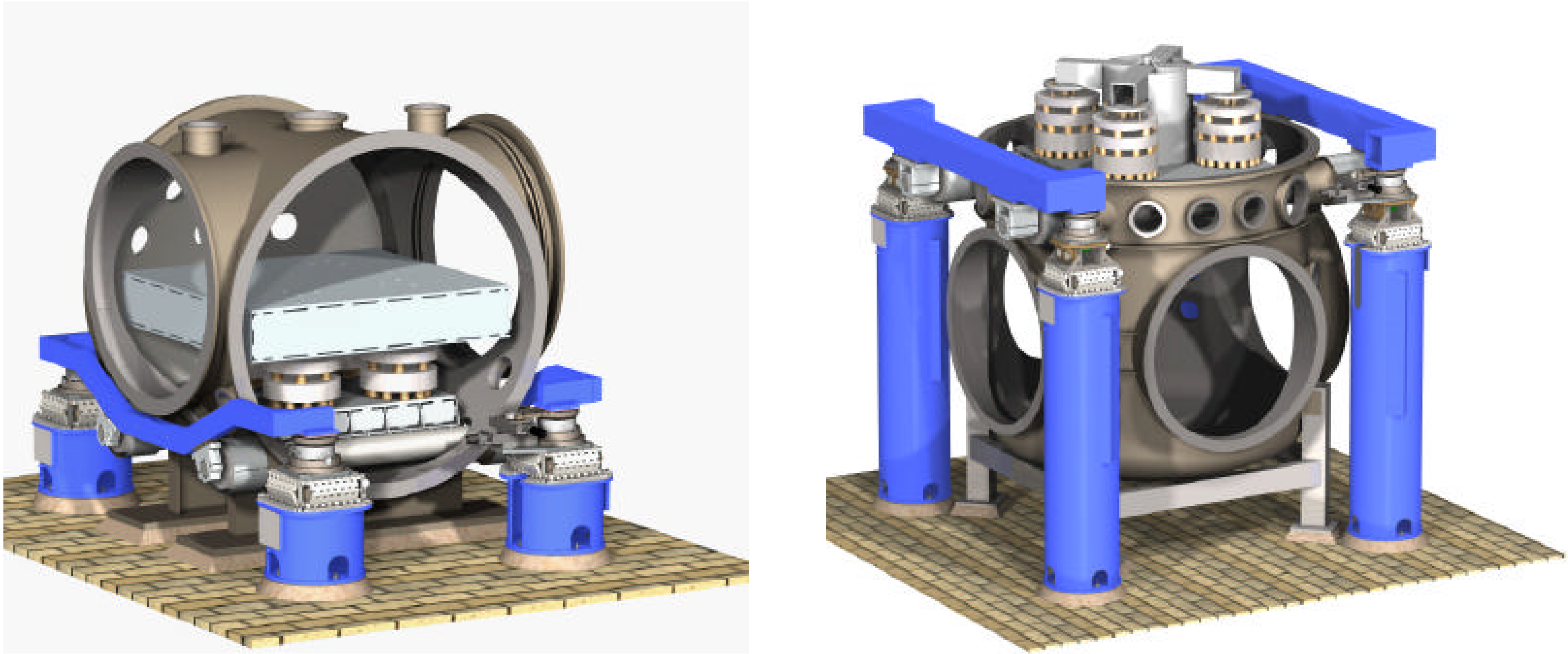
The noise gets in the way of seeing





Vacuum Chambers

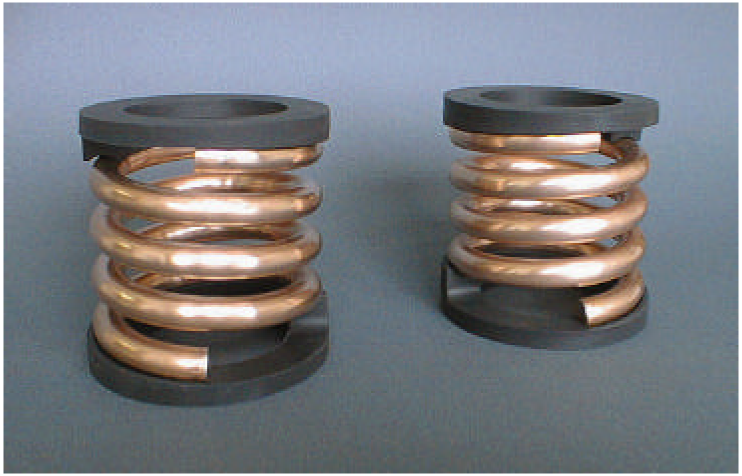
vibration isolation systems



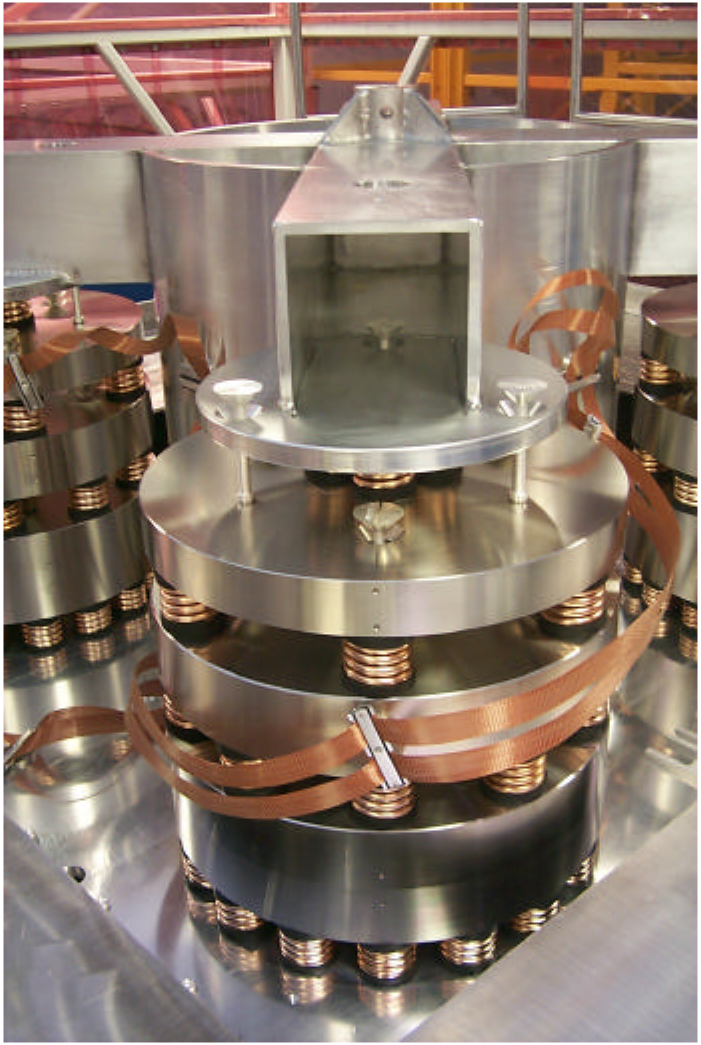
- » Reduce in-band seismic motion by 4 - 6 orders of magnitude
- » Compensate for microseism at 0.15 Hz by a factor of ten
- » Compensate (partially) for Earth tides

Seismic Isolation

springs and masses



Constrained Layer damped spring



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LIGO
vacuum equipment

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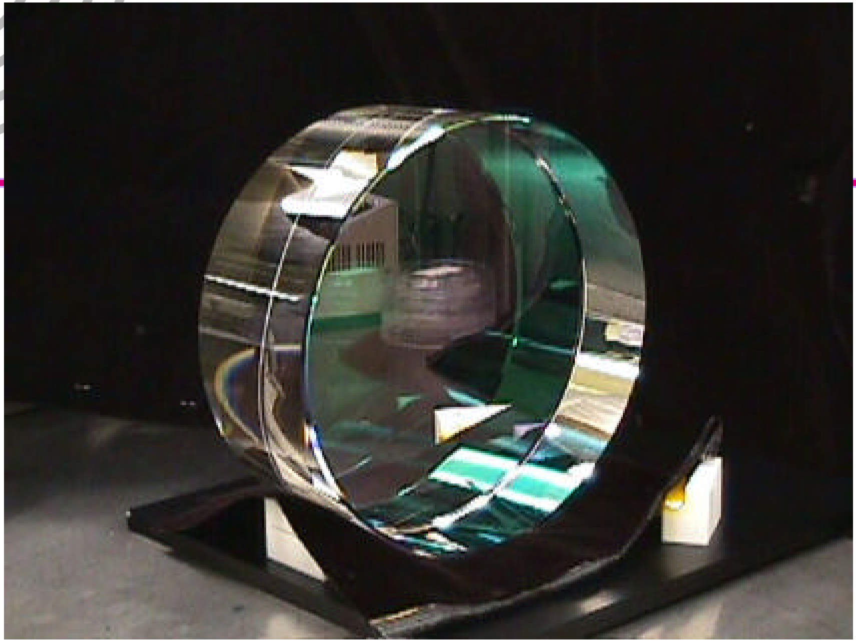
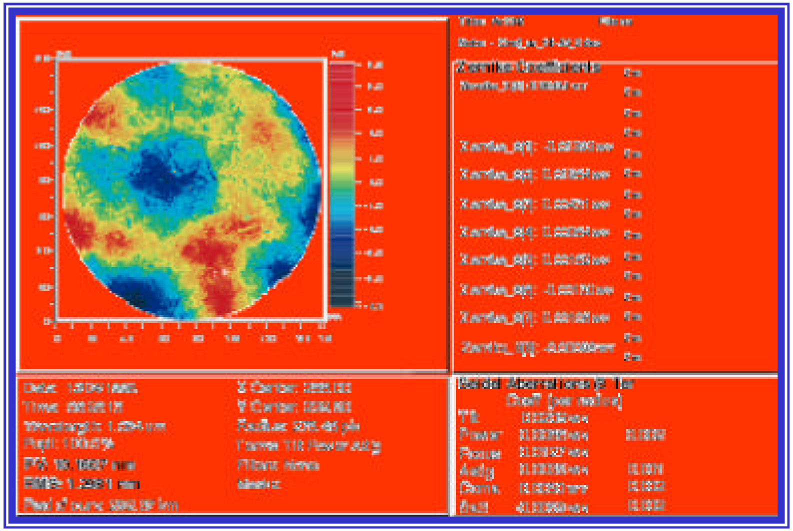
LIGO Optics

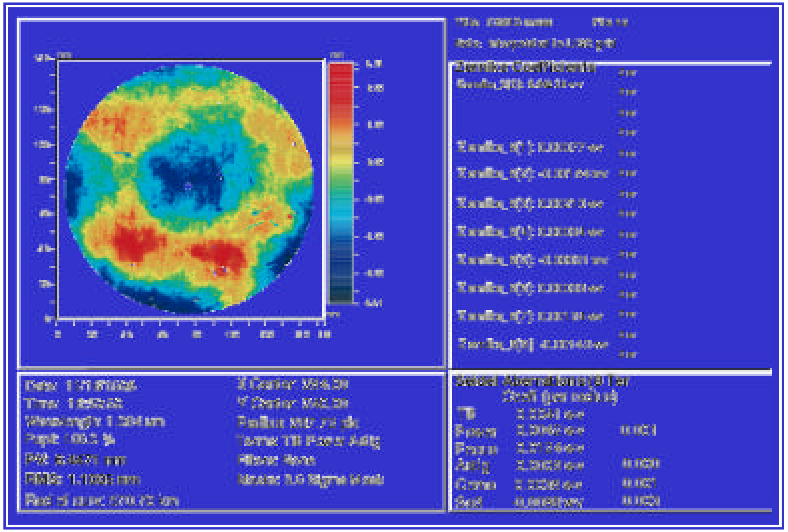
fused silica



- Surface uniformity < 1 nm rms
- Scatter < 50 ppm
- Absorption < 2 ppm
- ROC matched < 3%
- Internal mode Q’s > 2 x 10^6

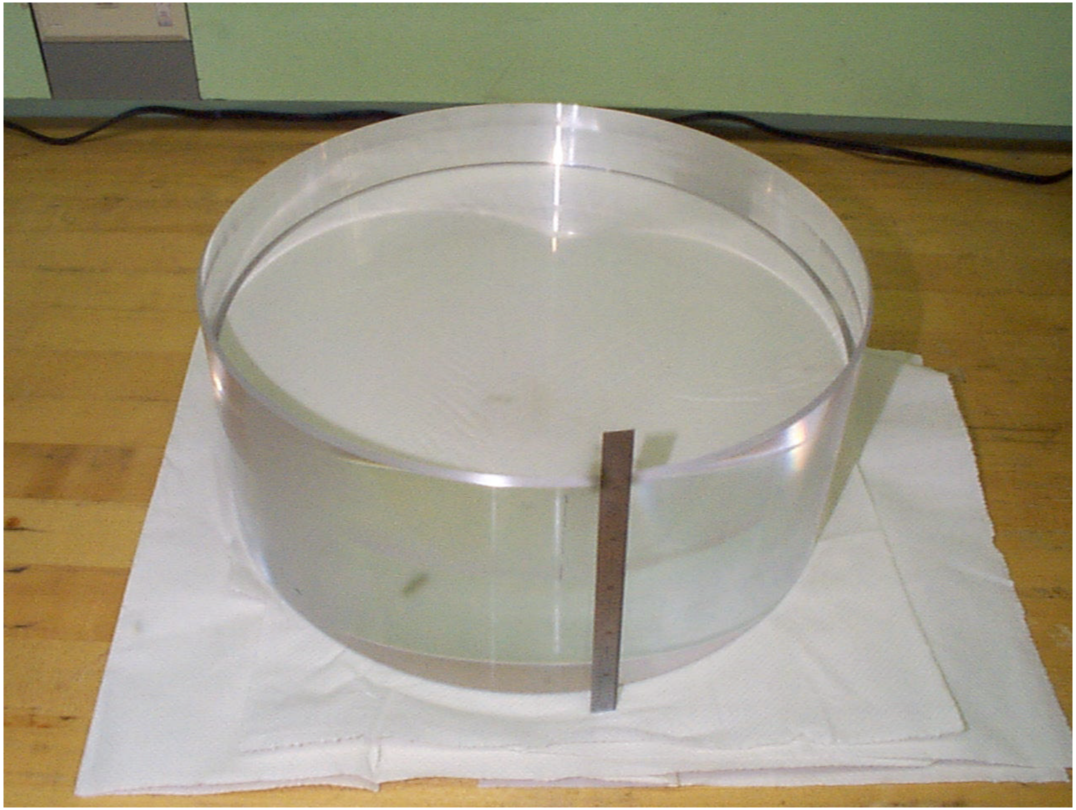


Caltech data



CSIRO data

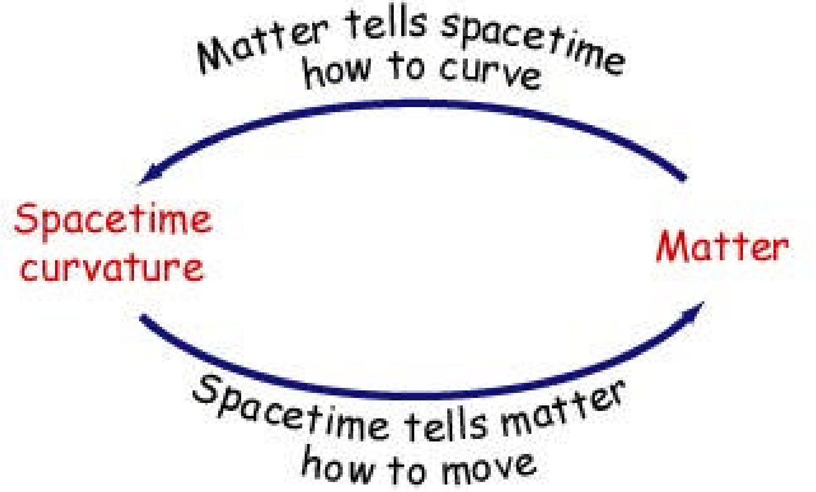
Test Masses / Core Optics



Full-size Advanced LIGO
sapphire substrate

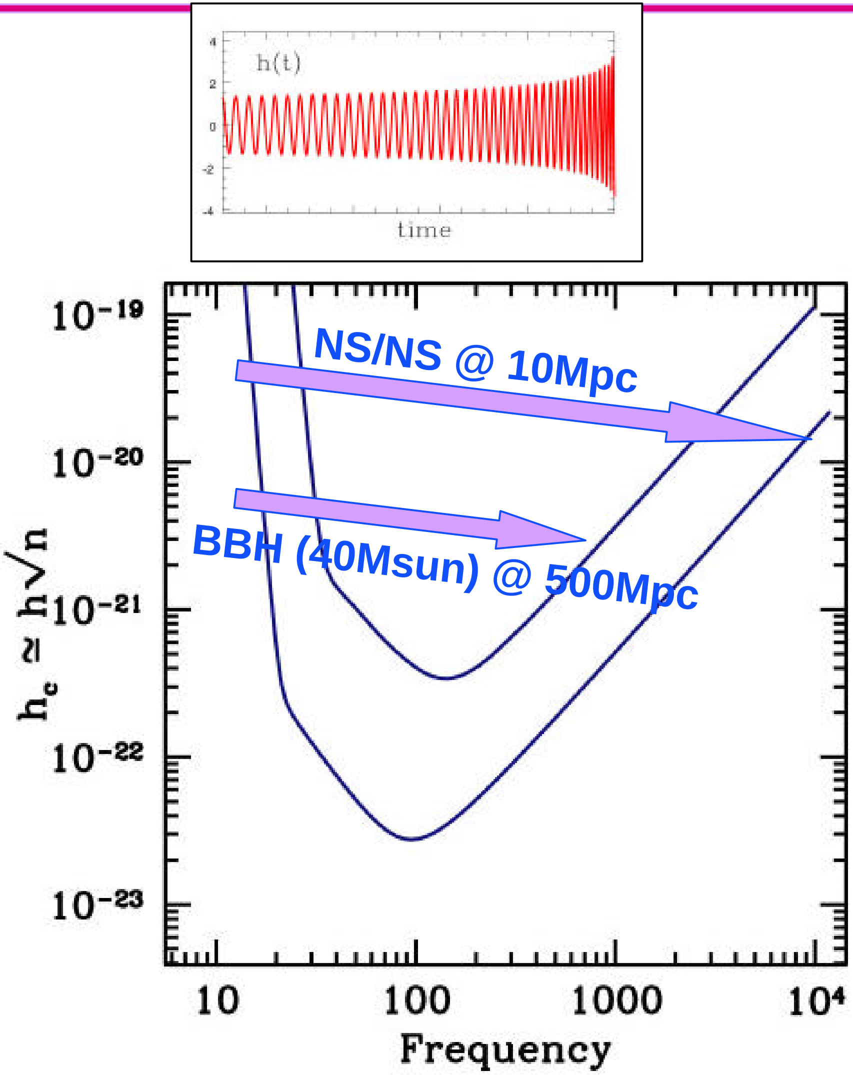
What does LIGO See?

- Einstein’s field equations (1915):
  - » Relate the curvature of spacetime to the stress-energy of matter
- Uber die Gravitationswellen (Einstein 1918):
  - » Shows that his equations reduce to wave-equations in weak-field limit



- Essence of EFE’s:
  - » When matter moves, or changes its configuration, its gravitational field changes.
  - » This change propagates outward as a ripple in the curvature of spacetime: a gravitational wave.

Neutron Star or Black Hole Binary Inspiral



- **General properties:**
  - » Well understood signal – chirps through the band
  - » Promising (but not optimistic) event rate
- Neutron Star Binaries
  - » Known to exist (Hulse-Taylor)
  - » Initial: D_{eff}=20Mpc, R< 1/(3yr)
  - » Advanced: 1/(yr)<R< 2/(day)
  - » EOS via tidal disruption (Vallisneri)
- NS/BH, BH/BH
  - » New science: rates, dynamics of gravitational field, merger waves
  - » Initial: D_{eff}<100Mpc, R< 1/(yr)
  - » Advanced: 1/(yr)<R< 10/(day)

-

Modeling signals from binaries

- Inspiraling neutron stars, are expected to be “clean” systems. Signal won’t be (much) affected by accretion disks.
- Scale: ns ~ 10km in radius
  orbit~ few 10’s of km
  frequency of signal ~ sweep from 10Hz -1000Hz
  duration ~ 10’s of seconds
- Tidal effects aren’t very important (until just before splat)
- Systems parameterized a few numbers, eg two masses
- Spins aren’t very important (for some systems)
- Method of calculation: Perturbative “post Newtonian” calcuation. Iterate in v/c and GM/rc^2. [Blanchet, Damour, Iyer Will, Wiseman: PRL 1996]
- Duration and unique characteristics allow for careful discrimination from “noise” events.
- Method of setting upper limits: “loudest event statistic”
  CQG: Brady, Creighton, Wiseman 2004

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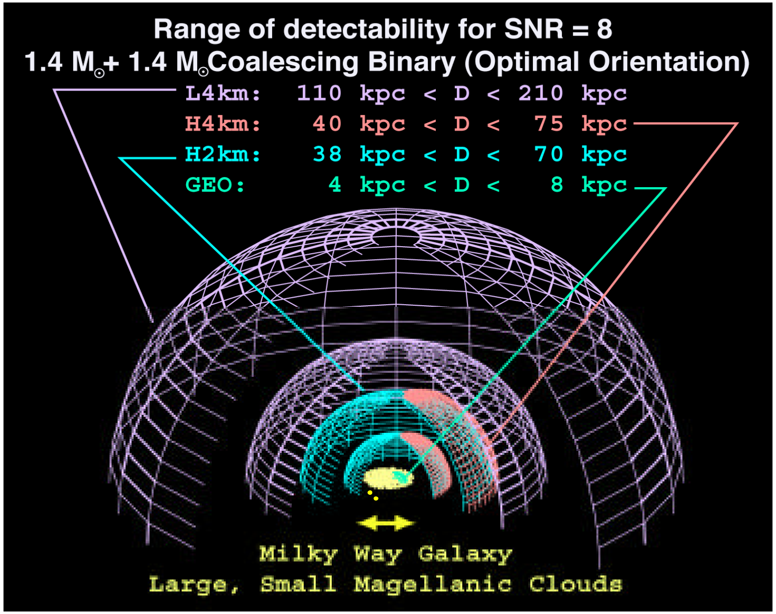
Results of Inspiral Search



Upper limit binary neutron star coalescence rate

LIGO S1 Data

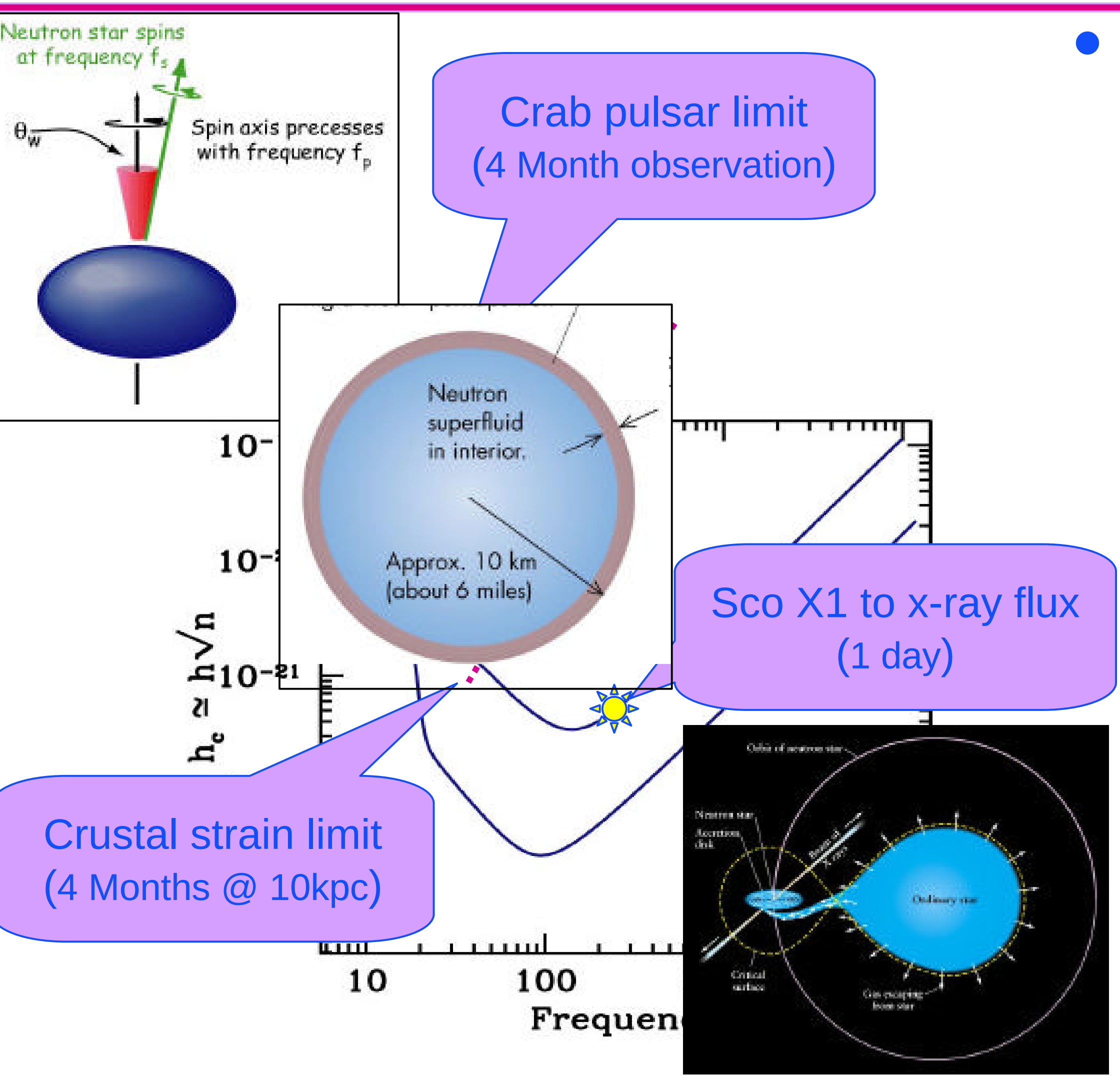
R[S1] < 160 / yr / MWEG

R[S2] < 50 /year/MWEG (preliminary)

- **Previous observational limits**
  - » **Japanese TAMA →   R < 30,000 / yr / MWEG**
  - » **Caltech 40m →   R < 4,000 / yr / MWEG**
- **Theoretical prediction   R < 2 x 10^{-5} / yr / MWEG**

Detectable Range of S2 data reaches Andromeda!

Spinning Neutron Stars



Crab pulsar limit
(4 Month observation)

Sco X1 to x-ray flux
(1 day)

Crustal strain limit
(4 Months @ 10kpc)

- General properties.
  - » **Long lasting, nearly periodic.**
  - » **Caused by "mountain" on the surface (a few cm)**
  - » **Signal at twice the spin frequency**
  - » **Dopler modulate due to**
    - – **Earth's rotatation**
    - – **Earth's orbit**
    - – **System may be in a binary**

Results:

- » **Eccen(S1)<2.9X10^-4 (single pulsar)**
- » **S2 28 Pulsars and improved by roughly factor of 10. (PRL soon)**

-

Searching for Pulsars

- Two types of search
  - » Known Pulsars:
    - **Sky position is known (therefore Dopler shift is known)**
    - **Spin frequency is known**
    - **Computationally easy (a few work stations)**
    - **Each science run, this search has been run**
    - **Placed limits on eccentricity [Ratio of quadrupole moments] on O[20] Known pulsars. [Soon to appear in PRL]**
    - **Also used GEO data in the original work.**
  - » Unknown spinning neutron stars
    - **Computationally impossible**
    - **All sky – all frequency**
    - **Public computing (similar to SETI@home) einstien@home**
      - **Down load a screen saver**
      - **Currently 0[30000] computers enrolled**

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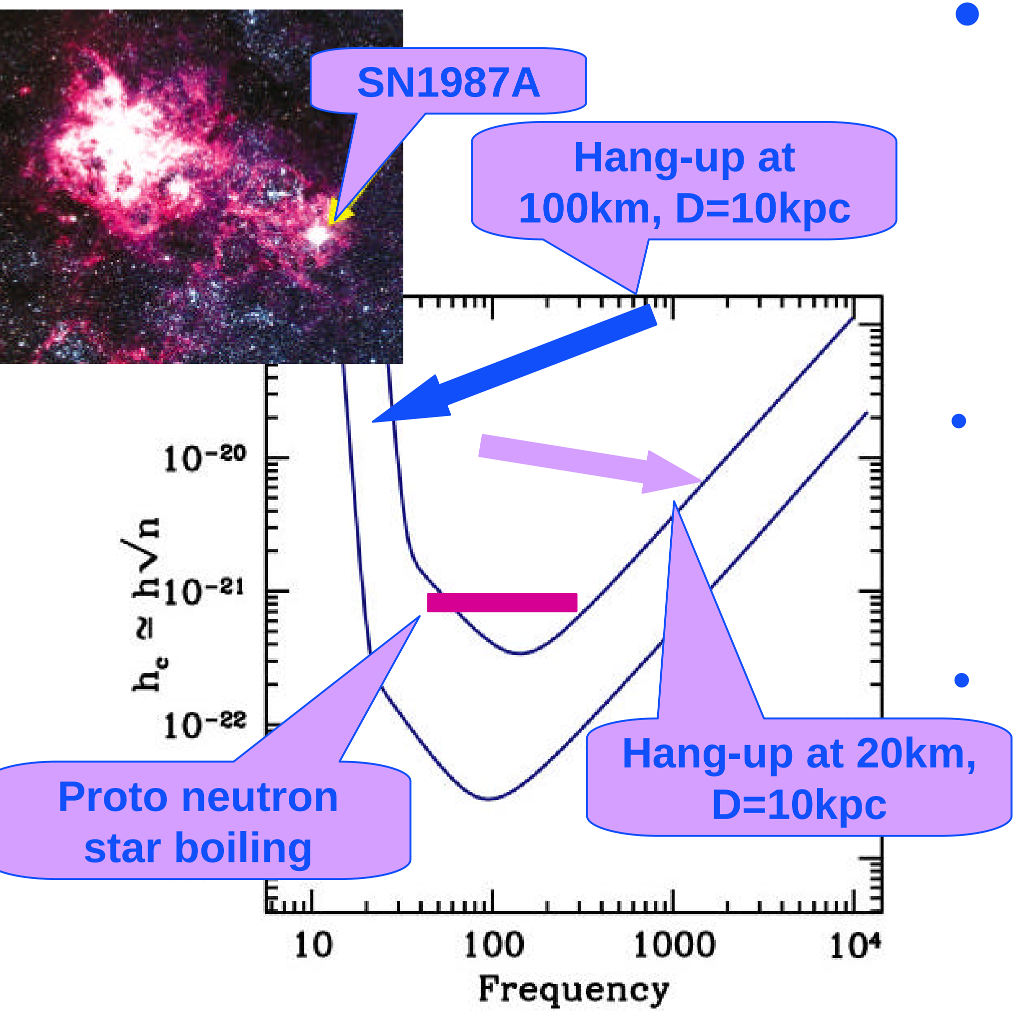
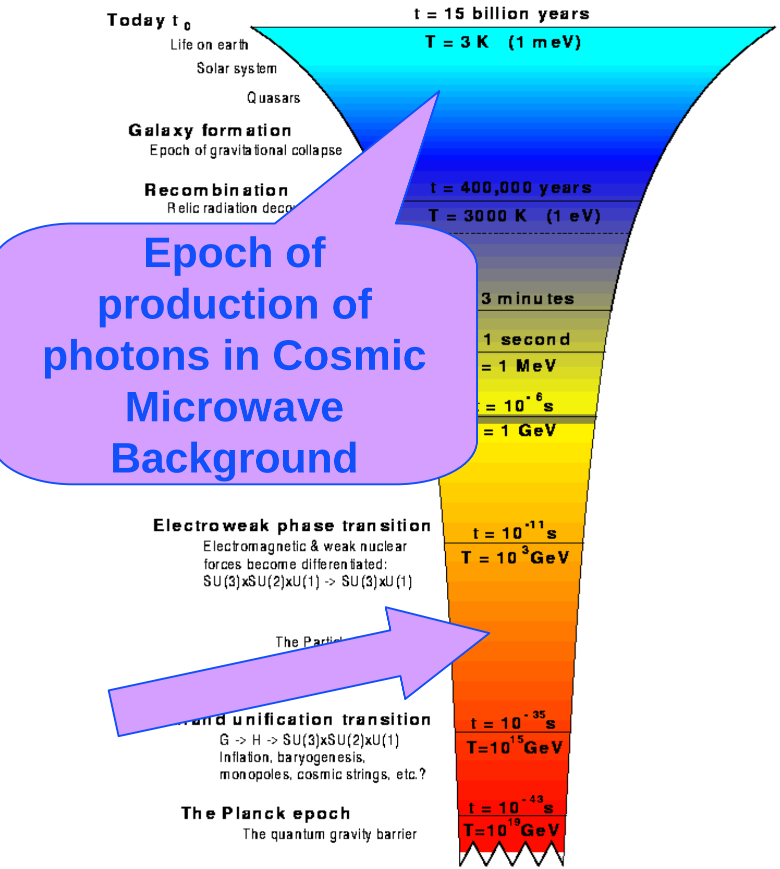
Burst Sources



- General properties.
  - » Duration << observation time.
  - » Modeled systems are dirty.
  - » NS merger, supernovae hang-up, instabilities in nascent NS, kinks on cosmic strings (Burrows, Centrella, Damour, Lai, Muller, Vilenkin…..).
- Promise
  - » Unexpected sources and serendipity.
  - » Detection uses minimal information (w Anderson, PRB, Creighton, Flanagan, Hughes…).
- Supernovae & core collapse
  - » Rapidly rotating NS progenitor.
  - » Hang-up at 100km (Muller), or at 20km (Brown).
  - » Boiling of proto-NS (Burrows).

Stochastic Background



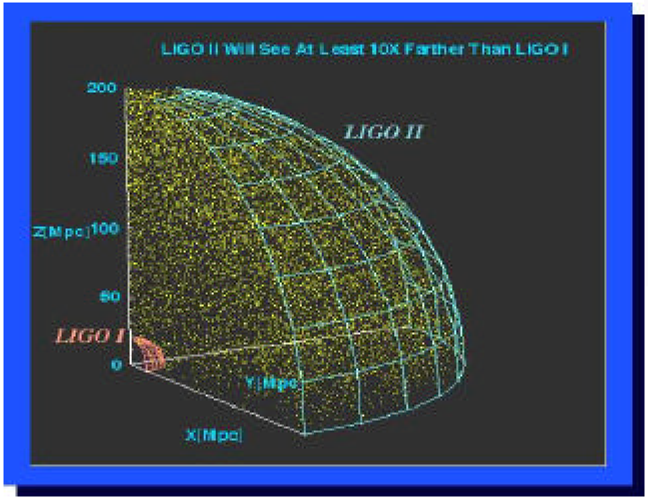
- General properties
  - Weak superposition of many incoherent sources.
  - Only characterized statistically.
  - Either early universe or contemporary.
- Method of search:
  - Cross-correlated the detector outputs being mindful of the time delay between sites.
  - S1 Result:
    $W < 23$ [64-265**Hz]**
- Contemporary sources
  - Unresolved supernovae, R-mode in nascent neutron stars (Blair, Vecchio, …).

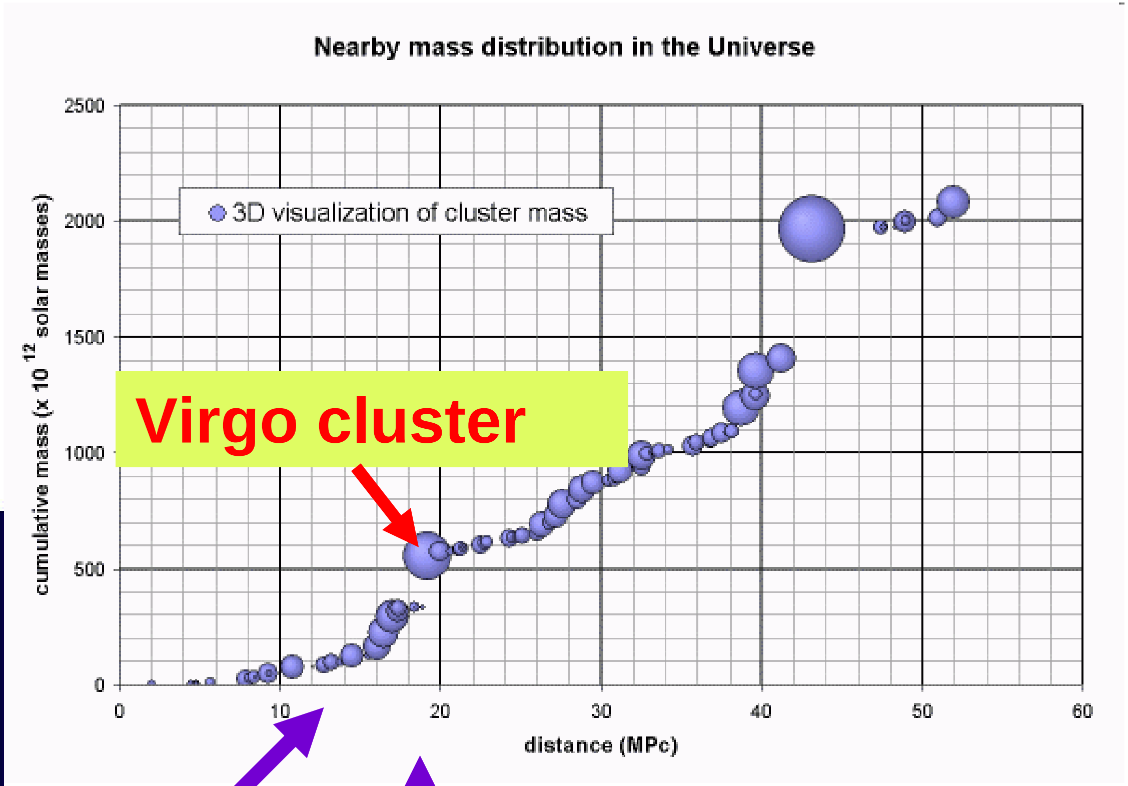
Advanced LIGO

Cubic Law for “*Window*” on the Universe

Improve amplitude sensitivity by a factor of <u>10x</u>…

…number of sources goes up <u>1000x</u>!





Virgo cluster

Today

Initial LIGO

Advanced LIGO

Light scattering Noise

- Mirrors aren’t perfect
  - » Light scatters and bounces off the beam-tube and reenters the beam.
  - » Can this be stopped?
  - » Detector has “baffles” to deflect the ligt
  - » Design criteria: Light scattering should never limit a future interferometer in this beam tube.

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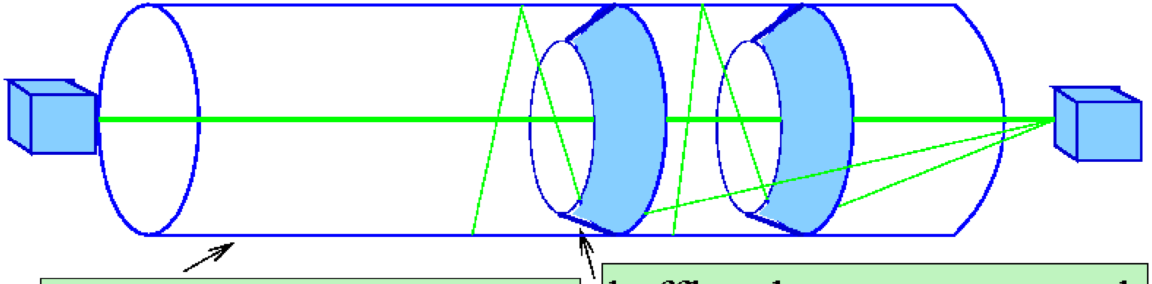
Baffle design

Solution: Install (100's of) optical baffles



beam tube is absorbtive so light attenuates rapidly

baffle edges are saw–tooth to disrupt Fresnel zones

No stray photon can take a simple path to the other mirror, but how many will make it to the other mirror by indirect paths?

— AGW and Scott Hughes used Fokker–Planck analysis to show that diffusion of photons does not contribute to the noise budget.

Goals and Priorities

- Interferometer performance
  - » Integrate commissioning and data taking consistent with obtaining one year of integrated data at $h = 10^{-21}$ by end of 2006 [Very close.]
- Physics results from LIGO I
  - » Initial upper limit results by early 2003 [Done, (late 2003)]
  - » First search results in 2005 [S4 Underway, S5 Soon]
  - » Reach LIGO I goals by 2007
- Advanced LIGO
  - » Proposal is winding its way through the process
  - » Possibly begin installation in 2007, or …

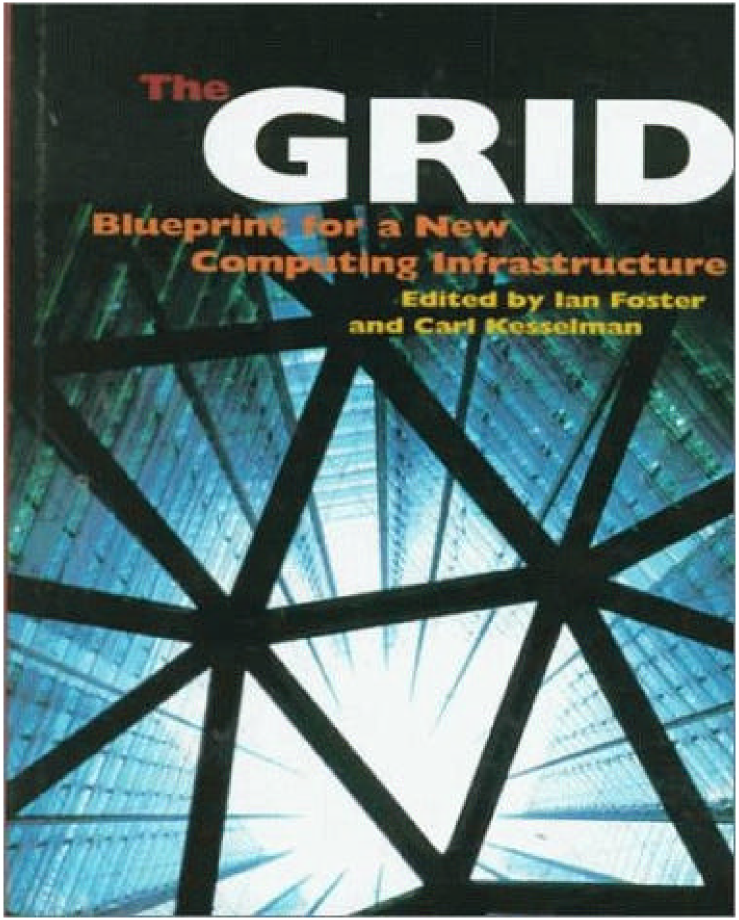
Organization of Collaborations and Data Analysis

- Two entities:
  - » LIGO Laboratory (Caltech, MIT, two observatories)
    - **Barry Barish Director**
    - **Procured the funding and built the instruments**
    - **Technically LIGO Lab “owns” the data**
  - » LIGO Scientific Collaboration (LSC)
    - **Peter Saulson is the “spokesperson” (elected). [Formerly Rai Weiss]**
    - **AGW “Data Analysis Coordinator”**
    - **40+ institutions, ie university groups. O[300] members**
    - **Each institution has an MOU with the Lab, agreeing to do some work in exchange for “rights” to the data.**
    - **LSC is tasked with producing the scientific results of LIGO, ie analyzing the data and writing the papers.**

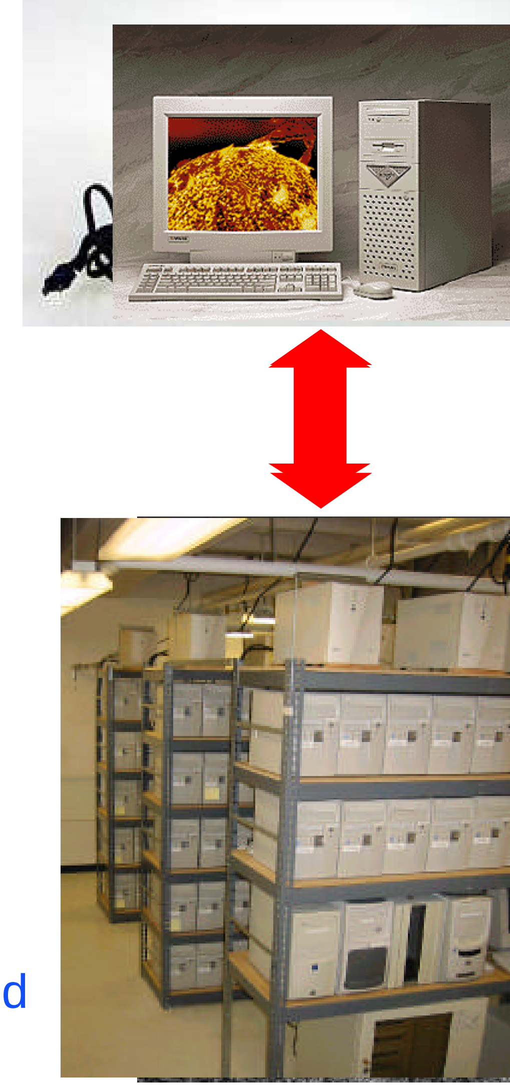
LIGO Data Analysis on the Grid

Question: How do 100’s of LSC scientists around the *world* analyze 100s of *tera*bytes of LIGO data?

Answer: Grid Computing


The GRID
Blueprint for a New Computing Infrastructure
Edited by Ian Foster and Carl Kesselman

The Grid in Grid Computing



- Analogy with the electrical power grid
  - » you don’t care where or how power for your toaster is generated
  - » you just want results (toast!)
- Grid computing to provide robust, uniform, access to distributed high performance computing resources
  - » don’t necessarily know (or care) from where cycles are delivered
  - » you just want to do science
- Evolve to include access to computing resources AND data
  - » robust access to data, both raw or “real” and derived or “virtual” data

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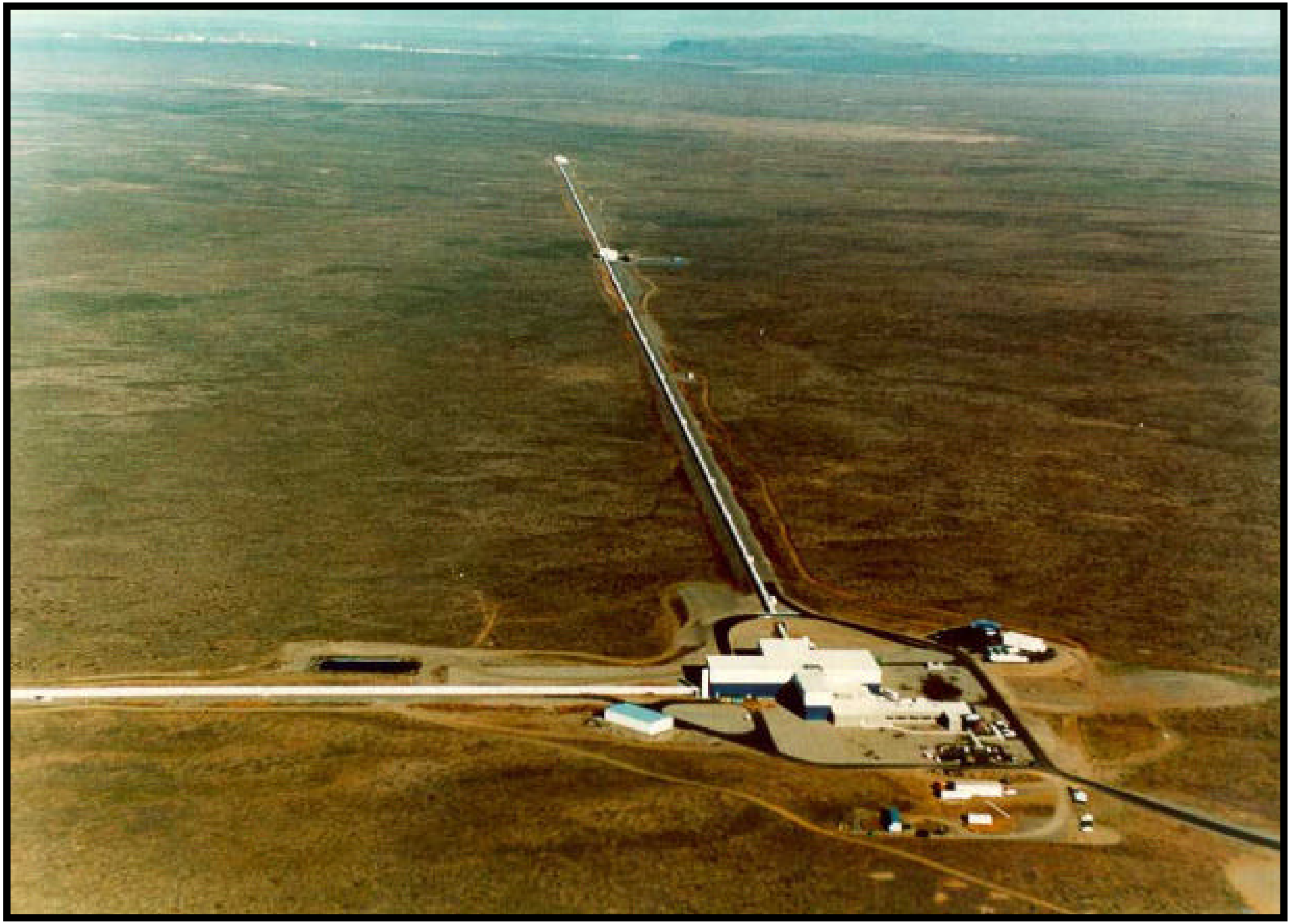
Worldwide Challenge

- Worldwide effort involves 6 kilometer-scale interferometers
- Statistical methods needed for upper limits and detection of astrophysical sources
- Computational tools and resources to deal with data from multiple detectors

…Form follows function …



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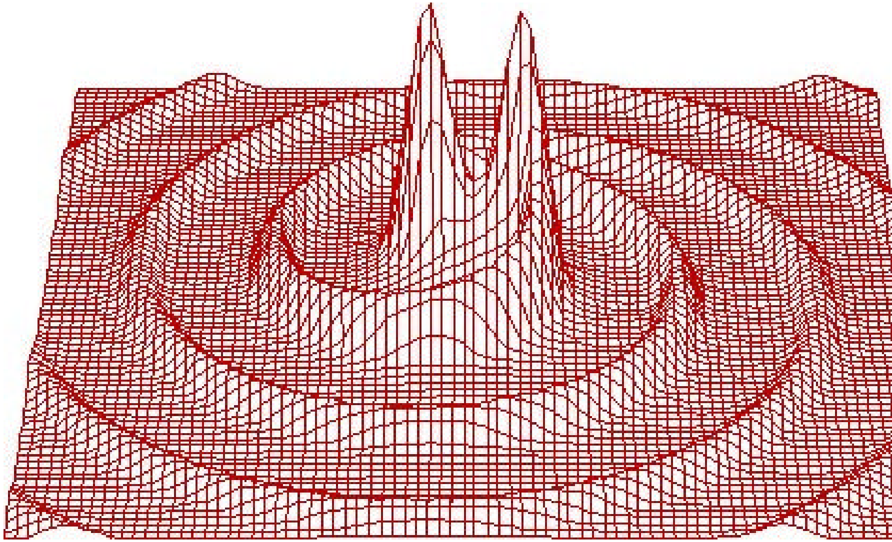
Einstein’s Theory of Gravitation

- **a necessary consequence of Special Relativity with its finite speed for information transfer**

- **gravitational waves come from the acceleration of masses and propagate away from their sources as a space-time warpage at the speed of light**



gravitational radiation
binary inspiral
of
compact objects

General Relativity

Einstein’s equations have form similar to the equations of elasticity.

P = E*h* (P = stress, *h* = strain, E = Young’s mod.)

T = (c^4/8p G)*h*   T = stress tensor, G = Curvature tensor and c^4/8p G ~ 10^{42}N is a space-time “stiffness” (energy density/unit curvature)

- **Space-time can carry waves.**
- **They have very small amplitude**
- **There is a large mismatch with ordinary matter, so very little energy is absorbed (very small cross-section)**