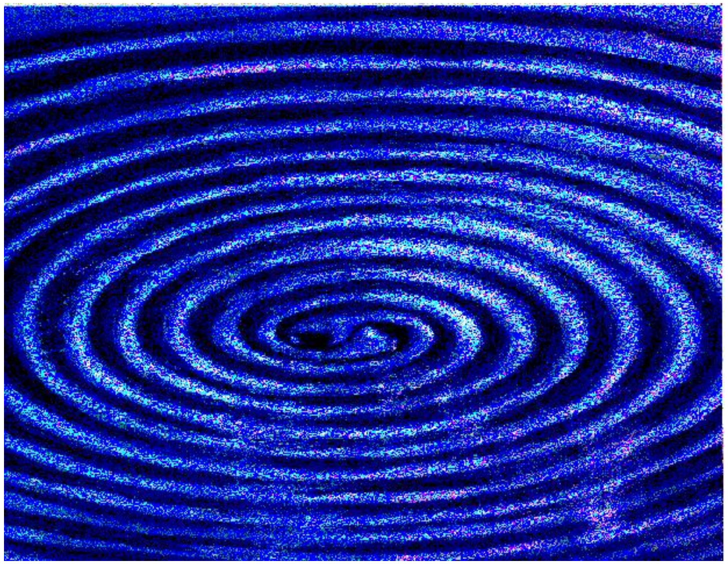
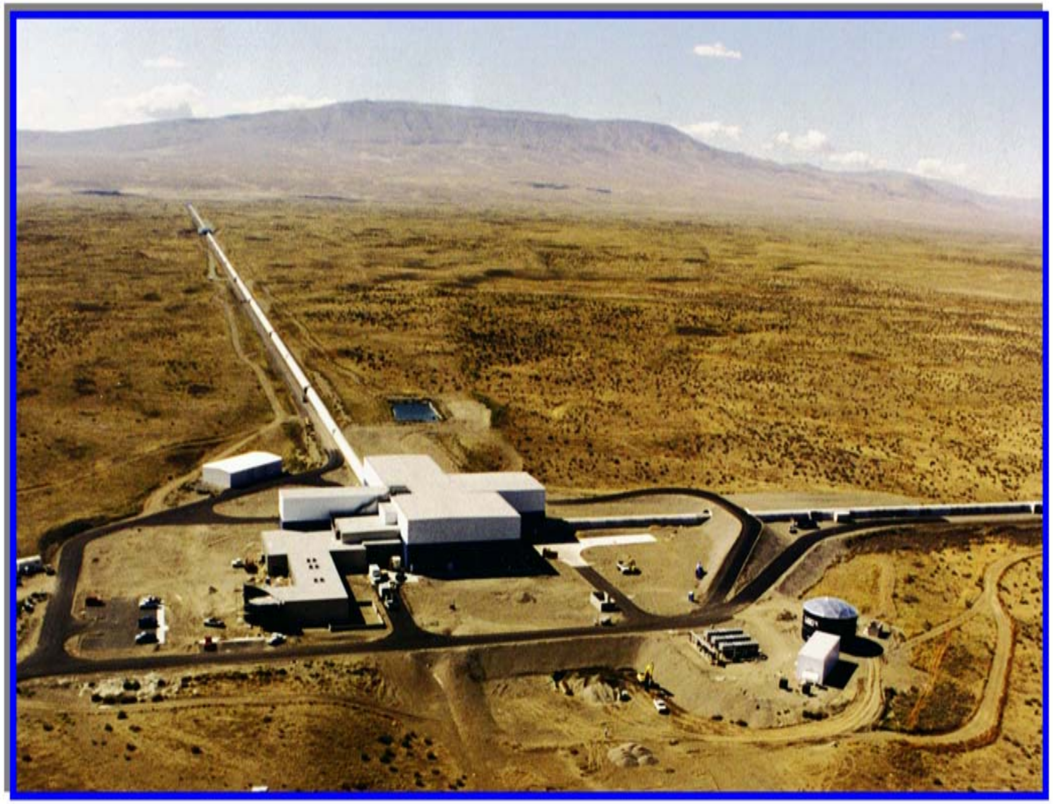
Search for Gravitational Waves with the LIGO Interferometers



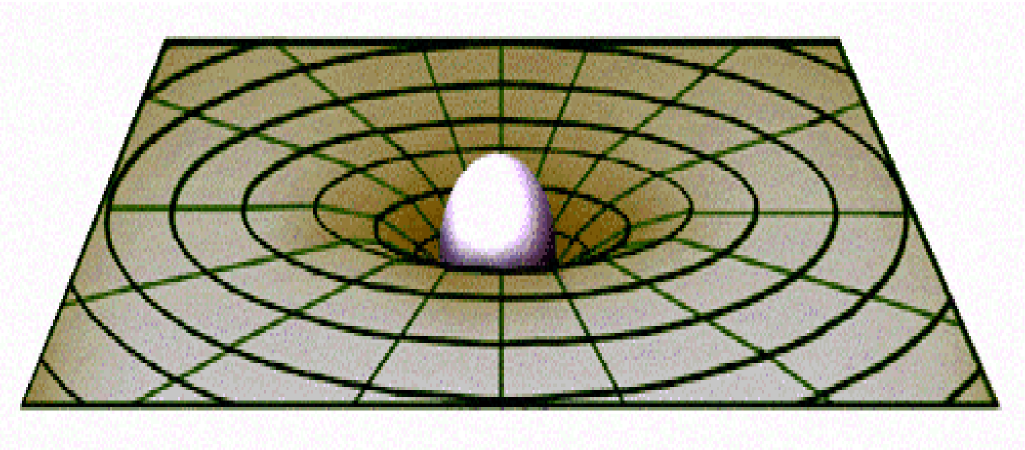


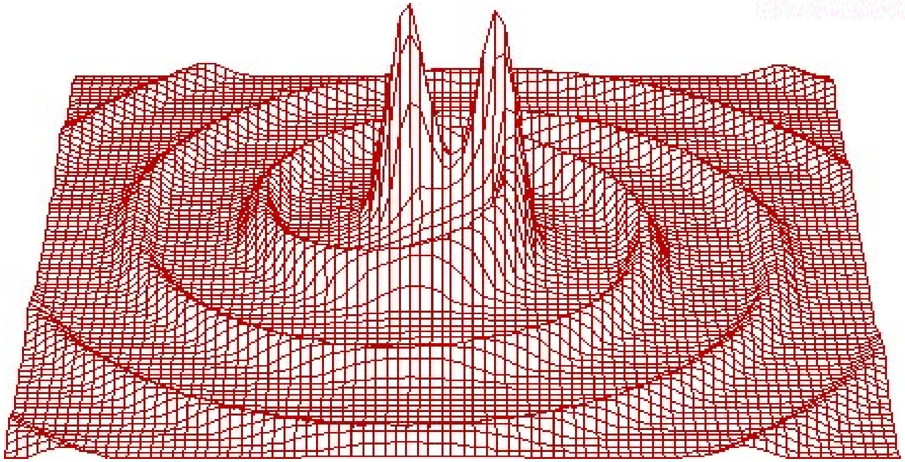
Dennis Ugolini
Trinity University

Joint Texas APS/AAPT Meeting
March 23, 2007

Changing Spacetime Curvature

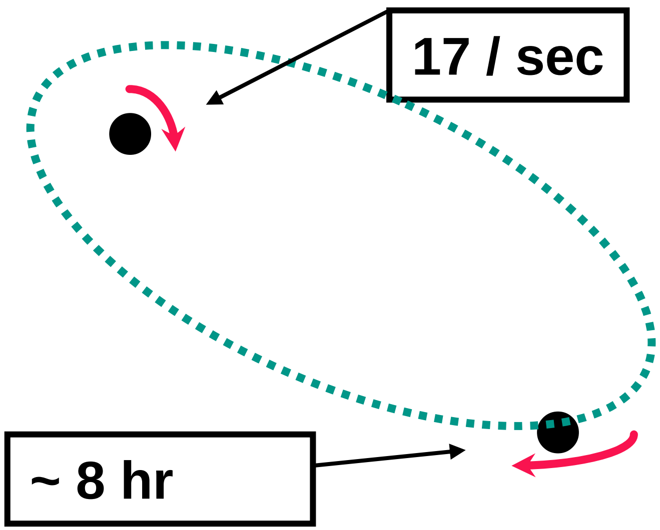
We envision gravity as a curvature of space; as a massive body moves, the curvature changes with it.

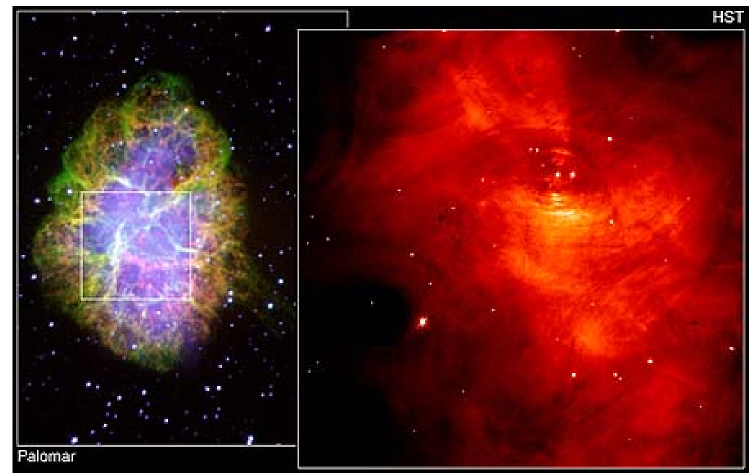




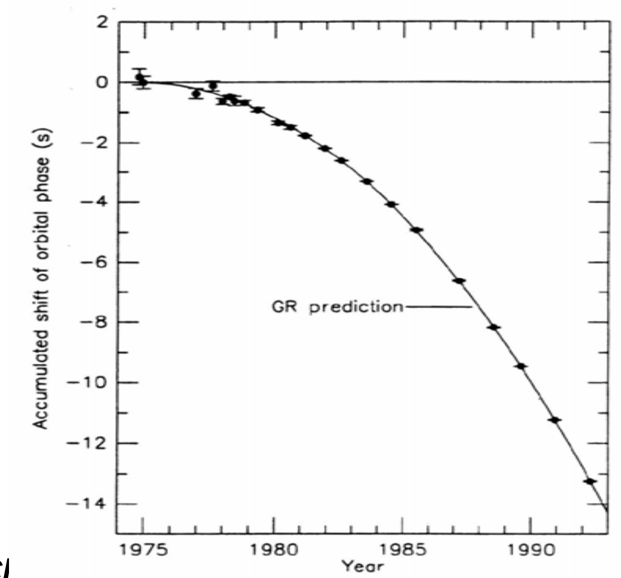
General relativity tells us that this information will be carried by gravitational radiation at the speed of light.

Hulse-Taylor Binary Pulsar





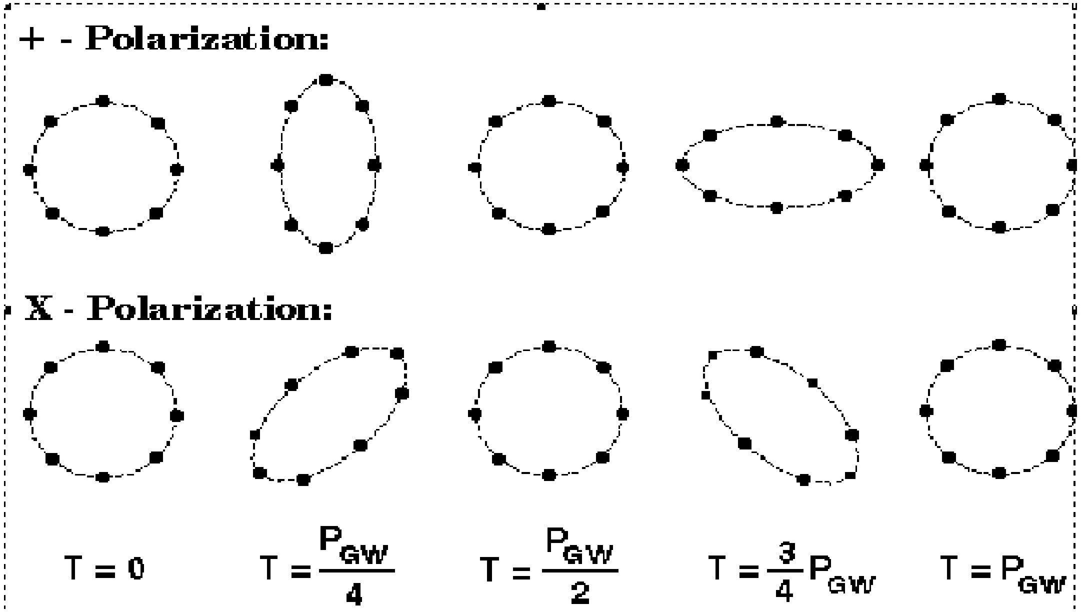
- PSR 1913 + 16, orbital parameters carefully measured in 1975
- System should lose energy through gravitational radiation
  - » Stars get closer together
  - » Orbital period gets shorter



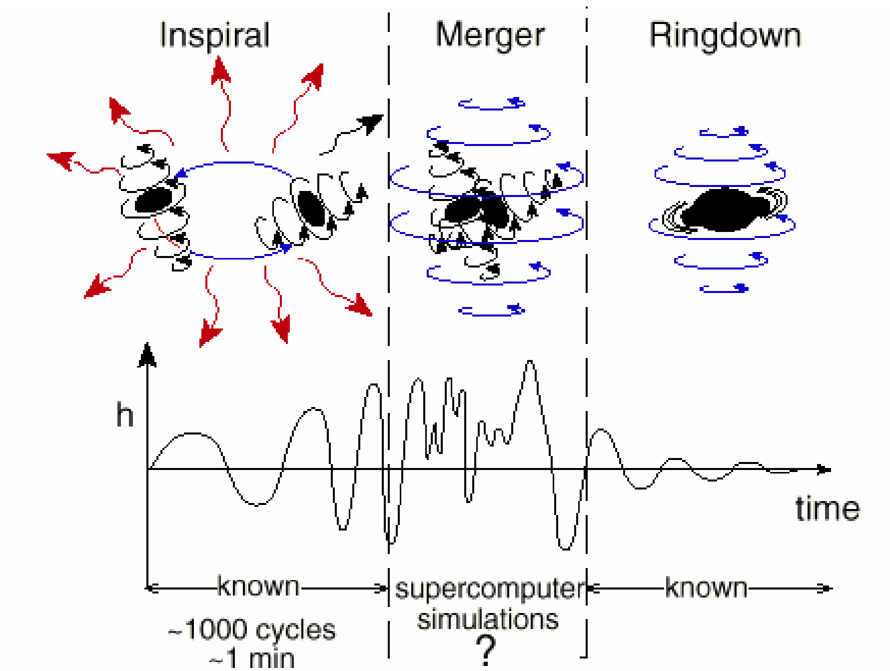
Nature of Gravitational Radiation

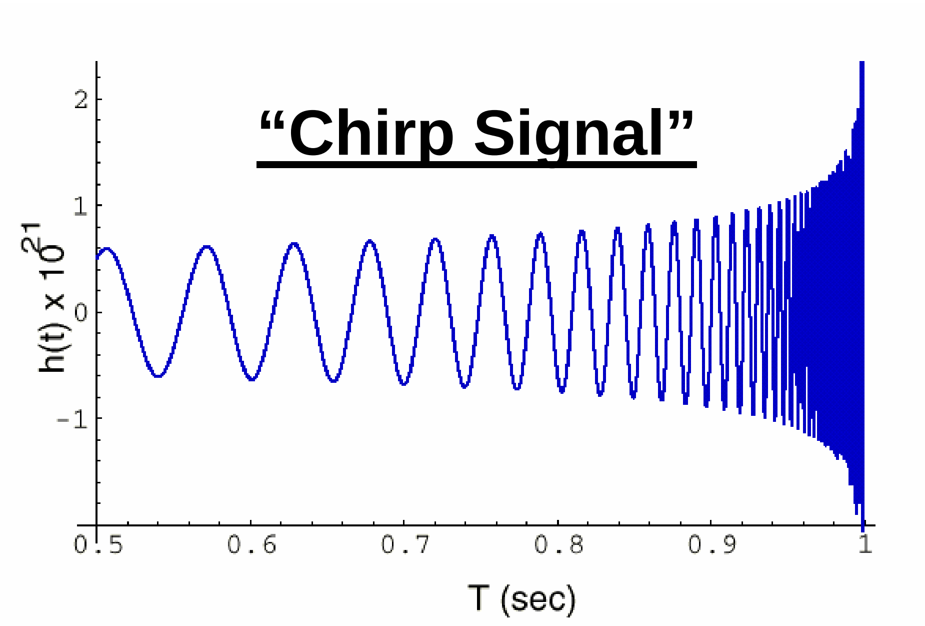
General Relativity predicts :

- transverse space-time distortions, freely propagating at speed of light
- expressed as a strain ($\Delta h = \Delta L/L$)
- Conservation laws:
    - Energy $\Rightarrow$ no monopole rad.
    - Momentum $\Rightarrow$ no dipole rad.
- Quadrupole wave (spin 2)
    - plus ($\oplus$) and cross ($\otimes$) polarizations



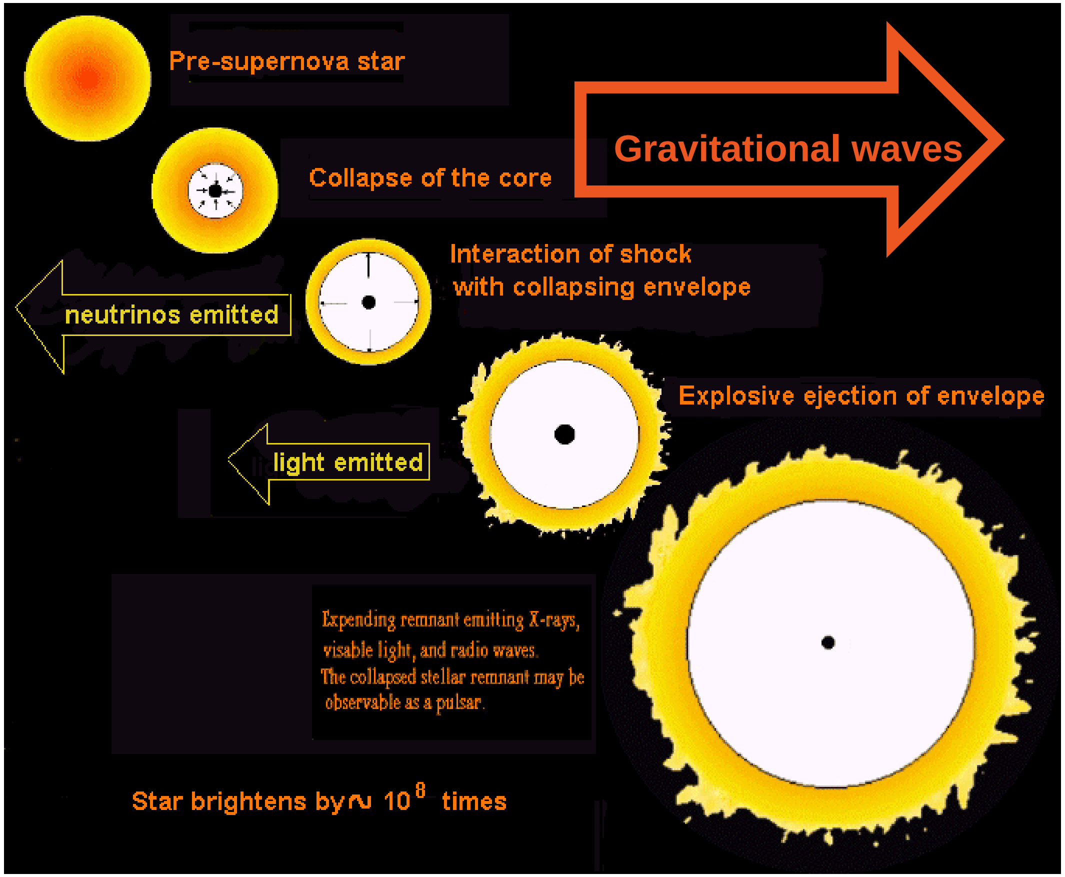
Binary Inspirals





We can use weak-field gravitational waves to study strong-field general relativity.

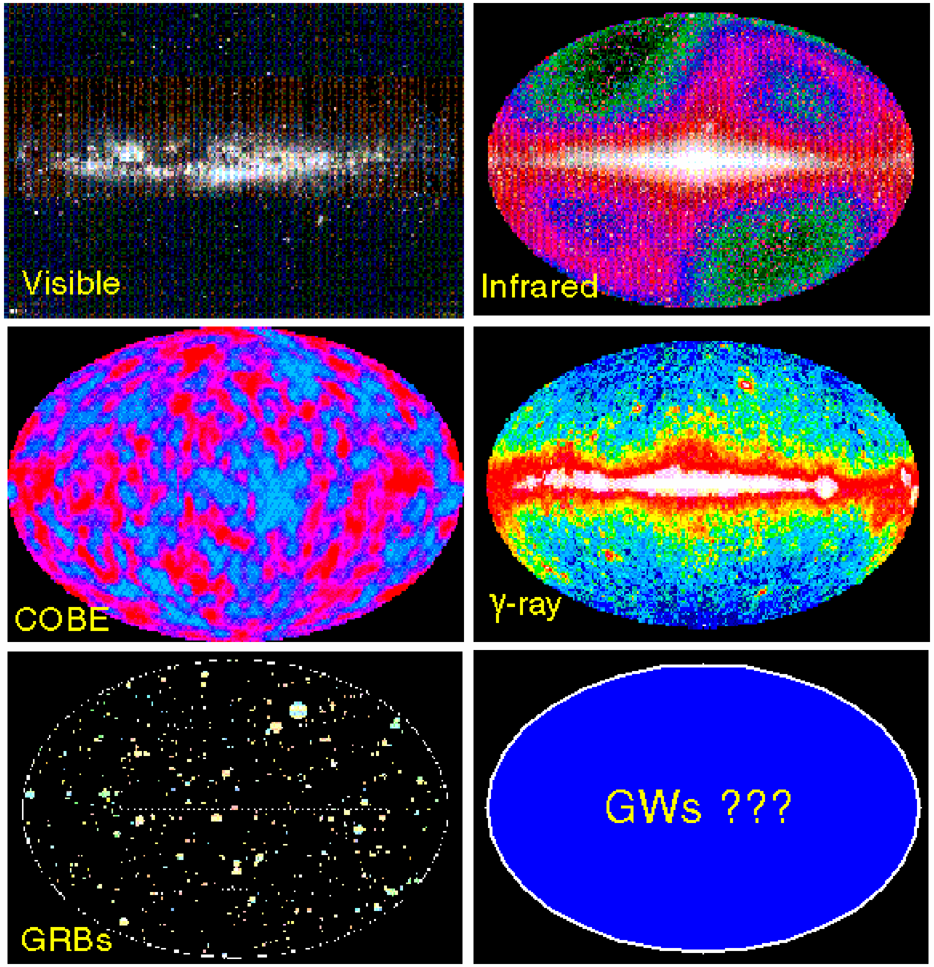
Supernova "Early Warning"



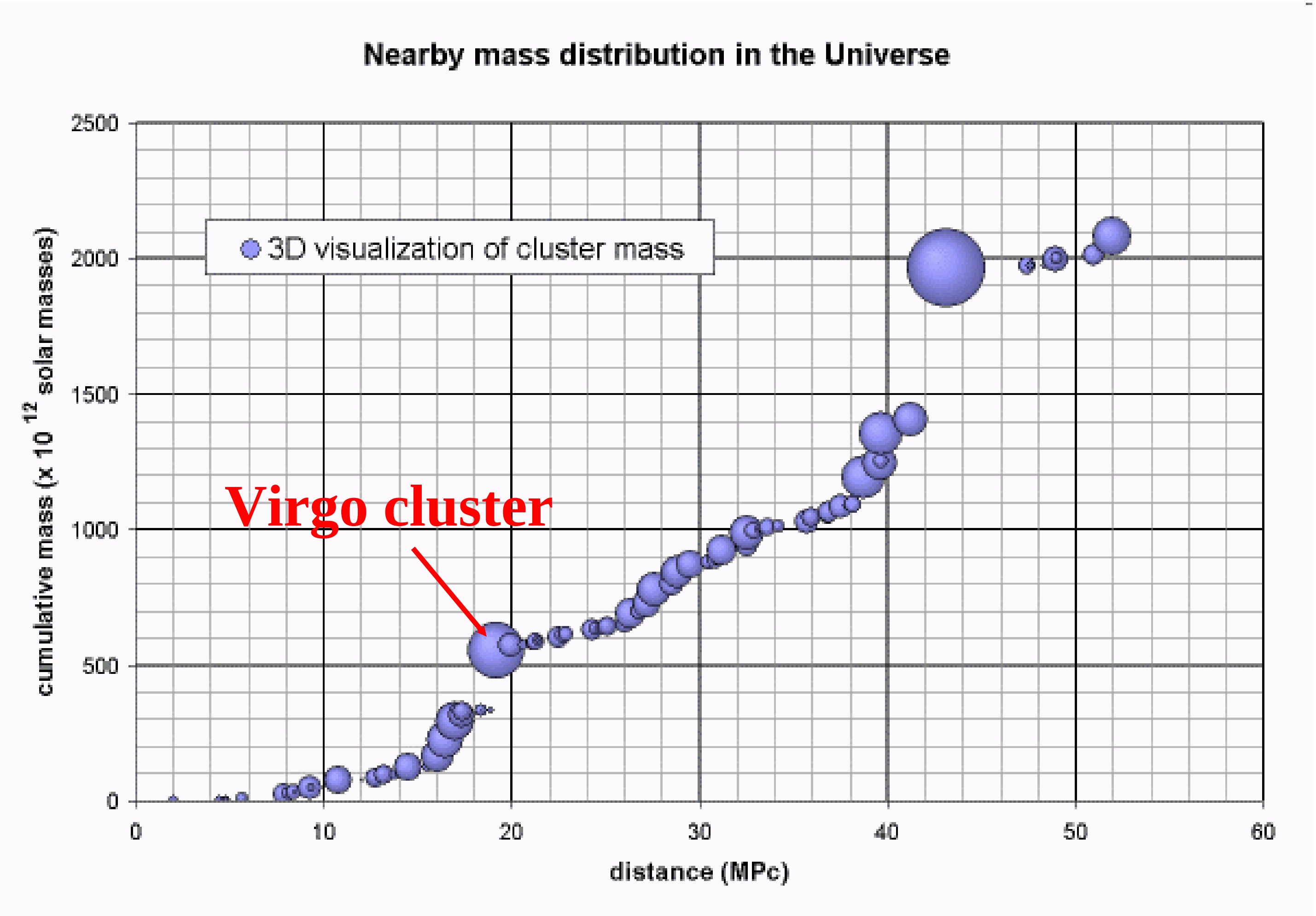
- Within about 0.1 second, the core collapses and gravitational waves are emitted.
- Over 2 hours later, the envelope of the star is explosively ejected.
- Supernova must be spherically asymmetric, or no net change in curvature at large distances

Other Gravitational Wave Sources

- Periodic sources – GWs from rotation of elliptical pulsars
- Stochastic sources – gravitational equivalent of the cosmic microwave background
- Who knows what else?



How Far Must We Look?



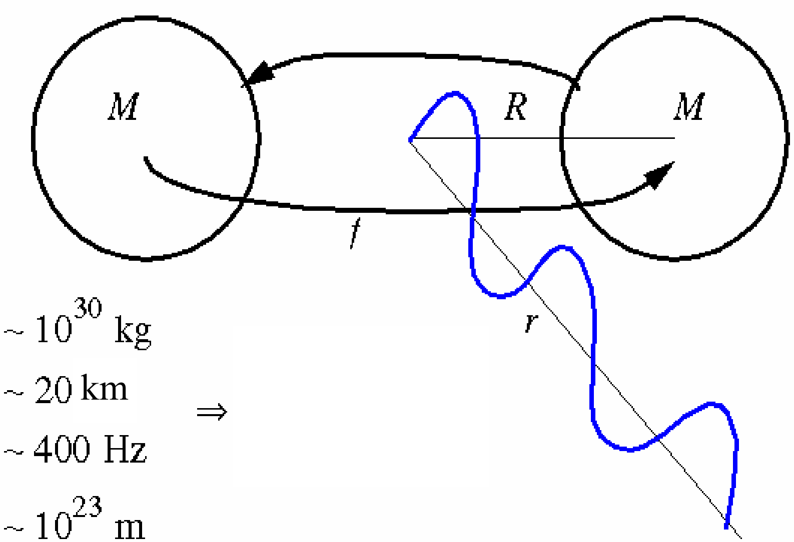
How Big Are They?

- Gravitational wave amplitude:

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

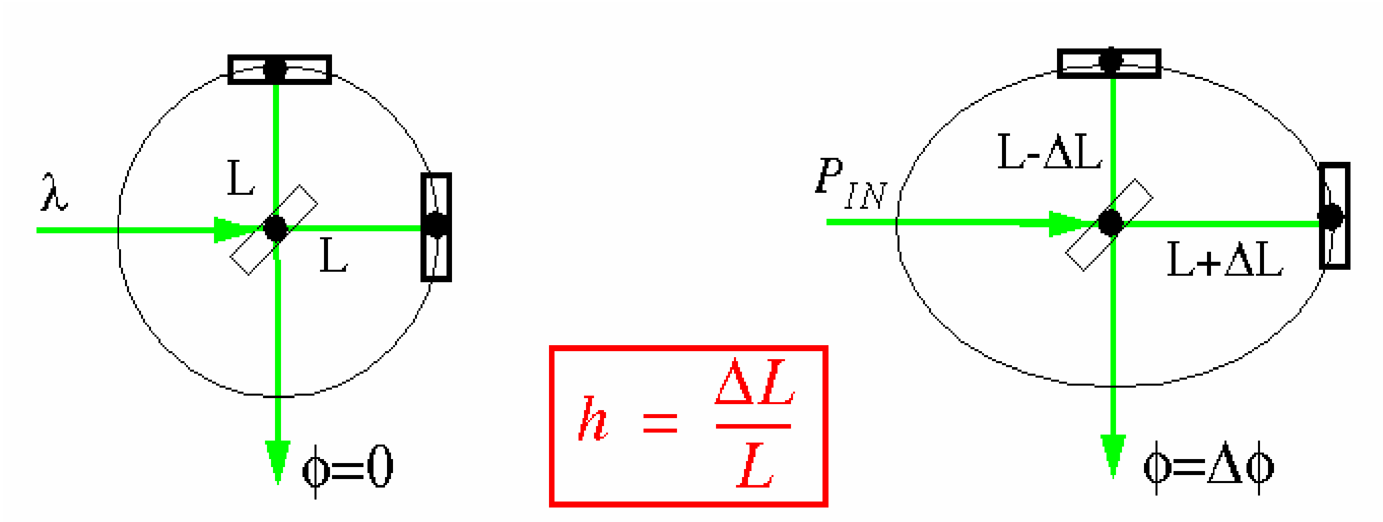
- Imagine two inspiraling neutron stars, each one solar mass, in the Virgo cluster.

- At the moment of collision, they are rotating at 400 Hz about their center of mass



$$\begin{aligned} M &\sim 10^{30}\ \text{kg} \\ R &\sim 20\ \text{km} \\ f &\sim 400\ \text{Hz} \\ r &\sim 10^{23}\ \text{m} \end{aligned} \quad \Rightarrow$$

The Michelson Interferometer



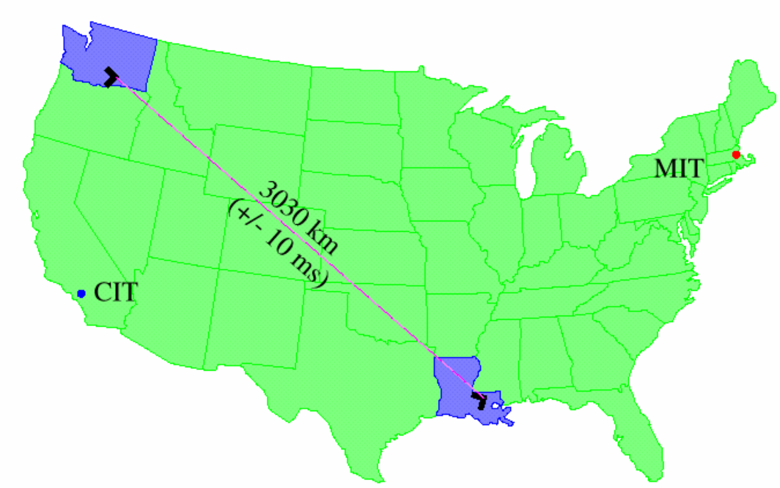
Ideally suited for quadrupole signal

- » One fringe = 10^{-6} m
- » Travel distance ~10 km = 10^{4} m
- » “Fold” arms for ~10^{3} round trips
- » Measure fringe to one part in 10^{8}
- » $\Delta L/L = (10^{-6})(10^{-8})/(10^{4})(10^{3}) = 10^{-21}$

The LIGO Project

LIGO: Laser Interferometer Gravitational-Wave Observatory

- Initial detection, followed by astronomy
- Funded by US National Science Foundation
- Each site capable of multiple interferometers
- Lifetime of > 20 years
- Goal: Achieve fundamental noise limits for terrestrial interferometers
- Collaboration of many institutions:



Max Planck Institute	Andrews University	Australian National Univ.	California Institute of Technology
Cardiff University	Carleton College	Charles Sturt University	Columbia University
Embry-Riddle Aero. Univ.	Hobart and William Smith	Centre for Astro., Pune	Louisiana State University
Loyola University	Mass. Institute of Tech.	Moscow State University	NASA/Goddard Space Flight Center
National Observatory, Japan	Northwestern University	Rochester Institute of Tech.	Rutherford Appleton Laboratory
San Jose State University	Southeastern Louisiana U.	Southern University	Stanford University
Syracuse University	Penn State University	Univ. of Texas, Brownsville	Trinity University
Universitat Hannover	Univ. de les Illes Balears	University of Adelaide	University of Birmingham
University of Florida	University of Glasgow	University of Maryland	University of Michigan
University of Oregon	University of Rochester	University of Salerno	Univ. of Sannio at Benevento
University of Southampton	University of Strathclyde	U. of Washington, Seattle	Univ. of Western Australia
U. of Wisconsin, Milwaukee	Washington State University		

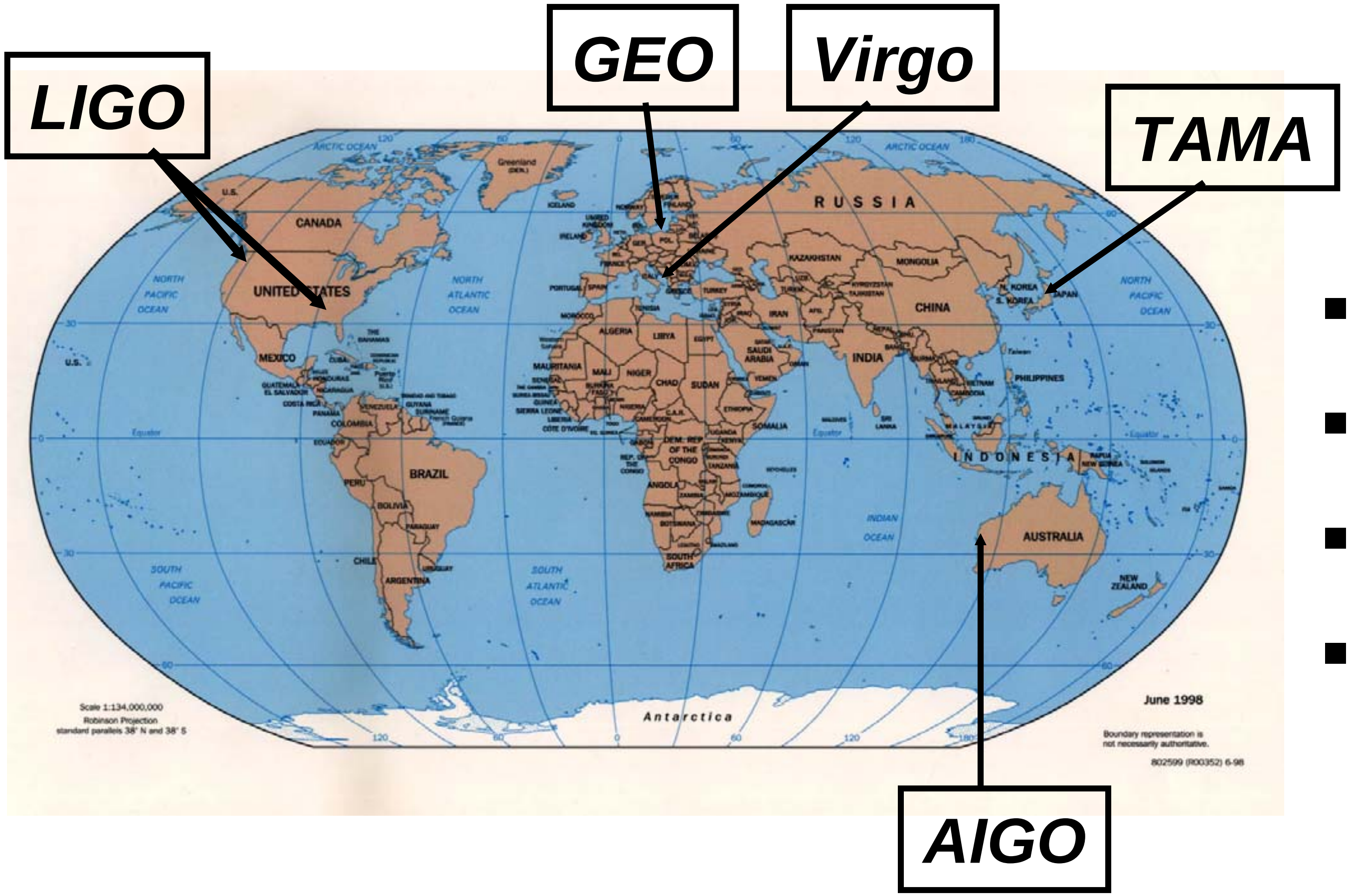
The LIGO Observatories

LIGO Hanford Observatory (LHO)

LIGO Livingston Observatory (LLO)

International Network

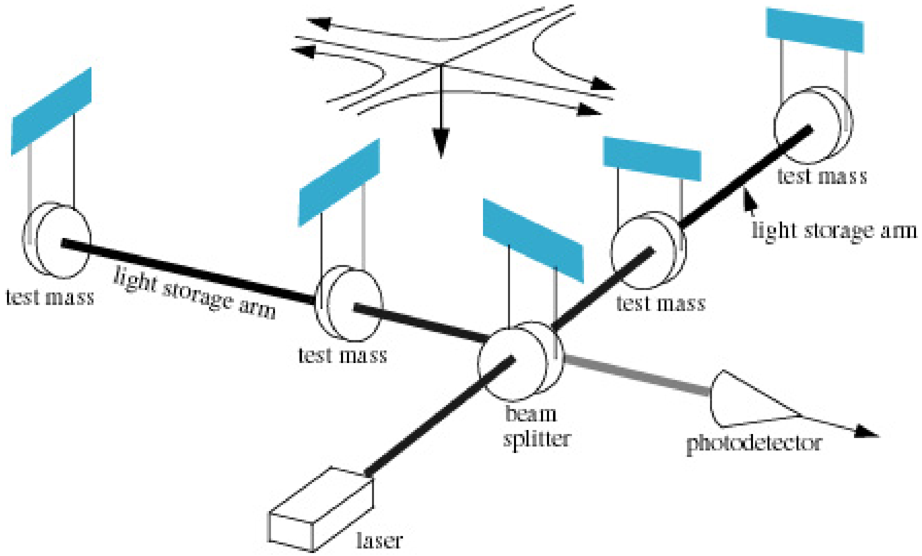
Simultaneously detect signal (within msec)

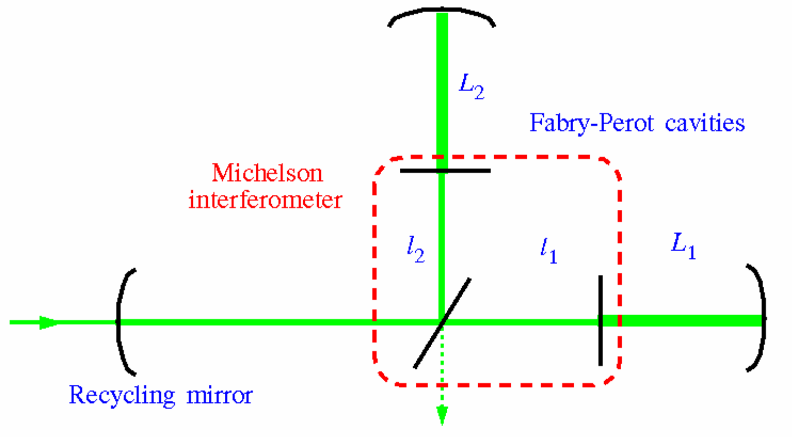


- Detection confidence
- Locate sources
- Speed of propagation
- Polarization of GWs

How Does LIGO Work?

- The interferometer arms are Fabry-Perot cavities
- The output is kept centered at a dark fringe to minimize shot noise
- This causes the light to be dumped back out toward the laser; a power recycling mirror forms a cavity that returns this light to the interferometer

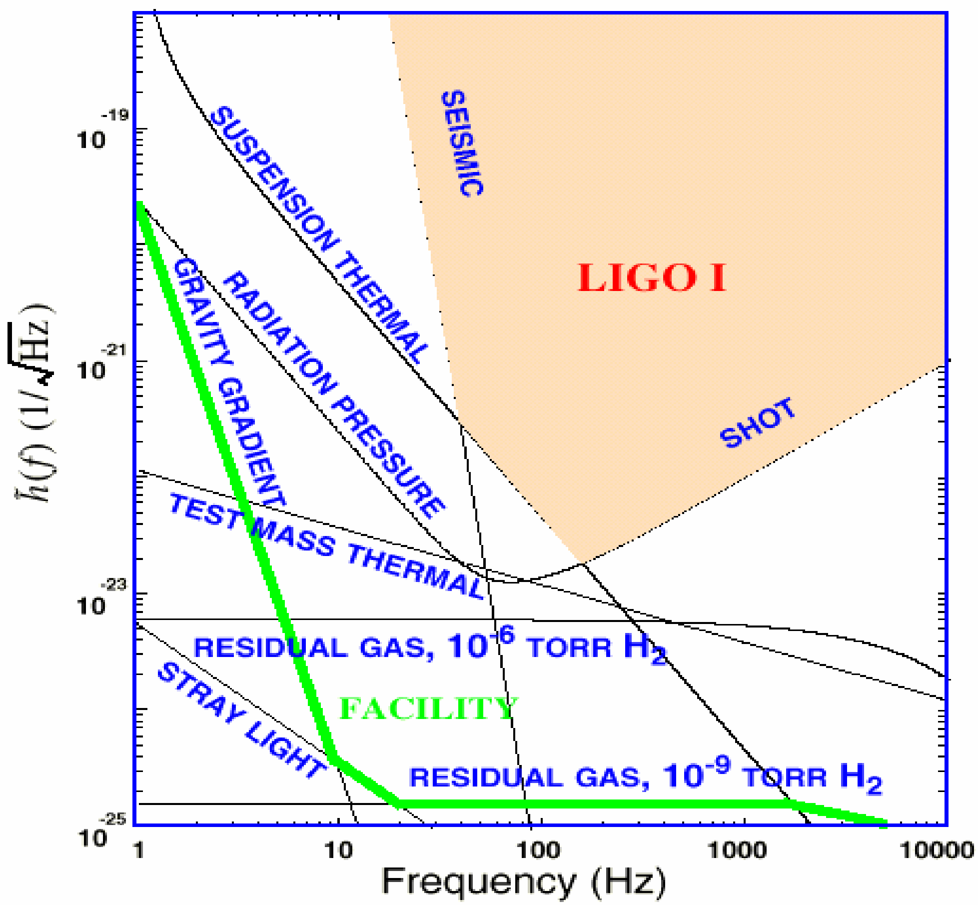




LIGO Vacuum System

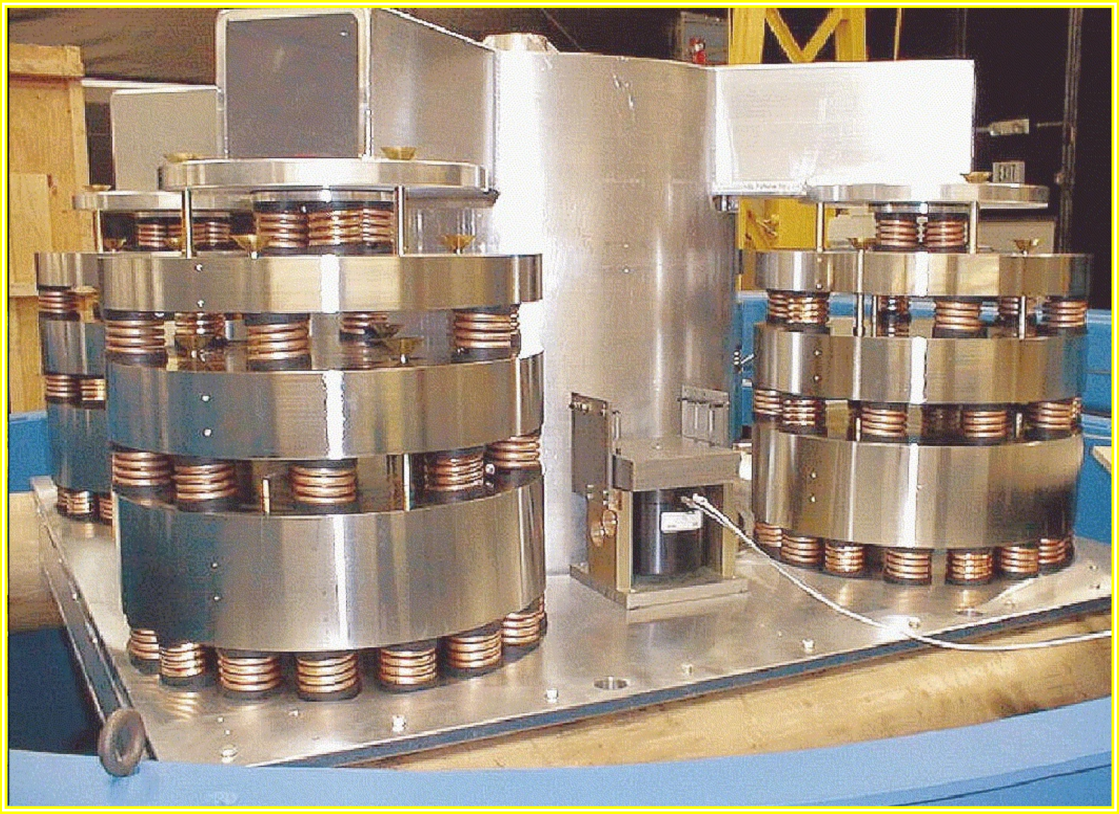
- Air in beam tube causes problems:
  - » Phase noise from refractive index
  - » Displacement noise from buffeting optics
  - » Scattering
  - » Contamination
- Kept at 10^{-9} torr
  - » Major bakeout required
  - » Only chambers ever exposed to air

LIGO Noise Expectations

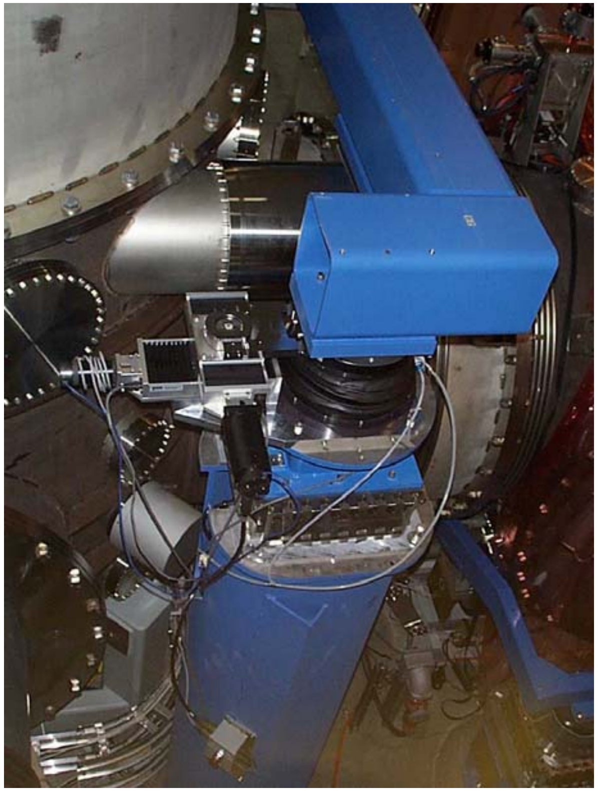


- Effective bandwidth of 40 Hz – 1 kHz
  - » Binaries, supermassive black holes are lower frequency
  - » Can see binary collisions, supernovae, pulsars, etc.
- High frequency limits:
  - » Shot noise
  - » Pole frequency
- Middle frequency limit – Thermal noise
- Low frequency limit – Seismic noise

Seismic Isolation



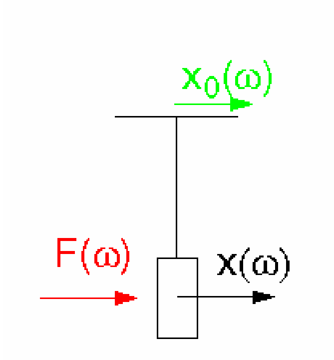
Passive (to reduce noise in sensitive freq. band)

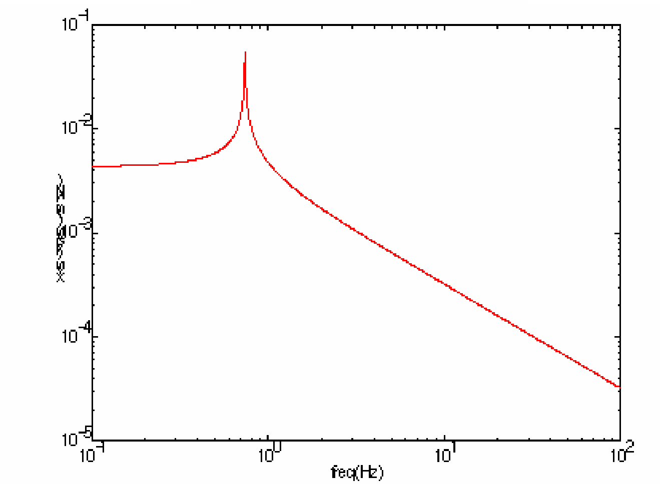


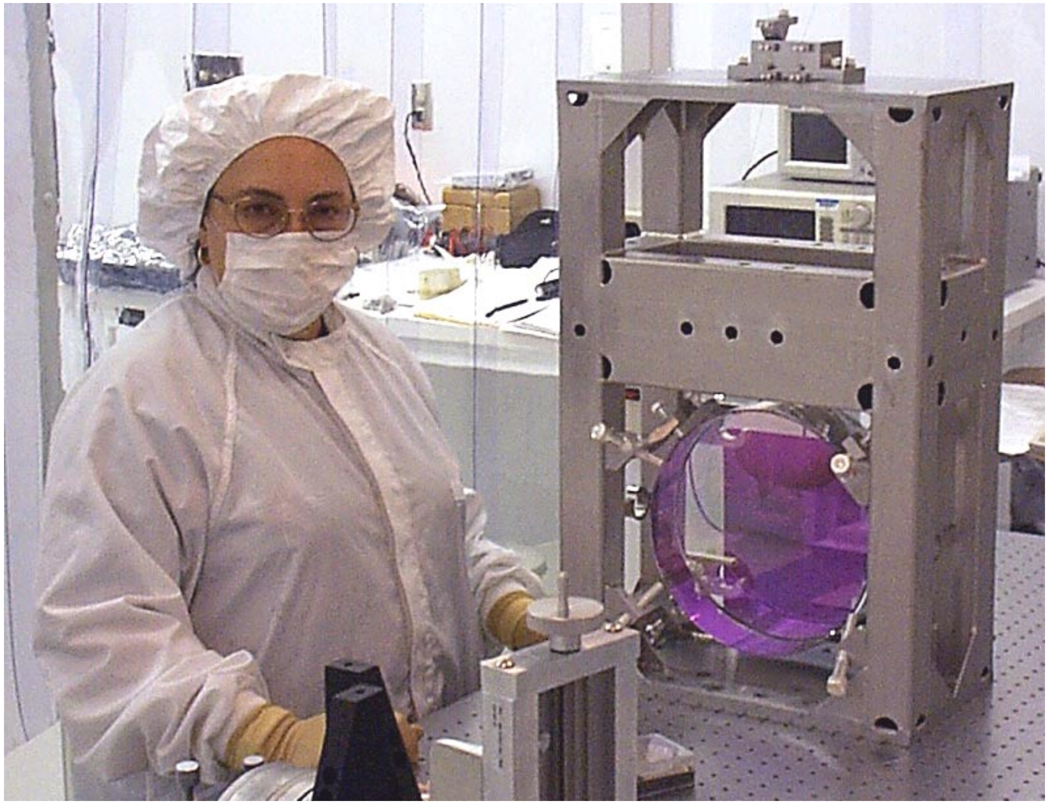
Active (to allow lock acquisition)

Suspended Test Masses

The LIGO test masses are 25cm in diameter, and suspended to improve seismic isolation ("freely falling bodies" above a certain frequency).

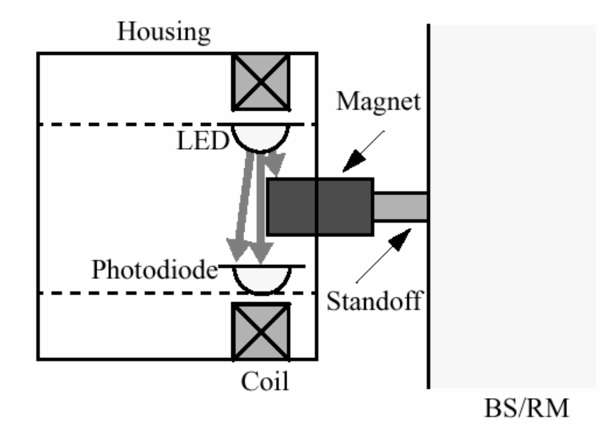


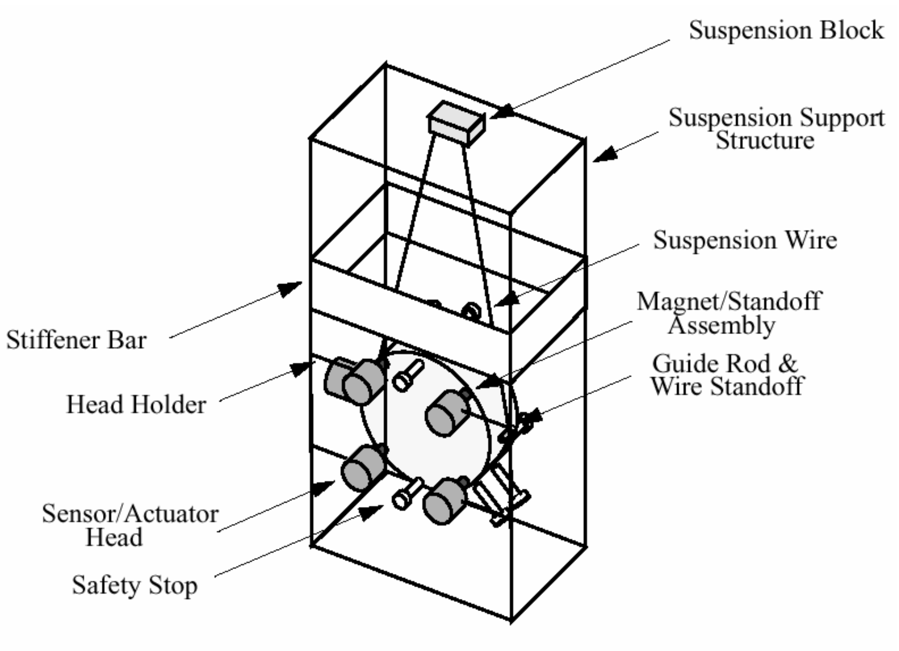




Length Sensing and Control

- Each optic has five OSEMs (magnet and coil assemblies), four on the back, one on the side





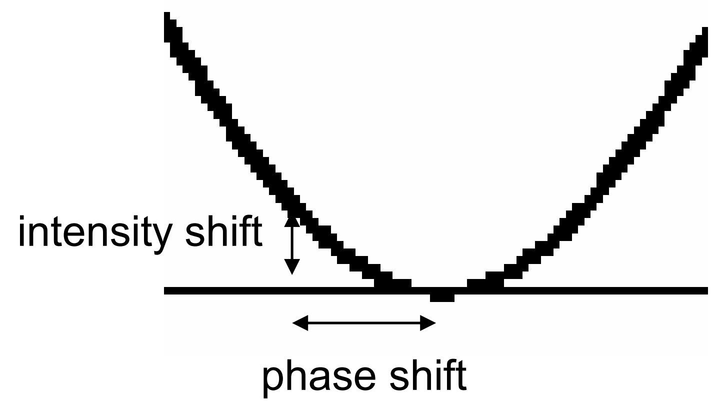
- The magnet occludes light from the LED, giving position

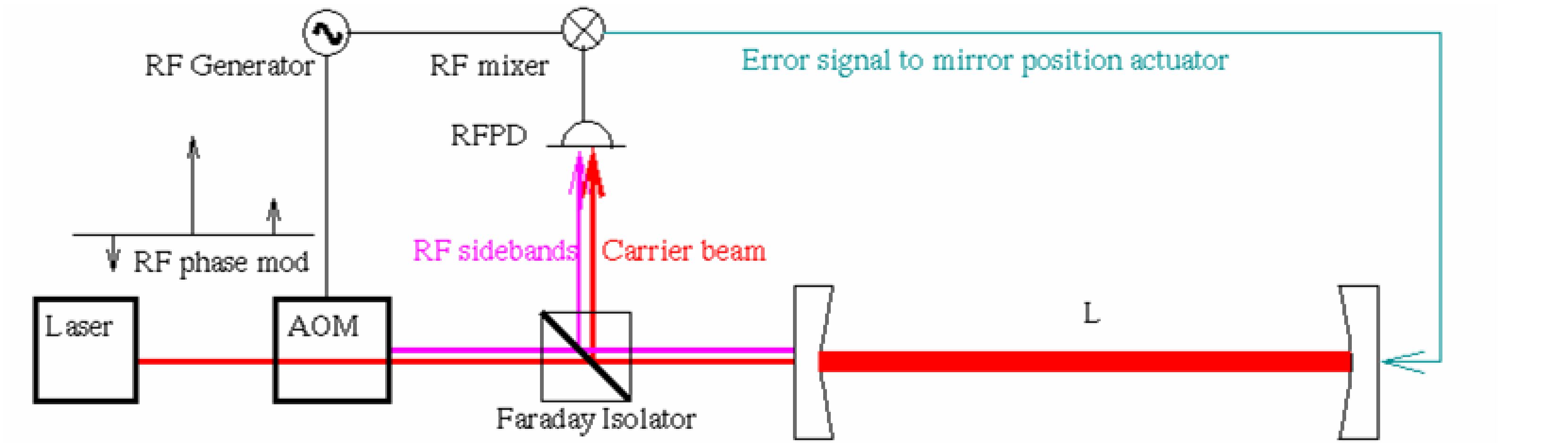
- Current through the coil creates a magnetic field, allowing mirror control

Cavity Control

If we operate at the "dark fringe", a large phase shift causes a small change in the output light.

Instead we use heterodyning. We add phase-modulated RF sidebands that are not resonant in the arm cavities.





Cavity Control (cont.)

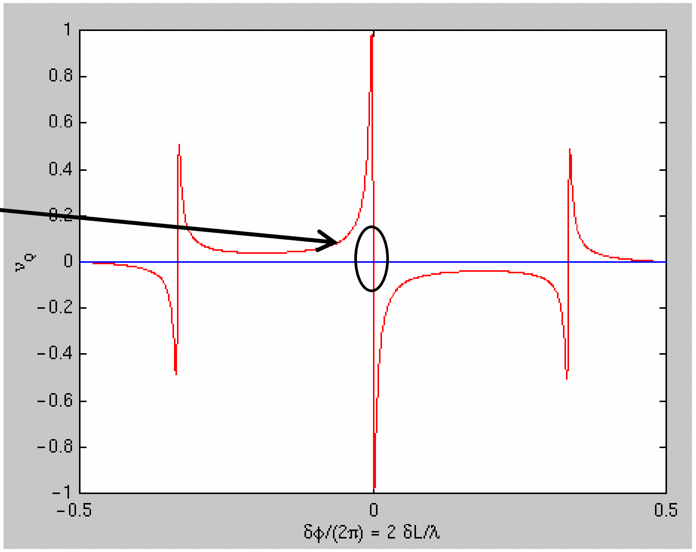
Modulated light = A cos (ωt) + B cos [(ω + ω_m)t] + B cos [(ω – ω_m)t]

Intensity (averaged over ω) ~ A^2 + AB cos (ω_mt) + B^2 cos (2ω_mt)

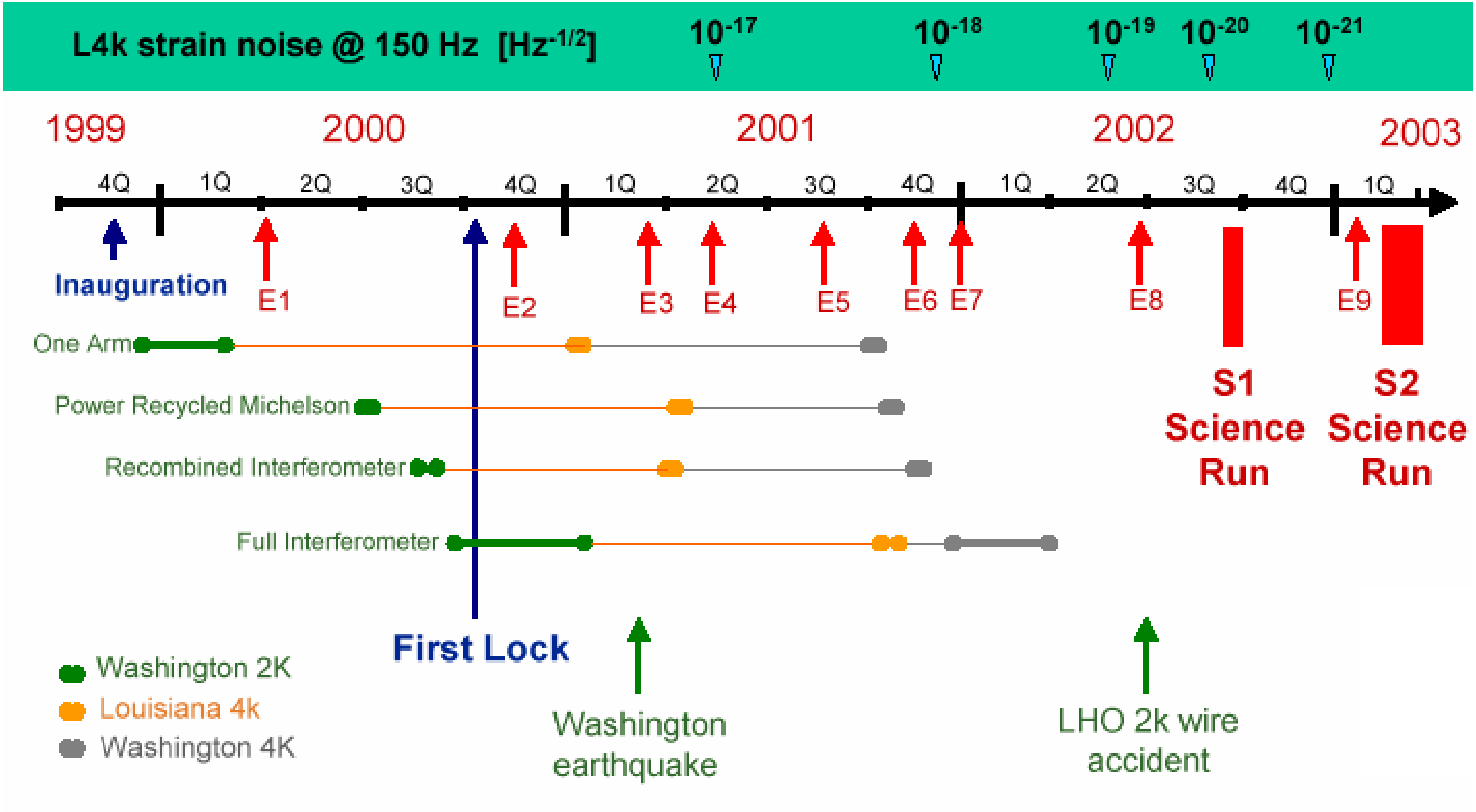
Mixing with cos (ω_mt) = A^2cos (ω_mt) + AB $\cos^2$ (ω_mt) + B^2 cos (2ω_mt) cos (ω_mt)]

Averaging over many cycles gives simply AB/2

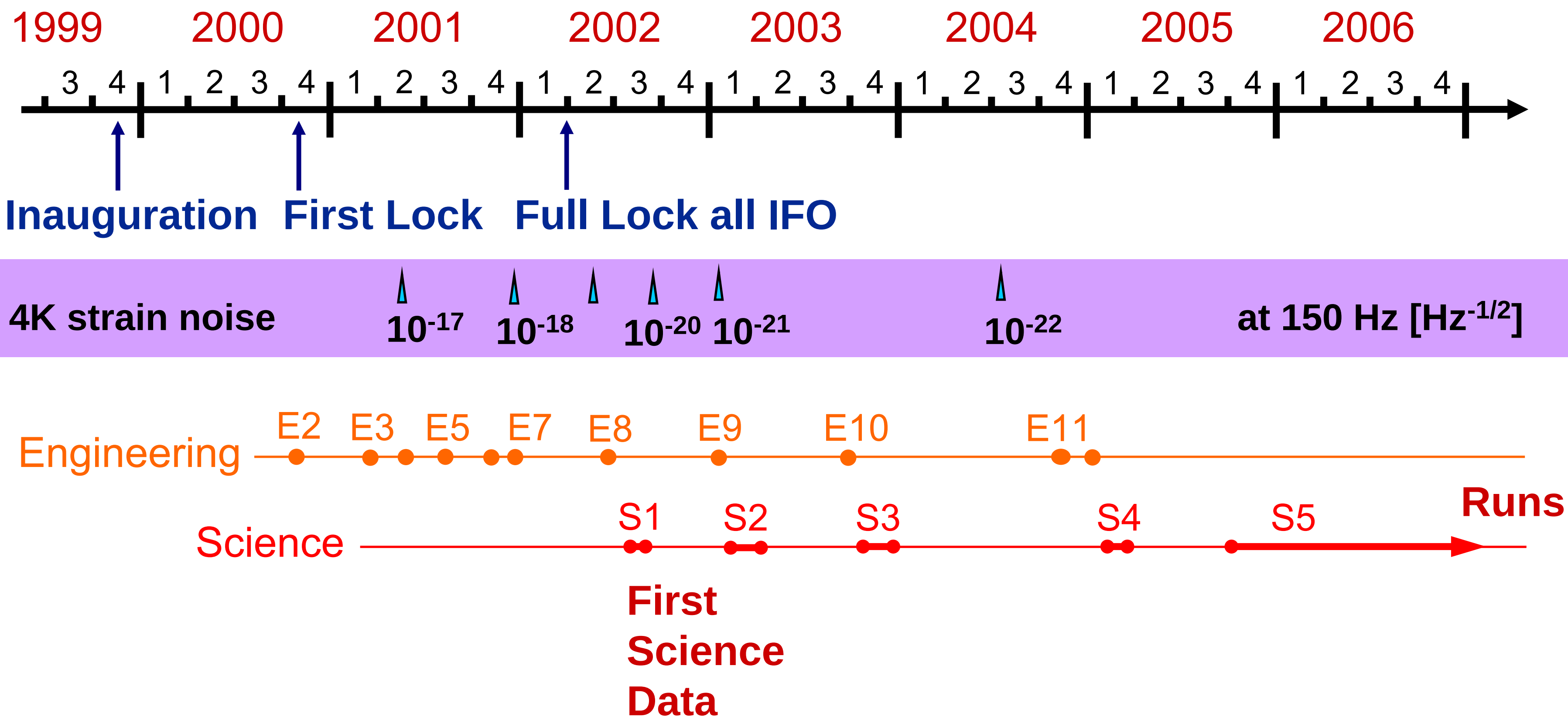
This term is linear in A, which senses the length of the arm cavities, and gives us our output and correction signal.

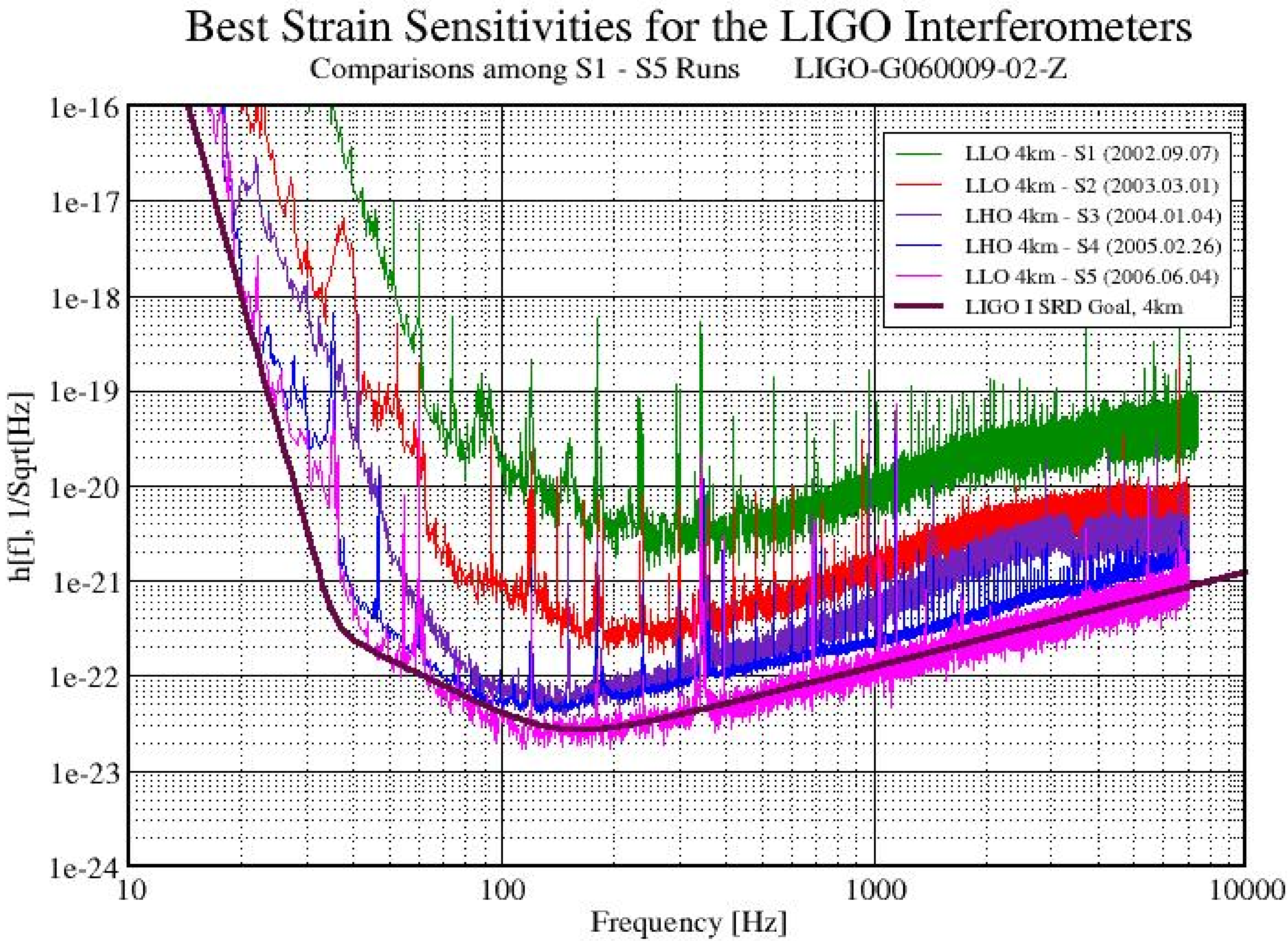


Early Timeline



More Recent Events





Best Strain Sensitivities for the LIGO Interferometers
Comparisons among S1 - S5 Runs
LIGO-G060009-02-Z
LLO 4km - S1 (2002.09.07)
LLO 4km - S2 (2003.03.01)
LHO 4km - S3 (2004.01.04)
LHO 4km - S4 (2005.02.26)
LLO 4km - S5 (2006.06.04)
LIGO I SRD Goal, 4km
h[f], 1/Sqrt[Hz]
1e-16
1e-17
1e-18
1e-19
1e-20
1e-21
1e-22
1e-23
1e-24
10
100
1000
10000
Frequency [Hz]

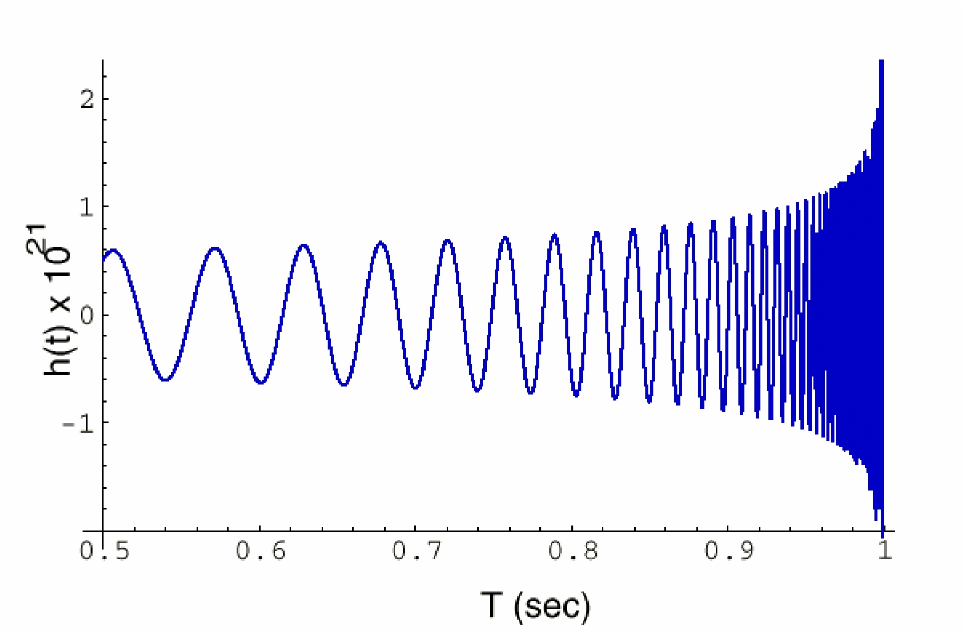
Sorry…

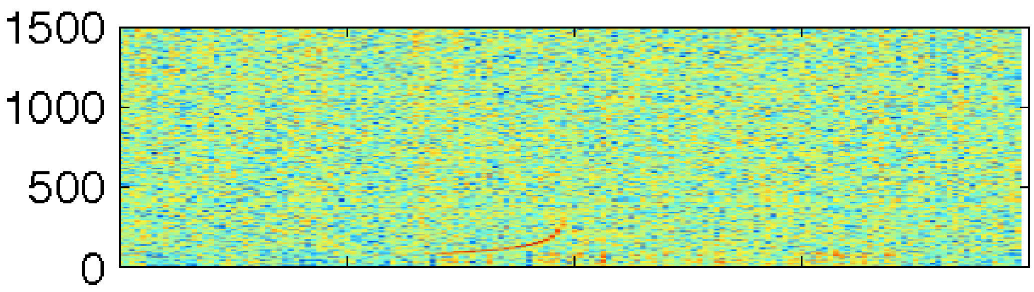
No detections

(yet…)

Inspirals: Matched Filtering

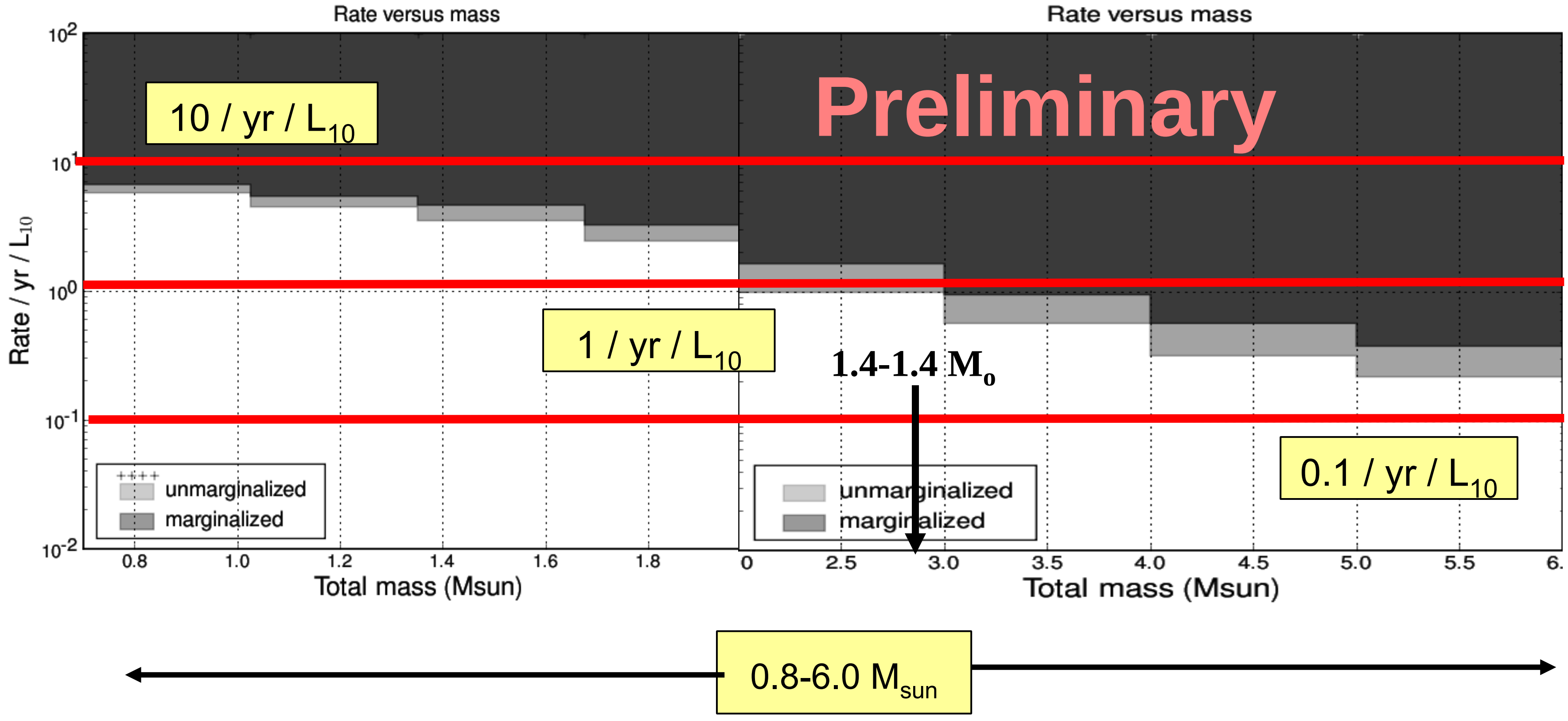
- Inspiral waveform can be modeled for different masses, positions, orbits
- ASIS – Astrophysical Source Identification and Signatures
- Use matched filtering to correlate each modeled waveform to data



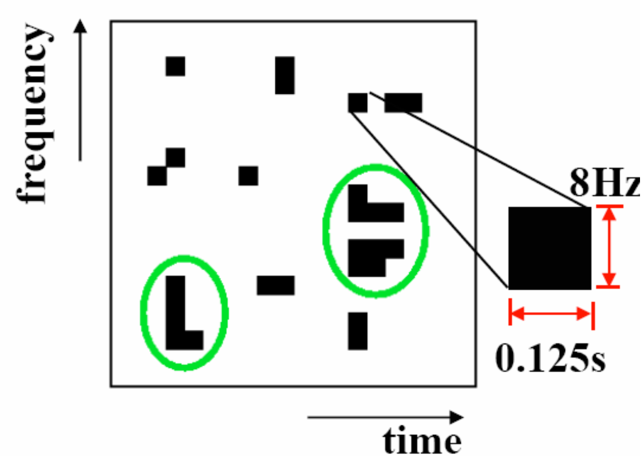


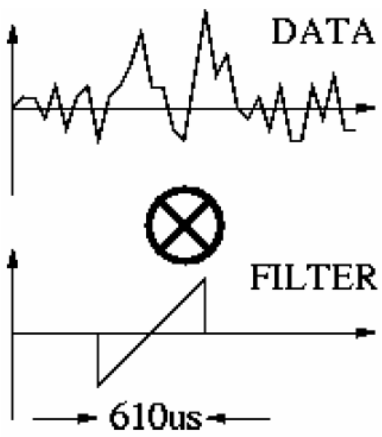
Inspiral Search Results

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



“Un-modeled” Burst Analysis





- Unlike inspirals, look for waveforms for which we have no accurate prediction (i.e., asymmetric supernova)
- Time-frequency search – look for connected regions of excess power
- Time domain search – look for rapid amplitude increase over certain rise time
- Also triggered searches – cross-correlations with 39 gamma ray bursts during S2, S3, S4 runs

Periodic Sources (Pulsars)

- 97 candidates in first 10 months of S5 data
- Look for signal at twice rotation frequency
- Lack of signal puts upper limit on pulsar ellipticity

Lowest GW strain upper limit:

PSR J1802-2124

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

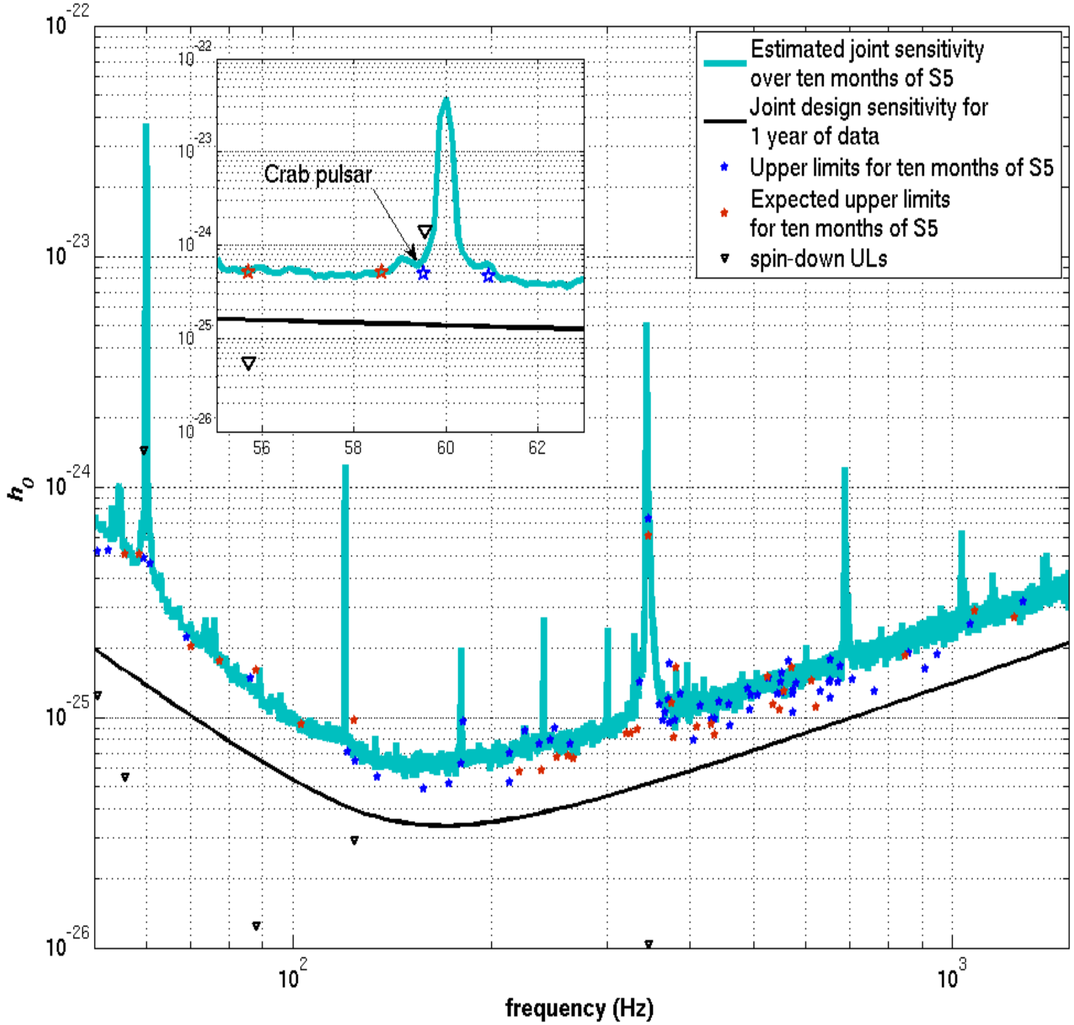
$\mathbf{h_0 < 4.9 \times 10^{-26}}$

Lowest ellipticity upper limit:

PSR J2124-3358

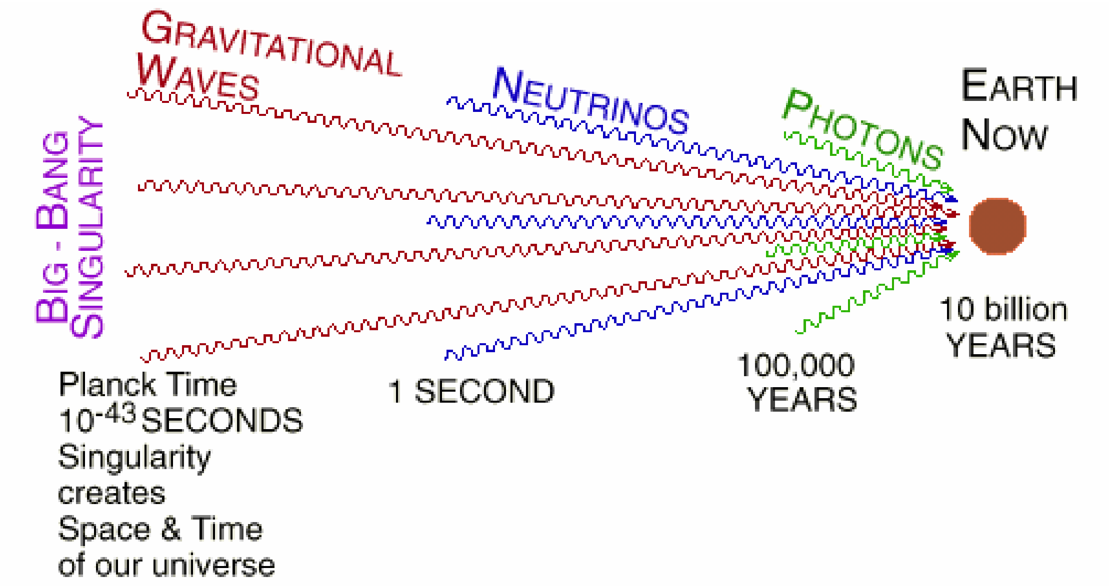
(f_{gw} = 405.6 Hz, r = 0.25 kpc)

$\boldsymbol{\varepsilon < 1.1 \times 10^{-7}}$



Stochastic Results

- "Random" GW signal produced by a large number of weak, independent GW sources



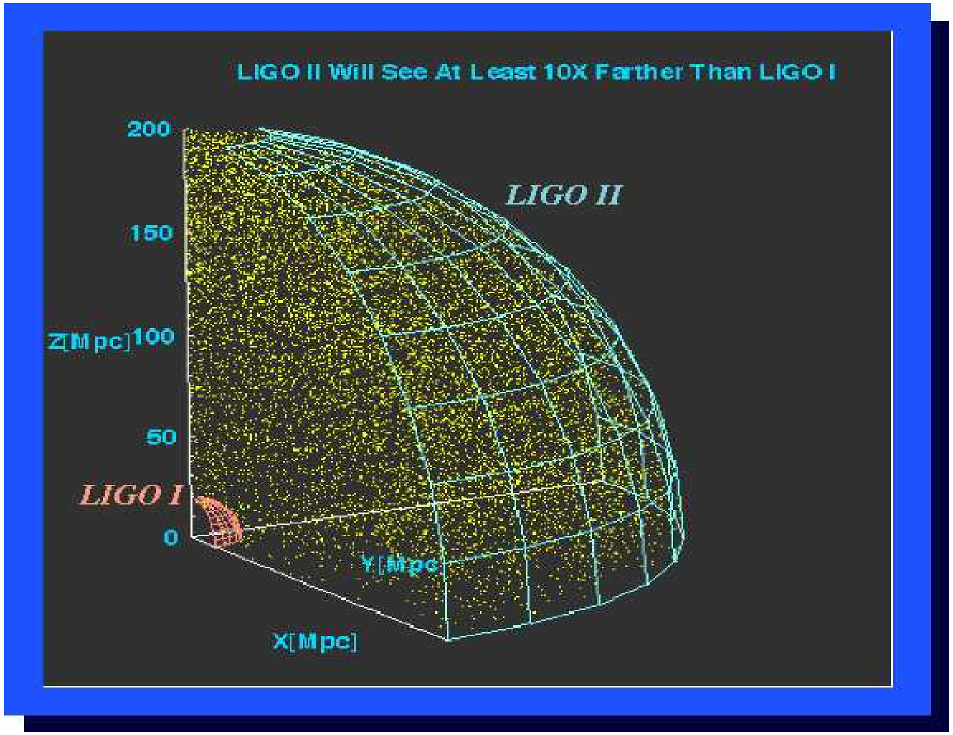
- Detected by cross-correlating the outputs of multiple interferometers

- Described by dimensionless spectrum $\Omega_{gw}(f)$:

$$\Omega_{gw}(f) = \frac{f}{\rho_c}\frac{d\rho_{gw}}{df}, \quad \rho_c = \text{crit. density} = \frac{3c^2 H_0^2}{8\pi G}$$

$< 8.4\text{x}10^{-4}$ (S3) $< 6.5\text{x}10^{-5}$ (S4)

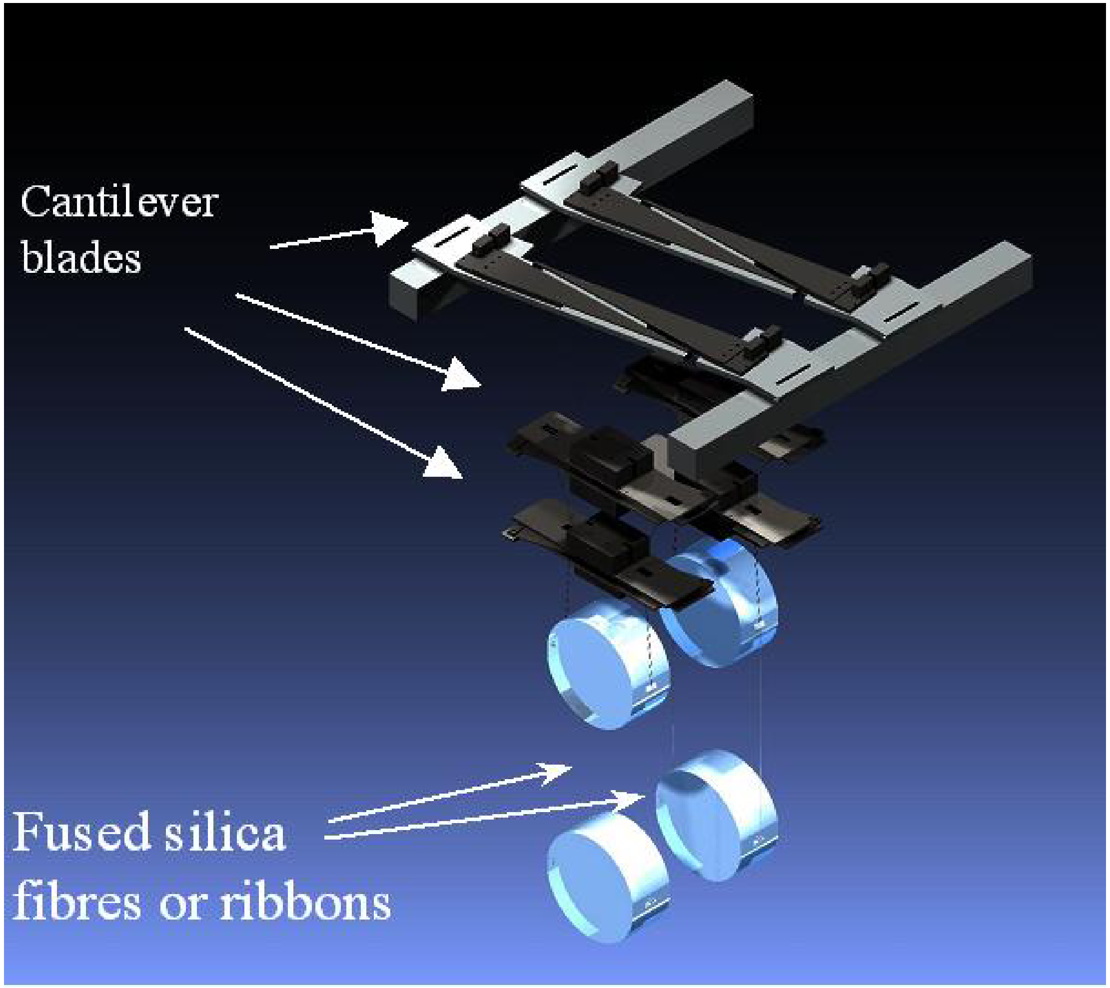
The Need for Advanced LIGO



- S5 run expected to end in September 2007
- Rapid commissioning period followed by “Enhanced” LIGO run
- Advanced LIGO construction to begin FY 2008, completed 2013-2014. Why?
  - » X10 increase in sensitivity = x1000 volume of sky searched
  - » Event rate weekly or better
  - » Mission is to do astronomy
- Factor of ten improvement needed at all frequencies

Multiple Pendulum Suspensions

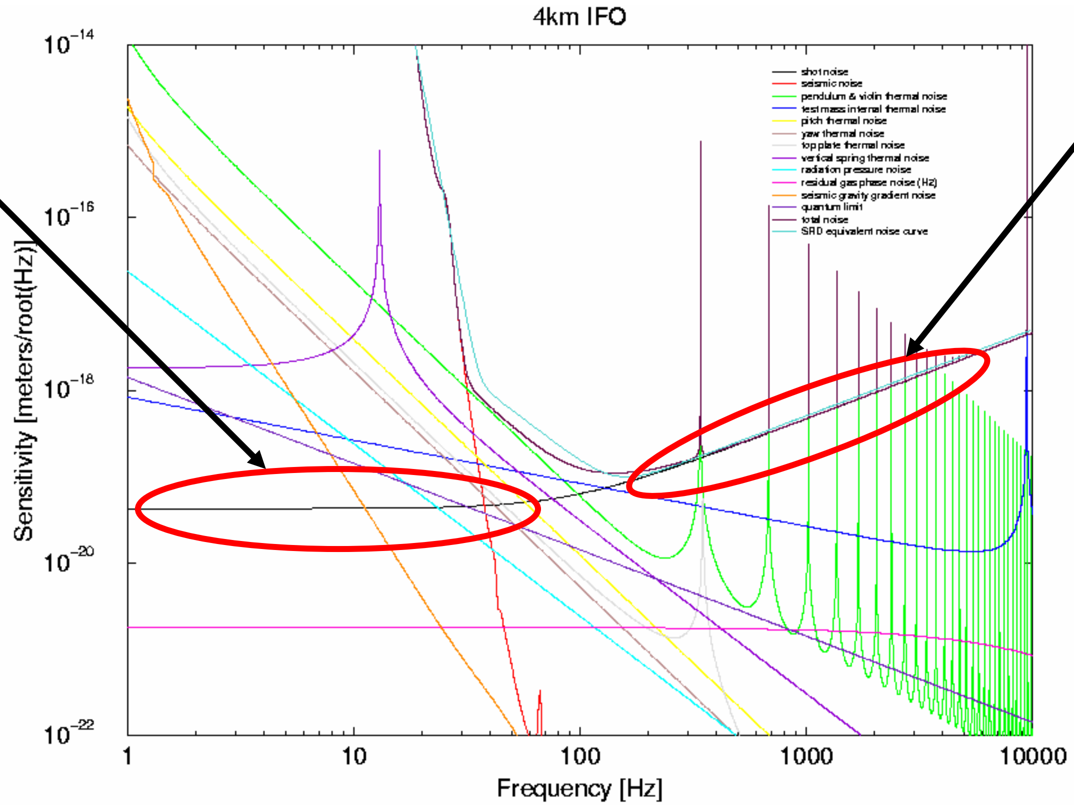
- Multiple pendula add more attenuation of seismic noise
- Positioning magnets no longer on test mass
- Fused silica ribbons replace suspension wires
- Both changes result in higher Q value for test mass, which reduces thermal noise away from normal mode frequencies



Arm Cavity Finesse and Noise

Shot noise:

Random fluctuations of laser intensity.

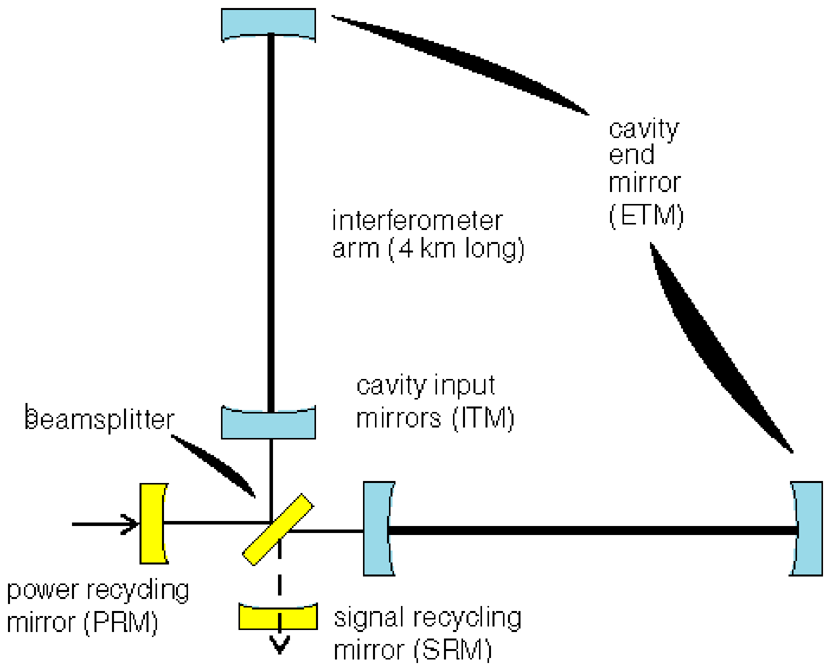


Cavity pole:

Loss of sensitivity past the frequency where more than ½ of a wavelength is stored in the arm cavities.

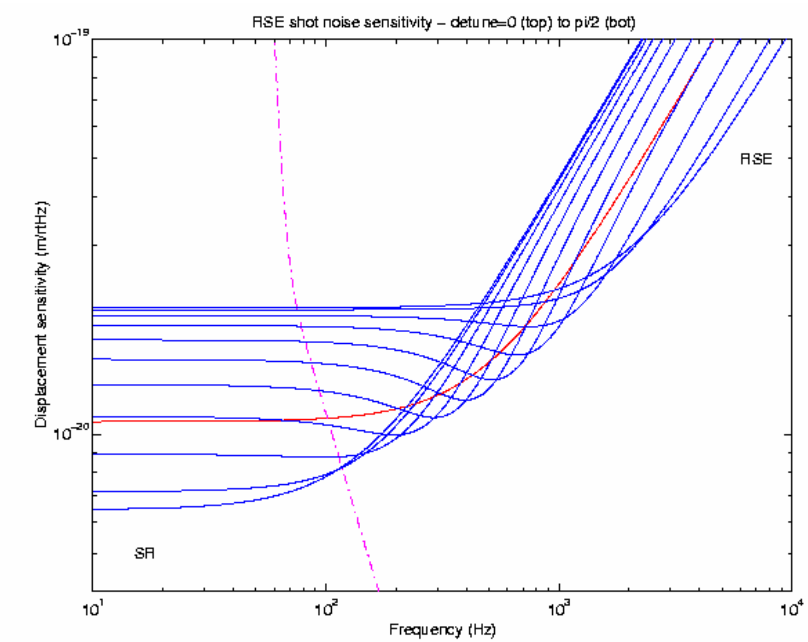
Changing the arm cavity finesse affects these two quantities inversely, for no net effect at our most sensitive frequencies.

Signal Recycling



In signal recycling, a mirror is added at the output port, creating a cavity resonant for the beats between the laser frequency and a periodic signal.

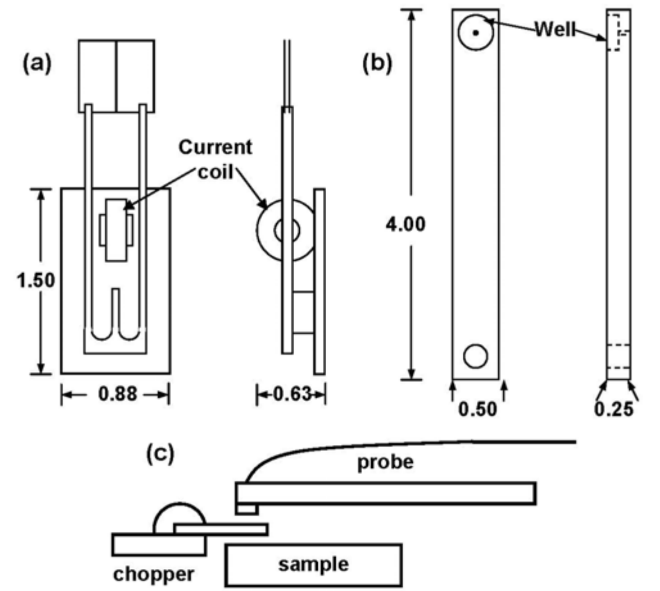
By tuning the length of this cavity, we can hug the thermal noise curve, or maximize sensitivity at a specific frequency for periodic sources.

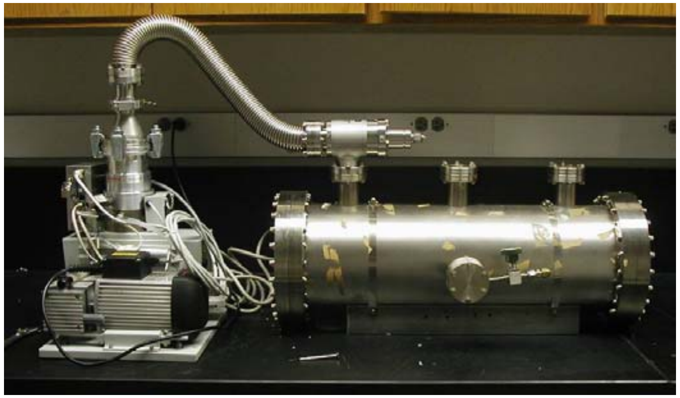


Charging Effects

- Buildup of charge on optical surfaces can effect interferometer:
  - » Interferes with magnetic position control
  - » Charge motion causes suspension noise
  - » Reduces reflectance by attracting dust

- Measurements underway to determine magnitude, relaxation time constant





LIGO

Summary

- The LIGO interferometers are running at design sensitivity, and will complete one year of integrated data collection in late summer 2007.
- No detection yet, but S5 analysis is ongoing.
- Expected improvement in sensitivity of ~2 by 2009 and ~10 by 2014. The latter corresponds to a x1000 increase in detection rate.