Discovery of Gravitational Waves

Avto Kharchilava

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University at Buffalo
The State University of New York

https://www.ligo.caltech.edu/news/ligo20160211

Gravity

- Einstein's General theory of relativity:

  Gravity is a manifestation of curvature of 4- dimensional (3 space + 1 time) space-time produced by matter (metric equation)

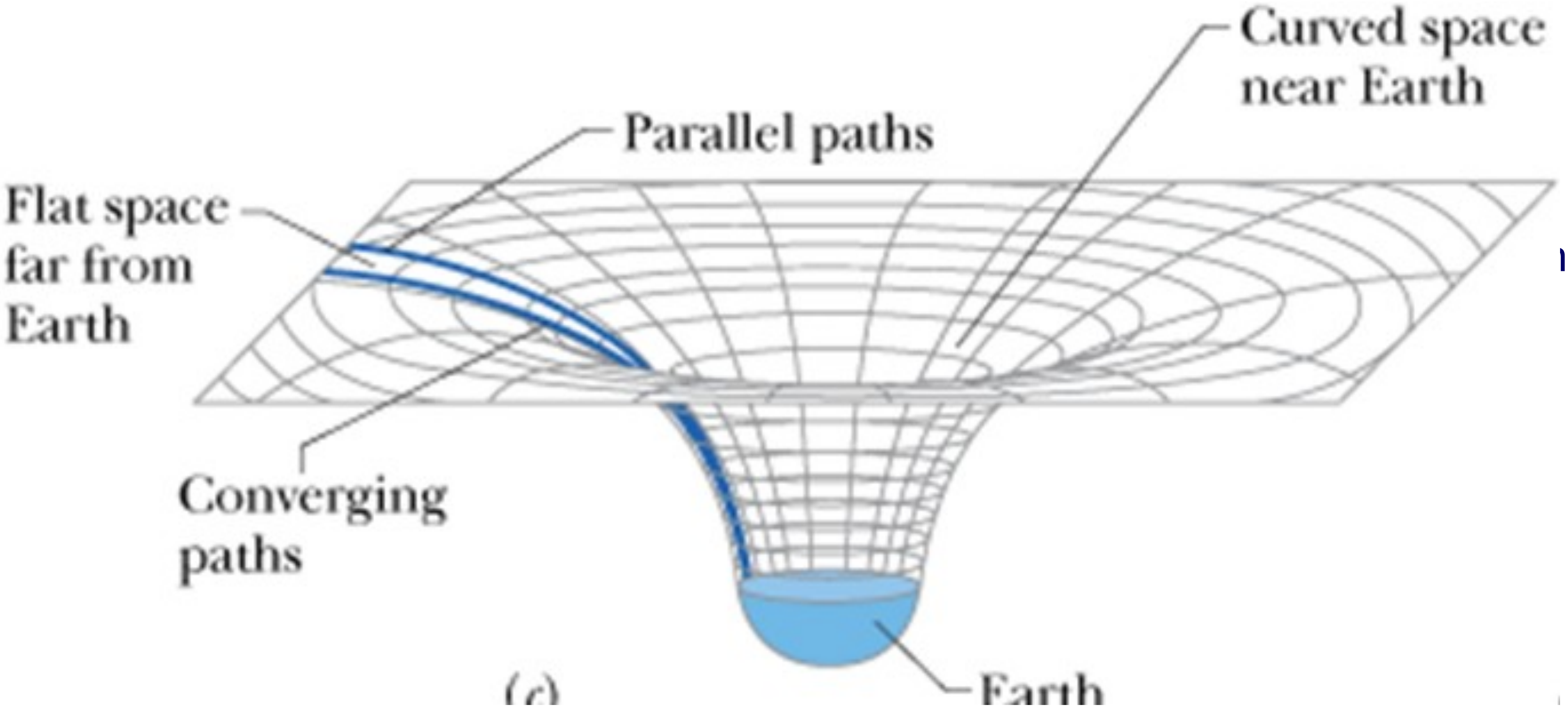
$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

- If the curvature is weak, it produces the familiar Newtonian gravity:

$$F = G\frac{m_1 m_2}{r^2}$$

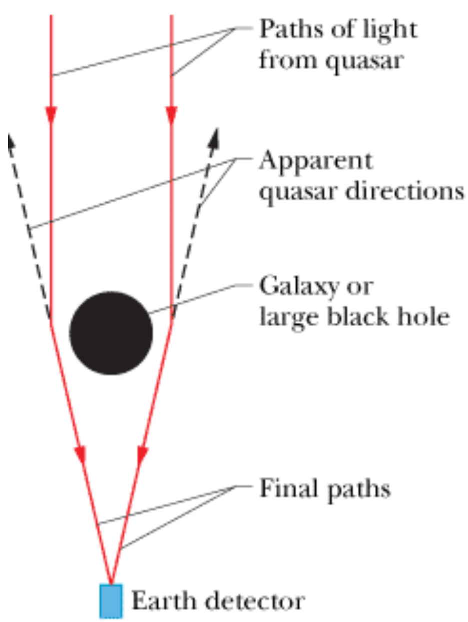
Predictions of General Relativity

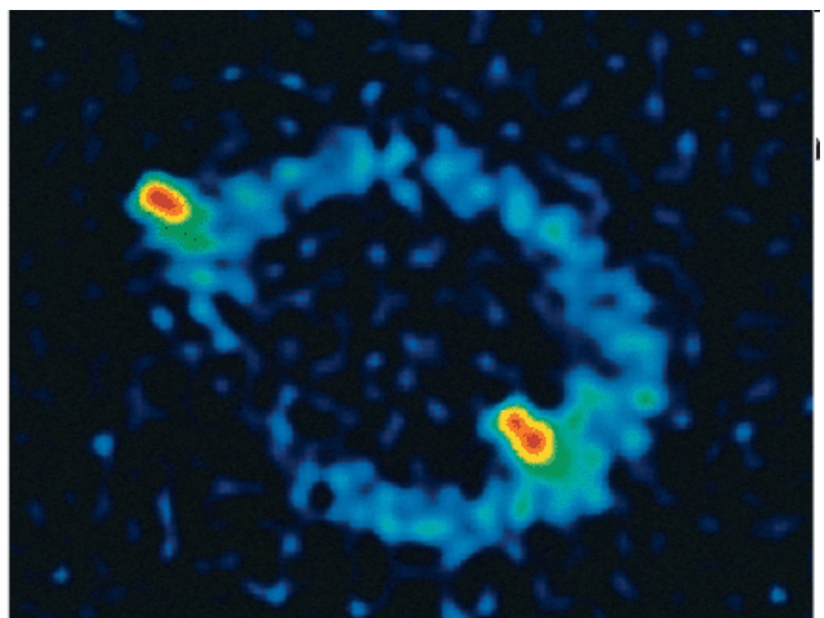
- According to GR, the gravitation is not due to a force but rather is a manifestation of curved space-time with the curvature being produced by the mass content of the space-time



Predictions of General Relativity

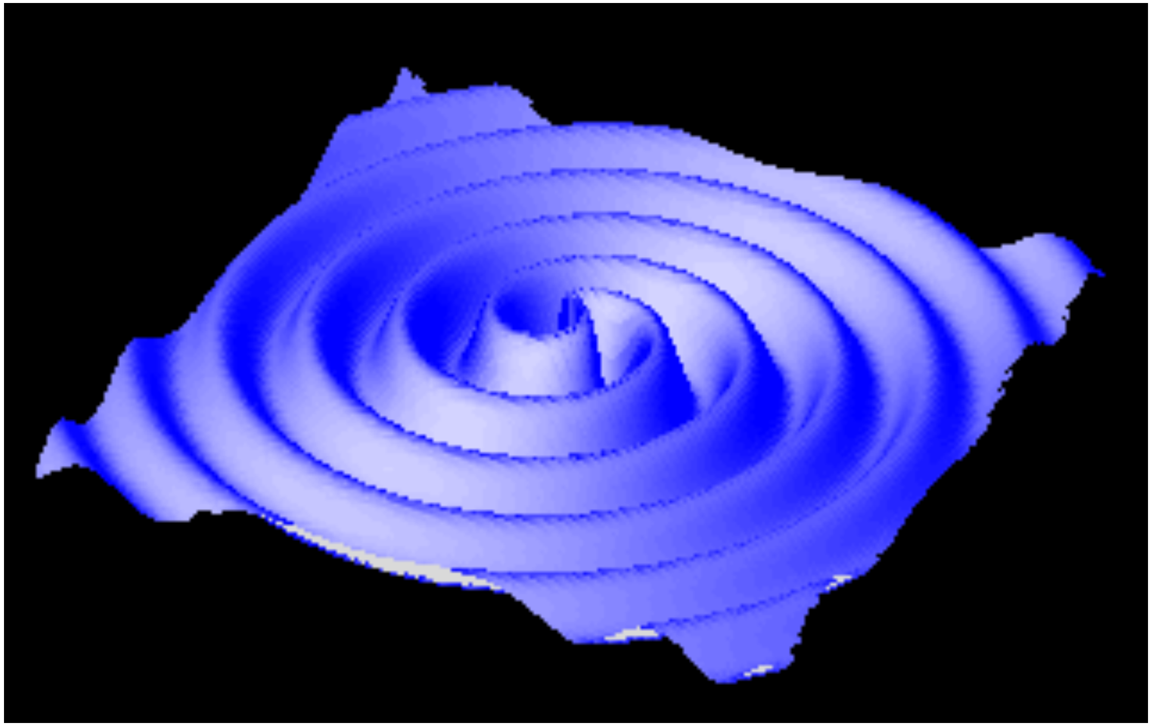
- According to GR, the gravitation is not due to a force but rather is a manifestation of curved space-time with the curvature being produced by the mass content of the space-time
- Predictions of GR
  - Black Hole, an object with a gravitational field so powerful that no form of matter or radiation (even light) can escape it
  - Bending of light by a massive object: Gravitational Lensing. If a massive object (e.g. black hole) is between us and a star, the light from the star can be bent. As a result we see the same star in different directions in the sky

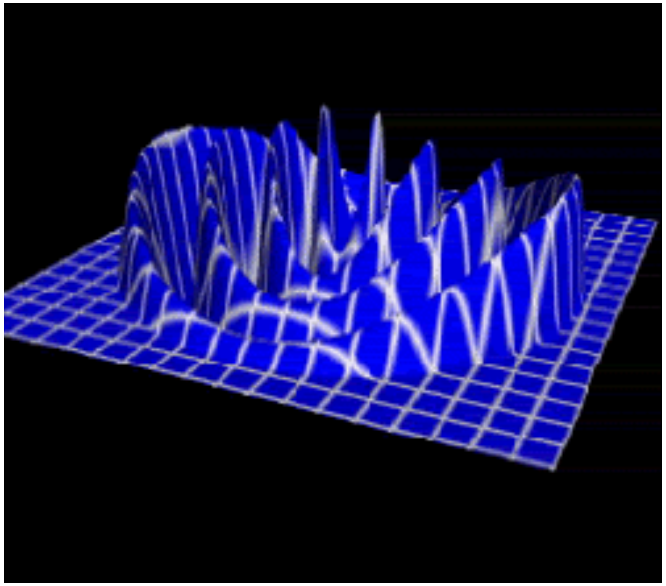




Gravitational Waves

- When the curvature varies rapidly due to motion of the object(s), curvature ripples are produced. These ripples of the space-time are Gravitational-waves.
- Gravitational-waves propagate at the speed of light.





http://focus.aps.org/story/v8/st3

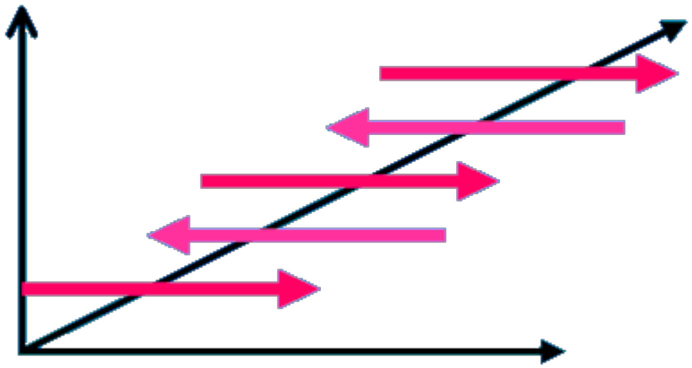
www.jointsolutions.co.uk/ docs/pages/leftnav.htm

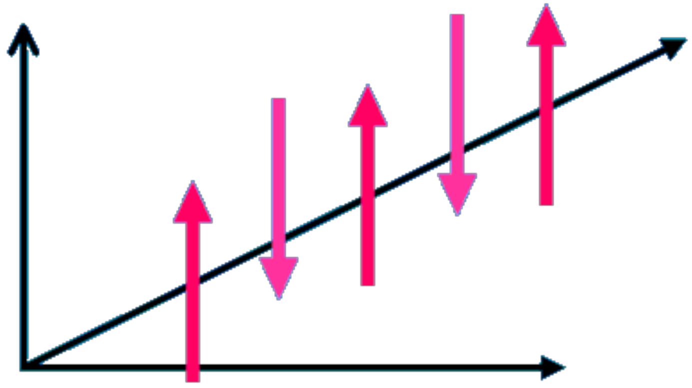
According to Einstein's theory of gravity, an accelerating mass causes the fabric of space-time to ripple like a pond disturbed by a rock. These ripples are Gravity Waves

This picture represents Gravity Waves produced by a pair of rotating neutron stars

This picture represents ripples in a pond disturbed by a rock.

Electromagnetic Waves

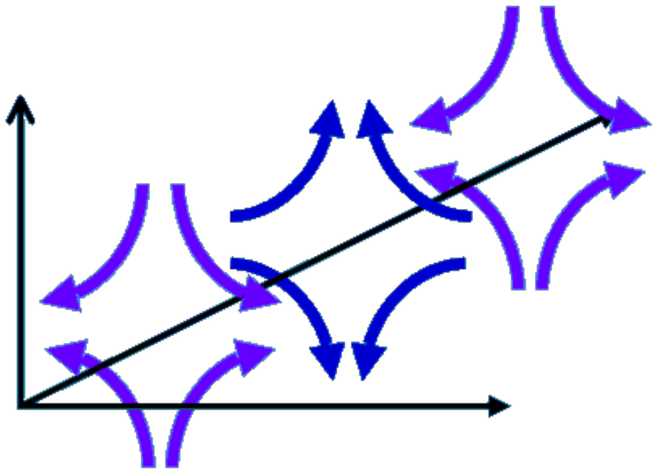


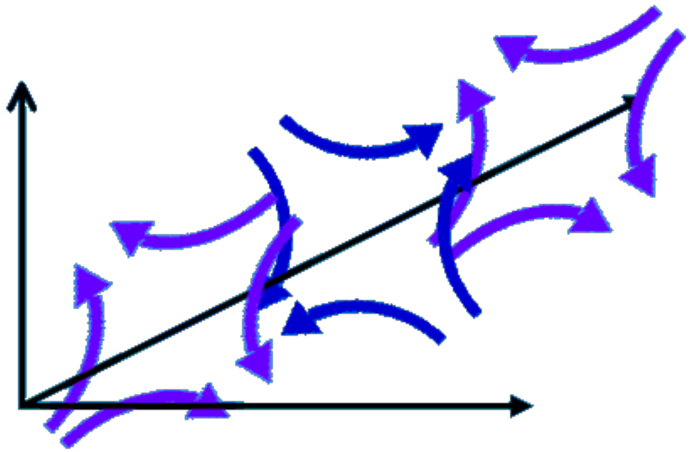


Electromagnetic Waves oscillate perpendicular to their motion

They oscillate in the X and Y directions and the wave moves in the Z direction

Gravitational Waves



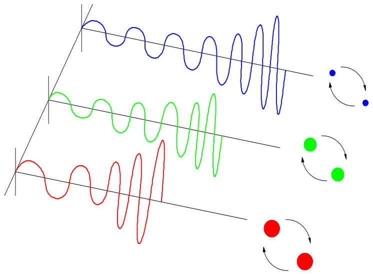


Gravitational waves have 2 polarizations like Electromagnetic Waves. The only difference is that Gravity Wave polarization lies in a horizontal-vertical "+" shape and 45 degrees to that in a "x" shape

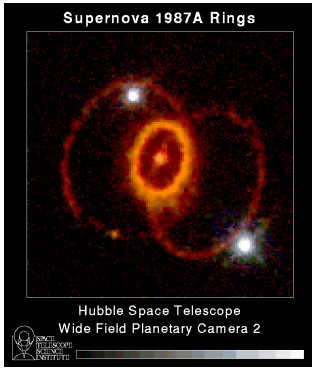
Electromagnetic vs Gravitational Waves

- EM waves are produced by accelerated charges, whereas GWs are produced by accelerated "masses".
- EM waves propogate through space-time, GWs are oscillations of space-time itself.
- Typical frequencies of EM waves range from (10^7 Hz – 10^{20} Hz) whereas GW frequencies range from ~ (10^{-9} Hz – 10^4 Hz). They are more like sound waves.

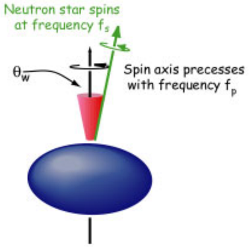
Astrophysical Sources of Gravitational Waves



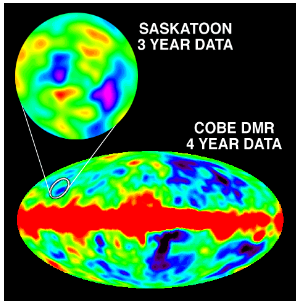
- Compact binary inspiral: ***"chirps"***
  - NS-NS waveforms are well described
  - BH-BH need better waveforms
  - search technique: matched templates



- Supernovae / GRBs: ***"bursts"***
  - burst signals in coincidence with signals in electromagnetic radiation
  - prompt alarm (~ one hour) with neutrino detectors
- Pulsars in our galaxy: ***"periodic"***
  - search for observed neutron stars (frequency, doppler shift)
  - all sky search (computing challenge)
  - r-modes

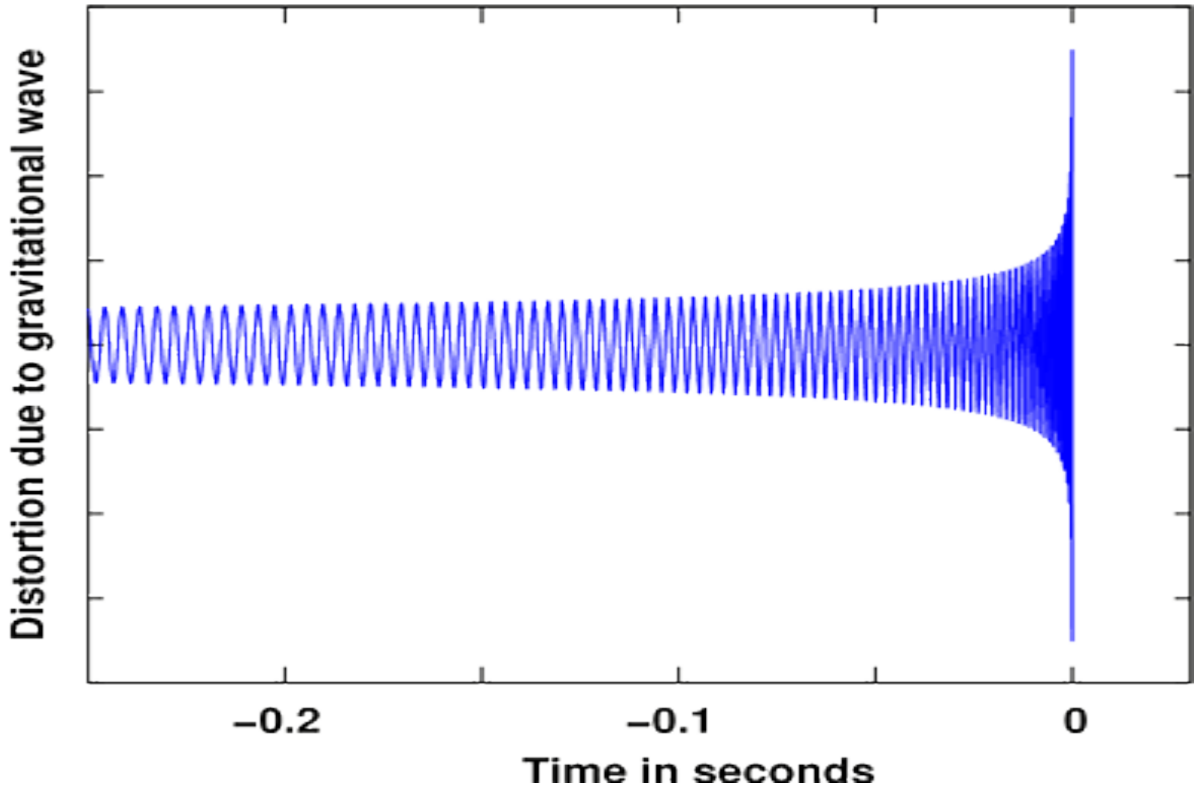


- Cosmological Signals: ***"stochastic background"***



Sources of GWs

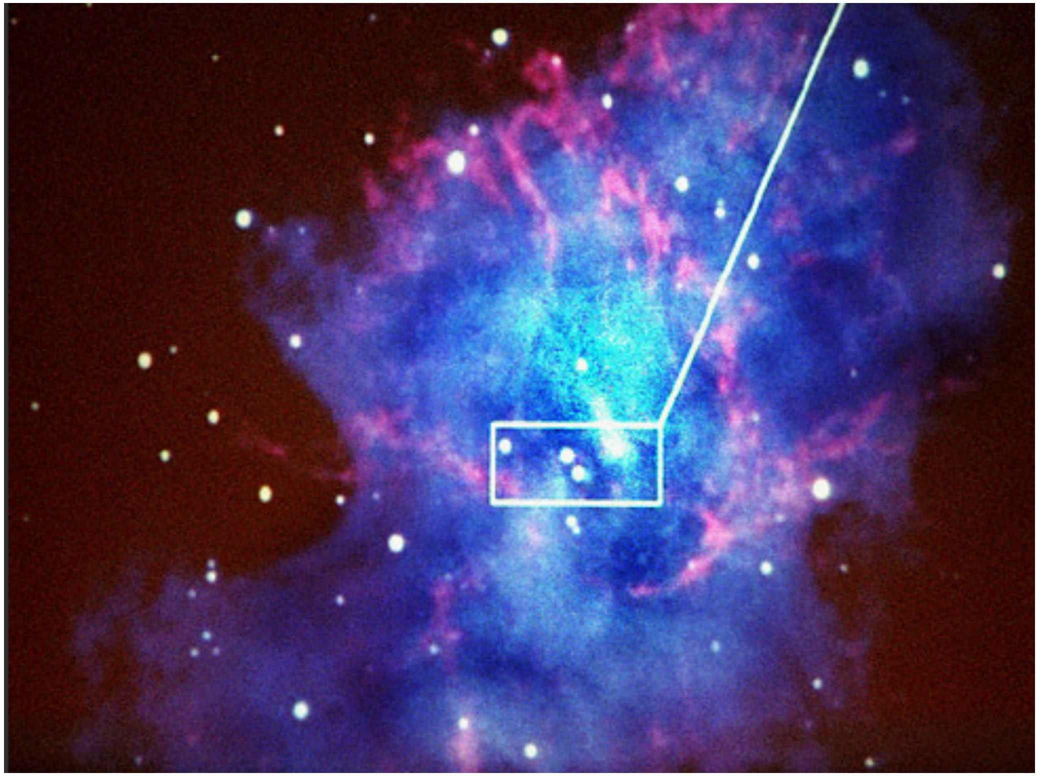
- **Inspiral sources**: Binary black holes, Binary Neutron stars (pulsars), Binary white-dwarfs or combination of these
  - As two stars orbit around each other, they steadily lose energy and angular momentum in the form of GWs
  - This makes the orbital separation to shrink slowly and they merge after some time (this time depends on their masses and orbital separation that we observe)



Inspiraling binary stars

Gravitational Radiation

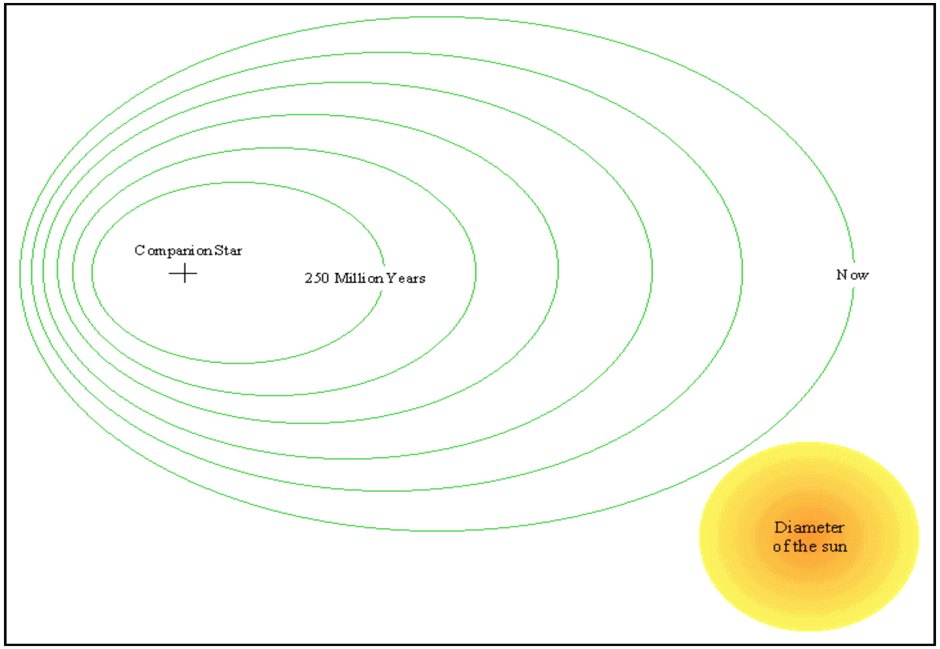
This was proved in the 1970s when Russell Hulse and Joseph Taylor observed that the binary pulsar system, which consists of two super-massive stars in close proximity, radiates energy such that it's period decreases 75 milliseconds every year. This proves the existence of Gravity Waves

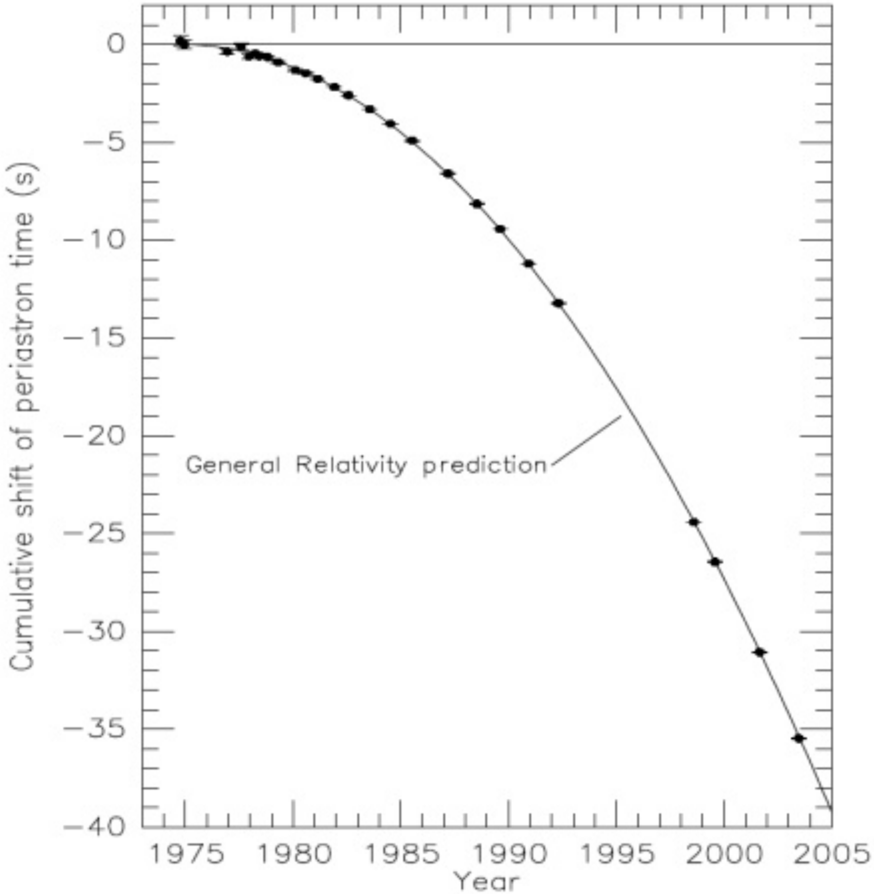


Binary pulsar

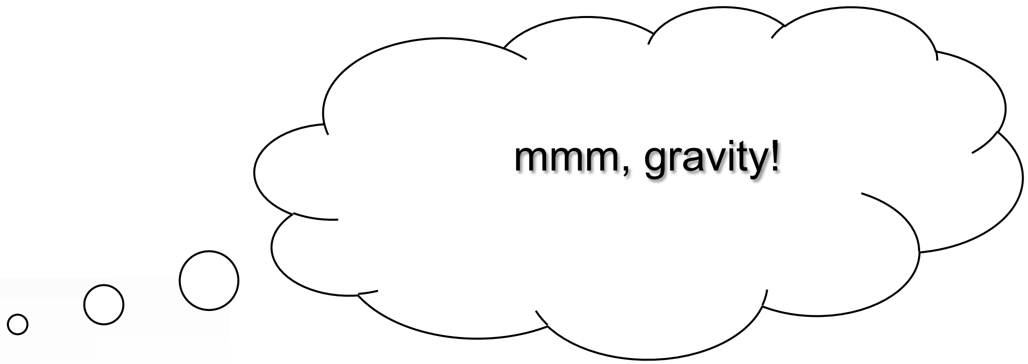
How do we know GWs exist ? Indirect proof

- Hulse-Taylor binary pulsar (Nobel prize 1993)
- Steady decrease in orbital separation due to loss of energy through GWs





How do we detect Gravity Waves?



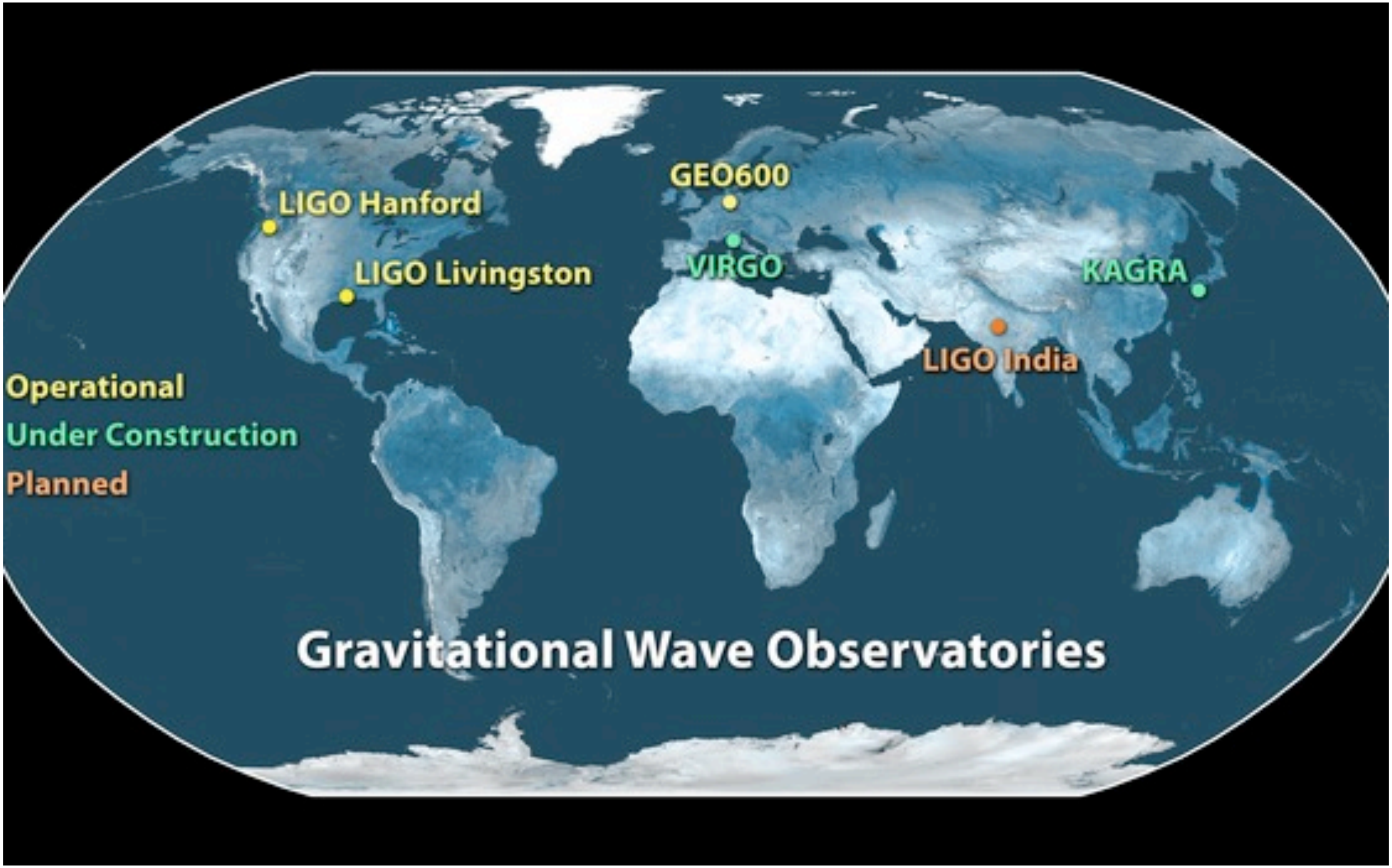
The answer is:

Very Carefully

Detection of Gravitational Waves

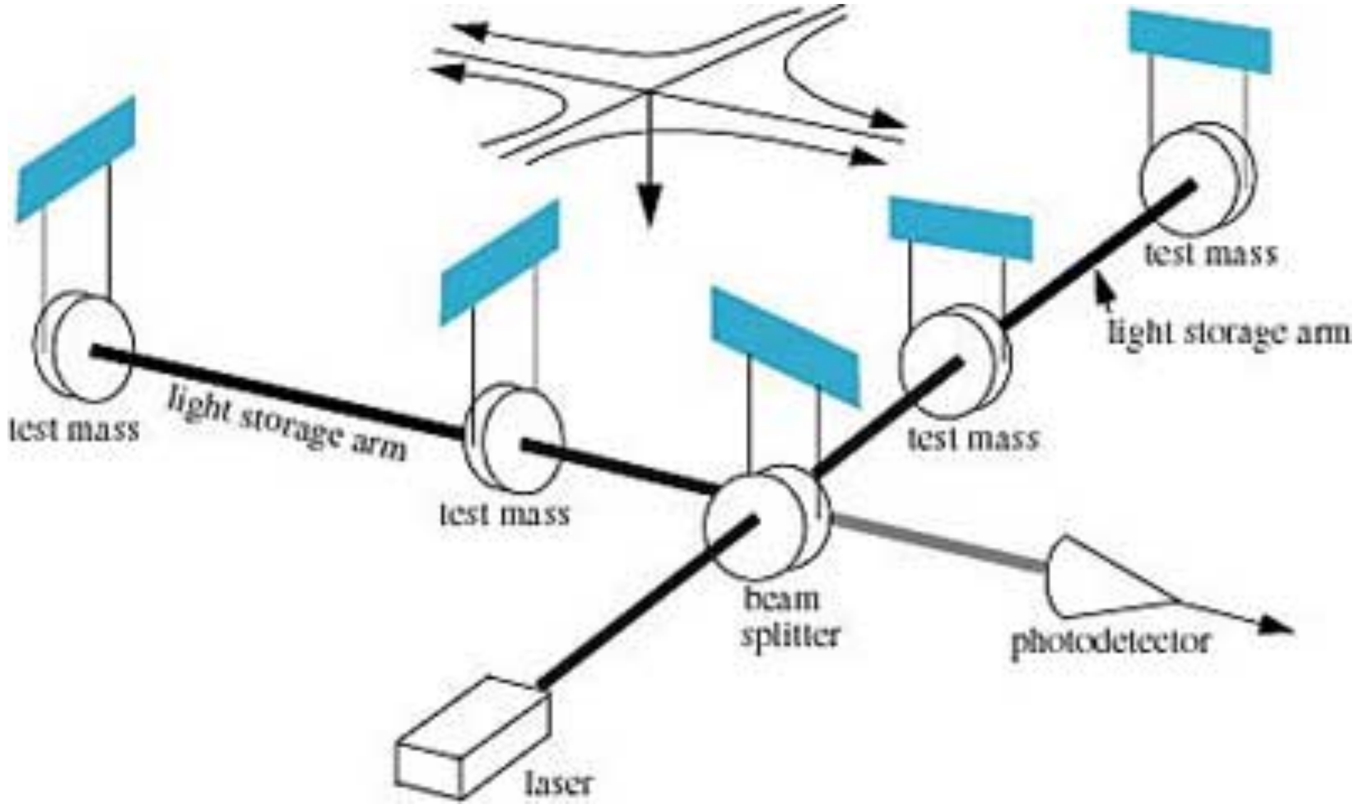
- Ground based detectors:

  LIGO (US), VIRGO (Italy), GEO (Germany), TAMA (Japan), AURIGA (Australia)
- (Proposed) Space-based detectors: LISA (NASA-ESA)



*L*aser *I*nterferometer *G*ravitaional Wave *O*bservatory

- LIGO

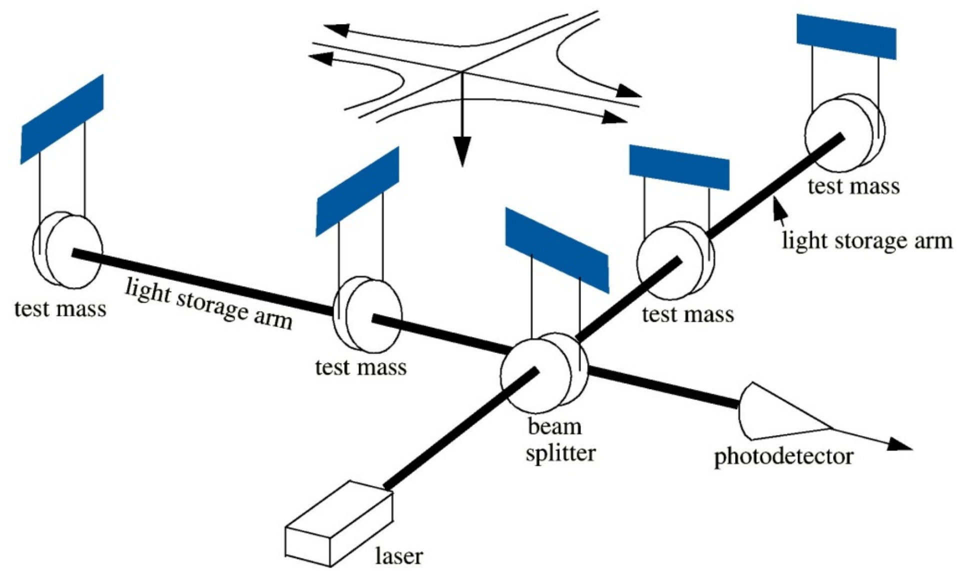


- Length of each arm, L = 4 km,
- frequency range , f = 10 Hz – 10^4 Hz
- $\Delta L \sim 10^{-18}$ meters, size of proton ~ 10^{-15} meters

Detecting GWs with Interferometry

Suspended mirrors act as "freely-falling" test masses in horizontal plane for frequencies $f >> f_{pend}$

$$h = \Delta L / L$$

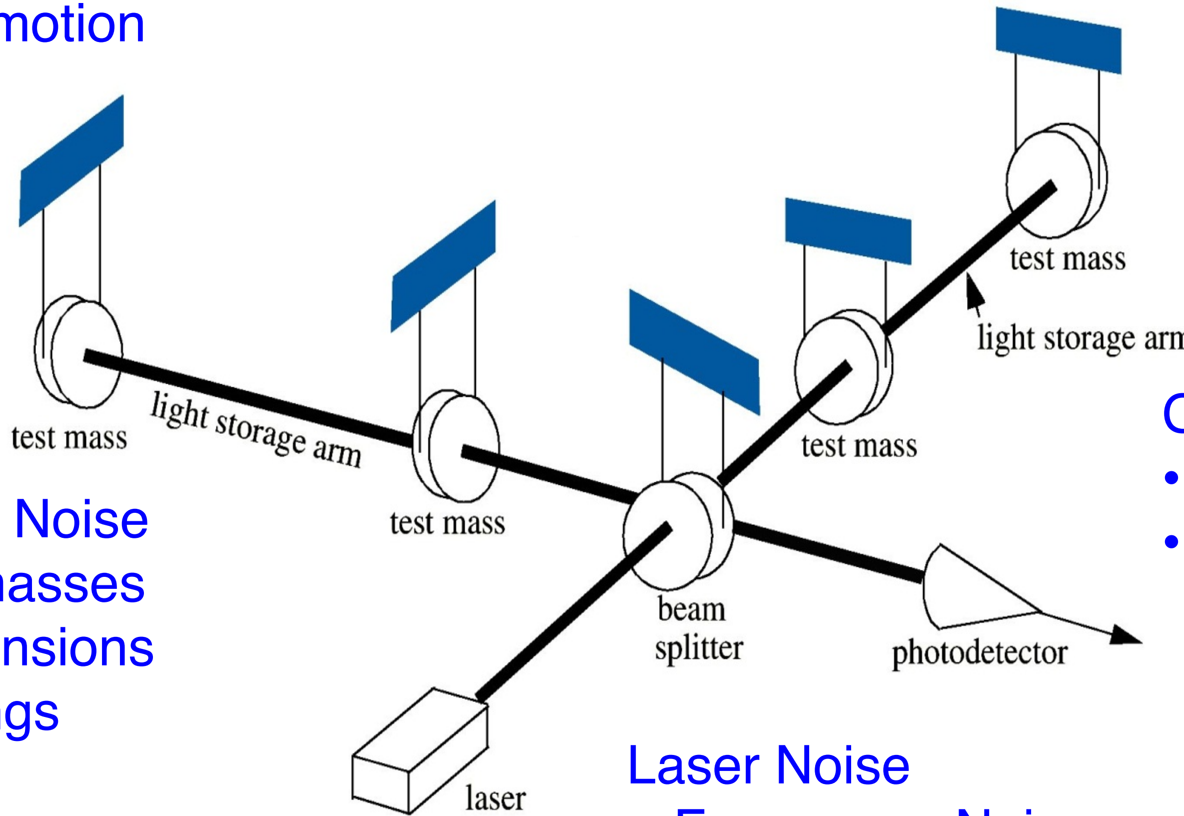


Terrestrial detector, L ~ 4 km
For $h \sim 10^{-22} - 10^{-21}$ (Initial LIGO) $\Delta L \sim 10^{-18}$ m. Useful bandwidth 10 Hz to 10 kHz, determined by "unavoidable" noise (at low frequencies) and expected maximum source frequencies (high frequencies)

Limits to Sensitivity

Vibrational Noise
- Ground motion
- Acoustic

Residual Gas Noise

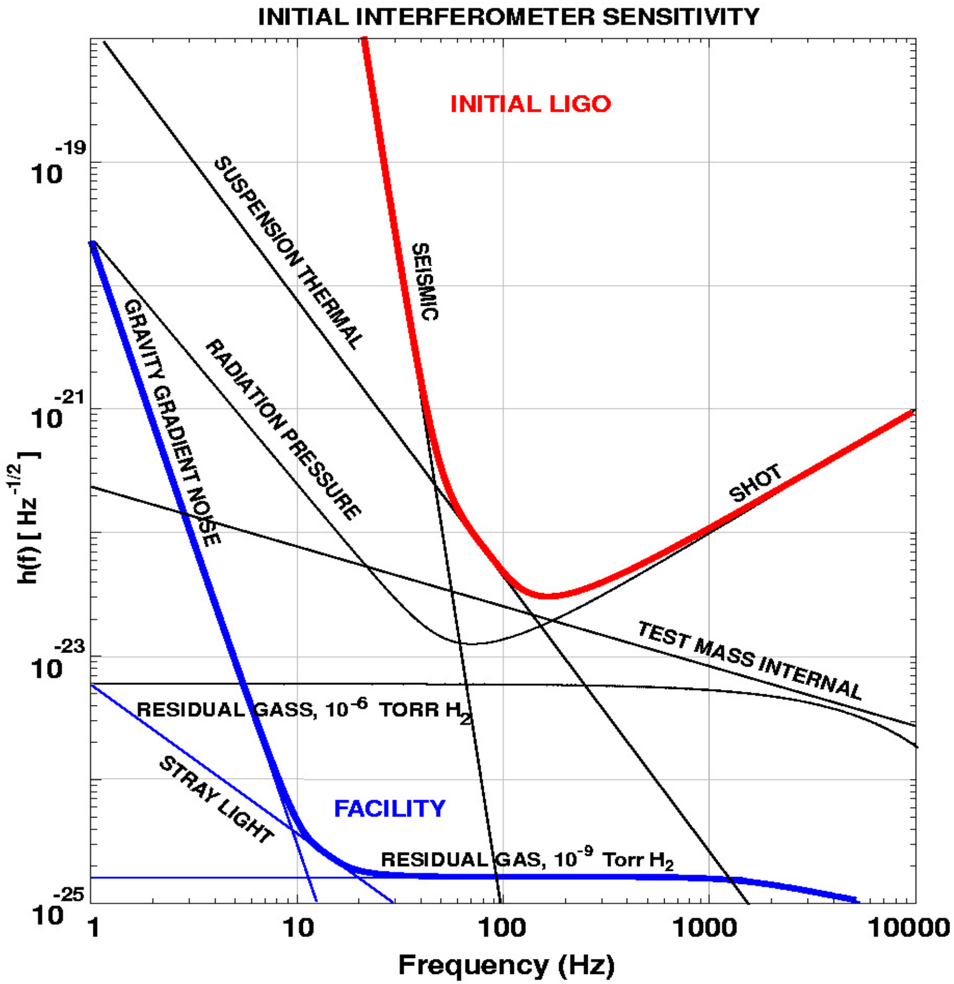


Quantum Noise
- Shot Noise
- Radiation pressure Noise

Thermal Noise
- Test masses
- Suspensions
- Coatings

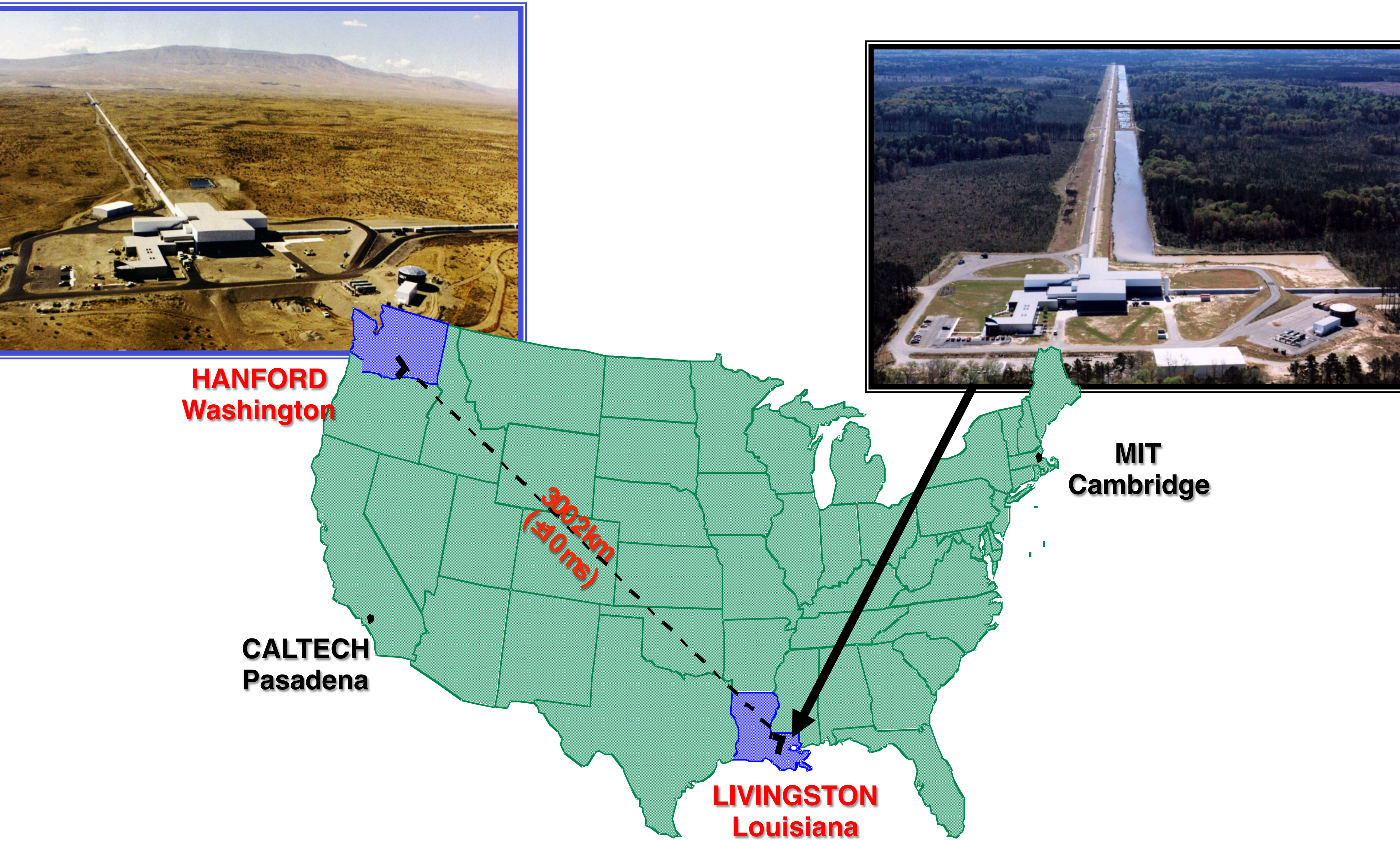
Laser Noise
- Frequency Noise
- Intensity Noise

Initial LIGO Sensitivity Goal



- Strain sensitivity $<3\times10^{-23}$ $1/Hz^{1/2}$ at 200 Hz
- Sensing Noise
  - Photon Shot Noise
  - Residual Gas
- Displacement Noise
  - Seismic motion
  - Thermal Noise
  - Radiation Pressure

Laser Interferometer Gravitational-wave Observatory (LIGO)



Beam Pipe and Enclosure

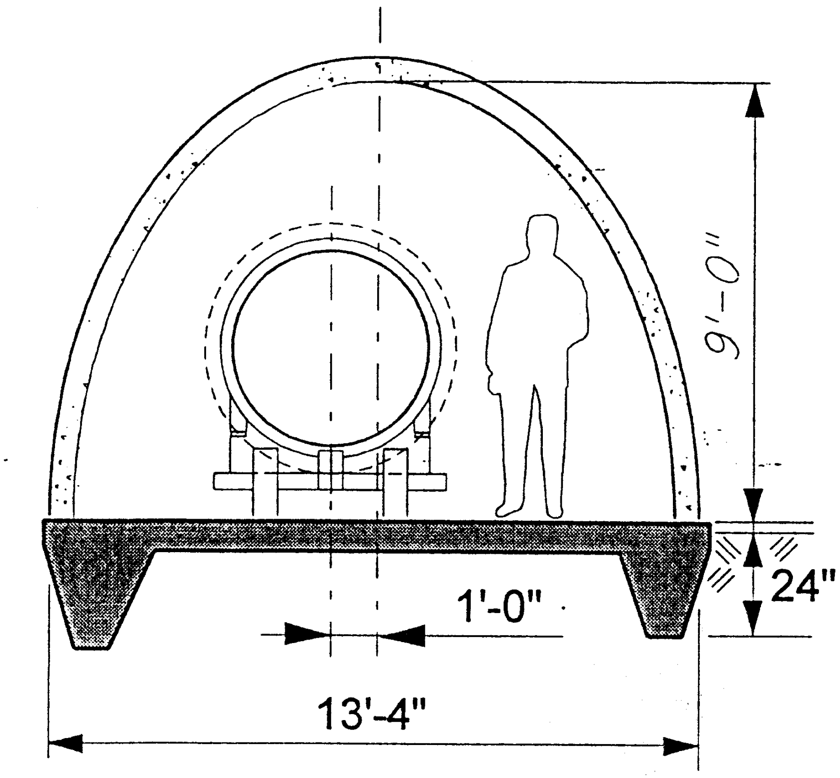
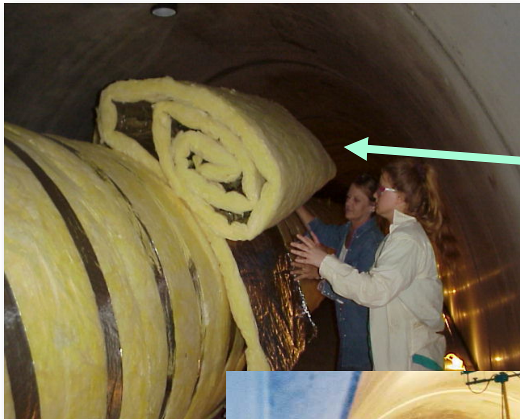


Figure 2.1-1 -- Cross Section of Design Baseline at Hanford

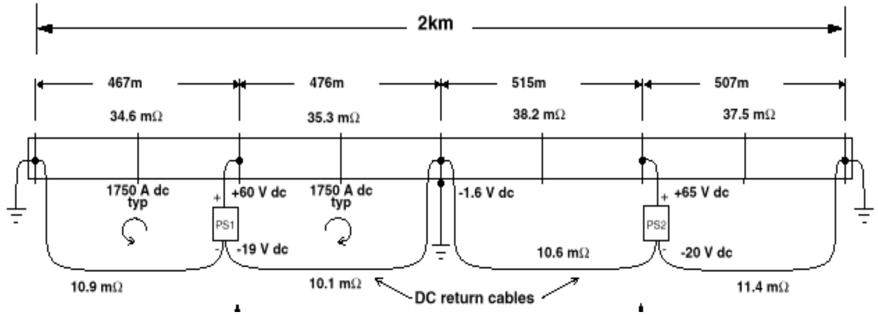
- Minimal Enclosure (no services)
- Beam Pipe
  - 1.2 m diam; 3 mm stainless
  - 65 ft spiral weld sections
  - 50 km of weld (NO LEAKS!)

Baking out the LIGO Beam Pipe

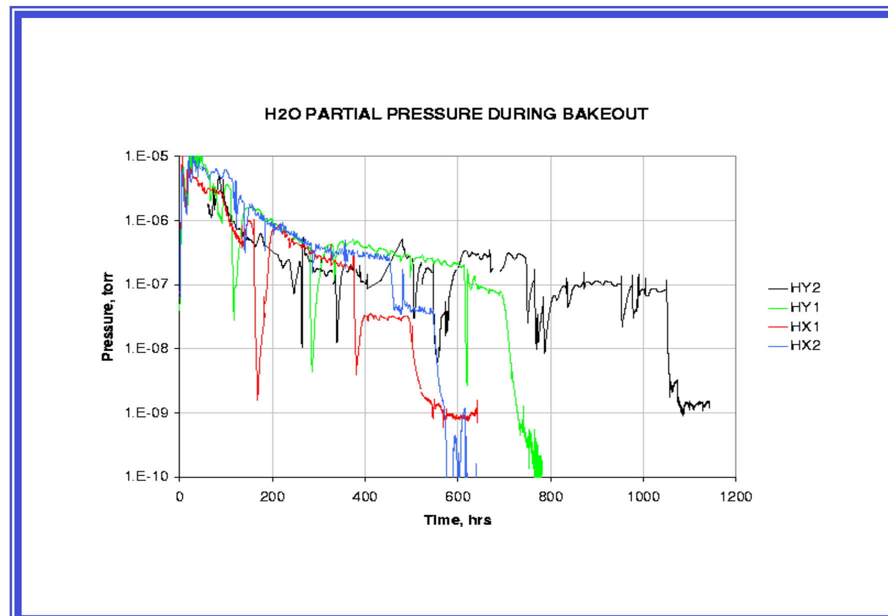


insulation

Fermilab Magnet Power Supply

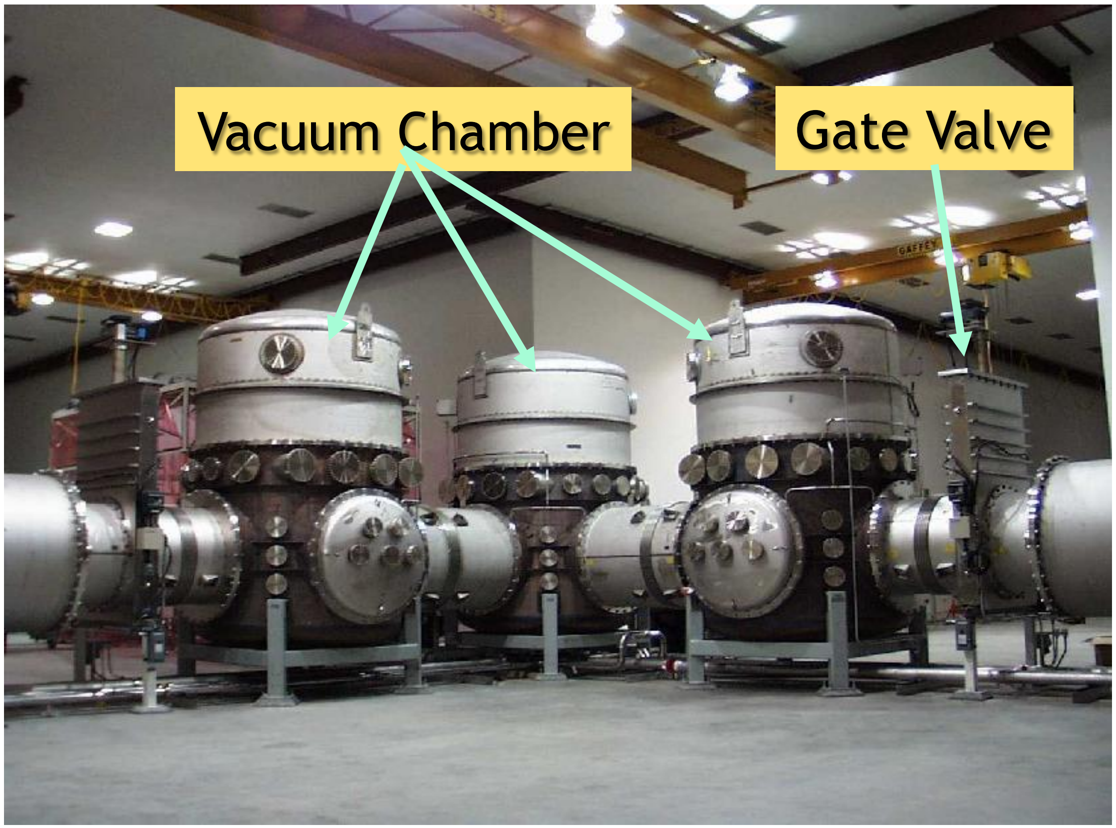


~ 2000 amps for one month

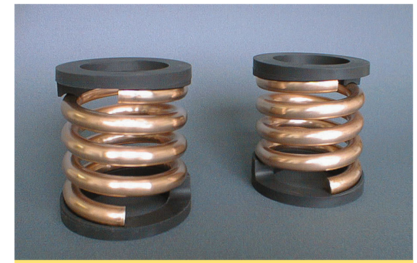


Vacuum Chambers and Seismic Isolation

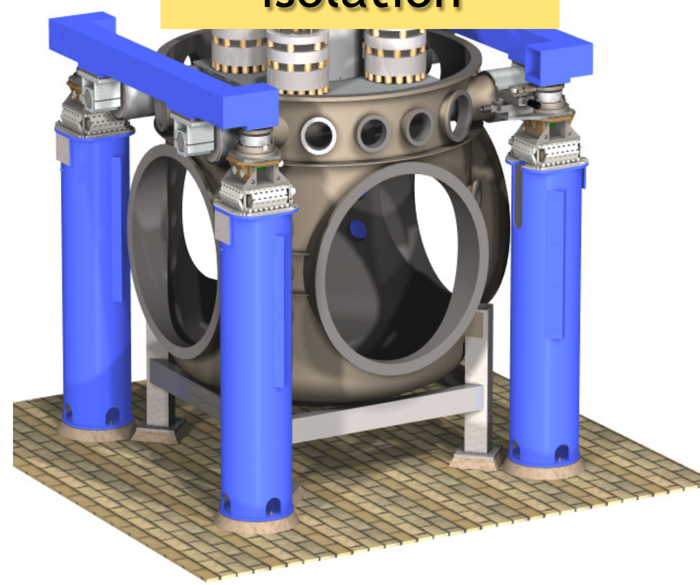
Vacuum Chambers



constrained layer damped springs



passive isolation

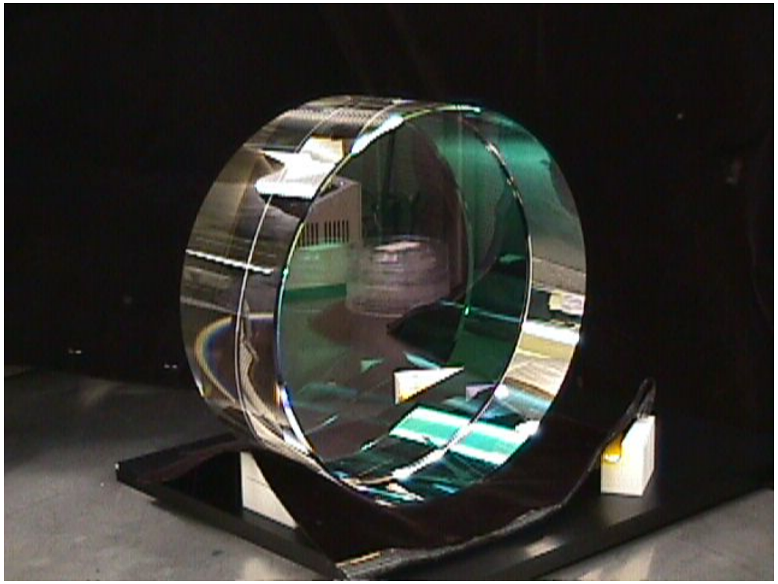


Initial LIGO Test Mass Suspension

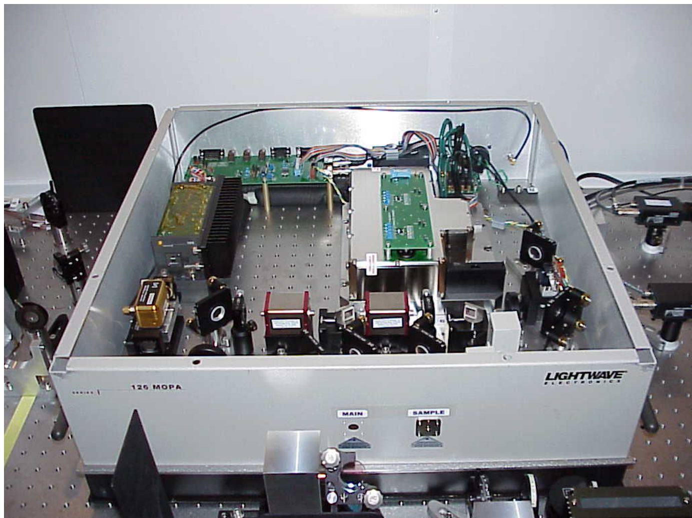
- Simple single-loop pendulum suspension
- Low loss steel wire
  - » Adequate thermal noise performance, but little margin
- Magnetic actuators for control

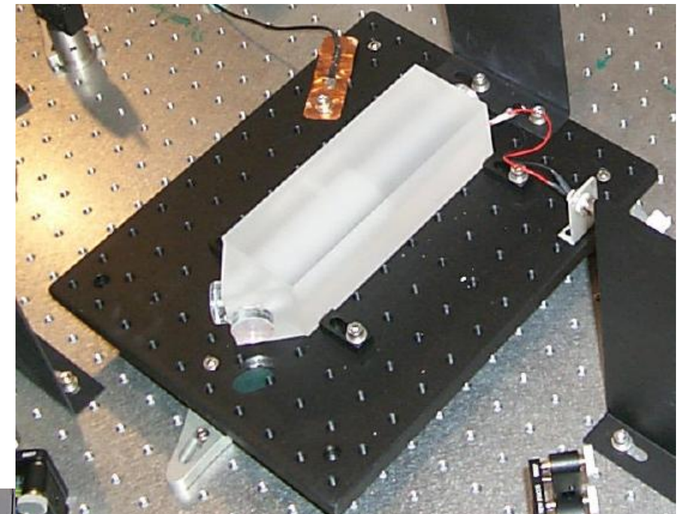
Initial LIGO Mirrors

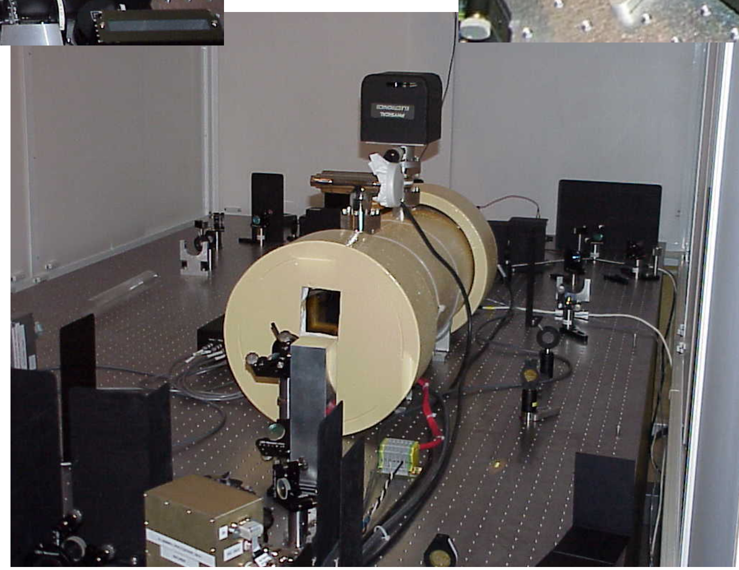
- Substrates: SiO_2
  - 25 cm Diameter, 10 cm thick
  - Homogeneity < 5 x 10^{-7}
  - Internal mode Q's > 2 x 10^{6}
- Polishing
  - Surface uniformity < 1 nm rms (λ / 1000)
  - Radii of curvature matched < 3%
- Coating
  - Scatter < 50 ppm
  - Absorption < 2 ppm
  - Uniformity <10^{-3}
- Production involved 5 companies, CSIRO, NIST, and LIGO



Initial LIGO Laser



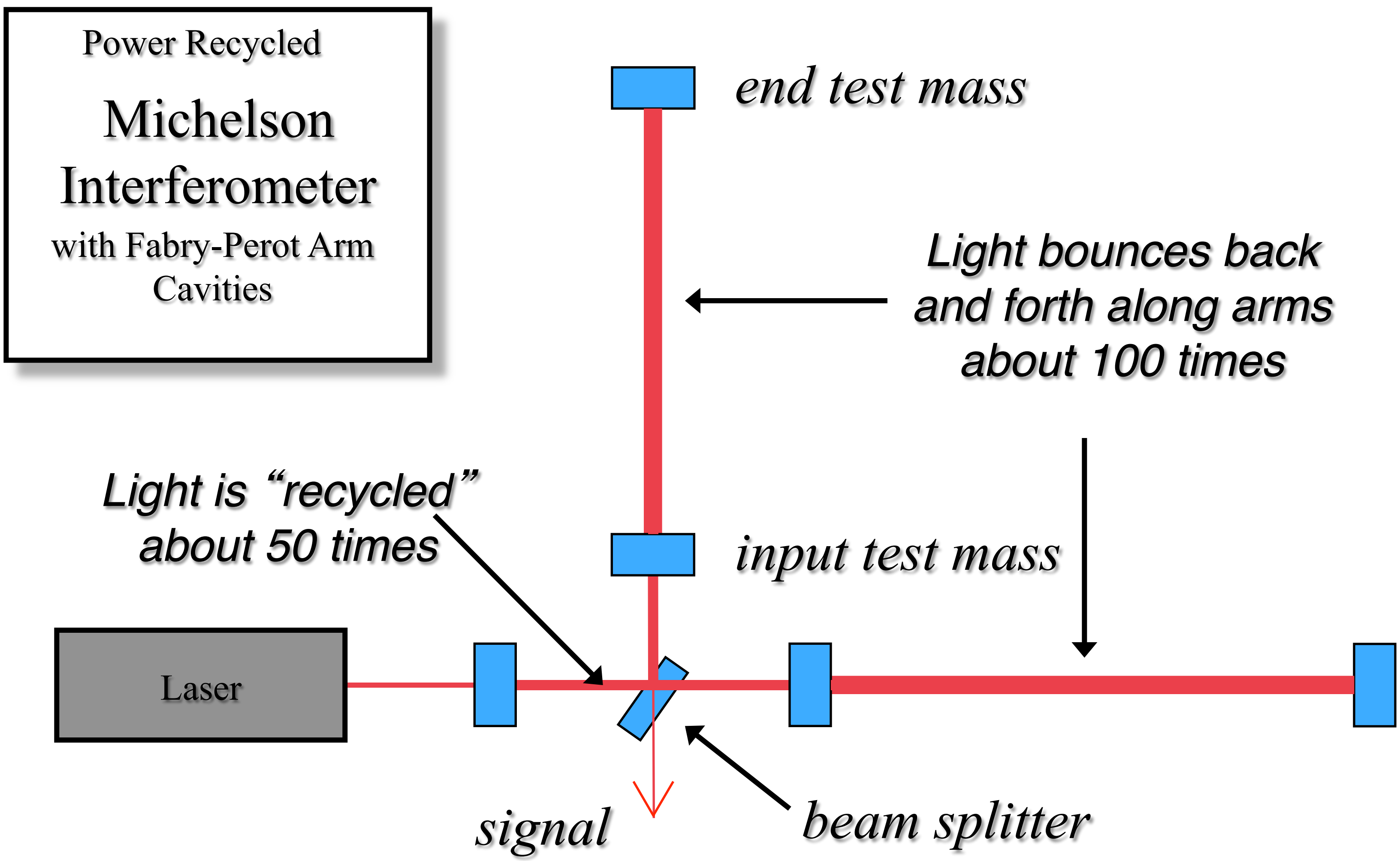




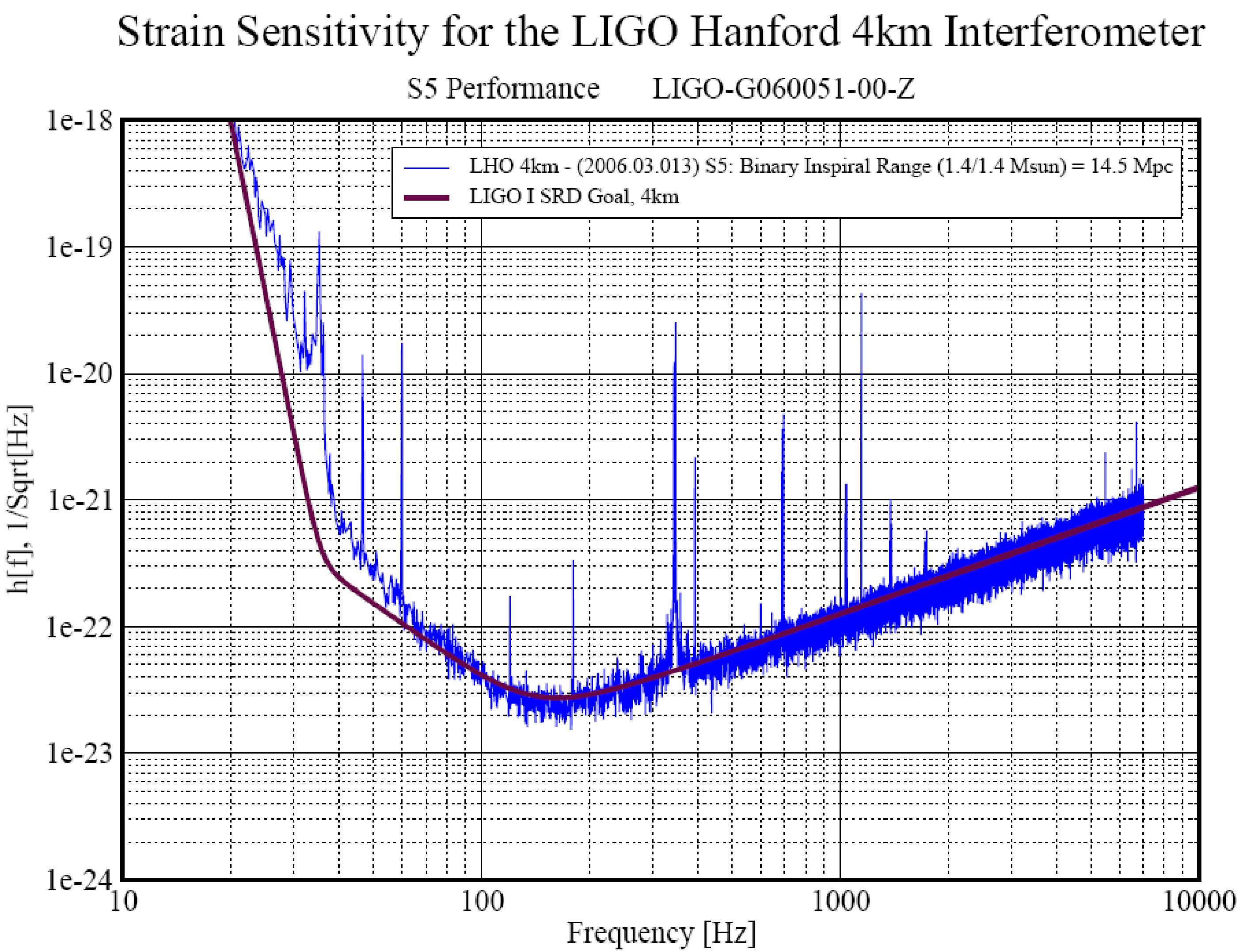
Custom-built
10 W Nd:YAG
Laser

Stabilization
cavities
for frequency
and beam shape

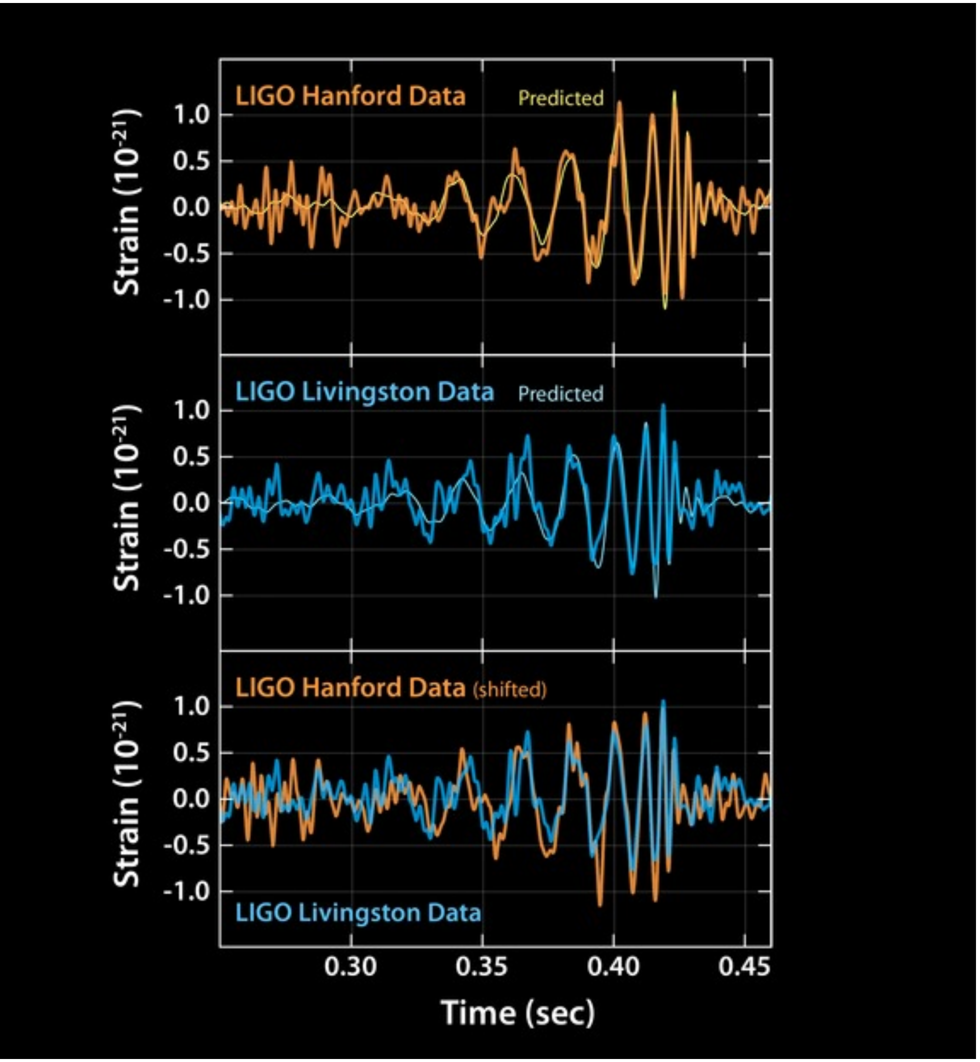
Initial LIGO Optical Configuration



Initial LIGO Sensitivity



Discovery



Signals of gravitational waves detected by the twin LIGO observatories at Livingston, Louisiana, and Hanford, Washington. The signals came from two merging black holes, each about 30 times the mass of our sun, lying 1.3 billion light-years away

Strain represents the fractional amount by which distances are distorted

As the plots reveal, the LIGO data very closely match Einstein's predictions

Discovery

For the first time, scientists have observed gravitational waves arriving at the Earth from a cataclysmic event in the distant universe on September 14, 2015 at 5:51 a.m. Eastern Daylight Time. This confirms a major prediction of Albert Einstein's 1915 general theory of relativity and opens an unprecedented new window onto the cosmos

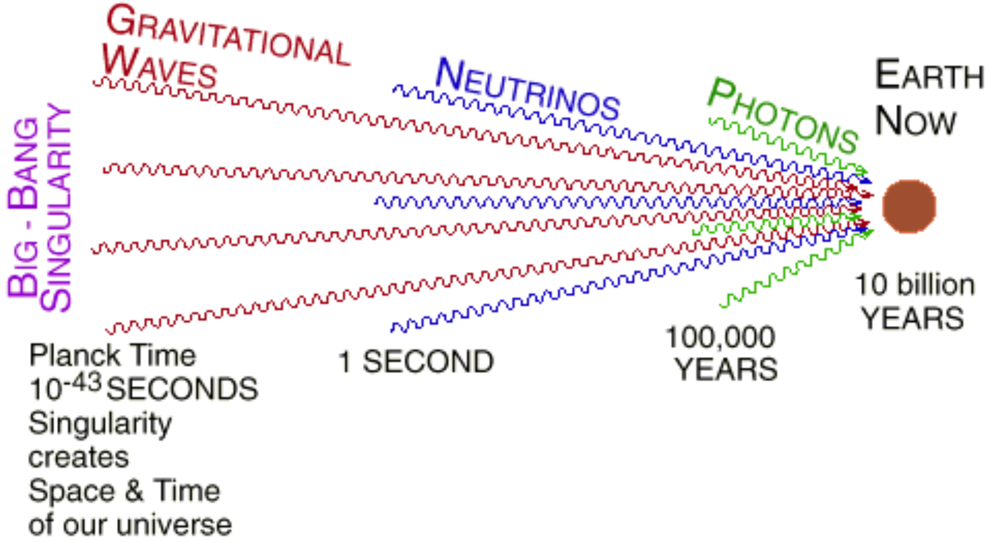
The detected gravitational waves were produced during the final fraction of a second of the merger of two black holes to produce a single, more massive spinning black hole. This collision of two black holes had been predicted but never observed

The gravitational waves were detected by both of the twin Laser Interferometer Gravitational Wave Observatory (LIGO) detectors, located in Livingston, Louisiana, and Hanford, Washington, USA

What's the big deal ?

- GWs bring info about objects that can not be seen with EM observations and vice-versa
- This is a radically different field than EM observations
- Measuring a length smaller than proton size is no longer a science fiction !!
- We talked about signals and sources that we **knows**about. Any new field has it' s own surprises.

"*....there are known knowns, there are known unknowns, But there are also unknown unknowns....*"



Backup

Space-based GW detection

- LISA (***L***aser ***I***nterferometer ***S***pace ***A***ntenna)