Gravity Waves:
A New Way of Searching for Black Holes and Other Exotic Astrophysical Oddities

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(LIGO Scientific Collaboration)

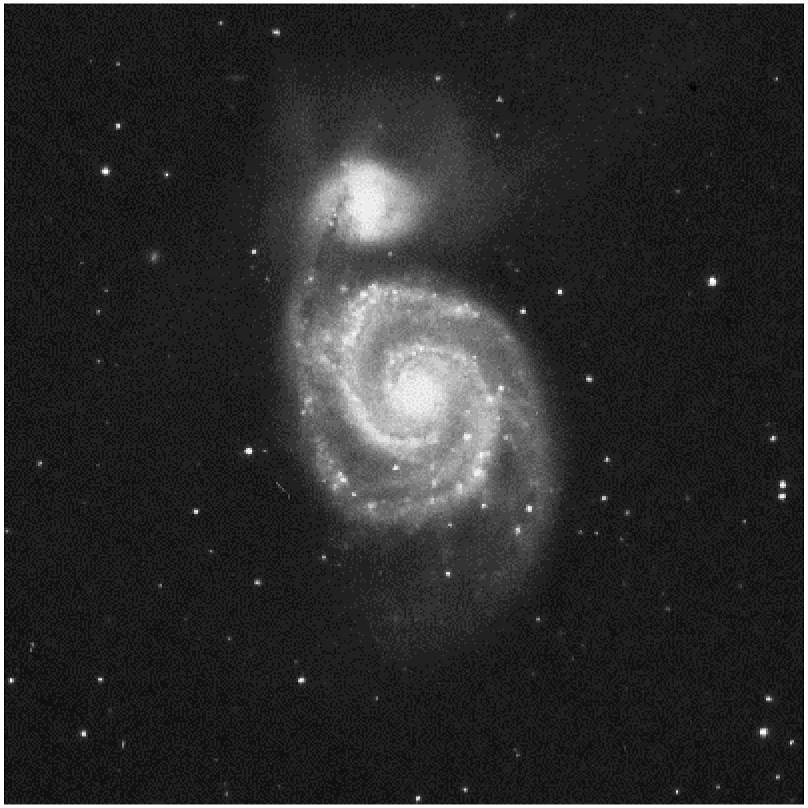
Einstein's Theories of Relativity

Black Holes

Gravity Waves

Neutron Stars

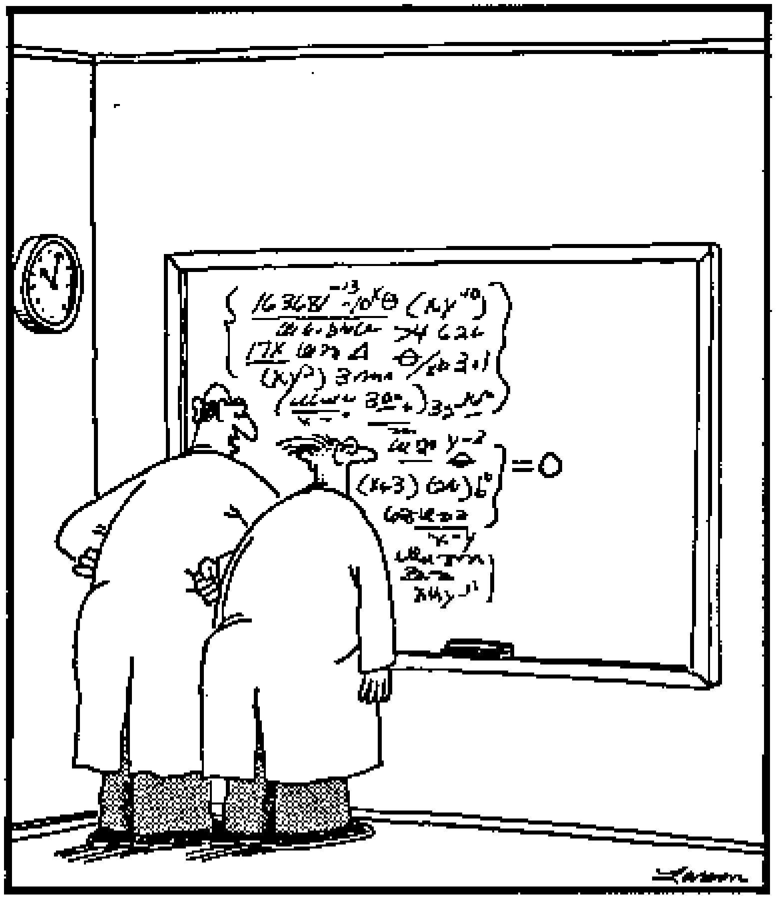
The Cosmos



Experimental High Energy Physics at the University of Oregon

- Study of matter/anti-matter asymmetry at the Stanford Linear Accelerator Center
- Search for Gravitational Radiation at LIGO
- Search for Higgs Bosons and Supersymmetric particles at a Linear Collider

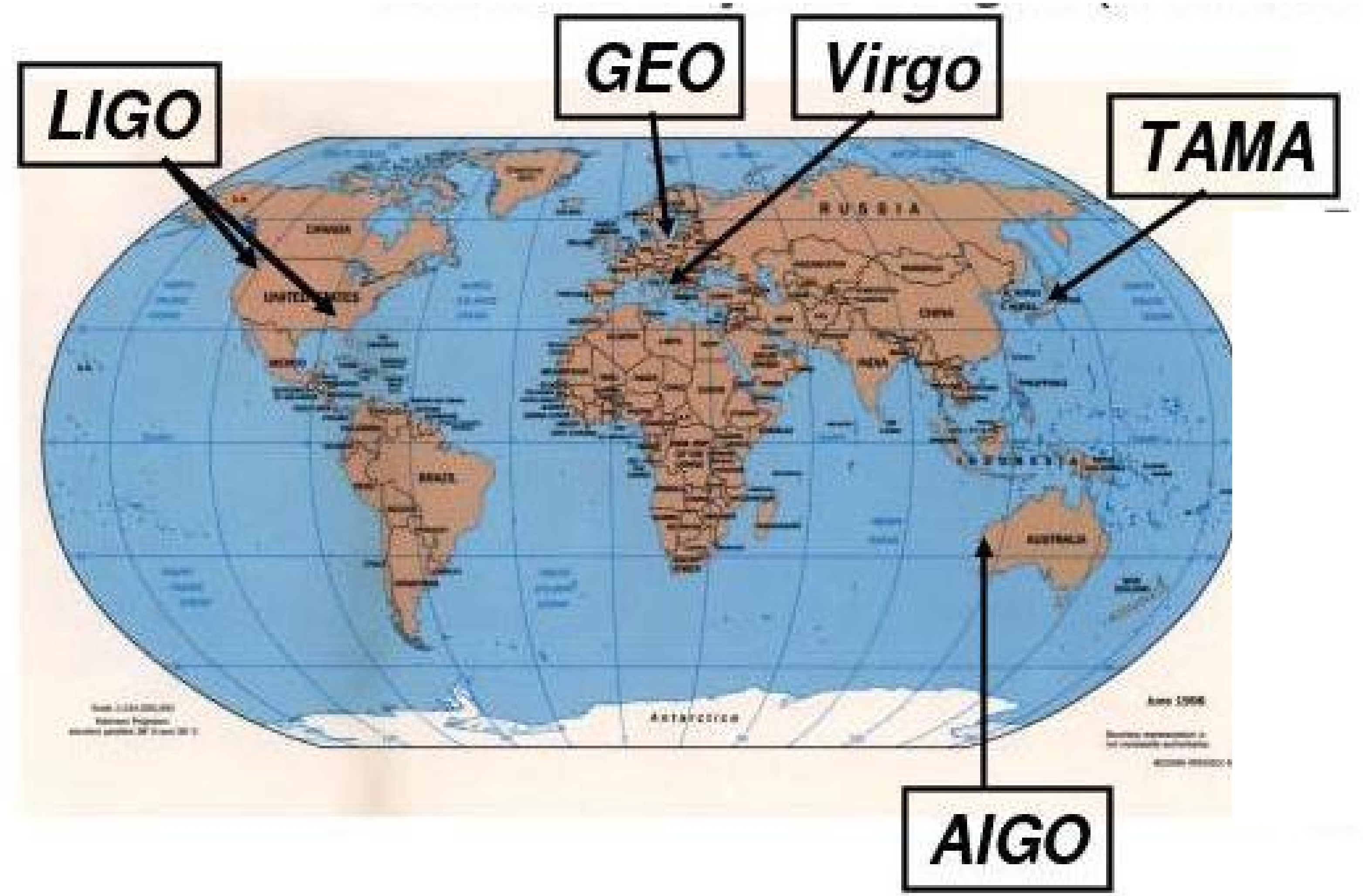
Mathematical Basis of Gravity Waves



“No doubt about it, Ellington—we’ve mathematically expressed the purpose of the universe. God, how I love the thrill of scientific discovery!”

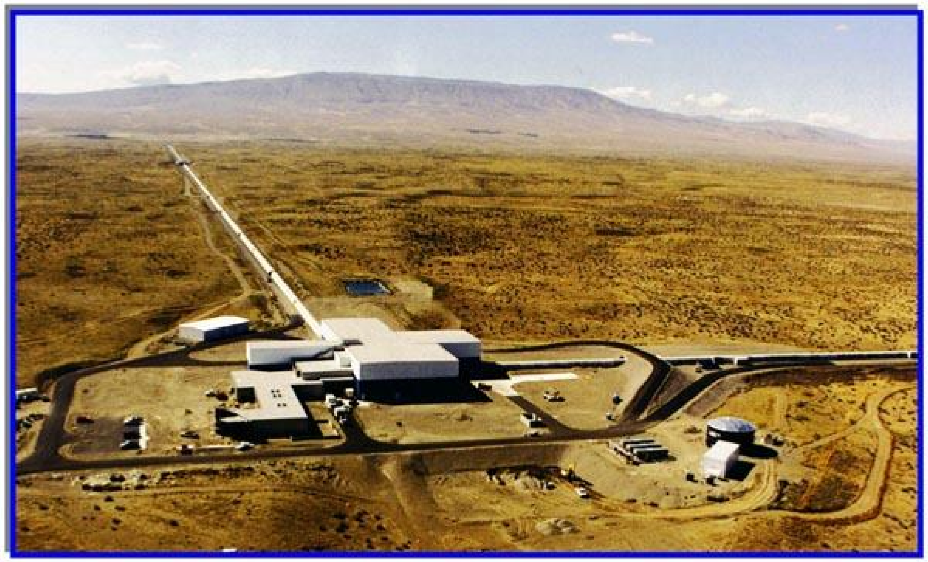
LIGO

Laser Interferometry Gravity-wave Observatory



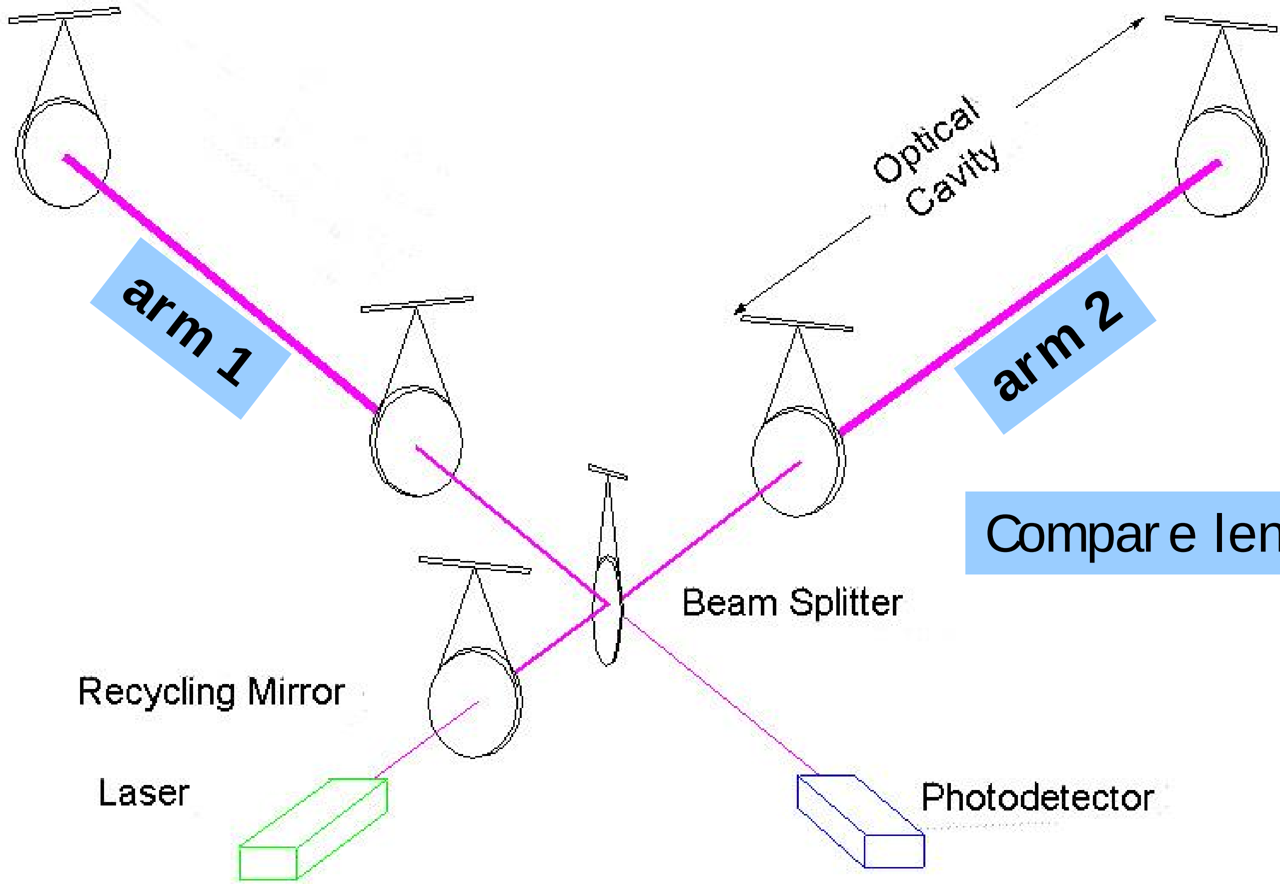
LI GO

Hanford, WA



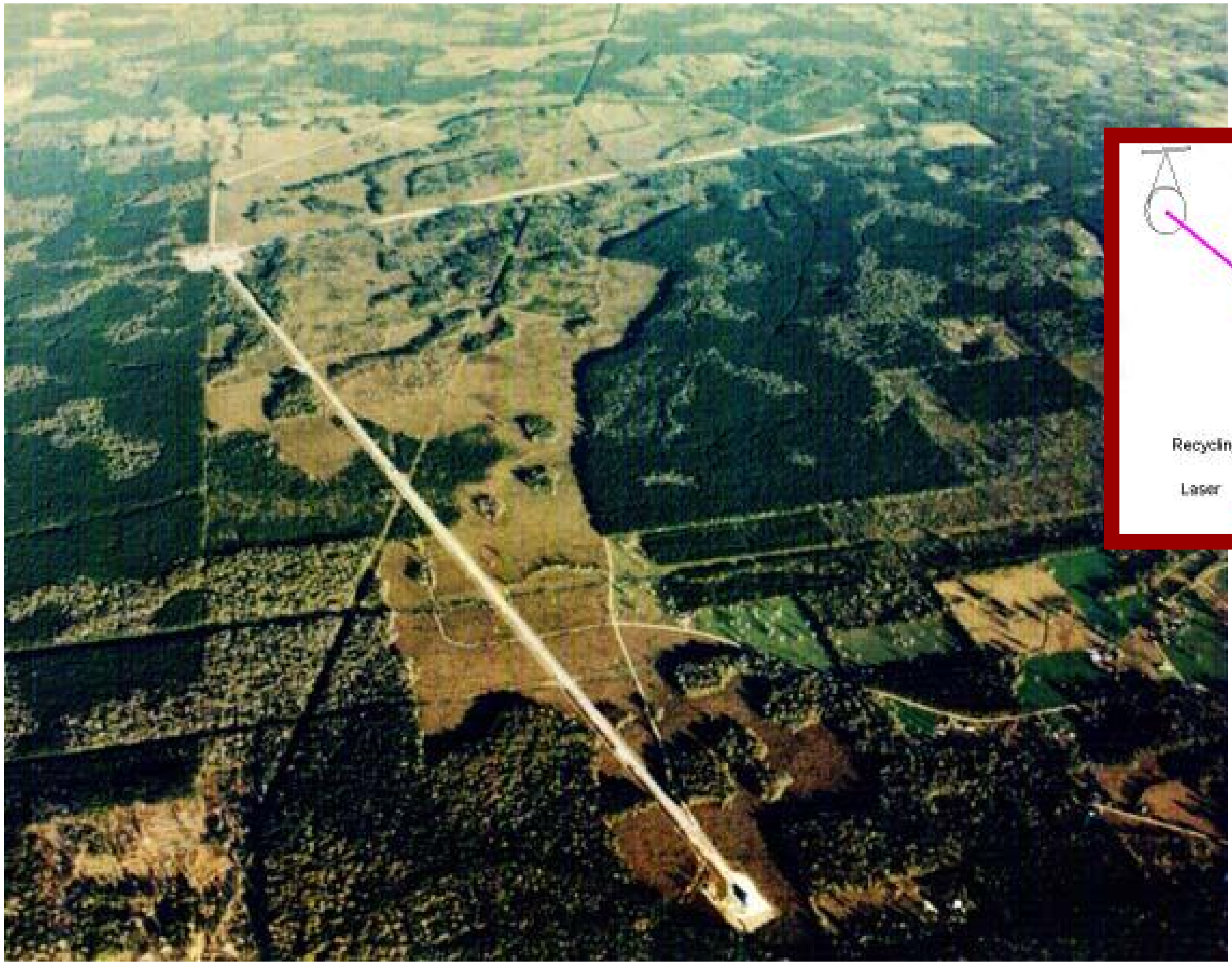
Livingston, LA

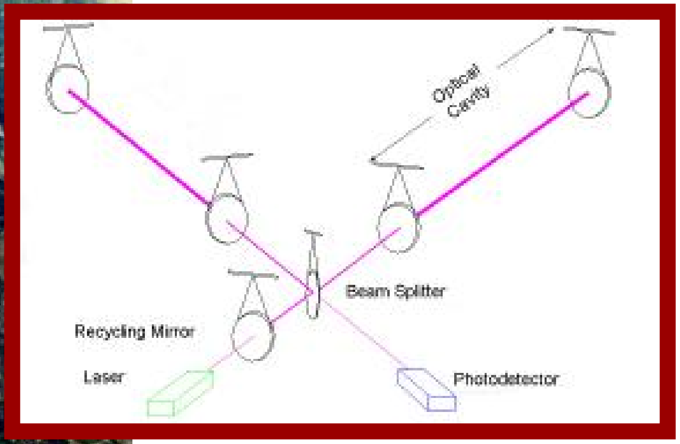
Laser Interferometer



Compare lengths of two arms

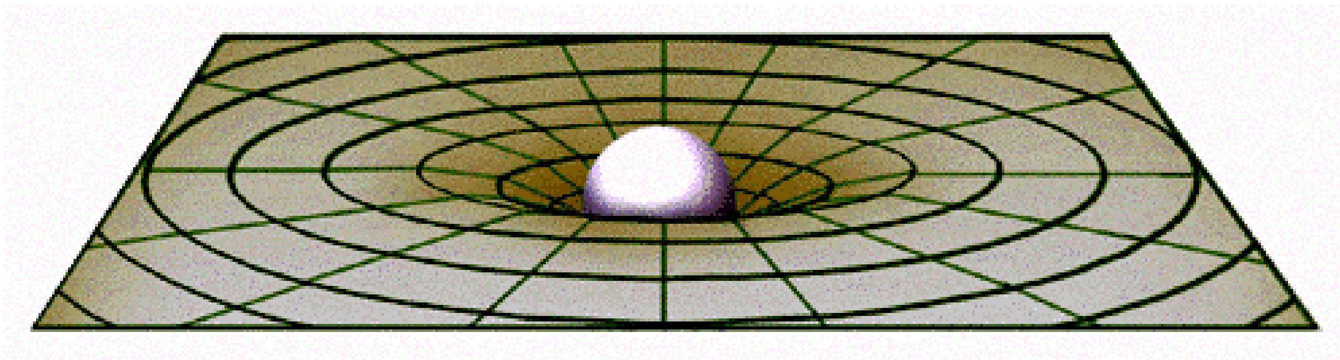
Laser Interferometer





LIGO's arms are 4 kilometers long (about 2.5 miles)

Space-time is warped by matter and energy



LIGO is measuring space with unprecedented precision

Letter of Introduction

13 April 1901

Professor Wilhelm Ostwald
University of Leipzig
Leipzig, Germany

Esteemed Herr Professor!

Please forgive a father who is so bold as to turn to you, esteemed Herr Professor, in the interest of his son.

I shall start by telling you that my son Albert is 22 years old, that he studied at the Zurich Polytechnikum for 4 years, and that he passed his diploma examinations in mathematics and physics with flying colors last summer. Since then, he has been trying unsuccessfully to obtain a position as Assistent, which would enable him to continue his education in theoretical & experimental physics. All those in position to give a judgement in the matter, praise his talents; in any case, I can assure you that he is extraordinarily studious and diligent and clings with great love to his science.

Letter of Introduction

My son therefore feels profoundly unhappy with his present lack of position, and his idea that he has gone off the tracks with his career & is now out of touch gets more and more entrenched each day. In addition, he is oppressed by the thought that he is a burden on us, people of modest means.

Since it is you, highly honored Herr Professor, whom my son seems to admire and esteem more than any other scholar currently active in physics, it is you to whom I have taken the liberty of turning with the humble request to read his paper published in the Annalen fur Physick and to write him, if possible, a few words of encouragement, so that he might recover his joy in living and working.

If, in addition, you could secure him an Assistant's position for now or next autumn, my gratitude would know no bounds.

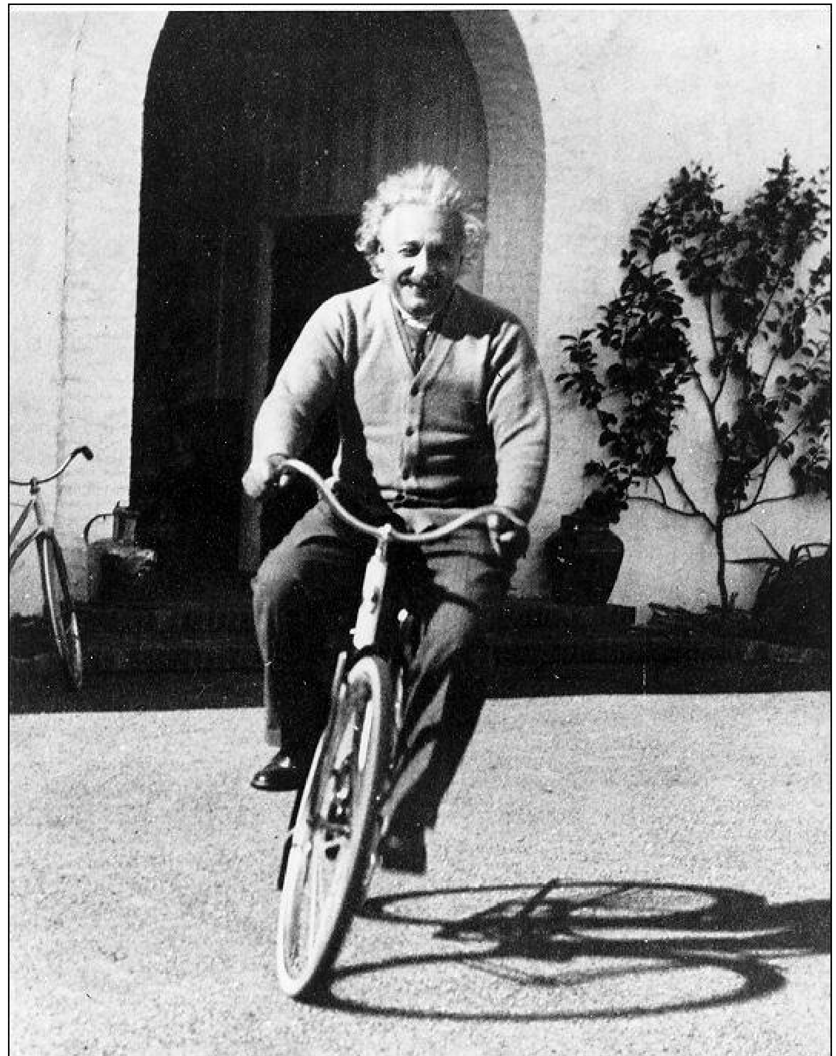
I beg you once again to forgive me for my impudence in writing to you, and I am also taking the liberty of mentioning that my son does not know anything about my unusual step.

I remain, highly esteemed Herr Professor, your devoted

Hermann Einstein

Albert Einstein
1879-1955

- 1901-1902
  - temporary high school teaching jobs
- 1902-
  - "technical expert third class"
  - Swiss Patent Office



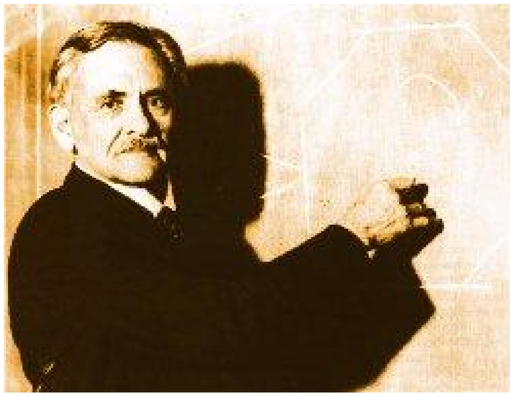
As this century began, Albert Einstein was a young physicist in Europe thinking about the Universe.

He developed two very successful theories about the nature of space and time, special relativity in 1905, and general relativity in 1915.

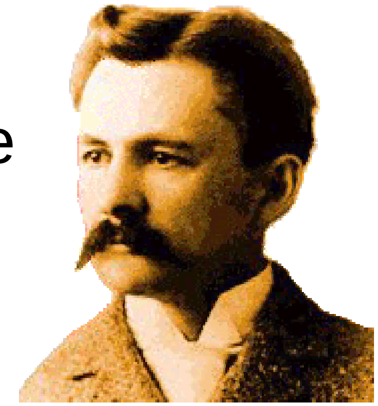
SPECIAL RELATIVITY

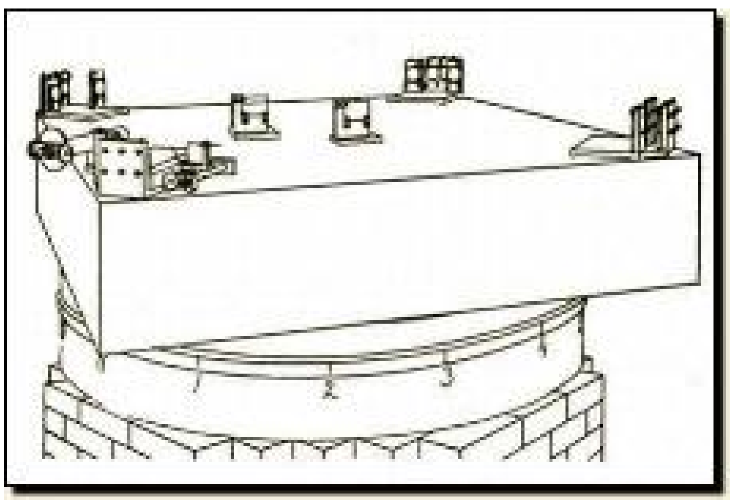
- The speed of light is constant
  - (this is true no matter what your relative motion)
- Nothing can move faster than the speed of light
- Space and time are mixed
- Time slows down when a system is in motion

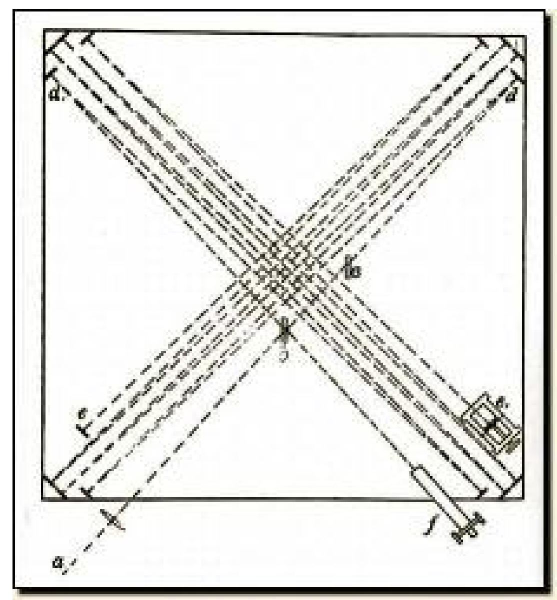
The Speed of Light is Constant



Michelson and Morely attempted to measure the motion of the Earth through space, 1887







The Speed of Light is Constant

- 186,000 miles per second
  - 300,000 kilometer per second

- Whether you are sitting <u>at rest</u> on the Earth, or <u>moving rapidly</u> on a spaceship, you will always find light travels at this speed

•And, NOTHING can travel faster than light

•Universal speed limit = 186,000 miles per sec

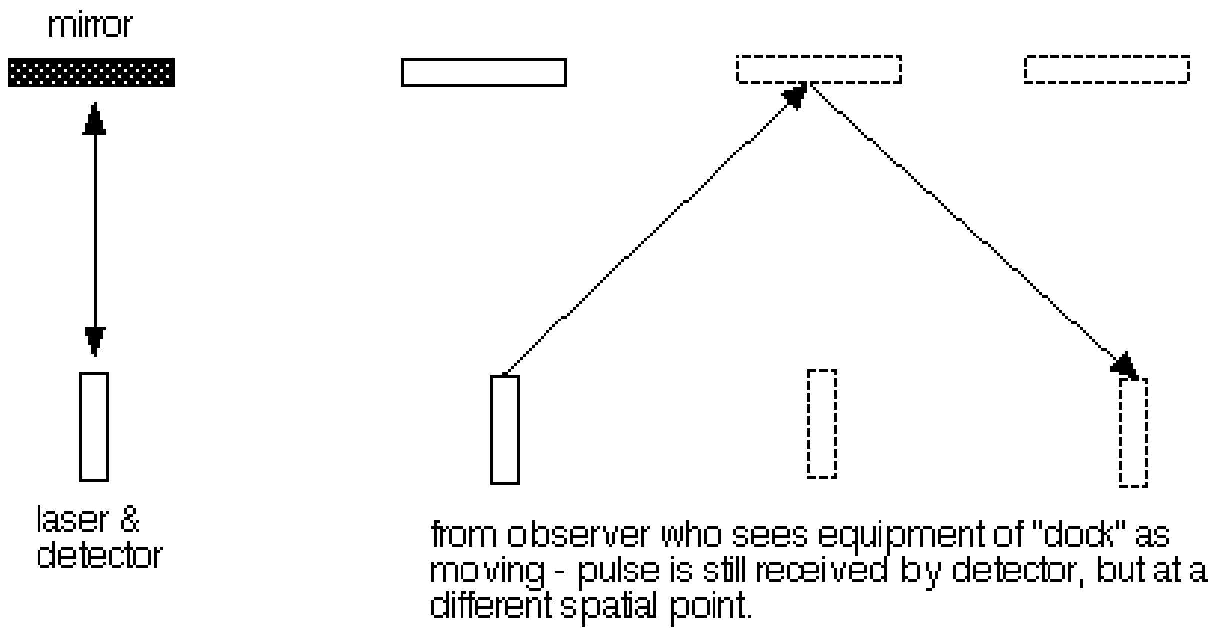
Time Travel?

There once was a lady named Bright
who traveled much faster than light.
She departed one day in a relative way,
and came home the previous night.

If we could travel faster than light,
we would be able to travel into the past

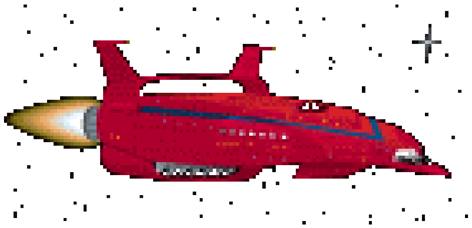
Time Dilation

- Now imagine the clock is moving.
- Since the speed of light is unchanged, it takes longer, and time is slowing down



First Quiz

- Two spaceships are moving toward one another at 90% of the speed of light



- From the Martian ship, what is the apparent speed of the Earth ship?
  - A. 180% of the speed of light
  - B. 99% of the speed of light
  - C. I have no clue

SPECIAL RELATIVITY

$$E = mc^2$$

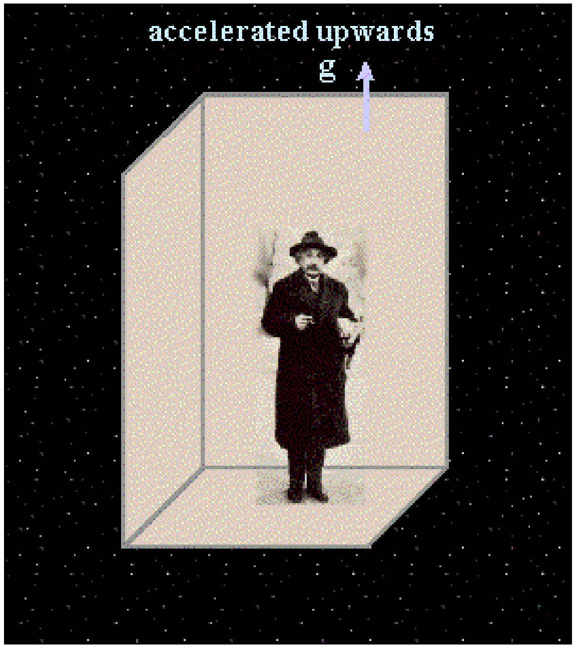
- The speed of light is constant
  - (this is true no matter what your relative motion)
- Nothing can move faster than the speed of light
- Space and time are mixed
- Time slows down when a system is in motion

GENERAL RELATIVITY

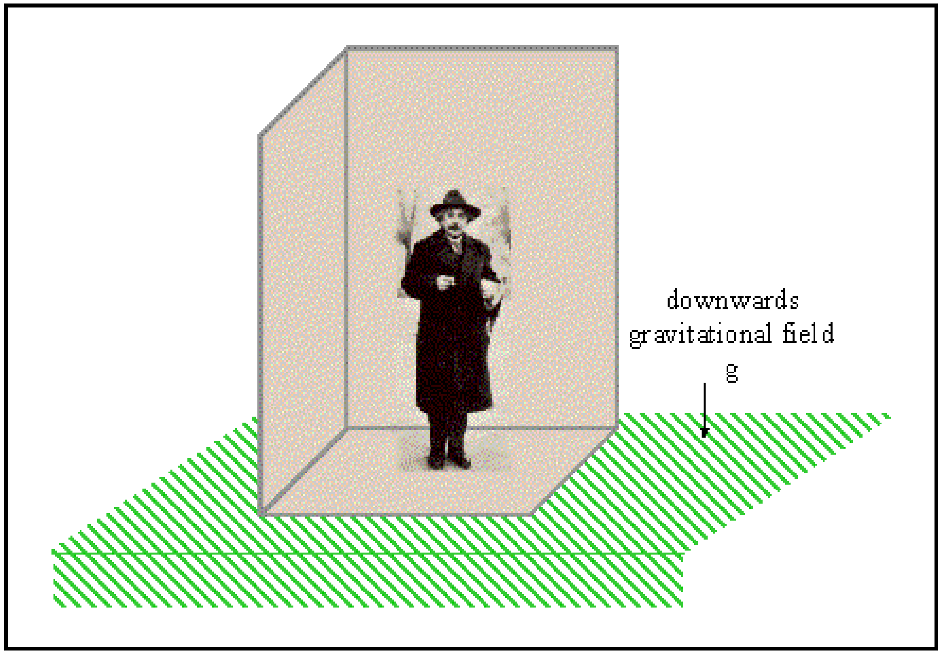
- Principal of Equivalence:

  Consider these two systems

A



B



GENERAL RELATIVITY

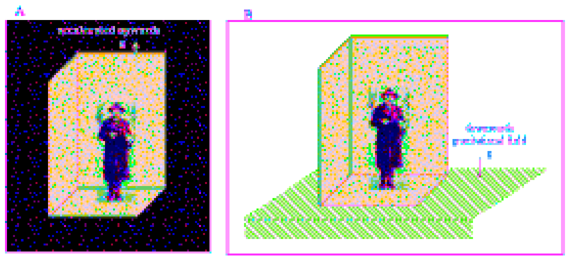
- Principal of Equivalence:

  Einstein -> You can't tell which system you are in from inside the enclosure

  The Laws of Physics are the same within each system

  acceleration = gravity

  inertial mass = gravitational mass



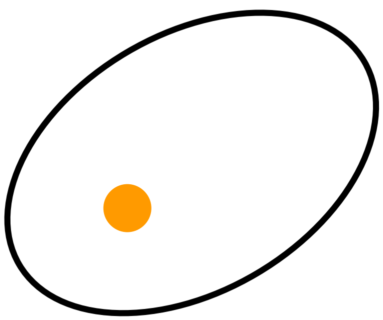
Predictions of Einstein's General Relativity (GR)

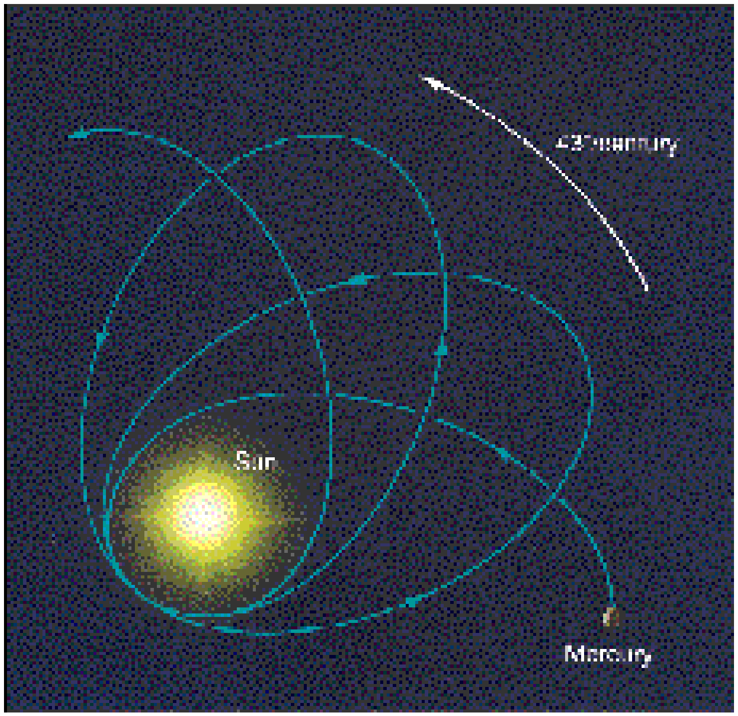
- Let's consider six predictions of GR
  - three are the classic tests of GR that convinced physicists of its validity
  - three are of current active scientific interest

    including the prediction of gravity waves, our focus today

Einstein's Three Tests of GR

1 Mercury's orbital precession
- – known but unexplained prior to General Relativity
- – in Newton's physics the orbit would not precess

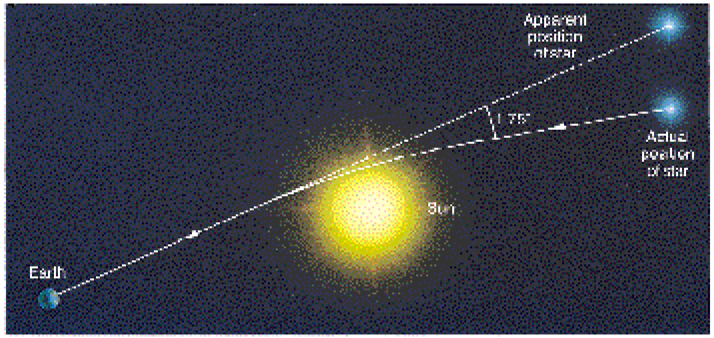




Einstein's Three Tests of GR

2 Bending of starlight

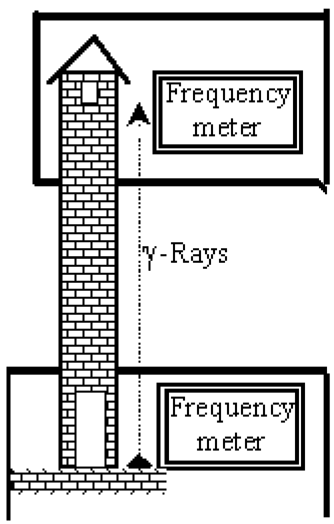
- the fabric of space is bent near massive objects and the bent space will turn light's trajectory
- 1919 Eddington mounts two expeditions during Solar eclipse
  - Principe (West coast of Africa)
  - Northern Brazil
- Einstein's prediction confirmed
- BIG NEWS
  - (New York Times)

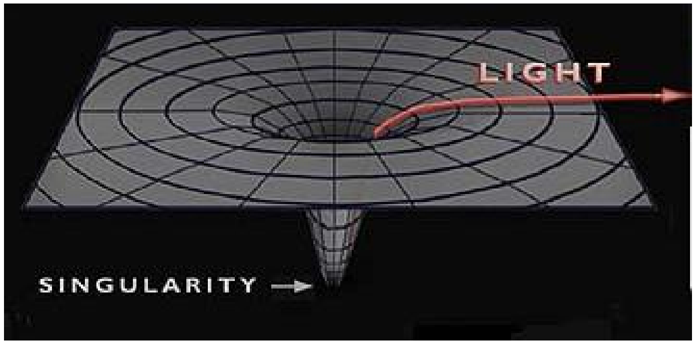


Einstein's Three Tests of GR

3 Gravitational redshift

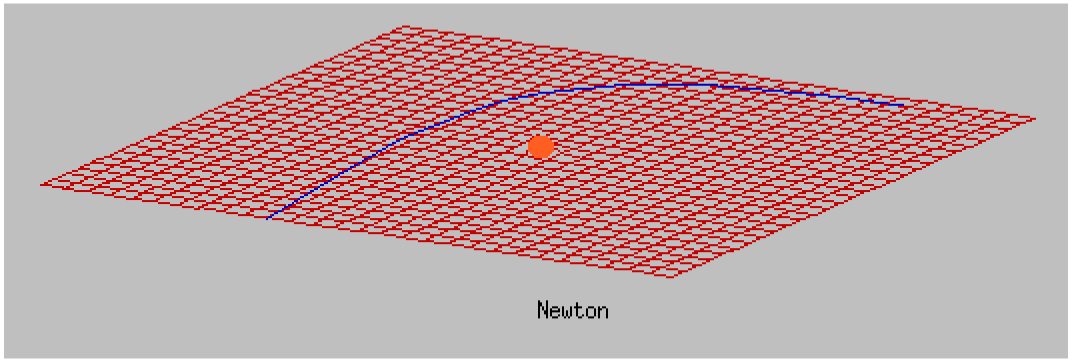
- Time runs slower in a gravitational field,
  - the stronger the gravity, the slower time runs
  - at the critical point, time will appear to stop
- Harvard Tower experiment (Pound and Rebka)



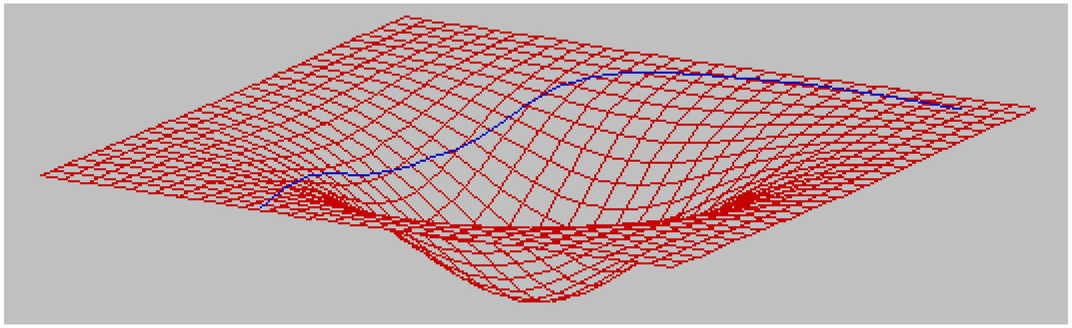


Curvature of Space

- Newton viewed gravitation as action through a distance



- Einstein introduced a different idea (General Relativity)
- **Matter** "tells" **space** how to curve
  and **space** "tells" **matter** how to move



However, space is stiff,
so it takes a lot of mass to bend space

Other Predictions of General Relativity

4 Expanding Universe

– Einstein did not like this concept and put a *fudge* factor into his equations to keep the Universe from expanding

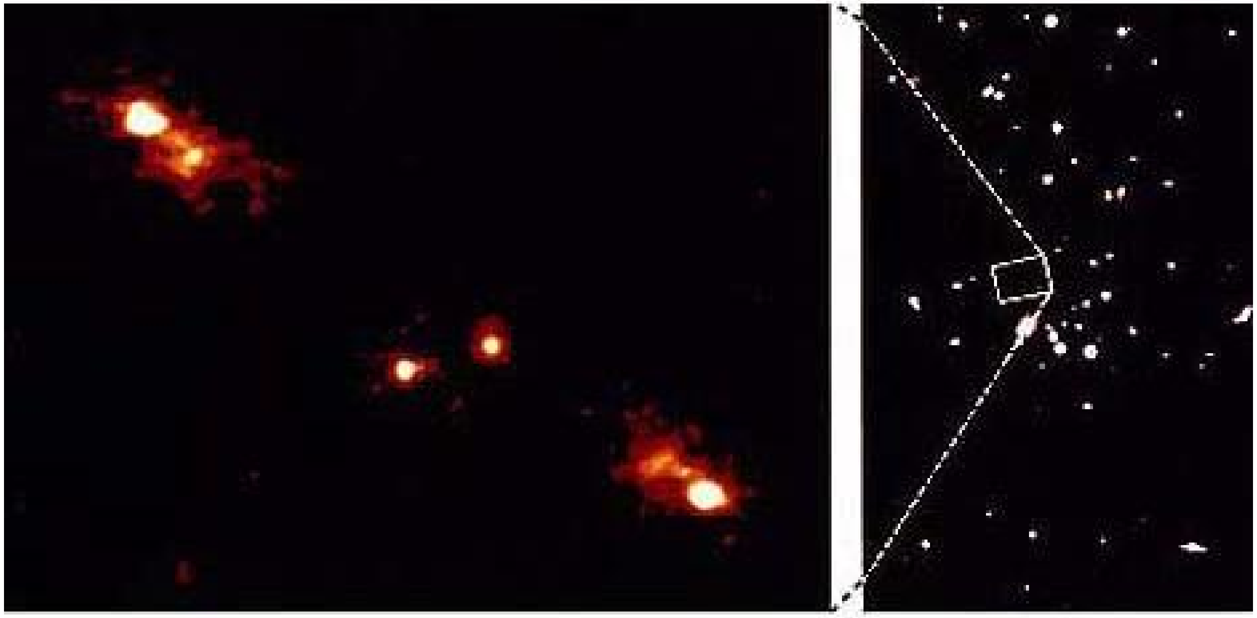
– 1925 - Hubble discovers the Universe is expanding

  – Big Bang

– Einstein calls his invention of this *fudge* factor his greatest blunder

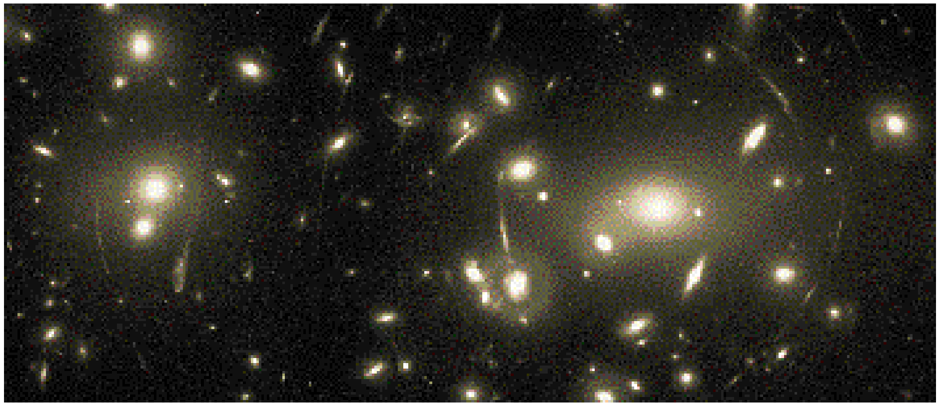
Other Predictions of General Relativity

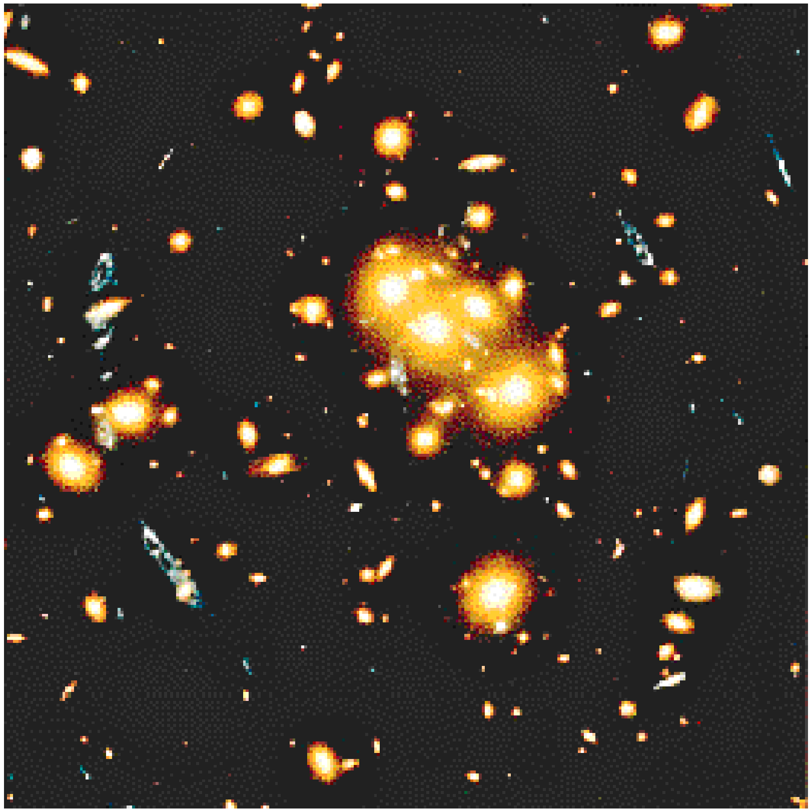
- Gravitational Lenses (and arcs)
  - Double quasar discovered in 1979



  - Recent photos from Hubble Space Telescope
    - 120 gravitational arcs

Gravitational Lens

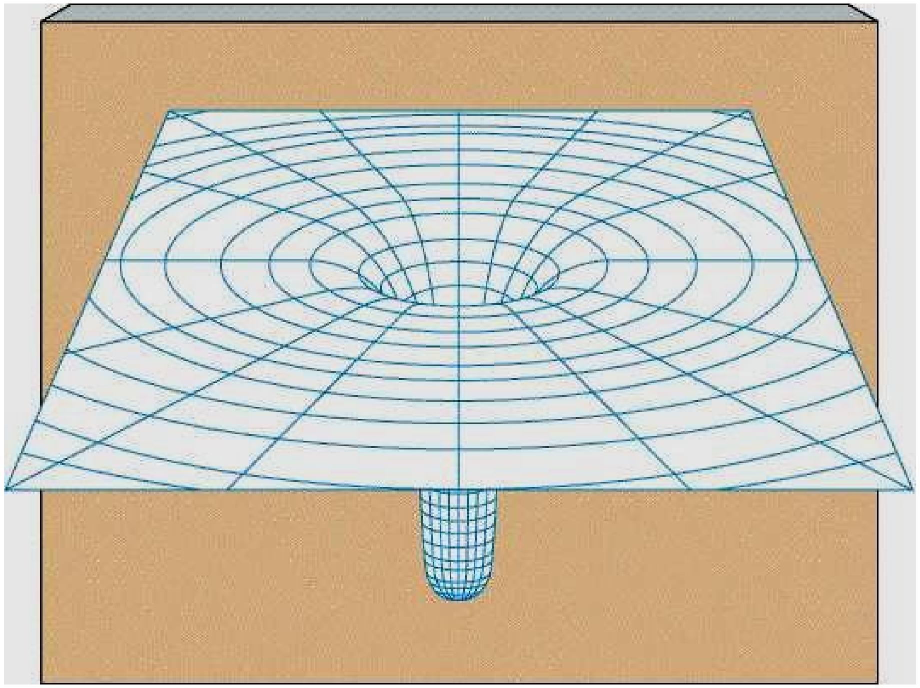




Other Predictions of General Relativity

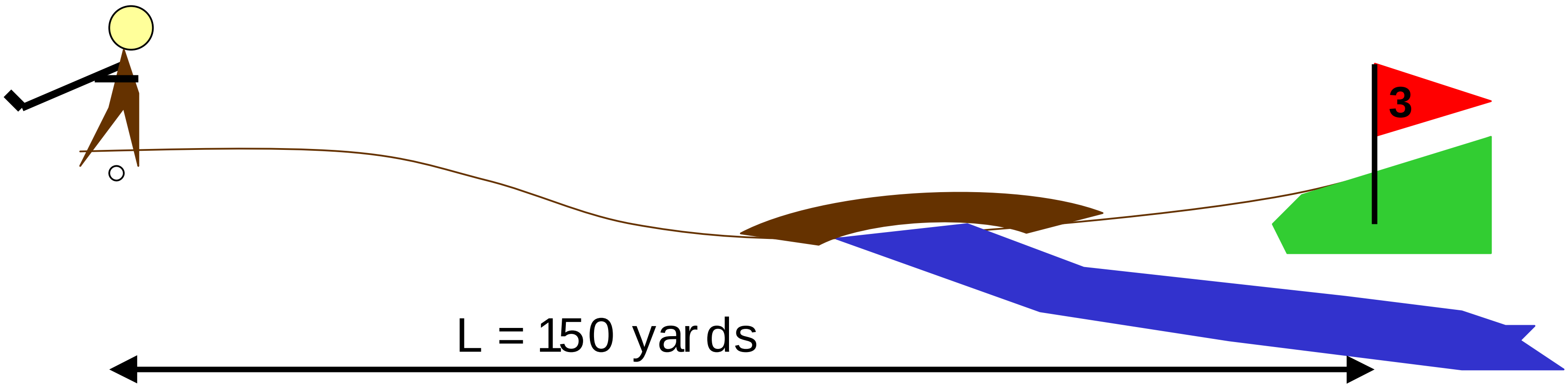
- Gravity Waves
  - Ripples on the fabric of space-time
  - Travel at the speed of light

  - **The curvature of space is not static if the mass which curves it is not static**



Gravity Waves

(distances are changing)



- Distance changes 100-1000 times per second

  $L \rightarrow L \pm \Delta L$ strain, $h = \Delta L / L$

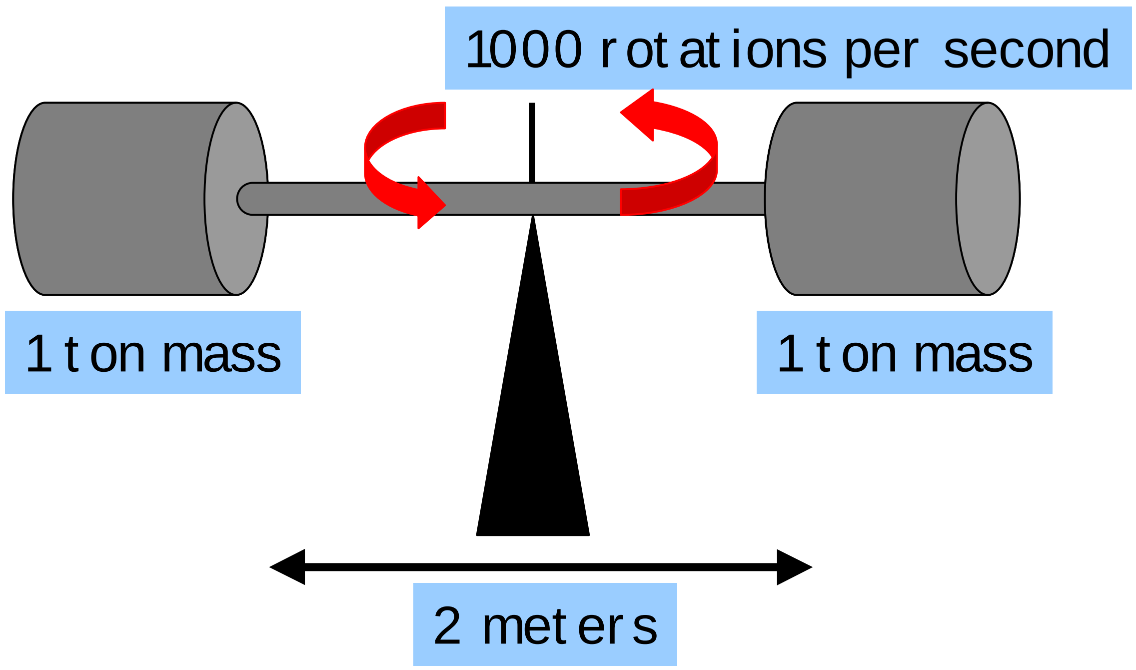
- But, h is only 0.000000000000000000001 = 10^{-21}
- $\Delta L = h\,L = 1.5 \times 10^{-19}$ yards
- ΔL = diameter of the atom / 1,000,000,000 !!!!!

Detection of Gravity Waves

- Recall the history of the discovery of electromagnetic waves
  - 1864 Maxwell predicted existence of electromagnetic waves
  - 1879 Prussian Academy of Science offered a prize for experimental proof of Maxwell's theory
  - 1886 Hertz created primitive transmitter and receiver of electromagnetic wave and detected the electromagnetic waves
- Can we envision a similar laboratory demonstration of gravity waves

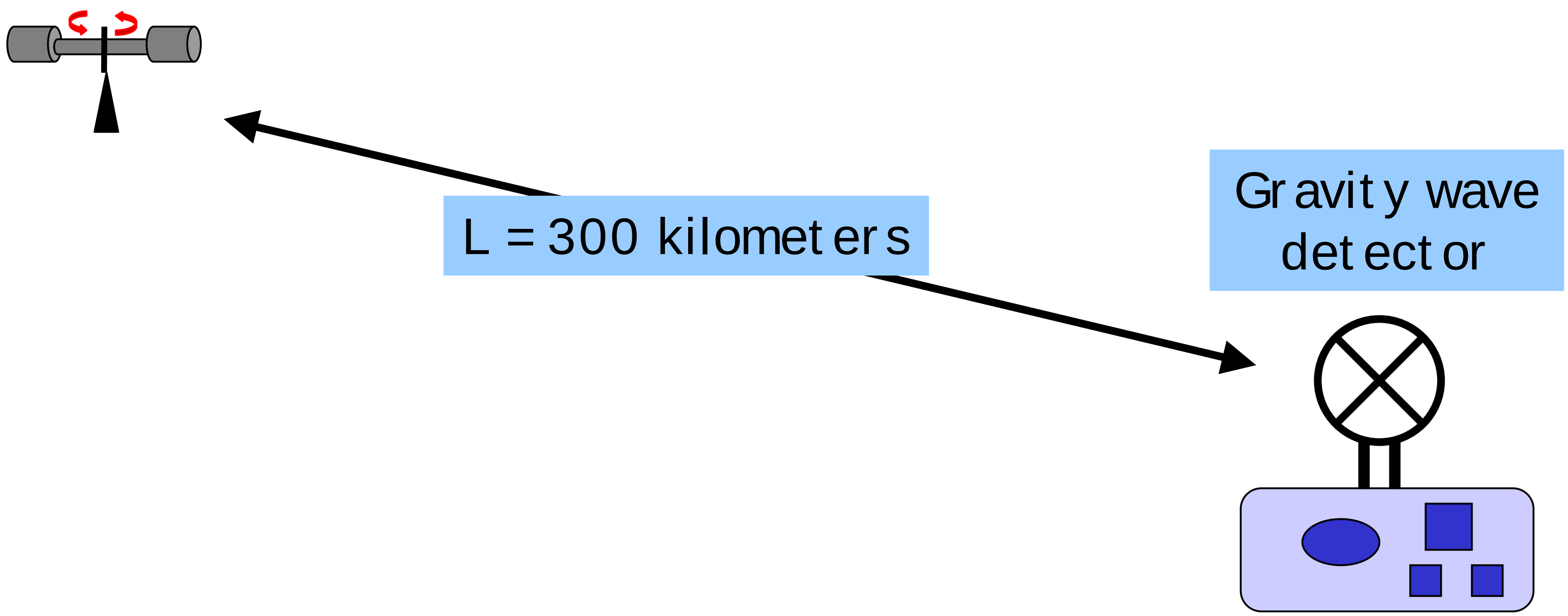
Laboratory demonstration

- Gravity waves are generated by moving masses, as electromagnetic waves are generated by moving charges



Laboratory demonstration

- Now look for waves from this source

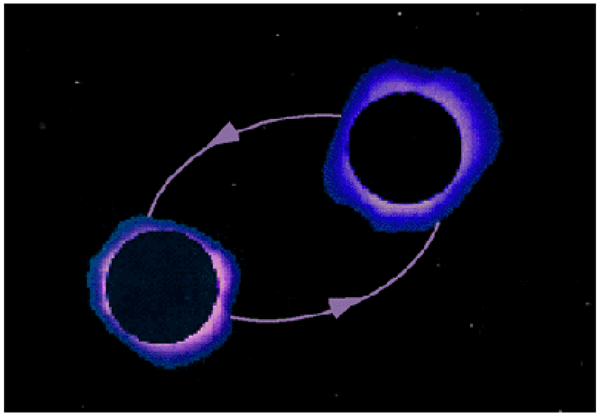


$h = \Delta L / L = 0.000000000000000000000000000000000000001 = 10^{-38}$

- No hope of detecting such a small change in length

Potential sources of Gravity Waves

- We cannot create in the laboratory a source of detectable waves
- We are therefore compelled to turn to astronomical bodies
  - much larger masses
- We need large mass accelerating rapidly
- Binary black-hole or binary neutron-star



Black Holes

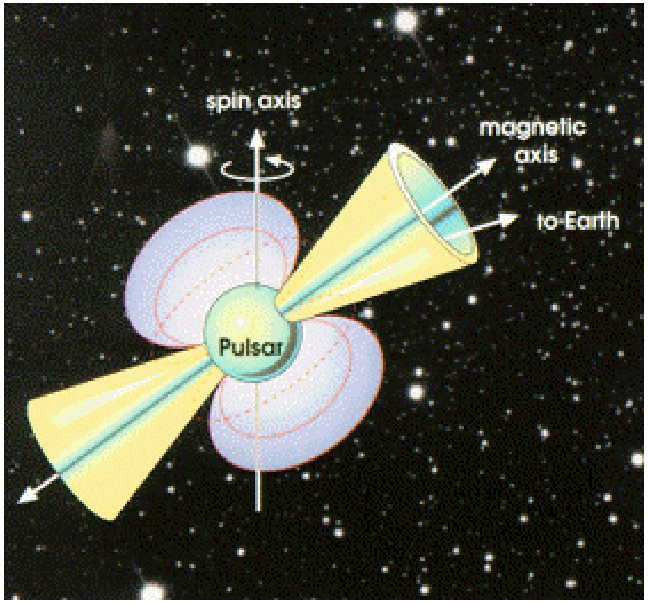
- Just as Earth has an escape velocity, every massive object has an escape velocity
  - escape velocity of the Earth
    - 7 miles/second = 25,000 miles/hour

- Now, imagine you gather so much mass into such a small space that the escape velocity exceeds the speed of light. Then, nothing can escape, not even light

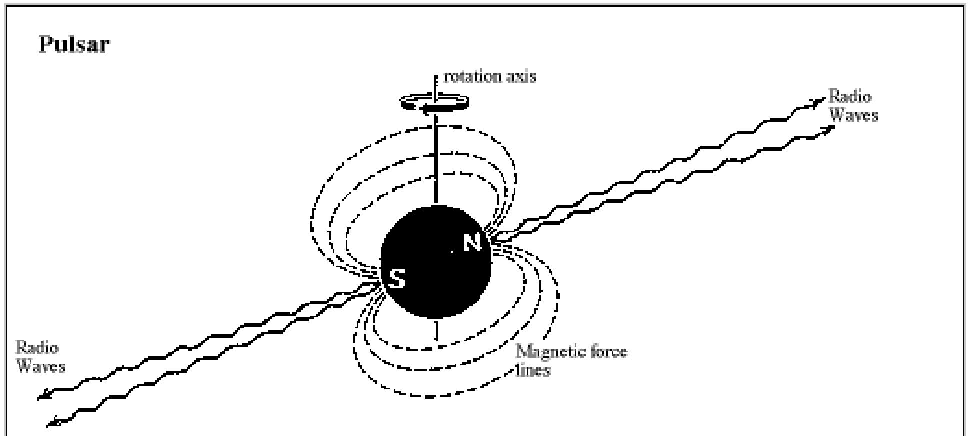
- Massive stars may collapse to black holes at the end of their burning phase

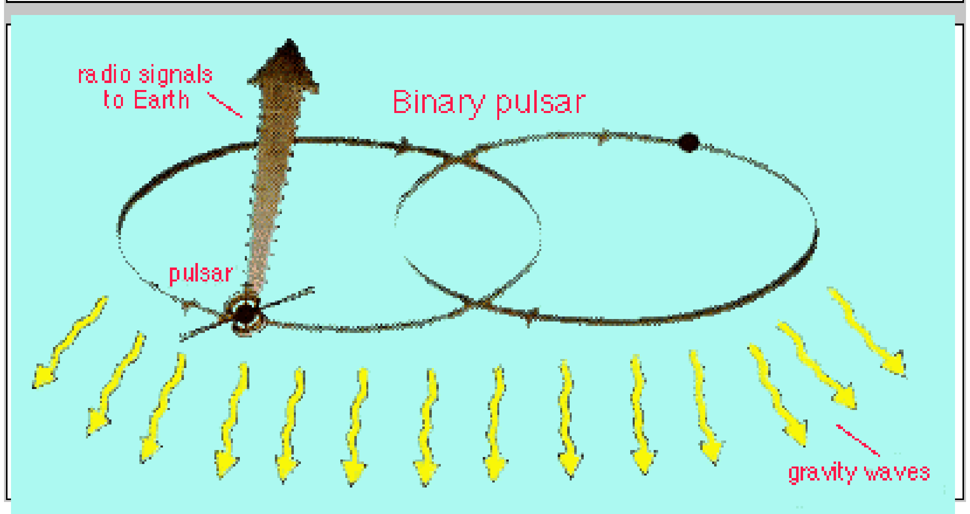
Neutron Stars

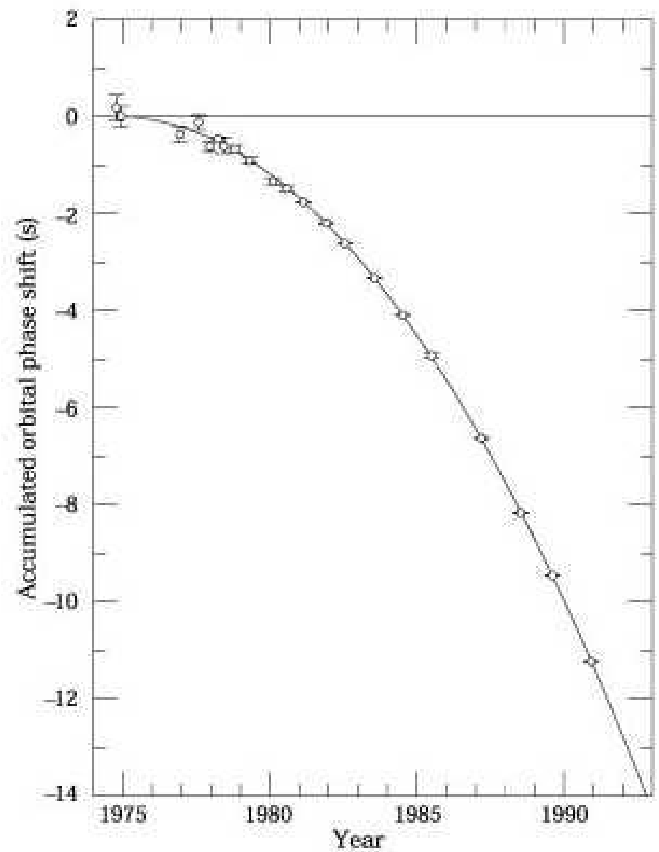
- At the end of life, some stars do not collapse to a black hole, but only to nuclear density
  - 1 teaspoon of this matter weighs a ton
- Such stars are seen as radio pulsars



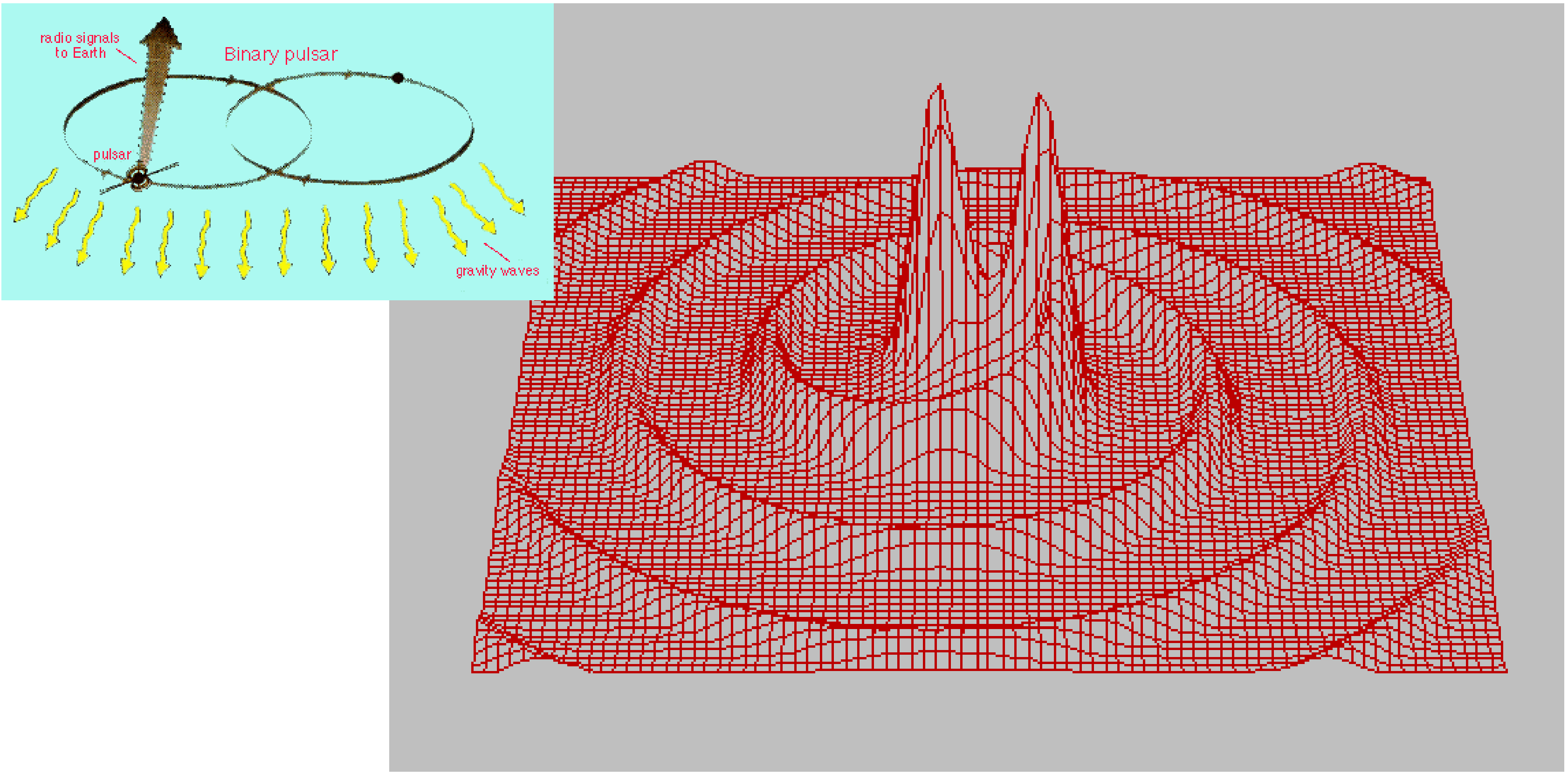
Experimental evidence for GrRad Taylor-Hulse Binary (PSR 1913+16)







Ripples in Space from the Binary Pulsar



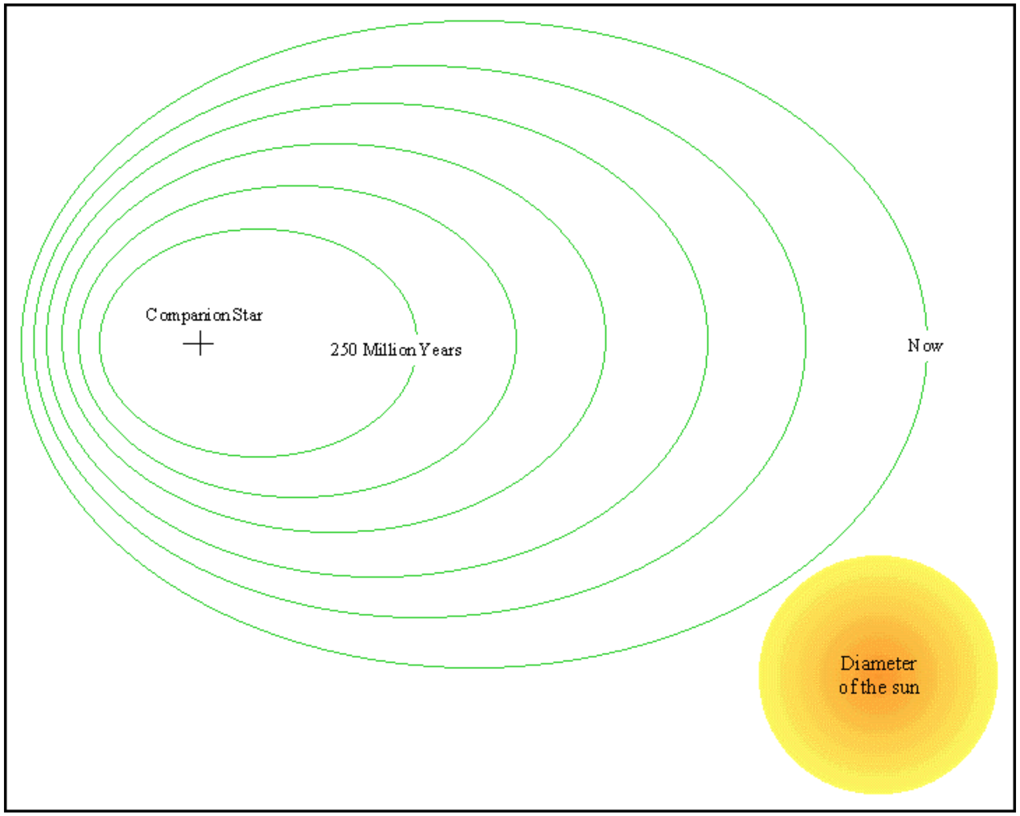
Future of the Taylor-Hulse

Radiating grav. energy

$$\frac{dE}{dt} = \frac{32GI^2 w^6}{5c^5}$$

Not much today

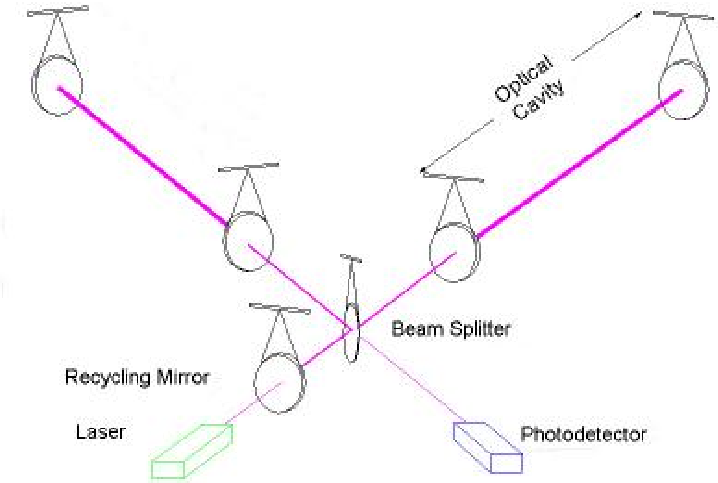
In 300,000,000 yrs
coalesce with a burst
of gravitational radiation

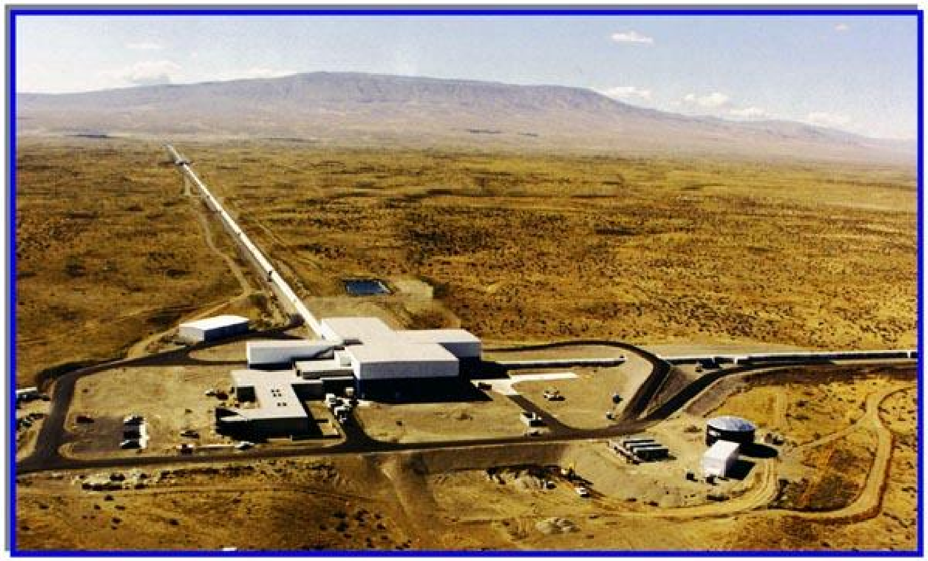


Detectors

- Bars

- Laser Interferometers





Hanford, WA

Livingston, LA

Laser Interferometer (Beam Tube)

- Light path in vacuum (10^{-6} torr initial)
- Beam tube with 1.22 meter diameter
- 10,000,000 liter vacuum systems

LIGO Vacuum Chambers

- All optical components are mounted in high vacuum chambers

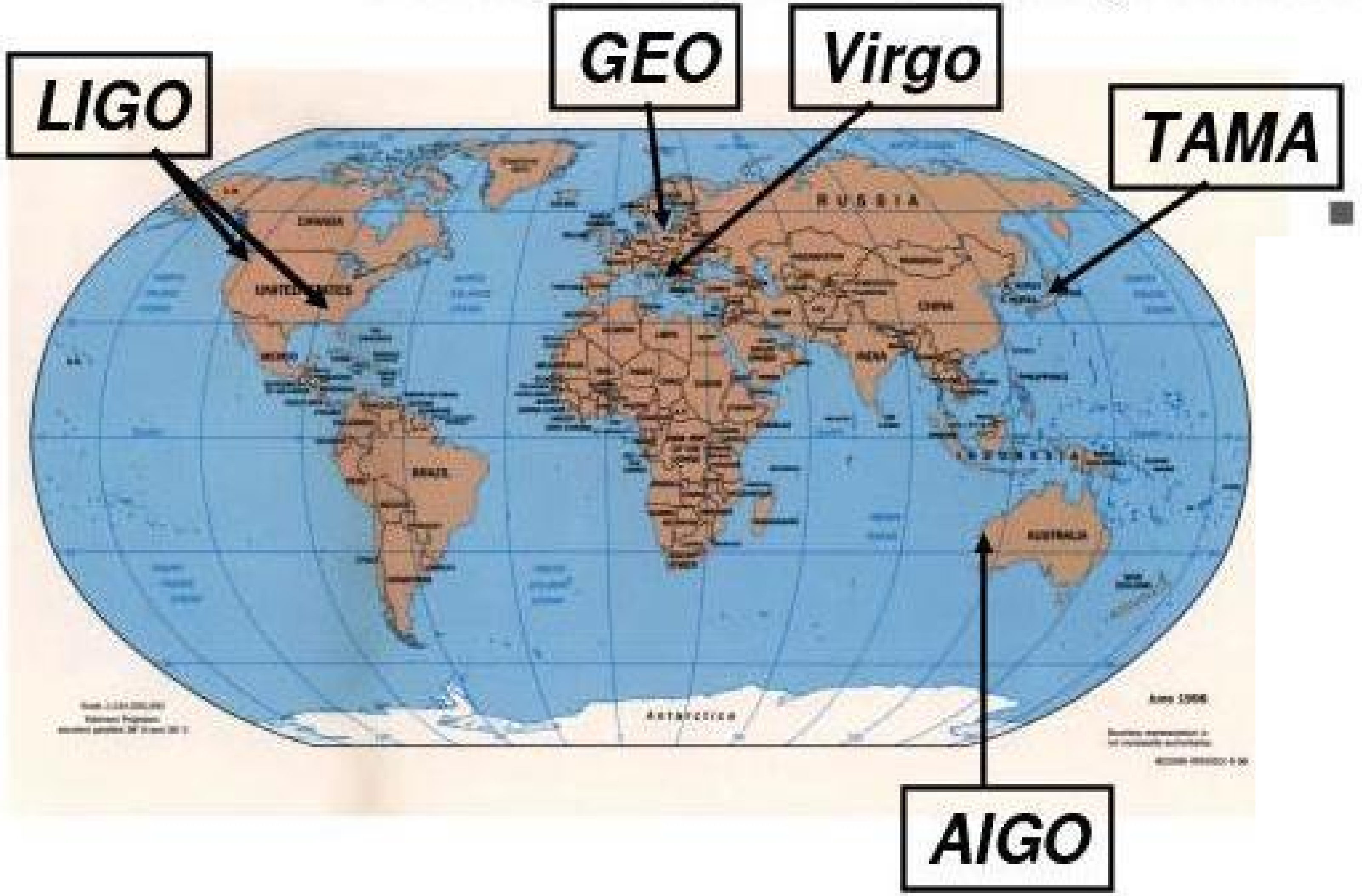
LIGO Vibration Isolation

- All optical components are mounted on spring stack in high vacuum

LIGO SCHEDULE

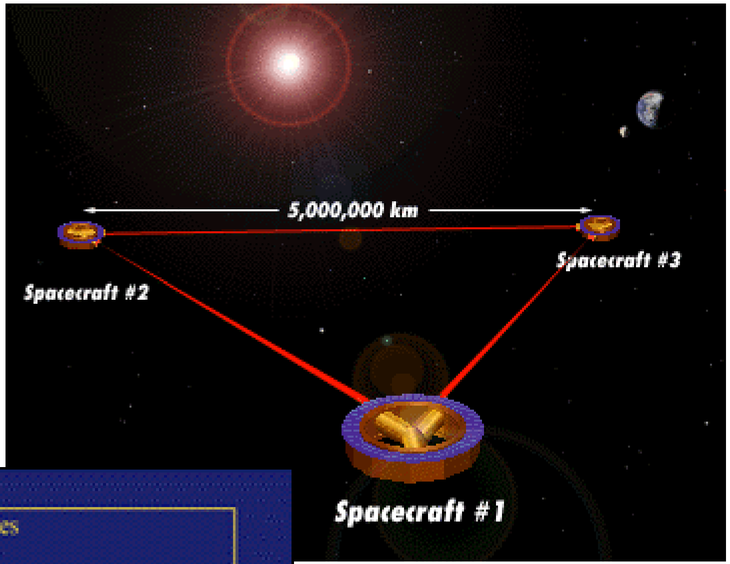
1995 NSF funding secured ($ 360M)
1996 Construction Underway (mostly civil)
1997 Facility Construction (vacuum system)
1998 Interferometer Construction (complete facilities)
1999 Construction Complete (interferometers in vacuum)
2000 Detector Installation (commissioning subsystems)
LHO 2km commissioning
Single arm test (summer 2000)
Power-recycled Michelson (Winter 2000)
2001 Commission Interferometers (first coincidences)
PRM with FP arm cavities (Summer 2001)
2002 Sensitivity studies (initiate LIGO I Science Run)
2003+ LIGO I data run (one year integrated data at $h \sim 10^{-21}$)
2005 Begin LIGO II upgrade installation

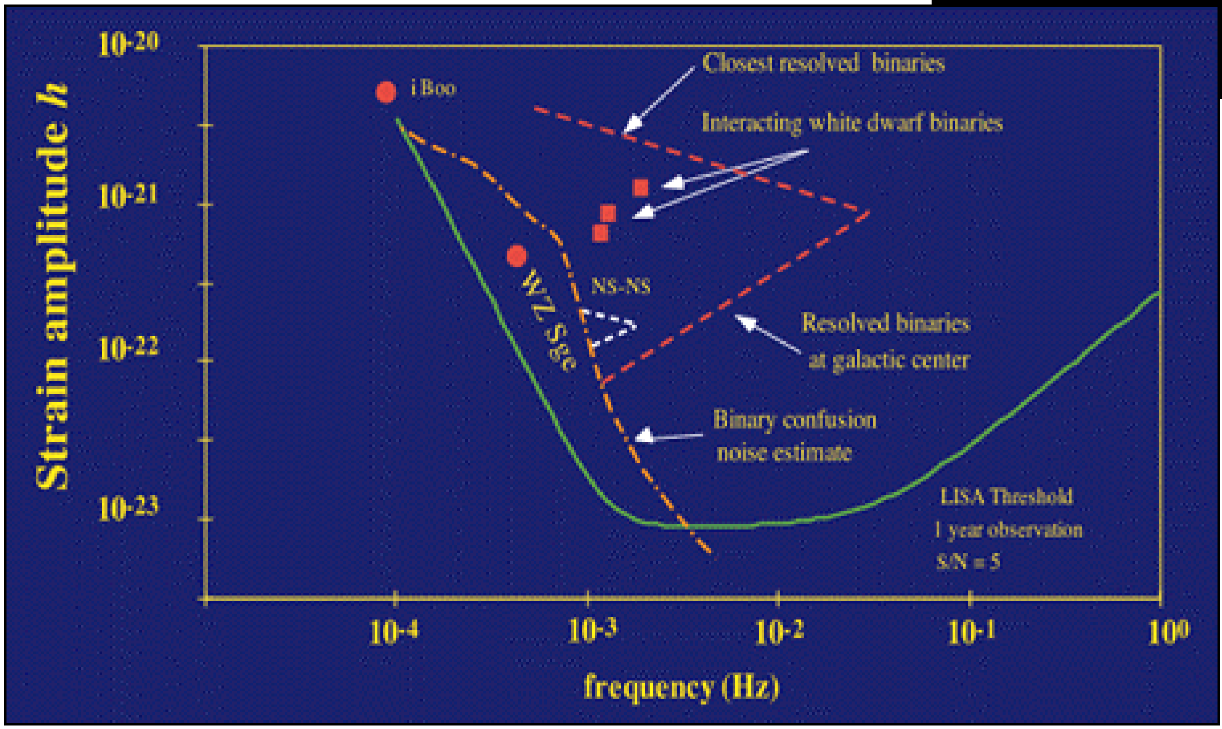
LIGO and the World-wide Network of Laser Interferometer Detectors



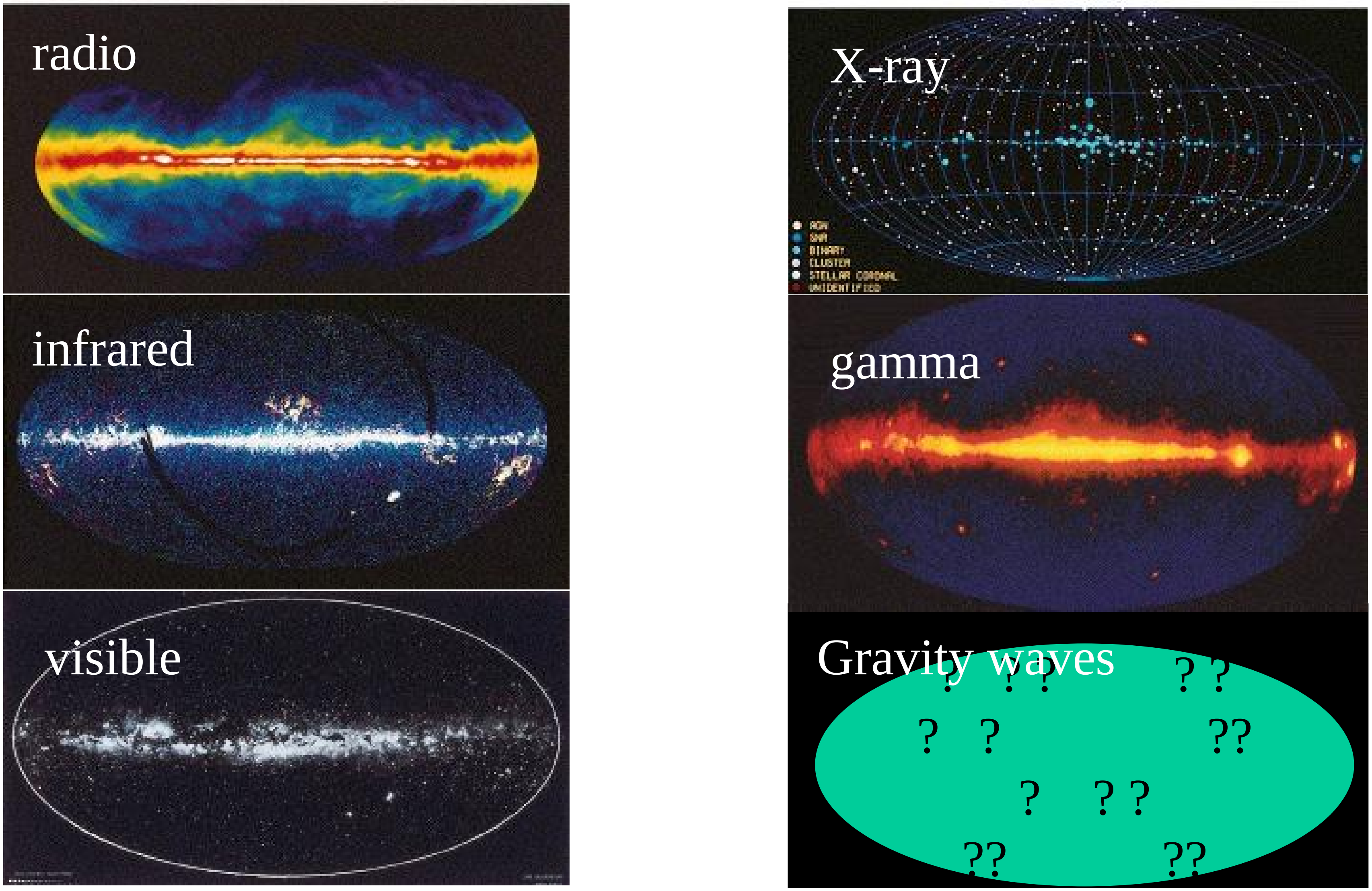
Laser Interferometer Space Antenna (LISA)

(the next generation)





Gravity waves open a new window



High Energy Physics at UO

- The search for gravity waves is part of the experimental high energy physics program at the University of Oregon which includes
  - study of matter/anti-matter asymmetry
  - search for the Higgs boson and supersymmetric particles
  - search for gravitational radiation (gravity waves)

– Professors Brau, Frey, Strom, Torrence

Summary

- Einstein's theory of General Relativity predicts that space itself is vibrating (gravity waves)
- The LIGO project will soon begin operation to search for these waves with unprecedented sensitivity
- There may be some BIG surprises if signals are found
  - Dark Matter
  - Extra Dimensions

That's All Folks

General Relativity "predicts" the existence of gravitational radiation

- Newton's laws assume action at a distance,
  - potential reacts instantly
  - there is no wave equation, no radiation
- General Relativity, being a relativistic theory, assumes a characteristic time for field response (c=speed of light), and yields a wave equation for this response

Two polarizations

- Wave will distort a ring of test masses like tidal deformation

- specific movement of the test masses during one period of the wave depend on polarization

+

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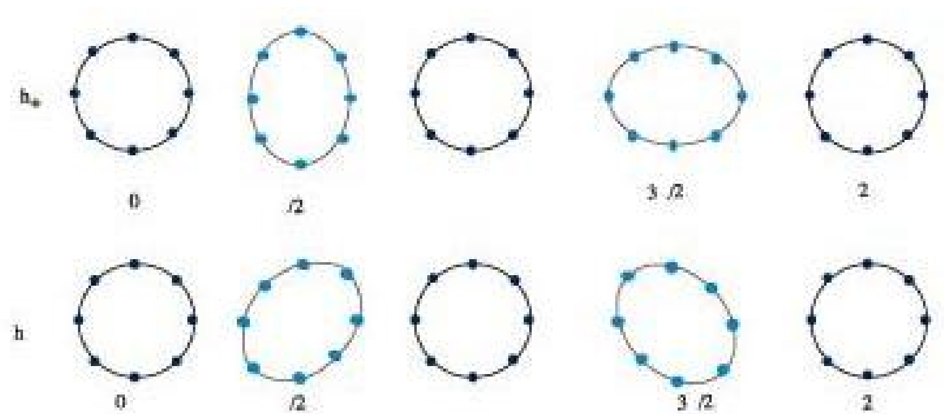


EM and Grav. radiation

	Electromagnetic	Gravitational
•Source	• accelerating charge	• accelerating mass
•Nature	• oscillating field propagates thru space	• oscillating space-time
•Interactions	• absorbed, scattered by matter	• negligible interaction with matter
•Frequency	• $f > 10^7$ Hz	• $f < 10^4$ Hz
•Detector	• detectors directional	• detectors omni-directional
•Measure of strength		• measure amplitude

Astrophysical Sources

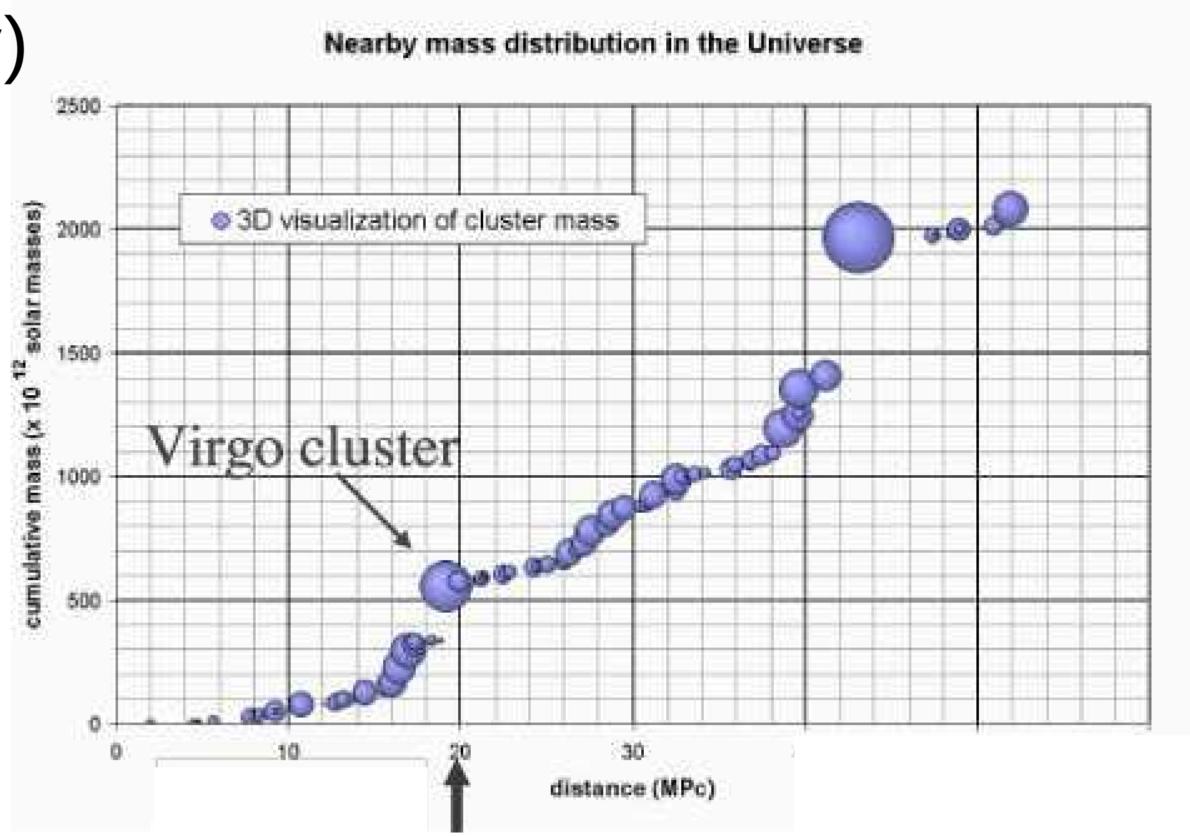
- Binary compact star systems
  - composed of neutron stars and/or black holes
- Non-axisymmetric supernova collapse
- Non-axisymmetric pulsar (periodic)
- Early universe
  - stochastic background radiation

$\Rightarrow$ most sources are not seen as EM emitters

$\Rightarrow$ good chance for surprises (unexpected sources)

Nearby stellar mass distribution

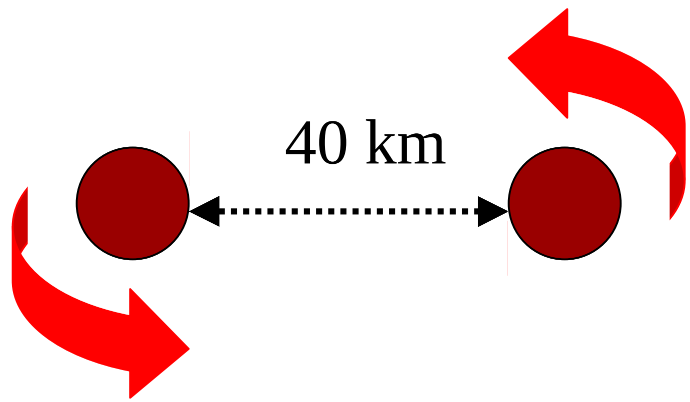
- These events are rare, so we need a reach to large distances to have a chance (r $\approx$ 65 Mly)



Back to the binary star system

- A benchmark system for grav. Radiation is a binary neutron star (compact)
- consider the strength

$$h_{\mu\nu} = \frac{2G}{c^4 r}\ddot{I}_{\mu\nu}$$



$M = 3 \times 10^{30}$ kg

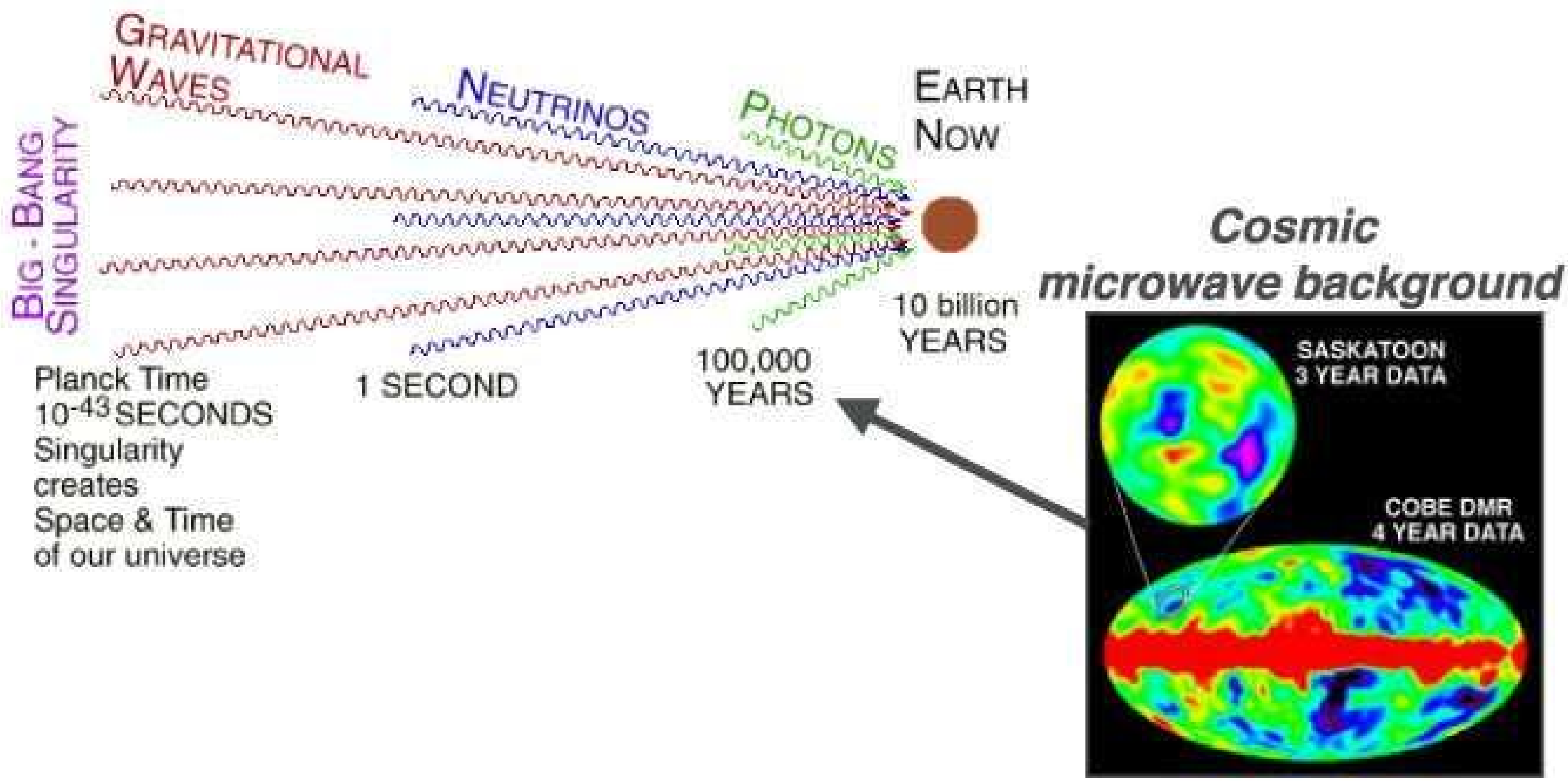
R = 20 km

f = 400 Hz

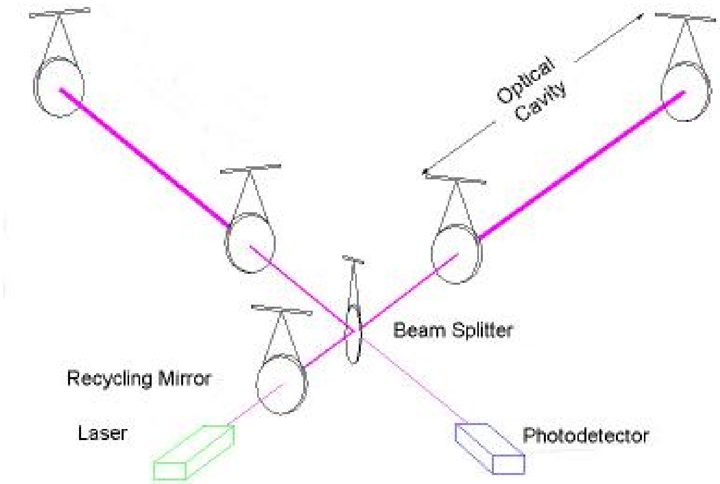
$r = 10^{23}$ m (10 Mly)

$h \approx 6 \times 10^{-21}$ (10 Mly / r)

Early universe
(stochastic background radiation)



Laser Interferometer



Power recycled Michelson

$\Delta L = L_1 - L_2$ = cavity length diff.

B = number of times light bounces (effective arm length BL)

λ = laser wavelength

- Requirements for sensitivity ($h = \Delta L / L$)

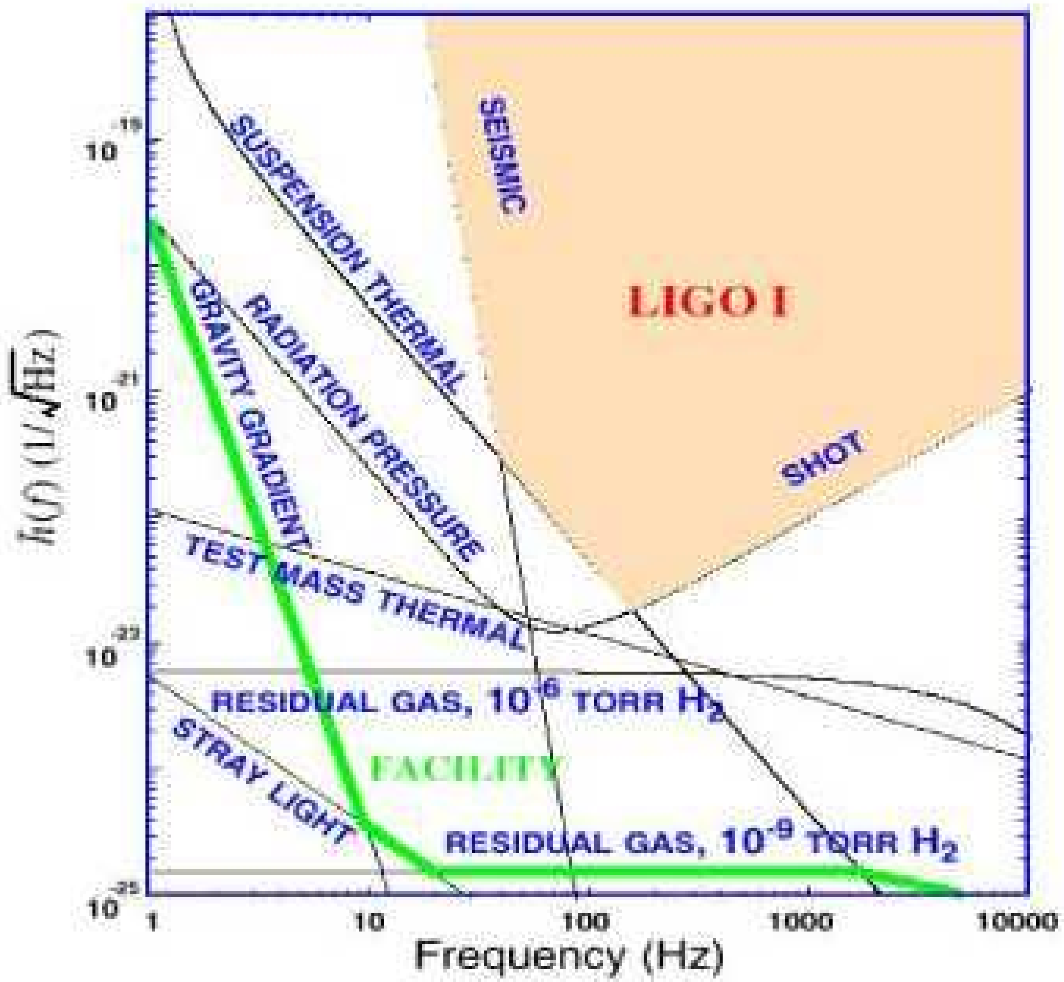
The relative phase change of light emerging from the two cavities is $\Delta\phi = B\,\Delta L / \lambda = B\,h\,L / \lambda$

So we need to maximize B and L, and minimize λ

eg. $B = 200$, $L = 4$ km, $\lambda = 1.06\ \mu m$

$\Delta\phi = 7.6 \times 10^{11}\ h$

Laser Interferometer (Noise)

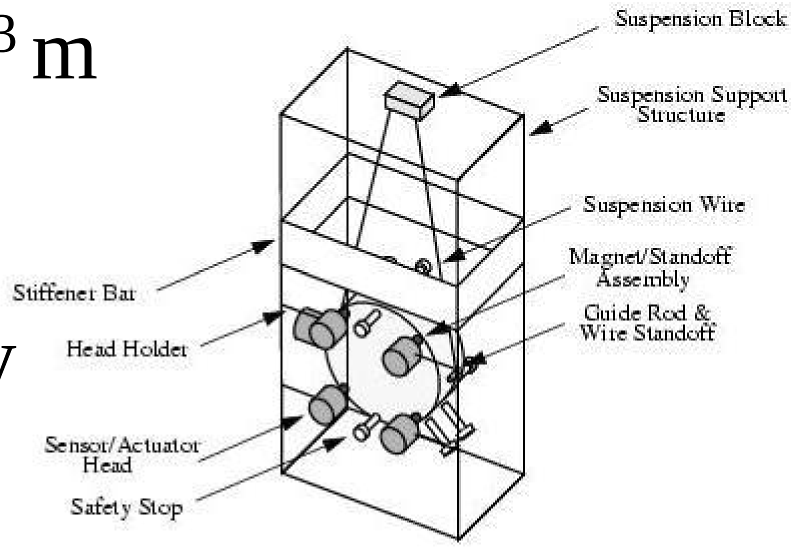


LIGO

- km-scale Laser interferometers at two sites
- Built by collaboration of Caltech and MIT
- Science will be done by LIGO Science Collaboration: ACIGA, Caltech, Carleton, Cornell, Florida, GEO, Harvard, IAP, India IUCAA, Iowa State, JILA, LSU, La. Tech, MIT, Michigan, Moscow State, NAOJ-TAMA, Oregon, Penn State, Southern, Stanford, Syracuse, Texas-Brownsville, Wisconsin-Milwaukee
- (Oregon group: JB, R. Frey, M. Ito, R. Rahkola, R. Schofield, D. Strom)

Sensing and Control System

- 4 length and 12 alignment degrees of freedom must be controlled to maintain strain sensitivity
- Must hold lengths to 10^{-13} m in presence of 10^{-5} m seismic noise
- Test masses controlled by electromagnets driven by feedback



Eigenfreq. of suspension 0.5 - 0.7 Hz

Cosmic Ray Monitor

Look for coinicidences to prevent false discovery

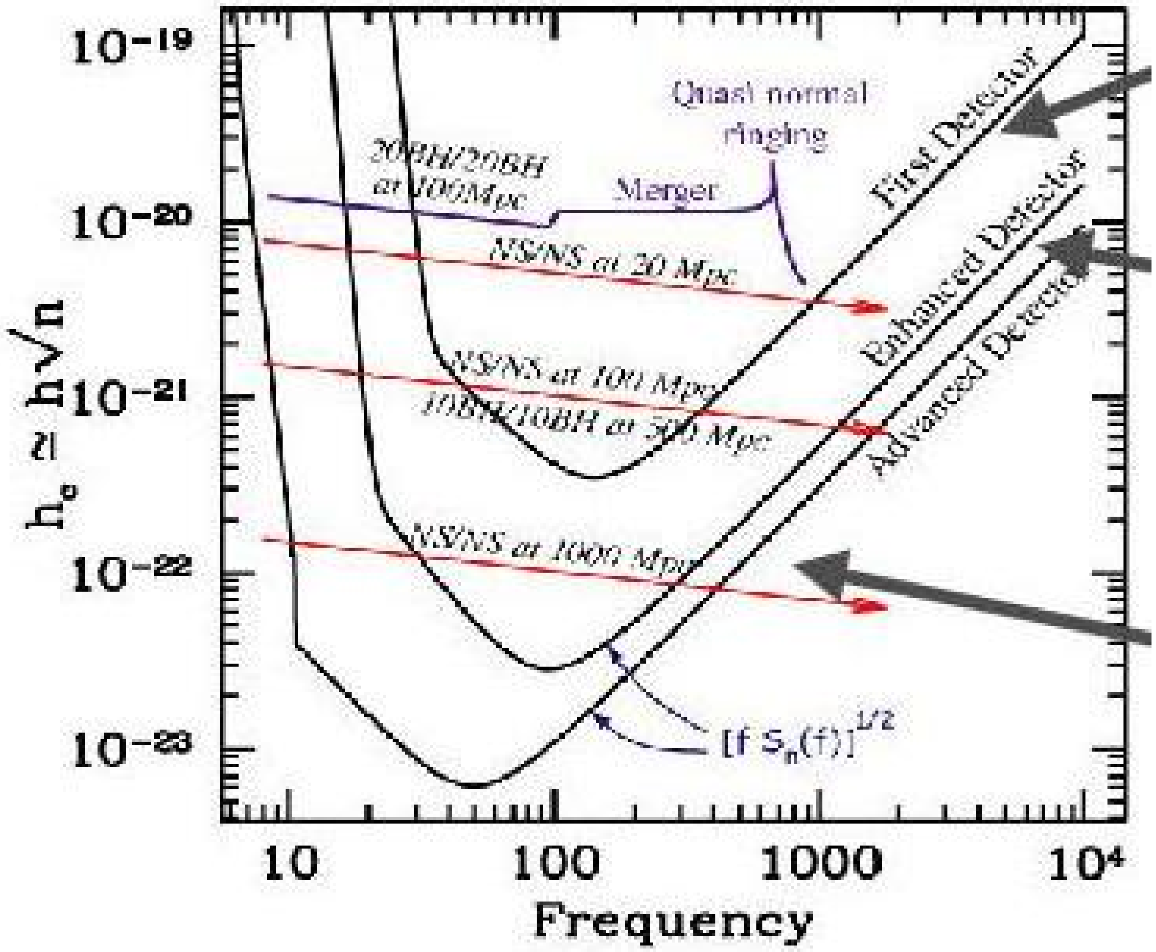
Data Acquisition

- Gravity wave channel is digitized at 16 kHz, but many other channels (about 2000 chan.)

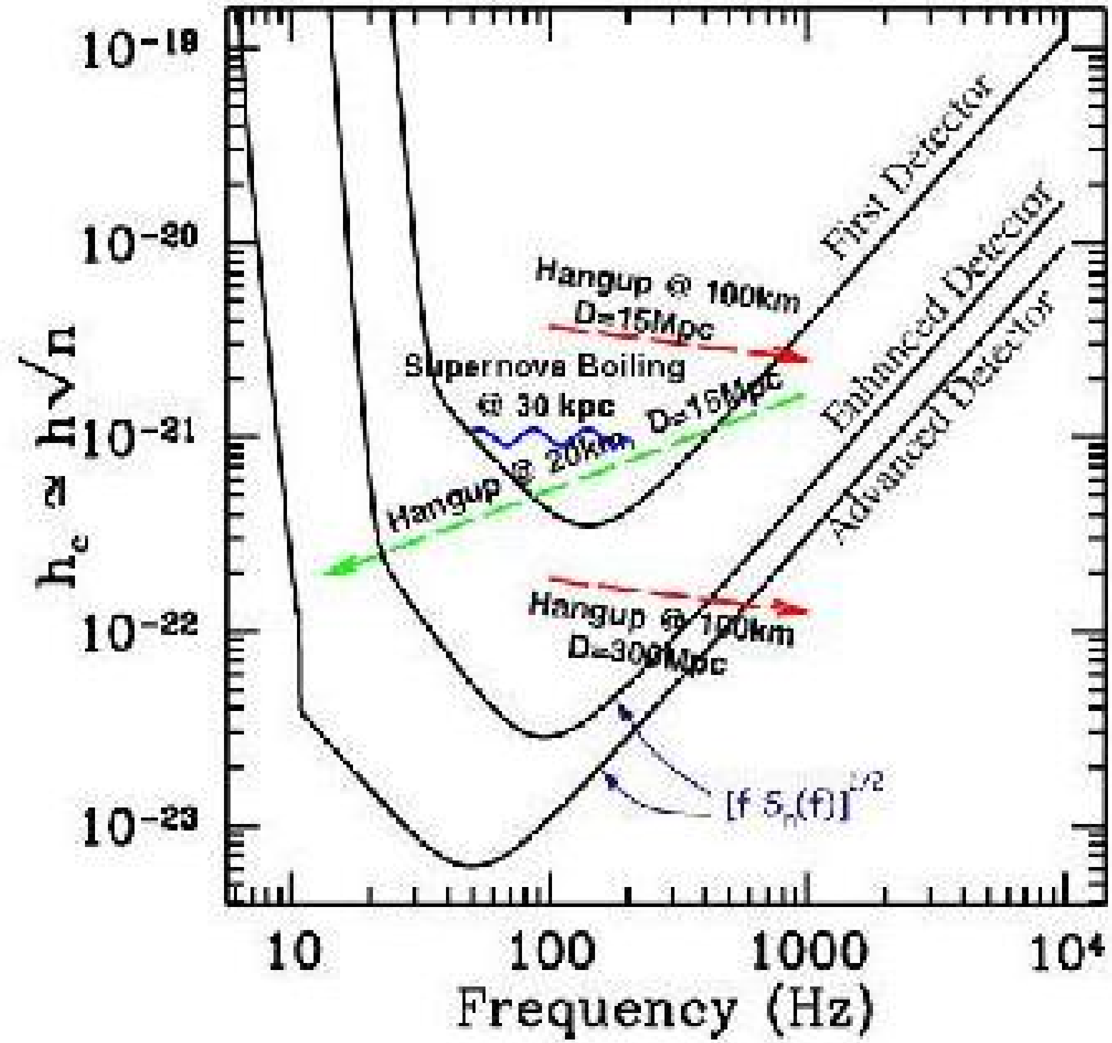
  $\Rightarrow$ very large data rate

  – monitor and control
  – PEM channels
- 14 Mbyte / sec
- store full data stream on disk for ~1 day
- reduce data to mini-data sets for analysis
  – archive rest

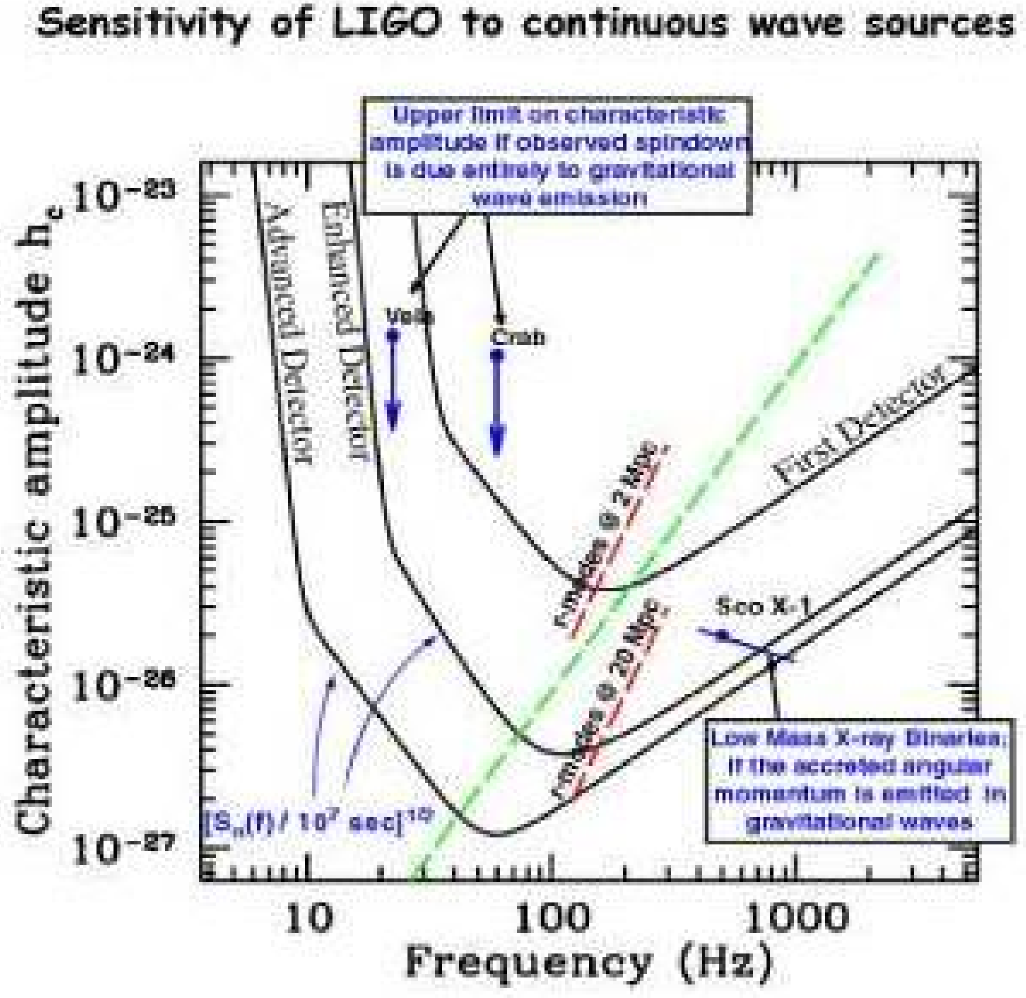
LIGO Sensitivity to Binaries



LIGO Sensitivity to Bursts



LIGO Sensitivity to Pulsars



CONCLUSIONS

- Gravitational radiation should be discovered in this decade
- With it should come advances in understanding General Relativity
- and, perhaps, discoveries of new phenomena in the universe

WATCH FOR SURPRISES

Gravitational Lens