

# 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

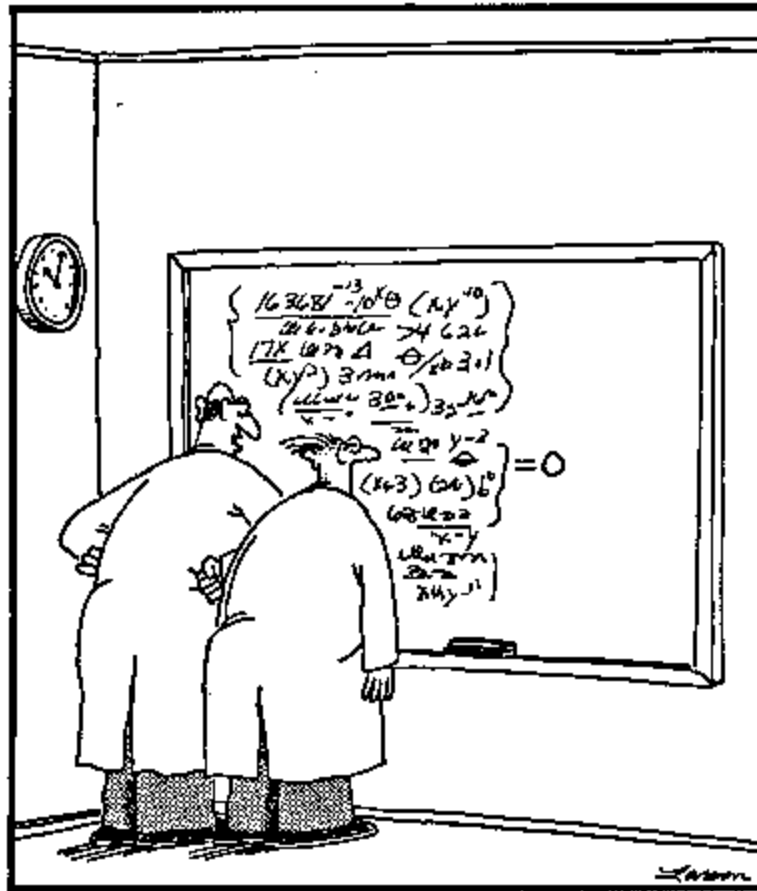
Gravity Waves

Neutron Stars

# The Cosmos



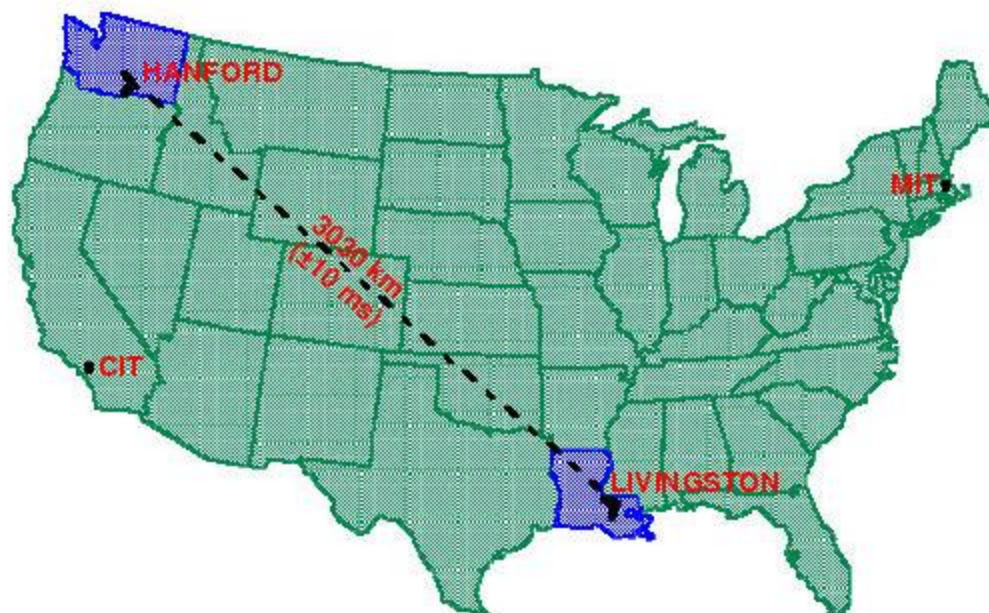
# Mathematical Basis of Gravity Waves



**“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



Built by MIT/Caltech, science being done by  
Collaboration including University of Oregon



# LIGO

**Hanford, WA**

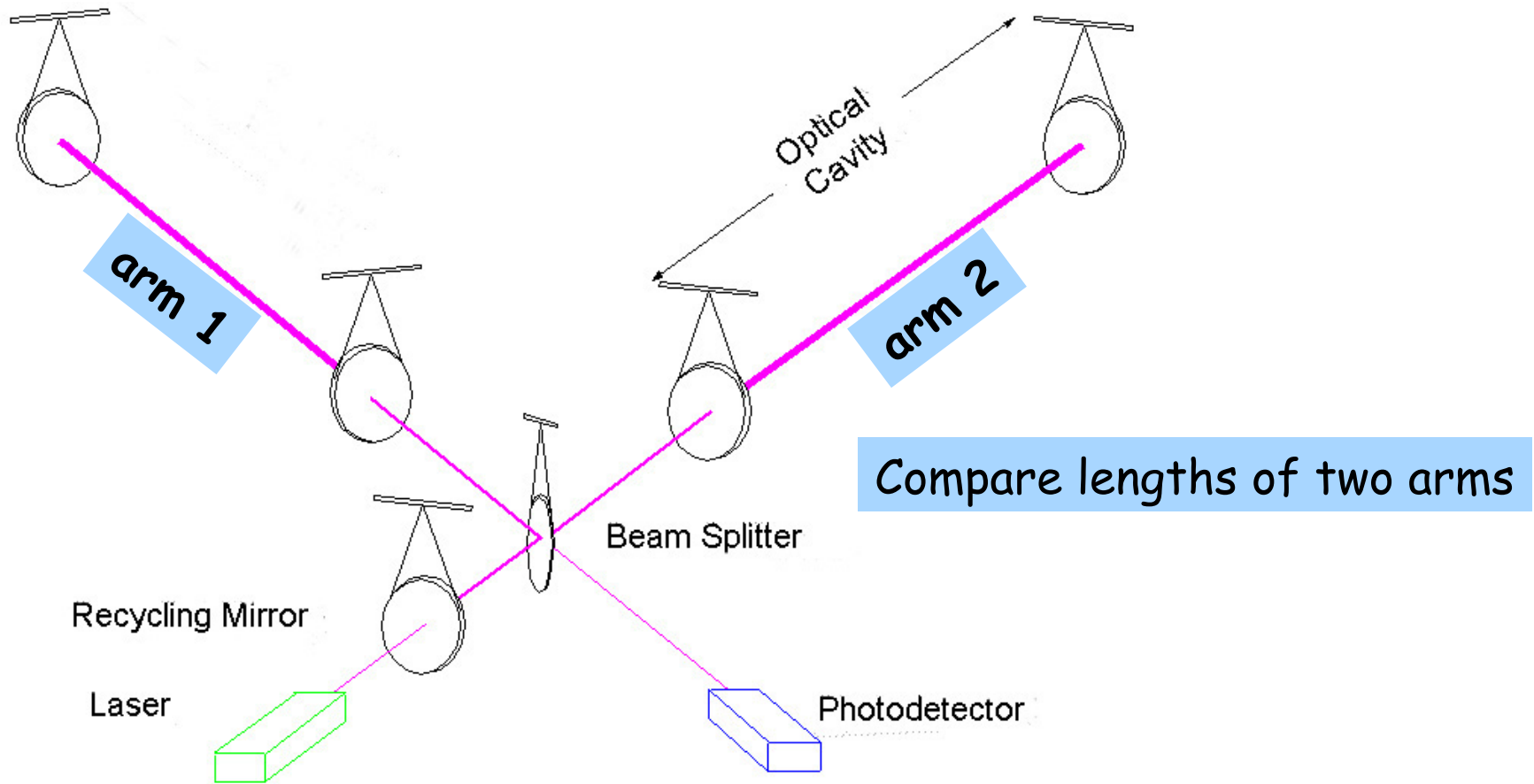


**Livingston, LA**

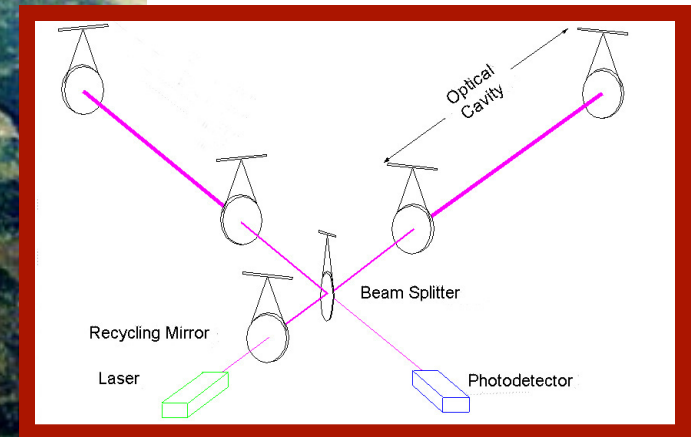
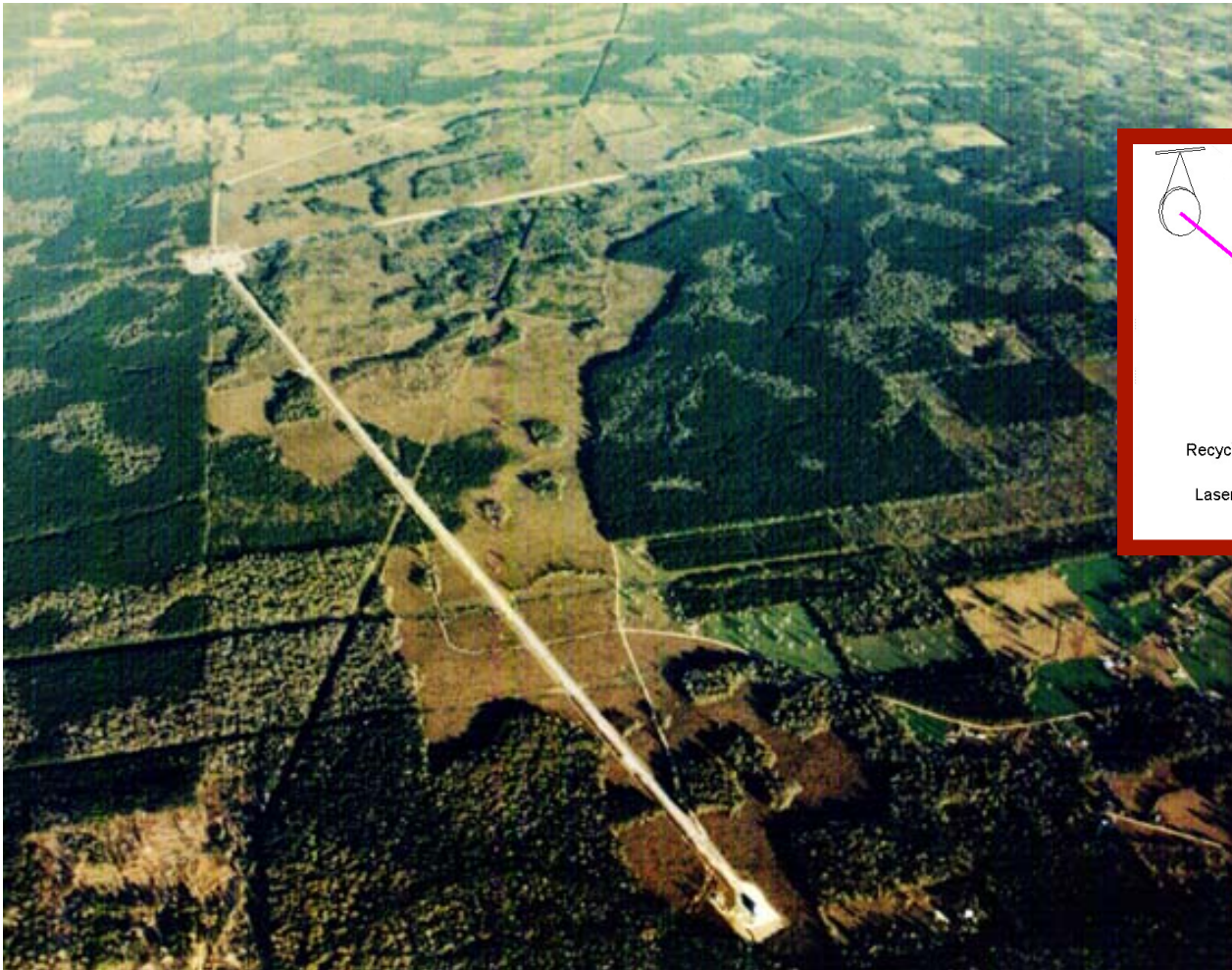


River Road, J. Brau, November 13, 2001

# Laser Interferometer



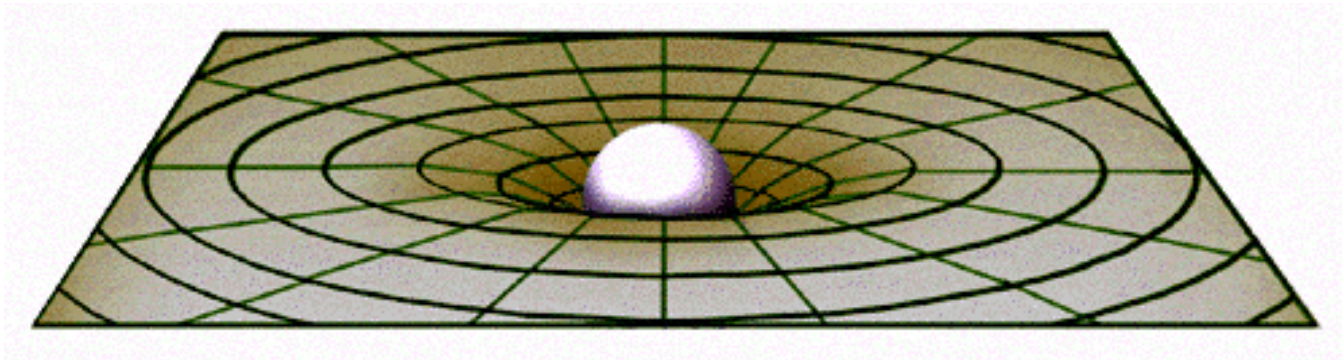
# Laser Interferometer



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

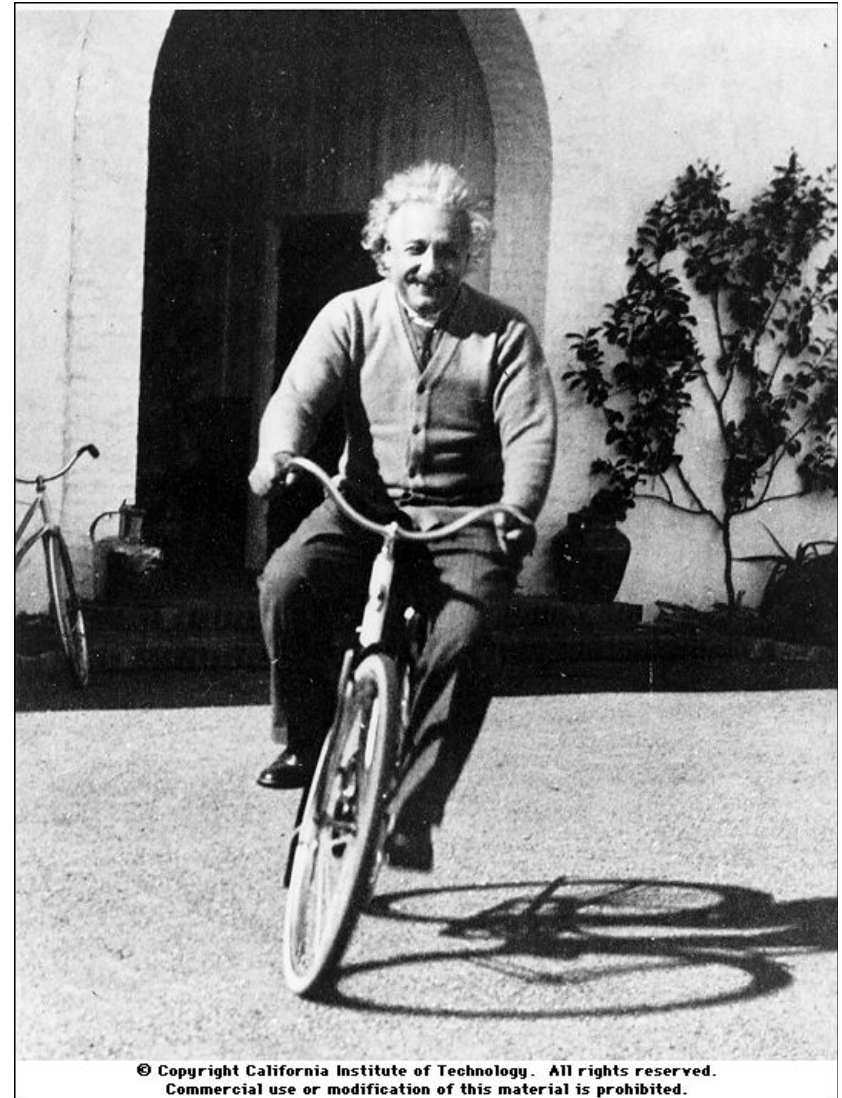
Hermann Einstein

# 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.

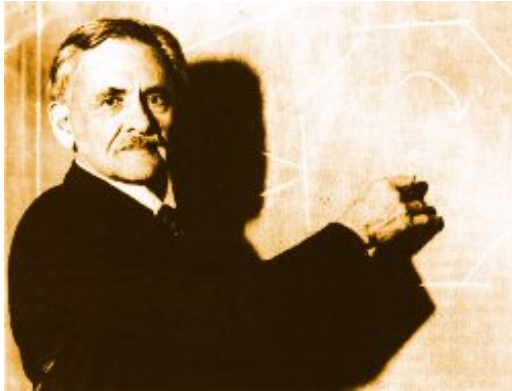


## SPECIAL RELATIVITY

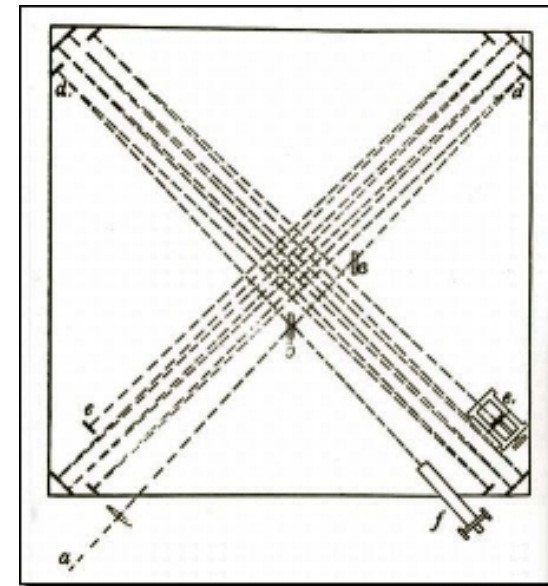
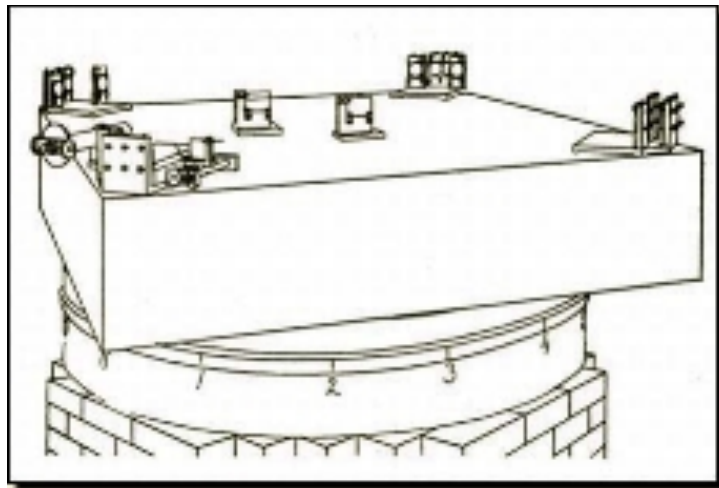
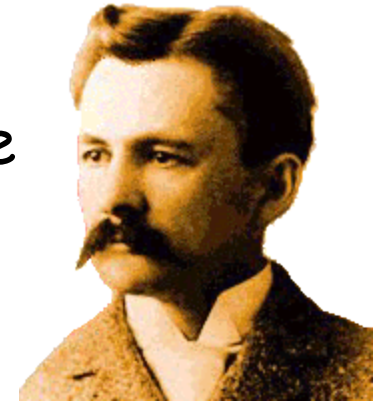
- The speed of light is constant
  - (this is true no matter what your relative motion)
- Nothing can move faster than the speed of light
- Space and time are mixed
- Time slows down when a system is in motion



# 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 at rest on the Earth, or moving rapidly 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**

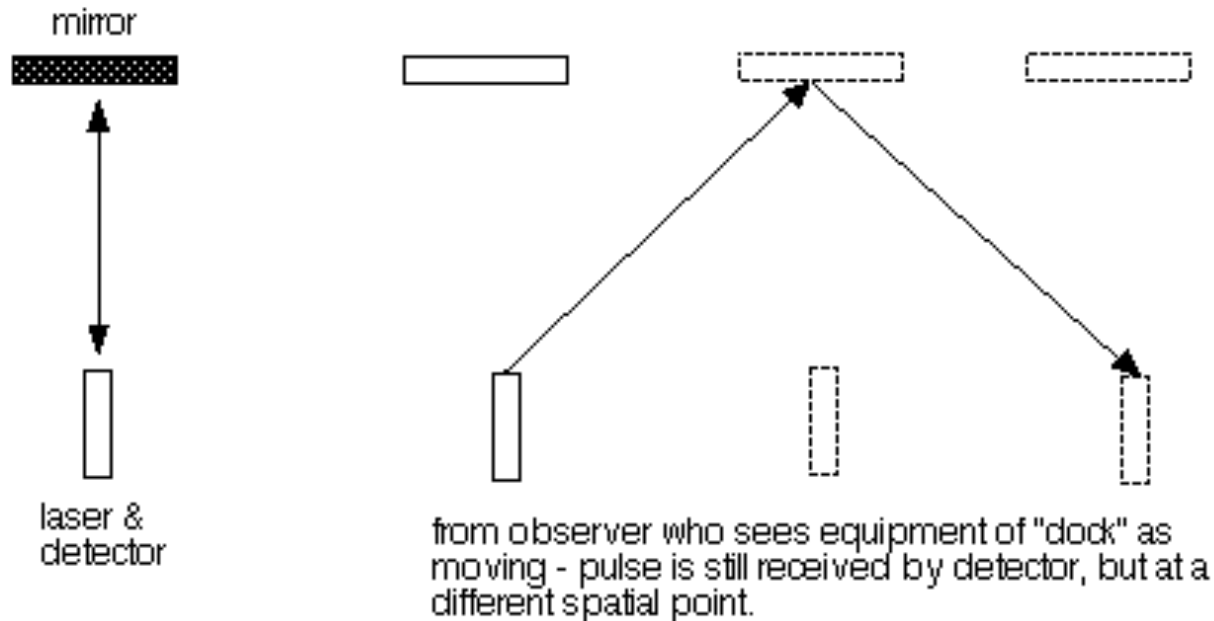
# Time Travel?

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

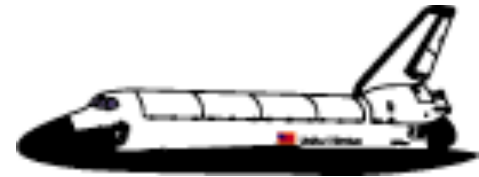
- Now imagine the clock is moving.
- Since the speed of light is unchanged, it takes longer, and time is slowing down





# 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 don't know

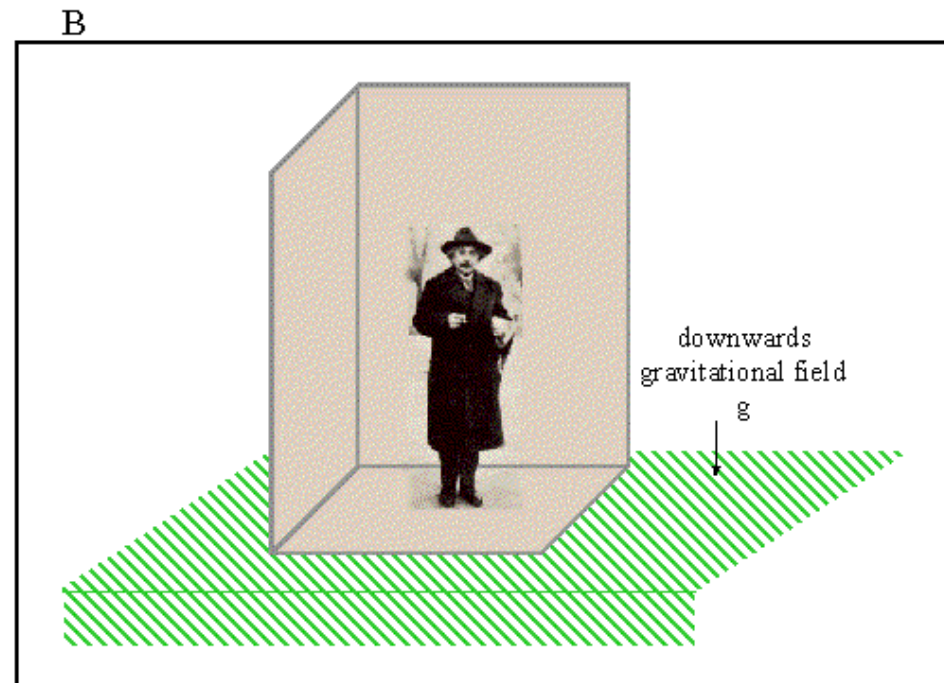
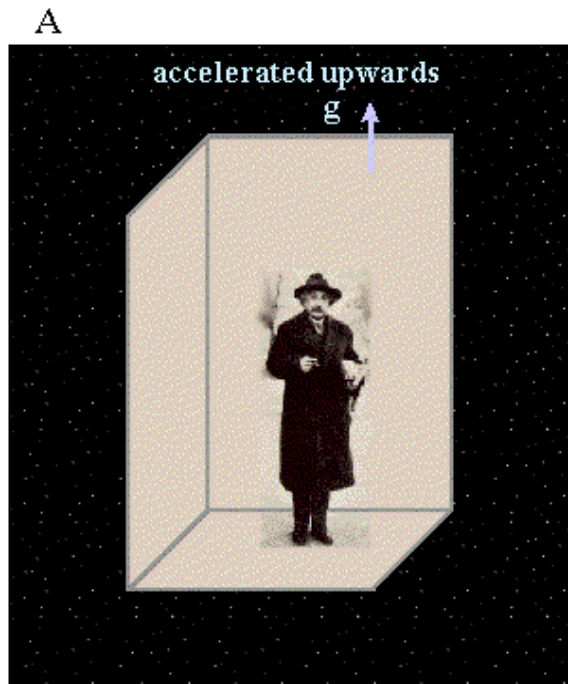
# SPECIAL RELATIVITY

$$E = mc^2$$

- 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



# 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 Gen. Rel.

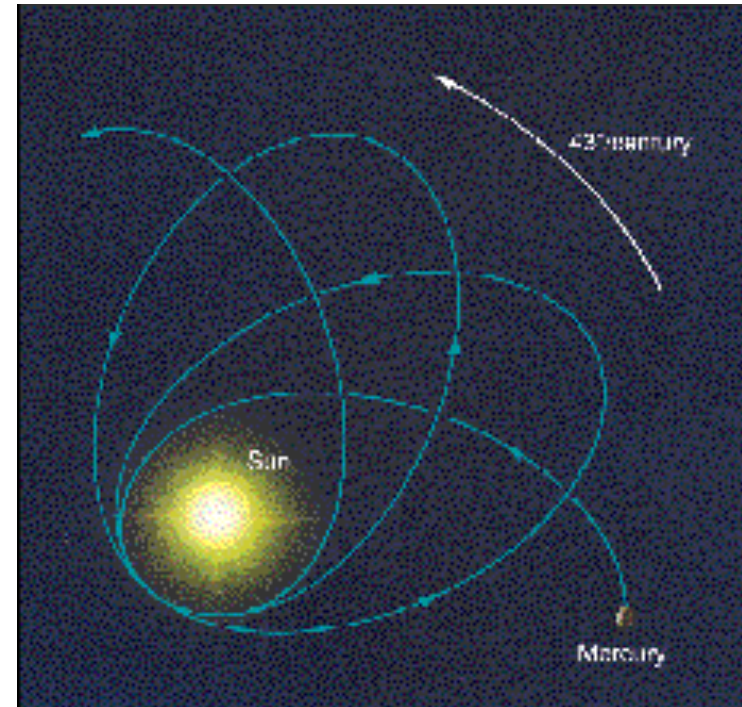
- I will talk about six predictions
  - three are the classic tests of GR that convinced physicists of its validity
  - three are of current active scientific interest

including the prediction of gravity waves,  
our focus today

# Einstein's Three Tests of GR

## 1 Mercury's orbital precession

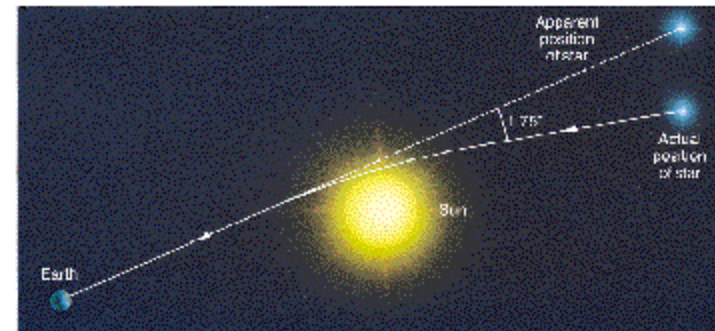
- known but unexplained prior to General Relativity
- in Newton's physics the orbit would not precess



# Einstein's Three Tests of GR

## 2 Bending of starlight

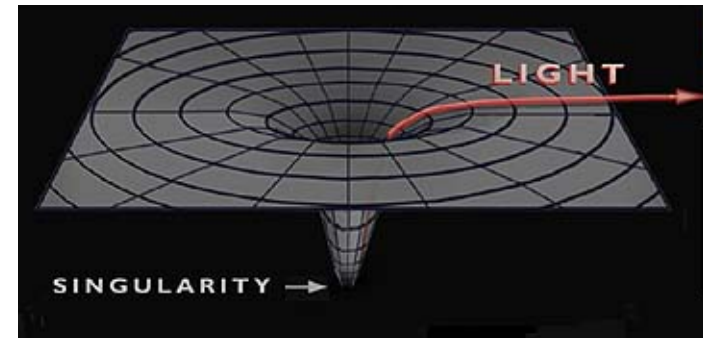
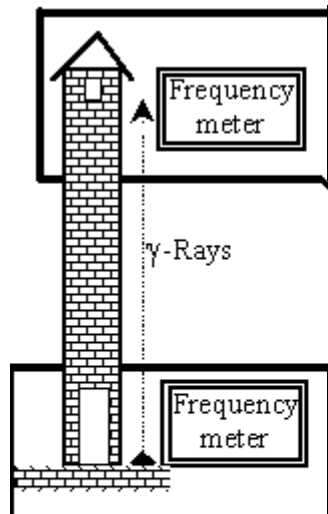
- the fabric of space is bent near massive objects and the bent space will turn light's trajectory
- 1919 Eddington mounts two expeditions during Solar eclipse
  - Principe (West coast of Africa)
  - Northern Brazil
- Einstein's prediction confirmed
- **BIG NEWS**
  - (New York Times)



# Einstein's Three Tests of GR

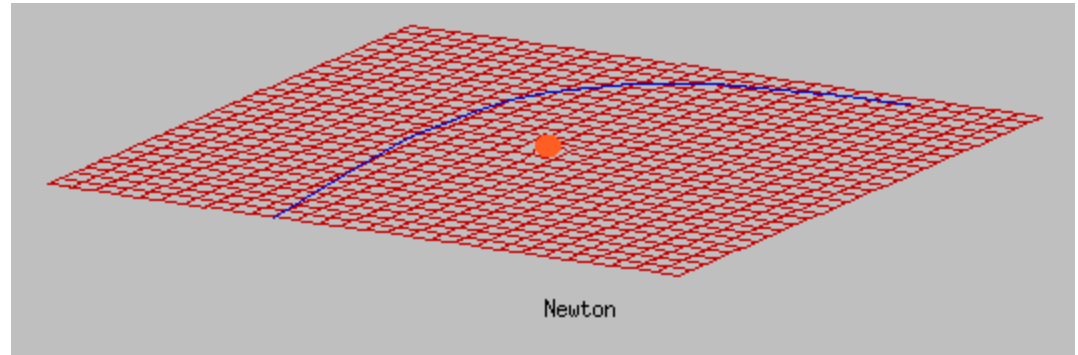
## 3 Gravitational redshift

- 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)

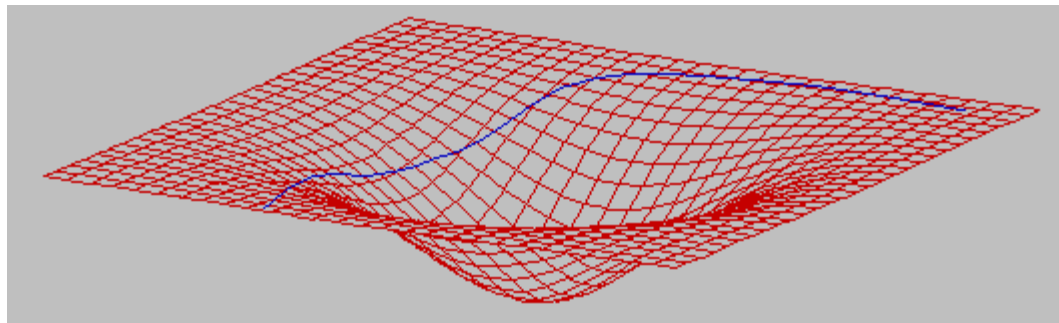


# Curvature of Space

- 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



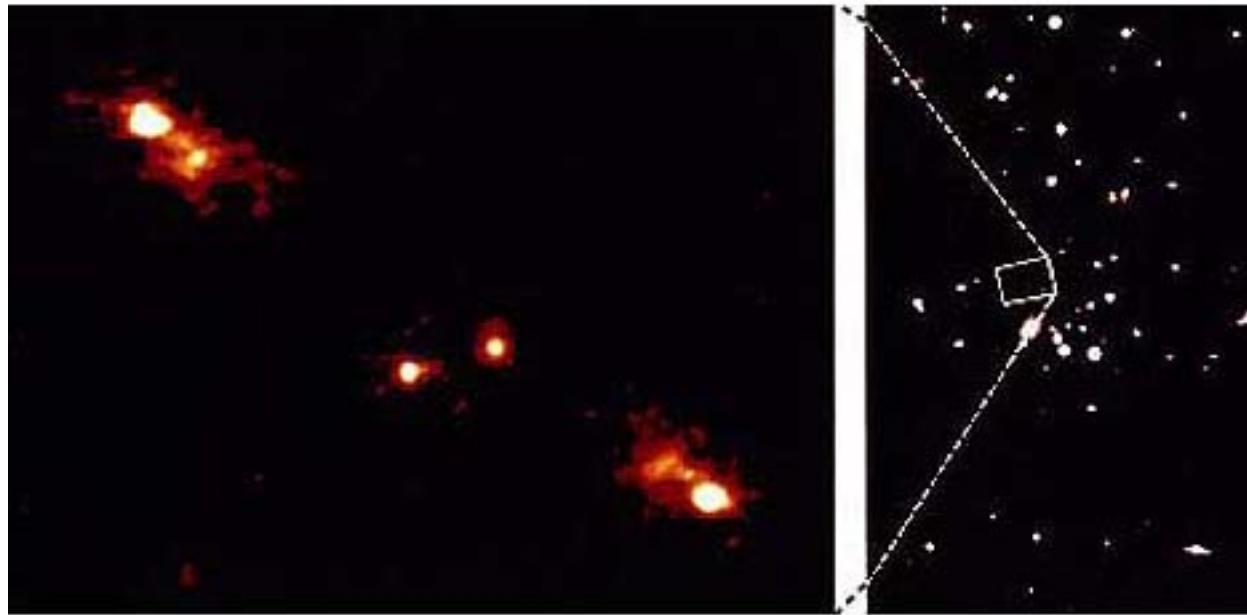
- Einstein calls his invention of this fudge factor his greatest blunder



# Other Predictions of General Relativity

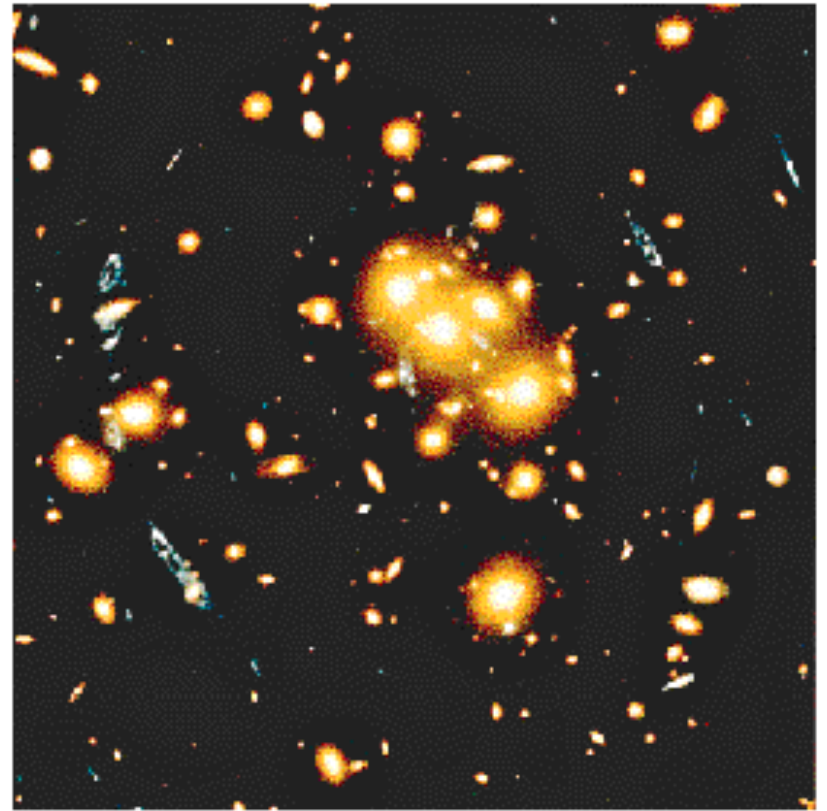
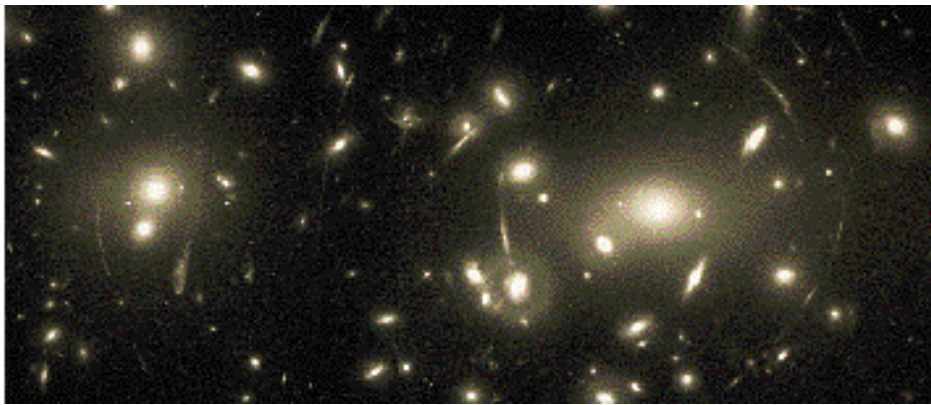
## 5 Gravitational Lenses (and arcs)

- Double quasar discovered in 1979



- Recent photos from Hubble Space Telescope
  - 120 gravitational arcs

# Gravitational Lens

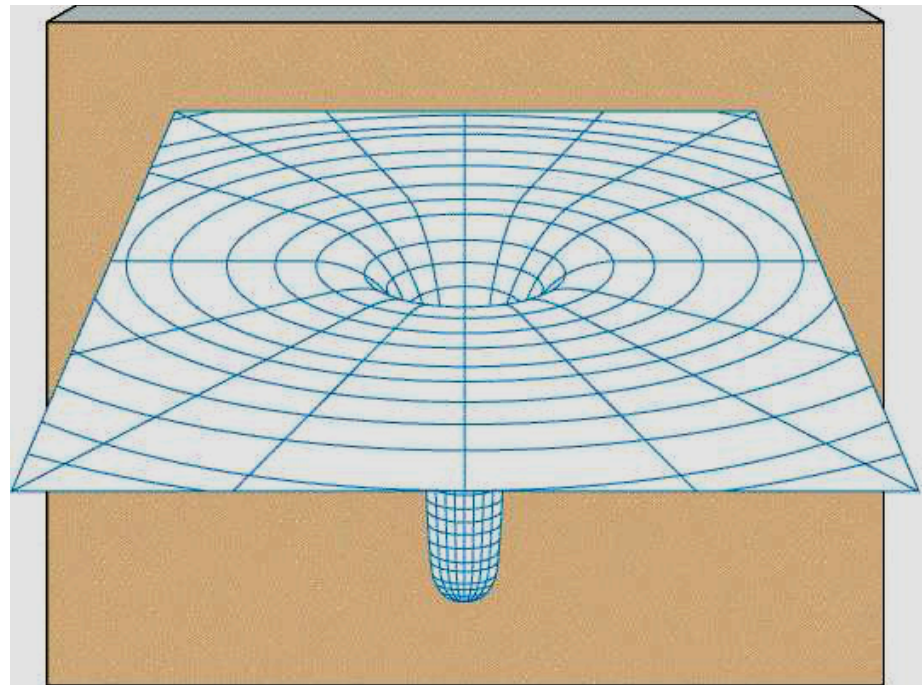


# Other Predictions of General Relativity

## 6 Gravity Waves

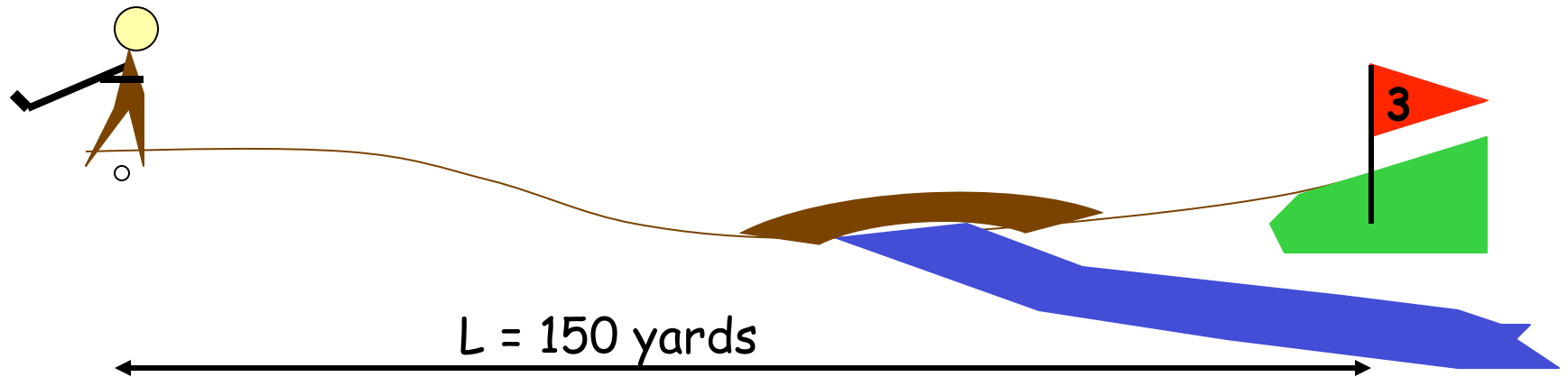
- Ripples on the fabric of space-time
- Travel at the speed of light

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



# Gravity Waves

(distances are changing)



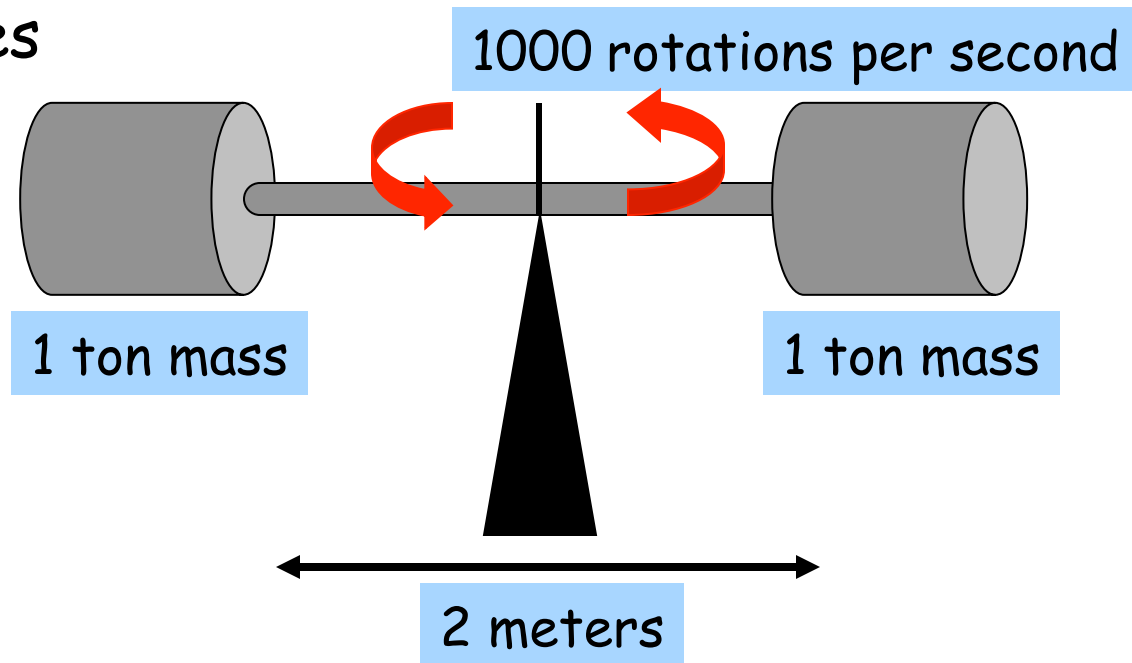
- Distance changes 100-1000 times per second  
 $L \rightarrow L \pm \Delta L$       strain,  $h = \Delta L / L$
- But,  $h$  is only 0.0000000000000000000000000001 =  $10^{-21}$
- $\Delta L = h L = 1.5 \times 10^{-19}$  yards
- $\Delta L = \text{diameter of the atom} / 1,000,000,000$  !!!!!

# Detection of Gravity Waves

- Maybe the history of the discovery of electromagnetic waves is useful
  - 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

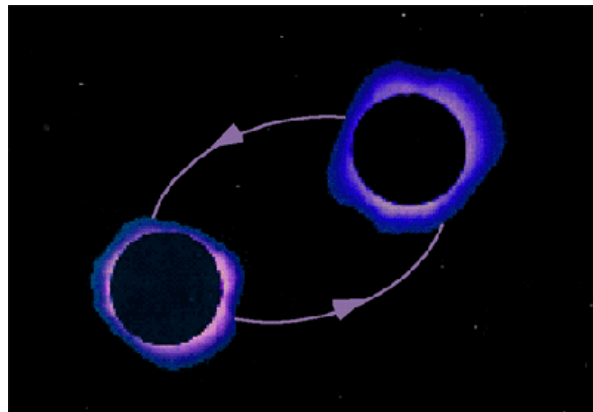






# Potential sources of Gravity Waves

- 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



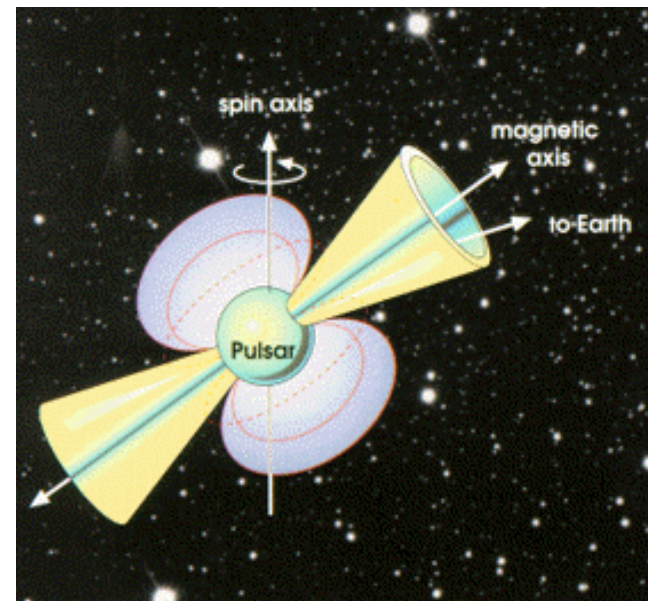
# Black Holes

- 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

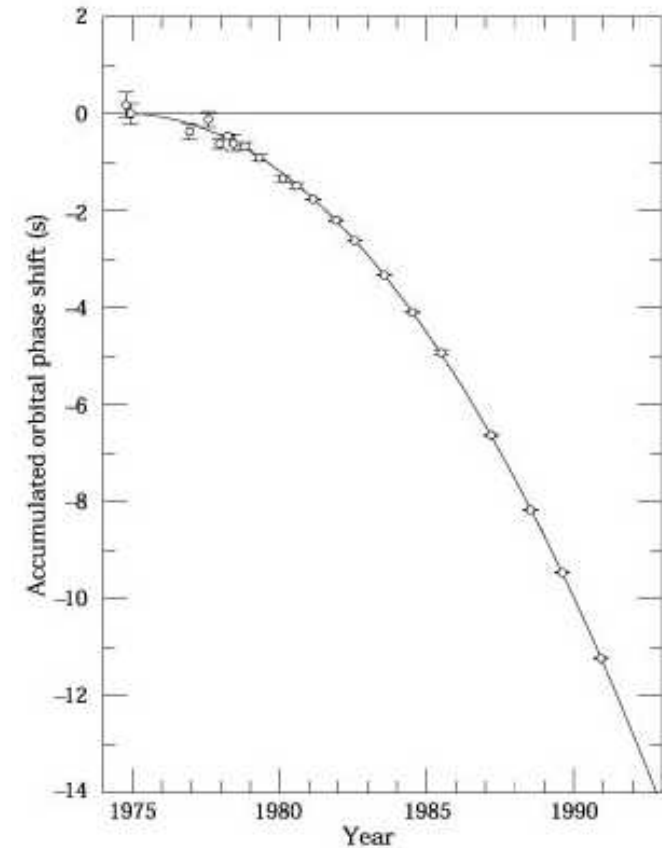
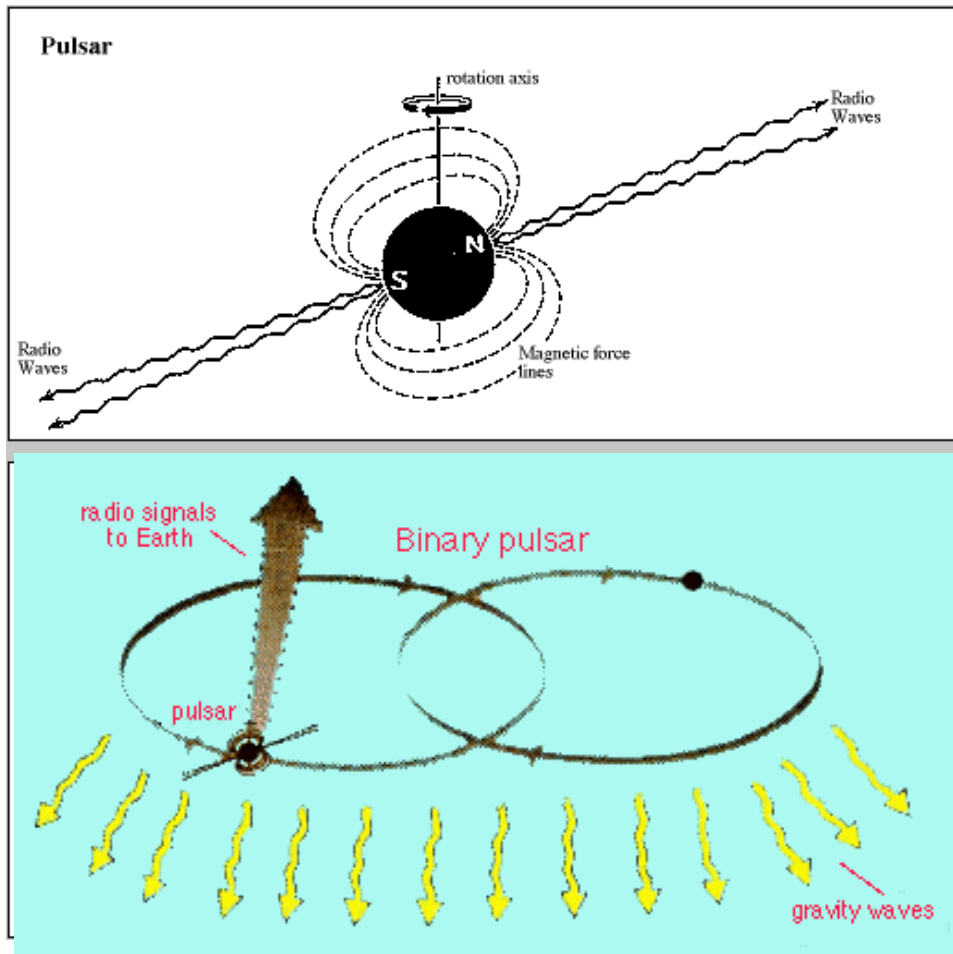


# Neutron Stars

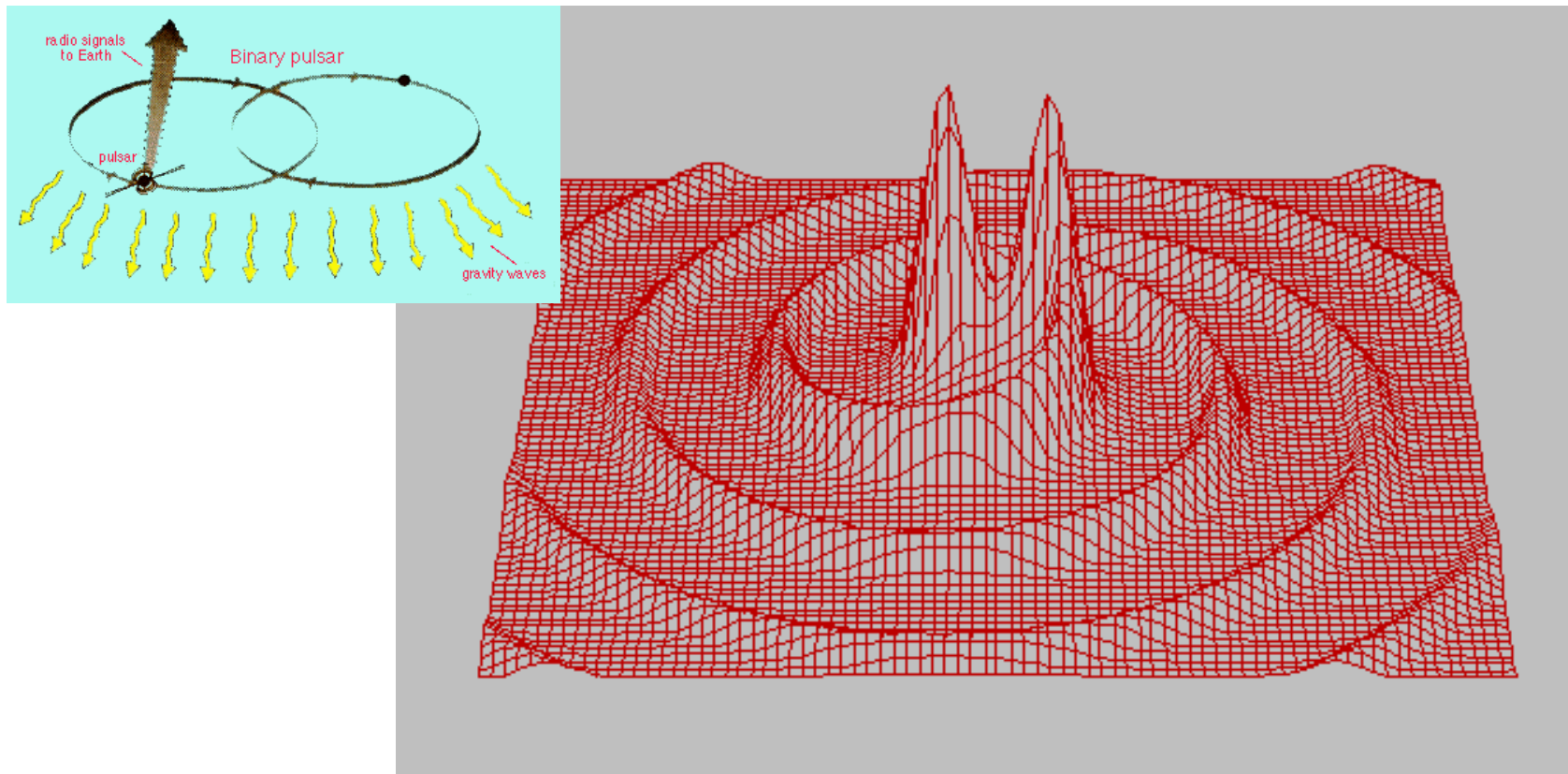
- At the end of life, some stars do not collapse to a black hole, but only to nuclear density
  - 1 teaspoon of this matter weighs a ton
- Such stars are seen as radio pulsars



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



# Ripples in Space from the Binary Pulsar





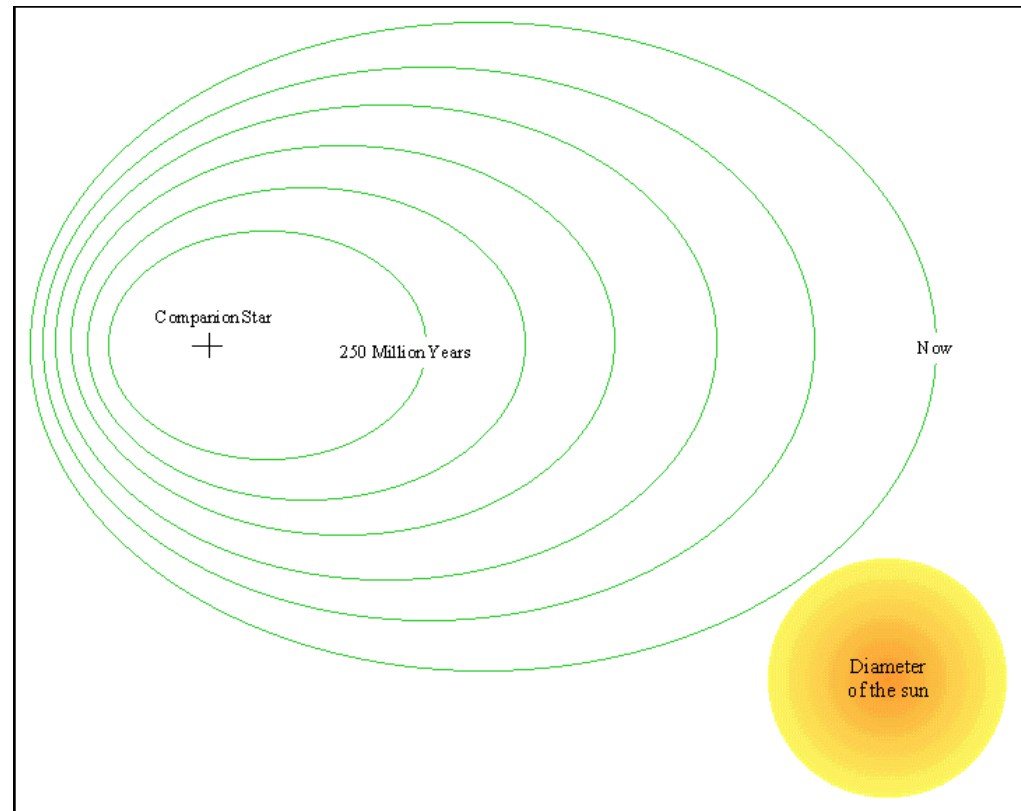
# Future of the Taylor-Hulse

Radiating grav. energy

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

Not much today

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

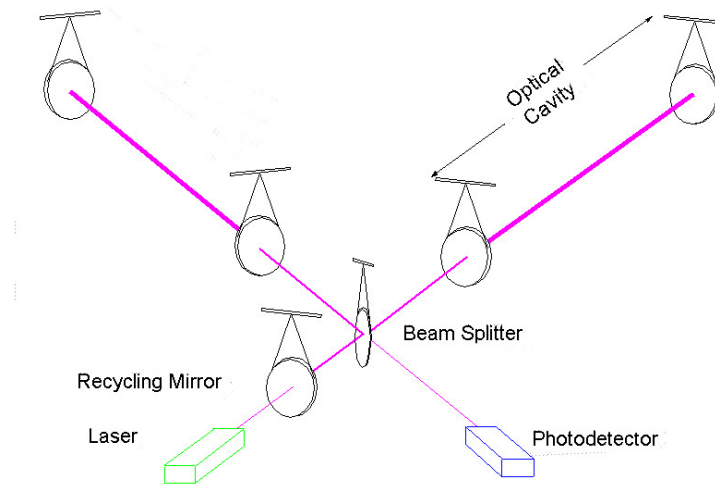


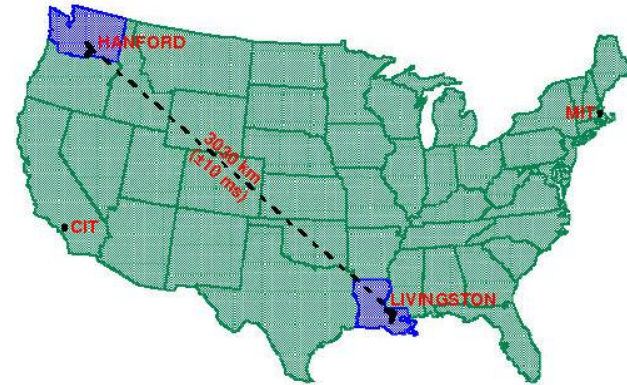
# Detectors

- Bars



- Laser Interferometers





**Hanford, WA**

**Livingston, LA**



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# 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



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# LIGO Vacuum Chambers

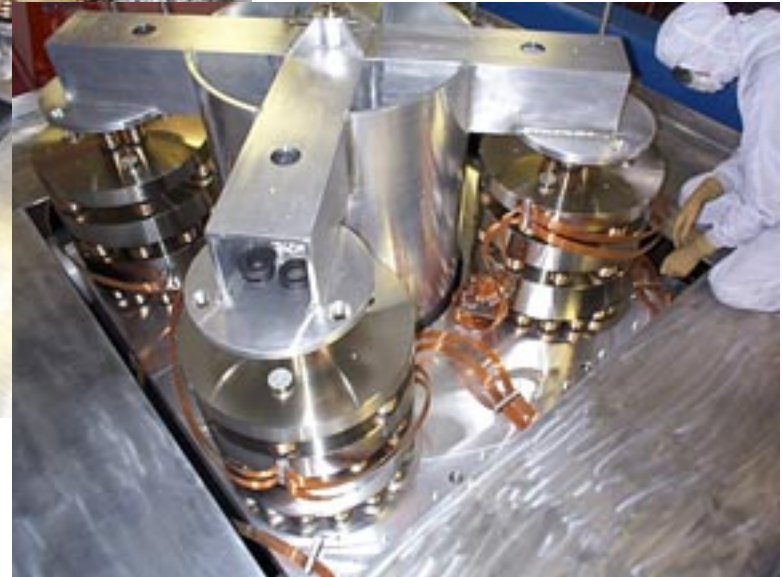
- All optical components are mounted in high vacuum chambers



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# LIGO Vibration Isolation

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

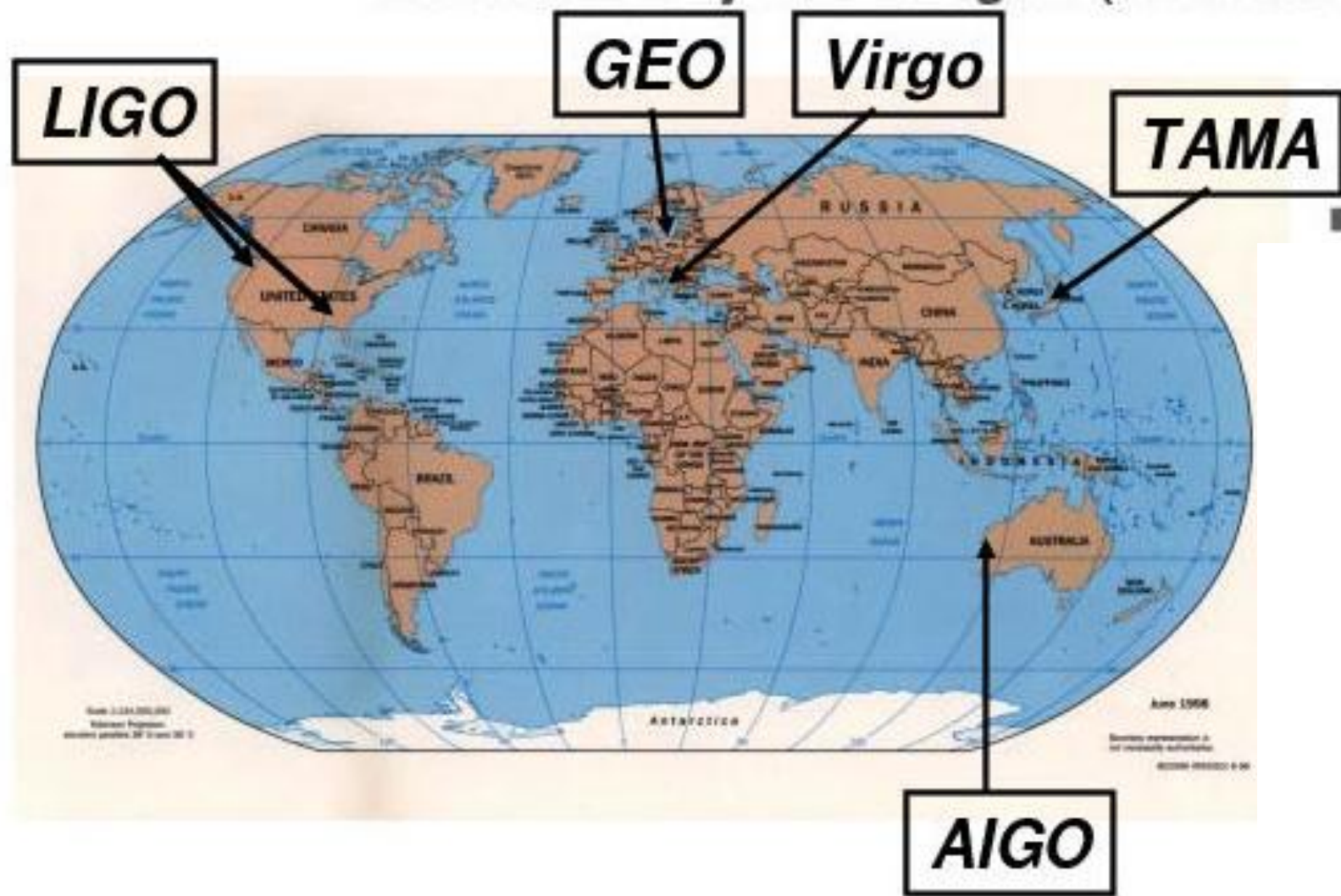




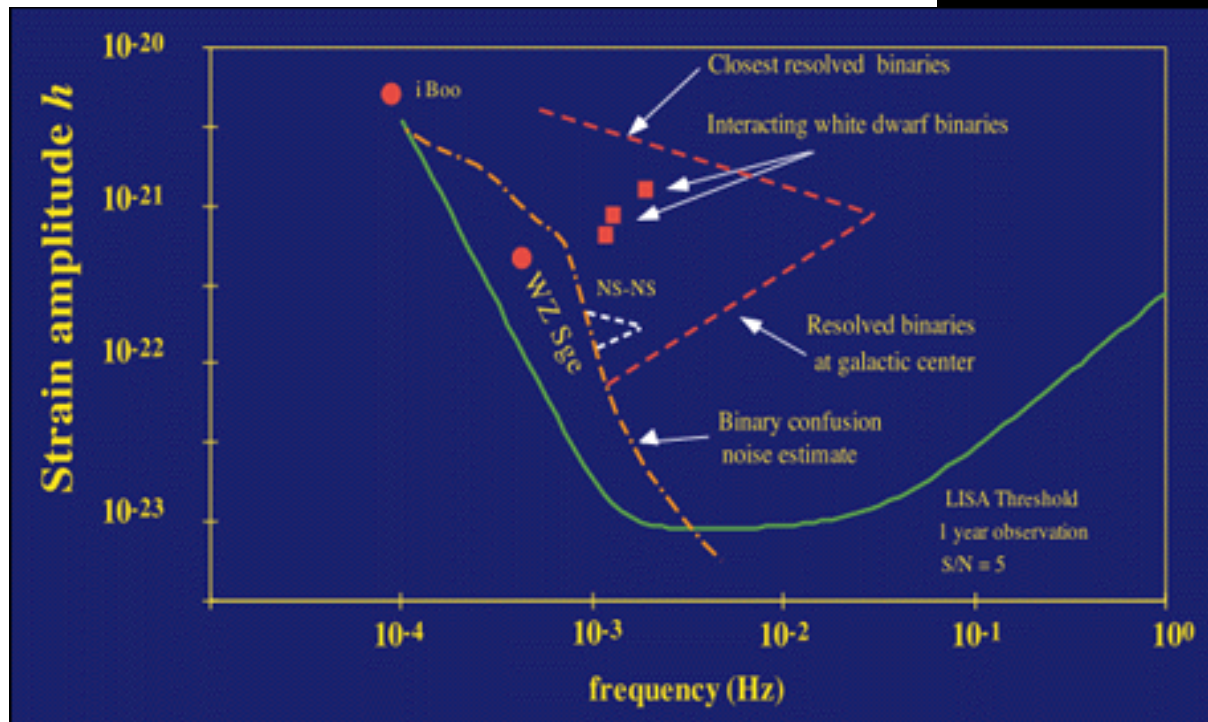
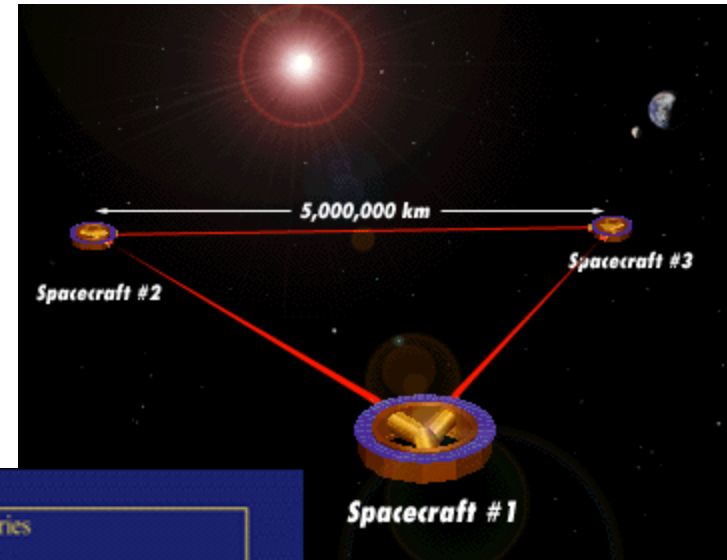
## LIGO SCHEDULE

- 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



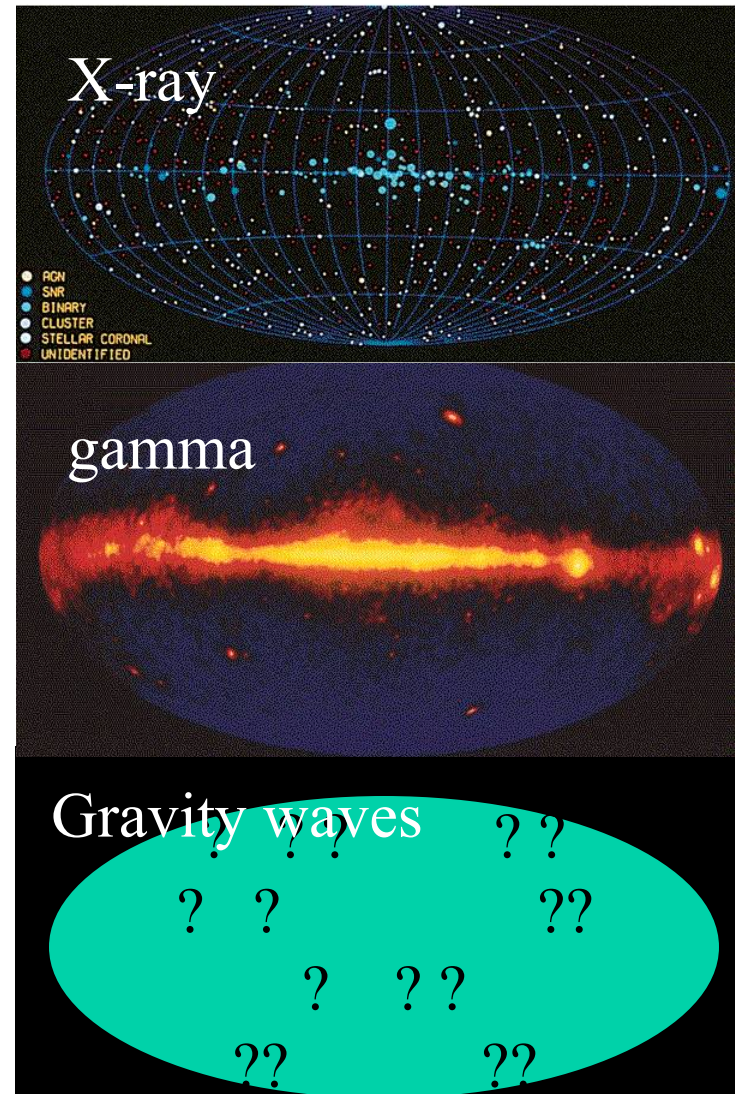
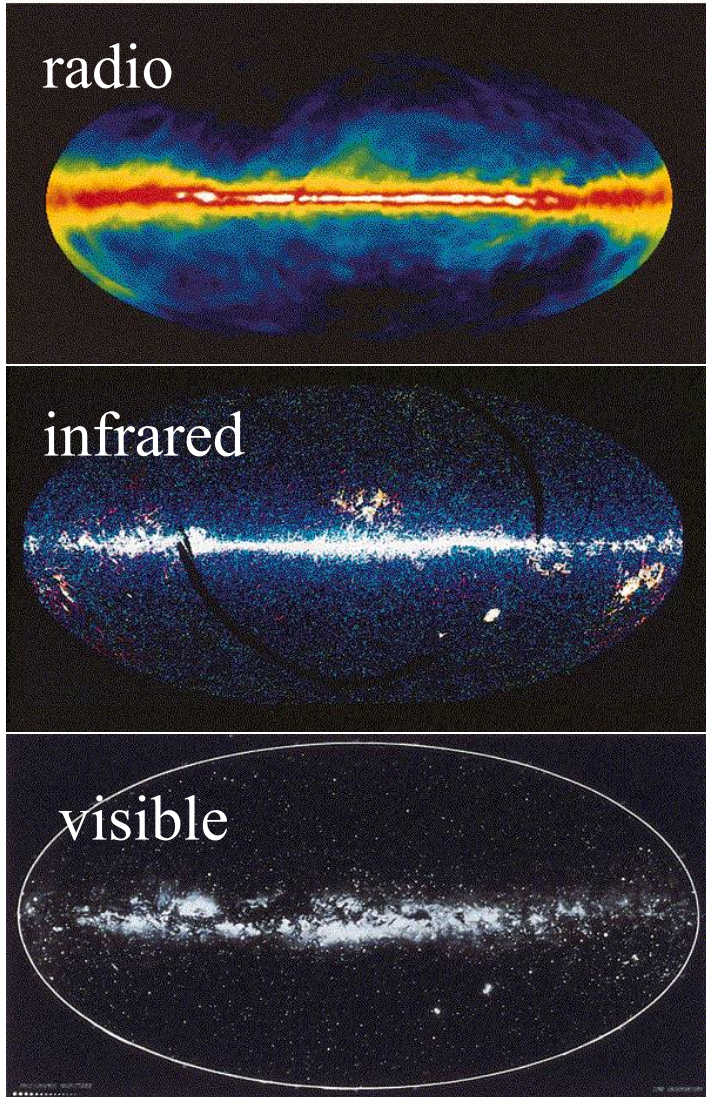
# Laser Interferometer Space Antenna (LISA) (the next generation)



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# Gravity waves open a new window

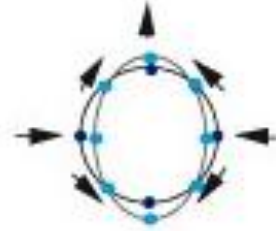


# General Relativity “predicts” the existence of gravitational radiation

- 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

+



x





# EM and Grav. radiation

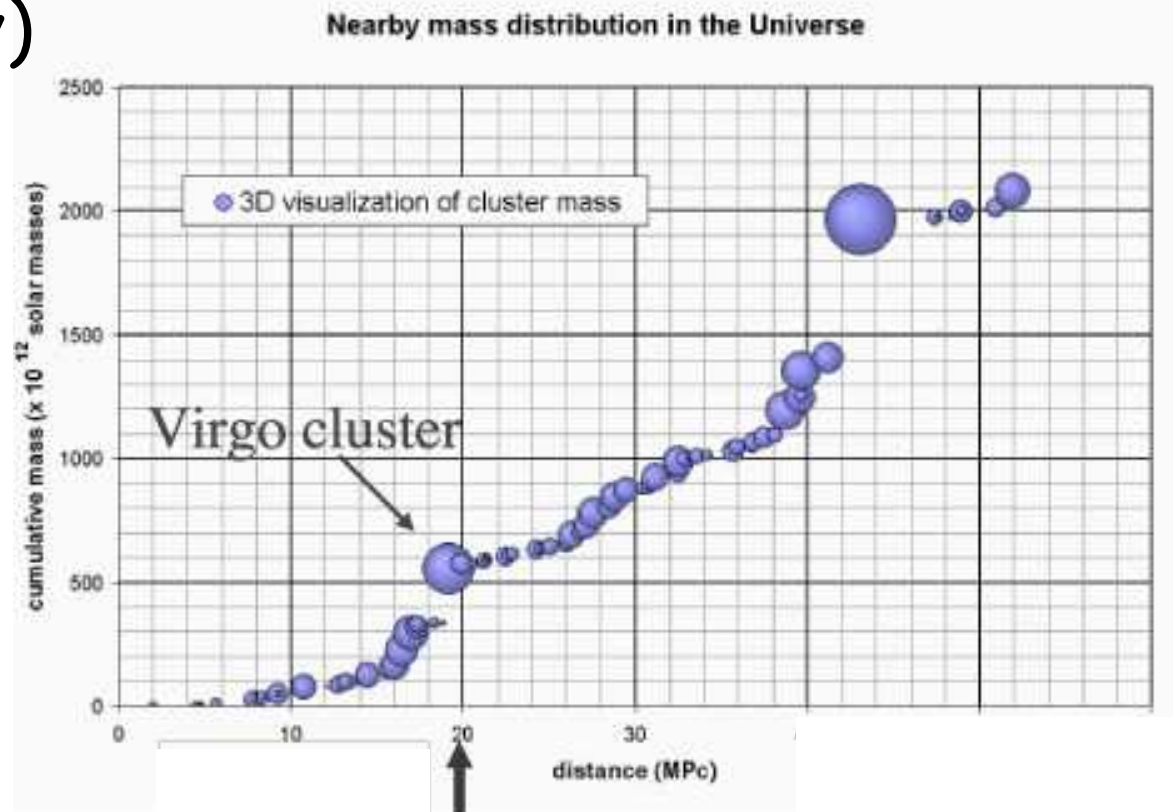
	<u>Electromagnetic</u>	<u>Gravitational</u>
•Source	• accelerating charge	• accelerating mass
•Nature	• oscillating field propagates thru space	• oscillating space-time
•Interactions	• absorbed, scattered by matter	• negligible interaction with matter
•Frequency	• $f > 10^7$ Hz	• $f < 10^4$ Hz
•Detector	• 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
  - ⇒ most sources are not seen as EM emitters
  - ⇒ 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

$$h_{\mu\nu} = \frac{2G}{c^3 r} \ddot{I}_{\mu\nu}$$

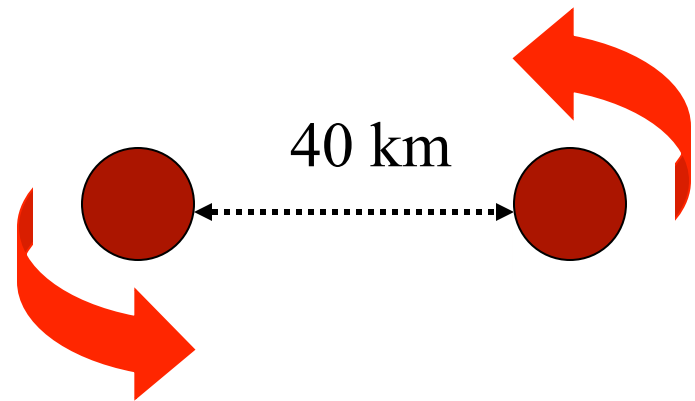
$$M = 3 \times 10^{30} \text{ kg}$$

$$R = 20 \text{ km}$$

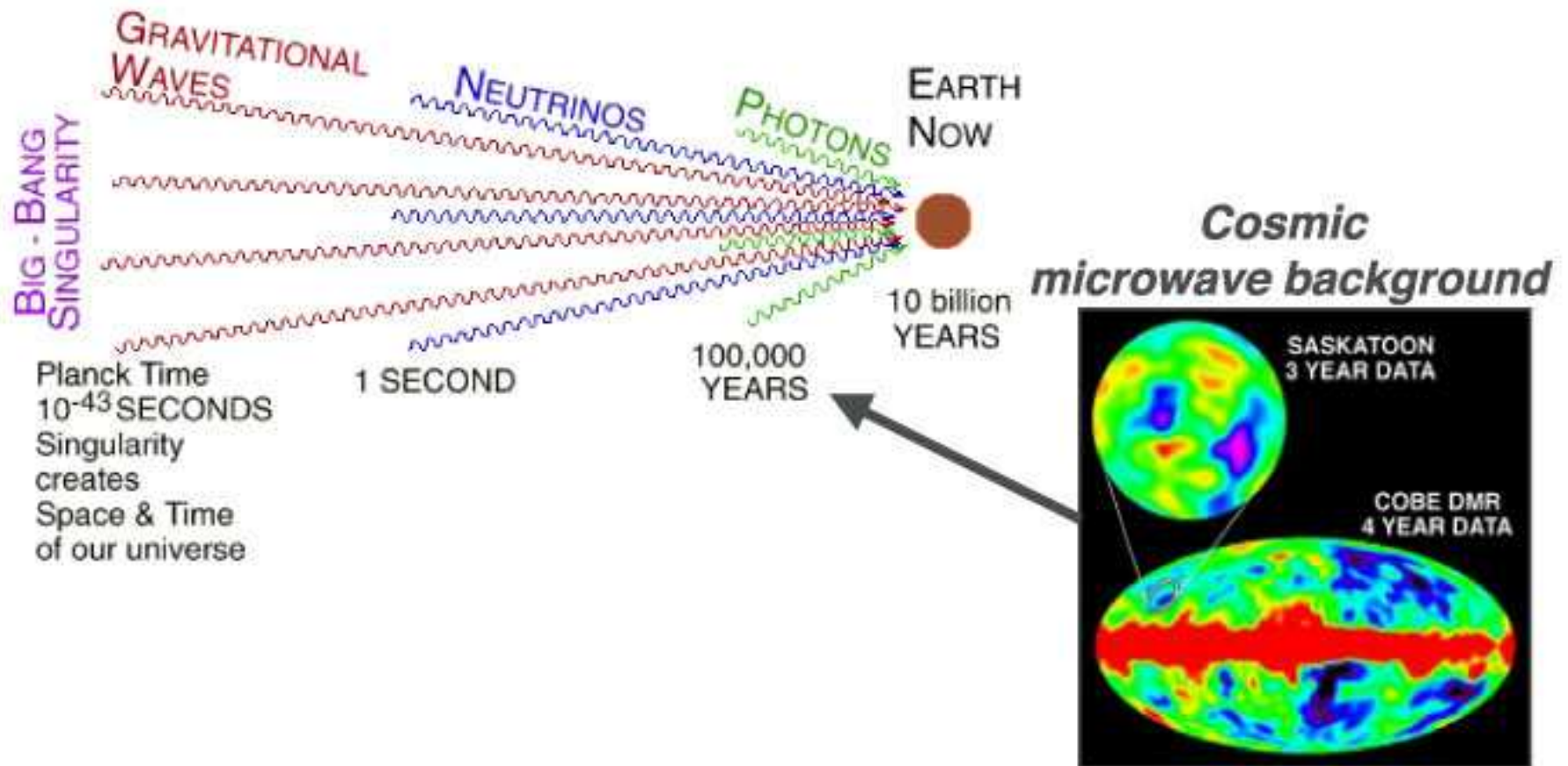
$$f = 400 \text{ Hz}$$

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

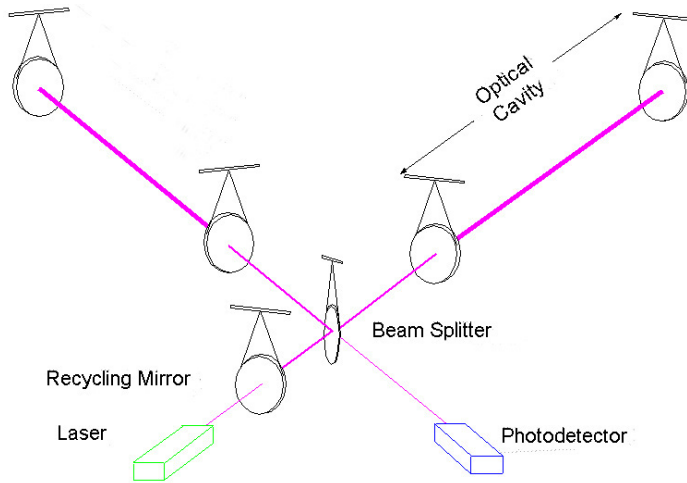
$$h \approx 6 \times 10^{-21} (10 \text{ Mly} / r)$$



# 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  $BL$ )

$\lambda =$  laser wavelength

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

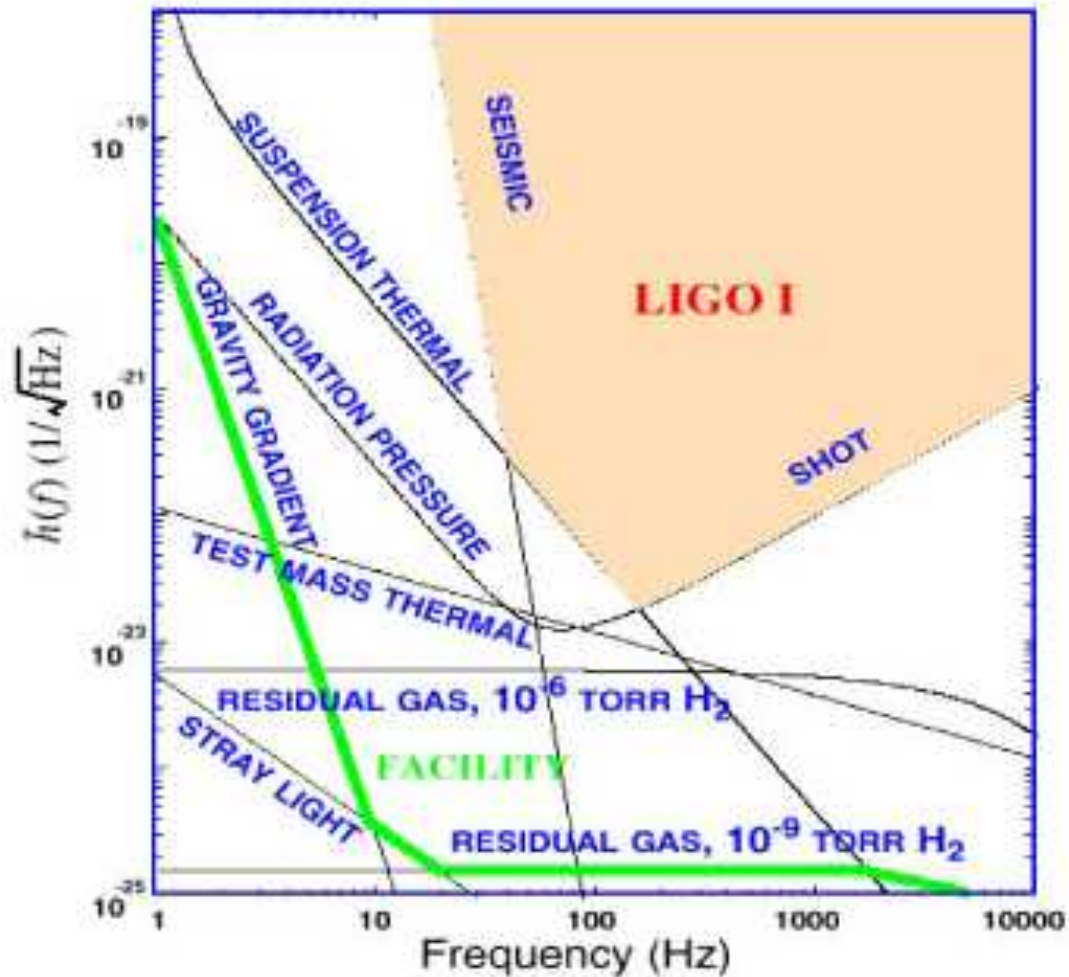
The relative phase change of light emerging from the two cavities is  $\Delta\phi = B \Delta L / \lambda = B h L / \lambda$

So we need to maximize  $B$  and  $L$ , and minimize  $\lambda$

eg.  $B = 200, L = 4 \text{ km}, \lambda = 1.06 \mu\text{m}$   
 $\Delta\phi = 7.6 \times 10^{11} h$



# Laser Interferometer (Noise)



# LIGO

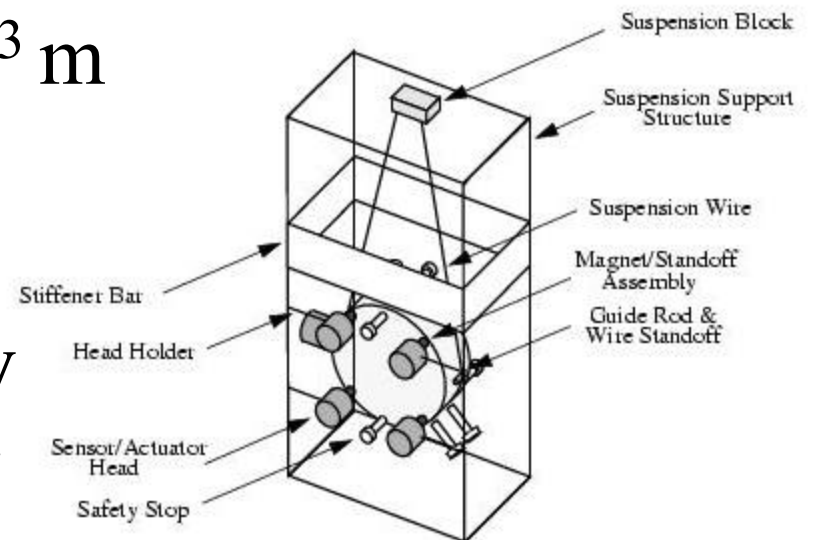
- km-scale Laser interferometers at two sites
- Built by collaboration of Caltech and MIT
- Science will be done by LIGO Science

**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

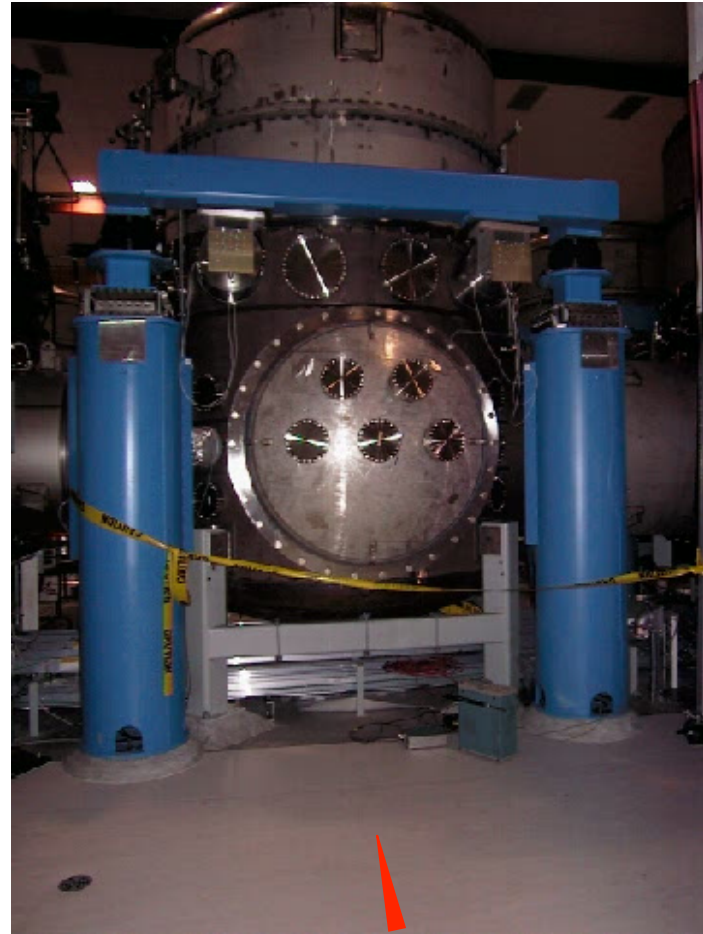
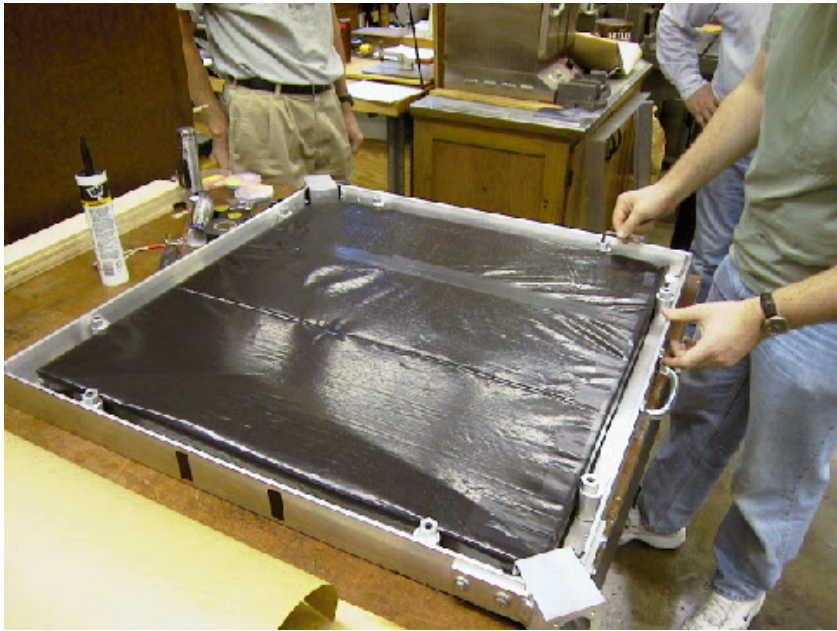
- 4 length and 12 alignment degrees of freedom must be controlled to maintain strain sensitivity
- Must hold lengths to  $10^{-13}$  m in presence of  $10^{-5}$  m seismic noise
- Test masses controlled by electromagnets driven by feedback



Eigenfreq. of suspension  
0.5 - 0.7 Hz

# Cosmic Ray Monitor

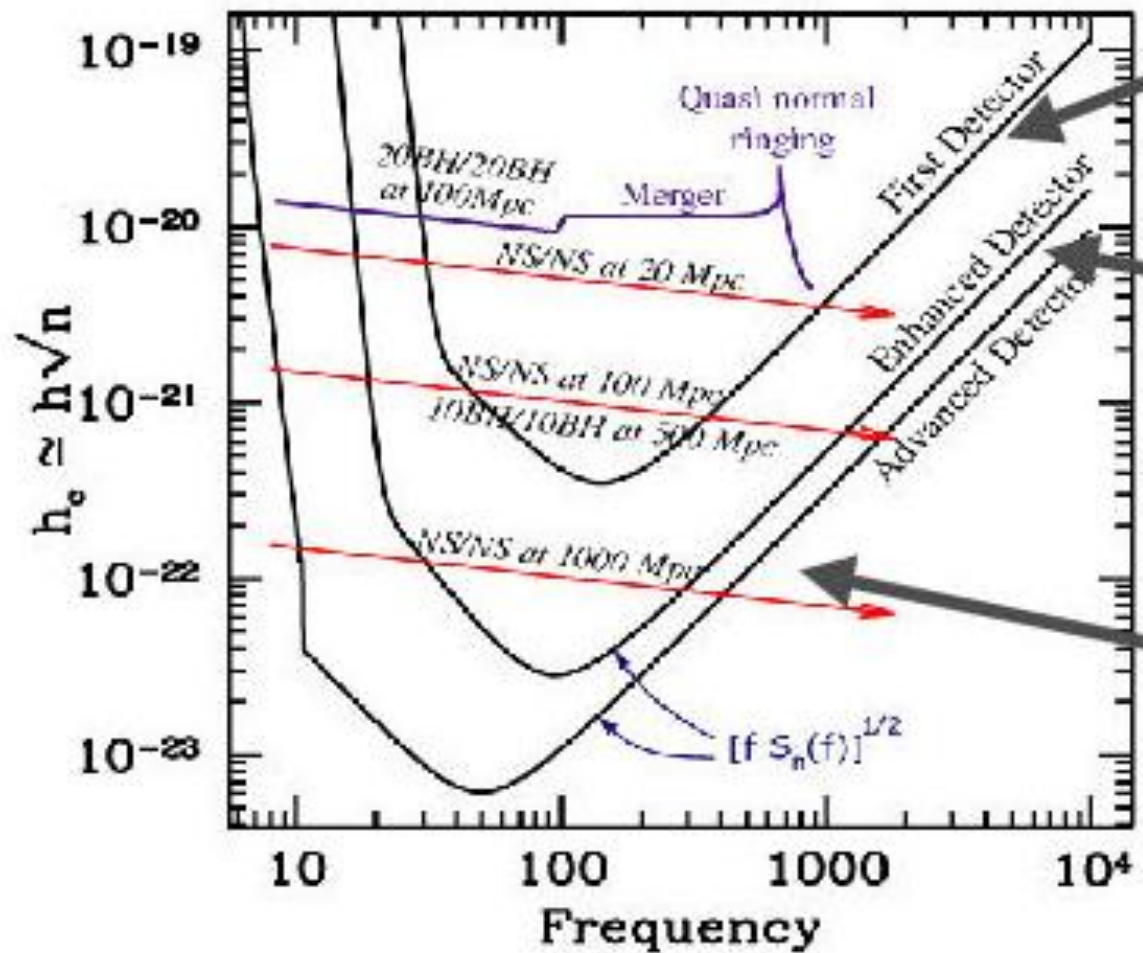
Look for coincidences to  
prevent false discovery



# Data Acquisition

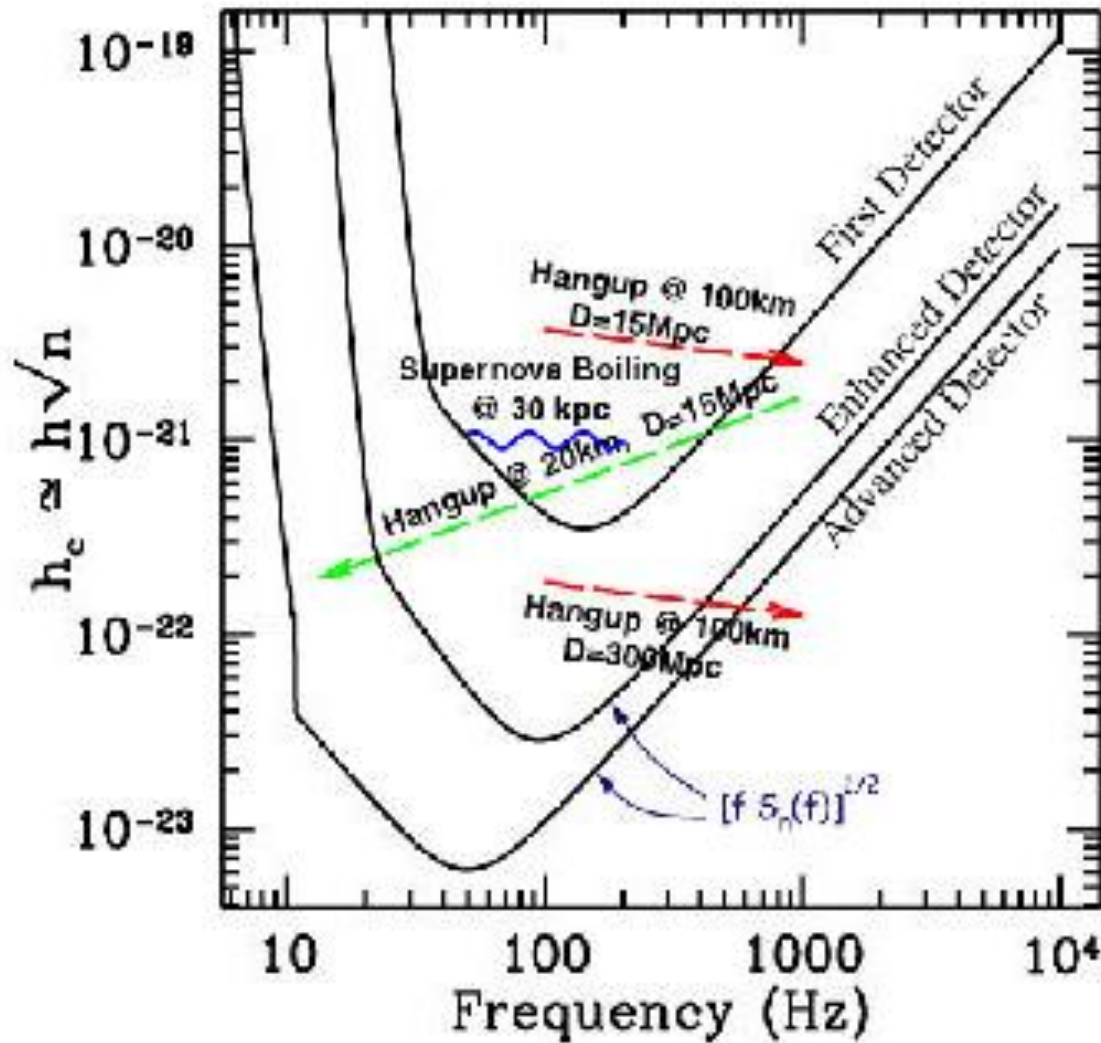
- Gravity wave channel is digitized at 16 kHz, but many other channels (about 2000 chan.)
  - ⇒ very large data rate
  - monitor and control
  - PEM channels
- 14 Mbyte / sec
- store full data stream on disk for ~1 day
- reduce data to mini-data sets for analysis
  - archive rest

# LIGO Sensitivity to Binaries



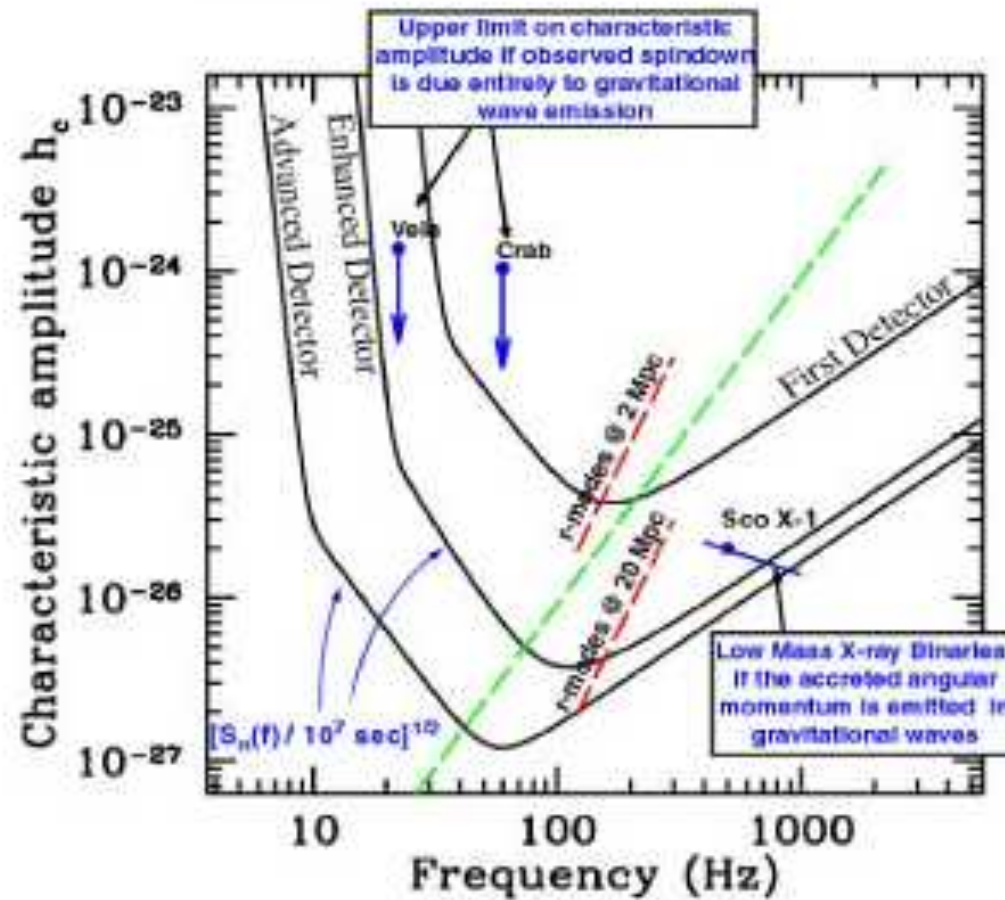


# LIGO Sensitivity to Bursts



# LIGO Sensitivity to Pulsars

Sensitivity of LIGO to continuous wave sources

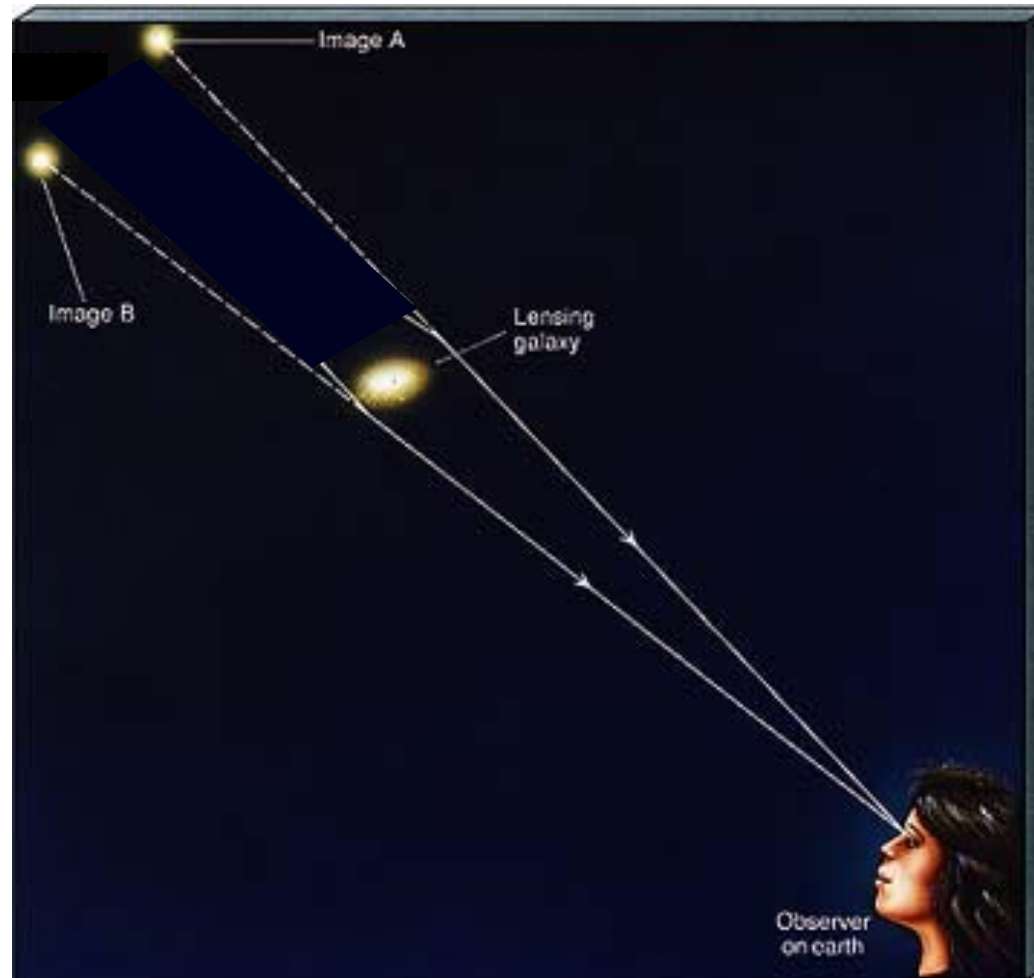


# CONCLUSIONS

- 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



River Road, J. Brau, November 13, 2001