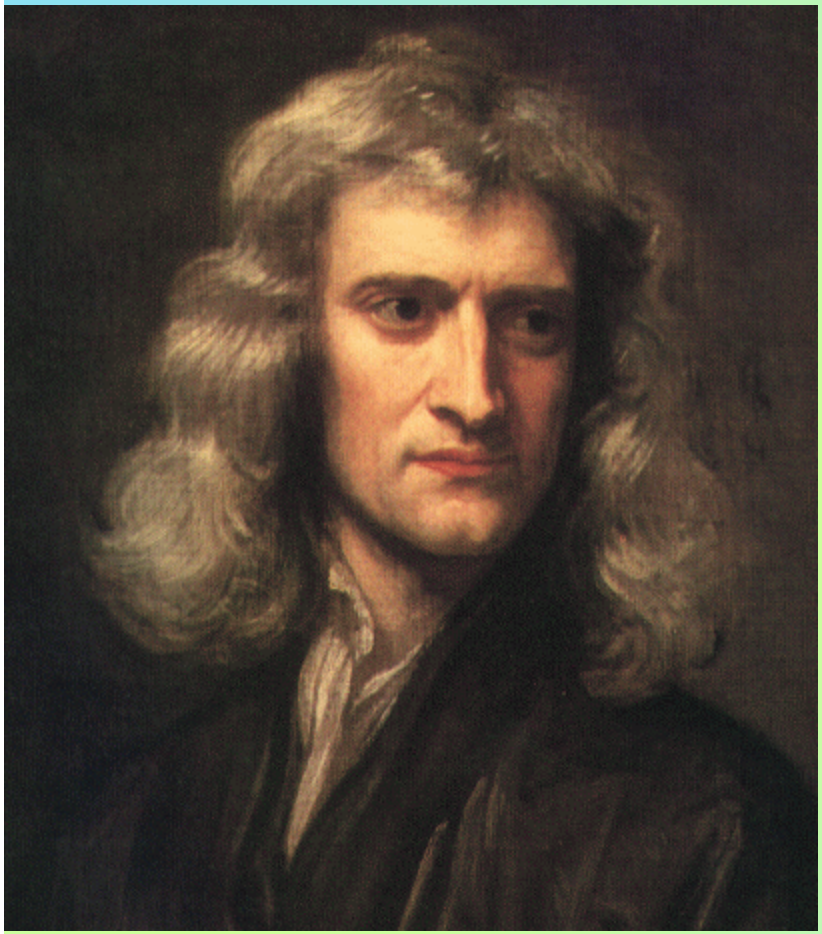
Listening to the Universe through Einstein's Waves

Stan Whitcomb
Hiro Yamamoto
Caltech

The Universe, unveiled by Gravitational Waves
30 May 2009

Newton's Theory of Gravity (1686)



PHILOSOPHIÆ
NATURALIS
PRINCIPIA
MATHEMATICA.

Autore *J. S. NEWTON, Trin. Coll. Cantab. Soc.* Matheſeos Profeſſore *Lucaſiano*, & Societatis Regalis Sodali.

IMPRIMATUR.
S. PEPYS, *Reg. Soc.* PRÆSES.
Julii 5. 1686.

LONDINI,
Juſſu *Societatis Regiæ* ac Typis *Joſephi Streater*. Proſtat apud plures Bibliopolas. *Anno* MDCLXXXVII.

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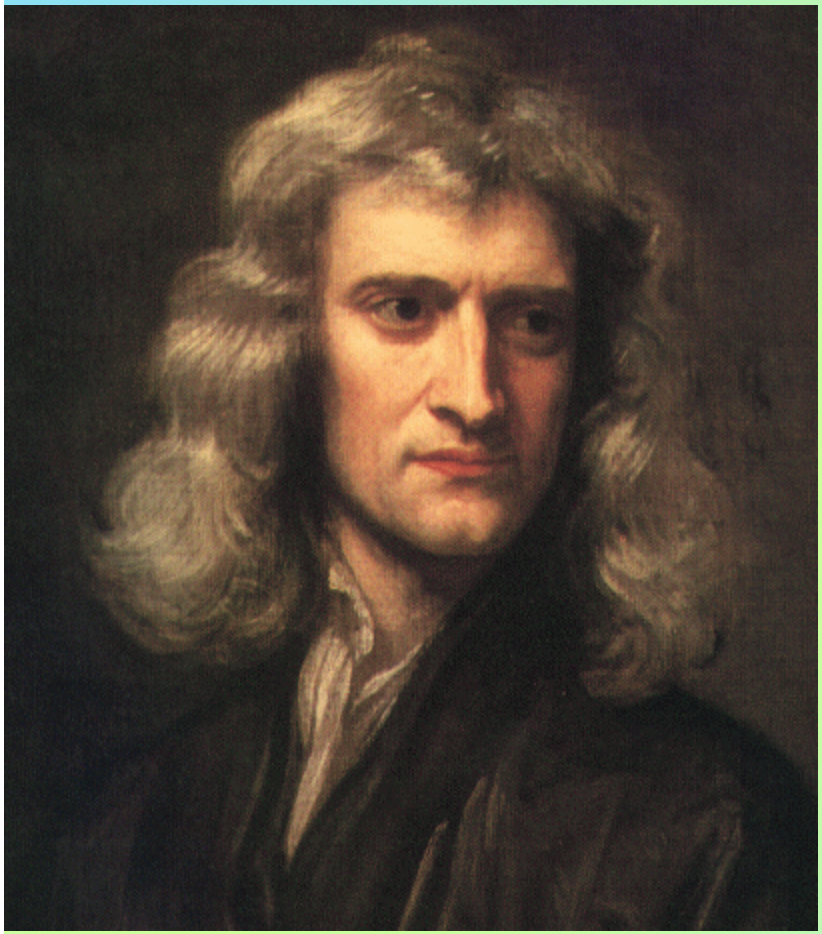
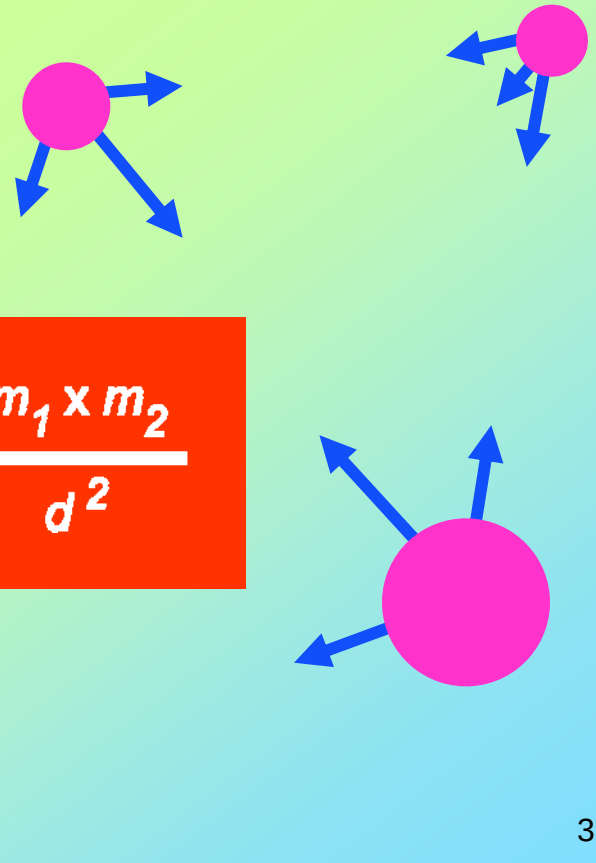
Newton's Theory of Gravity (1686)

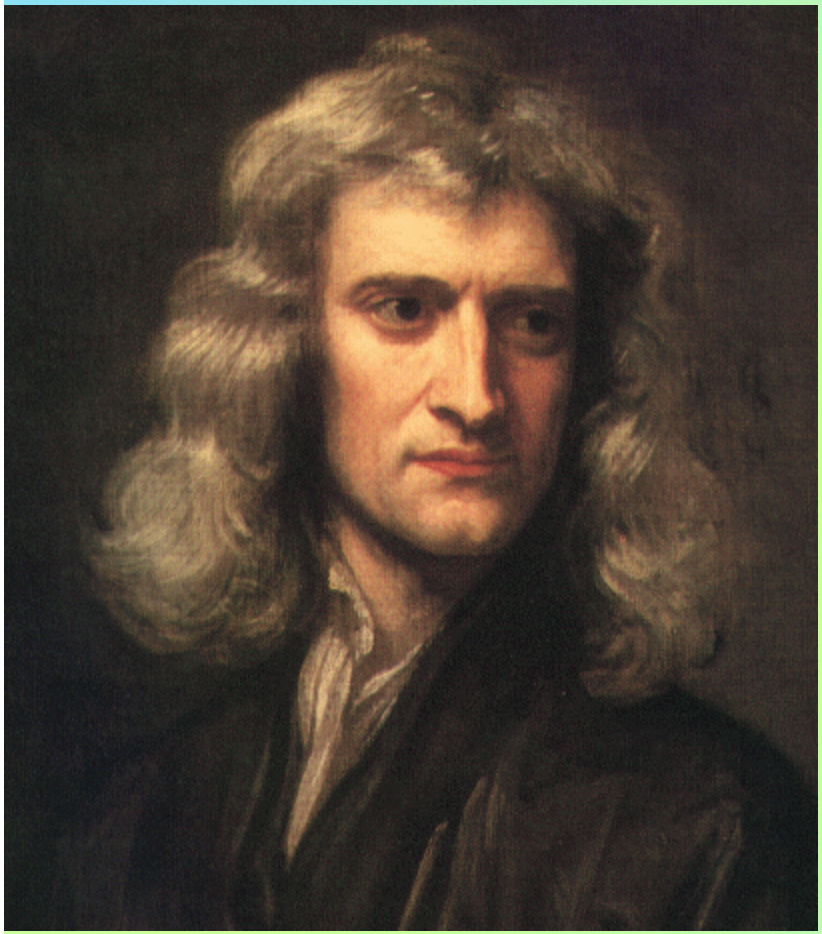


- Equal and opposite forces between pairs of bodies



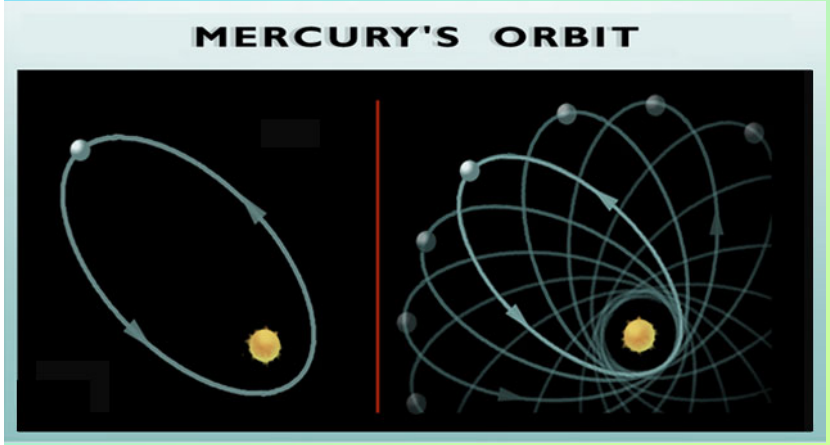
$$F = G \frac{m_1 \times m_2}{d^2}$$

Newton's Theory of Gravity (1686)



- Extremely successful theory
- Solved most known problems of astronomy and terrestrial physics
  - » eccentric orbits of comets
  - » tides and their variations
  - » the perturbation of the motion of the moon by gravity of the sun
- Unified the work of Galileo, Copernicus and Kepler

However, One Unexplained Fact and Two Mysteries



Astronomers observed perihelion of Mercury advances by 43”/century compared to Newton’s theory

What causes the mysterious force in Newton’s theory ?

How can a body know the instantaneous positions of all the other bodies in the Universe?

General Relativity
A Radical Idea

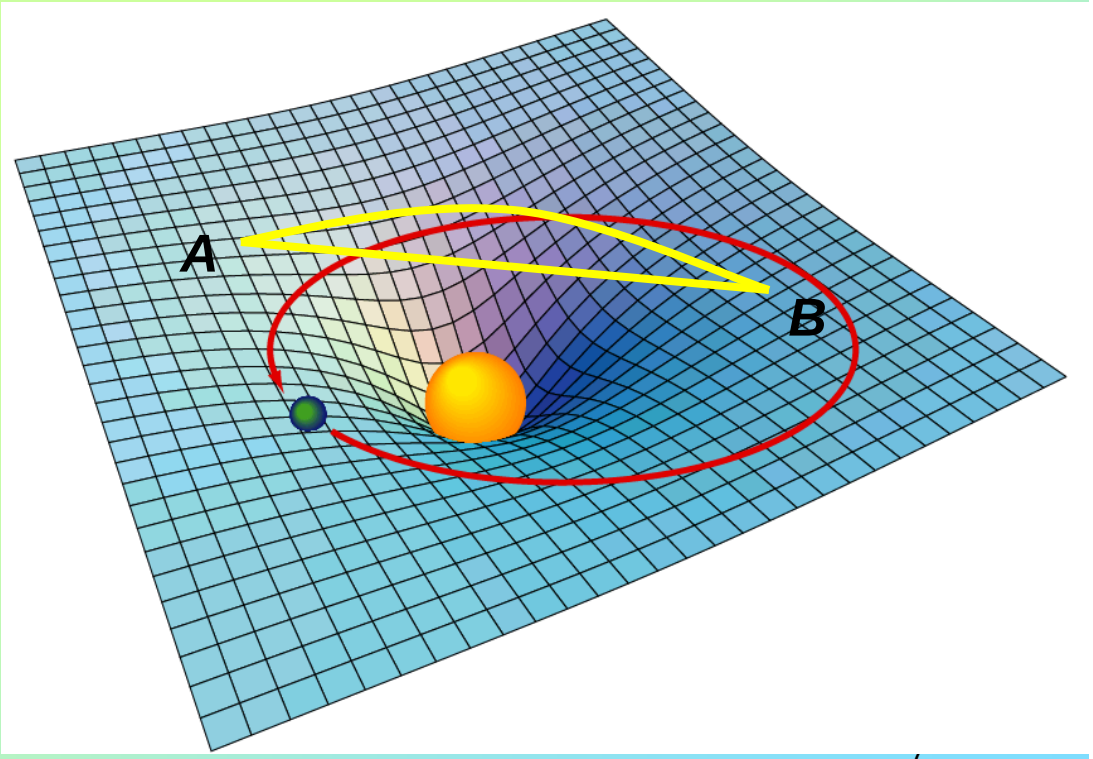
- **Overthrew the 19th-century concepts of absolute space and time**
- **Spacetime = 3 spatial dimensions + time**
- **Perception of space and time is relative**

AIP Emilio Segrè Visual Archives

General Relativity

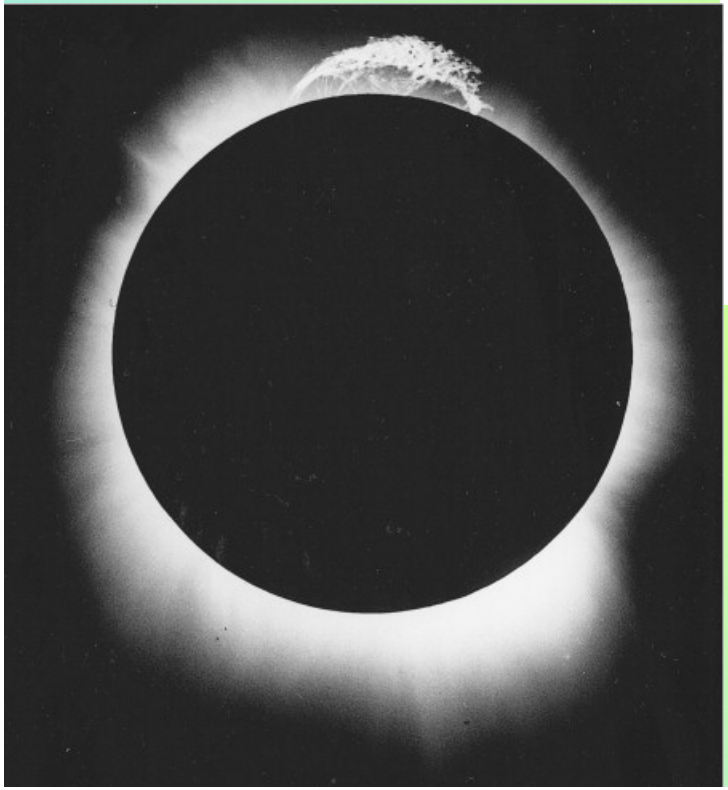
A Radical Idea

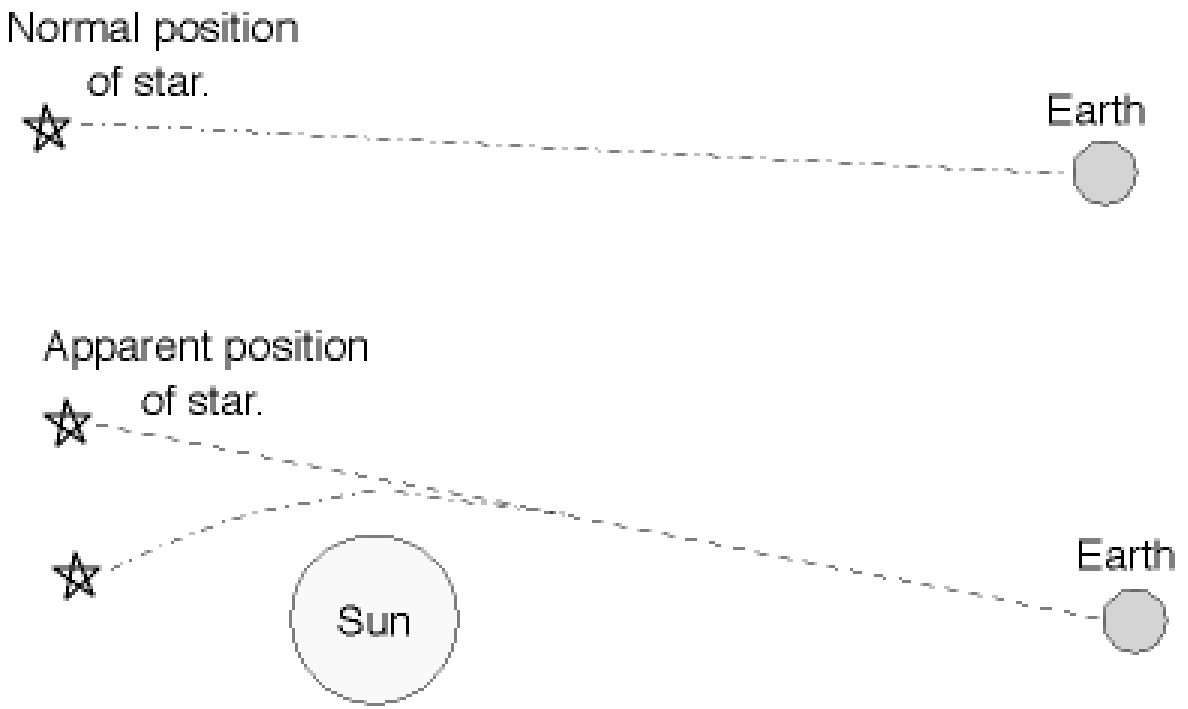
- Gravity is not a force, but a property of space & time
- Concentrations of mass or energy distort (warp) spacetime
- Objects follow shortest path through this warped spacetime
- Explained the precession of Mercury



A New Prediction of Einstein's Theory

The path of light will be "bent" when it passes near a massive object (like the sun)



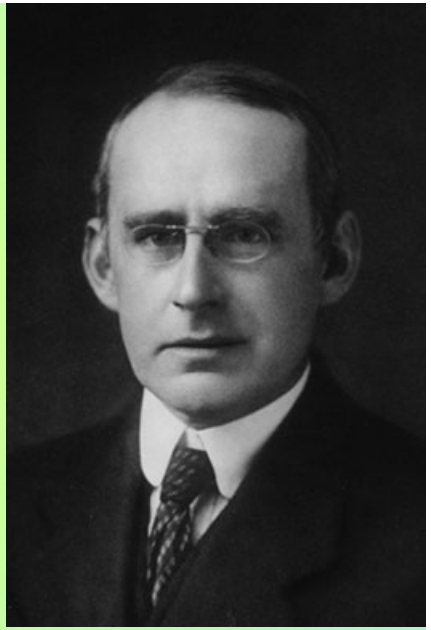


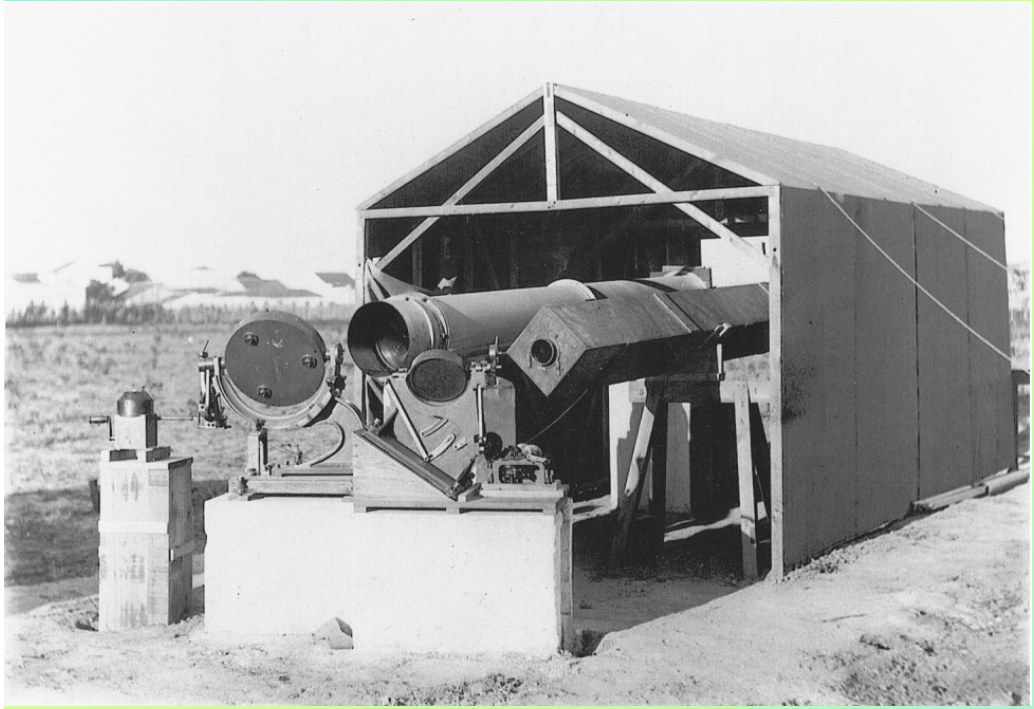
Inversely proportional to angle between sun and star

Could only be seen during eclipse

Confirming Einstein ….

- Famous British astronomer Sir Arthur Eddington led an expedition to photograph the solar eclipse of 29 May 1919 against Hyades star cluster





© Science Museum/Science and Society Picture Library

	Measured Deflection
No Deflection	0
“Newtonian”	0.87”
Einstein	1.75”
Principe	1.61” ± 0.30”
Sobral	1.98” ± 0.12”

Stunning Confirmation for Relativity

REVOLUTION IN SCIENCE.

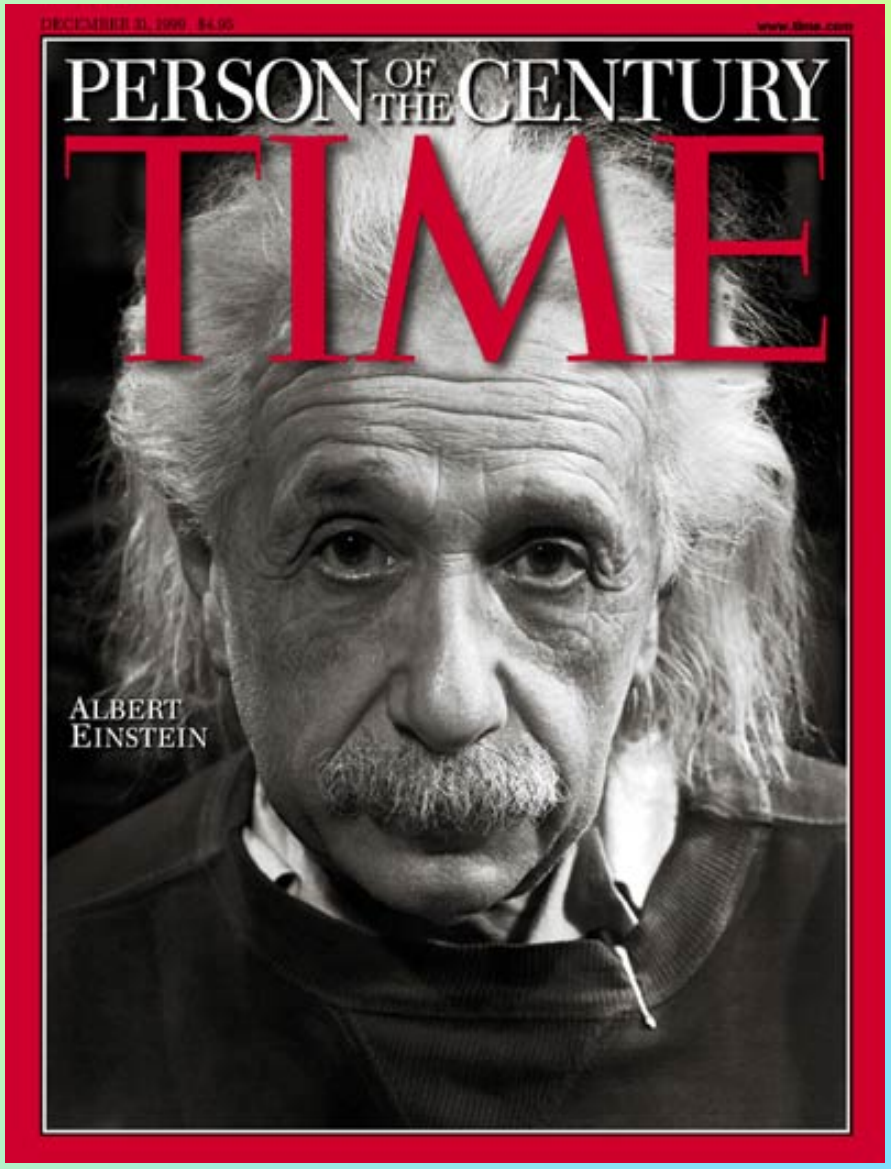
NEW THEORY OF THE UNIVERSE.

NEWTONIAN IDEAS OVERTHROWN.

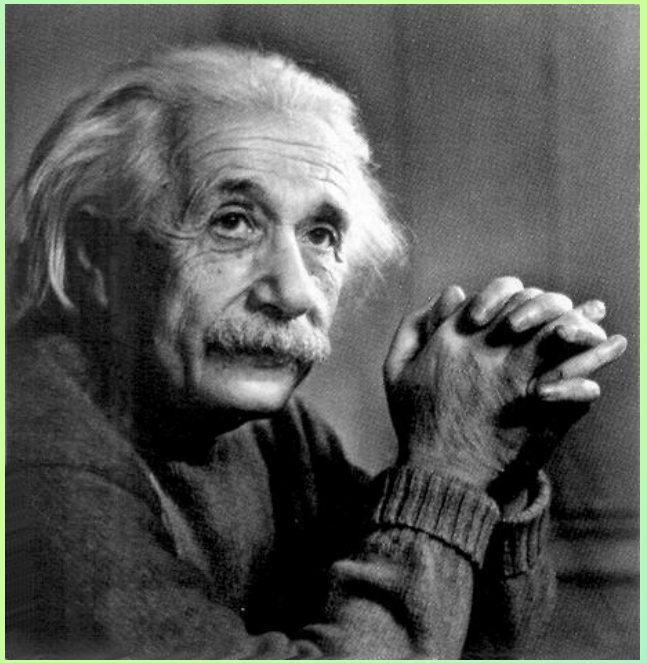
Yesterday afternoon in the rooms of the Royal Society, at a joint session of the Royal and Astronomical Societies, the results obtained by British observers of the total solar eclipse of May 29 were discussed.

The greatest possible interest had been aroused in scientific circles by the hope that rival theories of a fundamental physical problem would be put to the test, and there was a very large attendance of astronomers and physicists. It was generally accepted that the observations were decisive in the verifying of the prediction of the famous physicist, Einstein, stated by the President of the Royal Society as being the most remarkable scientific event since the discovery of the predicted existence of the planet Neptune. But there was differ-

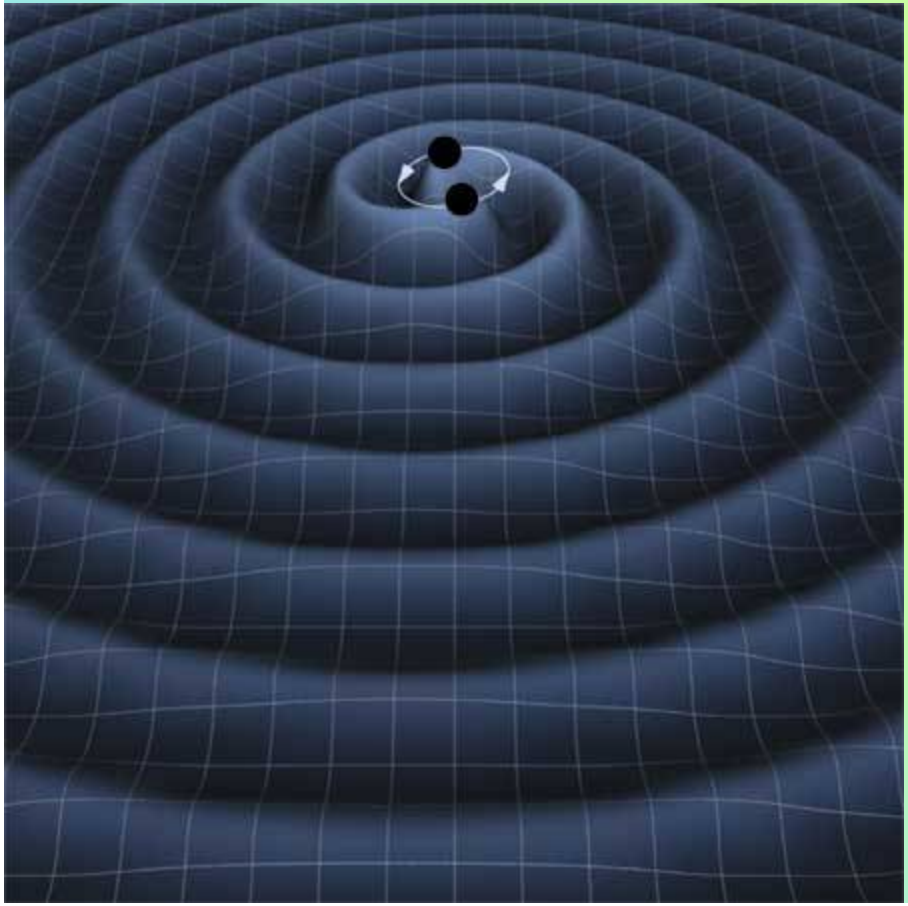
London Times, 6 November 1919



A New Prediction: Gravitational Waves



Photograph by Yousuf Karsh of Ottawa, courtesy AIP Emilio Segre Visual Archives

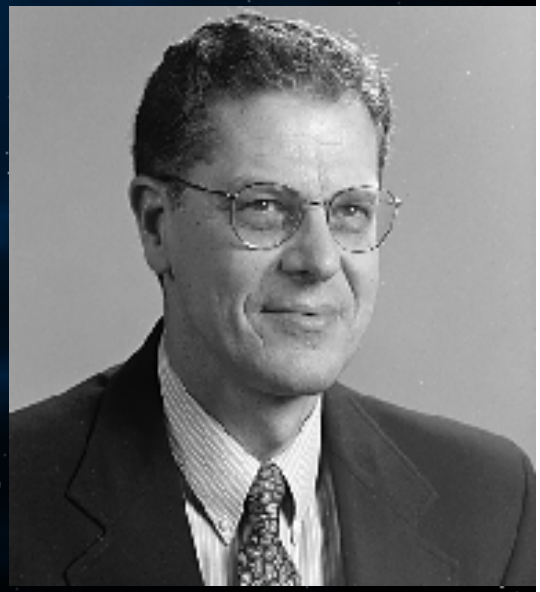


Ripples in spacetime moving at the speed of light

No Evidence For Gravitational Waves Until 1974

Russell A. Hulse

Discovered and Studied
Pulsar System
PSR 1913 + 16

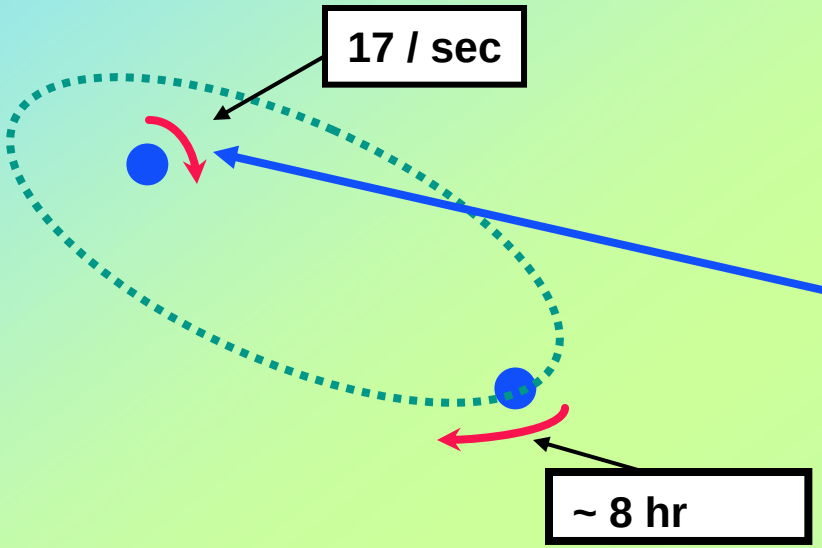


Joseph H.Taylor Jr

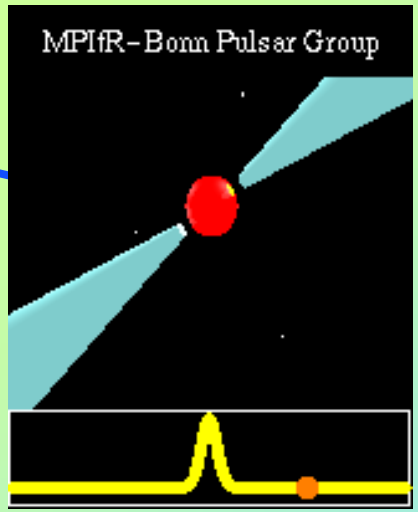
Source: www.NSF.gov

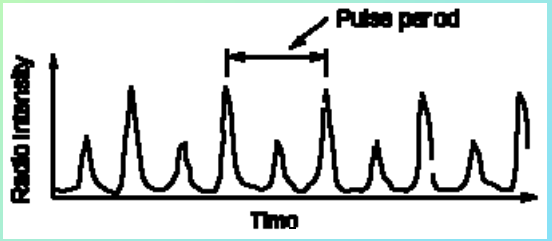
Neutron Binary System

PSR 1913 + 16



Similar mass to our sun but only 20 km in diameter





Two Neutron Stars in Orbit

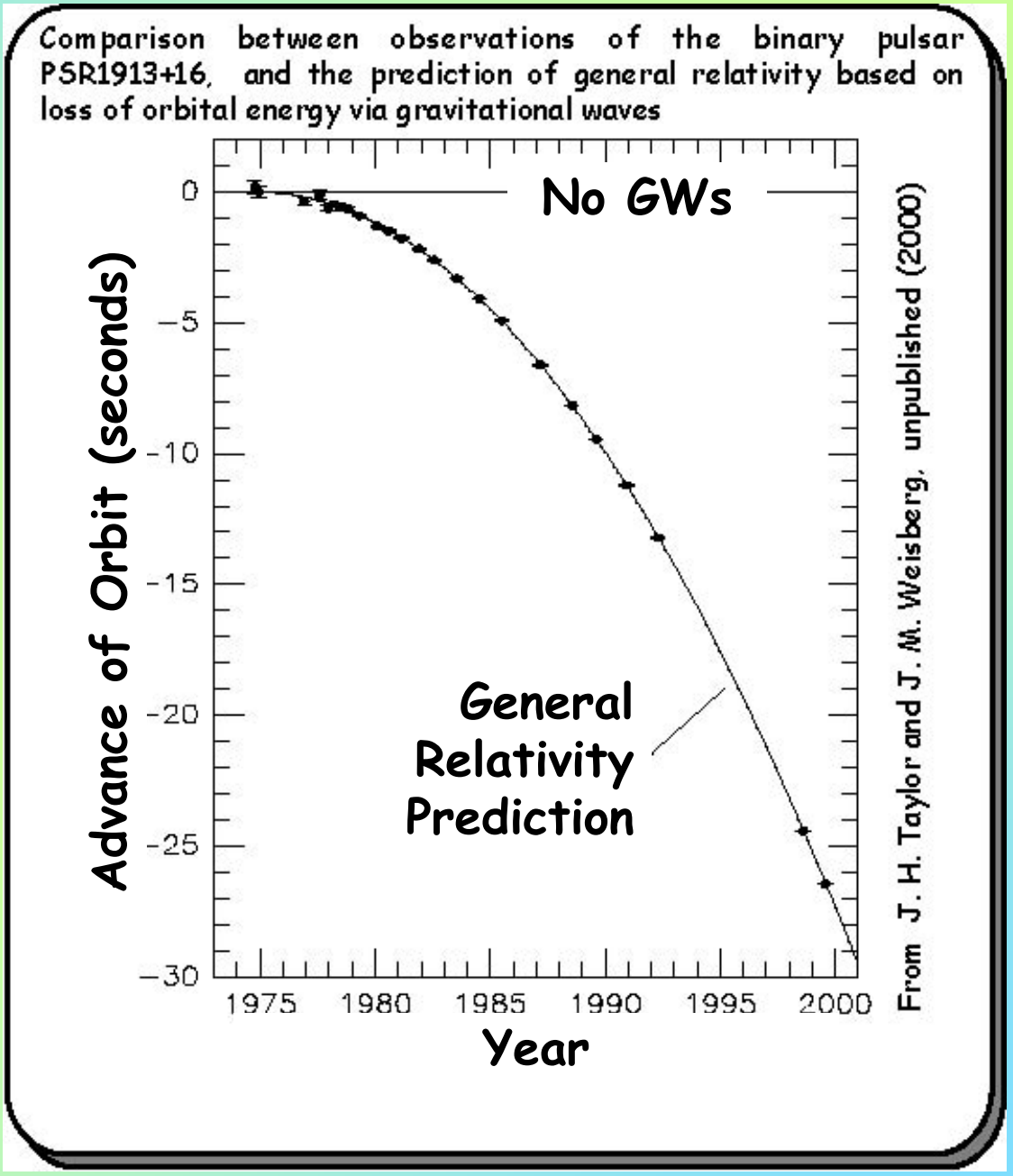
- **Separated by 1,000,000 km**

Prediction from General Relativity

- **Spiral in by 3 mm/orbit**
- **Rate of change orbital period**

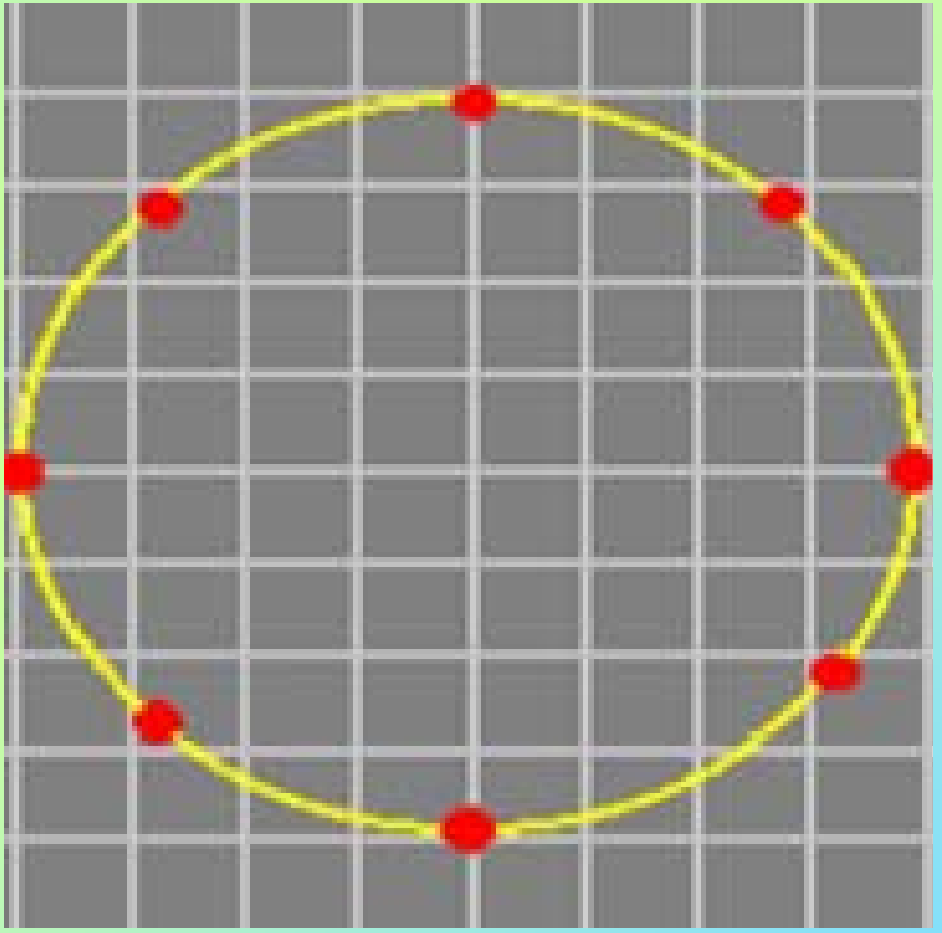
Evidence for gravitational waves!

Nobel Prize



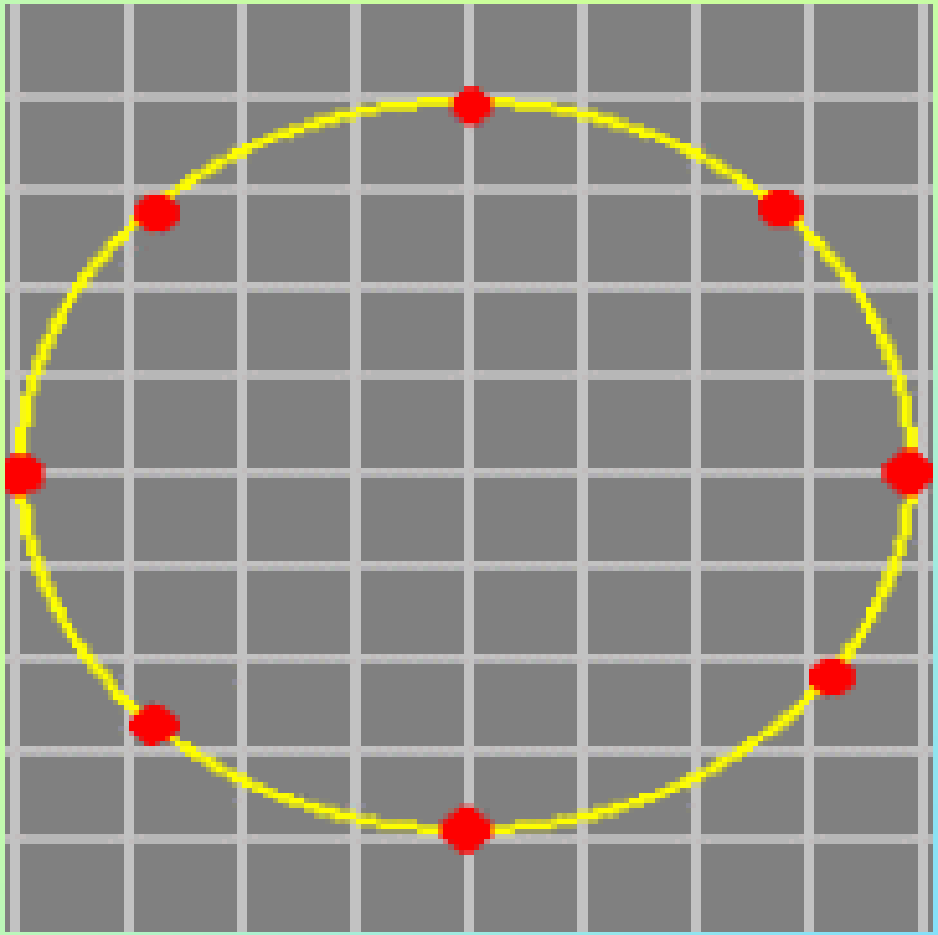
Effect of a Passing Gravitational Wave

- Imagine a circle of masses in space
- Free from all disturbances, except a gravitational wave



Effect of a Passing Gravitational Wave

- Gravitational wave traveling into the picture
- Change in separation (ΔL) proportional to initial separation (L)



Sources of Gravitational Waves

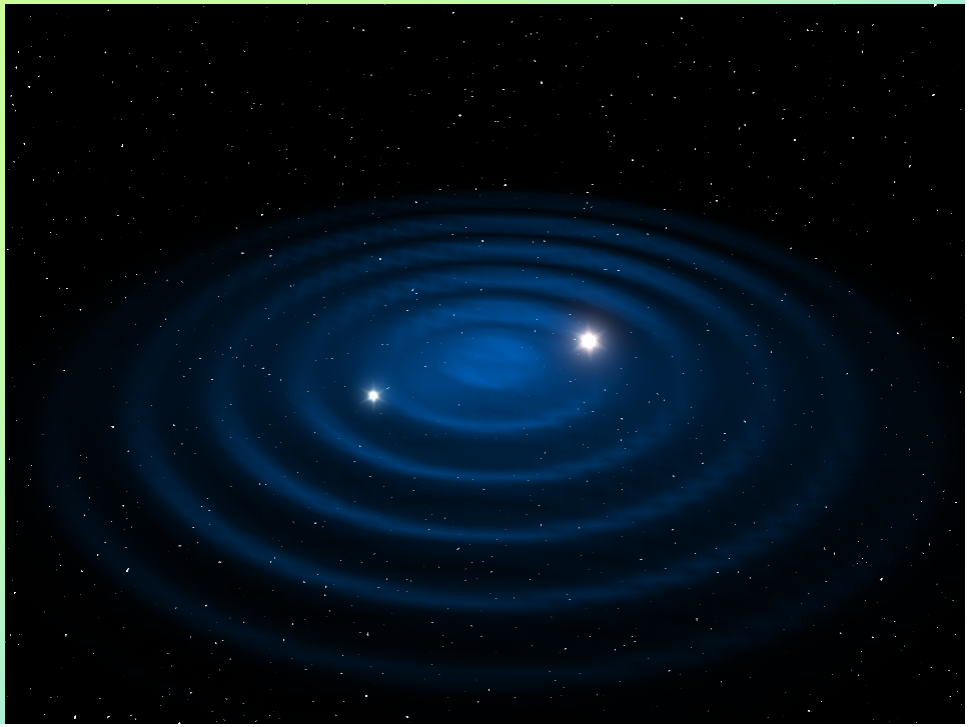
Requirements for Strong Gravitational Wave Sources

- (Almost) all moving masses produce gravitational waves
- But!
- Strong waves require:
  - Large Masses
  - Fast motions (large accelerations)

→ All measurable gravitational wave sources will be astronomical

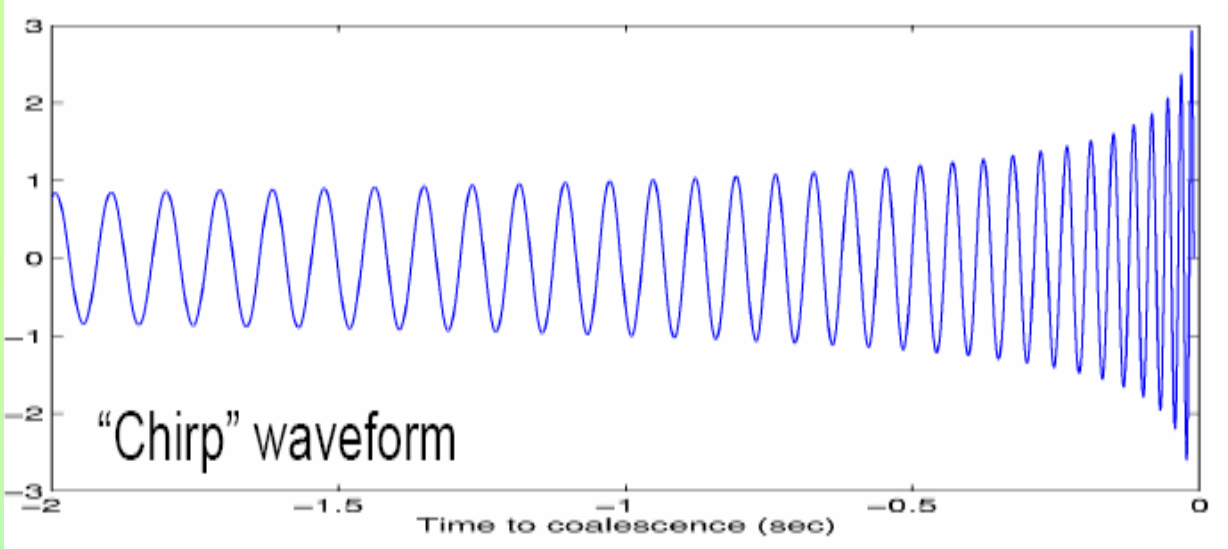
Binary Neutron Stars

- Systems like the Hulse-Taylor Binary Pulsar
- Losing energy as they radiate gravitational waves
- Spiralling together
  - » Slowly at first
  - » Faster and faster as the two neutron stars move toward each other
  - » Finally, crash together and merge



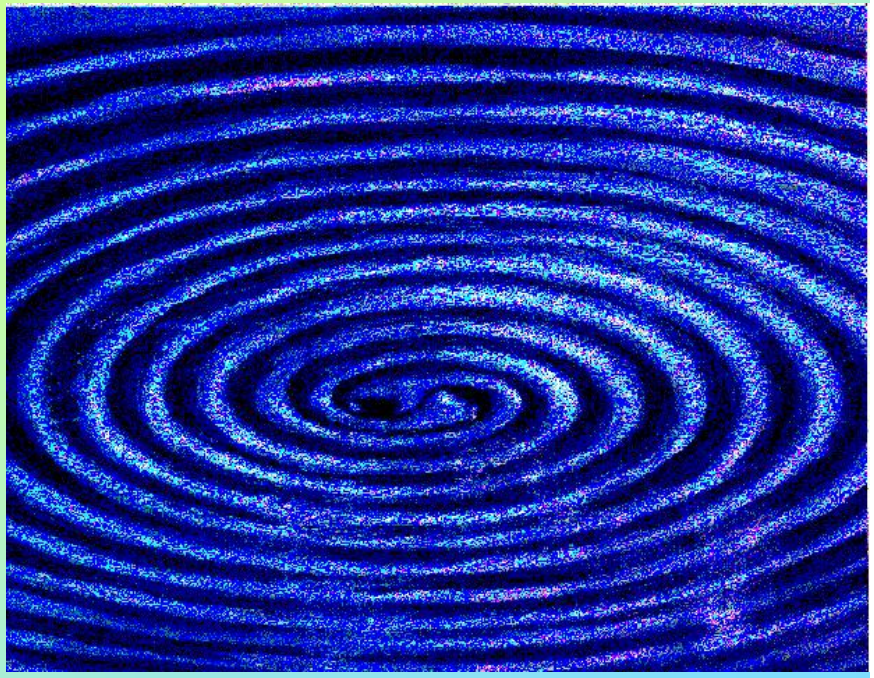
Binary Neutron Stars

- **Gravitational waves tell us the story of the inspiral**
  - » **Slow frequencies at first, then increasing**
  - » **Slowly growing amplitude**
- **Masses of each star, orbit, location, distance**
- **Final stages last about 1 minute**



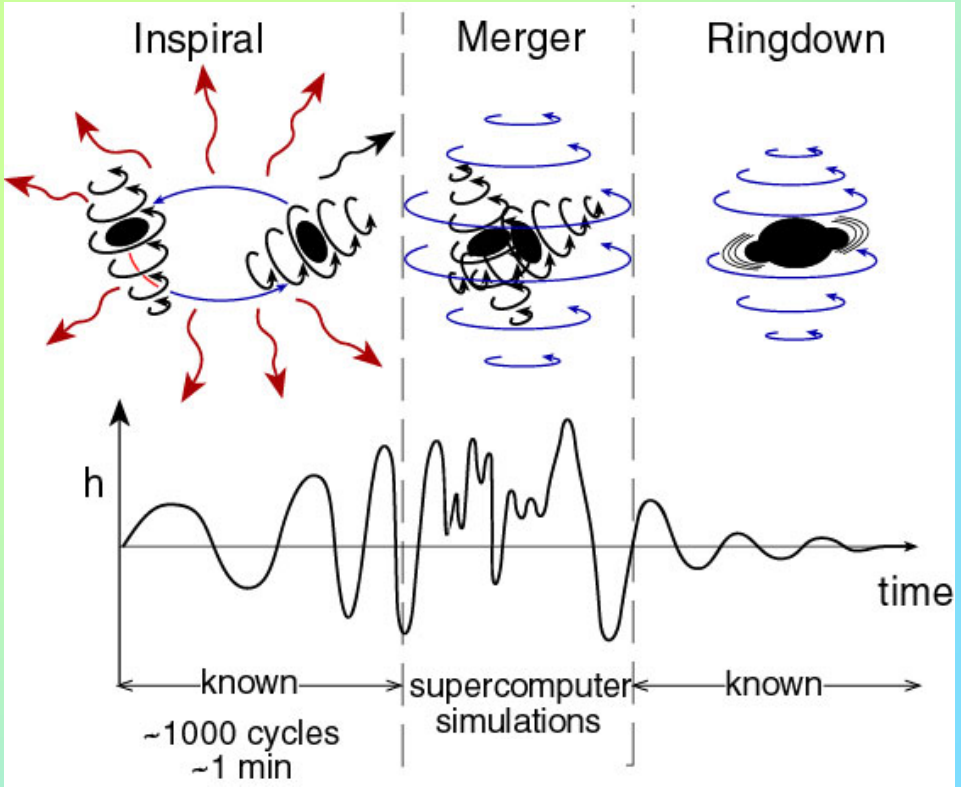
Black Holes

- Maybe there are binary systems with two black holes instead of neutron stars
  - » Formed from very massive binary stars?
  - » No clear evidence of such systems
- Would be very strong sources of gravitational waves
- No direct way to observe black holes except through gravitational waves



Black Hole Collisions

- **Black holes are one of the simplest objects in the universe yet one of the most mysterious**
  - » **Completely described by three numbers**
    - **Mass**
    - **Spin**
    - **Charge**
- **Gravitational waves probe to the very edge of the black hole**



Supernova: One of the Most Energetic Events in our Universe

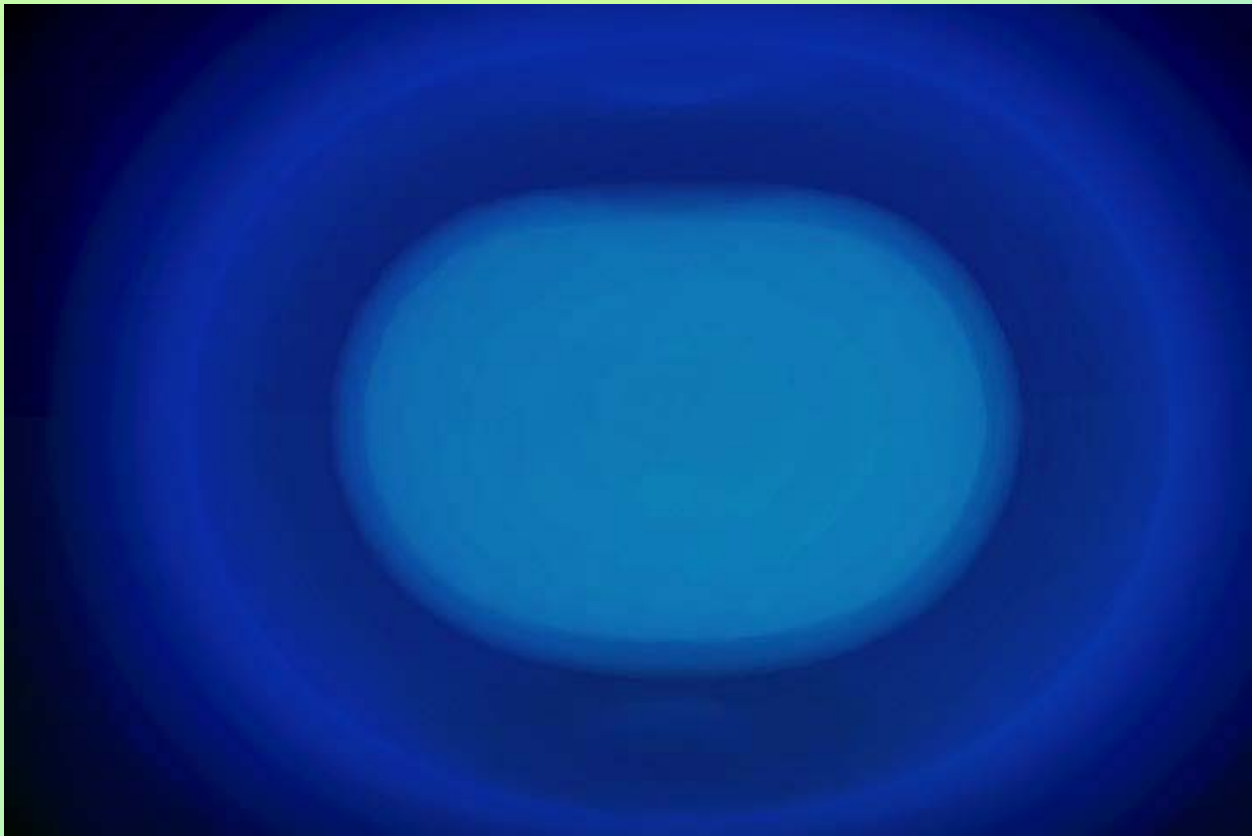
100,000,000,000 stars

One supernova

- **Massive star (>~7 times the mass of our sun) 'burns' all its hydrogen**
- **Grows to become a Red Giant as its 'burns' its remaining fuel**
- **Core collapses to form neutron star**
- **Collapsing material bounces and blows off outer regions of star**
- **As bright as an entire galaxy for a few days**

Gravitational Waves from a Supernova?

- **Visible supernova is spectacular, but it tells us little about what is causing the explosion**
- **Rapid motion**
  - » **Core collapses is very rapid (much less than 1 second)**
- **Massive star**
- **Meets all the criteria for strong gravitational waves**

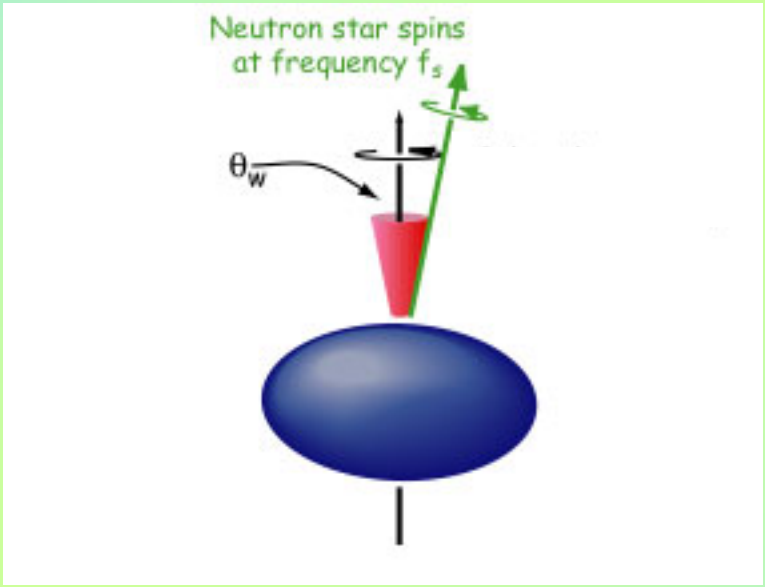


Simulation: Ott 2006, Ott et al. 2007

Visualization: R. Kaehler, Zuse Institute/AEI

Spinning Neutron Stars (Pulsars)

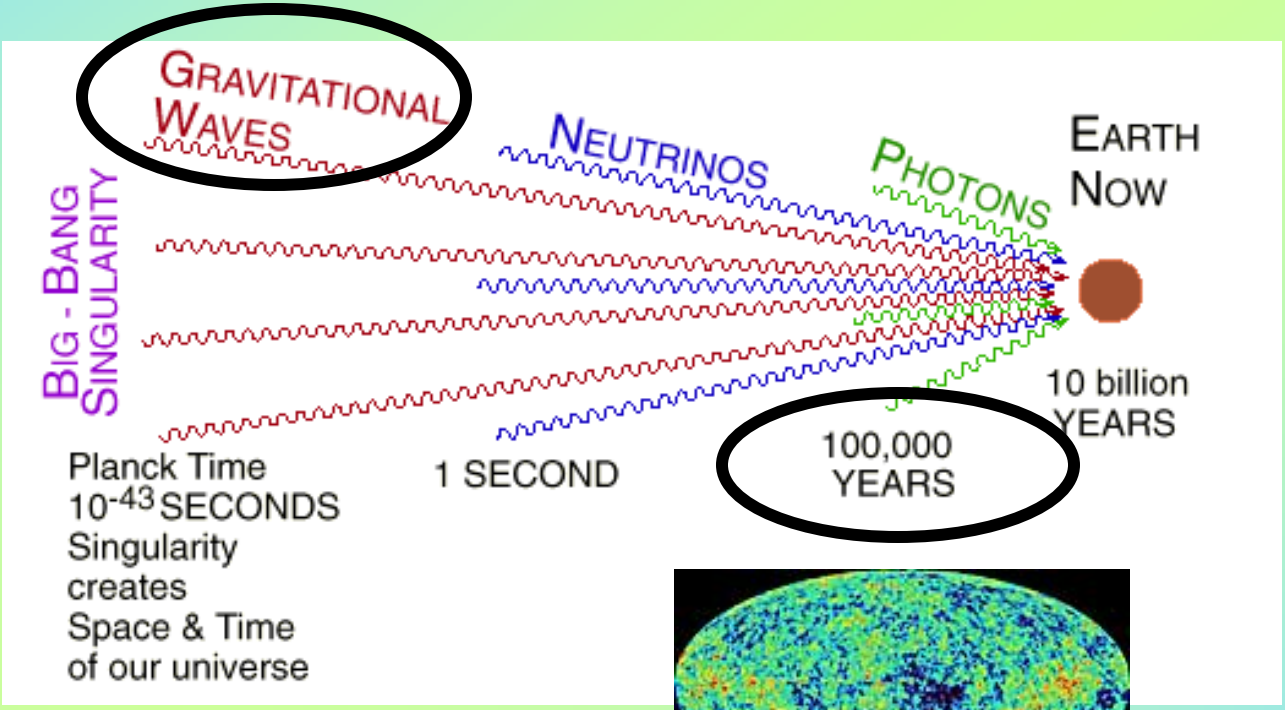
- Neutron stars are the remnants of many supernovas
- Typically 1.4 times as massive as the sun, but only 20 km in diameter
- Rapidly rotating with huge magnetic field (1 billion times stronger than any field on earth)
- Produce very regular pulses of radio energy

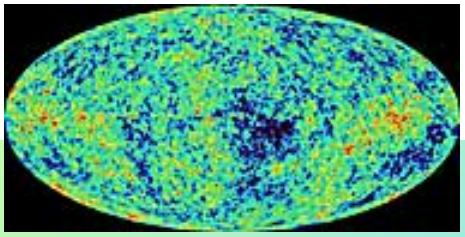


- Small “mountain” (~3 mm) or other imperfection would cause pure sinusoidal tone of gravitational waves

‘Murmurs’ from the Big Bang

signals from the early universe





Cosmic microwave background

‘Murmurs’ from the Big Bang

signals from the early universe

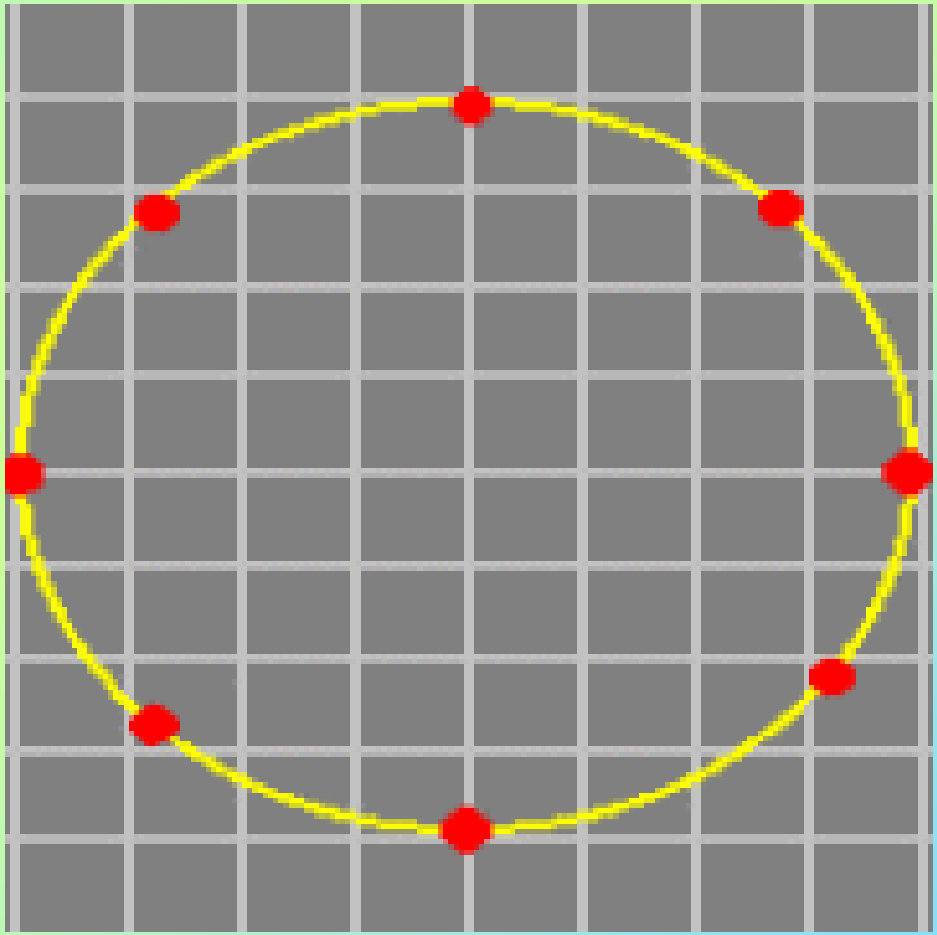
More from Professor Sato

Detecting Gravitational Waves

Effect of a Passing Gravitational Wave

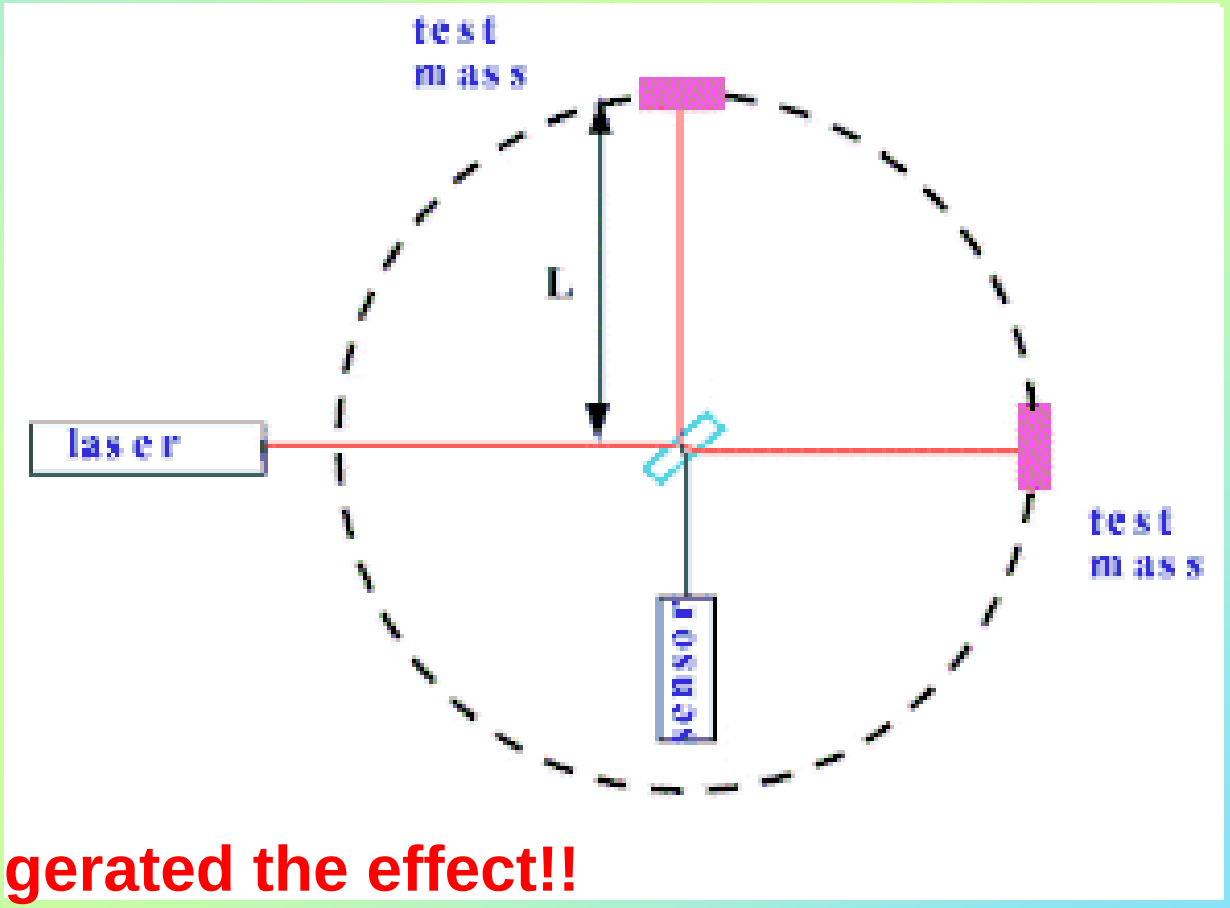
- **Most important quantities to describe the wave:**

  Strength ($\Delta L/L$)
  Frequency



Detecting a Gravitational Wave with Light

Michelson Interferometer



I have greatly exaggerated the effect!!

Strength ($\Delta L/L$) of a strong wave is about 10^{-21}

For L = 1 km, => $\Delta L = 10^{-18}$ m

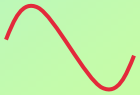
How Small is 10^{-18} Meter?

One meter

÷10,000

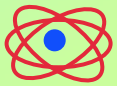
Human hair ~ 10^{-4} m (0.1 mm)

÷100



Wavelength of light ~ 10^{-6} m

÷10,000

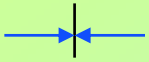


Atomic diameter 10^{-10} m

÷100,000

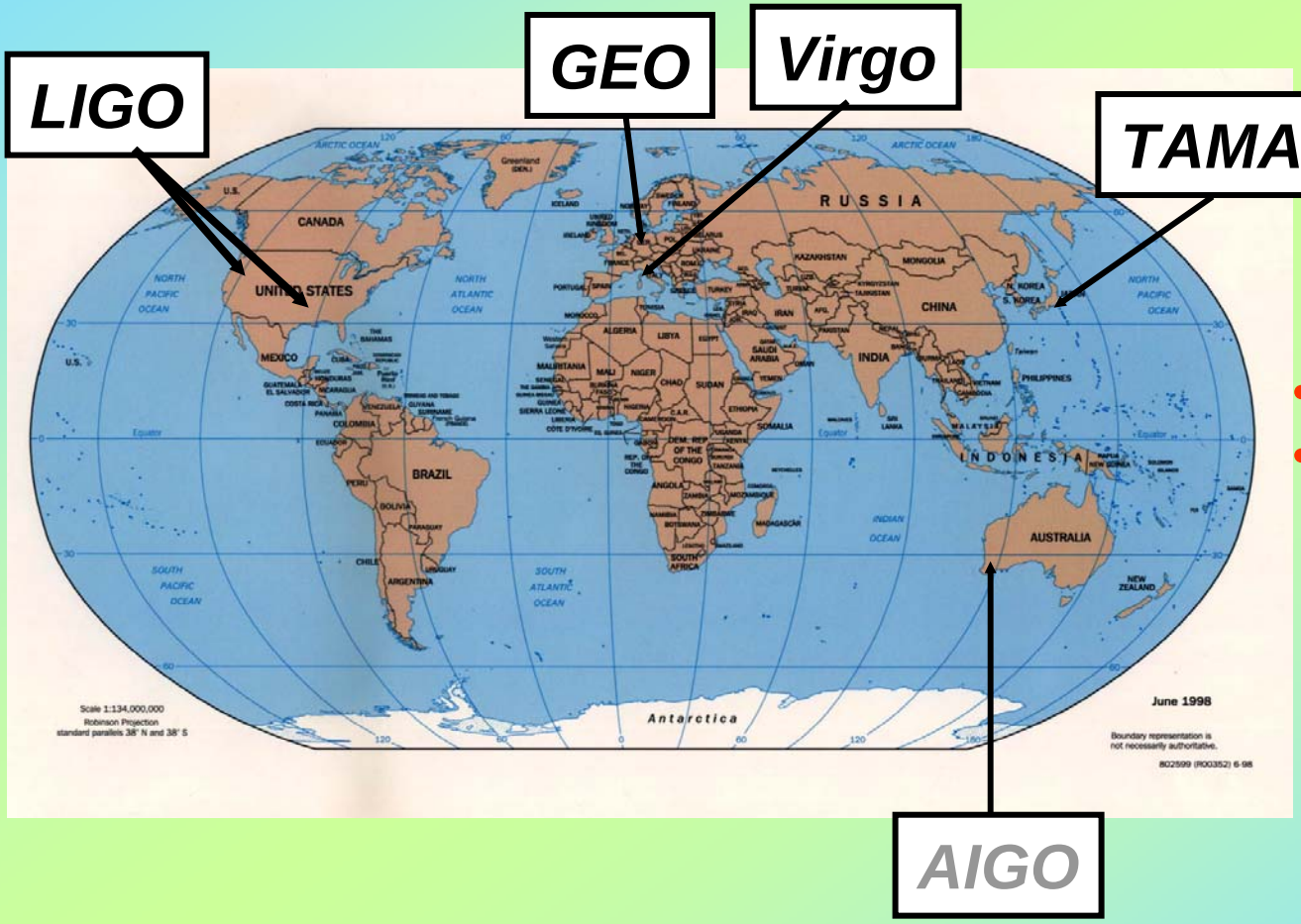
Nuclear diameter 10^{-15} m

÷1,000



GW detector 10^{-18} m

A Global Network of Gravitational Wave Interferometers



- Detection confidence
- Locate sources

Looking to the Future

- The existence of gravitational waves is beyond any reasonable doubt
- Their detection is one of the most challenging tasks ever undertaken by scientists
- They promise to give us new insights into the world of astronomy
- There will be surprises!