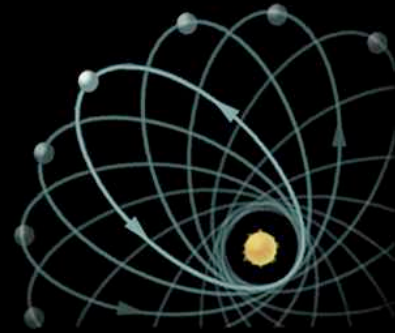
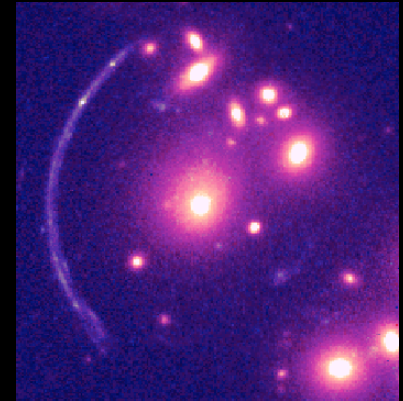


# EXPERIMENTAL TESTS OF GENERAL RELATIVITY

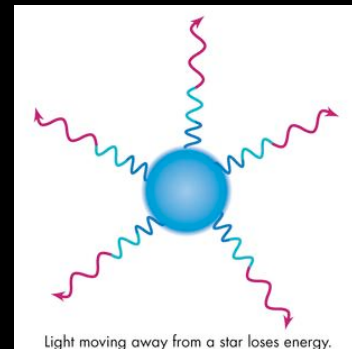
*Mercury's Precession*



*Gravitational Lensing*



*Gravitational Redshift*



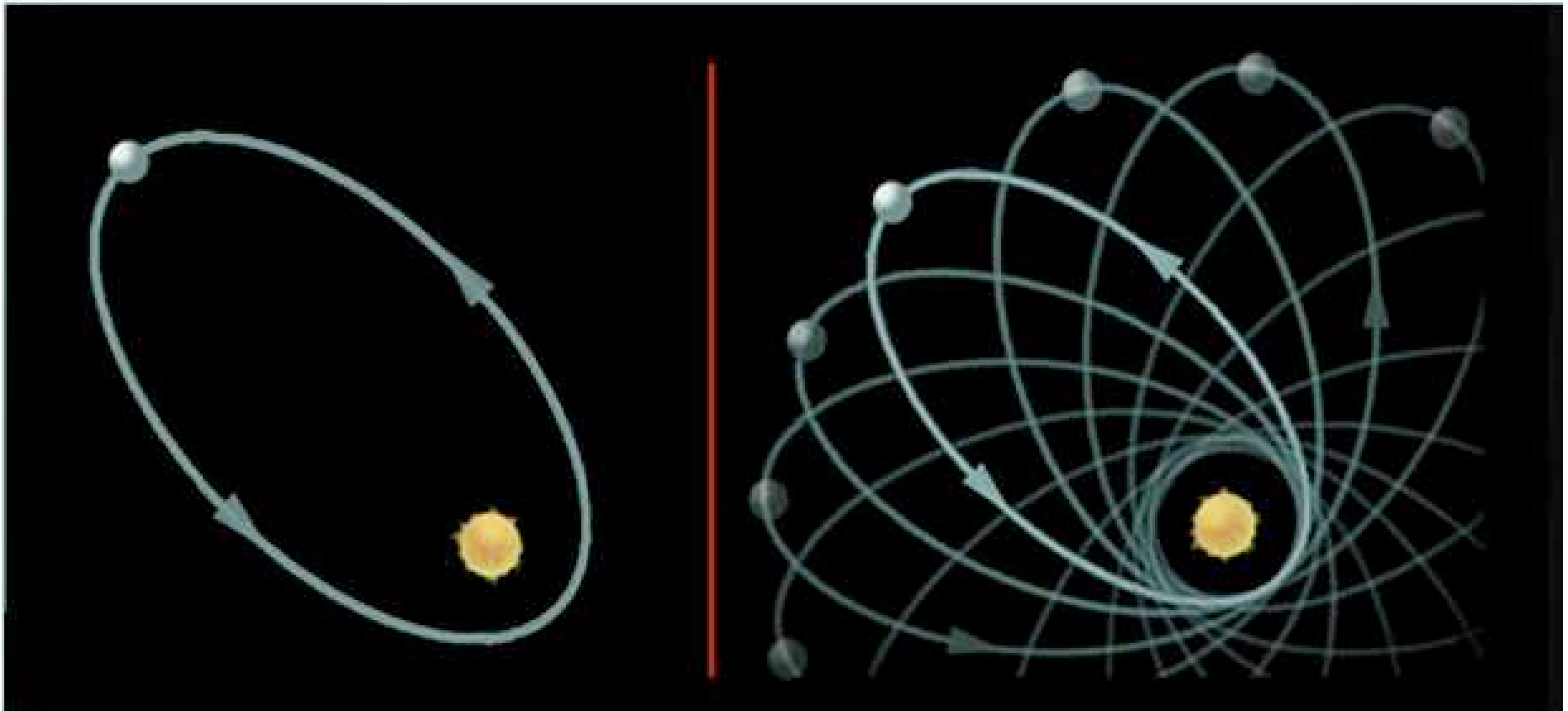
*Gravitational Waves*



## MERCURY'S PRECESSION

The theory of General relativity was able to precisely account for the observed precession of Mercury's orbit.

### MERCURY'S ORBIT



Newtonian gravity

*[Image from [www.gravitywarpedrive.com](http://www.gravitywarpedrive.com)]*

General relativistic gravity

(amount of precession not on scale -  
artist's view of Mercury's precession)

## MERCURY'S PRECESSION

If Mercury were the only planet orbiting the Sun, according to Newton's gravity law its orbit would be a perfect ellipses.

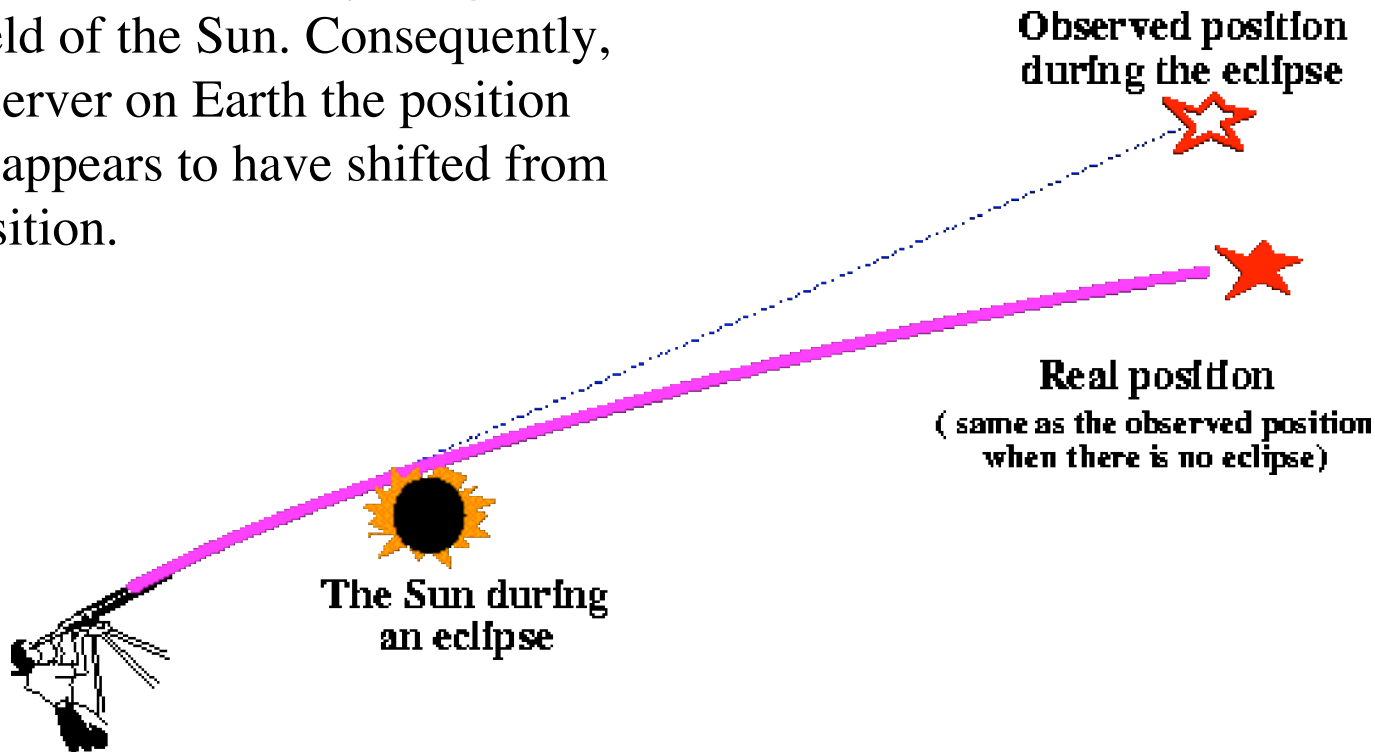
However, because of the gravitational influence of other planets, Newton's law of gravity predicts that Mercury's orbit should slowly preceed around the Sun.

Careful observations of Mercury's orbit during the 1900's showed that it does indeed preeced, but not quite what Newton's law predicted.

**The theory of General Relativity was able to perfectly account for the observed discrepancy.**

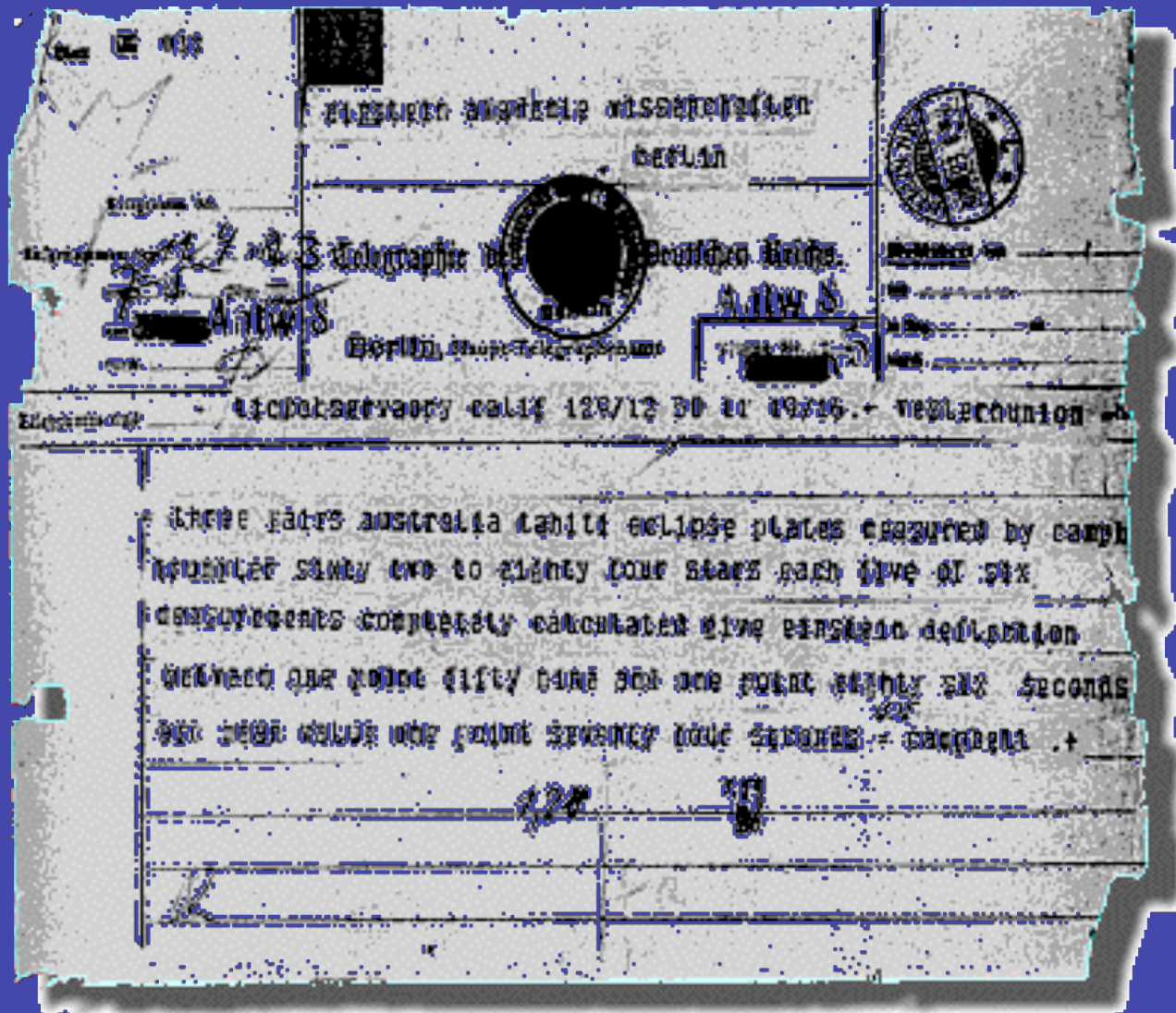
# GRAVITATIONAL DEFLECTION OF LIGHT

During the eclipses, the beam of light from the star is deflected by the gravitational field of the Sun. Consequently, for the observer on Earth the position of the star appears to have shifted from its true position.



First observational test of the prediction of General Relativity

Telegram from Sir Arthur Eddington (1919) announcing the observed apparent shift in the position of the star, due to the light deflection by the gravitational field of the Sun as predicted by GR.



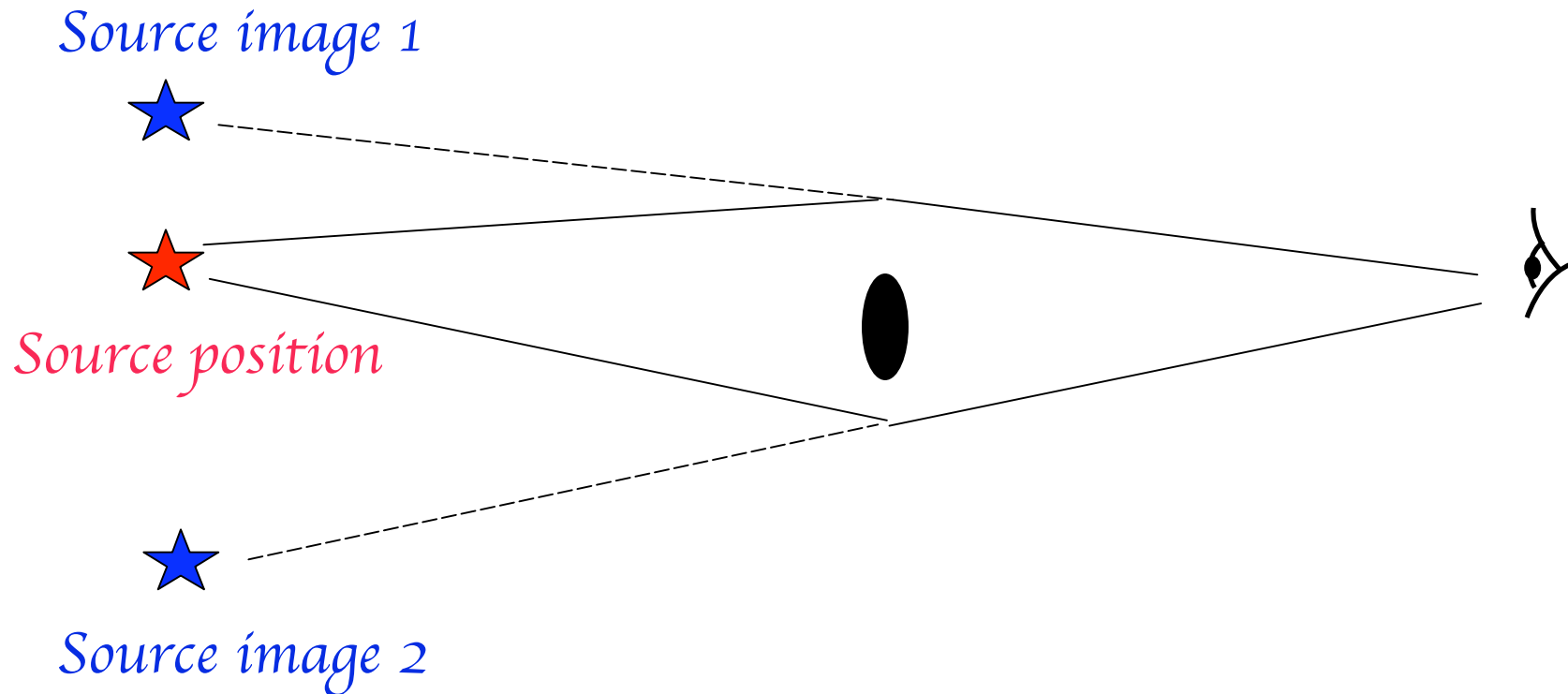
# GRAVITATIONAL LENSING



[Image from <http://cfa-harvard.edu/castels/>]

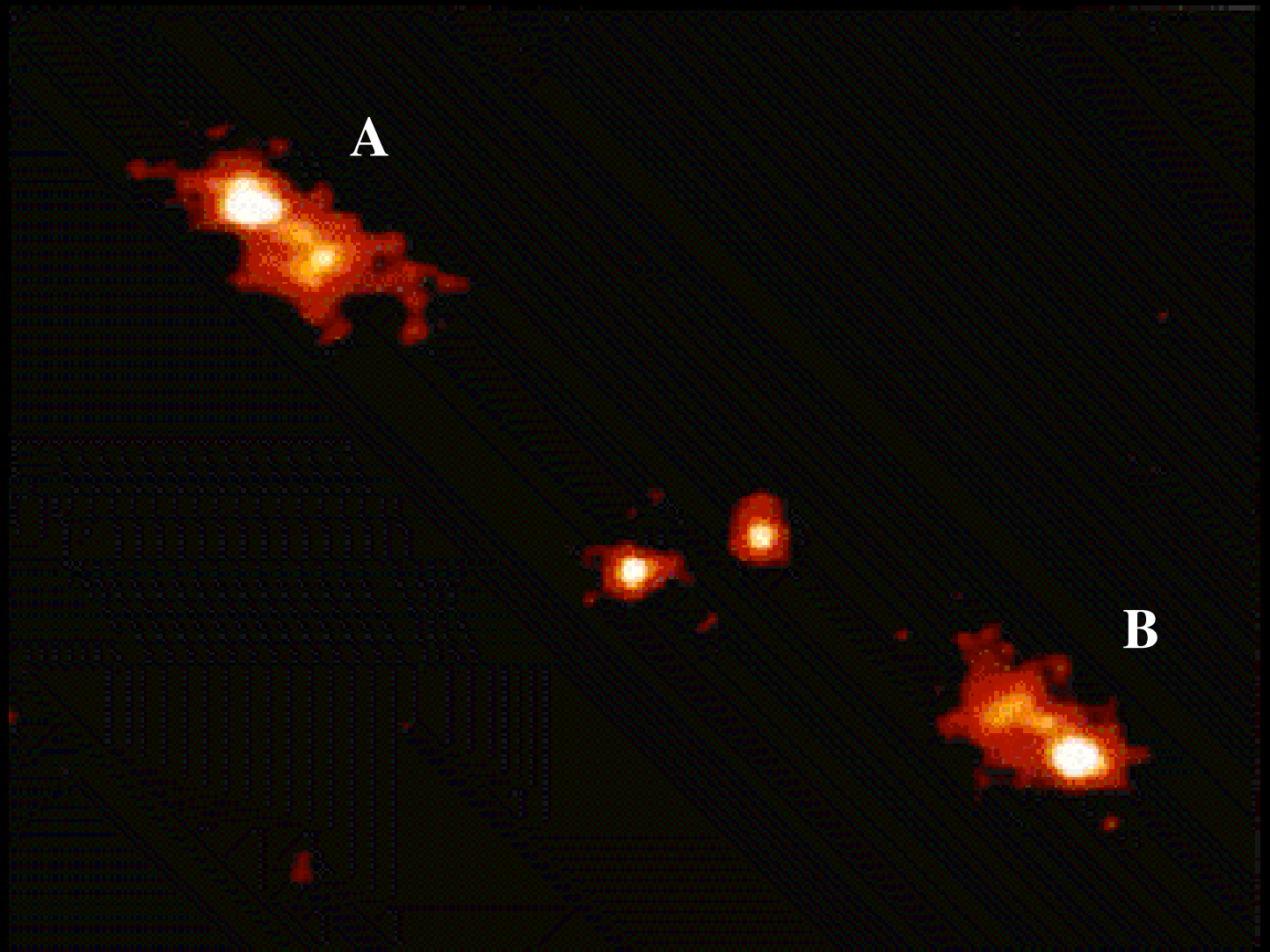
The general phenomenon of light deflection by massive bodies:

## GRAVITATIONAL LENSING



**The observer sees MULTIPLE IMAGES of the source:**  
depending on the geometry the images can be pointlike, arcs, rings, etc

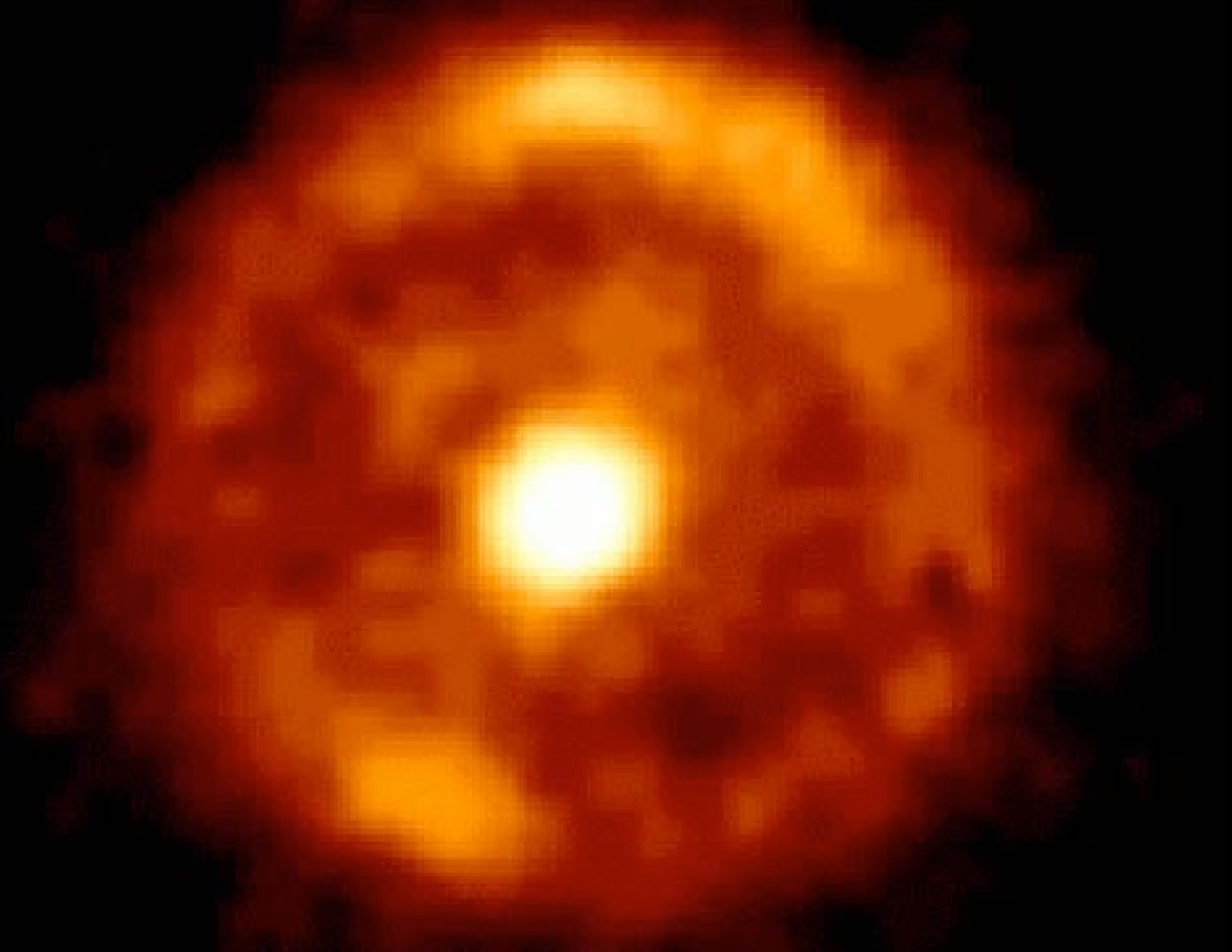
# Two images of a distant quasar



*[Image credit: R. Ellis  
& I. Smail with HST  
(NASA/STScI)]*



## Source behind the lens: EINSTEIN RING



*[Image credit: L. King with HST (NASA/STScI)]*

The arches  
are the  
result of  
gravitational  
lensing

*[Image credit:  
P. Natarajan with HST  
(NASA/STScI)]*



More arches  
due to  
gravitational  
lensing -  
the “lens”  
here is a giant  
galaxy cluster  
that you can  
see at the  
center of  
the image.

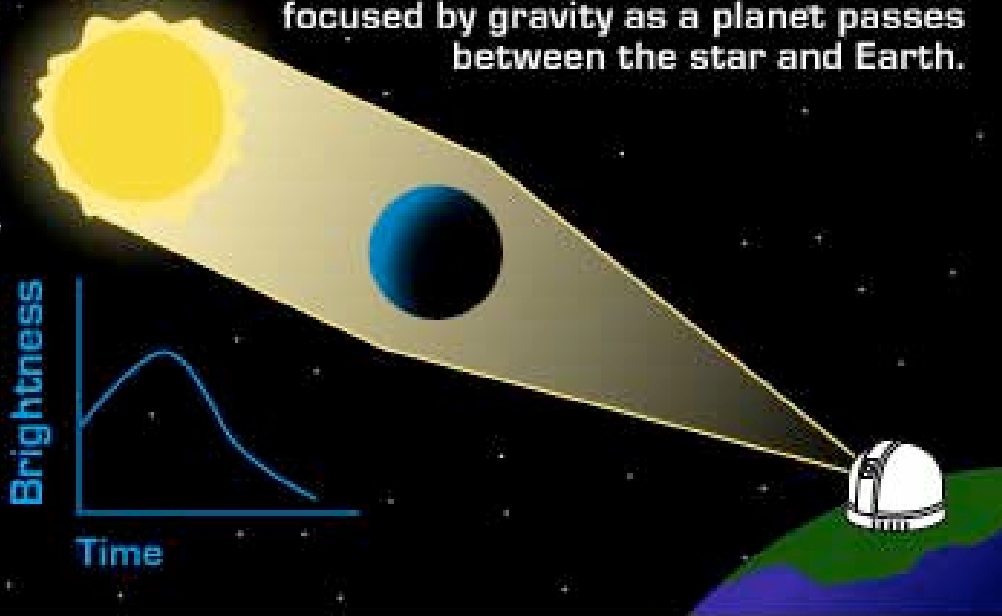
*[Image credit:  
W. Colley with  
HST (NASA/STScI)]*



# Gravitational MICROLENSING

## Gravitational Microlensing

Light from a distant star is bent and focused by gravity as a planet passes between the star and Earth.

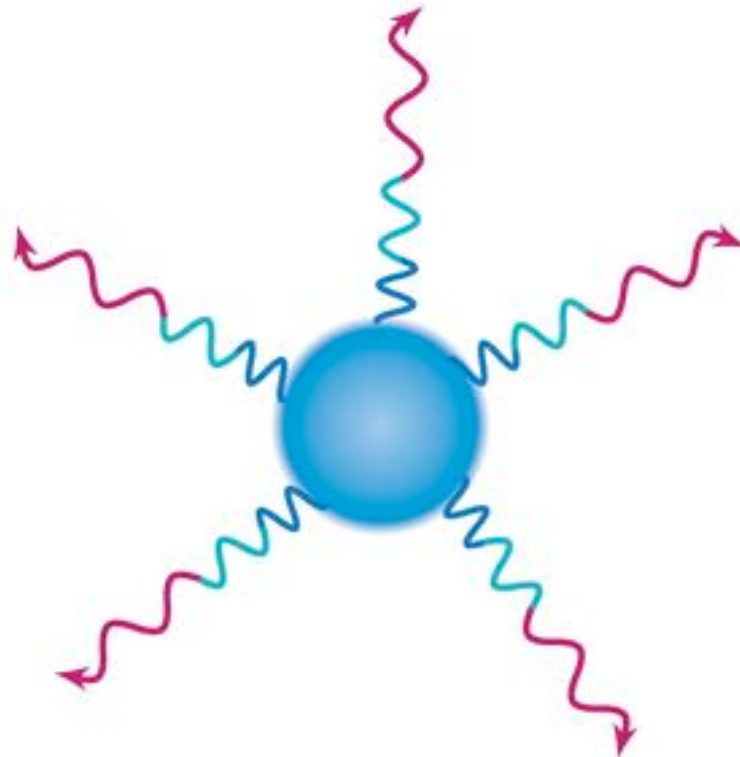


[Image credit: NASA/JPL]

If the “lens” (i.e. the object whose presence causes the light rays from the source to be deflected on their way to the observer) is small (star, planet), then the separation between the images of the sources is too small to be resolved, and what the observer sees is an overall increase in the brightness of the source.

If the lens moves in front of the source, then the source brightness varies with time. This phenomenon goes under the name of *MICROLENSING*.

# GRAVITATIONAL REDSHIFT/TIME DILATION



Light moving away from a star loses energy.

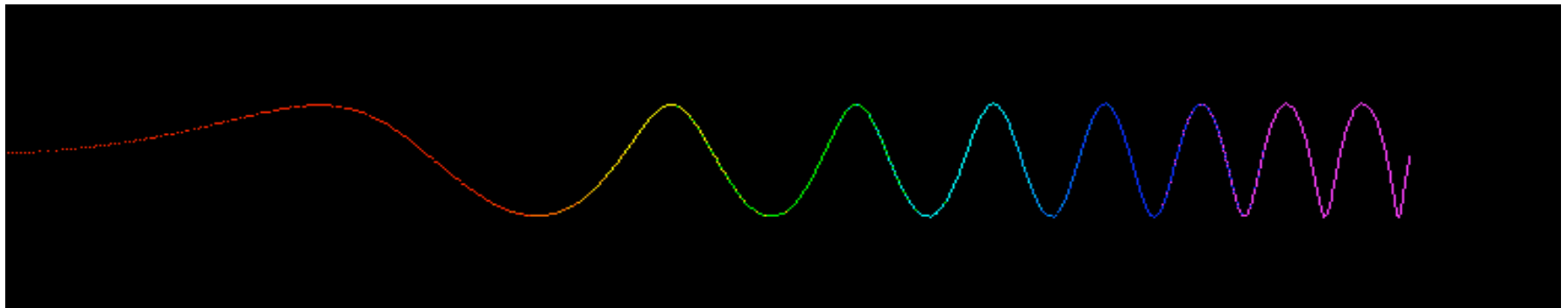
*[Image credit: T. Arny]*

An atom emitting radiation at a particular frequency acts like an atomic clock.

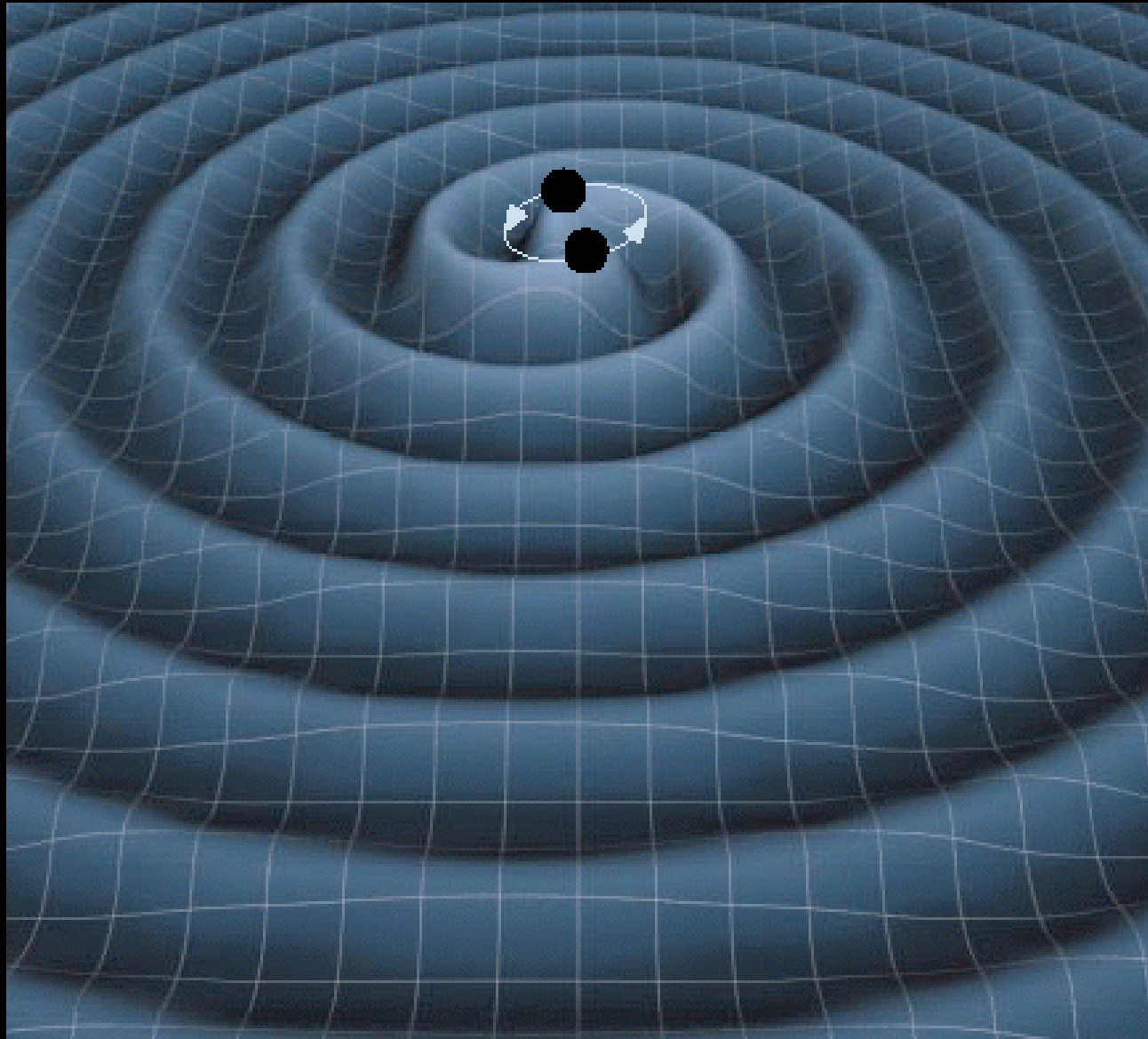
Sun more massive than Earth → stronger gravity

→ Compare identical atomic lines from Sun and Earth.

**Frequency of lines observed more redshifted for Sun than for Earth.**



# GRAVITATIONAL WAVES



*[Image credit: K. Thorne & T. Carnahan]*

# GRAVITATIONAL WAVES

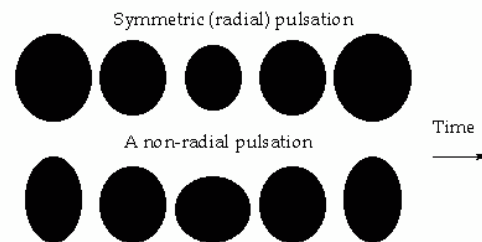
**Ripples of spacetime curvature that propagate at the speed of light.**

A prediction of General Relativity: a “perturbation” of the spacetime curvature that propagates from the disturbance point.

**Analogy:** dropping a stone (*perturbation*) in a pond (*spacetime*) produces waves in the water (*spacetime ripples*) that propagate.

Sources of gravitational waves include:

● Pulsations of Black Hole horizons;



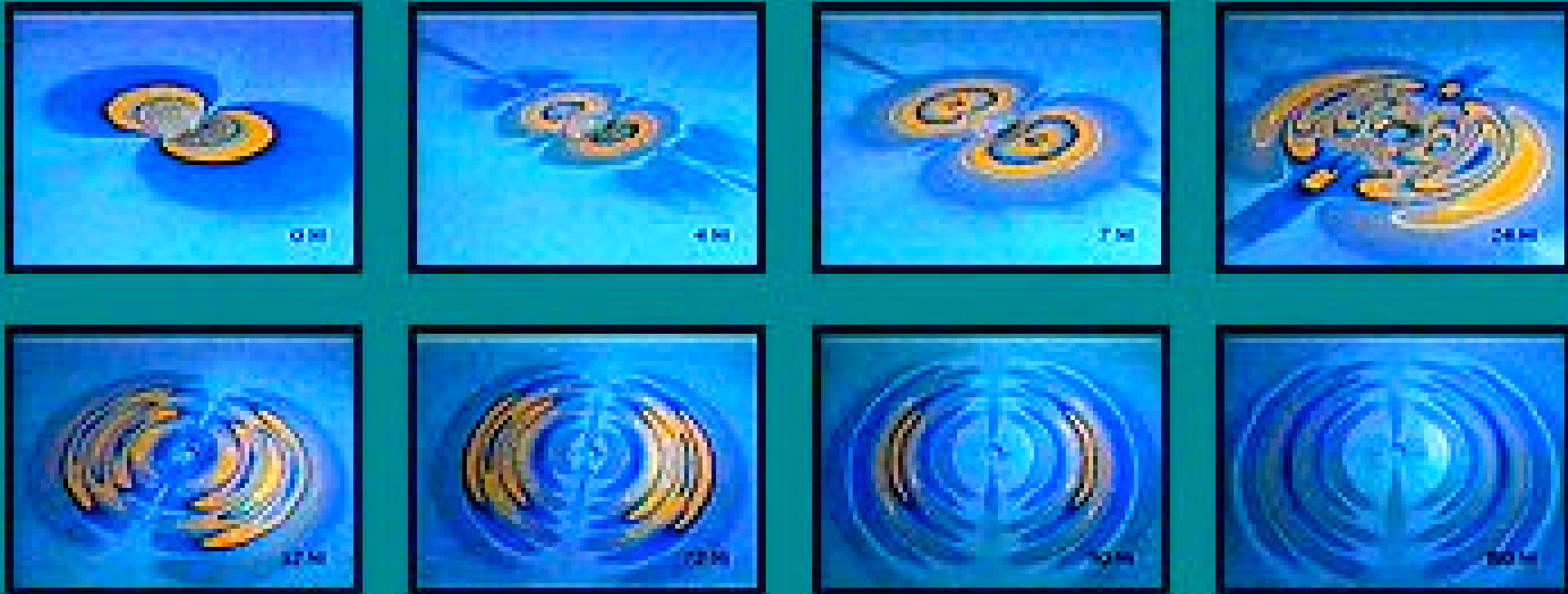
[drawing by  
D. Watson]

● An imploding star;

● Merger of two compact objects (i.e. neutron stars, black holes);

● Two massive stars orbiting each other closely and rapidly.

# Emission of gravitational waves as a result of the collision of two black holes

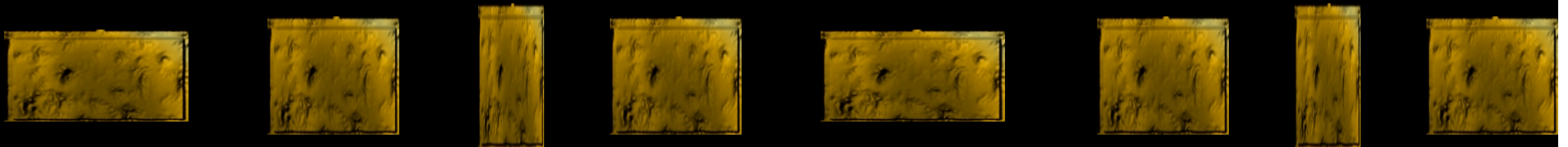


*[from Ed. Seidel et al. NCSA/U. Illinois]*



## A brick under the effect of a gravitational wave

If a brick were close to two merging black holes, it would be squeezed and stretched by as much as its size (humans would be killed!)



For merging black holes in a far away galaxy at 1 billion years away, the size change due to the gravitational wave would be  $\sim 10^{-21}$  - very small!

# Gravitational Wave detectors: LIGO

Kip Thorne

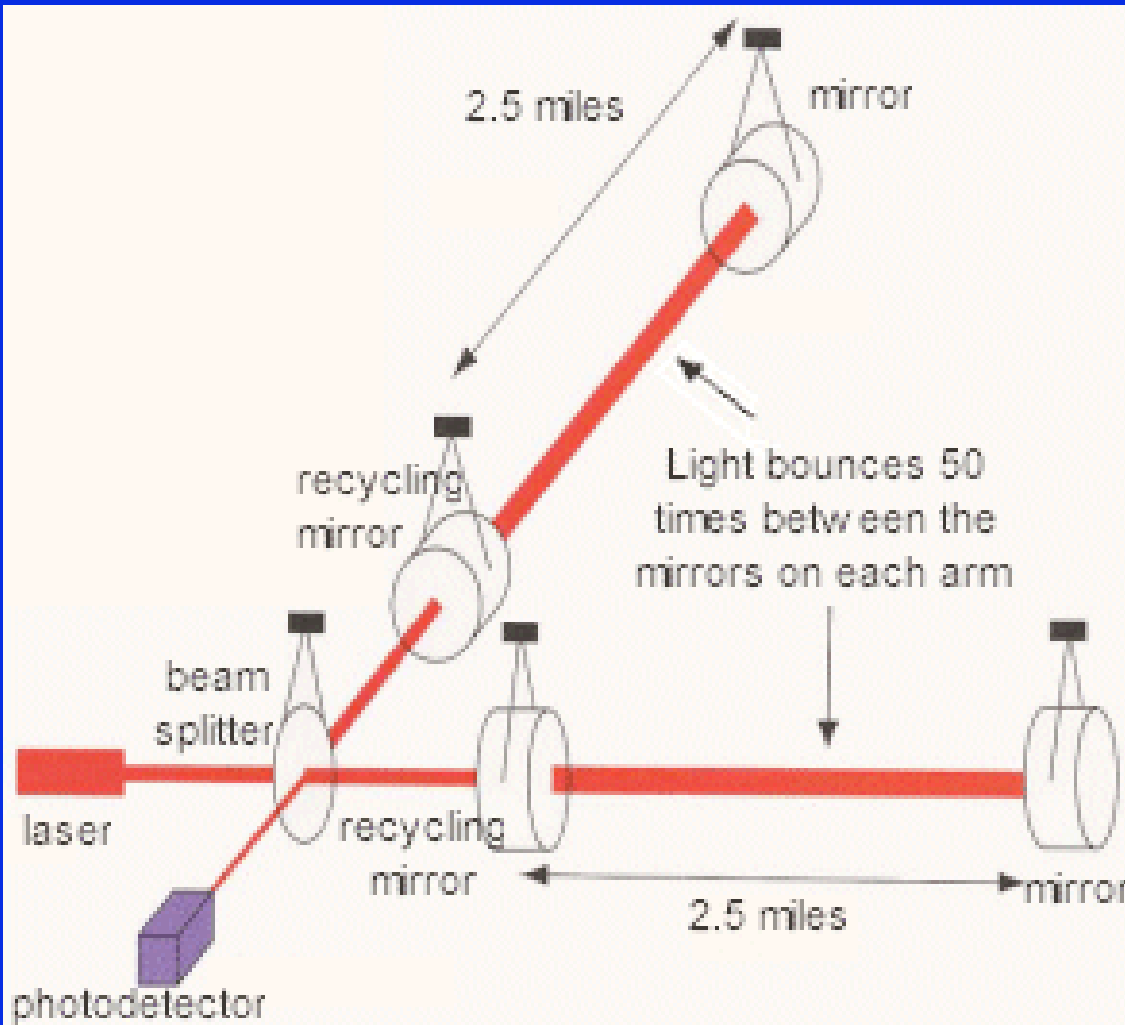


Louisiana



Washington

# Schematic view of LIGO

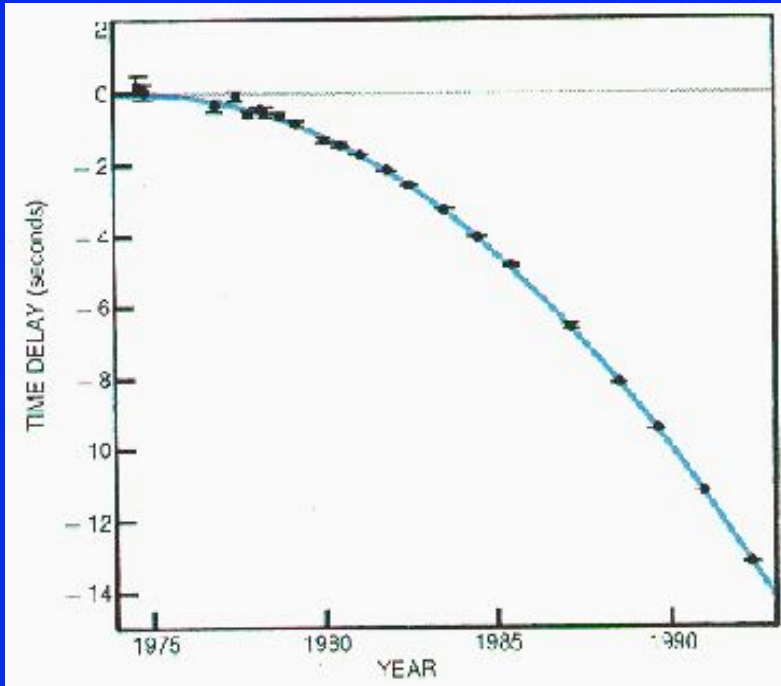


LIGO is a laser interferometric gravitational wave detector (similar idea to that of the Michelson-Morley experiment).

When a gravitational wave enters the laboratory, its tidal forces stretch the masses apart along one arm while squeezing them along the other arm.

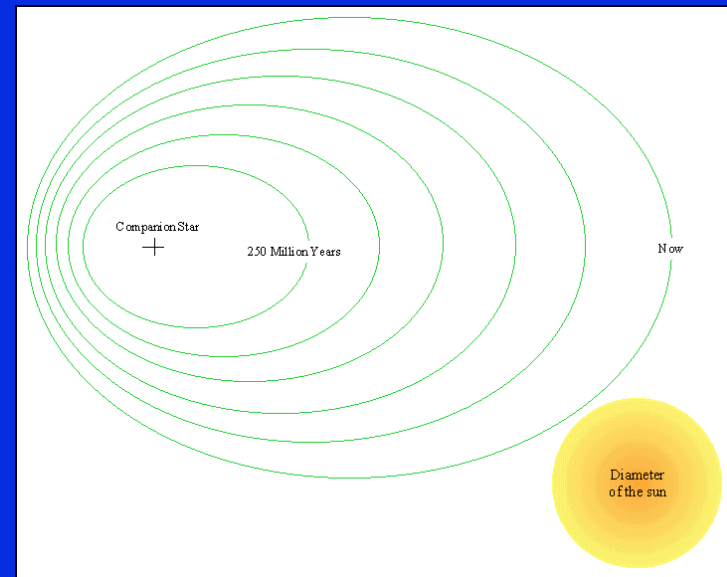
**LIGO will provide direct detection of gravitational waves.**

## Hulse-Taylor binary pulsar: experimental confirmation of gravitational waves (it is an indirect detection)



The binary pulsar consists of two neutron stars revolving around each other. With high-precision pulse timing Hulse & Taylor were able to conclude that:

**the orbit is shrinking**



*[from Weisberg, Taylor & Fowler 1981]*

**Shrinking → energy loss**

Rate of energy loss found to be in precise agreement with predictions of General Relativity for energy loss due to gravitational wave emission