General Relativity and Gravitation

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The Theory

- Einstein's Theory of General Relativity (1907-1915)

  Theory of Gravity supersedes Newton's Theory of Gravity (1684)

  Valid near very massive objects, high velocities, the Universe

What is the Theory of General Relativity ?

- It is a theory of gravity (1907-1915)

- Attraction between massive objects, i.e. the gravitational force, replaced by modification of space

- Mass (or energy) of matter modifies space
- Objects moving in this space change their motion because of the modification of space

Space ? Modify ?

- Space is the region in which all matter exists and physical phenomena occur

- Upto 20th c., space is unaffected by matter in it and physical phenomena

Flat Space

- Electron moving in free space. Unaffected by space. This bland, propertyless space assumed in old Physics (before GR) is called flat space (or, with time, Minkowski spacetime)

- Most scientific ideas are tested presuming this – atomic physics, collider experiments [modification of space is not relevant]

Curved Space

- Put a star of mass M and consider planet moving past it

- GR: Space is modified outside M and motion of planet is affected

- In the presence of massive bodies space is curved

Curved Space

- In the presence of massive bodies space is curved
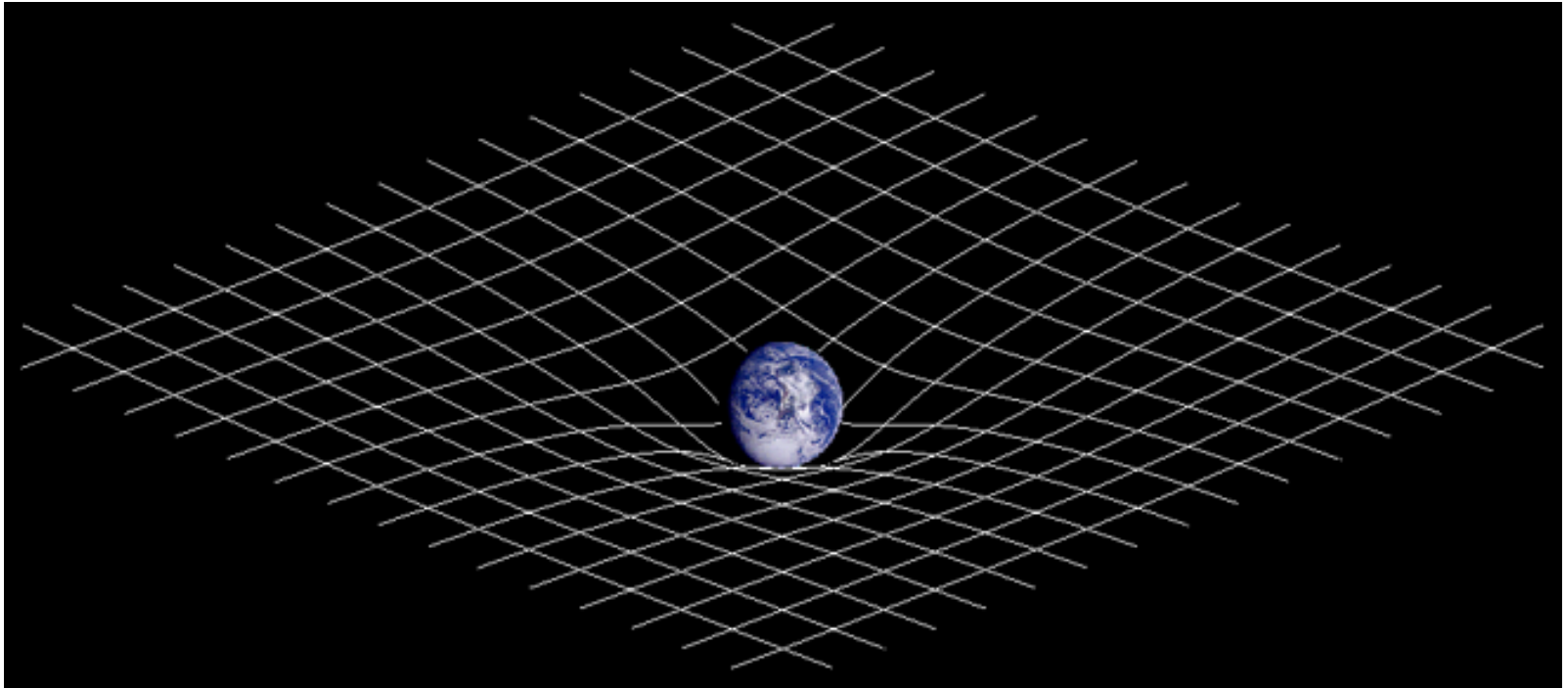
Gravity and curved space

- Gravitational force and gravitational effects are due to a modification of space.

- Can all forces be interpreted as due to modification of space?

- If a force's effect is equivalent to a property of space then at any point in space it affects motion of all bodies equally.

Gravity and curved space

Recall acceleration due to gravitational field = GM/r^2

acceleration due to electric field for a particle of mass m and charge $q = (q/m)\, Q/r^2$.

Latter also depends on particle – not due to space. So only gravity can be interpreted as due to modification of space which affects all bodies equally

The Theory of General Relativity

- Theory of Gravity – new way of understanding grav force

- Mass (or energy) curves space

- Objects moving in this space change their motion because of the curvature of space

- Gravitational field replaced by modification of space

- Space is dynamic – depends on energy/mass of matter in space

Einstein's equations

- Space affected by matter

$$G_{\mu\nu} = 8\pi\, G_N T_{\mu\nu}$$

- rhs includes energy density, momentum and pressure of matter
- lhs is a function of the metric which describes properties of space
- G_N is Newton's gravitational constant

Are these ideas correct?

Predicted differences from Newtonian gravity

- Close to a massive object (star/Earth-accuracy GPS)

- At relativistic speeds (v ~ c)

- Applied to the Universe

Precession of the perihelion of Mercury

- Planet around the Sun in an elliptical orbit with the Sun at a focus (Kepler's First Law)

- Perihelion (point of closest approach) is fixed if 2 bodies

- Precession of the perihelion of Mercury

Precession of the perihelion of Mercury
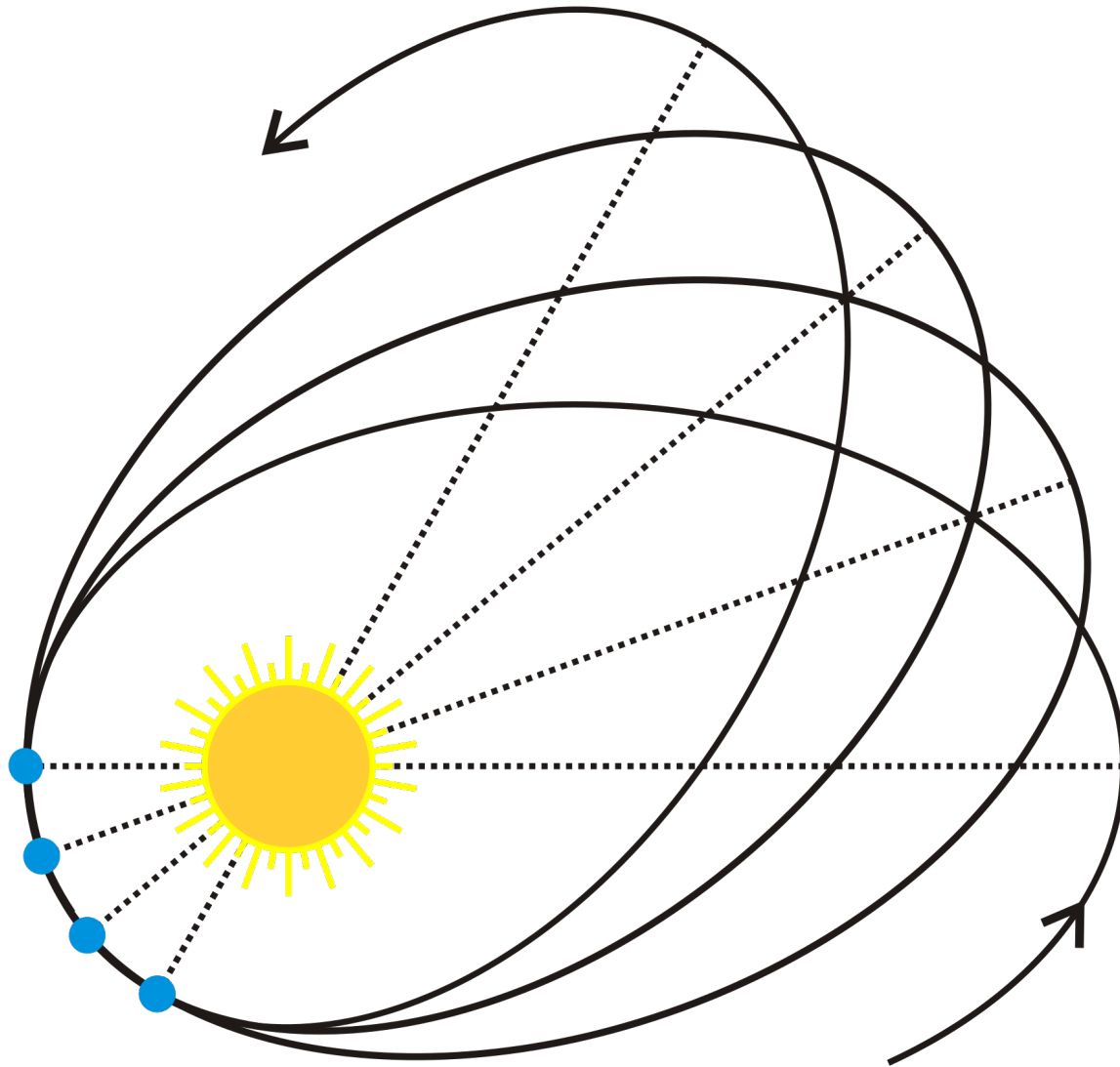
Precession of the perihelion of Mercury

- Other planets, oblateness of the Sun (minor)

- Not agree with Newtonian analysis
  1859 Le Verrier (observations of transits of Mercury over the Sun's disk from 1697 to 1848)

Precession of the perihelion of Mercury

- Observed 532 arc second per century
  Newtonian analysis was off by 45 +/- 5 arc
  second

- Discrepancy goes away in Einstein's
  analysis using General Relativity 1915
  GR correction 43 arc second per century

First exact solution of Einstein's eqns

- Einstein had to make some approximation to describe the gravity, or curvature of space, around the Sun

- Karl Schwarzchild gave the exact solution around a spherical star 1916

- First exact solution of eqns of General Relativity [results agreed for Mercury]

Schwarzchild solution

- Minor correction for gravity of the Earth
- Relevant for neutron stars and black holes

- GPS have to include GR corrections – high precision to locate person

Gravitational Bending of Light

- Space is curved due to the presence of massive bodies

- Property of space – affects all objects in this space

- Also affects light Einstein 1911, 1915

Gravitational Bending of Light

- Expedition was sent to measure gravitational bending of the light from stars near the sun during a solar eclipse

- Total solar eclipse August 21, 1914 in Russia (region of greatest eclipse)

Dodelson-2007

Dodelson-2007

1914 was not a good year to start a scientific expedition in Europe !

Dodelson-2007

- The astronomers were captured by Russian soldiers (and released a month later).

- Good thing. In the following years, Einstein revised his calculation.

- Confirmed by solar eclipse expeditions led by Eddington in 1919 to islands of Sao Tome and Principe on west coast of Africa (and Brazil-telescope issues)

Dodelson-2007

The Theory of General Relativity

- Einstein's Theory of General Relativity (1915)
  Theory of Gravity, Valid for very massive objects, high velocities, gravity of the universe

- Star, Bending of Light. Now the Universe

Our Universe

- Einstein 1917

- Universe is isotropic and homogeneous

- Mathematical simplicity

- Valid on very large scales -- isotropy of CMBR, radio sources, galaxy surveys

The Theory of General Relativity

- Static universe 1917 Einstein

Observations

Edwin Hubble

- Distant galaxies are moving away from us
  Vesto Slipher 1912 (redshift)

- At a speed proportional to their distance from us
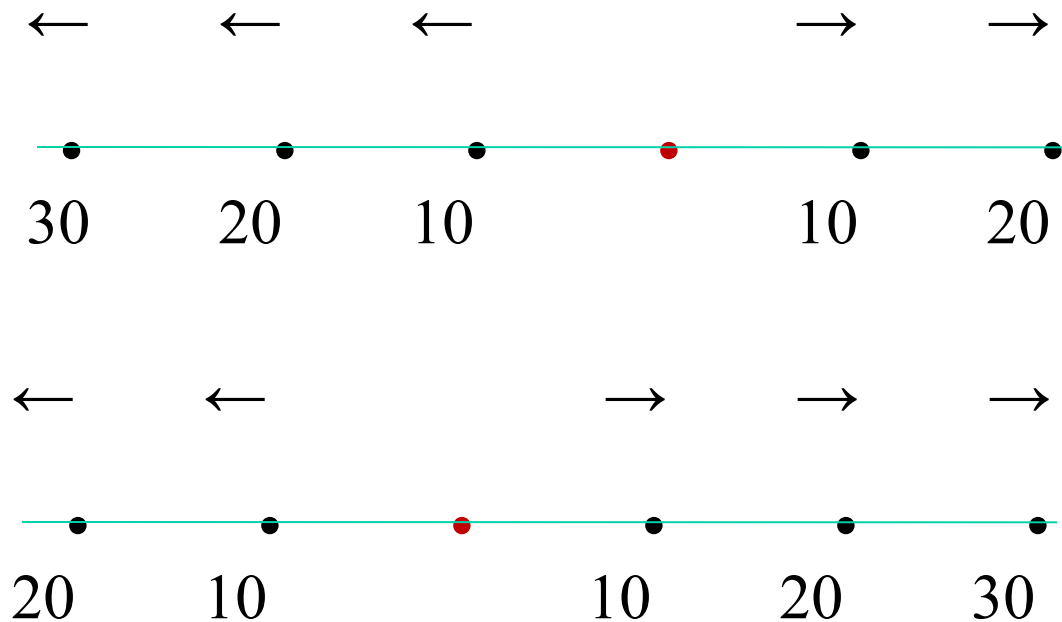 Edwin Hubble 1929 (and Milton Humason*)

* School dropout, muleskinner and janitor, astronomer

All distant galaxies are moving away from us at a speed proportional to their distance -- Hubble's Law: $v = H\,d$ [Lemaitre 1927]

All distant galaxies are moving away from us
at a speed proportional to their distance --
Hubble's Law: v = H d   [Lemaitre 1927]

$\leftarrow$ $\leftarrow$ $\leftarrow$ $\rightarrow$ $\rightarrow$

30   20   10   10   20

$\leftarrow$ $\leftarrow$ $\rightarrow$ $\rightarrow$ $\rightarrow$

20   10   10   20   30

Galaxies are moving away from each other
Universe is expanding.   [Space is expanding]

The Theory of General Relativity

- Static universe 1917 Einstein -- discarded

- Friedmann (1922) and Lemaitre (1927) expanding univ

- Hubble's discovery of expanding universe 1929

The Past

- Go back in time, all material that is in all galaxies around us was in a smaller and smaller region   Lemaitre 1931

INITIAL STATE (14 b years ago)

- At the earliest instant, density very high
- All matter breaks down to elementary particles at high energies
  All matter moving out very fast

The Past

- Go back in time, all material that is in all galaxies around us was in a smaller and smaller region

INITIAL STATE

- At the earliest instant, density/energy very high
- Expansion rate very high

THE BIG BANG

THE BIG BANG

- Not an explosion of concentrated matter in space

- An initial state of rapid expansion of space (filled with matter) everywhere

Coined by an opponent of the model

After the Big Bang

- First second – hot primordial plasma of electrons, protons, neutrons, dark matter
- 1 s – 3 min – light nuclei (helium, lithium, ..)
- 400,000 years – Atoms form
- 300 million years – First stars form
- 1 billion years – First galaxies form
- 9 billion years – Universe is accelerating
-                                      Solar system formed
- 14 billion years – Today

Our Universe – Big Bang Cosmology

- Using the Friedmann-Lemaitre (+ Robertson-Walker) solutions of the equations of General Relativity gives bgnd/time for all the processes

- Correctly predicted light element abundances

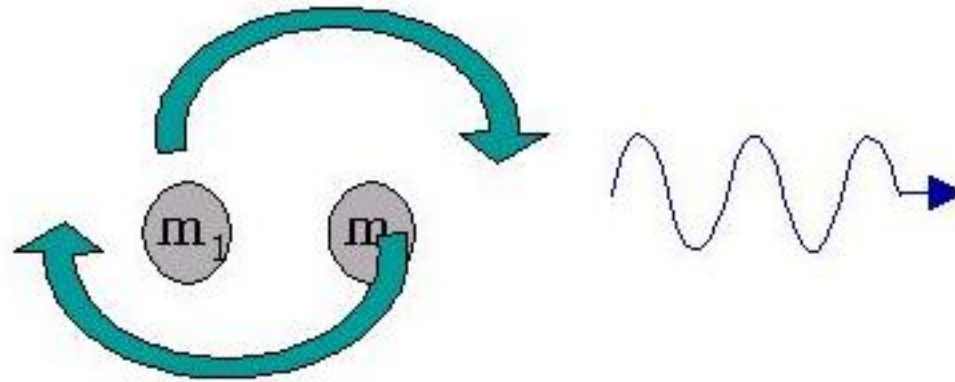- Correctly predicted the existence of the cosmic microwave background radiation

Gravitational Waves

- GR predicts the existence of gravitational waves

- Oscillating charge produces electromagnetic waves.

Gravitational Waves

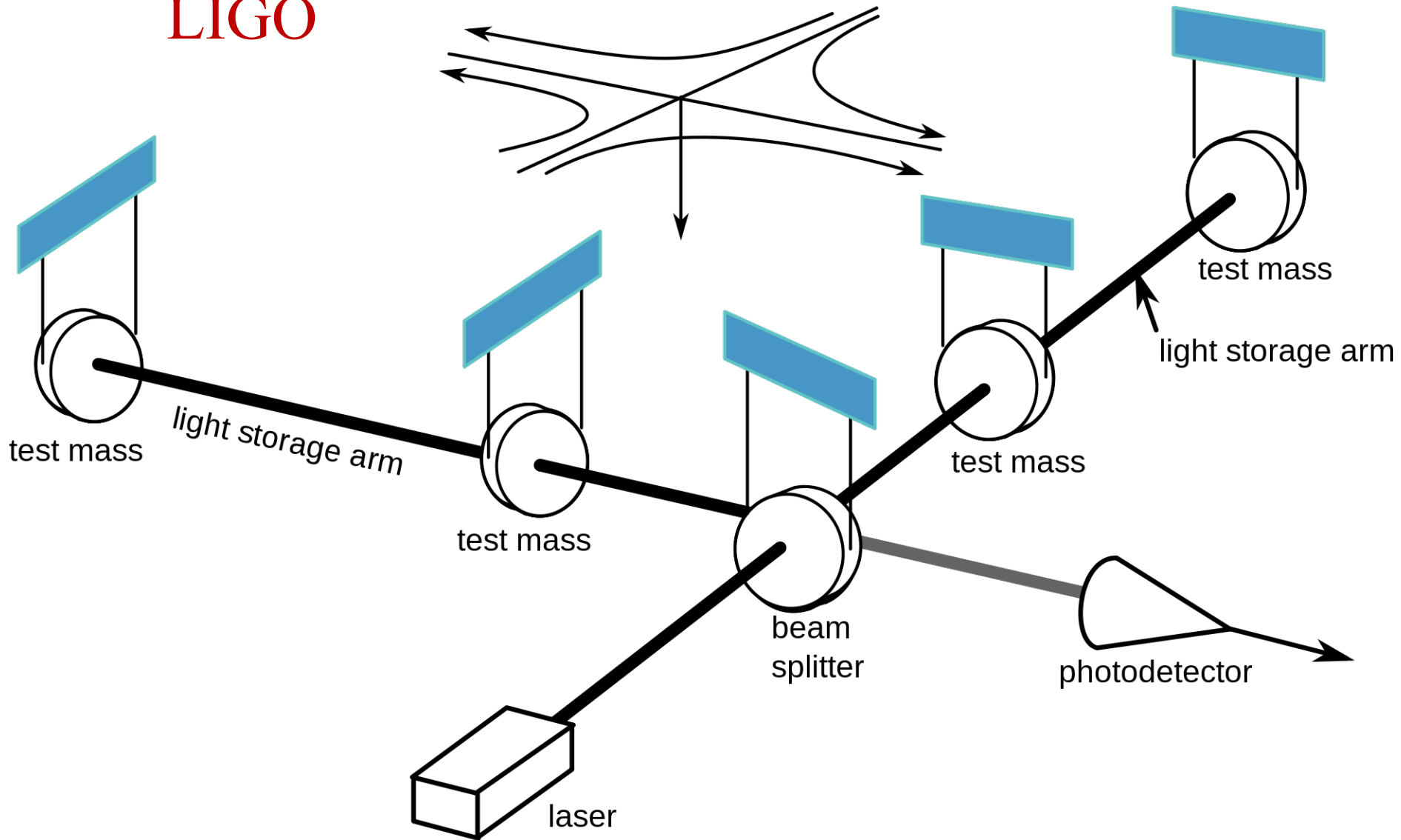- Binary star system, supernova explosion produces Gravitational Waves

- Detected effect of GW in decrease of binary pulsar period (as binary spiral in).

- Agrees with predictions of General Relativity
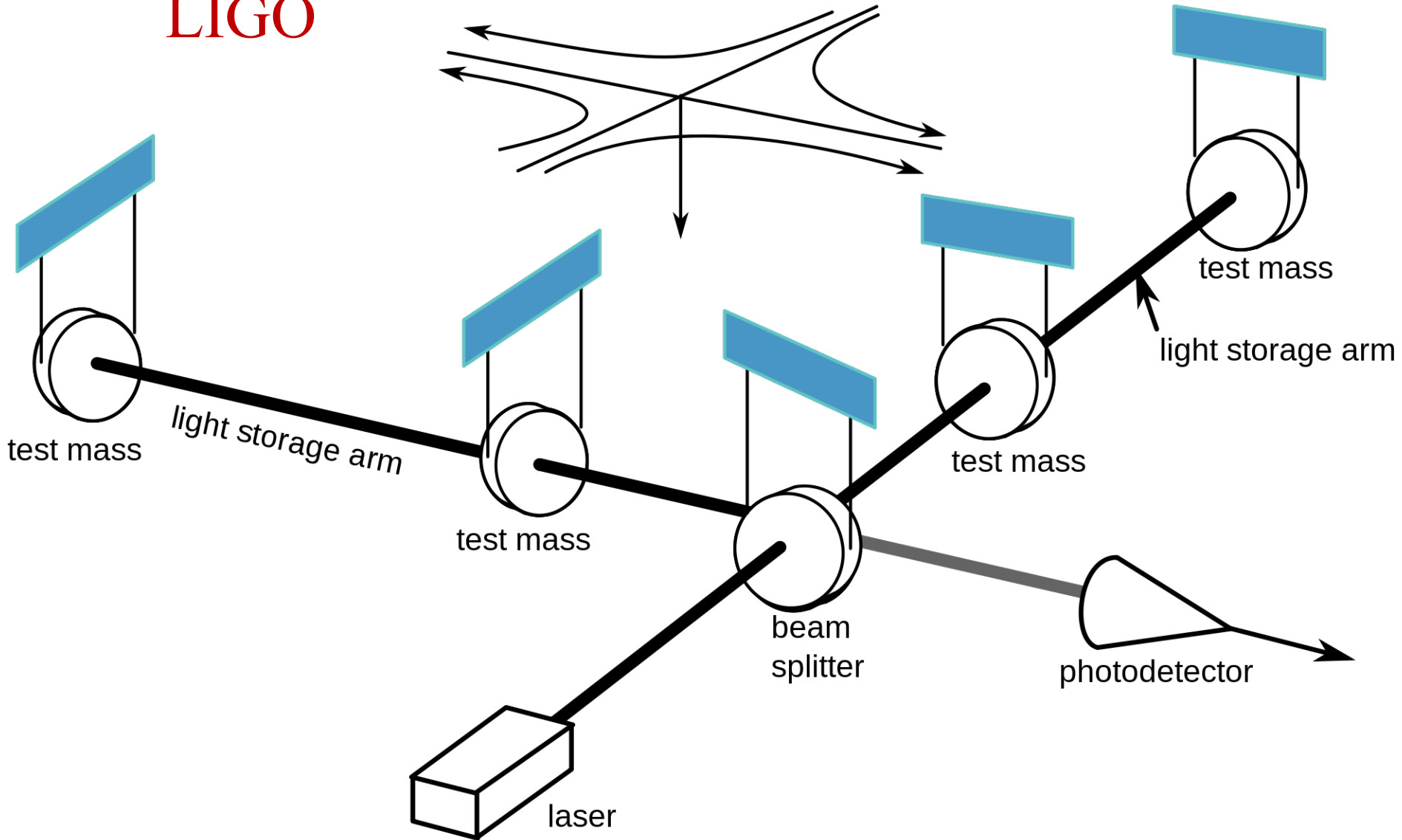
Gravitational Waves

- GW make masses move in a particular way

- Direct Detection by LIGO: Laser Interferometer Gravitational-Wave Observatory – February 2016

- LIGO-India

LIGO

test mass

light storage arm

test mass

light storage arm

test mass

test mass

beam splitter

photodetector

laser

- 4 km long leg; vacuum

LIGO

test mass

light storage arm

test mass

test mass

light storage arm

test mass

beam splitter

photodetector

laser

- 4 km long leg; Change in length by 10^{-18} m

India and Gravity

- NR Sen (Calcutta 1924-) and VV Narlikar (BHU 1932-)

- Vaidya metric (1943, 1950), Raychaudhuri equation (1955)

- Active area of research in India at several institutions – IUCAA, IMSc, …, PRL, ..

- LIGO-India ; IndIGO – Indian Initiative in Gravitational-wave Observations

- IAGRG – Indian Association for General Relativity and Gravitation

Summary

- General Relativity is a theory of gravity

- Relevant near very massive objects, high velocities, the Universe

- Passed all tests of validity

- Next frontier: direct detection of gravitiational waves