Lecture 18
Vacuum, General Relativity

Arán García-Bellido

UNIVERSITY of ROCHESTER

Standard Model recap

Fundamental particles | **Fundamental Forces** | **Strength**

Quarks (u, d, c, s, t, b)
fractional electric charge (2/3, -1/3)
bound by strong force:
qqq (baryons: proton, neutron)
$q\bar{q}$ (mesons: π, K)

Leptons (e, μ, τ, ν_e, ν_μ, ν_τ)
Don't feel the strong force

Gauge bosons (γ, W, Z, g, G)
Mediate forces
Electroweak: γ, W, Z
Strong: gluons
Gravity: gravitons

Higgs boson
Gives mass to all particles

Strong
gluon
range: nucleus
Strength: 30

Weak
W, Z
range: 10^{-18} m
Strength: 1

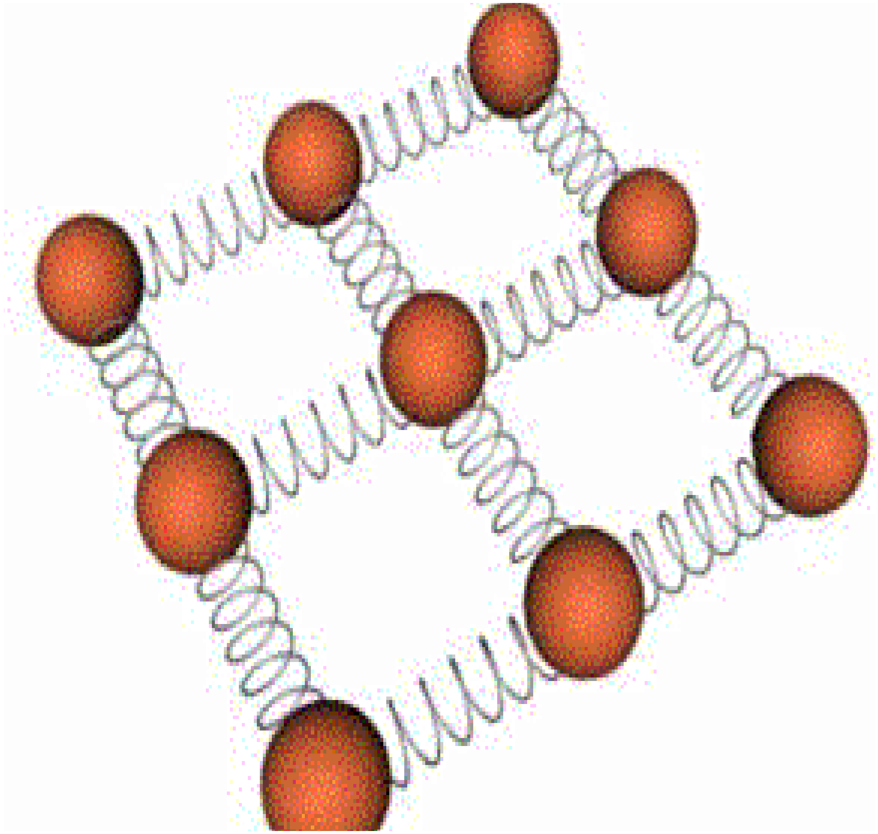
Electromagnetism
γ photon
range: infinity
Strength: 1

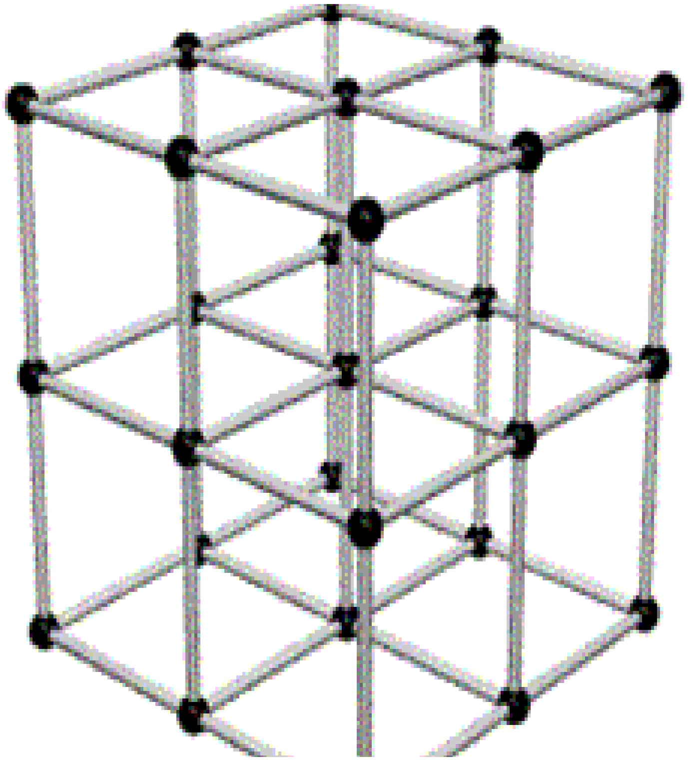
Gravity
graviton
range: infinity
Strength: 10^{-40}

The physics of nothing

- Classical view of the vacuum:
  - A passive “stage” where forces and motions are played
  - Space is static and unchanging
  - Geometry is Euclidean
  - Time marches according to an absolute universal clock
- Special relativity view:
  - The speed of light is constant, independent of the motion of the source or the observer
  - Space and time are intertwined: spacetime
- Quantum mechanical view (quantum fields):
  - Relativity + Quantum mechanics
  - Minimum possible energy of quantum oscillations (zero point energy): $E=\frac{1}{2}hf$
  - Each type of particle (photon, electron) is described by a field that fills all space
  - At each point in space, the field has the ability to oscillate at any frequency
  - Imagine a 3D lattice of connected springs

Quantum field analogy

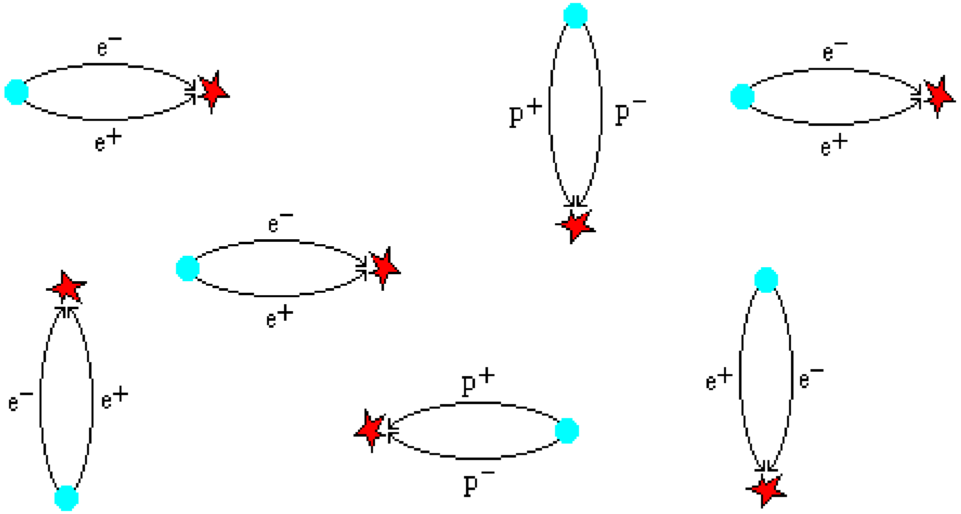




- Empty space: oscillators move with their random quantum fluctuations
- Particle present: a traveling disturbance in the lattice

The quantum vacuum

- Filled with fields corresponding to each particle
- Think of the field as describing the potential for particles to exist
- Quantum fluctuations of the field, even when no particles are present, mean that the vacuum contains a sea of “virtual particles”
  - Particles arise from the vacuum: you can borrow energy for a period of time by Heisenberg's uncertainty principle
  - Virtual particle-antiparticle pairs are continuously created and annihiliated: the quantum vacuum is full of activity

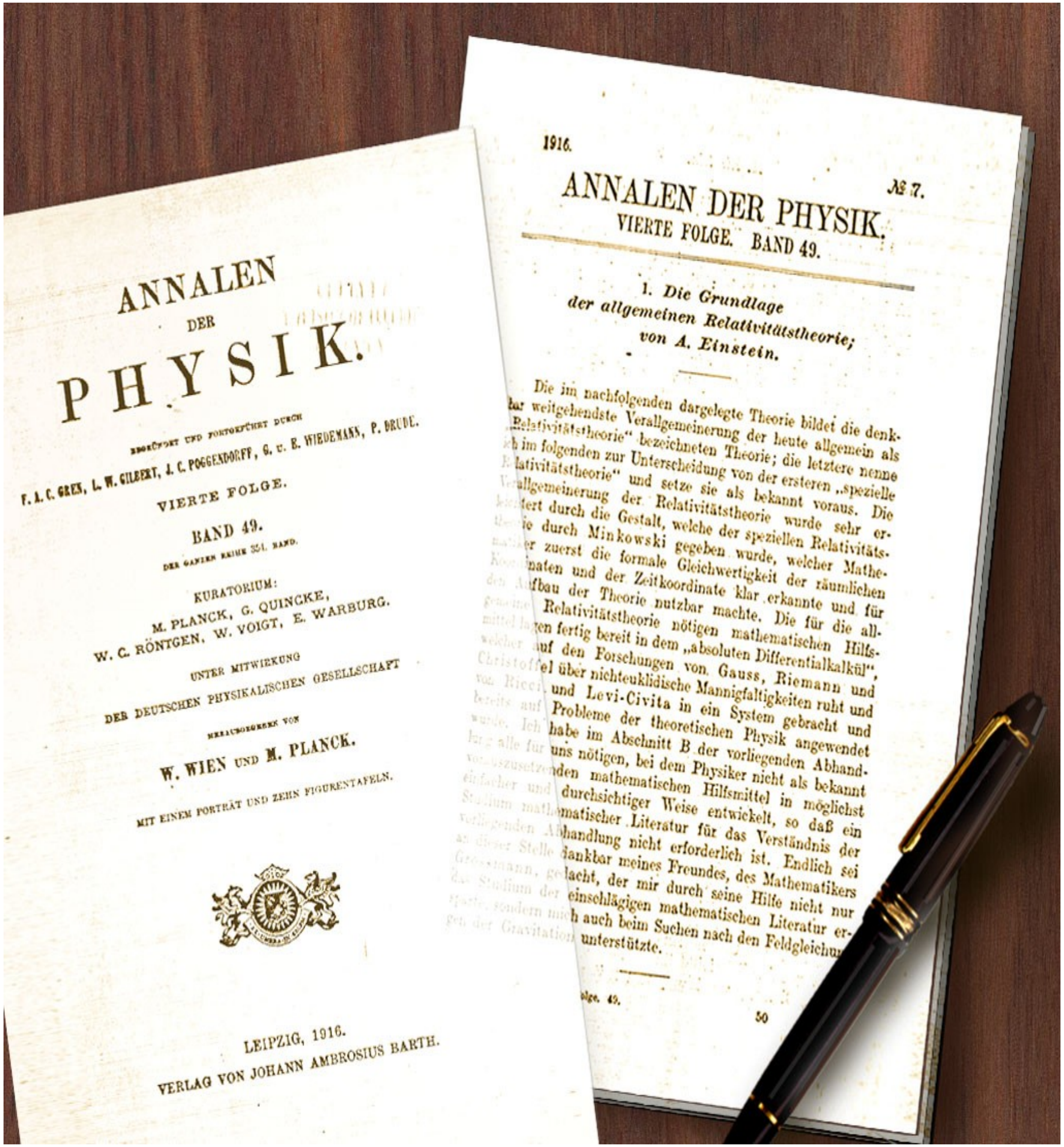


Heisenberg:
$\Delta E \Delta t \sim h$

- There is a temporary violation of the law of conservation of mass/energy, but this violation occurs within the timescale of the uncertainty principle and, thus, has no impact on macroscopic laws

The Theory of General Relativity

- Between 1907 and 1915, Einstein developed a new theory of gravity based on two observations:
  - Inertial mass ($F=ma$) appeared to be equal to the gravitational mass ($F=Gm_1m_2/r^2$)
  - Effect of gravity is mimicked by acceleration
- Special relativity relates observations in one reference frame with another moving at constant speed
- General relativity deals with accelerated reference frames


ANNALEN
DER
PHYSIK.
BEGRÜNDET UND FORTGEFÜHRT DURCH
F. A. C. GREN, L. W. GILBERT, J. C. POGGENDORFF, G. u. E. WIEDEMANN, P. DRUDE.
VIERTE FOLGE.
BAND 49.
DER GANZEN REIHE 354. BAND.
KURATORIUM:
M. PLANCK, G. QUINCKE,
W. C. RÖNTGEN, W. VOIGT, E. WARBURG.
UNTER MITWIRKUNG
DER DEUTSCHEN PHYSIKALISCHEN GESELLSCHAFT
HERAUSGEGEBEN VON
W. WIEN UND M. PLANCK.
MIT EINEM PORTRÄT UND ZEHN FIGURENTAFELN.
LEIPZIG, 1916.
VERLAG VON JOHANN AMBROSIUS BARTH.

1916. № 7.
ANNALEN DER PHYSIK.
VIERTE FOLGE. BAND 49.

1. *Die Grundlage der allgemeinen Relativitätstheorie; von A. Einstein.*

Die im nachfolgenden dargelegte Theorie bildet die denkbar weitgehendste Verallgemeinerung der heute allgemein als „Relativitätstheorie" bezeichneten Theorie; die letztere nenne ich im folgenden zur Unterscheidung von der ersteren „spezielle Relativitätstheorie" und setze sie als bekannt voraus. Die Verallgemeinerung der Relativitätstheorie wurde sehr erleichtert durch die Gestalt, welche der speziellen Relativitätstheorie durch Minkowski gegeben wurde, welcher Mathematiker zuerst die formale Gleichwertigkeit der räumlichen Koordinaten und der Zeitkoordinate klar erkannte und für den Aufbau der Theorie nutzbar machte. Die für die allgemeine Relativitätstheorie nötigen mathematischen Hilfsmittel lagen fertig bereit in dem „absoluten Differentialkalkül", welcher auf den Forschungen von Gauss, Riemann und Christoffel über nichteuklidische Mannigfaltigkeiten ruht und von Ricci und Levi-Civita in ein System gebracht und bereits auf Probleme der theoretischen Physik angewendet wurde. Ich habe im Abschnitt B der vorliegenden Abhandlung alle für uns nötigen, bei dem Physiker nicht als bekannt vorauszusetzenden mathematischen Hilfsmittel in möglichst einfacher und durchsichtiger Weise entwickelt, so daß ein Studium mathematischer Literatur für das Verständnis der vorliegenden Abhandlung nicht erforderlich ist. Endlich sei an dieser Stelle dankbar meines Freundes, des Mathematikers Grossmann, gedacht, der mir durch seine Hilfe nicht nur das Studium der einschlägigen mathematischen Literatur ersparte, sondern mich auch beim Suchen nach den Feldgleichungen der Gravitation unterstützte.

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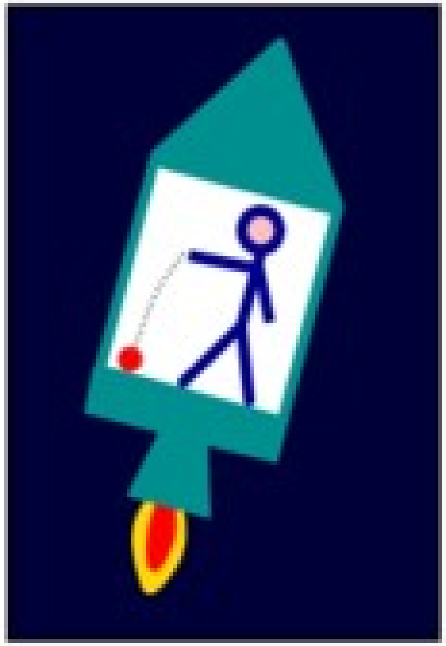
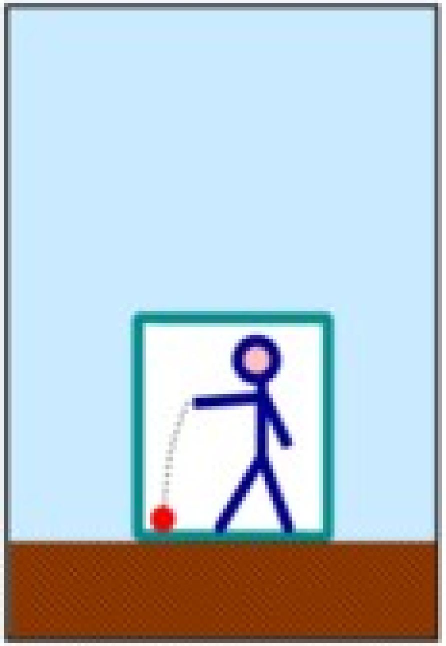
Gravity = acceleration

- Accelerated reference frames are identical to a gravitational field

If you are in a closed box, you can't tell if you are at rest on Earth's surface or accelerating in a rocket at 1 g = 9.8 m/s^2



1g accel. rocket

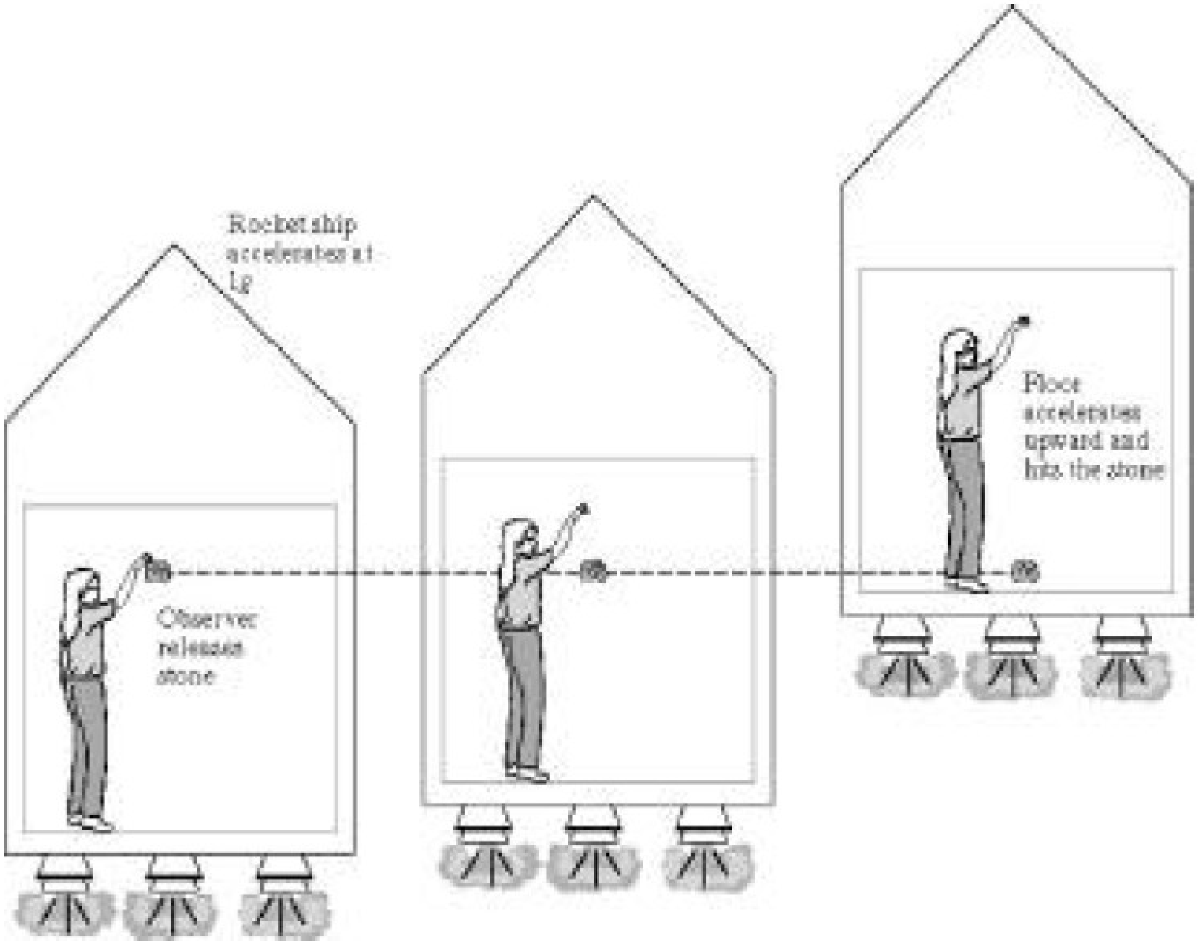


Earth

Nasa's 20g centrifuge

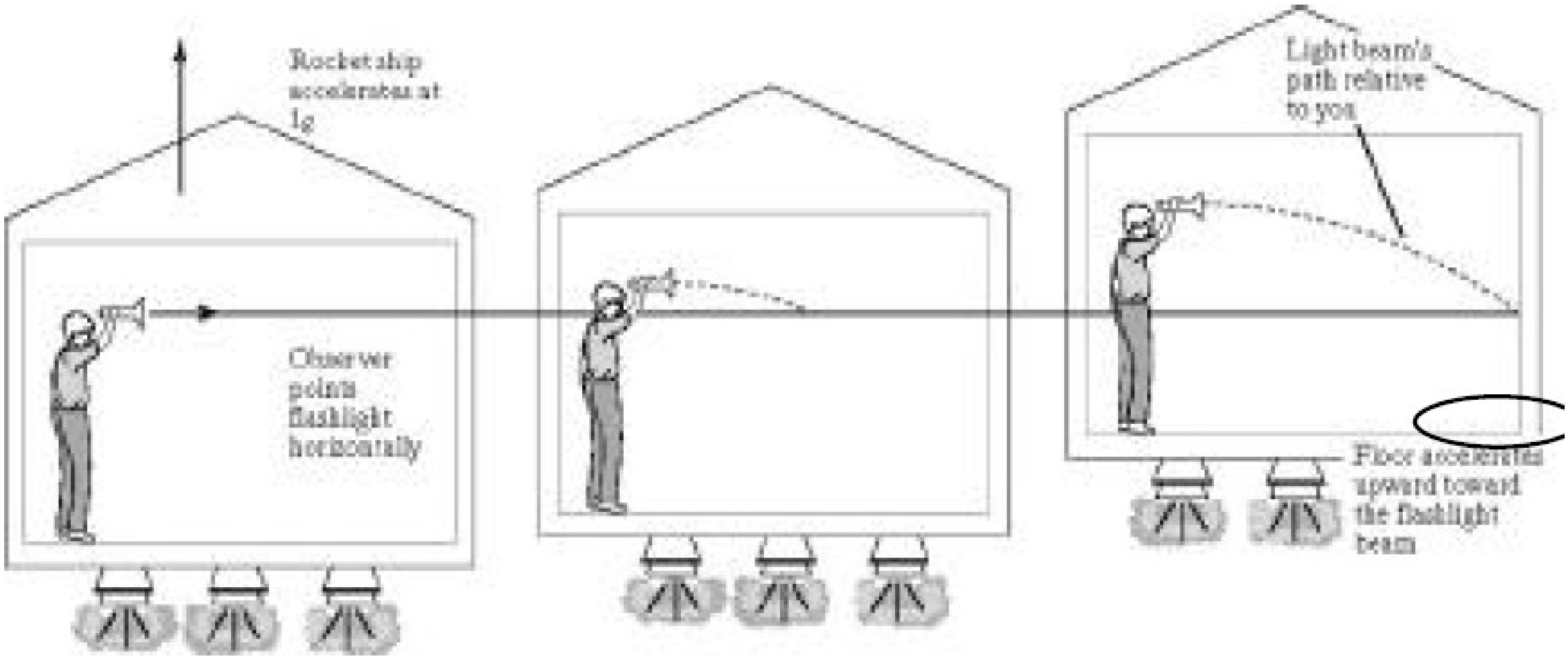
Equivalence Principle in GR

- Every accelerated observer experiences the same laws of Nature. In other words, no experiment inside a sealed room can tell you whether you are accelerating in the absence of gravity, or at rest in the presence of gravity
  - These two situations yield identical results…
  - Trajectory of stone inside rocket at 1 g is exactly the same as in Earth
  - Jumping up & down, etc… all the same!



Acceleration bends light

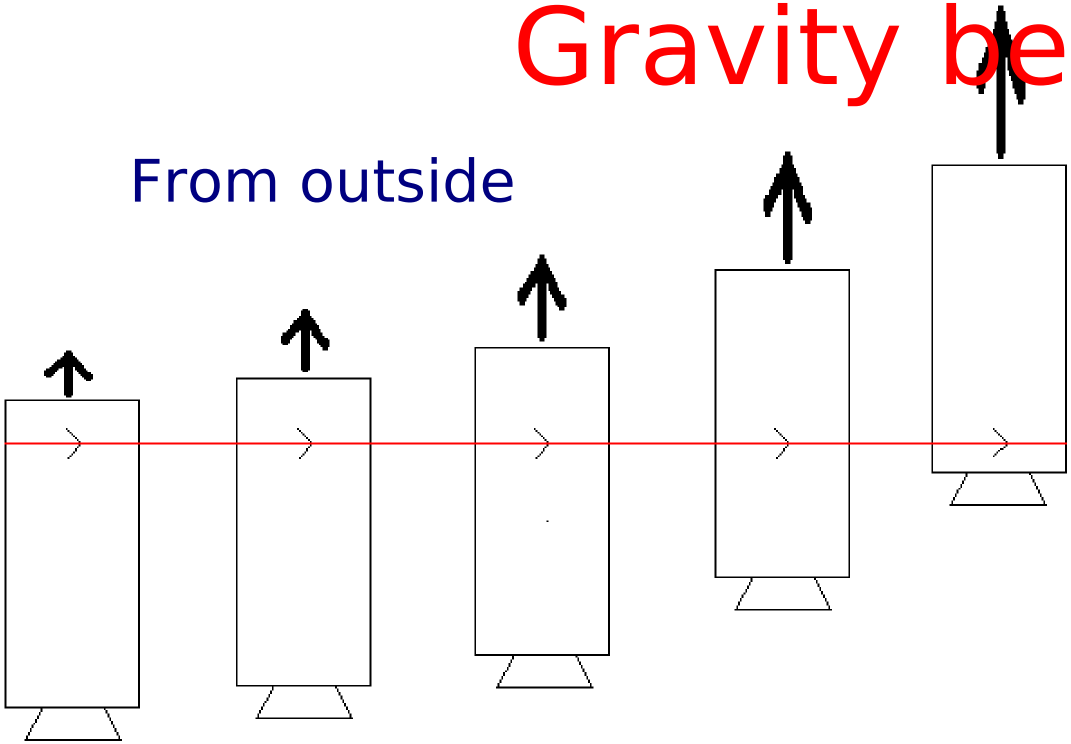
- Imagine you were accelerating upwards very rapidly and you shined a beam of light what would you see?



- You would observe that the light beam would appear to bend, since the light beam would hit lower on the wall than expected
- This is because during the time that the light is moving to the right, the floor is accelerating upward
- But if this happens in an accelerated system, it must also happen wherever there is gravity

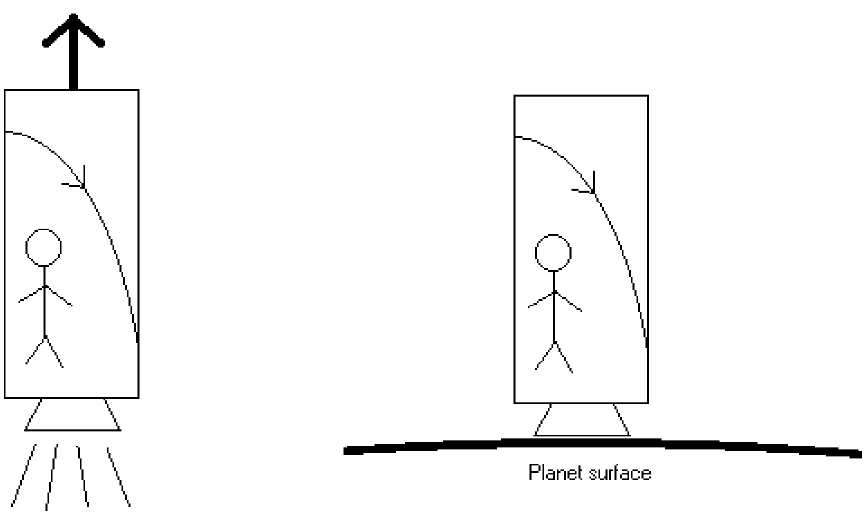
Gravity bends light

From outside



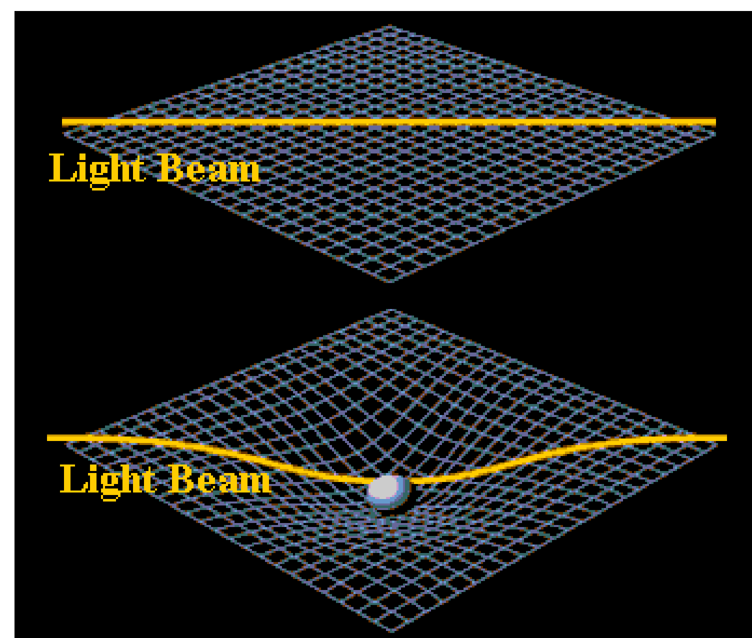
View of our accelerating elevator. The beam of light travels in a straight line (as respresented by the red line); it is the elevator that is accelerating. The time interval between each view of the elevator is the same. We can thus imagine that if we were standing in the elevator, the beam of light would thus appear to follow a curved path, as show below (lower left).

From inside



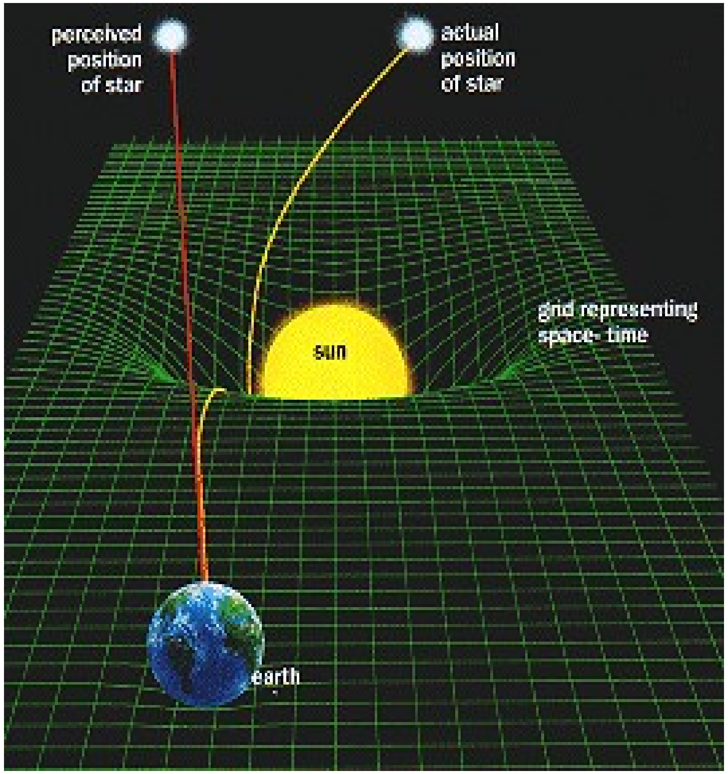
Due to the "equivalence principle," if you were to stand inside the elevator, it would not be possible to tell whether you were accelerating (above left) or whether you were instead placed in a gravitational field, on a planet's surface (above right). And because we know that in an accelerating frame like that in the elevator on the left, a beam of light would appear to follow a bent path, we ought to observe the same bending of light if we were on a planet's surface. (The effect of bending is extremely exaggerated here.) That's how we can conclude that gravity bends light!

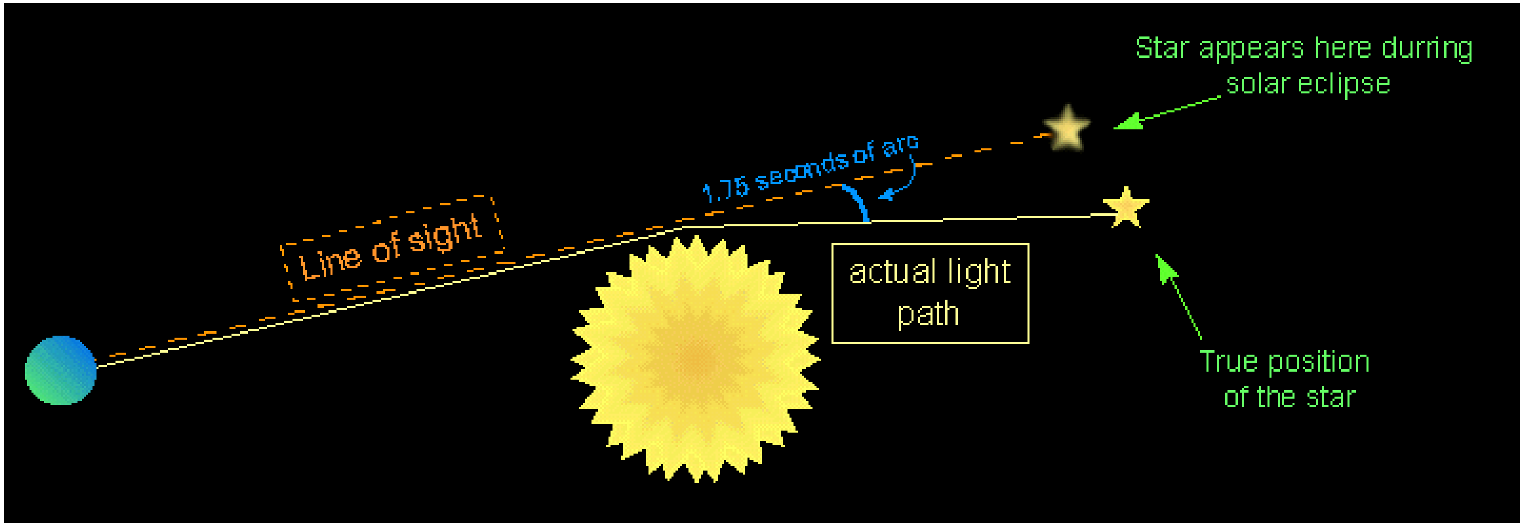
- Light is not bent because of the gravitational force 'per se'
- Light moves on a geodesic (=shortest distance between two points)
- So Einstein interprets gravitation as a curvature of spacetime
- Gravity warps spacetime
- Light just follows the curvature of space

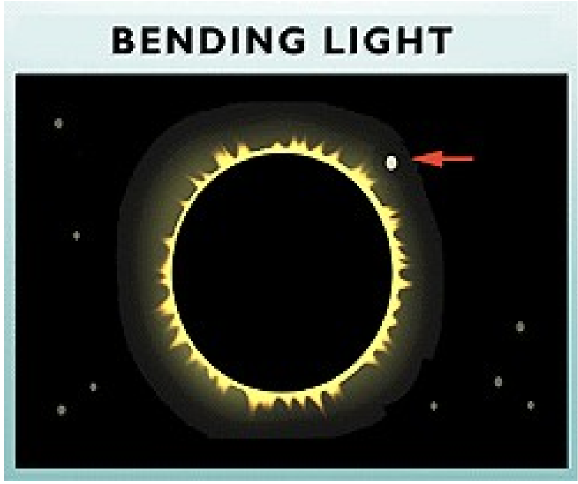


Experimental evidence

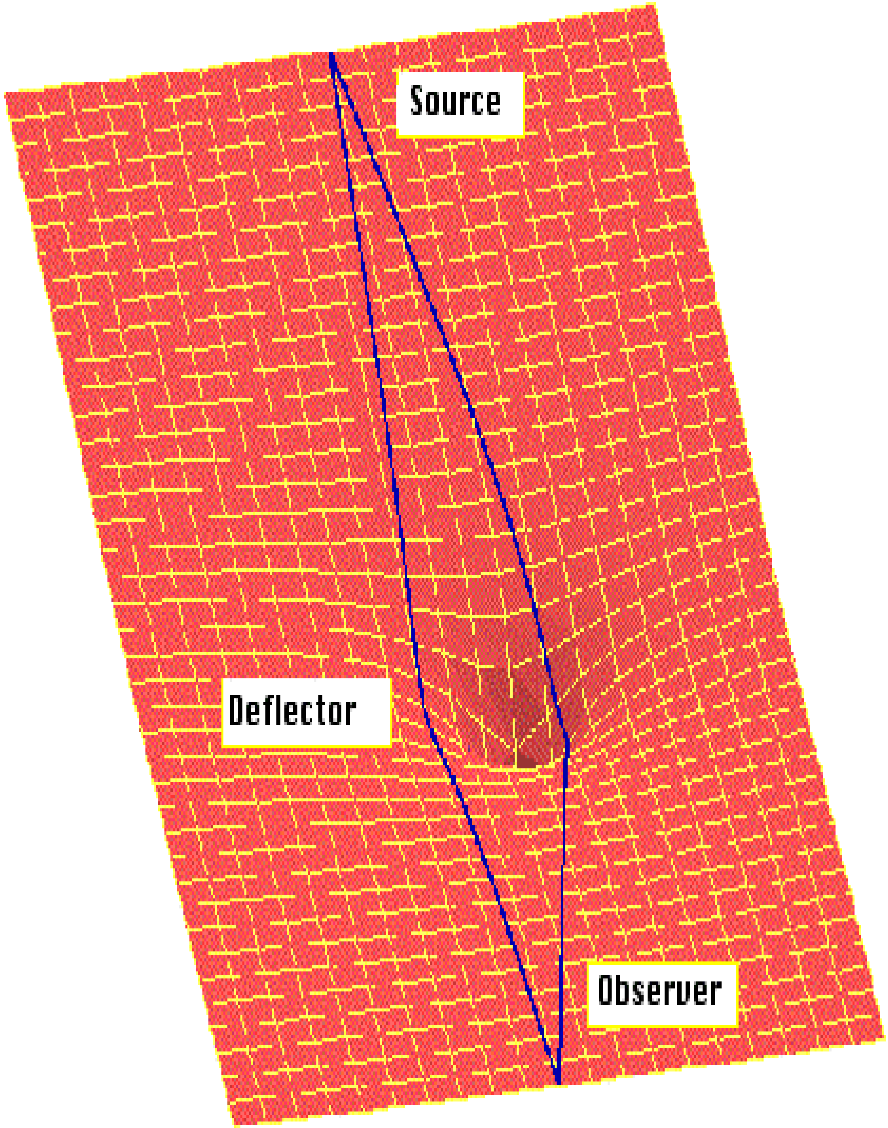
- Our Sun distorts spacetime into a gravity well
- As the Sun passes against the background of stars, their position seem to move slightly: 1/1000 of a degree
- Confirmed in 1919 eclipse

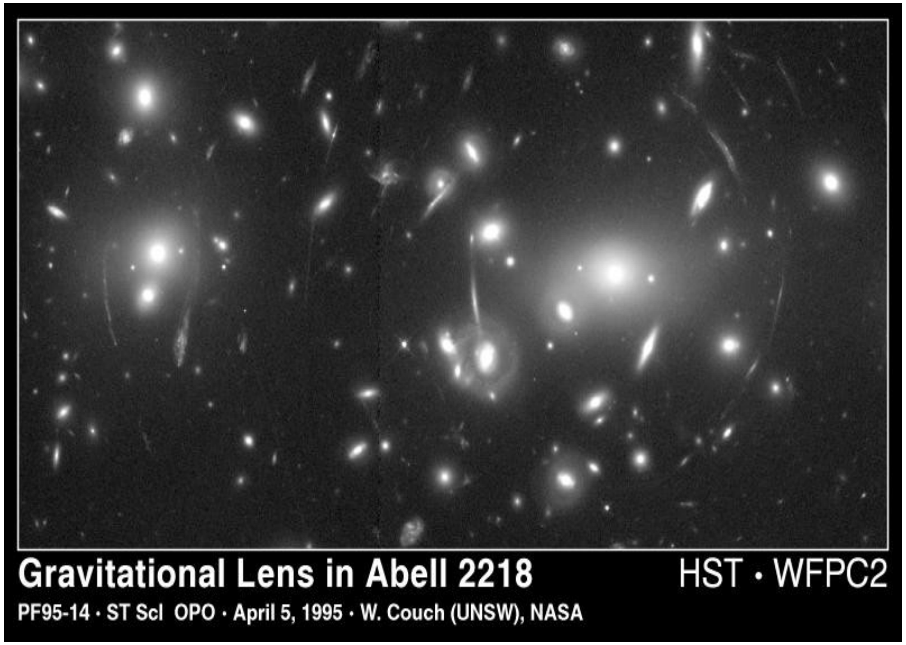


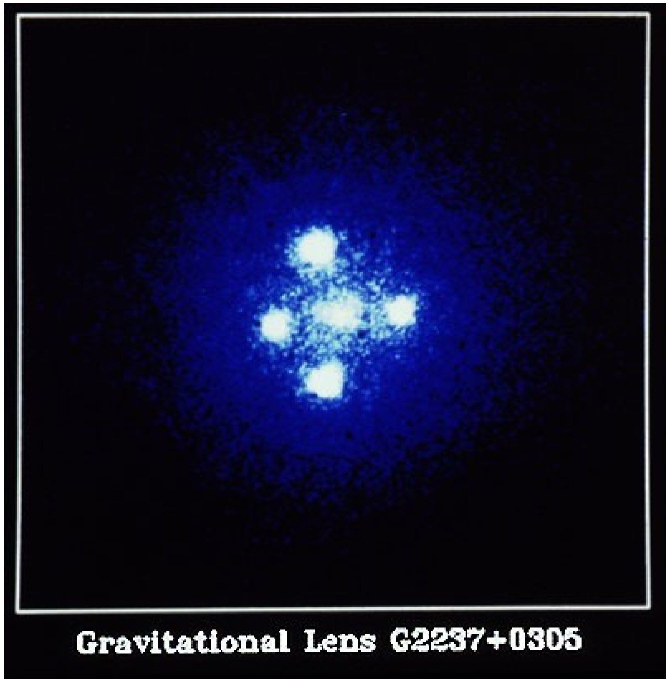




Gravitational lensing

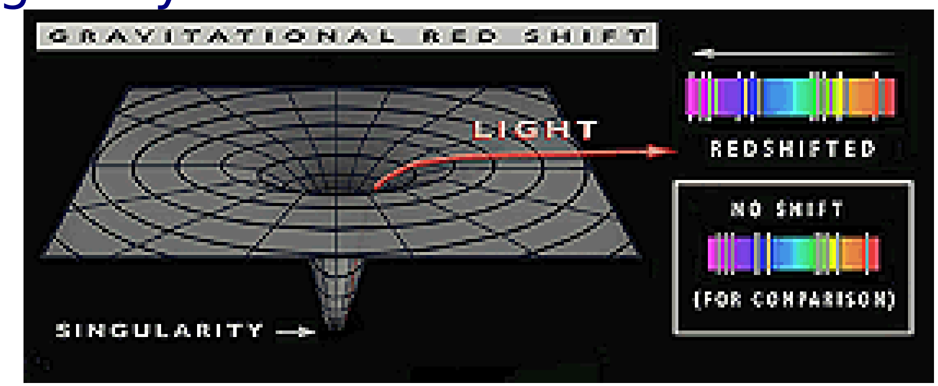


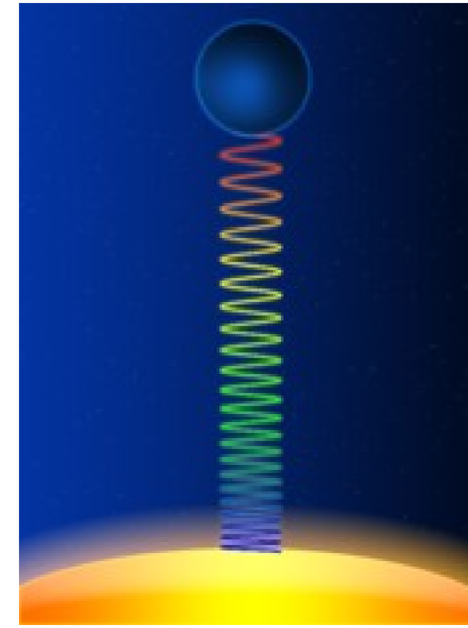


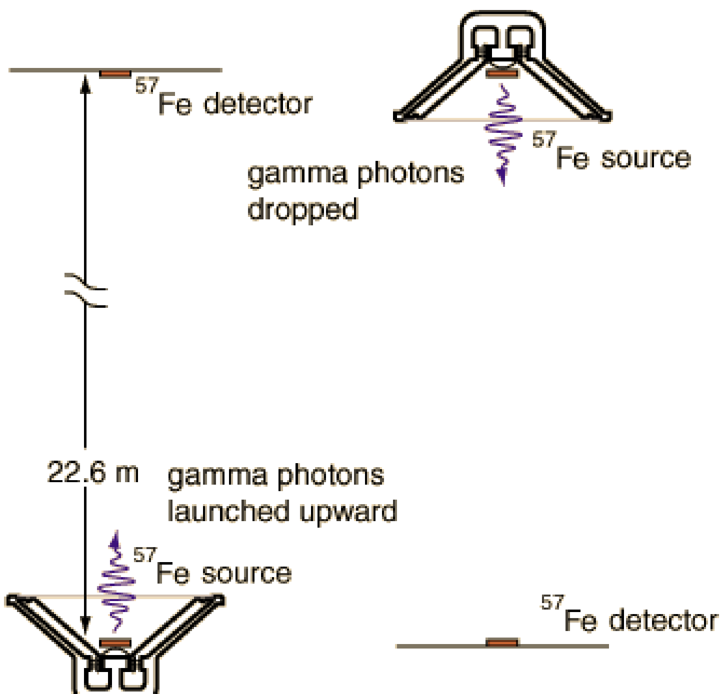


Pound-Rebka experiment

- Light loses energy fighting its way out of a gravitational well
- Frequency shifts lower (wavelength becomes longer)
- Stronger gravity ➔ more redshift



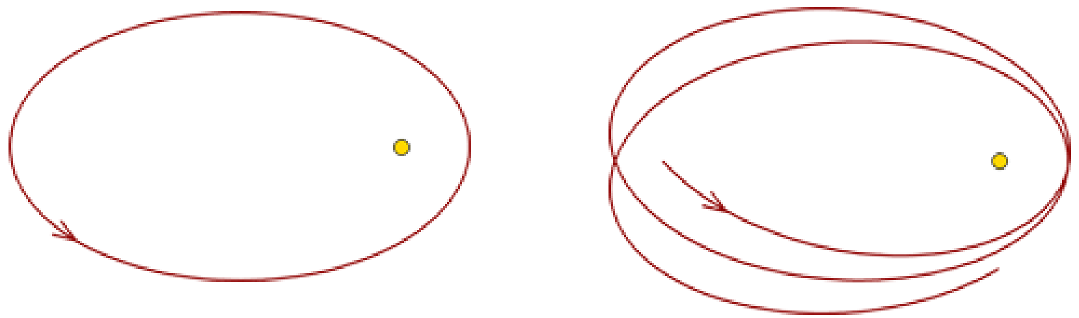




- In 1959 showed evidence for the gravitational redshift in the lab
- Used the Jefferson tower at Harvard (22.6 m ➔ expected energy shift $\Delta E/E = 5 \cdot 10^{-15}$)
- Need very short wavelength gamma rays
- Source was placed in a loud speaker to scan the source velocity
- When the velocity was right (compensated for the gravitational redshift), the detector absorbed the gamma rays

Perihelion advance of Mercury

- GR is needed to understand fine details of planetary orbits



Animation

- The perihelion (distance of closest approach) of Mercury to the Sun advances 2 degrees (120 seconds) every century
- 80 seconds are accounted for by perturbations from other planets, etc... but the remaining 40 seconds were unaccounted for
- General relativity predicts an additional 43 seconds of arc and was one of the first triumphs of Einstein's theory

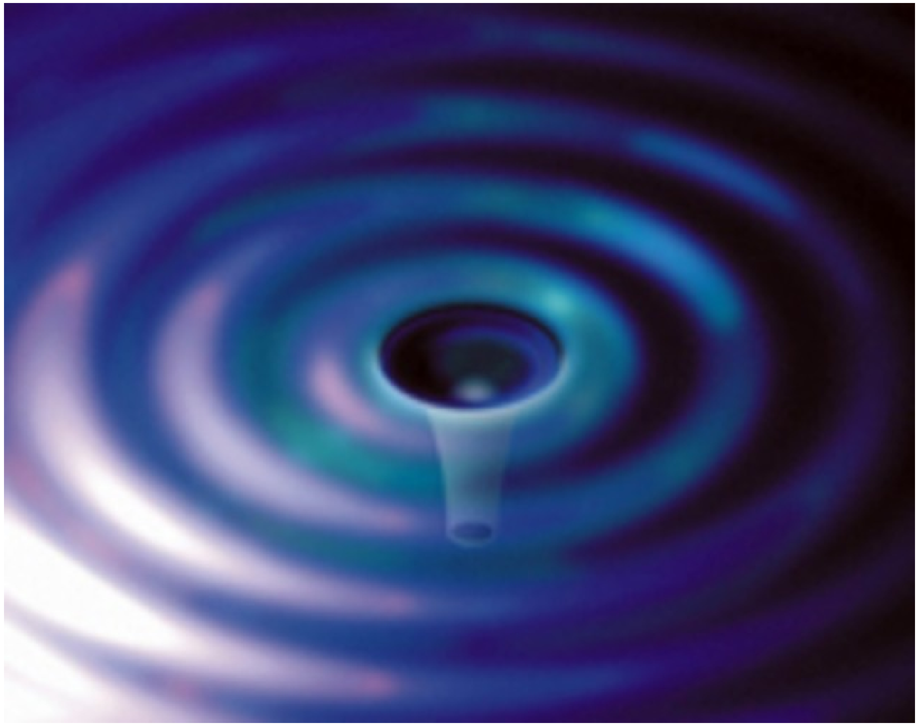
GPS

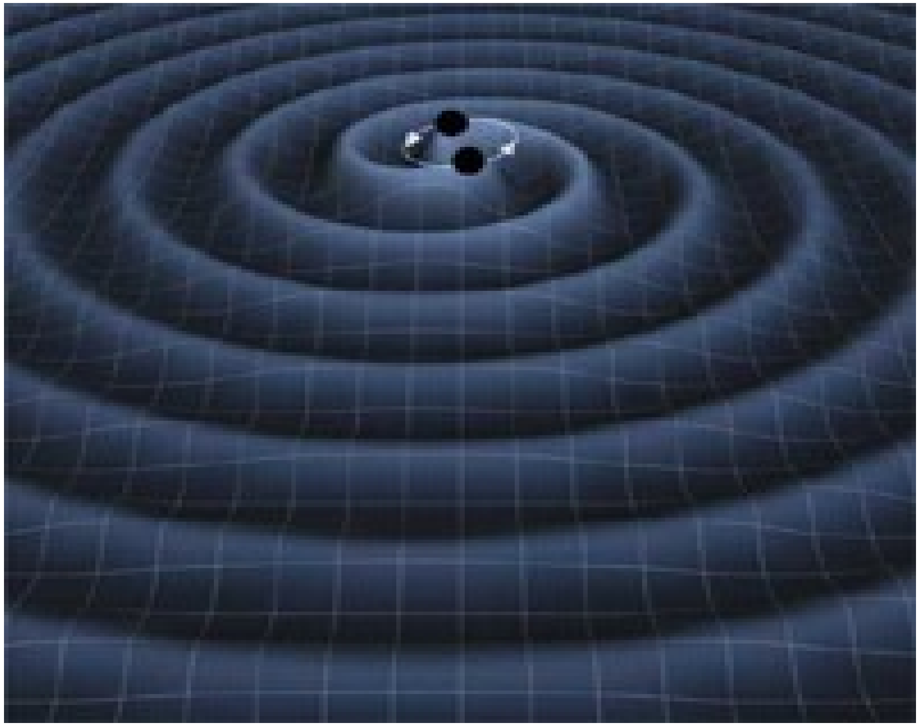
GPS operations would fail if we didn't account for relativity

- Special relativity:
  - **time dilation**: clocks on satellites will tick more slowly than clocks on the ground
  - 7 microsec per day
- General relativity: a clock closer to a massive object will tick more slowly
  - **Mass of Earth**: clocks on satellites are faster than close to the surface of Earth
  - 49 microsec per day
- Total shift of 38 microsec per day
- Or an error of 10 km per day would accumulate

Gravitational waves

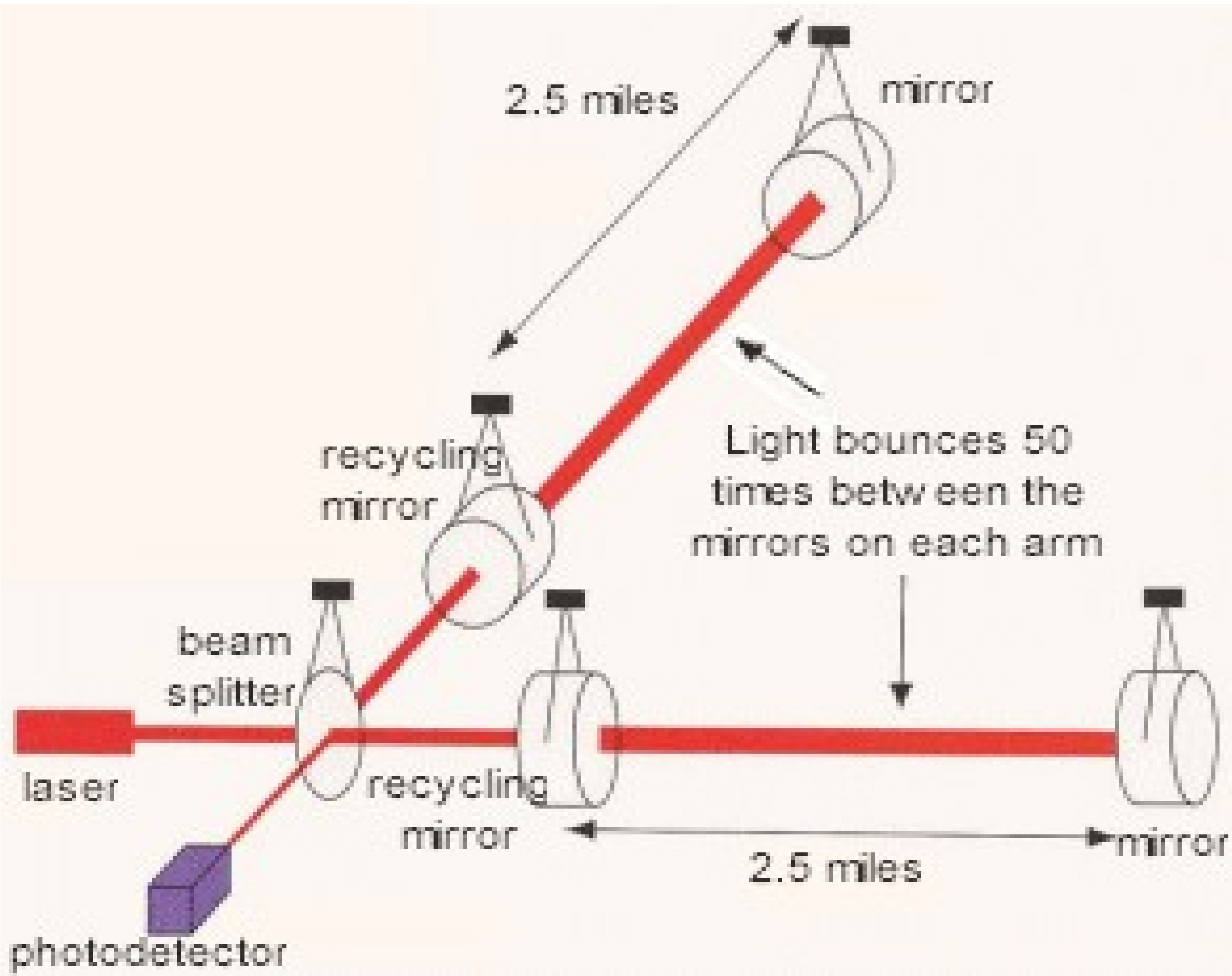
- Another fundamental prediction of GR is gravitational waves
- We saw that EM waves can be produced by accelerating charges
- Einstein's theory of General Relativity predicts that gravitational waves are emitted when a huge mass undergoes a rapid spatial change (acceleration)
- One way this could happen is when a huge star dies, it eventually collapses to form a super massive black hole, or when two massive stars orbit each other





LIGO

- Laser Interferometer Gravitational wave Observatory
- Experiment to observe gravitational waves from “out there”
- Gravitational wave has an amplitude of 10^{-22} m
- Like observing the orbit of Saturn shifting closer to the sun by the diameter of a single Hydrogen atom



- The light bounces back and forth on each arm
- If the lengths of the 2 arms are exactly the same, the light should come back and constructively interfere
- If a gravitational wave passes, and stretches one dimension and compresses the other, you will get destructive interference for a short time

Two sites for LIGO

Hanford, Wa

Livingston, La

Why 2.5 miles?

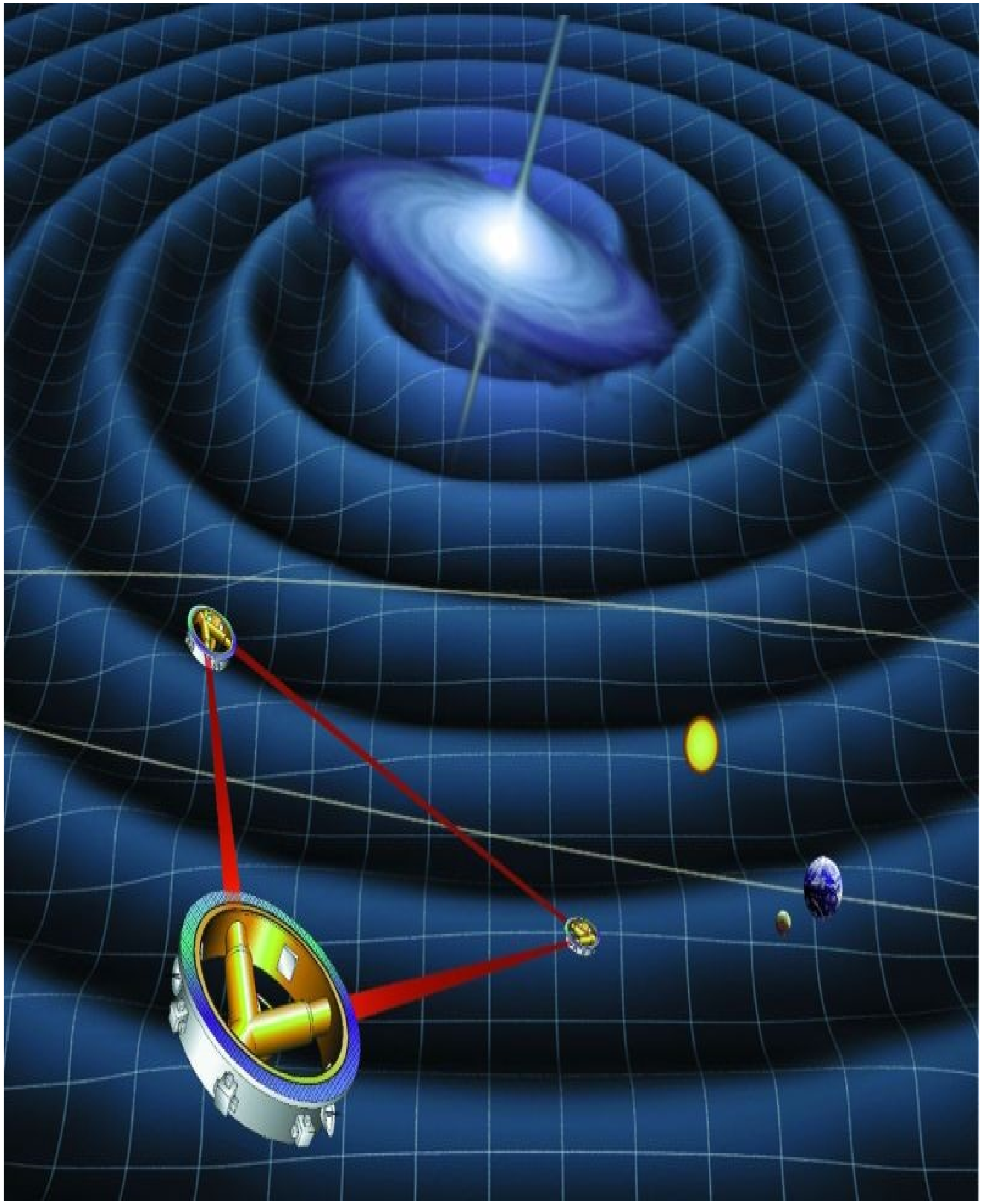
- The amount of stretching and compressing of space is a fraction of the size (~ $1/10^{22}$). So by making the arms bigger, one gets a larger displacement.

Why 2 laboratories?

- If a gravitational wave passes by/through the earth, you should see the expansion & contraction of space at both labs at ~same time. Useful for immediate rejection of events which are not at the same time (seismic activity, for example)

LISA

- Laser Interferometer Space Antenna: ESA + NASA
- Launch in 2019-2020
- 3 satellites widely separated in space
- Watch how the distance between them varies as the gravitational wave passes by
- Future gravitational wave astronomy possible?



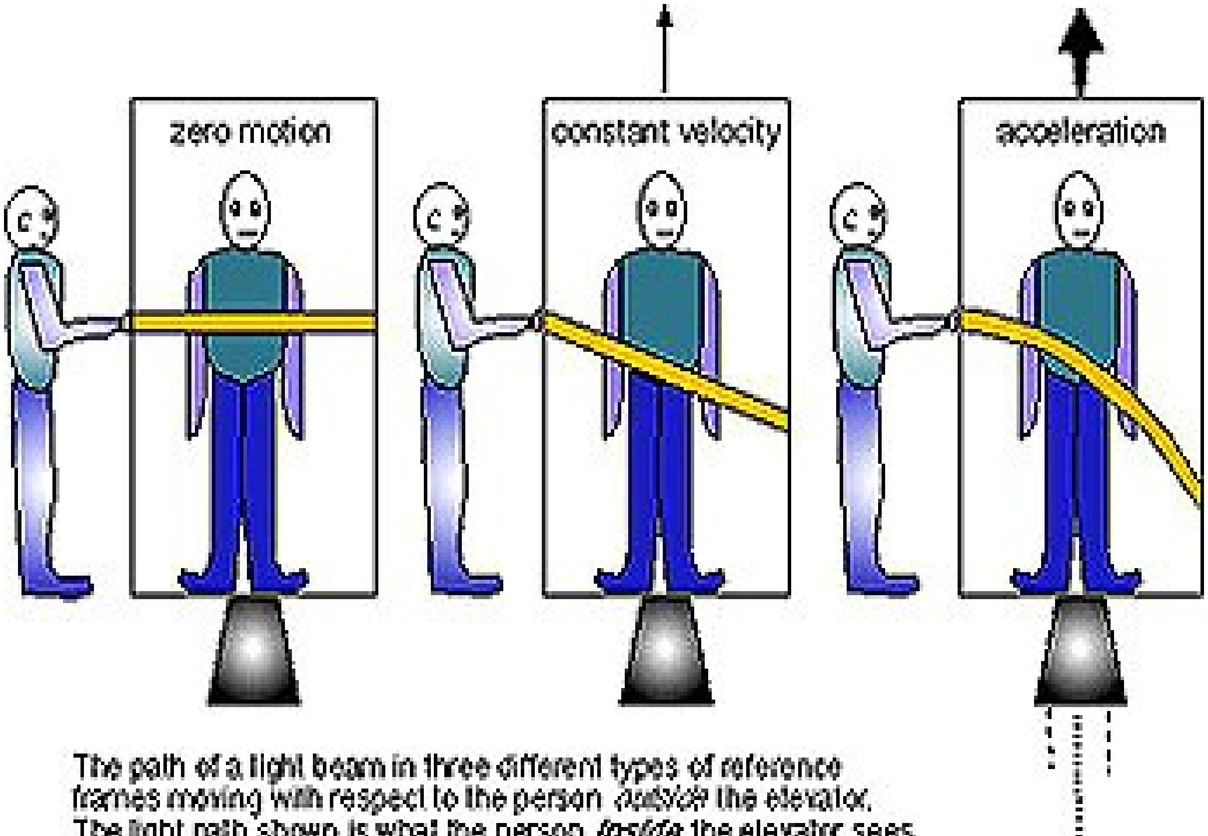
Relativity and vacuum

- Famous equation of Einstein's General Relativity:

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Geometry = Matter + Energy

- Geometry refers to a measure of how curved space is
- General Relativity in a nutshell:
  - Matter determines the curvature of space
  - The space determines how matter will move in it...
- Special Relativity: Space and time are intertwined
- Space can change: static Universe is hard to achieve!
- Geometry can be non-Euclidean
- **The dynamics of spacetime determines the fate of the Universe**
- We will see more about this in next lecture: Cosmology



The path of a light beam in three different types of reference frames moving with respect to the person *outside* the elevator. The light path shown is what the person *inside* the elevator sees. Under large acceleration, the beam of light will curve downward. It should also do that in a region of strong gravity.