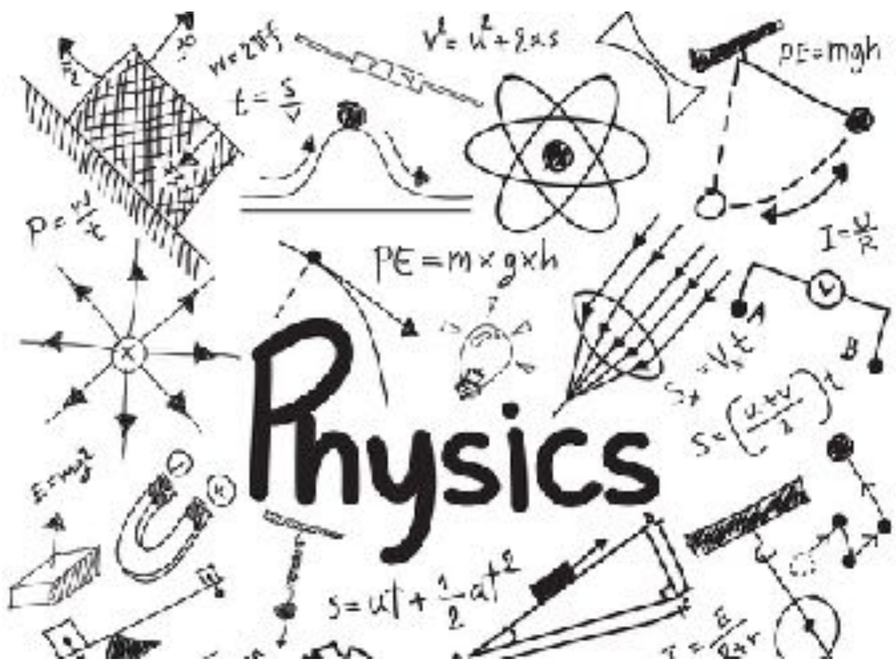
Frontiers in Physics and Astrophysics

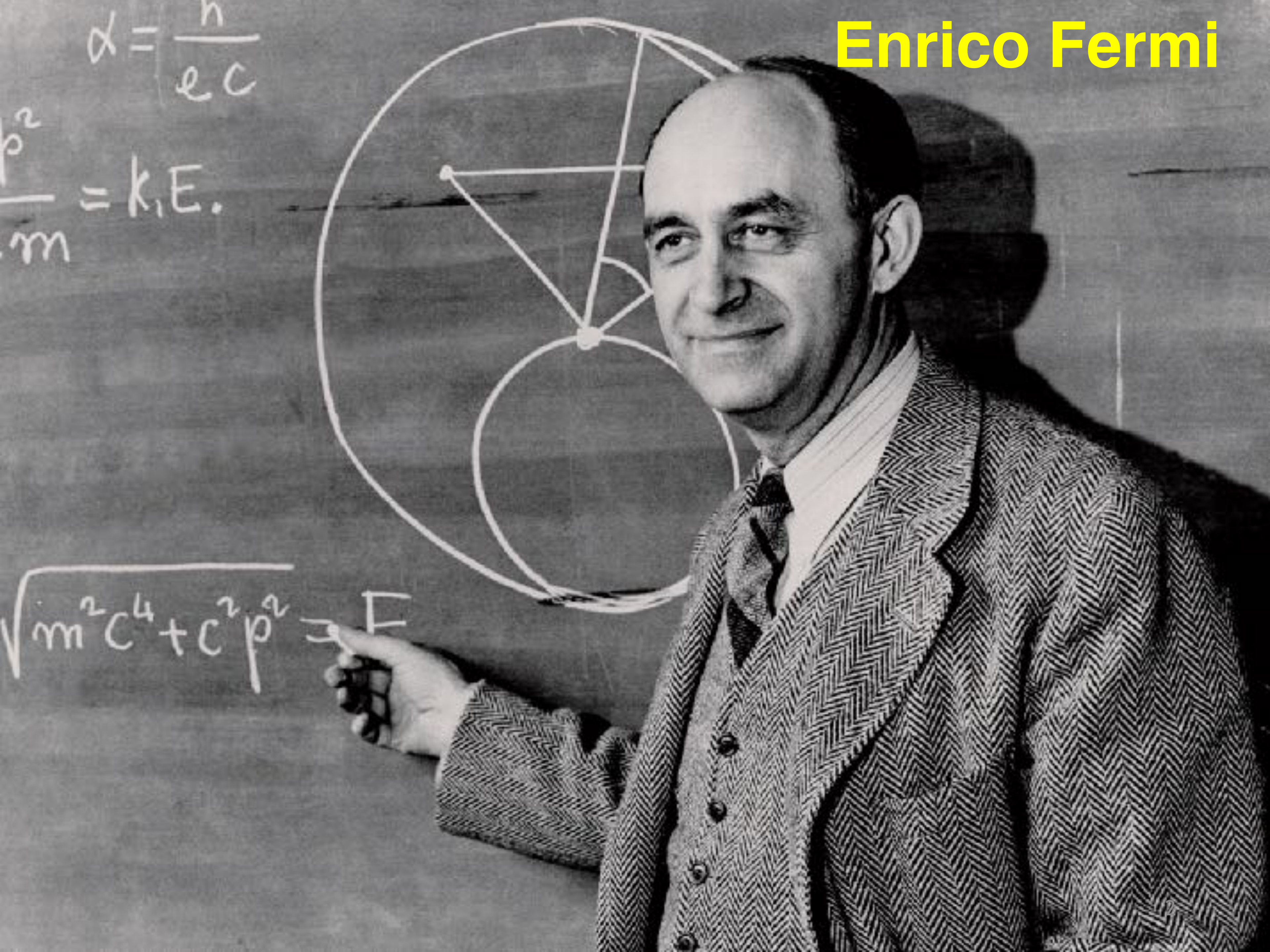
Fermi Lecture 12 –Gravitational Waves (1)



Barry C Barish

27-February 2020

Enrico Fermi



Enrico Fermi Lectures 2019-2020 Frontiers of Physics and Astrophysics

- Explore frontiers of Physics and Astrophysics from an Experimental Viewpoint
- Some History and Background for Each Frontier
- Emphasis on Large Facilities and Major Recent Discoveries
- Discuss Future Directions and Initiatives

- Thursdays 4-6 pm
- Oct 10,17,24,one week break, Nov 7
- Nov 28, Dec 5,12,19 Jan 9,16,23
- Feb 27, March 5,12,19

Frontiers

Fermi Lectures 2019-2020 - Barry C Barish

- Course Title: **Large Scale Facilities and the Frontiers of Physics**
- The Course will consist of 15 Lectures, which will be held **from 16:00 to 18:00** in **aula Amaldi**, Marconi building, according to the following schedule:
- 10 October 2019 - Introduction to Physics of the Universe
  17 October 2019 - Elementary Particles
  24 October 2019 - Quarks
  7 November 2019 – Particle Accelerators
  28 November 2019 – Big Discoveries and the Standard Model
  5 December 2019 – Force Carriers – Z, W
  12 December 2019 – Higgs Discovery, Supersymmetry?, Future??
  19 December 2019 – Introduction/History of Neutrinos
  9 January 2020 – Neutrino(2)
  16 January 2020 – Neutrinos(3)
  23 January 2020 – Neutrinos (4)
  27 February 2020 – Gravitational Waves (1)
  5 March 2020 – Gravitational Waves (2)
  12 March 2020 – Gravitational Waves (3)
  19 March 2020 – Future Perspectives
- All Lectures and the supporting teaching materials will be published by the Physics Department.

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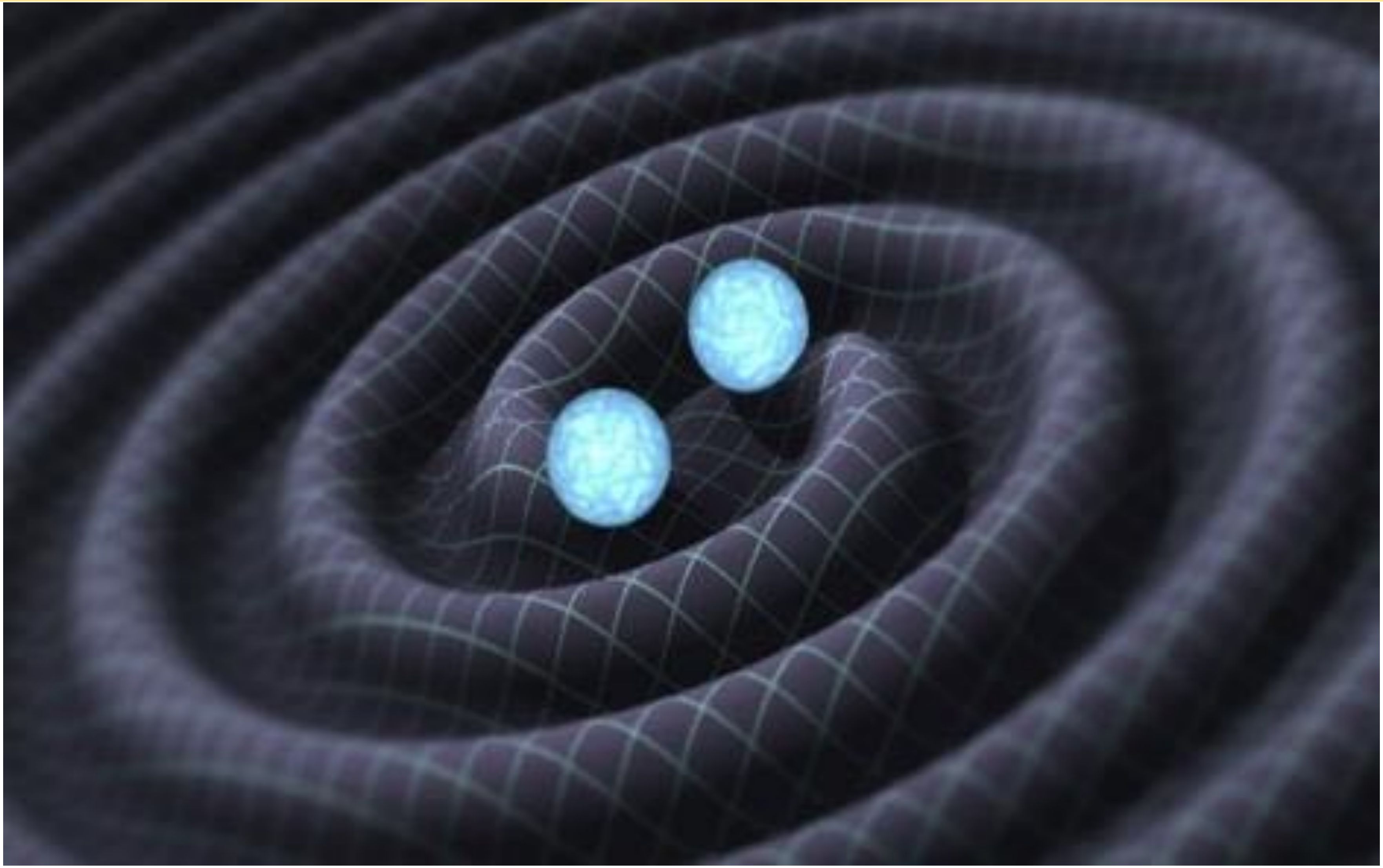
Gravitational Waves (1.3)



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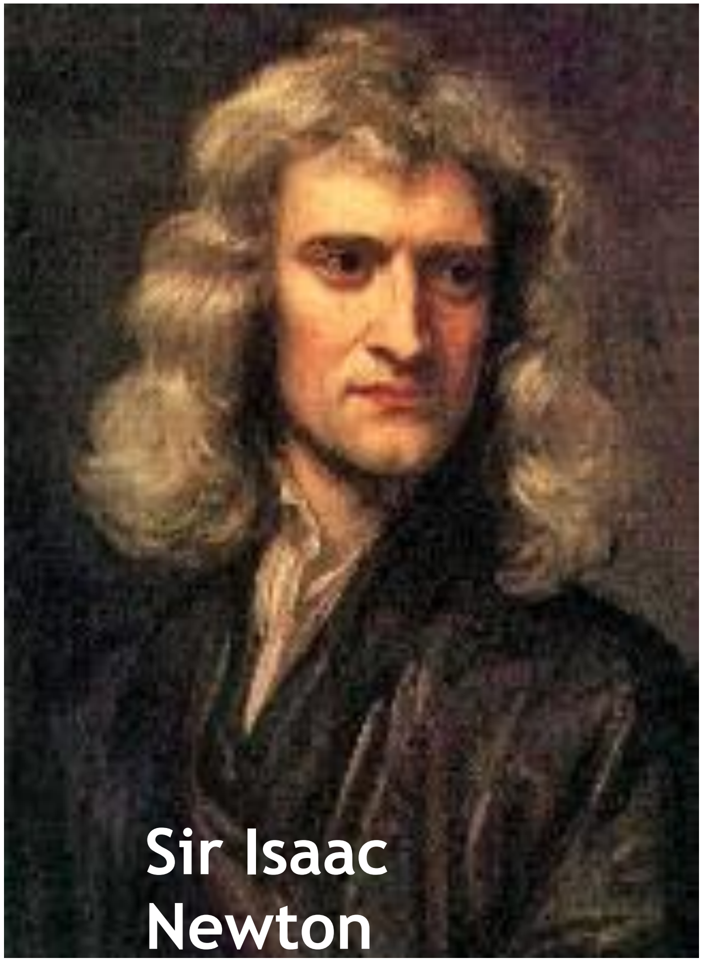
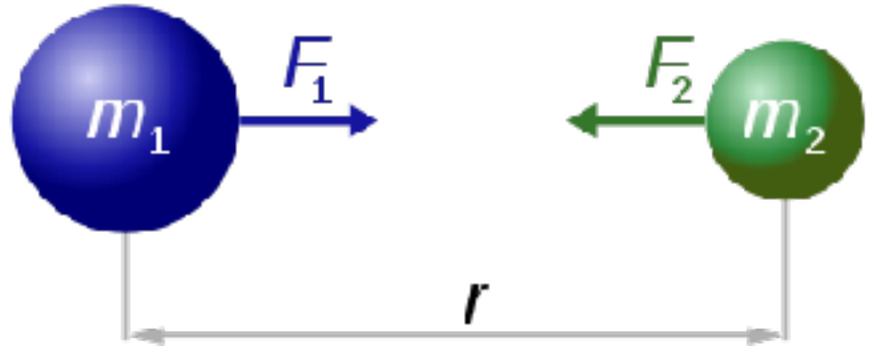
Newton's Theory of Gravity (1687)





$$F_1 = F_2 = G\frac{m_1 \times m_2}{r^2}$$

Universal Gravity: force between massive objects is directly proportional to the product of their masses, and inversely proportional to the square of the distance between them.

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How did Newton change our view of the universe?

Sir Isaac Newton (1642-1727)

- Realized that the same physical laws that operate on Earth also operate in the heavens
  - *one universe*
- Discovered laws of motion and gravity
  - Explained *why* Kepler's laws work
- Much more: Experiments with light; first reflecting telescope, calculus…

Newton's three laws of motion

Newton's first law of motion:

An object moves at constant velocity unless a net force acts to change its speed or direction.

Example: *A spaceship needs no fuel to keep moving in space.*

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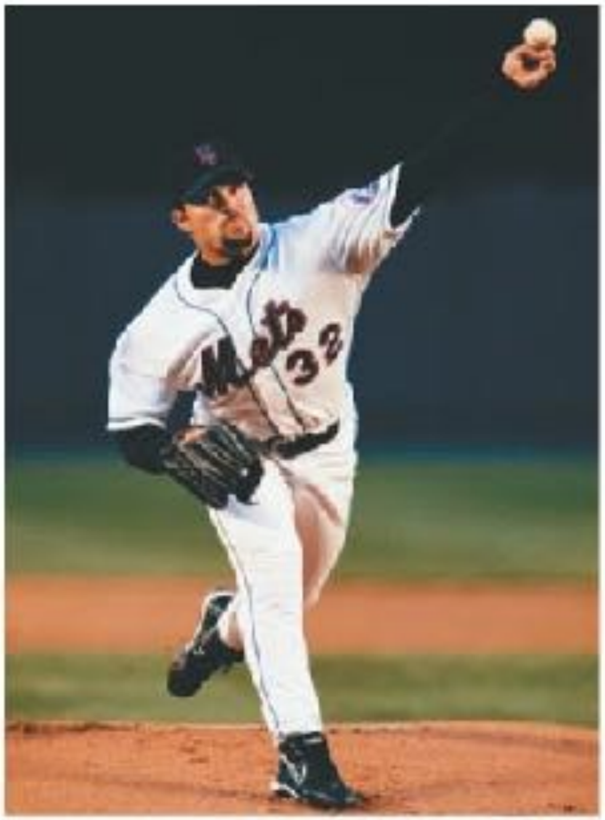
Newton's three laws of motion



Newton's second law of motio

Force = mass x acceleration

$$F = ma$$

Example: *A baseball accelerates as the pitcher applies a force by moving his arm. (Once the ball is released, the force from the pitcher's arm ceases, and the ball's path changes only because of the forces of gravity and air resistance.)*

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Newton's three laws of motion

Newton's third law of motion:

For every force, there is an *equal and opposite* reaction force.

Example: *A rocket is propelled upward by a force equal and opposite to the force with which gas is expelled out its back.*

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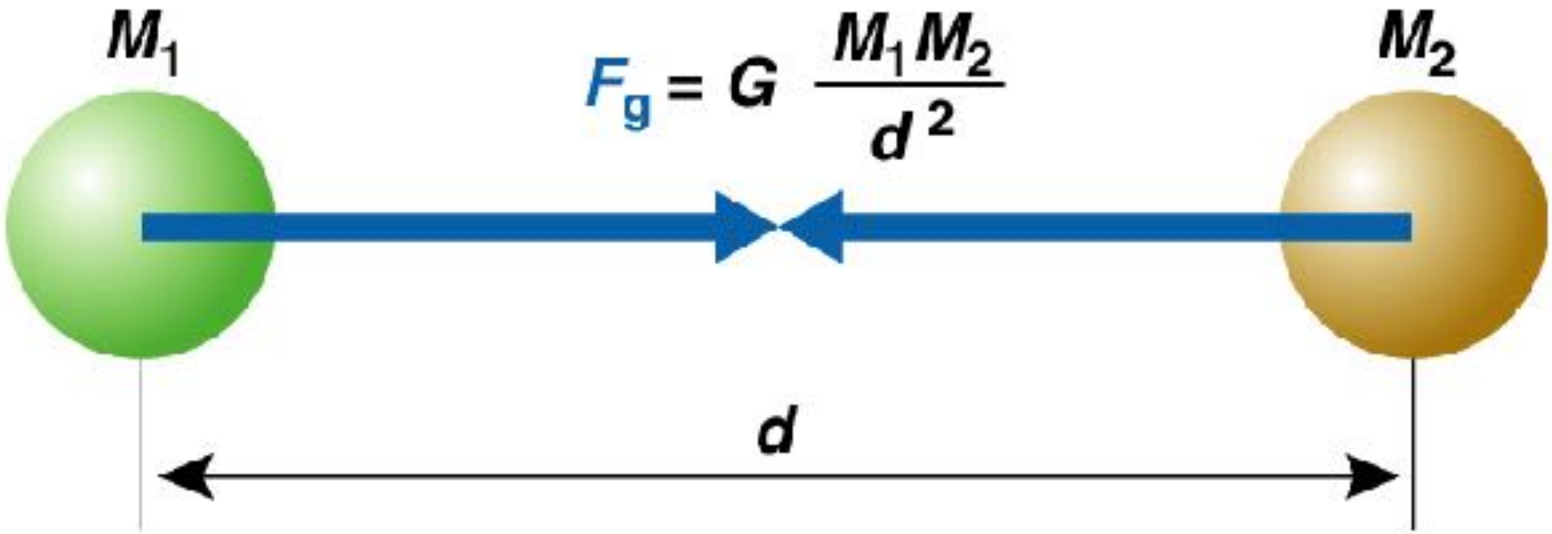
Newton's Universal Law of Gravitation

1. Every mass attracts every other mass.
2. Attraction is *directly* proportional to the product of their masses.
3. Attraction is *inversely* proportional to the *square* of the distance between their centers.



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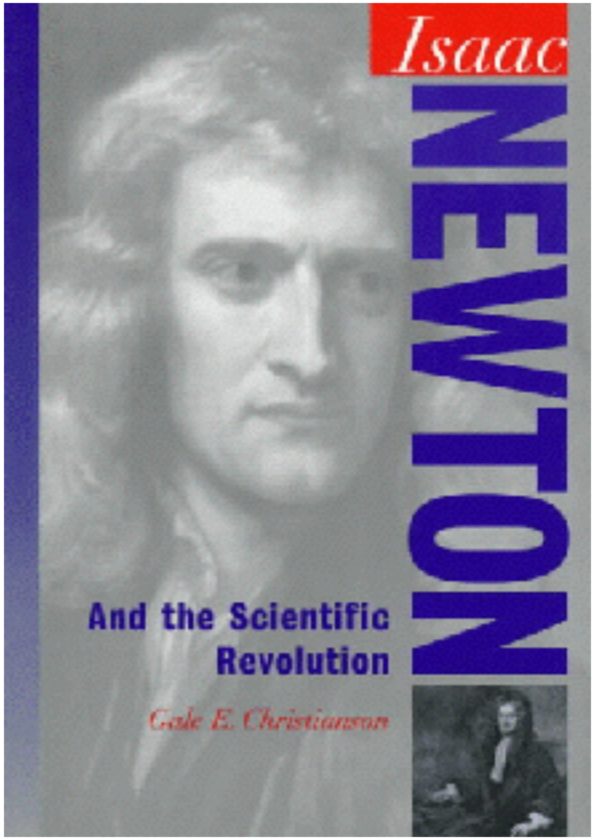
Newton's Universal Gravity

- Three laws of motion and law of gravitation (centripetal force) disparate phenomena
  - eccentric orbits of comets
  - cause of tides and their variations
  - the precession of the earth's axis
  - the perturbation of the motion of the moon by gravity of the sun

- Solved most known problems of astronomy and terrestrial physics
  - Work of Galileo, Copernicus and Kepler unified.



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“The Scientific Method in Newton’s *Principia*

Newton invented a scientific method, which was truly universal in its scope. Newton presented his methodology as a set of four rules for scientific reasoning. These rules were stated in the *Principia* where he proposed that

1) we are to admit no more causes of natural things such as are both true and sufficient to explain their appearances,
2) the same natural effects must be assigned to the same causes,
3) qualities of bodies are to be esteemed as universal, and
4) propositions deduced from observation of phenomena should be viewed as accurate until other phenomena contradict them.

"The Scientific Method"

These four concise and universal rules for investigation were truly revolutionary. By their application, Newton formulated the universal laws of nature with which he was able to unravel virtually all the unsolved problems of his day. Newton went much further than outlining his rules for reasoning, however, actually describing how they might be applied to the solution of a given problem. The analytic method he invented far exceeded the more philosophical and less scientifically rigorous approaches of Aristotle and Aquinas.

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“The Scientific Method”

Newton refined Galileo’s experimental method, creating the compositional method of experimentation still practiced today. In fact, the following description of the experimental method from Newton's *Optics* could easily be mistaken for a modern statement of current methods of investigation, if not for Newton's use of the words "natural philosophy" in place of the modern term "the physical sciences." Newton wrote, "As in mathematics, so in natural philosophy the investigation of difficult things by the method of analysis ought ever to precede the method of composition.

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"The Scientific Method"

This analysis consists of making experiments and observations, and in drawing general conclusions from them by induction...by this way of analysis we may proceed from compounds to ingredients, and from motions to the forces producing them; and in general from effects to their causes, and from particular causes to more general ones till the argument end in the most general. This is the method of analysis: and the synthesis consists in assuming the causes discovered and established as principles, and by them explaining the phenomena preceding from them, and proving the explanations."

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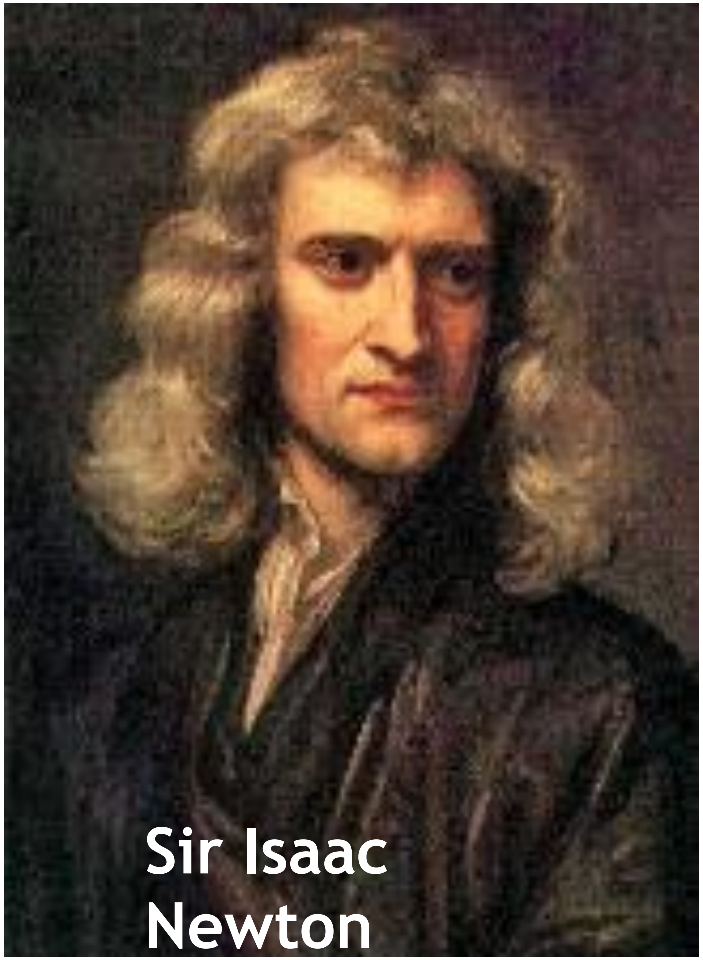
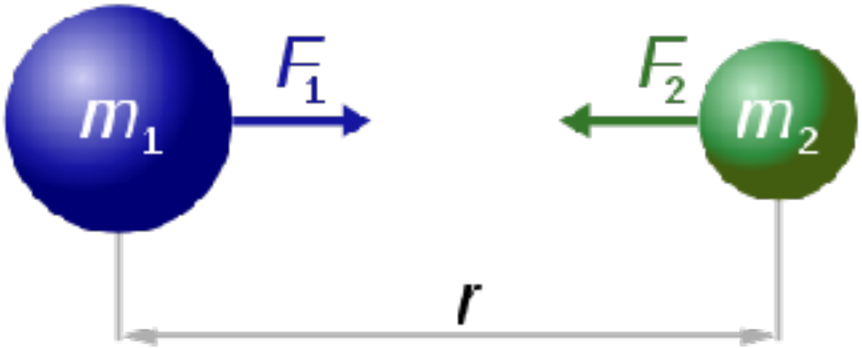
Newton's Theory of Gravity (1687)





$$F_1 = F_2 = G\frac{m_1 \times m_2}{r^2}$$

Universal Gravity: force between massive objects is directly proportional to the product of their masses, and inversely proportional to the square of the distance between them.

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But, Newton did not determine G !!

Henry Cavendish (1731-1810)

- Grandson of the Second Duke of Devonshire, he was considered nobility
- He attended Cambridge University from 1749 – 1753, but left without earning a degree
- His inherited fortune enabled him to pursue scientific studies
- Viewed as solitary and eccentric, he had no friends apart from his family

Discovered Hydrogen: In 1766, In a paper called *On Factitious Airs* Cavendish addresses a "inflammable air" which forms water as a result of combustion. (Antoine Lavoisier later reproduced the experiment giving Cavendish's element the name Hydrogen)

Established an accurate composition of the atmosphere

~79% "phlogisticated" air (nitrogen and argon)

~21% "dephlogisticated" air (oxygen)

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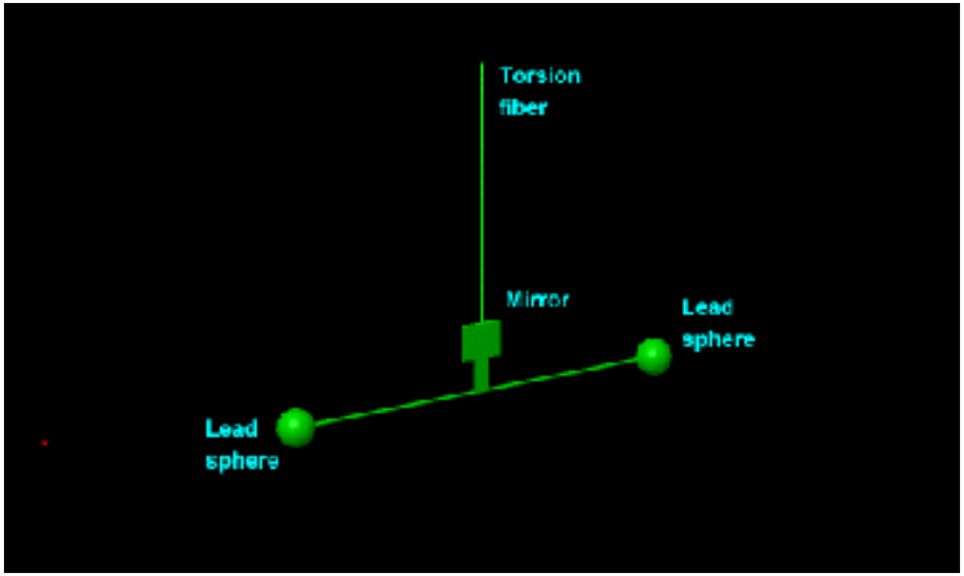
Cavendish – Weighing the Earth



Cavendish used a torsion balance to measure the attraction between two 350 pound lead spheres

He calculated the earth's mass to be 5.9725 10^{21} tons

From this ---

Cavendish: G = 6.75 10^{-11} Nm^2/kg^2

Now: G = 6.67259 10^{-11} Nm^2/kg^2

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Our Solar System

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Properties of our Solar System

1. Planets orbit roughly in the ecliptic plane.
2. Planetary orbits are slightly elliptical, and very nearly circular.
3. Planets and Sun revolve and orbit in a west-to-east direction. The planets obliquity (tilt of rotation axes to their orbits) are small. Uranus and Venus are exceptions.
4. The planets differ in composition. Their composition varies roughly with distance from the Sun: dense, metal-rich planets are in the inner part and giant, hydrogen-rich planets are in the outer part.
5. Meteorites differ in chemical and geologic properties from the planets and the Moon.
6. The rotation rates of the planets and asteroids are similar (5 to 15 hours).
7. Planet distances from the Sun obey Bode's law.
8. Planet-satellite systems resemble the solar system.
9. The Oort Cloud and Kuiper Belt of comets.
10. Planets contain ~99% of the solar system's AM but Sun contains >99% of solar system's mass.

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Orbits of the Planets

- Planets moves around the Sun in an orbit effected by the Sun’s mass, and to a less extent, by other bodies in the Solar System.

- Laws governing planetary motion were formulated by Johannes Kepler and based on Tycho Brahe’s observations.

- Kepler’s Laws:

  1. Planets have elliptical orbits with the Sun at one focus.
  2. As a planet orbits, a line connecting the planet to the Sun sweeps out equal areas in equal times.
  3. The square of the orbital period is proportional to the cube of the semimajor axis of the orbit.

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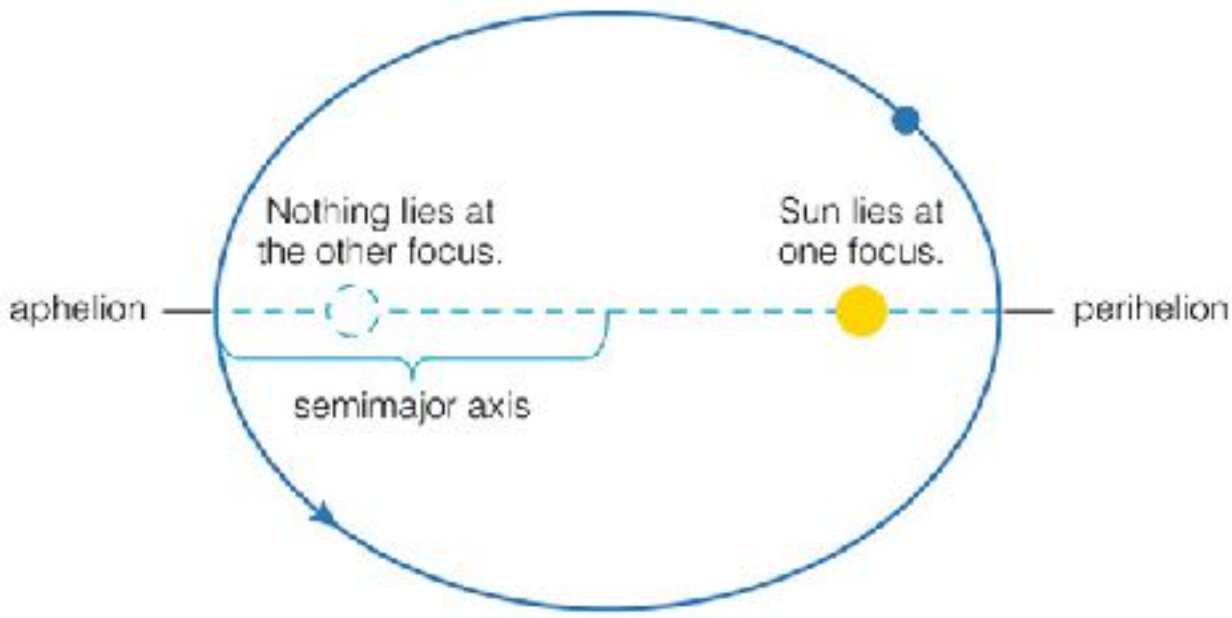
Kepler's 1st Law

- Implies that a planet's distance from the Sun varies during its orbit.
  - Closest point to Sun: *perihelion*.
  - Farthest point from Sun: *aphelion*.
  - Average of perihelion and aphelion is called the *semimajor axis*.



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Kepler's 2nd Law

- Angular momentum of planet: $L = r \times p = m\,(r \times v)$.

- During Δt, radius vector sweeps through $\Delta\theta = v_t\,\Delta t / r$, where v_t is the component of v perpendicular to r.

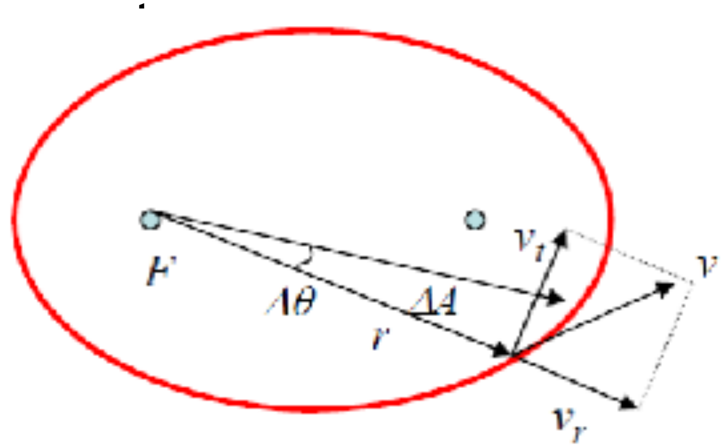
- During this time, the radius vector
  out the triangle, of area $A = r v_t\,\Delta t / 2$.

- As $\Delta t \to 0$, $dA/dt = r v_t / 2 = 1/2\, r^2\, (d\theta/$

- Now, the magnitude of L is given by

  $$L = m\, v_t\, r = m\, r^2\, d\theta/dt.$$

  $$\Rightarrow dA/dt = L / 2m = const$$



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Kepler's 3rd Law

- *The square of the orbital period is proportional to the cube of the semimajor axis of the orbit:*

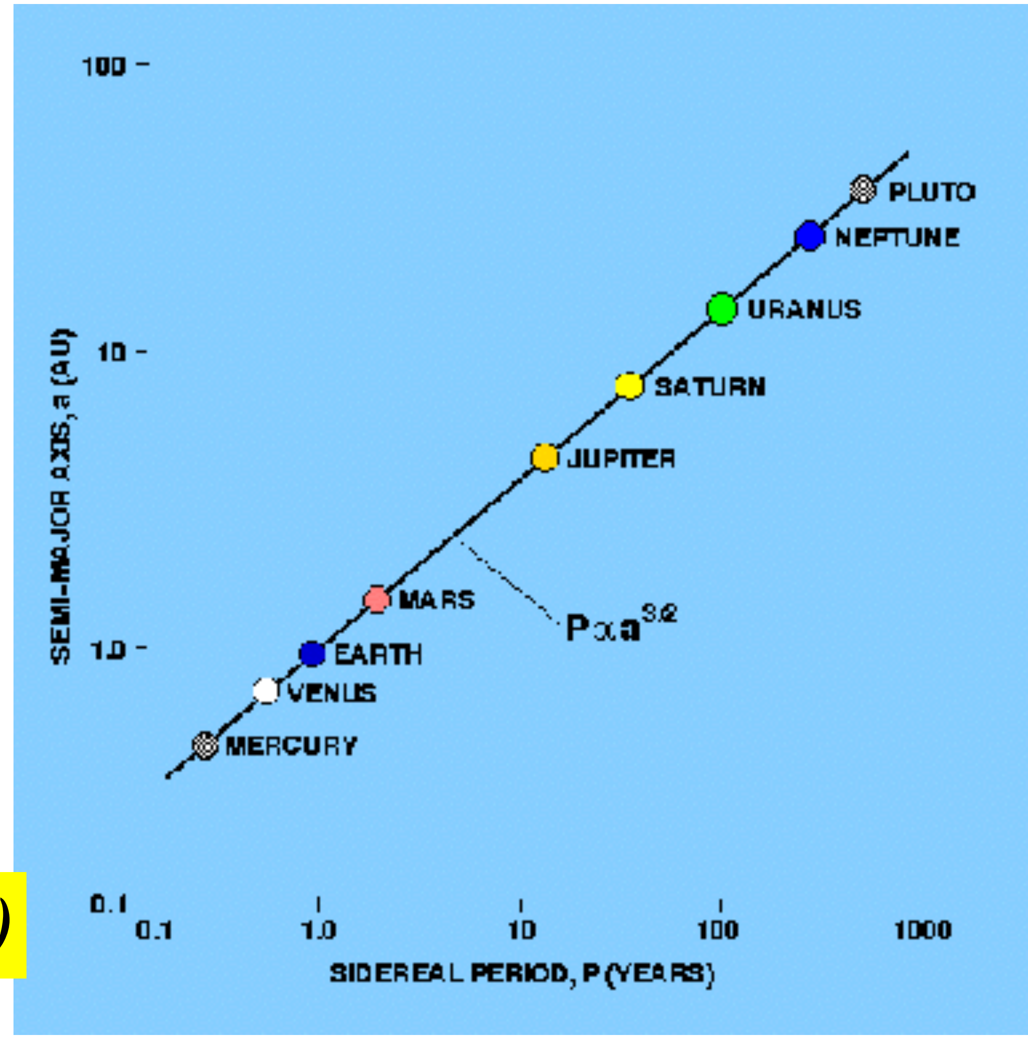
$$P^2 \propto a^3$$

- P is the period measured in years and a is the semimajor axis in AU.
- Consider m_1 and m_2 orbiting at r_1 and r_2. Both complete one orbit in period P. Forces due to centripetal accelerations are:

$$F_1 = m_1\, v_1^2 \;/\; r_1 = 4\,\pi^2\; m_1\, r_1 \;/\; P^2$$

$$F_2 = m_1\, v_2^2 \;/\; r_2 = 4\,\pi^2\; m_2\, r_2 \;/\; P^2$$

us $P^2 = 4\,\pi^2\, a^3 \;/\; G(m_1 + m_2)$



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Titius-Bode Law

$$a = 0.4 + 0.3 \times 2^n$$

where a is the semimajor axis in (AU) and the exponent, n, takes values minus infinity, 1,2,3, ...

Planet	n	Predicted	Accepted
Mercury	- infinity	0.4	0.387
Venus	0	0.7	0.723
Earth	1	1	1
Mars	2	1.6	1.524
Asteroid belt	3	2.8	~2.8
Jupiter	4	5.2	5.204
Saturn	5	10	9.582
Uranus	6	19.6	19.201

The first test of the law occurred a few years later (1781) when William Herschel discovered Uranus --- at the distance predicted by the relationship.

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Bode's Law (cont.)

- Law lead Bode to predict existence of another planet between Mars and Jupiter - asteroids belt later found.
- Uranus fitted law when discovered.
- <u>Neptune was discovered in 1846 at the position predicted by Verrier and Adams, to explain the deviation of Uranus from its predicted orbit.</u>
- Pluto's orbit when discovered in 1930 did not fit the relation. Not a "planet" anymore!

Planet	***Distance (AU)***	r_n ***(AU)***
Uranus	19.2	19.6
Neptune	30.07	38.8
Pluto	39.5	77.2

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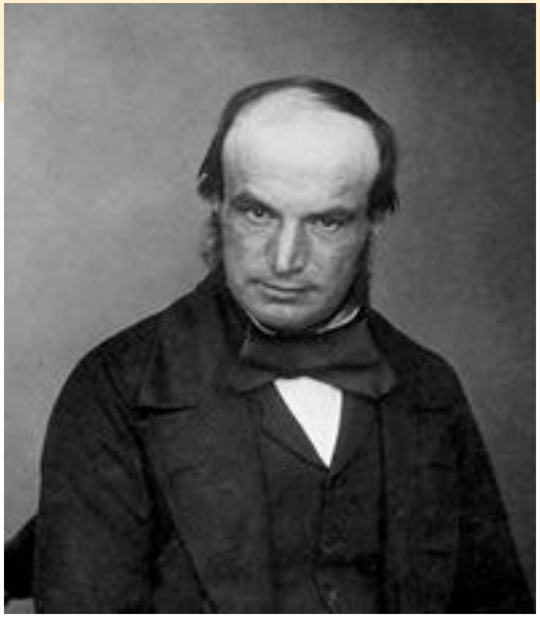
Discovery of Neptune



John Couch Adams
1819-1892

Urbain Le Verrier
1811 - 1877

- After the discovery of Uranus, it was noticed that its orbit was not as it should be in accordance with Newton's laws. It was therefore predicted that another more distant planet must be perturbing Uranus' orbit. Neptune was first observed by Galle and d'Arrest on 1846 Sept 23 very near to the locations independently predicted by Adams and Le Verrier from calculations based on the observed positions of Jupiter, Saturn and Uranus.

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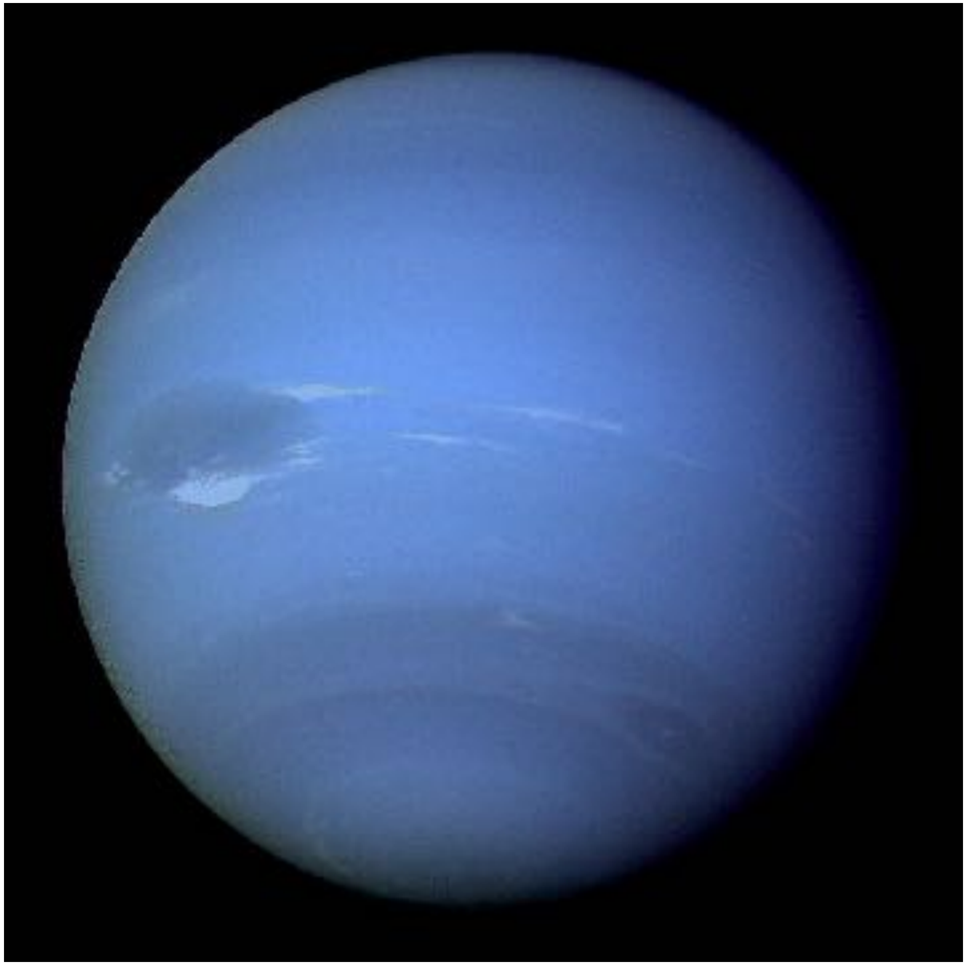
Independent Discovery of Neptune

Le Verrier was a co-predictor of the existence and position of Neptune, along with J.C. Adams. Le Verrier was better served by the German astronomer Galle (who found the planet in one hour) than Adams was by Airy who gave the task to Challis, the director of the Cambridge Observatory. He observed the planet first but did not recognize it.



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Urbain Jean Joseph Le Verrier

- Arago, the director of the Paris observatory who had first suggested that Le Verrier work on this problem, said

  In the eyes of all impartial men, this discovery will remain one of the most magnificent triumphs of theoretical astronomy, one of the glories of the Académie and one of the most beautiful distinctions of our country.

- Le Verrier received many honours and widespread recognition for this achievement. The London *Times* carried the headline on the 1 October 1846:-

  Le Verrier's planet found.

- He was awarded the Copley Medal of the Royal Society of London and, in France, became an officer in the Legion of Honour.

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Independent Discovery of Neptune

- An international dispute arose between the English and French (though not, apparently between Adams and Le Verrier personally) over priority and the right to name the new planet; they are now jointly credited with Neptune's discovery.
  - *Subsequent observations have shown that the orbits calculated by Adams and Le Verrier diverge from Neptune's actual orbit fairly quickly. Had the search for the planet taken place a few years earlier or later it would not have been found anywhere near the predicted location.*

- More than two centuries earlier, in 1613, Galileo observed Neptune when it happened to be very near Jupiter, but he thought it was just a star. On two successive nights he actually noticed that it moved slightly with respect to another nearby star. But on the subsequent nights it was out of his field of view. Had he seen it on the previous few nights Neptune's motion would have been obvious to him. But, alas, cloudy skies prevented observations on those few critical days.

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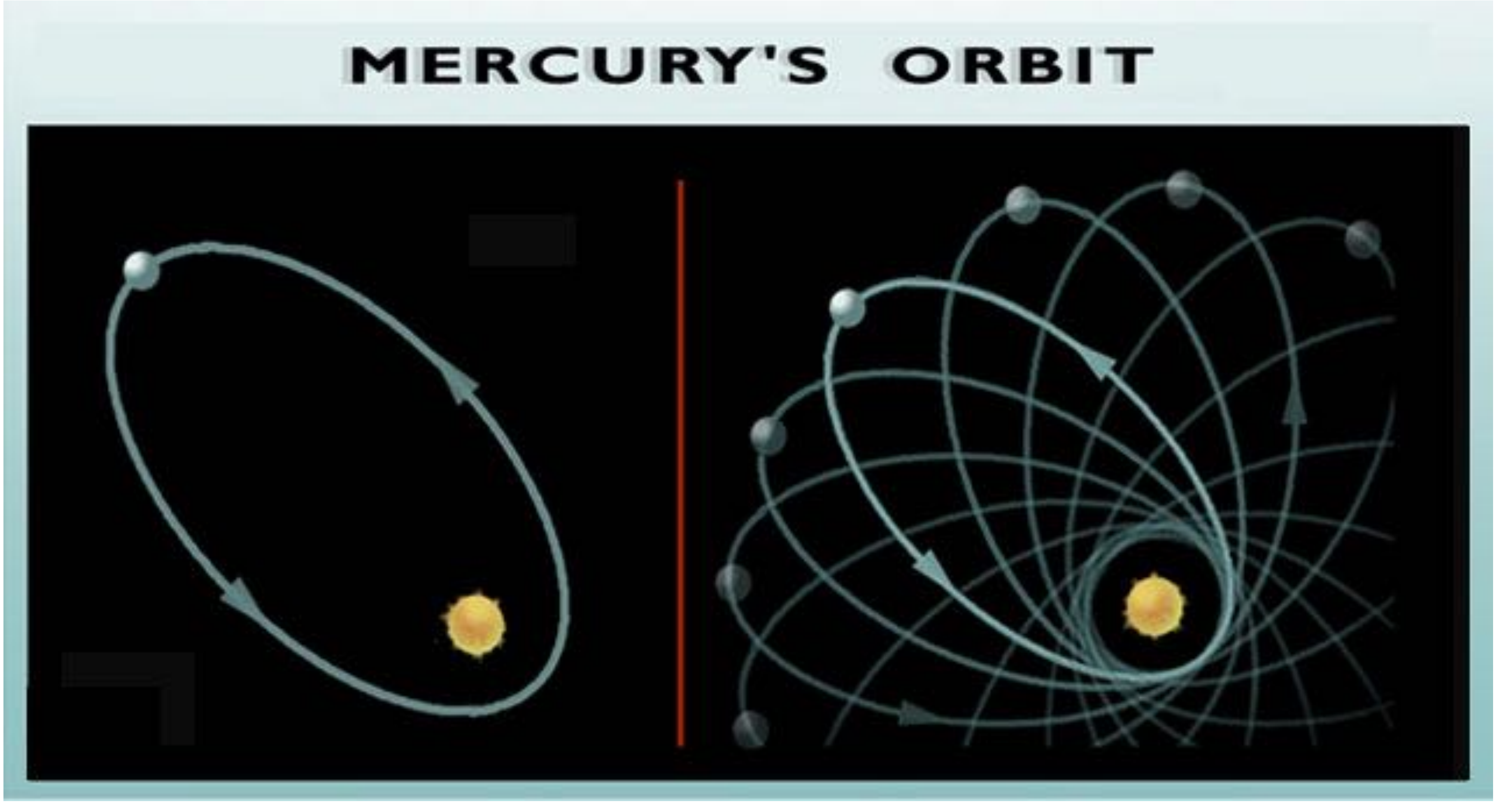

Mercury's elliptical path around the Sun. Perihelion shifts forward with each pass. (Newton 532 arc-sec/century vs Observed 575 arc-sec/century)

(1 arc-sec = 1/3600 degree).

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Urban le Verrier

Verrier predicted the existence of a small body or bodies between Mercury and the Sun and called it **"VULCAN"** (1859)

There were a series of 'false' discoveries

There was no evidence of "Vulcan" by the time Einstein developed his theory of gravity

Later searched for by NASA. Nothing found

Finally, re-invented for **STAR TREK**

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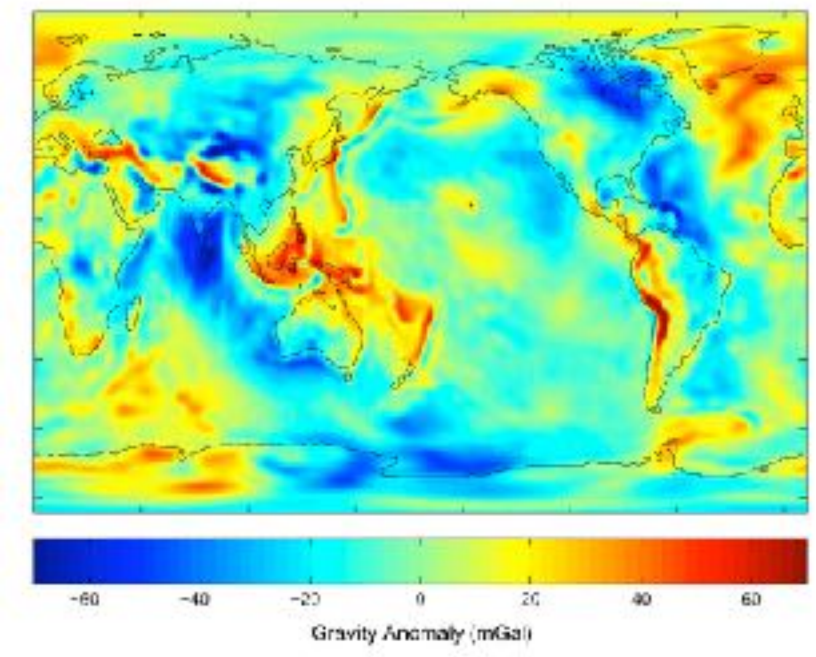
Newton Gravity tremendously successful theory, but …



- There are variations in the earth's gravitational fields
- Newton didn't know what ***caused*** gravity, although he knew that all objects with mass *have* gravity and *respond to* gravity.

- To Newton, gravity was simply a property of objects with mass.
- Newton also couldn't explain how gravity was able to span between objects that weren't touching.
  - He didn't like the idea of "action-at-a-distance".

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Conceptual Problems with Newton's Universal Gravity

- Newton's Theory formulates how the earth attracts the apple, BUT not Why?

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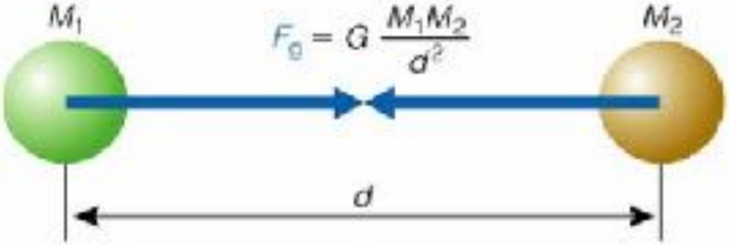
Conceptual Problems with Newton's Universal Gravity

- Newton proposes gravity must act instantaneously, regardless of distance (else angular momentum not conserved).
- *"actio in distans"* (action at a distance), no mechanism proposed to transmit gravity

Sir Isaac Newton (1643-1727)

"...that one body may act upon another at a distance through a vacuum without the mediation of anything else, by and through which their action and force may be conveyed from one to another, is to me so great an absurdity that, I believe no man, who has in philosophic matters a competent faculty of thinking, could ever fall into it." -Newton



How does moon "know" the earth is there to fall towards it?

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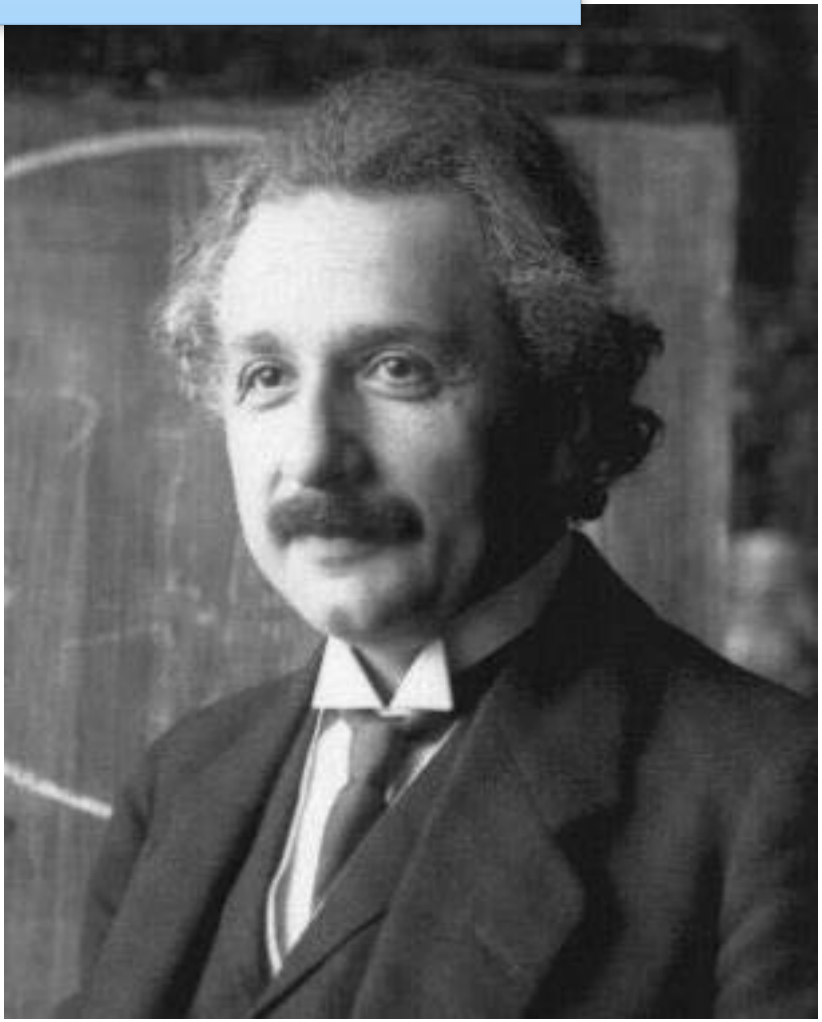
...stein's Theory of Gravity
1915



$$G_{ab} = R_{ab} - \frac{1}{2} g_{ab} R = \frac{8\pi G}{c^4} T_{ab}$$

Space *and* Time are ***unified*** in a four dimensional

spacetime

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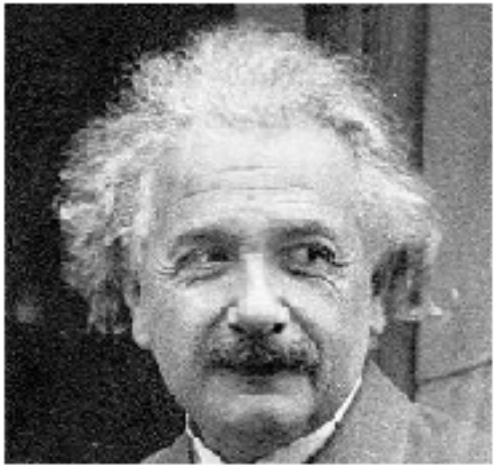
General Relativity: Einstein's account of gravity

In 1915, Einstein reformed our understanding of gravity for the first time since Isaac Newton (1686).

Gravity isn't a force that acts <u>in</u> space and time, but instead is <u>built into the actual structure</u> of space and time.

Space and time are *curved*; nothing can avoid feeling that curved structure. <u>That</u> is what makes gravity *universal*.



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

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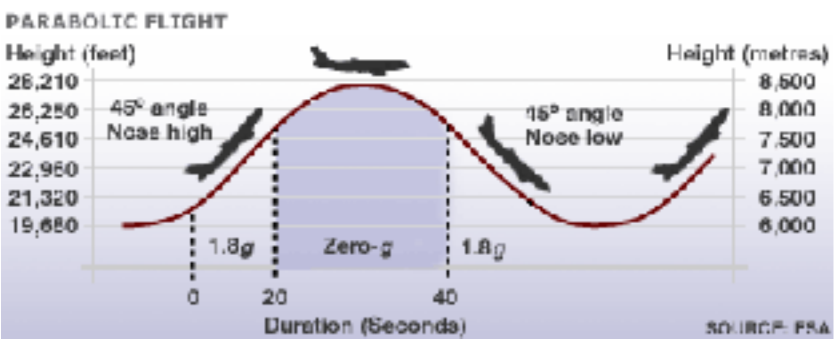
Ideas of General Relativity

- **The Special Theory of Relativity (1905)**
  - Observers at rest *or in uniform motion* observe the same laws of physics
  - including the same speed of light
- **The General Theory (1915)**
  - Also applies to observers *falling freely in a gravitational field*
  - this is the Principle of Equivalence
- **Key Point**
  - ***all objects experience the same acceleration in a gravitational field***

- Examples of the Equivalence Principle
  - Astronauts in the International Space Station
    - altitude of ISS = 400 km
    - radius of Earth = 6370 km
    - g at ISS = 88.5% of surface g

  - Airplane on a ballistic trajectory



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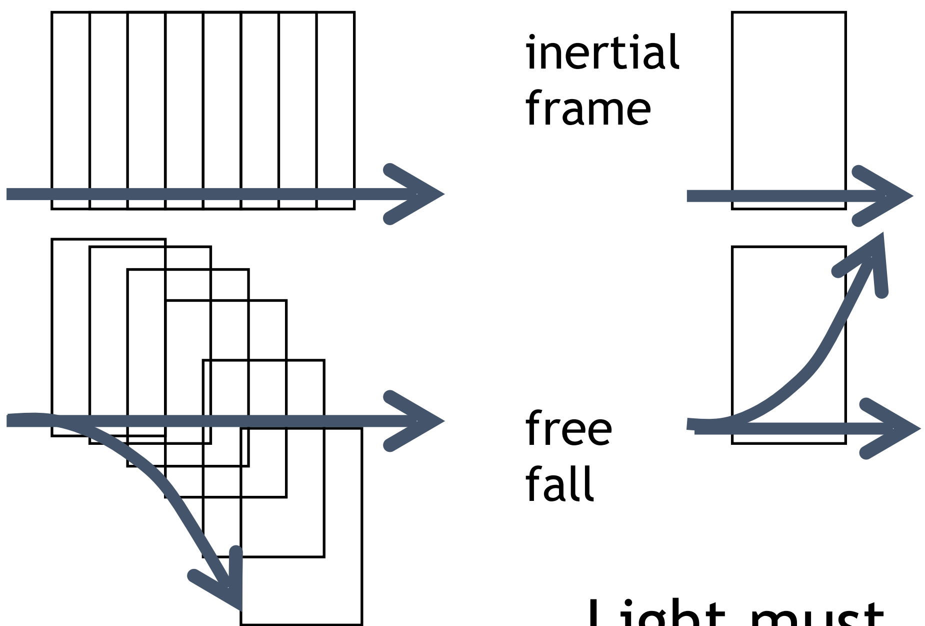
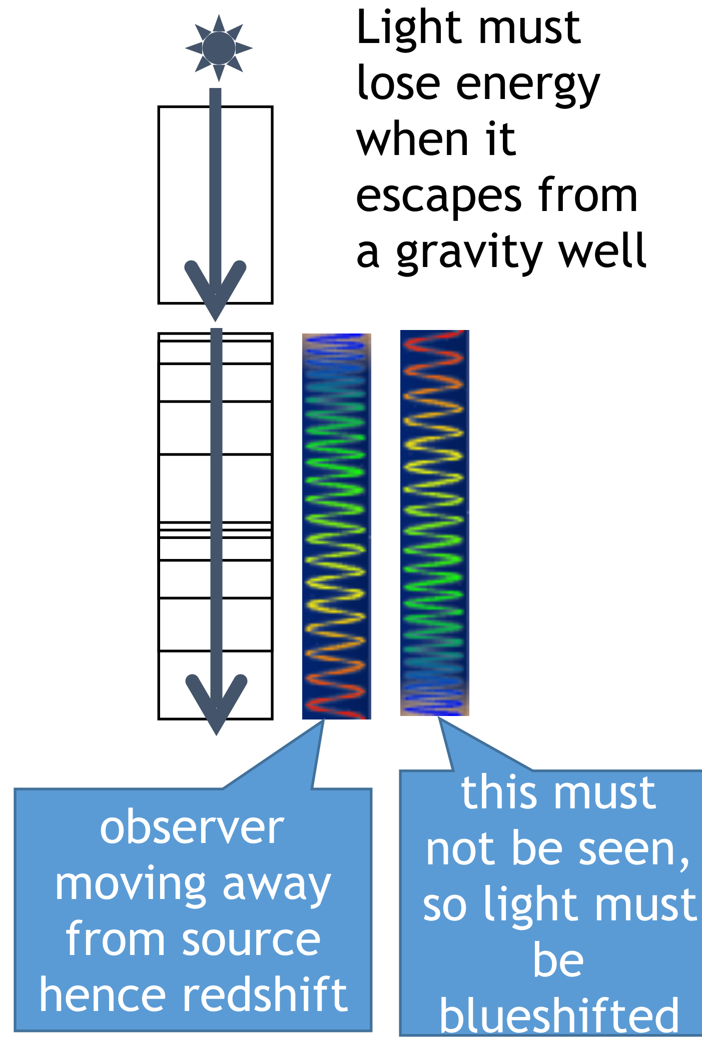
Consequences



Light must bend in a gravitational field



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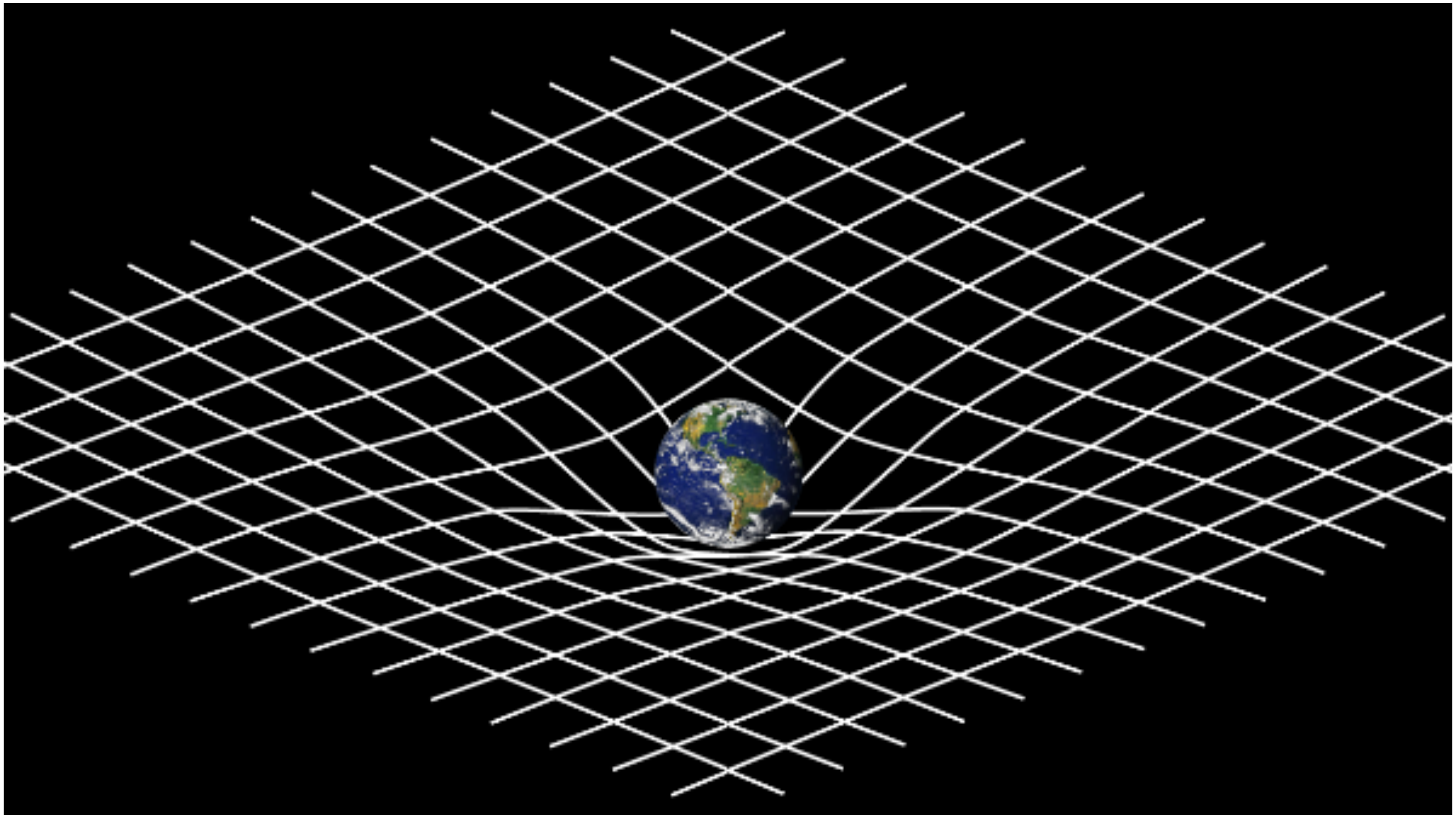
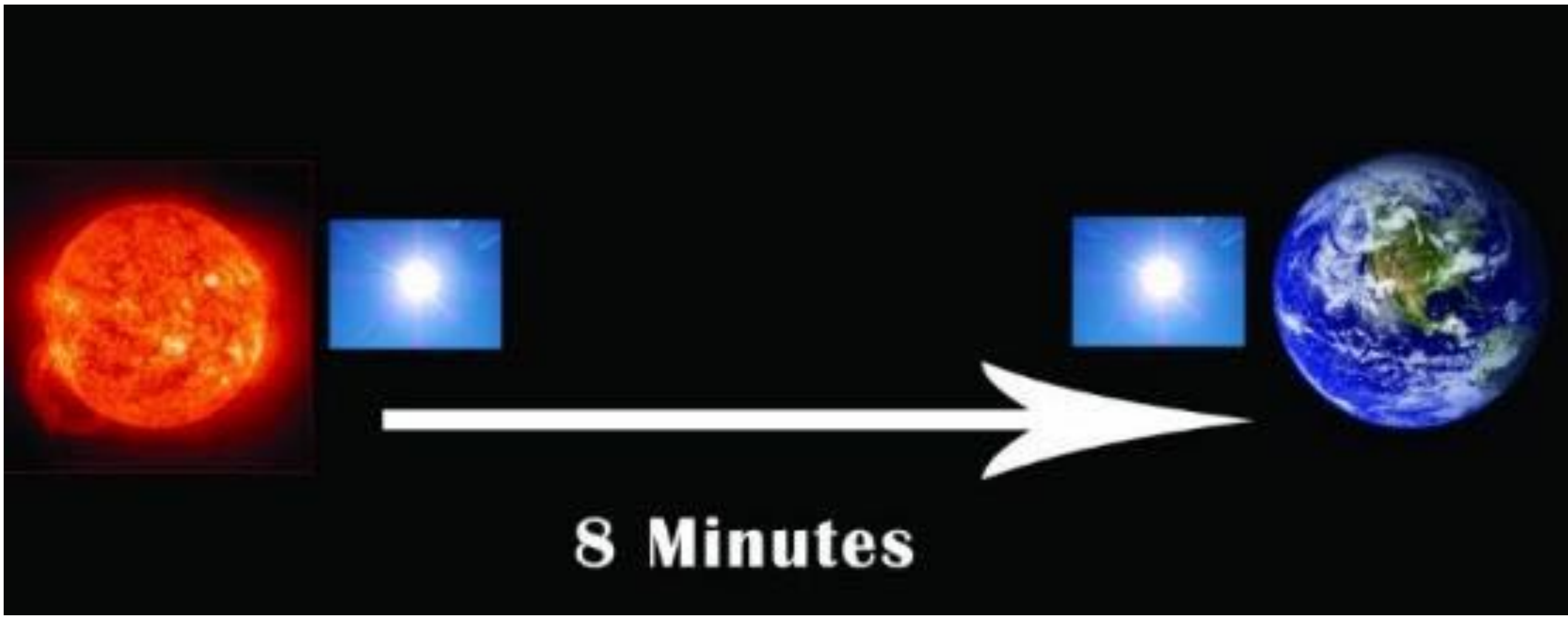
Einstein's Theory of Gravity
1915



Earth distorts spacetime

Einstein Solves a Conceptual Problem with Newtons Theory of Gravity

"Instantaneous Action at a Distance"



It takes ~ 8 minutes for the light (heat) to travel from the sun to the earth. How long for the gravitation?

BREAK

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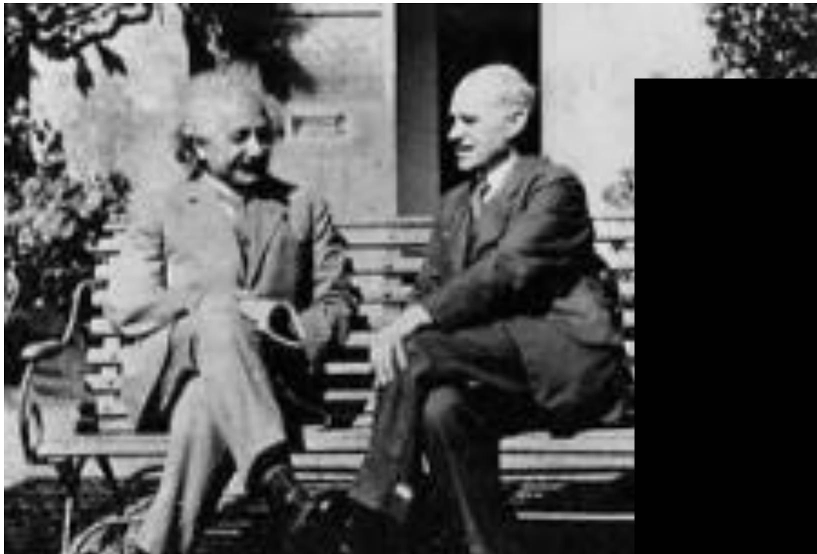
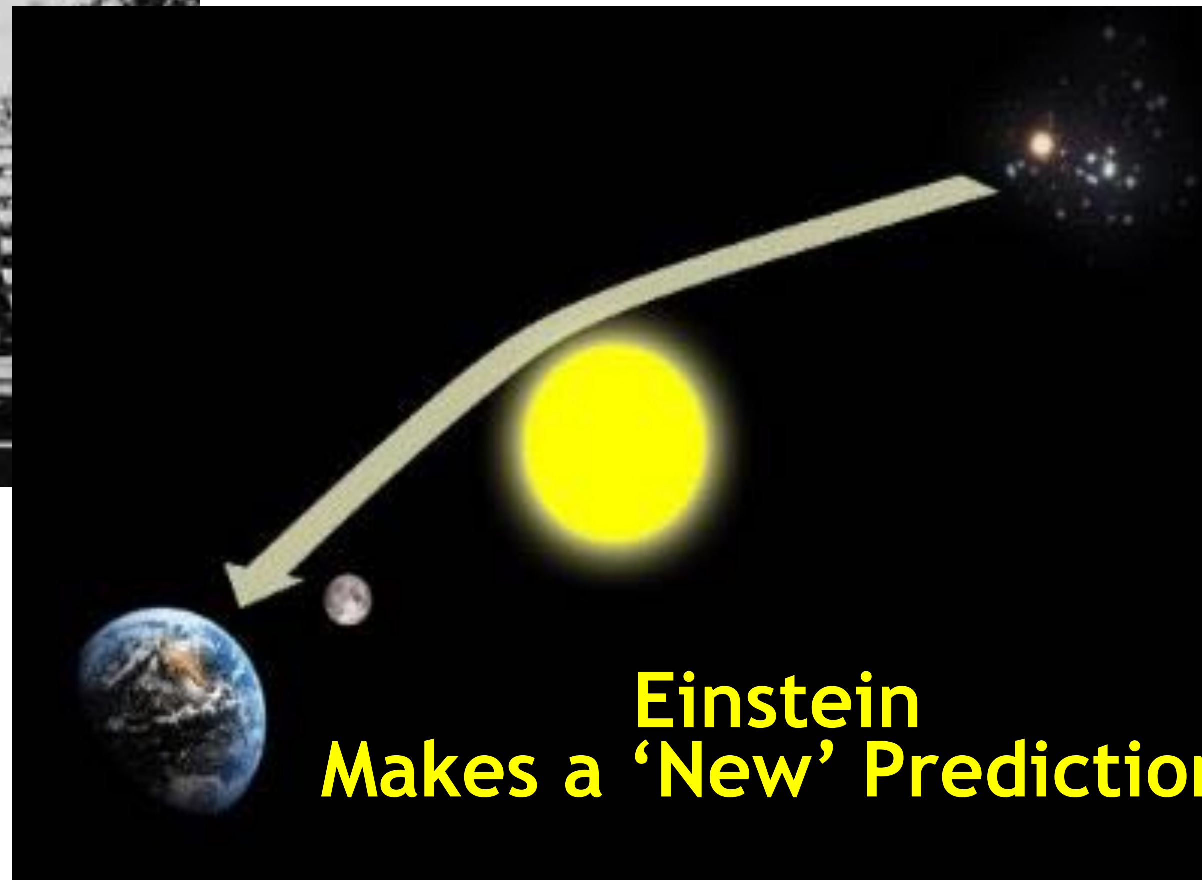


Einstein Eddington



"Not only is the universe stranger than we imagine, it is stranger than we can imagine.

Sir Arthur Eddington

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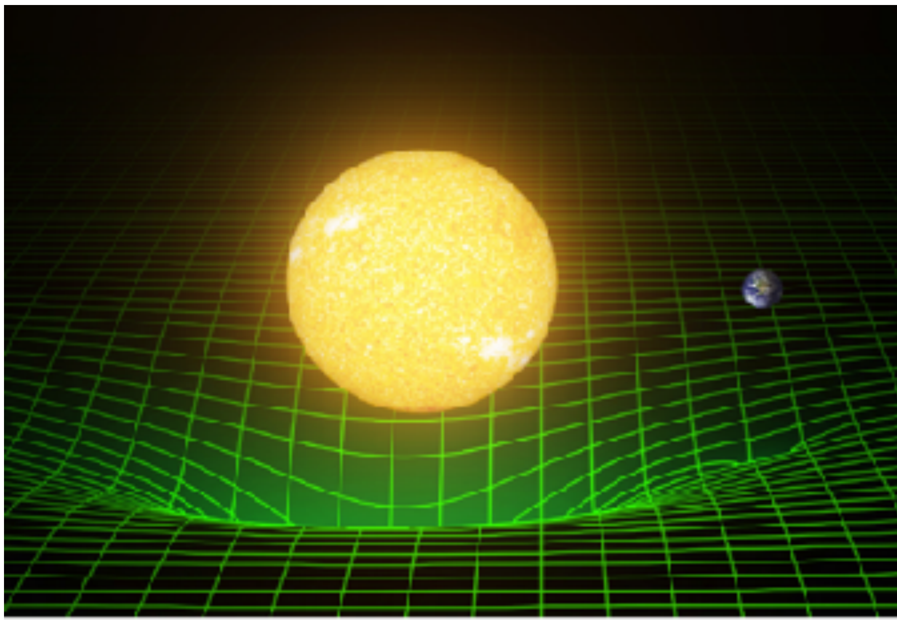

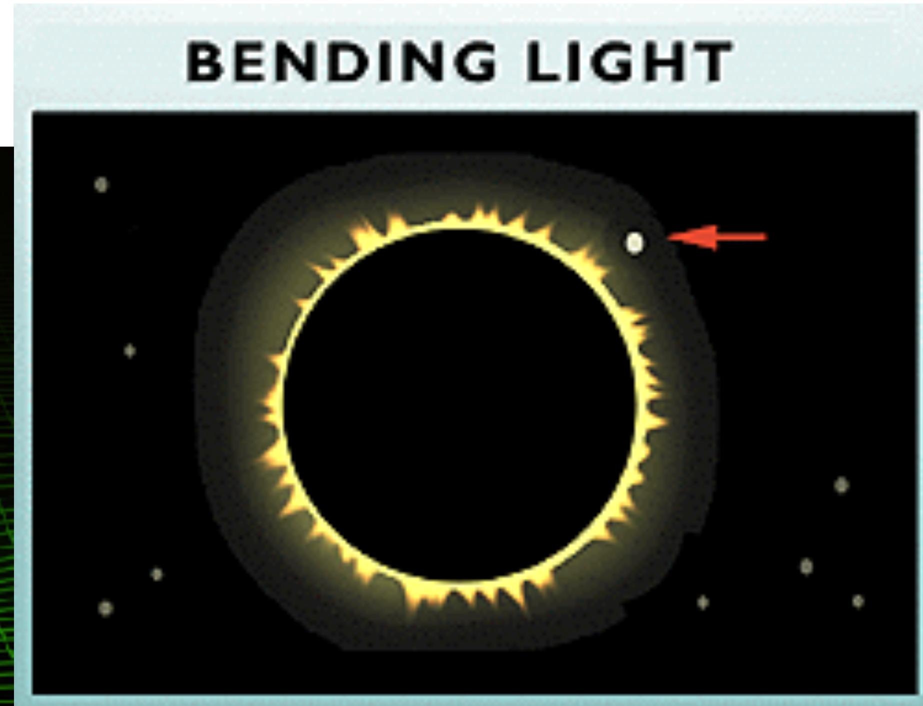

Bending of light was first observed during the solar eclipse of 1919 by Sir Arthur Eddington, when the Sun was silhouetted against the Hyades star cluster

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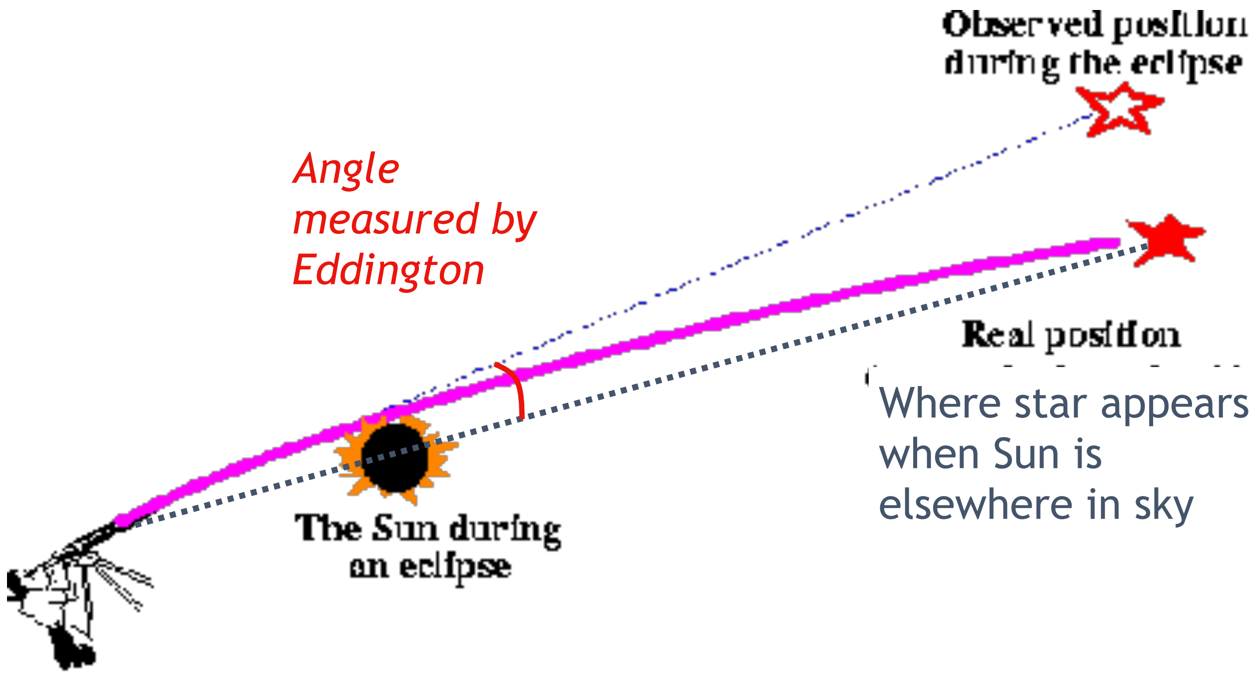
The Eddington Test

- 1919 – the first “accessible” total Solar eclipse since Einstein postulated SEP
  - Eddington lead expedition to South America to observe eclipse
  - Was looking for effects of gravitational light bending by searching for shifts in positions of stars just next to the Sun.



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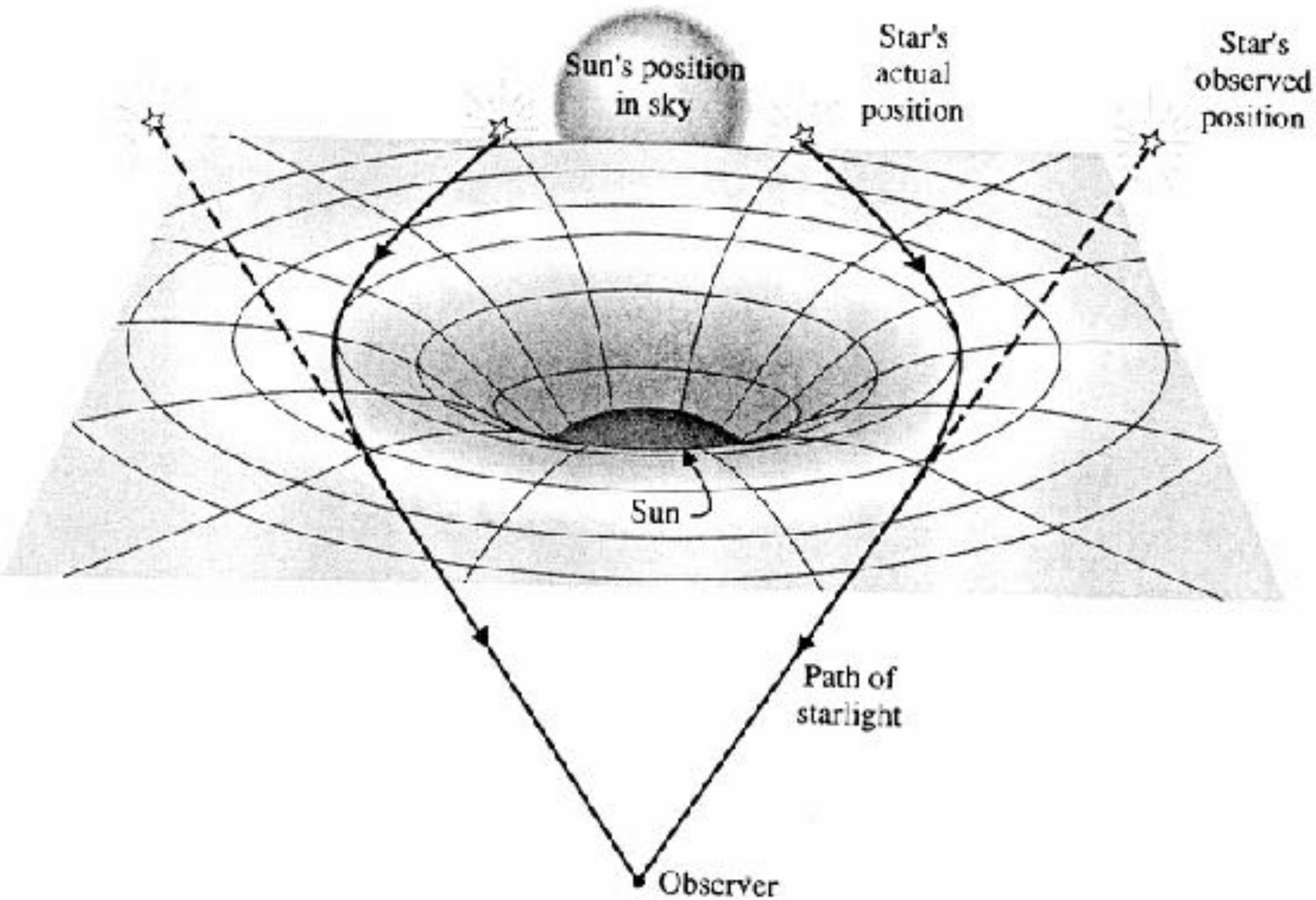

Bending of starlight measured during a solar eclipse.

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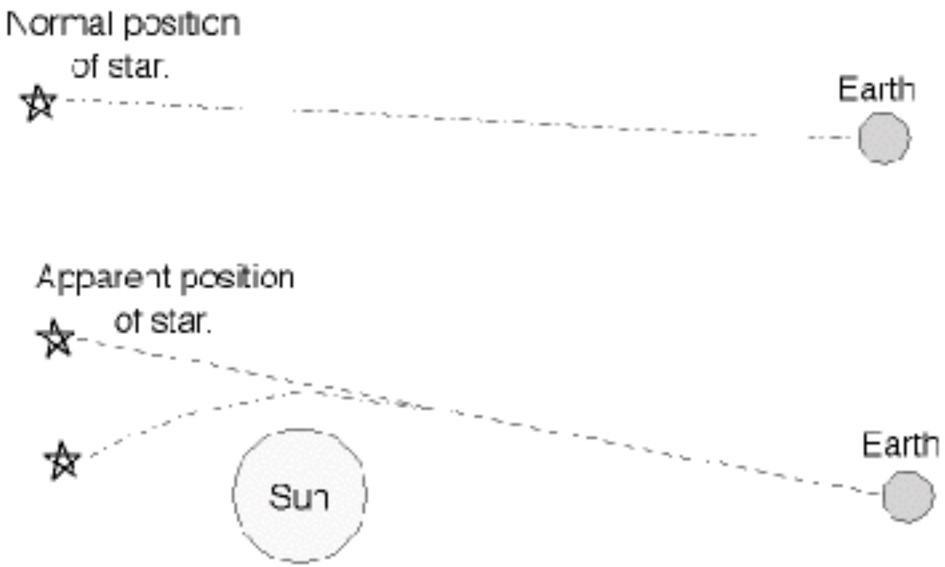
<u>GENERAL RELATIVITY PREDICTION: Light bends when it passes by massive objects. The more the mass the larger it bends.</u>



Observation: During solar eclipse stars along the same line of sight with the Sun are seen on a shifted position.

- GR gives accurate prediction. SR half of the observed shift.
- Newton no shift

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The 1919 eclipse expedition

- November 1917 the Joint Permanent Eclipse Committee of the Royal Society "decided, if possible, to send expeditions to Sobral in North Brazil, and to the island of Principe" [off the west coast of Africa]
  - To be organised by Sir Frank Dyson (Astronomer Royal), Prof. Arthur Eddington, Prof. Alfred Fowler and Prof. Herbert Turner
    - This is a fairly impressive decision considering that the First World War was still raging at the time
  - Sobral expedition (Crommelin and Davidson) arrived in Sobral on 1919 April 30 and set up on "the race-course of the Jockey Club, which was provided with a covered grand stand"
  - Principe expedition (Eddington and Cottingham) arrived April 23 and set up in a walled garden belonging to Sr Carneiro, owner of a cocoa plantation, who "had postponed a visit to Europe in order to entertain us"

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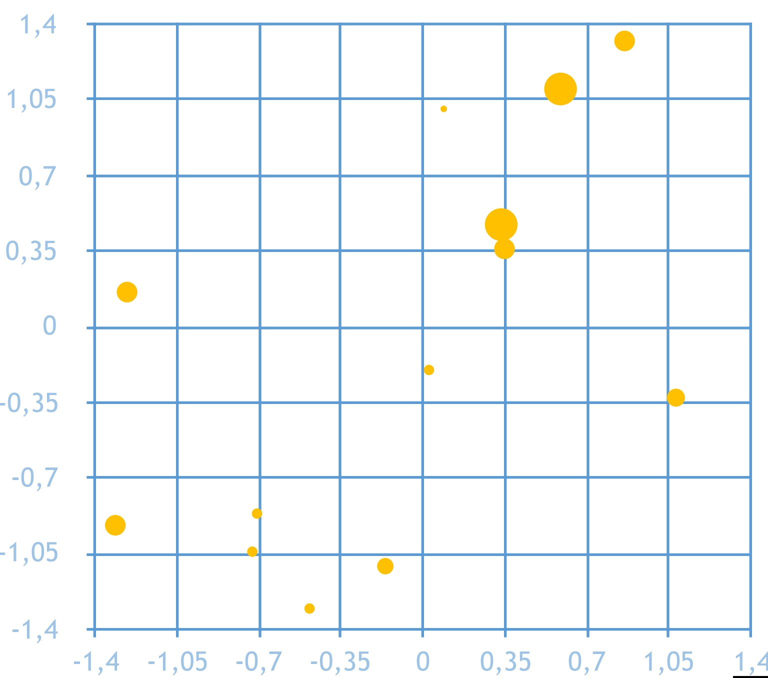
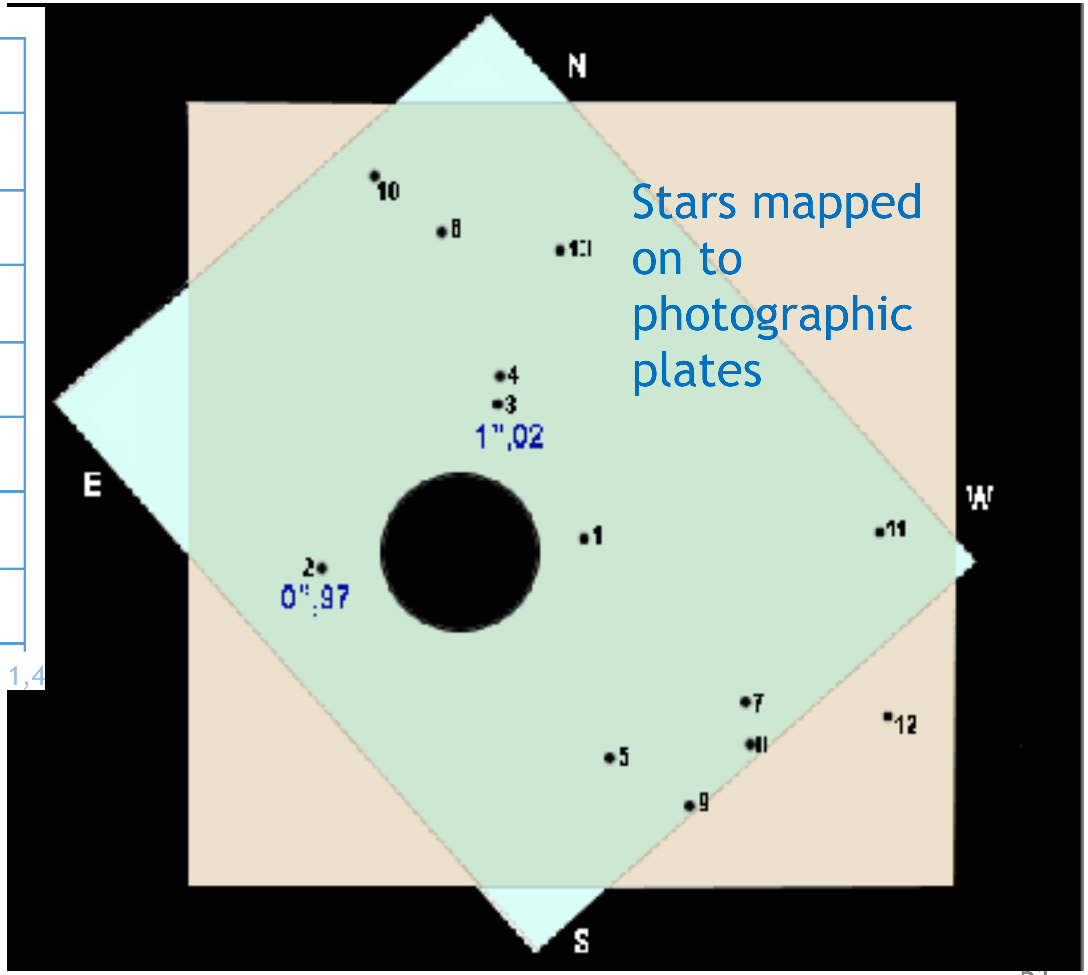
The 1919 solar eclipse



Coordinates (in units of 50') and magnitudes of stars in field, from paper by Dyson, Eddington and Davidson



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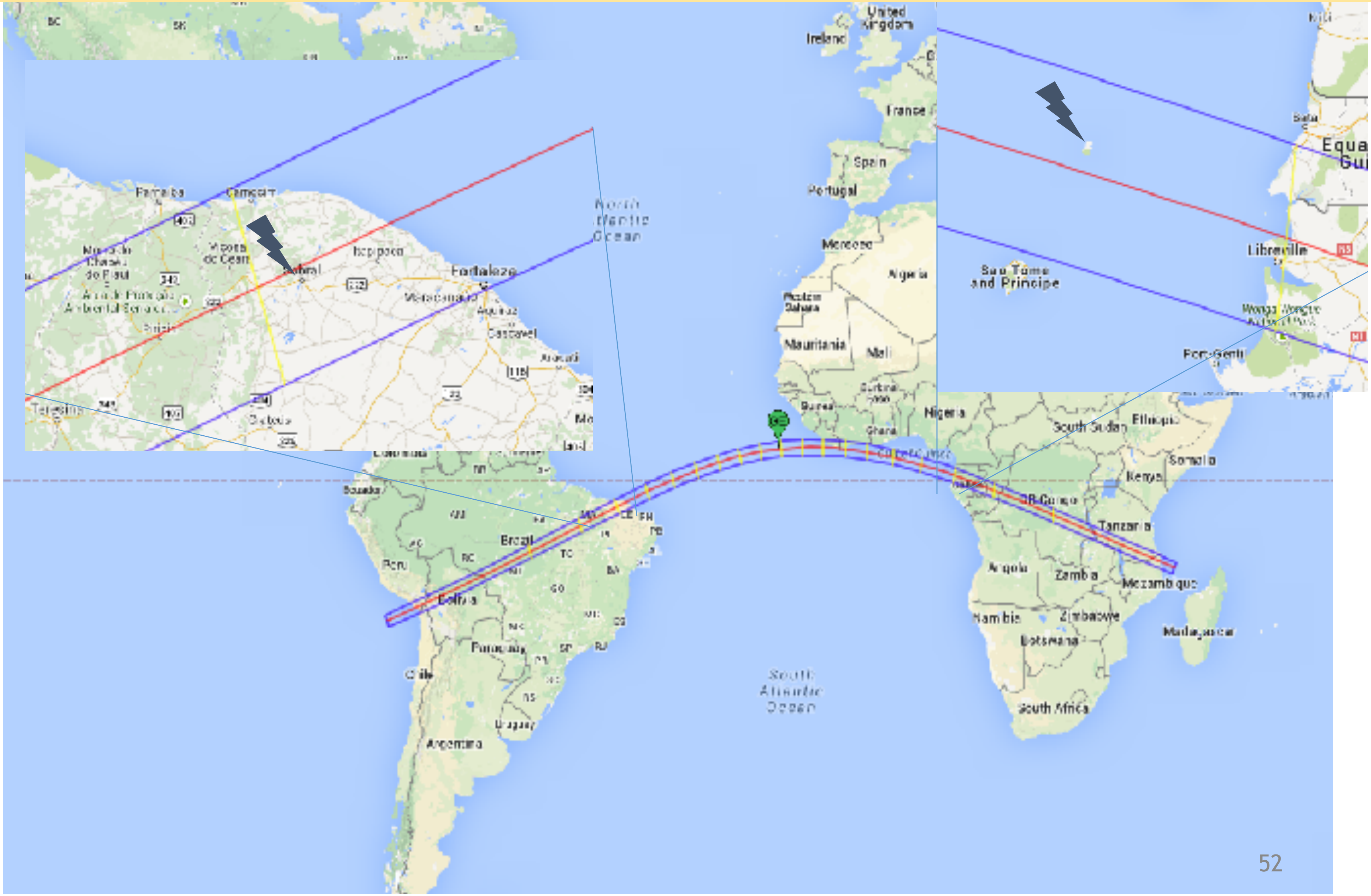
The 1919 Total Solar Eclipse



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Results

- The Sobral team took 8 plates with a 4-inch objective and 19 with a 13-inch astrograph stopped down to 8 in
  - unfortunately the plates from the astrograph turned out to be "very disappointing. The images were diffused and apparently out of focus"
  - they suspected that this was due to distortion of the optics as a consequence of use in the heat of the Sun rather than at night
- The Principe team took 16 plates using a similar astrograph, also stopped to 8 in
  - though the first 9 show no star images owing to poor weather
  - the remaining 7 show between 4 and 6 stars (the Sobral 4-in plates show seven), but only two were satisfactory as star 5 is needed for accurate alignment of plates

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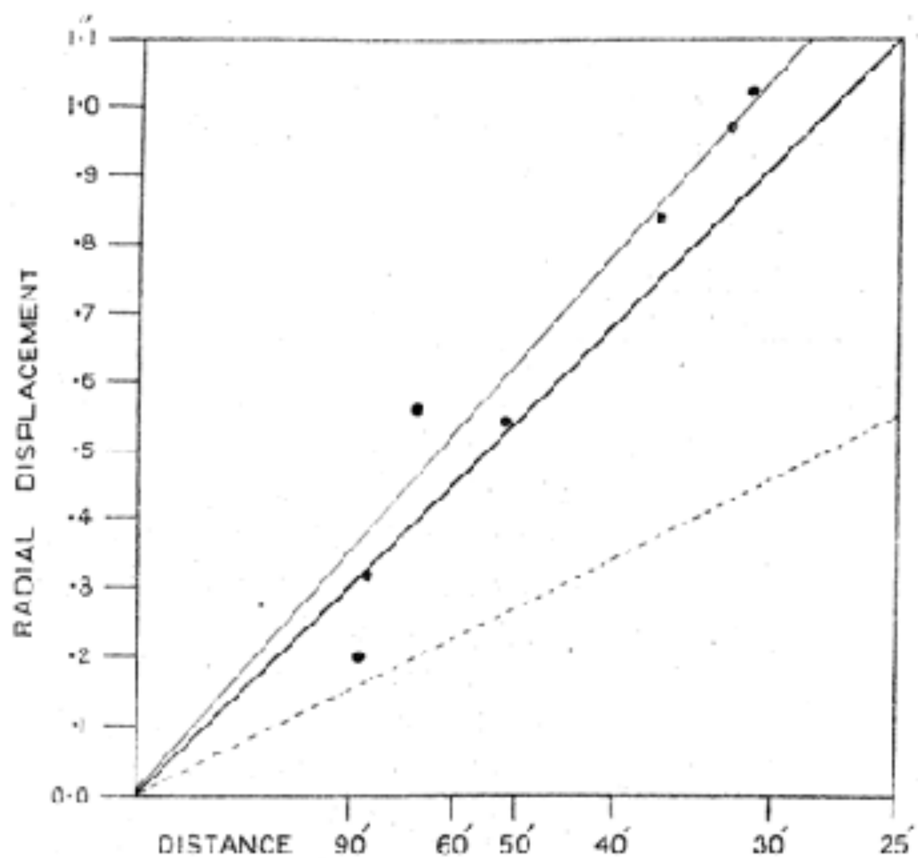
Results

- Comparison plates for Principe were taken at Oxford before the expedition
  - Results from four sets of measurements (the two Principe plates, each compared with two different reference plates) gave 1.61±0.30 arcsec
- Comparison plates for Sobral were taken at Sobral in July
  - the 4-inch gave 1.98±0.12
  - the astrograph gave 0.93”, b recall poor quality plates
    - later reanalysis gave 1.52”



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Headline News

A report of the results in November 1919 made (rather exaggerated) headlines, and established Einstein as a media figure.

Scientific response was more muted, which is fair considering quality of data.

The Times, 1919 Nov 7

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-

New York Times, 1919 Nov 10

LIGHTS ALL ASKEW IN THE HEAVENS

Special Cable to THE NEW YORK TIMES.

LIGHTS ALL ASKEW IN THE HEAVENS

Men of Science More or Less Agog Over Results of Eclipse Observations.

EINSTEIN THEORY TRIUMPHS

Stars Not Where They Seemed or Were Calculated to be, but Nobody Need Worry.

A BOOK FOR 12 WISE MEN

No More in All the World Could Comprehend It, Said Einstein When His Daring Publishers Accepted It.

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Confirmation

- Lick Observatory mounted expedition to Australia to observe 1922 solar eclipse
  - results: 15 ft camera 1.72±0.11”
    5 ft camera 1.82±0.15”
    weighted mean 1.75±0.09”

This measurement included 24 stars and established the correctness of the 1919 results.

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Gravitational Redshift

- The predicted gravitational redshift is another small effect—the fractional shift in the wavelength is approximately GM/c^2R where M is the mass of the body and R is the distance between the centre of mass and the point at which the light is emitted
  - The obvious test of this is extremely dense astrophysical compact objects
    - white dwarfs: mass ~0.5 – 1.0 solar masses, radius ~10000 km
    - neutron stars: mass ~1.5 solar masses, radius ~10 km
  - Problem: to test Einstein's prediction, need to *know* both mass and radius
    - for most astrophysical objects this is a serious challenge

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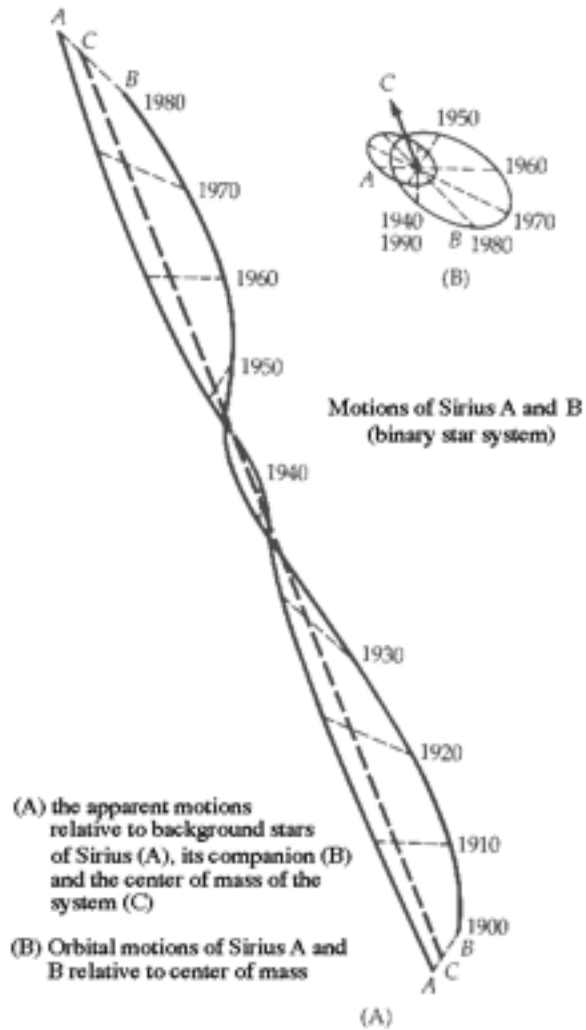
Gravitational Redshift

- First observed in the spectrum of Sirius B by Walter Adams in 1925
  - mass of this white dwarf well established from orbital parameters of the Sirius binary system
  - spectral line shift of 0.032 nm, consistent with a radius of order 20000 km for the white dwarf
- This measurement is difficult (because of contamination of Sirius B's spectrum from much brighter Sirius A) and was not regarded as definitive



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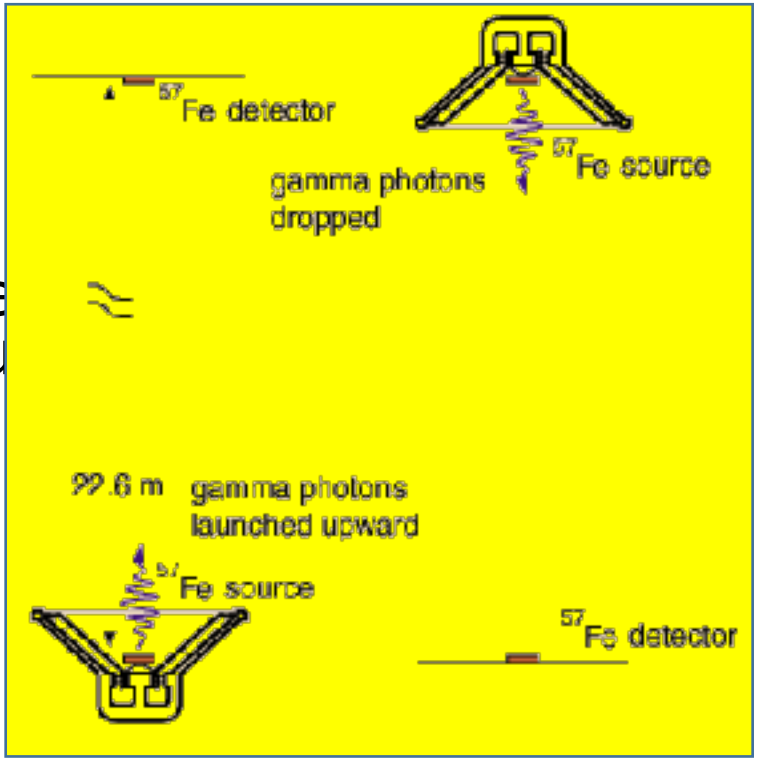
Gravitational Redshift

- Definitive evidence was provided by laboratory measurements by RV Pound and GA Rebka in 1960
  - unfortunately published on April 1…
- Measured wavelength shift from top to bottom of 22.5 m high "tower" of Jefferson Physical Lab in Harvard
  - result: net fractional shift (differe between "source at top" and "sou at bottom" of $-(5.13\pm0.51)\times10^{-15}$
    - one part in 200 trillion!
  - relativity prediction: -4.92×10^{-15}



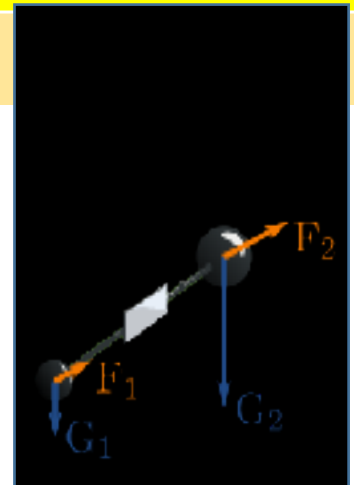
Frontiers 12

Modern tests of General Relativity

- Laboratory tests
- Gravitational lensing
- Gravity Probe B
- Binary pulsars
- Gravitational waves

Frontiers 12

Laboratory Tests



- Tests of the equivalence principle

  - Looking for differences between M_{inertial} (as in $F = Ma$) and M_{gravity} (as in $F = GMm/r^2$)
    - Standard experiment: torsion balance measuring ratio of gravitational force to string tension

  - No differences in acceleration found, at the 10^{-15} (1 in a quadrillion) level
    - Tests the Equivalence Principle and set limits on the existence of new ultraweak forces

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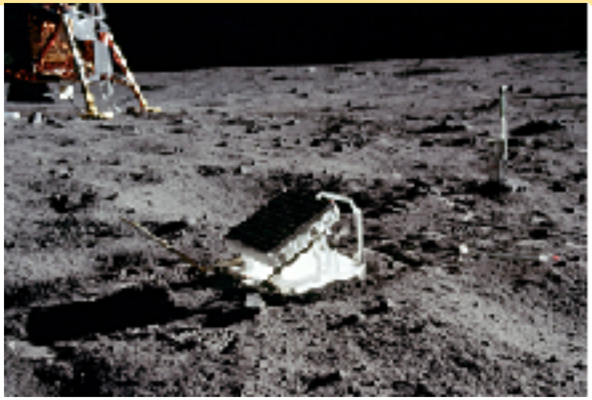
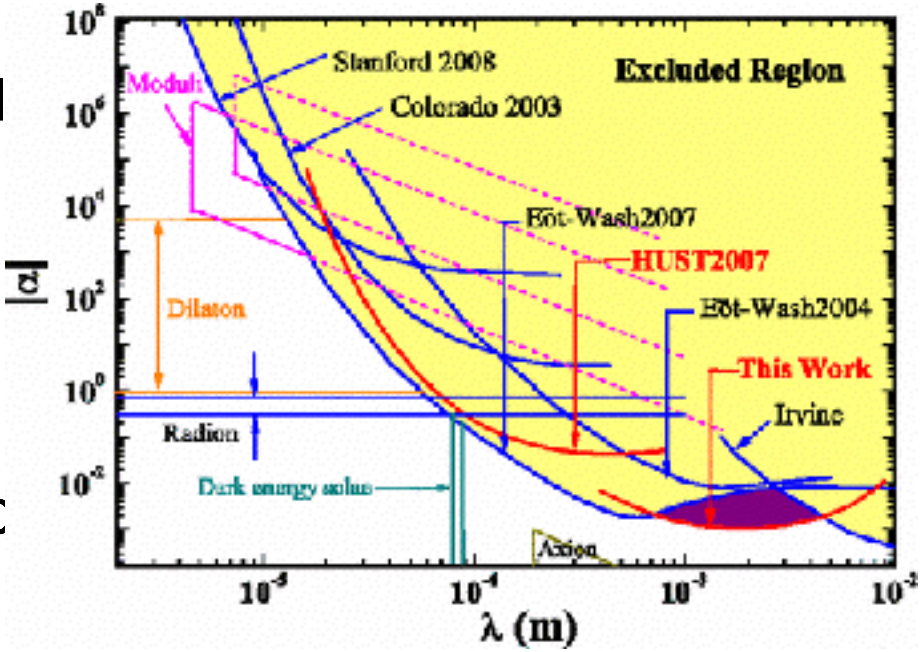
Laboratory tests



- Tests of the inverse square law
  - potentially sensitive to the existence of extra space dimensions
- Short range tests
  - typically torsion balance experiments, see previous slid
- Long range tests
  - lunar laser ranging (monitors distance of Moon with mm precision)
    - tests inverse square law and equivalence principle
- No deviations from expectatic seen



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Gravitational Lensing

- Early measurements of gravitational bending of starlight were heroic attempts to measure tiny effects
- These days, gravitational lensing is a powerful tool for cosmology
  - measuring the mass distribution in galaxy clusters
    - a tool for studying dark matter
  - determining the Hubble constant
  - constructing mass maps of the universe
  - investigating the structure of the Galactic bulge and looking for dark objects in the Galactic halo
  - detecting extrasolar planets

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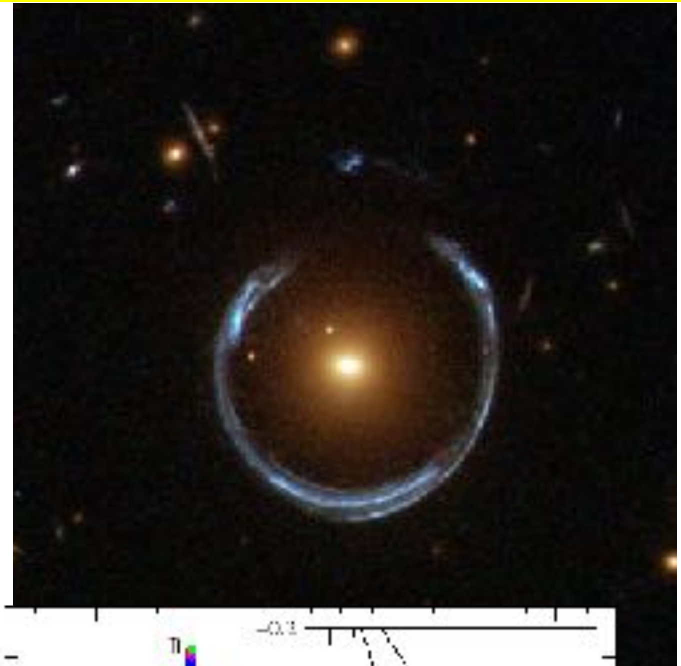

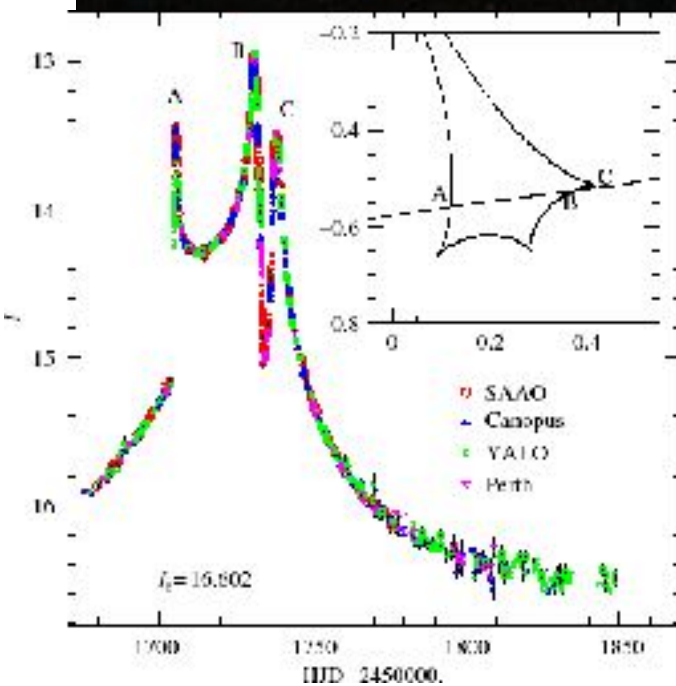

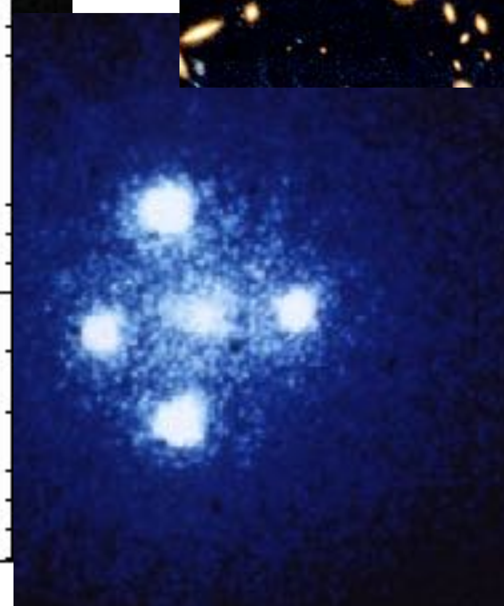

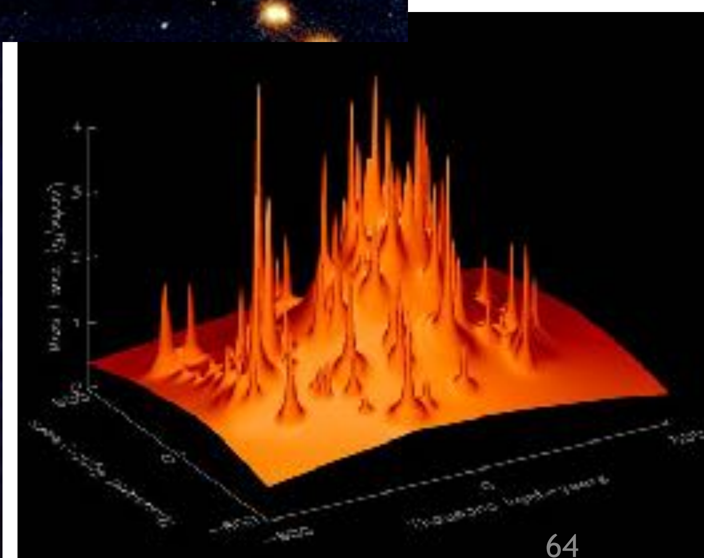

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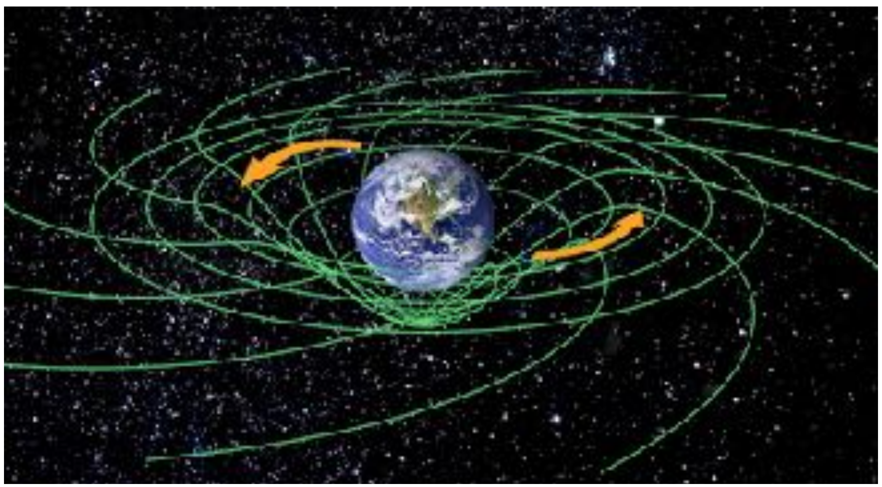
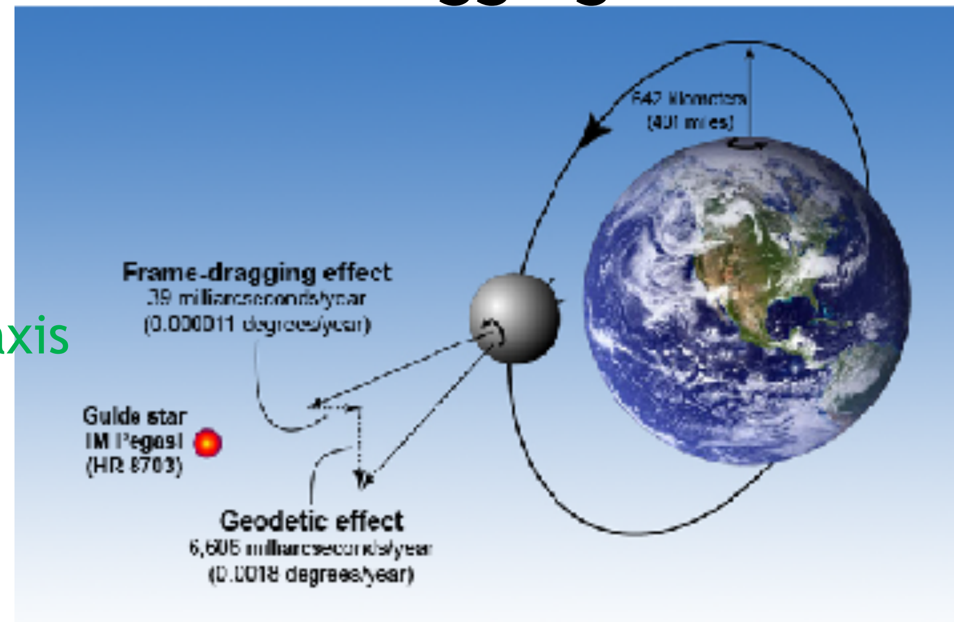
Gravity Probe B

- Test of space curvature and "frame dragging" in Earth orbit
  - satellite in polar orbit containing four precision gyroscopes
    - measure precession of gyro axis





	Measured	Predicted
Geodetic precession (mas)	6602 ± 18	6606
Frame-dragging (mas)	37.2 ± 7.2	39.2

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Binary Pulsars

- The ideal test of General Relativity is an accurate clock in a strong gravitational field
  - Precisely this is provided by pulsars in close binary systems with other compact objects (other neutron stars, white dwarfs, potentially—but not yet observed—black holes)
- First example: Hulse-Taylor pulsar, PSR B1913+16
  - System consists of a pulsar and another neutron star (not observed as a pulsar)
- Most spectacular example: PSR J0737−3039
  - A double neutron star system in which *both* neutron stars are seen as pulsars

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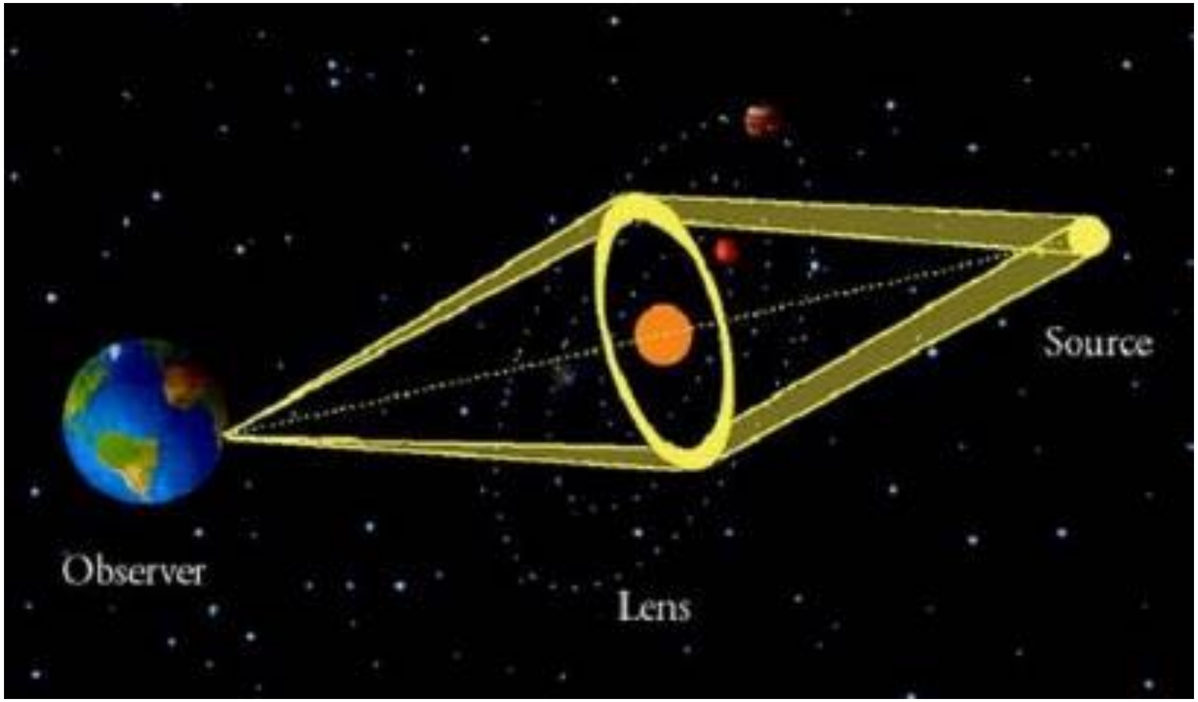
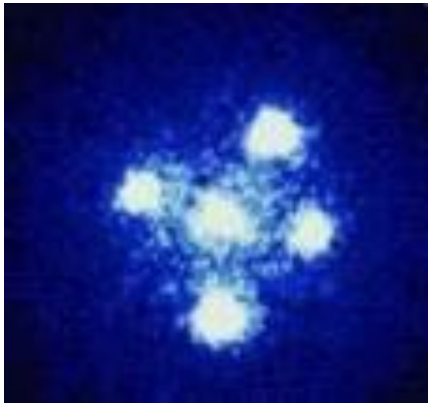
In Modern Astronomy: Gravitational Lensing





Einstein Cross

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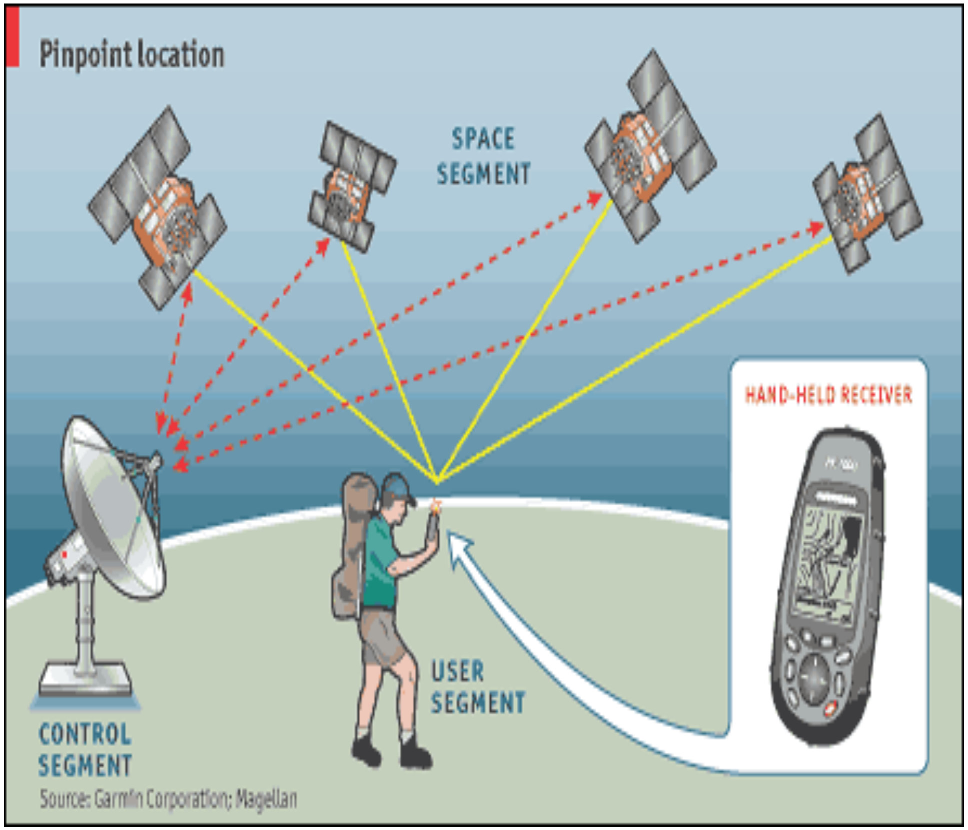
GPS: General Relativity in Everyday Life



Special Relativity

(Satellites v = 14,000 km/hour

"moving clocks tick more slowly"

Correction = - 7 microsec/day

General Relativity

Gravity: Satellites = 1/4 x Earth

Clocks faster = + 45 microsec/day

GPS Correction = + 38 microsec/day

(Accuracy required ~ 30 nanoseconds to give 10 meter resolution

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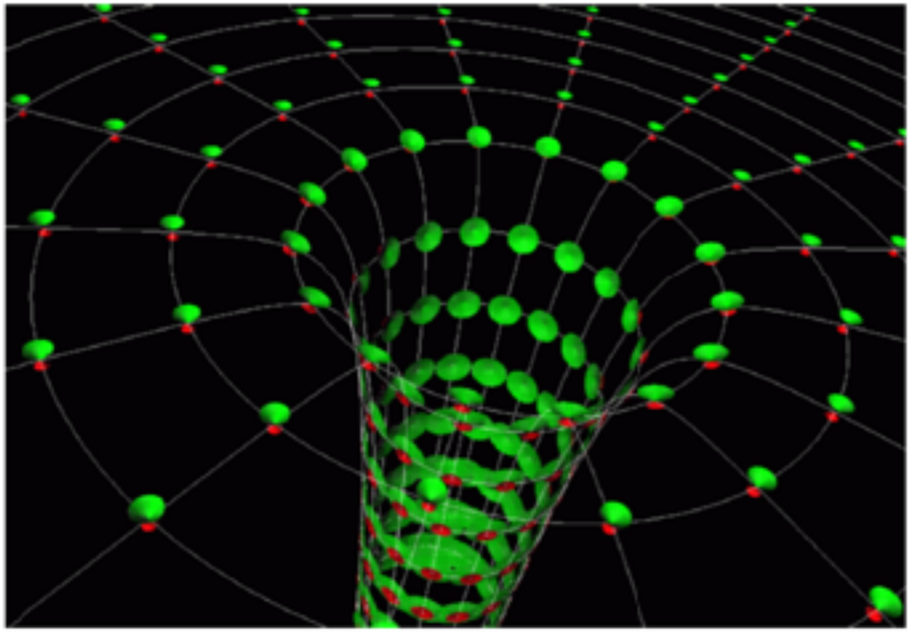
Strong Field Gravity

- Most tests of GR focus on small deviations from Newtonian dynamics (post-Newtonian weak-field approximation)
- Space-time curvature is a *tiny* effect everywhere except:
  - The universe in the early moments of the big bang
  - Near/in the horizon of black holes
- This is where GR gets *non-linear* and interesting!
- We aren't very close to any black holes (fortunately!), and can't see them with light or other EM radiation…



But we can search for (*weak-field*) gravitational waves as a signal of their presence and dynamics

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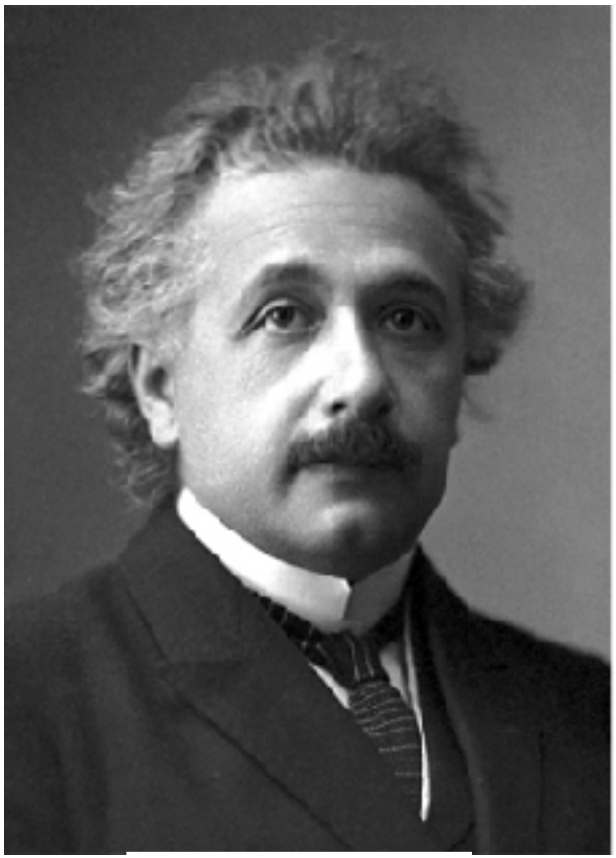
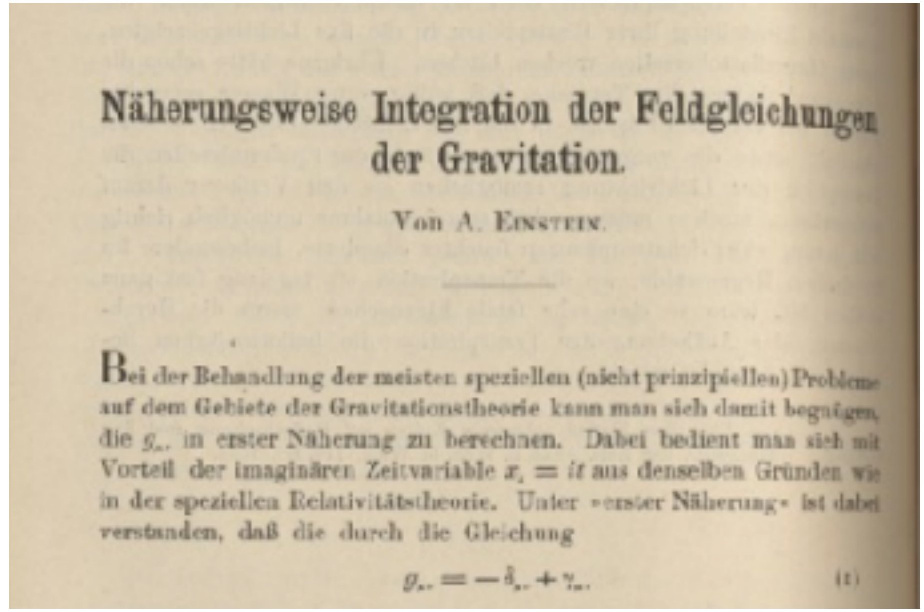
Einstein Predicted Gravitational Waves in 1916





Näherungsweise Integration der Feldgleichungen der Gravitation.

Von A. Einstein.

Bei der Behandlung der meisten speziellen (nicht prinzipiellen) Probleme auf dem Gebiete der Gravitationstheorie kann man sich damit begnügen, die $g_{\mu\nu}$ in erster Näherung zu berechnen. Dabei bedient man sich mit Vorteil der imaginären Zeitvariable $x_4 = it$ aus denselben Gründen wie in der speziellen Relativitätstheorie. Unter »erster Näherung« ist dabei verstanden, daß die durch die Gleichung

$$g_{\mu\nu} = -\delta_{\mu\nu} + \gamma_{\mu\nu} \quad (1)$$

- 1st publication indicating the existence of gravitational waves by Einstein in 1916
  - Contained errors relating wave amplitude to source motions
- 1918 paper corrected earlier errors (factor of 2), and it contains the quadrupole formula for radiating source

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Gravitational Waves

- Gravity needs to obey the principle of relativity (no signals faster than light).

- What about gravity from rapidly accelerating stars? Their gravitational effects at large distances can't change instantaneously. (If they did, that would violate relativity.)

- Gravitational changes "ripple out" from an accelerating object. Those ripples in the structure of space-time, moving at the speed of light, are *gravitational waves*.