Einstein's Theories

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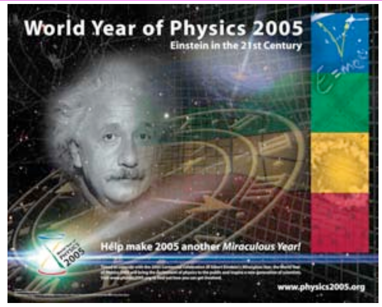
The Year 2005: The 100th Anniversary of Einstein's Miraculous Year.



Outline

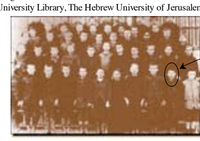
- Einstein's life (1879 - 1955)
- Brief descriptions of Einstein's theories from 1905:
  - The photoelectric effect
  - An experimental test of the kinetic theory of heat
  - The special theory of relativity
- The main focus:
  - Einstein's theories of relativity (special and general)
  - Impact of the theory of relativity
- Concluding remarks

Resources

- Many resources are available to provide more in-depth information about Einstein and his theories.
- Some excellent resources are available on the WEB:
  - The World Year of Physics homepage:
    URL: http://www.physics2005.org/
  - The American Institute of Physics:
    URL: http://www.aip.org/history/einstein/
  - Compilation of links to information about Einstein:
    URL: http://www.aip.org/history/einstein/einlinks.htm
  - Compilation of books about and books by Einstein:
    URL: http://www.aip.org/history/einstein/bibliog.htm
  - The Albert Einstein Archives:
    URL: http://www.albert-einstein.org/
- This lecture can be found at the following URL:
  http://teacher.pas.rochester.edu/wyp2005/presentations/index.htm

Einstein's Life: The early years.

- Einstein was born in 1879 in Ulm (Germany). His parents were middle-class German Jews. Soon after his birth, the family moved to Munich.
- In 1895 Einstein quit high school and moved with his family to Italy.
- Einstein eventually finished high school by attending school in Switzerland.
- Einstein continued his education at the Federal Institute of Technology in Zürich and graduated in 1900. He eventually found a job in the patent office in Bern (Switzerland).



Einstein (1889)

Einstein's Life: The miraculous year 1905.

- Einstein published three papers in 1905 that fundamentally changed our understanding of physics:
  - March 1905: Einstein showed that the photoelectric effect can be understood if we assume that light consists of discreet quanta.
  - May 1905: Einstein proposed a way to test the kinetic energy theory of heat by observing Brownian motion.
  - June 1905: Einstein showed that the electro-magnetic theory and ordinary motion are connected. His new theory was called the special theory of relativity.
- Einstein stated:
  "I want to know how God created this world. I am not interested in this or that phenomenon, the the spectrum of this or that element. I want to know his thoughts; the rest are details."

Einstein's Life: Finally a full-time physics job.

- In 1909 Einstein became an assistant professor at the University of Zürich.
- In 1911 Einstein accepted a faculty position at the German University of Prague.
- In 1912 Einstein was appointed as Professor at the Federal Institute of Technology in Zürich.
- In 1914 Einstein accepted a research position in Berlin.
- At the start of World War 1 Einstein started his involvement in politics and supported the formation of a pacifist group in Germany.

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Einstein's Life: The general theory of relativity.

- In 1915 Einstein completed his general theory of relativity which changed our views of space forever. The theory predicted that space is curved as a result of the gravitational force, and this curvature effects anything that moves though this space (event objects with no mass).
- Einstein's predictions were confirmed in 1919 with observations made during a solar eclipse.
- Einstein wrote to his mother:
  "Dear Mother, -- Good news today. H.A. Lorentz has wired me that the British expeditions have actually proved the light deflection near the sun. "

© Albert Einstein Archives.

Einstein's Life: Development of quantum theory.

- Einstein received the 1921 Nobel Prize of Physics for "his services to Theoretical Physics, and especially for his discovery of the law of the photoelectric effect."
- Quantum theory was successful in describing the motion of electrons in atoms, using wave functions to provide information about the probability to find the electrons in a particular state.
- Einstein could not accept the lack of certainty. He stated "I, at any rate, am convinced the He is not playing dice."

Image © Institut international de physique Solvay
Courtesy AIP Emilio Segrè Visual Archives.

Einstein's Life: Einstein moves to the United States.

- In 1933 Einstein left Germany and joined the Institute of Advanced Study in Princeton.
- During the 1930s, scientists confirmed Einstein's famous formula $E = mc^2$.
- In 1939 physicists realized that the fission of Uranium could be used to build devastating bombs.
- Einstein wrote a letter to President Roosevelt warning him that the German may try to build nuclear weapons.
- In 1940 Einstein became a citizen of the United States.

Image © The Albert Einstein Archives, The Jewish National & University Library, The Hebrew University of Jerusalem, Israel.

Einstein's Life: World War II.

- The government of the United States started to prepare for nuclear warfare.
- Einstein did not play any role in the nuclear bomb program of the United States (he was denied a security clearance based on his German background).
- Einstein continued his quest to develop a truly unified theory of physics. This quest would dominate his efforts until his death.

Image © Keystone Press Agency, New York.

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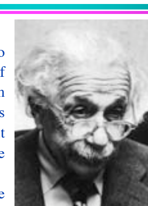
Einstein's Life: The final years.

- In 1952 Einstein was asked to become the second president of the State of Israel. Einstein declined stating that he was deeply touched by the offer, but did not feel suited for the position.
- Einstein died in 1955 while preparing a draft for a television appearance celebrating the 7th anniversary of the creation of the State of Israel.



The University of Frankfurt's Archives.

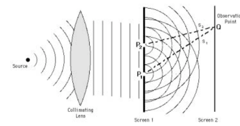
Einstein's Theories: The miraculous year 1905.

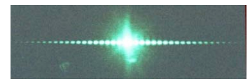
- In 1905 Einstein submitted three famous papers to the *Annalen der Physik* (a German physics journal) covering the following topics:
  - The photoelectric effect.
  - An experimental test of the kinetic theory of heat.
  - The special theory of relativity.
- We will now briefly describe how these theories changed the world of physics before focusing in more detail on Einstein's theories of relativity (special and general).

Electrodynamics of Moving Bodies (1905)

Einstein's Theories: The photoelectric effect.

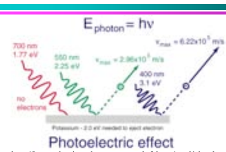
- Before 1905, light was assumed to be an electromagnetic wave, characterized by an amplitude and a wavelength.
- Most phenomena could be understood in terms of the wave nature of light. Diffraction and interference provided compelling evidence that the wave picture of light was correct.
- But …… the photoelectric effect (emission of electrons from metals) could not be understood in terms of the wave model of light.



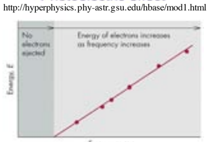


Einstein's Theories: The photoelectric effect.

- Experiments showed that light can liberate electrons from a material (the photoelectrons).
- The following surprising observations were made:
  - No electrons are liberated if the wavelength of the light is larger than some critical value (independent of the intensity of the light).
  - The maximum energy of the electrons liberated does not depend on the intensity of the light. It only depends on the wavelength of the incident light.



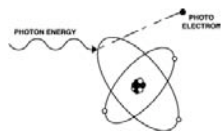
http://hyperphysics.phy-astr.gsu.edu/hbase/mod1.html



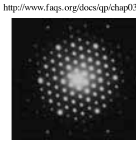
http://www.mhhe.com/physsci/astronomy/fix/student/chapter6/06f07.html

Einstein's Theories: The photoelectric effect.

- Einstein explained this effect by interpreting light as a collection of photons with a discreet energy.
- Einstein proposed that the photon energy is only determined by the wavelength of the light.
- Changes in light intensity reflect changes in the number of photons, not the energy of the individual photon.
- The resulting wave-particle duality also predicted that "particles" can behave like waves. It was observed that for example electrons can behave like waves (electron diffraction).



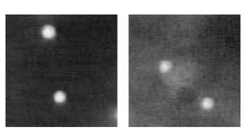
http://www.faqs.org/docs/qp/chap03.html



http://www.matter.org.uk/diffraction/electron/electron_diffraction.htm

Einstein's Theories: Brownian motion.

- Einstein showed how the macroscopic motion of an object, located in a fluid or a gas, is effected by the microscopic motion of the constituents of the medium.
- Einstein's predictions for Brownian motion were in excellent agreement with the observations and confirmed the statistical theory of heat.
- Another prediction of his theory was the so called blackbody radiation.



http://www.deas.harvard.edu/projects/weitzlab/research/brownian.html

Einstein's Theories: The special theory of relativity.

- Einstein developed his theory of relativity on the basis of two assumptions:
  - The principle of relativity: all laws of physics take the same form in any inertial reference frame.
  - The principle of the constancy of the speed of light: the speed of light is the same in any inertial reference frame.
- Newton's laws of mechanics were inconsistent with the last assumption.
- We will now focus in detail on these assumptions, how they differed from the accepted views of mechanics, and how Einstein's theory of relativity changed the world of physics.

Before Einstein: Newton's laws of motion and gravity.

- Using Newton's laws of motion, physicists could explain many phenomena in astronomy:
  - The orbits of planets around the sun.
  - The orbits of the moons around the planets.
  - The tides.
  - The existence of undiscovered planets and moons (such as Uranus, Neptune, and Pluto).

Sir Isaac Newton, a portrait by Kneller in 1702.
National Portrait Gallery in London.

Before Einstein: Newton's laws of motion and gravity.

- Newton's laws of motion assume that space is three dimensional.
- Newton's laws of motion assume that space is absolute: the dimensions of objects are the same for all observers, regardless of their motion.
- Newton's laws of motion assume that time is absolute: the duration of events is the same for all observers, regardless of their motion.

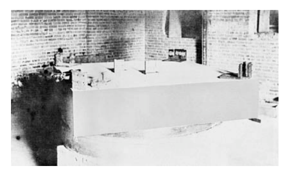
Sir Isaac Newton, a portrait by Kneller in 1702.
National Portrait Gallery in London.

Albert Michelson (1852 - 1931): Measuring the velocity of light.

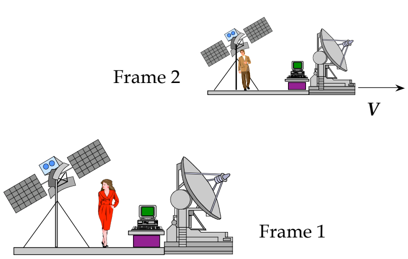
- The foundation of Newton's laws of motion started to break down when Albert Michelson measured the velocity of light.
- According to Newton's theories, a measurement of the speed of light must depend on the velocity of the reference frame of the observer, and the direction of the light with respect to the motion of this reference frame.
- Since the earth is moving through absolute space, the velocity of light was expected to change with changes in direction.

Albert Michelson (1852 - 1931): The Michelson interferometer.

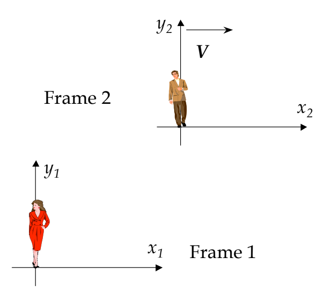
- Michelson measured the velocity of light using an interferometer.
- The experiment was sensitive enough to be able to detect the differences resulting from a 30 km/sec motion through absolute space due to the orbital motion of the earth.
- Michelson observed that the speed of light is always the same, independent of its direction relative to the direction of motion of the Earth.
- He concluded that either Cleveland is always at rest in absolute space, or Newton's laws are breaking down.



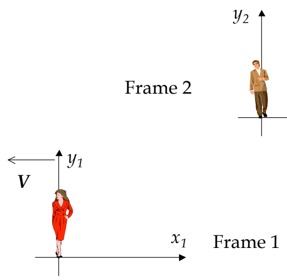
Let's go back to the basics and compare notes between two observers.



Coordinates systems and reference frames as seen by observer 1.



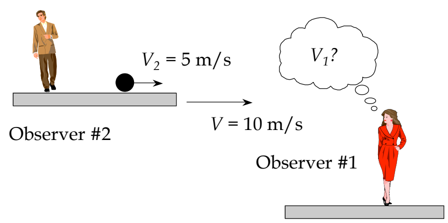
Coordinates systems and reference frames as seen by observer 2.



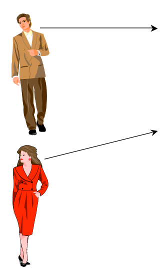
Different observers make different observations.

- The two observers observe each other and the reports of their observations differ.
- The two observers compare notes on experiments they observe.
- They conclude that in certain cases, their observations are the same, while in others they differ.
- A good example to focus on is the measurement of the velocity of an object by the two observers.

Measuring velocity.



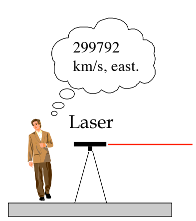
Measuring velocity: velocity = change in position/change in time.



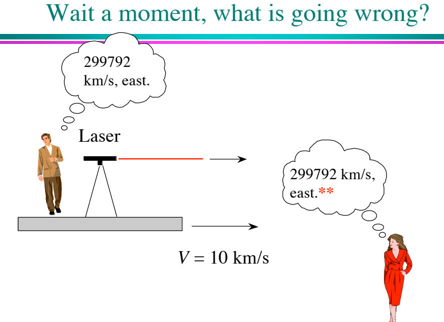
- In 1 second I see the ball move 5 m. Its velocity is thus dx/dt = 5/1 = 5 m/s.
- In 1 second I see observer 2 move 10 m. The velocity of observer 2 is thus dx/dt = 10 m/s.
- In 1 second I also see the ball move (10 + 5) = 15 m. Its velocity is thus dx/dt = 15 m/s.
- The velocity I observe is higher than the velocity he observes!

Measuring velocity.

- The two observers in our experiment measure different velocities.
- Observer 1 will always measures a higher velocity than observer 2 for any object moving east with respect to observer 2.
- If observer 2 would be looking at an object moving east with the velocity of light, observer 1 would conclude that the object has a velocity higher than the velocity of light.



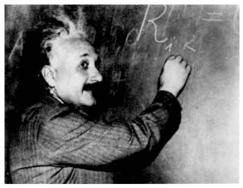
Measuring velocity. Wait a moment, what is going wrong?



** Not 299802 km/s!

Einstein's solution to the problem: The special theory of relativity.

- Velocities of moving objects are still relative, but the relation is no longer as before, owing to the relativity of length and time.
- The speed of light is special, though: it is **absolute**, independent of reference frame. Note: the speed of light is measured to be 299,792.458 km/s.



Albert Einstein

Consequences of Einstein's special theory of relativity.

- **Space-time warping:** "distance" in a given reference frame is a mixture of distance and time from other reference frames.
- **Length contraction:** objects seen in moving reference frames appear to be shorter along their direction of motion than the same object seen at rest (Lorentz-Fitzgerald contraction).
- **Time dilation:** time intervals seen in moving reference frames appear longer than the same interval seen at rest.
- **Velocities are relative:** "velocity" is a function of the velocity of the observer. Velocities add up in such a way that no velocity exceeds the speed of light.
- **There is no frame of reference in which light can appear to be at rest.**

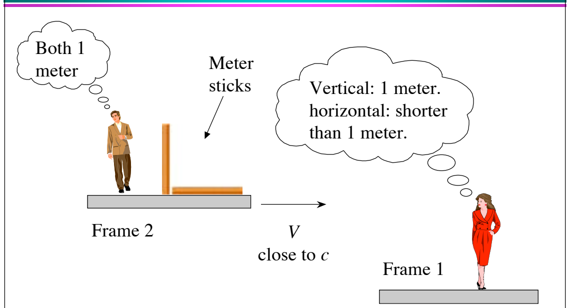
Consequences of Einstein's special theory of relativity.

- **Simultaneity is relative:** events that occur simultaneously in one reference frame do not appear to occur simultaneously in other, differently-moving, reference frames.
- **Mass is relative:** an object seen in a moving reference frame appears to be *more massive* than the same object seen at rest; its mass approaches infinity as the speed of the reference frame approaches the speed of light. (This is why nothing can go faster than light.)
- **Mass and energy are equivalent:** Energy can play the role of mass, endowing inertia to objects, exerting gravitational forces, *etc*. This is embodied in the famous equation $E=mc^2$.

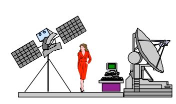
Einstein's special theory of relativity.

- Einstein's special theory of relativity was so revolutionary that many great physicists had great difficulty accepting it.
- Einstein's special theory of relativity changed the foundation of physics. Its "design" was largely based on aesthetic arguments, rather than an extensive set of observations that could not be explained in any other way.
- The only experimental information that was used by Einstein (the Michelson-Morley experiment) could also be explained by making small changes to existing theories, although it required the introduction of unknown forces.

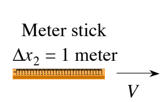
Consequences of Einstein's special theory of relativity: Length contraction.



Consequences of Einstein's special theory of relativity: Length contraction.



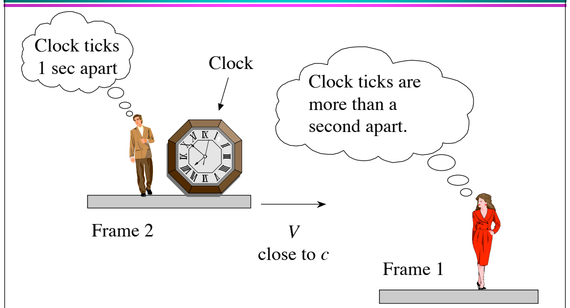
Observer 1 measures the length of the meter stick. Her observations are summarized in the following table.



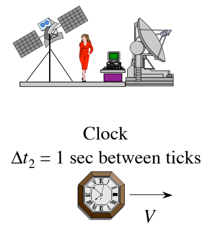
V	Δx_1
0 km/s	1 m
10 km/s	1 m
1000 km/s	0.999994 m
100000 km/s	0.943 m
200000 km/s	0.745 m
290000 km/s	0.253 m

Note: 10 km/s = 22,500 mi/h

Consequences of Einstein's special theory of relativity: Time dilation.



Consequences of Einstein's special theory of relativity: Time dilation.



Observer 1 measures the time interval between the ticks of the clock. Her observations are summarized in the following table.

V	Δt_1
0 km/s	1 sec
10 km/sec	1 sec
1000 km/sec	1.000006 sec
100000 km/sec	1.061 sec
200000 km/sec	1.34 sec
290000 km/sec	3.94 sec

Note: 10 km/s = 22,500 mi/h

Verification of Einstein's theory of special relativity.

- Einstein's theory of relativity changed the foundations of physics.
- Many basic concepts, such as the relativity of space and time, are a direct consequence of the "absoluteness" of the speed of light.
- The new theory is logically consistent and mathematically very elegant.
- The new theory "contains" Newtonian physics as an approximation valid for speeds much smaller than the speed of light.
- However, the new theory would be worthless if it didn't agree with reality (i.e. experiments) better than classical physics.

Newton's gravitational law.

- Newton's gravitational law states that two objects attract each other with a force that is proportional to the product of their masses and inversely proportional to the square of their distance:

$F_{grav} = G\, M_1\, M_2 / r_{12}^2$

- Newton's gravitational law was very successful in describing the motion of the moon, the planets, and many other objects in our universe.
- However, Newton's gravitational law was also clearly inconsistent with Einstein's special theory of relativity.
- Why …….. since the distance r_{12} depends on the reference frame, the force also depends on the reference frame used.

The limitations of special relativity. Yes … Einstein had problems too!

- Special relativity could only be used to describe anything involving motion in a straight line with constant velocity.
- The special theory of relativity could not be applied to situations involving **forces**, such as electromagnetic forces or the force of gravity, since they seldom involve motion in a straight line with constant velocity.
- Einstein was able to show that no simple modification of the special theory of relativity could fix these problems. A new theory was required:

The General Theory of Relativity

The general theory of relativity

- In the general theory of relativity space and time are closely connected (space-time) and may be curved.
- When particles and light travel in space-time, they follow the shortest paths between two points (the geodesic). The geodesics are in general not straight lines; they are only straight if space and time are not curved.
- Masses and energies present in space and time determine how space and time are warped. This process is what we call gravity.
- The general theory of relativity can be summed up in one statement:

"Space-time, with its curvature, tells masses how to move; masses tell space-time how to curve."

What changes in curved space? Everything we learned about geometry!

- In flat space, parallel lines never intersect.
- In curved space, parallel lines can intersect. Consider lines of longitude, which are obviously parallel when they cross the equator.

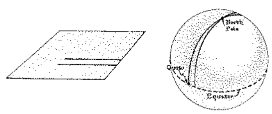


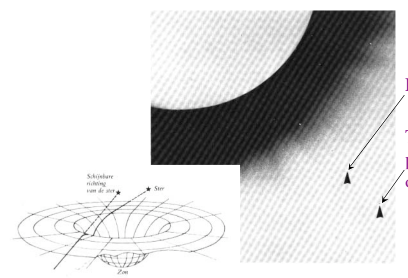
Figure from Thorne, *Black holes and time warps*

Consequences of the general theory of relativity: gravitational time dilation.

- To a distant observer, time appears to pass more slowly in places where gravity is strong.
- To an observer in a place where gravity is strong, time appears to pass more quickly in places where gravity is weak.
- Both statements embody the idea that **gravity warps time**.
- Experiments have shown that the predictions of gravitational time dilation are correct.

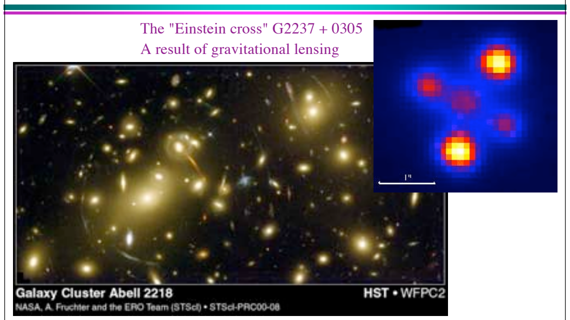
Verifying gravitational time dilation.

Gravitational lensing: A verification of the theory of relativity.



Gravitational lensing: A verification of the theory of relativity.

The "Einstein cross" G2237 + 0305
A result of gravitational lensing



Einstein's field equation.

- The mathematical form of the theory of general relativity:

$$\frac{1}{2}\left[\frac{\partial^2 g^{\lambda}_{\lambda}}{\partial x^{\kappa}\partial x^{\mu}} - \frac{\partial^2 g_{\mu\lambda}}{\partial x^{\kappa}\partial x_{\lambda}} - \frac{\partial^2 g_{\lambda\kappa}}{\partial x_{\lambda}\partial x^{\mu}} + \frac{\partial^2 g_{\mu\kappa}}{\partial x^{\lambda}\partial x_{\lambda}}\right] + g_{\eta\sigma}\left[\frac{\partial x^{\eta}}{\partial \xi^{\alpha}}\frac{\partial^2 \xi^{\alpha}}{\partial x^{\lambda}\partial x_{\lambda}}\frac{\partial x^{\sigma}}{\partial \xi^{\alpha}}\frac{\partial^2 \xi^{\alpha}}{\partial x^{\mu}\partial x^{\kappa}} - \frac{\partial x^{\eta}}{\partial \xi^{\alpha}}\frac{\partial^2 \xi^{\alpha}}{\partial x^{\kappa}\partial x_{\lambda}}\frac{\partial x^{\sigma}}{\partial \xi^{\alpha}}\frac{\partial^2 \xi^{\alpha}}{\partial x^{\mu}\partial x^{\lambda}}\right]$$

$$-\frac{1}{2}g_{\mu\kappa}\left(\frac{1}{2}\left[2\frac{\partial^2 g^{\lambda}_{\lambda}}{\partial x^{\mu}\partial x_{\mu}} - \frac{\partial^2 g^{\mu}_{\lambda}}{\partial x^{\mu}\partial x_{\lambda}} - \frac{\partial^2 g_{\lambda\mu}}{\partial x_{\lambda}\partial x_{\mu}}\right] + g_{\eta\sigma}\left[\frac{\partial x^{\eta}}{\partial \xi^{\alpha}}\frac{\partial^2 \xi^{\alpha}}{\partial x^{\lambda}\partial x_{\lambda}}\frac{\partial x^{\sigma}}{\partial \xi^{\alpha}}\frac{\partial^2 \xi^{\alpha}}{\partial x_{\mu}\partial x^{\mu}} - \frac{\partial x^{\eta}}{\partial \xi^{\alpha}}\frac{\partial^2 \xi^{\alpha}}{\partial x^{\mu}\partial x_{\lambda}}\frac{\partial x^{\sigma}}{\partial \xi^{\alpha}}\frac{\partial^2 \xi^{\alpha}}{\partial x_{\mu}\partial x^{\lambda}}\right]\right)$$

$$= -8\pi G\sum_{n} p_{n\mu}\frac{dx_{n\kappa}}{dt}\delta^3(x - x_n)$$

- Einstein's field equation was solved by Karl Schwarzschild while he was on the battle field in World War I where he died in 1916.

Karl Schwarzschild (1873 - 1916): The existence of black holes.

- Schwarzschild was interested in the physics of stars, and he solved Einstein's field equation for the region outside a massive spherical object.
- In the process he discovered some techniques, and ways of visualizing curved space-time, that benefited others who were doing research in general relativity.
- His solution of Einstein's field equation revealed the existence of black holes.

Karl Schwarzschild

The prediction of black holes.

- The black holes predicted by Schwarzschild were so heavy that event light could not escape (this is why they are called black holes).
- Einstein did not accept this prediction. He and Arthur Eddington, a British astro-physicist, stated that "they did not like the smell of black holes".
- The controversy did not get a lot of attention since Einstein and Eddington were considered the experts on general relativity.

Albert Einstein

Sir Arthur Eddington (1882-1944)

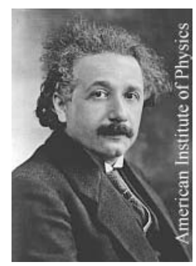
The prediction of black holes.

- Einstein viewed a star of any size as a cluster of particles; each particle orbiting the center of the star.
- When the size of the star decreases, the orbital velocity of these particles will increase.
- Einstein calculated that when the radius of the star would be 1.5 times the Schwarzschild radius, the orbital speed would be the speed of light.
- Since only light can move with the speed of light, such a star can not exist, Einstein argued. But …. maybe Einstein's model of a star is not correct.

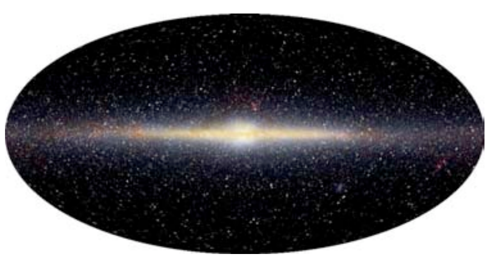
Albert Einstein in his study at home in Princeton, New Jersey, in 1938.

The prediction of black holes.

- Einstein tried to modify his theory by adding a constant such that it would not predict the existence of black holes. This constant became known as the cosmological constant and accounted for all missing physics in the theory.
- Eventually Einstein gave up; there appeared to be no need for the cosmological constant, and Einstein called it "his greatest blunder".



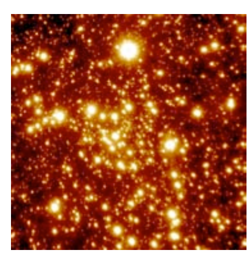
Evidence for black holes: Look at the center of galaxies.



The Milky Way in Infrared
Credit: E. L. Wright (UCLA), The COBE Project, DIRBE, NASA

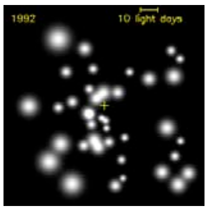
Finding black holes.

- It is believed that black holes exist in the center of most galaxies.
- The existence of black holes is often inferred from the motion of stars around the center of the galaxy.
- However, in most cases, alternative and exotic explanations for the observed motion can also explain the observed motion.



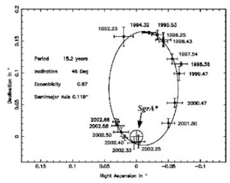
Center of the Milky Way. Credit: MPE and UCLA

Finding black holes: Motion of stars in the center of our galaxy.



Center of the Milky Way. Credit: MPE and UCLA.

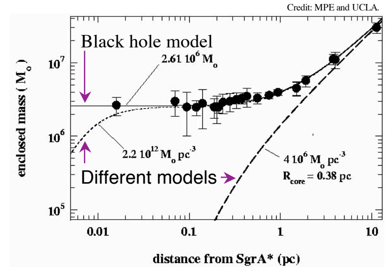
The MPE/UCLA group studied in detail the motion of stars around Sagittarius A*.



Motion of S2 around Sgr A*. Credit: MPE and UCLA.

Finding black holes: Motion close to Sgr A* leaves only one option.

Credit: MPE and UCLA.

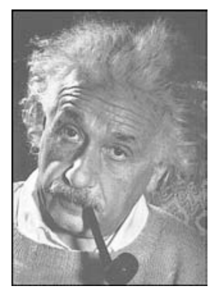


Experimental tests of relativity.

- All reproducible experiments to date have confirmed the predictions of Einstein's theories of relativity.
- Few scientific theories are so well-supported by experimental data.
- We keep using Einstein's theories to predict new effects. Experimental tests of these newly-predicted effects are in many cases even sterner tests of the theories.

In conclusion …….

- There is little doubt in my mind that we will never again see a single individual have as much of an impact on science as Einstein had.
- Einstein's theories, especially his theories of relativity, dramatically changed our views of the world.
- Just as remarkable as the theories themselves is that fact that Einstein developed them on the basis of mainly aesthetic arguments, rather than experimental data.



The University of Frankfurt's Archives.

In conclusion …… Quotes from Albert Einstein.

- "If the facts don't fit the theory, change the facts."
- "Only two things are infinite, the universe and human stupidity, and I'm not sure about the former."
- "God doesn't play dice."
- "If we knew what it was we were doing, it would not be called research, would it? "
- "Teaching should be such that what is offered is perceived as a valuable gift and not as a hard duty."