

Lecture 24: The Takehome Message

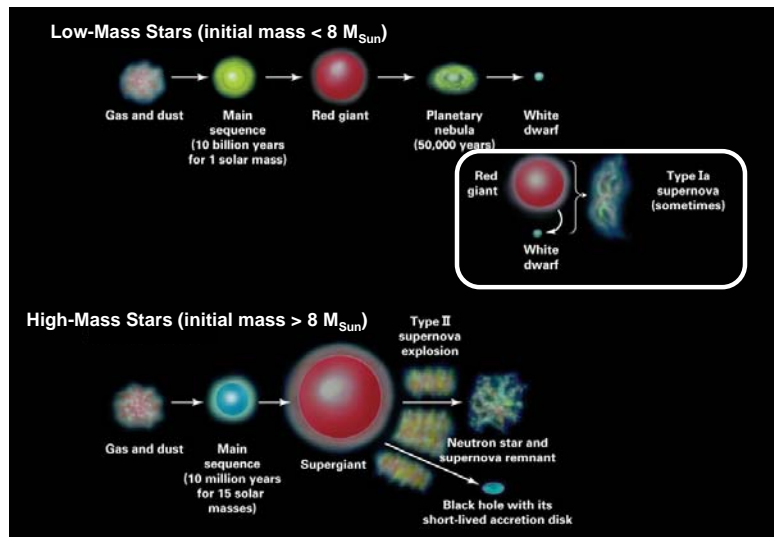
Black holes have been convincingly demonstrated to exist in nature, by examining the gravitational effects they have on their surroundings.

In case you missed it!

SDSU Live! Broadcast from last Wed., April 15, 2009:
“When Stars Explode”

Available on YouTube, and at (link at course website):
<http://www.sdsuniverse.info/sdsuniverse/news.aspx?s=71147>

The Evolution of Stars: From Birth to Death 255



(Pasachoff & Filippenko, *The Cosmos*, 3rd Edition, Figure 12-19, Page 290)

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How to Discover a Black Hole in a Binary System

- Identify an X-Ray burst coming from a star with an invisible companion.
- Measure the shifting radial velocity of the star as it orbits around the invisible companion.
- Apply Newton's version of Kepler's Third Law to the data.

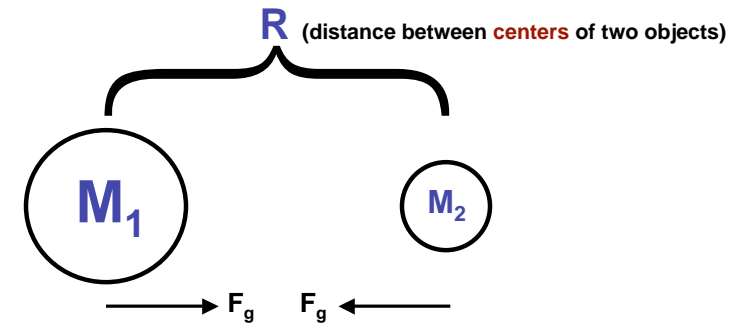
$$R^3 = (M_1 + M_2)P^2$$

- If the minimum mass of the unseen companion is greater than $3M_{\text{Sun}}$, then you have discovered a black hole!

Black Hole: A completely gravitationally collapsed object;
A region of space from which neither matter nor light can escape.

Escape velocity: The velocity a body needs to escape the gravity
of another body and never return to it.

Newton's Law of Gravitation

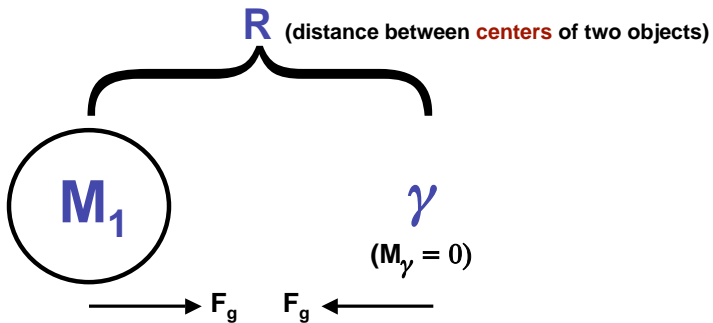


$$F_g = \frac{GM_1M_2}{R^2}$$

According to Newton's Law of gravity:

Gravity is a force of attraction that exists between objects that have mass.

Newton's Law of Gravitation



$$F_g = \frac{GM_1M_2}{R^2}$$

According to Newton's Law of gravity:

Gravity is a force of attraction that exists between objects that have mass.

Since light has no mass, it should **NOT** be affected by gravity!



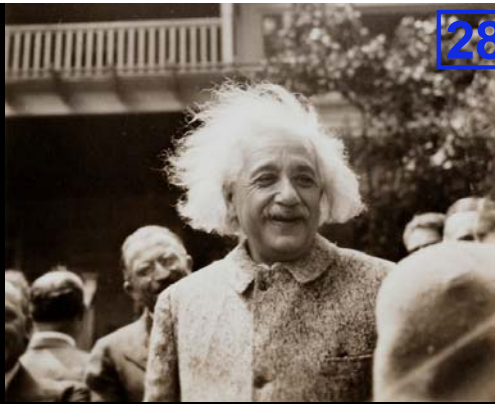
Isaac Newton (1643 - 1727)



Albert Einstein (1879 - 1955)



Isaac Newton (1643 - 1727)

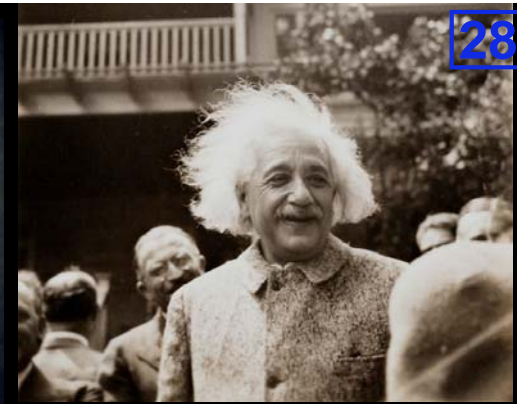


Albert Einstein (1879 - 1955)

General theory of relativity: Albert Einstein's theory of gravity (1916).



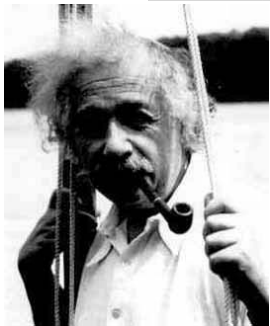
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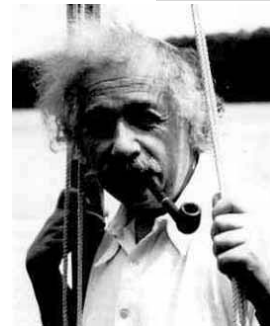
General theory of relativity: Albert Einstein's theory of gravity (1916).

Einstein's General Theory of Relativity (1916) 285

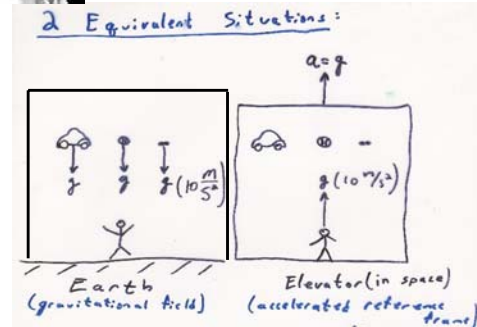


Einstein regarded Galileo's observation that all objects fall at the same rate in a gravitational field as a deep clue into Nature's workings...

Einstein's General Theory of Relativity (1916) 285

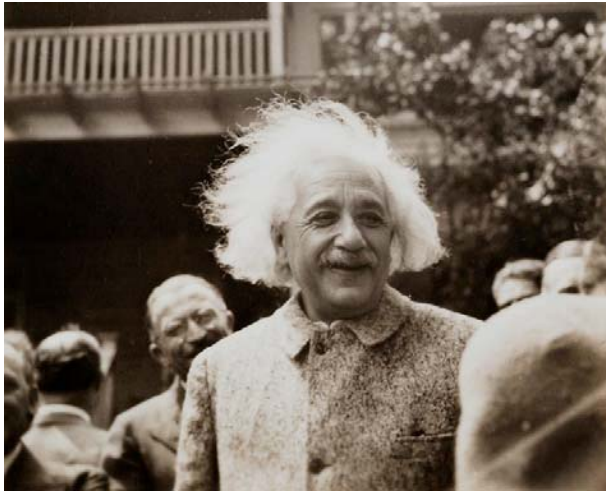


Einstein regarded Galileo's observation that all objects fall at the same rate in a gravitational field as a deep clue into Nature's workings...



Basic Postulate of General Relativity 286

Principle of Equivalence: There is no way to tell locally the difference between gravity and acceleration.



Galileo's Contributions to Science and Mechanics 82

Mechanics: The branch of physics that concerns the study of motion and the action of forces on bodies.

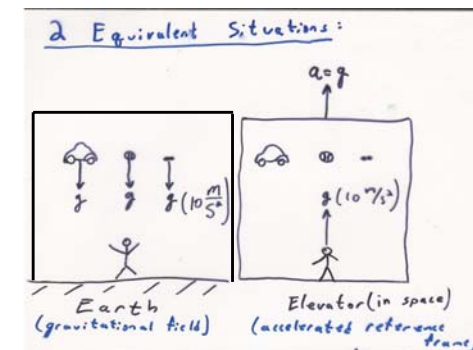
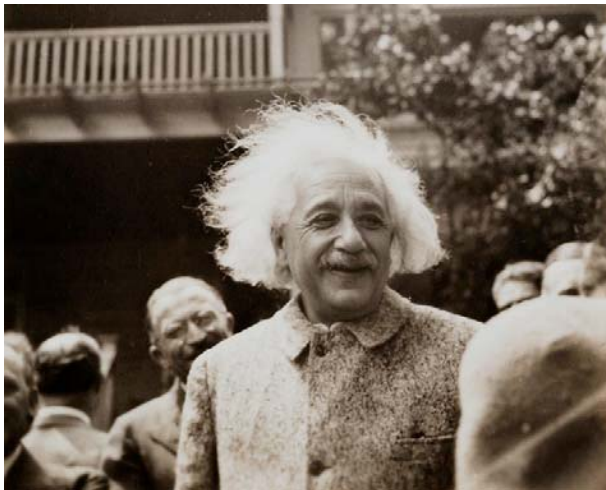
- Emphasized absolute necessity of *experimentation*.
- **Law of Falling Bodies:** In the absence of air-resistance, all bodies fall at the same rate.
- **Law of Inertia:** Every body tends to continue doing what it is already doing -- being in a state of rest, or moving uniformly in a straight line -- unless it is compelled to change by an outside force.

→ Only a change in motion requires a force.

→ **Galileo's Principle of Equivalence:** There is no way to tell locally the difference between rest and constant velocity.

Basic Postulate of General Relativity 286

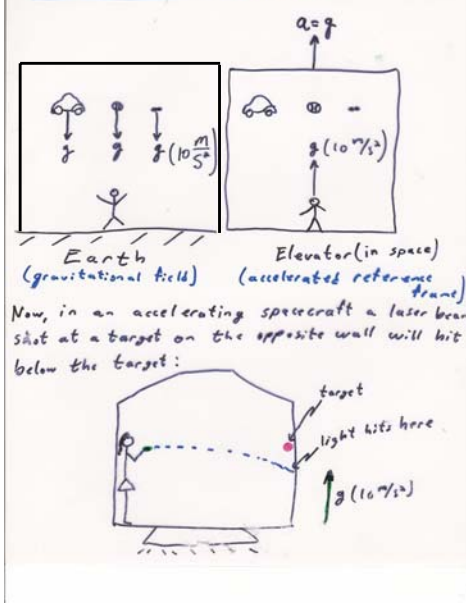
Principle of Equivalence: There is no way to tell locally the difference between gravity and acceleration.



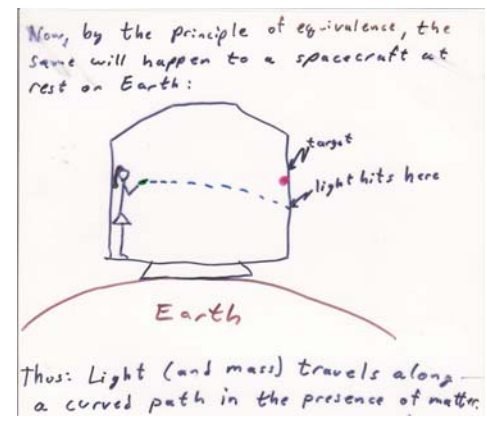
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2 Equivalent Situations:

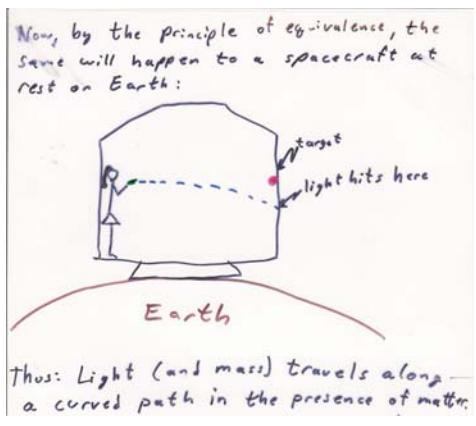
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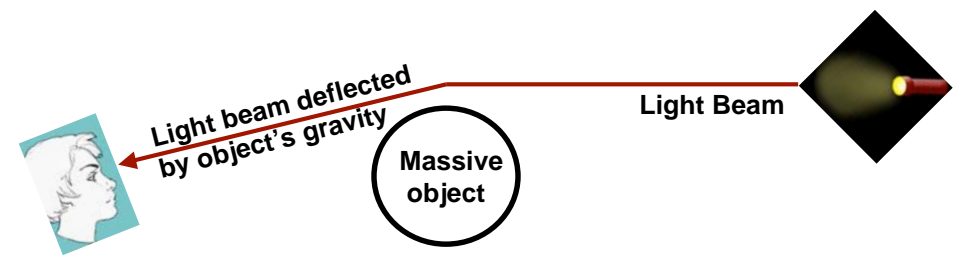
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Testing General Relativity: The "Bending" of Light by Gravity 289



Light should appear to be "bent" by gravity!

Properties of Light

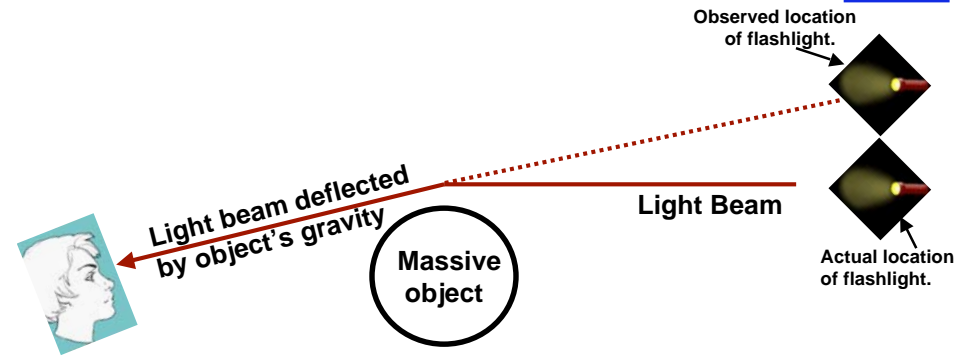
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Refraction: The bending of light when it passes from one transparent medium to another.



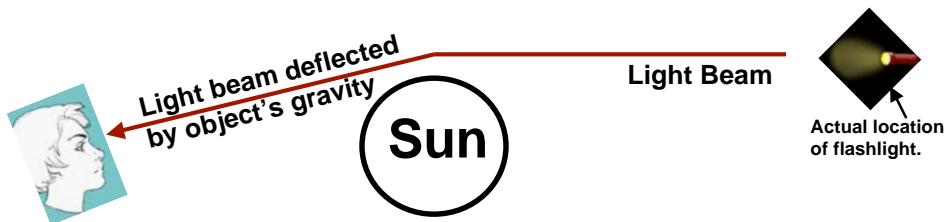
Testing General Relativity: The "Bending" of Light by Gravity

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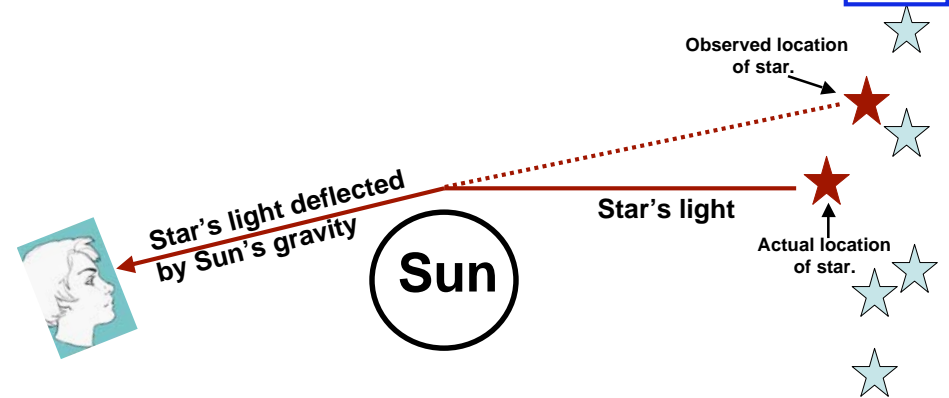
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Testing General Relativity: The "Bending" of Light by Gravity

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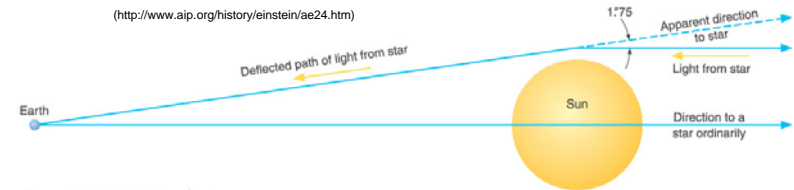
Testing General Relativity: Deflection of Starlight

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← Einstein's Letter Urging Astronomers to Detect Deflection of Starlight

(<http://www.aip.org/history/einstein/ae24.htm>)

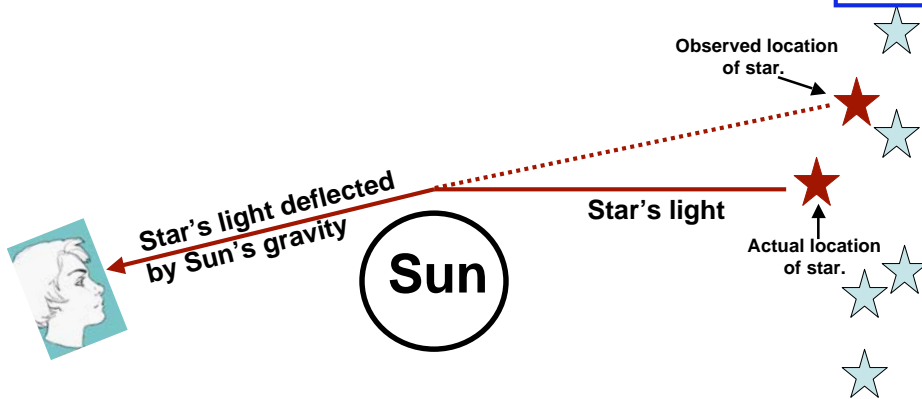


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(Fracnoi, Morrison, & Wolff: Voyages to the Stars and Galaxies, 3rd Edition, Table 15.8, Page 343)

Testing General Relativity: The "Bending" of Light by Gravity

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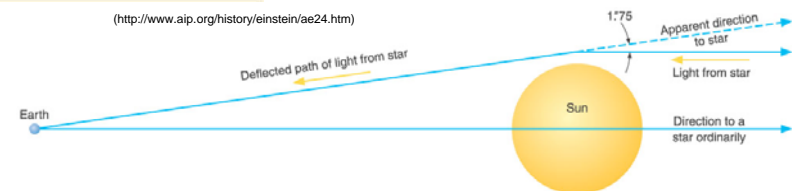
Testing General Relativity: Deflection of Starlight

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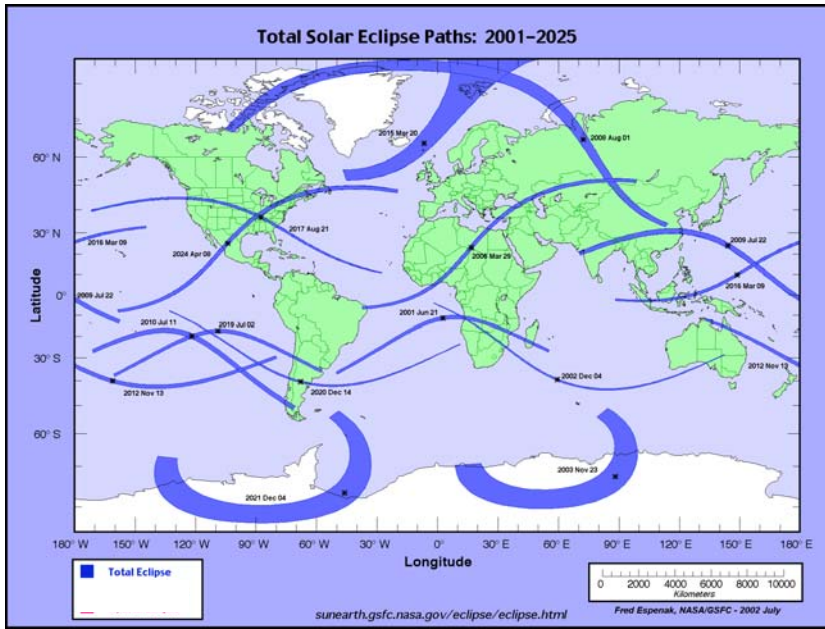
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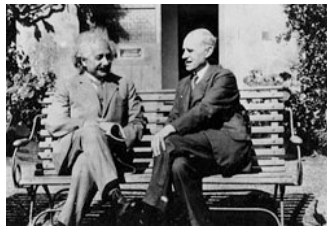


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(Fracnoi, Morrison, & Wolff: Voyages to the Stars and Galaxies, 3rd Edition, Table 15.8, Page 343)



May 29, 1919 Eclipse Expedition



Einstein and Eddington

NY Times: November 10, 1919

LIGHTS ALL ASKEW IN THE HEAVENS

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

EINSTEIN THEORY TRIUMPHS

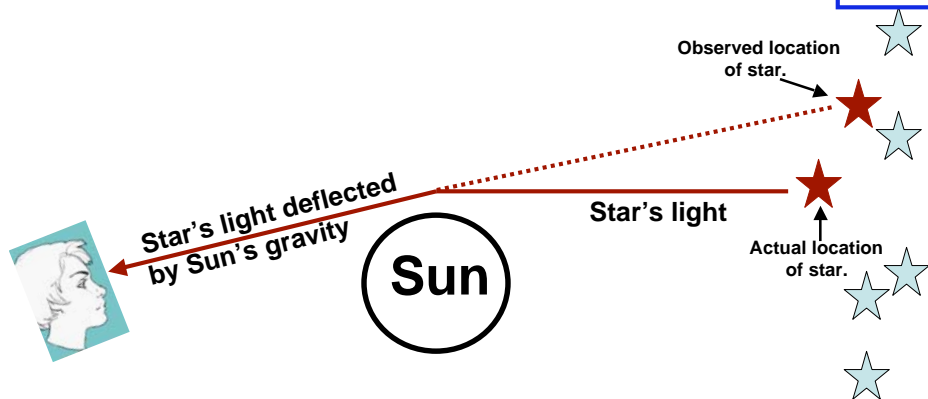
Stars Not Where They Seemed
or Were Calculated to be,
but Nobody Need Worry.

A BOOK FOR 12 WISE MEN

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

Testing General Relativity: The "Bending" of Light by Gravity

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Two Views of GRAVITY

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Newton: Gravitation represents a universal force of attraction between bodies with mass. In turn, mass acts as the source that generates the force of gravitation.

Two Views of GRAVITY

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Curvature around WHAT?

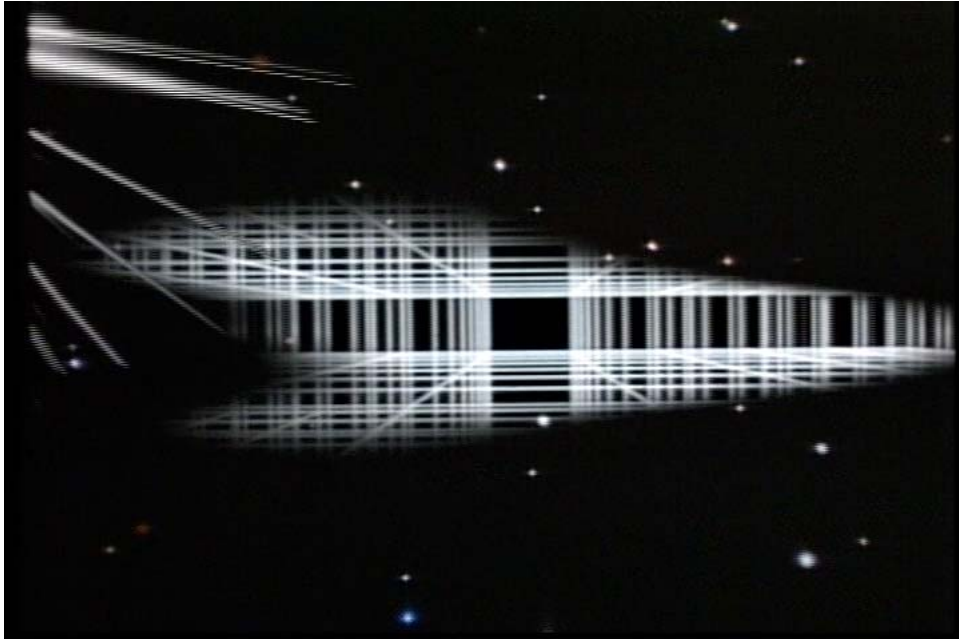
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Curvature around WHAT?

An unseen 4th spatial dimension.



Two Views of GRAVITY 292

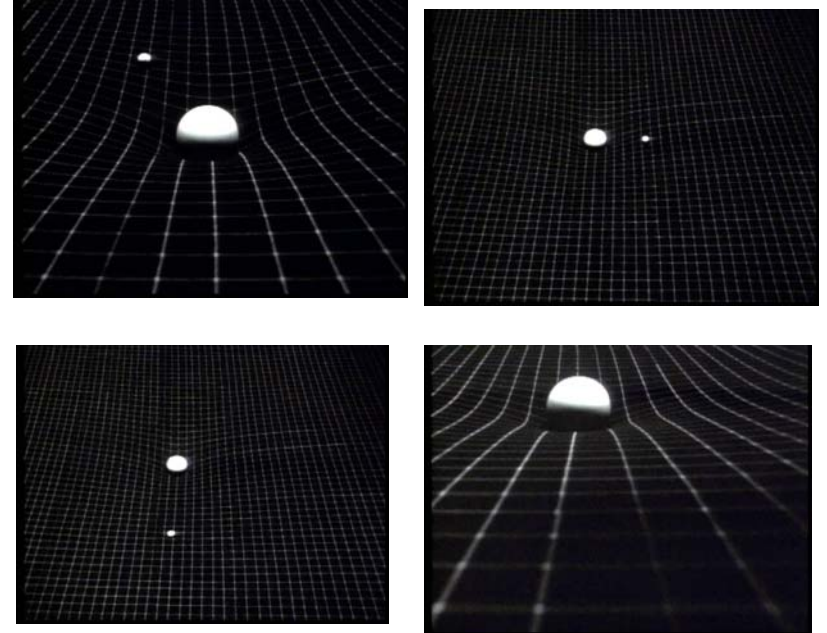
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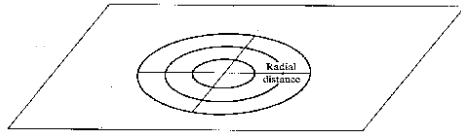
WHAT does this mean?



Embedding Diagrams

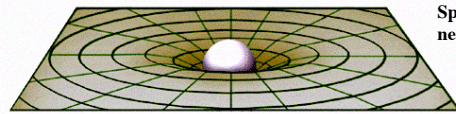
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No massive object present:

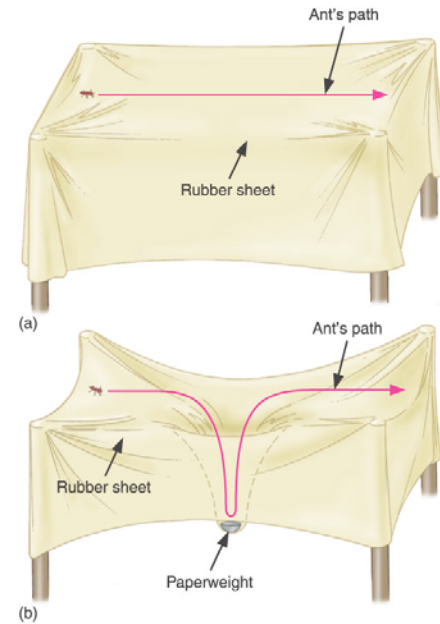


"Flat" space.

Massive object present:



Space is "curved" or "warped" near massive object.



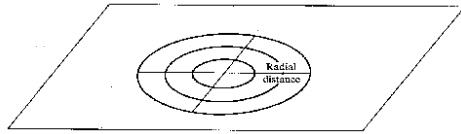
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© 2004 Thomson - Brooks/Cole (Frankel, Morrison, & Wolf: Voyages to the Stars and Galaxies, 3rd Edition, Figure 15.6, Page 342)

Embedding Diagrams

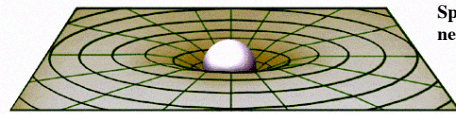
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No massive object present:

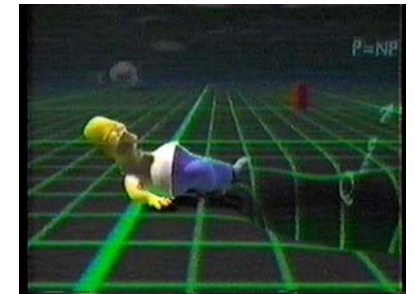


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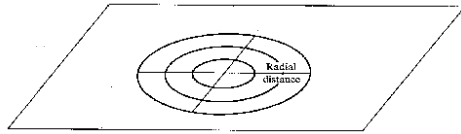
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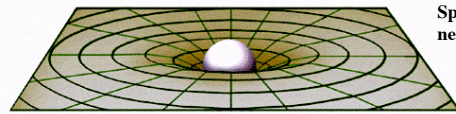
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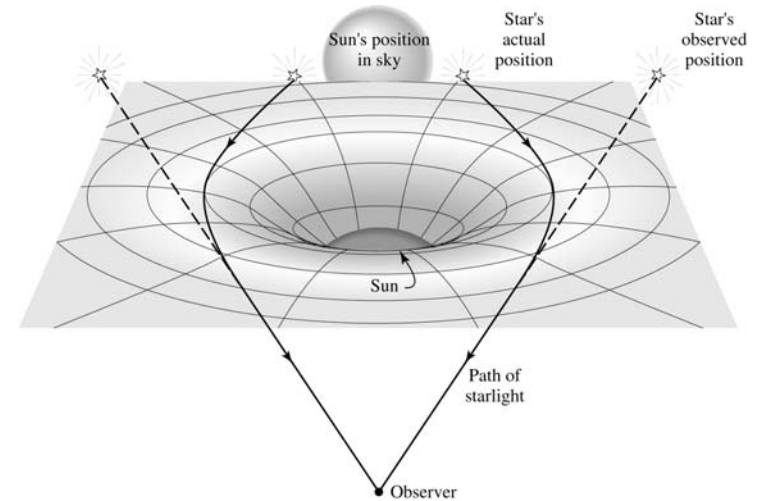


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Massive object present:



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(Carroll & Ostlie, *Modern Astrophysics*, Second edition, Figure 17.5, Page 613)

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Curvature around WHAT?

An unseen 4th spatial dimension.

Space curvature: The apparent warping of space into an unobservable 4th spatial dimension due to the presence of gravity.

Basic Effects of General Relativity

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➤ **Space Curvature:** Space is 'curved' or 'warped' near massive objects.

Basic Effects of General Relativity

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- **Space Curvature:** Space is 'curved' or 'warped' near massive objects.
- **Gravitational Time Dilation:** The stronger the gravity, the slower the pace of time.

Lecture 25: The Takehome Message

To study black holes in detail, we need a new theory of gravity: Einstein's General Theory of Relativity.