Earth 101
Introduction to Astronomy

Relativity

Instructor:
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$$\Delta E \Delta t \geq \hbar$$

OpenStax Ch 24
Relativity
Black Holes & Spacetime

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- Fred Marschak
- Dr. Jatila van der Veen
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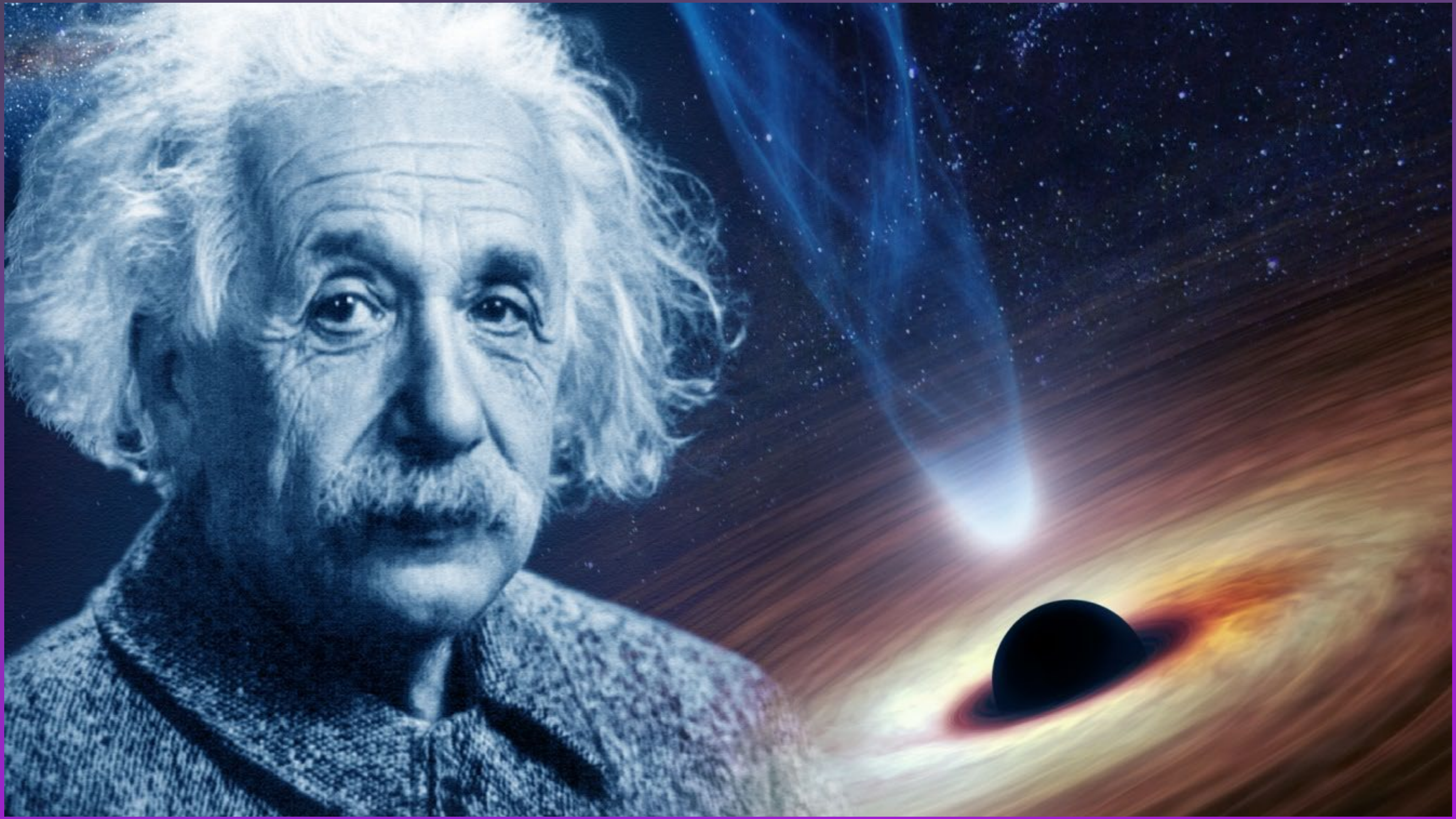
NGC 2359 Thor's Helmet © 2022 Hector Jimenez

Relativity & Black Holes

Relativity



Albert Einstein

Relativity

Everything is relative

Motion - What is still?

Time - Looking back in time

Time is the 4th dimension = spacetime

Depends on your <u>Frame of Reference</u>

1905

Special Theory of Relativity

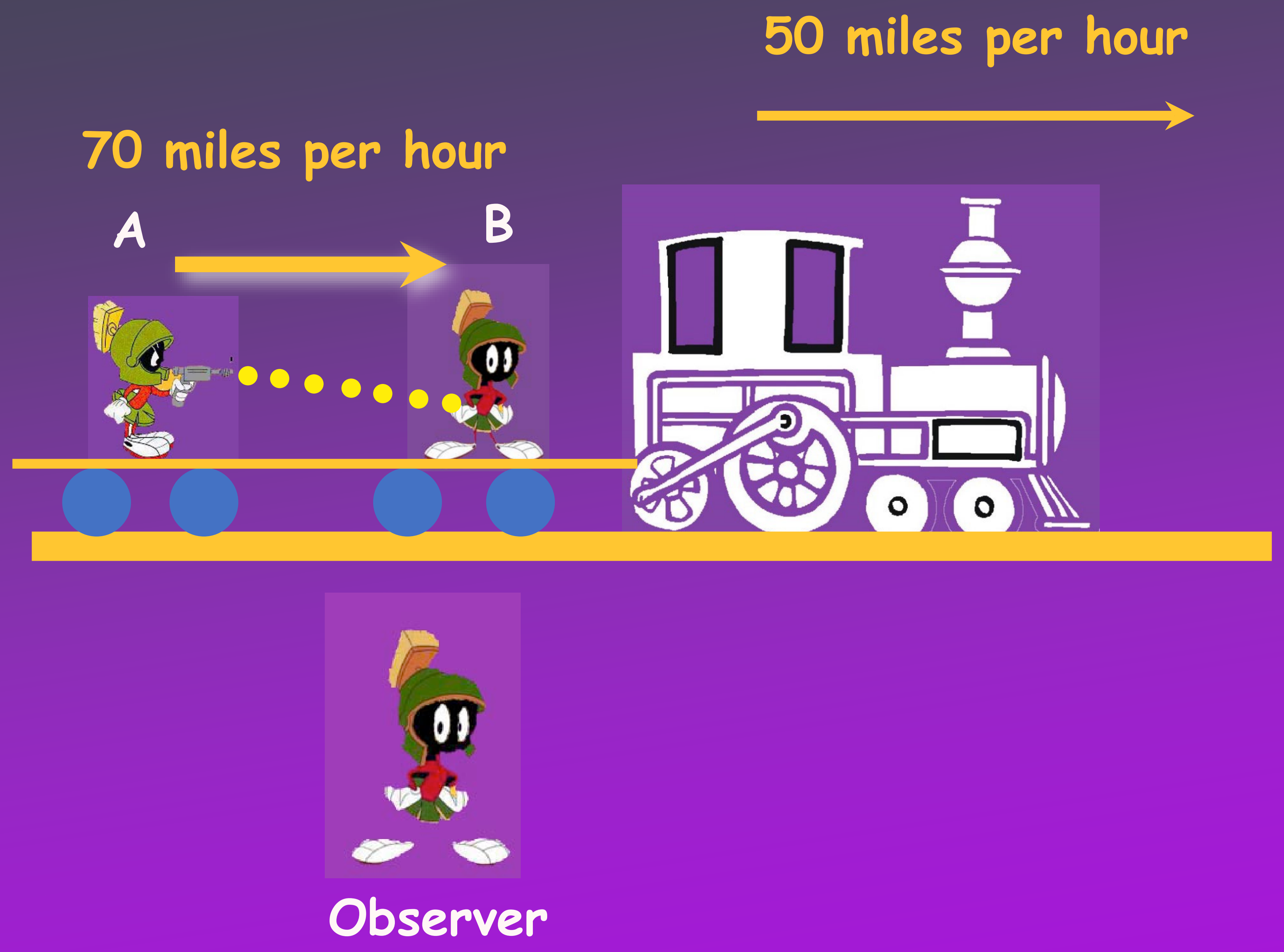
... preferred status of the speed of light

Speed of light = c

$E = mc^2$

First Postulate

The laws of physics are the same for all observers in a uniformly moving frame of reference.


50 miles per hour
70 miles per hour
A
B
Observer

Second Postulate

The velocity of light is the same for all observers in space regardless of the motion of the source or the observer.

Lorentz Contractions

as approach c ...

Length	shorter
Mass	HEAVIER
Time	S l o w e r

1916

General Theory of Relativity

... a better theory of gravity than ....

Newton's ideas

Principle of Equivalence

A gravitational force can be replaced by an inertial force that is due to accelerated motion without any change in the physical activity.

Principle of Equivalence

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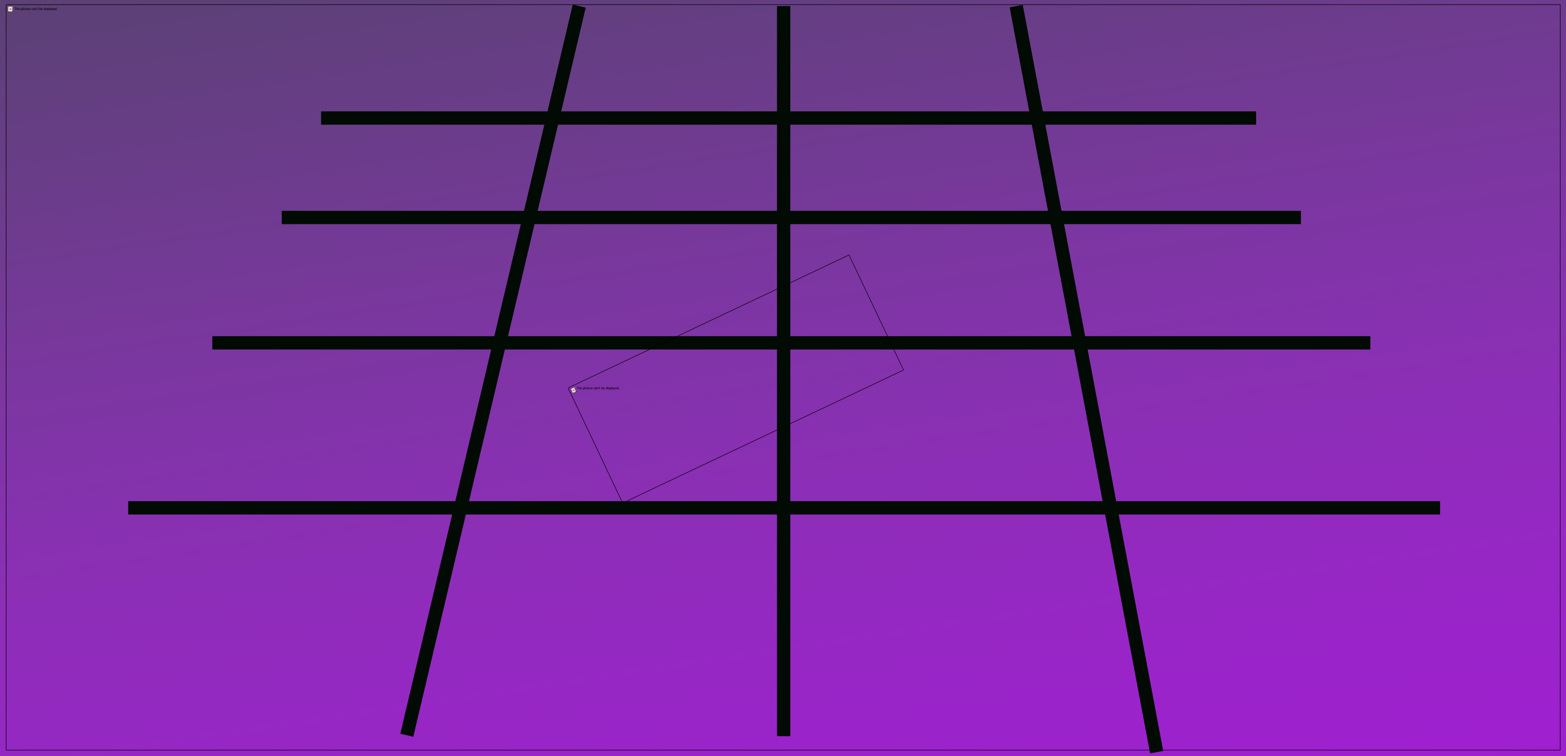
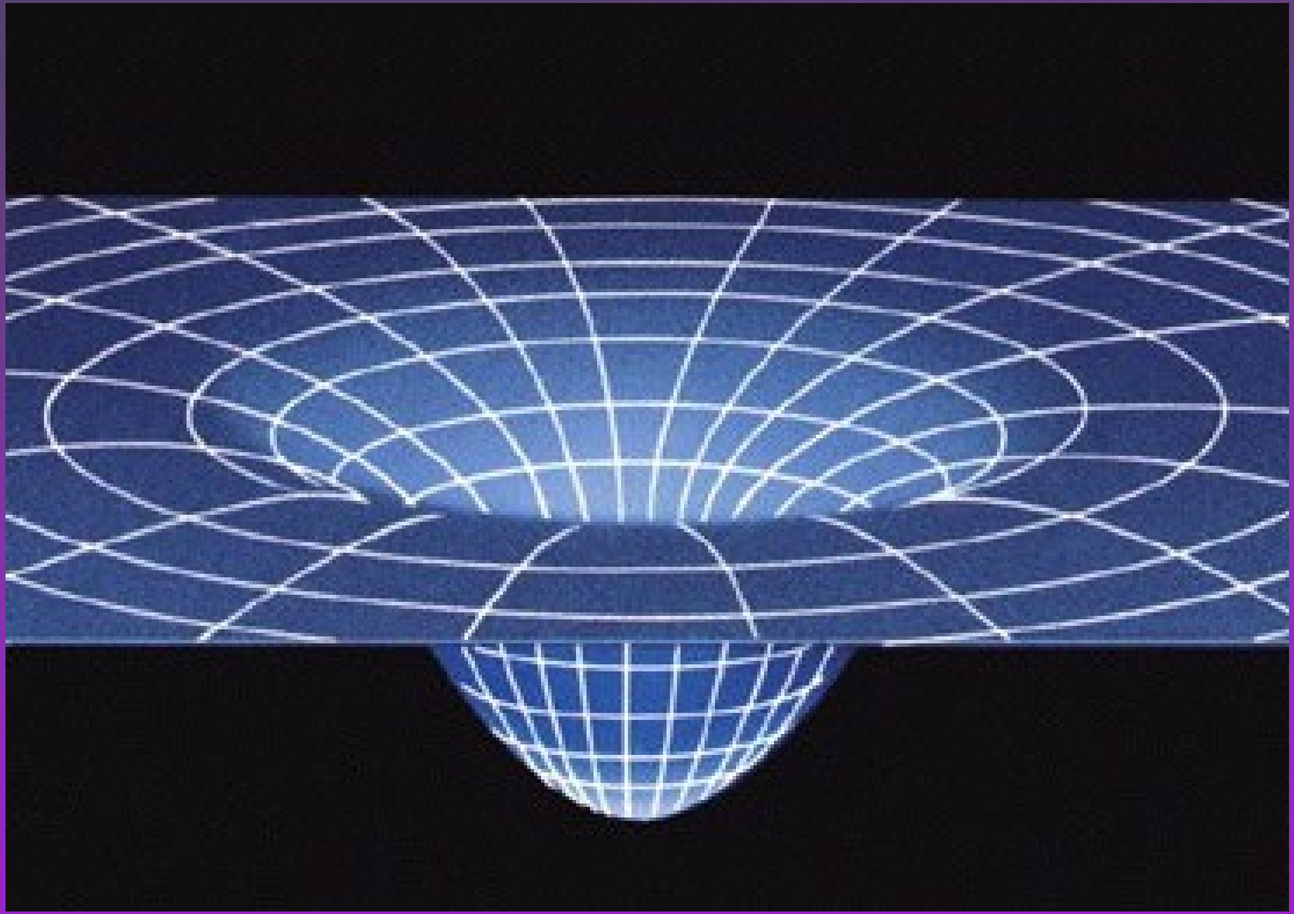
SPACETIME



“fabric’ of spacetime



Matter tells spacetime how to ....

curve and curved spacetime
tells matter how to ...

move.

1919

Total Solar Eclipse

Recall what we said in the beginning of the course, that all advances in science begin with someone asking the right question in a way which was never asked before, and often coming up with a new mathematical technique with which to model the answer to the question, as well as someone inventing a new instrument which can give more refined measurements.

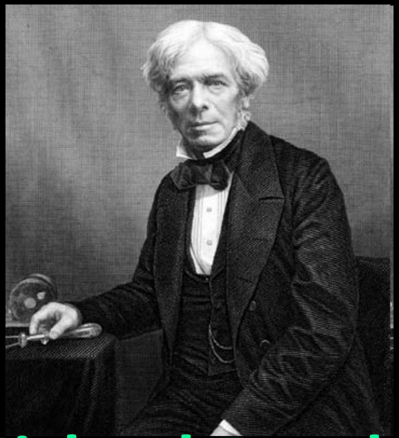
Examples we have looked at include:

1. Galileo Galilei – confirmation of the heliocentric theory, using the recent invention of the telescope

2. Isaac Newton – 3 Force Laws and his Universal Law of Gravitation, and his invention of the calculus as a new mathematical technique with which he could verify his new Laws of Physics

Classical Laws of Physics

Carl Friedrich Gauss
1777 – 1855



Michael Faraday
1791-1867

J. C. Maxwell
1831 – 1879

Around the end of the 19th century, James Clerk Maxwell, building on work of Gauss, Faraday, and many others, on the nature of electric and magnetic fields, **predicted that light is an electromagnetic wave, which travels in a vacuum at a constant speed**.

This was a tremendous breakthrough: That the speed of light, approximately 3.0 x 10^8 meters/second, is ENTIRELY a result of the electromagnetic properties of space itself!

Thus the speed of light is a characteristic property of our universe! If it had been even less than one percent different from what it is, the entire evolution of our universe would have been different, maybe not resulting in sufficient time for life, as we know it, to develop.

Here's Maxwell's breakthrough defining the speed of light in a vacuum by the electric and magnetic properties of space itself:

$$c = \frac{1}{\sqrt{\varepsilon_0 \mu_0}}$$

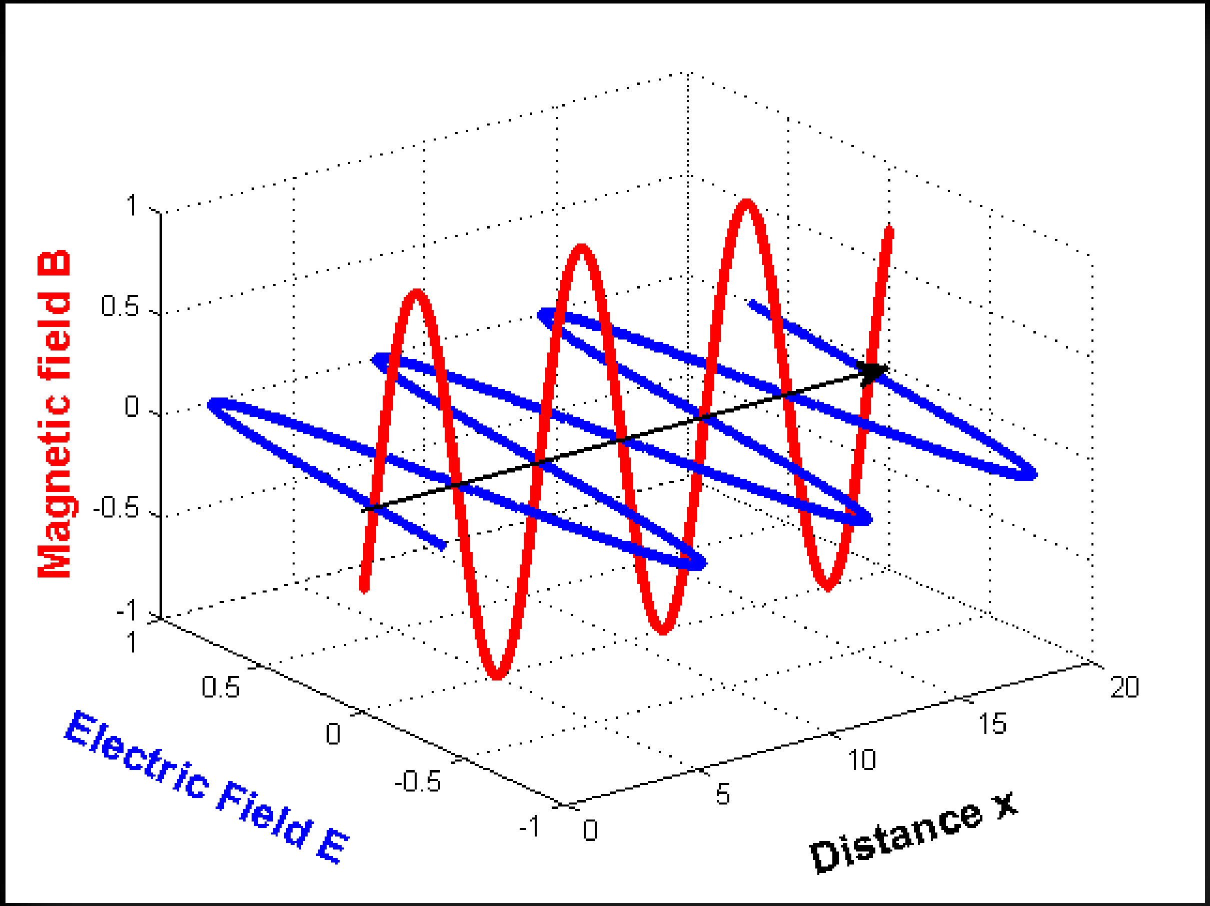
ε_0 = electric permittivity

μ_0 = magnetic permeability

$\varepsilon_0 = 8.85$ Farad/meter

$\mu_0 = 4\pi \times 10^{-7}$ Henry/meter

$$\frac{1}{\sqrt{\mu_0 \varepsilon_0}} = 2.9986 \times 10^{8} \text{ m/sec}$$



Animation of an electromagnetic wave, **<u>greatly</u>** slowed down!

The collective opinion of science at the end of the nineteenth century was that electromagnetic waves can NOT travel in a vacuum. They must have a medium in which they can propagate, as sound waves need air, seismic waves need the Earth, and water waves need...well, water.   So it was hypothesized that there must be a “lumeniferous ether” permeating space, through which light can travel.

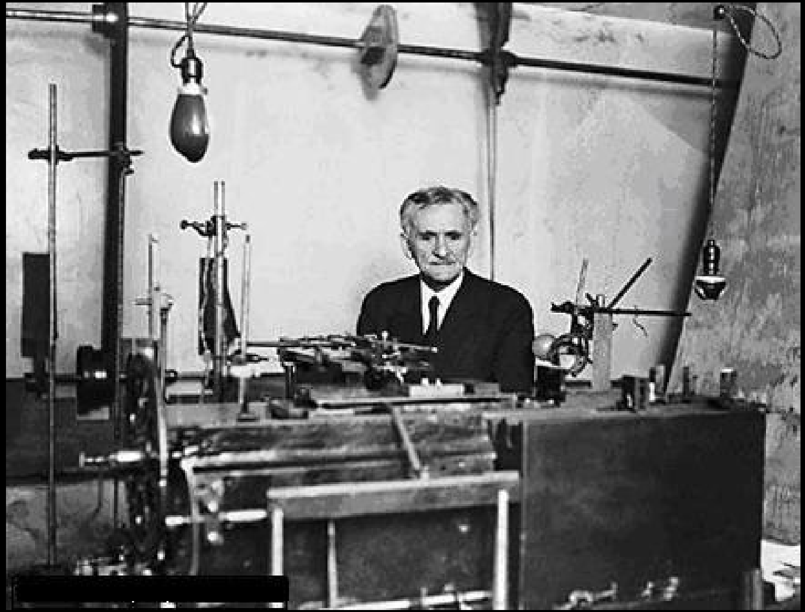
Albert A. Michaelson
1852-1931

Edward Morley
1828 - 1923

So Albert Michaelson and Edward Morley devised their famous experiment in 1887 to demonstrate the presence of “luminiferous ether” that was expected to permeate space.

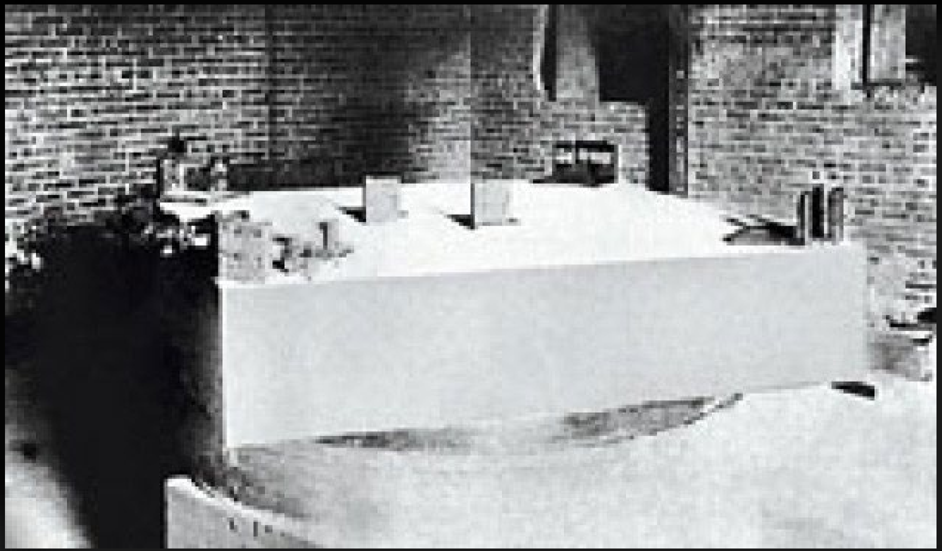
Their hypothesis was that the luminiferous ether should have a preferred direction of “flow” in space. As the Earth orbited the Sun, it should be traveling with, against, or at some angle, relative to this ether.

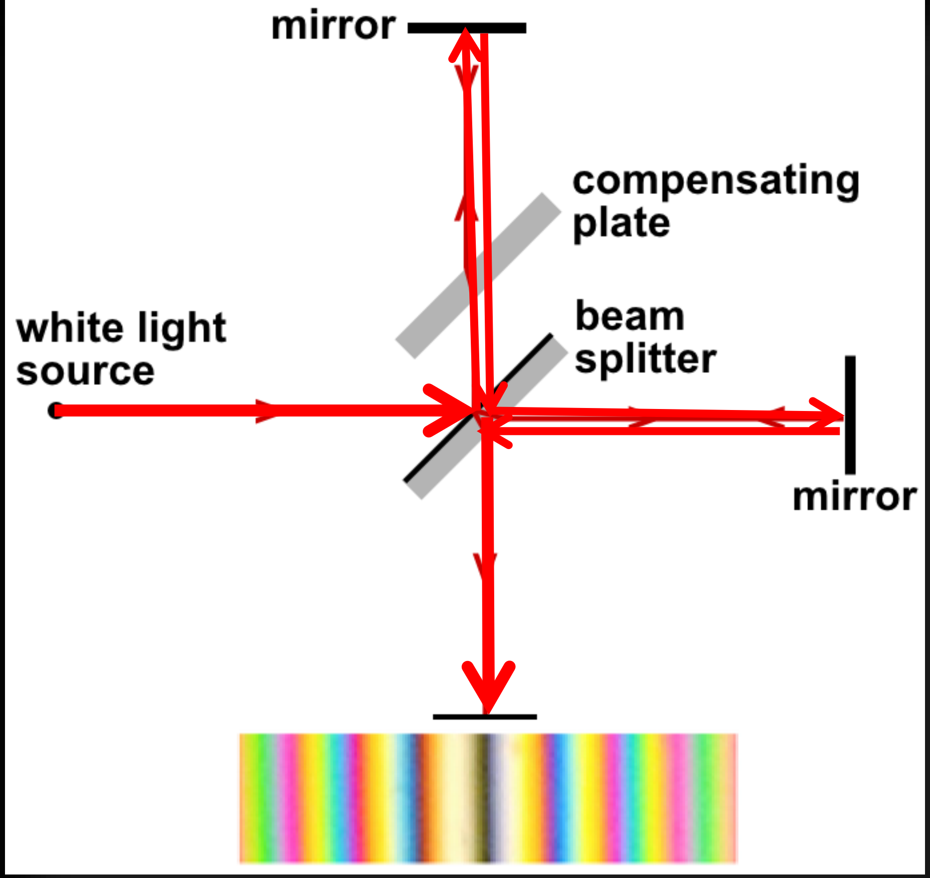
They designed an ***interferometer*** to measure the differences in arrival time of two perpendicular light beams over the course of a year.



Michaelson & Moreley's interferometer

Michelson and Morley's interferometer, mounted on a stone slab that floats in an annular trough of mercury (Wikipedia). This experiment was performed at what is now Case Western Reserve University in Cleveland, Ohio, in 1887.

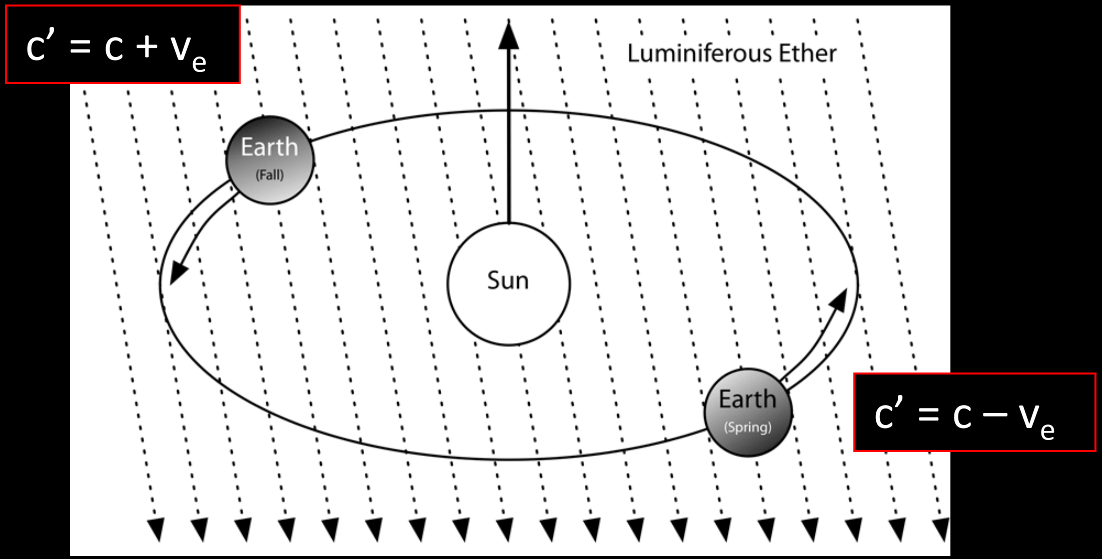




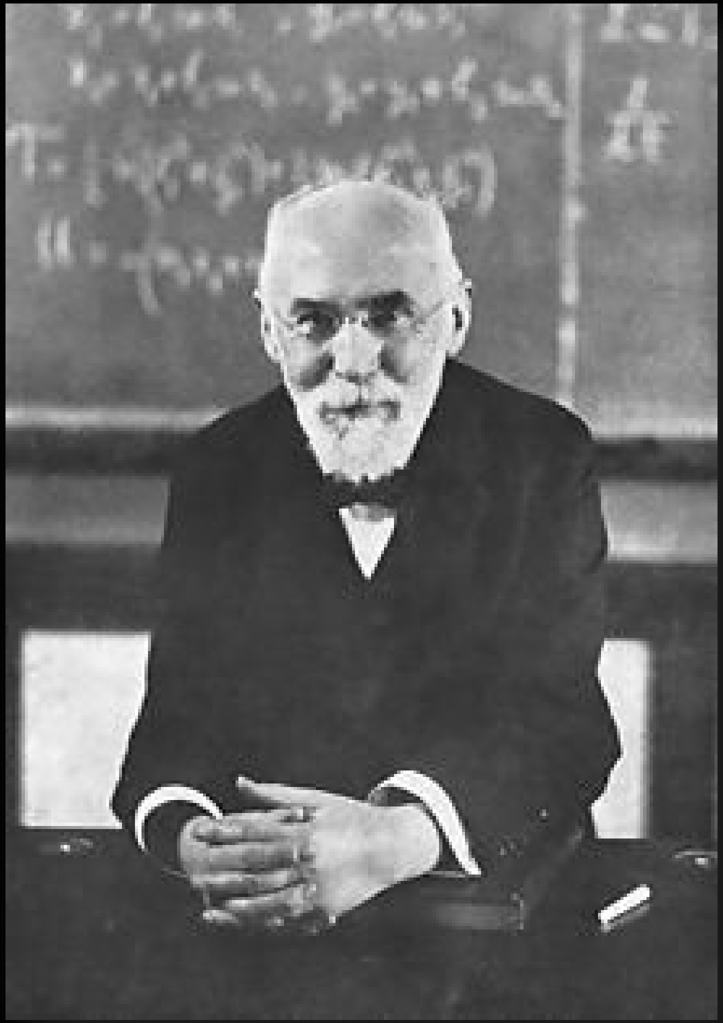
How the Michaelson-Morely interferometer works: Light shines, from the left, onto a beam splitter, which divides the intensity of light in half, such that one half is reflected to a mirror at 90^0 to the path of the incoming light. The other half goes through the beam splitter. Each light beam is then reflected back along its path by the two mirrors.

The two light beams recombine at the beam splitter, where they are added together, and the combined light beam is reflected to a screen which will measure any interference. If the two beams are IN phase when they recombine, there will be no interference. If they are OUT OF phase, there will be dark fringes. ***The two light waves would be OUT OF phase if the speed of light in one direction is different from that in the other.***

They expected that the speed of light, measured on Earth at different times of the year, should vary, depending on the direction of flow of the ether, relative to the Earth, over the course of a year. They fully expected that, with their experiment, they would be able to accurately determine the speed of the ether by knowing the speed of light as determined by Maxwell, and measuring the difference in the speed of light through the ether at different times of the year!



But they did not observe what they expected to see! They found that the speed of light was the same no matter what time of year it was, i.e., where the Earth was in its orbit.



Hendrik Antoon Lorentz
(1853 – 1928)

It was the Dutch physicist, Hendrik Lorentz, who first proposed that if the speed of light is constant, independent of the speed of an observer, then it must be that moving bodies experience a difference in time and length measurements, relative to a ‘local frame.’

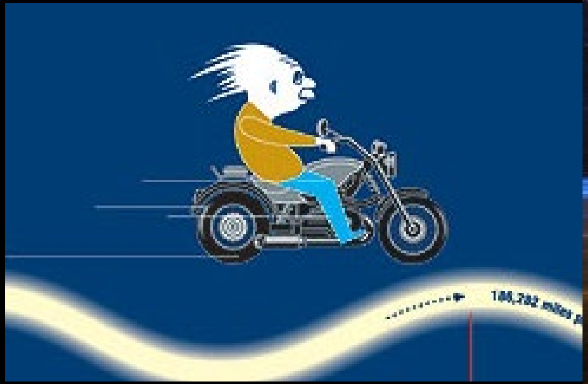
Further, Lorentz concluded that it would be impossible for either observer to tell which one was moving, and which one was not.

This idea, that time and length measurements depend on the reference frame of the observer, was shocking to the world at the turn of the 20th Century!

See Appendix A: Visualizing length contraction and time dilation with muons.

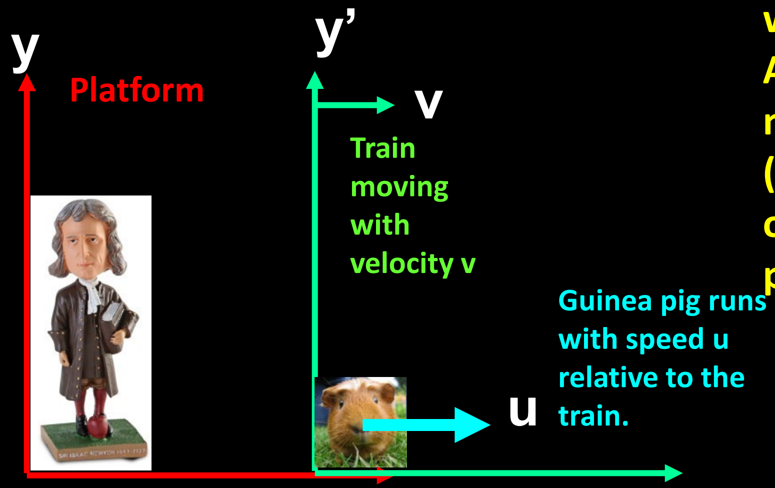
Around the same time, in the early 1900’s, Albert Einstein was working as a patent clerk in the Swiss Patent Office in Bern. It is reported that during this time, when he had a rather boring job, he spent a lot of time thinking about the recent advances in physics: Maxwell’s calculations of the speed of light as a constant of Nature, the failure of Michaelson and Morely to measure any difference in the speed of light, and Lorentz’s proposal that if the speed of light is constant for all observers, maybe time and length measurements are different!

The breakthrough question Einstein asked, which led to his developing his theory of Special Relativity was, “What would a person see if he could *ride a light beam, traveling at the speed of light?*



This question led to a complete reorganization of our understanding of our universe...

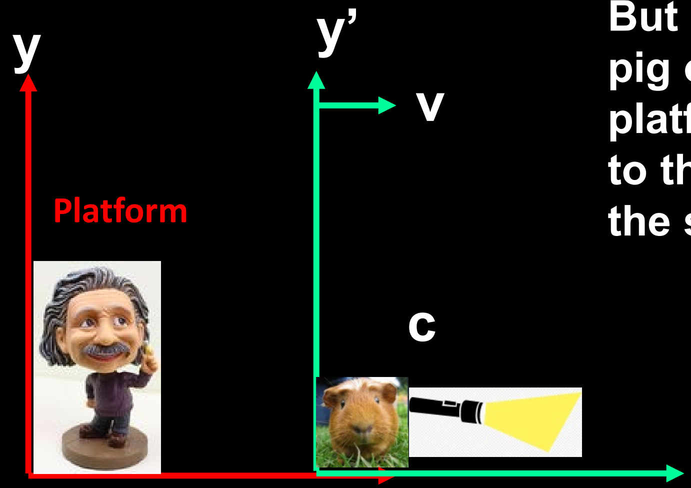
From the days of Newton in the 1600's to the early 1900's motion was completely described by the equations of Newton and Galileo. In classical physics – the physics of every day motion – we add or subtract velocities of moving observers to calculate their relative velocities:



Suppose there is a train moving with velocity "v" and a guinea pig in the train who is running (or throwing a ball) with velocity "u" relative to the train.

A person on the platform watching the train go by would measure the velocity of the moving person on the train, u' (u-prime) relative to the platform as the sum of the speed of the train relative to the platform + the speed of the person relative to the train.

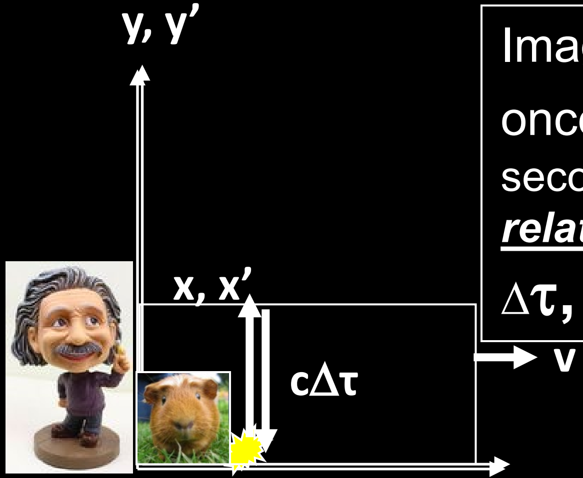
$$u' = v + u$$



But Einstein (and Lorentz) proposed that if the Guinea pig on the train shines a flashlight, an observer on the platform would NOT measure the speed of light relative to the platform as the sum of the speed of the train and the speed of light!

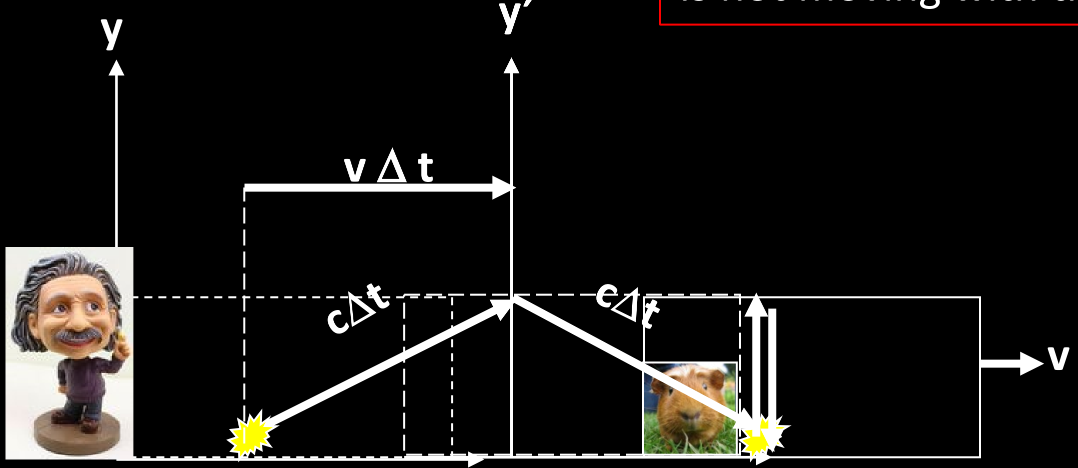
$$c' \cancel{=} v + c$$

Rather, BOTH an observer on the platform AND an observer on the moving train would *measure the SAME speed for light!*

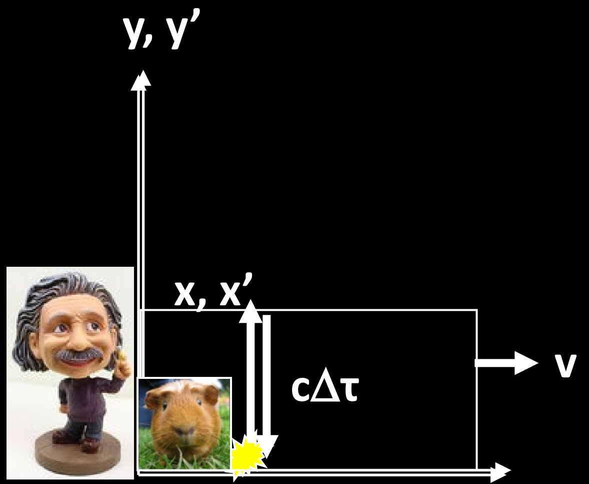


Imagine a train with a light clock that “ticks” with a pulse of light once/second. We will define $\Delta\tau$ as the “proper time interval” (1 second, e.g.) as measured ***on*** the train, by an observer who is ***at rest relative to moving the train.*** The pulse of light takes one time interval $\Delta\tau$, to cross the train from floor to ceiling.

We define “Δt” as the time interval (1 second) for events that are measured by an observer on the platform, who is not moving with the train.

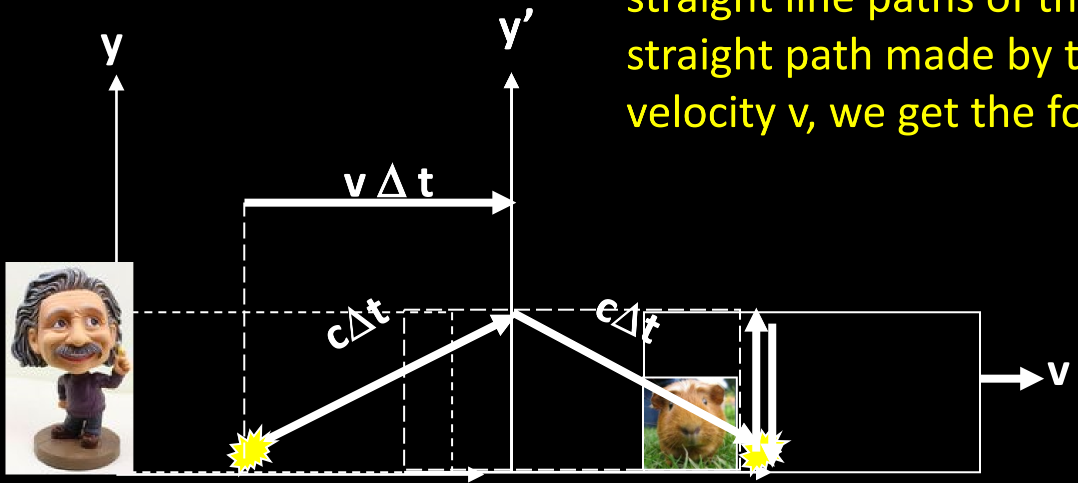


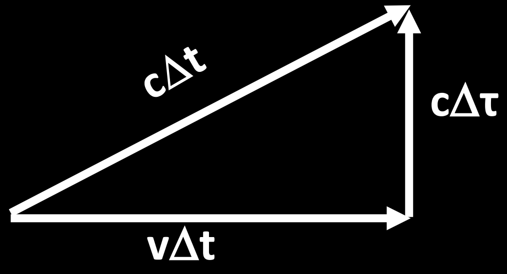
Each observer sees a different travel path for the light beam, but each one observes *the same speed for light, c.*



The person in the train sees the pulse of light travel directly up to a point overhead in a time interval **Δτ. The one-way distance traveled by the light is cΔτ .**

The person on the platform sees the light pulse move on a diagonal path from the floor to the ceiling, **covering a one-way distance of cΔt.** The train, moving at speed v, travels a distance **vΔt at** the same time that the light is traveling, independent of the train. If we imagine seeing ONLY the straight line paths of the light traveling at speed c, and the straight path made by the train, traveling at a constant velocity v, we get the following right triangle:





$$c^2\,\Delta t^2 = v^2\,\Delta t^2 + c^2\,\Delta\tau^{\,2}$$

We recognize this equation as simply the Pythagorean Theorem for a right triangle! This allows us to calculate what time each observer will observe for the other, depending on the speed v of the train!

Expression for the time measured on the train, relative to the time measured on the platform:

$$\Delta\tau = \Delta t\sqrt{(1-\frac{v^2}{c^2})}$$

$$c^2\,\Delta t^2 = v^2\,\Delta t^2 + c^2\,\Delta\tau^2$$

Expression for the time measured on the patform, relative to the time measured on the train:

$$\Delta t = \frac{\Delta\tau}{\sqrt{\left(1-\frac{v^2}{c^2}\right)}}$$

What happens to time as v approaches c?

As v → c, $\Delta\tau \rightarrow 0$

Time ceases to exist for a light beam.

As v → c, $\Delta t \rightarrow \infty$

The length of a second on a light beam approaches infinity as seen by an observer who is NOT on the light beam.

What happens as v approaches zero?

As v → 0, $\Delta\tau \rightarrow \Delta t$ which is just our classical understanding, that time is the same for all observers moving at slow speeds.

Einstein's breakthrough question led him to publish his
Special Theory of Relativity,
in 1905, which demonstrates the following **radical new ideas about space and time:**

1) Space and time are not separate dimensions! Thus we no longer think about space as static and fixed, and time as separate from space and ticking at a constant rate for all observers. Instead, we consider only SPACETIME.

2) The speed of light in a vacuum is constant, and independent of the motion of the observer.

3) The laws of physics are the same for all non-accelerating observers.

4) And, not only is the speed of light a characteristic property of the universe, but
NOTHING can go faster than the speed of light.

To answer Einstein's original question, "What would a person who is traveling with a light beam see?" here is an animation of what your surroundings would look like to you, if you could accelerate to 99% of the speed of light and slow down again – without getting ripped to shreds in the process:

A relativistic bike ride through Tubingen, Germany
Prof. Ute Kraus http://www.spacetimetravel.org/tuebingen/tuebingen.html

The next problem that Einstein pondered was GRAVITY.

For over 300 years, Newton's Universal Law of Gravity was the only mathematical model of gravity that was known, and it worked for everything from calculating the masses of stars and planets to explaining why falling objects on Earth and the Moon in orbit are both governed by the same law.

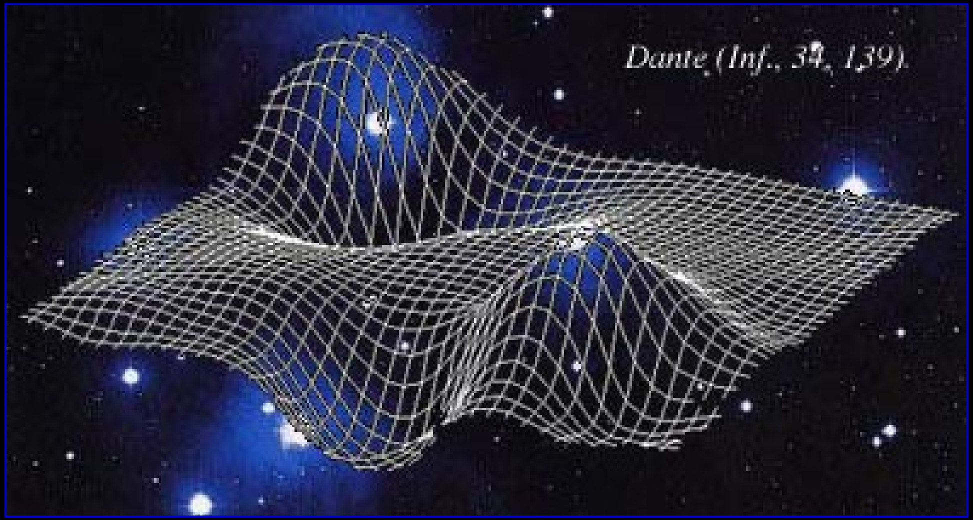
$$F = G\frac{m_1 m_2}{r^2}$$

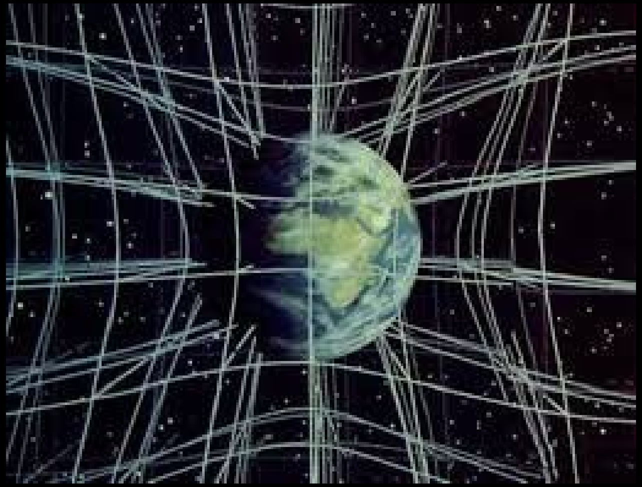
But Einstein had concluded that nothing in the universe can travel faster than the speed of light. Newton's law of gravity implies that any change in a gravitational force would be felt everywhere INSTANTANEOUSLY. ***This is impossible.***

Einstein concluded that mass and energy curve spacetime. The larger the curvature, the stronger the ‘force’ of gravity that we experience. (This is a VERY simplified version of history!)

Mass and energy curve spacetime. The larger the mass, the greater the curvature. Also, mass and energy are equivalent, related by Einstein’s famous equation

$$E = mc^2$$





Two important conclusions that emerge from the equivalence of mass and energy, and the view that gravity is not a force but a result of the curvature of spacetime due to the presence of mass and energy:

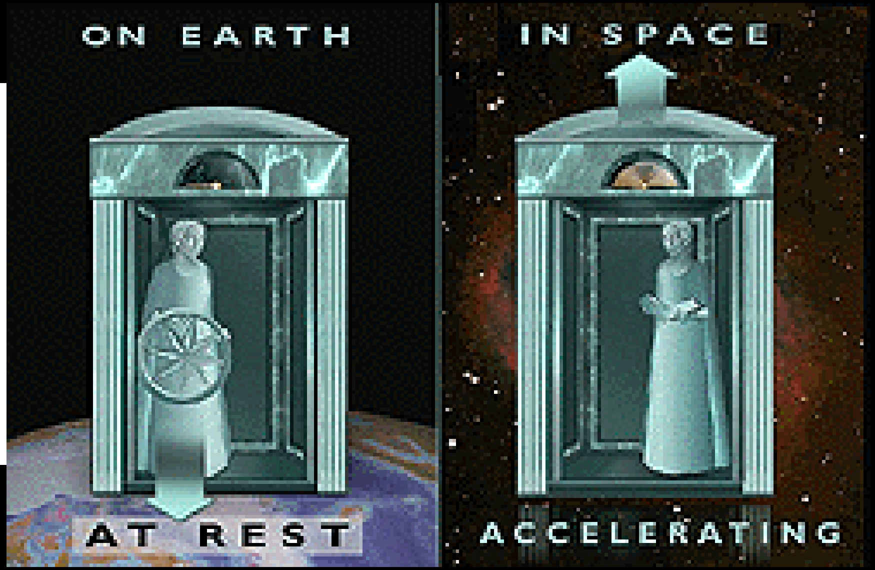
1) Gravitational mass and inertial mass are equivalent. This means that if you measure your mass by standing on a scale on Earth, or by accelerating yourself with an acceleration of 9.81m/sec^2 you will get the same measurement for your mass.

2) *All* accelerations cause a change in local gravity (curvature of spacetime).

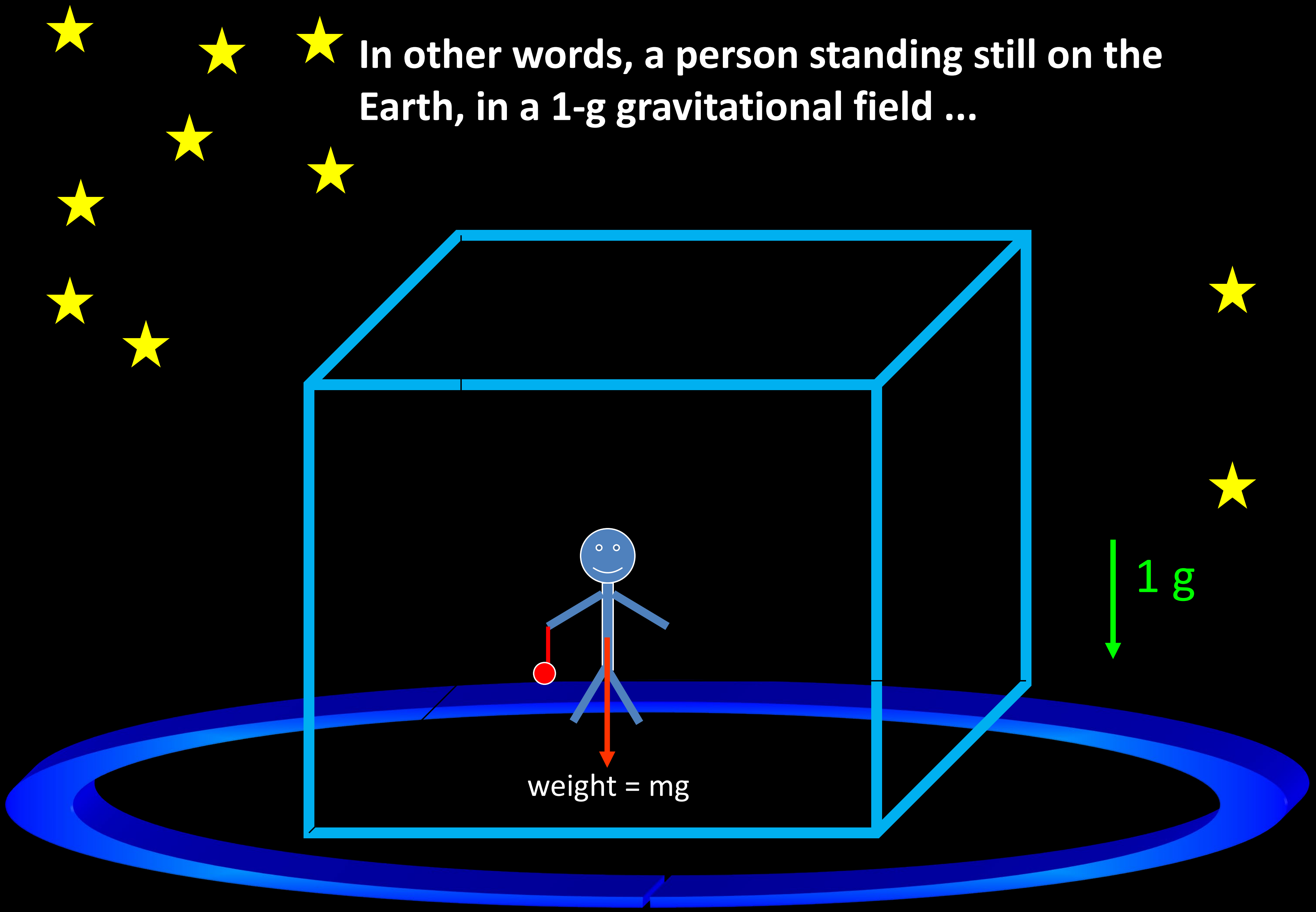
Left: Weight = mg
Right: Force = ma

mg = ma if
a = 9.81 m/sec^2 (1g)

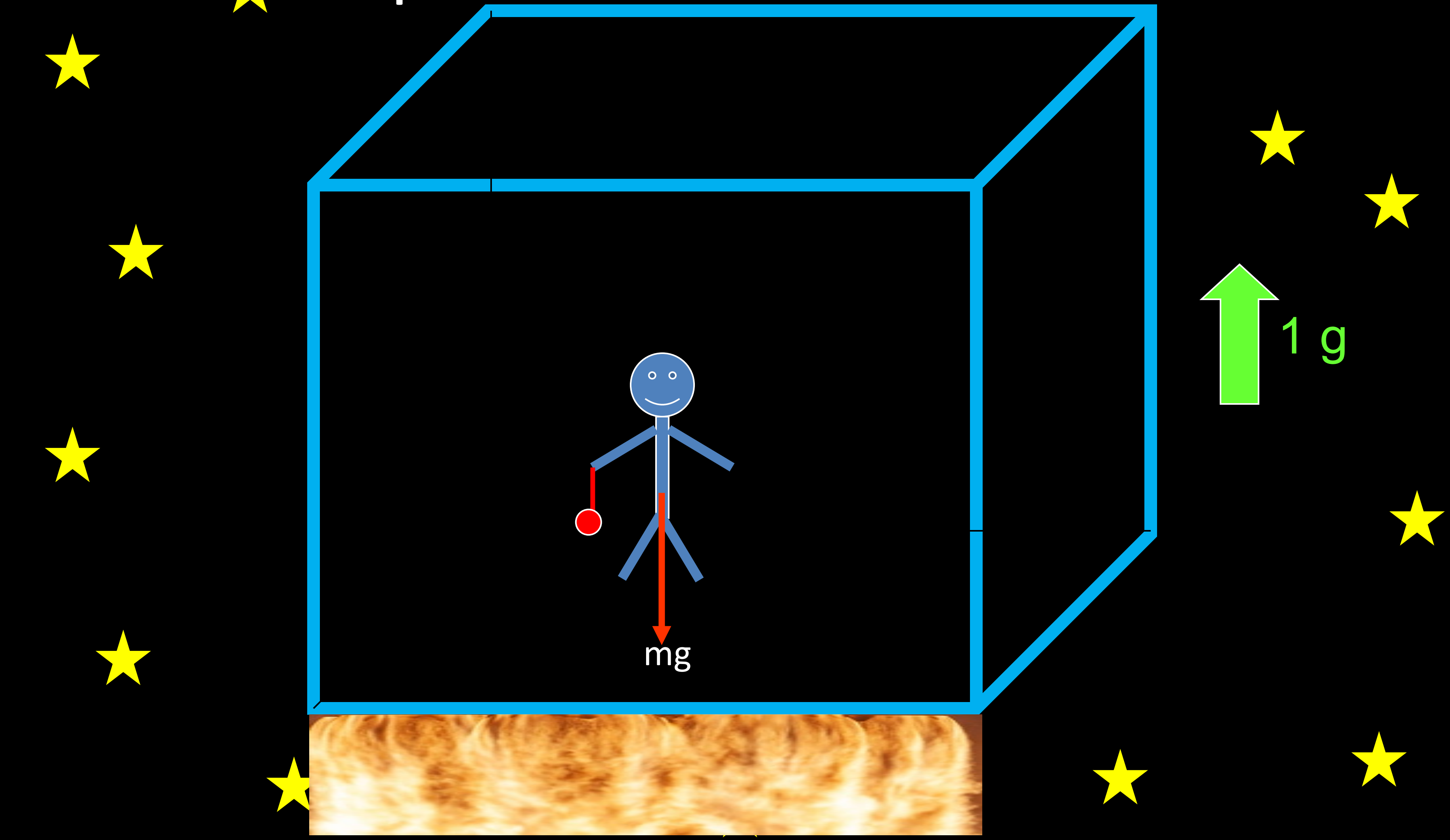
thus it must be true that
$m_{gravitational} = m_{inertial}$



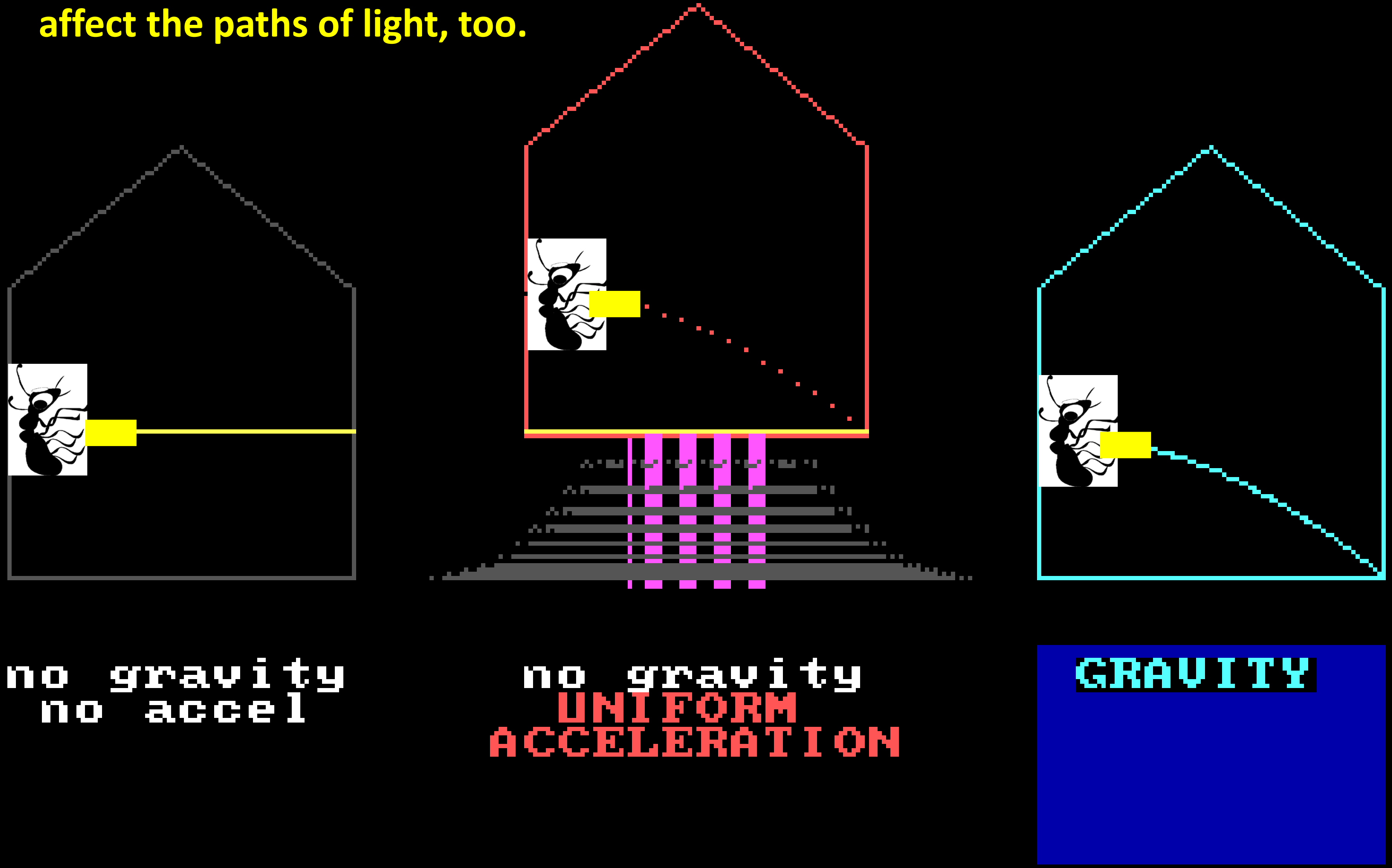
In other words, a person standing still on the Earth, in a 1-g gravitational field ...



could not tell the difference between their weight on Earth, and the weight they would measure if they were accelerating at 1 g somewhere out in space.



Another consequence is that LIGHT follows the path of minimum energy in curved spacetime. Thus light rays appear to BEND due to the curvature of spacetime. Because gravity and accelerations both curve local spacetime, they affect the paths of light, too.



Moreover, just as in Special Relativity Einstein redefined space and time as spacetime, he also showed that mass and energy are not separate concepts either. Rather, instead of mass and energy, we have MASS-ENERGY.

The equivalence of mass and energy is expressed, in the rest frame of the mass, as Einstein's famous equation

$$E = m_0 c^2$$

which, as you learned in the chapters about the Sun, is the reason why fusion reactions produce energy by converting matter to energy!

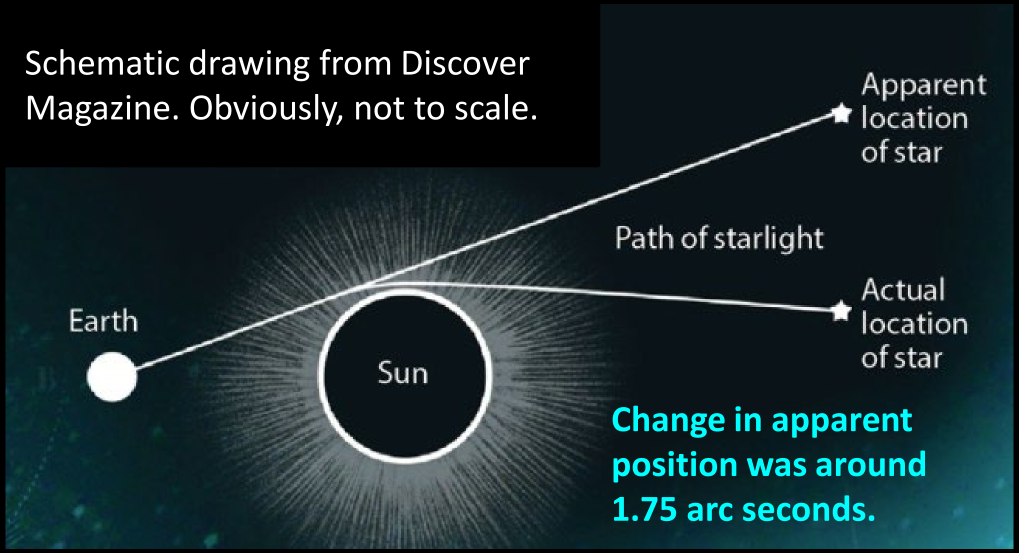
The conclusions of Einstein's Special and General Theories of Relativity are very profound for astronomy and astrophysics! Both have been verified by numerous experiments.

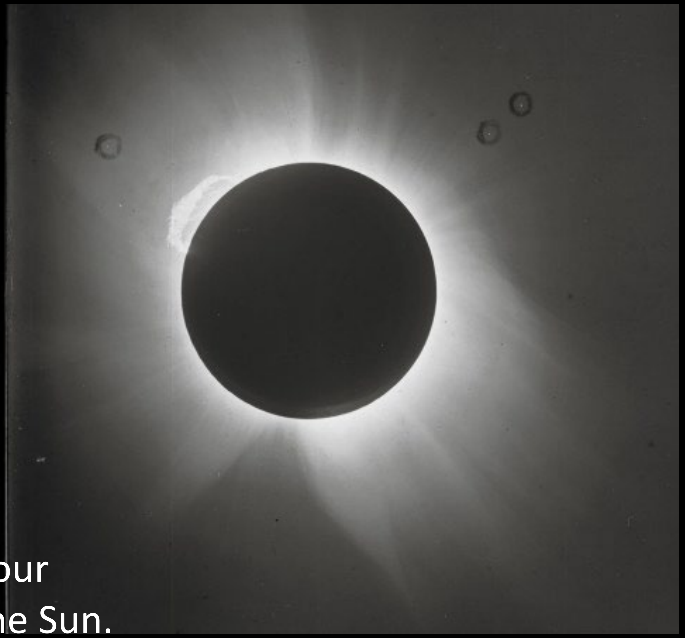
Some of the consequences of General Relativity are described on the next slides...

General Relativity predicts that since mass curves spacetime, then light must follow the curvature of spacetime. That is, light rays bend around the curvature mass causes in spacetime. The effect is small for 'small' masses like the Sun, but it is measurable.

The curvature of spacetime due to the presence of the Sun was first measured during a solar eclipse in 1919 by Sir Arthur Eddington and Sir Frank Watson Dyson. Although their measurements were a bit shy of the predicted value, they were later verified with more sophisticated instruments in the 1960s.

Schematic drawing from Discover Magazine. Obviously, not to scale.

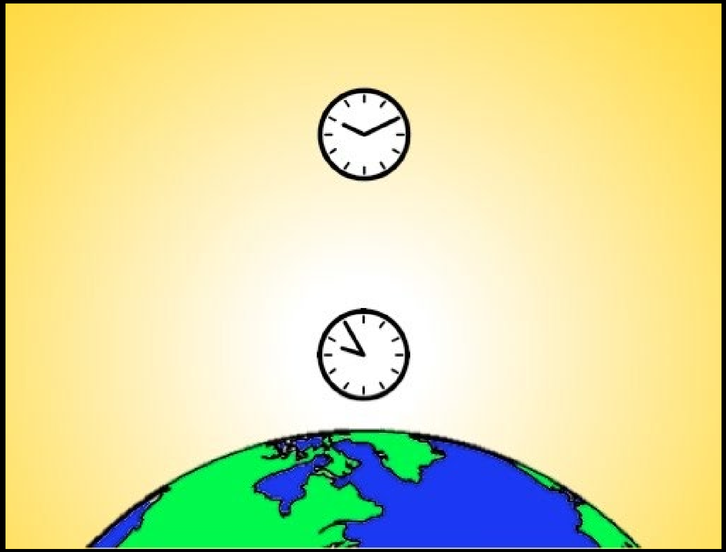




During the eclipse of 1919 a star that was "behind" the Sun from our viewpoint was visible due to the bending of light by the mass of the Sun.

We now rely on the concept of gravitational bending of light to understand gravitational lenses – concentrations of dark matter that distorts the light of galaxies behind it.

The stronger the gravitational field, the slower clocks run. A consequence is that clocks run faster the higher up you go from the Earth. Clocks run slower near the surface of a neutron star than they do near the surface of the Earth, and time stops inside a black hole.



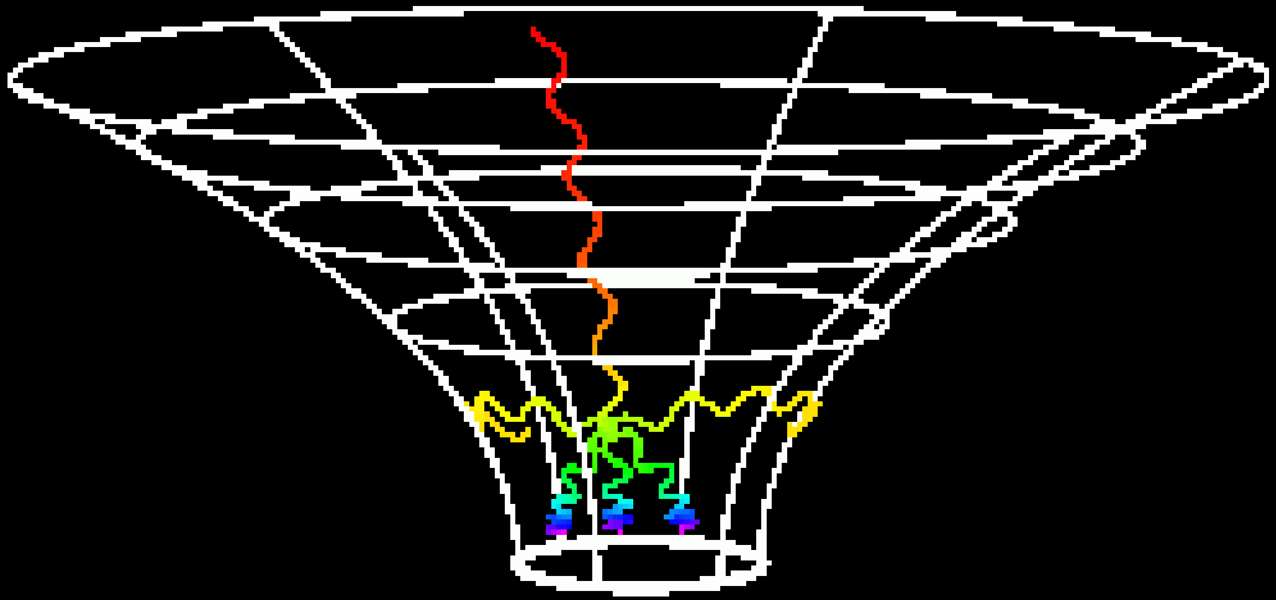
General Relativity explanation for projectile motion:

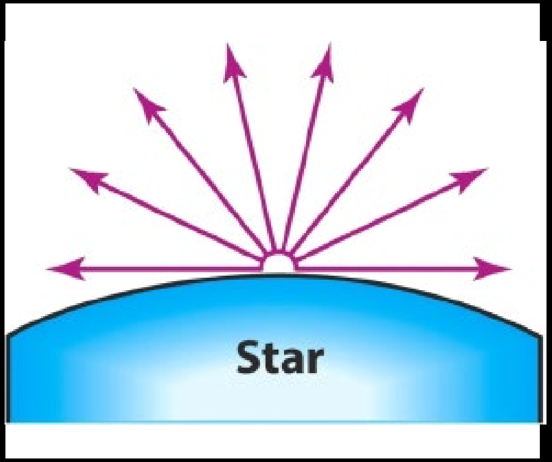
A ball thrown near the surface of the Earth follows the curvature of spacetime near the Earth. The path appears to us to be bent because *the ball is traveling through a strong curvature in time!*

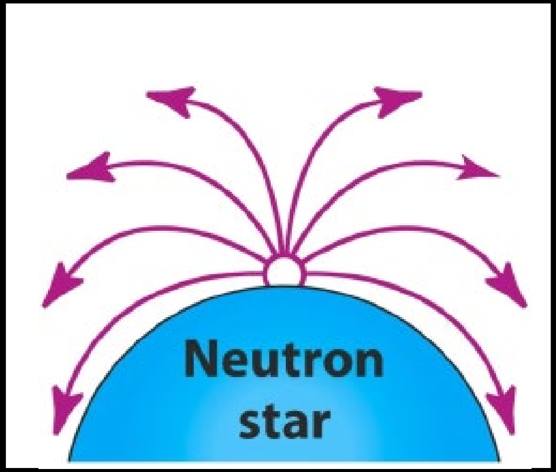
Another consequence of GR is explaining GRAVITATIONAL REDSHIFT: Light loses energy when climbing out of the gravitational field close to a planet or star. Although light loses energy it does not slow down! Rather, the wavelengths are stretched.

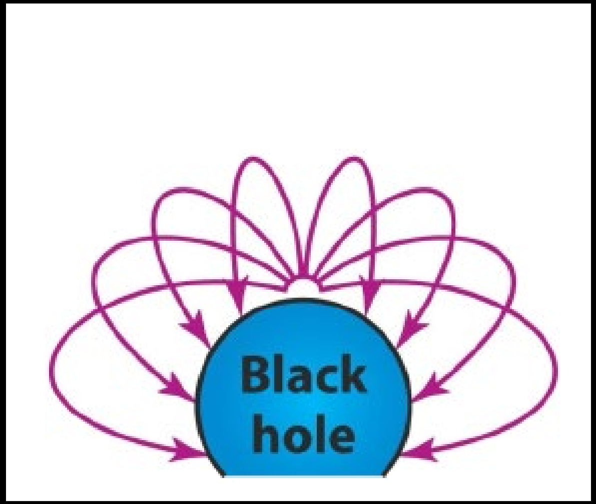
This effect is imperceptible to us on the Earth, but measurable by sensitive instruments, and must be accounted for in communicating with geostationary satellites that control our GPS devices.

The curvature is EXTREME for neutron stars, and INFINITE for black holes.



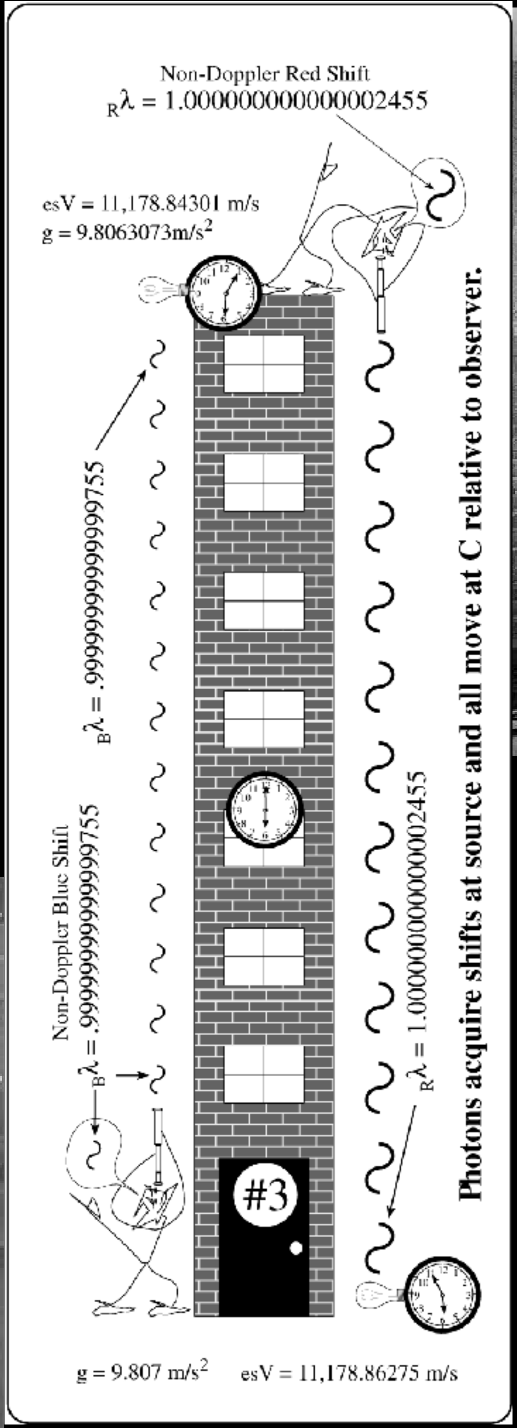


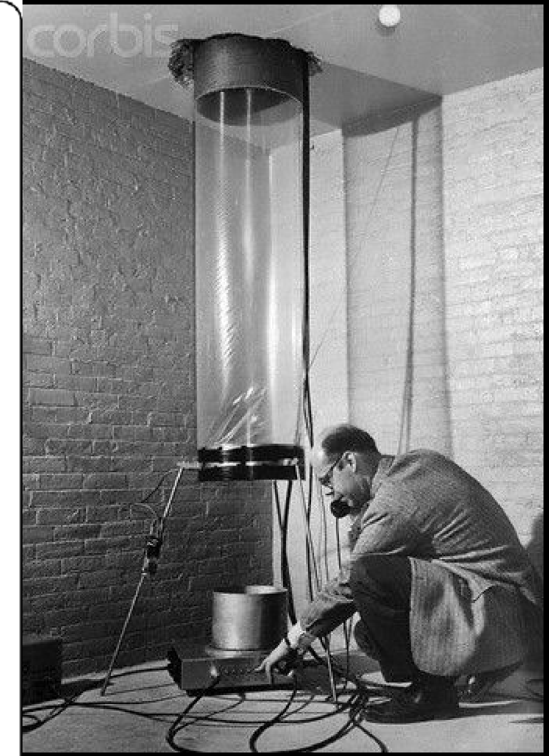




Schematic drawings showing how light rays are bent by a strong gravitational field.

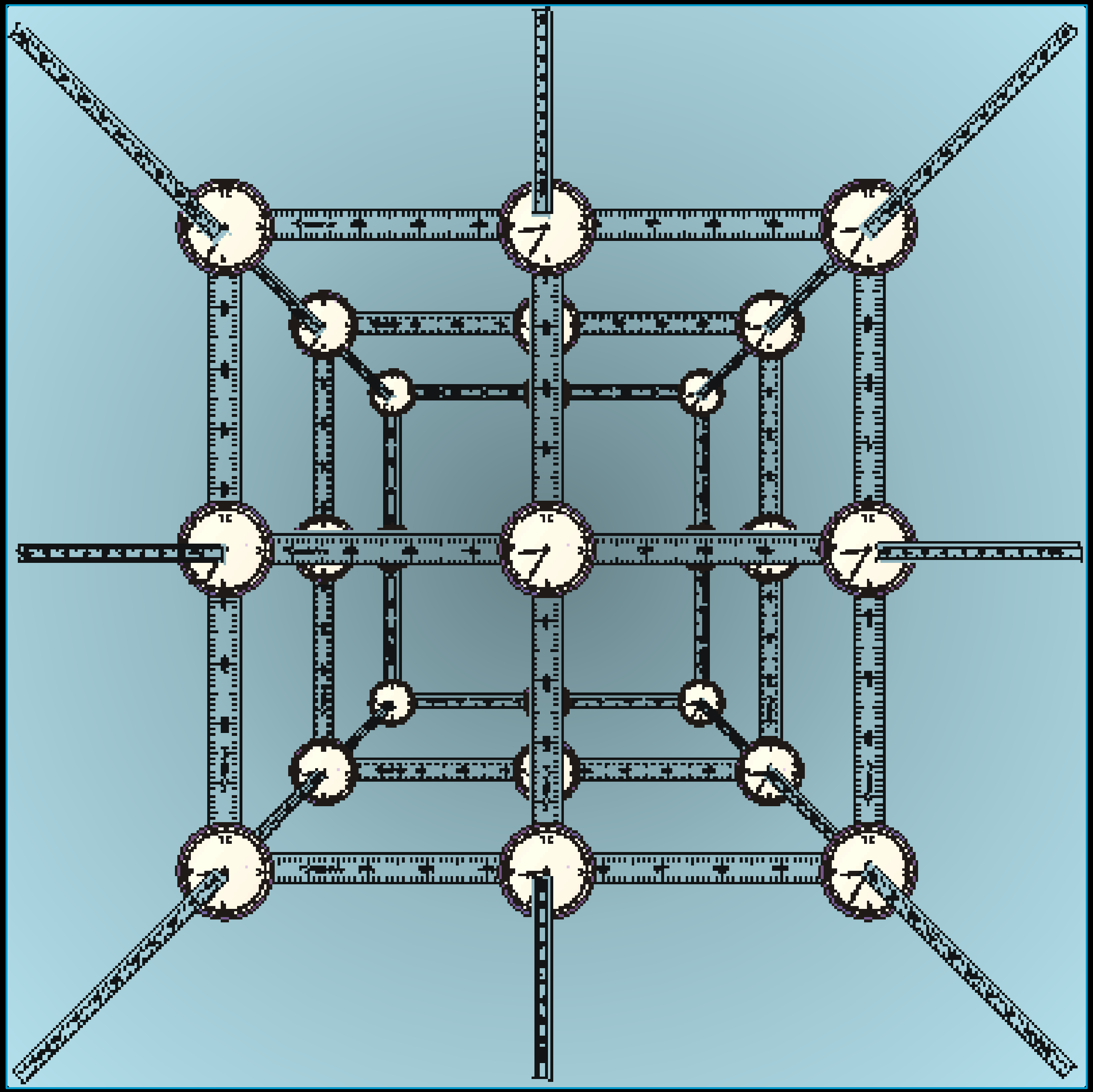
In 1959, two physicists at Harvard, Robert Pound and Glen Rebka, demonstrated the concept of gravitational redshift.



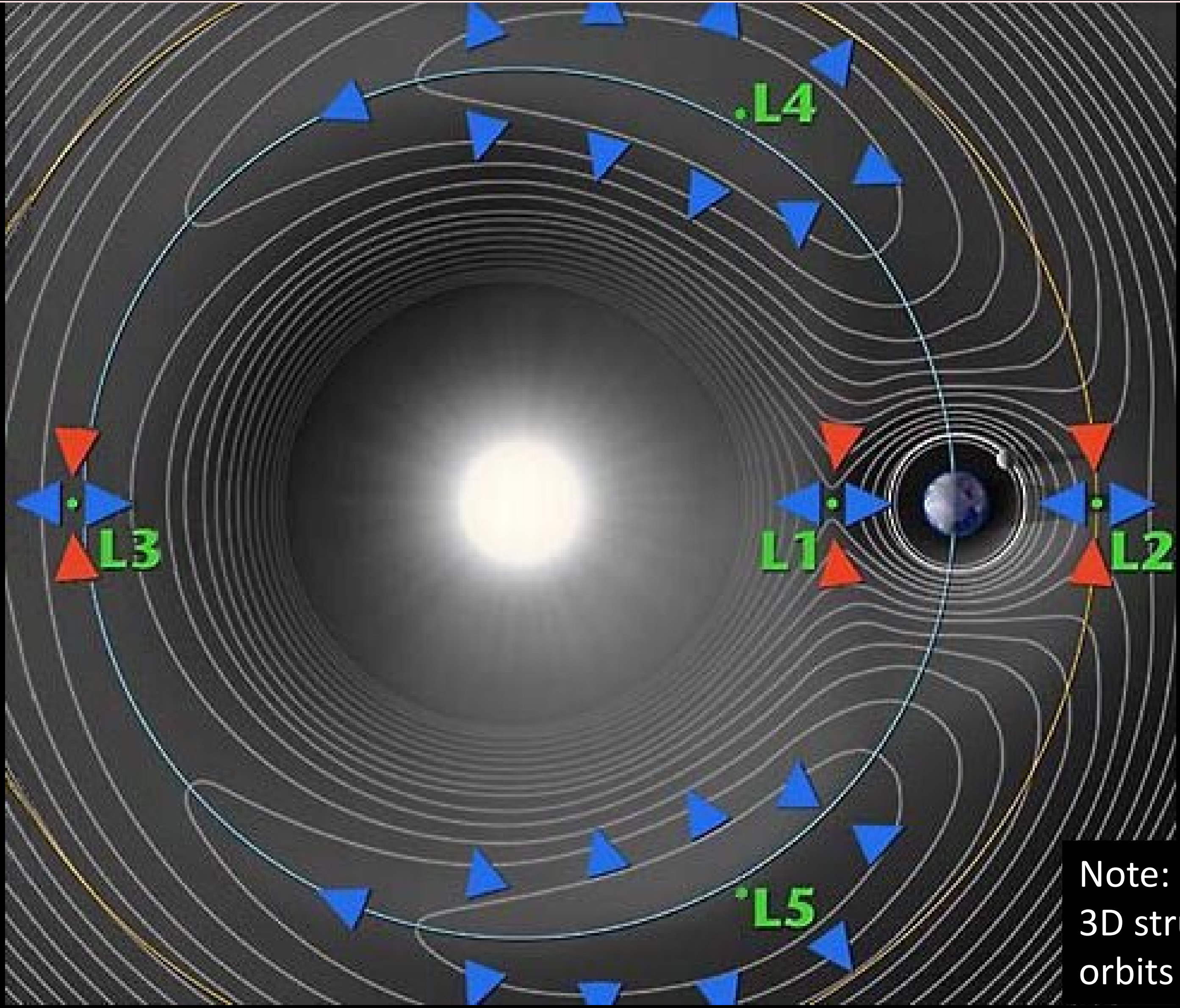


They measured the change in frequency of high energy gamma rays when projected from the roof of the physics building toward the ground, and from the basement upward.

We now understand that curved spacetime is equivalent to a gravitational field, and clocks placed at different locations in that gravitational field will run at different rates!



Another consequence of GR: We can map the 'topography' of spacetime around the Earth-Moon-Sun system, and for any body.

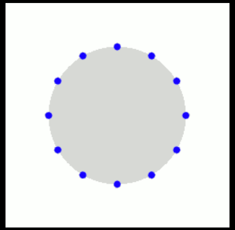


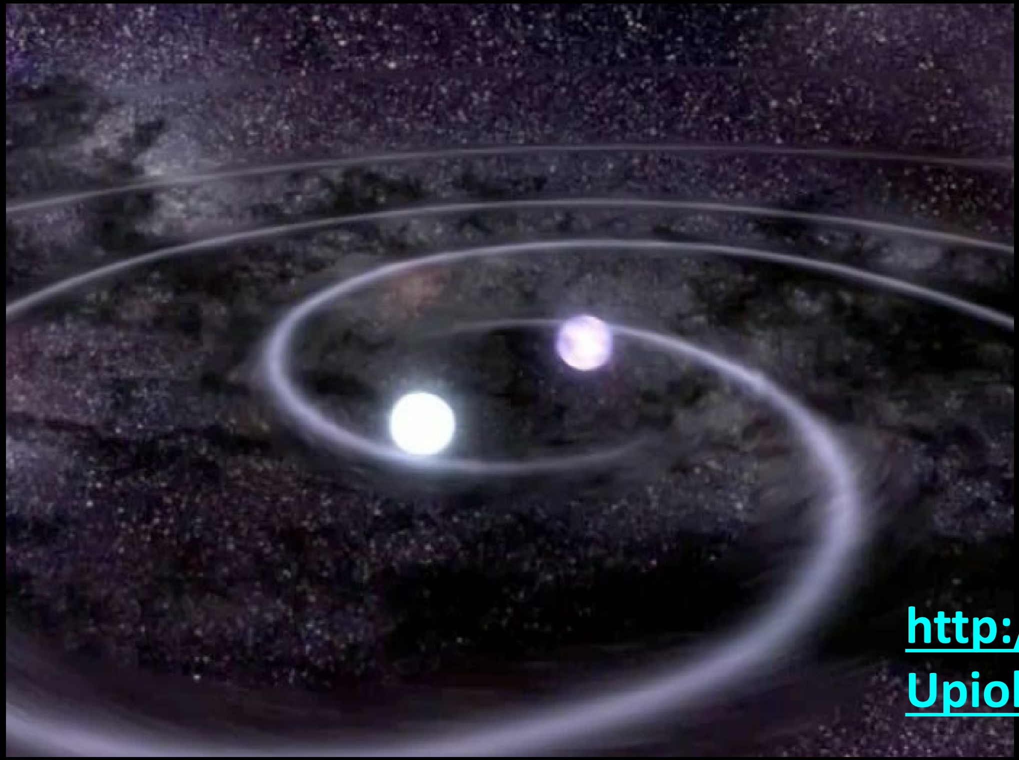
Note: This whole 3D structure orbits the Sun!

Another consequence of Einstein's equations: Rotating black holes should produce GRAVITATIONAL WAVES!

Time changes, and space curves as the waves pass through!

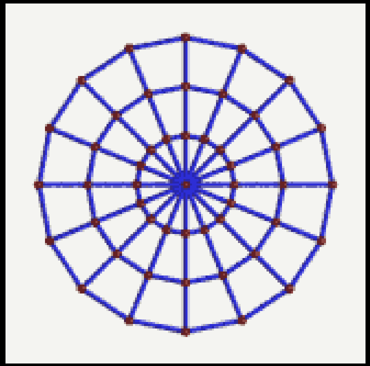
Animation of a gravity wave:
http://www.youtube.com/watch?v=aVFf8UcX1A8





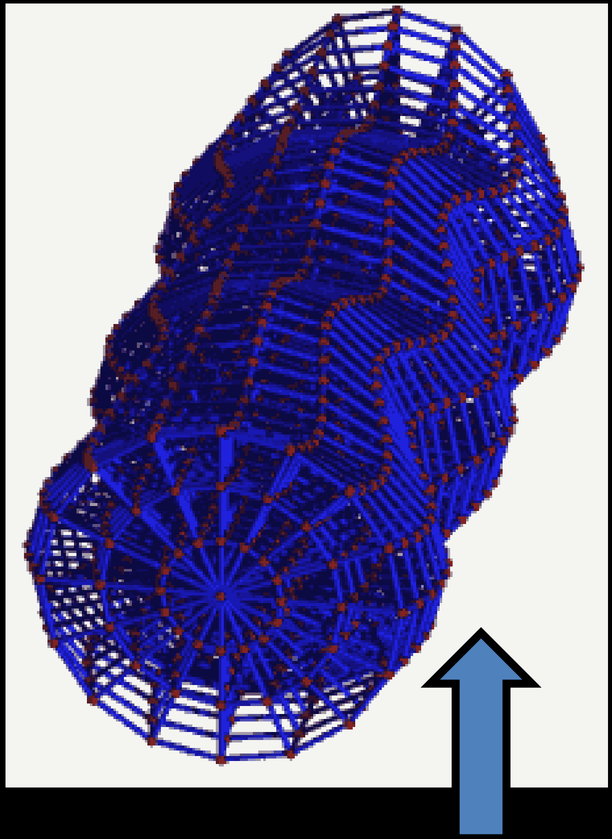
Simulation of two rotating white dwarfs merging and producing gravity waves:

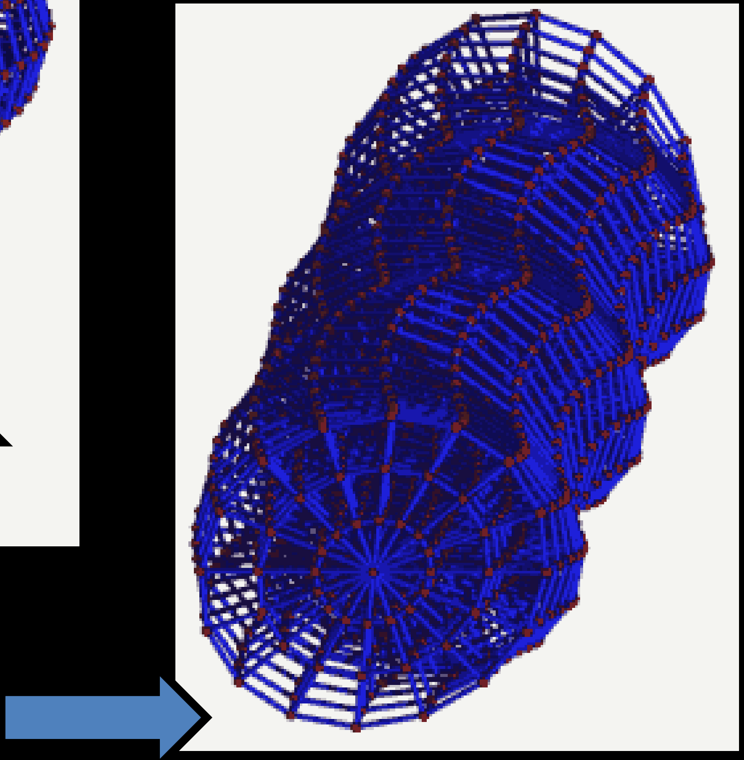
http://www.youtube.com/watch?v=tUpiohbBv6o



Animations of gravity waves distorting 3D space

Animations visible in the slide show





Gravitational waves have teensy amplitudes, so are very difficult to measure.

For this reason you need a very long baseline to amplify the signal sufficiently to detect them.

In 2015 the gravitational waves created by the collision of two black holes were detected by the LIGO gravitational wave interferometer.

LIGO Gravitational Wave Observatory – a very long baseline interferometer:
the same idea as Michaelson & Moreley’s interferometer.

Watch this explanation by physicist Brian Greene of the first detection of gravitational waves in 2015:
https://youtu.be/s06_jRK939I

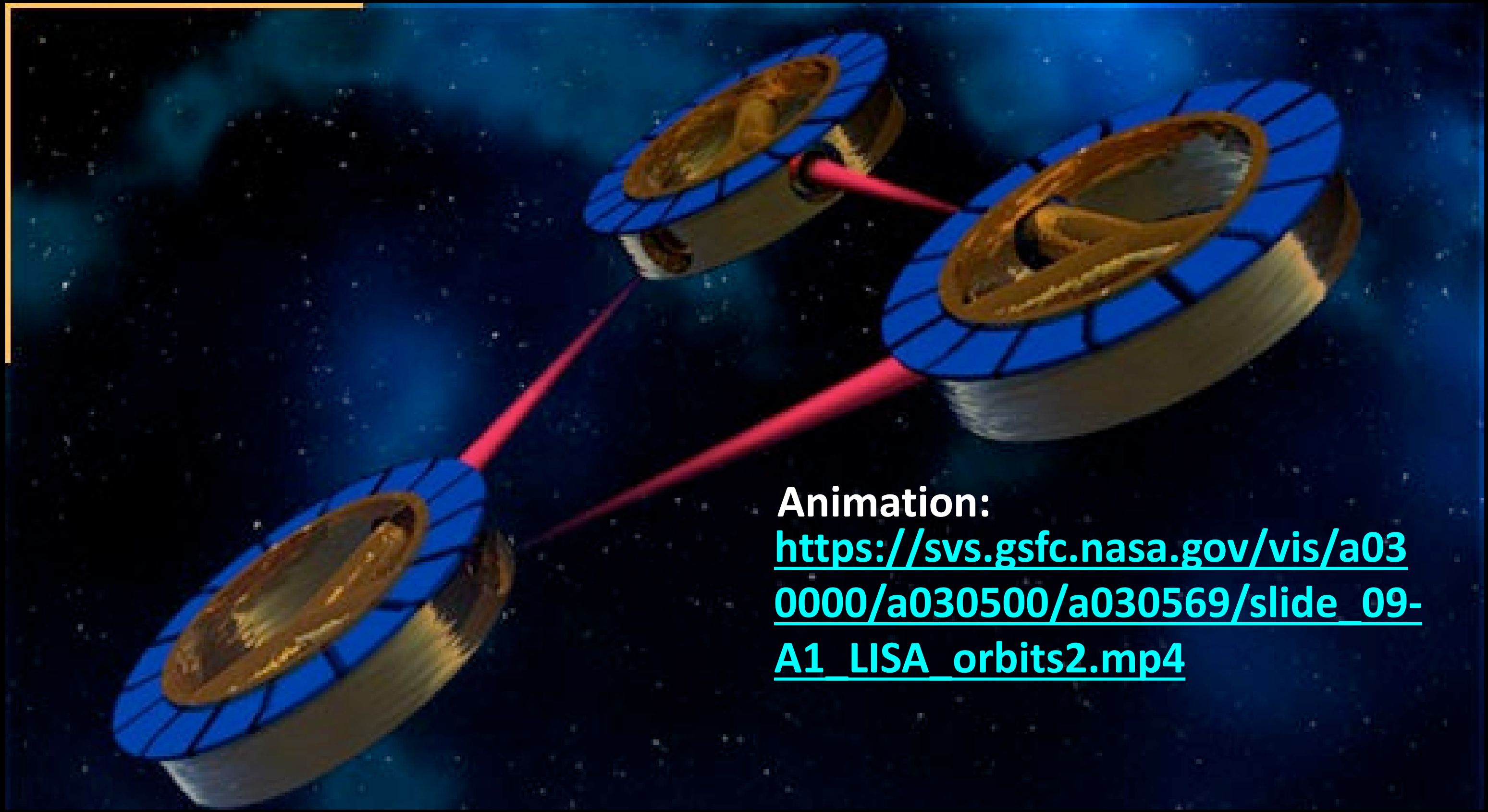
The "stiffness" of spacetime is proportional to $\frac{c^2}{G} \cong \frac{\left(3\ x\ 10^8\right)^2}{6.67\ x\ 10^{-11}}$ = 1.35 x 10^{27} kg/m/sec^2

That is why the displacement of spacetime by gravitational waves is so small – less than the diameter of an atom.

Until now we have observed the universe with electromagnetic radiation.
Now we can observe it with gravitational radiation!

NASA and ESA plan to send three satellites into orbit, with a 1,000,000 km baseline, to detect gravitational waves in space and time.

Called LISA: Laser Interferometer Space Antenna, planned for launch in 2034. LISA Pathfinder Mission was launched in 2015 as proof of concept mission, and it demonstrated that it is possible to fly satellites in precise formation. See: http://lisa.nasa.gov/



Animation:
https://svs.gsfc.nasa.gov/vis/a030000/a030500/a030569/slide_09-A1_LISA_orbits2.mp4

Appendix A: Length contraction and time dilation demonstrated by muons (unstable particles made of 1 quark and 1 antiquark) that are created by cosmic ray collisions in the upper atmosphere, and which cascade down to Earth.

Muons have a half life of around 10^{-6} seconds. Without the effects of Special Relativity, we should not measure any muons by the time they reach the ground.

But – the opposite is true. Tons of muons hit the ground every second, so that particle accelerators have to be buried underground to shield from muons that go through quite a bit of ground before they are absorbed.

So how does this happen?

TIME DILATION: In the muon rest frame, their half life is longer than we measure it from our perspective on Earth.

LENGTH CONTRACTION: In the muon frame, the atmosphere appears to be shortened to around 4 km, whereas in our rest frame, at rest with respect to the atmosphere, it is around 10 km.

We define the "proper" frame as the frame in which the observer is at rest.
Define: τ = proper time measured by observer in his/her rest frame
Define: L_0 = proper length measured by observer in his/her rest frame
Define: t' = time as measured in the "other" frame
Define: L' = length as measured in the "other" frame

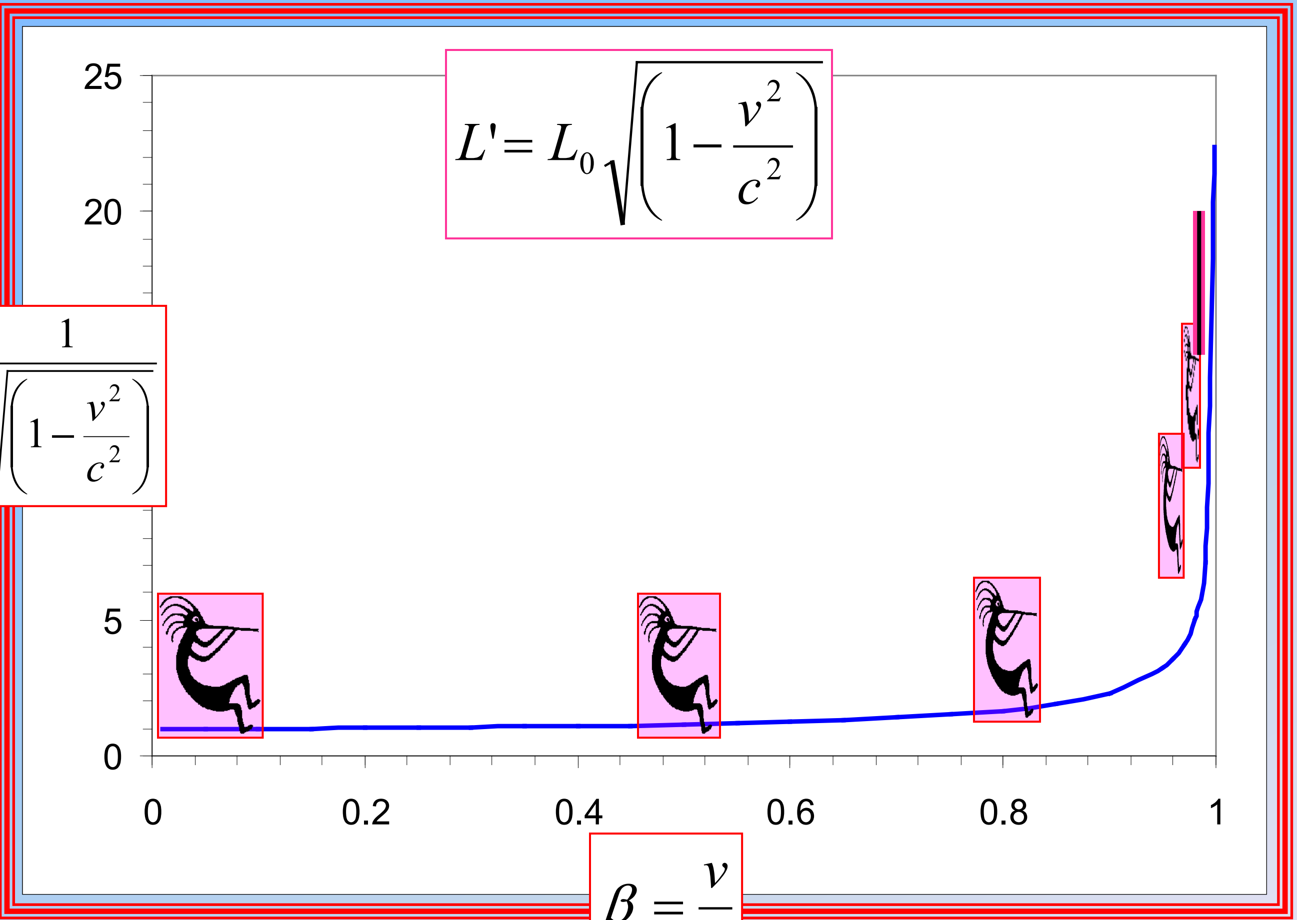
$$L' = L_0 / \gamma = L_0 \sqrt{1 - \tfrac{v^2}{c^2}}$$

$$t' = \gamma\tau = \frac{\tau}{\sqrt{1 - \tfrac{v^2}{c^2}}}$$

Foreshortening of length in the direction of travel as observer approaches the speed of light

v/c	gamma
0.01	1.00005
0.05	1.001252
0.1	1.005038
0.15	1.011443
0.2	1.020621
0.25	1.032796
0.3	1.048285
0.35	1.067521
0.4	1.091089
0.45	1.119785
0.5	1.154701
0.55	1.197369
0.6	1.25
0.65	1.315903
0.7	1.40028
0.75	1.511858
0.8	1.666667
0.85	1.898316
0.9	2.294157
0.95	3.202563
0.96	3.571429
0.97	4.11345
0.98	5.025189
0.99	7.088812
0.999	22.36627
0.9999	70.71245
0.99999	223.6074

$$\gamma = \frac{1}{\sqrt{\left(1-\frac{v^2}{c^2}\right)}}$$



$$L' = L_0\sqrt{\left(1-\frac{v^2}{c^2}\right)}$$

$$\beta = \frac{v}{c}$$

Objects in front of you appear squished when you are moving straight towards them.

J. van der Veen, 2007

EXAMPLE: MUONS IN THE UPPER ATMOSPHERE

$$L' = L_0\sqrt{1-\frac{v^2}{c^2}}$$

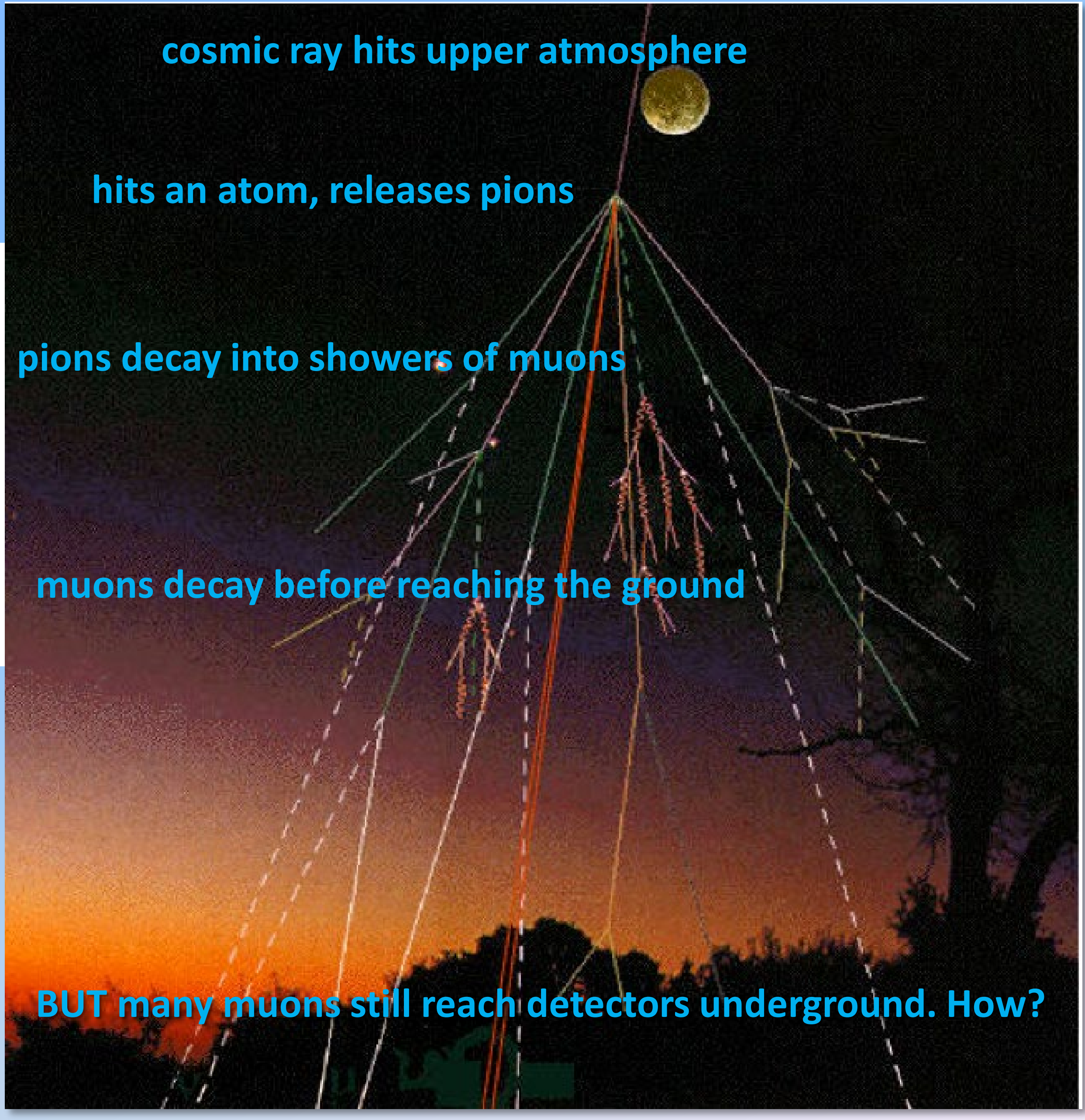
$$t' = \frac{\tau}{\sqrt{1-\frac{v^2}{c^2}}}$$

In Earth rest frame:
L_0 = 10 km = height of the atmosphere, for a person standing on the ground

In rest frame of muons:
τ= half life = 2.2 x 10^{-6} sec for the muons, traveling at .98c

What is L' of atmosphere, as seen by muons which travel at .98c?

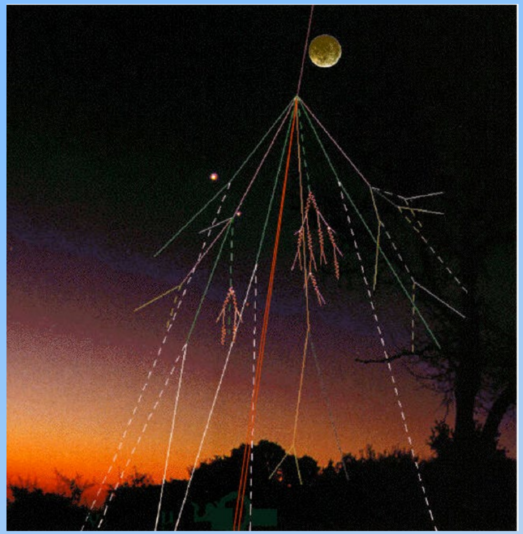
What is the half life of muons as observed in the Earth frame?



What is L' of atmosphere, as seen by muons which travel at .98c?

$$L' = L_0\sqrt{1-\frac{v^2}{c^2}}$$

$$t' = \frac{\tau}{\sqrt{1-\frac{v^2}{c^2}}}$$



$$\sqrt{1-\frac{(.98c)^2}{c^2}} = \sqrt{1-.98^2}$$

$$\cong \sqrt{.04} = .2$$

So $L' = .2L_0 = (.2) \times 10\text{km} = 2$ km

This result tells us that from the reference frame of the muons, moving at .98c relative to the ground, the length of the atmosphere appears to be only 2 km instead of 10 km!

What is the half life of muons as observed in the Earth frame?

Half life as seen by an observer on Earth is longer than the half life as measured in the muons' rest frame:

$$t' = \frac{2.2\times10^{-6}\ \text{sec}}{.2} = 1.1\times10^{-5}\ \text{sec}$$

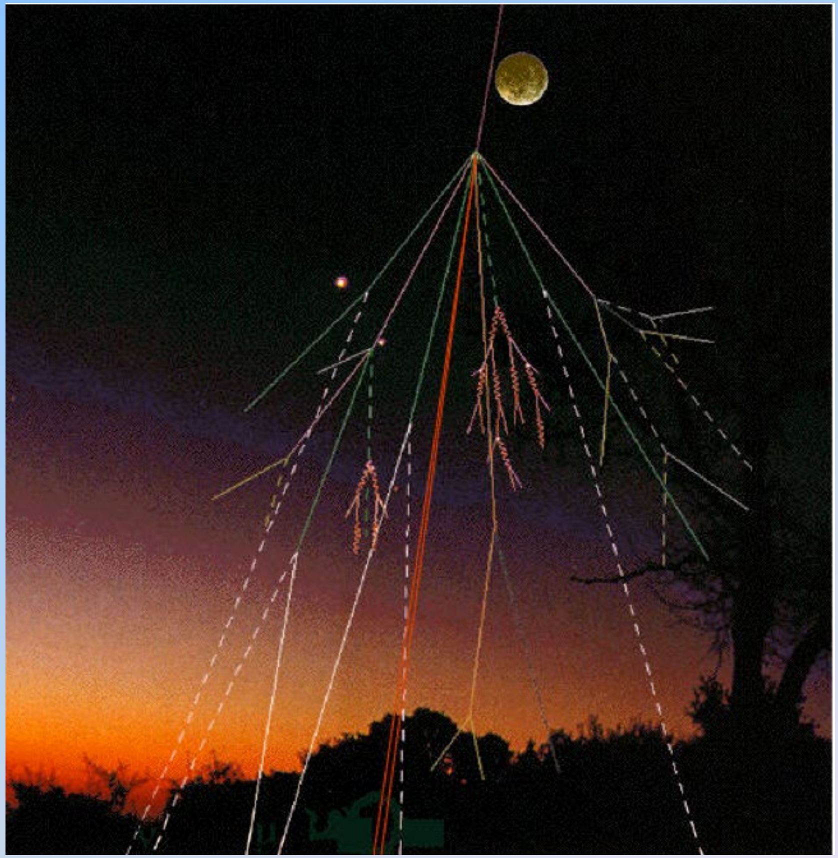
$$L' = \frac{L_0}{\gamma} = .199(10km) = 1.99km \approx 2km$$

length of atmosphere as seen by muons in their frame

$$t' = \gamma\tau = 5(2.2\times10^{-6}\ \sec) = 1.1\times10^{-5}\ \sec$$

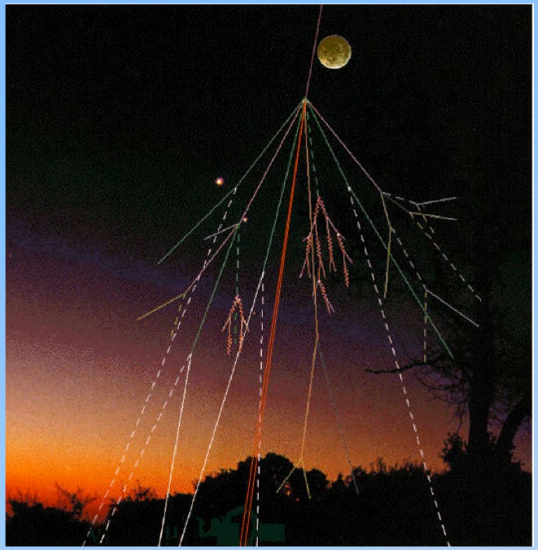
half-life of muons as measured in Earth frame

How many muon half-lives pass before the muon shower hits the ground?



Remember: The Earth observer sees the muons traveling at .98c “down” and the muons see the ground traveling “up” at .98c!

3a. How much time passes in each observer's frame?
3b. How many half lives go by in each observer's frame?



Earth observer sees the muons moving down at a constant speed of .98c, and the muons see the ground moving up towards them at a constant speed of .98c. Using the relationship that time elapsed = distance/speed:

Earth observer measures:

$$t = \frac{L_0}{v} = \frac{10^4 m}{(.98 \times 3 \times 10^8 m/\sec)} = 3.4 \times 10^{-5} \sec$$ for the muons to traverse the atmosphere

$$\frac{3.4 \times 10^{-5} \sec}{1.1 \times 10^{-5} \sec} = 3.09$$ half lives

muons measure:

$$t_0 = \frac{L'}{v} = \frac{1.99 \times 10^4 m}{(.98 \times 3 \times 10^8 m/\sec)} = 6.77 \times 10^{-6} \sec$$ for the muons to traverse the atmosphere

$$\frac{6.77 \times 10^{-6} \sec}{2.2 \times 10^{-6} \sec} = 3.09$$ half lives

Artists' renditions of the view through the front window of a space vehicle traveling near light speed.

Einstein's Special Theory of Relativity deals with:

A. T
B. d
C. r
D. λ
E. c

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A. T
B. d
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Einstein predicts that the closer you get to going the speed of light, the ______ time passes.

A. faster
B. slower
C. trick question: there is no difference

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Einstein's General Relativity Theory replaces the old ideas of:

A. Gravity
B. Warped Spacetime
C. Equivalence
D. Mass
E. Light Speed

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According to Einstein, Mercury moves around the Sun the way it does because:

A. of the gravity between the Sun and Venus
B. of its mass and its distance from Venus
C. of the Sun's warping of spacetime at the distance of Mercury
D. of Kepler's Laws
E. of Newton's Laws

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