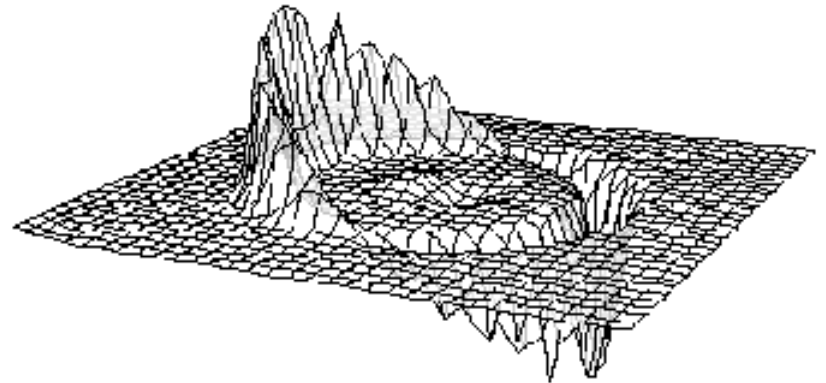
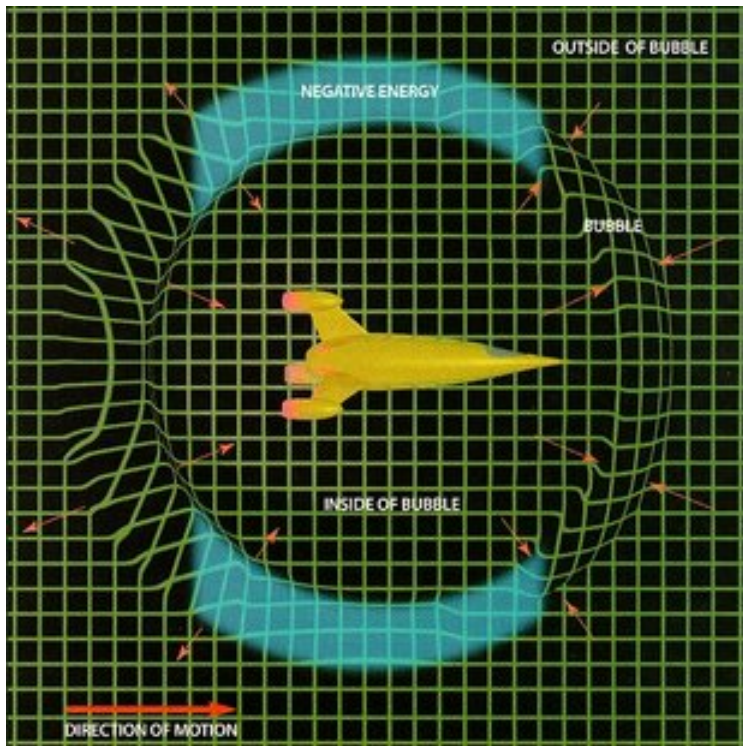


# Warp drive

- Alcubierre metric – a (inaccurate) solution of Einstein Field Equation:

$$ds^2 = (\alpha^2 - \beta_i \beta^i) dt^2 - 2\beta_i dx^i dt + \gamma_{ij} dx^i dx^j$$



# Physics 311

## General Relativity

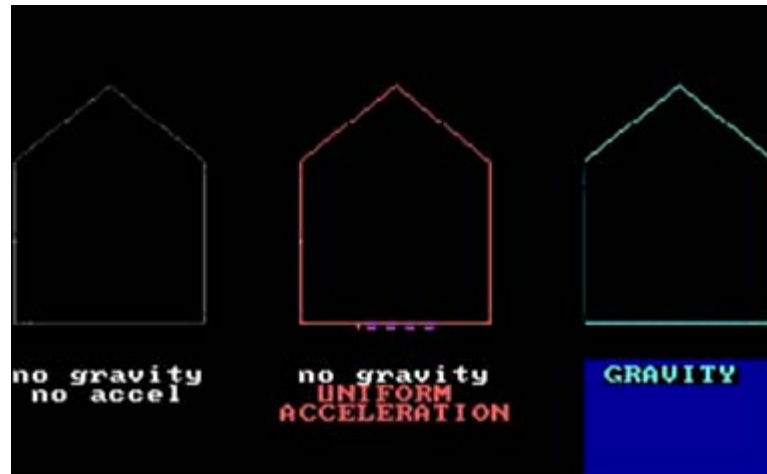
### Lecture 16: Equivalence Principle

# Today's lecture:

- Acceleration or gravitation – observer cannot tell
- “Weak equivalence principle”
- Bending of starlight
- Experimental test of equivalence principle
- “Strong equivalence principle” and falling into a black hole

# Motion in accelerated frame and in gravitational field

- Our poor observer is locked up inside a sound-proof elevator cabin with no windows, no means to communicate with the outside world. The cabin is being accelerated or placed on the Earth surface.
- The observer throws stones and watches their motion. What does the observer see?



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# Acceleration and gravitation give same result!

- To the elevator observer, results of the measurements are the same in the gravitation field and in an accelerated frame.
- In fact, the observer ***cannot tell*** between the two. Acceleration and gravitation produce the same effect.
- Free-falling observer experiences no gravity, and thus no acceleration!
- Wait a minute... Aren't we accelerating as we fall? What about the "free-fall acceleration" and such?
- Let's see another movie!

# Free-falling observer: no gravity!

- We now compare observations of an observer in the absence of gravity, in free-fall near Earth, and standing still on surface of Earth.



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# Free-falling observer measurements are identical to the zero-gravity observer

- Observer in the absence of gravity measures the same results as does the free-falling observer.
- Why? Because as the free-falling observer is moving in the Earth's gravitation field, so does the object.
- The outcome is that the object moves along a straight line! Free-fall frame is truly *inertial* (as long as it is small enough – *local*); gravity does not exist for a free-falling observer.

# Weak equivalence principle

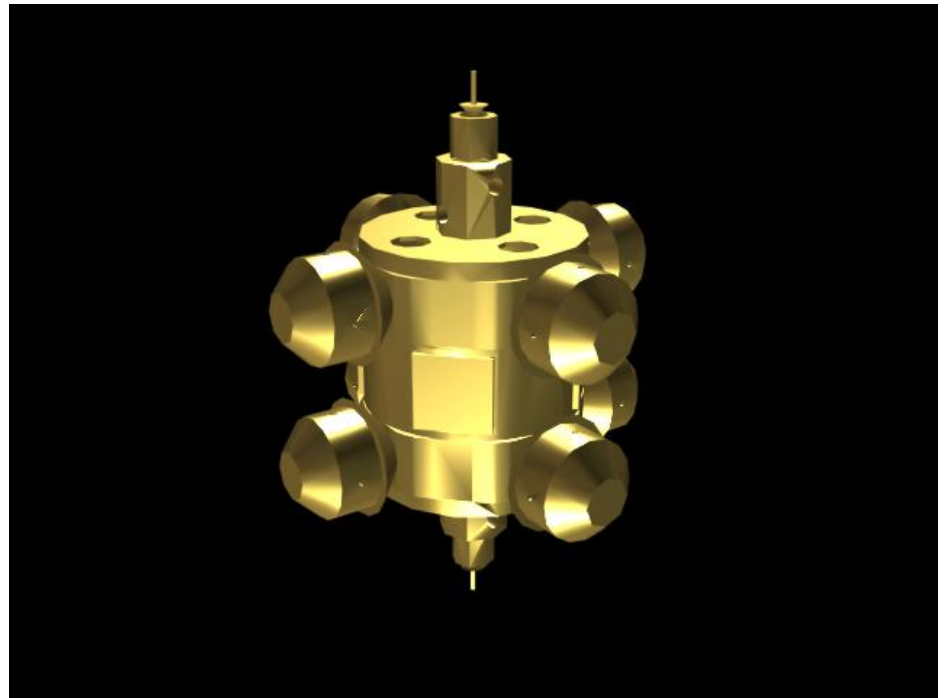
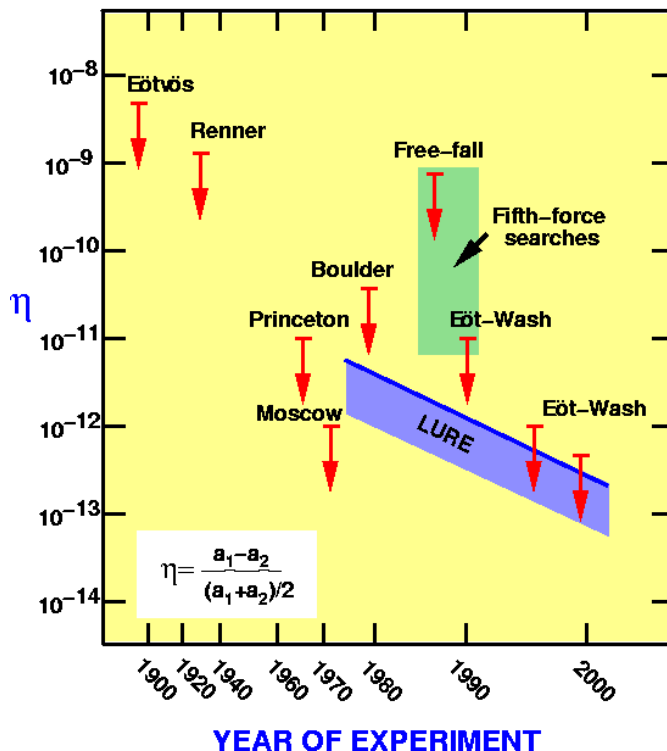
- Weak equivalence principle (WEP), also known as *universality of freefall*, states that the ***trajectory of a free-falling body depends only on its initial velocity and not on its composition.***
- This principle only holds true for small bodies where tidal forces are negligible, and light bodies, such that their presence does not substantially change gravitational field.
- As such, WEP is *local* (just like Special Relativity) and is basically the statement that there is no local gravity, and freefall is the same for all.
- WEP is one of the most thoroughly tested principles of Relativity, if not of all Physics. In fact, the most precise tests of WEP are taking place here at UW right now!



# UW Eot-Wash experiment

- Measures difference in acceleration due to gravitation for objects of different density (Be, Al, Cu and Si).
- Measured attraction to different bodies – stellar and Earthly (Earth, Sun, Galaxy, 3 tons of  $U^{238}$ )

## TESTS OF THE WEAK EQUIVALENCE PRINCIPLE



# Other test of WEP

- There is a long history of experimental test of the WEP...

Researcher	Year	Method	Result
John Philoponus	6th Century	Described correctly the effect of dropping balls of different masses	no detectable difference
Galileo Galilei	~1610	Rolling balls down inclined planes	no detectable difference
Isaac Newton	~1680	measure the period of pendulums of different mass but identical length	no measurable difference
Friedrich Bessel	1832	measure the period of pendulums of different mass but identical length	no measurable difference
Roland Eötvös	1908	measure the torsion on a wire, suspending a balance beam, between two nearly identical masses under the acceleration of gravity and the rotation of the Earth	difference is less than 1 part in a billion
Roll, Krotkov and Dicke	1964	Torsion balance experiment, dropping aluminum and gold test masses	difference is less than one part in one hundred billion
David Scott	1971	Dropped an eagle feather and a hammer at the same time on the Moon	no detectable difference (Not a very good experiment, but it was the first lunar one.)
Branginsky and Panov	1971	Torsion balance, aluminum and platinum test masses, measuring acceleration towards the sun	difference is less than 1 part in a trillion (most accurate to date)
Eöt-Wash	1987–	Torsion balance, measuring acceleration of different masses towards the earth, sun and galactic center, using several different kinds of masses	difference is less than a few parts in a trillion

# Headlight effect

- A test object can be a beam of light! Like a laser beam.
- For a moving observer, the speed of light is conserved (of course!), but the *direction* of the beam of light is, generally speaking, not. (When would it be conserved?)
- This is known as the “headlight effect”. The strongest deviation is experienced by the light emitted at right angles (in the lab frame), smaller angles experience less deviation. The result is that for the moving observer light is concentrated in a narrow cone – the headlight.

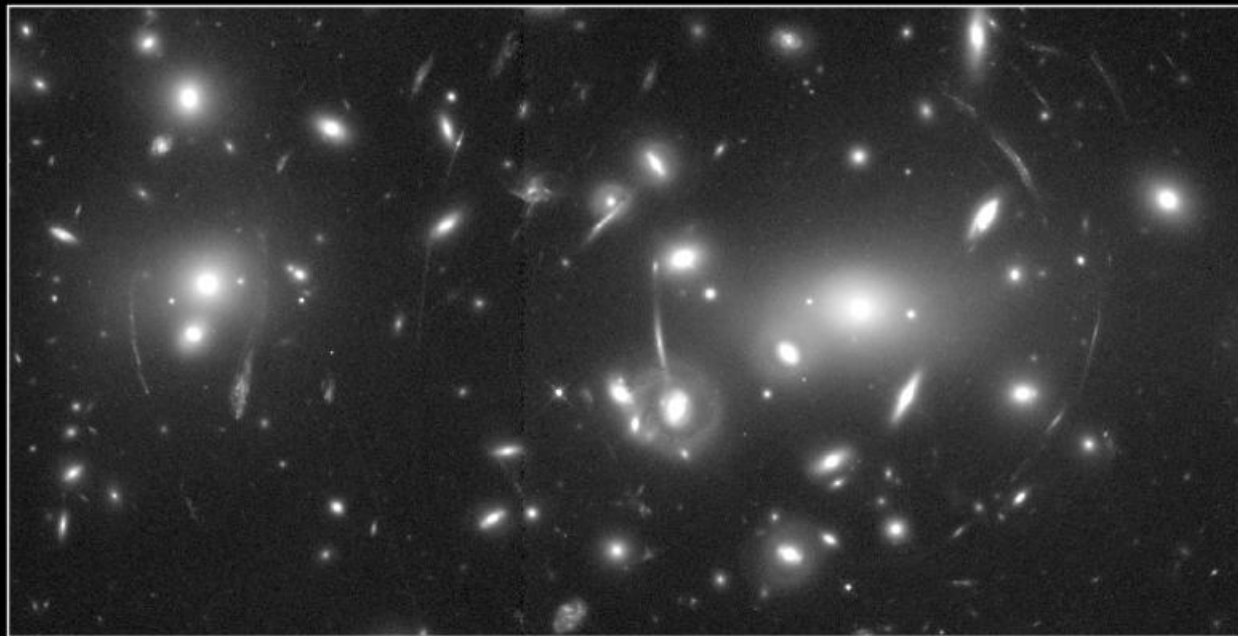
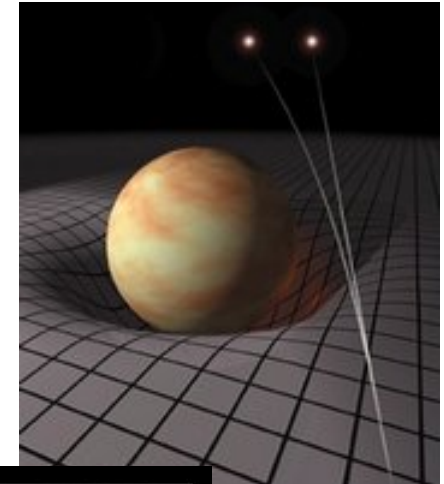
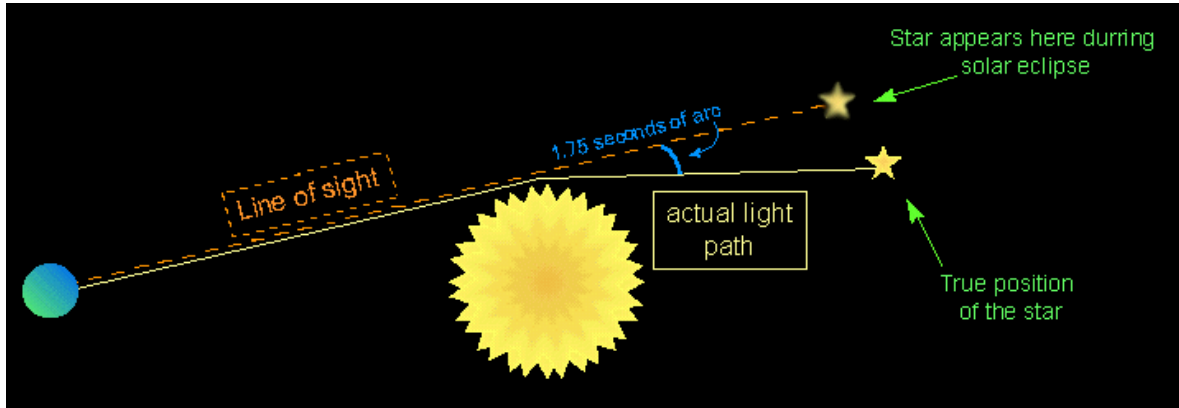


# Bending of starlight

The angle of deviation of the beam of light depends on the relative velocity of the observer frame and the source. The acceleration – changing of that relative velocity - would thus lead to **angle changing** with time – or **“bending”** of the light beam.

- Equivalence principle states that measurements in an **accelerated frame** are identical to those in a **gravitational field**. Thus, we must accept that gravity bends light.

# Bending of starlight



**Gravitational Lens in Abell 2218**

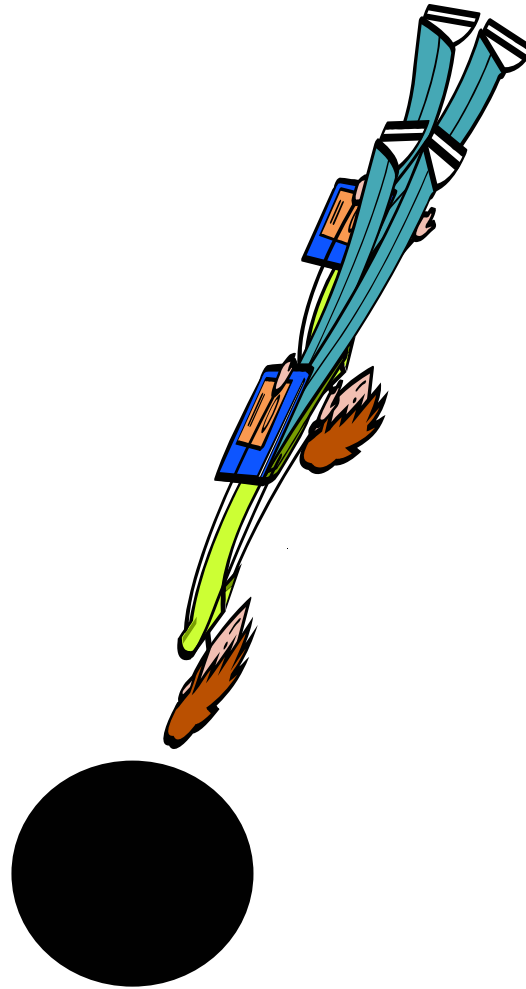
HST • WFPC2

PF95-14 • ST ScI OPO • April 5, 1995 • W. Couch (UNSW), NASA

# Strong equivalence principle

- *The outcome of any local experiment, whether gravitational or not, in a laboratory moving in an inertial frame of reference is independent of the velocity of the laboratory, or its location in spacetime.*
- Difference between WEP and SEP is the “gravitational” part. WEP only applies to *small test masses* that do not noticeably disturb the gravitational field. SEP applies to large, *self-gravitating* objects like stars and black holes.
- Strong equivalence principle inclusion of self-gravitating objects changes the effects observed in a *local free-fall* frame.
- For example, and observer free-falling into a black hole head first will notice larger force on his head than his feet.

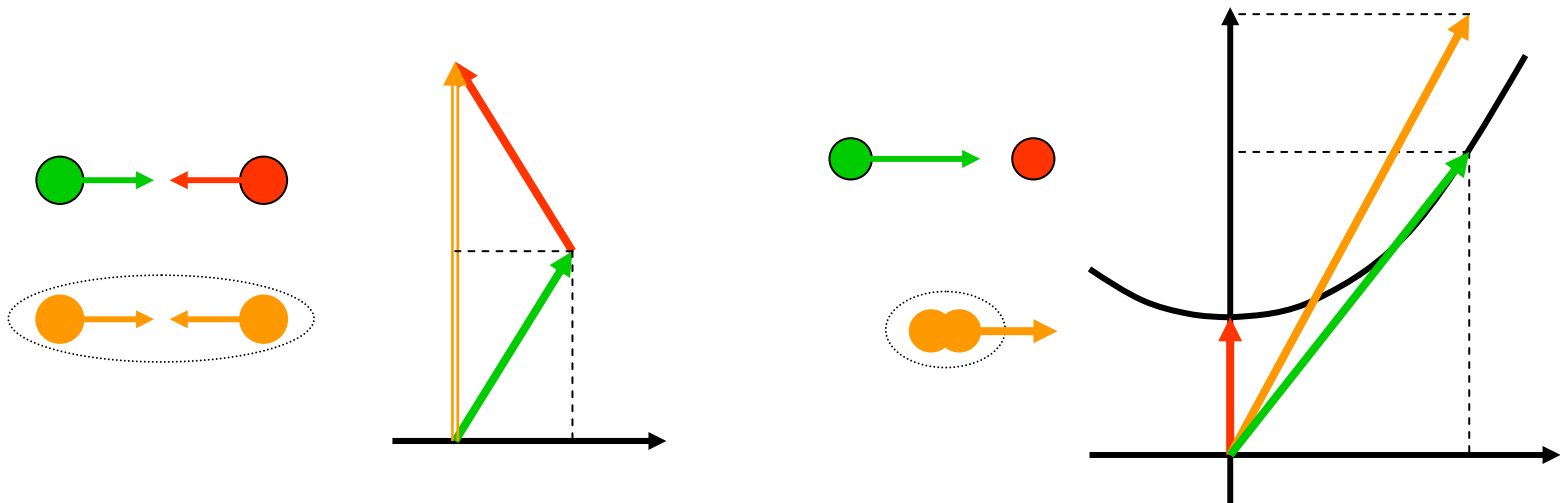
# Falling into a Black Hole...



# Mass, energy and momentum – Q&A

Q: Does the mass of an isolated system remain constant? Is it the same in all inertial frames?

A: Yes, and Yes. Mass of a system is the *magnitude* of its energy-momentum 4-vector. Because of energy-momentum conservation, this quantity remains the same no matter what happens within the system. A magnitude of a 4-vector is a property that is also invariant under Lorentz transformations, thus it is the same in all inertial frames.

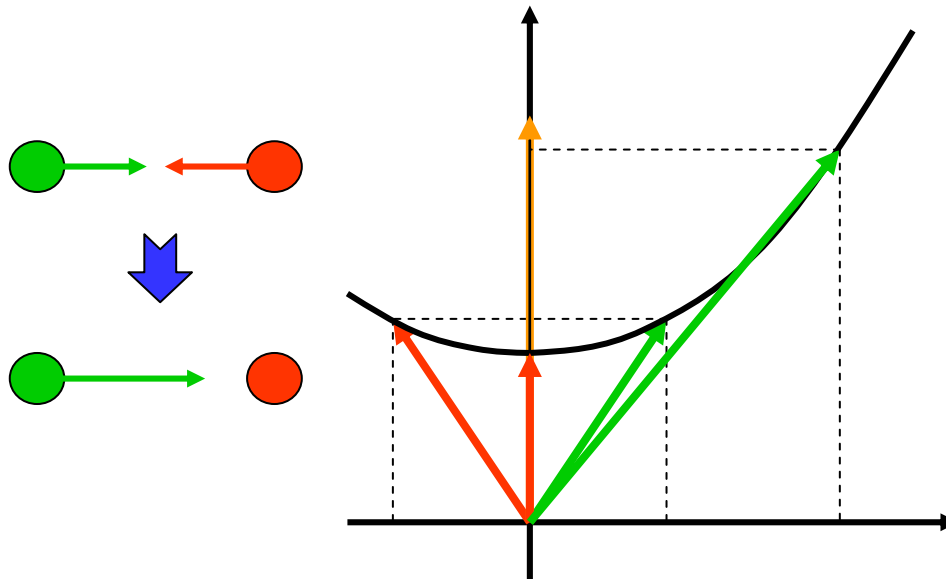




# Mass, energy and momentum – Q&A

Q: Are energy and momentum of an isolated system the same in all frames?

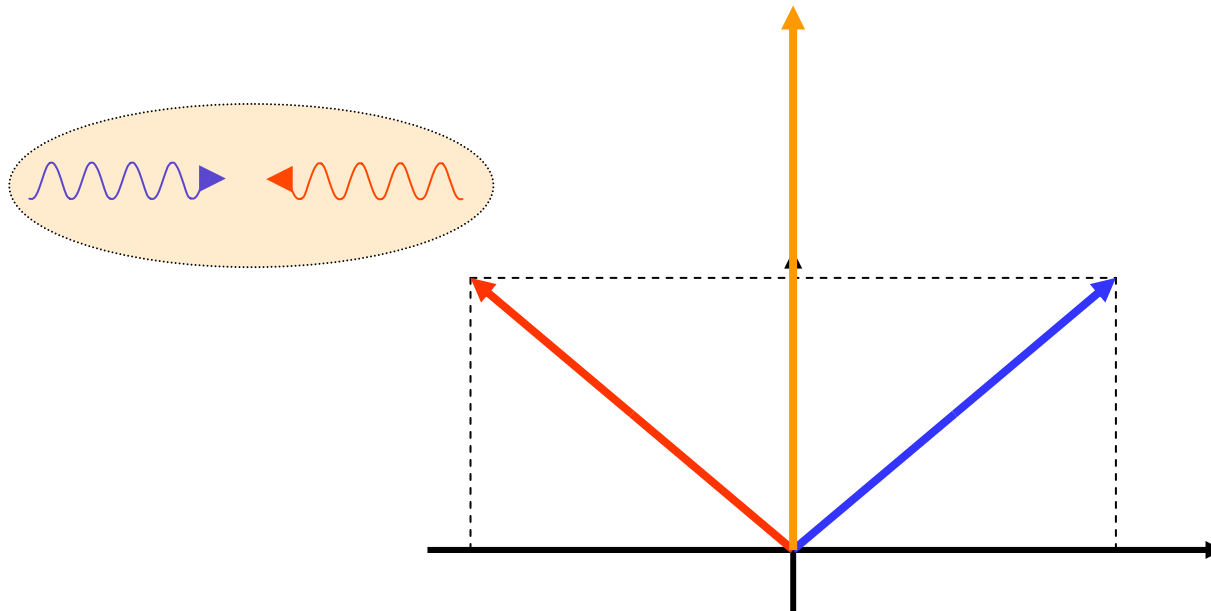
A: No. Energy of the system is  $E = m + K = m\gamma$ , while momentum is  $\mathbf{p} = m\mathbf{v}\gamma$ . The stretch factor  $\gamma$  is different in different inertial frames.



# Mass, energy and momentum – Q&A

Q: Do massless particles (photons) have energy? Can massless particles add mass to a system?

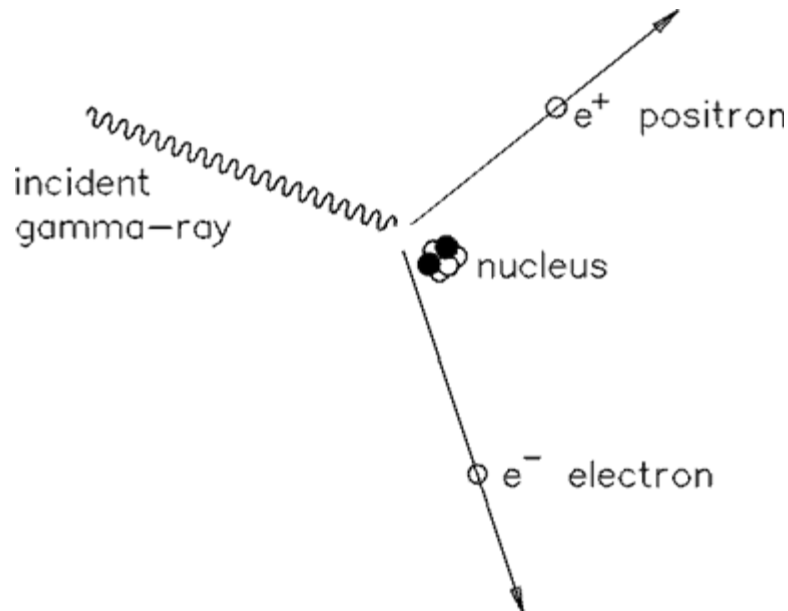
A: Yes, and Yes. Energy of a massless particle is all in its motion, so we can say that it is equal to its kinetic energy  $K$ , and is also equal to the magnitude of its momentum  $|p|$ . When considered a part of a system, a photon adds mass to it, proportional to the photon's energy (momentum).



# Mass, energy and momentum – Q&A

Q: If mass of a system is conserved, then is it true that individual masses of its constituents, and the constituents themselves, also remain the same?

A: Not necessarily. In inelastic collisions, objects heat up and gain mass. In annihilation, massive objects convert into massless photons. In pair production, massless particles create massive ones.



# Mass, energy and momentum – Q&A

Q: What is the meaning of the statement that mass and energy are equivalent?

A: At zero momentum, energy of an object is the same as its mass (the *rest mass*), when proper units are used. If the object is moving, its total energy is increased by the amount of the kinetic energy of motion; the object's rest mass remains the same in all inertial frames.

Q: What about “relativistic mass” – doesn't an object moving at near speed of light become heavier?

A: No! Mass of an object is the magnitude of its energy-momentum, and is the same in any and all inertial frames. Do you think that if you move at  $v = 0.99$  you will feel heavier? Let me assure you, even as we speak we are moving vary-very fast with respect to some high-energy cosmic ray particles, or some far-away galaxies.

# Mass, energy and momentum – Q&A

Q: How do we measure mass of a system?

A: Weighing is a good way to measure mass. Gravitational pull of Earth is proportional to the mass, so... Make sure you're weighing the entire system, not just its parts. If the system is too big (or too small) to fit on a scale, use other methods – gravitational red shift, for example.

