- Exam #2 on Friday, November 14th!

Outline

- What is Special and General Relativity– Welcome to the world of Einstein.
- In a closed moving system (constant velocity), there are no experiments that you can do to show that you are moving.
- The speed of light is the same for all observers
- For speeds near light– distance contraction and time dilation.
- Gravity changes space and time– light is bent by large gravity
- Black Holes are formed from stars > ~25 solar masses
- What are blackholes?

Exam #2

- **Date:** Friday, Nov 14th
- **Place and Time**: In class, at the normal 12:00-12:50 pm time.
- **Format**: 40 multiple choice problems and 2 bonus questions (extra credit).
- **Bring:**
  - Yourself, well-rested and well-studied
  - A #2 pencil
  - On the test you will be given numbers or equations (if any) that you will need. You may **not** use your book or your class notes.

Exam #2

- **Topics included**: All material from the Sun through blackholes. Lecture and reading material are both included. My goal is to test for understanding of the concepts we have discussed, and how they fit together.
- **Study tips.** We have covered a lot of material in a short time, so here are some tips on how to approach your studies for the exam.
  - Topics covered in lectures should be stressed.
  - Homework questions have good examples of questions that may show up on the exam. An excellent way to begin studying is to review the homework problems, particularly those you missed (or got right but were not so sure about). Be sure you understand what the right answer is, and more importantly, **why** it is right.
  - You will need to understand and be able to use any equations that have been introduced in class. Calculations using these equations will be kept simple--it is possible to do the exam without a calculator, but you can bring one if you wish.

Exam #2

- **In-Class Q and A:** On Wed., Nov. 5th, some time will be allotted in class to ask questions about material on the exam. For example, if there are homework answers you do not understand, this would be an excellent time to ask. To get the most out of this time, you are strongly encouraged to begin studying prior to this class.
- **Out of Class Q and A:** On Thursday, Nov. 13th, I will have office hours from 10:30 to 11:30am and Justin will have TA office hours at 4:00 to 6:00pm. You should bring questions.

Relativity deals with the question:

How do the laws of nature appear to change when you change your state of motion …

Special Relativity

… when your velocity relative to something else is close to the speed of light?

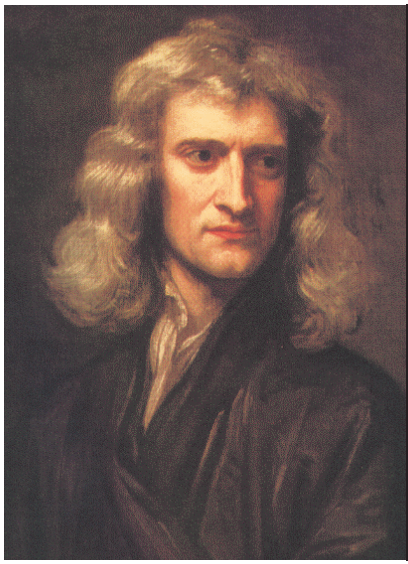
General Relativity

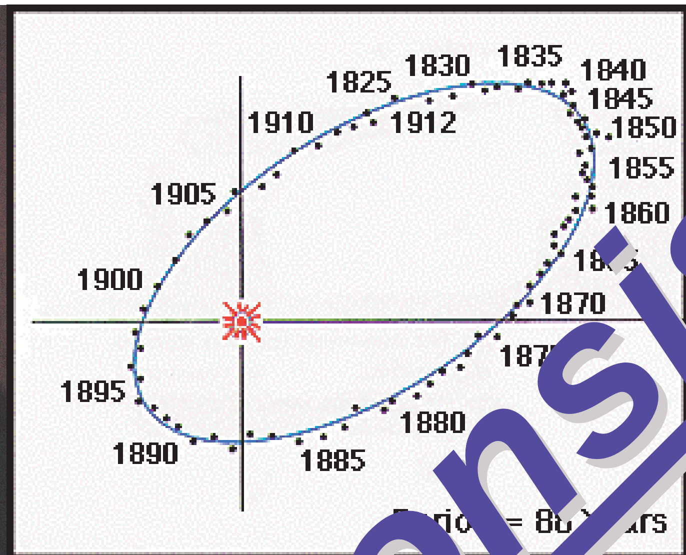
… when you are in a strong gravitational field?

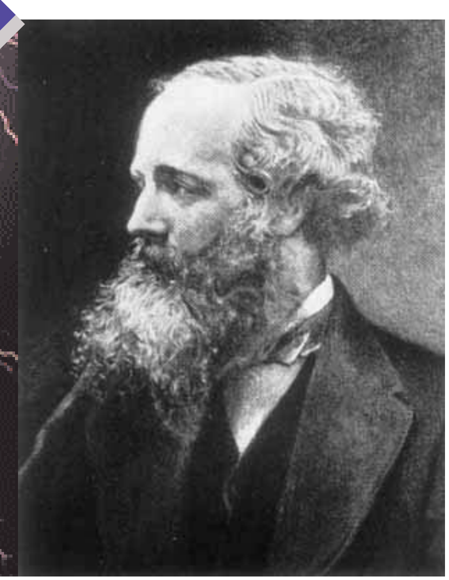
Two Threads of Thought in Physics up to 1900

Mechanics
(Newton's Laws)

Electromagnetism
(Maxwell's Equations)







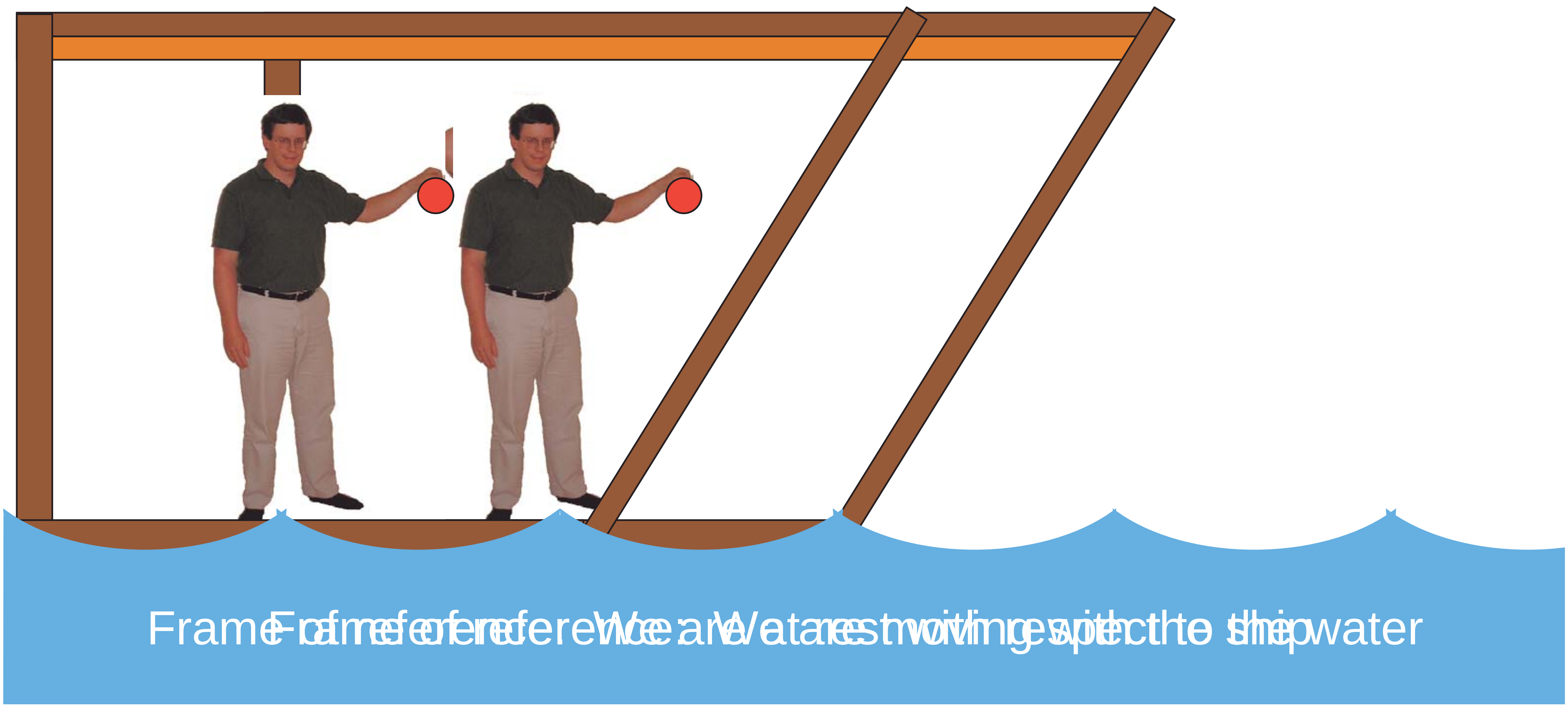
Inconsistent!

All motion is relative
No speed is special

The speed of light is the **same** for all observers

Galileo's ship thought experiment

No experiment within the ship's cabin can detect the ship's motion if the ship moves in the same direction at a constant velocity. This is still true, even when considering the speed of light.



Why Galileo and Maxwell Can't Both Be Right

Consider two locomotives emitting light from their headlamps:

At rest

Moving at some speed *v*

Why Galileo and Maxwell Can't Both Be Right

If light emitted by #2 moves relative to #2 at speed *c*, Galileo says that #1 must see it move at $c + v$.

But light emitted by #1 moves relative to #1 at speed *c* – or at speed $c - v$ relative to #2!

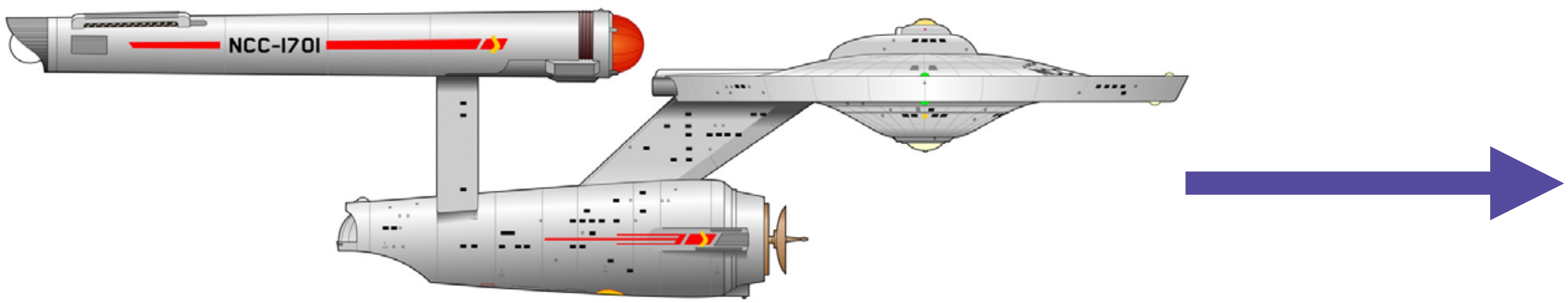
So the speed of light can't be the same for everyone if Galileo – and our intuition – are right. But Maxwell says it is constant!

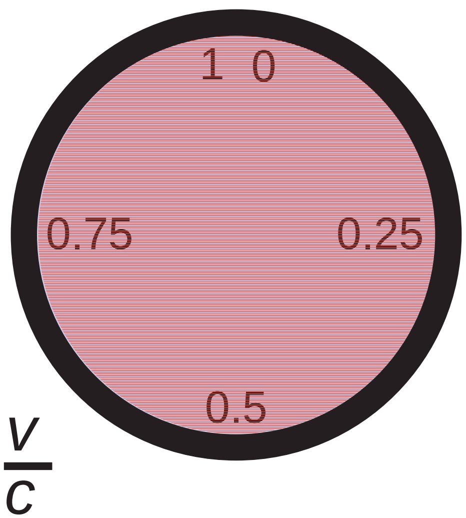
Something must happen. And what must happen for Galileo and Maxwell to be both right, is that there is a modification of time and distance. Remember

$$speed = \frac{dist}{time}$$

Counterintuitive Result #1

Moving objects appear shorter in the direction of relative motion (<u>Lorentz contraction</u>)

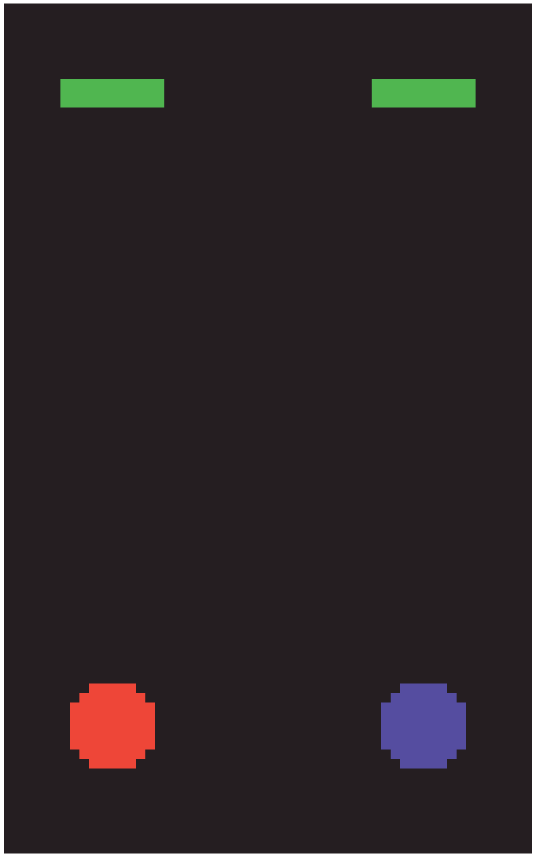




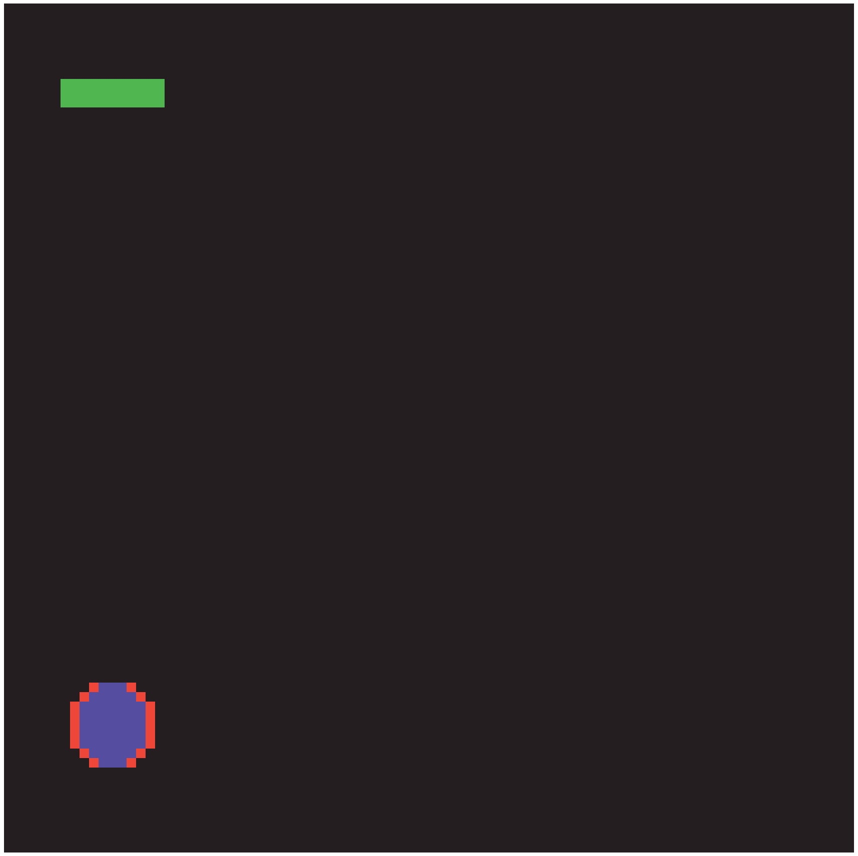
Fraction of the speed of light	% of original length
0.00	100%
0.001	99.99995%
0.01	99.995%
0.1	99.5%
0.5	86.6%
0.9	43.6%
0.99	14.1%

Counterintuitive Result #2

Time appears to advance more slowly for moving objects (time dilation)



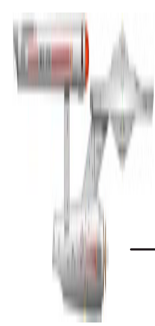
Red & blue at rest



Blue moving to right

So, what does that mean?

- If you’re on a 100m spaceship going near the speed of light (.99 c), the spaceship would look 100m long, but someone on the Earth would observe the spaceship to only be 14m long.
- As you speed by the Earth your clock would tick 1 second, and an observer would tick about 7 seconds.



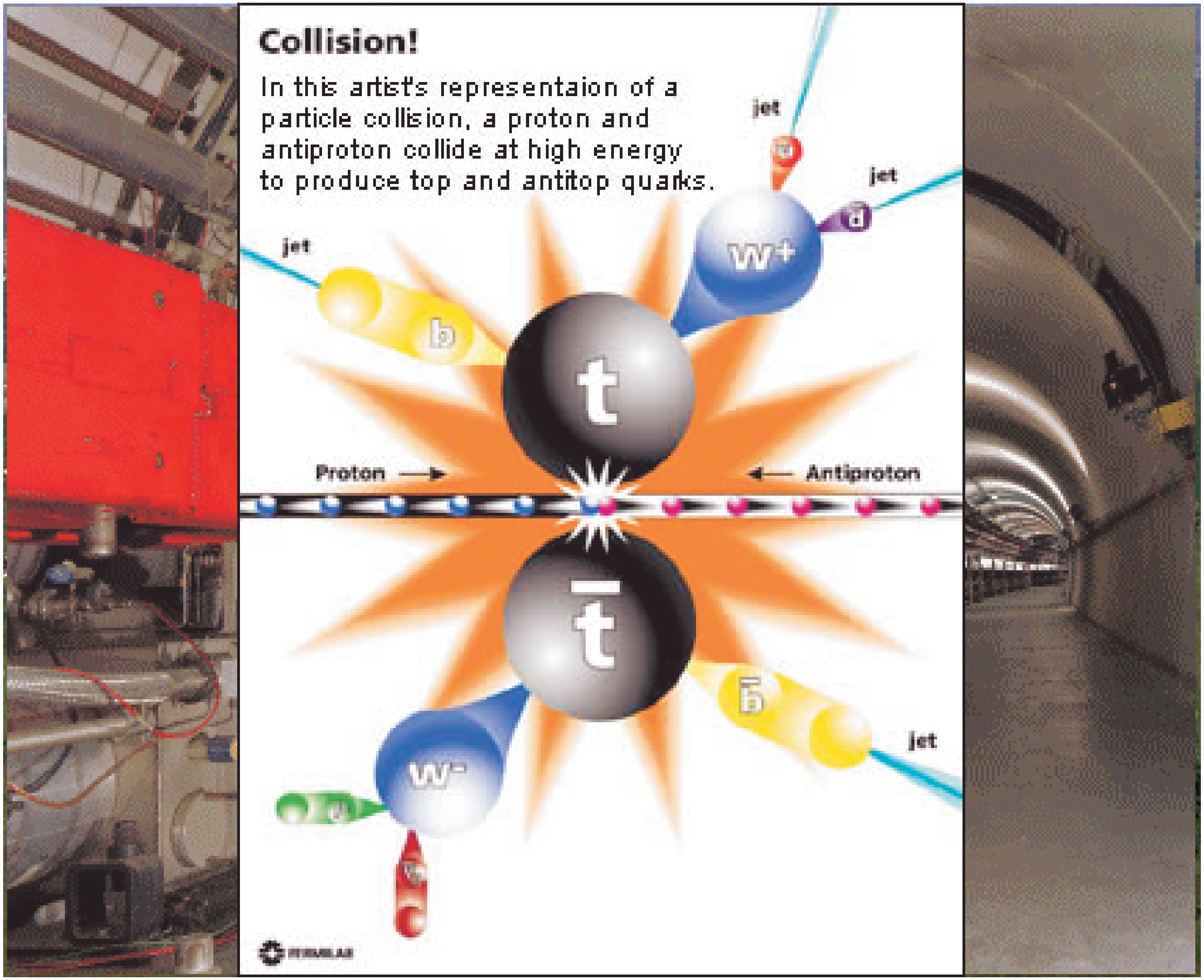
0.99 c

14m

And your mass increases with speed.

Paul’s Twin brother (on the Earth) is at least 7 seconds older.

All in a Day's Work



Fermilab – Batavia, IL

Special Relativity Summary

All motion is relative, except for that of light. Light travels at the same speed in all frames of reference.

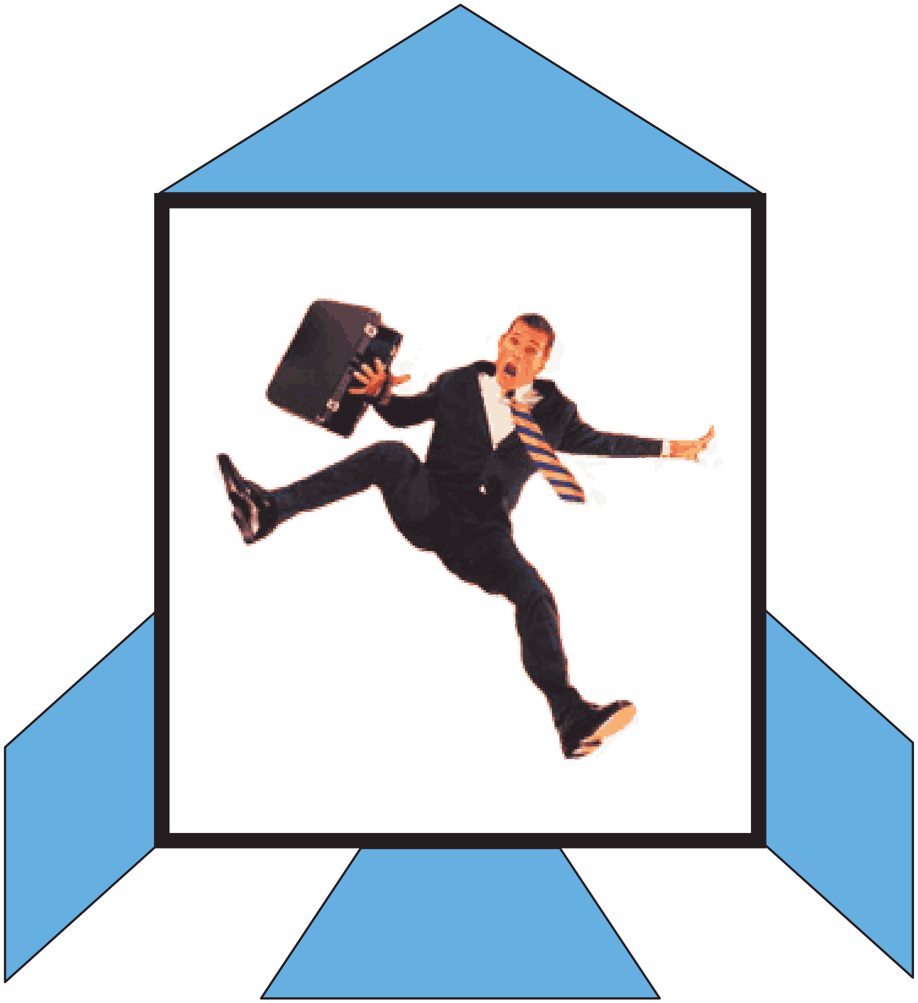
Objects moving close to the speed of light appear to shrink in the direction of travel.

Time appears to advance more slowly for objects moving close to the speed of light.

The Second Big Conceptual Leap

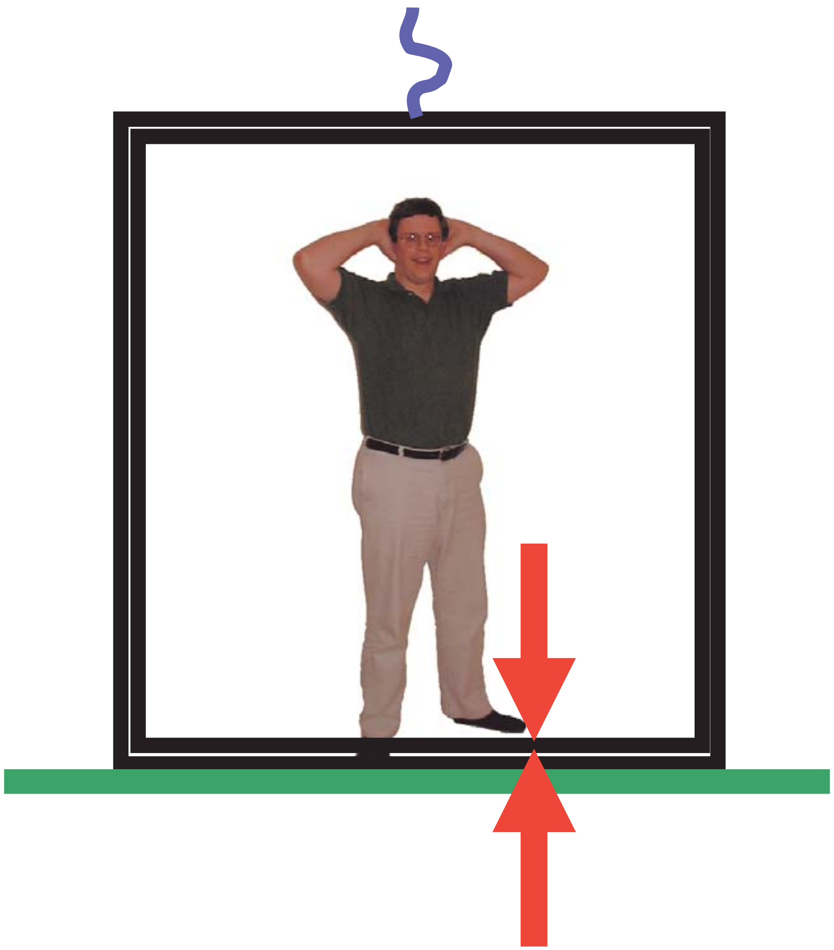
Free fall in a constant gravitational field is indistinguishable from motion at constant velocity far from any source of gravity.

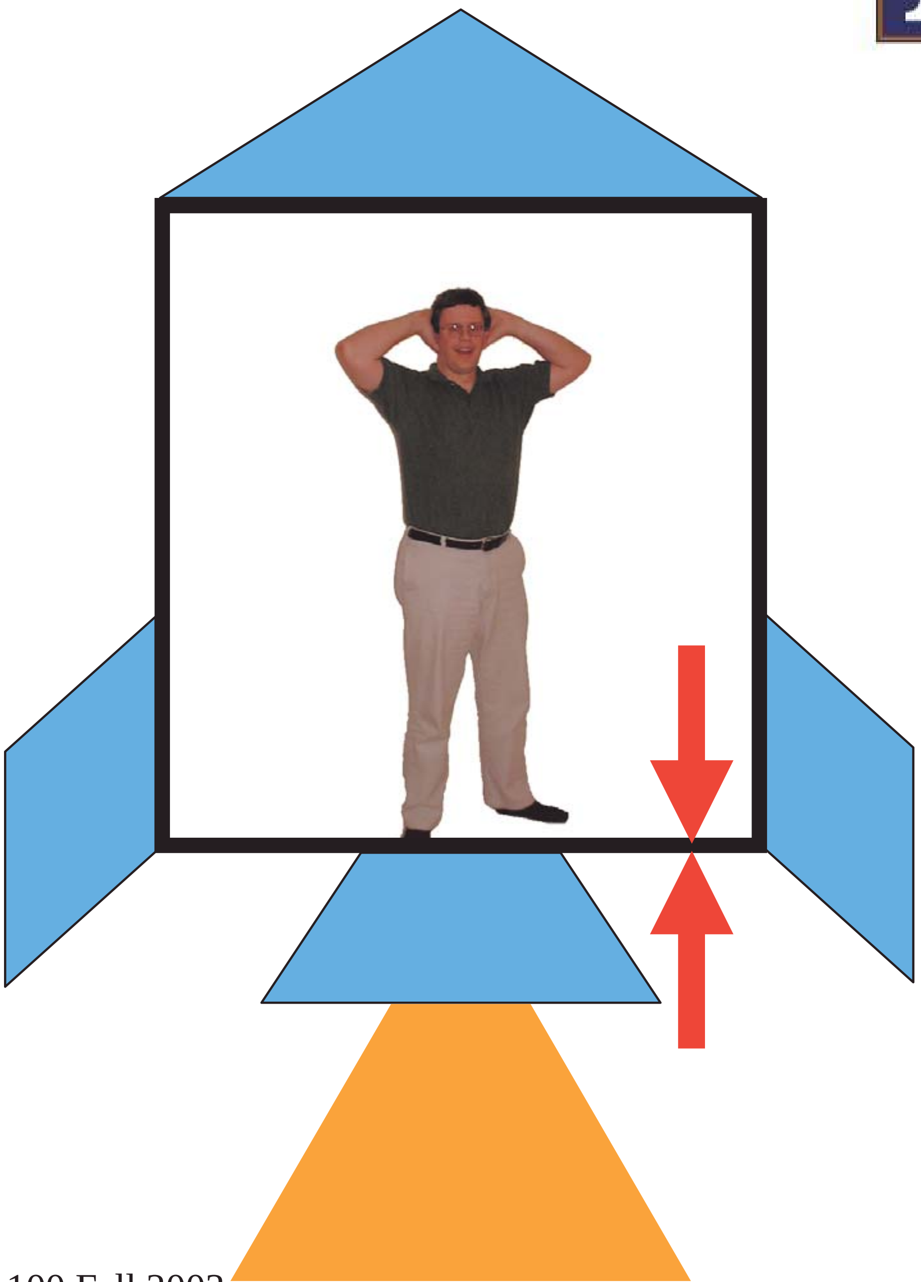
Elevator and contents accelerate together



Constant velocity

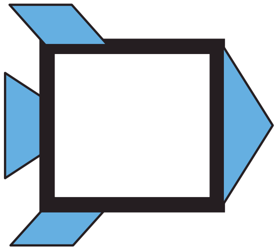
We only feel the effect of gravity when we are not freely falling.



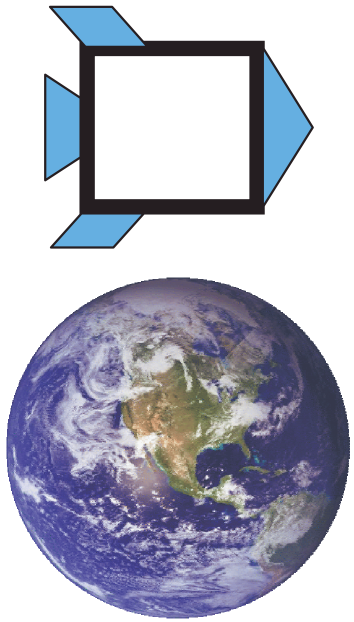


Gravity Changes the Geometry of Space and Time

In a gravitational field, a “straight” line is no longer straight.

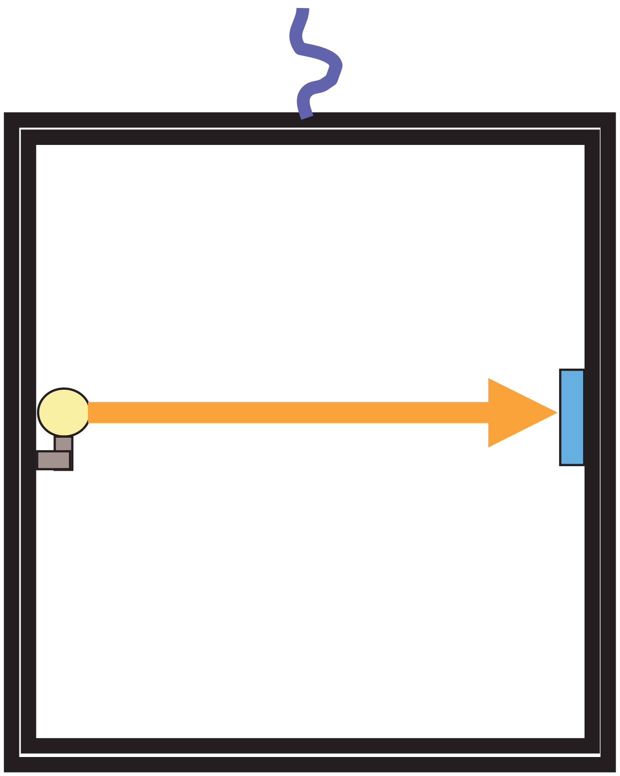


No forces: moves in a straight line at constant speed.

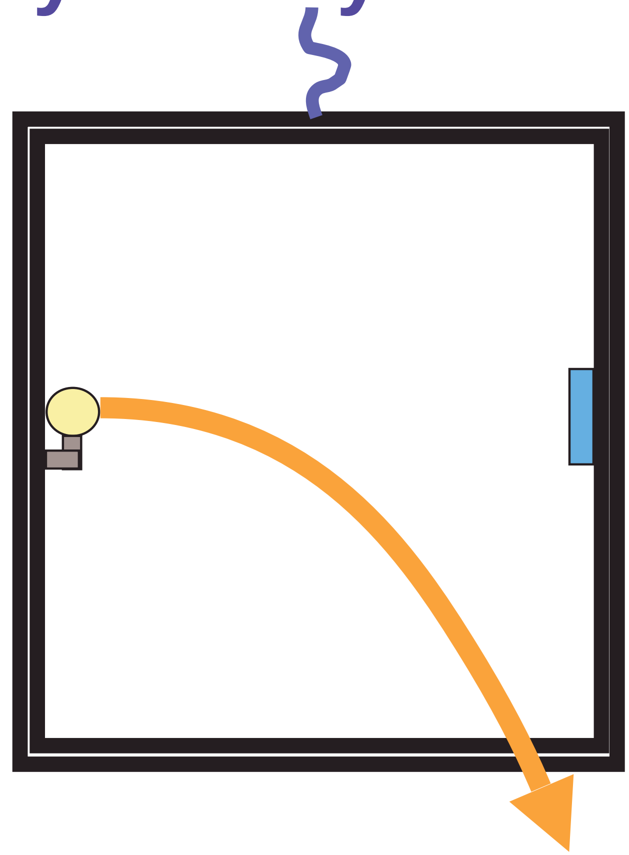


In a gravitational field: also moves in a “straight” line. But the definition of a “straight line” has changed!

Light Too Is Bent by Gravity

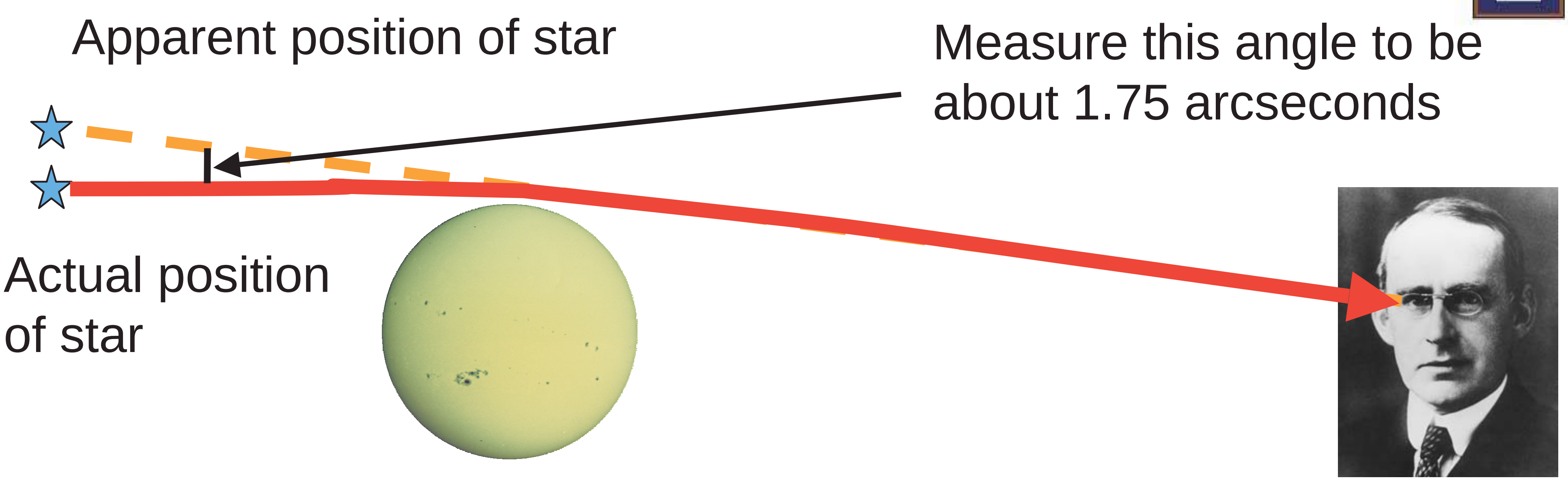


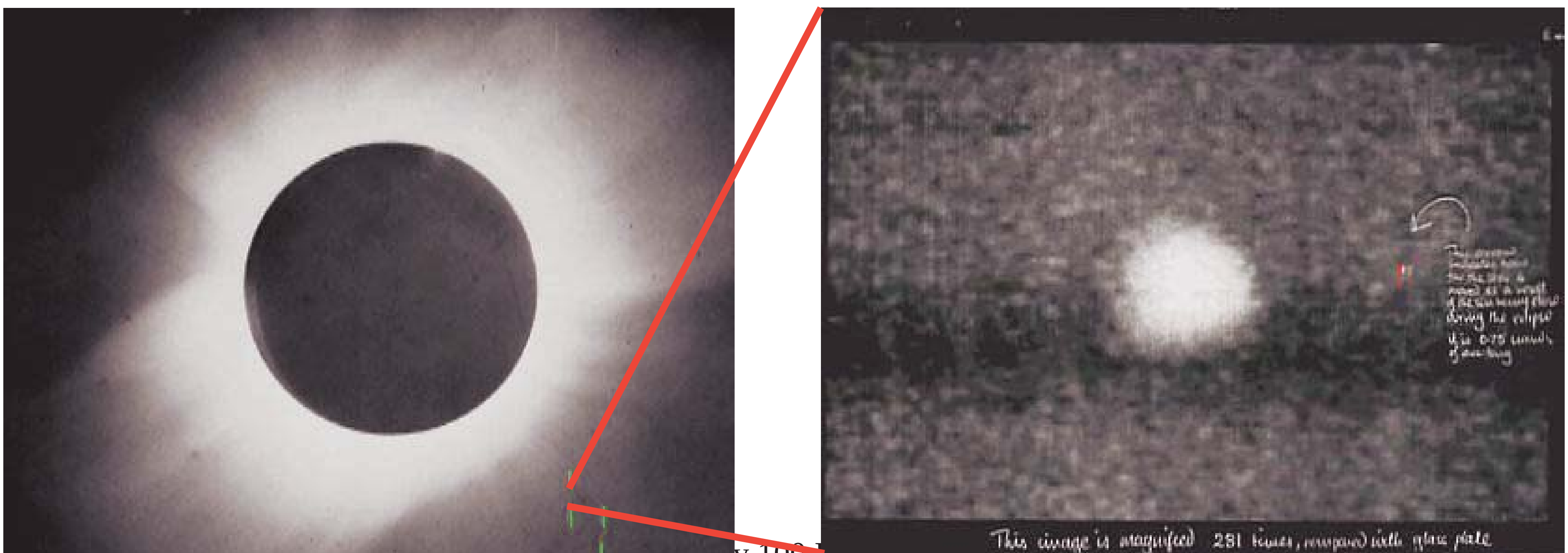
As seen within the freely falling elevator



As seen from the ground

Eddington and the Total Eclipse of 1919



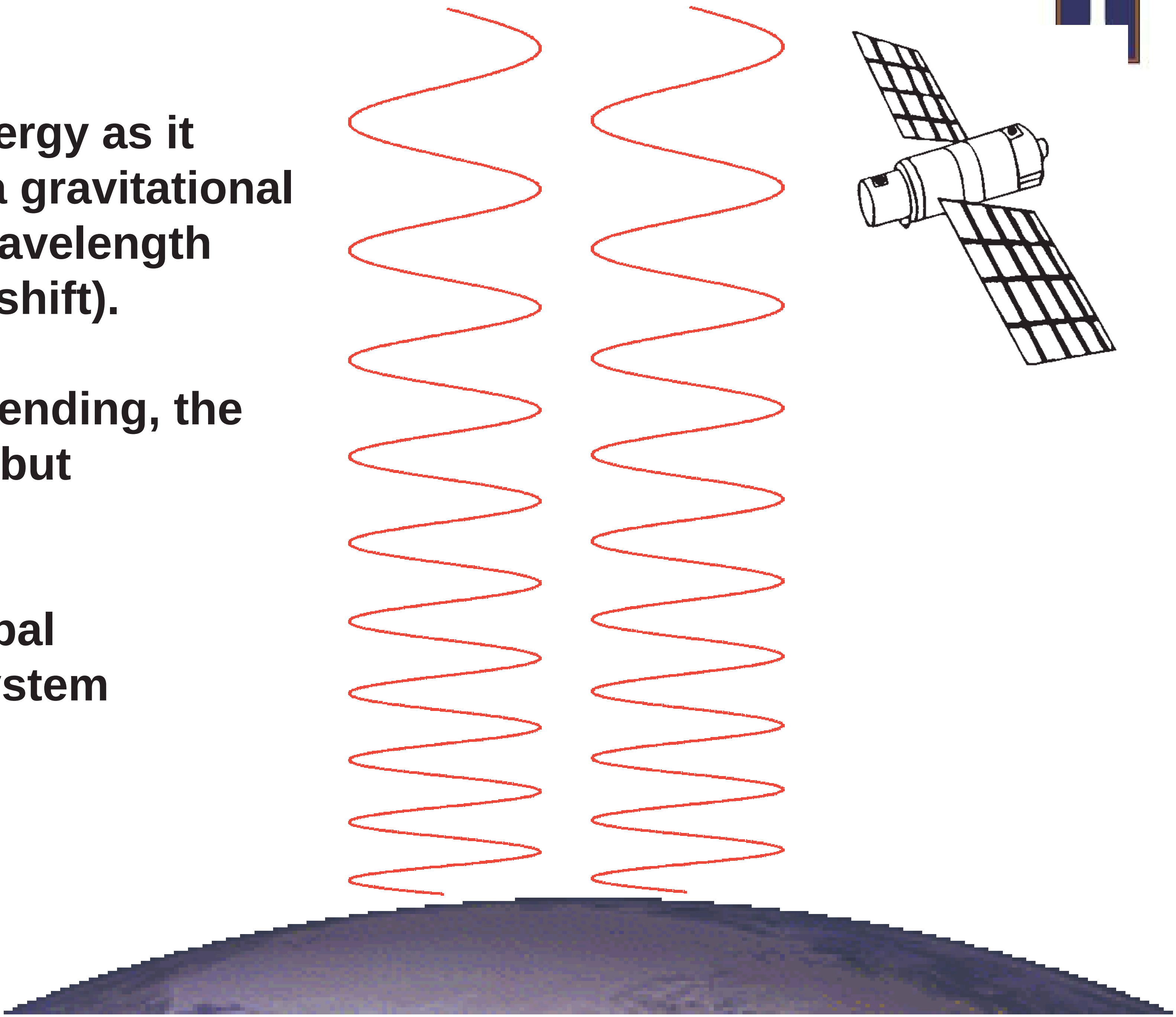


Gravity Also Redshifts Light

Light loses energy as it climbs out of a gravitational field – so its wavelength increases (redshift).

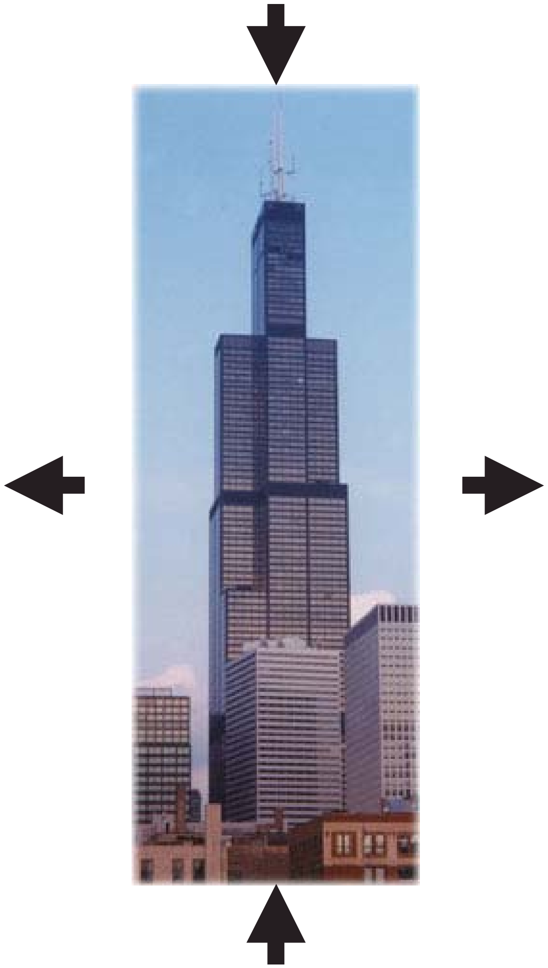
As with light bending, the effect is small but measurable.

Example: Global Positioning System



Gravitational Radiation

The gravitational field can “ripple” just like the electromagnetic field. These gravitational waves are traveling distortions in spacetime.



Amount of distortion is **very** small – smaller than an atomic nucleus

Laser Interferometric Gravitational Wave Observatory (LIGO), Hanford, WA

LIGO Hanford Obs.

General Relativity Summary

Freefall in a constant gravitational field is indistinguishable from moving at constant velocity far from any source of gravity.

A gravitational field alters the geometry of space and time. Light travels along “straight” lines that look curved in this altered geometry.

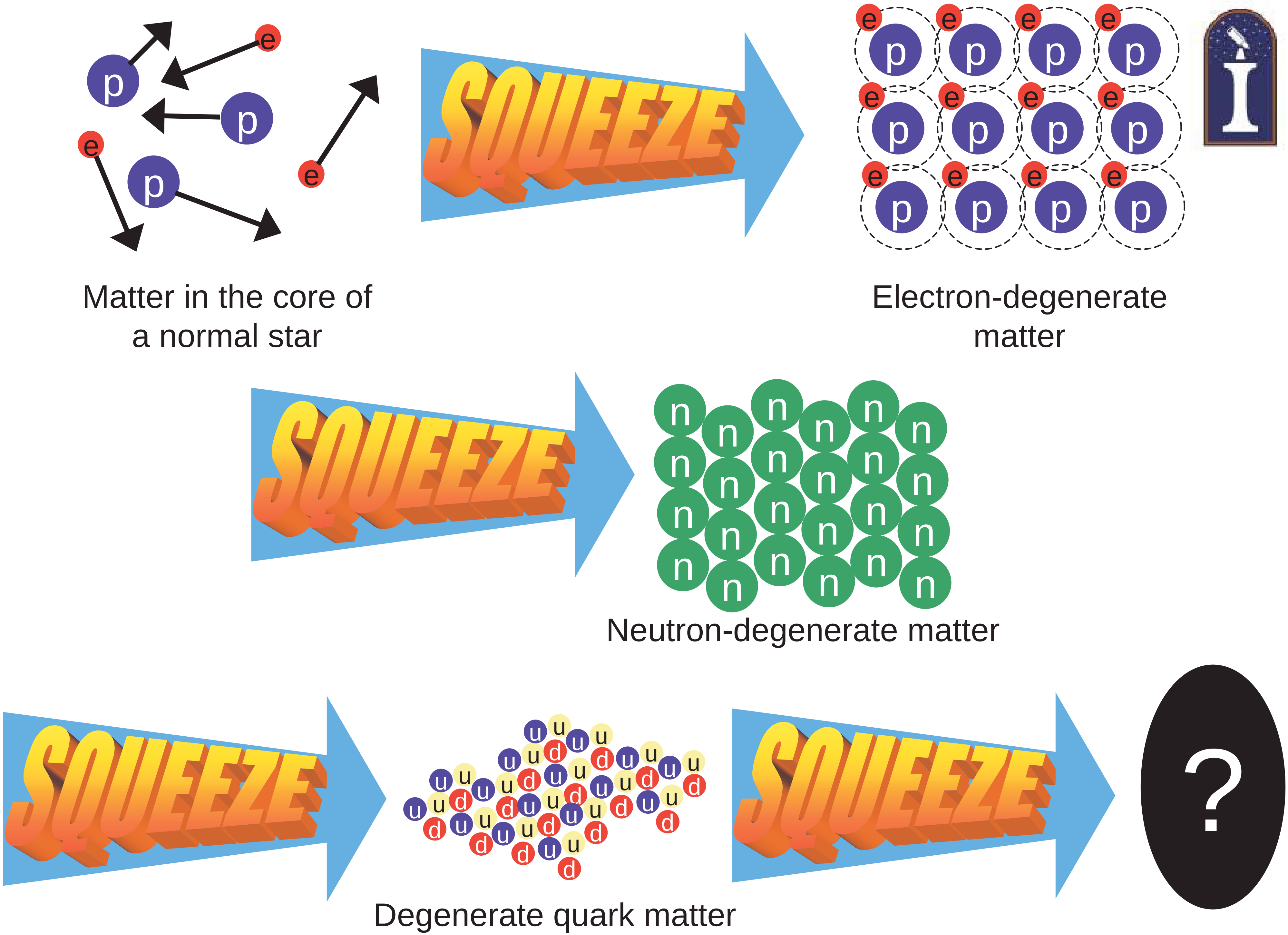
Light is redshifted as it climbs out of a gravitational field.

Gravitational fields can “ripple” just like electromagnetic fields can (gravitational radiation).

Okay, that's our brief explanation of Relativity

- Back to stars….

- What happens to stars around 25 solar masses?
  - After the supergiant and supernova stage, the remaining star is more neutron degeneracy can stand and the star collapses further to a black hole.
  - Near the black hole, space is warped so much that light can not escape. Nothing can get off the surface of the dying star.
  - The matter in the star gets compressed to a singularity– a single point in space-time
  - The laws of Newton and Einstein no longer apply!



p
e
Matter in the core of
a normal star
SQUEEZE
Electron-degenerate
matter
SQUEEZE
n
Neutron-degenerate matter
SQUEEZE
u
d
Degenerate quark matter
SQUEEZE
?

The Event Horizon

Where the escape velocity = the speed of light

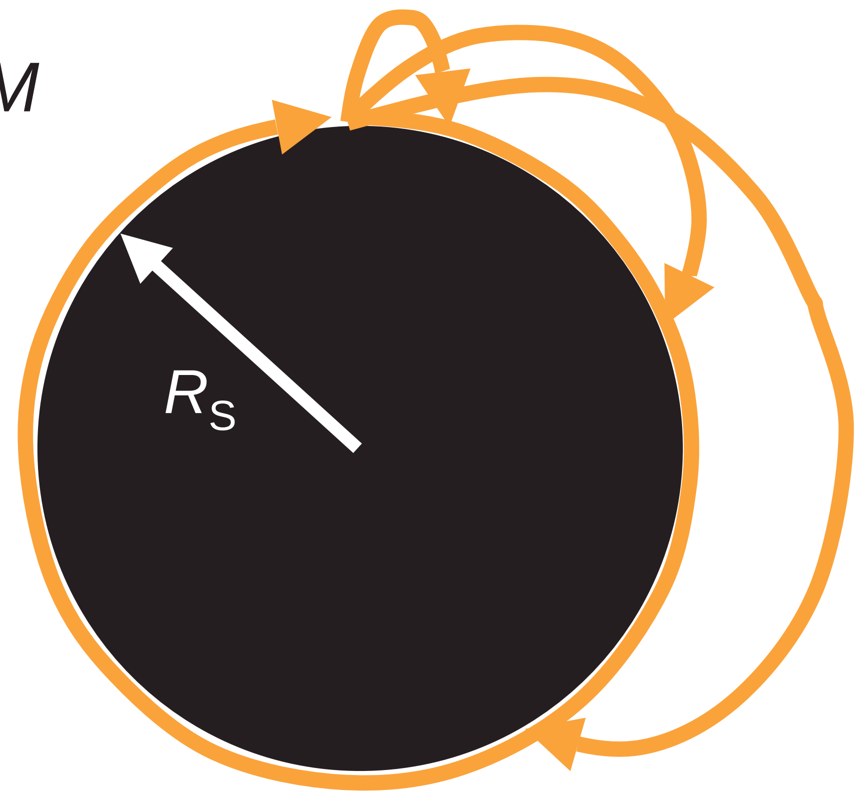
Nothing can escape from within that radius

Schwarzschild radius for mass *M*

$$R_S = \frac{2GM}{c^2}$$

For the Sun, R_S = 3 km, so

$$R_S = 3(M/M_{Sun})\ \text{km}$$



Well outside of a black hole – It looks just like any other mass