Astronomy 122

<u>This Class (Lecture 19):</u>

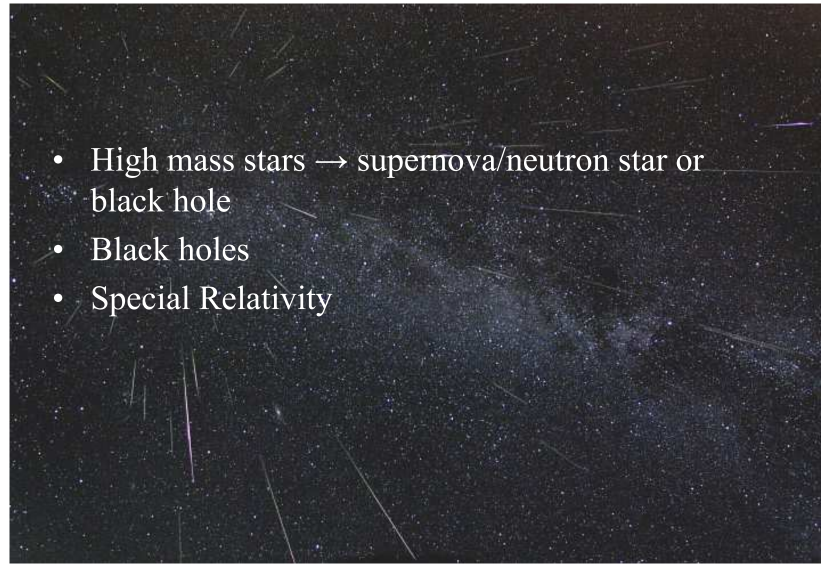
Death by Black Hole:
Spaghetti-fication

<u>Next Class:</u>

Is there anybody out there?

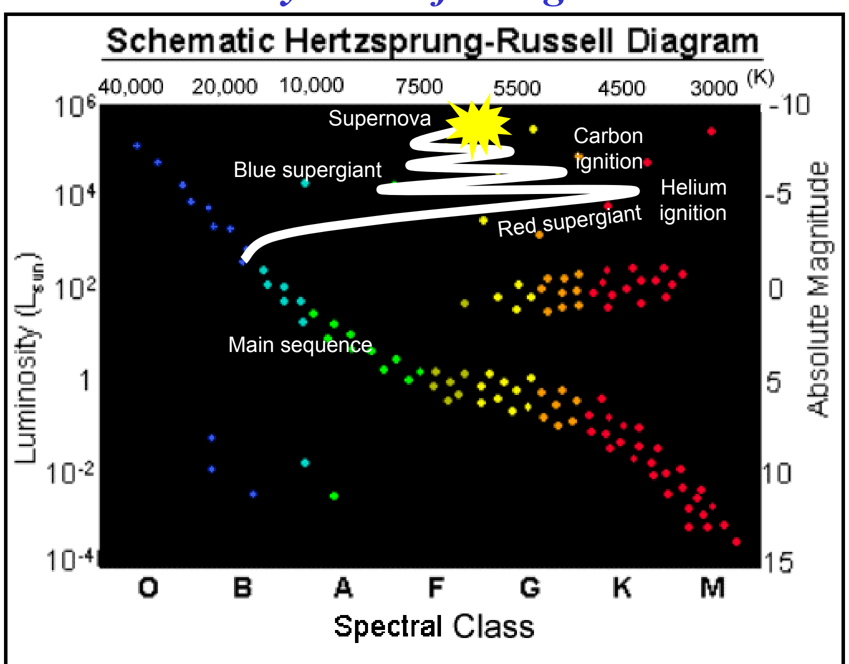
Music: *Black Hole Sun* – Soundgarden

Outline



- High mass stars → supernova/neutron star or black hole
- Black holes
- Special Relativity

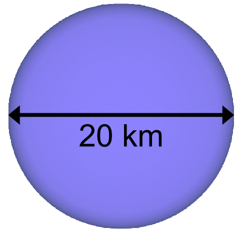
Evolutionary Path of a High-Mass Star



Death throes

- What triggers a supernova?
  - Hydrostatic equilibrium is lost, gravity wins
  - Iron core with $M > M_{Chandra}$
- What happens?
  - Quick core collapse overcoming electron degeneracy pressure.
  - Outer layers rebound off the core, explosion of envelope
- What are end products?
  - Enriched ejecta and compact neutron star (if core mass < 3 solar masses)

Relative Sizes of Stellar Corpses



Question

So what supports a neutron star from collapsing?

a) Pressure from fusion
b) Pressure from CNO fusion
c) Electron degeneracy pressure
d) Gravity pressure
e) Neutron degeneracy pressure

What are Pulsars?

- When the core collapses, its spin and magnetic field strength increases
- Typically
  - Surface field strength over 1 trillion times that of the Earth
  - Rotation rate up to 1000 times per second
- Magnetic field beams radiation into space
- If the Earth is in the beam's path, we see the pulsar

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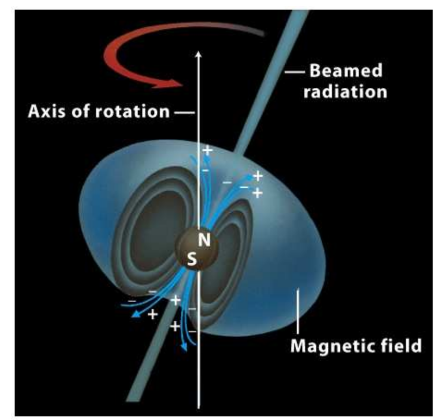
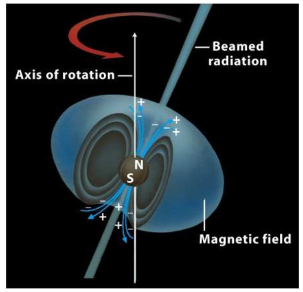


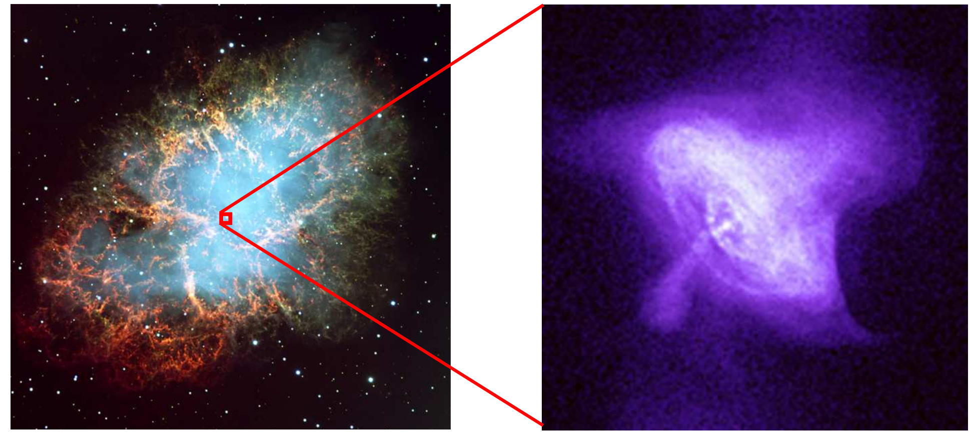
Kinda like a Lighthouse?

- Intense beams of radiation emanate from regions near the north and south magnetic poles of a neutron star
- These beams are produced by streams of charged particles moving in the star's intense magnetic field
- As the Pulsar gives energy to its surroundings, it slows down.
- The periods increase (few billionths of a second each day)



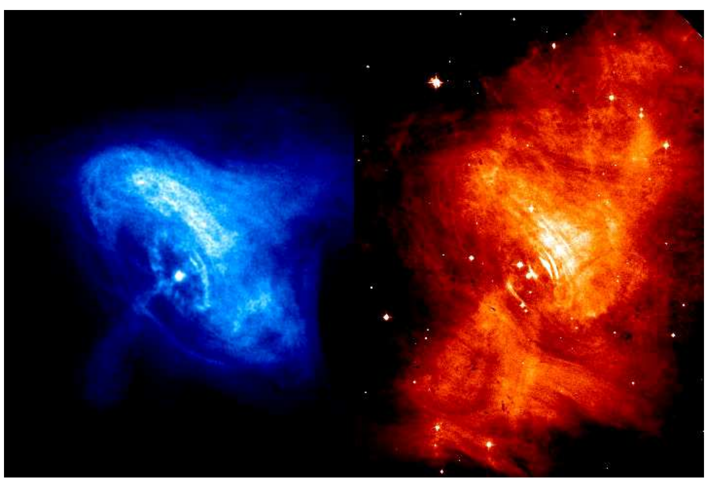
http://blogs.families.com/media/lighthouse.jpg

Crab Nebula – Remnant of the Supernova of 1054

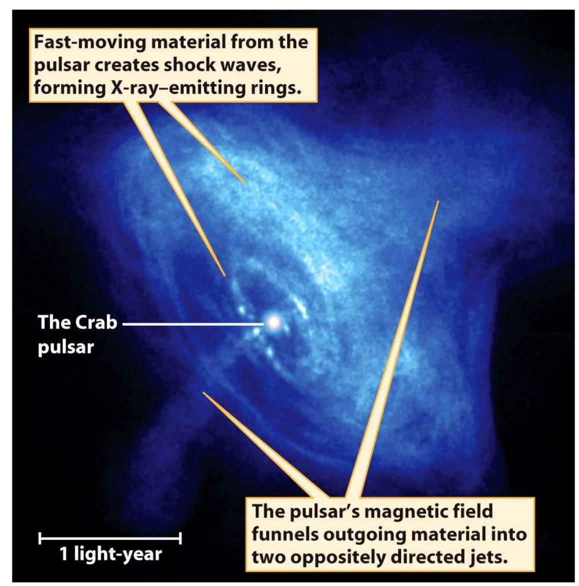


Optical - ESO X-ray - Chandra

Crab Nebula – Remnant of the Supernova of 1054

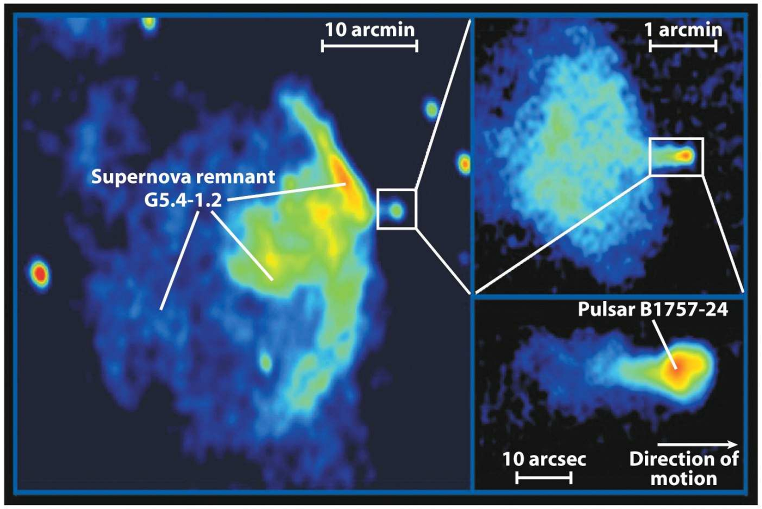


The Crab



Escaping Pulsars

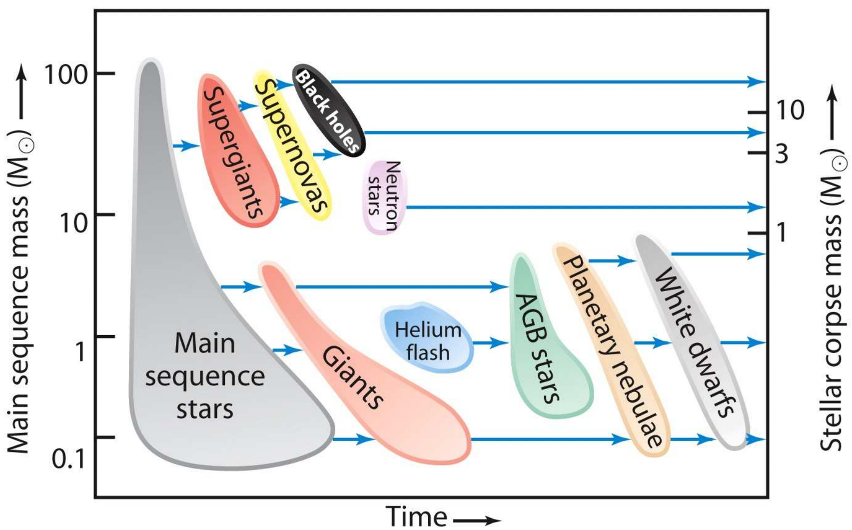
- Some Pulsars are ejected during the supernovae.
- Can outrun the explosion.
- This one is 600 km/s



When Neutron Degeneracy Isn't Enough

- Maximum neutron star mass
  - About 3.0 $M_\odot$
  - Original star around 30$M_\odot$
- Beyond this mass, neutron degeneracy cannot stop gravity
- Nothing left to stop, so total collapse– gravity rules!
- **A black hole**
  - $v_{esc} > c$

Stellar Evolution Recap

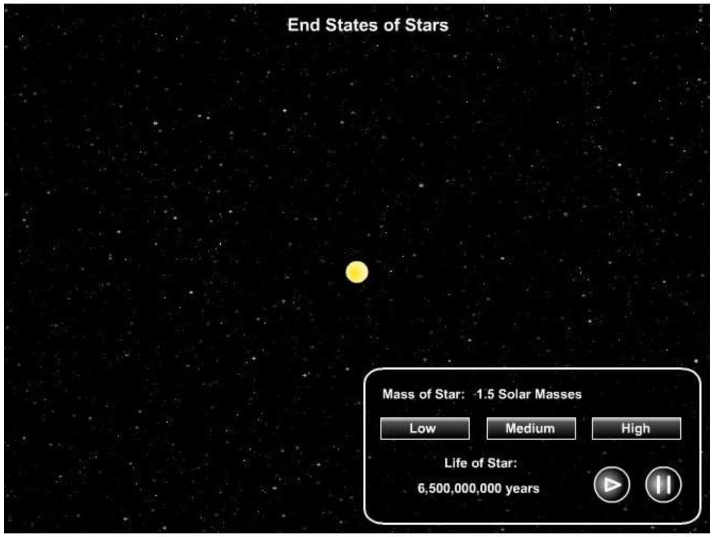


Question

So what supports a black hole from collapsing?

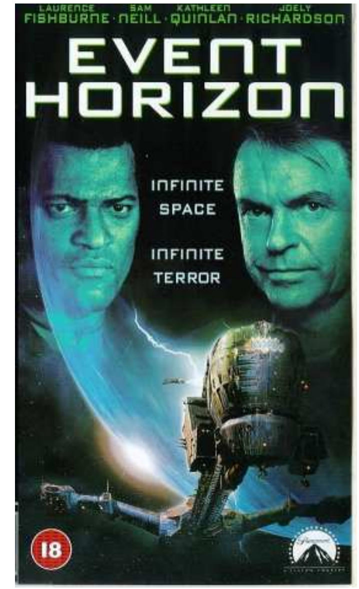
a) Pressure from fusion
b) Nothing it is collapsed to a single point
c) Electron degeneracy pressure
d) Gravity pressure
e) Neutron degeneracy pressure

The Life and Death of Stars



Black Holes

- Black holes inspire fear, awe, uncertainty, and bad science fiction
- Many people think that black holes are dangerous
  - That they suck matter in like "cosmic vacuums"
- Black holes follow the same laws of gravity as everything else

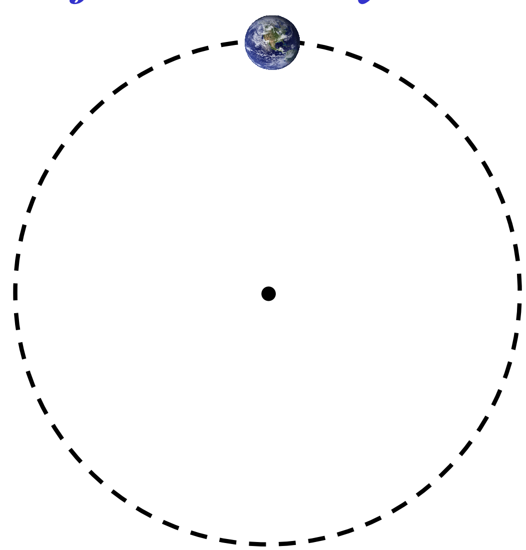


Thought Question

What do you think would happen to the Earth if the Sun collapsed into a black hole?

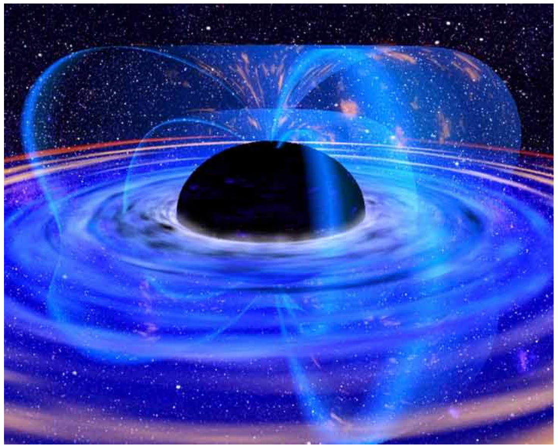
a) Fall in directly
b) Slowly spiral in
c) Stay in its orbit
d) Slowly spiral away
e) Fly away in a straight line

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



Physics of Black Holes

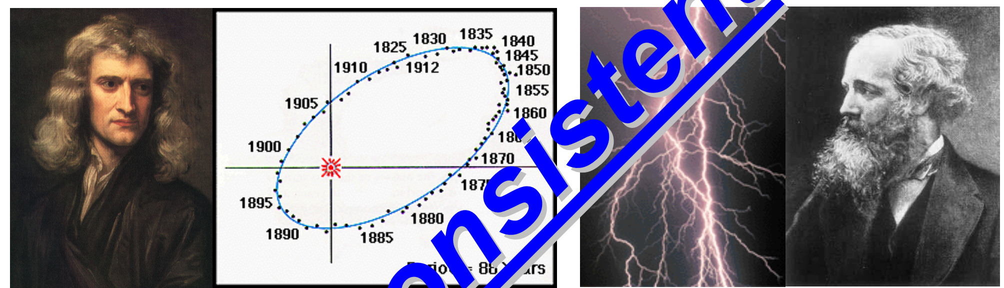
- Black holes are simple, yet strange objects
- Intense gravity due to compactness
- Newton's Laws cannot describe what happens in the nearby presence of such an intense gravitational field
- We need Einstein's *Theory of Relativity*



Two Threads of Thought in Physics up to 1900

Mechanics
(Newton's Laws)

Electromagnetism
(Maxwell's Equations)

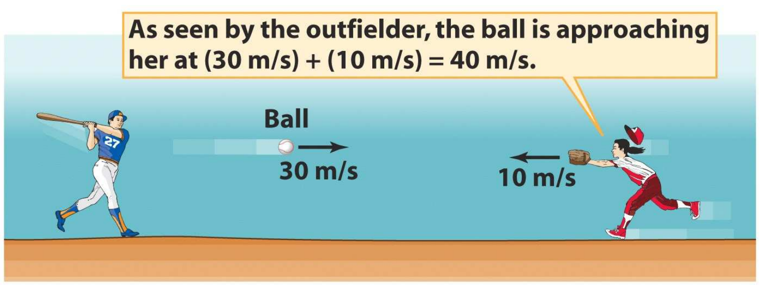


All motion is relative
No speed is special

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

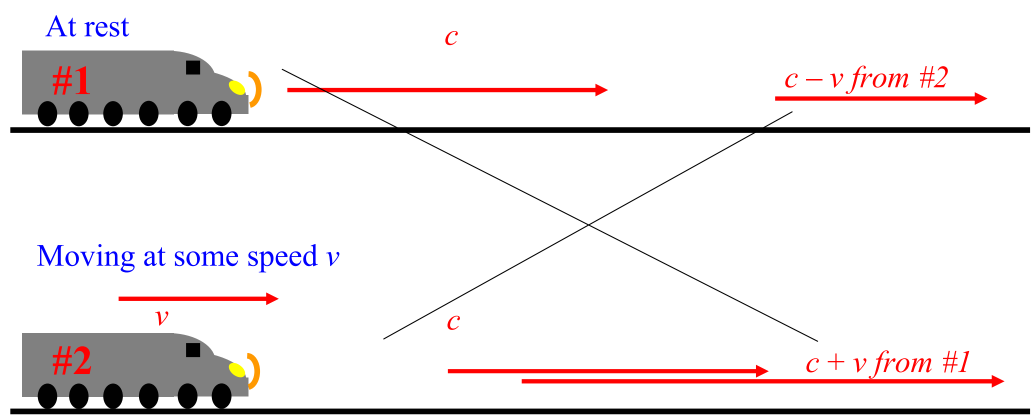
Inconsistent.

Why Galileo and Maxwell Can't Both Be Right

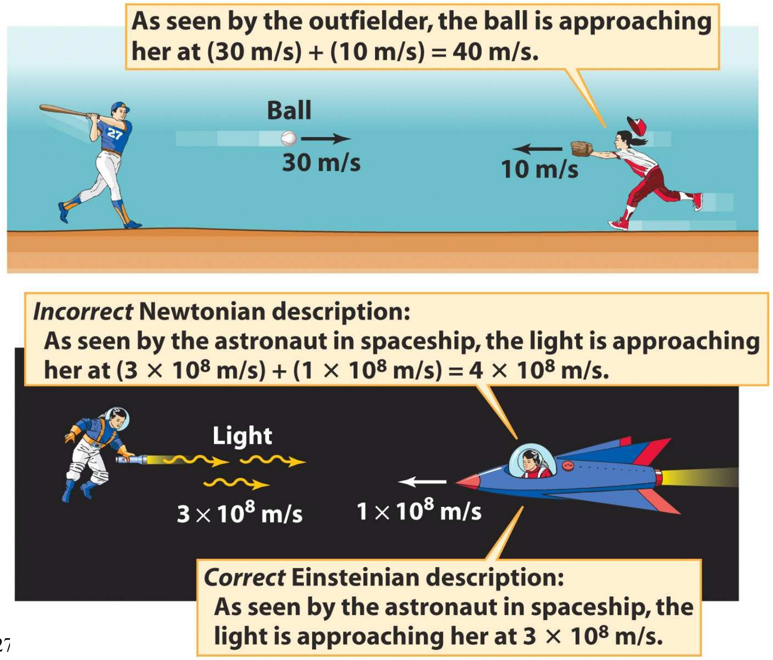


Why Galileo and Maxwell Can't Both Be Right

Consider two locomotives emitting light from their headlamps:



Why Galileo and Maxwell Can't Both Be Right



Why Galileo and Maxwell Can't Both Be Right

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

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

Distance and time become relative to the observer.

Approaching the "c"

- Time dilation – Moving clocks run slow.
- Length contraction – Moving objects contract along direction of motion.
- Mass increase – moving clocks get more massive

http://www.richard-seaman.com/Travel/Japan/Hiroshima/AtomicBombMuseum/IndividualArtifacts/

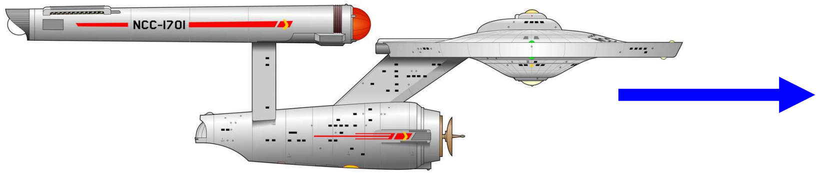
Gamma

The factor by which all of these changes occur is called "gamma"

$$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$$

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 #1

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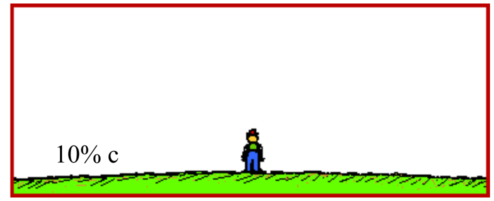
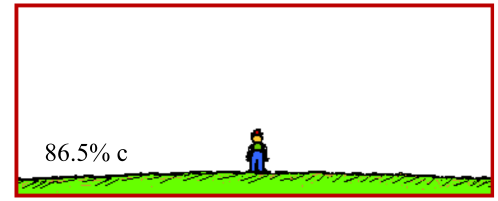
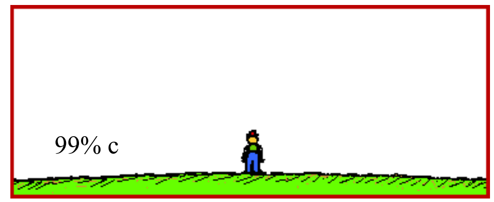
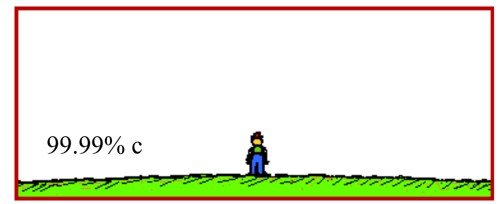








http://www.physicsclassroom.com/mmedia/specrel/lc.html

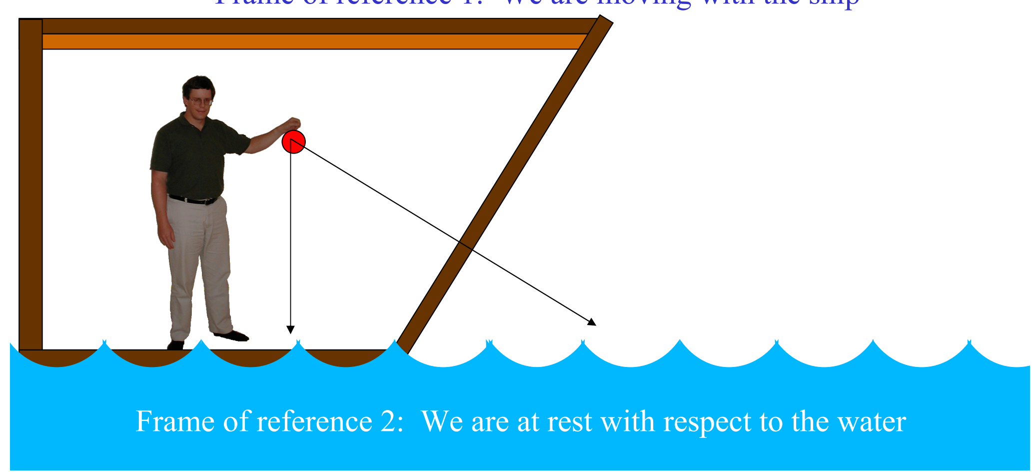
Length Contraction

- This effect has some benefits:
  - Outside observers will see that the length of the spaceship has shrunk.
    - This doesn't really help or harm us
  - But, from the astronaut point of view, the entire universe outside their window has shrunk in the direction of motion, making the trip shorter!
- It's all relative.

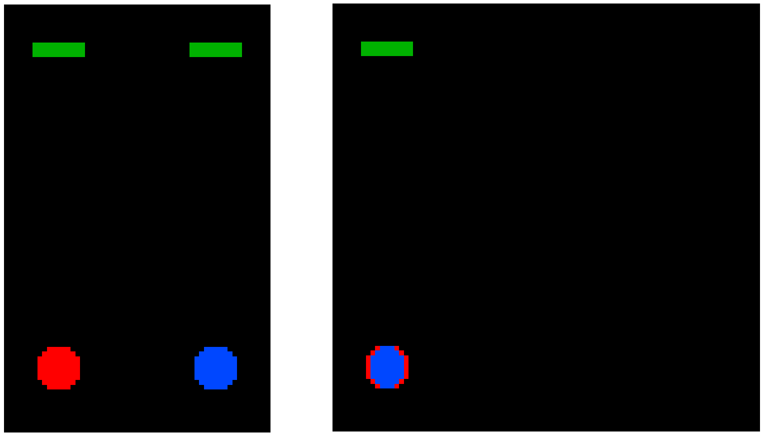
Galileo's ship thought experiment

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.

Frame of reference 1: We are moving with the ship



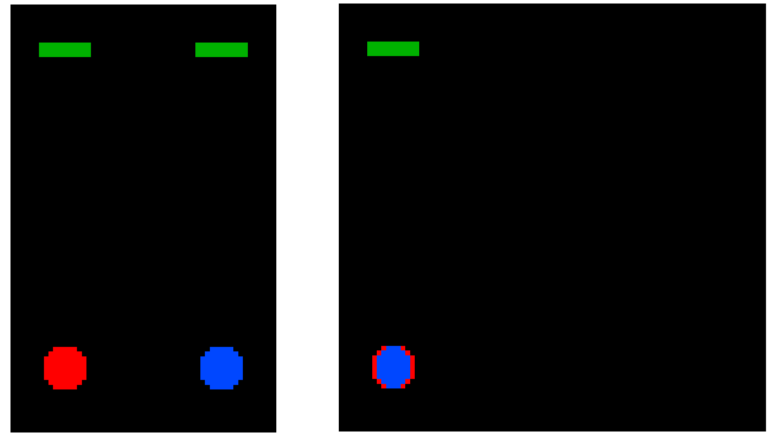
If the Ball is light?



A. Hamilton (Colorado)

Counterintuitive Result #2

Time appears to advance more slowly for moving objects (<u>time dilation</u>)



Red & blue at rest　　Blue moving to right

A. Hamilton (Colorado)

Time Dilation

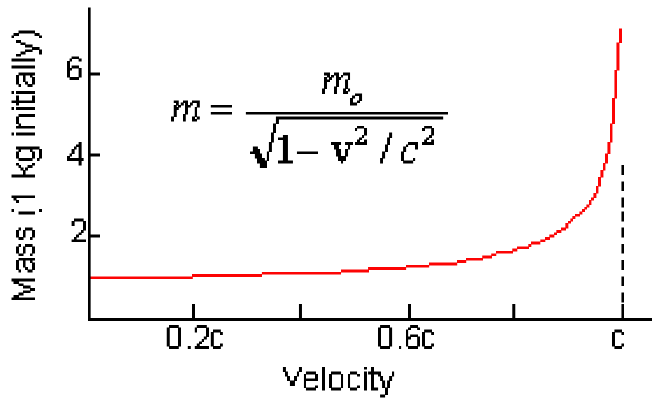
- The effects of time dilation are curious but not prohibitive for space travel
  - Astronauts will age less than the Earth-bound folks waiting for the return. Can spoil the homecoming celebrations.
  - The faster you go, the bigger difference between astronaut time and Earth time
- Example: Trip to the center of the Galaxy and back. Accelerate at 1g for the first half and decelerate for second half and you can go 30,000 ly in 20 years! But more than 30,000 years has elapsed on Earth!

Mass Increase

- The increase of effective mass (and kinetic energy) with velocity makes acceleration and deceleration more difficult if you intend to travel close to “c”
  - This translates to very costly starflight in terms of required energy.
  - And now the interstellar dust that you strike at relativistic speeds appears as larger mass.
  - For 99% speed of light travel, 5.5 meters of shield would erode every year.

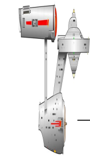
The gamma factor and mass:

Infinite Mass!!!!



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– $\gamma = 7$.

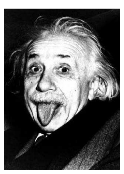


0.99 c

14.2m

Paul's Twin brother (on the Earth) is 7 seconds older for ever second.

And Paul's mass increased by a factor of 7.



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.

Mass of the moving object appears to rapidly increase as an objects moves close to the speed of light.

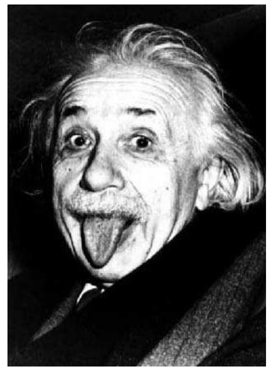
Question

Okay, so length and time can change, then what exactly is a constant?

a) The speed of light.
b) The length of an iron pipe.
c) The time it takes for a photon to cross the Universe.
d) The speed of sound.
e) The speed of a class.. it is always too slow.

The Theory of General Relativity

- Recall Galileo: for free body motion is straight line, constant speed
- Important to note that ALL free bodies move this way. straight line, constant speed, INDEP of size, mass
- Q: Why?
- A: That's the way it is!
- Q: Be more specific: that's the way WHAT is?
- A: Einstein: that's the way space and time are if nothing else going on (no forces) space and time constructed so that free bodies move in straight lines at constant speed independent of nature of the object
- **That's the way space and time are**



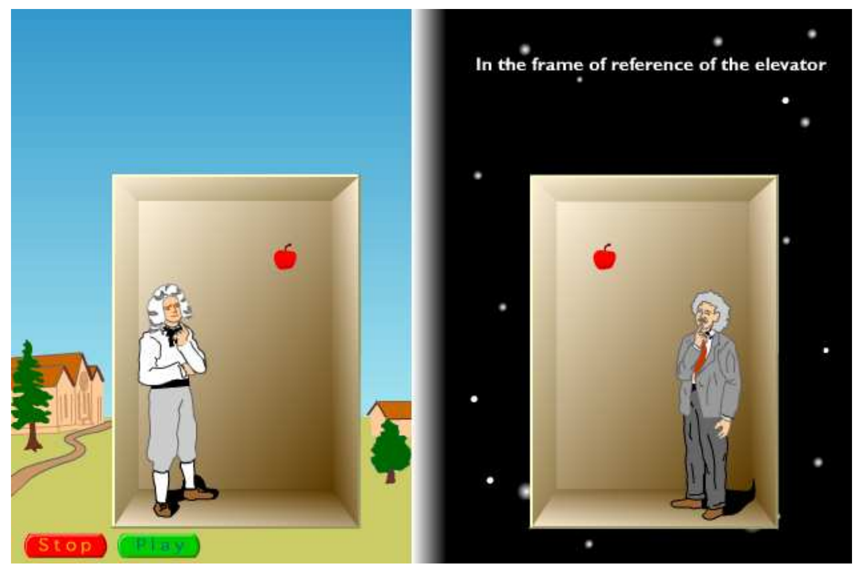
Free Fall

- Recall Galileo's experiment.
- The objects in the gravity field, move independent to mass or even object.
- For Newton, the object mass cancels out of the gravity equation.

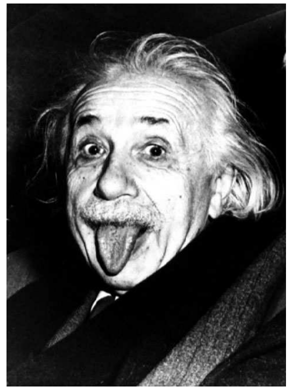
The Theory of General Relativity

- Since objects move the same in a gravity field, INDEPENDENT of object, then gravity is not a force, but also a feature of space-time!
- Objects do their best to move in a straight line.
- **Newton:** Matter causes force (gravity) ⇒ particles follow curved lines in "flat" (Euclidean geometry) space
- **Einstein:** Matter causes spacetime to be "curved" ⇒ particles follow straight lines ("geodesics") in curved space

The Theory of General Relativity



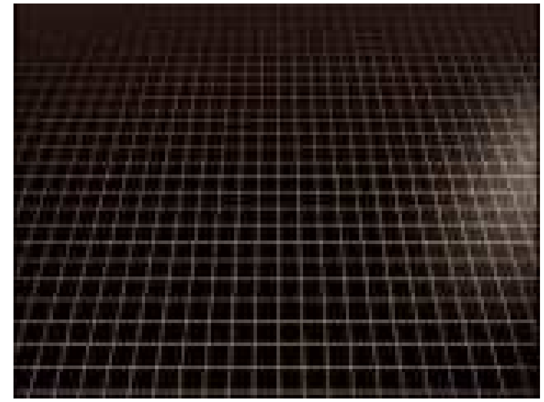
The Theory of General Relativity



- Einstein's Theory of Relativity tells us how gravity works
  - Space and time are not distinct
  - They are bound together in 4-dimensional **spacetime**
  - Matter tells spacetime how to curve
  - Curved spacetime tells matter how to move

Curved Spacetime

- No matter = Flat Spacetime
- Massive object = Dent in Spacetime
  - Everything follows curvature of spacetime including light (photons)



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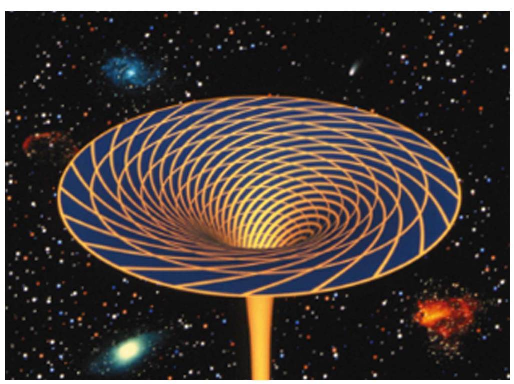
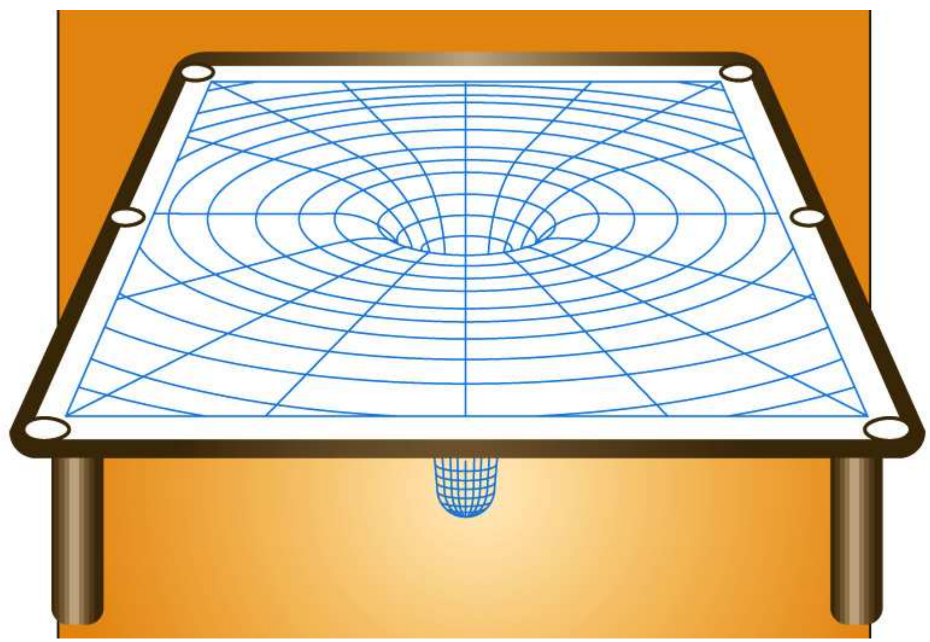
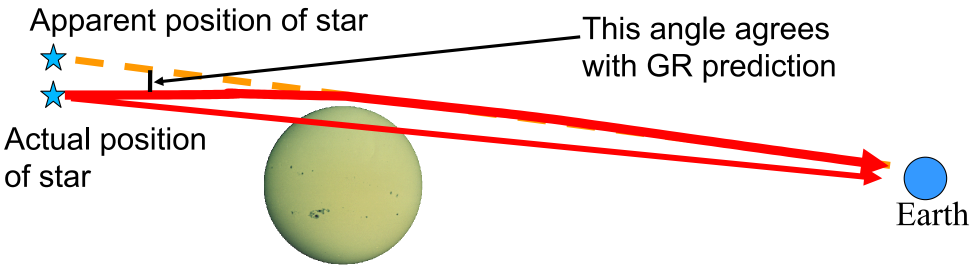
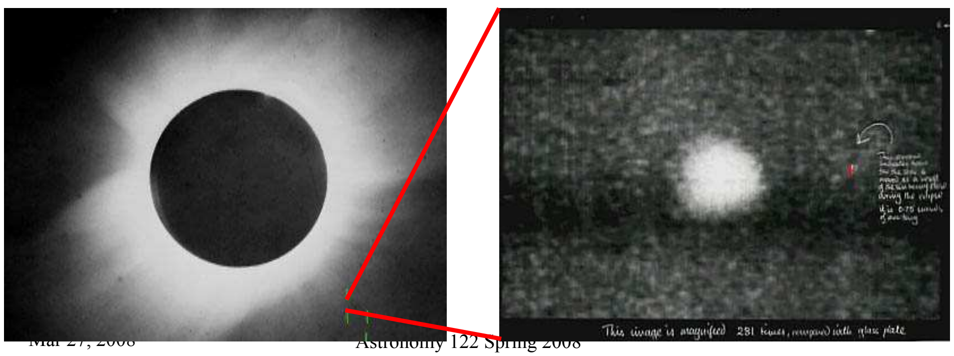


Curved Space

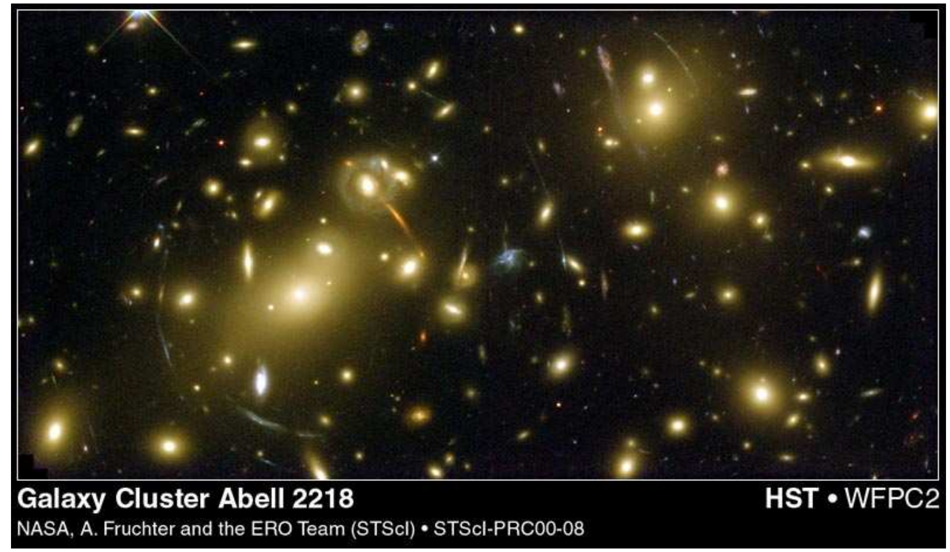


Eddington and the 1919 Eclipse





Einstein Lens



http://antwrp.gsfc.nasa.gov/apod/ap000201.html

General relativity

- Gravitational fields can also change space and time
  - A clock runs more slowly on Earth than it does in outer space away from any mass, e.g. planets.
- Einstein revealed that gravity is really ‘warped’ space-time.
- A black hole is an extreme example.