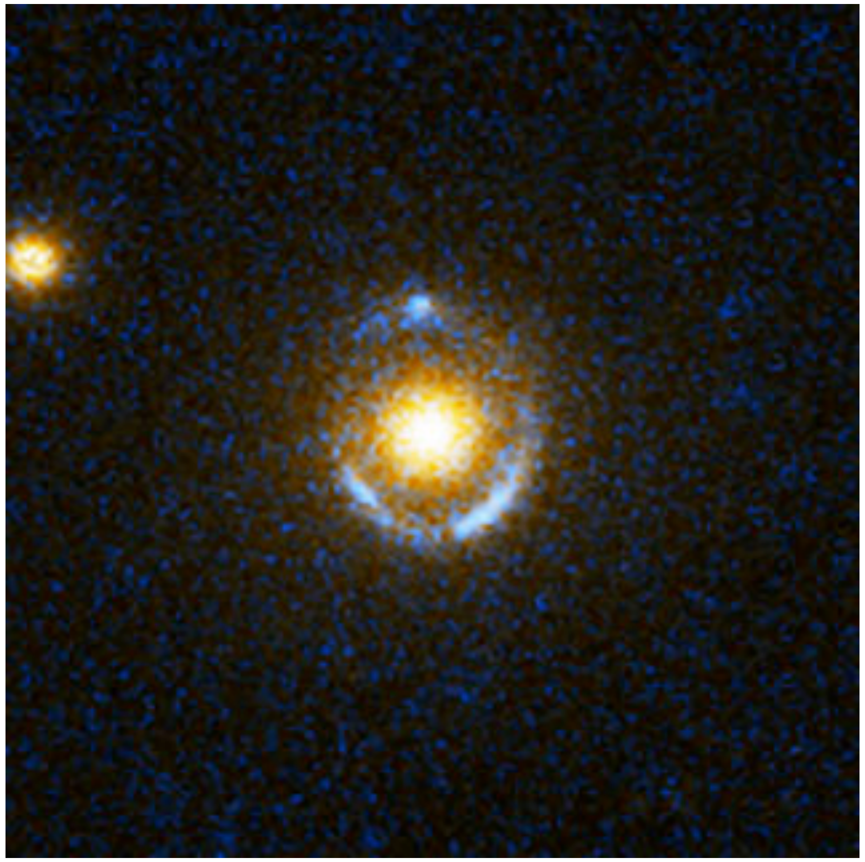
Astronomy 150: Killer Skies
Lecture 28, April 2

Assignments:

- Good news: no homework this week
- Bad news: Hour Exam 2 on Friday
  information on Course Website
- Also next week: Solar Observing this week

Last time: Gamma-Ray Burst Damage: Past and Future

Today: Black Holes--General Relativity



http://www.nasa.gov/vision/universe/starsgalaxies/hubble-20051117.html

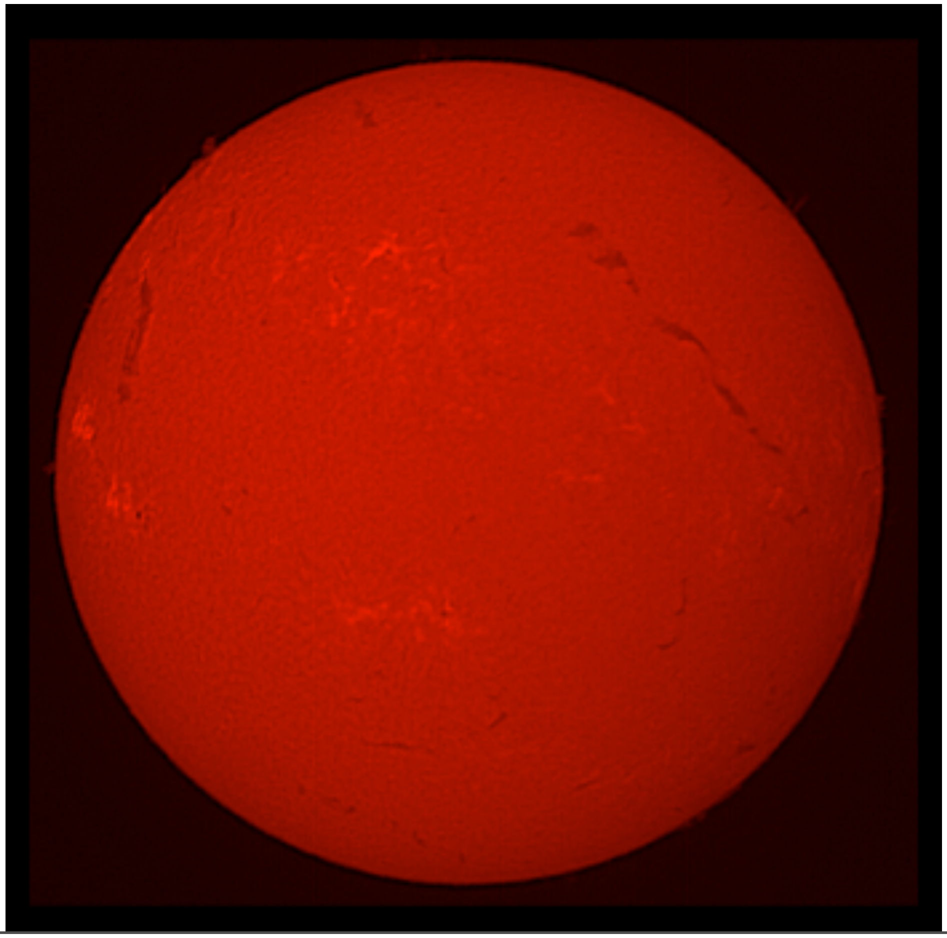
http://apod.nasa.gov/apod/ap011007.html

Solar Observing This Week

Happens this week:

- M-Th, 10:30am-3:30pm, weather permitting
- At Campus Observatory (upstairs in dome)
- Assignment details and report form on class website
- Report due April 13th
- Subscribe to Solar Observing Status Blog for weather-related notices

http://illinois.edu/blog/view/414



Recap: Stellar Evolution and Black Holes

Black holes are an inevitable part of star formation

- most stars too low-mass to make black holes
- but stars above 30 M_{sun} have huge gravity, crush their cores leaving behind black holes

Black holes are regions of ultra-strong gravity

What does the solar system teach?

- no black holes!
- but Mercury feels strongest gravity of all planets
  moves at highest speeds

Orbits of Mercury disagrees with predictions of Newton's gravity theory

- Need new theory for high speeds, strong gravity

Relativity

Einstein's relativity revolutionizes how we think about space, time, and motion

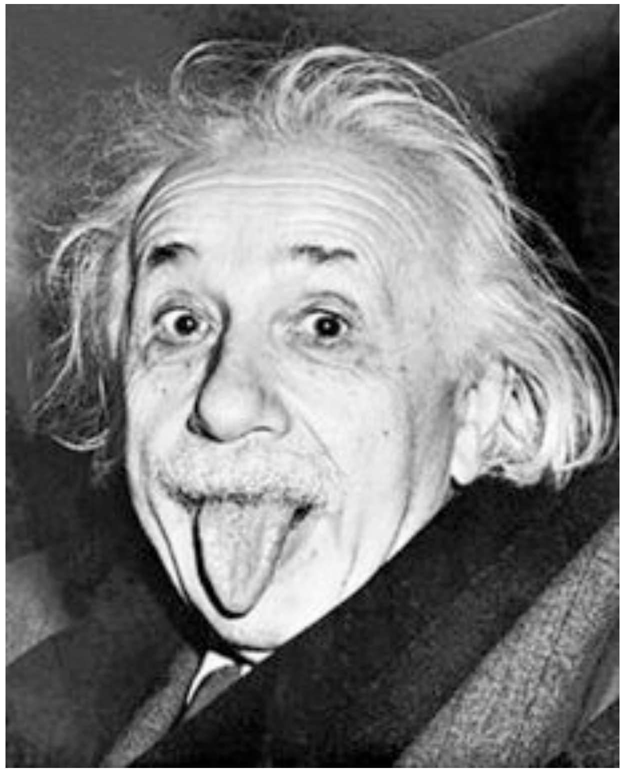
Really, two theories of relativity

Special Relativity

- space, time, and motion, and the role of high speeds near speed of light
- but all in the special case when gravity not present

General Relativity

- generalizes ideas of special relativity to include effects of gravity



Gameplan for Today:

- why we need relativity
- theory: key ideas in relativity
- observation: testing relativity

Special Relativity and the Speed of Light

Recall: speed of light is enormous but not infinite

c = 186,000 miles/sec = 300,000 km/sec

Key ideas in special and general relativity:

- light always moves at speed c regardless of motion of light source
  - so if spaceship moving at speed v = c/2 turns on headlights, observer at rest sees still beams move at speed c !?!
- nothing can move past you at speeds faster than c
- only light (i.e., photons) and other massless ($m=0$) particles move at speed c
- particles with mass ($m>0$) will always move past you at speeds $< c$
- in general: information must travel at speeds $< c$
- speed of light is cosmic speed limit

Doppler Shift

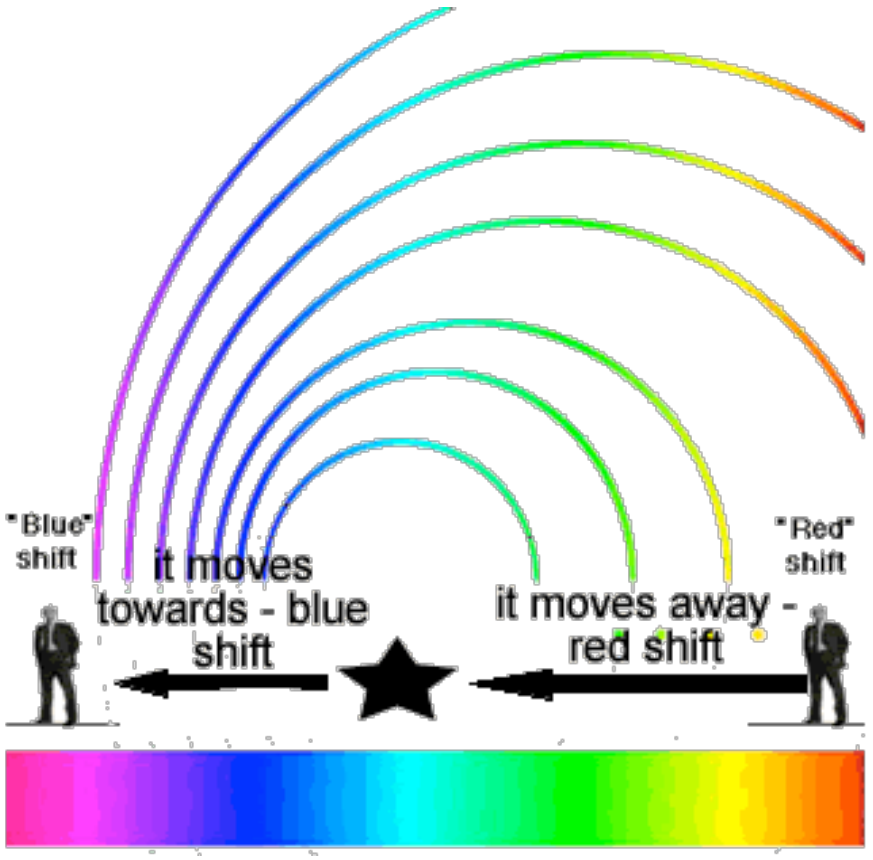
If light source moves relative to an observer

measured wavelength different from emitted wavelength

demo: http://www.cbu.edu/~jvarrian/applets/doppler1/doppler.htm

shift depends on speed and direction

- approaching source: wavelengths shorter
  - if visible light, becomes bluer: blueshift
- receding source: wavelengths longer
  - becomes redder: redshift



why?

- light pulses always move at same speed
- so if moving source:
  - "bunch up" in front
  - "spread out" behind

Doppler Shift: Applications

Nature has been kind: Doppler shift useful as speedometer

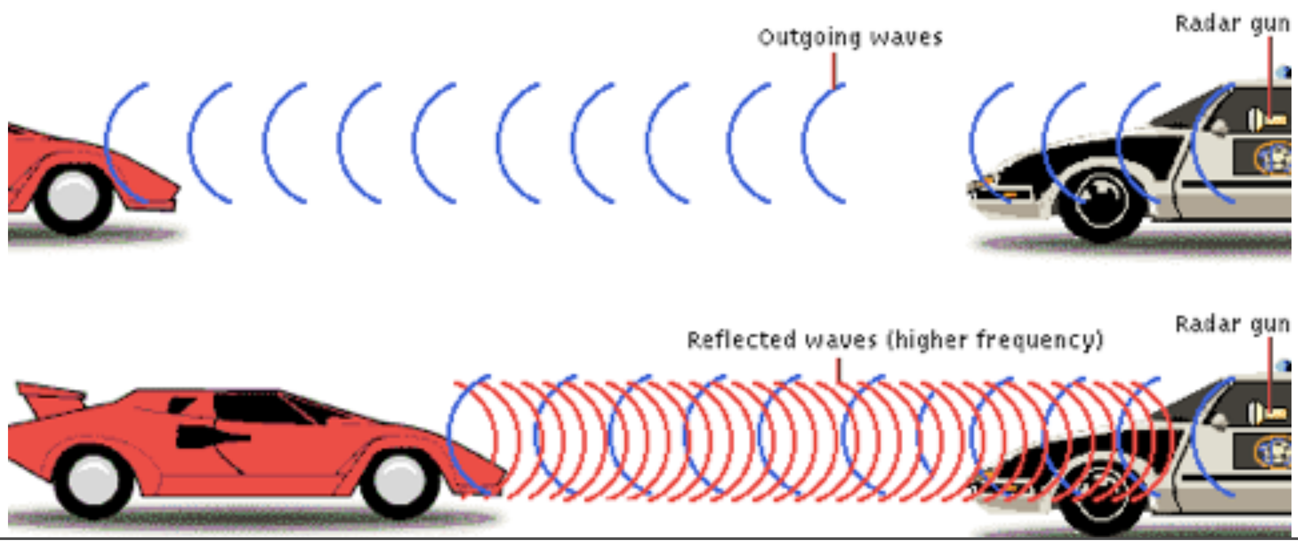
- how we know speeds of stars, planets, galaxies

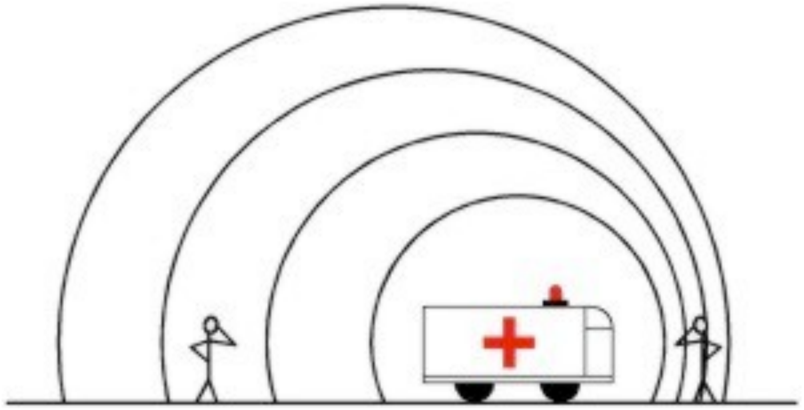
also used on Earth:

- weather diagnostics
- speed limit enforcement ("radar gun")

Note: Doppler shift not only for light waves but also occurs in sound waves

- siren pitch shift in passing ambulance
- shift used to measure heartbeats in medical ultrasound images





Special Relativity and Gravity

What About Gravity?

Special relativity ignores gravity: How to include it?

Consider Newton gravity force law

$$F_{\text{grav}} = G\frac{Mm}{R^2}$$

- gravity force due to mass M depends on distance R and spreads over all space, acts on all other masses in Universe
- that is: F > 0 for any $R < \infty$

but what if M moves?

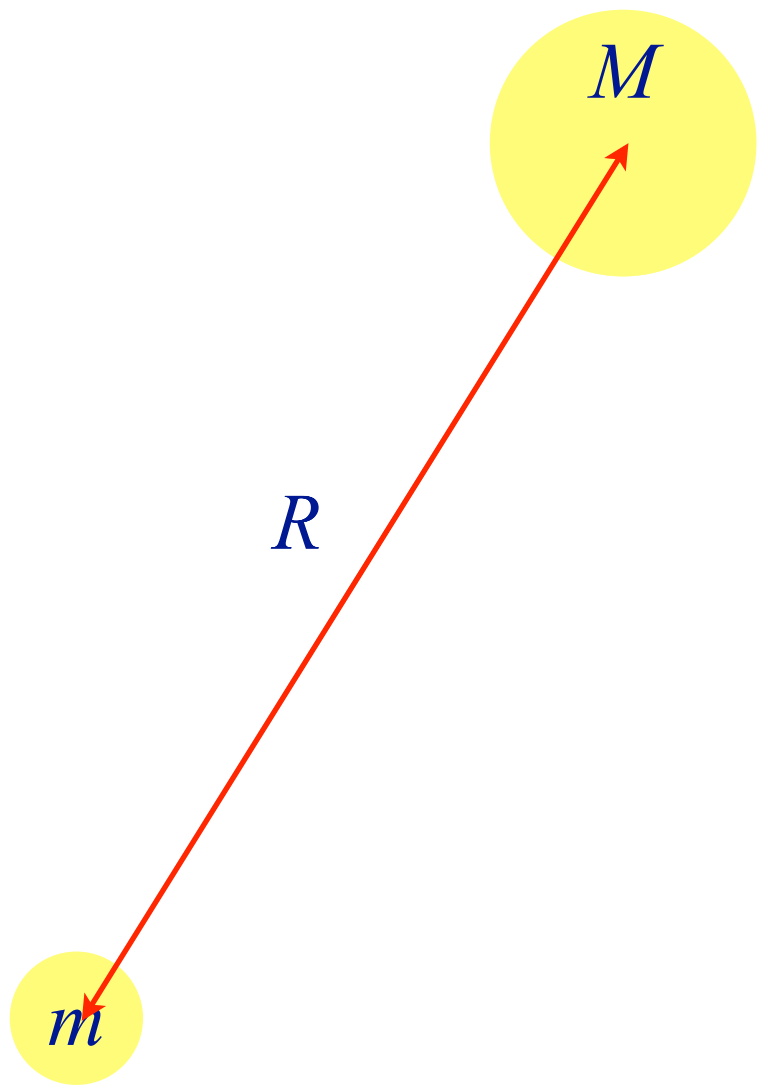
- *Q: how does that affect forces on other masses?*
- R changes, so F must change for all masses in Universe!

when does the force change, according to Newton's inverse square law?

- gravity force changes instantaneously over all space!
- *Q: why is this a Big Deal?*

Einstein sez: this is totally illegal! an unmitigated disaster! no signal–including gravity–can move faster than c!

- special relativity and Newton's gravity are inconsistent
  - first know error in Newton's work, >200 years after he did it
- a conceptual/theoretical reason that Newton's gravity is wrong/incomplete
- goes along with Mercury's orbit problem, an observational failing of Newtonian gravity



General Relativity: Free Fall

Special Relativity:

- covers high speeds near c
- but does not allow for gravity

Special Case of Motion: Free Fall

- motion only due to gravity
- recall: falling objects change speed: gravity causes acceleration

Recall Galileo's "Tower of Pisa" experiment

- objects fall at same rate if dropped together
- same regardless of size, shape, composition

Einstein's Equivalence Principle

Einstein notes:

- Gravity causes acceleration, but in "democratic" way:
- all objects accelerate the same

Einstein's Equivalence Principle:

- in a closed room, no experiment can distinguish between acceleration and gravity

But note:

- acceleration is aspect of motion
- relates to objects' travel through space and time
- so equivalence of gravity=acceleration will have impact (=bizarreness) on nature of space and time

Experiments Inside an Accelerating Rocket

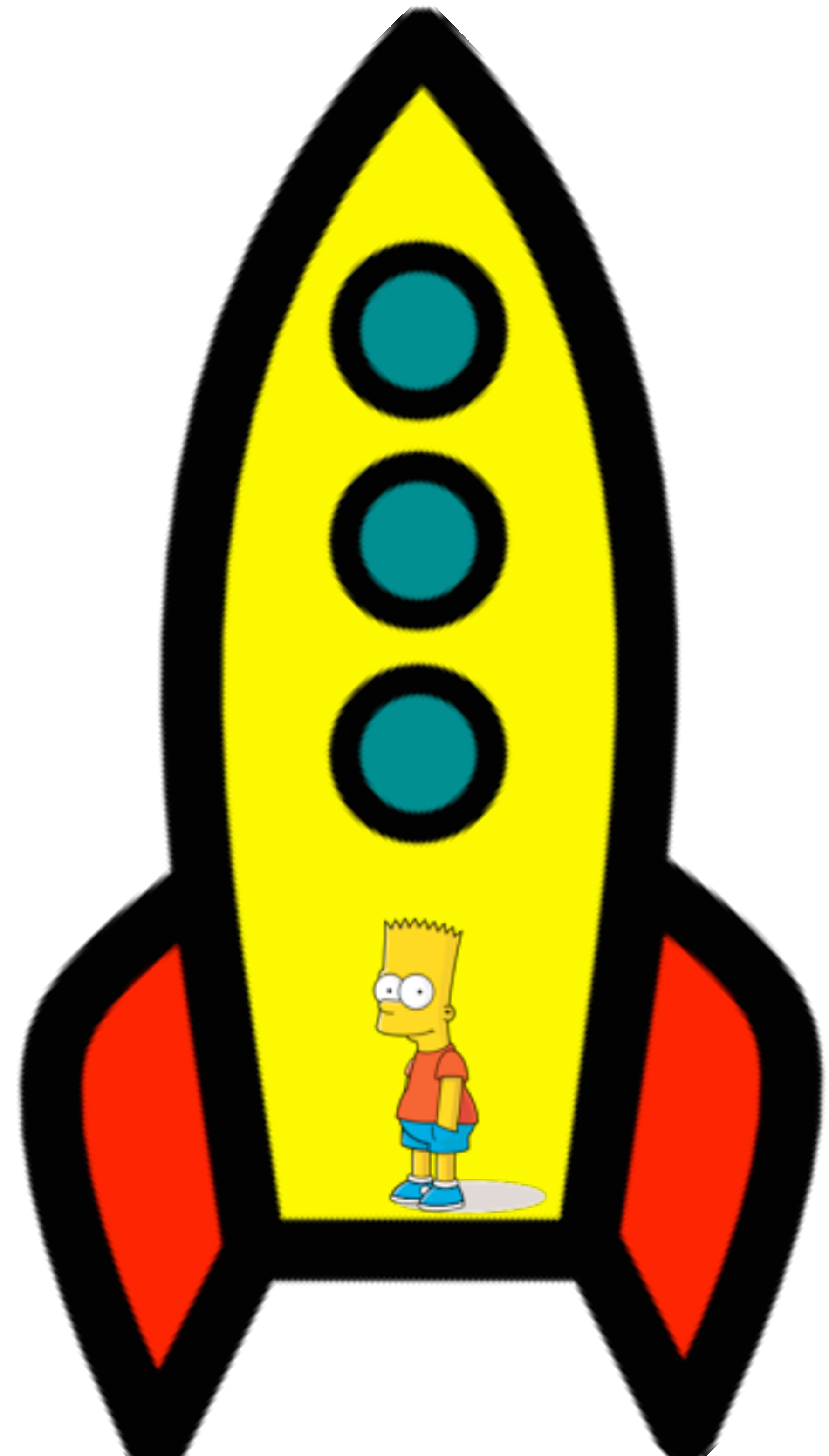
Consider a rocket in otherwise empty space

- that is, no gravity!

rocket moves with constant acceleration

Experiment: Astronaut Bart, standing on floor of rocket, has flashlight

- holds flashlight at height h
- points horizontally
- shines towards wall



iClicker Poll: Light Beam in Accelerating Rocket

in rocket with constant acceleration Bart hold flashlight at height h, shoots beam horizontally

At what height will beam hit opposite wall?

A. at same h

B. higher than h

C. lower than h

hint: easier to think about when looking at experiment from non-accelerating viewpoint

Rocket Experiment

key ideas:

- light takes time to move across spaceship
- during light travel time, spaceship accelerates
  - → gains speed, moves vertically

in non-accelerating viewpoint (bystander "frame"), see that

- light path is straight (horizontal) line
- but spaceship has vertical motion
  - → far wall moved higher
  - ⇒ light hits below where aimed

animation here: http://www.phy.syr.edu/courses/modules/LIGHTCONE/equivalence.html

in accelerating frame (i.e., according to Bart):

- agrees that light hits below where aimed,
  and so concludes
- light ray deflected
- entire light path bent (in fact, a parabola!)

Q: but what does this mean, according to Big Al's Equivalence Principle?

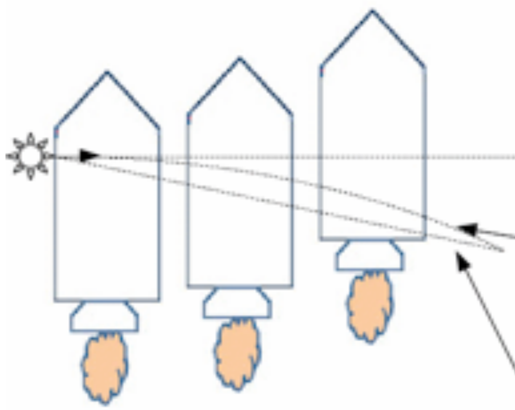
Gravitational Lensing

In accelerating spaceship:

- light rays observed as bent!

But by equivalence principle:

- must find same result due to gravity
- so: gravity bends light rays
- light "falls" too!
- gravitating objects "attract" light rays
- distorts light paths differently depending on how strong the gravity over each path



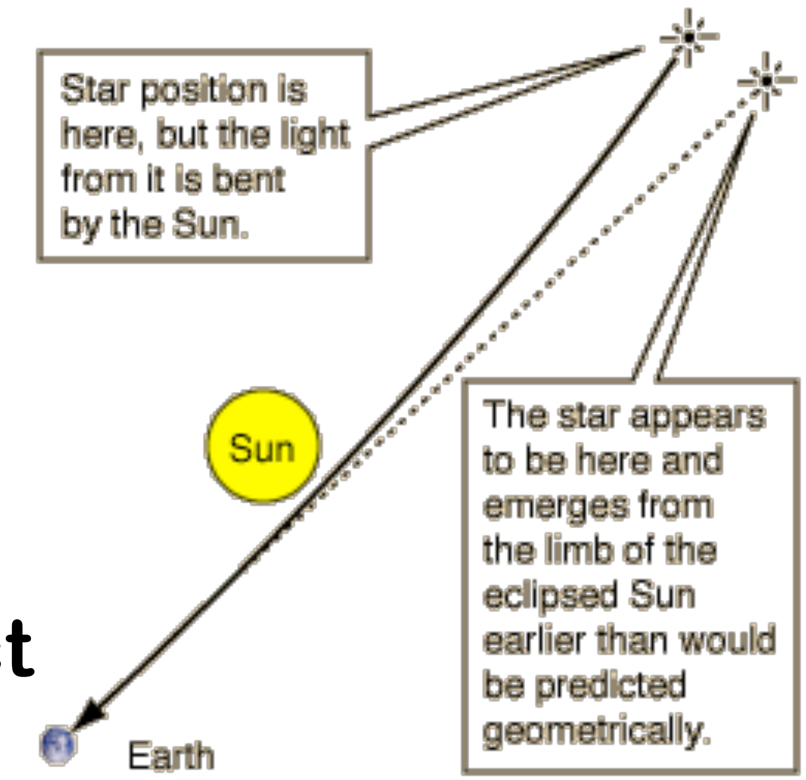
gravitating objects distort passing light

leads to distorted images of objects behind gravity sources

- gravitational lensing
- observable effect, and in fact
- an increasingly powerful tool!

Q: but this is all theory--how to test in real world?

Light Bending: The Sun



In principle:

- all gravitating objects bend light

  including you, me, the earth...

In practice:

- need strong gravity source to create effect large enough to observe

Einstein (1915) devised first test: the Sun

- Sun's gravity deflects starlight rays
- the stronger the gravity along the path the bigger the deflection
- light paths closest to Sun: biggest effect

so want to look at starlight just "grazing" edge of Sun

Q: why is this technically challenging to see?

Q: how to get around the problem?

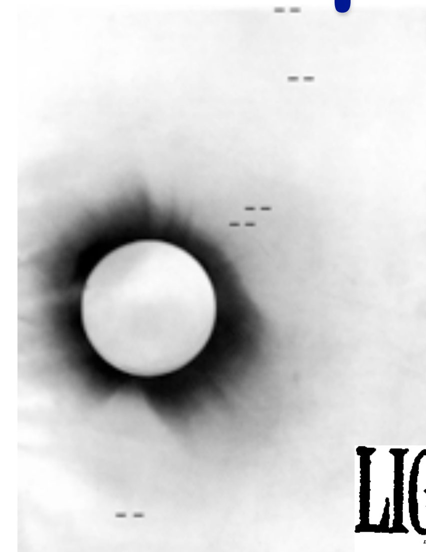
1919 Eclipse: The Crucial Experiment

Problem:

- Sun's glare obscures surrounding starlight

Solution:

- block glare with eclipse!



1919: total solar eclipse in Southern hemisphere

- expedition led by Sir Arthur Eddington
- starlight bent! Woo hoo!
- relativistic gravity confirmed!
- Einstein an instant celebrity

Now tested many times, and very accurately

- all starlight bending experiments confirm Einstein!
- Moreover, once established, gravitation lensing is a very powerful tool

Q: why would it be useful?

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.

Special Cable to THE NEW YORK TIMES.

NY Times November 10, 1919

http://query.nytimes.com/gst/abstract.html?

Gravitational Lensing: Modern Data

Galaxies: big clumps of stars (and more stuff too!)

- huge masses: excellent lenses
- also light up: excellent sources

Consider special case:

- one galaxy behind another
  perfect alignment

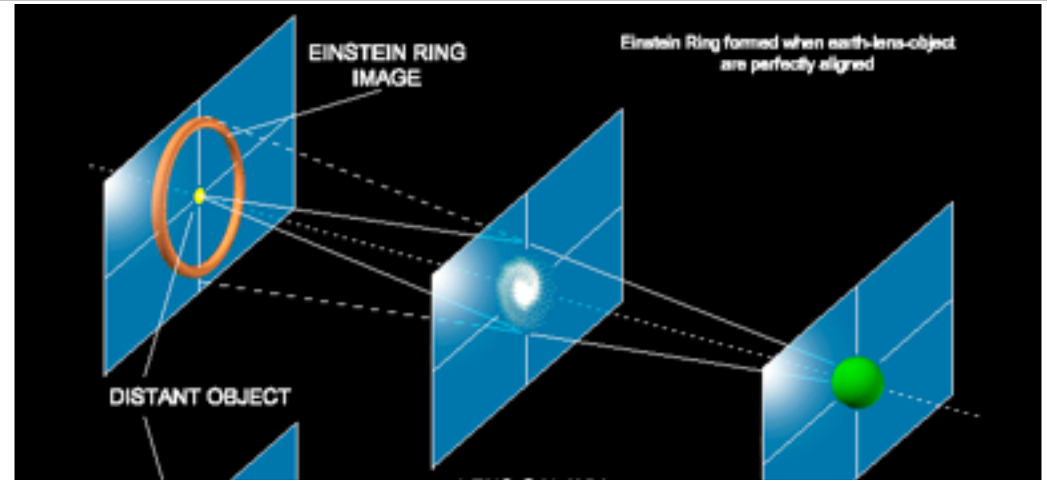
Q: what will the image we see look like?

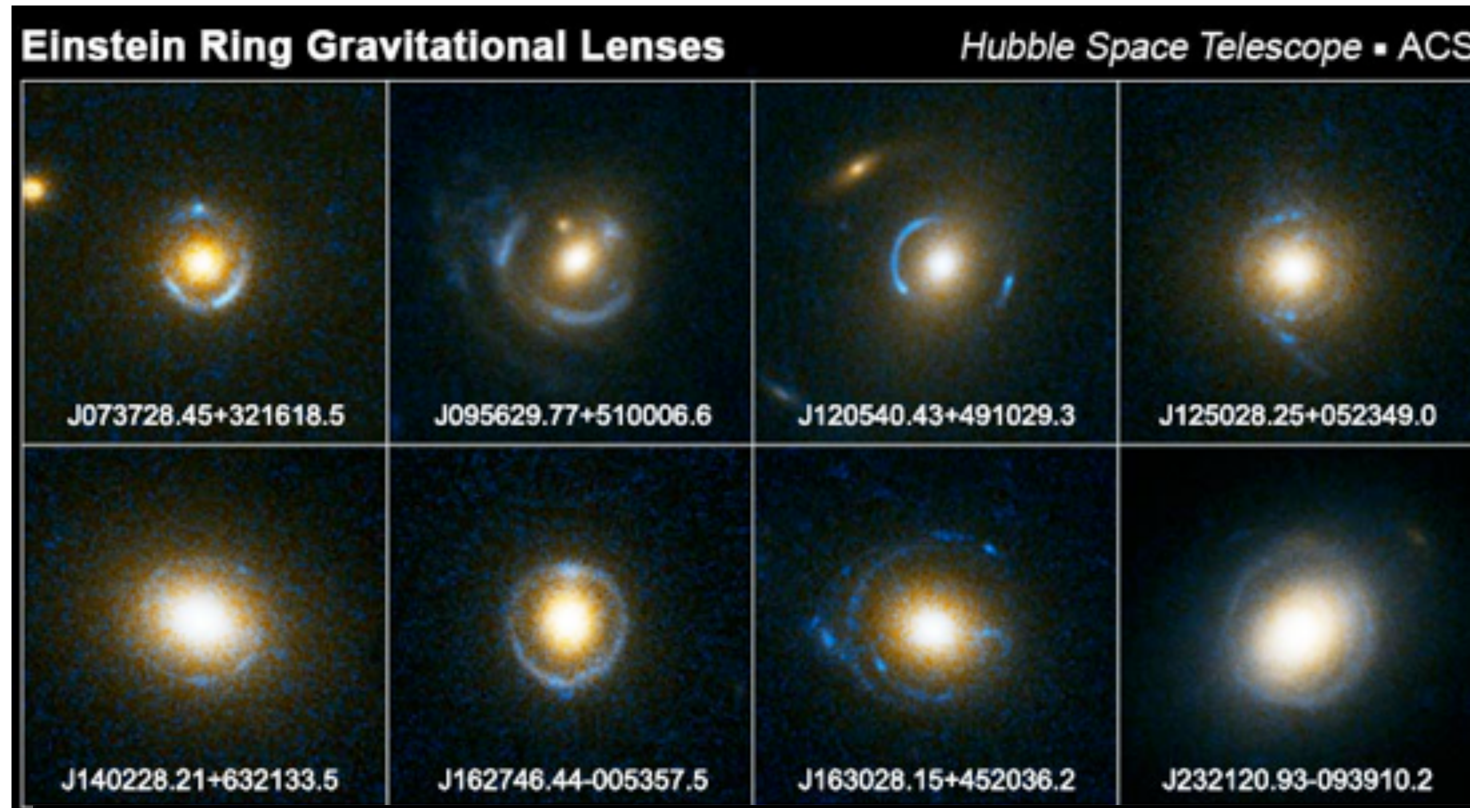
source lensed to circle around lens

- "Einstein ring"
- if not perfect alignment:
  arcs instead of perfect circle

Also can use even more massive galaxy clusters as lenses

- more arcs
- distortions of background source galaxy are huge





http://www.nasa.gov/vision/universe/starsgalaxies/hubble-20051117.html

http://apod.nasa.gov/apod/ap011007.html