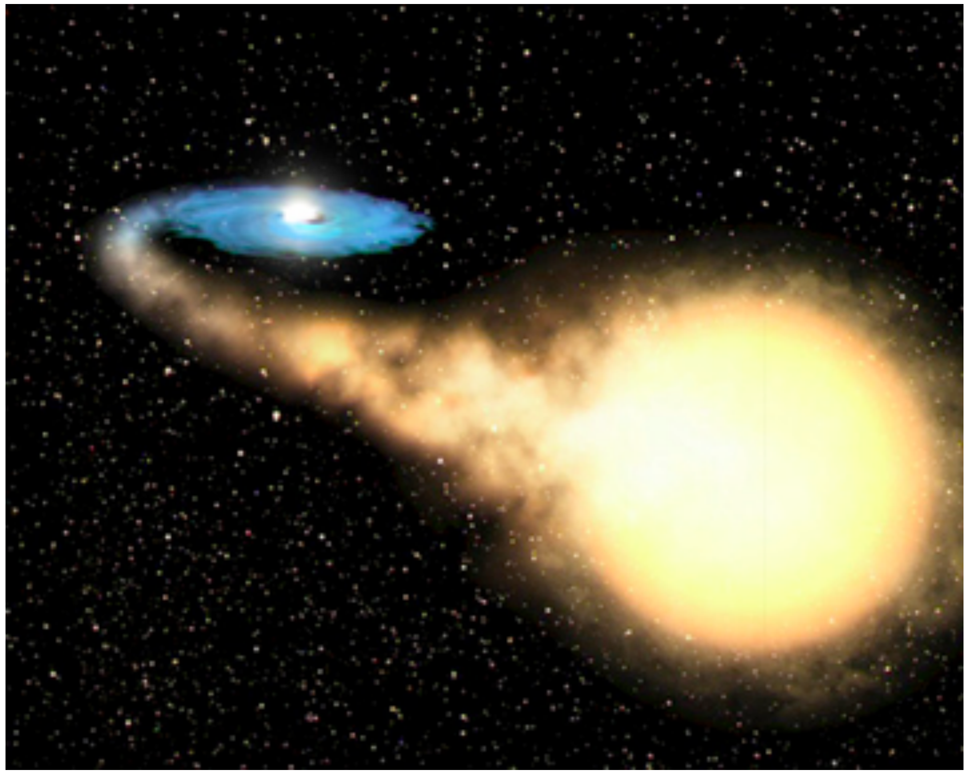
Astronomy 150: Killer Skies
Lecture 29, April 4

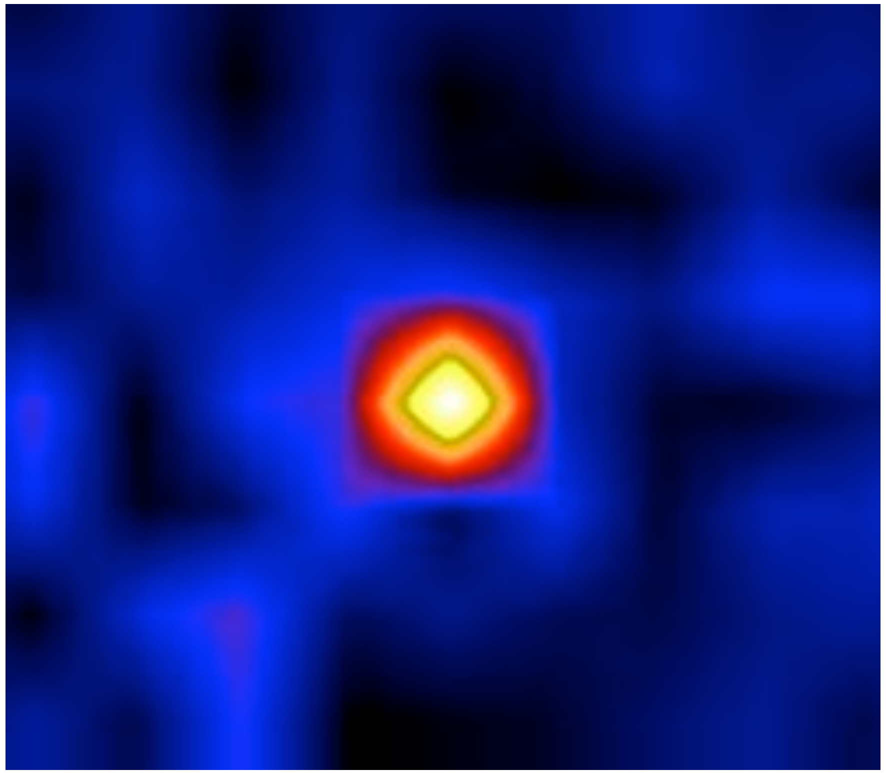
Assignments:

- Good news: no homework this week
- Bad news: Hour Exam 2 on Friday
  - information on Course Website
  - brief review today
  - Office Hours after class
- Also: Solar Observing this week

Last time: General Relativity

Today: Black Holes



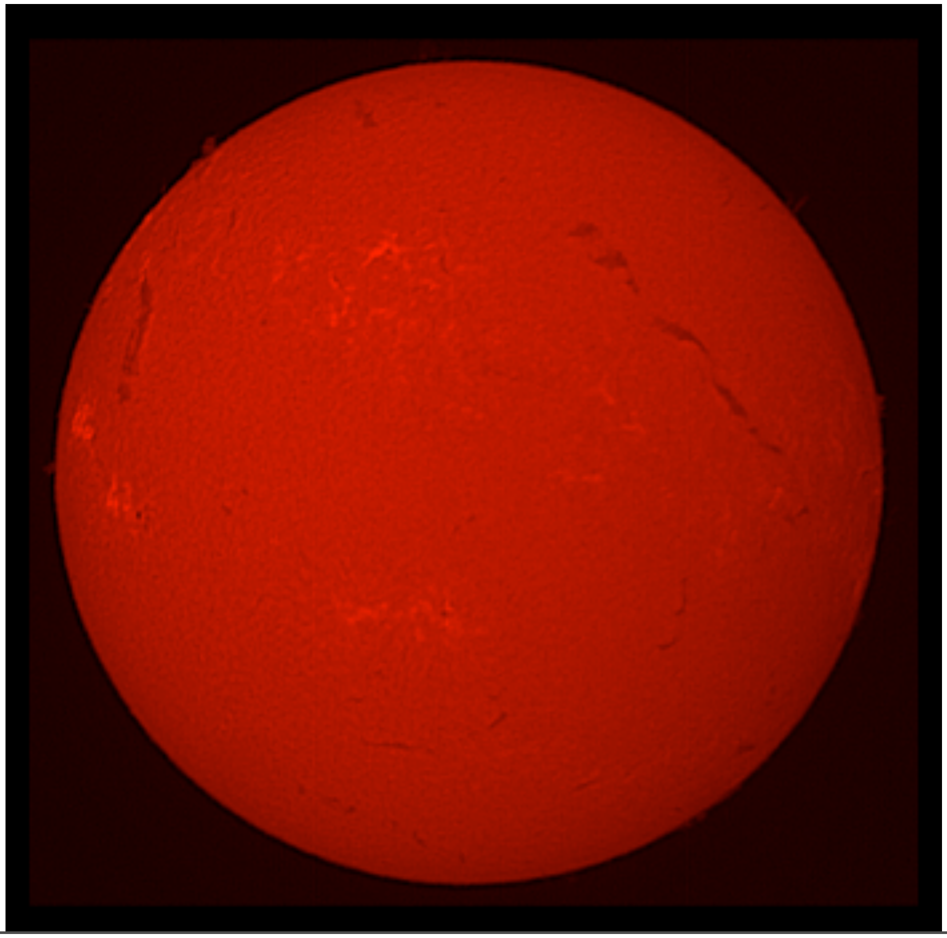


Solar Observing This Week

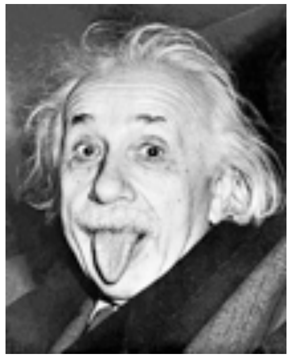
Happens this week:

- M-Th, 10:30am-3:30pm, weather permitting
- At Campus Observatory
  (upstairs in dome)
- allow about 30min
- 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: Relativity



Special Relativity

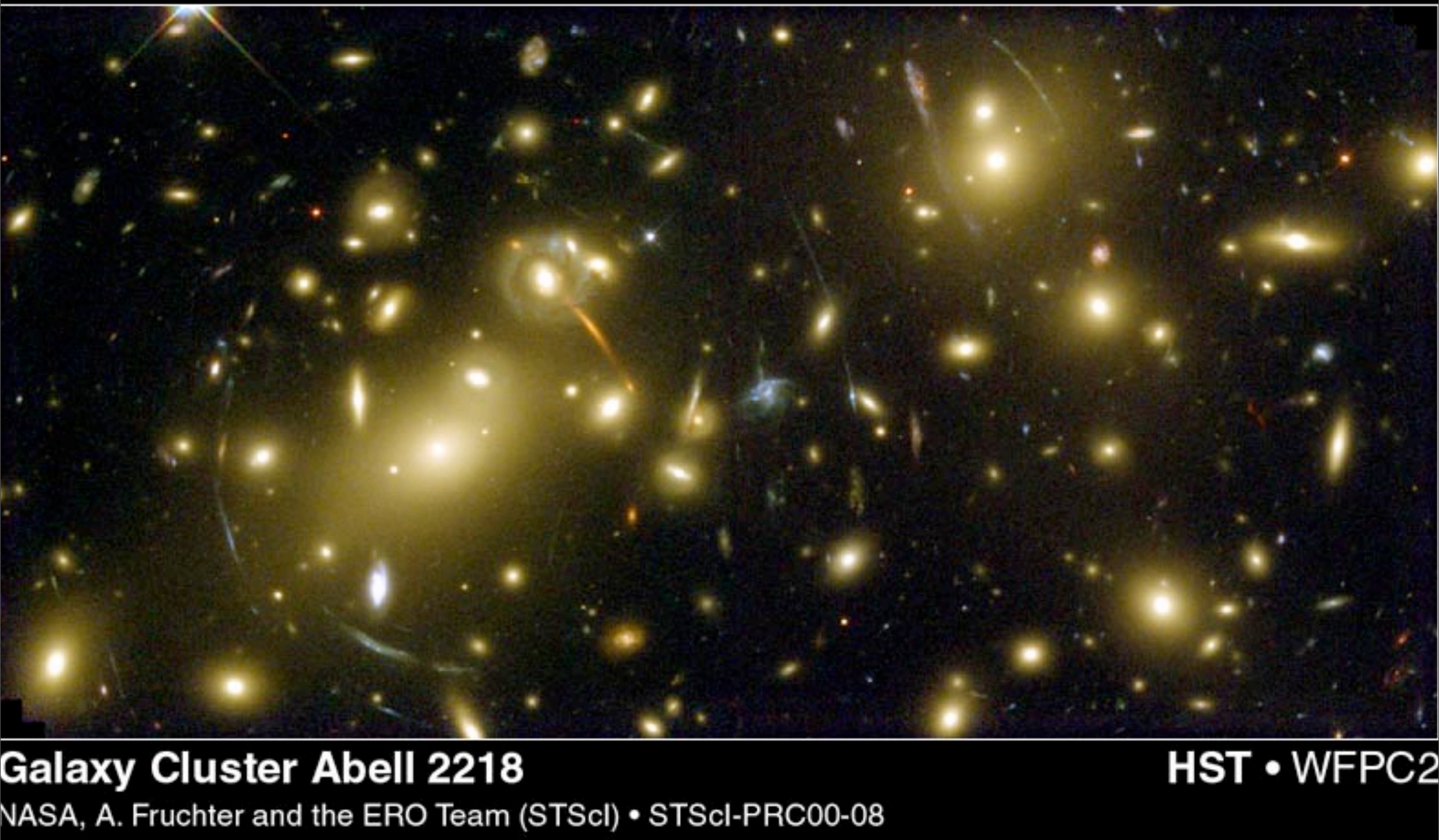
- describes space, time, and motion when no sources of gravity

- revises/replaces Newton's laws of motion
- speed of light c is universe speed limit

General Relativity

- generalizes ideas of special relativity to include effects of gravity
- revises/replaces Newton's law of gravity
- equivalence principle: acceleration and gravity are indistinguishable
- consequences:
  - gravity bends light: gravitational lensing
  - gravity alters space and time

Gravitational Lensing: Cluster of Galaxies



The General Theory of Relativity

1915: Einstein publishes General Theory of Relativity

- a.k.a. General Relativity, a.k.a. GR
- landmark intellectual achievement

GR keeps all key concepts from Special Relativity, including

- light always moves at c, matter $v<c$
- causality: no particles, signals, info travel $>c$
- mass-energy equivalence $E = mc^2$

but now fully includes gravity:

GR is the modern theory of gravity

Key GR Idea I:

- equivalence principle → gravity affects all objects the same
- so: gravity is not a force but a property of space & time!
- but gravity source is matter, so:

GR is theory connecting matter, space, and time!

Key GR Idea II:

according to GR, gravity is "curvature" of space & time!?!

- i.e., gravity can "warp" both space and time
- space & time "curved"

gravitational redshifting, time dilation, light bending

- are all manifestations of this
- curved orbits of particles due to gravity in GR:
  - are really responses to spacetime curvature!

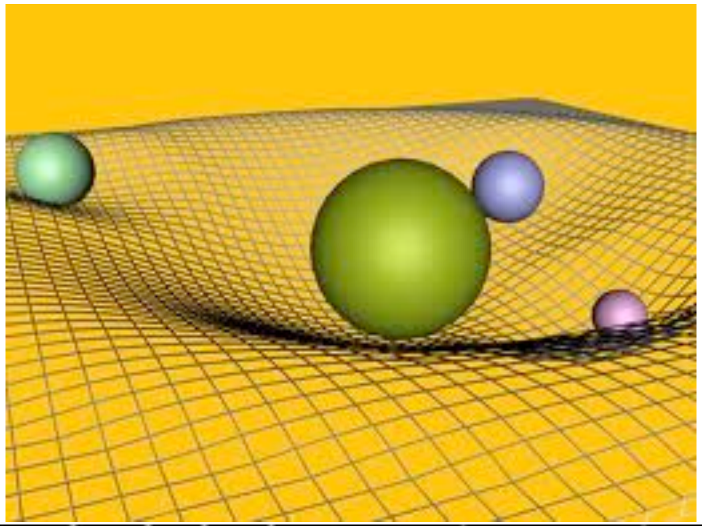
note: gravity = geometry!

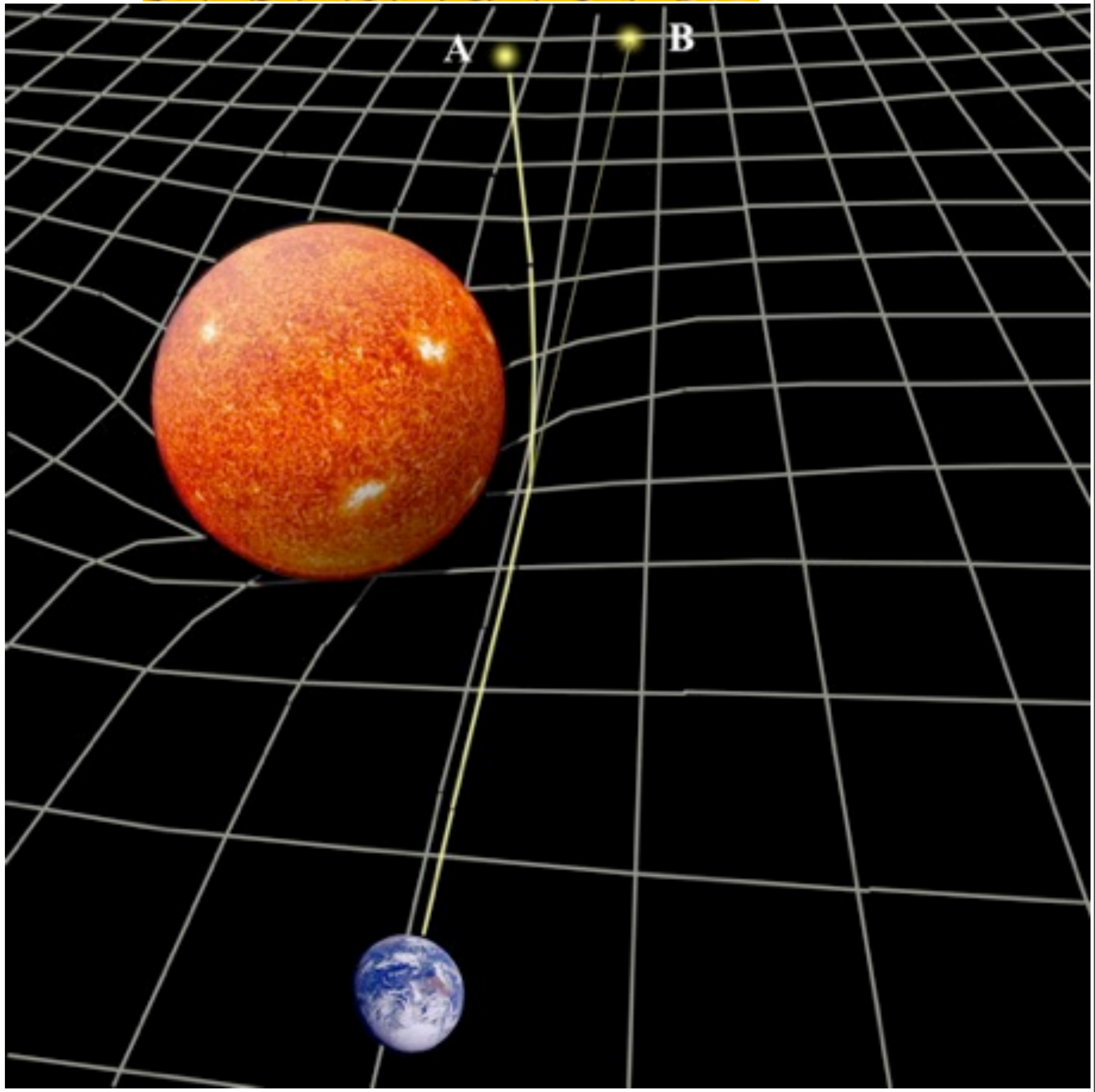
- harkens back to Greeks!

GR Slogans (T-Shirt/bumper sticker/text msg):

- matter tells space & time how to curve
- curvature tells matter how to move

General Relativity:
Planet Motion and Light Bending





General Relativity:

- gravity warps space & time

but mass is source of gravity

- so space and time warped / "curved" near massive objects

Free fall: only gravity acts

- for Newton: curved paths due to gravitational forces
- in GR: no gravity force at all!

  light & particles are free bodies!

  ...but moving in curved space & time

  try to go as straight as possible but still deflected by curvature

  example: spandex demo

  example: light bending

Living with General Relativity

these ideas are beautiful and powerful

- but also not (for most people) intuitive or trivial

best way to learn is from examples

will focus on two key examples of relativistic gravity

- example #2: the Universe

  rest of the course starting next week

- today: example #1...

Questions so far?

Gravity Interlude: Escape Speed

Forget relativity for a minute, back to Newton

Gravity force: inverse square

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

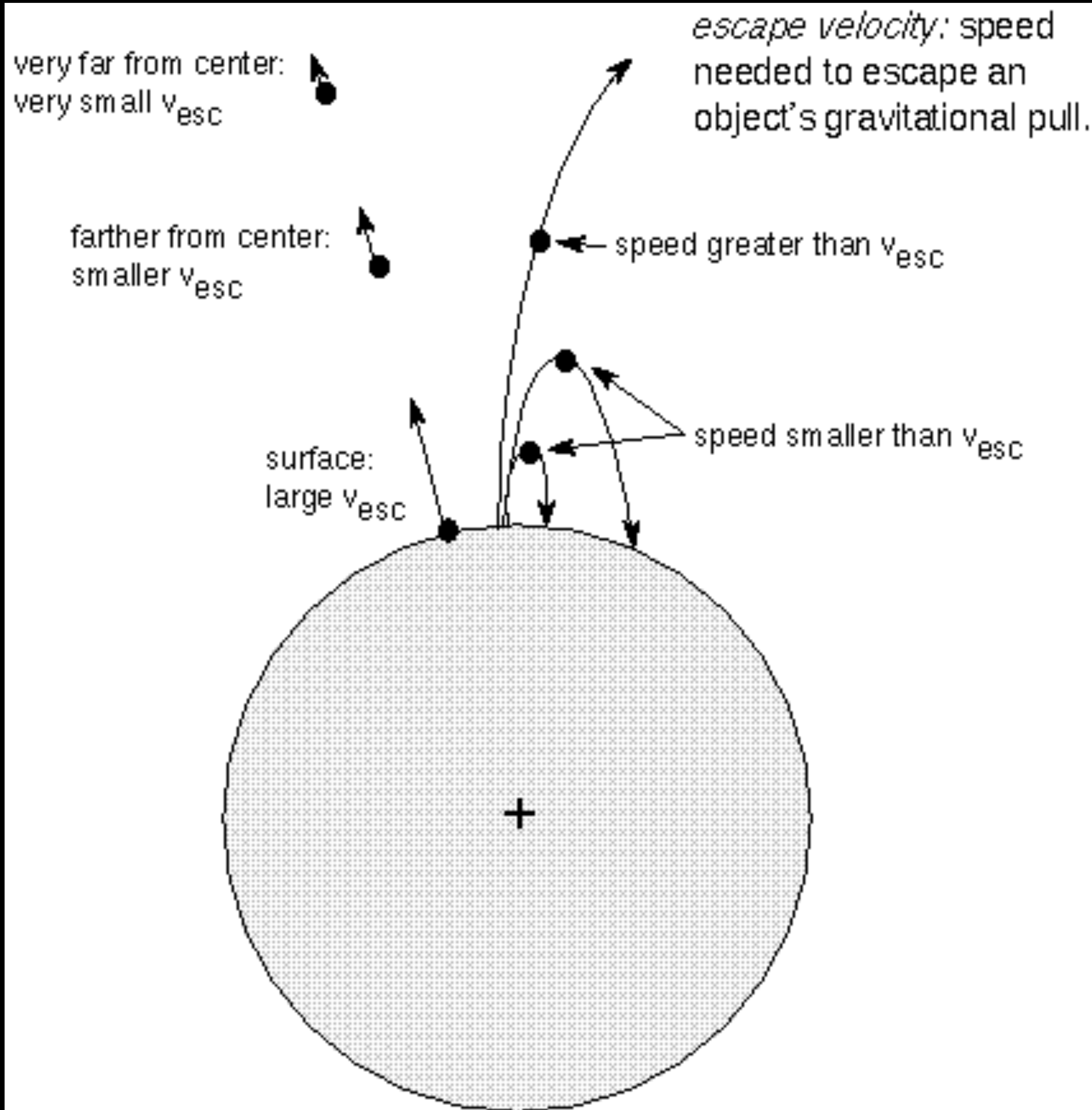
- for objects close to gravity source M
  - small R: big force
  - What if you want to leave and not fall back ("escape")?
    - want outward acceleration:
      - need net outward force
    - will have to exert more force than gravity
    - closer objects: harder to escape

if launching rockets from surface: speed needed to leave depends on

- mass M of object you want to leave
- radius R of object

for a given M and R:

- can find escape speed v_{esc} needed to leave
  - if launch faster: will leave and not return
  - if launch slower: fall back
- trends: v_{esc} increases with M and decreases with R


escape velocity: speed needed to escape an object's gravitational pull.
very far from center: very small v_{esc}
farther from center: smaller v_{esc}
speed greater than v_{esc}
speed smaller than v_{esc}
surface: large v_{esc}

Escape Speed: Examples

Escape speed defined for any gravitating object

anything with mass!

for experts: $v_{\rm esc} = \sqrt{2GM/R}$

Examples

medium-sized asteroid:

- v_{esc} = 20 cm/sec
- you can easily jump this fast
- you can escape a small asteroid without rockets!

Earth

- v_{esc} = 11 km/sec = 24,000 mph
- does this make sense?

pop fly: v_{launch}=100 mph: too small, falls back to Earth

need huge speed to escape: rockets!

Jupiter

- v_{esc} = 60 km/sec

White Dwarf

- v_{esc} = 7000 km/sec = 2% c

Neutron Star

- v_{esc} = 100,000 km/sec = 33% c

Trend: when more mass in smaller region, harder to escape

Black Holes

Laplace (1790's astronomer):

What if star has

- very large mass M, and
- very small R
- then: gravity strong and escape speed high

if mass large enough and/or size small enough

- can have $v_{esc} > c$!
- light cannot escape! → black hole
- Wrong argument (Newtonian gravitation)
- ...but right answer!

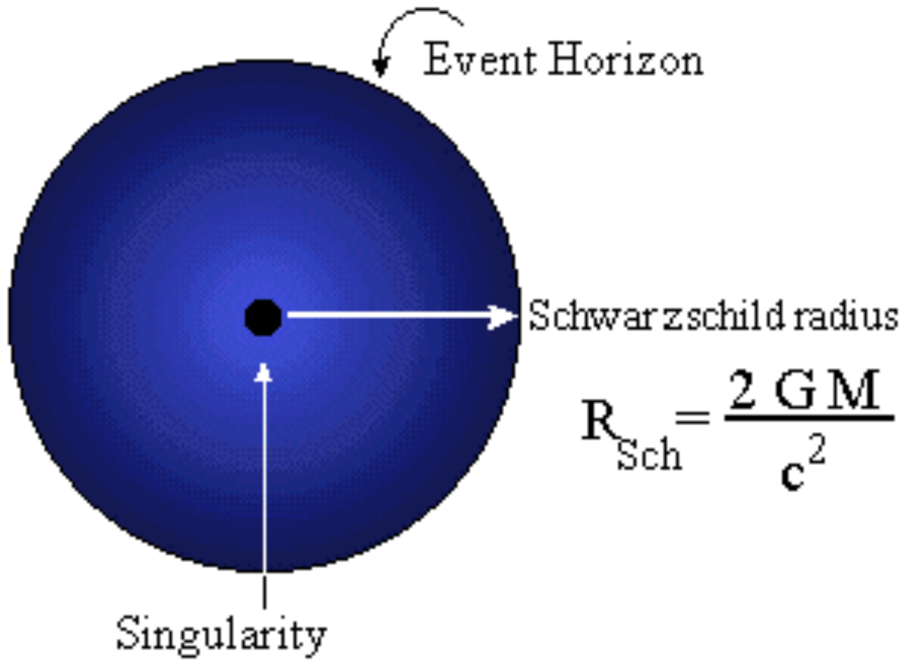
General relativity predicts existence of black holes and their properties

Black Hole Properties

any object of any mass M can (in principle) become a black hole!

- size: Schwarzchild radius

$$R_{\text{Sch}} = \frac{2GM}{c^2}$$



radius also provides BH "recipe":

- crush object M smaller than R_{Sch}
- get BH!

example: for mass of Sun

- BH size: $R_{\text{Sch},\odot} = \frac{2GM_\odot}{c^2} = 3.0 \text{ km}$
- but actual Sun's radius: $R_\odot = 7 \times 10^6 \text{ km}$
- so: the Sun is not a black hole! (whew!)

for mass of Earth: $R_{Sch,Earth}$ = 1 cm!

- to make Earth a BH: crush to smaller than this

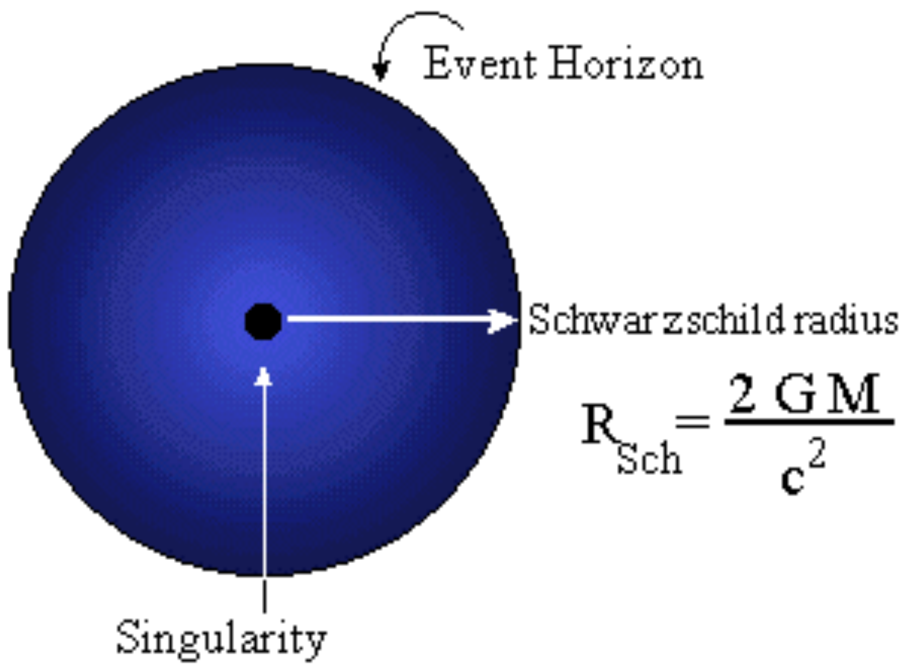
Black Hole Size

Schwarzchild radius
$$R_{\rm Sch} = \frac{2GM}{c^2}$$

But G, c are constants, so:
$$R_{\rm Sch} \propto M$$

black hole size depends on its mass!

feed a black hole and it grows!



Also notice:

black hole size does not depend on what it is made of:

- mass is all that counts, not what form it takes
- black hole seems to "forget" nature what fell into it, other than total mass

Note: all of the above is for non-rotating black hole

- if rotating, black hole also has "memory" of total spin of all things fallen onto it

The Black Hole Horizon

Why call R_{Sch} the BH radius?

nothing is there!

True, but: R_{Sch} marks "point of no return"

horizon: surface enclosing the BH

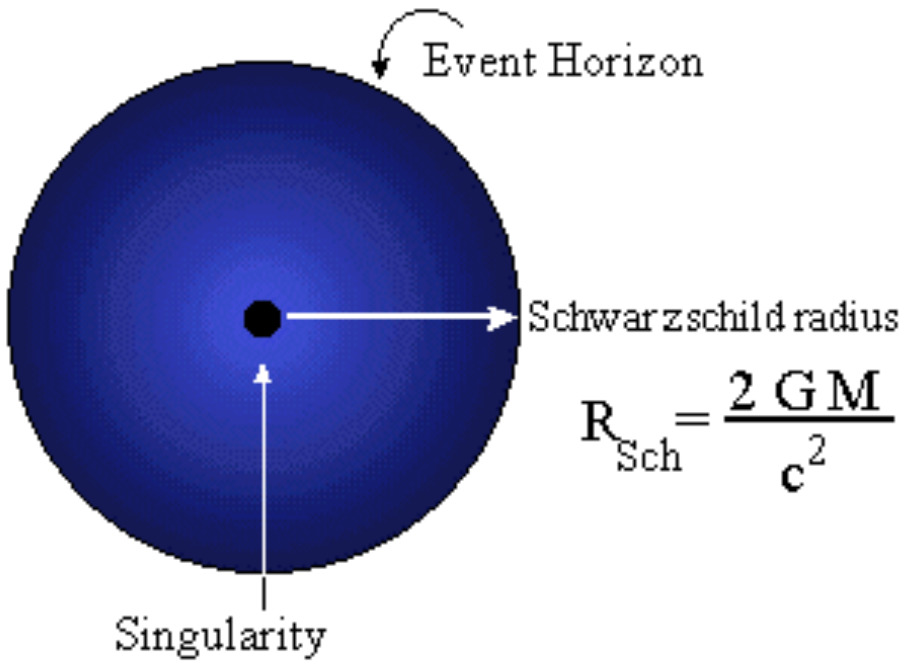
- i.e., horizon is surface of sphere w/ radius R_{Sch}
- sometimes also called "event horizon"

horizon is one-way "membrane"

- once inside $r \le R_{Sch}$, escape speed > c
- nothing can escape
- ...even light!
- cosmic roach motel!

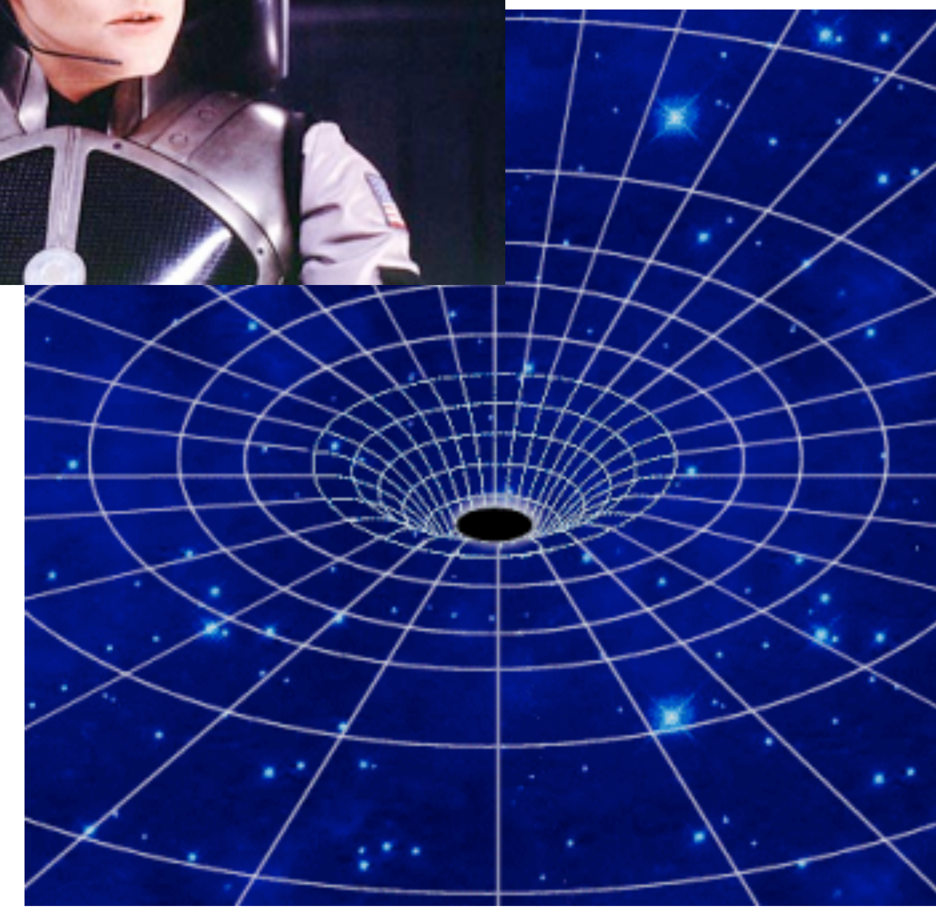
Hence:

- no light escapes → black
- but nothing else moves as fast → nothing else escapes → hole



$$R_{Sch} = \frac{2GM}{c^2}$$

Life Near a Black Hole



Experiment:

lower astronaut (Jodie) near black hole

- r_{Jodie} near but > R_{Sch}

we are at mission control, far away

- $r_{\text{us}} \gg R_{\text{Sch}}$

communicate with light signals

for now: unrealistically ignore tidal effects on Jodie
so that she will survive to tell us about her trip

What do we see?

to us, Jodie's watch appears to tick slowly

- at first, when she hovers far from the BH, small effect:
  her secondhand ticks 59 times for every minute of our time
- but as she hovers close to R_{Sch}:
  dramatic effect: ticks slower and slower--her secondhand ticks once for every hour of our time, then even slower as even closer to horizon
- a problem with her watch?
  No! her computers appear to run slow, voice slows, heart rate slows

Also: her light signals arrive with wavelengths altered:

- longer than manufacturer's settings: redshifted!

Life Near a Black Hole

What does Jodie see as she hovers near horizon?

Q: when she looks at her own watch?

Q: when she looks at us?

Looking at her own watch

- time appears to flow normally
- computer not running slow
- heart rate normal

  or maybe even a little fast due to all the excitement

But looking at us far away at Mission Control:

- to Jodie: we appear to be moving quickly!

  at first speedup appears slight

  our watches seem to tick 61 seconds for every minute of her time
- but when really close to horizon, we appear to be in a frenzy

  in one second of her time, our watches appear to tick off one hour
- Also: our light signals received with wavelengths shorter than manufacturers specifications: blueshift

Reunited!

When Jodie returns to Mission Control:

- her watch ticks the same rate as ours
- her computer runs at same speed
- her radio signals have same wavelengths

But:

- the elapsed time is shorter on her watch
- she is younger than her twin!

Black Hole Lifestyles

Q: who was right and who was wrong?

Both are right!

- Both observers faithfully reporting what they see

Relativity is democratic:

- no apparent weirdness in yourself and in experiment performed nearby and at rest with respect to you
- but objects at high speeds or in regions of stronger gravity (or weaker!) can seem weird

Q: what lessons do we learn about black holes--what are their effects?

Black holes distort space and time

- gravity: strong curvature

time "slows" near regions of strong gravity

- relative to regions of weak gravity
- known as "time dilation"

wavelengths "stretched" coming away from regions of strong gravity

- photon light particles losing energy as leaving
- "gravitational redshifts"

Life Inside a Black Hole

once inside horizon ($r<R_{Sch}$):

no escape!

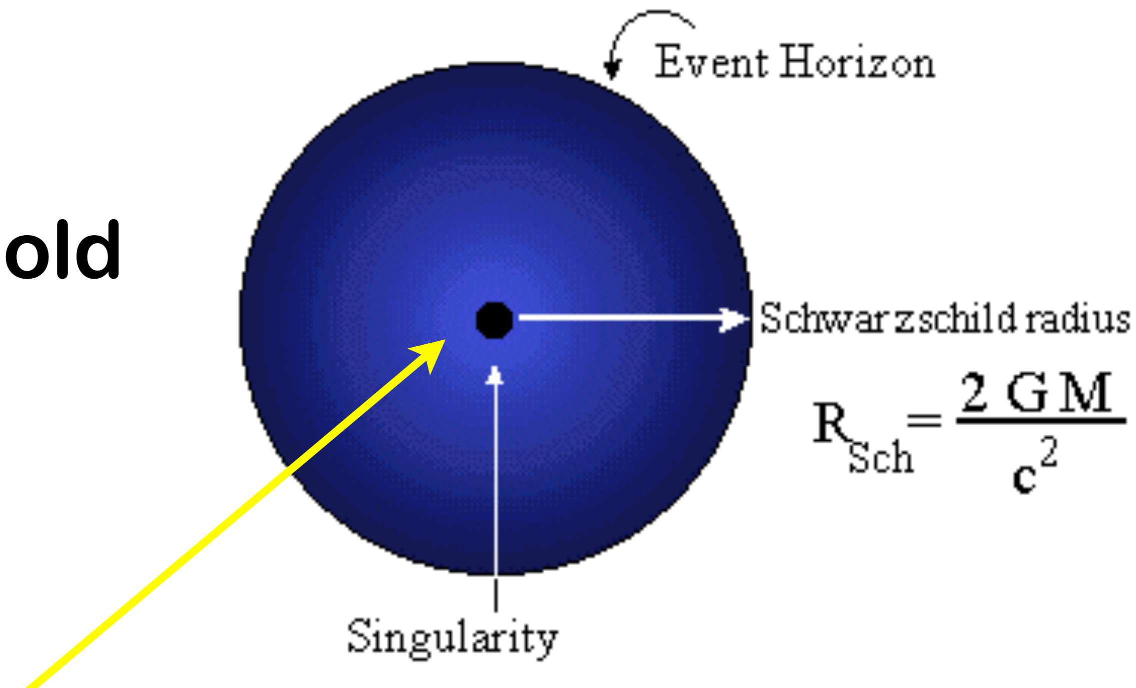
all light, all matter unavoidably falls to center

- no rockets or anything can even hold anything still

much less allow for climbing out

everything falls to center

crushed into a single point (?): "singularity"



i.e., finite mass M in volume $V = 0$

→ density $\rho = M/V \rightarrow \infty$!

D'oh! known laws of physics break down

Black Hole Singularity: The Frontier

Black hole singularity is subject of intense research

- there is much we don't know

A few remarks:

- we do know that all infalling stuff travels to center
- don't know what happens once there
- regardless, certain that you die if you go in
- in a way, it's not a relevant question
  can't get info out even if went in (no Nobel Prize!)
- once crushed to < 10^{-33} cm, quantum mechanics important
  i.e., to understand, need quantum theory of relativistic gravity!
  a theory of gravity that includes both relativity and quantum mechanics
  ... but there isn't one...yet
- if you have quantum gravity theory, please tell instructor
  and we'll publish it (your name may even go first!)

iClicker Poll: Life Far Away From a Black Hole

Future industrial accident ("mistakes were made") causes Sun to be crushed to black hole without gain or loss of mass

What happens to Earth's orbit?

A. nothing: same orbit!
B. spirals in: aaargh!
C. stronger gravity, orbit closer, more elliptical but does not fall in
D. weaker gravity, orbit closer, more elliptical but does not fall in

Black Hole Sun

If Sun crushed to black hole:

- No change in orbit!

when outside of Sun, gravity acceleration is

$$a = \frac{GM_{\rm sun}}{r^2}$$

- only Sun's mass M_{sun} matters
- gravity same as if Sun were $1M_{sun}$ BH

gravity outside star not increased by becoming BH

- no more pull than before!
- "black hole threat" not any more dangerous than "nearby star gravity" threat

So sleep well tonight!

Note: so far, BH discussed as theoretical objects

Q: how to "see" one to test theory? No light escapes!!

Exam Review

Exam next time, in class

Detailed information on course website

along with list of topics to help your review

Sample Question

A large CME happened last week. What's the most likely reason why Earth was not affected?

A. it didn't hit the Earth

B. it didn't have strong enough magnetic fields

C. it didn't have enough mass

D. NASA satellites gave enough warning to protect everyone

E. it was deflected by the Earth's magnetic field

Sample Question

Star A and star B have the same apparent brightness (flux), but star A is twice as far from us as star B. The luminosity of star A is thus ________ the luminosity of star B.

A. the same as
B. 2 times larger than
C. 2 times smaller than
D. 4 times larger than
E. 4 times smaller than

Sample Question

Four main-sequence stars are shown on the HR diagram at right.

Which star has the longest lifespan?

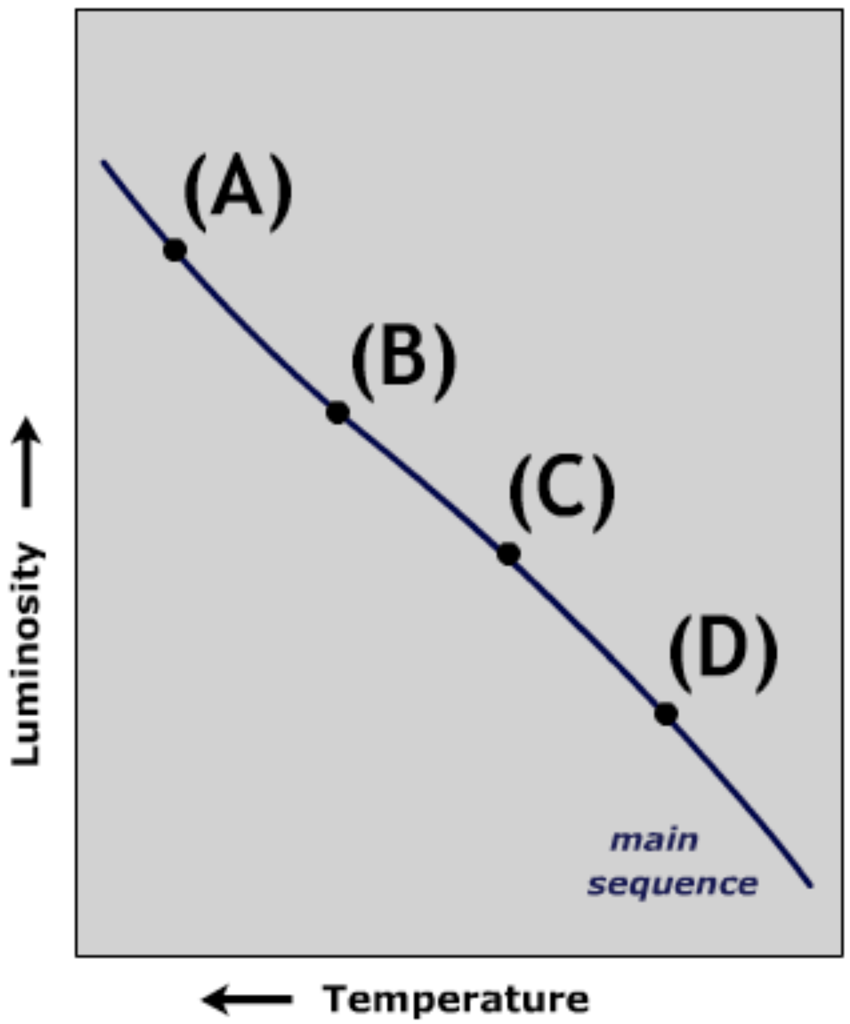
A. star A

B. star B

C. star C

D. star D

E. all stars have the same lifespan



Sample Question

What is the danger from a nearby supernova to the Earth in the next million years?

A. 100%, eventually it will happen and 1 million years is a long time.

B. Zero. No stars of any kind are within the supernova kill radius

C. 100%, the massive star Betelgeuse is going to blow!

D. Zero. There are no stars close enough and massive enough