Astro 210
Lecture 35
April 18, 2018

Announcements:

- **HW10 due Friday 5:00 pm online**

- Office hours: instructor 2:00–3:00 pm today
  TA 3:30–4:30 tomorrow

- Hour Exam 2 grades posted. Most did well. Bravo!

Massive Stars: James Dean of the Cosmos

- *live fast*: high mass $\rightarrow$ strong gravity, high T
  rapidly pass through nuke burning stages until iron core
- *die young*: in spectacular supernova explosion
- *leave a beautiful corpse*: high-velocity, superheated,
  metal-rich gas ejected, plus compact object at center

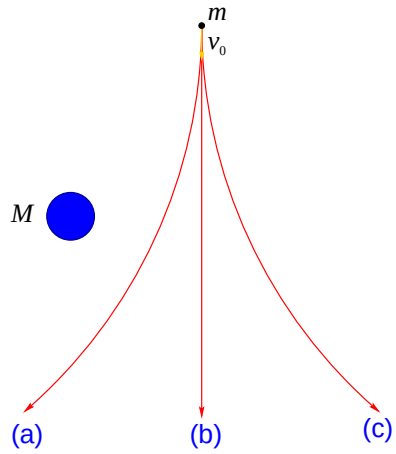
Q: what do astronomers mean by "metal" rich?

compact object: sometimes a **neutron star**
some of which are observed as pulsars
Q: how? what is detected?

iClicker Polls: Gravitation Warmup Twofer

Recall your (Newtonian) gravitation

a test particle, mass m,
launched from "infinity" with *speed* $v_0 > 0$
passes gravitating mass M
What is the path of the particle?



A deflected towards M

B no deflection: straight line

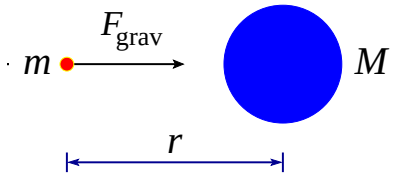
C deflected away from M

Same question, but for *massless* test particle, $m = 0$

Gravitation Revisited

Newton gravity force law

$$F_{\text{grav}} = \frac{GMm}{r^2}$$



implies that *if M moves* and thus r *changes:*

$\longrightarrow$ *gravity force changes instantaneously* over all space!

"signal" of motion instantaneously transmitted

throughout the universe

Einstein sez: *this is totally illegal! an unmitigated disaster!*

no signal–including gravity–can move faster than c!

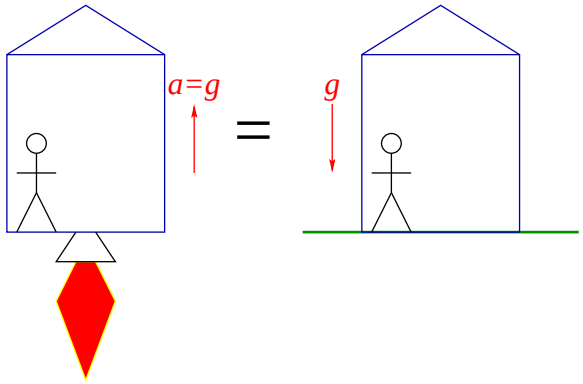
violates basic principles of special relativity

Einstein 1905: **Special Relativity**

- rewrote dynamics to include motions with speeds near c
- but did not include gravity

Gravity and Acceleration are One

Einstein 1905-1915: struggled to reconcile
special relativity and *gravity*



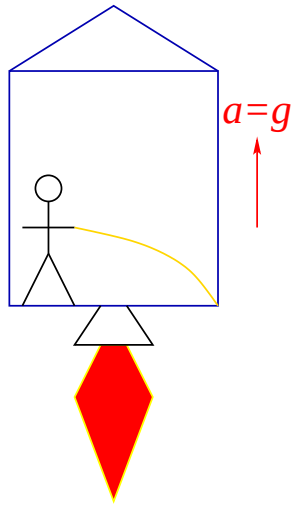
Key step:
Einstein's Equivalence Principle:
in a closed room
no experiment can distinguish
gravity-free acceleration vs *gravity and no acceleration*

Q: explain ball weight–Earth's surface vs accelerating rocket?
Q: explain ball drop–Earth's surface vs accelerating rocket?
Q: what about horizontal ball toss?
Q: what about horizontal light beam?

Gravity Bends Light

Rocket Experiment: `www: illuminating animation`
in accelerating rocket, shoot a horizontal beam

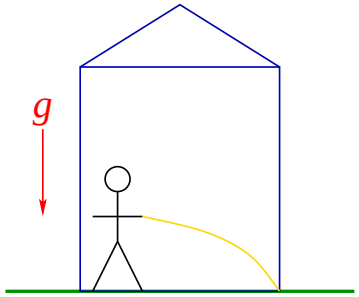
- ⋆ light ray deflected
- ⋆ entire light path bent (in fact, a parabola!)



But by equivalence principle:
must find same result due to gravity, so:

- ⋆ gravity bends light rays

gravitational lensing



Q: what if shine light from basement to attic?

Gravitational Redshifting

Also: in accelerating spaceship:

⋆ shine light from basement to attic

spacecraft & attic speed increases during light travel

$\rightarrow$ attic observer seed light *redshifted*

similarly, basement observer sees attic light *blueshifted*

Gravitational Redshift

And there's more:

redshift = decrease in light frequency f

but $f = 1/P$, light wave oscillation period

so redshift $\rightarrow$ P increases

but light oscillations are like clock ticking, so...

Gravitational Time Dilation

⋆ clocks in basement appear to run slow
when viewed from attic!
and attic clocks appear fast when viewed from basement!

in fact, attic clocks faster by $\Delta t = t_{\text{attic}} - t_{\text{basement}} = g\Delta h/c^2$

⋆ time "warping" due to gravity:
"**gravitational time dilation**"
⋆ gravity influences "flow" of time!

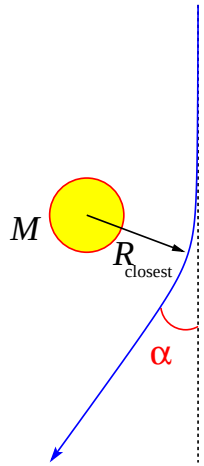
Q: how to test these effects in real world?

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
  bending angle $\alpha = 4GM_\odot/R_{\text{closest}}c^2$



biggest effect for starlight "grazing" Sun edge: $R_{\text{closest}} = R_\odot$
Q: why is this technically challenging to see?
Q: how to get around the problem?

1919 Eclipse: Give it up for Big Al!

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

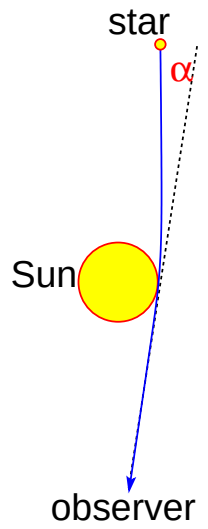
`www: expedition results paper to Royal Society`

★ starlight bent! Woo hoo!

★ relativistic gravity confirmed!

★ Einstein an instant celebrity

`www: NY Times announcement`



Now tested many times, and very accurately
seen in clusters of Galaxies

`www: HST gravitational lens Abell 2218`

• all starlight bending experiments confirm Einstein!

General Relativity

Einstein's gravity: General Relativity
relativity generalized to include fast motion *and* gravity

Newton: matter causes force (gravity)
$\longrightarrow$ particles follow curved lines in
"flat" (Euclidean geometry) space

Einstein: bold leap, rejected Newton
matter causes spacetime to be "curved"
$\longrightarrow$ particles follow straight lines ("geodesics")
in curved space

space and time dynamic
not fixed once and for all

Black Holes

Laplace (1790's)
recall: escape velocity $v_{\rm esc} = \sqrt{2GM/R}$
HW 3: What if star has M, R with $2GM/c^2R > 1$?
then $v_{\rm esc} > c$!
light cannot escape! $\rightarrow$ black hole

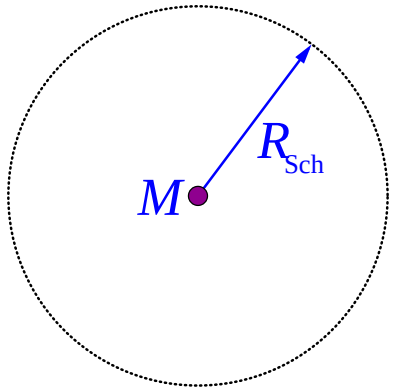
Wrong argument (Newtonian gravitation)
...but right answer!

in death of $M > 30 M_\odot{}^*$: gravity wins
collapse unstoppable
black hole formed $\Rightarrow$ inevitable part of star formation

*Exact "threshold mass" for SN $\rightarrow$ BH uncertain

Black Hole Properties

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



size: Schwarzschild radius

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

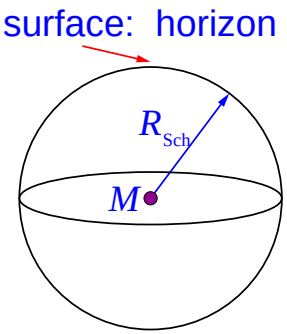
radius also provides BH "recipe":

- *crush* object M *smaller than* $R_{\rm Sch}$ $\rightarrow$ *get BH!*
- example: for mass of Sun $R_{\rm Sch} = 2GM_\odot/c^2 = 3.0$ km
  but actual $R_\odot = 7 \times 10^6$ km
  $\rightarrow$ the Sun is not a black hole! (whew!)
- for mass of Earth: $R_{\rm Sch} \approx 1$ cm!

The Black Hole Horizon

Why call $R_{\rm Sch}$ the BH radius? nothing is there!

True, but: $R_{\rm Sch}$ marks "point of no return"
horizon: surface enclosing the BH
i.e., horizon is surface of sphere w/ radius $R_{\rm Sch}$



horizon is one-way "membrane"
once inside $r \leq R_{\rm Sch}$ nothing can escape...even light!
cosmic roach motel!

Hence:
no light escapes $\rightarrow$ black
but nothing else moves as fast $\rightarrow$ nothing else escapes $\rightarrow$ hole

Life Near a Black Hole

Experiment: lower astronaut (Jodie) near $R_{\rm Sch}$
we are at mission control, far away ($r_{\rm us} \gg R_{\rm Sch}$)
communicate w/ light signals

when viewing photons (or clock ticks)
emitted at $r_{\rm em}$, observed at $r_{\rm obs}$
general rule:

$$\frac{\Delta t_{\rm obs}}{\Delta t_{\rm em}} = \frac{\lambda_{\rm obs}}{\lambda_{\rm em}} = \sqrt{\frac{1 - R_{\rm Sch}/r_{\rm obs}}{1 - R_{\rm Sch}/r_{\rm em}}} \qquad (1)$$

What do we see?

obs=us: $r_{\rm obs} \to \infty$; em=Jodie: $r_{\rm em} > R_{\rm Sch}$

- Jodie's watch: $\Delta t_{\rm obs}/\Delta t_{\rm em} = 1/\sqrt{1 - R_{\rm Sch}/r_{\rm em}} > 1$
  $\to$ $\Delta t_{\rm obs} > \Delta t_{\rm em}$! appears to tick slow! time dilation !
- wavelengths: $\lambda_{\rm obs} > \lambda_{\rm em}$! redshift !

Q: and Jodie?

$$\frac{\Delta t_{\rm obs}}{\Delta t_{\rm em}} = \frac{\lambda_{\rm obs}}{\lambda_{\rm em}} = \sqrt{\frac{1 - R_{\rm Sch}/r_{\rm obs}}{1 - R_{\rm Sch}/r_{\rm em}}} \qquad (2)$$

What does Jodie see?

intuitively: expect inequalities to reverse...and they do

obs=Jodie: $r_{\rm obs} > R_{\rm Sch}$; em=us: $r_{\rm em} \to \infty$:

- *our watches*: $\Delta t_{\rm obs}/\Delta t_{\rm em} = \sqrt{1 - R_{\rm Sch}/r_{\rm em}} < 1$
  $\to \Delta t_{\rm obs} < \Delta t_{\rm em}$! *appear to tick fast!*
- wavelengths: $\lambda_{\rm obs} < \lambda_{\rm em}$! *blueshift!*

When Jodie returns:

then $r_{\rm em} = r_{\rm obs}$

- $\Delta t_{\rm obs} = \Delta t_{\rm em}$: her watch ticks at same rate as ours!
- but the *elapsed time* is shorter on her watch
  and so she is younger than her twin!