Astro 404

Lecture 37

Dec. 2, 2019

- **Problem Set 12 out, due Friday Dec 6**
- Note: lowest of 12 homework scores dropped!
  But: you are still responsible for material on **all HW**
- **Hour Exam scores posted today, returned Wed!**

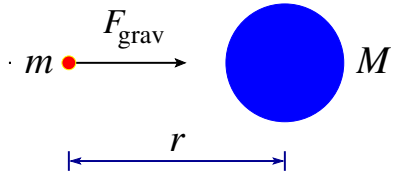
Before break: relativistic gravity

Q: why does Einstein object to Newtonian gravity?

Q: equivalence principle–what's equivalent? what's the principle?

Newton gravity force law

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



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

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

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

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

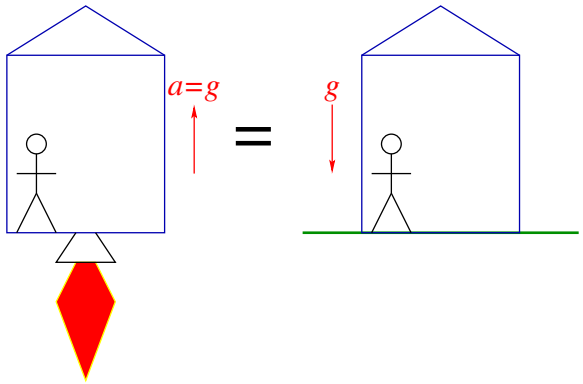
Einstein's Equivalence Principle:

in a closed room

no experiment can distinguish

gravity-free acceleration vs

gravity and no acceleration



Q: what does the equivalence principle imply when comparing an observer on planet with g, and accelerating rocket $a = g$?

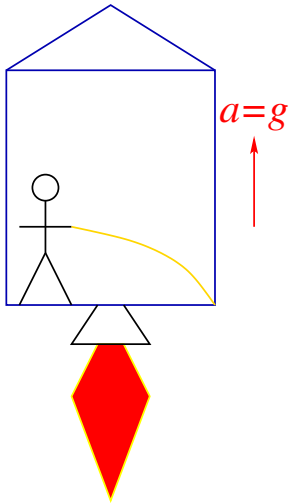
Gravity Bends Light

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

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

shooting a vertical beam

⋆ upstairs sees redshift, downstairs sees blueshift



equiv. principle: gravity gives same results, so:

⋆ gravity bends light rays

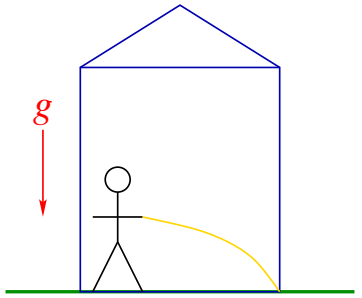
gravitational lensing

confirmed in 1919 total solar eclipse!

⋆ gravity changes photon wavelengths

gravitational redshifting

confirmed in lab: Pound-Rebka expt



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

Q: and so?

Gravitational Time Dilation

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

viewed from attic, basement clocks appear slower by

$$\Delta t = t_{\text{basement}} - t_{\text{attic}} = \frac{gh}{c^2} = \frac{\phi}{c^2} \qquad (1)$$

where $\phi = gh$ is gravitational potential

⋆ time "warping" due to gravity:
"**gravitational time dilation**"
⋆ gravity influences "flow" of time!
deeper potential $\rightarrow$ slower apparent "time flow"
Q: so which clock is really right?

General Relativity

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

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

Einstein: bold leap, rejected Newton
matter causes spacetime to be "curved"
$\rightarrow$ 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 $v_{\rm esc} = \sqrt{2GM/R}$
What if star has M, R with $2GM/c^2R > 1$?
then $v_{\rm esc} > c$!
light cannot escape! $\rightarrow$ black hole

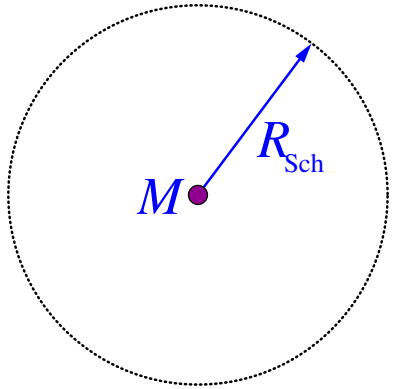
Wrong argument (Newtonian gravitation)
...but right answer!

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

* "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

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

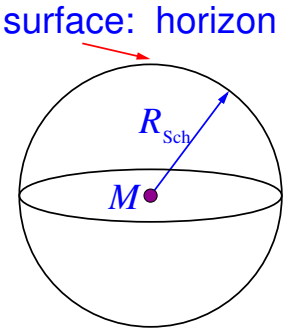
radius also provides BH "recipe":

- *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_{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}



horizon is one-way "membrane"
once inside $r \leq R_{\text{Sch}}$ 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, handy for PS12:

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

What 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?

$$\frac{\Delta t_{\rm obs}}{\Delta t_{\rm em}} = \frac{\lambda_{\rm obs}}{\lambda_{\rm em}} = \sqrt{\frac{1 - R_{\rm Sch}/r_{\rm obs}}{1 - R_{\rm Sch}/r_{\rm em}}} \qquad (3)$$

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!

iClicker Poll: Black Holes

From a safe distance, you drop an object (nuclear waste? Voldemort?) on an isolated black hole.

Will you see it fall in?

A yes, no matter your distance from the hole

B maybe, depends on how far you are from the hole

C no, because it never actually falls in

D no, although it does actually fall in

Falling Into a Black Hole

No barrier, bells, or whistles at horizon
infalling objects go right through

seen from afar, time dilation and redshift progressively severe
as object approaches horizon

progressively strong relativistic flux reduction

so as seen from afar:

- time elapse slows until appears "frozen"
- signal redshifts
- image fades until last photon emitted before horizon crossing and then object gone–and black hole mass higher

Life Inside a Black Hole

once inside $R_{\rm Sch}$, no getting out
all matter $\rightarrow$ center $\rightarrow$ point (?): "singularity"
i.e., finite mass M in volume $V = 0 \rightarrow$ density $\rho \rightarrow \infty$!
D'oh! known laws of physics break down

A few remarks:

- we know that all observers travel 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, since can't get info out even if went in (no Nobel Prize!)
- once crushed to $< 10^{-33}$ cm, quantum mechanics important
  i.e., need quantum theory of relativistic gravity!
  ... 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: You Thought the BP Spill Was Bad

Experiment:
Industrial accident causes Sun to be crushed to black hole
Spokesdroid from Interplanetary BP: "Mistakes were made."

Vote your conscience!

What happens to Earth's orbit?

A nothing: same orbit!

B spirals in: aaargh!

C stronger gravity, but does not fall in

Life Far From a Black Hole

No change in orbit!

Newtonian explanation: wrong in detail, but correct spirit:
when **outside** of Sun, gravity acceleration is
$a = GM_\odot/r^2$: only M matters
gravity same as if Sun were $1M_\odot$ BH

gravity outside star **not** increased by becoming BH
no more pull than before!
$\rightarrow$ "black hole threat" not any more dangerous than
"nearby star gravity" threat

So sleep well tonight!

Black Holes: From Theory to Observations??

So far: discussed *predicted* black hole properties

that is: General Relativity says

black holes *can* exist in nature

but question remains: is there *evidence*

that black holes *do* exist in nature?

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

Evidence for Black Holes

recall: in death of some massive stars (perhaps $M > 30 M_\odot$?):
gravity wins, collapse unstoppable
black hole formed $\rightarrow$ should be inevitable part of star formation

how detect? no light emitted from BH, but:
can observe matter interacting with BH

X-ray binaries: stellar-mass black holes (few $M_\odot$)
massive star born in bound system with less massive star
larger star $\rightarrow$ SN $\rightarrow$ BH left behind
if supergiant companion, close orbit:
some gas falls onto BH $\rightarrow$ compressed, heated $\rightarrow$ X-rays

what you see: giant star orbiting unseen massive companion,
and emitting X-rays
`www: Cygnus X-1`

Our Own Galactic Center

central ~ 30 pc of Galaxy:
can't see optically (*Q: why?*), but can in other wavelengths:
extended (non-point) radio emission (Sagittarius A)
from high-energy electrons

radio source at center: Sgr A*
size 2.4 AU(!), variable emission in radio, X-ray
`www: X-ray Sgr A*`

in infrared wavelengths: can see stars near Sgr A*
and they move! `www: Sgr A* movie`
elliptical paths! closest: period $P = 15.2$ yr
semi-major axis: $a = 4.64 \times 10^{-3}$ pc
$\rightarrow$ enclosed mass $(3.7 \pm 1.5) \times 10^6 M_\odot$
Q: and so?

the center of our Galaxy contains a black hole!

Sgr A* Schwarzschild radius

$$r_{\rm Sch} = 1.1 \times 10^7 \text{ km} = 0.74 \text{ AU} = 3.6 \times 10^{-7} \text{ pc} \qquad (4)$$

$\rightarrow$ not resolved (yet) but: *Event Horizon Telescope*
has data and right now is processing possible first images!

Galactic black hole raises many questions:

- how did it get there?
- Sgr A* low luminosity, "quiet"
  compared to more "active" galactic nuclei `www: AGN: M87`
  why? open question....
- in last few months: discovery of high-energy "bubbles"
  above & below Galactic center `www: gamma-ray images`
  $\rightarrow$ remains of the most recent Sgr A* belch?

Galaxies and Black Holes

The Milky Way is not the only galaxy with a central black hole

active galaxies: most L from non-star sources
emission is from galactic nucleus:
active galactic nuclei = AGN
spectral lines broad $\rightarrow v_{\rm rms} \gtrsim 10,000$ km/s!

AGN vary w/ time: large luminosity fluctuations over $t \sim$ weeks
$\rightarrow$ size $d \lesssim ct \sim 1000$ AU
but $M \sim v^2 d/G \sim 10^8 M_\odot$
Huge mass in tiny region: $\rightarrow$ black hole, supermassive!

Hubble Telescope: QSO (point) + resolved hosts
`www: HST SQO hosts`
some: merging galaxies
others: "undisturbed" galaxy?!

The Nearest AGN: M87

our Milky Way galaxy is a "collar county" near
a huge concentration of galaxies: the Virgo cluster `www: Virgo cluster`

at the center of Virgo lies a huge ball of stars:
the giant elliptical galaxy **M87**

M87 is ejecting jet of matter from its center:
hot gas moving at $v \approx c$, Lorentz $\gamma \approx 100$
`www: M87 jet`

motions of stars at M87 center point to unseen mass $> 10^9 M_\odot$
⋆ *M87 hosts a supermassive black hole:* **M87***
⋆ M87 is the nearest AGN!
nearby, huge black hole: excellent candidate for Event Horizon Telescope

Event Horizon Telescope and M87

Event Horizon Telescope (EHT) goal: image black holes
most promising candidates: M87* and SgrA*

challenge (PS12): tiny angular size of emitting region
need unprecedented angular resolution

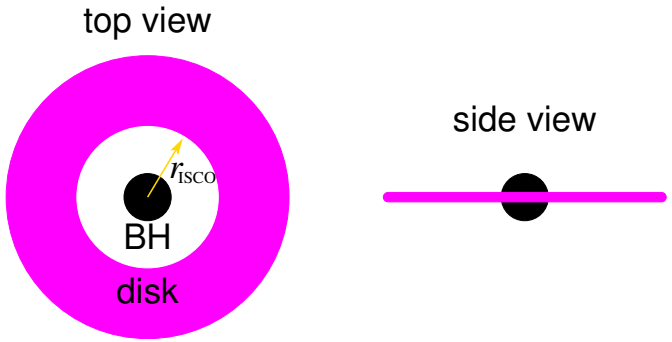
solution: spread telescopes over entire Earth
"very long baseline interferometry"
combined resolution is that of Earth's diameter!

April 2019: success! EHT presents image of M87*

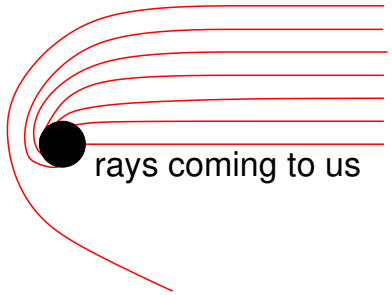
Imaging a Black Hole: Expectations

physical picture:

- gas accreted onto BH orbits in disk
- friction drags gas inward, until orbits unstable $\rightarrow$ fall to BH
- "point of no return" – innermost stable circular orbit (ISCO) for non-rotating black hole, $r_{\rm isco} = 6GM/c^2$



gas emits light as it falls in:
mostly near ISCO
photons bent by BH gravity
we can see behind the hole!

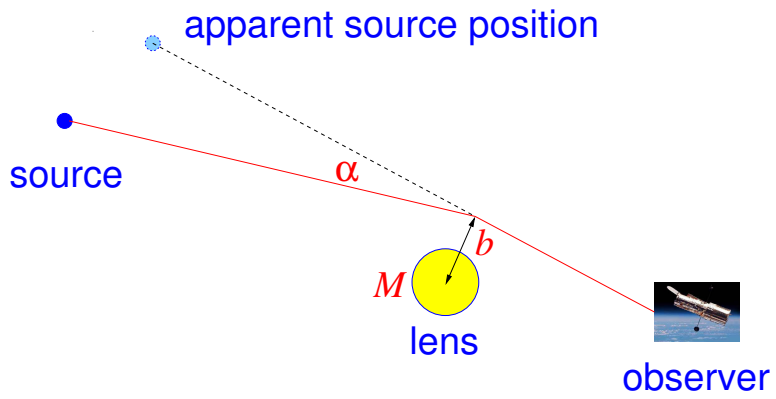


Director's Cut Extras

Light Bending Quantified: Point Mass

the setup:

- light ray incident on
- a point mass M
- with distance of closest approach b



Einstein result: light deflected by angle

$$\alpha = \frac{4GM}{c^2 b} \tag{5}$$

Q: how could this be useful as a tool?

Supermassive Black Holes

MH has supermassive BH: quiet
QSO have supermassive BH: active

recent result:
all galaxies have supermassive BH! ...but most quiet
$\rightarrow$ maybe active galaxies are phase in evolution?

BH mass **correlated** with host gal stellar (spheroid) mass
$\rightarrow$ $M_{\mathsf{BH}}/M_{\mathsf{sph}} \sim const \sim 0.006$
constant "BH fraction"
$\rightarrow$ supermassive BH formation is part of gal formation!

Open Questions:

- how does a $10^{7-8} M_\odot$ BH ($R_{\rm Sch} \sim$ AU)
  know about the $10^{11-12} M_\odot$ galaxy it lives in (and vice versa)?
- how does a SMBH "grow" – what are the "seeds,"
  and how are they "fed"?
- Are there any galaxies without SMBH?
  Are there any SMBH without galaxies?
  Either way, what does this mean?