Astro 404

Lecture 38

December 1, 2021

Announcements:

- **PS12–last one!–due this Friday Dec 3**
  Note: lowest HW score is dropped
  but all HW are fair game on final exam
- Also: bonus question–predict the future of stellar astrophysics!
- Office Hours: BDF today after class to noon
  TA tomorrow 2:30–3:30pm

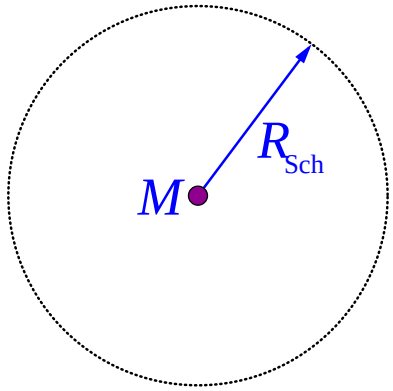
Last Time: **black holes**

- *Q: why black? why a hole? how to make a BH?*
- *Q: what do observers near the BH see looking out??*
- *Q: what do observers far from the BH see looking in?*

any mass M can become a black hole!

size: Schwarzschild radius

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



noting at R_{Sch}, but marks "point of no return"

horizon: surface enclosing the BH

i.e., horizon is surface of sphere w/ radius R_{Sch}

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

near R_{Sch}: see outside world blueshifted, sped up

from afar: objects near R_{Sch} redshifted, slowed

$\rightarrow$ infalling objects slow and fade away

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?

recall: in death of some massive stars
- core collapse
- crush to high density: proto neutron star

we observe neutron stars and pulsars
thus: some proto neutron stars stable against collapse
...but not necessarily all!

Do Black Holes Exist in the Cosmos?

observational hints of black hole formation:

rate of massive star formation $>$ *rate of supernova explosions*

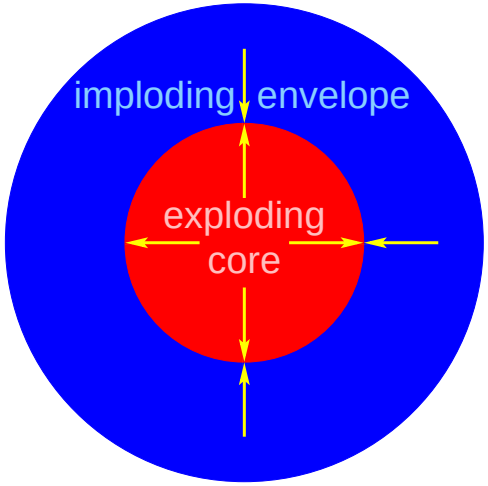
Q: How does this imply black hole formation?

Black Hole Creation in Stellar Evolution

proposed black hole formation routes in core collapse

black holes from direct collapse

- if core explosion too weak to overcome implosion of the rest of the star
- then *the whole star implodes!* and a **black hole** formed promptly
- with little to *no explosion* seen: "failed supernova" but neutrinos still emitted



Who wins?

- observers would see the star just *disappear*! two candidate events found for disappearing supergiants! data suggests $4-39\%$ of massive stars could die this way!

Black Holes From Fallback

"delayed" black hole formation also possible
after possible that explosion launched, proto-neutron-star formed
if surrounding matter *falls back* onto neutron star
and increases mass above maximum $\rightarrow$ collapse to **black hole**

Candidate: SN 1987A. Not BH at birth
because 10 sec neutrino escape time requires neutron star
but no neutron star seen yet in remnant...though hints reported

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Lesson:
black holes are an inevitable part of star formation

Q: how could we detect black holes? No light escapes!

Evidence for Black Holes

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

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

$$r_{\rm Sch} = 1.1 \times 10^7 \text{ km} = 0.74 \text{ AU} = 3.6 \times 10^{-7} \text{ pc} \qquad (2)$$

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

Galactic black hole is a triumph: **Nobel Prize 2020**!
But also 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 years: 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?!

Poll: Infall and Angular Momentum

two objects fall towards a black hole

- one has zero angular momentum: $L = 0$
- one has nonzero angular momentum: $L > 0$

What happens to the objects?

A both fall straight onto the BH

B $L = 0$ falls straight onto BH, $L > 0$ orbits it

C $L > 0$ falls straight onto BH, $L = 0$ orbits it

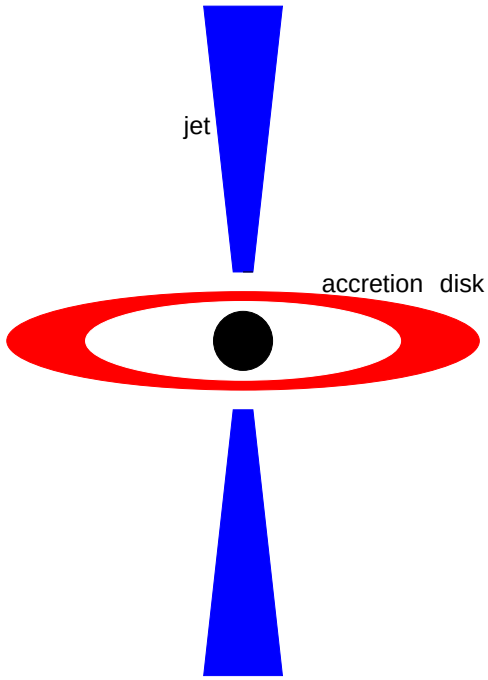
D both orbit the BH

Feeding the Monster: Black Hole Accretion

Black hole feeding: accretion

orbiting mass has angular momentum

- tidal forces shred into **accretion disk**
- friction/magnetic stresses drag matter inward until reaching innermost stable circular orbit
- then matter plunges in and lost



but if infalling matter is *magnetized*

- field lines wind up along orbit axis
- generates strong magnetic forces and pressure
- launches *relativistic jet* along spin axis

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: $v \approx c$, Lorentz $\gamma \approx 100$, pointed nearly at us
`www: M87 jet`

motions of stars at M87 center point to unseen mass $> 10^9 M_\odot$
⋆ *M87 hosts a supermassive black hole:* **M87***
also seen as the radio source Virgo A
⋆ M87 is the nearest AGN!

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

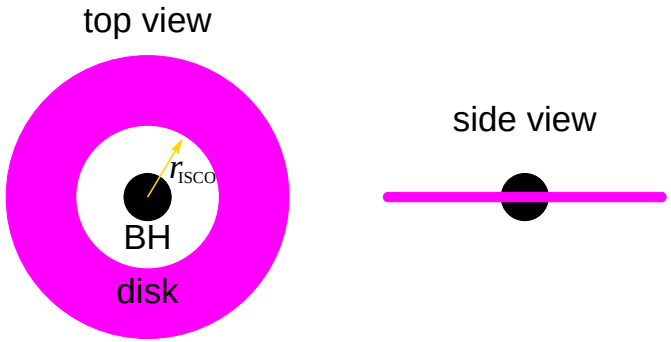
solution: spread telescopes over entire Earth
"very long baseline interferometry"
combined resolution is that of Earth's diameter!

April 2019: success! EHT presents image of M87*

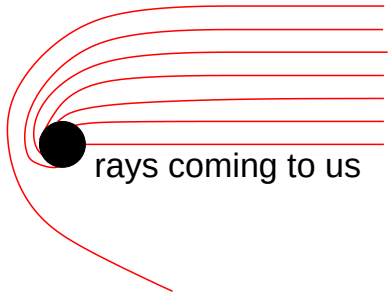
Imaging a Black Hole: Expectations

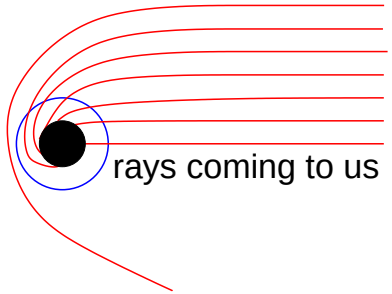
physical picture:

- 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!





note: at $r = 3R_{\rm Sch} = r_{\rm isco}/2$, gravity so strong
light bent into (unstable) circular orbit: "photon ring"

Q: so what should image look like on sky?
Q: how will image depend on orientation of accretion disk?

`www: EHT Image of M87*` *This is data! What do you notice?*

The Image of M87*

Amazing! Revealed a wealth of physics:

- **observation:** dark region surrounded by ring
  ring brighter on one side
- **interpretation:** we see the shadow of the black hole!
  direct evidence of an event horizon!
- ring size larger than Schwarzschild (nonrotating) prediction
  required black hole spin!
- surrounding ring due to accretion disk
- edge-on disk would be visible across diameter
  so disk almost in plane of aky
- disk perpendicular to M87 jet
- disk asymmetry due to high orbit speed: relativistic beaming
  bright side is from approaching blueshifted gas

More data to come–for both M87* and SgrA*!

Awards and Bragging Rights

Event Horizon Telescope awarded 2019 Breakthrough Prize

$2.5M shared among collaboration

Illinois plays leading role

- Prof. Charles Gammie and group lead theory effort
  their models used to compare with observations
  and infer black hole properties
- South Pole Telescope is part of EHT network

Supermassive Black Holes: Outlook

observations suggest most (all?) galaxies
have supermassive black hole at center

black hole mass correlated with (spheroid) stellar mass
they seem to grow together–but why?

accretion grows BH mass
but open question: what is initial "seed" black hole?
- stellar-mass black holes hard to grow fast enough
- but not clear where else to start

This remains an open research question!

Q: other questions on black holes?