Astro 404

Lecture 37

Dec. 2, 2019

- **Problem Set 12 due today at 5:00 pm**
- Good news: no more problem sets!
- Bad news: **Final Exam Next Friday, Dec 13, 7:00-10:00pm**
  info on Compass
- grad Hour Exams available

Last time: evidence for black holes

*Q: General Relativity allows black holes to exist, but does Nature make then?*

*Q: what's the evidence for stellar-mass black holes?*

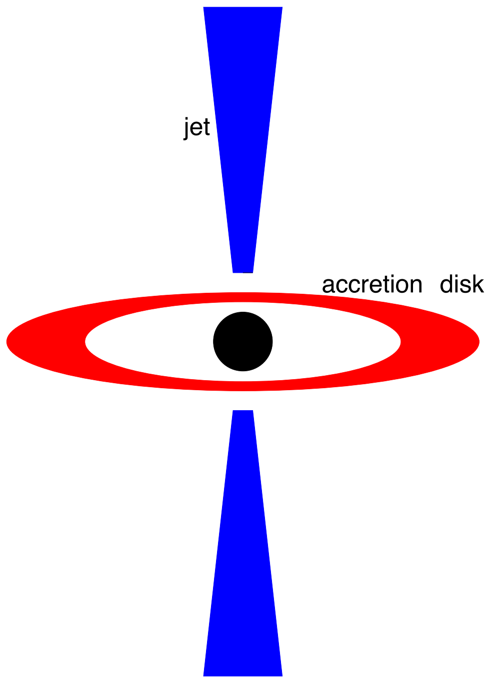
*Q: what's the evidence for supermassive black holes?*

# Feeding the Monster: Black Hole Accretion

Black hole feeding: accretion

orbiting mass has angular momentum

- tidal forces shred into **accretion disk**
- friction/magnetic stres 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***
⋆ 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

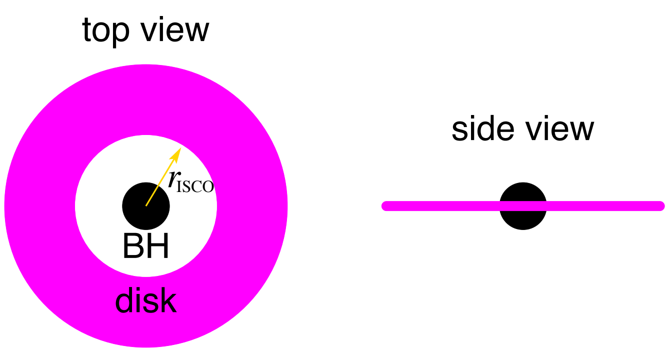
solution: spread telescopes over entire Earth
"very long baseline interferometry"
combined resolution is that of Earth's diameter!

April 2019: success! EHT presents image of M87*

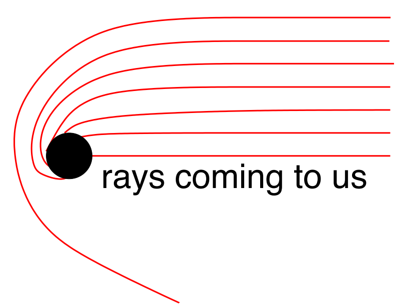
# Imaging a Black Hole: Expectations

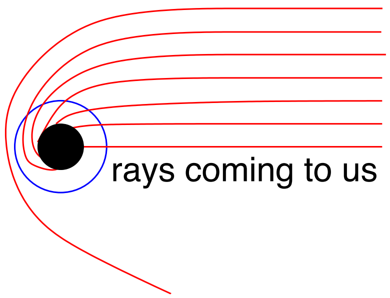
physical picture:

- 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 $r = 3R_{\mathrm{Sch}} = r_{\mathrm{isco}}/2$, gravity so strong
light bent into (unstable) circular oribt: "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 brigher 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 obth 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 (spheriod) 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?*

# Binary Systems and Stellar Explosions

# Evolution of Binary Stars

for most of this course: considered evolution of stars that are

- non-rotating
- non-magnetic
- in insolation – **no binary partner**

for many stars, these are good or even excellent approximations
but *there are stars where these features a critical!*

for the rest of the course: binary stars that evolve explosively!

recall: most stars are in binaries!
observed separations span a few AUs to fractions of parsecs
and orbital eccentricities vary widely

# iClicker Poll: Evolution of Binary Stars

consider two stars in a binary

**which of these will evolve most differently**
compared to the same two stars in isolation

**A** two *main sequence stars*, with *wide* separation

**B** two *main sequence stars*, with *close* separation

**C** 1 or 2 *post-main-sequence stars*, with *wide* separation

**D** 1 or 2 *post-main-sequence stars*, with *close* separation

# Binary Stars and Mass Transfer

binarity effect are most drastic when there is *mass transfer*

- one star loses mass by giving it to the other
- for this to occur, matter must become unbound in one star and move to the other

this happens when

- one star becomes a giant $\rightarrow$ atmosphere loosely bound
- two stars orbit decays until they merge
  *Q: how can orbits decay?*

# Binar Star Orbit Decay

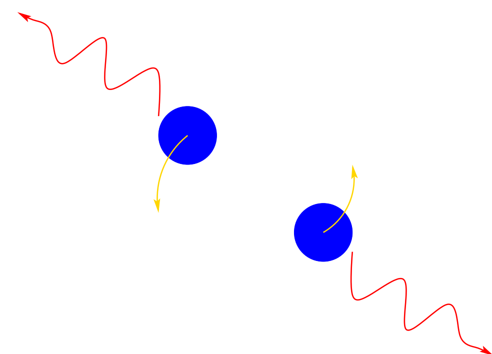
In *Newtonian* gravity, *point mass* binary orbits *in vacuum*

- are perfect ellipses
- never change in time

but orbits *do change* if one of these conditions is violated

- *one star becomes giant*, other moves in its atmosphere
  slows down due to drag forces

- *two white* dwarfs, no atmosphere
  but energy lost due to General Relativity effect:
  **gravitational radiation**
  acceleration launches spacetime ripples
  that carry away energy and angular momentum
  shrinks binary orbit: *inspiral*



# Type Ia Supernovae

## Type Ia Supernovae Observed

- SN Type I $\rightarrow$ no H in spectrum
- Type Ia: He, Si lines *are* seen
- peak luminosity: $\sim 1^{\rm mag}$ = factor 2.5 brighter than SN II
  $\rightarrow$ easier to find, probe larger distances (higher $z$)
- ejecta somewhat faster than Type II events
- blast energies $\sim 1$ foe $= 10^{51}$ erg
- host galaxies: all types, including "red and dead" elliptical
- observed Type Ia rate $\sim 20\% - 50\%$ of Type II
  but beware selection effects: easier to see Type Ia

*Q: what physical ingredients needed to produce SN Ia?*

## Type Ia Supernovae: Ingredients

- no hydrogen $\rightarrow$ "stripped" star
  need either wind or companion
- found in all galaxies
  $\rightarrow$ not correlated with active in star formation
  $\rightarrow$ progenitors not short-lived: low/intermediate mass stars
- faster ejecta, brighter events $\rightarrow$ progenitors less massive
- regularity of light curves $\rightarrow$ fairly uniform path to formation

putting it all together... *Q: what do you think?*

# Type Ia Supernovae: White Dwarf Explosions

all viable scenarios invoke:

⋆ *binary system*

⋆ a *white dwarf*, usually a CO dwarf

*What's a CO white dwarf?*

→ end-product of intermediate-mass star

recall – after main seq:

1. H shell burn → red giant
2. He ignition: degenerate → explosive: *helium flash*
3. core expands, burns He → C+O

*Q: and what happens when core is CO? Hint: it depends!*

4(a). if $M \lesssim 4M_\odot$, CO core supported by $e^-$ degeneracy pressure
never contracts, remains as *CO white dwarf*

4(b). if $M \sim 4 - 8M_\odot$, shell He burning increases CO core mass
until $M_{\rm core} > M_{\rm Chandra}$: core contracts, burn to O, Ne, Mg
results in ONeMg white dwarf

thus: CO white dwarfs are outcomes of $\sim 1 - 4M_\odot$ evolution
but lower-mass stars are the most abundant
$\rightarrow$ CO white dwarfs are the most common type

*Q: so what if WD has binary companion which donates mass?*

# SN Ia: Thermonuclear Explosions

if WD in close binary/merger:

- companion donates mass
- when $M_{\rm WD} > M_{\rm Chandra}$: star contracts
  ignites degenerate C burning ("carbon flash")

runaway nucleosynthesis $\rightarrow$ WD detonates
heated $\rightarrow$ achieve *nuclear statistical equilibrium*
*Q: which will make what?*

energy release:

- $^{12}\mathrm{C} \rightarrow {}^{56}\mathrm{Fe}$ burning gives
  $Q = B_{56}/56 - B_{12}/12 = 0.86$ MeV per nucleon
  if inner 50% of $M_{\rm Chandra}$ is carbon, then
  release $E_{\rm nuke} \sim Q M_{\rm core}/m_u \sim 1.6 \times 10^{51}$ erg $= 0.6$ foe
- compare to core gravitational binding:
  for uniform sphere $E_{\rm grav} = 3/5\, G M_{\rm core}^2/R \sim 10^{50}$ erg $= 0.1$ foe

*Q: and so?*

# Type Ia Explosion Physics

**thermonuclear energy** powers explosion

*not* gravitational energy!

`www: Type Ia simulation movie, Chicago group`

white dwarf entirely unbound, disrupted, ejected

- Type Ia should leave *no compact remnant*
- all nucleosynthesis products ejected

Neutrinos?

- expect some relatively low-energy $\sim 3$ MeV emission from $\beta$ decays, but a "fizzle" compared to core-collapse

# Type Ia Supernova Nucleosynthesis

in thermonuke explosion:

*all* nucleosynthesis is from *explosive burning*

(in contrast to core-collapse case)

most of star "cooked" to $T \sim 1$MeV

driven to nuclear statistical equilibrium

- favors most tightly-bound elements: *iron peak*

- yields peak at $m_{\rm Ia,ej}(^{56}{\rm Fe}) \sim 0.5 M_\odot$
  $\sim 5 - 10$ times more than typical core-collapse Fe yields
  also large amounts of Cr–Ni

- but traces of Mg Si, S, Ca observed: not all star in NSE
  requires some burning occur at lower $T$:
  "deflagration–detonation" transition

# Type Ia Supernovae: Whodunit?

general agreement: SN Ia require white dwarf & companion
good news: binary systems common
bad news: *still* no consensus, and no direct evidence,
on nature of binary companion

**single degenerate**
binary companion is a star in giant phase
mass transfer to white dwarf
companion survives explosion

**double degenerate**
binary companion is another white dwarf
merge after inspiral due to gravitational radiation

Problems with either!

*Single-Degenerate:*

- explosion should evaporate some of companion atmosphere
  why no H seen in supernova spectrum?
- No success (yet?) in direct searches for runaway companions
  in Type Ia SN remnants
  $\rightarrow$ limits imply companion must be dim $\rightarrow$ low mass
  but then must be very close binary to transfer mass
  so why no H in spectrum?

*Double-Degenerate:*

- WD-WD inspiral times long unless very close binary
  *no* WD binaries seen with $\tau_{\text{inspiral}} < t_0$
  ...but could this be a selection effect?
- WD-WD merger could lead to neutron star formation
  "accretion induced collapse," inward burning

## SN Ia Population Studies: Everybody Does It?

SN Ia population constraints: (Maoz 2008)

observed SNIa rate $\approx$ 15% *all* $3 - 8M_\odot$ star death rate

but SNIa candidates

- *must* (?) be in binaries ... and can't double-count: $\leq 1$ SN Ia per binary! and so $\leq 0.5$ SN Ia/star,
- *and must* have total mass $m_{\text{tot}} > M_{\text{Chandra}}$,
- *and must* have short periods = close orbits

Relevant comparison:

SNIa $\sim$ 100% $3 - 8M_\odot$ close binaries $> M_{\text{Chandra}}$ !



Type Ia path must be dominant $3 - 8M_\odot$ endpoint!

$\rightarrow$ strains all models!

# Supernovae and Abundance Signatures

Core collapse:
$\alpha$-elements ($^{16}$O, $^{12}$C, $^{20}$Ne, $^{24}$Mg, $^{28}$Si, $^{22}$S)
Fe group (Ca, Fe, Ni)

Thermonuke:
dominated by Fe group

Composition of an astrophysical object
gives clue to supernova contributors $\rightarrow$ past evolution
$\rightarrow$ *abundances encode nucleosynthesis history*

*Q: which occurs first in the universe? testable consequences?*

# Evolution of Supernova Nucleosynthesis

Evolution timescales very different:

- SN II: massive stars, short lived
- SN Ia: need WD → intermediate mass → longer lived

⇒ time ordering: first SN II, then later SN Ia

*Solar system*: mix of both `www: Solar Abundances`

*oldest stars* (globular clusters and "halo stars"):

→ SN II only and so expect

$$\left(\frac{\mathrm{O}}{\mathrm{Fe}}\right)_{\odot} = \frac{\mathrm{O}_{\mathrm{II}}}{\mathrm{Fe}_{\mathrm{II}}+\mathrm{Fe}_{\mathrm{Ia}}} \tag{1}$$

$$\left(\frac{\mathrm{O}}{\mathrm{Fe}}\right)_{\mathrm{halo}\star} = \frac{\mathrm{O}_{\mathrm{II}}}{\mathrm{Fe}_{\mathrm{II}}} > \left(\frac{\mathrm{O}}{\mathrm{Fe}}\right)_{\odot} \tag{2}$$

Observed!

also expect $(\mathrm{O/Si})_{\odot} \simeq (\mathrm{O/Si})_{\mathrm{II}}$
and so $(\mathrm{O/Si})_{\mathrm{halo}} \simeq (\mathrm{O/Si})_{\odot}$
Observed!