Astro 350

Lecture 24

March 23, 2022

Announcements:

- **Discussion 6 due Wednesday**
- **Homework 6 due Friday**
- Office Hours after class today

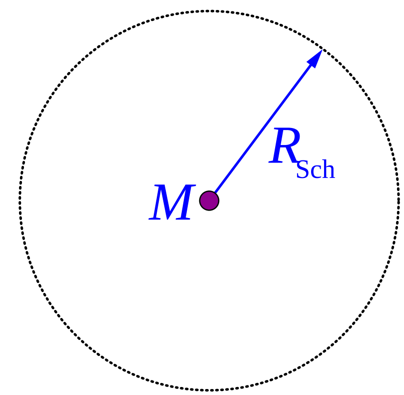
Last time: **black holes**

- *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**

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




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

**horizon**: surface enclosing the BH

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

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

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

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

$\rightarrow$ infalling objects slow and fade away

# Our Own Galactic Center

central $\sim 30$ 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

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

→ 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 months: discovery of high-energy "bubbles"
  above & below Galactic center `www: gamma-ray images`
  → 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

orbits near center $\rightarrow$ rotation curves
allow us to find mass: typically $M \sim v^2 r/G \sim 10^8 M_\odot$!

Huge masses in tiny regions:
**most (all?) galaxies host supermassive black holes!**

But note: impressive as supermassive BHs are
they represent a tiny part of thier host galaxy's mass
they are not what holds galaxies together, still need dark matter

# 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 $> 10^9 M_\odot$
$\star$ *M87 hosts a supermassive black hole:* **M87***
$\star$ 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:
*make the first* **images** *and* **movies** *of black holes!*
most promising candidates: M87* and SgrA*

challenge: tiny angular size of emitting region
need unprecedented angular resolution

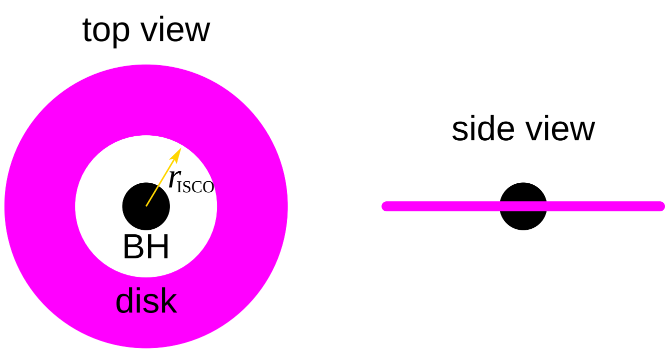
solution: spread telescopes over entire Earth
"very long baseline interferometry"
combined resolution is that of Earth's diameter!

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!

# 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 sky
- 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*!

# Supermassive Black Holes: Outlook

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

black hole mass correlated with host mass
galaxies and supermassive BHs seem to grow together–why?

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

These remain open research questions!

# Gravitational Radiation

Black hole weirdness illustrates key aspects of General Relativity:
⋆ gravity and spacetime linked
⋆ spacetime is *dynamic*, affected by gravitating objects
like weights on a rubber sheet

Consequence: moving masses cause "ripples in spacetime"
like accelerating charges cause ripples in electromagnetic field
= EM radiation!
⇒ moving masses emit **gravitational radiation**
propagating distortion in spacetime
also carries away energy (and angular momentum)

*Q: what does this wave emission mean for the orbits?*

# Gravitational Wave Sources

expected signal is amazingly tiny
only hope to see strongest sources:
most violent disturbances, highest gravity, fastest motions

- **binary pair of neutron stars**

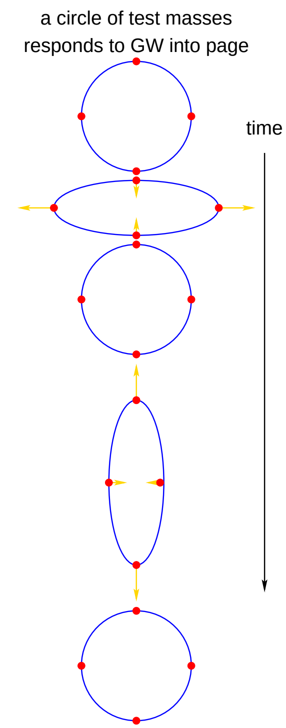
neutron stars in pairs (binaries)
orbit $\rightarrow$ emit gravity waves $\rightarrow$ lose energy
$\rightarrow$ fall in $\rightarrow$ decrease period $P$

strategy: search for a pulsar in a binary system
with a neutron star as the partner


observed! "binary pulsar" shows exactly the expected orbit decay
indirect evidence of GW! $\rightarrow$ Nobel Prize!

# Gravitational Wave Effects

EM waves: oscillating EM fields
effect: charges accelerated
measure by: currents in antenna (power!)




gravity waves: oscillating spacetime ripple
  expansion $\leftrightarrow$ contraction
effect: test masses accelerated
measure with: compare lengths of perpendicular arms
  tiny effect $\rightarrow$ mind-boggling precision needed
  arm length change: *strain* $h \equiv \Delta L/L \sim 10^{-21}$!

to detect directly: measure time-changing strain due to wave

- very long arms $L \sim 2$ km
- compare lengths via gigantic interferometer
- build multiple observatories to confirm (and localize) signal

www: LIGO, Virgo

# Director's Cut Extras

# Time Dilation and Falling Light

consider light wave:
emitted with wavelength $\lambda_{\text{em}}$, frequency $f_{\text{em}}$
$\rightarrow$ wave crest emitted every $(\Delta t)_{\text{em}} = 1/f_{\text{em}}$ seconds

But observer in region with stronger gravity
will see downgoing wave crests every $(\Delta t)_{\text{obs}} < (\Delta t)_{\text{em}}$ sec
while observer in region with weaker gravity
will see upcoming wave crests every $(\Delta t)_{\text{obs}} > (\Delta t)_{\text{em}}$ sec

*Q: what does this mean for observed light properties:* $f_{\text{obs}}$? $\lambda_{\text{obs}}$?

# Gravitational Redshifting of Light

When distant emitted in *strong* gravity region
seen by observer in *weak* gravity region
upcoming light crests at intervals $(\Delta t)_{\rm obs} > (\Delta t)_{\rm em}$
and so frequency is *lower*: $f_{\rm obs} = 1/(\Delta t)_{\rm obs} < f_{\rm em}$
while wavelength is *longer*: $\lambda_{\rm obs} = c/f_{\rm obs} = c(\Delta t)_{\rm obs} > \lambda_{\rm em}$
$\Rightarrow$ longer $\lambda \rightarrow$ redshift: **gravitational redshift**

Similarly, when downgoing light observed, grav blueshift

1960s: gravity redshifts observed in lab
Harvard experiment: laser from basement to attic!
(big technical challenge due to small shift in weak Earth gravity)
$\rightarrow$ Big AI confirmed again (but of course!)

# Supermassive Black Holes

our Milky Way galaxy has supermassive BH: "quiet" $=$ low $L$
active galaxies have supermassive BH: huge $L$

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
$\rightarrow$ $\boxed{M_{\rm BH}/M_{\rm sph} \sim const \sim 0.006}$
constant "BH fraction"
$\rightarrow$ supermassive BH formation is part of gal formation!

Open Questions:

- how does a $10^{7-8} M_\odot$ BH ($R_{\mathrm{Sch}} \sim$ 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?