Astro 404

Lecture 39

December 3, 2021

Announcements:

- **PS12–last one!–due today**
- Good news: no homework next week!
- Bad news: Final Exam Mon Dec 13, 1:30–4:30 pm
  info is on Canvas

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?

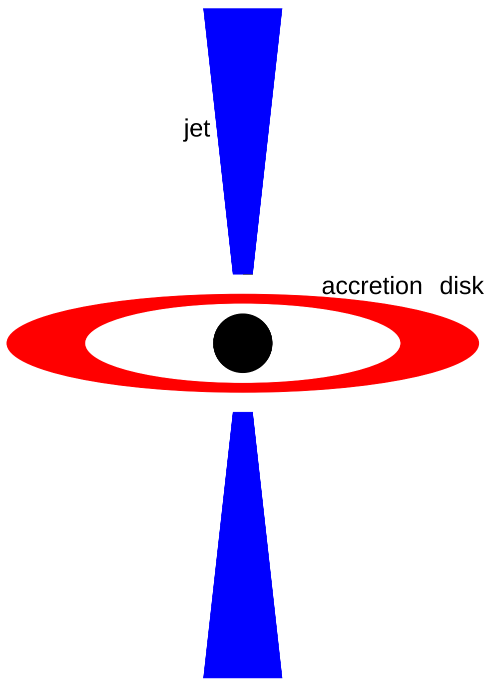
Stellar Mass Holes $\sim 5 - 10 M_\odot$

- found in binaries–inferred from effect on companion star
- companion moves around unseen massive object
- X rays seen from infalling accreting gas

Supermassive Black Holes $\sim 10^6 - 10^9 M_\odot$

- seen at centers of Galaxies–including ours!
- Milky Way: Sgr A^* seen via stellar orbits

Supermassive black holes inhabit most galaxies
seen via feeding: accretion
infalling material forms a disk
ejects high-energy jet



disk and jet are huge luminosity sources
accreting SMBHs: **active galactic nuclei: AGN**
f

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

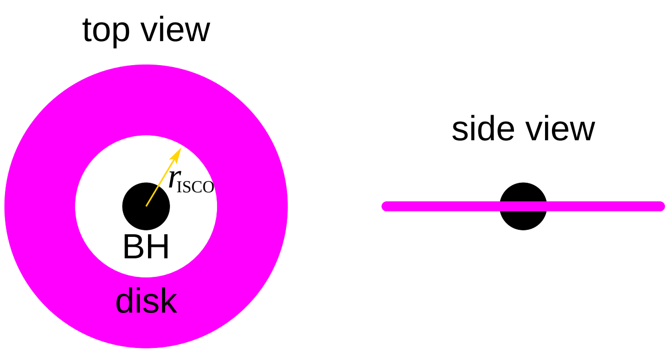
solution: spread telescopes over entire Earth
"very long baseline interferometry"
combined resolution is that of Earth's diameter!

April 2019: success! EHT presents image of M87*

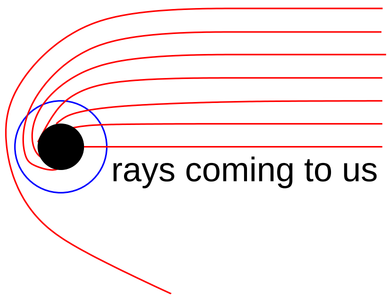
Imaging a Black Hole: Expectations

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, $r_{\text{isco}} = 6GM/c^2$



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?

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

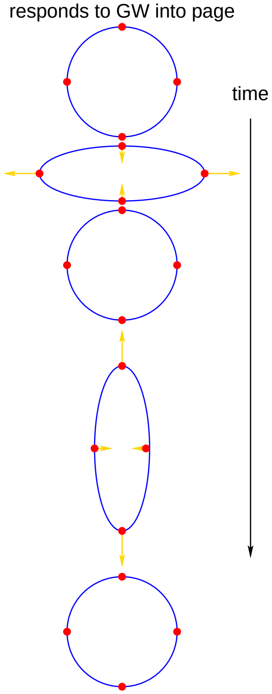
• **binary pair of neutron stars**
neutron stars in pairs (binaries)
orbit $\rightarrow$ emit gravity waves $\rightarrow$ lose energy
$\rightarrow$ fall in $\rightarrow$ decrease period P

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: test charges accelerated
measure by: currents in antenna $\to$ power!



gravity waves: oscillating spacetime ripple
  expansion $\leftrightarrow$ contraction
effect: test masses accelerated
measure with: compare lengths of perpendicular arms
  tiny effect $\to$ 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`

Gravitational Wave Observatories

online now: ground-based detectors sensitive to binary mergers with stellar masses

Advanced LIGO: operational since 2015 `www: LIGO`
interferometers (detectors) in Washington state and Louisiana

VIRGO: operational since 2017
one detectors near Pisa, Italy; less

when possible signal reported:

- confirm with multiple detectors
- localize on the sky
- scan that region with telescopes!

GW 150914

Sept. 14, 2015:
gravitational wave signal appears in both LIGO detectors!
`www: GW 150914 signal`

strain pattern $h(t)$ matches textbook predictions
for **merging black holes**!!

- early signal: increasing frequency and amplitude – **inspiral**
- peak signal: maximum amplitude, very rapid variability – **merger**
- late signal: decreasing amplitude – **ringdown**

binary masses: $36^{+5}_{-4} M_\odot$ and $29^{+4}_{-4} M_\odot$
final mass: $62^{+4}_{-4} M_\odot$
converted to gravity wave energy: $3.0^{+5}{-5} M_\odot c^2$
distance: ~ 400 Mpc ≈ 1 billion light years

AMAZING! *Q: because?*

First LIGO Event: Revolution

this single detection of binary black hole merger
which lasted ~ 0.1 sec in total
has profound implications

LIGO for the first time:
- directly detected gravitational radiation
- revealed nature produces black holes $> 10 M_{\odot}$
- showed that BH binary systems exist
- ...and can collide within the age of the Universe
- observed the birth of the final black hole
- verified and quantified the gravity wave energy release

And: **LIGO inaugurated the age of gravity wave astronomy**

Update: LIGO/Virgo Black Holes

LIGO/Virgo ran until COVID shutdown
90 gravitational wave events detected!

signal is strongest for nearest, most massive events
$\rightarrow$ biased towards binary black holes (BH-BH) mergers

`www: LIGO/Virgo detections`

detected black hole masses before merger:

- lowest: $5.9^{+4.4}_{-1.3} M_{\odot}$
  consistent with origin in core-collapse explosion
- highest: $87^{+40}_{-23} M_{\odot}$ – very massive!
  could this be the result of a prior merger?

Open questions:

- how and where are these binaries formed?
- what is the (unbiased) distribution of black hole masses?
- do BH mergers have a detectable electromagnetic signal?

Stay tuned!

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 isolation – **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

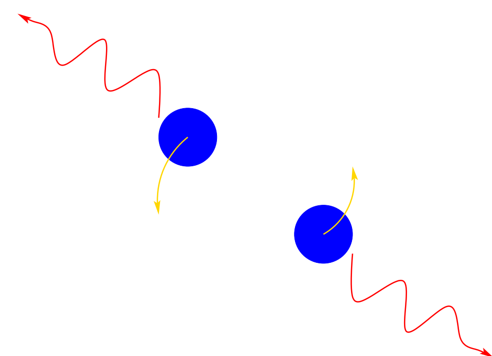
In *Newtonian* gravity, *point mass* binary orbits *in vacuum*

- 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*



Director's Cut Extras

Gravitational vs Electromagnetic Radiation

Electromagnetic Radiation

- EM sources are electric charges
- accelerating charges are sources of radiation
- most elementary source: time-varying electric dipole

Gravitational Radiation

- gravity sources are masses
- accelerating masses are sources of radiation
  but no negative mass $\rightarrow$ no gravitational dipoles
- most elementary source: time-varying mass quadrupole