Astro 404
Lecture 37
Dec. 2, 2019

- **Problem Set 12 out, due Friday Dec 6**
  Office Hours: instructor: after class or by appt
  TA: Thurs noon-1pm or by appt
- Note: lowest of 12 homework scores dropped!
  But: you are still responsible for material on **all HW**

- **Hour Exam returned today, Scores on Compass**

- **Research Opportunitiy**

Professor Karin Dahmen (Physics) looking for students
for project bringing novel tools and models to astronomy
study involves stellar astrophysics!
contact her via email: `dahmen@illinois.edu`

Anachronistic News Network
Point⇔Counterpoint: Gravity

Moderator–G. Galilei: The discussion today–what is gravity? Ike, what say you?

I. Newton: Gal, gravity is but one example of a **force**–a particularly beautiful one, to be sure (did I mention I invented it?) but a force like any other (e.g., the electrostatic force of that Frenchman, Coulomb).

Galilei: Let me stop you right there, Ike. My work in Pisa has shown that all objects fall at the same rate, regardless of their mass, shape, or composition. If you understood my work, you'd realize that that gravity is a uniquely special force!

Newton: There you go again, Gal. If you'd let me finish, I was going to explain. Any object has an **inertial mass**, which determines its response to acceleration–making massive objects harder to speed up: $a \propto F/m_{\text{intertial}}$. But an object also has **gravitational mass** which sets the strength of its coupling to the gravitational field–making massive objects heavier: $F_{\text{grav}} = m_{\text{grav}}\, g$. Now it so happens that an object's inertial mass is the *same* as ist gravitational mass. This particular accident leads to the result you observed and I explained.

A. Einstein: I have to jump in here. We know that objects fall the same way, regardless of any of their properties. This is the **equivalence principle**. Gravity is a unique interaction in being so democratic in its influence. Ike would have us believe that this is just a curious coincidence. But since falling is so universal, its origin is obviously best found in the very structure of space and time, not in some miraculous force. This is the heart of General Relativity (which by the way behaves the same as Newton's theory when gravity is weak). GR says that spacetime is "curved" and that motion in a gravity field ("falling") is a response to this curvature, much as a ball rolling on a dimpled, rubber sheet.

A. Einstein: I might add that this curvature has many consequences, one of which is that even light rays should be bent by gravity. Which by the way I predicted and was confirmed in observations during the 1919 solar eclipse. In your face, Ike!

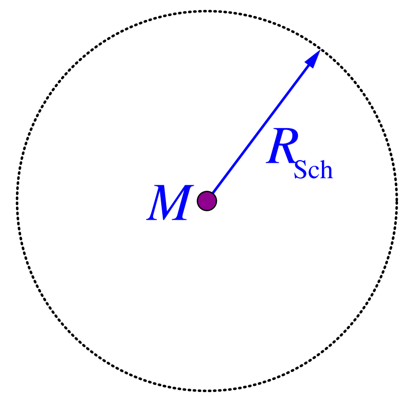
Galileo: Oooh–snap! More when we come back after these important messages from our sponsors...

Last Time: General Relativity & Black Holes–Theory

black hole of mass M has

size: Schwarzschild radius

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



- recipe: to turn *any* mass M into a black hole crush to size smaller than R_{Sch}

Q: what is a black hole? key features?

Q: how's it black? how's it a hole?

Q: what's life like near and far from a black hole?

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

$$r_{\mathrm{Sch}} = 1.1 \times 10^7 \ \mathrm{km} = 0.74 \ \mathrm{AU} = 3.6 \times 10^{-7} \ \mathrm{pc} \qquad (1)$$

→ 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
  why? open question....
- in the past few years: 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
spectral lines broad $\rightarrow v_{\mathrm{rms}} \gtrsim 10,000$ 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: $v \approx c$, 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

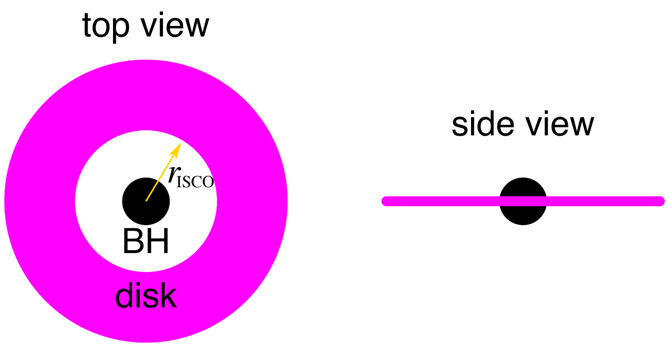
solution: spread telescopes over entire Earth
"very long baseline interferometry"
combined resolution is that of Earth's diameter!

April 2019: success! EHT presents image of M87*

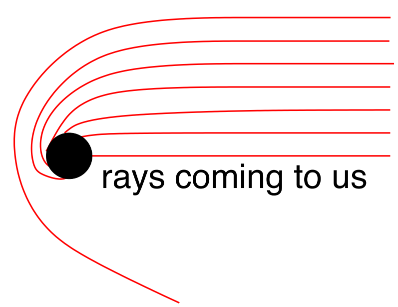
Imaging a Black Hole: Expectations

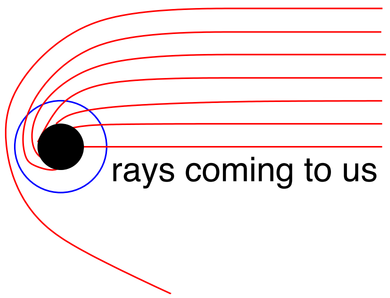
physical picture:

- 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 $r = 3R_{\text{Sch}} = r_{\text{isco}}/2$, 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