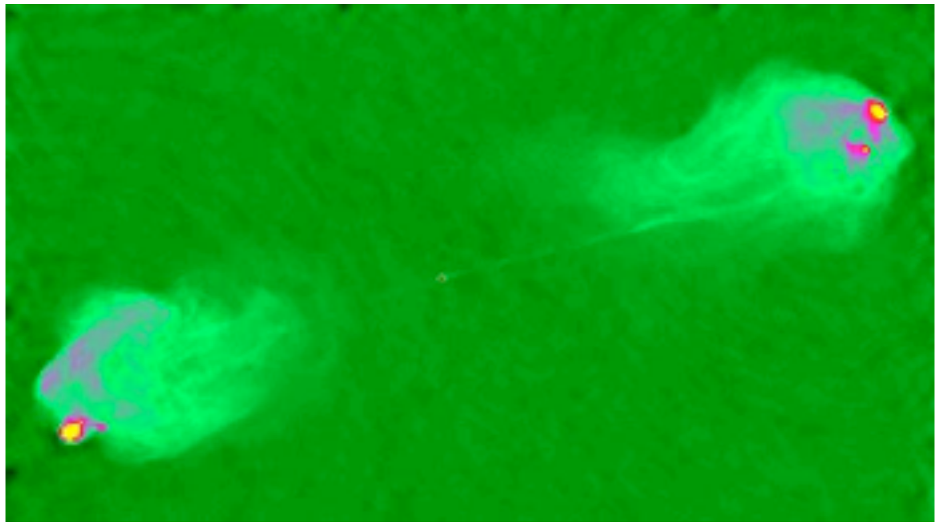
Astronomy 150: Killer Skies
Lecture 30, April 9

Assignments:

- HW9 due Friday
- Computer Lab 2 posted, due April 20
- Solar Observing last chance today!

Last time: Black Holes

Today: Death by Black Hole



Anachronistic News Network
Point⇔Counterpoint: Gravity

Moderator–Galileo Galilei:

The discussion today–**what is gravity**?

Ike, what say you?

Isaac Newton:

Gal--I can call you Gal, right?--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 electric force of that cheese-eating Frenchman, Coulomb).

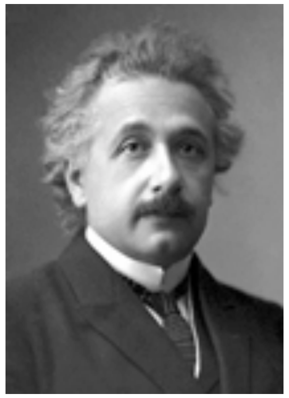
Galilei:

Let me stop you right there. My work in Pisa has shown that all objects fall at the same rate, regardless of their mass, shape, or composition. Seems like a pretty special force to me!

Newton:

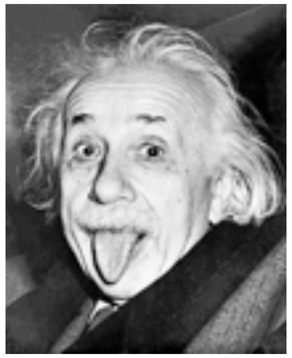
There you go again, Gal. If you'd let me finish, I was going to explain. Any object has an inertial mass, which determines its response to acceleration–making massive objects harder to speed up: $a \propto F/m_{\text{intertial}}$. But an object also has gravitational mass which sets the strength of its 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.

Albert 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.

Einstein:



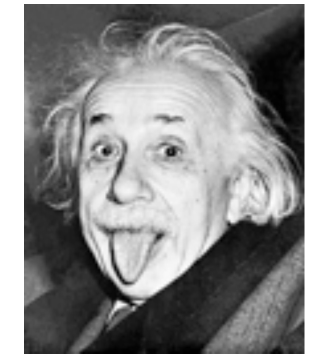
This is the heart of General Relativity (which by the way behaves like Newton's gravity when the gravity is weak). General Relativity says that space and time are "curved" or "warped," and that motion in a gravity field ("falling") is a response to this curvature, much as a ball rolling on a dimpled, rubber sheet.

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...

Recap: Black Holes

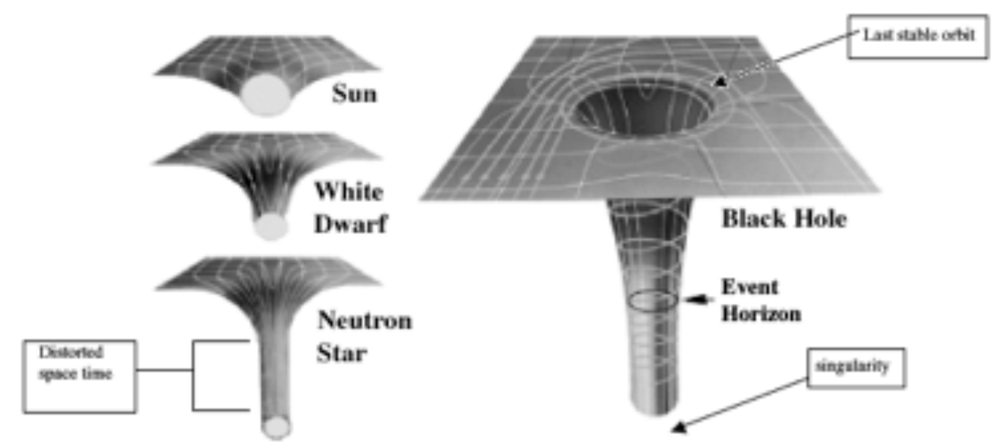


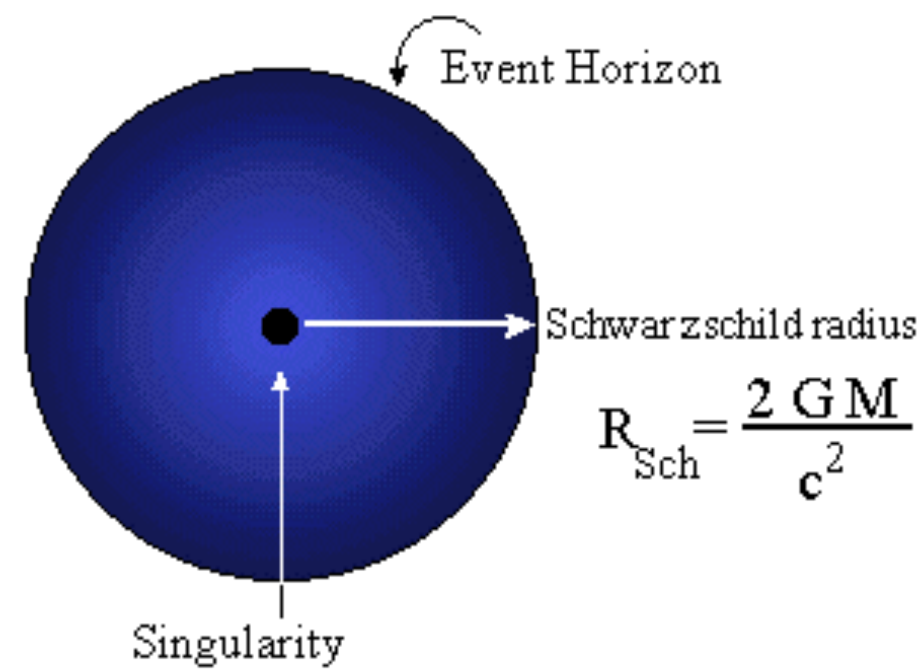
Black Hole Anatomy

- any object of any mass M can be a black hole
- **Schwarzchild radius**:

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

- black hole recipe: crush mass M to size $<R_{\rm Sch}$
- **horizon**: spherical surface at
  one-way membrane: "point of no return"
  inside: escape speed $> c$
- if pass through horizon, unavoidably fall to center
  point(?) at center: **singularity**
  all BH mass in zero volume!? laws of physics break down
- infalling mass grows BH mass and size: $R_{\rm Sch} \propto M$

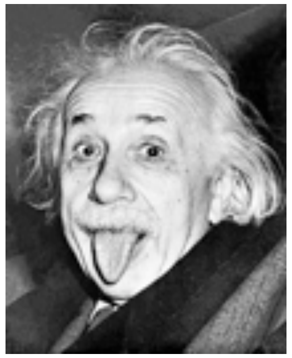




Black Hole Lifestyles

- to an **observer far away**:
  clocks near horizon appear to run slowly
  light emitted from near horizon arrives with longer wavelengths
- to an **observer near horizon**:
  clocks far away appear fast,
  light from afar has shorter wavelengths
- black hole gravity "warps" space and time

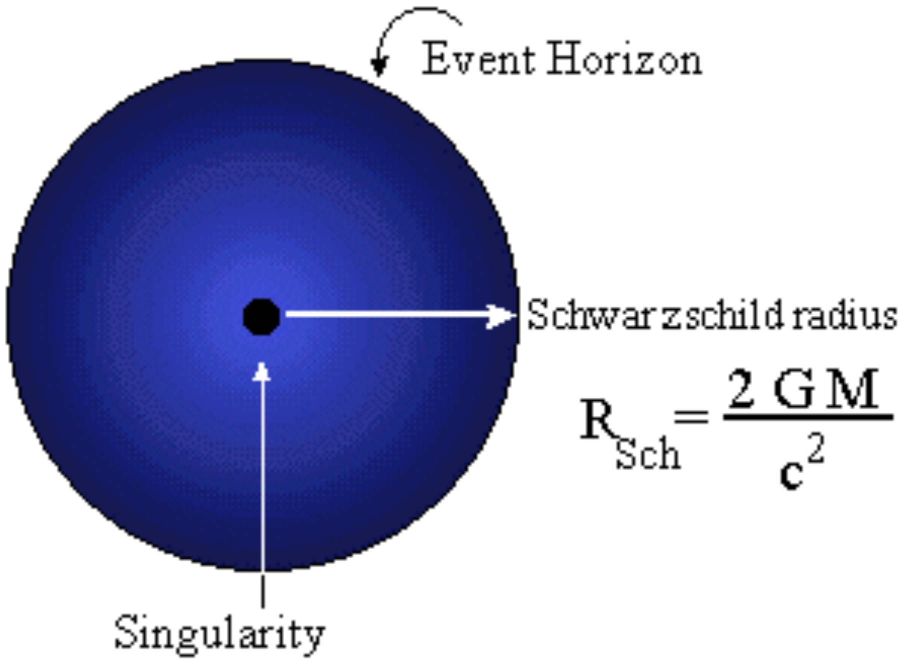
Recap: Black Holes



Black Hole Gravity

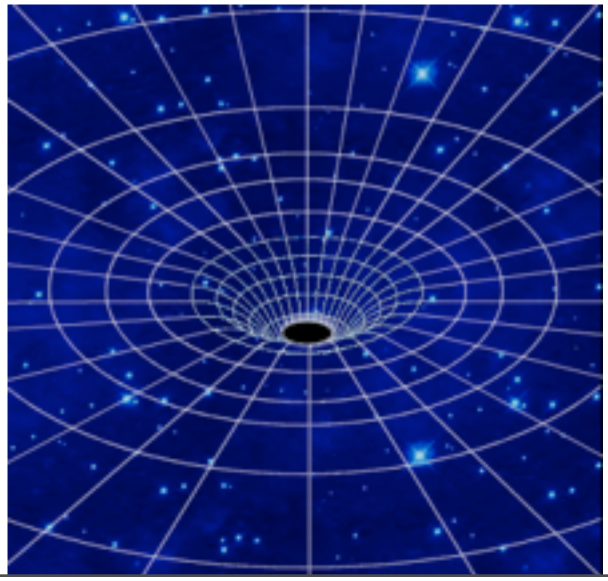
- near horizon: very intense and dangerous
- much more on that today
- but from afar--same gravity as non-BH of mass *M*
- black holes only a threat when nearby

  otherwise gravity no worse than an ordinary nearby star



Note: so far, BH discussed as theoretical objects

Q: how to "see" one to test theory? No light escapes!!



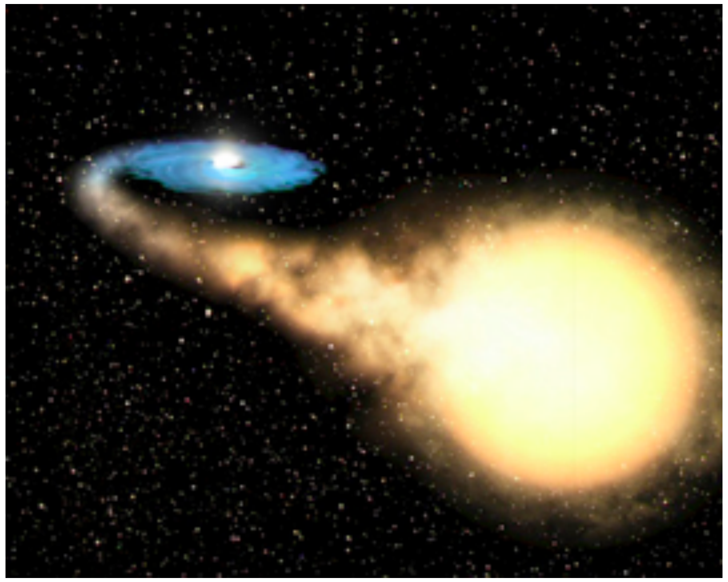
Evidence for Black Holes

recall: in death of $M > 30M_{sun}$:

- gravity wins, collapse unstoppable
- black hole formed
- should be inevitable part of star formation

how detect?

- no light emitted from BH, can't see directly. but:
- can observe matter interacting with BH before falling in

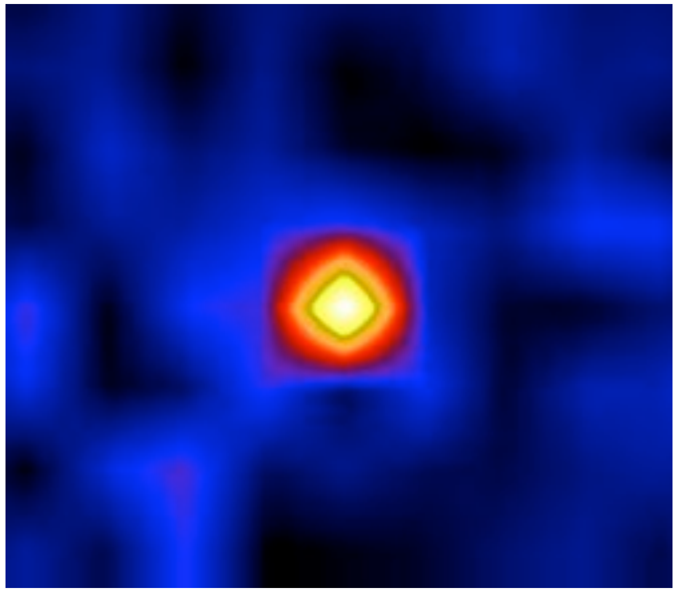


X-ray Binaries:

stellar-mass black holes (mass of a few M_{sun}) with partner star in binary

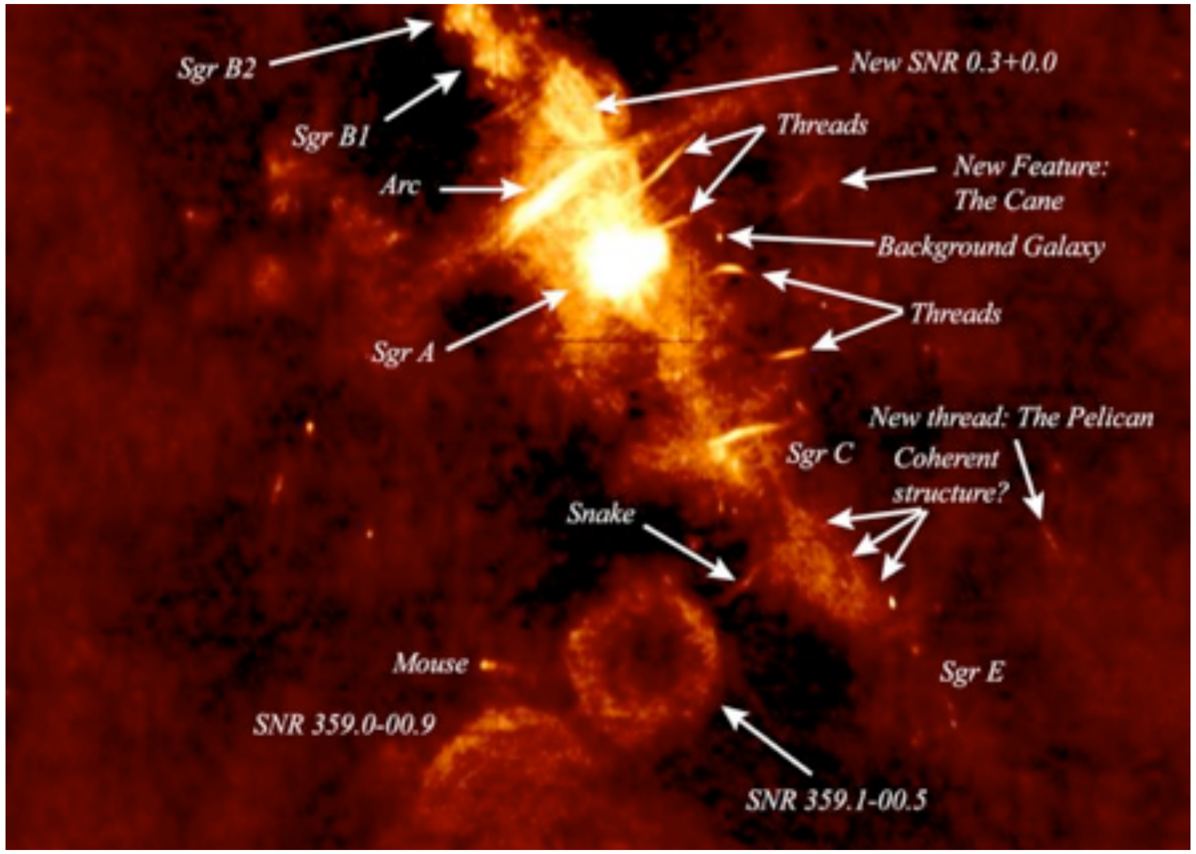
- how? massive star born in bound system with less massive star
  - larger star → SN → BH left behind
- if supergiant companion, close orbit:
  - some gas falls onto BH
- compressed, heated → X-rays

what you see: giant star orbiting unseen massive companion, and emitting X-rays



Cygnus X-1
X-ray binary with black hole

Our Own Galactic Center



at center of our own Milky Way Galaxy:

- can't see optically
  - stuff between here and there blocks visible light
- but see can in other wavelengths:
  - radio emission (Sagittarius A) from high-energy electrons e
  - radio source at exact center (?): Sgr A*

Sagittarius A*: object at the very center of the Galaxy

- size 2.4 AU(!),
- variable emission in radio, X-ray
- in infrared wavelengths: can see stars near Sgr A*
- and they move!
- in elliptical paths!

closest star S0-2:

- period P = 15.2 yr
- semi-major axis: a = 0.005 pc
- star orbits unseen mass of $4 \times 10^6 M_{sun}$
  - 4 million Suns!

Q: and so?

The Monster Lurks

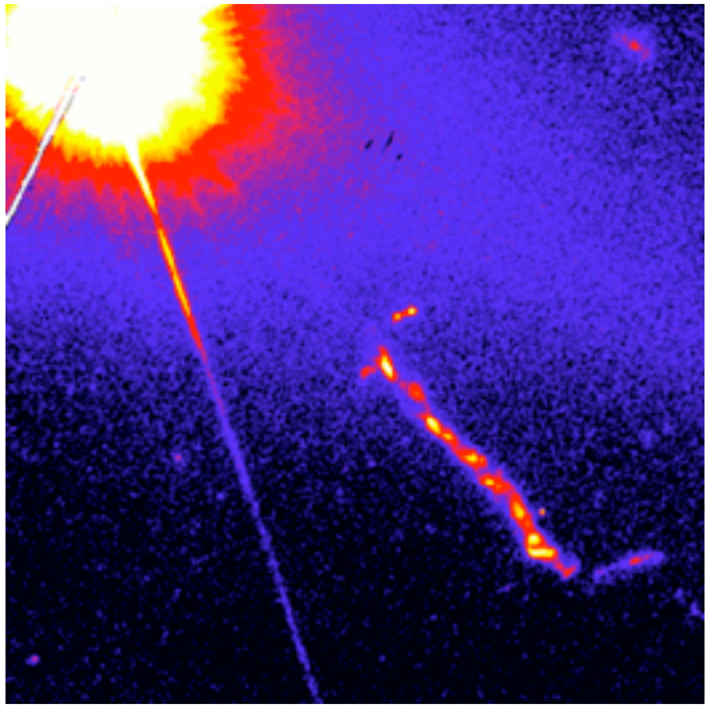
the center of our Galaxy contains a black hole!

- **supermassive**:
  mass >>black hole from supernova
- Sgr A* Schwarzchild radius
  $R_{\rm Sch}$ = 11 million km = 0.74 AU = 3.6×10^{-7} pc
- radius too small for current telescopes to see
  but upcoming missions should see horizon!

Many questions for astronomy and cosmology:

- how did it get there?
- Sgr A* low luminosity, "quiet"
  compared to what is seen a centers of "active" galaxies
  why? open question....

Galaxies and Black Holes



The Milky Way is not the only galaxy with a central black hole!

a small fraction of galaxies are "active":

- most light (luminosity) not from stars but from galactic central nucleus:
- active galactic nuclei = AGN

spectrum of material near nucleus:

- big doppler shifts→ orbit speeds > 10, 000 km/s!

to maintain such huge speed, need huge gravity

- and thus huge mass
- typical AGN mass: 10^8 M_{sun} = 100 million suns!
- much more massive than our own Sgr A*!

AGN vary w/ time:

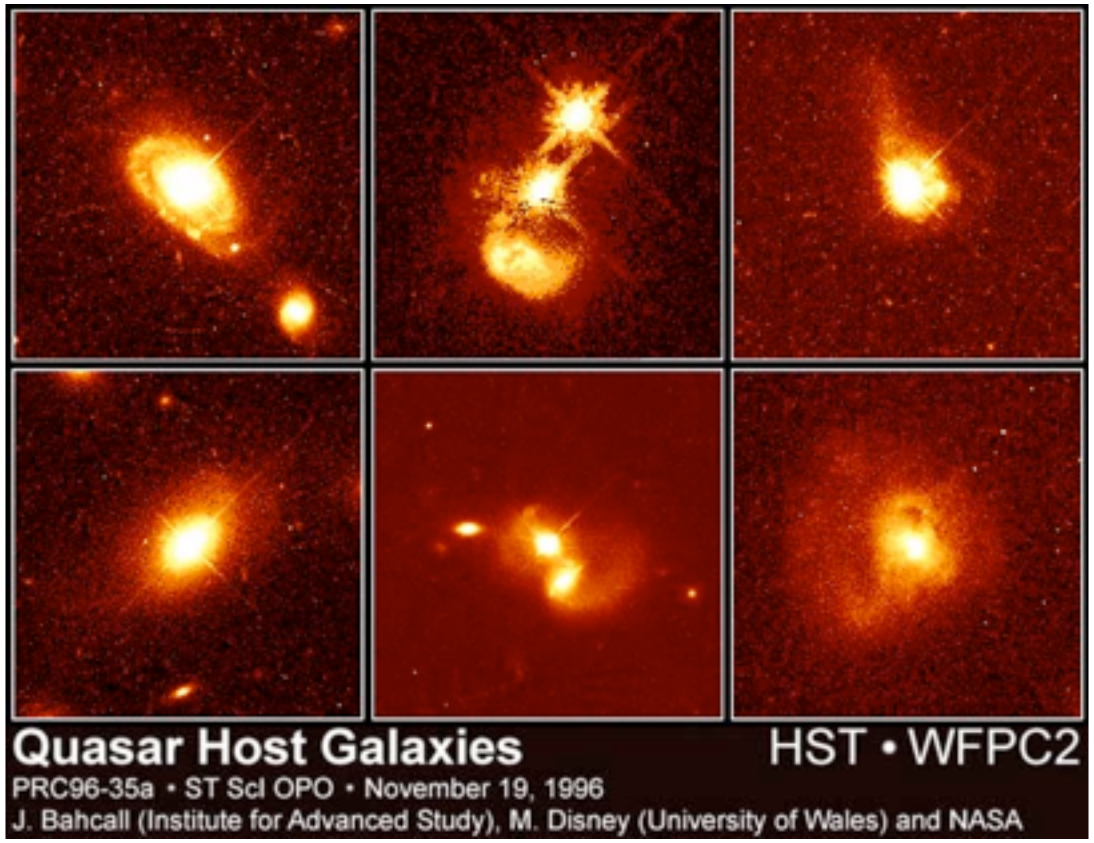
- large fluctuations in brightness over times of t ~ weeks
- so size d< ct = 1000 AU: tiny!

Huge mass in tiny region:

- black hole, supermassive!

AGN are galaxies with huge supermassive BH in center

- Hubble Telescope: AGN + "host" galaxy
- some: merging galaxies others: "undisturbed" galaxy?!



Jets and Black Hole Indigestion

Many active galaxies show unusual features:

- elongated steams of material
- stream found to be moving at speeds > 99% c!
- “relativistic jet”

AGN Jets

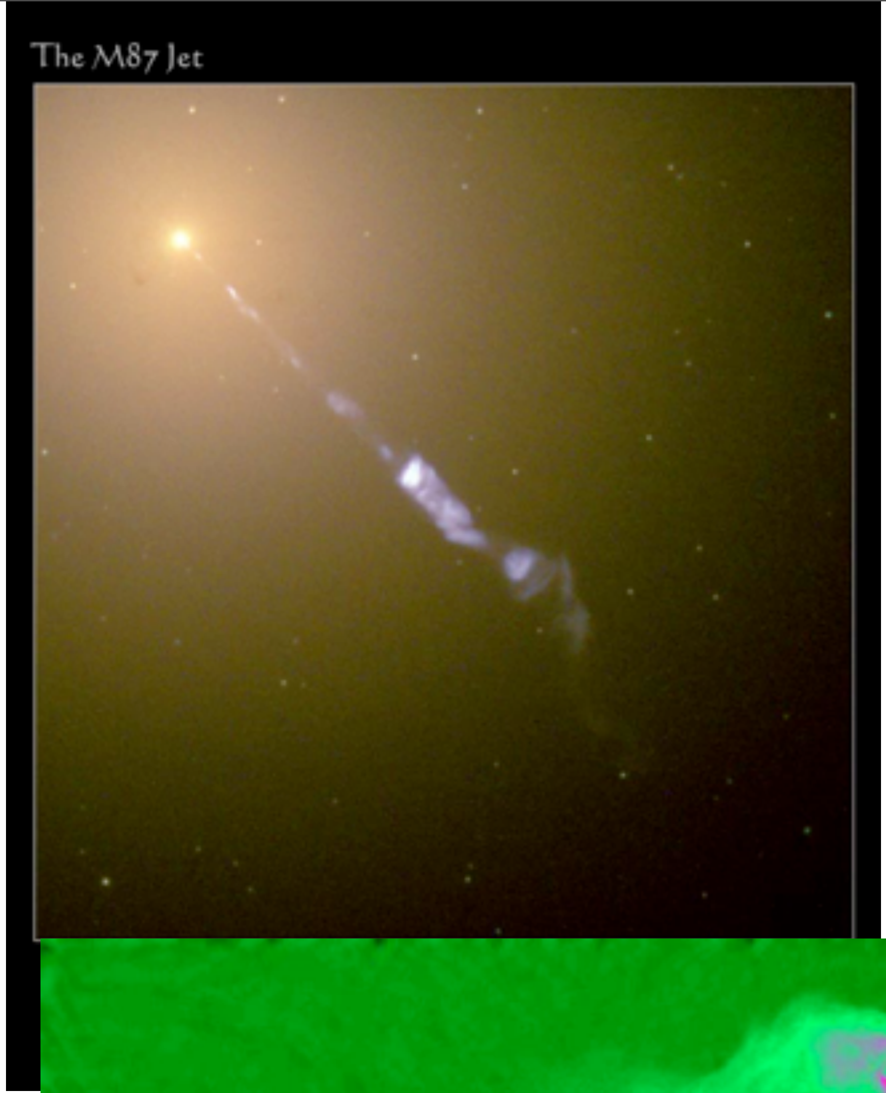
- come out of galactic center
- stretch far beyond host galaxy to huge distances
- lasts for millions of years or more (?)
- carries huge energy and intensely bright
  - would be very bad to be in this beam
  - more on this later...

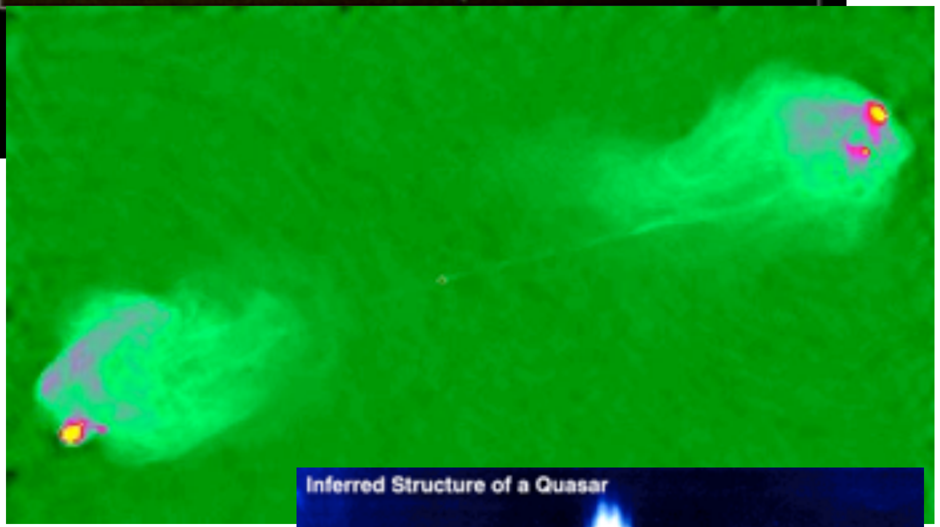
What’s going on?

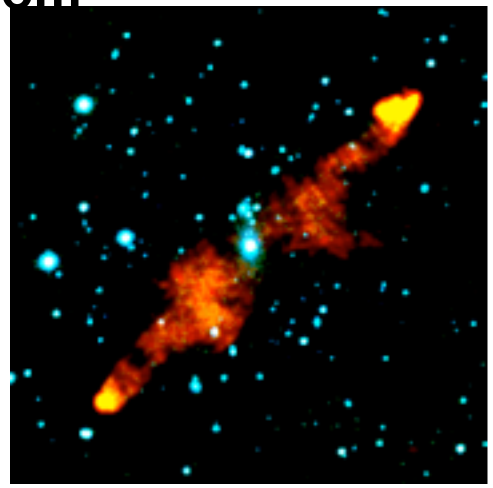
- supermassive black holes at galaxy centers are feeding, form accretion disk
- but black holes are “messy eaters”
- material that doesn’t fall in is ejected at high speed from poles

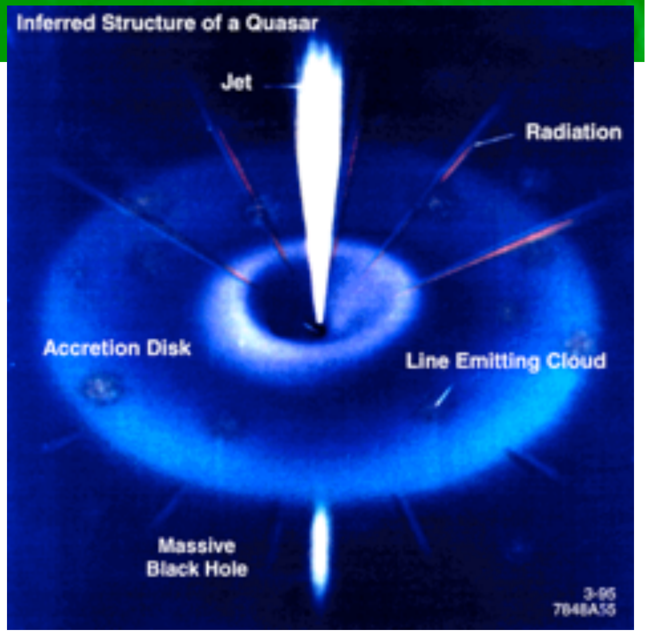
What accelerates the jet?

- still not clear! subject of active research
- some of world leaders at at Illinois (Prof Gammie)
- likely: magnetic fields of infalling gas are crucial





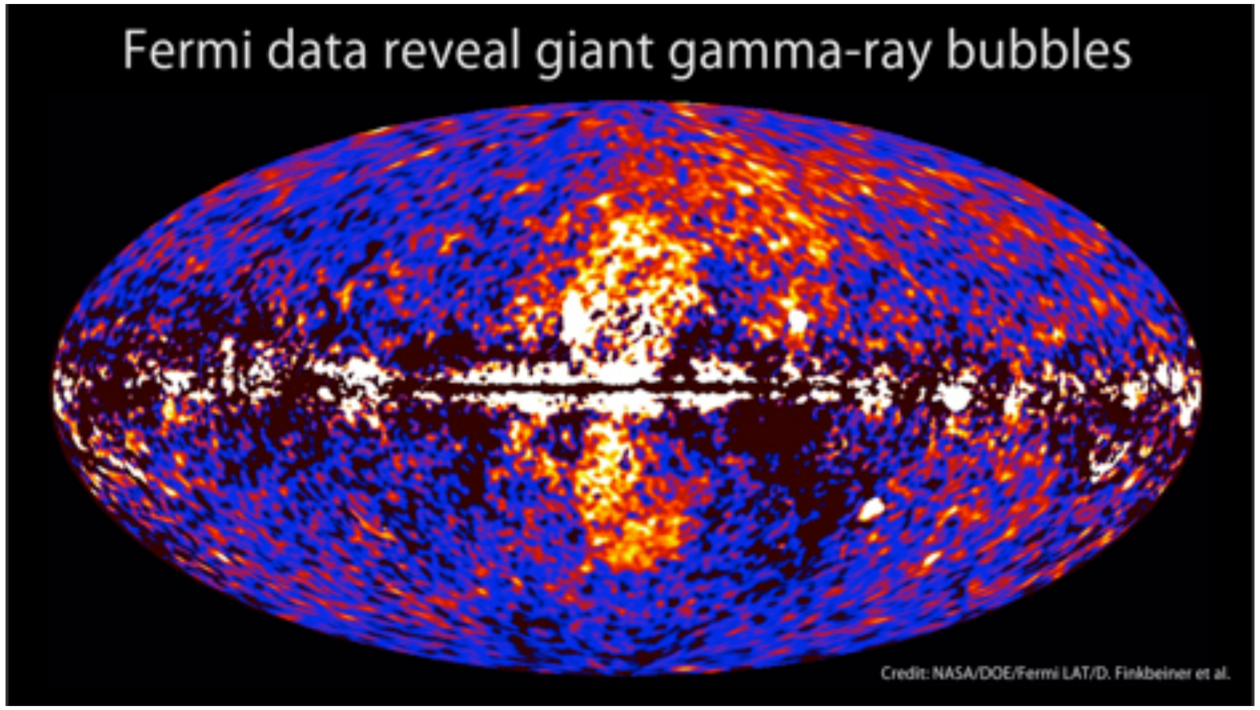




Supermassive Black Holes Everywhere

Our own Milky Way galaxy has supermassive BH:

- “modest” mass
- quiet: BH not feeding right now
- but note: 2010 discovery of “gamma ray bubbles”
  - above and below Milky Way center
  - perhaps from earlier phase of Sgr A* activity?



Active galaxies also have supermassive BH:

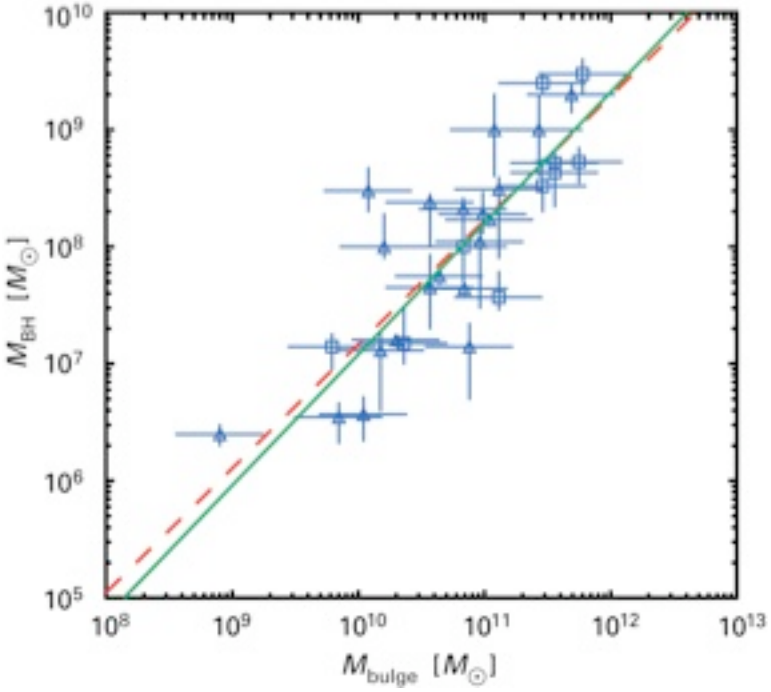
- BH is feeding: huge accretion

recent result: all galaxies have supermassive BH!

- ...but most quiet
- maybe active galaxies are phase in evolution?

BH mass correlated with host galaxy central stars (“bulge”)

- M_{BH}/M_{stars} = const = 0.006
- constant “BH fraction”



But galaxies grow and make more stars over time

- M_{stars} increases
- so to keep ratio M_{BH}/M_{stars} constant, MBH must also increase
- somehow the supermassive black holes also grow

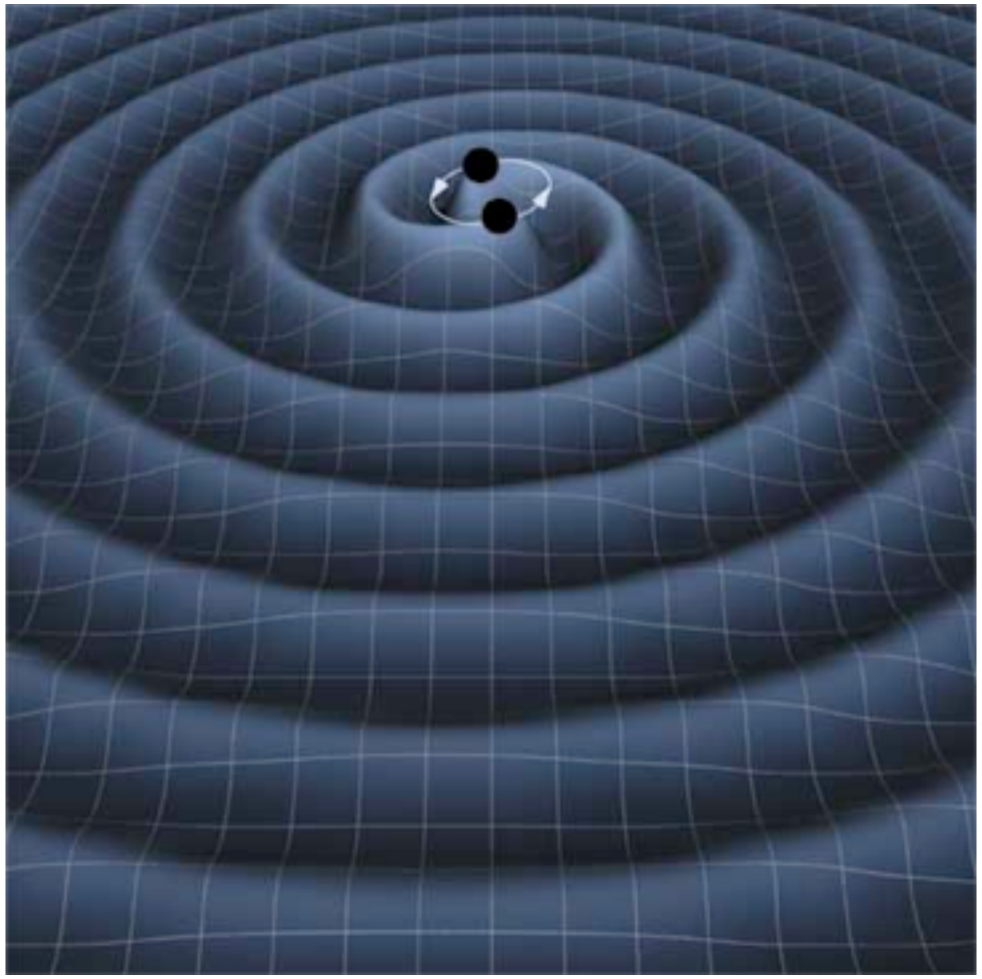
Supermassive BH formation is part of galaxy formation!

- how this happens is a huge question
  - what made the first black hole “seeds”?
  - how did they eat enough to grow? how are they fed?
  - are there any galaxies without supermassive BHs? SMBH without galaxies?

Gravitational Radiation

Black hole weirdness illustrates key aspects of General Relativity:

- gravity, space, and time linked
- space and time are dynamic and changeable
  - affected by gravitating objects
  - like weights on a rubber sheet



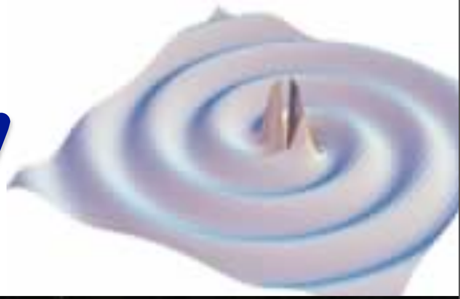
Consequence:

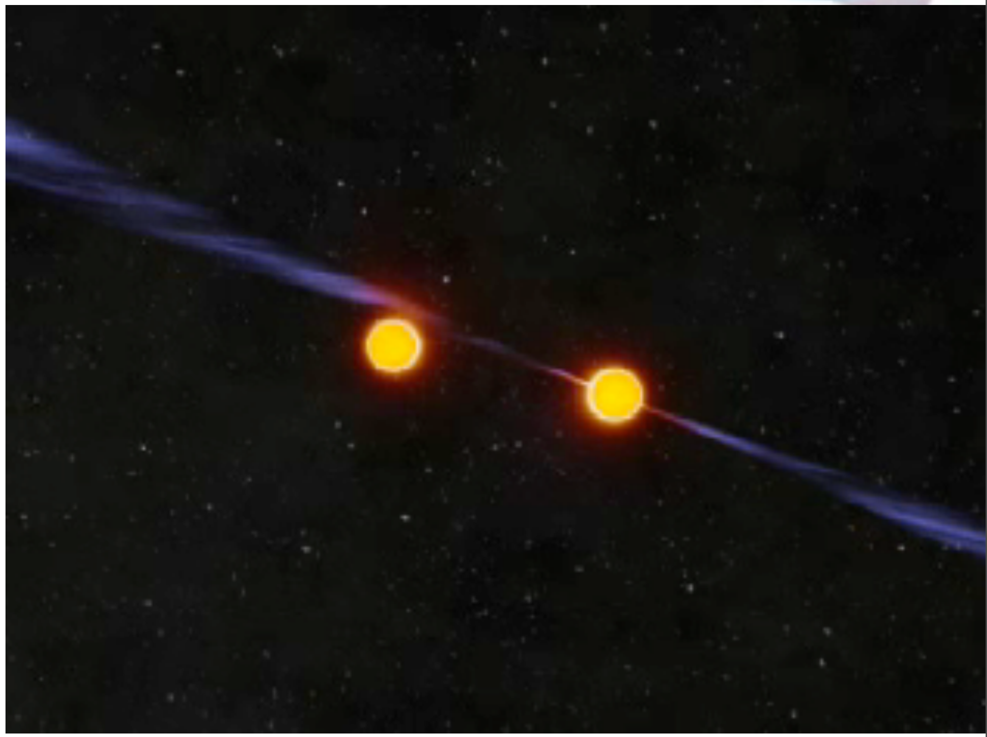
- moving masses cause "ripples in spacetime"
- like moving charges cause ripples in electromagnetic field = EM radiation!

moving masses emit gravitational radiation:

- "gravity waves"
- gravitational equivalent of light waves
- like light waves, gravity waves carry energy

Gravitational Wave Astronomy





Gravitational Radiation is key prediction of General Relativity

Test 1: Indirect

watch objects respond to losing energy via gravity waves

example: binary pair of neutron stars

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

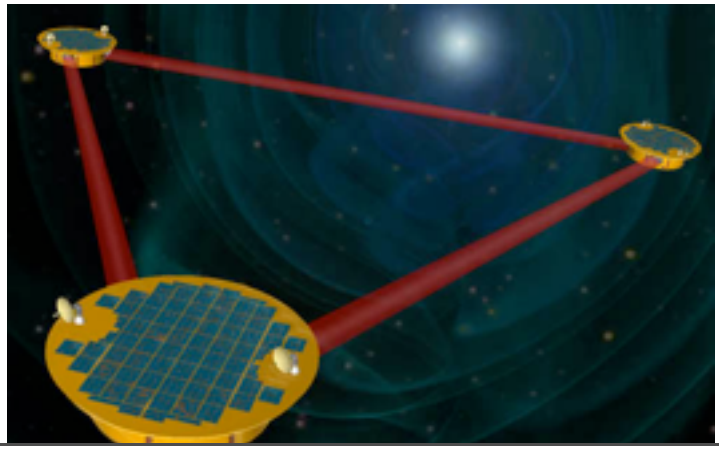
So go look for this:

- period decrease observed!
- agrees with GR prediction!
- indirect evidence of GW! Nobel Prize!

Test 2: Direct

soon will directly measure gravity waves

- gravity waves make test masses wiggle
- measure with these sensitive lasers
- can use gravity waves to watch birth of black holes from binaries, and maybe from merging of supermassive BHs



Black Hole Threat

From afar:

- black hole gravity no stronger than ordinary star of same mass
- no particular reason to worry

But nearby = near horizon:

- black hole gravity very strong
- danger is very real!

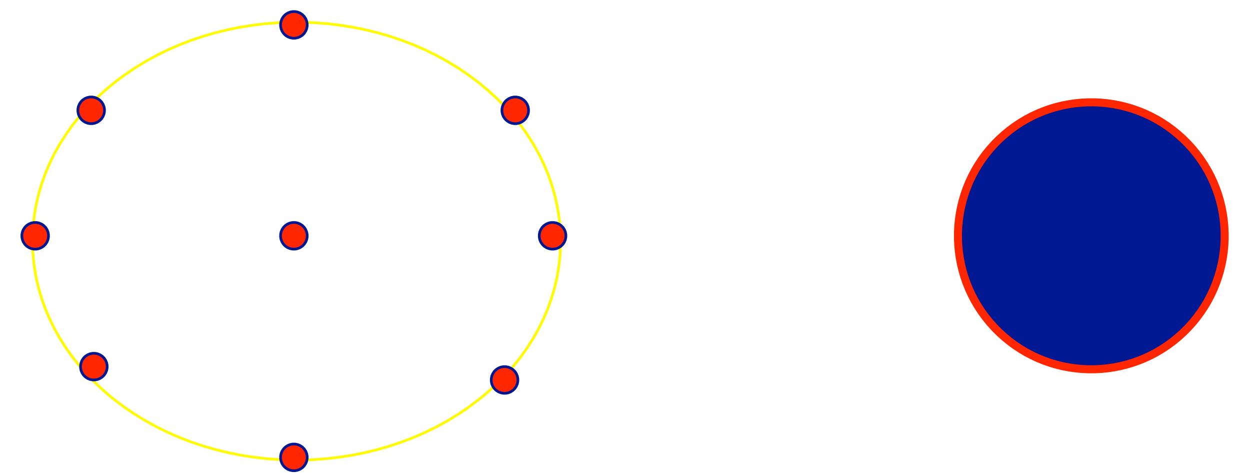
Lesson: black holes are like tigers

- dangerous when provoked
- but you can choose not to provoke:
- keep your distance and nobody gets hurt

Interlude: Gravity and Tides

Key aspects of gravity:

- strength weakens with distance
- points towards center of source

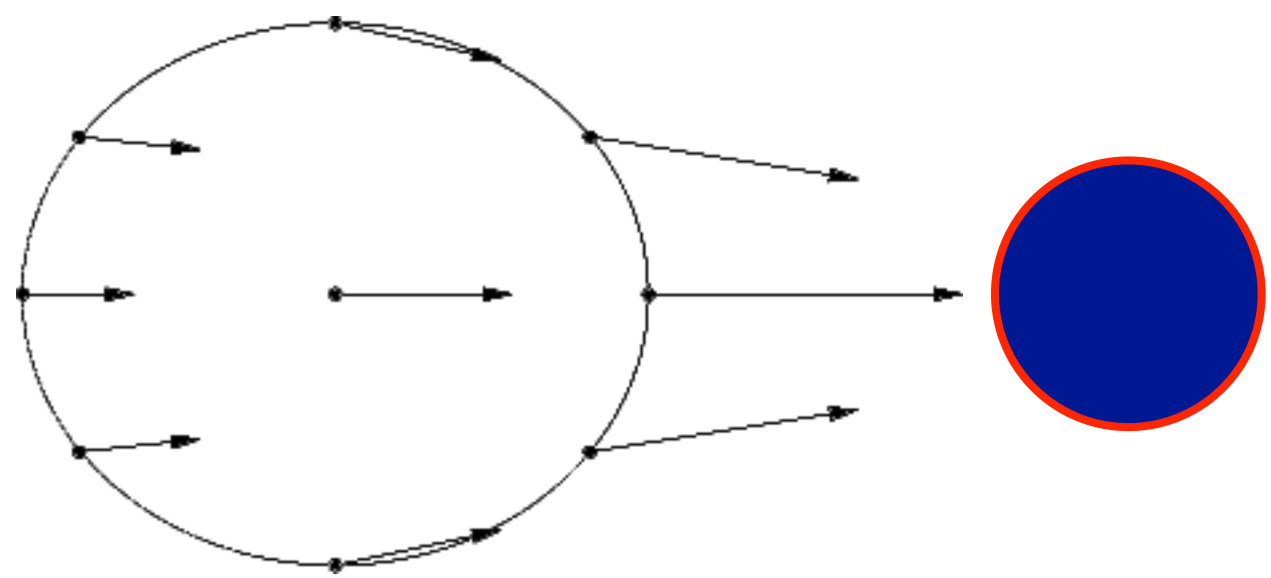


Experiment:

- get a set of small particles of equal mass
- place in a circle
- near a source of gravity

Pattern of forces:

- strongest on side closest to source
- weakest on side farthest from source
- medium strength at center
- above center angled down
- below center angled up

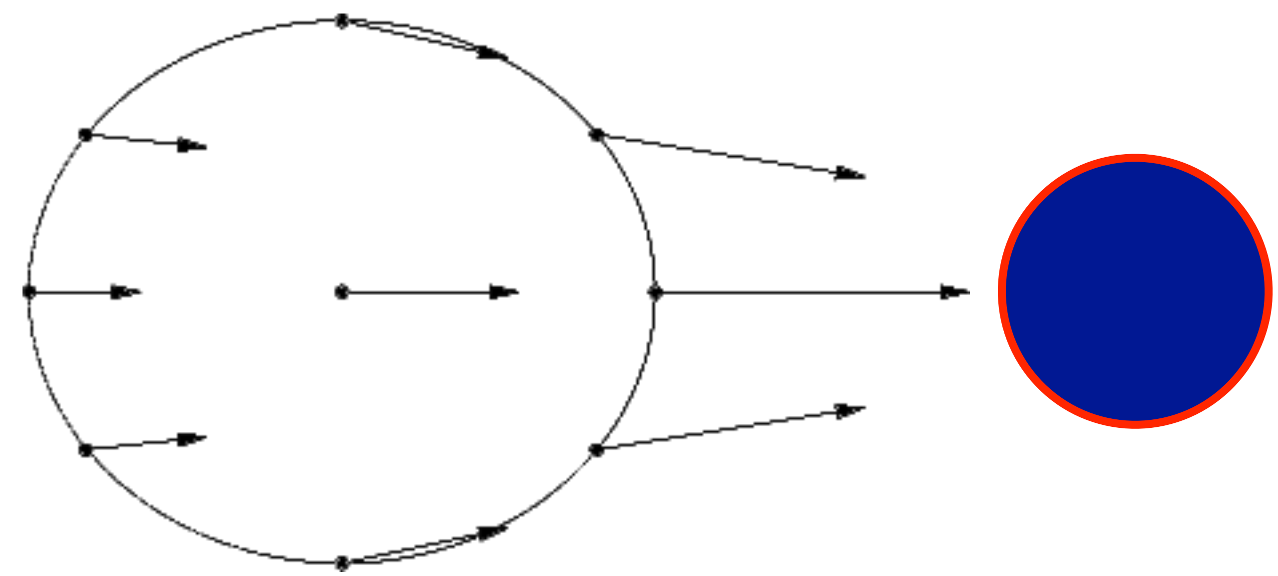


*Q: so compared to point at center, what is **pattern of force differences** on surrounding circle?*

Interlude: Gravity and Tides

Compared to center:

- stronger force on side near source
- weaker force on side away from source
- downward force above
- upward force below



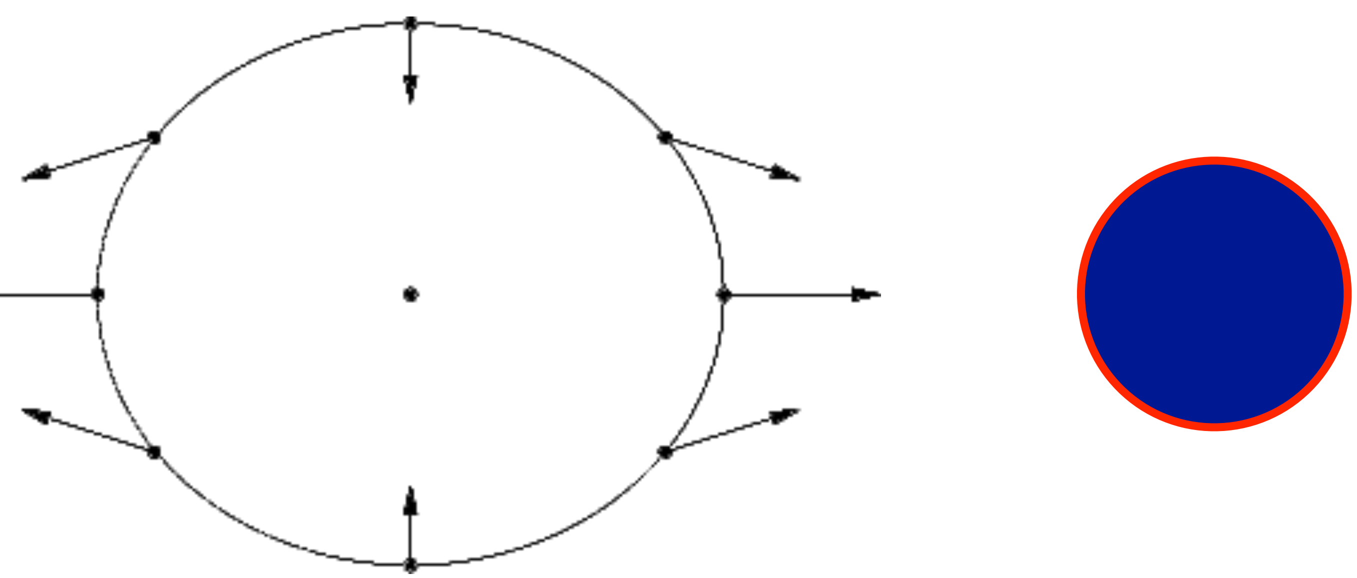
To summarize:

along direction towards source:

- forces pull away from center
- stretch!

perpendicular to direction to source

- forces push toward center
- squeeze!



Notice: all of this this is true not only for strong gravity but even for normal weak gravity

Tides on Earth

Earth experiences gravity of Moon

compared to center of Earth

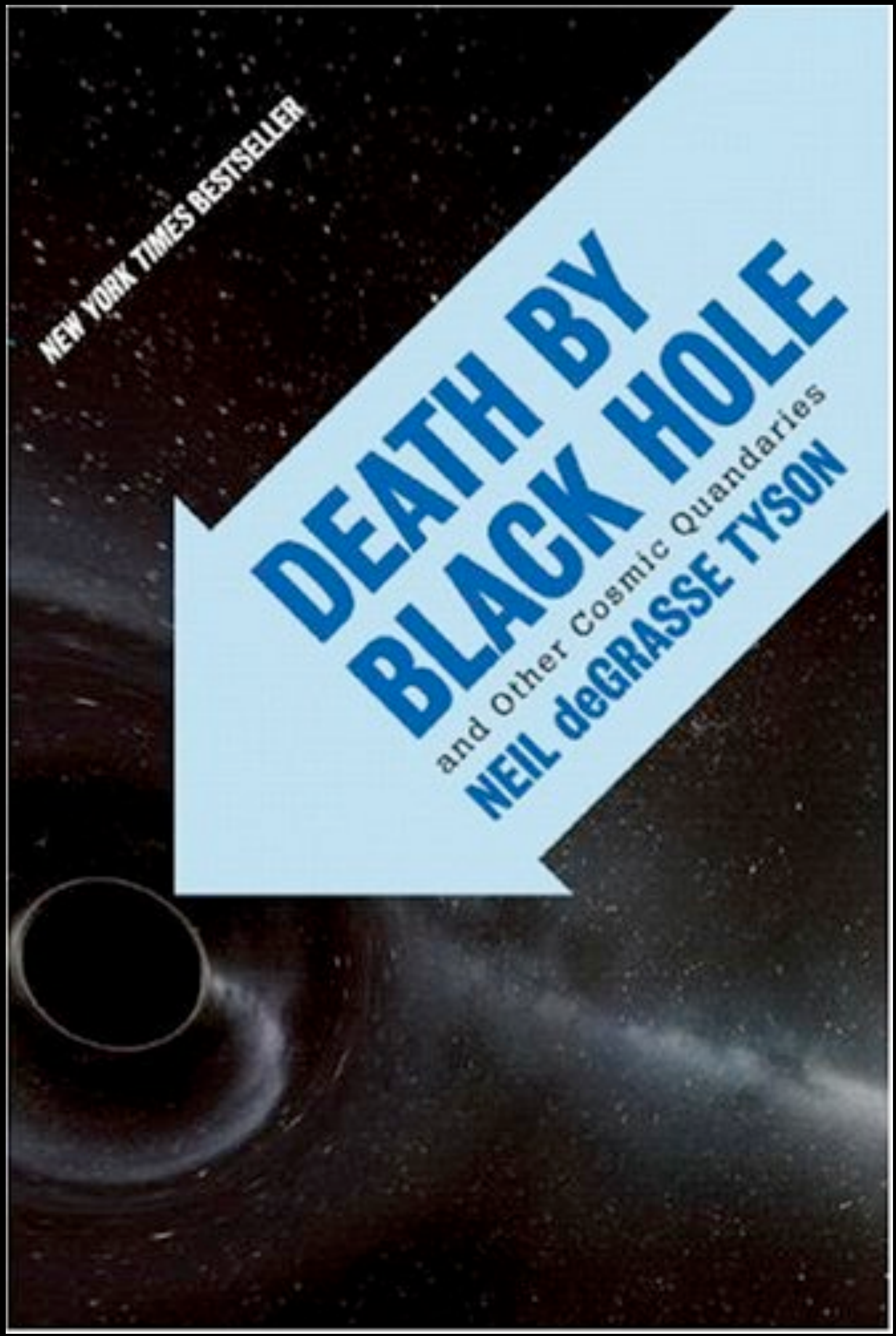
- near and far side stretched
- above an below squeezed

What is affect of these forces?

- rocky Earth feels these forces but resists them
- but watery oceans flow
- shape deformed
- this is the origin of the ocean tides!

What would it be like to fall into a black hole?

- Imagine you and a ~~friend~~ enemy are orbiting a black hole at a safe distance
- He jumps out of the airlock on a trajectory to fall into the black hole
- What would happen to him?
-



iClicker Question: Falling on a Black Hole

Your “friend” falls into a black hole, in a spacecraft covered with floodlights so that it is visible.

Will you see your friend fall in?

A. yes, and quickly

B. yes, but it could take years

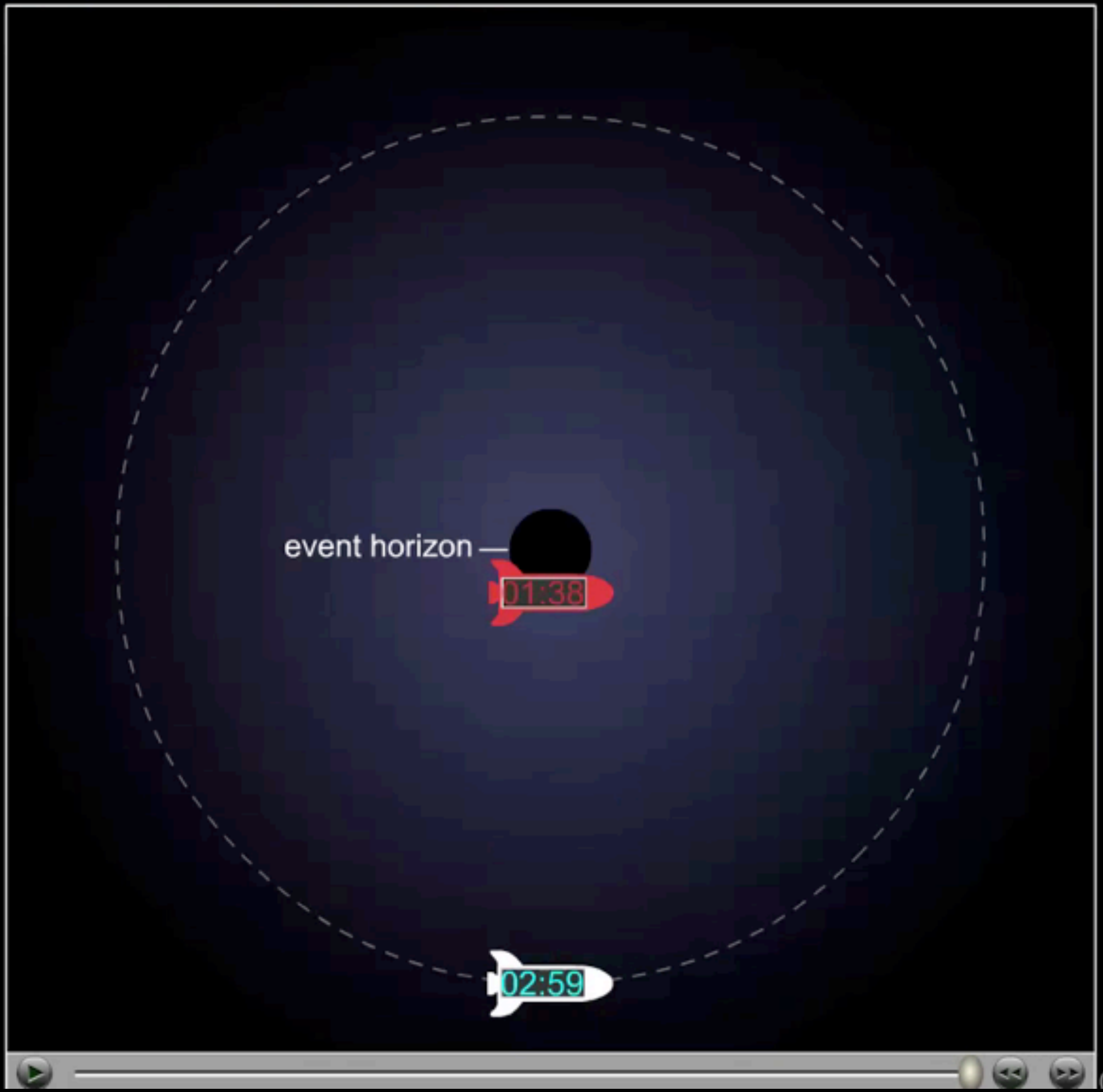
C. no, you never see it fall in because it doesn’t really fall in

D. no, you never see it fall in but it does really fall in

What you observe

- As your "friend" falls toward the black hole:
- His clock slows down
- Light from his clock becomes **dim** and **red**
- You never see him cross the **event horizon!**

Gravitational Time Dilation and Redshift



What happens to your ~~friend~~ enemy - from his perspective

- His clock keeps ticking, stays bright and blue
- You appear to speed up! Light from your clock is blueshifted!
- He crosses the event horizon when his clock reads 1:39
- No barrier - the event horizon is not a physical boundary

Uh Oh.

- Unfortunately, he does not live to experience crossing the event horizon
- Near the event horizon, gravity would act more strongly on his feet than his head
- Tidal forces become strong
  - stretching in direction towards center
  - squeezing in direction perpendicular