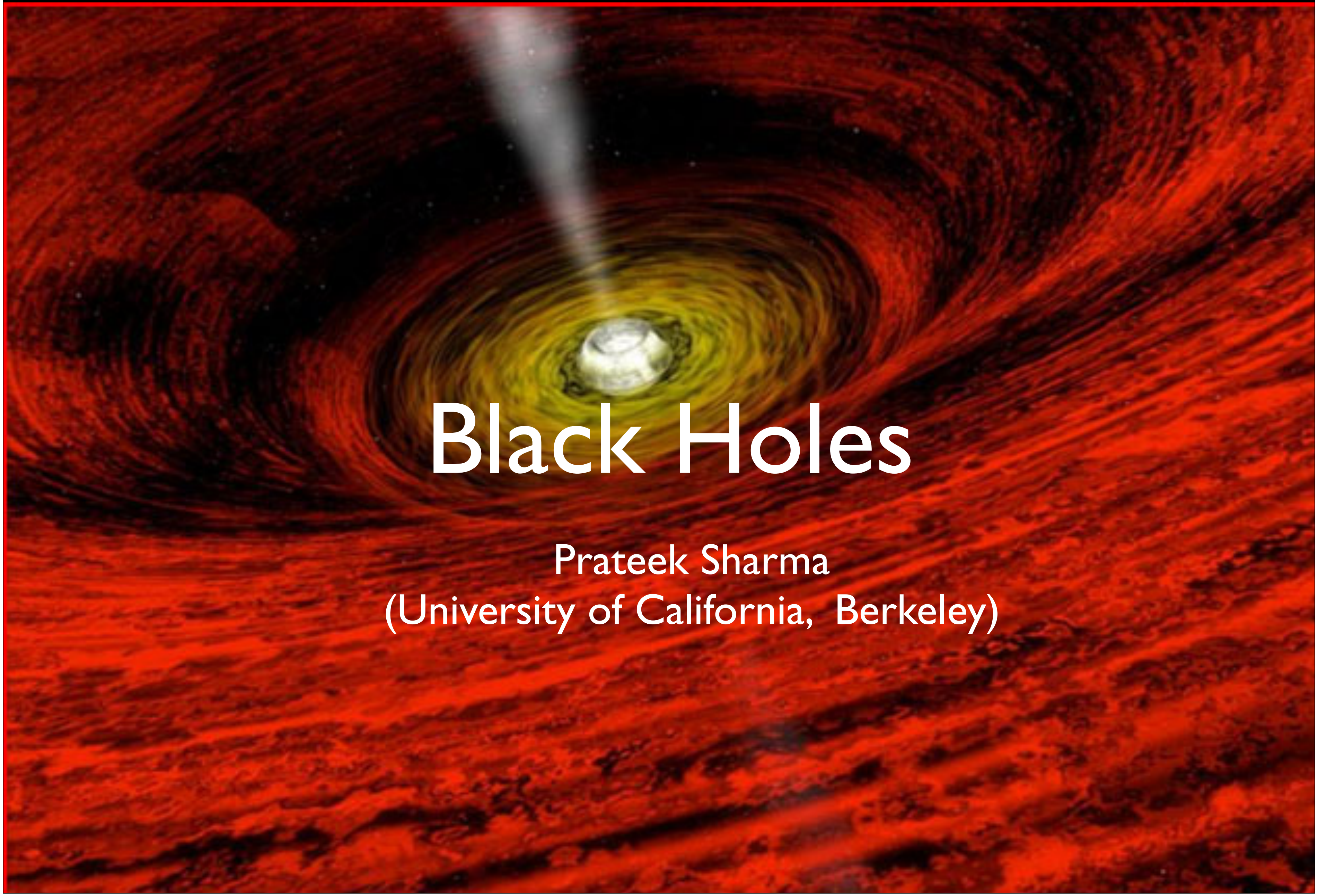
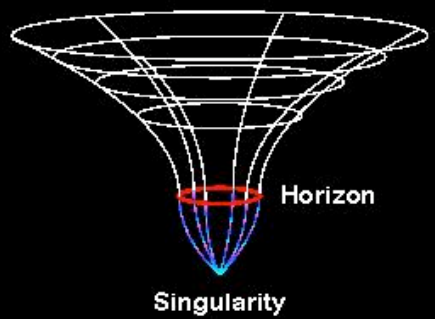


Black Holes

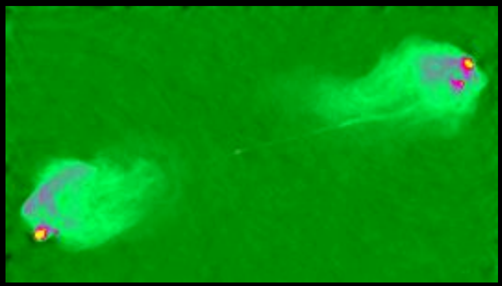
Prateek Sharma
(University of California, Berkeley)

What is a BH?

- gravity so strong that even light can't escape
- can we make BHs in the lab?



- do BHs exist in nature? YES!
- how do we find them?



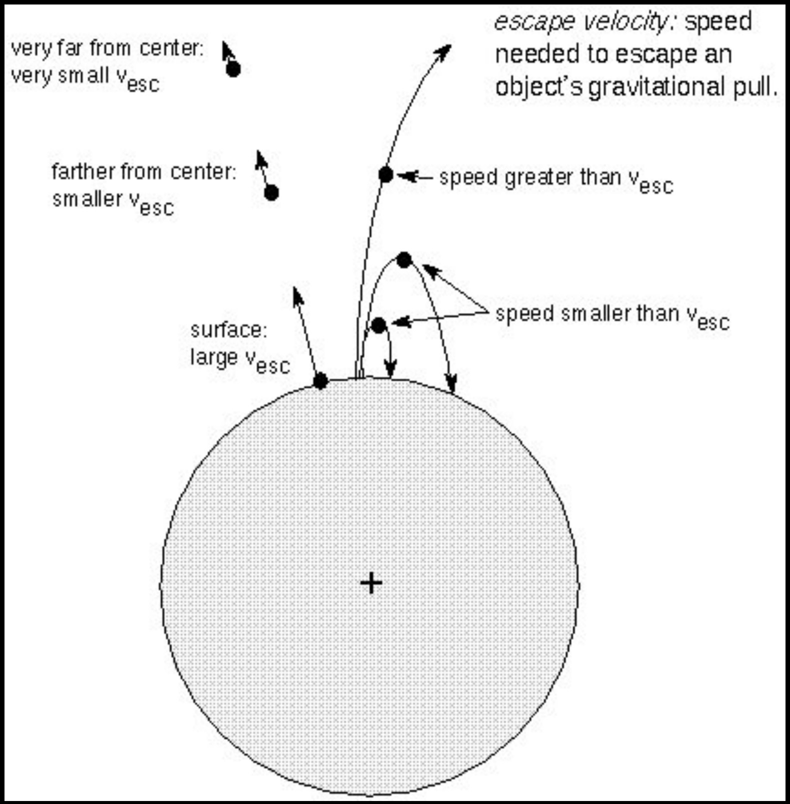
- how do they look like?

Escaping gravity's pull

escape velocity: minimum speed needed to escape an object's gravity

$v_{esc}=(2GM/r)^{1/2}$, M:mass, r:radius

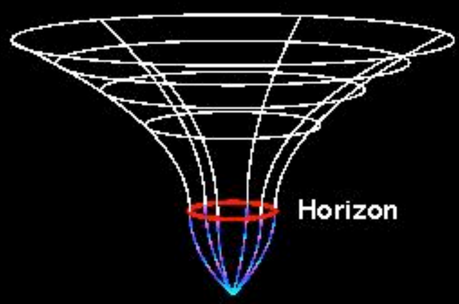
earth: 11km/s
sun: 1000km/s (more difficult to launch rocket from the sun!)



Size of a BH

Rev. John Michell (1783) & Pierre-Simon Laplace (1796) thought of dark stars!

- what if v_{esc}>c? even light can't escape
- requirement? $c^2<2GM/r$
- or, radius < event horizon $\equiv r_S = 2GM/c^2$



- examples:
  - solar mass BH : r_S=3km
  - earth mass BH : r_S=1cm
  - 1 kg BH : $r_S=1.5\times10^{-25}$cm quantum effects important at small scales!

QM affects even BHs!

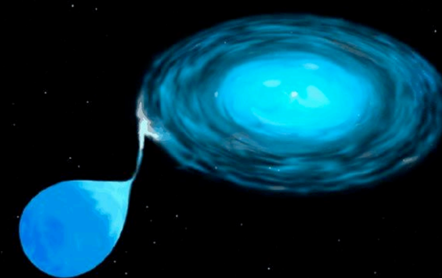
- QM allows for light to escape from BH!

- the almighty uncertainty principle: $xp \sim h/2\pi$
- uncertainty in photon position $x \sim r_S \sim 2GM/c^2$
- $p(=h/\lambda) \sim h/2\pi r_S \sim hc^2/4\pi GM$

- for a BB: $kT \sim h\nu = hc/\lambda \Rightarrow T \sim hc^3/8\pi kGM$
- $T = 6 \times 10^{-8} K \, (M/M_{\odot})^{-1}$ Hawking radiation!
- $L = 4\pi r_S^2 \sigma T^4 \propto M^{-2}$

- lighter BHs evaporate quickly due to energy loss via radiation (thus, stable BHs can't be formed in lab)

Do BHs exist in nature?



- Stellar mass BHs:
  - stars w. $M>3M_{\odot}$ form BH in the end
  - ~ million such BHs in our Galaxy
  - detected in binaries

- Supermassive BHs:
  - 10^6-$10^9 M_{\odot}$ BH at centers of galaxies
  - $4 \times 10^6 M_{\odot}$ BH in center of our Galaxy
  - formation not understood

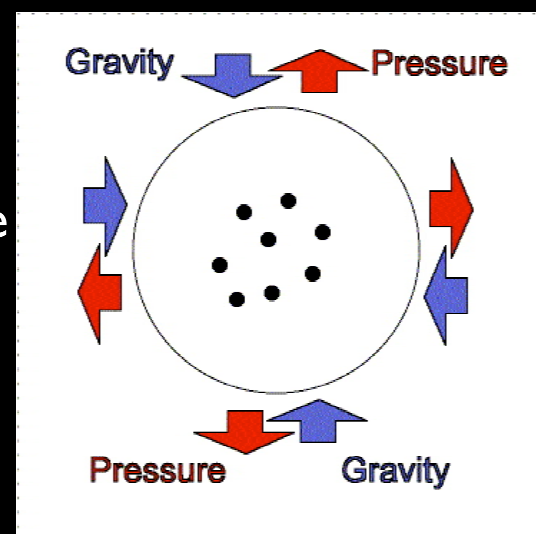
Stars: Pressure balances gravity


The Sun

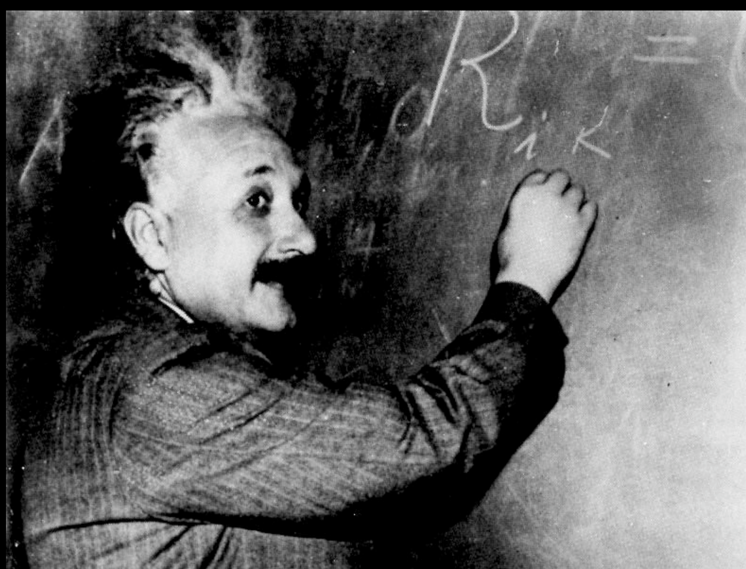
- normal stars: gas pressure balances gravity
- death of stars: nuclear fuel exhausted in center

=>gravitational collapse

- Chandrasekhar's limit
  - $M<1.4M_\odot$ white dwarfs, e^- degeneracy pressure
  - $1.4M_\odot<M<3M_\odot$ neutron star, neutron degeneracy pressure
  - $M>3M_\odot$ BH, gravity wins



1915: General Relativity, Einstein's Theory of Gravity
1916: Schwarzschild's Discovery of BHs in GR
BHs only understood & accepted in the 1960s
(Term "Black Hole" coined by John Wheeler in 1967)

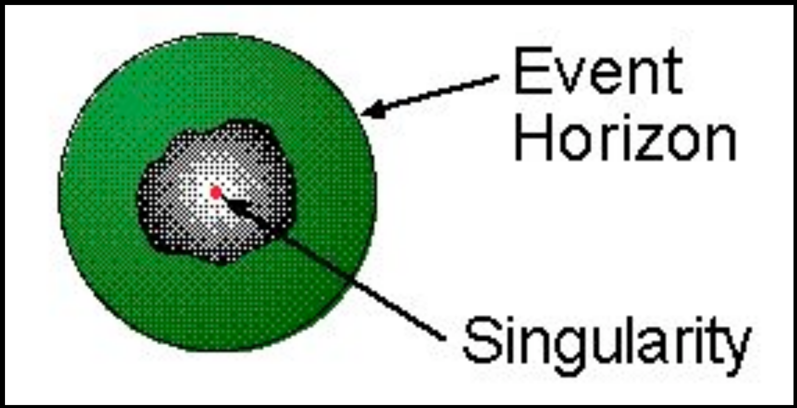


Albert Einstein

Karl Schwarzschild

BHs in GR

If an object is small enough, gravity overwhelms pressure and the object collapses. Gravity is so strong that nothing, not even light, can escape.



"Radius" of a BH

3 km for a solar mass
1 cm for an Earth mass

NOT a solid surface

All Mass at the Center
(GR not valid there; no complete theory of quantum gravity)

Uncovering BH myths

BHs are *not* cosmic vacuum cleaners: only inside the horizon (r_S) is matter pulled inward

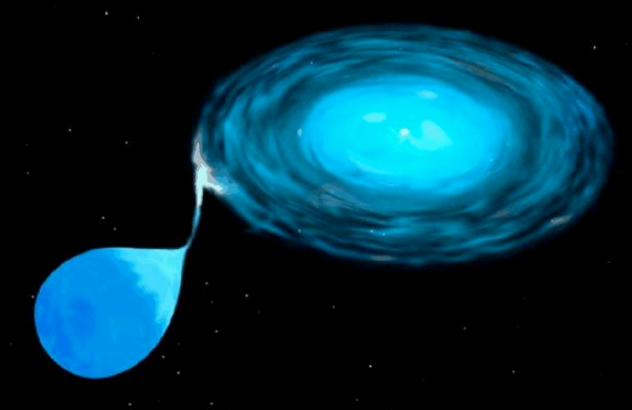
Far away from a BH, gravity is **no different** than for any other object with the same mass

If a BH were to replace the sun, the orbits of planets, asteroids, moons, etc., would be **unchanged** (though it would get really really cold).

How to find BHs?

If two stars orbit close enough to each other, mass gets pulled from one and falls (accretes) onto the other. The smaller the target object, the faster the gas moves and the hotter it gets.

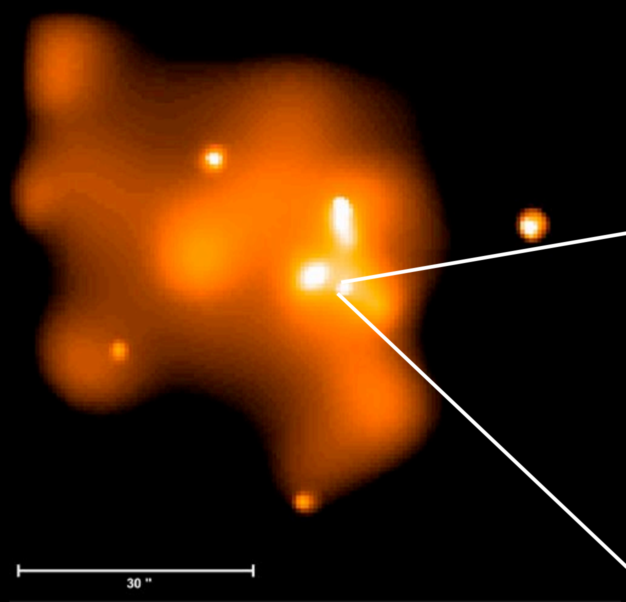
measure mass by the motion of companion to verify its a BH

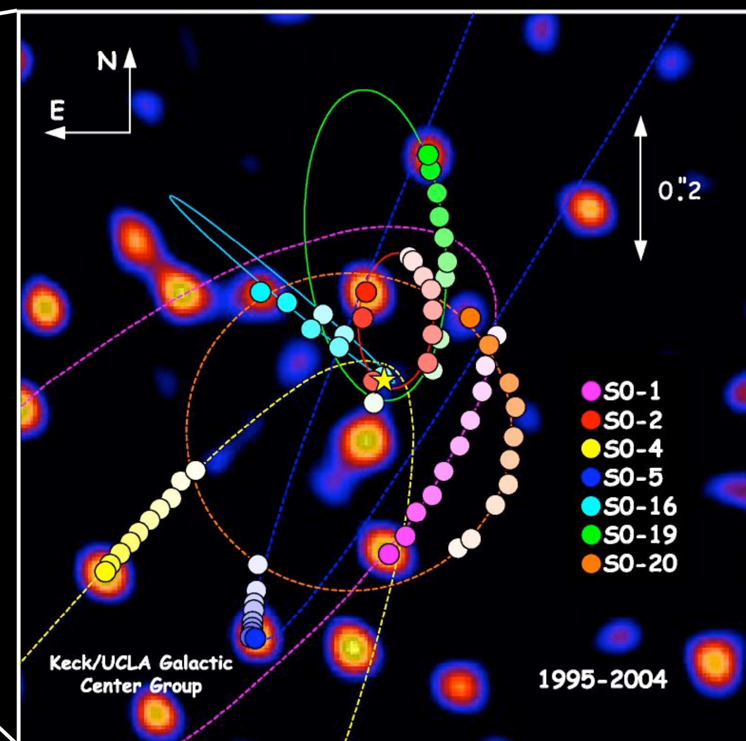


Gas falling into a BH gets *very hot* and emits *lots* of radiation in X-rays

Accretion is how we “see” a black hole

BH in center of Galaxy

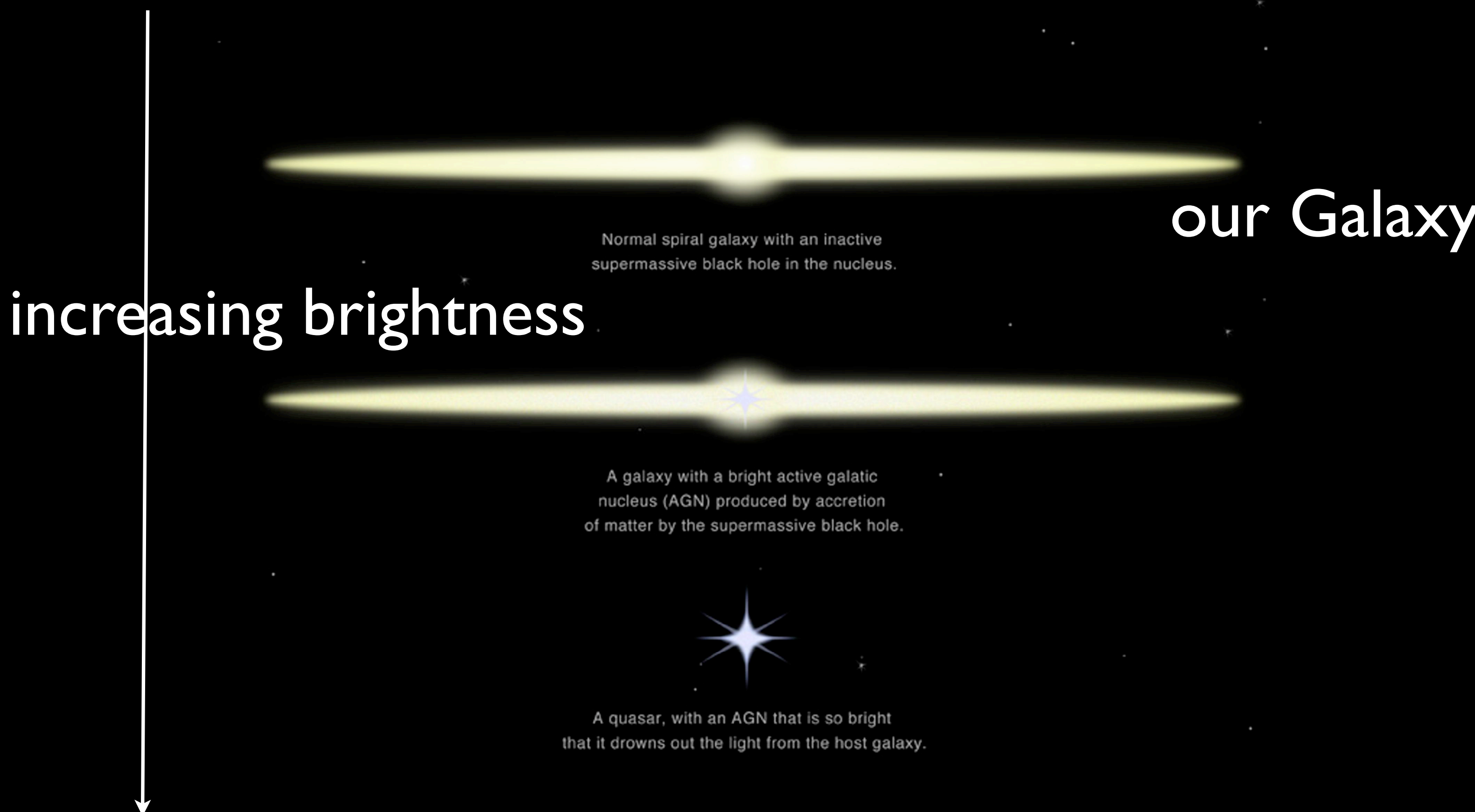




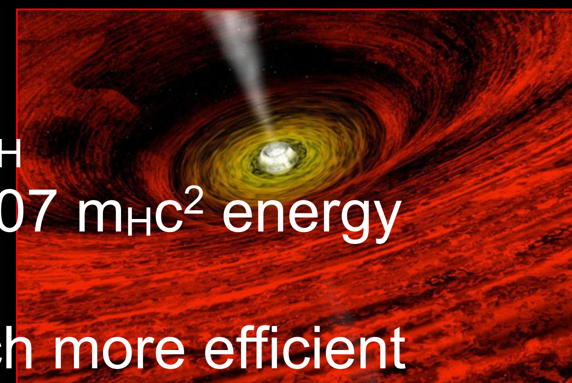
Chandra X-ray image

BHs makes its surroundings hot and hot gas radiates

Variety of massive BHs



Energy from Accretion



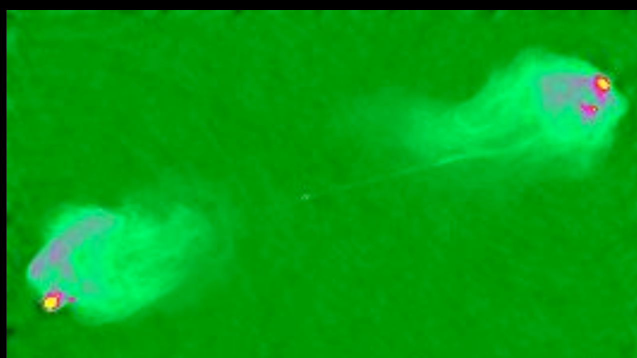
nuclear fusion: $4\,^1H \rightarrow \,^4He$+energy; $m_{He} < 4m_H$
efficiency~0.007; burning 1g of H gives 0.007 $m_H c^2$ energy

accretion: gravitational energy source; much more efficient

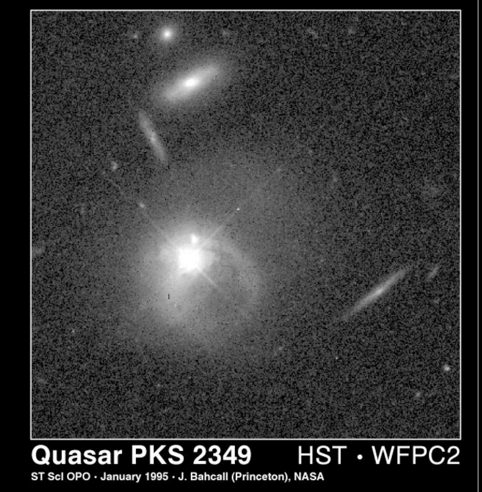
mass far away from BH: energy = zero
close to the BH: energy = $-GMm/2r$; r~few r_S => $E=mc^2/(4*\text{few})$
energy is conserved => energy~$GM/2r$ is emitted as radiation
efficiency of accretion ~ 0.1>>0.007, efficiency of fusion

Manifestations of energy

radio jets & lobes



The BH ejects beams (“jets”) of matter & energy far outside its host galaxy into the surrounding universe



The BH can outshine all of the stars in its host galaxy!

To conclude:

- BHs: gravity wins over other forces
- QM plays a role in BH thermodynamics; evaporation of smaller BHs
- 1 massive BH per galaxy; millions stellar BHs in galaxy
- accretion responsible for most energetic phenomena in universe: AGN, jets; more efficient than fusion
- BHs "seen" via light (mostly X-rays) produced by infalling gas or by its gravitational pull on nearby objects