Annoucements

- The second exam will be during class on Wednesday, October 26
- E-mail questions before review on Monday, October 24
- Astronomy tutorial: Tuesday 3-5, 7-9 pm in 310 VAN
- Office hours: Tuesday 1–3 pm, Wednesday 10-11 am, or by appointment in 702 VAN

Black Holes

- Observed properties of black holes
- Accretion disks
- Gravitational energy
- Rotating black holes
- Eddington luminosity

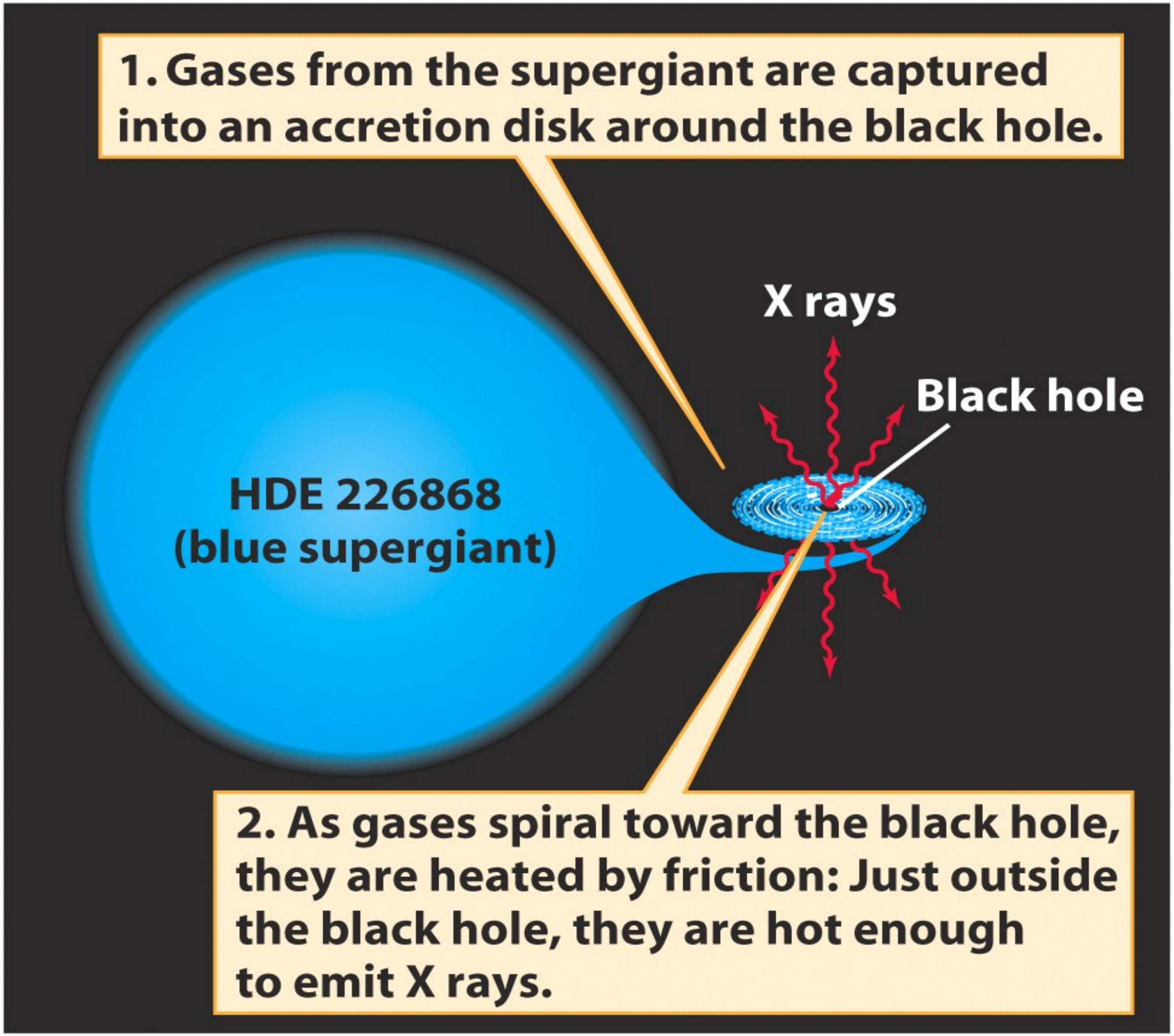
The principle of equivalence in general relativity equates the effects of

A) Gravity and acceleration
B) Mass and energy
C) Gravity and energy
D) Acceleration and deceleration

If we could see the last few seconds of the collapse of a star to form a black hole, we would see the star grow steadily redder. Why?

A) The star moves away from us at an increasing speed.
B) The star grows steadily cooler.
C) The star's gravitational redshift increases.
D) The star becomes obscured by more and more interstellar dust.

Seeing black holes

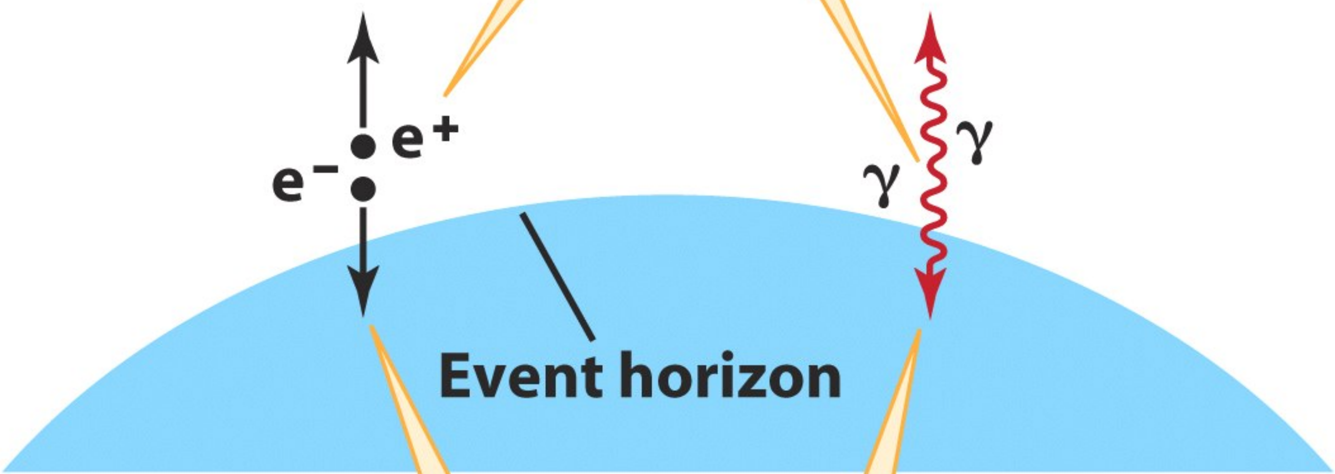


A schematic diagram of Cygnus X-1

Black holes evaporate

1. Pairs of virtual particles spontaneously appear and annihilate everywhere in the universe.

2. If a pair appears just outside a black hole's event horizon, tidal forces can pull the pair apart, preventing them from annihilating each other.

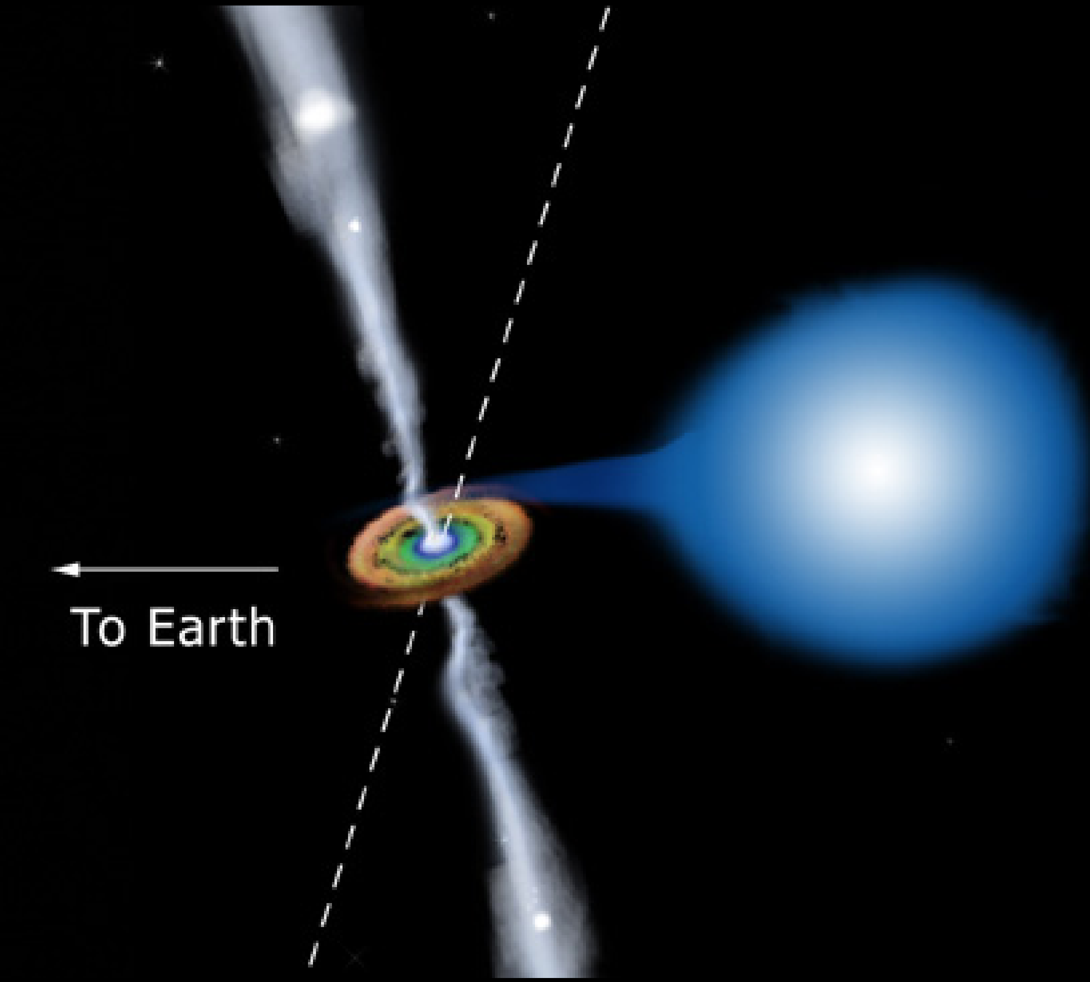


3. If one member of the pair crosses the event horizon, the other can escape into space, carrying energy away from the black hole.

Black Holes

- Fundamental properties of black holes
  - Mass
  - Spin
  - Charge = zero for astrophysical black holes

Observed properties of black holes



Luminosity

Orientation

Jets

The Hoover dam generates 4 billion kilowatt hours of power per year.

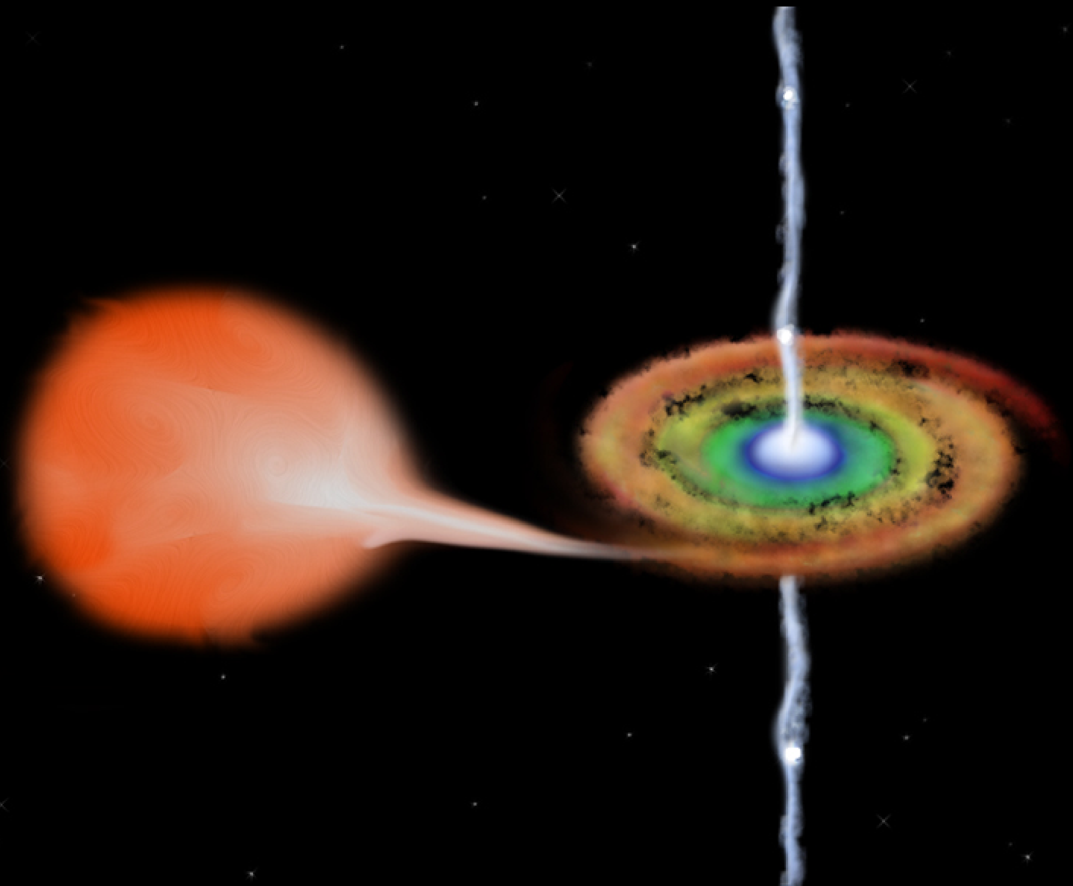
Where does the energy come from?

Water falling down to the generators at the base of the dam accelerates to 80 mph.

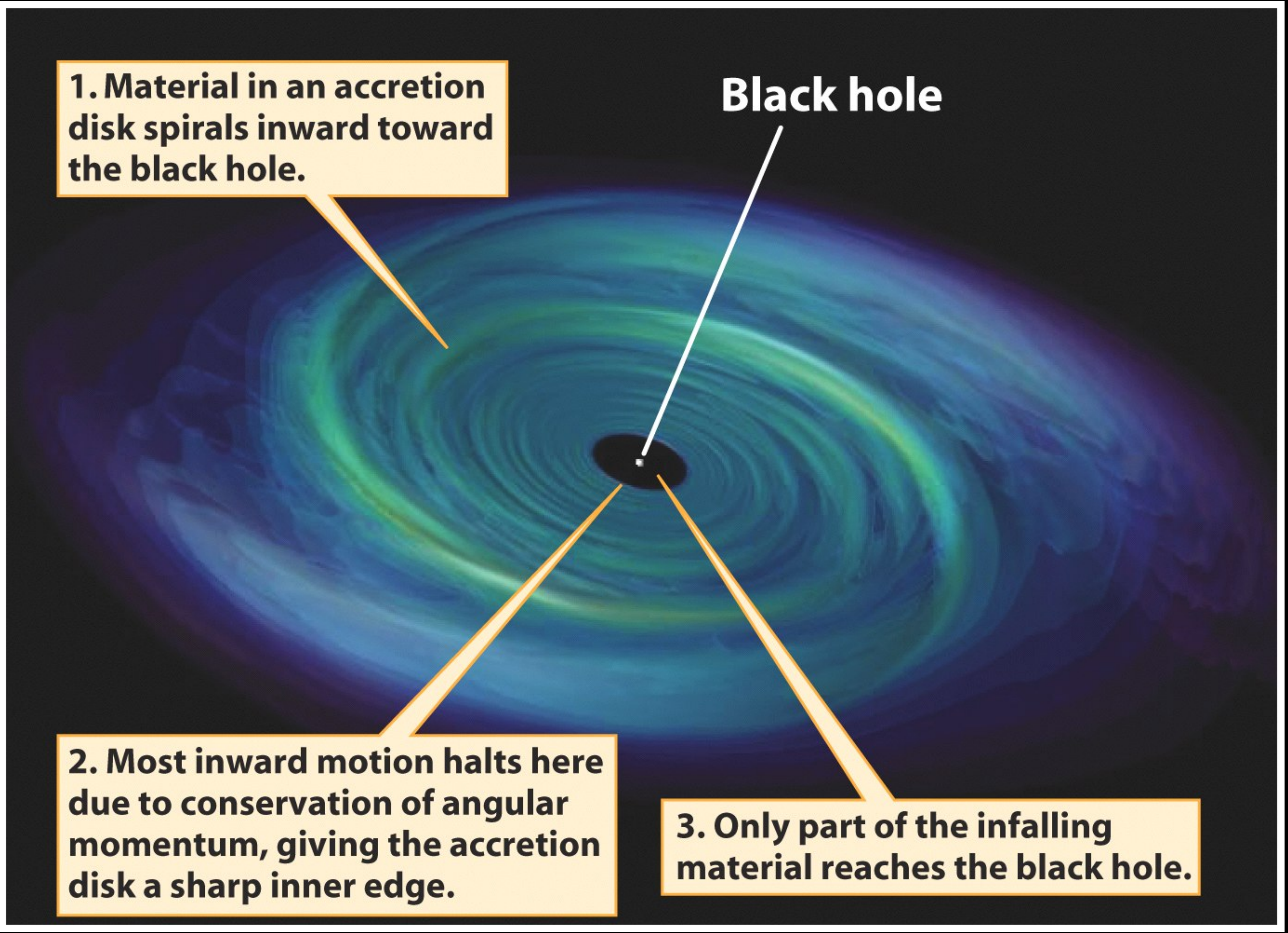
The same water leaving the turbines moves at only 10 mph.

The gravitational energy of the water at the top of the dam is converted to kinetic energy by falling. The turbines convert kinetic energy to electricity.

Gravitational energy



Black holes generate energy from matter falling into them.


1. Material in an accretion disk spirals inward toward the black hole.
Black hole
2. Most inward motion halts here due to conservation of angular momentum, giving the accretion disk a sharp inner edge.
3. Only part of the infalling material reaches the black hole.

Rotating black holes

For non-rotating black holes:

- event horizon is at the Schwarzschild radius
- inner edge of the disk is at 3 Schwarzschild radii

For maximally rotating black holes:

- event horizon is at ½ Schwarzschild radius
- inner edge of the disk is at ½ Schwarzschild radius

Schwarzschild radius $= 3$ km (M/M_{Sun})

Efficiency for converting mass into energy

- Gravitational energy is converted to kinetic energy as particles fall towards BH
- Maximum efficiency $E = mc^2$ with all m converted to energy
- Efficiency of generators:
  - Chemical burning < 0.000001%
  - Nuclear burning < 1%
  - Non-rotating black hole = 6%
  - Rotating black hole = 42%

What is the radius of the event horizon of a 10 solar mass non-rotating black hole?

A) 0.3 m
B) 15 km
C) 30 km
D) 90 km

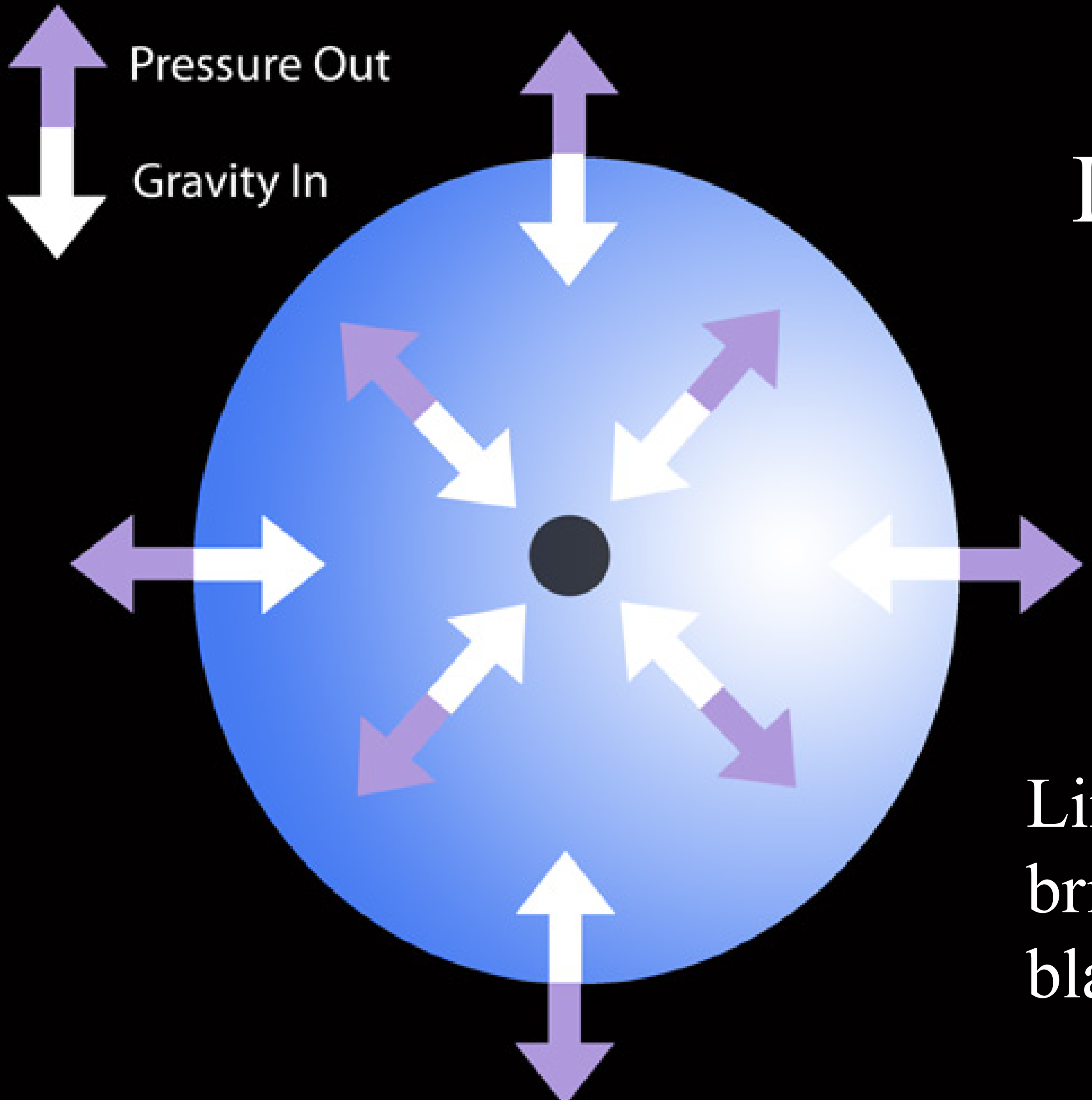
What is the radius of the event horizon of a maximally rotating 10 solar mass black hole?

A) 0.3 m
B) 15 km
C) 30 km
D) 90 km

What is the radius of the inner edge of the accretion disk surrounding a non-rotating 10 solar mass black hole?

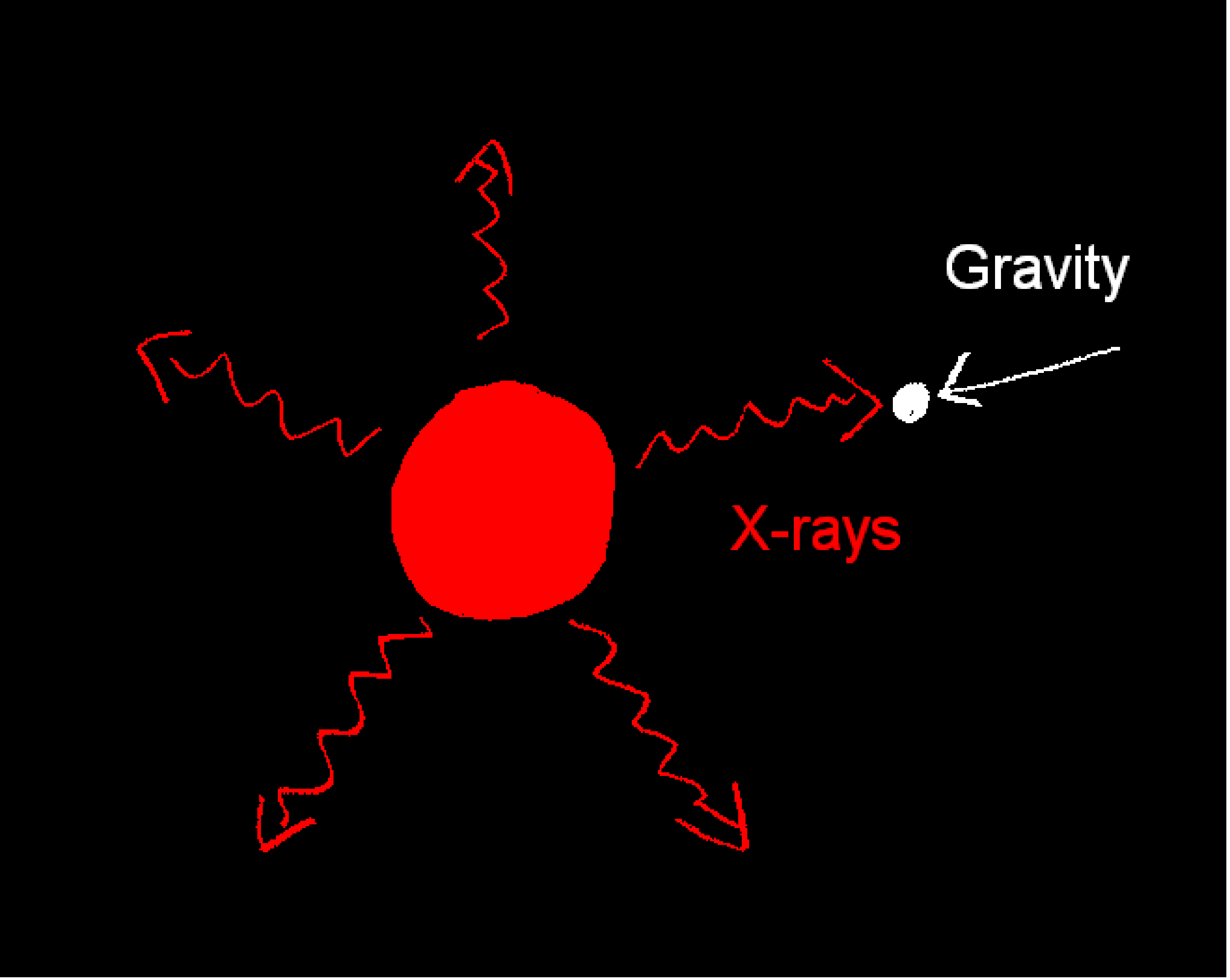
A) 0.3 m
B) 15 km
C) 30 km
D) 90 km

Eddington Luminosity



Limit on the brightness of a black hole

Eddington Luminosity



$$L_{\mathrm{Edd}} = 30{,}000\, L_{\Theta} \left(\frac{M}{M_{\Theta}} \right)$$

A black hole is observed at a luminosity of 300,000 solar luminosities. The black hole mass must be

A) at least 10 solar masses
B) less than 10 solar masses
C) exactly 10 solar masses
D) impossible to determine

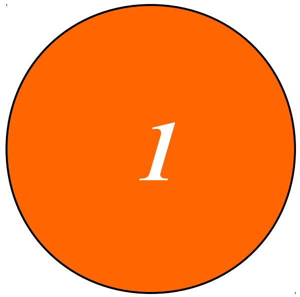
Accretion disks

- Disks form because in-falling matter has angular momentum.
- Gravitational energy is released in the accretion disk.
- Inner regions of disks rotate very rapidly – near the speed of light.
- The luminosity of a black hole is limited by its mass.

Black holes shine brightest in X-rays

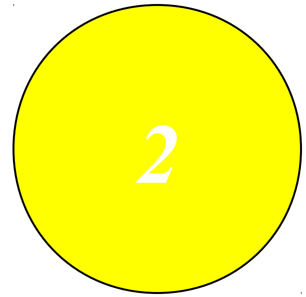
Why?

Luminosity versus radius and temperature



$R = R_{\mathrm{Sun}}$

$T = T_{\mathrm{Sun}}$



$R = R_{\mathrm{Sun}}$

$T = 2T_{\mathrm{Sun}}$

Which star is more luminous?

The hotter star is more luminous.

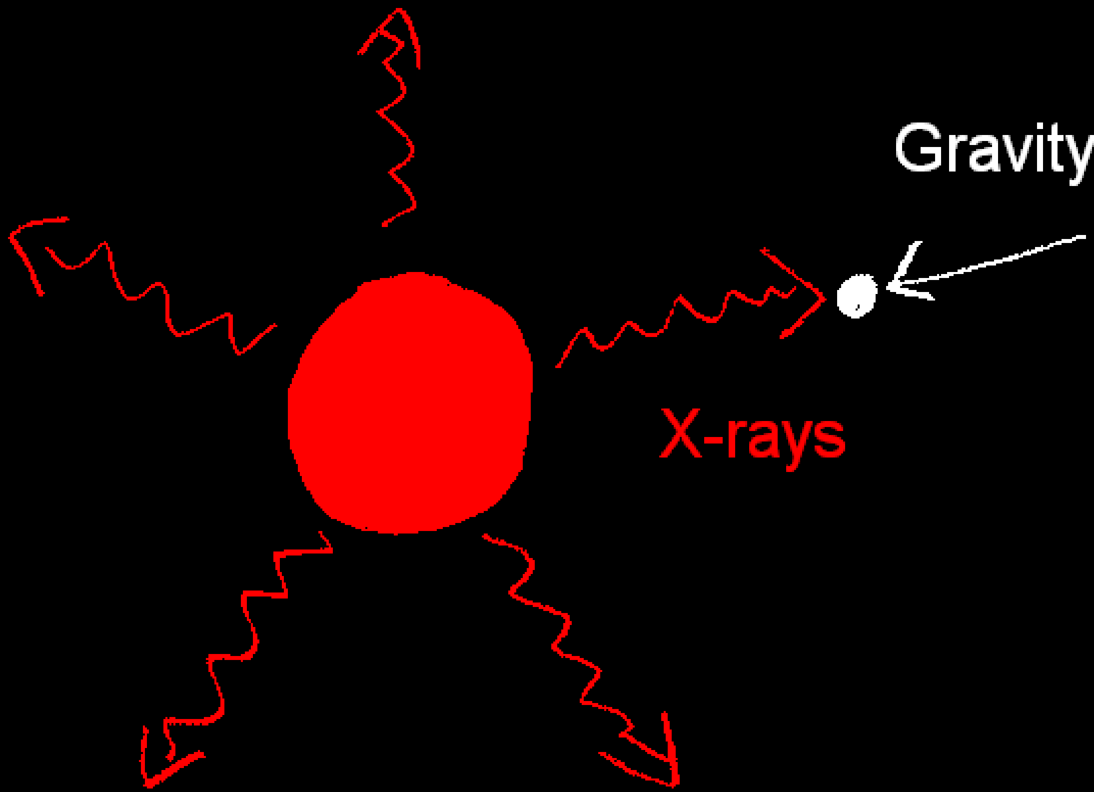
Luminosity varies as T^4 (Stefan-Boltzmann Law)

Luminosity Law

$$\frac{L_A}{L_B} = \frac{R_A^2 T_A^4}{R_B^2 T_B^4}$$

If star A is 2 times as hot as star B, and the same radius, then it will be $2^4 = 16$ times as luminous.

Eddington Luminosity



Black holes shine brightest in X-rays

- Take BH of 10 solar masses
- Inner edge of accretion disk is 90 km or 1/8000 of Sun’s radius
- Luminosity can be 300,000 time the Sun’s luminosity

Black holes shine brightest in X-rays

$$\frac{T_{BH}}{T_{Sun}} = \left(\frac{R_{BH}}{R_{Sun}}\right)^{-1/2} \left(\frac{L_{BH}}{L_{Sun}}\right)^{1/4}$$

$$\frac{T_{BH}}{T_{Sun}} = \left(\frac{1}{7777}\right)^{-1/2} (300000)^{1/4}$$

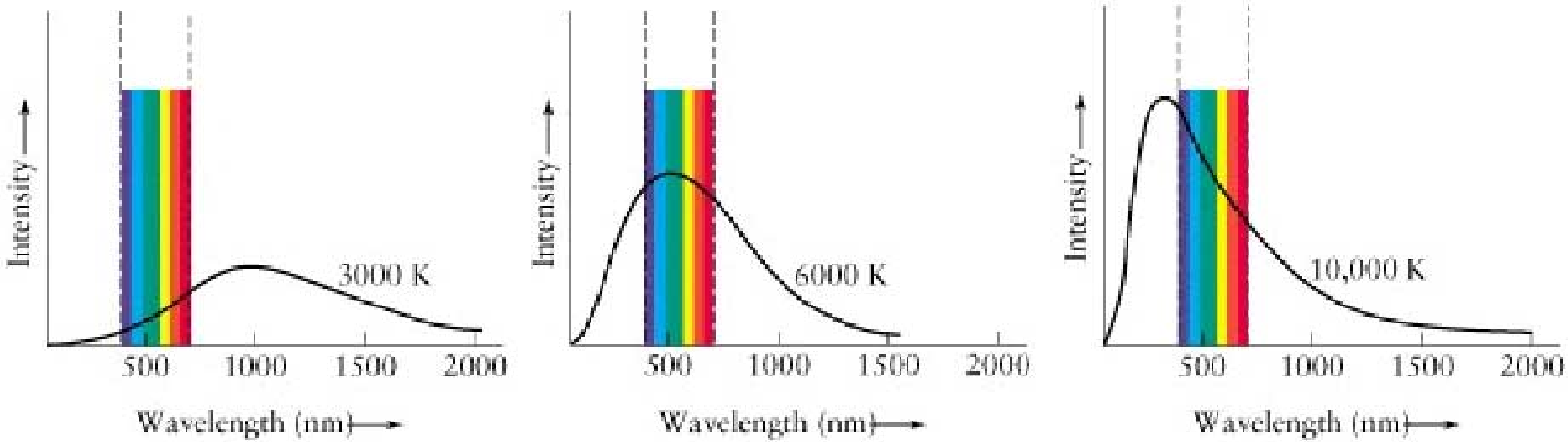
Black holes shine brightest in X-rays

$$\frac{T_{BH}}{T_{Sun}} = \left(1/7777\right)^{-1/2}\left(300000\right)^{1/4}$$

$$T_{BH} \approx 88 \times 23\, T_{Sun} \approx 2000\, T_{Sun}$$

$$T_{BH} \approx 2000 \times 6000\,\mathrm{K} \approx 12{,}000{,}000\,\mathrm{K}$$

A star’s color depends on its surface temperature

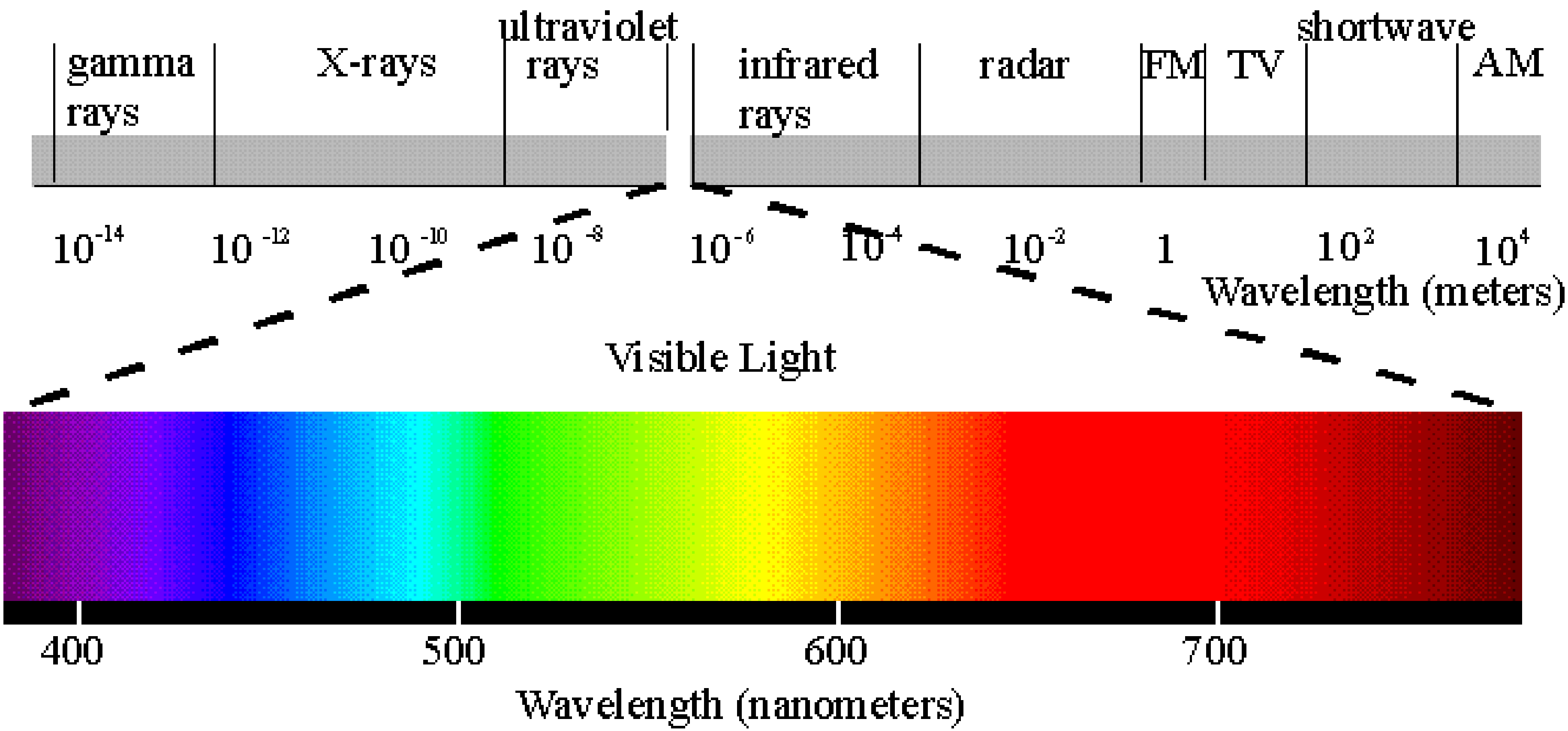


a This star looks red

b This star looks yellow-white

c This star looks blue-white

Electromagnetic spectrum



Black holes are so hot that they mainly produce X-rays

In X-rays, the night sky glows with the light of black holes, not normal stars

Accretion disks around black holes are extremely hot because

A) The spin rapidly

B) The black hole focuses light onto the disk

C) A large amount of energy is released in a small region

D) They're smoking

Review Questions

- What are fundamental versus observed properties of black holes?
- What is the efficiency of a BH for conversion of matter to energy?
- What is the maximum luminosity for a BH of a given mass?
- Why do black holes shine brightest in X-rays?
- Do black hole last forever?