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

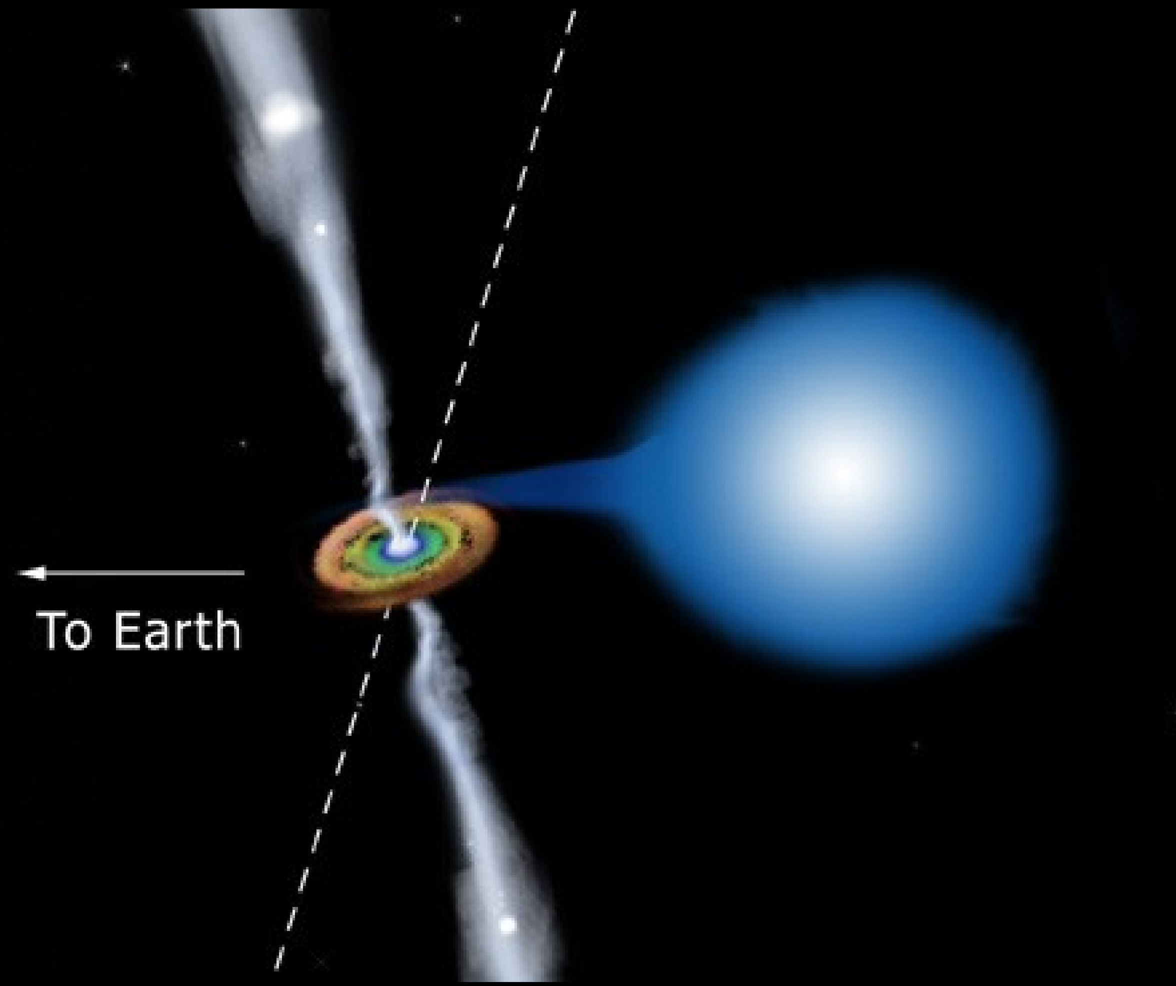
If we could see the last few seconds of the collapse of a star to form a black hole, we would see the star grow steadily redder. Why?

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.

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.

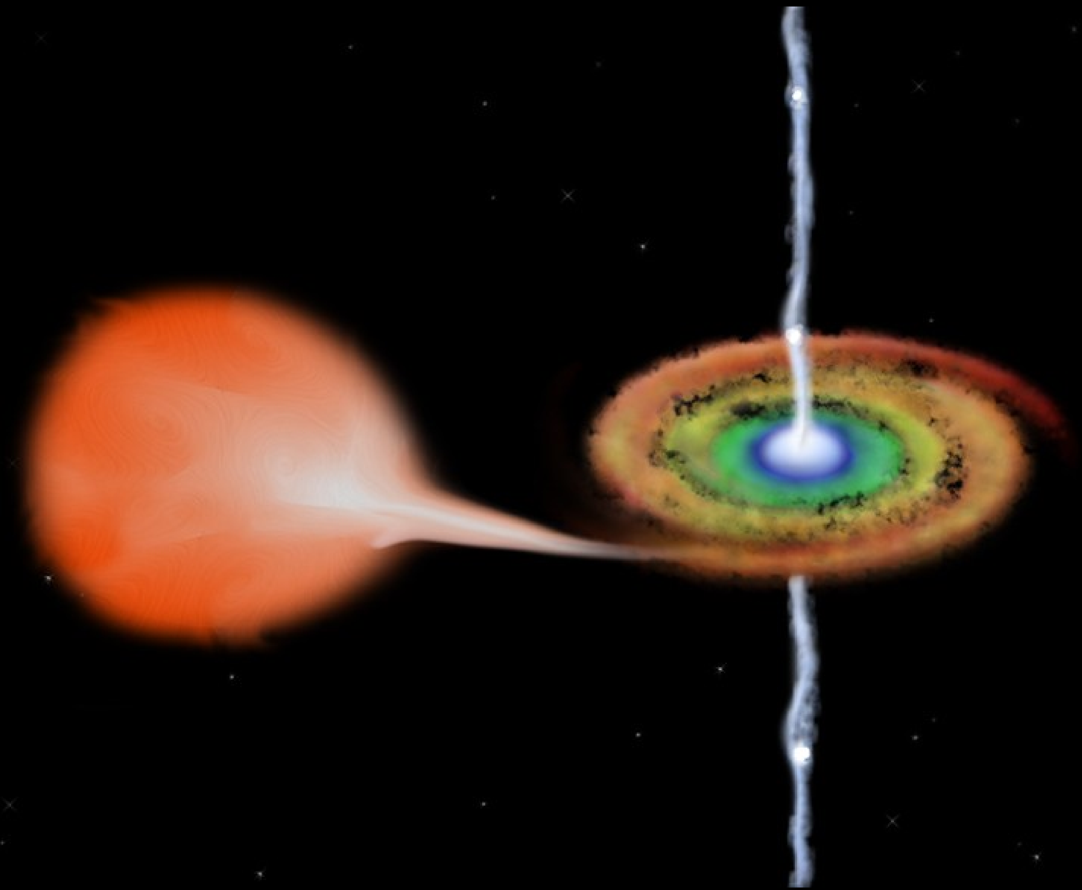
Where does the energy come from?

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

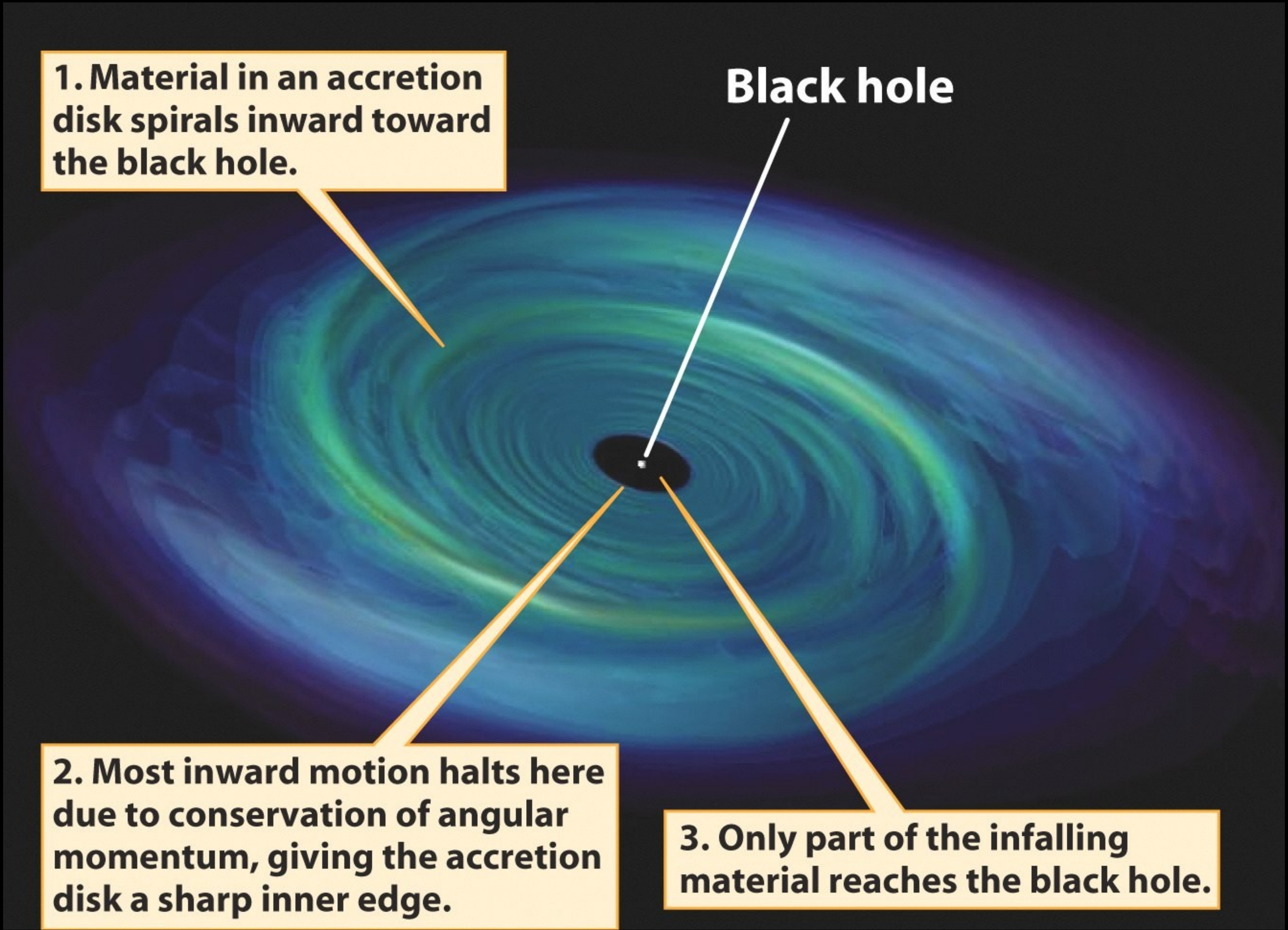
The same water leaving the turbines moves at only 10 mph.

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 $= 3\ \text{km}\ (M/M_{\text{Sun}})$

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 $= 42\%$

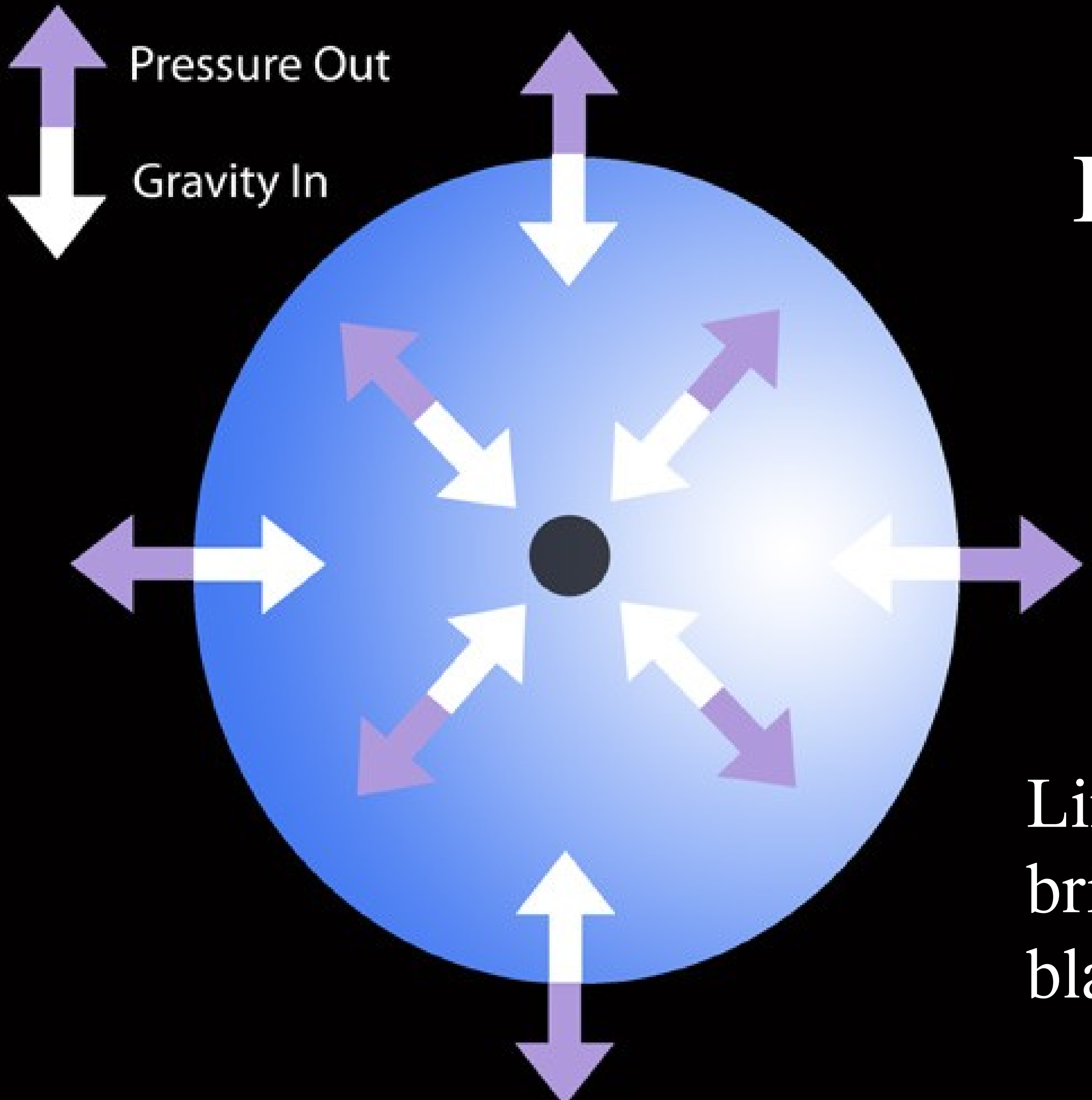
The event horizon radius of a non-rotating 10 solar mass black hole is about 30 km. How large is the radius of the event horizon of a 1000 solar mass non-rotating black hole?

A) 0.3 km
B) 30 km
C) 3000 km
D) 300,000 km

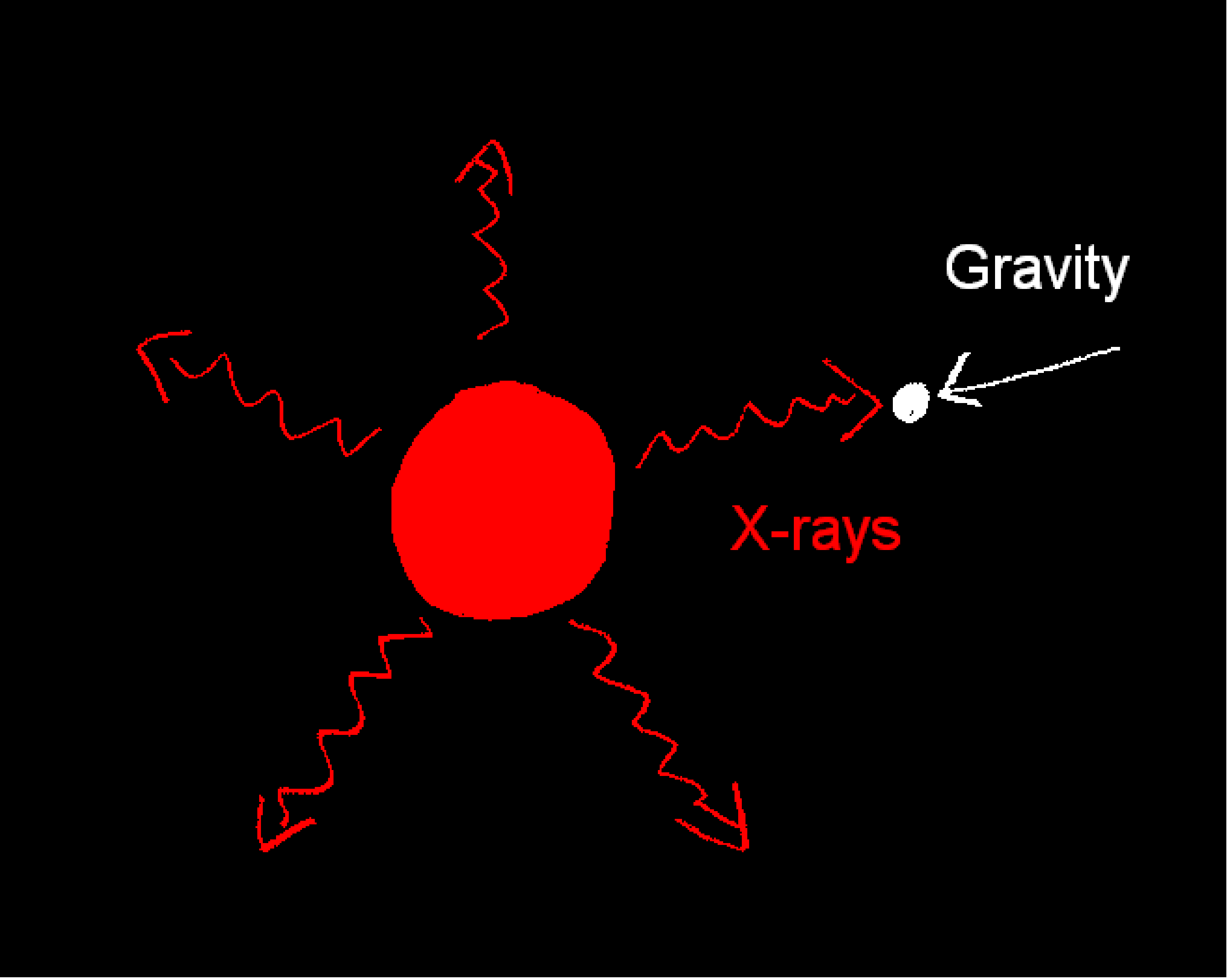
How large is the radius of the event horizon of a 1000 solar mass maximally rotating black hole?

A) 1000 km
B) 1500 km
C) 3000 km
D) 6000 km

Eddington Luminosity



Limit on the brightness of a black hole



Eddington Luminosity

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

A black hole is observed at a luminosity of 60,000 solar luminosities. The black hole mass must be

A) at least 2 solar masses
B) less than 2 solar masses
C) exactly 2 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.

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?