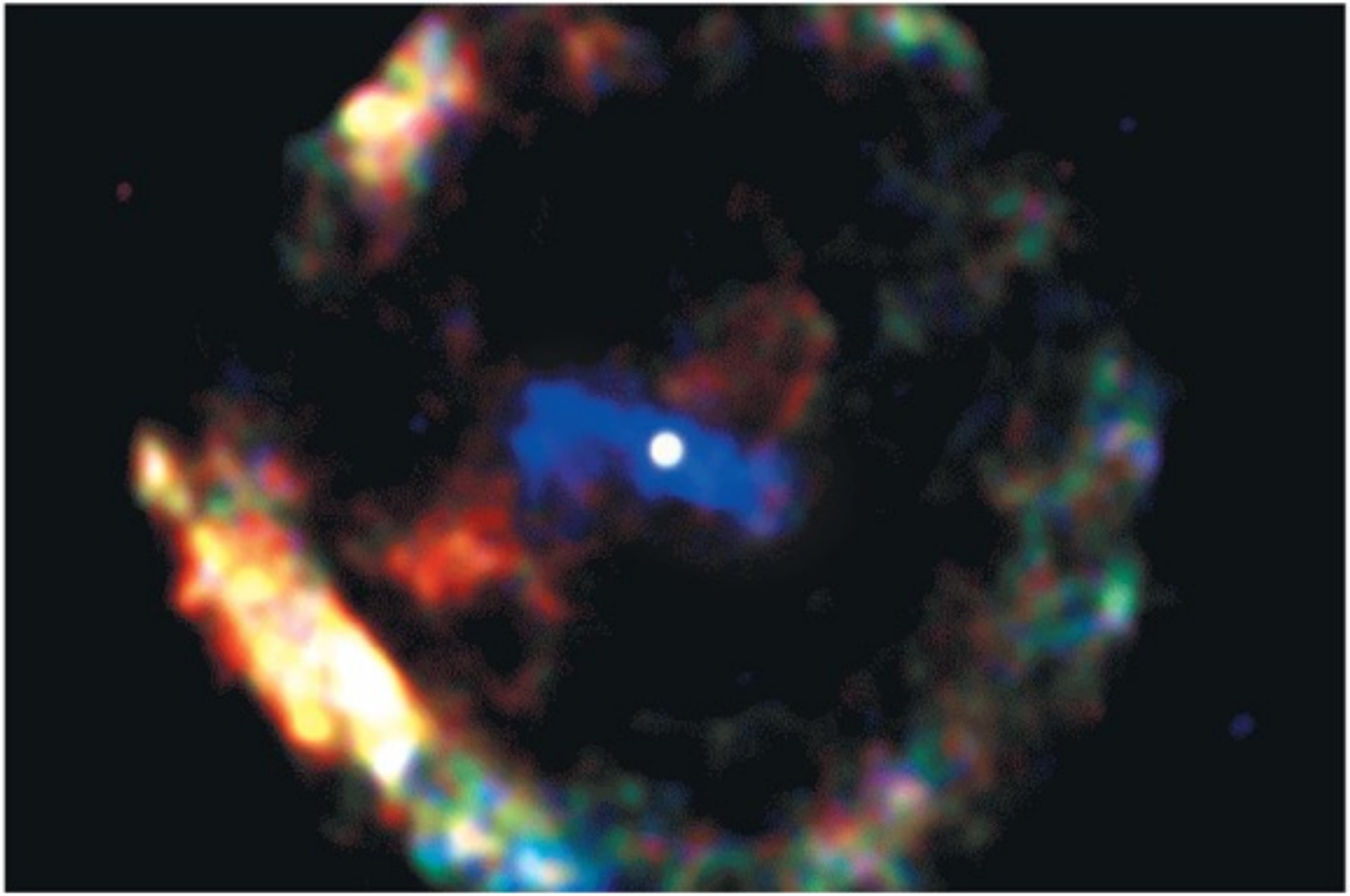
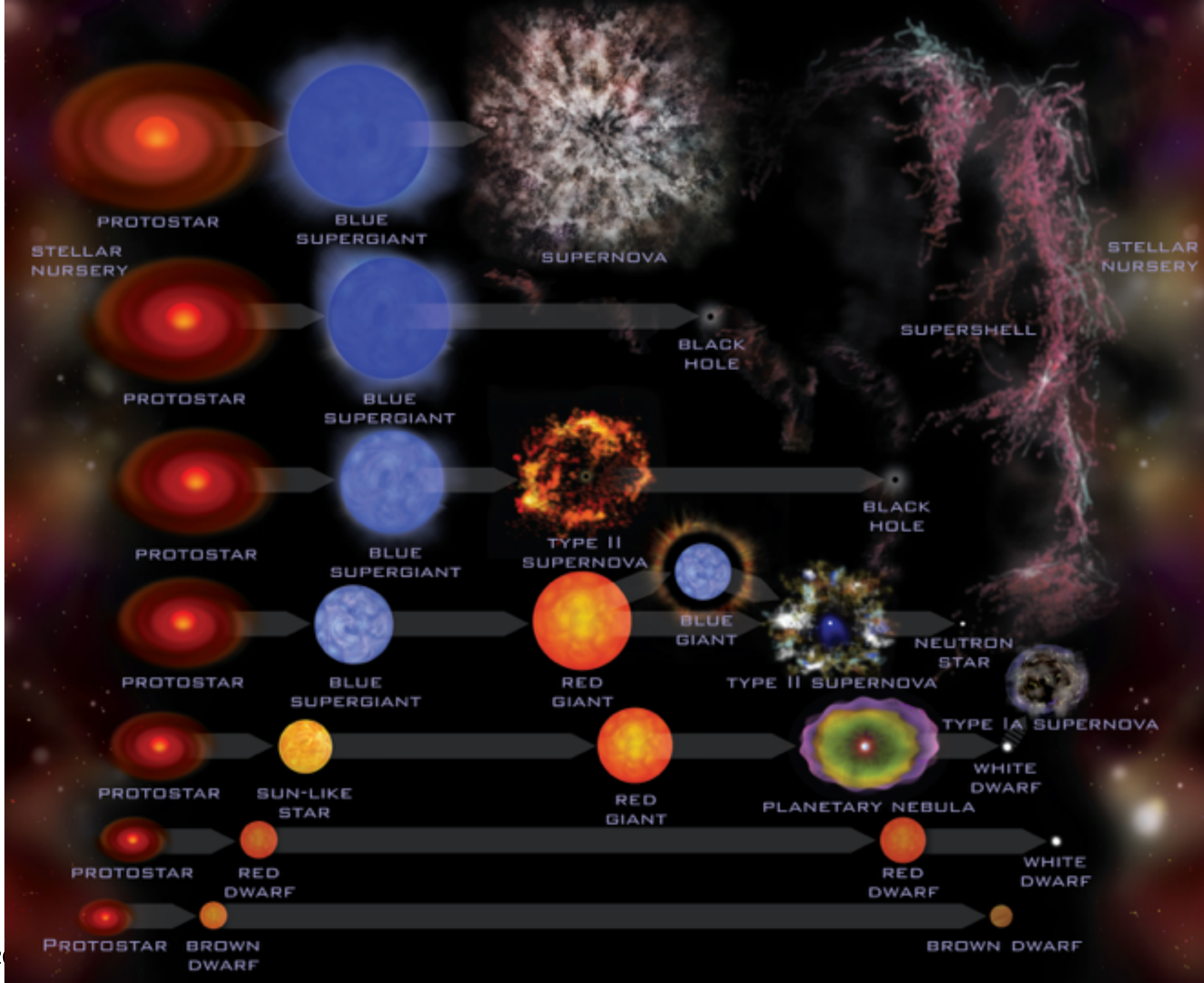
The Bizarre Stellar Graveyard




PROTOSTAR
BLUE SUPERGIANT
SUPERNOVA
STELLAR NURSERY
STELLAR NURSERY
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BLACK HOLE
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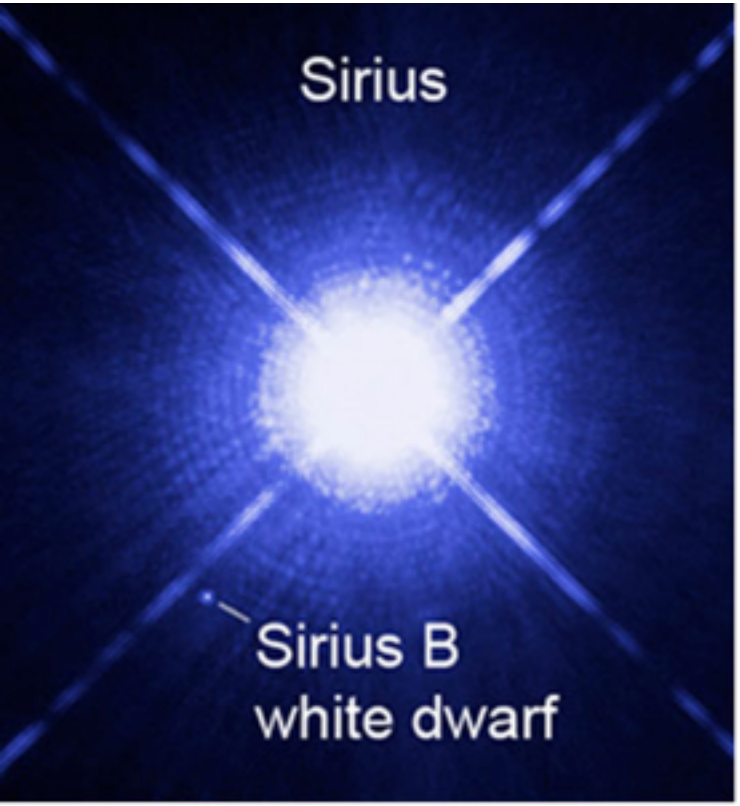
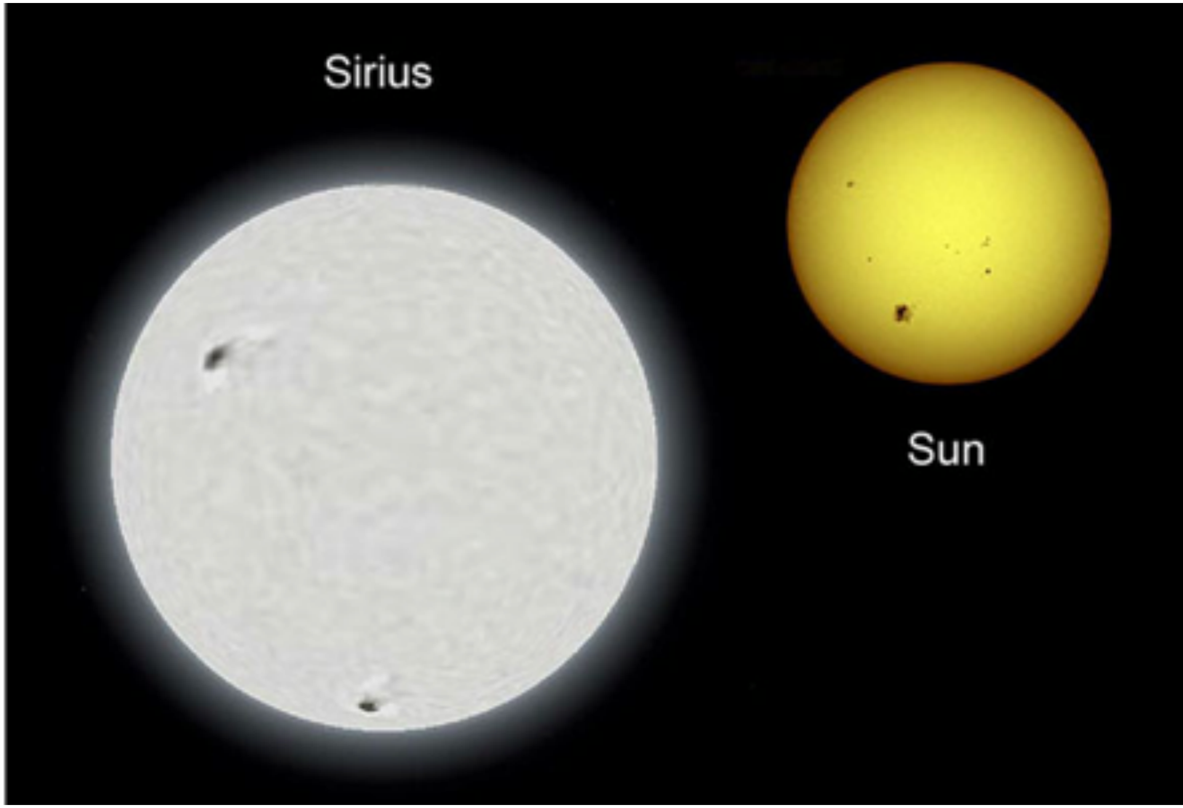
BLUE SUPERGIANT
TYPE II SUPERNOVA
BLACK HOLE
PROTOSTAR
BLUE SUPERGIANT
RED GIANT
BLUE GIANT
TYPE II SUPERNOVA
NEUTRON STAR
TYPE IA SUPERNOVA
PROTOSTAR
SUN-LIKE STAR
RED GIANT
PLANETARY NEBULA
WHITE DWARF
PROTOSTAR
RED DWARF
RED DWARF
WHITE DWARF
PROTOSTAR
BROWN DWARF
BROWN DWARF

White Dwarfs

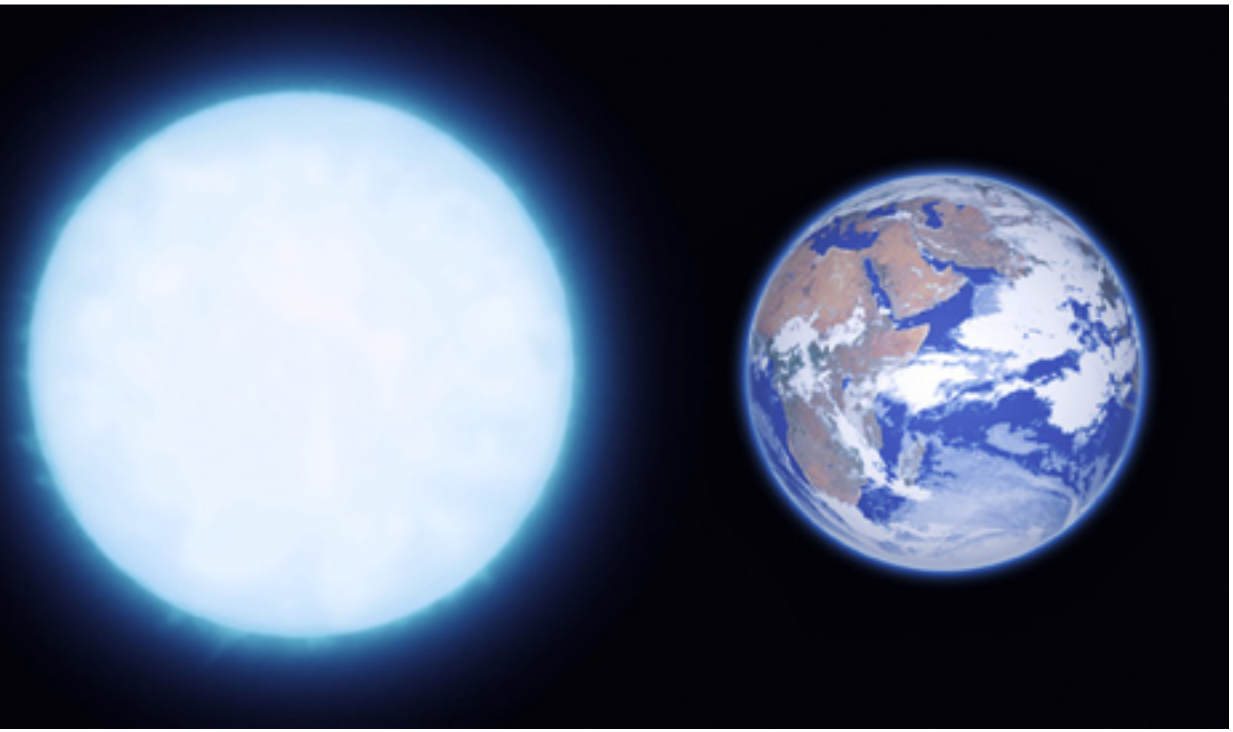
- What is a white dwarf?
- What can happen to a white dwarf in a close binary system?

What is a white dwarf?



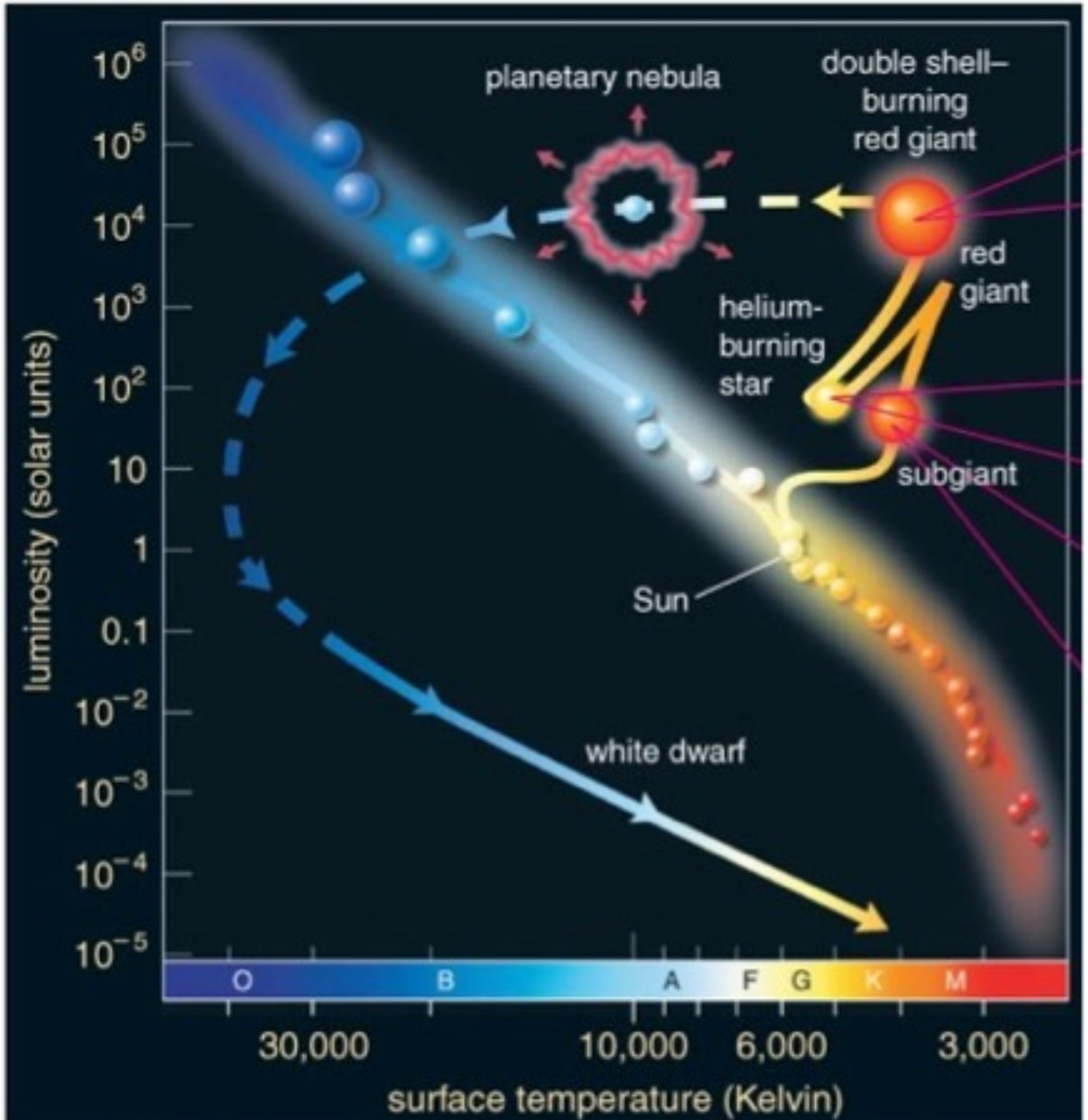


White Dwarfs



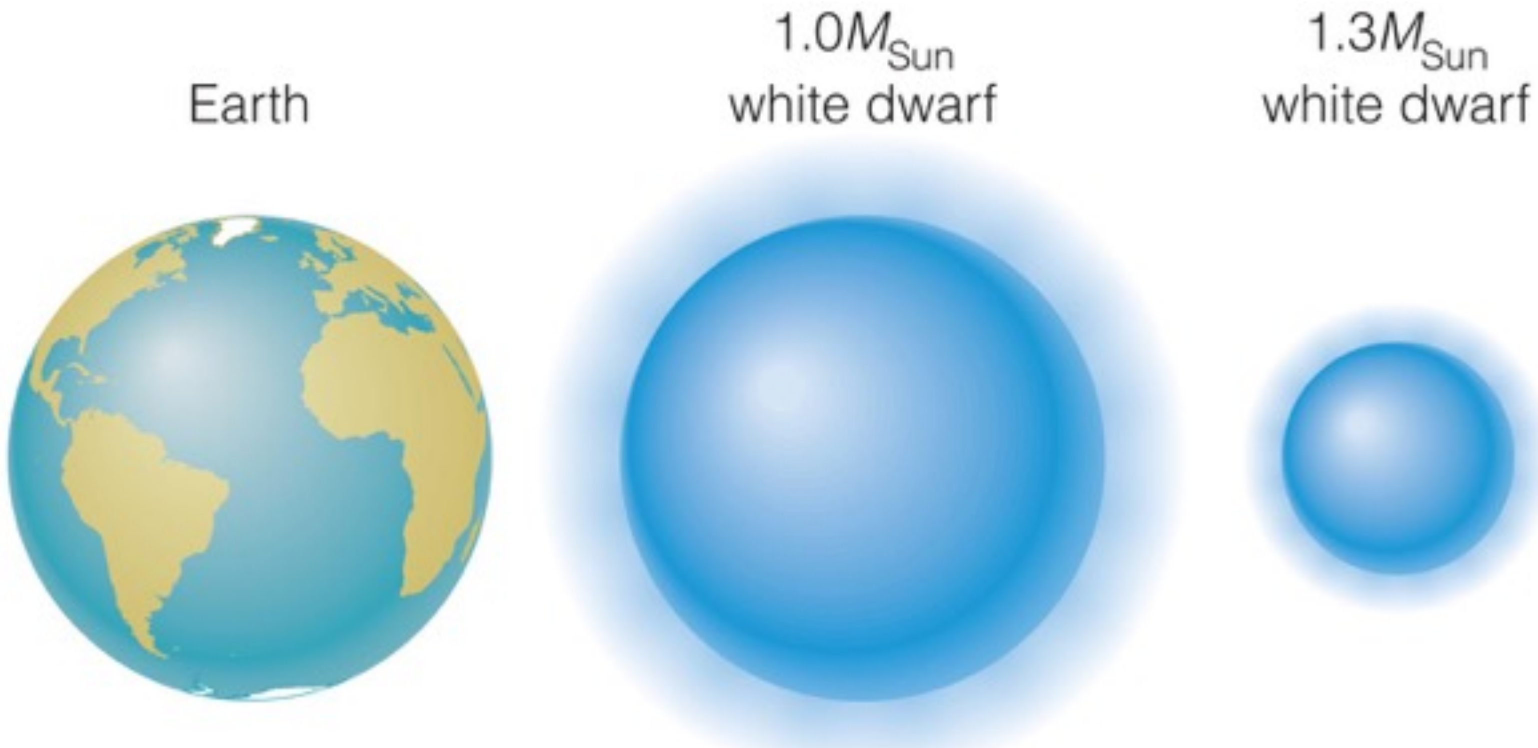
White dwarfs are the remaining cores of dead stars.

Electron degeneracy pressure supports them against the crush of gravity.



White dwarfs cool off and grow dimmer with time.

Size of a White Dwarf

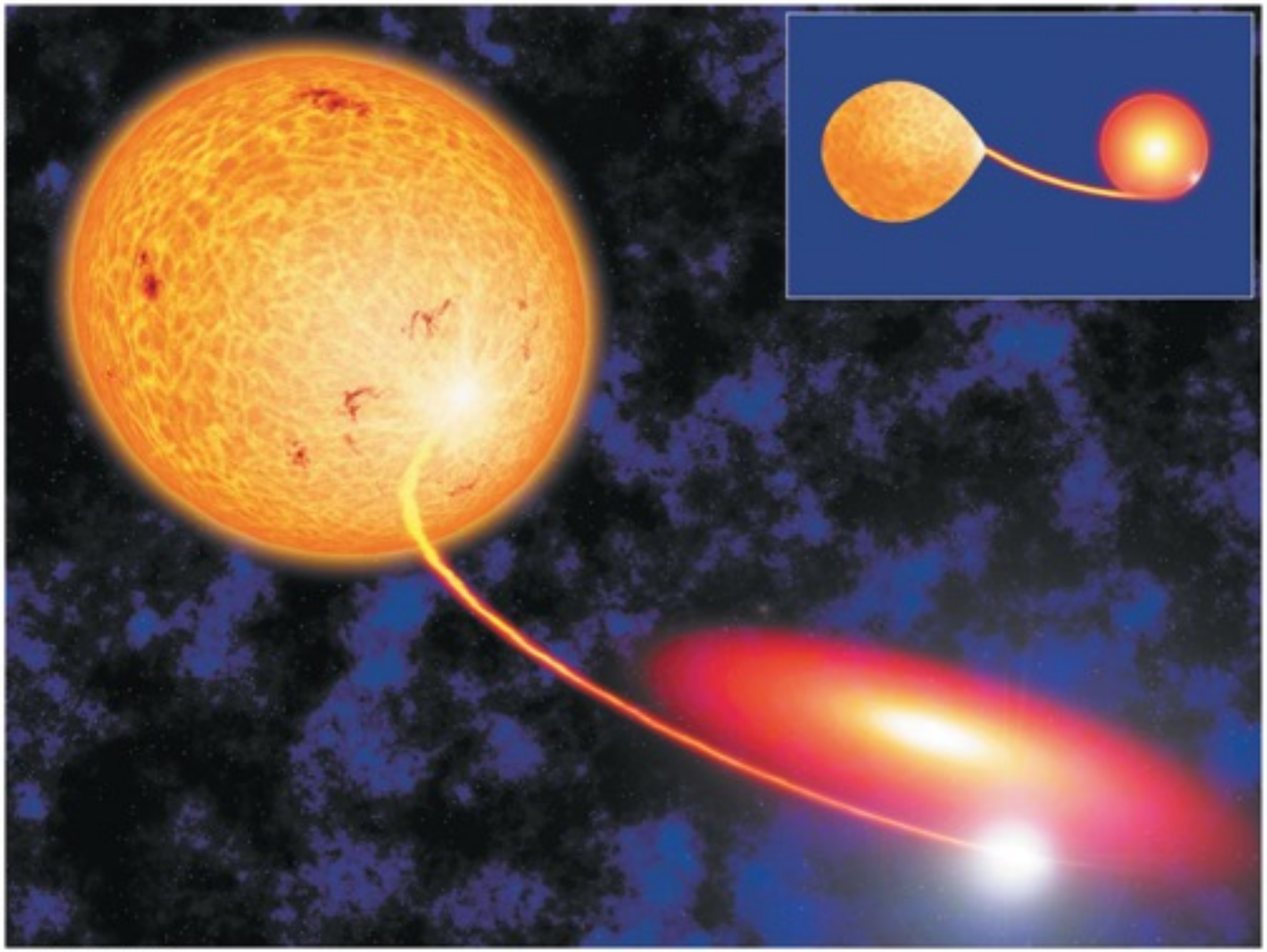


- White dwarfs with same mass as Sun are about same size as Earth.
- Higher-mass white dwarfs are smaller.

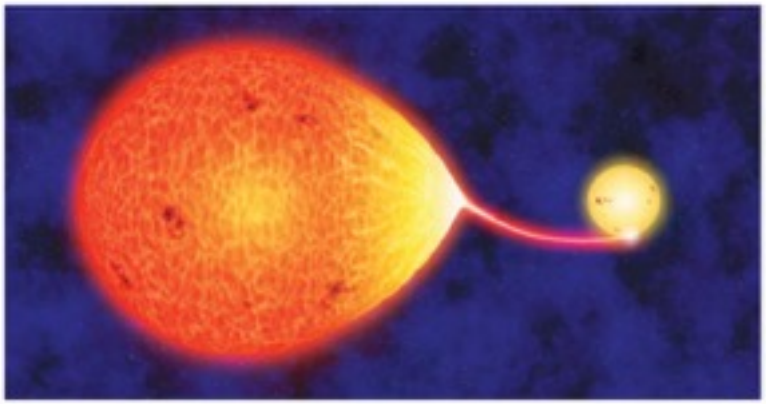
The White Dwarf Limit

- Quantum mechanics says that electrons must move faster as they are squeezed into a very small space.
- As a white dwarf's mass approaches $1.4M_{Sun}$, its electrons must move at nearly the speed of light.
- Because nothing can move faster than light, a white dwarf cannot be more massive than $1.4M_{Sun}$, the white dwarf limit (or Chandrasekhar limit).

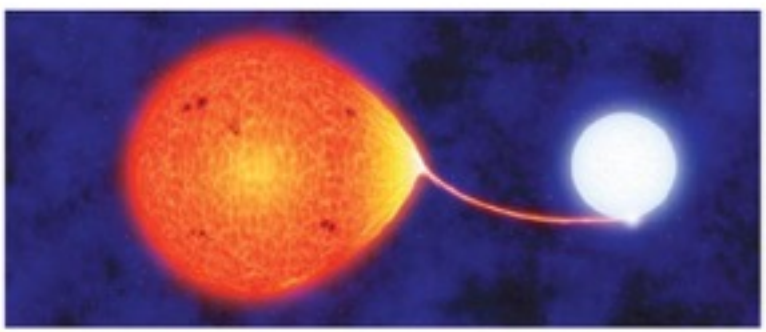
What can happen to a white dwarf in a close binary system?



Algol shortly after its birth. The higher-mass star (left) evolved more quickly than its lower-mass companion (right).



Algol at onset of mass transfer. When the more massive star expanded into a red giant, it began losing some of its mass to its normal, hydrogen-burning companion.



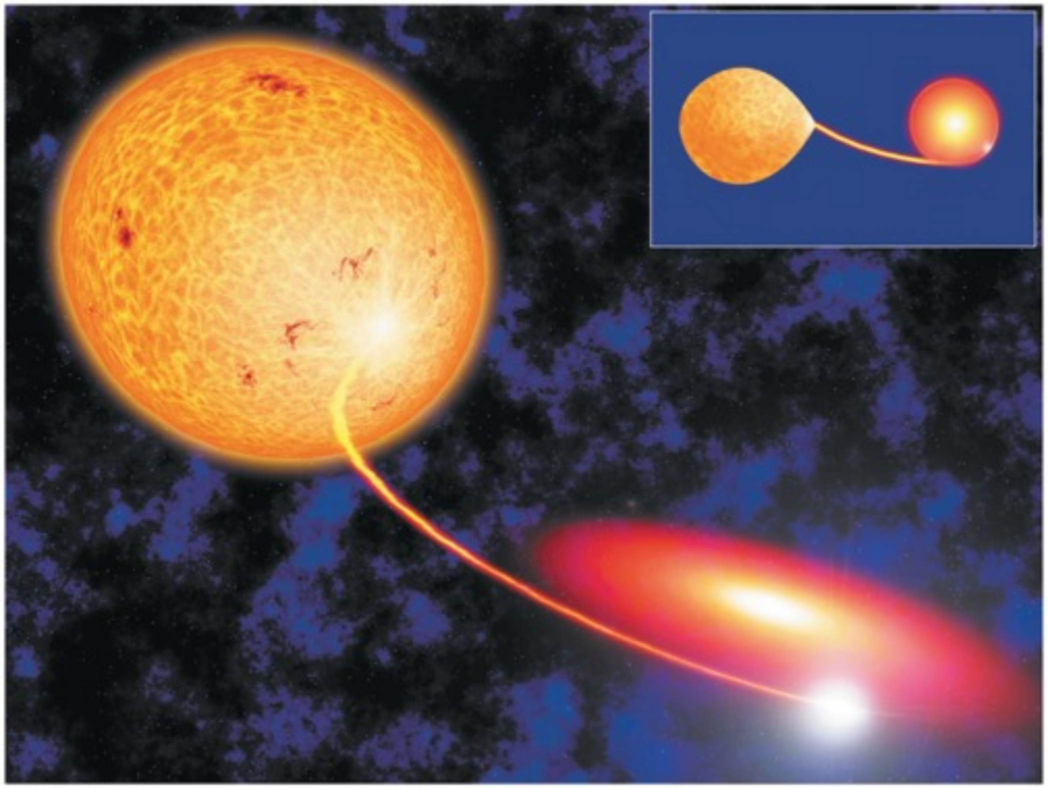
Algol today. As a result of the mass transfer, the red giant has shrunk to a subgiant, and the normal star on the right is now the more massive of the two stars.

A star that started with less mass gains mass from its companion.

Eventually, the mass-losing star will become a white dwarf.

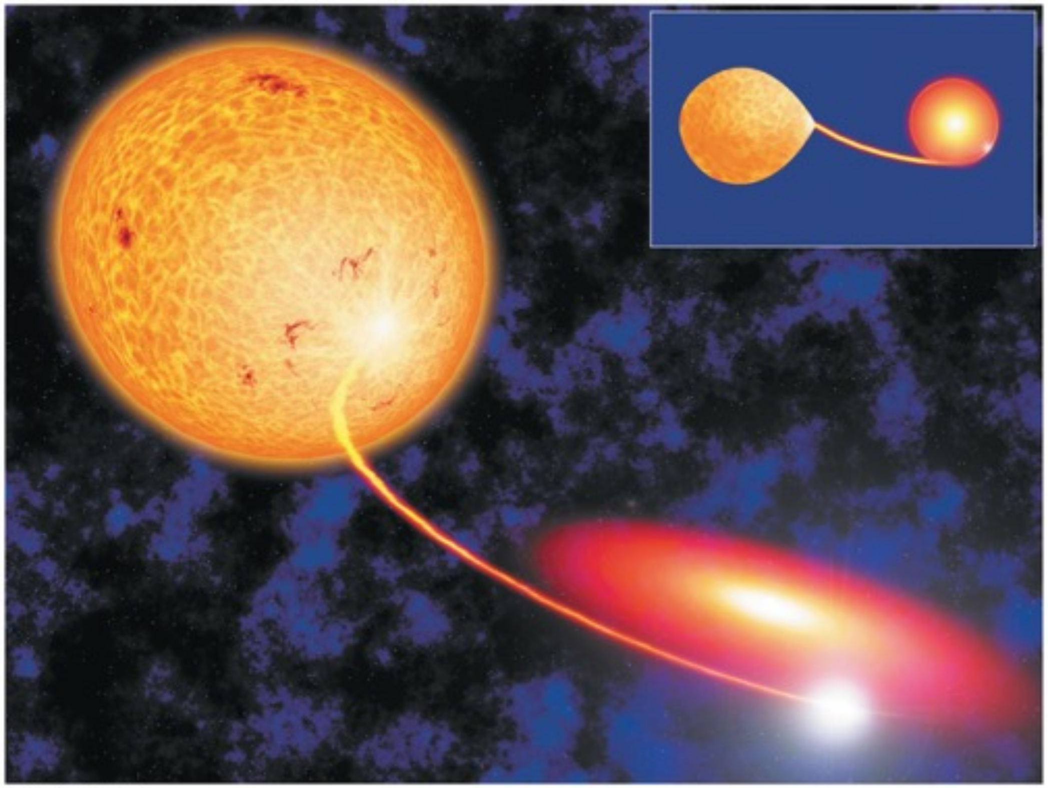
What happens next?

Accretion Disks



- Mass falling toward a white dwarf from its close binary companion has some angular momentum.
- The matter therefore orbits the white dwarf in an accretion disk.

Accretion Disks



- Friction between orbiting rings of matter in the disk transfers angular momentum outward and causes the disk to heat up and glow.

Thought Question

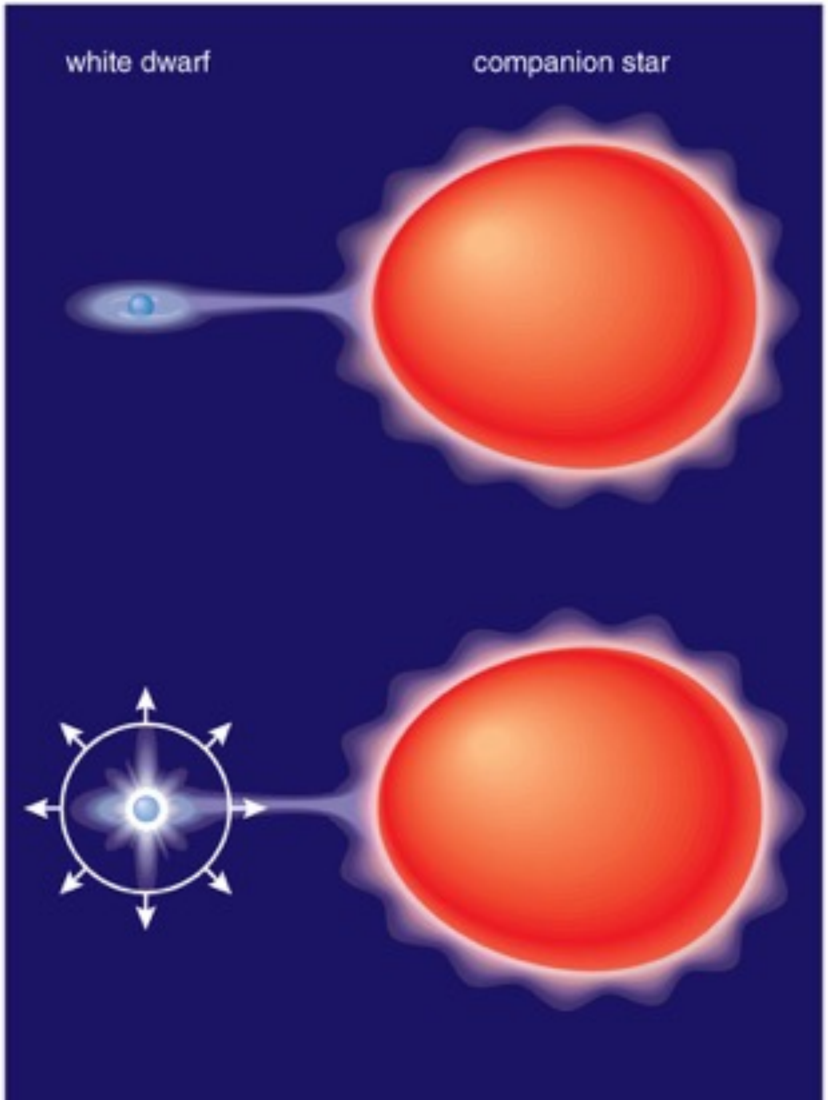
What would gas in disk do if there were no friction?

A. It would orbit indefinitely.
B. It would eventually fall in.
C. It would blow away.

What is the mass limit of a white dwarf?

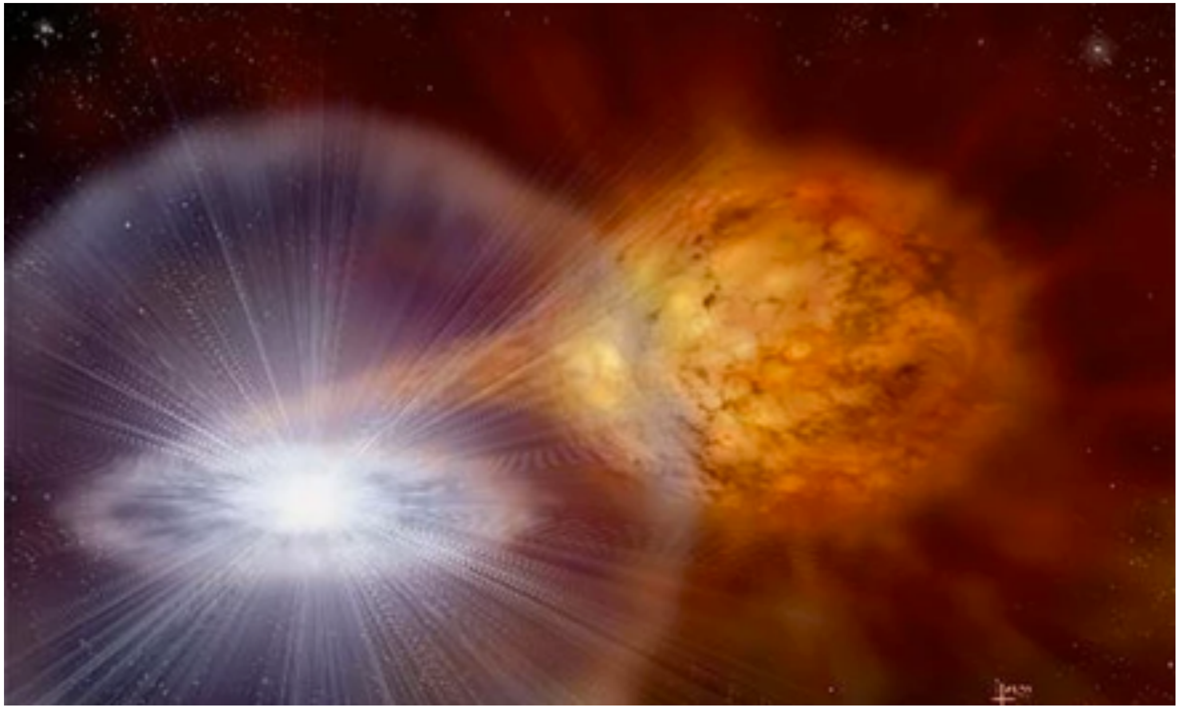
a) 0.8 solar masses
b) 1.1 solar masses
c) 1.4 solar masses
d) 2.0 solar masses
e) 8.0 solar masses

Nova



- The temperature of accreted matter eventually becomes hot enough for hydrogen fusion.

- Fusion begins suddenly and explosively, causing a nova.



Nova

- The nova star system temporarily appears much brighter.
- The explosion drives accreted matter out into space.

Thought Question

What happens to a white dwarf when it accretes enough matter to reach the $1.4M_{Sun}$ limit?

A. It explodes.
B. It collapses into a neutron star.
C. It gradually begins fusing carbon in its core.

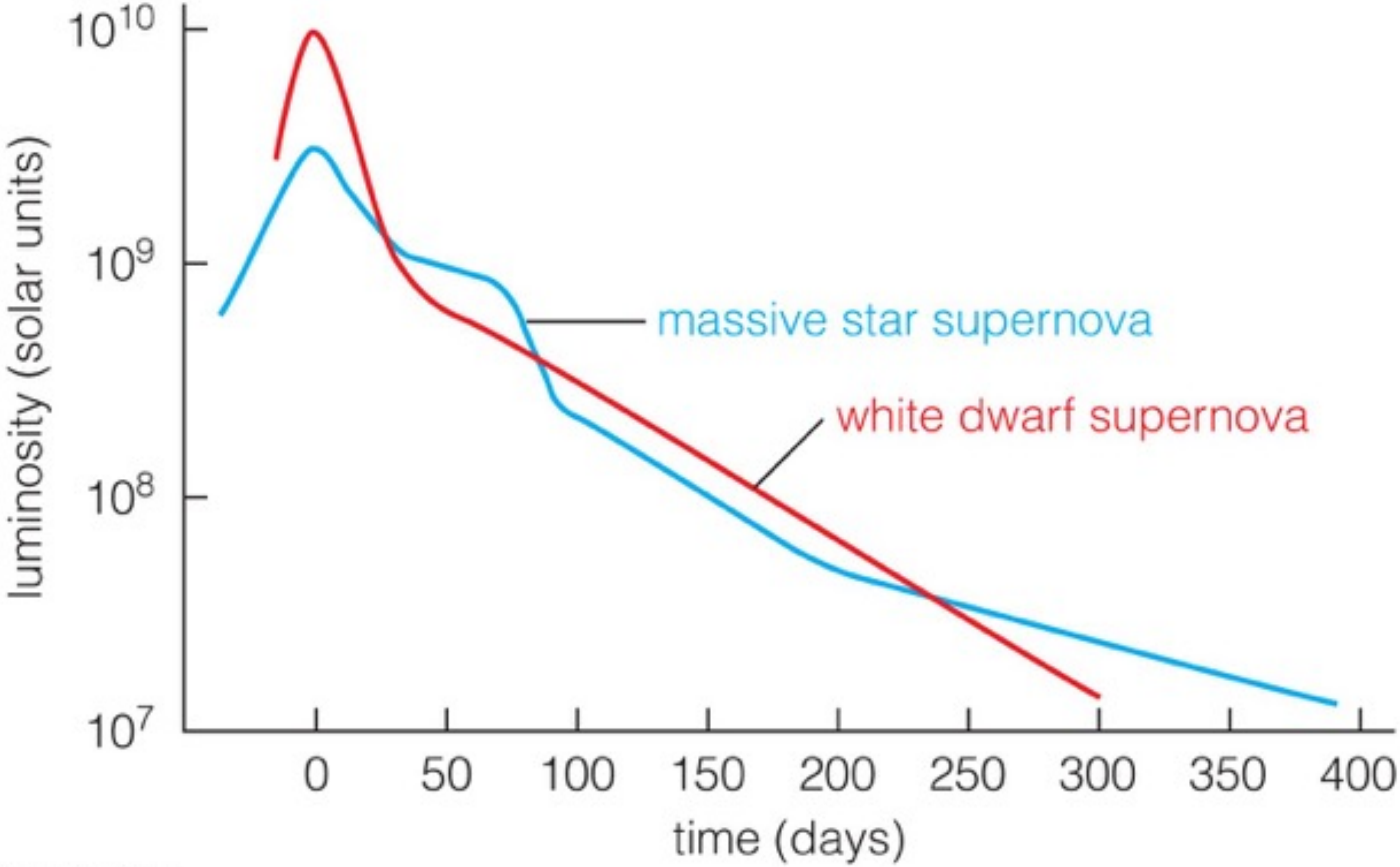
Two Types of Supernova

Massive star supernova:

Iron core of a massive star reaches white dwarf limit and collapses into a neutron star, causing total explosion.

White dwarf supernova:

Carbon fusion suddenly begins as a white dwarf in close binary system reaches white dwarf limit, causing total explosion.



One way to tell supernova types apart is with a light curve showing how luminosity changes with time.

Nova or Supernova?

- Supernovae are MUCH MUCH more luminous (about 10 thousand times)!!!
- Nova: H to He fusion of a layer of accreted matter, white dwarf left intact
- Supernova: complete explosion of white dwarf, nothing left behind

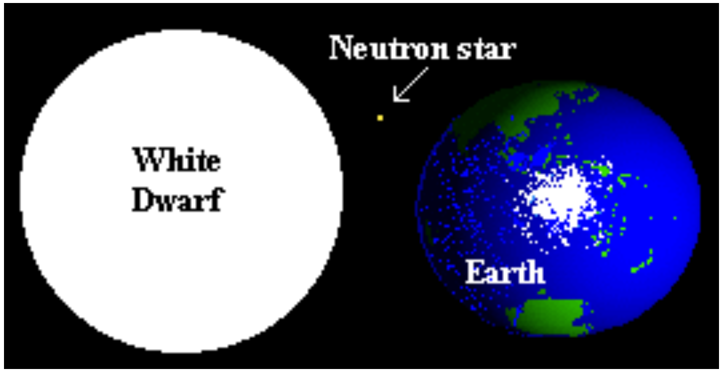
Supernova Type: Massive Star or White Dwarf?

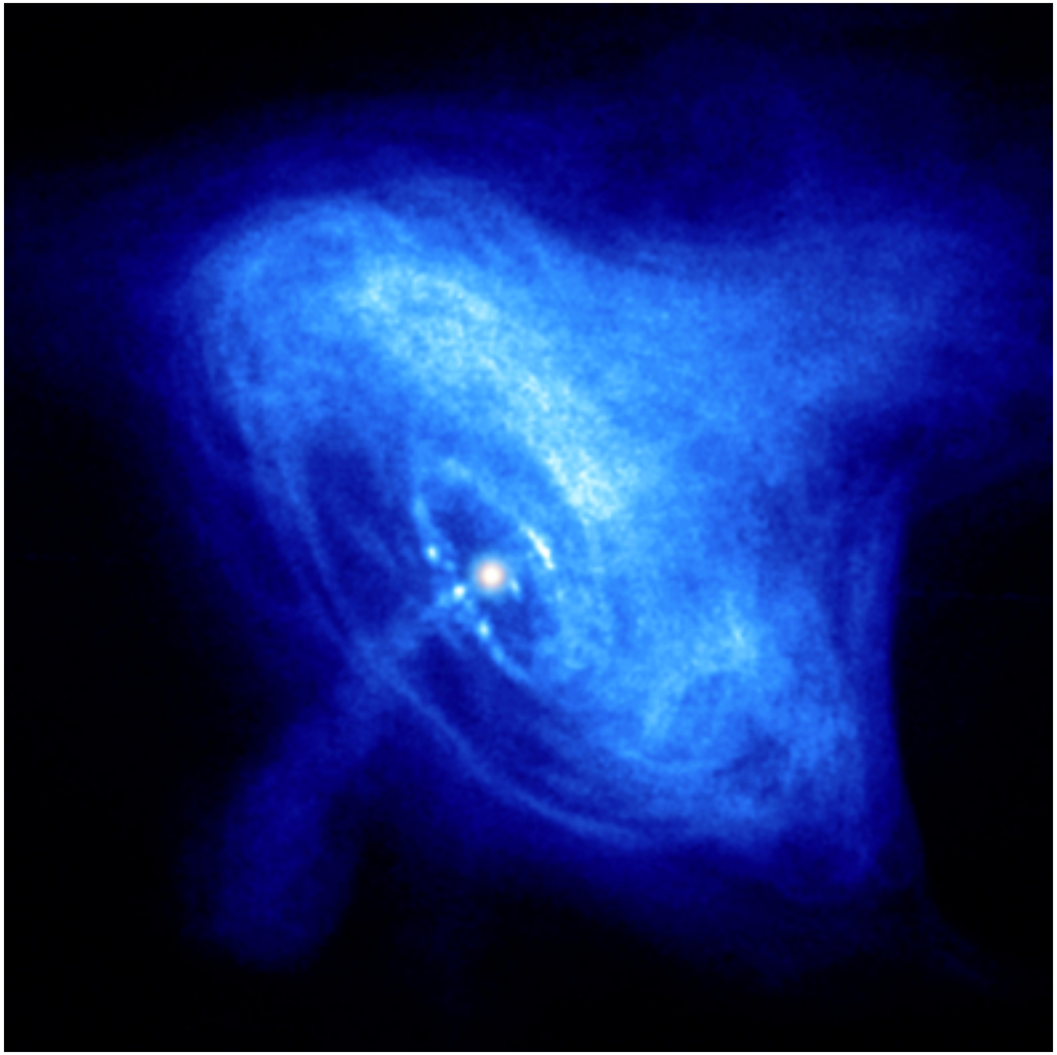
- Light curves differ.
- Spectra differ (exploding white dwarfs don't have hydrogen absorption lines).

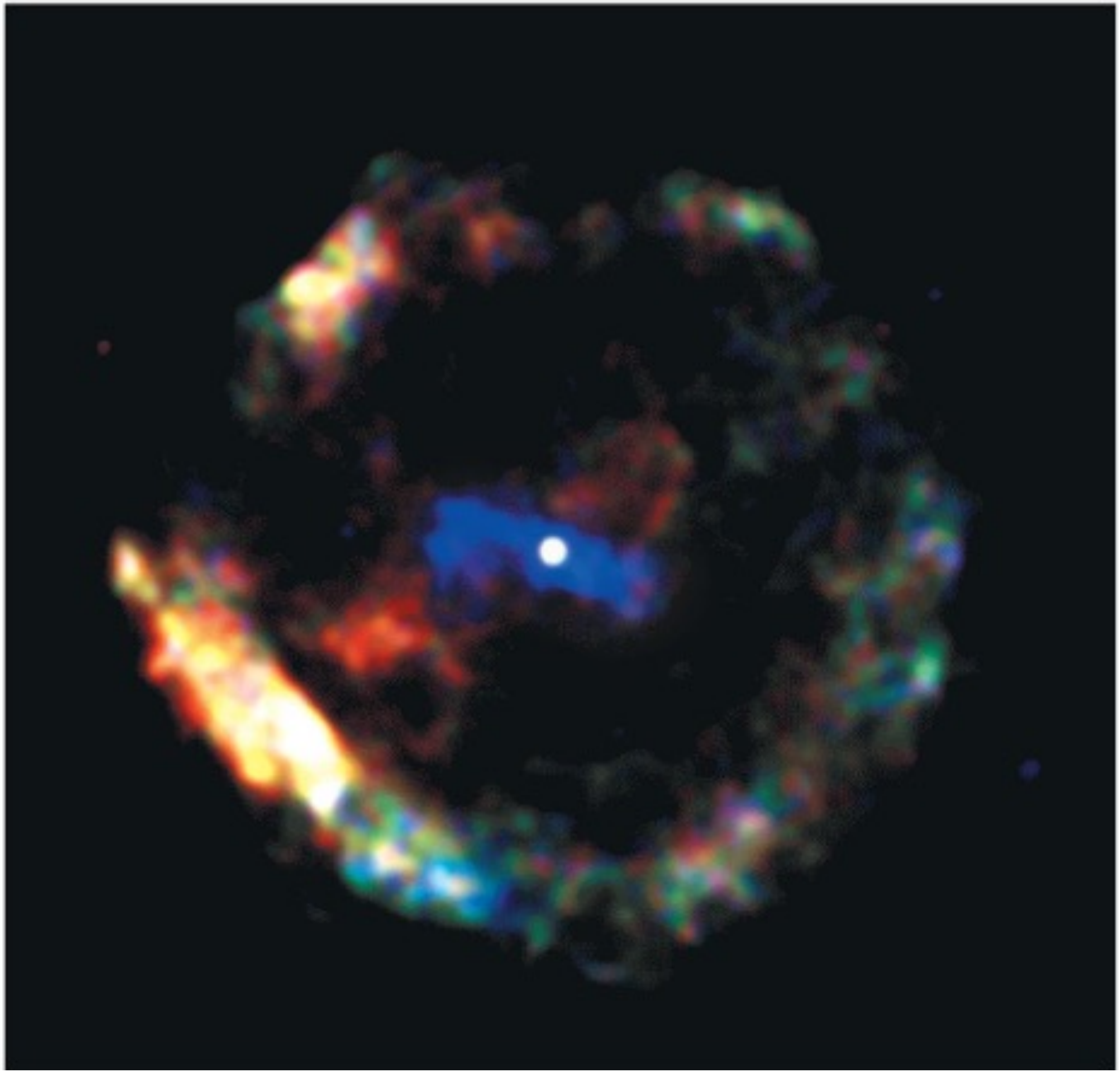
Neutron Stars

- What is a neutron star?
- How were neutron stars discovered?
- What can happen to a neutron star in a close binary system?

What is a neutron star?

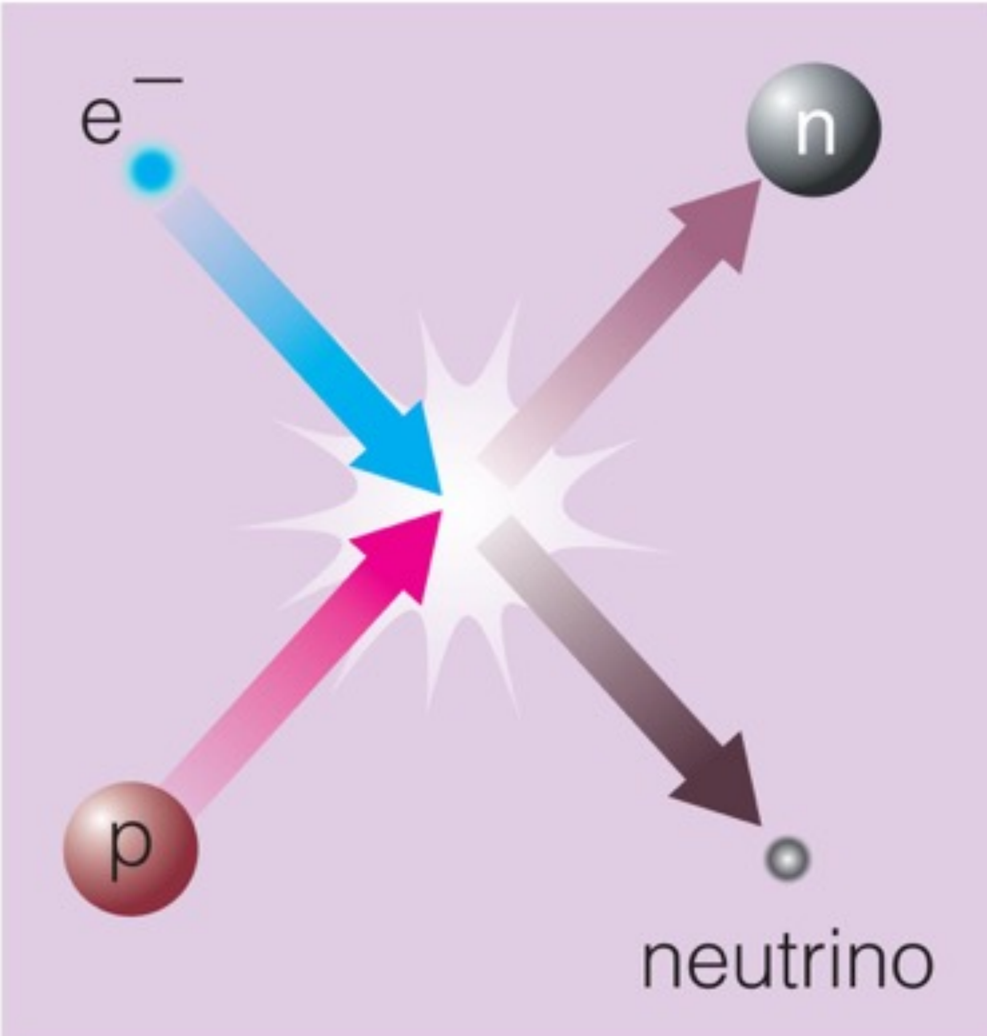






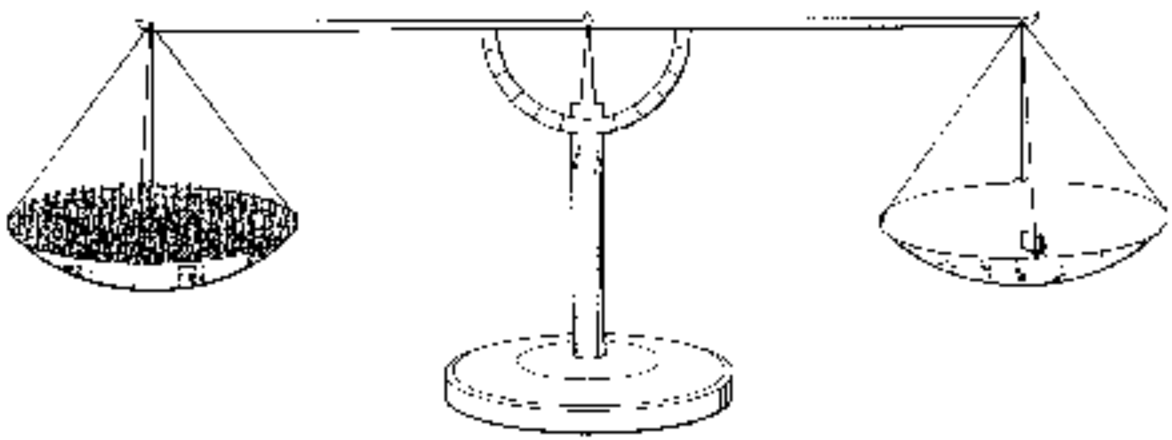
-A neutron star is the ball of neutrons left behind by a massive-star supernova.

-Degeneracy pressure of neutrons supports a neutron star against gravity.



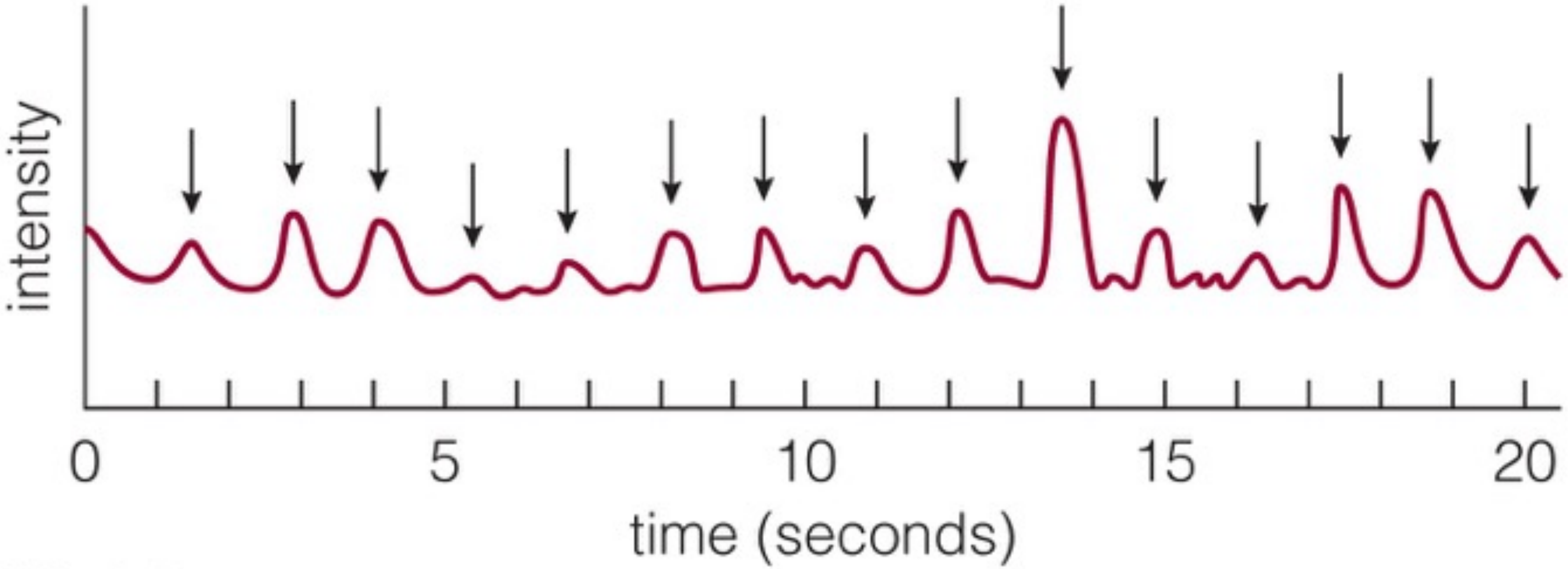
Electron degeneracy pressure goes away because electrons combine with protons, making neutrons and neutrinos.

Neutrons collapse to the center, forming a neutron star.

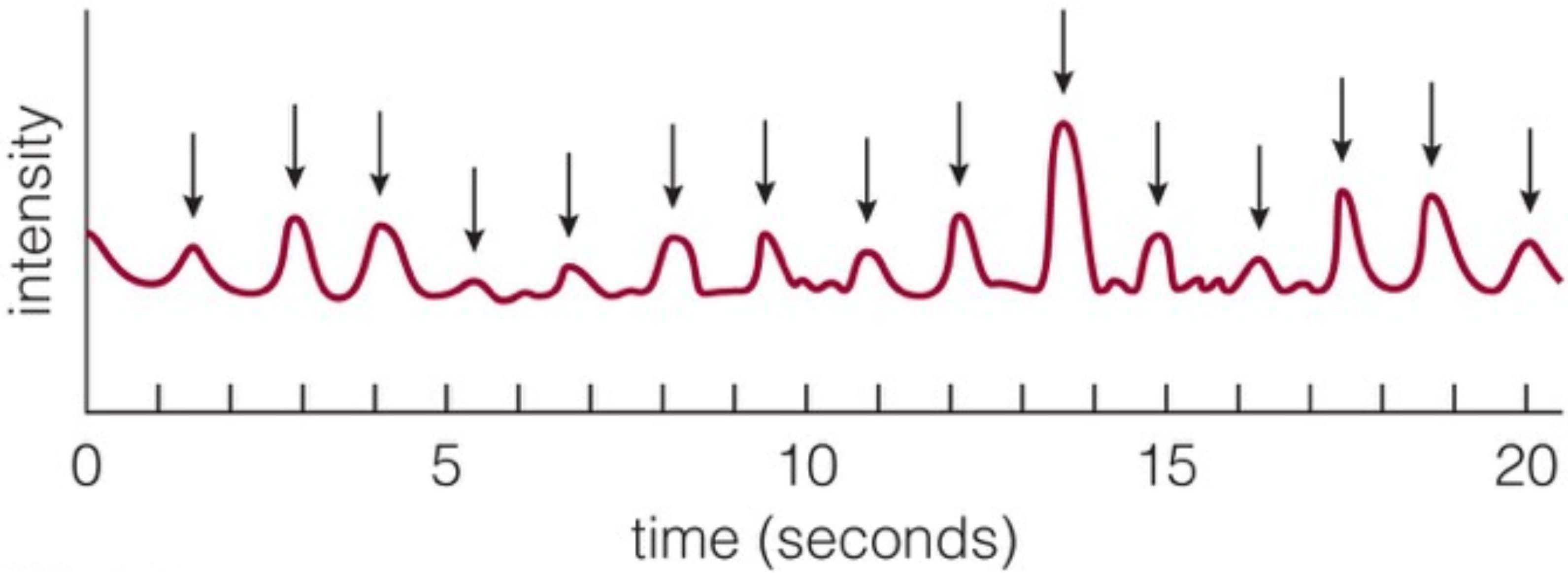


A neutron star is about the same size as a small city.

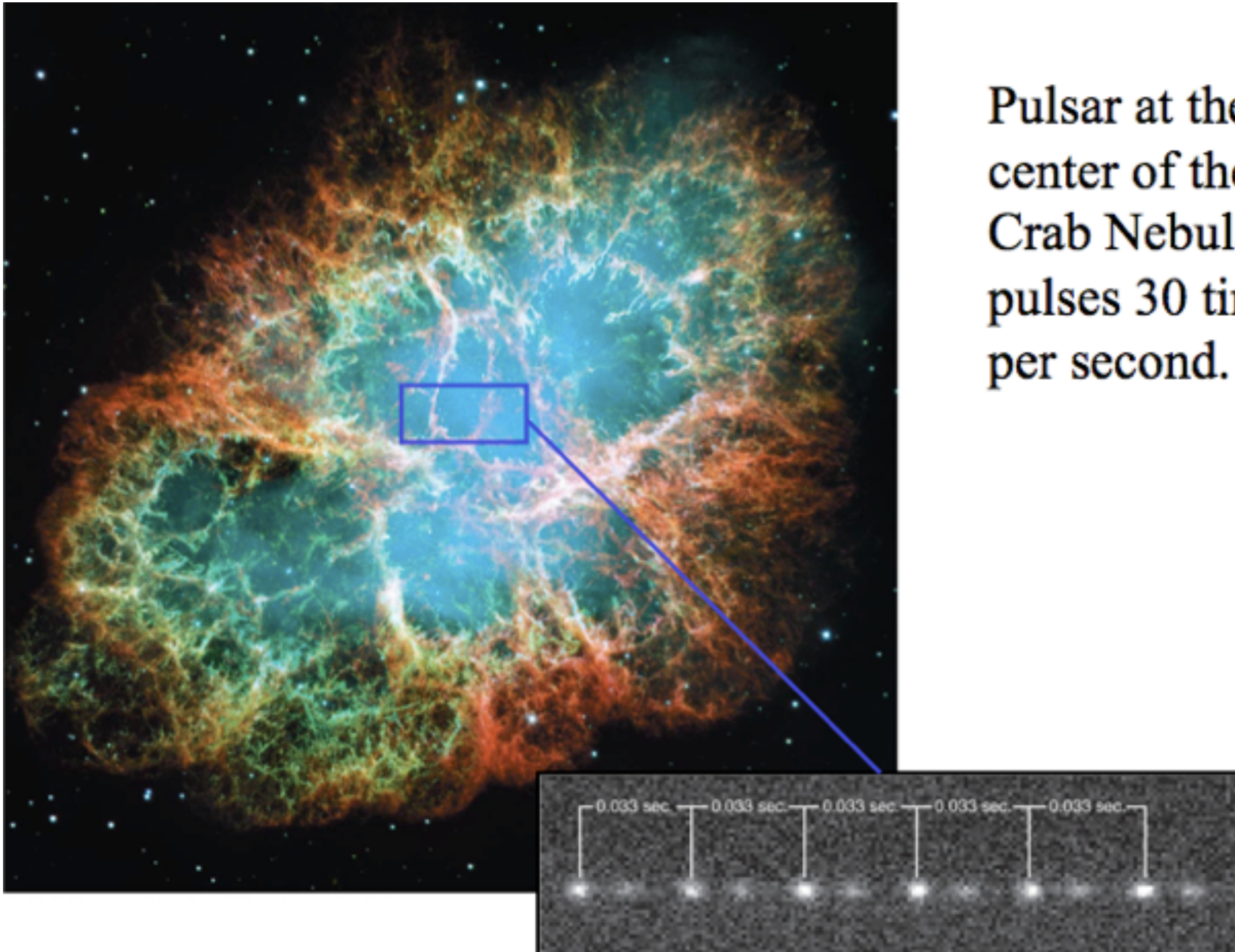
How were neutron stars discovered?



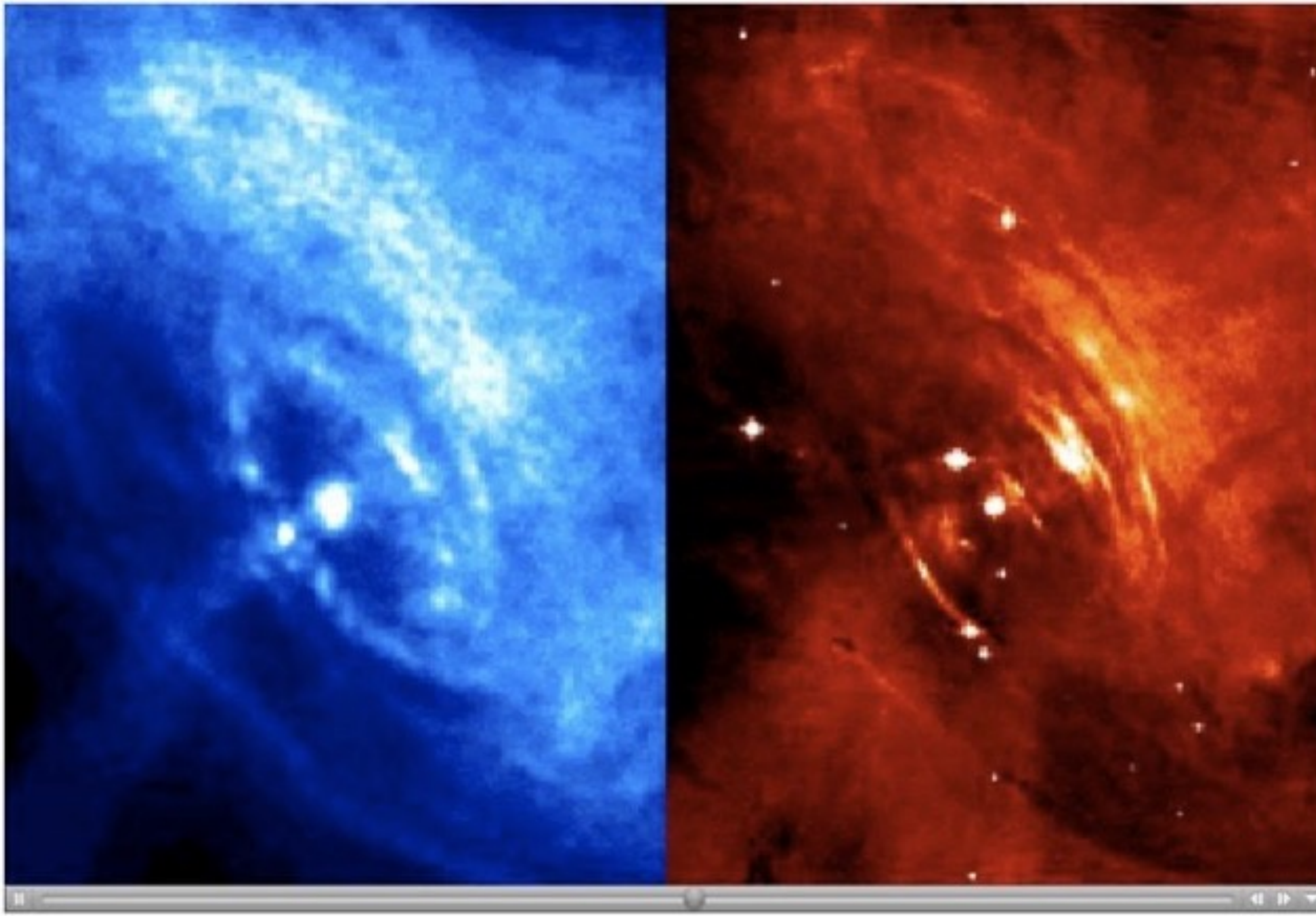
Discovery of Neutron Stars



- Using a radio telescope in 1967, Jocelyn Bell noticed very regular pulses of radio emission coming from a single part of the sky.
- The pulses were coming from a spinning neutron star—a pulsar.



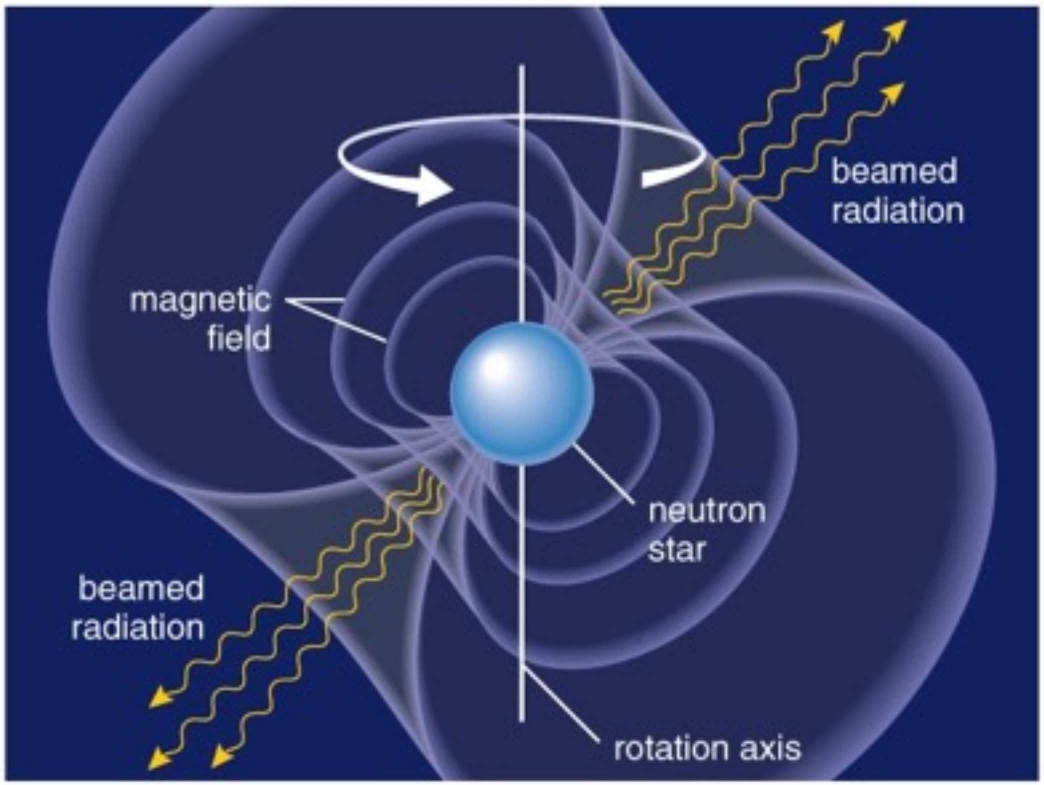
Pulsar at the center of the Crab Nebula pulses 30 times per second.



X rays

Visible light

Pulsars



- *A* **pulsar** is a neutron star that beams radiation along a magnetic axis that is not aligned with the rotation axis.

Pulsars

- The radiation beams sweep through space like lighthouse beams as the neutron star rotates.

Why Pulsars Must Be Neutron Stars

Circumference of NS = 2π (radius) ~ 60 km

Spin rate of fast pulsars ~ 1000 cycles per second

Surface rotation velocity ~ 60,000 km/s
~ 20% speed of light
~ escape velocity from NS

Anything else would be torn to pieces!

Pulsars spin fast because a stellar core's spin speeds up as it collapses into neutron star.

Conservation of angular momentum

Thought Question

Could there be neutron stars that appear as pulsars to other civilizations but not to us?

A. Yes
B. No

Chapter 18

What is a pulsar?

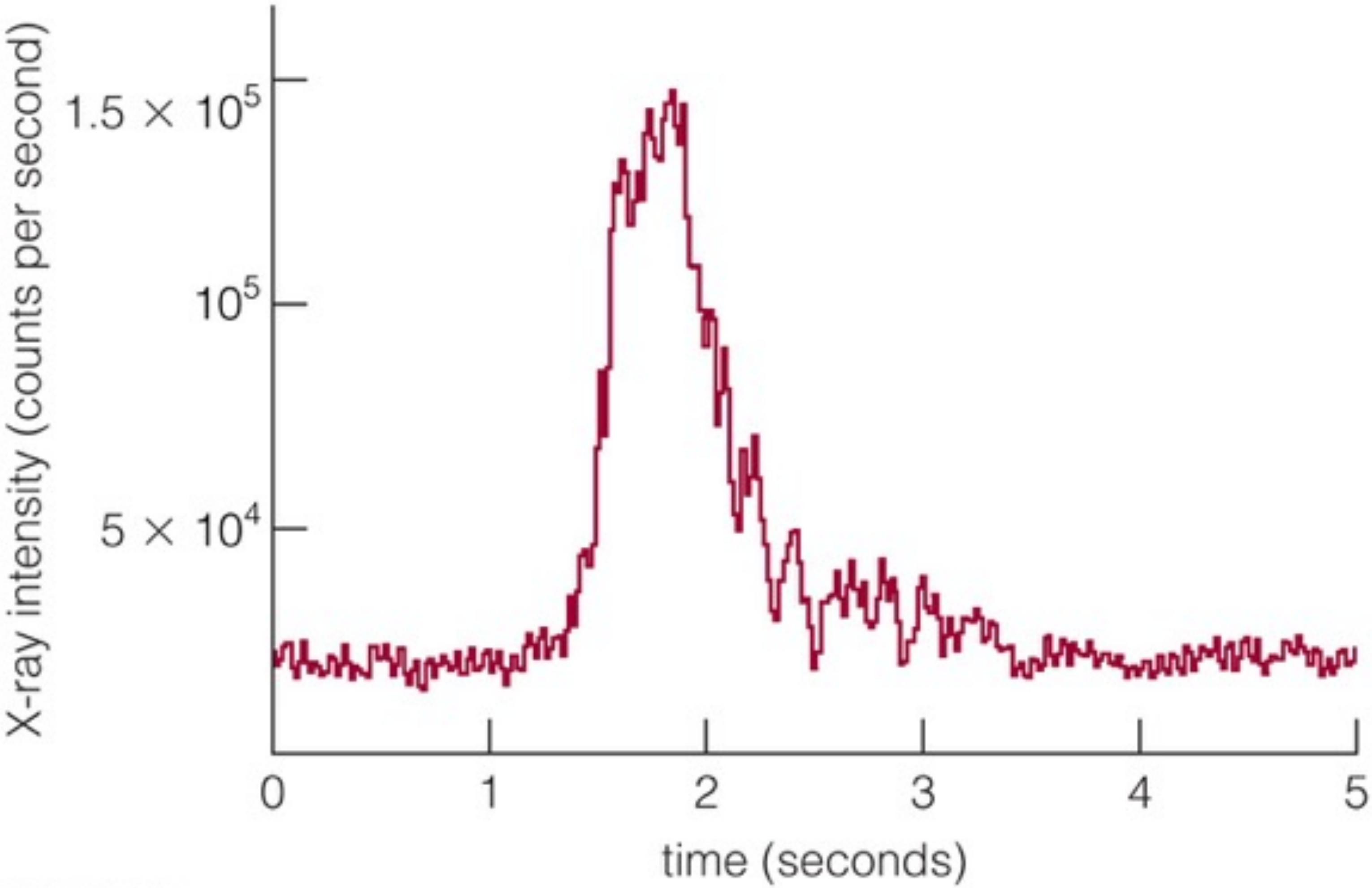
a) a high-mass star undergoing thermal pulses due to new shell fusion layers in the interior
b) a white dwarf in a binary system periodically going nova as it accretes mass from the binary star
c) a white dwarf in a binary system with a hot accretion spot that periodically comes into view as the stars orbit each other
d) a rotating neutron star beaming radiation along its magnetic axis

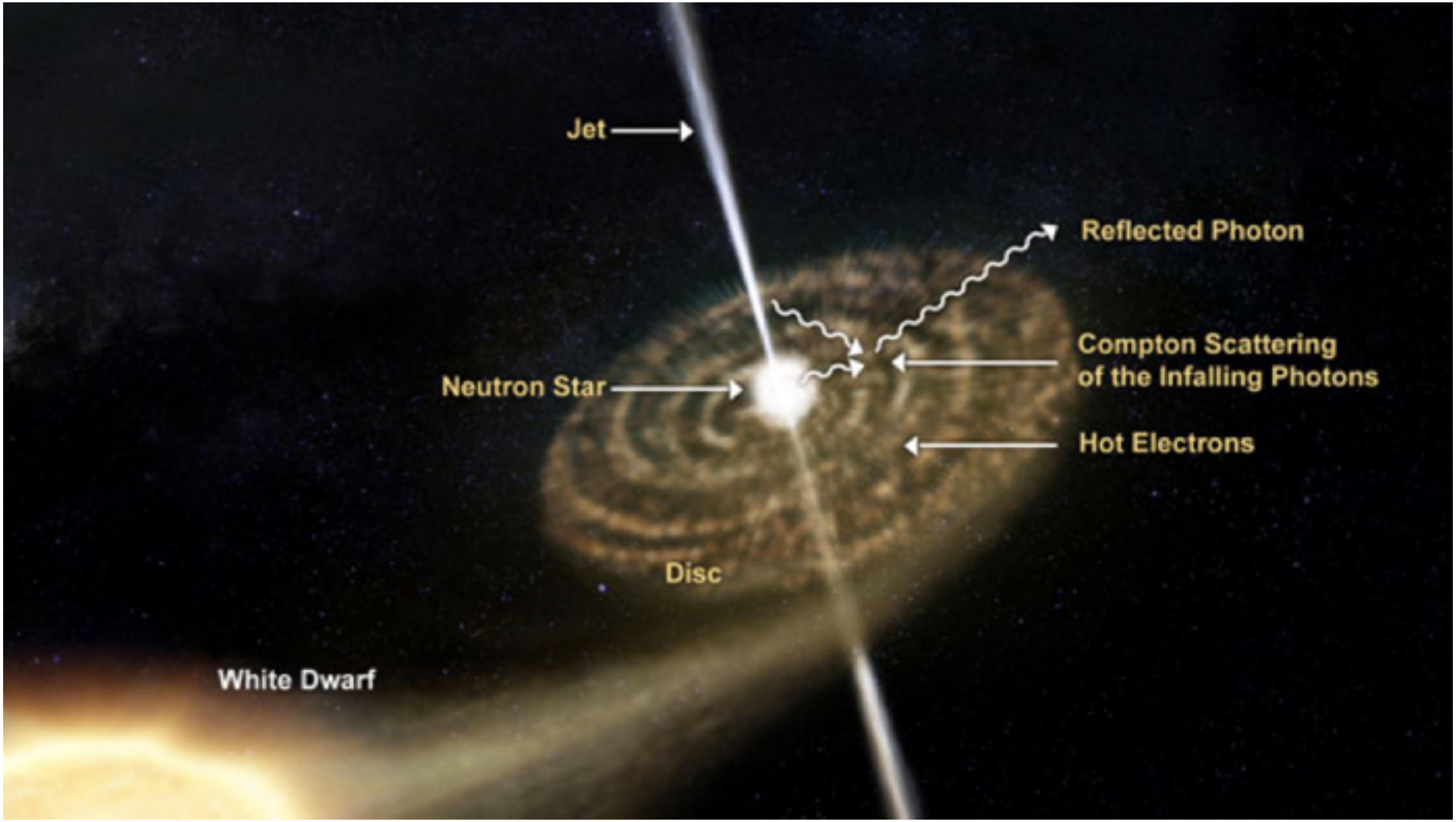
Chapter 18

How big is a neutron star?

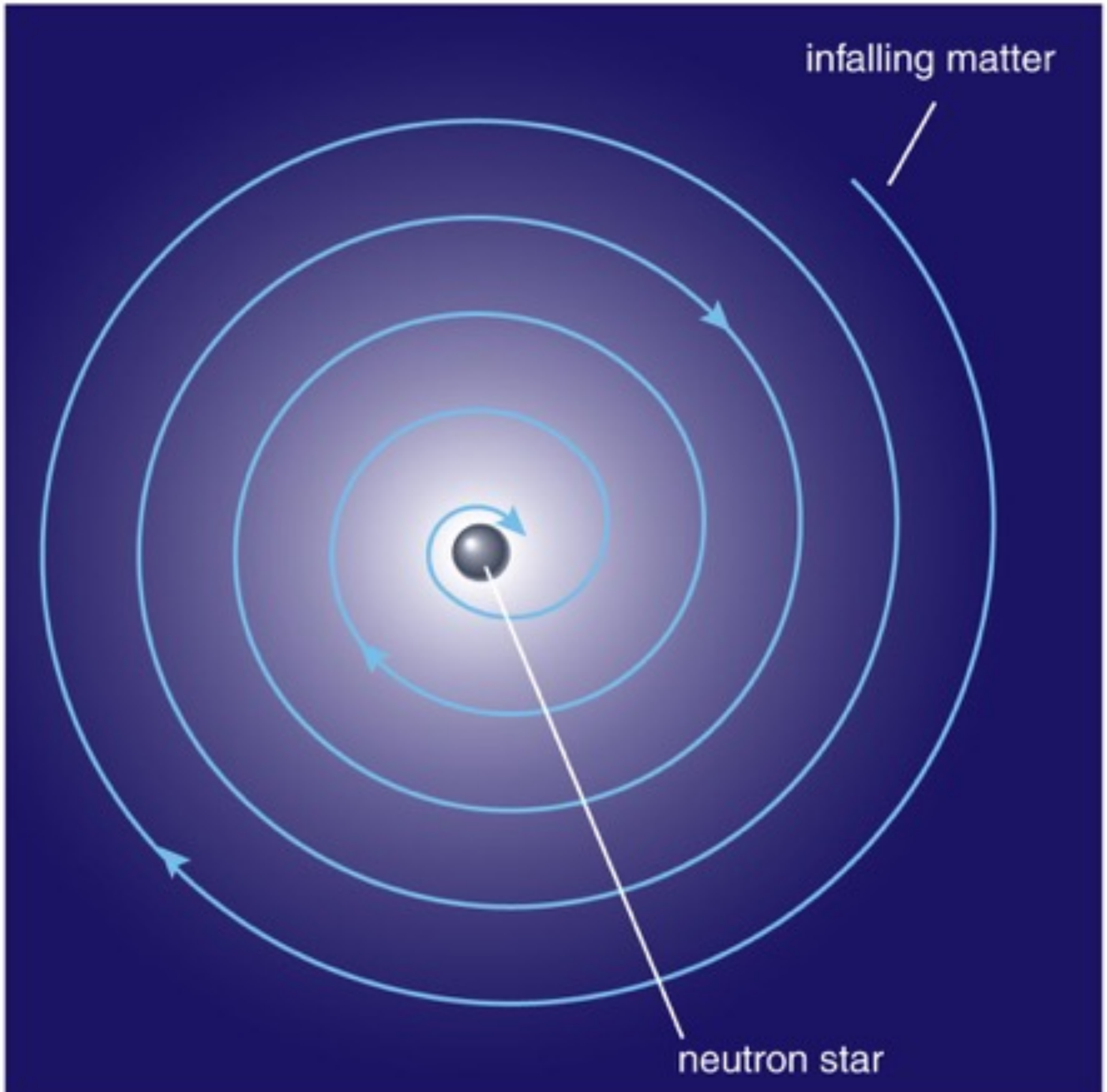
a) the size of a football field
b) the size of a city
c) the size of the Moon
d) the size of Earth
e) the size of Jupiter

What can happen to a neutron star in a close binary system?





Matter falling toward a neutron star forms an accretion disk, just as in a white dwarf binary.



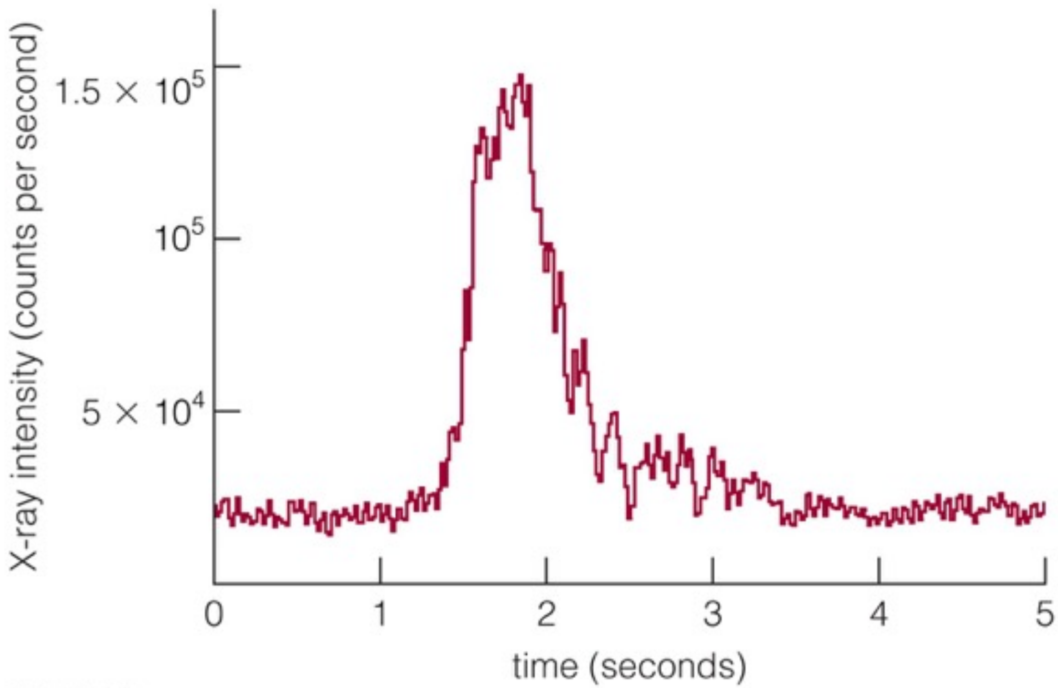
Accreting matter adds angular momentum to a neutron star, increasing its spin.

Thought Question

According to the conservation of angular momentum, what would happen if a star orbiting in a direction <u>opposite</u> the neutron's star rotation fell onto a neutron star?

A. The neutron star's rotation would speed up.
B. The neutron star's rotation would slow down.
C. Nothing. The directions would cancel each other out.

X-Ray Bursts

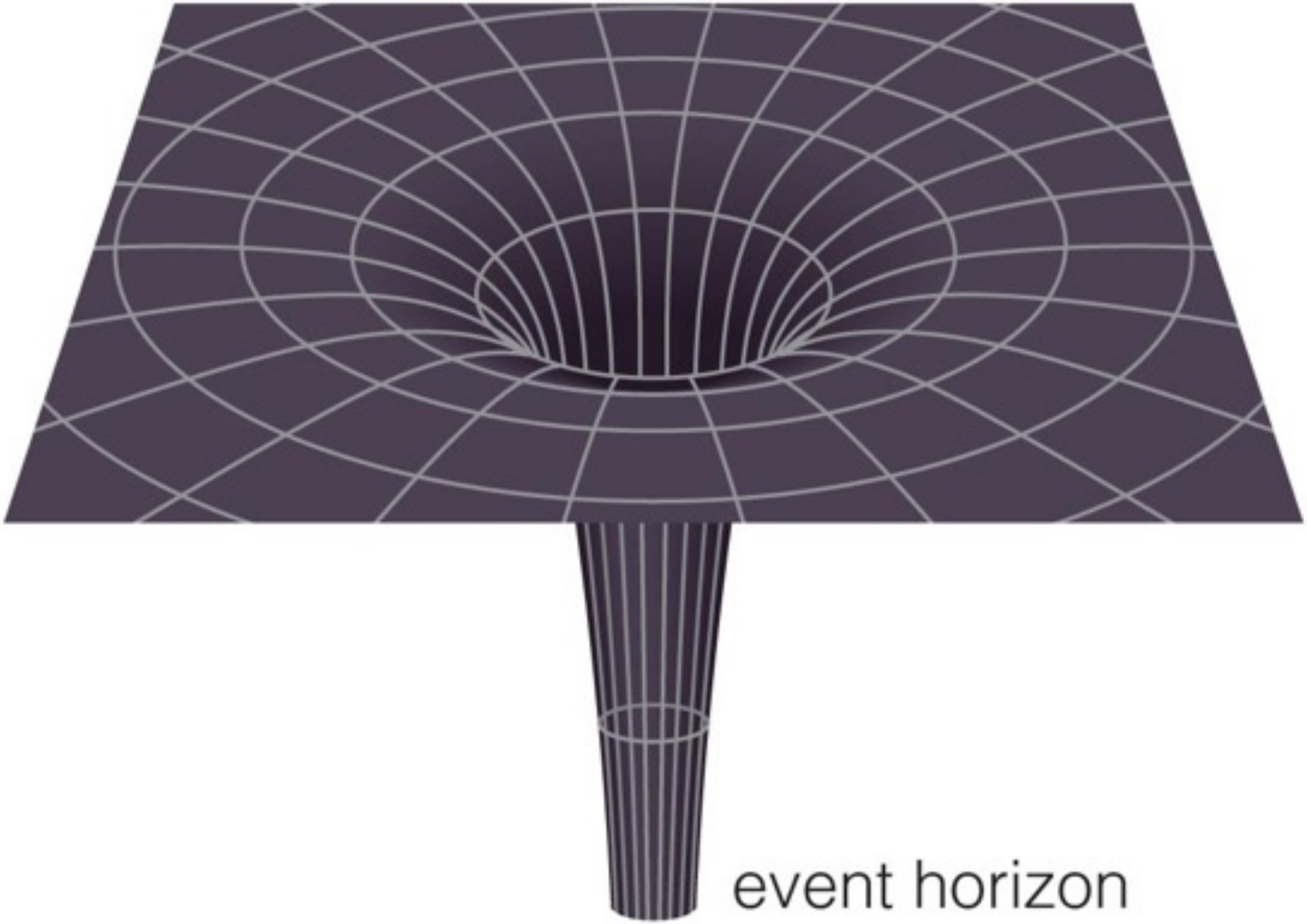


- Matter accreting onto a neutron star can eventually become hot enough for helium fusion.
- The sudden onset of fusion produces a burst of X rays.

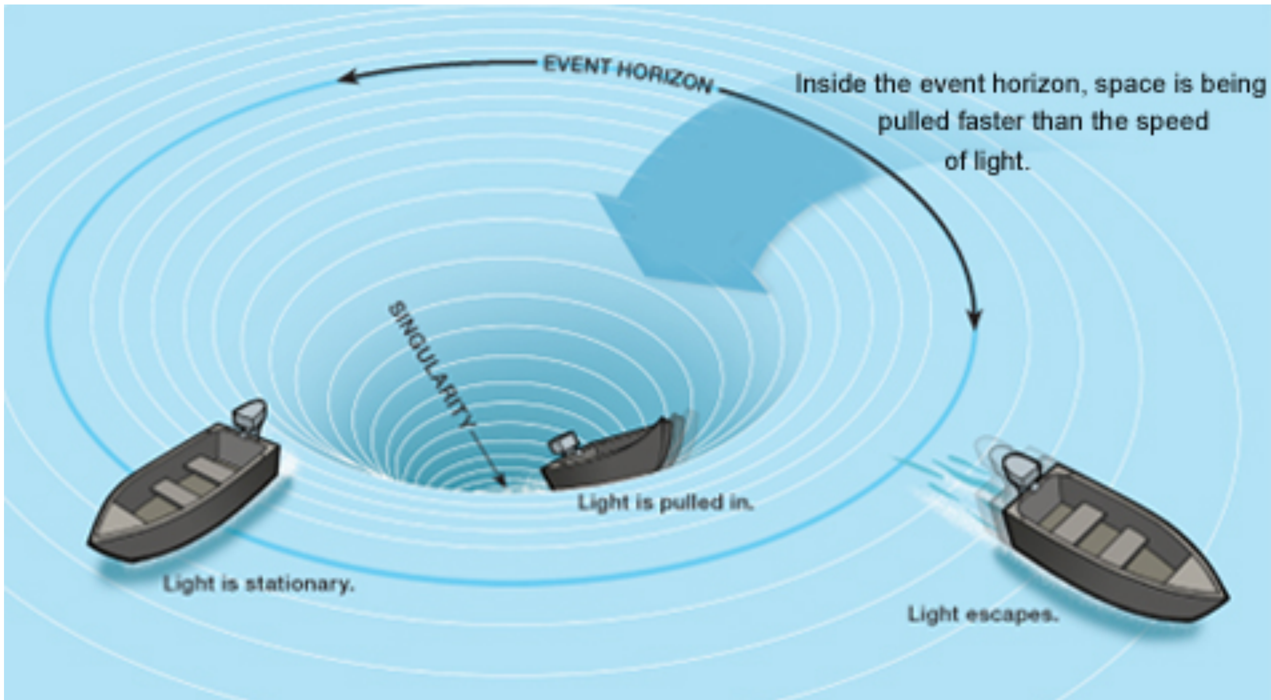
Black Holes: Gravity's Ultimate Victory

- What is a black hole?
- What would it be like to visit a black hole?
- Do black holes really exist?

What is a black hole?



A black hole is an object whose gravity is so powerful that not even light can escape it.

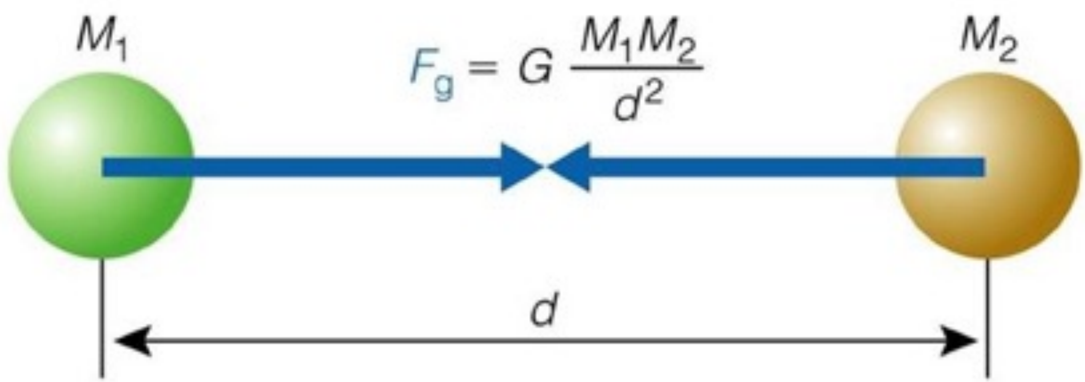


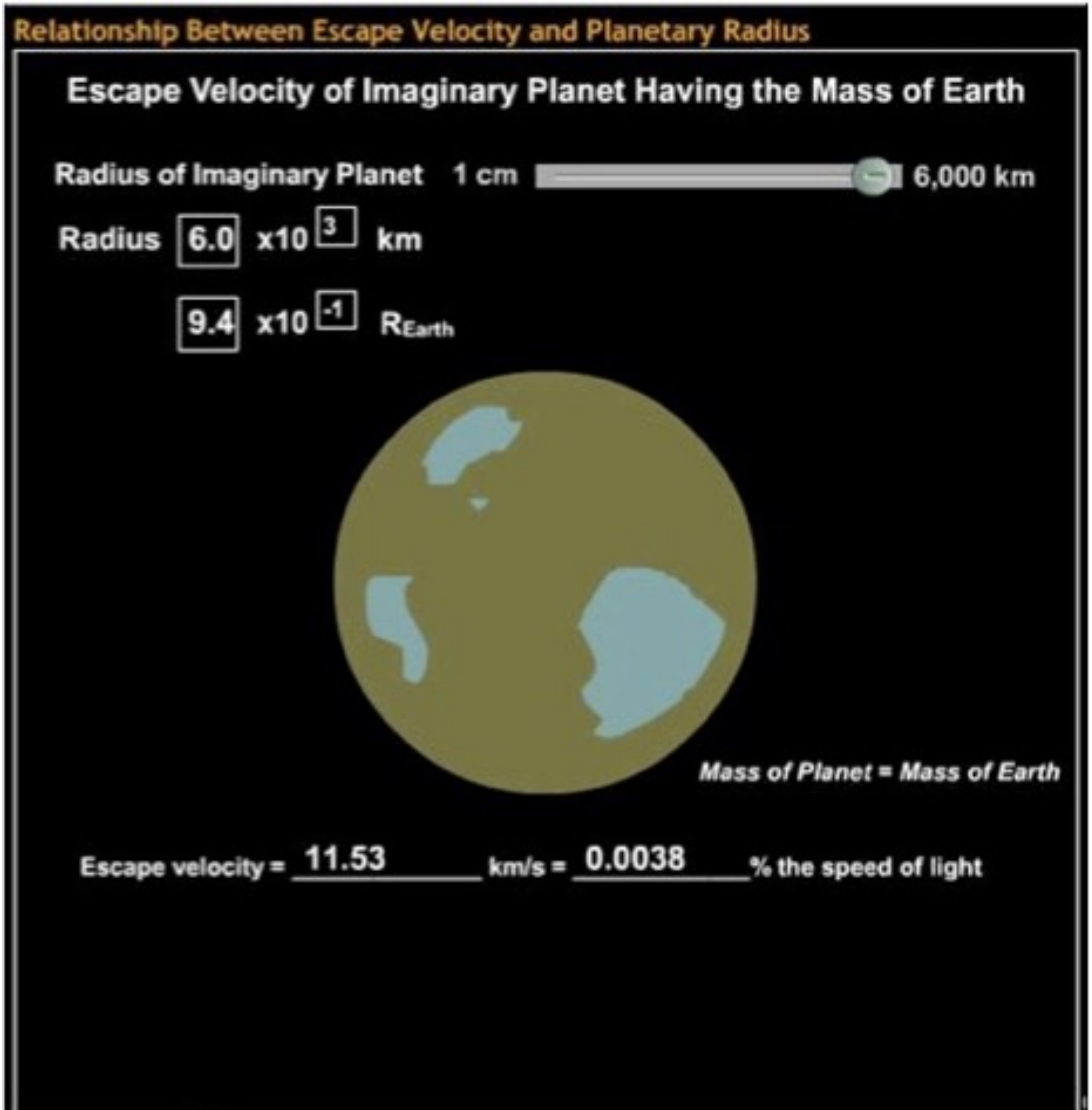
Thought Question

What happens to the escape velocity from an object if you shrink it?

A. It increases.
B. It decreases.
C. It stays the same.

Hint:

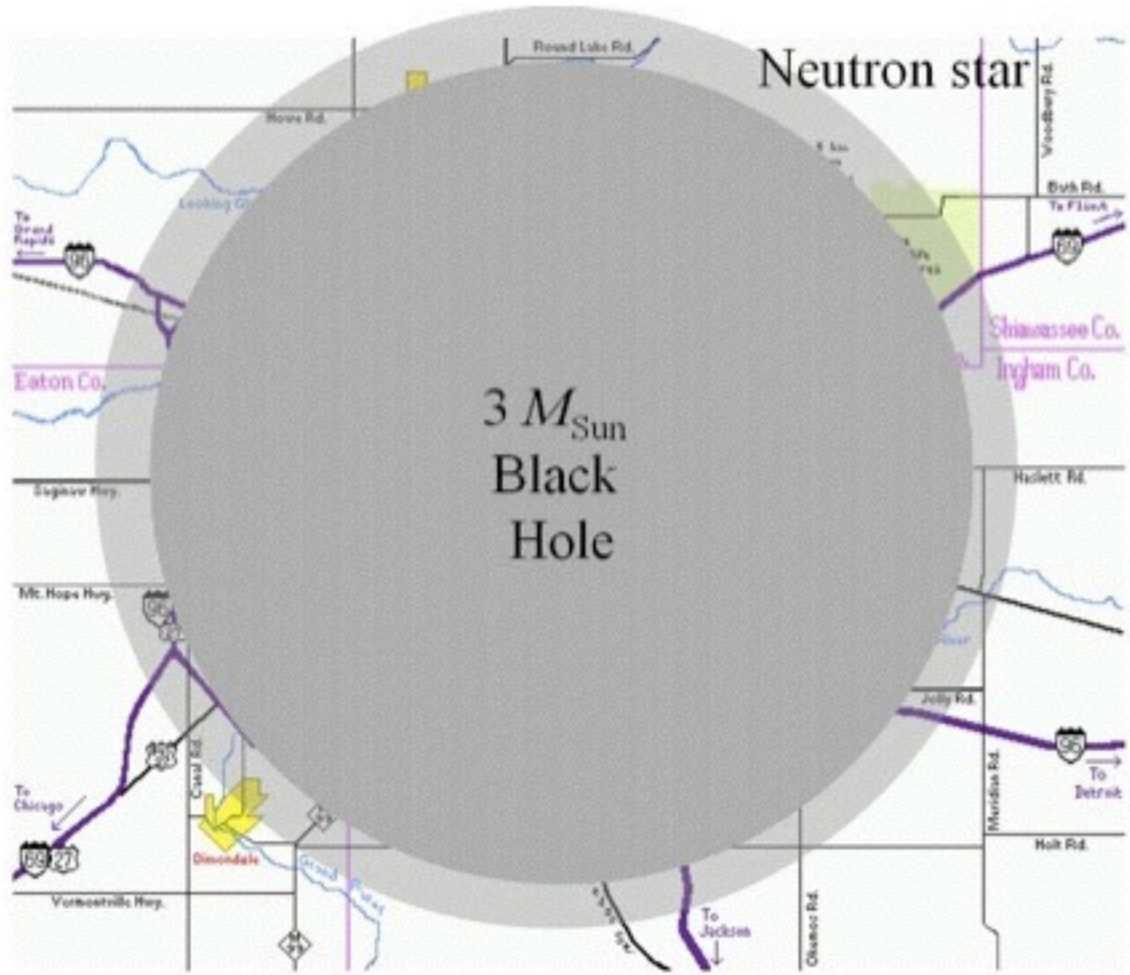




Light would not be able to escape Earth's surface if you could shrink it to < 1 centimeter.

"Surface" of a Black Hole

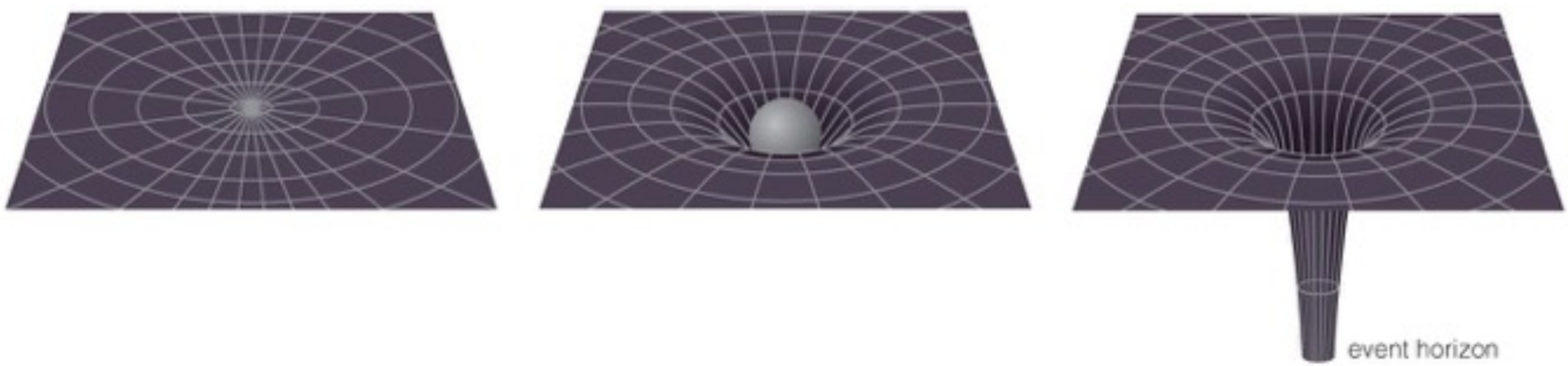
- The "surface" of a black hole is the radius at which the escape velocity equals the speed of light.
- This spherical surface is known as the **event horizon**.
- The radius of the event horizon is known as the **Schwarzschild radius**.



The event horizon is larger for black holes of larger mass.

The event horizon of a $3M_{Sun}$ black hole is also about as big as a small city.

A black hole's mass strongly warps space and time in the vicinity of its event horizon.



No Escape

- Nothing can escape from within the event horizon because nothing can go faster than light.
- No escape means there is no more contact with something that falls in. It increases the hole mass, changes the spin or charge, but otherwise loses its identity.

Neutron Star Limit

- Quantum mechanics says that neutrons in the same place cannot be in the same state.
- Neutron degeneracy pressure can no longer support a neutron star against gravity if its mass exceeds about $3M_{sun}$.
- Some massive star supernovae can make a black hole if enough mass falls onto core.

Singularity

- Beyond the neutron star limit, no known force can resist the crush of gravity.

- As far as we know, gravity crushes all the matter into a single point known as a **singularity**.

Thought Question

How does the radius of the event horizon change when you add mass to a black hole?

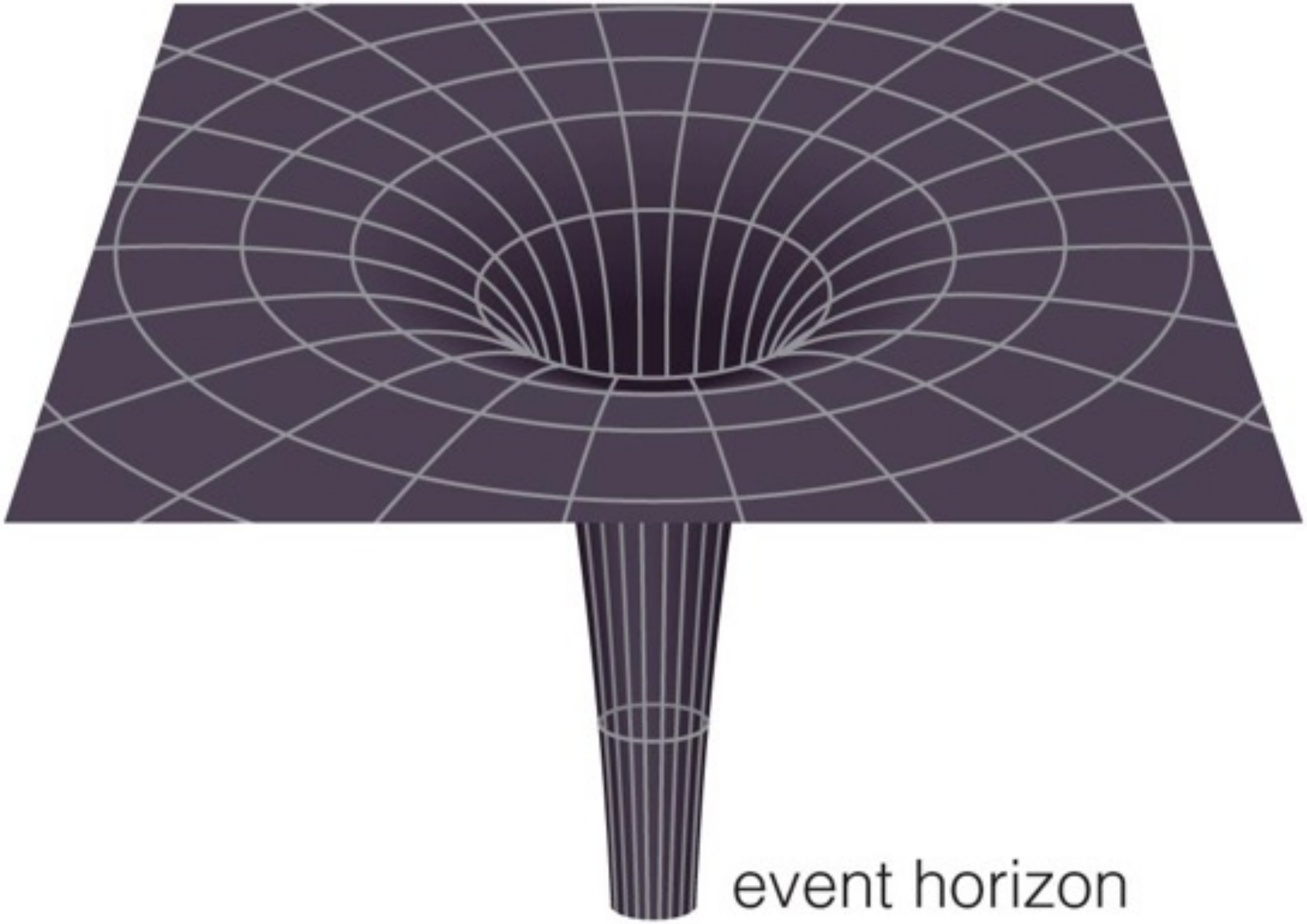
A. It increases.
B. It decreases.
C. It stays the same.

Chapter 18

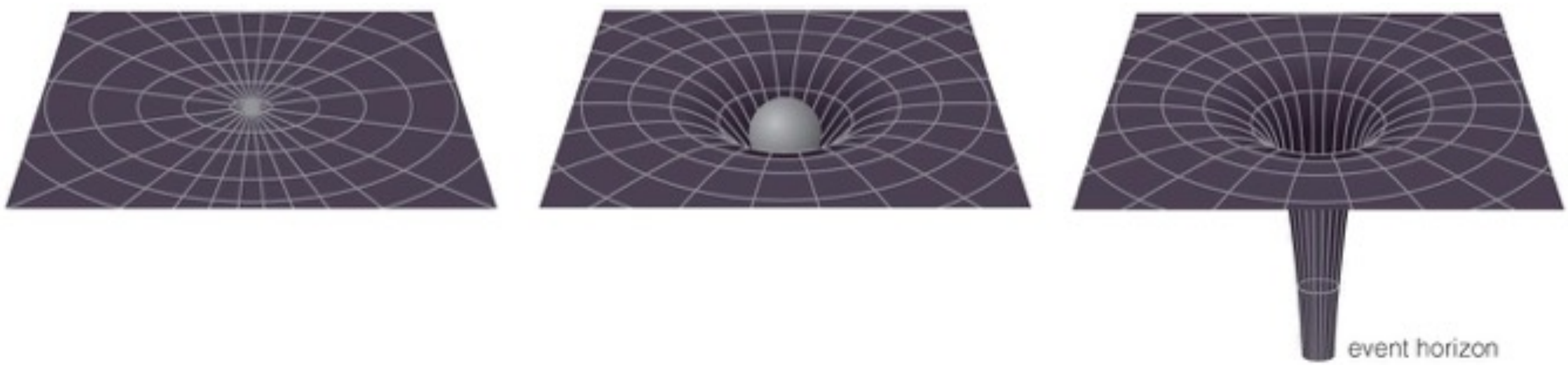
What defines the event horizon?

a) the physical surface of a black hole
b) the boundary of the observable universe
c) the distance from a black hole where the escape velocity equals the speed of light
d) the point at which the mass in a star's core cannot be supported and collapses into a black hole

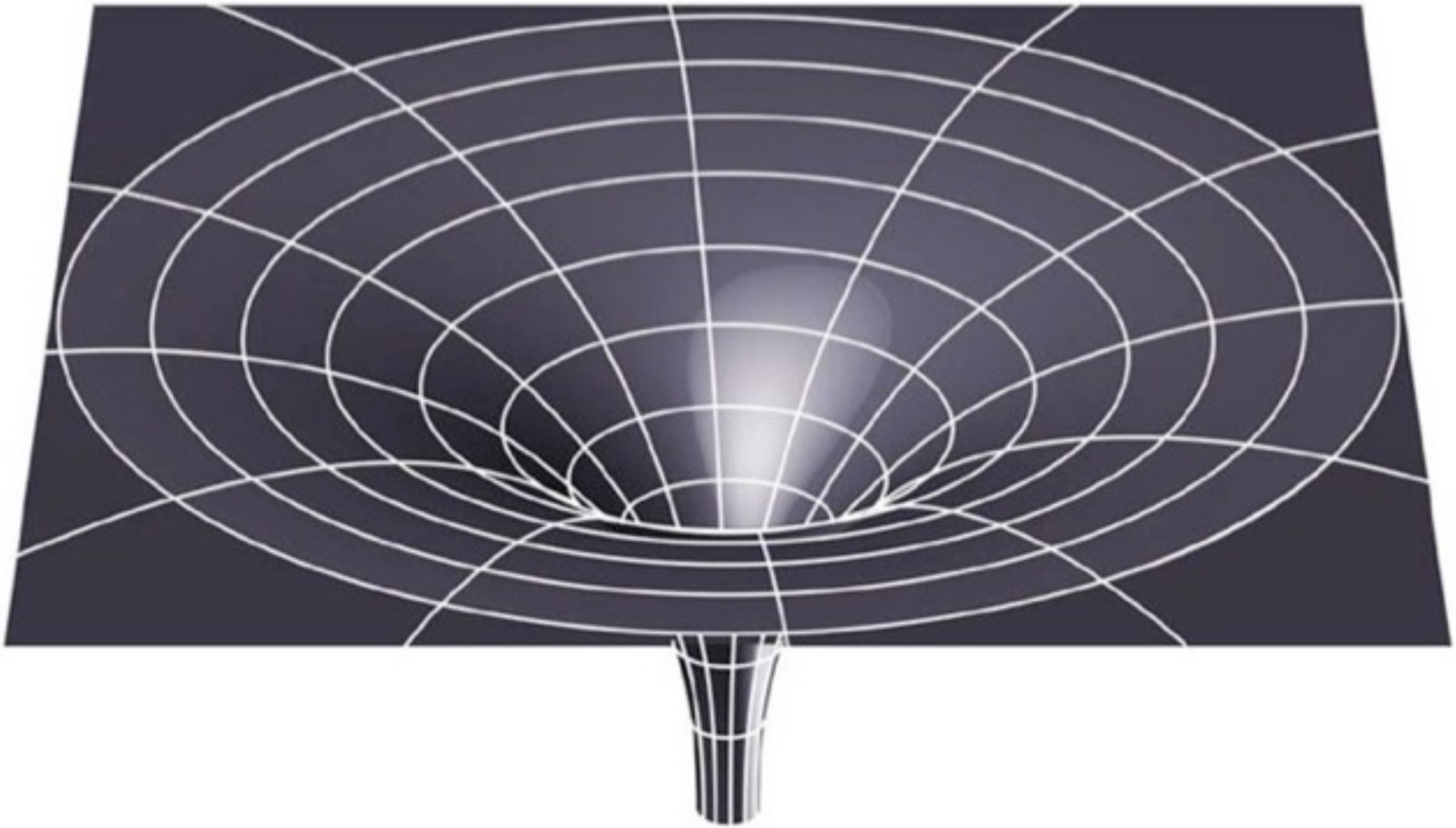
What would it be like to visit a black hole?



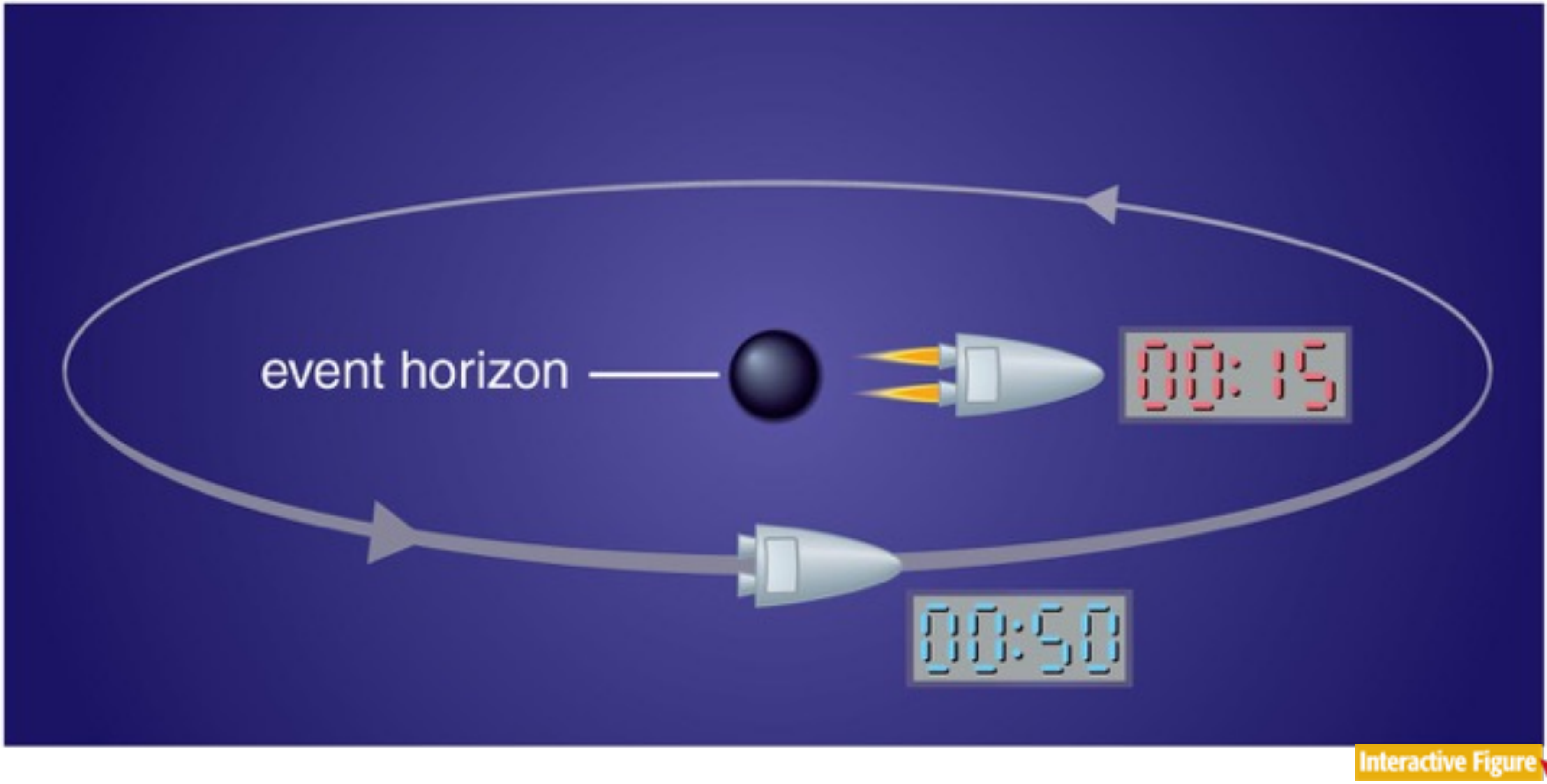
If the Sun became a black hole, its gravity would be different only near the event horizon.



Black holes don't suck!



Light waves take extra time to climb out of a deep hole in spacetime, leading to a gravitational redshift.



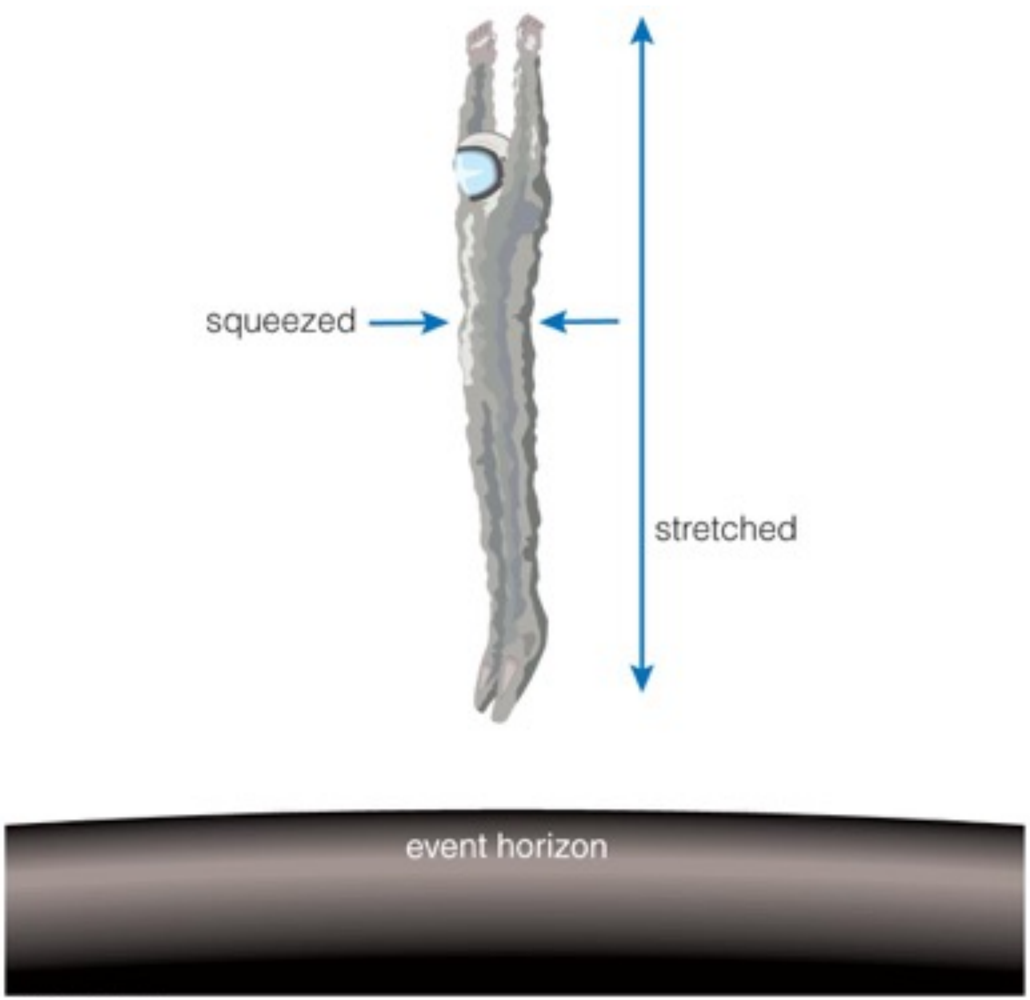
Time passes more slowly near the event horizon.

Thought Question

Is it easy or hard to fall into a black hole?

A. easy
B. hard

Hint: A black hole with the same mass as the Sun wouldn't be much bigger than a college campus.

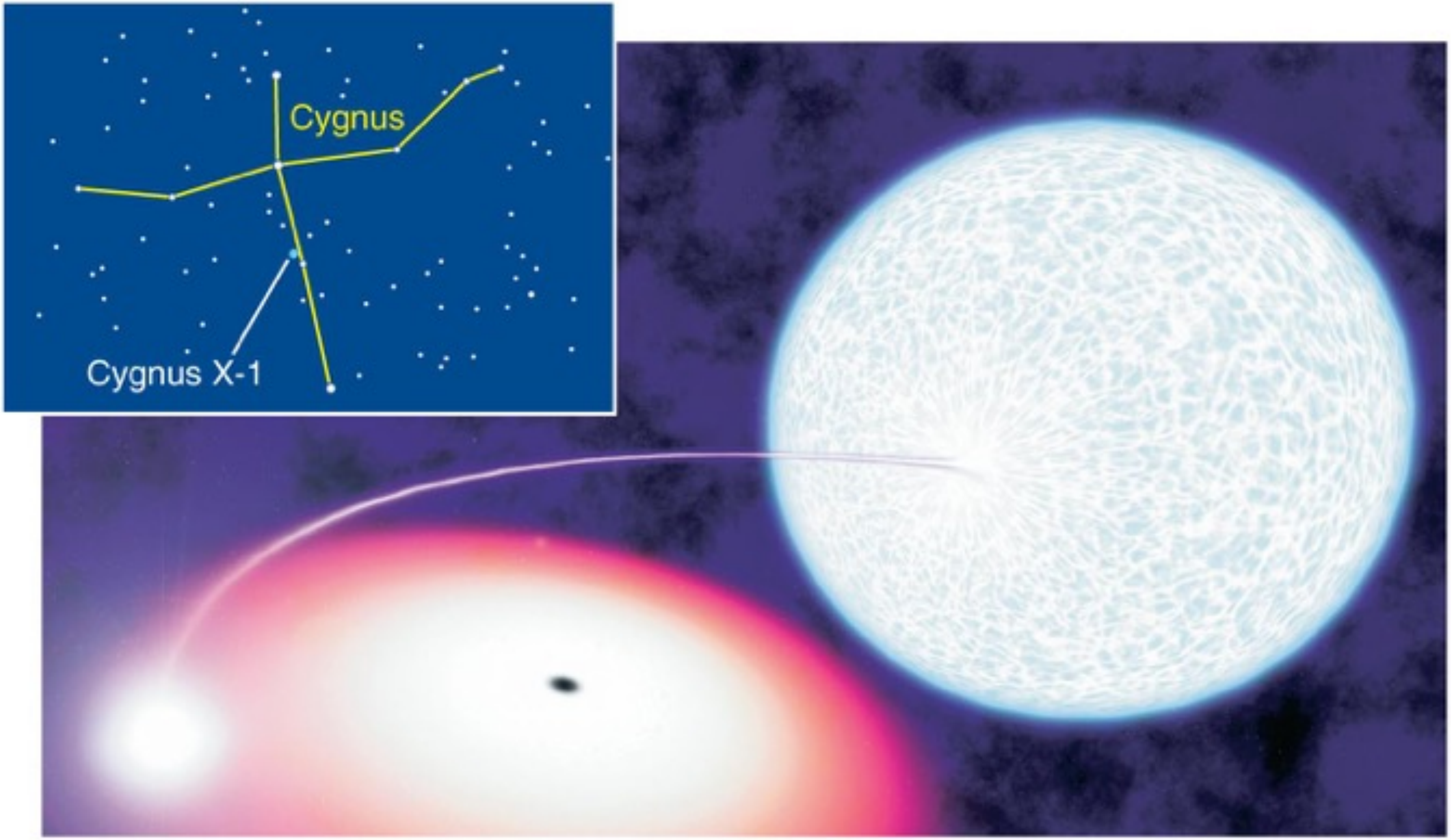


Tidal forces near the event horizon of a $3M_{Sun}$ black hole would be lethal to humans.

Tidal forces would be gentler near a supermassive black hole because its radius is much

http://jila.colorado.edu/~ajsh/insidebh/rn.html

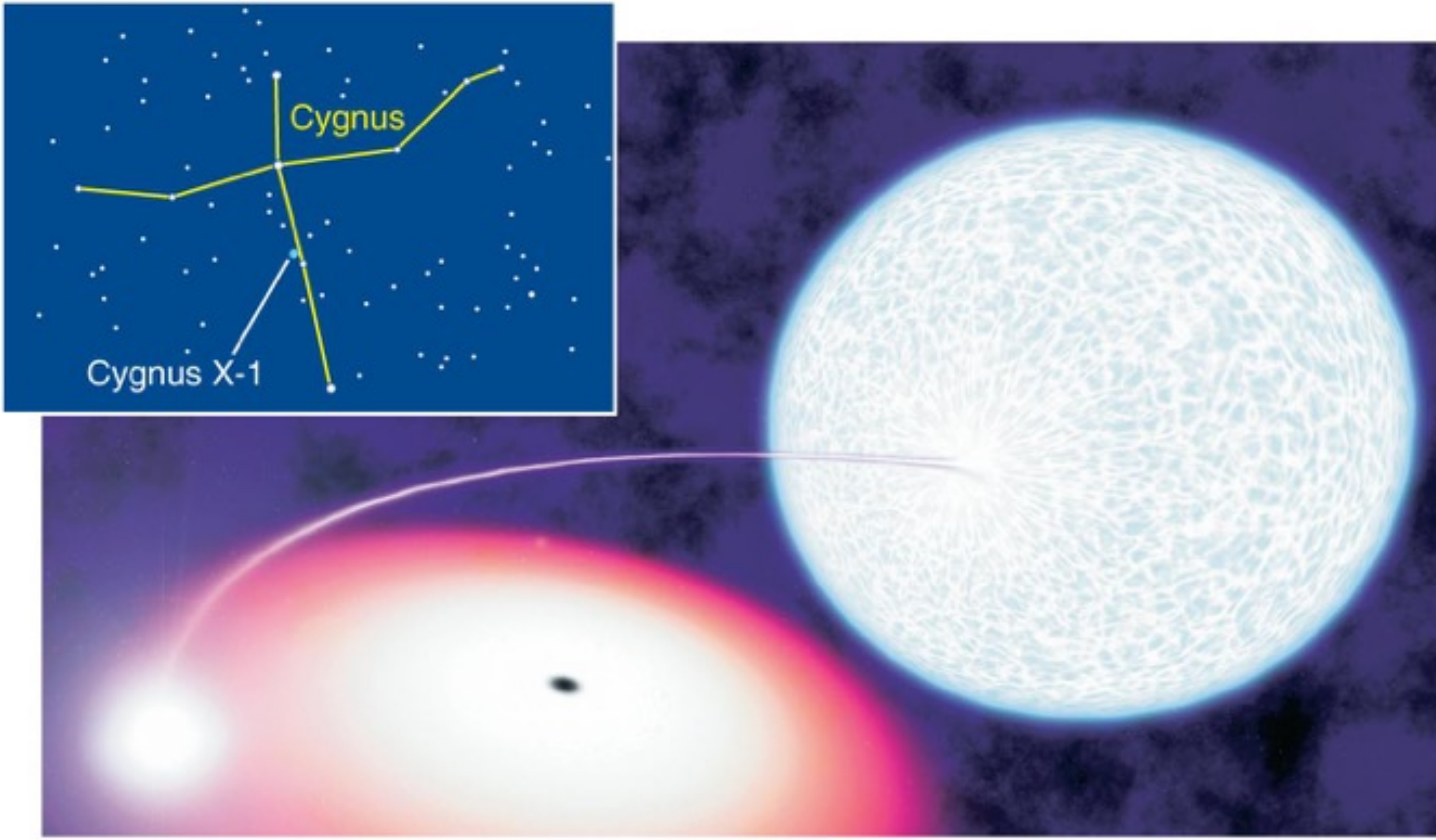
Do black holes really exist?



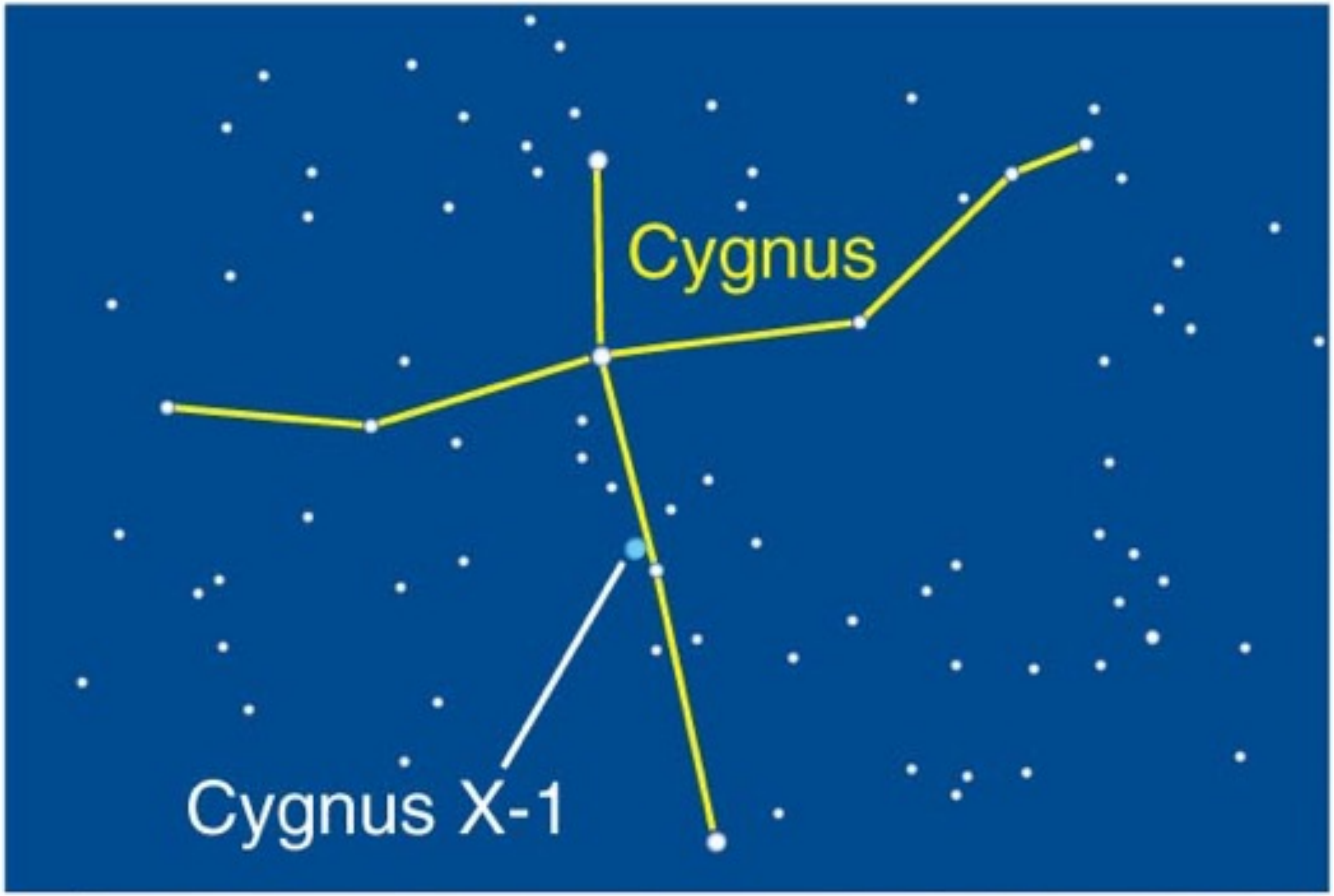
Black Hole Verification

- We need to measure mass by:
  - Using orbital properties of a companion
  - Measuring the velocity and distance of orbiting gas

- It's a black hole if it's not a star and its mass exceeds the neutron star limit ($\sim 3M_{Sun}$)

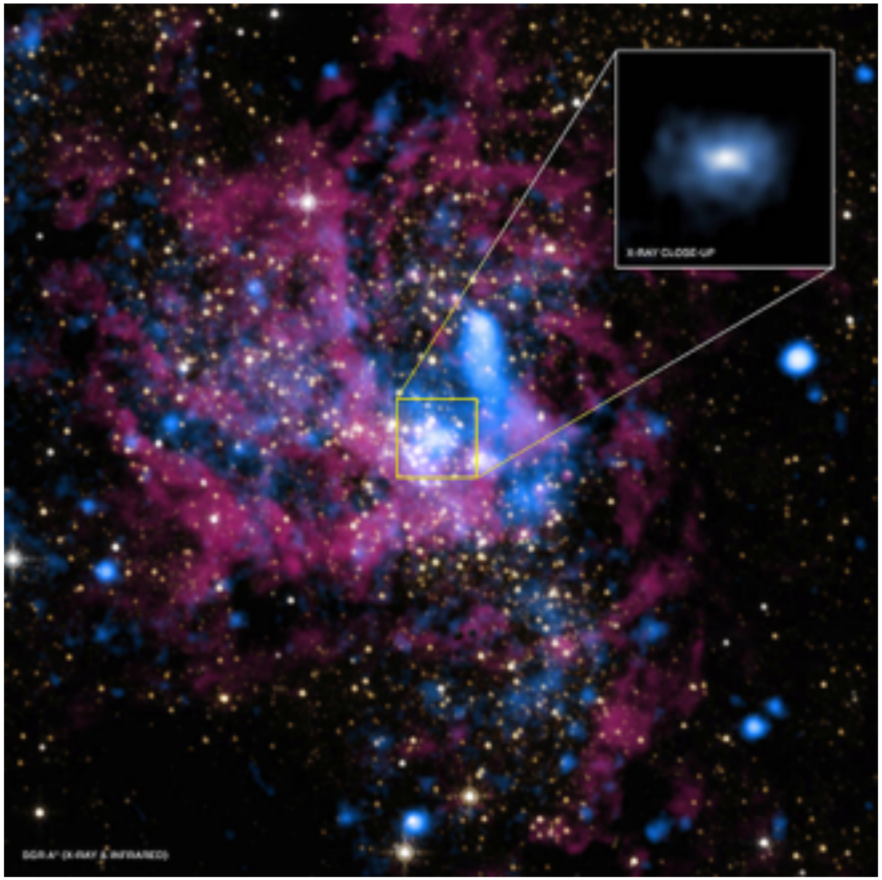


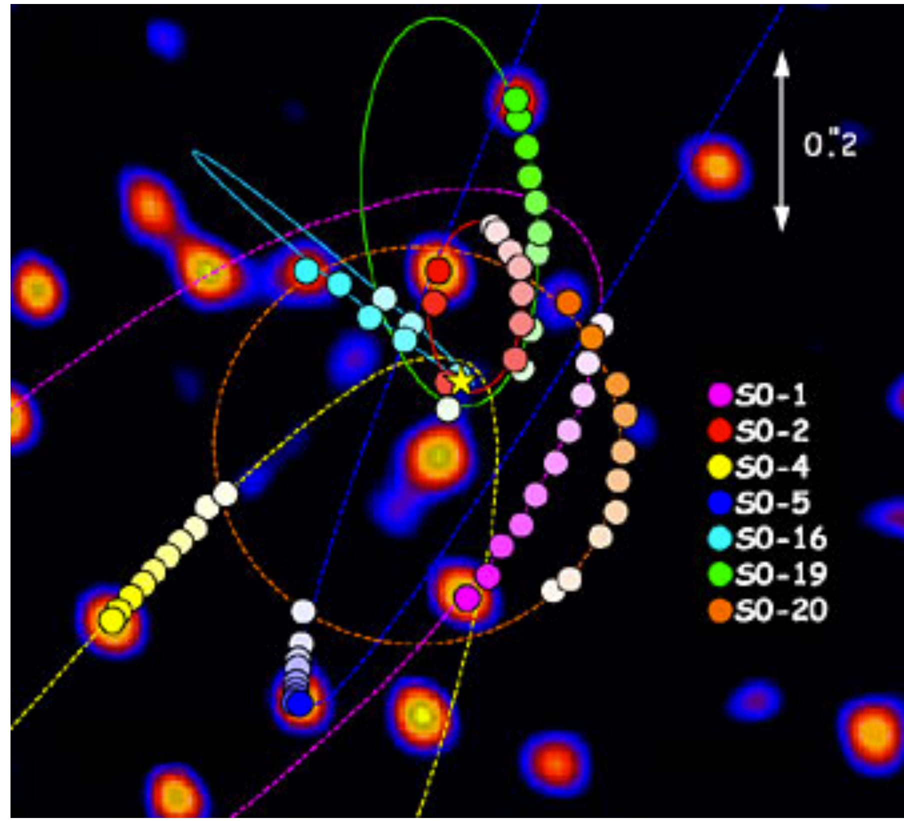
Some X-ray binaries contain compact objects of mass exceeding $3M_{Sun}$, which are likely to be black holes.



One famous X-ray binary with a likely black hole is in the constellation Cygnus.

Sgr A*





https://www.youtube.com/watch?v=duoHtJpo4GY

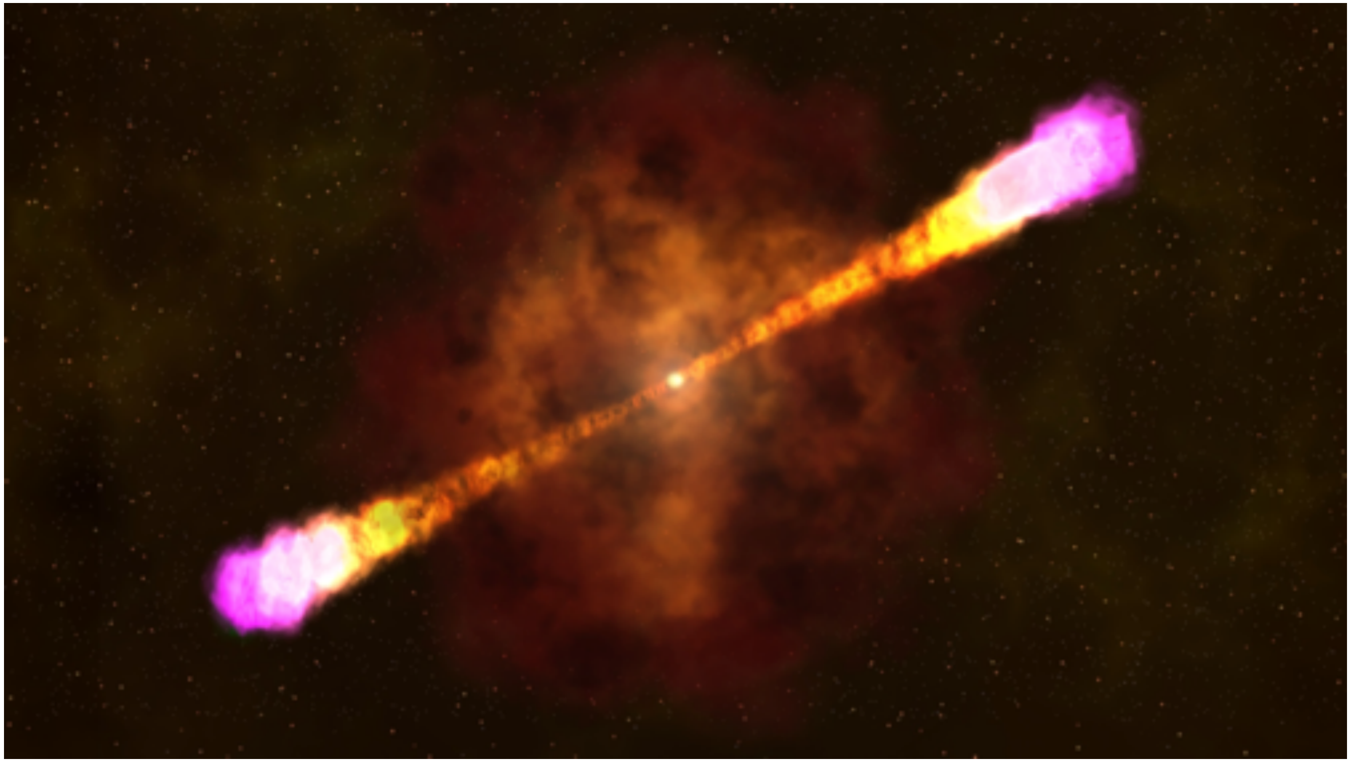
Chapter 18

How can we detect a black hole?

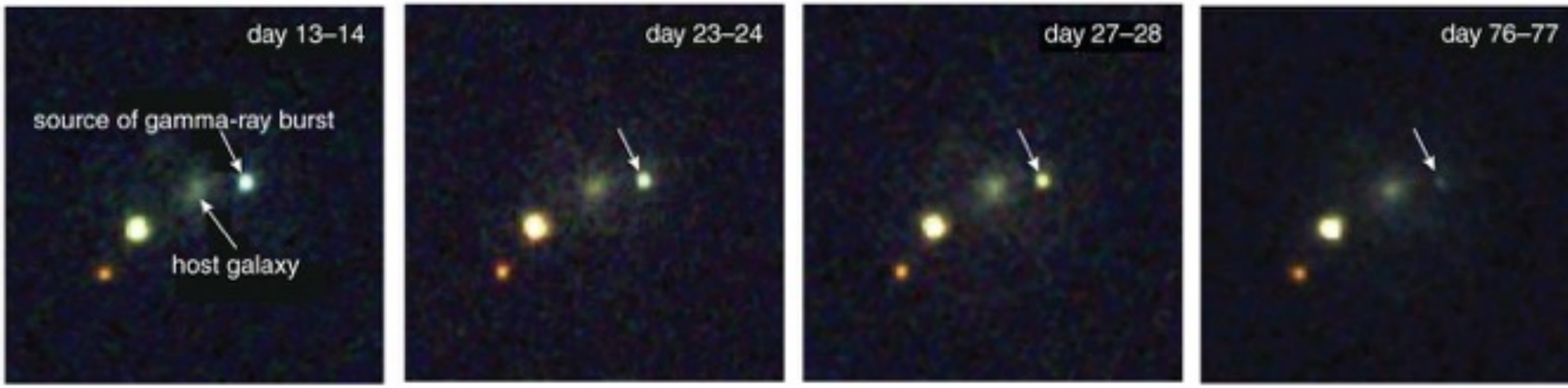
a) Emission from a black hole accretion disk has a characteristic X-ray spectrum.
b) Observing a massive star supernova reveals the mass of the stellar remnant, and if it exceeds 3 solar masses it must be a black hole.
c) Observing the orbital motion of a star around a stellar remnant reveals the mass of the stellar remnant, and if it exceeds 3 solar masses it must be a black hole.
d) Observation of an X-ray burst reveals the mass of the central object through the gravitational redshift of the X-rays.

The Origin of Gamma-Ray Bursts

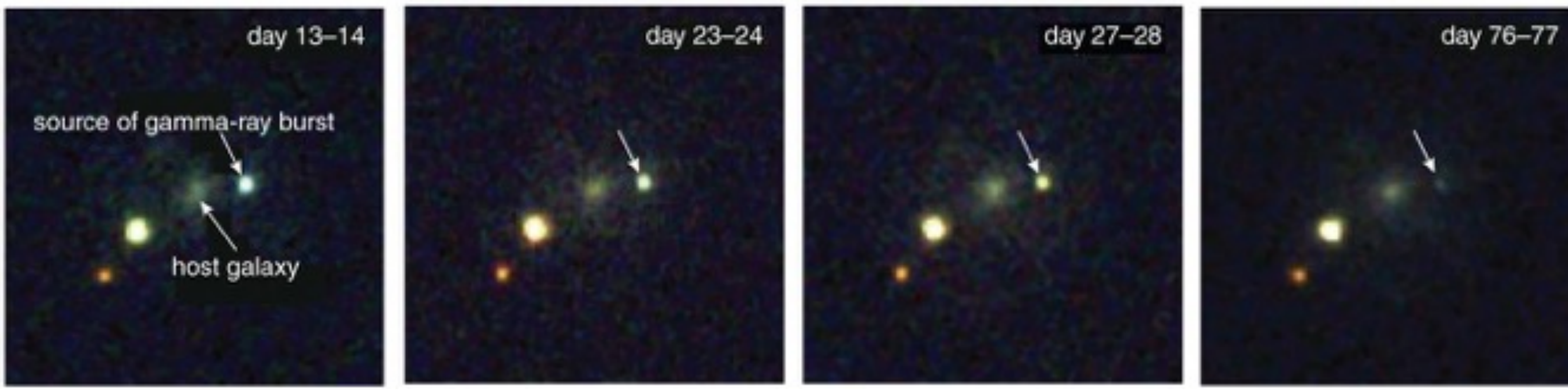
- Where do gamma-ray bursts come from?
- What causes gamma-ray bursts?



What causes gamma-ray bursts?

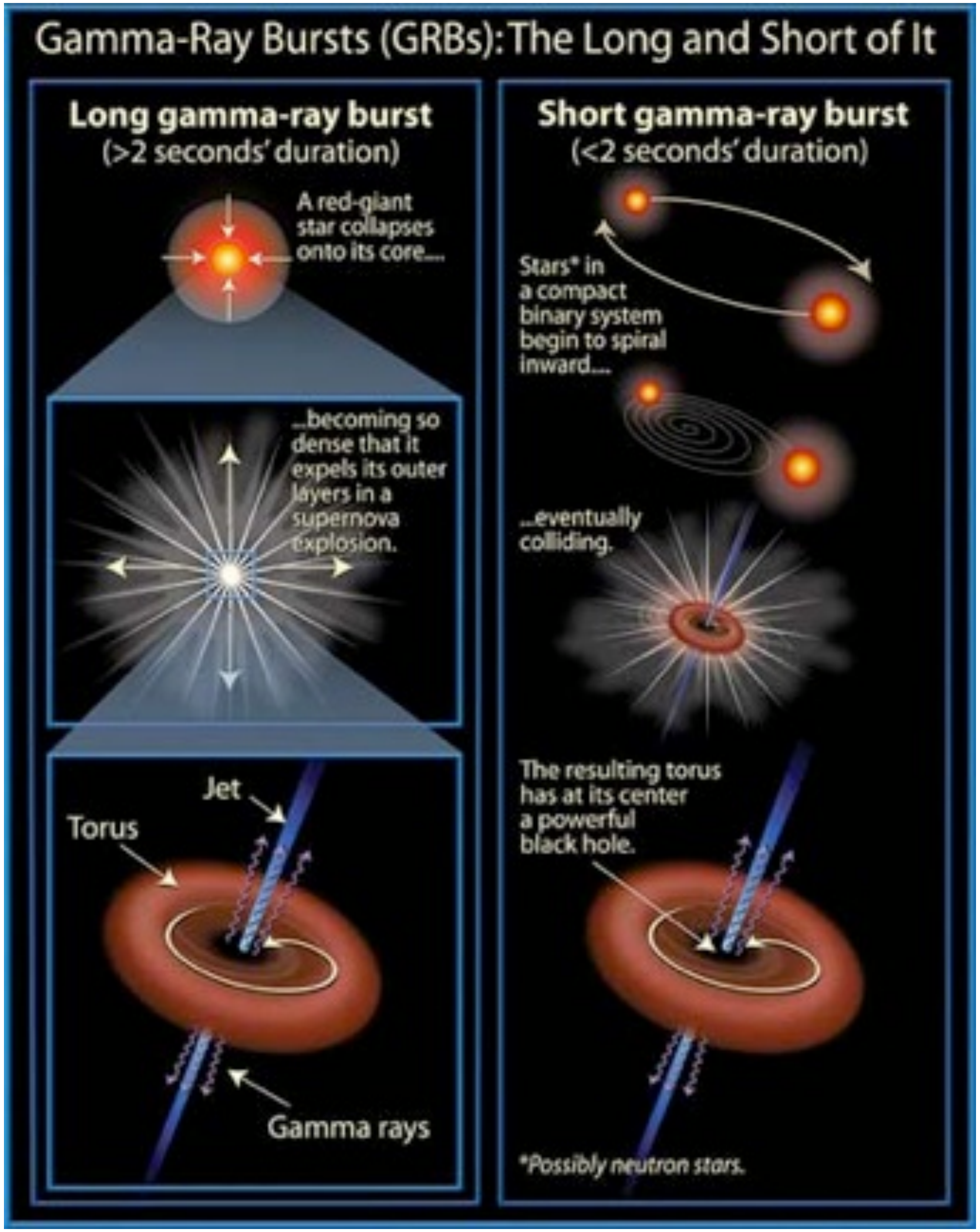


Supernovae and Gamma-Ray Bursts

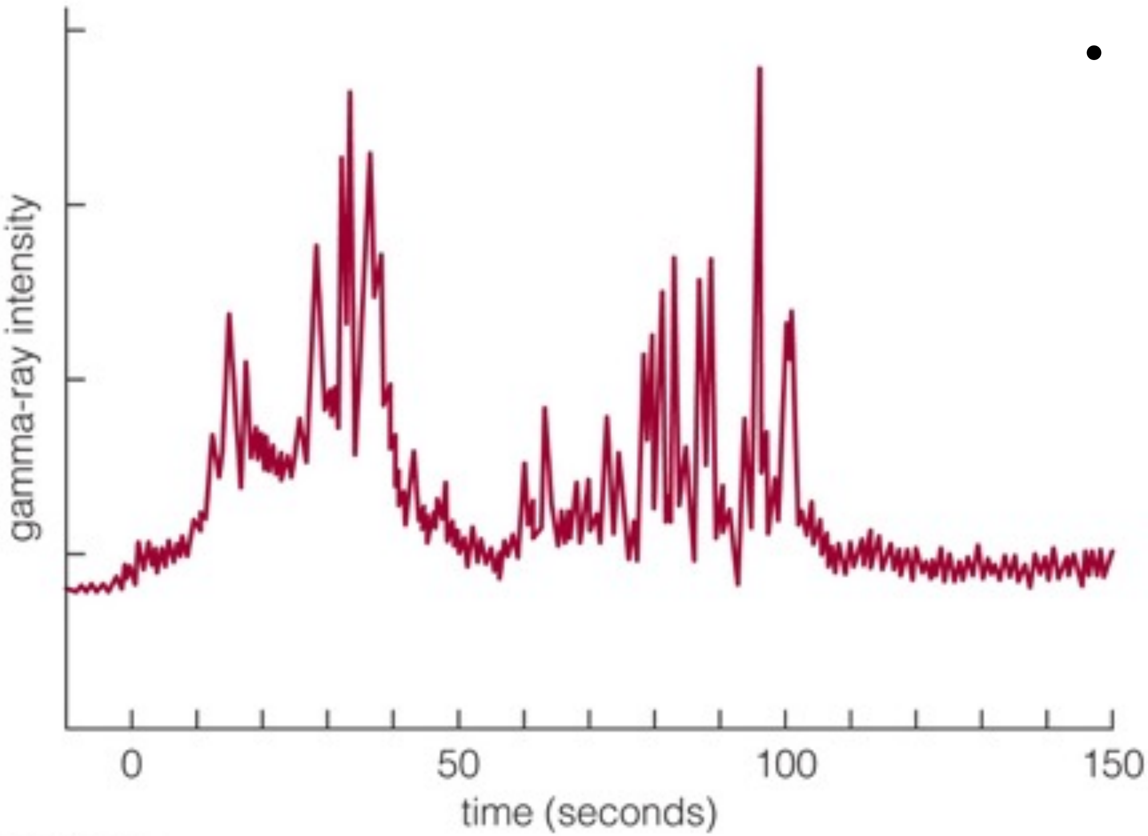


- Observations show that at least some gamma-ray bursts are produced by supernova explosions.
- Others may come from collisions between neutron stars.

Where do gamma-ray bursts come from?



Gamma-Ray Bursts



- Brief bursts of gamma rays coming from space were first detected in the 1960s.

- Observations in the 1990s showed that many gamma-ray bursts were coming from very distant galaxies.
- They must be among the most powerful explosions in the universe—could be the formation of a black hole.

http://www.nasa.gov/content/goddard/nasa-sees-watershed-cosmic-blast-in-unique-detail/#.ViVopxCrSRs