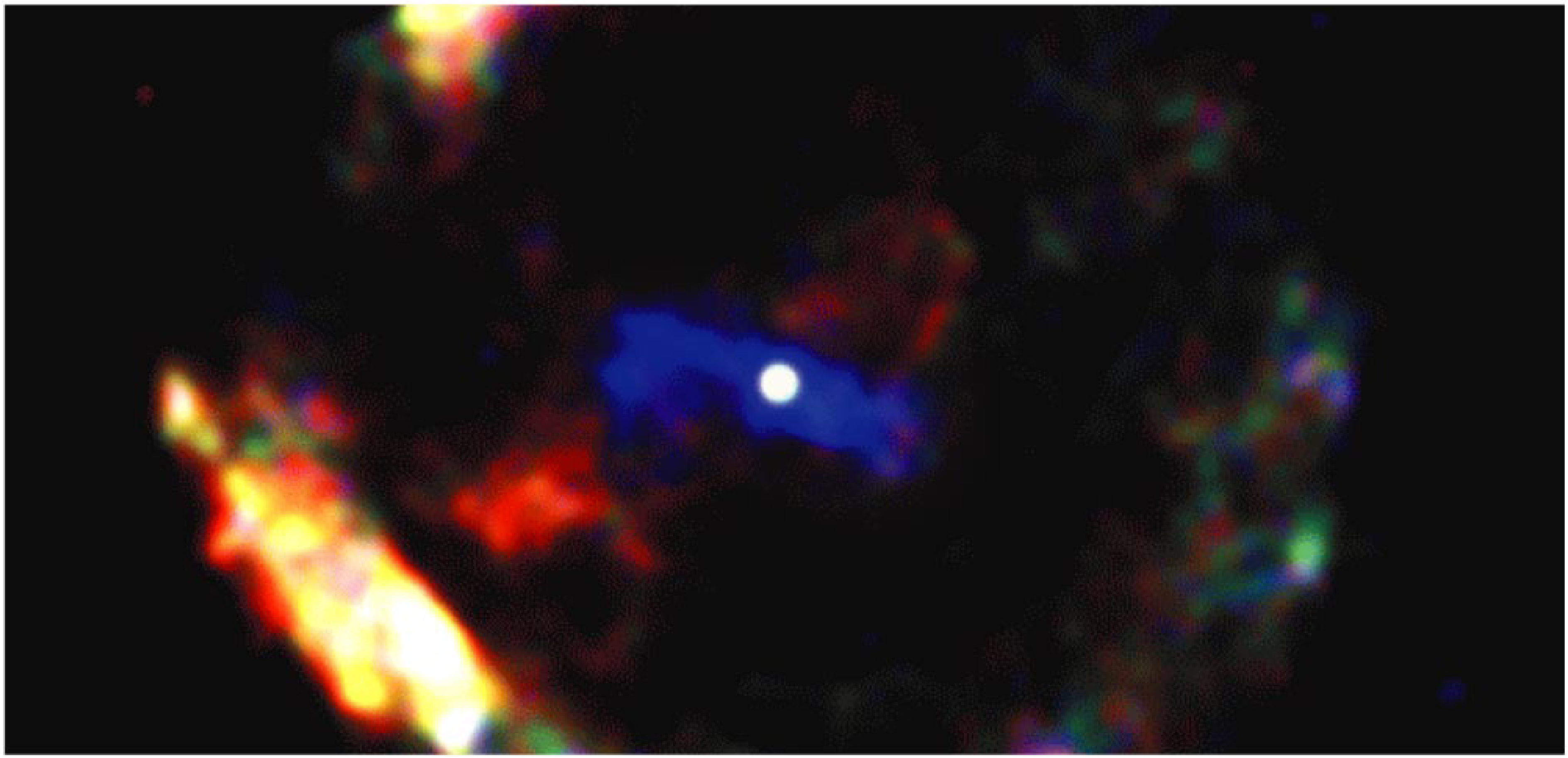
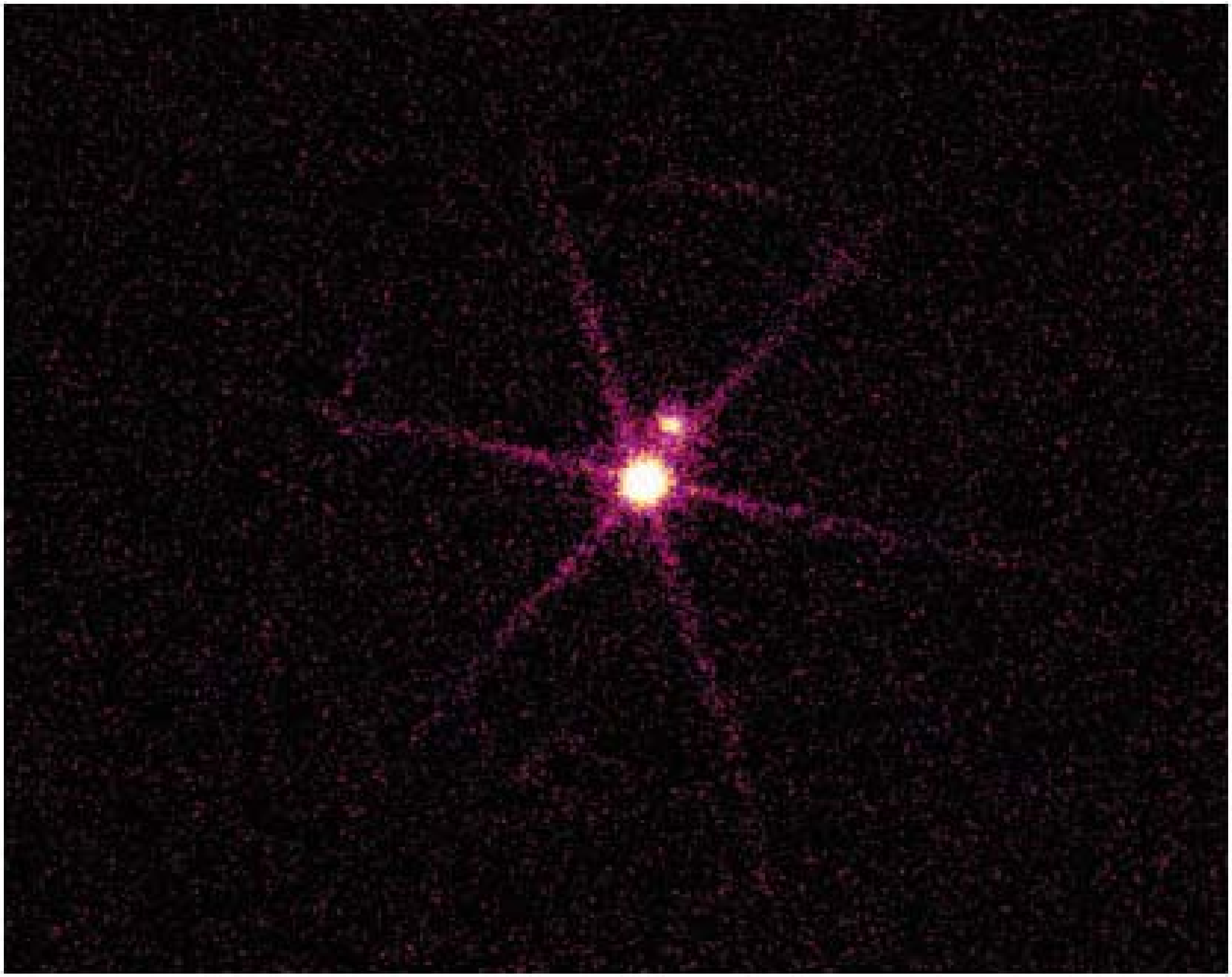
# Chapter 18
# The Bizarre Stellar Graveyard



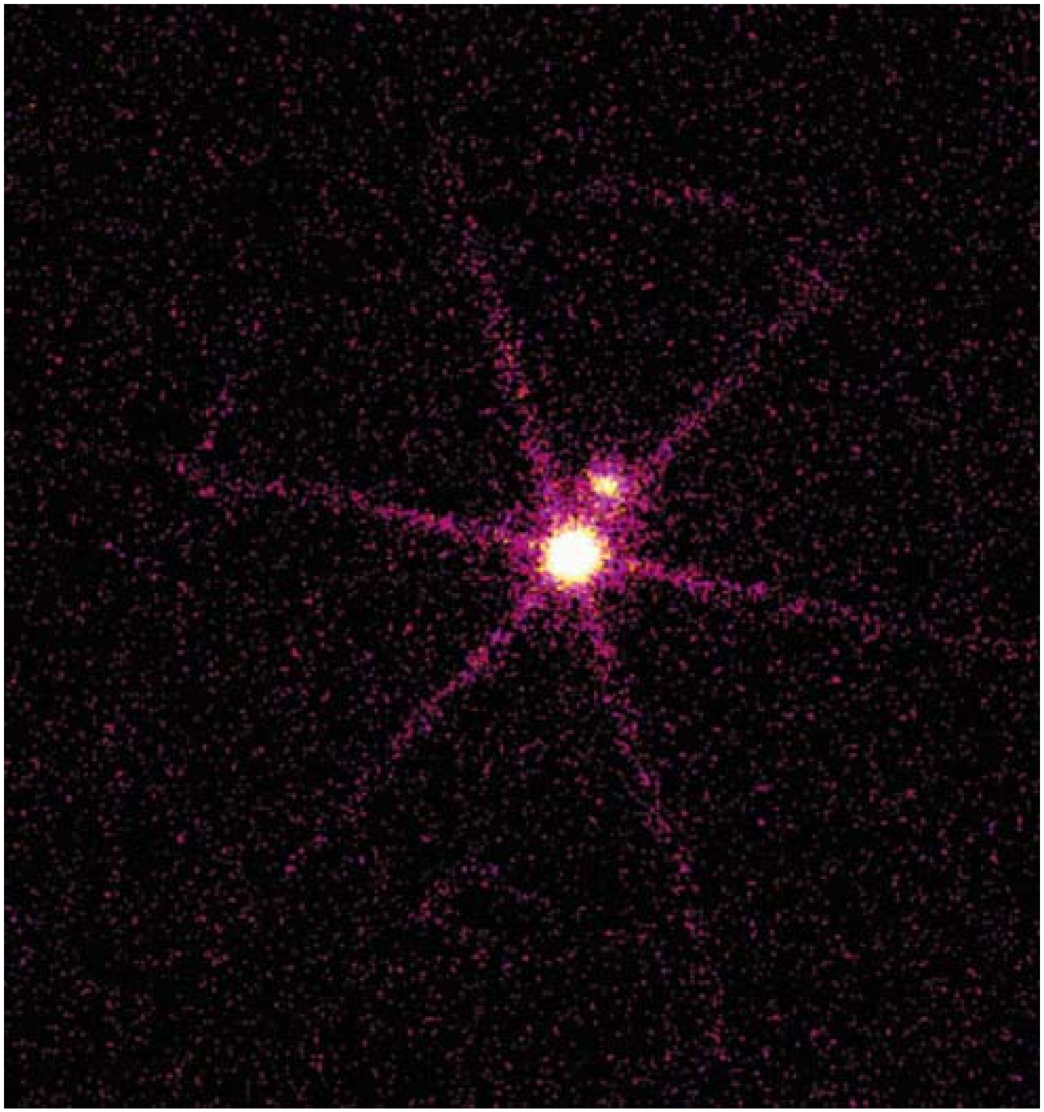
# 18.1 White Dwarfs

- Our goals for learning
- What is a white dwarf?
- What can happen to a white dwarf in a close binary system?

# What is a white dwarf?

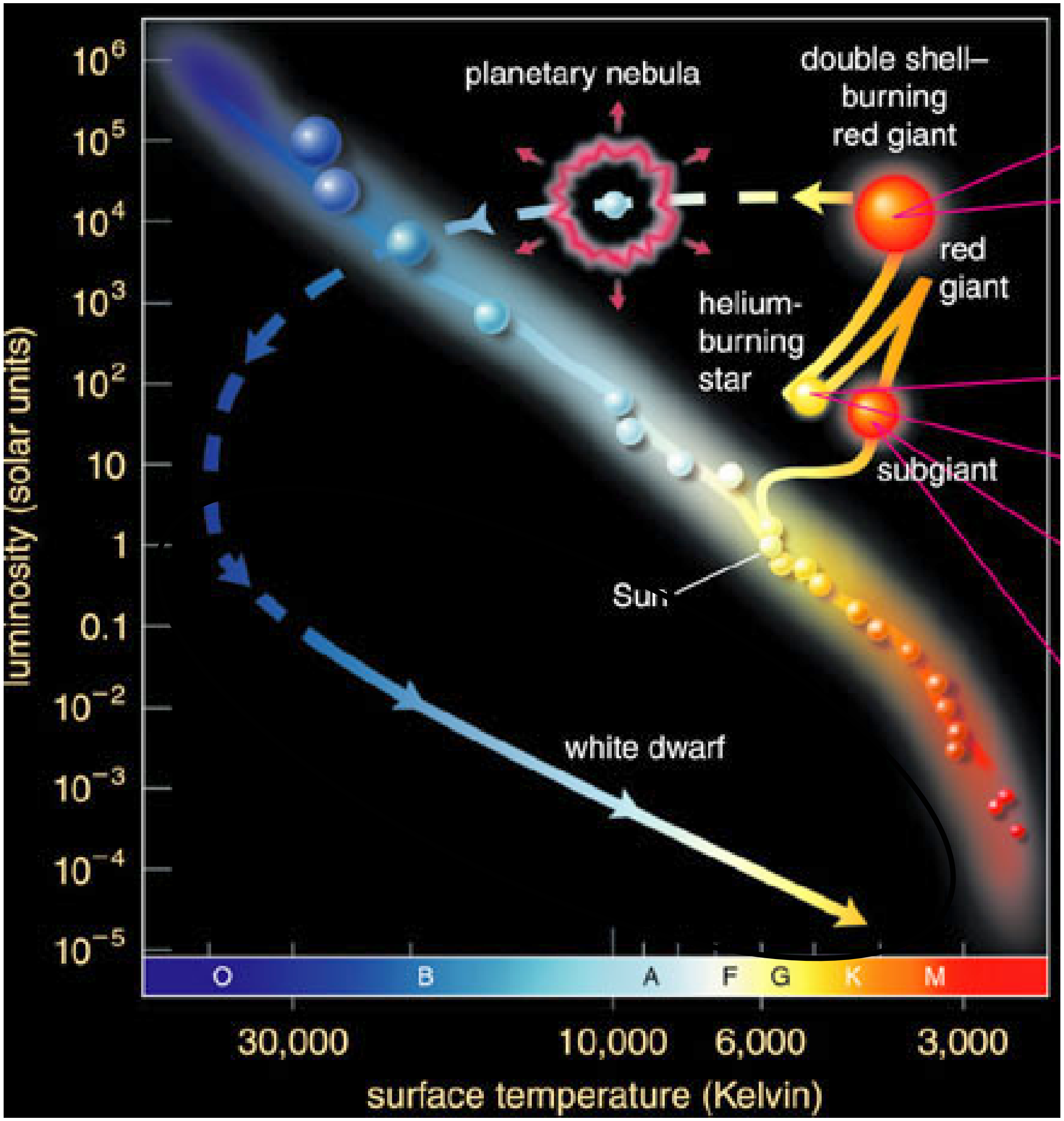


# White Dwarfs



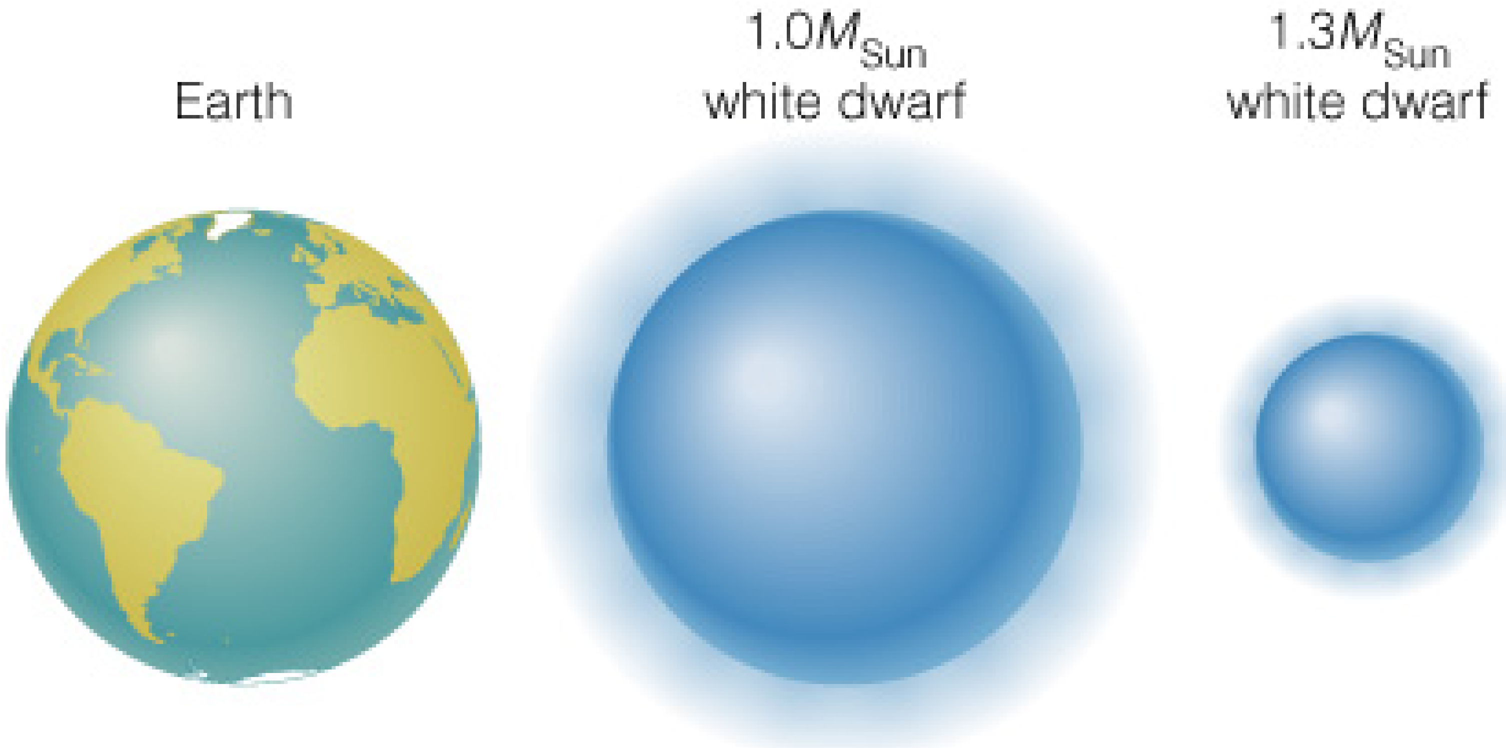


- White dwarfs are the remaining cores of dead stars
- Electron degeneracy pressure supports them against gravity




White dwarfs cool off and grow dimmer with time

# Size of a White Dwarf

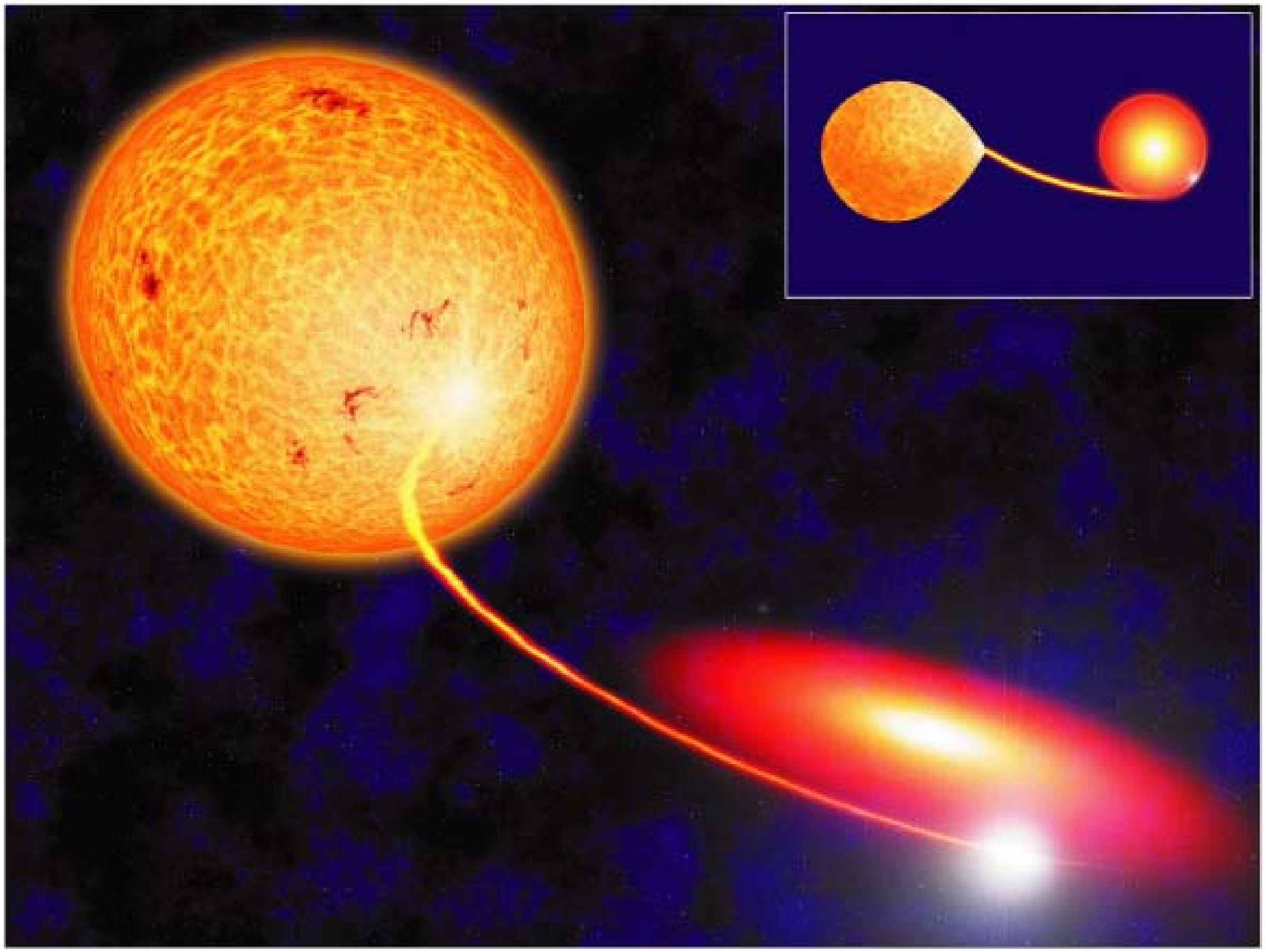


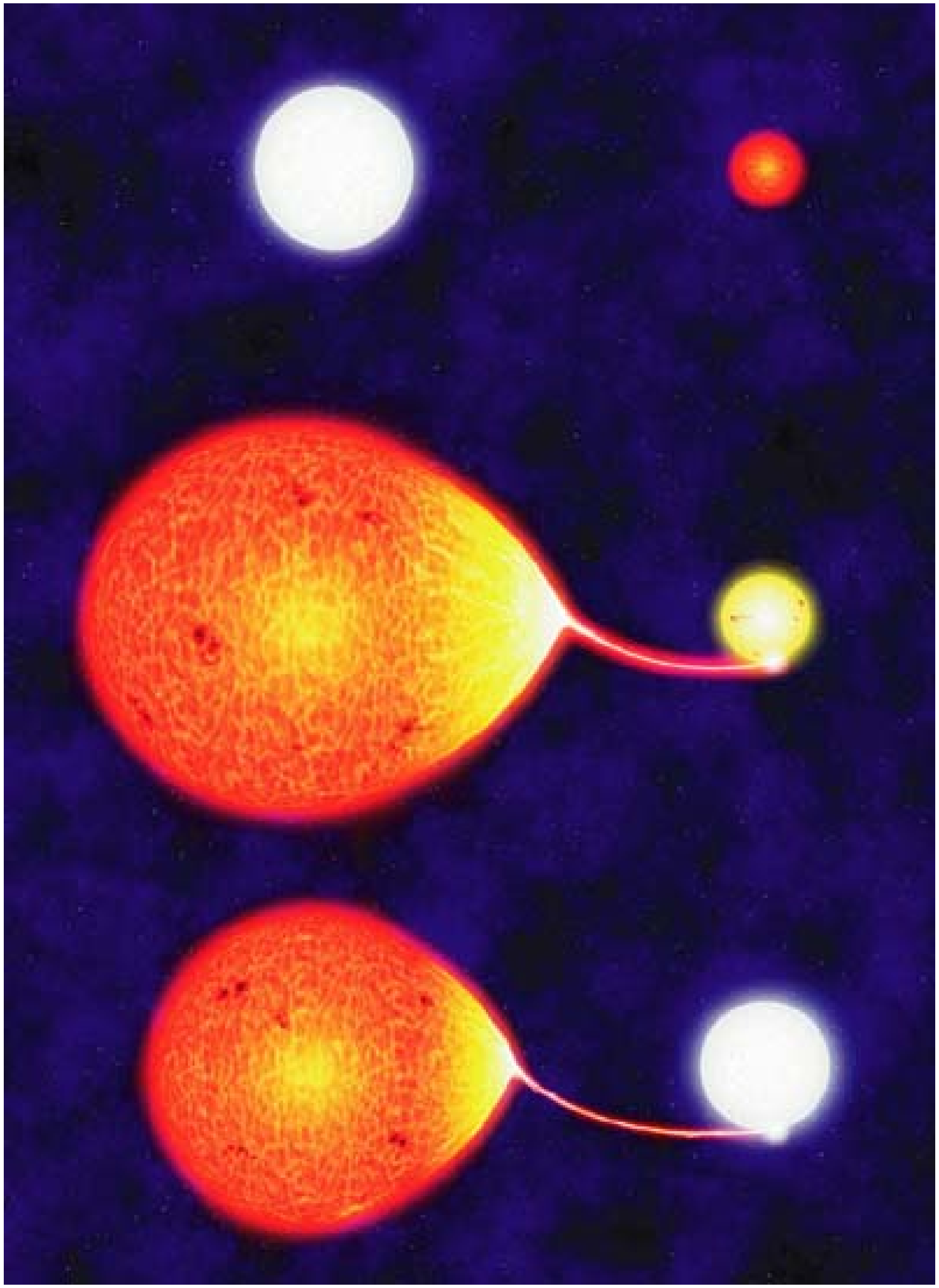

- White dwarfs with same mass as Sun are about same size as Earth
- Higher mass white dwarfs are smaller

# 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 $1.4M_{\text{Sun}}$, 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 $1.4M_{\text{Sun}}$, the *white dwarf limit* (or *Chandrasekhar limit*)

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





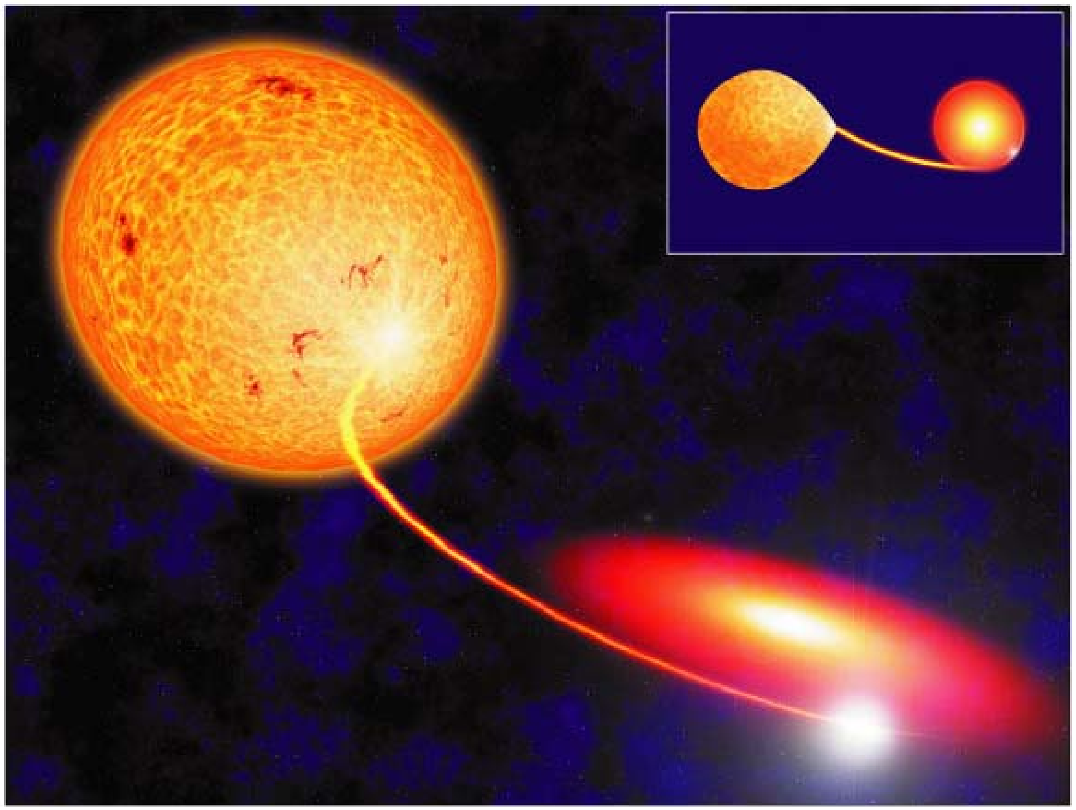


Star that started with less mass gains mass from its companion

Eventually the mass-losing star will become a white dwarf

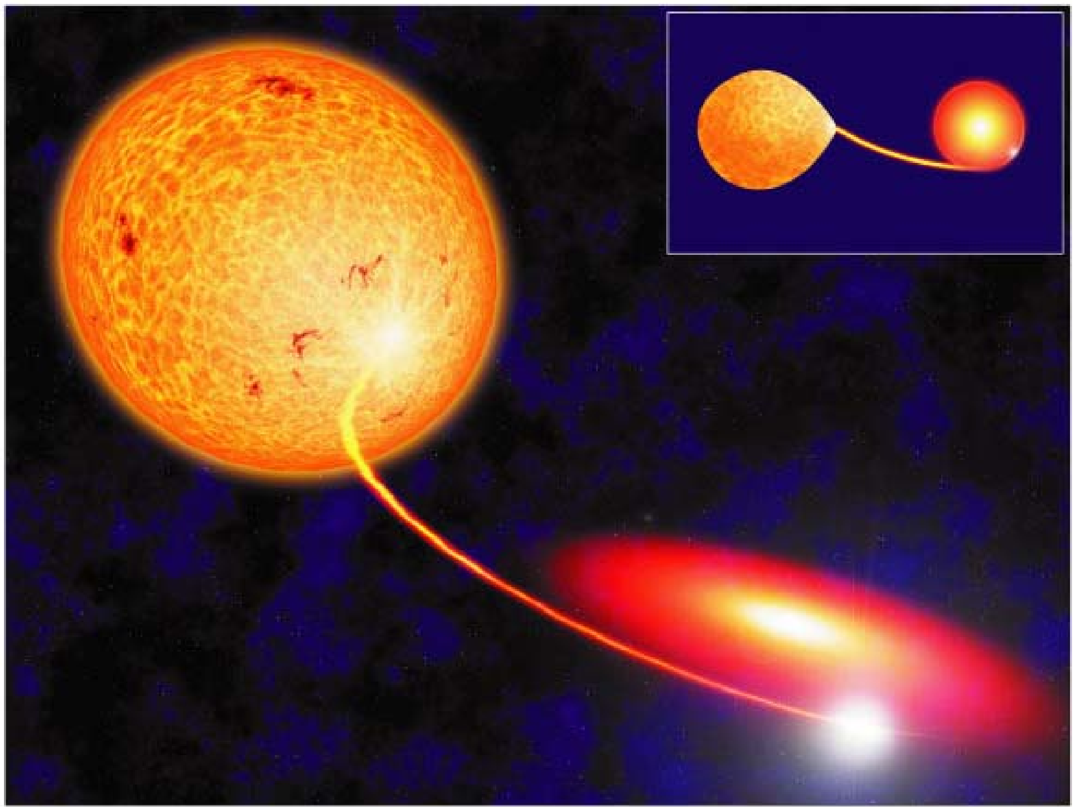
What happens next?

# Accretion Disks



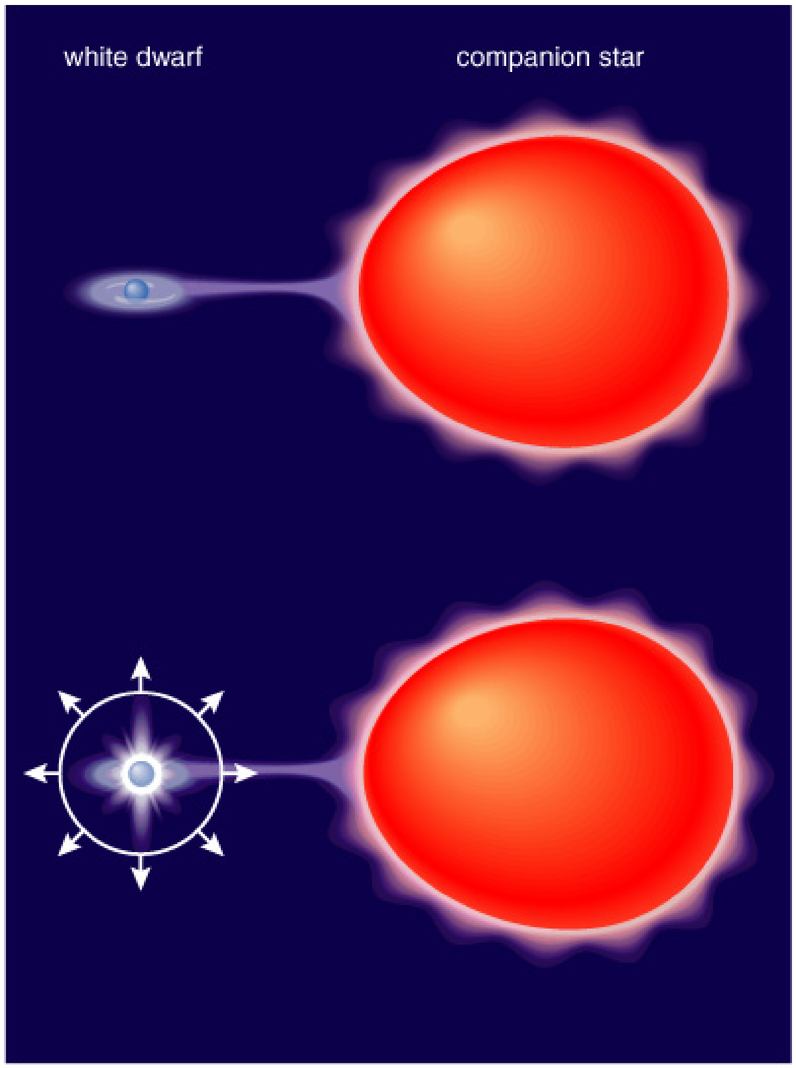
- Mass falling toward a white dwarf from its close binary companion has some angular momentum
- The matter therefore orbits the white dwarf in an *accretion disk*

# Accretion Disks



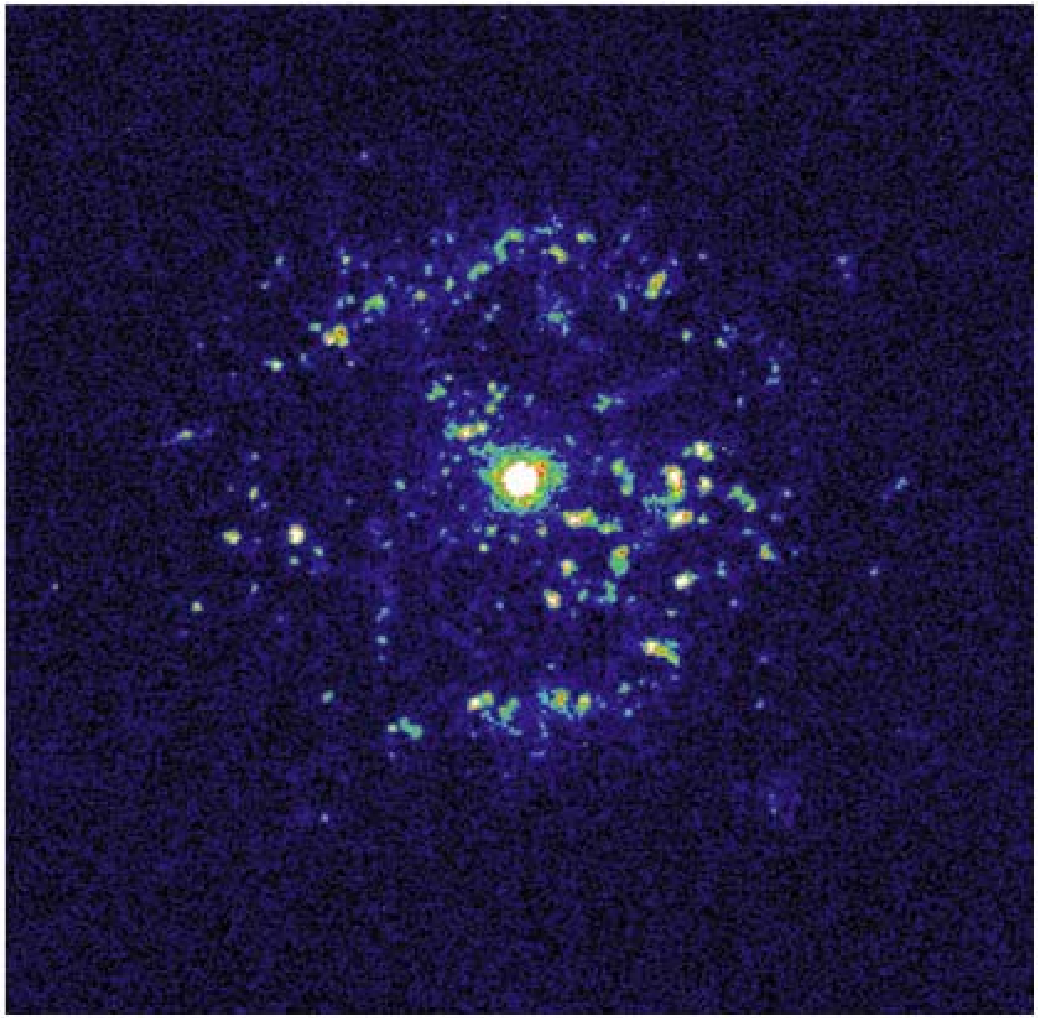
- Friction between orbiting rings of matter in the disk transfers angular momentum outward and causes the disk to heat up and glow

# 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

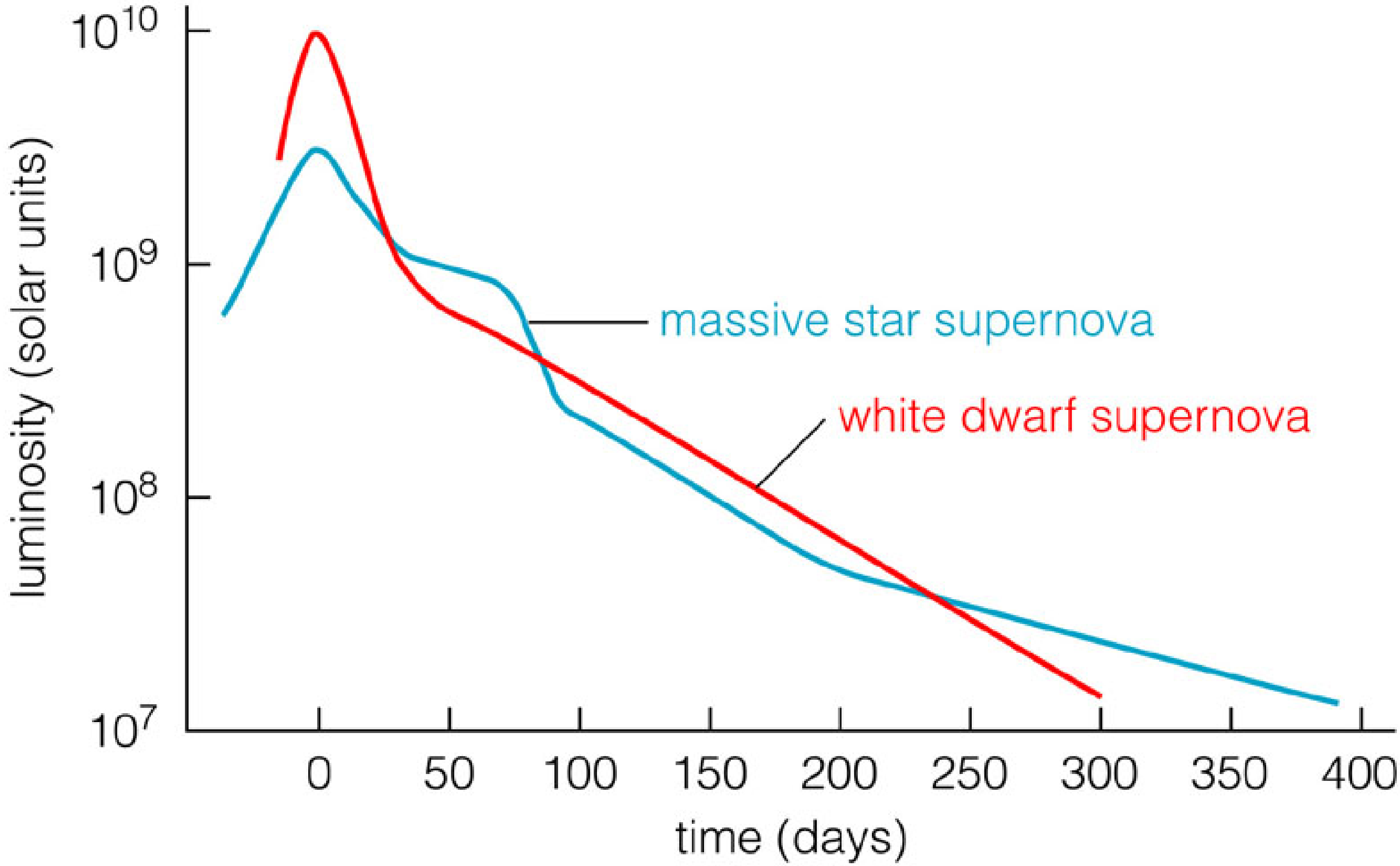
# Two Types of Supernova

***Massive star supernova:***

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

***White dwarf supernova:***

Carbon fusion suddenly begins as 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 million 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)

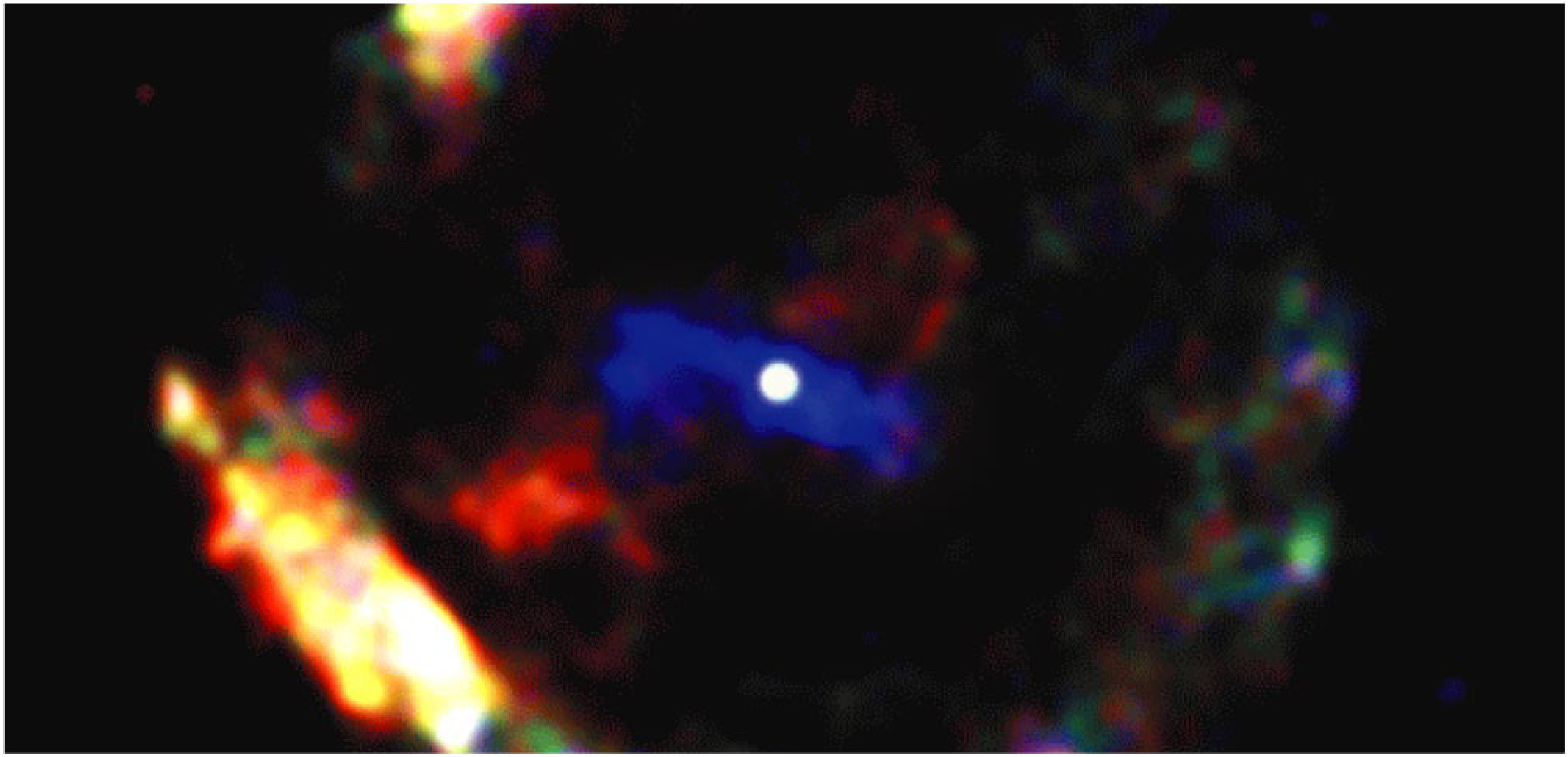
# What have we learned?

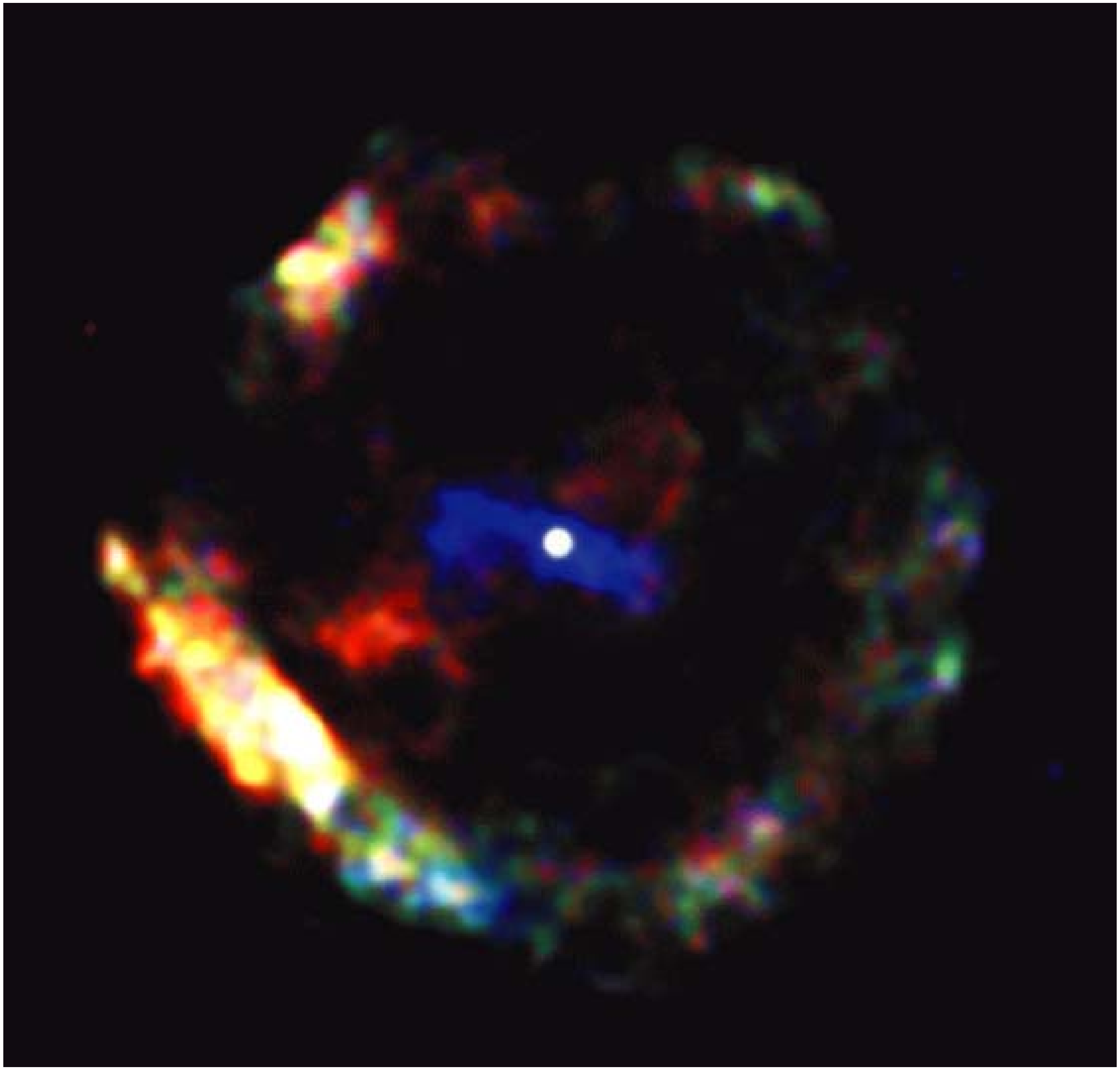
- What is a white dwarf?
  - A white dwarf is the inert core of a dead star
  - Electron degeneracy pressure balances the inward pull of gravity
- What can happen to a white dwarf in a close binary system?
  - Matter from its close binary companion can fall onto the white dwarf through an accretion disk
  - Accretion of matter can lead to novae and white dwarf supernovae

# 18.2 Neutron Stars

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

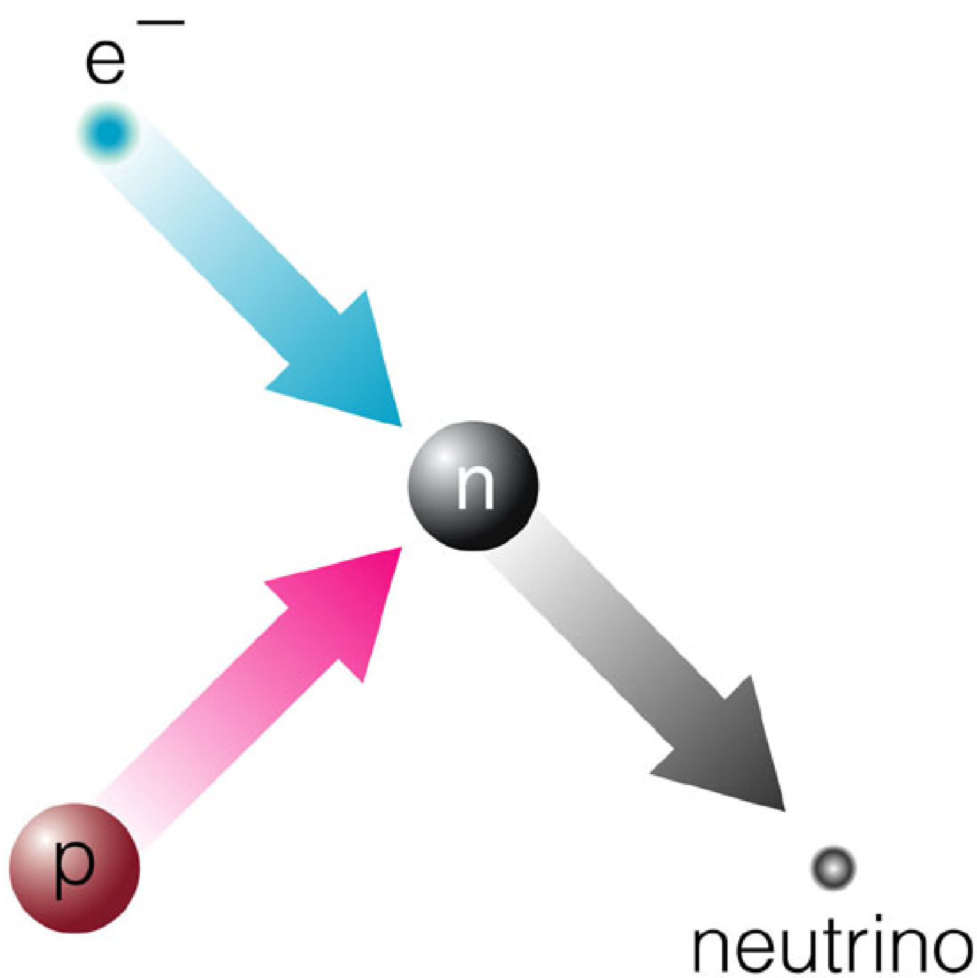
# What is a neutron star?





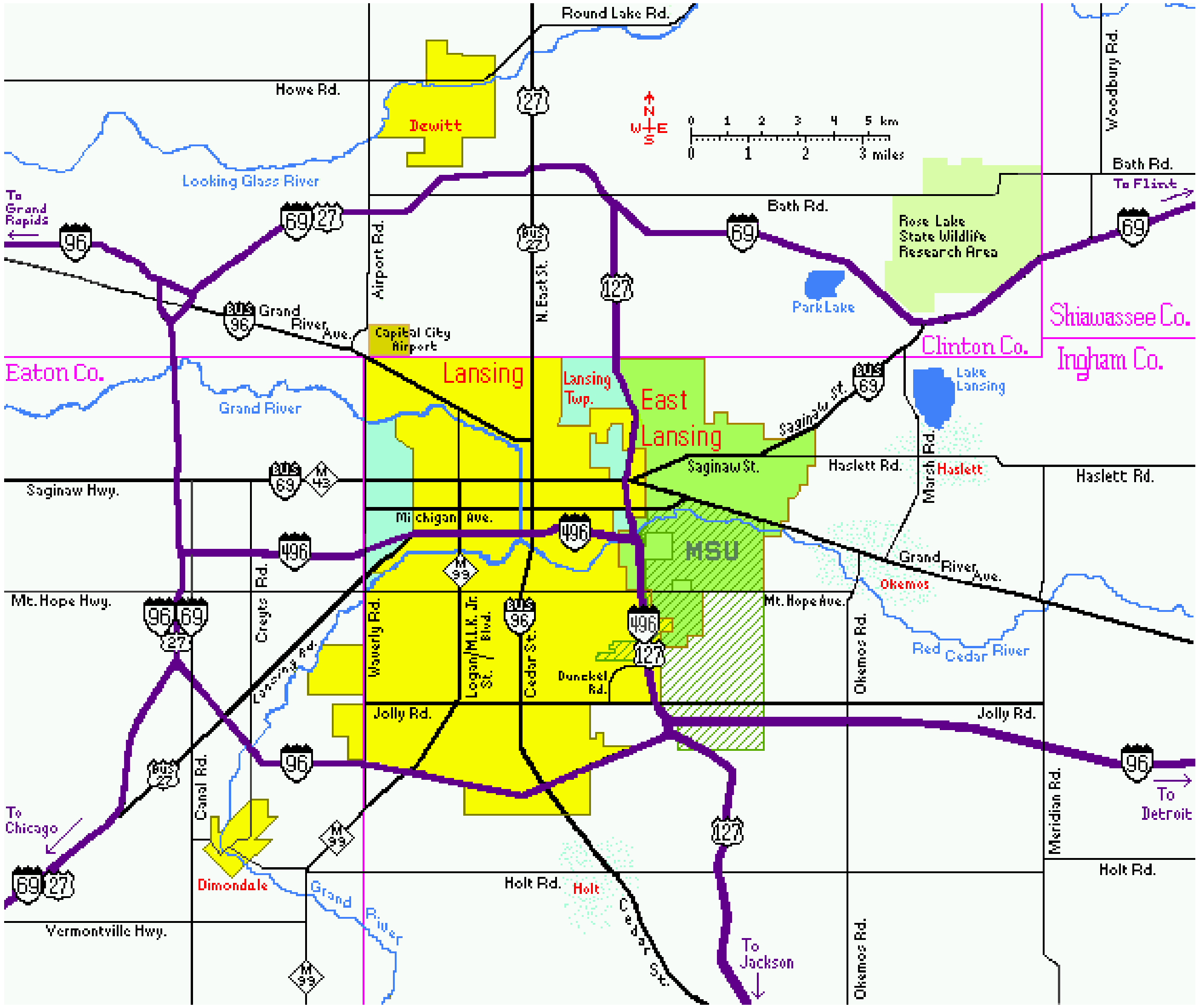
A neutron star is the ball of neutrons left behind by a massive-star supernova

Degeneracy pressure of neutrons supports a neutron star against gravity



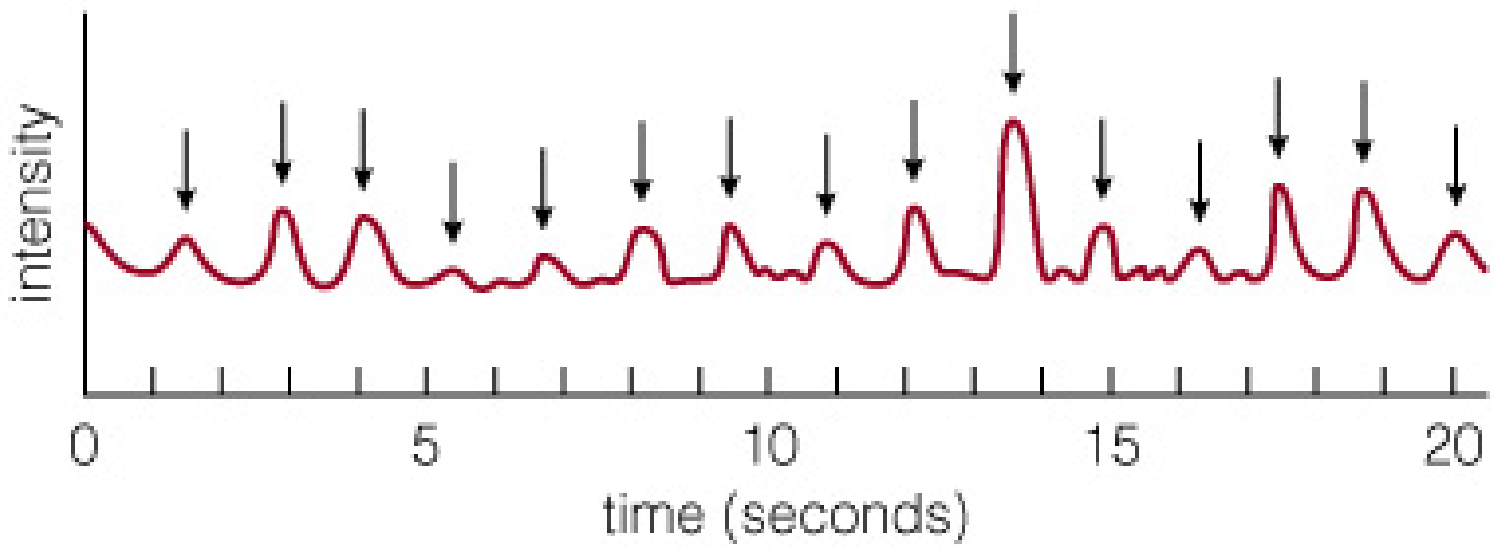

Electron degeneracy pressure goes away because electrons combine with protons, making neutrons and neutrinos

Neutrons collapse to the center, forming a ***neutron star***

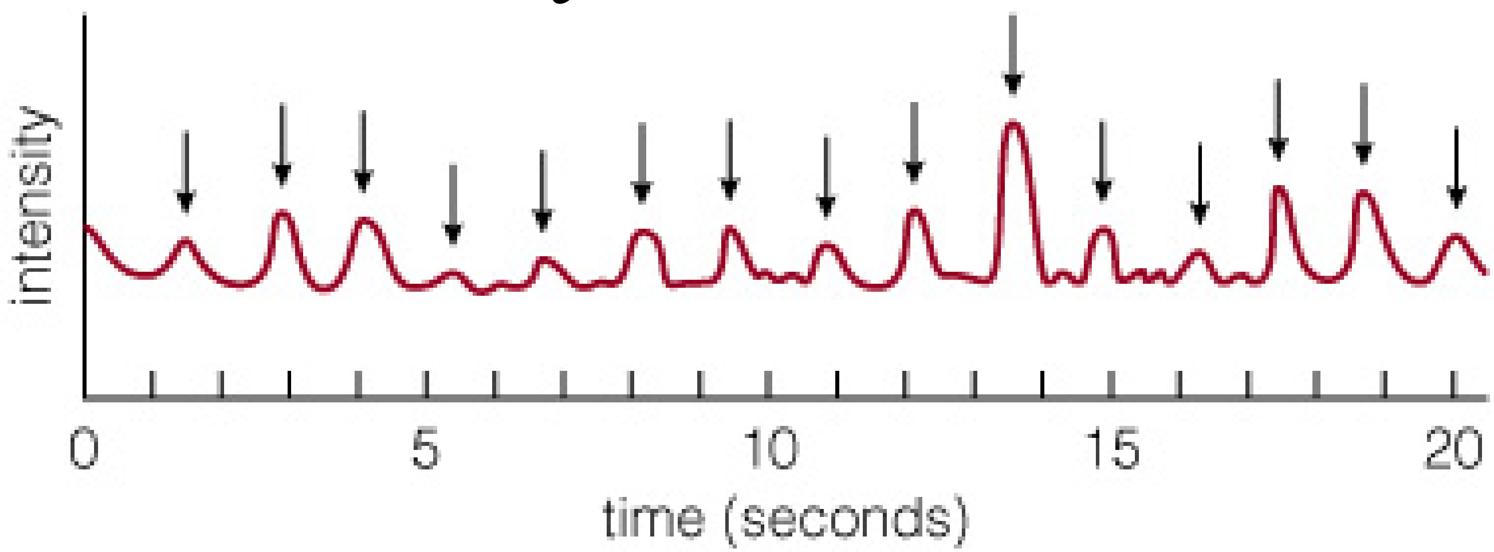



# A neutron star is about the same size as a small city

# How were neutron stars discovered?

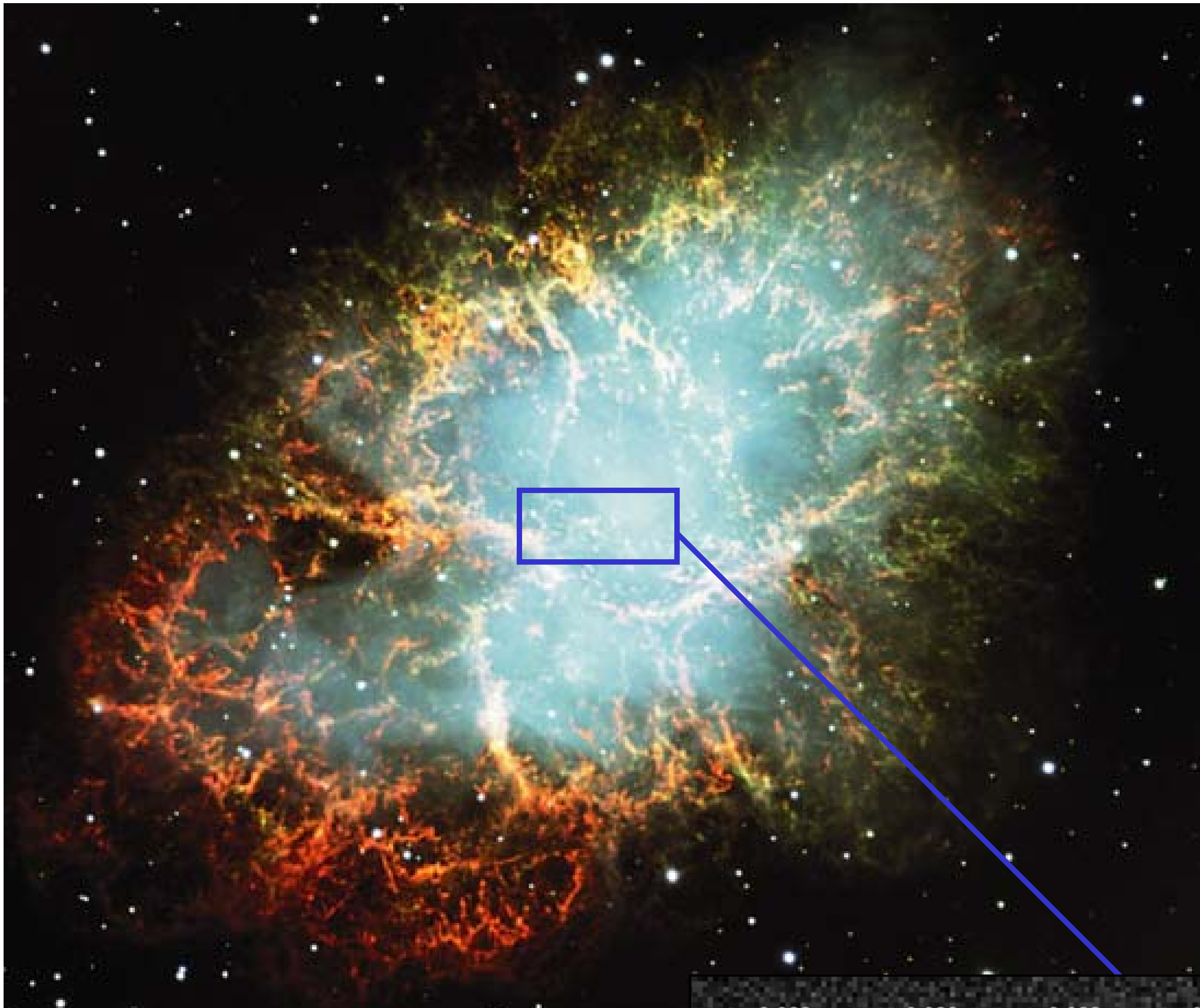


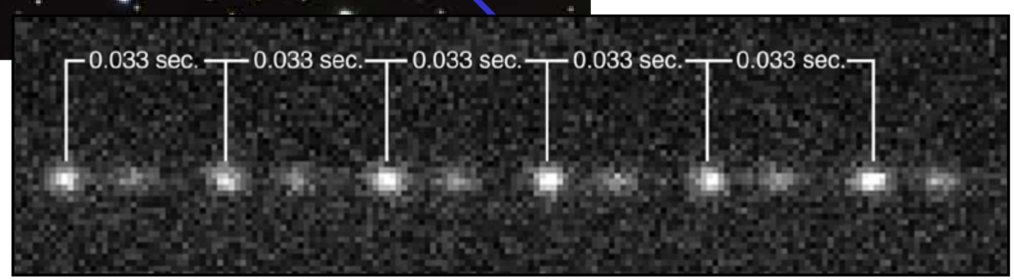
# Discovery of Neutron Stars

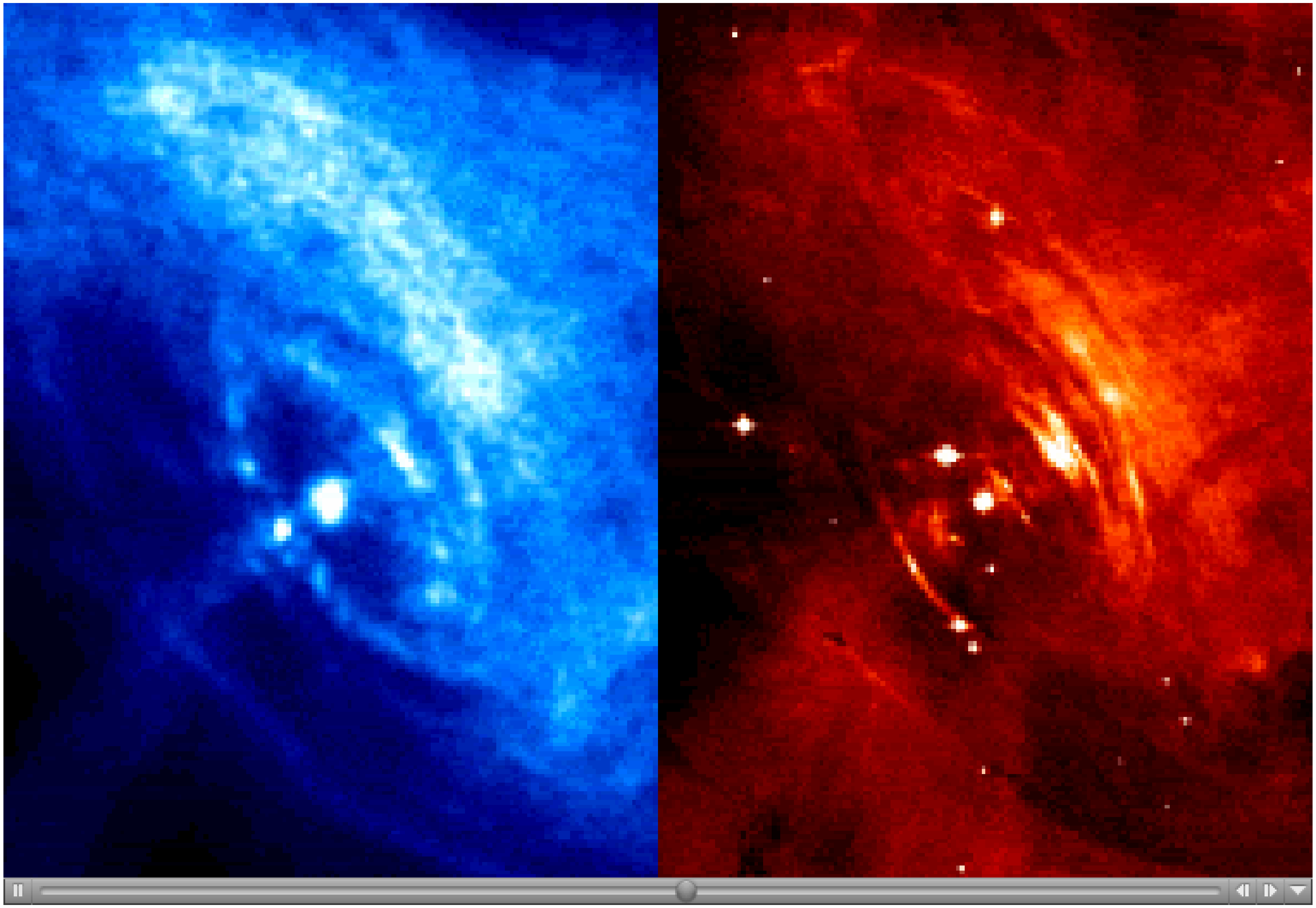



- Using a radio telescope in 1967, Jocelyn Bell noticed very regular pulses of radio emission coming from a single part of the sky
- The pulses were coming from a spinning neutron star—a *pulsar*

Pulsar at center of Crab Nebula pulses 30 times per second



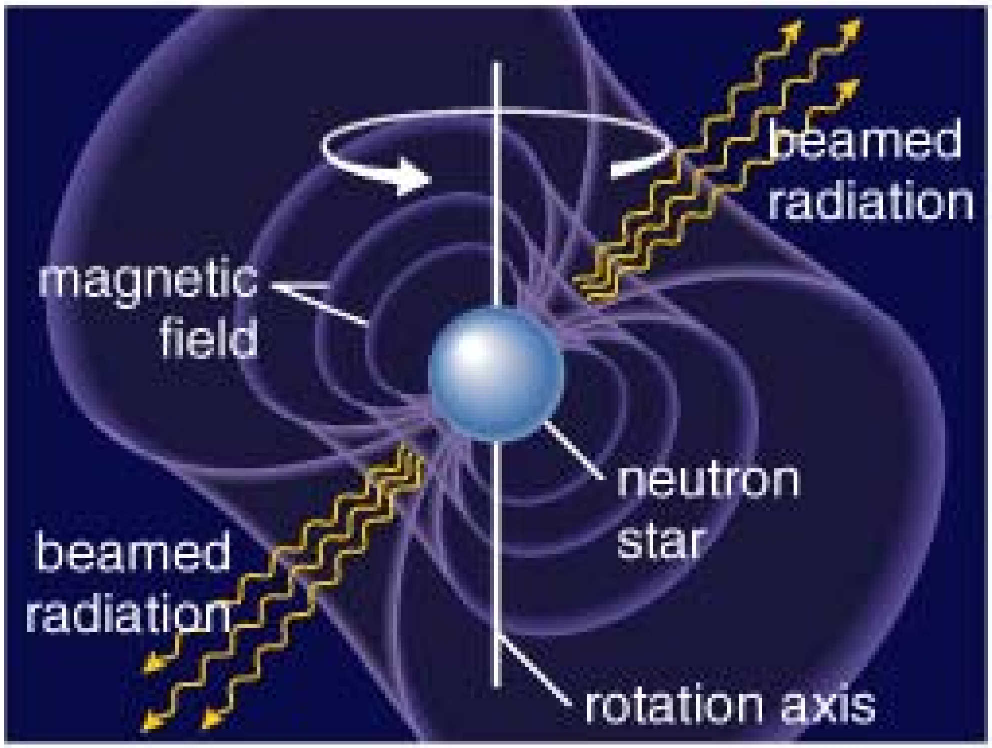




X-rays

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 = $2\pi$ (radius) ~ 60 km

Spin Rate of Fast Pulsars ~ 1000 cycles per second

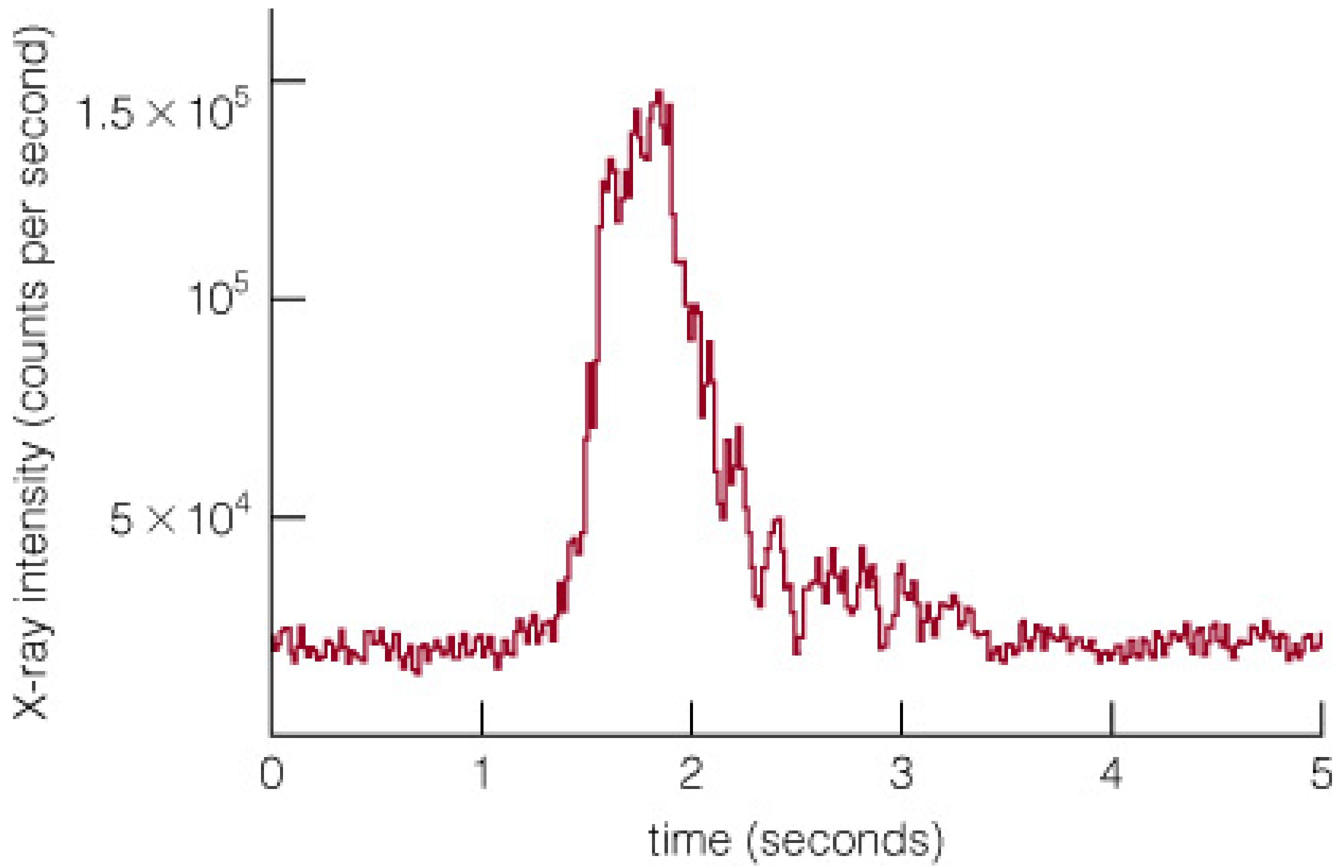
Surface Rotation Velocity ~ 60,000 km/s
~ 20% speed of light
~ escape velocity from NS

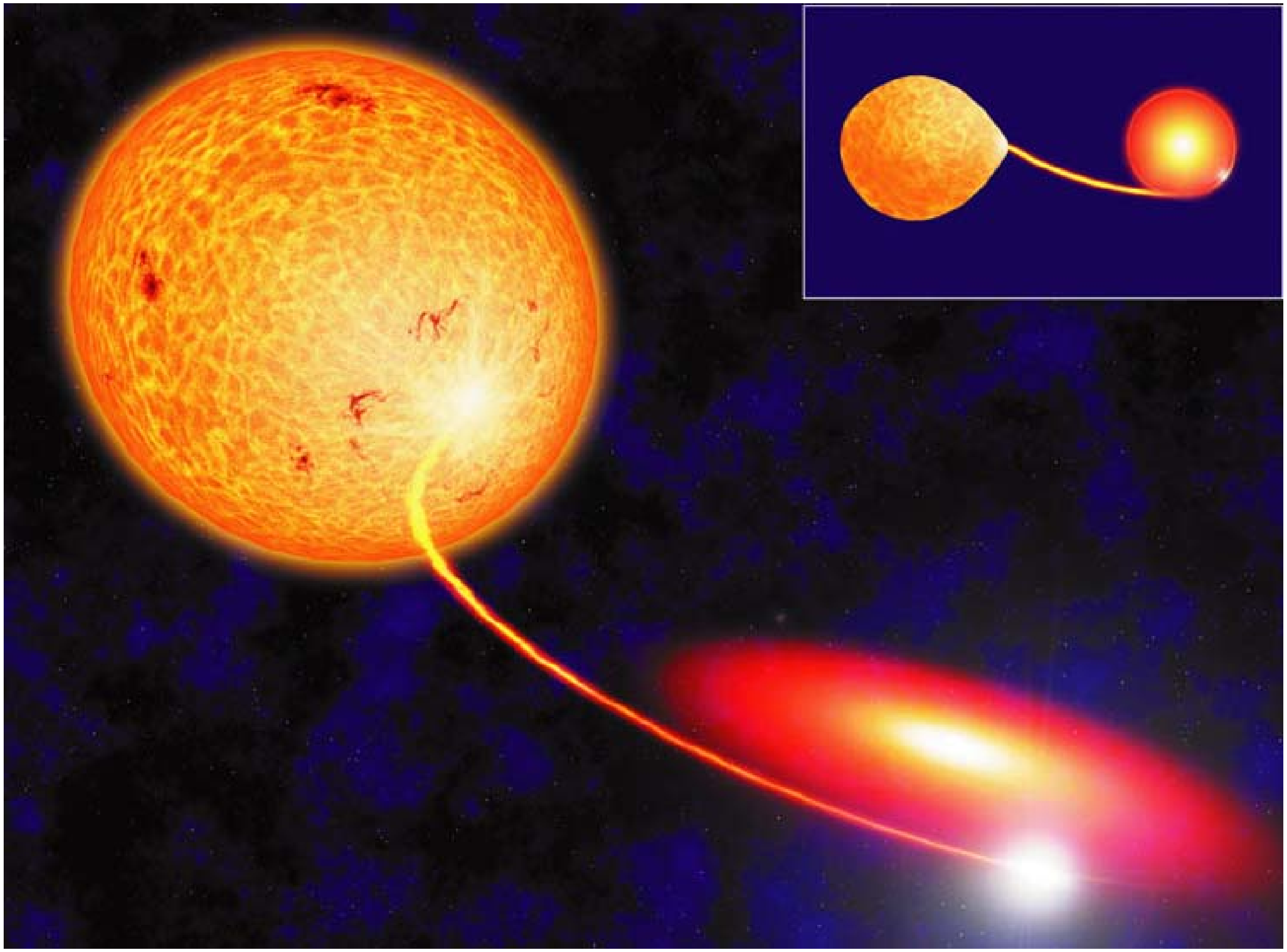
***Anything else would be torn to pieces!***


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

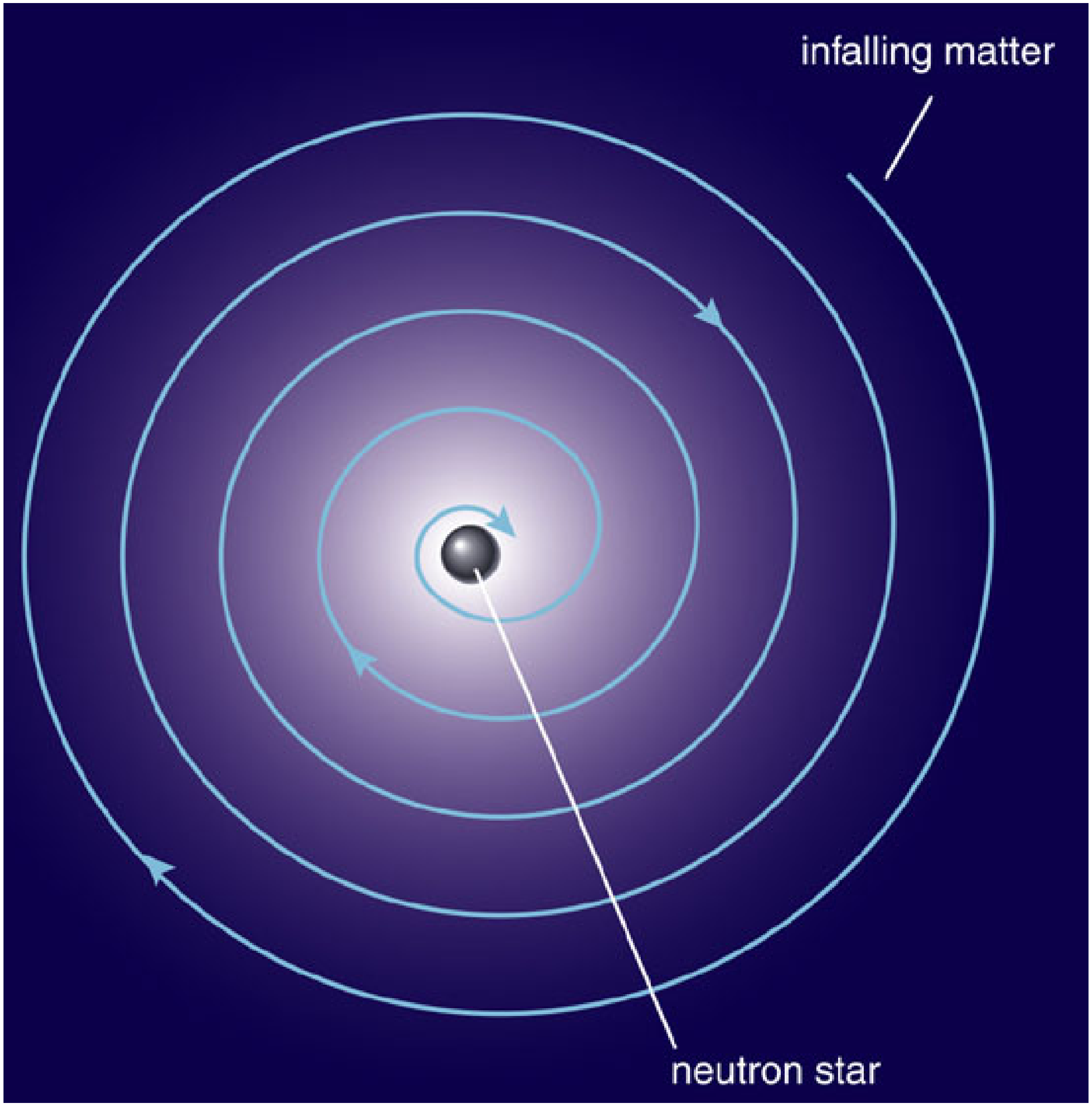
***Conservation of angular momentum***

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





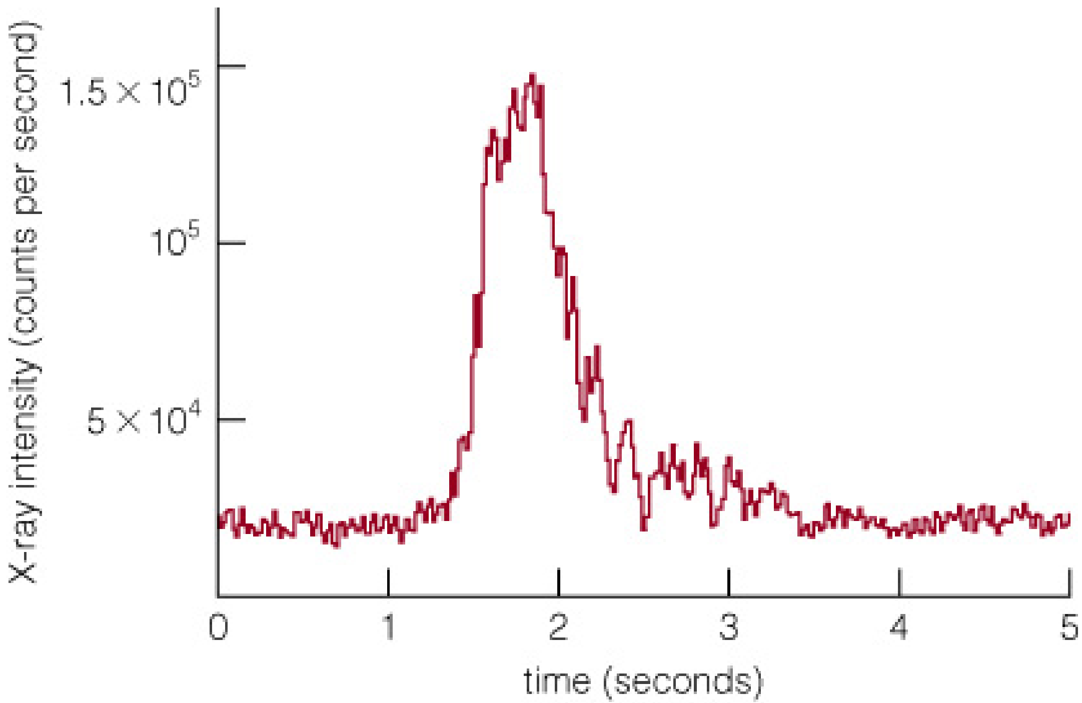
Matter falling toward a neutron star forms an accretion disk, just as in a white-dwarf binary




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

Episodes of fusion on the surface lead to X-ray bursts

# 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

# What have we learned?

- What is a neutron star?
  - A ball of neutrons left over from a massive star supernova and supported by neutron degeneracy pressure
- How were neutron stars discovered?
  - Beams of radiation from a rotating neutron star sweep through space like lighthouse beams, making them appear to pulse
  - Observations of these pulses were the first evidence for neutron stars

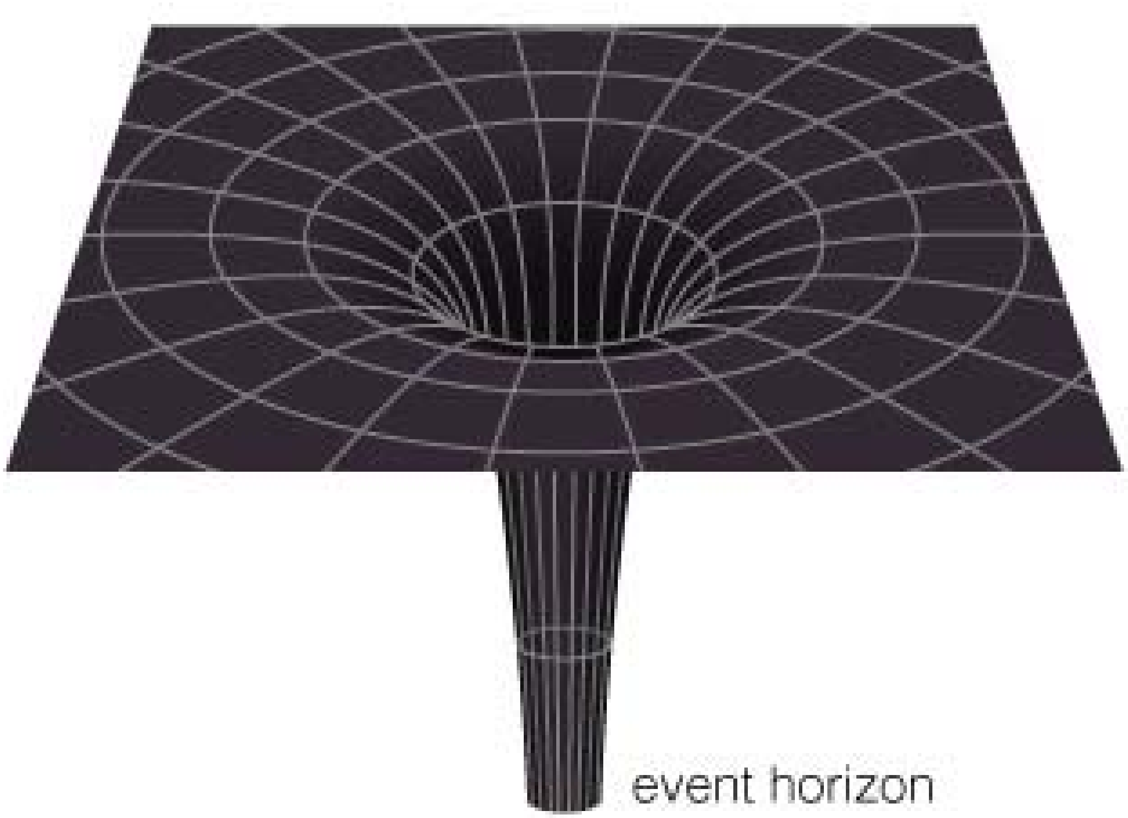
# What have we learned?

- What can happen to a neutron star in a close binary system?
  - The accretion disk around a neutron star gets hot enough to produce X-rays, making the system an X-ray binary
  - Sudden fusion events periodically occur on a the surface of an accreting neutron star, producing X-ray bursts

# 18.3 Black Holes: Gravity's Ultimate Victory

- Our goals for learning
- 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?

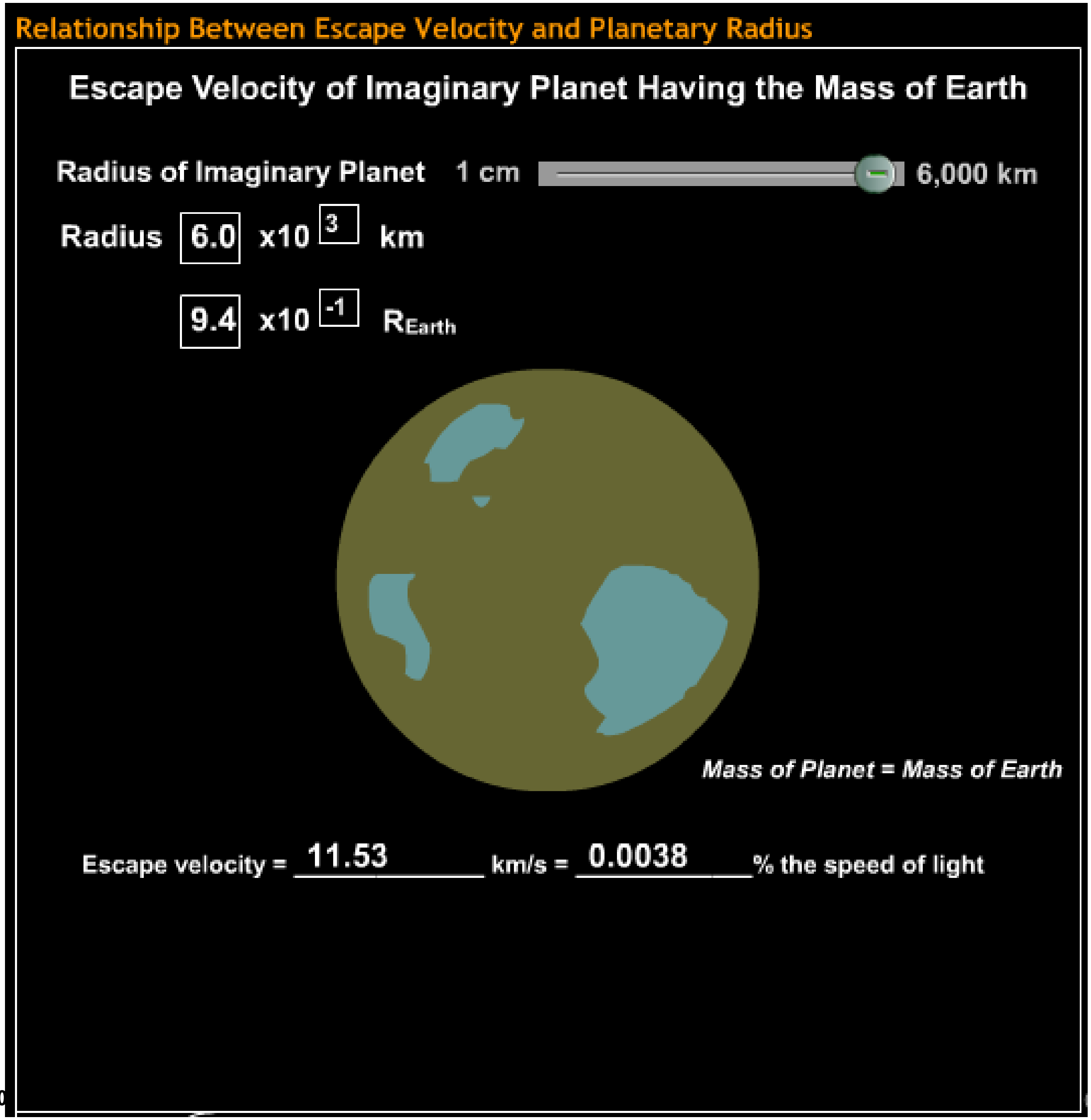


A ***black hole*** is an object whose gravity is so powerful that not even light can escape it.

# Escape Velocity

Initial Kinetic Energy = Final Gravitational Potential Energy

$$\frac{(\text{escape velocity})^2}{2} = \frac{G \times (\text{mass})}{(\text{radius})}$$



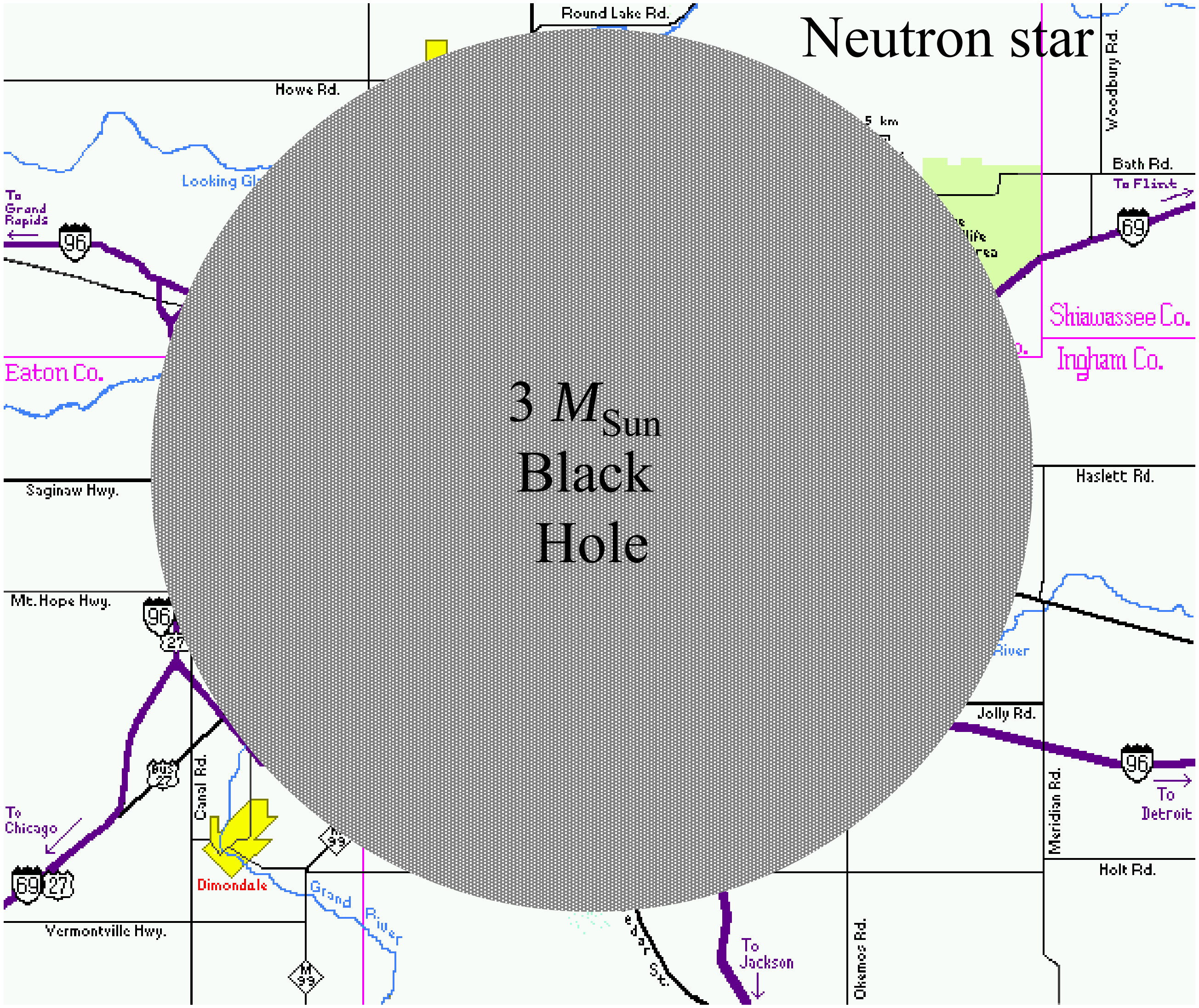

Light would not be able to escape Earth’s surface if you could shrink it to < 1 cm

# “Surface” of a Black Hole

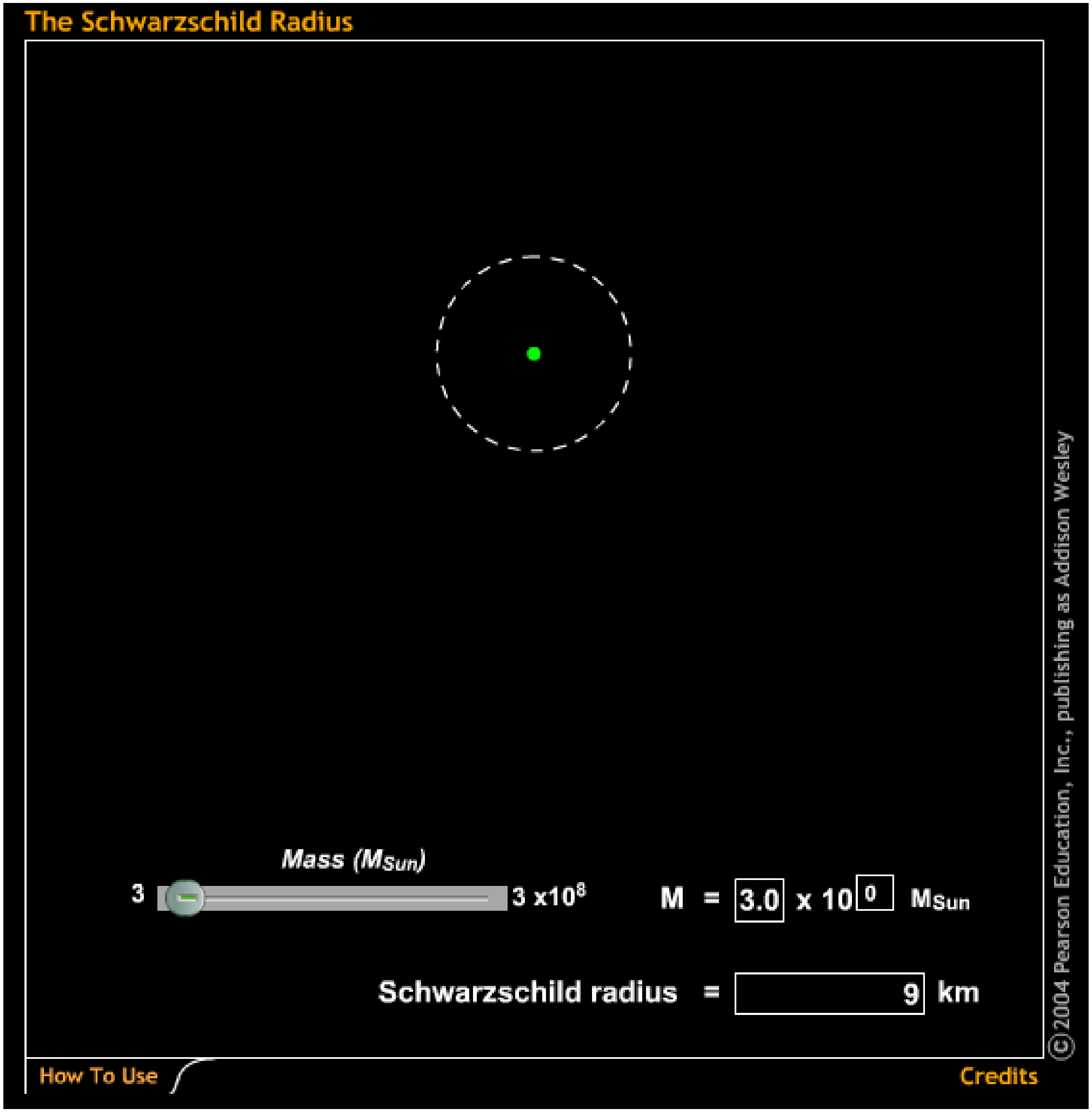
- The “surface” of a black hole is the radius at which the escape velocity equals the speed of light.

- This spherical surface is known as the ***event horizon.***

- The radius of the event horizon is known as the ***Schwarzschild radius.***

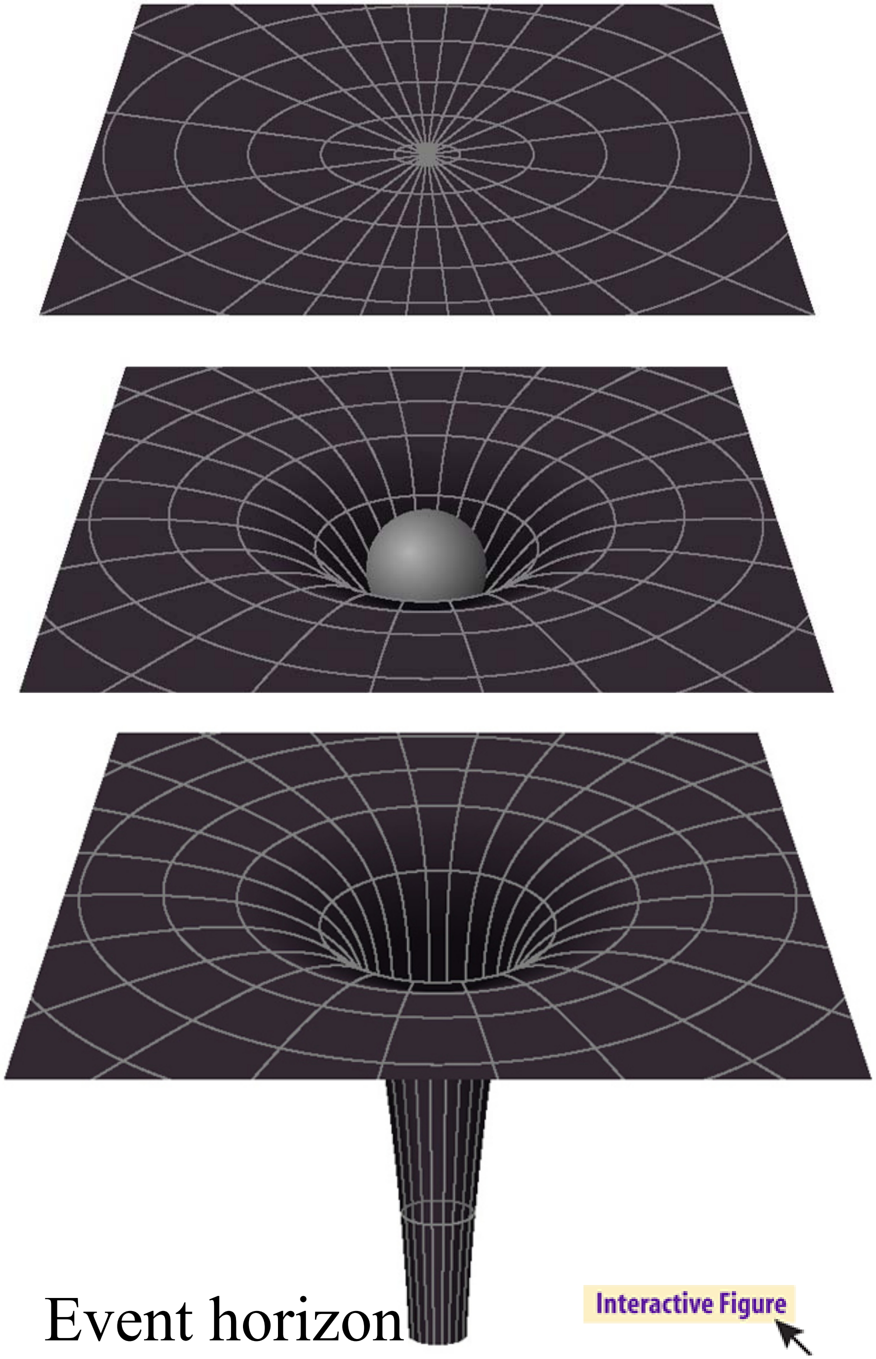



The event horizon of a 3 $M_{Sun}$ black hole is also about as big as a small city




Event horizon is larger for black holes of larger mass

A black hole's mass strongly warps space and time in vicinity of 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

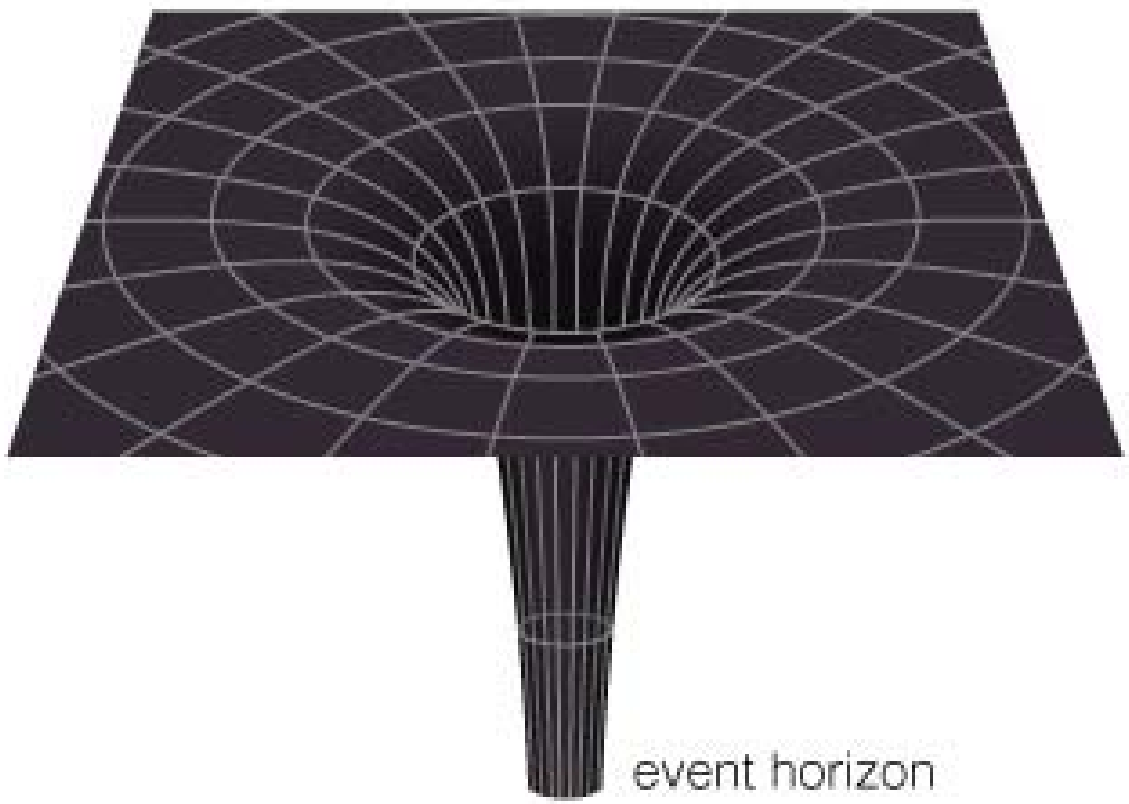
- Quantum mechanics says that neutrons in the same place cannot be in the same state
- Neutron degeneracy pressure can no longer support a neutron star against gravity if its mass exceeds about $3\ M_{sun}$
- Some massive star supernovae can make black hole if enough mass falls onto core

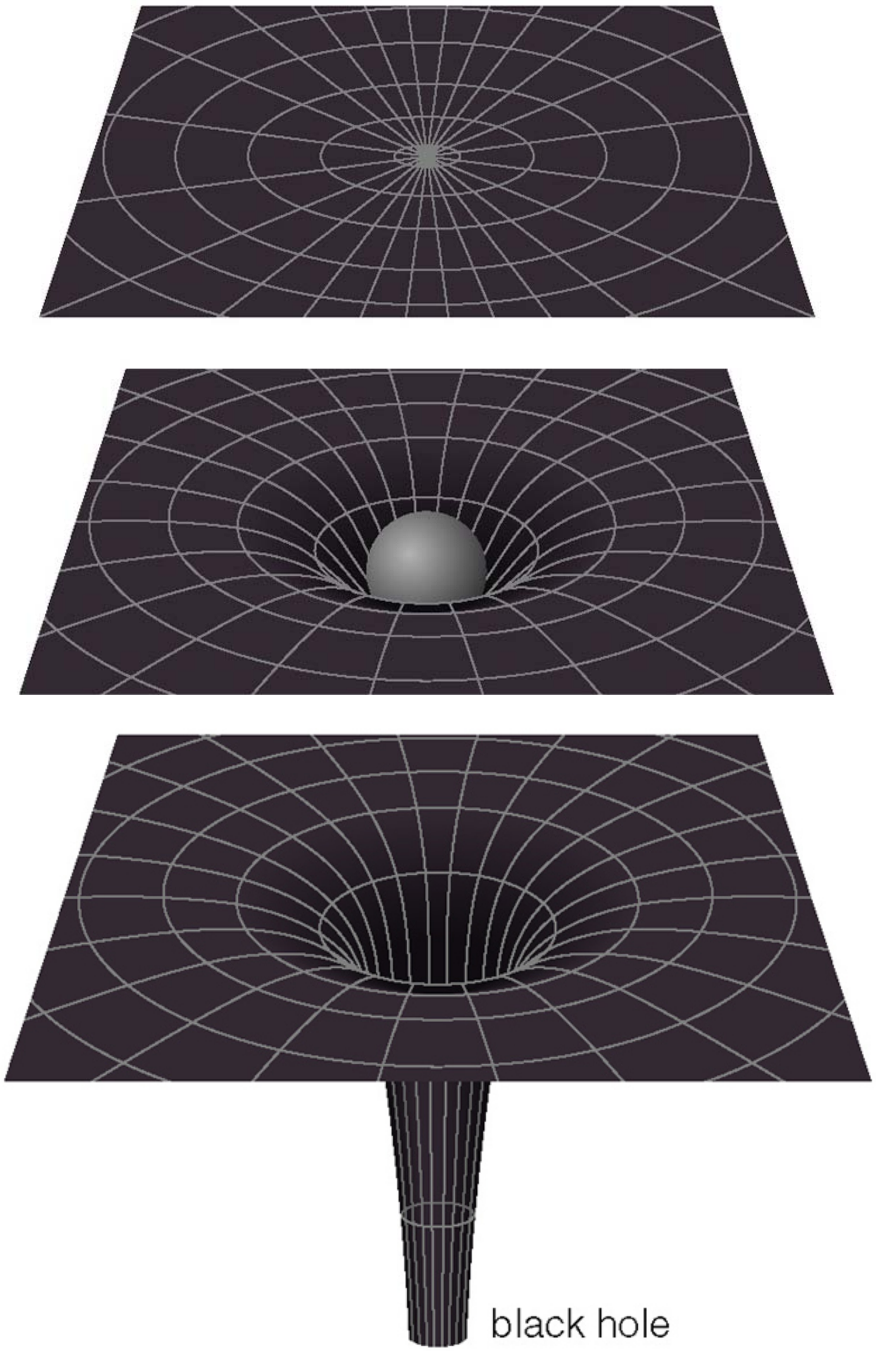
# Singularity

- 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.***

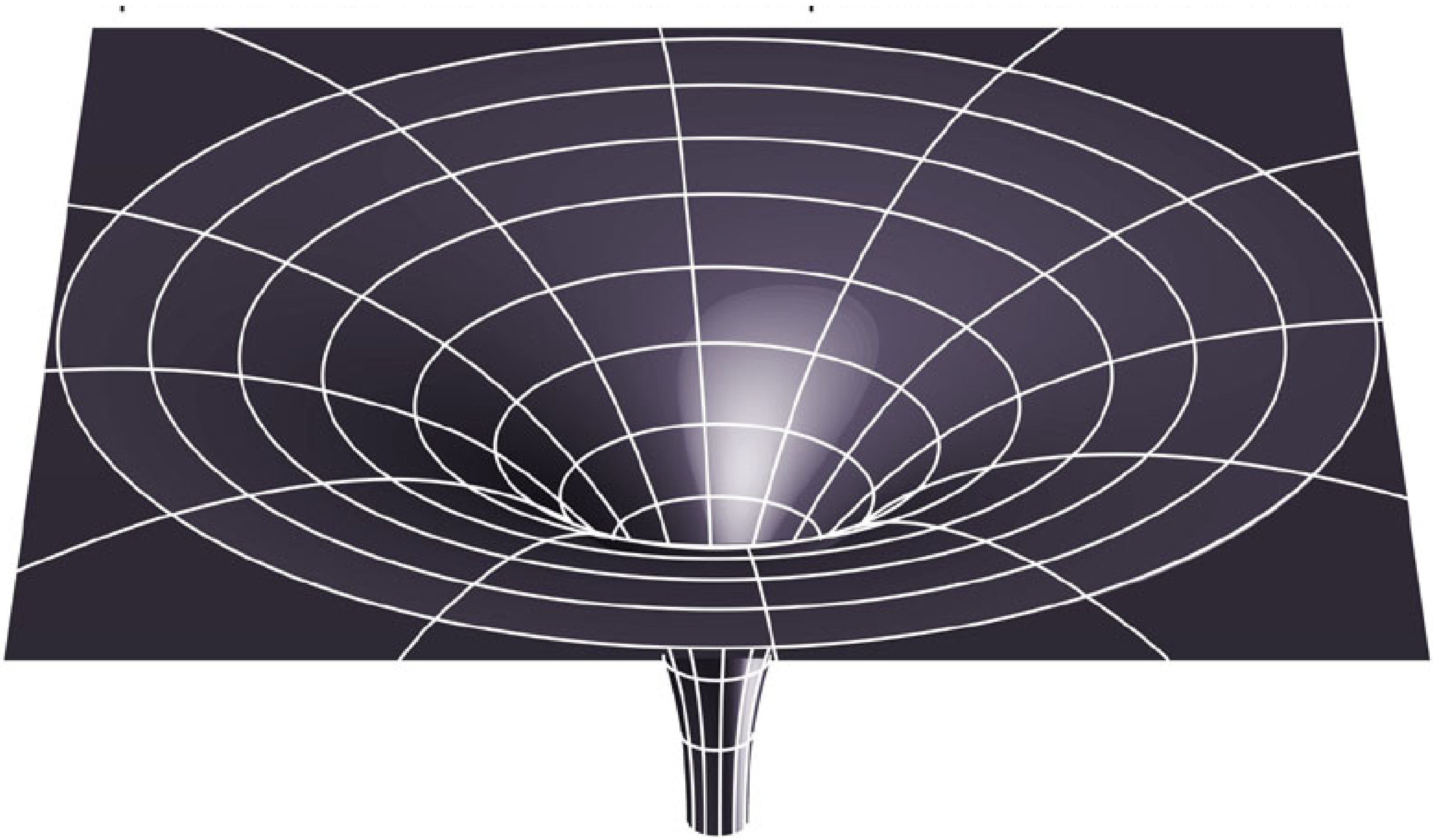
# What would it be like to visit a black hole?



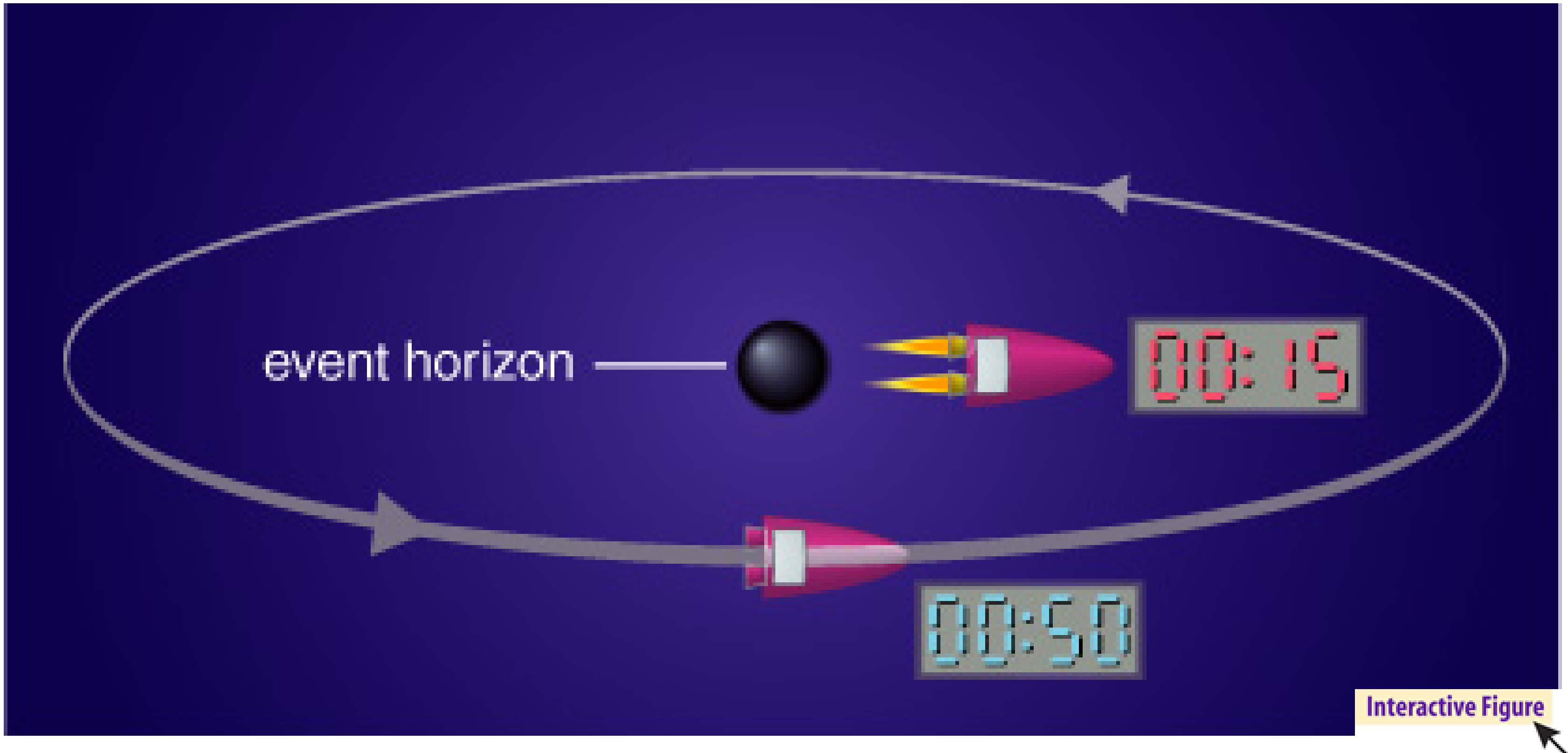



If the Sun shrank into a black hole, its gravity would be different only near the event horizon

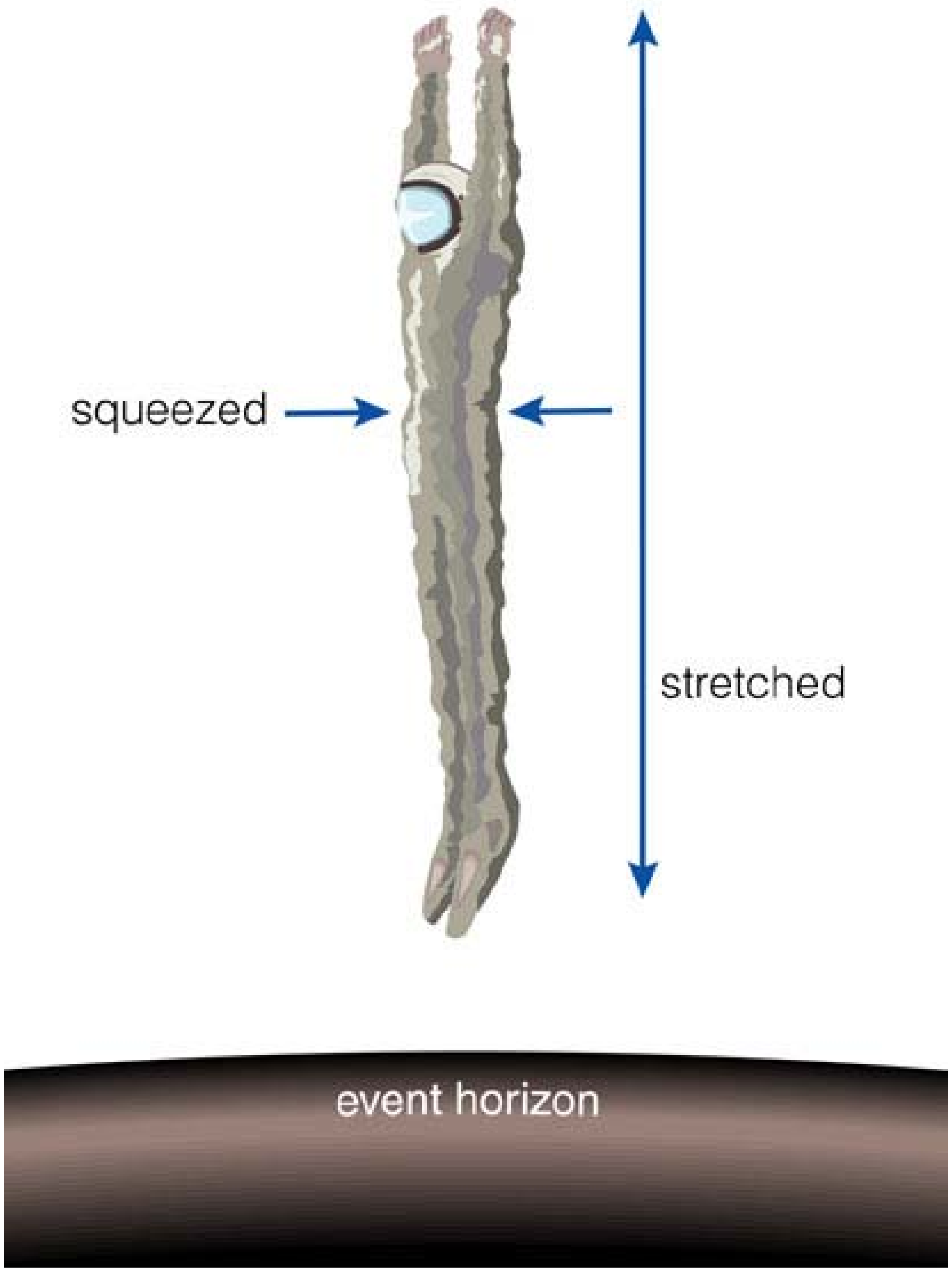
***Black holes don't suck!***



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

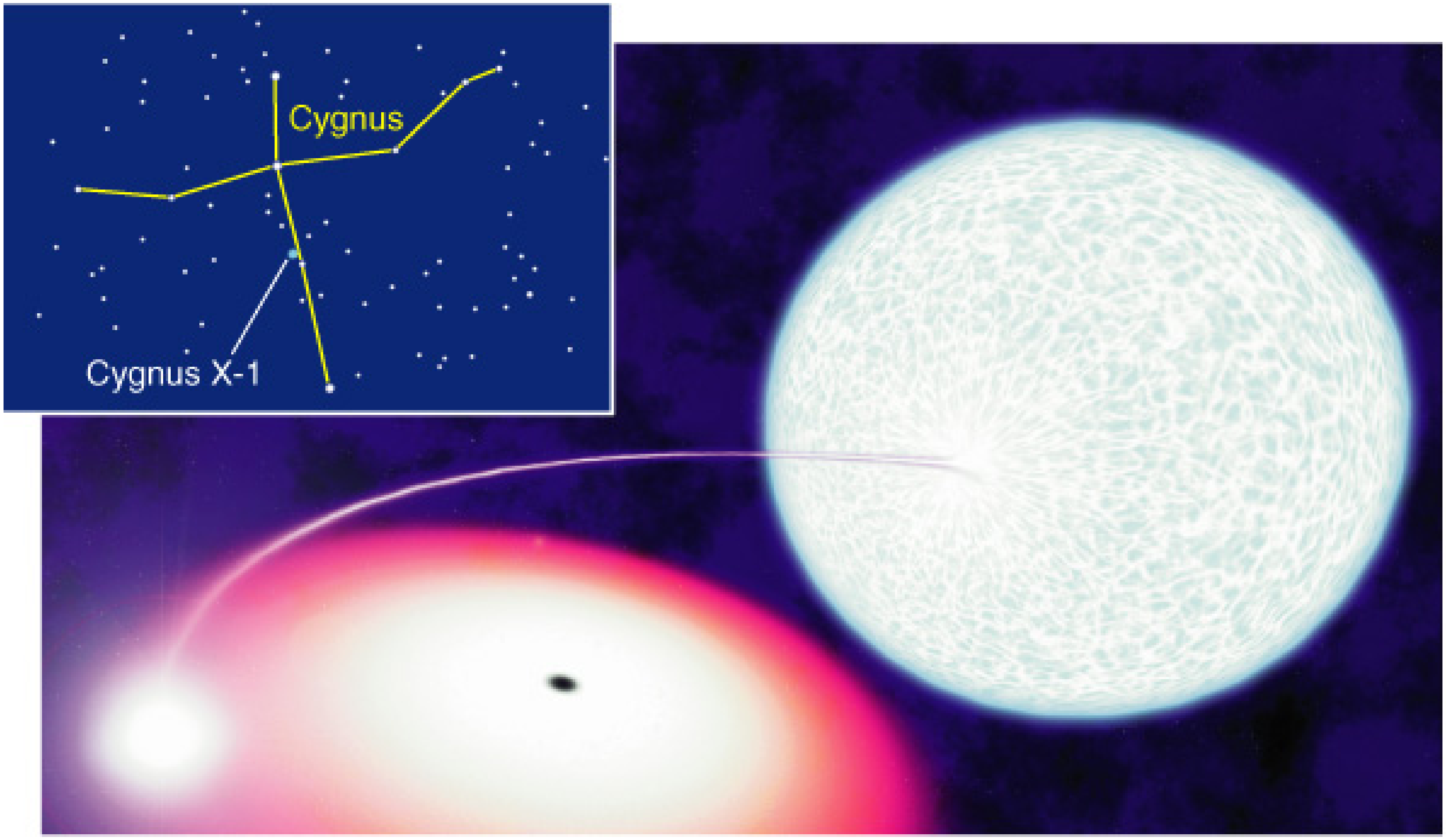





Tidal forces near the event horizon of a 3 $M_{Sun}$ black hole would be lethal to humans

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

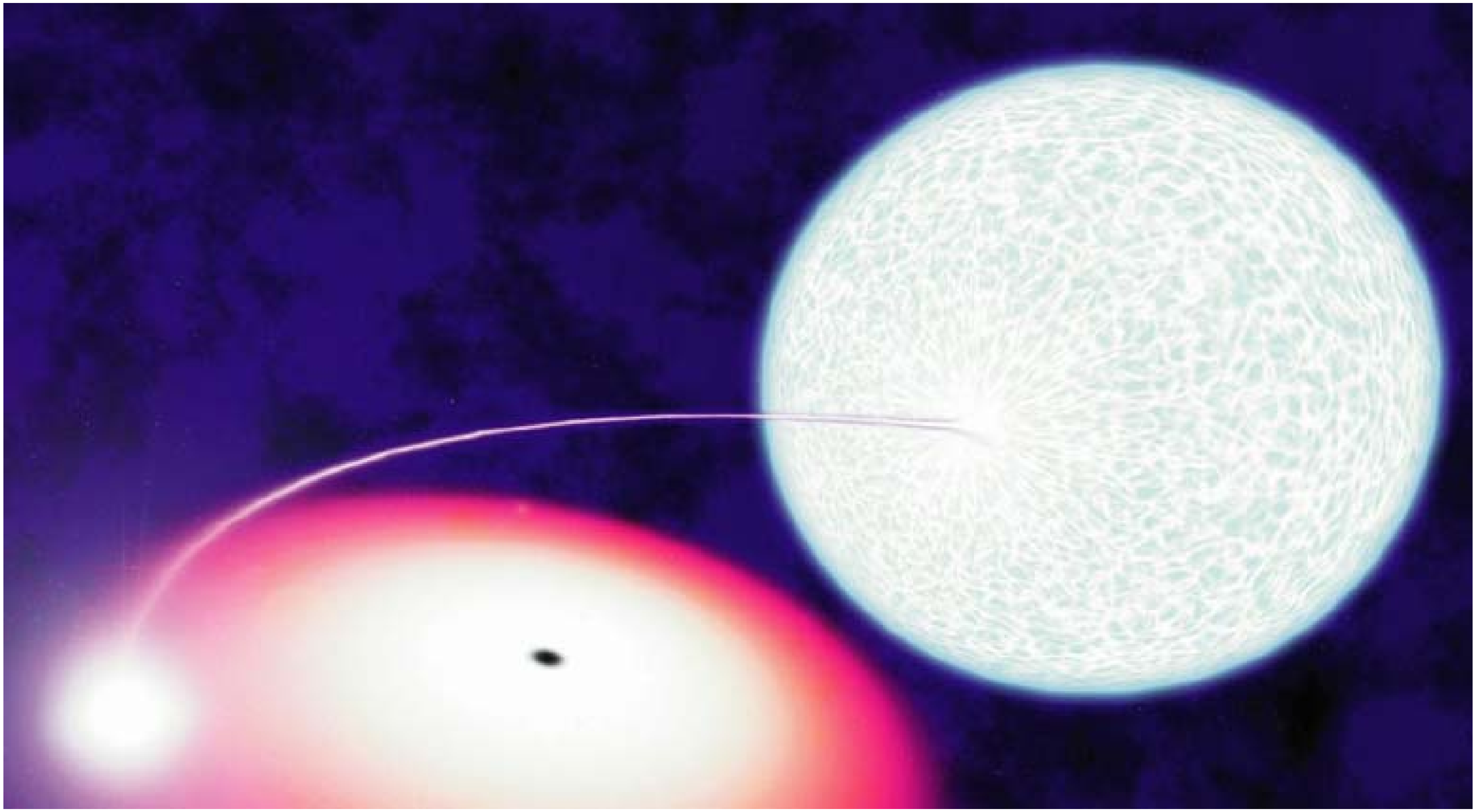
# Do black holes really exist?



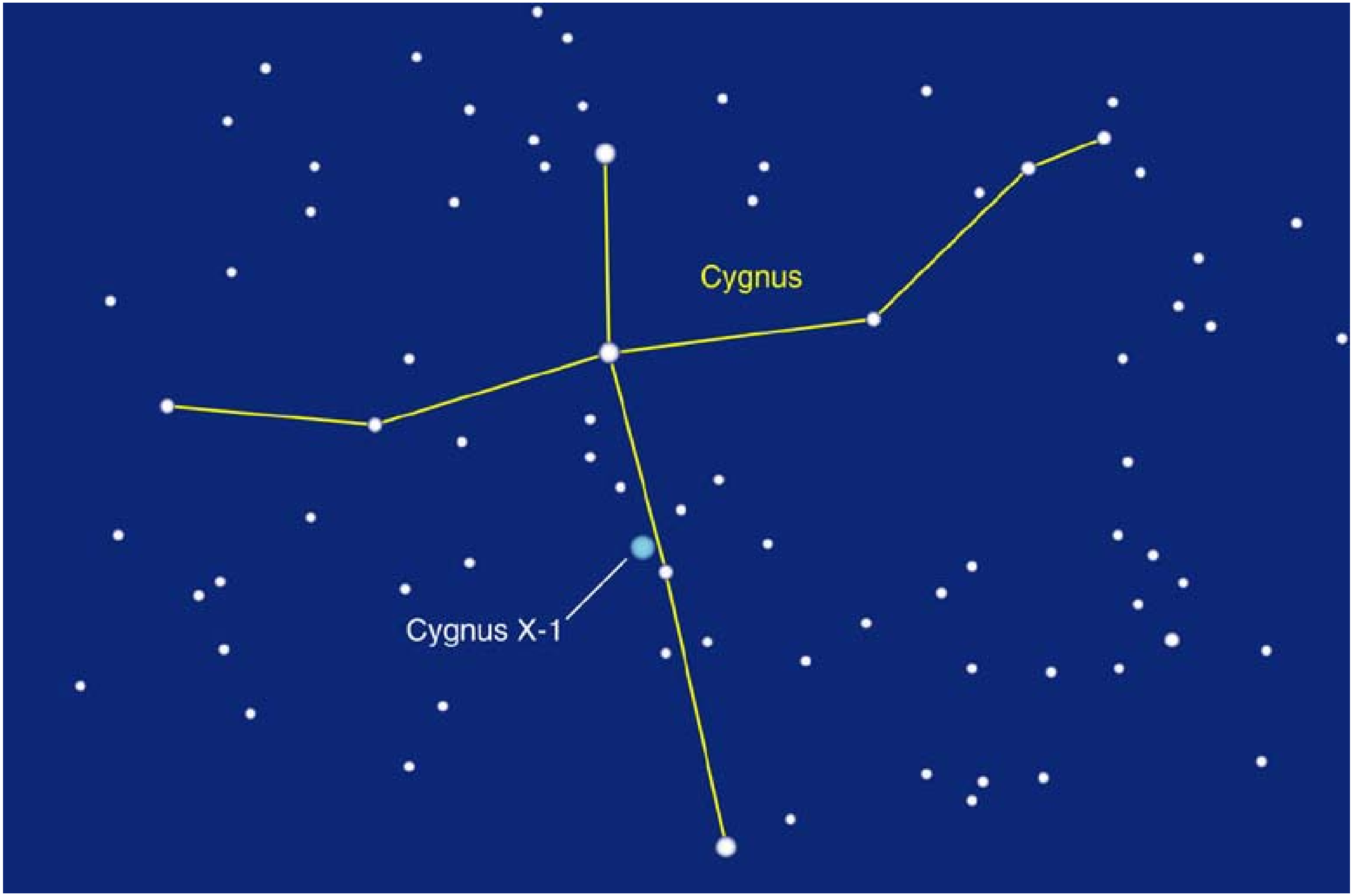
# Black Hole Verification

- Need to measure mass
  - — Use orbital properties of companion
  - — Measure 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 (~3 $M_{\text{Sun}}$)



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




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

# What have we learned?

- What is a black hole?
  - A black hole is a massive object whose radius is so small that the escape velocity exceeds the speed of light
- What would it be like to visit a black hole?
  - You can orbit a black hole like any other object of the same mass—black holes don't suck!
  - Near the event horizon time slows down and tidal forces are very strong

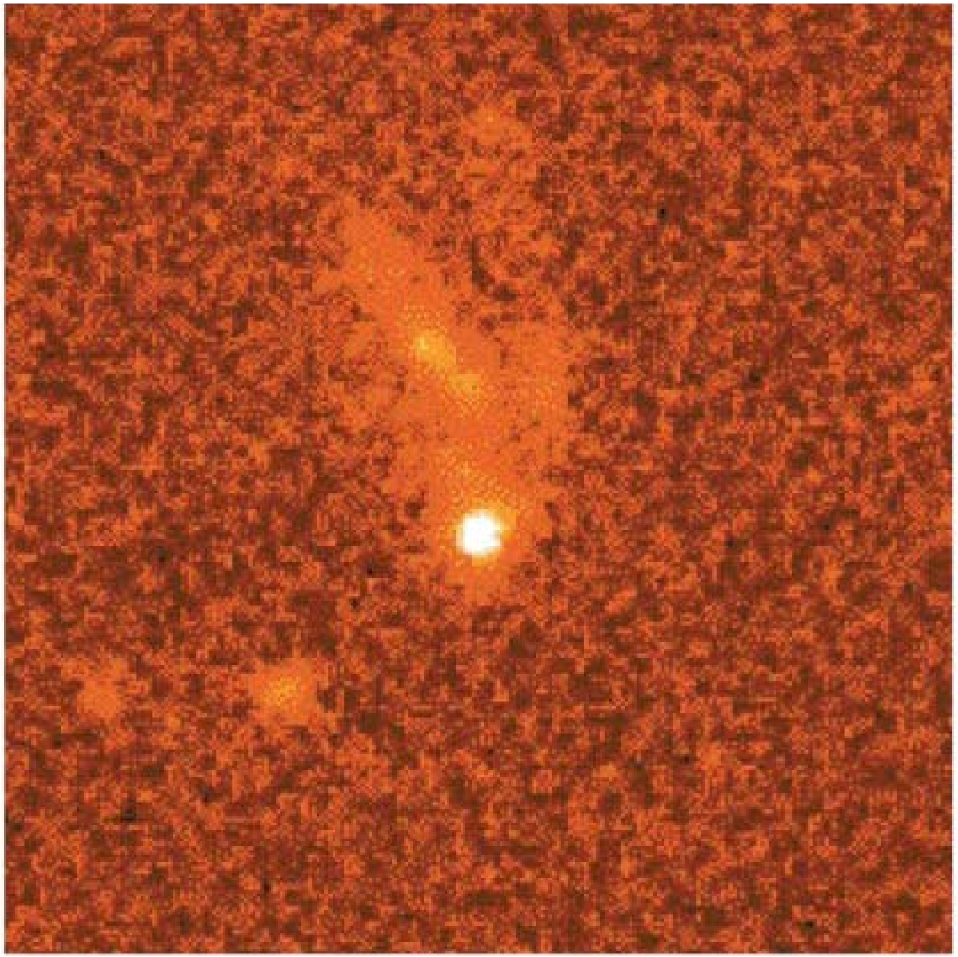
# What have we learned?

- Do black holes really exist?
  - Some X-ray binaries contain compact objects to massive to be neutron stars—they are almost certainly black holes

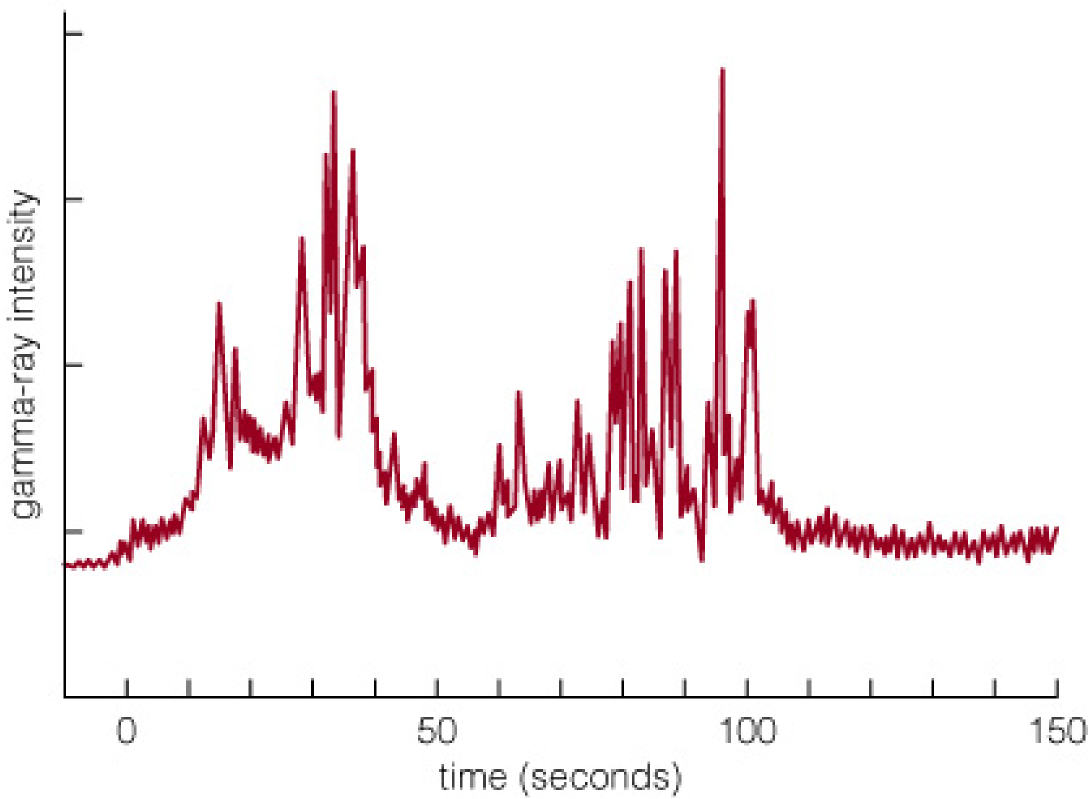
# 18.4 The Mystery of Gamma Ray Bursts

- Our goals for learning
- Where do gamma-ray bursts come from?
- What causes gamma-ray bursts?

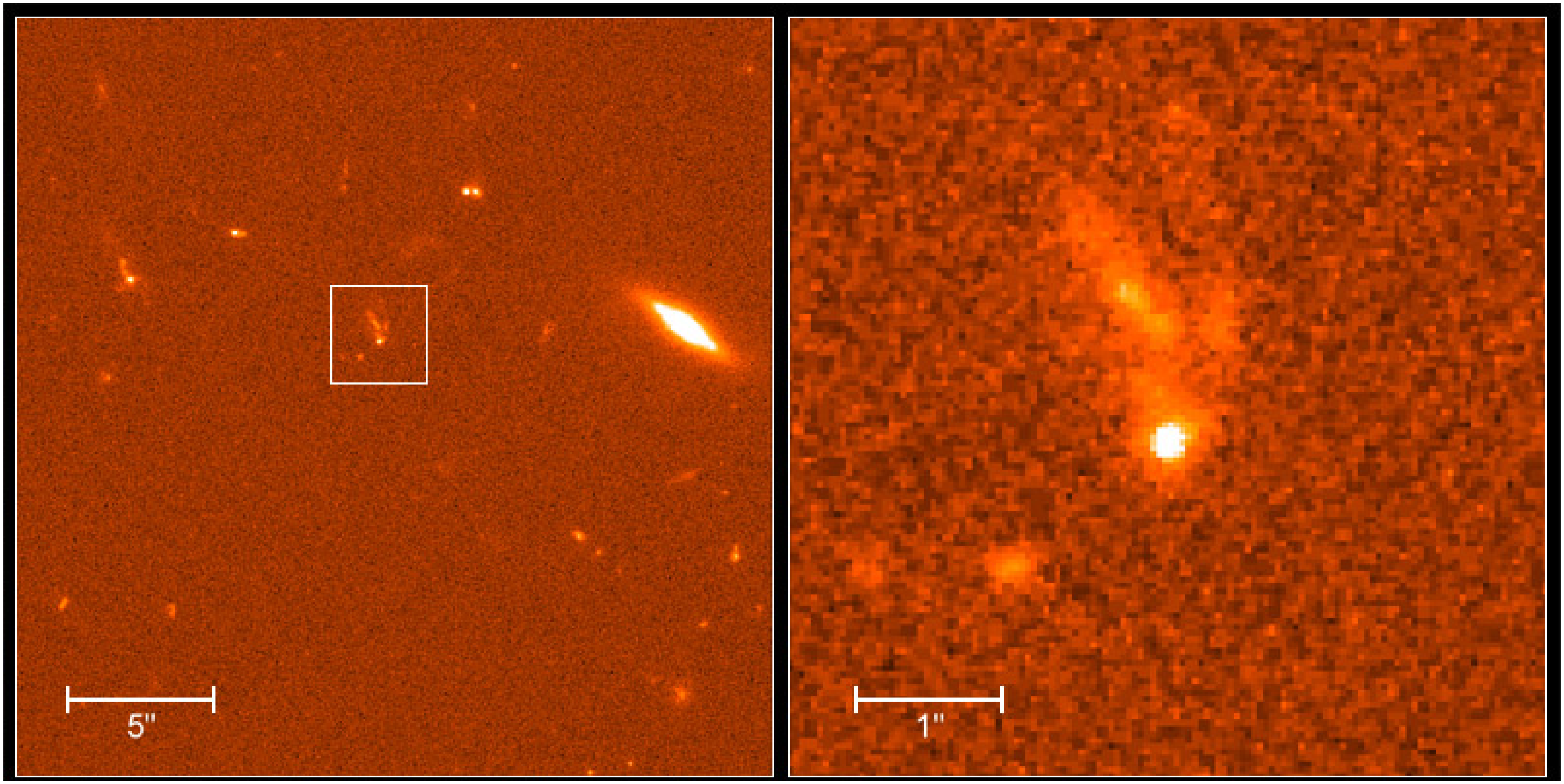
# Where do gamma-ray bursts come from?



# Gamma-Ray Bursts

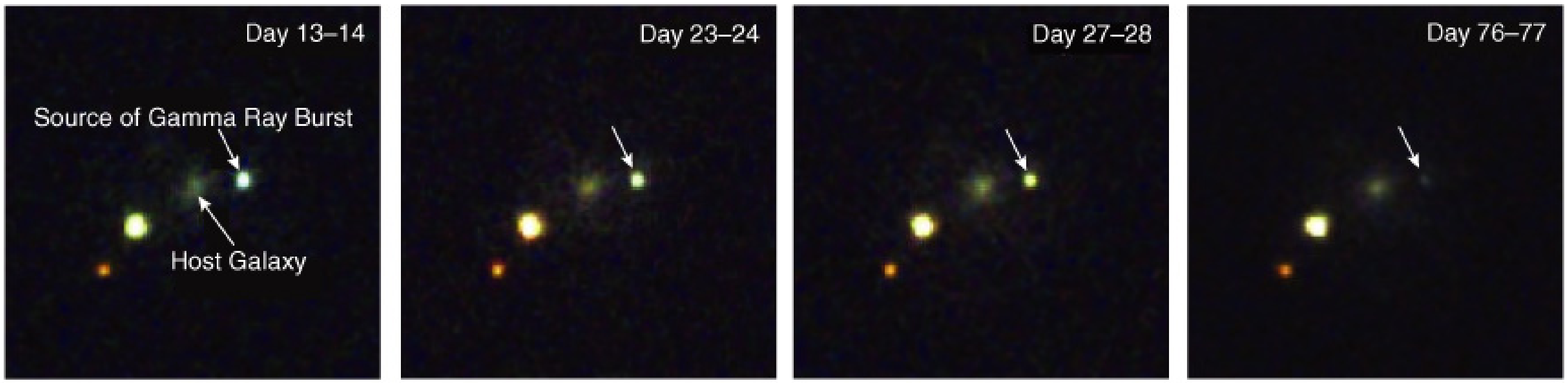



- Brief bursts of gamma-rays coming from space were first detected in the 1960s

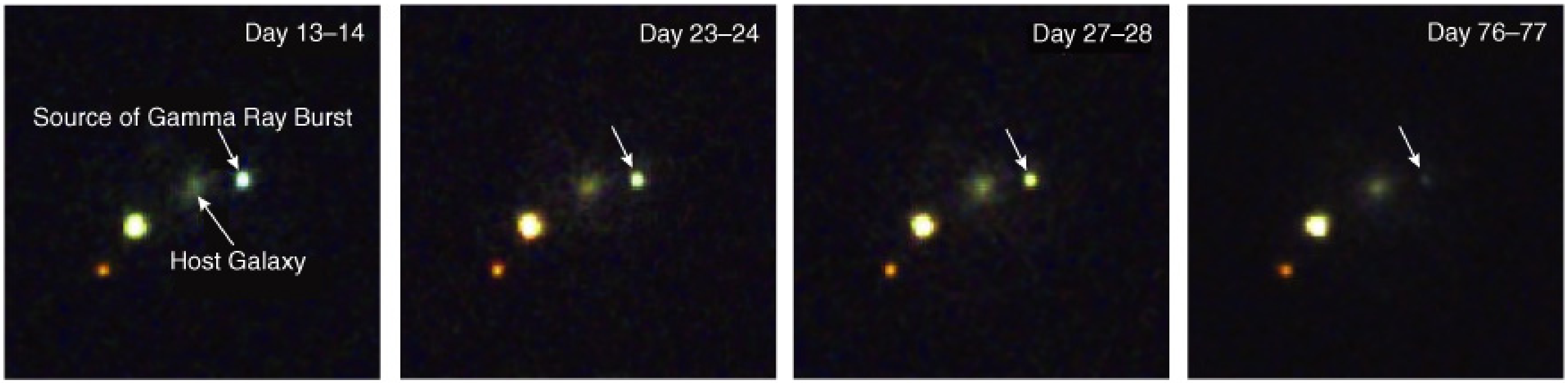



- Observations in the 1990s showed that many gamma-ray bursts were coming from very distant galaxies
- They must be among the most powerful explosions in the universe—could be the formation of a black hole

# What causes gamma-ray bursts?



# Supernovae and Gamma-Ray Bursts




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

# What have we learned?

- Where do gamma-ray bursts come from?
  - Most gamma-ray bursts come from distant galaxies
  - They must be among the most powerful explosions in the universe, probably signifying the formation of black holes
- What causes gamma-ray bursts?
  - At least some gamma-ray bursts come from supernova explosions