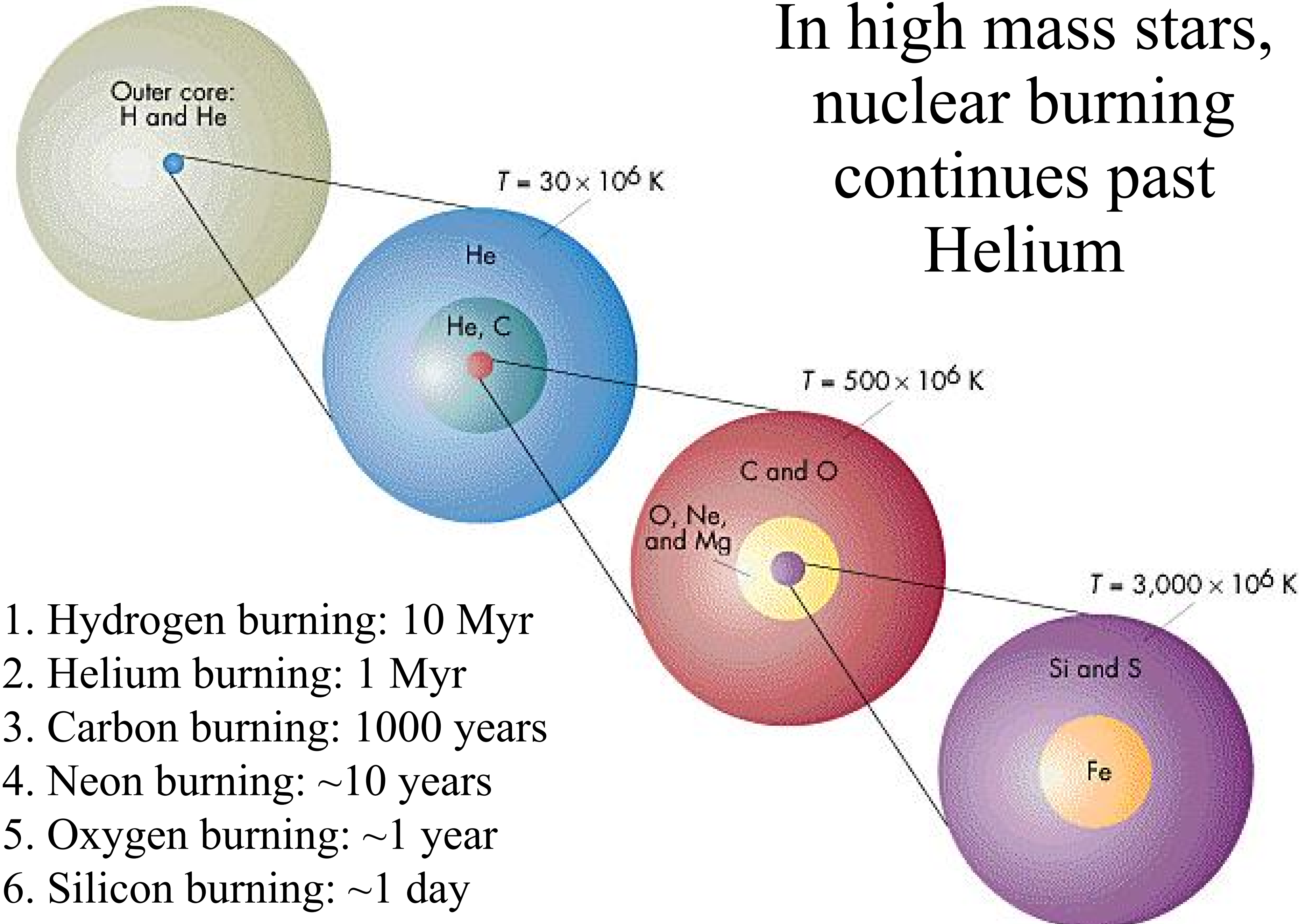
Deaths of stars

- Evolution of high mass stars
- Where were the elements in your body made?

- Stellar remnants
- Degenerate gases
- White dwarfs
- Neutron stars

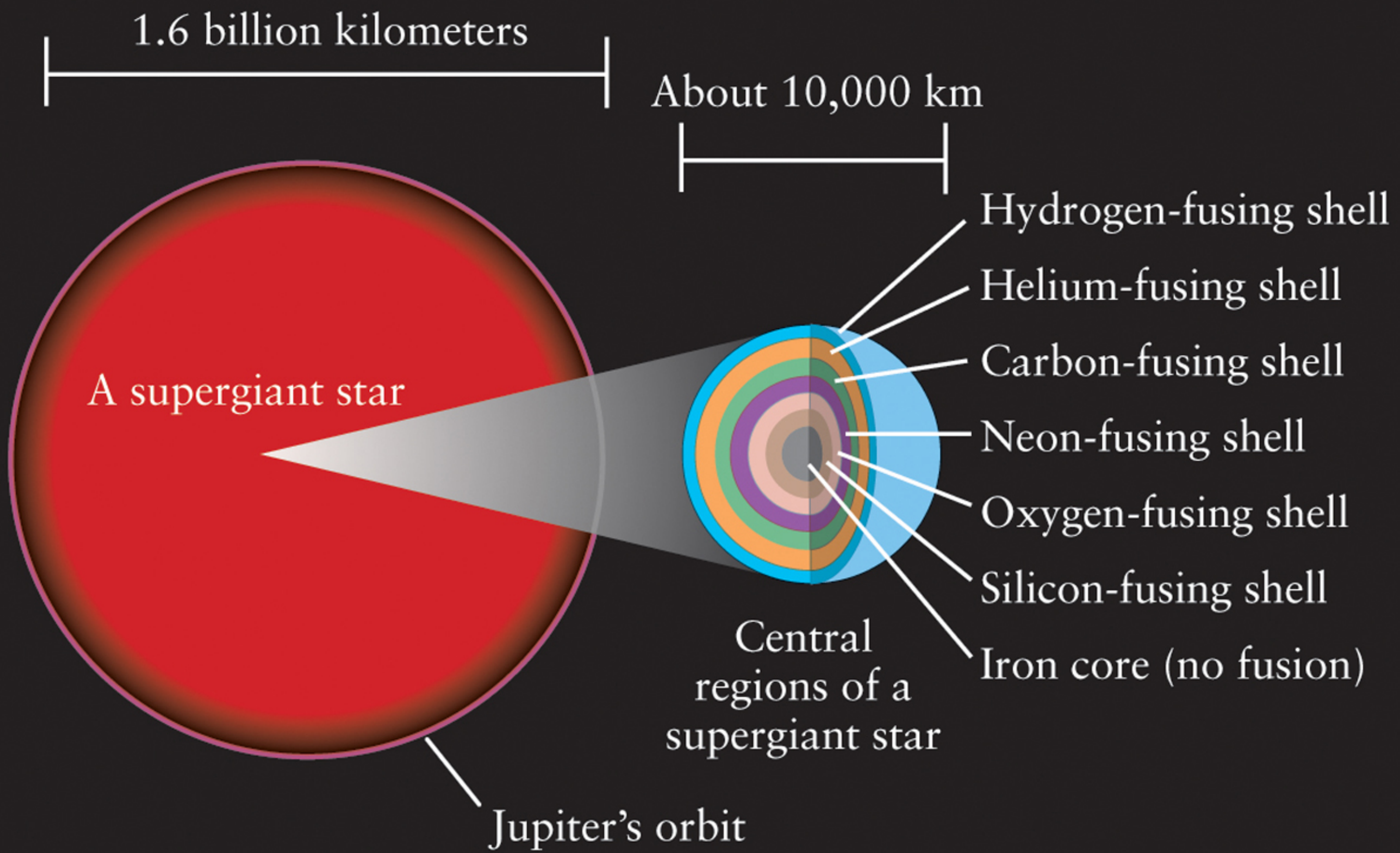
In high mass stars, nuclear burning continues past Helium



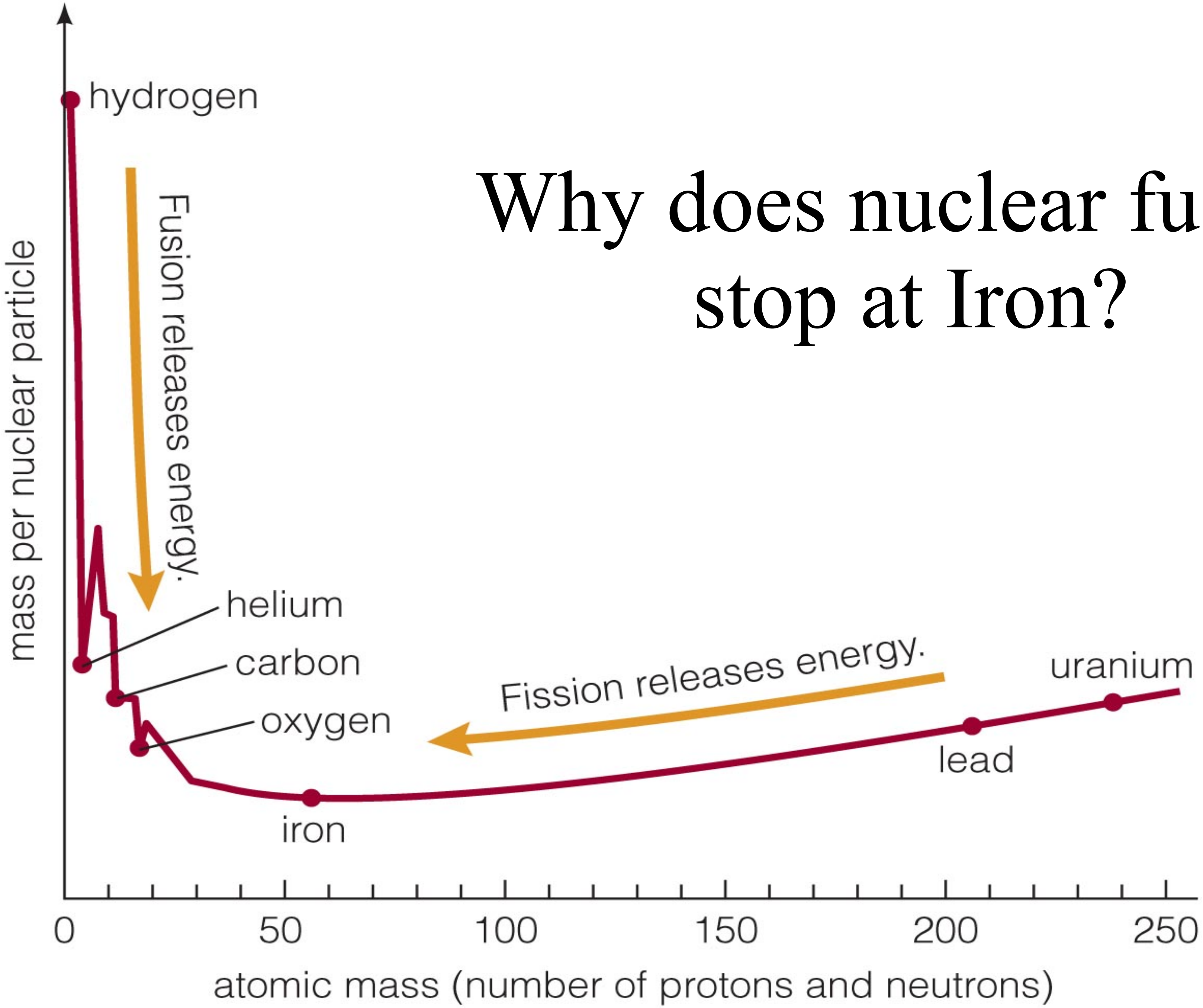
1. Hydrogen burning: 10 Myr
2. Helium burning: 1 Myr
3. Carbon burning: 1000 years
4. Neon burning: ~10 years
5. Oxygen burning: ~1 year
6. Silicon burning: ~1 day

Finally builds up an inert Iron core

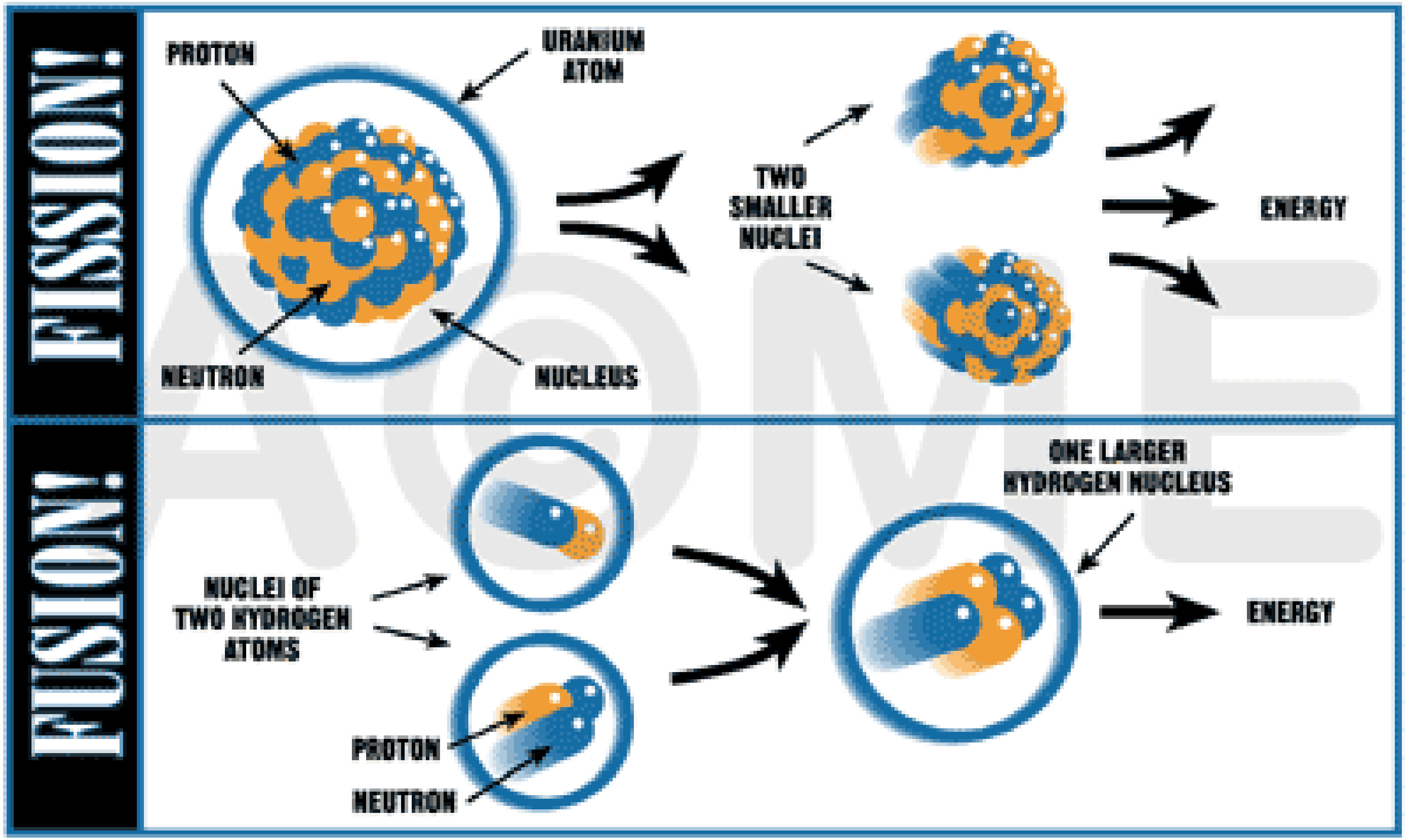
Structure of an Old High-Mass Star

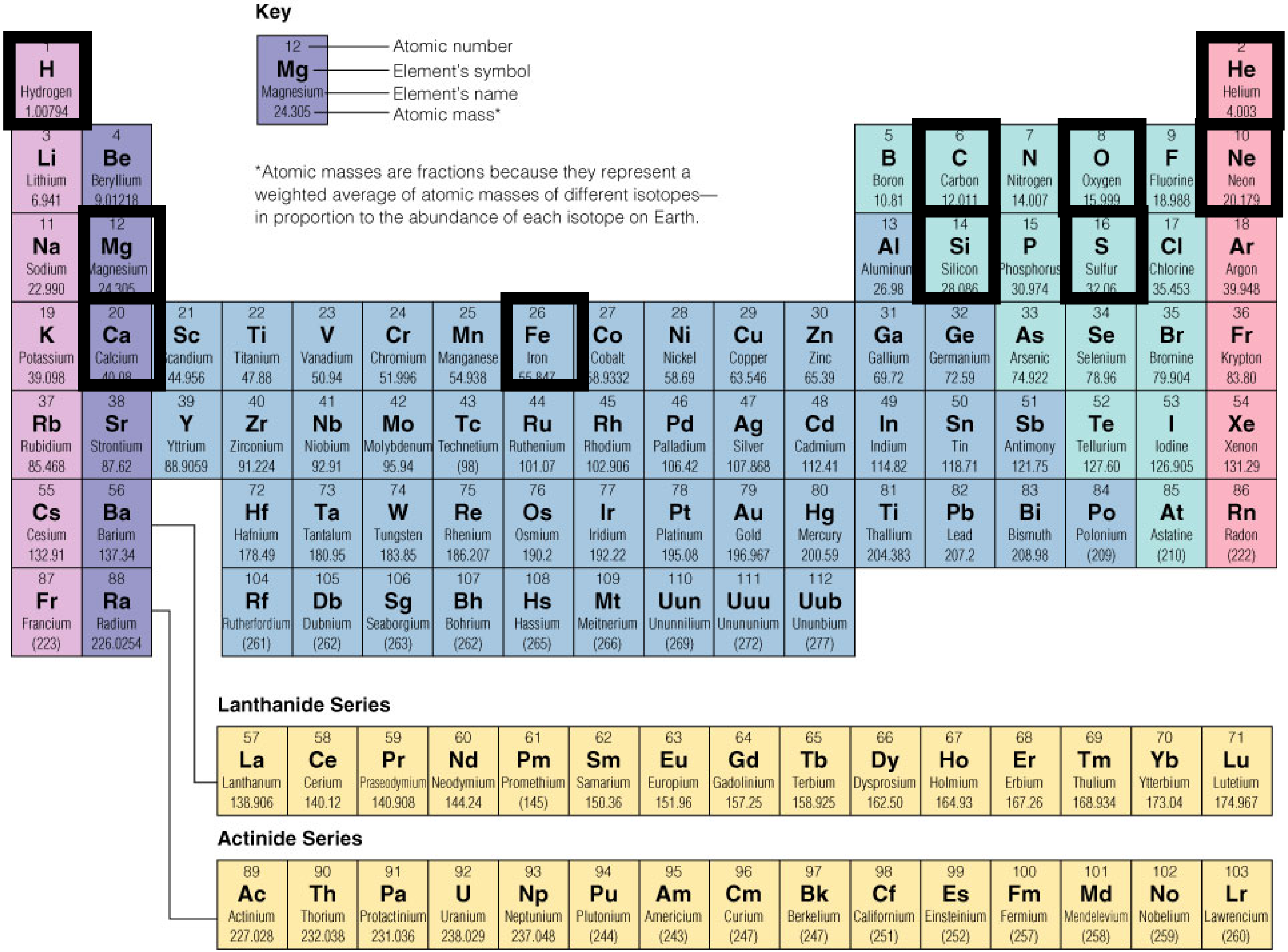


Why does nuclear fusion stop at Iron?



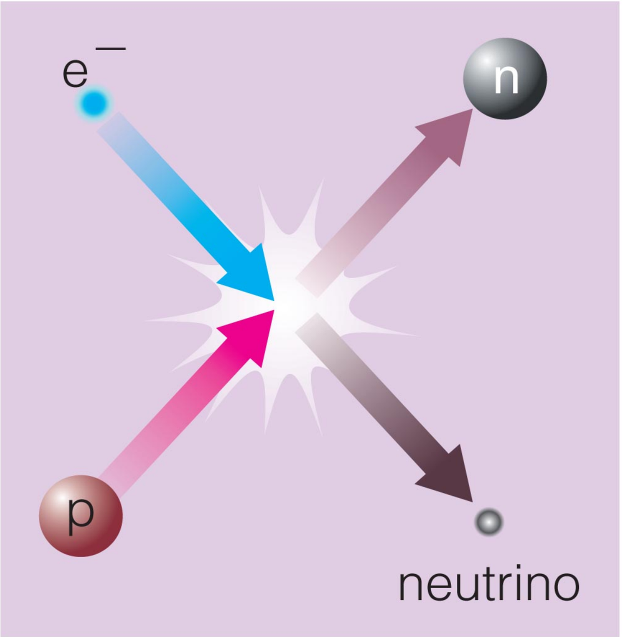
Fusion versus Fission





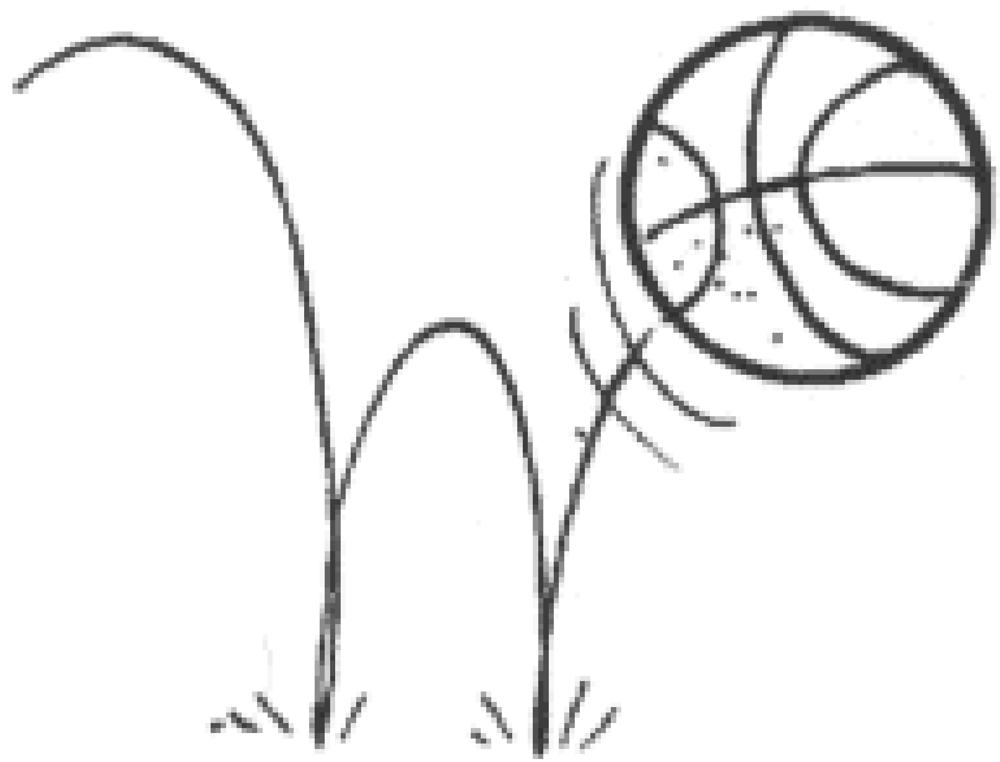
Fusion in massive stars makes elements like Ne, Si, S, Ca, Fe

Core collapse

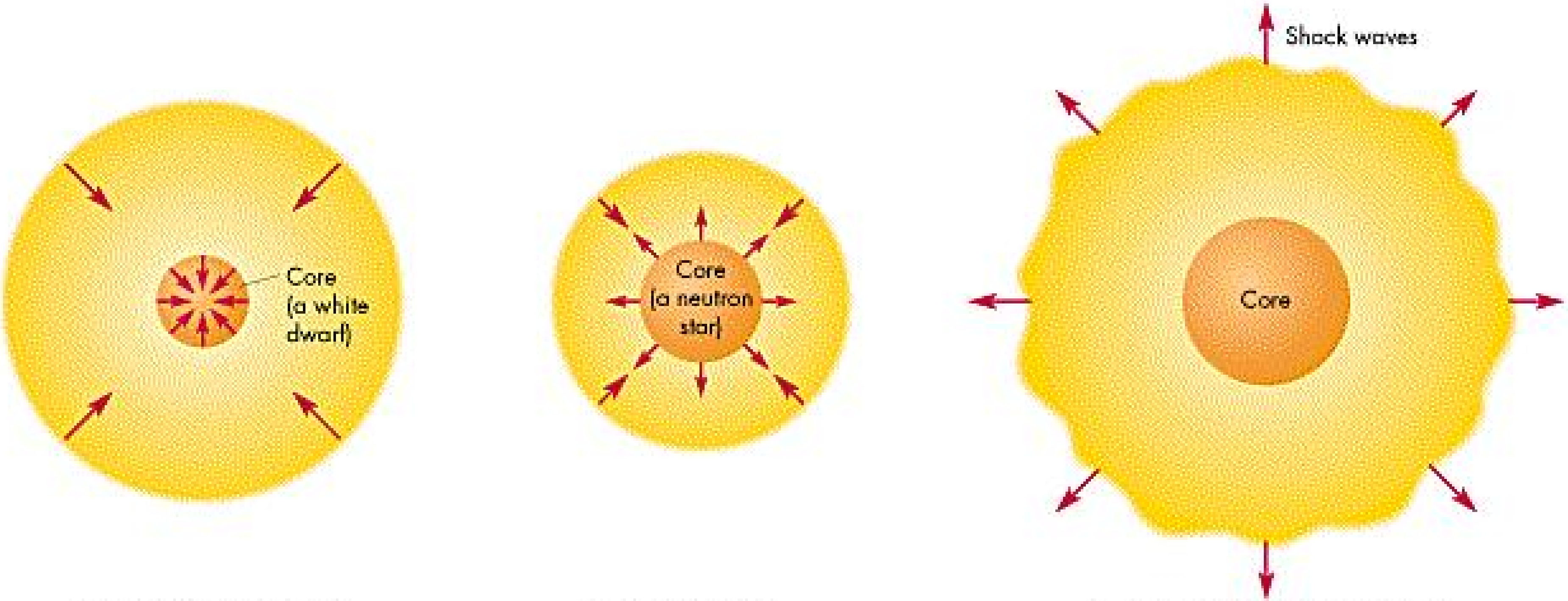


- Iron core is degenerate
- Core grows until it is too heavy to support itself
- Core collapses, density increases, normal iron nuclei are converted into neutrons with the emission of neutrinos
- Core collapse stops, neutron star is formed
- Rest of the star collapses in on the core, but bounces off the new neutron star

If I drop a ball, will it bounce higher than it began?



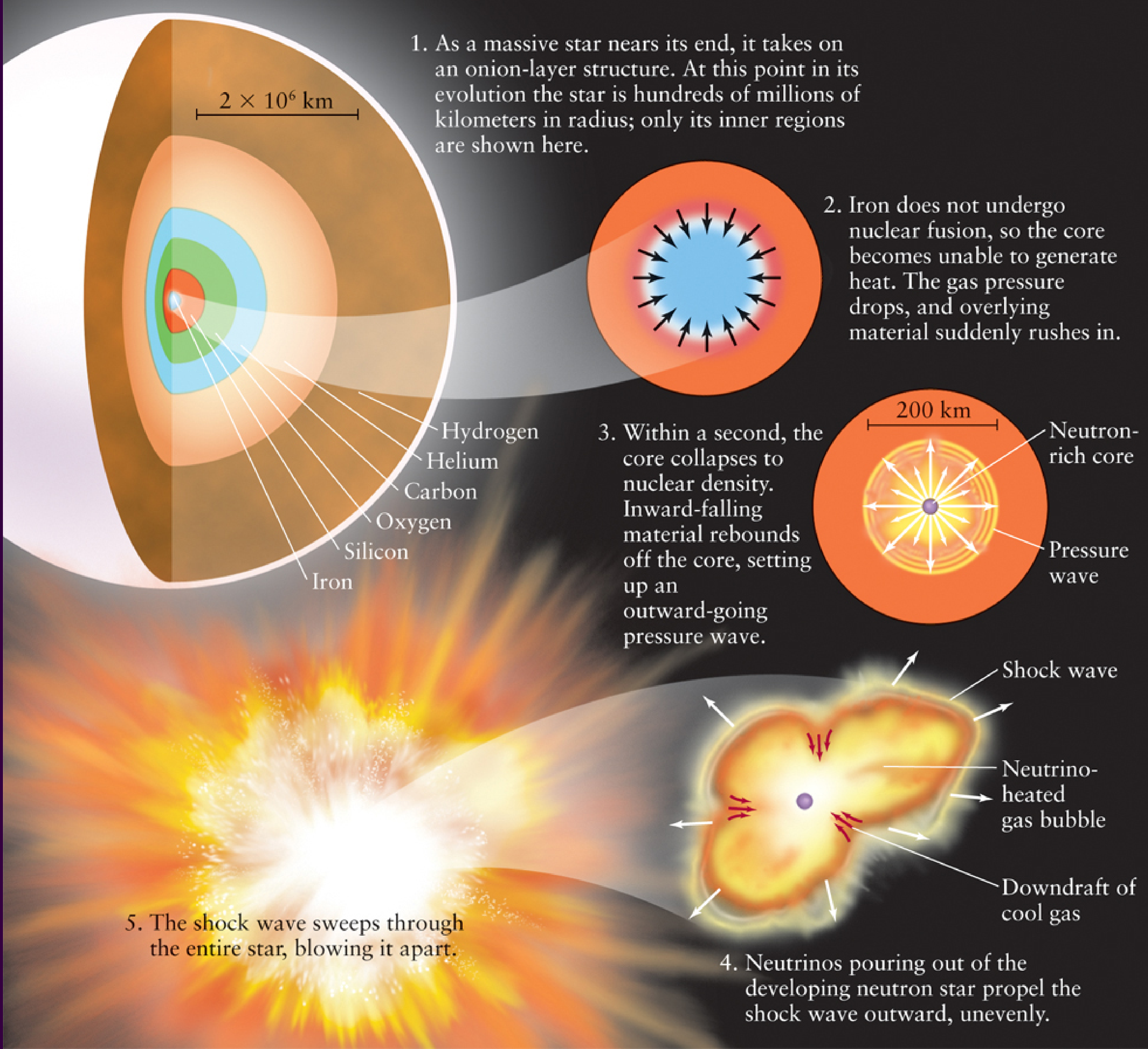
Supernova explosion



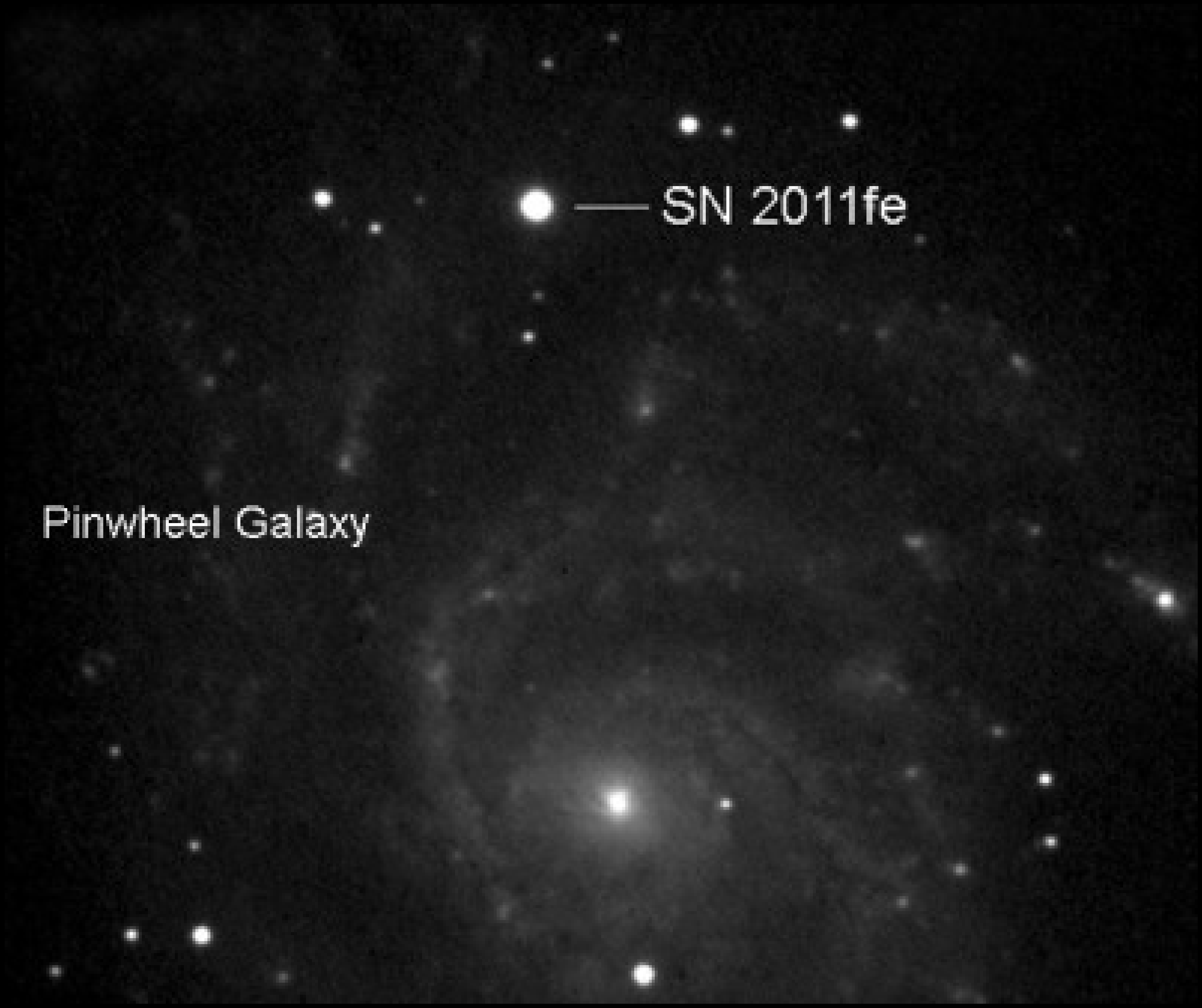
A Step 1: The iron core of the red giant collapses

B Step 2: Neutron-rich core rebounds

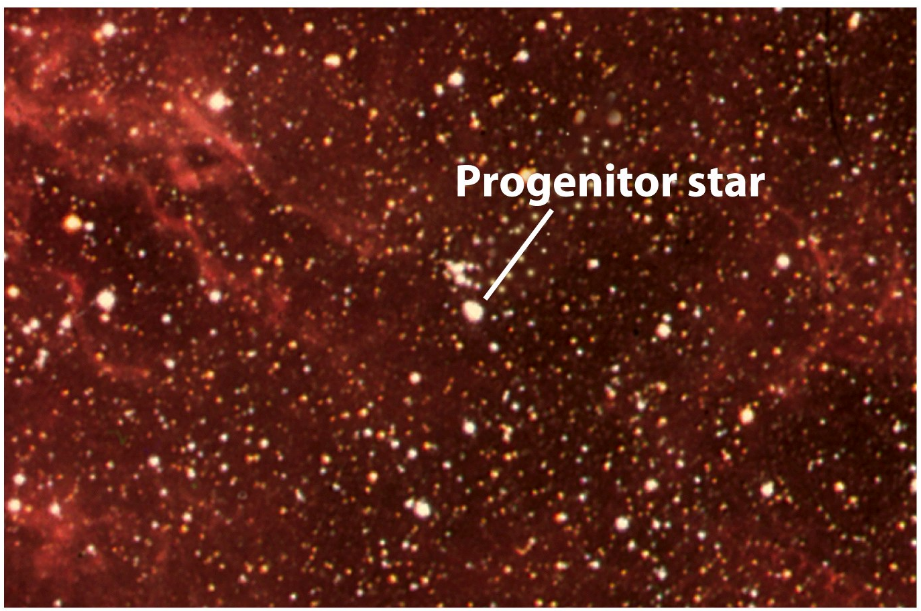
C Step 3: The shock wave moves outward through the star


1. As a massive star nears its end, it takes on an onion-layer structure. At this point in its evolution the star is hundreds of millions of kilometers in radius; only its inner regions are shown here.
2 × 10⁶ km
Hydrogen
Helium
Carbon
Oxygen
Silicon
Iron
2. Iron does not undergo nuclear fusion, so the core becomes unable to generate heat. The gas pressure drops, and overlying material suddenly rushes in.
3. Within a second, the core collapses to nuclear density. Inward-falling material rebounds off the core, setting up an outward-going pressure wave.
200 km
Neutron-rich core
Pressure wave
Shock wave
Neutrino-heated gas bubble
Downdraft of cool gas
4. Neutrinos pouring out of the developing neutron star propel the shock wave outward, unevenly.
5. The shock wave sweeps through the entire star, blowing it apart.

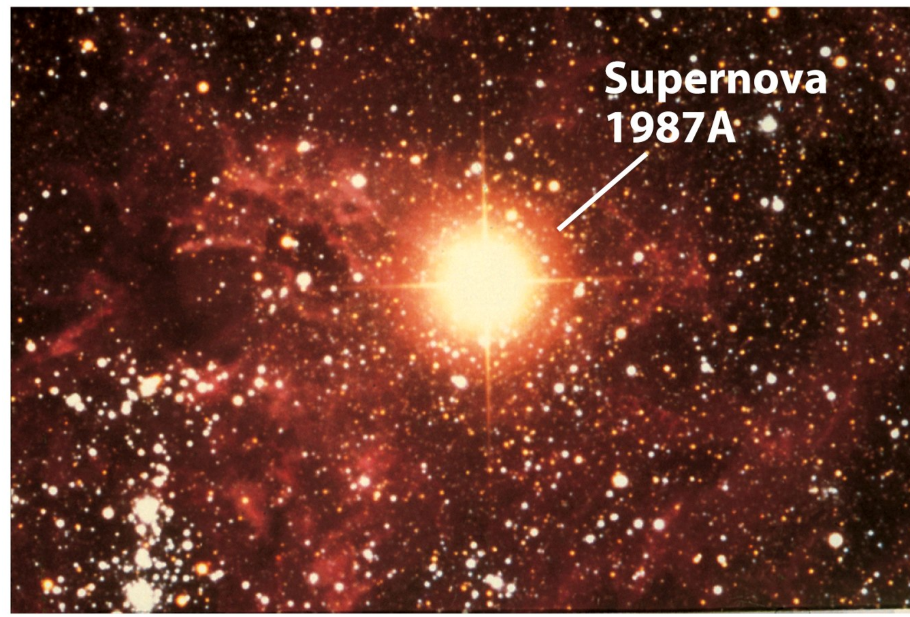
SN 2011fe in M101 (Pinwheel)



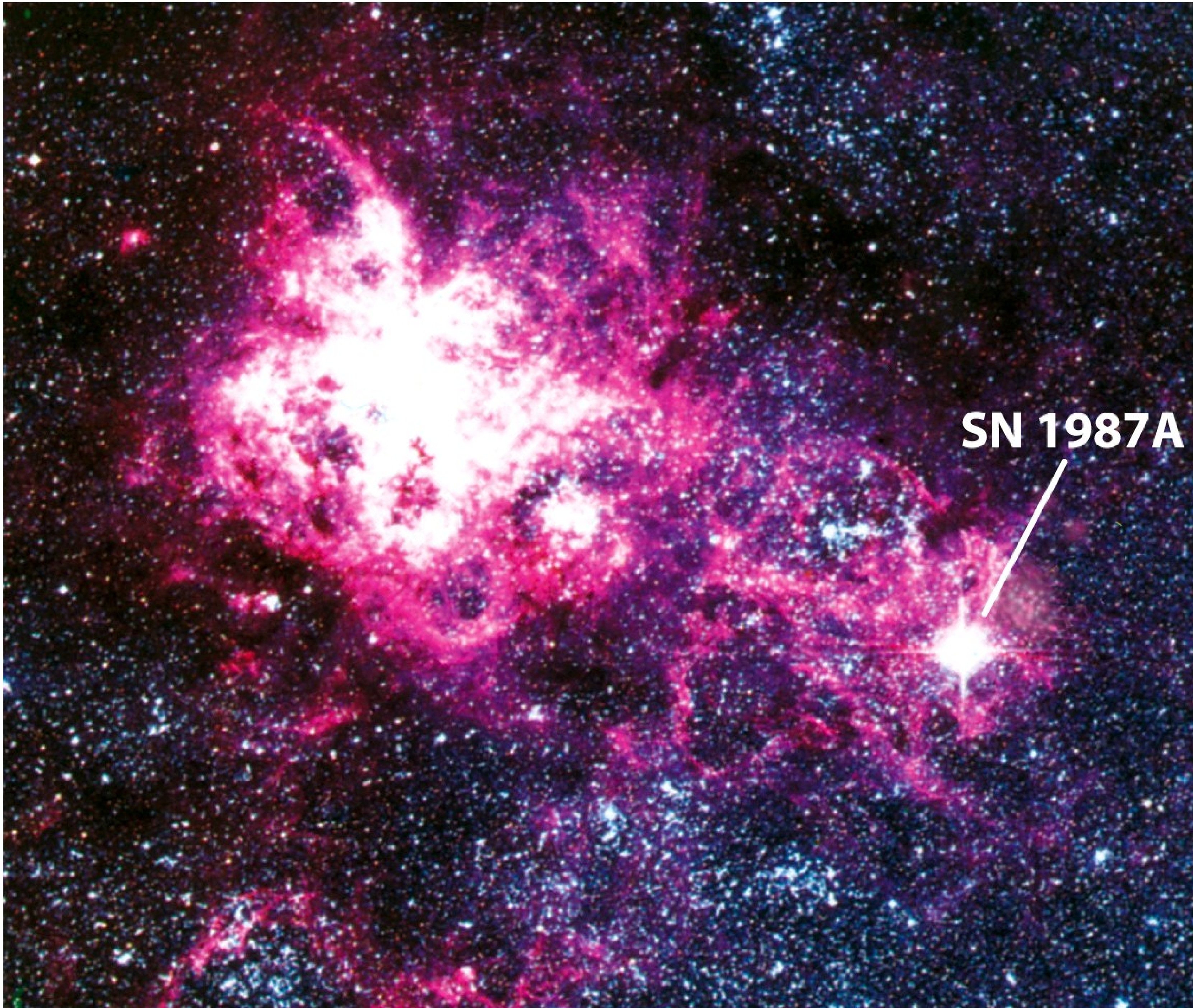
In 1987 a nearby supernova gave us a close-up look at the death of a massive star



Before the star exploded

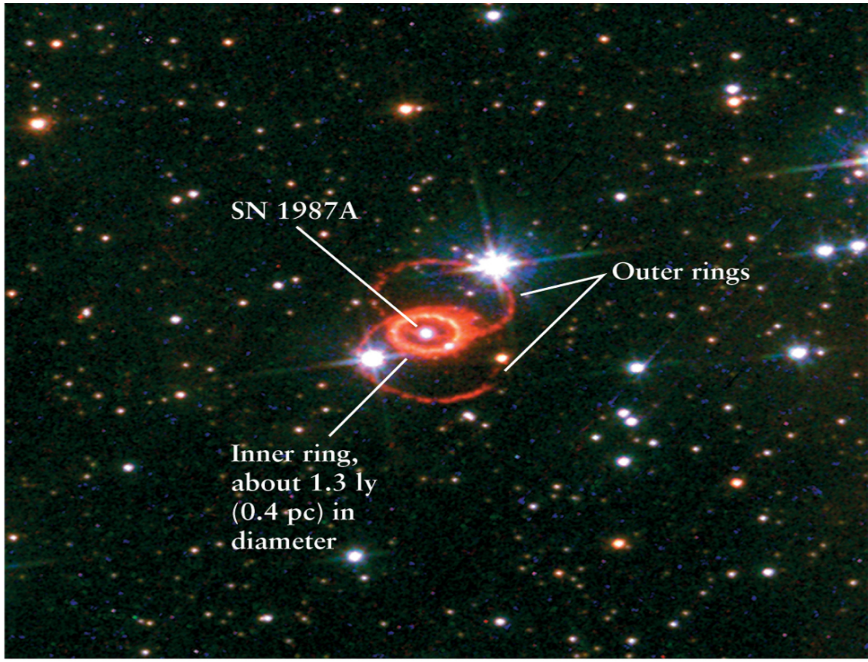


After the star exploded

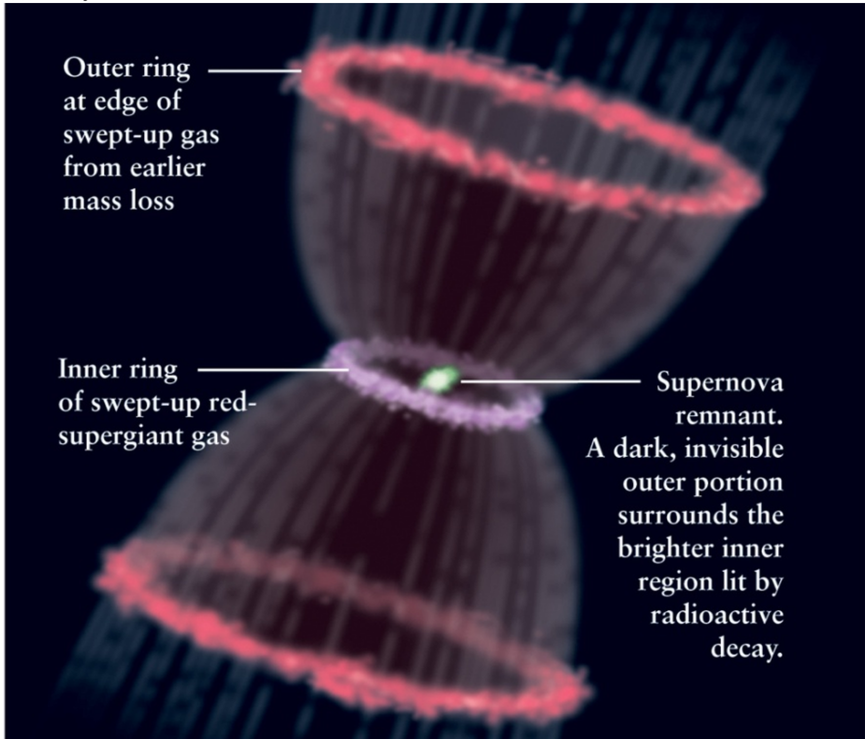

SN 1987A

An Unusual Supernova

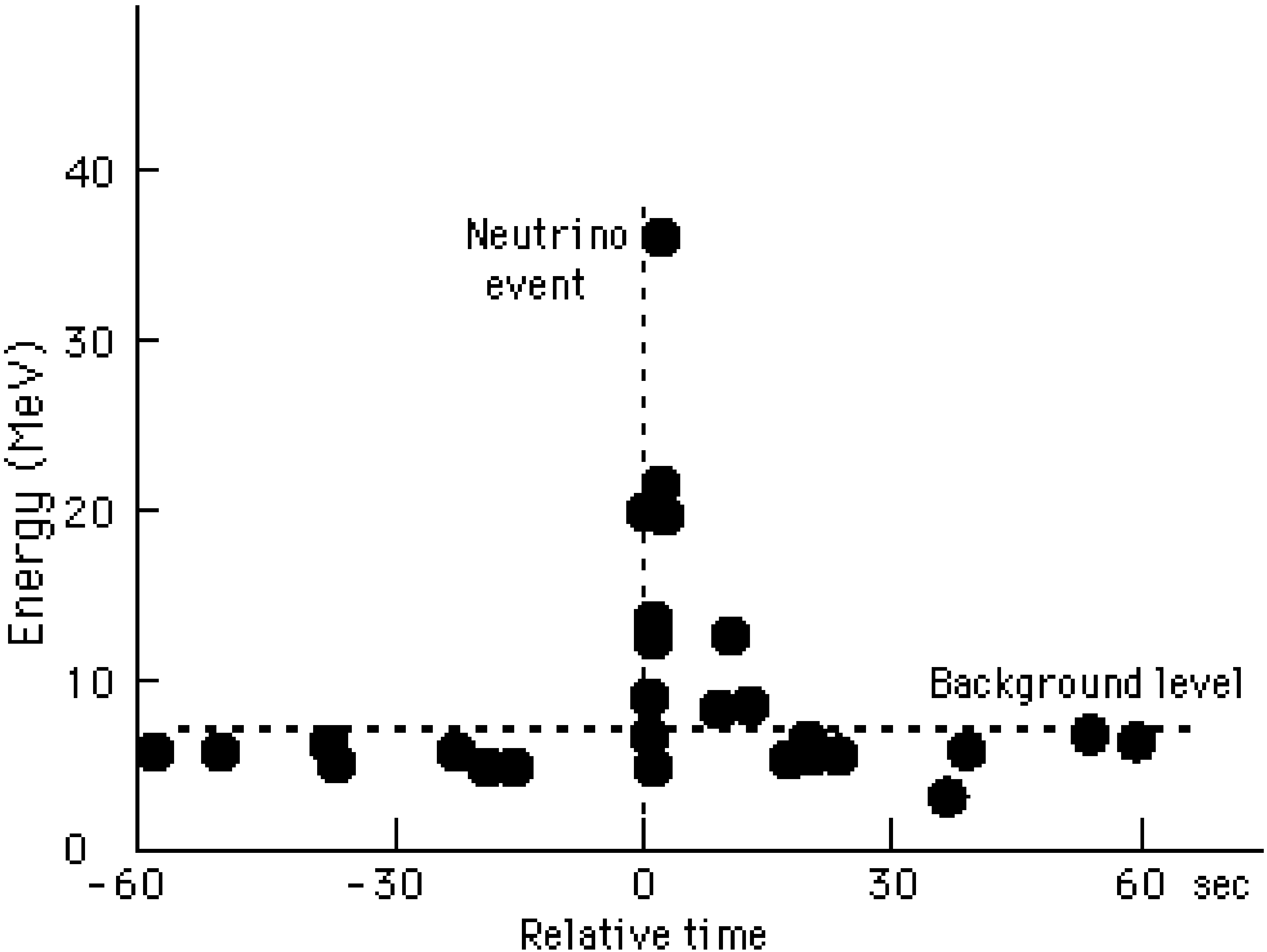
- SN 1987A appears to have a set of three glowing rings
- Relics of a hydrogen-rich outer atmosphere, ejected by gentle stellar winds from the star when it was a red supergiant.
- The gas expanded in a hourglass shape because it was blocked from expanding around the star's equator either by a preexisting ring of gas or by the orbit of an as-yet- unseen companion star.
- These rings were ionized by the initial flash of ultraviolet radiation from the supernova.



(a) Supernova 1987A seen in 1996



Neutrinos from SN1987A



Historical Supernovae

- Historically, supernovae were recorded as “guest stars”
- The supernova that produced the “Crab” pulsar went off in 1054 AD and was brighter than Venus. It was recorded by Arab, Chinese, and Japanese astronomers.
- This Anasazi drawing dates from around 1054 AD.

The Crab Nebula in Taurus (VLT KUEYEN + FORS2)

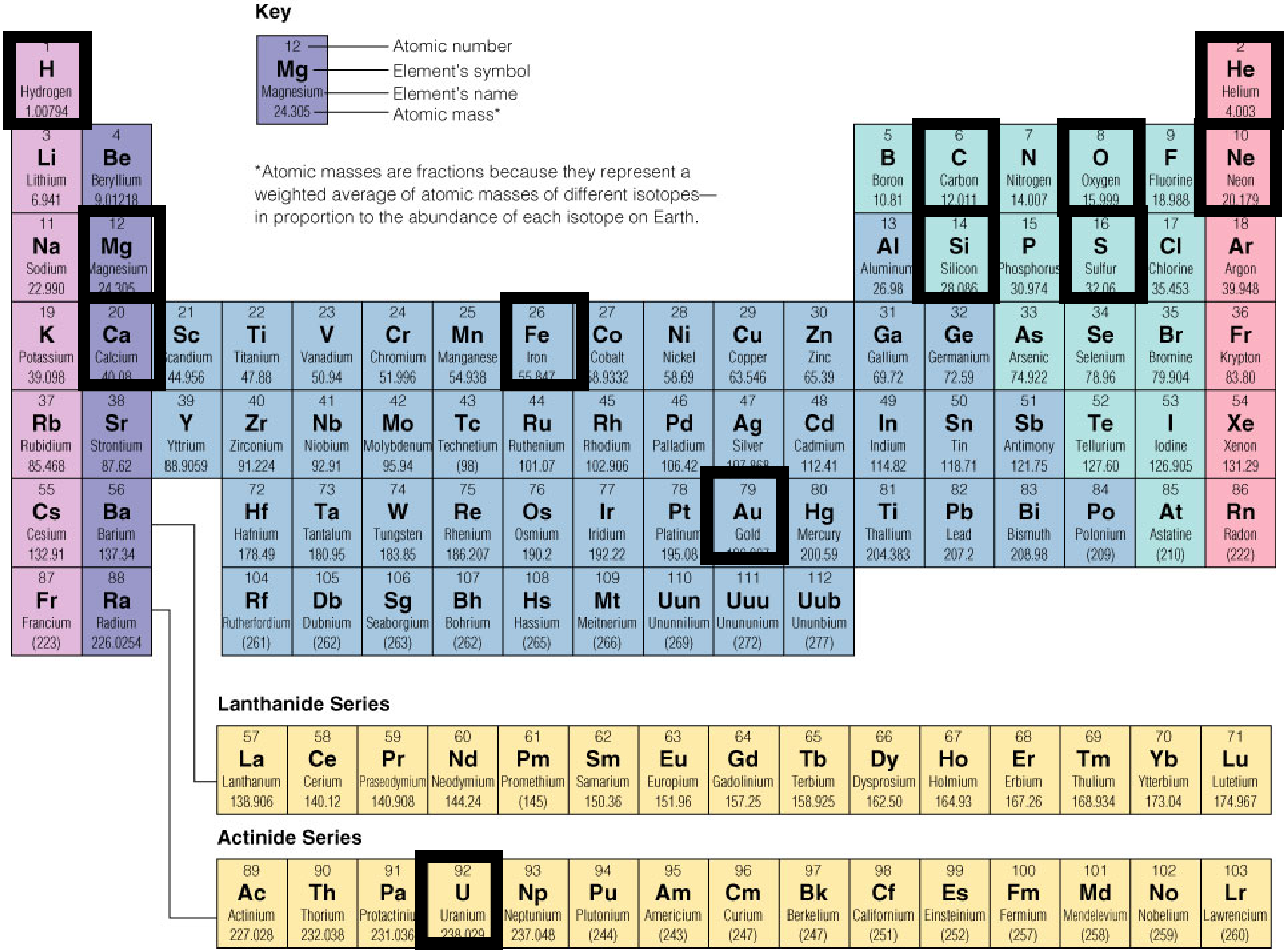
ESO PR Photo 40f/99 (17 November 1999)

Nearby Supernova

- The Gum Nebula exploded around 9000 B.C.
- At maximum brilliance, the exploding star probably was as bright as the first-quarter moon.

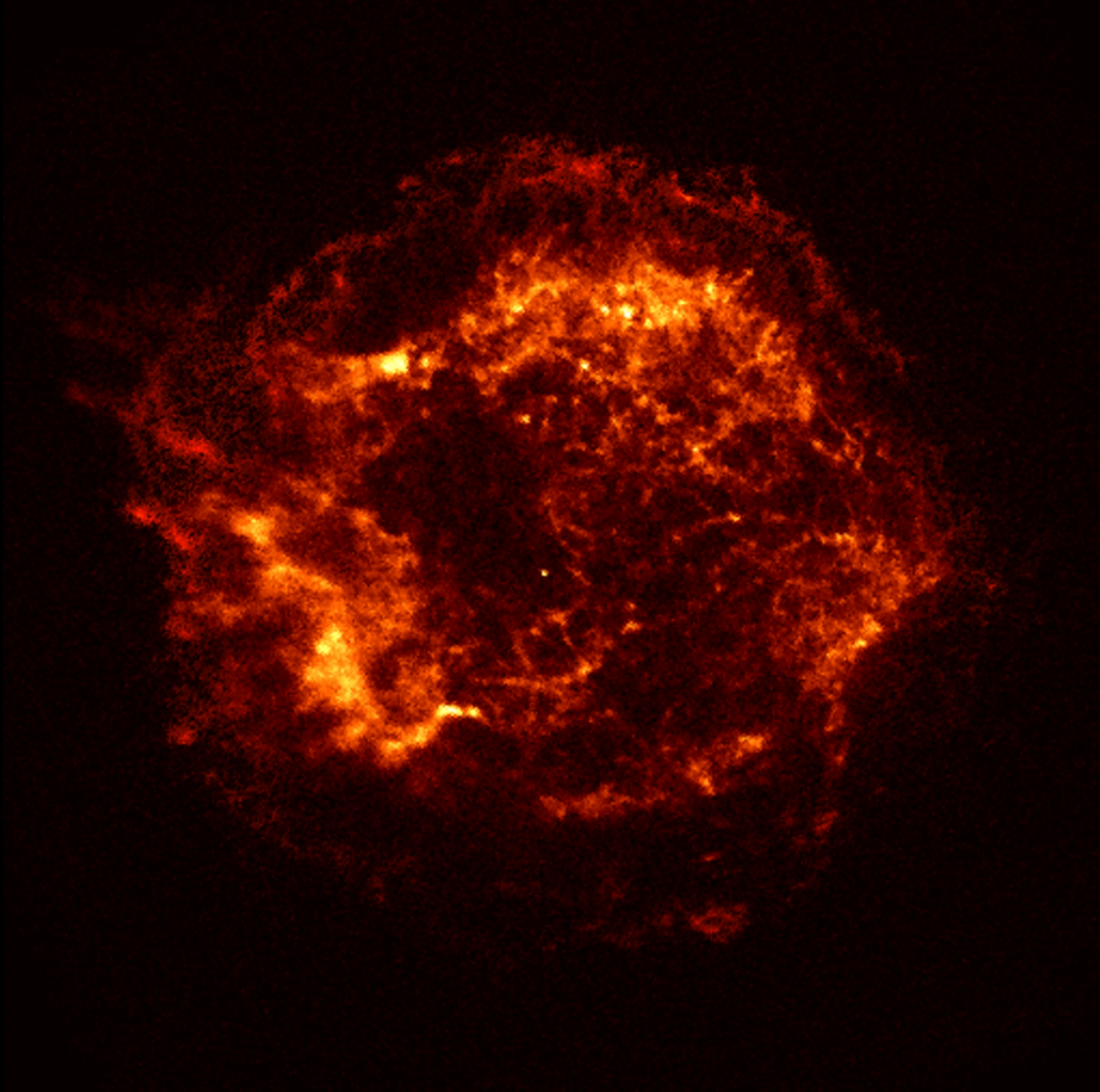
Where do the elements in your body come from?

- Solar mass star produce elements up to Carbon and Oxygen – these are ejected into planetary nebula and then recycled into new stars and planets
- Supernova produce all of the heavier elements
  - Elements up to Iron can be produced by fusion
  - Elements heavier than Iron are produced by the neutrons and neutrinos interacting with nuclei in the supernova explosion



Energy and neutrons in supernova form heavy elements.

Decay of radioactive elements powers supernova after explosion.



How does the life of a high mass star differ from the Sun's life?

A) It forms much faster

B) It lives a shorter time on the main sequence

C) It makes elements heavier than carbon via fusion

D) When it dies it explodes in a tremendous supernova explosion

E) All of the above

The most massive stars end all fusion with a core composed of

A) carbon
B) neon
C) iron
D) silicon
E) sulfur

How long does the neon fusion stage last in a one solar mass star?

A) 1 year

B) 10 years

C) 1000 years

D) A one solar mass star never fuses neon

After the initial explosion of a massive star, how does a supernova continue to radiate?

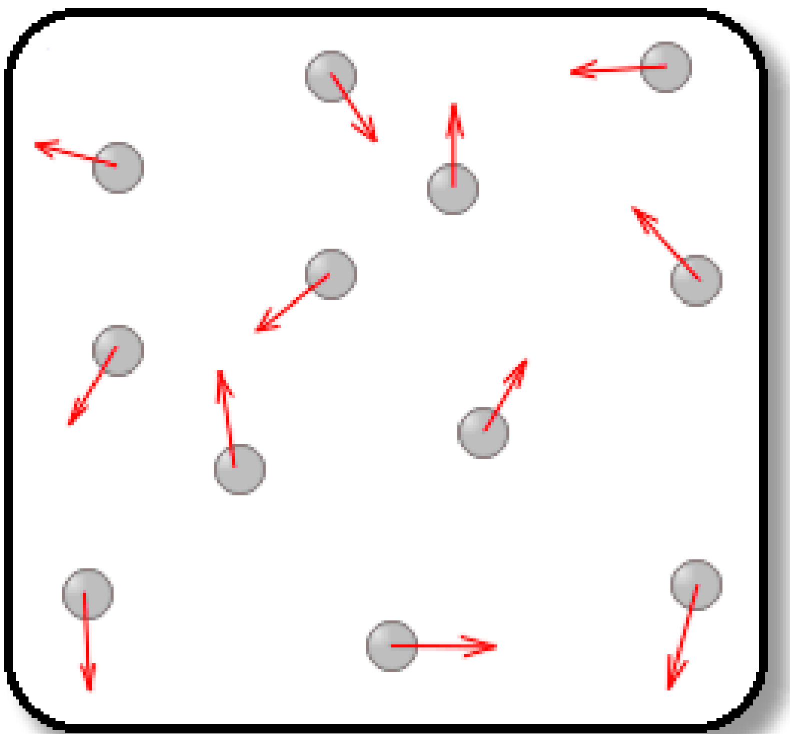
A) High-speed winds from the core remains ionize the ejected material.

B) High-energy radiation is emitted from the core remains due to its high temperature.

C) Unstable elements created in the explosion radioactively decay and emit gamma rays.

Pressure and Temperature

- Pressure is the force exerted by atoms in a gas
- Temperature is a measure of how fast the atoms in a gas move



- Hotter → atoms move faster → higher pressure
- Cooler → atoms move slower → lower pressure

Do cold balloon demo

Degenerate gas

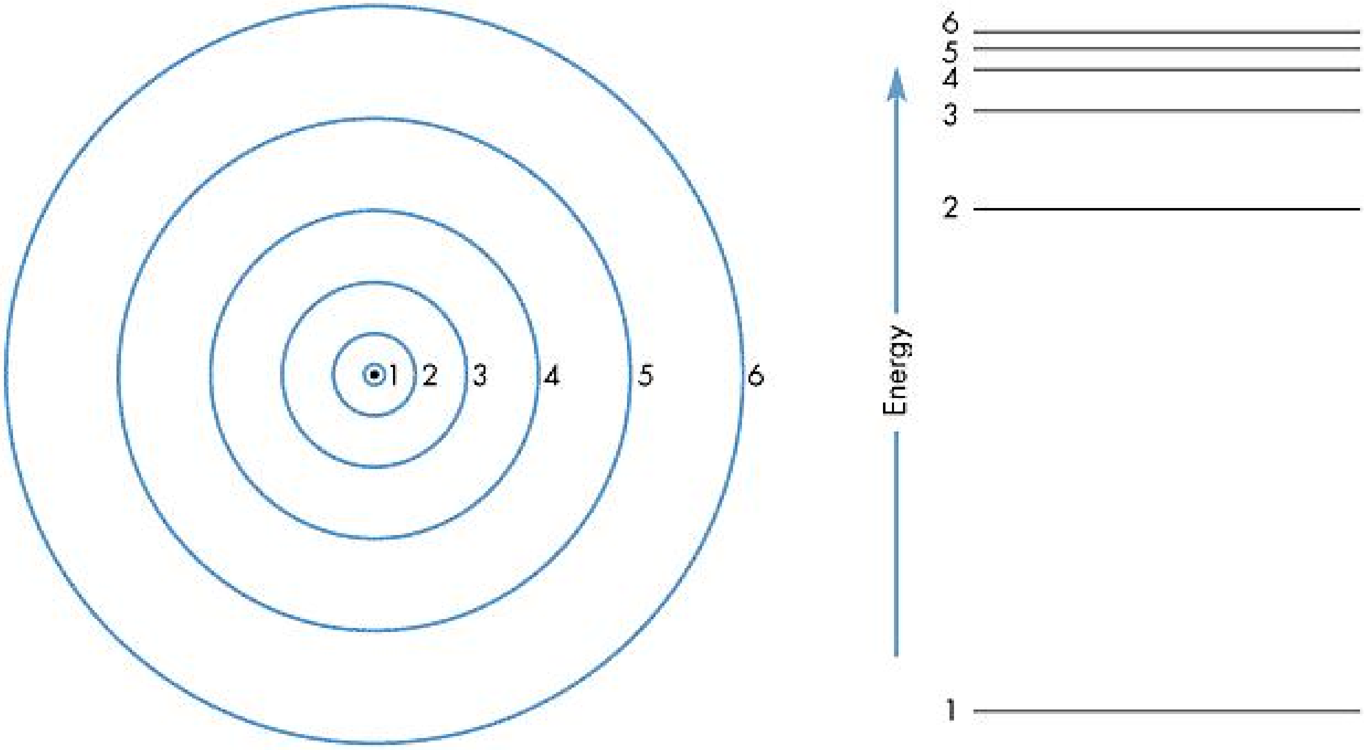
- Very high density
- Motion of atoms is not due to kinetic energy, but instead due to quantum mechanical motions
- Pressure no longer depends on temperature

- This type of gas is sometimes found in the cores of stars

Pauli exclusion principle

- No two electrons can occupy the same quantum state

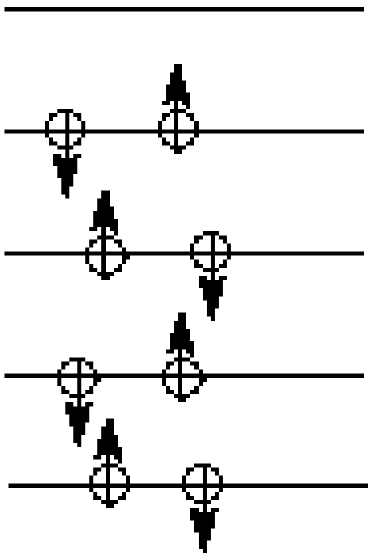
Electron orbits



A Possible distances of the electron in a hydrogen atom **B** Energy levels for the hydrogen atom

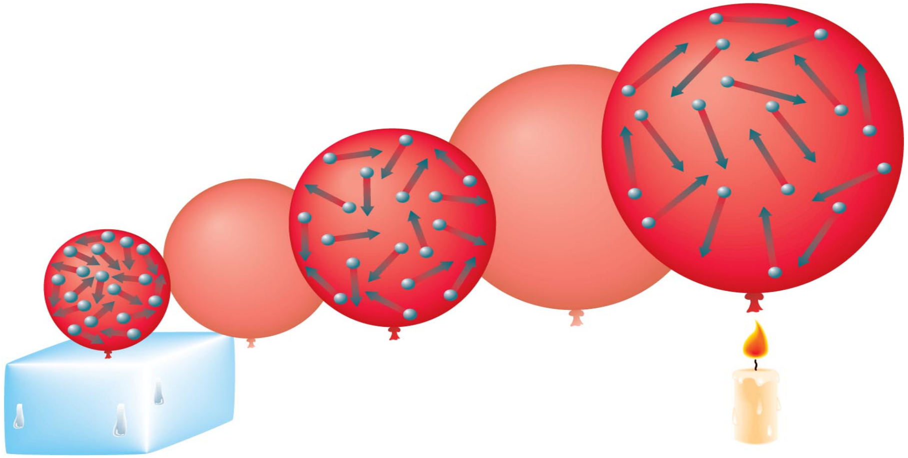
Only two electrons (one up, one down) can go into each energy level

Electron energy levels



Degenerate gas: all lower energy levels filled with two particles each (opposite spins). Particles **locked** in place.

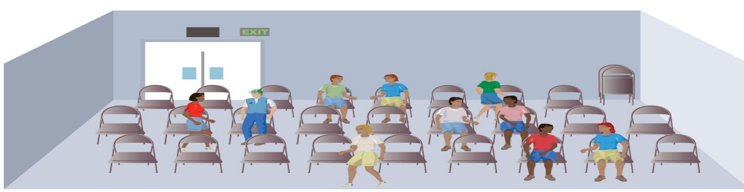
- Only two electrons (one up, one down) can go into each energy level.
- In a degenerate gas, all low energy levels are filled.
- Electrons have energy, and therefore are in motion and exert pressure even if temperature is zero.



Thermal Pressure:

Depends on heat content

The main form of pressure in most stars



a When there are many more available quantum states (chairs) than electrons (people), an electron is unlikely to try to enter the same state as another electron. The only pressure comes from the temperature-related motion of the electrons, which is the thermal pressure.

b When the number of electrons (people) approaches the number of available quantum states (chairs), finding an available state requires that the electrons move faster than they would otherwise. This extra motion creates degeneracy pressure.

Degeneracy Pressure:

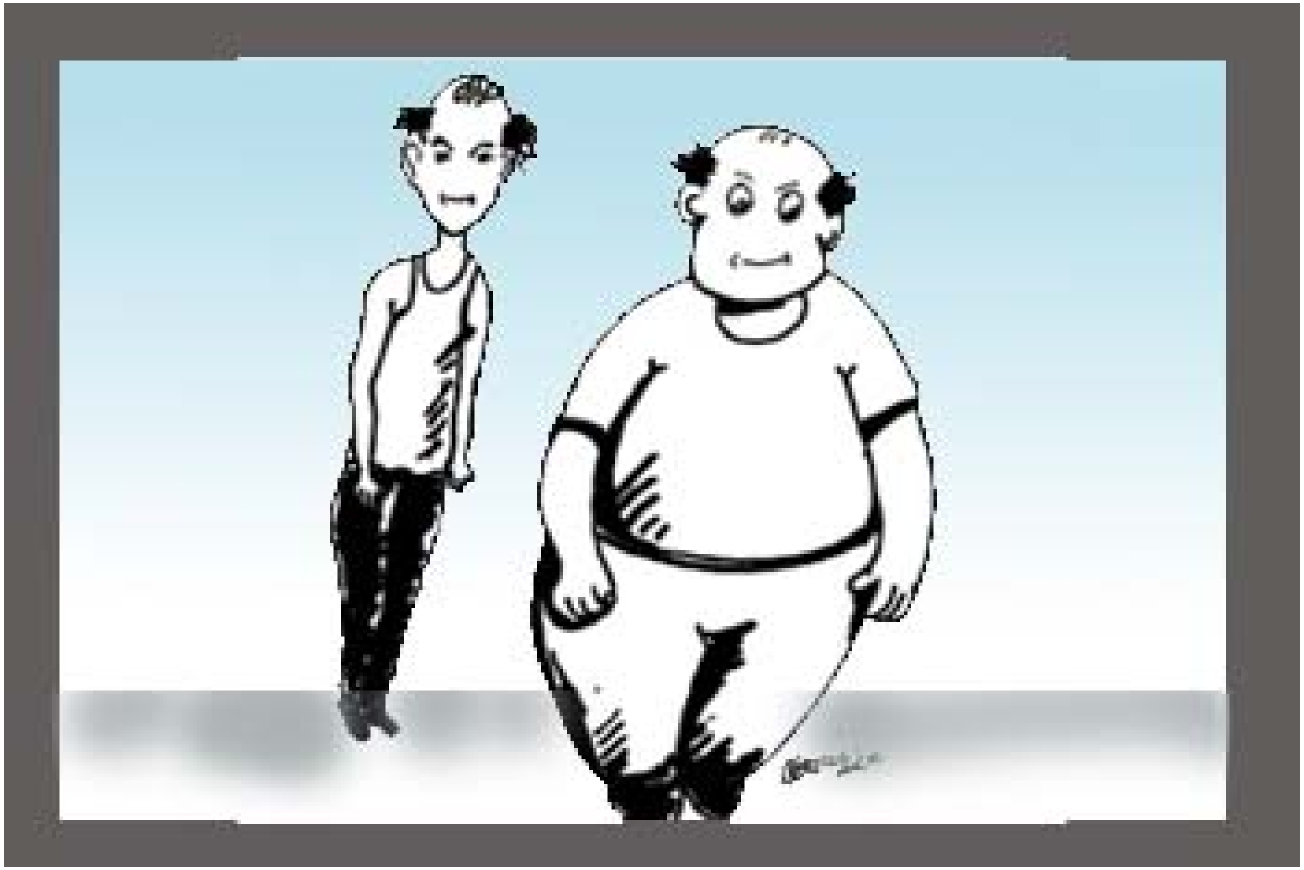
Particles can’t be in same state in same place

Doesn’t depend on heat content

White dwarf

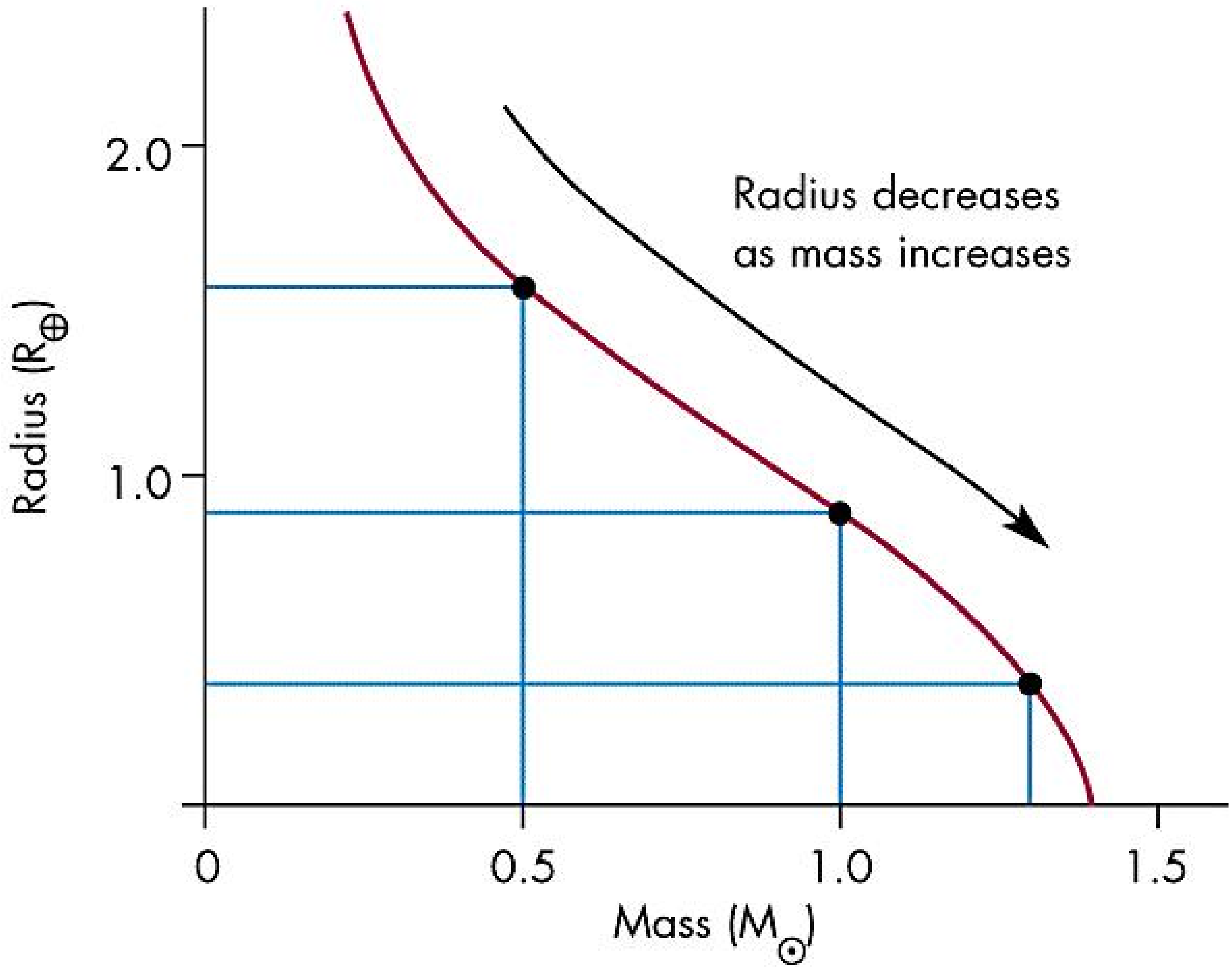
- Core of solar mass star
- Degenerate gas of oxygen and carbon
- No energy from fusion or gravitational contraction

Mass versus radius relation



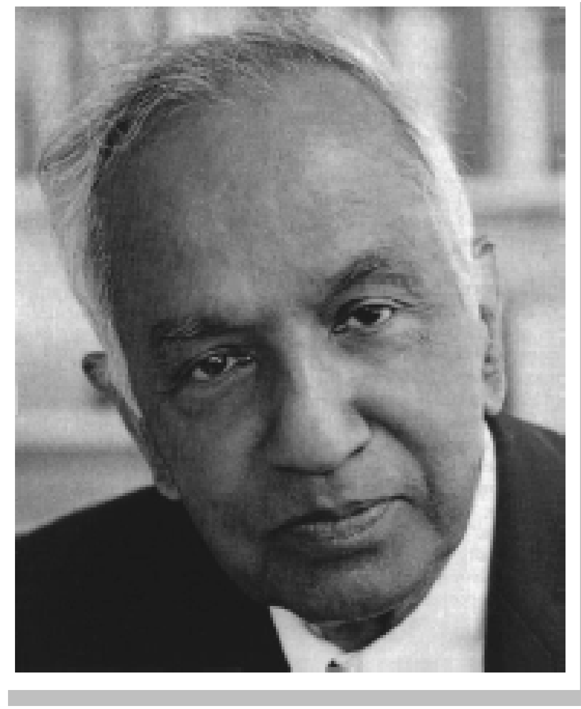
- For objects made of normal matter, radius tends to increase with mass

Mass versus radius relation



Maximum white dwarf mass

- Electron degeneracy cannot support a white dwarf heavier than 1.4 solar masses
- This is the "Chandrasekhar limit"
- Won Chandrasekhar the 1983 Nobel prize in Physics



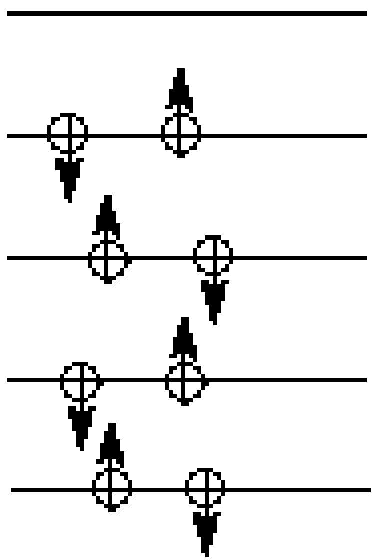
What happens to a star more massive than 1.4 solar masses?

A) There aren’t any
B) They shrink to zero size
C) They explode
D) They become something else

Neutron Stars

- Degenerate stars heavier than 1.4 solar masses collapse to become neutron stars
- Formed in supernova explosions
- Electrons are not separate
  - Combine with nuclei to form neutrons
- Neutron stars are degenerate gas of neutrons

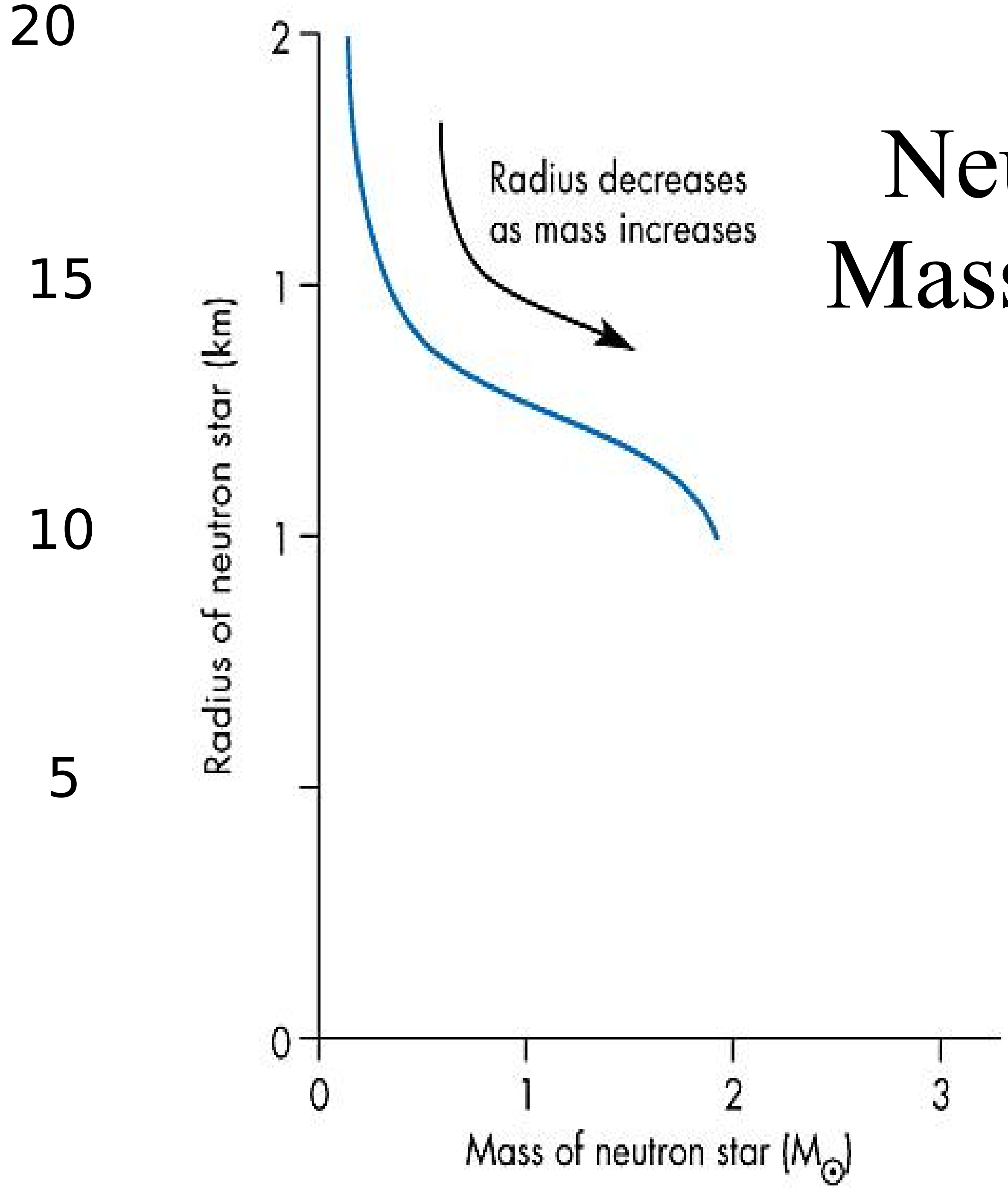
Neutron energy levels



Degenerate gas: all lower energy levels filled with two particles each (opposite spins). Particles **locked** in place.

- Only two neutrons (one up, one down) can go into each energy level.
- In a degenerate gas, all low energy levels are filled.
- Neutrons have energy, and therefore are in motion and exert pressure even if temperature is zero.
- Neutron star are supported by neutron degeneracy.

Neutron Star Mass vs Radius

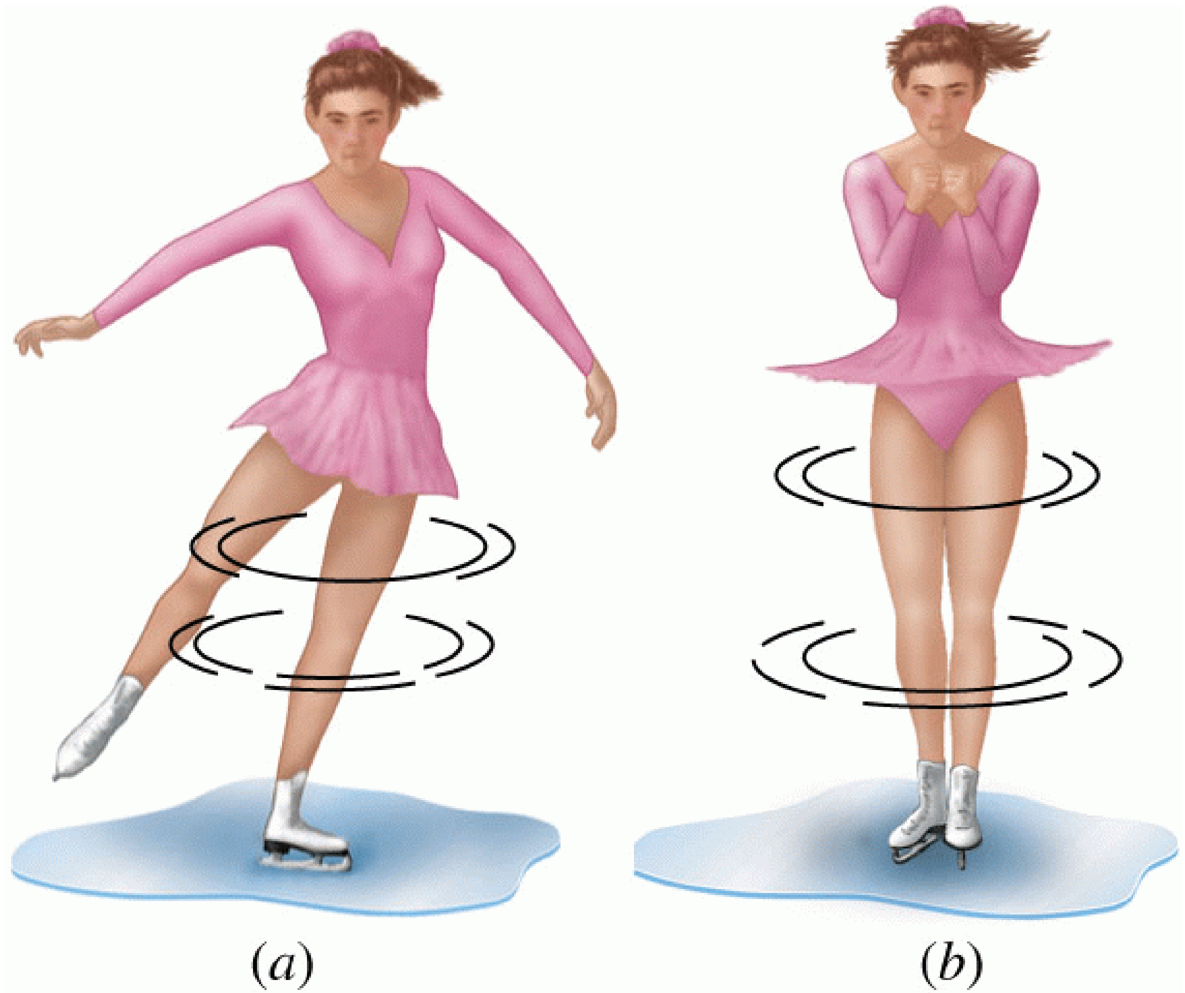


Neutron Stars

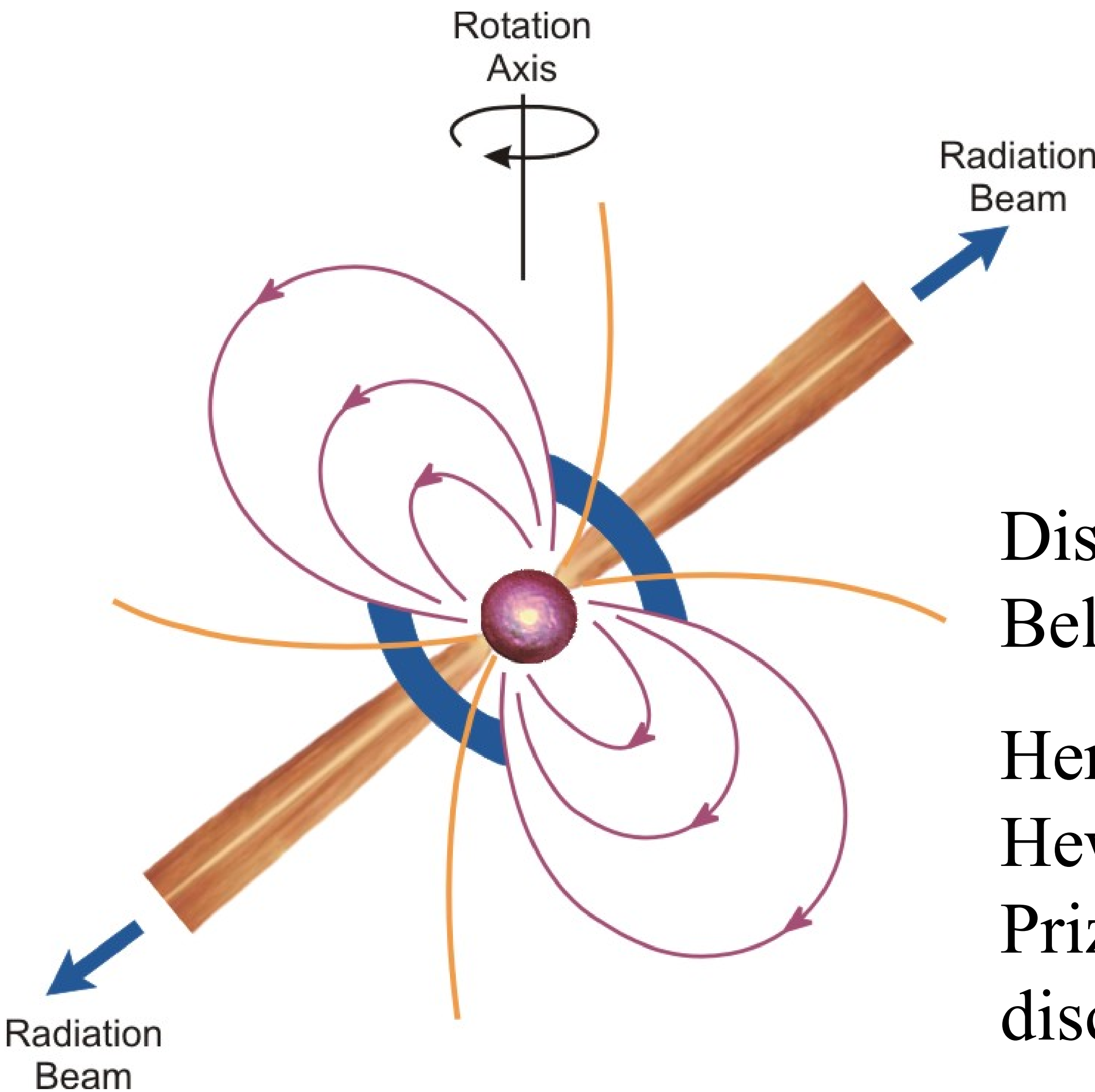
- Very compact – about 10 km radius
- Very dense – one teaspoon of neutron star material weighs as much as all the buildings in Manhattan
- Spin rapidly – as fast as 600 times per second
- High magnetic fields – compressed from magnetic field of progenitor star

Spin up of neutron star

Collapse of star increases both spin and magnetic field



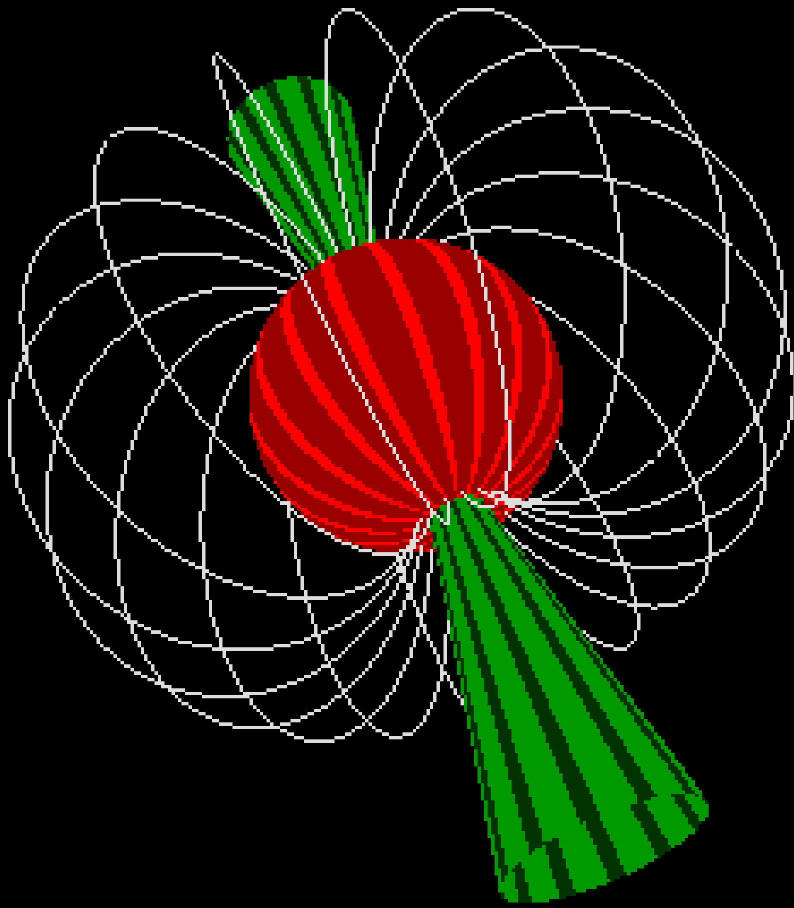
Pulsars



Discovered by Jocelyn Bell in 1967.

Her advisor, Anthony Hewish, won the Nobel Prize in Physics for the discovery in 1974.

Pulsars

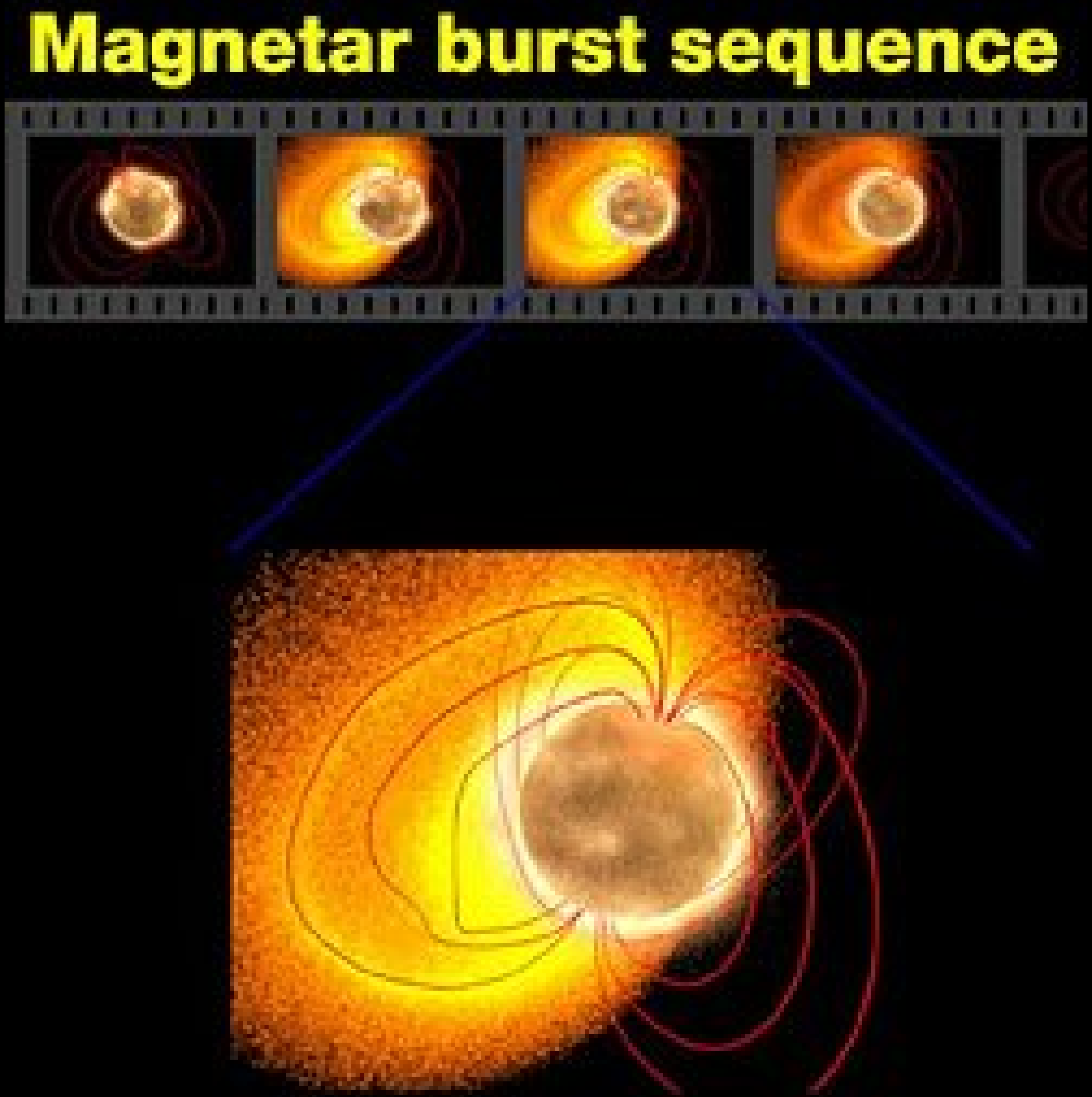


Energy source is spin down of neutron star.

Must lie along pulsar beam to see pulsed signals.

Crab Pulsar

Magnetars

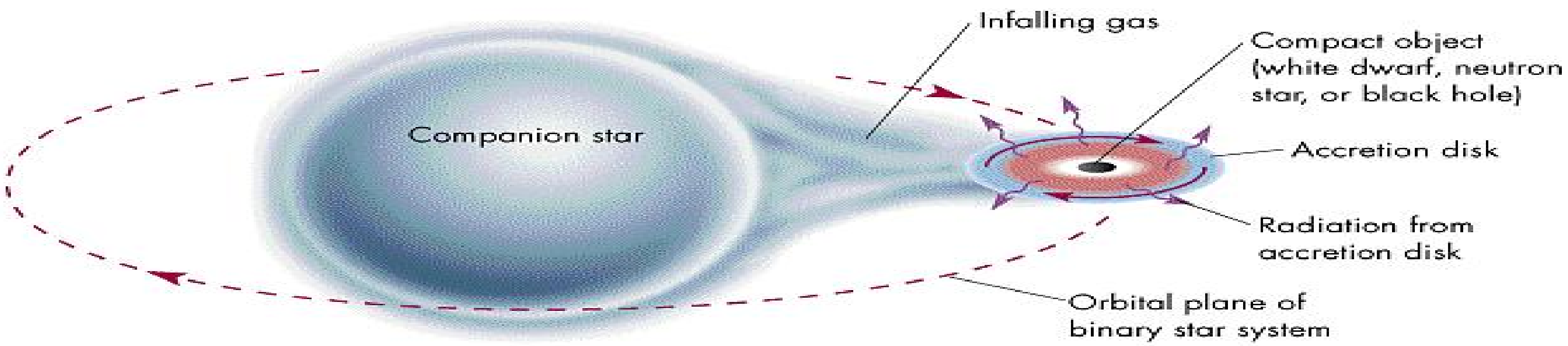


Magnetic fields so strong that they produce starquakes on the neutron star surface.

These quakes produce huge flashes of X-rays and Gamma-rays.

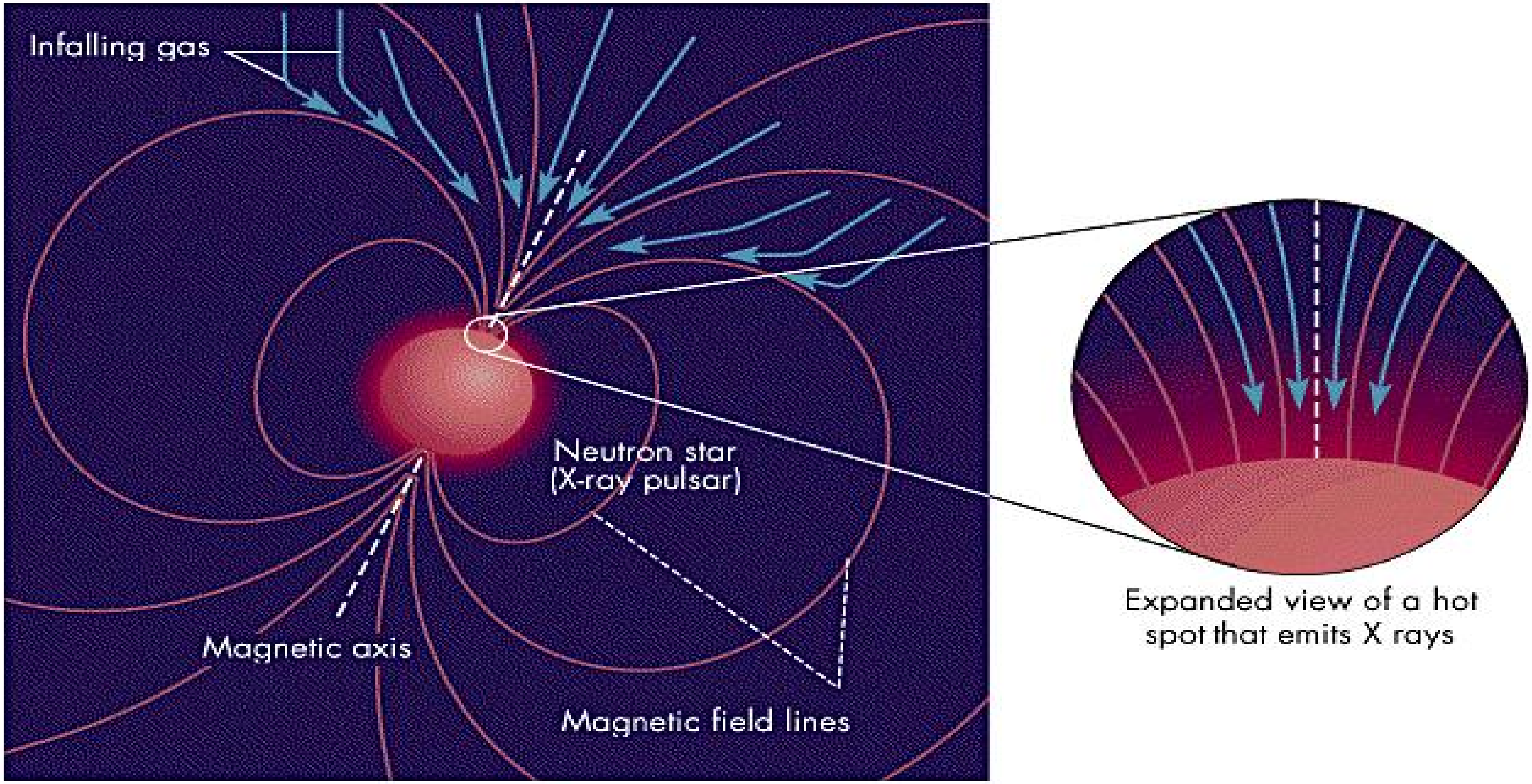
Energy source is magnetic field.

X-Ray Pulsars



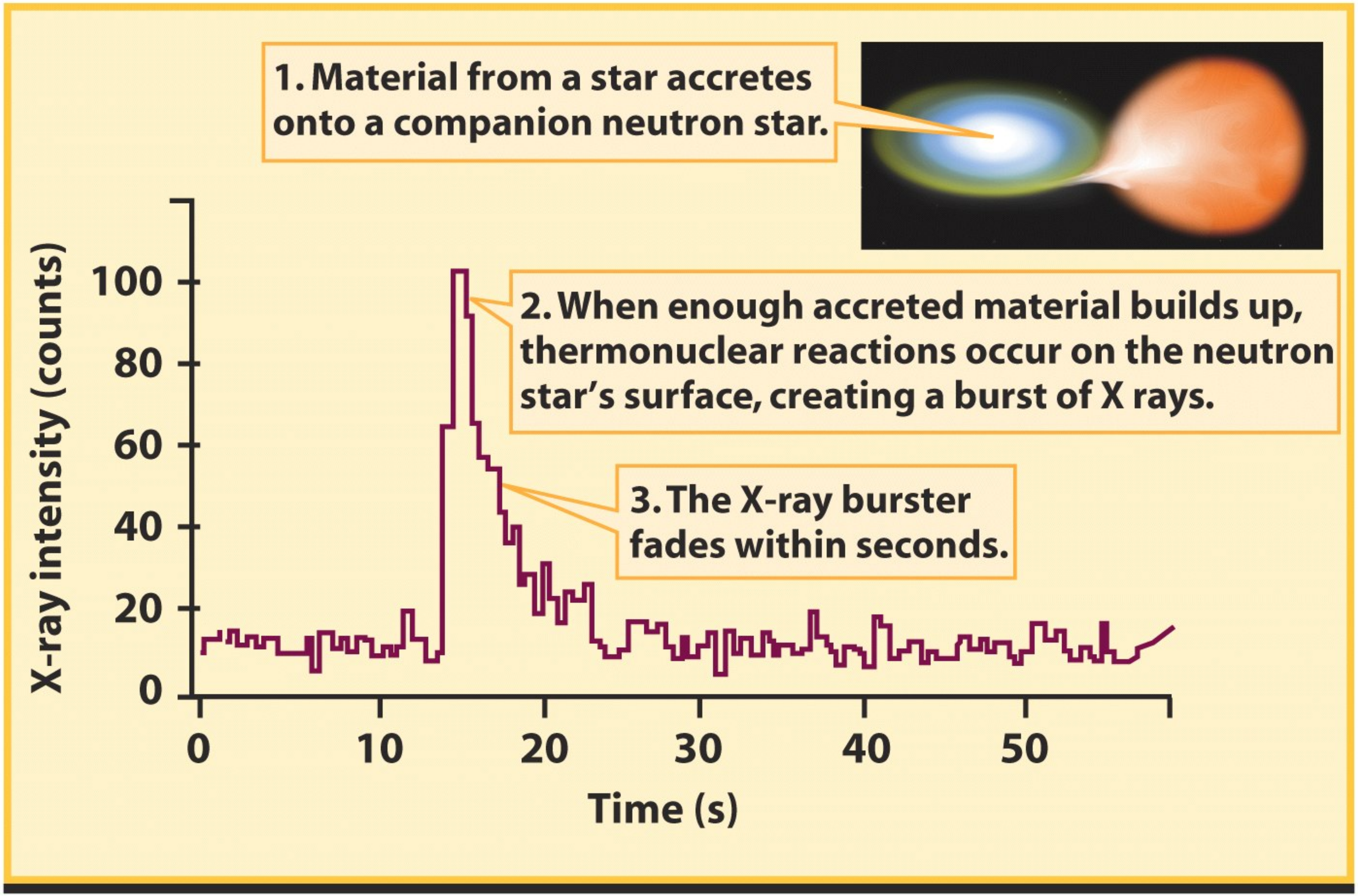
Neutron star in binary system with a normal star

X-Ray Pulsars



High magnetic field neutron stars make regular pulsations. Energy source is gravitational energy of infalling matter.

X-ray Bursters



X-ray Burst

Low magnetic field neutron stars make X-ray bursts.

Source of energy is nuclear burning.

A pulsar is a rapidly rotating

A) White dwarf
B) Neutron star
C) Black hole
D) Any of the above

Review Questions

- How does the evolution of a high mass star differ from that of a low mass star?
- How can the age of a cluster of stars, all formed at the same time, be determined?
- Why does fusion stop at Iron?
- How are heavy elements produced?

Review Questions

- What is the Fermi exclusion principle?
- Does a more massive white dwarf have a larger or smaller radius than a less massive one?
- What is the maximum mass of a white dwarf?
- What are some of the properties of neutron stars?
- Why do many neutron stars spin rapidly?
- In what different forms does one find neutron stars?