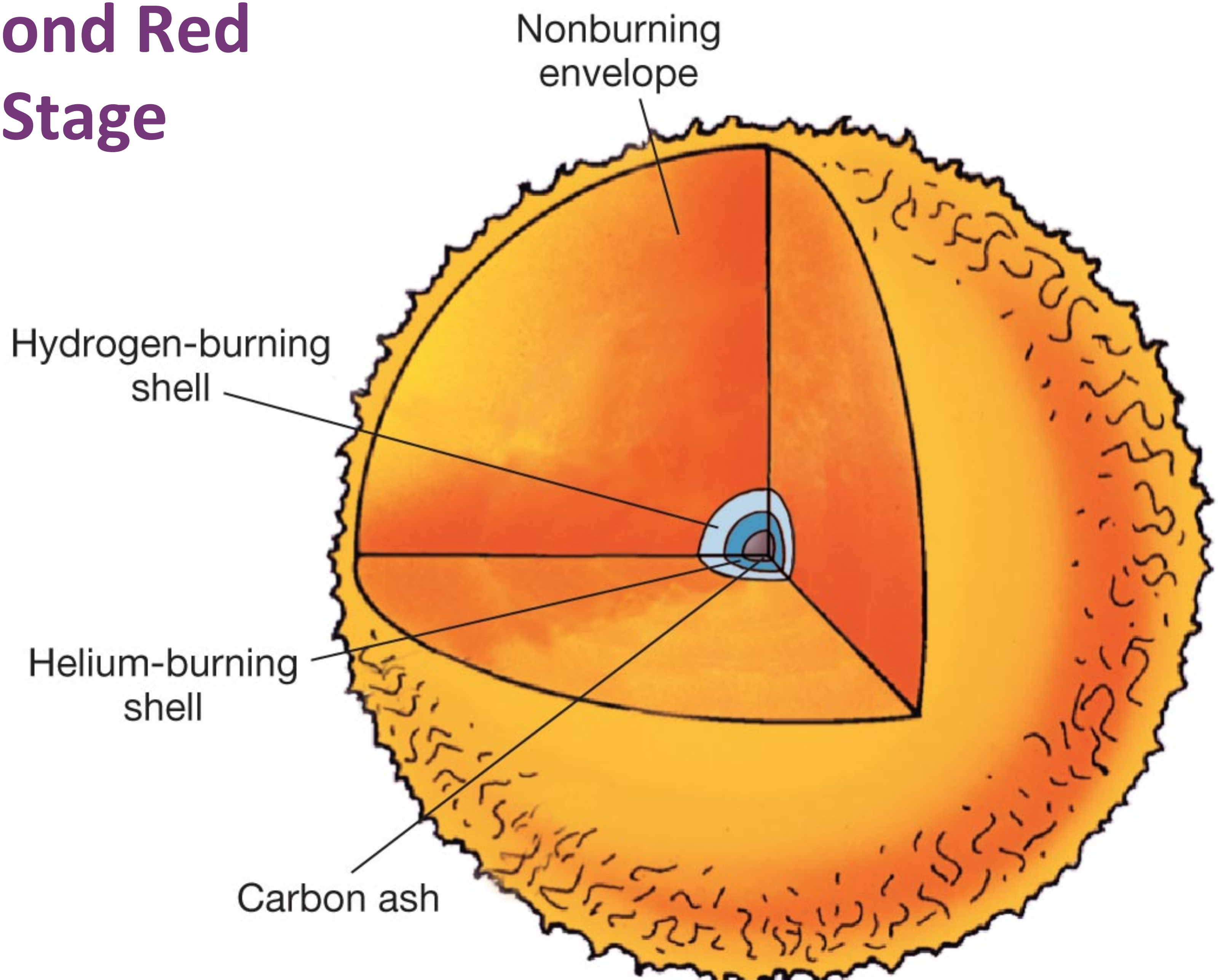
Announcements

- **Quiz 7** due on Monday – Chapters 10 and 11
- **Problem Set 7** for practice
- Today and Monday: Chapter 12
- Next week: Chapter 13, neutron stars and black holes
- Next **midterm** will be Wednesday after spring break – more info next week

Astronomy 103

The Lives and Deaths of Stars
and the Origin of the Elements
Please read chapter 12

V. Second Red Giant Stage



Now we have 3 sources of energy
- Contraction of the core
- Ferocious fusion of helium to carbon in a shell around the core
- Rapid fusion of hydrogen to helium in a second shell

With more energy from these reactions than in its first red giant stage, the star becomes even larger than it did the first time.

Eventually, driven by the increasing temperature of the core, its outer layers are blown entirely off the star, creating a **planetary nebula.**

VI. The Death of Stars like the Sun: Ejection of planetary nebula and white dwarf formation
(book stages 12-13)

With the hydrogen shell gone, the hydrogen and helium burning shells runs out of fuel and the carbon core slowly cools off. If gravity would have its way, the carbon core would heat up and ignite, but before it does degeneracy pressure takes over.

If you try to cram too many electrons into a small enough space, the electron's quantum mechanics prevent you from squeezing them any more tightly together – this is called **degeneracy pressure**.

Degeneracy pressure in metals gives them their resistance to compression

To support a star's core against gravity, the degeneracy pressure is much larger than it would be for any metal on earth. These stars that are supported by degeneracy pressure are called **white dwarfs**

- The Sun itself will end as a white dwarf, compressed to about the size of the Earth. A typical white dwarf radius is then about the radius of the Earth. Its density is about **5 tons per teaspoon.**

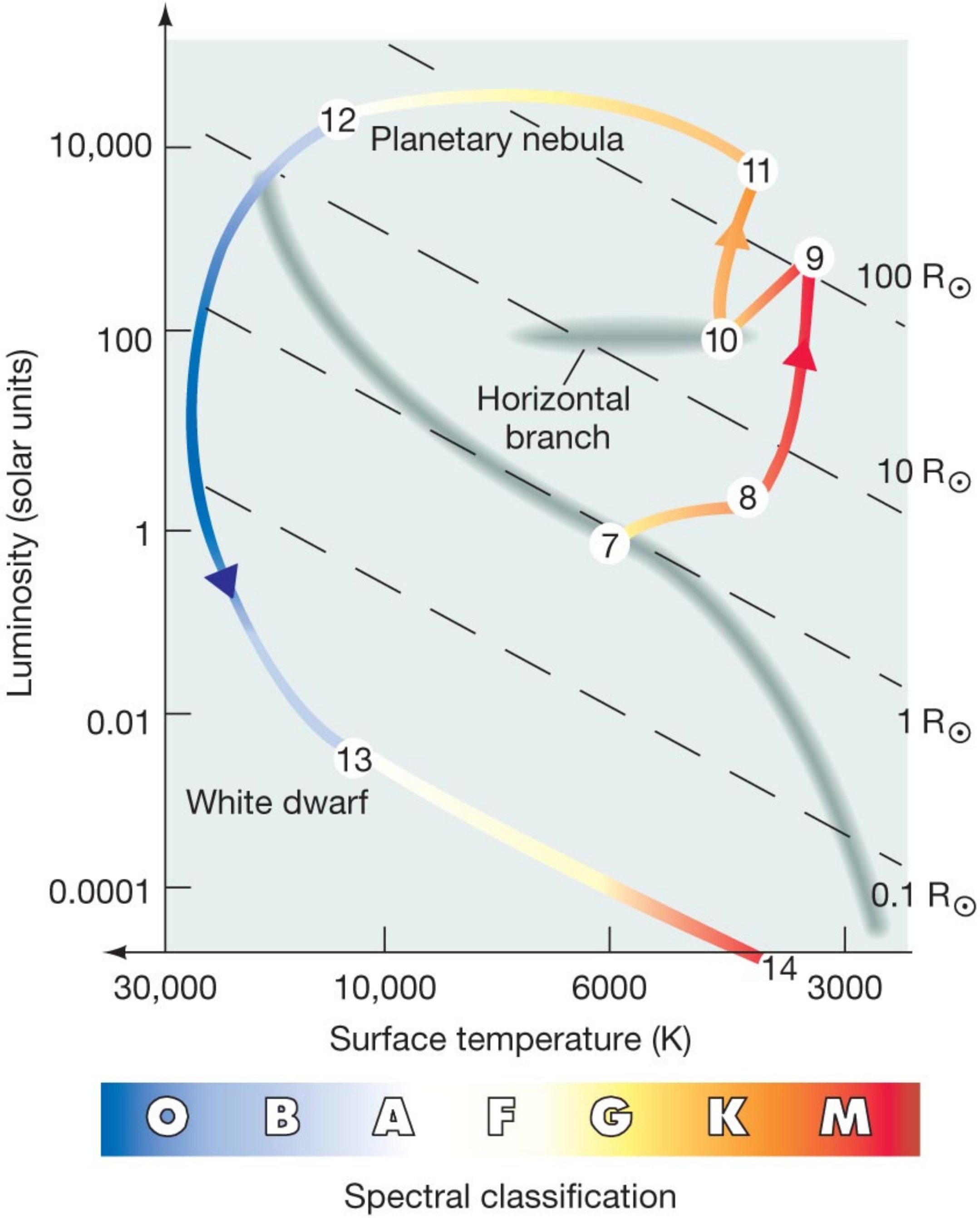
- A star **smaller than 4 solar masses** ends its life by ejecting a planetary nebula and settling down to become a white dwarf.

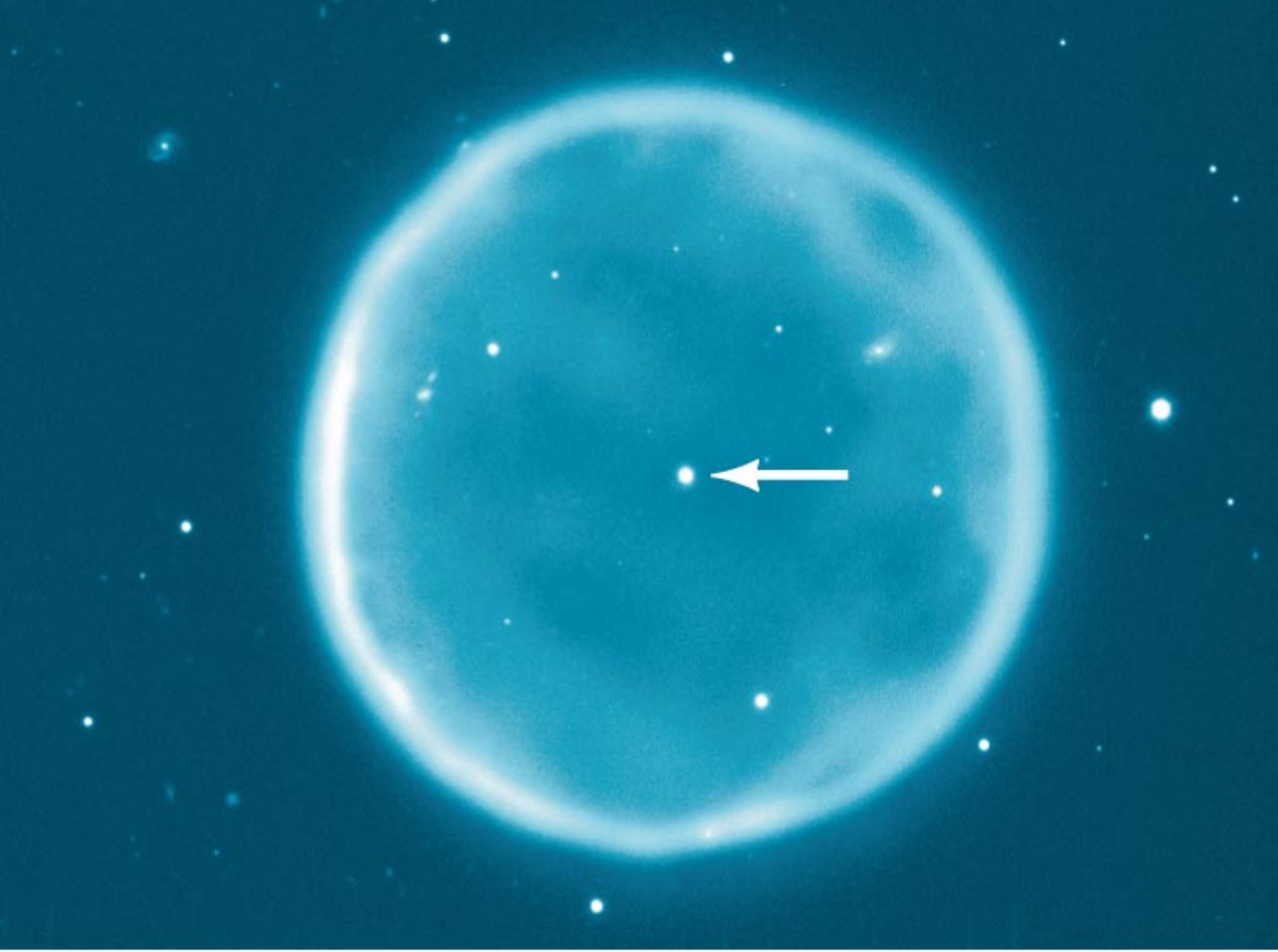
- Planetary nebulae are thus found around white dwarfs.

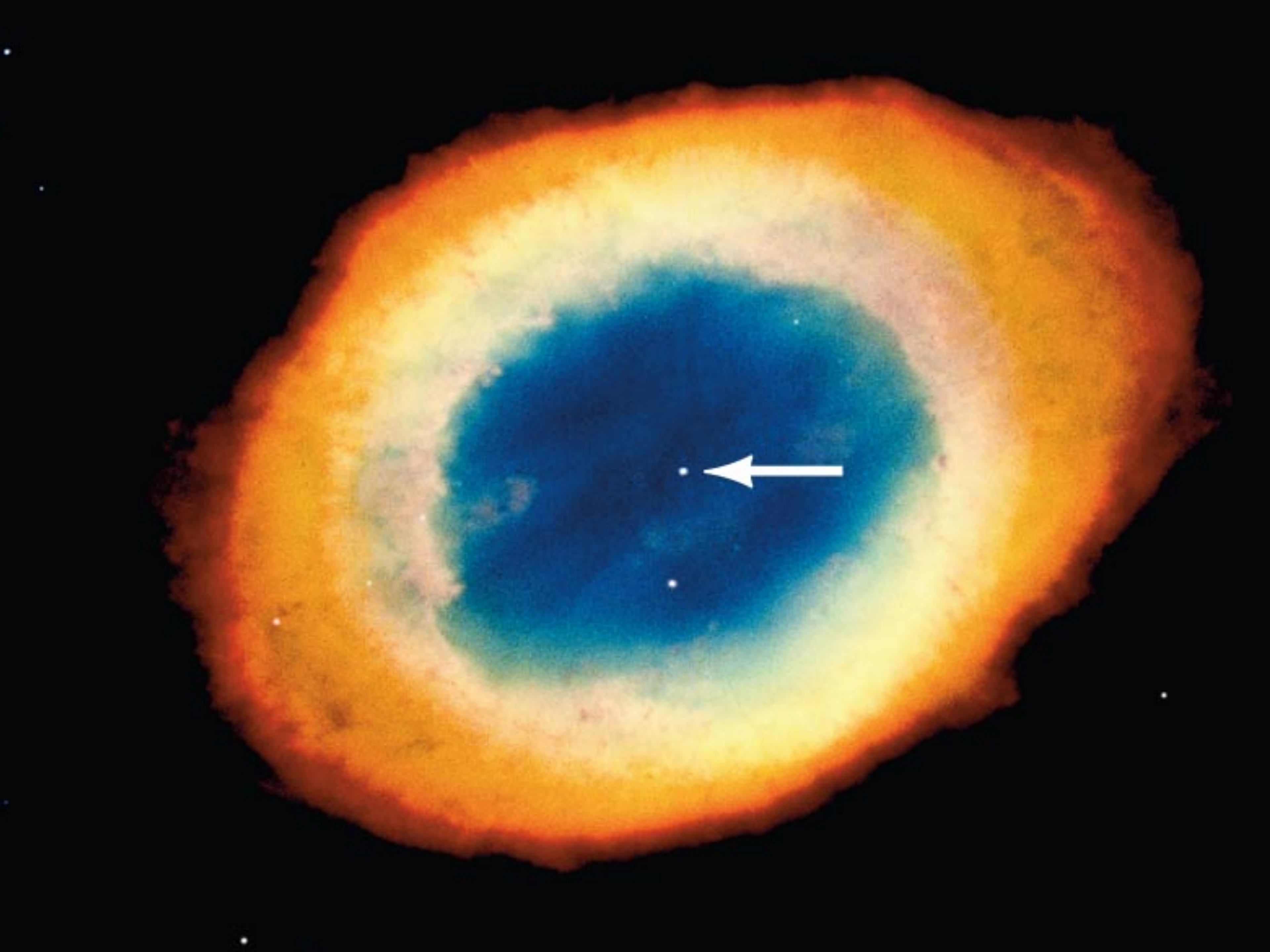
The star burns so brightly that it sheds a planetary nebula—gas that travels away from the star (12).

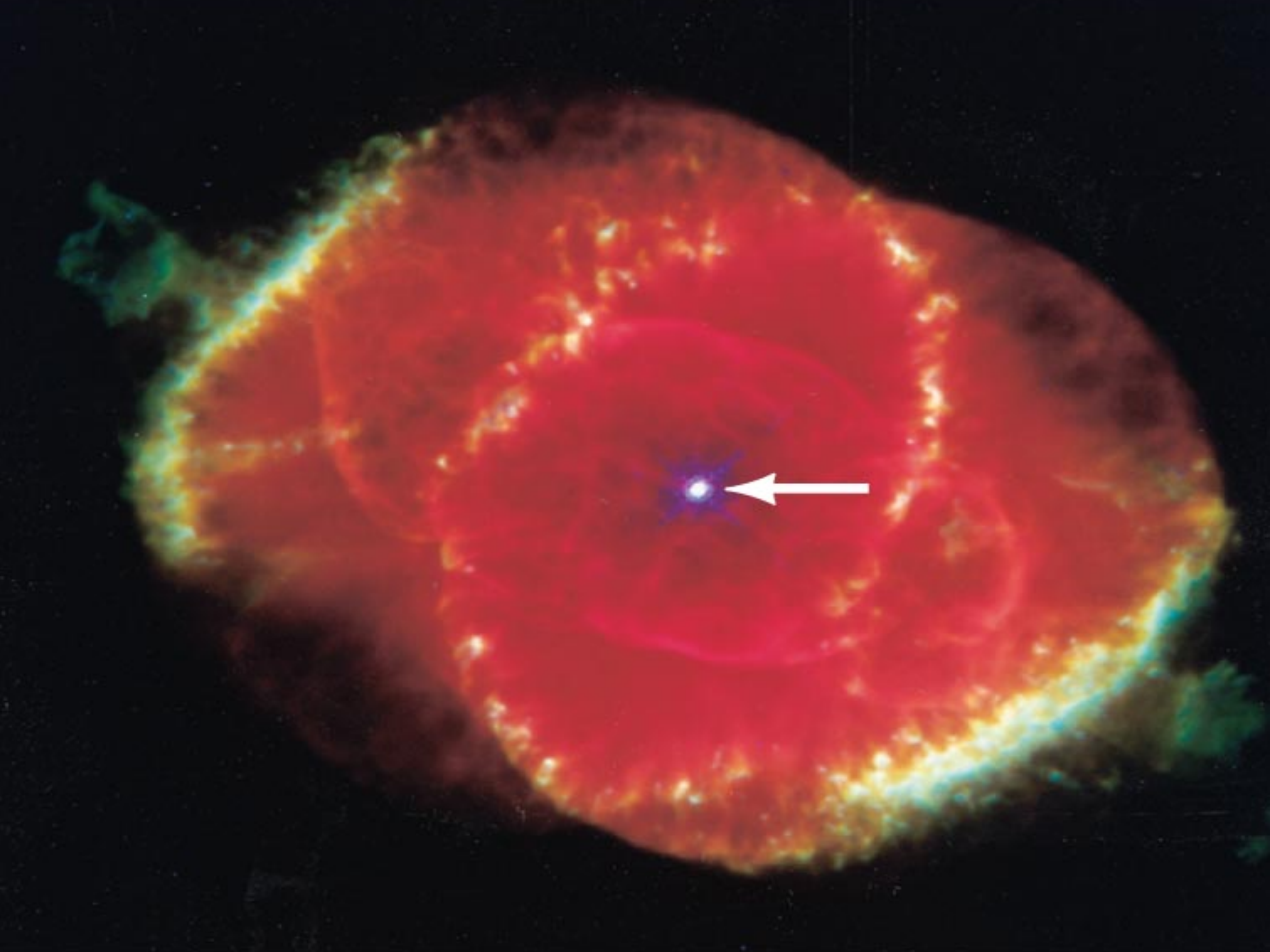
Once the star runs completely out of nuclear fuel what remains of the star contracts and forms a white dwarf (13).

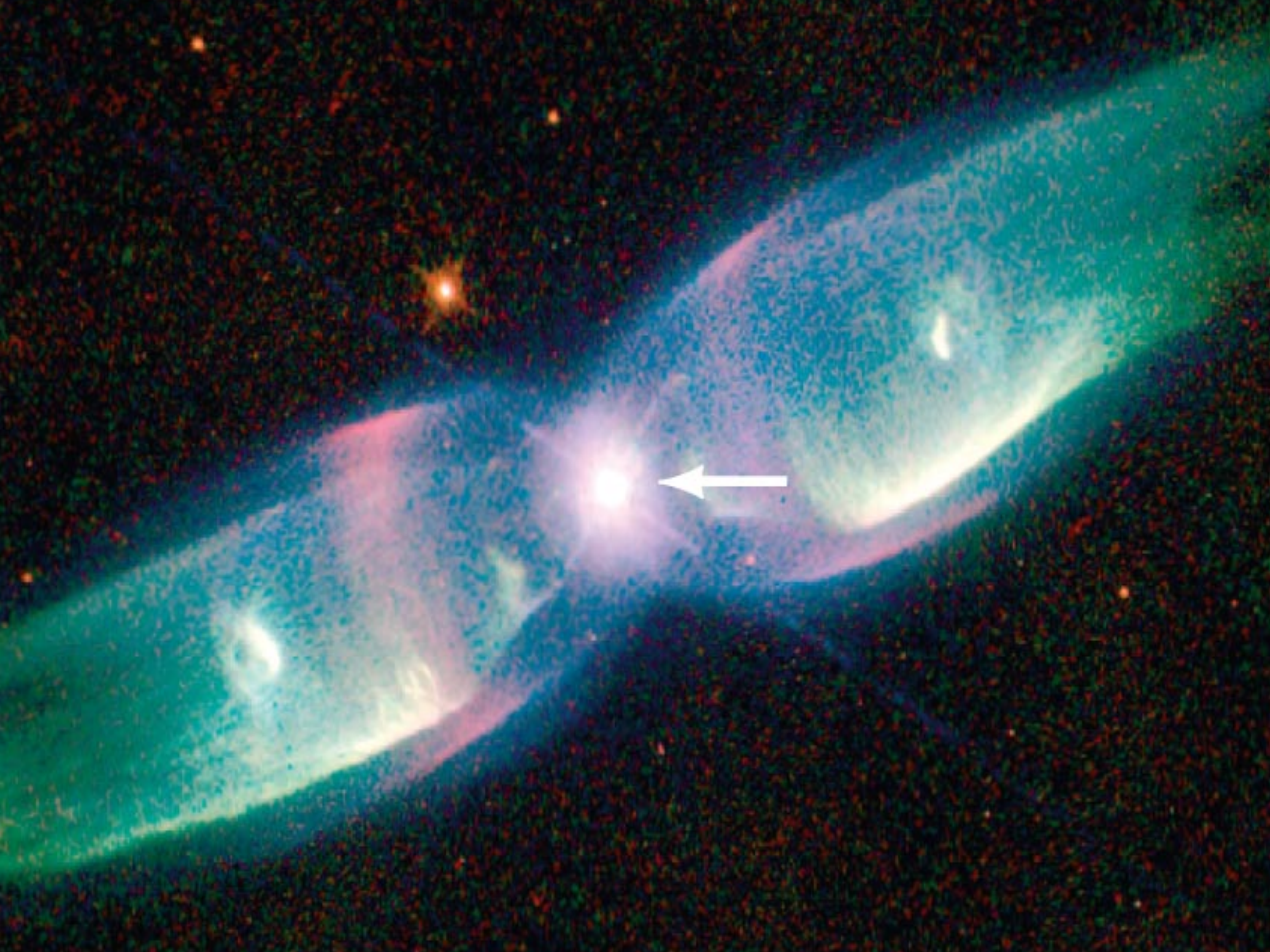
The star cools eventually becoming a black dwarf, too small and faint to see (14).











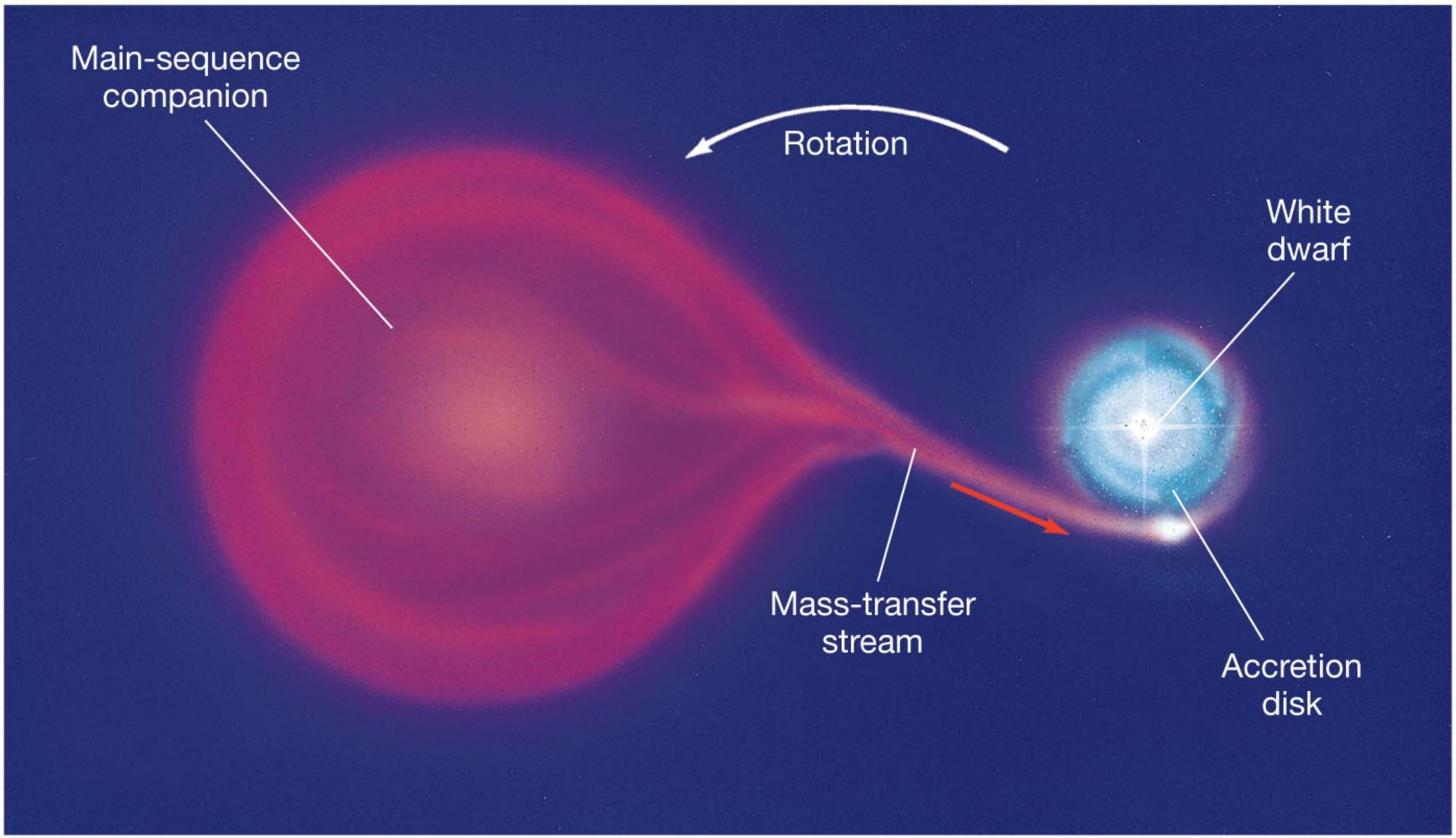
Novae: H-bombs at the surface of white dwarfs

Some white dwarfs are in binary systems with another star.

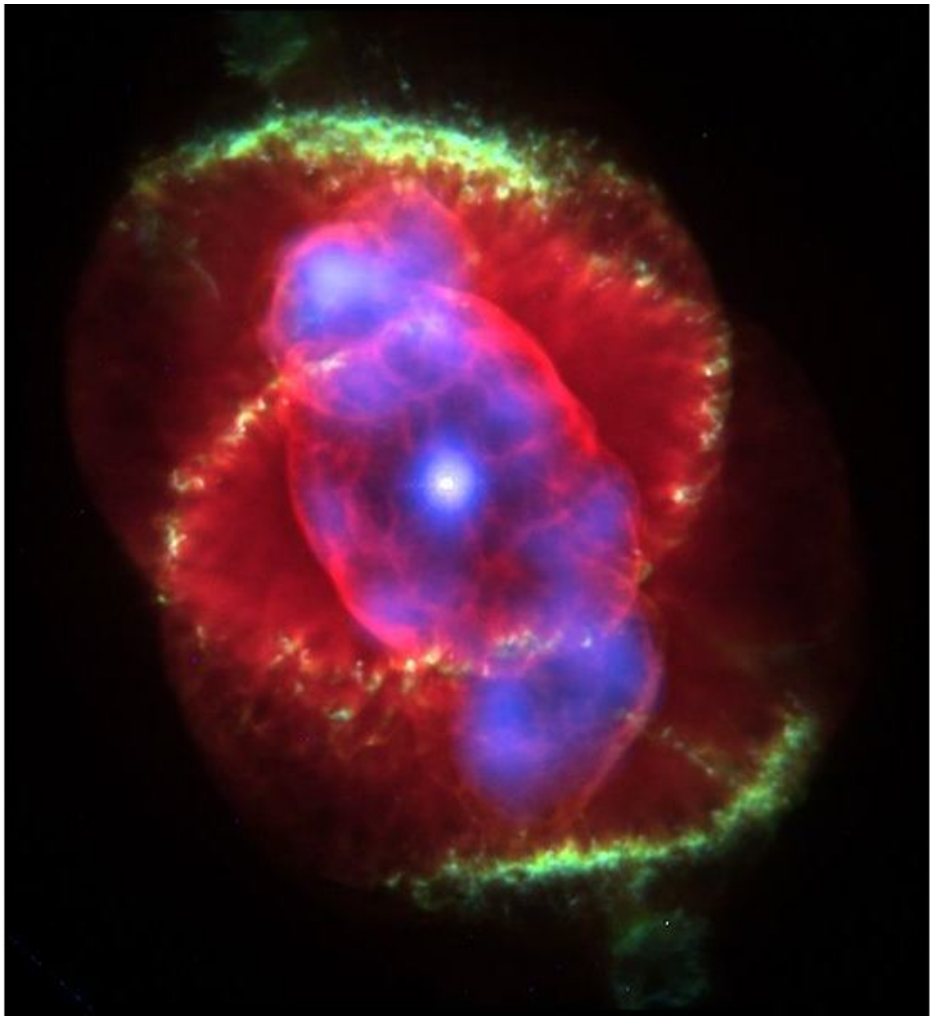
In a close binary, or when the other star becomes a red giant and is sufficiently large, hydrogen from the surface of the other star falls onto the white dwarf.

Once enough hydrogen builds up on a white dwarf, it will suddenly fuse to helium. This is a **nova**, the sudden fusion of hydrogen to helium on the surface of a dwarf.

Nova, the sudden fusion of hydrogen to helium at the surface of a dwarf due to built up matter on a white dwarf



This is an image of the Cat's Eye planetary nebula. What kind of star is at the center?



A Protostar

B Blue supergiant

C White dwarf

D Main sequence

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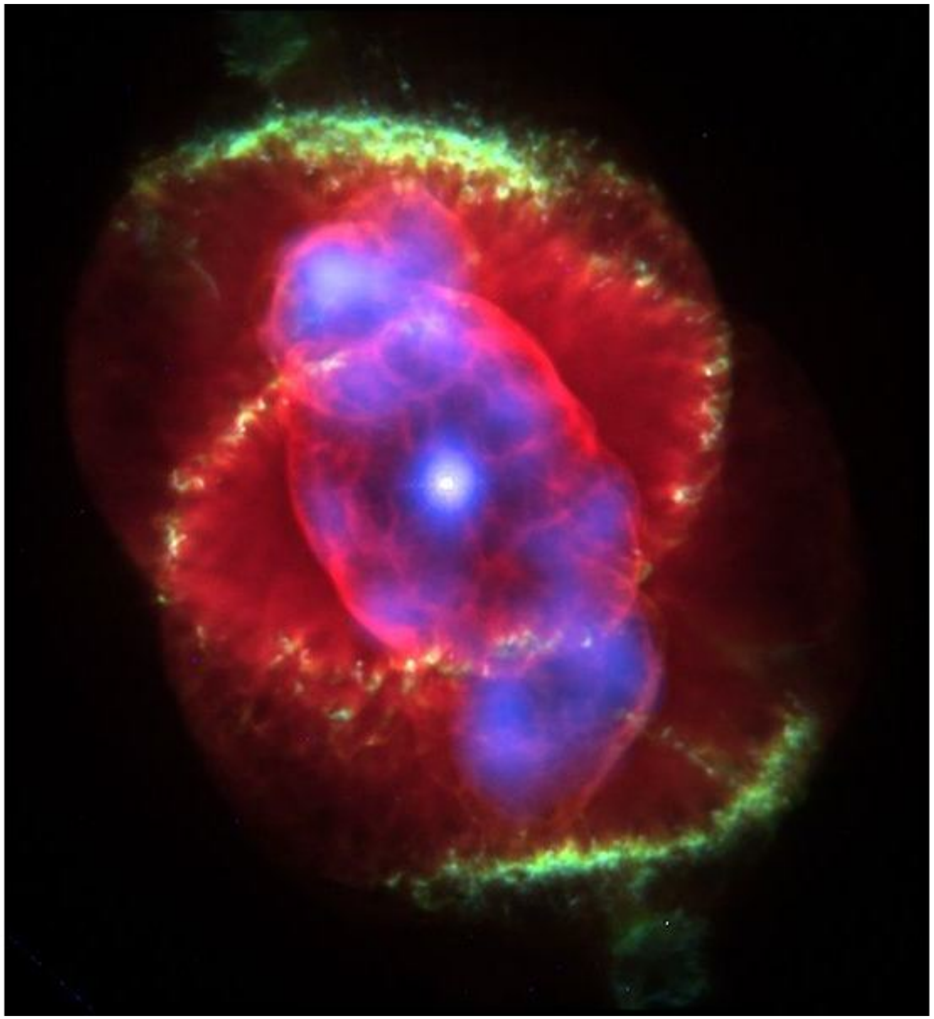

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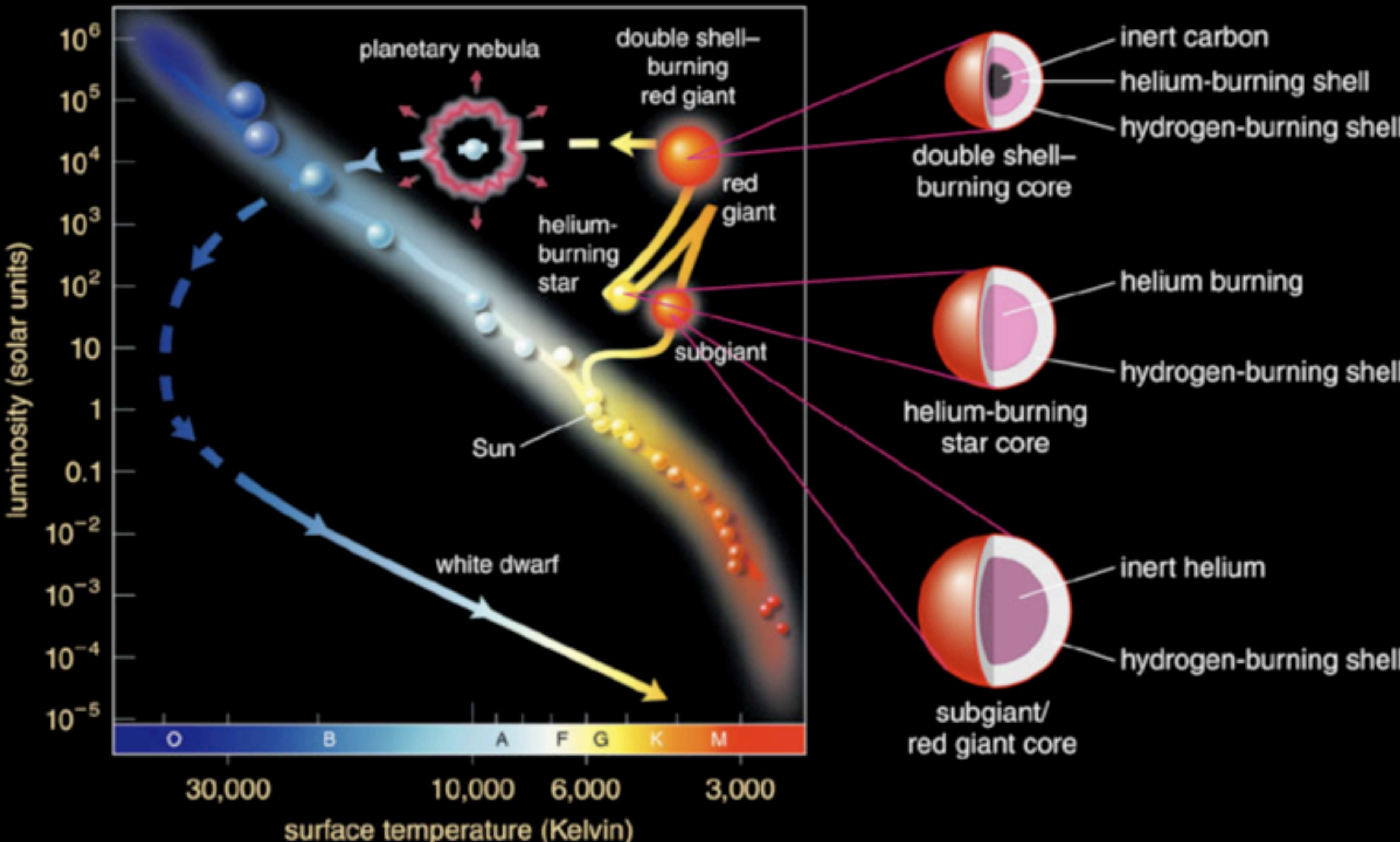
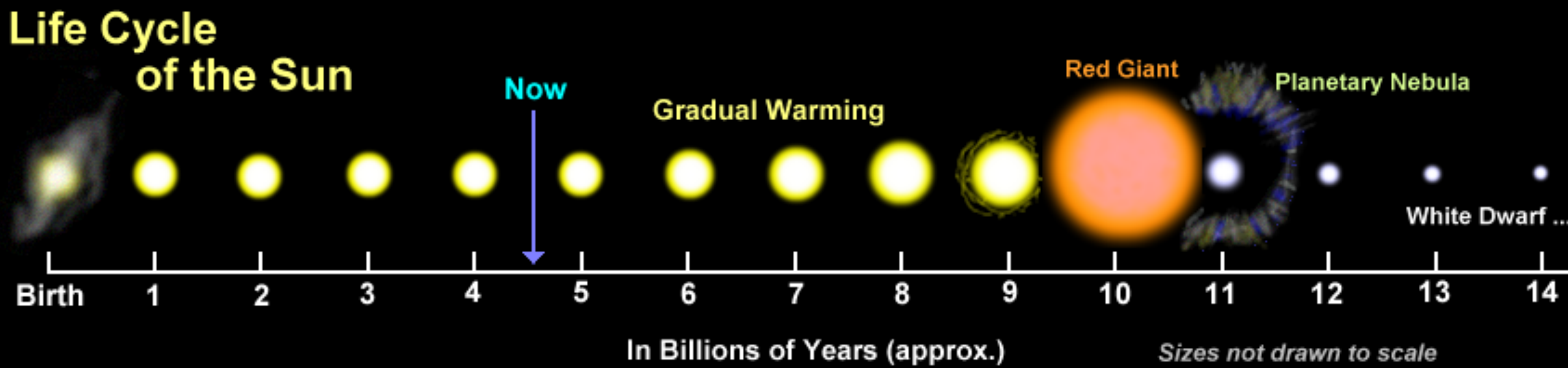
Evolution of the Sun



Evolution of the Sun



A star like the Sun spends most of its life on the main sequence, and then a shorter and shorter amount of time in each phase until it cools as a white dwarf.

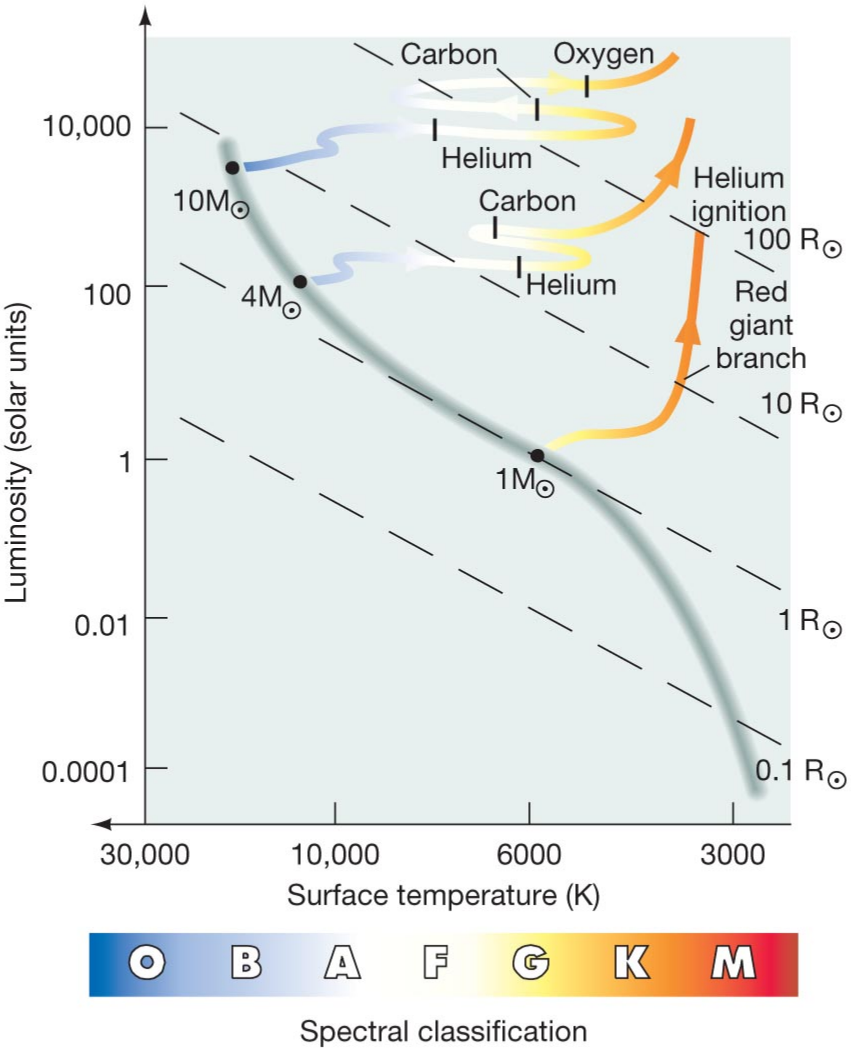
Late evolution of stars more massive than the Sun and the formation of the elements

More massive stars will build heavier elements up from carbon:

$M < \frac{1}{12}M_\odot$	No fusion at all
$\frac{1}{12}M_\odot - 0.4M_\odot$	H → He only
$0.4M_\odot - 4M_\odot$	H → He, He → C
$4M_\odot - 8M_\odot$	C → Ne, Na, Mg, O
$M > 8M_\odot$	Ne and O fuse to form higher mass elements up to Fe

Evolution of Stars More Massive than the Sun

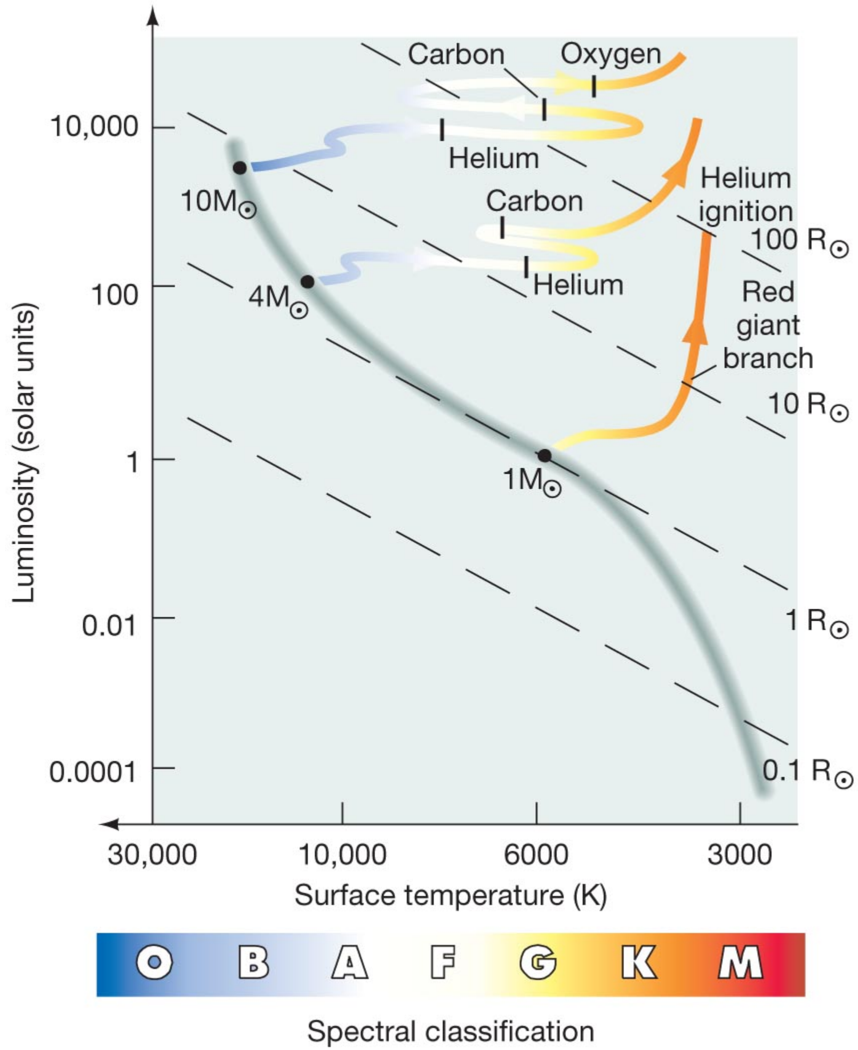
It can be seen from this H–R diagram that stars more massive than the Sun follow very different paths when leaving the main sequence.



Evolution of Stars More Massive than the Sun

High-mass stars, like all stars, leave the main sequence when there is no more hydrogen fuel in their cores.

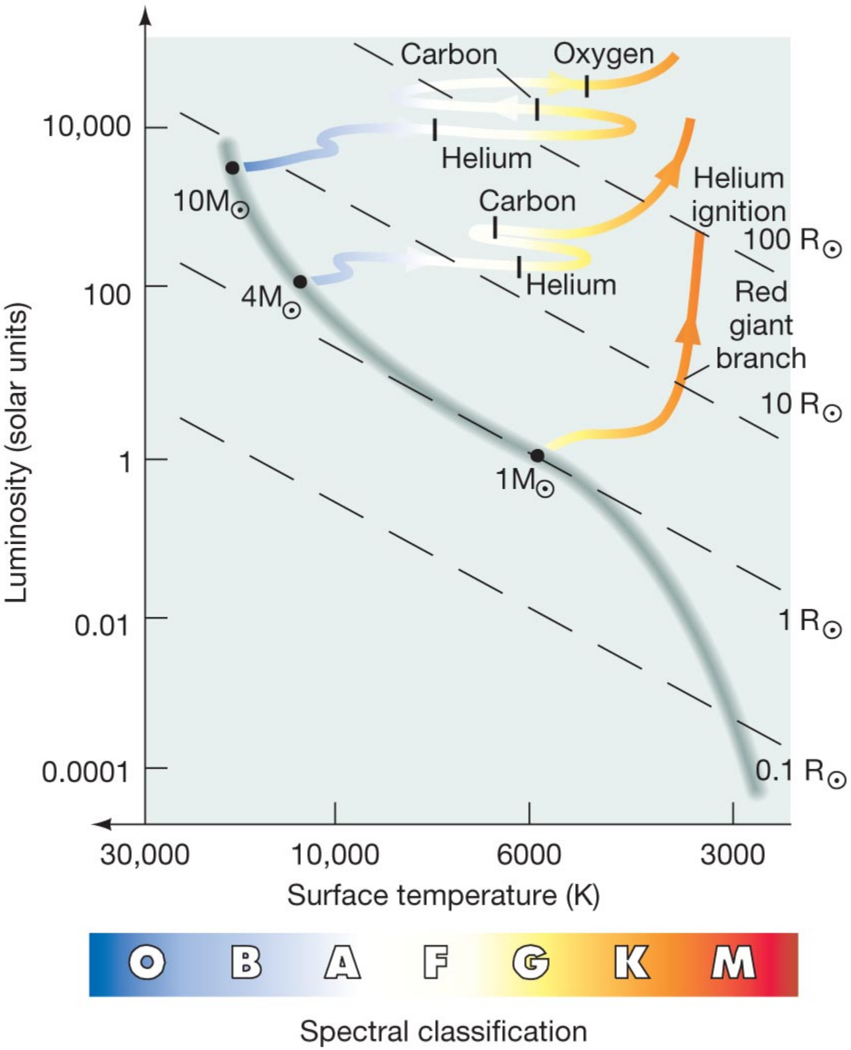
The first few events are similar to those in lower-mass stars – first a hydrogen shell, then a core burning helium to carbon, surrounded by helium- and hydrogen-burning shells.



Evolution of Stars More Massive than the Sun

Stars with masses more than 2.5 solar masses do not experience a helium flash – helium burning starts gradually.

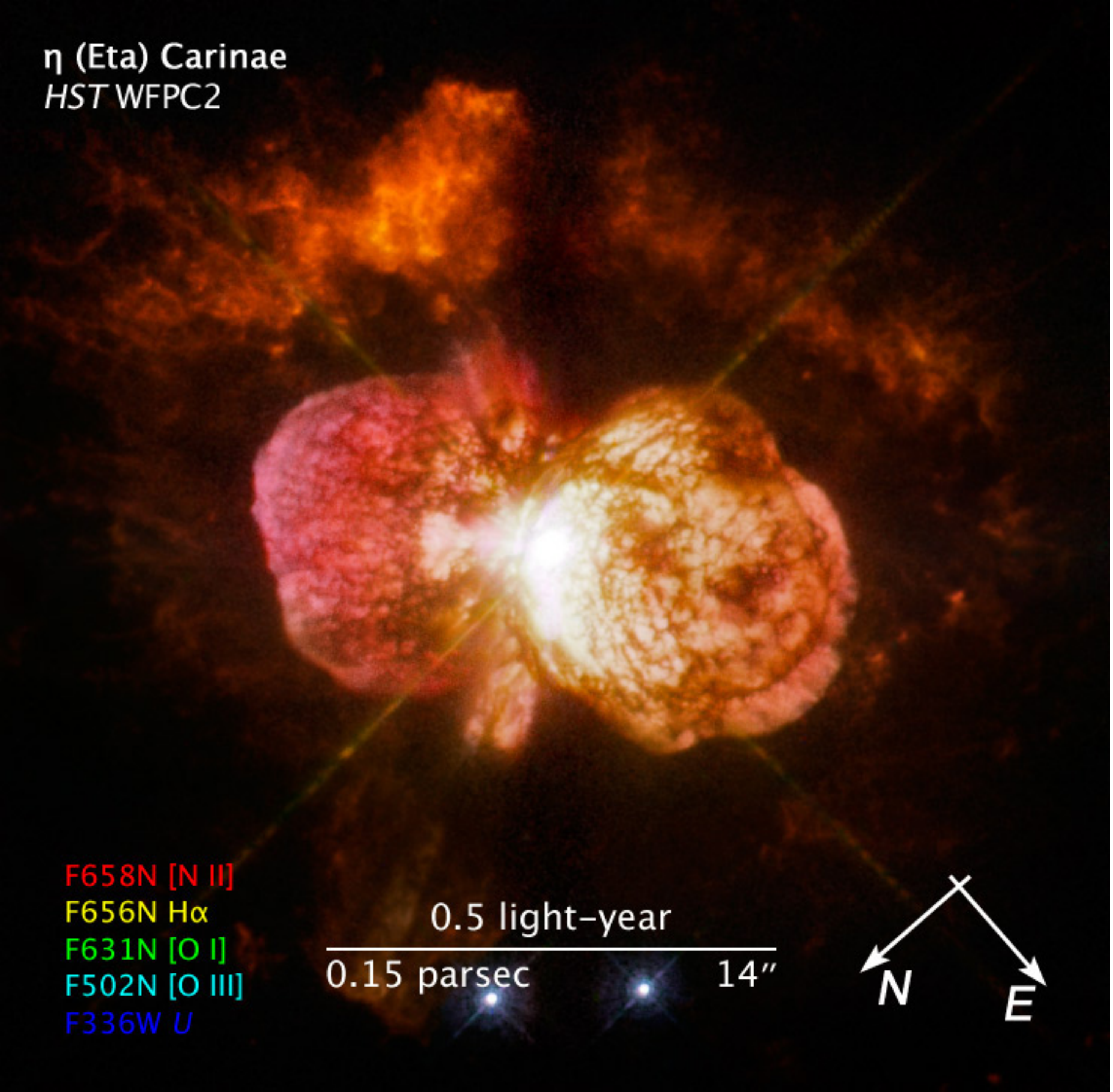
A 4-solar-mass star makes no sharp moves on the H–R diagram – it moves smoothly back and forth.



Evolution of Stars More Massive than the Sun

The sequence below, of actual *Hubble* images, shows first a very massive star, then a very unstable red giant star as it emits a burst of light, illuminating the dust around it.

(a)



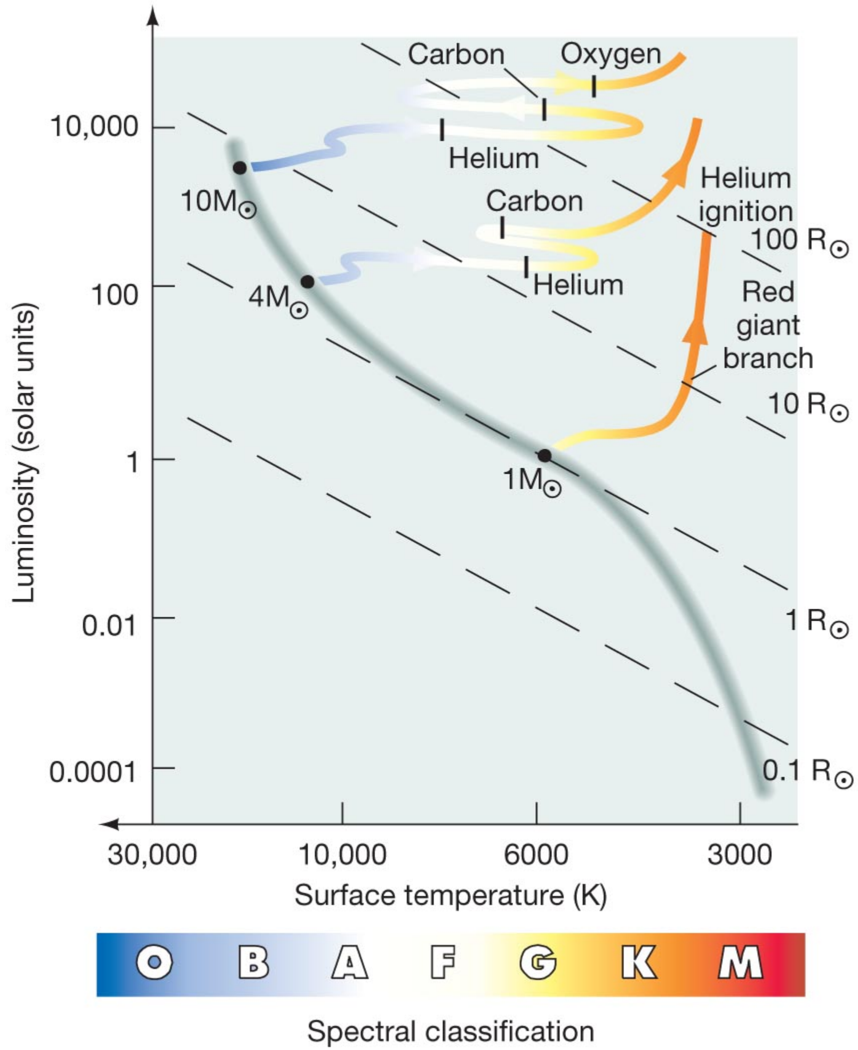
Very massive stars become unstable towards the end of their lives. They develop strong winds and can blow a tenth or more of their total mass into space.

This is one of the most famous examples, the massive star Eta Carinae. The nebula surrounding the star is gas that has been blown off – Eta Carinae has probably lost 2-3 times the mass of the Sun.

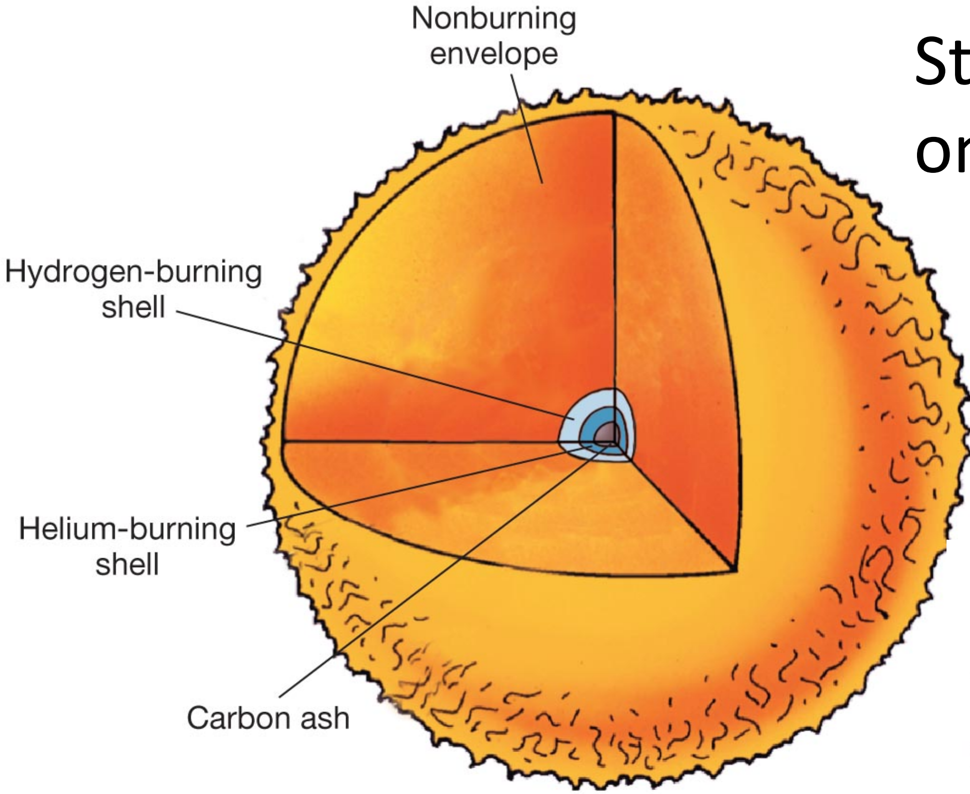
Evolution of Stars More Massive than the Sun

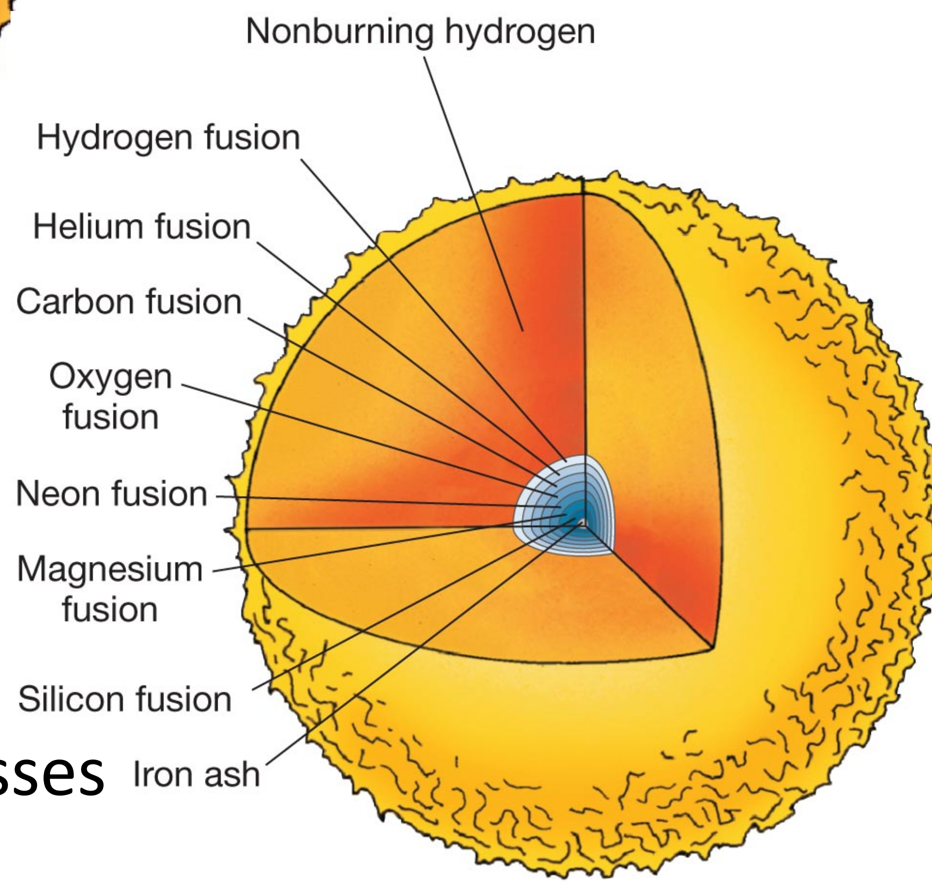
A star of more than 8 solar masses can fuse elements far beyond carbon in its core, leading to a very different fate.

Its path across the H–R diagram is essentially a straight line – it stays at just about the same luminosity as it cools off.



Stars with lower masses only produce Carbon

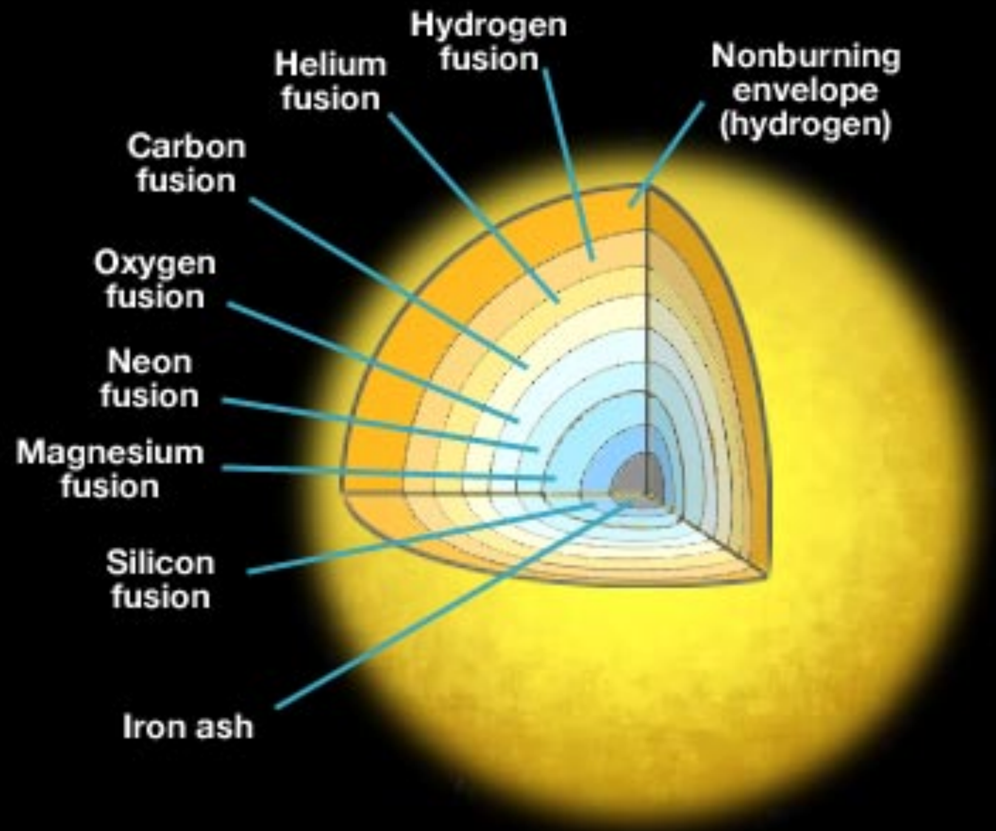




Stars with higher masses produce Iron

Evolution of the most massive stars

- The most massive stars are hot enough to fuse heavier and heavier elements in their cores
- Fusion of the heaviest element occurs in the center, surrounded by shells burning each of the lighter elements
- Star has an "onion" structure
- This happens until the core of the star has been fused into iron



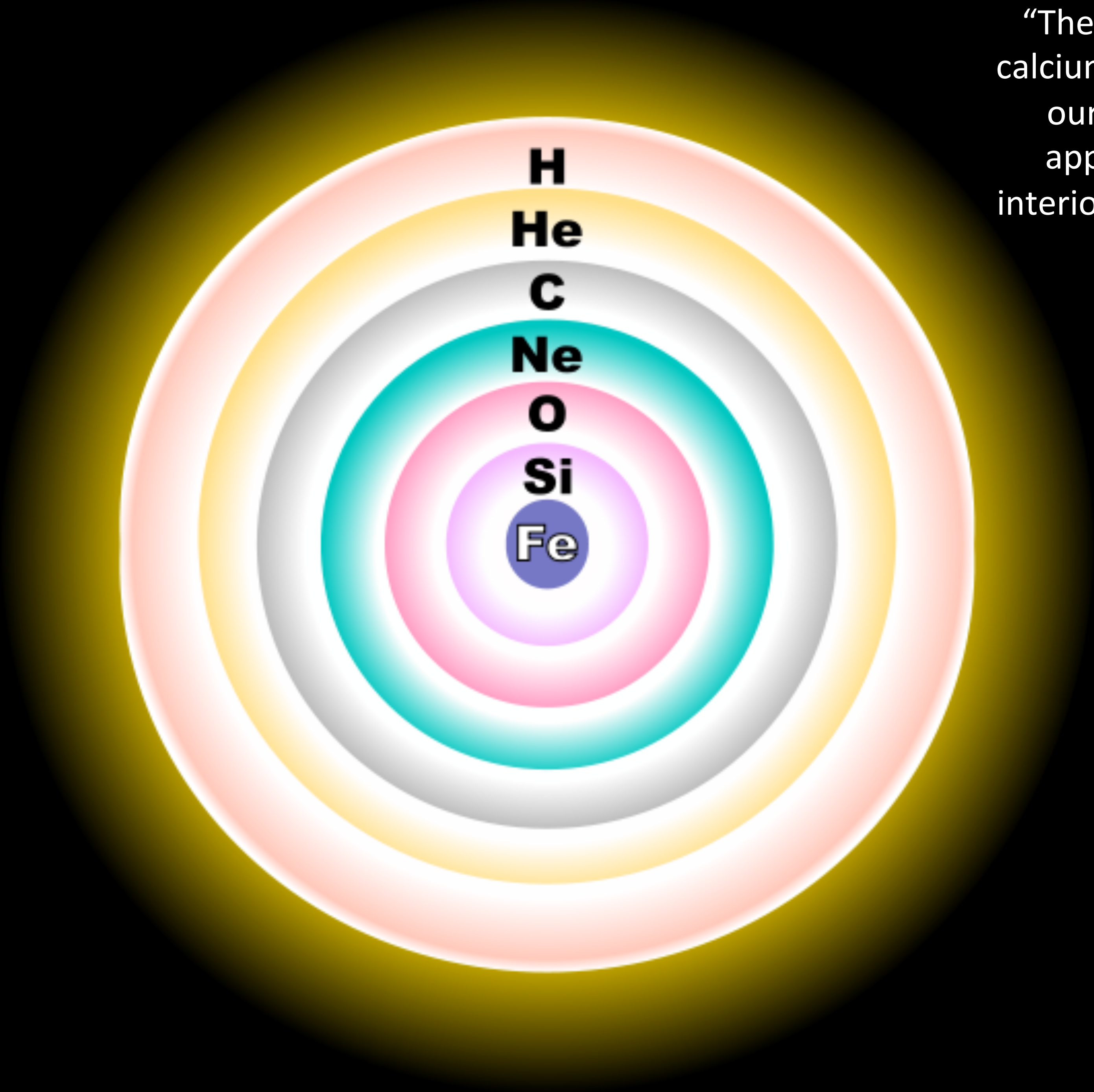
Not to scale! The core containing the layers of fusion is only a small part of the star.

Iron is the most stable element – it has the most tightly bound nucleus.

The heavy elements up to iron are built in the cores of stars.

You are made of stardust

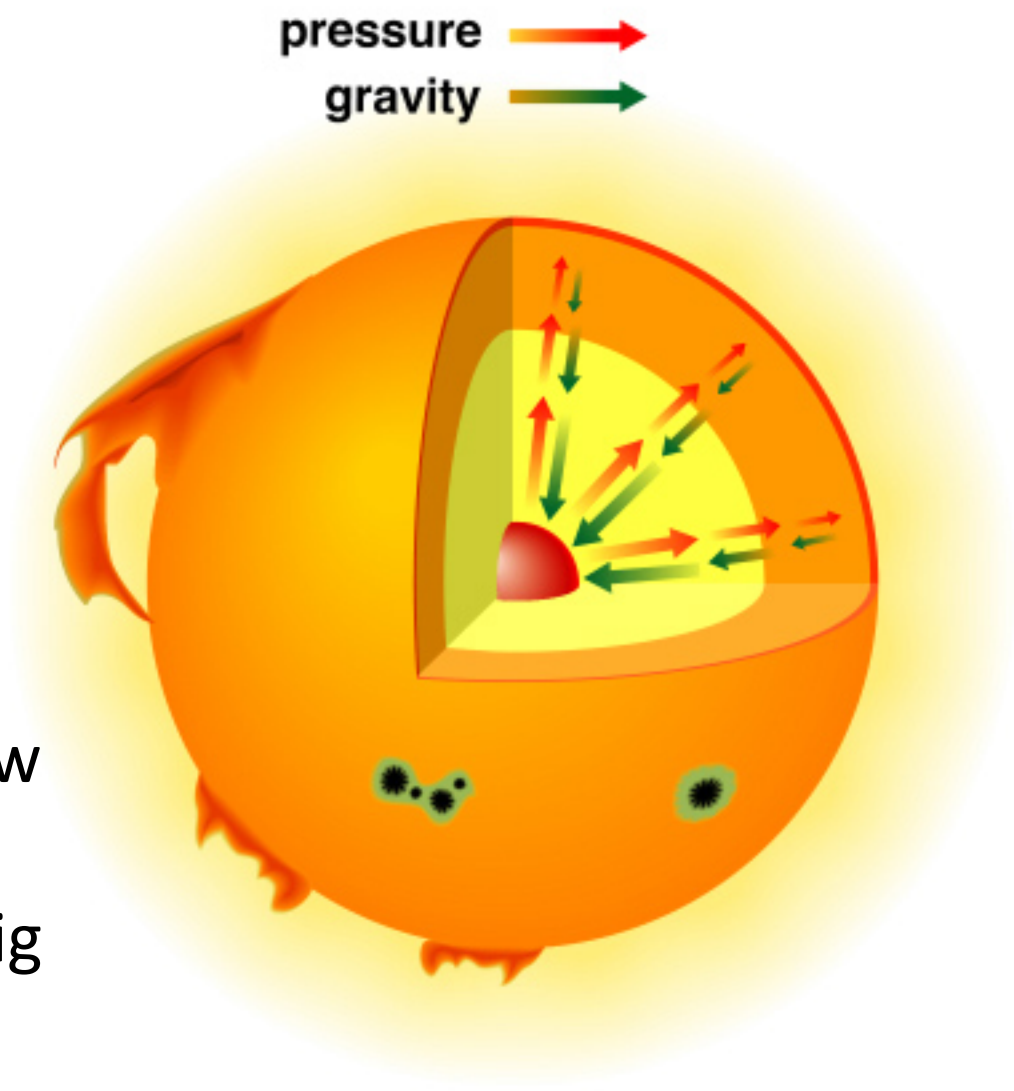
All the atoms in you that are heavier than helium first formed in a star, and nearly all atoms between helium and iron were forged in the core of a massive star. **The story of a star's life is also the story of the how the elements were built.**



"The nitrogen in our DNA, the calcium in our teeth, the iron in our blood, the carbon in our apple pies were made in the interiors of collapsing stars. We are made of starstuff."
— Carl Sagan, Cosmos

Evolution of the most massive stars

- Recall that stars are in **hydrostatic equilibrium**: nuclear fusion at the center produces enough **pressure** to balance the force of **gravity** and keep the star from collapsing
- Our very massive star now has a core made out of iron… and this is a very big problem!

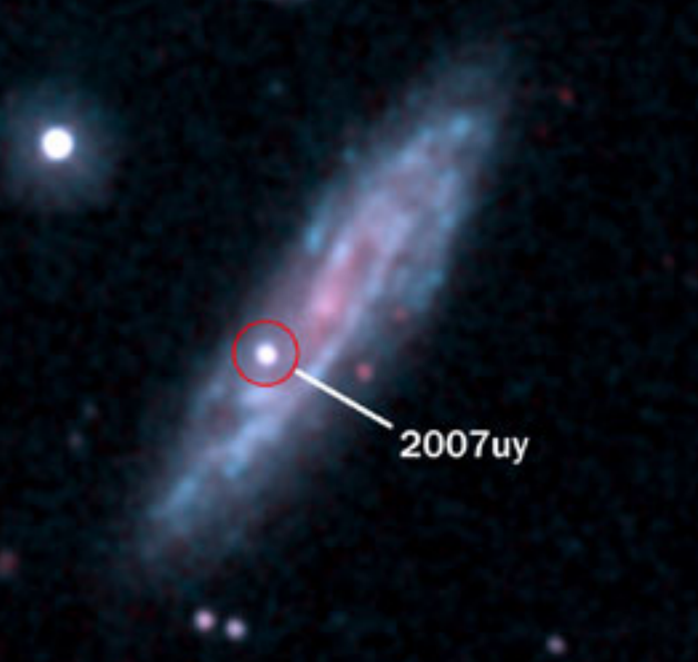


Evolution of the most massive stars

- Iron is the most stable element – it has the most tightly bound nucleus
- For elements lighter than iron, fusing them into heavier elements **produces energy**
- This doesn't work for iron: fusing iron atoms together into heavier atoms does **not** create energy

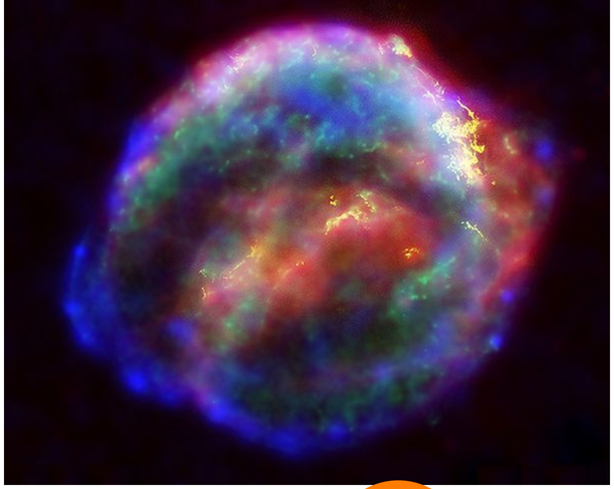
Evolution of the most massive stars

- So our massive star suddenly no longer has fusion at its core, and it can't create the pressure needed to support itself against gravity
- This results in a sudden, catastrophic collapse of the star: a **supernova**

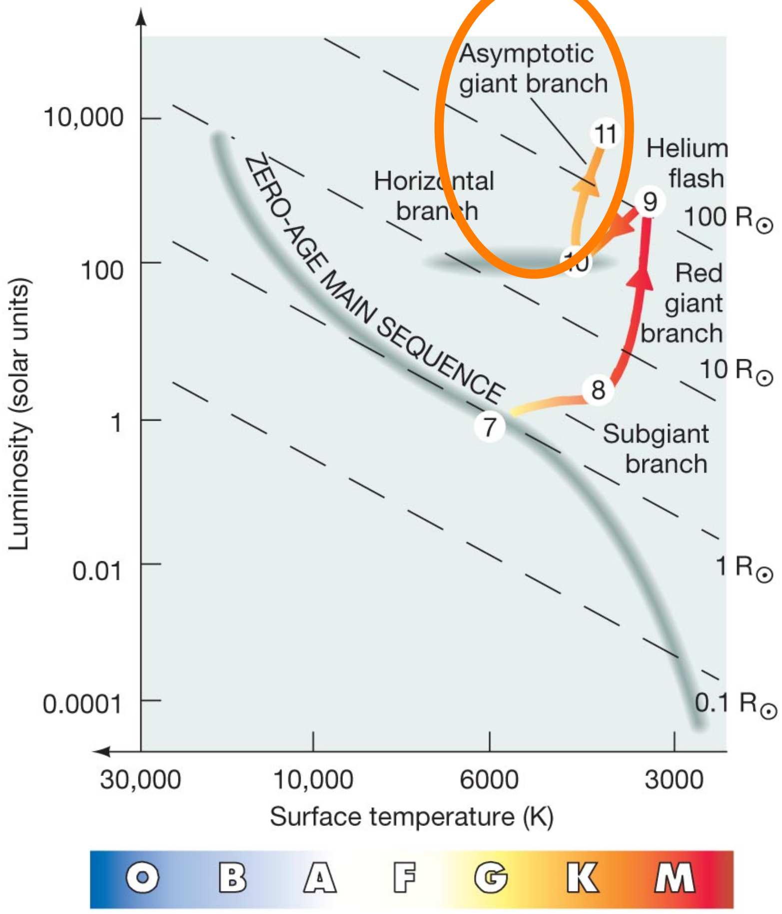


Supernovae can be brighter than all of the other stars in the galaxy combined!

Where do elements heavier than iron come from?



- **Supernova** nucleosynthesis: heavy elements can be created during supernovae via a process involving rapid capture of neutrons by heavy nuclei like iron
- There is also a slow neutron capture process which occurs in late stages of stellar evolution, mostly in **Asymptotic Giant Branch** (AGB) stars
- These two processes account for most of the elements heavier than iron



Supernovae and the death of stars much more massive than the Sun

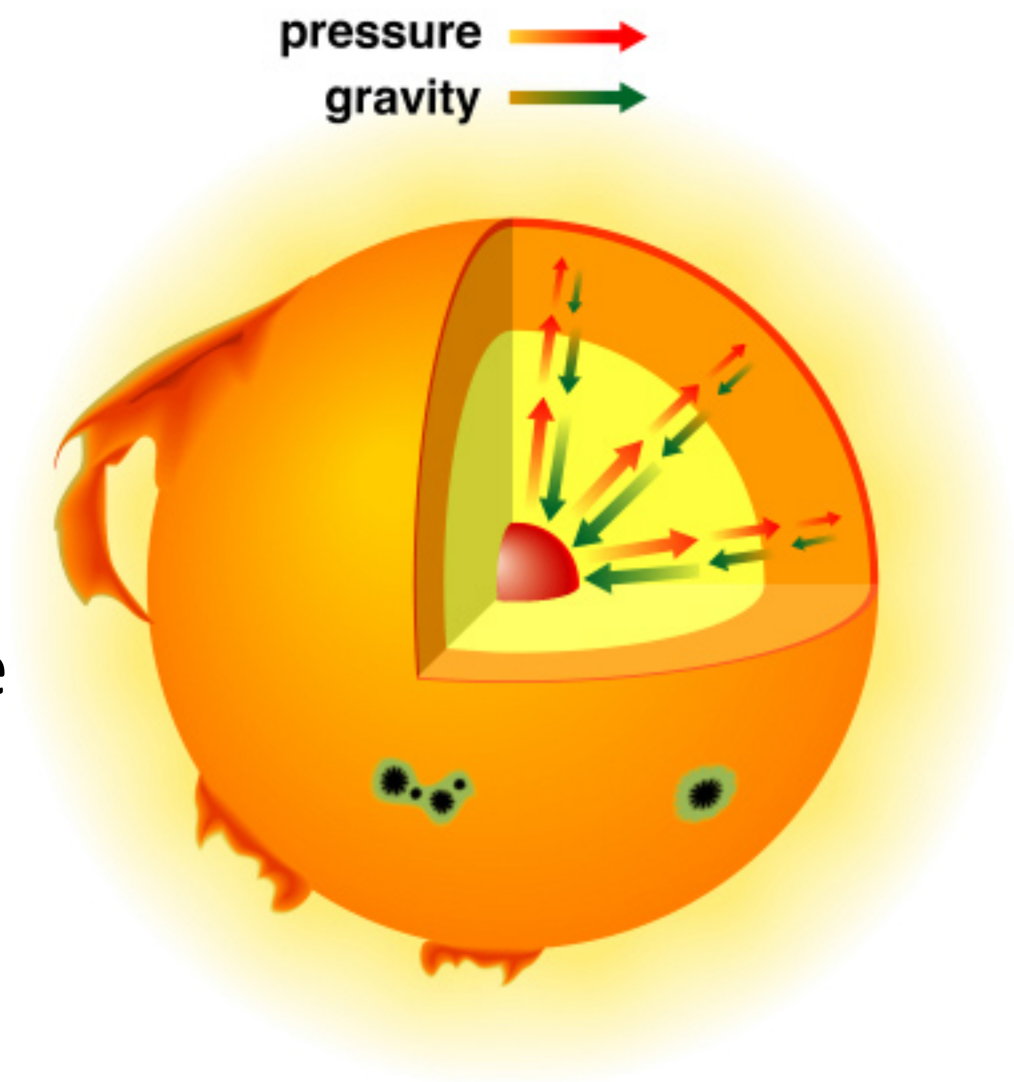
The Crab Nebula: A supernova remnant from 1054

Supernovae are the explosions of dead stars: the dead core of a massive star or the dead matter in a white dwarf.

There is an important relation between the universe's speed limit (the speed of light) and the upper limit on the mass of these dead remnants of stars.

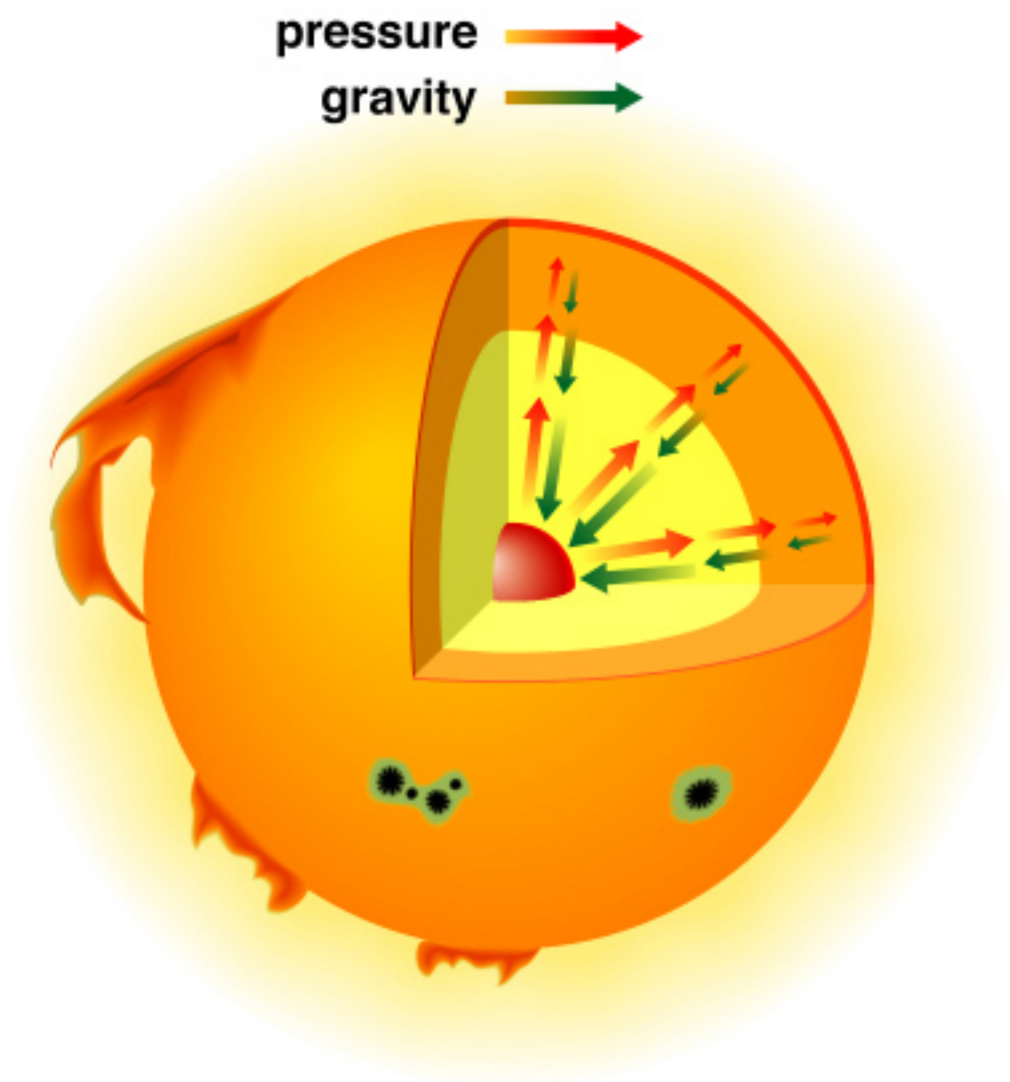
Chandrasekhar's upper mass limit

Any star is held apart by pressure and pulled together by gravity. Pressure is due to the motion of the particles that comprise a star; the faster the particles move, the greater the pressure.



Chandrasekhar's upper mass limit

But there is an upper limit on pressure, because there is an upper limit on the speed of the particles: nothing can go faster than light. If we add mass to a white dwarf, it gets denser, and the gravity that pulls it together grows stronger.



Chandrasekhar's upper mass limit

The pressure also increases as we add mass, but there is no limit on the force of gravity pulling the star together. And there is a limit to the pressure.

So as we add mass to a white dwarf, the gravity pulling it together will always beat the pressure pushing it apart, and the mass at which gravity wins — for which the electrons would have to go faster than light to keep the star apart — is **1.4 solar masses.**

Chandrasekhar's upper mass limit

This means that no white dwarf can have a mass greater than 1.4 solar masses!

Its electrons would have to travel faster than light to supply the pressure needed to keep it from collapsing.

This limit was discovered in 1930 by a 20 year-old student, **Subrahmanyan Chandrasekhar**, who was on a ship traveling from India to England, where he was going to do graduate work with Eddington (who we met when discussing hydrogen fusion in the Sun).

The argument explained the last great mystery of ancient astronomy, the sudden appearance and fading of new bright stars, called "guest stars" by the Chinese, new stars by the Europeans.

Because Eddington (the leading astrophysicist of his day) did not accept the argument — he thought that some new physics would arise to protect white dwarfs from collapse — it took decades before Chandrasekhar's work was understood and accepted by astronomers.

Fifty years after his discovery, in 1983, the Nobel committee finally gave Chandra the prize.

Chandrasekhar at about the time he found that the upper limit on the mass of white dwarfs was set by the upper limit *c* on the speed at which electrons can travel.

The Chandra X-ray Observatory, shown here in a composite image with a supernova remnant, is named for Chandrasekhar.

Matter is supported against gravity by its pressure, and the pressure of a collection of particles depends on the particles' speed. There is an upper limit on the speed at which a particle can travel — and hence an upper limit on the pressure that matter can exert. But there is no upper limit on the gravitational force.

When the mass of a dense object is too large, gravity overwhelms pressure and the object **collapses**.

If a white dwarf accretes too much mass from a companion, or if it merges with another white dwarf, its mass will exceed the Chandrasekhar limit. What happens then?


OMG, IF YOU KEEP ACCRETING CAT BISCUITS AT THAT RATE YOU'RE GOING TO REACH THE CHANDRASEKHAR LIMIT SOON

Supernovae

If a white dwarf accretes too much mass from a companion, or if it merges with another white dwarf, its mass will exceed the Chandrasekhar limit. What happens then?

Nearly all the electrons in the star are pulled onto the protons in the helium and carbon nuclei, turning the protons into neutrons and turning the star into a giant atomic nucleus, called a neutron star.

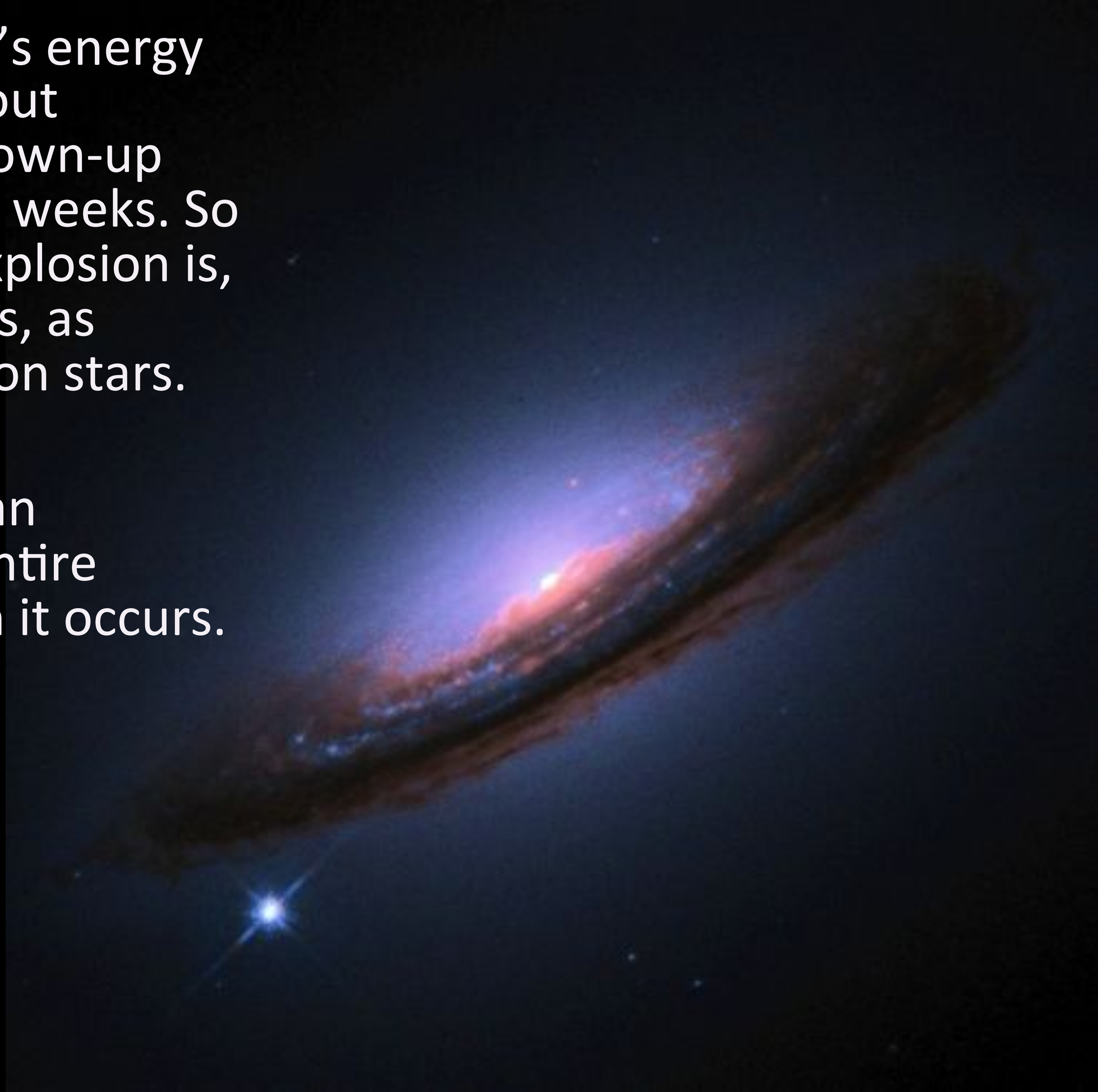
Remember that an atom is mostly empty space — our scale model was a marble in the center of the Astrodome, with the electrons at the dome and nothing inside.

When a white dwarf collapses, the electrons are pushed down onto the nuclei — the astrodome collapses to the size of a marble. When each of its atoms collapses, the star collapses from the size of the Earth to the size of Milwaukee, about 20 km (13 mi) in diameter.

More energy is released in a few seconds by the collapse than by the slow contraction of a red giant's core that helps power the giant for 100 million years.

The supernova's energy works its way out through the blown-up star over a few weeks. So a supernova explosion is, for a few weeks, as bright as a billion stars.

A supernova can outshine the entire galaxy in which it occurs.



A **Type I supernova** is the violent gravitational collapse of a white dwarf pushed over its upper mass limit.