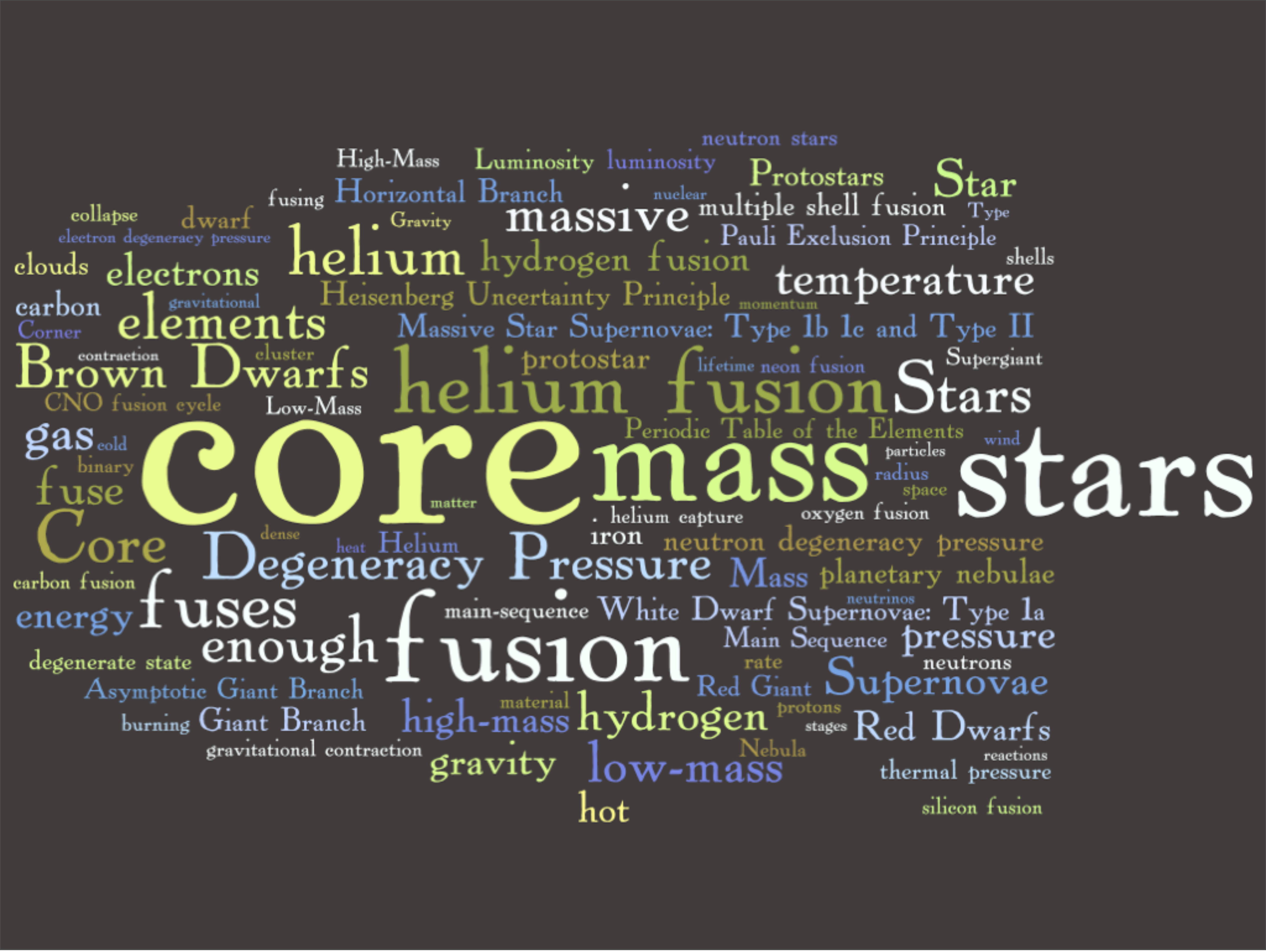
Star Stuff

Chapter 12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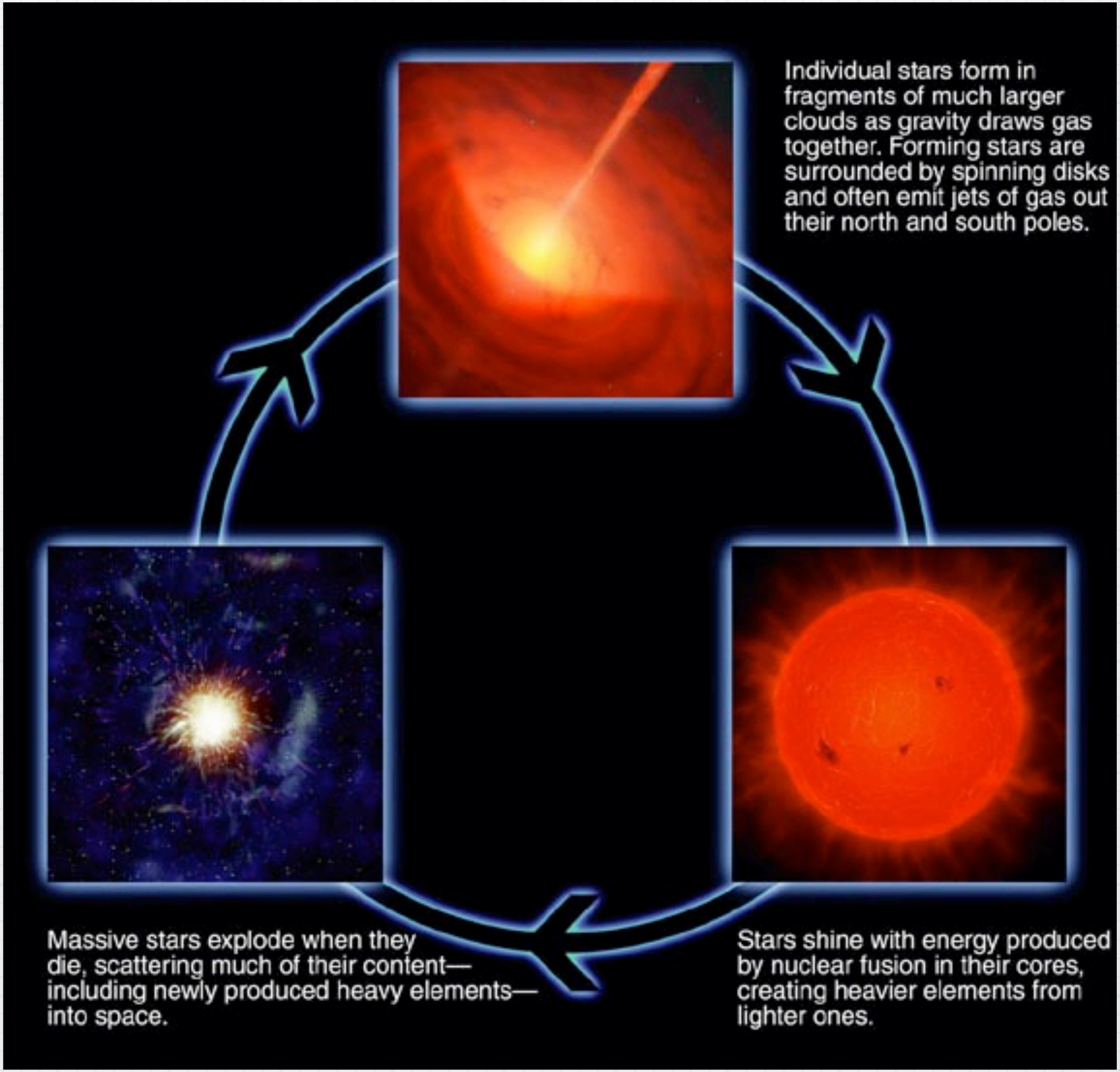
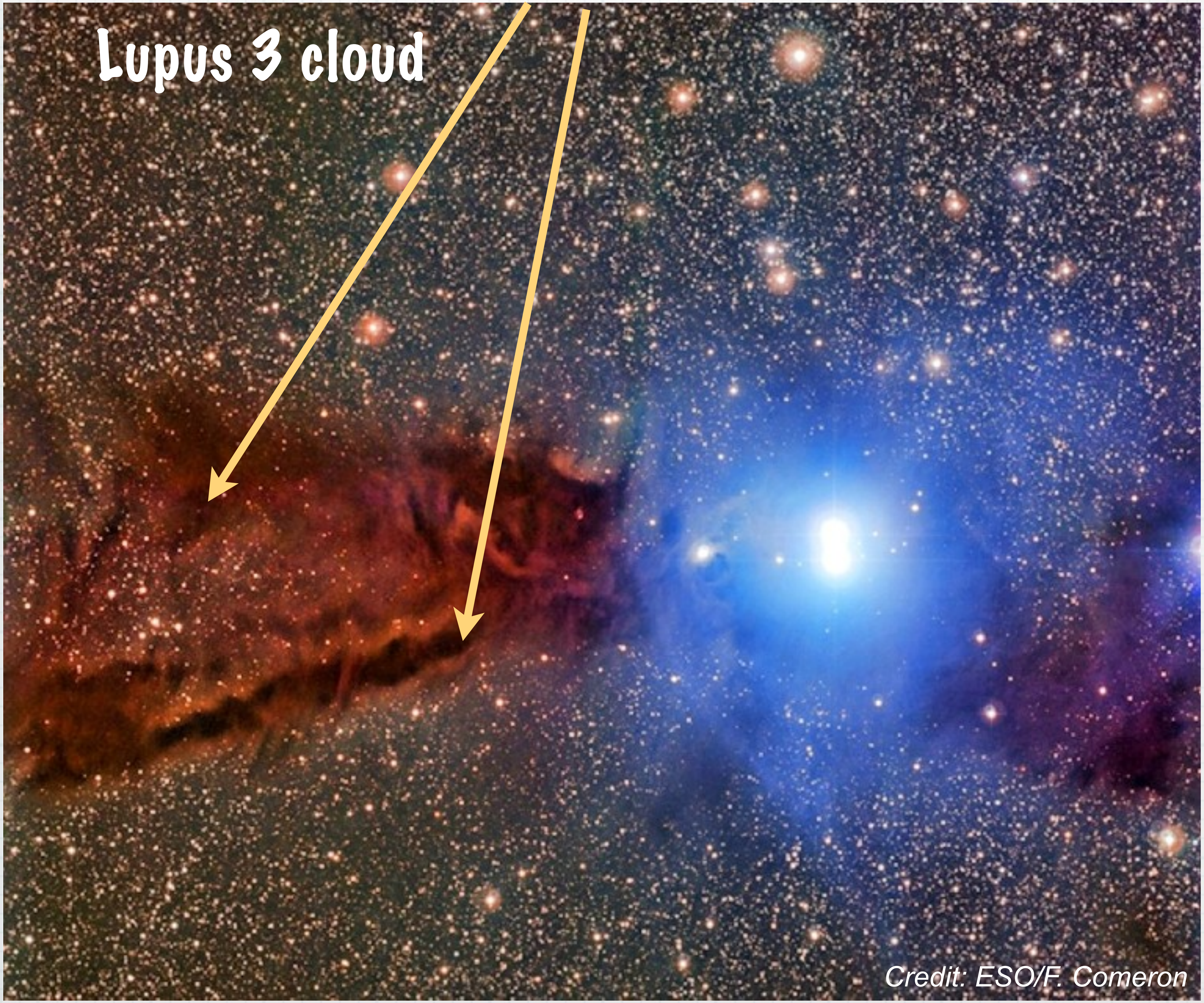
Stars seed their birth galaxies with heavier elements



Star Birth

* Stars form **in cold, dense clouds** made of hydrogen and helium
* They are called **molecular clouds** because H_2 molecules form (cold enough) and heavier elements are there too and can form more complex molecules

Stars are born in molecular clouds consisting mostly of hydrogen molecules

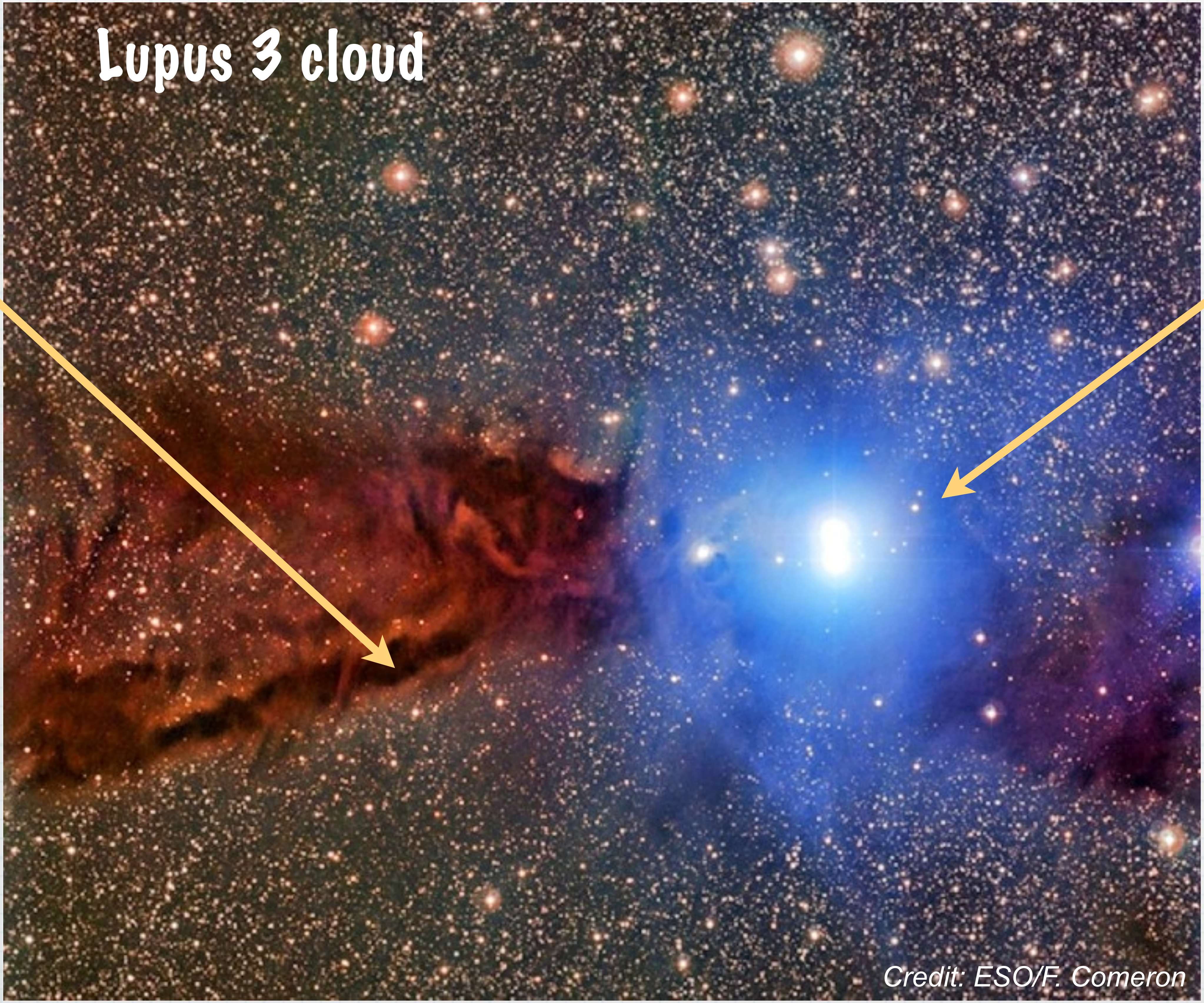


Star Birth...

* How do stars form?
  * Gravity compresses each cloud toward their densest regions
  * and they fragment there in numerous pieces - each one will form one or more stars

Stars form in places where gravity can overcome thermal pressure in a cloud

cold gas

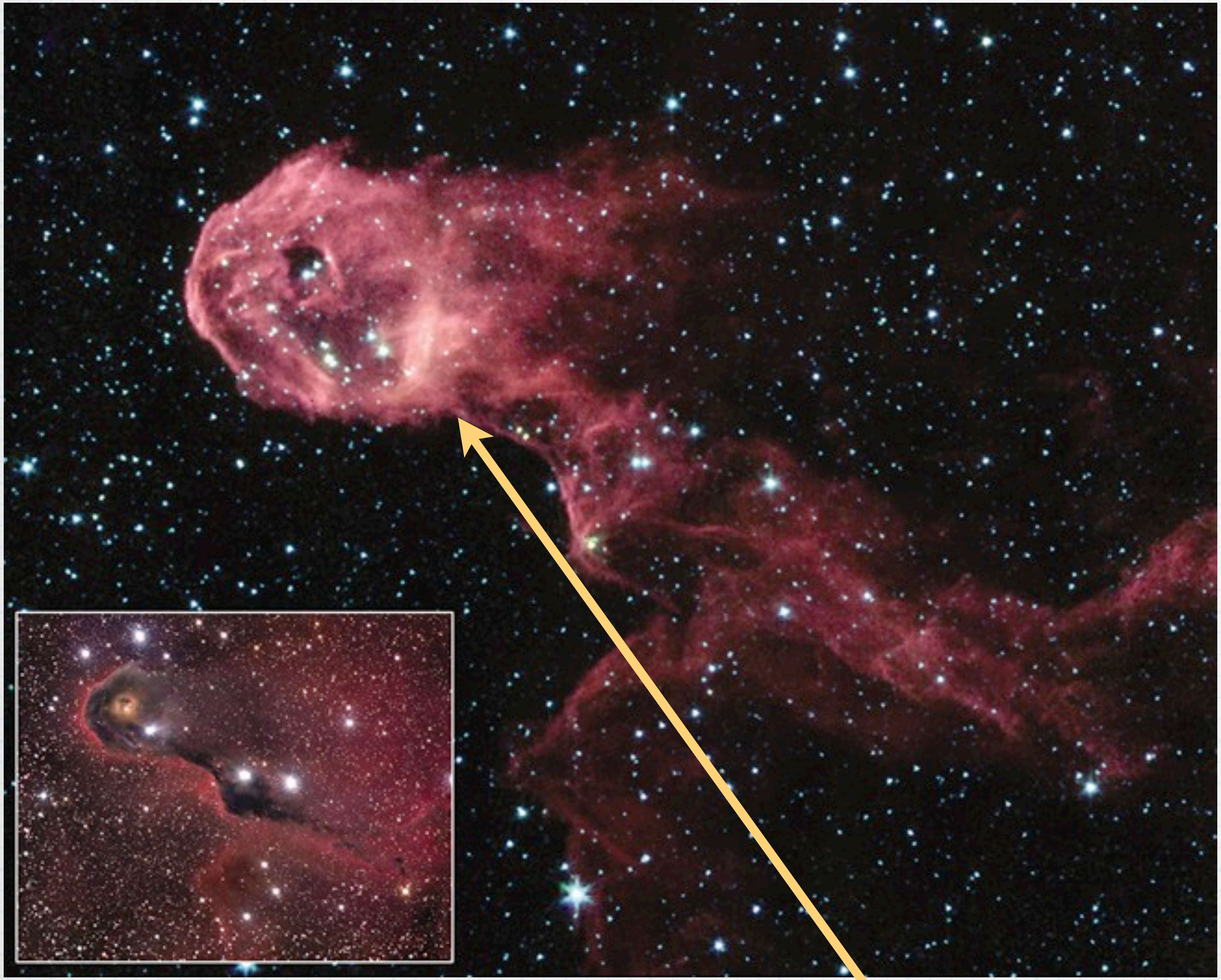


hot gas

Cloud heats up as gravity causes it to contract

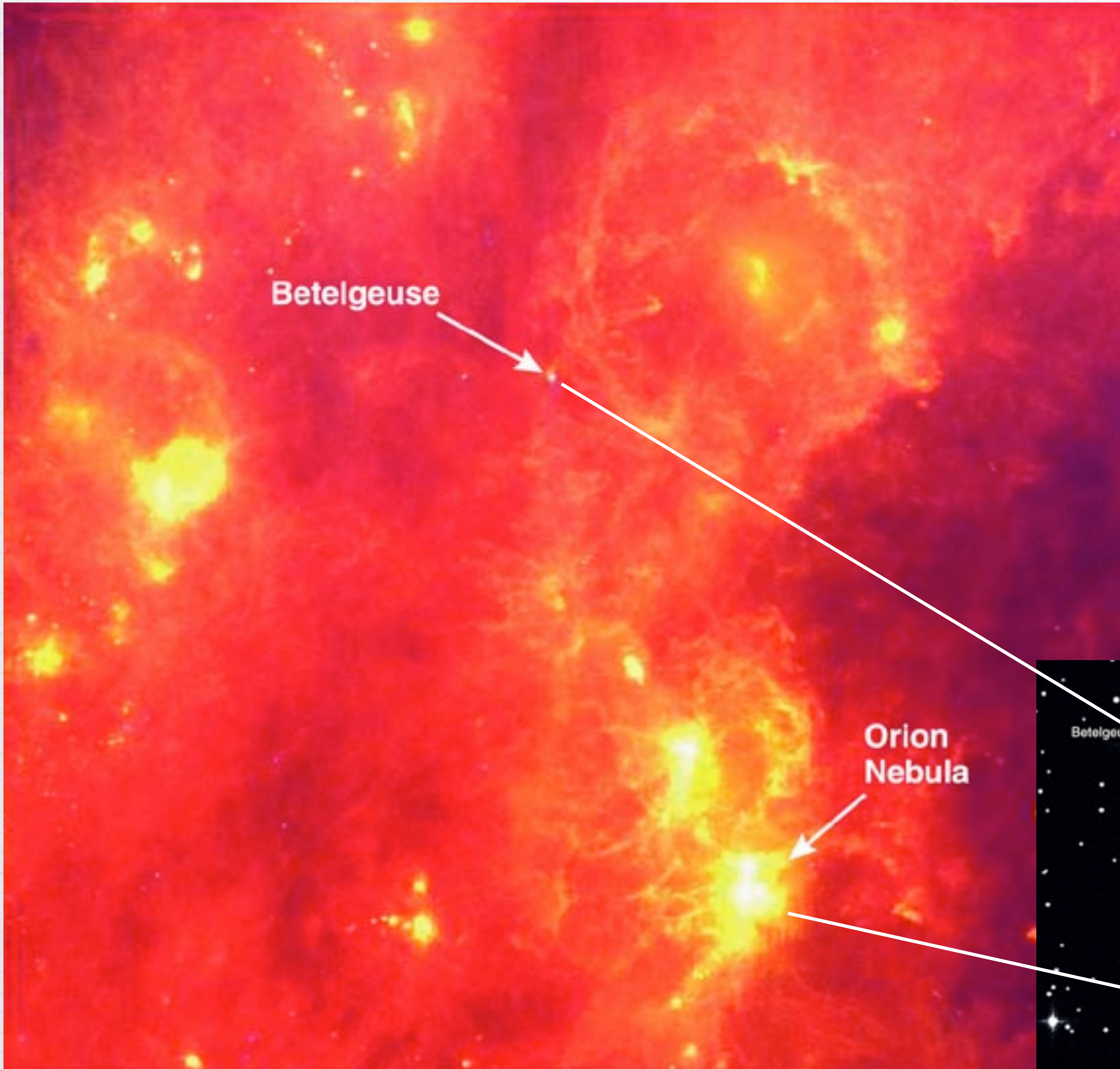
(due to the conservation of energy laws)

Contraction can continue if thermal energy is radiated away (cold gas does not have much internal pressure)



Star-forming clouds emit infrared light because of the heat generated as stars form

Infrared light from Orion



Orion Nebula is one of the closest star-forming clouds

hotter cooler

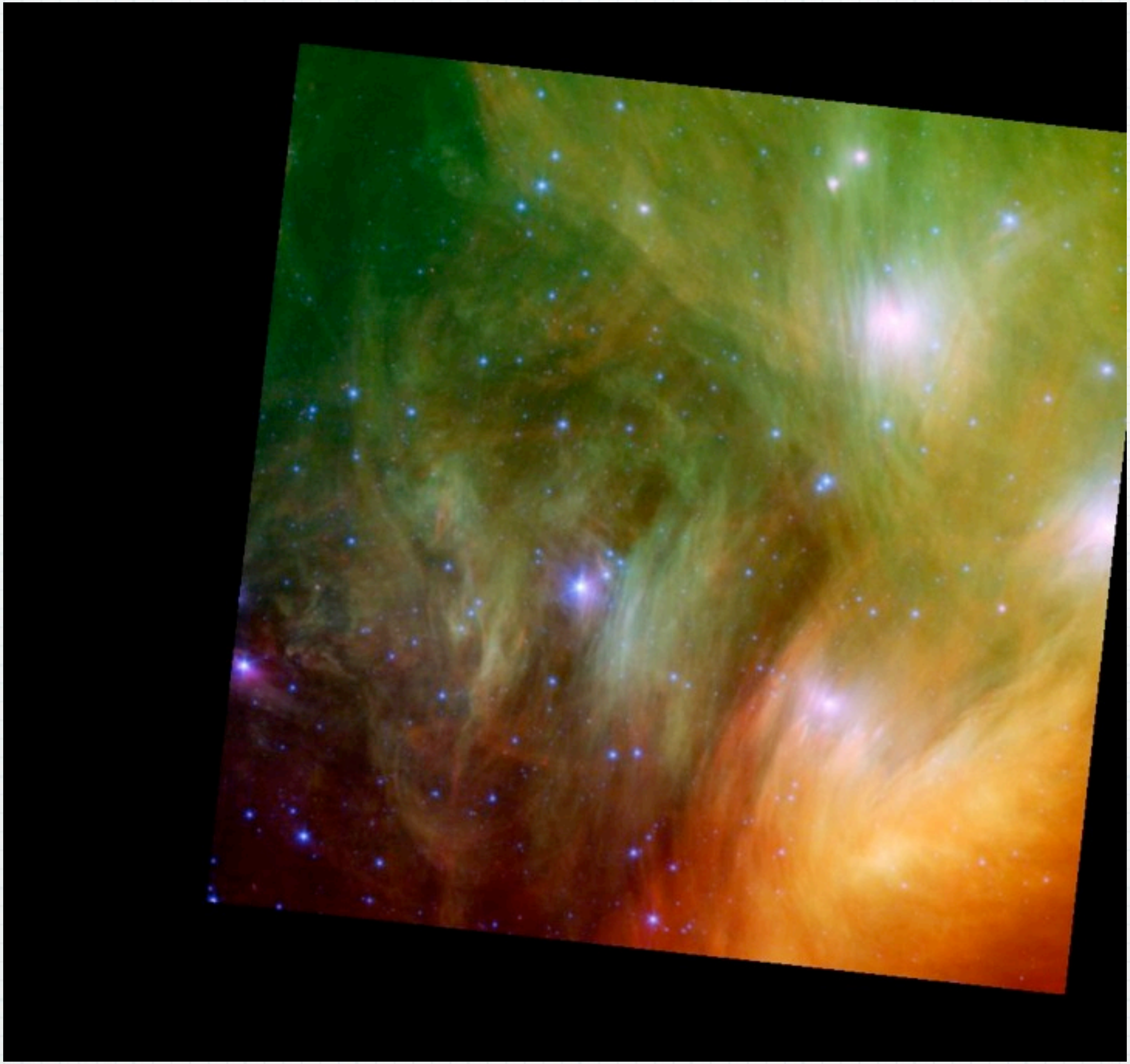
Visible Light

The Pleiades

A new star cluster

Some gas and dust can be "seen"

IR Light



The Pleiades

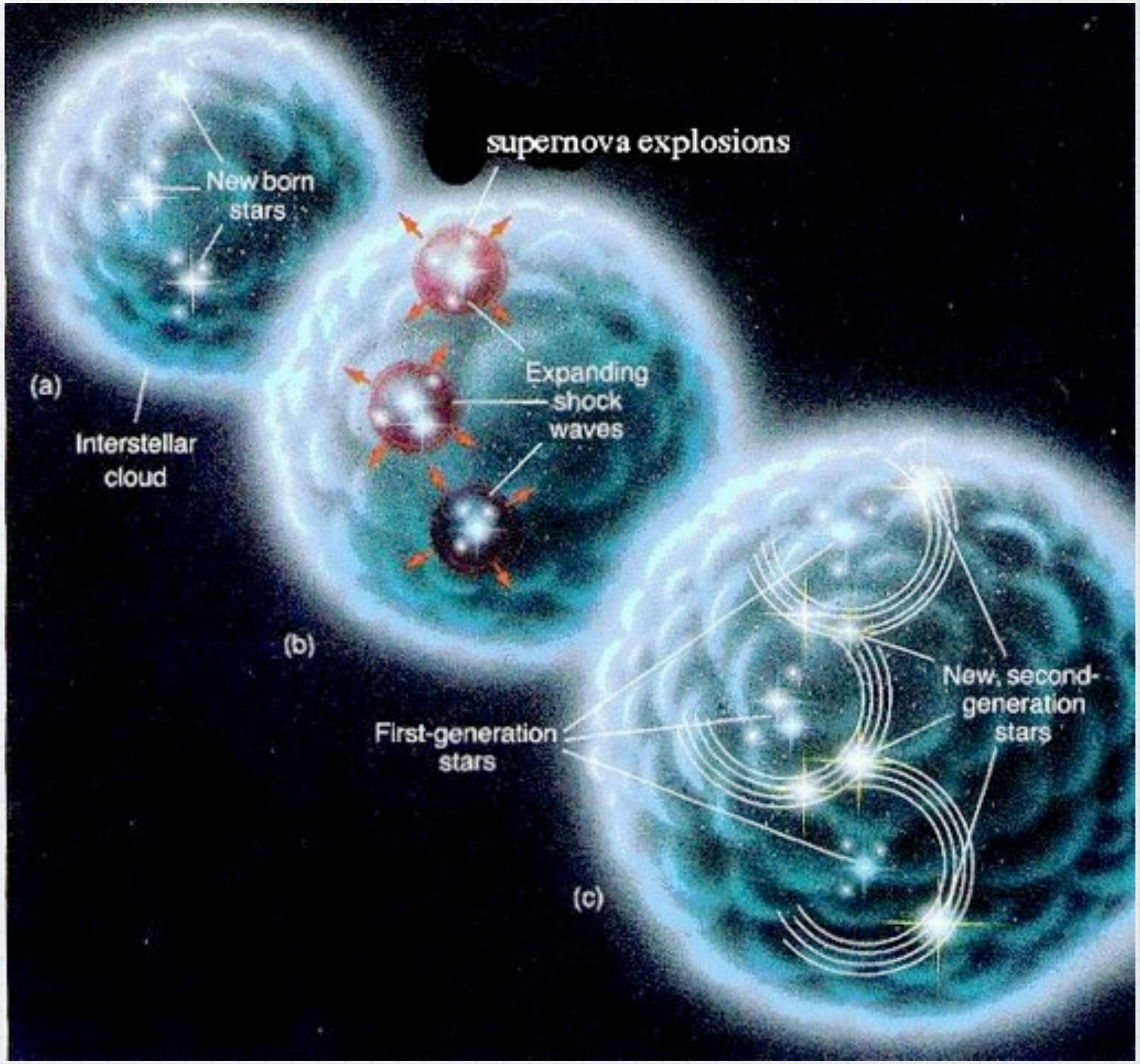
A new star cluster

Gas and dust are quite obvious now

Triggering Star Formation

* Several events might occur to compress a molecular cloud and initiate its gravitational collapse
* Molecular clouds may collide with each other, or a nearby supernova explosion can be a trigger, sending shocked matter into the cloud at very high speeds
* Alternatively, galactic collisions can trigger massive starbursts of star formation as the gas clouds in each galaxy are compressed and agitated by tidal forces.

Supernovae trigger star formation by disturbing nebular clouds



Colliding galaxies are common in galaxy evolution - it leads to a merging of the material

Protostars

* We have talked at length before on how a cloud collapses, heats up, spins, flattens and forms a solar nebula
* Let's see in more details how a star forms out of it

Protostars...

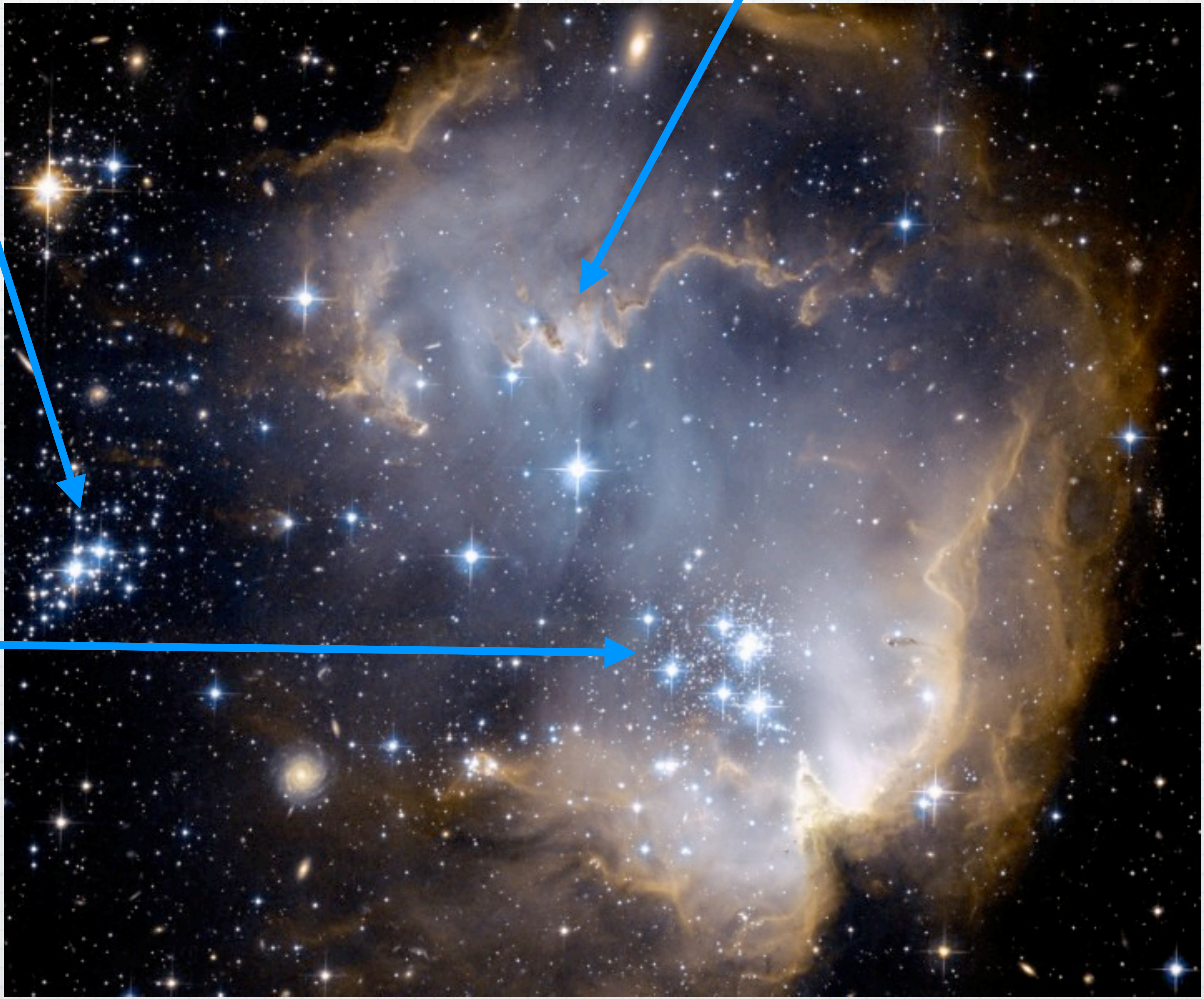
* Gravity pulls material inward and condenses it
* Gravity also tends to fragment the contracting cloud into smaller and smaller pieces - leading to a star cluster
* Such fragmentation may also inhibit the formation of massive stars

Star cluster NGC 602

3) Those are forming now

1) These stars formed first

2) These were next



Protostars...

* The now many (smaller) clouds continue their contractions
* At some point, the heat is trapped as each central region becomes dense enough to trap infrared radiation

➡ The central temperature and pressure then rises dramatically

Protostars...

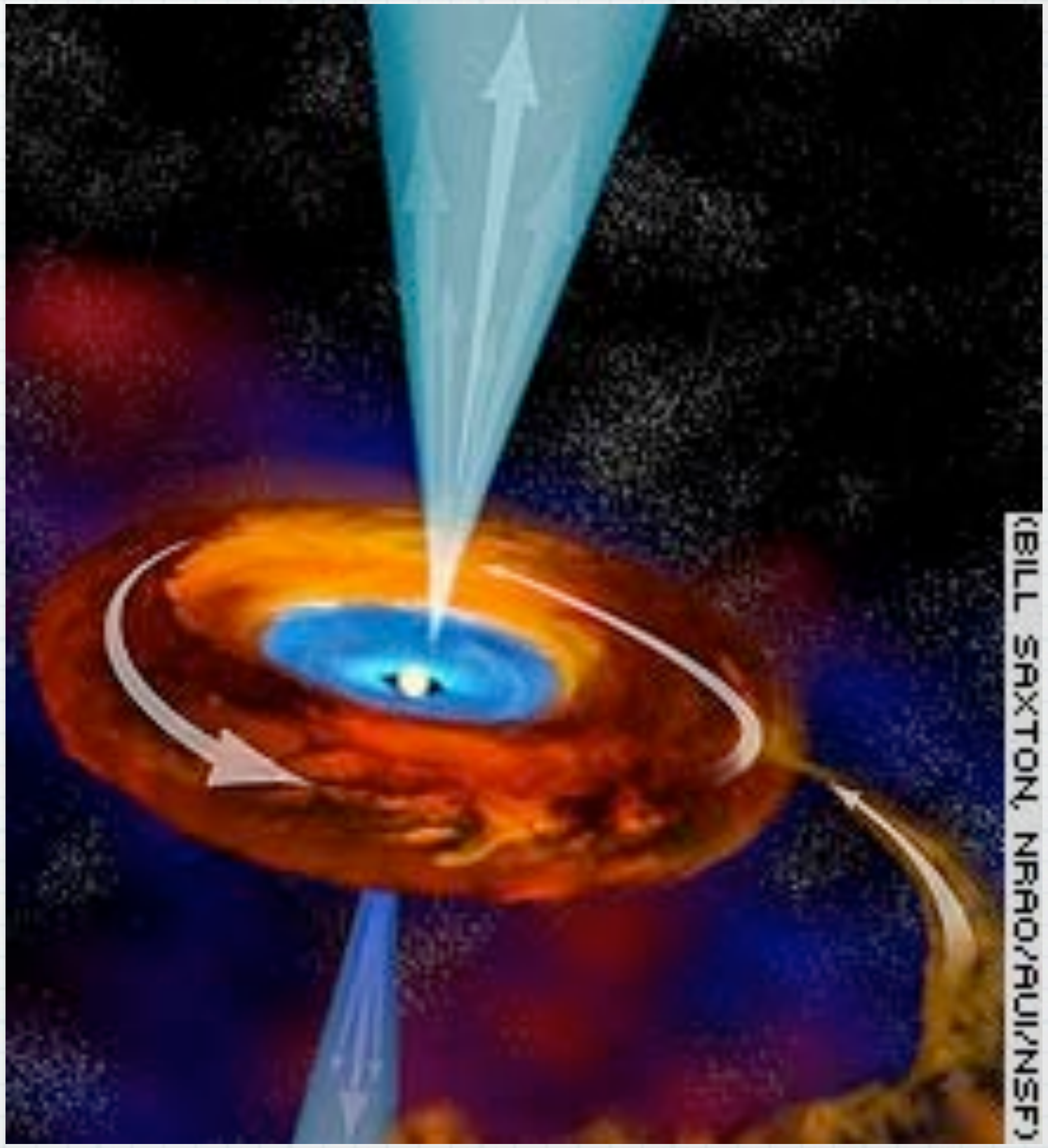
* The rising thermal pressure pushes back against the gravitational contraction, slowing it down
* Turbulences also develop and allow more material to be added to the cloud centers
* The dense center of each cloud is now a **protostar**

Protostars...

* Each protostar keeps on growing by adding gas from its surrounding cloud
* Those clouds spin faster and faster as they keeps on contracting
* Some may spins too fast and will split in two (or more) and will form a binary star system called a close binary system

Protostars...

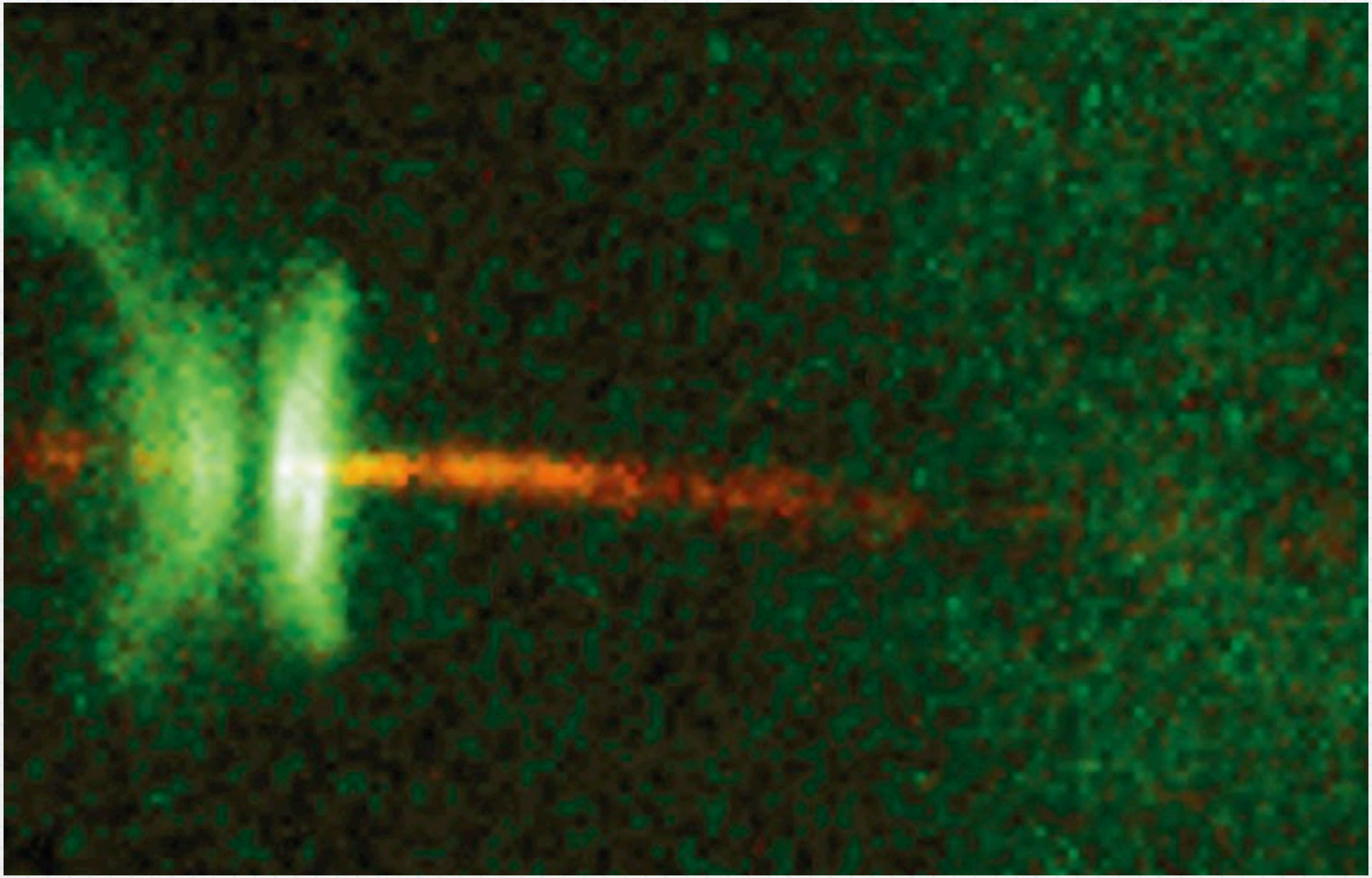
* Protostars can have violent stages
* It is not uncommon to observe them firing high-speed streams of gas into interstellar space
  * Those jets are probably due to magnetic fields



Protostars...

* At that time, a strong stellar wind starts clearing up gas around the forming star
* It also helps the protostar shed some angular momentum by carrying material off
* And the protostar's rotation slows down

Close-up view of jets (orange) and a disk of gas (green) around a protostar



Carina nebula: Dust pillars and protostars jets

Credit: NASA, ESA, and M. Livio and the Hubble 20th Anniversary Team (STScI)

Protostar to Main Sequence

* A that stage, the protostar's core temperature is 1 million K, **not hot enough for fusion**
* The protostar keeps contracting and heats until the core temperature is sufficient for **hydrogen fusion at about 10 million K**

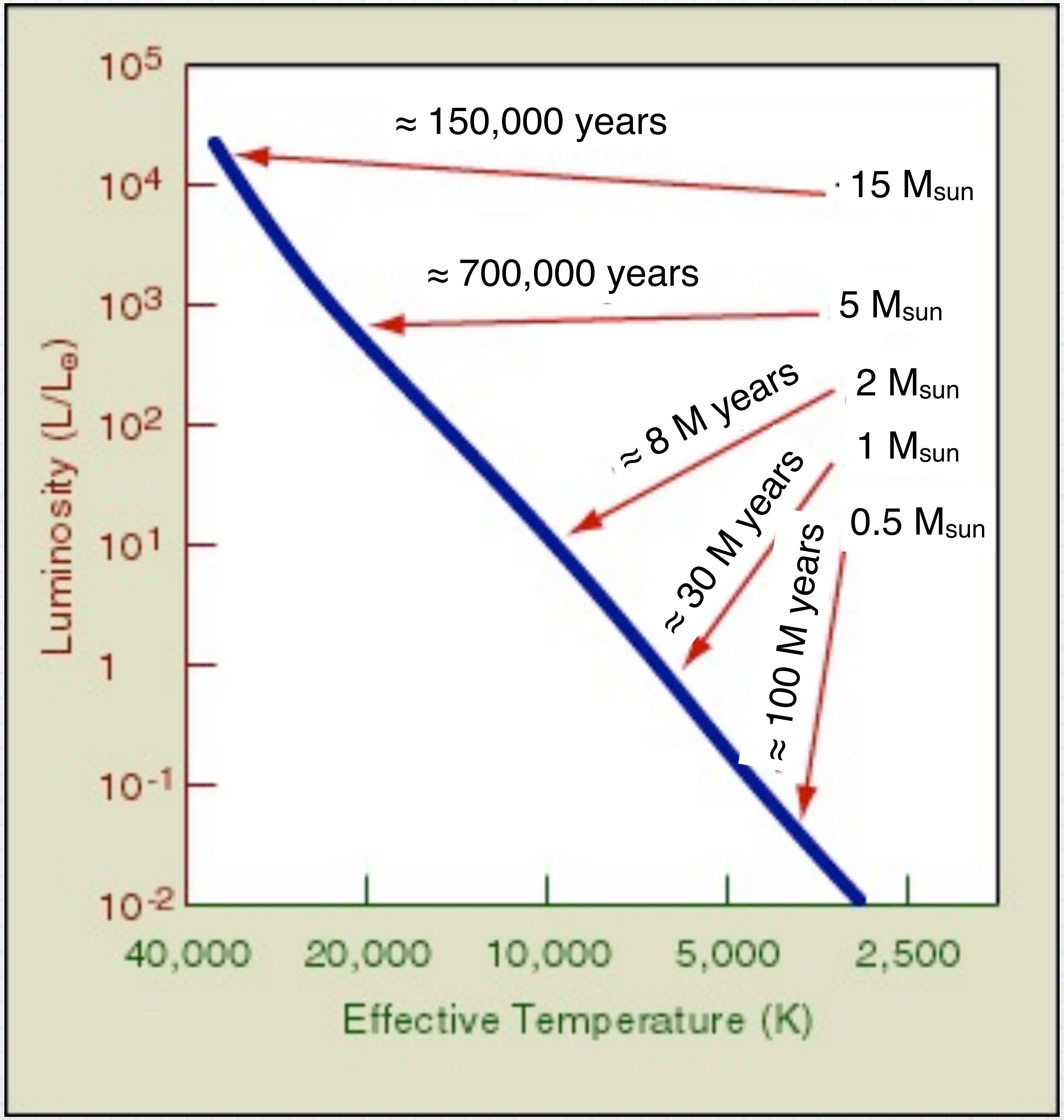
Protostar to Main Sequence...

* It takes about 30 million years for a star like the Sun (G) to fuse hydrogen
* O spectral type star may take about 150,000 years to get there
* M spectral type star may take over 100 million years
* The star is about to become a main-sequence star

Protostar to Main Sequence...

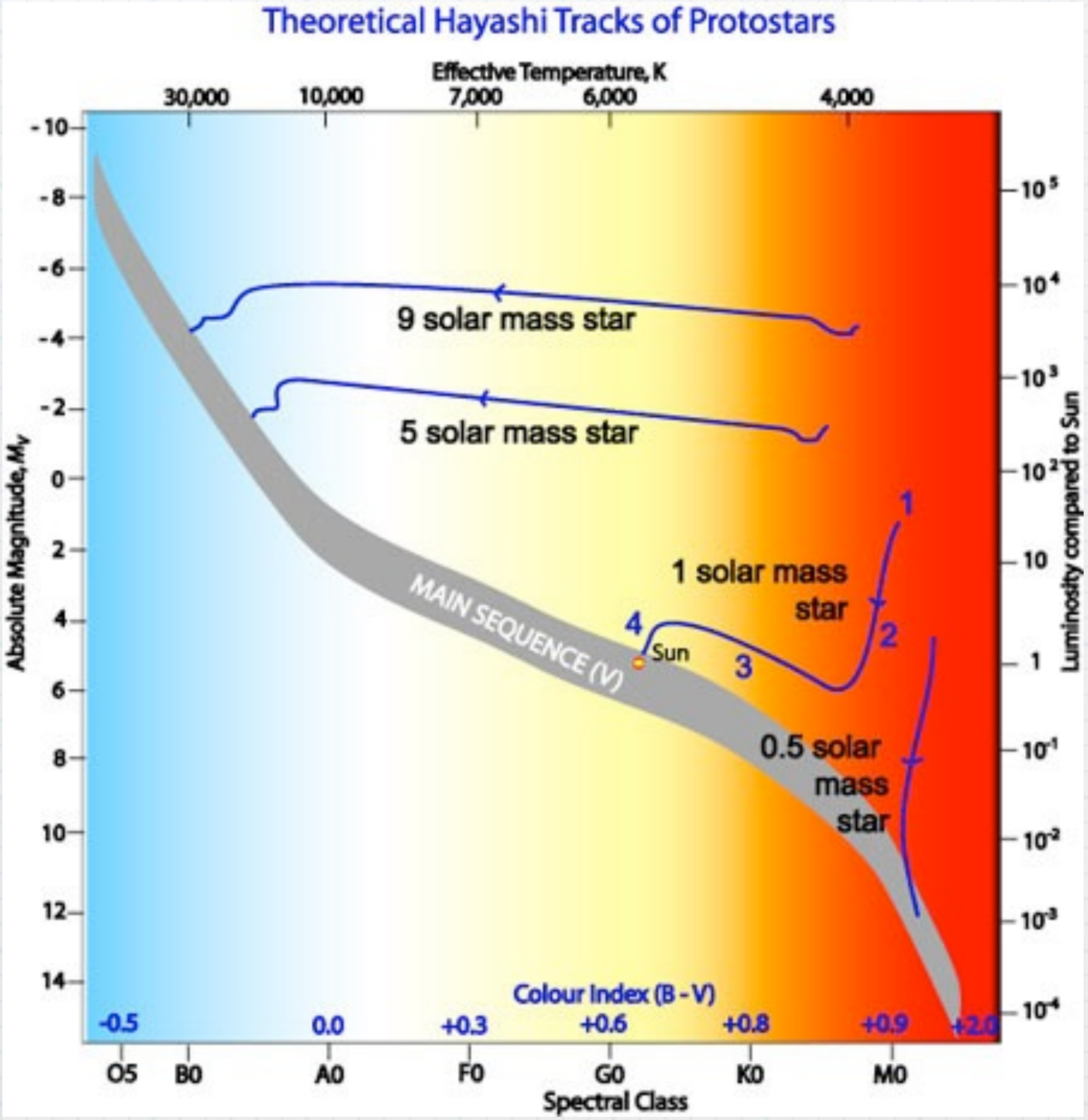
Approximate time for a star of a particular mass to reach the main sequence from birth

Note: It is possible for an O or B star to live and die before a M type starts fusing hydrogen in its core



Protostar to Main Sequence...

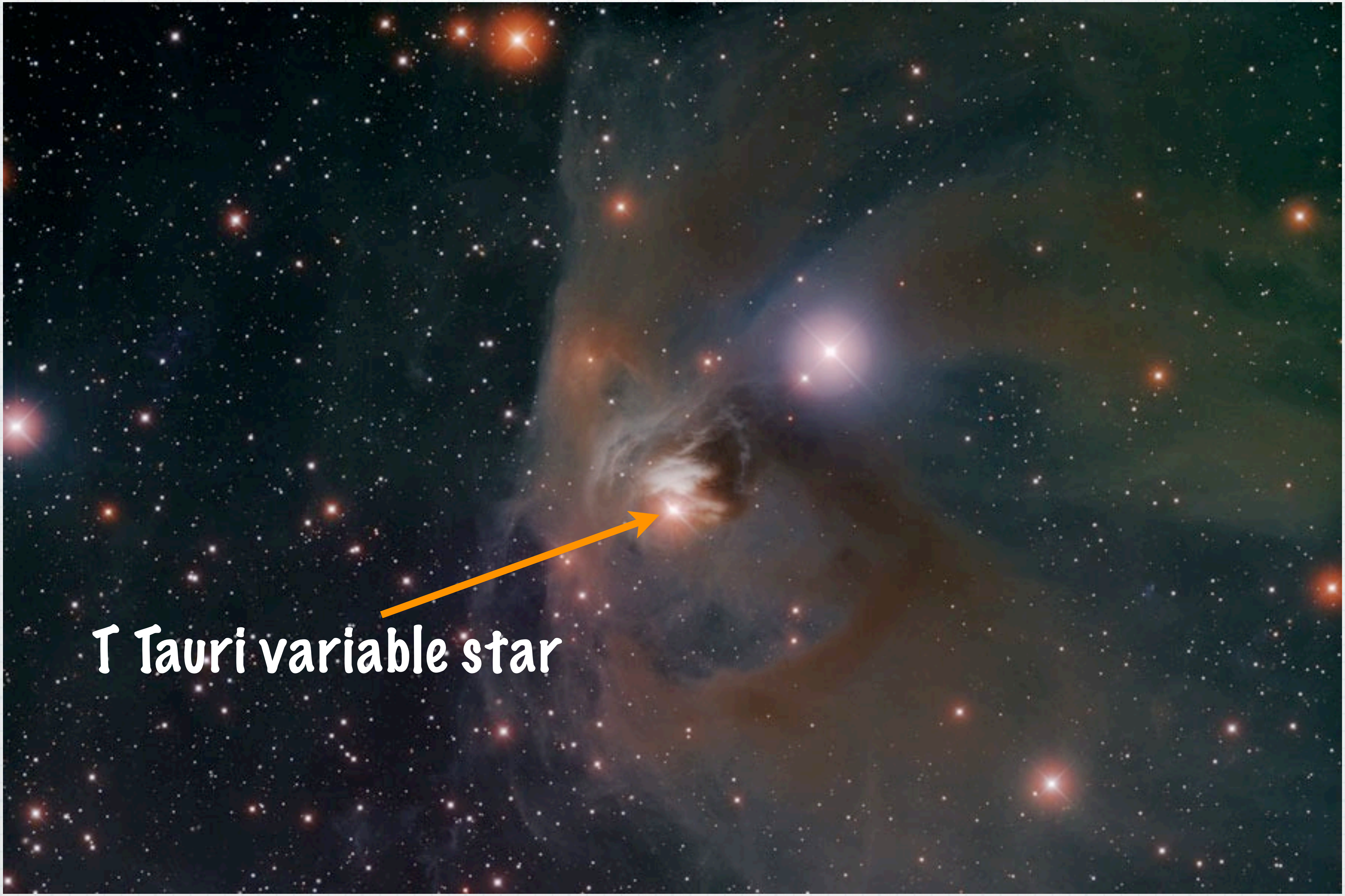
Approximate H-R path for a star of a particular mass to reach the main sequence from birth



T-Tauri Stars

* It is an intermediate stage between a protostar and a full fledged star
* When the star starts its fusion, a strong stellar wind blows part of the envelope and the rest of the gas near the star
* The light output is not constant: the star is "breaking in" its fusion engine

The Hind's Variable Nebula
(NGC 1554/1555)



Credit & Copyright: T. Rector & H. Schweiker

T-Tauri Stars...

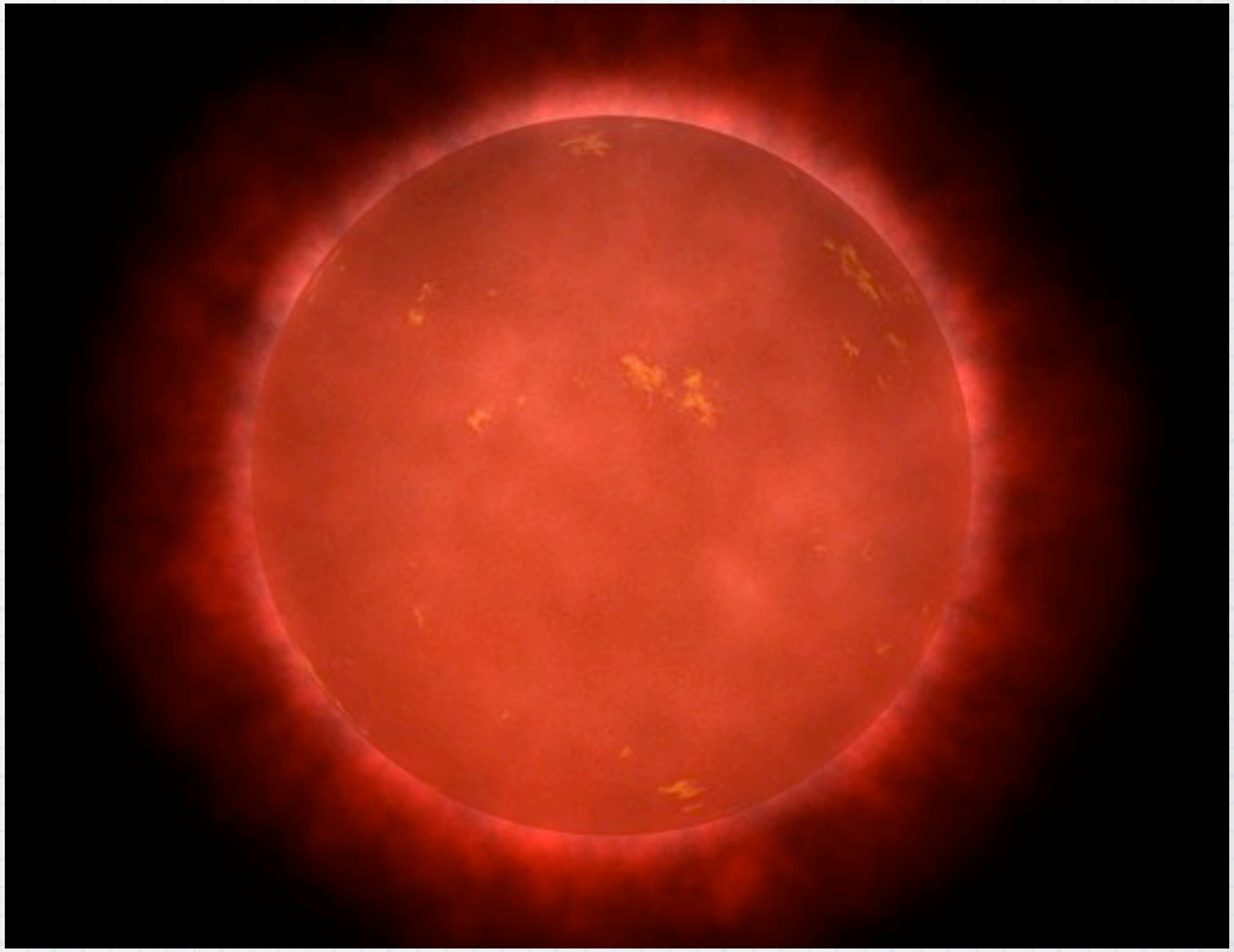
* T-Tauri type stars will eventually form stars of spectral types G, K, or M (red dwarf)
* A star in its T-Tauri phase can lose up to 50% of its mass
* Thus, **they may lose enough material that they fail to become stars and become brown dwarfs instead**

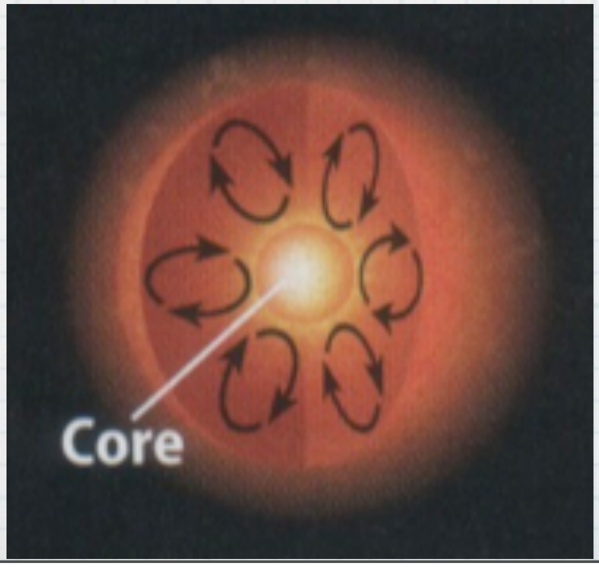
Red Dwarfs

* A red dwarf is a star with less than 0.4 the mass of the Sun but more than 0.08
* They have relatively low temperatures in their cores and fusion is happening at a slow rate
* In general red dwarfs transport energy from the core to the surface by convection as their radiation zone is very small (to non-existent)

Red Dwarfs...

* They "shine" in red and infrared
* Their lifetime can exceed 10 trillion years (for mass less than 0.1 solar mass)





Red Dwarfs...

* Red dwarfs are the most common star type in our Galaxy, at least in the neighborhood of the Sun
* Proxima Centauri, the nearest star to the Sun, is a red dwarf as are twenty of the next thirty nearest stars
* Due to their low luminosity, individual red dwarfs cannot easily be observed. None are visible to the naked eye

Brown Dwarfs

* A brown dwarf is a failed star (bottom right of main-sequence in a H-R diagram)
* It is a star which is not massive enough (less than 8% of the Sun mass) to start hydrogen nuclear fusion in its core (it will fuse deuterium for a little while)
* They shine in infrared as the energy from their gravitational collapse is converted to heat and light

Brown Dwarfs...

* Jupiter is too light to be classified as a brown dwarf
* A gas planet 13 times Jupiter mass would be classified as a brown dwarf (to about 75 Jupiter masses)
* In a stellar nursery, most objects are brown dwarfs

Brown Dwarf Schematic

Although brown dwarfs are similar in size to Jupiter, they are much more dense and produce their own light whereas Jupiter shines with reflected light from the Sun

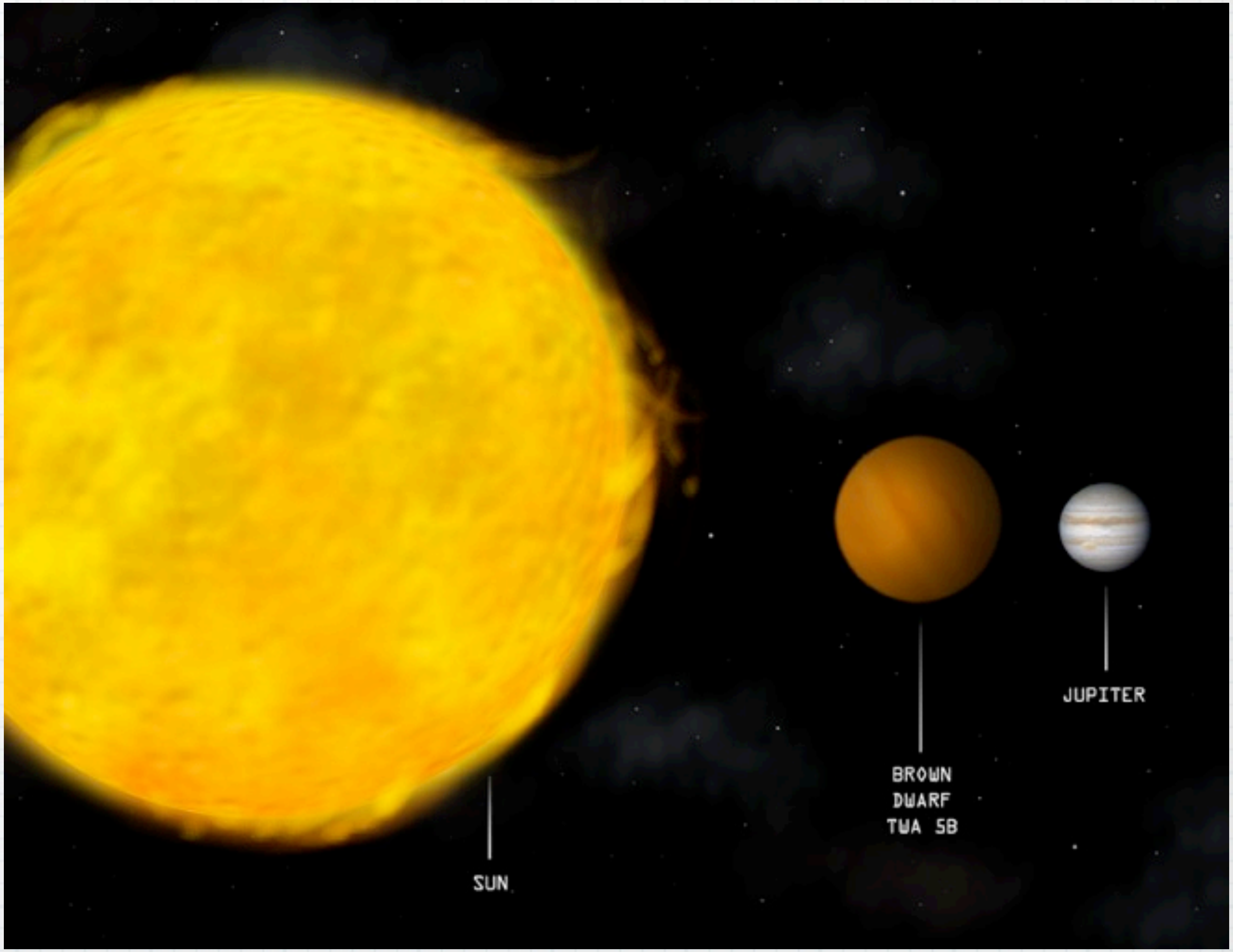
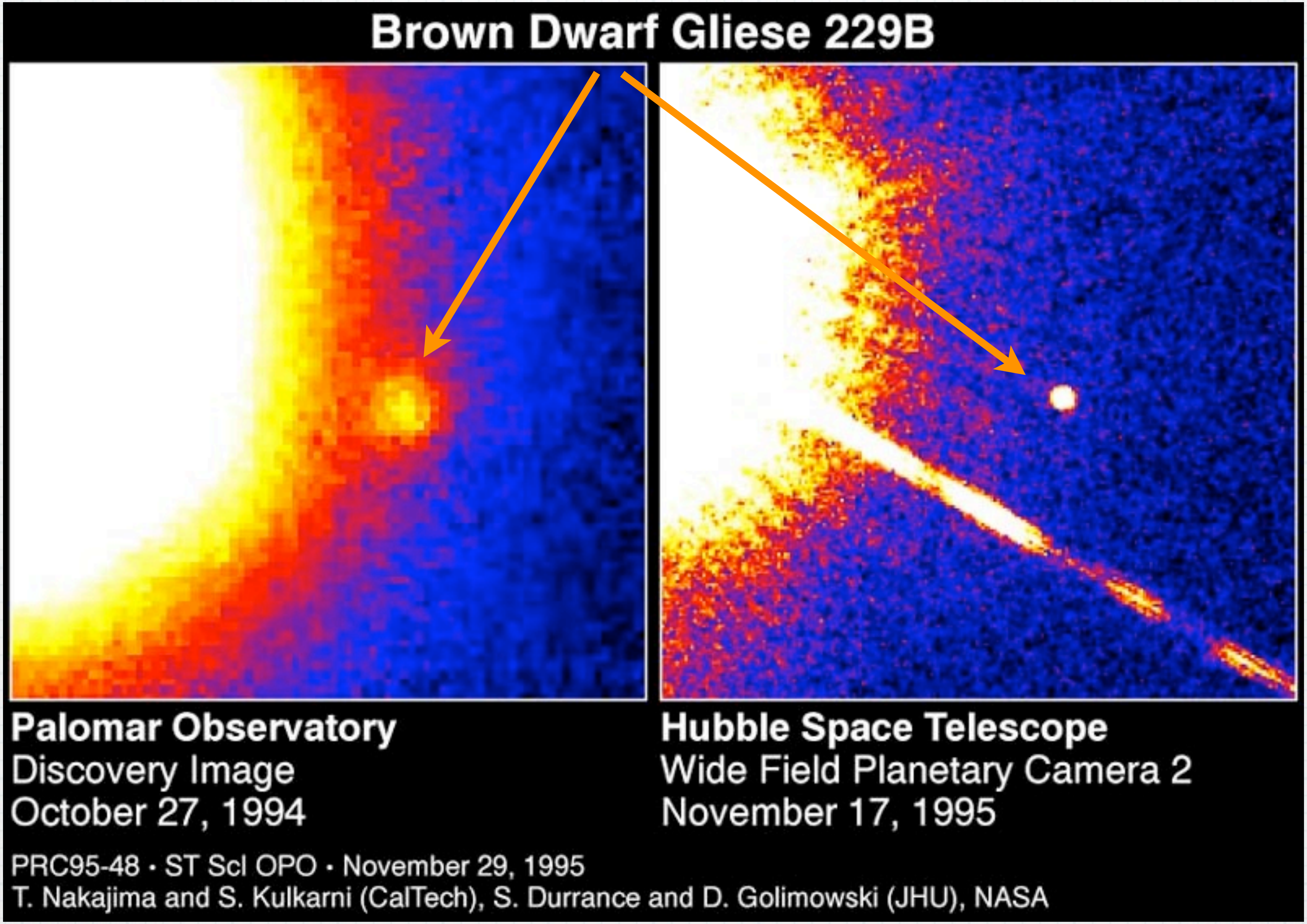


Illustration: NASA/CXC/M.Weiss

The approximate size of a brown dwarf (center) compared to the Sun (left) and Jupiter (right)

10 to 50 times Jupiter's mass



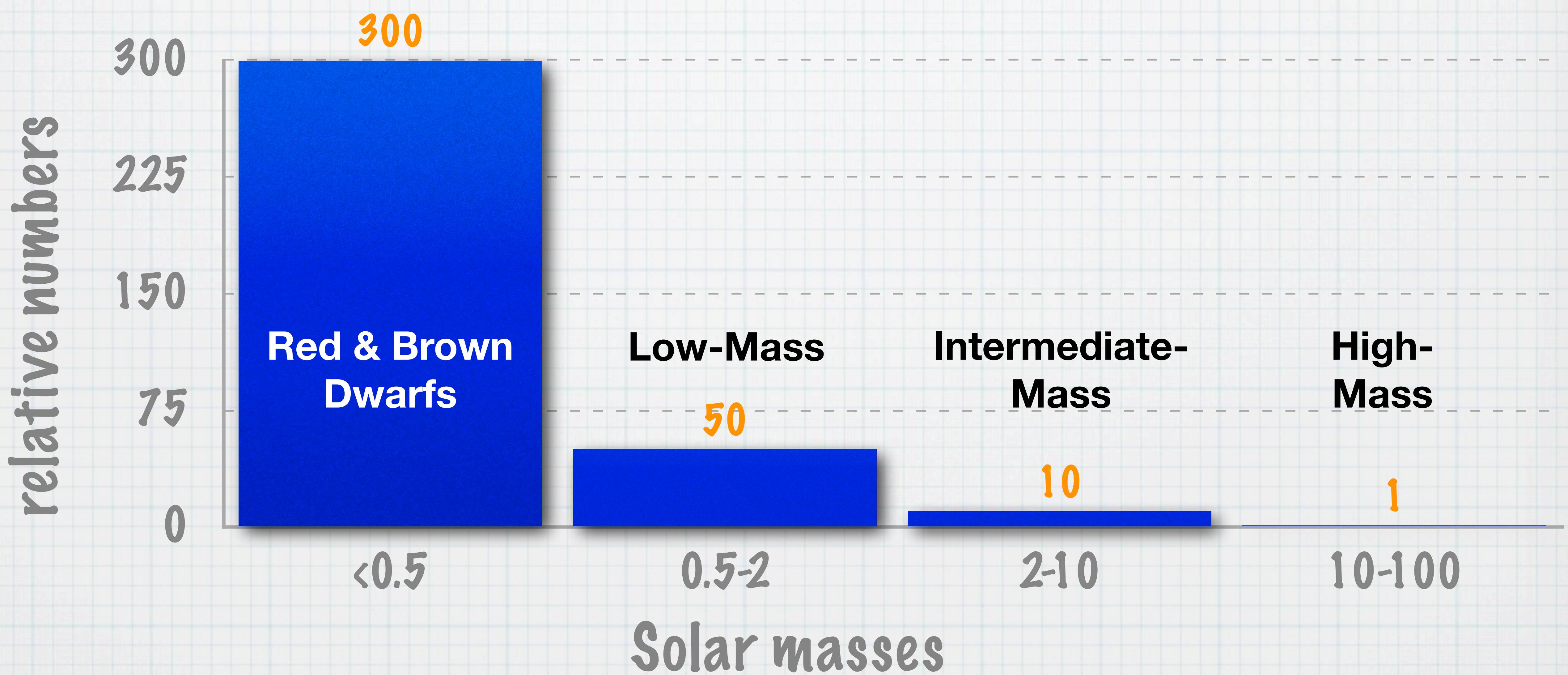
How massive are newborn stars?

* Mass is everything for a star
* There are many more low-mass stars forming from a cloud than high-mass ones
* And even many many more red and brown dwarfs

How massive are newborn stars?...

* For every **one** **10-100** solar mass star
* there are **ten** **2-10** solar mass ones,
* **fifty** **0.5-2** solar mass ones, and
* a **few hundreds** < 0.5 solar mass
* and we know low mass stars way outlive high mass stars

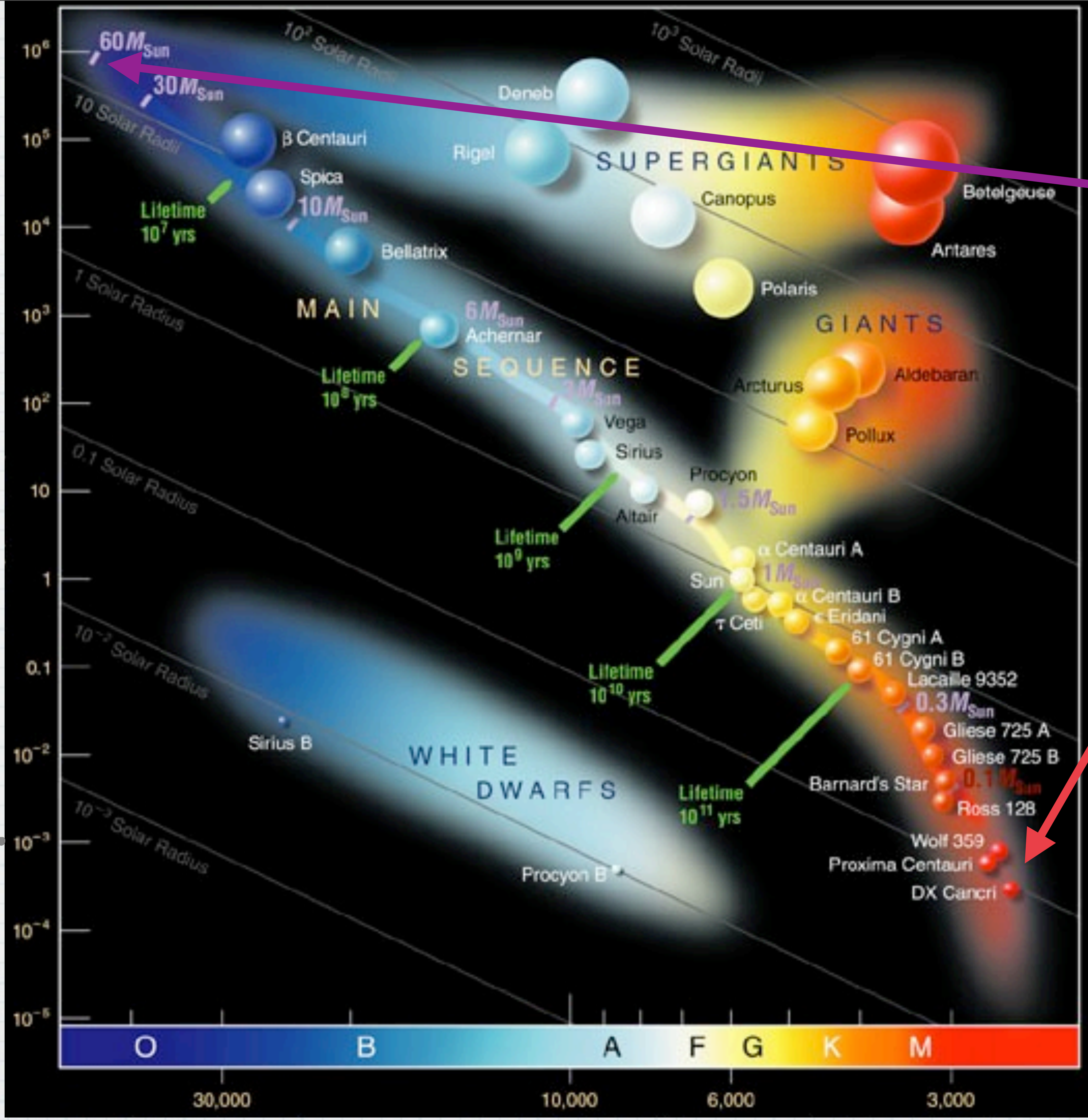
Relative number of stars of different masses



M45, The Pleiades, a young open star cluster

Many stars can form out of a single cloud

M45 is composed of about 1,000 stars with a total mass of about 800 M_{Sun}

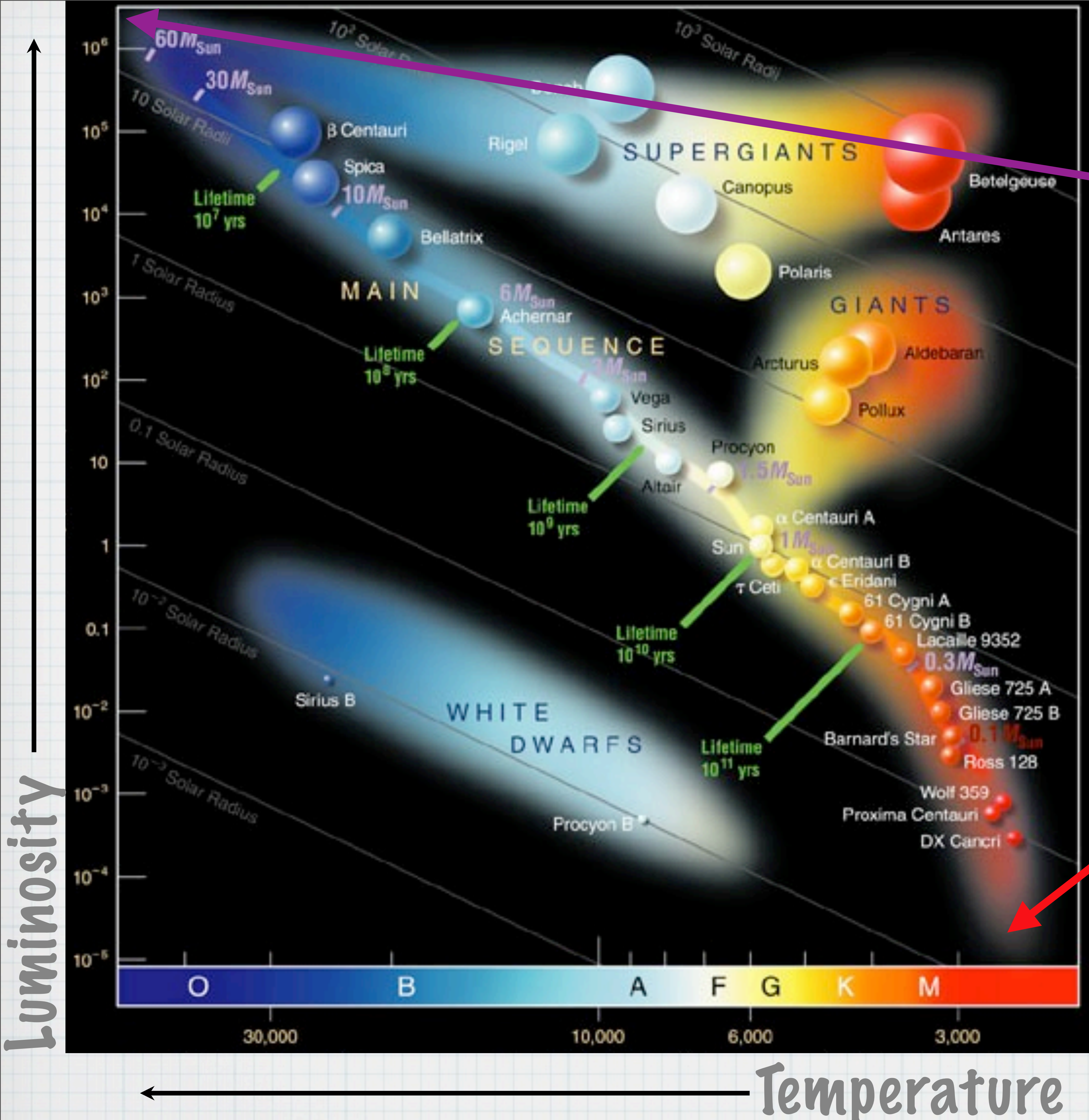


Luminosity

Temperature

Very massive stars are rare

Low-mass stars are common



Stars more massive than about 150 MSun would blow apart when they start fusion

Stars less massive than 0.08 MSun can't sustain fusion

Pressure ⟷ Gravity

- If $M > 0.08\ M_{Sun}$ then gravitational contraction heats the core until fusion begins

- If $M < 0.08\ M_{Sun}$ then **electron degeneracy pressure** stops gravitational contraction before fusion can begin

Physics Corner
Pauli Exclusion Principle

* The **Pauli exclusion principle** is a quantum mechanical principle formulated by Wolfgang Pauli in 1925
* It states that **particles that compose matter cannot be identical** (have the same state) **when near each other**
* **For example, electrons in a single atom cannot be identical** (they have different states)

Physics Corner
Particle Properties (state)

	quark	electron	neutrino
mass	X	X	X*
spin	X	X	X
charge	X	X	
color charge	X		

* neutrinos can change mass as they travel

Physics Corner
Fermions

* Fermions are the particles that compose matter
* Quarks, neutrinos and electrons (and their corresponding anti-particles) are fermions
* Composite fermions (such as protons and neutrons) are essential building blocks of matter

Physics Corner
Uncertainty Principle

$$\Delta x \,.\, \Delta p \geq \frac{h}{4\,\pi}$$

* In quantum physics, the Heisenberg uncertainty principle states that certain physical quantities, like the position (x) and momentum (p) of a particle, cannot be measured precisely at the same time
* The better we can measure one, the less we know the other

Physics Corner
Degeneracy Pressure

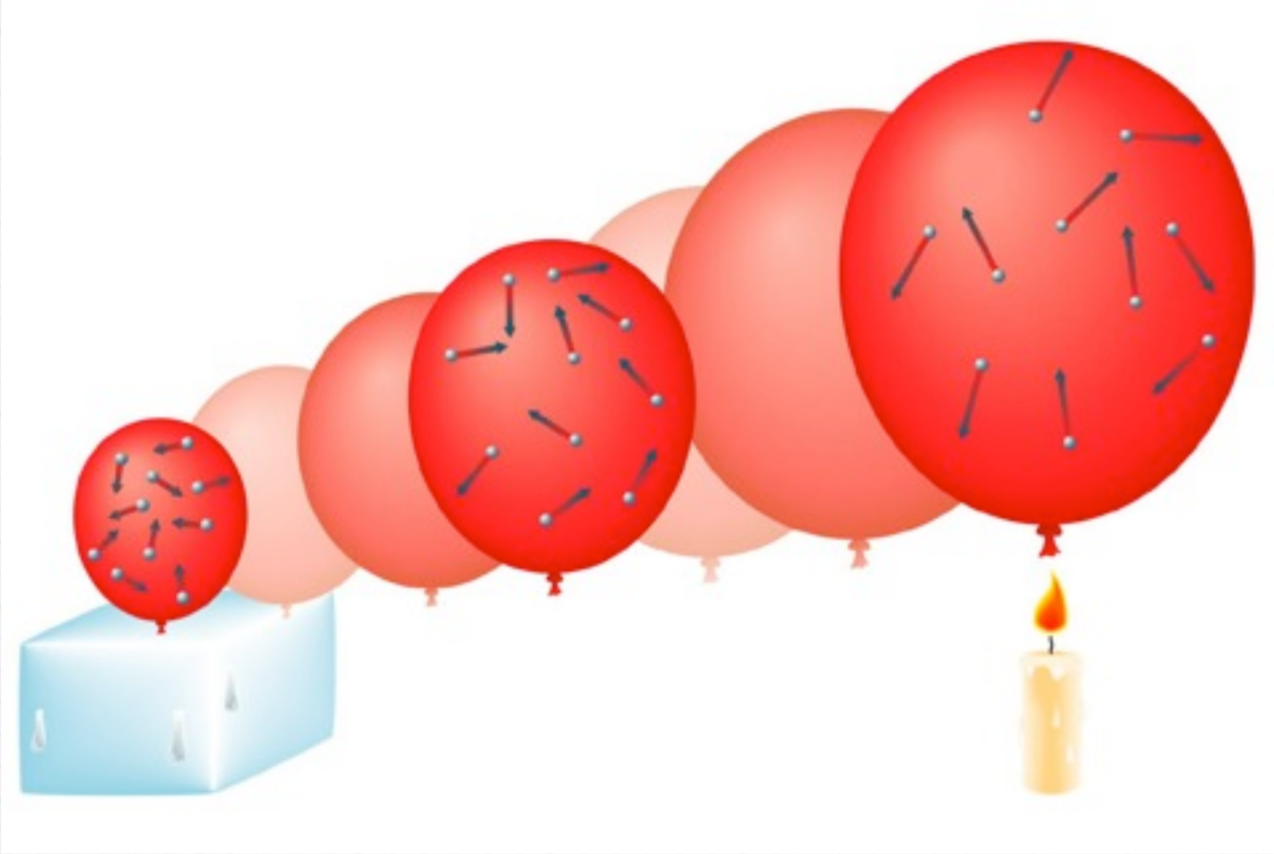
* The more you try to pin, say, electrons down in a certain position, the more they try to escape by moving faster (Heisenberg's Uncertainty Principle)

$$\Delta x \,.\, \Delta p \geq \frac{h}{4\,\pi}$$

* "Squishing" electrons is akin to pinning them down to a location
* So electrons resist further compression, i.e. they exert a counteracting pressure: the **degeneracy pressure**

Physics Corner
Degeneracy Pressure

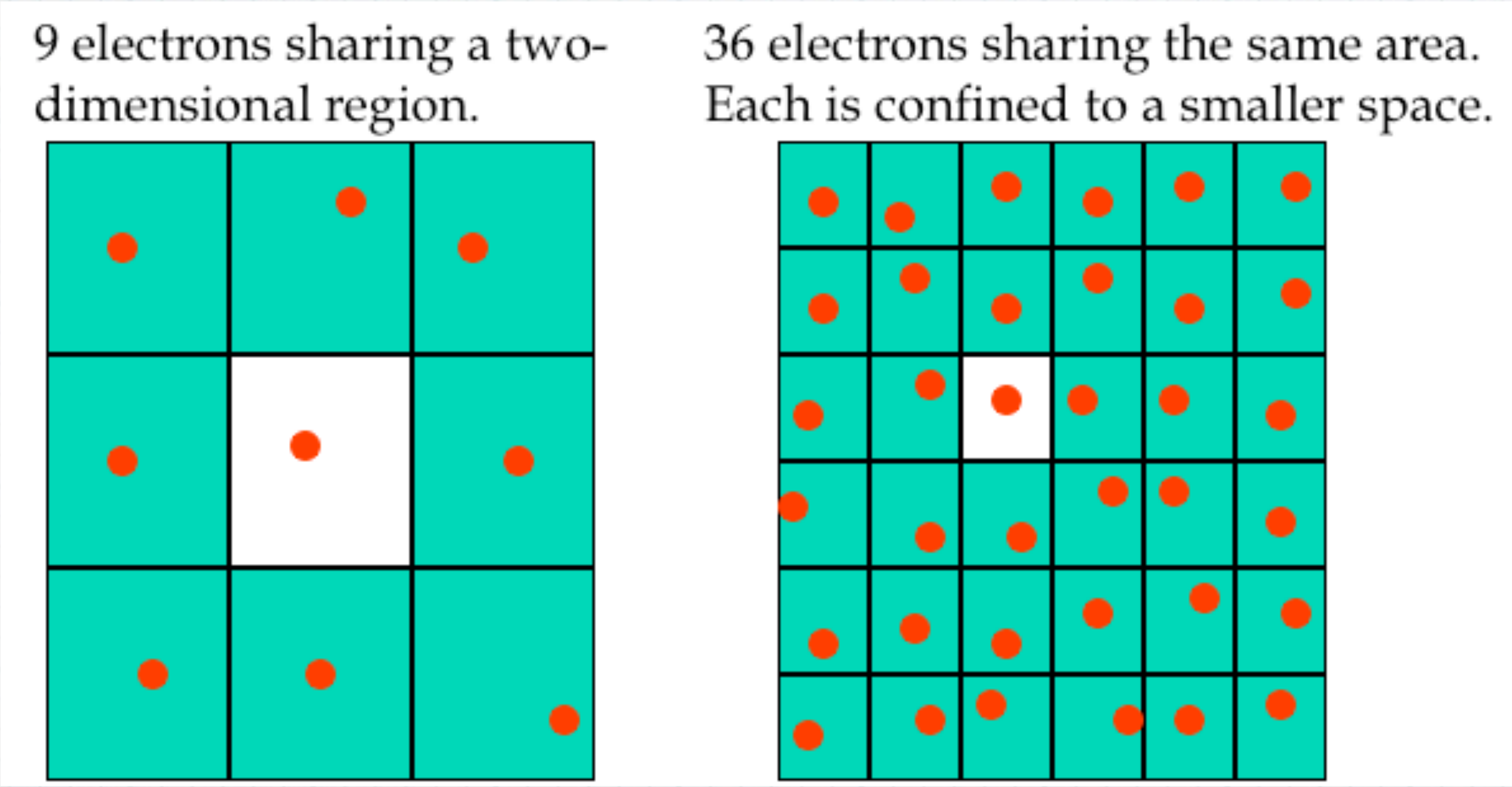
* How is degeneracy pressure different from gas pressure?
* Degeneracy pressure exists even if T = 0 K
* Degeneracy pressure exists only when certain particles (fermions) come too close to one another as they cannot share a state
* Fermions are: electrons, protons and neutrons



Thermal Pressure

Depends on heat content

The main form of pressure in most stars

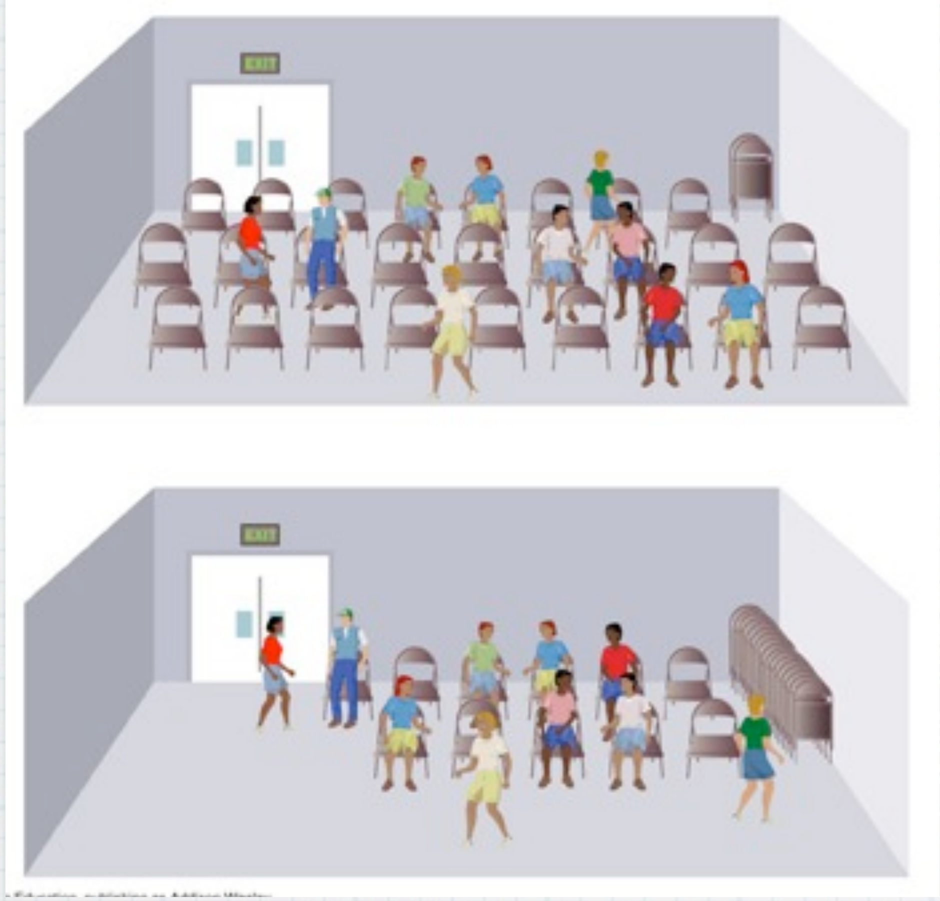


Degeneracy Pressure:

Particles can't be localized

Doesn't depend on heat content

Electron Degeneracy Pressure Explained



The electrons (people) are constantly changing chairs. Usually, there are always a lot more free chairs than people

But there are case when there are almost as many people than free chairs

Since there is virtually no open seating, the people (electrons) who must move, must wait before an open chair (room) opens up for them. They then move faster to find one. This creates a resistance

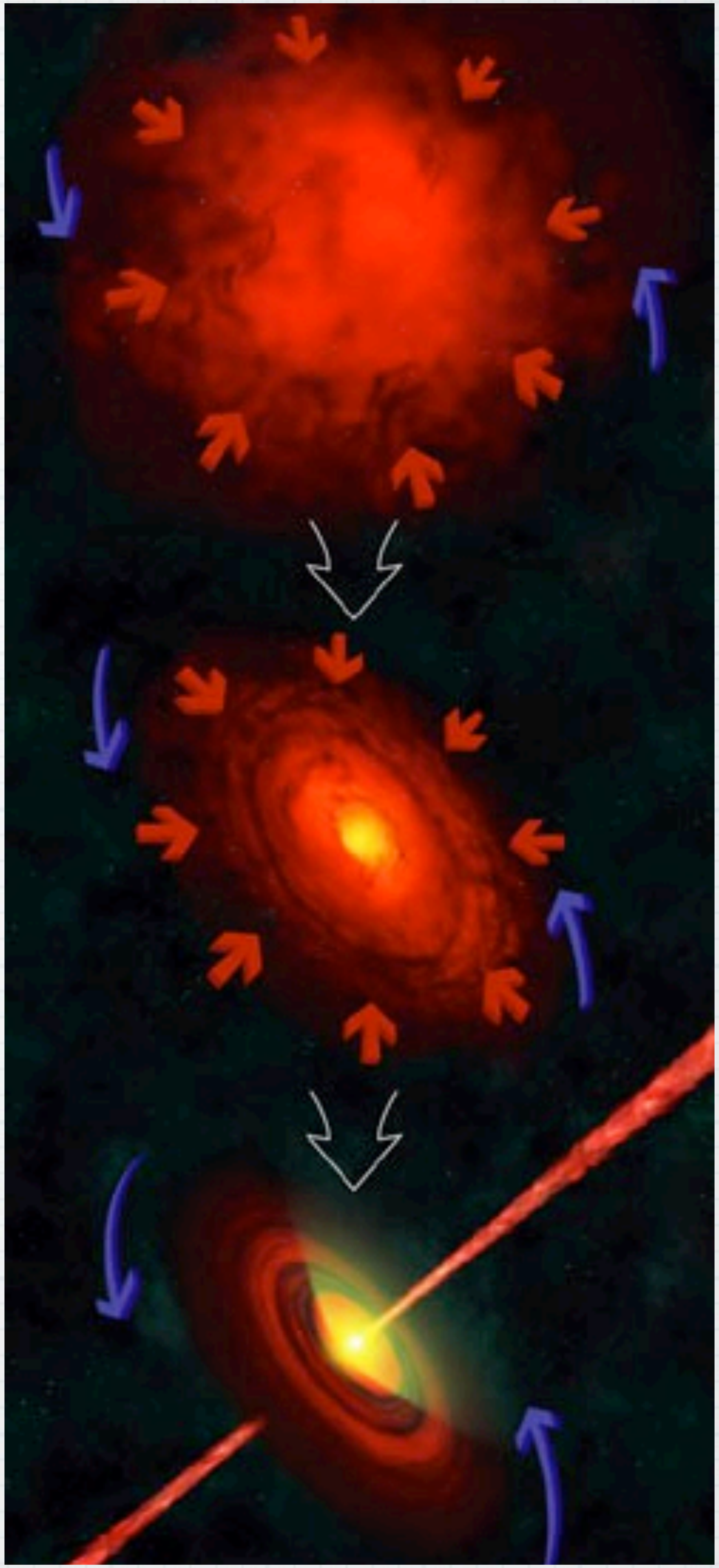
This resistance is the origin of degeneracy pressure

While the electrons are moving faster, it has nothing to do with temperature

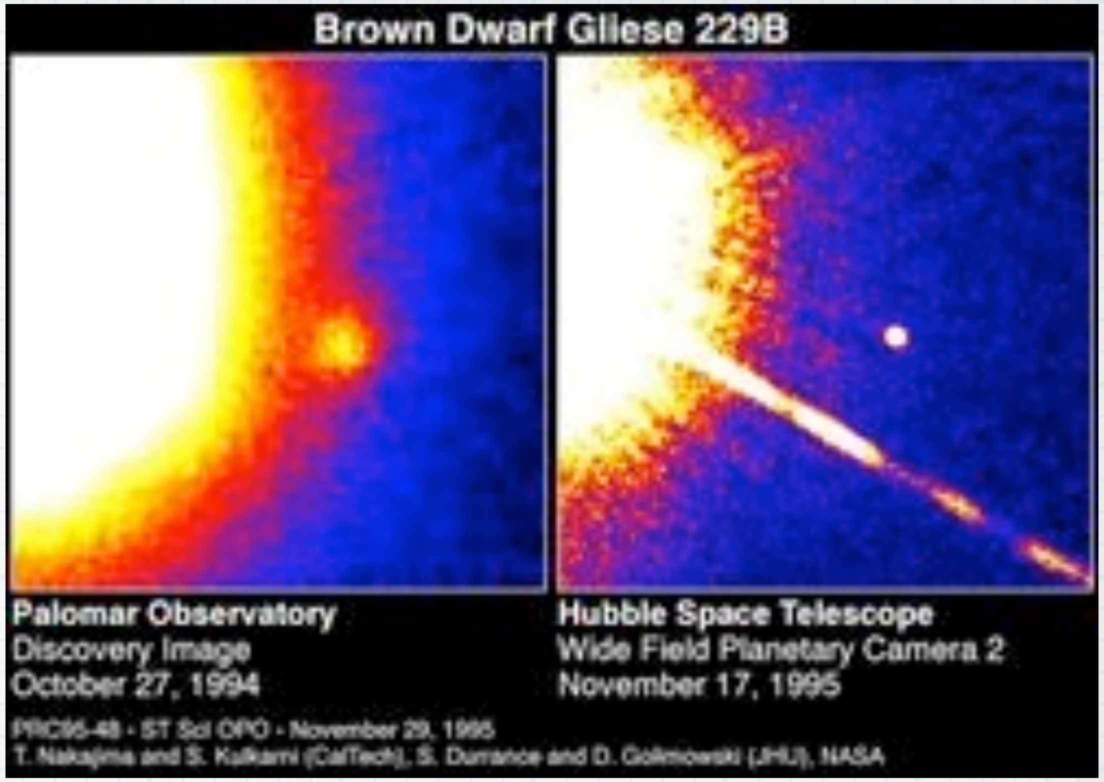
Snapshot

How do stars form?

- Stars are born in cold, relatively dense molecular clouds
- As a cloud fragment collapses under gravity, it becomes a protostar surrounded by a spinning disk of gas
- The protostar may also fire jets of matter outward along its poles. Protostars rotate rapidly, and some may spin so fast that they split to form close binary star systems



Snapshot



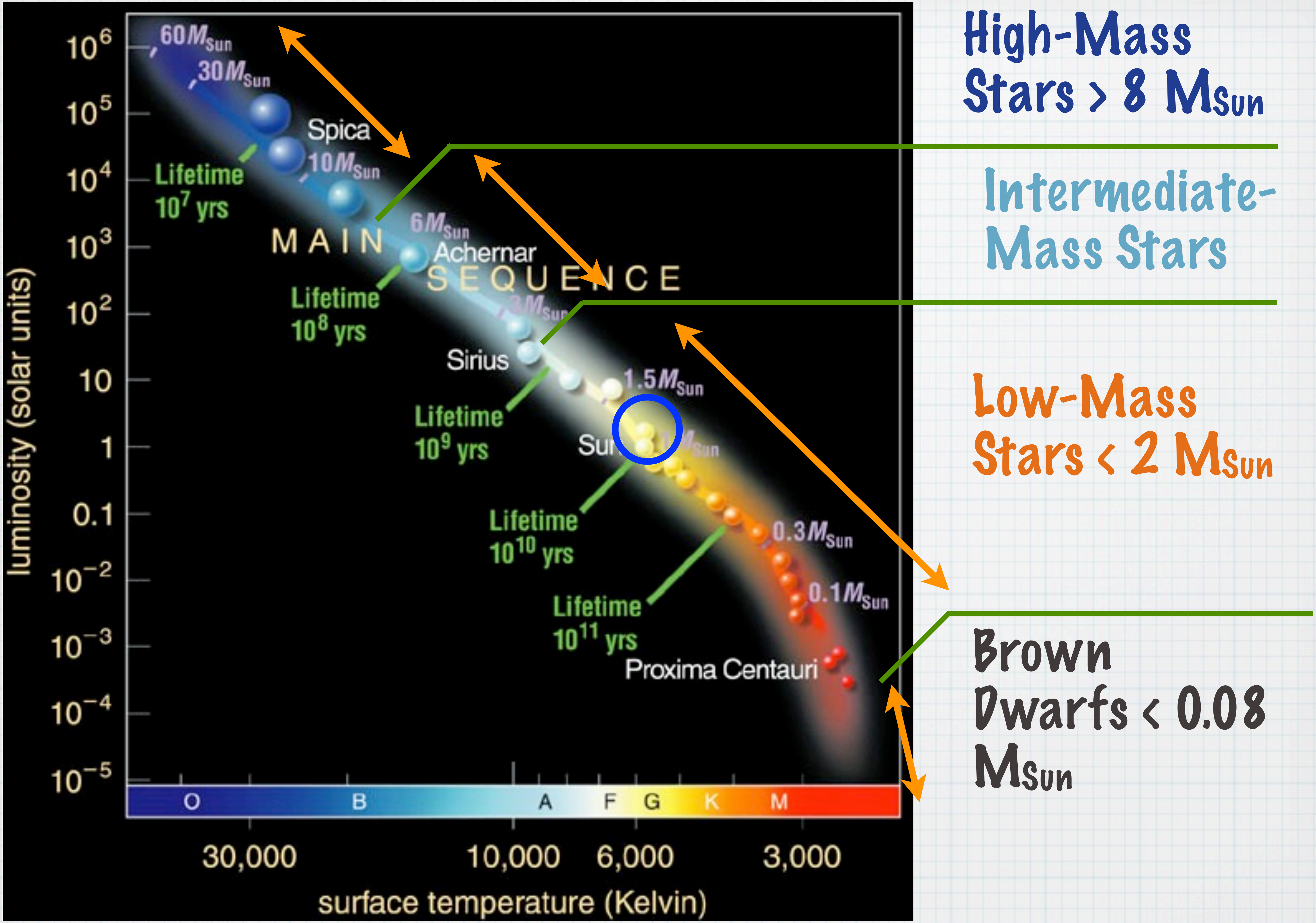
How massive are newborn stars?

Newborn stars come in a range of masses, but cannot be less massive than 0.08 M_{Sun}

Below this mass, degeneracy pressure prevents gravity from making the core hot enough for efficient hydrogen fusion, and the object becomes a "failed star" known as a brown dwarf

Star Life Stages

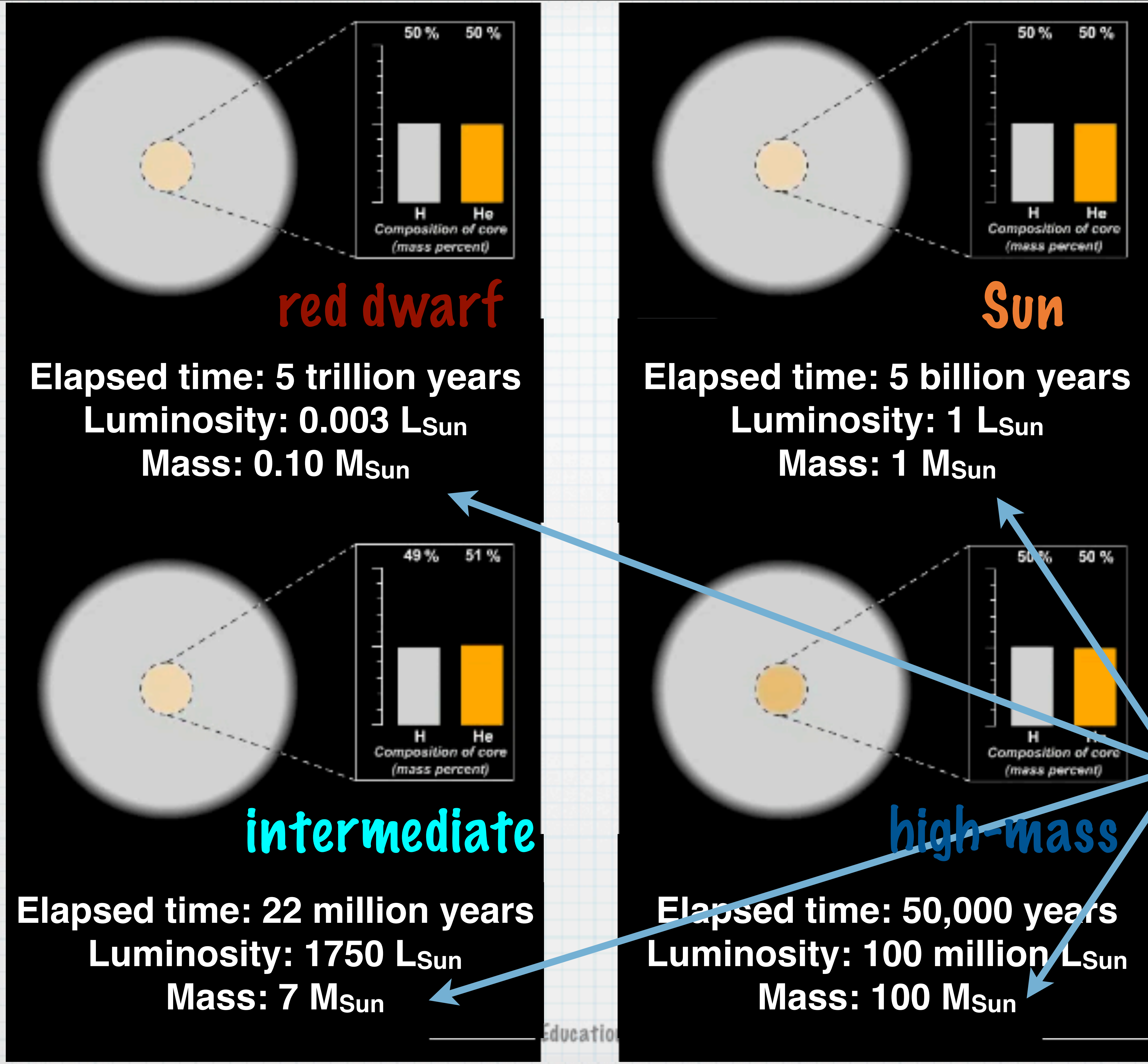
* A star's birth mass (and composition) determines its luminosity, surface temperature, and lifetime
* We know this due to extensive computer modeling which match our observations on all the life phases of stars of varying mass



60 MSun
30 MSun
Spica
10 MSun
Lifetime 10^7 yrs
MAIN SEQUENCE
6 MSun
Achernar
Lifetime 10^8 yrs
3 MSun
Sirius
1.5 MSun
Lifetime 10^9 yrs
Sun
1 MSun
Lifetime 10^10 yrs
0.3 MSun
0.1 MSun
Lifetime 10^11 yrs
Proxima Centauri
luminosity (solar units)
10^6
10^5
10^4
10^3
10^2
10
1
0.1
10^-2
10^-3
10^-4
10^-5
O B A F G K M
30,000 10,000 6,000 3,000
surface temperature (Kelvin)
High-Mass Stars > 8 MSun
Intermediate-Mass Stars
Low-Mass Stars < 2 MSun
Brown Dwarfs < 0.08 MSun

Life as a Low-Mass Star

* Our Sun is a low-mass star. It will live 10 billion years as a main-sequence star
* 5 billion years from now, hydrogen will be depleted in the core and fusion will cease
* The core will begin to shrink, being crushed by gravity



Fusing hydrogen to helium means being a main-sequence star

The hydrogen burn rate is mass dependent

Question

* What happens when a star can no longer fuse hydrogen to helium in its core?

A. Core cools off

B. Core shrinks and heats up

C. Core expands and heats up

D. Helium fusion immediately begins

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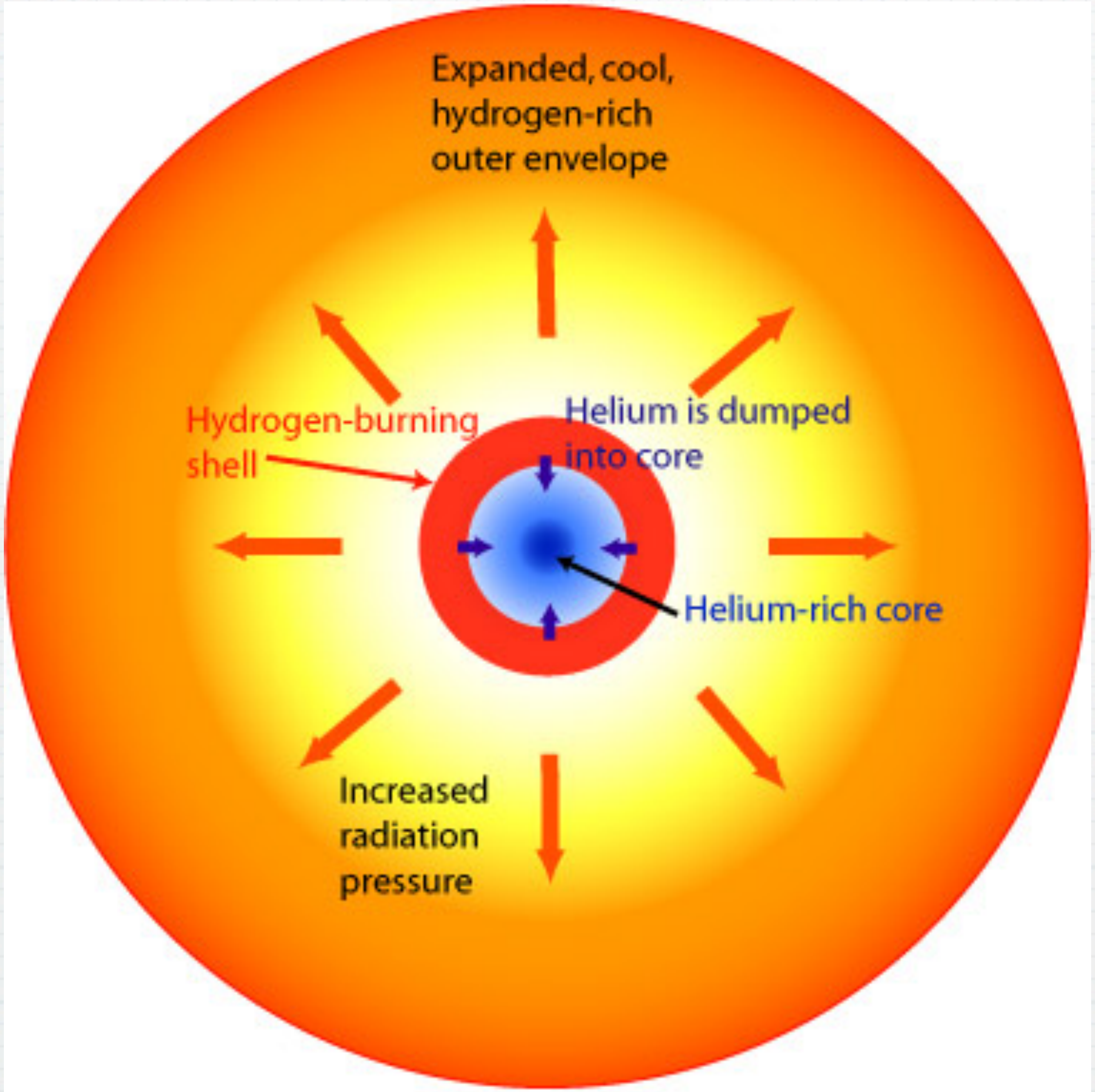
Red Giant Stage

* The core is shrinking and heating up
* The Sun's outer envelope expands, being pushed from the inside:
  * There is a hydrogen fusing shell around the core
  * That fusion has a higher-rate than before (the bottom of the layer [the core] is extremely hot!)

Broken thermostat: rising fusion rate in shell does not expand core, so luminosity continues to rise



Hydrogen Shell Burning on the Red Giant Branch

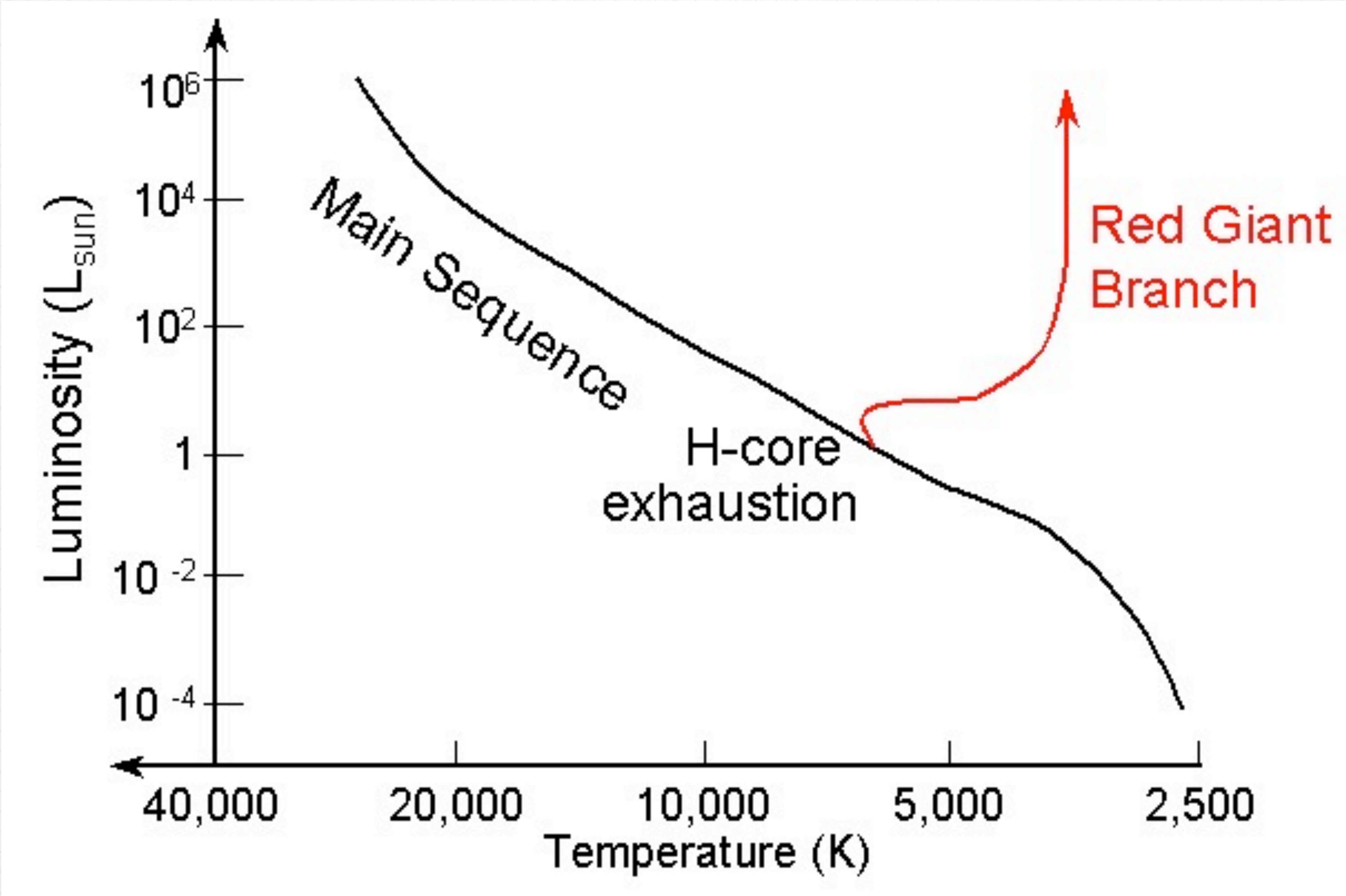
Red Giant Stage...

* Over the next billion years,
* the Sun's radius grows 100-fold as radiation pressure exceeds local gravity
* the luminosity grows even more
* the Sun expands to be a red giant
* Expansion keeps on happening until the core starts fusing helium

Red Giant Stage...

* The Sun's outer envelope is shedding large amount of mass as stellar wind
  * its large radius implies a weak pull of gravity at the surface
* If a low-mass star is not hot enough to burn helium in the core, the core collapse will be halted by degeneracy pressure and become a helium white dwarf

Climbing the Red Giant Branch



Question

* What happens as a star's inert helium core starts to shrink?

A. Hydrogen fuses in shell around core

B. Helium fusion slowly begins

C. Helium fusion rate rapidly rises

D. Core pressure sharply drops

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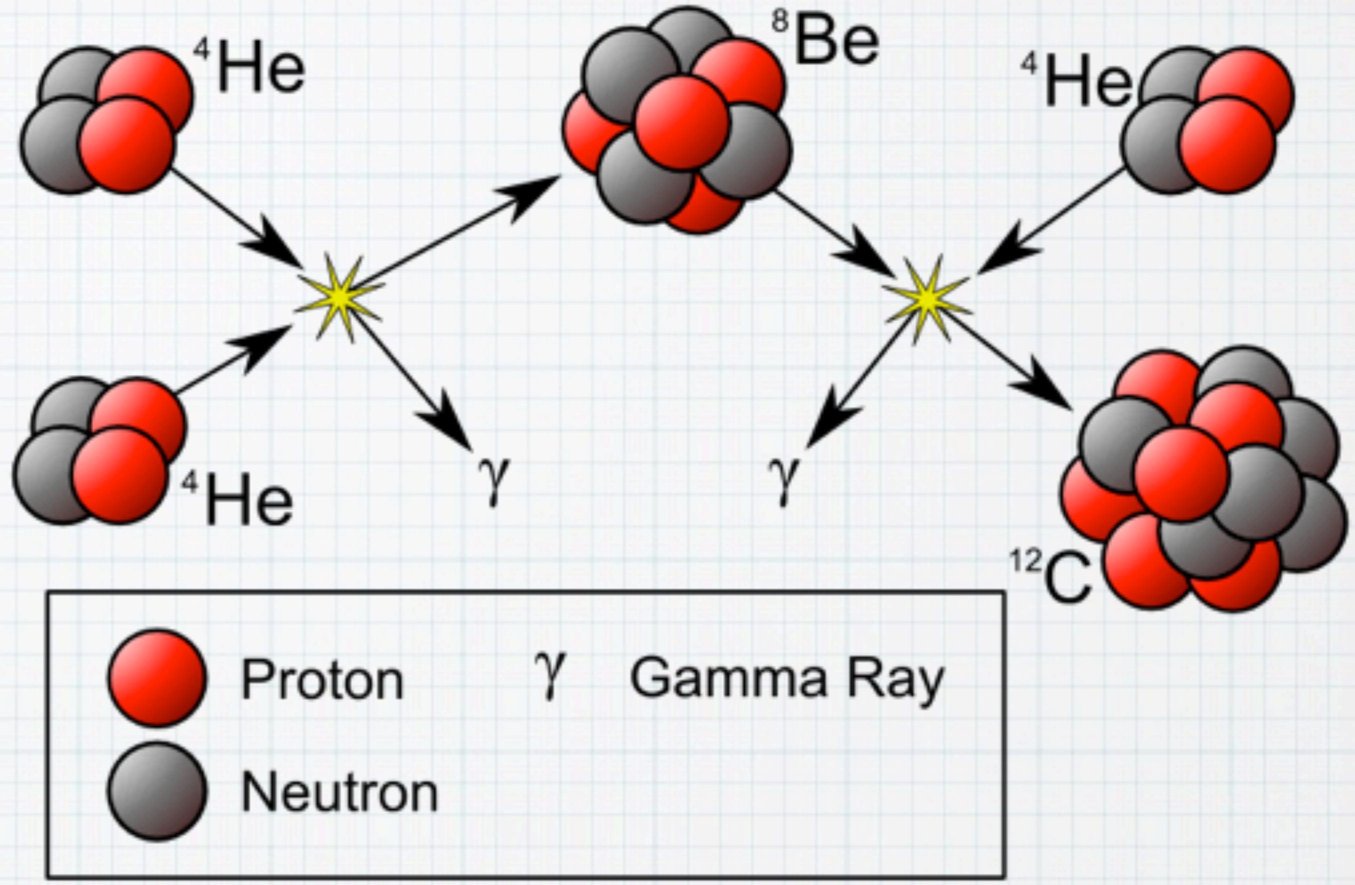
Helium Fusion (triple-alpha)



* Helium fusion requires higher temperatures than hydrogen fusion because larger charge leads to greater repulsion

* Fusion of two helium nuclei doesn't really work (Beryllium-8 is unstable), so **helium fusion must combine three He nuclei to make carbon**

Helium Fusion...

* When the core's temperature reaches 100 million K, helium fusion into carbon starts
* In a low-mass star like the Sun (and up to 2.25 M_{Sun}), the core is in a state of electron degenerate pressure as well
* This results in a helium flash

Helium Fusion...

* The helium flash lasts only a few minutes
* The flash energy output is tremendous (100,000,000,000 L_{Sun}) but is not observed (over 200,000 years for energy to reach the surface of the star!)
* The star is now stable for about 1 to 2% of its main-sequence lifetime

Question

* What happens in a low-mass star when core temperature rises enough for helium fusion to begin but the core's pressure is in a degenerate state?

A. Helium fusion slowly starts up

B. Hydrogen fusion stops

C. Helium fusion rises very sharply

Question

* What happens in a low-mass star when core temperature rises enough for helium fusion to begin but the core's pressure is in a degenerate state?

A. Helium fusion slowly starts up

B. Hydrogen fusion stops

C. Helium fusion rises very sharply

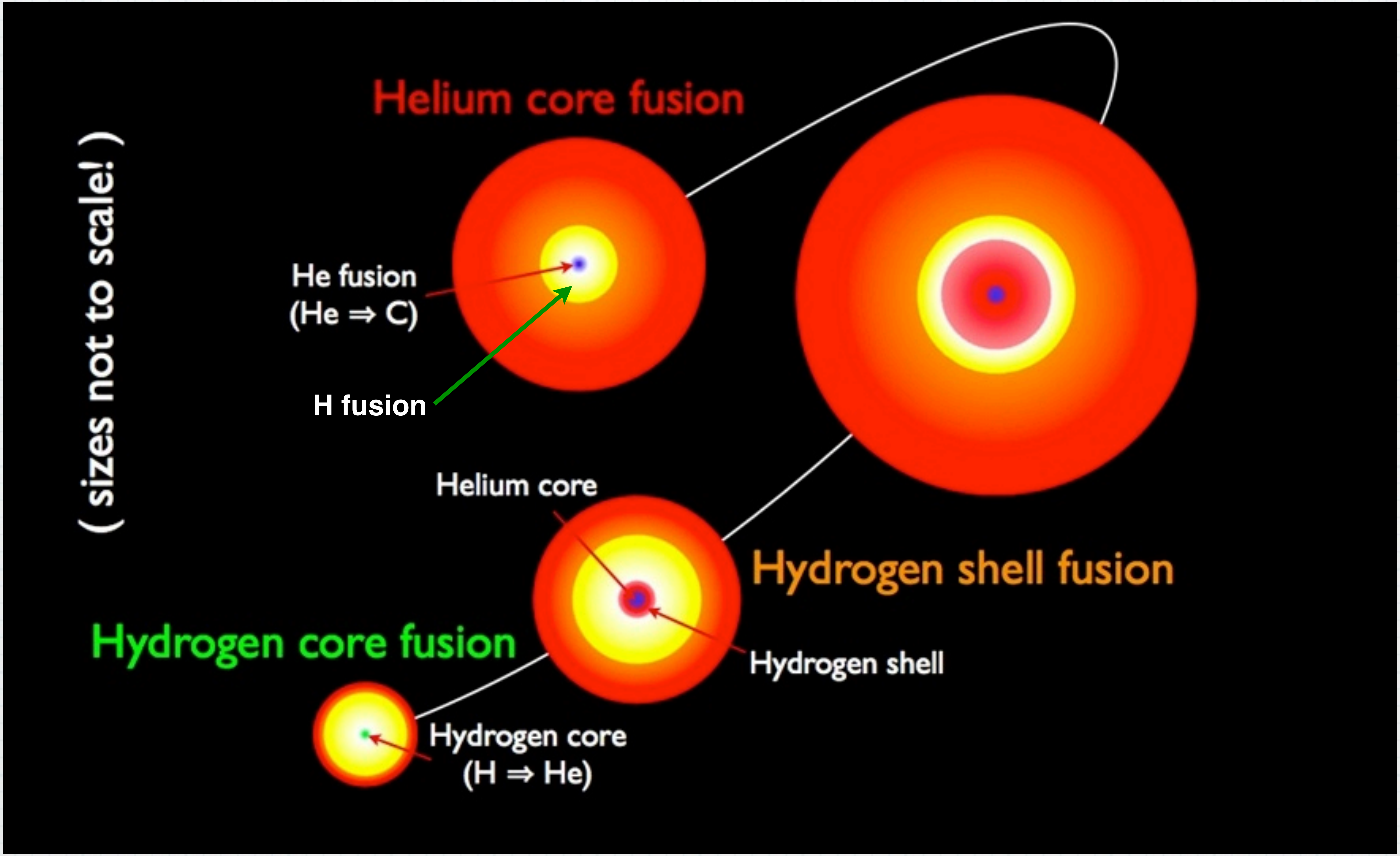
Helium Burning Star

* The total energy output is now lower than when helium was not burning as the auto-regulating fusion in the core is back on
* After spending 1 billion years expanding into a luminous red giant, its size and luminosity will decline while it fuses helium in its core

Helium Burning Star...

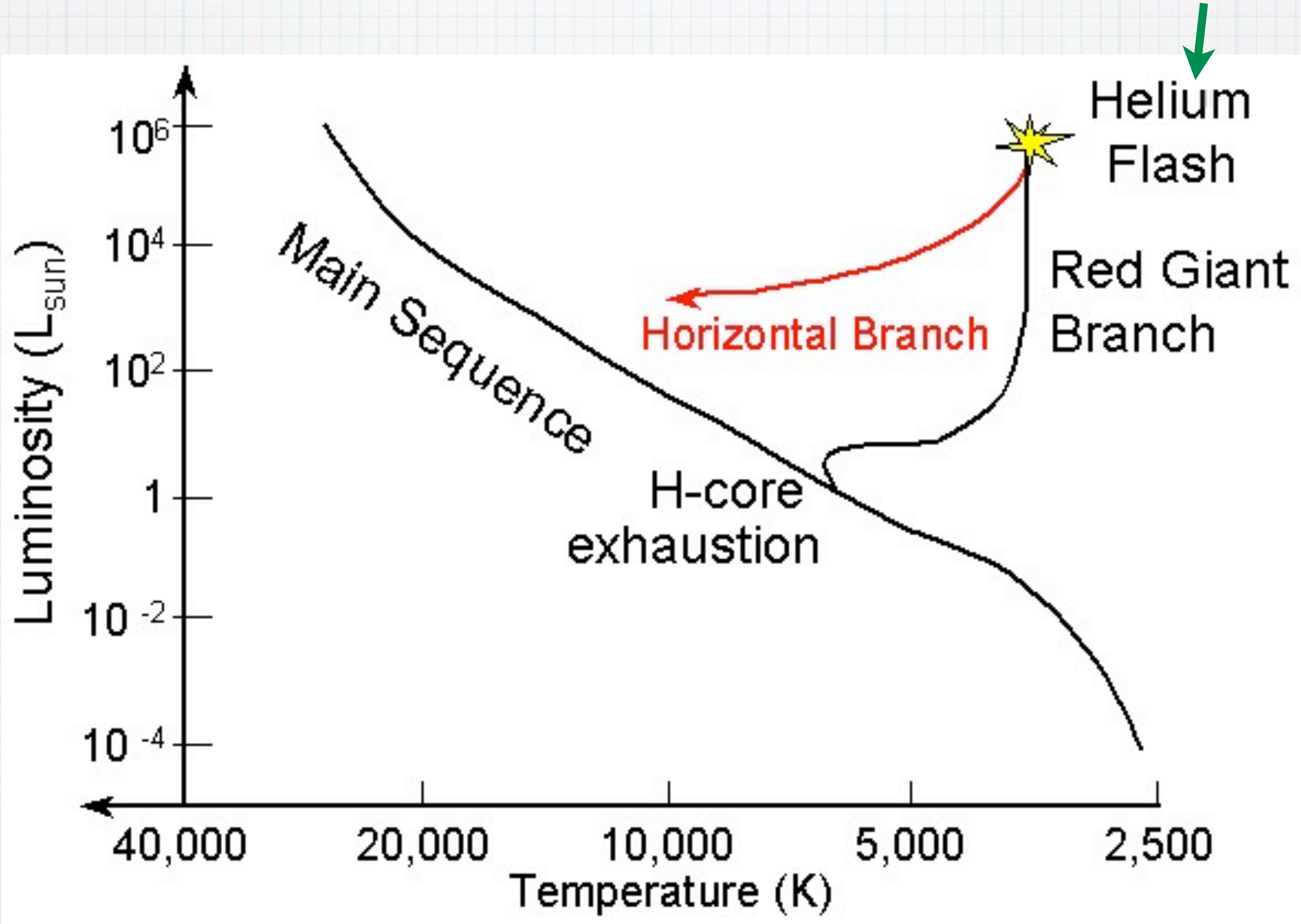
* Carbon is not the only element generated by the fusion of Helium, but some Oxygen is made as well as a side effect

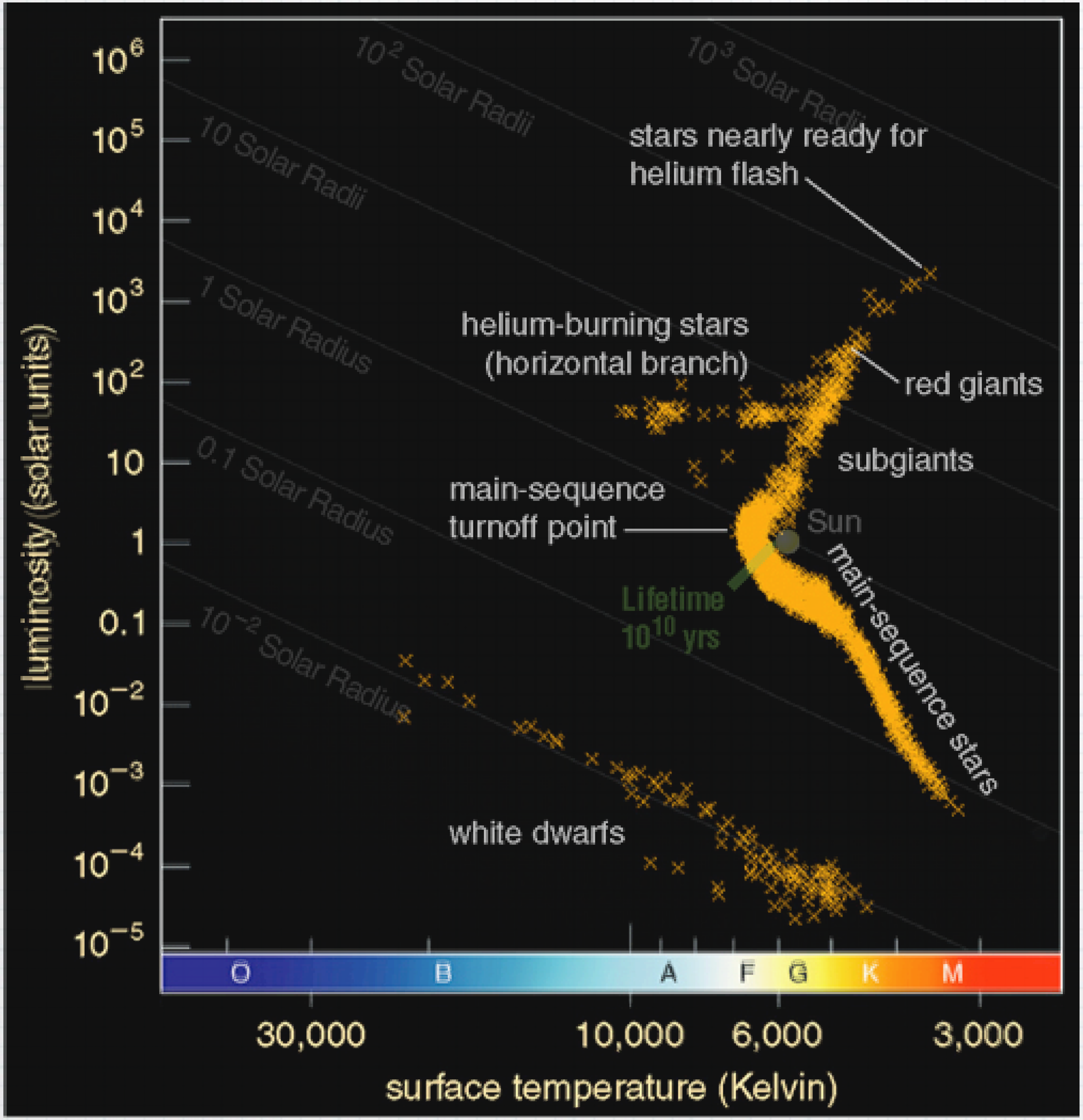
Stellar evolution: from fusing H to He in the core



Horizontal Branch Phase

This is not seen as it happens only in the core





An H-R diagram of a globular cluster showing low-mass stars in several different life stages

Last Gasps

* One hundred million years later, the core will run out of helium
* The core is mostly full of carbon with some oxygen
* Once again the core will shrink, crushed by gravity

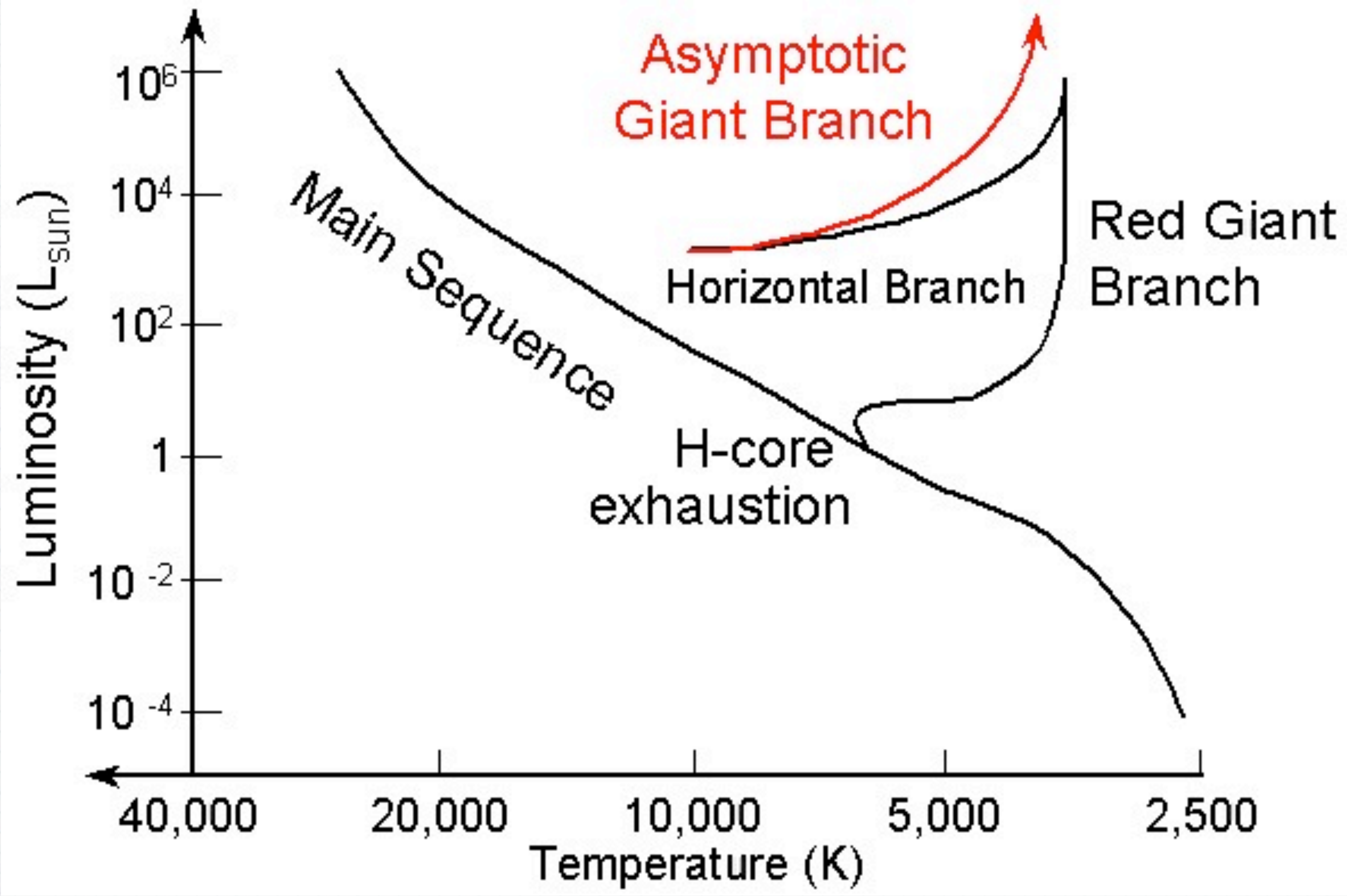
Last Gasps...

* The Sun expands again!
* There is an inert He core being crushed, followed by a shell of fusing He, followed by a shell of fusing H
* The Sun will then be a double-shell burning star

Last Gasps...

* Now we have two fusing shells being contracted around an inert core
* The Sun expands to an even greater size and luminosity than it had in its previous red giant phase
* In an H-R diagram, the Sun enters the asymptotic giant branch
* This lasts for a few million years

The Asymptotic Giant Branch



Question

* What happens when the star's core runs out of helium?

A. The star explodes

B. Carbon fusion begins

C. The core cools off

D. Helium fuses in a shell around the core

Question

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A. The star explodes

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Last Gasps...

* The Sun is not massive enough to fuse carbon in the core. The temperature needed for this is 600 million K
* The core's contraction stops when the electron degenerate pressure in the core balances gravity's crush

Death of a low-mass star

* The Sun is so huge it has very little hold on its outer layers
* The solar wind grows with the radius and luminosity and blows material away in interstellar space
* Heavier elements will condense to dust particles eventually seeding the next generation of stars

Death of a low-mass star...

* Through solar wind and other yet found processes **the Sun will eject its outer layers into space**
* **This creates a huge shell of gas expanding away** from the very hot carbon-oxygen core which radiates intense UV radiation

Death of a low-mass star...

* The expanding gas shell is ionized and glows very brightly as a **planetary nebula**
* The nebula will disappear within a million years
* Only a **carbon white dwarf** is left behind

Question

* What happens to Earth's orbit as the Sun loses mass late in its life?

A. Earth's orbit gets bigger

B. Earth's orbit gets smaller

C. Earth's orbit stays the same

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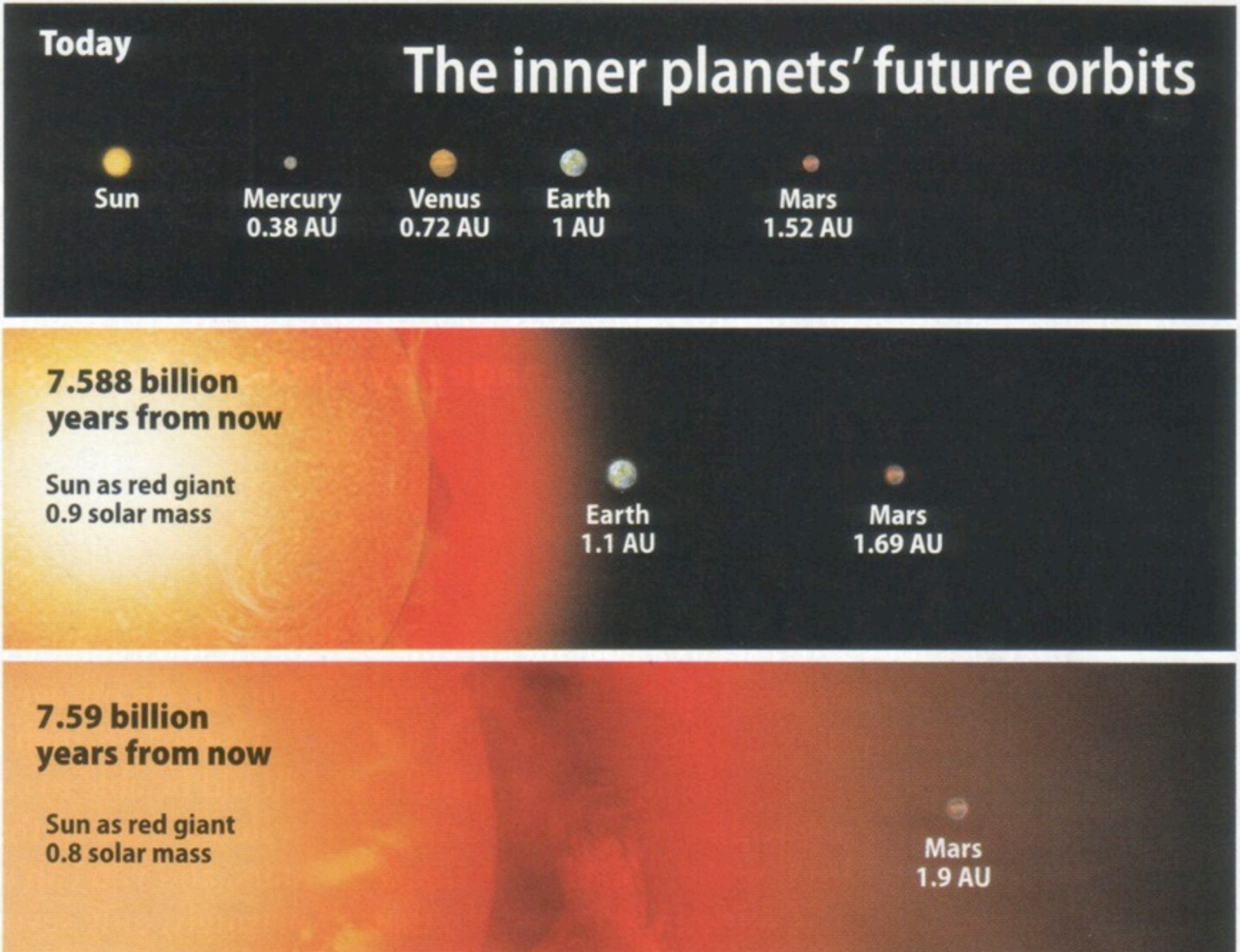


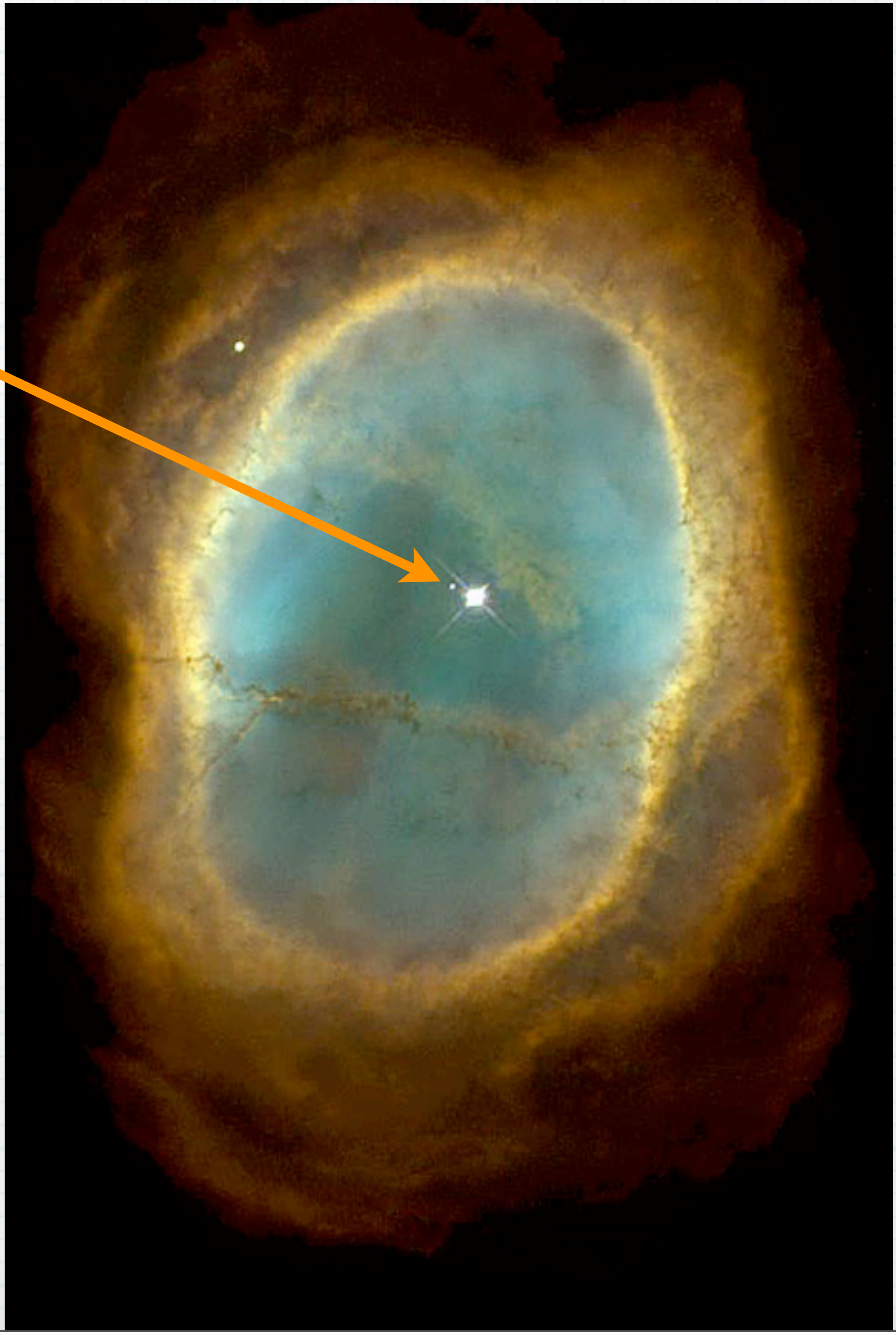
The Sun will grow larger and extend beyond Earth's current orbit (an astronomical unit, or AU). Our star will also blow away mass in a steady wind. So our planet's orbit will expand and Earth should be safe — until the Sun's gravitational tides pull it in. *Astronomy*: Roen Kelly, after Klaus-Peter Shroeder and Robert Cannon Smith

Sun-like star dying (NGC 3132)

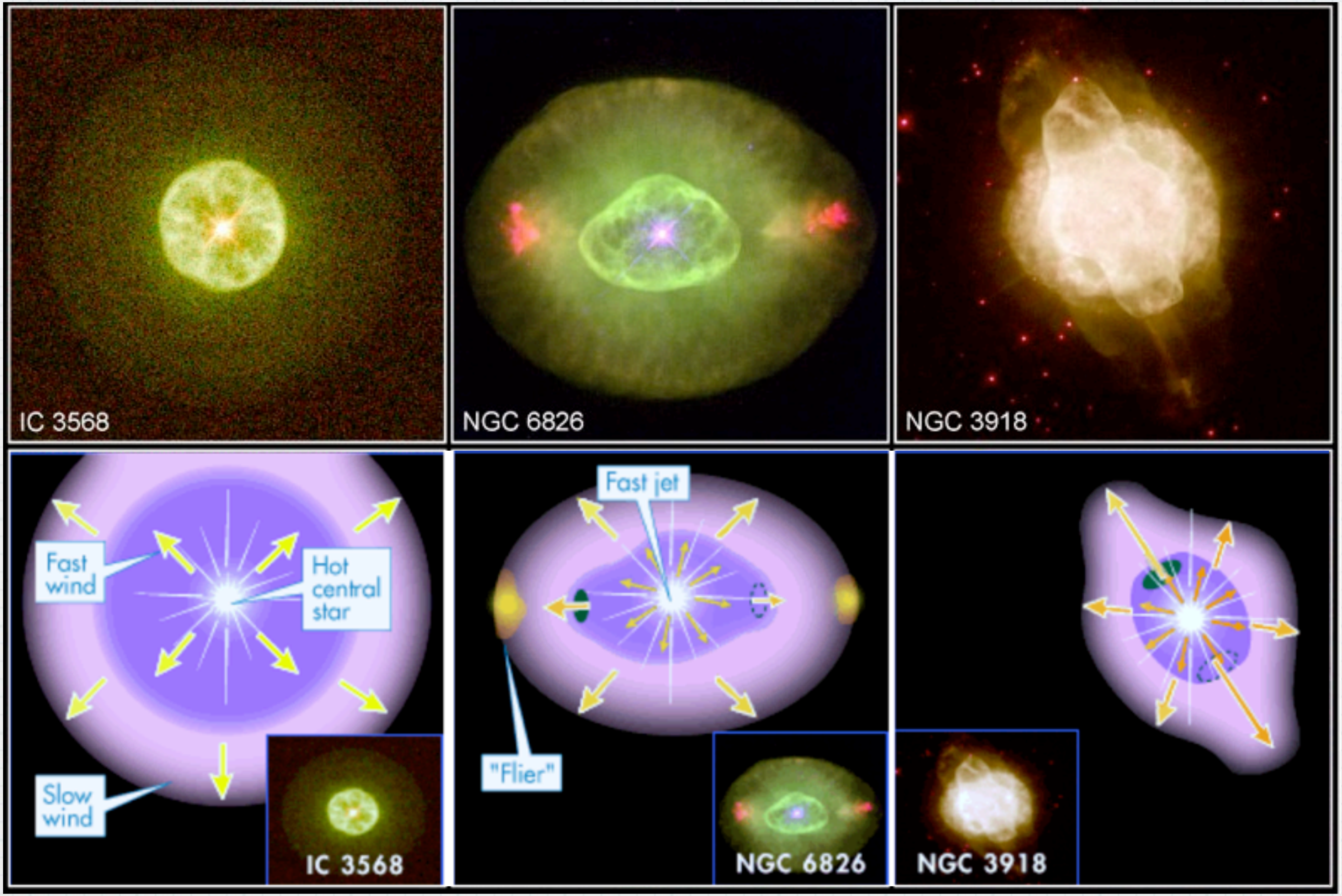
white dwarf

The star is ending its life by casting off its outer layers of gas

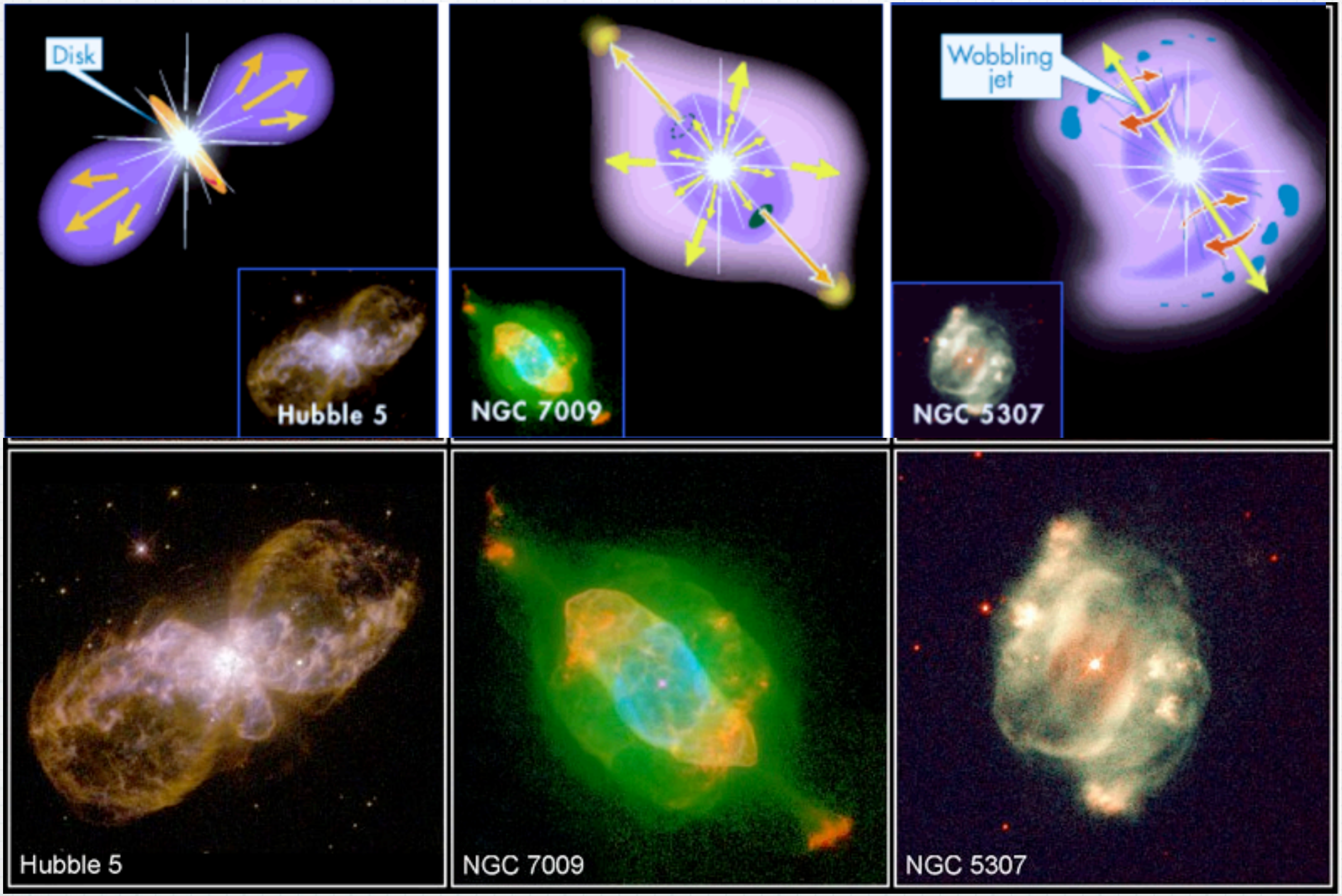
Ultraviolet light from the dying star then makes the material glow



Planetary Nebula Gallery



Planetary Nebula Gallery

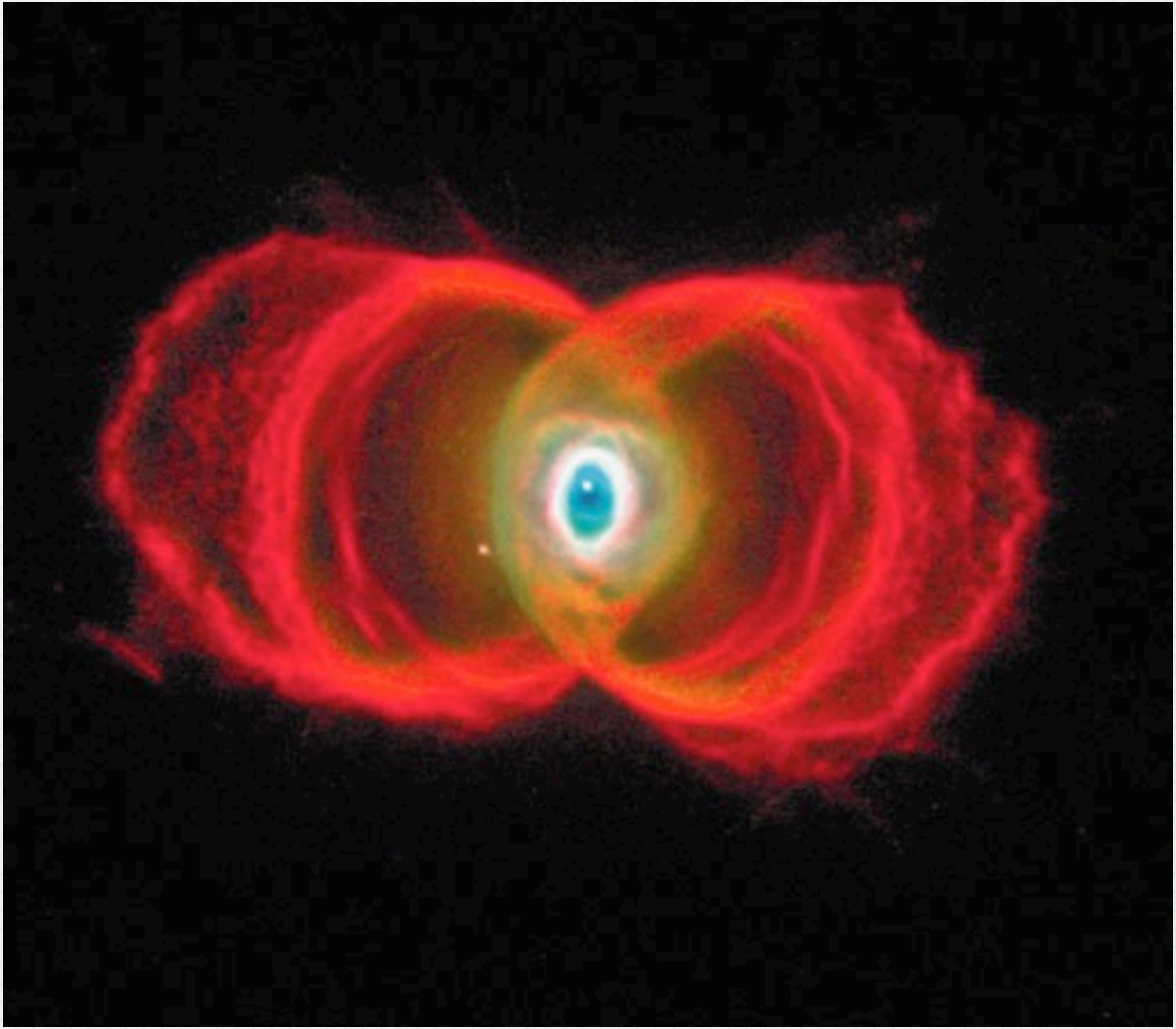


The asymmetries seen are thought to come from an unseen (fainter) companion star

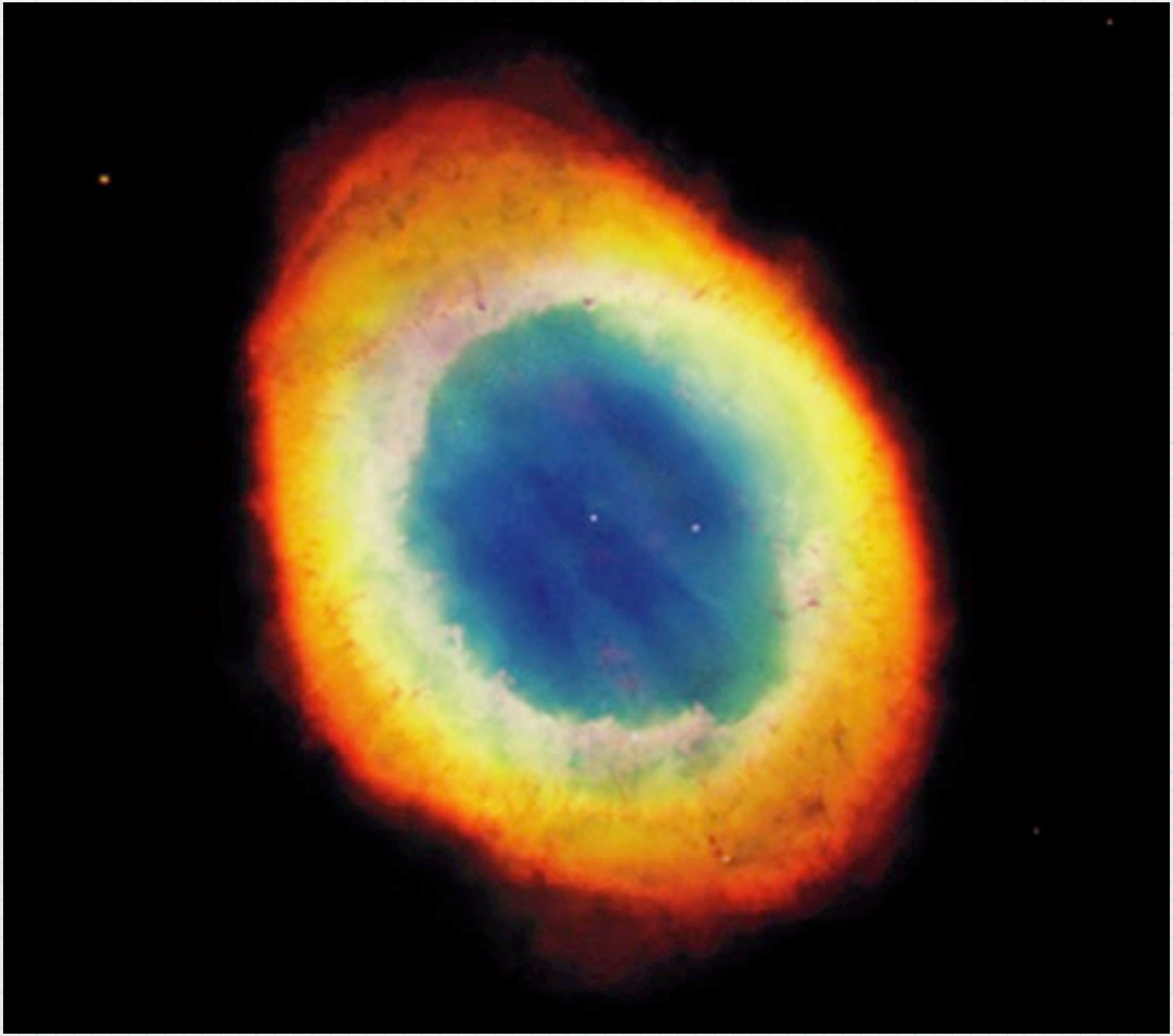
The Eskimo Nebula

The Spirograph Nebula

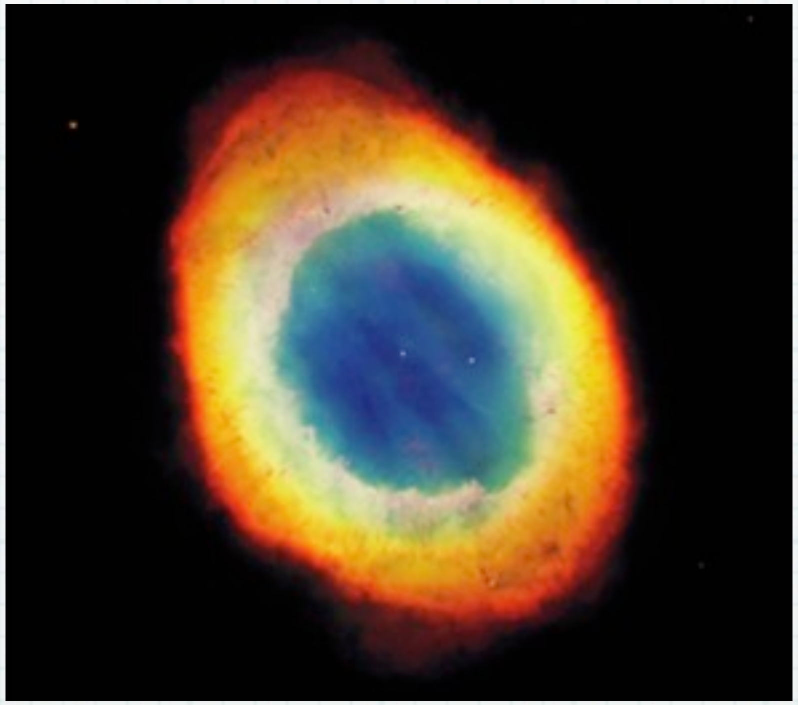
The Hourglass Nebula



The Ring Nebula M 57



The Ring Nebula M 57



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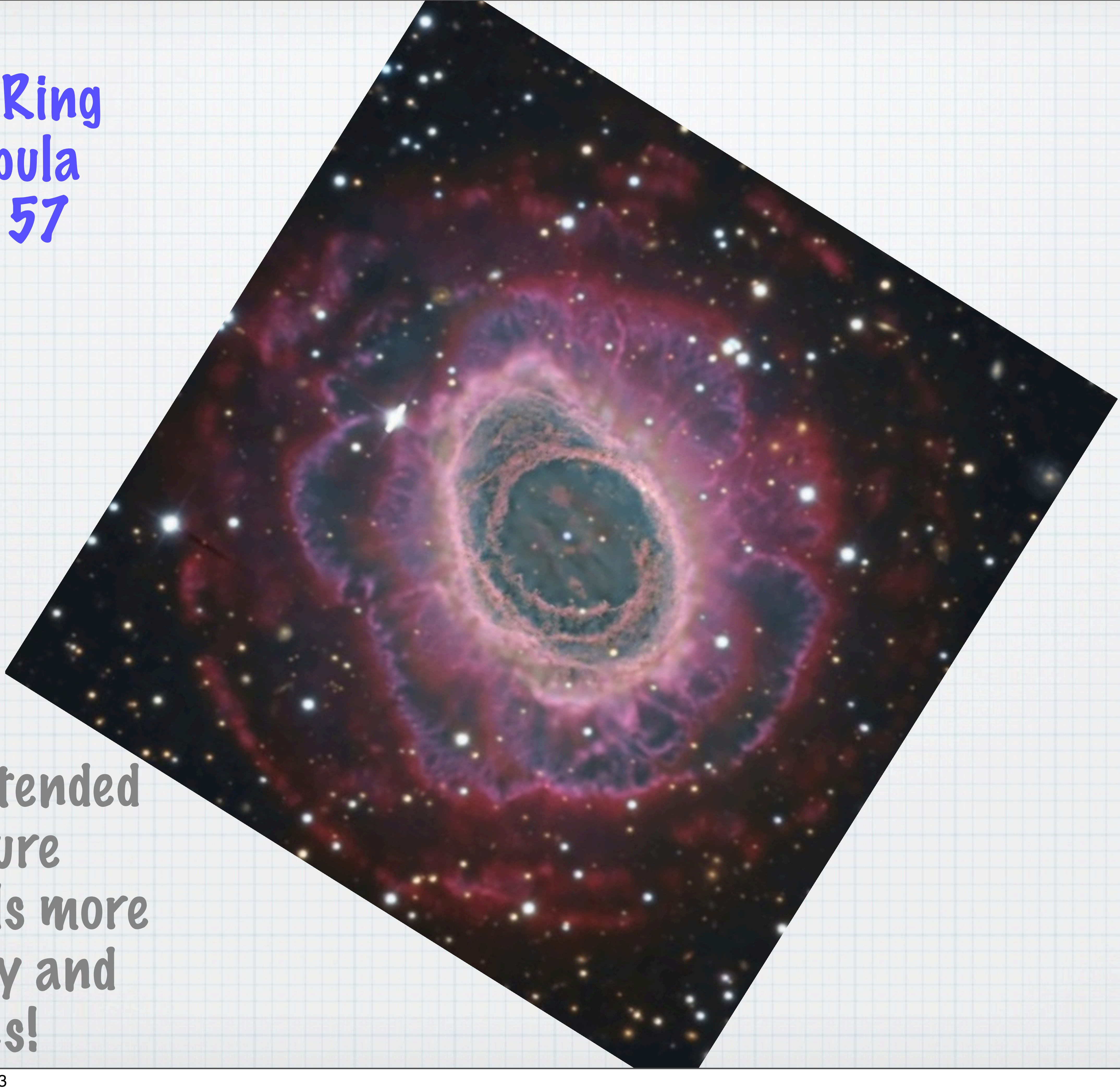
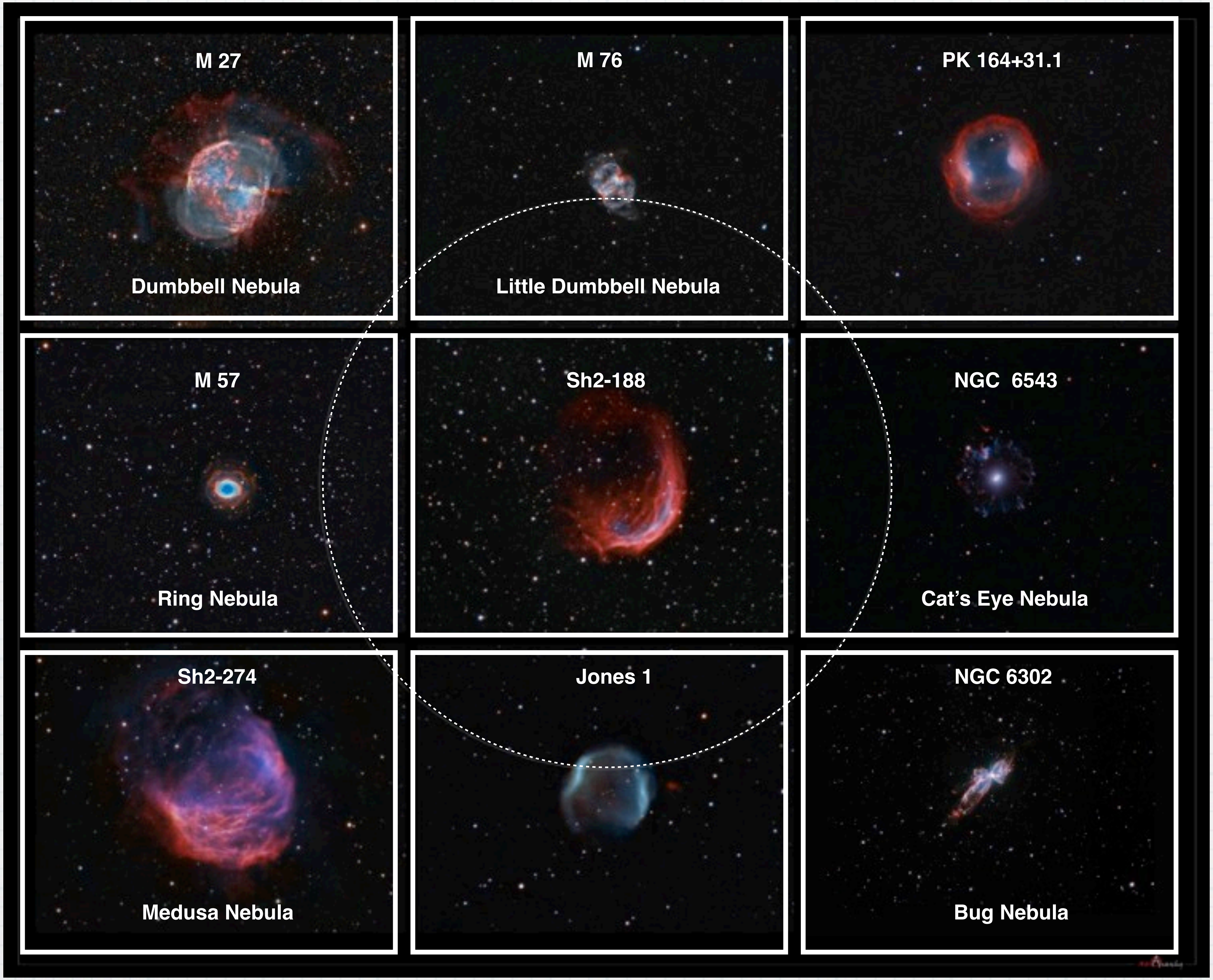


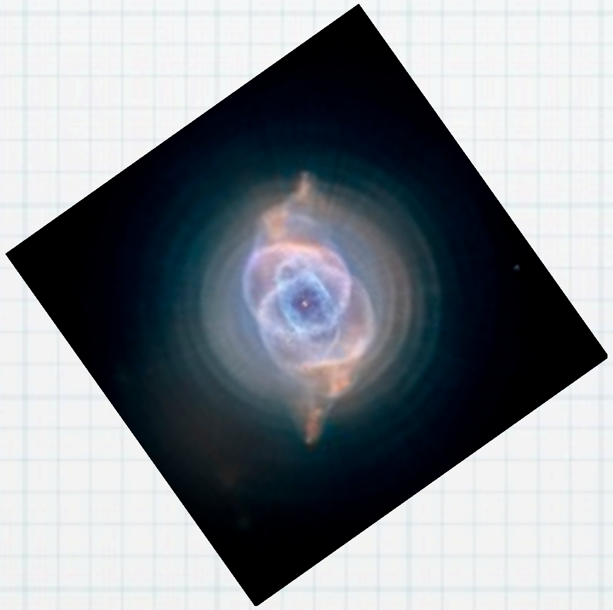
An extended exposure reveals more beauty and physics!

Planetary Nebulae sizes to scale (with the Moon)



Cat's Eye Planetary nebula

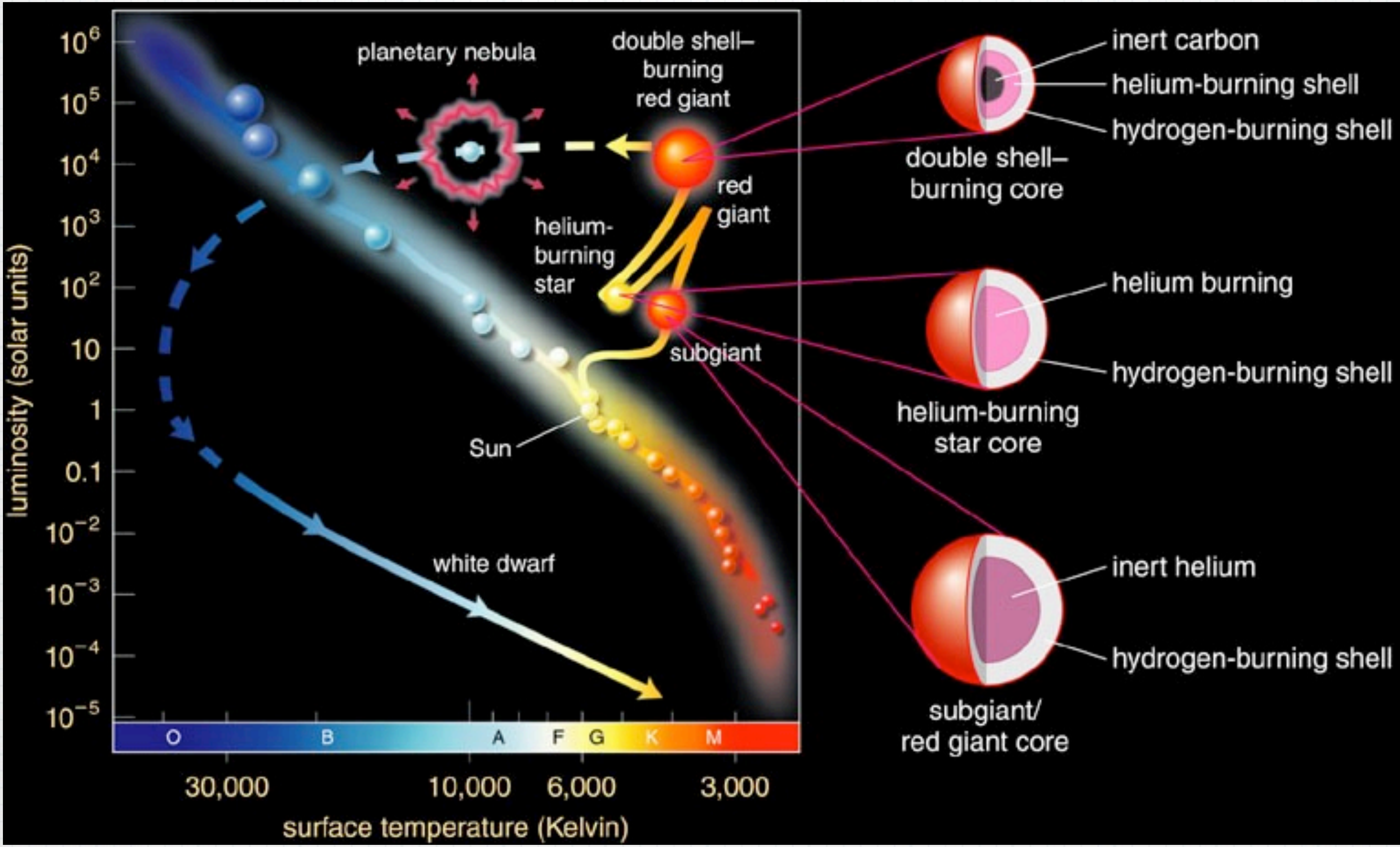
Cat's Eye Planetary nebula



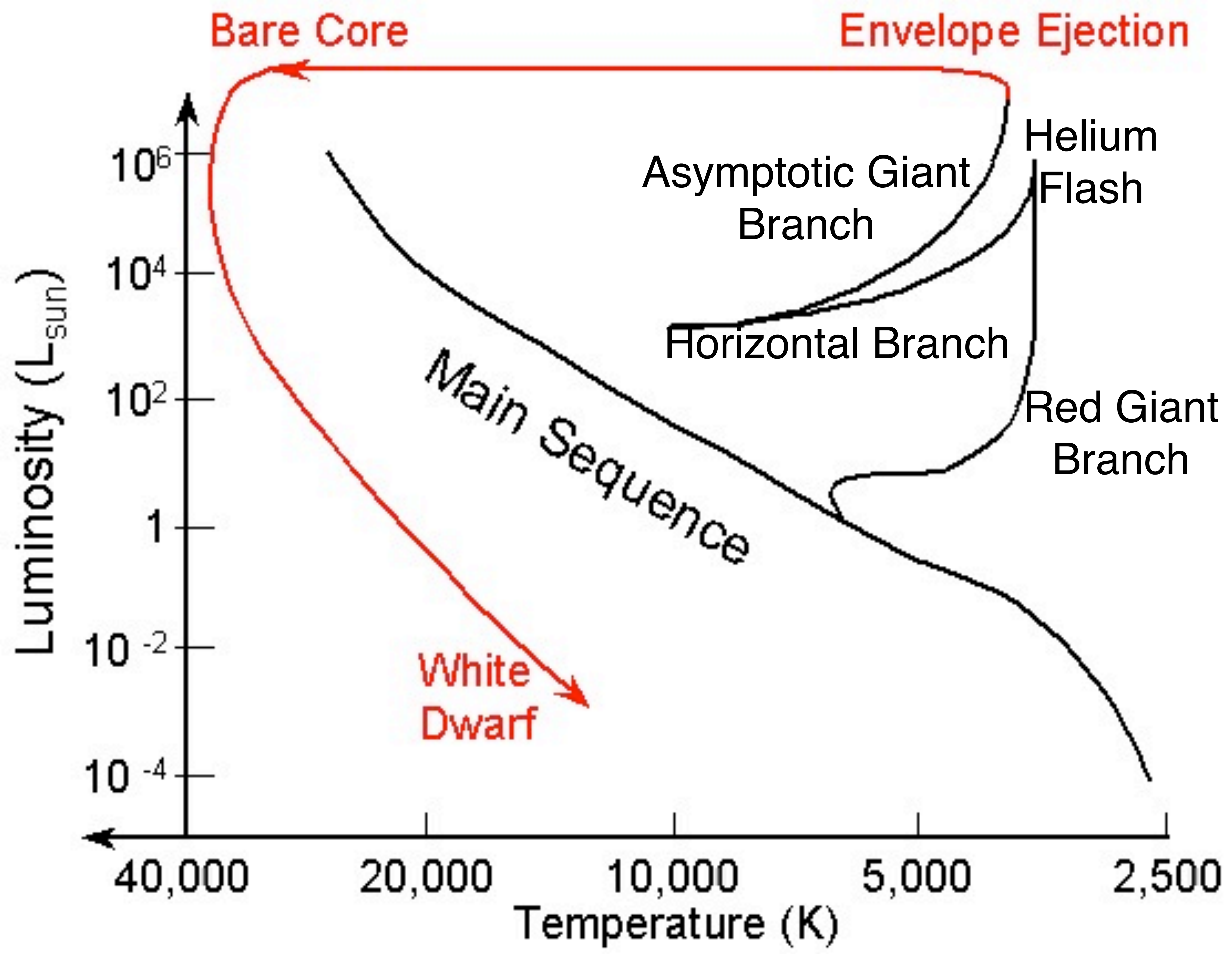
Cat's Eye Planetary nebula very long exposure

White Dwarf

* White dwarfs have a very small radius, yet they have a high mass and temperature
* They are the exposed cores of dead stars

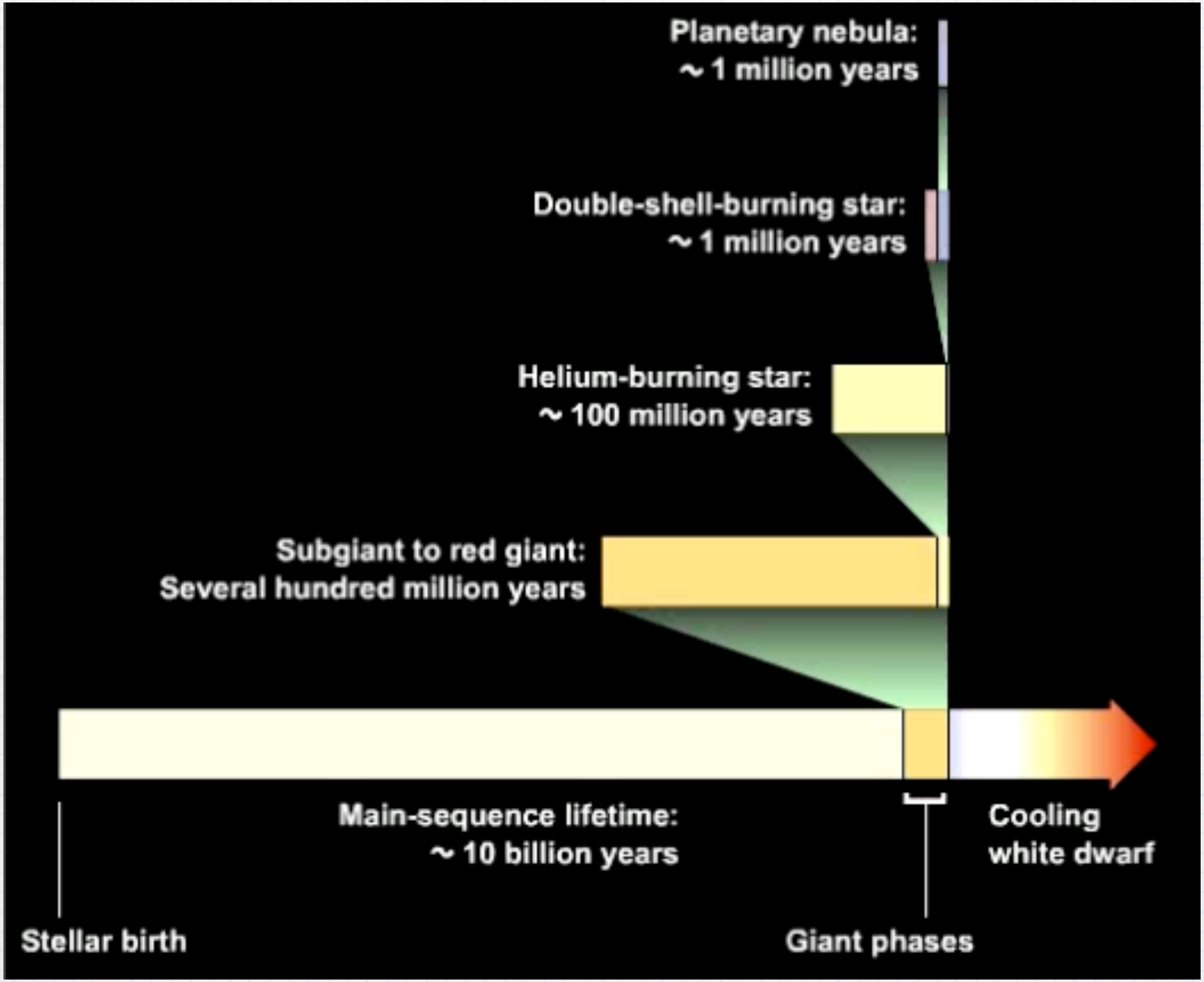


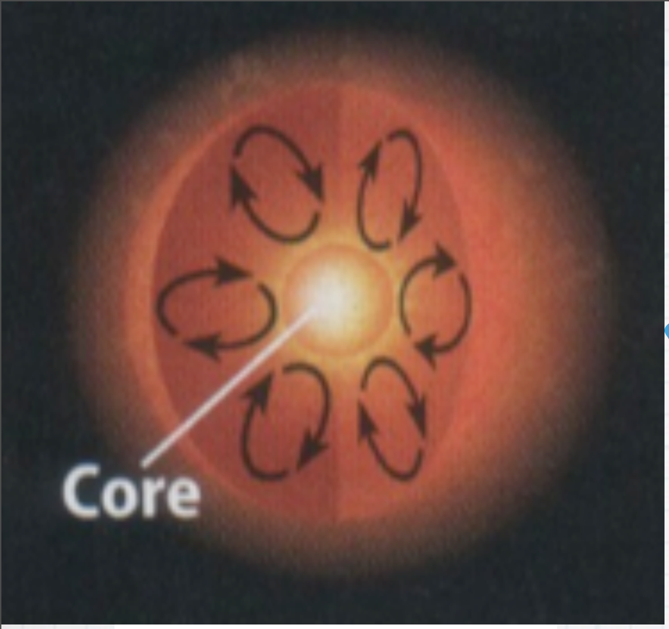
luminosity (solar units)
10^6
10^5
10^4
10^3
10^2
10
1
0.1
10^{-2}
10^{-3}
10^{-4}
10^{-5}
planetary nebula
double shell–burning red giant
red giant
helium-burning star
subgiant
Sun
white dwarf
O
B
A
F
G
K
M
30,000
10,000
6,000
3,000
surface temperature (Kelvin)
inert carbon
helium-burning shell
hydrogen-burning shell
double shell–burning core
helium burning
hydrogen-burning shell
helium-burning star core
inert helium
hydrogen-burning shell
subgiant/ red giant core



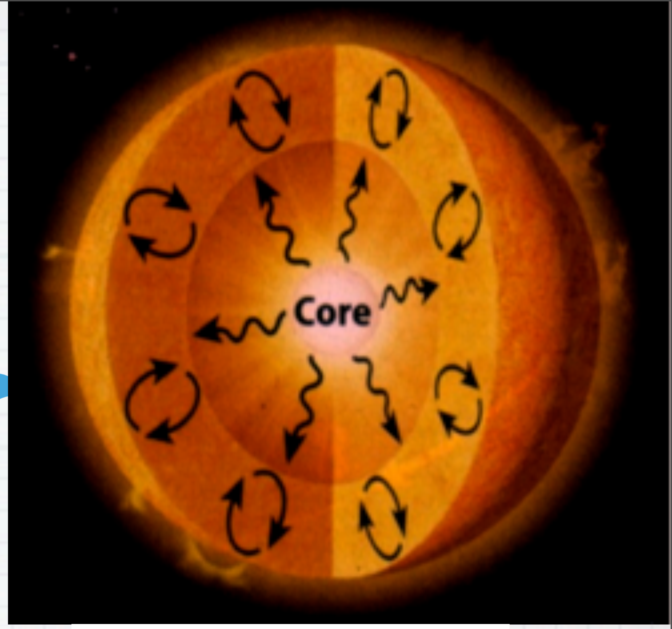
Bare Core
Envelope Ejection
Helium Flash
Asymptotic Giant Branch
Horizontal Branch
Red Giant Branch
Main Sequence
White Dwarf
Luminosity (L_{sun})
10^6
10^4
10^2
1
10^{-2}
10^{-4}
40,000
20,000
10,000
5,000
2,500
Temperature (K)

Timeline of a 1 solar mass star





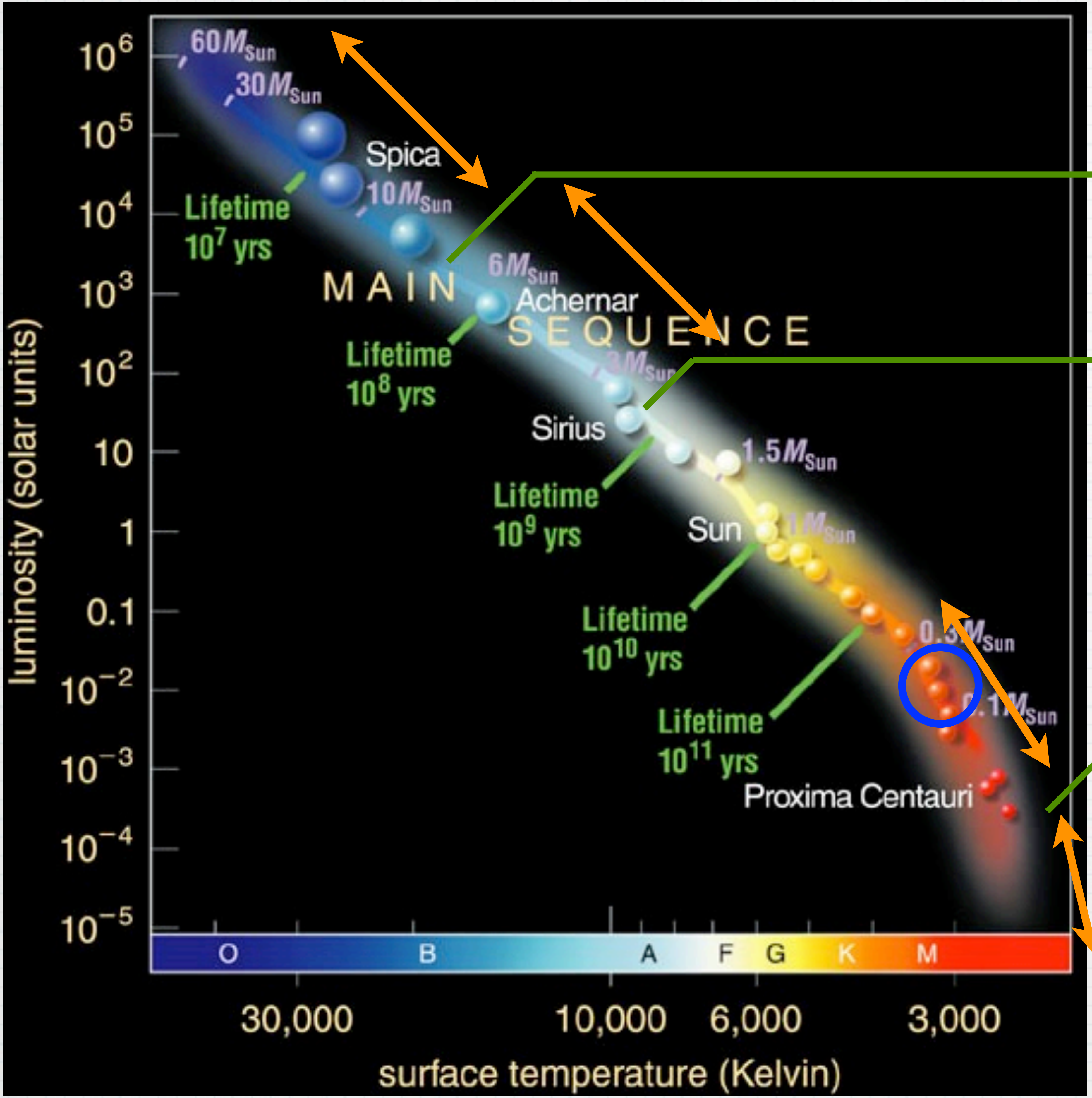
Life as a Very Low-Mass Star



M < 0.25

M ≈ 0.50

* If a star is less massive than about 0.50 solar mass, its life will be quite uneventful
* It will quietly and steadily fuse **all its hydrogen to helium** for hundreds of billions of years (5 trillion years for 0.1 solar mass)
* And eventually become a **helium white dwarf**



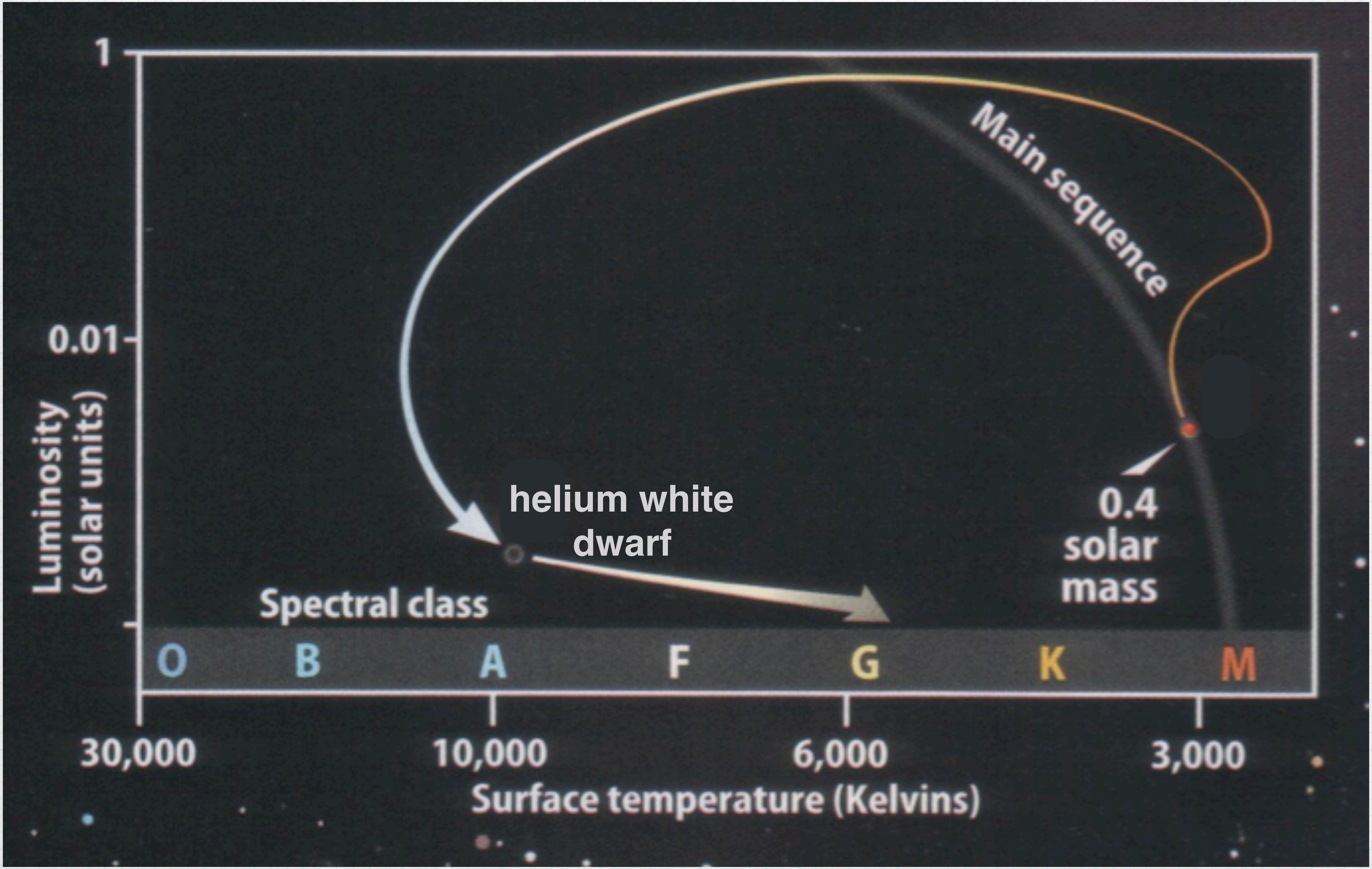
High-Mass Stars > 8 MSun

Intermediate-Mass Stars

Low-Mass Stars < 2 MSun

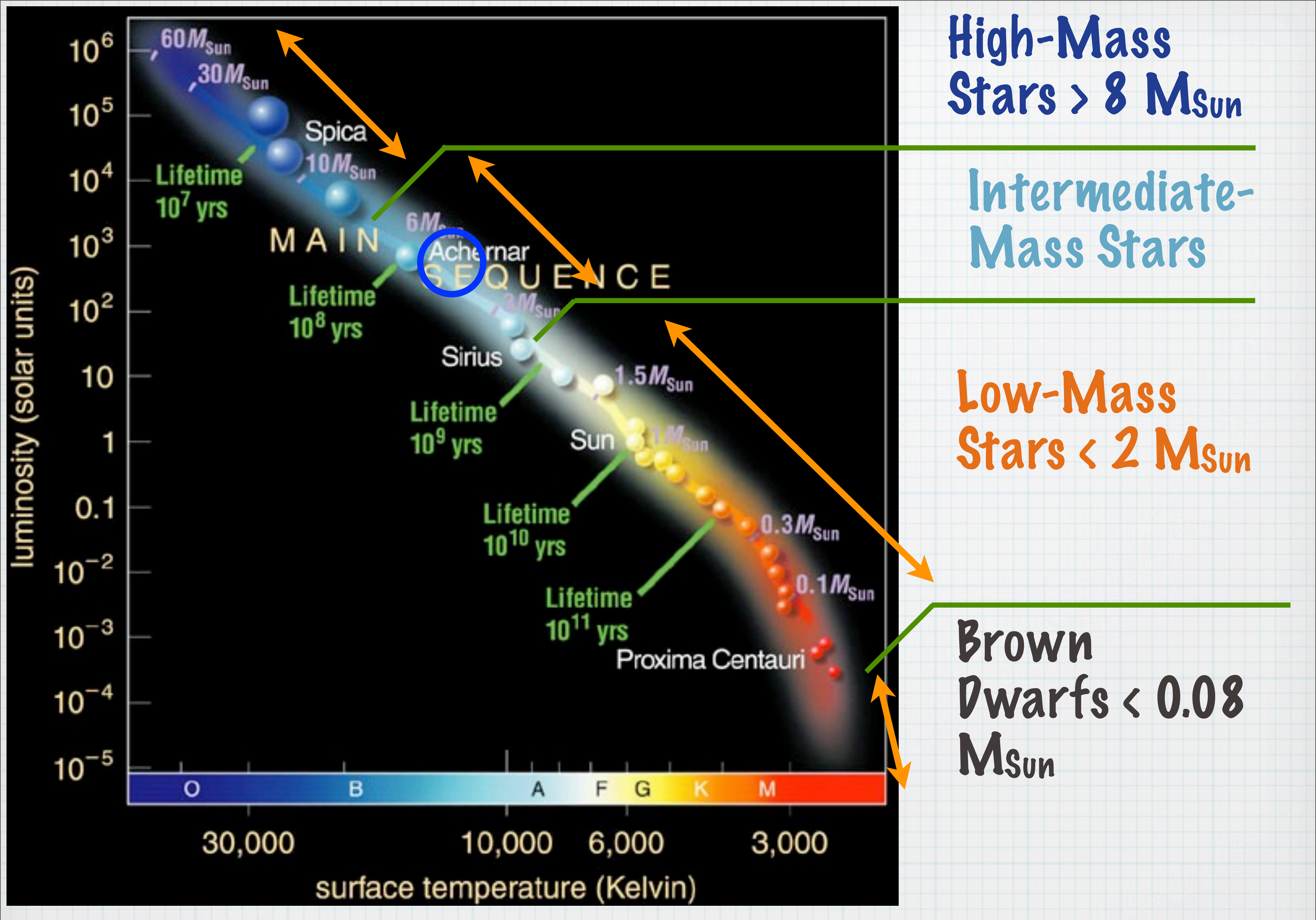
Brown Dwarfs < 0.08 MSun

Low-mass star HR diagram evolution



Life as an Intermediate-Mass Star

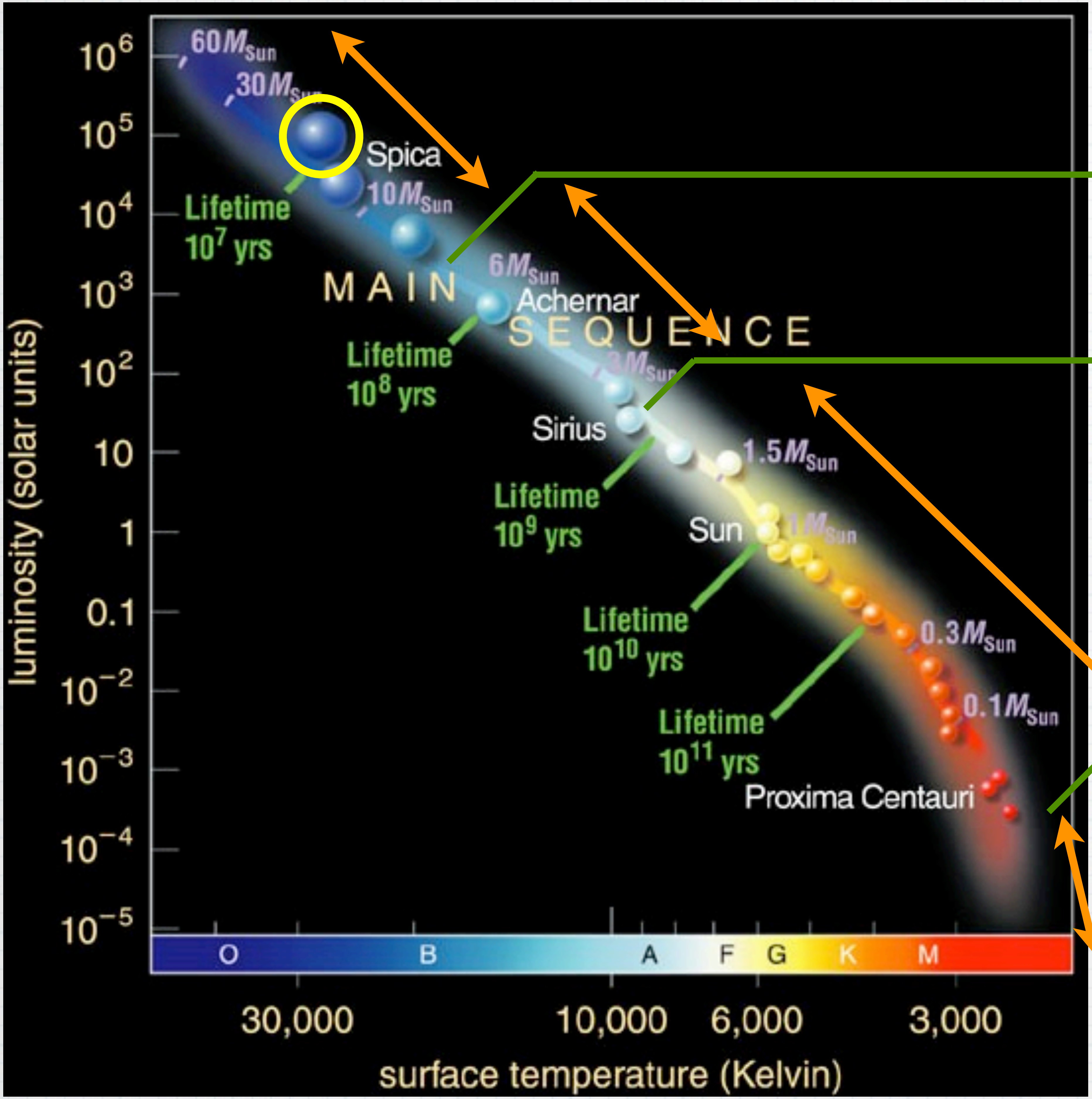
* An intermediate-mass star's life is similar to a low-mass one except that it proceeds at a faster pace (about 100 times faster)
* Like a low-mass star, it won't be able to fuse carbon in its core
* It, too, will end up as a white dwarf after creating a planetary nebula



60 M_{Sun}
30 M_{Sun}
Spica
10 M_{Sun}
6 M_{Sun}
Achernar
MAIN SEQUENCE
3 M_{Sun}
Sirius
1.5 M_{Sun}
Sun
1 M_{Sun}
0.3 M_{Sun}
0.1 M_{Sun}
Proxima Centauri
Lifetime 10^7 yrs
Lifetime 10^8 yrs
Lifetime 10^9 yrs
Lifetime 10^{10} yrs
Lifetime 10^{11} yrs
luminosity (solar units)
10^6
10^5
10^4
10^3
10^2
10
1
0.1
10^{-2}
10^{-3}
10^{-4}
10^{-5}
O B A F G K M
30,000 10,000 6,000 3,000
surface temperature (Kelvin)
High-Mass Stars > 8 MSun
Intermediate-Mass Stars
Low-Mass Stars < 2 MSun
Brown Dwarfs < 0.08 MSun

Life as a High-Mass Star

* Only the high-mass stars produce the heavy elements life depends on
* A high-mass star's early life is similar to a low-mass one except that it proceeds at a **much** faster pace (>1000)
* Let's look at a star whose mass is 25 M_{Sun}



High-Mass Stars > 8 Msun

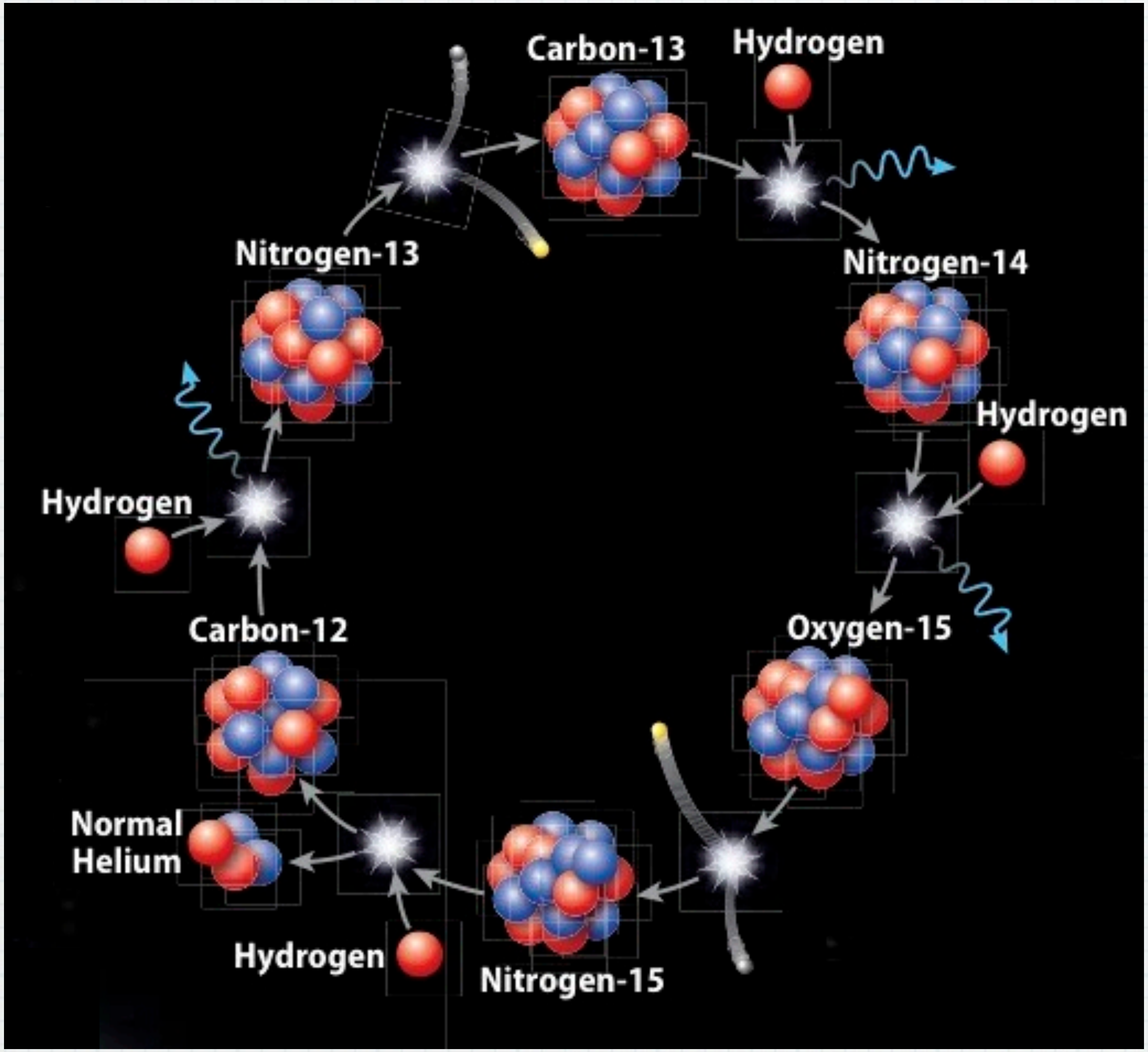
Intermediate-Mass Stars

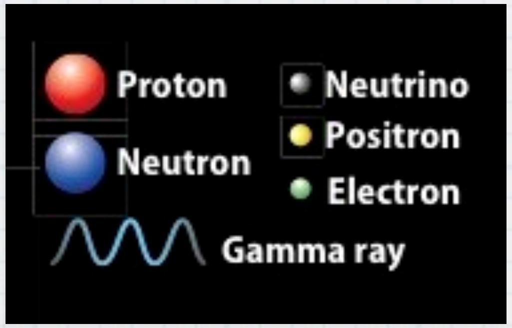
Low-Mass Stars < 2 Msun

Brown Dwarfs < 0.08 Msun

High-Mass Star's Life

* Main-sequence: H fuses to He in core
* The fusion mechanism is different
* It is called the CNO cycle
    * Carbon, Nitrogen, Oxygen
* Recall that the H to He fusion process for a low-mass star is called the proton-proton chain





The CNO cycle is just another way to fuse H into He, using carbon, nitrogen, and oxygen as catalysts

CNO cycle is main mechanism for H fusion in high mass stars because core temperature is higher

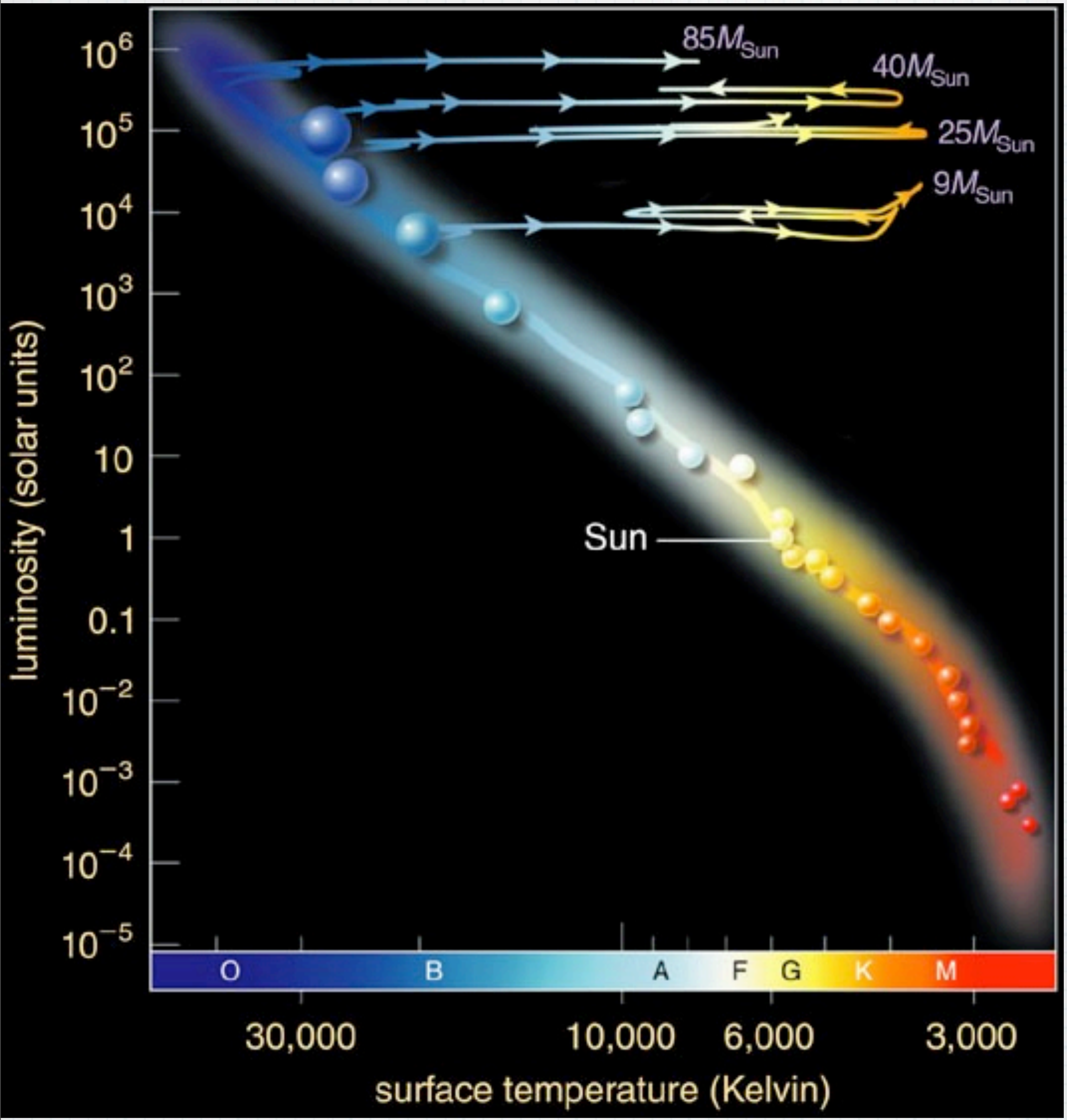
CNO also happens in stars like the Sun but it is a minor (1 %)contributor to fusion

High-Mass Star's Life...

* Main-sequence: H fuses to He in core using the CNO cycle
* The fusion rate is much higher because
  * core temperature is higher
  * there is more than one way to fuse H into He
* Result: much more luminous but much shorter lifetime in main-sequence

Becoming a Supergiant

* After just a few million years
* **Red Supergiant**: H fuses to He in shell around inert He core, and
* **Helium Core Burning**: He fuses to C in core (**no He flash** as there is no core degeneracy)



High-mass stars become supergiants after core H runs out

Luminosity doesn't change much but radius gets far larger

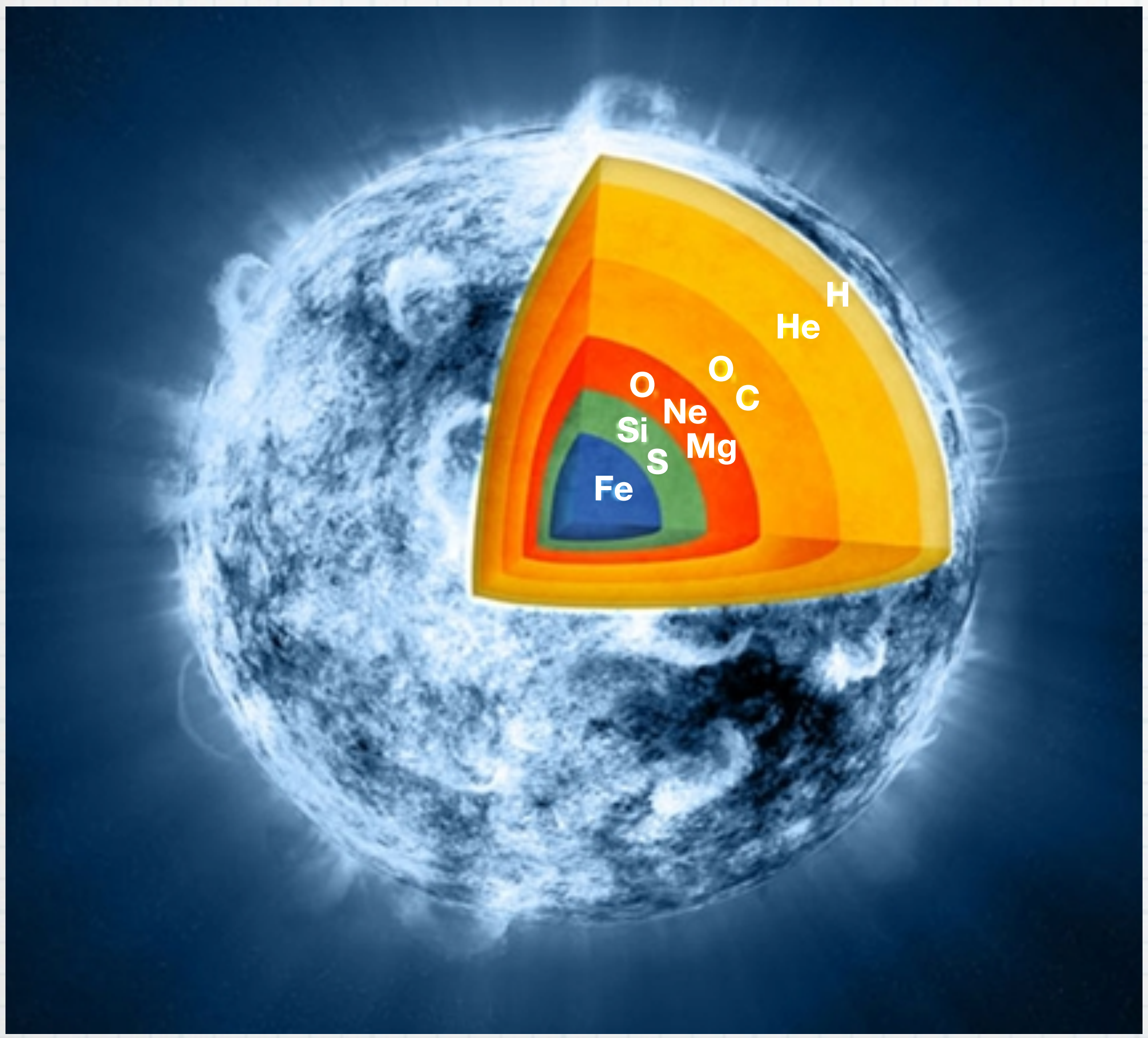
Becoming a Supergiant...

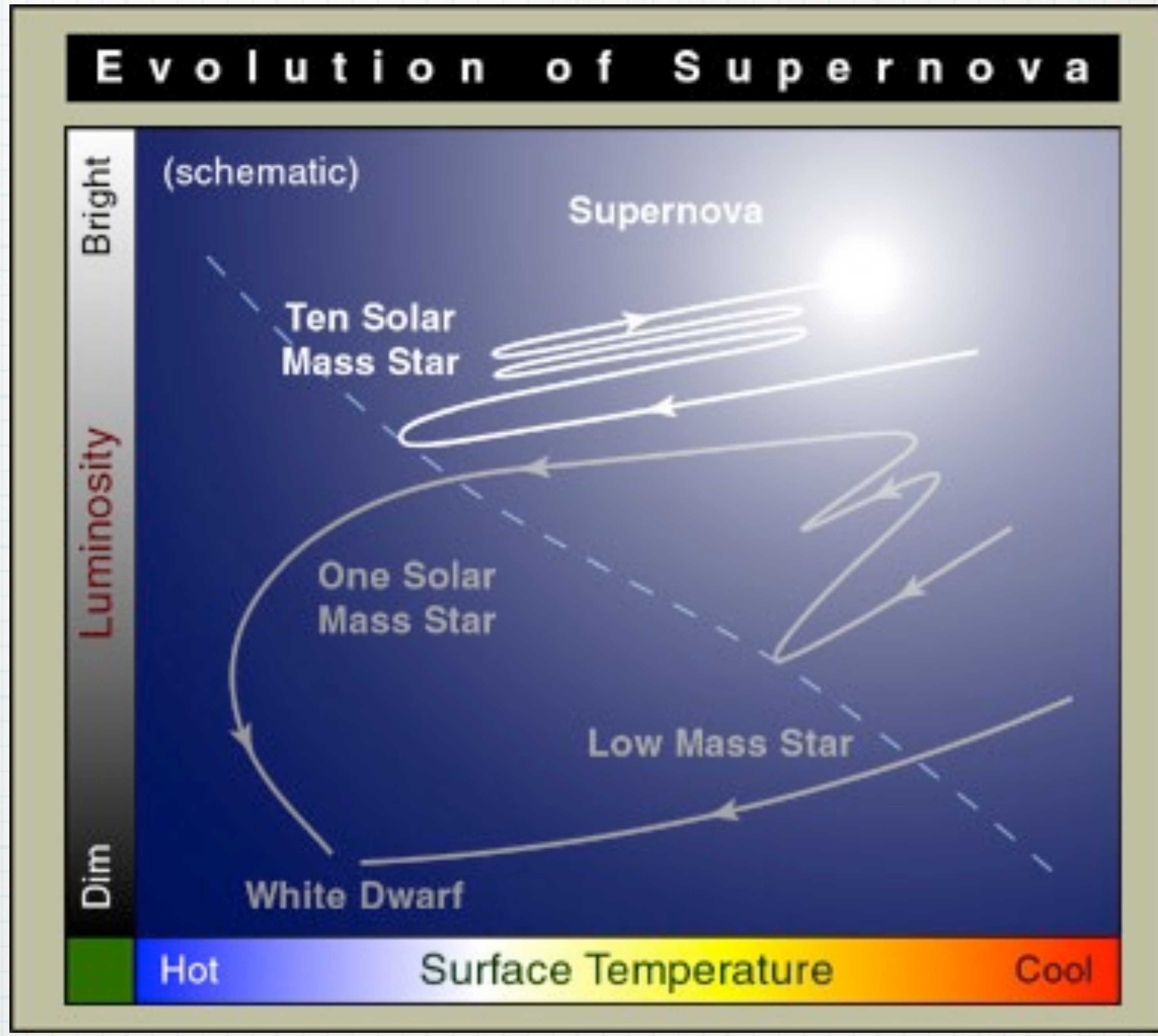
* Then He runs out in core now made of carbon. He fuses to C in shell around inert C core, H fuses to He in shell around He shell
* **Carbon Core Burning**: lasts only a few hundred thousand years as C fuses to Oxygen-Neon-Magnesium in core (**no flash**)
* The shrinking core gets hotter and hotter as it gets compressed by gravity during each non-fusing core period

Becoming a Supergiant...

* Several more fusion phases will succeed one another
  * each one adds a fusion shell
  * each one lasts a much shorter time than the previous one
  * each one creates heavier elements than the preceding one

Becoming a Supergiant...





Heavy Elements Making

* How do high mass stars make the elements necessary for life?
* Let's find out

Periodic Table of the Elements

Group → / ↓ Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	*	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	**															

* Lanthanides	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
** Actinides	89 Ac	90 Th	91 Pa	92 U											

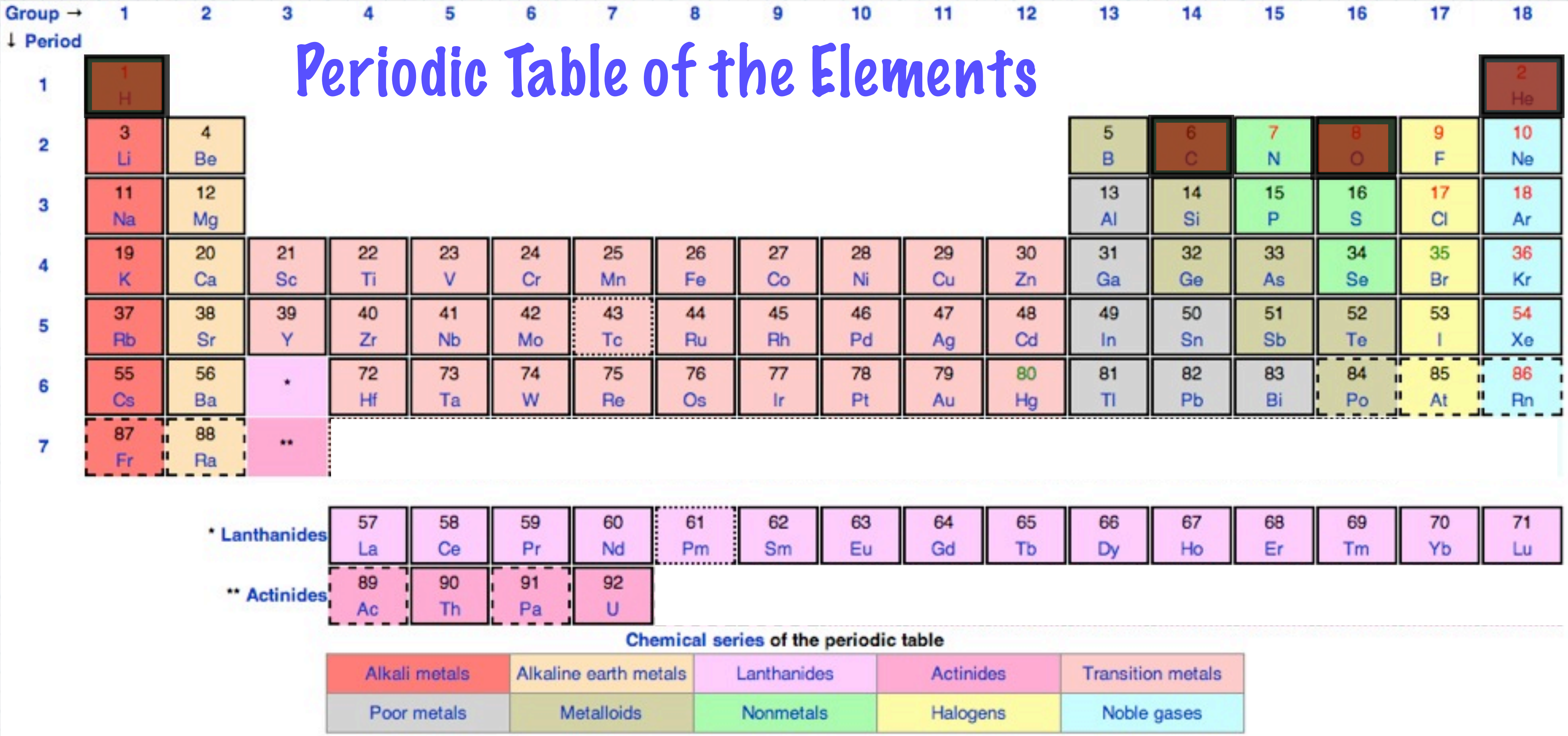
Chemical series of the periodic table

Alkali metals	Alkaline earth metals	Lanthanides	Actinides	Transition metals
Poor metals	Metalloids	Nonmetals	Halogens	Noble gases

Big Bang event made 75% H and 25% He

Stars make everything else

Periodic Table of the Elements



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Helium fusion can make carbon and some oxygen in low-mass stars

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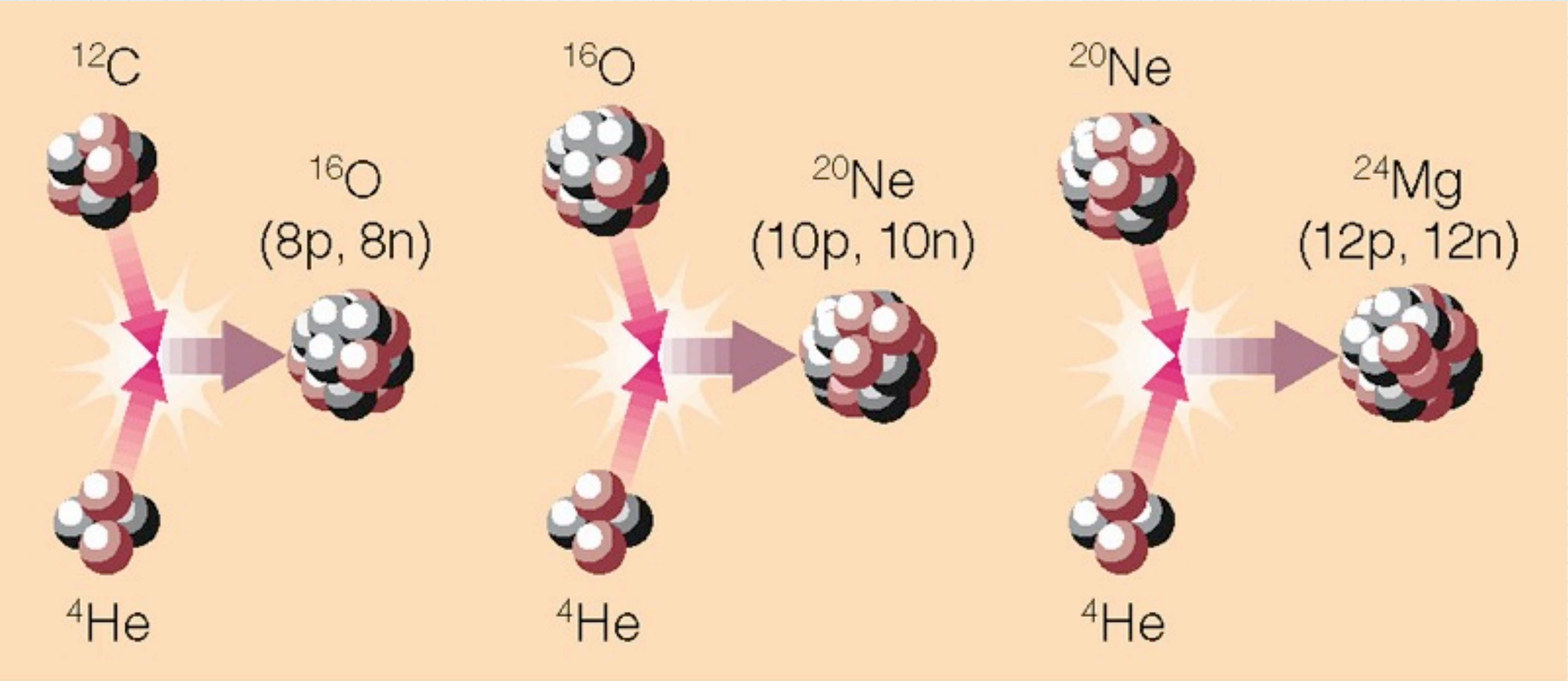
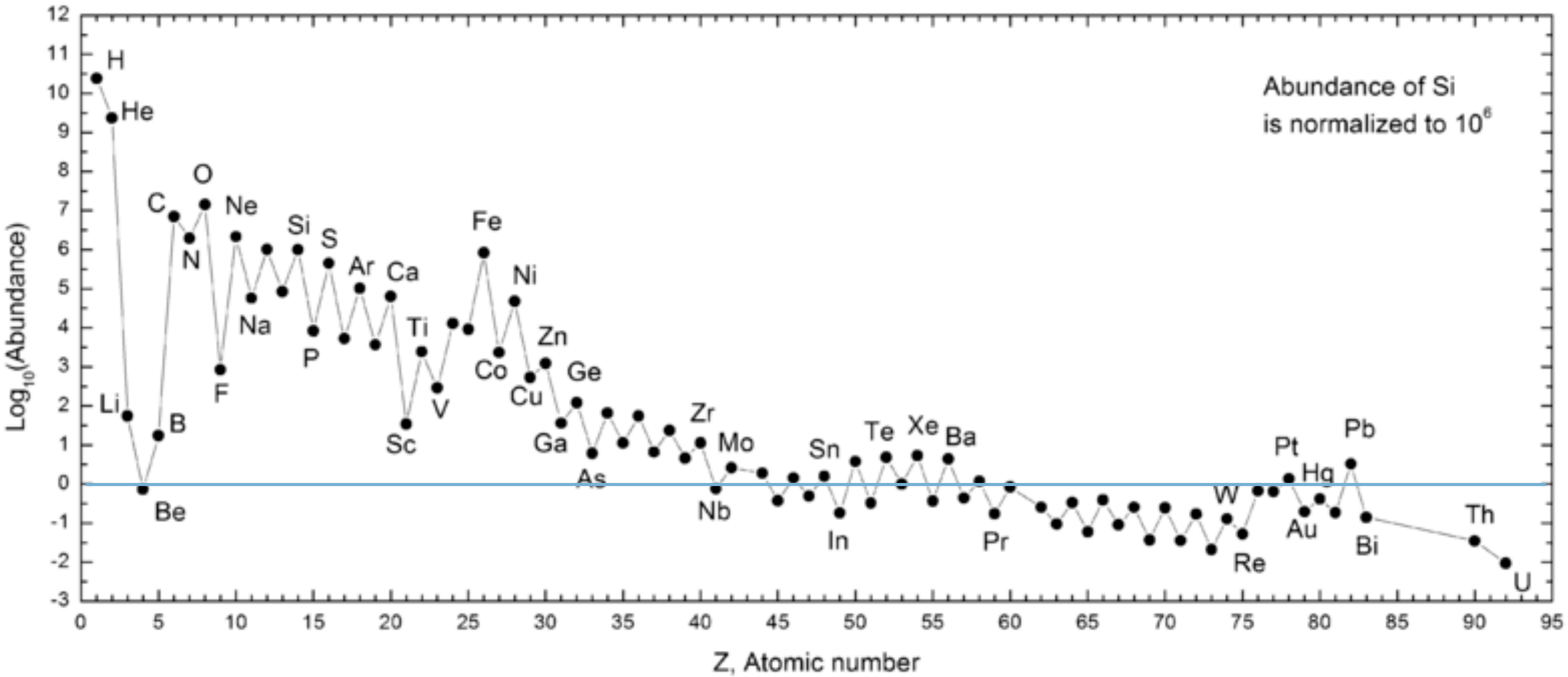
CNO cycle can change C into N and O



Helium-capture reactions
add two protons at a time

Evidence for helium capture



Higher abundances of elements with even numbers of protons

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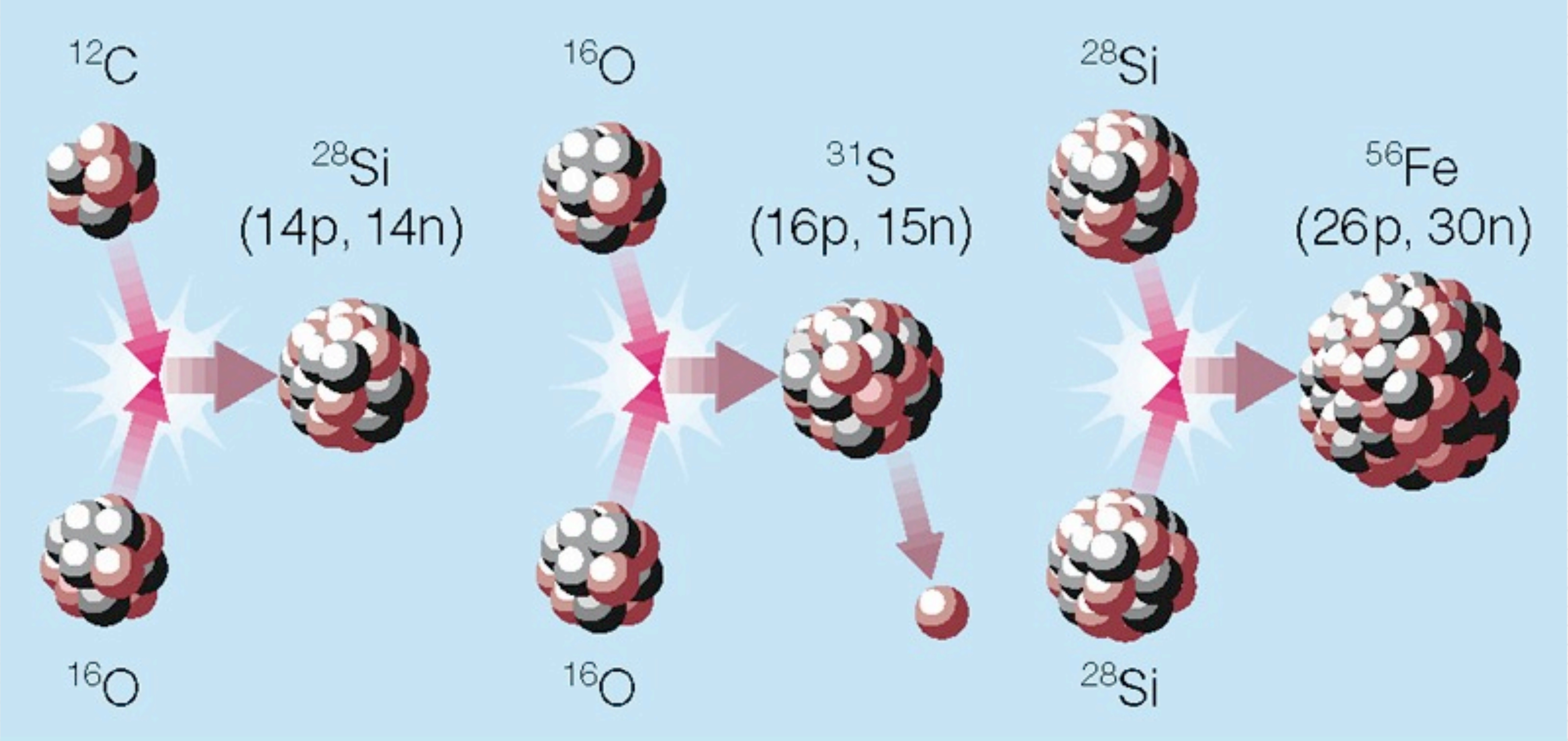
Helium capture builds C into O, Ne, Mg, ...



Advanced nuclear fusion reactions require extremely high temperatures

Only high-mass stars can attain high enough core temperatures before degeneracy pressure stops contraction

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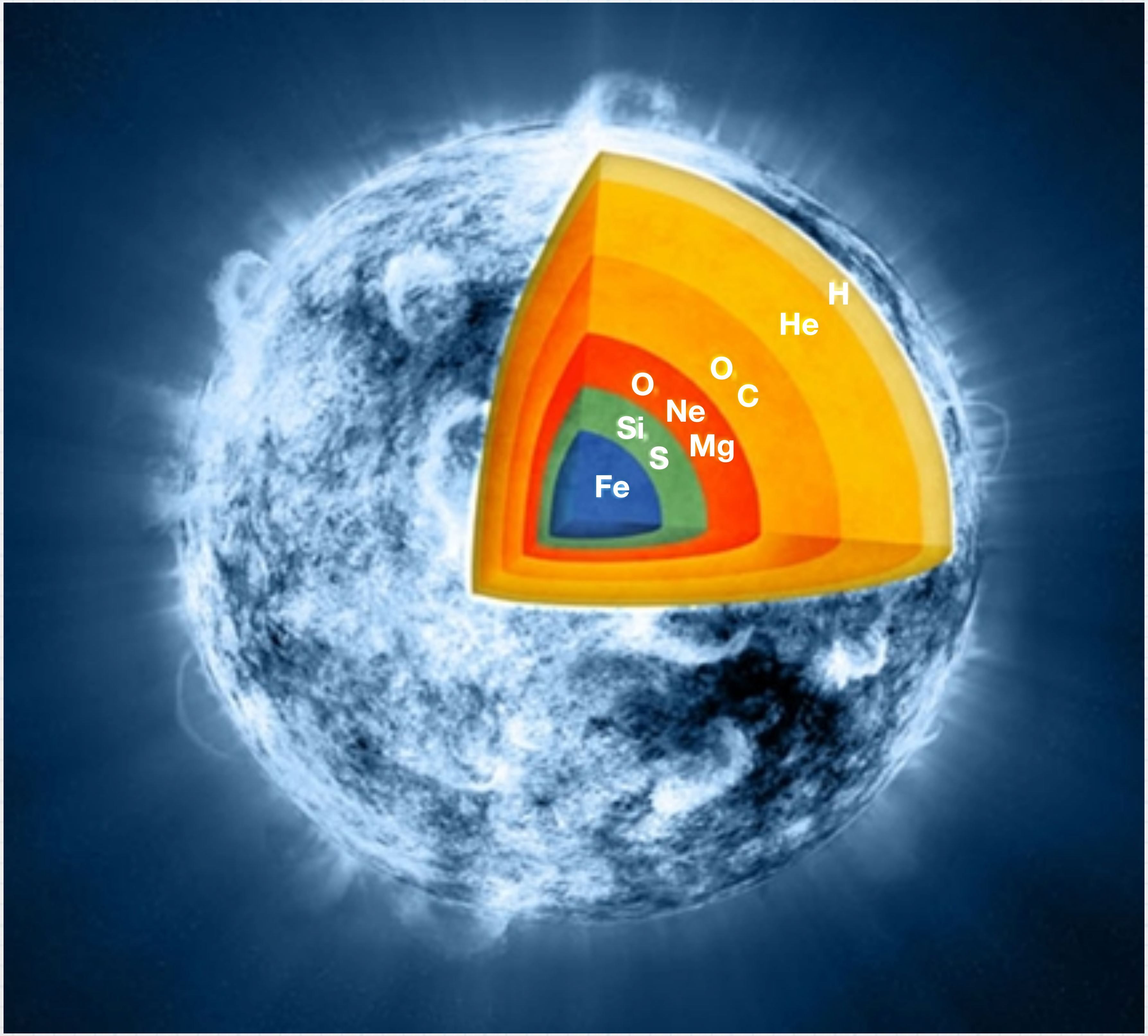
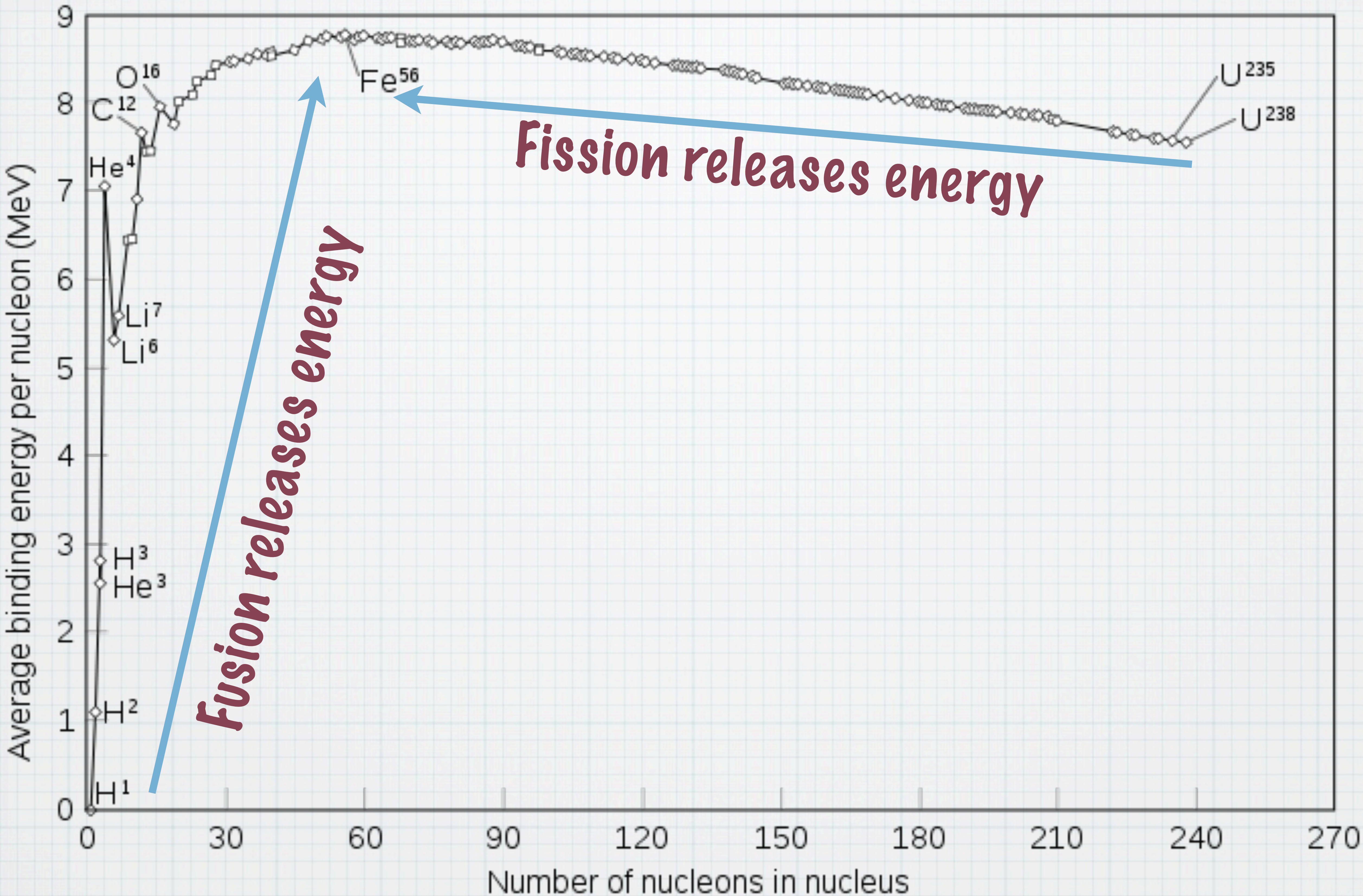
Advanced reactions make heavier elements

Advanced nuclear burning occurs in multiple shells



Iron in the Core

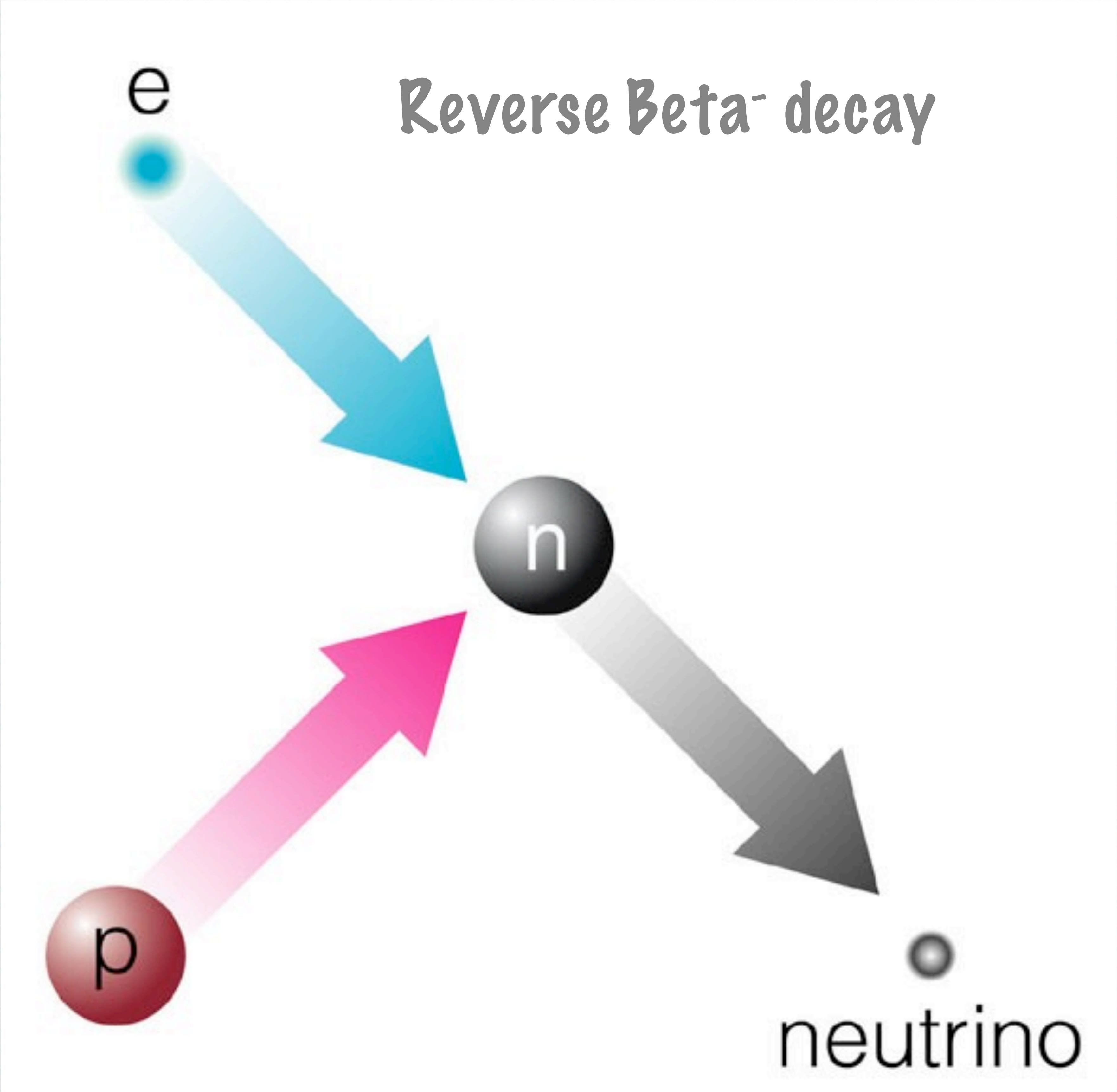
* When the core fuses silicon, iron is the resulting element
* When silicon fusion stops and the core contracts one more time, no additional amount of temperature will be able to make iron fuse into anything
* No energy can be released by iron fusion



Iron is dead end for fusion because nuclear reactions involving iron do not release energy

How does a high mass star die?

* Only electron degeneracy pressure could stop the iron core from contracting further
* But electron degeneracy pressure is overwhelmed by the force of gravity
* Gravity forces the electrons to merge with protons and form neutrons while releasing neutrinos in the process



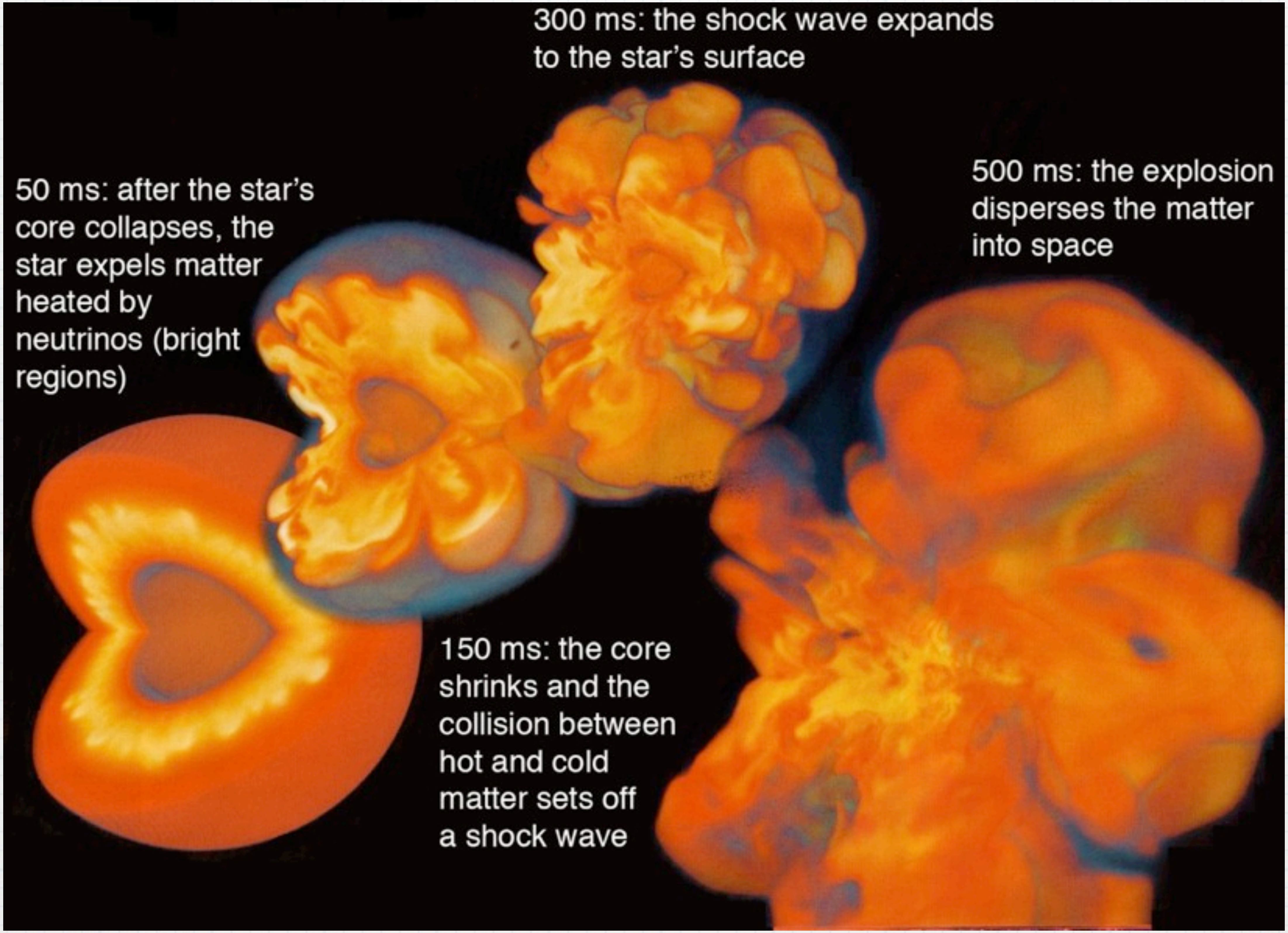
Core degeneracy pressure goes away because electrons combine with protons, making neutrons and neutrinos

Neutrons collapse to the center, forming a neutron star, or even a black hole if the neutrons collapse as well

Massive Star Supernova

* The gravitational collapse of the core releases more energy in a fraction of a second than 100 Suns will release while being in their 10 billion year main-sequence lifetime
* The energy released is thought to come from the neutrinos escaping the core and drive a shock wave that propels the star's upper layers into space

Type II Supernova: a 1/2 second event!



Massive Star Supernova

* The nuclear flash will last a few months
* It will shine as 10 billion Suns
* This is more brilliant than the entire galaxy the star is in
* Astronomers have classified such supernovae in 3 sub-classes
    * Type Ib, Ic and Type II

Supernovae

* Astronomers have classified supernovae in 3 classes
  * Type Ia: a white dwarf supernova (to be seen next week)
  * Type Ib, Ic: massive stars that have shed most of their outer envelope / shells (Hydrogen Ib and Helium Ic)
  * Type II: massive stars still having their H and He shells

Supernova Types

- Type I: no or little hydrogen-helium spectral lines
- Type II: hydrogen-helium spectral lines are seen

Periodic Table of the Elements

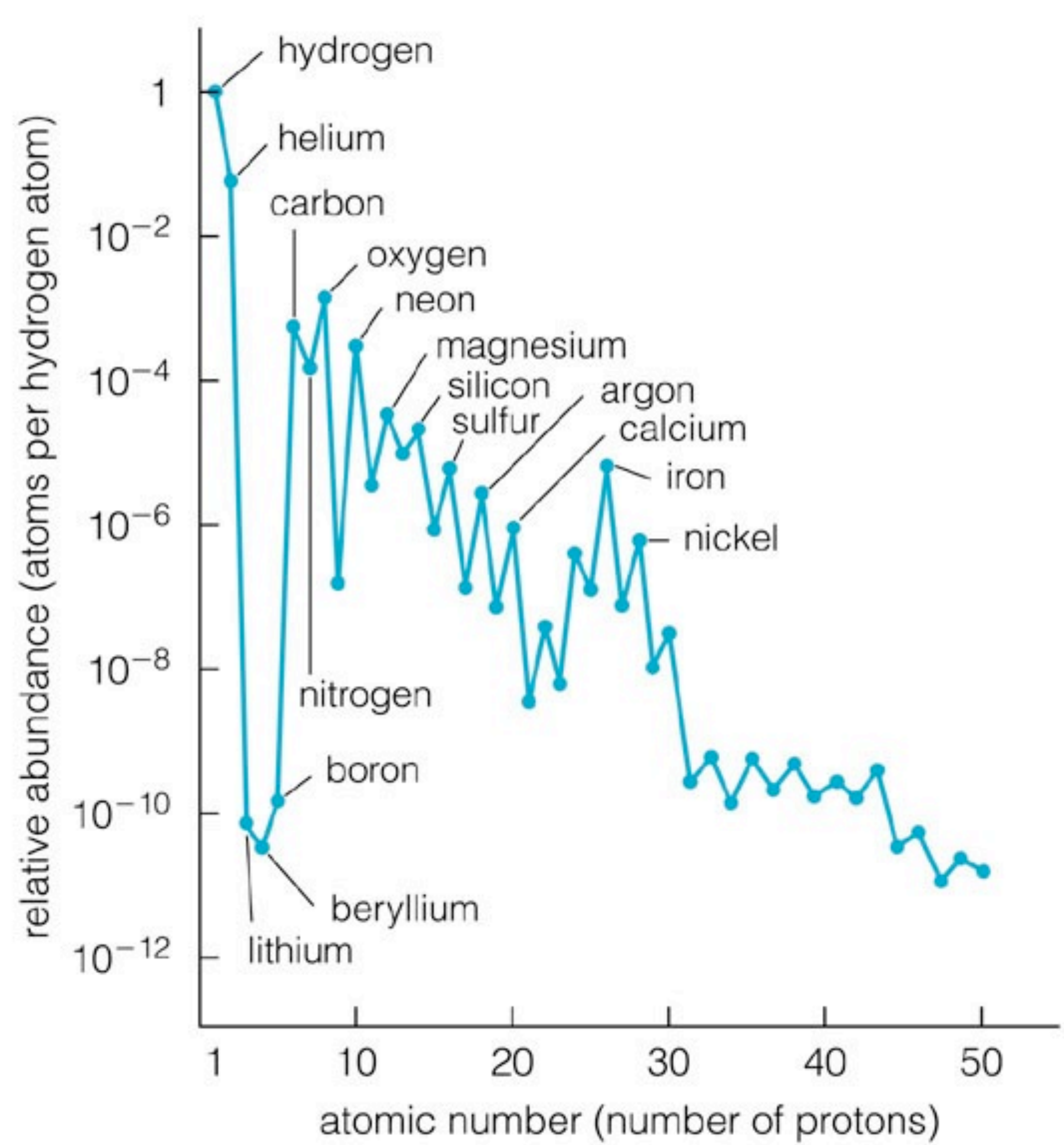
Group → / ↓ Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	*	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	**															

* Lanthanides	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
** Actinides	89 Ac	90 Th	91 Pa	92 U											

Chemical series of the periodic table

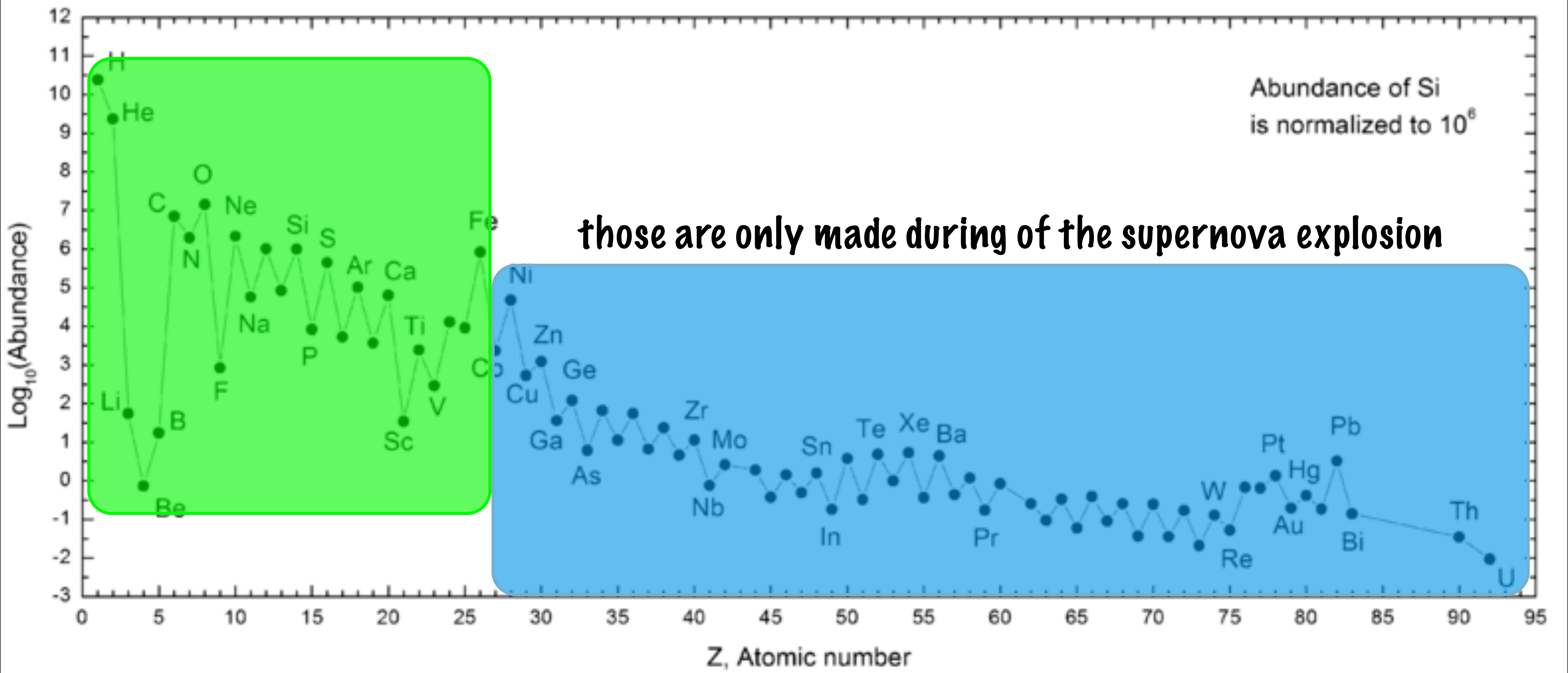
Alkali metals	Alkaline earth metals	Lanthanides	Actinides	Transition metals
Poor metals	Metalloids	Nonmetals	Halogens	Noble gases

Energy and neutrons released in supernovae explosions enables elements much heavier than iron to form

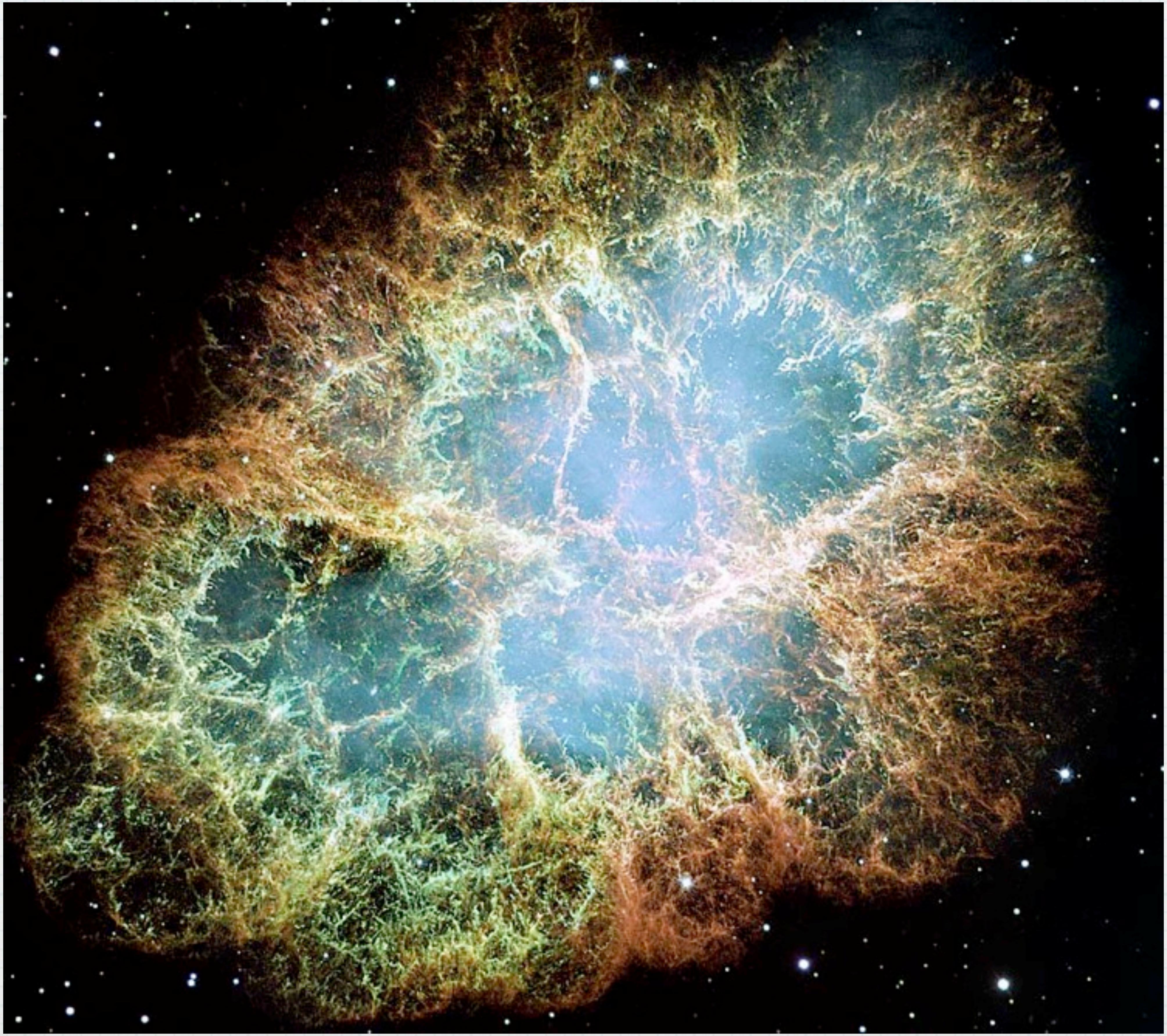


Elements made during supernova explosion

Elements made during supernova explosion



Crab Nebula: Remnant of supernova observed in 1054 A.D.



before

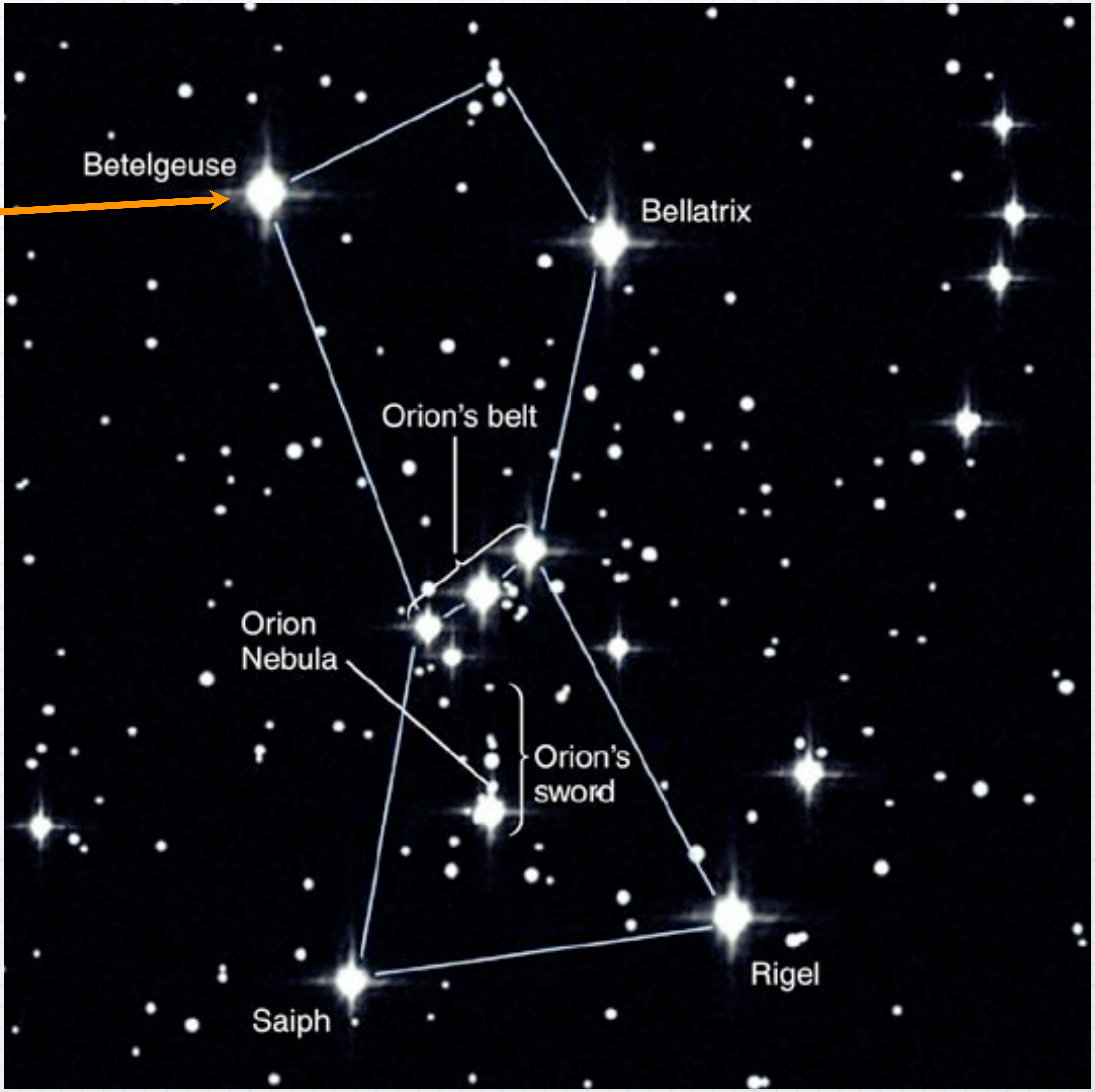
after

Supernova 1987A is the nearest supernova observed in the last 400 years
It happened in the Large Magellanic Cloud (150,000 light-years away)

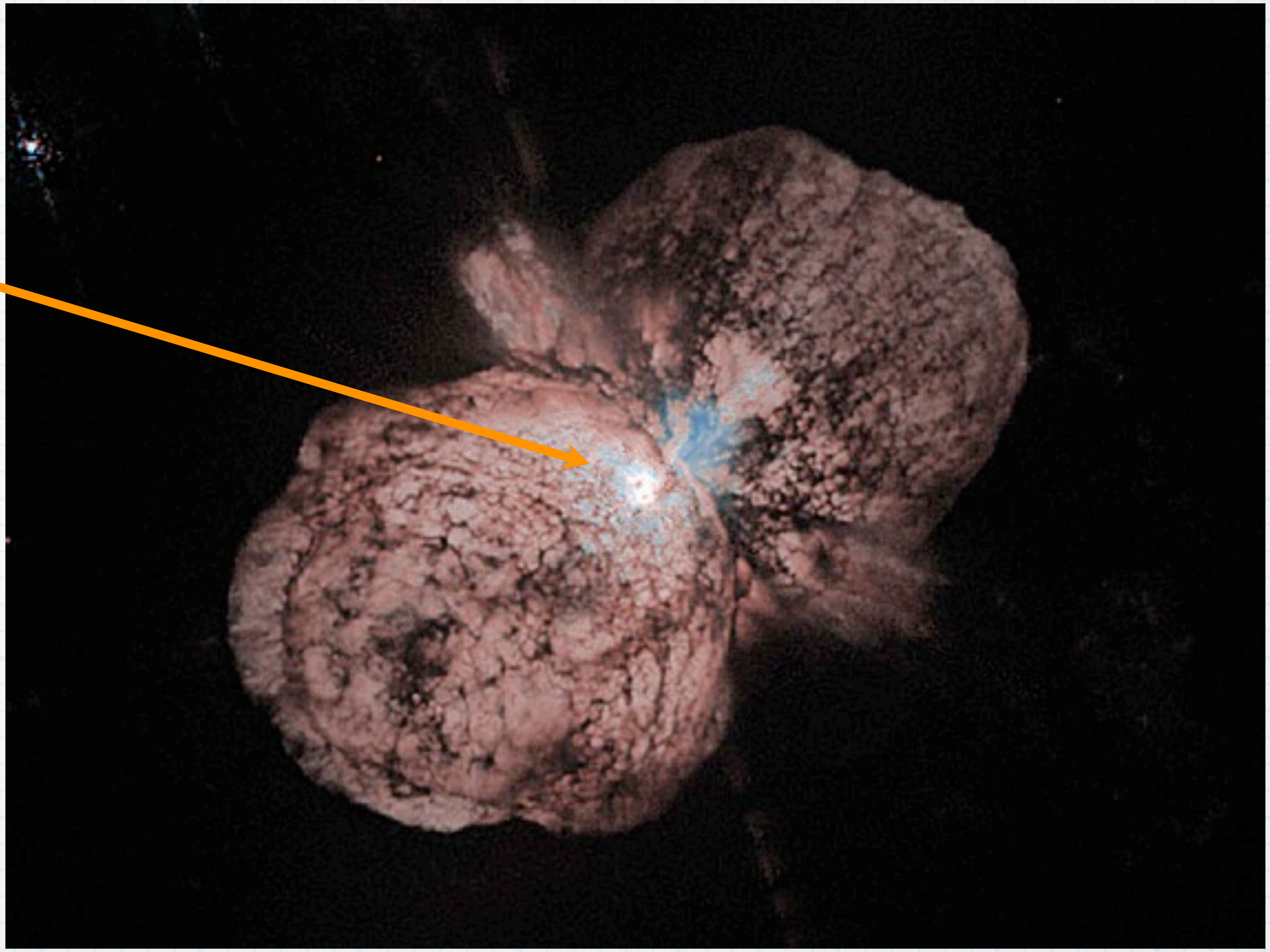
Neutrino detectors observed a burst of such particles when the supernova was detected

The next nearby supernova?

When Betelgeuse goes supernova, it will be 10 times as bright as the full moon



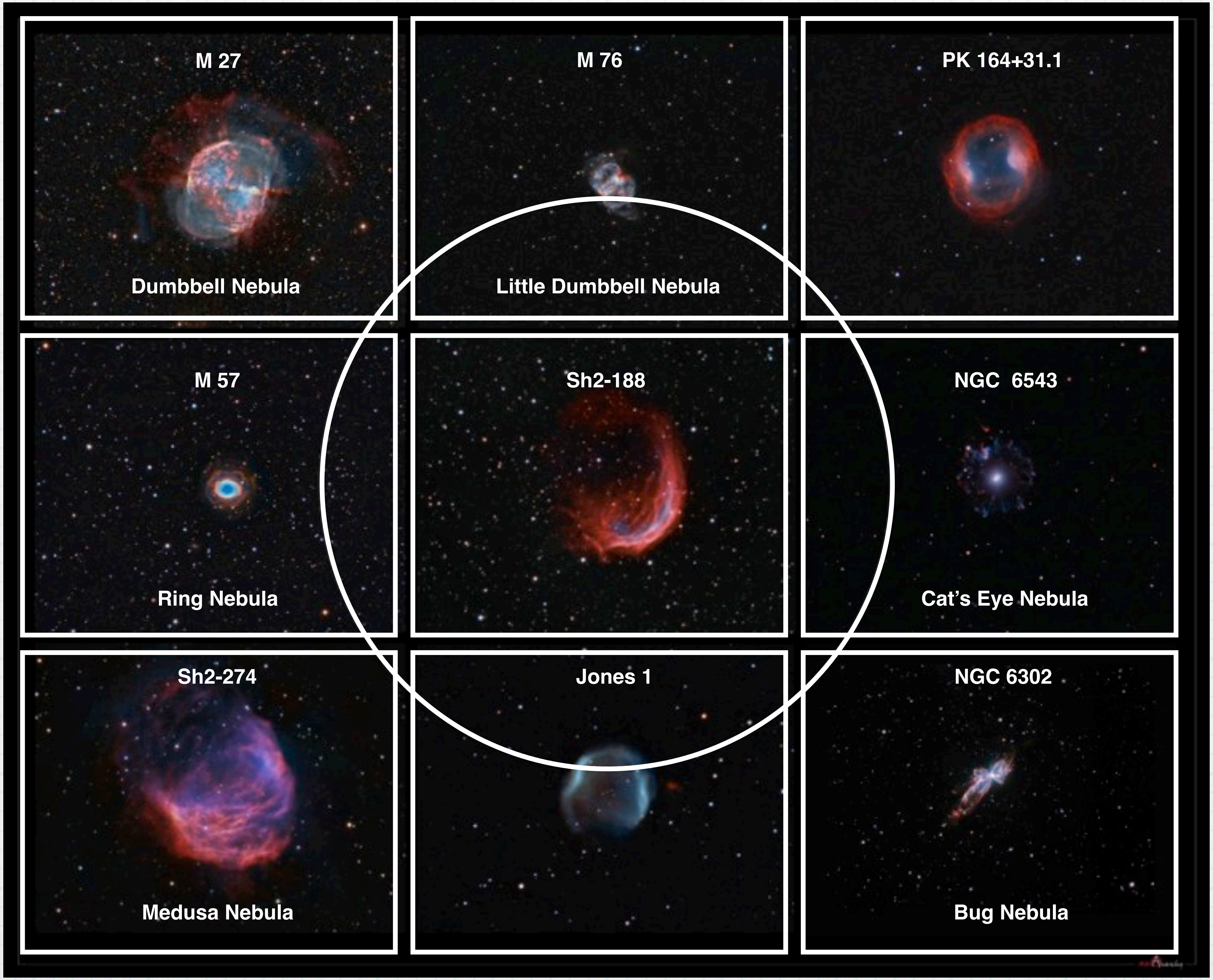
Or this one?



Eta Carinae may be about to explode. But no one knows when - it may be next year, it may be one million years from now

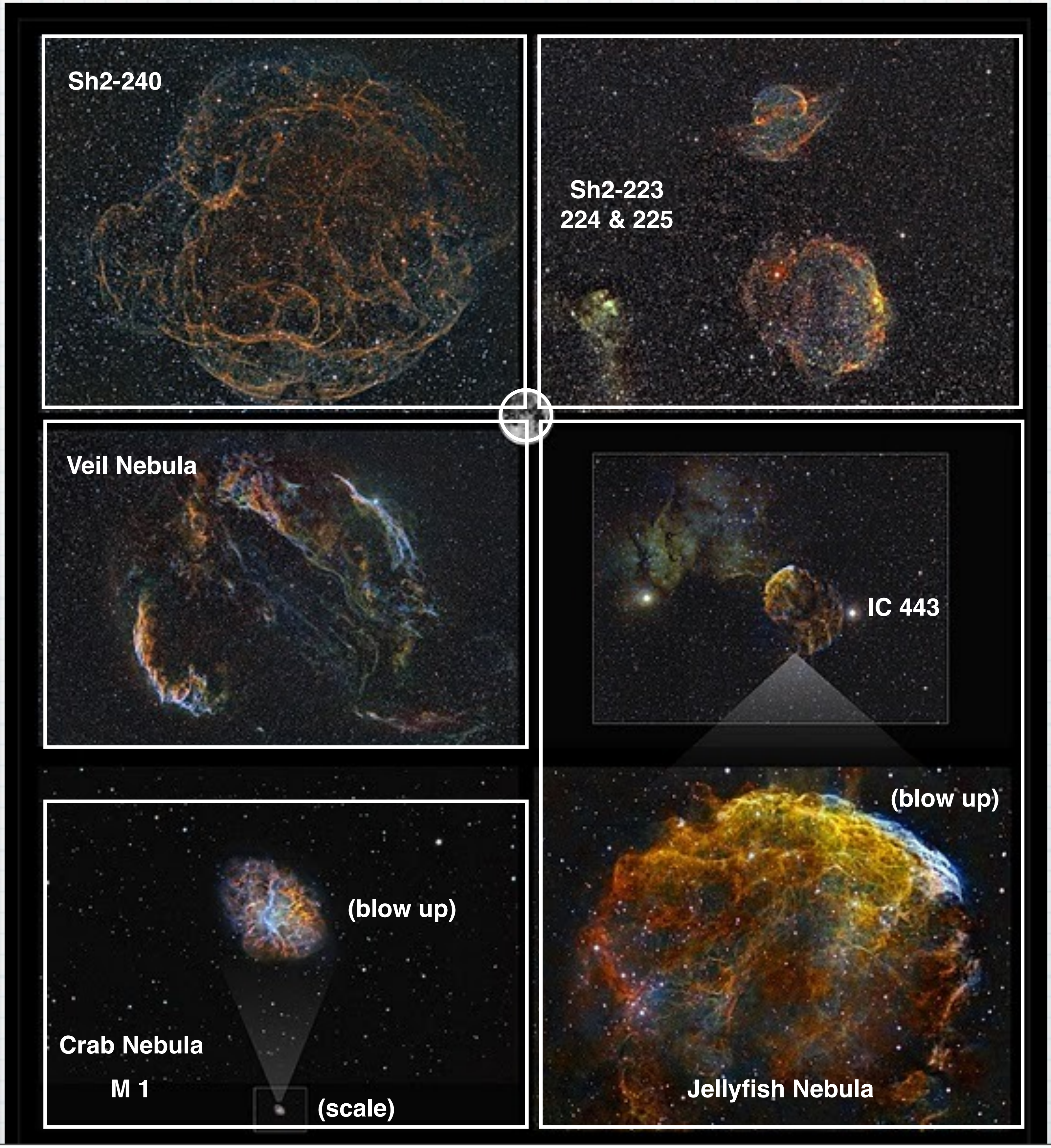
Eta Carinae's mass - about 100 times greater than our Sun - makes it an excellent candidate for a full blown supernova. Historical records do show that about 150 years ago Eta Carinae underwent an unusual outburst that made it one of the brightest stars in the southern sky

Let's recall the relative angular sizes of a planetary nebula
Planetary Nebulae sizes to scale (with the Moon)



Supernovae Remnants sizes to scale (with the Moon)
Supernova = death of a massive star

A lot more energy!



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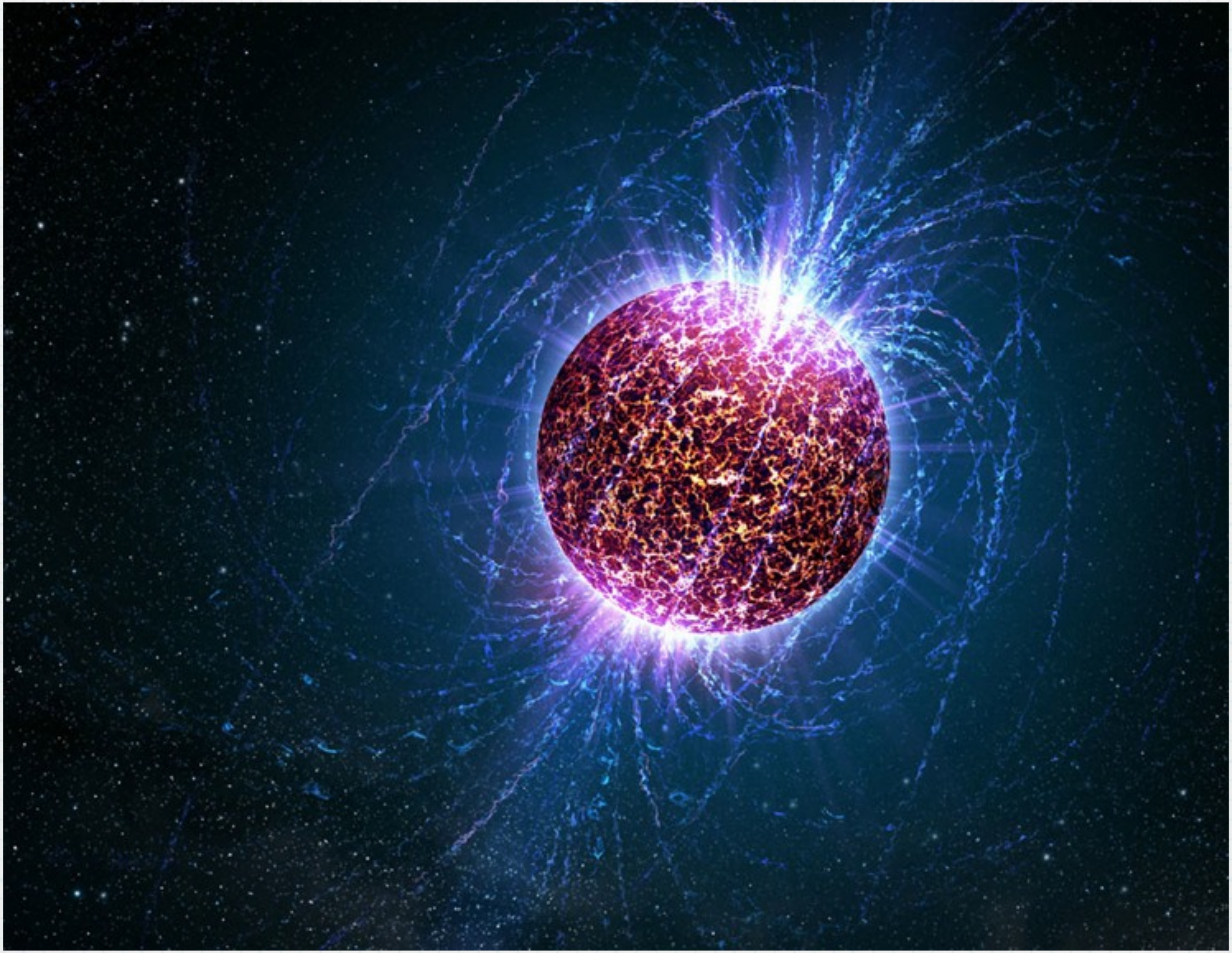
Neutron Stars: Supernova remnants

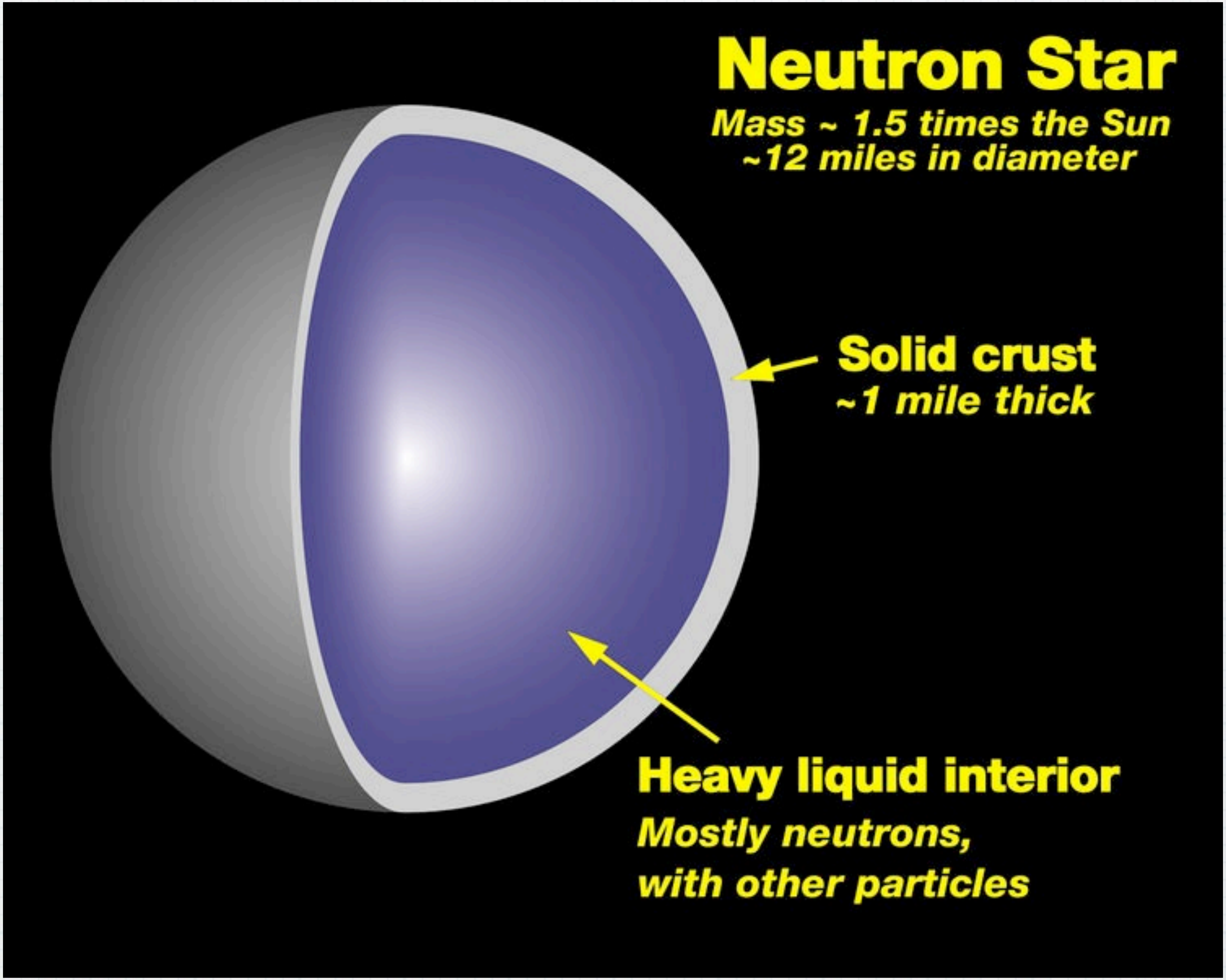
* The iron core (the size of the Earth) is squished to a ball of neutron just a few kilometers across in a fraction of a second
* That collapse is itself stopped by the neutron degeneracy pressure
* The core is now packed with neutrons and its density is extraordinarily high

Neutron Stars...

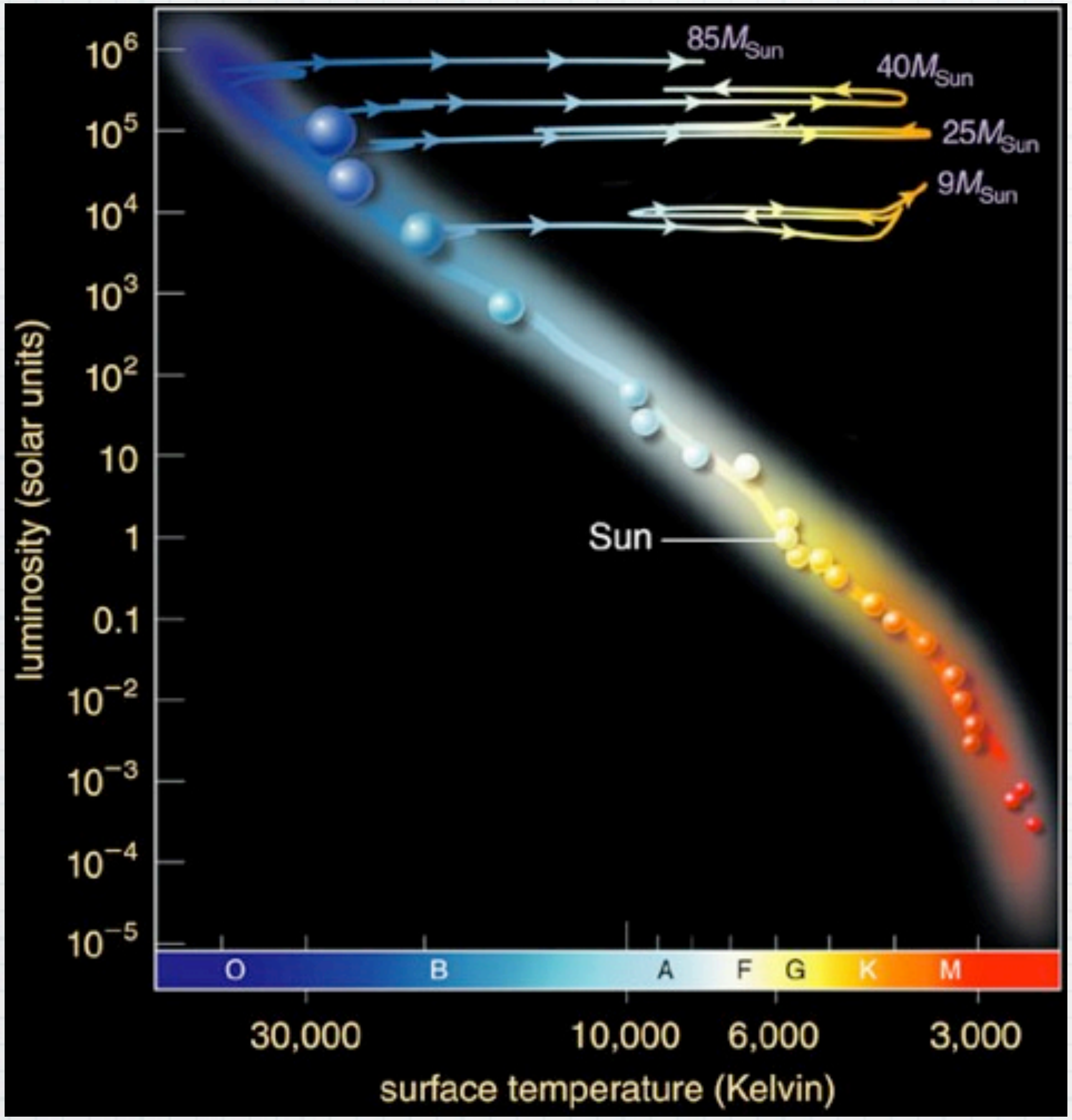
* 80 million tonnes to 2 billion tonnes per cubic centimeter or...
* 5.4 millions tons to 134 millions tons per cubic inch
* A typical neutron star is between 1.35 to 2.1 solar masses with a corresponding radius between 16 to 10 km (10 to 6.3 miles)

A Neutron Star




Neutron Star
Mass ~ 1.5 times the Sun
~12 miles in diameter
Solid crust
~1 mile thick
Heavy liquid interior
Mostly neutrons,
with other particles

Snapshot



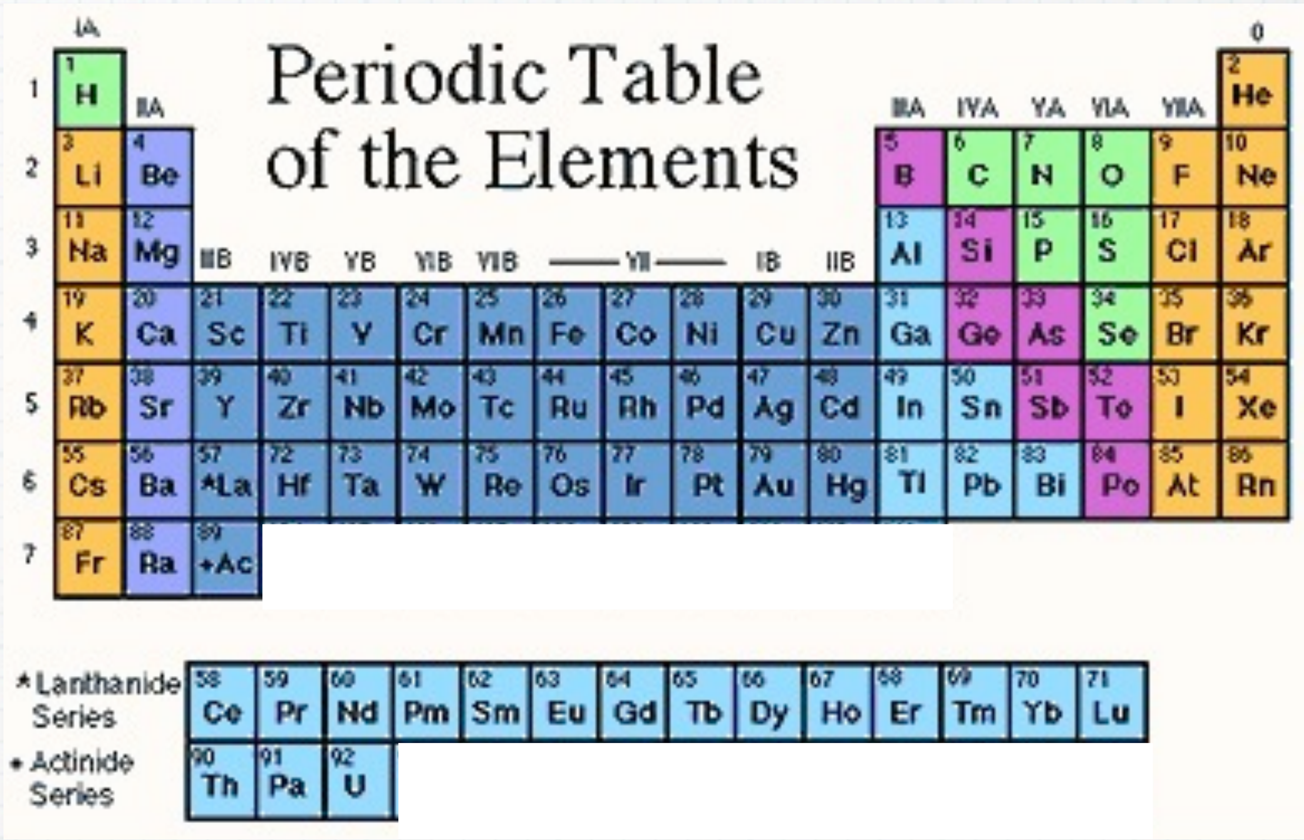
What are the life stages of a high-mass star?

A high-mass star lives a much shorter life than a low-mass star, fusing hydrogen into helium via the CNO cycle. After exhausting its core hydrogen, a high-mass star begins hydrogen shell burning and then goes through a series of stages burning successively heavier elements. The furious rate of this fusion makes the star swell in size to become a supergiant

Snapshot...

How do high-mass stars make the elements necessary for life?

In its final stages of life, a high-mass star's core becomes hot enough **to fuse carbon and other heavy elements**. The variety of different fusion reactions produces a wide range of elements— including all the elements necessary for life—that are then released into space when the star dies.



How does a high-mass star die?

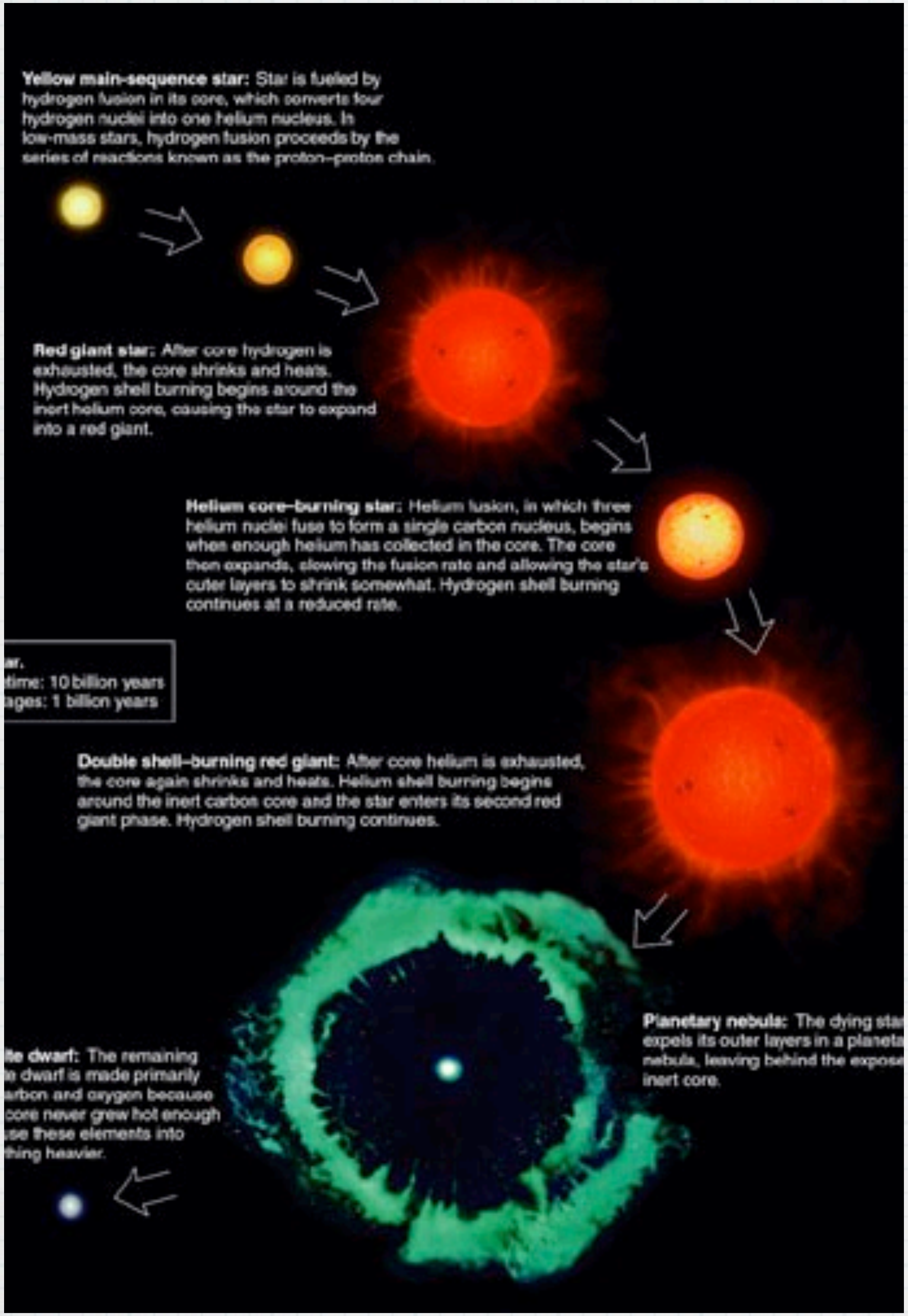
Snapshot...

A high-mass star dies in the explosion of a supernova, scattering newly produced elements into space and leaving a neutron star or black hole behind

The supernova occurs after fusion begins to pile up iron in the high-mass star's core. Because iron fusion cannot release energy, the core cannot hold off the crush of gravity for long. In the instant that gravity overcomes degeneracy pressure, the core collapses and the star explodes

Summary of Stellar Lives

* How does a star's mass determine its life story?



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Low-Mass Star Summary

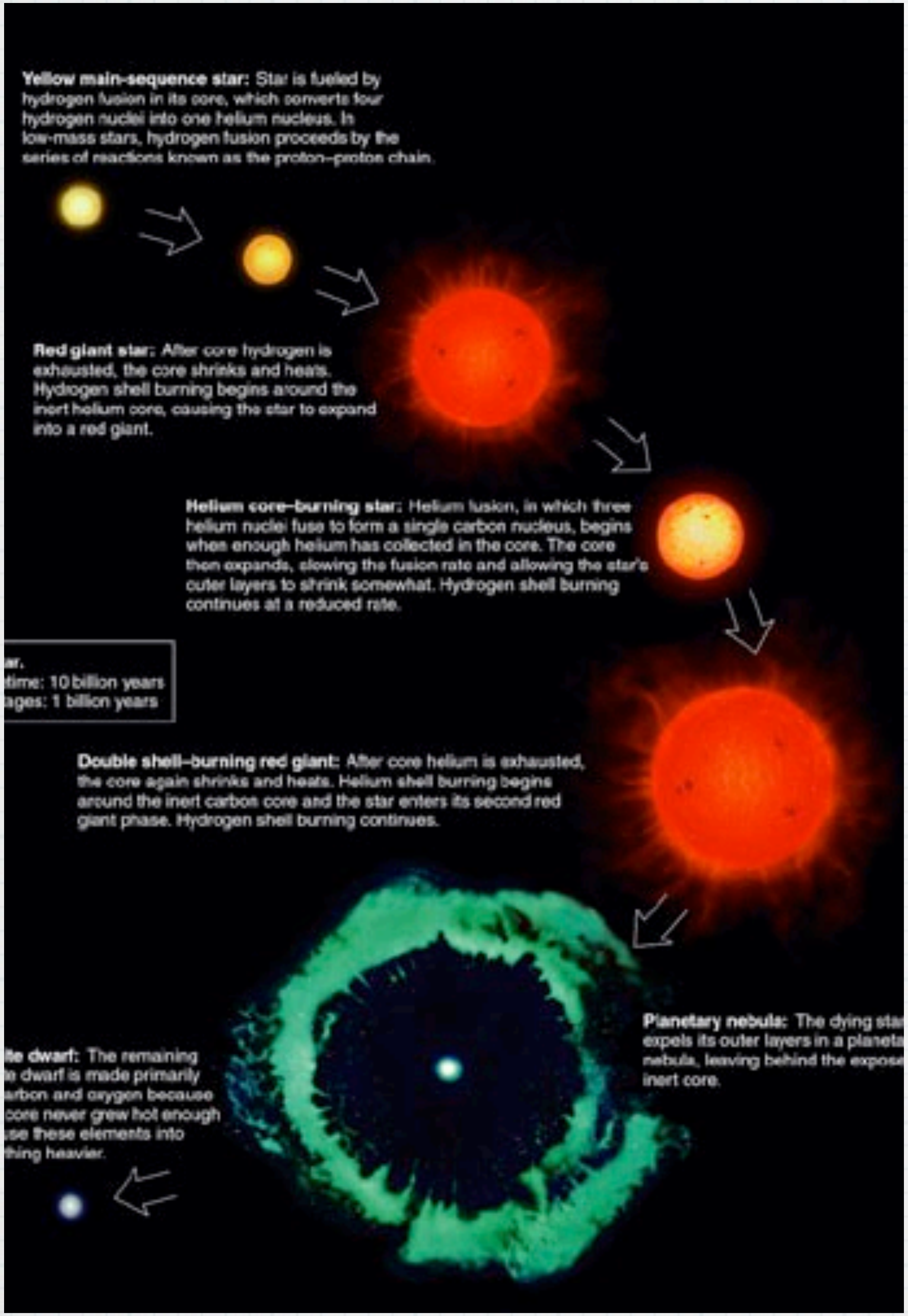
1. Main Sequence: H fuses to He in core

2. Red Giant: H fuses to He in shell around He core

3. Helium Core Burning:
   He fuses to C in core while H fuses to He in shell

4. Double Shell Burning:
   H and He both fuse in shells

5. Planetary Nebula leaves white dwarf behind



Reasons for Life Stages

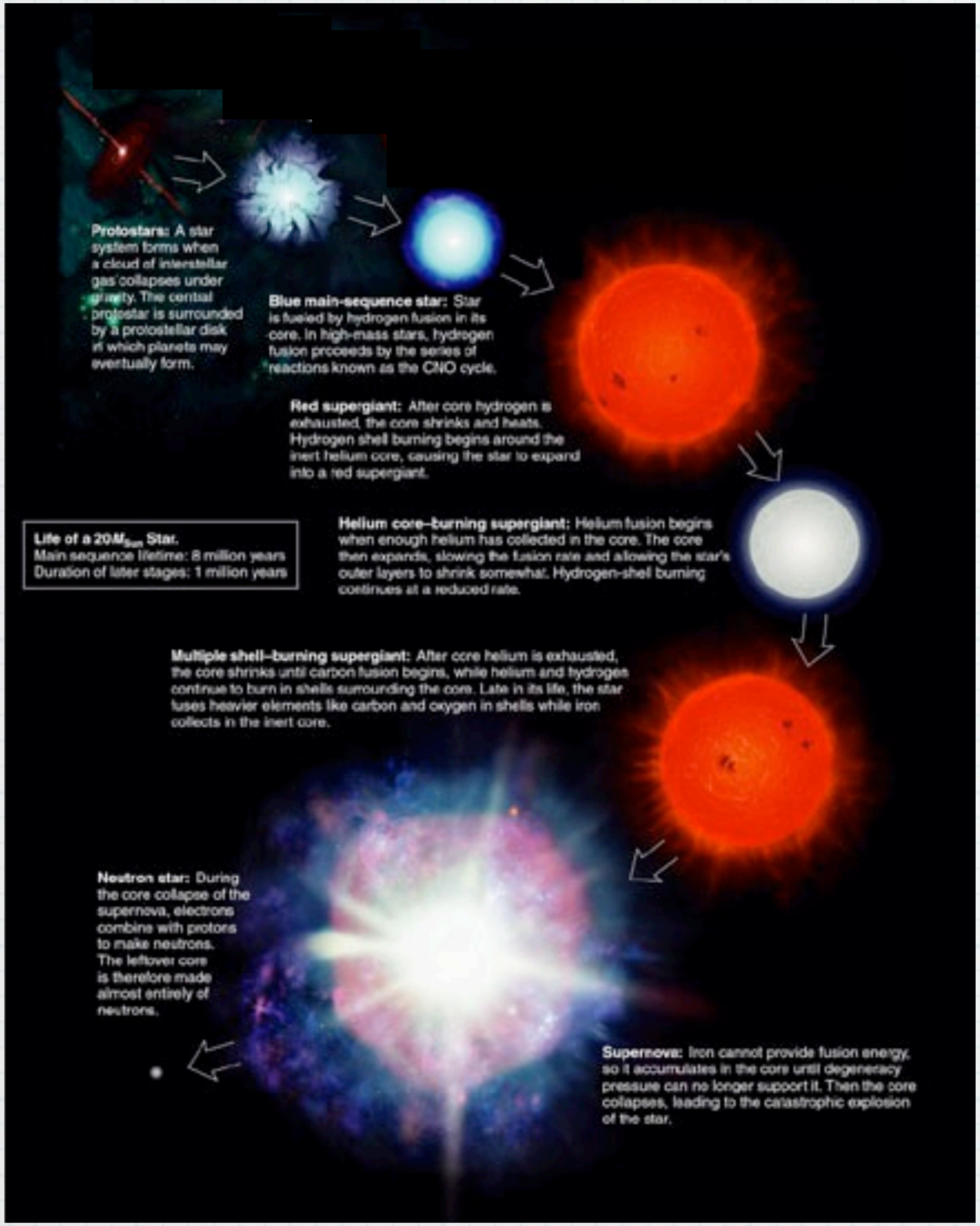
Core shrinks and heats until it's hot enough for fusion

Nuclei with larger charge require higher temperature for fusion

Core thermostat is broken while core is not hot enough for fusion (shell burning)

Core fusion can't happen if degeneracy pressure keeps core from shrinking

Life Stages of High-Mass Star



1. Main Sequence: H fuses to He in core

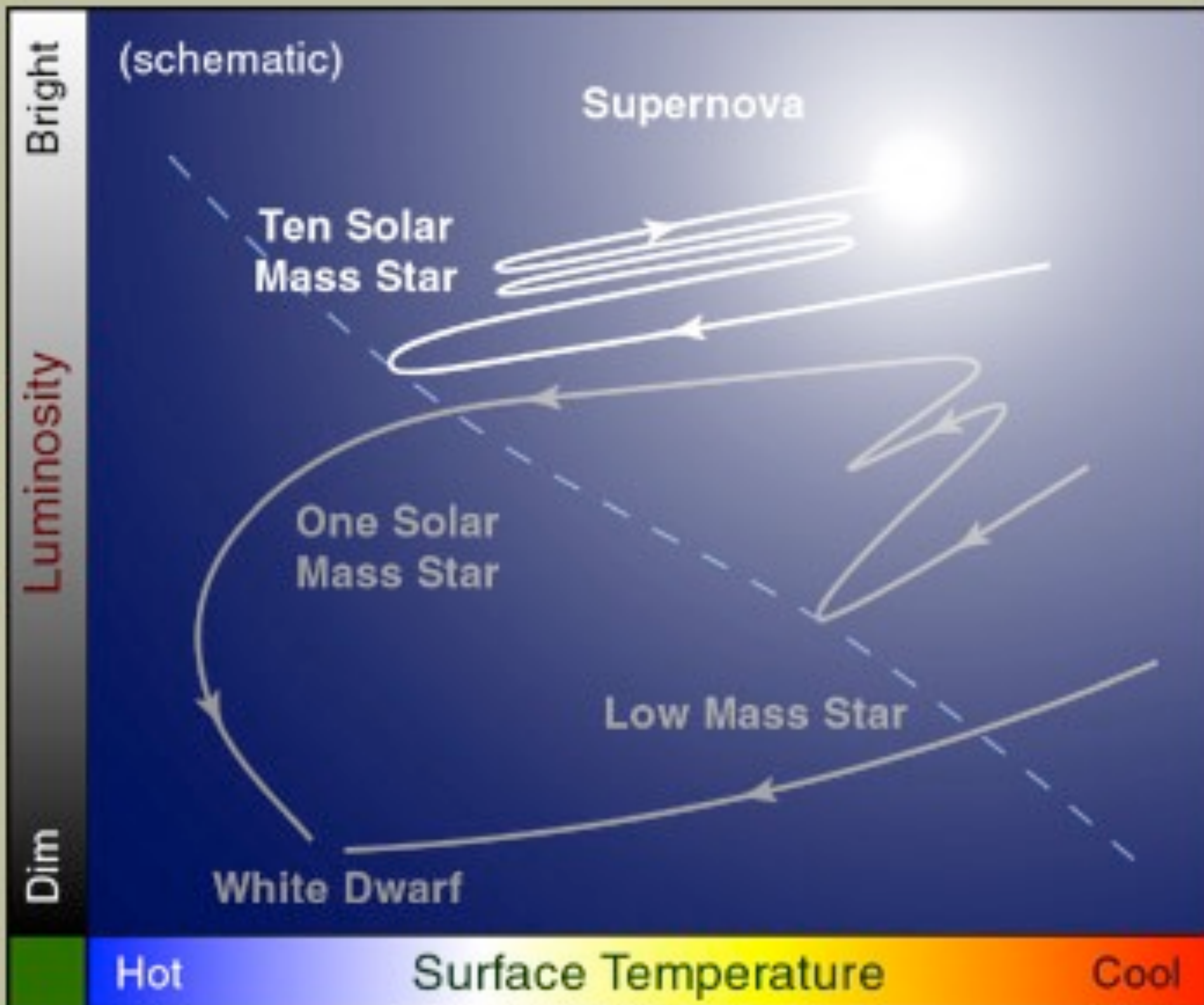
2. Red Supergiant: H fuses to He in shell around He core

3. Helium Core Burning: He fuses to C in core while H fuses to He in shell

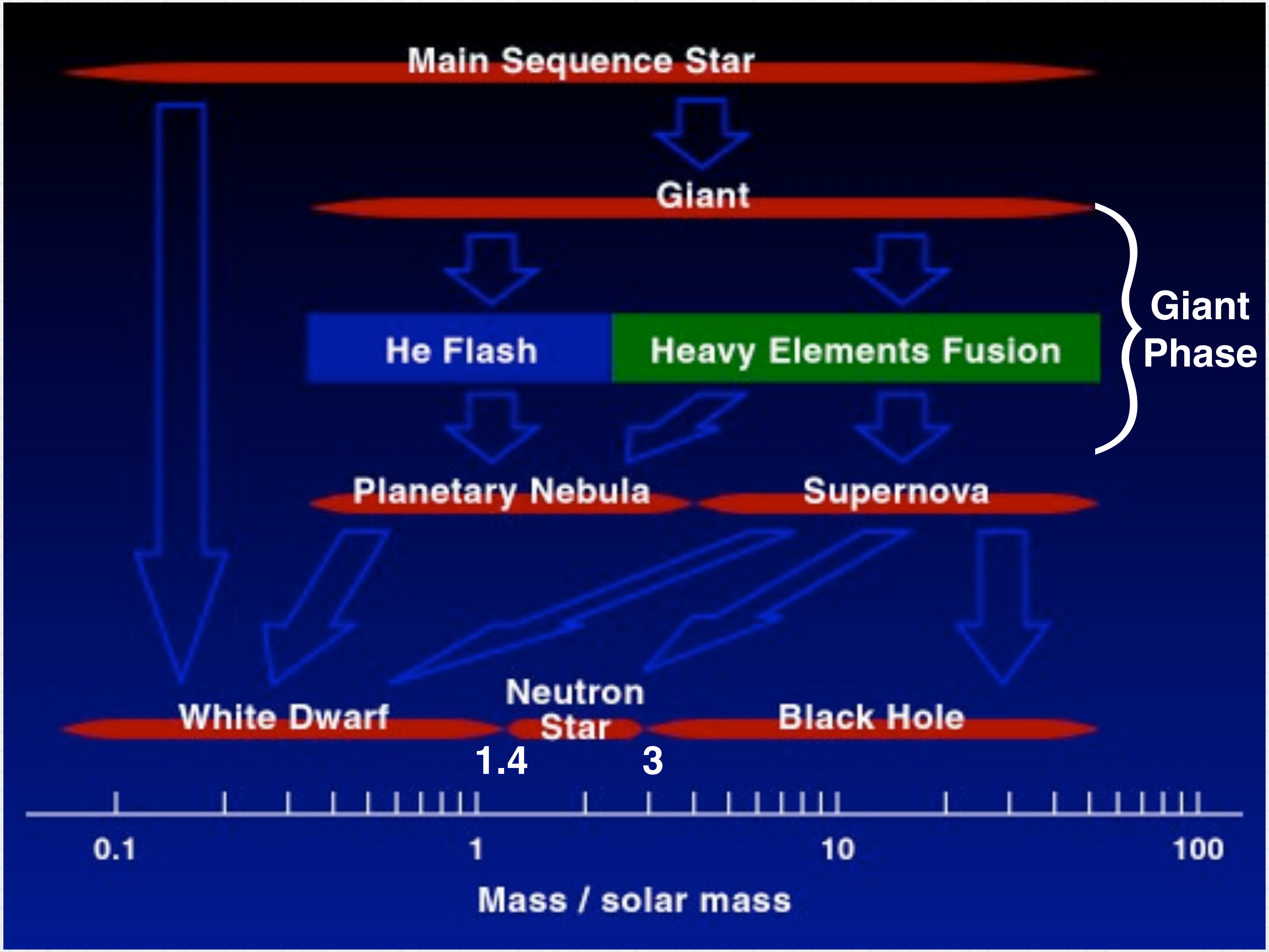
4. Multiple Shell Burning: Many elements fuse in shells

5. Supernova leaves neutron star (or black hole) behind

Evolution of stars of different mass

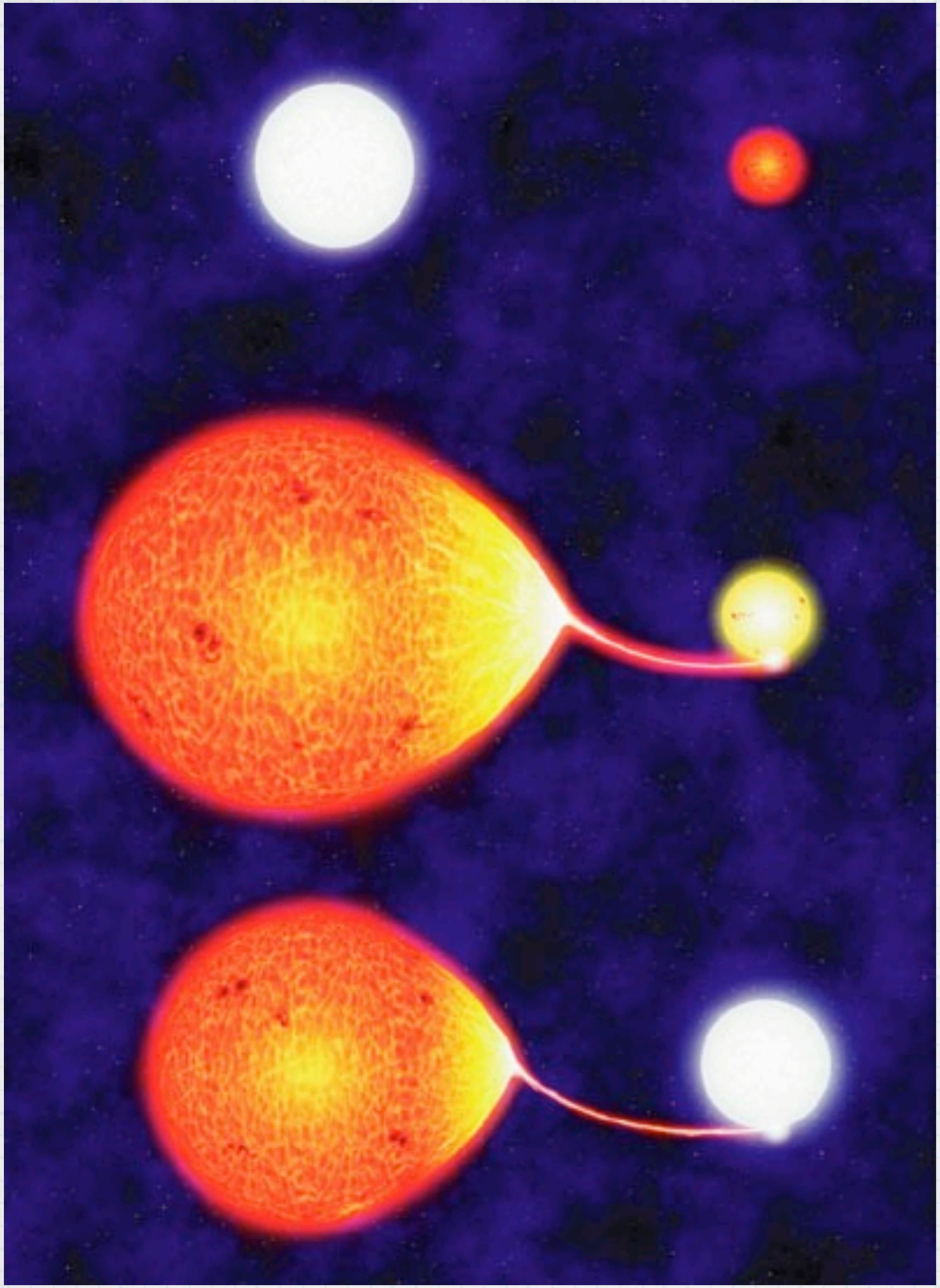


Path of the Death of a Star

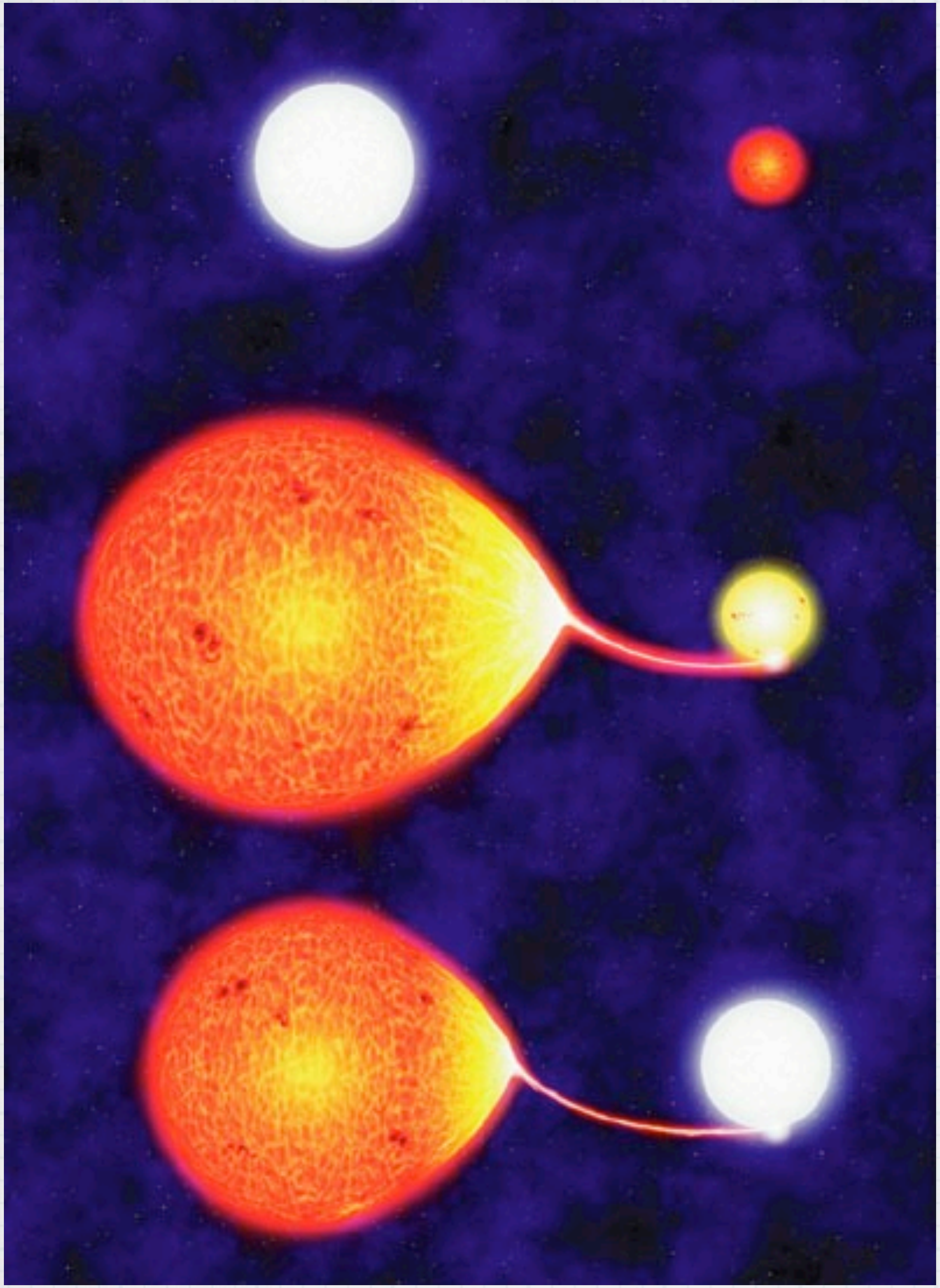


Stars with close companions

* How are the lives of stars with close companions different?
* The binary star Algol consists of a 3.7 M_{Sun} main sequence star and a 0.8 M_{Sun} subgiant star
* The low mass star is in a more advanced stage than its heavier companion
* How did it come about?



Stars in Algol are close enough that matter can flow from subgiant onto main-sequence star



Star that is now a subgiant was originally more massive

As it reached the end of its life and started to grow, it began to transfer mass to its companion

Now the companion star is more massive

Snapshot

How does a star's mass determine its life story?

A star's mass determines how it lives its life

- Low- and intermediate-mass stars never get hot enough to fuse carbon or heavier elements in their cores, and end their lives by expelling their outer layers and leaving a white dwarf behind

- High-mass stars live short but brilliant lives, ultimately dying in supernova explosions

Snapshot

How are the lives of stars with close companions different?

When one star in a close binary system begins to swell in size at the end of its hydrogen-burning life, it can begin to transfer mass to its companion. This mass exchange can then change the remaining life histories of both stars