

TODAY

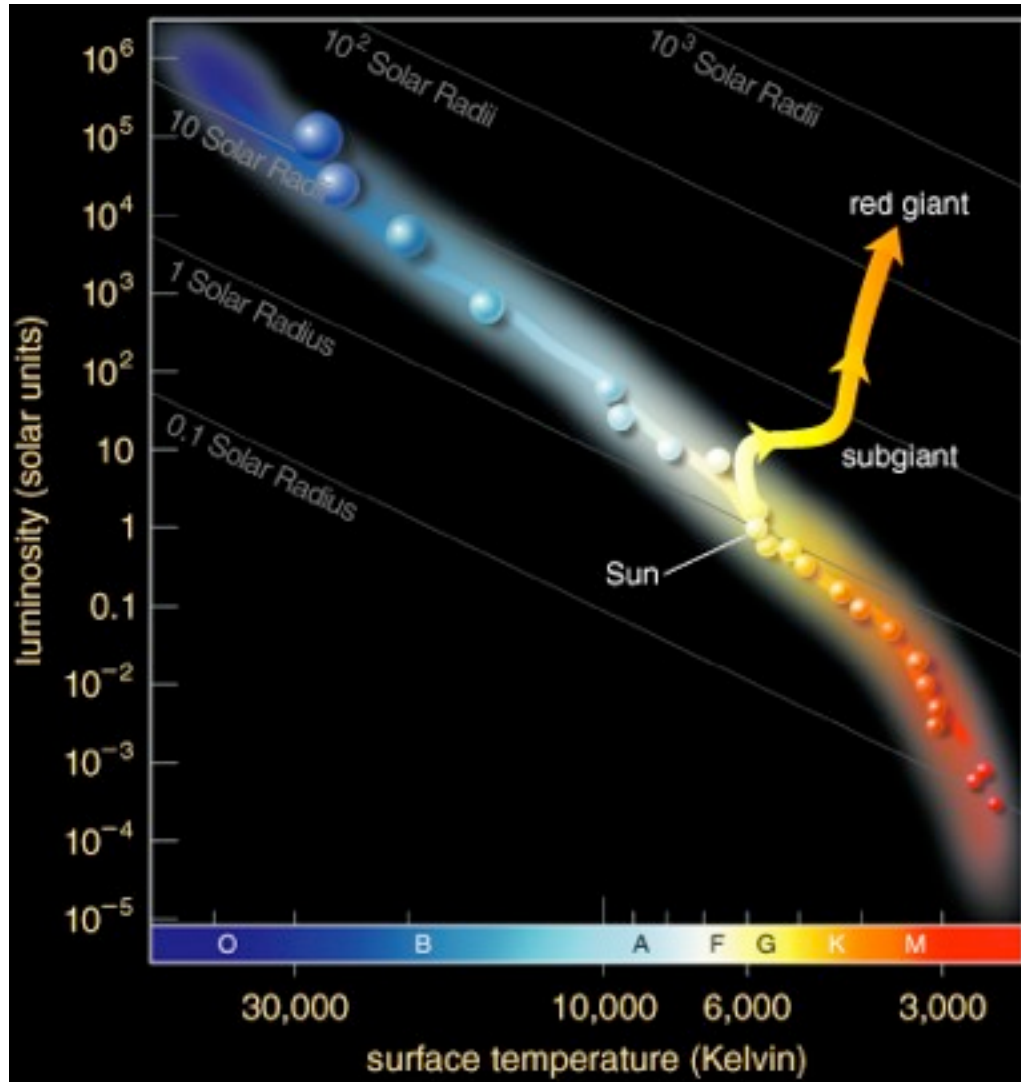
- STARS
- EVOLUTION OF LOW AND HIGH MASS STARS
- NUCLEOSYNTHESIS
- SUPERNOVAE - THE EXPLOSIVE DEATHS OF MASSIVE STARS



The life stages of a low-mass star

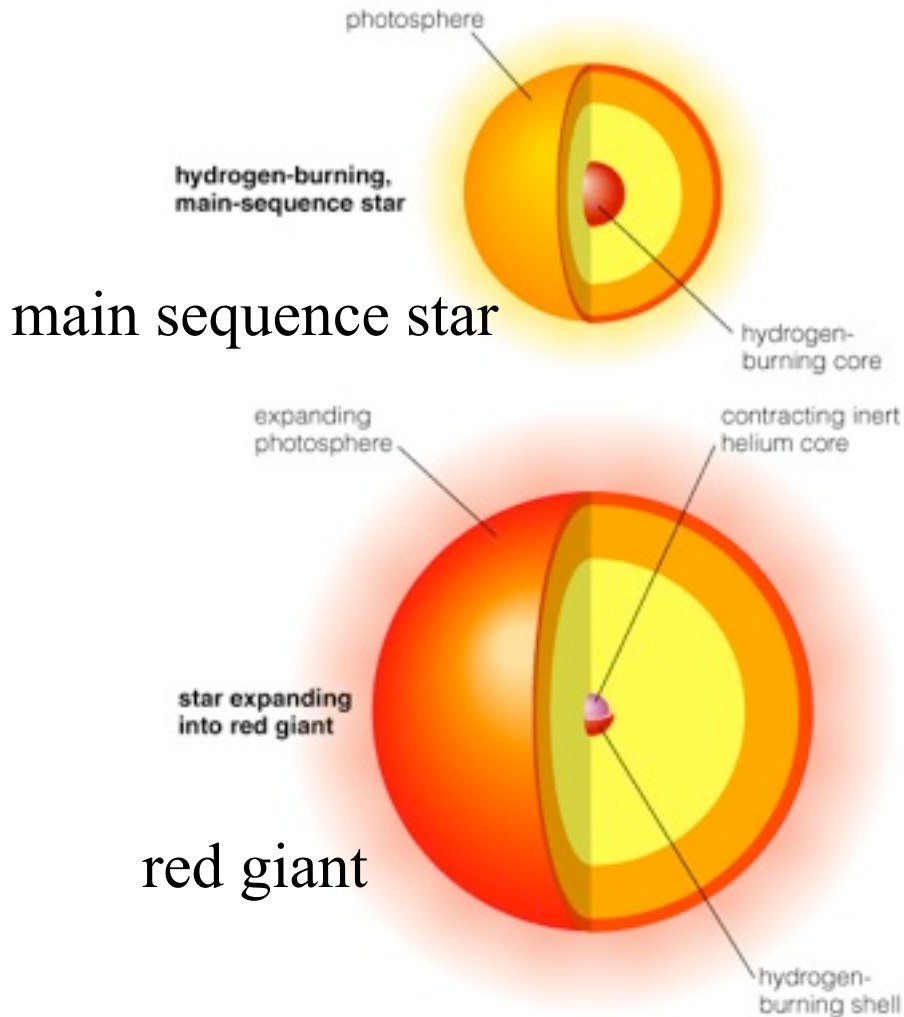


Life Track After Main Sequence



- Observations of star clusters show that a star becomes larger, redder, and more luminous after its time on the main sequence is over.
- At the end of their main sequence life time - when hydrogen in the core is exhausted - stars ascend the **red giant branch**.

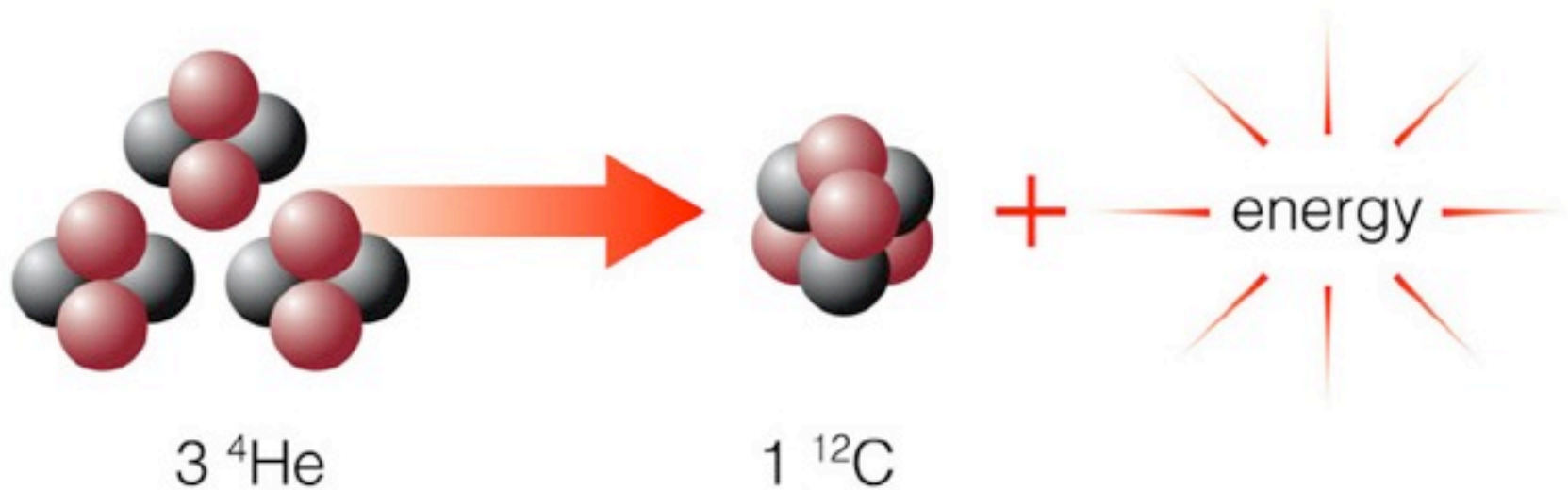
After hydrogen fuel is spent



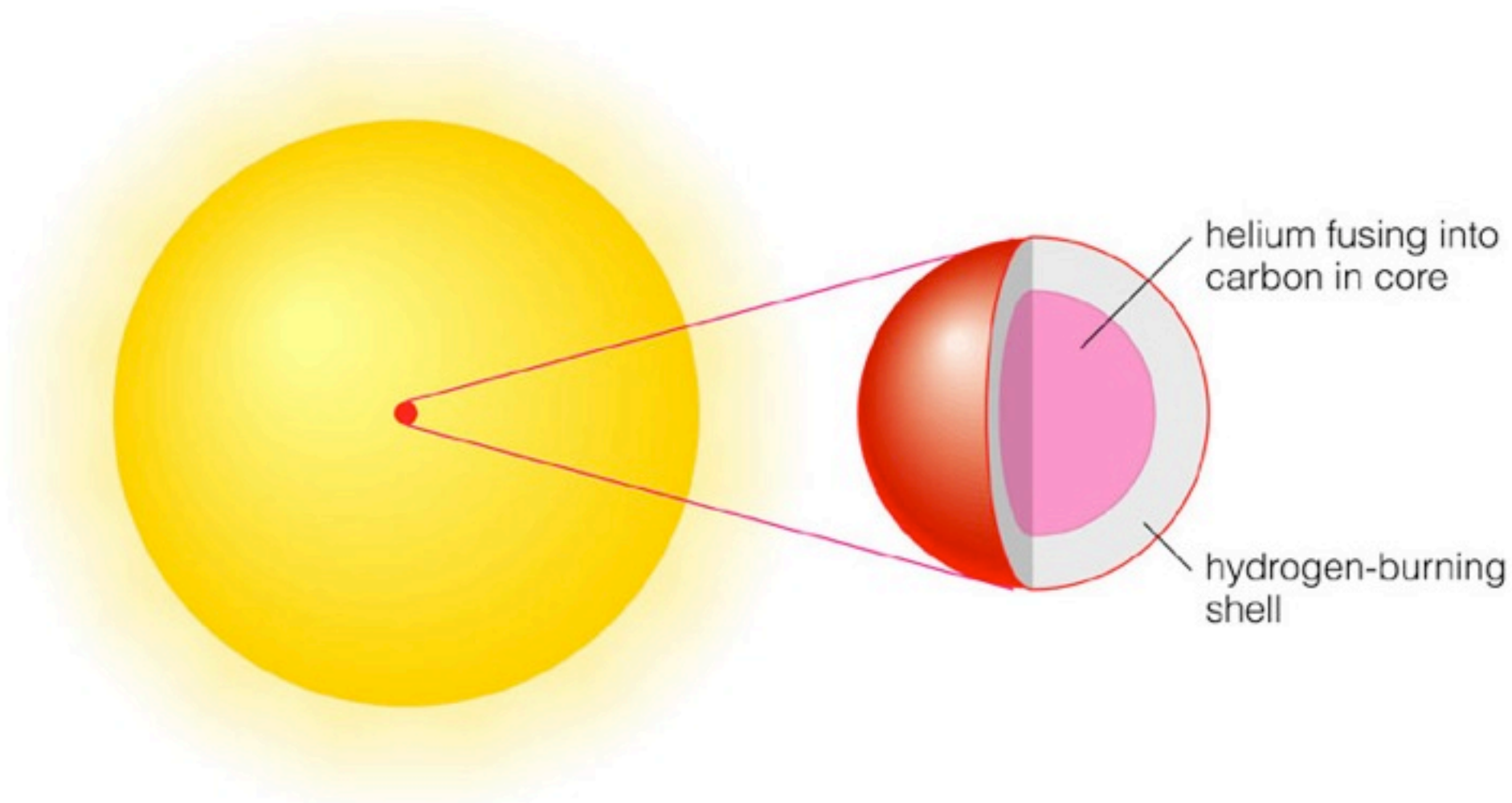
- Without further fusion, the core contracts. H begins fusing to He in a shell around the core.
- As the core contracts, temperature increases, nuclear reaction rates increase (in the shell), and the Luminosity increases.

Helium Flash

- The core continues to shrink and heat as the rest of the star expands and becomes more luminous.
 - Ascends giant branch for a billion years
- At a critical temperature and density, helium fusion suddenly begins.
 - The Helium Flash
- The star evolves rapidly, finding a new equilibrium with He burning in core and H burning in a shell surrounding the core.

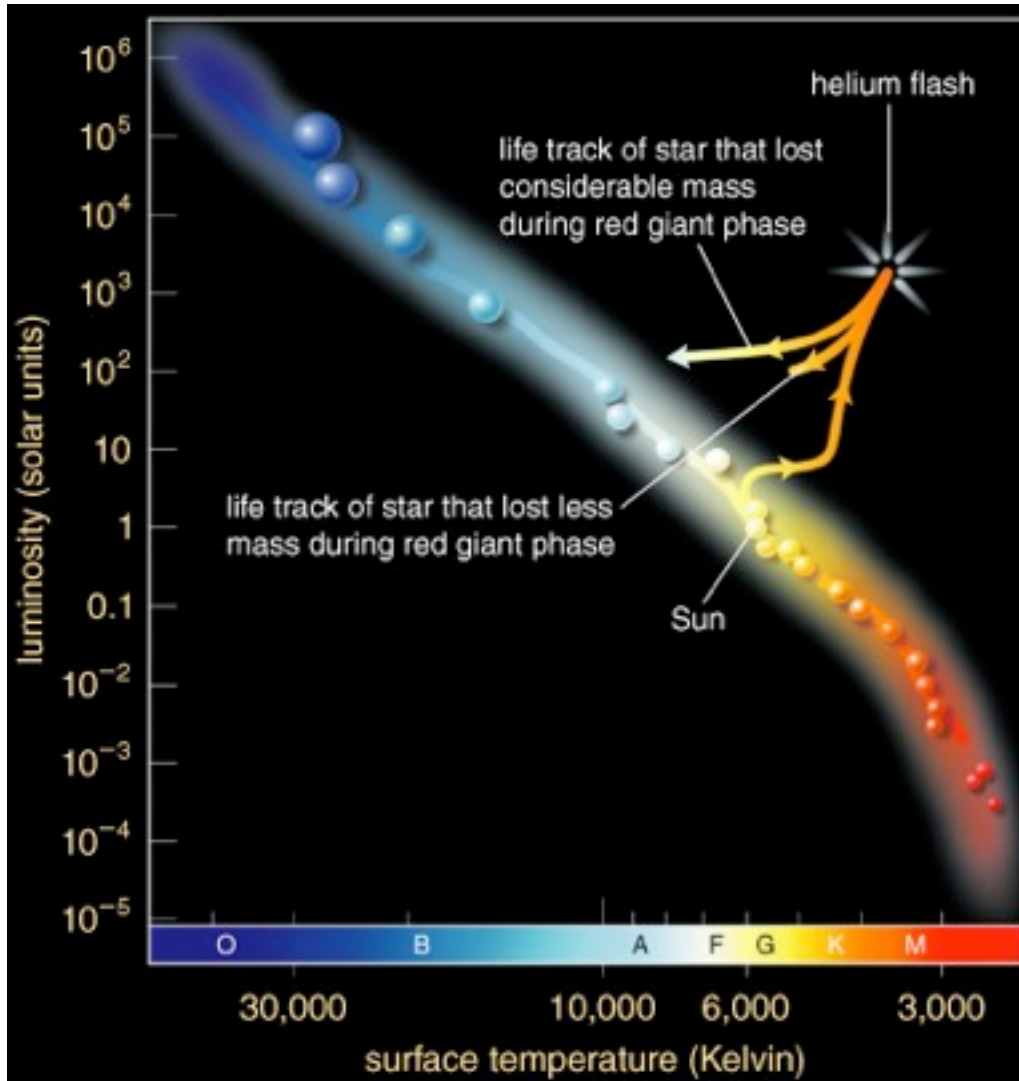


Helium fusion tough—larger charge leads to greater repulsion. Worse, the fusion of two helium nuclei doesn't work; ${}^4\text{He}$ more stable than Beryllium (${}^8\text{Be}$). Need three ${}^4\text{He}$ nuclei to make carbon (${}^{12}\text{C}$). Only works because of resonant state of carbon predicted by Fred Hoyle.



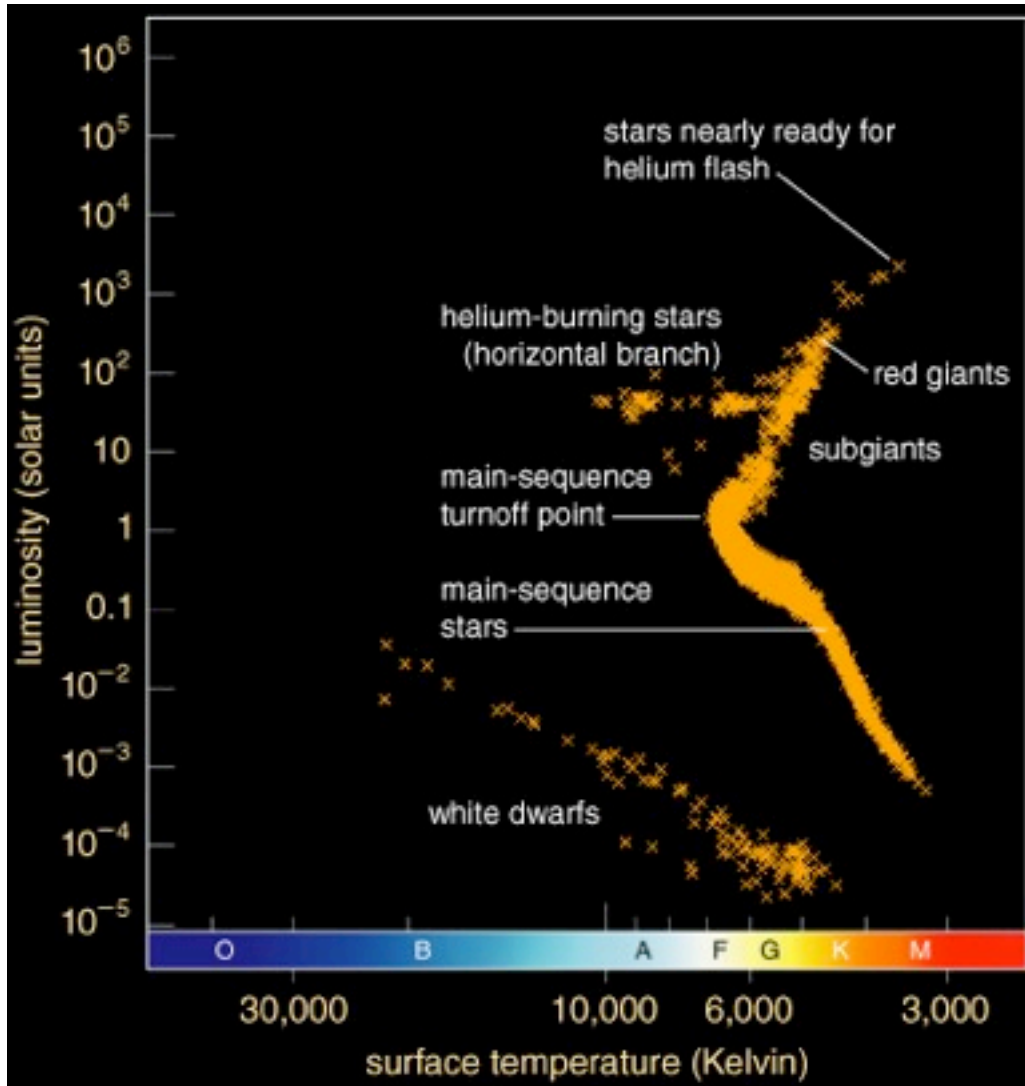
Helium burning stars reside for a brief time on the **Horizontal Branch**.

Life Track After Helium Flash



- Red giants shrink and become less luminous after helium fusion begins in the core.

Life Track After Helium Flash

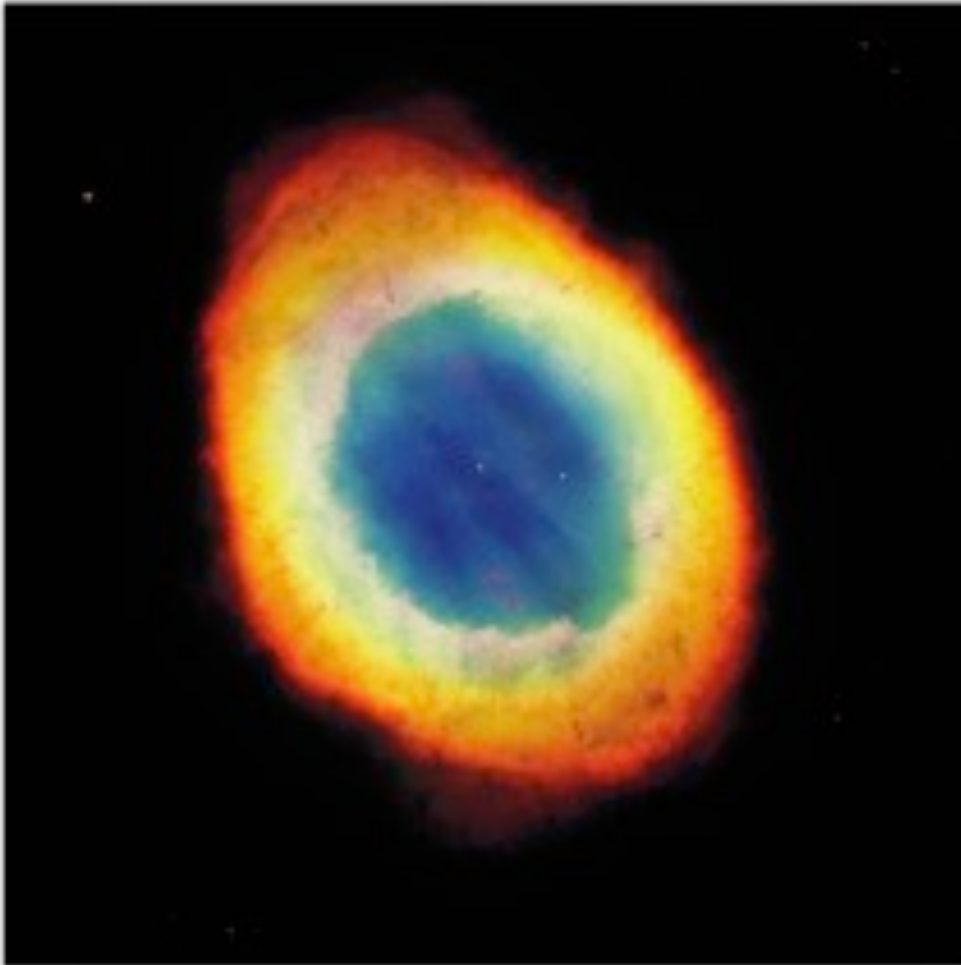


- Helium-burning stars are found in a *horizontal branch* on the H-R diagram.

Double-Shell Burning

- Helium also gets used up. He continues to fuse into carbon in a shell around the carbon core, and H fuses to He in a shell around the helium layer.
- The star expands again, ascending the **Asymptotic Giant Branch**
- This double-shell-burning stage never reaches equilibrium—the fusion rate periodically spikes upward in a series of *thermal pulses*.
- With each spike, some of the outer layers may be lost to space.

Planetary Nebulae

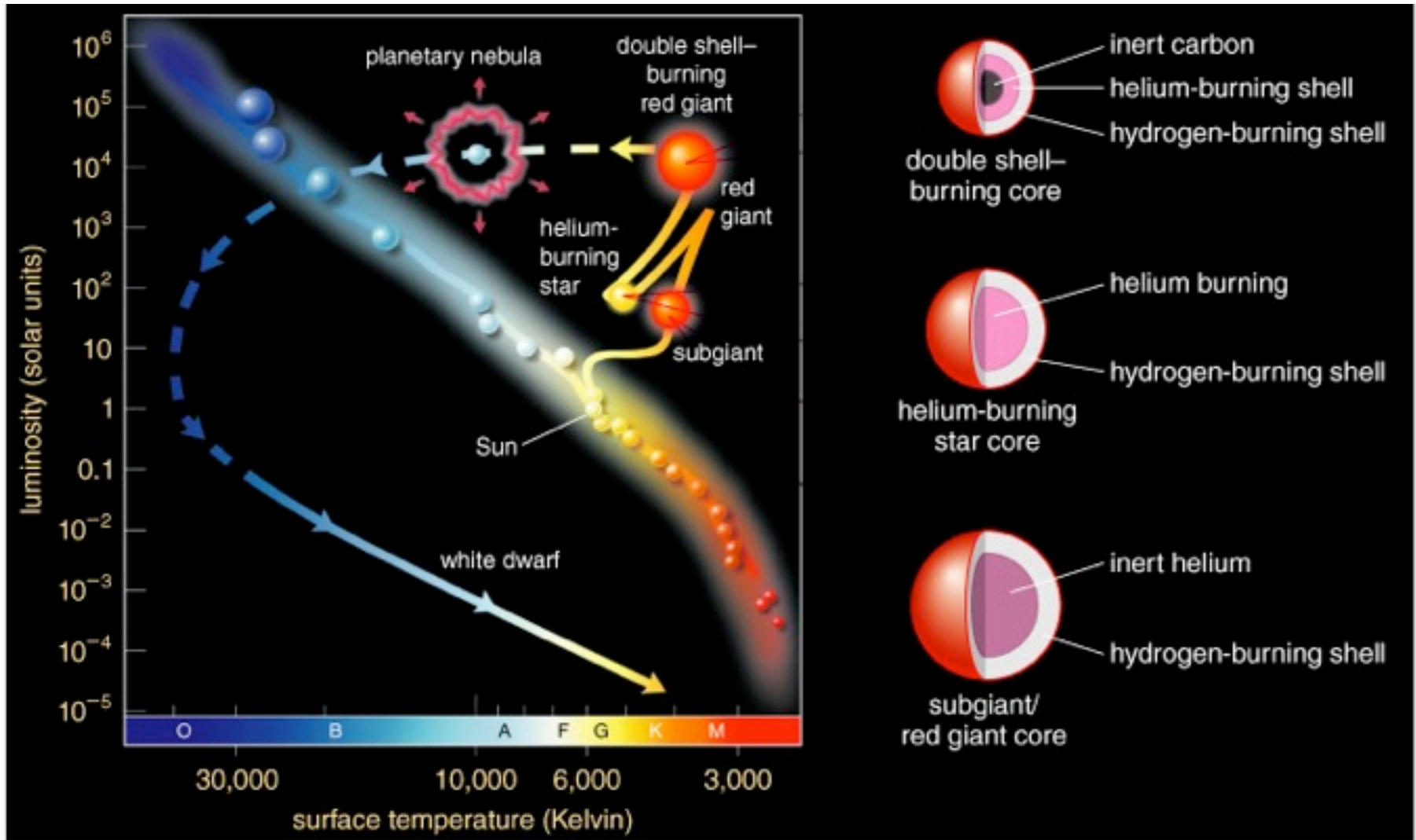


- Double-shell burning ends with a pulse that ejects the H and He into space as a *planetary nebula*.
- The core left behind becomes a white dwarf.

End of Fusion

- Fusion progresses no further in a low-mass star because the core temperature never grows hot enough for fusion of heavier elements (some He fuses to C to make oxygen).
- Degeneracy pressure supports the white dwarf against gravity.
- White dwarf spend eternity cooling off, eventually going dark entirely.

Life Track of a Sun-Like Star



Life story of a solar mass star

Main sequence star
~10 billion years

subgiant/Red Giant
~1 billion years

Helium Flash

Horizontal Branch star
~100 million years

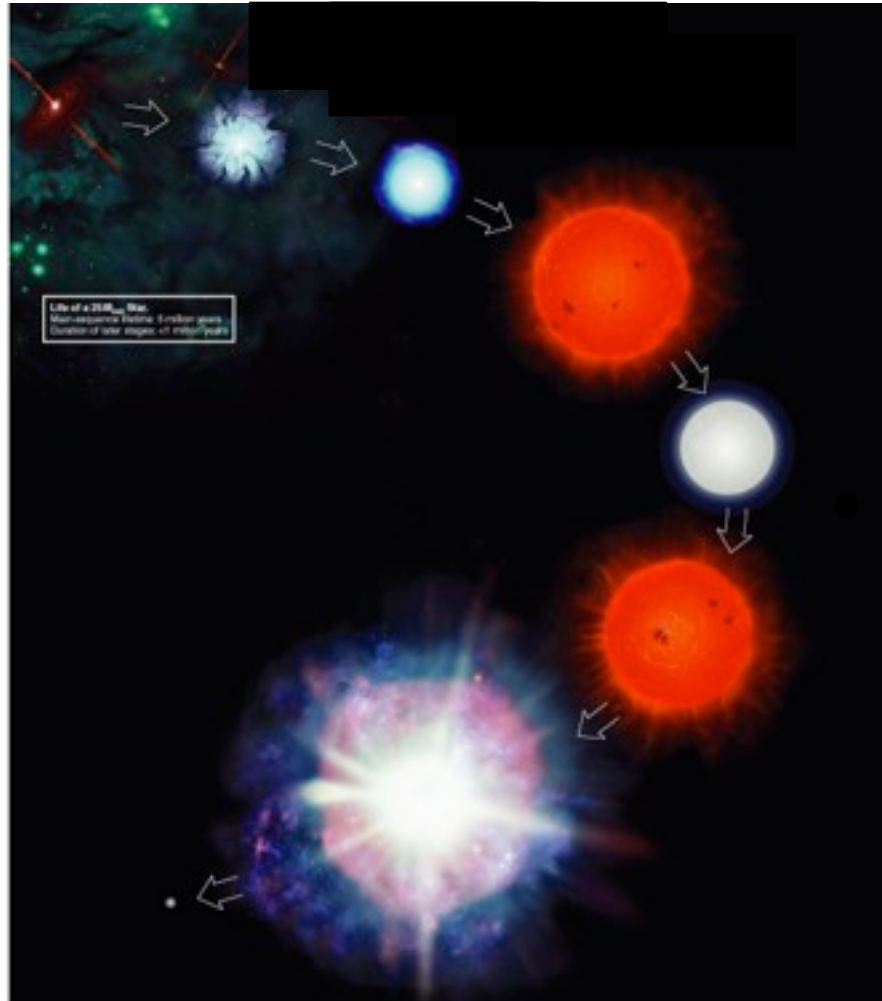
Asymptotic Giant
~10 million years

Planetary Nebula
~10 thousand years

White Dwarf
eternity

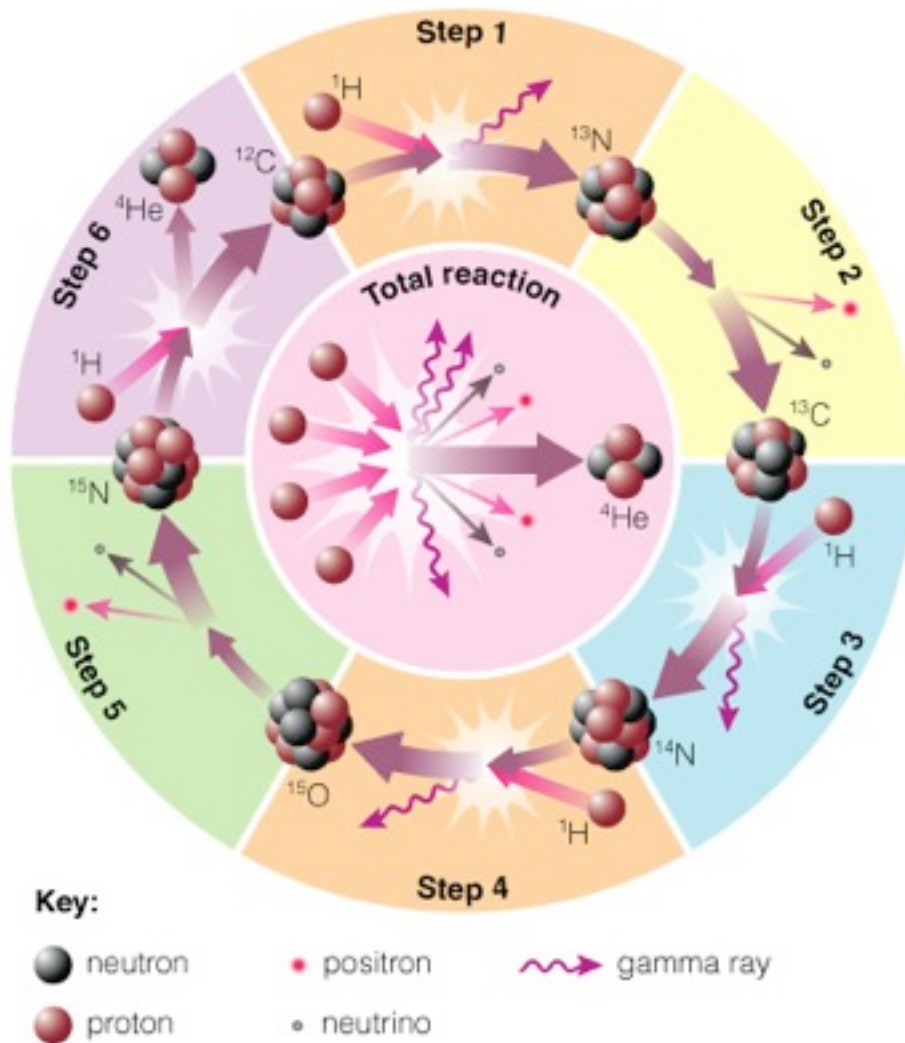


The evolution of high-mass stars



$$M > 8M_{\text{Sun}}$$

CNO Cycle



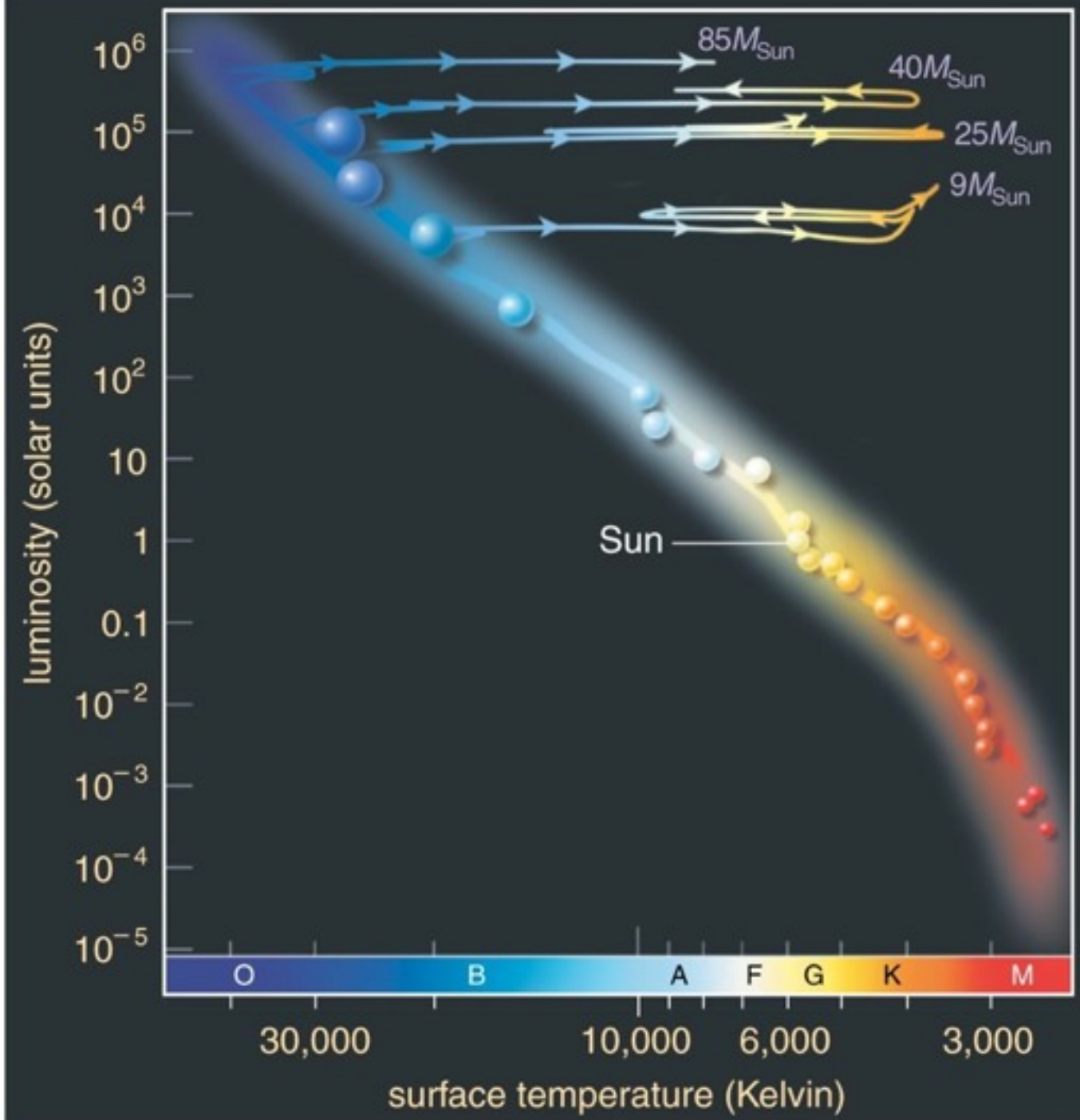
- High-mass main-sequence stars fuse H to He at a higher rate using carbon, nitrogen, and oxygen as catalysts.
- The CNO cycle is more efficient than the proton-proton chain in stars more massive than 1.5 solar masses.

Life Stages of High-Mass Stars

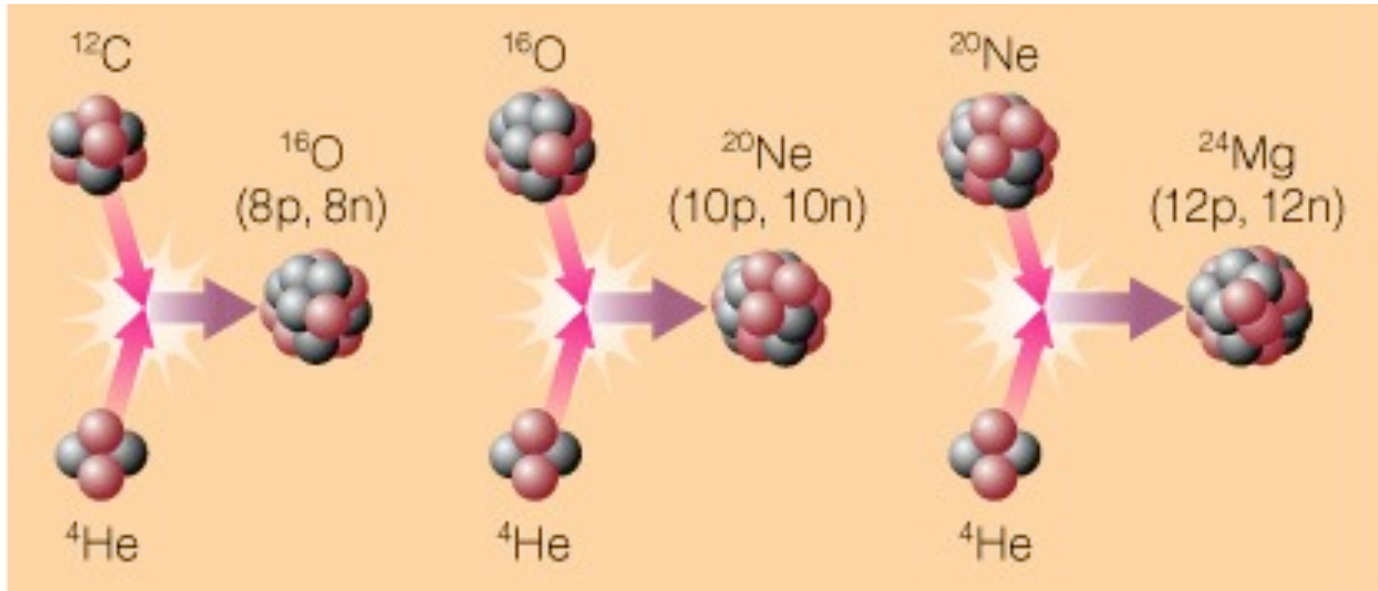
- Late life stages of high-mass stars are similar to those of low-mass stars:
 - Hydrogen core fusion (main sequence)
 - Hydrogen shell burning (supergiant)
 - Helium core fusion (supergiant)

 - Etc:
 - more stages of nuclear burning as well
 - C, O, Ne, Mg, Si, all the way up to Fe (iron)

Supergiants



High mass stars make the elements necessary for life



The oxygen and heavier elements in our bodies were made in the nuclear furnace of high mass stars.

Key	
12	Atomic number
Mg	Element's symbol
Magnesium	Element's name
24.305	Atomic mass*

*Atomic masses are fractions because they represent a weighted average of atomic masses of different isotopes—in proportion to the abundance of each isotope on Earth.

1	2																	10									
H	He																	Ne									
Hydrogen	Helium																	Neon									
1.00794	4.003																	20.179									
3	4																	10									
Li	Be																	Ne									
Lithium	Beryllium																	Neon									
6.941	9.01218																	20.179									
11	12																	18									
Na	Mg																	Ar									
Sodium	Magnesium																	Argon									
22.990	24.305																	39.948									
19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36										
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Fr										
Potassium	Calcium	Scandium	Titanium	Vanadium	Chromium	Manganese	Iron	Cobalt	Nickel	Copper	Zinc	Gallium	Germanium	Arsenic	Selenium	Bromine	Krypton										
39.098	40.08	44.956	47.88	50.94	51.996	54.938	55.847	58.9332	58.69	63.546	65.39	69.72	72.59	74.922	78.96	79.904	83.80										
37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54										
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe										
Rubidium	Strontium	Yttrium	Zirconium	Niobium	Molybdenum	Technetium (98)	Ruthenium	Rhodium	Palladium	Silver	Cadmium	Indium	Tin	Antimony	Tellurium	Iodine	Xenon										
85.468	87.62	88.9059	91.224	92.91	95.94	(98)	101.07	102.906	106.42	107.868	112.41	114.82	118.71	121.75	127.60	126.905	131.29										
55	56											72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	
Cs	Ba											Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn	
Cesium	Barium											Hafnium	Tantalum	Tungsten	Rhenium	Osmium	Iridium	Platinum	Gold	Mercury	Thallium	Lead	Bismuth	Polonium (209)	Astatine (210)	Radon (222)	
132.91	137.34											178.49	180.95	183.85	186.207	190.2	192.22	195.08	196.967	200.59	204.383	207.2	208.98	(209)	(210)	(222)	
87	88											104	105	106	107	108	109	110	111	112							
Fr	Ra											Rf	Db	Sg	Bh	Hs	Mt	Uun	Uuu	Uub							
Francium (223)	Radium (226.0254)											Rutherfordium (261)	Dubnium (262)	Seaborgium (263)	Bohrium (262)	Hassium (265)	Meitnerium (266)	Ununium (269)	Ununium (272)	Ununium (277)							

Lanthanide Series

57	58	59	60	61	62	63	64	65	66	67	68	69	70	71
La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
Lanthanum	Cerium	Praseodymium	Neodymium	Promethium (145)	Samarium	Europium	Gadolinium	Terbium	Dysprosium	Holmium	Erbium	Thulium	Ytterbium	Lutetium
138.906	140.12	140.908	144.24	(145)	150.36	151.96	157.25	158.925	162.50	164.93	167.26	168.934	173.04	174.967

Actinide Series

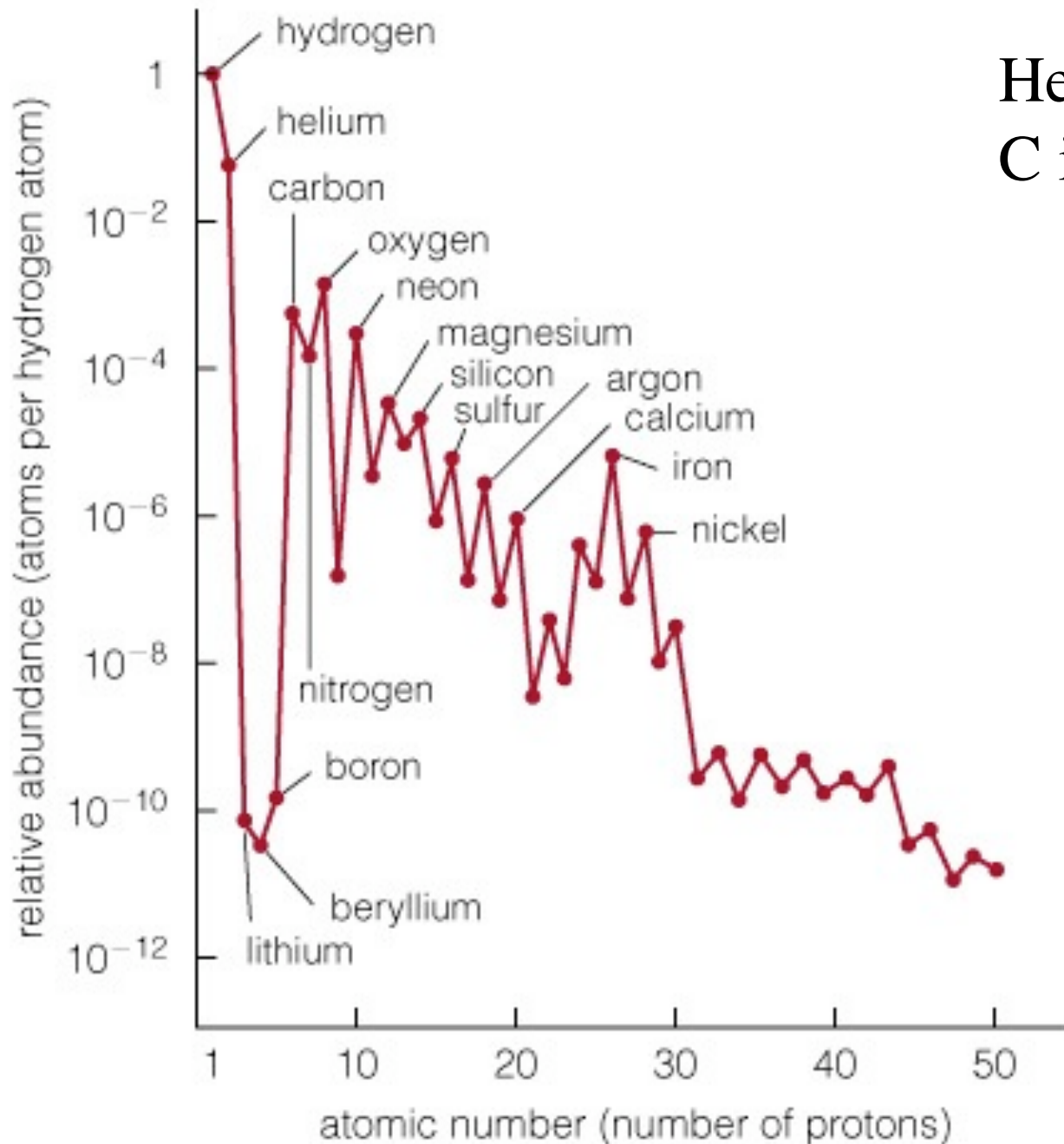
89	90	91	92	93	94	95	96	97	98	99	100	101	102	103
Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr
Actinium	Thorium	Protactinium	Uranium	Neptunium	Plutonium (244)	Americium (243)	Curium (247)	Berkelium (247)	Californium (251)	Einsteinium (252)	Fermium (257)	Mendelevium (258)	Nobelium (259)	Lawrencium (260)
227.028	232.038	231.036	238.029	237.048	(244)	(243)	(247)	(247)	(251)	(252)	(257)	(258)	(259)	(260)

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

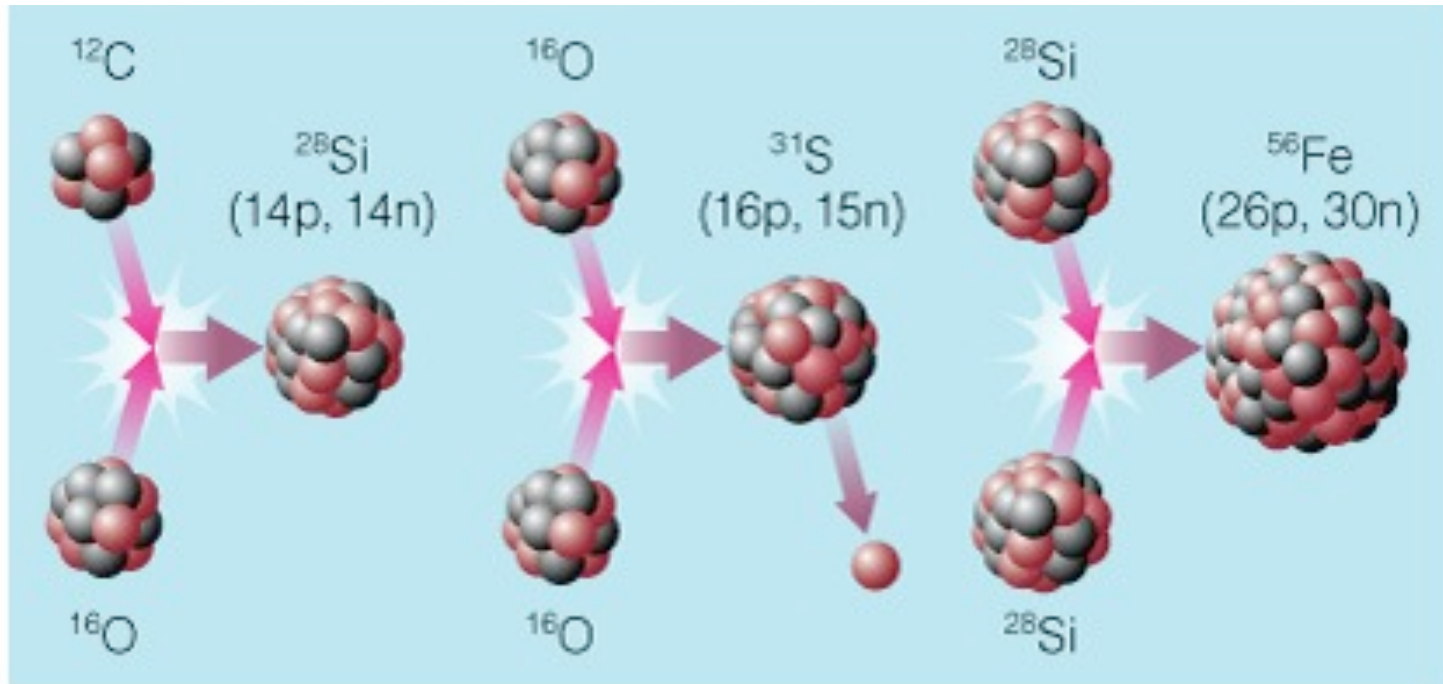
Helium capture builds
C into O, Ne, Mg ...

Results in a higher
abundances of
elements with an
even numbers of
protons -

“alpha elements”



Advanced Nuclear Burning



- Core temperatures in stars with $>8M_{\text{Sun}}$ allow fusion of elements as heavy as iron.

1 H Hydrogen 1.00794	2 He Helium 4.003																
3 Li Lithium 6.941	4 Be Beryllium 9.01218	5 B Boron 10.81	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.998	10 Ne Neon 20.179										
11 Na Sodium 22.990	12 Mg Magnesium 24.305	13 Al Aluminum 26.98	14 Si Silicon 28.086	15 P Phosphorus 30.974	16 S Sulfur 32.06	17 Cl Chlorine 35.453	18 Ar Argon 39.948										
19 K Potassium 39.098	20 Ca Calcium 40.08	21 Sc Scandium 44.956	22 Ti Titanium 47.88	23 V Vanadium 50.94	24 Cr Chromium 51.996	25 Mn Manganese 54.938	26 Fe Iron 55.847	27 Co Cobalt 58.9332	28 Ni Nickel 58.69	29 Cu Copper 63.546	30 Zn Zinc 65.39	31 Ga Gallium 69.72	32 Ge Germanium 72.59	33 As Arsenic 74.922	34 Se Selenium 78.96	35 Br Bromine 79.904	36 Fr Francium 83.80
37 Rb Rubidium 85.468	38 Sr Strontium 87.62	39 Y Yttrium 88.9059	40 Zr Zirconium 91.224	41 Nb Niobium 92.91	42 Mo Molybdenum 95.94	43 Tc Technetium (98)	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.906	46 Pd Palladium 106.42	47 Ag Silver 107.868	48 Cd Cadmium 112.41	49 In Indium 114.82	50 Sn Tin 118.71	51 Sb Antimony 121.75	52 Te Tellurium 127.60	53 I Iodine 126.905	54 Xe Xenon 131.29
55 Cs Cesium 132.91	56 Ba Barium 137.34	72 Hf Hafnium 178.49	73 Ta Tantalum 180.95	74 W Tungsten 183.85	75 Re Rhenium 186.207	76 Os Osmium 190.2	77 Ir Iridium 192.22	78 Pt Platinum 195.08	79 Au Gold 196.967	80 Hg Mercury 200.59	81 Tl Thallium 204.383	82 Pb Lead 207.2	83 Bi Bismuth 208.98	84 Po Polonium (209)	85 At Astatine (210)	86 Rn Radon (222)	
87 Fr Francium (223)	88 Ra Radium 226.0254	104 Rf Rutherfordium (261)	105 Db Dubnium (262)	106 Sg Seaborgium (263)	107 Bh Bohrium (262)	108 Hs Hassium (265)	109 Mt Meitnerium (266)	110 Uun Ununium (269)	111 Uuu Ununium (272)	112 Uub Ununium (277)							

Key

- 12 — Atomic number
- Mg** — Element's symbol
- Magnesium — Element's name
- 24.305 — Atomic mass*

*Atomic masses are fractions because they represent a weighted average of atomic masses of different isotopes—in proportion to the abundance of each isotope on Earth.

Lanthanide Series

57 La Lanthanum 138.906	58 Ce Cerium 140.12	59 Pr Praseodymium 140.908	60 Nd Neodymium 144.24	61 Pm Promethium (145)	62 Sm Samarium 150.36	63 Eu Europium 151.96	64 Gd Gadolinium 157.25	65 Tb Terbium 158.925	66 Dy Dysprosium 162.50	67 Ho Holmium 164.93	68 Er Erbium 167.26	69 Tm Thulium 168.934	70 Yb Ytterbium 173.04	71 Lu Lutetium 174.967
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Actinide Series

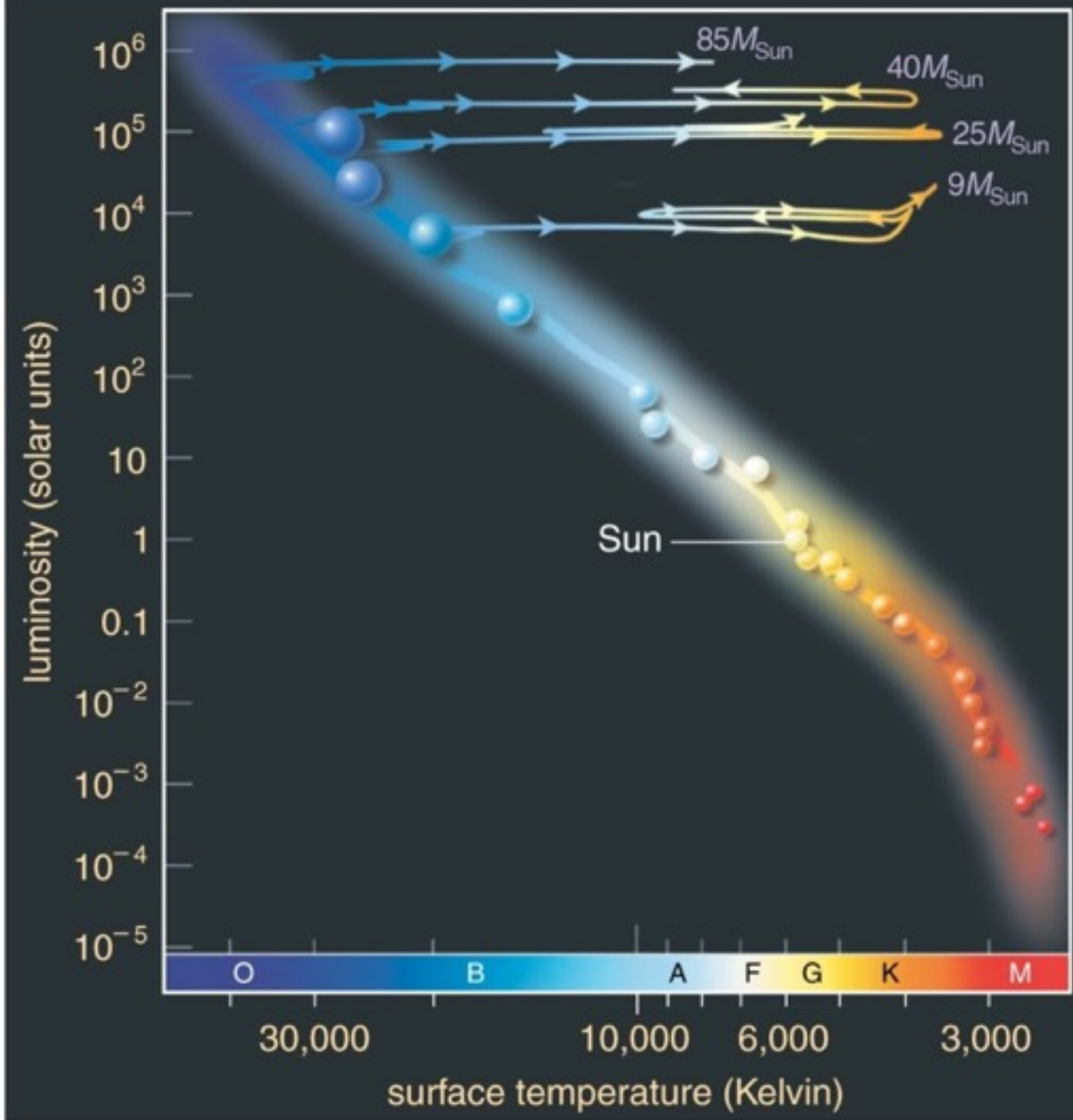
89 Ac Actinium 227.028	90 Th Thorium 232.038	91 Pa Protactinium 231.036	92 U Uranium 238.029	93 Np Neptunium 237.048	94 Pu Plutonium (244)	95 Am Americium (243)	96 Cm Curium (247)	97 Bk Berkelium (247)	98 Cf Californium (251)	99 Es Einsteinium (252)	100 Fm Fermium (257)	101 Md Mendelevium (258)	102 No Nobelium (259)	103 Lr Lawrencium (260)
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Advanced reactions in stars make elements like Si, S, Ca, and Fe.

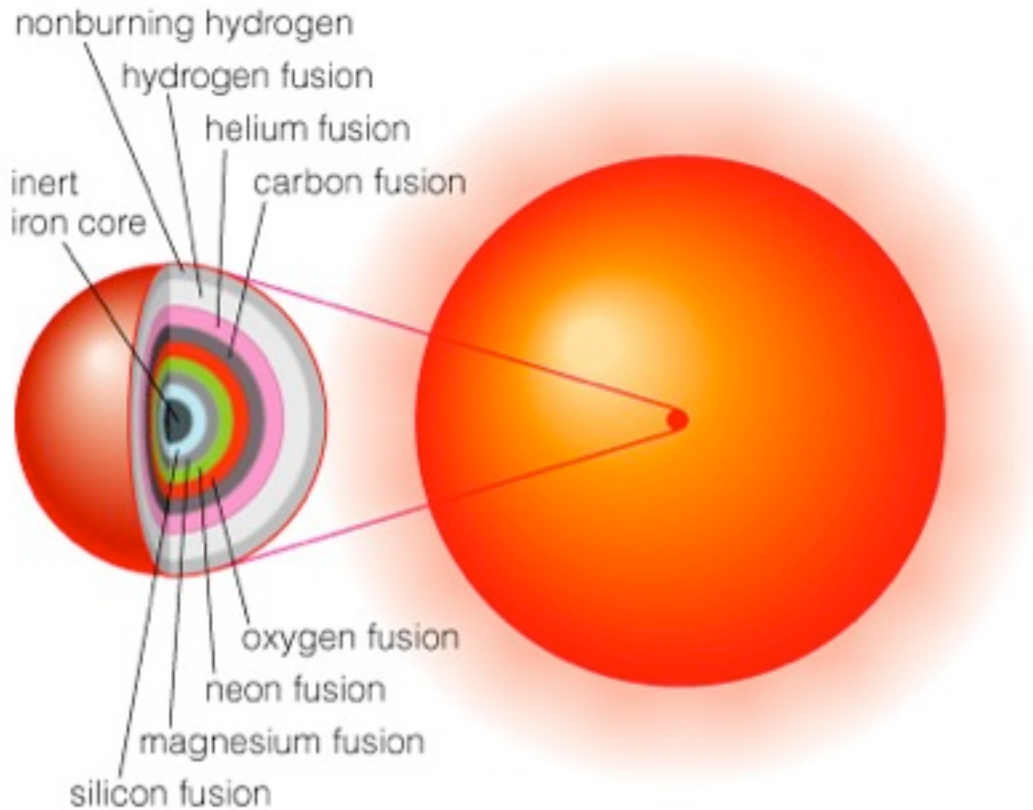
Supergiants

can get a wiggle
in evolutionary
track as each
fuel supply is
exhausted.

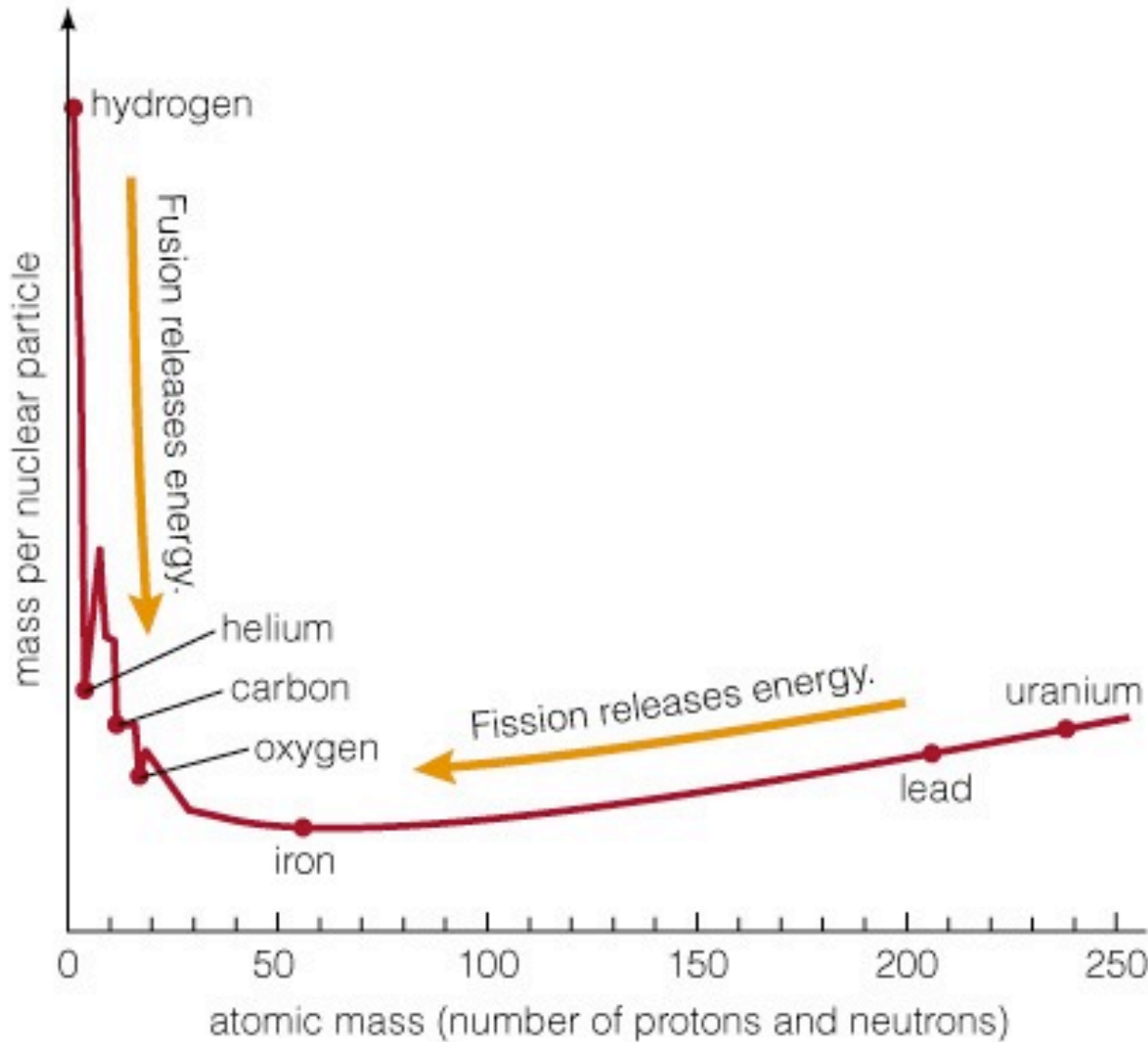
Evolution
very rapid -
massive stars
live “only”
millions of years



Multiple-Shell Burning

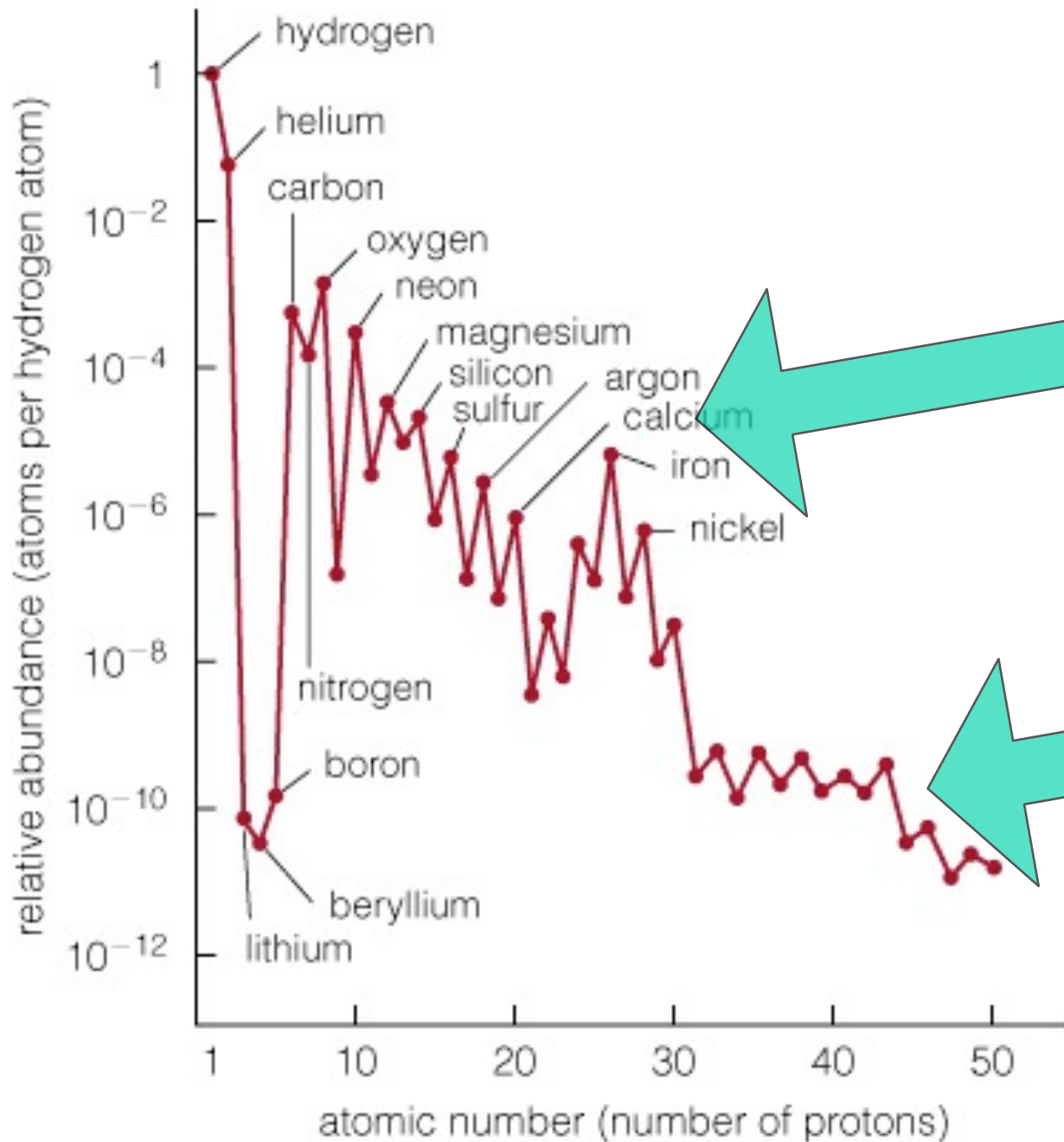


- Advanced nuclear burning proceeds in a series of nested shells.
- Core of high mass ($> 8M_{sun}$) near the end of its life



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

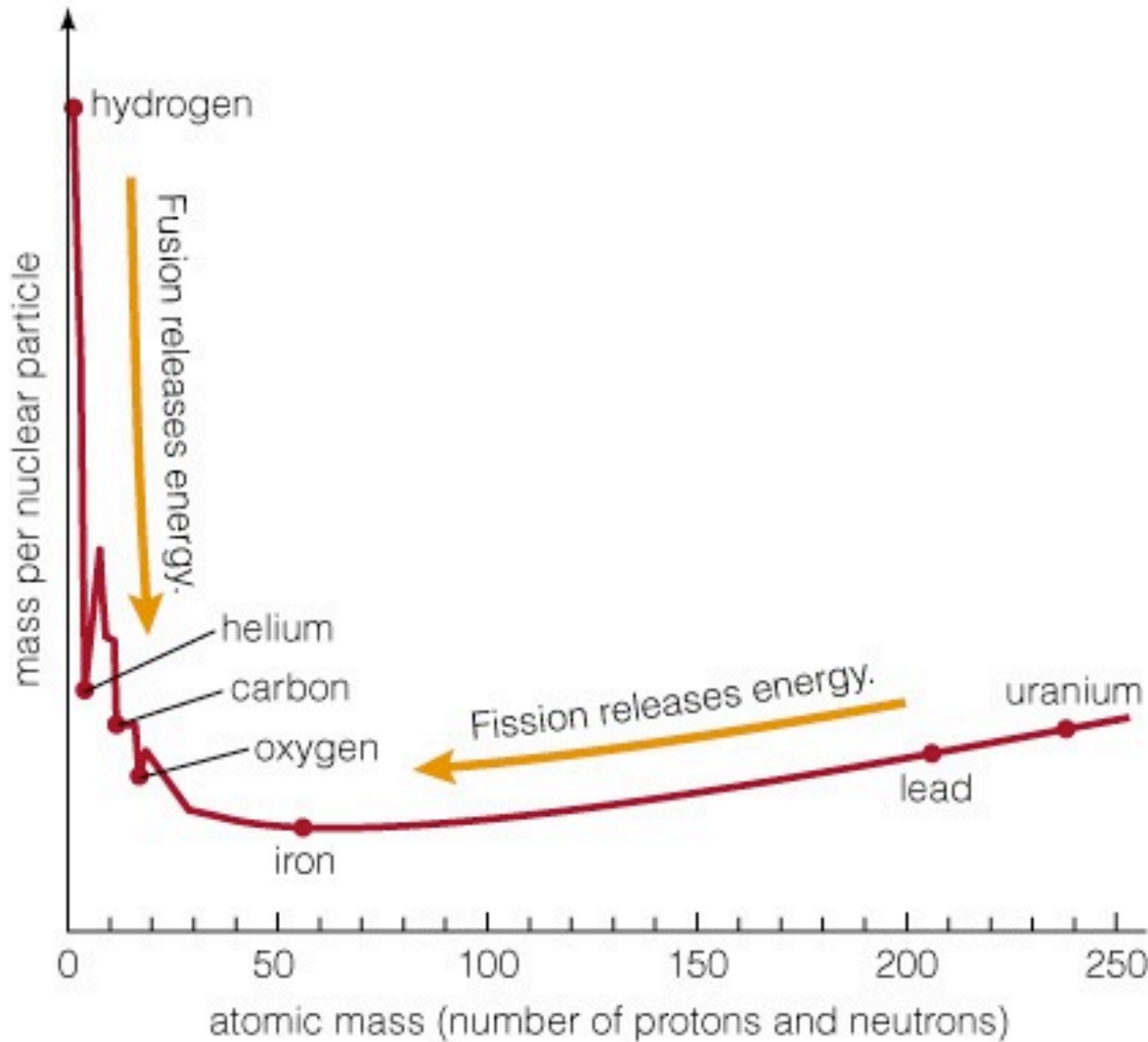
(Fe has lowest mass per nucleon.)



Iron peak

Where do elements heavier than iron come from?

Supernovae!



Iron is the ultimate ash.

With nothing left to support it, the core collapses and the outer parts explode, carrying elements into space.

Key

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- 24.305 — Atomic mass*

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Energy and neutrons released in a supernova explosion enable elements heavier than iron to form, including Au (gold) and Uranium.

Made in Early Universe

Made in Stars

Made in Supernovae

Made in the laboratory

The periodic table is color-coded and annotated with red boxes and text labels indicating the origin of elements:

- Made in Early Universe:** Elements 1 (H) and 2 (He).
- Made in Stars:** Elements 3 (Li) through 10 (Ne).
- Made in Supernovae:** Elements 11 (Na) through 26 (Fe).
- Made in the laboratory:** Elements 27 (Co) through 118 (Og).

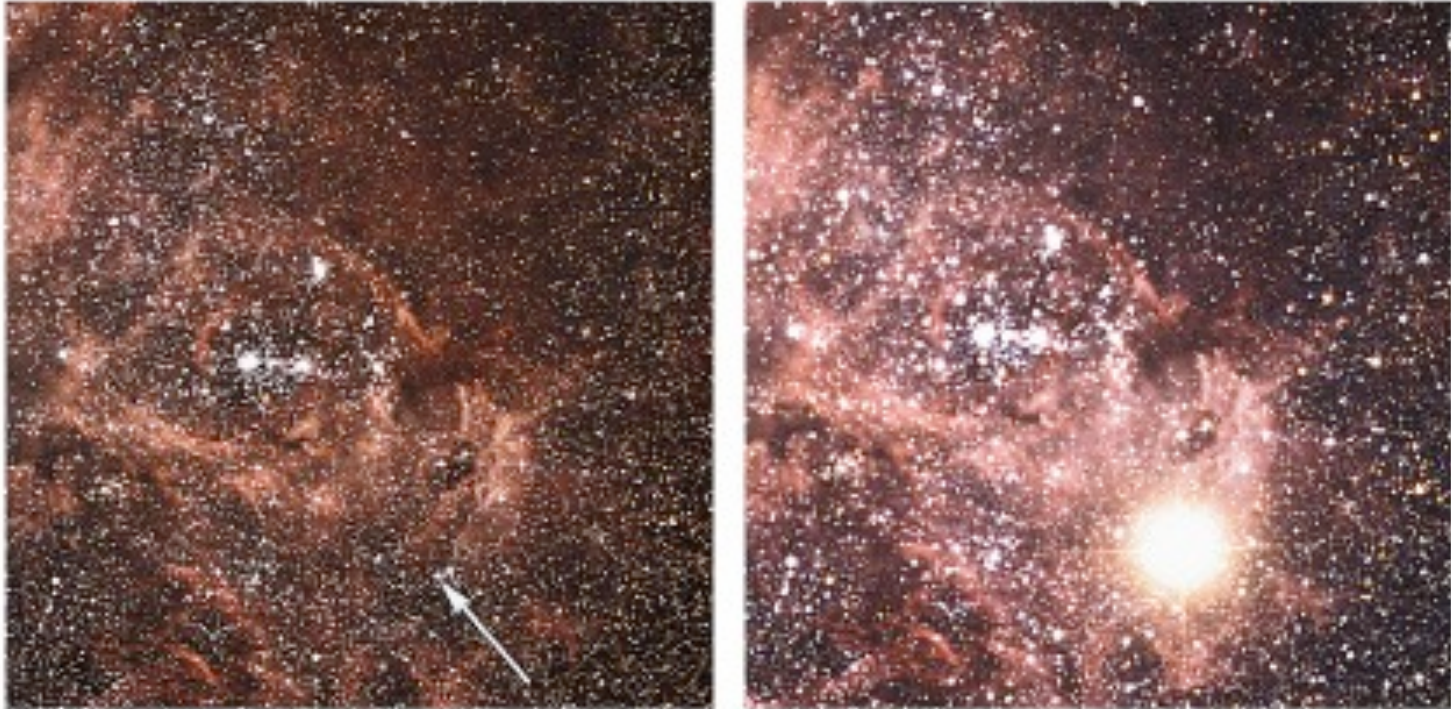
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37 Rb Rubidium	38 Sr Strontium	39 Y Yttrium	40 Zr Zirconium	41 Nb Niobium	42 Mo Molybdenum	43 Tc Technetium	44 Ru Ruthenium	45 Rh Rhodium	46 Pd Palladium	47 Ag Silver	48 Cd Cadmium	49 In Indium	50 Sn Tin	51 Sb Antimony	52 Te Tellurium	53 I Iodine	54 Xe Xenon
55 Cs Cesium	56 Ba Barium	71 Lu Lutetium	72 Hf Hafnium	73 Ta Tantalum	74 W Tungsten	75 Re Rhenium	76 Os Osmium	77 Ir Iridium	78 Pt Platinum	79 Au Gold	80 Hg Mercury	81 Tl Thallium	82 Pb Lead	83 Bi Bismuth	84 Po Polonium	85 At Astatine	86 Rn Radon
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Supernova Remnant

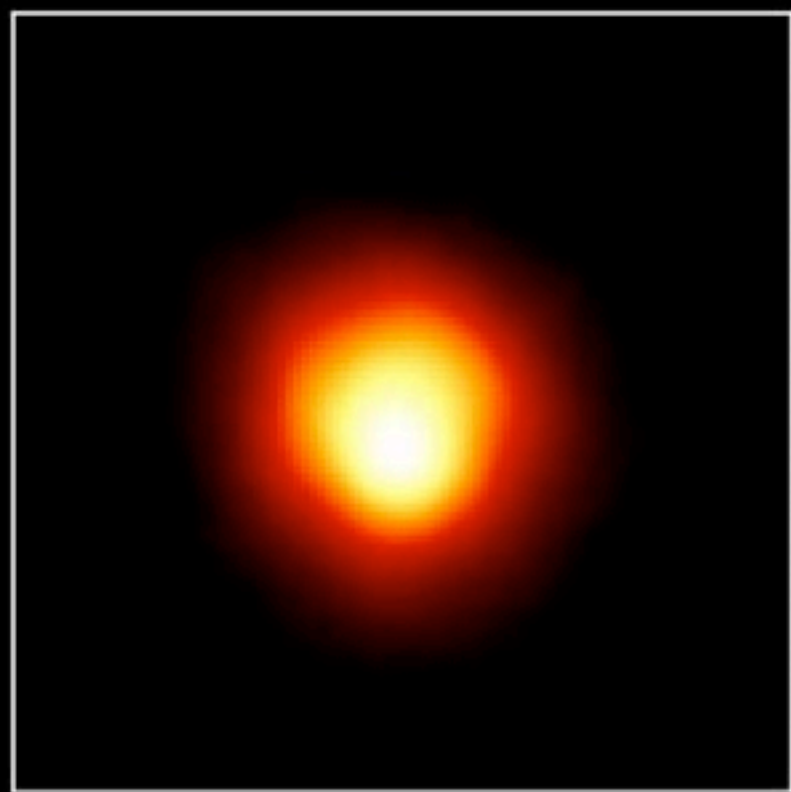


- Energy released by the collapse of the core drives outer layers into space.
- The Crab Nebula is the remnant of the supernova seen in A.D. 1054.

Supernova 1987A



- The closest supernova in the last four centuries was seen in 1987 in the LMC.
- who's next? Betelgeuse? eta Carina?



Size of Star



Size of Earth's Orbit



Size of Jupiter's Orbit



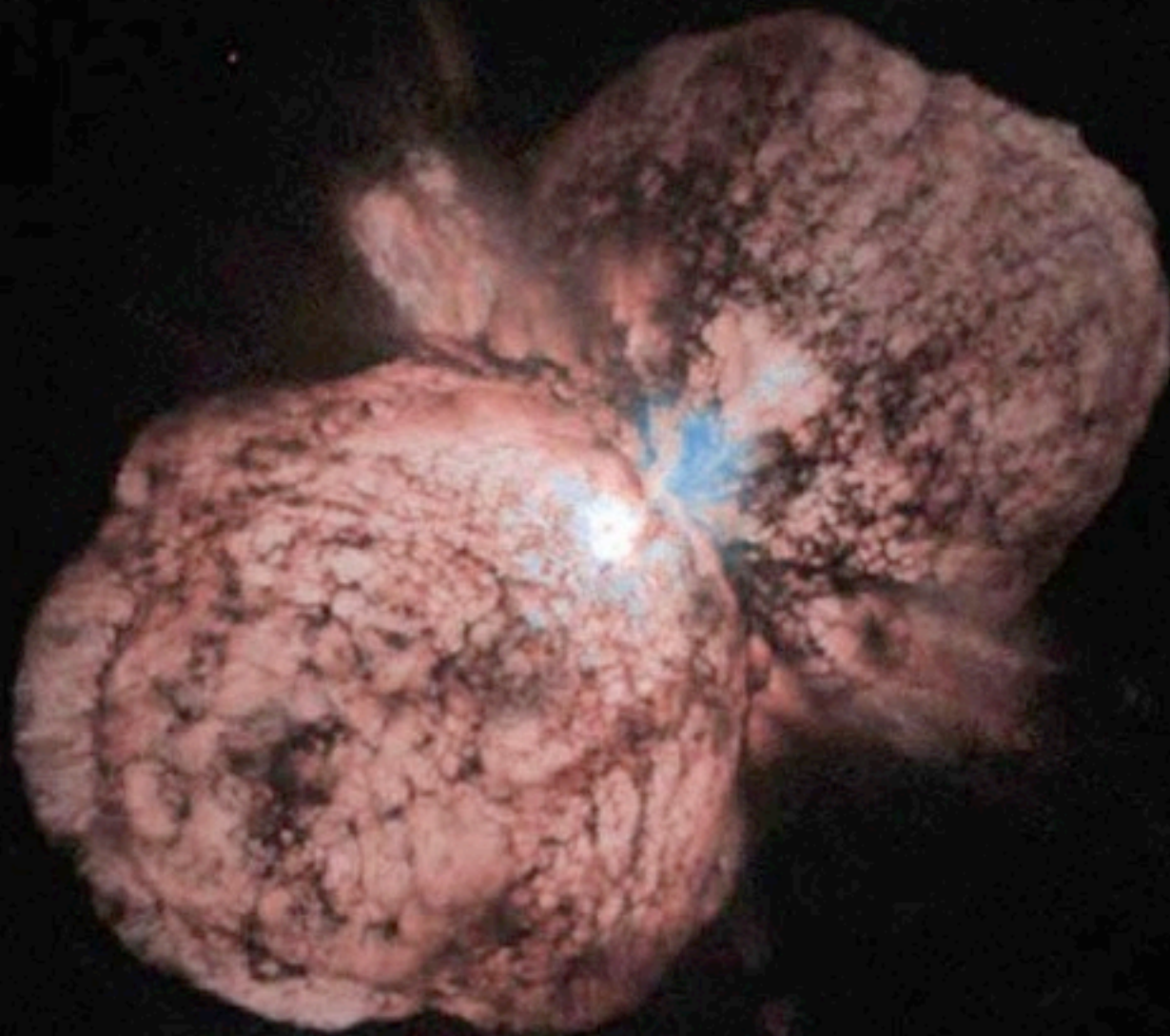
Betelgeuse

Atmosphere of Betelgeuse

HST ·

PRC96-04 · ST ScI OPO · January 15, 1995 · A. Dupree (CfA), NASA

Eta Carinae



(southern hemisphere)

Role of Mass

- A star's mass determines its entire life story because it determines its core temperature.
- High-mass stars have short lives, eventually becoming hot enough to make iron, and end in supernova explosions.
- Low-mass stars have long lives, never become hot enough to fuse beyond carbon nuclei, and end as white dwarfs.