

TODAY

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



Another good job on exam!

- Class average was 71%
 - Given the difficulty of the exam, this was an exceptional performance
- Between this and your previous exam, you are easily the best ASTR 100 class I've ever had
- Exams will be handed back in your sections

Extra credit (2 points)

- What is the final state of a star like our Sun?
- Be sure to include your name and section number
- You may consult your notes, but do not communicate with anyone else

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

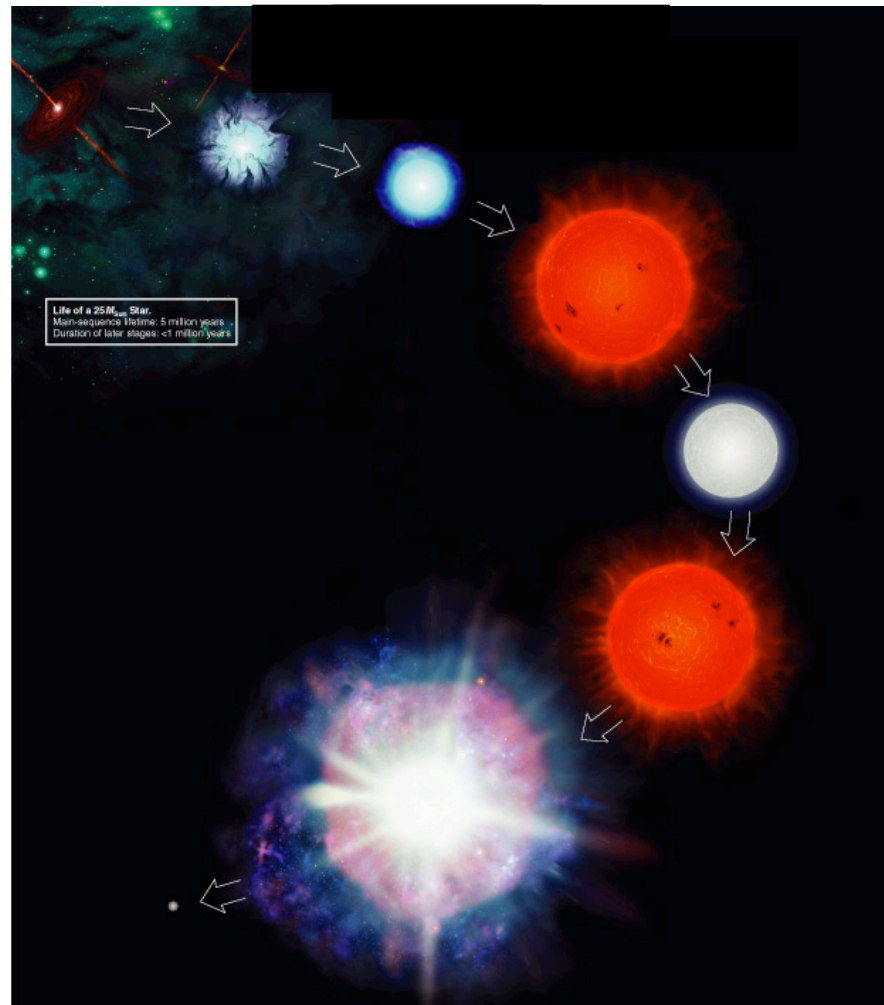
Asymptotic Giant
~10 million years

Planetary Nebula
~10 thousand years

White Dwarf
eternity



The evolution of high-mass stars



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

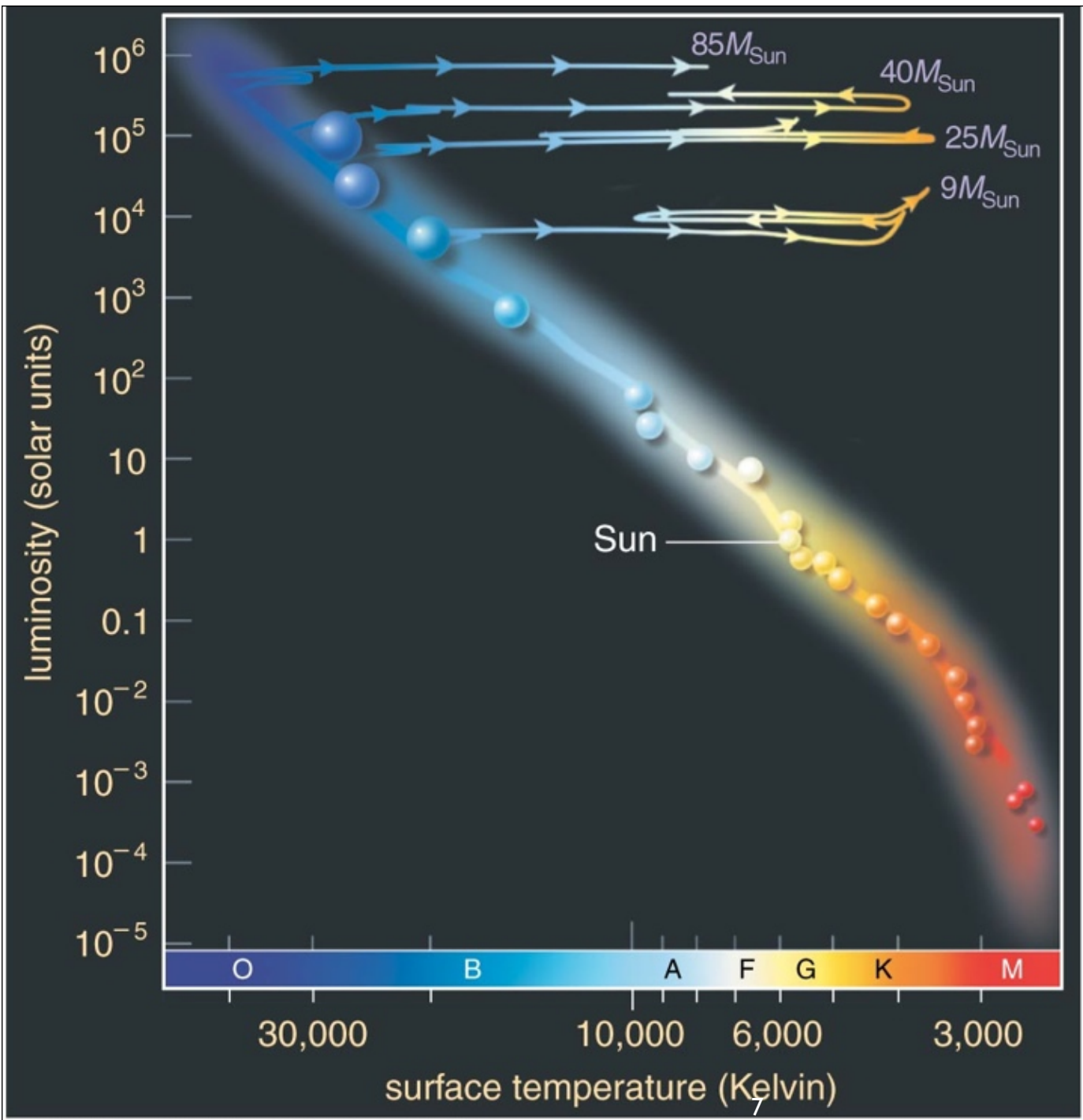
Life video

Life Stages of High-Mass Stars

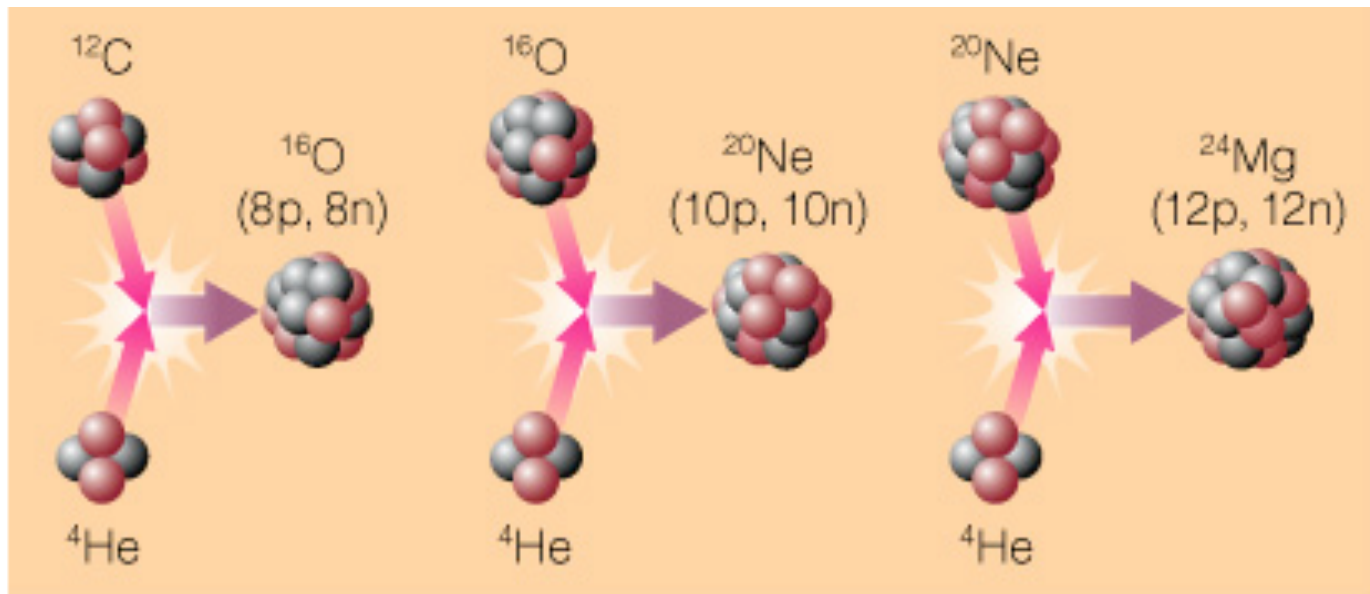
- Late life stages of high-mass stars are similar to those of low-mass stars:
 - Hydrogen core fusion (main sequence)
 - Hydrogen shell burning (supergiant)
 - Helium core fusion (supergiant)

 - 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.

H Hydrogen 1.00794												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 18.988	10 Ne Neon 20.179									
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Lanthanide Series

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75% H, 25% He is the starting point
— stars make everything else.

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Helium fusion can make carbon in low-mass stars. ¹⁰

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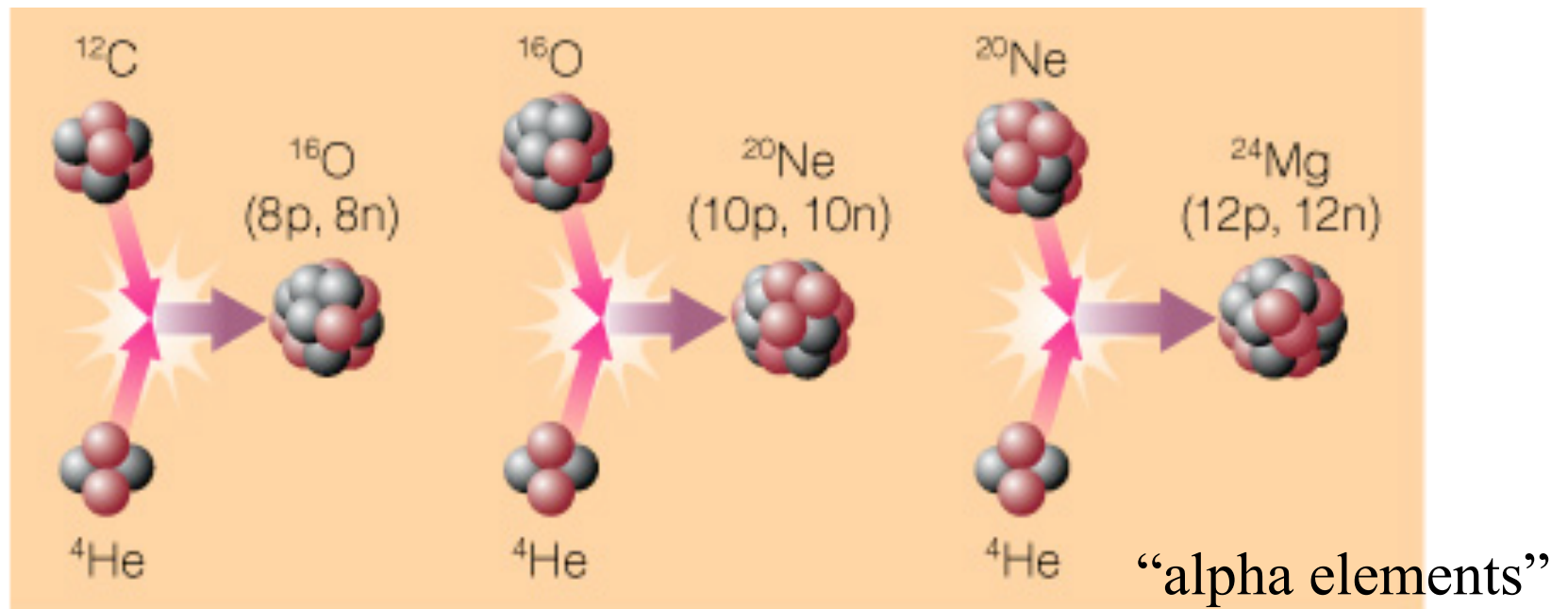
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Fusion can also produce heavier elements

Helium Capture



- High core temperatures allow helium to fuse with heavier elements.

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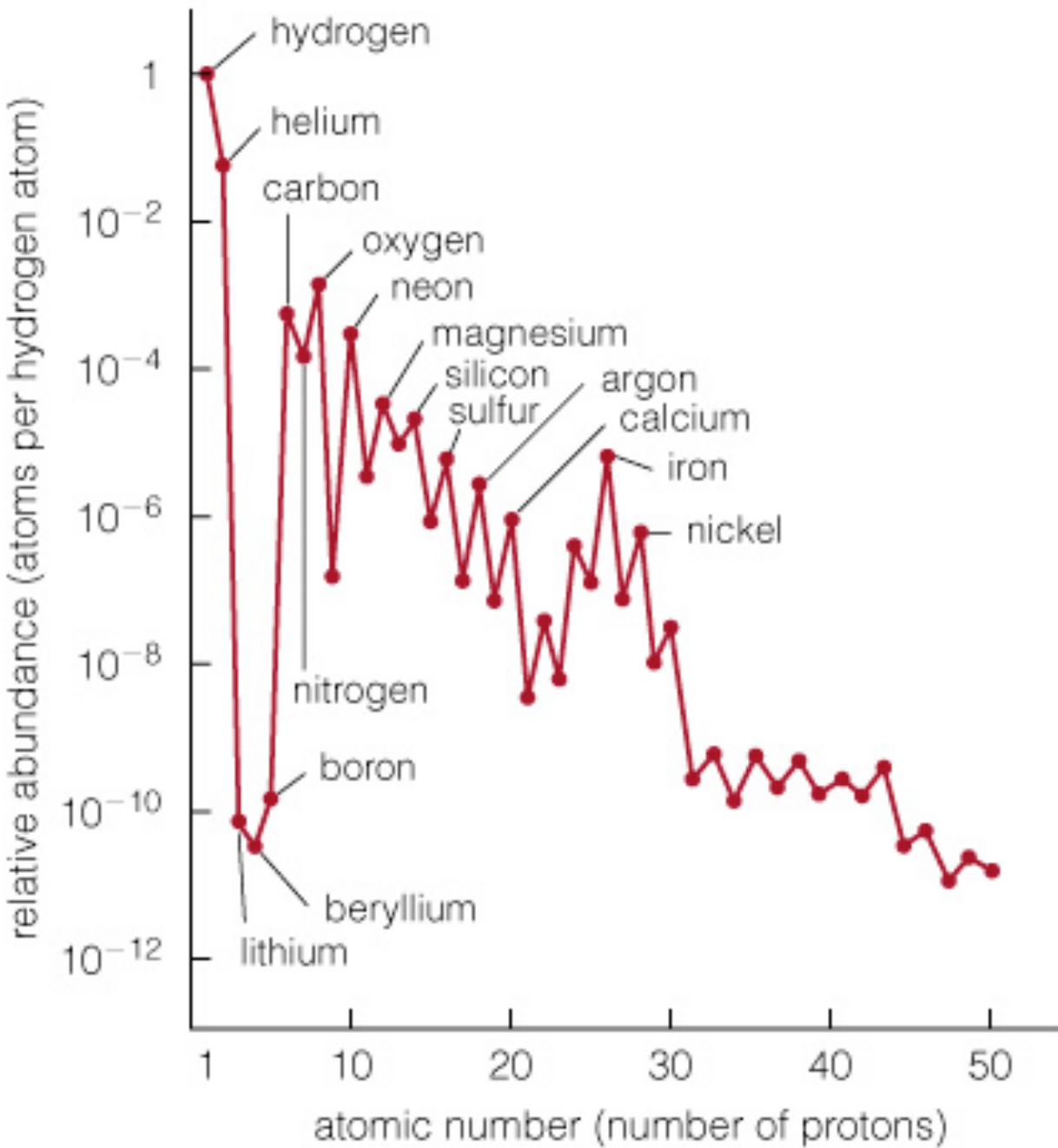
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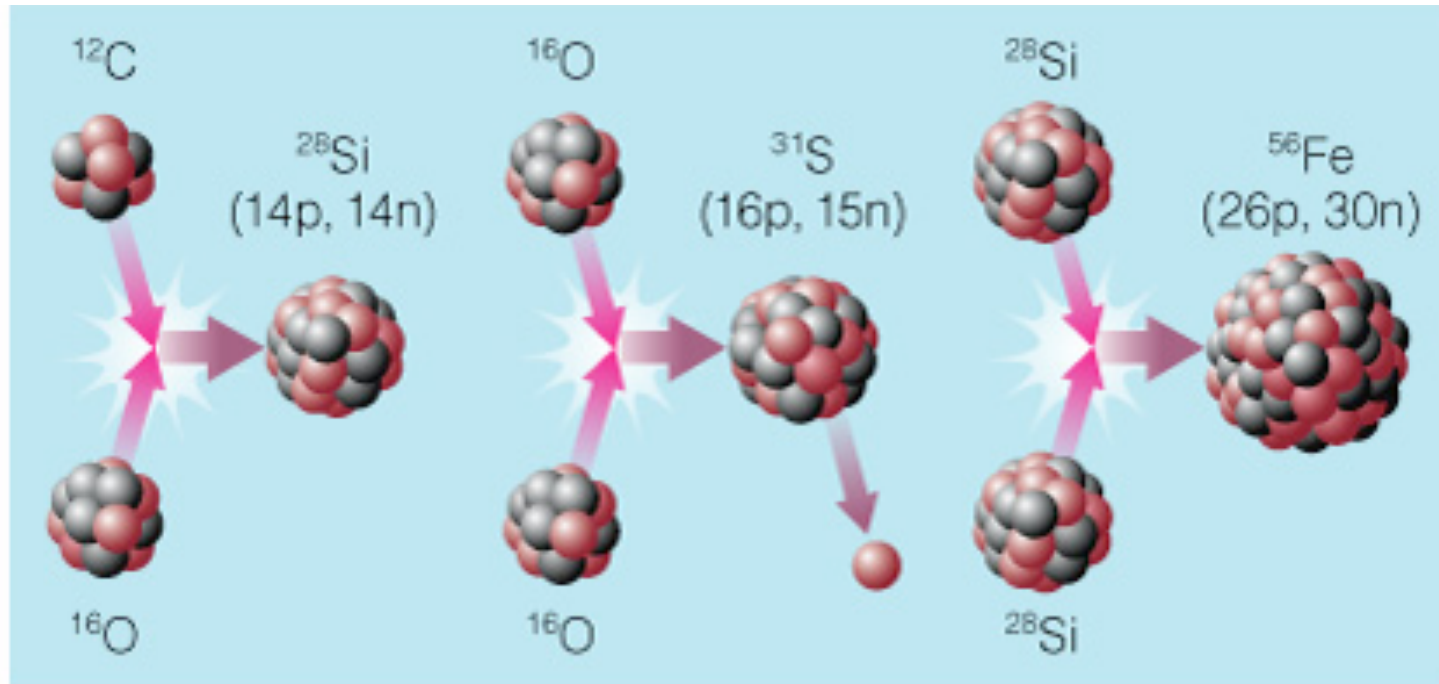
Helium capture builds C into O, Ne, Mg ... 13



Evidence for
helium
capture:

Higher
abundances of
elements with
even numbers
of protons
“alpha elements”

Advanced Nuclear Burning



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

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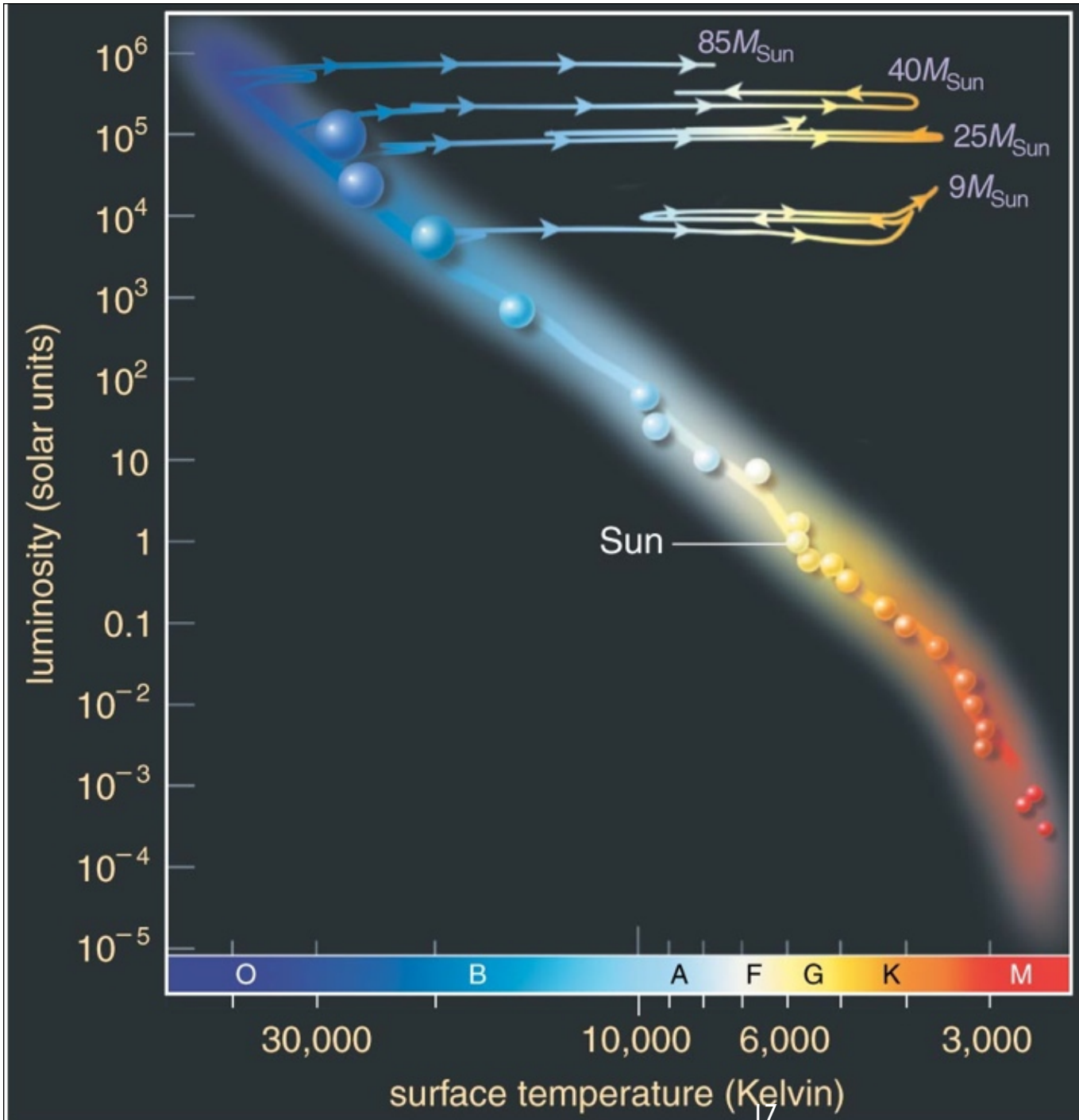
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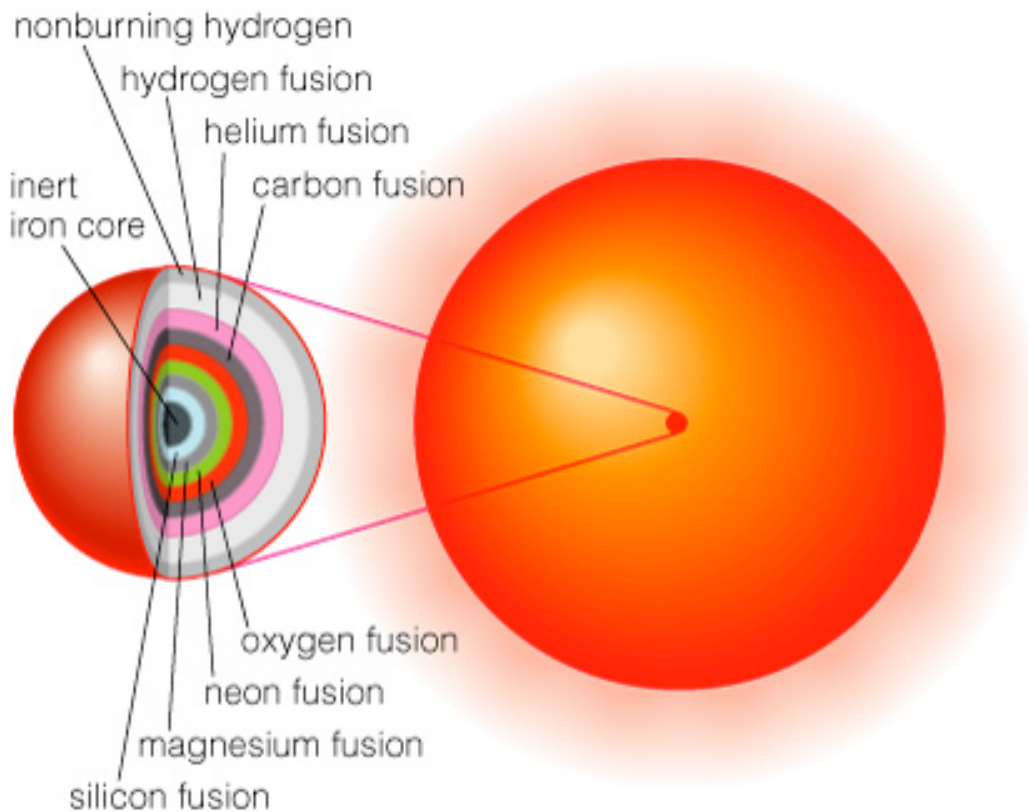
Advanced reactions in stars make elements like Si, S, Ca, and Fe.



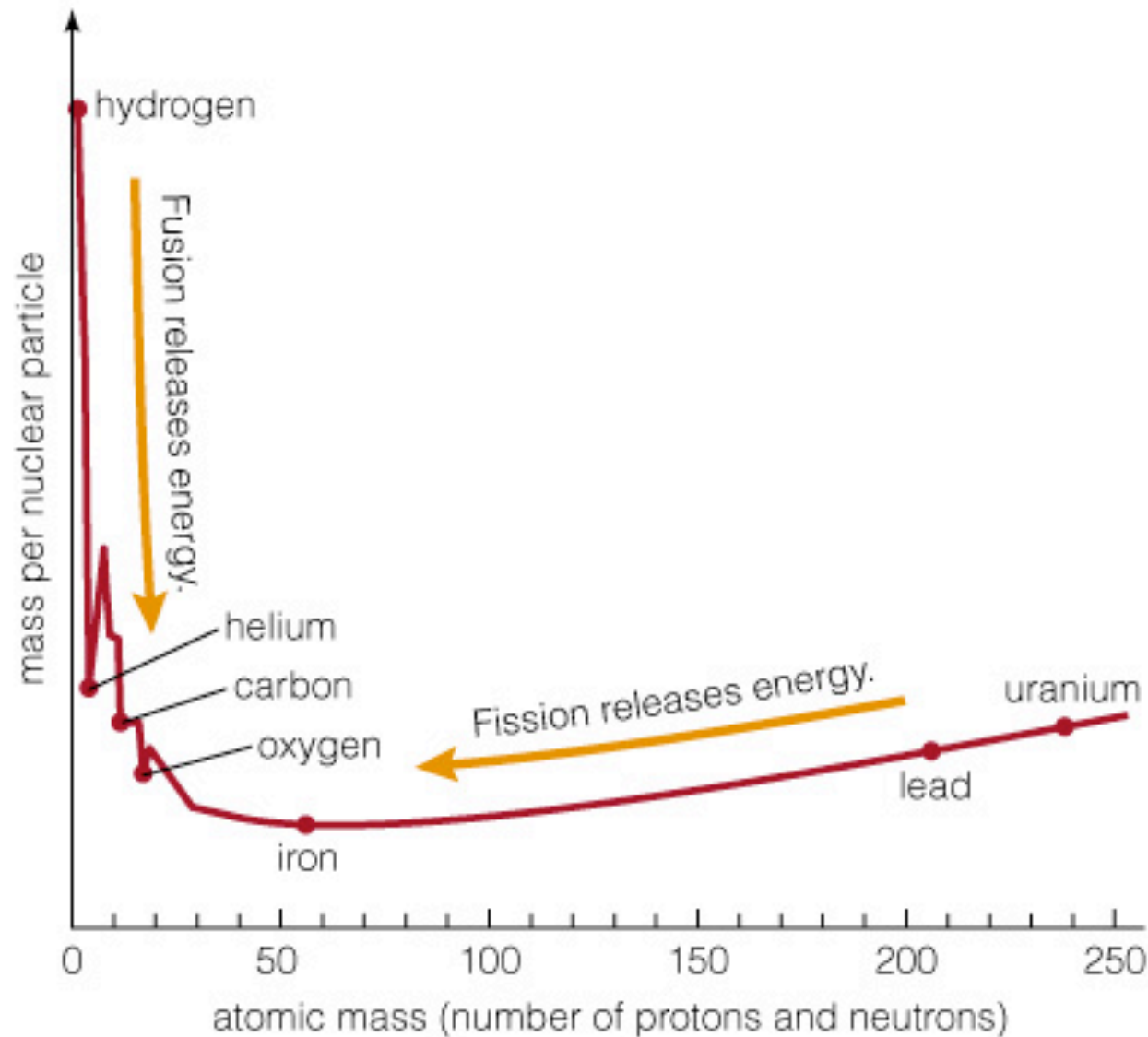
Supergiants
 can get a wiggle
 in evolutionary
 track as each
 fuel supply is
 exhausted.

Evolution
 very rapid -
 massive stars
 live "only"
 millions of years

Multiple-Shell Burning

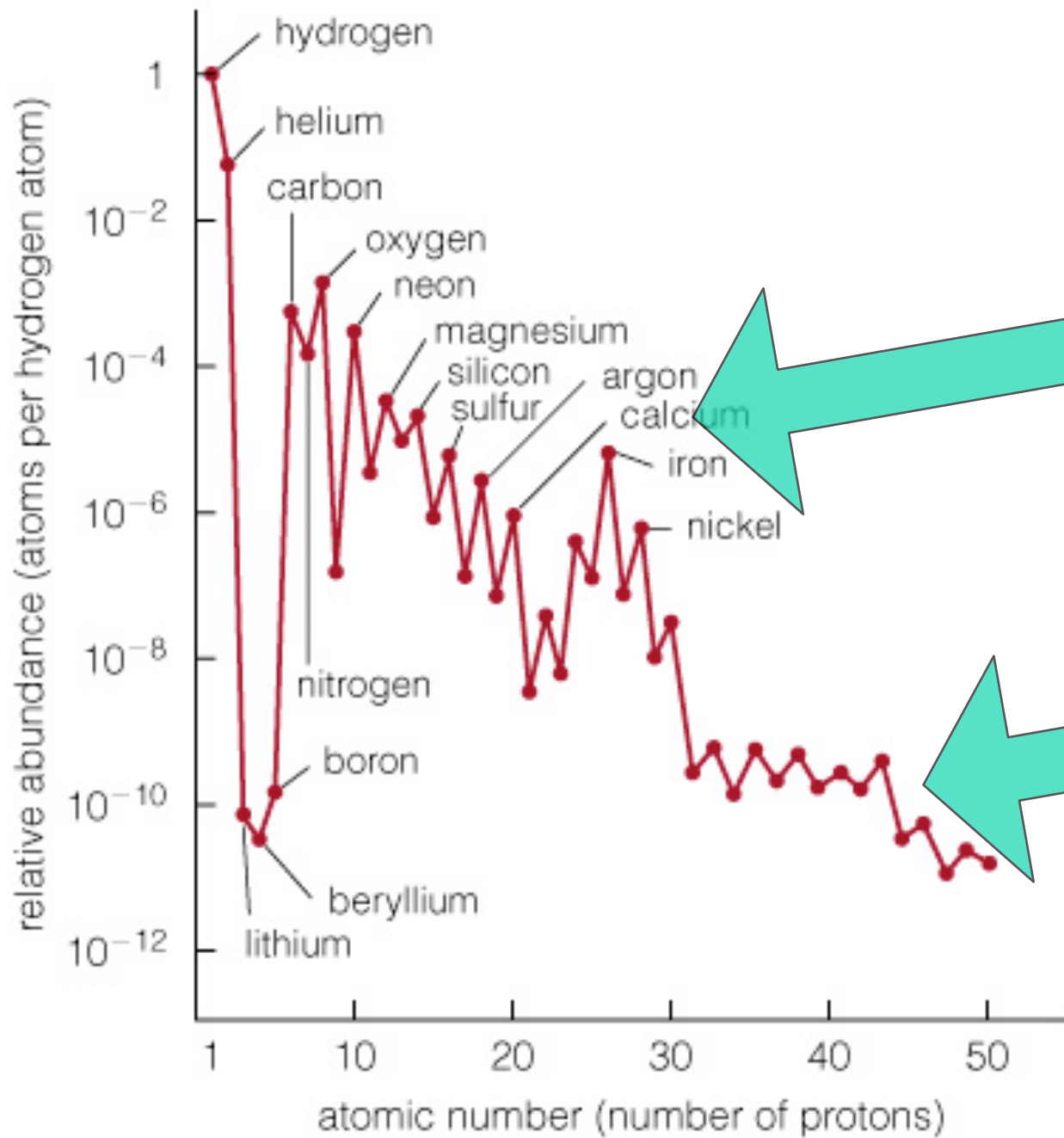


- Advanced nuclear burning proceeds in a series of nested shells.
- Core of high mass ($> 8M_{sun}$) near the end of its life



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

(Fe has lowest mass per nucleon.)



Iron peak

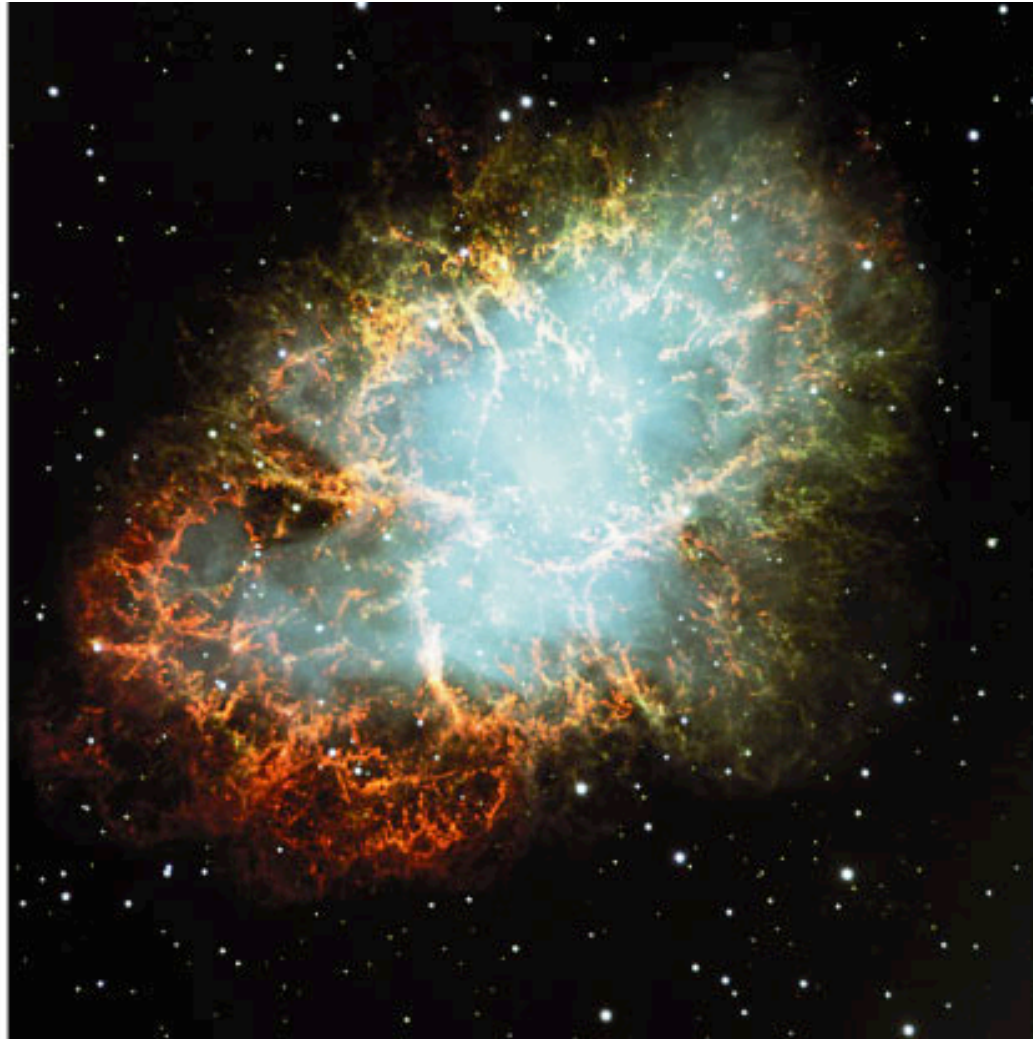
Where do elements heavier than iron come from?

Elements heavier than iron

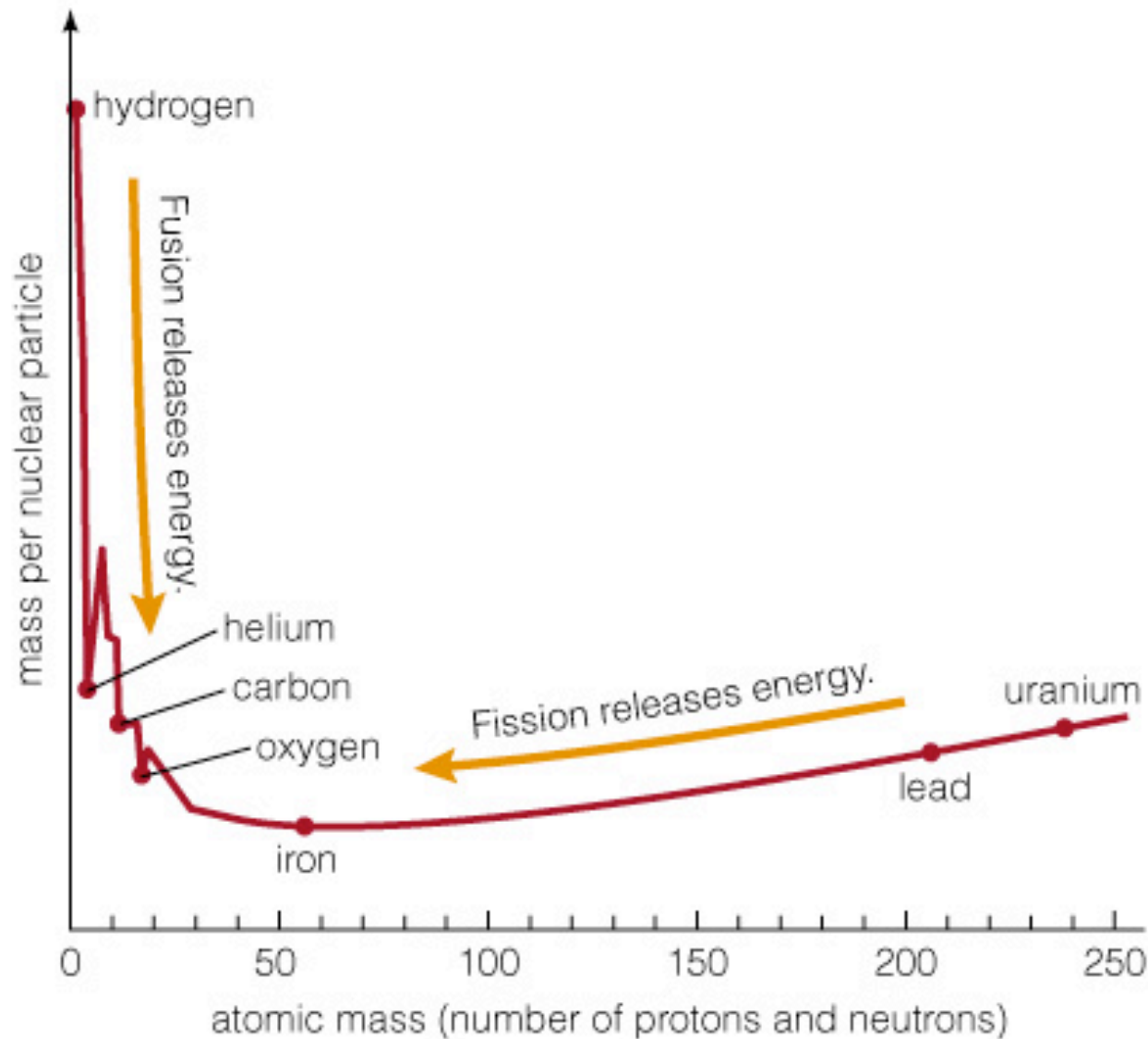
If we can get to iron by fusion in stars, how do we get elements heavier than iron?

- A. A source of energy is required to get heavier elements
- B. Fission of iron gives heavier elements
- C. Fusion of iron releases energy and produces heavier elements
- D. Heavier elements are produced by low mass stars
- E. I don't know

Supernovae!



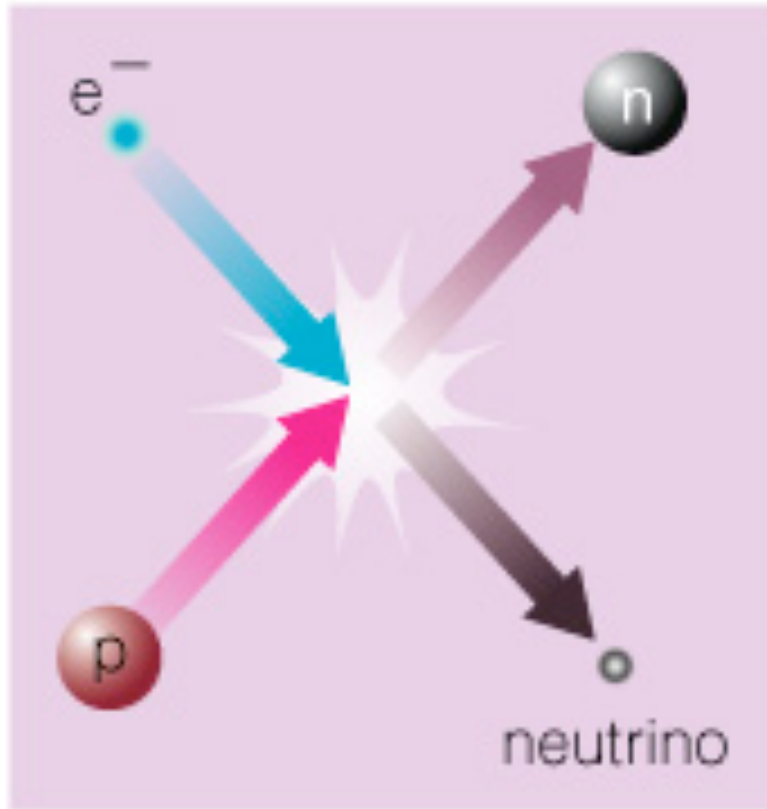
The Elements



Iron is the ultimate ash.

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

Supernova Explosion



Simulation, demo

- Core degeneracy pressure goes away because electrons combine with protons, making neutrons and neutrinos.
- Neutrons collapse to the center, forming a **neutron star**.

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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 Ununnilium (269)	111 Uuu Unununium (272)	112 Uub Ununbium (277)																							

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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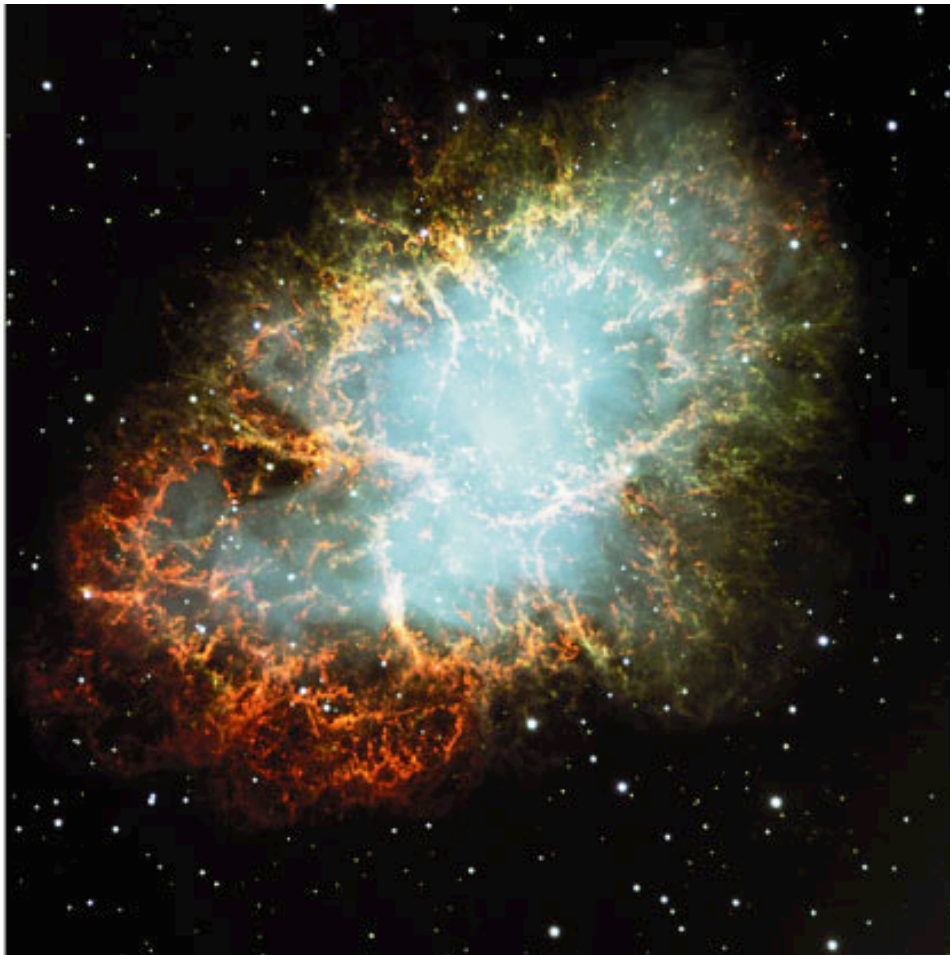
Actinide Series

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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Energy and neutrons released in a supernova explosion enable elements heavier than iron to form, including Au and U. ²⁵

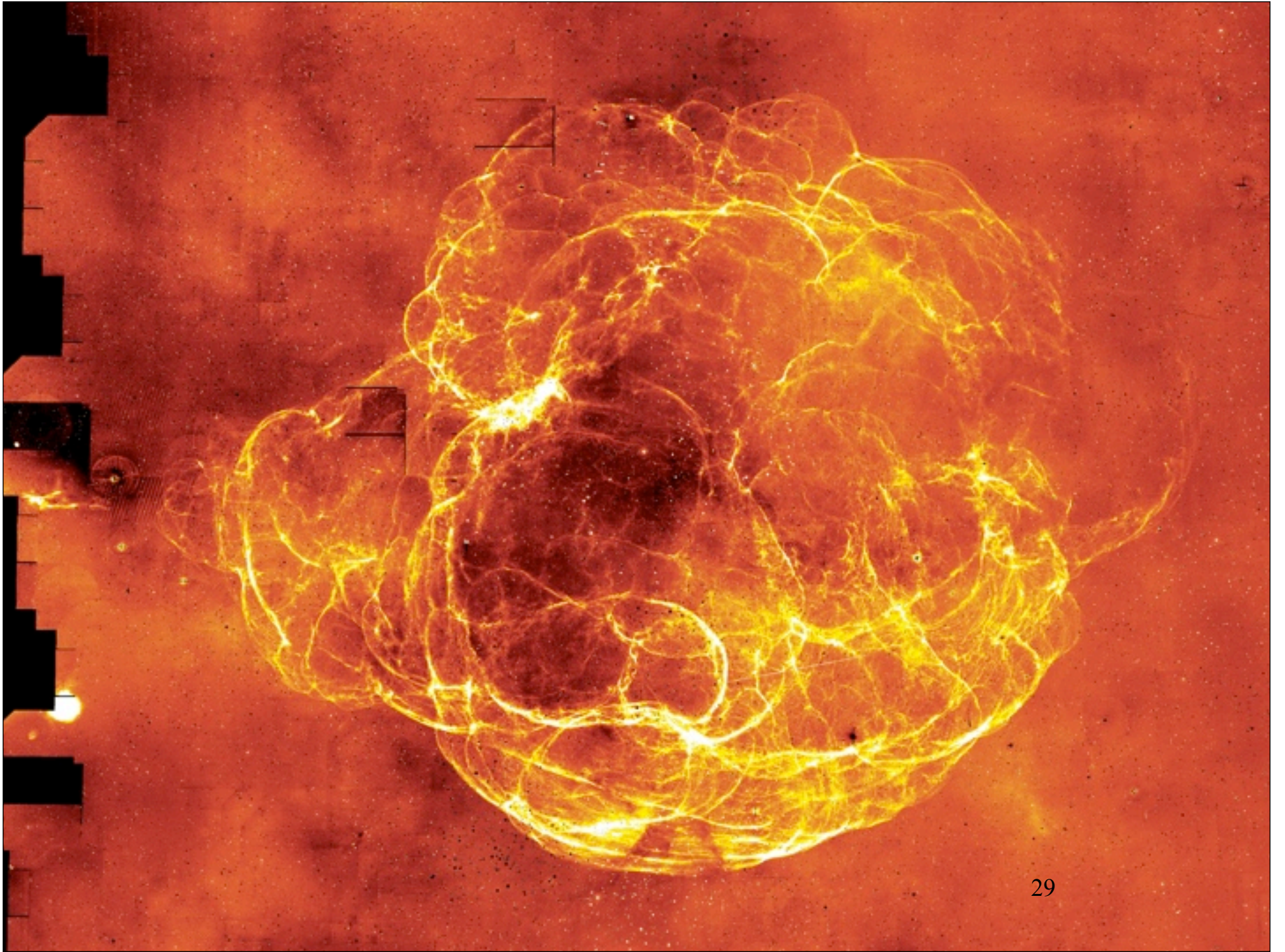
1 H Hydrogen	Made in Early Universe																2 He Helium
3 Li Lithium	4 Be Beryllium	Made in Stars										5 B Boron	6 C Carbon	7 N Nitrogen	8 O Oxygen	9 F Fluorine	10 Ne Neon
11 Na Sodium	12 Mg Magnesium											13 Al Aluminum	14 Si Silicon	15 P Phosphorus	16 S Sulfur	17 Cl Chlorine	18 Ar Argon
19 K Potassium	20 Ca Calcium	21 Sc Scandium	22 Ti Titanium	23 V Vanadium	24 Cr Chromium	25 Mn Manganese	26 Fe Iron	27 Co Cobalt	28 Ni Nickel	29 Cu Copper	30 Zn Zinc	31 Ga Gallium	32 Ge Germanium	33 As Arsenic	34 Se Selenium	35 Br Bromine	36 Kr Krypton
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
87 Fr Francium	88 Ra Radium	103 Lr Lawrencium	104 Rf Rutherfordium	105 Db Dubnium	106 Sg Seaborgium	107 Bh Bohrium	108 Hs Hassium	109 Mt Meitnerium	110 Ds Darmstadtium	111	112	113	114	115	116	117	118
Made in the laboratory																	
57 La Lanthanum	58 Ce Cerium	59 Pr Praseodymium	60 Nd Neodymium	61 Pm Promethium	62 Sm Samarium	63 Eu Europium	64 Gd Gadolinium	65 Tb Terbium	66 Dy Dysprosium	67 Ho Holmium	68 Er Erbium	69 Tm Thulium	70 Yb Ytterbium				
89 Ac Actinium	90 Th Thorium	91 Pa Protactinium	92 U Uranium	93 Np Neptunium	94 Pu Plutonium	95 Am Americium	96 Cm Curium	97 Bk Berkelium	98 Cf Californium	99 Es Einsteinium	100 Fm Fermium	101 Md Mendelevium	102 No Nobelium				

Supernova Remnant

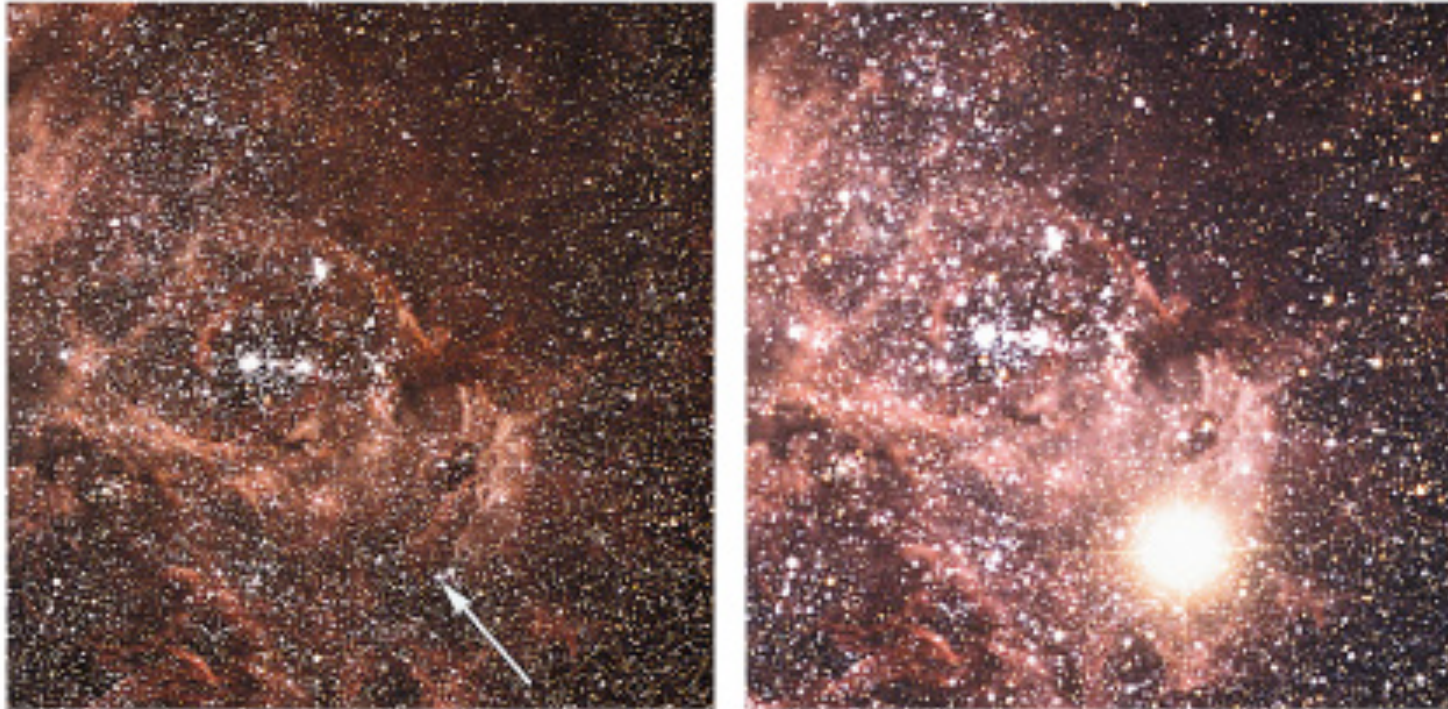


- Energy released by the collapse of the core drives outer layers into space.
- The Crab Nebula is the remnant of the supernova seen in A.D. 1054.





Supernova 1987A



- The closest supernova in the last four centuries was seen in 1987 in the Large Magellanic Cloud.
- Recent discoveries in other galaxies (video)

Betelgeuse

Bellatrix

Alnitak, Alnilam, Mintaka

Orion Nebula

Rigel

Saiph

Size of Star

Size of Earth's

Size of Jupiter's

Atmosphere of

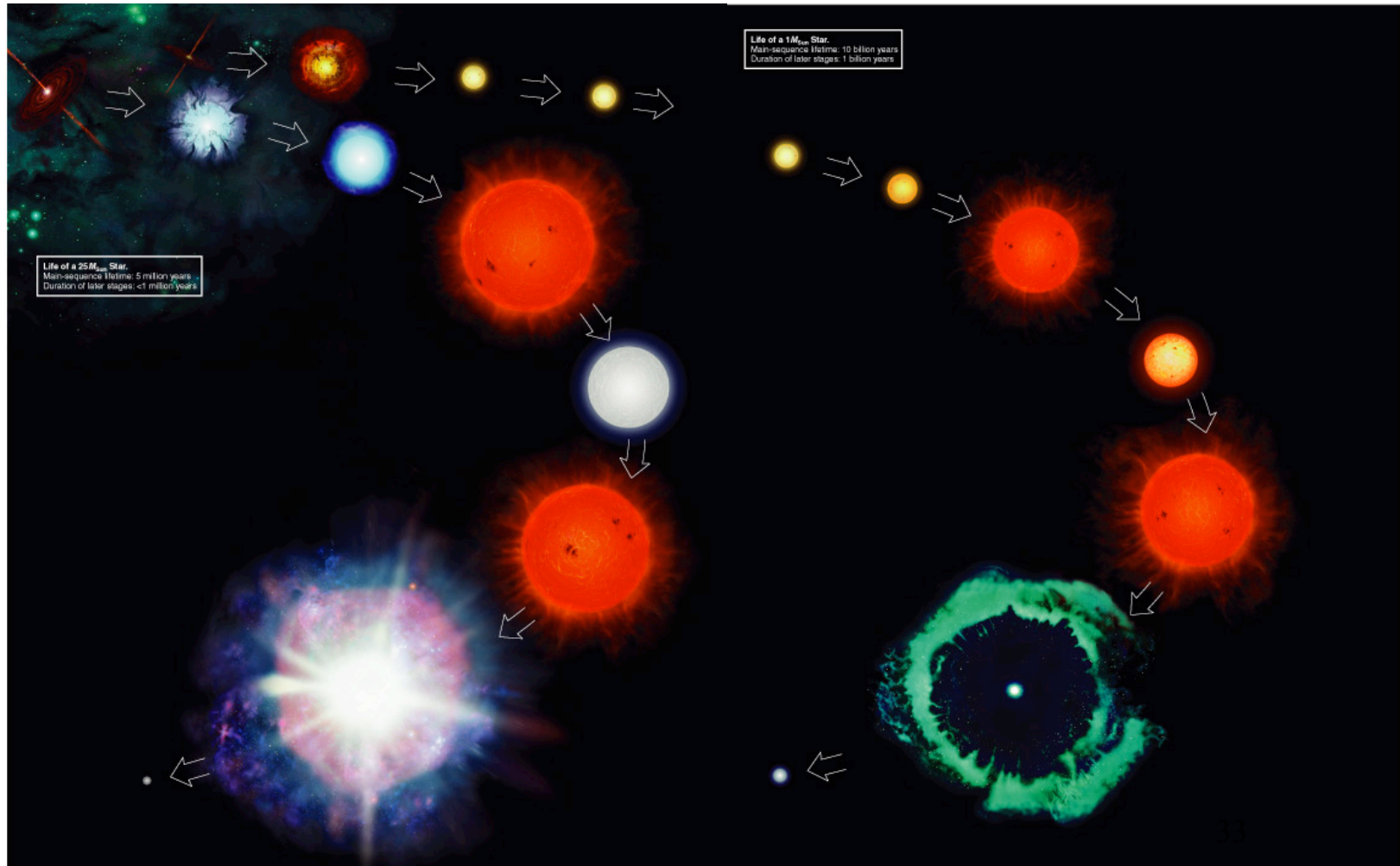
PRC96-04 · ST Sci OPO ·

Eta Carinae



(southern hemisphere)

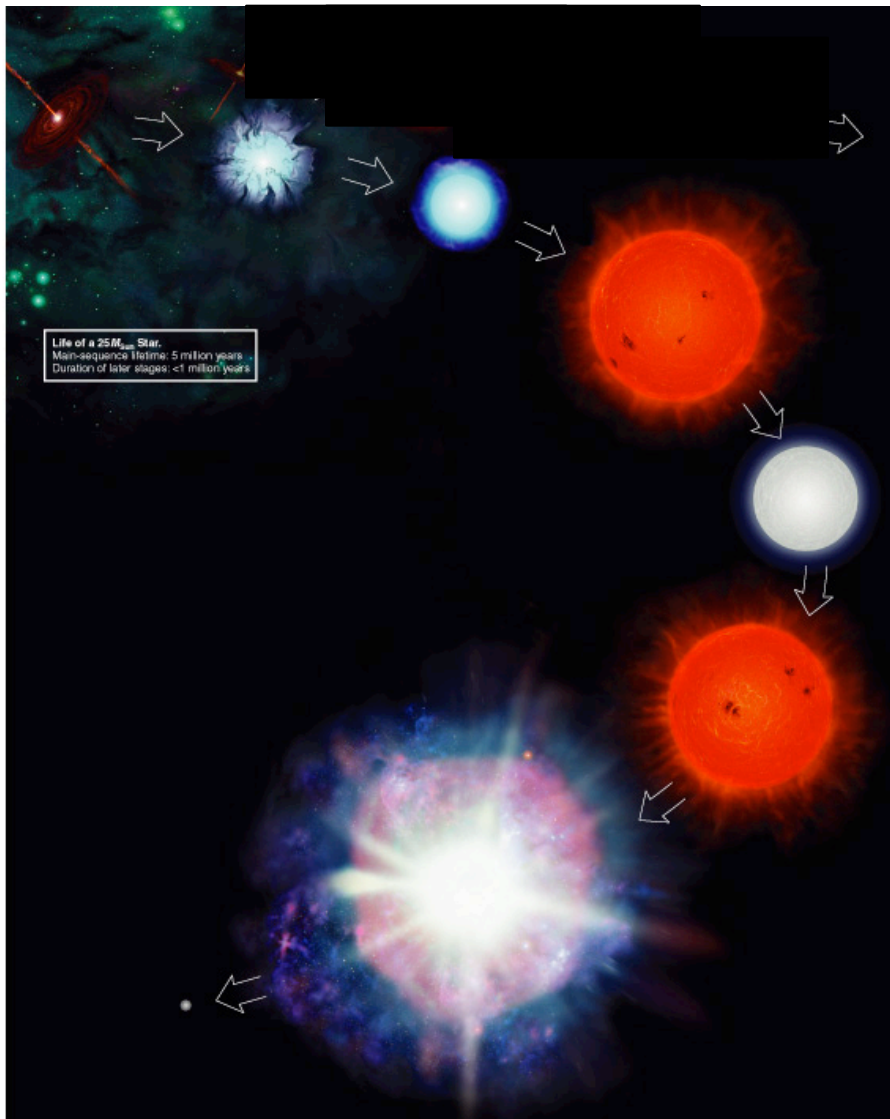
How does a star's mass determine its life story?



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.

Life Stages of High-Mass Star

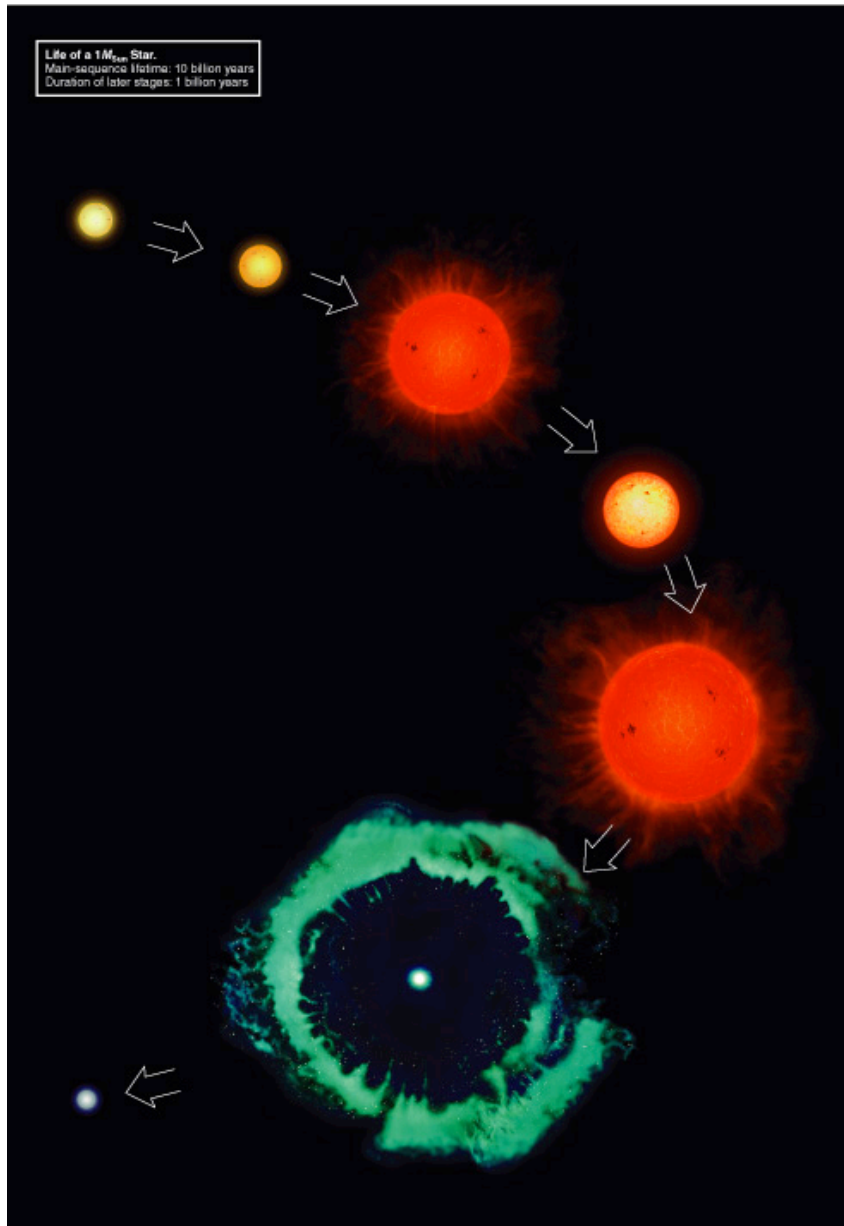


Not to scale!

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

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

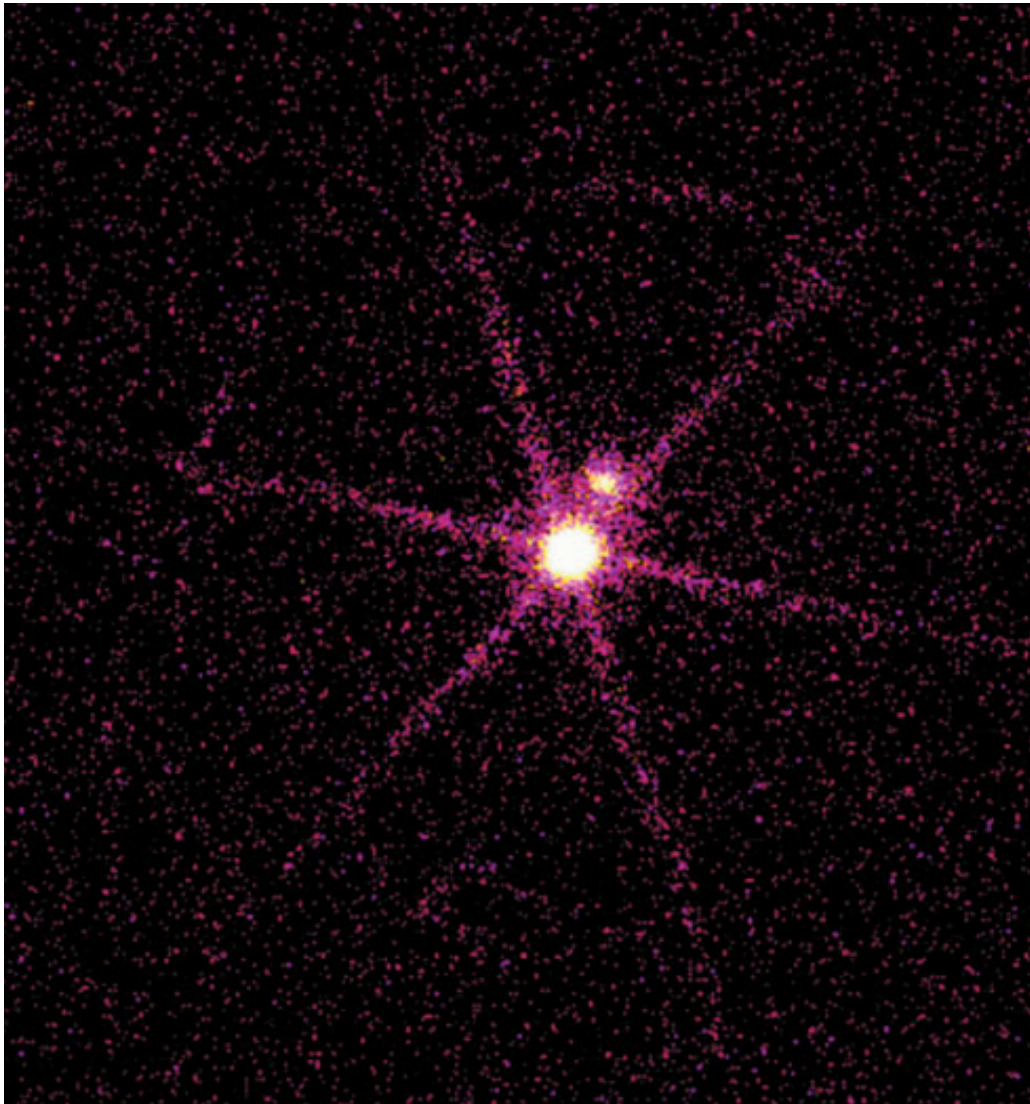


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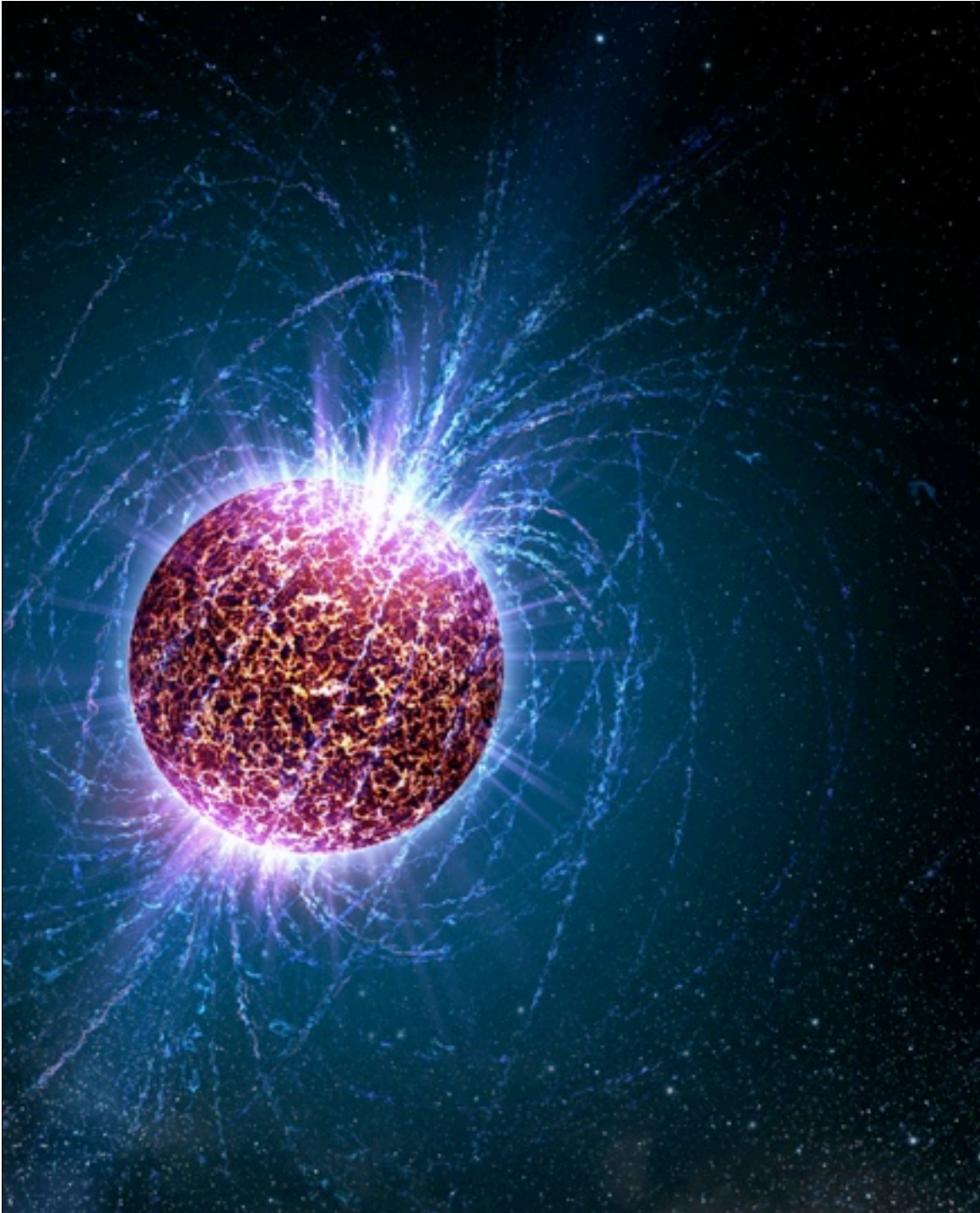
Dead Stars leave corpses

- White dwarfs
 - remnant core of low mass star
 - supported by electron degeneracy pressure
- Neutron stars
 - remnant core of high mass star
 - supported by neutron degeneracy pressure
- Black Holes
 - remnant of some massive stars
 - gravity's ultimate victory

White Dwarfs



- White dwarfs are the remaining cores of low mass dead stars.
- The mass of a star compressed into roughly the size of the Earth



Neutron Stars

Neutron stars are the remnants of massive stars that exploded as supernovae.

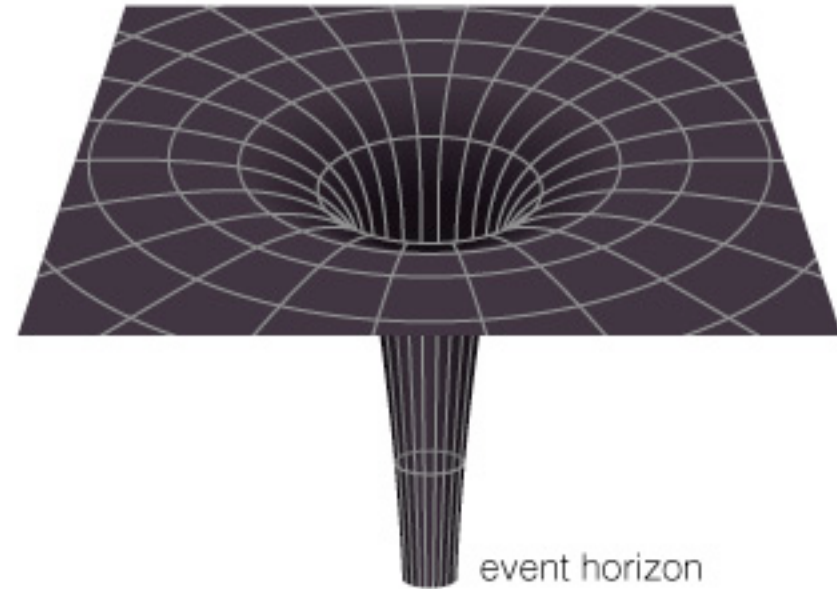
The mass of a star compressed to roughly the size of a city (~ 10 km).

Black Holes

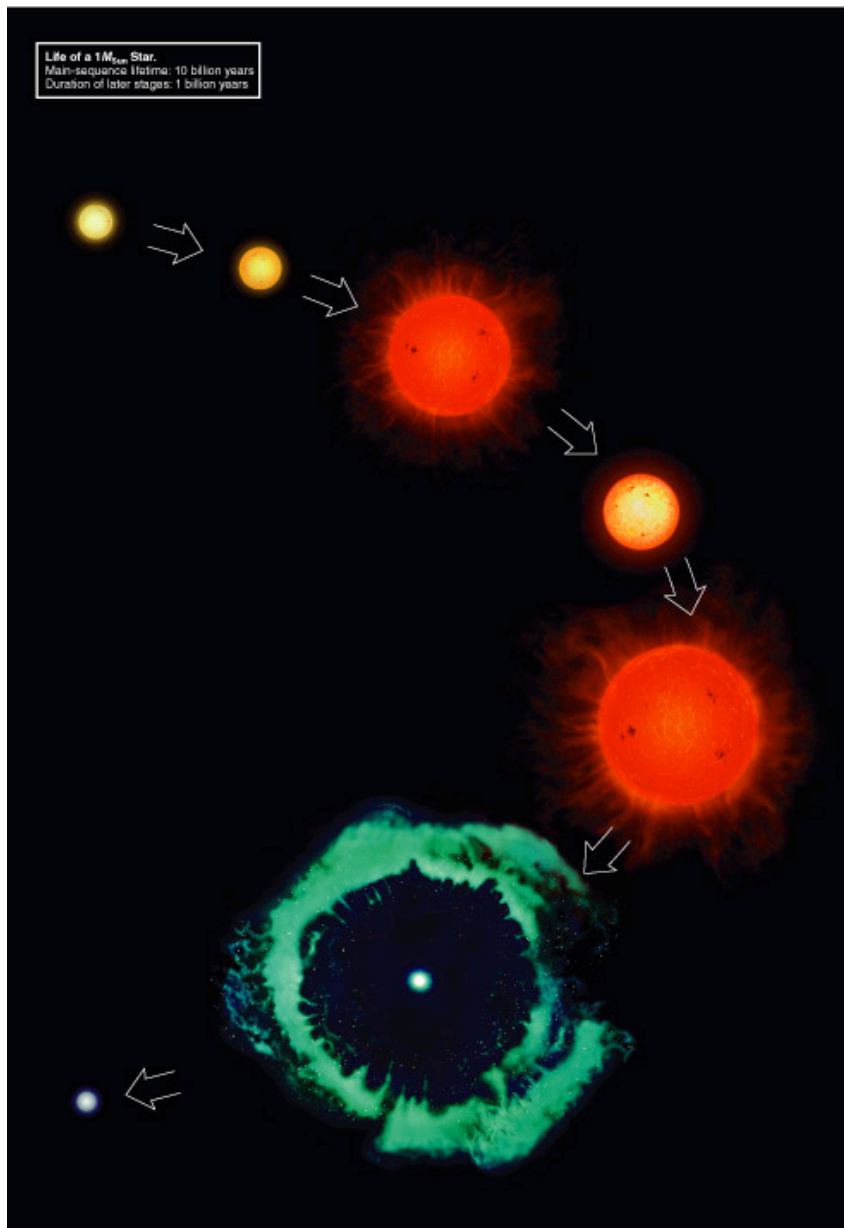
A *black hole* is an object whose gravity is so powerful that not even light can escape it.

Some massive star supernovae can make a black hole if enough mass falls onto the core.

All mass compressed to a mathematical point.



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Not to scale!

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