[06] Life as a High-mass Star (2/13/18)

Upcoming Items

1. Homework #1 due now.
2. Read Ch. 18.1 for next class and do the self-study quizzes.
3. Read degeneracy.pdf in Files->derivations
4. Homework #2 due in two weeks.

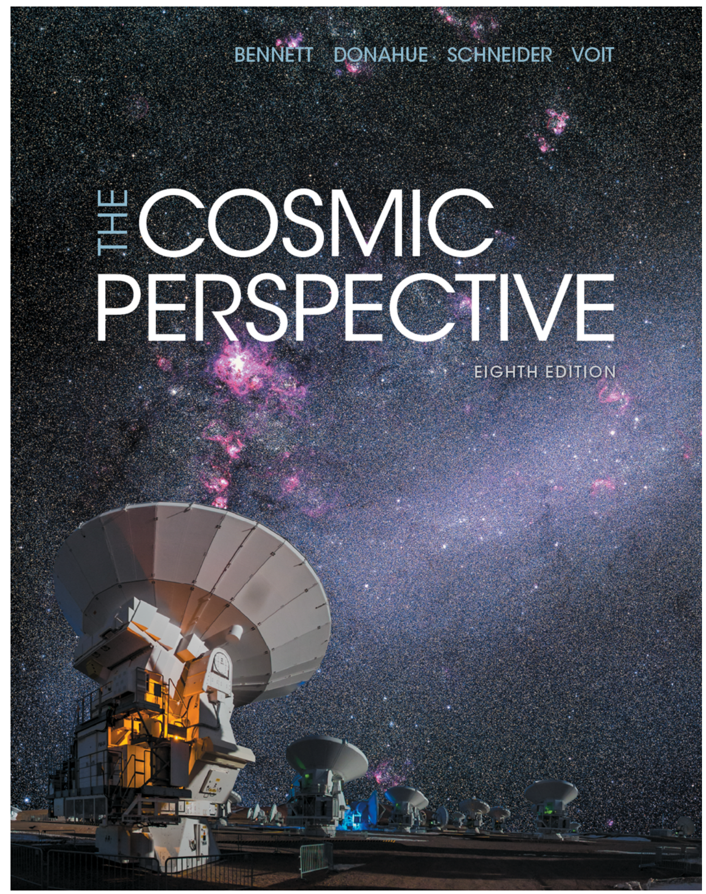
APOD 2/14/17: Rosette Nebula

LEARNING GOALS

Ch. 17.3–17.4

For this class, you should be able to…

- … *sketch the approximate life track of a high-mass star on an H-R diagram;*
- … *explain why a high-mass star is able to create a greater variety of elements than a low-mass star, keeping in mind that some elements may be formed after the star reaches the end of its life;*



Any astro questions?

Life as a High-mass Star ($M > 8\ M_\odot$)

- Most of the elements in the universe heavier than helium are formed in high-mass stars, because higher core temperatures permit more advanced fusion reactions.
  - Supernovae generate some to most of the remaining elements by fusion and fission. The remainder: neutron star mergers?
- Stages:
  1. *Contraction of protostar to main sequence.*
  2. Main sequence: H fuses to He in core, like low-mass star.
  3. Red supergiant: H fuses to He in shell around He core (no flash).
  4. He core fusion: He fuses to C in core, H fuses to He in shell.
  5. Multiple shell fusion: many elements fuse in shells.
  6. *Supernova* leaves *neutron star* or *black hole* behind.
- Things get complicated if stars change mass suddenly…

Preview: Most Heavy Elements Are Created by Stars

- Recall: low-mass stars can only fuse elements up to He (why?).
- High-mass stars can make elements as heavy as iron in their cores, and their explosive deaths—supernovae!—create a large fraction of the heavy elements on the periodic table.
  But some elements may be made primarily in the inspirals and mergers of neutron stars with other neutron stars or black holes!

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 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 18.988	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 Kr Krypton 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 Ti 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 (263)	105 Db Dubnium (262)	106 Sg Seaborgium (266)	107 Bh Bohrium (267)	108 Hs Hassium (277)	109 Mt Meitnerium (268)	110 Ds Darmstadtium (281)	111 Rg Roentgenium (272)	112 Cn Copernicium (285)	113 Uut Ununtrium (284)	114 Uuq Ununquadium (289)	115 Uup Ununpentium (288)	116 Uuh Ununhexium (292)	117 Uus Ununseptium (294)	118 Uuo Ununoctium (294)

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

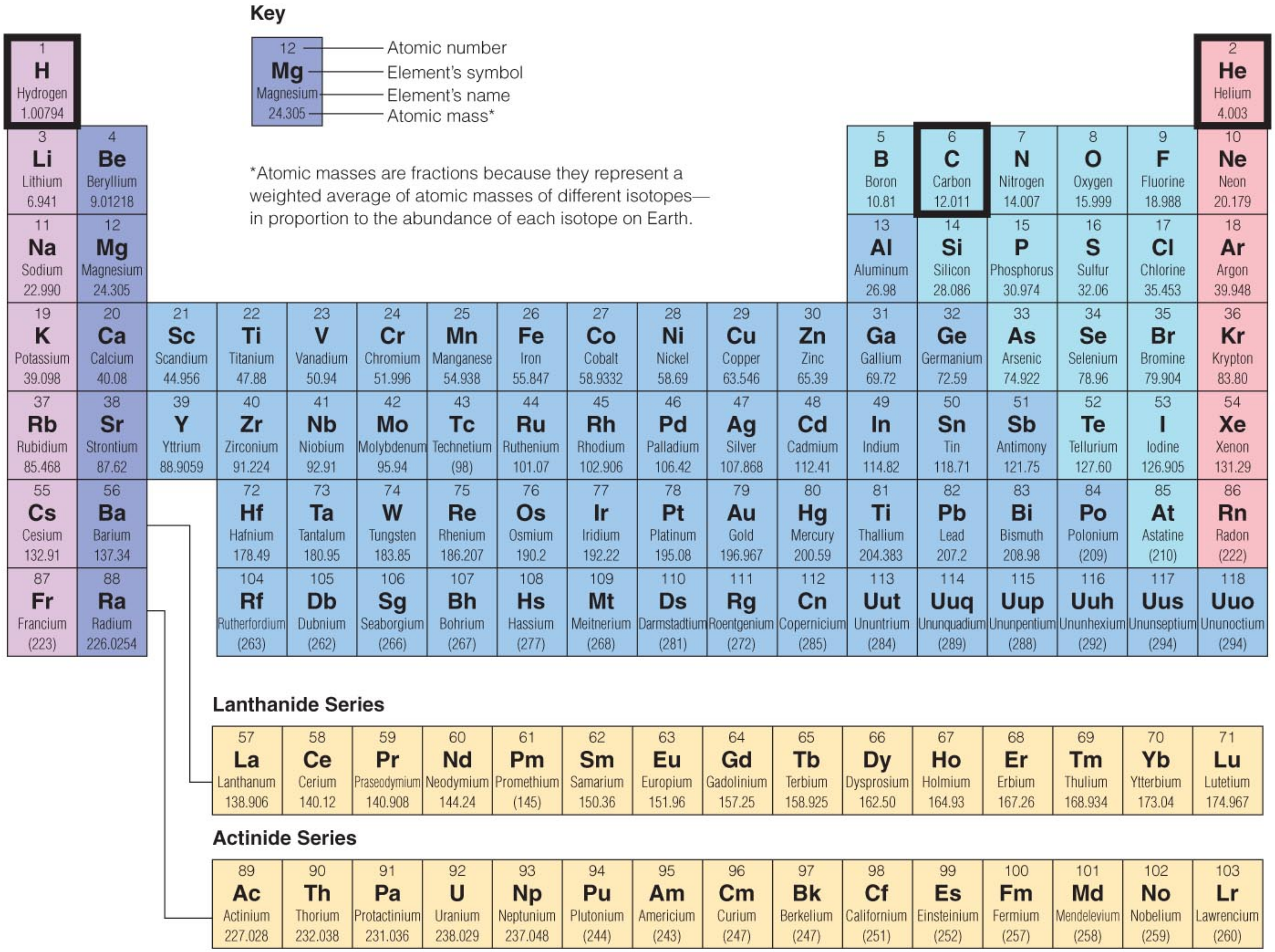
Actinide Series

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)

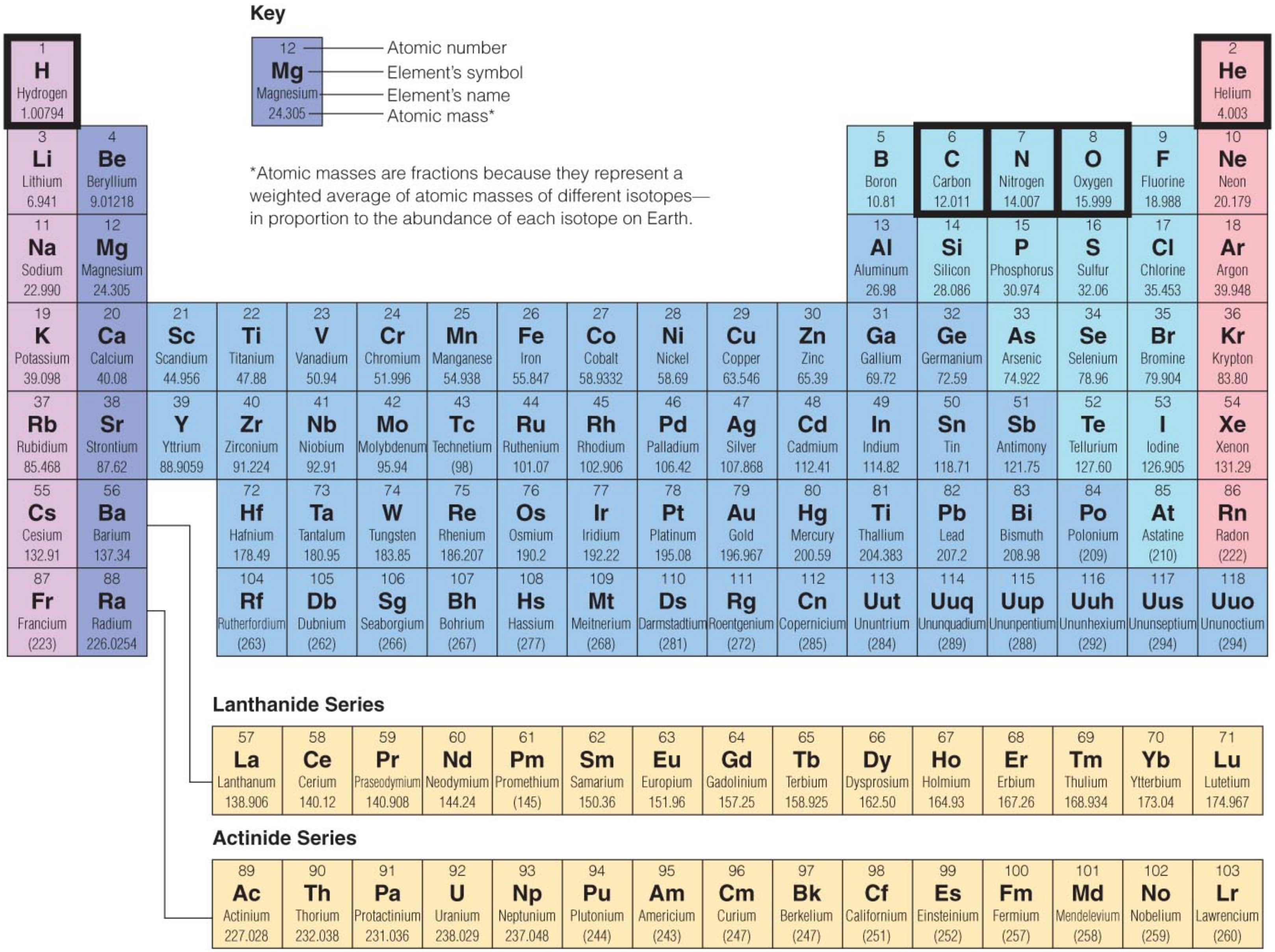
- Big Bang made 75% H, 25% He (and a tiny amount of Li, Be).
- Almost everything else comes from stars or mergers.

Life Stages of High-mass Stars

- Late life stages of high-mass stars start out similar to those of low-mass stars…
  - Hydrogen core fusion (main sequence).
  - Hydrogen shell fusion (supergiant).
  - Helium core fusion (supergiant).

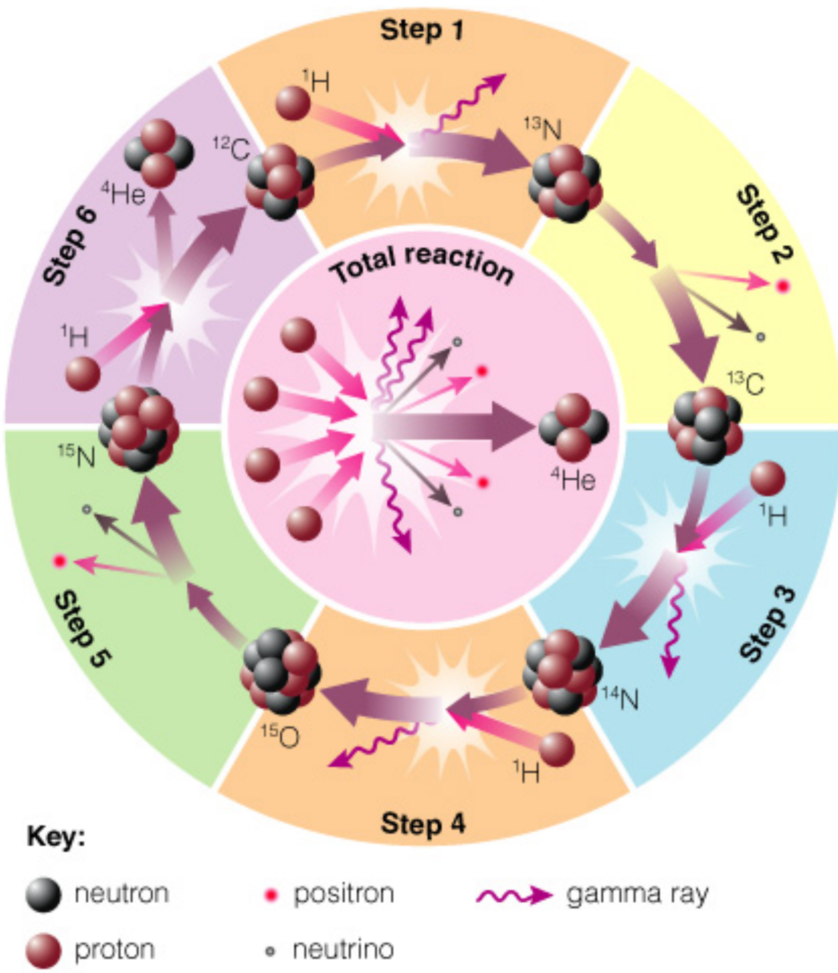


- Helium fusion can make carbon in low-mass stars.



- CNO cycle can change carbon to nitrogen and oxygen.

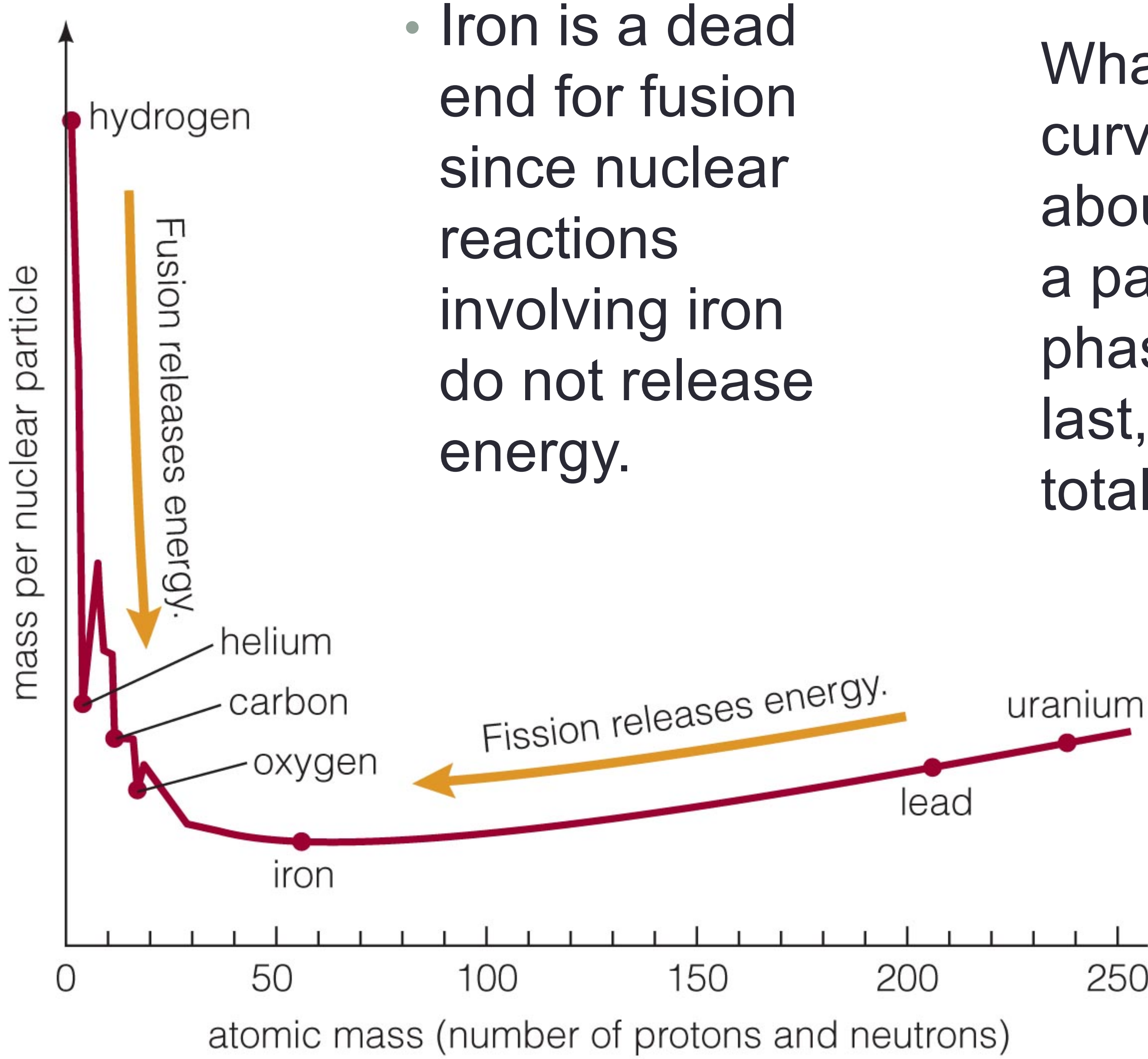
Recall: CNO Cycle



- Mid- to high-mass main-sequence stars fuse H to He at a higher rate using carbon, nitrogen, and oxygen as “catalysts.”
- Greater core temperature enables hydrogen nuclei to overcome greater repulsion.

Group Q: Nuclear Binding Energy

- You may know that nuclear fusion can't continue past iron, and you may also know that this is because iron has nearly the highest "binding energy" per nucleon of any nucleus
  Means energy needed per nucleon to fully disperse the nucleus
- But why?
- A hint: the electromagnetic force scales as $1/r^2$, where r is the distance between charges
- The strong force scales exponentially: $\sim e^{-r/d}$, where $d \sim 10^{-15}$ m
- At $\sim 10^{-15}$ m (~size of proton or neutron), strong force is ~100x stronger than electromagnetic force
- Strong force binds nuclei together, and its strongest binding is when there are an equal number of protons and neutrons in the nucleus
- With this in mind, your two group questions are:
  1. Why should there be a maximum binding energy per nucleon?
  2. For bigger nuclei, what do you expect to happen to the ratio of neutrons to protons in a nucleus?



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

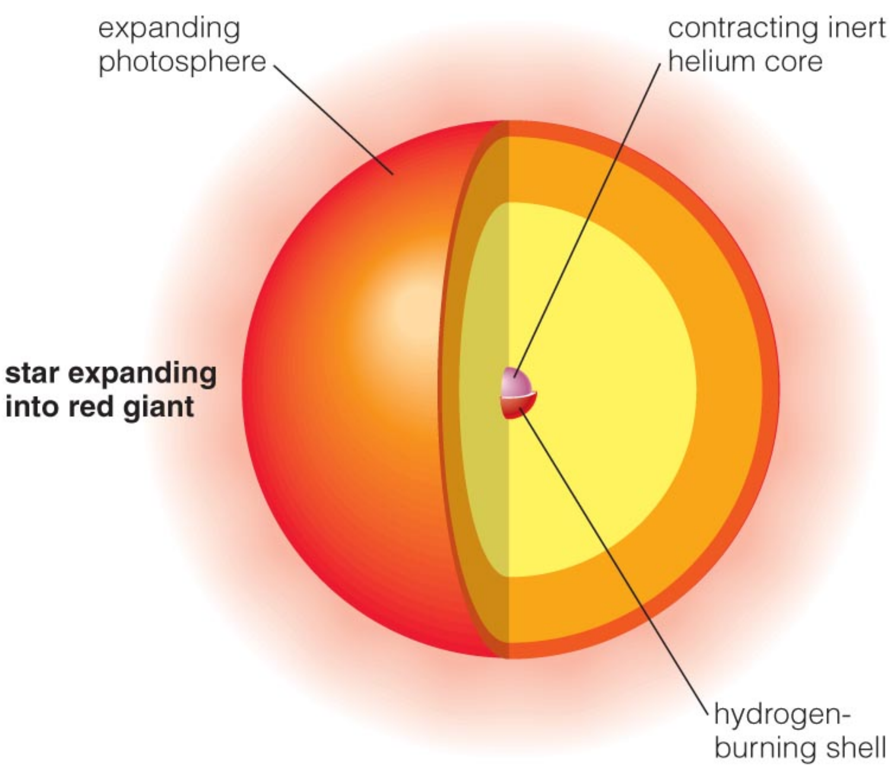
What does this curve tell you about how long a particular fusion phase should last, for a given total energy release?

Helium Flash for Low-Mass Stars

- We mentioned last time that there are some circumstances in which nuclear fusion can run away, in a burst
- This can occur for low-mass stars, when a helium shell is burning
- Why?
- Pressure gradients oppose gravity
- If the region is hot enough, it’s thermal pressure; thus extra heat increases the pressure, and the region expands and therefore cools
- But at lower temperatures, it is quantum-mechanical degeneracy pressure (more in the next class) that matters; this is independent of the temperature
- Thus in that situation, an increased fusion rate does not increase the pressure much, and thus does not cause significant expansion and cooling

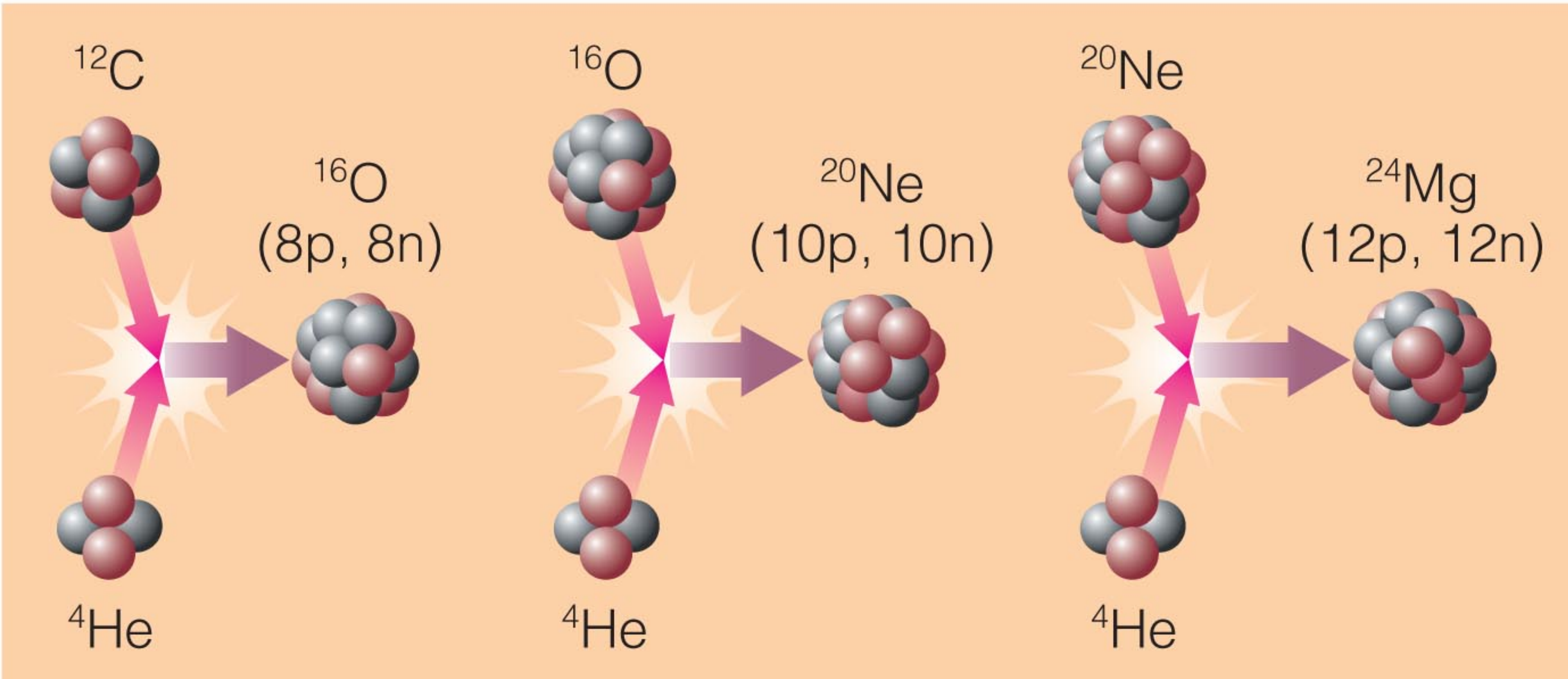
  Recipe for runaway fusion, until hot enough for thermal pressure...

Onset of Helium Fusion

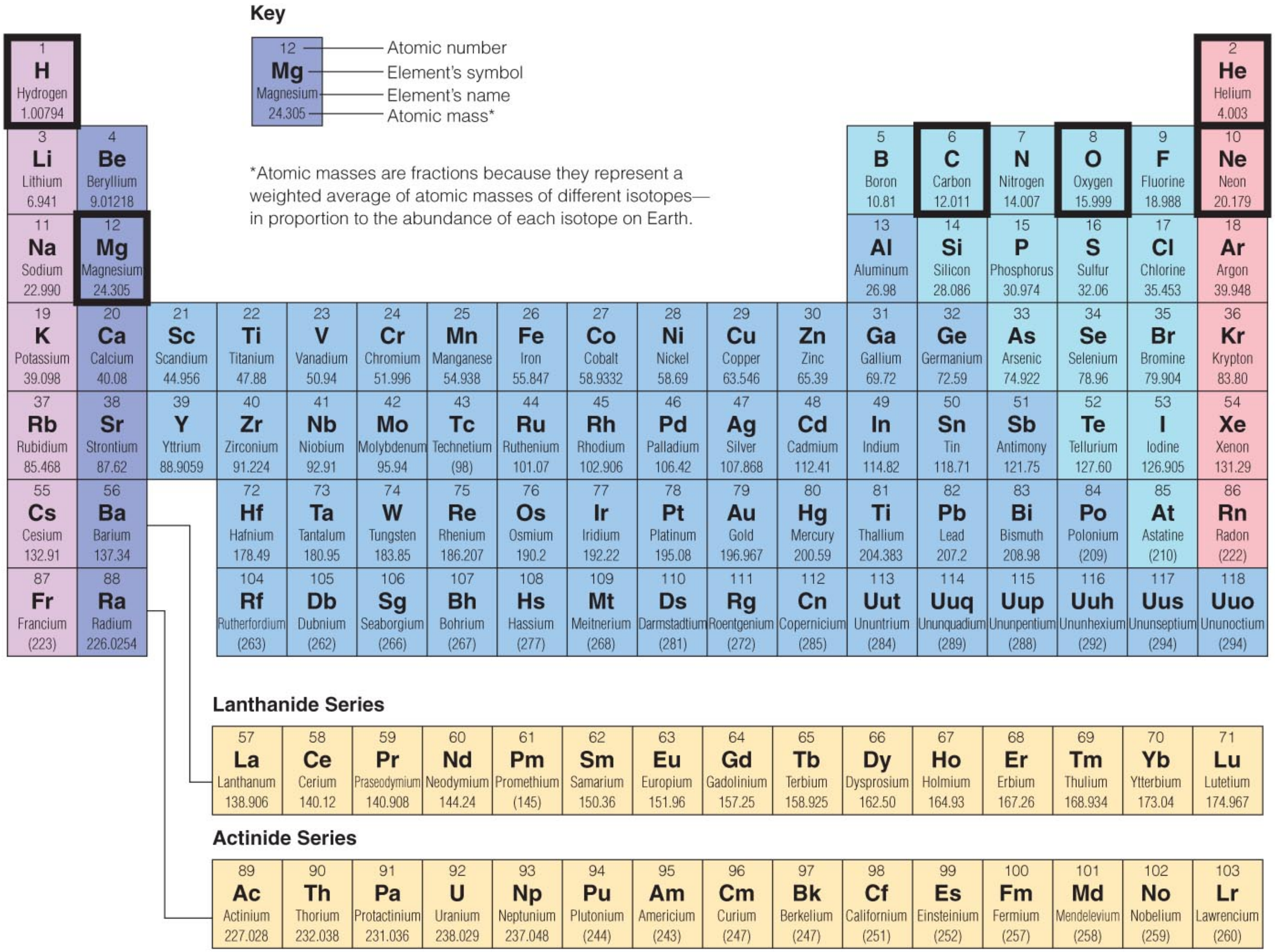


- Unlike low-mass stars ($< 2\ M_{\odot}$), mid- and high-mass stars do not start He fusion in a flash.
- Core temperature is hot enough that thermal pressure, not degeneracy pressure, supports it against gravity.

Helium Capture

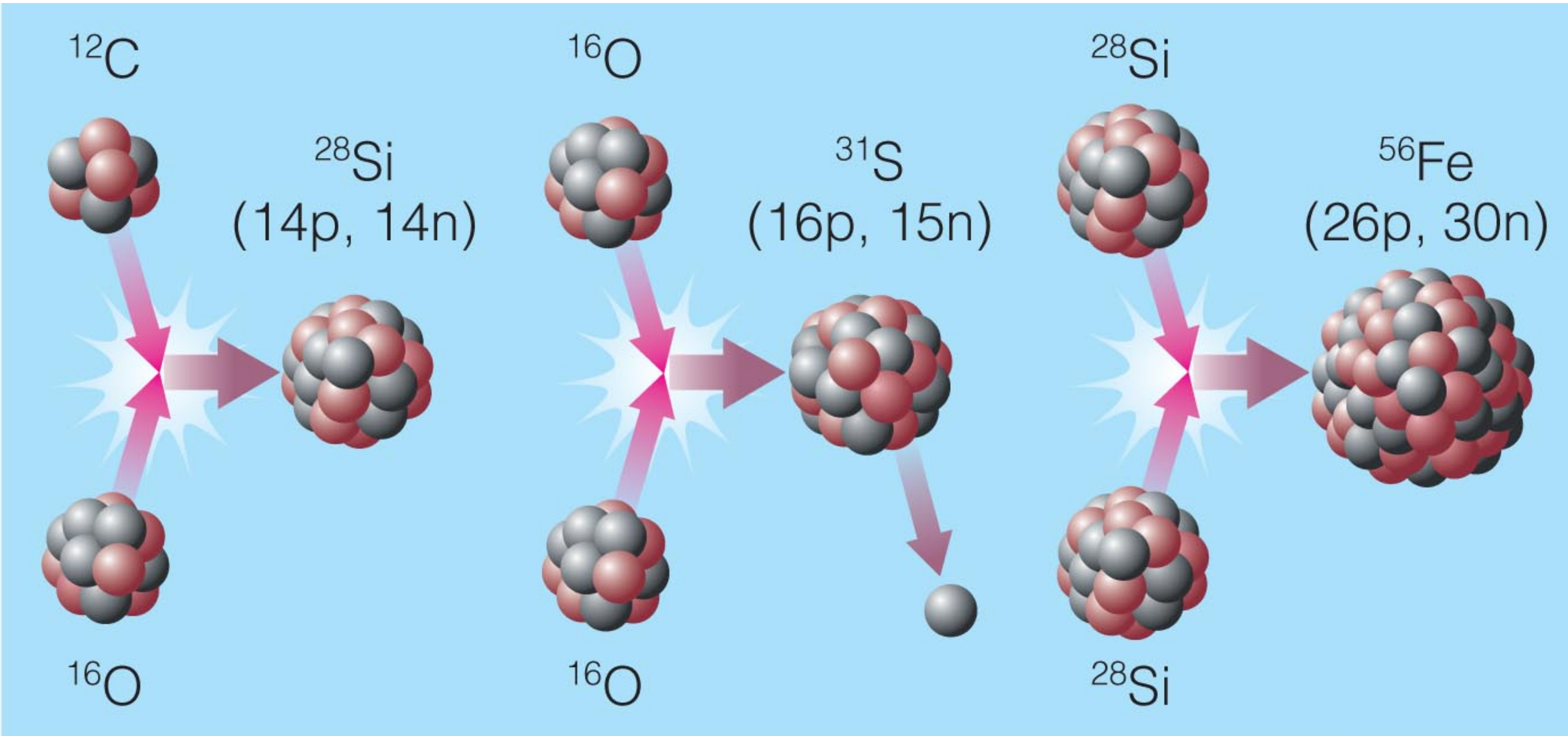


- High core temperatures allow helium to fuse with heavier elements.

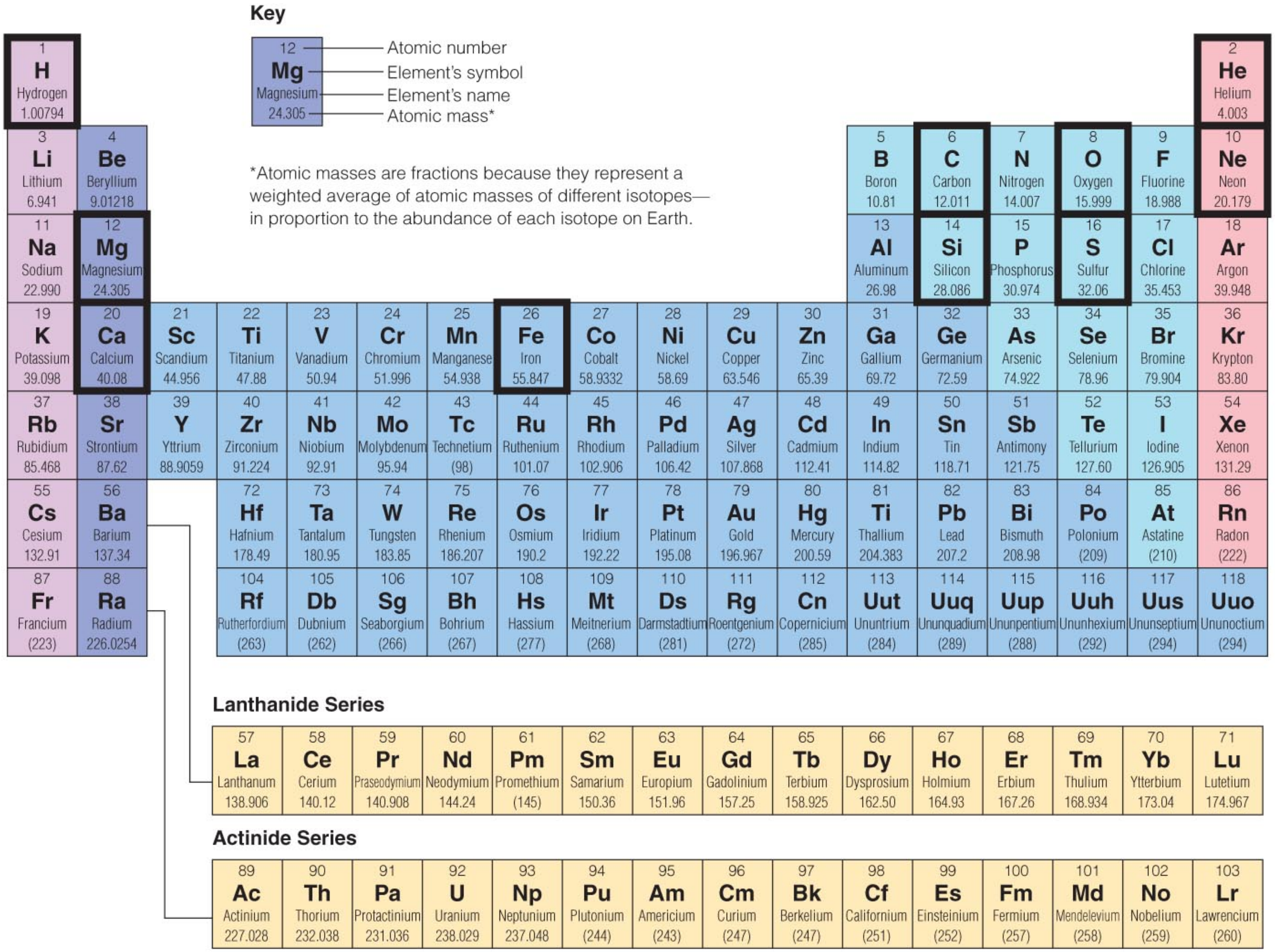


- Helium capture builds carbon into oxygen, neon, magnesium, and other elements.

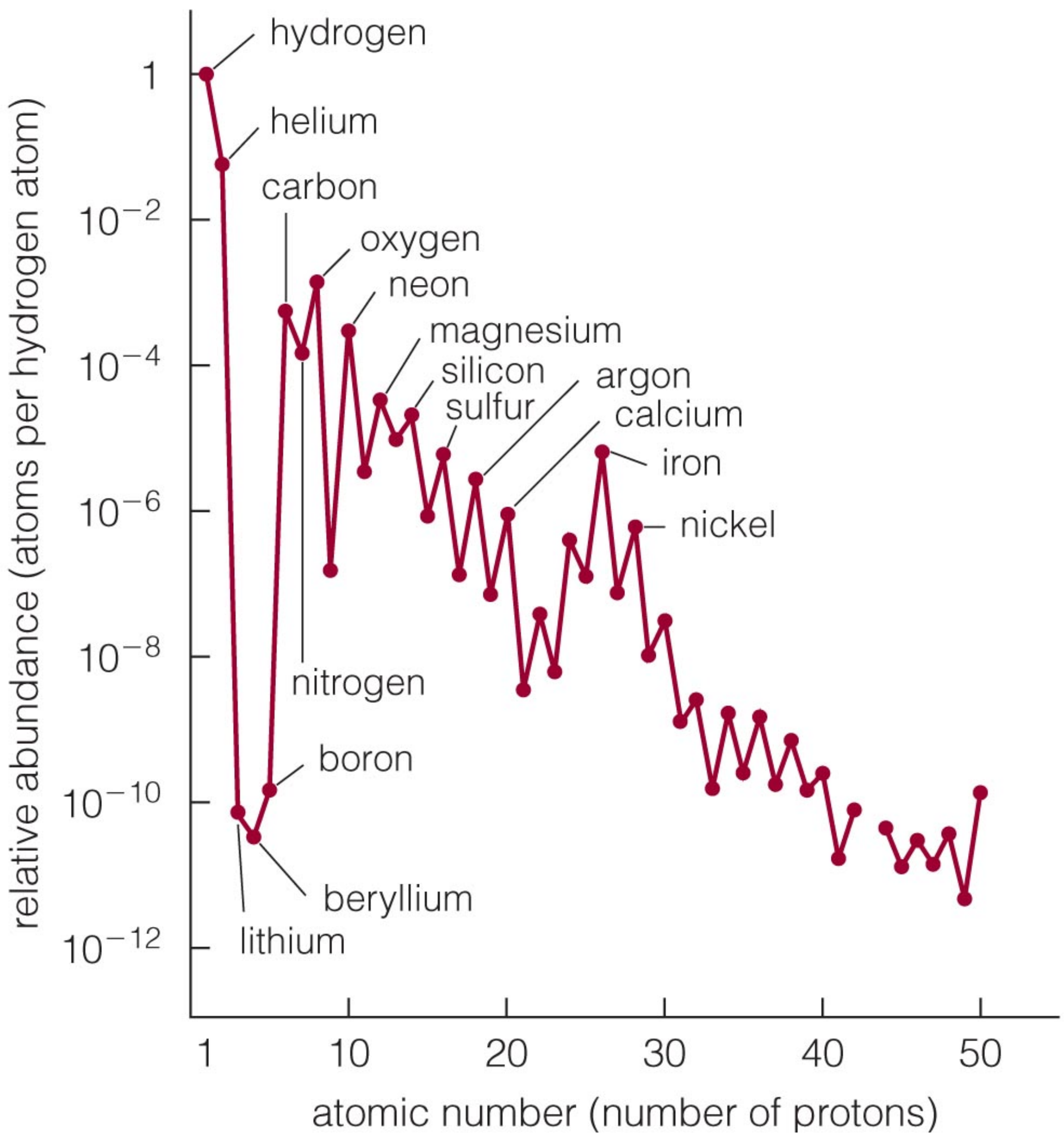
Advanced Nuclear Burning



- Core temperatures in stars $> 8\ M_\odot$ allow fusion to elements as heavy as iron.

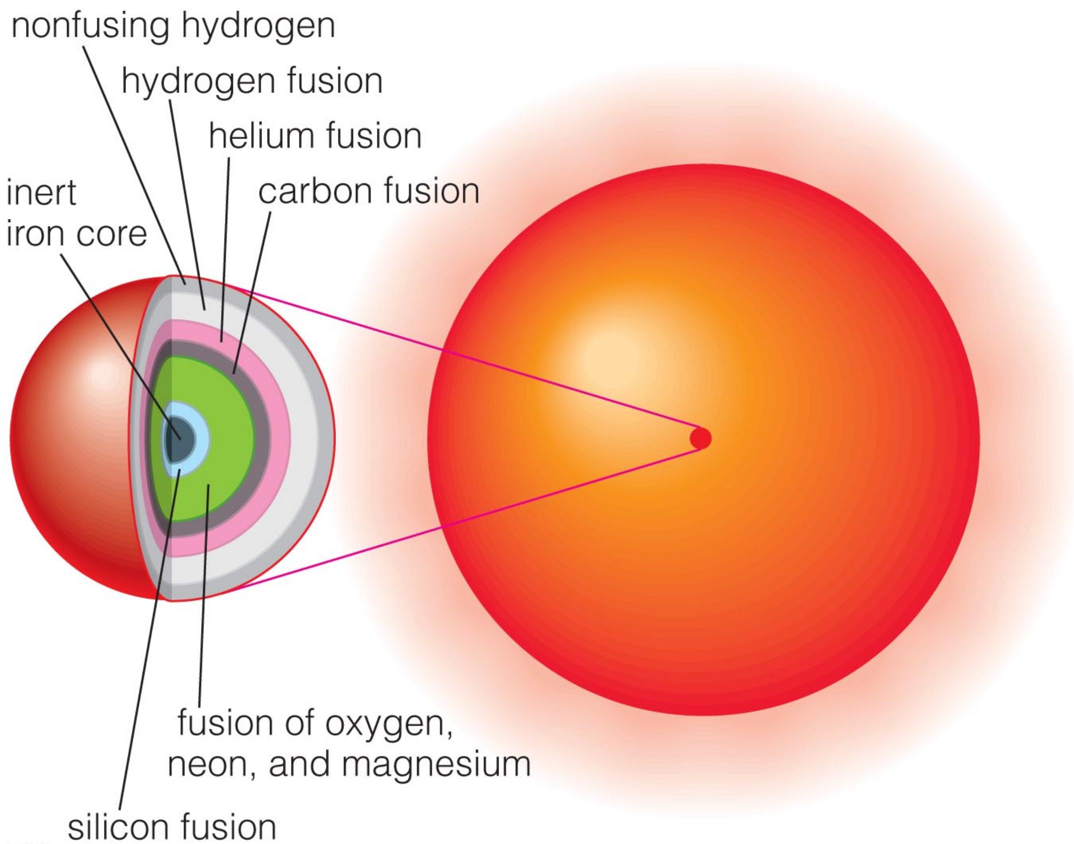


- Advanced reactions in stars make elements like silicon, sulfur, calcium, and iron.

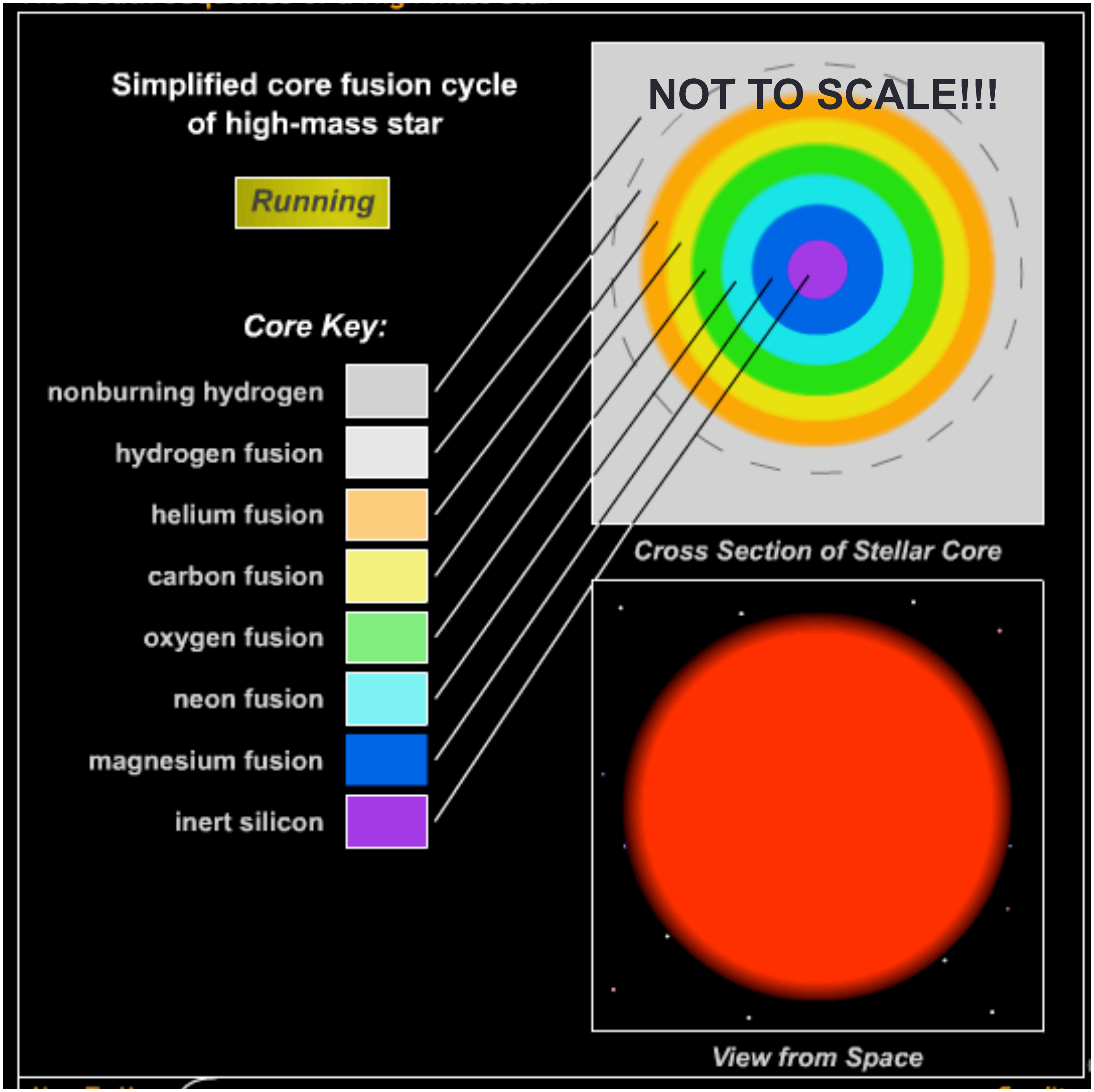


- Evidence for He capture: higher abundances of elements with even numbers of protons.

Multiple Shell Burning



- Advanced nuclear burning proceeds in a series of nested shells.



- Iron builds up in core until degeneracy pressure can no longer resist gravity.
- The core then suddenly collapses, creating a *supernova* explosion.

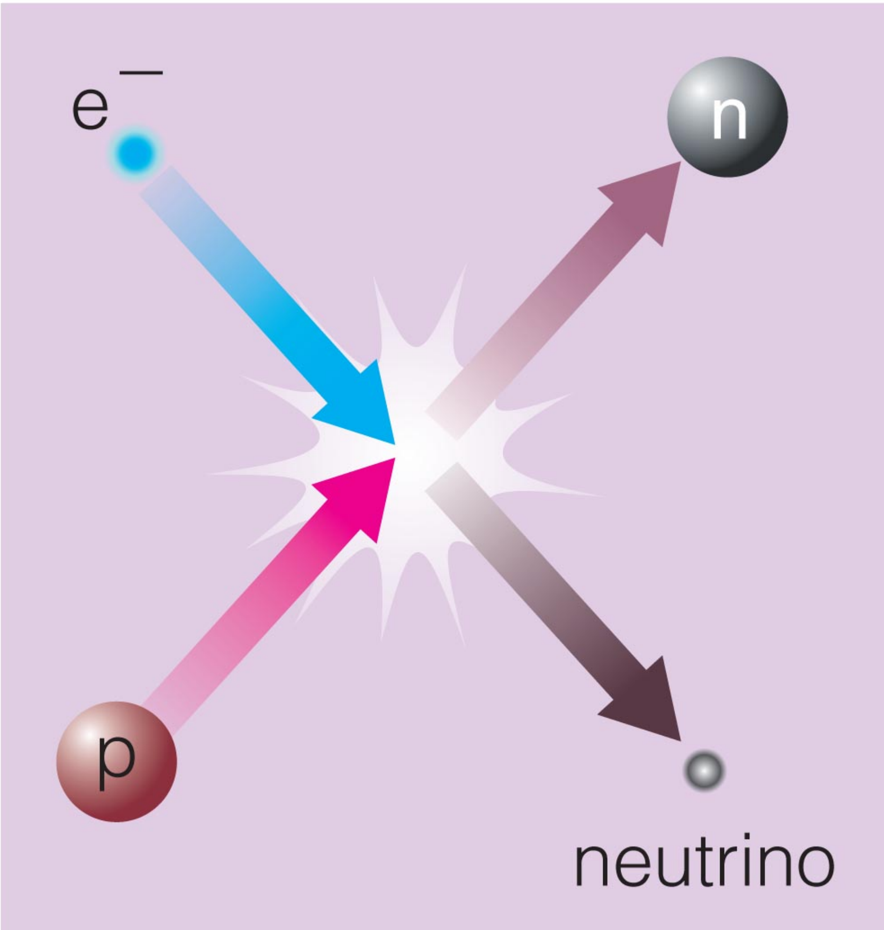
Table 20-1 Evolutionary Stages of a 25-$M_\odot$ Star

Stage	Core temperature (K)	Core density (kg/m^3)	Duration of stage
Hydrogen fusion	4×10^7	5×10^3	7×10^6 years
Helium fusion	2×10^8	7×10^5	7×10^5 years
Carbon fusion	6×10^8	2×10^8	600 years
Neon fusion	1.2×10^9	4×10^9	1 year
Oxygen fusion	1.5×10^9	10^{10}	6 months
Silicon fusion	2.7×10^9	3×10^{10}	1 day
Core collapse	5.4×10^9	3×10^{12}	$^1/_4$ second
Core bounce	2.3×10^{10}	4×10^{15}	milliseconds
Explosive (supernova)	about 10^9	varies	10 seconds

Based on calculations by Stanford Woosley (University of California, Santa Cruz) and Thomas Weaver (Lawrence Livermore National Laboratory).

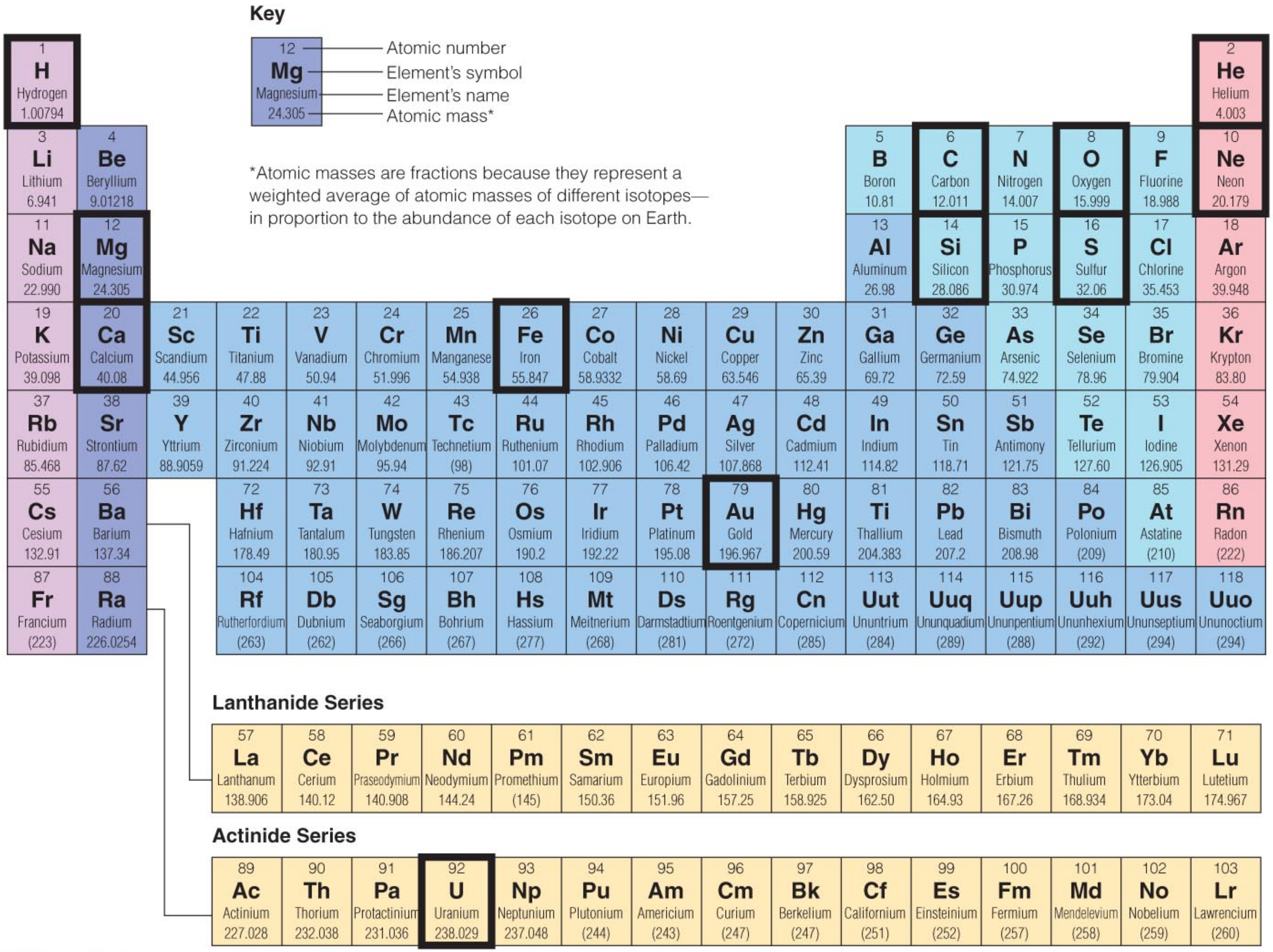
Supernova Simulation

Supernova Explosion



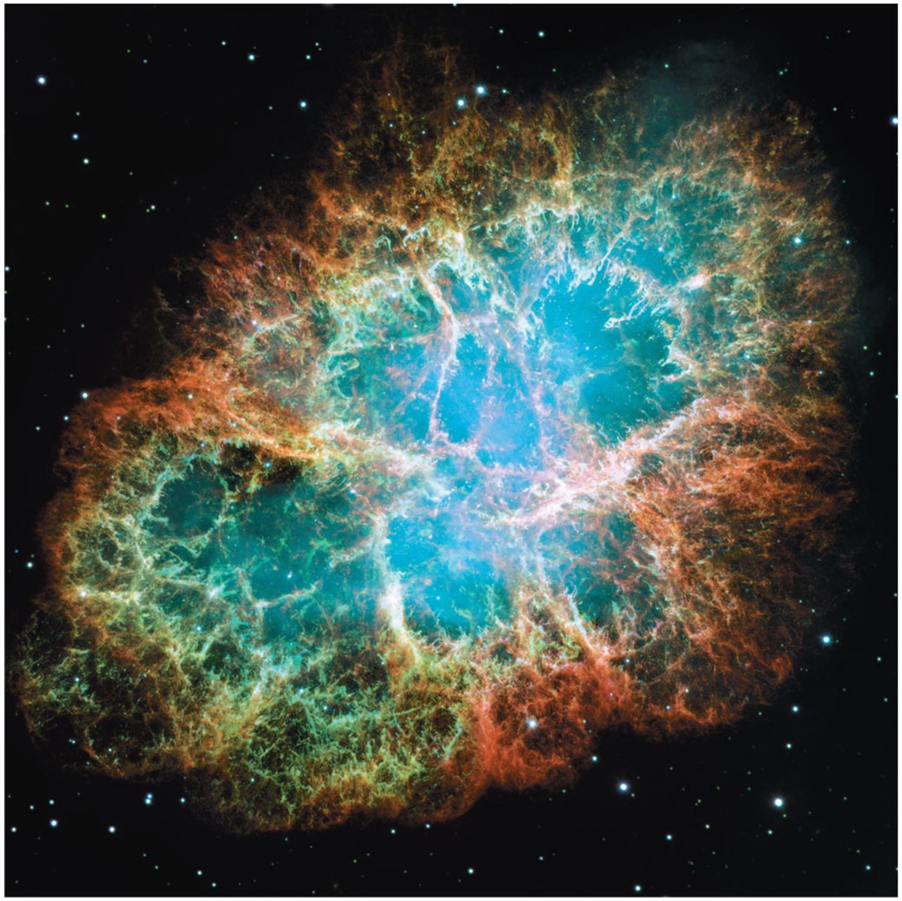
- Core degeneracy pressure goes away because electrons combine with protons, making neutrons and neutrinos.

- Neutrons collapse to the center, forming a **neutron star**.

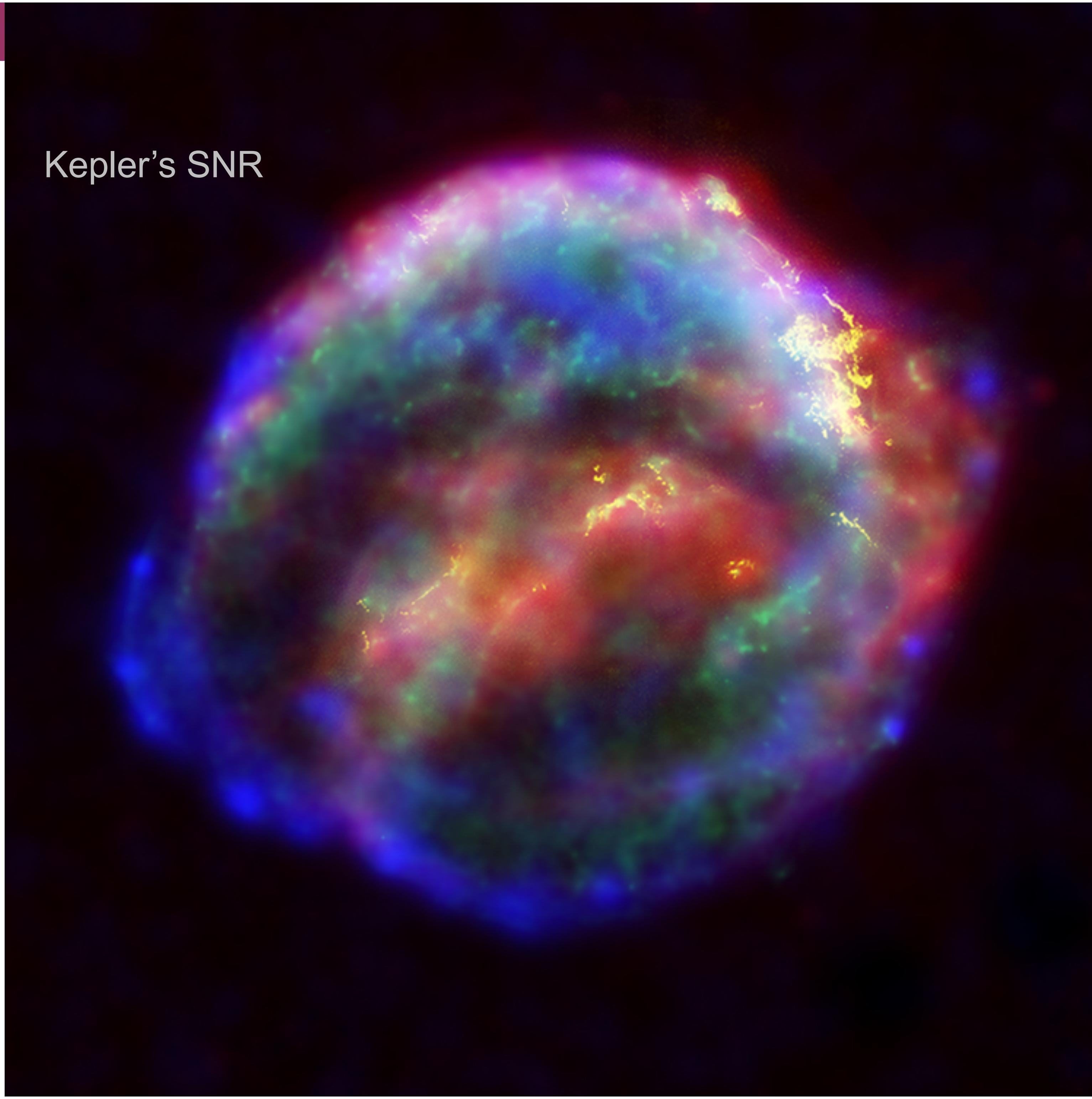


- Energy and neutrons released in supernova explosion enable elements heavier than iron to form, including gold and uranium. But again, many of those elements formed in NS-NS inspiral...

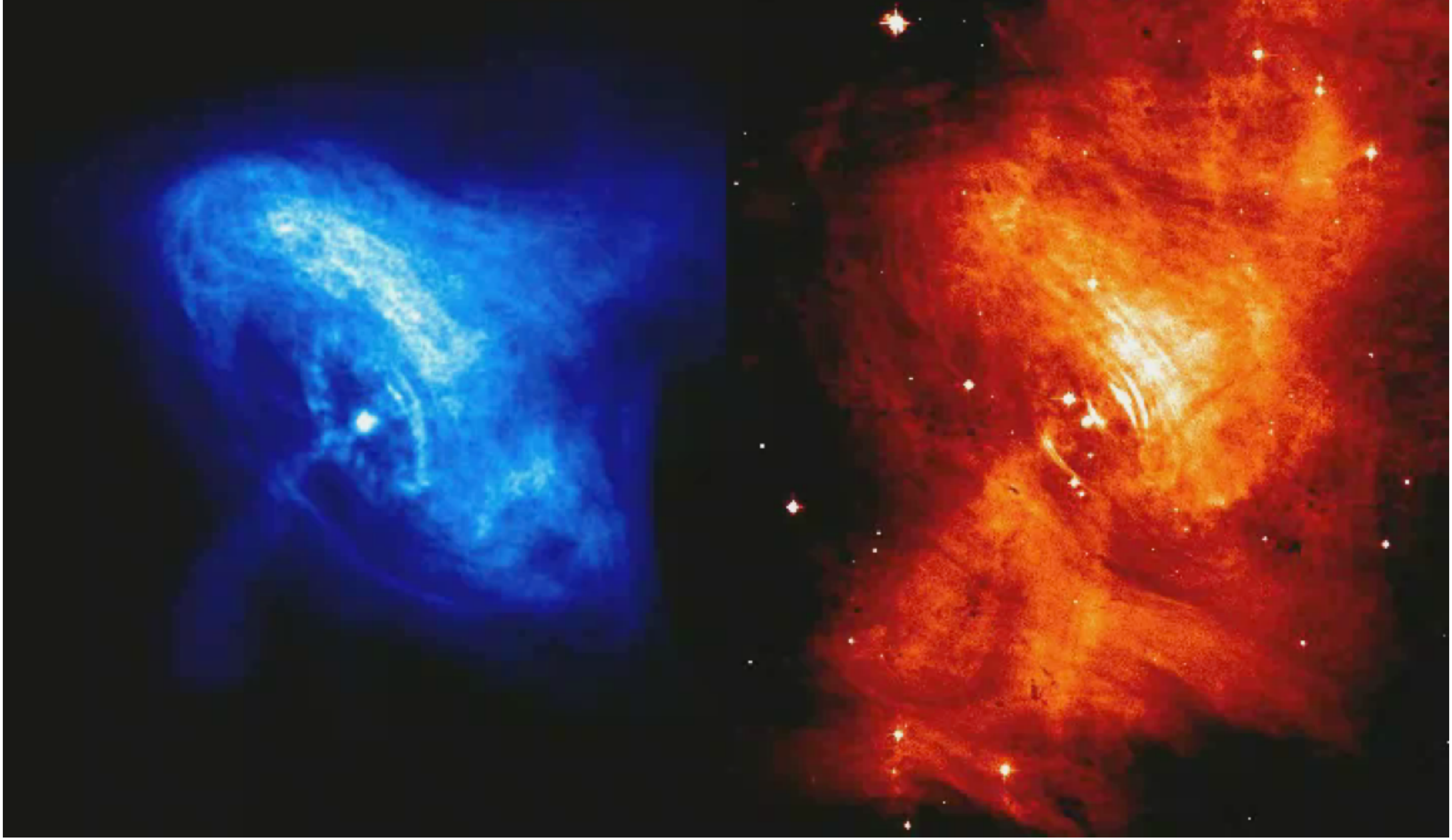
Supernova Remnant



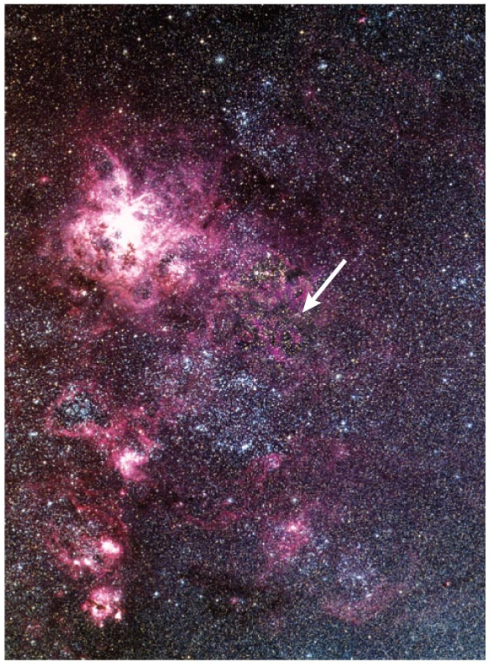
- Energy released by the collapse of the core drives the star's outer layers into space.
- The Crab Nebula is the remnant of the supernova seen in A.D. 1054.


Kepler's SNR

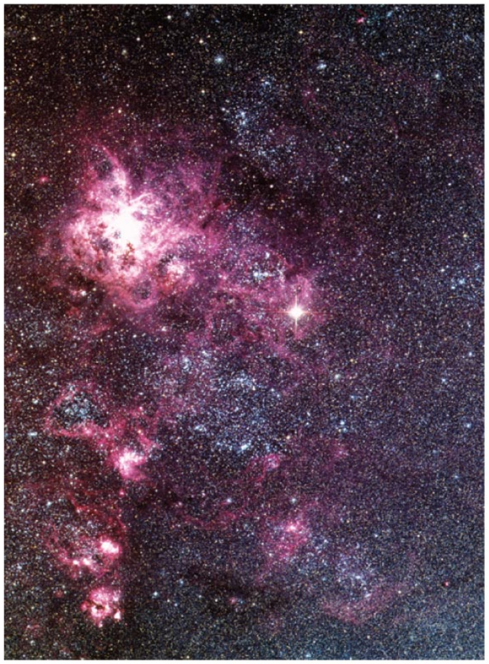
Crab Nebula



Supernova 1987A



Before. The arrow points to the star observed to explode in 1987.



After. The supernova actually appeared as a bright point of light. It appears larger than a point in this photograph only because of overexposure.

- The closest supernova in the last four centuries was seen in 1987.