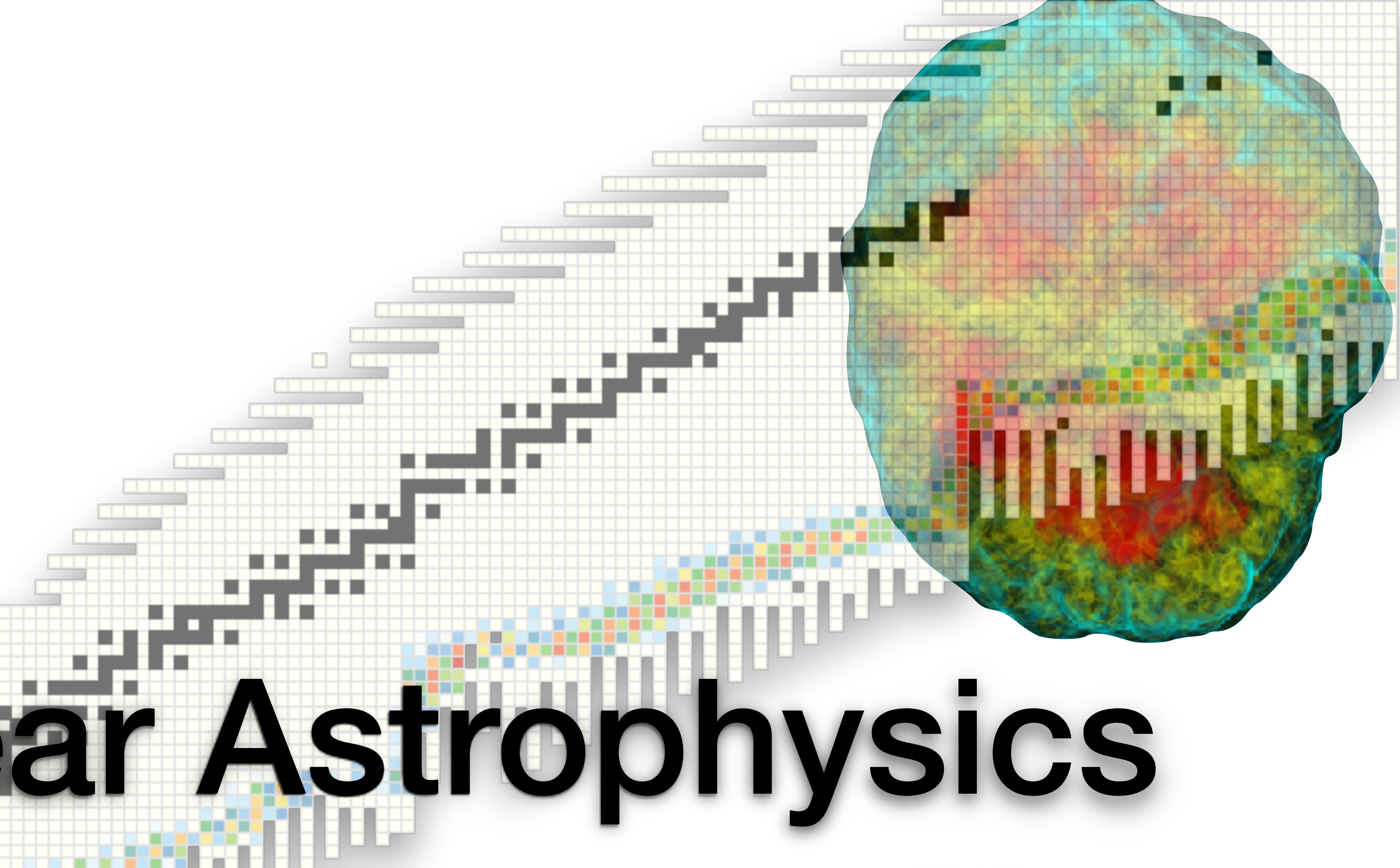
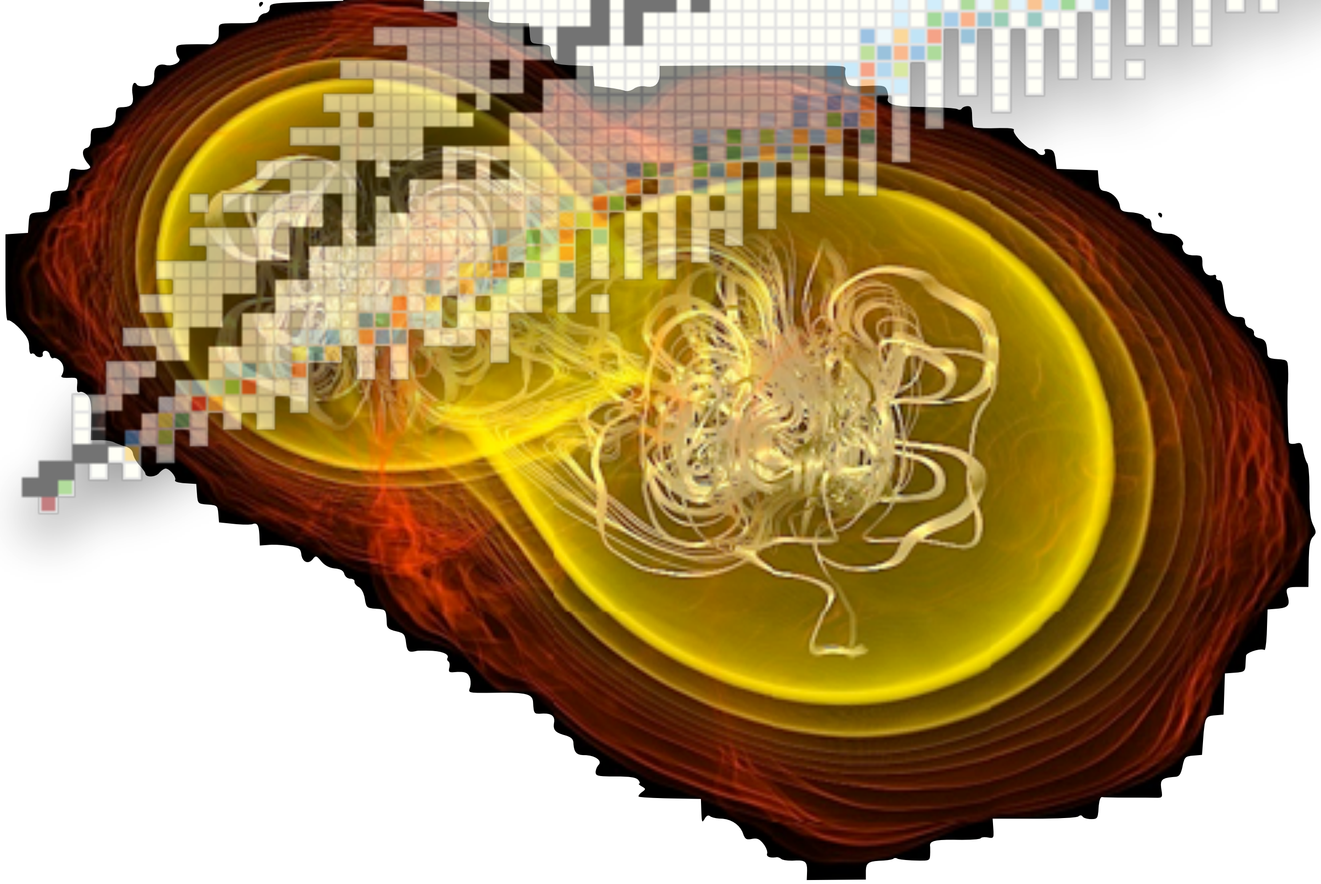
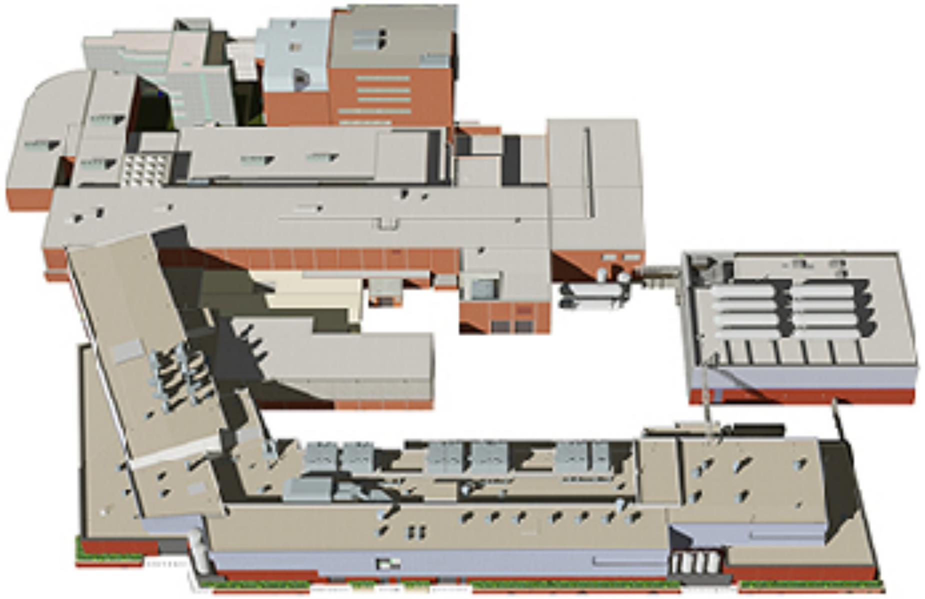


Nuclear Astrophysics





Luke Roberts, NSCL

The Central Question of Nuclear Astrophysics:

How did the stuff our solar system and humans are made of come to be?

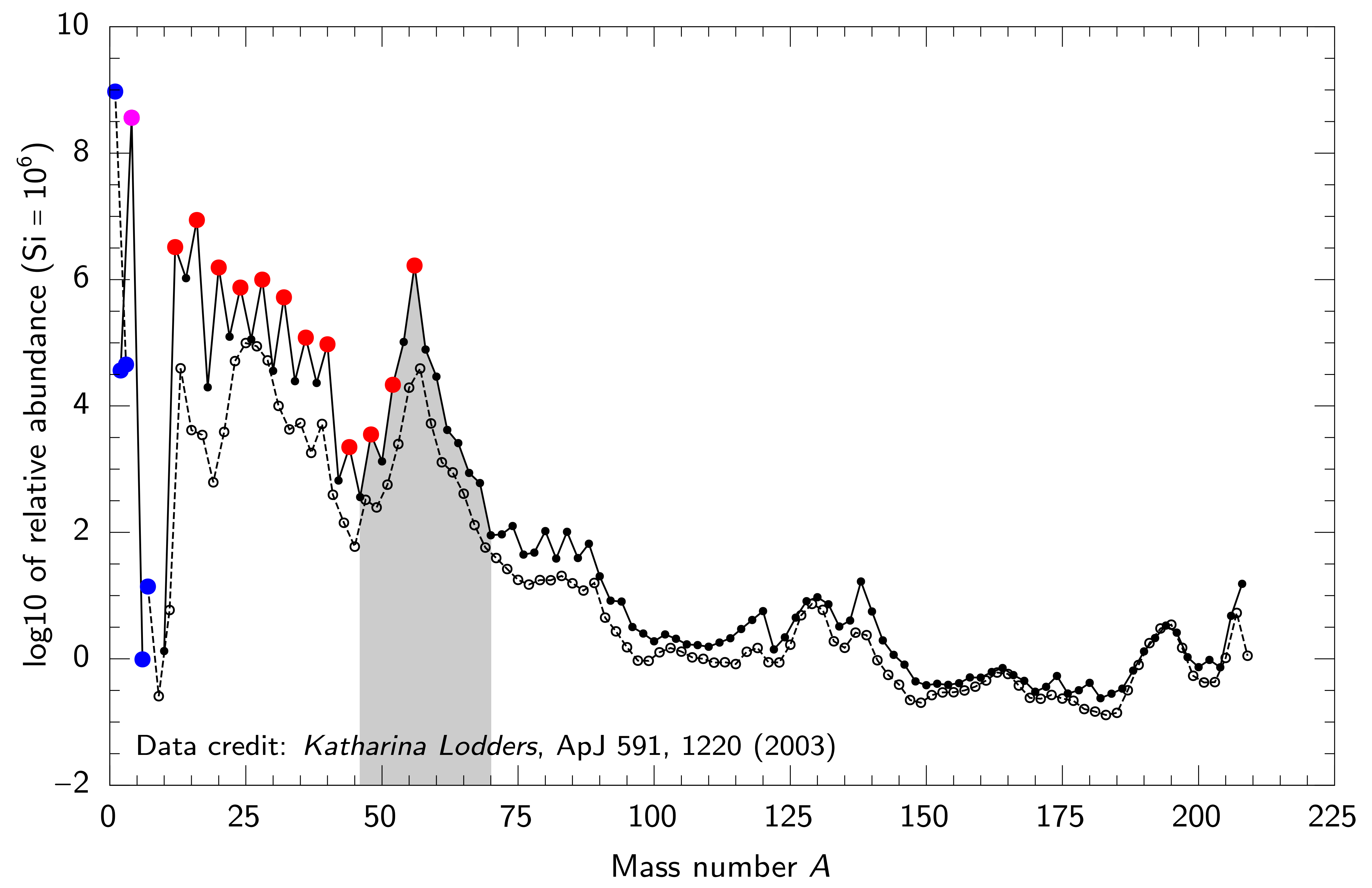
The Central Question of Nuclear Astrophysics:

How did the stuff our solar system and humans are made of come to be?

Also:

- **How do the stars shine?**
- **How do stars explode?**
- **What are neutron stars?**
- **…**

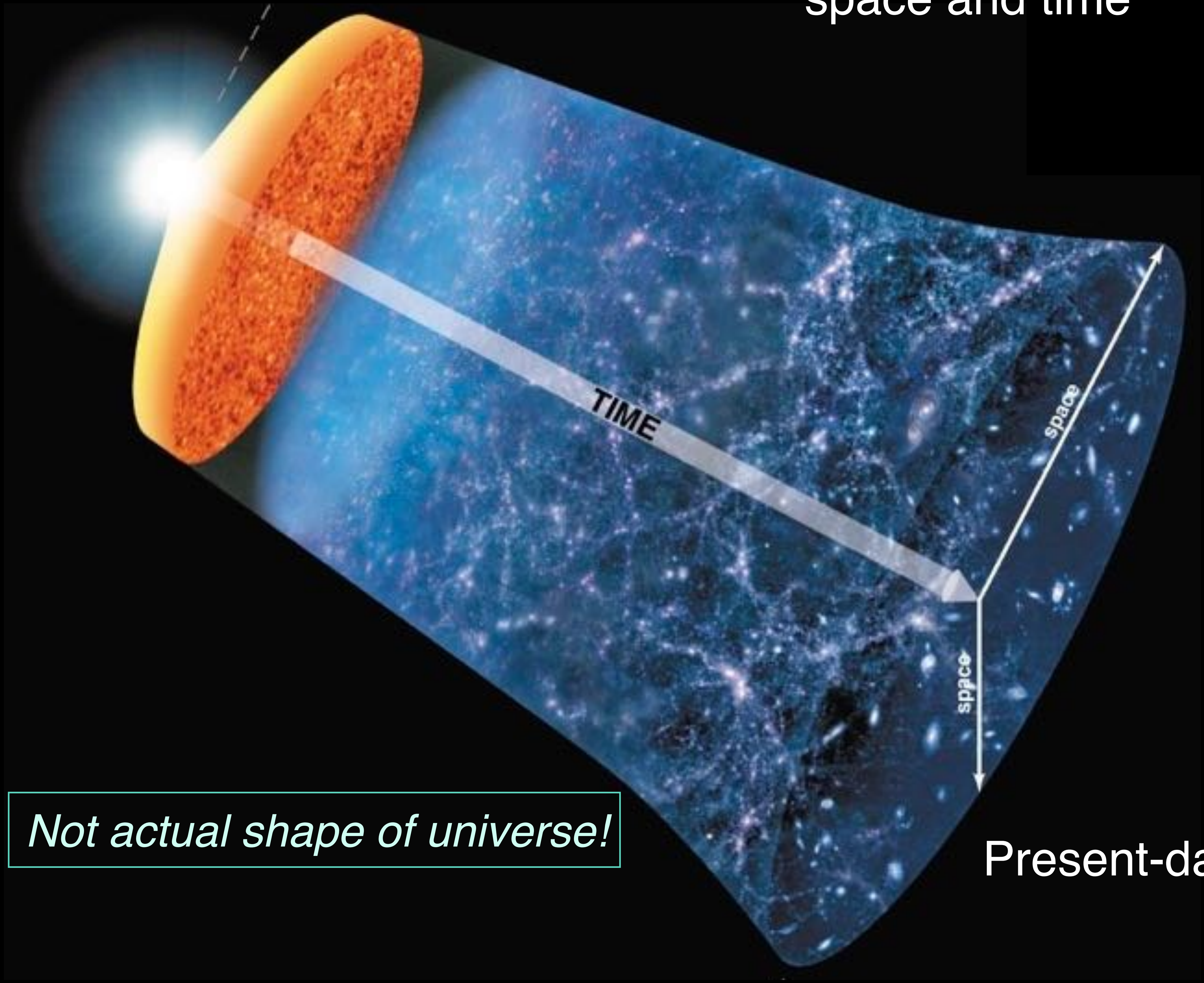
The abundances of isotopes in our solar system



Data credit: *Katharina Lodders*, ApJ 591, 1220 (2003)

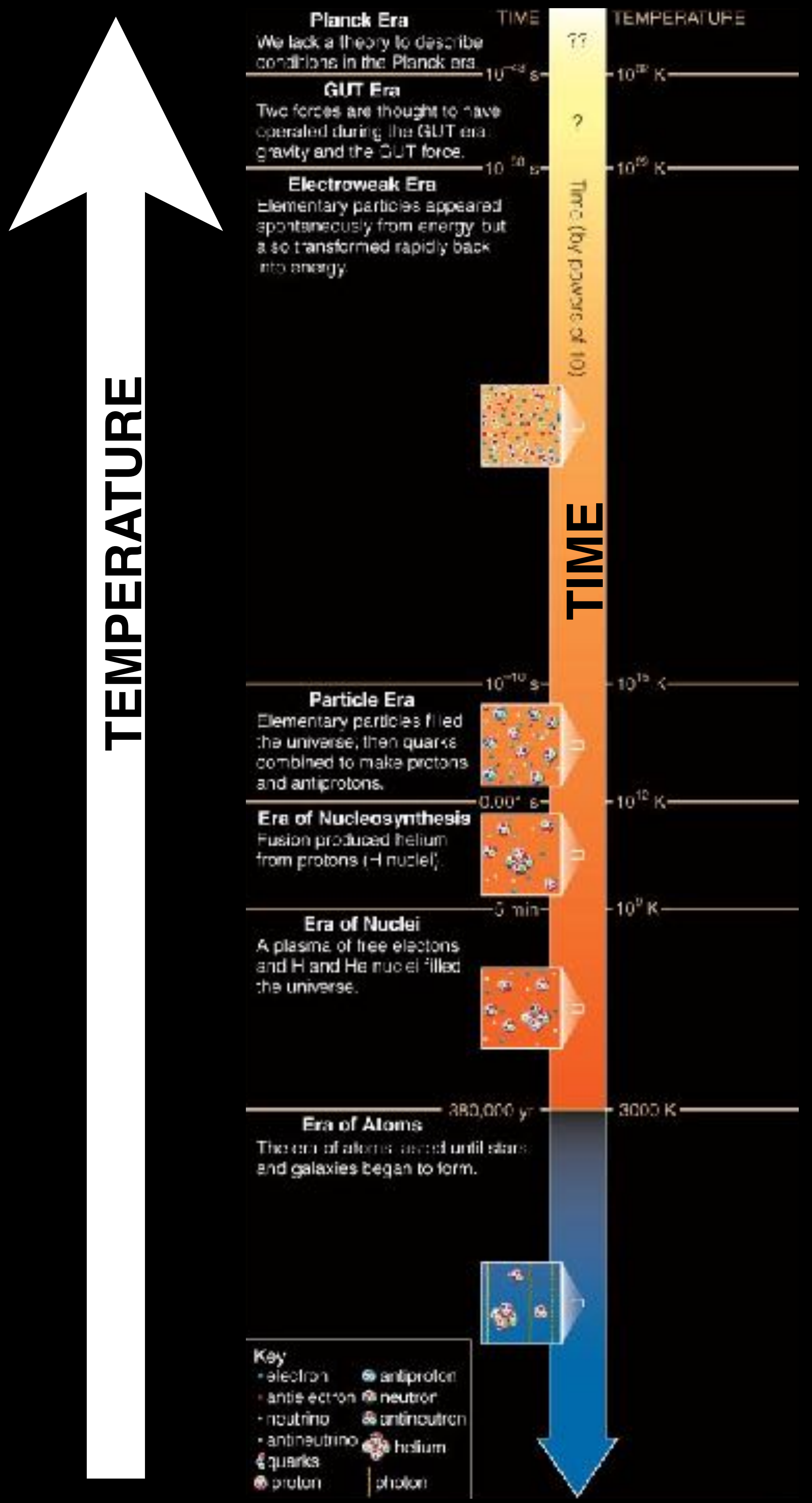
Moment of Big Bang

Schematic diagram showing development of the universe in space and time



Not actual shape of universe!

Present-day



TEMPERATURE

TIME

Planck Era
We lack a theory to describe conditions in the Planck era.

GUT Era
Two forces are thought to have operated during the GUT era: gravity and the GUT force.

Electroweak Era
Elementary particles appeared spontaneously from energy but also transformed rapidly back into energy.

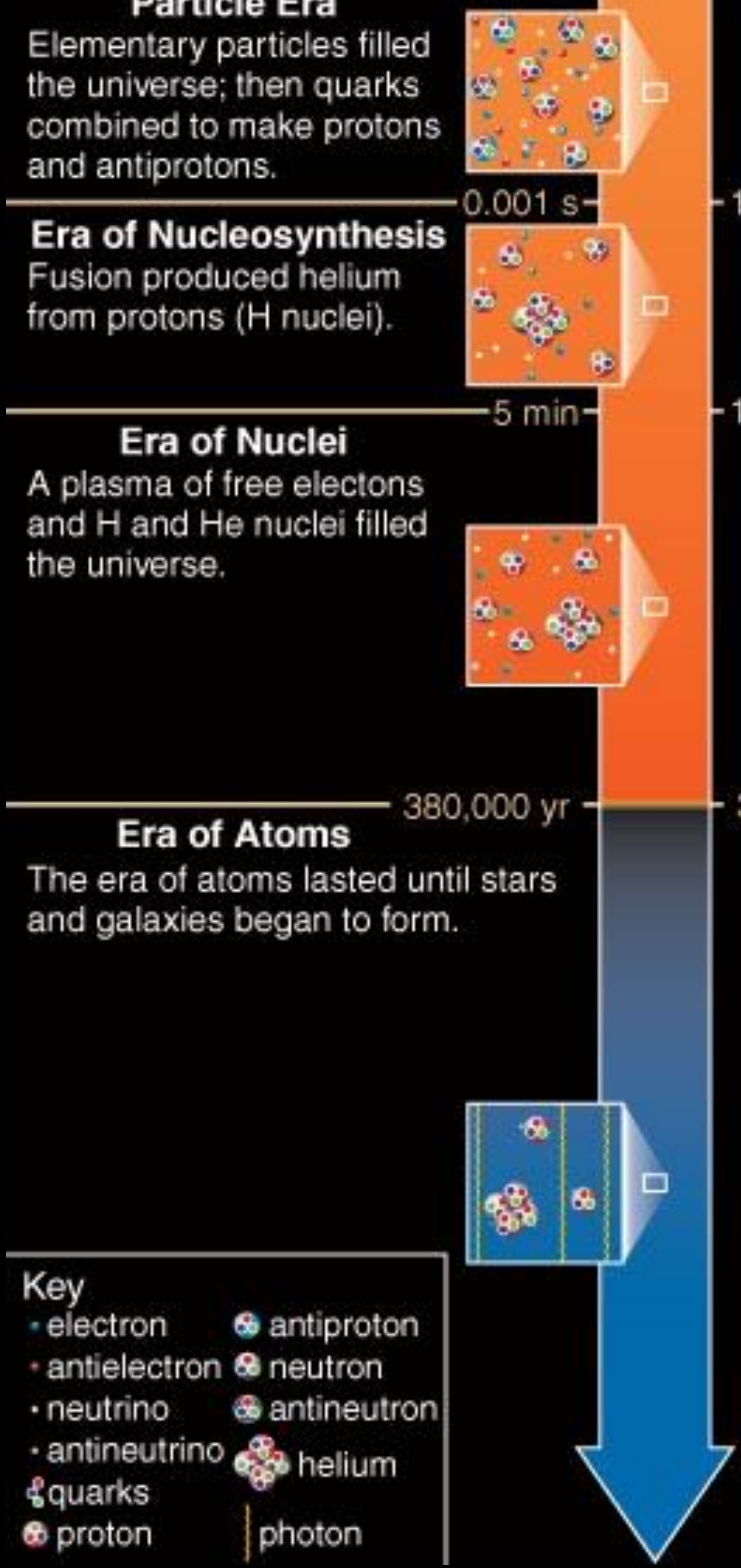
Particle Era
Elementary particles filled the universe, then quarks combined to make protons and antiprotons.

Era of Nucleosynthesis
Fusion produced helium from protons (H nuclei).

Era of Nuclei
A plasma of free electrons and H and He nuclei filled the universe.

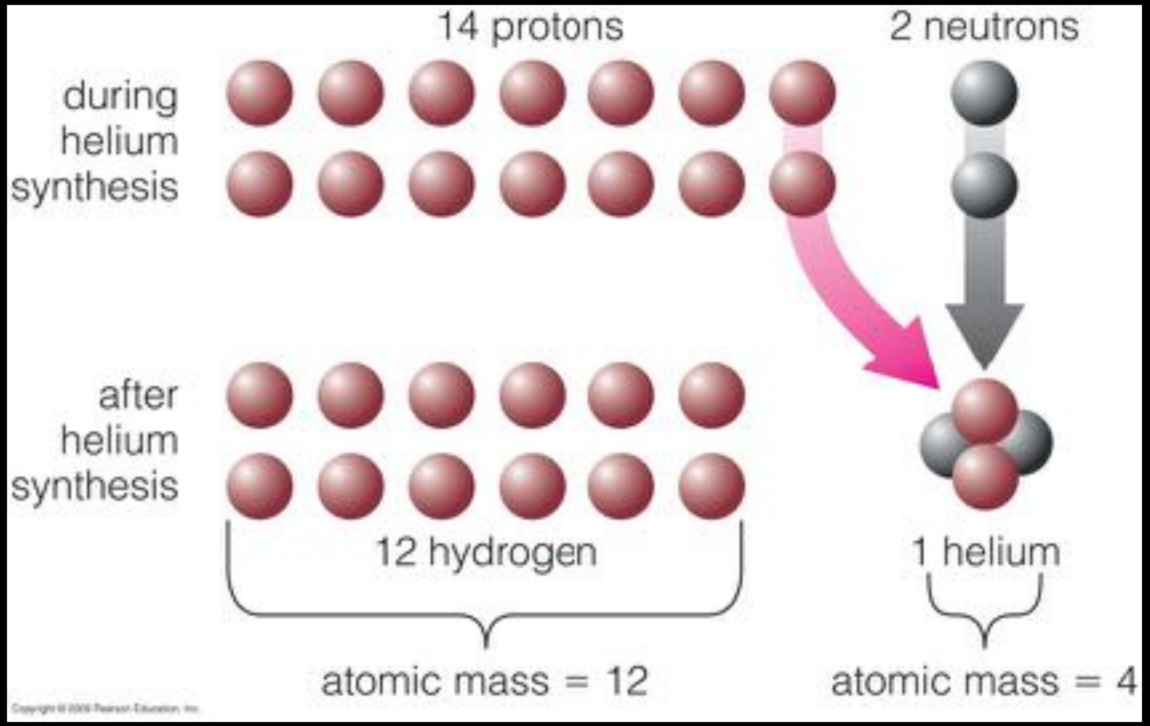
Era of Atoms
The era of atoms lasted until stars and galaxies began to form.

Era of Nucleosynthesis



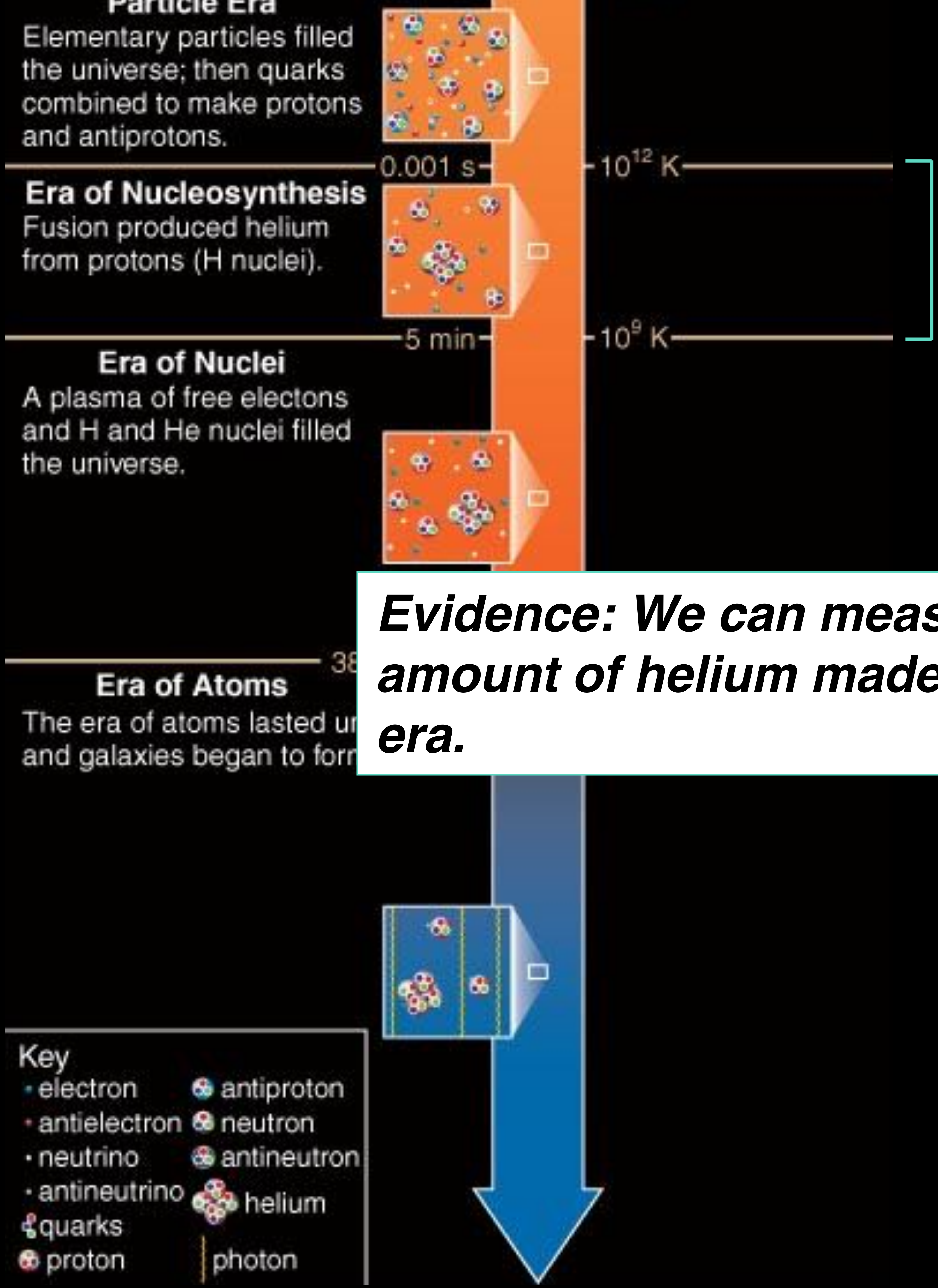
Began ~0.001 second after Big Bang when universe became too cool to produce protons and neutrons

Cooling allowed protons and neutrons to fuse into long-lasting He

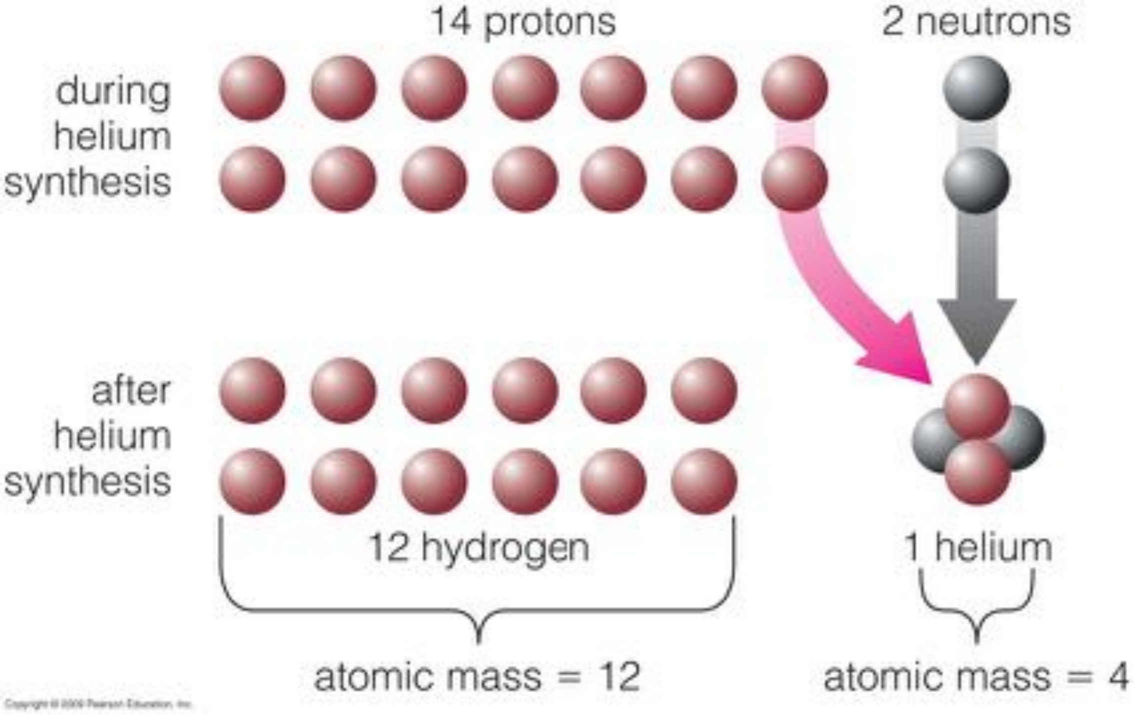


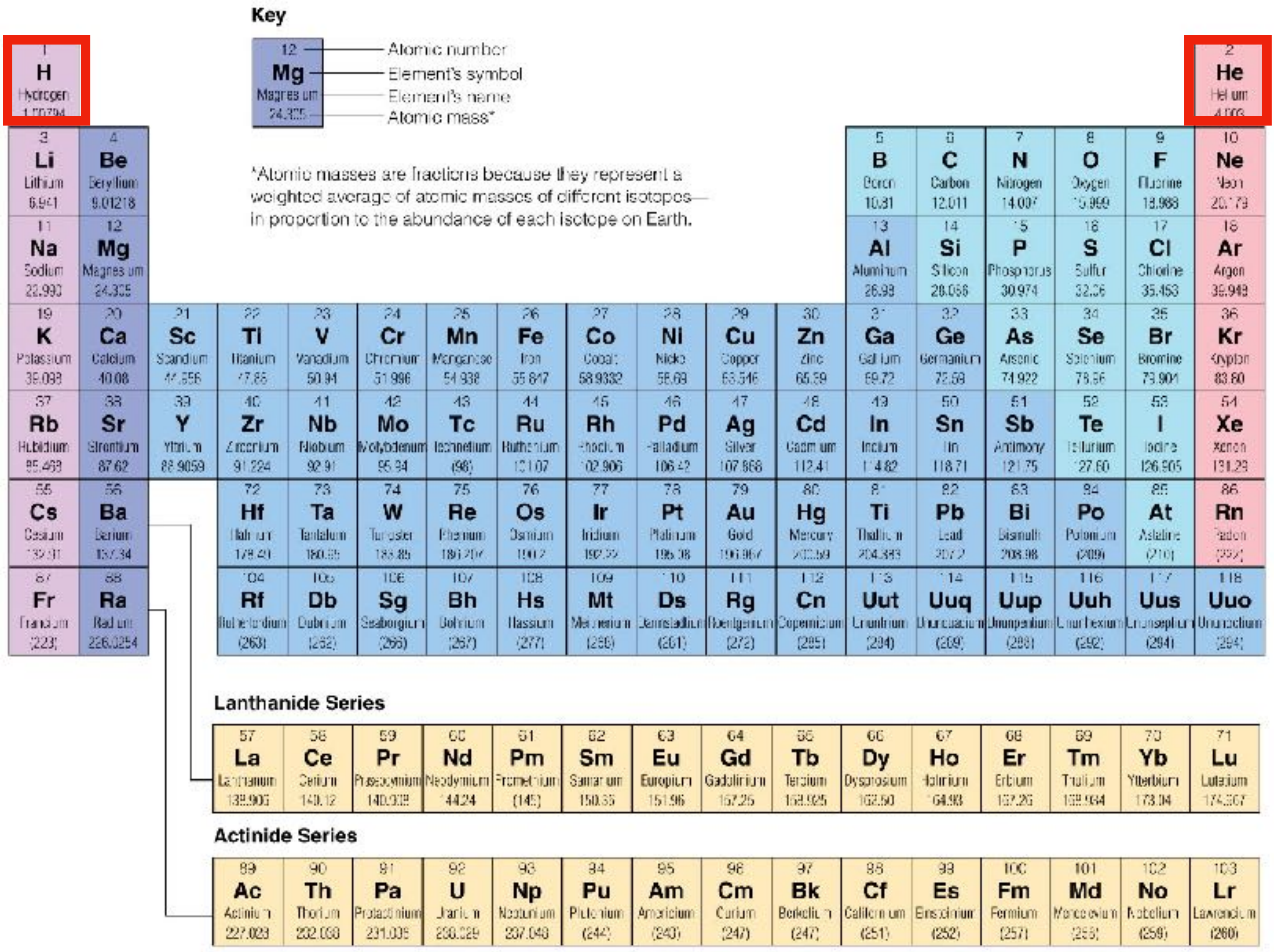
Era of Nucleosynthesis

Most of the helium now in the universe was made during this era.



Evidence: We can measure the amount of helium made during this era.





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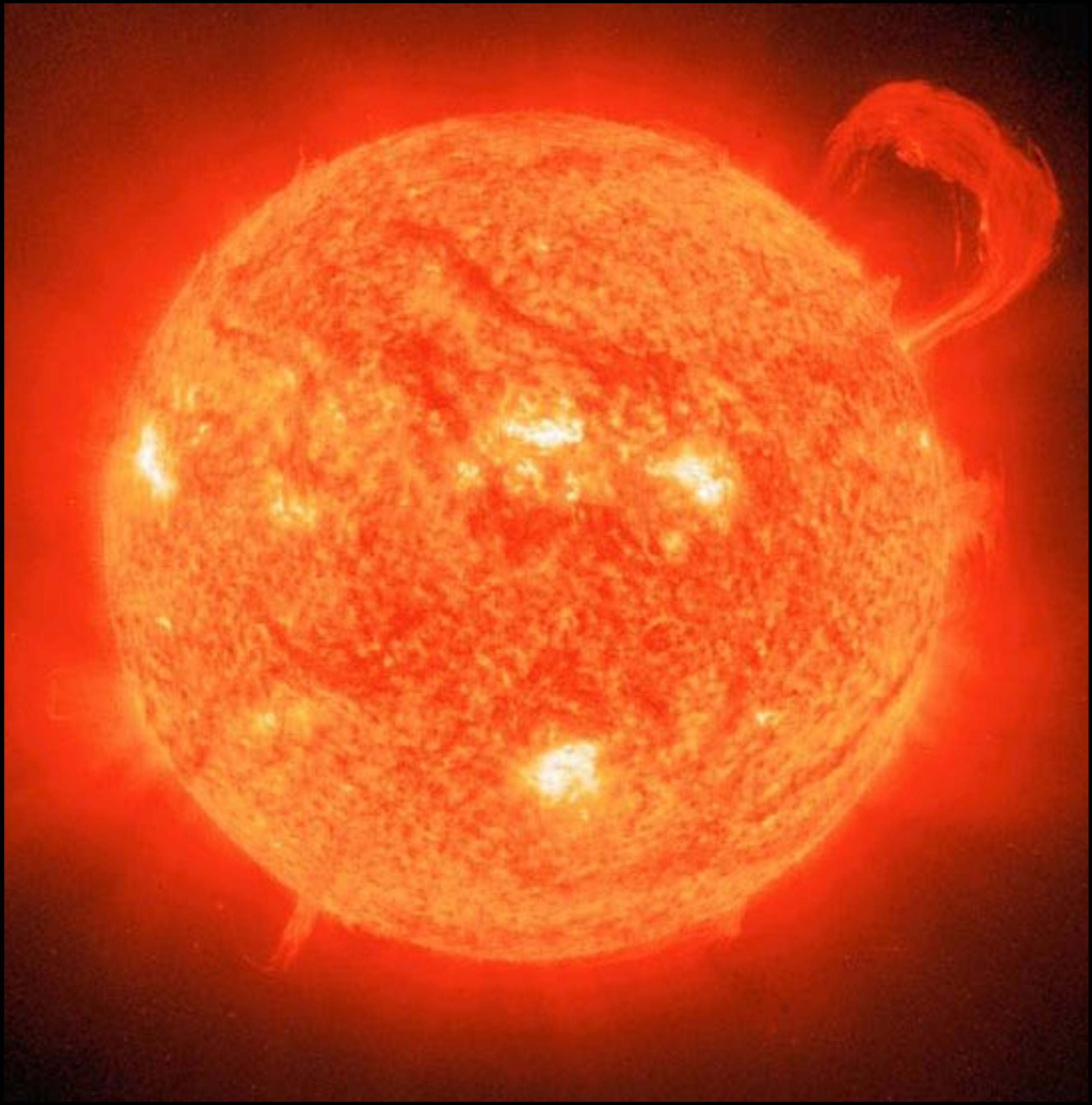
Big Bang made 75% H, 25% He.

First, lets think about how stars shine



The Sun

***Radius*:**

6.9 x 10^8 m

(109 times Earth)

Mass:

2 x 10^{30} kg

(300,000 Earths)

Luminosity:

3.8 x 10^{26} watts

(3.8 x 10^{26} J/s)

$$\textbf{power} = \frac{\text{energy}}{\text{time}}$$

luminosity = power output in form of radiative energy

$$\textbf{Lifetime} = \frac{\text{Total Energy Stored}}{\text{luminosity}}$$

Sun’s Energy Content

Chem. energy = 4 x 10^{38} J (~ 30,000 yr)

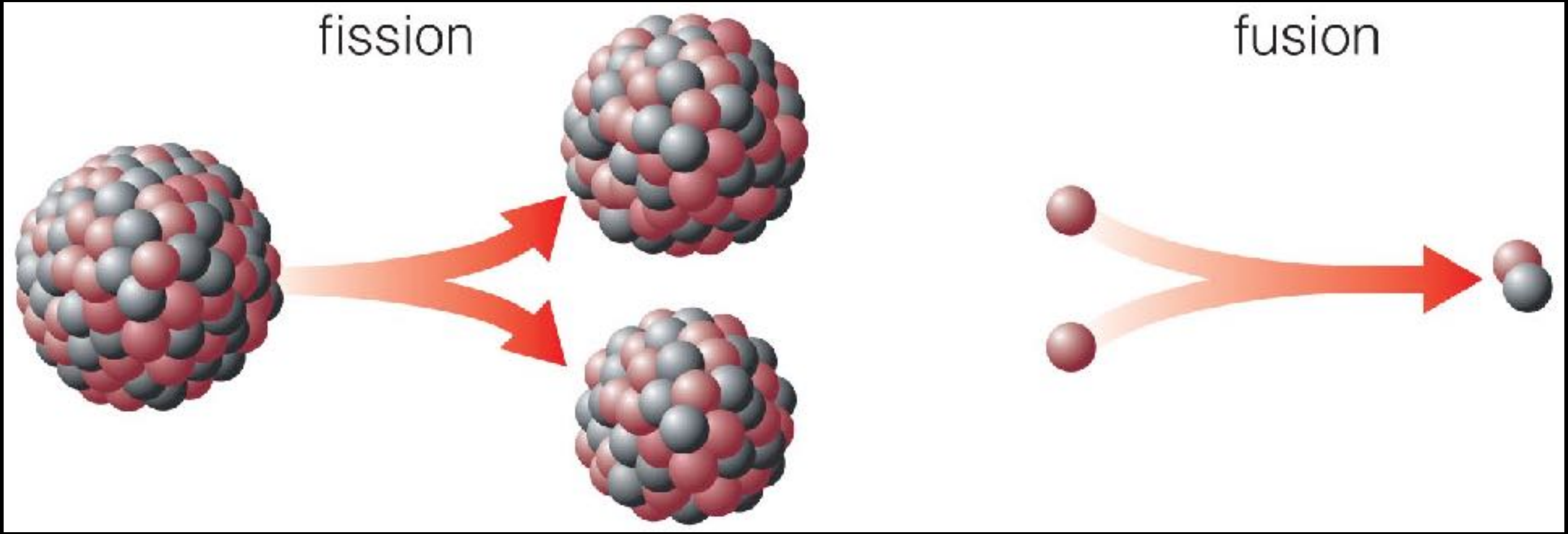
Grav. energy = 4 x 10^{41} J (~ 30 million yr)

Nuclear energy = 1 x 10^{45} J (~ 100 billion yr)*

Mass-energy = 2 x 10^{47} J (~ 10 trillion yr)

The sun can live in an unchanging state for about 10 billion years burning hydrogen to helium in its core. Currently, the sun is about 5 billion years old. This burning is not so interesting for nucleosynthesis since it is only producing already abundant helium.

*Only about 10% will be used



Fission

Big nucleus splits into smaller pieces.

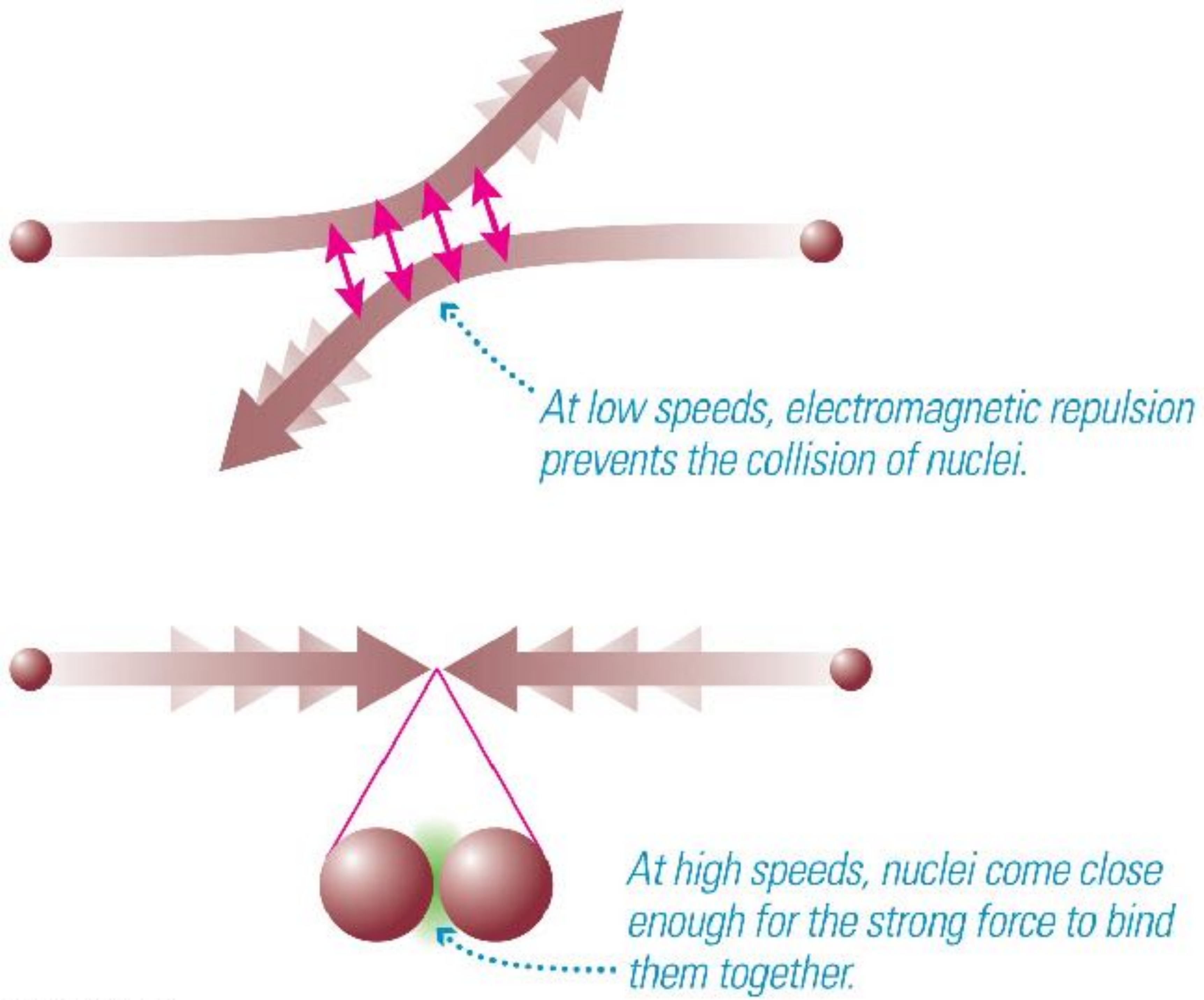
(Nuclear power plants)

Fusion

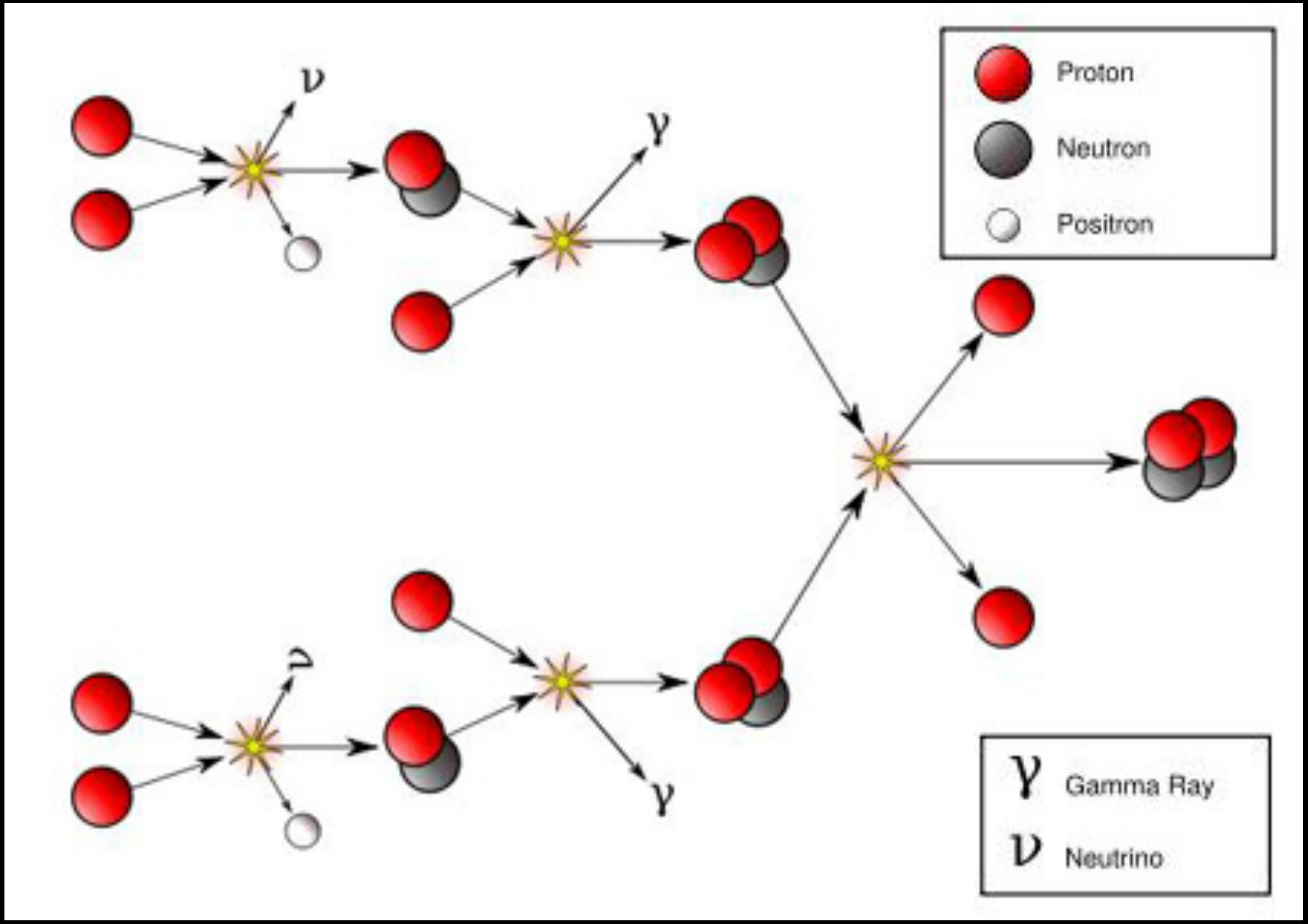
Small nuclei stick together to make a bigger one.

(Sun, stars)

In both cases, the mass of the initial system is more than the total mass of the final system, so energy is released.



High temperatures enable nuclear fusion to happen in the core of a star.

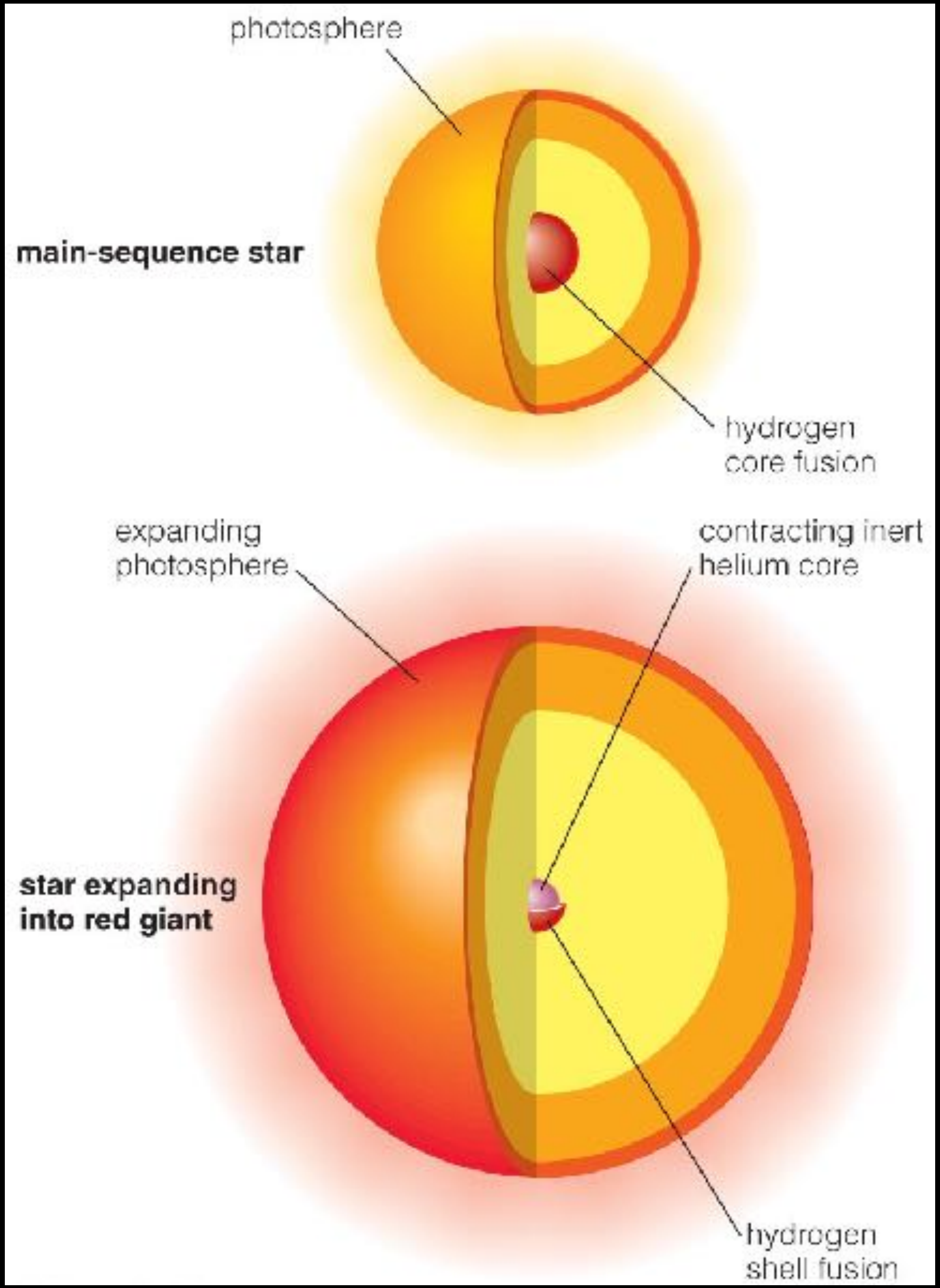


The Sun releases energy by fusing four hydrogen nuclei into one helium nucleus.

Total mass is 0.7% lower -> Energy Released

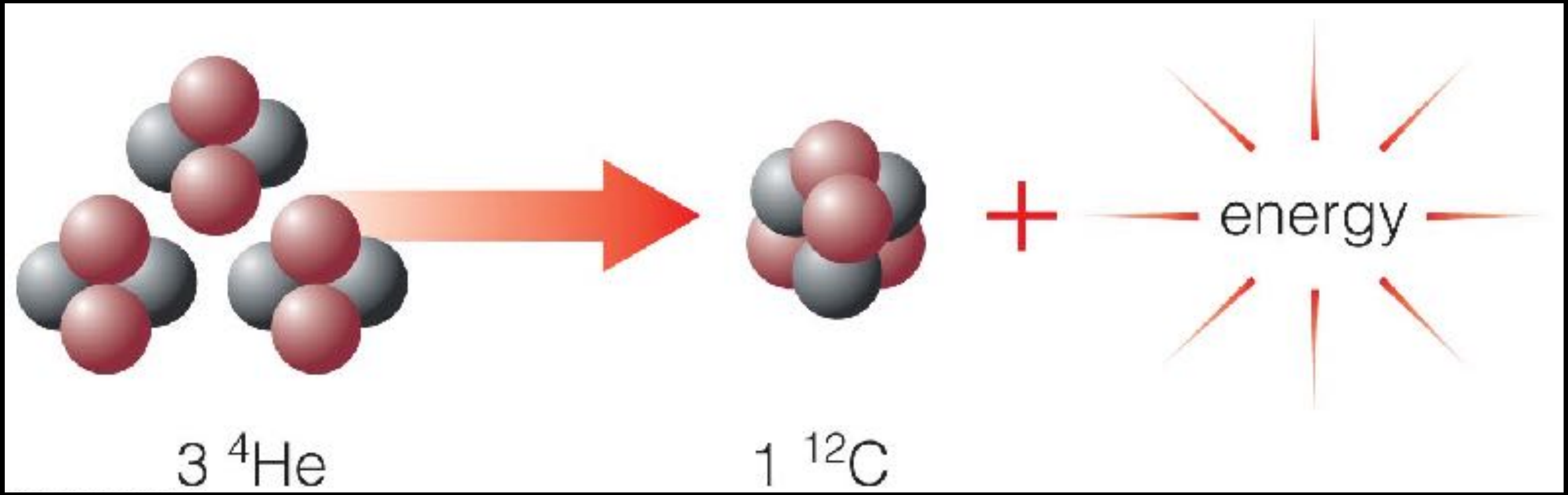
The ***Proton–proton chain*** is how hydrogen fuses into helium in the Sun. Figured out by Bethe 1937, Nobel prize in 1967.

What happens when the hydrogen runs out?



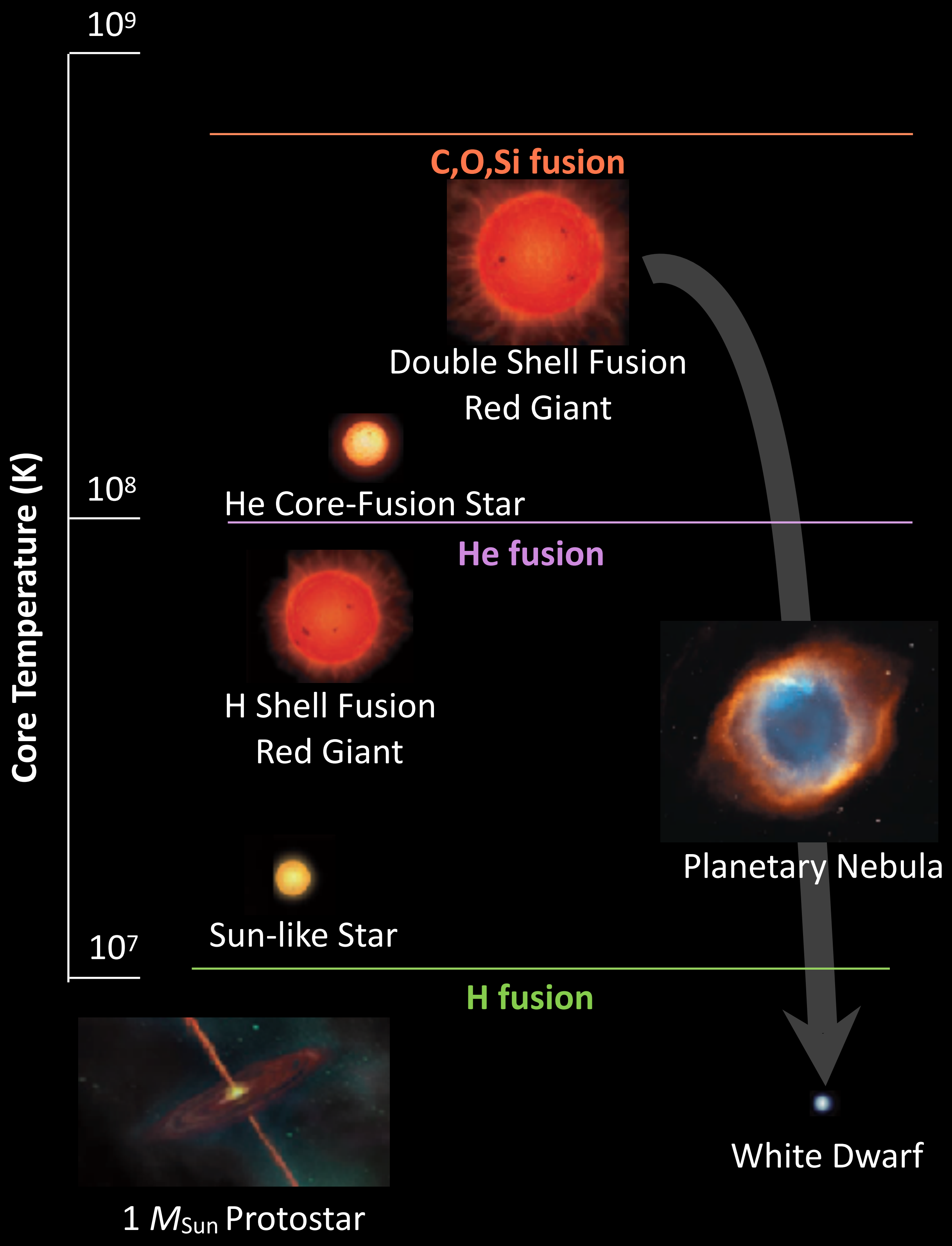
- No more energy is released from nuclear burning in the core, so core loses pressure support and begins to contract
- The core heats up due to contraction and eventually ignites a new fuel (and hydrogen burning may begin in a shell outside of the core)

What Happens When the Hydrogen Runs Out?



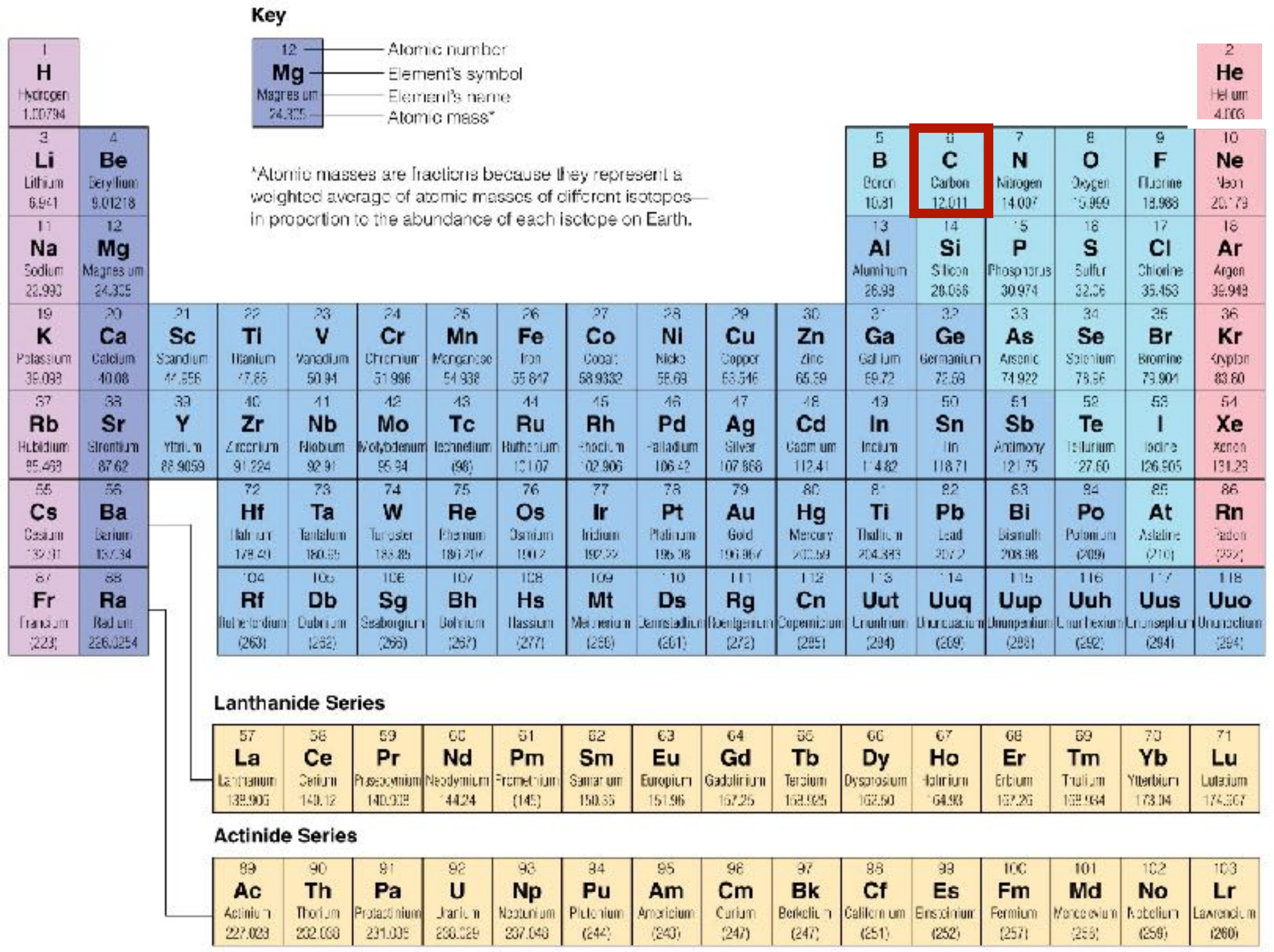
- Helium fusion does not begin right away because it requires higher temperatures than hydrogen fusion—larger charge leads to greater repulsion.
- The fusion of two helium nuclei doesn't work, so helium fusion must combine three He nuclei to make carbon.

Life Stages of a Low-Mass Star



Not to scale!

1. ***Main Sequence:*** H fuses to He in core.
2. ***Red Giant:*** H fuses to He in shell around He core.
3. ***Helium Core Fusion:*** He fuses to C in core while H fuses to He in shell
4. ***Double Shell Fusion:*** H and He both fuse in shell.
5. ***Planetary Nebula:*** leaves white dwarf behind



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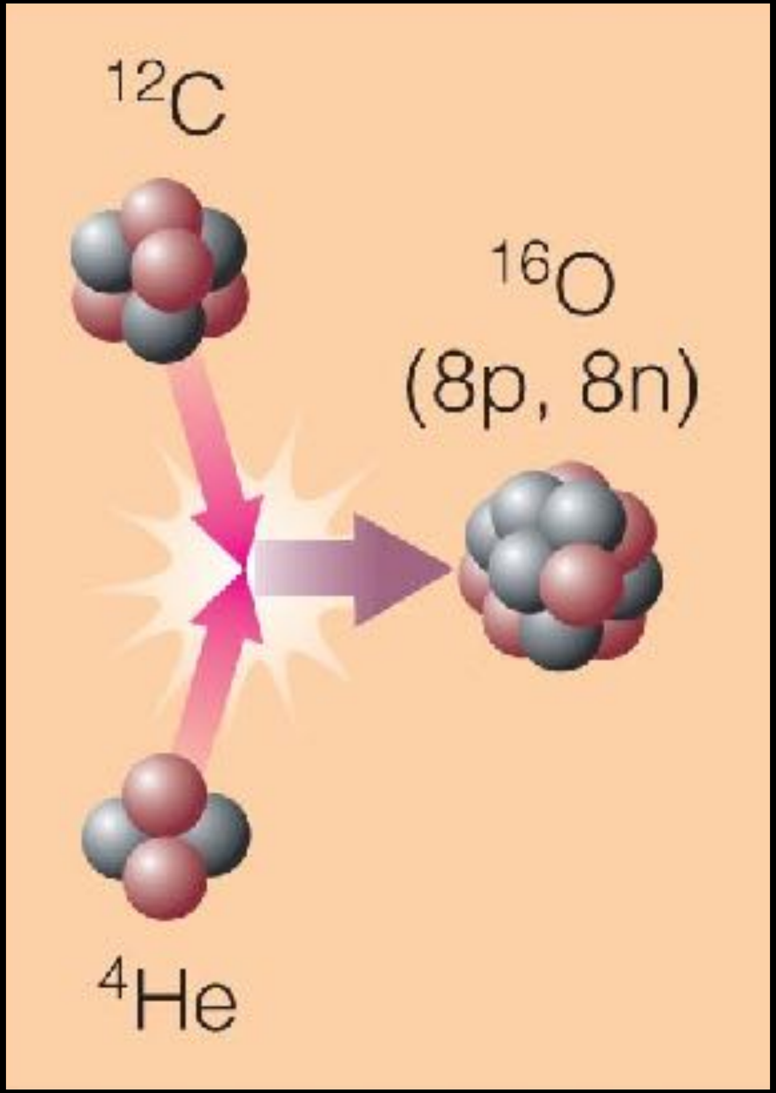
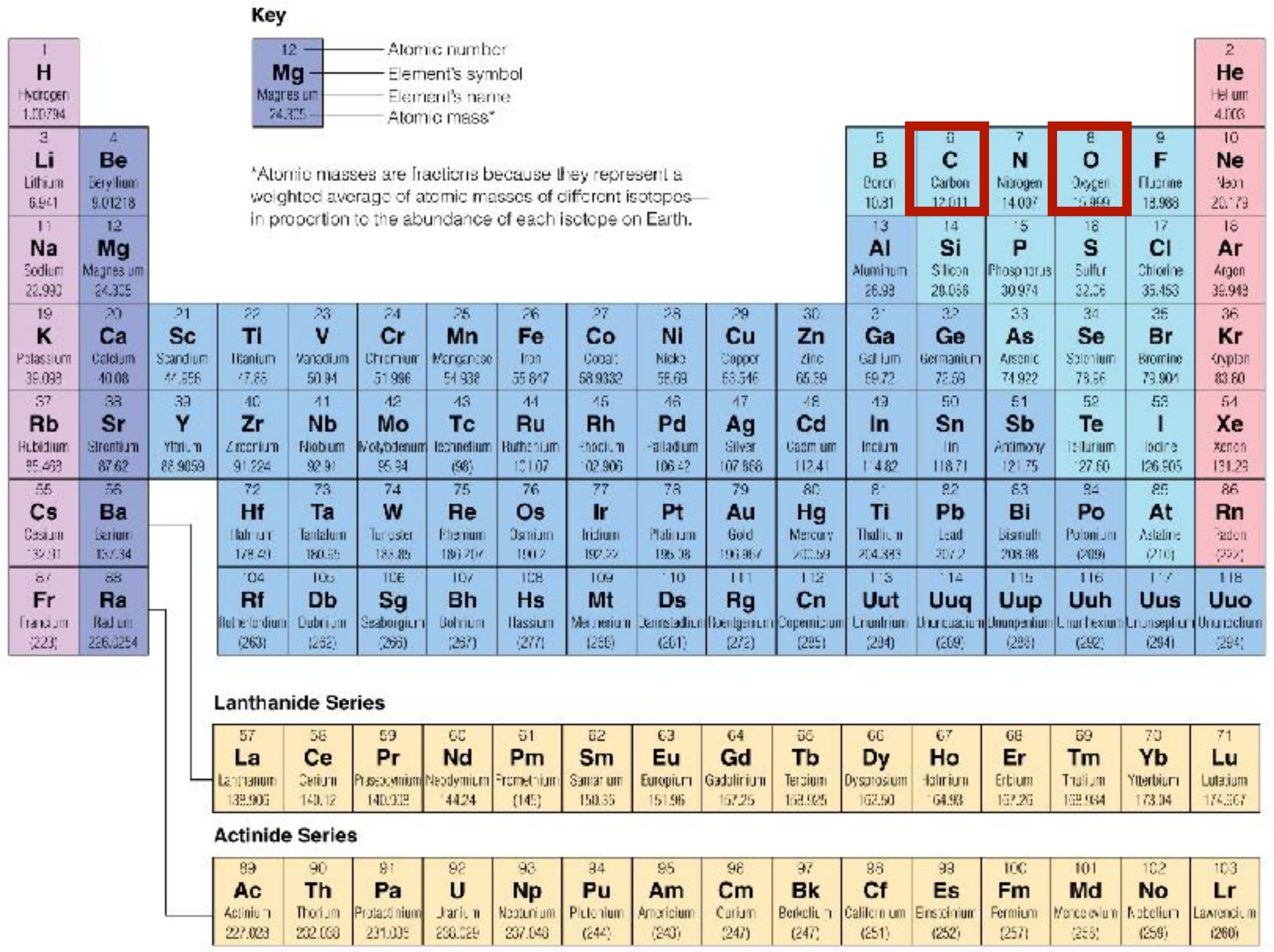
Helium fusion can make carbon in low-mass stars like the sun, but that is about it.

What happens in more massive stars?

Helium Capture



- High core temperatures in more massive stars allows helium to fuse with carbon.



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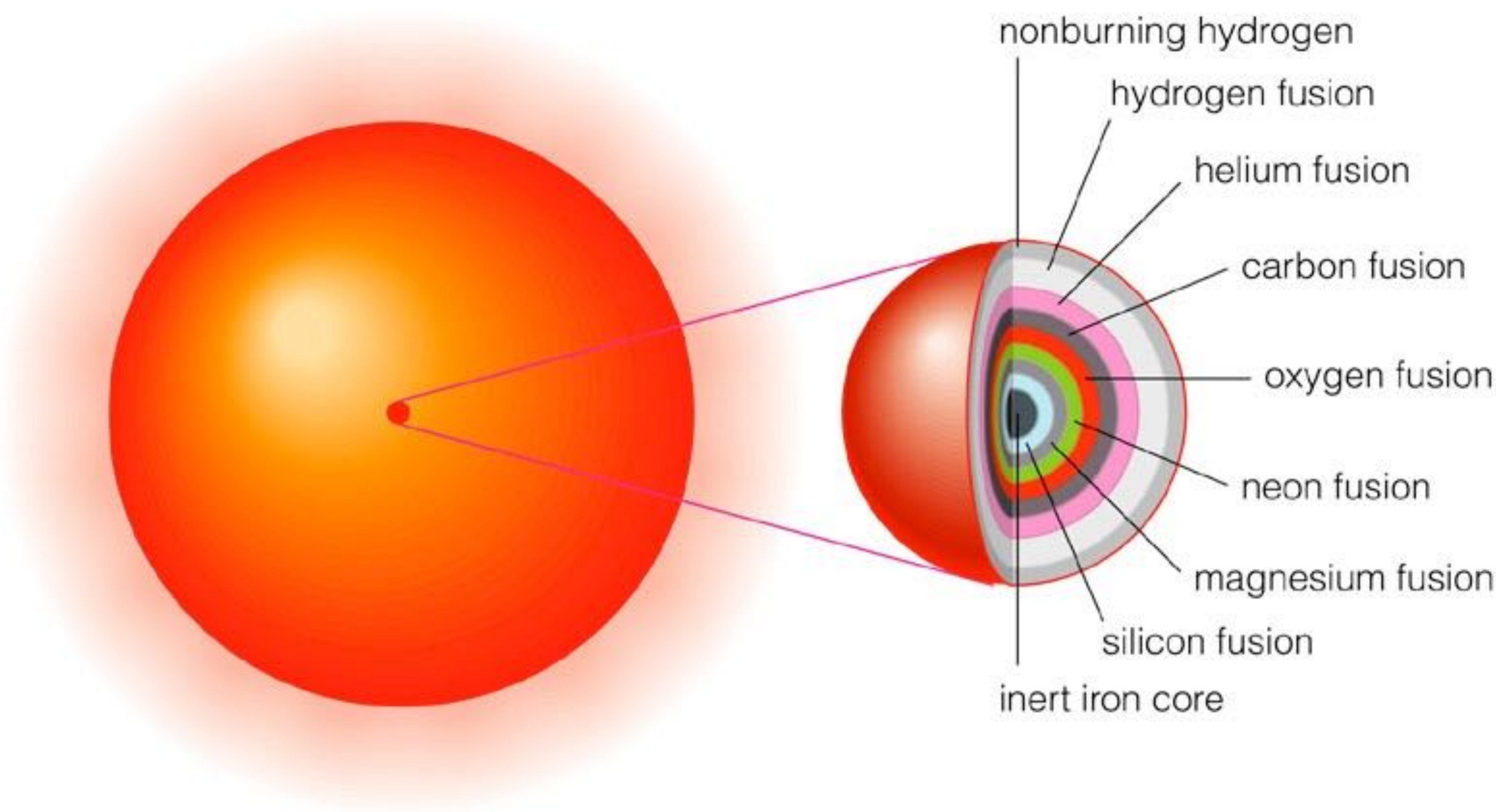
Helium capture builds C into O

SUMMARY

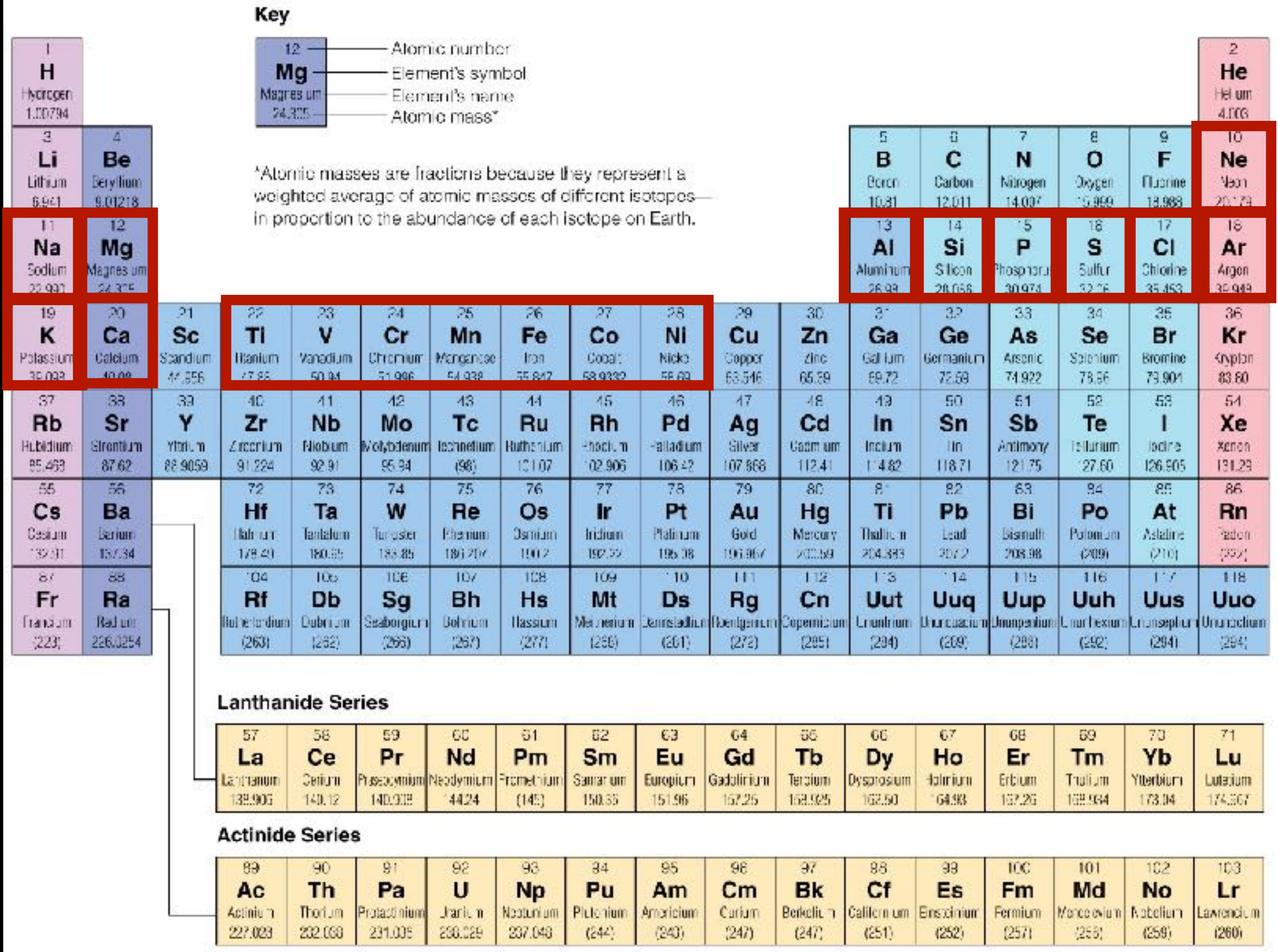
Advanced Nuclear Burning Stages

(e.g., 20 solar masses)

Fuel	Main Product	Secondary Products	Temp (10^9 K)	Time (yr)
H	He	^{14}N	0.02	10^7
He	C,O	^{18}O, ^{22}Ne s- process	0.2	10^6
C	Ne, Mg	Na	0.8	10^3
Ne	O, Mg	Al, P	1.5	3
O	Si, S	Cl, Ar K, Ca	2.0	0.8
Si	Fe	Ti, V, Cr Mn, Co, Ni	3.5	1 week



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



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*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 18.998	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 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 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 (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

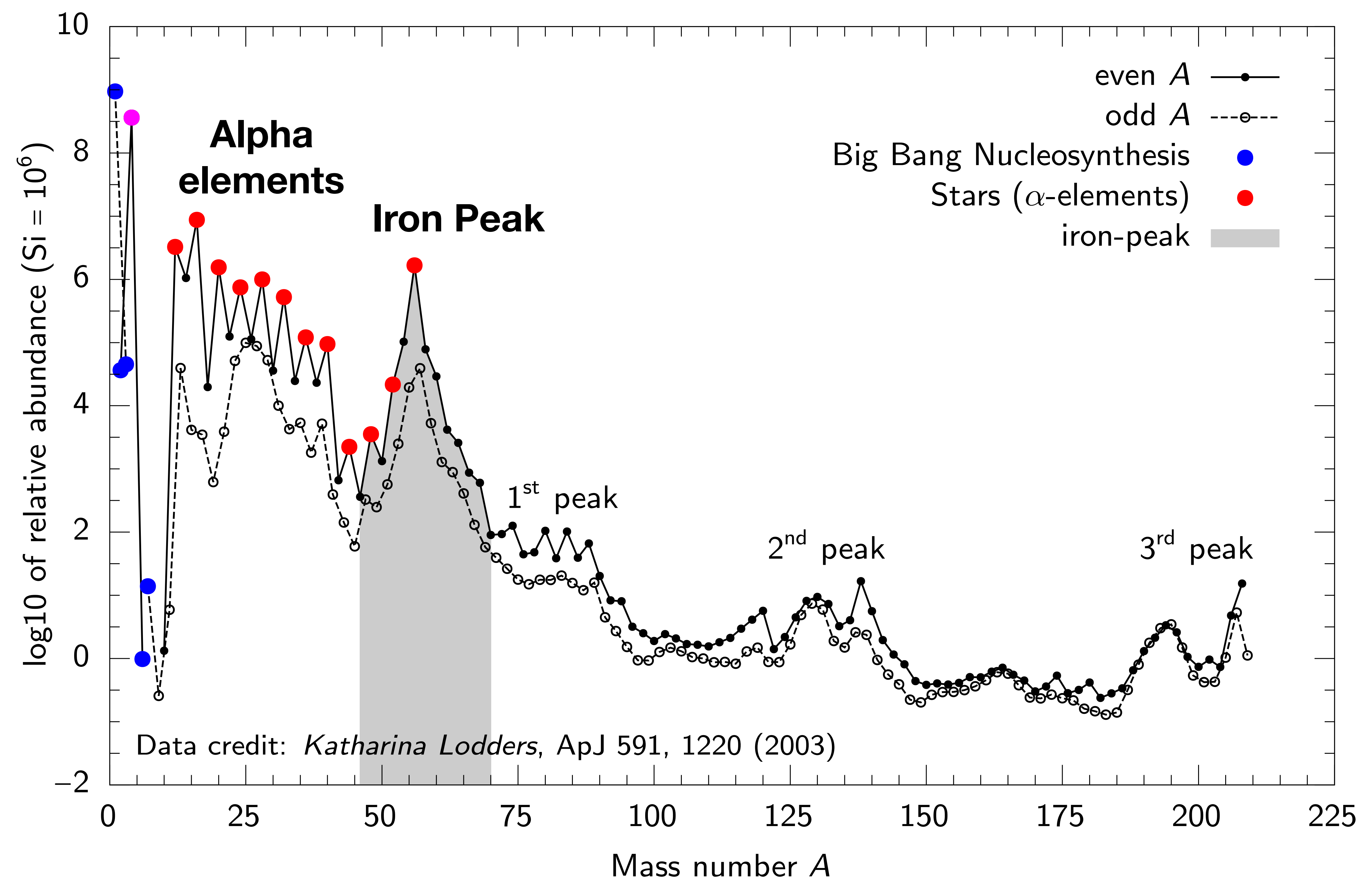
57 La Lanthanum 138.906	58 Ce Cerium 140.12	59 Pr Praseodymium 140.908	60 Nd Neodymium 144.24	61 Pm Promethium (145)	62 Sm Samarium 150.35	63 Eu Europium 151.96	64 Gd Gadolinium 157.25	65 Tb Terbium 158.925	66 Dy Dysprosium 162.50	67 Ho Holmium 164.93	68 Er Erbium 167.26	69 Tm Thulium 168.934	70 Yb Ytterbium 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)

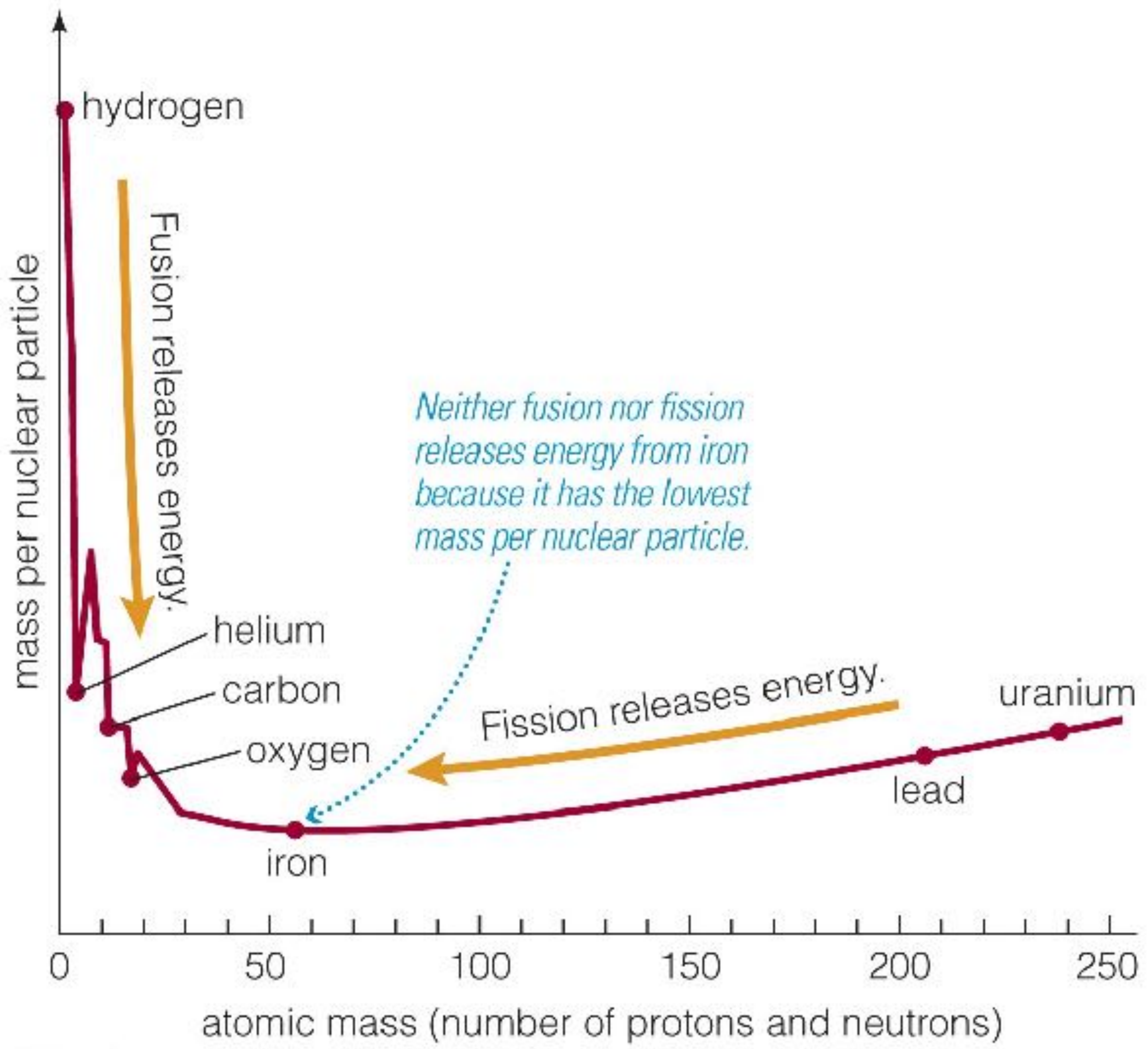
Advanced reactions in stars make elements such as Si, S, Ca, and Fe.

Evidence for Stellar Nucleosynthesis



Data credit: *Katharina Lodders*, ApJ 591, 1220 (2003)

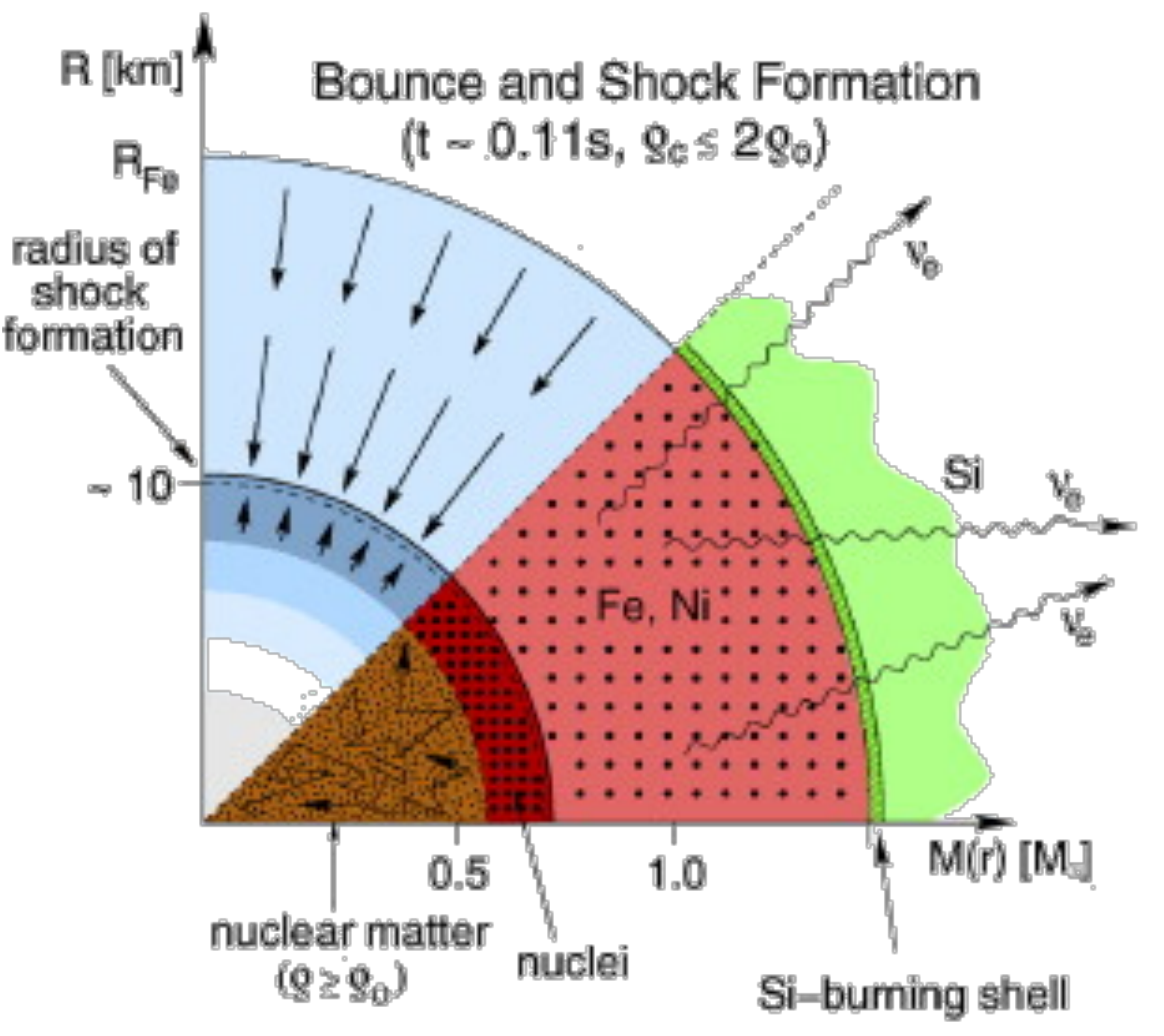
The abundances of nuclei in our solar system



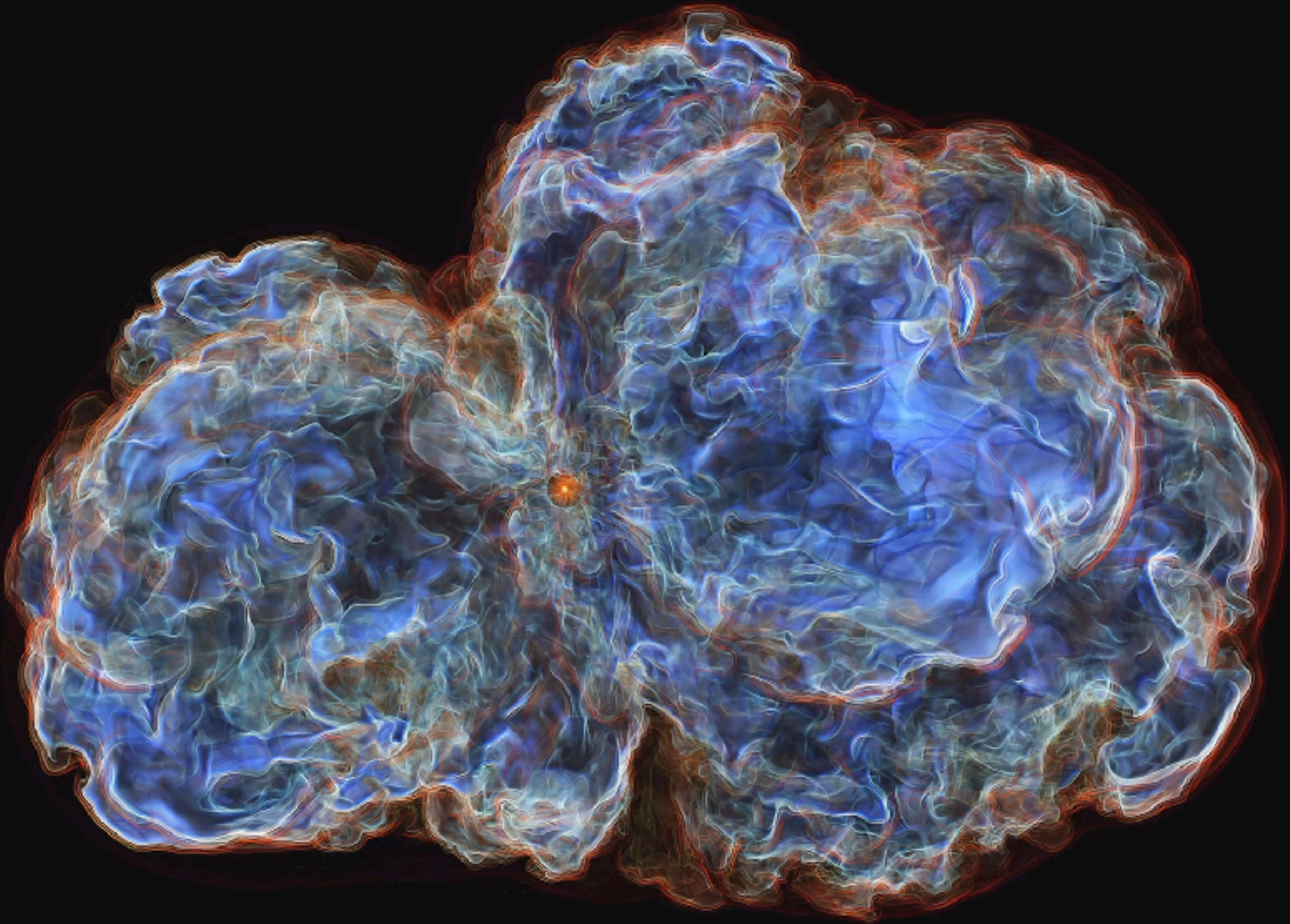
Iron is a dead end for fusion because nuclear reactions involving iron do not release energy.

(Fe has lowest mass per nuclear particle.)

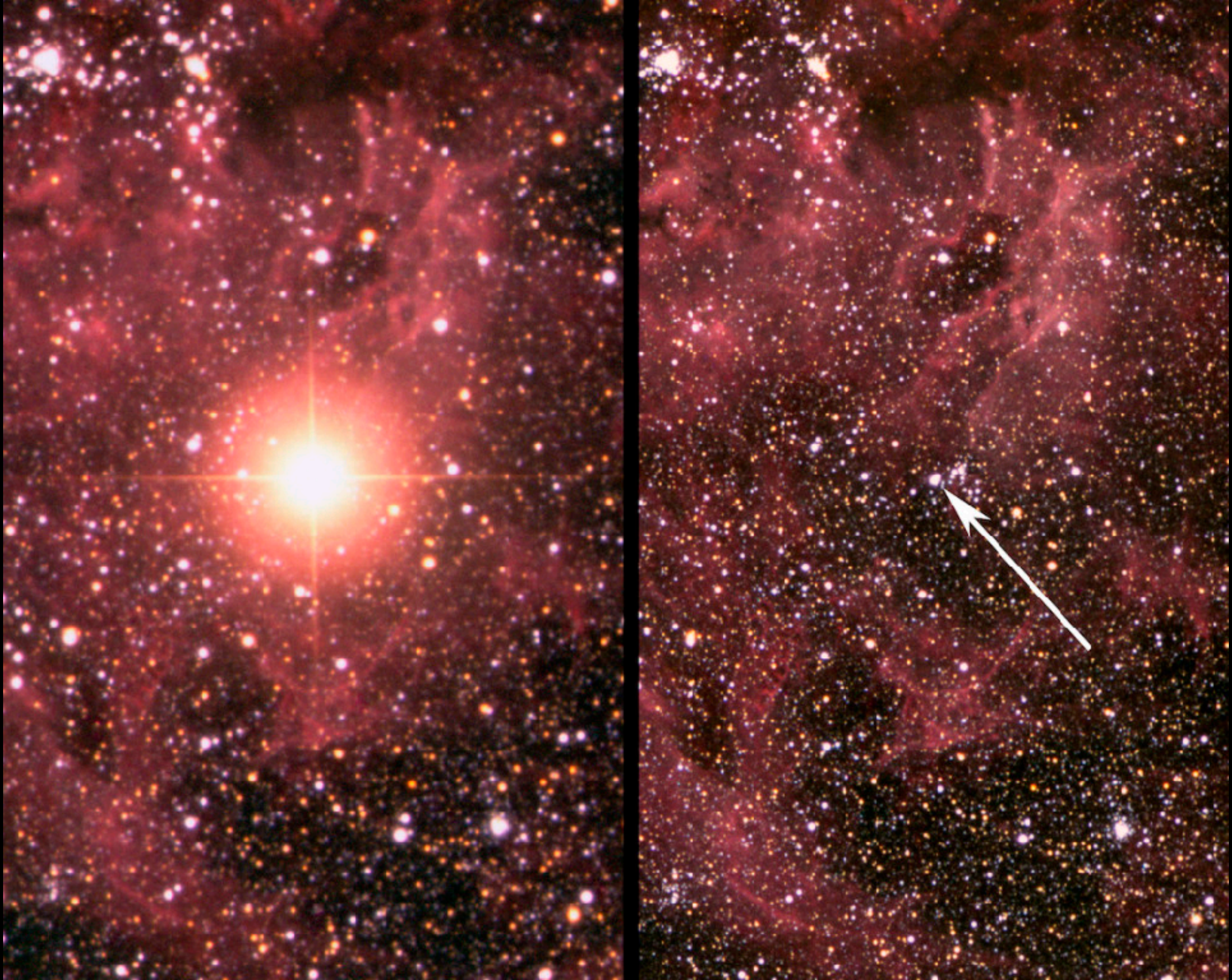
What happens once you reach iron?

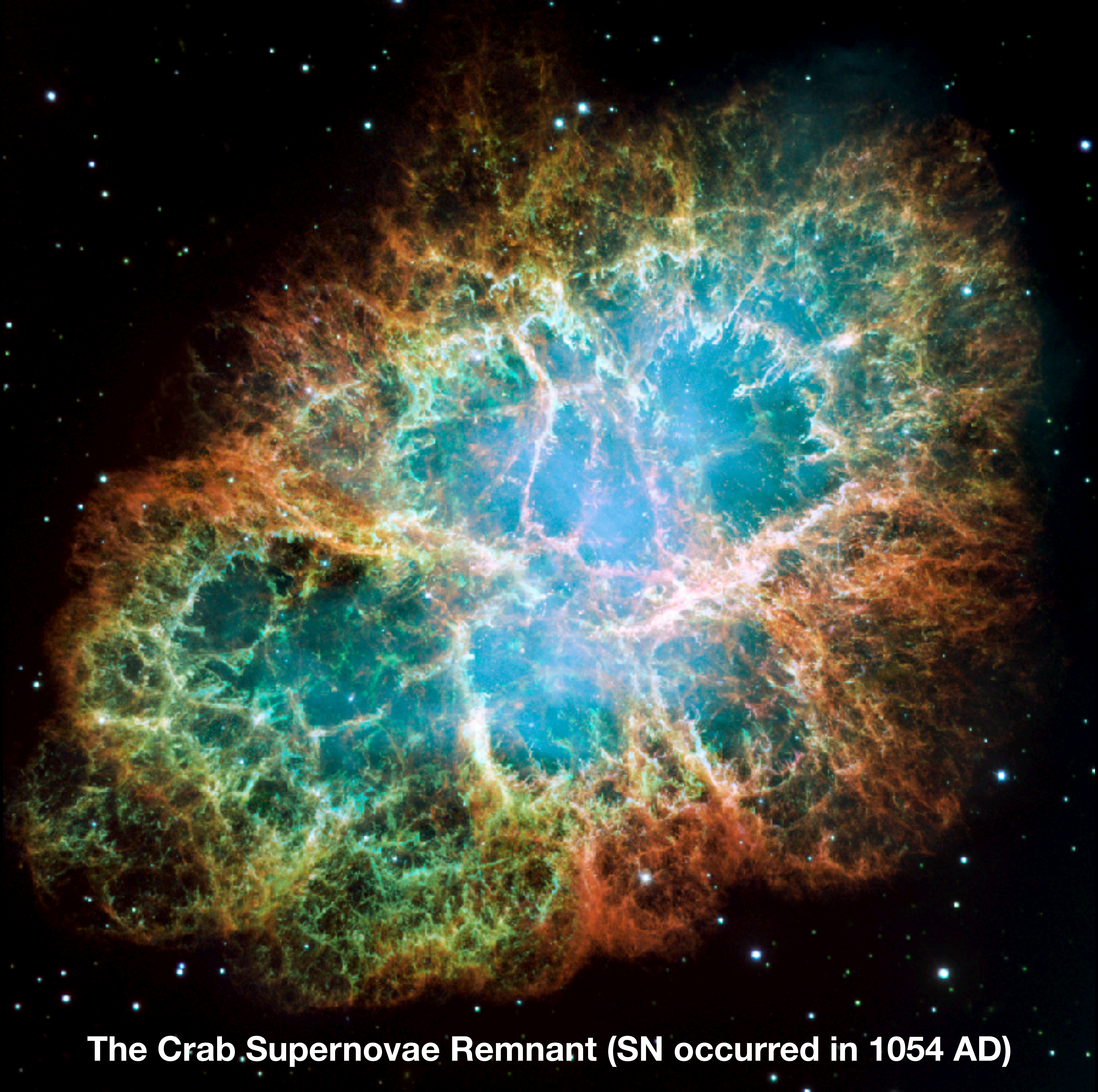


- Iron builds up in the core of massive stars until electron pressure can no longer resist gravity.
- The core then suddenly collapses, the released gravitational bindings energy powers a **supernova explosion** of the outer layers of the star and leaves behind a neutron star or a black hole.
- This explosion ejects nucleosynthesis products back into the interstellar gas
- Some of the largest explosions in the universe, energy release equivalent to 100 million billion billion billion (10^{35}) tons of TNT

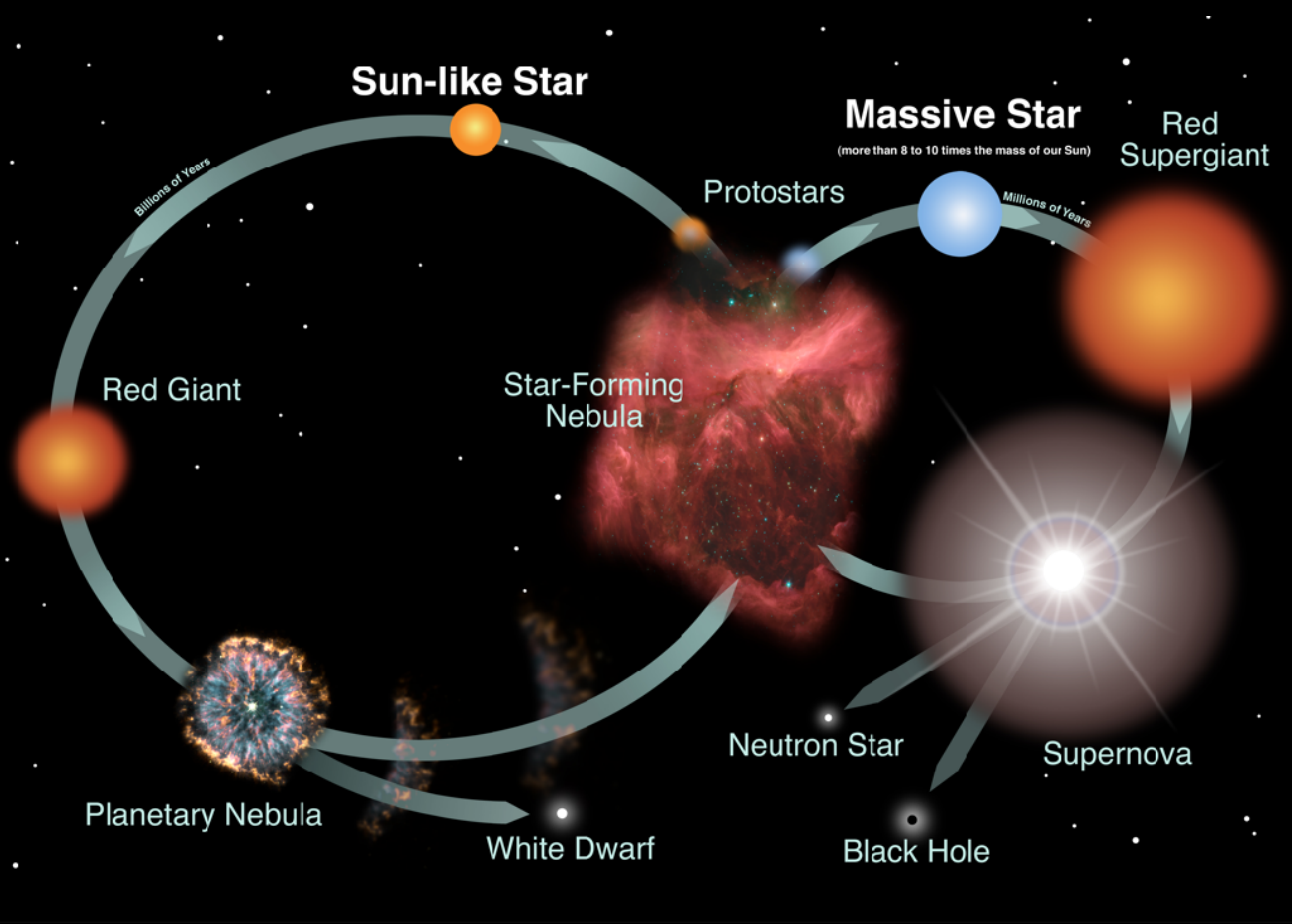



ECOphlex
CRAY





The Crab Supernovae Remnant (SN occurred in 1054 AD)



Sun-like Star

Billions of Years

Protostars

Massive Star

(more than 8 to 10 times the mass of our Sun)

Millions of Years

Red Supergiant

Red Giant

Star-Forming Nebula

Supernova

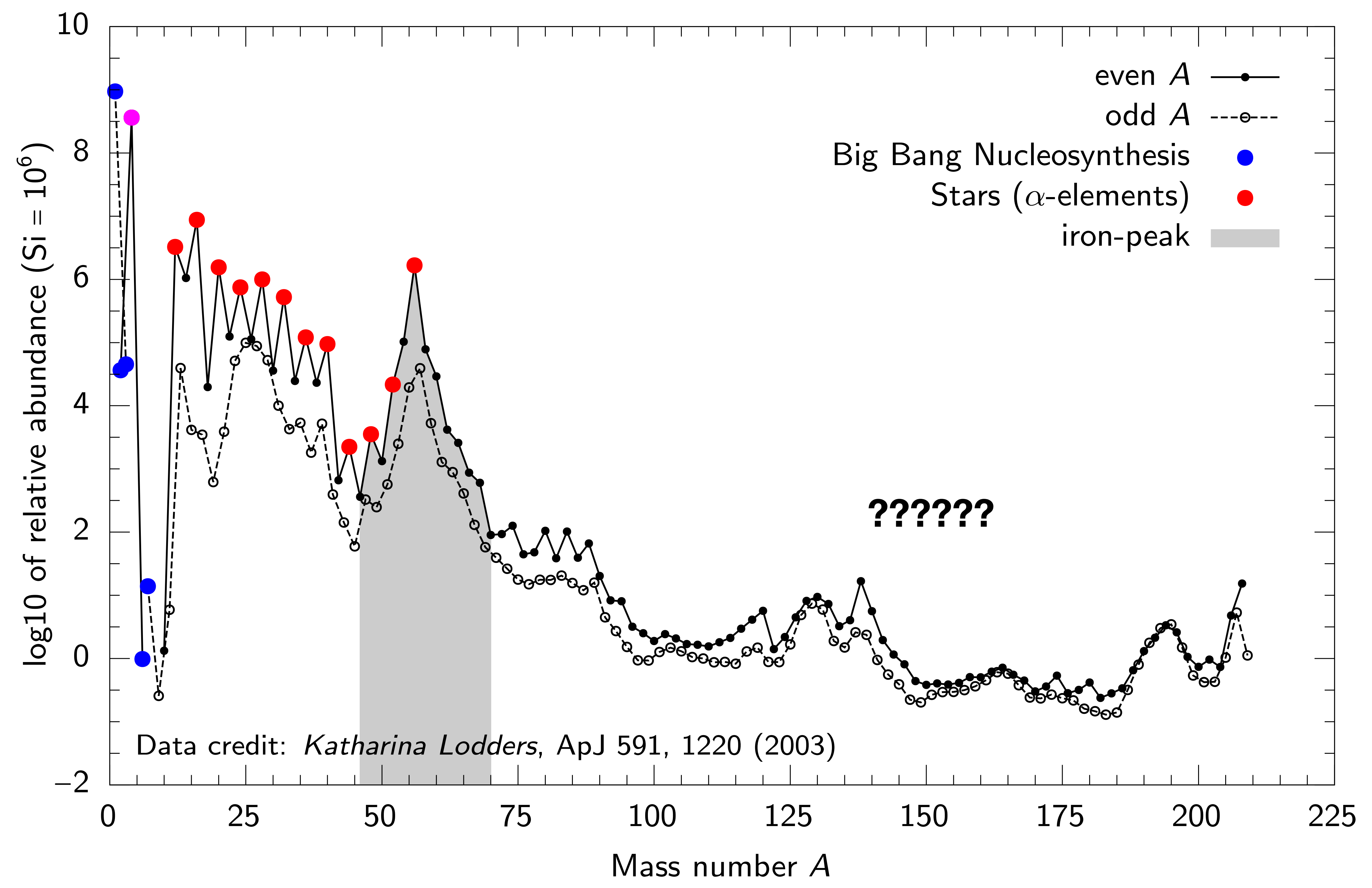
Neutron Star

Black Hole

Planetary Nebula

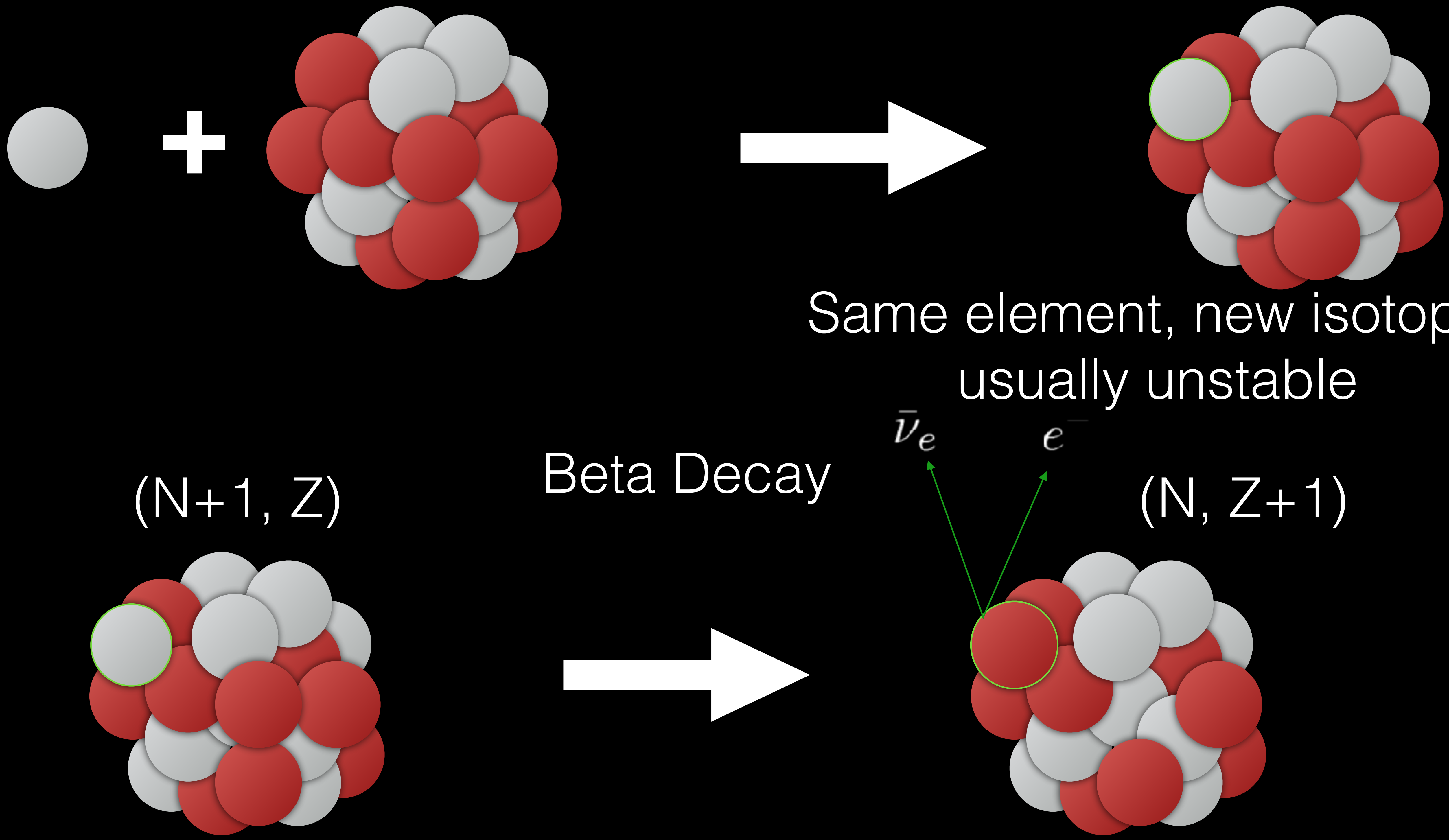
White Dwarf

Evidence for Stellar Nucleosynthesis



The abundances of nuclei in our solar system

Neutron Capture



Same element, new isotope, usually unstable

Beta Decay

New Element!

Two ways to capture neutrons

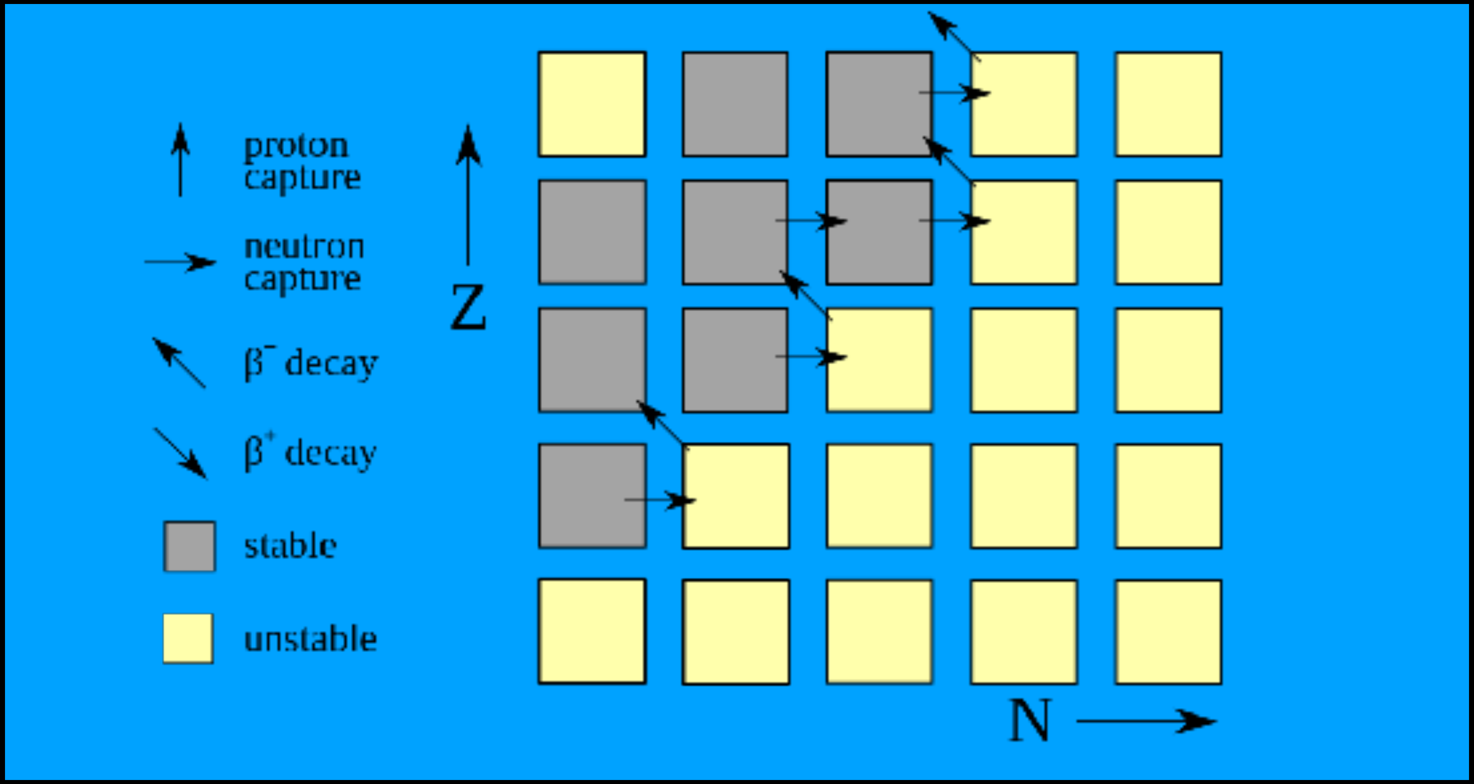
Slowly (s-process):

Capture a neutron and then beta-decay back to stability, then repeat. This process occurs during later stages of stellar burning as a secondary process, responsible for about half of the elements heavier than iron.

Get neutrons from:

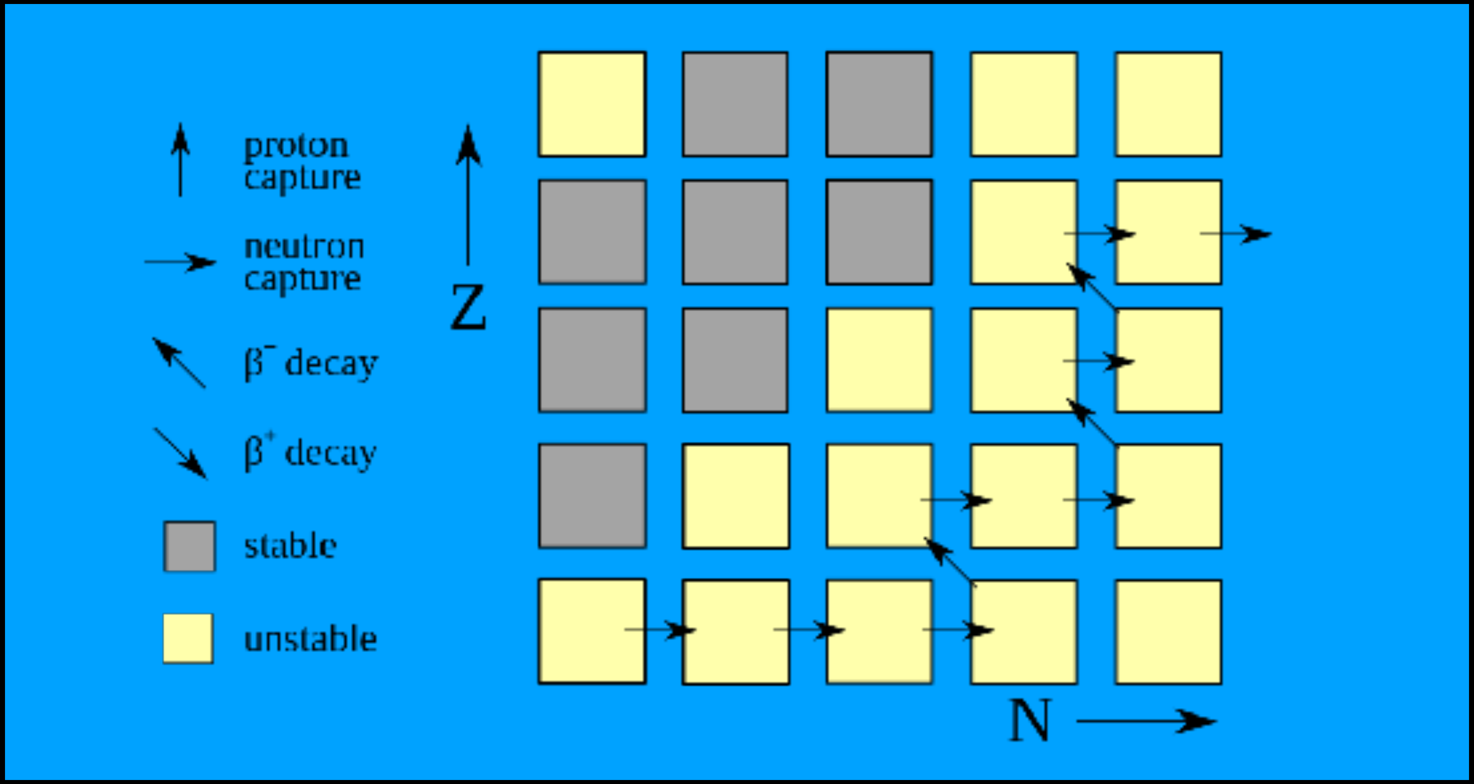
$^{13}C + ^{4}He \rightarrow ^{16}O + n$

$^{22}Ne + ^{4}He \rightarrow ^{25}Mg + n$

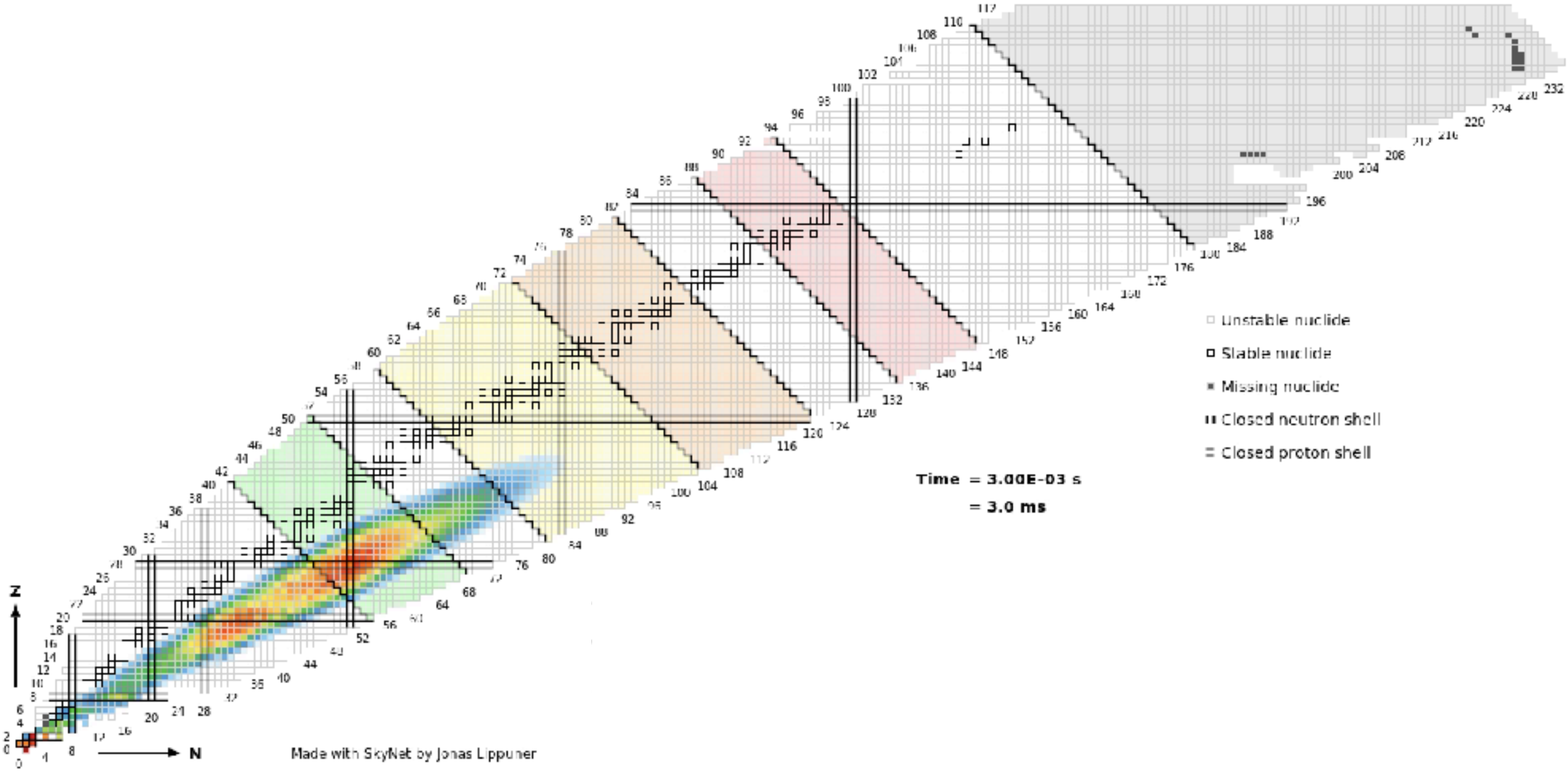


Rapidly (r-process):

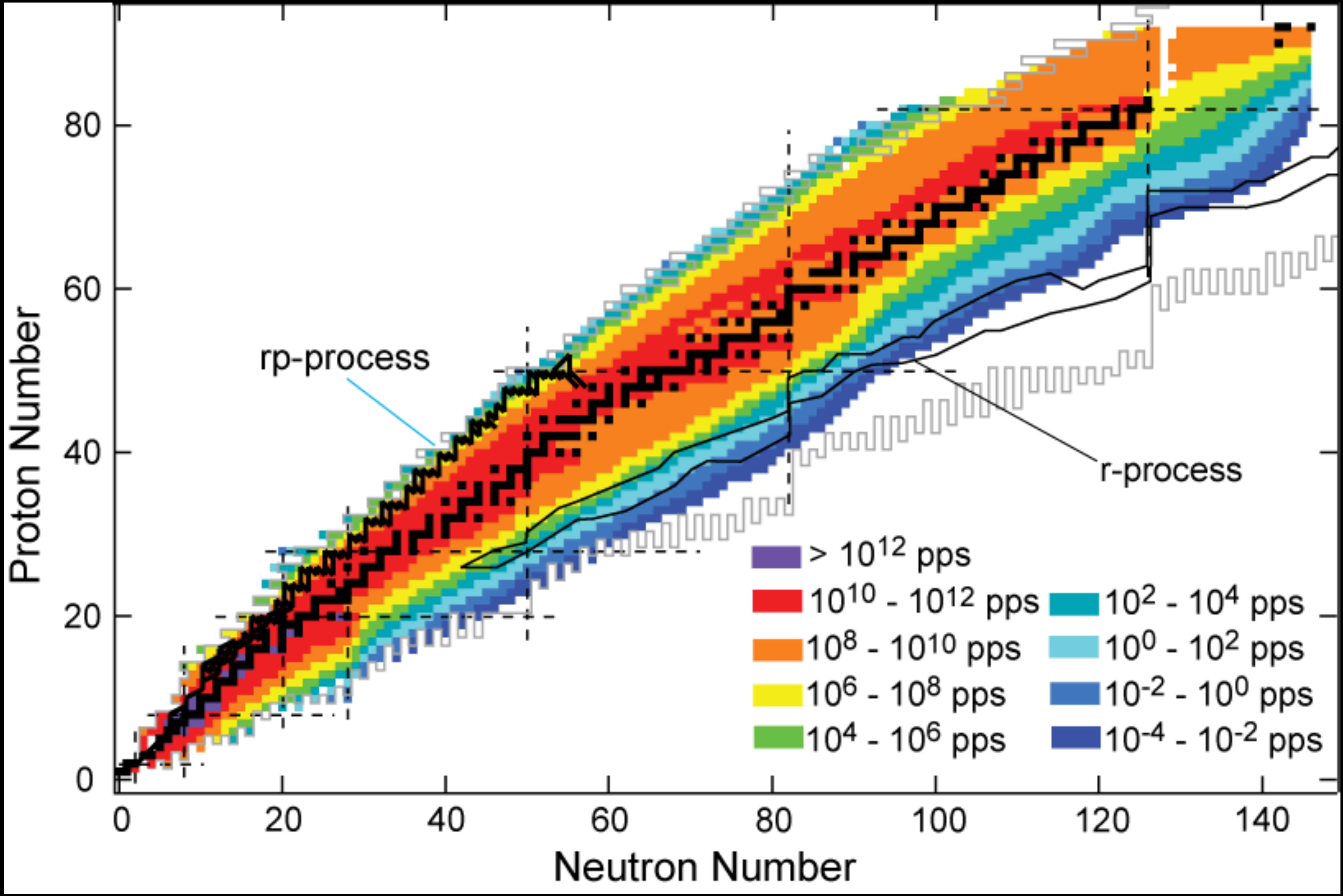
Capture many neutrons before beta-decay and move far from stability. We know this must happen somewhere, but the exact site is uncertain. Need **lots** of free neutrons.



r-process flow

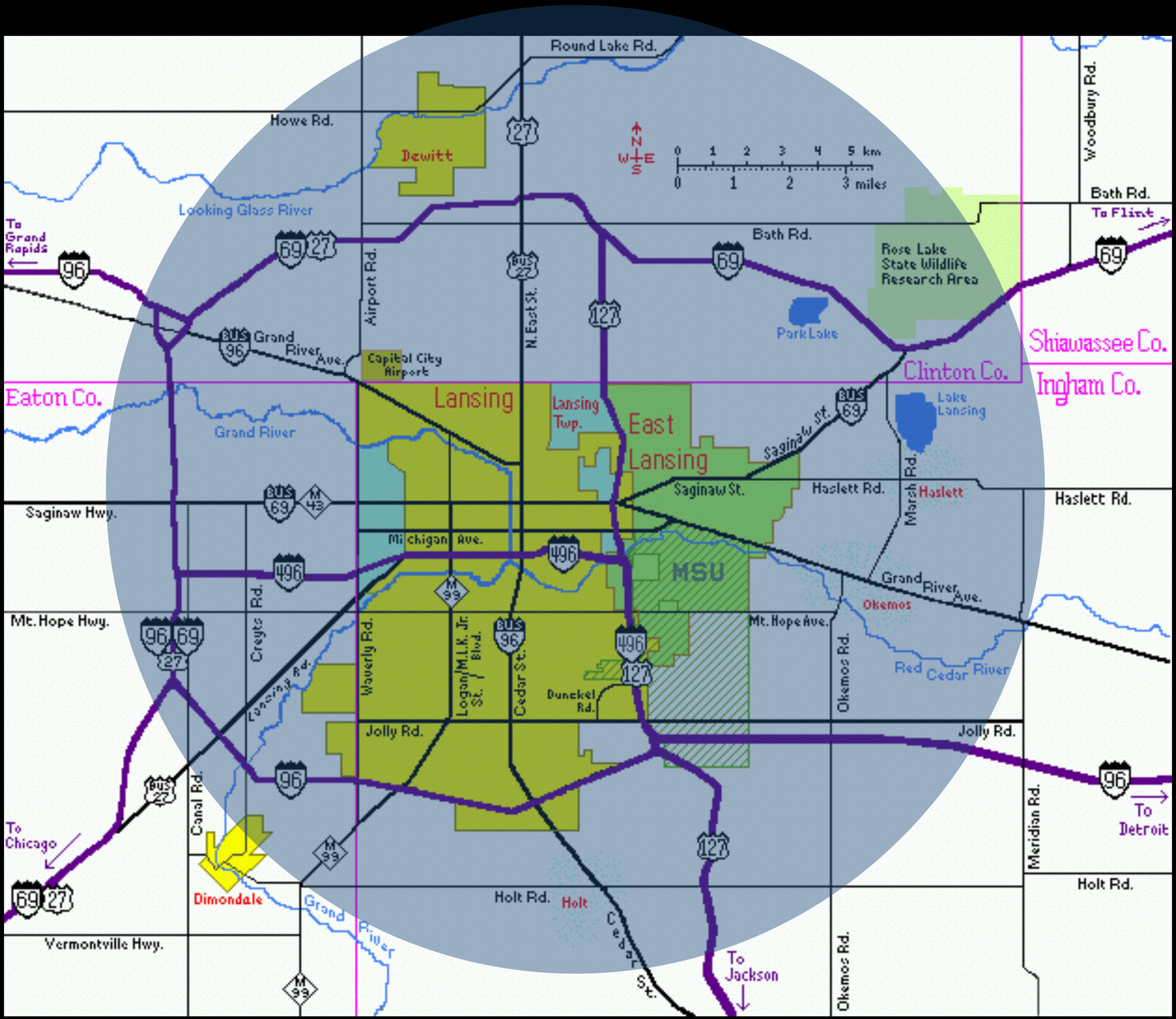


FRIB will help us understand the r-process path



FACILITY FOR
RARE ISOTOPE BEAMS

Where can we get lots of neutrons? Neutron Stars!



A neutron star is about the same size as the Lansing area, but with a mass comparable to that of the sun.

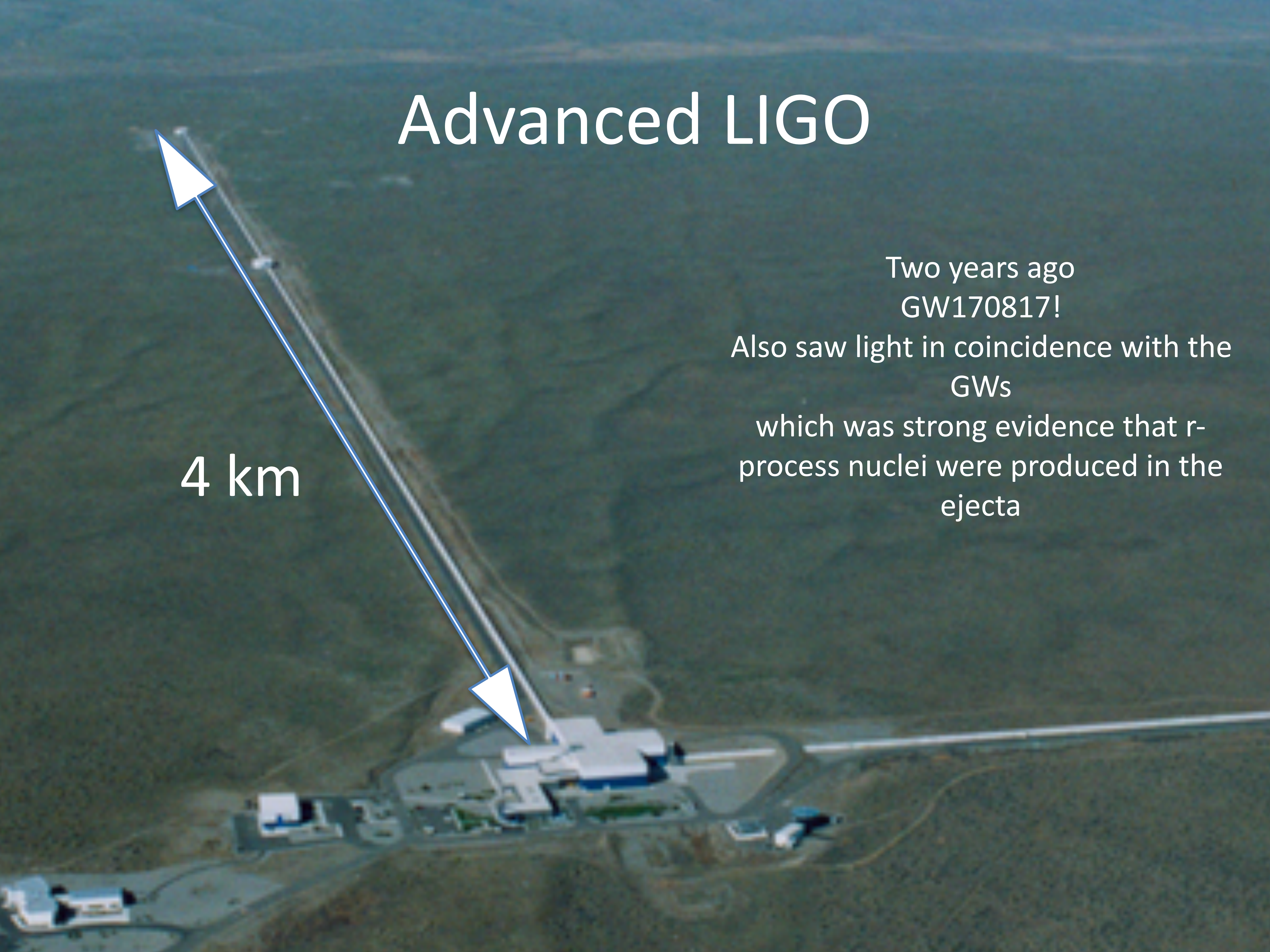
Which of these objects has about the same mass as one cubic centimeter of neutron-star matter?

(~ 10^{9} g) (~ 10^{12} g) (~ 10^{15} g)

Neutron Star Mergers

- Neutron stars in binaries spiral towards one another through gravitational wave emission
- Eventually tear one another apart, eject a little bit of material, and form either another more massive neutron star or a black hole.
- The material thrown out into space is very neutron rich, can undergo rapid neutron capture process

Advanced LIGO



Two years ago
GW170817!
Also saw light in coincidence with the GWs
which was strong evidence that r-process nuclei were produced in the ejecta

The Central Question of Nuclear Astrophysics:

How did the stuff our solar system and humans are made of come to be?

The Big Bang, Stars, Supernovae, Neutron star mergers…