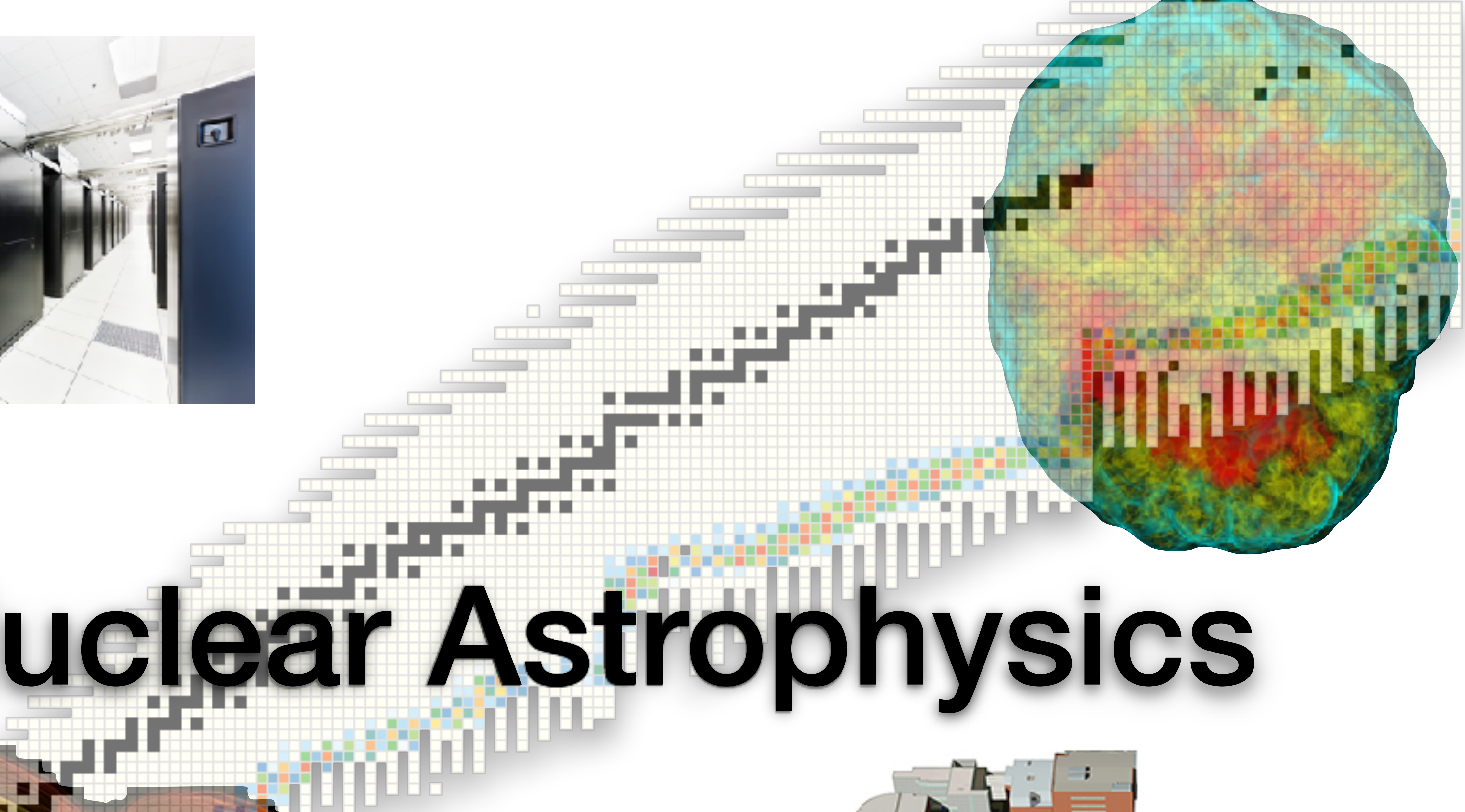
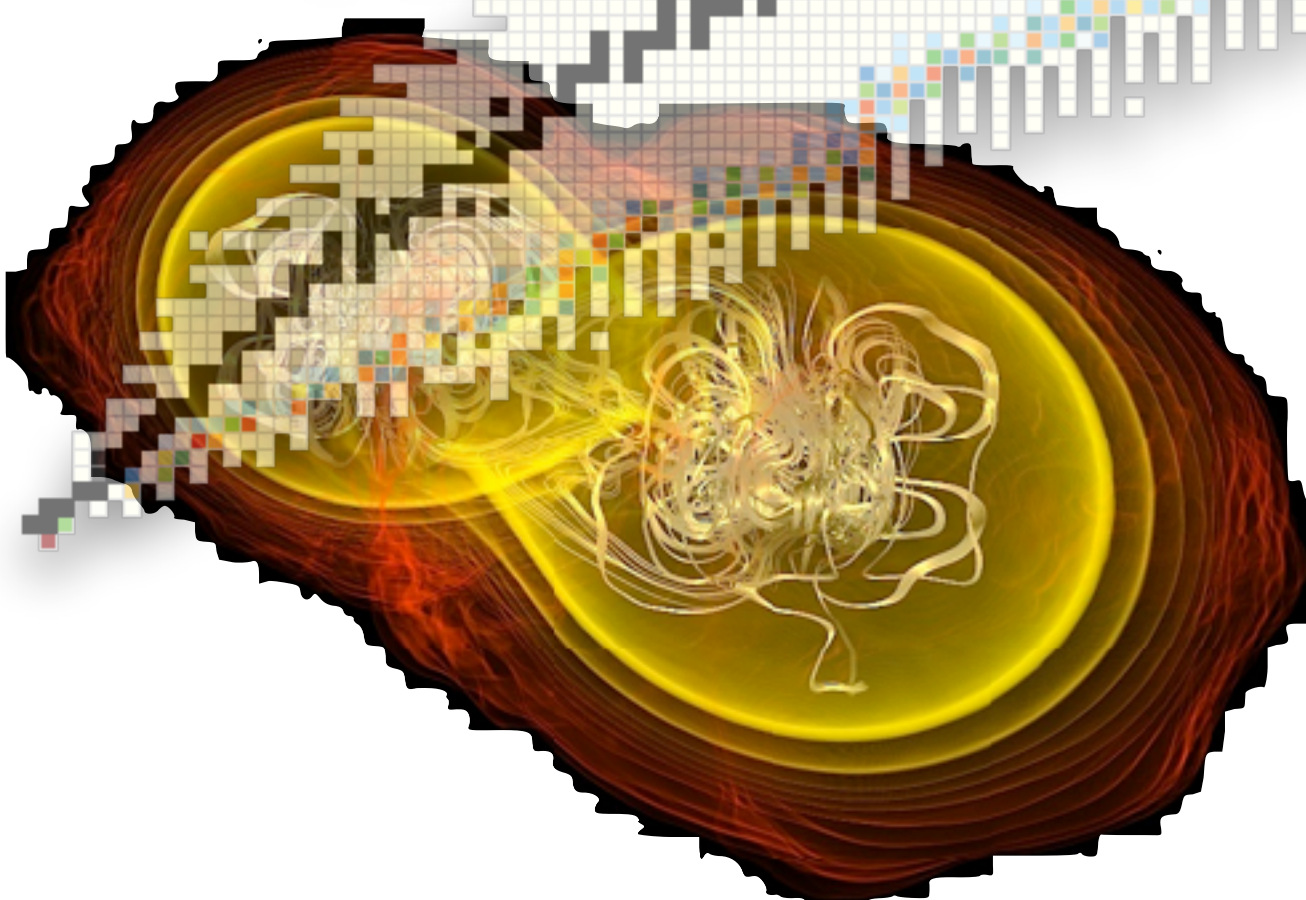
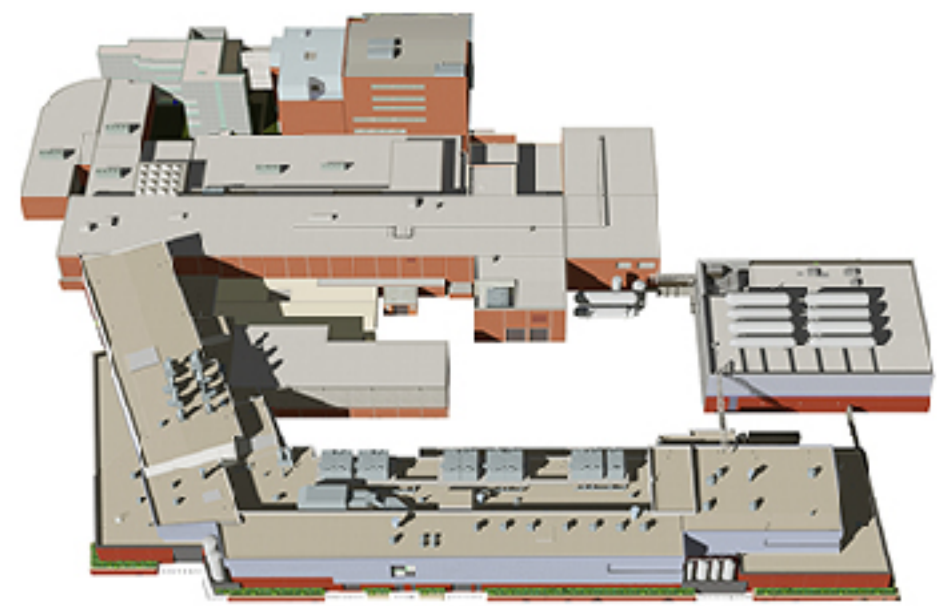


Nuclear Astrophysics





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:

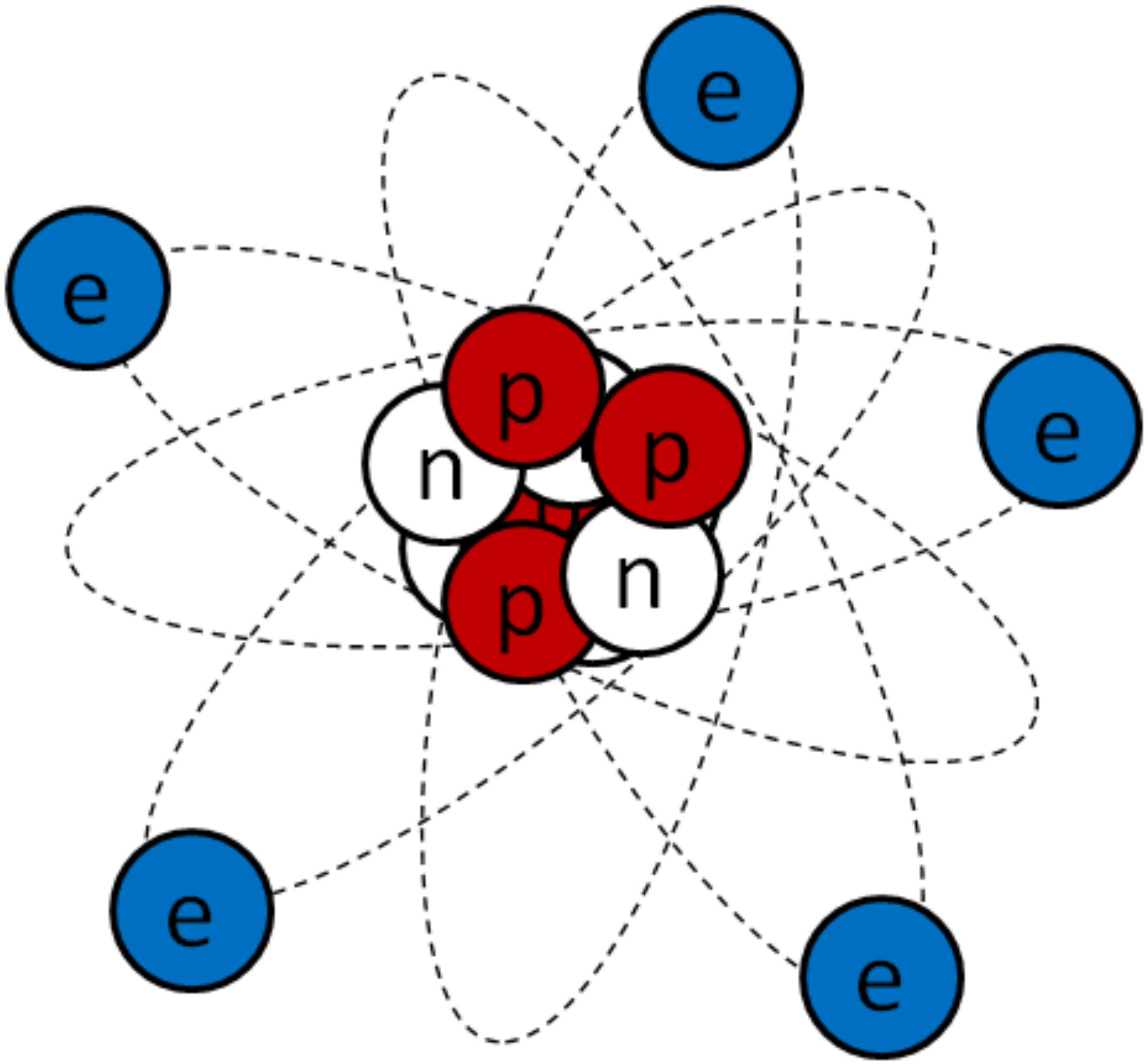
How did the stuff our solar system and humans are made of come to be?

Also:

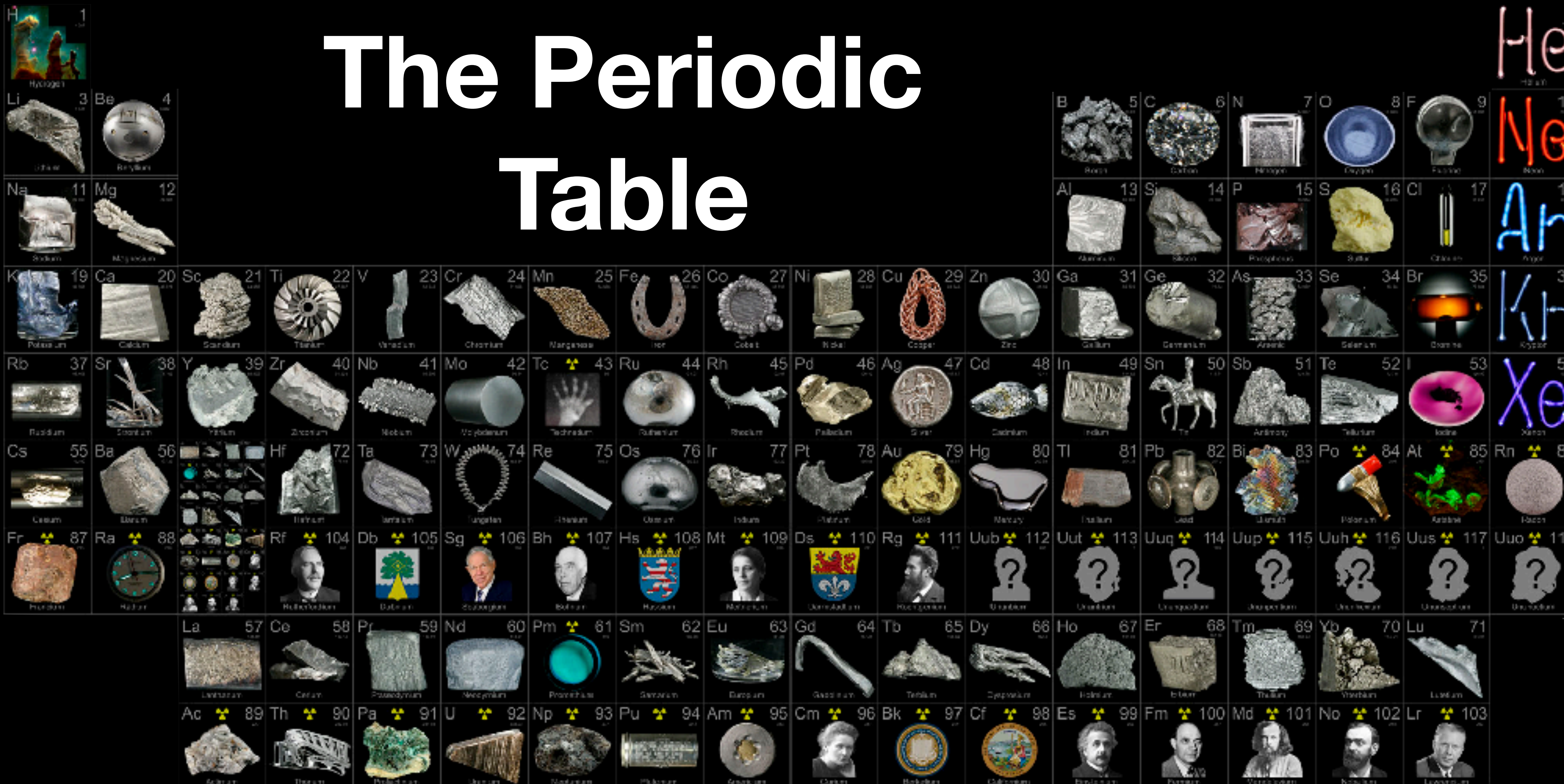
- **How do the stars shine?**
- **How do stars explode?**
- **What are neutron stars?**
- **...**

Atomic Number Z = # Electrons = # Protons

Neutron Number N = # Neutrons



The Periodic Table



The Periodic Table

...

The periodic table ignoring the properties of electrons

The Periodic Table

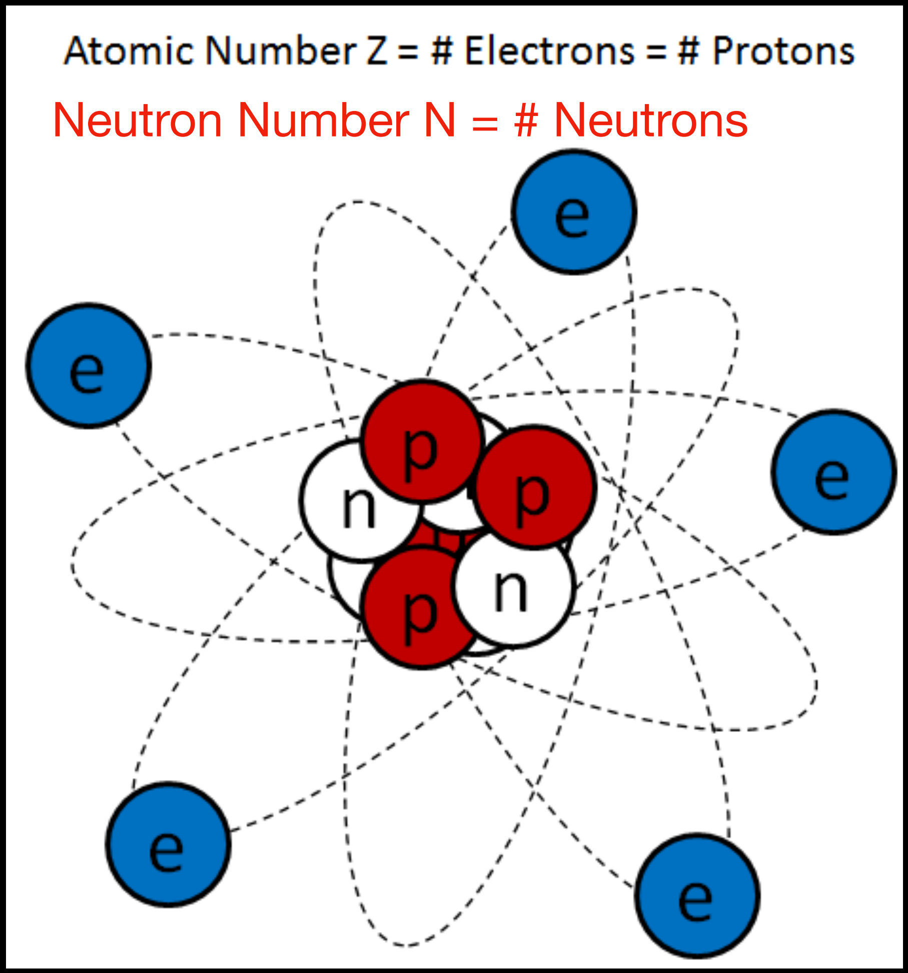


Chart of the Nuclides

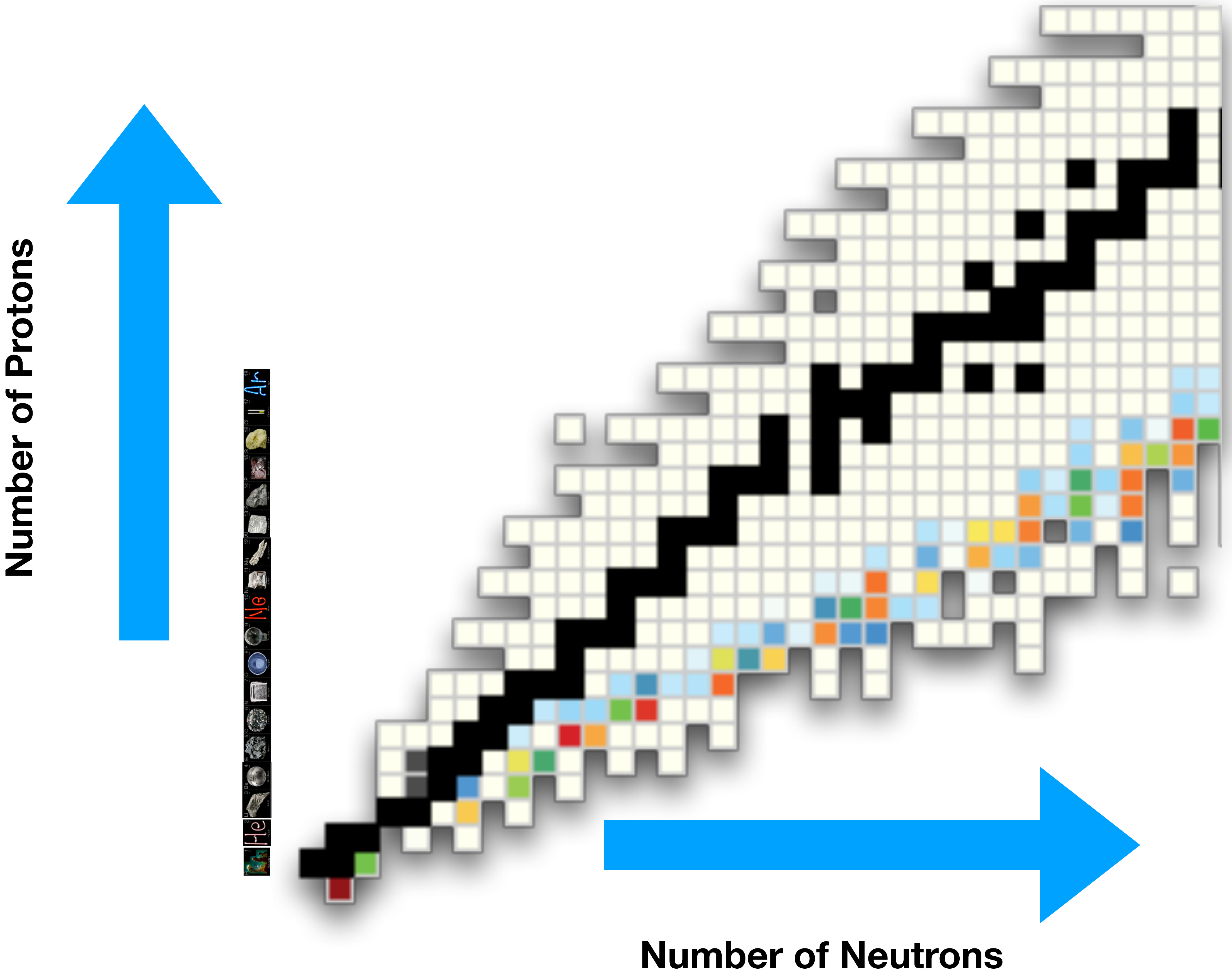
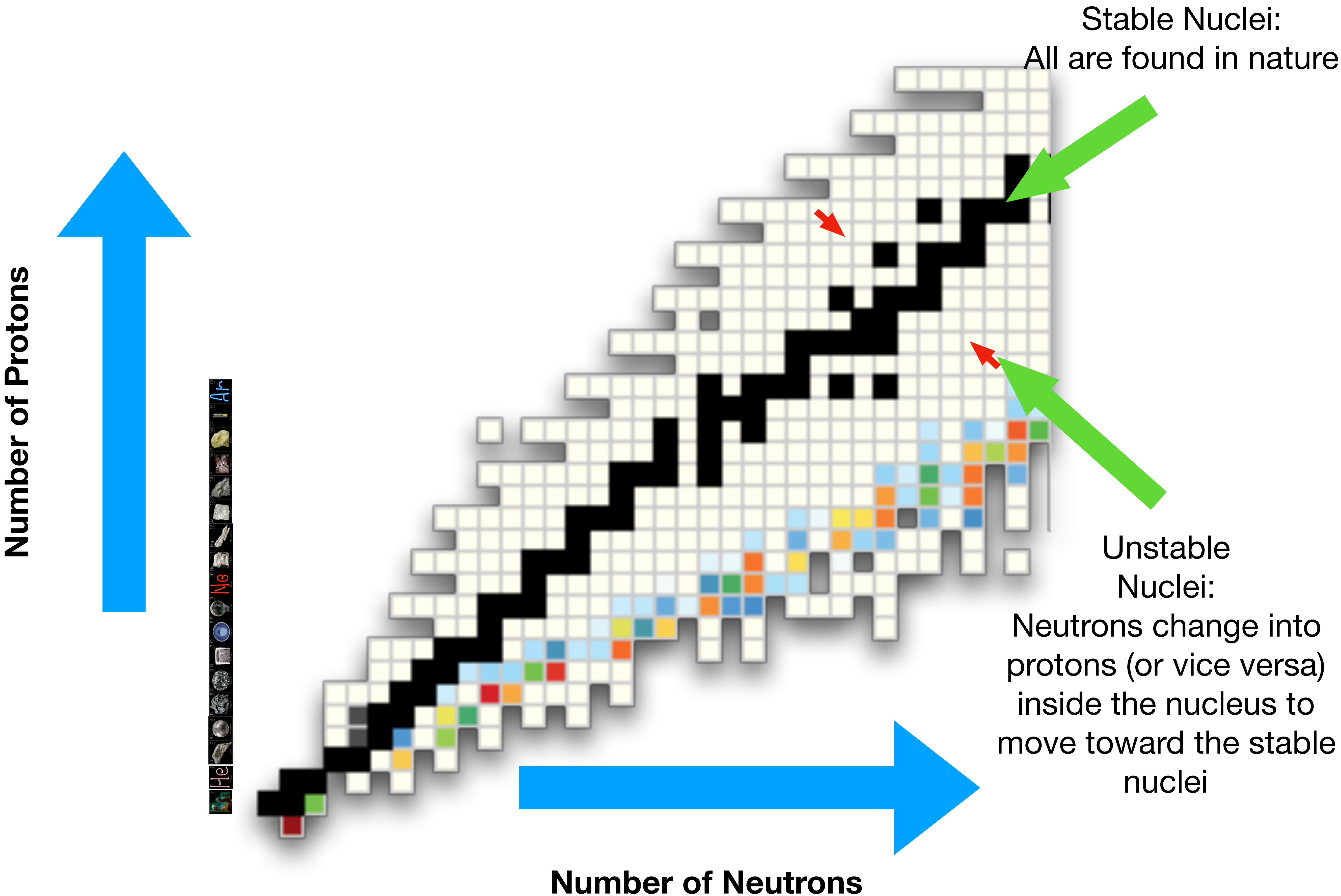
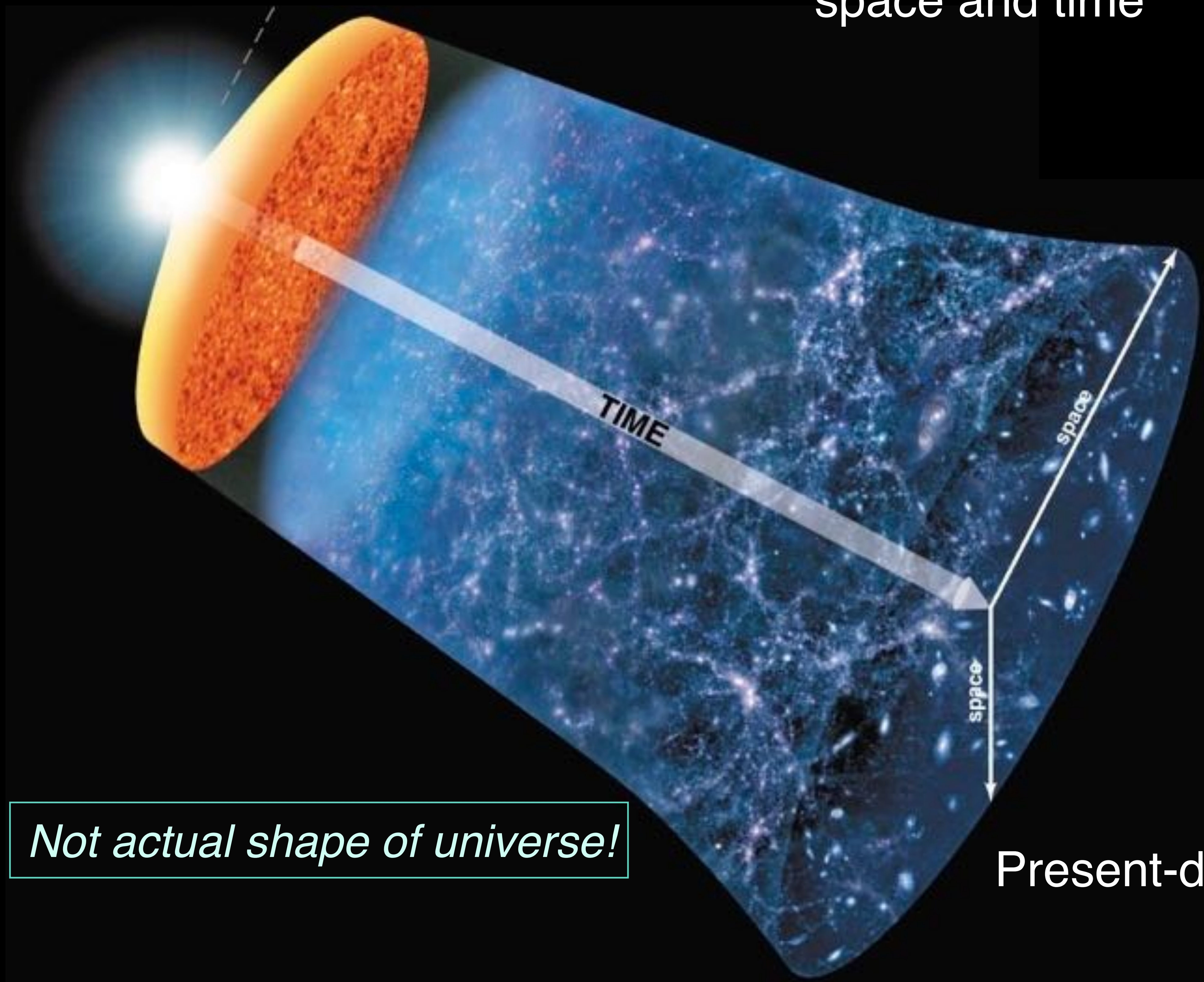


Chart of the Nuclides



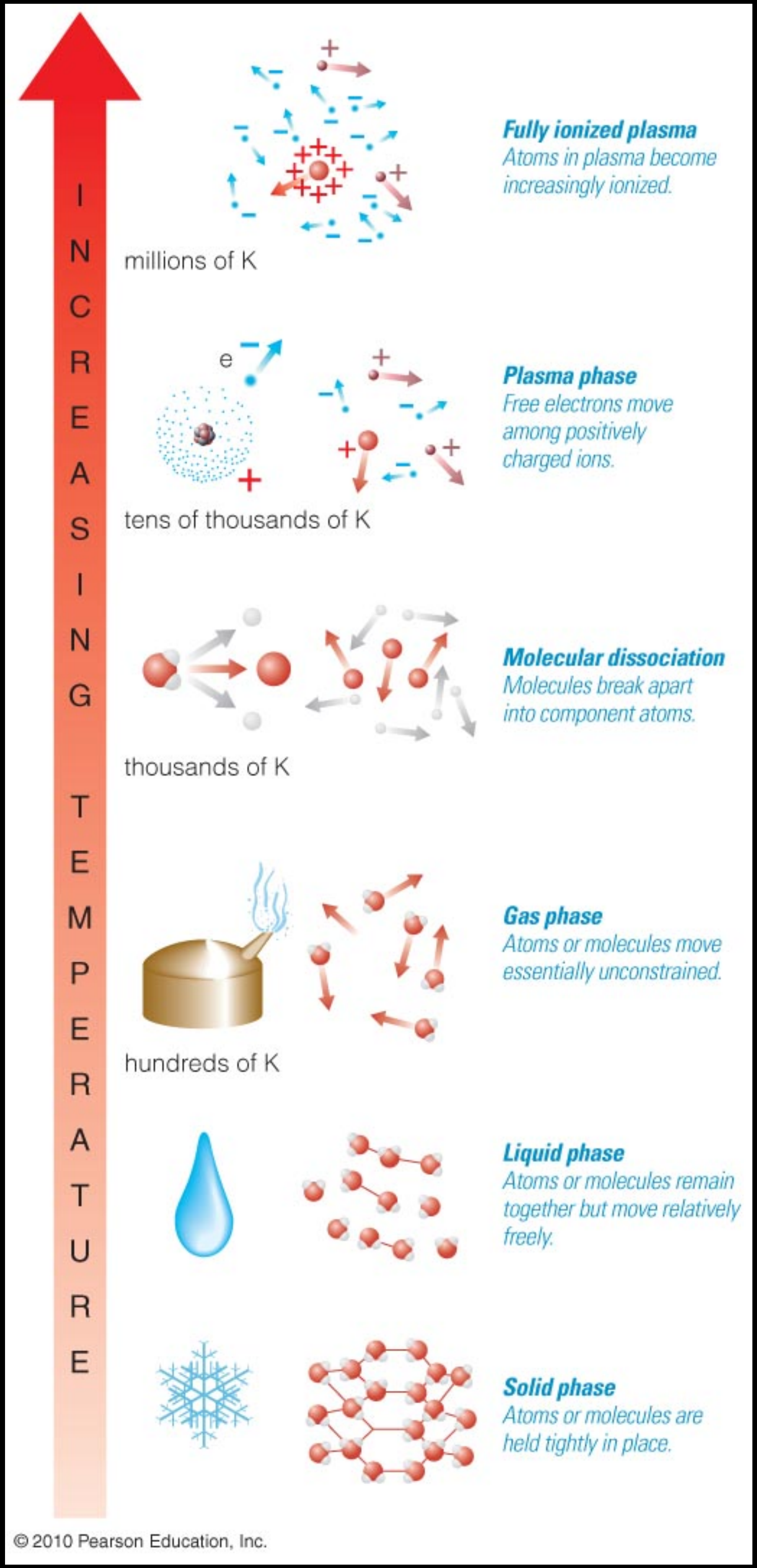
Moment of Big Bang

Schematic diagram showing development of the universe in space and time

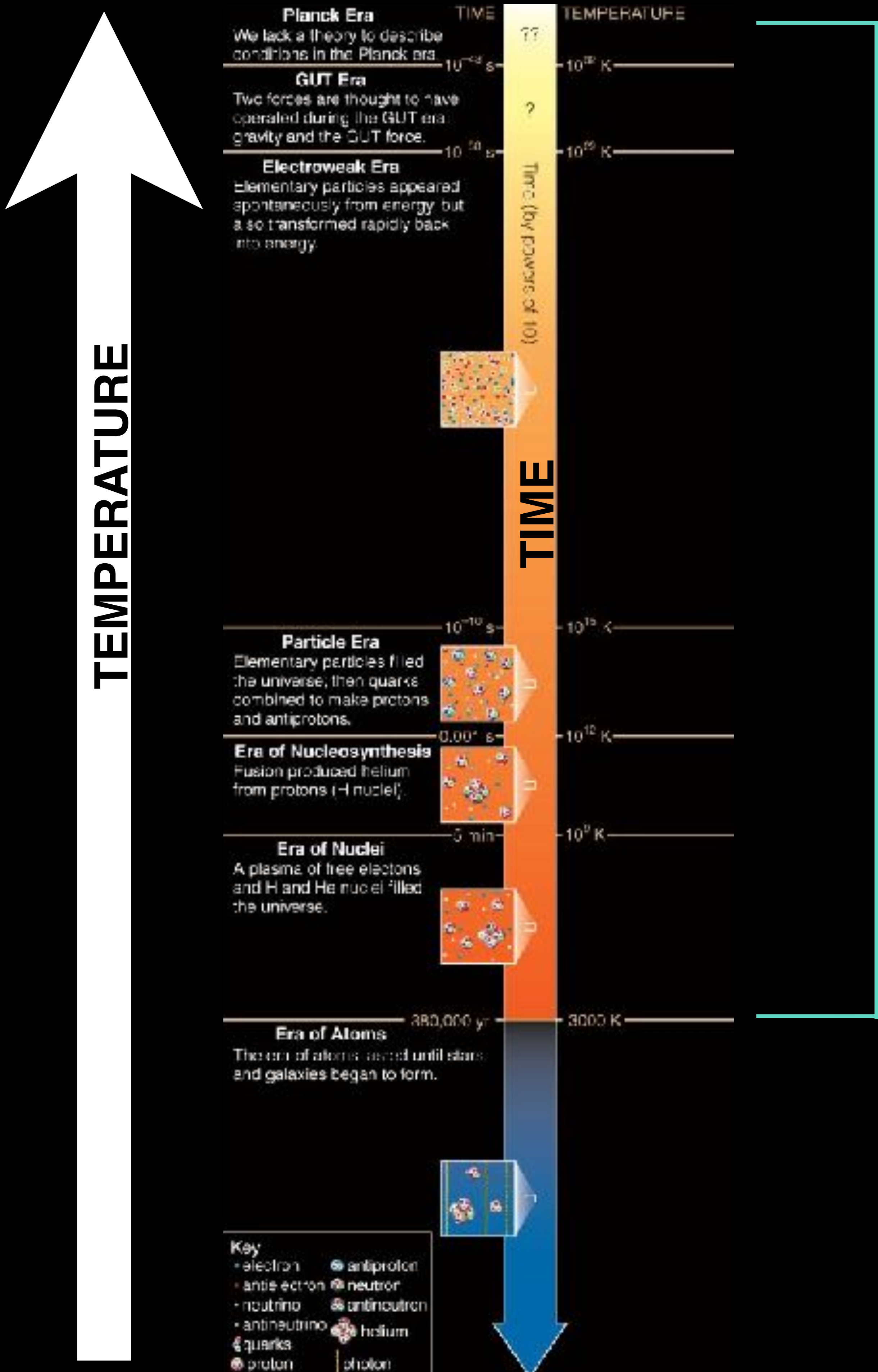


Not actual shape of universe!

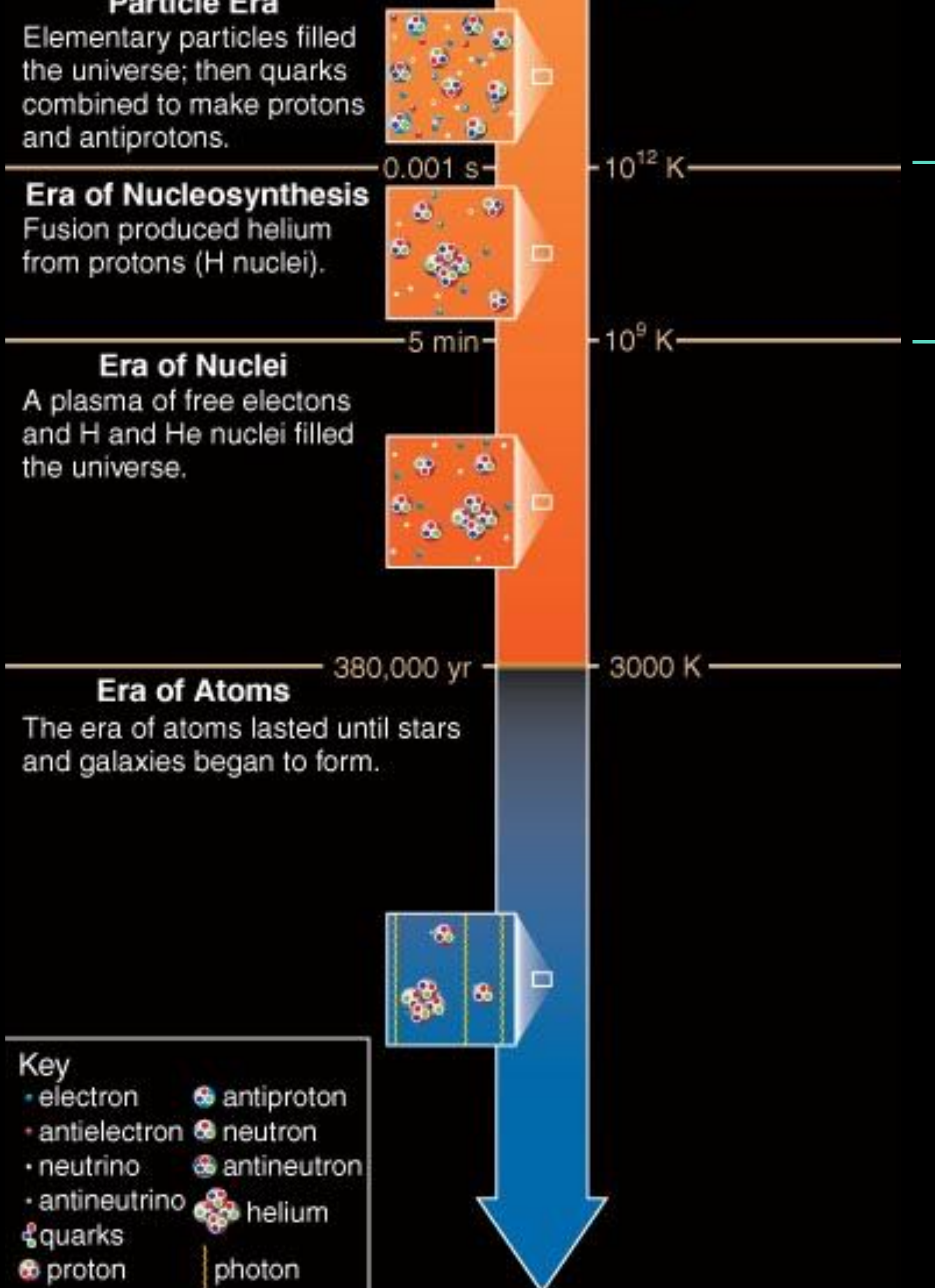
Present-day



As temperature increases, particles move faster and break apart into smaller particles.



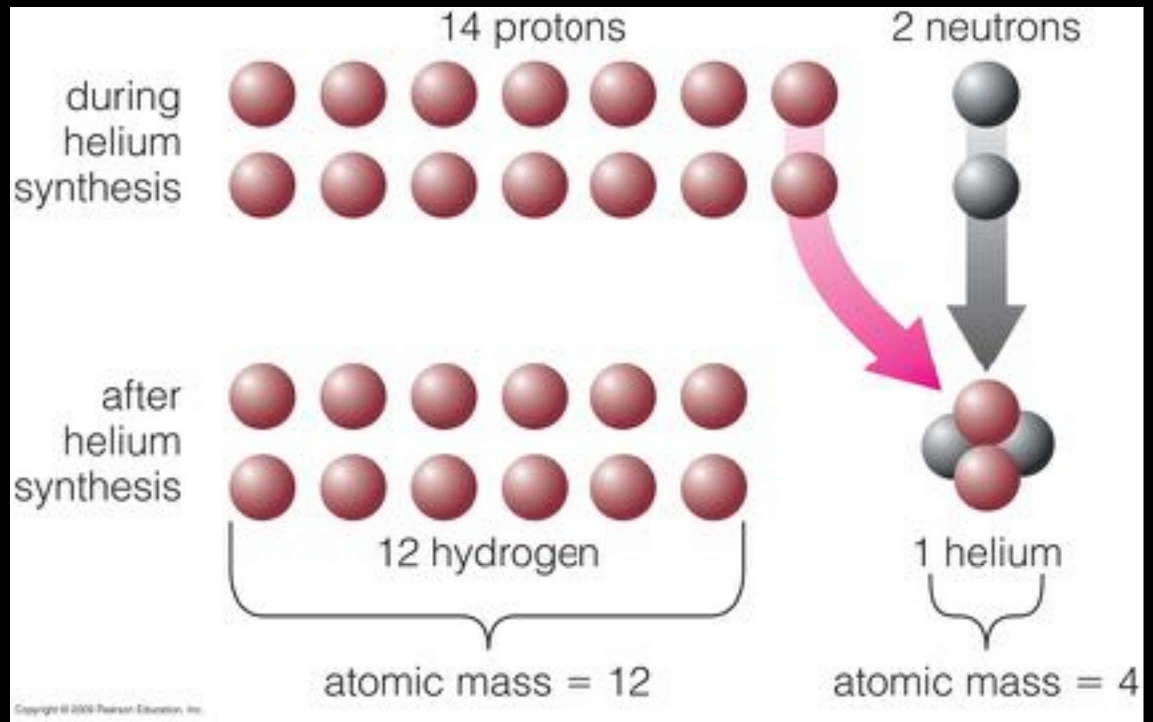
Our knowledge of what happened before the Era of Atoms is based on mathematical modeling and indirect evidence.

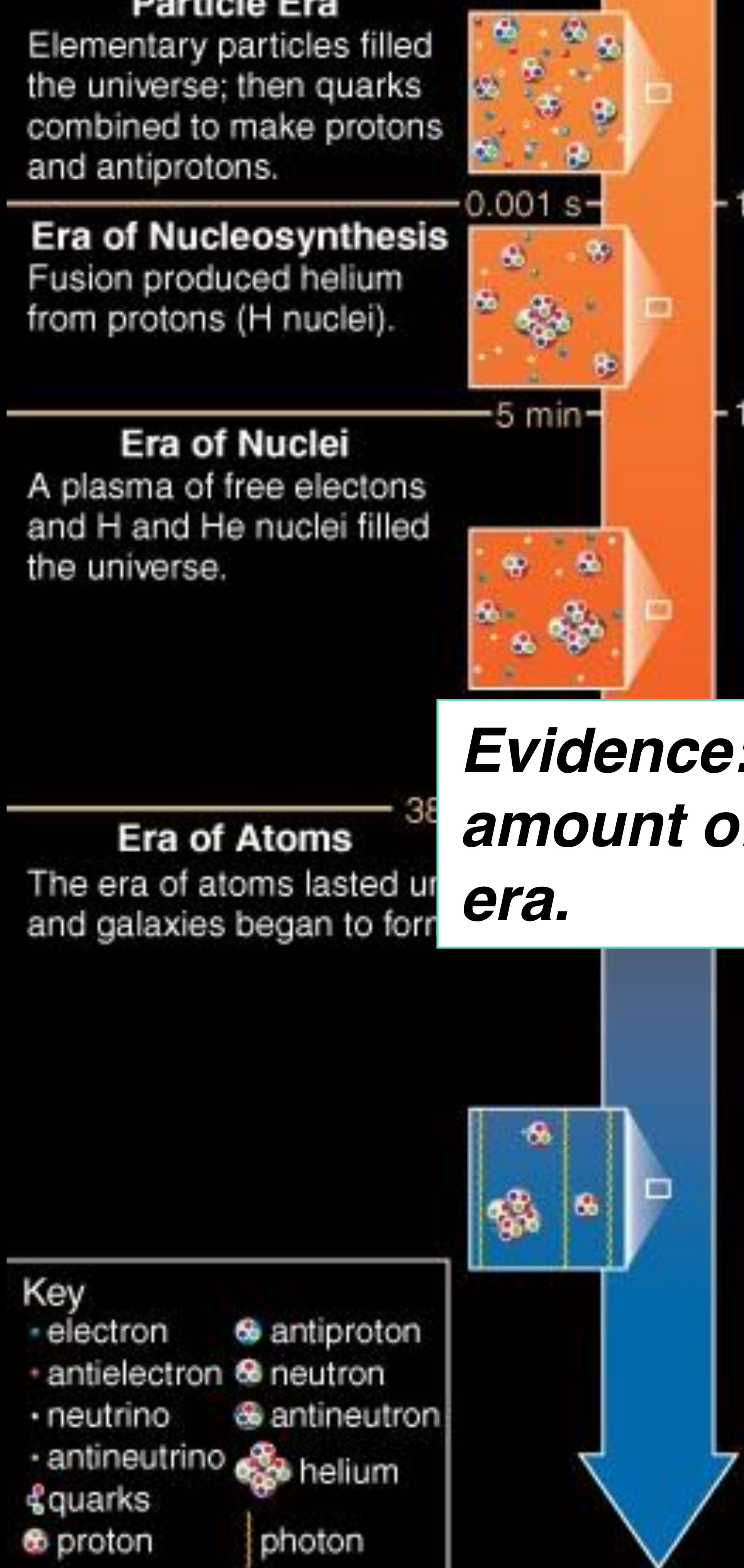


Era of Nucleosynthesis

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

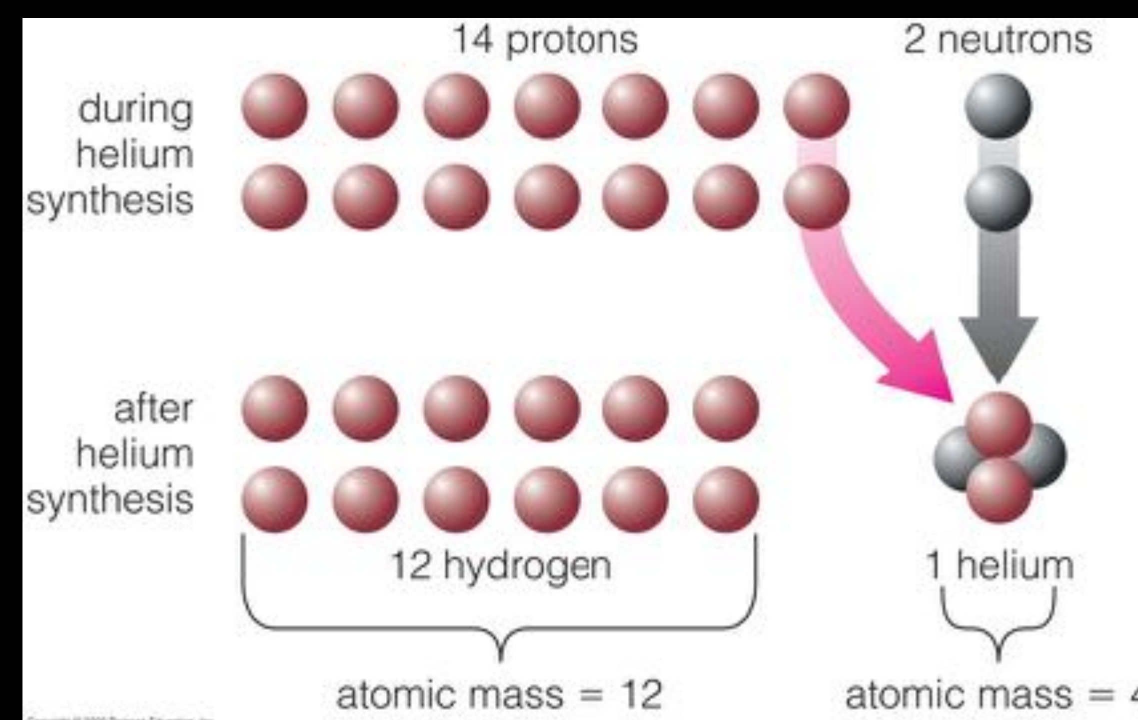




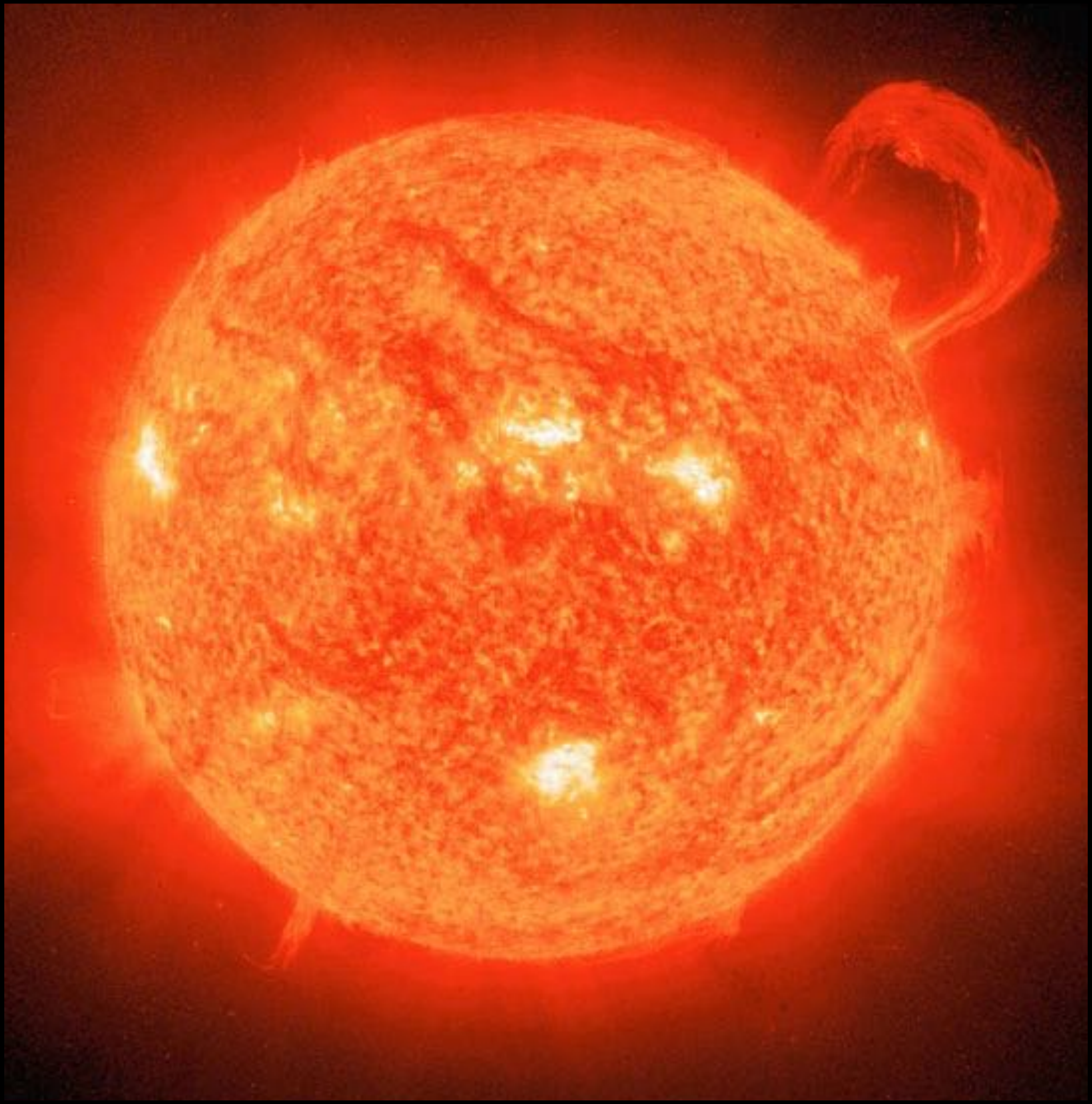
Era of Nucleosynthesis

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.



How do we make the rest? Also, how do stars shine?



The Sun

***Radius*:**
6.9×10^8 m
(109 times Earth)

Mass:
2×10^{30} kg
(300,000 Earths)

Luminosity:
3.8×10^{26} watts
(3.8×10^{26} J/s)

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

luminosity = power output in form of radiative energy

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

Thought Question

A 100-watt light bulb uses 100 J/s. How long will it glow if it's attached to a battery containing 10^5 J = 100,000 J?

A. 100 seconds

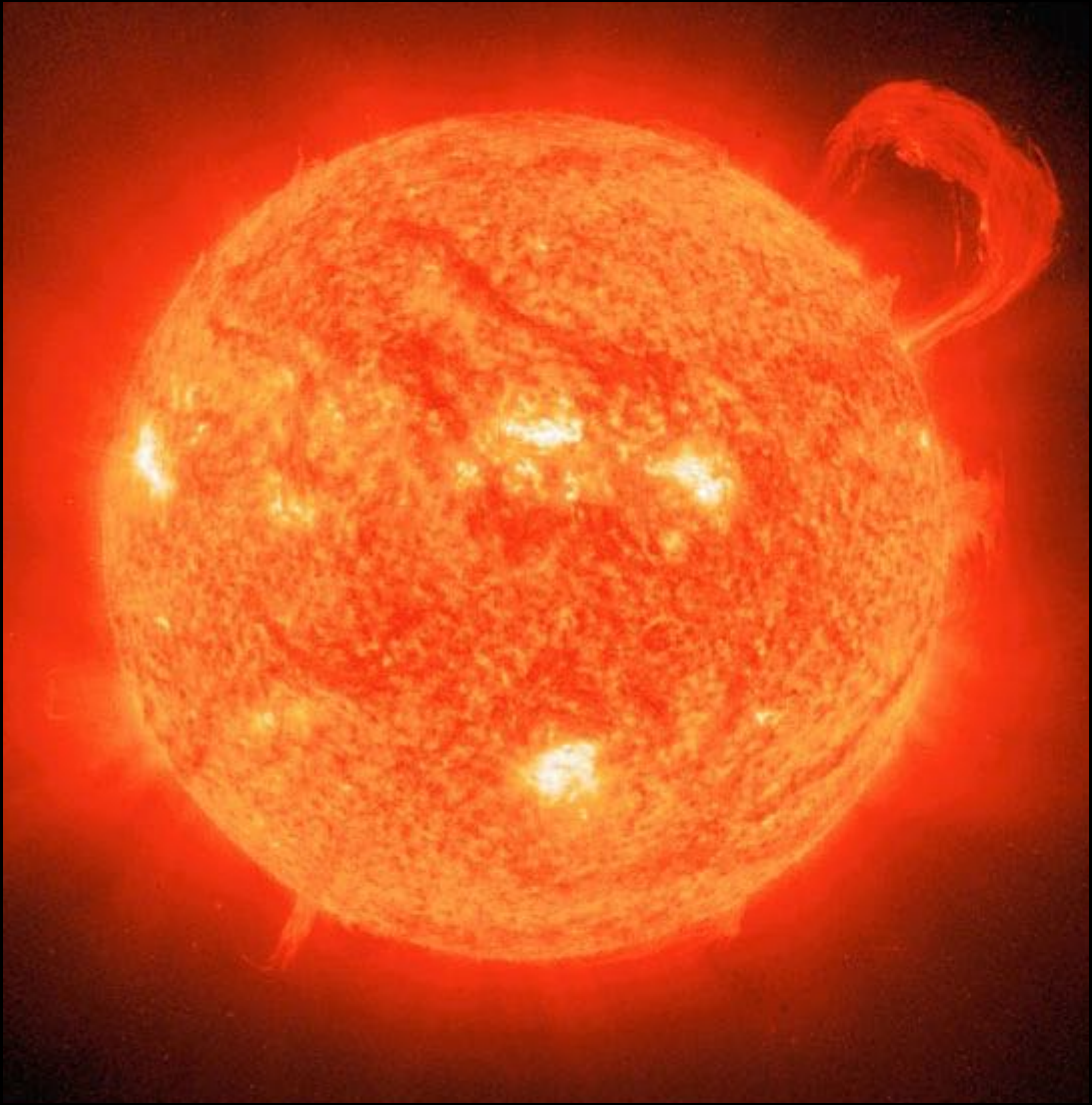
B. 1,000 seconds

C. 10,000 seconds

D. 100,000 seconds

Is it on FIRE (i.e. is it powered by chemical reactions)?

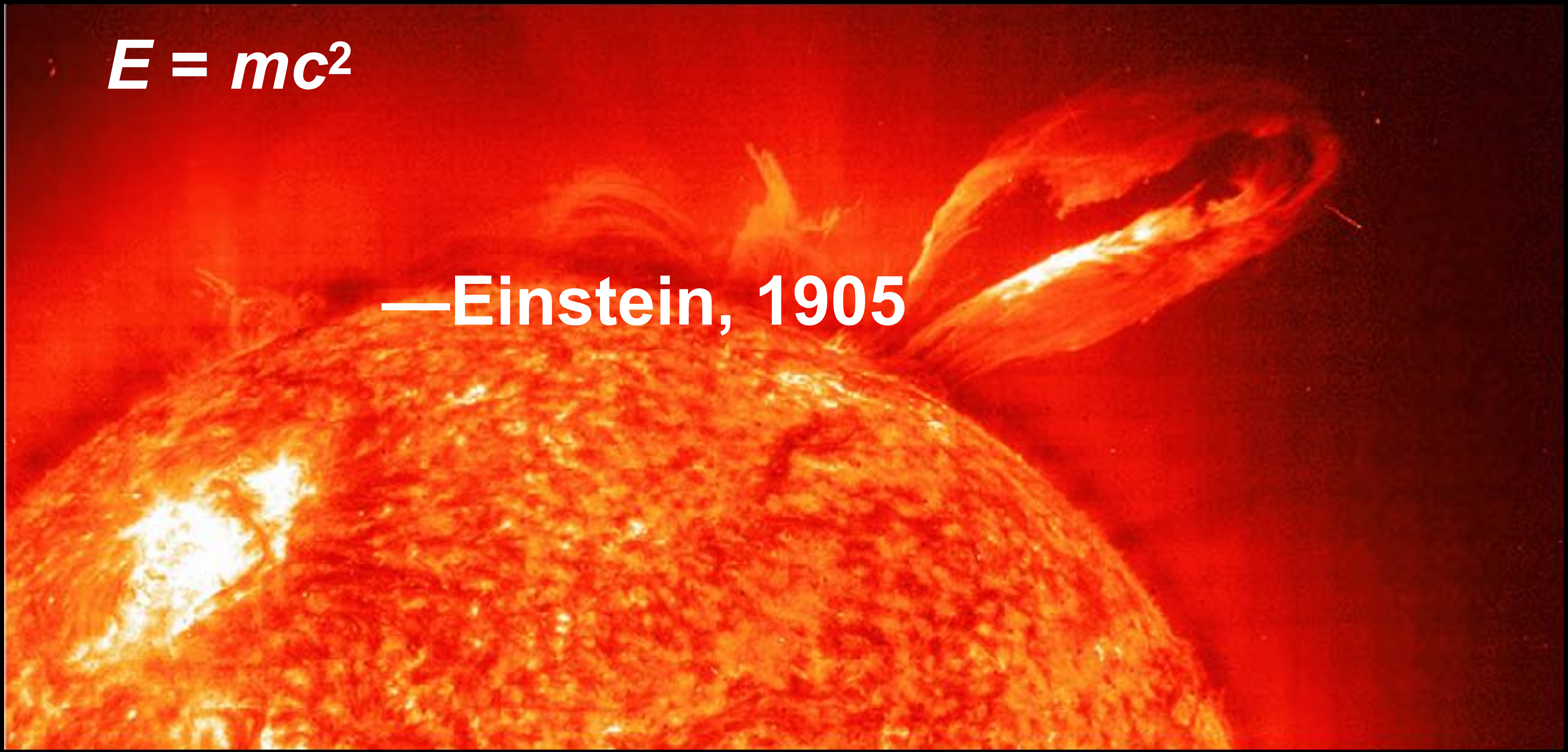
$$\frac{\text{Chemical Energy Content}}{\text{Luminosity}} \sim 10{,}000 \text{ years}$$



A contracting ball of gas turns gravitational potential energy into thermal energy

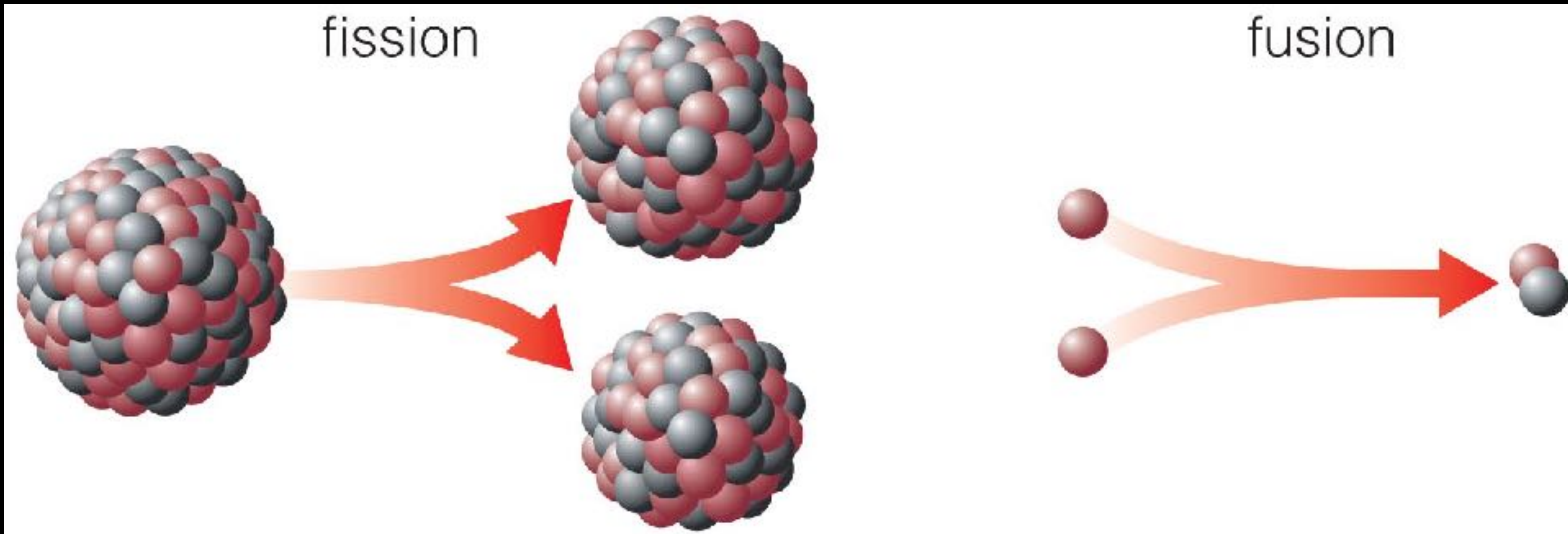
Is it CONTRACTING?

$$\frac{\text{Gravitational Potential Energy}}{\text{Luminosity}} \sim 25 \text{ million years}$$



Is it powered by nuclear energy?

$$\frac{\text{Nuclear Potential Energy (core)}}{\text{Luminosity}} \sim 10 \text{ billion years}$$



Fission

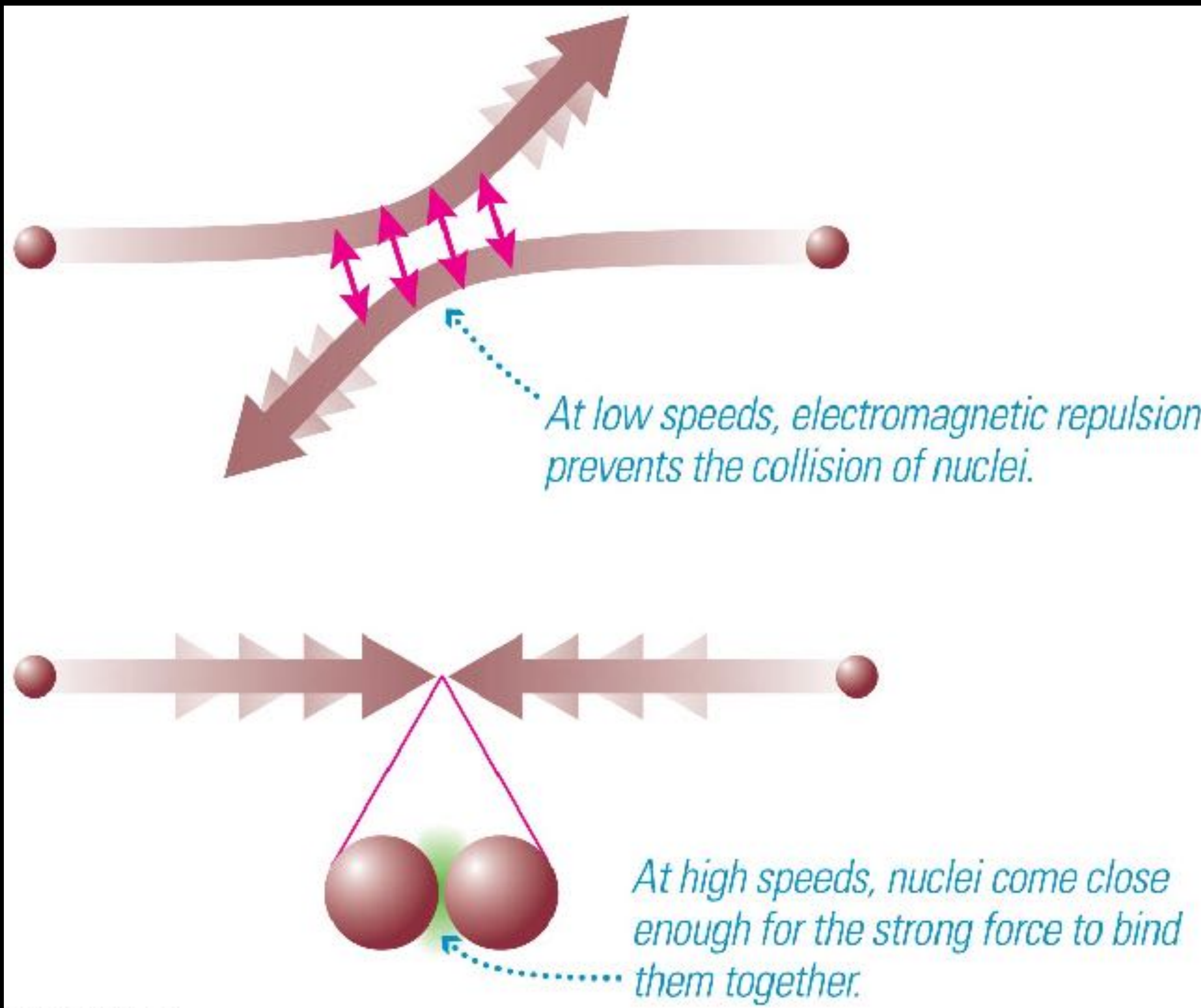
Big nucleus splits into smaller pieces.

(Nuclear power plants)

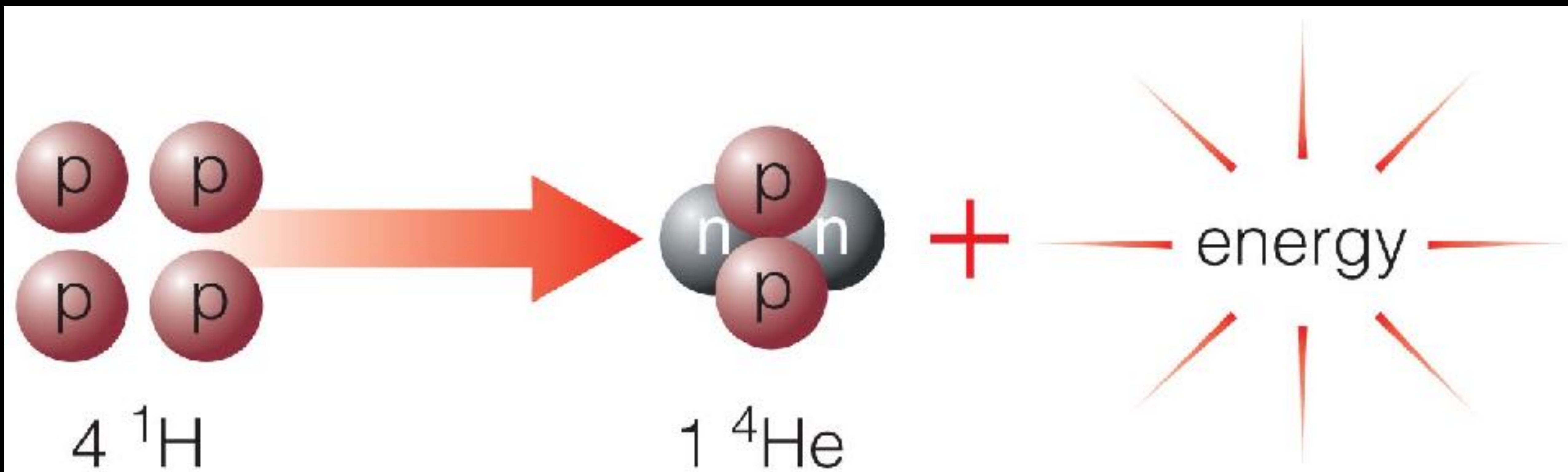
Fusion

Small nuclei stick together to make a bigger one.

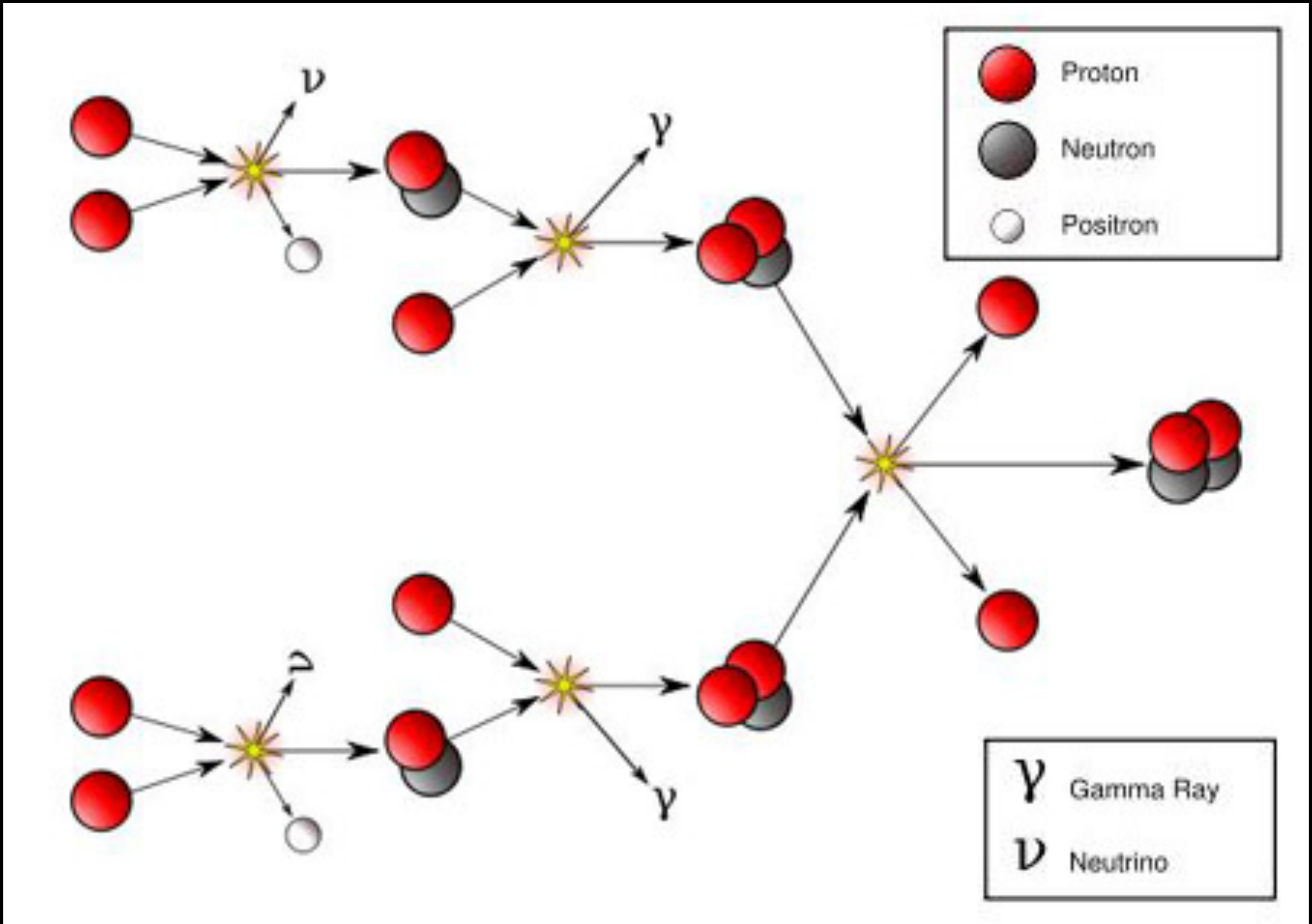
(Sun, stars)



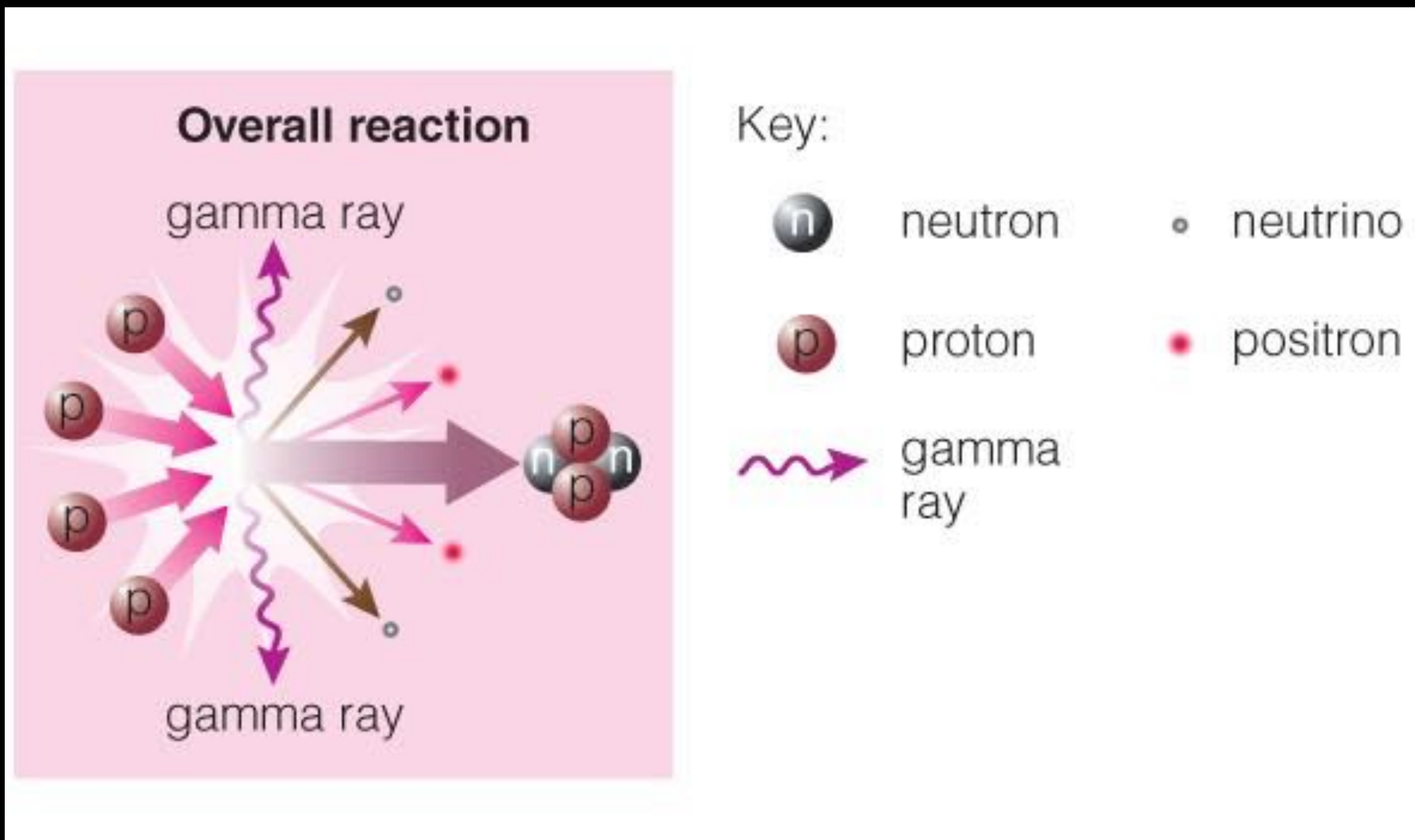
High temperatures enable nuclear fusion to happen in the core of a star.



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



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



__IN__
4 protons

__OUT__
^{4}He nucleus
2 gamma rays
2 positrons
2 neutrinos

Total mass is 0.7% lower.

Sun's Energy Content

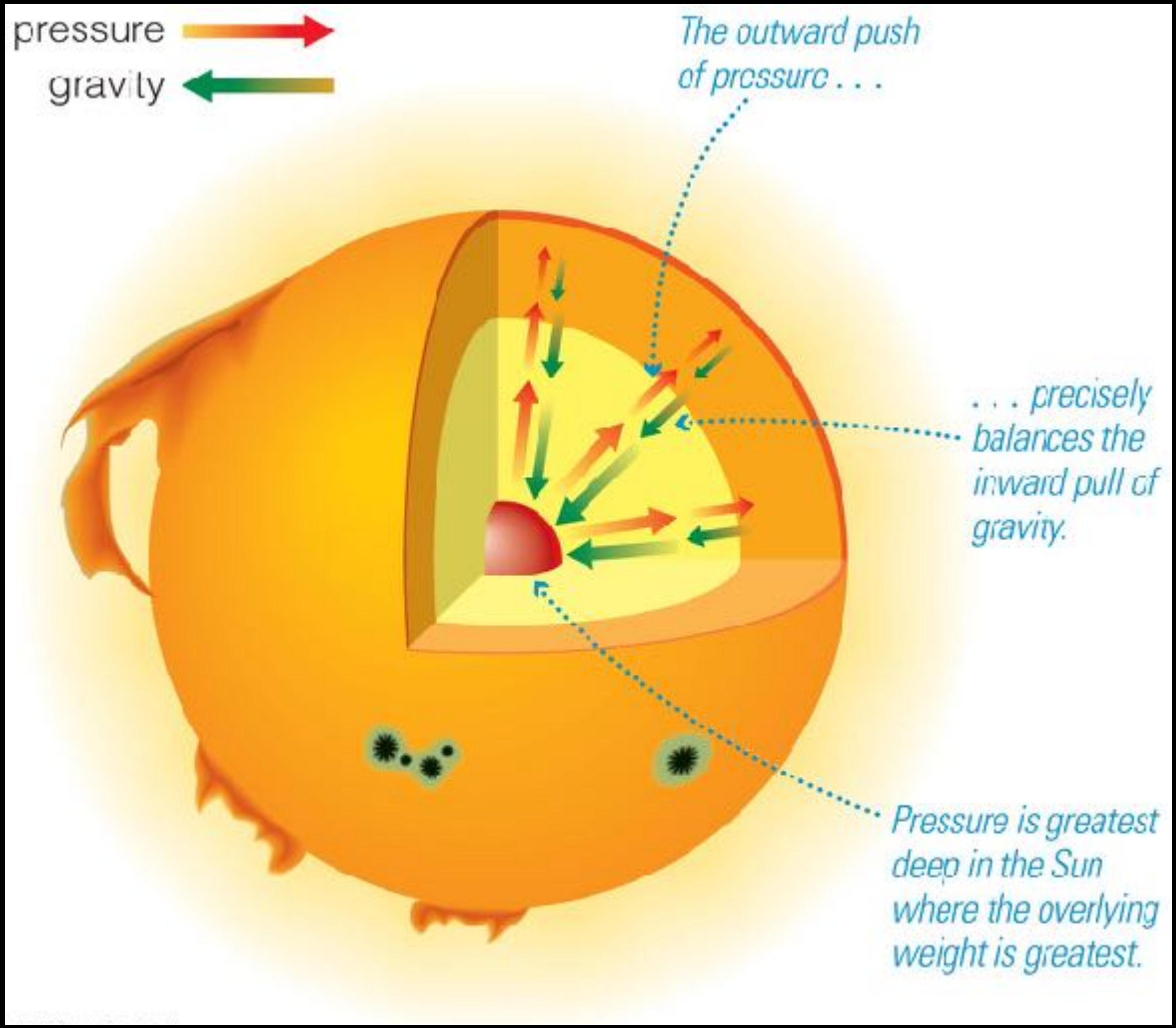
Chem. energy = 4×10^{38} J (~ 30,000 yr)

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

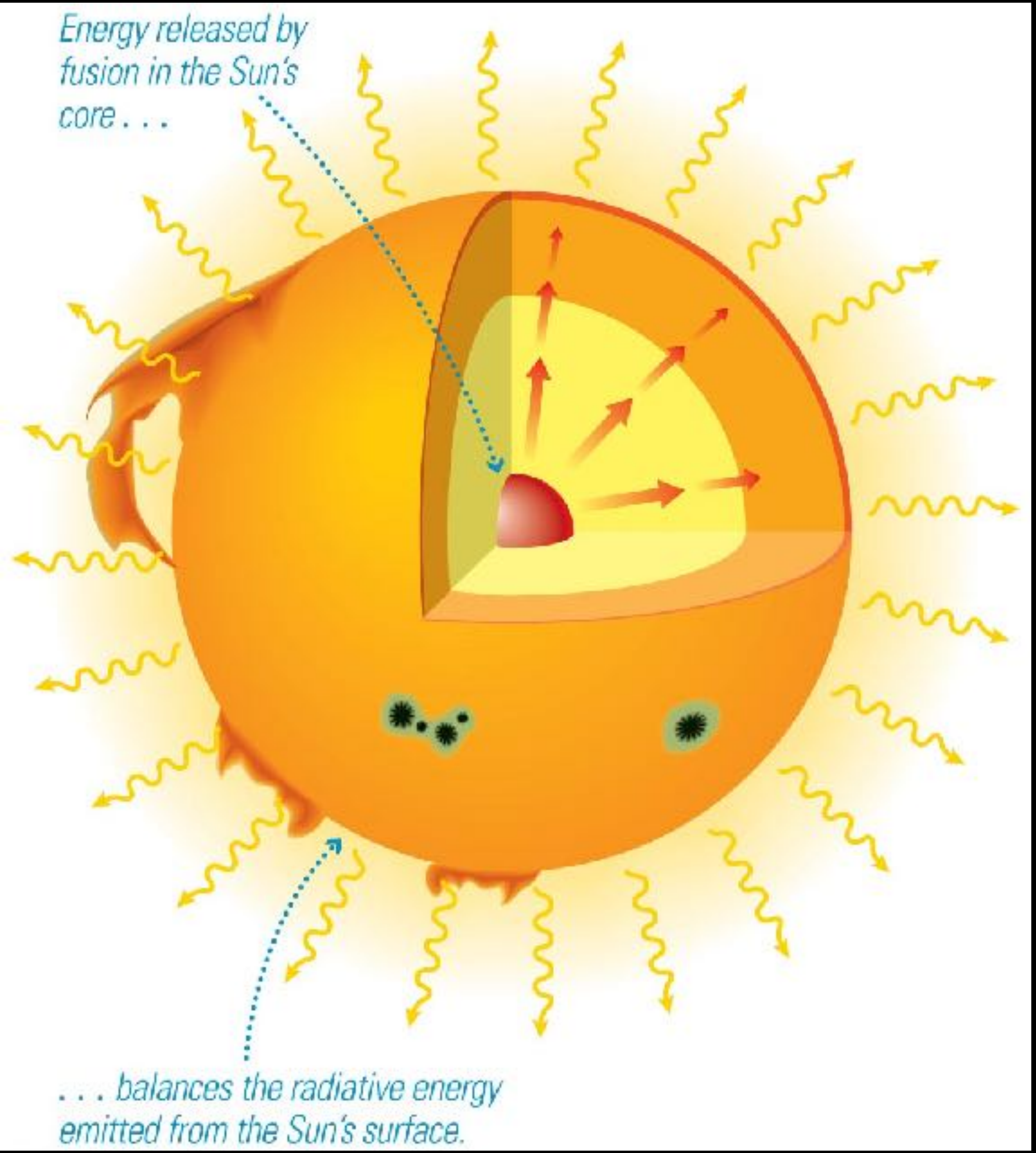
Nuclear energy = 1×10^{45} J (~ 100 billion yr)*

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

*Only about 10% will be used

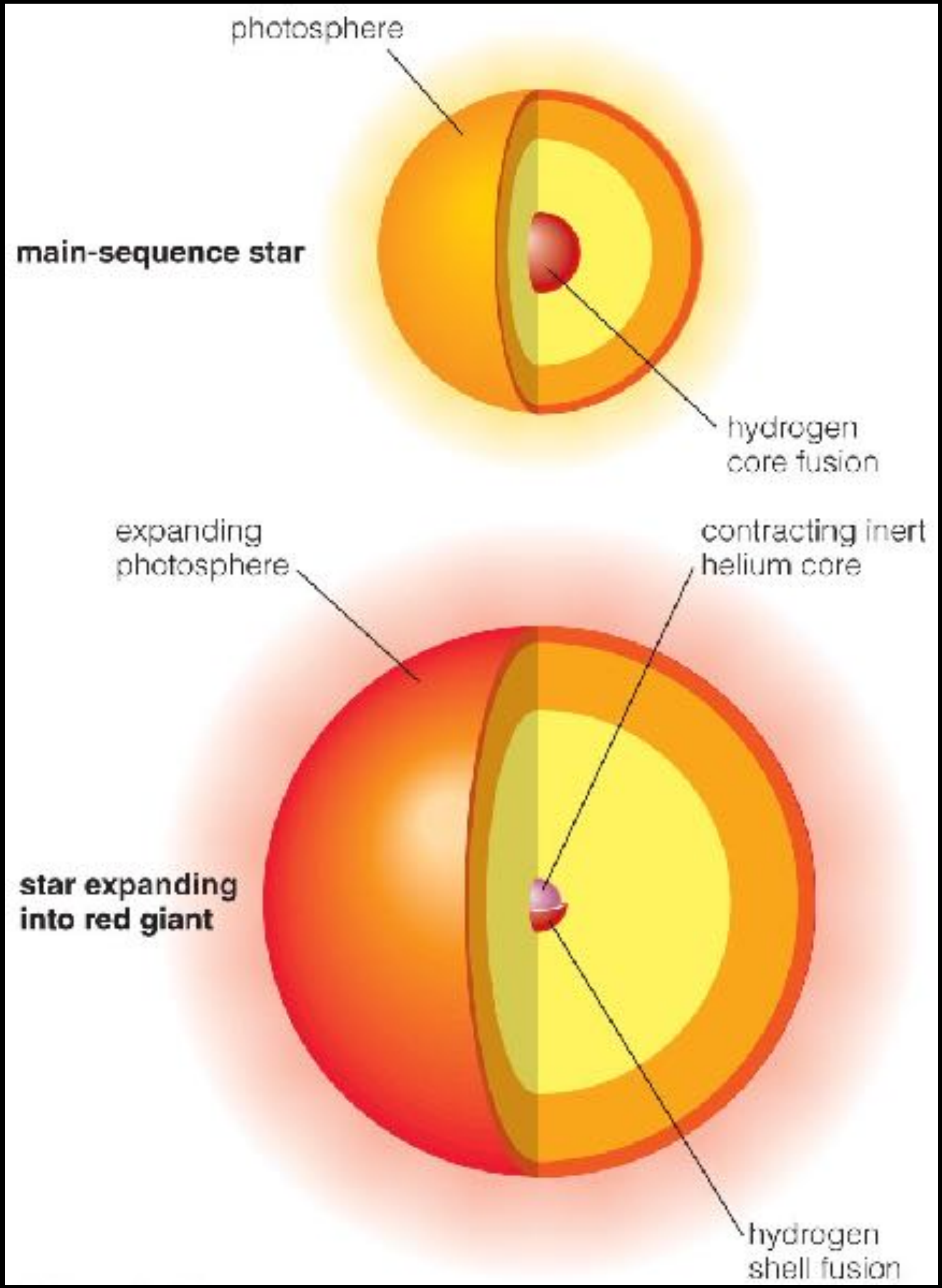


Gravitational equilibrium: Gravity pulling in balances pressure pushing out.



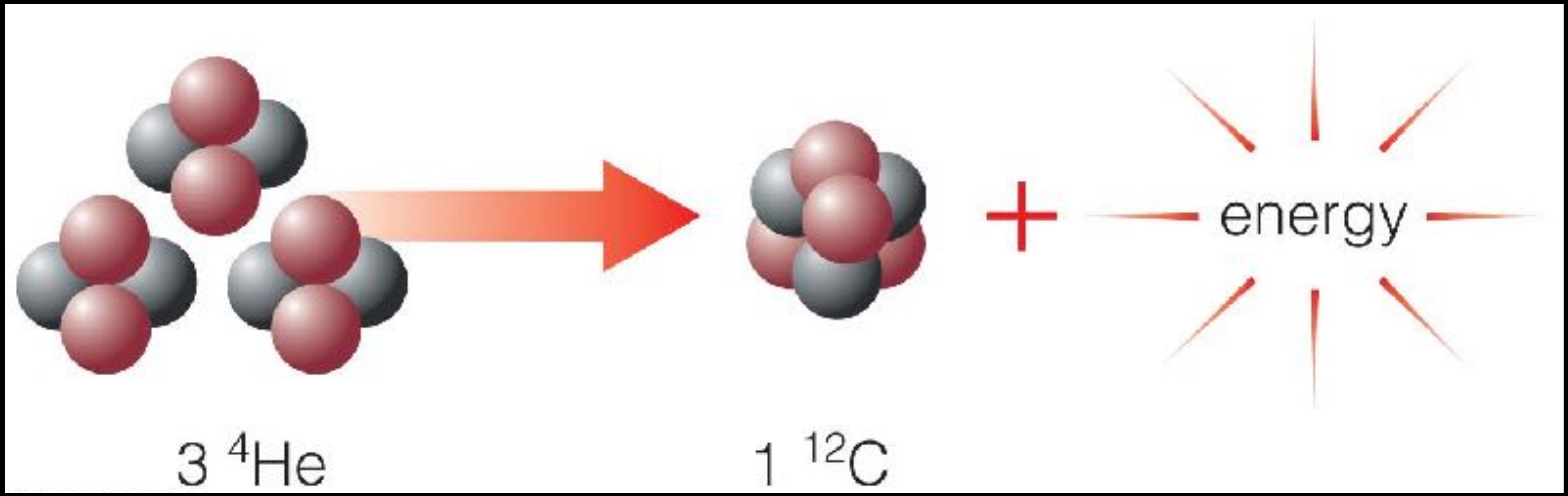
Energy balance: Thermal energy released by fusion in core balances radiative energy lost from surface.

Broken Thermostat



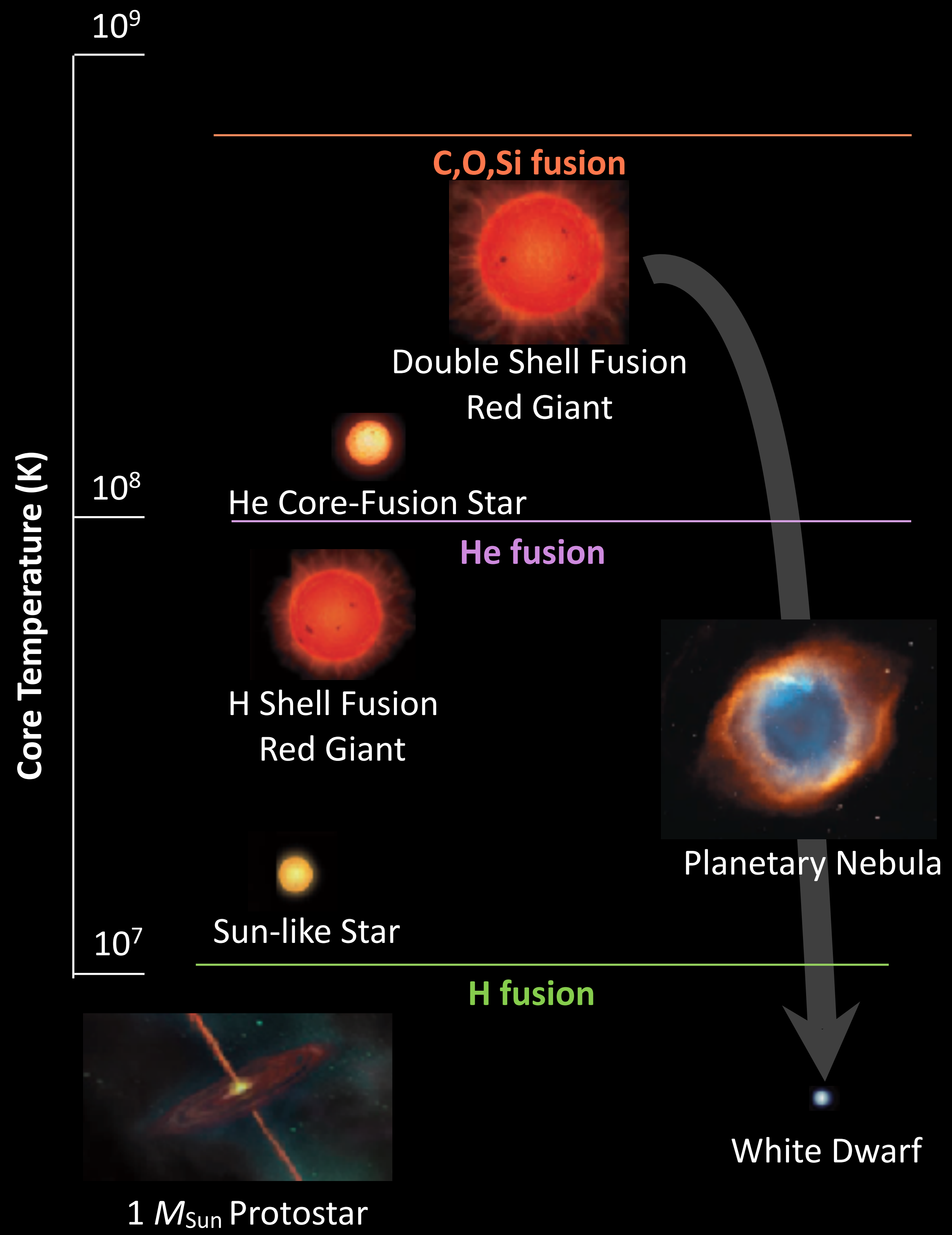
- As the core contracts, H begins fusing to He in a shell around the core.
- Luminosity increases because the core thermostat is broken—the increasing fusion rate in the shell does not stop the core from contracting.

What Happens When the Hydrogen Runs Out?



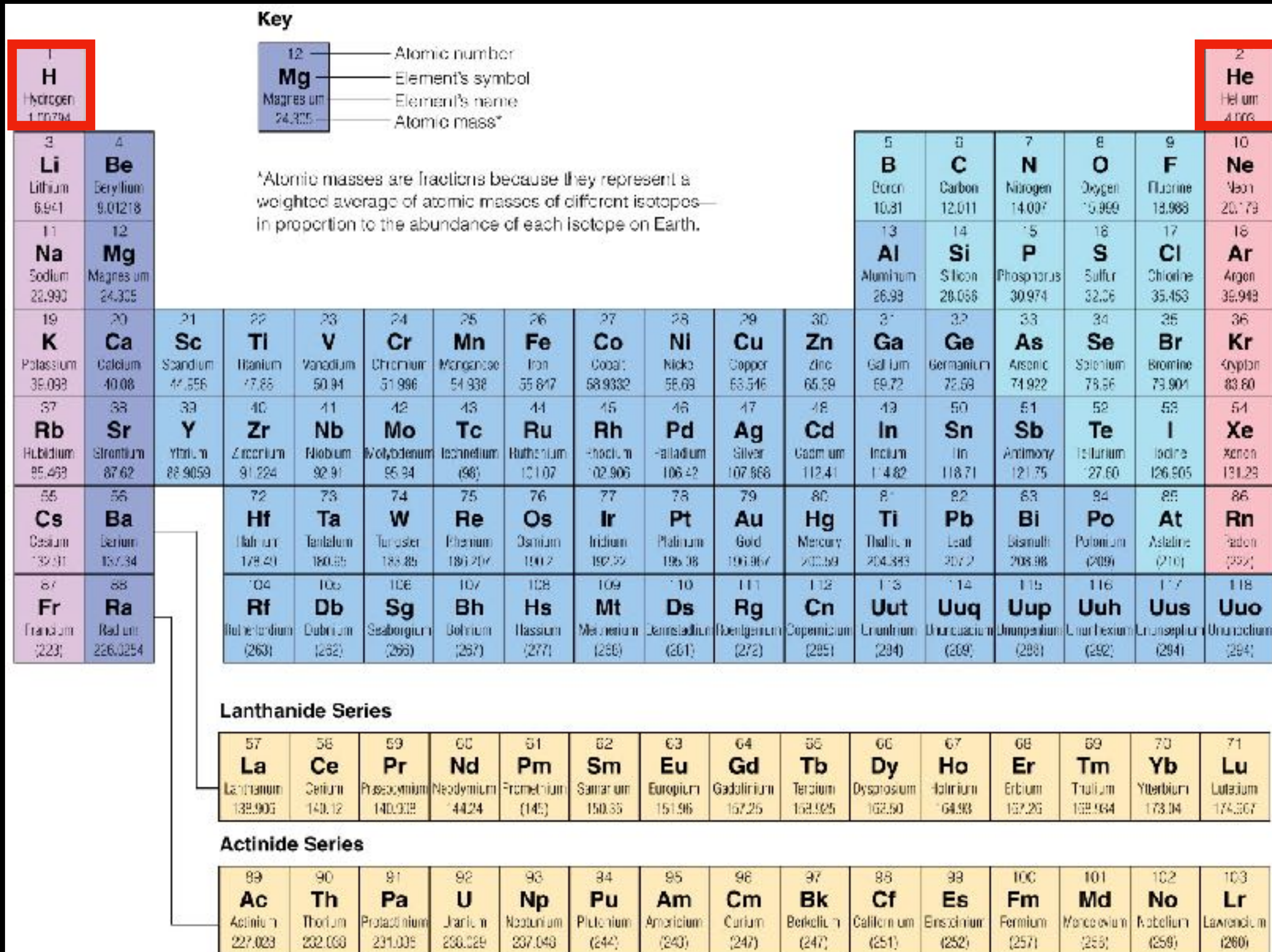
- Helium fusion does not begin right away because it requires higher temperatures than hydrogen fusion—larger charge leads to greater repulsion.
- The fusion of two helium nuclei doesn't work, so helium fusion must combine three He nuclei to make carbon.

Life Stages of a Low-Mass Star

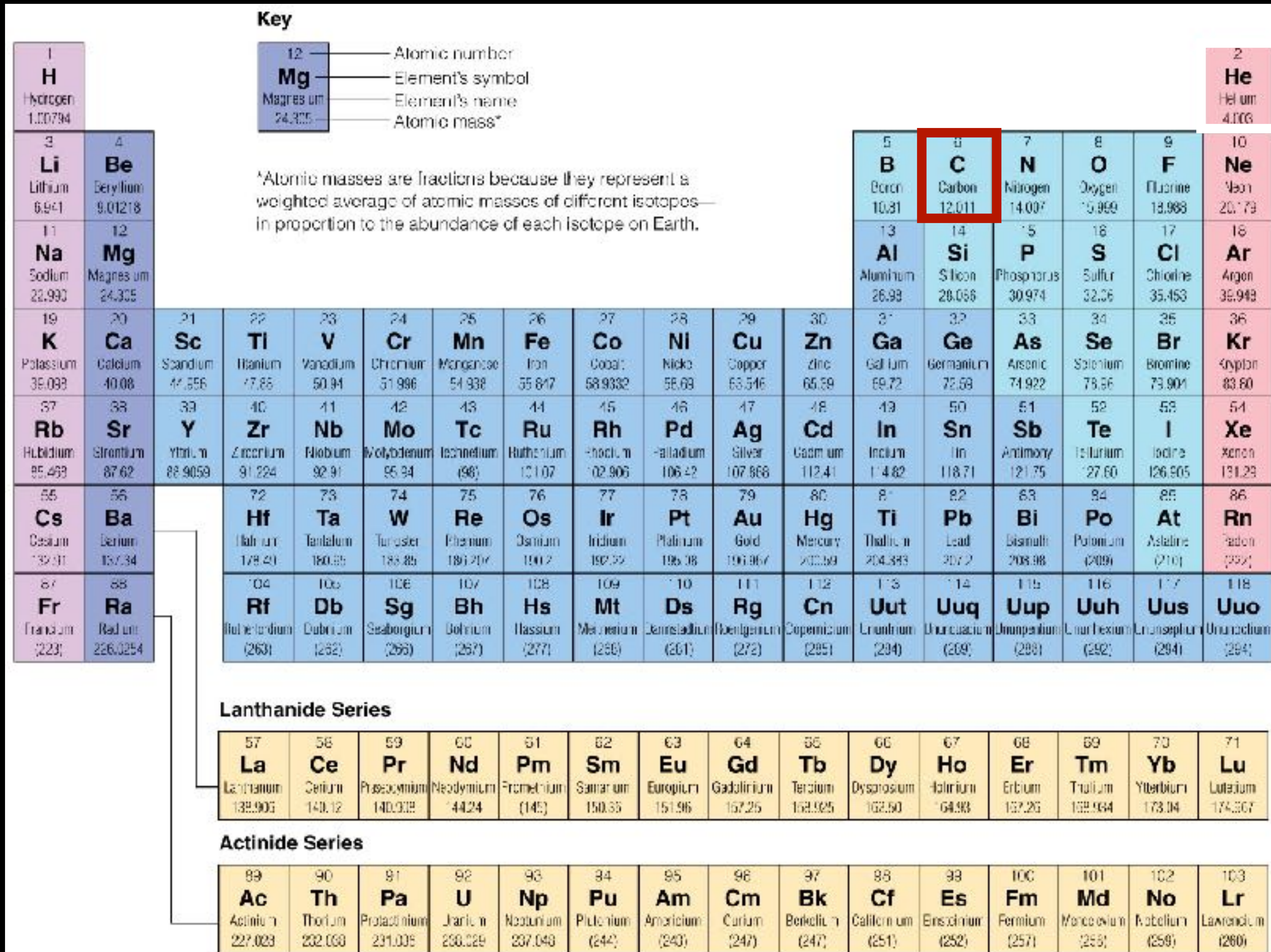


Not to scale!

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



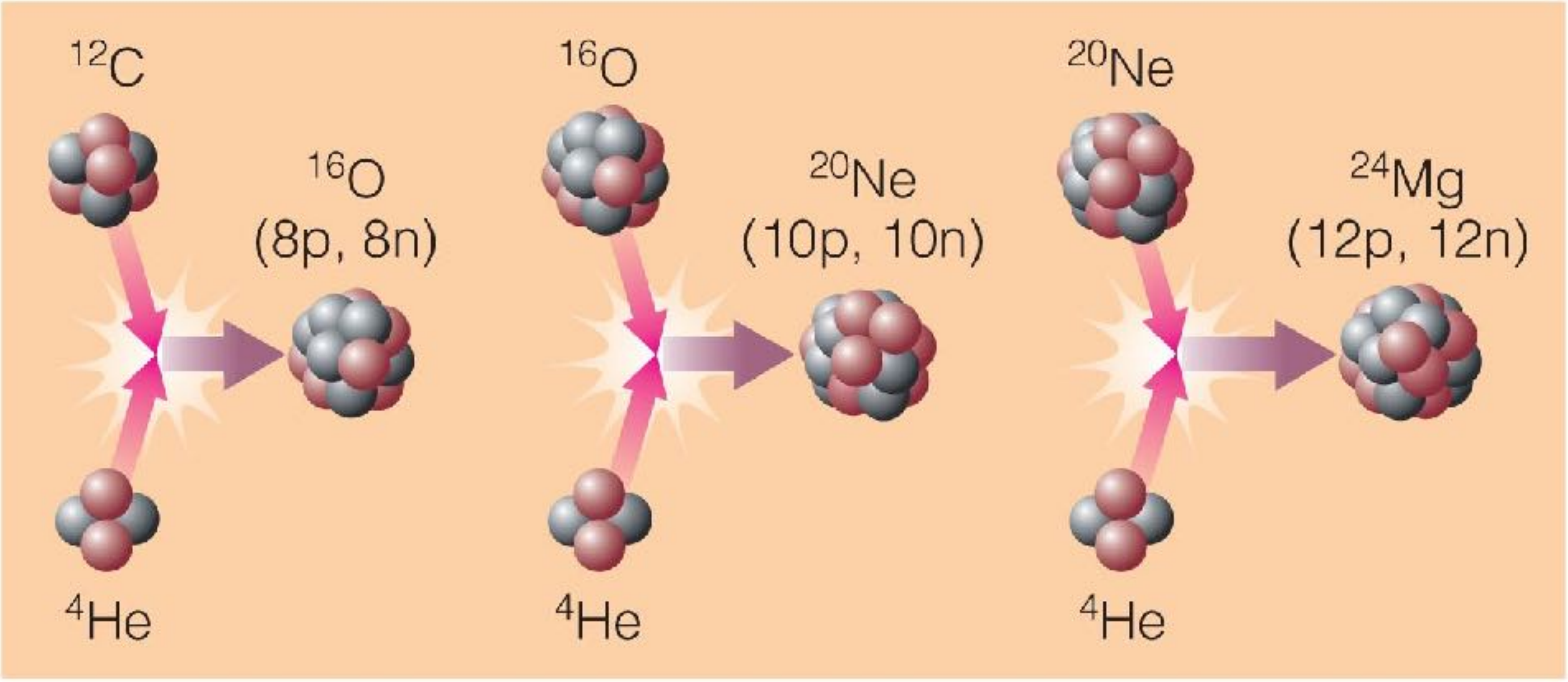
Big Bang made 75% H, 25% He—stars make everything else.



Helium fusion can make carbon in low-mass stars.

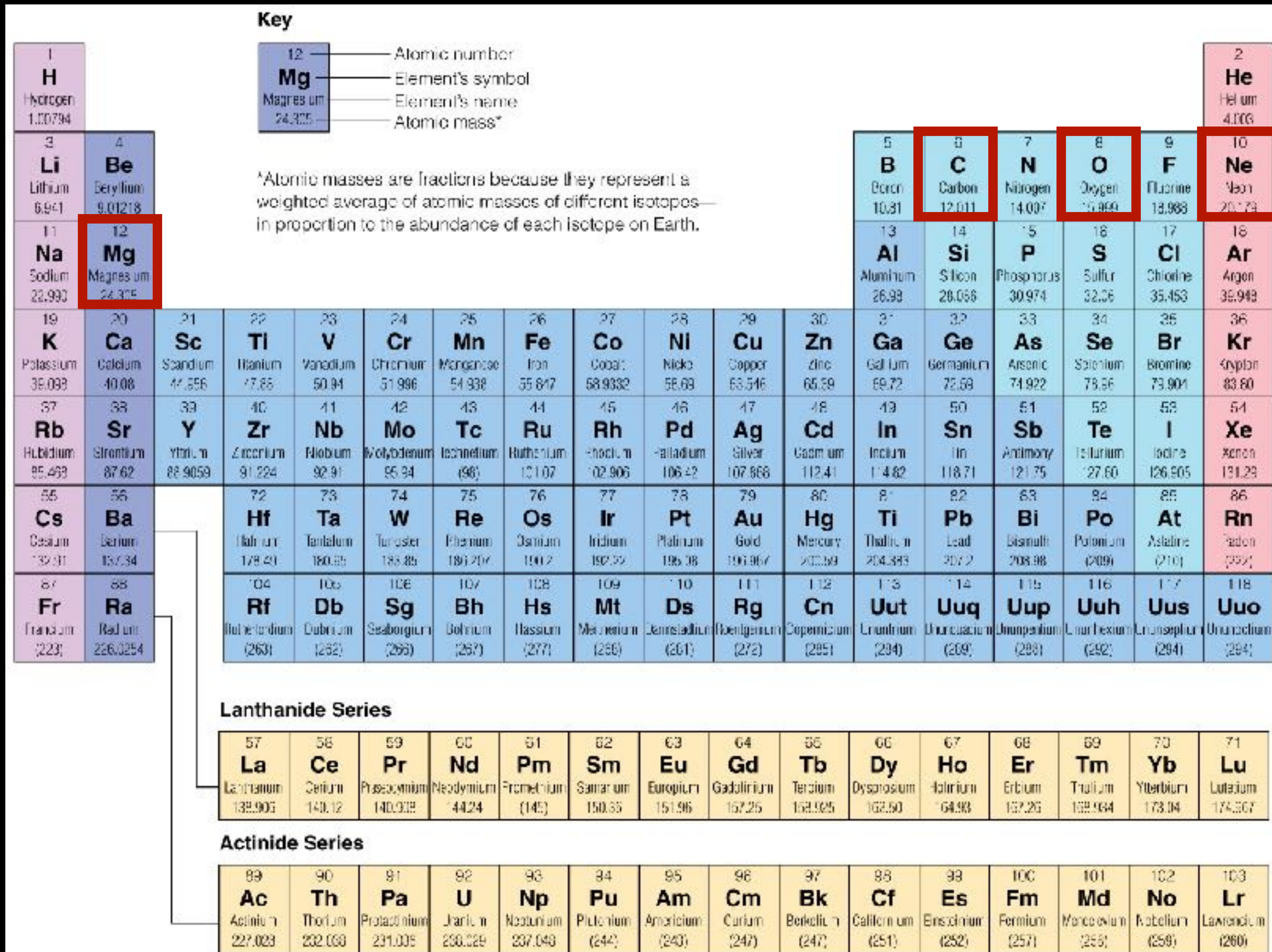
What happens in more massive stars?

Helium Capture



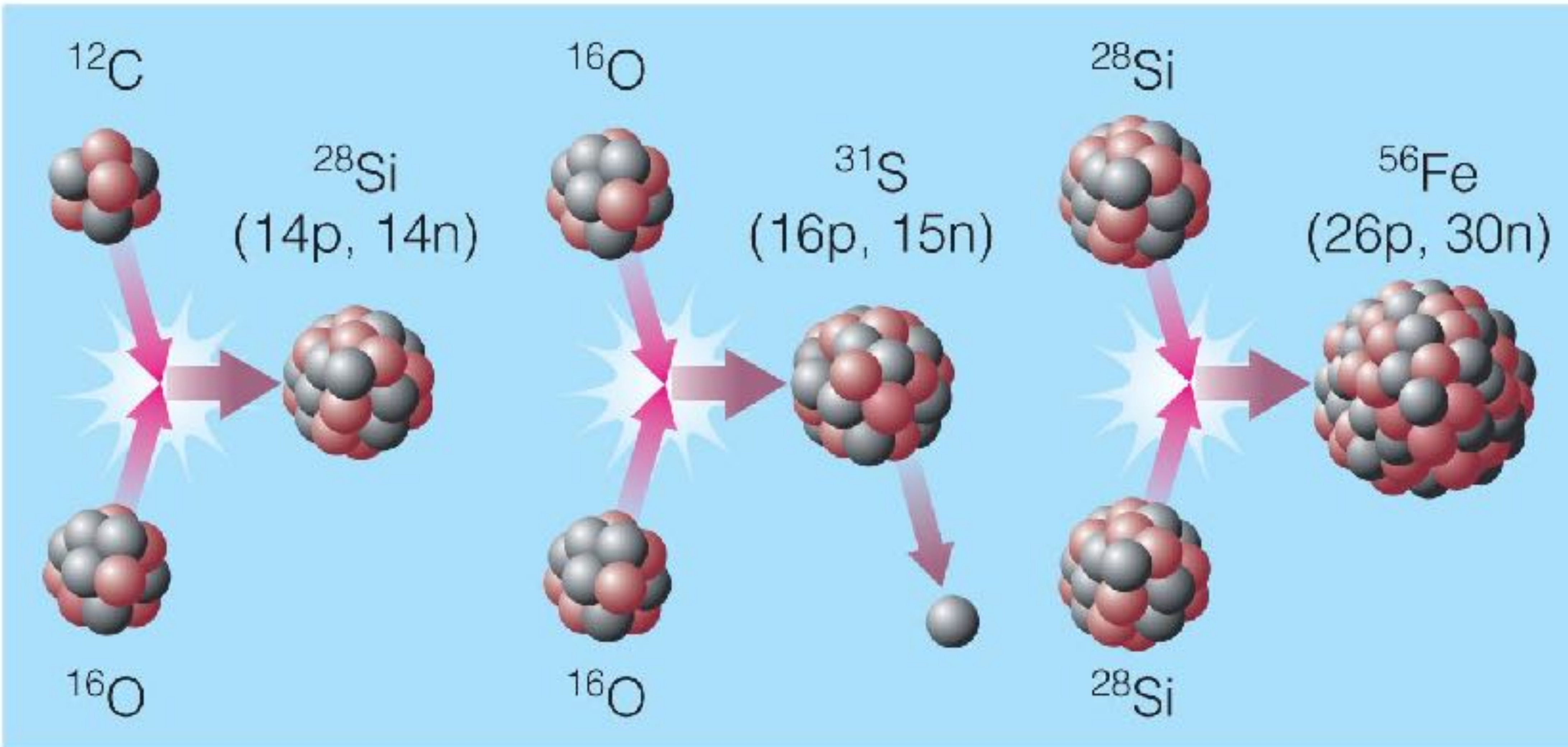
a Helium-capture reactions.

- High core temperatures in more massive stars allow helium to fuse with heavier elements.



Helium capture builds C into O, Ne, Mg …

Advanced Nuclear Burning



b Other reactions. (Note: Fusion of two silicon nuclei first produces nickel-56, which decays rapidly to cobalt-56 and then to iron-56.)

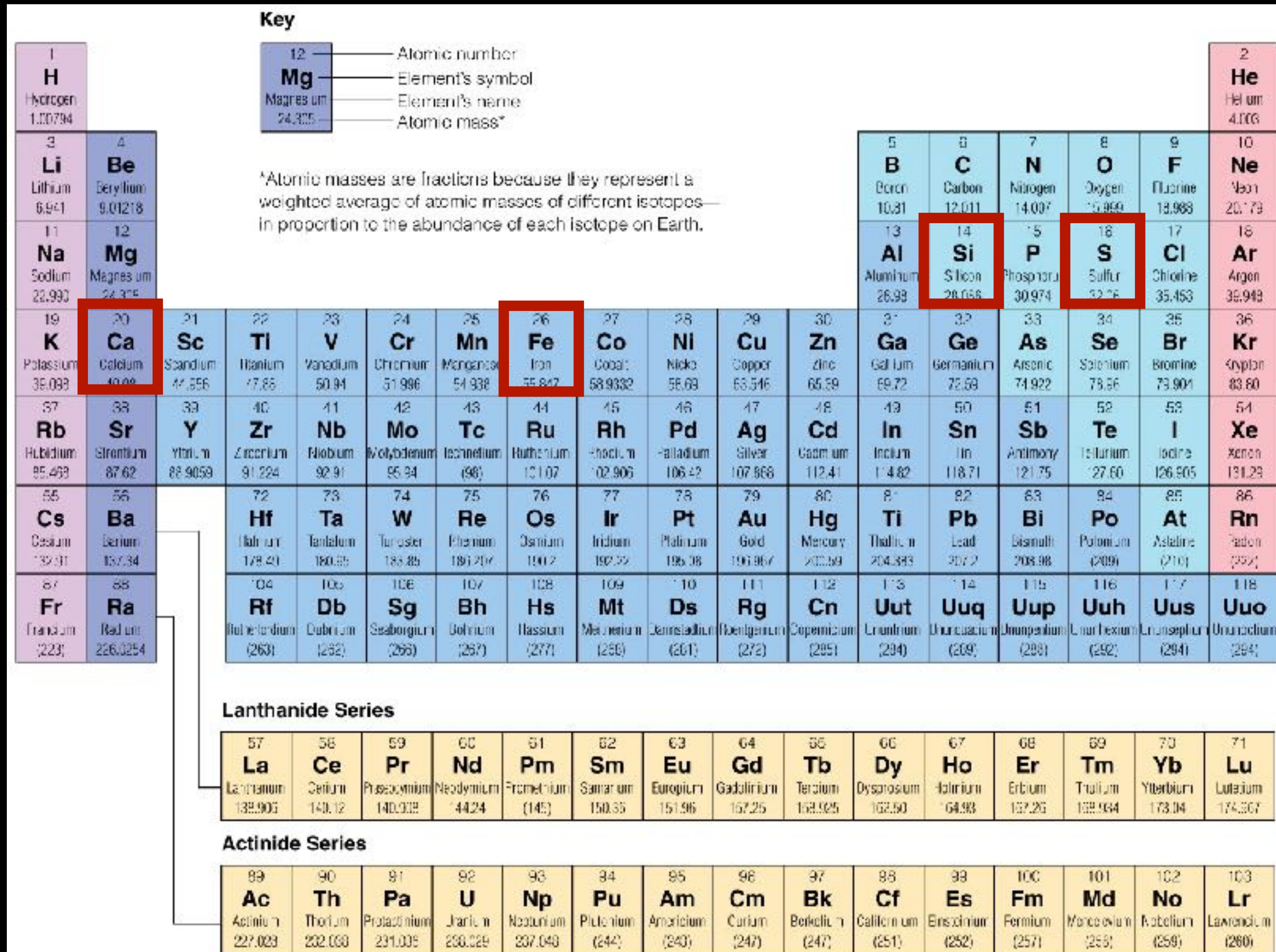
Core temperatures in stars with $>8M_{Sun}$ allow fusion of elements as heavy as iron.

SUMMARY

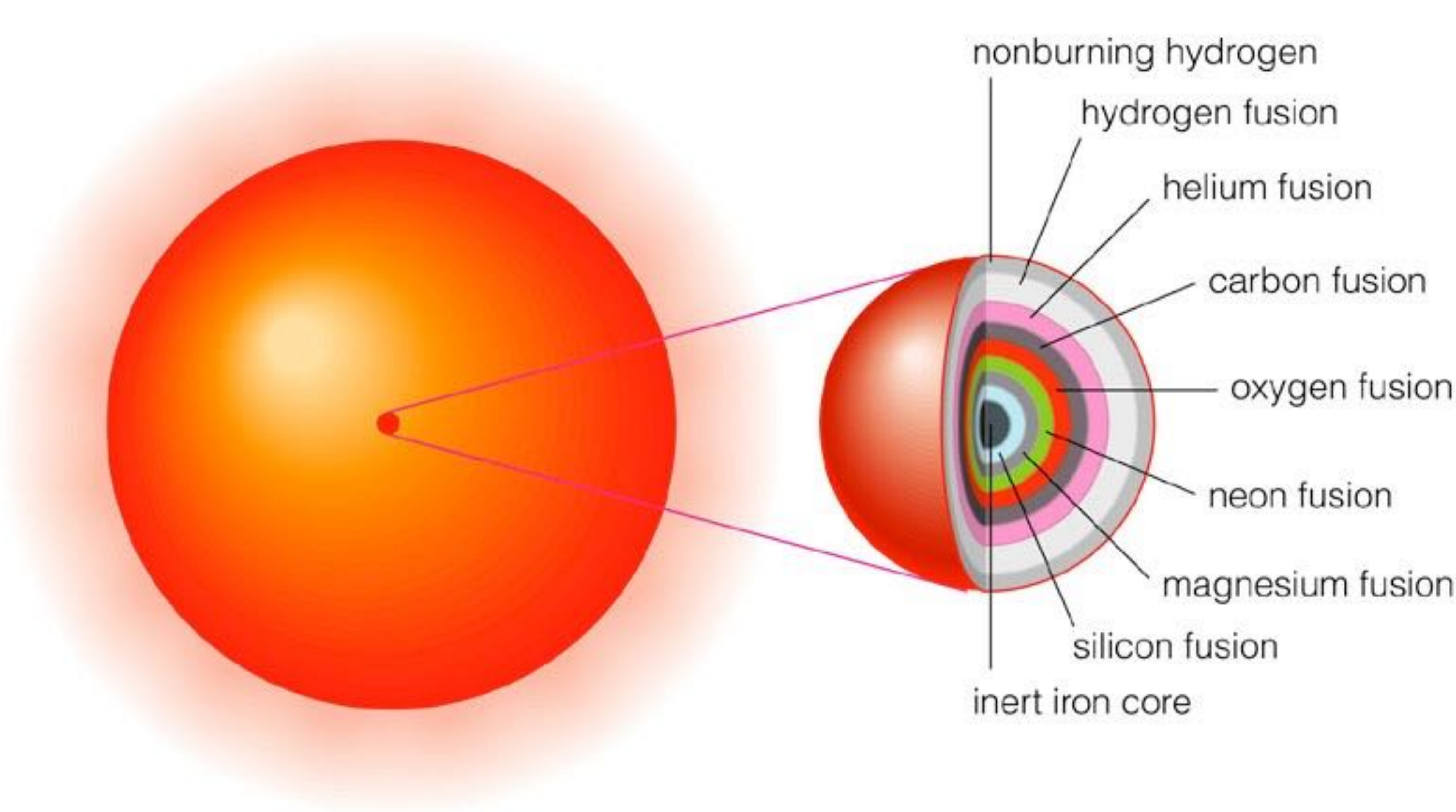
Advanced Nuclear Burning Stages

(e.g., 20 solar masses)

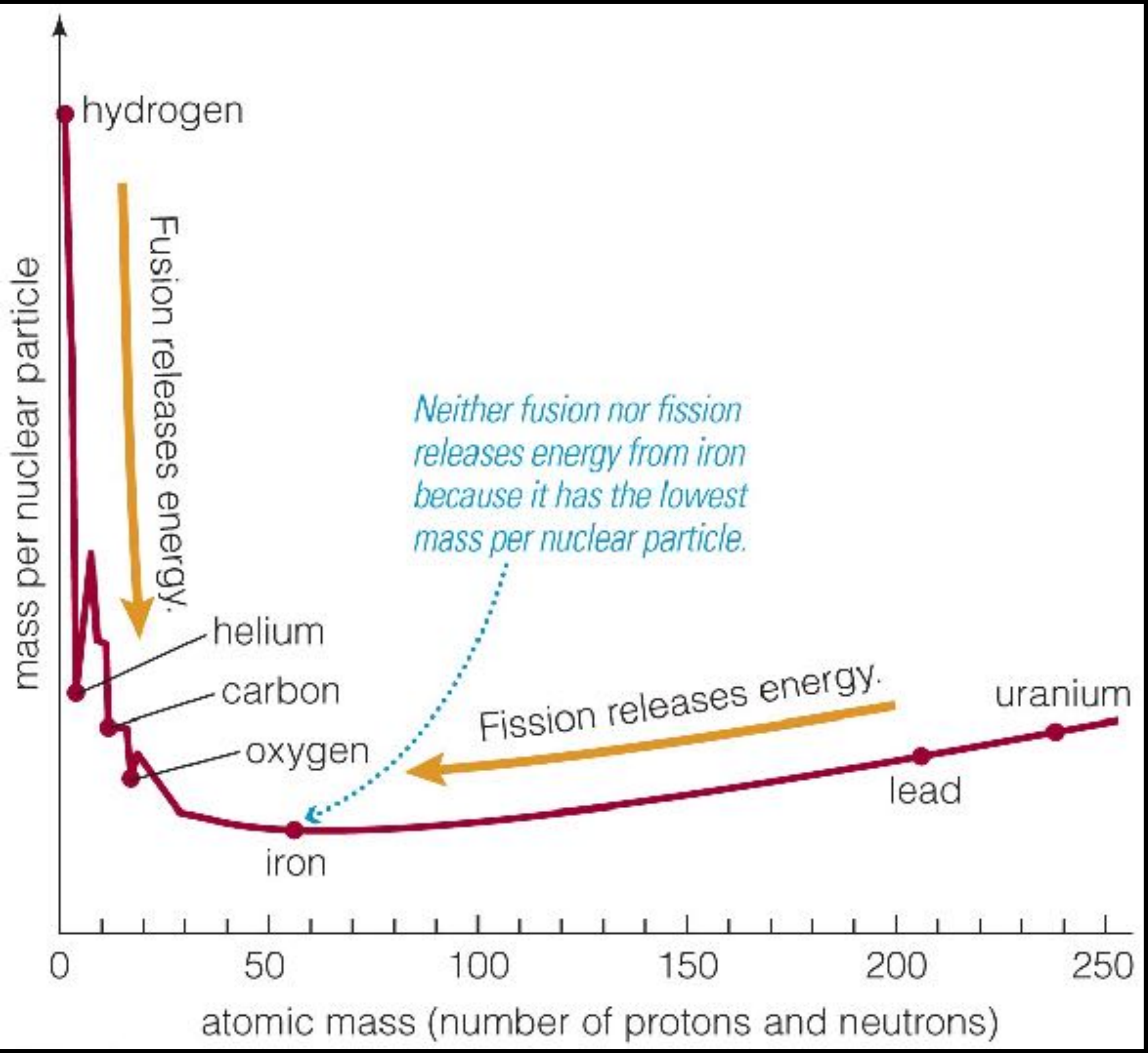
Fuel	Main Product	Secondary Products	Temp (10^9 K)	Time (yr)
H	He	^{14}N	0.02	10^7
He	C,O	^{18}O, ^{22}Ne s- process	0.2	10^6
C	Ne, Mg	Na	0.8	10^3
Ne	O, Mg	Al, P	1.5	3
O	Si, S	Cl, Ar K, Ca	2.0	0.8
Si	Fe	Ti, V, Cr Mn, Co, Ni	3.5	1 week



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



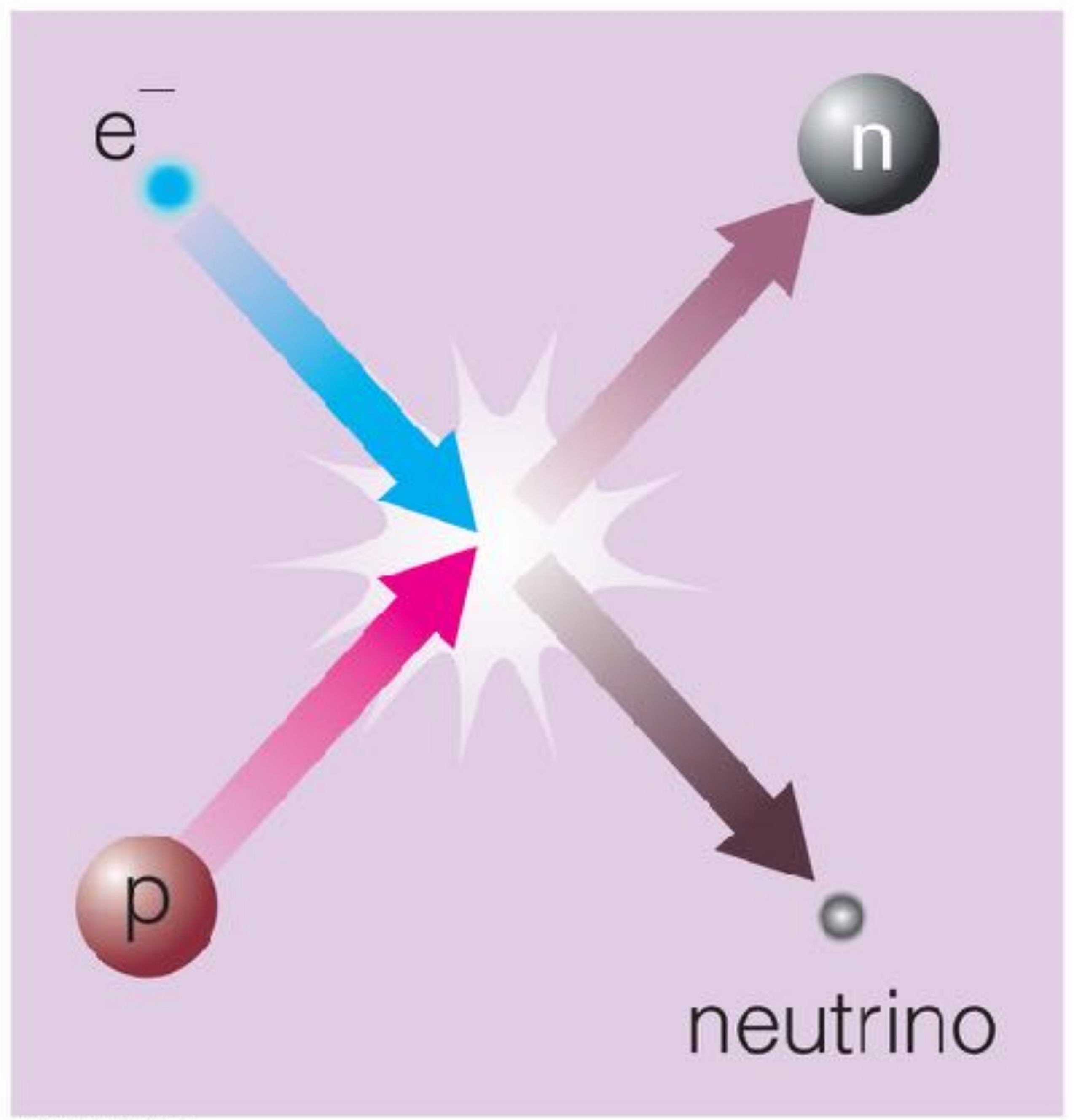
- Advanced nuclear burning proceeds in a series of nested shells.



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

(Fe has lowest mass per nuclear particle.)

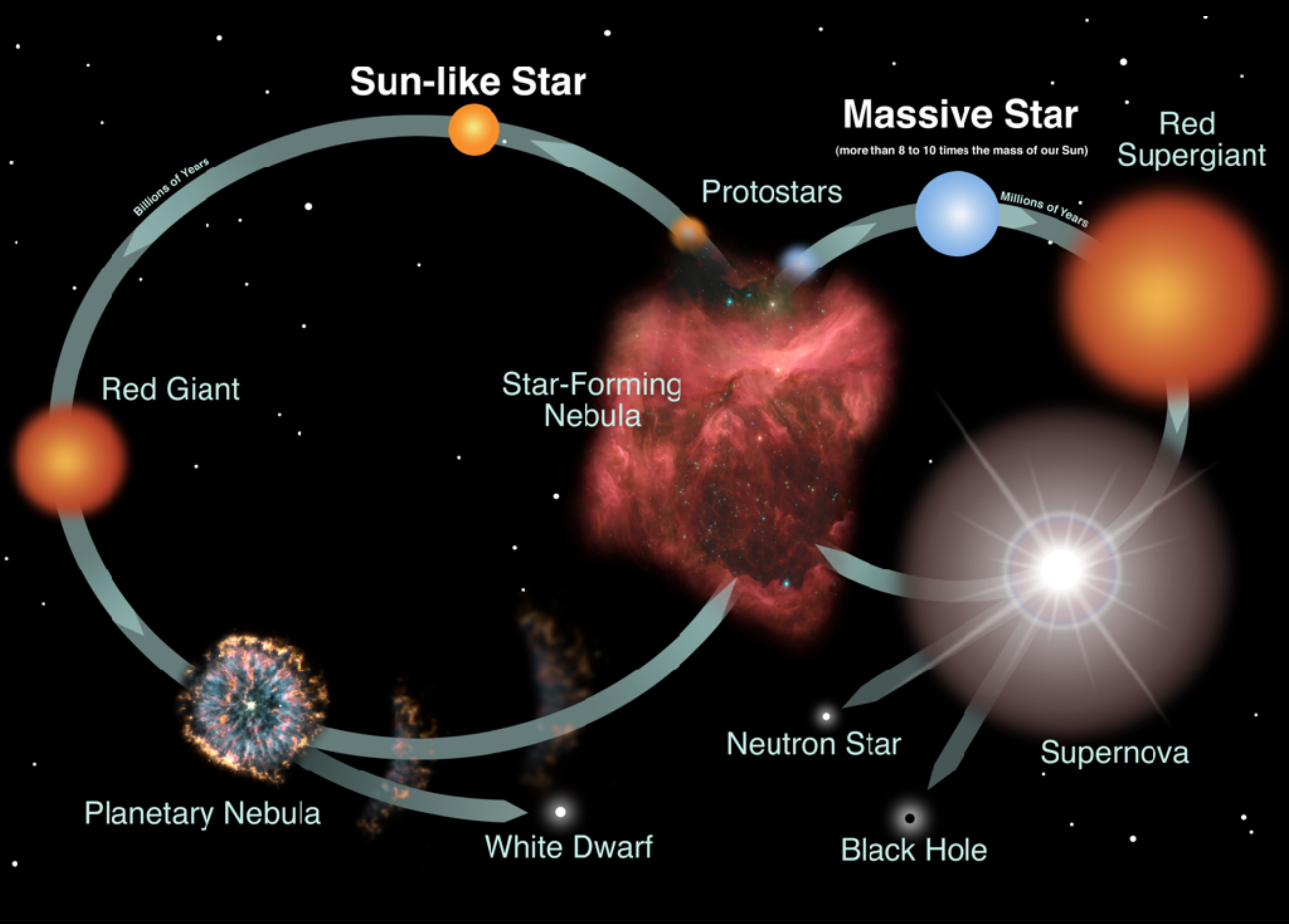
What happens once you reach iron?



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

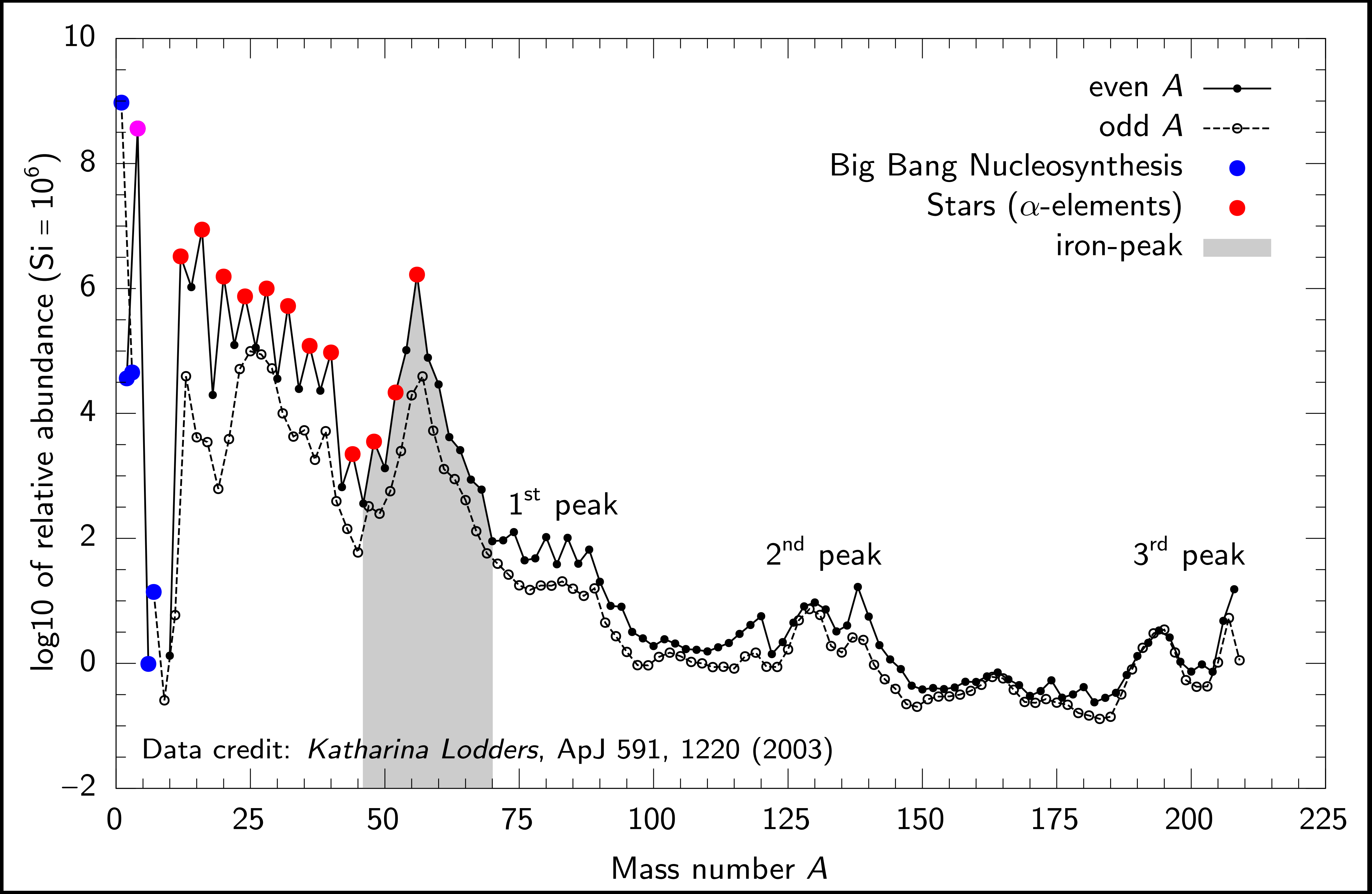
Chimera model: B12-WH07

-258.2 ms



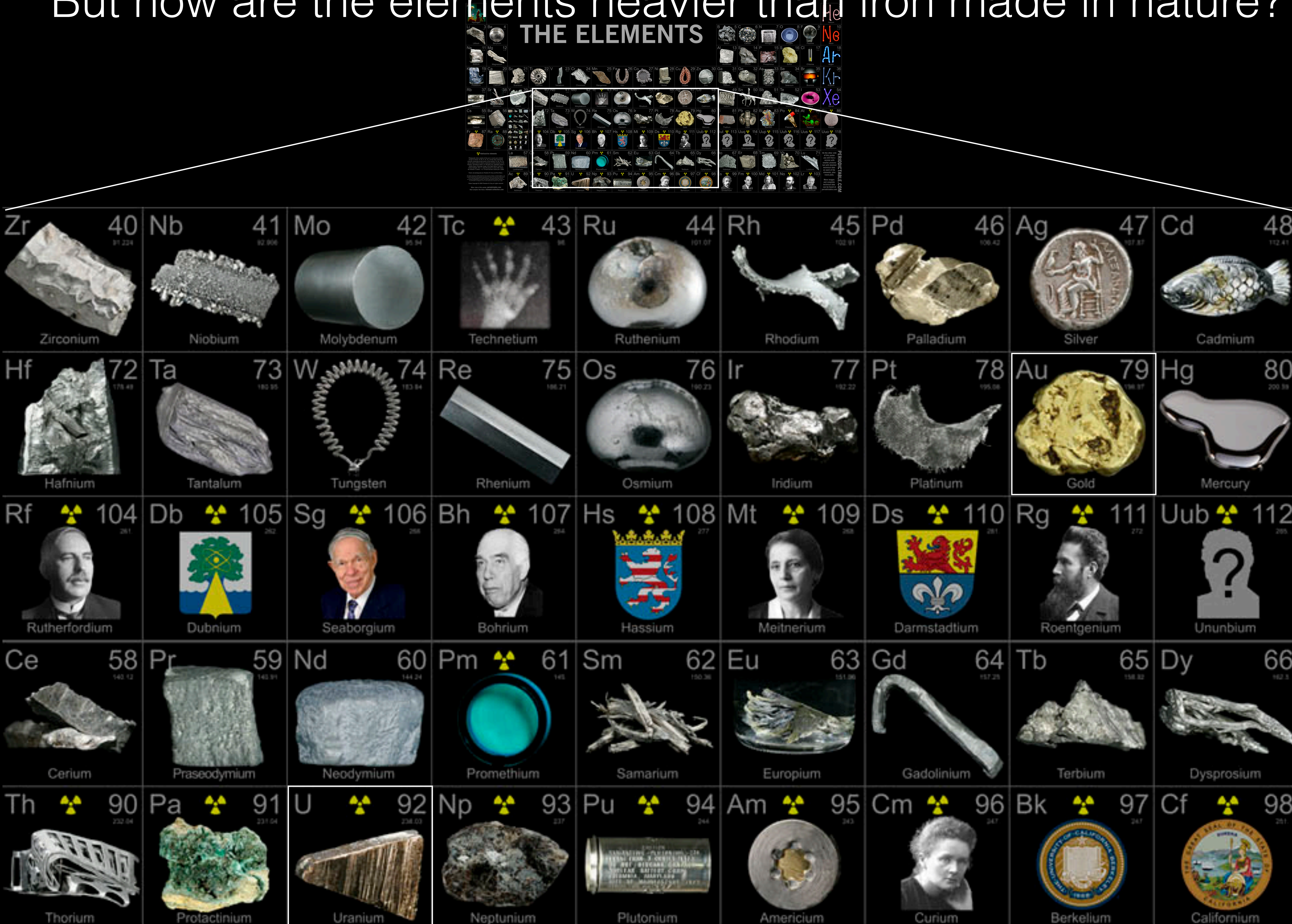
Sun-like Star
Massive Star
(more than 8 to 10 times the mass of our Sun)
Red Supergiant
Protostars
Billions of Years
Millions of Years
Red Giant
Star-Forming Nebula
Planetary Nebula
White Dwarf
Neutron Star
Supernova
Black Hole

Evidence for Stellar Nucleosynthesis

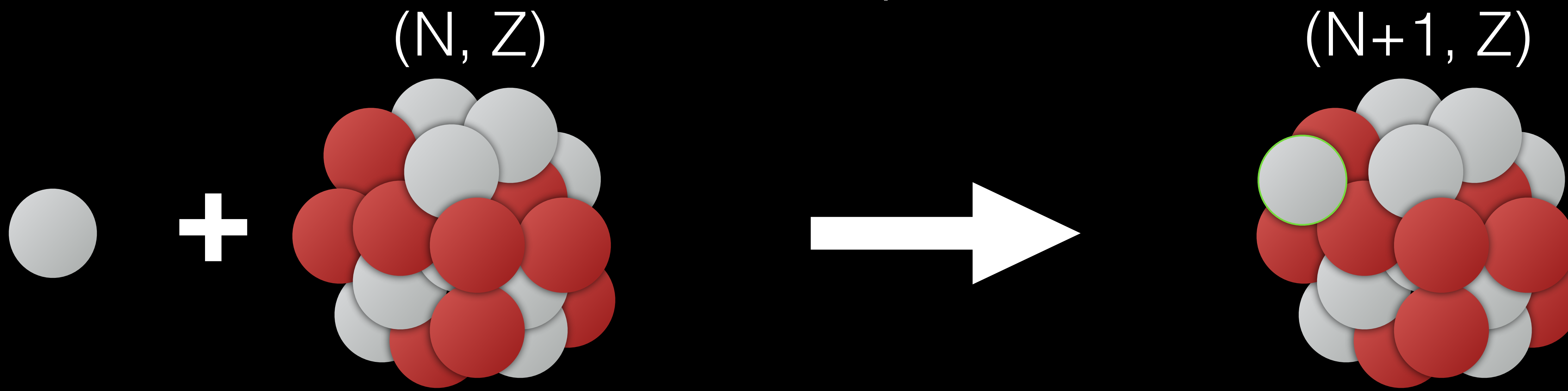


The abundances of nuclei in our solar system

But how are the elements heavier than iron made in nature?

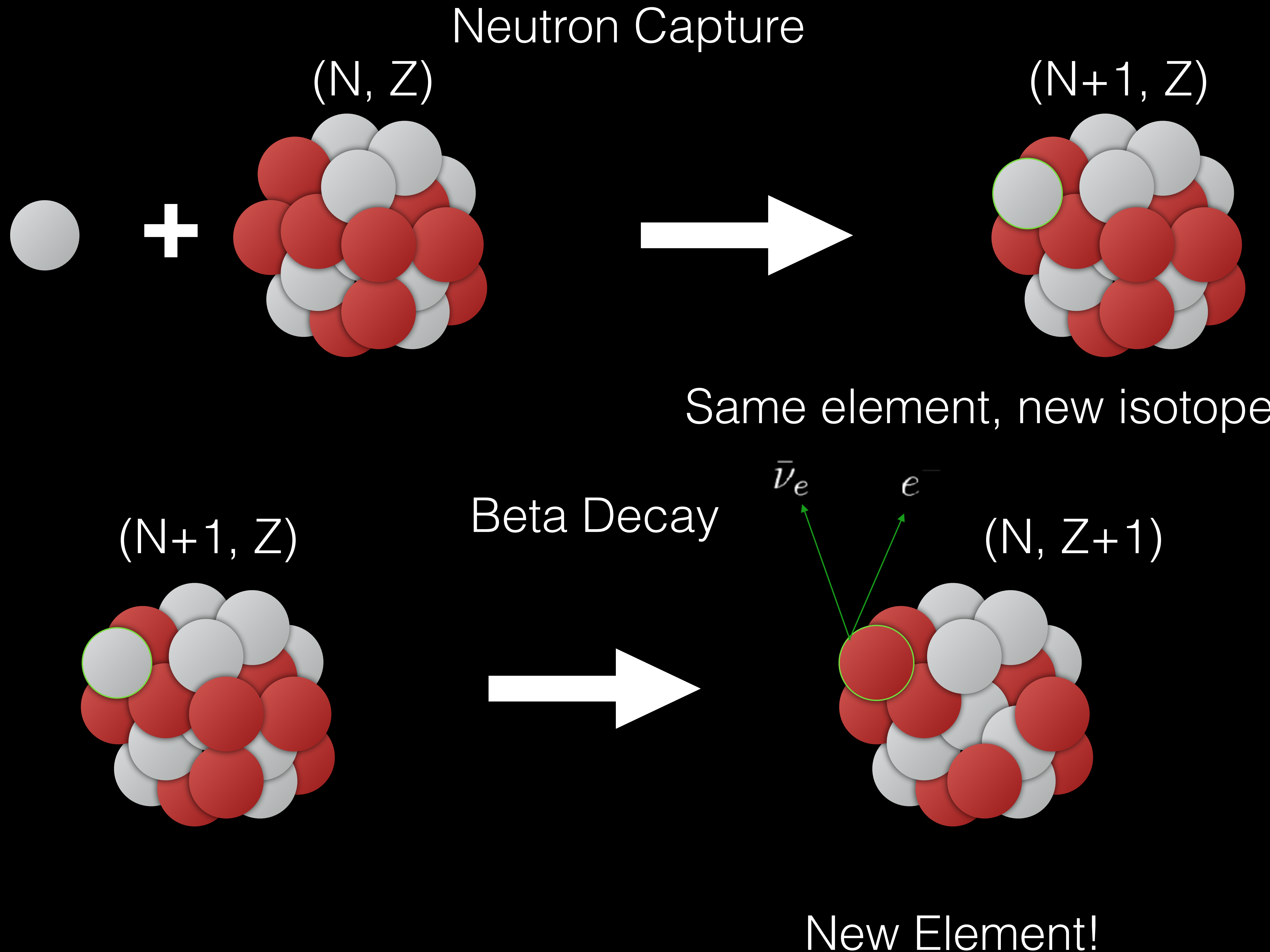


Neutron Capture



No electrical repulsion to deal with

Same element, new isotope



Neutron Capture
(N, Z)
(N+1, Z)
Same element, new isotope
Beta Decay
(N+1, Z)
$\bar{\nu}_e$
e^-
(N, Z+1)
New Element!

Two ways to capture neutrons

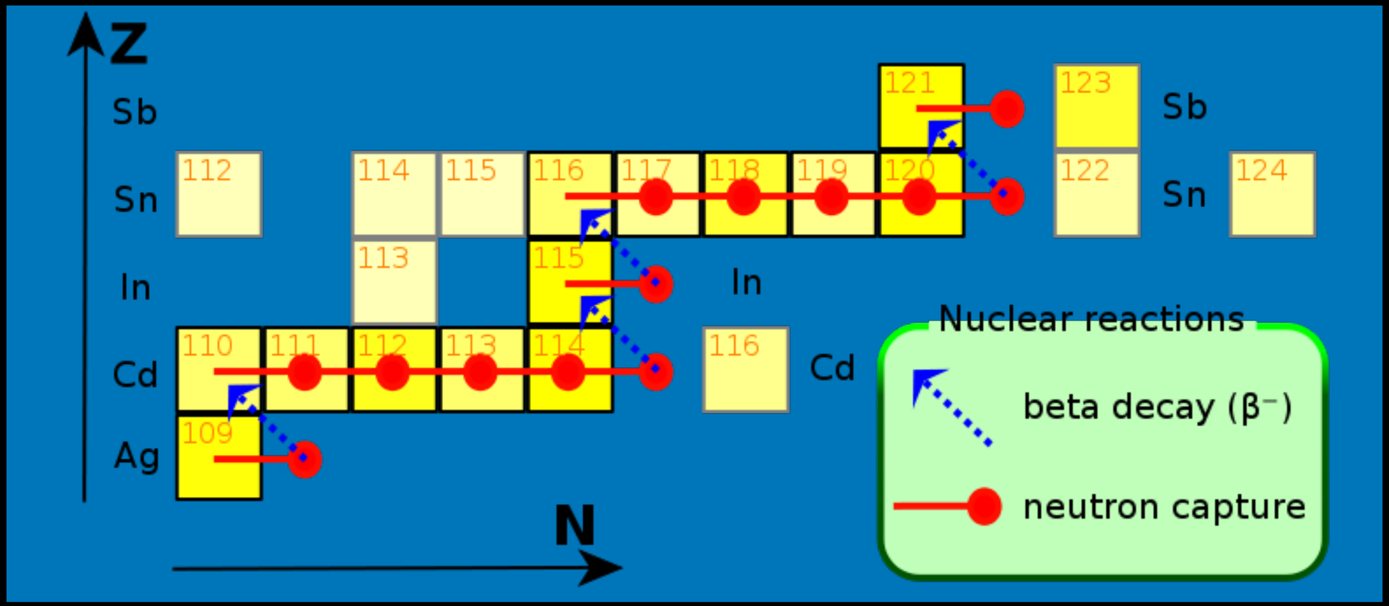
Slowly (s-process):

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

Get neutrons from:

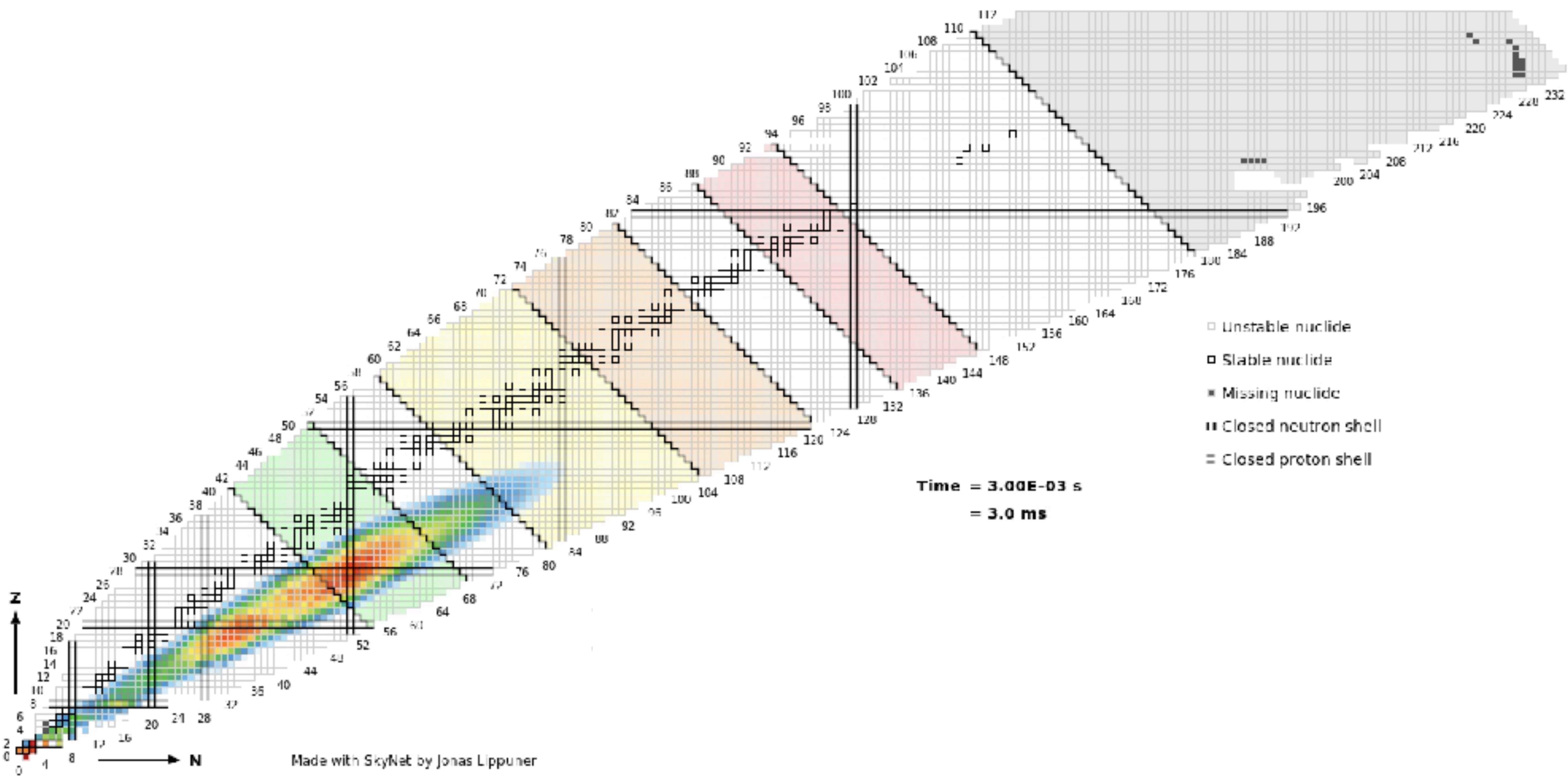
$^{13}C + ^{4}He \dashrightarrow ^{16}O + n$

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

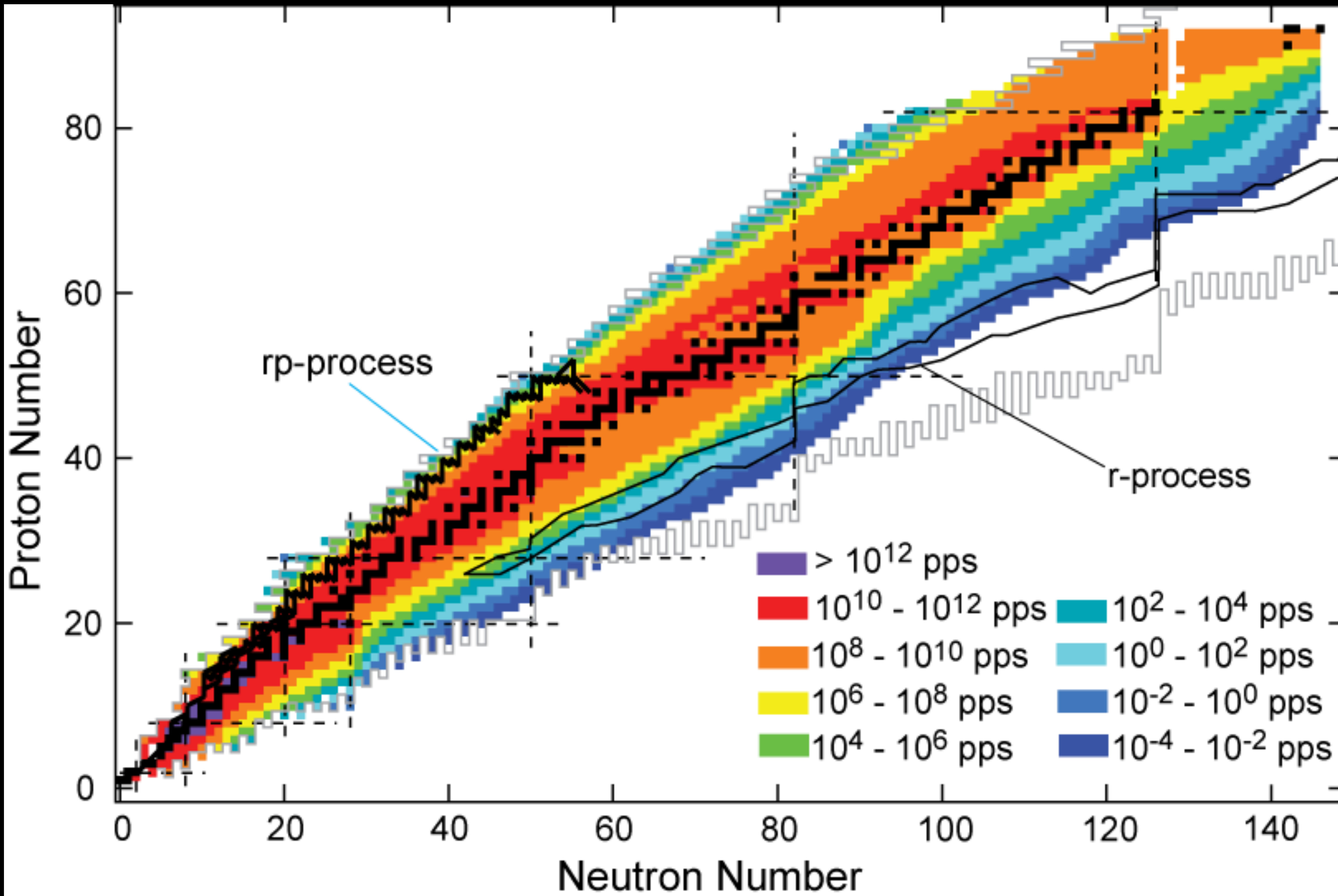


Rapidly (r-process):

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.

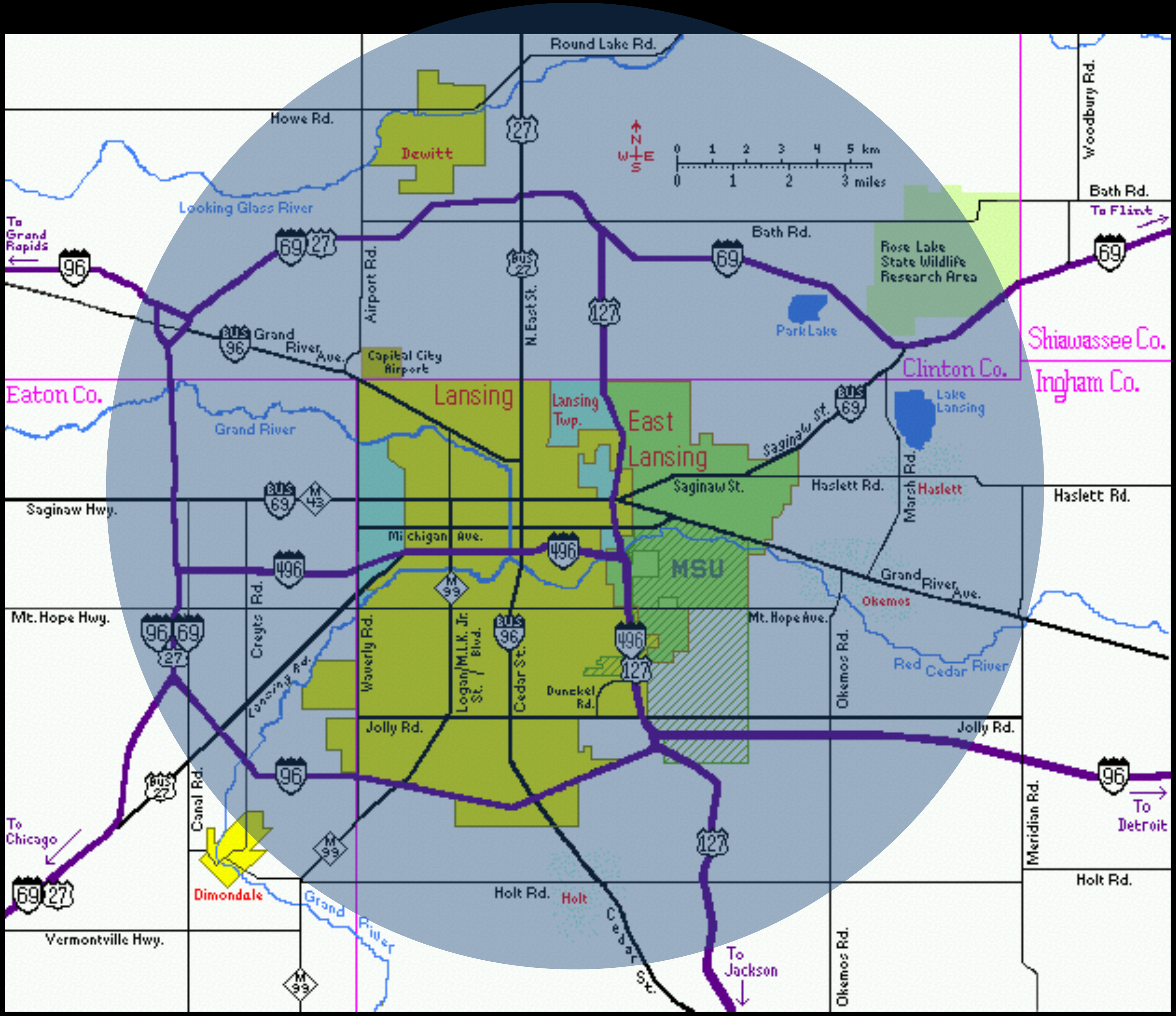

Unstable nuclide
Stable nuclide
Missing nuclide
Closed neutron shell
Closed proton shell
Time = 3.00E-03 s
= 3.0 ms
Z
N
Made with SkyNet by Jonas Lippuner

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.

Thought Question

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

A (~ 10^9 g)

B (~ 10^{12} g)

C (~ 10^{15} g)

MERGING BINARY NEUTRON STARS: A SIMULATION IN FULL GENERAL RELATIVITY

- Cosima Breu (ITP, Germany)
- David Radice (Caltech, USA)
- Luciano Rezzolla (ITP, Germany)

COST Action MP1340
Exploring fundamental physics
with compact stars
(NewCompStar)

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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, heavy elements can form through a series of rapid neutron captures and beta decays

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…