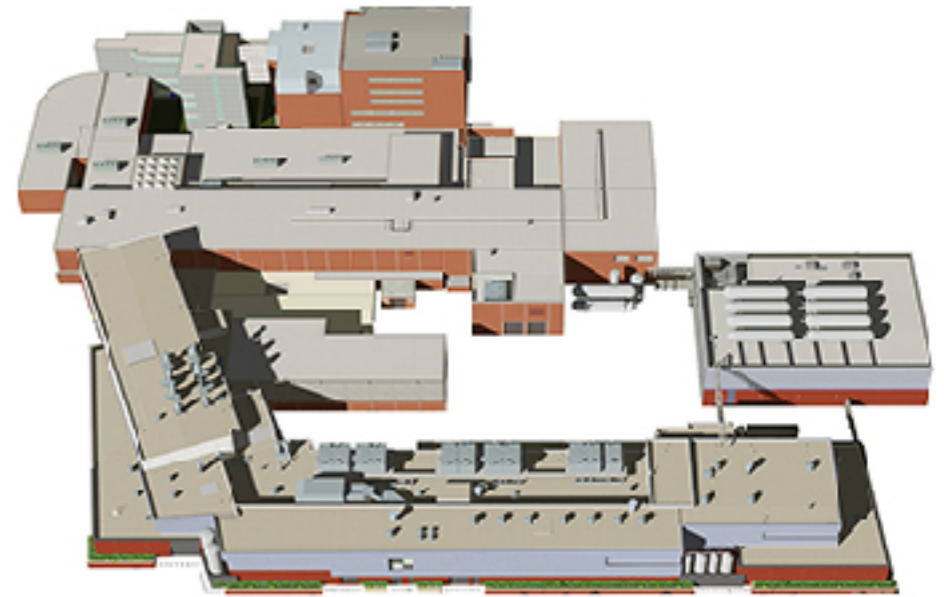
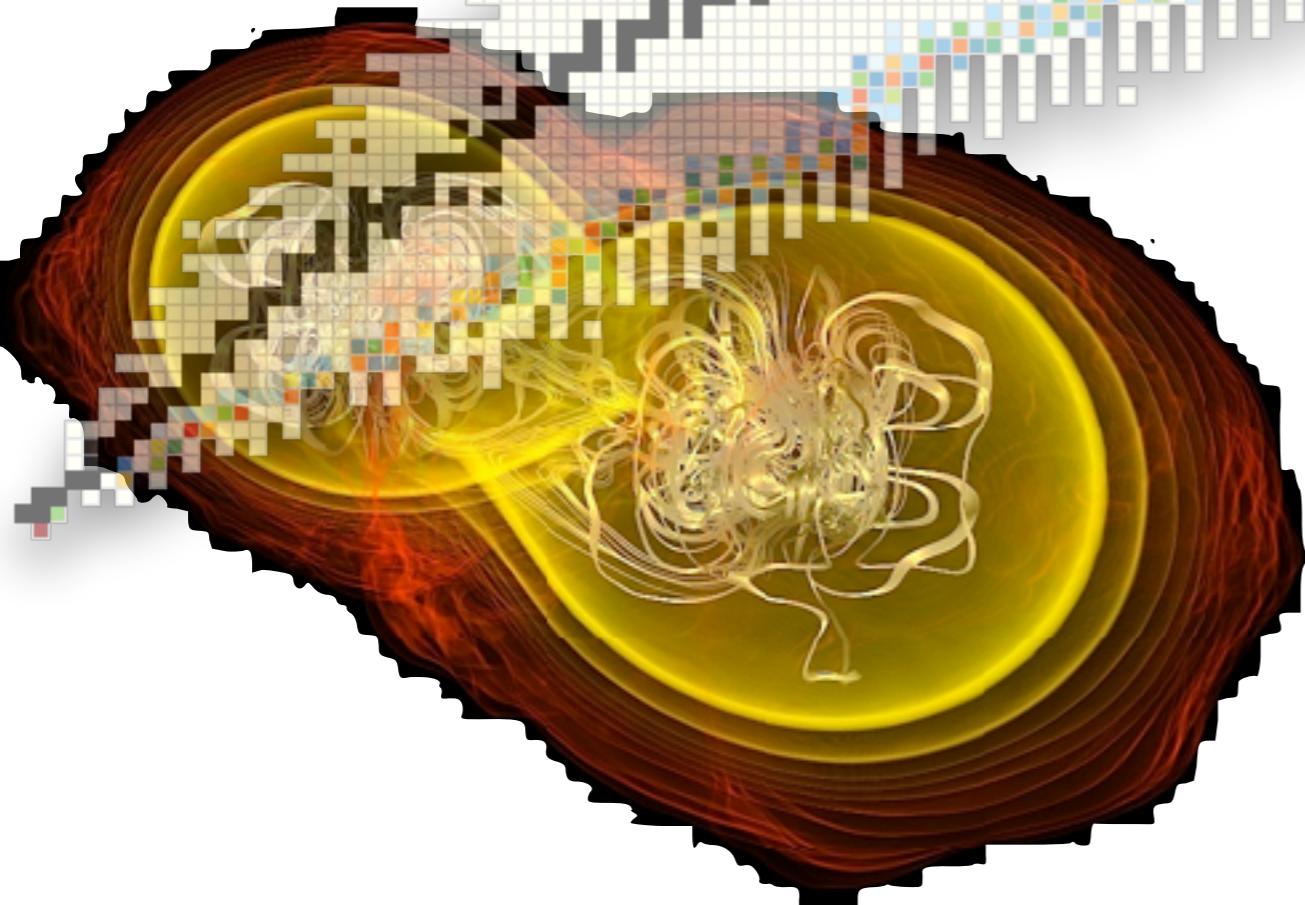


Nuclear Astrophysics



Luke Roberts, NSCL

The Central Question of Nuclear Astrophysics:

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

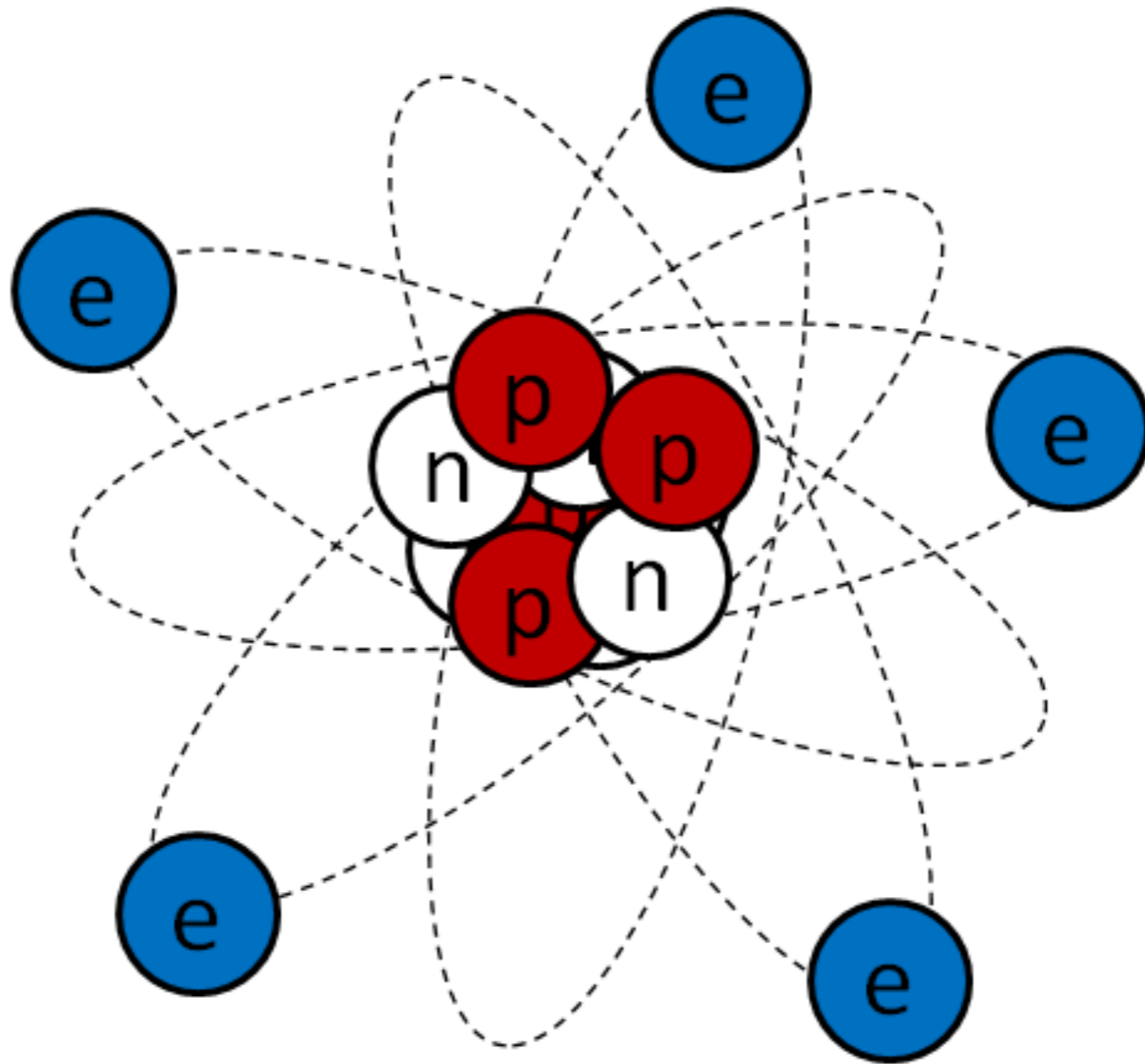
The Central Question of Nuclear Astrophysics:

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






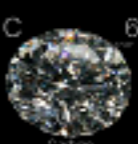













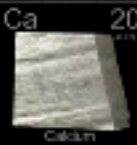























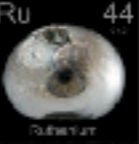
























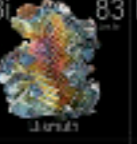

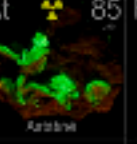



















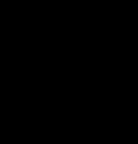
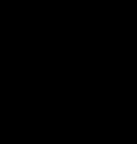













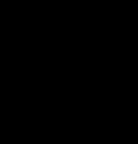
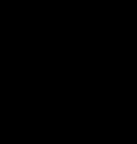













Also:

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

Atomic Number $Z = \# \text{ Electrons} = \# \text{ Protons}$
Neutron Number $N = \# \text{ Neutrons}$



The Periodic Table

 H 1 Hydrogen																	 He 2 Helium						
 Li 3 Lithium	 Be 4 Beryllium																	 B 5 Boron	 C 6 Carbon	 N 7 Nitrogen	 O 8 Oxygen	 F 9 Fluorine	 Ne 10 Neon
 Na 11 Sodium	 Mg 12 Magnesium																	 Al 13 Aluminum	 Si 14 Silicon	 P 15 Phosphorus	 S 16 Sulfur	 Cl 17 Chlorine	 Ar 18 Argon
 K 19 Potassium	 Ca 20 Calcium	 Sc 21 Scandium	 Ti 22 Titanium	 V 23 Vanadium	 Cr 24 Chromium	 Mn 25 Manganese	 Fe 26 Iron	 Co 27 Cobalt	 Ni 28 Nickel	 Cu 29 Copper	 Zn 30 Zinc	 Ga 31 Gallium	 Ge 32 Germanium	 As 33 Arsenic	 Se 34 Selenium	 Br 35 Bromine	 Kr 36 Krypton						
 Rb 37 Rubidium	 Sr 38 Strontium	 Y 39 Yttrium	 Zr 40 Zirconium	 Nb 41 Niobium	 Mo 42 Molybdenum	 Tc 43 Technetium	 Ru 44 Ruthenium	 Rh 45 Rhodium	 Pd 46 Palladium	 Ag 47 Silver	 Cd 48 Cadmium	 In 49 Indium	 Sn 50 Tin	 Sb 51 Antimony	 Te 52 Tellurium	 I 53 Iodine	 Xe 54 Xenon						
 Cs 55 Cesium	 Ba 56 Barium	 La 57 Lanthanum	 Hf 72 Hafnium	 Ta 73 Tantalum	 W 74 Tungsten	 Re 75 Rhenium	 Os 76 Osmium	 Ir 77 Iridium	 Pt 78 Platinum	 Au 79 Gold	 Hg 80 Mercury	 Tl 81 Thallium	 Pb 82 Lead	 Bi 83 Bismuth	 Po 84 Polonium	 At 85 Astatine	 Rn 86 Radon						
 Fr 87 Francium	 Ra 88 Radium	 Ac 89 Actinium	 Rf 104 Rutherfordium	 Db 105 Dubnium	 Sg 106 Seaborgium	 Bh 107 Bohrium	 Hs 108 Hassium	 Mt 109 Meitnerium	 Ds 110 Darmstadtium	 Rg 111 Roentgenium	 Uub 112 Uubium	 Uut 113 Uutium	 Uuq 114 Uuqium	 Uup 115 Uupium	 Uuh 116 Uuhium	 Uus 117 Uusium	 Uuo 118 Uuoium						
 La 57 Lanthanum	 Ce 58 Cerium	 Pr 59 Praseodymium	 Nd 60 Neodymium	 Pm 61 Promethium	 Sm 62 Samarium	 Eu 63 Europium	 Gd 64 Gadolinium	 Tb 65 Terbium	 Dy 66 Dysprosium	 Ho 67 Holmium	 Er 68 Erbium	 Tm 69 Thulium	 Yb 70 Ytterbium	 Lu 71 Lutetium									
 Ac 89 Actinium	 Th 90 Thorium	 Pa 91 Protactinium	 U 92 Uranium	 Np 93 Neptunium	 Pu 94 Plutonium	 Am 95 Americium	 Cm 96 Curium	 Bk 97 Berkelium	 Cf 98 Californium	 Es 99 Einsteinium	 Fm 100 Fermium	 Md 101 Mendelevium	 No 102 Nobelium	 Lr 103 Lawrencium									

The Periodic Table

 H Hydrogen	 He Helium	 Li Lithium	 Be Beryllium	 B Boron	 C Carbon	 N Nitrogen	 O Oxygen	 F Fluorine	 Ne Neon	 Na Sodium	 Mg Magnesium	 Al Aluminum	 Si Silicon	 P Phosphorus	 S Sulfur	 Cl Chlorine	 Ar Argon
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The periodic table ignoring the properties of electrons

The Periodic Table

1 H Hydrogen	2 He Helium	3 Li Lithium	4 Be Beryllium	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
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Atomic Number $Z = \# \text{ Electrons} = \# \text{ Protons}$

Neutron Number $N = \# \text{ Neutrons}$

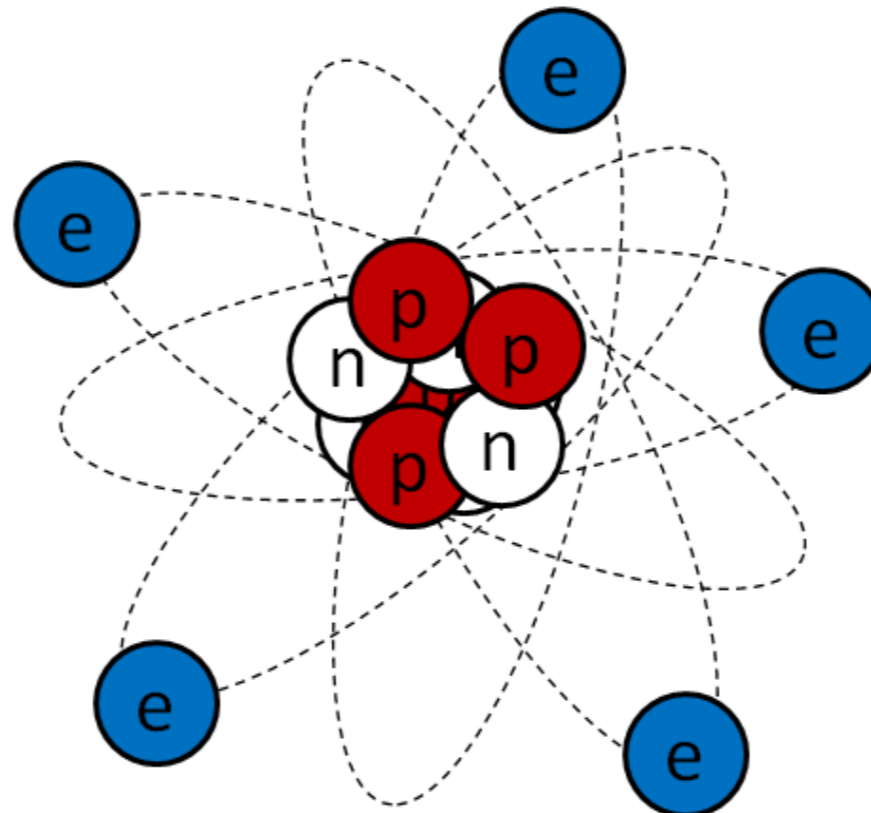
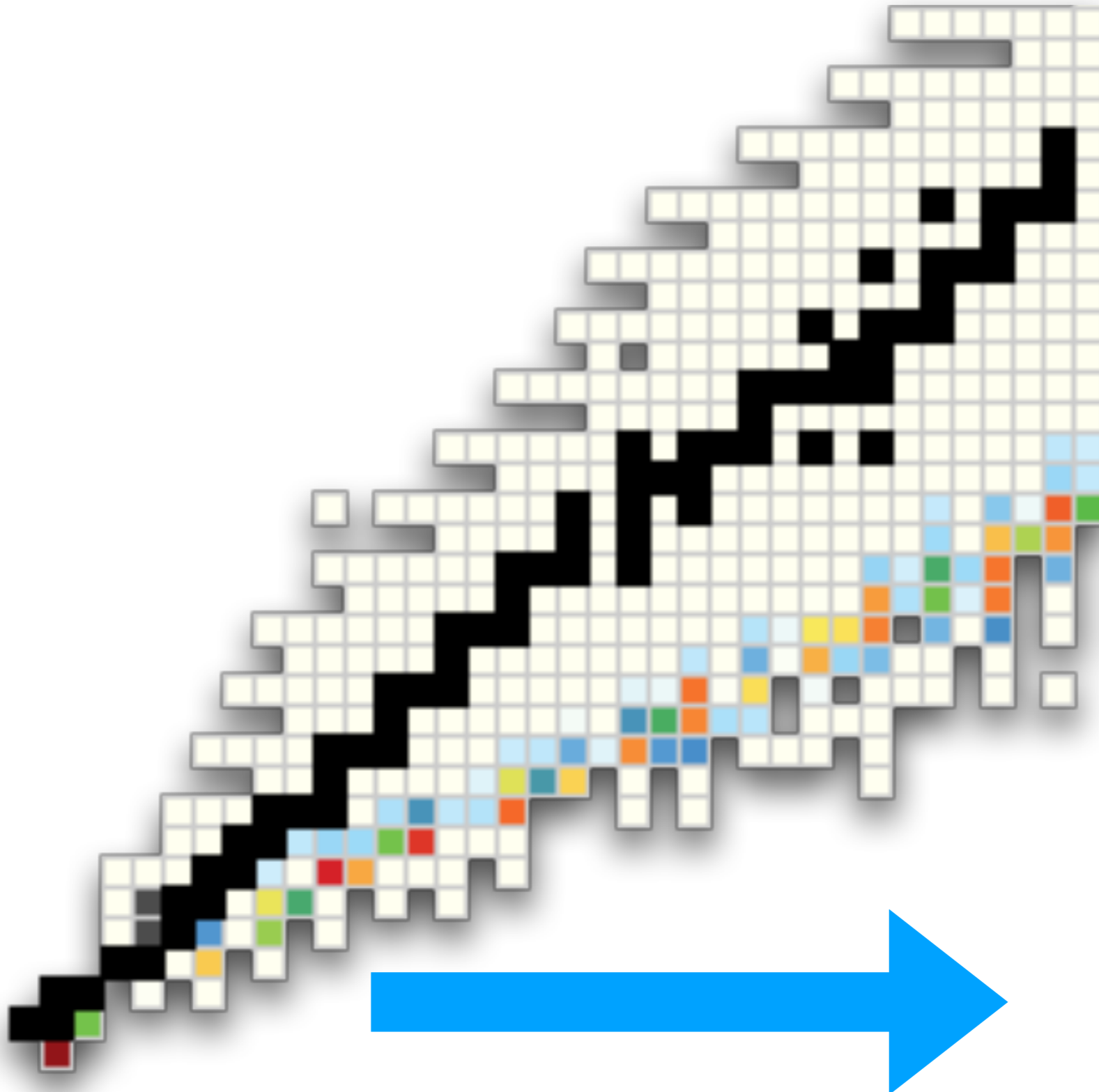
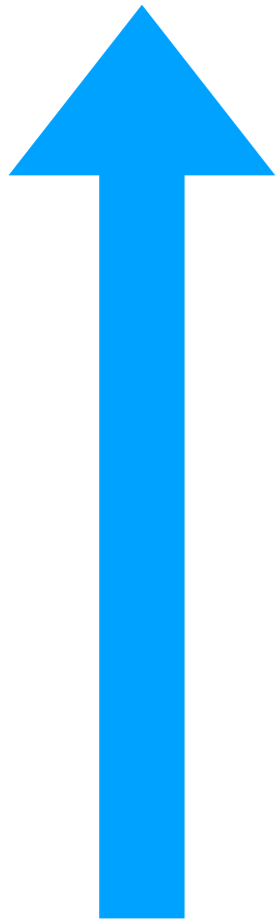


Chart of the Nuclides

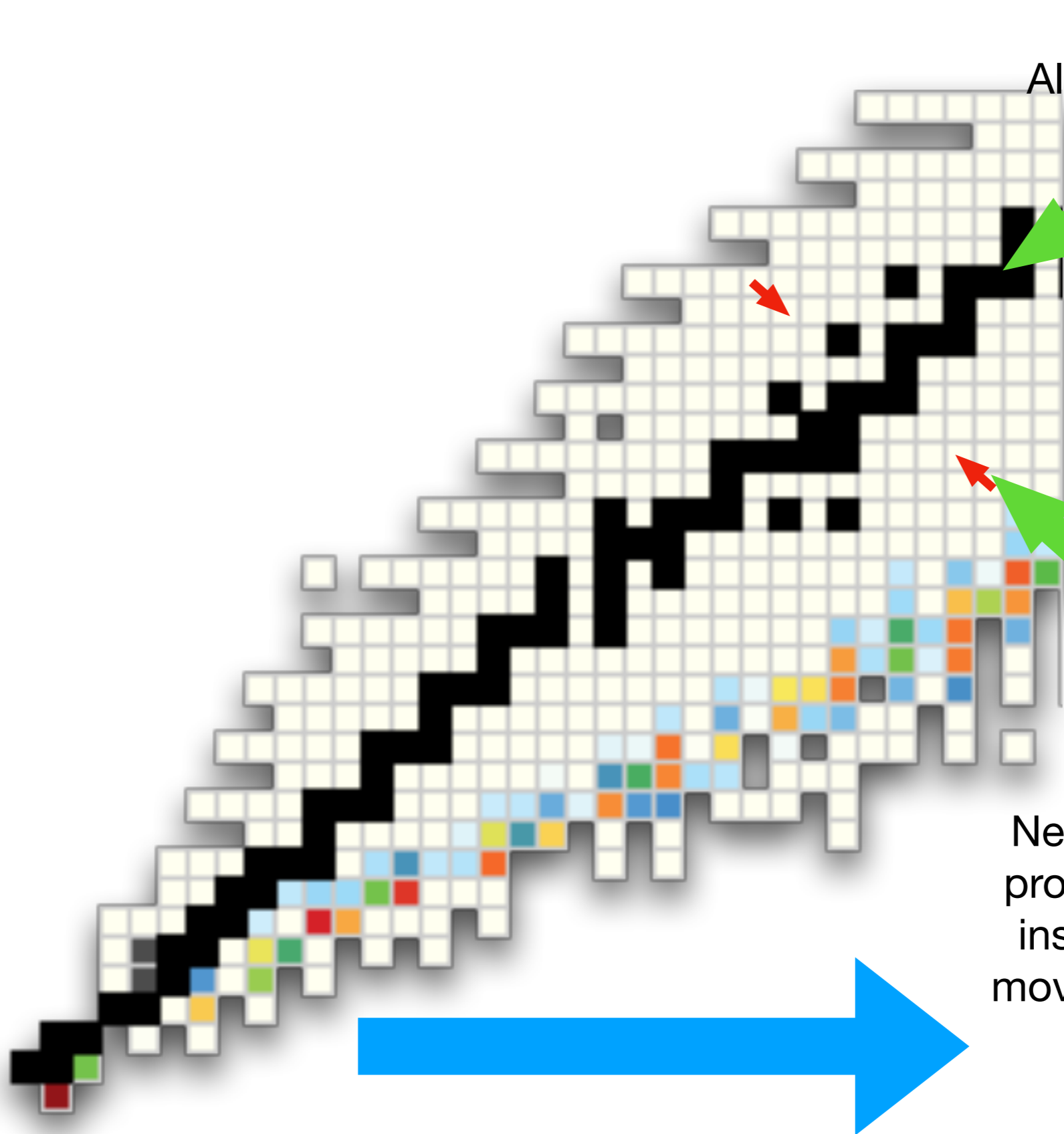
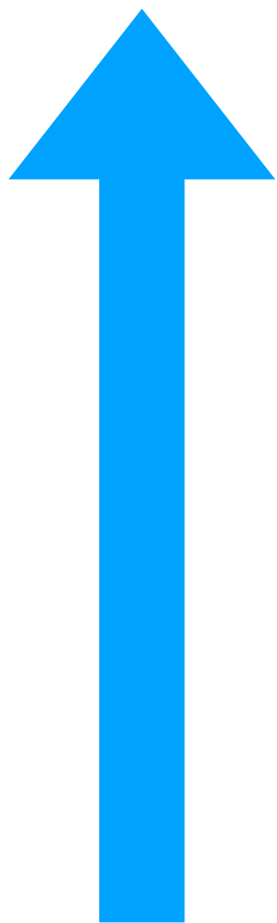
Number of Protons



Number of Neutrons

Chart of the Nuclides

Number of Protons



Stable Nuclei:
All are found in nature

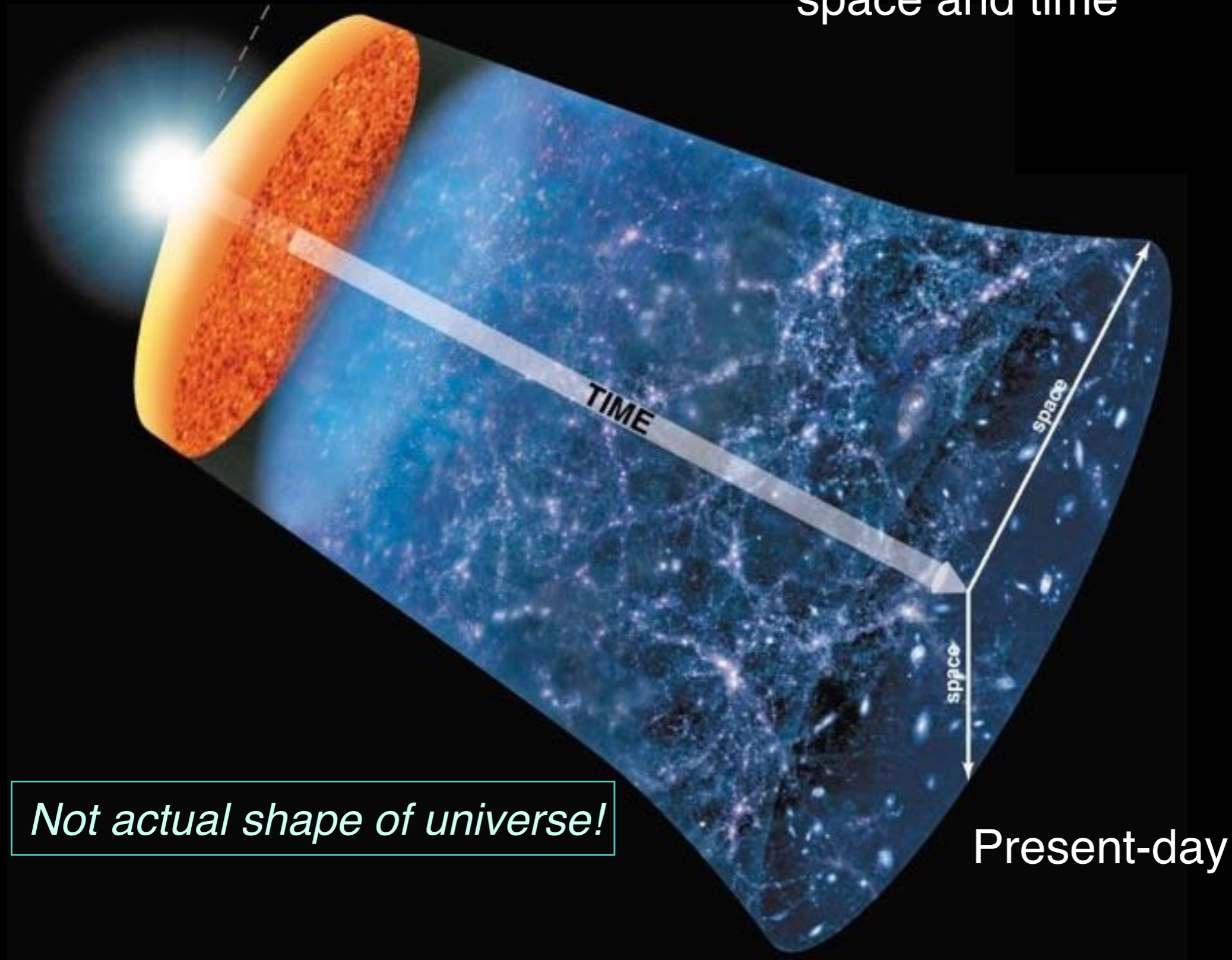
Unstable Nuclei:
Neutrons change into protons (or vice versa) inside the nucleus to move toward the stable nuclei

Number of Neutrons



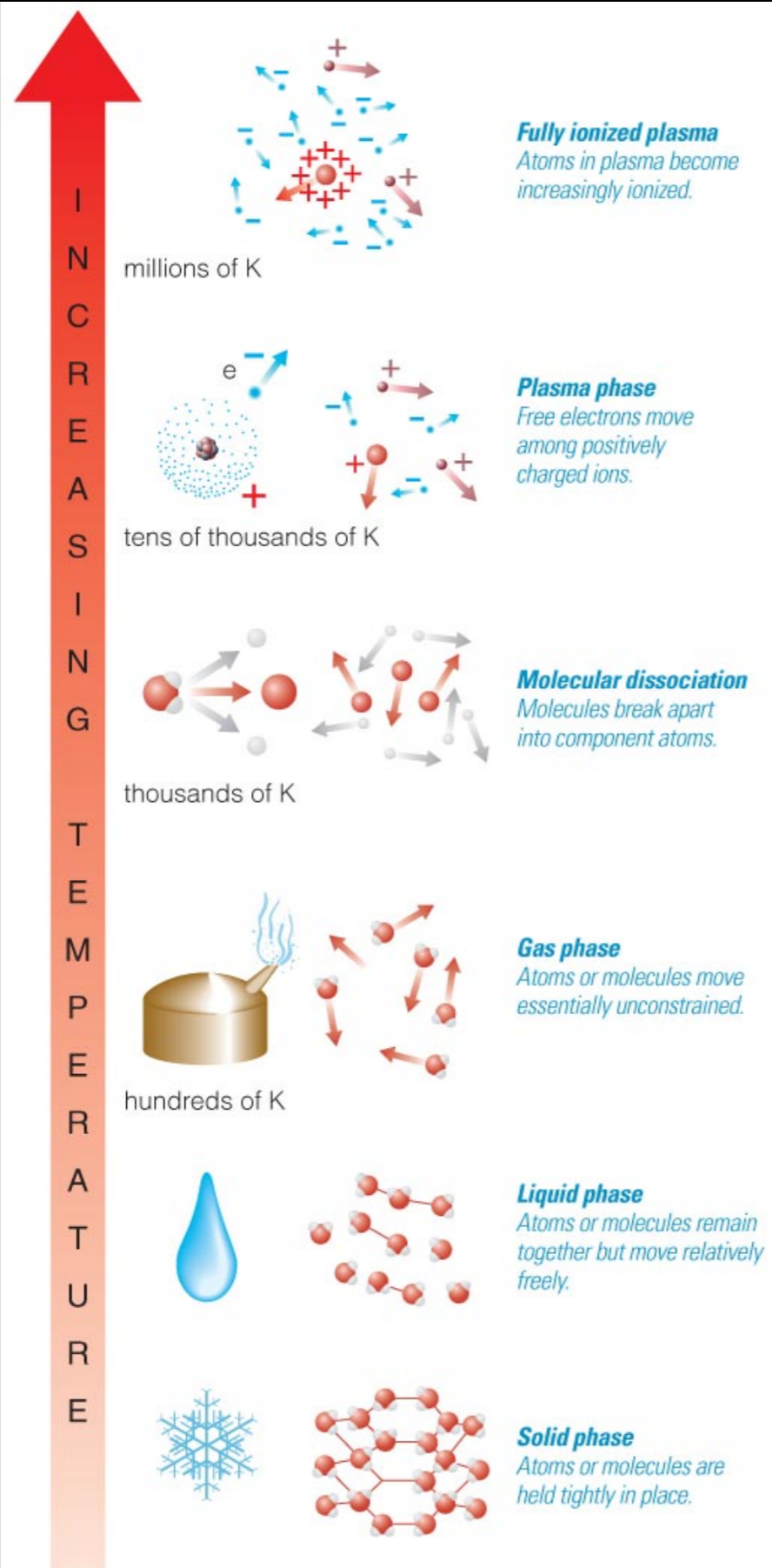
Moment of Big Bang

Schematic diagram showing development of the universe in space and time

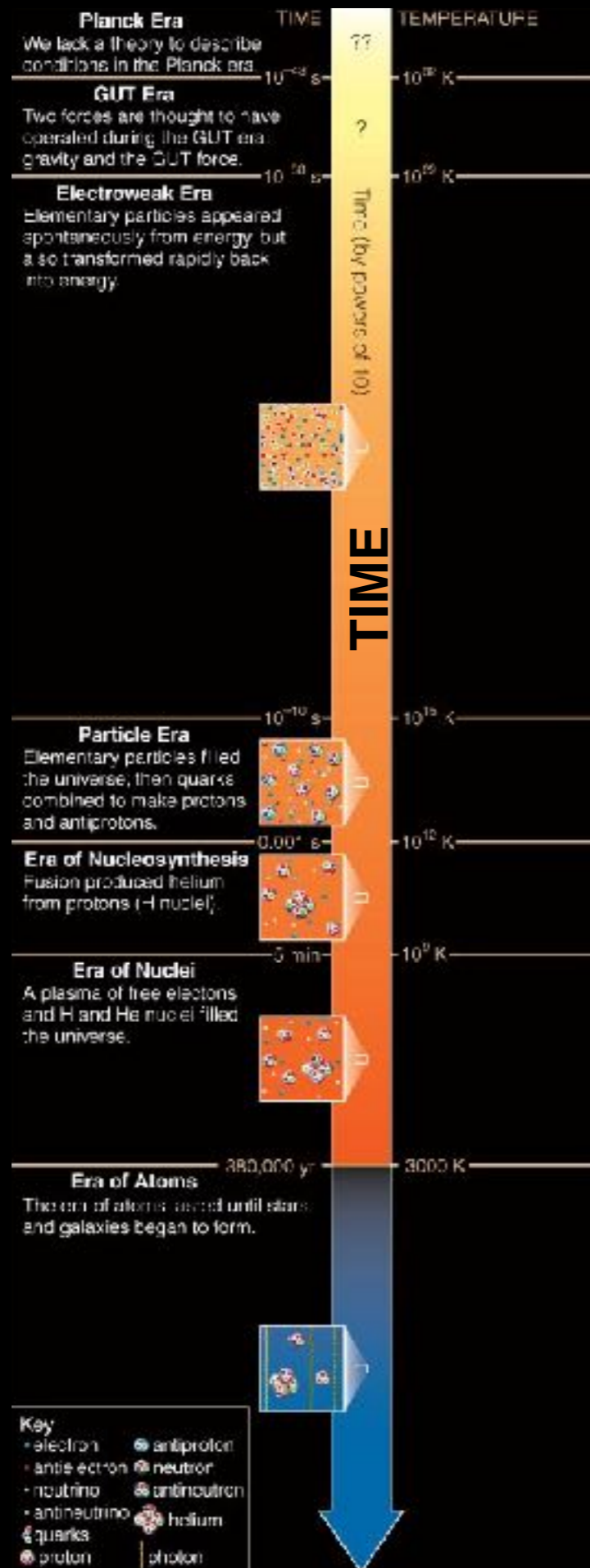
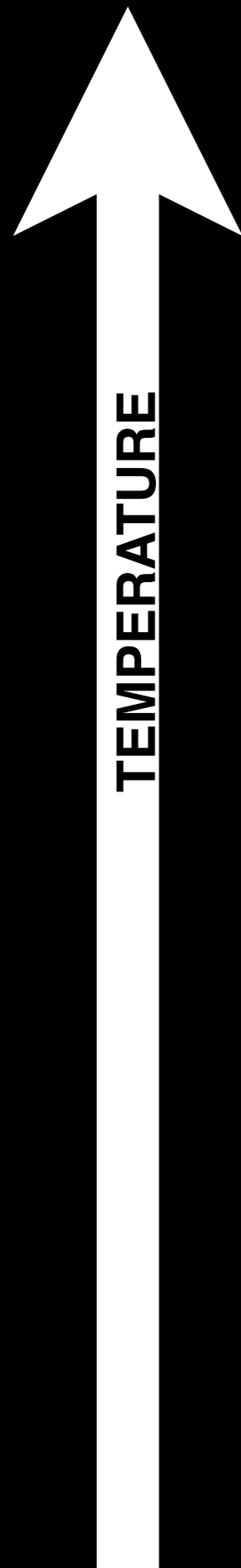


Not actual shape of universe!

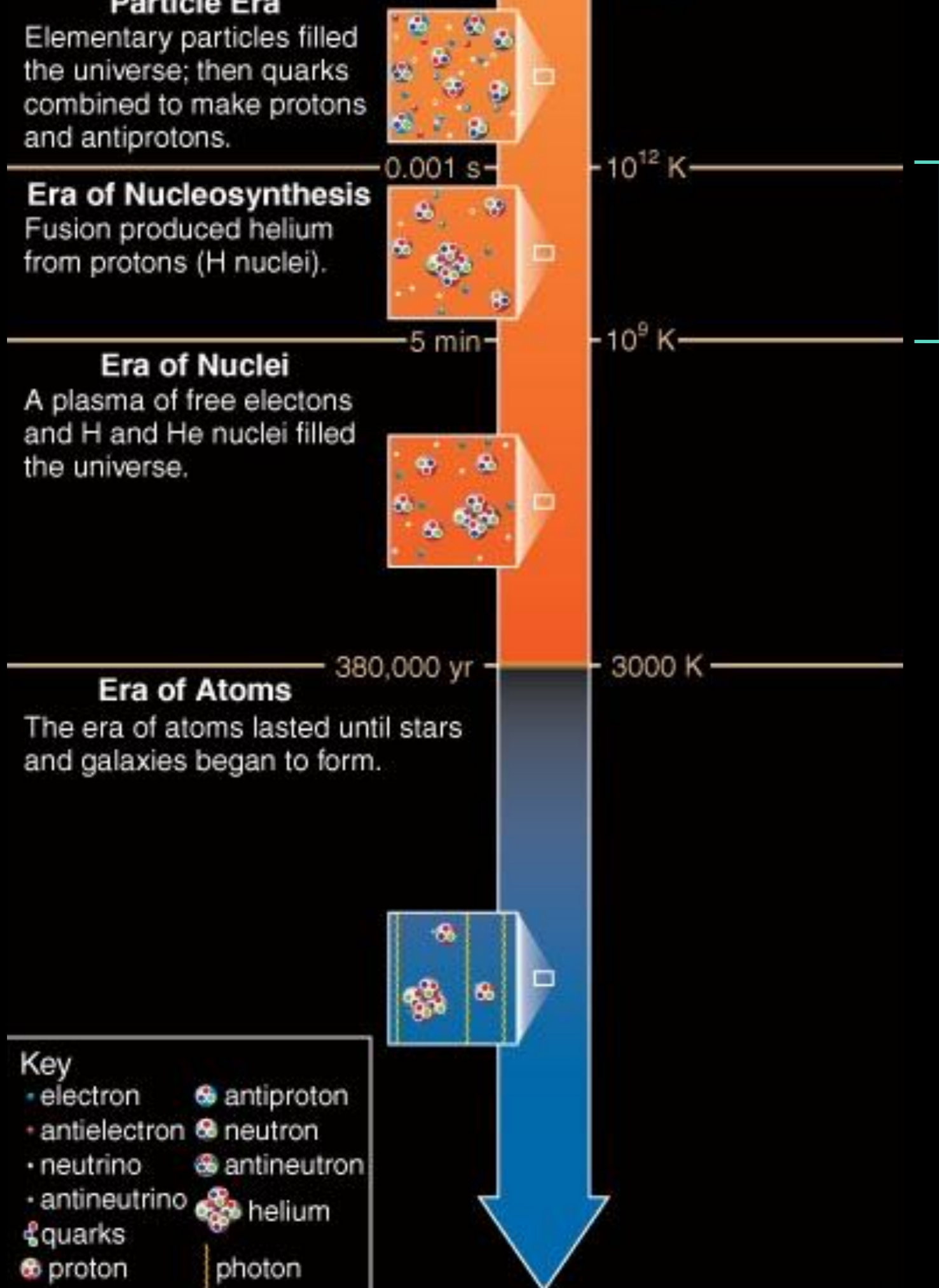
Present-day



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



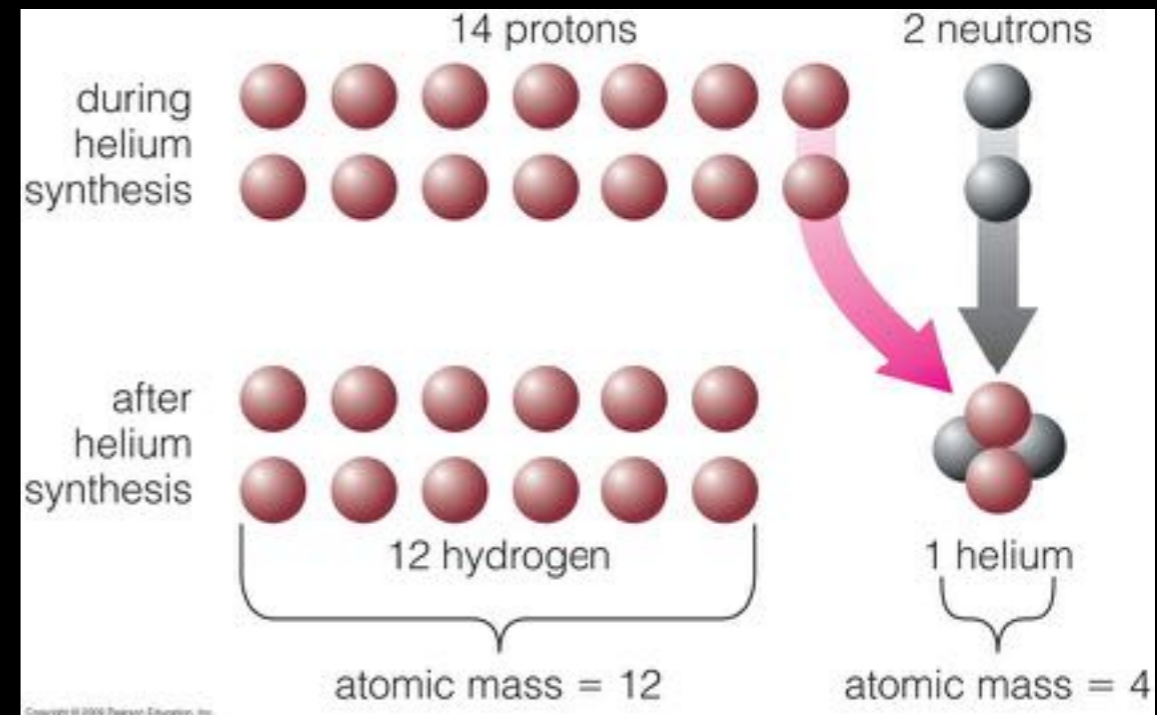
Our knowledge of what happened before the Era of Atoms is based on mathematical modeling and indirect evidence.

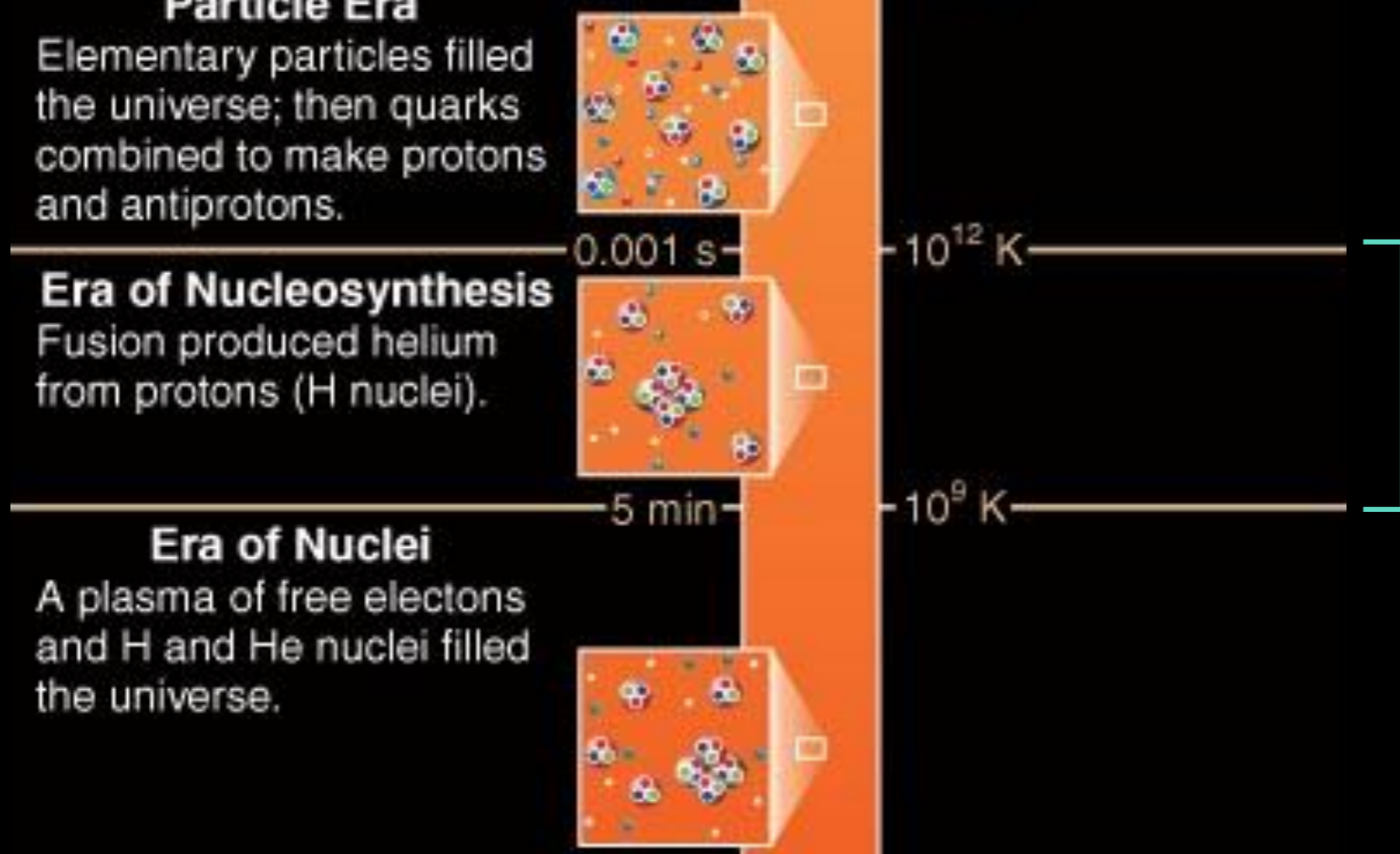


Era of Nucleosynthesis

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

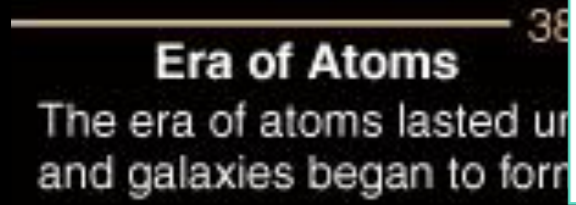




Era of Nucleosynthesis

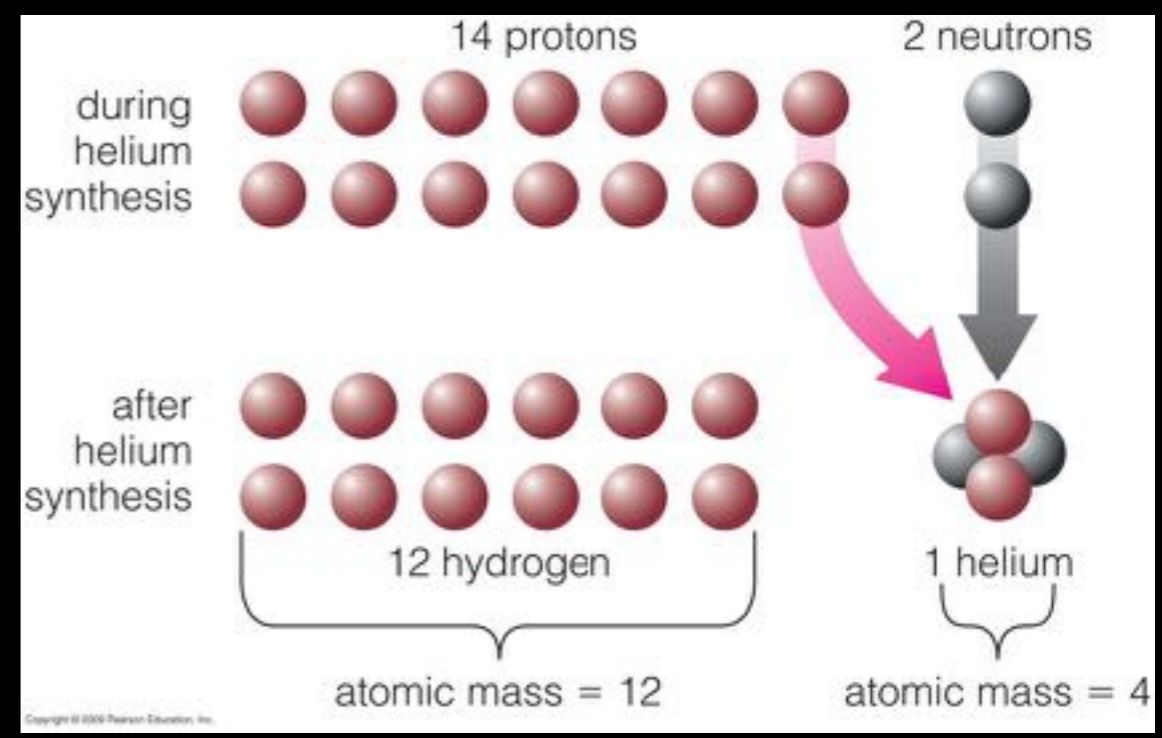
Most of the helium now in the universe was made during this era.

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

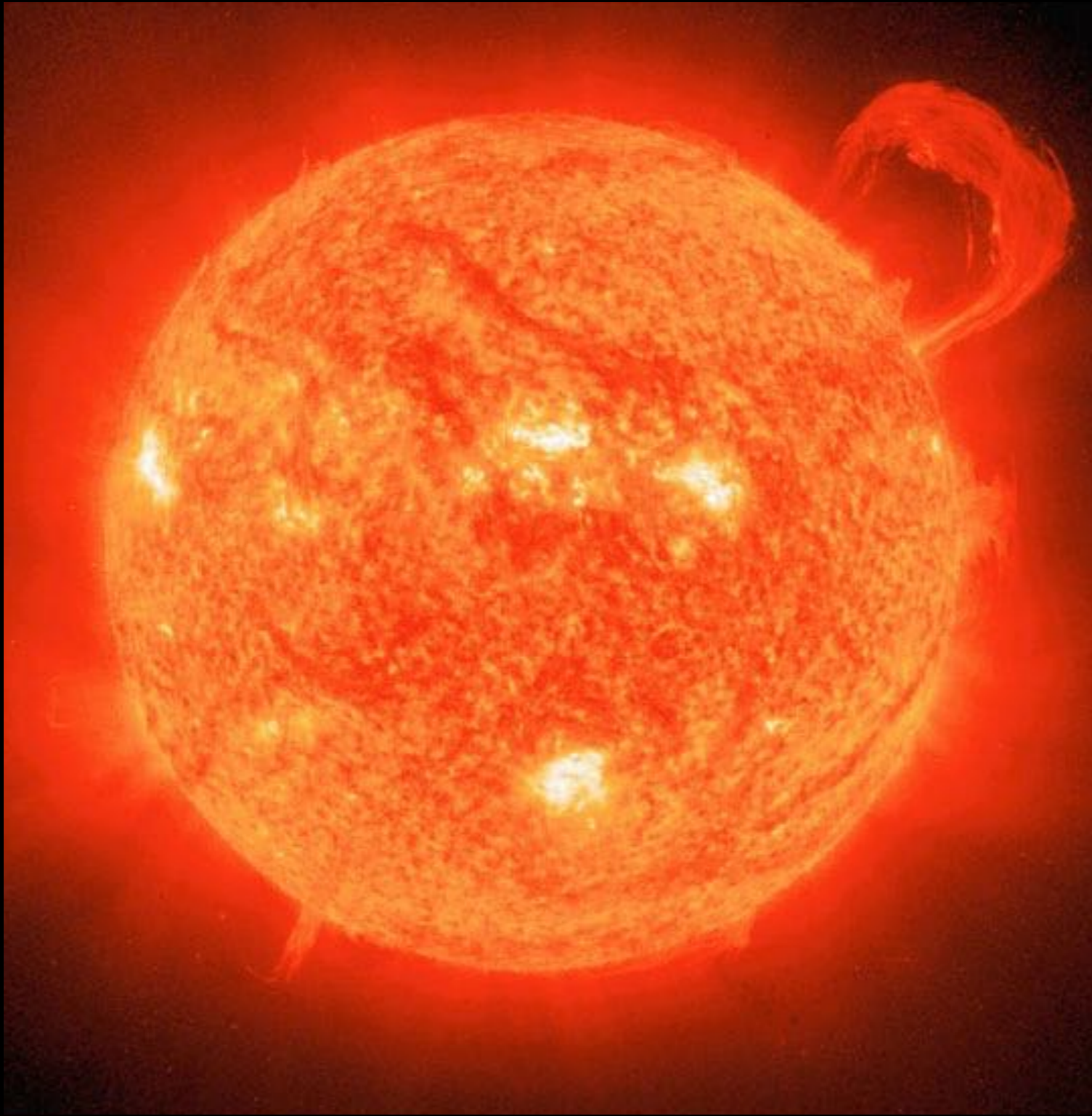


Key

- electron
- antielectron
- neutrino
- antineutrino
- quarks
- proton
- antiproton
- neutron
- antineutron
- helium
- photon



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



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)

The Sun

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

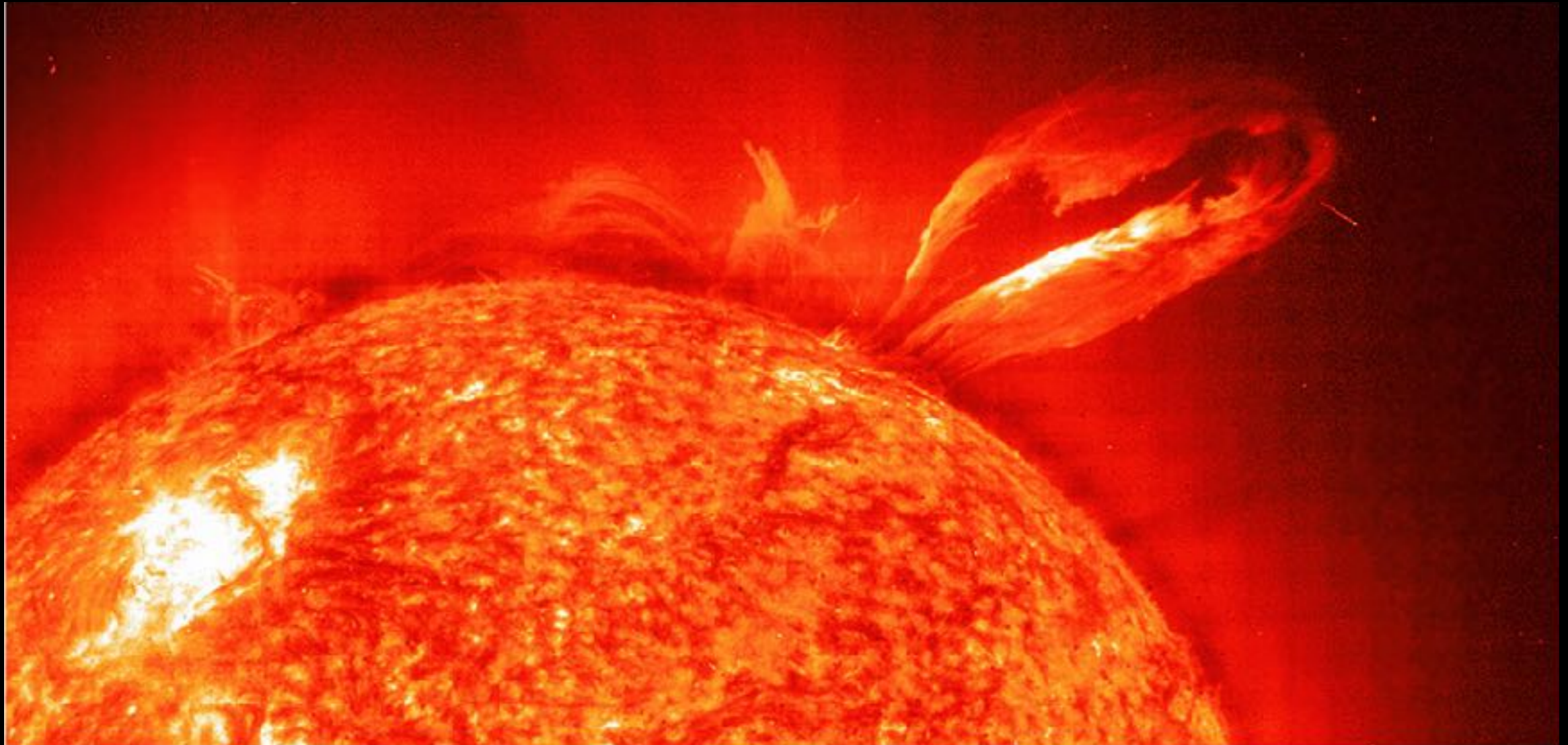
$$\text{luminosity} = \text{power output in form of radiative energy}$$

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

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

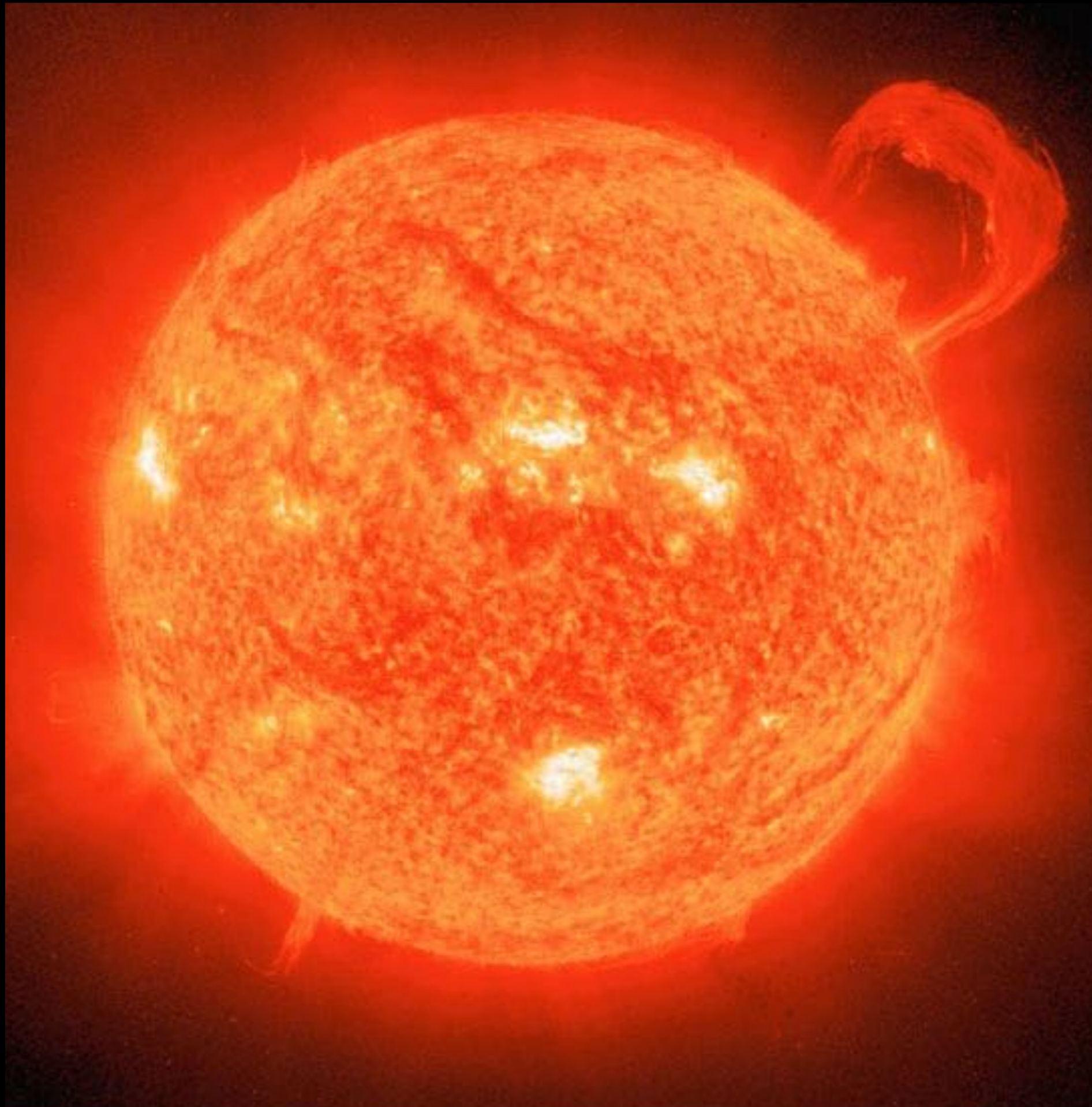


Is it on FIRE (i.e. is it powered by chemical reactions)?

Chemical Energy Content

Luminosity

~ 10,000 years



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



Is it CONTRACTING?

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

$$E = mc^2$$

—Einstein, 1905

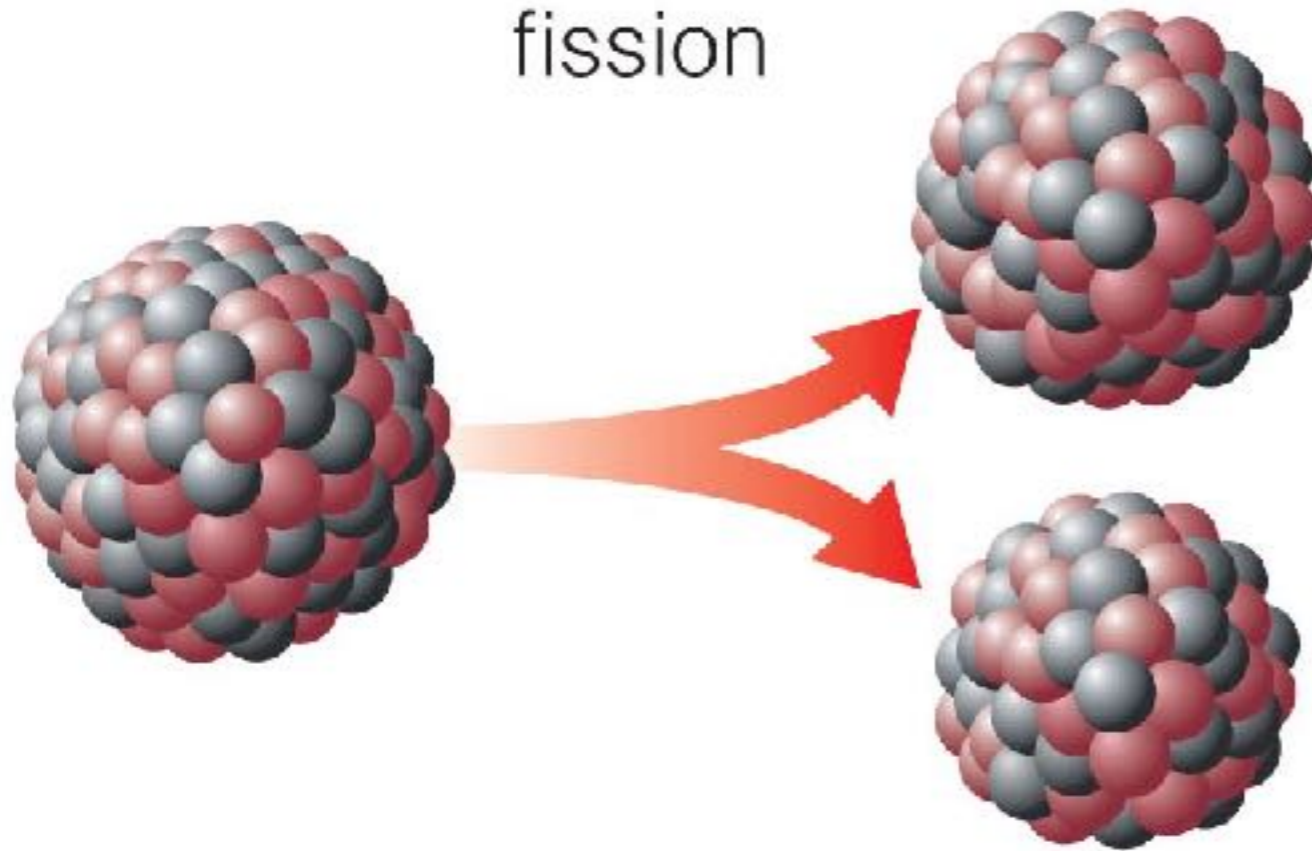
Is it powered by nuclear energy?

Nuclear Potential Energy (core)

Luminosity

~ 10 billion years

fission



fusion



Fission

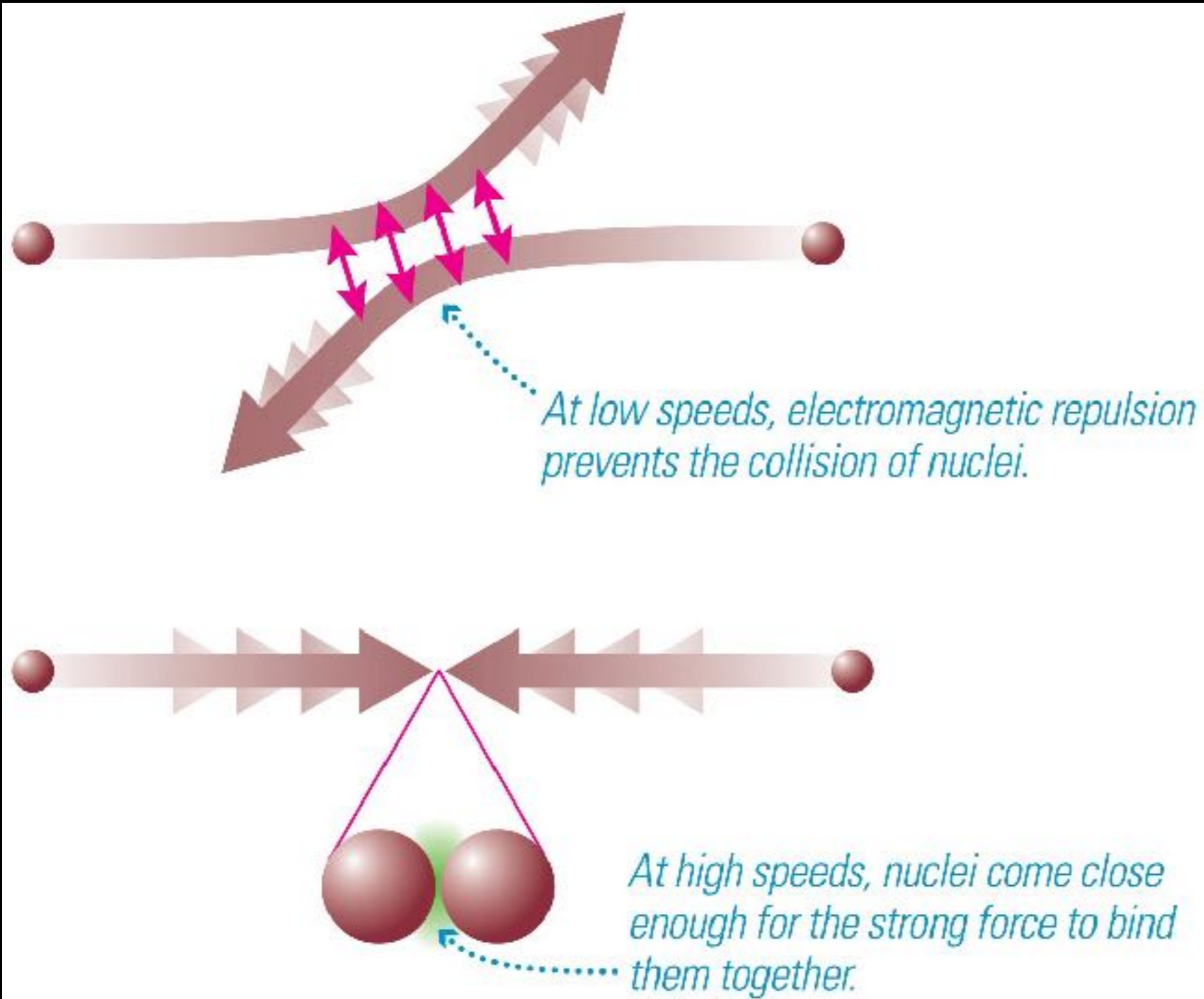
Big nucleus splits into smaller pieces.

(Nuclear power plants)

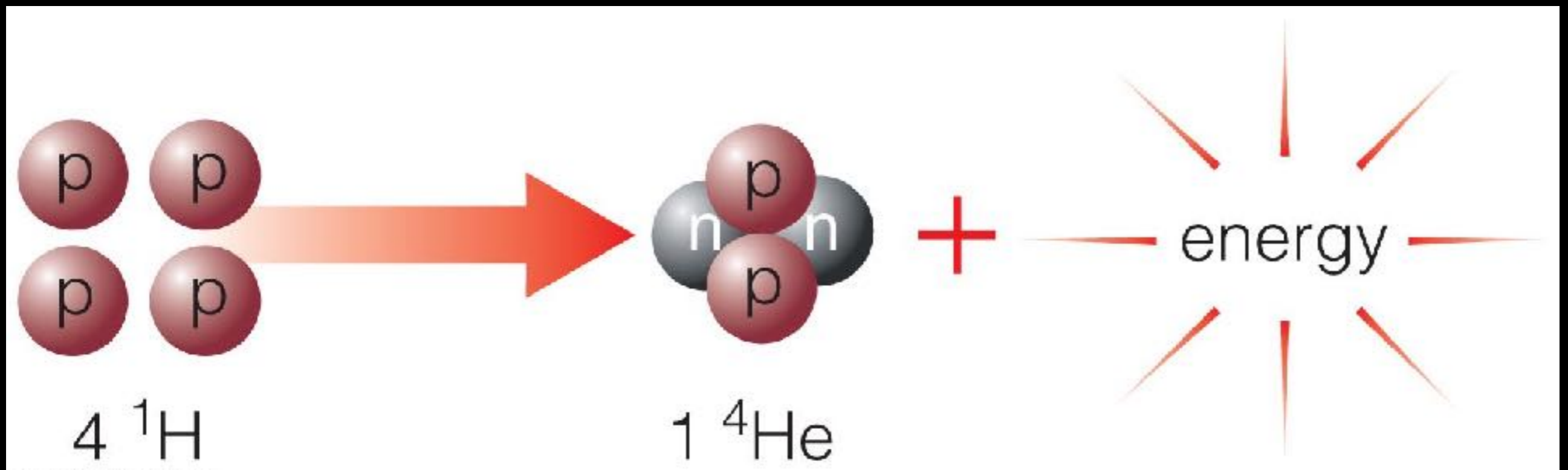
Fusion

Small nuclei stick together to make a bigger one.

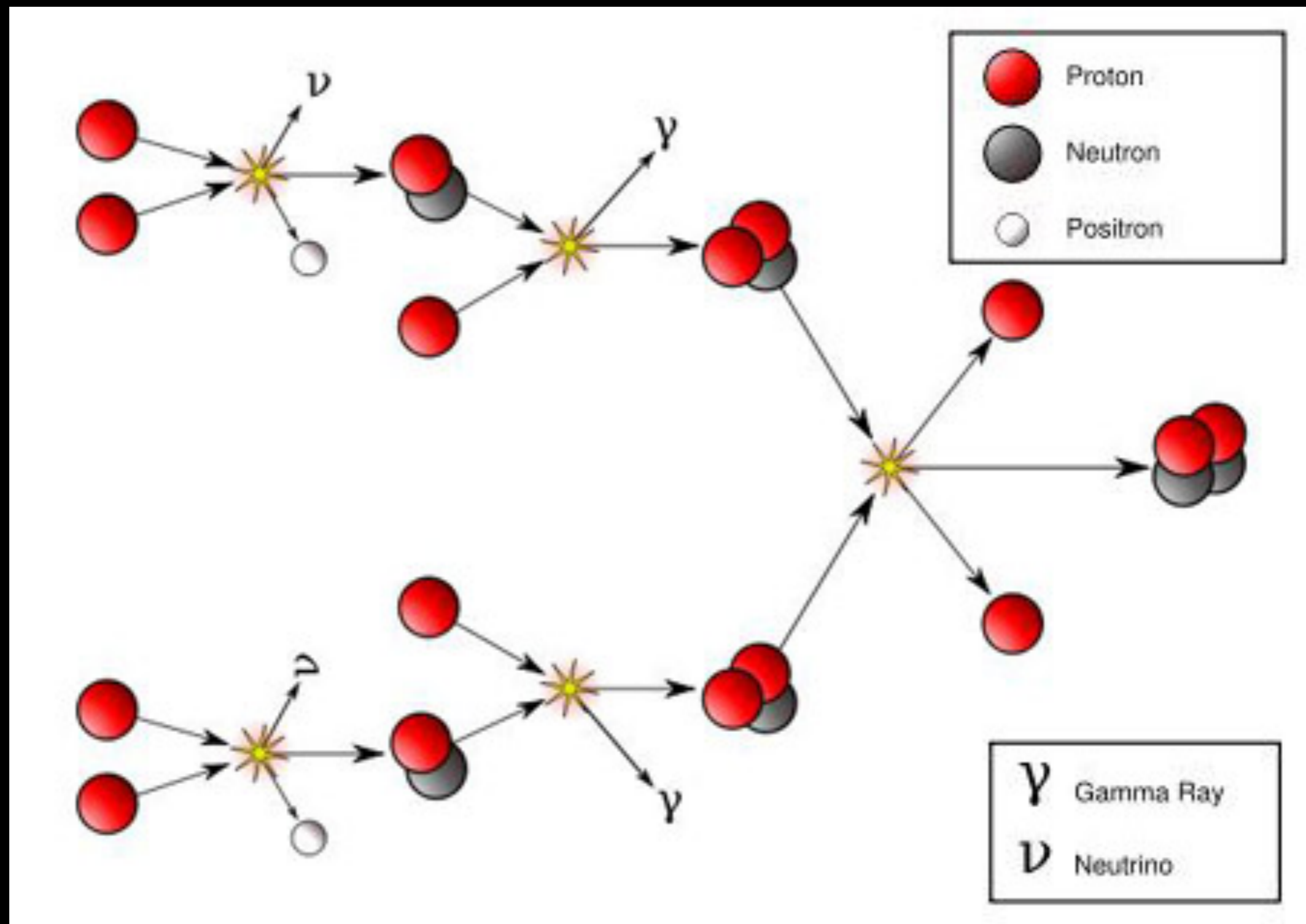
(Sun, stars)



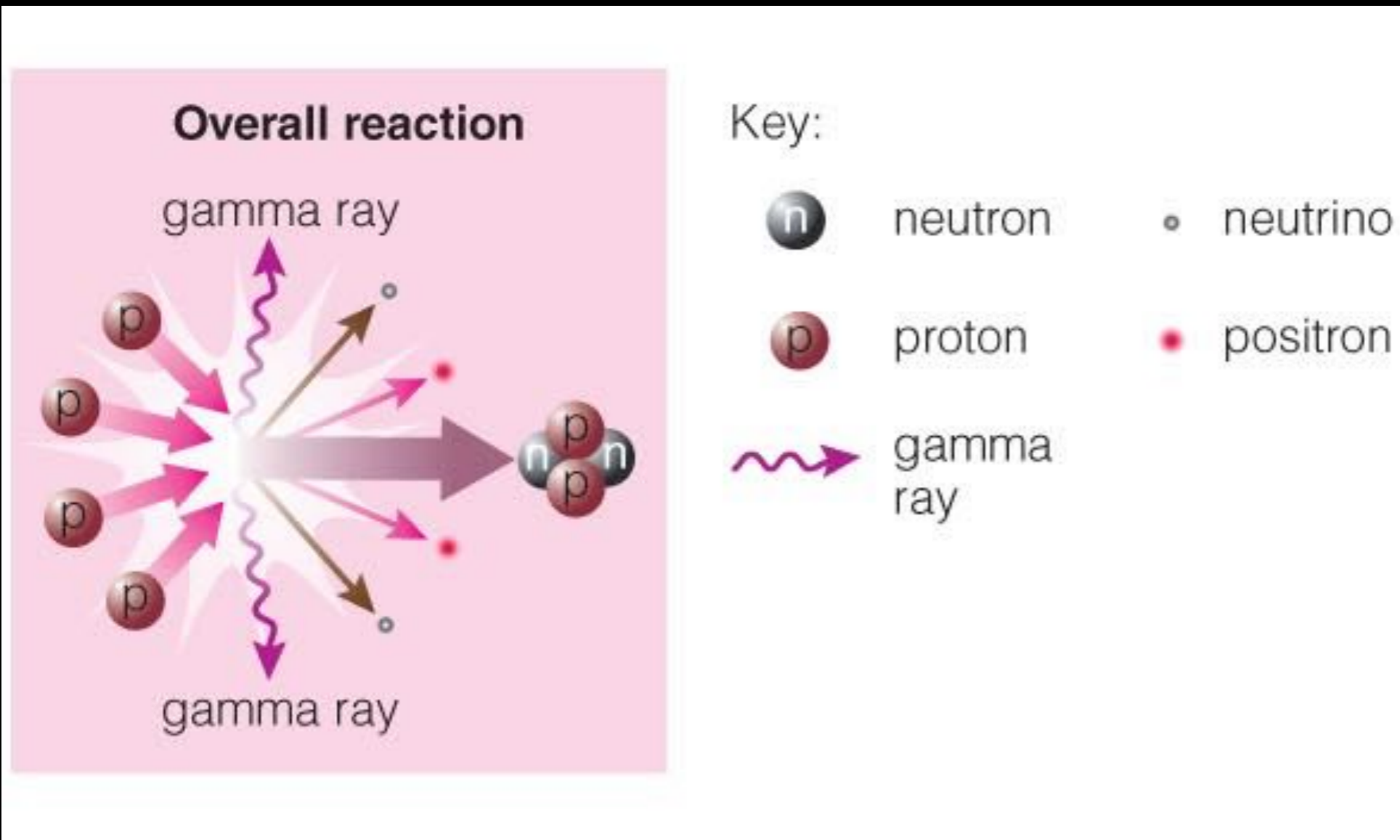
High temperatures enable nuclear fusion to happen in the core of a star.



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
 ^4He nucleus
 2 gamma rays
 2 positrons
 2 neutrinos

**Total mass is
0.7% lower.**

Sun's Energy Content

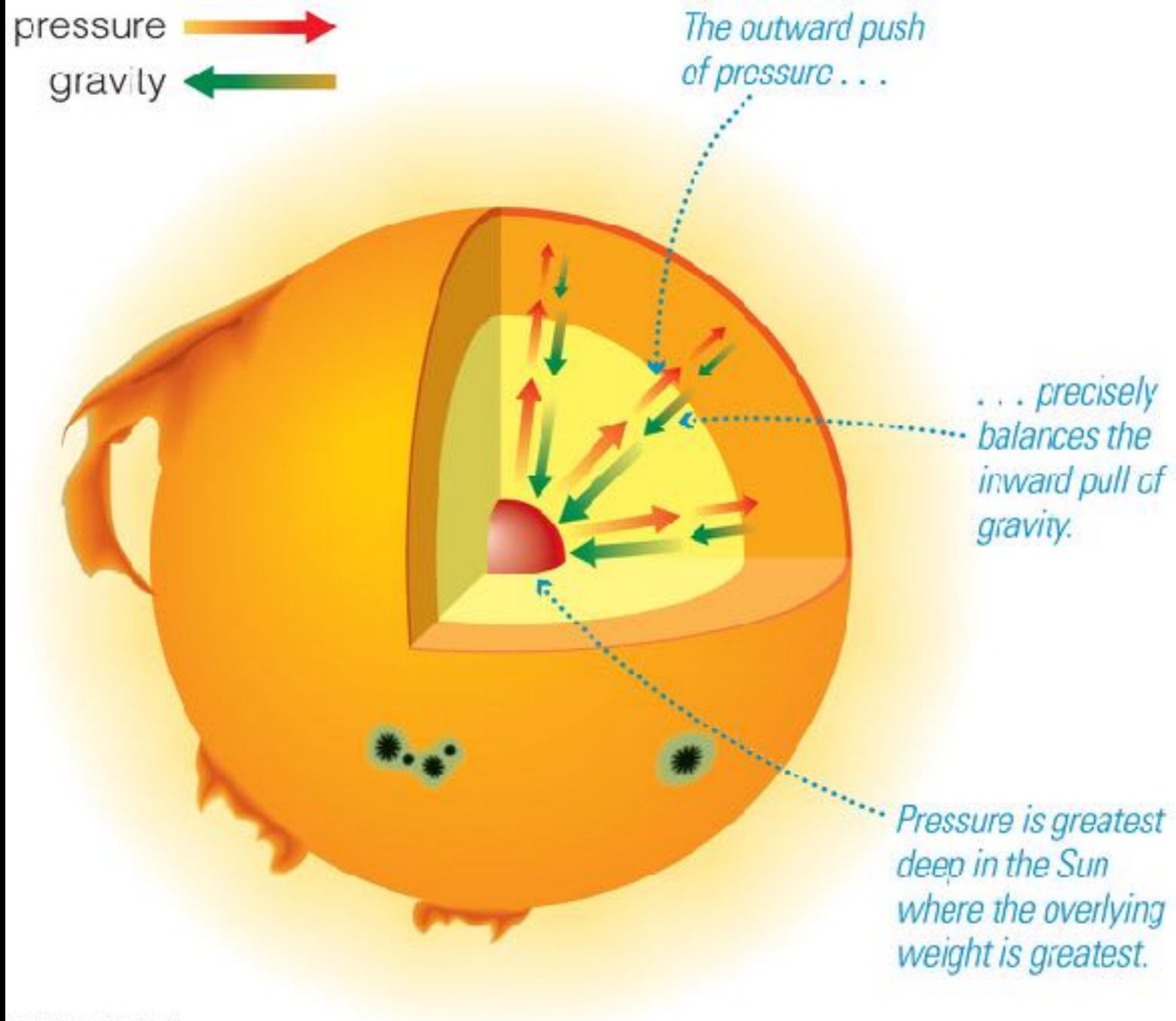
Chem. energy = 4×10^{38} J (~ 30,000 yr)

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

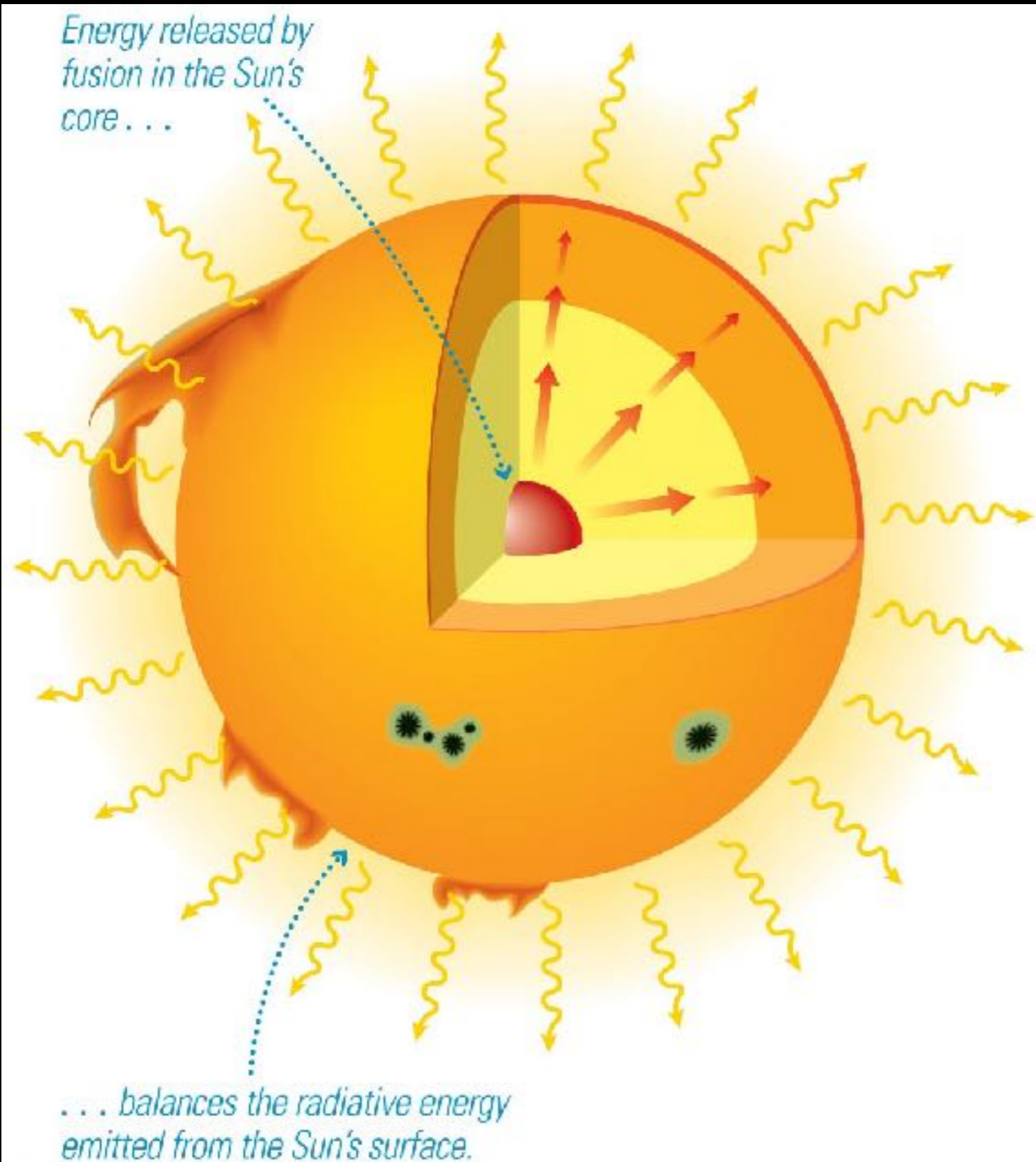
Nuclear energy = 1×10^{45} J (~ 100 billion yr)*

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

*Only about 10% will be used

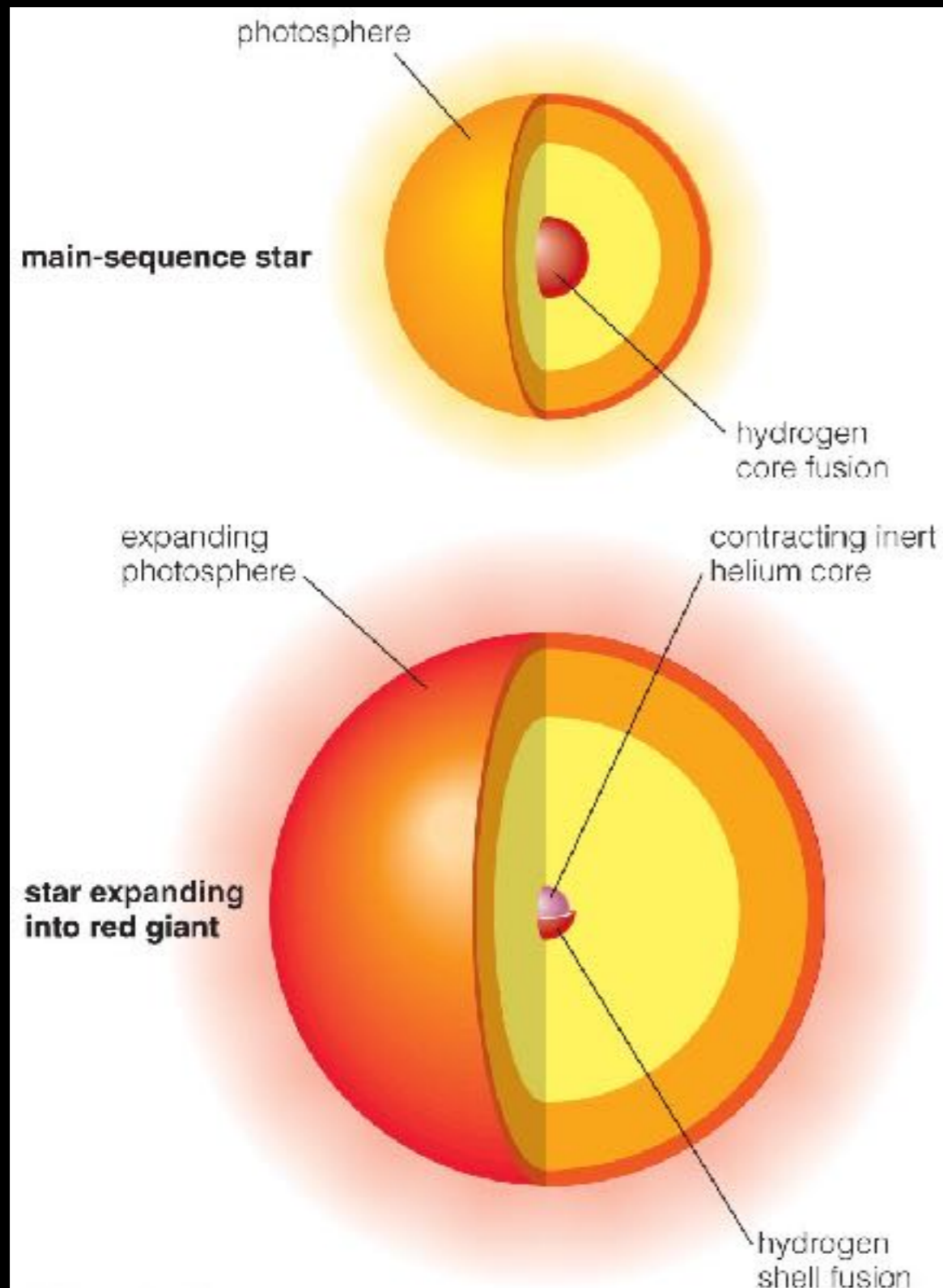


Gravitational equilibrium: Gravity pulling in balances pressure pushing out.



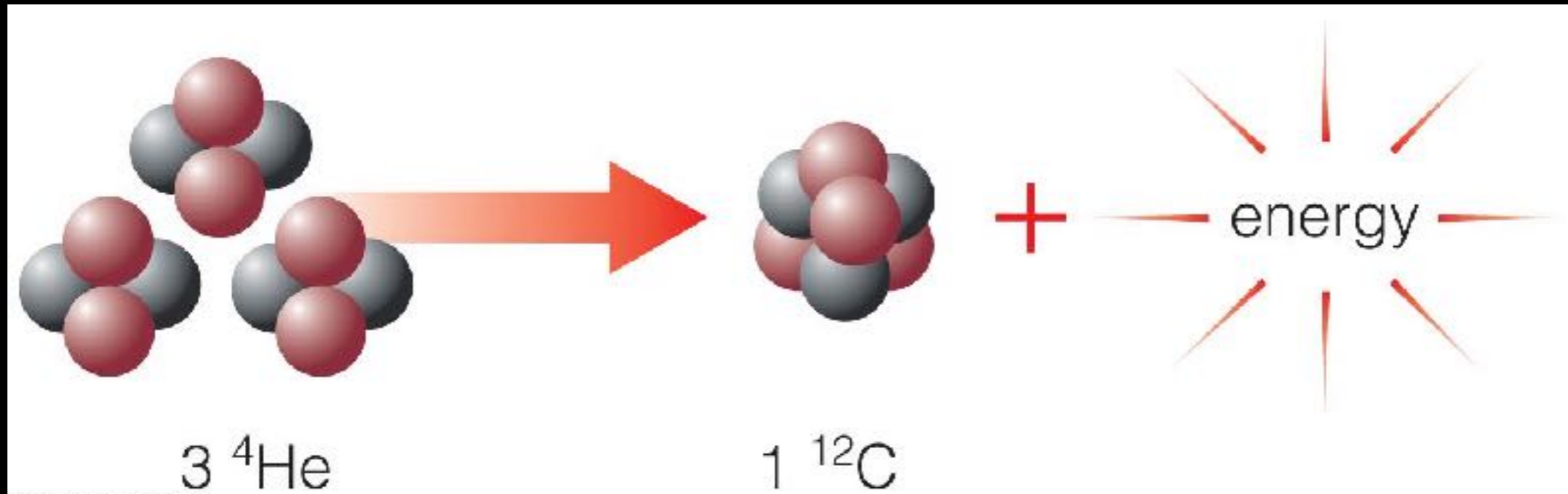
Energy balance:
Thermal energy released by fusion in core balances radiative energy lost from surface.

Broken Thermostat



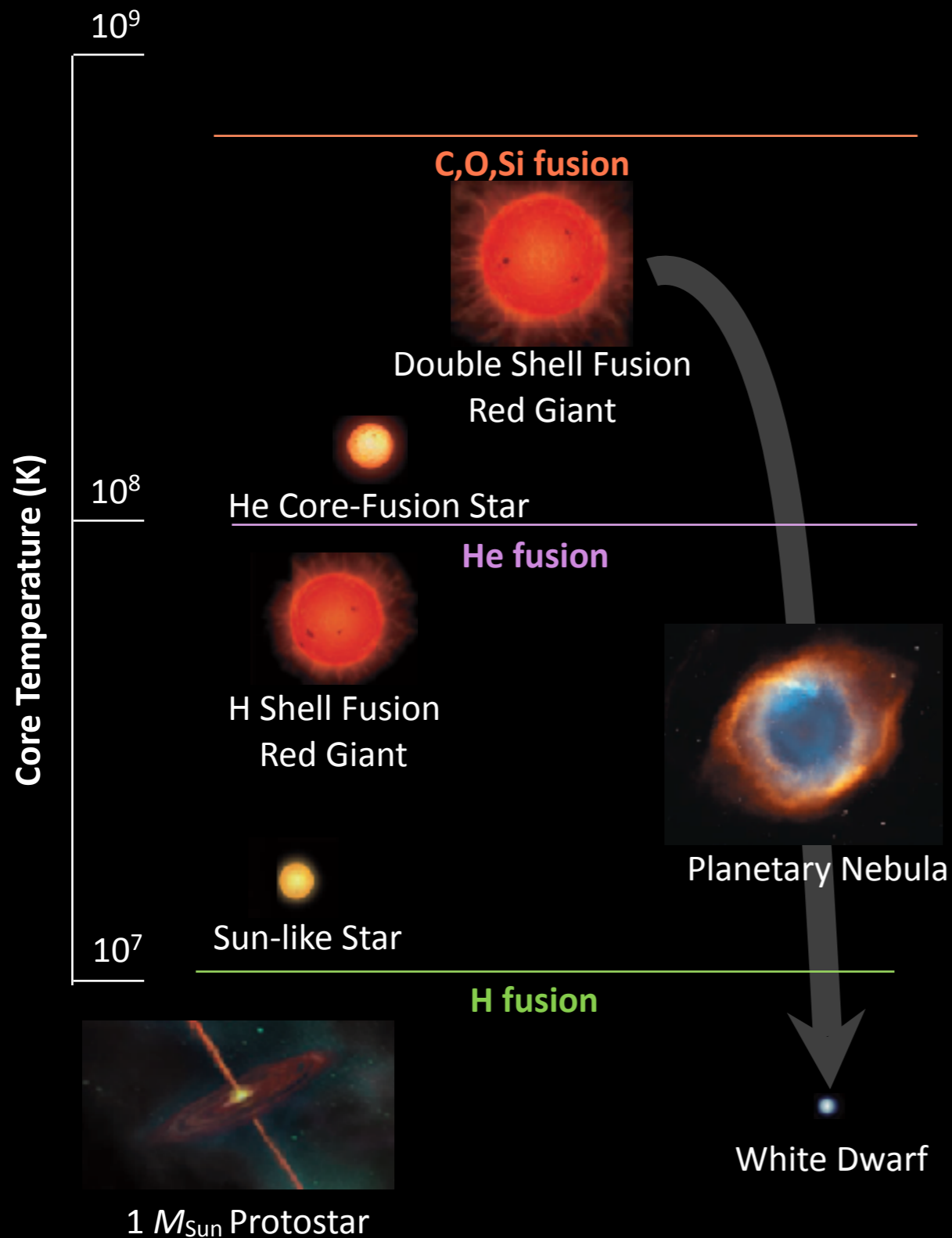
- As the core contracts, H begins fusing to He in a shell around the core.
- Luminosity increases because the core thermostat is broken—the increasing fusion rate in the shell does not stop the core from contracting.

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



- 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

Not to scale!

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 18.998	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 72.63	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 88.9058	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																	61 Tl Thallium 204.383	62 Pb Lead 207.2	63 Bi Bismuth 208.98	64 Po Polonium (209)	65 At Astatine (210)	66 Rn Radon (222)
87 Fr Francium (223)	88 Ra Radium 226.0254																	81 Tl Thallium (204)	82 Pb Lead (209)	83 Bi Bismuth (208)	84 Po Polonium (209)	85 At Astatine (210)	86 Rn Radon (222)
		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)							
		104 Rf Rutherfordium (261)	105 Db Dubnium (262)	106 Sg Seaborgium (266)	107 Bh Bohrium (267)	108 Hs Hassium (277)	109 Mt Meitnerium (268)	110 Ds Darmstadtium (261)	111 Rg Roentgenium (272)	112 Cn Copernicium (285)	113 Uut Ununtrium (284)	114 Uuq Ununquadium (289)	115 Uup Ununpentium (288)	116 Uuh Ununhexium (282)	117 Uus Ununseptium (284)	118 Uuo Ununoctium (284)							

Lanthanide Series

57 La Lanthanum 138.905	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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Big Bang made 75% H, 25% He—stars make everything else.

Key

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- 24.305 — Atomic mass*

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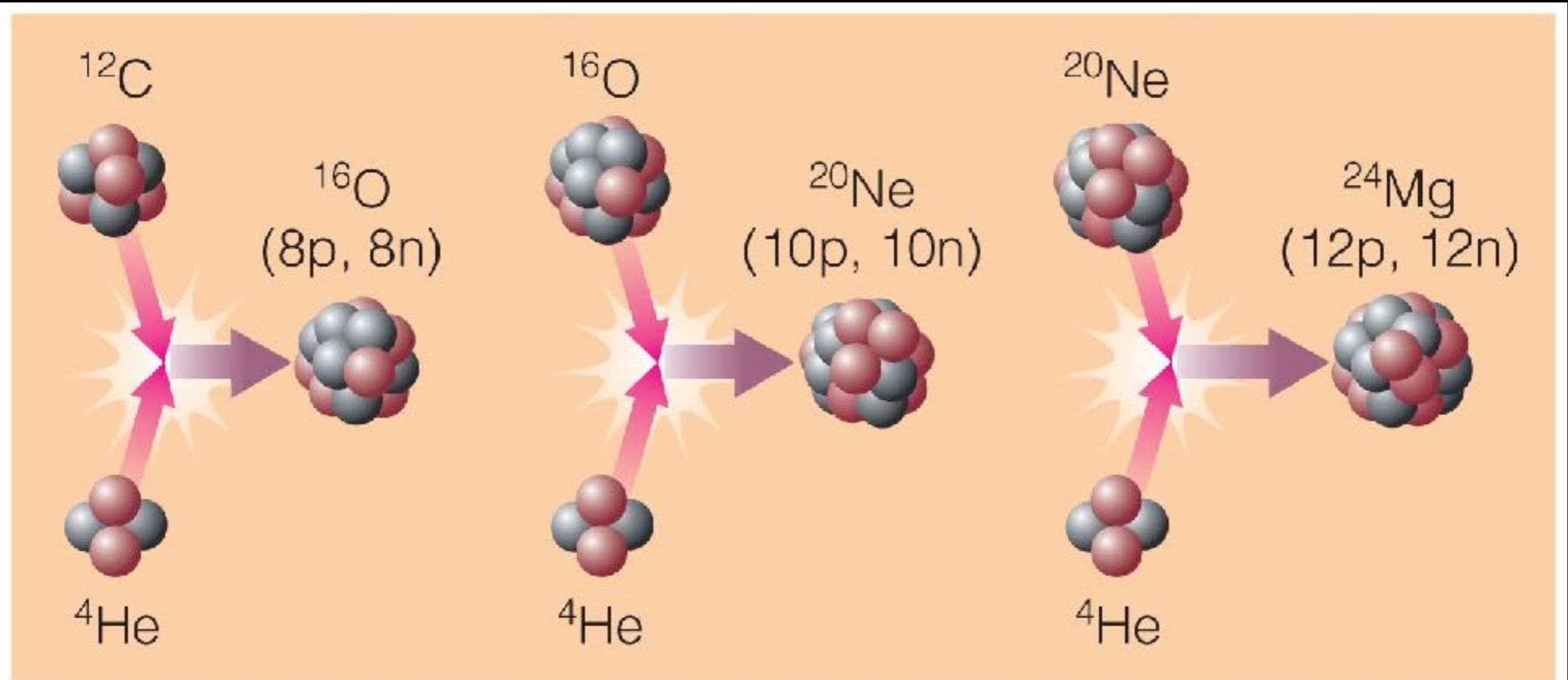
Actinide Series

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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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.

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 18.998	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 72.69	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 (261)	105 Db Dubnium (262)	106 Sg Seaborgium (266)	107 Bh Bohrium (267)	108 Hs Hassium (277)	109 Mt Meitnerium (268)	110 Ds Darmstadtium (261)	111 Rg Roentgenium (272)	112 Cn Copernicium (285)	113 Uut Ununtrium (294)	114 Uuq Ununquadium (289)	115 Uup Ununpentium (288)	116 Uuh Ununhexium (292)	117 Uus Ununseptium (294)	118 Uuo Ununoctium (294)

Lanthanide Series

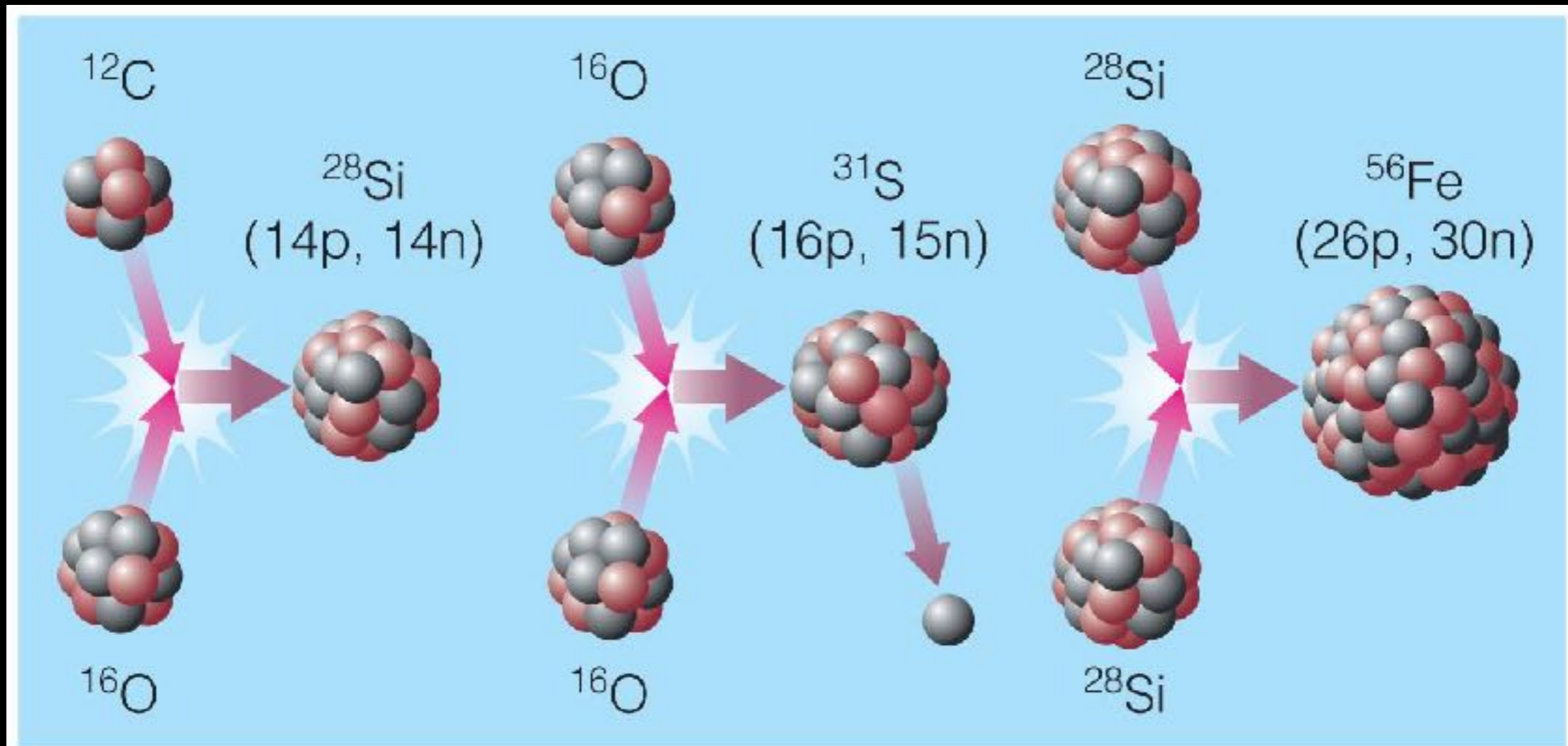
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Helium capture builds C into O, Ne, Mg ...

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 $>8M_{\text{Sun}}$ 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	$^{18}\text{O}, ^{22}\text{Ne}$ 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

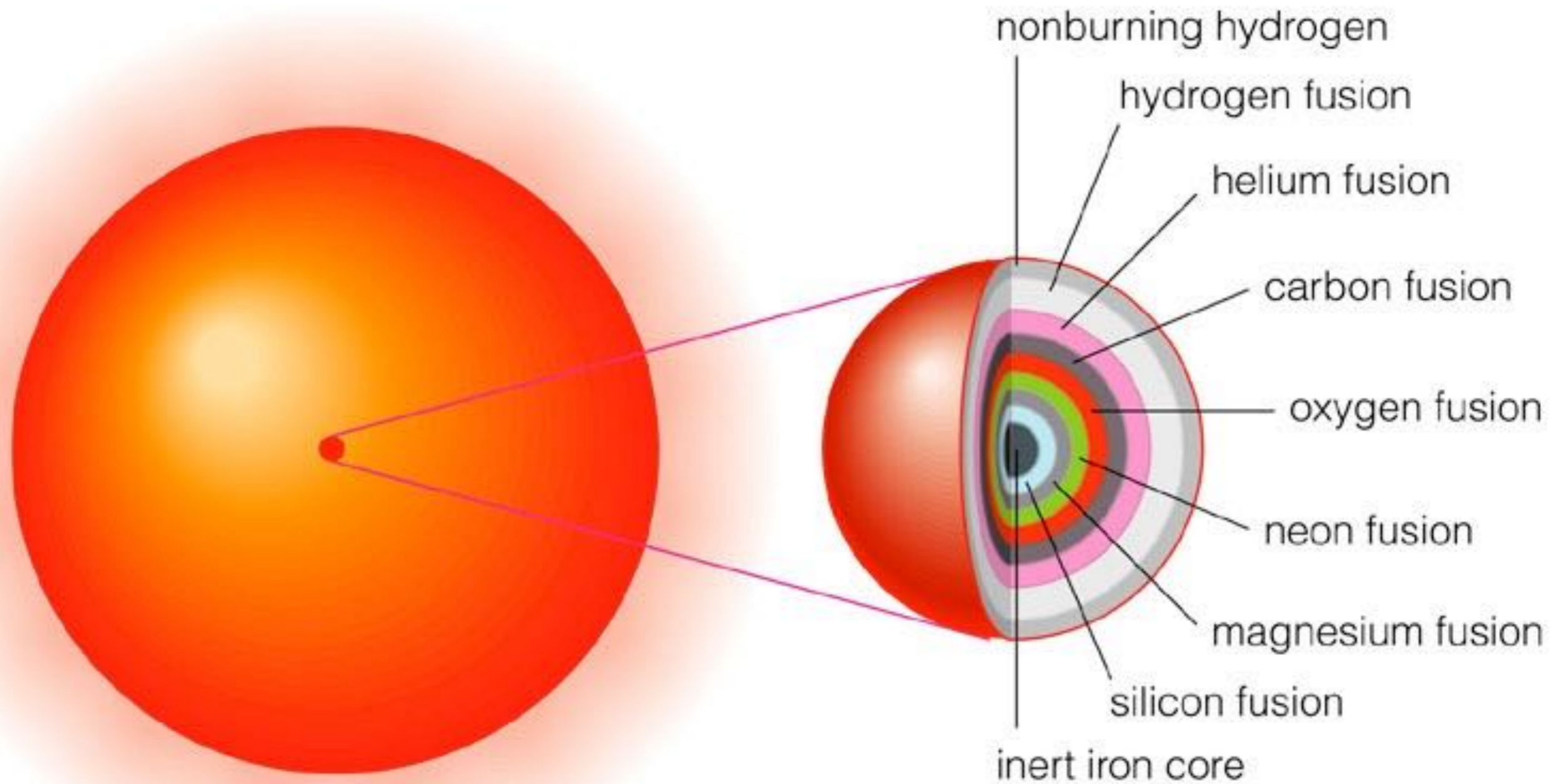
Key

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

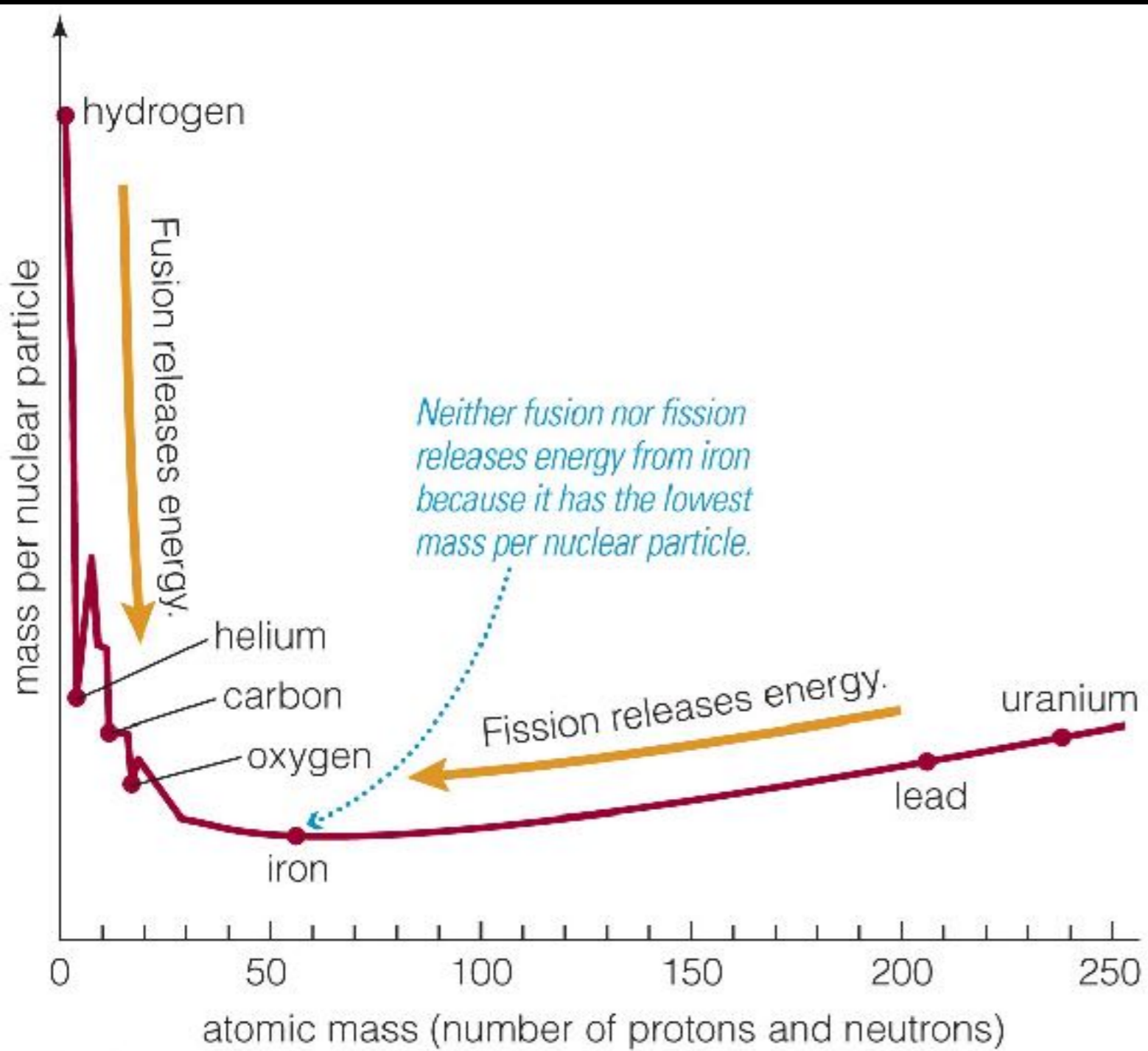
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Advanced reactions in stars make elements such as Si, S, Ca, and Fe.



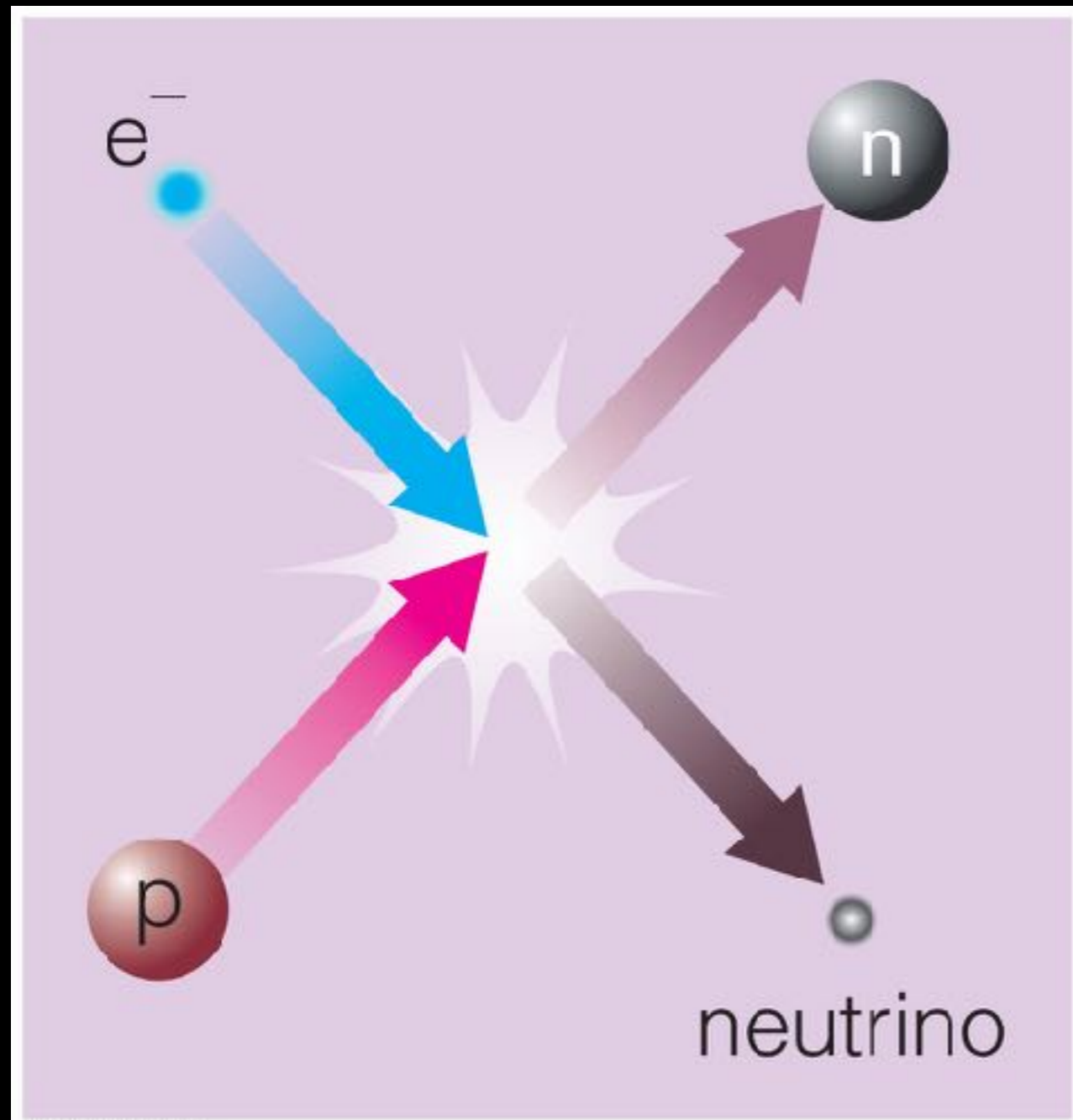
- Advanced nuclear burning proceeds in a series of nested shells.



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

(Fe has lowest mass per nucleon.)

What happens once you reach iron?

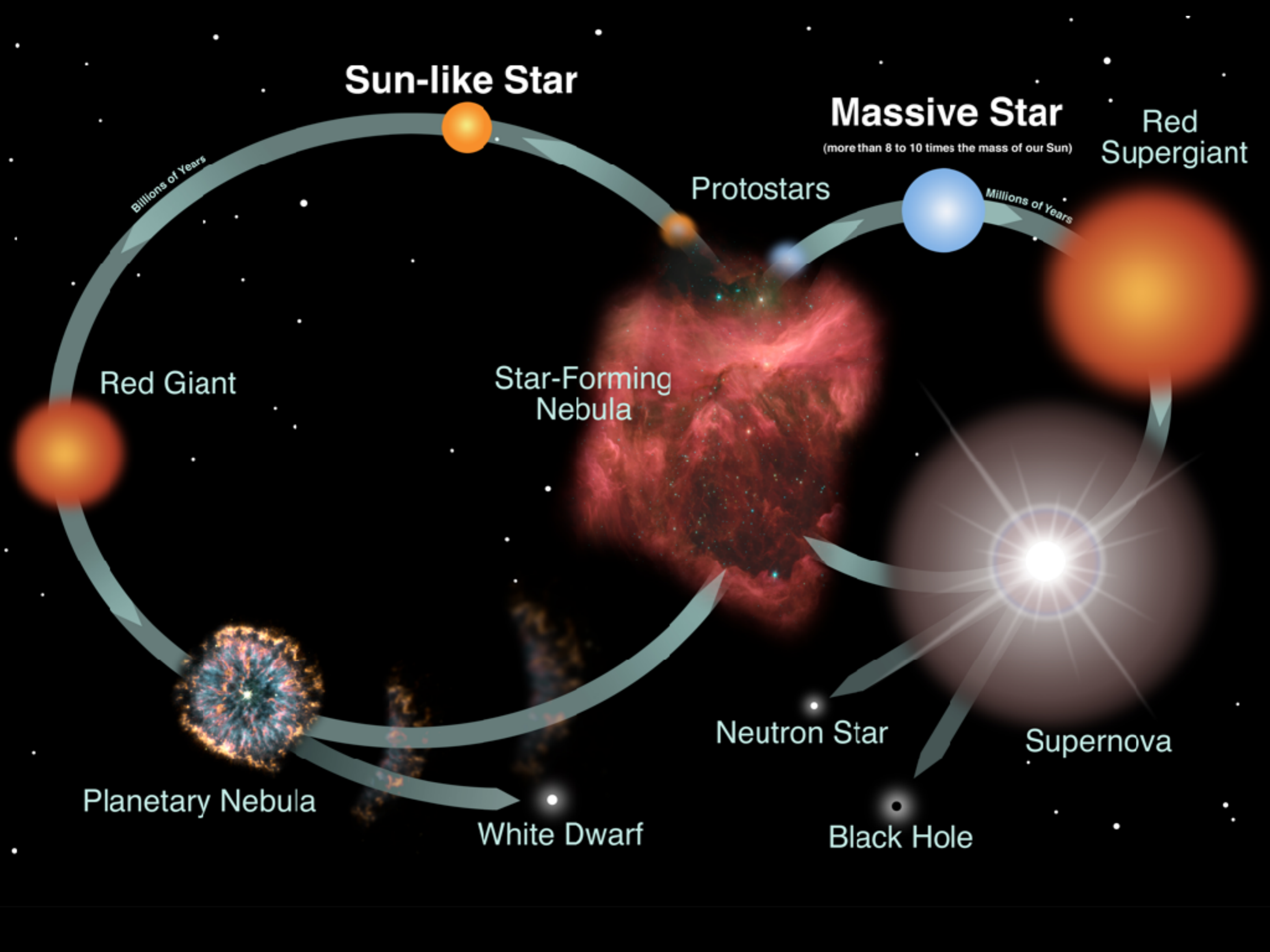


- Iron builds up in the core of massive stars until electron pressure can no longer resist gravity.
- The core then suddenly collapses, creating a **supernova explosion**.
- This explosion ejects nucleosynthesis products back into the interstellar gas
- Some of the largest explosions in the universe, energy release equivalent to 100 million billion billion billion (10^{35}) tons of TNT

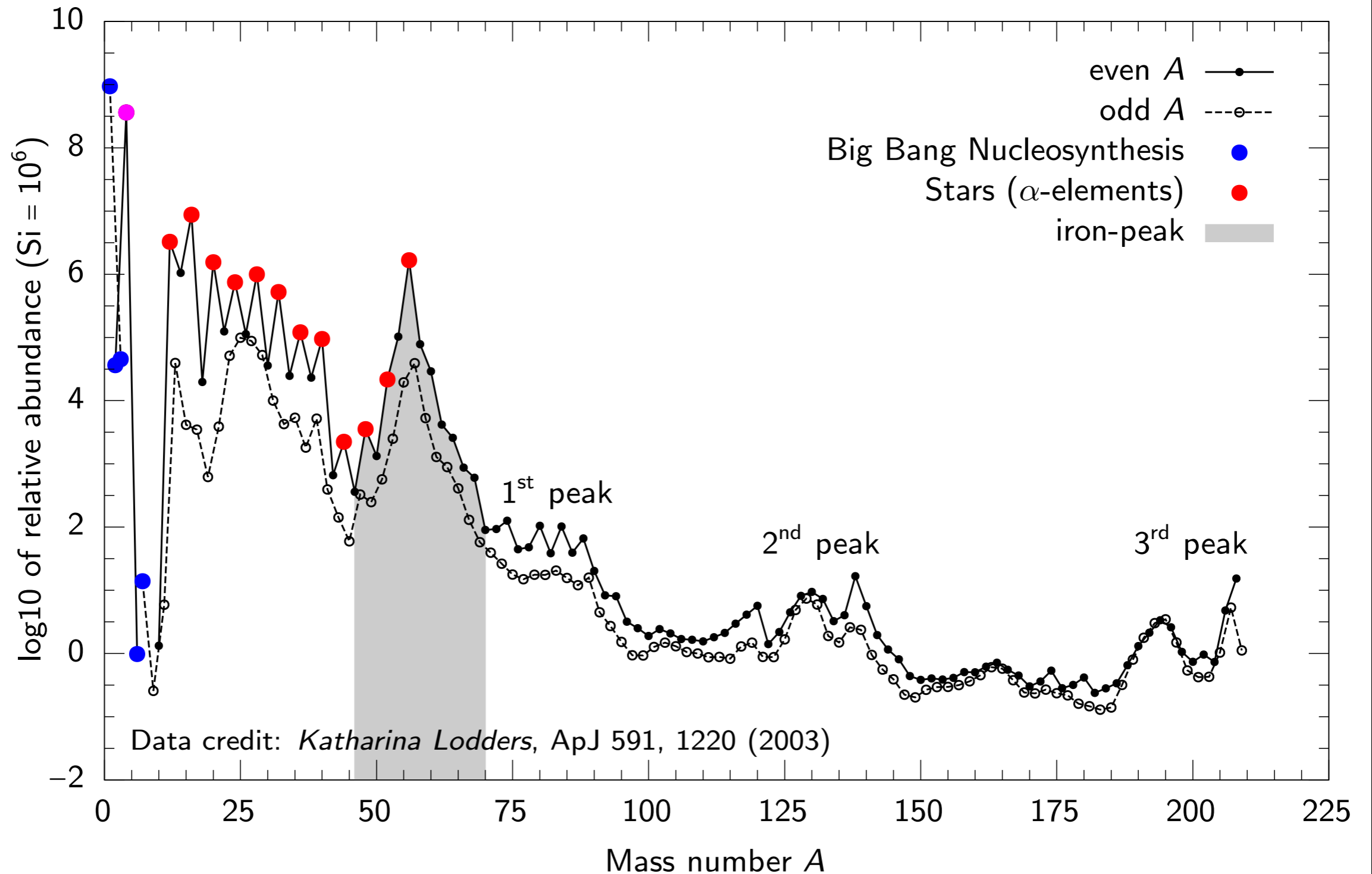
Chimera model: B12-WH07

-258.2 ms






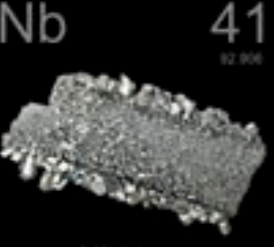

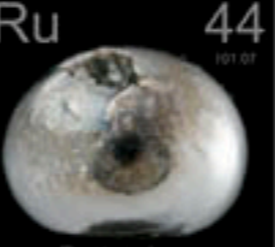
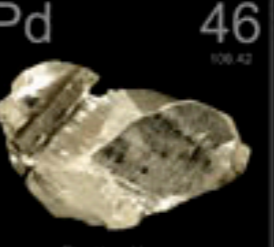

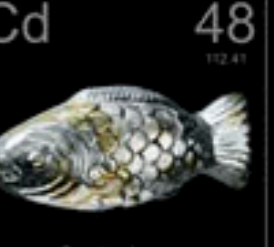

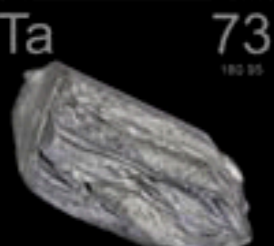

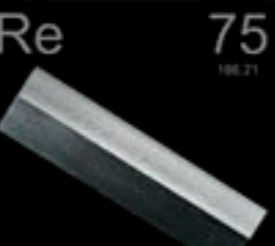
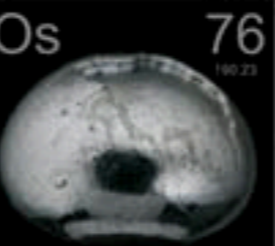






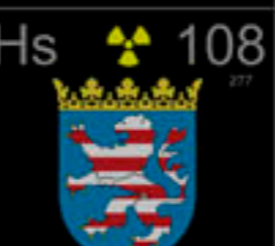


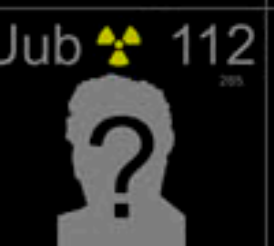
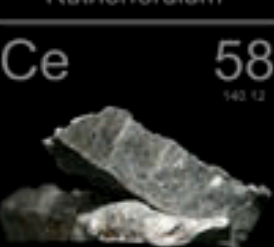
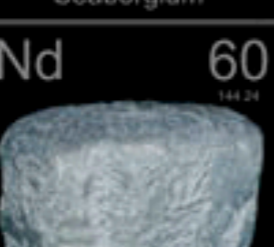



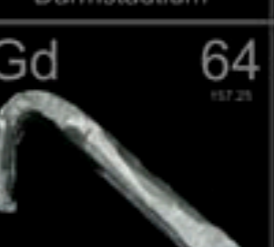

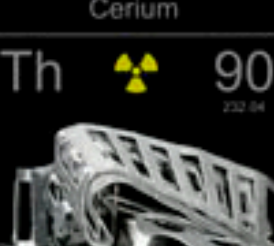


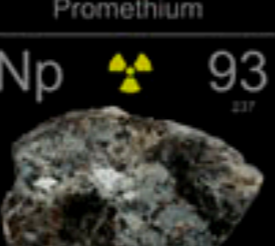
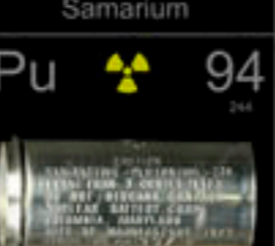


Evidence for Stellar Nucleosynthesis



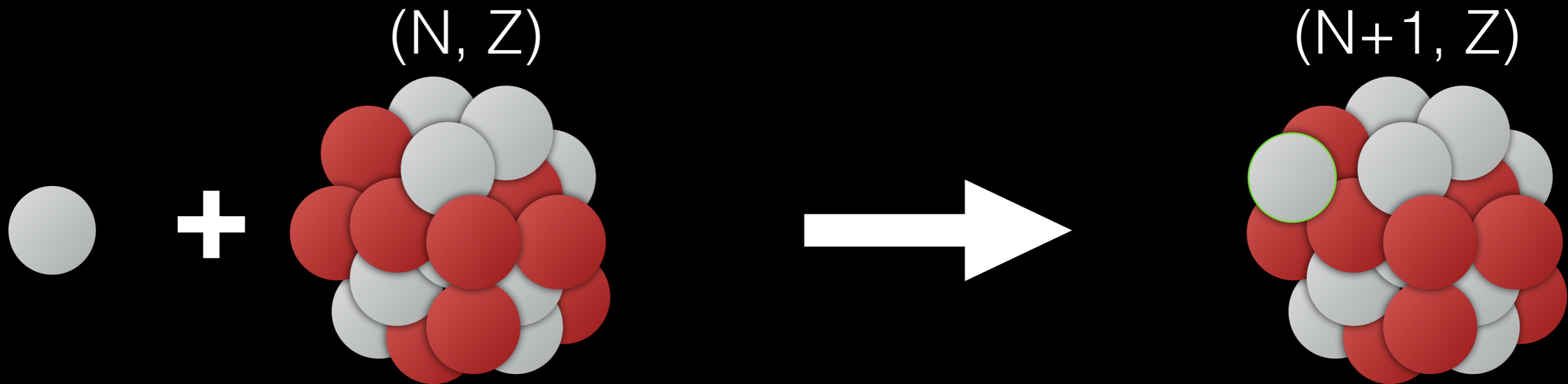
The abundances of nuclei in our solar system

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



Zr 40 91.224  Zirconium	Nb 41 92.906  Niobium	Mo 42 95.94  Molybdenum	Tc 43 98  Technetium	Ru 44 101.07  Ruthenium	Rh 45 102.91  Rhodium	Pd 46 106.42  Palladium	Ag 47 107.87  Silver	Cd 48 112.41  Cadmium
Hf 72 178.49  Hafnium	Ta 73 180.95  Tantalum	W 74 183.84  Tungsten	Re 75 186.21  Rhenium	Os 76 190.23  Osmium	Ir 77 192.22  Iridium	Pt 78 195.08  Platinum	Au 79 196.97  Gold	Hg 80 200.59  Mercury
Rf 104 261  Rutherfordium	Db 105 262  Dubnium	Sg 106 266  Seaborgium	Bh 107 264  Bohrium	Hs 108 277  Hassium	Mt 109 268  Meitnerium	Ds 110 281  Darmstadtium	Rg 111 272  Roentgenium	Uub 112 285  Ununbium
Ce 58 140.12  Cerium	Pr 59 140.91  Praseodymium	Nd 60 144.24  Neodymium	Pm 61 145  Promethium	Sm 62 150.36  Samarium	Eu 63 151.96  Europium	Gd 64 157.25  Gadolinium	Tb 65 158.92  Terbium	Dy 66 162.5  Dysprosium
Th 90 232.04  Thorium	Pa 91 231.04  Protactinium	U 92 238.03  Uranium	Np 93 237  Neptunium	Pu 94 244  Plutonium	Am 95 243  Americium	Cm 96 247  Curium	Bk 97 247  Berkelium	Cf 98 251  Californium

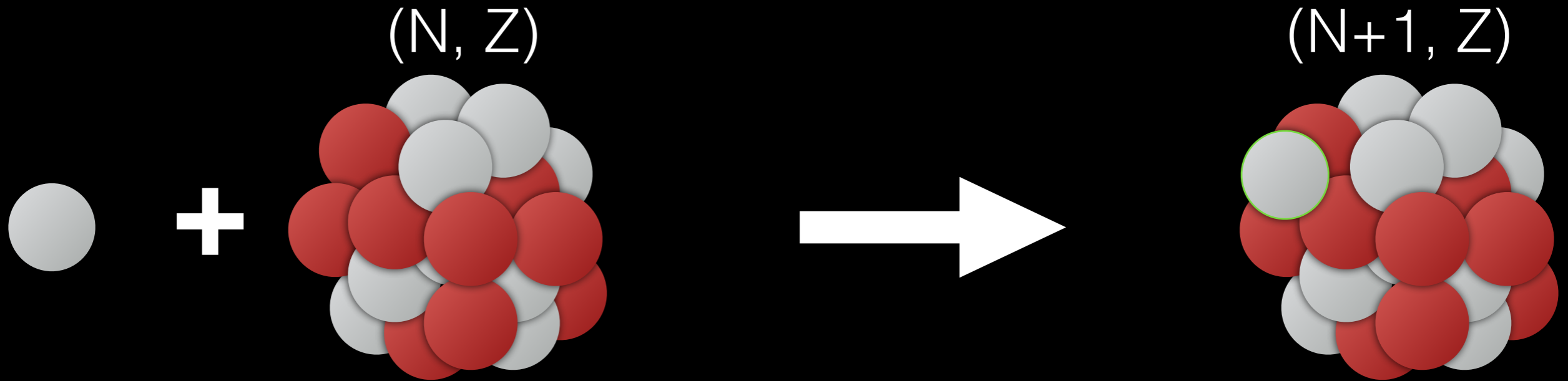
Neutron Capture



No electrical repulsion
to deal with

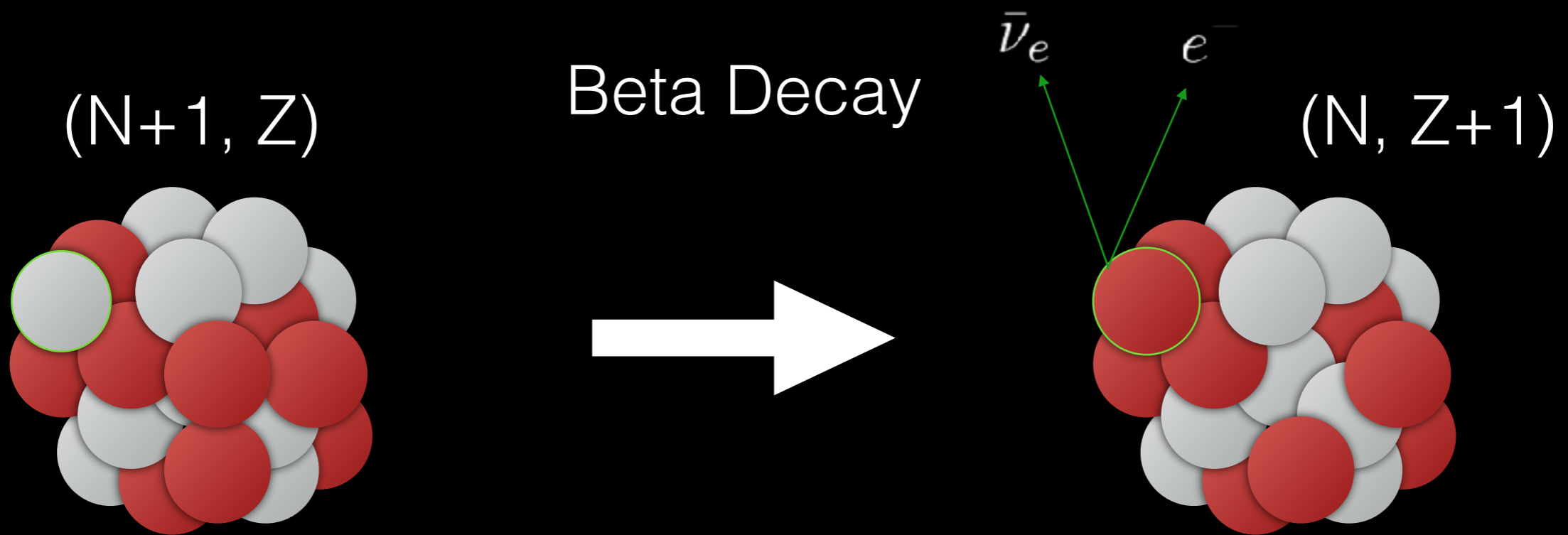
Same element, new isotope

Neutron Capture



Same element, new isotope

Beta Decay



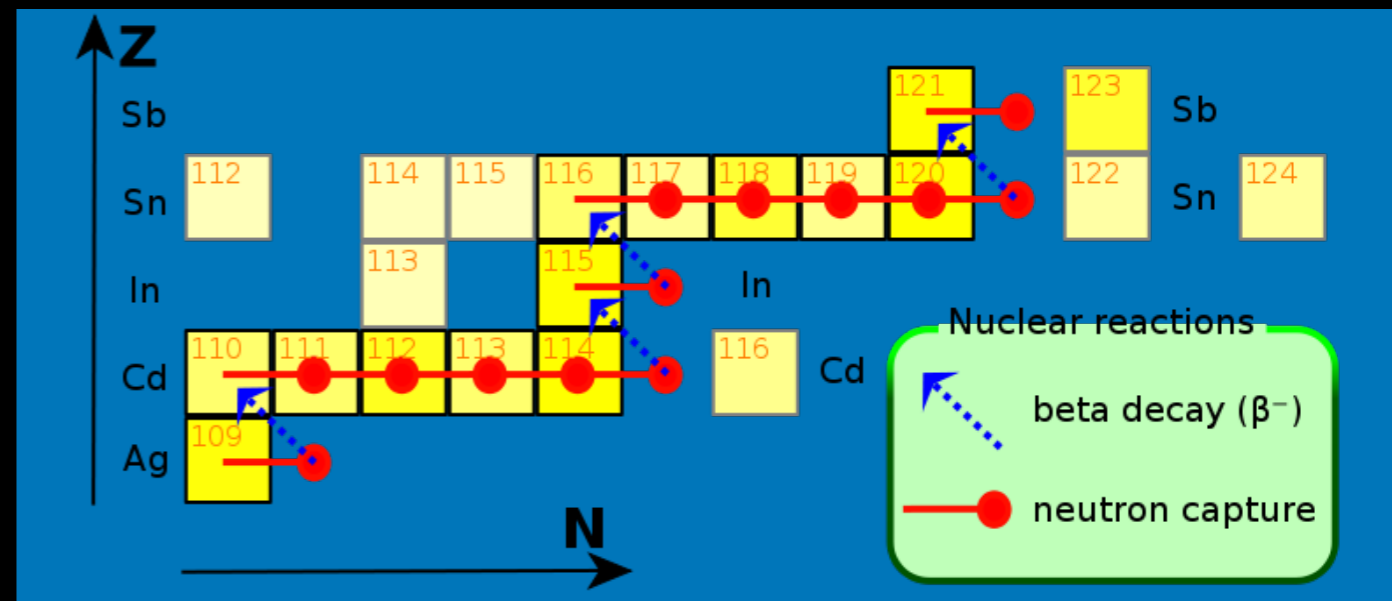
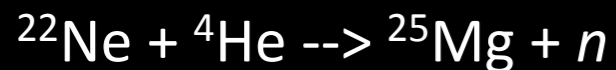
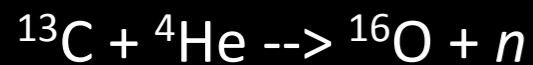
New Element!

Two ways to capture neutrons

Slowly (s-process):

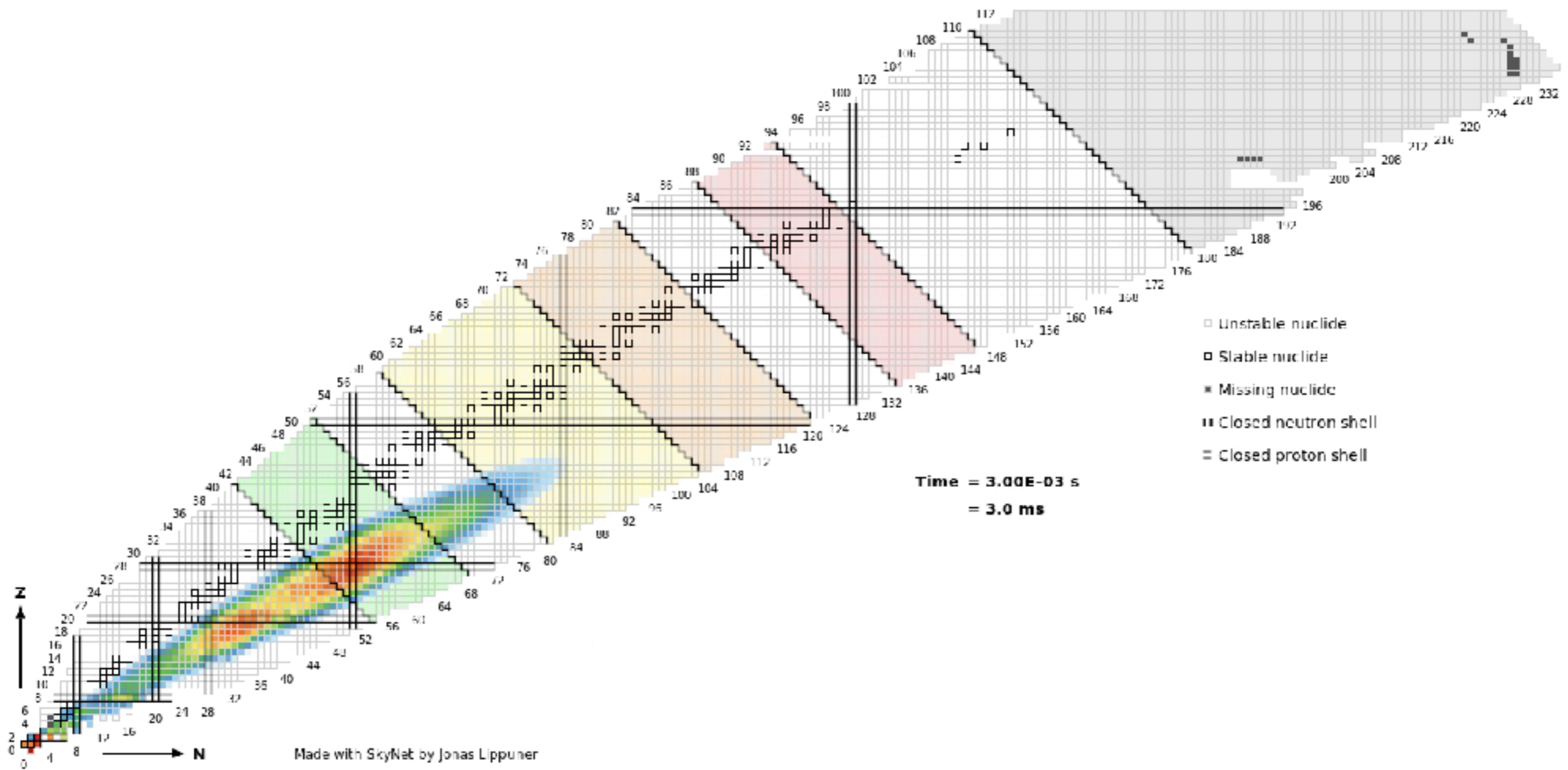
Capture a neutron and then beta-decay back to stability, then repeat. This process occurs during later stages of stellar burning, responsible for about half of the elements heavier than iron.

Get neutrons from:



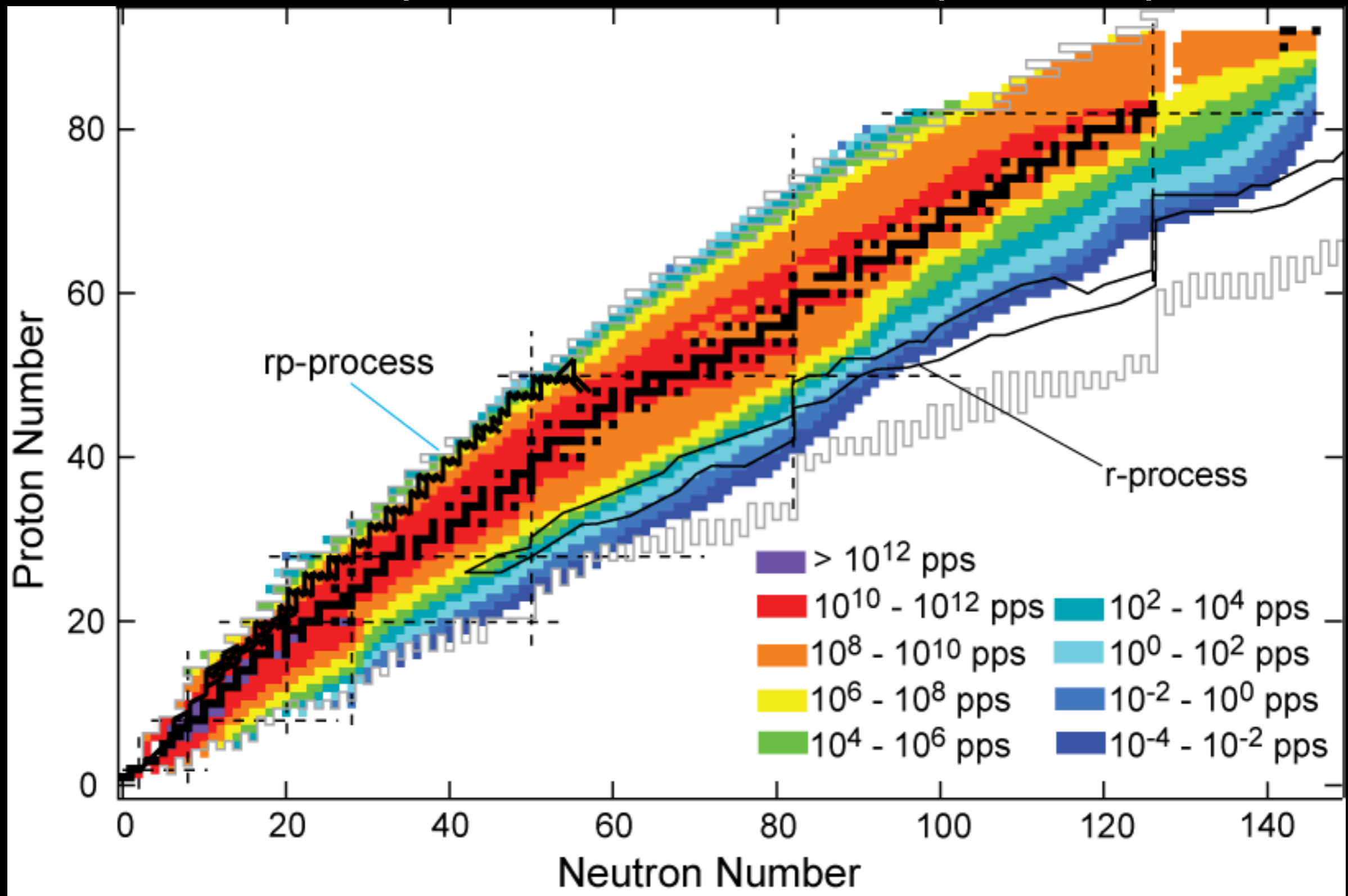
Rapidly (r-process):

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.

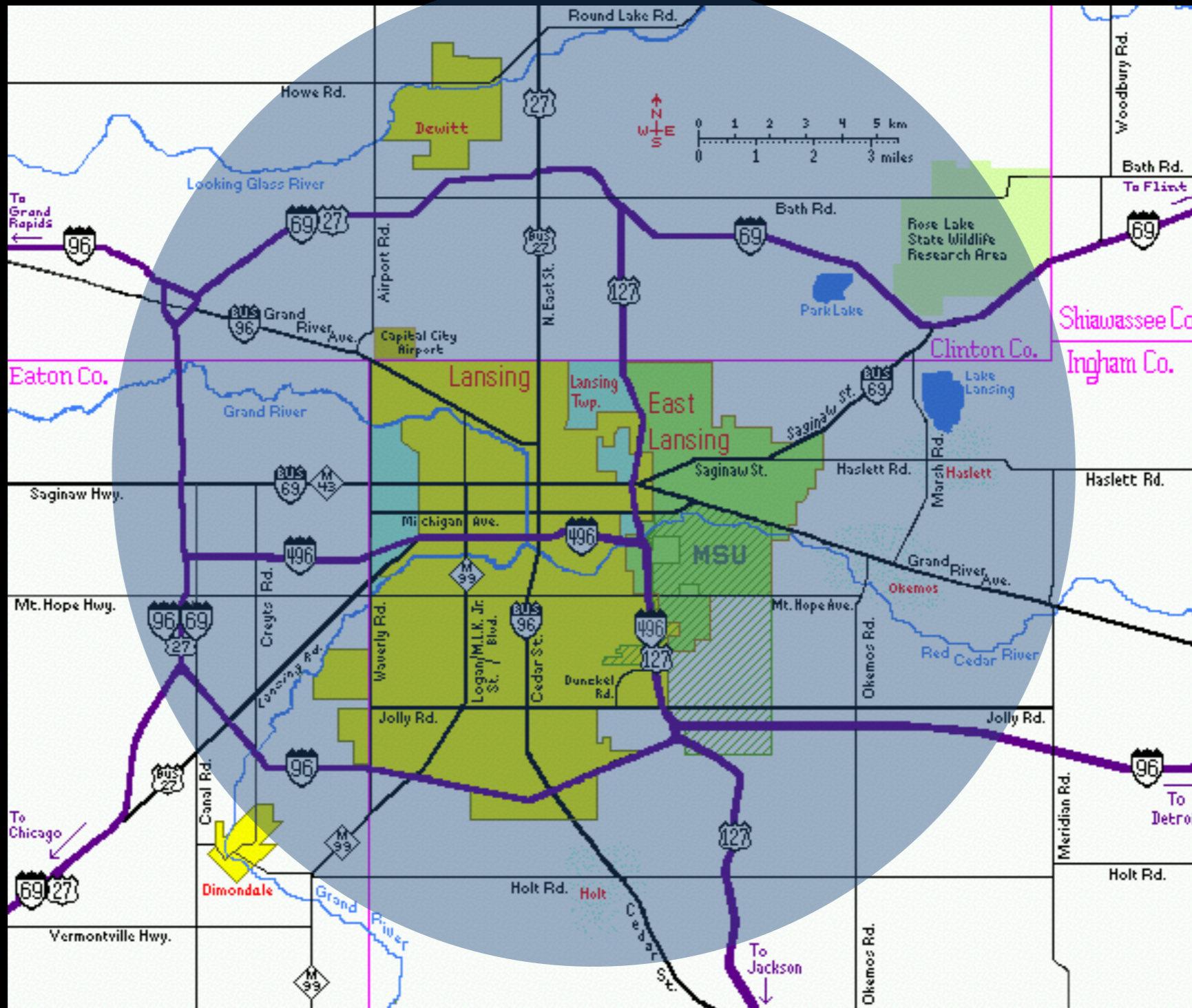


- Unstable nuclide
- ◻ Stable nuclide
- ✖ Missing nuclide
- ▣ Closed neutron shell
- ▢ Closed proton shell

FRIB will help us understand the r-process path



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 ($\sim 10^9$ g)



B ($\sim 10^{12}$ g)



C ($\sim 10^{15}$ 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 MPI 340
Exploring fundamental physics
with compact stars
(NewCompStar)



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...