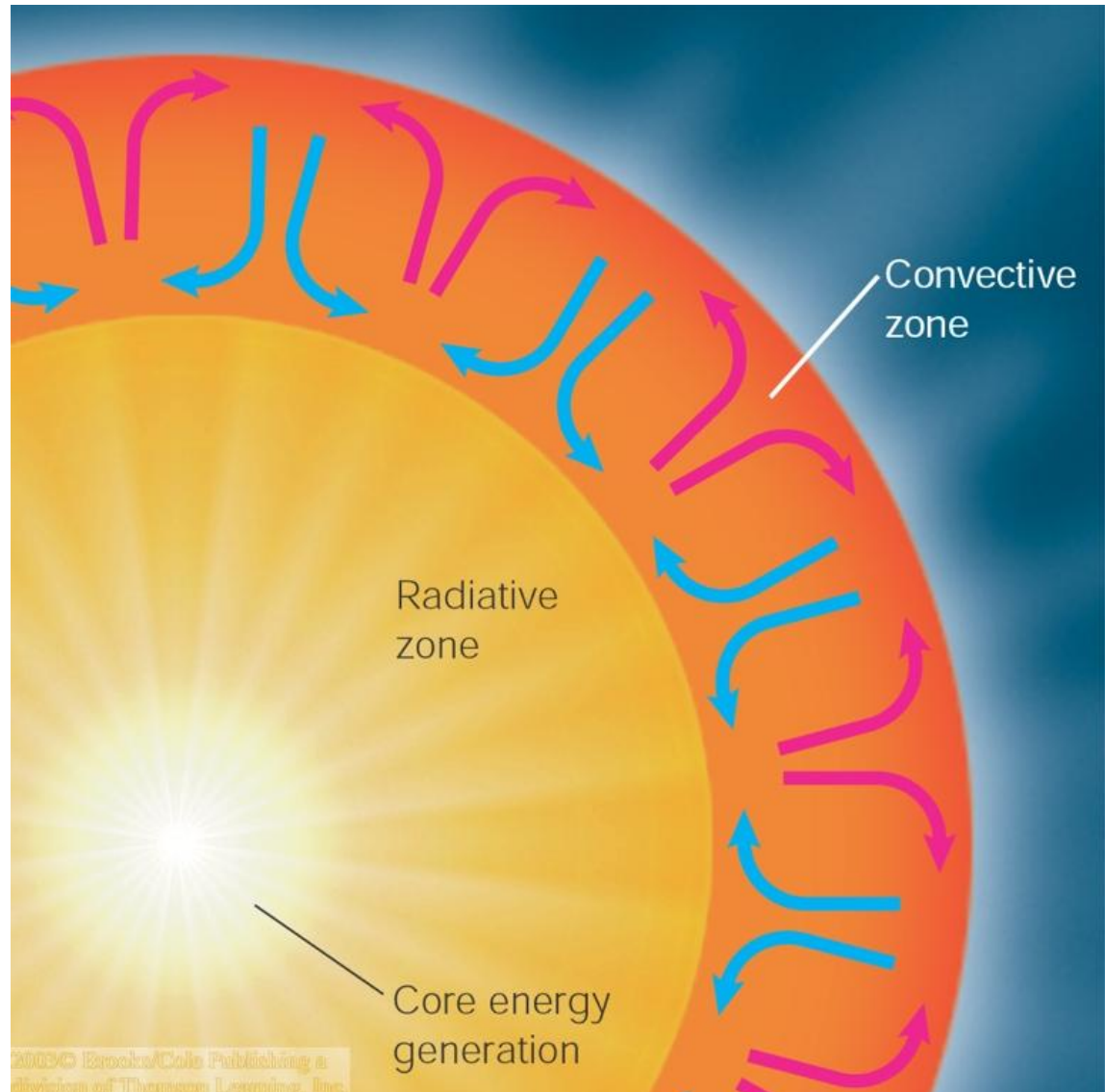
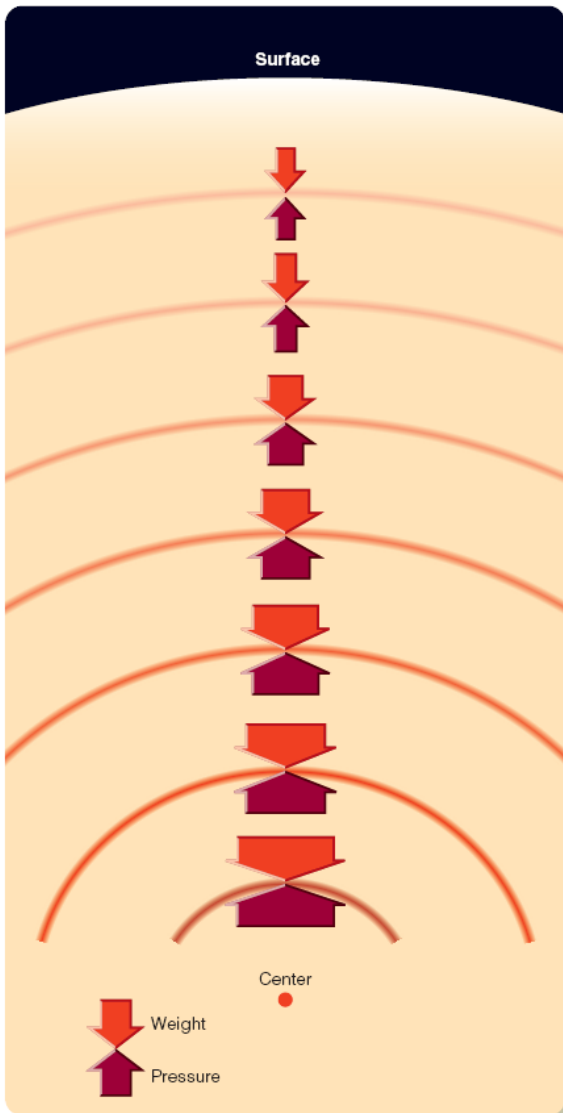


Nuclear Reactions in Stars

Interior Structure of Sun



What Powers the Sun?

- Gravitational energy (potential plus kinetic, according to virial theorem) as function of radius:

$$E_{tot} = -\frac{3}{10} \frac{GM^2}{R}$$

- Therefore, maximum amount of energy “generated” by Sun through contraction to present radius:

$$E_{tot} = -\frac{3}{10} \frac{6.674 \cdot 10^{-11} (1.989 \cdot 10^{30})^2}{6.955 \cdot 10^8} \text{ J} = 1.14 \cdot 10^{41} \text{ J}$$

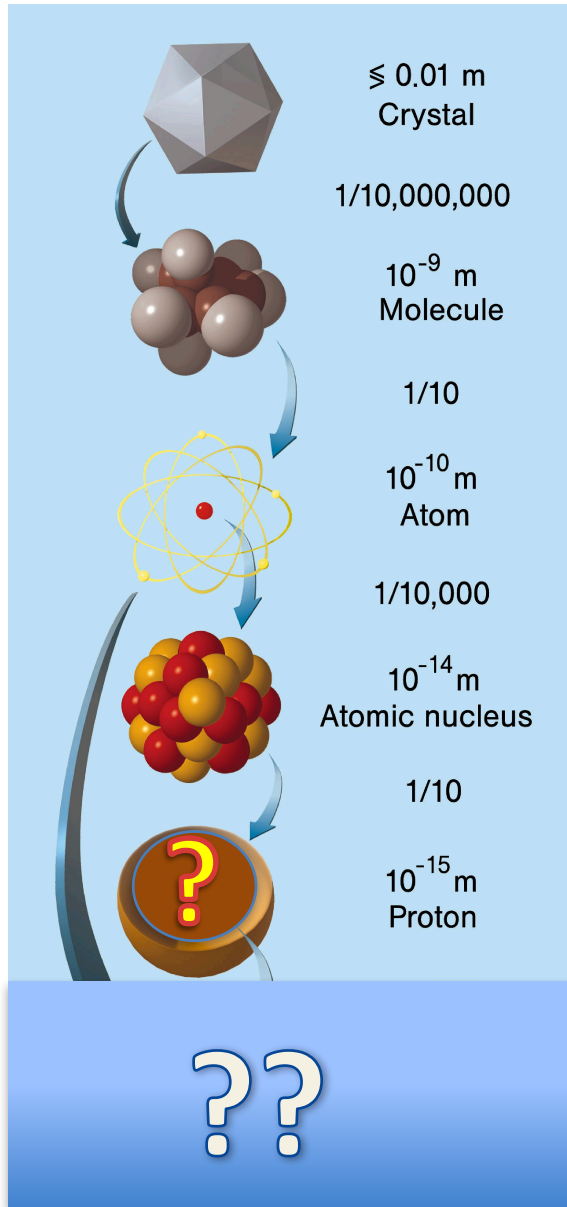
- Energy actually radiated by Sun over last 4.5 B yrs

$$E_{rad} = L_{Sun} \cdot T = 3.84 \cdot 10^{26} \text{ W} \cdot 1.42 \cdot 10^{17} \text{ s} = 5.45 \cdot 10^{43} \text{ J}$$

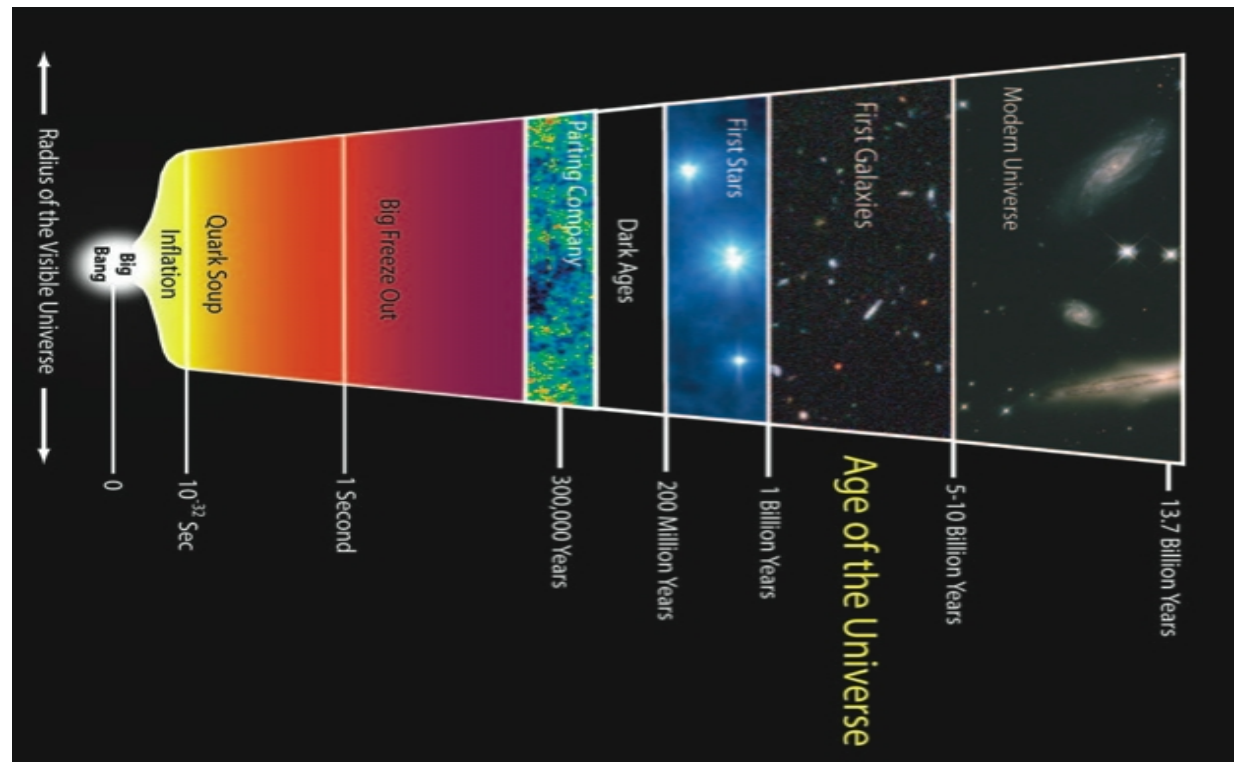
= 500 times more! (Or Sun must be less than 9 M yrs old!)

- Solution: Must be something else → nuclear fusion

The Structure of Matter



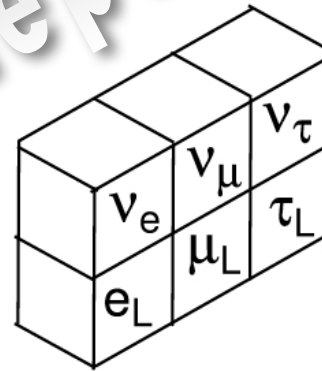
- What is the Universe made off?
- What are the most fundamental objects in Nature?
- What particles were there in the beginning (right after the big bang)?
- How do they interact?
- How do they form composite objects?



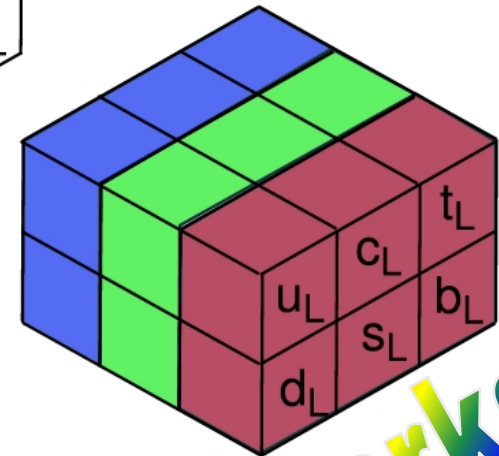
Matter Particles

- Make up visible matter
- Pointlike ($<10^{-18}$ m), Fundamental *)
- Have mass (from $< \frac{1}{2}$ eV to 178,000,000,000 eV = 178 GeV)
- Distinct from their antiparticles *)
- Fermions (Spin $\frac{1}{2}$) \Rightarrow they “defend” their space (Pauli Principle) and can only be created in particle-antiparticle pairs
- Can be “virtual”, but make up matter being (nearly) “real”
- “stable” (against strong decays; lifetimes from ∞ to 10^{-24} s)

Leptons



3 “colors” = 3 different charges: red, green, blue



Quarks

x2 for R, x2 for antiparticles

*) Until further notice

Forces and Force Carriers

- Mediate Interactions (Forces) - form “Waves”
- Pointlike, Fundamental
- Massless *)
- Some are their own antiparticles (photon, Z^0 , graviton)
- Spin 1, 2 \rightarrow Bosons (tend to cluster together, can be produced in arbitrary numbers)
- Can be real, but carry forces as virtual particles
- Some are absolutely stable (γ , gluons, gravitons)

*) See next slide

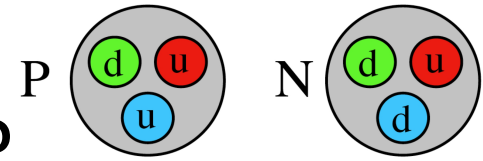
BOSONS			force carriers spin = 0, 1, 2, ...		
Unified Electroweak spin = 1			Strong (color) spin = 1		
Name	Mass GeV/c ²	Electric charge	Name	Mass GeV/c ²	Electric charge
γ photon	0	0	g gluon	0	0
W^-	80.4	-1	Gravitation spin = 2		
W^+	80.4	+1	Name	Mass GeV/c ²	Electric charge
Z^0	91.187	0	g graviton	0	0

Note: gluons come in 8 possible combinations of color/anticolor (9th is “sterile” – doesn’t exist)



Hadronic Particle Zoo

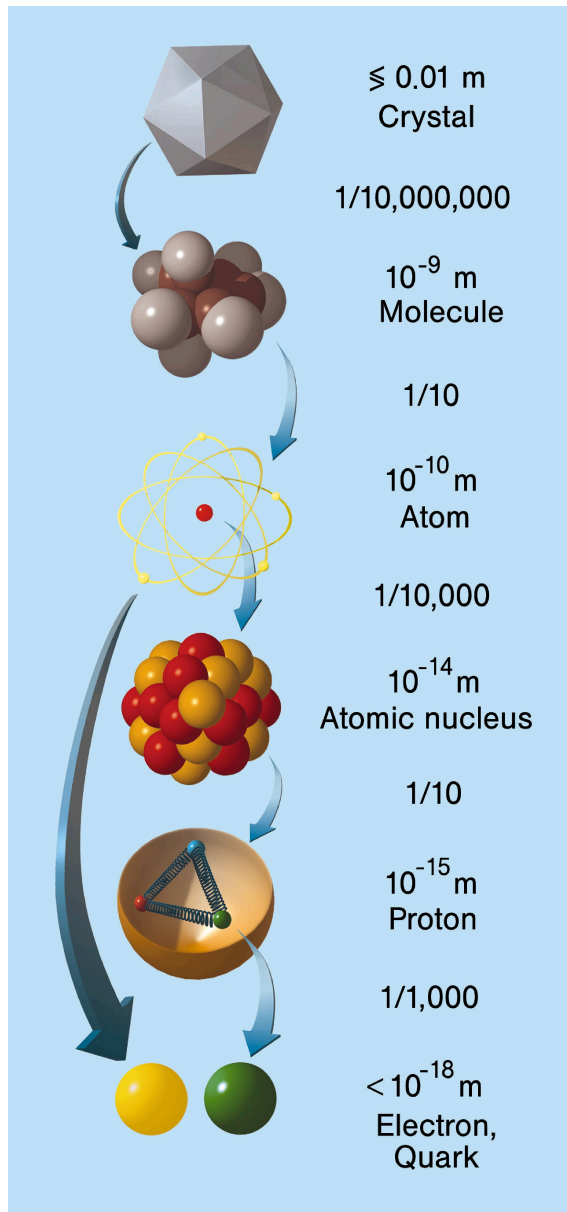
- what can one build from quarks?



HADRONS								
Family Name	Particle Name	Particle Symbol	Antiparticle Symbol	Composition	Mass	Electric Charge	Lifetime in Seconds	
baryon	proton	p or p ⁺	\bar{p}	uud	1,836	+1	stable	
	neutron	n or n ⁰	\bar{n}	udd	1,839	0	887	
	lambda	Λ^0	$\bar{\Lambda}^0$	uds	2,183	0	2.6×10^{-10}	
	lambda-c	Λ_c^+	$\bar{\Lambda}_c^+$	udc	4,471	+1	2.1×10^{-13}	
	lambda-b	Λ_b^0	$\bar{\Lambda}_b^0$	udb	11,000	0	1.1×10^{-12}	
	sigma		Σ^+	$\bar{\Sigma}^+$	uus	2,328	+1	0.8×10^{-10}
			Σ^0	$\bar{\Sigma}^0$	$(u\bar{d} + d\bar{u})/\sqrt{2}$	2,334	0	7.4×10^{-20}
	xi		Σ^-	$\bar{\Sigma}^-$	dds	2,343	-1	1.5×10^{-10}
			Ξ^0	$\bar{\Xi}^0$	uss	2,573	0	2.9×10^{-10}
	xi-c		Ξ^+	$\bar{\Xi}^+$	dss	2,585	-1	1.6×10^{-10}
			Ξ_c^+	$\bar{\Xi}_c^+$	dsc	4,834	0	9.8×10^{-14}
omega		Ξ_c^0	$\bar{\Xi}_c^0$	usc	4,826	+1	3.5×10^{-13}	
		Ω^-	$\bar{\Omega}^-$	sss	3,272	-1	0.8×10^{-10}	
omega-c		Ω_c^0	$\bar{\Omega}_c^0$	ssc	5,292	0	6.4×10^{-14}	
meson	pion	π^+	π^-	$u\bar{d}$	273	+1	2.6×10^{-8}	
		π^0	π^0	$(u\bar{u} - d\bar{d})/\sqrt{2}$	264	0	8.4×10^{-17}	
	kaon*	K^+	K^-	$u\bar{s}$	966	+1	1.2×10^{-8}	
		K^0	\bar{K}^0	$d\bar{s}$	974	0	8.9×10^{-11}	
	J/psi	J or Ψ	J or Ψ	$c\bar{c}$	6,060	0	1.0×10^{-20}	
	omega		ω	ω	$(u\bar{u} + d\bar{d})/\sqrt{2}$	1,532	0	6.6×10^{-23}
			eta	η	η	$(u\bar{u} + d\bar{d})/\sqrt{2}$	1,071	0
	eta-c		η_c	η_c	$c\bar{c}$	5,832	0	3.1×10^{-22}
	B		B^0	\bar{B}^0	$d\bar{b}$	10,331	0	1.6×10^{-12}
			B^+	B^-	$u\bar{b}$	10,331	+1	1.6×10^{-12}
	B-s		B_s^0	\bar{B}_s^0	$s\bar{b}$	10,507	0	1.6×10^{-12}
	D		D_0	\bar{D}_0	$c\bar{u}$	3,649	0	4.2×10^{-13}
			D^+	D^-	$c\bar{d}$	3,658	+1	1.1×10^{-12}
	D-s		D_s^+	D_s^-	$c\bar{s}$	3,852	+1	4.7×10^{-13}
	chi		χ_c^0	$\bar{\chi}_c^0$	$c\bar{c}$	6,687	0	3.0×10^{-23}
psi		Ψ_c^0	$\bar{\Psi}_c^0$	$c\bar{c}$	7,213	0	1.5×10^{-20}	
upsilon		Y	Y	$b\bar{b}$	18,513	0	8.0×10^{-20}	

* The neutral kaon is composed of two particles; the average lifetime of each particle is given.

The Structure of Matter



The Nucleus

$(1-10) \times 10^{-15}$ m

At the center of the atom is a nucleus formed from **nucleons**—protons and neutrons. Each nucleon is made from three **quarks** held together by their strong interactions, which are mediated by gluons. In turn, the nucleus is held together by the **strong** interactions between the gluon and quark constituents of neighboring nucleons. Nuclear physicists often use the exchange of mesons—particles which consist of a quark and an antiquark, such as the **pion**—to describe interactions among the nucleons.

neutron
 10^{-15} m
proton

strong field
quark
 $< 10^{-19}$ m
electromagnetic field

In an atom, **electrons** range around the nucleus at distances typically up to 10,000 times the nuclear diameter. If the electron cloud were shown to scale, this chart would cover a small town.

Periodic Table

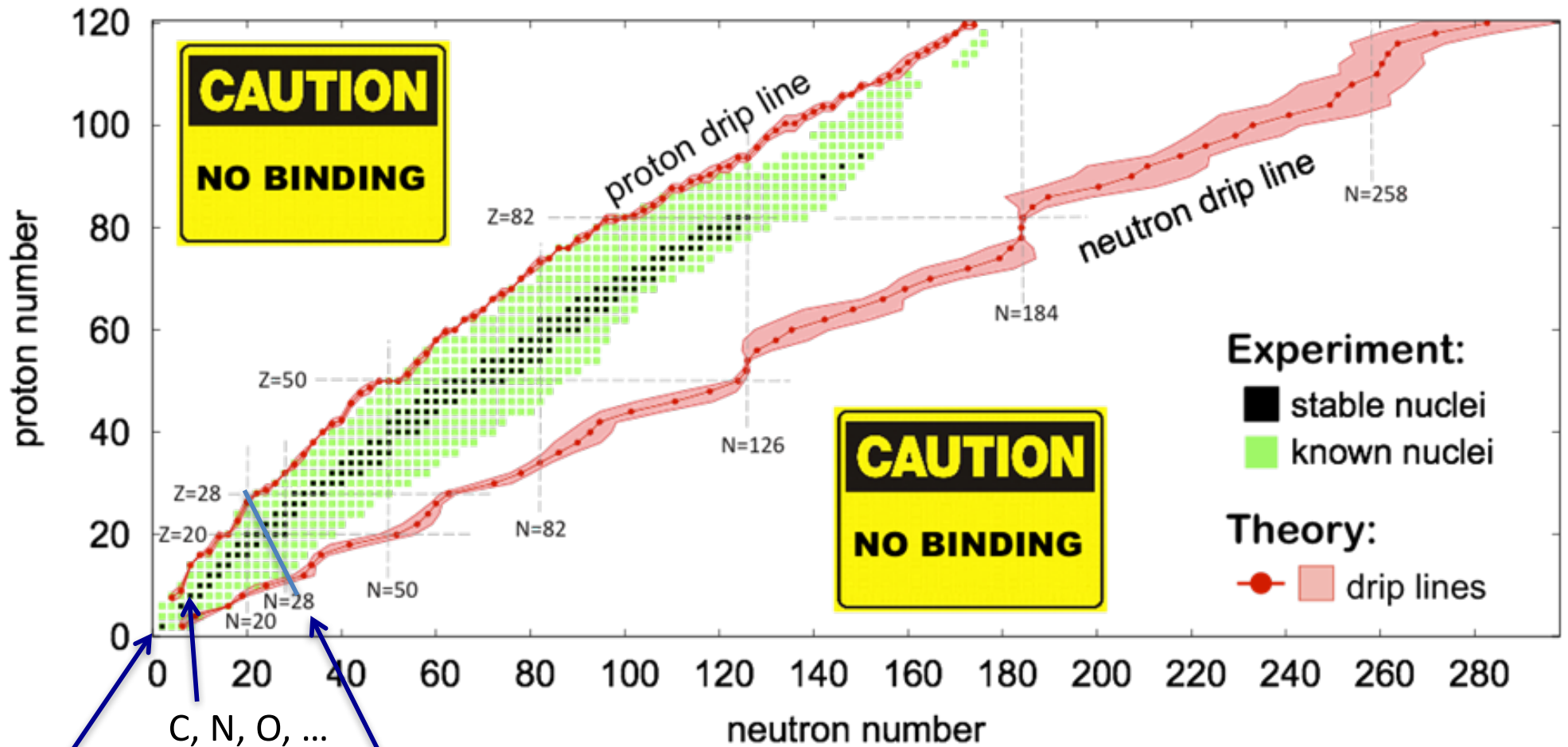
hydrogen 1 H 1.0079																			helium 2 He 4.0026
lithium 3 Li 6.941	beryllium 4 Be 9.0122													boron 5 B 10.811	carbon 6 C 12.011	nitrogen 7 N 14.007	oxygen 8 O 15.999	fluorine 9 F 18.998	neon 10 Ne 20.180
sodium 11 Na 22.990	magnesium 12 Mg 24.305													aluminum 13 Al 26.982	silicon 14 Si 28.086	phosphorus 15 P 30.974	sulfur 16 S 32.065	chlorine 17 Cl 35.453	argon 18 Ar 39.948
potassium 19 K 39.098	calcium 20 Ca 40.078	scandium 21 Sc 44.956	titanium 22 Ti 47.867	vanadium 23 V 50.942	chromium 24 Cr 51.996	manganese 25 Mn 54.938	iron 26 Fe 55.845	cobalt 27 Co 58.933	nickel 28 Ni 58.693	copper 29 Cu 63.546	zinc 30 Zn 65.39	gallium 31 Ga 69.723	germanium 32 Ge 72.61	arsenic 33 As 74.922	selenium 34 Se 78.96	bromine 35 Br 79.904	krypton 36 Kr 83.80		
rubidium 37 Rb 85.468	strontium 38 Sr 87.62	yttrium 39 Y 88.906	zirconium 40 Zr 91.224	niobium 41 Nb 92.906	molybdenum 42 Mo 95.94	technetium 43 Tc [98]	ruthenium 44 Ru 101.07	rhodium 45 Rh 102.91	palladium 46 Pd 106.42	silver 47 Ag 107.87	cadmium 48 Cd 112.41	indium 49 In 114.82	tin 50 Sn 118.71	antimony 51 Sb 121.76	tellurium 52 Te 127.60	iodine 53 I 126.90	xenon 54 Xe 131.29		
caesium 55 Cs 132.91	barium 56 Ba 137.33	57-70 *	lutetium 71 Lu 174.97	hafnium 72 Hf 178.49	tantalum 73 Ta 180.95	tungsten 74 W 183.84	rhenium 75 Re 186.21	osmium 76 Os 190.23	iridium 77 Ir 192.22	platinum 78 Pt 195.08	gold 79 Au 196.97	mercury 80 Hg 200.59	thallium 81 Tl 204.38	lead 82 Pb 207.2	bismuth 83 Bi 208.98	polonium 84 Po [209]	astatine 85 At [210]	radon 86 Rn [222]	
francium 87 Fr [223]	radium 88 Ra [226]	89-102 **	lawrencium 103 Lr [262]	rutherfordium 104 Rf [261]	dubnium 105 Db [262]	seaborgium 106 Sg [266]	bohrium 107 Bh [264]	hassium 108 Hs [269]	meitnerium 109 Mt [268]	ununnilium 110 Uun [271]	unununium 111 Uuu [272]	ununbium 112 Uub [277]		ununquadium 114 Uuq [289]					

* Lanthanide series

lanthanum 57 La 138.91	cerium 58 Ce 140.12	praseodymium 59 Pr 140.91	neodymium 60 Nd 144.24	promethium 61 Pm [145]	samarium 62 Sm 150.36	europium 63 Eu 151.96	gadolinium 64 Gd 157.25	terbium 65 Tb 158.93	dysprosium 66 Dy 162.50	holmium 67 Ho 164.93	erbium 68 Er 167.26	thulium 69 Tm 168.93	ytterbium 70 Yb 173.04
actinium 89 Ac [227]	thorium 90 Th 232.04	protactinium 91 Pa 231.04	uranium 92 U 238.03	neptunium 93 Np [237]	plutonium 94 Pu [244]	americium 95 Am [243]	curium 96 Cm [247]	berkelium 97 Bk [247]	californium 98 Cf [251]	einsteinium 99 Es [252]	fermium 100 Fm [257]	mendelevium 101 Md [258]	nobelium 102 No [259]

** Actinide series

Related Question: Where do all the heavier nuclei come from?



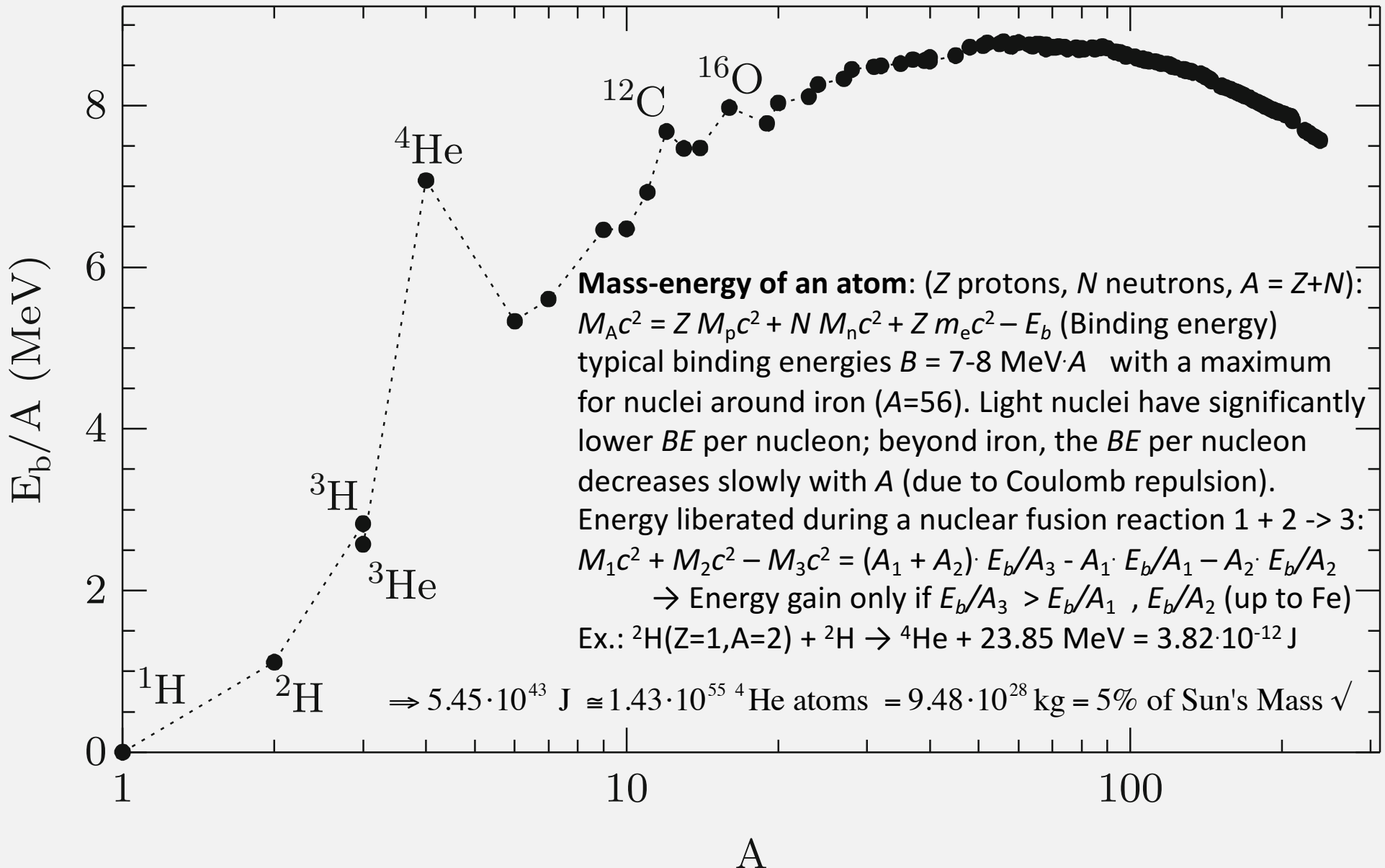
H, ⁴He, Li,...

C, N, O, ...

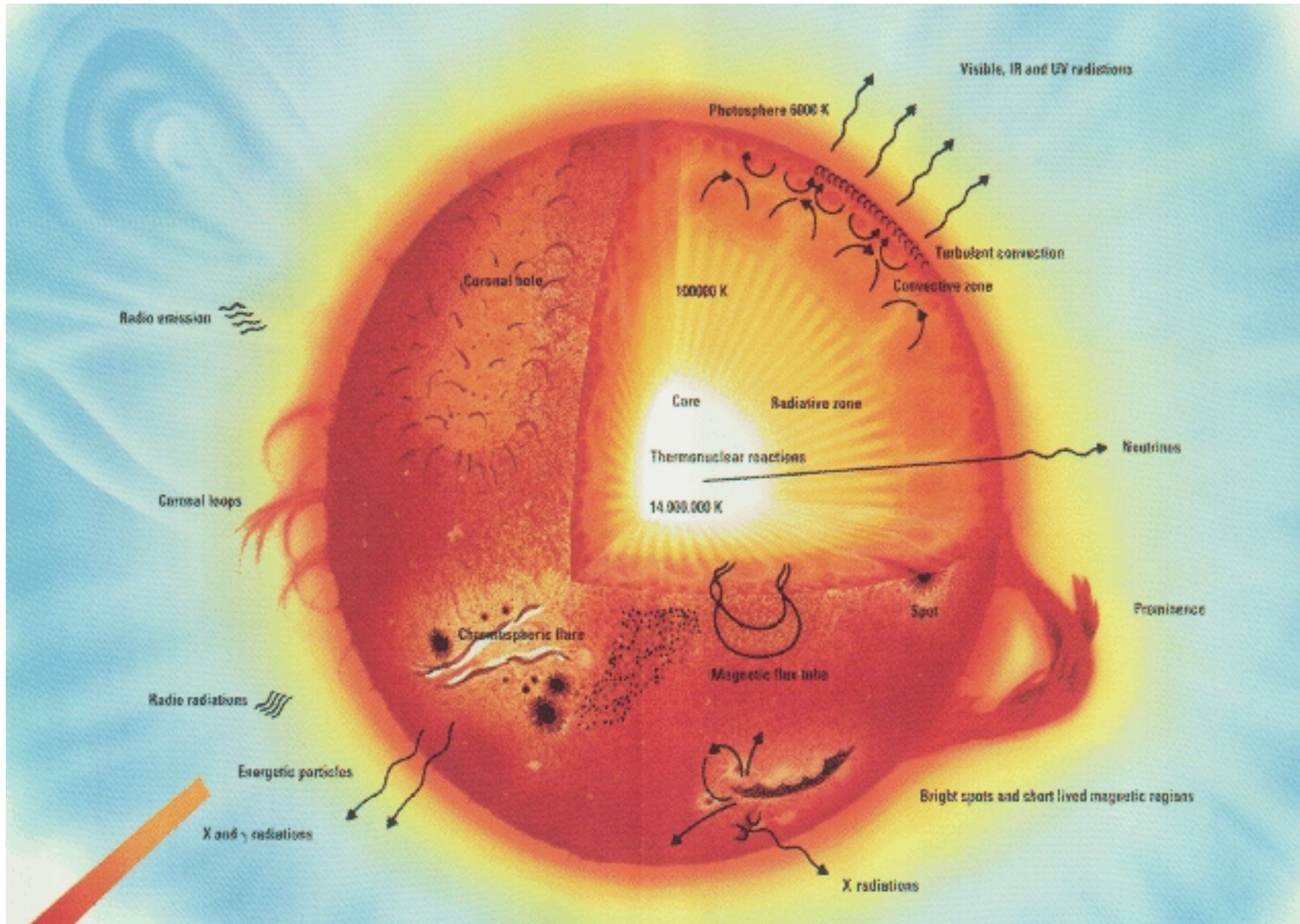
Fe, Ni,...

Challenge: Big Bang created only hydrogen, helium and a tiny smattering of lithium (as we will see). Yet Earth (and we!) are made of C, N, O, metals,...

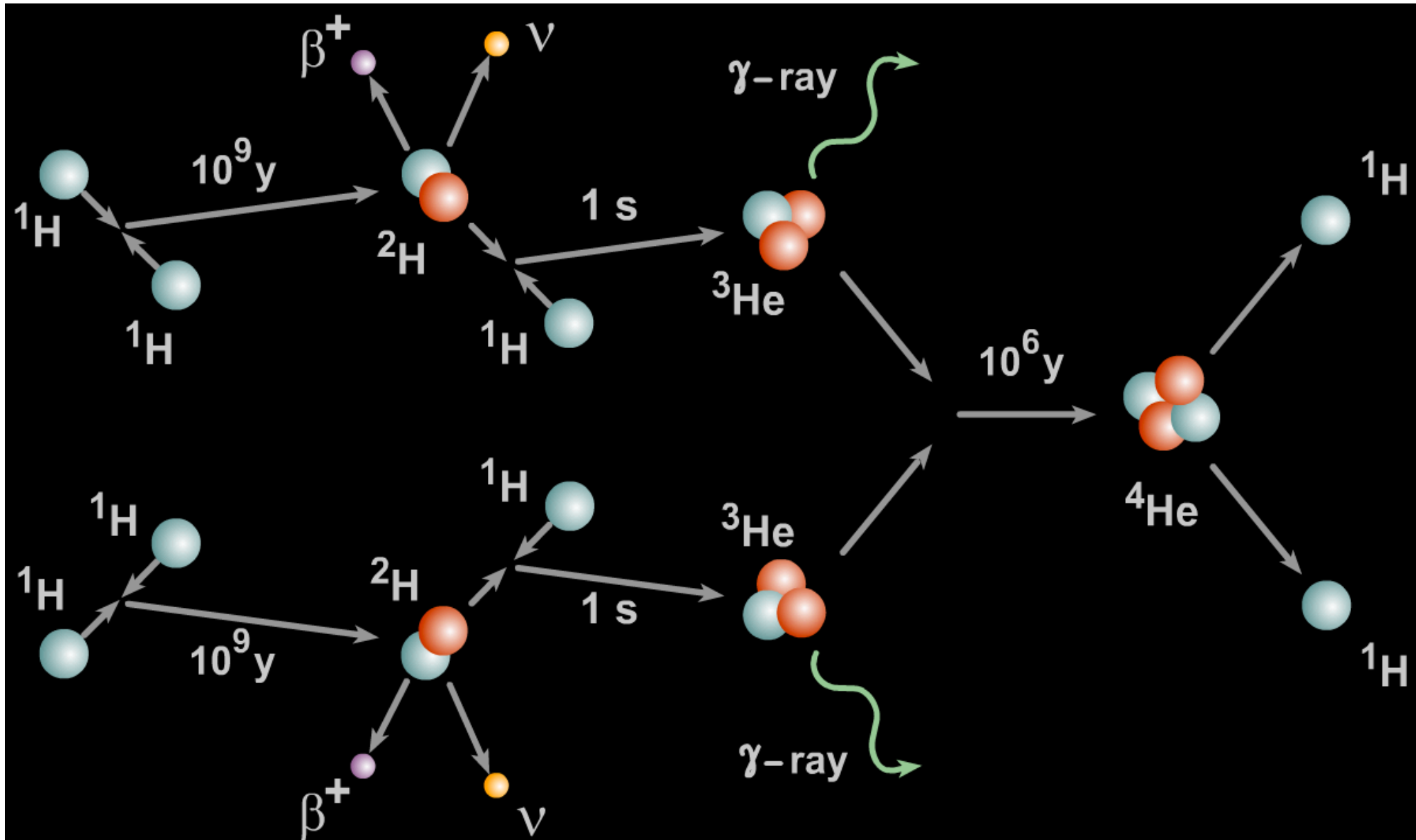
Nuclear Binding energies



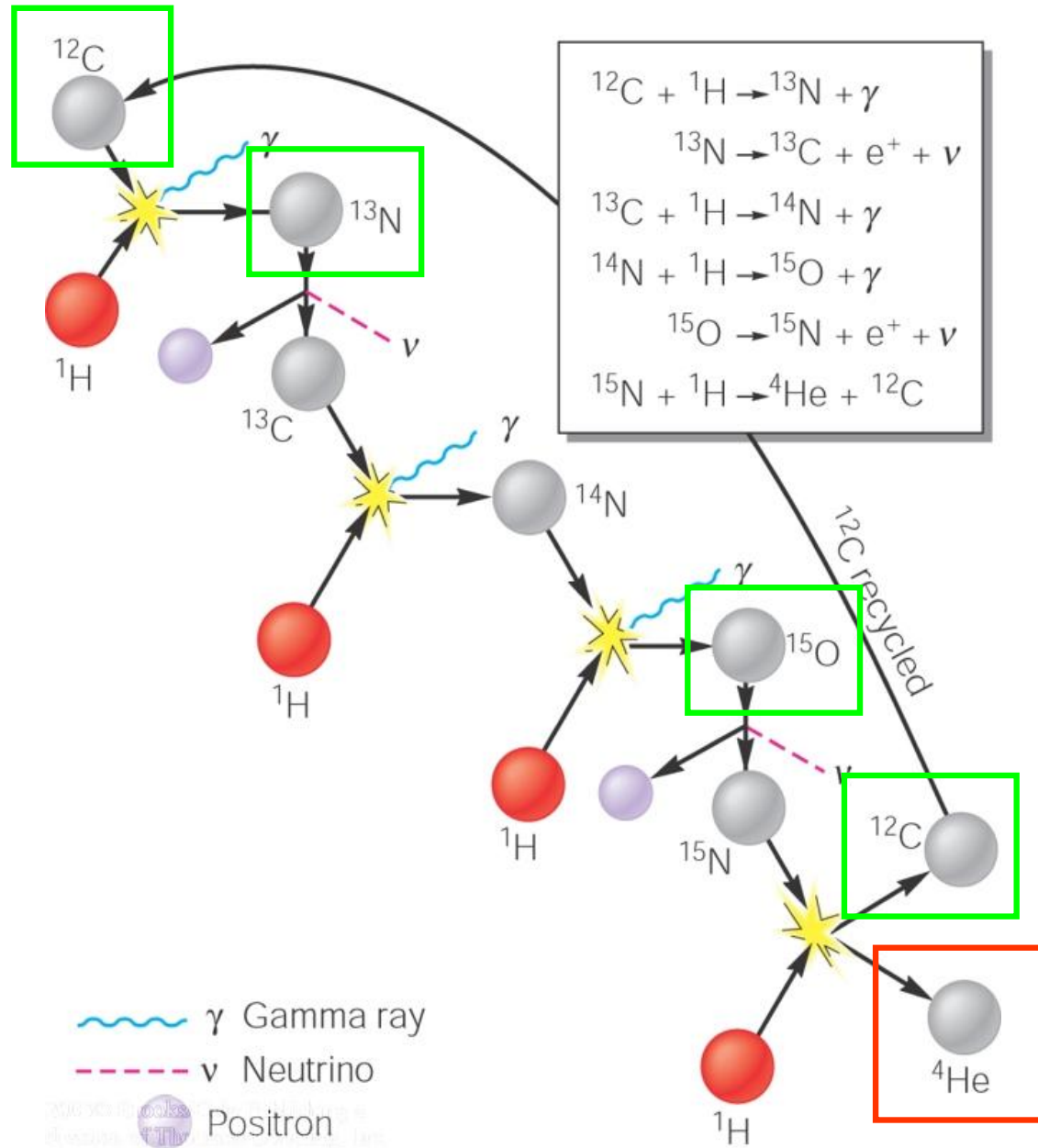
Interior of the Sun



Nuclear Power Generation



The CNO Cycle

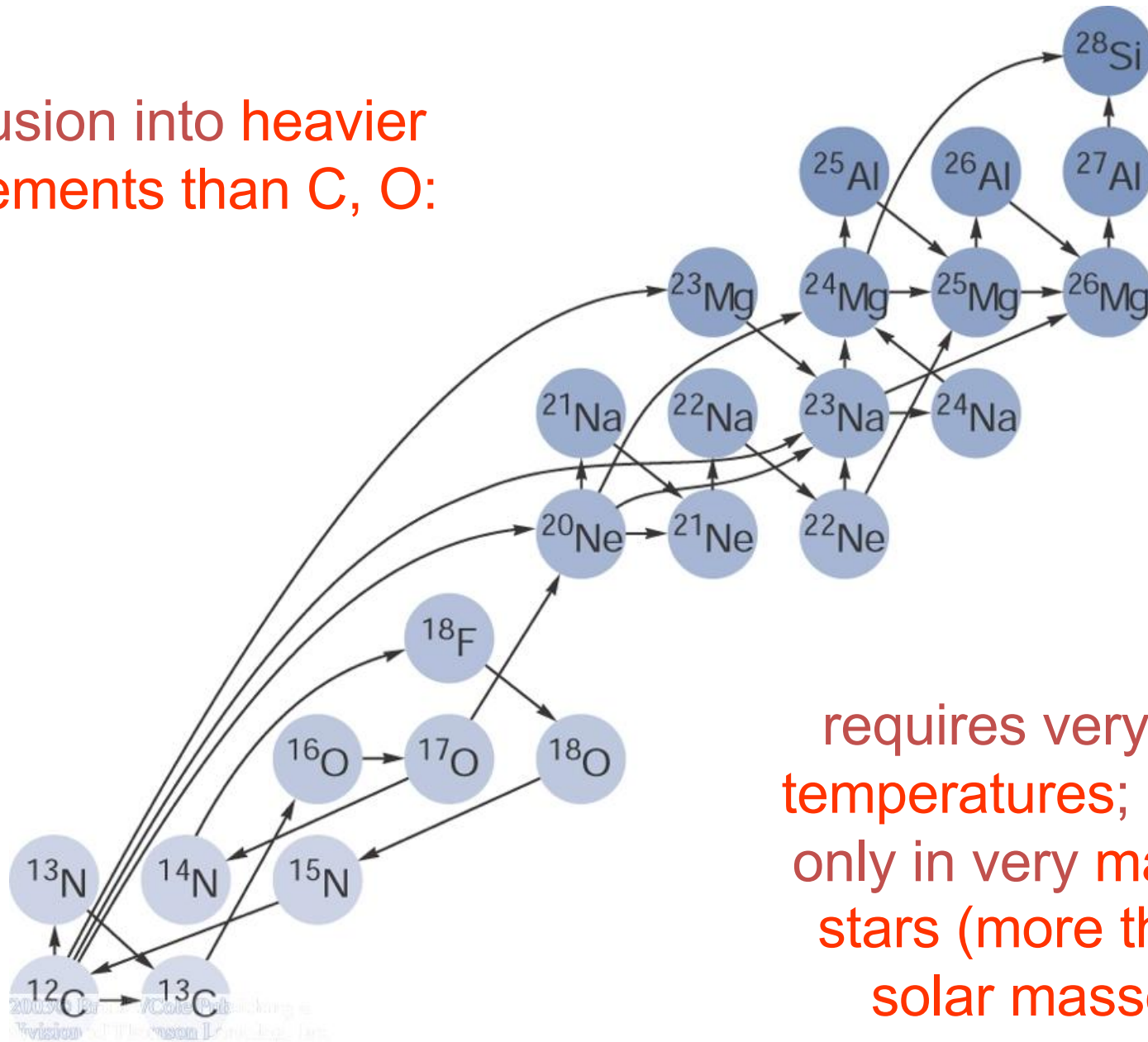


In stars slightly more massive than the sun, a more powerful energy generation mechanism than the PP chain takes over.

The CNO Cycle

Fusion into Heavier Elements

Fusion into heavier elements than C, O:



requires very high temperatures; occurs only in very massive stars (more than 8 solar masses)