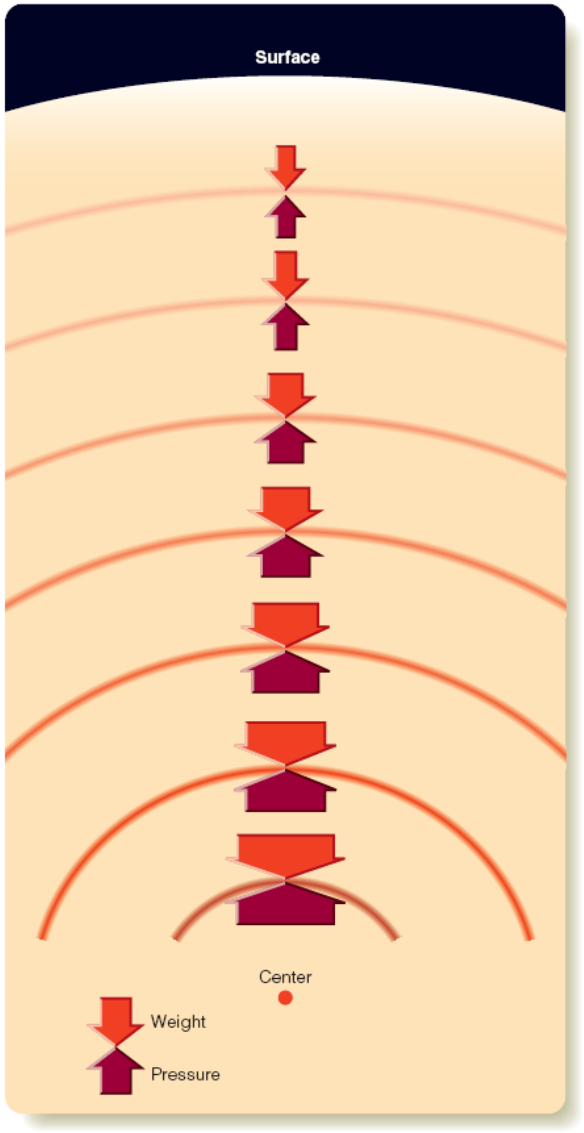
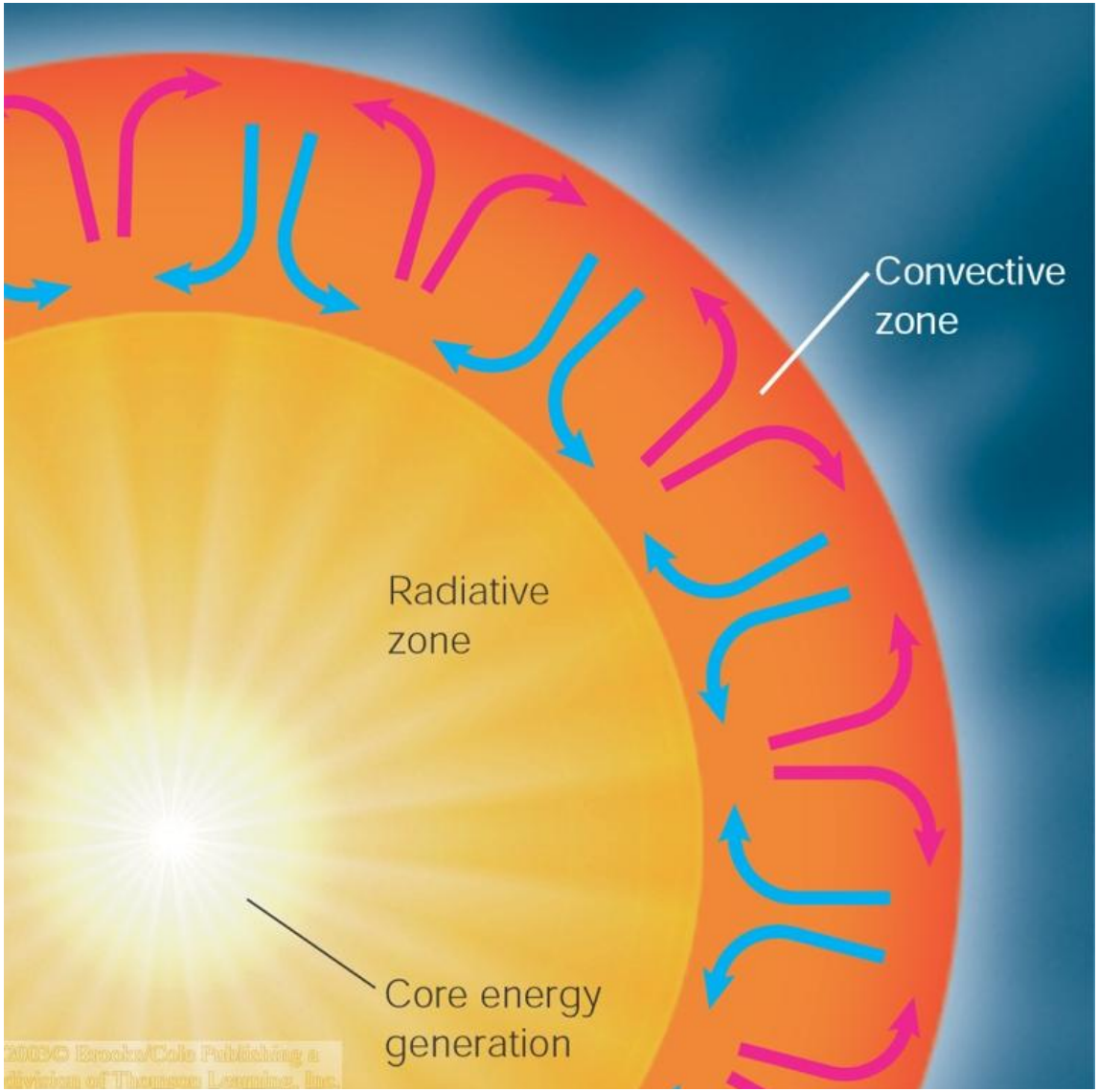
Nuclear Reactions in Stars

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:

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

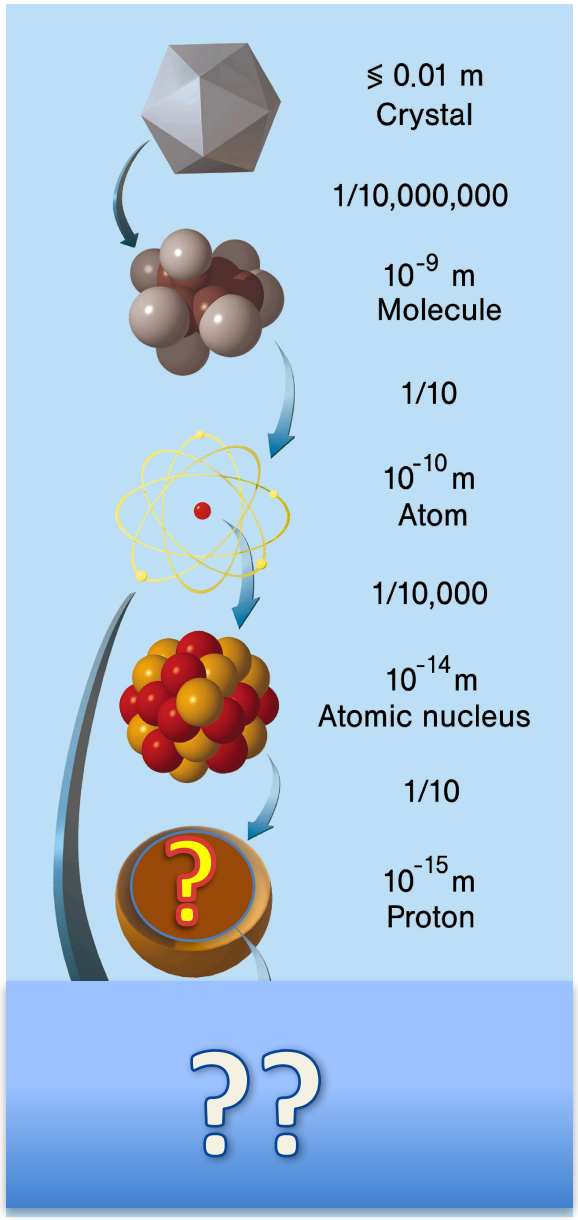
- Energy actually radiated by Sun over last 4.5 B yrs

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

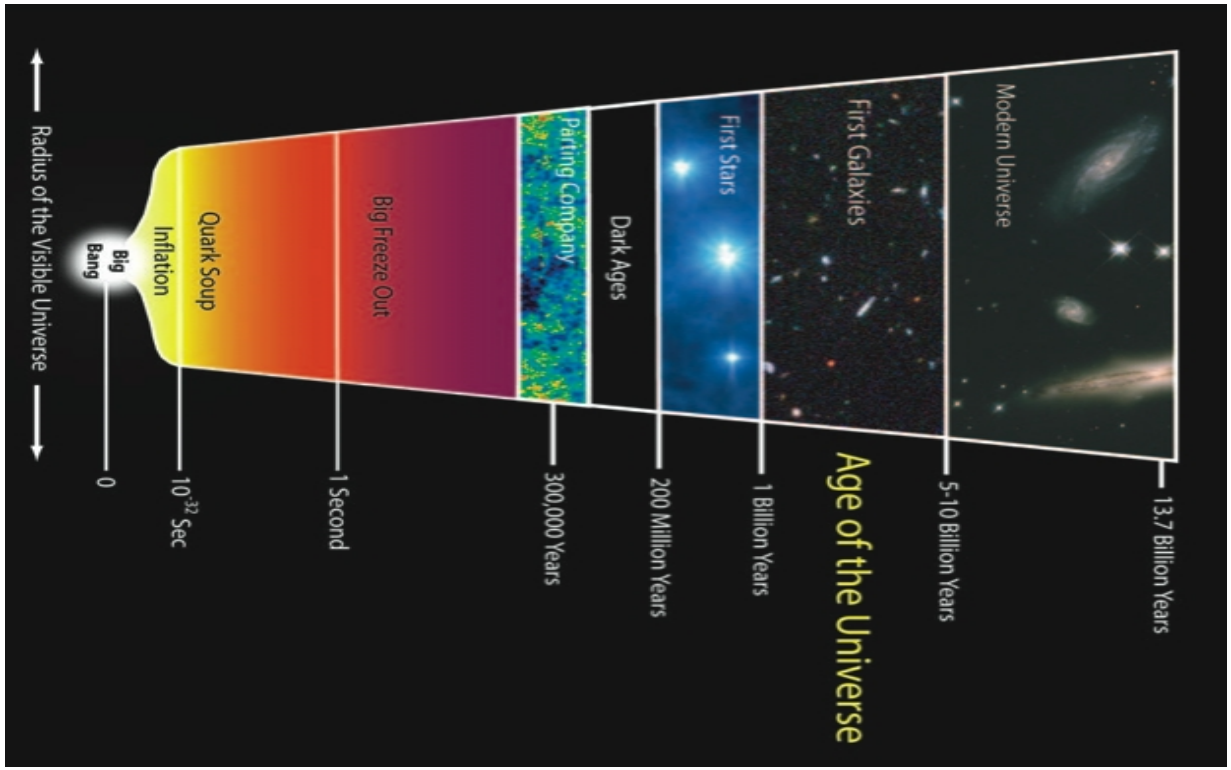
  = 500 times more! (Or Sun must be less than 9 M yrs old!)

- Solution: Must be something else → nuclear fusion

The Structure of Matter

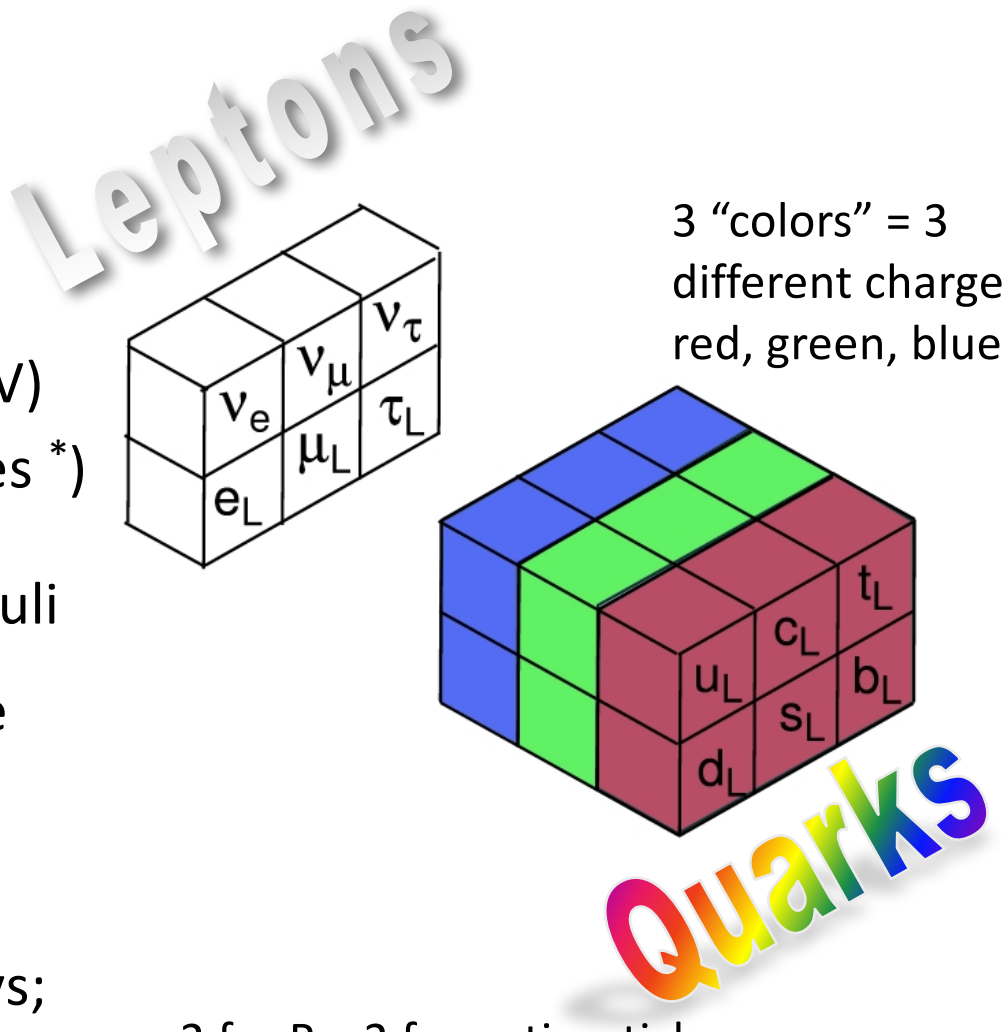


- What is the Universe made off?
- What are the most fundamental objects in Nature?
- What particles where there in the beginning (right after the big bang)?
- How do they interact?
- How do they form composite objects?



Matter Particles

- Make up visible matter
- Pointlike (<10^{-18} m), Fundamental *)
- Have mass (from < ½ eV to 178,000,000,000 eV = 178 GeV)
- Distinct from their antiparticles *)
- Fermions (Spin ½) ⇒ 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)



*) 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 -> 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

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	–1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

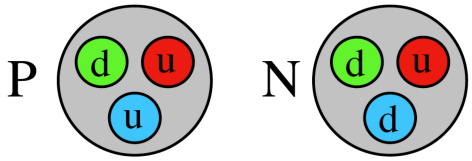
Gravitation spin = 2

Name	Mass GeV/c^2	Electric charge
g graviton	0	0

Note: gluons come in 8 possible combinations of color/anticolor (9^{th} is "sterile" – doesn't exist)

Hadronic Particle Zoo

- what can one build from quarks?

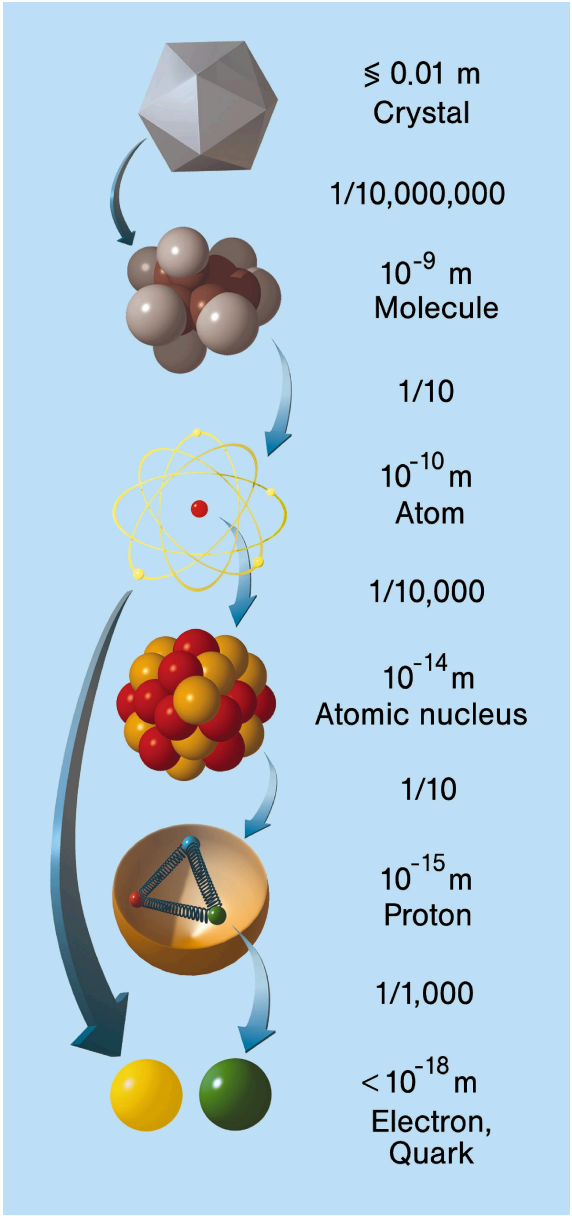


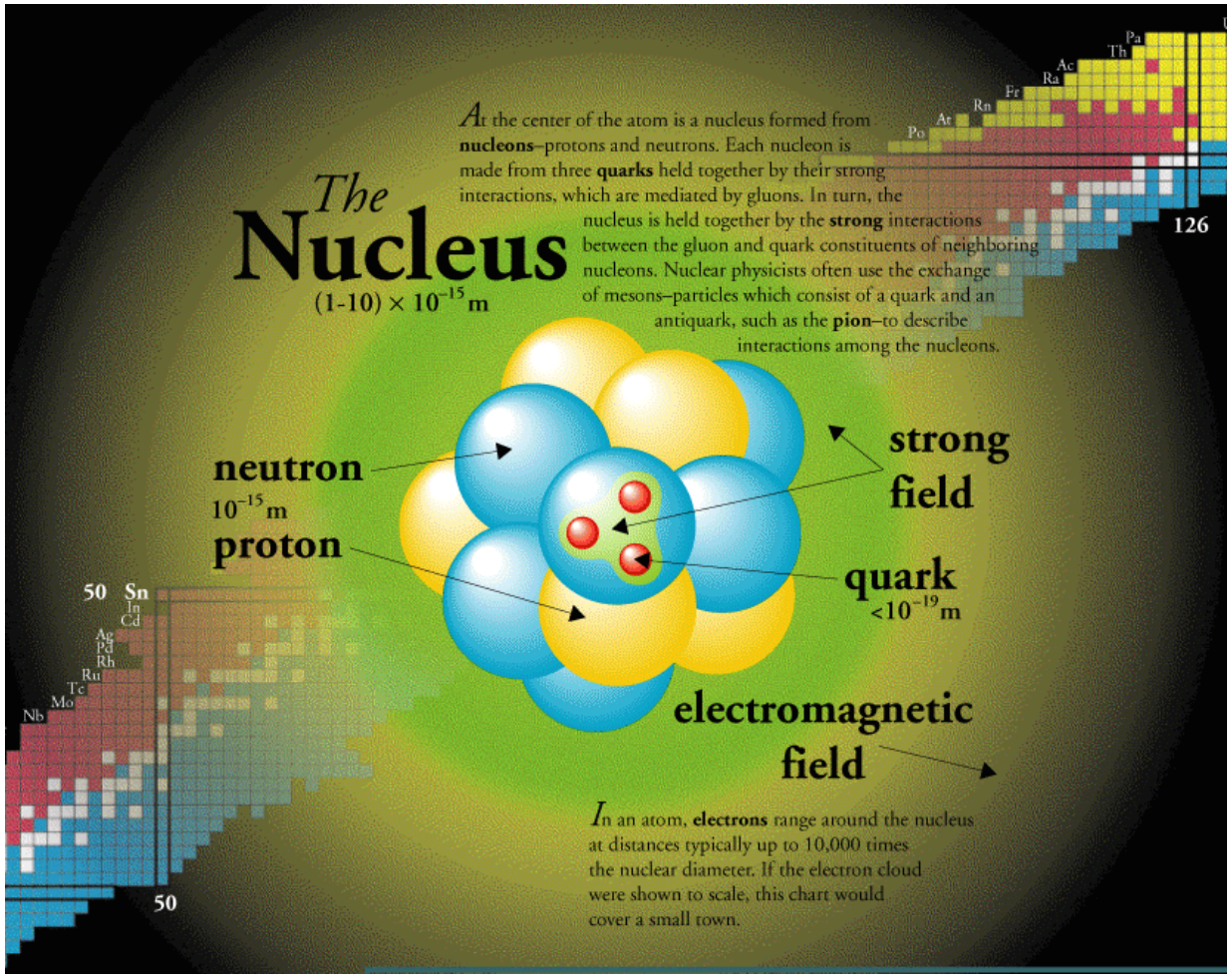
HADRONS

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^0_b	$\bar{\Lambda}^0_b$	udb	11,000	0	1.1×10^{-12}
	sigma	Σ^+	$\bar{\Sigma}^+$	uus	2,328	+1	0.8×10^{-10}
		Σ^0	$\bar{\Sigma}^0$	$\frac{(ud \pm du)s}{\sqrt{2}}$	2,334	0	7.4×10^{-20}
		Σ^-	$\bar{\Sigma}^-$	dds	2,343	−1	1.5×10^{-10}
	xi	Ξ^0	$\bar{\Xi}^0$	uss	2,573	0	2.9×10^{-10}
		Ξ^-	$\bar{\Xi}^+$	dss	2,585	−1	1.6×10^{-10}
	xi-c	Ξ^0_c	$\bar{\Xi}^0_c$	dsc	4,834	0	9.8×10^{-14}
		Ξ^+_c	$\bar{\Xi}^-_c$	usc	4,826	+1	3.5×10^{-13}
	omega	Ω^-	$\bar{\Omega}^+$	sss	3,272	−1	0.8×10^{-10}
	omega-c	Ω^0_c	$\bar{\Omega}^0_c$	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	$\frac{(u\bar{u}-d\bar{d})}{\sqrt{2}}$	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} 5.2×10^{-8}
	J/psi	J or Ψ	J or Ψ	$c\bar{c}$	6,060	0	1.0×10^{-20}
	omega	ω	ω	$\frac{(u\bar{u}+d\bar{d})}{\sqrt{2}}$	1,532	0	6.6×10^{-23}
	eta	η	η	$\frac{(u\bar{u}+d\bar{d})}{\sqrt{2}}$	1,071	0	3.5×10^{-22}
	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^0_s	$\bar{B}^0_s$	$s\bar{b}$	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^0_c	χ^0_c	$c\bar{c}$	6,687	0	3.0×10^{-22}
	psi	Ψ^0_c	Ψ^0_c	$c\bar{c}$	7,213	0	1.5×10^{-20}
	upsilon	Υ	Υ	$b\bar{b}$	18,513	0	8.0×10^{-21}

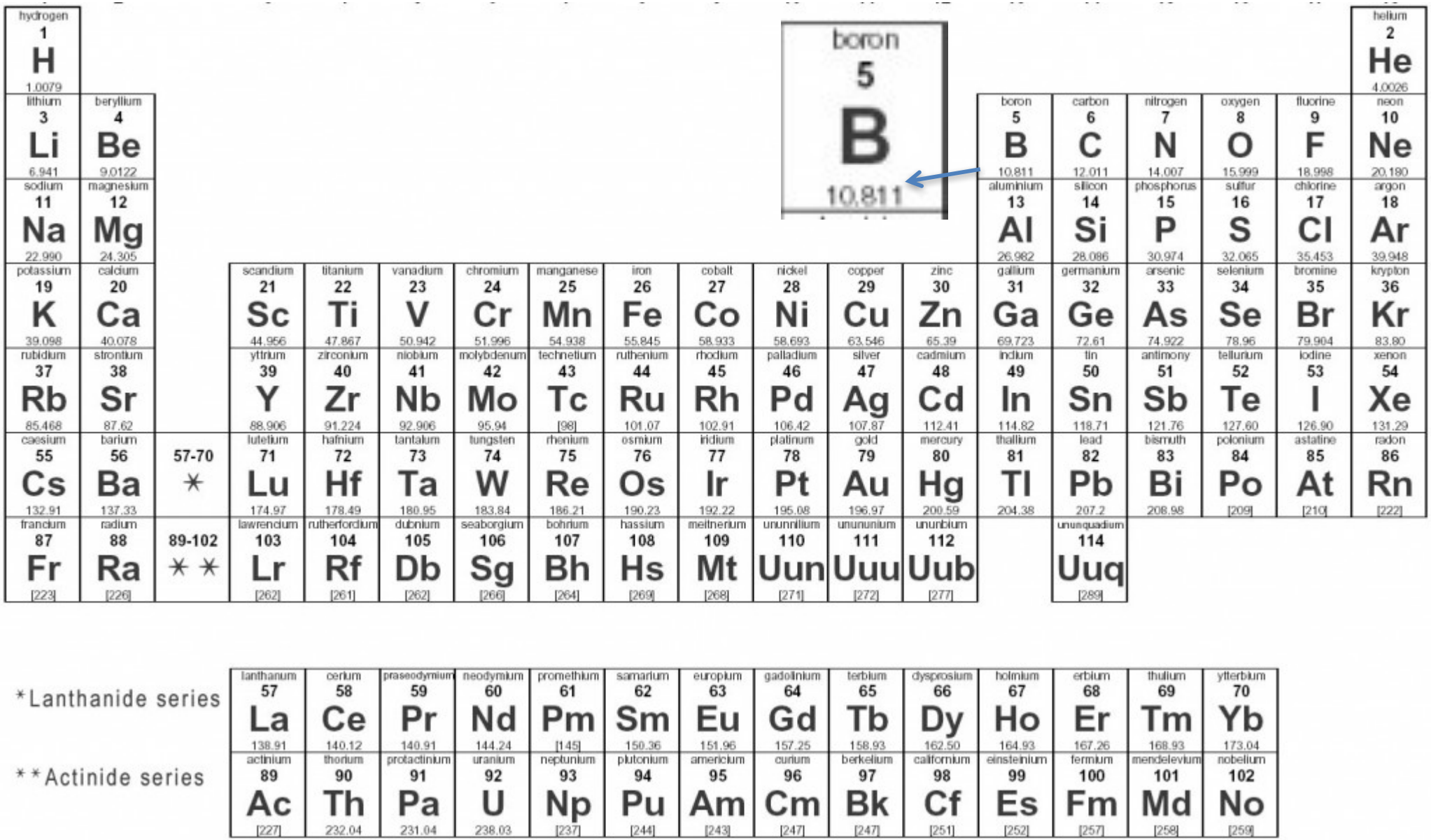
*The neutral kaon is composed of two particles; the average lifetime of each particle is given.

The Structure of Matter

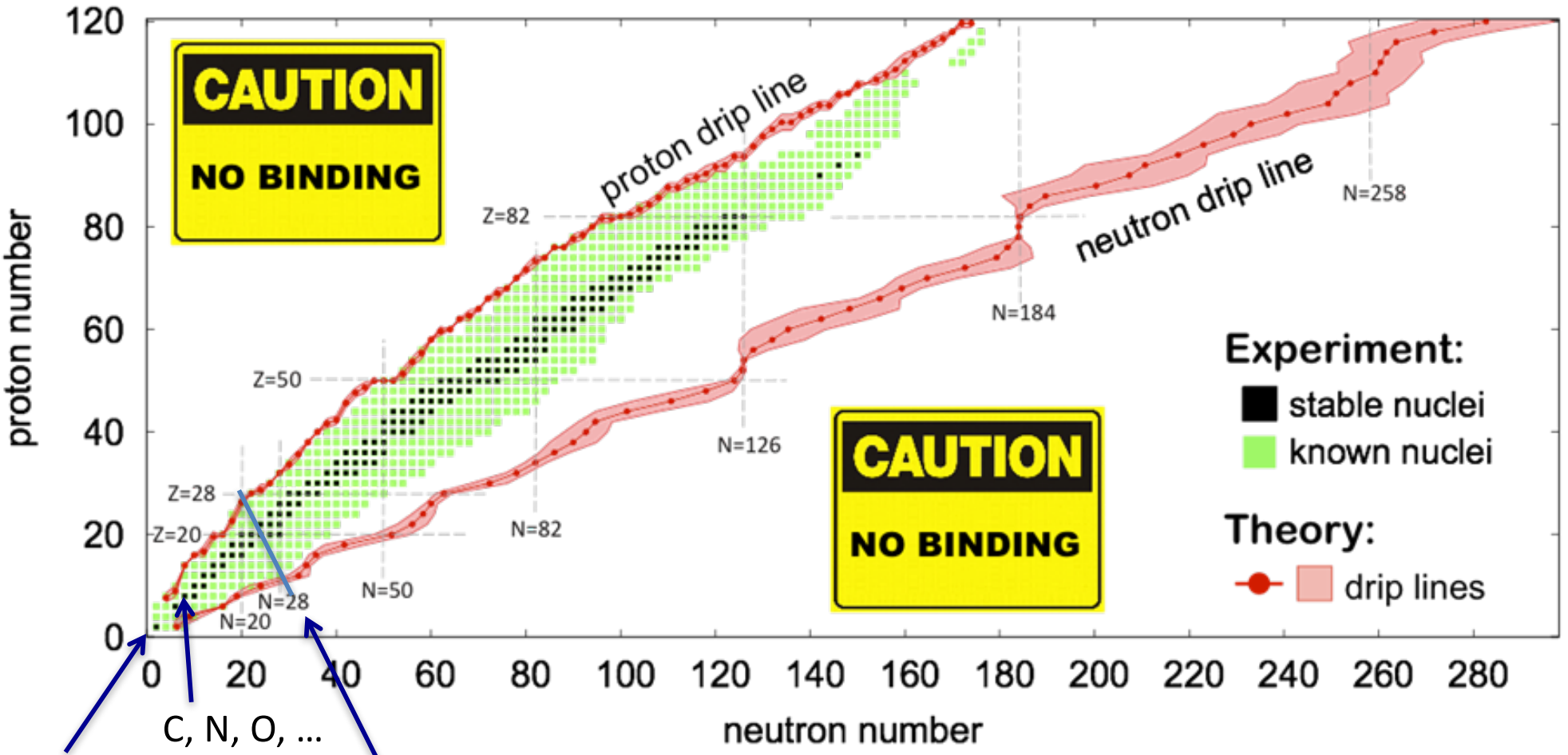




Periodic Table



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



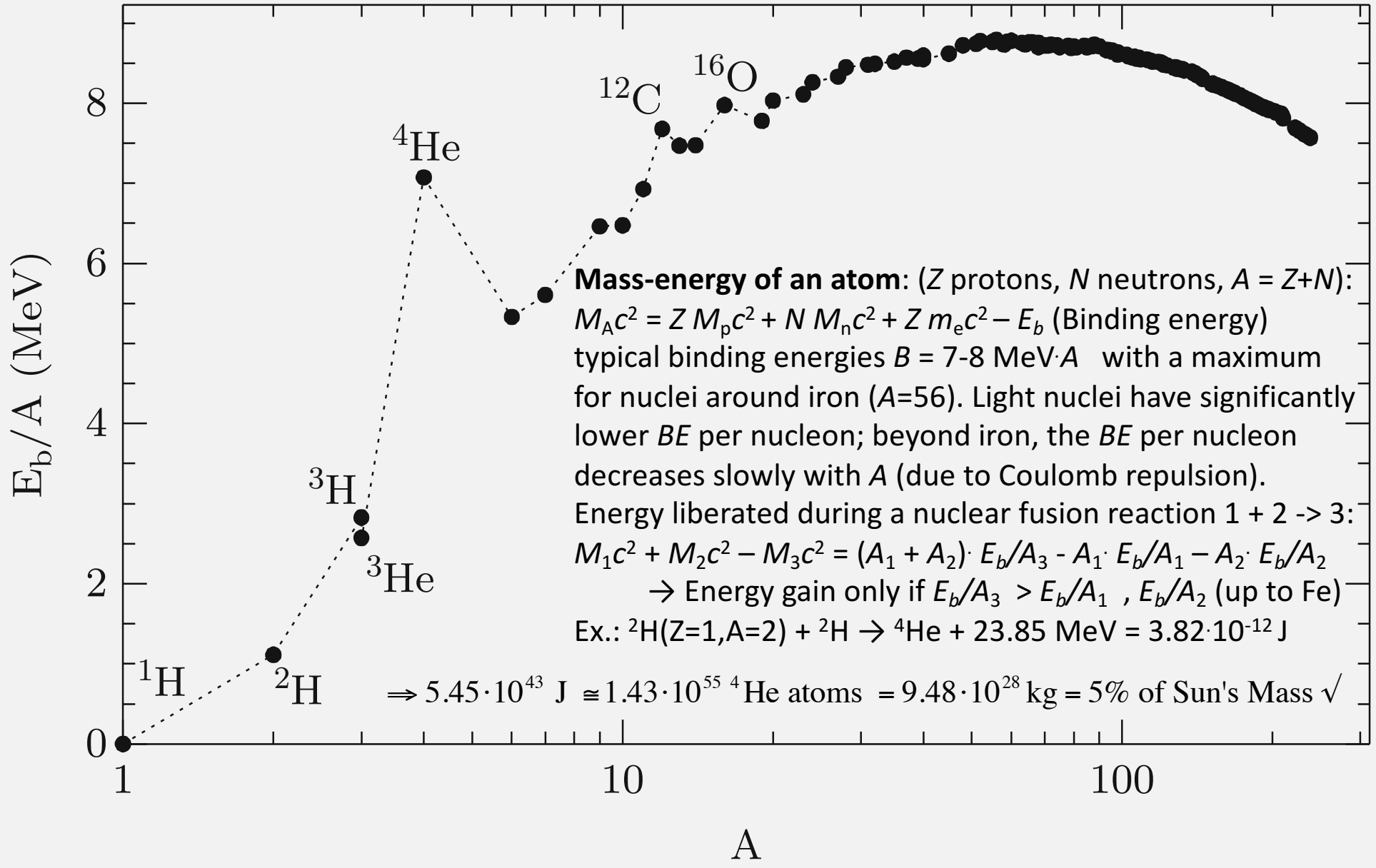
H, ^{4}He, Li,…

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,…

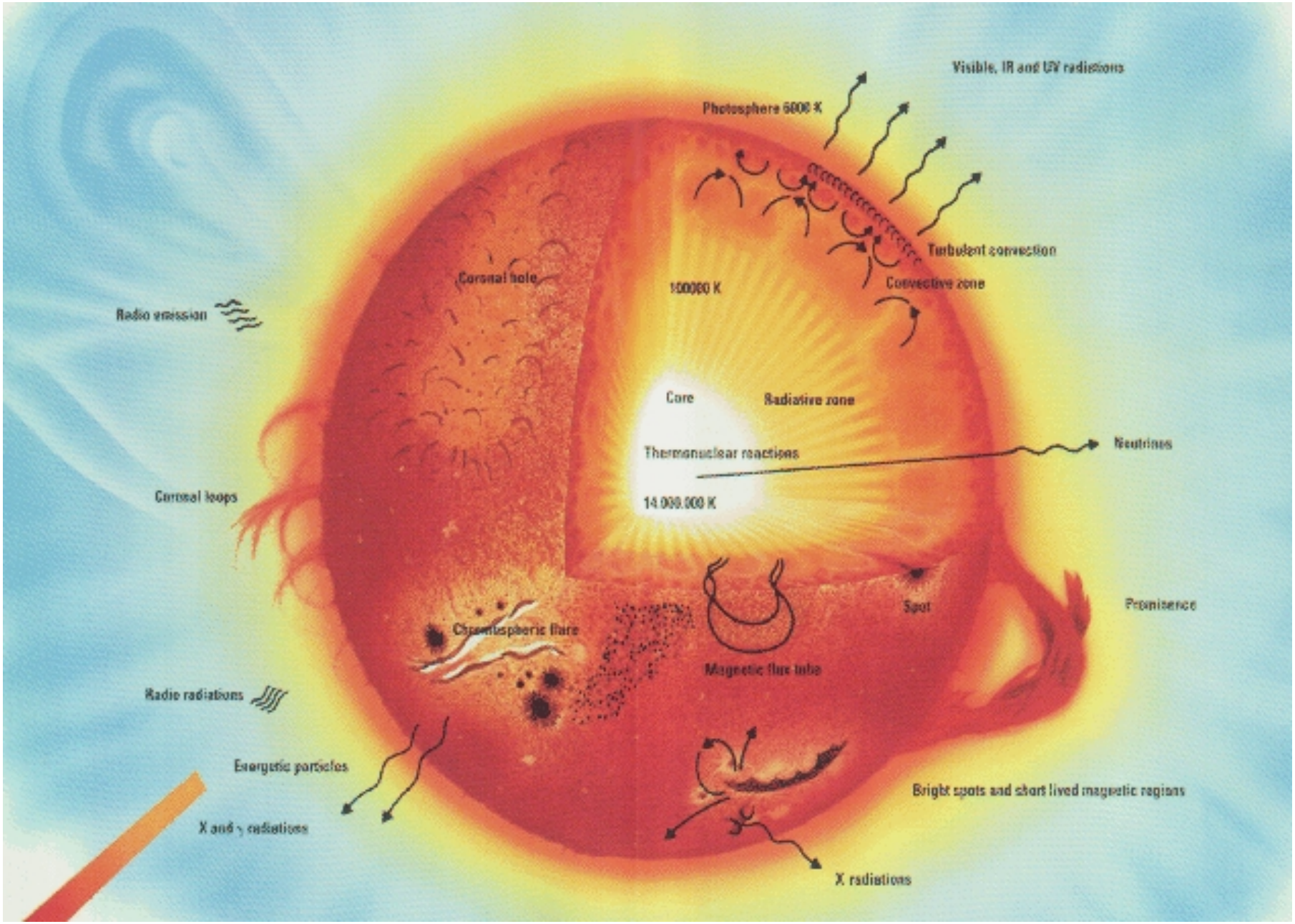
Nuclear Binding energies



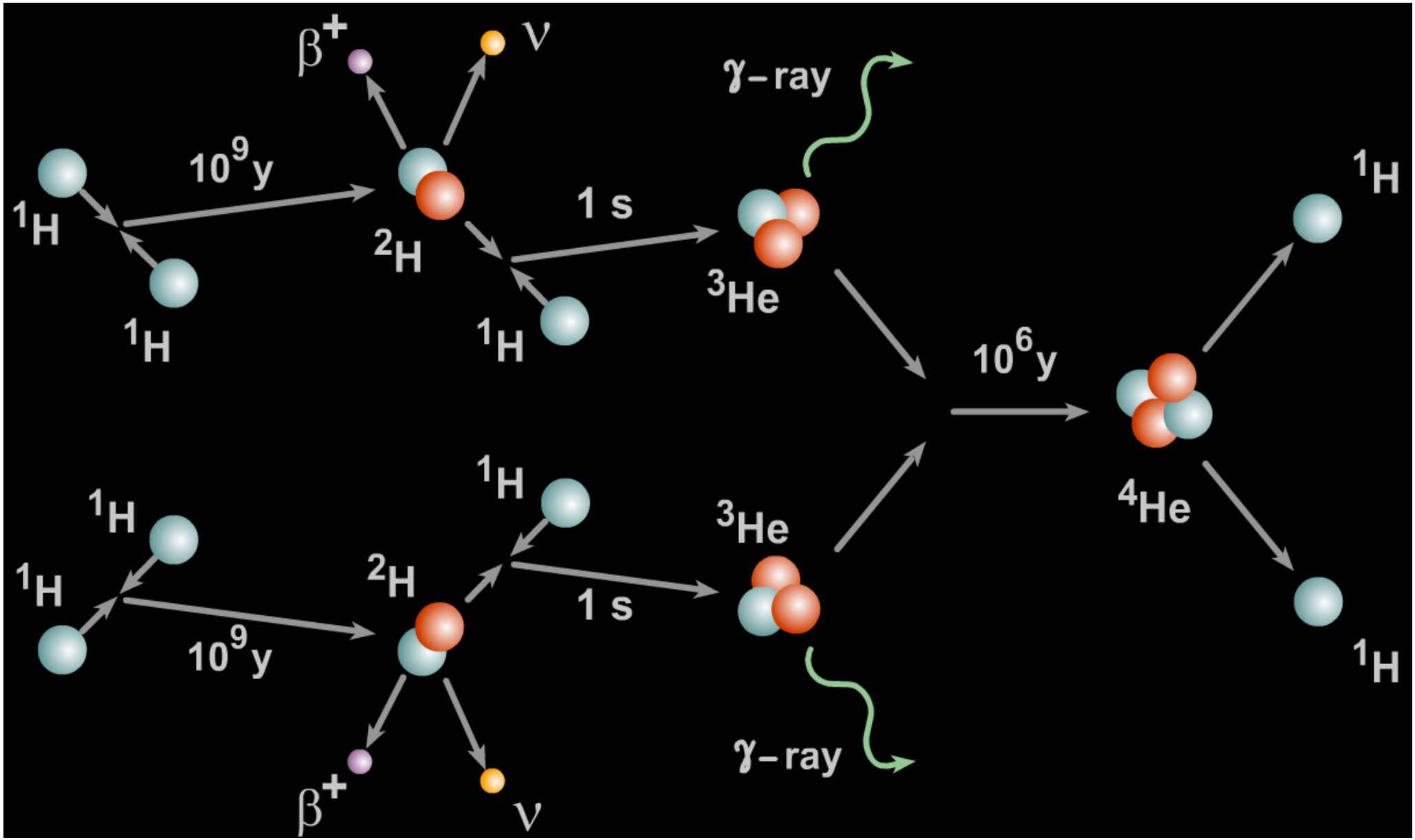
Mass-energy of an atom: (*Z* protons, *N* neutrons, *A* = *Z*+*N*):
$M_A c^2 = Z\,M_p c^2 + N\,M_n c^2 + Z\,m_e c^2 - E_b$ (Binding energy)
typical binding energies *B* = 7-8 MeV·*A* with a maximum for nuclei around iron (*A*=56). Light nuclei have significantly lower *BE* per nucleon; beyond iron, the *BE* per nucleon decreases slowly with *A* (due to Coulomb repulsion).
Energy liberated during a nuclear fusion reaction 1 + 2 -> 3:
$M_1c^2 + M_2c^2 - M_3c^2 = (A_1 + A_2)\cdot E_b/A_3 - A_1\cdot E_b/A_1 - A_2\cdot E_b/A_2$
→ Energy gain only if $E_b/A_3 > E_b/A_1$, E_b/A_2 (up to Fe)
Ex.: ^{2}H(Z=1,A=2) + ^{2}H → ^{4}He + 23.85 MeV = $3.82\cdot10^{-12}$ J

$\Rightarrow 5.45\cdot10^{43}$ J $\cong 1.43\cdot10^{55}$ ^{4}He atoms $= 9.48\cdot10^{28}$ kg = 5% of Sun's Mass √

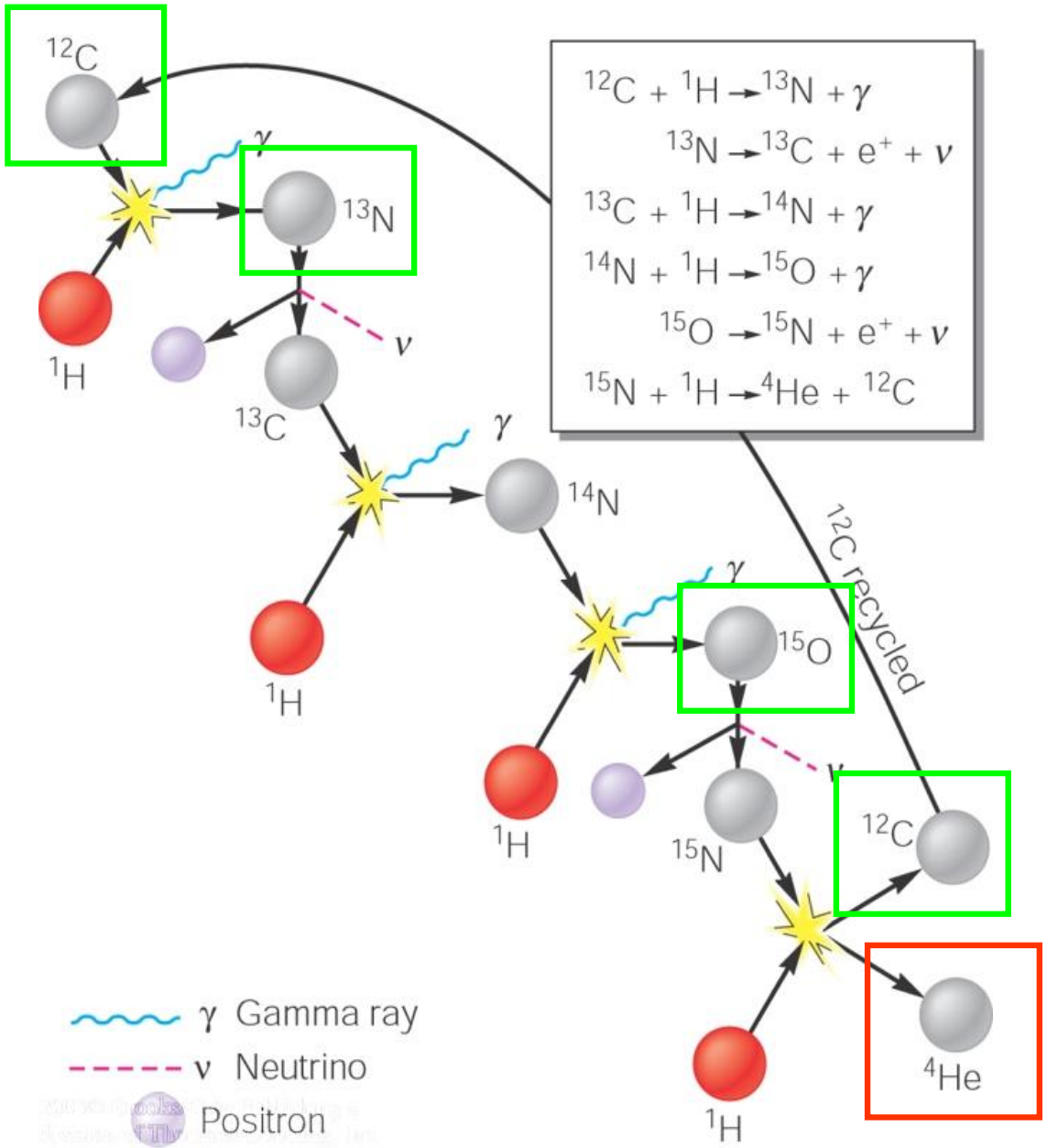
Interior of the Sun



Nuclear Power Generation



The CNO Cycle

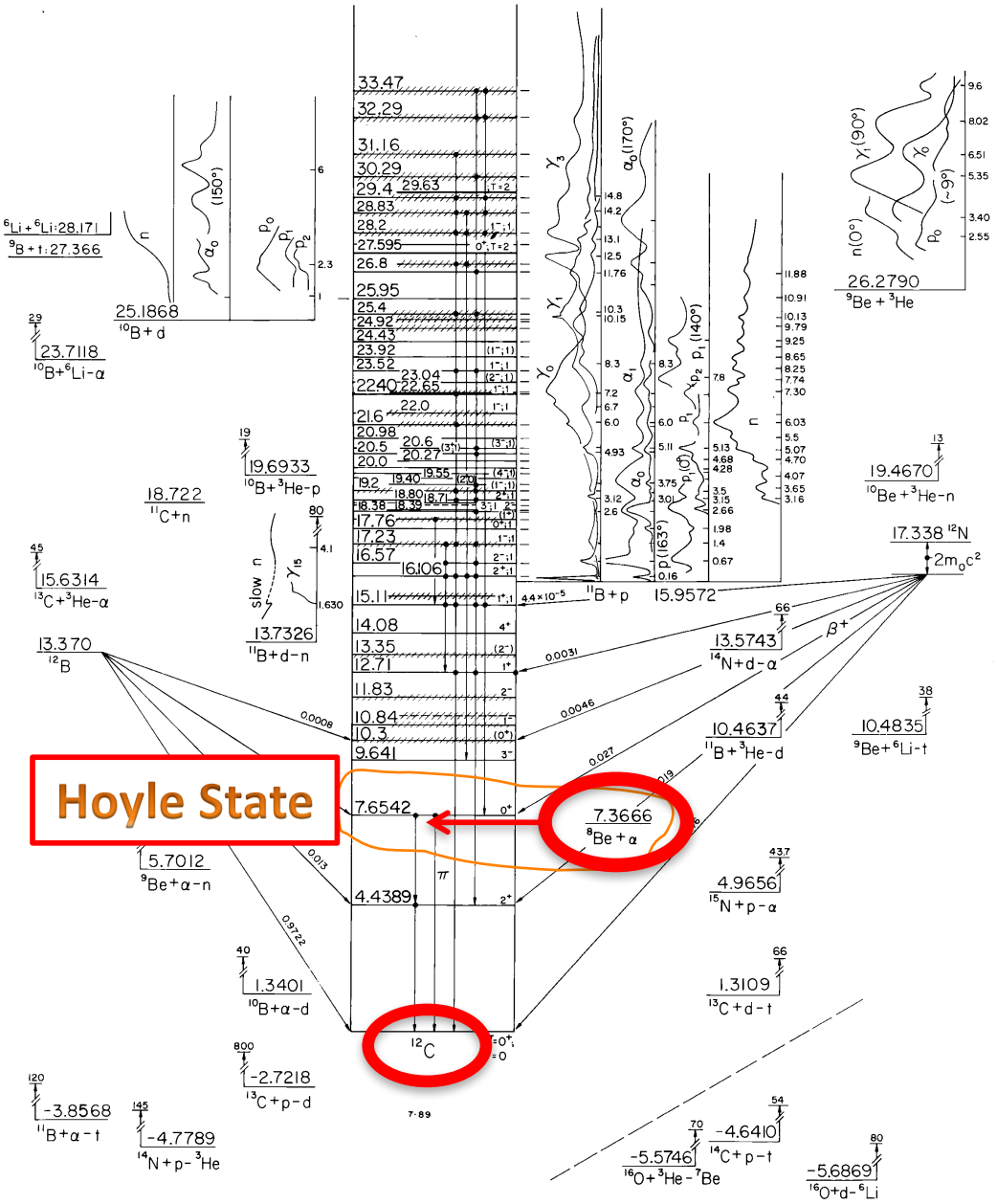


In stars slightly more massive than the sun, a more powerful energy generation mechanism than the PP chain takes over.

The CNO Cycle

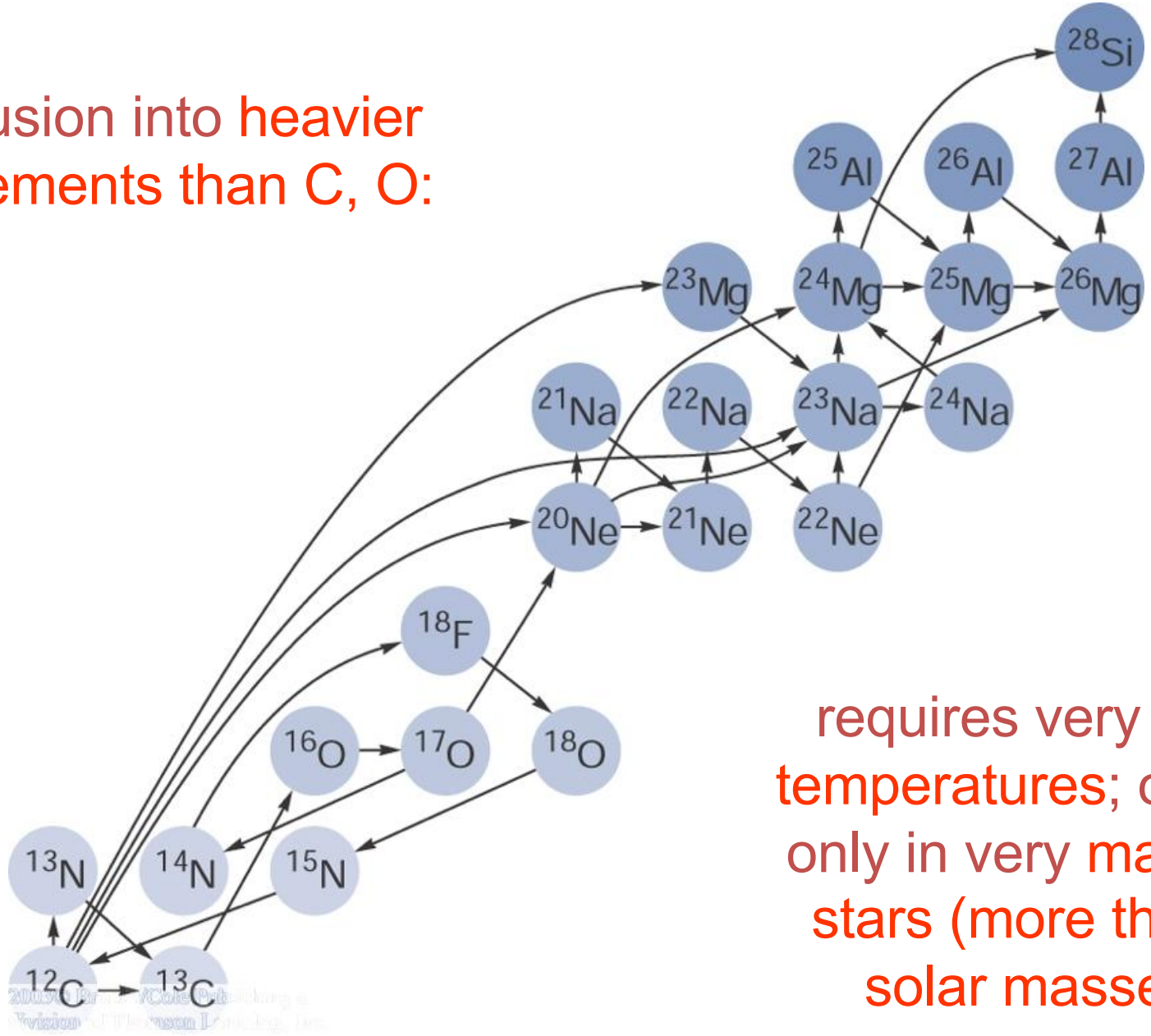
Helium Burning

- Requires temperatures above 10^8 K (8.6 keV)
- ^{8}Be is unstable -> $\alpha\alpha$! Only at high temperature are there a few ^{8}Be in equilibrium with ^{4}He (energy sink!)
- ^{8}Be + α –> ^{12}C would be too slow if not for ^{12}C excited state
- Predicted by Hoyle!
- Some α get eaten by ^{12}C -> ^{16}O admixture



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)