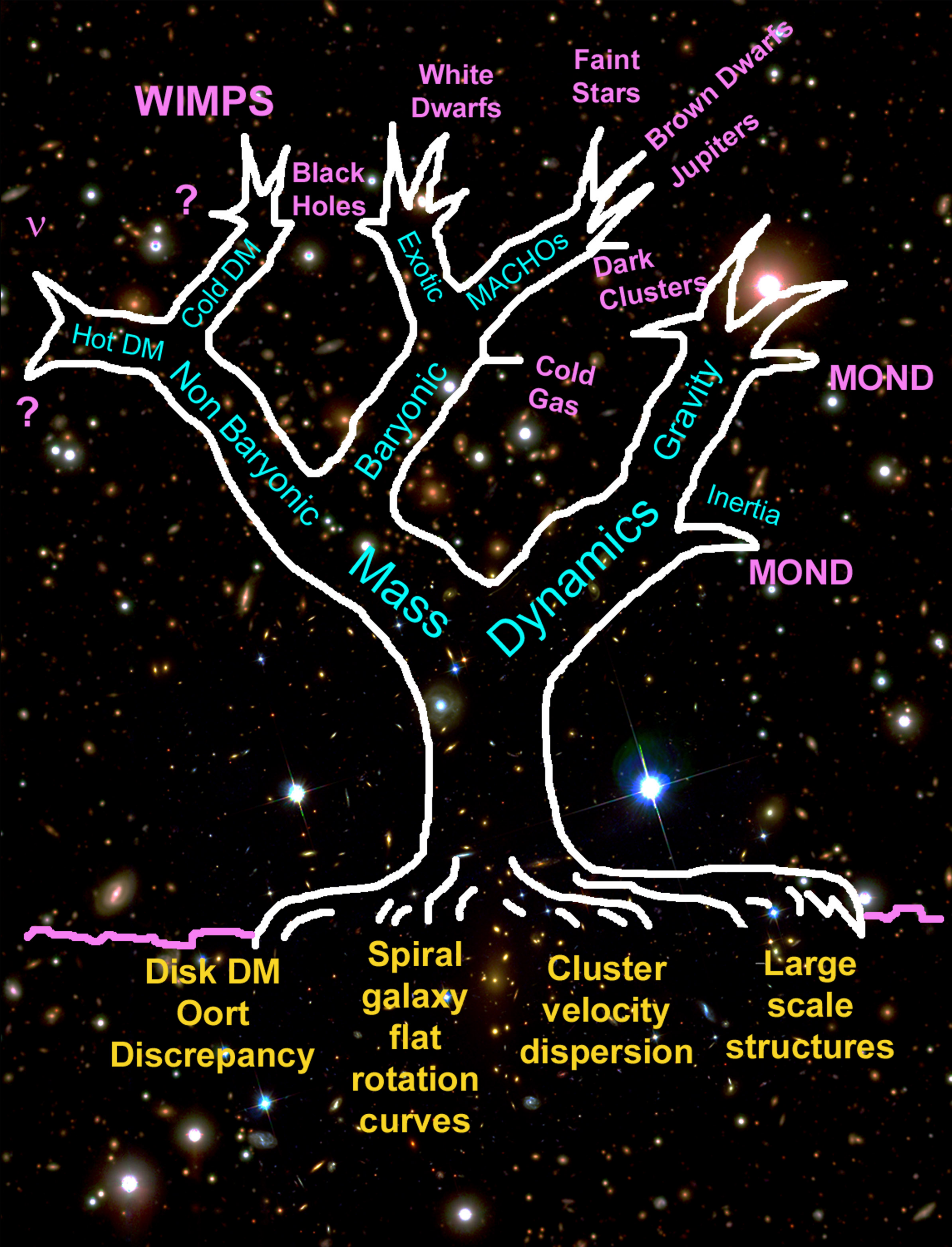
Dark Matter

ASTR 333/433

TODAY

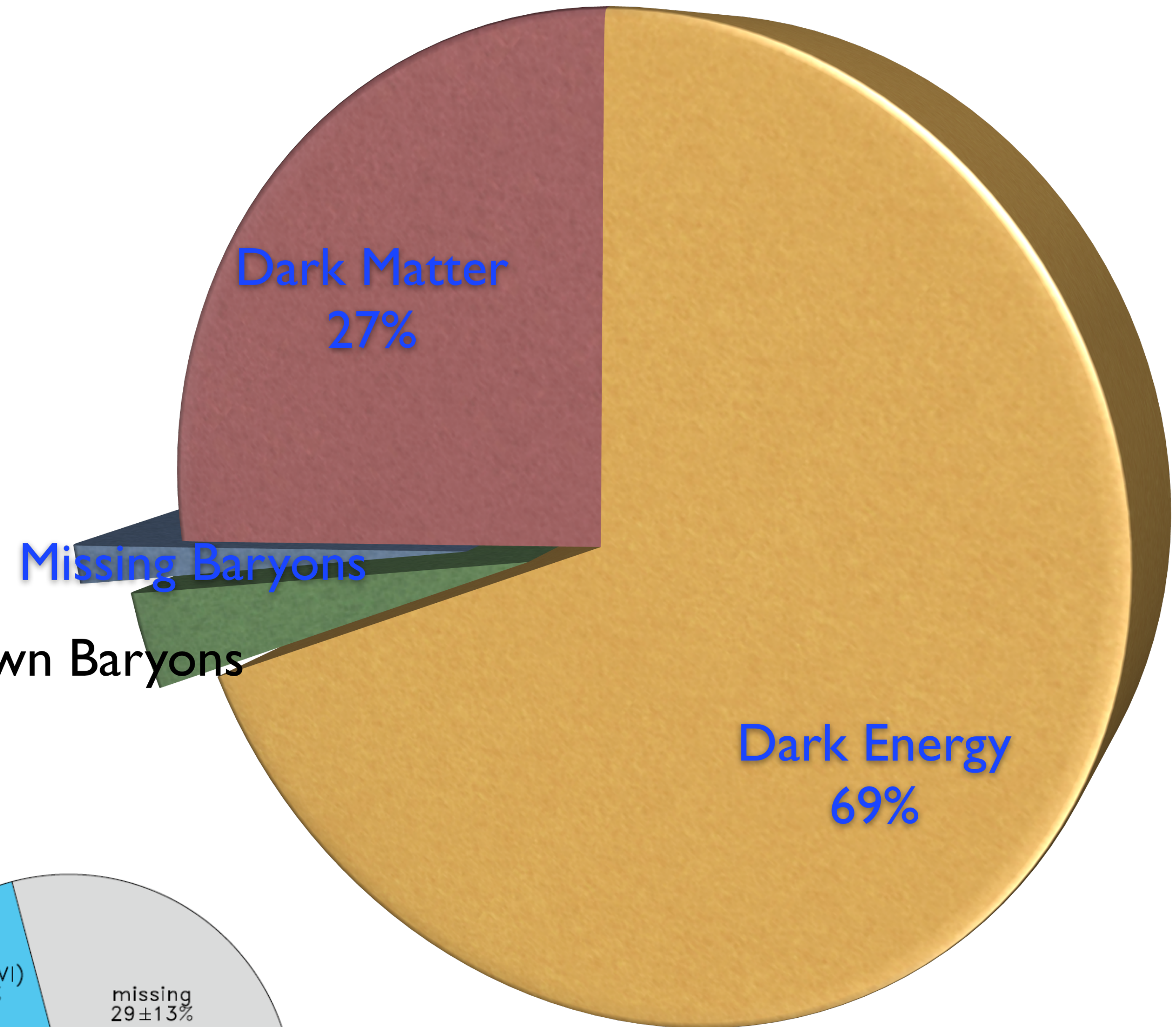
Big Bang Nucleosynthesis

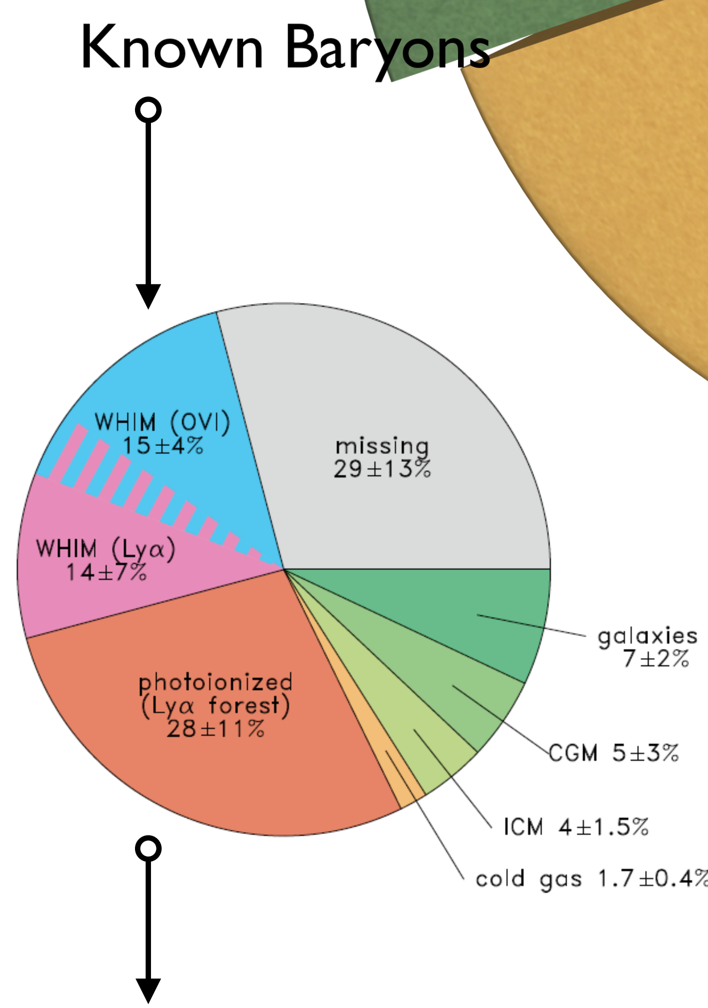
welcome to the
shy new world
24 March 2020



ΛCDM Cosmology

- non-baryonic cold dark matter
  - whatever it is (e.g., WIMPs)
- dark energy
  - whatever that even means
- dark baryons
  - 29% not accounted for



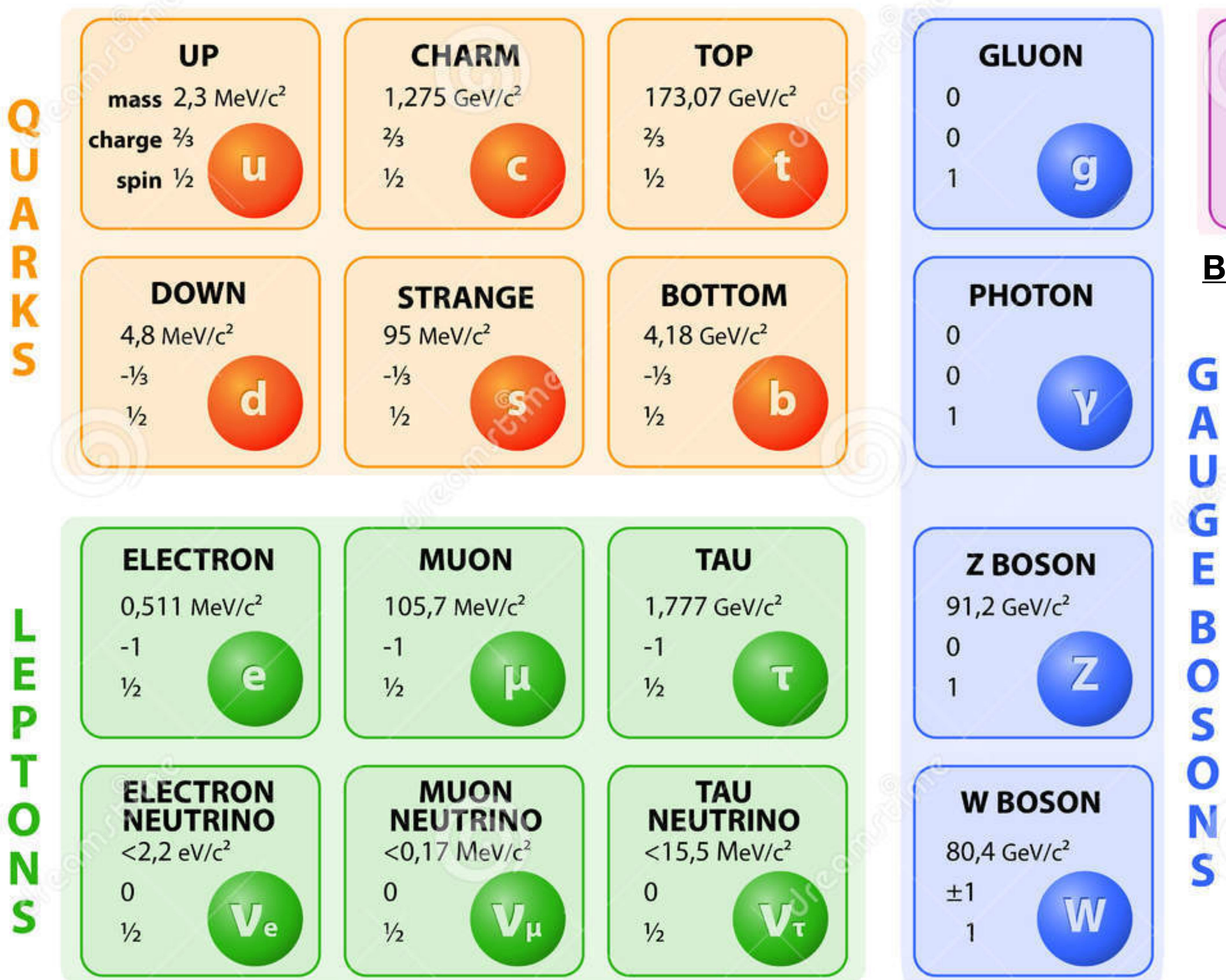


We have direct knowledge of only 4% of the total mass-energy density of the universe

Basic parameters of cosmology

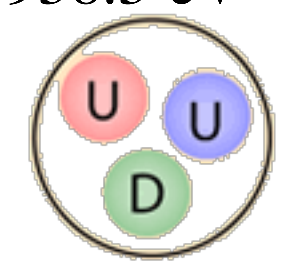
	H_0	Expansion rate		72 km/s/Mpc	
mass density	Ω_m			0.3	
		Ω_b	0.05		baryons
		Ω_{CDM}	0.25		not baryons
	Ω_Λ			0.7	dark energy
	σ_8	power spectrum		0.8	
	n_s	power spectrum		0.96	

STANDARD MODEL OF ELEMENTARY PARTICLES



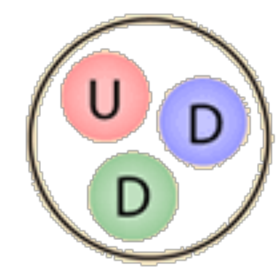
Baryons (3 quarks)

$m_p = 938.3$ eV



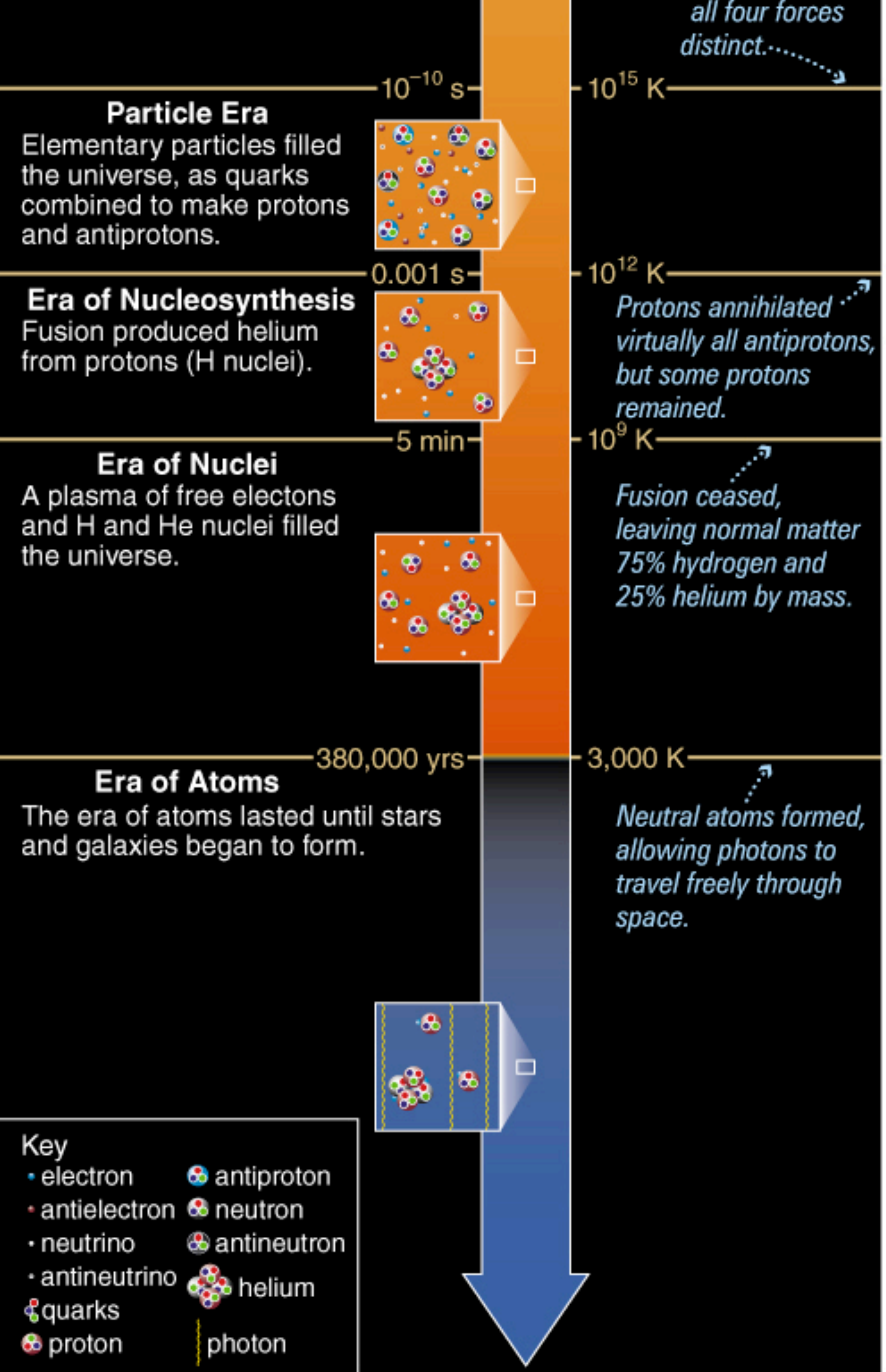
Proton

$m_n = 939.6$ eV



Neutron

Up & down quarks are light: most of the rest mass is binding energy



particle soup

< millisecond

T ~ 10^{14} K

nucleosynthesis (BBN)

~ 3 minutes

T ~ 10^{10} K

Early Universe

recombination

~380,000 year

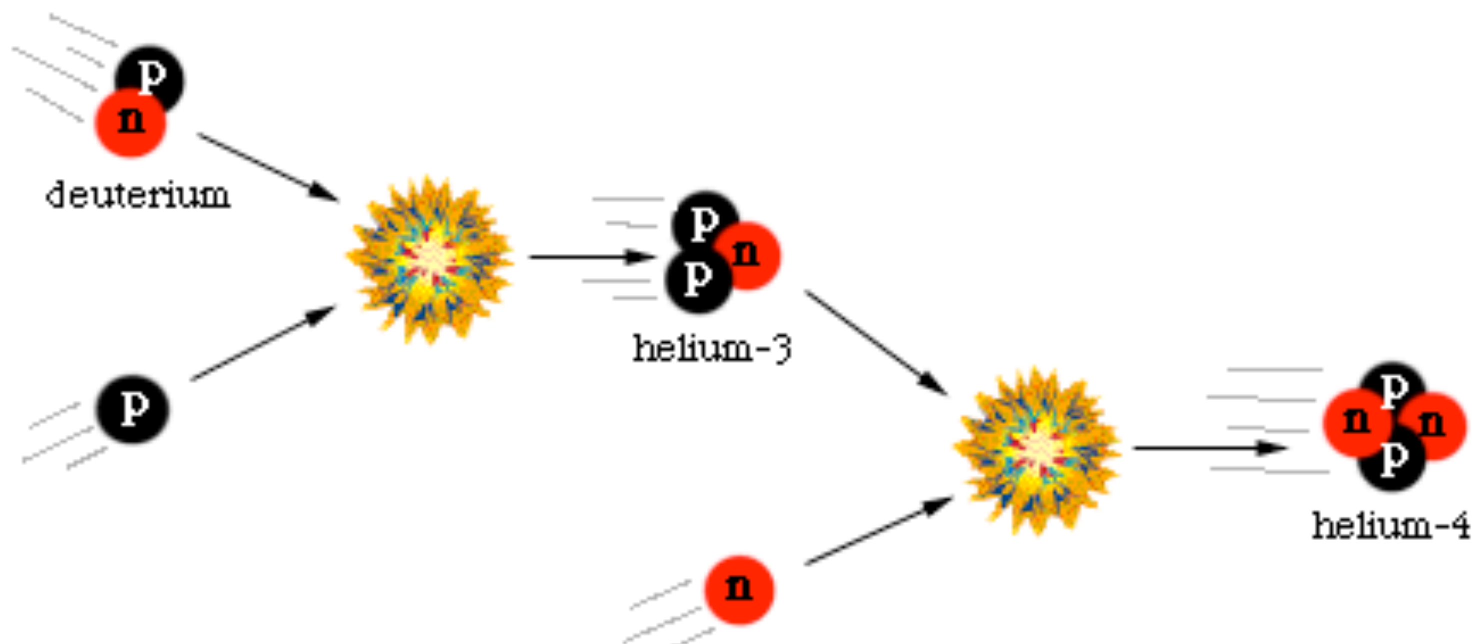
T ~ 3000 K

emission of CMB: surface of last scattering

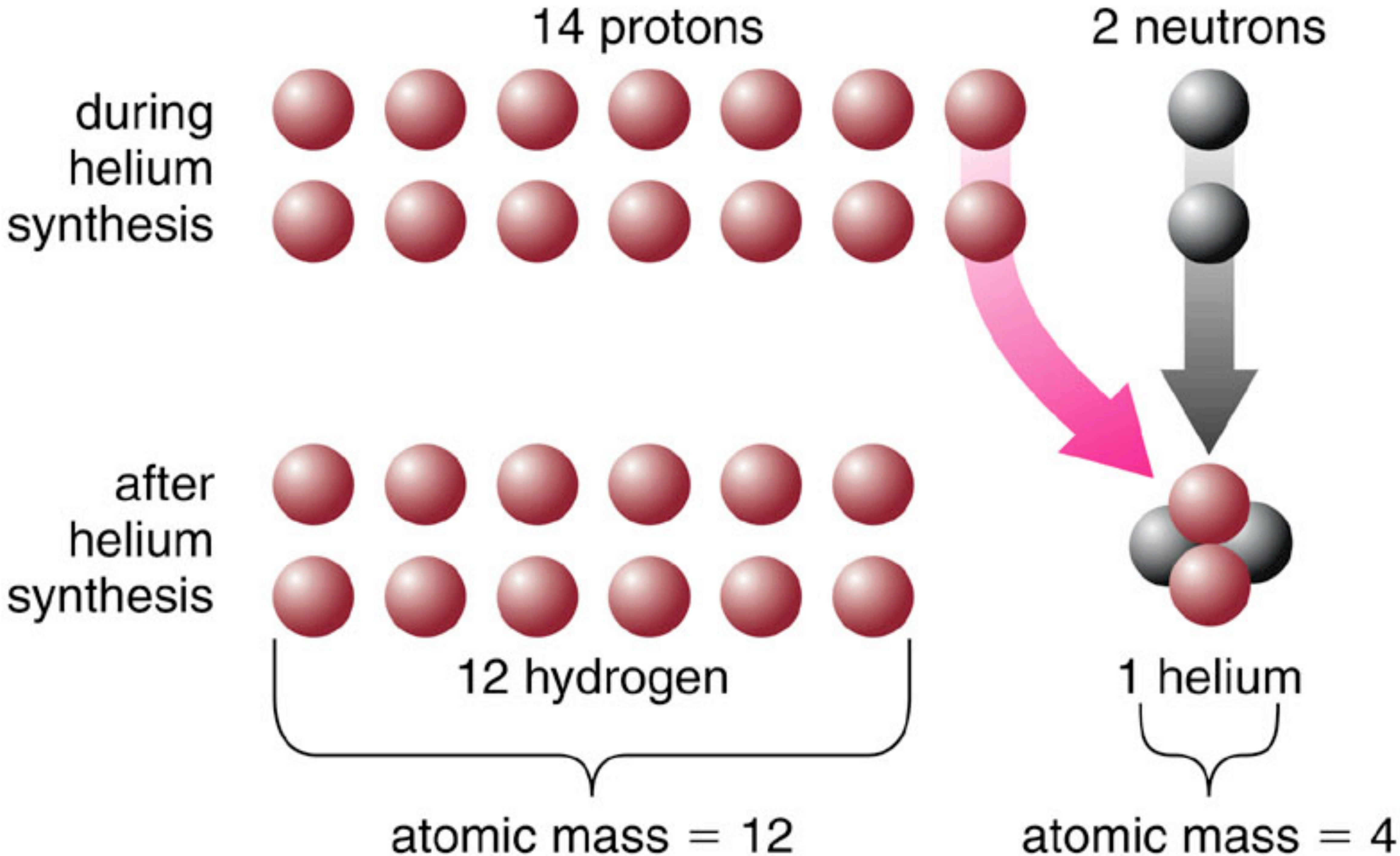
Primordial Nucleosynthesis (BBN):

Gamow

When the universe is just a few minutes old, the Temperature and Density are just right for it to be one Big Nuclear Furnace:



The light elements
Hydrogen, Helium, and Lithium
are made at this time.



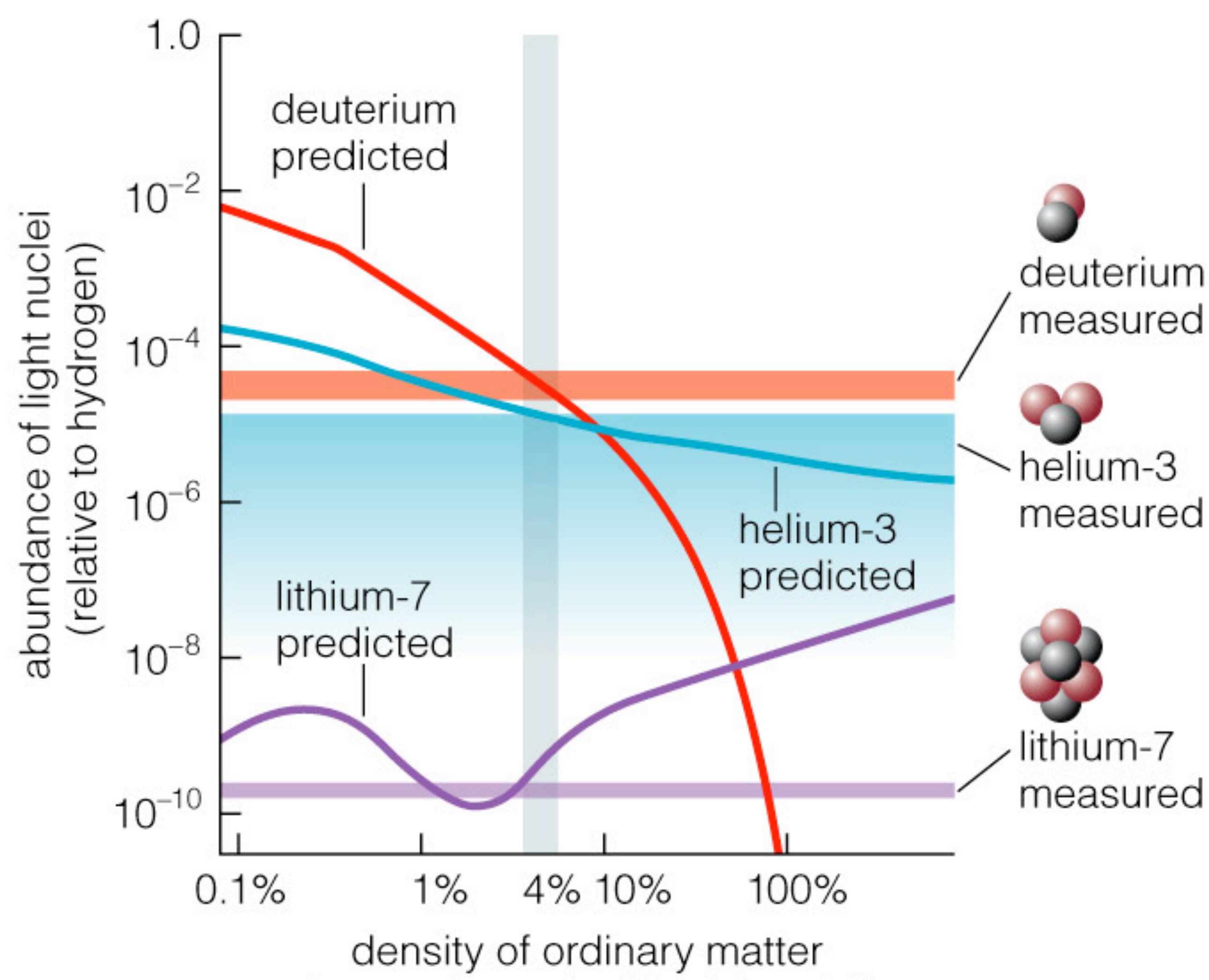
Big Bang theory prediction: 75% H, 25% He (by mass)

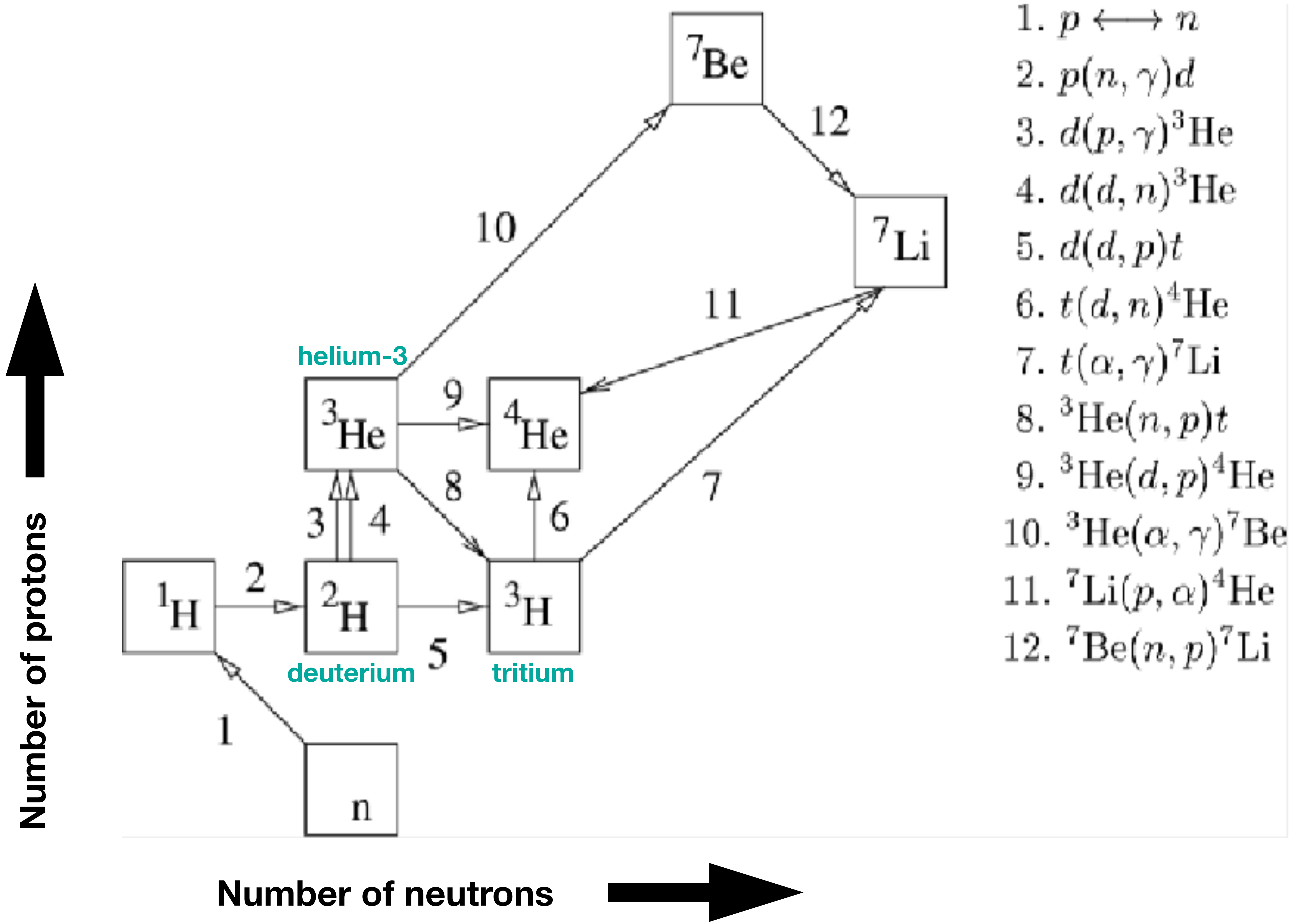
Matches observations of nearly primordial gases

BBN products:

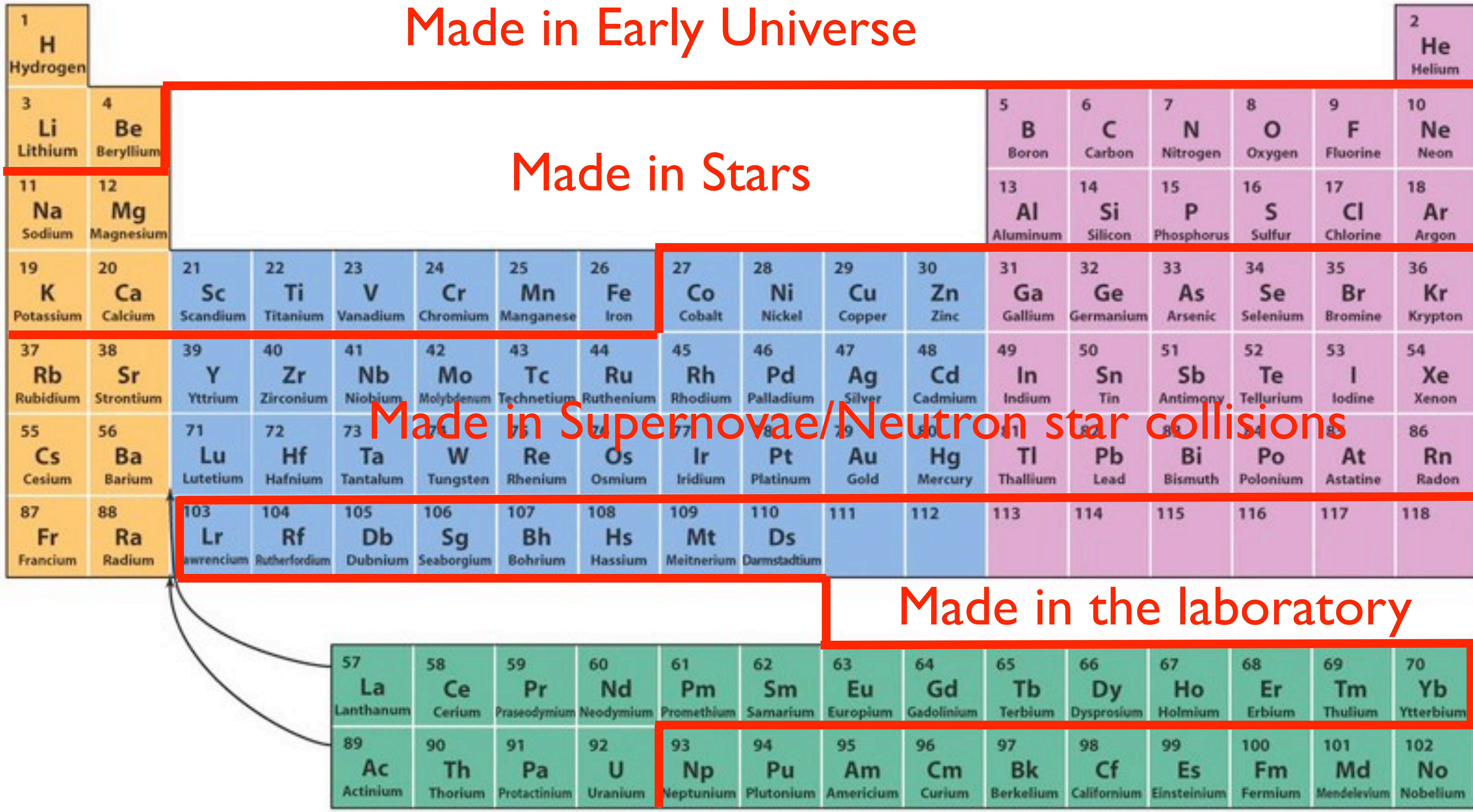
- 3/4 Hydrogen
- 1/4 Helium
- Traces of
  - deuterium
  - tritium
  - helium 3
  - lithium
  - berylium

Abundances depend on the density of matter. The higher the density parameter (Ω_b), the more helium.





^{7}Be
^{7}Li
^{3}He
^{4}He
^{1}H
^{2}H
^{3}H
n
helium-3
deuterium
tritium
1
2
3
4
5
6
7
8
9
10
11
12
1. $p \longleftrightarrow n$
2. $p(n,\gamma)d$
3. $d(p,\gamma)^{3}$He
4. $d(d,n)^{3}$He
5. $d(d,p)t$
6. $t(d,n)^{4}$He
7. $t(\alpha,\gamma)^{7}$Li
8. ^{3}He$(n,p)t$
9. ^{3}He$(d,p)^{4}$He
10. ^{3}He$(\alpha,\gamma)^{7}$Be
11. ^{7}Li$(p,\alpha)^{4}$He
12. ^{7}Be$(n,p)^{7}$Li
Number of protons
Number of neutrons


Made in Early Universe
Made in Stars
Made in Supernovae/Neutron star collisions
Made in the laboratory
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
19 K Potassium
20 Ca Calcium
21 Sc Scandium
22 Ti Titanium
23 V Vanadium
24 Cr Chromium
25 Mn Manganese
26 Fe Iron
27 Co Cobalt
28 Ni Nickel
29 Cu Copper
30 Zn Zinc
31 Ga Gallium
32 Ge Germanium
33 As Arsenic
34 Se Selenium
35 Br Bromine
36 Kr Krypton
37 Rb Rubidium
38 Sr Strontium
39 Y Yttrium
40 Zr Zirconium
41 Nb Niobium
42 Mo Molybdenum
43 Tc Technetium
44 Ru Ruthenium
45 Rh Rhodium
46 Pd Palladium
47 Ag Silver
48 Cd Cadmium
49 In Indium
50 Sn Tin
51 Sb Antimony
52 Te Tellurium
53 I Iodine
54 Xe Xenon
55 Cs Cesium
56 Ba Barium
71 Lu Lutetium
72 Hf Hafnium
73 Ta Tantalum
W Tungsten
Re Rhenium
Os Osmium
Ir Iridium
Pt Platinum
Au Gold
Hg Mercury
Tl Thallium
Pb Lead
Bi Bismuth
Po Polonium
At Astatine
86 Rn Radon
87 Fr Francium
88 Ra Radium
103 Lr awrencium
104 Rf Rutherfordium
105 Db Dubnium
106 Sg Seaborgium
107 Bh Bohrium
108 Hs Hassium
109 Mt Meitnerium
110 Ds Darmstadtium
111
112
113
114
115
116
117
118
57 La Lanthanum
58 Ce Cerium
59 Pr Praseodymium
60 Nd Neodymium
61 Pm Promethium
62 Sm Samarium
63 Eu Europium
64 Gd Gadolinium
65 Tb Terbium
66 Dy Dysprosium
67 Ho Holmium
68 Er Erbium
69 Tm Thulium
70 Yb Ytterbium
89 Ac Actinium
90 Th Thorium
91 Pa Protactinium
92 U Uranium
93 Np Neptunium
94 Pu Plutonium
95 Am Americium
96 Cm Curium
97 Bk Berkelium
98 Cf Californium
99 Es Einsteinium
100 Fm Fermium
101 Md Mendelevium
102 No Nobelium

no stable mass 5 or 8

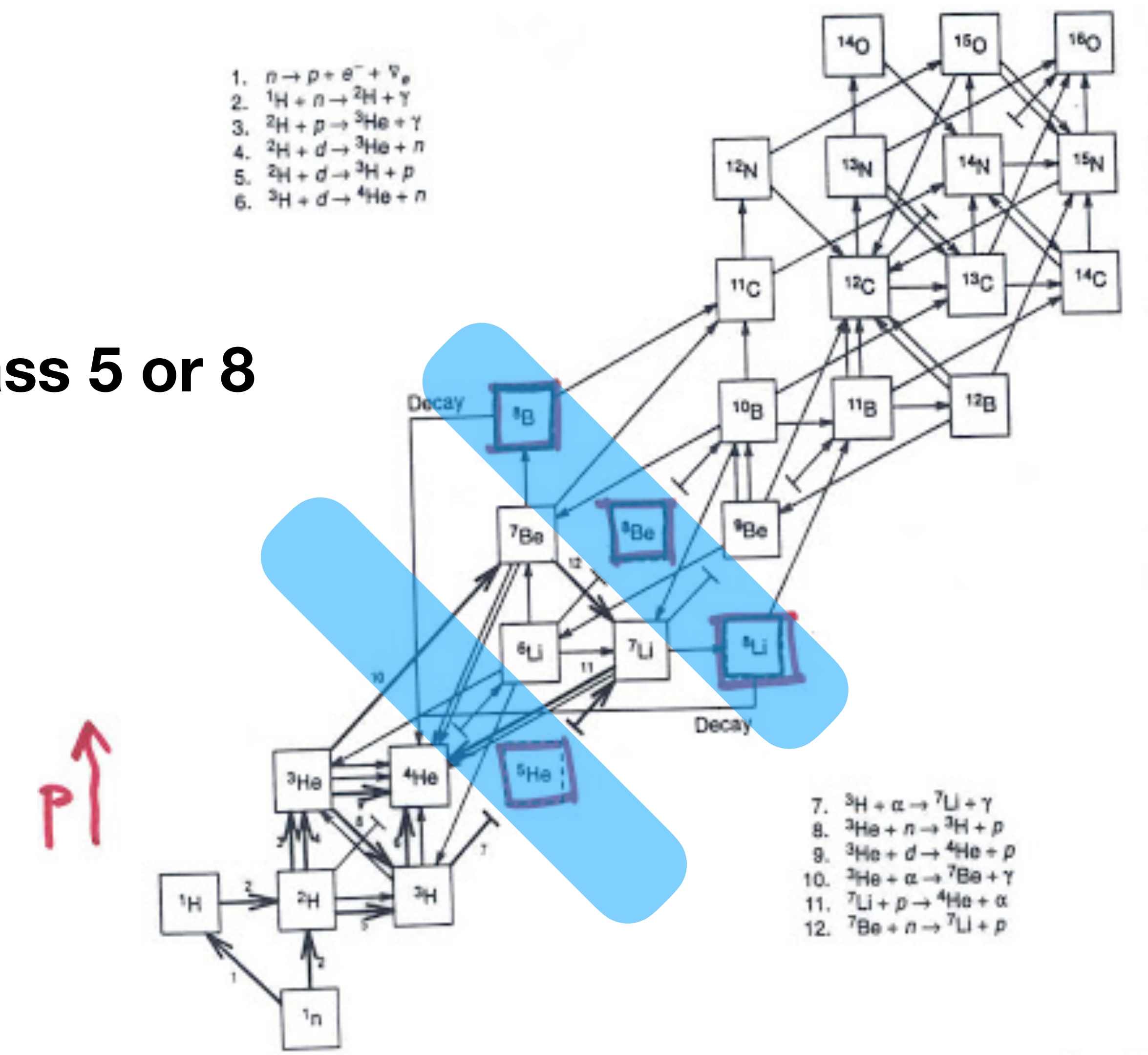


Fig. 2. The nuclear reaction network used for big-bang nucleosynthesis; the most important reactions are numbered and have bold arrows. The broken boxes for mass 5 and 8 indicate that all nuclides of this mass are very unstable.

n

BBN restricted to elements

Stars skip over the mass bottleneck via the triple alpha reaction

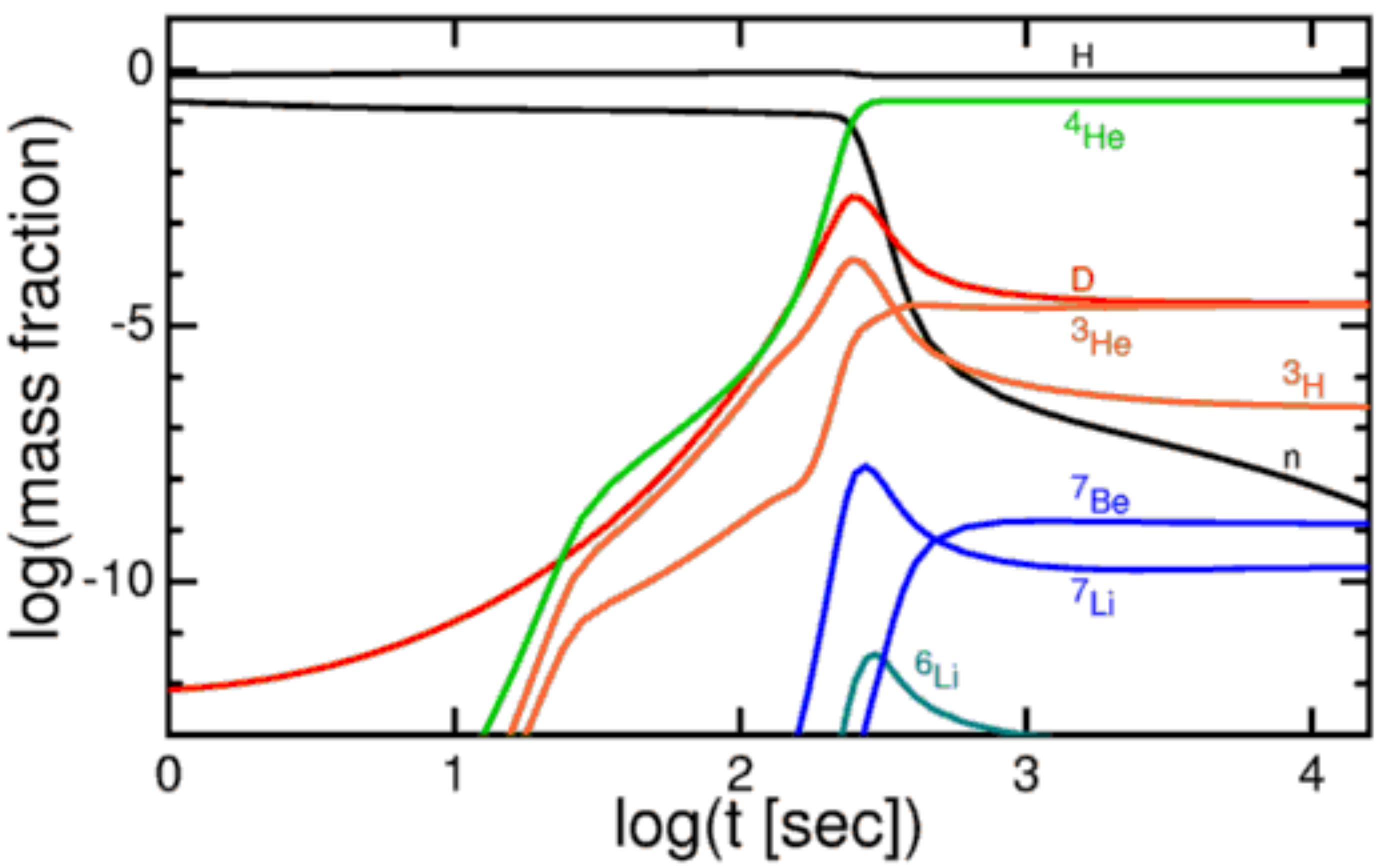
$$3\ .^4\mathrm{He} \rightarrow .^{12}\mathrm{C}^*$$

BBN reactions

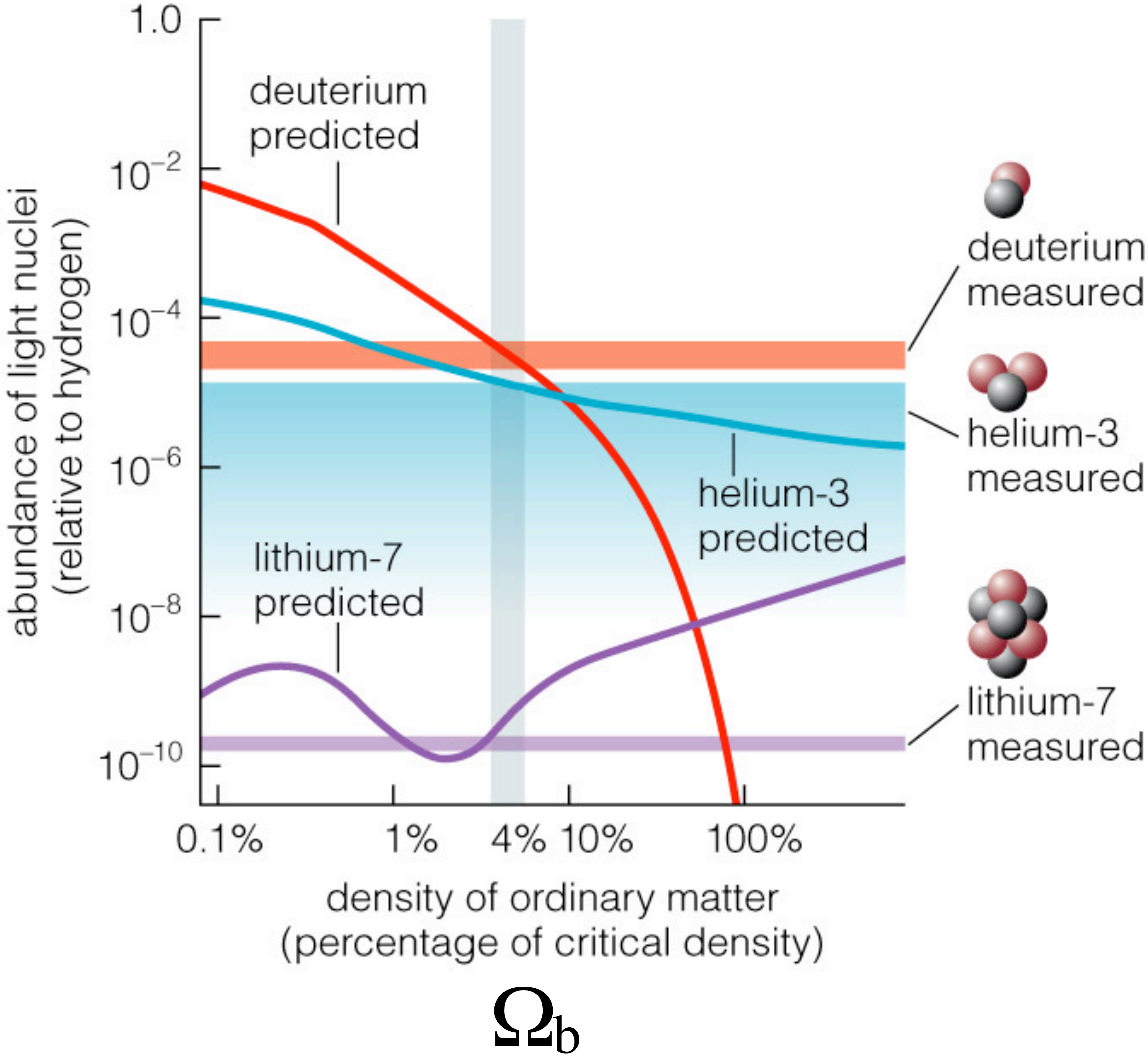
The following stages occur during the first few minutes of the Universe:

Less than 1 second after the Big Bang, the reactions shown at right maintain the neutron:proton ratio in thermal equilibrium. About 1 second after the Big Bang, the temperature is slightly less than the neutron-proton mass difference, these weak reactions become slower than the expansion rate of the Universe, and the neutron:proton ratio *freezes out* at about 1:6.	$p + e^- \longleftrightarrow n + \nu$ $n + e^+ \longleftrightarrow p + \bar{\nu}$
After 1 second, the only reaction that appreciably changes the number of neutrons is neutron decay, shown at right. The half-life of the neutron is 615 seconds. Without further reactions to preserve neutrons within stable nuclei, the Universe would be pure hydrogen.	$n \longrightarrow p + e^- + \bar{\nu}$
The reaction that preserves the neutrons is deuteron formation. The deuteron is the nucleus of deuterium, which is the heavy form of hydrogen (H^2). This reaction is exothermic with an energy difference of 2.2 MeV, but since photons are a billion times more numerous than protons, the reaction does not proceed until the temperature of the Universe falls to 1 billion K or kT = 0.1 MeV, about 100 seconds after the Big Bang. At this time, the neutron:proton ratio is about 1:7.	$p + n \longleftrightarrow d + \gamma$
Once deuteron formation has occurred, further reactions proceed to make helium nuclei. Both light helium (He^3) and normal helium (He^4) are made, along with the radioactive form of hydrogen (H^3). These reactions can be photoreactions as shown here. Because the helium nucleus is 28 MeV more bound than the deuterons, and the temperature has already fallen so far that kT = 0.1 MeV, these reactions only go one way.	$d + n \longrightarrow H^3 + \gamma$ $H^3 + p \longrightarrow He^4 + \gamma$ $d + p \longrightarrow He^3 + \gamma$ $He^3 + n \longrightarrow He^4 + \gamma$
The reactions at right also produce helium and usually go faster since they do not involve the relatively slow process of photon emission.	$d + d \longrightarrow He^3 + n$ $d + d \longrightarrow H^3 + p$ $H^3 + d \longrightarrow He^4 + n$ $He^3 + d \longrightarrow He^4 + p$
The net effect is shown at right. Eventually the temperature gets so low that the electrostatic repulsion of the deuterons causes the reaction to stop. The deuteron:proton ratio when the reactions stop is quite small, and essentially inversely proportional to the total density in protons and neutrons. Almost all the neutrons in the Universe end up in normal helium nuclei. For a neutron:proton ratio of 1:7 at the time of deuteron formation, 25% of the mass ends up in helium.	$d + d \longrightarrow He^4 + \gamma$

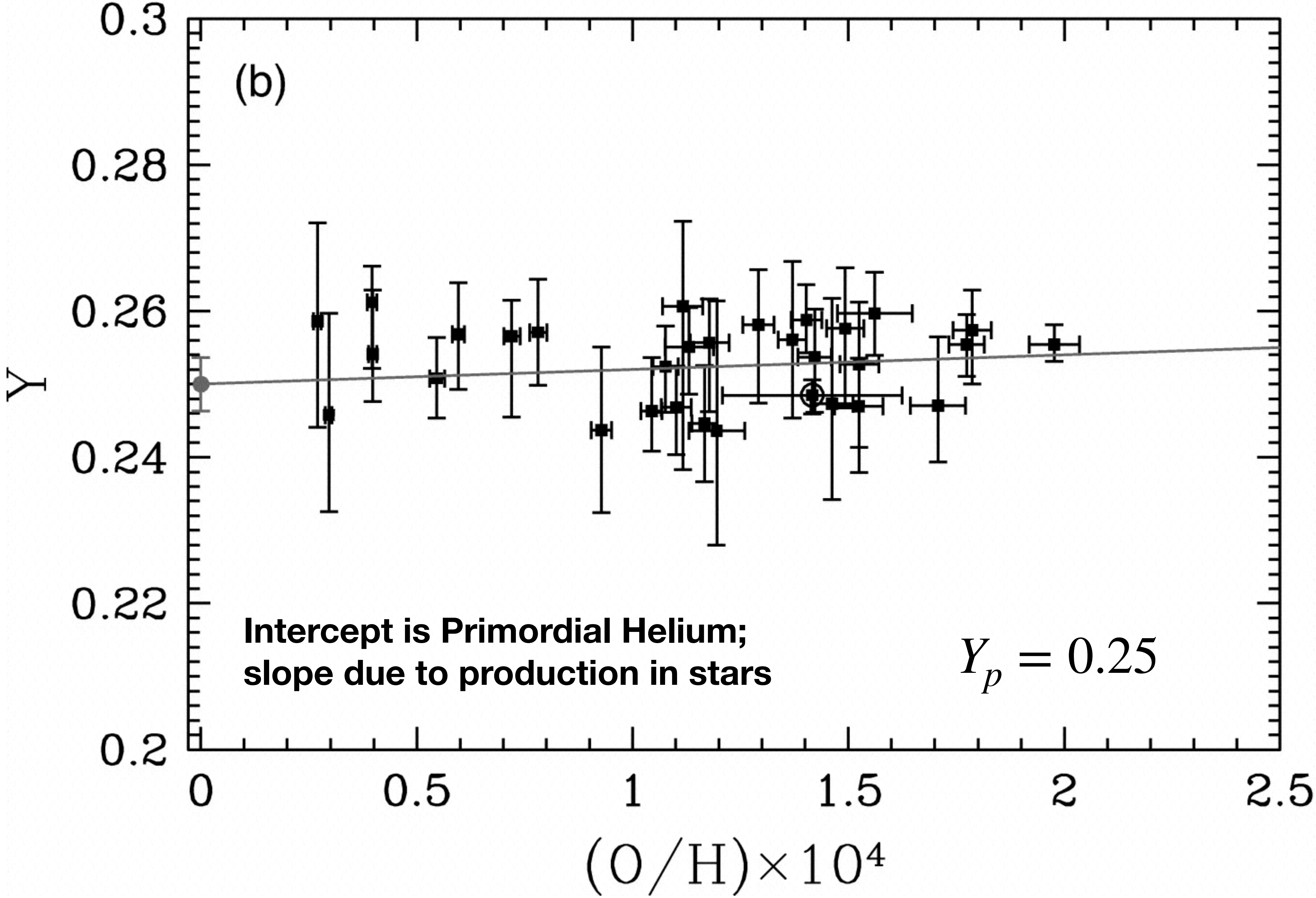
Source: Ned Wright: http://www.astro.ucla.edu/~wright/BBNS.html



log(mass fraction)
log(t [sec])
0
-5
-10
0
1
2
3
4
H
4He
D
3He
3H
n
7Be
7Li
6Li



BBN gets the abundances of deuterium, helium, and lithium right if the mass density is about 4% of the critical density.



Fukugita & Kawasaki (2006)