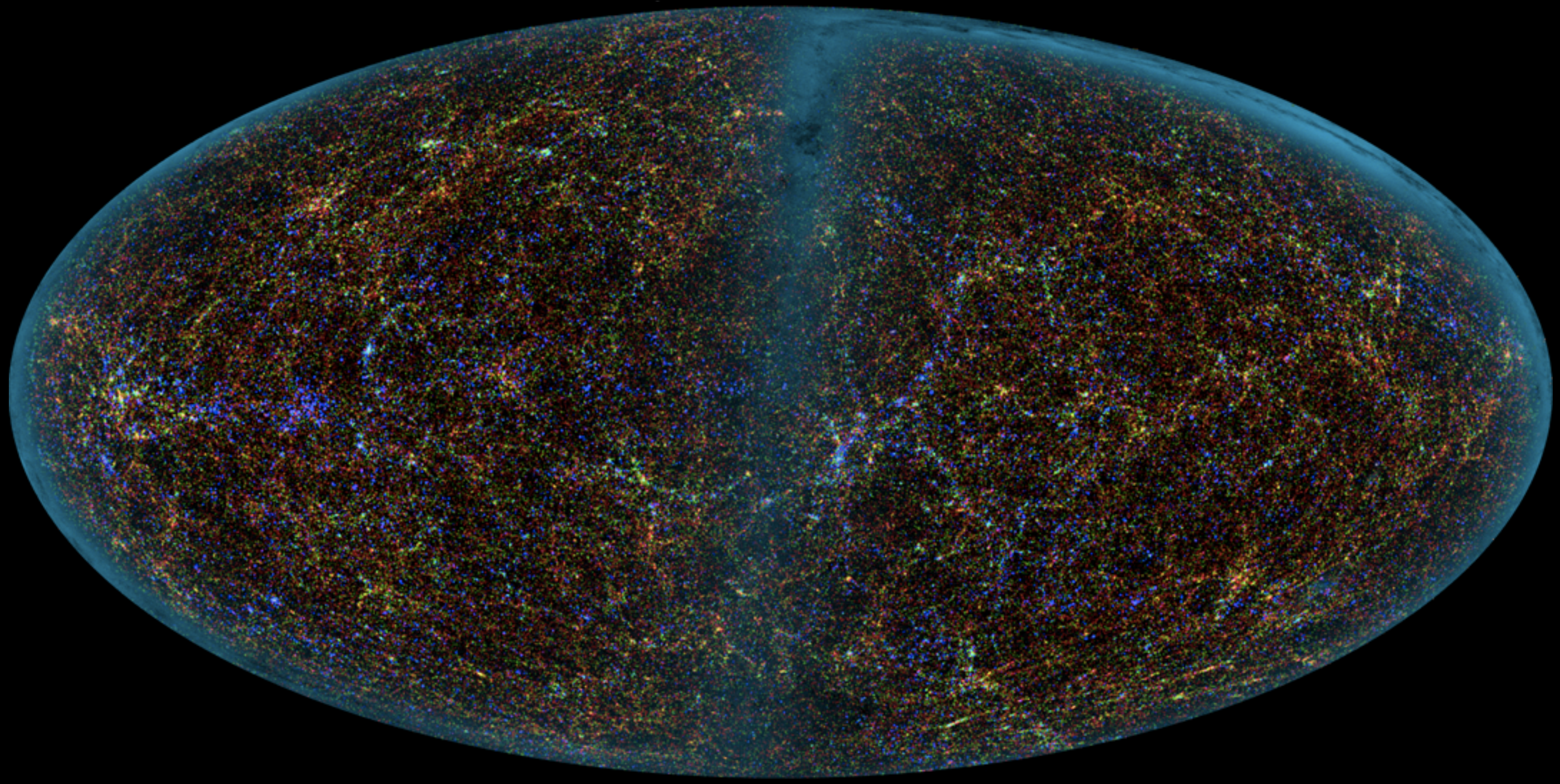
Cosmology

and Large Scale Structure



Today

Empirical Pillars
of the Hot Big Bang

Nucleosynthesis

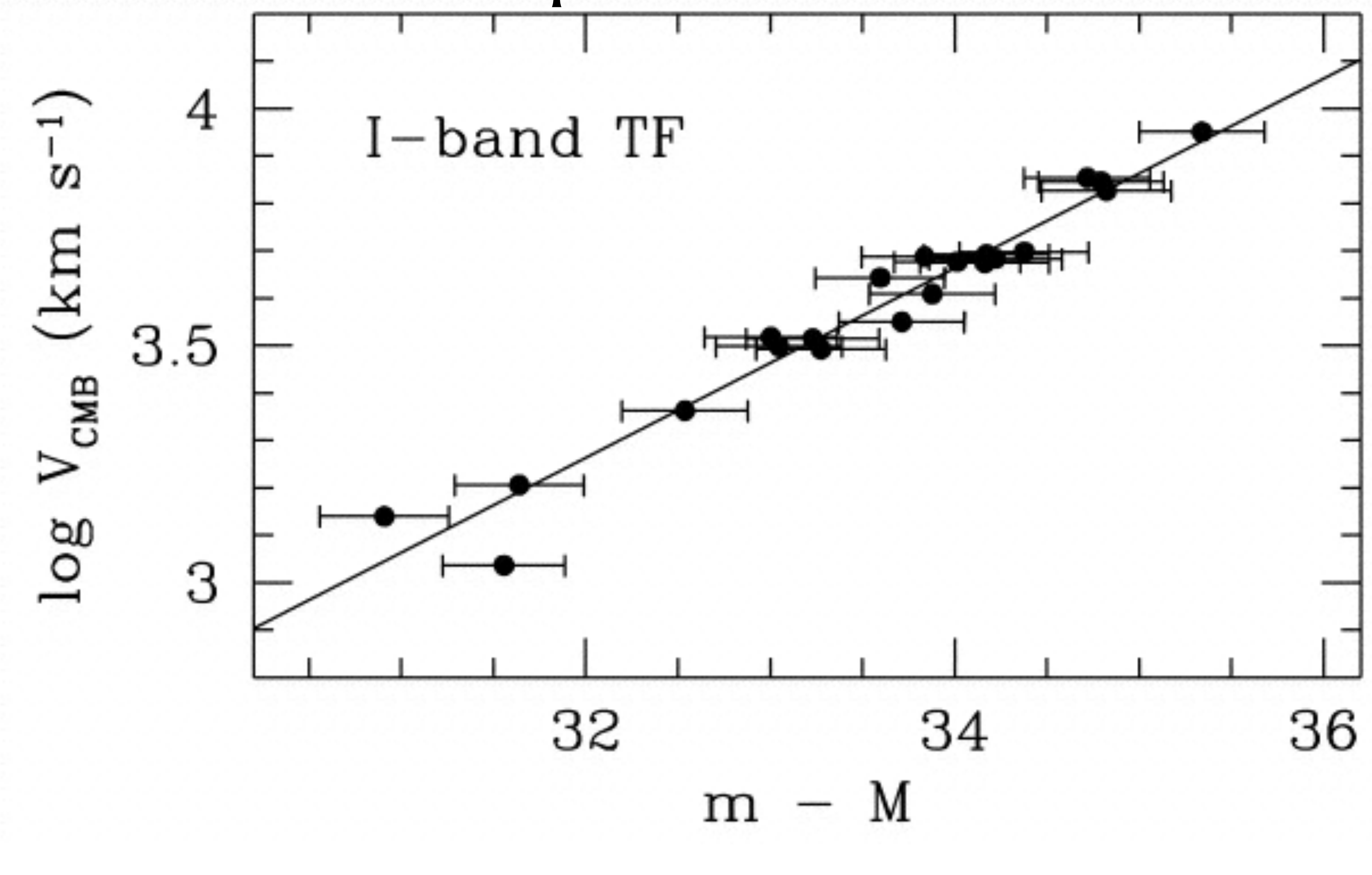
9 September 2020

http://astroweb.case.edu/ssm/astr328/

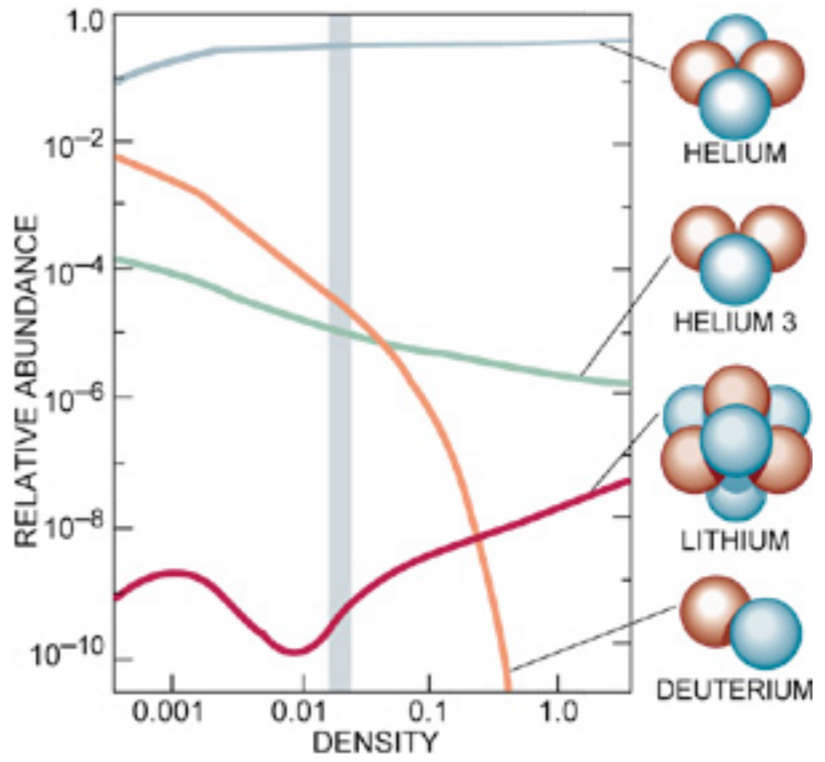
Empirical Pillars of the Hot Big Bang

1. Hubble Expansion — Hubble (1930)
2. Big Bang Nucleosynthesis (BBN) — Alpher, [Bethe], & Gamow (1948) — $\alpha\beta\gamma$ paper
3. Cosmic Microwave Background (CMB) — Penzias & Wilson; Peebles & Dicke (1965)

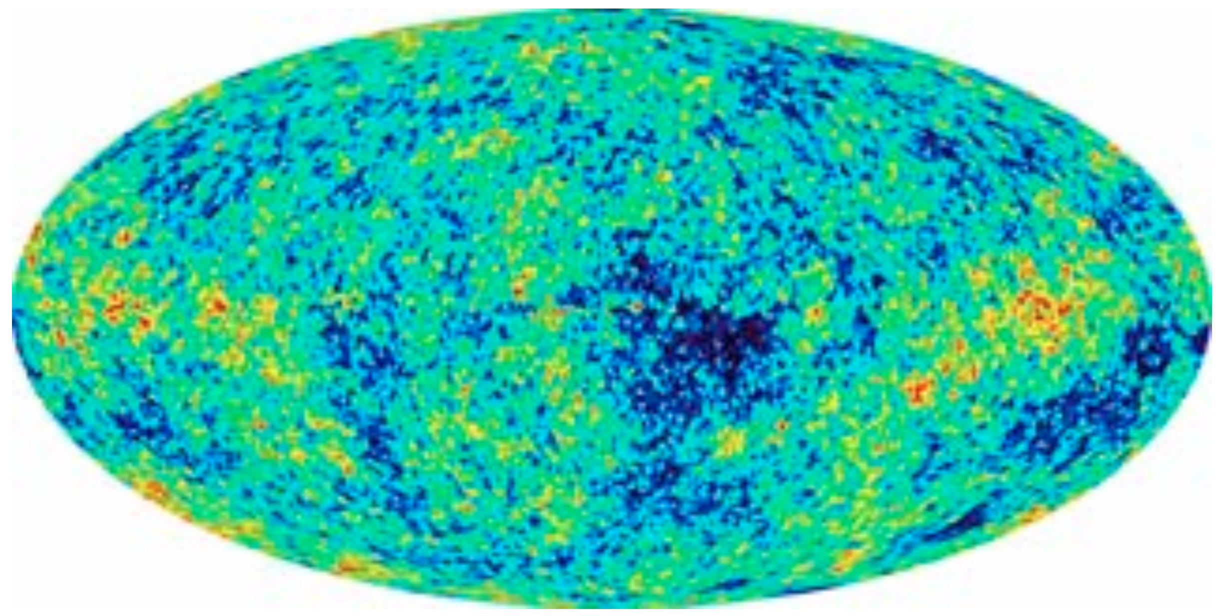
Hubble expansion



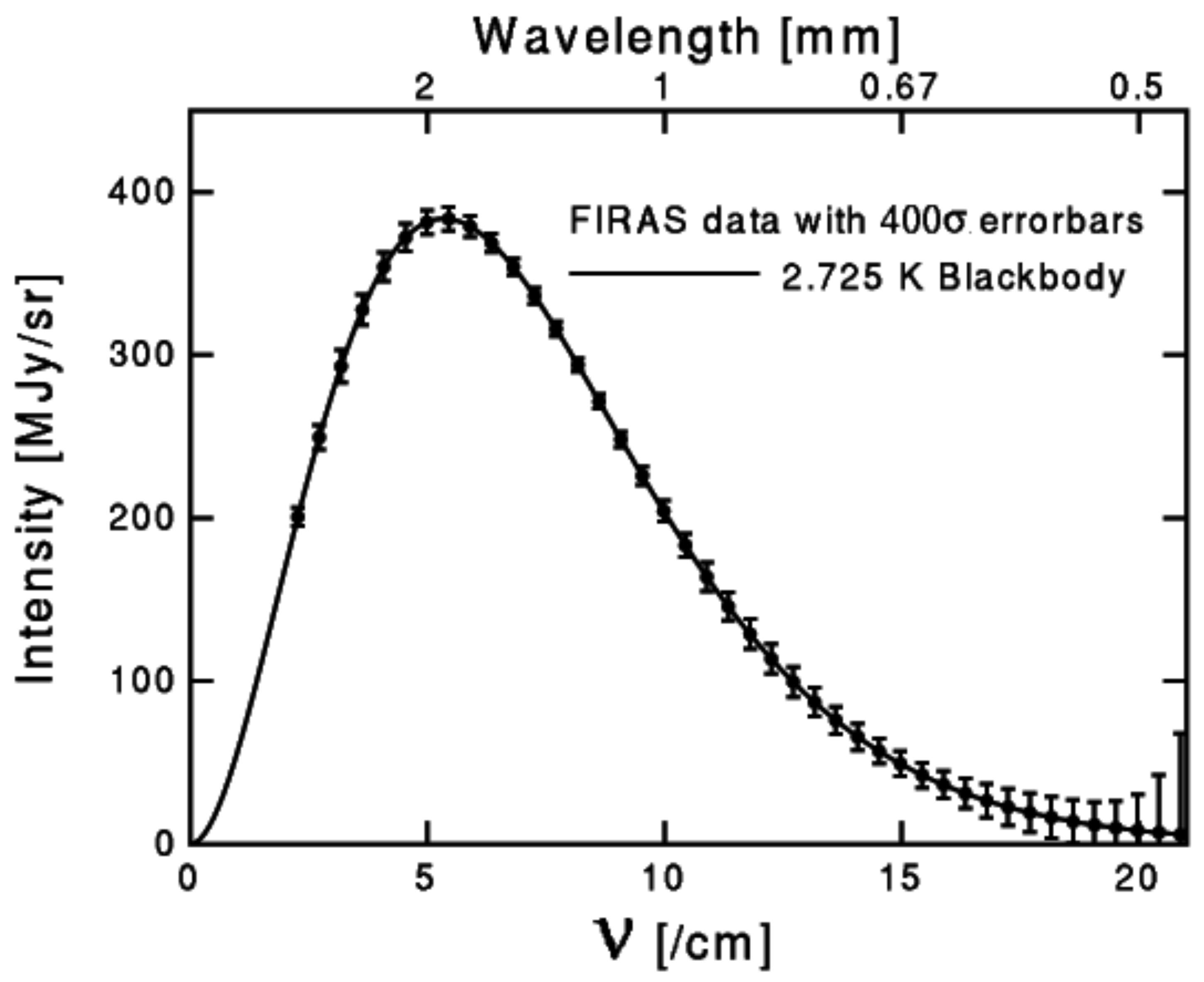
BBN
t ~ 3 minutes



CMB
z = 1090
t = 380,000 yr



Cosmic Microwave Background



The Cosmic Microwave Background (CMB) is the relic radiation field of the Hot Big Bang. It has an essentially a perfect thermal spectrum with a current temperature of 2.725 K.

This was higher in the past by (1+z), so T ~ 3,000 K at the epoch of recombination. This is the point at which the high-energy tail of the blackbody distribution no longer had enough photons in excess of 1 Rydberg to keep the universe ionized.

Photon energy density measured in CMB

Current temperature $T_0 = 2.725\ \mathrm{K}$

Energy density $\varepsilon_0 = \alpha T_0^4 = 0.261\ \mathrm{MeV\,m^{-3}}$

α is the radiation density constant

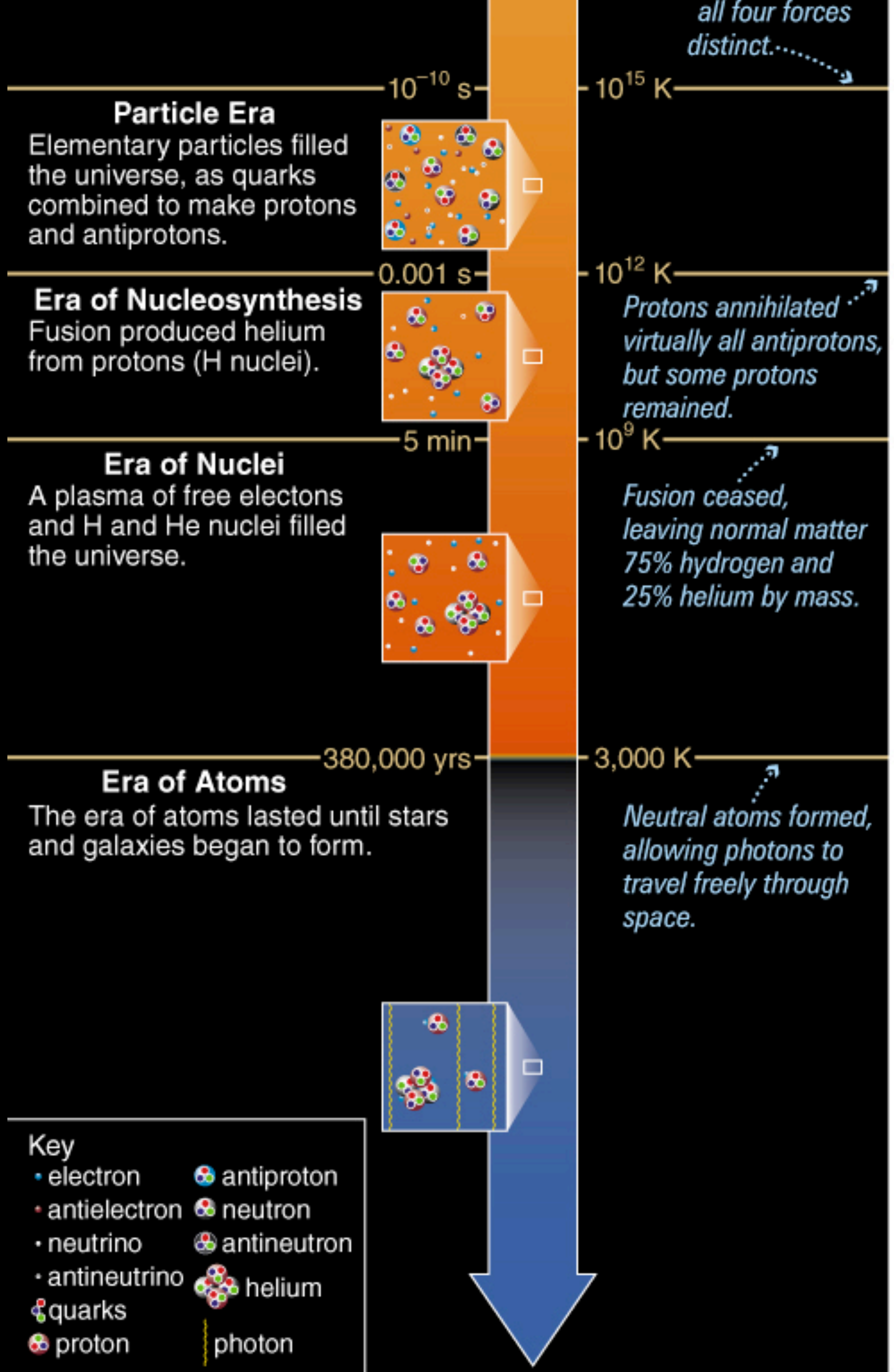
Relative to the critical density $\Omega_r = 5 \times 10^{-5}$ $\quad \Omega_r = \dfrac{\varepsilon_0}{\rho_c c^2}$

Number density of photons $n_{\gamma,0} = 4.11 \times 10^8\ \mathrm{m^{-3}}$

This greatly exceeds all the photons produced by all the stars throughout the universe over all time.

Current mass-energy content of the universe

mass density	Ω_m	0.3	give or take a bit	
normal matter	Ω_b	0.05	baryons - known from BBN	
mass that is *not* normal matter	$\Omega_{\rm CDM}$	0.25	cold dark matter	
cosmic background radiation	Ω_r	5×10^{-5}	photons	$n_\nu = \frac{9}{11} n_\gamma$
		4×10^{-5}	neutrinos	for 3 neutrino flavors
dark energy	Ω_Λ	0.7	energy density of vacuum	



Early Universe

particle soup

< millisecond

T ~ 10^{14} K

nucleosynthesis (BBN)

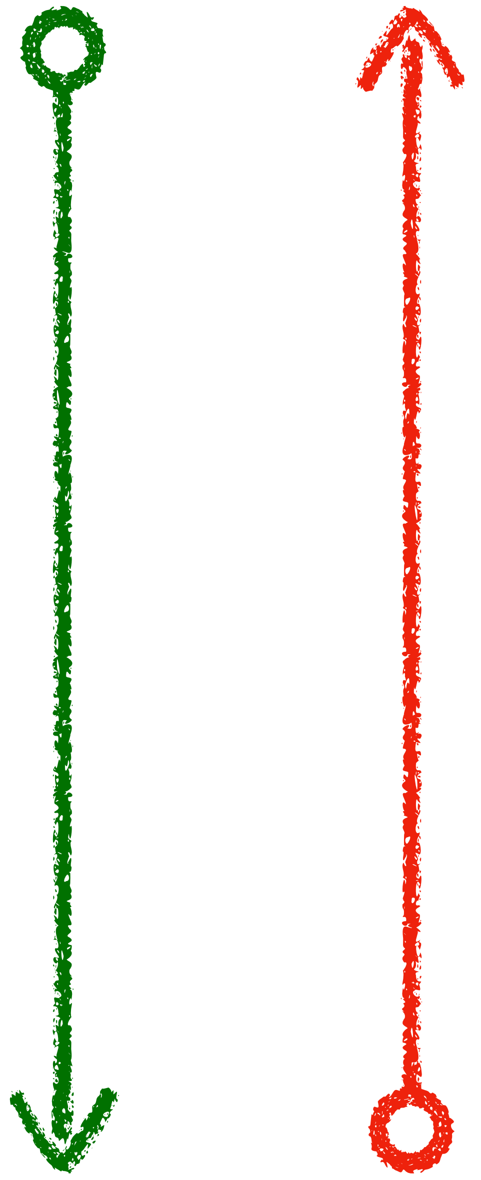
~ 3 minutes

T ~ 10^{10} K

BBN occurs during radiation domination

$a(t) \propto t^{1/2}$

time **Temp**



recombination

~380,000 year

T ~ 3000 K

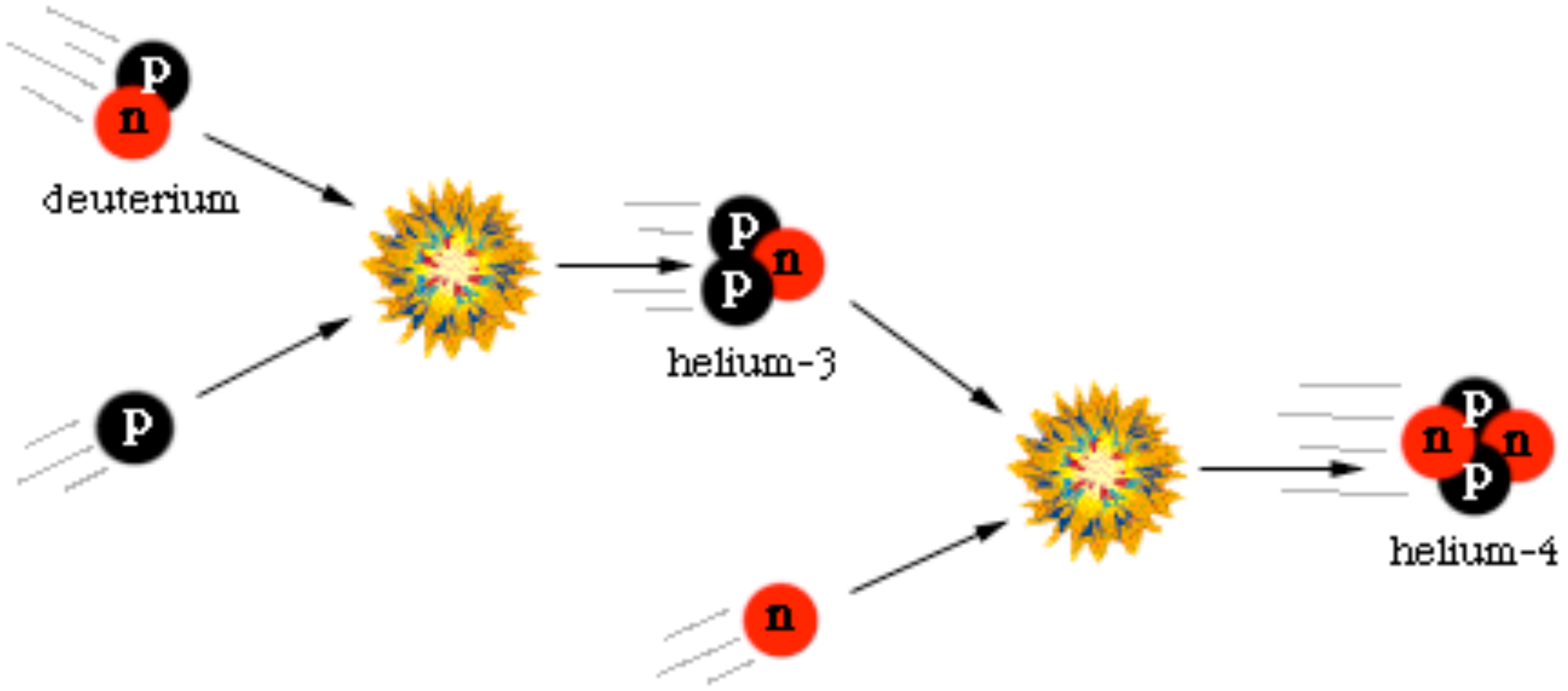
emission of CMB:

surface of last scattering - transition from opaque plasma to transparent neutral gas

Big Bang Nucleosynthesis (BBN)

Gamow

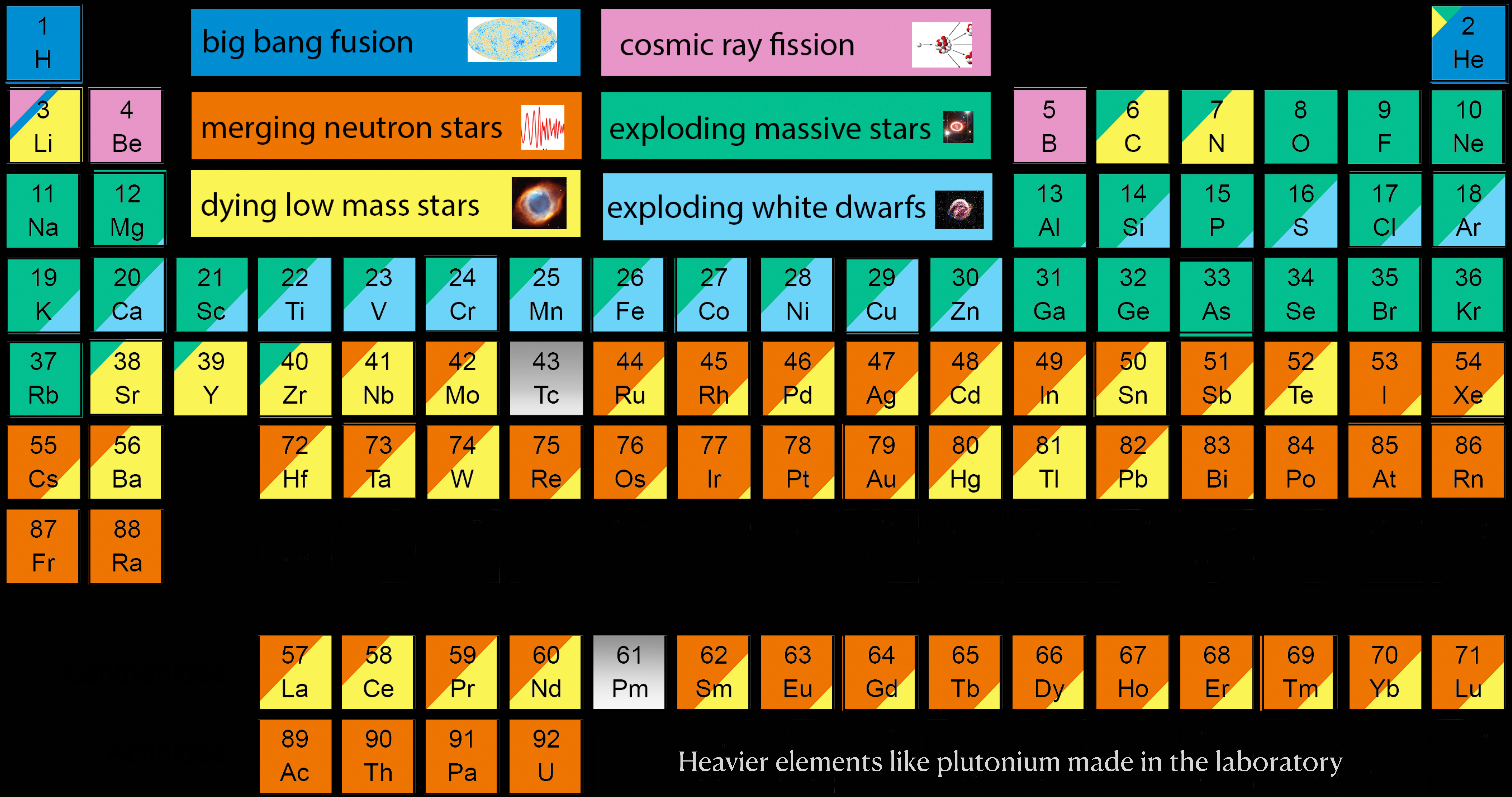
When the universe is just a few minutes old,
the temperature and density are right
for it to be one big nuclear furnace: $T \sim 10^{10}$ K



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

Alpher & Gamow initially thought that they could make *all* of the elements through neutron capture.
This was wrong; only the light elements are made because of the helium bottleneck.
Heavier elements are made in stars and supernovae.

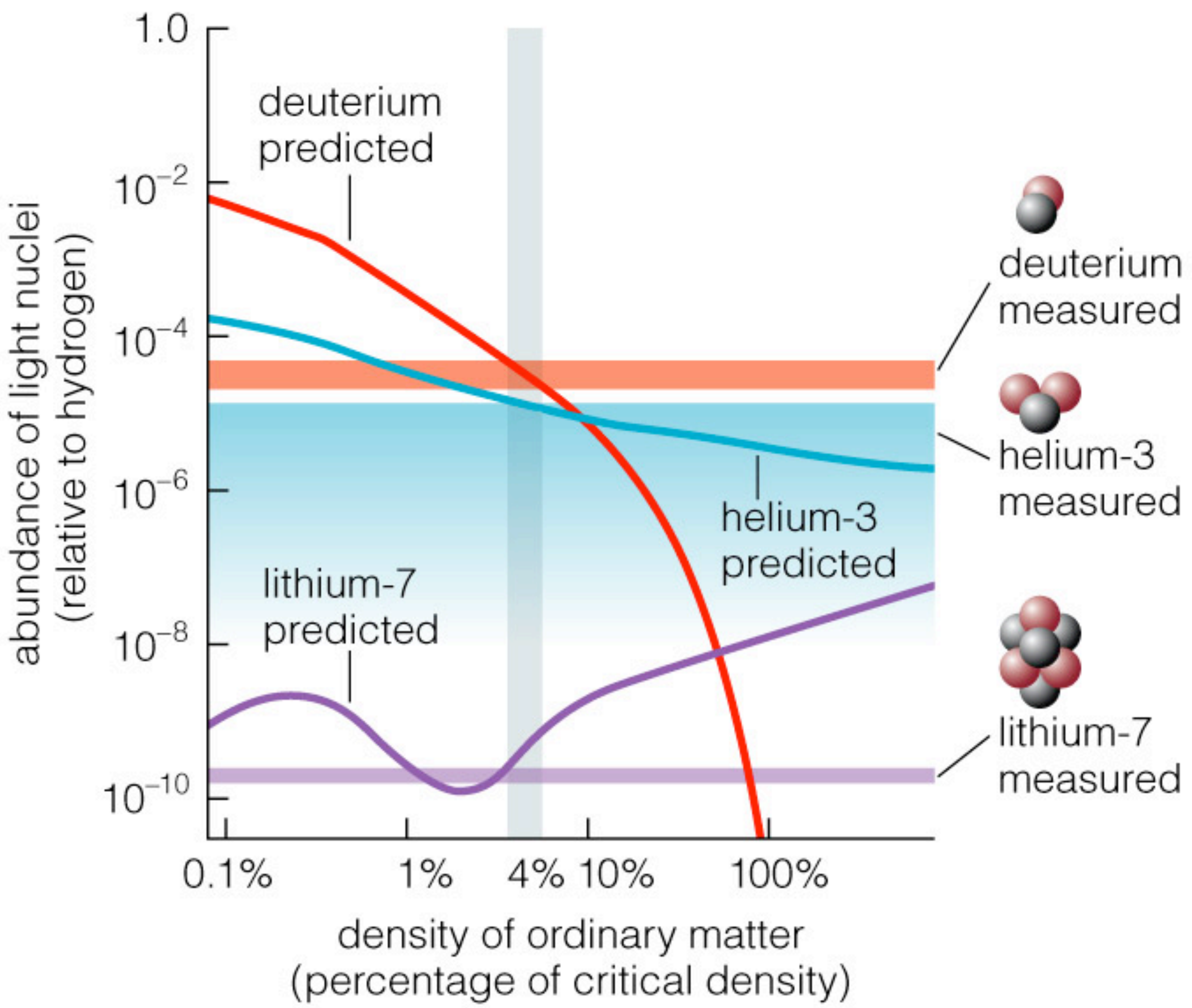
The Origin of the Solar System Elements



BBN products:

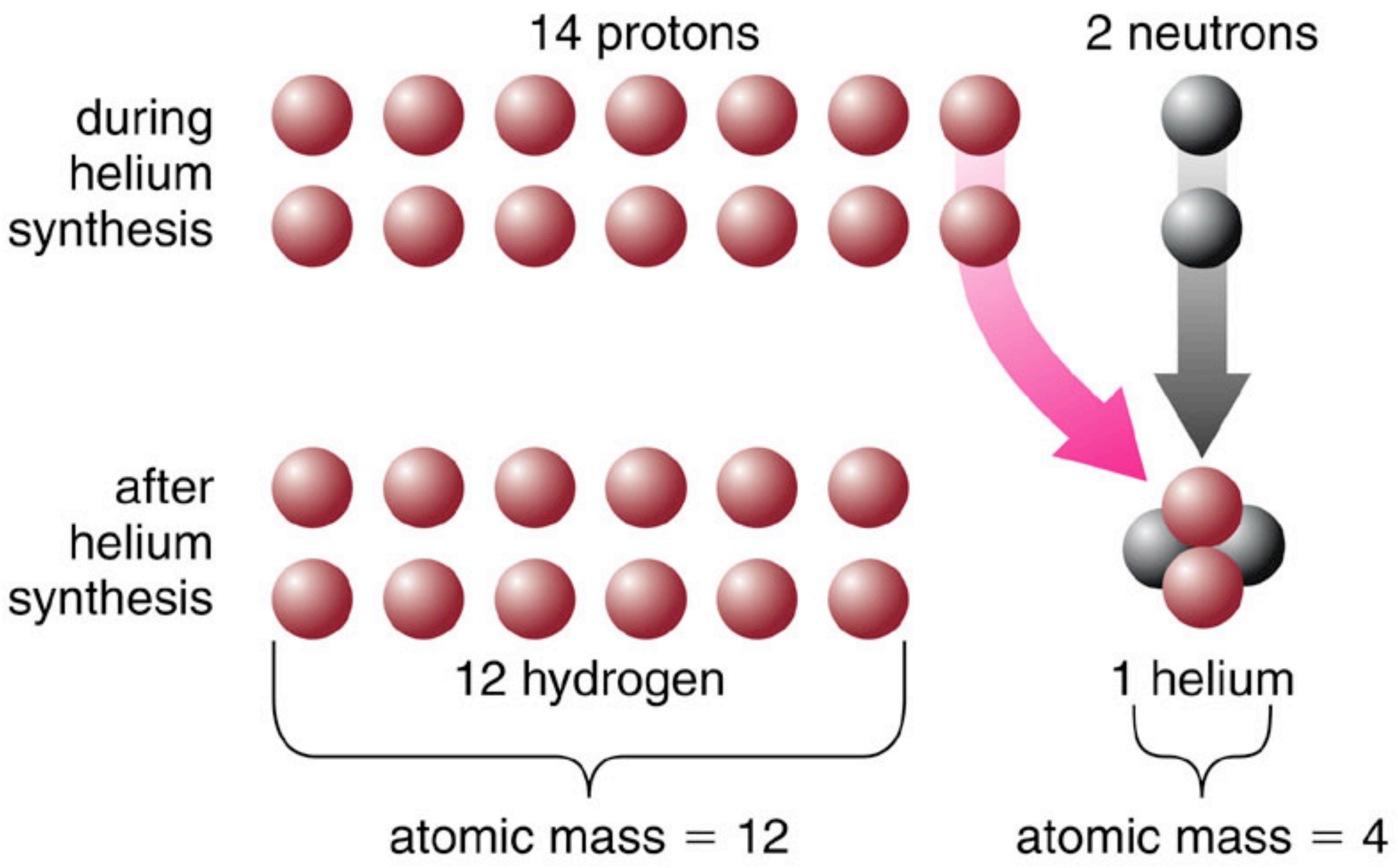
- 3/4 Hydrogen
- 1/4 Helium
- Traces of
  - deuterium
  - tritium
  - helium 3
  - lithium
  - beryllium

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



Beryllium decays into lithium after a few months.

To first order, BBN is just book-keeping: most of the available neutrons wind up in helium



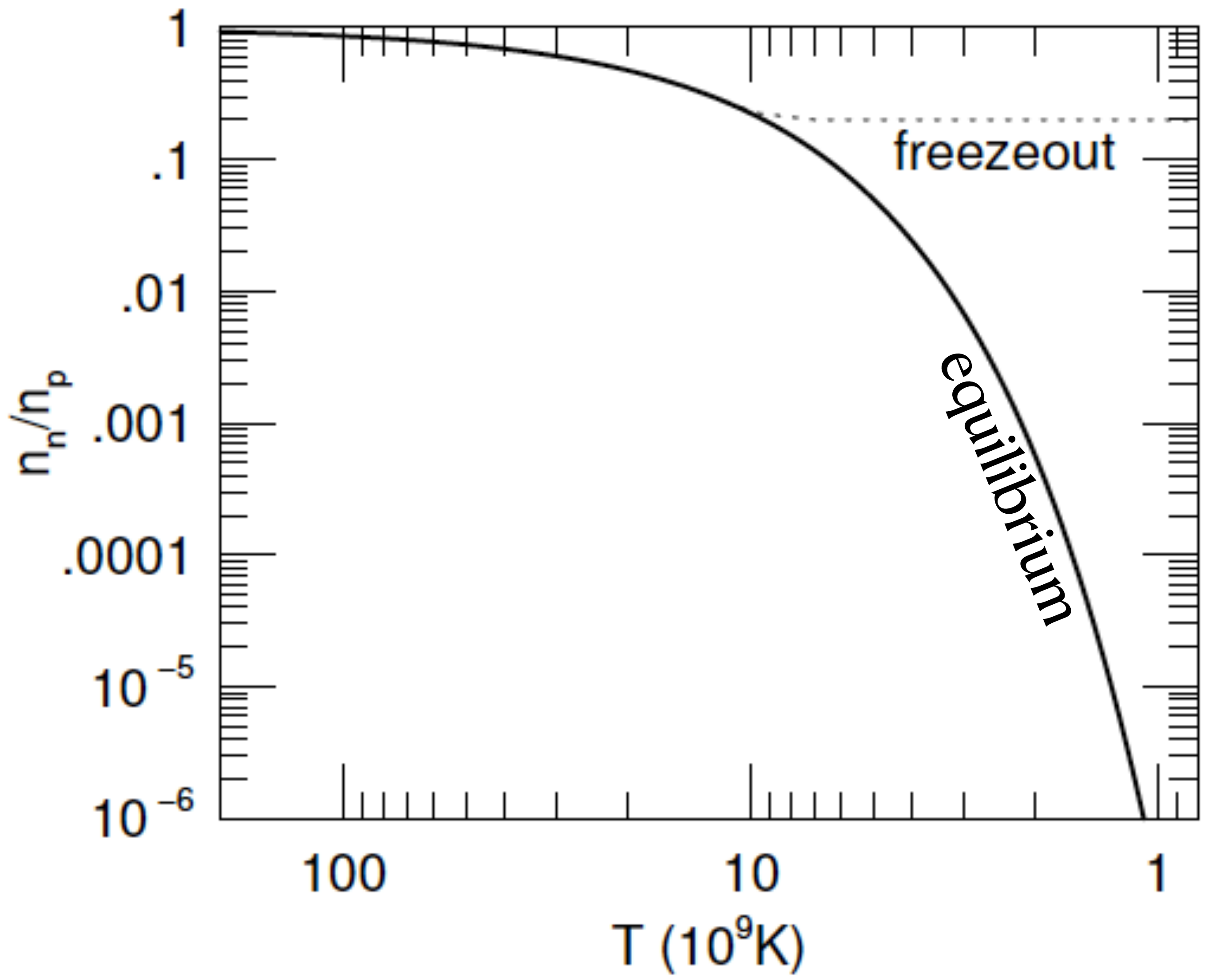
Big Bang theory prediction: 3/4 H, 1/4 He (by mass)

Matches observations of nearly primordial gases

There are fewer neutrons than protons at the time of BBN for several reasons…

High temperatures in the early universe mean all species start in thermal equilibrium

$$\frac{n_n}{n_p} \approx e^{-\frac{\Delta mc^2}{kT}}$$



$\Delta mc^2 = 1.29$ MeV

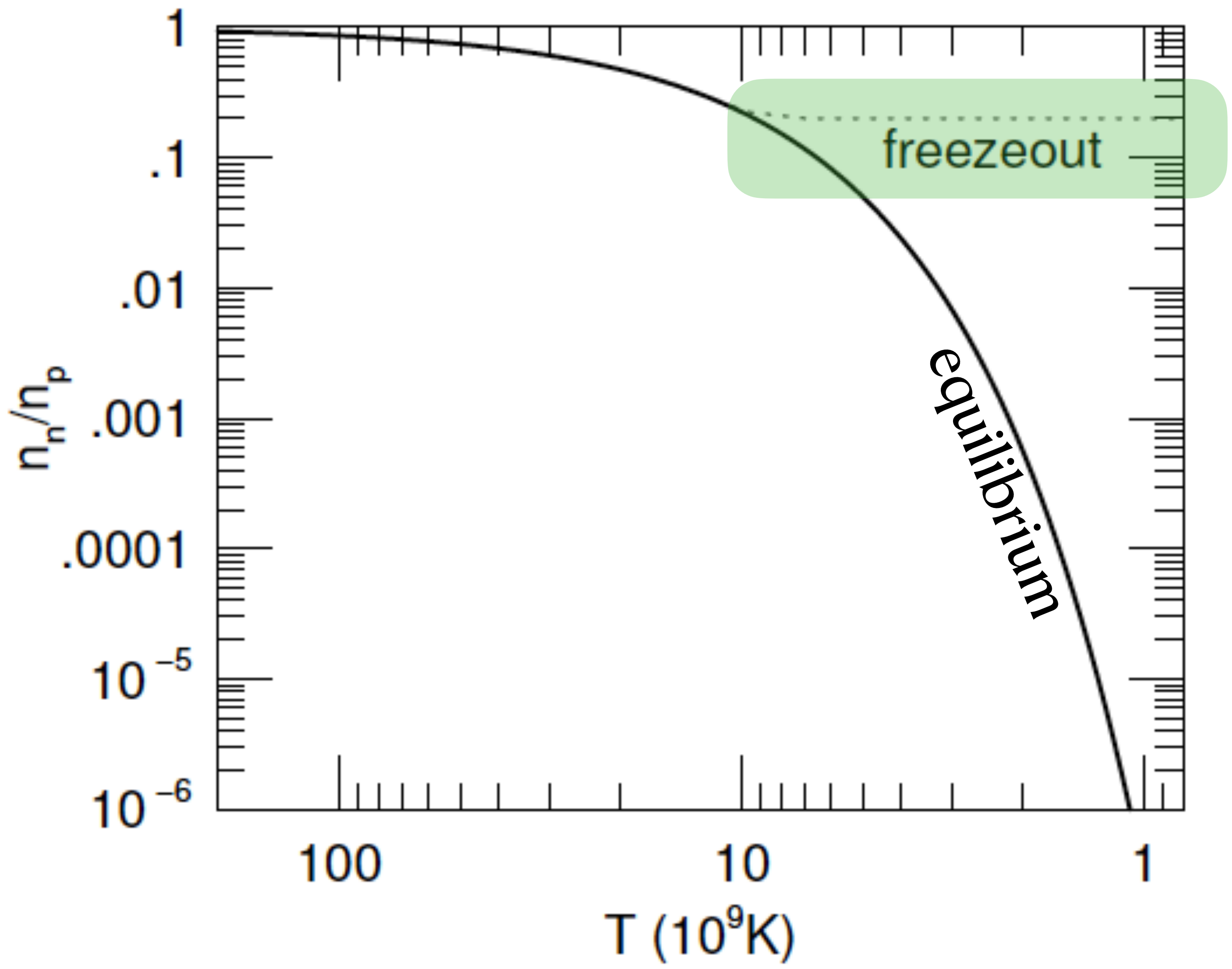
Neutrons are a little heavier than protons, so are disfavored as the universe cools

There are fewer neutrons than protons at the time of BBN for several reasons...

The neutron-proton equilibrium is mediated by the weak nuclear force.
These interactions "freeze out" when the expansion rate of the universe out-competes the interaction rate.

$$\frac{n_n}{n_p} \approx e^{-\frac{\Delta mc^2}{kT}}$$

$\Delta mc^2 = 1.29$ MeV



Freeze out occurs when

weak interaction rate $n_\nu c \sigma_W \approx H$ expansion rate

$$kT_{freeze} = 0.8 \text{ MeV}$$

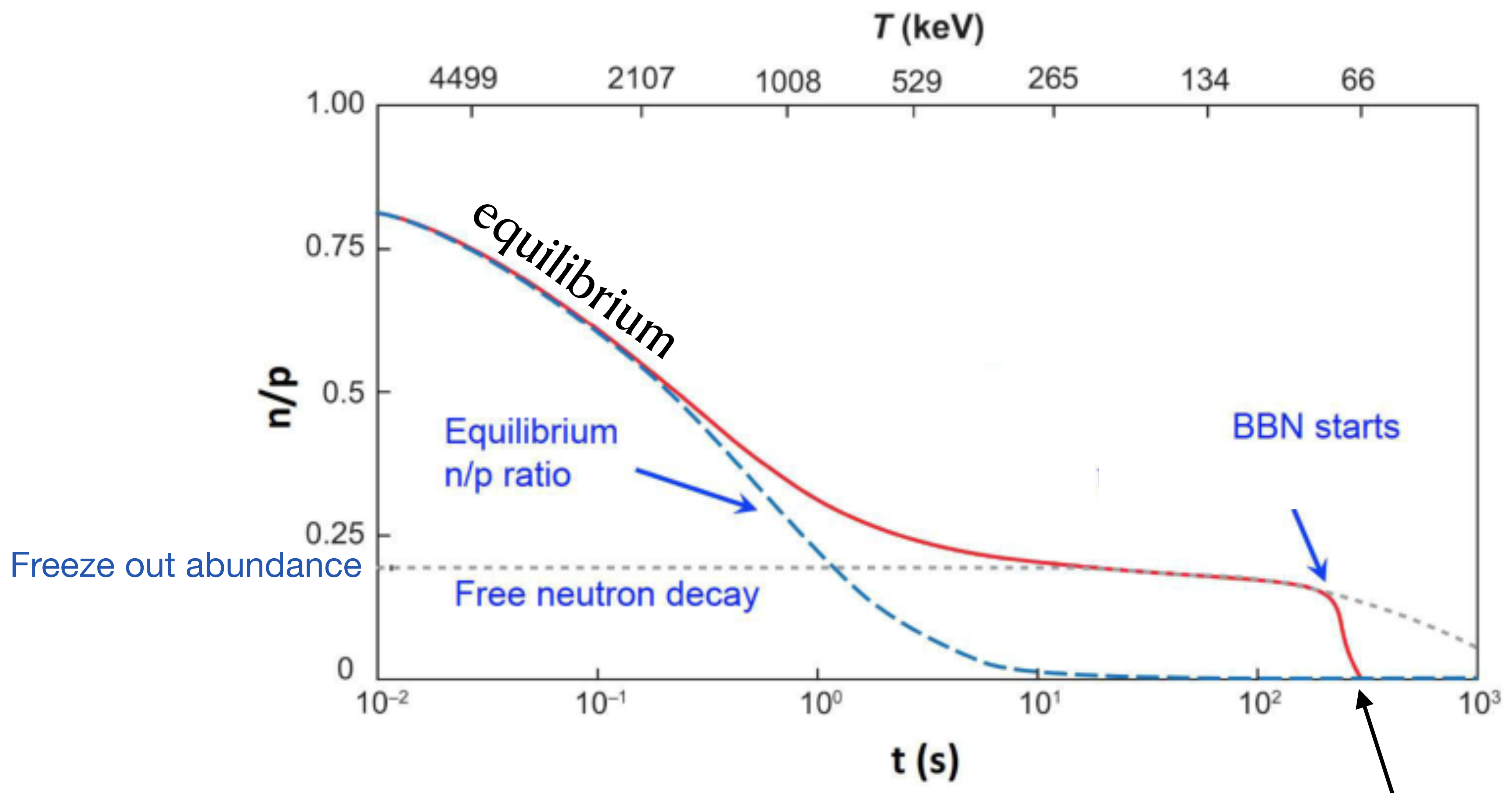
$$\frac{n_n}{n_p} \approx e^{-\frac{1.29}{0.8}} \approx 0.2$$

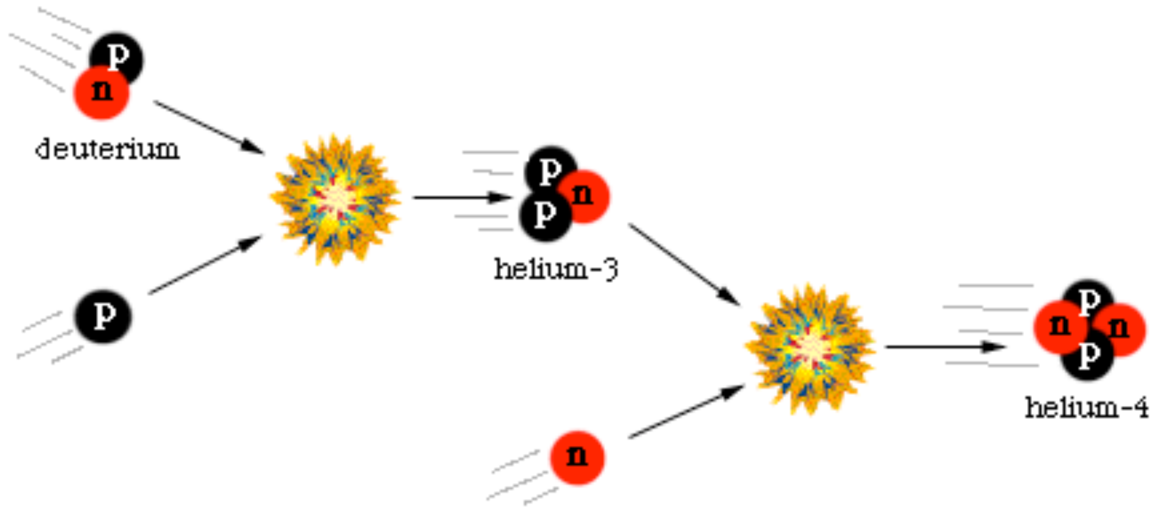
is the neutron-proton ratio after freeze out.

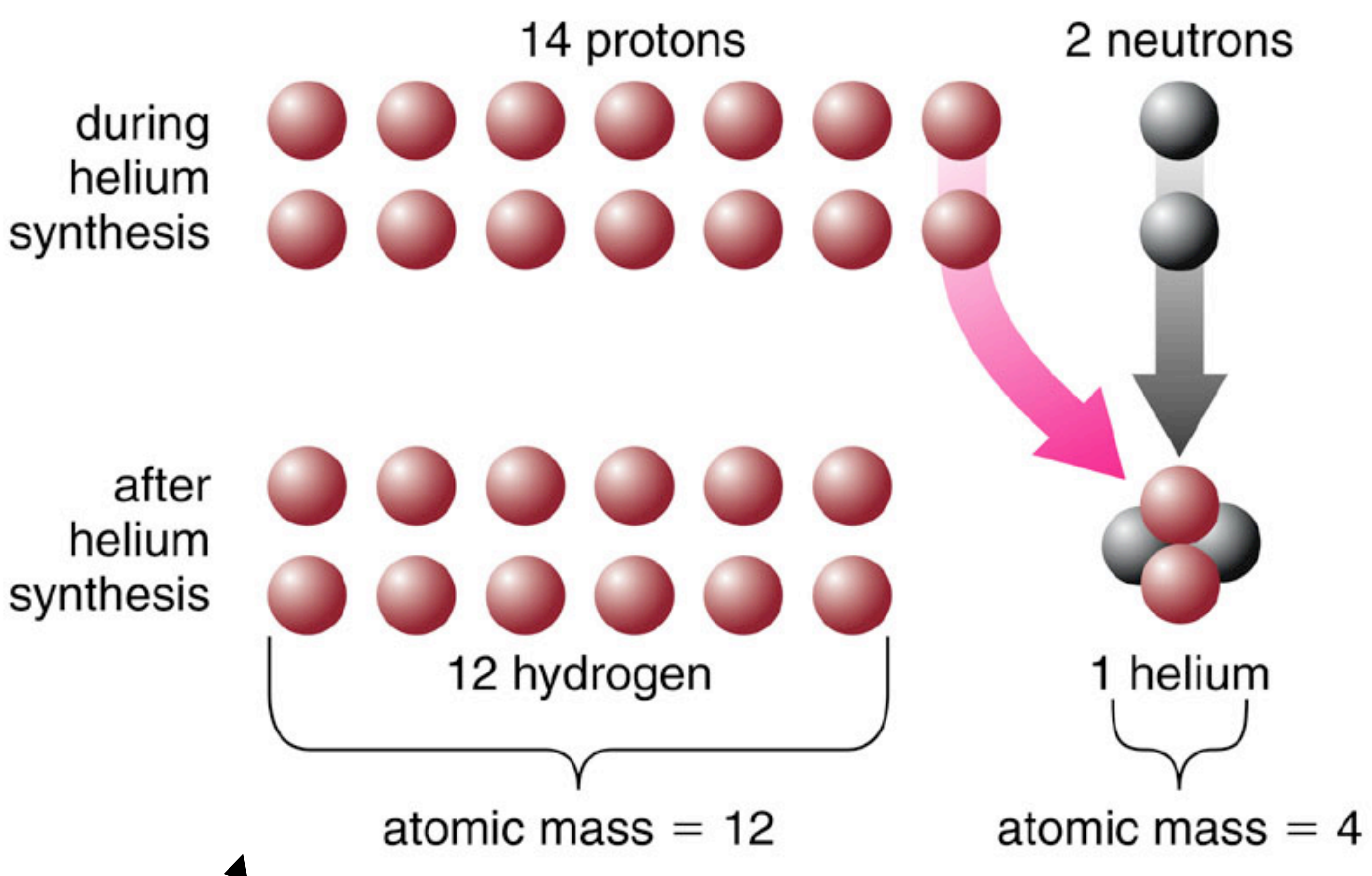
There are fewer neutrons than protons at the time of BBN for several reasons...

In addition, neutron in free space are unstable, with a half-life of $\tau_n = 611\ \mathrm{s}$ — a little over 10 minutes.

Neutrons have just started to decay when BBN happens, but the uncertainty in the half-life is important.

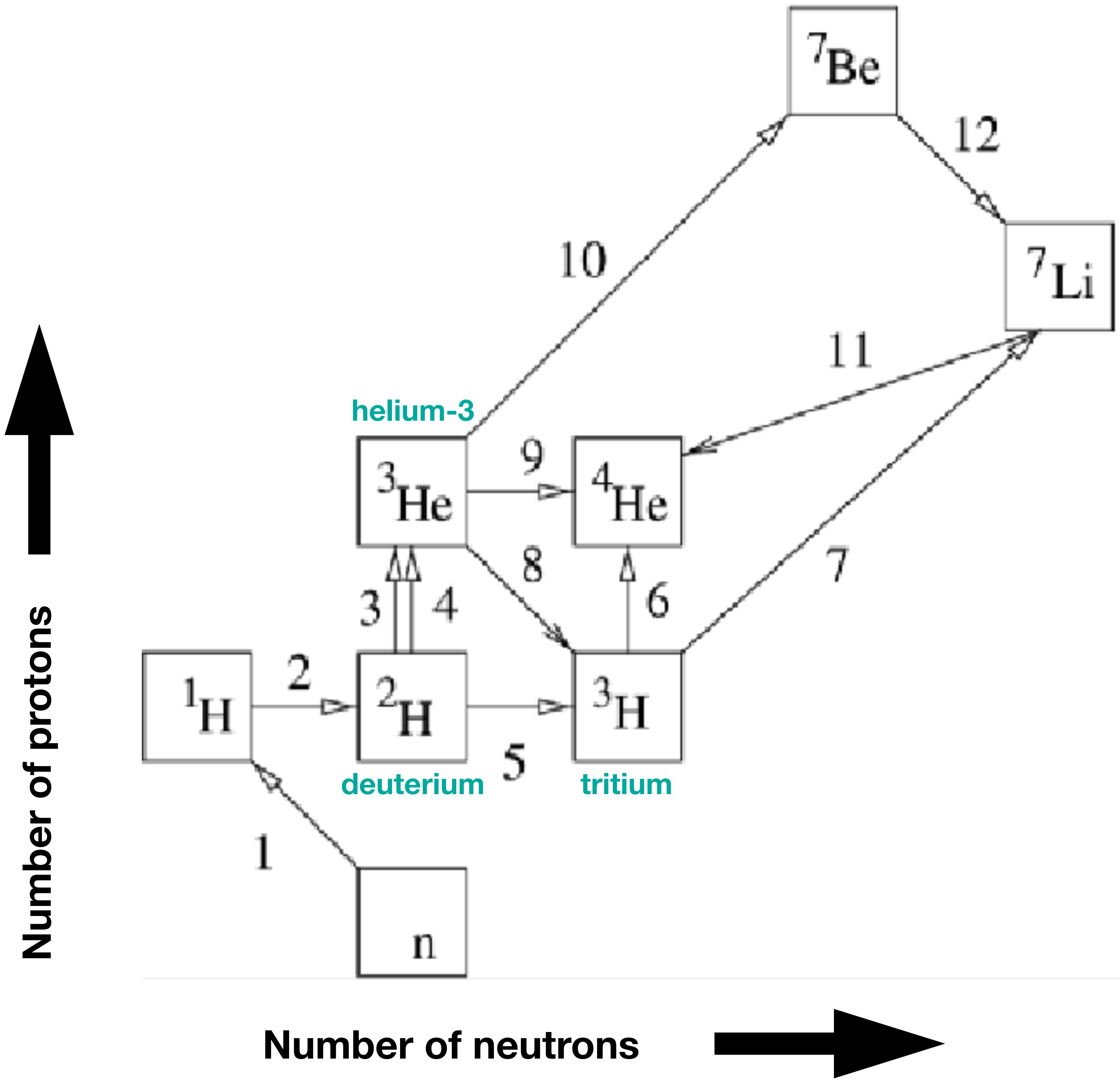






Remaining neutrons are mostly gobbled up by helium

In detail, need to keep track of all relevant nuclear reactions



1. $p \longleftrightarrow n$ — proton-neutron equilibrium
2. $p(n, \gamma)d$ — proton-neutron fusion to form deuterium
3. $d(p, \gamma)^3\mathrm{He}$ — deuterium-proton fusion to form helium 3
4. $d(d, n)^3\mathrm{He}$ — deuterium-deuterium fusion to form helium 3
5. $d(d, p)t$ — deuterium-proton fusion to form tritium
6. $t(d, n)^4\mathrm{He}$ — tritium-deuterium fusion to form helium 4
7. $t(\alpha, \gamma)^7\mathrm{Li}$ — tritium-helium fusion to form lithium
8. $^3\mathrm{He}(n, p)t$
9. $^3\mathrm{He}(d, p)^4\mathrm{He}$ — helium 3-deuterium fusion to form helium 4
10. $^3\mathrm{He}(\alpha, \gamma)^7\mathrm{Be}$ — helium 3-helium 4 fusion to form beryllium
11. $^7\mathrm{Li}(p, \alpha)^4\mathrm{He}$
12. $^7\mathrm{Be}(n, p)^7\mathrm{Li}$ — beryllium decay into lithium

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

Reaction rates depend on the temperature & number density, both of which decrease as the universe expands.
The absence of stable A = 5 & A = 8 nuclei causes a bottleneck.

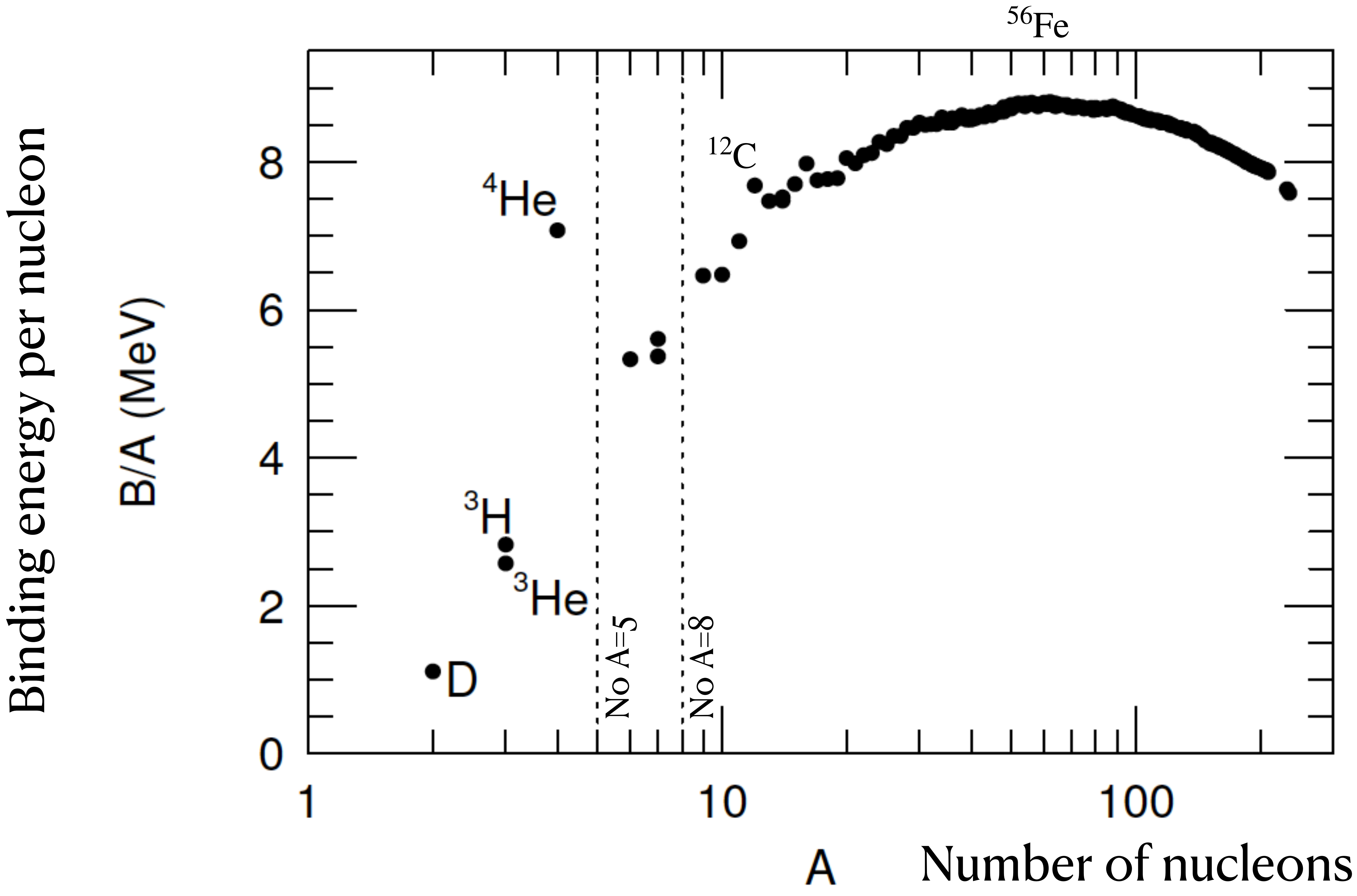


Figure 10.1: The binding energy per nucleon (B/A) as a function of the number of nucleons (protons and neutrons) in an atomic nucleus. Note the absence of nuclei at $A = 5$ and $A = 8$.

no stable mass 5 or 8

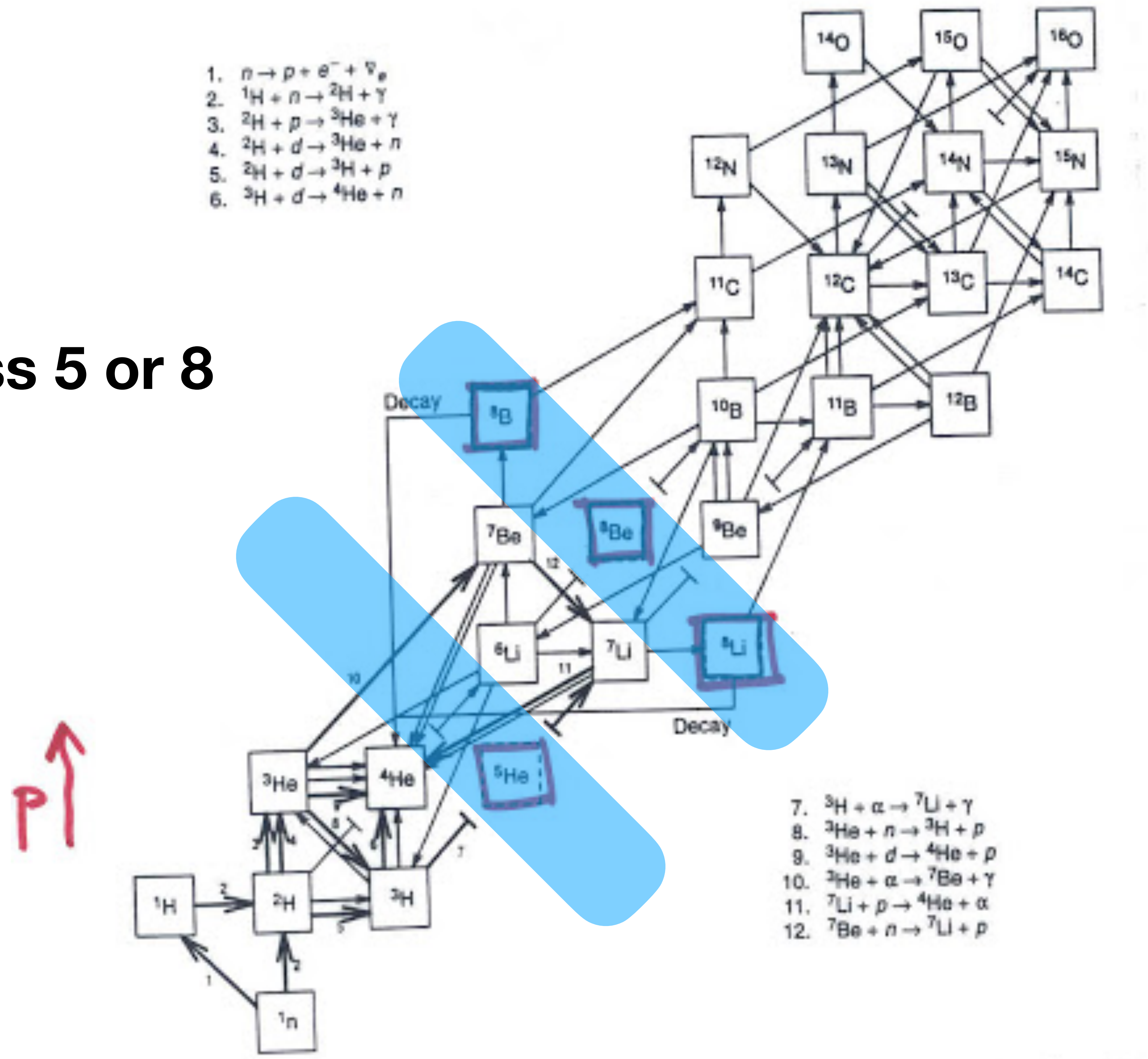


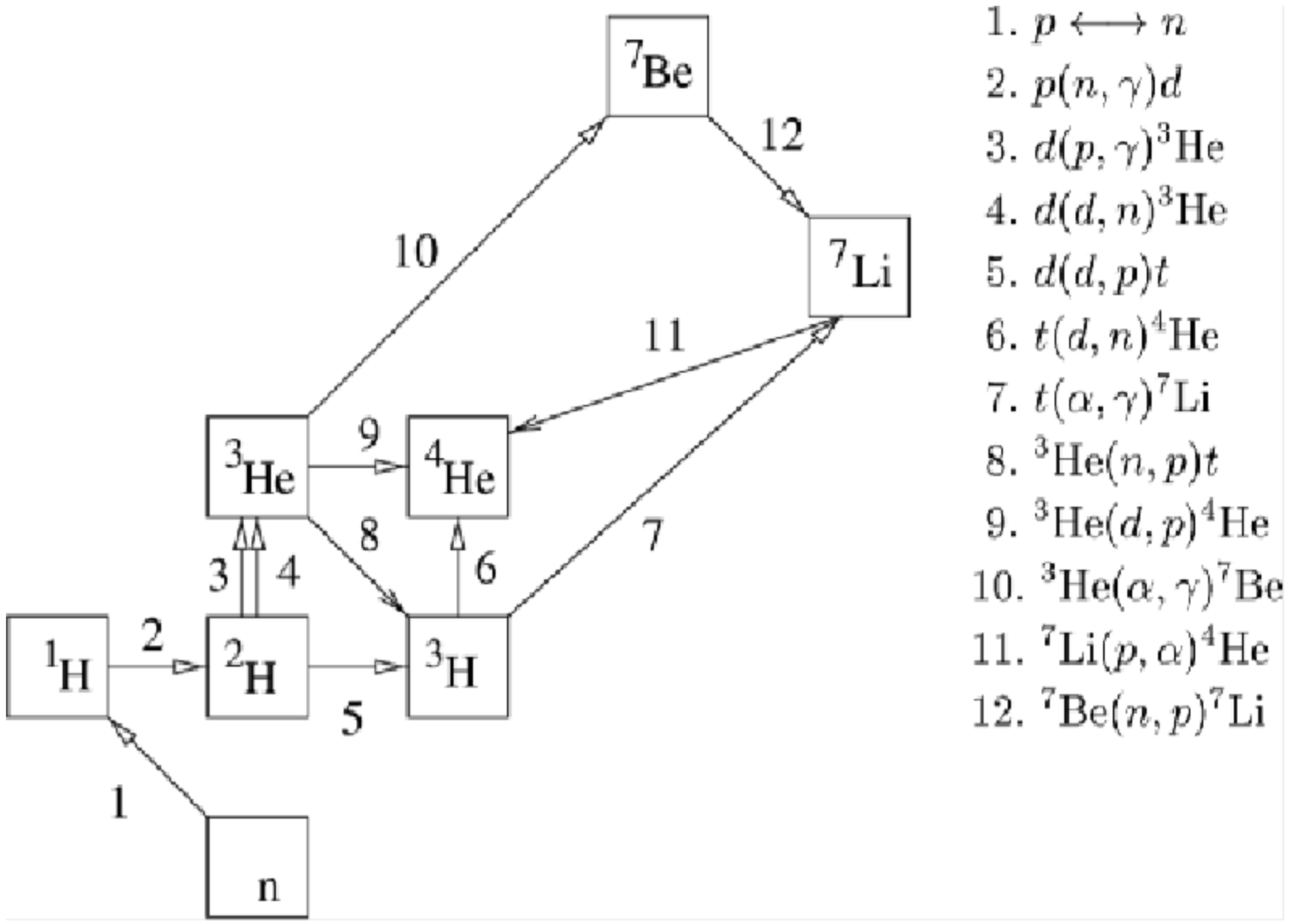
Fig. 2. The nuclear reaction network used for big-bang nucleosynthesis; the most important reactions are numbered and have bold arrows. The broken boxes for mass 5 and 8 indicate that all nuclides of this mass are very unstable.

n

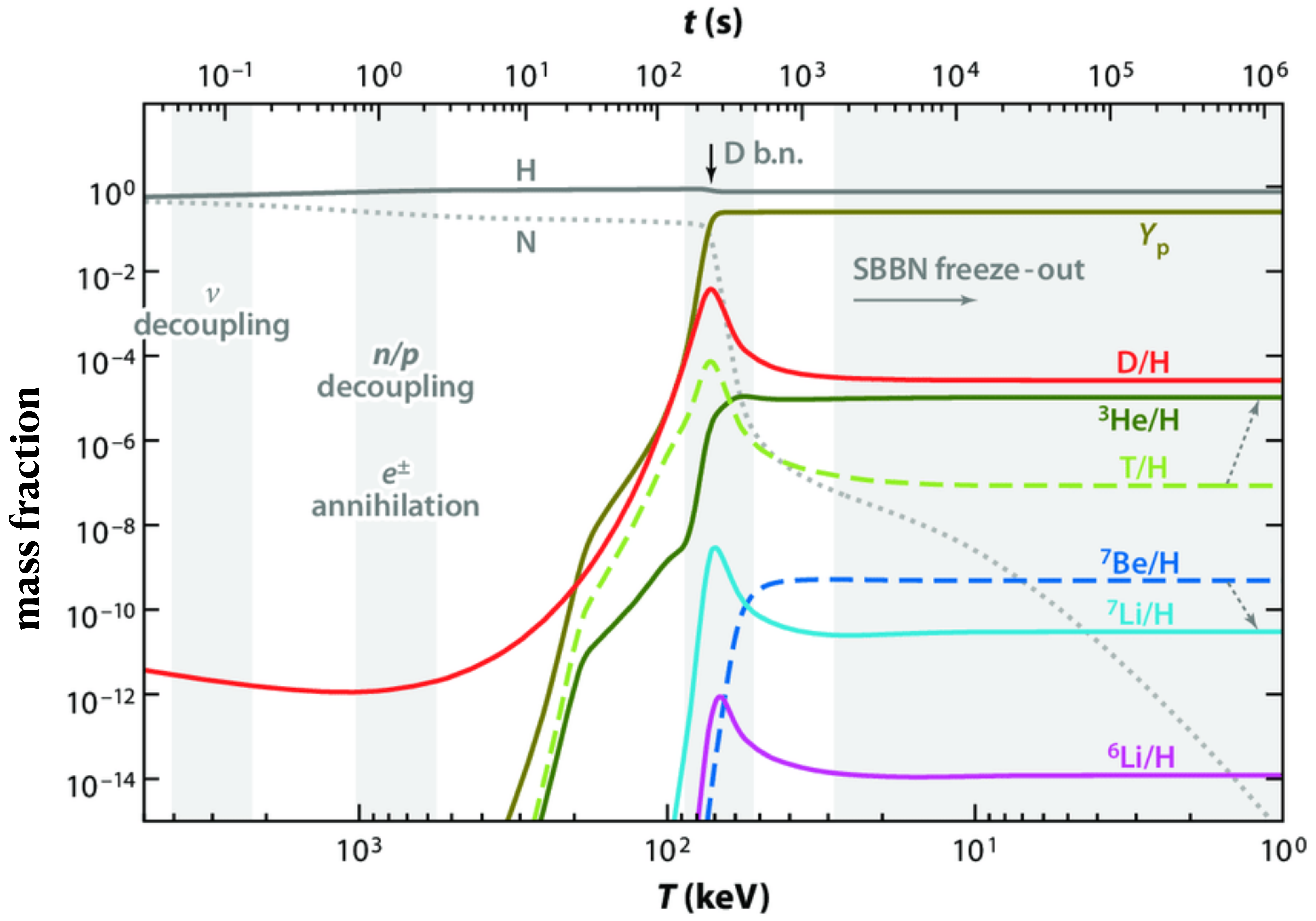
BBN restricted to the light elements by mass 5 & 8 bottlenecks.

Some stars skip over the mass bottleneck via the triple alpha reaction: $3\ {}^4_2He \rightarrow {}^{12}_6C^*$

Big Bang Nucleosynthesis occurs during the radiation dominated era



$$a(t) \propto t^{1/2}$$



Solve nuclear reaction chain as the universe expands and cools.
Must also keep track of neutron decay!

$$T(a)\ ;\ \rho_m(a)\ ;\ \rho_r(a)$$

$$\tau_N = 10.2 \text{ minutes}$$