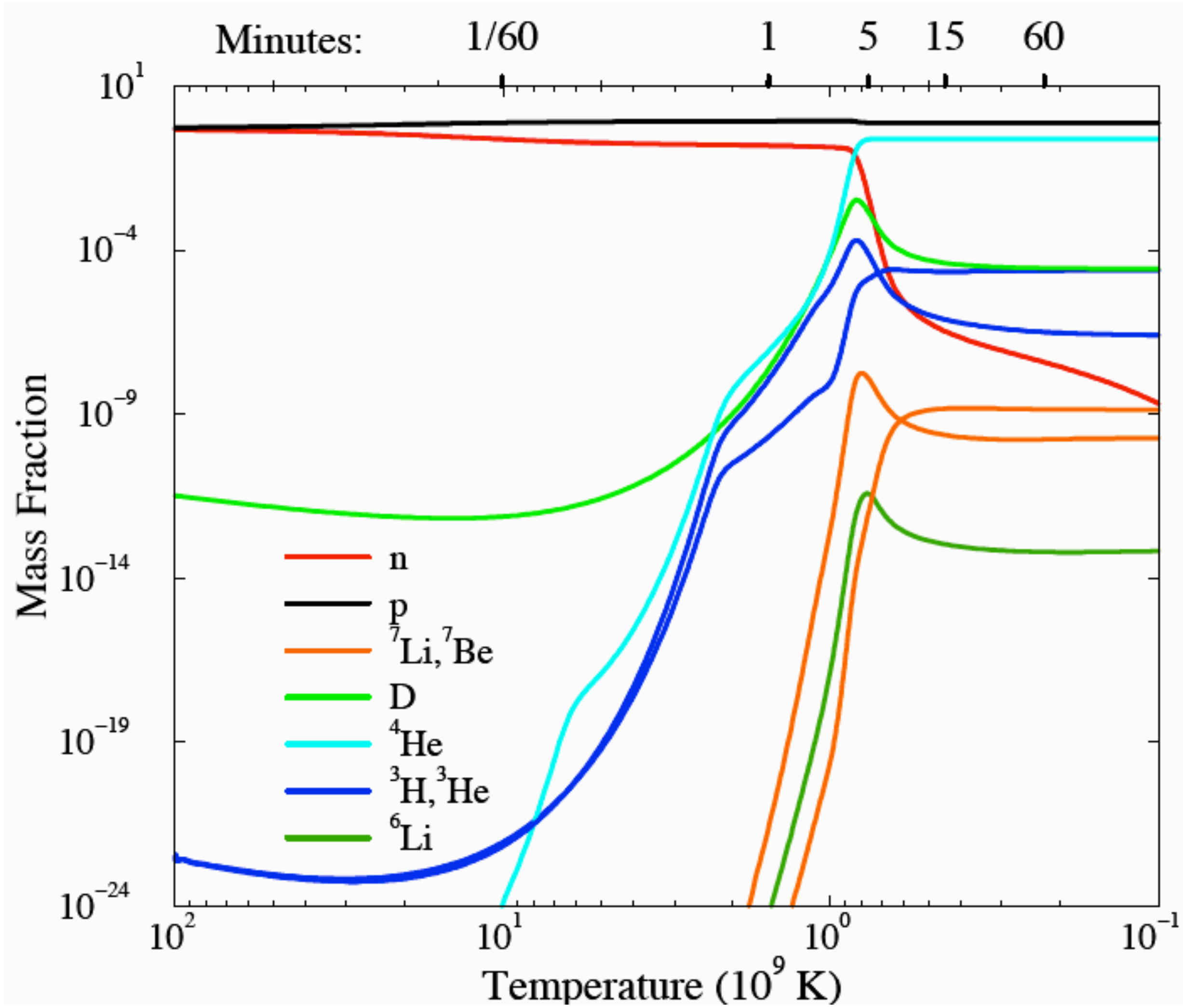
The Big Bang Nucleosynthesis (BBNS)



Into the Nucleosynthesis Era

- In the pre-nucleosynthesis universe, the radiation produces pairs of electrons and positrons, as well as protons and antiprotons, neutrons and antineutrons, and they can annihilate; *e+ e-* reactions produce electron neutrinos (ν_e) and antineutrinos:

$$e^- + e^+ \longleftrightarrow \nu_e + \nu_e$$

$$e^- + p \longleftrightarrow n + \nu_e,\ \nu_e + p \longleftrightarrow n + e^+$$

$$n \longleftrightarrow p + e^- + \nu_e$$

$$e^- + e^+ \longleftrightarrow \gamma + \gamma$$

- This occurs until the temperature drops to $T \sim 10^{10}$ K, t ~ 1 sec
- In equilibrium there will slightly more protons than neutrons since the neutron mass is slightly (1.293 MeV) larger
- This leads to an asymmetry between protons and neutrons …

Asymmetry in Neutron / Proton Ratio

Mass difference between *n* and *p* causes an asymmetry via reactions:

$$n + \nu_e \leftrightarrow p + e^-$$

$$n + e^+ \leftrightarrow p + \bar{\nu}_e$$

It is slightly easier (requires less energy) to produce *p* than *n*:

$$n \rightarrow p + e^- + \bar{\nu}_e$$

$$p \not\rightarrow n + e^+ + \nu_e$$

Thus, once e^+, e^- annihilation occurs only neutrons can decay

We can calculate the equilibrium ratio of *n* to *p* via the Boltzmann equation,

$$X_n = \frac{N_n}{N_n + N_p} \sim 0.16 \exp\left(-\frac{t}{1013\text{s}}\right)$$

at T~ 10^{12} K, *n/p* = 0.985

The *n/p* ratio is "frozen" at the value it had at when T= 10^{10} K , *n/p* = 0.223, i.e., for every 1000 protons, there are 223 neutrons

Big Bang Nucleosynthesis (BBNS)

Free neutrons are unstable to beta decay, with *mean lifetime* = 886 sec, $n \rightarrow p + e^- + \nu_e$. This destroys ~ 25% of them, before they can combine with the protons

When the temperature drops to ~ 10^9 K (t=230s), neutrons and protons combine to form deuterium, and then helium:

$$n + p \leftrightarrow {}^2H + \gamma$$

$${}^2H + {}^2H \leftrightarrow {}^3He + n$$

$${}^3He + n \leftrightarrow {}^3H + p$$

$${}^3H + {}^2H \leftrightarrow {}^4He + n$$

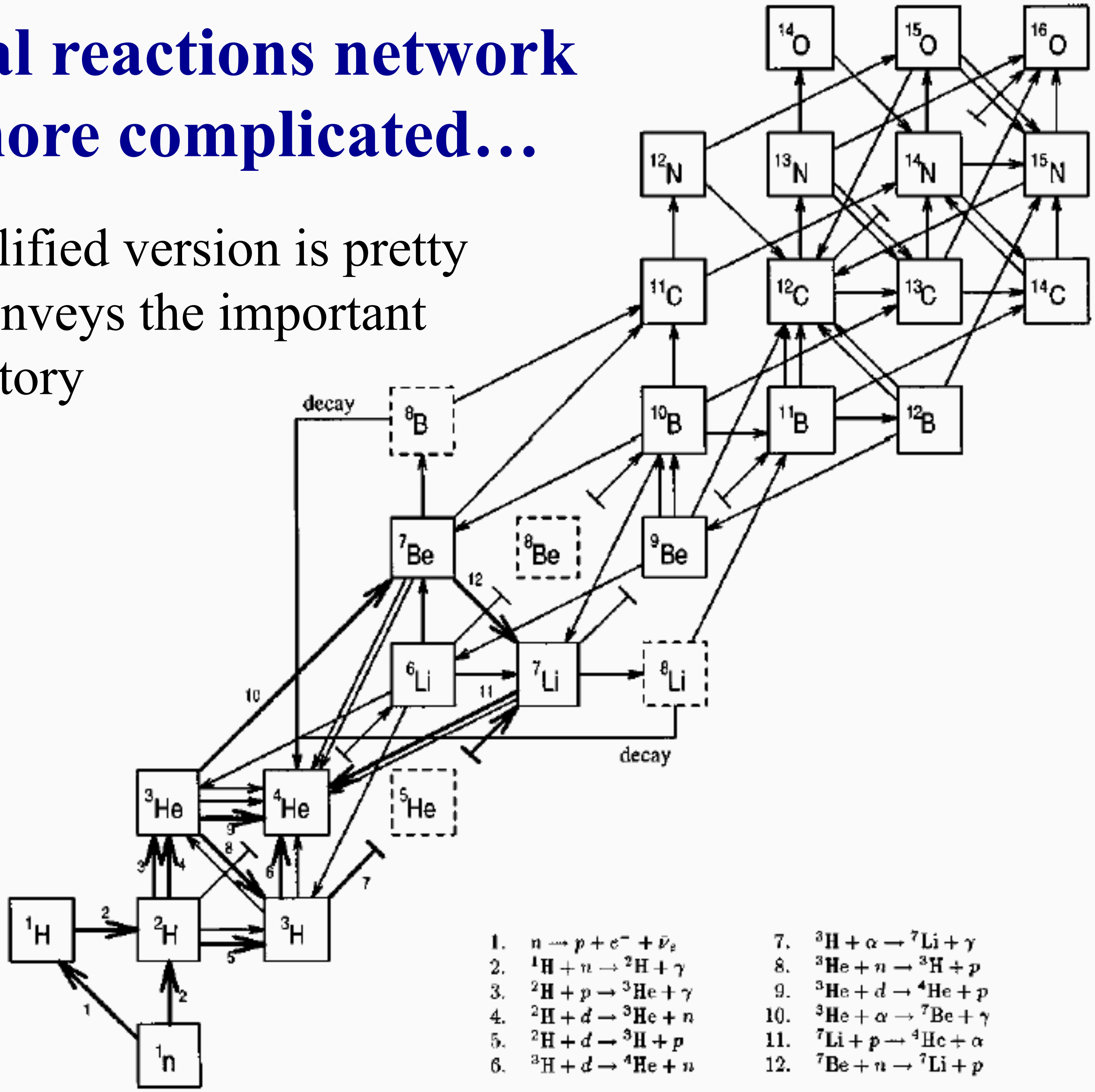
Note that these are not the same reactions as in stars (the *pp* chain)!

Photons break the newly created nuclei, but as the temperature drops, the photodissociation stops

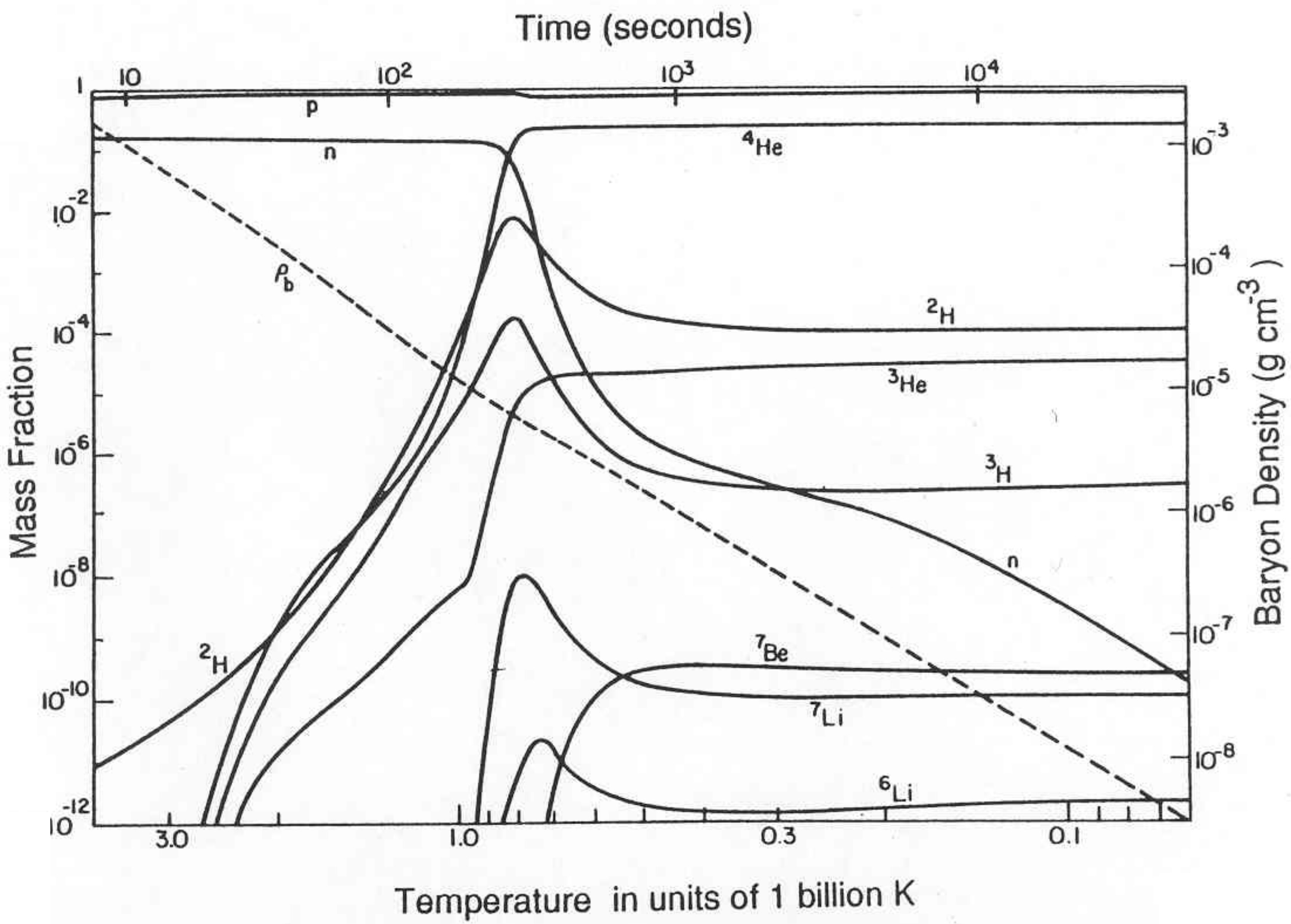
At $t \sim 10^3$ sec and T < 3×10^8 K, the density also becomes too low for fusion, and BBN ends. This is another "freeze-out", as no new nuclei are created and none are destroyed

The actual reactions network is a tad more complicated…

But the simplified version is pretty close, and conveys the important parts of the story



The Evolution of Abundances in BBNS



Big Bang Nucleosynthesis End

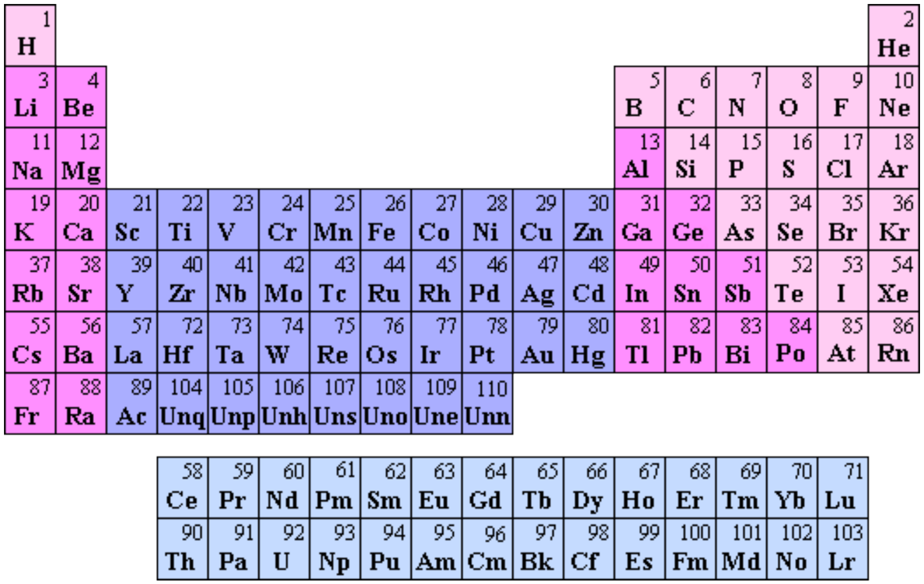
At this point *n/p* ratio has dropped to ~ 0.14. The excess protons account for about 75% of the total mass, and since essentially all neutrons are incorporated into He nuclei, the predicted primordial He abundance is ~ 25% - about as measured

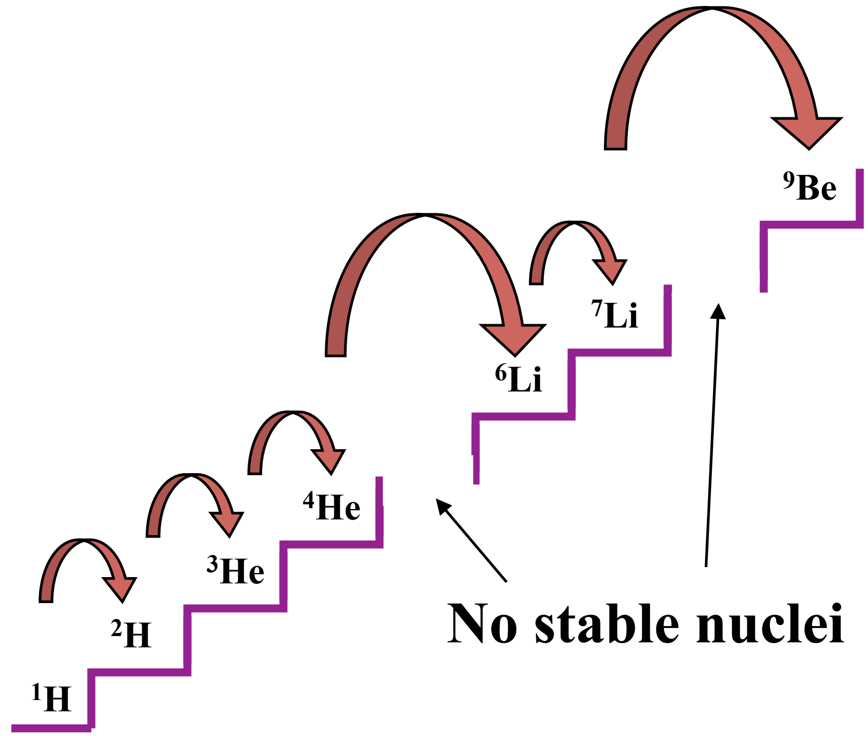
Thus neutron/proton asymmetry caused by their mass difference and the beta decay of neutrons determines primordial abundance of He and other light elements

Because all the neutrons are tied up in He, its abundance is not sensitive to the matter density. In contrast, the abundances of other elements produces in the early universe, D, ^{3}He, and ^{7}Li are dependent on the amount of baryonic matter in the universe

The universe expanded to rapidly to build up heavier elements!

Stable Mass Gaps in the Periodic Table





Since there are no stable mass-5 nuclides, combining He and tritium to get Li requires overcoming the Coulomb repulsion. So almost all of the neutrons end up in He instead!

There is another gap at mass-8, so BBN ends with Li, with only trace amounts of Be produced

BBNS Predictions

- The BBNS makes detailed predictions of the abundances of light elements: ^{2}D, ^{3}He, ^{4}He, ^{7}Li, ^{8}Be
- These are generally given as a function of the baryon to photon ratio $\eta = n_n/n_\gamma$, usually defined in units of 10^{10}, and directly related to the baryon density Ω_b: $\eta_{10} = 10^{10}(n_n/n_\gamma) = 274\ \Omega_b h^2$
- As the universe evolves η is preserved, so that what we observe today should reflect the conditions in the early universe
- Comparison with observations (consistent among the different elements) gives:

$$\Omega_{baryons} h^2 = 0.021 \rightarrow 0.025$$

- This is in a spectacularly good agreement with the value from the CMB fluctuations:

$$\Omega_{baryons} h^2 = 0.024 \pm 0.001$$

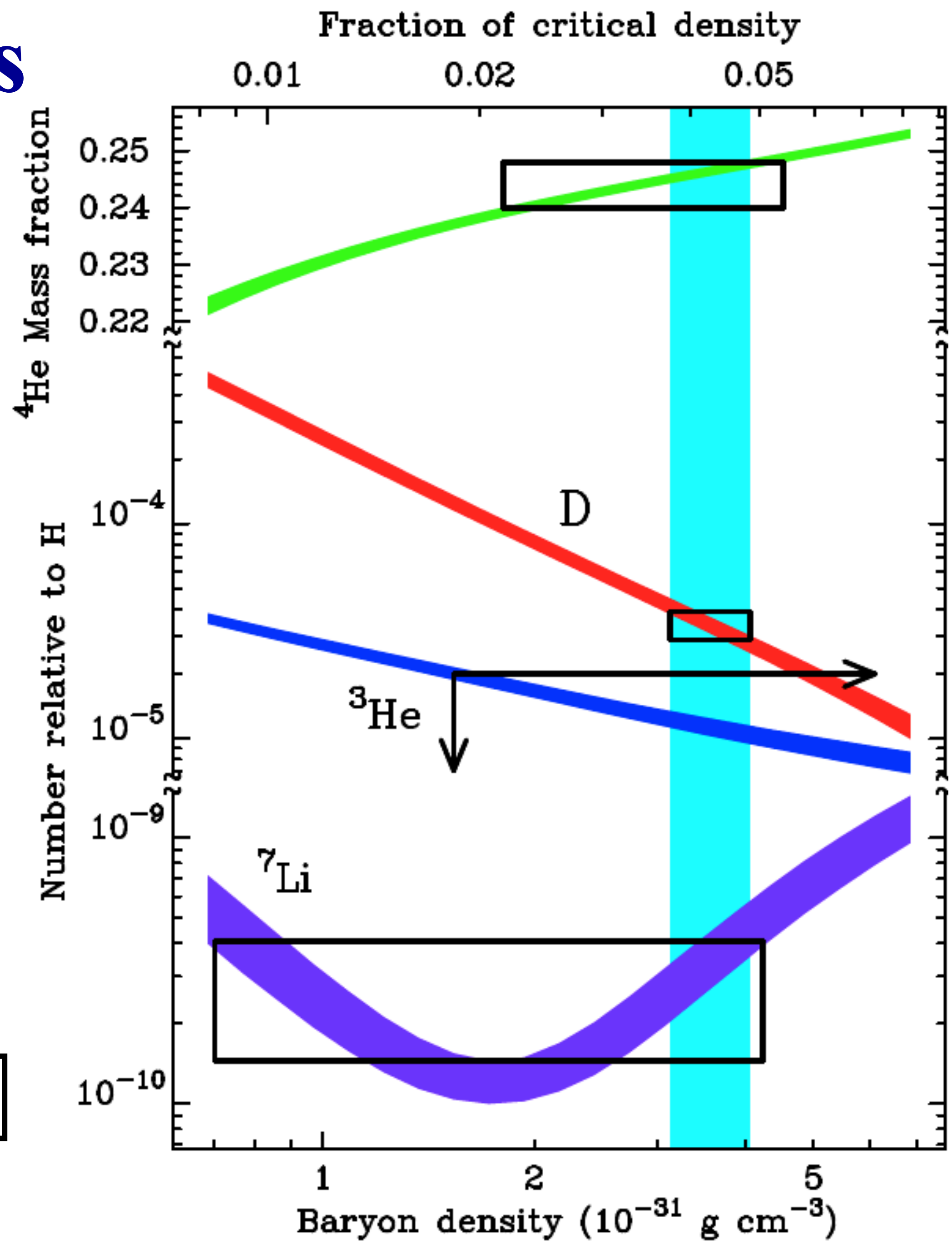
BBNS Predictions

^{4}He: the higher the density, the more of it is made ➔

^{2}D, ^{3}He: easily burned into ^{4}He, so abundances are lower at higher densities ➔

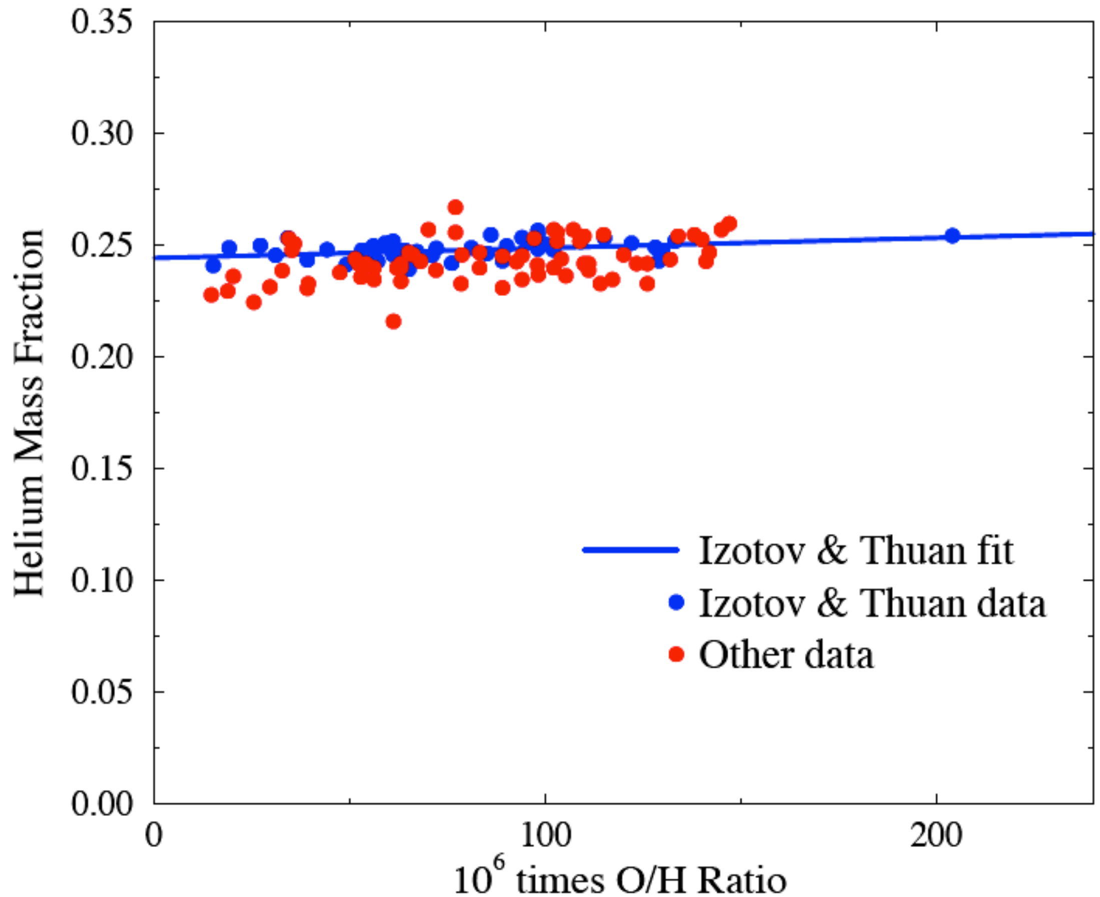
^{7}Li: … complicated ➔

Boxes indicate observed values



Helium-4 Measurements

- He is also produced in stars, but this "secondary" abundance is expected to correlate with abundances of other nucleosynthetic products, e.g., oxygen



- Observe ^{4}He from recombination lines in extragalactic HII regions in low-metallicity starforming galaxies

- The intercept at the zero oxygen abundance should represent the primordial (BBNS) value
- The result is: $\mathbf{Y_{BBNS} = 0.238 \pm 0.005}$

Deuterium Measurements

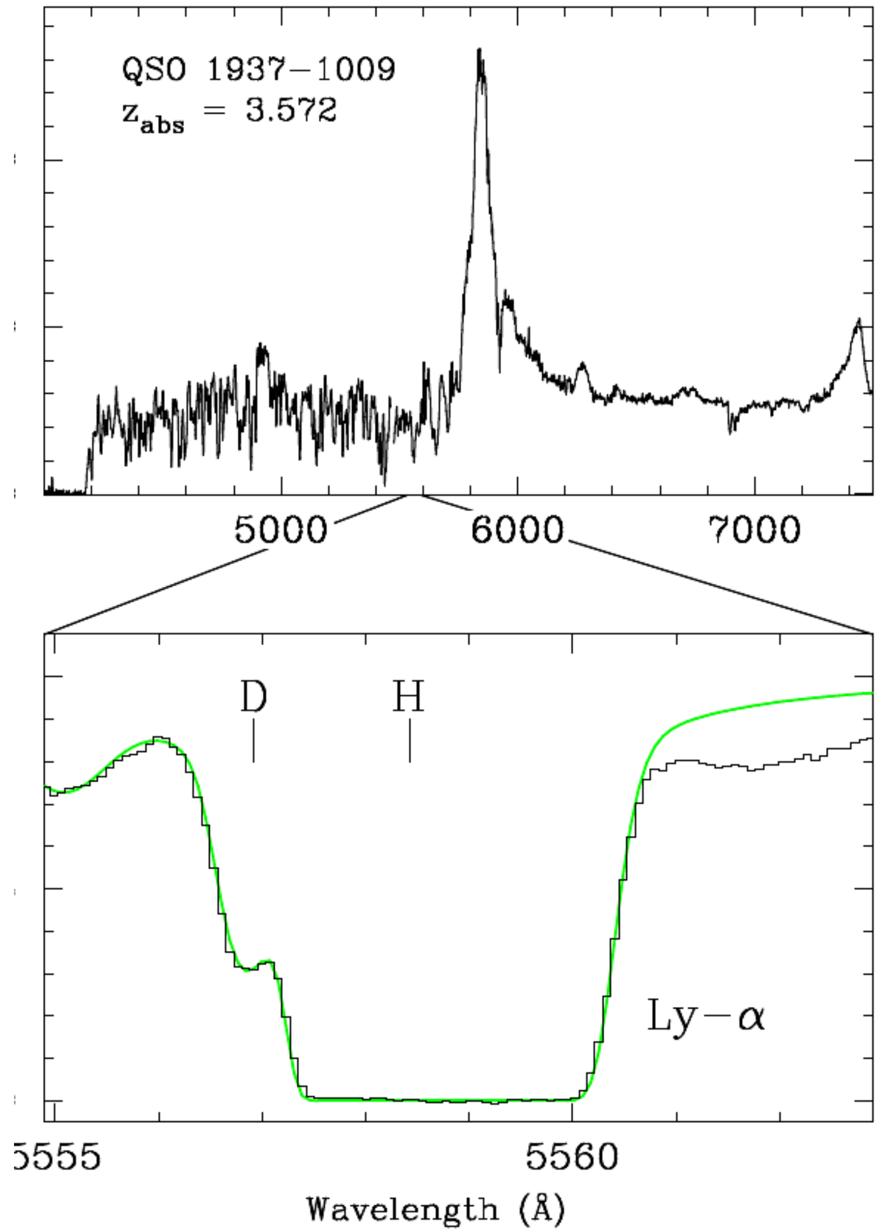
Deuterium is easily destroyed in stars, and there is no known astrophysical process where it can be created in large amounts after the BBNS

Thus, we need to measure it in a "pristine" environment, e.g., in QSO absorption line systems

It is a tricky measurement and it requires high resolution spectra from 8-10 m class telescopes

The result is:

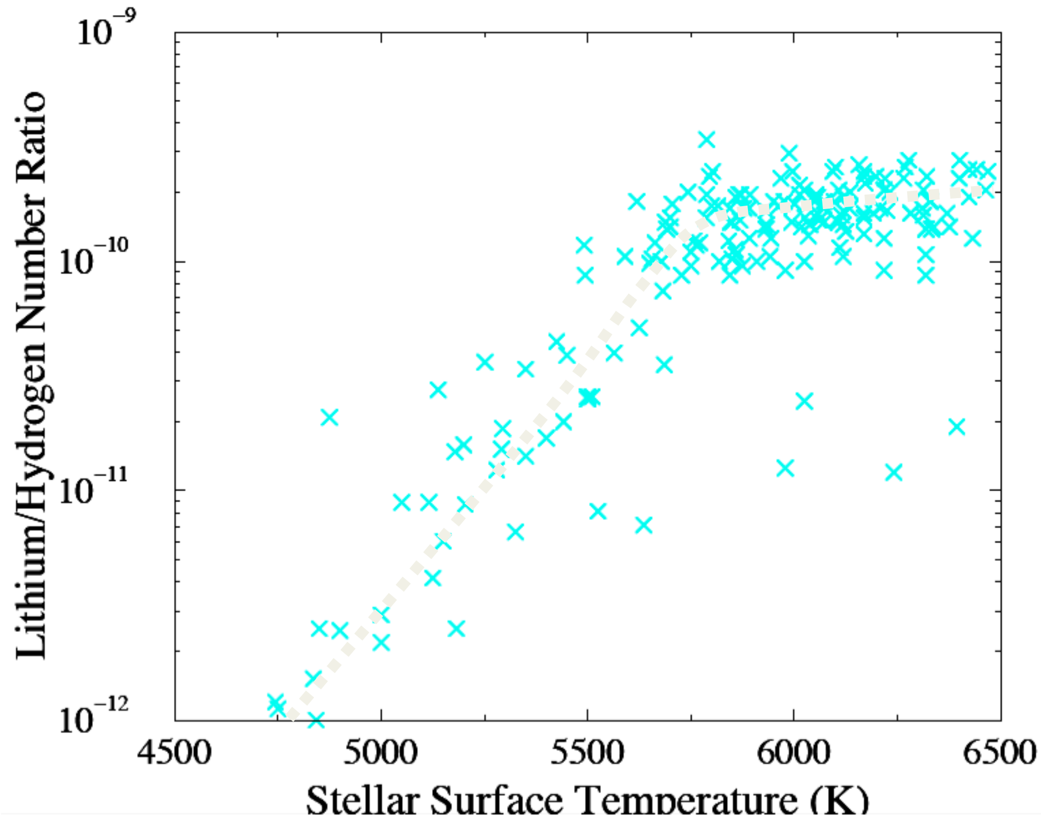
$$\frac{D}{H} = 2.74 \times 10^{-5}$$



Lithium Measurements

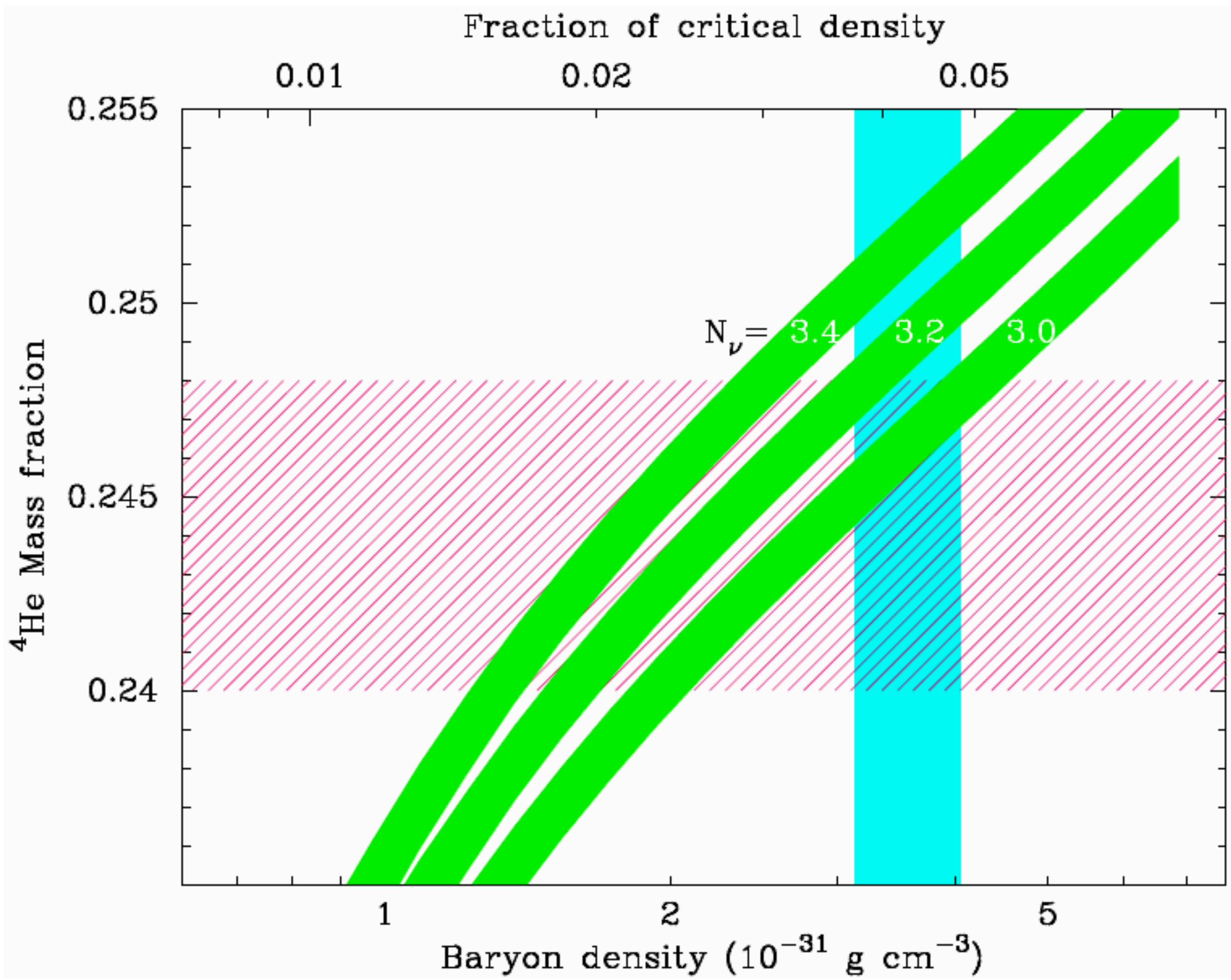
- Like D, ^{7}Li burns in stars at a relatively low temperature, and is easily destroyed. However it is also difficult for stars to create new ^{7}Li or to return any newly synthesized ^{7}Li to the ISM
- Observed in absorption in the atmospheres of cool, metal-poor, Population II halo stars

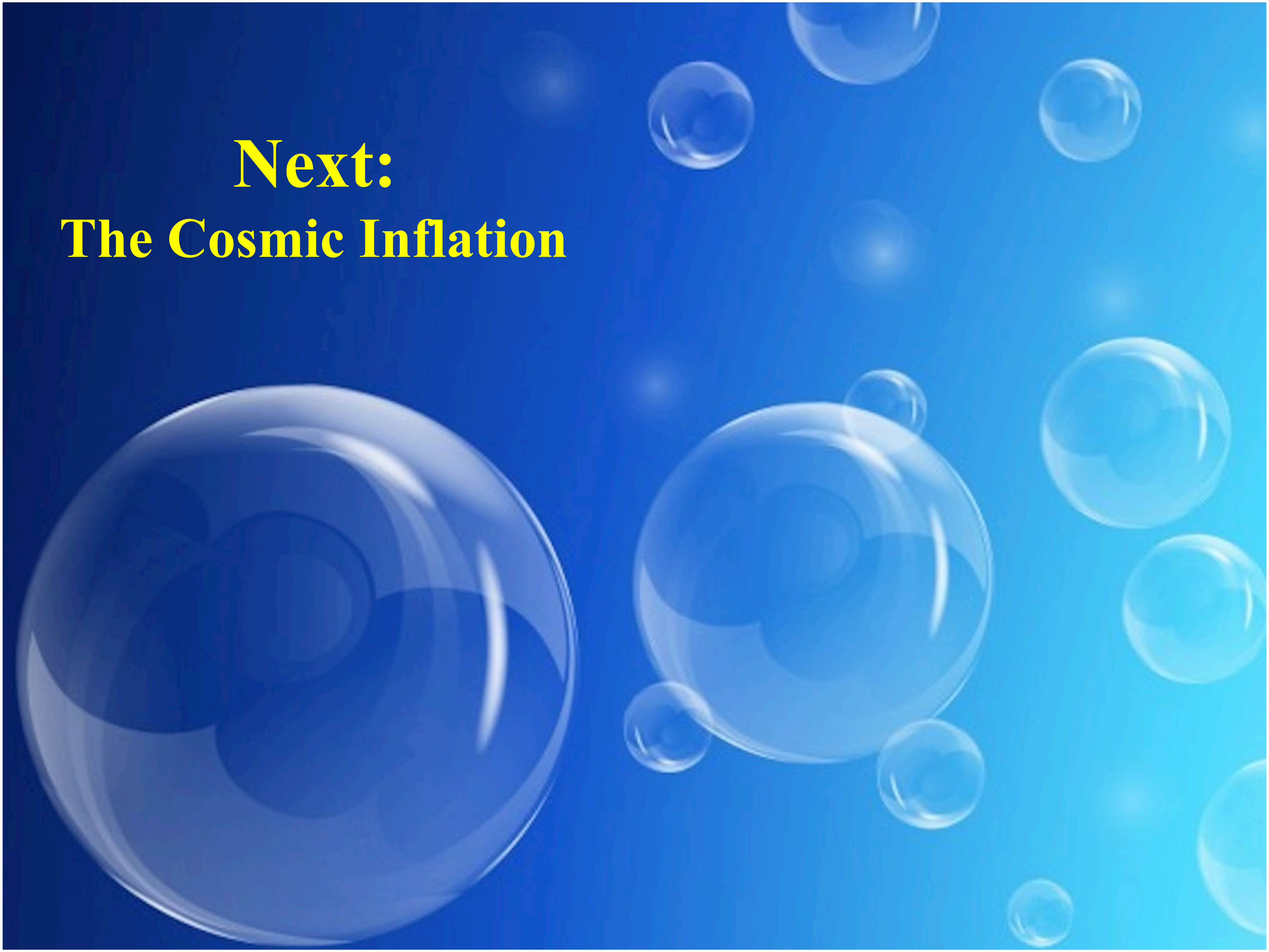
- We expect a plateau in ^{7}Li in low metallicity environments
- There are observational uncertainties, and model dependencies in stellar atmospheres



BBNS and Particle Physics

BBNS predictions also depend on the number of lepton (neutrino) families. Indeed, only 3 are allowed:

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