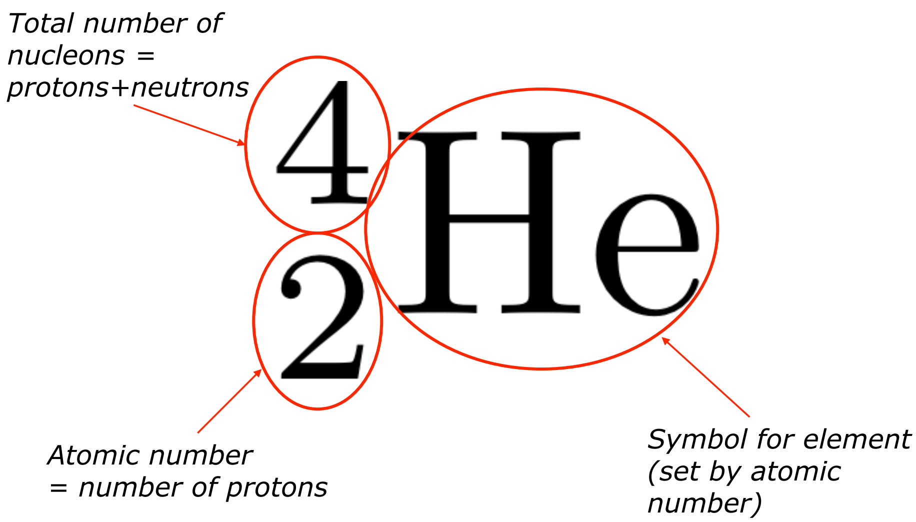
## Class 20 : Primordial nucleosynthesis

- This class
  - The basics of primordial nucleosynthesis
  - Constraints on the baryon density
  - Constraints on the number of neutrino species

## I : The "CMB Barrier"

- "Seeing is believing". But it is impossible to directly observe any e/m process from before recombination… the CMB is the edge of an impenetrable fog-bank.
- How can we proceed?

## Notation…




## II : Before nucleosynthesis…

- At the end of the lepton epoch (t=10s)…
  - T~3x10⁹K
  - Mass difference leads to excess of protons over neutrons

$$\frac{n_n}{n_p} = \frac{1}{5}$$

  - High-energy photons prevent deuterium formation

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

  - Why is deuterium destroyed even when the typical photon energy is below the binding energy of deuterium?

# III : The onset of nucleosythesis

- At t≈340s, T≈6x10$^8$K…
  - Universe cool enough for deuterium to survive.
  - During this time, some neutrons have decayed ($t_{1/2}$=614s for a free neutron)

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

  - Thus, neutron/proton ratio is now even smaller…

$$\frac{n_n}{n_p} \approx \frac{1}{7}$$

  - From this point on, nuclear reactions proceed fairly quickly…

- The nuclear reactions…
  - Actually quite a complex network of nuclear reactions. But the main ones are…

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

$${}^2H + p \rightarrow {}^3He$$
$${}^2H + {}^2H \rightarrow {}^3He + p$$
$${}^3He + {}^2H \rightarrow {}^4He + p$$

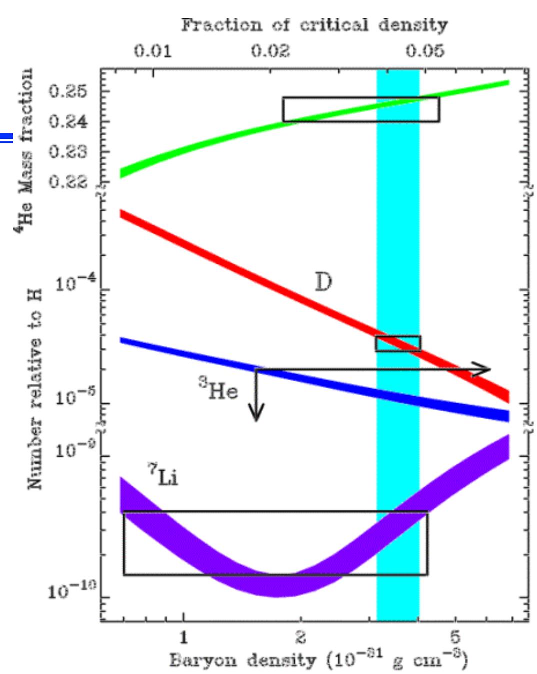
$${}^4He + {}^3H \rightarrow {}^7Li + \gamma$$

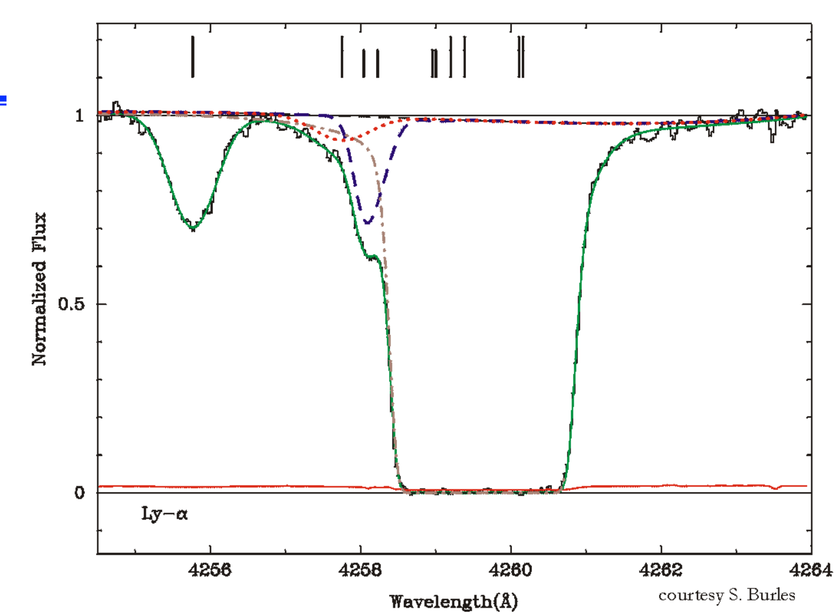
  - To a first approximation, all of the neutrons are locked up into Helium-4… thus the amount of He-4 is a direct consequence of the neutron:proton ratio.

# IV : Nucleosynthesis as a diagnostic tool

- Primordial nucleosynthesis is a competition…
  - Nuclear reactions are trying to lock the neutrons into Helium-4 (with Deuterium, Helium-3, Lithium-7 as intermediate products and by-products)
  - In the meantime…
    - Neutrons are decaying (half life 614s)
    - Universe is cooling
    - Density is dropping

  } *Reactions are slowing*
- The final products depend upon three factors
  - The correctness of the homogeneity assumption
  - The baryon density
  - The expansion rate (i.e. "H" at this time)… neutrinos!






| Parameter | Symbol | Value |
|---|---|---|
| Hubble parameter | $h$ | $0.72 \pm 0.03$ |
| Total matter density | $\Omega_{\rm m}$ | $\Omega_{\rm m}h^2 = 0.133 \pm 0.006$ |
| Baryon density | $\Omega_{\rm b}$ | $\Omega_{\rm b}h^2 = 0.0227 \pm 0.0006$ |
| Cosmological constant | $\Omega_\Lambda$ | $\Omega_\Lambda = 0.74 \pm 0.03$ |
| Radiation density | $\Omega_{\rm r}$ | $\Omega_{\rm r}h^2 = 2.47 \times 10^{-5}$ |
| Neutrino density | $\Omega_\nu$ | See Sec. 1.1.2 |
| Density perturbation amplitude | $\Delta^2_{\mathcal{R}}(k = 0.002\,{\rm Mpc})$ | $(2.41 \pm 0.11) \times 10^{-9}$ |
| Density perturbation spectral index | $n$ | $n = 0.963^{+0.014}_{-0.015}$ |
| Tensor to scalar ratio | $r$ | $r < 0.43$ (95% conf.) |
| Ionization optical depth | $\tau$ | $\tau = 0.087 \pm 0.017$ |
| Bias parameter | $b$ | See Sec. 1.3.4 |

*Lahav & Liddle (2010)*
*ArXive:1002.3488*