Neutrinos and the early universe

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Big Bang Nucleosynthesis

- Big Bang Nucleosynthesis (BBN) occurs when the temperature of the universe drops low enough to allow protons and neutrons to enter bound states ($\sim$ 1 MeV, starting around 10 s after the Big Bang)
- At temperatures above 0.7 MeV, the weak interaction is fast in comparison to the universe's expansion rate.
- At that point, the forward and backward reaction rates of proton to neutron conversion rate are roughly equal.

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

- As the temperature falls, the conversion of neutrons to protons is much slower than the proton to neutron conversion rate.

BBN and Neutrinos

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

- Obviously, this rate depends on the flux of electron neutrinos available!
- Flux of electron neutrinos depends on the flux of *all* neutrino flavors, given mixing.
- By the end of BBN, the proton-to-neutron ratio is fixed at around 1 to 7.
- The vast majority of the neutrons are incorporated into helium nuclei. About 1 in 10,000 are incorporated into deuterium. Very small amounts of tritium, lithium-7, lithium-8, and beryllium-7 are also produced.

Exotic particles and BBN

$$\frac{1}{R}\frac{dR}{dt} \approx \pm \left(\frac{8\pi G}{3}\rho\right)^{1/2} \quad (1)$$

$$R \propto T^{-1} \quad (2)$$

$$X(i) \approx 10^{-10} X(j) X(k) \rho_b T_9^{-3/2} e^{Q/kT} \quad (3)$$

- Equations from Wagoner, Fowler and Hoyle (1967), where X(j) and X(k) are the abundances of the precursors, ρ_b is the baryon density, T_9 is temperature * 10^9 K, Q is the energy release of the reaction,
- Additional energy density – for instance, from sterile neutrinos – makes the expansion rate of the universe faster.
- This causes BBN to occur earlier, and so X(i) increases for elements created during BBN.

Limits on BBN

- Pettini and Cooke (2013) report errors of $< 2\%$ in their measurements of deuterium: (2.535$\pm$0.05)*10^{-5} through measurements absorption lines of high-redshift quasars
- Thirty Meter Telescope data from metal-poor stars could reduce this further, to within nuclear reaction rate errors
- While deuterium is not the most common element from BBN, it is the best analysis tool; He-4 measurements are far less certain, and lithium measurements have known issues.

Limits

	D/H ($*\,10^{-5}$)	Y_p
3+1 thermalized	2.972	0.2582
3+2 thermalized	3.320	0.2691
3+1, $T_{\nu_s} = 0.4T_\nu$	2.631	0.2461
3+2, 1 $T_{\nu_s} = 0.4T_\nu$	2.981	0.2585
3+2, both $T_{\nu_s} = 0.4T_\nu$	2.640	0.2464

- With Pettini and Cooke's measurement – (2.535±0.05)*10^{-5} – none of these scenarios are consistent with experimental data.
- If we use a more generous measurement of D/H – Pettini and Cooke cite 2.6 ± 0.1 as the mean of eleven such studies – that still excludes fully thermalized sterile neutrinos.
- Working on a full framework to robustly test neutrino properties against BBN constaints

Questions?