Active-Sterile Neutrino Mixing In Big Bang Nucleosynthesis

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Sterile Neutrinos

The neutrino sector is perhaps the least well-understood aspect of the Standard Model. Multiple experiments have detected non-Standard Model behavior – most notably, the reactor anomaly [?], the MiniBoone anomaly, and the gallium anomaly [?] – suggesting the possibility of one or more additional neutrino species. However, a sterile neutrino at the same temperature as the active neutrinos – that is, one with a substantial mixing angle – is not consistent with the radiation energy density measurements of the early universe from Planck and WMAP [?]. However, there are numerous mechanisms to create a sterile neutrino that does not conflict with current cosmological bounds.

For instance, such a neutrino could be produced by Mikheyev-Smirnov-Wolfenstein (MSW) resonant conversion of active neutrinos driven by a net lepton number [?]. Since this production mechanism requires adiabaticity, it would only convert low-energy active neutrinos – resulting in a non-thermal spectrum [?]. These neutrinos would also be non-relativistic at much earlier epochs than a thermal sterile neutrino, and could provide a candidate for cold dark matter [?].

Since the n-p ratio at big bang nucleosynthesis (BBN) depends sensitively on the flux of electron neutrinos [?], any conversion between active and sterile neutrinos would affect primordial elemental abundances. Current primordial deuterium measurements have an error bar of <2% [?]. This allows us to probe the weak interactions at the BBN epoch with precision, as described in Smith et al. [?].

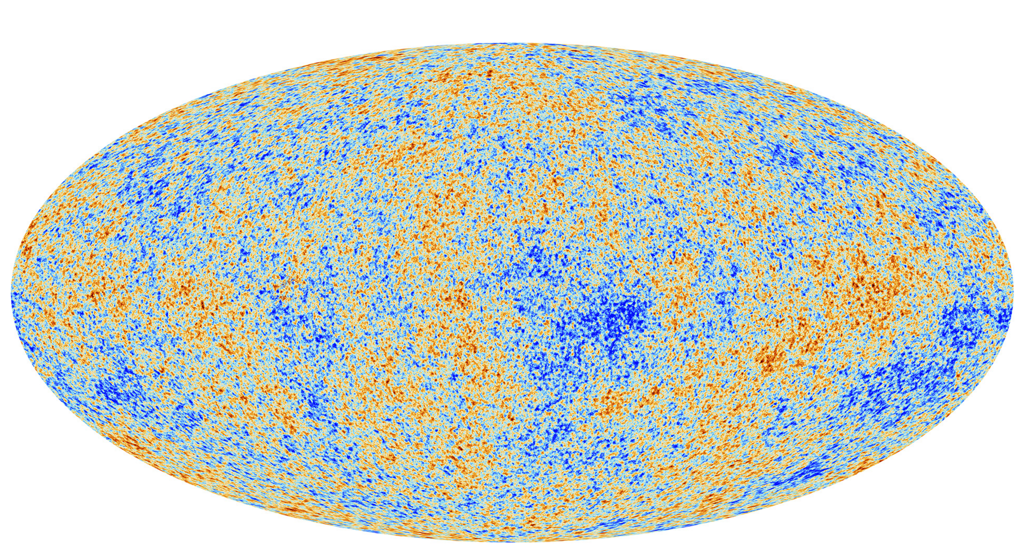


Figure 1: The CMB, as imaged by Planck.

MSW-like Mixing

We use a self-consistent treatment of weak interactions and neutrino physics through the weak decoupling, big bang nucleosynthesis, and photon decoupling epochs as developed in Grohs et al. [?].

We consider a swap between electron neutrinos and sterile neutrinos only, with some adiabaticity parameter α that determines the fraction of the energy bin that is swapped.

This adiabaticity parameter is equal to the Landau-Zeener jump probability, as below:

$$\alpha = P_{LZ} = 1 - e^{-\pi\gamma/2} \tag{1}$$

$$\mathcal{H} = \left(\frac{1}{V}\frac{dV}{dt}\right)^{-1} \tan 2\theta \tag{2}$$

$$L_{osc}^{res} = \frac{4\pi E_\nu}{\delta m^2 \sin 2\theta} \tag{3}$$

$$\gamma = \frac{2\pi\mathcal{H}}{(\hbar c) L_{osc}^{res}} = \frac{1}{2}\left(\frac{1}{V}\frac{dV}{dt}\right)^{-1} \frac{\delta m^2}{(\hbar c) E_\nu} \frac{\sin^2 2\theta}{\cos 2\theta} \tag{4}$$

In order to evaluate $\mathcal{H}$, we must determine the potential seen by an electron neutrino (the potential seen by a sterile being zero). There are two major components to this potential; the so-called "thermal" term and the density term.

We first consider the density term:

$$H(\nu_s) = 0 \tag{5}$$

$$H(\nu_e) = \frac{3\sqrt{2}}{2} G_F n_b \left(y_e - \frac{1}{3}\right) + \sqrt{2} G_F \left(2\left(n_{\nu_e} - n_{\bar{\nu}_e}\right) + \left(n_{\nu_\mu} - n_{\bar{\nu}_\mu}\right) + \left(n_{\nu_\tau} - n_{\bar{\nu}_\tau}\right)\right) \tag{6}$$

$$\eta = \frac{n_b}{n_\gamma} \tag{7}$$

$$\mathcal{L}_e = \frac{2\left(n_{\nu_e} - n_{\bar{\nu}_e}\right) + \left(n_{\nu_\mu} - n_{\bar{\nu}_\mu}\right) + \left(n_{\nu_\tau} - n_{\bar{\nu}_\tau}\right)}{n_\gamma} \tag{8}$$

$$n_\gamma = \frac{2\zeta(3) T^3}{\pi^2} \tag{9}$$

$$n_b = \frac{2\zeta(3) T^3 \eta}{\pi^2} \tag{10}$$

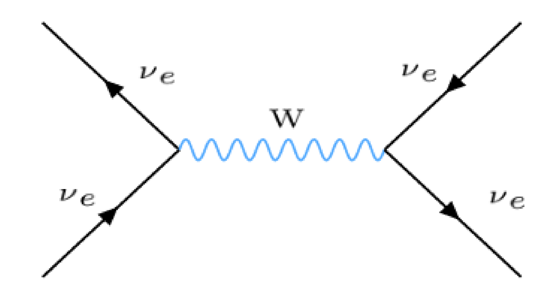
$$Y_e \approx \frac{1}{2} \tag{11}$$

$$V_D \approx \frac{2\sqrt{2}\zeta(3) G_F T^3}{\pi^2}\left(\mathcal{L}_e + \frac{\eta}{4}\right) \tag{12}$$

MSW-like Mixing

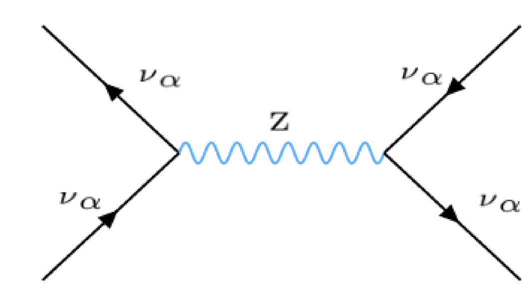
We then consider the thermal term, which is based on two possible interactions.

For electron neutrinos only:



$$V_T = -\frac{8\sqrt{2} G_F P_n}{3 m_Z^2}\left[\langle E_{e^-}\rangle n_{e^-} + \langle E_{e^+}\rangle n_{e^+}\right] \tag{13}$$

For a neutrino of any flavor,



$$V_T = -\frac{8\sqrt{2} G_F P_n}{3 m_W^2}\left[\langle E_{\nu_\alpha}\rangle n_{\nu_\alpha} + \langle E_{\bar{\nu}_\alpha}\rangle n_{\bar{\nu}_\alpha}\right] \tag{14}$$

Since $\langle E_{\nu_\alpha}\rangle n_{\nu_\alpha} \propto T^4$ and $\epsilon = E_\nu / T$ we can write this in the form:

$$V = -r_\alpha G_F^2 \epsilon T^5 \tag{15}$$

So we can write the total potential as:

$$V = \frac{2\sqrt{2}\zeta(3) G_F T^3}{\pi^2}\left(\mathcal{L}_e + \frac{3}{2}\left(Y_e - \frac{1}{3}\right)\eta\right) - r_\alpha G_F^2 \epsilon T^5 \tag{16}$$

We then apply the MSW resonance condition:

$$V = \frac{\delta m^2 \cos 2\theta}{2 E_\nu} \tag{17}$$

$$m_{eff}^2 = \delta m^2 \cos 2\theta = 2\epsilon T V \tag{18}$$

$$m_{eff}^2 = \frac{4\sqrt{2}\zeta(3) G_F T^4 \epsilon}{\pi^2}\left(\mathcal{L}_e + \frac{3}{2}\left(Y_e - \frac{1}{3}\right)\eta\right) - 2 r_\alpha G_F^2 \epsilon^2 T^6 \tag{19}$$

To satisfy this condition, the following must be true:

$$\frac{4(\zeta(3))^2 G_F}{\pi^2 m_{eff}^2 r_\alpha T^2}\left(\mathcal{L}_e + \frac{3}{2}\left(Y_e - \frac{1}{3}\right)\eta\right) \geq 1 \tag{20}$$

We are implementing this swap in the BURST code architecture. We intend to compare our results to current limits of BBN parameters.

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