64. Sum of Neutrino Masses

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Neutrinos decouple from thermal equilibrium in the early universe at temperatures $\mathcal{O}(1)$ MeV. The limits on low mass ($m_\nu \lesssim 1$ MeV) neutrinos apply to $m_{\rm tot}$ given by

$$m_{\rm tot} = \sum_\nu m_\nu \ .$$

Stable neutrinos in this mass range decouple from the thermal bath while still relativistic and make a contribution to the total energy density of the Universe which is given by

$$\rho_\nu = m_{\rm tot} n_\nu \simeq m_{\rm tot}(3/11)(3.045/3)^{3/4} n_\gamma \ ,$$

where the factor 3/11 is the ratio of (light) neutrinos to photons and the factor $(3.045/3)^{3/4}$ corrects for the fact that the effective number of neutrinos in the standard model is 3.045 when taking into account e^+e^- annihilation during neutrino decoupling. Writing $\Omega_\nu = \rho_\nu/\rho_c$, where ρ_c is the critical energy density of the Universe, and using $n_\gamma = 410.7$ cm^{-3}, we have

$$\Omega_\nu h^2 \simeq m_{\rm tot}/(93 \ \text{eV}) \ .$$

While an upper limit to the matter density of $\Omega_m h^2 < 0.12$ would constrain $m_{\rm tot} < 11$ eV, much stronger constraints are obtained from a combination of observations of the CMB, the amplitude of density fluctuations on smaller scales from the clustering of galaxies and the Lyman-α forest, baryon acoustic oscillations, and new Hubble parameter data. These combine to give an upper limit of around 0.15 eV, and may, in the near future, be able to provide a lower bound on the sum of the neutrino masses. The current lower bound of $m_{\rm tot} > 0.06$ eV implies a lower limit of $\Omega_\nu h^2 > 6 \times 10^{-4}$. See Sec. 25 of this *Review* for more details.