64. Sum of Neutrino Masses

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

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

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

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

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 $\rho_c$ is the critical energy density of the Universe, and using $n_{\gamma} = 410.7$ cm$^{-3}$, we have

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

While an upper limit to the matter density of $\Omega_m h^2 < 0.12$ would constrain $m_{\text{tot}} < 11$ 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 $m_{\text{tot}} > 0.06$ eV implies a lower limit of $\Omega_{\nu} h^2 > 6 \times 10^{-4}$. See Sec. 25 of this Review for more details.