

## SUM OF NEUTRINO MASSES

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The limits on low mass ( $m_\nu \lesssim 1$  MeV) neutrinos apply to  $m_{\text{tot}}$  given by

$$m_{\text{tot}} = \sum_{\nu} (g_\nu/2) m_\nu ,$$

where  $g_\nu$  is the number of spin degrees of freedom for  $\nu$  plus  $\bar{\nu}$ :  $g_\nu = 4$  for neutrinos with Dirac masses;  $g_\nu = 2$  for Majorana neutrinos. Stable neutrinos in this mass range make a contribution to the total energy density of the Universe which is given by

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

where the factor 3/11 is the ratio of (light) neutrinos to photons. Writing  $\Omega_\nu = \rho_\nu/\rho_c$ , where  $\rho_c$  is the critical energy density of the Universe, and using  $n_\gamma = 412 \text{ cm}^{-3}$ , we have

$$\Omega_\nu h^2 = m_{\text{tot}} / (94 \text{ eV}) .$$

Therefore, a limit on  $\Omega_\nu h^2$  such as  $\Omega_\nu h^2 < 0.25$  gives the limit

$$m_{\text{tot}} < 24 \text{ eV} .$$

The limits on high mass ( $m_\nu > 1$  MeV) neutrinos apply separately to each neutrino type.