## SUM OF NEUTRINO MASSES

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

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

where  $g_{\nu}$  is the number of spin degrees of freedom for  $\nu$  plus  $\overline{\nu}$ :  $g_{\nu} = 4$  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

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

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 and the amplitude of density fluctuations on smaller scales from the clustering of galaxies and the Lyman- $\alpha$  forest. These combine to give an upper limit around 0.5 eV.