

## 67. 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

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

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- $\alpha$  forest, baryon acoustic oscillations, and new Hubble parameter data. These combine to give an upper limit of around 0.2 eV, and may, in the near future, be able to provide a lower bound on the sum of the neutrino masses. See Sec. 26 of this *Review* for more details.