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Cosmological Bound on the Neutrino Mass:

So far we have considered neutrinos as massless particles (which happens to be the case in the standard model). There are experimental pieces of evidence from atmospheric and solar neutrino oscillations that (some of the) neutrinos are massive. This is the first experimental confirmation of physics beyond the standard model.

Oscillation experiments indicate to mass scales related to the mass splittings in the mass eigenstates:

$$\boxed{\Delta m^2_{atm} \sim O(10^{-3})\ eV^2 \quad , \quad \Delta m^2_{sol} \sim O(10^{-5})\ eV^2}$$

The upper bounds on the mass of neutrinos from laboratory experiments are:

$$\boxed{m_{\nu_e} \lesssim 1\ eV \quad , \quad m_{\nu_\mu} \lesssim 150\ keV \quad , \quad m_{\nu_\tau} \lesssim 15\ MeV}$$

These are only upper bounds though. As we will see, cosmological bounds on the neutrino mass are considerably much tighter. Also note that three neutrinos with their masses close to the upper bounds from lab experiments cannot explain solar and atmospheric data.

We distinguish between two cases of massive neutrinos:

(a) Light neutrinos: meaning that the three neutrinos are much lighter than O(MeV), i.e. $m_\nu \ll 1\,\text{MeV}$.

In this case the neutrinos are relativistic when they decouple from the plasma. As we found in the previous lecture:

$$\frac{n_\nu}{n_\gamma} = \frac{3}{11} \quad \text{(per family)}$$

The total contribution of the neutrinos to the energy density of the universe reads:

$$\rho_\nu = n_\nu \sum_\nu E_\nu$$

At the present time $T \sim 0.0003\ eV$, and hence even very light neutrinos are in the non-relativistic regime.

Thus:

$$\rho_\nu^0 = n_\nu^0 \sum_\nu m_\nu$$

On the other hand:

$$\rho_B^0 \simeq n_B^0 \times \underbrace{(1\ GeV)}_{\text{nucleon mass}}$$

The contribution of neutrinos, which are massive non-relativistic particles, cannot exceed that from the dark matter (which is ~ 6 times that from baryons). Hence:

$$\rho_\nu^0 \lesssim 6 \rho_B^0 \Rightarrow \frac{n_\nu^0}{n_\gamma^0} \sum_\nu m_\nu \lesssim 6 \frac{n_B^0}{n_\gamma^0} \times (1\ GeV)$$

... that n_ν^0 ... $= 3$ ... and n_B^0 ... $\sim 6 \times 10^{-10}$

(the latter from BBN) we find:

$$\boxed{\sum_{\nu} m_{\nu} \lesssim 10 \text{ eV}}.$$

This is the so-called Cowsik-McClleland bound. We note that this a very strong bound when compared to upper bound from lab experiments. However, it is only an upper bound from cosmology. It is saturated if all of the dark matter is in the form of light neutrinos. Neutrinos much lighter than O(MeV) will be hot dark matter, i.e. they are relativistic particles when decouple from the plasma. We know from observations that a hot component must be subdominant in the dark matter. Otherwise inhomogeneities at small scale would have been erased. To be precise, inflation (for which we have accumulating evidence) plus hot dark matter is ruled out.

The tightest bound from cosmology arises when CMB data and larg scale structure (LSS) data are combined. Currently the strongest bound is $\underline{\underline{\sum_{\nu} m_{\nu} < 0.6\ eV}}$, which is much tighter than the Cowsik-McClleland bound.

We note that it is much tighter than the best bound from lab on the neutrino mass $m_{\nu_e} < 1eV$.

It is expected than the KATRIN experiment will improve this bound by one order of magnitude. Future experiments in cosmology can attain a much better bound than that from lab experiments (in particular bounds from the 21 cm cosmology will be very tight).

This is one example of how cosmology can set strong constraints on the properties of fundamental particles, which are much tighter than can be obtained in the lab.