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Dark Matter (Cont'd):

We found the free-streaming length λ_{FS} for dark matter particles that are relativistic at the time of decoupling t_{dec} to be:

$$\lambda_{FS} \sim 0.2 \text{ Mpc} \left(\frac{1 \text{ keV}}{m_{DM}}\right)\left(\frac{T_{DM}}{T}\right)\left[\ln\left(\frac{t_{eq}}{t_{NR}}\right) + 2\right] \quad (I)$$

Here:

$$\frac{t_{eq}}{t_{NR}} \sim \left[\left(\frac{m_{DM}}{1 \text{ eV}}\right)\left(\frac{T}{T_{DM}}\right)\right]^2 \quad (II)$$

Let us now consider a specific example, namely light neutrinos in the standard model as dark matter candidate. In this case, $t_{dec} \sim 1$ sec resulting in $\frac{T_{DM}}{T} = \left(\frac{4}{11}\right)^{\frac{1}{3}}$ as seen before. We recall from the Cowsik-McClelland bound that $\sum_\nu m_\nu \lesssim 10$ eV if light neutrinos are dark matter. After plugging these numbers in Eqs (I, II), we find:

$$\lambda^{\nu}_{FS} \sim 30 \text{ Mpc}$$

This, however, implies that inhomogeneities with a comoving size < 30 Mpc were washad out due to free streaming of neutrinos. This is the supercluster size, which implies the first structures to form in a neutrino-dominated universe are of the size of a supercluster. The question then is how much smaller objects like galaxies (~ 0.2 Mpc in size) were formed. Zel'dovich argued that when fluctuations on the scale $\lambda_{FS} \sim 30$ Mpc become nonlinear, they do so in a highly non-spherical way, and the resulting structures should be two-dimensional objects like a pancake. Once a pancake form, the baryons within it can collid with one another and dissipate their gravitational energy. They can therefore fragment and condense into smaller (e.g., galaxy-sized) objects. In consequence, in a "hot" dark matter universe (like that in the case of neutrino dark matter) the structure forms in a "top-down" fashion.

However, a number of potential problems with hot dark matter had emerged by the mid 1980's:

(1) From studies in both nonlinear and linear regimes, it follows that supercluster collapse most have occured recently $z_{sc} < 2$. However, the best limits on galaxy ages coming from globular clusters (and other stellar populations) indicate that galaxy formation took place before $z \gtrsim 3$. Moreover, if quasars are associated with galaxies, the abundance of quasars at $z > 2$ is also inconsistent with the "top-down" formation of structure in a hot dark matter universe.

(2) Numerical simulations of the nonlinear "pancake" collapse showed that at least 85% of the baryons are so heated by the associated shock that they are unable to condense, and eventually form galaxies. With the BBN Constraint

on n_B, there would be difficulty having enough baryonic matter to form the luminosity that we actually observe. And, where are the X-rays from the shock-heated pancakes?

(3) The hot dark matter scenario predicts that there should be a factor of ~ 5 increase in $\frac{M_{total}}{M_{bar}}$ between large galaxies and large clusters. The reason being that large clusters have higher escape velocities, and hence are able to trap a considerably larger number of light dark matter particles. The ratio of total to luminous mass $\frac{M_{total}}{M_{lum}}$, however, is roughly the same for galaxies with large halos and for rich clusters.

(4) The above problems, while serious, would perhaps not been fatal for the hot dark matter scenario. But an even more serious problem for hot dark matter arose from the amplitude of CMB fluctuations detected by the COBE satellite in

the 1990's. Because of the large free-streaming cut off in the hot dark matter scenario, the amplitude of CMB fluctuations must be considerably higher than the observed value of $\sim 10^{-5}$ in order to form any structure by the present.

Therefore, the evidence against the standard hot dark matter is convincing. At the very least, it indicates that structure formation in a hot dark matter universe must be significantly more complicated than in the standard model of cosmology.

The main alternative that has been considered is cosmic strings plus hot dark matter. However, strings and other topological defects have been now essentially ruled out by the observed acoustic oscillations in the CMB spectrum.

The viable alternative to the "top-down" scheme of structure formation is the "bottom-up" scheme. In this case smallest structures (such as galaxies) form first and the larger structures (like clusters and superclusters) start to grow. In this scheme, it is required that $\lambda_{FS} \lesssim 0.2\,Mp$, which results in a lower bound on the dark matter mass:

$$m_{DM} \gtrsim 1\ keV$$

Therefore, dark matter cannot be "hot" (ultrarelativistic), but it can be "warm" (relativistic). It can also be "cold" meaning that dark matter particles were non-relativistic at the time of decoupling t_{dec}. In this case, λ_{FS} will be much smaller than that given in Eq. (I), and hence structures much smaller than milky-way-sized galaxies can form. In fact, cold dark matter (CDM) is the dominant scenario that arises in the Standard Cosmological Model. Its predictions are in very good agreement with the CMB and large scale structure data, with some potential problems at small scales (galactic size).