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Hot Dark Matter

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Hot Dark Matter

Dark matter made of light neutrinos, with masses of a few electron-volts (eV) or less, is called 'hot dark matter' (HDM) by cosmologists. Light neutrinos would have been 'hot', moving at nearly the speed of light, in the early universe. For a few years in the late 1970s and early 1980s, hot dark matter looked like the best dark-matter candidate. However, HDM models of cosmological structure formation led to a 'top-down' formation scenario, in which superclusters of galaxies are the first objects to form after the big bang, with galaxies and clusters forming through a subsequent process of fragmentation. Such models were abandoned by the mid-1980s after cosmologists realized that if galaxies had formed early enough to agree with observations, their distribution would be much more inhomogeneous than is the case.

Since 1984, the most successful structure-formation models have been those in which most of the mass in the universe comes in the form of cold dark matter (CDM)—particles that were moving sluggishly in the early universe. For a while in the mid-1990s it appeared that a mixture of mostly CDM with 20–30% HDM gave a better fit to the observations than either one or the other. This 'cold plus hot dark matter' (CHDM) theory fitted data on nearby galaxies and clusters only if the average density of matter in the universe were at or close to the critical density ($\Omega_m = 1$). However, like all such critical-density models, CHDM required that galaxies and clusters must have formed fairly recently. It is now clear that this disagrees with observations. The evidence now increasingly favors Λ CDM models, in which CDM and a little ordinary matter make up about a third of the critical density, with a cosmological constant or some other form of 'dark energy' contributing the remainder. This model also helped resolve a crisis regarding the age of the universe. The HDM question has now become how much room is left for neutrinos in such a universe.

To understand the possible role of neutrinos as dark matter, consider how structures such as galaxies formed as the universe expanded. The expansion itself is described by our modern theory of gravity and spacetime, Einstein's theory of general relativity. In order for structure to form, there must have been some small fluctuations in the initial density of matter. The only alternative is that some mechanism generated such fluctuations after the big bang, but the only such mechanisms that have been investigated are 'cosmic defects' such as cosmic strings, and the pattern of fluctuations produced by such defects is inconsistent with the temperature fluctuations observed in the cosmic microwave background (CMB) radiation. However, 'adiabatic' fluctuations—in which all components of matter and energy fluctuate together—occur naturally in the simplest cosmic infla-

tion models and are in excellent agreement with the latest CMB results. The evolution of adiabatic fluctuations into galaxies and clusters is easy to understand: the rich always become richer and the poor become poorer. A 'rich' region of the universe is one that has more matter than average. Although the average density of the universe steadily decreases owing to its expansion, those regions that start out with a little higher density than average expand a little slower than average and become relatively more dense, while those with lower density expand a little faster and become relatively less dense. When any region has attained a density about twice the average, it stops expanding and begins to collapse—typically first in one direction, forming a pancake-shaped structure, and then in the other two directions.

The first HDM boom occurred about two decades ago. By about 1980, improving upper limits on CMB anisotropies were ruling out the previously favored cosmological model, which included only ordinary matter. There was also evidence from a Moscow experiment suggesting an electron neutrino mass of about 20 eV, which would have corresponded to a nearly-critical-density universe in which neutrinos would have constituted most of the matter. In such a cosmology, the primordial fluctuations on galaxy scales are erased by 'free streaming' of the relativistic neutrinos in the early universe. About 1 yr after the big bang, a region about 1 ly across contained the amount of matter in a large galaxy like our own Milky Way. However, the temperature was then about 100 million kelvins (10^4 eV), so each particle had a thermal energy far higher than the rest energy of light neutrinos. As they would therefore have been moving at nearly the speed of light, these neutrinos would have rapidly spread out, and any fluctuations in density on the scale of galaxies would soon have been smoothed back to the average density. The first scales to collapse in such a HDM scenario would therefore correspond to the mass inside the cosmic horizon when the temperature dropped to a few eV and the neutrinos inside it became non-relativistic. This mass turns out to be about 10 000 times the mass of our galaxy, including its dark halo. Evidence was just then becoming available from the first large-scale galaxy surveys that the largest cosmic structures—superclusters—have masses of approximately this size, which at first glance appeared to be a success for the HDM scenario. Superclusters of roughly pancake shape were observed to surround roughly spherical voids (regions where few galaxies are found), in agreement with the first cosmological computer simulations, which were run for the HDM model. In this picture superclusters should have formed first, since any smaller-scale fluctuations in the dominant HDM would have been erased by free streaming. Galaxies then had to form by fragmentation of the superclusters. However, it was already becoming clear from observations that galaxies

are much older than superclusters, contrary to what the HDM scenario implies. Also, the apparent detection of electron neutrino mass by the Moscow experiment was soon contradicted by results from other laboratories. Hot dark matter fell into decline.

The CDM model originated in 1982–1984, just as the problems with the HDM model were becoming clear. Proto-galaxies form first in a CDM cosmology, and galaxies and larger-scale objects form by aggregation of these smaller lumps—although the cross-talk between smaller and larger scales in the CDM theory naturally leads to galaxies forming earlier in clusters than in lower-density regions. In this and other respects, CDM models appeared to fit observations much better than HDM. The first great triumph of CDM was that it successfully predicted (to within a normalization uncertainty factor of about 2) the magnitude of the CMB temperature fluctuations, which were discovered in 1992 using the COBE satellite. However, the simplest CDM model, standard CDM (SCDM) with the matter density equal to the critical value ($\Omega_m = 1$), had already begun to run into trouble.

Cosmological theories predict statistical properties of the universe—for example, the size of density fluctuations on various scales, described mathematically by a power spectrum. Sound or other fluctuation phenomena can be described in the same way—for example, low frequencies might be loud, corresponding to relatively high power at long wavelengths. With a given amount of fluctuation power on the large scales probed by COBE (billions of light-years), SCDM has a little too much power on small scales relevant to galaxies and clusters (millions of light-years and less). However, the fact that the SCDM theory could work fairly well across such a wide range of size scales suggested that it had a kernel of truth. Cosmologists began to examine whether some variant of SCDM might work better. For example, in the late 1980s, my former student Jon Holtzman calculated detailed expectations for 96 variants of CDM. When we compared these predictions with the data available in early 1992, it was clear that the best bets were CHDM and Λ CDM, each of which could fit the data on small scales better than SCDM. Both of these variants had been proposed in 1984, when CDM was still a new idea, but their detailed consequences were not worked out until the problems with SCDM began to surface.

Even if most of the dark matter is cold, a little HDM can still have dramatic effects on the small scales relevant to the formation and distribution of galaxies. In the early universe, the free streaming of fast-moving neutrinos would have washed out any spatial inhomogeneities in the neutrino component on the scales that later became galaxies, just as in the HDM scenario. Consequently, fluctuations in the CDM component grew more slowly on these scales, and at the relatively late times when galaxies formed there was less fluctuation power on small

scales in CHDM models. Adding a little HDM appeared to be just what was needed to solve the SCDM problem that the galaxy-scale inhomogeneities are too big. Also, there was even a hint from an accelerator experiment that neutrino mass might lie in the relevant range. This was the Liquid Scintillator Neutrino Detector (LSND) experiment at Los Alamos National Laboratory, which recorded a number of events that appear to be $\nu_\mu \rightarrow \nu_e$ neutrino oscillations. Comparison of the LSND data with results from other neutrino experiments allows two discrete values of $|m^2(\nu_\mu) - m^2(\nu_e)|$, around 10.5 and 5.5 eV², or a range of values between 0.2 and 2 eV². If true, this means that at least one neutrino has a mass greater than 0.5 eV, which would imply that the contribution of HDM to the cosmological density is much greater than that of all the visible stars. Such an important conclusion requires independent confirmation. The Karlsruhe Rutherford Medium Energy Neutrino (KARMEN) experiment results exclude a significant portion (but not all) of the LSND parameter space, and the numbers quoted above take into account the current KARMEN limits. The Booster Neutrino Experiment (BooNE) at Fermilab should attain greater sensitivity and help to resolve this issue.

By 1995 simulation techniques and supercomputer technology had advanced to the point where it was possible to do reasonably high-resolution cosmological-scale simulations including the random velocities of an HDM component. The results at first appeared very favorable to CHDM. Indeed, as late as 1998 a CHDM model with Hubble parameter $h = 0.5$, mass density $\Omega_m = 1$ and neutrino density $\Omega_\nu = 0.2$ was found to be the best fit of any cosmological model to the galaxy distribution in the nearby universe. However, cosmological data were steadily improving, and even by 1998 it had become clear that $h = 0.5$ and $\Omega_m = 1$ were increasingly inconsistent with observations, and that $h \sim 0.7$ and $\Omega_m \sim 1/3$ worked much better. For example, CHDM predicts that galaxies and clusters formed relatively recently, but around 1998 increasing numbers of galaxies were discovered to have formed in the first few billion years after the big bang. Also, the fraction of baryons found in clusters, together with the reasonable assumption that this fraction is representative of the universe as a whole, again gives $\Omega_m \sim 1/3$. That there is a large cosmological constant (or some other form of dark energy) yielding $\Omega_\Lambda \sim 2/3$ then follows from any two of the following three results: (1) $\Omega_m \sim 0/3$, (2) CMB anisotropy data implying that $\Omega_m + \Omega_\Lambda = 1$, and (3) high-redshift supernova data implying that $\Omega_\Lambda - \Omega_m \sim 0.4$. The abundance of galaxies and clusters in the early universe agrees well with the predictions of the Λ CDM model. However, the highest-resolution simulations of this model that were possible in the mid-1990s gave a dark matter spectrum that had more power on scales of a few million light-years than did the observed galaxy power

spectrum, although the simulations and data agreed on larger scales. This result was inconsistent with the expectations that galaxies would be more clustered than the dark matter on small scales, not less. When it became possible to do even higher-resolution simulations that allowed the identification of the dark matter halos of individual galaxies, however, their power spectrum turned out to be in excellent agreement with that of galaxies. The galaxies were less clustered than dark matter because galaxies had merged or were destroyed in very dense regions owing to interactions with each other and with cluster centers. This explanation turned a troubling discrepancy into a triumph for Λ CDM.

Thus Λ CDM is the favorite theory today. However, we know from the Super-Kamiokande evidence for atmospheric neutrino oscillations that there is enough neutrino mass to correspond to some HDM, at least $\Omega_{\nu} \approx 10^{-3}$, about one-fourth as much as the visible stars. How much room remains for a little HDM in Λ CDM cosmologies? The reason there is any upper limit at all from cosmology is because the free streaming of neutrinos in the early universe must have slowed the growth of the remaining CDM fluctuations on small scales. Thus, to have the galaxy structures we see today, there must be much more cold than hot dark matter. From the shape of the galaxy power spectrum observed by the 2dF galaxy redshift survey, the limit on the sum of the neutrino masses is $m(\nu) < 2.2$ eV, corresponding to $\Omega_{\nu} < 0.05$. This limit on $m(\mu)$ is much stronger than the best current laboratory limit. Astronomical observations that may soon lead to stronger upper limits on neutrino mass—or perhaps a detection—include more precise measurements of the power spectrum from galaxy redshift surveys, data on the distribution of low-density clouds of hydrogen (the ‘Lyman-alpha forest’) at high redshifts, large-scale weak gravitational lensing data and improved measurements of the cosmic background radiation temperature fluctuations on small angular scales. These types of data can be used to probe for the effects of any free streaming of neutrinos in the early universe, which can lead to less power on small scales depending on the values of the neutrino masses.

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