4. DARK MATTER

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There is increasing evidence for the existence of large quantities of dark matter in the Universe. The most direct evidence comes from the astronomical observation of the motion of visible matter (stars and regions of neutral hydrogen gas) in galaxies. The observed velocities due to rotational motion in spiral galaxies are measured to be largely independent of the distance to the center of these galaxies [1](they are said to have "flat rotational curves"). In the absence of any unseen component, we would expect that the velocity falls off with increasing distance, $v^2 \approx G_N\, M_{\rm vis}/r$. In contrast, a flat rotation curve implies a total mass $M_{\rm tot} \approx G_N^{-1}\; v_{\rm obs}^2 r$ [$\approx 10^{11} M_\odot$ $(v_{\rm obs}/200$ km s$^{-1})^2$ $(r/10$ kpc)] in excess of the visible mass $M_{\rm vis}$. It can be inferred from these observations that there exists a dark matter component distributed in a (roughly) spherical halo about the galaxy. The dynamics of groups of galaxies and clusters, as well as the presence of very hot gas in elliptical galaxies require large quantities of unseen matter as well [2]. More recent observations of hot x-ray emitting gas in clusters of galaxies [3], and of gravitational lensing of high redshift background galaxies by foreground clusters [4] (which do not require the cluster to be relaxed), also indicate the presence of dark matter on cluster scales. In addition, theories of cosmological inflation predict that the density parameter of the Universe $\Omega_{\rm tot} = 1$, whereas standard Big Bang nucleosynthesis requires $\Omega_{\rm baryon} \lesssim 0.1$ [5]. This implies the existence of nonbaryonic dark matter. Further indirect evidence comes from our theoretical understanding of the growth of density perturbations as seeds for galaxy formation. Without the presence of dark matter, it is very difficult to reconcile the existence of galaxies (and quasars) at high redshifts with the new measurements by COBE of the anisotropy of the microwave background radiation [6]. Perturbations in baryon density can grow only after the time of recombination, *i.e.* when the baryons decouple from the microwave background. When $\Omega_{\rm tot} = 1$ due to dark matter, matter domination occurs much earlier and dark matter perturbations grow for a longer period, thus avoiding a conflict with the magnitude of the microwave background anisotropy.

In our own galaxy, the distribution of the visible matter and its observed circular motion determine the local (solar neighborhood) dark matter density $\rho^{\rm DM} \approx 0.3$ GeV cm^{-3} [7]. Regardless of the nature of the dark matter, it must behave as a collisionless gas, with a broad velocity distribution (typically assumed to be Maxwellian); $\langle v\rangle \approx \triangle v \approx 300$ km s^{-1}.

We do not know the identity of the dark matter nor whether there is more than one type of dark matter. Baryons are difficult to conceal [8] and in the standard Big Bang model cannot make up all of the dark matter if $\Omega_{\rm tot} = 1$. By the same token, by comparing the lower limit of $\Omega_{\rm baryon} \gtrsim 0.01$ from nucleosynthesis [5], it is very likely that some of the baryons are dark. Though it is theoretically unlikely that galactic halos could be made of very dim objects, such as low-mass stars with masses $\lesssim 0.1 M_\odot$, recent gravitational microlensing searches for such objects may have a positive detection [9] (these objects are sometimes referred to as MACHOS, massive compact halo objects). There are several theoretical elementary particle candidates (WIMPs, weakly interacting massive particles) that could explain the existence of dark matter, of which the most commonly discussed are: a neutrino (if massive), a neutralino (from supersymmetry), and the axion (from the strong CP problem). These are summarized in Table 4.1.

Table 4.1: Dark Matter Candidates

Type	Candidate	Possible mass
Hot	neutrino	1–10 eV
Cold	neutralino: photino, Higgsino, or bino	20–350 GeV
Cold	axion	10^{-5}–10^{-3} eV

Regardless of the exact identity of the dark matter (DM), its kinetic energy at the time when dark-matter domination begins determines the subsequent evolution of the density perturbations that seed galactic and large structures [10]. If the dark matter is relativistic (hot dark matter, HDM) only the largest (supercluster) structures survive and they must fragment to form galactic structure, whereas if it is nonrelativistic (cold dark matter, CDM), structure on all scales is preserved. The large-scale distribution of matter in n-body simulations of a HDM-dominated universe is not compatible with observations (unless there are point-like density perturbations), whereas a flat CDM-dominated universe requires that the visible matter be predominantly concentrated in the denser regions of the DM distribution (biased galaxy formation). In point of fact, both the HDM- and CDM-dominated universes have some degree of difficulty with the size of the microwave background anisotropy measured by COBE. A mixture of cold and hot dark matter may provide a better solution to the problem of generating large scale structures. An example of such a mixture would be a ν_τ with a mass of order a few eV *and* a more massive neutralino.

For a cold dark matter particle species with equal particle (X) and antiparticle $(\overline{X})$ densities (except for the axions), its cosmological density at present is [11]

$$\Omega_X\, h^2 \approx 1.6\times 10^{-10}\; N_F^{1/2} \left(\frac{T_X}{T_\gamma}\right)^3 \left(a + \tfrac{1}{12} b\, \langle v^2\rangle_f\right)^{-1} \langle v^2\rangle_f^{-1} \quad (4.1)$$

with a and b determined from the (velocity averaged) annihilation cross section, expanded in powers of momentum, $\langle v\, \sigma_{X\overline{X}}\,\rangle = a + \frac{1}{6} b\, \langle v^2\rangle_f$, at freezeout temperature T_f ($\langle v^2\rangle_f = 6T_f/M_X$) at which the X's drop from thermal equilibrium (typically $T_f \approx \frac{1}{20} M_X$). In Eq. (4.1), N_F is the total number of relativistic degrees of freedom at T_f and (T_X/T_γ) is the ratio of the temperatures of X's and photons at T_f. In the halo of our galaxy $\langle v^2\rangle \approx 10^{-6}$, thus $\langle v\, \sigma_{X\overline{X}}\,\rangle_{\rm halo}$ and Ω_X are closely related.

Several proposals or experiments exist to detect cold dark matter candidates. For the case of heavy ($M \gtrsim 1$ GeV) particles, elastic scattering from nuclei would produce nuclear recoils with energies of $\gtrsim 1$ keV, and several techniques have been proposed to detect these recoils. The expected collision rate for a target nucleus mass m_N is:

$$R = 4.3\ {\rm kg}^{-1}\ {\rm day}^{-1} \left(\frac{1\ {\rm GeV}^2}{m_N\; m_x}\right)\left(\frac{\sigma_{\rm el}}{10^{-38}\ {\rm cm}^2}\right) \times \left(\frac{\rho^{\rm DM}}{0.3\ {\rm GeV\ cm}^{-3}}\right)\left(\frac{\langle |v_E|\rangle}{300\ {\rm km\ s}^{-1}}\right), \quad (4.2)$$

where $\langle |v_E|\rangle$ is the average velocity at which they strike the detector. Since crossing symmetry relates $\sigma_{\rm el}$ to $\sigma_{X\overline{X}}$, R is closely related to Ω_X. Dirac neutrinos (and sneutrinos) with masses 0.012–4.7 TeV have already been excluded by searches done using double-β decay detectors [12]. Axions could be detected by their expected coherent conversion to microwave photons in a tuned cavity. Products of DM annihilation in the halo (*e.g.*, cosmic ray $\overline{p}$'s, e^+'s, γ's) and the core of the Sun (ν's) would indirectly signal the existence of particle DM. The absence of a signal in high energy solar-ν searches using underground detectors rules out sneutrinos whereas cosmic ray searches do not constrain theory so far. Experimental limits concerning a number of dark matter candidates are given in the Full Listings. See the index under "Dark matter limits."

Recent LEP results when combined with the above experimental constraints now completely eliminate massive 4th-generation neutrinos or sneutrinos as dark matter candidates. Sneutrinos and additional Dirac and Majorana neutrinos with masses $\lesssim 40$ GeV are excluded by LEP. This alone eliminates a Majorana neutrino, since the relic abundance for the neutrinos with masses $\gtrsim 40$ GeV would be $\Omega h^2 \lesssim 2\times 10^{-3}$, making them cosmologically uninteresting. In the case of Dirac neutrinos, if there were a density asymmetry between ν and $\overline{\nu}$, it would in principle be possible to have a cosmologically interesting density even though $m_\nu > 40$ GeV. However, as described in the previous paragraph, Dirac neutrinos (and sneutrinos) below 4.7 TeV are ruled out by direct cold dark matter searches.