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A Selection of Dark Matter Candidates

Dark matter was first introduced as a solution to the unexpected shape of our galactic rotation curve; instead of showing the predicted fall-off as $r^{-1/2}$ toward the edges of the disk, where the visible mass becomes negligible compared to the bulk of the galaxy, the measured velocities rather remain roughly constant, indicating the presence of a great deal of mass in the outer reaches of the galaxy which we do not see. Further observations showed similar "missing mass" in other galaxies as well, and in other gravitationally bound structures such as galaxy clusters and satellite galaxies orbiting larger spiral galaxies (Bertone et al. 2005). The evidence for the existence of dark matter is now quite considerable, but what precisely the dark matter is made of is a much murkier issue. The candidates for dark matter I shall focus on can be broadly broken into two main categories: baryonic and non-baryonic.

Baryonic dark matter is in the form of MACHOs, or MAssive Compact Halo Objects. MACHOs include red dwarfs, white dwarfs, brown dwarfs, neutron stars, planets, and black holes (Evans and Belokurov 2004). The amount of mass in our galaxy's dark matter halo can be determined by looking for microlensing events that occur while observing a specific region (such as the Large Magellanic Cloud) and comparing the observations to predictions from models (Lasserre et al. 2000). Studies of the Magellanic Cloud have ruled out MACHOs in the range of 10^{-7} to 4 solar masses as the sole component of the dark matter halo, thus microlensing fairly convincingly eliminates baryonic dark matter as a large component of dark matter.

Neutrinos are one possible non-baryonic dark matter candidate, though they cannot fully solve the dark matter problem (Bertone et al. 2005). Two issues keep neutrinos from being a good solution; the first issue is that neutrinos simply do not have enough mass. Lab experiments have restricted the mass of the most massive neutrino species to be less than 2.05 eV, resulting in a calculated relic density, or density at the time of neutrino freeze-out, of roughly $\Omega_\nu h^2 \leq 0.07$. Studies of large-scale structure and anisotropies in the cosmic microwave background have further limited the neutrino masses to less than 0.23 eV (assuming 3 neutrino species) and a relic density of $\Omega_\nu h^2 < 0.0067$, which is clearly not enough to make up the "missing" mass, $\Omega_{DM} h^2 \sim 0.12$, in the universe. Further evidence against the neutrino is its free-streaming length of roughly 40 Mpc. Movements of the neutrinos, being relativistic and having very small cross-sections, would remove any density fluctuations on scales of less than 40 Mpc, and so we would expect to see large structures forming first, with smaller structures forming later. What we observe, however, seems to actually be the opposite.

A variation on the neutrino is the sterile neutrino, which is the right-handed counterpart of the standard neutrino (Dodelson & Widrow 1994). While this particle, unlike the standard neutrino, is not known to exist, one might suspect its existence since the neutrino is the only fermion in the Standard Model lacking a right-handed counterpart. They would be produced by oscillations of the left-handed neutrinos – the tau, electron, and mu neutrinos - and would be more massive. The sterile neutrino was originally proposed as a warm dark matter candidate, thus having a smaller free-streaming length than the standard neutrino, and allowing smaller structures like galaxies to form earlier. However, the smaller free-streaming length is still not enough to reconcile the model of the sterile neutrino as warm dark matter with observations. The particle's existence though could be detectable in the amount of primordial helium produced during Big Bang nucleosynthesis. Shi and Fuller (1999), though, have modeled a sterile neutrino that is cooler than the warm dark matter sterile neutrino by changing the means of production. They propose that a lepton number asymmetry results in a resonant transformation from left-handed or "active" neutrinos to the right-handed, sterile neutrinos, as opposed to the oscillation during Big Bang nucleosythesis suggested by the warm sterile neutrino model. The cooler sterile neutrinos then have a smaller free-streaming length than the warm sterile neutrinos, allowing formation of structures the sizes of observed dwarf galaxies, much like the cold dark matter models. The cool sterile neutrino model differs then from the cold dark matter model only at scales smaller than galaxies. If the sterile neutrino has a mass of more than 10keV, though, the sterile neutrino becomes cold dark matter instead.

Axions are the third non-baryonic candidate for dark matter. They were first suggested in order to solve the strong charge-parity violation in quantum chromodynamics (Bergstrom 2000). The axion must be relatively light (less than 0.01 eV) based on laboratory experiments, stellar cooling, and studies of supernova 1987A. The axion is a cold dark matter candidate, since it interacts so weakly with matter that it was never in thermal equilibrium early on. If the axion has a mass of between 0.00001 eV and 0.01 eV, it could still satisfy the observational constraints placed on it as a cold dark matter candidate. This range is due to the uncertainty of the relationship between the expected relic density and the mass, since there are several possible methods of producing an axion, such as emission from cosmic strings or vacuum misalignment.

Supersymmetry theories produce a variety of possible dark matter particles. In general, supersymmetry assigns a fermion as a superpartner to every boson in the Standard Model and a boson as a superpartner for all fermions in the Standard Model (Bertone et al. 2005). Also added to the Standard Model are an extra Higgs boson and a fermion to correspond to each of the Higgs bosons. Lastly, R-parity must be conserved. R is a quantum number that equals 1 for Standard Model particles and –1 for the superpartners. This R-parity conservation is what makes the lightest supersymmetric particles stable and thus good candidates for dark matter. Neutralinos are the most popular dark matter candidate resulting from supersymmetry, and they are a combination of the superpartners of the B and W_3 gauge boson and the neutral Higgs bosons (which are often called binos, winos, and higgsinos). The neutralinos are eigenvalues of mass of this combination, and the lightest neutralino is really the dark matter candidate here. Other supersymmetric dark matter candidates are the gravitino (partner to the graviton), sneutrino (partner to the neutrino), and axinos (partner to the axion). In some models, the gravitino, not the neutralino, is the lightest supersymmetric particle and thus becomes favored as the dark matter candidate. The sneutrino is generally disregarded as a good dark matter candidate because it typically has a large annihilation cross-section and is strongly coupled to baryonic matter, though some models are still able to make the sneutrino work as dark matter within very tight constraints (Bergstrom 2000).

Other possible types of non-baryonic dark matter are superheavy particles, with masses greater than 10^{10} GeV (Bertone et al. 2005). These are referred to as "wimpzillas" and are not in thermal equilibrium at freeze-out. They might be produced at the end of inflation by the process of gravitational production.

All of the weakly interacting massive particles (or WIMPs) could potentially be detected directly by means of scattering (Bertone et al. 2005). This scattering could be in the form of elastic scattering, where the WIMP interacts with a nucleus, creating a measurable recoil of the nucleus. The current lower limit on this method is a recoil of about 1-10 keV. Inelastic scattering is also possible, where the WIMP either interacts with the electrons of the target and excites or ionizes them, or interacts with the nucleus, creating an excited nuclear state. In the case of an excited nuclear state, one would detect the recoil of the nucleus and then the emission of a photon as the nucleus returned to its lower energy state. This effect, however, is masked by normal radioactive processes.

Indirect detection methods include looking for the products of annihilations of WIMPs (Bertone et al. 2005). Gamma rays, neutrinos, positrons, and anti-protons are some of the products that are currently of interest. Gamma rays can either be detected directly from space or from the ground by looking for the secondary particles produced when the gamma ray interacts with our atmosphere. Neutrinos can be detected by the muon tracks they produce within the detector. Positron detection achieved some success in the mid-1990s with the project HEAT (High Energy Antimatter Telescope). HEAT detected possible dark matter around 9GeV, as it saw an excess of positrons at that energy and higher. Dark matter annihilation can also produce electrons and protons, which can then be detected in radio by their synchrotron emission as they move through magnetic fields within the galaxy.

Many candidates exist for dark matter. MACHOs, while contributing somewhat to the total mass, have been ruled out as the dominant dark matter component. Particle physics, especially supersymmetry, however, provides a whole host of potential candidates. As the supersymmetry models become more refined and detection methods become more sophisticated, eventually we might have a better idea of just what the dark matter is made of.

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