PHYS480/581 Cosmology
Dark Matter 2

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As we discussed last time, dark matter is necessary to explain the difference between the observed baryon abundance $\Omega_{\rm b} \simeq 0.05$ and the observed total matter abundance $\Omega_{\rm m} \simeq 0.3$. Dark matter also appears to be dynamically relevant at galaxy scale, where it is necessary to explain the nearly flat galaxy rotation curves that are observed. In this picture, galaxies are surrounded by large dark matter halos (essentially large balls of dark matter), which tend to dominate in mass over that of the visible matter.

I. DARK MATTER IN GALAXY CLUSTERS

One of the first hint that something like dark matter must exist in our Universe was discovered in the 1930s by Zwicky, who was examining the motion of galaxies within the Coma galaxy cluster. A galaxy cluster is basically a large group of galaxies that are bound gravitationally to each other. Zwicky noticed that the galaxies within the Coma cluster were moving way too fast compared to their apparent gravitational potential energy gotten from just counting the visible baryonic matter. This means that either the galaxy cluster is not actually gravitationally bound and in the process of being destroyed (by all the galaxies flying away from the cluster), or something else is holding the galaxy cluster together. Zwicky called this "Dunkle Materie" which can be translated as dark matter. No one took Zwicky's proposal seriously at the time, and it took about 50 years for dark matter to become mainstream (which the discovery of flat galaxy rotation curves by Rubin and collaborators).

We now know that galaxy clusters are full of dark matter. We know this because we can use gravitational lensing to map the matter distribution within galaxy clusters. An example of this is shown in Fig. 1, where we show a composite image of cluster Abell 370. The blue shade indicates where most of the dark matter is, according to the gravitational lensing signatures we see in this image.

FIG. 1. Galaxy cluster Abell-370. The blue shade indicates where most of the dark matter is located, according to the strong gravitational lensing features that can be seen in this image. This cluster is at $z = 0.375$.

II. POSSIBLE DARK MATTER CANDIDATES

- **Weakly interacting massive particles (WIMPs):** WIMPs are dark matter particles that interact with the Standard Model of particle physics via the weak force. Such particles arise naturally in many extension of the Standard Model, including supersymmetry. One thing in favor of WIMPs is that, if one uses a typical cross section expected for the weak interaction, one automatically gets the correct relic abundance corresponding to $\Omega_{\rm c} \simeq 0.25$. This is called the WIMP miracle. For the last 2.5 decades, there has been a large experimental effort to discover WIMPs in the laboratory. Nothing has been found so far. The lab searches continue, but already the prime parameter space for WIMPs has been excluded.

- **Axions:** The axion was originally invented to solve an important problem in particle physics: The strong charge-parity (CP) problem. In essence, the question that the axion tries to answer is why is the strong interaction (quantum chromodynamics) invariant under a joint charge and parity transformation. Axions solve this by providing a dynamical mechanism that effectively sets the CP-violating effects to zero. As an added bonus, the axion (which is a pseudo-scalar field) oscillates around the minimum of its potential and thus behaves like cold dark matter. Axions can be searched for in the lab by exploiting photon-to-axion conversion in a strong magnetic field. Searches are ongoing.

- **Primordial black holes:** Primordial black holes (PBHs) are thought to have formed very early in the history of the Universe during the radiation-dominated era. Forming them in sufficient abundance for them to be dark matter today likely requires an initial spectrum of density fluctuations that is characterized by very large values on small scales. The abundance of PBHs is constrained a whole range of observations, including gravitational lensing, dynamical effects in stellar binaries and star clusters, large-scale structure , and the cosmic microwave background, among others. Taken together, this tells us that PBHs in the mass range $10^{-11}M_{\odot} \lesssim M_{\rm PBH} \lesssim 10^{13}M_{\odot}$ are unlikely to form *all* of the dark matter if all PBHs have the same mass. If PBHs can have a broad range of masses, constraints are weaker but engineering the formation of such PBHs is much harder. PBHs lighter than $\sim 10^{15}$ g have likely already evaporated via Hawking radiation and thus cannot form dark matter.

- **Sterile neutrinos:** Sterile neutrinos are neutrinos that do not participate in the weak interaction, in contrast to their Standard Model counterpart. Sterile neutrino can however mix with the active neutrinos, and this mixing could "create" enough sterile neutrinos to explain the dark matter abundance today. This would happen if the sterile neutrino mass is in the keV range. The interesting thing is that this does not necessarily create *cold* dark matter, but could also result in *warm* dark matter, that is dark matter that is created relativistic and then becomes colder at later times. This can suppress small-scale structure in such model, and provide important constraints on sterile neutrinos.

- **Hidden-sector dark matter:** This refers to a general category of dark matter theories that live in their own *dark sector*, that may not interact at all (except through gravity) with the Standard Model. The physics within such dark sector could be as rich as in the Standard Model, with things such as dark atoms, dark version of electromagnetism, or dark nuclear-like physics possible. Entire copies of the Standard Model are possible. The only requirement is that the dominant particle(s) in the dark sector look like CDM on large cosmological scales. This category of models can lead to a lot of interesting phenomenologies in astrophysics, including giving dark matter significant self-interaction.

This is by no mean an exhaustive list, but it captures a lot of the main ideas for what dark matter could be.