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# Research and Analysis of The Basic Dark Matter

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**Abstract:** For centuries, dark matter has been one of the most attractive topics among physicists, because it seems to be essential for the explanation of various current cosmological observations. In this report, I first introduce some basic concepts that are essential for the understanding of dark matter. Then some important observational facts are briefly summarized and alternative approaches in order to rule out dark matter are introduced. Detailed discussions on the nature of dark matter with observational evidence and researching methods are followed where basics concepts are revised and extended. Finally, a concise introduction of different categories of dark matter candidates is provided.

## 1. Introduction

With an increasing number of new observations with regard to the universe being discovered, the profundity of knowledge concerning astrophysical working principles has been experiencing enormous improvement during the previous few decades. As a result, the presence of dark matter has been revealed by data and dark energy has been shown to be the prevailing contribution to the mean energy density of the universe. However, our understanding of dark matter is still limited since the underlying relative particle physics description remains opaque.

In order to understand dark matter (DM), several currently favored basic theories and methods are introduced in the research process. Being regarded as the foundation of cosmology, the ΛCDM model plays an important role in constructing our understanding of DM. In the ΛCDM model, the universe is described as containing three major elements, which are a cosmological constant that is connected with dark energy and denoted by $\Lambda$, along with cold dark matter (CDM) as well as ordinary matter. The great importance of this framework lies in its predictions for several important characteristics of the universe. Among these predictions, the structure of the cosmic microwave background (CMB) and the matter power spectrum $P(k)$, the spectrum showing fluctuations of density in matter, are closely related to the understanding of dark matter. The data of CMB radiation contains imprints of the annihilation and decay of DM because these processes alter the cosmic reionization process. And $P(k)$ provides a good measure of DM density fluctuations since DM is a dominant part of matter in the universe. These concepts provide a solid foundation for later discussions and will be more deeply examined in the following sections.

## 2. Evidence for the existence of dark matter

Since the first appearance of the concept of dark matter, the existence of DM has been supported by various observations, including temperature anisotropies of the CMB, rotation curves of galaxies, type Ia supernovae and baryonic acoustic oscillations[1, 2]. Since no suitable particle provided by the Standard Model (SM) of particle physics can be used to explain these observations, DM also represents an arguable glance at the physics beyond the SM.

Although compelling evidence supporting dark matter has been arising and dominant for a long period of time, this topic still remains controversial, and its opponents are constantly proposing contrary theories. Since the innovative development of the Modified Newtonian Dynamics (MOND) lay the foundation in 1982[3], a considerable number of attempts have been made, such as Emergent Gravity[4] and Modified Gravity[5], to diminish the influence of DM by adjusting Einstein's theory of

General Relativity. However successful they were, these theories are largely based on limitations, especially on rotation curves of galaxies. Moreover, it is evident now that these theories need to essentially imitate the behavior of CDM on cosmological scales in order to reconcile with observations. Additionally, observational data from GW170817[6] indicating that the discrepancy between the propagation velocity of gravitational waves and the speed of light does not exceed one part in $10^{15}$ strictly confines all theories of modified gravity stating that gravitational waves follow different geodesics from the pulse of photons and neutrinos[7, 8].

## 3. Nature of dark matter

As introduced before, the matter power spectrum $P(k)$ acts as an effective tool with the intention of studying the nature of dark matter. In fact, $P(k)$ directly encodes the clustering of DM because it shows the possible behavior of DM[9]. The matter power spectrum is a quantity that is dependent on the value of redshift, and Fig. 1 shows the measurement of $P(k)$ at $z=0$, where $\Delta^2(k) \equiv 4\pi(k/2\pi)^3 P(k)$ is the dimensionless power spectrum with the comoving wavenumber $k$, which is in great accordance with the ΛCDM prediction. Combining the shaded region, which means reliable measurements are deficient, we can have a boundary for well-measured power spectra with $k \lesssim 10-20\ \mathrm{Mpc}^{-1}$ and $M \gtrsim 10^{10} M_{\odot}$[9].

One of the most important nature of dark matter is that it is not luminous in the observed universe today. Also, combining the discussions above, observations of CMB and the matter power spectrum demand containing matter to have only gravitational interactions. Therefore, DM is expected to have an extremely low rate of interaction with SM particles because these interactions will limit DM density perturbations and suppress the power spectrum eventually as shown in the ADM (atomic dark matter) line in Fig. 1.

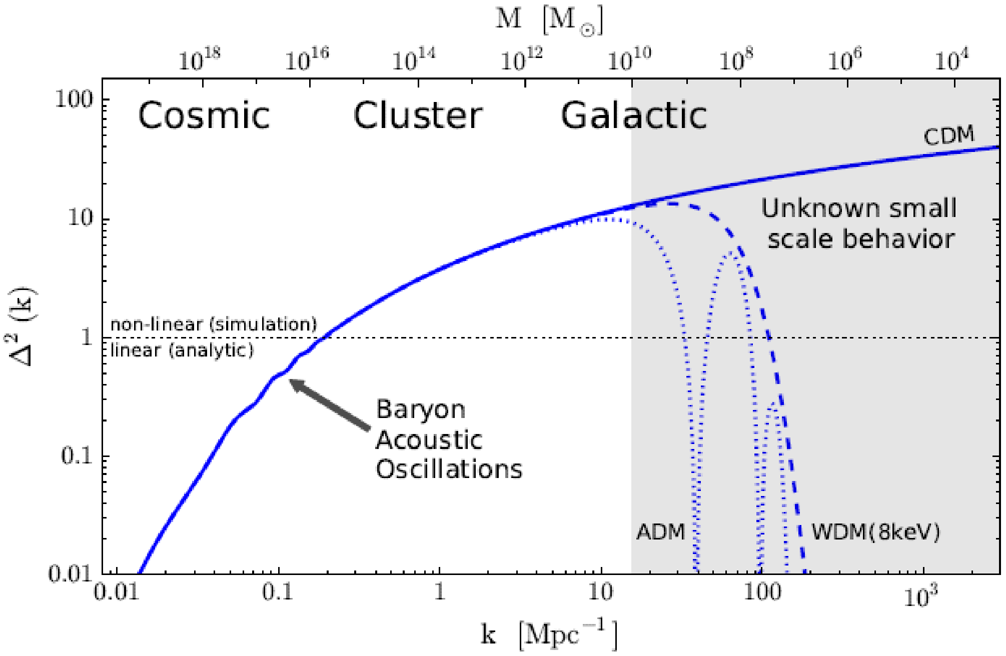

Fig. 1 The matter power spectrum of density perturbations at $z=0$, with $\Delta^2(k)$ stands for the dimensionless power spectrum. The solid blue line represents ΛCDM model while the ADM line show the model of atomic dark matter and the WDM line represents the model of warm dark matter with a mass of 8 keV. Adapted from Lin, T. (2019). TASI lectures on dark matter models and direct detection. *arXiv preprint arXiv:1904.07915*.

Another important property that can also be seen in Fig. 1 is that by $z \sim 10^7$, DM is considered sufficiently cold, which means nonrelativistic. If DM is relativistic, then the motion of the DM can eliminate its perturbations within a horizon. As a result, the power spectrum will be suppressed for any mode that enters the horizon while the DM is still relativistic, which is also shown in Fig. 1 with the WDM (warm dark matter) line[9].

Except for the popular properties mentioned above, during the research for dark matter, there are also some controversial features that are still in debate. Among them, a key property of DM that cosmological examinations might help invalidating is its collisionless nature. As discussed above, the behavior of DM at small cosmological scales is still very uncertain where disjunctions between numerical simulations and measurements are found. However, this incoherence might in fact be alleviated with dark matter self-interactions10, 11. There are many ways for searching imprint of DM self-interaction. Firstly, the evidence can be found in the shapes of DM halos because the central parts of DM halos tend to be more spherically symmetric taking self-interaction into account comparing with collisionless situations10. Another trace lies in merging systems such as minor infalls and cluster mergers12, 13. The observations are related to the offset between DM and the galaxies along with the galaxies around the center of DM halos14, 15. Moreover, it is in general worthy to search for disconnections in the ΛCDM model while cautiously looking into their inherent assumptions and predictions because DM self-interaction can in principle lead to discernable differences between observations and ΛCDM predictions15.

## 4. Candidates of dark matter

With enormous effort being put into the research for dark matter, an overwhelming number of candidates have been put forward and examined. Ranging from ultra-light DM ($\sim 10^{-22}$ eV $-$ $O$(keV)), which is also known as "fuzzy dark matter", to massive primordial black holes ($\gtrsim 10M_\odot$), DM candidates' mass cover over 90 orders of magnitude.

Besides the categories relating to the masses, thermal DM candidates, which are closely related to the concept of neutrino freezeout, have been attracting increasing attention. Thermal DM candidates are those that were in thermal equilibrium with the thermal bath of SM particles. Then only a few factors are required to determine the density and relic density of the early universe. These candidates are enticing because a large amount of information of these DM can be extracted out from the neutrino bath that can be observed in an easier way because they were in thermal equilibrium with each other throughout the early universe. Furthermore, the assumed thermal equilibrium indicates the DM and SM interactions to some extent, which is an interesting direction considering the dark nature of DM discussed above.

Another important scenario is the freeze-in, which is not strictly a thermal DM candidate. Freeze-in can be understood as a procedure in which the DM rarely interacts with the thermal bath of SM particles while the relic abundance of DM is slowly built up so that the DM is never in thermal equilibrium with the dominant thermal bath through the development of the universe. These two scenarios may lead to extremely different developments of DM and place distinctive constraints on DM candidates.

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