# Astrophysical probes of dark matter properties

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**Abstract**

Inferring the microscopic properties of dark matter from observations of cosmic structures on small scales, where viable dark matter candidates make very different predictions, is an important scientific problem for the next decade. This problem should be addressed using a combination of observational and theoretical tools. The results of this research will guide astronomical observations, will help in design and data analysis of direct and indirect detection experiments, and will ultimately facilitate identification of dark matter.

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There is overwhelming evidence that most of the matter in the universe is not ordinary atomic matter, but that it is made up of new, yet undiscovered particles. Dark matter signals new physics; its discovery will have far-reaching fundamental ramifications for astrophysics, cosmology, and high-energy physics.

Identification of dark matter must rely on some non-gravitational interactions of dark-matter particles with matter (in a direct detection experiment), or on dark matter annihilation or decay into known particles. However, nothing is known about the dark matter particles beyond their ability to interact via gravity. The route to identifying dark matter depends on the nature of its self-interactions and its interactions with the standard model particles, which have to be inferred from observations or fundamental theory. A number of candidates have been proposed based on compelling theoretical ideas and some observational clues [1]. The approaches to their experimental detection differ dramatically. Direct detection experiments searching for axion dark matter use RF photon detectors [2]. Experiments searching for supersymmetric weakly interacting massive particles (WIMPs) look for nuclear recoil in their detectors [3]. Large size detectors are used to look for very massive particles, such as supersymmetric Q-balls [4]. Among indirect detection experiments, X-ray telescopes are used to search for decays of sterile neutrino dark matter [5, 6], while gamma-ray telescopes and anti-matter detectors are used to search for WIMP self-annihilation products from our own and nearby galaxies [1]. Any data from astrophysical observations or high-energy laboratory experiments that could be used to narrow down the list of candidates would be extremely helpful in focusing the dark matter search on the right candidate(s).

At present, new observational data, coupled with advances in numerical cosmology, promise to revolutionize the field and facilitate dark matter detection via synergy between particle physics and astrophysics. Astronomical observations, for the first time, are able to determine or put stringent constraints on the micro-physical properties of dark matter by elucidating the structure on the smallest scales. Coincidentally, these are also the scales where the cold dark matter paradigm faces its biggest challenges. While all viable dark matter candidates predict the same structure on the large scales, their predictions differ dramatically on the small (sub-galactic) scales. For instance, if dark matter is made up by axions, then the small-scale cutoff in the matter power spectrum is as small as $10^{-15}M_\oplus$ [7]. Supersymmetric WIMPs would produce a much larger cutoff $(10^{-6} - 10^{2})M_\oplus$ [8]. The dark matter in the form of SuperWIMPs [9, 10] in supersymmetric theories or sterile neutrinos [11] can generate structure with a model-dependent free-streaming length in a broad range of allowed values [12, 13, 14, 15, 16] with cutoffs in the matter power spectrum on mass scales as large as $10^{8}\mathrm{M}_\odot$. Finally, there is a possibility that two or more relic particle species with different clustering properties contribute to dark matter [12, 17]. An improved understanding of the small-scale power spectrum can provide one with a powerful discriminator between different candidates.

The primordial phase-space density of dark matter gives an indication of how cold the dark matter is. It is not necessarily in a one-to-one correspondence with the filtering mass in the power spectrum, i.e. the minimum possible halo mass [18]. Since dark matter is almost collisionless, the primordial phase-space density sets the maximum density dark matter halos can have in their centers [19, 20, 12]. WIMPs, SUSY Q-balls, and axions have a very high primordial phase-space density compared to *average* phase space densities in galaxies; halos formed of these particles would show a sharp rise in density towards the center. On the other hand, warmer types of dark matter, such as sterile neutrinos and SuperWIMPs have lower primordial phase-space densities and can produce observable flat density cores in the dark matter halos of small galaxies. These cores would only be observable in the smallest galaxies because the ratio of core size to total extent is larger for smaller dark matter halos. Definitive observation of these cores in a small galaxies would favor some dark matter candidates over the others.

Dwarf spheroidal galaxies exemplify this synergy between particle physics and astrophysics and offer excellent opportunities in dark-matter research. They are low surface-brightness, gas-poor galaxies, in which the gravitational potential is dominated by dark matter. Most of the satellites of the Milky Way are dwarf spheroidal galaxies (dSphs). The internal motions of member stars can be used to map out the gravitational potential and study the spatial distribution of dark matter in the dSph [21]. A comparison of these observations with theoretical predictions of various dark matter candidates inferred from numerical calculations can be a powerful tool for understanding dark matter [22, 23]. The census of dSphs provides constraints on the small-scale matter power spectrum, while the density profile of dark matter in a dSph provides constraints on the primordial phase-space density of dark matter. In addition, the large dark matter content and the proximity of some of the dSphs makes them attractive astrophysical sources for indirect detection of dark matter. In the next decade, the astrophysical probes of dark matter using dwarf spheroidal galaxies, are likely to shed light on the microscopic properties of dark matter. An independent information on the small-scale power spectrum can be inferred from observations of Lyman-$\alpha$ forest [24, 25]. The results of this research will further focus the search for dark matter and will, hopefully, usher in the discovery of new physics responsible for cosmological dark matter.

The solution to the dark matter puzzle will require a combination of several complementary and multi-disciplinary efforts.

- Dwarf spheroidal galaxies offer unparalleled opportunities to study structure formation on small scales. Discovering the faint dSphs requires deep full-sky optical surveys, and velocity measurements require wide-field multi-object spectroscopy on large telescopes.
- Strong gravitational lensing is a powerful way to study the clustering of dark matter on the sub-galactic scales. Strong lensing of galaxies or quasars provides a unique glimpse into the substructure of the lens galaxy. Future optical and radio surveys will provide a lot of new data on the strongly lensed systems (e.g., [26]).
- Indirect detection of dark matter through its decay or self-annihilation products should be pursued using existing and future gamma-ray and X-ray telescopes such as *Fermi, Suzaku, Chandra, XMM-Newton,* as well as the future *Astro-H*. The dwarf spheroidal galaxies are ideally suited targets for future large ground-based Imaging Atmospheric Cerenkov Telescopes.
- Observations of kinematics of stars in the local galactic neighborhood will provide

important constraints on the local dark matter phase-space distribution in the Milky Way halo. This is crucial input for the direct detection experiments.

- Theoretical work is required to understand the observed small-scale structure in dark matter, to connect it to particle physics models, and to take full advantage of the data that we expect in the next decade. This includes greatly improved numerical simulations of small-scale structure formation and the Local Group in cold and warm dark matter models (see, e.g., [27]).

The combination of theoretical work, observations, and direct detection experiments can lead to major breakthroughs in understanding the nature of dark matter in the next decade.

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