Snowmass2021 - Letter of Interest

Testing the Nature of Dark Matter with Extremely Large Telescopes

Thematic Areas: (check all that apply ☐/■)

☐ (CF1) Dark Matter: Particle Like
☐ (CF2) Dark Matter: Wavelike
■ (CF3) Dark Matter: Cosmic Probes
☐ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
☐ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
☐ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
☐ (CF7) Cosmic Probes of Fundamental Physics
☐ (Other) *[Please specify frontier/topical group]*

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Abstract: For nearly 40 years, dark matter has been widely assumed to be cold and collisionless. Cold dark matter (CDM) models make fundamental predictions for the behavior of dark matter on small ($\lesssim$ 10 kpc) scales. One of the key CDM predictions is that dark matter halos should have cuspy ($\rho \propto r^{-1}$) central density profiles. We argue for an experimental program relying on extremely large telescopes (ELTs) to critically test this prediction, and thus shed new light on the nature of dark matter. By combining adaptive optics-enabled imaging with deep spectroscopy to measure the three-dimensional motions of stars within a sample of Local Group dwarf galaxies that are the cleanest dark matter laboratories known in the nearby universe, the inner slope of the dark matter density profile can be determined with an accuracy of 0.20 dex, enabling a central cusp to be distinguished from a core at 5σ significance. This experiment will produce important constraints on the properties of dark matter on small scales, allowing conclusive tests of alternative warm, fuzzy, and self-interacting dark matter models.

The nature of dark matter remains one of the most important questions in physics. Because of the tremendous overall successes of the dark energy + cold dark matter (ΛCDM) model, dark matter is widely assumed to consist of a massive, weakly-interacting particle. However, decades of effort to detect such a particle with accelerators, direct detection experiments, and indirect searches for the products of dark matter annihilation or decay have thus far failed to identify any signature of the dark matter particle. At present, astrophysical measurements still represent our only means of directly studying the properties of dark matter.

1 The Cusp-Core Problem

Although the large-scale structure of the universe is described extremely well by the ΛCDM paradigm, numerical simulations have identified possible discrepancies with the observed properties of galaxies on small scales (< 10 kpc). In particular, in the absence of self-interactions or interactions with baryons, halos composed of massive dark matter particles should follow a universal density profile, with $\rho \propto r^{-1}$ at small radii and $\rho \propto r^{-3}$ at large radii (e.g., Navarro et al., 1996). However, observations of dark matter-dominated galaxies and galaxy clusters generally find shallower density profiles, in some cases with nearly constant-density central cores (e.g., Flores & Primack, 1994; Moore, 1994; Oh et al., 2011; Newman et al., 2013; Adams et al., 2014; Relatores et al., 2019). This cusp-core problem has persisted for 25 years despite major improvements in both simulations and observations. Currently-favored explanations for the problem include modifications to the gravitational potential of galaxies by repeated episodes of strong stellar feedback (e.g., Governato et al., 2012) or alternative dark matter models (e.g., Spergel & Steinhardt, 2000; Kaplinghat et al., 2016; Zavala et al., 2019). Although shallow density profiles can plausibly be explained without invoking a crisis for the ΛCDM model, new observations are required to verify the proposed solution and demonstrate that the predictions of ΛCDM on small scales are accurate.

Dark matter density profile measurements in the nearby universe have generally focused on low-mass disk galaxies, which contain significant baryonic components. Vigorous star formation in these systems may alter the original distribution of dark matter (e.g., Di Cintio et al., 2014), complicating the comparison between observations and dark matter model predictions. Ideally, one would prefer to determine the density profiles of the most dark matter-dominated objects known, the dwarf satellites of the Milky Way. The smallest dwarf galaxies are so dark matter-dominated that stellar feedback is unlikely to have affected their dark matter halos on ~ 100 pc scales (e.g., Bullock & Boylan-Kolchin 2017). Many studies have attempted to constrain the dark matter distribution in Milky Way dwarf spheroidals via line-of-sight velocity measurements, but the degeneracy between the mass profile and the stellar orbital anisotropy has led to conflicting results (e.g., Battaglia et al., 2008; Amorisco & Evans, 2012; Breddels et al., 2013; Strigari et al., 2017).

2 An Observational Path Forward

Combining radial velocity and proper motion measurements for stars in a dwarf galaxy would tightly constrain the stellar orbits within the galaxy and break the degeneracies that have plagued previous density profile studies. Obtaining such 3D motions requires both spectroscopy and high-precision astrometry. Theoretical modeling suggests that velocity measurements accurate to $\sim$ 3 km s^{-1} in each dimension for a sample of ~ 300 stars is the minimum necessary to reliably recover the gravitational potential (e.g., Strigari et al., 2007). Proper motions of faint dwarf galaxy stars at the required accuracy can only be measured with ground-based telescopes via laser guide star adaptive optics (AO) imaging. Here the AO field of view is critical, because the surface density of member stars at the relevant magnitudes is < 0.1 arcsec^{-2}, requiring large fields to obtain the sample needed to determine the tangential velocity dispersion. A velocity uncertainty of 3 km s^{-1} translates to a proper motion uncertainty of 6.3 $(100\,\mathrm{kpc}/d)$ μas yr^{-1}, or 7.9 (21.0) μas yr^{-1} at a distance of 80 (30) kpc. With the anticipated ~ 15 μas astrometric error floor of a 30 m telescope (Wright et al., 2016), these proper motions could be measured over a time baseline of a few years.

Radial velocities for dwarf galaxy member stars can be obtained with multi-object spectrographs on large (> 6 m) telescopes. Velocity measurements for faint stars have been demonstrated at the 1.5 km s^{-1} level at $R = 6000$ (Keck/DEIMOS; Kirby et al., 2015) and the 1.0 km s^{-1} level at $R = 12000$ (Magellan/IMACS; Simon et al., 2017) with existing instruments. We recommend that future spectrographs on large telescopes (1) plan to incorporate gratings that will provide a spectral resolution of at least $R = 6000$ at the wavelength of the Ca triplet absorption lines (~ 8500 Å) and/or the Mg b triplet (~ 5200 Å), and (2) are designed to maximize stability. Milky Way satellite galaxies typically have half-light radii of $\sim 10'$, so the larger the field of view and multiplexing that can be achieved, the more efficiently the observations can be obtained.

Whether ELTs or space-based observing platforms will ultimately prove most capable for the necessary astrometry is currently not clear. ELTs offer several key advantages (angular resolution, collecting area, required time baseline), while space telescopes offer others (field of view, stability, number of possible targets). Given the technical challenges in making astrometric measurements at the required accuracy with either approach, pursuing both appears wise.

A key goal of the US ELT program should therefore be to obtain radial velocities and measure proper motions of $\gtrsim 300$ stars per galaxy in several Milky Way satellites, with a typical accuracy per star of 3 km s^{-1} (Fig. 1). These measurements will directly determine the velocity anisotropy of the stellar orbits within each dwarf, enabling tight constraints to be placed on the inner density profiles of their dark matter halos. Observations of multiple dwarf galaxies will determine the range of halo profiles that exist and avoid the possibility of being misled by the unique history of any individual galaxy.

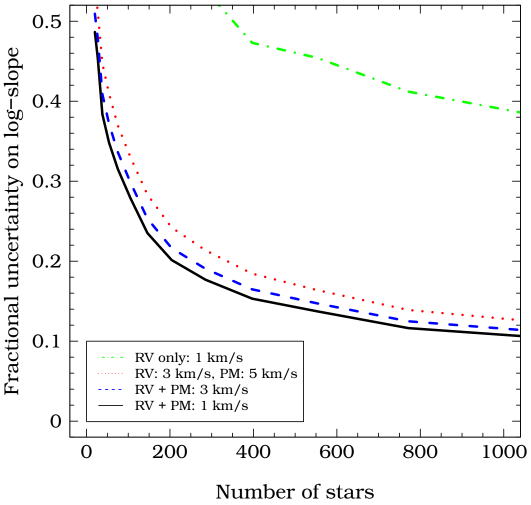

Figure 1: Simulated recovery of the dark matter density profile of a dwarf spheroidal galaxy via stellar kinematic data (based on the results of Strigari et al. 2007). Including 3D stellar velocities (red/blue/black curves) dramatically reduces the uncertainty on the central slope of the density profile relative to a data set consisting only of radial velocities (green curve). For a sample of 300 stars with proper motion and radial velocity uncertainties of 3 km s^{-1}, the expected measurement uncertainty on the slope is 0.2, enabling a 5σ detection of a central density cusp.

The ideal targets for an ELT-based density profile experiment should satisfy the following criteria: (1) Low stellar mass ($< 10^6\ M_\odot$), to minimize stellar feedback effects on the galaxy's mass distribution; (2) High stellar surface density, to minimize the number of pointings needed to reach a sample of 300 proper motion measurements; (3) Large velocity dispersion, to increase the expected proper motion signal; (4) Small distance, to increase the expected proper motion signal and maximize the brightness of each star; and (5) An orbit that does not approach the Milky Way too closely, to minimize the impact of Galactic tides on the structure of the dwarf. Clear choices include Draco and Ursa Minor in the north, and Sculptor and Carina in the south. Simple ELT exposure time estimates indicate that the required tangential velocity accuracy of 3 km s^{-1} can be obtained with ~ 16 hr integrations per pointing and a time baseline of 5 years. Imaging of 5 pointings per galaxy would provide a sample size of 300 stars in each target. The dark matter density profile of one dwarf could therefore be measured with a total investment of ~ 160 hrs.

We recommend that the Snowmass process endorses ELTs as key facilities for next-generation cosmic dark matter probes and considers supporting ELT instrumentation that will enable dark matter experiments.

References

Adams, J. J., Simon, J. D., Fabricius, M. H., et al. 2014, ApJ, 789, 63

Amorisco, N. C., & Evans, N. W. 2012, MNRAS, 419, 184

Battaglia, G., Helmi, A., Tolstoy, E., et al. 2008, ApJ, 681, L13

Breddels, M. A., Helmi, A., van den Bosch, R. C. E., van de Ven, G., & Battaglia, G. 2013, MNRAS, 433, 3173

Bullock, J. S., & Boylan-Kolchin, M. 2017, ARA&A, 55, 343

Di Cintio, A., Brook, C. B., Macciò, A. V., et al. 2014, MNRAS, 437, 415

Flores, R. A., & Primack, J. R. 1994, ApJ, 427, L1

Governato, F., Zolotov, A., Pontzen, A., et al. 2012, MNRAS, 422, 1231

Kaplinghat, M., Tulin, S., & Yu, H.-B. 2016, Phys. Rev. Lett., 116, 041302

Kirby, E. N., Simon, J. D., & Cohen, J. G. 2015, ApJ, 810, 56

Moore, B. 1994, Nature, 370, 629

Navarro, J. F., Frenk, C. S., & White, S. D. M. 1996, ApJ, 462, 563

Newman, A. B., Treu, T., Ellis, R. S., & Sand, D. J. 2013, ApJ, 765, 25

Oh, S.-H., Brook, C., Governato, F., et al. 2011, AJ, 142, 24

Relatores, N. C., Newman, A. B., Simon, J. D., et al. 2019, ApJ, 887, 94

Simon, J. D., Li, T. S., Drlica-Wagner, A., et al. 2017, ApJ, 838, 11

Spergel, D. N., & Steinhardt, P. J. 2000, Phys. Rev. Lett., 84, 3760

Strigari, L. E., Bullock, J. S., Kaplinghat, M., et al. 2007, ApJ, 669, 676

Strigari, L. E., Frenk, C. S., & White, S. D. M. 2017, ApJ, 838, 123

Wright, S. A., Walth, G., Do, T., et al. 2016, in Proc. SPIE, Vol. 9909, Adaptive Optics Systems V, 990905

Zavala, J., Lovell, M. R., Vogelsberger, M., & Burger, J. D. 2019, Phys. Rev. D, 100, 063007