Snowmass2021 - Letter of Interest

Novel dynamical probes of dark matter on small scales

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: We outline new dynamical probes of dark matter on small scales in our Galaxy that will be observationally feasible within the next decade. Uncertainties in characterizing the local, small-scale distribution of dark matter are the key limitation for both particle dark matter searches as well as testing the concordance CDM paradigm. Accurate maps of the Galactic potential derived from studies that combine nearby (< 10 kpc from the Sun) and distant probes that extend into the stellar halo have the potential to transform our understanding of dark matter by revealing its detailed sub-structure. Measuring Galactic accelerations by using high precision spectrographs can realize this goal within the next decade. Unlike density estimates using velocity profiles, which depend on the assumption of dynamical equilibrium, Galactic accelerations allow dark matter densities to be calculated directly from the Poisson equation given an accounting of the baryon budget via luminous matter. The analysis of high resolution simulations that include both cold dark matter models and alternatives can provide a testing bed relative to the data to ultimately determine the nature of dark matter. At the same time, planned and proposed astrometric, spectroscopic and photometric surveys, building on recent advances by the *Gaia* astrometric survey will lead to a complete multidimensional view of our Galaxy. Multidimensional studies of the Milky Way beyond the *Gaia* frontier—from the edge of the Galactic disk to the edge of our Galaxy's dark matter halo—will unlock new scientific advances in both fundamental physics and across astrophysics, from constraints on dark matter to insights into galaxy formation.

The upcoming decade can help to reframe our understanding of the nature of dark matter, due to upcoming observational facilities, alongside sophisticated computational modeling to understand the interplay of different dark matter models within a realistic framework that includes baryons. The Milky Way (MW) offers a unique physical laboratory as current particle searches are hamstrung by uncertainties in the local dark matter density. There is also a history of mismatches between theoretical predictions of CDM and observations that have challenged the current paradigm[2]. We discuss a new approach to directly measure the local acceleration that provides a measurement of the density and dark matter sub-structure (down to $\sim$ Earth-mass scale sub-halos for current facilities). This new probe, feasible with current and upcoming facilities, offers a very powerful discriminant of dark matter models on the smallest scales. We discuss here dynamical methods to investigate dark matter nearby ($\sim$ 10 kpc from the Sun), and distant probes that extend into the stellar halo.

Nearby Probes: To constrain the nature of dark matter from direct detection experiments requires an independent measure of the dark matter density[13]. A commonly used method infers the total density from the Jeans analysis (which assumes equilibrium) using stellar velocity dispersions[10;11;13], and the dark matter density, given an accounting of the baryon budget. Recent work has shown that there are significant differences between the *true* density measured in a simulation and the density inferred from using the Jeans approximation, especially in regions where the Galaxy is perturbed[8]. Analysis of *Gaia* data has revealed the so-called phase-space spiral[1], as well as the Enceladus merger[9], clearly indicating a Galaxy out of equilibrium. Thus, methods that assume spherical symmetry and equilibrium are likely inaccurate for the MW.

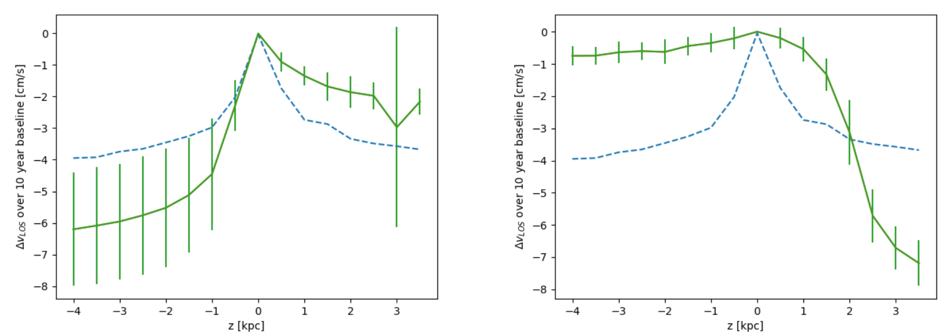

Figure 1: (a) Change in the line-of-sight velocity over a ten year baseline for a simulation of MW interacting with the Antlia 2 dwarf galaxy at present day (solid line) and at early times prior to the interaction with Antlia 2 (dashed line)[3]; solid line shows the average over a ring of radius r = 8 kpc, and the error bars show the standard deviation along the azimuth (b) $\Delta v_{LOS,z}$ for the interaction of the Sagittarius dwarf galaxy with the MW[3], with the dashed line displaying the acceleration profile at early times, and the solid line corresponding to the present day. Adopted from Chakrabarti et al. 2020.

Accelerations of stars several kpc from the Galactic mid-plane that can be measured with current and future high resolution spectrographs give *the most direct constraint* on the total density[4;17], i.e., from the Poisson equation. This measurement can also yield constraints on sub-structure along the line-of-sight. Figure 1 depicts the change in the line-of-sight velocity over a time baseline of ten years, Δv_{LOS}, for a simulation of the Antlia 2 dwarf interacting with the Milky Way, and a simulation of the Sgr dwarf interaction, as described in earlier work[3]. The simulations are evolved forwards from the recent cosmological past to present day. The present day vertical acceleration profile is shown in the solid lines, and the vertical acceleration profile at early times (prior to the interaction with the dwarf galaxy) is shown in the dashed line.

The Sun is taken to be along a ring of radius r = 8.1 kpc, and the vertical acceleration is calculated at various azimuths. Both these interacting simulations show a clear asymmetry in the acceleration profile, particularly for $|z| > 1$ kpc relative to the Galactic mid-plane. Moreover, the acceleration profile develops this asymmetry following the interaction, as is clear from comparing the early-time (i.e., prior to the interaction) acceleration profile (shown in the dashed lines) with the present-day acceleration profile, where the latter is distinctly more asymmetric. Chakrabarti et al.[4] demonstrate that contaminants (planets and binaries) to the Galactic signal are only a very small fraction of the signal in the regime where one would make this measurement. This shows that the measurement is indeed viable in the coming decade.

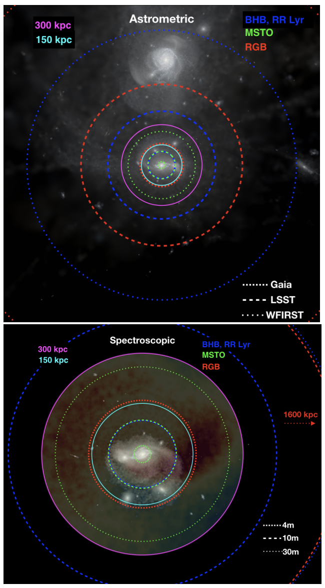

Figure 2: Distances to which individual stellar tracers will be detected by astrometric (top), and spectroscopic (bottom) instruments proposed for the next decade, superimposed on a simulated pair of galaxies resembling the MW and M31[6], Adopted from Sanderson et al. (2019).

While analysis of cold-dark matter models from controlled simulations show clear asymmetries[4] in the vertical acceleration profile, we have yet to explore alternate dark matter models for this new observable. Alternative dark matter scenarios, such as SIDM, WDM and FDM, predict characteristic cut-off scales in the linear power spectrum, which could lead to distinct signatures in the minimal halo mass and abundance of sub-structures. It will be of interest to analyze benchmark simulations for these scenarios, which can be tested using high precision RV measurements. Cosmological simulations may also have more complex acceleration profiles than controlled simulations. Pulsar timing is a complementary approach to constraining sub-structure[12], which with Square Kilometer Array, may extend to nearby galaxies.

Probes for the distant stellar halo: Sanderson et al.[15] describe expected advances from synthetic observations of simulations[7;16] that are focused on improvements in the stellar halo. *Gaia* will measure proper motions (PMs) for over 1 billion stars; however, because of its limiting magnitude of $G \sim 20$, the most distant stars in the *Gaia* sample will be at 100 kpc, only $\sim 1/3$ of the way to the virial radius (Figure 2). The panels have different scales; Galactocentric radii of 150 kpc (cyan; the limit of current tracer populations) and 300 kpc (magenta; the approximate virial radius of the MW) are shown for reference. In addition, beyond $\sim$ 15 kpc in the halo, *Gaia* (and subsequent spectroscopic follow-up programs) cannot provide kinematic information for individual main sequence stars. The bottom panel shows also a prediction for the dark-matter wake induced by the LMC[5]. LSST will provide phenomenal photometric depth over the southern sky, and return PMs for stars in the magnitude range $r \sim 19$–24, but the PM measurement uncertainties are too large to study individual stars at large distances. At $R_{Vir} \sim 300$ kpc, projected LSST PM uncertainties (~ 0.5 mas/yr at $r \simeq 23$) correspond to a velocity uncertainty of ~ 700 km/s, while the circular speed is $\sim$150 km/s. The Wide Field Imager (WFI) planned for the Roman telescope will provide the ideal complement to the Vera Rubin Observatory. With 100 times the FOV area and similar image quality to *HST*, Roman will achieve both the precision and depth of astrometry needed to target the faint MW stellar halo with measurement uncertainties as low as 25 μas yr^{-1} in the High Latitude Survey[19] of about 2200 deg^2.

Measuring 3D motions of dynamical tracers in the halo can constrain both the mass profile and the total MW mass; our current understanding is confined to $r < 40$ kpc from the Galactic center. The shape of the Galactic halo could differentiate between different DM models[14;18] but current constraints are inconclusive, hampered by insufficient data and simplistic models. ***More sophisticated models coupled with observations from current and upcoming facilities can fundamentally reshape our thinking about the nature of dark matter in the coming decade, if PIs, and collaborations between theorists and observers are supported.***

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