Snowmass2021 - Letter of Interest

Halometry: Searching for Dark Structures with Astrometric Surveys

Thematic Areas:

☐ (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
■ (TF09) Astroparticle Physics & Cosmology

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Abstract:

In this research program, we aim to detect low-mass dark matter substructures in the Milky Way solely through their gravitational lensing signatures on luminous background sources. We have developed several analysis techniques and protocols that can tease out these lensing-induced angular deflections, which imprint correlated distortions on the motions of background stars, quasars, and galaxies. Ongoing astrometric surveys such as *Gaia* will probe large parts of viable parameter space where structure formation is enhanced at small scales. Upcoming and proposed surveys such as the Nancy Grace Roman Space Telescope, Square Kilometer Array, and *Theia* will greatly extend the discovery reach, and may be sufficiently sensitive to detect dark subhalos, entirely devoid of stars. Such a discovery would have far-reaching implications for early structure formation, astroparticle physics, and (in)direct detection of dark matter.

Background: The precise nature of the constituents of the dark matter (DM) and their microphysical properties is not known. While a wealth of information has been collected about its macroscopic properties and behavior, detection of smaller DM structures is increasingly challenging due to their lower light-to-mass ratios; DM halos with masses below $\lesssim 10^8\,M_\odot$ do not harbor conditions for star formation and are thus effectively dark[1–3]. Methods reliant on the minimal coupling to gravity include fluctuations in extragalactic strong gravitational lenses[4–24], wakes in the MW stellar halo[25;26], diffraction of gravitational waves[27], photometric irregularities of micro-caustic light curves[28], and perturbations of cold stellar streams[29–35] (with tentative detections[36;37]). These techniques show promise but are indirect and/or applicable to extragalactic structures only. Direct searches for MW substructure have so far been confined to transients in photometric lensing[38–43] and pulsar timing[44–50], which would produce detectable signals for ultracompact objects such as black holes but not for more extended structures such as halos that collapse after matter-radiation equality.

Inferring Galactic Substructure with Astrometry: Astrometry—the precise measurement of the positions and motions of celestial objects—is currently in a golden age, with high quality astrometric datasets available via the *Gaia* satellite. Gravitational lensing of luminous sources by foreground Galactic DM subhalos would induce angular deflections in the apparent positions of the background sources. Ref.[51] suggested detecting this lensing effect in the *time-domain*, *i.e.*, looking for the apparent motion—angular velocity and acceleration—of celestial objects. Several categories of observables were presented with the goal of characterizing the properties of DM subhalos within the Milky Way halo—*halometry*—through astrometric effects measurable by upcoming surveys. Two subsets of these observables were investigated more thoroughly and validated on *Gaia* astrometric data in Refs.[52;53], both described in more detail below. With this Letter, we express our intent to pursue this program of qualitatively new searches for Galactic DM substructure using time-domain astrometric weak gravitational lensing.

A discovery of dark low-mass substructures with the techniques presented, possible with future astrometric surveys, would be a watershed event. Because of the absence of baryonic feedback, their abundance, mass function, and density profiles would provide a transparent window on the primordial fluctuation spectrum and the DM transfer function on comoving scales below $\sim 0.1\,\mathrm{Mpc}$. It would probe the spectrum of adiabatic perturbations produced from the inflationary stage after the one measured in the CMB[54;55] and the Ly-α forest[56], and of small-scale isocurvature fluctuations produced from *e.g.* a late phase transition in the DM sector[57;58]. This would rule out or provide evidence for small-scale structure suppression—an unavoidable prediction of, among others, light fermion ("warm")[59–61] and ultralight scalar ("fuzzy")[62–64] DM models. Enhanced-density subhalos can result from dissipation and self-interactions in the DM sector[65–67], or early-time structure growth in axion DM models with large misalignment[68]. A localized detection and characterization of a dark subhalo would also be a supreme target for indirect detection signatures from DM annihilation or decay, due to a (likely) small baryonic background[69].

Local Astrometric Searches: The lensing correction assumes a characteristic spatial pattern that can be searched for in large astrometric catalogs of luminous sources. The first method, originally introduced in Ref.[51], proposes the detection of the local lensing pattern through a matched-filter velocity template. The aim is to detect individual lenses by computing the degree of overlap between the velocity field of background sources and the one induced by a tentative lens candidate, marginalizing over possible lens and background characteristics. Ref.[52] presented a simulation-based data analysis pipeline to search for the lensing signal, which includes appropriate sample selection, background subtraction, handling of systematics, and evaluation of the test statistic. Applying the analysis to stars in the Magellanic Clouds (MCs) from *Gaia* DR2, an upper bound on the population of Galactic subhalos was obtained, with the best sensitivity corresponding to lens masses of $\sim 10^8 M_\odot$ and sizes $\lesssim 1$ pc. While these results currently only constrain an $\mathcal{O}(1)$ fraction of the DM abundance in compact halos, the sensitivity reach is expected to improve rapidly over time, and with the use of data from upcoming surveys.

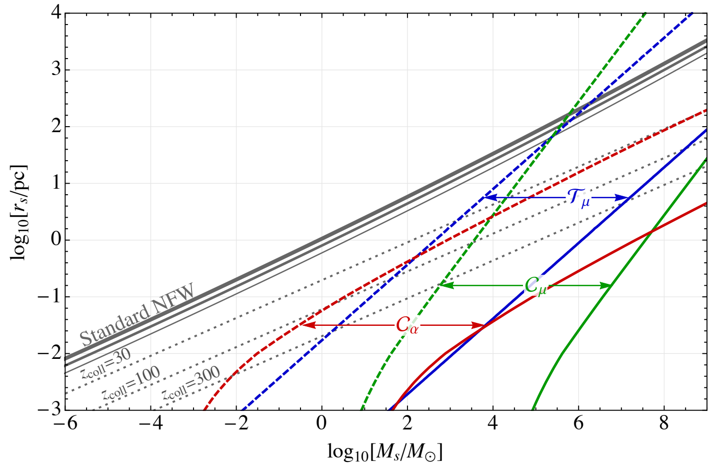

Figure 1: Sensitivity projections for subhalos as a function of NFW (Navarro-Frenk-White) core mass M_s and scale radius r_s. The blue solid (dashed) curves corresponds to the template velocity search $\mathcal{T}_\mu$, assuming a proper motion error of $\sigma_{\mu,\rm eff} = 200(1)$ μas y^{-1}, number of stars $N_0 = 10^7(10^8)$, and angular area $\Delta\Omega = 0.01(4\pi)$, representative of *Gaia* observations toward the MCs (SKA radio astrometry of quasars). The green solid (dashed) curves show the global $\mathcal{C}_\mu$ velocity correlation sensitivity for $\sigma_{\mu,\rm eff} = 10(1)$ μas y^{-1}, $N_0 = 10^6(10^8)$, and $\Delta\Omega = 4\pi$, representative of near-future (far-future) astrometric observations of quasars in the radio and visible bands. The red solid (dashed) curve depicts the sensitivity for global acceleration correlations $\mathcal{C}_\alpha$, assuming an angular acceleration precision of $\sigma_{\alpha,\rm eff} = 10(0.1)$ μas y^{-2}, $N_0 = 10^9(10^{10})$, and $\Delta\Omega = 0.2$ for *Gaia* (*Theia*) observations of Galactic disk stars. The "standard" NFW subhalo expectation is shown in solid gray ref.[78] for subhalo distance $\{240, 10, 5\}$ kpc from the Galactic Center (closer ones being denser), as well estimates for nonstandard collapse redshifts $z_{\rm coll}$ (dotted gray).

Global Astrometric Searches: Complementary to local searches for individual dark subhalos, astrometric observations can also be used to search for the *global* effects of a Galactic substructure population. Methods based on looking at correlations of the substructure-induced proper motion fields, first presented in Ref.[51], were extended and recast in the ubiquitous language of angular power spectra in Ref.[53]. The power spectrum approach can be used to effectively tease out the astrometric lensing effects of a substructure population using data collected over large regions of the sky. By leveraging the aggregate population signal, these methods can be preferentially sensitive to more extended subhalos than those probed by local approaches. A power spectrum decomposition of the celestial proper motion field also provides a number of cross checks—based on the unique spectral properties of a lensing signal—that can be used to distinguish a signal sourced by a subhalo population from that arising due to unmodeled backgrounds. A proof-of-principle application was demonstrated in Ref.[53] by performing a vector power spectrum decomposition of the *Gaia* DR2 quasar proper motion field, with significant gains expected from future surveys and datasets.

Sensitivity Projections and Future Astrometric Surveys: With limited integration time $t_{\rm int}$, currently at 22 months for *Gaia* DR2, astrometric constraints are statistics-limited now and for the foreseeable future. This dataset still contains partial instrumental calibration errors, inadequate background estimation, underestimates of centroid location uncertainties, and mislabeling of the sources' properties, among other uncertainties[70;71]. The improvement of such issues in view of the fivefold increase of *Gaia's* operational time span warrants that the proper motion (proper motion acceleration) error will scale with time at least as fast as $t_{\rm int}^{-3/2}$ ($t_{\rm int}^{-5/2}$), boosting the sensitivity of the analyses developed and delivering parametric leaps in reach in the near future. The dashed lines in Fig. 1 show the end-of-mission sensitivity of *Gaia* to NFW subhalos[72] (solid lines) through the use of correlation ($\mathcal{C}$) and template ($\mathcal{T}$) observables of the proper motion (μ) and proper motion acceleration (α). Beyond *Gaia*, upcoming and proposed missions with astrometric capabilities such as *Theia*[73], Nancy Grace Roman Space Telescope[74], and Square Kilometer Array (SKA)[75–77] will greatly expand the discovery reach by opening up the sub-μas astrometry frontier. Figure 1 also displays the corresponding projected sensitivities of SKA and *Theia* (dashed lines) to NFW subhalos.

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