

Dark Matter on small scales: Precise dynamical analysis of dwarf spheroidal galaxies with Roman and Subaru-PFS

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Required Observation Plans of Subaru Telescope:

- Subaru instruments: Prime Focus Spectrograph (PFS)

No requirements for number of nights, condition, time criticality with respect to Subaru observations. This is because the PFS observations for the Galactic dwarf spheroidal galaxies (dSphs) are planned for the Subaru Strategic Program (SSP) survey, which will start from this semester (25A). We have scheduled a total of 72 hours for six dSphs (Boötes I, Draco, Ursa Minor, Sextans, Sculptor, and Fornax).

Relevance to the Roman Core Community Survey (CCS) or other Roman programs:

Our study is relevant to:

1. High Latitude Wide Area Survey (HLWAS),
2. Roman Infrared Nearby Galaxy Survey (RINGS),
3. the CCS science pitch by Prof. Ting Li (titled as Exploring Milky Way's stellar streams, dwarf galaxies, and star clusters with Roman),
4. RomAndromeda: The Roman Survey of the Andromeda Halo led by Prof. Arjun Dey.

The HLWAS definition committee has proposed that HLWAS will observe not only 2400 deg² with Y, J, H-bands plus grism spectroscopy, but also 2700 deg² with H-band. The Galactic dSphs as PFS targets (Fornax, Sculptor, Sextans) can be included in HLWAS field.

Relevance Scientific Rationale/Justification:

Background

Dwarf spheroidal galaxies (dSphs) in the Milky Way are excellent laboratories to shed light on the basic properties of dark matter because these galaxies are largely dark matter dominated systems with total dynamical mass to light ratio of 10 to 1000. Because of their proximity, the line-of-sight velocities for resolved stars of these dSphs can be measured precisely by high-resolution spectroscopy (e.g., Simon & Geha 2007; Walker et al. 2009). Consequently, many studies have used their kinematic data to estimate dark matter distributions, which can be compared with the predictions of the standard Λ -dominated Cold Dark Matter (Λ CDM) model. These estimates also provide robust constraints on dark matter candidates, such as self-interacting dark matter and fuzzy dark matter (see Bullock & Boylan-Kolchin 2017 for a review), as well as indirect dark matter searches for eV- to TeV-scale dark matter.

Recent dynamical studies of the Galactic dSphs suggest that these galaxies exhibit a diversity of inner dark matter density slopes (Read et al. 2019; Hayashi et al. 2020). However, significant uncertainties remain in the estimated dark matter density profiles due to limitations in data volume, kinematic information, and dynamical modeling.

One of the major challenges is the complete lack of direct constraints on the velocity anisotropy of stars in the dSphs, as only their line-of-sight velocities are observable. This anisotropy is therefore treated as a free parameter, leading to a strong degeneracy with the inferred dark matter density profile – a problem known as the “mass-anisotropy degeneracy”. To break or mitigate this degeneracy, it is essential to complement line-of-sight velocity measurements with proper motions of individual stars within dSphs (Read et al. 2021).

Recently, Vitral et al. (2024) analyzed four epochs of Hubble Space Telescope (HST) imaging over 18 years as part of the HSTPROMO campaign for the Draco dSph. They measured the proper motions of 364 stars and combined them with existing line-of-sight velocities to obtain, for the first time, resolved 3D velocities of Draco. Using this 3D velocity data, they found that Draco most likely has a cusped dark matter density profile. However, large uncertainties still remain in their estimated dark matter density profile because the number of 3D data points is yet be statistically insufficient to place robust constraints on it.

Here we propose to measure the line-of-sight velocities and proper motions of their member stars through a synergistic observational campaign combining the Subaru Prime Focus Spectrograph (PFS) and the Nancy Grace Roman space telescope (Roman).

Subaru-PFS dwarf galaxy survey

The PFS attached on the Subaru telescope has spectra from 2,394 fibers distributed in 1.25 square degrees hexagonal field-of-view and covers a wide wavelength range (380-1260 nm) in a single exposure (Takada et al. 2014). Therefore, the PFS will have remarkable capability to obtain large number of line-of-sight velocity data of individual stars within the dSphs.

Figure 1 shows the planned PFS pointings (black hexagons) for Draco dSph, which is one of the primary targets of the PFS observations. PFS will be able to cover a large area inside and beyond the tidal radius of the dSph (dashed ellipse in Figure 1). Regarding the data volume, the PFS will obtain thousands of stellar spectra of their member stars down to $g \sim 23$ mag. This will increase the number of velocity measurements to ten times that of the currently available data.

Figure 2 demonstrates the dynamical analysis (axisymmetric, second-velocity moment Jeans analysis) applied to mock data for a Draco-like dSph. The current data are limited both in the number of kinematic samples (approximately 500 stars) and in the extent of the survey area. On the other hand, thanks to the wide and deep PFS observations, we will obtain line-of-sight velocities for approximately 5,000 stars. This will allow us to recover the input dark matter density profile across the full range of radii probed by the spectroscopic sample.

Notably, the large spectroscopic survey of the Galactic dSphs by the PFS is one of the primary scientific goals of the Subaru Strategic Survey Program (SSP), which will begin in March 2025. In the Subaru-SSP, we have scheduled a total of 72 hours for six dSphs (Boötes I, Draco, Ursa Minor, Sextans, Sculptor, and Fornax).

Roman astrometry and synergy with Subaru-PFS

The Roman space telescope will be capable of measuring precise astrometry for resolved stars across the wide field of view of the Wide-Field Instrument (WFI), enabling us to obtain proper motions of individual stars within dSphs. Given that the typical internal velocities of these stars are around 10 km/s, we expect proper motions of approximately 30 microarcsec/yr for a dSph at 70 kpc from the Sun. This expected proper motion should be achievable with Roman astrometry over five years coordinated observations of stellar positions. Figure 1 shows the proposed Roman printings (magenta) for Draco. Owing to its large Field-of-view, Roman will enable us to obtain proper motions of member stars across the entire region of the dSph.

The synergistic observations between Roman and Subaru-PFS for these Milky Way's dSphs will provide a large number of 3D stellar motions for their resolved stars, placing new and stringent constraints on the dark matter distributions of the dSphs.

Here we propose an initial two-epoch Roman survey of the Galactic dSphs, which will yield proper motions for all RGB stars brighter than $F146 \approx 24.0$ AB mag. We request two-band Roman observations using the F146 and F062 filters. The F146 broad-band filter provides the deepest imaging due to its wide wavelength coverage, while F062 offers the smallest Point Spread Function (PSF), which can help improve the centroid measurements derived from the F146 data. To achieve the highest precision in proper motion measurements, we propose maximizing the time baseline by scheduling the three epochs in the first, third, and fifth years of Roman’s science operations.

Optionally, this survey plan can be partially accomplished through the HLWAS. The current HLWAS plan includes observations of 2,400 square degrees using the Y, J, and H bands (F106, F129, and F158 filters) along with grism spectroscopy, as well as 2,700 square degrees in the H band. The Fornax, Sculptor, and Sextans dSphs, which are PFS targets, should be included in the HLWAS survey area. Although the F062 and F146 filters are not part of the HLWAS survey plan, proper motions of stars can still be obtained using the J and H bands as an alternative approach (The WFIRST Astrometry Working Group 2019).

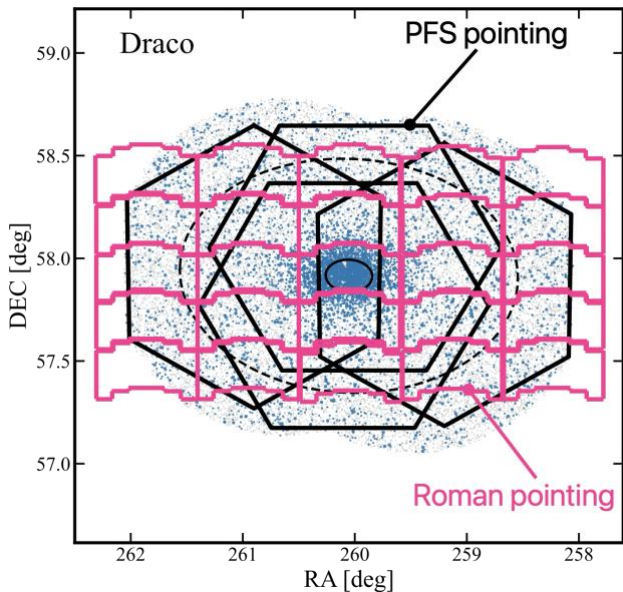


Figure 1: The planned PFS (black hexagon) and Roman (Magenta) pointings for Draco dSph. The blue and gray dots in each panel are member and non-member star candidates selected by Subaru Hyper Suprime Cam photometry. The solid and dashed ellipses show the core and tidal radius fitted by King models.

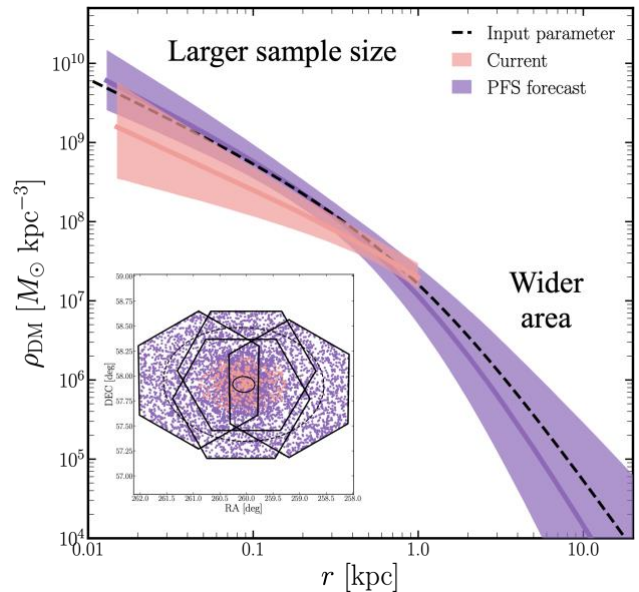


Figure 2: Dark matter density profiles are derived through dynamical analysis using the Jeans equations. The underlying Draco-like model is represented by the dashed line. The shaded curves correspond to the recovered density profiles based on the “Current” $N = 500$ sample and the “PFS forecast” ($N = 5,000$) sample, as shown in the inset. The ellipses indicate the half-light radius and tidal radius.

References:

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