Astro2020 Science White Paper

Dark Matter Physics with Wide Field Spectroscopic Surveys

Thematic Areas: ☐ Planetary Systems ☐ Star and Planet Formation
☐ Formation and Evolution of Compact Objects ☑ Cosmology and Fundamental Physics
☐ Stars and Stellar Evolution ☐ Resolved Stellar Populations and their Environments
☐ Galaxy Evolution ☐ Multi-Messenger Astronomy and Astrophysics

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Abstract:

We discuss the potential to discover the nature of dark matter particles with spectroscopy of (1) a large number of faint stars in the Milky Way's halo and streams, (2) nearby dwarf spheroidal galaxies, (3) galaxies in the local volume ($z < 0.05$) to map the faint end of the luminosity function, and (4) strongly lensed galaxies beyond the local volume. N-body and hydrodynamical simulations of cold, warm, fuzzy and self-interacting dark matter show that non-trivial dynamics in the dark sector will leave an imprint on structure formation, with much of this science having been developed in last few years. Sensitivity to these imprints will require extensive and unprecedented kinematic datasets for stars down to $g \sim 23$ mag and redshifts for galaxies down to $g \sim 24$ mag. We conclude that a 10m class wide-field, high-multiplex spectroscopic survey facility is required in the next decade to provide a definitive search for deviations from the cold collisionless dark matter model.

1 Motivation

Dark matter has been detected through its gravitational influence on galaxies and clusters of galaxies, the large-scale distribution of galaxies, and the cosmic microwave background. But, the kinds of particles or fields that make up the dark matter have not been identified despite decades of dark matter searches deep underground, in particle colliders, and through multimessenger astronomy. At the same time, there has been a flowering of ideas for the nature of dark matter that have exciting signatures in astrophysical or terrestrial searches, and new production mechanisms.[1]

Astrophysical observables are critical to constraining models of dark matter across a range of mass scales from $10^{-23}\,\mathrm{eV}$ to $100\,M_\odot$; see Figure 1 for an illustration. We will enter a new era of high resolution and fast sky surveys when these astrophysical observables have the potential to zero in on viable theory spaces. Recent progress in N-body and hydrodynamical simulations of cold collisionless dark matter (CDM), warm dark matter (WDM), fuzzy dark matter (FDM), and self-interacting dark matter (SIDM) have helped to bolster this case, while a wealth of new observations from dwarf galaxies to galaxy clusters have opened up the exciting possibility that non-trivial dynamics in the hidden sector could have left an imprint on structure formation (see Table 1).

In this White Paper, we discuss concrete ways in which astrophysical probes can elucidate the particle nature of dark matter and highlight the need for next generation wide field, multi-object spectroscopic surveys on 10 m class telescopes. We have grouped the science cases into the following four sections based on the distance of the objects being targeted – from nearby to the distant Universe. We highlight a few science cases here and we note that a longer discussion is available

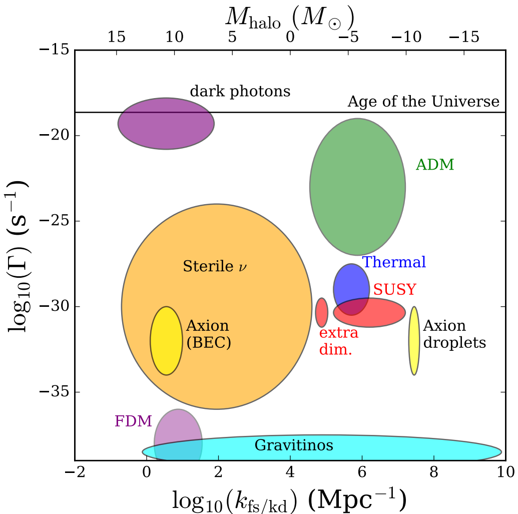

Figure 1: Various dark matter candidates in a parameter space that directly influences structure formation.[2] The horizontal axis is the characteristic free-streaming wavenumber of the model (set in the early universe) and the corresponding halo mass is shown on the top. The vertical axis is the characteristic interaction or decay rate, which directly impacts the structure of the halos at late times.

Halo property	WDM	SIDM	FDM
Central slope of halo density (satellite and field dwarf galaxies)	N	Y	Y
Central halo density (satellite and field dwarf galaxies)	Y	Y	Y
Central halo density profile (larger spirals)	N	Y	N
Mass function (halos and subhalos)	Y	Y/N	Y

Table 1: A partial list of how different models of dark matter, with parameters in the allowed range, can impact the halo and subhalo properties in comparison to the CDM predictions. "Y/N": SIDM predictions depend on the model; "Y" if the dark force mediator (responsible for self interactions) is massless (e.g., atomic dark matter) and "N" if the mediator is massive (e.g., hidden neutrons).

on the arXiv review.[3] Although the review is written using the specifications for Maunakea Spectroscopic Explorer (MSE), the science cases discussed are generic to a 8-10 meter class telescope with high-multiplex, wide field-of-view (FOV) spectroscopic capability dedicated to surveys. A further discussion of the critical need for such a capability appears in Section 6.

2 Stars and stellar streams in the Milky Way

Stellar streams are created by the tidal disruption of globular clusters and dwarf galaxies. The passage of a subhalo near or through a cold globular cluster stream can perturb the orbits of part of the stream stars and cause gaps and wiggles to form.[4,5,6,7] This is one of a small number of methods currently known that is sensitive to the subhalo mass function down to small masses ($M \lesssim 10^8\,M_\odot$).[8] As Figure 1 shows, this will provide critical information about the nature of dark matter.

Each subhalo flyby produces a unique signature on the stream density and orbit, which when combined with radial velocities of individual stream stars provides enough information to reconstruct the perturber properties, i.e. its mass, scale radius, relative velocity, and impact parameter[9]. The left panel of Figure 2 shows a gap in a GD-1 like stream from a $10^6 M_\odot$ subhalo. The right panel of Figure 2 shows the maximum velocity kick imparted to stream stars from the expected distribution of ΛCDM subhalos over a period of 5 Gyr. In order to be able to probe subhalos down to $10^5 - 10^7 M_\odot$, a radial velocity precision of $100 - 300$ m s^{-1} is required. The expected stream gap size is a few degrees for a $10^6 M_\odot$ subhalo and the low surface brightnesses of stellar streams require a limiting magnitude of $g \sim 23.5$ to obtain large enough sample sizes. Therefore, a large aperture telescope (to probe fainter stars) with high precision for velocity measurements ($\lesssim 1\,\mathrm{km\,s^{-1}}$) is necessary for this science.

To date, about 50 streams have been discovered in our Galaxy;[10,11,12,13] the next generation of imaging surveys, such as LSST, are expected to find many more streams. A dedicated spectroscopic follow-up program for stellar streams requires both a wide field-of-view and large aperture.

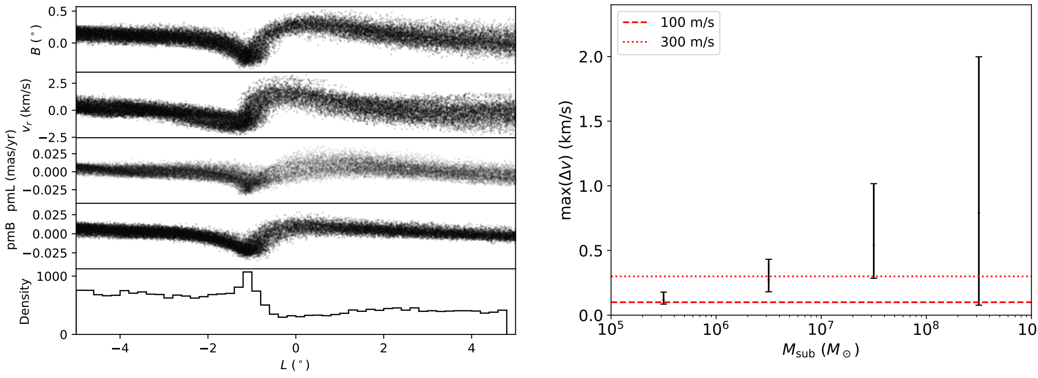

Figure 2: *(left)* Gap in a simulated GD-1 like stream from a $10^6 M_\odot$ subhalo. This signal would be readily detectable in the density (bottom), on the sky (top), and in the radial velocities (second panel). However, the proper motions (third and fourth panel) would be undetectable even with Gaia DR2. *(right)* Median and $1-\sigma$ spread for the maximum velocity kick in a GD-1 like stream over a 5 Gyr duration from 1000 realizations of ΛCDM subhalos over 4 decades of subhalo mass. A systematic error of $\sim 100-300$ m s^{-1} is required to be sensitive to subhalos down to $10^5-10^7 M_\odot$.

This has the potential to measure the dark matter subhalo mass function in the Milky Way below $10^8 M_\odot$, the regime where dark matter halos are no longer able to form stars or a galaxy.

In addition to stellar streams, the ability to measure 3D positions and 3D velocities of individual stars in the Milky Way improves our determination of both the mass and the shape of the Milky Way's dark matter halo.[14] These halo properties are necessary to compare the Milky Way to simulated galaxies which will assess the consistency of our observations with predictions sensitive to the dark matter model, such as the number of satellite galaxies for the "missing satellite problem".[15,16] They could also potentially differentiate between different dark matter models, for example between CDM and SIDM[17;18] or superfluid dark matter[19]. Furthermore, improving our understanding of the smooth dark matter density and velocity distribution is necessary for the interpretation of direct-detection laboratory experiments and for indirect searches in gamma-rays, X-rays, radio wave and neutrinos. For both science cases, a dedicated spectroscopic survey is needed to obtain the measurements of line-of-sight velocities to a precision of 1 to 5 $\mathrm{km\,s^{-1}}$ for extremely large numbers of stellar tracers down to $g \sim 23$.

3 Dwarf galaxies in the Milky Way and beyond with resolved stars

The properties of dark matter particles can produce several observable signatures in dwarf galaxies by affecting their abundance, changing the distribution of dark matter within them, or producing energetic standard model particles through the annihilation or decay of dark matter. A dedicated survey program with a limiting magnitude of $g \sim 23.5$ will enable characterization of the new discoveries, for example the roughly 200 satellite dwarf galaxies[20,21] LSST is supposed to find, and it will significantly increase the stellar sample sizes in known dwarf galaxies. In the left-hand panel of Figure 3, we show how well the dark matter density profile can be inferred for a mock dwarf galaxy with sample sizes of 10^2, 10^3, and 10^4 stars. Current data sets in classical dwarf galaxies have 200 to 2500 stellar velocities[22], and larger sample sizes are required to measure the distribution of dark matter well enough to distinguish between models like SIDM with cross section over mass $\sigma/m \simeq 1\,\mathrm{cm^2/g}$ and CDM (right panel of Figure 3).

We will be able understand ultra-faint dwarf galaxies at a level that is only possible in classical satellites today and they will no longer be limited by statistics. This is exciting because the dark matter halos of ultra-faint galaxies should be much less affected by baryonic (feedback) processes and hence provide a more pristine view of the dark matter density, albeit processed through the tidal field of the Milky Way, which we can model well.[23] There will be systematic effects to grapple with (mainly triaxiality, non- equilibrium effects and unresolved binary stars) but these are things we can take into account or marginalize over.[24] For example, unresolved binary stars can inflate the velocity dispersion, and hence bias the inferred dark matter mass profiles of the smallest systems; a repeat cadence of months with a dedicated spectroscopic survey can reduce or eliminate this systematic.

The large numbers of ultrafaint dwarfs, with widely different stellar distributions, orbits and dark matter densities, will be critical when comparing one dark matter model to another.[25,26] Furthermore, it will be possible to create large samples of nearby, isolated dwarf galaxies to compare against the Milky Way satellites, which will be critical for anchoring the feedback models (for the field galaxies) and using the Milky Way dwarfs as an incisive test of dark matter physics.[27,28]

For searches of dark matter annihilation or decay into Standard Model particles, dwarf spheroidal galaxies are the ideal target since they are nearby, dark matter dominated, and background free.

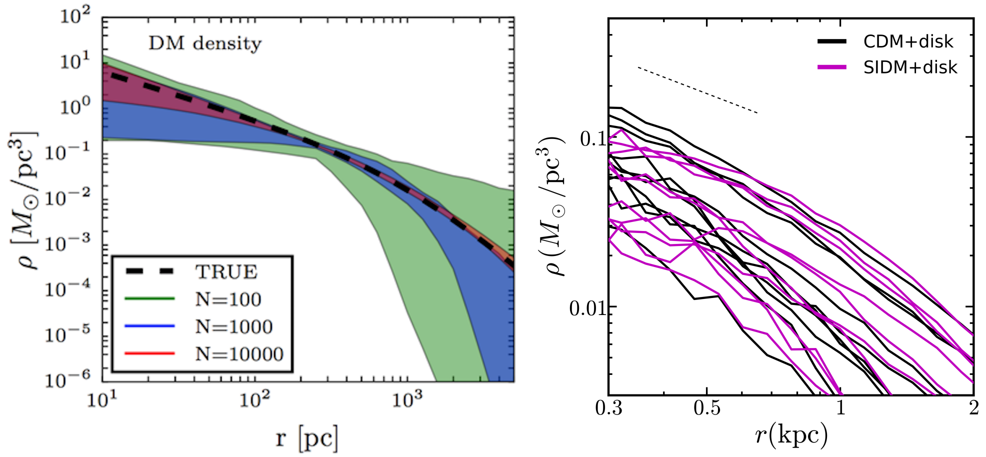

Figure 3: *(left)* Inferred dark matter density profiles for mock data with a spectroscopic sample of 10^2, 10^3 and 10^4 stars with median velocity error $2\,\mathrm{km}^{-1}$. Shaded regions represent 95% credible intervals from a standard Jeans analysis of the mock data. *(right)* Density profiles of the most massive subhalos (as measured by their peak circular velocities) in a SIDM model with elastic scattering cross section over mass of $1\,\mathrm{cm}^2/\mathrm{g}$, compared to a CDM model.[26] The host halo is chosen to be similar to the Milky Way and has an evolving baryonic potential that is well-matched to the stellar disk and bulge of the Milky Way.

The expected annihilation and decay rates are dependent on the dark matter density profile within a dwarf galaxy, and significantly larger sample sizes with a future facility will improve this prediction. The indirect searches can use the inferred dark matter density from stellar kinematics, and compare signals from correlated observations with X-ray and γ-ray telescopes, to constrain the dark matter self-annihilation cross sections or decay lifetimes. This is a well developed science program that will have a renaissance in the LSST era.

4 Galaxies in the low redshift Universe

Spectroscopy is essential to probing the low-redshift ($z < 0.05$) dwarf galaxy population, linking galaxies to halos, and making inferences about the nature of dark matter. A spectroscopic survey down to $r \sim 24$, combined with efficient target selection, can produce a near-complete dwarf galaxy sample for Leo I like dwarf galaxies ($M_r \sim -12$) at $z < 0.05$. This allows us to obtain the satellite luminosity function at the faint end beyond the Milky Way and M31, which is a critical discriminant of the too-big-to-fail problem and its proposed solutions.[29,30]

The observations discussed above can also search for planes of satellites (similar to the Vast Polar Structure in the Milky Way, Great Plane of Andromeda, Centaurus A plane) around other hosts (e.g. in M101 and NGC3109 there are already hints of planes[31,32]). This is an issue that has attracted a lot of attention recently and a more complete picture of the phase space distribution of satellites will lead an incisive test of the standard cosmological paradigm with dark matter.[33]

Weak gravitational lensing in low mass dwarf galaxies ($M_h < 10^{11} M_\odot$) provides a direct unbiased measurement of the total mass, and this is critical for an accurate assessment of the implications of the too-big-to-fail problem. Since these low mass galaxies are only detectable at low redshift ($z < 0.2$), contamination of high-redshift galaxies in the lens sample could either smear out the lensing signal or produce catastrophic photo-z outliers, resulting in a bias in the inferred mass profile. A spectroscopic survey alleviates both these issues.

5 Galaxies beyond the low redshift Universe

Strong gravitational lensing by galaxies provides powerful ways to constrain the mass function of low-mass dark halos and subhalos, since lensing is sensitive to all the mass along the line of sight. For unresolved sources such as lensed quasars, the presence of substructure is manifested in the flux-ratio anomalies: differences between the relative magnifications of lensed images as compared to the predictions of smooth mass models.[34] Surveys with the next generation spectroscopic facilities will be essential for confirming quasars lenses from a vast amount of lensing systems found by LSST, and selecting ideal candidates for high spatial resolution imaging with Adaptive Optics or space-based telescopes. These systems can then be used to infer the presence of dark matter substructure within or along the line of sight to the lens, or place constraints when they are not found.

For resolved sources (galaxies), measurements of the surface-brightness perturbations of the lensed images (e.g. arcs) can reveal the presence of unseen mass and this provides stringent constraints on the subhalo mass function.[35] Galaxy redshift surveys (using SDSS) have proven to be an excellent source for the discovery of new galaxy-galaxy strong lensing systems.[36,37,38,39,40] A wide field-of-view spectrograph on a 10m class telescope, combined with dedicated survey operations mission, can enable flux-limited galaxy surveys ten times larger than the original SDSS, delivering a sample of thousands of strong galaxy-galaxy lenses, from which we may expect dozens of substructure detections. The redshifts obtained for these systems via the spectroscopy survey will be an essential component in the lens modeling.

6 Facilitating the Science

While there are many planned spectroscopic surveys with 4-m class telescopes (e.g. WEAVE, 4MOST, DESI), there are no current plans for a spectroscopic survey with a 10-m class telescope. The only two planned facilities for similar purposes are Subaru/PFS (8-m with a FOV of 1.3 deg in diameter, starting 2020)[41] and CFHT/MSE (11.25 meter with a FOV of 1.4 deg in diameter, currently unfunded)[42], both in the northern hemisphere. A facility in the southern hemisphere would maximize overlap with LSST and benefit from both more efficient target selection and joint science analysis.[43] On the other hand, the deep photometric surveys ($g \sim 24$) that would be required to select targets for the spectroscopic surveys we have discussed will likely exist within a decade over the entire sky.

Considering the large sky area that needs to be covered and the relatively small FOV of the 10m class telescopes compared to the 4-m class telescopes (e.g., Mayall/DESI has a FOV of 3 deg in diameter), it seems a dedicated survey telescope is necessary to conduct the proposed programs for Dark Matter and other science. There is *no* capability on existing 10m class telescopes to conduct such a survey. Among the fourteen 8-10m telescopes (2 x Keck, 2 x LBT, 4 x VLT, HET, 2 x Gemini, Subaru, GTC, SALT), only Subaru has a relatively large FOV (VLT is next with a 25' FOV in diameter). *Therefore, the next generation of deep and wide spectroscopic surveys require either (1) a major upgrade on an existing telescope to larger FOV with a survey instrument, (2) building a new telescope, (3) expanding dedicated telescope time significantly with US community access on an existing telescope (Subaru/PFS), or (4) funding existing projects (CFHT/MSE).*

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