# Snowmass2021 - Letter of Interest

# *MegaMapping Dark Matter*

**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:** MegaMapper is a proposed cosmology experiment consisting of an ultra-wide field of view 6.5 m optical telescope outfitted with an array of fiber spectrographs capable of observing 20,000 targets at a time. The primary goal of the project is to provide strong new constraints on inflation, dark energy, and gravity through a massive galaxy redshift survey at $z > 2$. However, we point out that ancillary science observations made simultaneously with the redshift survey could substantially improve our knowledge of the behavior of dark matter on small scales. Specifically, MegaMapper would enable us to detect interactions between low-mass dark matter subhalos and stellar streams within the Milky Way halo, determine the mass of the Milky Way with unprecedented accuracy, tighten limits on the minimum halo mass occupied by galaxies, and constrain the dark matter density profiles of the smallest galaxies. These measurements will have the power to tighten existing constraints on the mass and self-interaction cross-section of dark matter particles and rule out some proposed dark matter models.

The astrophysics and cosmology community in the US has recognized for more than a decade that a key missing component of the upcoming landscape of astronomical facilities is a massively multiplexed spectroscopic capability on a large telescope (e.g., Matheson et al., 2013; Elmegreen et al., 2015; Najita et al., 2016; Dodelson et al., 2016). Maximizing the scientific returns from the flagship Vera Rubin Observatory, currently slated to be operational in 3 years, will require spectroscopy on a scale that is not possible with existing telescopes. As of now, the only instrument approaching the necessary parameters is the Prime Focus Spectrograph (PFS) on the Subaru Telescope. However, the planned PFS survey is modest in scope (300 nights), the multiplexing is limited (2400 fibers), only $\sim 50\%$ of the Rubin Wide-Fast-Deep sky footprint is visible from Hawaii, and US data access will be limited to astronomers at a handful of institutions (Takada et al., 2014).

MegaMapper is a facility designed to meet this need, substantially improving the measurements of dark energy and dark matter that can be made with Rubin while relying largely on existing technology and minimizing costs through strategic design choices. Here we present an overview of the dark matter science enabled by MegaMapper, and in two companion LOIs we discuss the observatory and instrument in more detail and describe its impact on cosmology.

## Dark Matter Science with MegaMapper

As astronomers and physicists have investigated an expanding array of dark matter models over the past $\sim$ 20 years, it has become clear that different particle physics models of dark matter predict different behavior on scales of $\lesssim 1$ kpc. In particular, if dark matter is cold, then dark matter halos follow a mass function $dN/dM \propto M^{-1.9}$ down to well below 1 $M_{\odot}$, and each halo is formed with a cuspy density profile. On the other hand, warm dark matter erases structure below $10^{7-8}$ $M_{\odot}$, and self-interacting or fuzzy dark matter models generally produce shallower density profiles. One of the best laboratories for testing these predictions is in the halo of the Milky Way.

Cold streams of stars produced when globular clusters and dwarf galaxies are tidally disrupted by the Galaxy are sensitive accelerometers for probing the gravitational potential in which they are orbiting. Consequently, the kinematics of streams are expected to provide the best available measurements of the abundance of low-mass dark matter halos (e.g., Carlberg, 2009; Erkal & Belokurov, 2015; Bonaca et al., 2019), as well the mass and shape of the dark matter halo of the Milky Way (e.g., Bonaca & Hogg, 2018). In ΛCDM, the hierarchy of dark matter halos spans $\sim$ 20 orders of magnitude, but halos smaller than $\sim 10^8$ $M_{\odot}$ are unlikely to form any stars, leaving them invisible to most astrophysical probes. Because the existence of such halos is a fundamental prediction of the ΛCDM model, and they should be absent in most alternative dark matter scenarios, detecting subgalactic concentrations of dark matter is a high priority for improving our understanding of the nature of dark matter (Bullock & Boylan-Kolchin, 2017).

When a dark matter subhalo passes close to a tidal stream, it perturbs the stars in the stream. Over time, these perturbations result in under- and over-densities along the stream, spurs and loops drawn out of the stream, and even bends in the orbit of the stream in the case of a massive perturber (e.g., Carlberg, 2009; Bonaca et al., 2019; Erkal et al., 2018). However, similar features can also be caused by encounters with molecular clouds and spiral arms, as well as by epicyclic motions. Identifying dark matter-based perturbations and maximizing the accuracy with which the properties of the perturber can be recovered and the sensitivity to lower-mass subhalos requires spectroscopy to measure radial velocities for the stream stars (Erkal & Belokurov, 2015; Bovy et al., 2017). The typical surface density of a stellar stream is $\sim$ 2 stars deg$^{-2}$ brighter than $g = 19$, $\sim$ 20 stars deg$^{-2}$ brighter than $g = 21$, or $\sim$ 40 stars deg$^{-2}$ brighter than $g = 22$ (e.g., Li et al., 2019). A wide-field spectrograph on a large-aperture telescope is therefore the only way to obtain significant spectroscopic samples of stream stars. The required velocity accuracy in order to detect perturbations from subhalos at $M < 10^7$ $M_{\odot}$ and to distinguish these interactions from other sources of density variations within streams is $\sim 1$ km s$^{-1}$ (e.g., Erkal & Belokurov, 2015; Bonaca et al., 2020). MegaMapper would provide at least an order of magnitude gain in stream survey power compared to any existing facility, enabling measurements of the internal kinematics of many streams for the first time. A magnitude-limited MegaMapper survey of 10 streams targeting every member star at $g < 22$ could be carried out simultaneously with the main cosmology survey, and with just a small fraction of the total fibers would likely yield the first conclusive dynamical detections of dark matter subhalo collisions with stellar streams. Precise technical requirements on velocity accuracy, depth, and multi-epoch detection of binary stars to ensure such detections will be presented in a future white paper. The resulting dense stellar samples would also allow stringent tests of cosmological systematics such as errors in the photometric calibration or dust extinction in these areas, furthering the goals of the cosmology survey.

Stream spectroscopy will also play a key role in determining the remarkably poorly-known mass of the Milky Way. At present, mass estimates for the Galaxy span a range of $\sim 50\%$, significantly hampering our ability to compare the Milky Way to simulations. As shown by Bonaca & Hogg (2018), 6-D kinematic measurements (including MegaMapper velocities) for a sample of 10 streams can in principle provide $\sim 1\%$ measurements of the Milky Way gravitational potential. The mass of the Milky Way is directly related to both the local density of dark matter in the solar neighborhood (e.g., Sofue, 2020), which is a critical parameter for direct detection experiments, and the predicted satellite population (e.g., Kravtsov et al., 2004).

In addition, stellar spectroscopy with MegaMapper will be an essential complement to Rubin Observatory's exploration of dark matter via detecting new Milky Way satellite galaxies. Such dwarf galaxies can only be confirmed as dark matter-dominated systems with stellar spectroscopy (e.g., Simon & Geha, 2007), and obtaining these observations for the large population of anticipated Rubin discoveries requires either higher multiplexing or larger aperture telescopes than is currently available (Najita et al., 2016; Bechtol et al., 2019; Drlica-Wagner et al., 2019). The confirmed dwarf galaxy population maps directly to the minimum dark matter halo mass in which galaxies can form, which currently places the tightest limits to date on warm and fuzzy dark matter models (e.g., Nadler et al., 2020). Dwarf galaxies also provide a pristine target for indirect dark matter searches with current and future X-ray and $\gamma$-ray observatories. Finally, MegaMapper will enable the measurement of unprecedentedly large samples of stellar velocities over unprecedentedly wide areas in faint Milky Way satellite galaxies, which will substantially improve the measured masses and density profiles of these highly dark matter-dominated systems (e.g., Read et al., 2019).

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