Snowmass2021 - Letter of Interest

Probing the particle nature of dark matter using stellar streams

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: Stellar streams originating as a result of tidal disruption of globular clusters and dwarf galaxies are one of the most promising probes on the particle nature of dark matter. Globular cluster streams are dynamically cold and so gravitational encounters with subhalos of mass as low as $10^5 - 10^6$ M$_\odot$ can lead to observable density variations along the stream. Analysis of these density variations over the entire stream can be used to strongly constrain the subhalo mass function, allowing us to put strong limits on different dark matter model parameters. The stellar distribution along leading and trailing arms of dwarf galaxy streams can be sensitive to dark matter self-interactions that lead to an effective drag on the dwarf galaxy's halo. The effectiveness of stellar streams as a dark matter probe depends not only on discovering and analyzing more streams but also on reducing the observational noise in the stream density so that our analyses are sensitive to the lower mass spectrum of the subhalo population. Upcoming surveys such as the Vera Rubin Observatory, the Roman Space Telescope and the MaunaKea Spectroscopic Explorer (MSE) will be pivotal in both these aspects.

Introduction: A key prediction of the standard Lambda cold dark matter (ΛCDM) framework of structure formation is that a Milky Way sized halo contains a very large number of dark matter substructures with masses smaller, by many orders of magnitude, than that of dwarf galaxies. Devoid of stars, these structures remain undetected. Detecting these low mass structures, in particular, the ones that are $\lesssim 10^7$ $M_\odot$ will allow us to test different models of dark matter, especially the ones that predict suppression of small scale structures, such as the so-called warm dark matter models (WDM) and Fuzzy dark matter (FDM).

Stellar streams that originate when a globular cluster gets accreted onto our galaxy and gets tidally disrupted are thin and almost one dimensional due to very low velocity dispersion among its member stars. Gravitational encounters with dark subhalos with mass as low as $10^5 - 10^6$ $M_\odot$ leaves detectable variations in the stellar density along the stream as shown in Figure 1[4;5].

By analyzing the level of density variations at different angular scales over the entire stream, strong inferences of the entire subhalo population within the stream's orbit can be made[4]. These can be translated to constraints on the subhalo mass function (SHMF) which is intimately related to the particle physics model of dark matter[1]. Furthermore, inferences from multiple streams can be combined which allows us to probe substructures in different regions of our galactic halo.

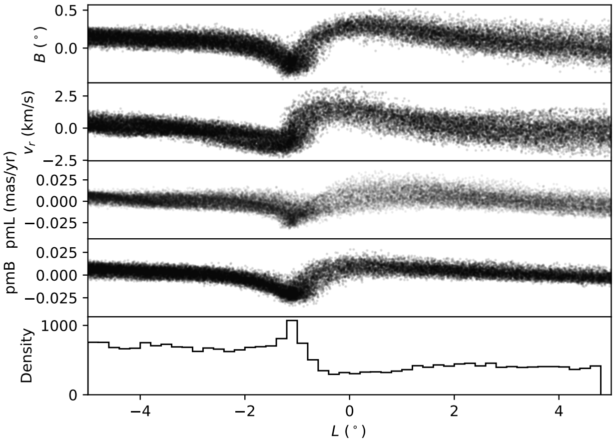

Figure 1: Properties of a mock GD-1 stream that was impacted by a 10^6 $M_\odot$ subhalo[12]. The resulting gap can be seen at $L \sim 0°$ in the observed stream (top panel), in the radial velocity (second panel) and in its density (bottom panel). The variations in the proper motions (third and fourth panel) are much less prominent and will be hard to detect with the level of precision of Gaia DR2.

Self-interacting DM (SIDM) is a promising alternative to the collisionless CDM that can alleviate the "core-cusp problem" of structure formation. Previous efforts have shown that certain anisotropic versions of SIDM lead to an effective "drag" force on the DM particles[8;15] For a DM dominated satellite galaxy such as the Sagittarius (Sgr) dwarf, that is falling in through the Milky Way halo, this drag force will act only on the satellite's halo. When such a satellite is tidally disrupted, the stars will preferentially escape on to the leading arm, similar to previously proposed dark matter mechanisms[9], leading to a stellar count asymmetry between the leading and trailing arm. Since this asymmetry is proportional to the drag force and hence the scattering cross section, measuring the star count asymmetry in the observed dwarf galaxy stream will allow us to put tight constraints on the SIDM model parameters. *All these features make stellar streams one of the strongest Astrophysical probes of the particle nature of dark matter*.

Recent results and challenges: Recently, constraints on the subhalo population in the mass range $10^6 - 10^9$ $M_\odot$ were derived using observed data on the GD-1 and the Pal 5 streams, see Figure 2. Combining this with the number counts of classical Milky Way satellites produced one of the strongest constraints on the mass bounds of thermal dark matter particles, with $m_{\rm WDM} > 6.3$ keV at 95% confidence[2;3].

In addition, these constraints on the SHMF was used to derive mass constraints of Fuzzy Dark Matter models in which dark matter is made up of ultralight bosons of mass $\sim 10^{-22}$ eV with de Broglie wavelength ~ 1 kpc[14]. In such models, in addition to subhalos, there will also be a turbulent field of density clumps of size their de Broglie wavelength and mass $\sim 10^5 M_\odot$ due to the interfering wavefunctions of the ultralight bosons. A globular cluster stream orbiting in a field of such clumps will be gravitationally heated up which will make the stream thickness to grow[7].

One of the biggest challenges in using globular cluster streams as a dark matter probe comes from the level of noise in the stream data which prevents us from probing smaller mass subhalos. Shot noise is one of the main contributors to the overall noise in stellar density along the stream. This is due to the fact that globular clusters are composed of very low mass and low brightness stars and so often a large fraction of the stars are below the detection power of the observing telescope because of which only a small sample of stars along the stream are detected. The other big factor is the difficulty in removing stellar contamination due to foreground and background stars.

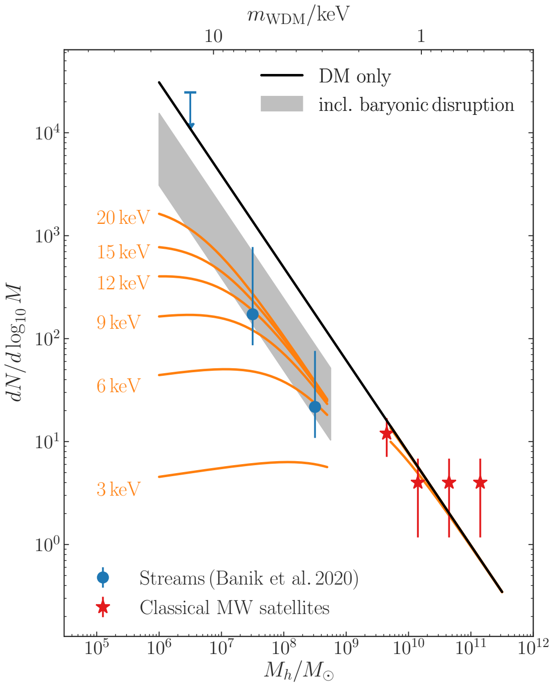

Figure 2: SHMF in the mass range $10^6 - 10^9 \mathrm{M}_\odot$ reconstructed from the analysis of perturbations induced on the GD-1 and Pal 5 streams[3]. Red data points show the observed classical Milky Way satellites. The blue downward arrow and data points show the 68% upper bound, and the measurement and 68% error, respectively, in 3 mass bins below the scale of dwarfs[2]. The shaded area show the CDM mass function taking into account the baryonic disruption of the subhalos. The orange lines show the predicted mass function for thermal WDM candidates of different mass, taking into account the expected subhalo depletion due to baryonic disruption for the low-mass ($M < 10^9 \mathrm{M}_\odot$) measurements from the inner Milky Way.

In order to use streams to their full effectiveness, we need to heavily invest in detecting and modeling streams based on the data from future ground and space based observatories. Imaging facilities such as the Vera Rubin Observatory and the Roman Space Telescope will provide deeper and more precise photometry dramatically increasing the signal-to-noise ratio of the detected stream density. Additionally, follow-up from massively multiplexed spectroscopic facilities such as the MaunaKea Spectroscopic Explore will help to reduce stellar contamination. These advances will enable us to be sensitive to the feeblest density variations caused by the low mass subhalos. We also need major improvements in modeling the Milky Way, especially in the light of recent results which claim that the passage of the Large Magellanic Cloud can have observable implications on the Milky Way potential[6;10;11]. Furthermore, we need a better understanding of the origin of globular clusters which still remains a mystery. Some recent works have claimed that the observed shroud of stars around the GD-1 stream is a strong evidence for the GD-1 stream to have arrived into our galaxy within a dwarf satellite[13]. If this is indeed true then we need further investigation of the effects of the progenitor dwarf on the evolution of the stream and on its density which can have strong effects in deriving constraints on dark matter models. In the context of dwarf galaxy streams, one of the major challenges is to be able to segregate the observed stars into leading and trailing arms based on their stellar kinematic data. In this context, future surveys such as MSE, the Vera Rubin Observatory, and the Roman Space Telescope will play a vital role in improving our understanding of stellar kinematics in dwarf systems.

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