Snowmass2021 - Letter of Interest

Giving shape to the darkness: dark matter profiles in faint dwarf galaxies

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: The nature of dark matter will be discerned in part through complementary probes of the galaxy matter distribution. One of the cleanest such probes is the accurate measurement of dark matter profiles in isolated dwarf galaxies: it is in this regime where predictions for the dark matter density profile diverge most strongly between different models, and also the systematic uncertainty from galaxy formation processes is minimised. We therefore propose a dedicated observation programme to obtain high precision stellar kinematics in observationally suitable dwarf galaxies.

1 Dark matter particles and the halo density profile

The shape of the dark matter density profile in macroscopic, cosmological dark matter haloes is a key prediction of all models of microscopic, particle dark matter. Properties such as the thermal motions of the particles when they were first formed, their subsequent temperature evolution, their interactions with baryons and with other dark matter particles, and their quantum mechanical nature, can have a significant impact on the distribution of the dark matter within haloes and therefore within galaxies.

We show this variation between models in cartoon form in Fig. 1. We include here idealised spherical density profiles in four dark matter models that are thought to be consistent with the most conservative available constraints: cold dark matter (CDM), warm dark matter (WDM), self-interacting dark matter (SIDM) and fuzzy dark matter (FDM). These four cosmological dark matter models each correspond to at least one particle physics candidate: examples include the supersymmetric neutralino for CDM[1], the resonantly produced sterile neutrino for WDM[2], a complex hidden sector of dark atoms for SIDM[3], and string theory axion-like particles (ALPs) for FDM[4].

Each of these cosmological dark matter models give rise to a distinctive dark matter profile shape. CDM exhibits a Navarro–Frenk–White profile that evolves from r^{-3} at large radii to r^{-1} at small radii[5]. WDM quickly transitions to a slope shallower than r^{-3} and then maintains a steep $r^{-1.2}$ profile towards the centre[6;7]. SIDM exhibits a cored profile[8], except where the core undergoes gravothermal collapse after tidal stripping and / or high collision rates at low velocities to produce a cusp steeper than -2 (not shown). FDM instead generates a very dense, central core embedded in a shallower outer profile[9]. The differences between the shapes are such that it is plausible to tell the models apart by inferring the dark matter density at 1 kpc, 500 pc, and 200 pc at the 10s of per cent level: this set of radii and densities should be sufficient to discern which of the above models best describes the ensemble of dwarf galaxy kinematics.

2 Measuring the halo density profile: challenges and plans

The path to determining the density profile with sufficient precision to discern between these models is confronted by two connected challenges. First, the baryonic components of galaxies – stars and gas – exhibit a back reaction on the dark matter that blurs the particle properties of the dark matter itself, typically inducing a steeper outer profile and in some models a shallow core in the galaxy centre, c.f.[10;11]. Second, the objects in which astrophysical processes are at their least effective are by definition very difficult to analyse for their dark matter content, since there is a paucity of kinematic tracers with which to discern the quantity and extent of the dark matter. A third challenge concerning the galaxies that are most dark matter-dominated – dwarf spheroidal (dSph) galaxies – is that these objects are primarily satellites of the Milky Way and M31 galaxies, and therefore the observed kinematics of these satellites are further complicated by the gravitational interaction with massive galaxies.

Never the less, observations of galaxies that are as isolated and as faint as is practicable are a very rewarding target for kinematic studies, as and when such studies are technically feasible. Not only is the influence of the baryons minimised as discussed above, it is also the regime in which the peculiarities of the particle nature of dark matter are most strongly expressed.

We therefore propose a series of observations and telescope facilities with which to measure the phase space properties of stellar tracers in nearby dwarf galaxies. The kinematics of these tracers will then be used to determine the local, spherically averaged dark matter density at radii between 200 pc and 1 kpc. The focus for M. Lovell's group will be to generate a series of predictions for the properties of such galaxies in competitive dark matter models.

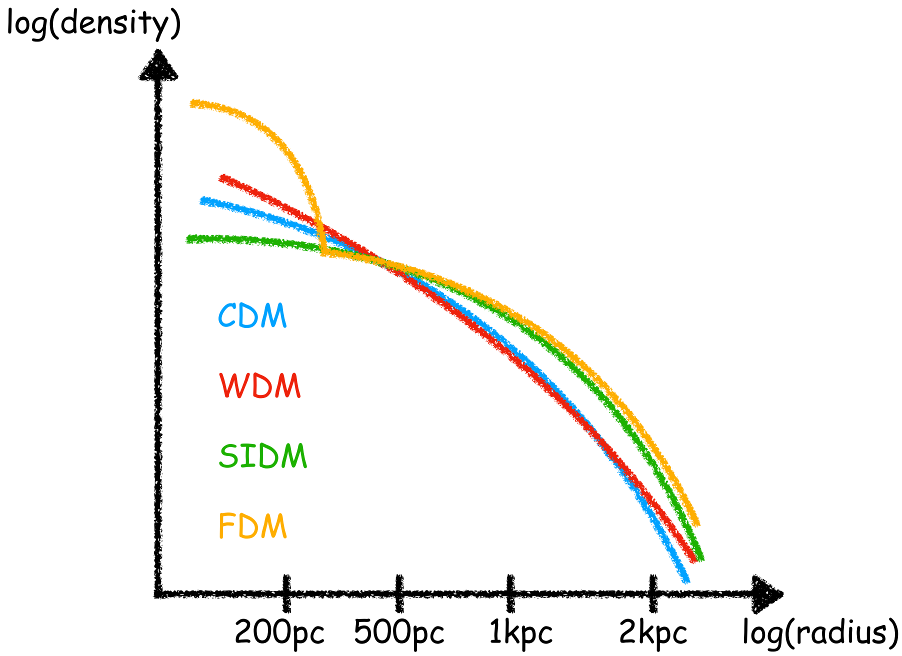

Figure 1: Cartoon of dark matter density profiles in low mass ($\sim 10^9\ M_\odot$) haloes. We show four models: CDM (blue), WDM (red, thermal relic mass ~ 3 keV), SIDM (green, $\sim 3\ \mathrm{cm^2 gr^{-1}}$ at $v_{\rm rel} < 100\ \mathrm{kms^{-1}}$), and FDM (orange). The curves are normalised to approximately the same density at 500 pc.

For the observations, we adapt the work from Astro2020 Decadal survey white paper[12]. We propose two observations of Local Dwarfs 12 years apart, first with HST and second with the upcoming space-based facilities JWST and NGRST (formerly known as WFIRST), and an extra follow up observation at least six years further in the future. These astrometric data will then be combined with ground-based spectroscopy for line-of-sight velocities, which may be either already available or acquired from ELT-class facilities depending on the galaxy. We expect that this approach will enable us to measure the 3D velocities to a precision of $1.5\ \mathrm{kms^{-1}}$ over an 18 year baseline. We will then estimate the amplitude of the dark matter density profiles at 200 pc, 500 pc, and 1 kpc with a precision better than 10 per cent. With these data we will be able to determine whether the dark matter is best described by CDM, WDM, SIDM, or FDM with a degree of confidence to be obtained from tailored hydrodynamical simulations, which can account for interactions with the Milky Way disc and with state-of-the-art feedback prescriptions. Still further in the future, we envisage a dedicated, GAIA-style observatory with a 3 m mirror that will improve on GAIA by an order of magnitude in target flux.

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