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Citation
Zoutendijk, S. L. (2021). Constraining dark matter with ultra-faint dwarf galaxies. *Hypatia Colloquium 2021: Early Career Astronomer Series At Eso*, 56-57. doi:10.5281/zenodo.5607414

Constraining dark matter with ultra-faint dwarf galaxies

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Constraining the nature and properties of dark matter is a long-running, but important effort. In the ΛCDM paradigm, dark matter is the dominant component at the scale of galaxies and for a large part of cosmic history was also the dominant component for the entire Universe. Understanding dark matter is therefore very important to understand the evolution of galaxies and of the Universe as a whole. Understanding what dark matter is also has the potential to revolutionize physics. If dark matter is found to be a new, yet unknown particle, we have proof of physics beyond the Standard Model. Conversely, if dark matter is found to be the apparent effect of a modification to the theory of gravity, we will have to revise a fundamental law of physics. Furthermore, the nature and history of the Universe are profound questions of science with philosophical value.

Different theories of dark matter predict different dark-matter density profiles. However, baryonic feedback can alter those profiles, either contracting the profile or forming a core, obscuring the original profile and its dark-matter physics along with it. Additionally, baryonic processes can create spectral features that obscure possible spectral signatures of dark matter. Ultra-faint dwarf galaxies (UFDs) are the most dark-matter dominated galaxies known and are expected to host so few baryons that their density profiles remain pristine (for a review, see [1]). For this reason UFDs are one of the best classes of objects for the constraining of the nature and properties of dark matter.

In this contribution, I will discuss constraints on a few different types of dark matter, which can phenomenologically be broadly divided into three categories. In cold dark matter (CDM), gravity is the only significant interaction between a dark-matter particle and any other particle and the density profile will be the cuspy Navarro–Frenk–White (NFW) profile in the absence of baryons. This kind of dark matter includes both proposed elementary particles, such as the axion or axion-like particles (ALPs), and massive compact halo objects (MACHOs), such as primordial black holes. If there is a significant interaction between dark-matter particles, then we are in the territory of self-interacting dark matter (SIDM). Different kinds of self-interaction have been proposed, including scattering and annihilation. These interactions result in a cored profile. Lastly, in fuzzy dark matter (FDM), the dark-matter particles are ultra-light bosons (which could be, but not necessarily are, ultra-light ALPs) with de Broglie wavelengths of astronomical sizes. This causes an alteration of the density profile by large-scale quantum-mechanical effects and might explain the cores of classical dwarf galaxies if the boson mass is $\sim 10^{-22}\,\mathrm{eV}\,c^{-2}$.

Several constraints on dark matter from UFDs are already available in the literature. Examples include the following: the mass and abundance of MACHOs has been constrained by the survival of the star cluster in the UFD Eridanus 2 (Eri 2) and by the stellar distribution of the UFD Segue 1, because the disruptive effects of mass segregation between MACHOs and stars are not observed [2, 3]. Also in Eri 2, the mass and abundance of FDM is constrained in a similar way as those of MACHOs, because the quantum-mechanical density fluctuations would also destroy the cluster [4, 5]. Another example is the non-detection of γ-ray signatures from Segue 1 and other dwarf galaxies; this absence constrains the cross section of dark-matter annihilation [6].

Here, I report on results obtained from MUSE-Faint [7], a survey of UFDs with MUSE. Because MUSE is an integral-field spectrograph, it is possible to measure velocities from stellar spectra in the centres of these very dense stellar systems, which would not be possible with fibre spectrographs. Additionally, the field of view of MUSE is large enough to cover the half-light radii of most UFDs with one or a few pointings. Over the entire 100-hour guaranteed-time survey, MUSE-Faint will collect data for ten UFDs, UFD candidates, and other faint dwarf galaxies, with a range of half-light radii and absolute magnitudes. The results presented here are based on the completed observations of Eri 2 and Leo T, both having ~ 100 member stars after combining the MUSE-Faint velocities [8; Vaz et al. in prep.] with literature data [9, 10] from larger radii.

Results

The literature constraints [2] on MACHOs based on the cluster of Eri 2 are based on the assumption that this cluster is at the centre of that UFD. At the time, no spectroscopy of cluster stars was available, therefore it was not known whether the cluster was associated with Eri 2 or merely seen in projection. The first results [7] of MUSE-Faint showed that the systemic velocity of the cluster and the bulk of Eri 2 are very similar, $79.7^{+3.1}_{-3.8}\,\mathrm{km\,s^{-1}}$ and $76.0^{+3.2}_{-3.7}\,\mathrm{km\,s^{-1}}$, respectively. This is consistent with an association between the two. With the new velocities of cluster members and stars in the centre of Eri 2, we could update the MACHO constraints on mass and abundance. If one assumes MACHOs constitute all dark matter, we find MACHOs must be less massive than $44\,M_\odot$ (95% confidence level).

Observations of Leo T from MUSE-Faint have been used in a study [11] to constrain the properties of ALPs decaying into photons. Such a process would create an emission line coming from the dark-matter halo. The strength and wavelength of the line are related to the coupling strength and the ALP mass. Finding no detection, we placed an upper limit to the coupling strength of a few times $10^{-13}\,\mathrm{GeV}^{-1}$ (95% confidence level) for masses that produce an emission line visible with MUSE, ~ 2.5–$5.5\,\mathrm{eV}\,c^{-2}$. This constraint is over two orders of magnitude stronger than previous results [12, 13] for this mass range. I note that this is a very different mass regime than that of ultra-light ALPs in FDM.

Finally, through a Jeans analysis, the stellar velocities can constrain the dark-matter density profiles of UFDs. By fitting and comparing different profile models, we can constrain dark-matter properties and compare different dark-matter theories. In Figure 1, I show the result of this analysis [8] for Eri 2, with models for CDM, annihilating SIDM, and FDM. The overall agreement between the models is good, though in the centre, where data are sparse, the models start to diverge. The models can be compared using Bayesian evidence, which favours FDM the most and SIDM the least. The difference in evidence between FDM and SIDM is substantial, but not significant, therefore none of the models can be ruled out.

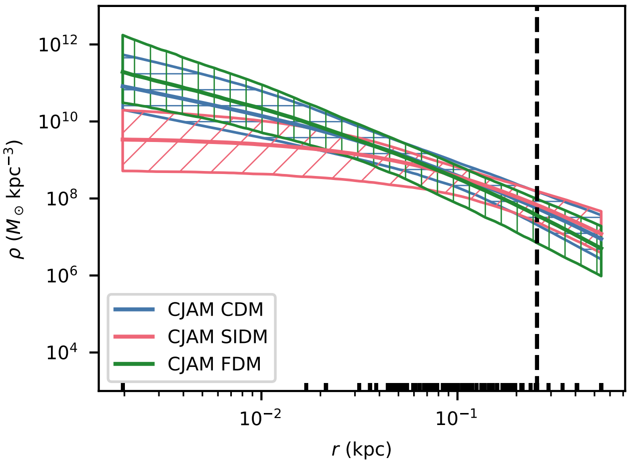

Figure 1: Recovered dark-matter density profiles of Eridanus 2. Displayed are the median density and its 68% confidence interval as a function of radius from the centre. The projected half-light radius is indicated with the vertical dashed line and the projected locations of the stars used to trace the dark matter are indicated with markers along the bottom axis. Reproduced from [8].

From the shape of the SIDM and FDM models we can also derive constraints on dark-matter properties. Annihilating SIDM lowers the density in the centre of the profile, where interactions are the most frequent, thus creating a core of constant density. In FDM, the quantum-mechanical behaviour of the dark matter results in a quantum pressure that prevents a gravitational collapse into a cusp. This creates a core in the very centre, but at intermediate radii the density increases steeply. The altered part of the profile is known as the soliton.

For the SIDM model we do not detect a core [8], but there is a limit to the scales we can probe. The upper limit to the core radius corresponds to an interaction rate that translates into a cross section per unit mass of $\sim 10^{-36}\,\mathrm{cm}^2\,\mathrm{eV}^{-1}\,c^2$ (95% confidence level). This is not as strong as the γ-ray results of [6], but our constraint has the benefit of being valid for all dark-matter particle masses and all annihilation products.

Similarly, we can place an upper limit to the soliton radius, which corresponds to a lower limit of $10^{-20.40}\,\mathrm{eV}\,c^{-2}$ (95% confidence level) on the mass of the ultra-light boson [8]. This is inconsistent with the $\sim 10^{-22}\,\mathrm{eV}\,c^{-2}$ required to explain the cores in more massive dwarf galaxies (e.g., [14, 15]). This discrepancy is problematic for FDM, because the boson mass should be the same in every galaxy. One possibility is that, although an FDM profile can fit these dwarf galaxies, FDM is not the cause of their cores, but rather baryonic processes. These would be almost absent in UFDs, resulting in the non-detection of cores.

Outlook

The three MUSE-Faint studies I have presented here were each based on a single galaxy, with only two different galaxies in total. The strength of the results can be improved by analysing the full MUSE-Faint sample that will span ten galaxies once completed. The larger sample would add robustness due to being less sensitive to possible anomalous galaxies in the sample, and will also enable the improvement of the constraints though a joint analysis. It may also be possible to observe trends in galaxy or halo properties over the range of half-light radii and absolute magnitudes.

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