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The 4MOST Survey of Dwarf Galaxies and their Stellar Streams (4DWARFS)

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The present-day Milky Way is the result of a long history of mergers and interactions with smaller galaxies. The 4DWARFS survey will target the dwarf galaxies and stellar streams in the 4MOST footprint, and unveil their chrono-chemo-kinematical properties. The survey will provide radial velocities, chemical abundances and stellar ages for 140 000 stars, and thus increase the number of stars with detailed information in such systems by several orders of magnitude. 4DWARFS will provide a new, deeper view of the Milky Way environment, shedding light on the first stars, chemical evolution, dark matter halos, and hierarchical galaxy formation down to the smallest scales.

Scientific context

The Milky Way environment is rich in satellite galaxies, stellar streams and accreted systems, that trace galaxy evolution and chemical enrichment throughout cosmic time. Because they are close by, these relics of early galaxy formation can be studied in extraordinary detail, star by star, giving invaluable insight into stellar evolution and nucleosynthesis, as well as the Milky Way’s hierarchical growth. This provides a clear motivation for the 4MOST survey of dwarf galaxies and their stellar streams (4DWARFS) which aims to study and map these individual structures. 4DWARFS will target all ~ 50 of the known Milky Way satellite dwarf galaxies in the southern hemisphere, covering over three orders of magnitude in galaxy mass. Additionally, 4DWARFS will observe dozens of already identified stellar streams in the Galactic halo which are the remnants of currently interacting or previously dissolved systems (Figure 1).

The dwarf galaxy satellites of the Milky Way are intrinsically metal-poor, with a dominant old stellar population, making them ideal fossils with which to study the imprints of the first stars in the Universe. Their star formation was inefficient, making the effects of delayed nucleosynthetic channels (type Ia supernovae [SN Ia], asymptotic giant branch [AGB] stars, neutron star mergers) especially prominent and straightforward to study, at various metallicities and star formation histories (for example, Tolstoy, Hill & Tosi, 2009), providing unique insights into chemical evolution and nucleosynthesis.

These small systems are relics of hierarchical structure formation, opening up the possibility of tracing mass assembly, and both *ex-situ* and *in-situ* star formation in the Milky Way environment. Dwarf galaxies are dominated by dark matter, and can be used as probes of cosmology and galaxy formation. Those that halted star formation long ago are likely the best examples of pristine dark-matter halos in the Universe, and they are the ideal probes to understand the nature of dark matter through the study of their stellar 3D kinematics (for example, Massari et al., 2018). Furthermore, the stellar streams observed in the Galactic halo represent clear evidence of systems currently being accreted, allowing us to study their tidal disruption in incomparable detail. In particular, the Sagittarius dwarf spheroidal (dSph) is the prime example of a tidally disrupted Milky Way satellite galaxy, and it leaves a trail of stars that wraps more than a full orbit around the Galaxy (Figure 1). This makes it a major contributor to the Milky Way stellar halo along with other past mergers. Sagittarius and its stream therefore provide one of the best opportunities to study a galaxy that is currently undergoing disruption.

A careful study of dwarf galaxies and their stellar streams is thus of fundamental importance to obtaining a complete picture of the evolution of our Galaxy. Furthermore, this will enable us to understand in detail the properties of the dwarf galaxies themselves, which are the earliest and most common type of galaxy in the Universe.

Specific scientific goals

The main goal of 4DWARFS is to characterise dwarf galaxies and stellar streams by mapping their chrono-chemo-kinematical properties. We will derive radial velocities, chemical abundances and stellar ages (for example, Feuillet et al., 2016) for stars in all known dwarf galaxies (smaller than the Small Magellanic Cloud) and stellar streams in the 4MOST footprint of the Milky Way halo. Using both high-resolution (HR) and low-resolution (LR) spectra, our survey will provide 10–25 elemental abundances for 100 000 stars in dwarf galaxies, and 30 000 stars in stellar streams (Figure 1). In addition, we will push down to the fainter dwarf galaxies and smaller stellar streams, retrieving abundances of around five elements for a further 10 000 stars. The homogeneity of this sample will be unprecedented in comparison to the present literature.

The 4DWARFS dataset is therefore incredibly rich, and will impact several fields, ranging from cosmology to stellar physics. The key scientific questions that 4DWARFS will attack are listed below.

What are the properties of the first stars?

The chemical yields of the first stars (Pop III) are thought to be preserved on the surfaces of low-metallicity, low-mass, long-lived stars (for example, Hansen et al., 2020). 4DWARFS will identify the most metal-poor stars of dwarf galaxies, increasing their numbers by more than an order of magnitude. Furthermore, we will quantify the properties of metal-poor stars across different galaxies, for example the fraction of carbon-enhanced metal-poor stars which are thought to be the descendants of faint Pop III supernovae (for example, Iwamoto et al., 2005). We will search for and identify rare fossils and descendants of the first stars (Rossi, Salvadori & Skúladóttir, 2021), such as those formed in the ejecta of zero-metallicity pair-instability supernovae, and high-energy Pop III supernovae. This will allow us to put constraints on the intrinsic properties of the first stellar population, such as their mass distribution and the energy distribution of their supernovae.

How are the chemical elements created and distributed?

Even after decades of study, the fundamental physical conditions of major nucleosynthetic sites remain obscure. Investigating different galaxies with a variety of star formation and chemical enrichment histories is key to breaking degeneracies in chemical evolution (for example, Skúladóttir & Salvadori, 2020). Dwarf galaxies have intrinsically low star formation rates compared to larger galaxies, and all long-timescale nucleosynthetic channels, such as SN Ia, AGB stars and neutron star mergers are thus more prominent relative to core-collapse SN (short timescales). Compared to the Milky Way, dwarf galaxies have much simpler star formation histories, which makes them easier to model, providing a more detailed understanding. 4DWARFS will constrain the fundamental physics of nucleosynthetic sites: their rates, yields, metallicity dependence and time-delay distribution functions. In this way, 4DWARFS will provide key insights into the elusive progenitors of SN Ia (for example, Maoz, Mannucci & Nelemans, 2014), as well as the various production sites of neutron-capture elements, such as AGB stars (s- and i-processes) and the kilonovae of neutron star mergers (r-process).

What are the dynamical properties of dwarf galaxies?

By providing an unprecedented sample of precise radial velocities and coupling those with Gaia proper motion measurements, 4DWARFS will determine the dark matter profile of almost 50 galaxies, thereby shedding light on the nature of dark matter itself. We will drastically increase observations in the outskirts of these galaxies, which will allow us to test whether dwarf galaxies are in equilibrium, as commonly assumed, or if they exhibit more complex kinematics (for example, Martin et al., 2016). These dynamical studies will benefit hugely from the fact that 4DWARS will constrain the binary fraction and period distribution of stars in dwarf galaxies, which are currently essentially unknown. Understanding their binary properties will also provide fresh insights into star formation and stellar evolution at low metallicities.

What are the small-scale limits of hierarchical galaxy formation?

In recent years the complexity in the Milky Way environment has been revealed, with dozens of identified structures. The progenitors of these systems are still being investigated, but they are likely a mixed bag of objects: a variety of dwarf galaxies and disrupted globular clusters with different ages and metallicities. 4DWARFS will characterise the accreted systems of the Galactic halo both kinematically and chemically, uncovering their metallicity distribution, chemical evolution and star formation history. This will allow us to understand the progenitors of these streams and the systems that build up the Milky Way halo (for example, Ibata et al., 2021). In particular, we will map and characterise the currently ongoing disruption of the Sagittarius dSph in extraordinary detail. Finally, we will move to even smaller scales of accretion, and for the first time identify in a systematic way mergers that have happened within the dwarf galaxies themselves (for example, Cicuendez & Battaglia, 2018), thus quantifying hierarchical galaxy formation down to the smallest scales.

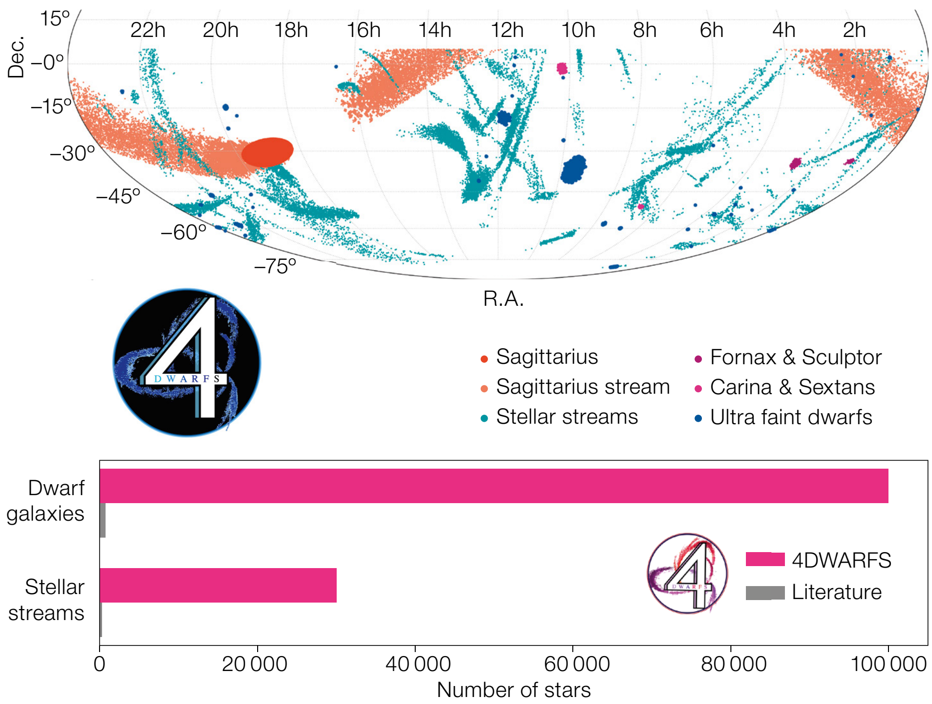

Figure 1. The scope of 4DWARFS. Top: the distribution of 4DWARFS targets on the sky. Bottom: the number of stars in 4DWARFS with ≥ 10 elemental abundances, compared to what is currently available in the literature. The 4DWARFS logo was designed by M. Rossi.

The 4DWARFS survey will therefore provide the most complete overview available of the evolution of dwarf galaxies, reconstructing their histories from formation to disruption.

Target selection and survey area

The 4DWARFS survey will target all known dwarf galaxies and stellar streams in the Milky Way halo observable from the Southern hemisphere, –80° < Dec. < +5° (Figure 1), at |b| ≥ 20. The density of our target catalogue varies drastically, from fewer than five targets per square degree in the more diffuse stellar streams, to more than 1000 in the central fields of larger dwarf galaxies.

The largest dSph galaxies, Sagittarius, Fornax, and Sculptor, will be targeted with both LR and HR fibres, and their central fields will be covered by longer exposure times (≥ 6 hours) compared to the fiducial 2-hour 4MOST footprint. The smaller dwarf galaxies, Carina, Sextans and the more than 40 ultra-faint dwarf galaxies, will be observed in LR, following the 4MOST footprint. Furthermore, 4DWARFS will target the prominent Sagittarius stream, along with all southern stellar streams that have been identified in the Milky Way halo through Gaia DR3. The streams will be observed with both HR and LR within the fiducial 4MOST footprint, taking advantage of existing deep fields. We emphasise that both HR and LR spectra will be used for chemical analysis, as well as radial velocities.

The 4DWARFS target catalogue is based on Gaia DR3. The member stars of the Sagittarius dSph main body are selected following the approach of the Gaia collaboration et al. (2018), taking into account photometry, proper motions, and parallaxes from Gaia. The target catalogues of all other dwarf galaxies are adopted from Battaglia et al. (2022), which is based on Gaia early DR3 photometry and astrometry. The target selection of the stream stars is done with the STREAMFINDER algorithm, as described in Ibata et al. (2021). Furthermore, special emphasis will be placed on observing metal-poor stars in dwarf galaxies and stellar streams, following an approach similar to that presented in Xylakis-Dornbusch et al. (2022).

The selection of our targets is highly complementary to other 4MOST surveys, in particular the Milky Way halo surveys, and the Magellanic Clouds survey. The combination of 4DWARFS and other Galactic surveys within 4MOST will therefore allow us to paint a comprehensive picture of the formation and evolution of the Milky Way environment, from cosmic dawn until the present day.

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