Scientific justification

StreamInG@4MOST: Stellar Streams in the Inner Galaxy with S-PLUS and 4MOST

Stellar streams are fossil records of the hierarchical assembly of the Milky Way, formed through the tidal disruption of accreted dwarf galaxies and globular clusters [Ibata et al., 1994, Odenkirchen et al., 2003, Belokurov et al., 2006, Newberg and Carlin, 2016]. By characterizing these systems, we can reconstruct the events in our Galaxy's past that shaped the structures we observe today [Helmi et al., 1999, 2018]. Streams originating from globular clusters can act as dynamical tracers to map the structure of our Galaxy [Küpper et al., 2015], including those that formed or migrated to the inner Galaxy [Bernard et al., 2014], while streams of accreted origin help constrain models of merger events and their impact on Galactic evolution [Vasiliev et al., 2021]. The chemical composition of these populations further reveals the relative contributions of different nucleosynthetic processes, either in unevolved stars [Hansen et al., 2020] that preserve the imprint of the early Milky Way or in debris of dwarf galaxies with distinct enrichment histories [Hasselquist et al., 2021].

Detecting stream debris in the inner Galaxy is challenging, as the dense thin/thick disks and bar/bulge foregrounds overlap the phase space of low Galactic latitude streams [Rocha-Pinto et al., 2003]. To overcome this issue, we employ an accreted/in-situ classification based on the 12-filter photometry of the S-PLUS survey [Mendes de Oliveira et al., 2019], which allows us to clean the sample from the foreground contaminants, extending the region where members of the stream can be detected and analyzed. This method is based on the classical [Al/Fe] $\times$ [Mg/Mn] diagram [Hawkins et al., 2015, Das et al., 2020] to select the accreted and unevolved stellar populations [Horta et al., 2021]. We reproduce the classical locus of this category of stars by applying a machine learning method to APOGEE-selected stars and giving as input all 66 S-PLUS colors. This method (Bolutavicius et al., in prep.) has proven to be more precise (88% precision with 82% completeness) than a simple metallicity cut, as the S-PLUS narrow-band filters are sensitive to metallicity [Whitten et al., 2021, Molina-Jorquera et al., 2024], including the metal-poor regime [Placco et al., 2022, Almeida-Fernandes et al., 2023], and both to Mg and Al abundances [Ferreira Lopes et al., 2025]. By targeting low Galactic-latitude streams we expect our study to offer unique information on the transition between halo, disk, and bulge, bridging the gaps of previous studies by combining S-PLUS photometric classification with spectroscopy.

Our target catalog covers a magnitude range between 12 and 16 (AB-magnitude) in the G-band, which is adequate for the high resolution spectroscopy. At 4000 Å, we expect to achieve SNR$\sim$75 for our brightest targets, and $\sim$20 for our faintest targets, which is sufficient for radial velocities and chemical abundance determinations. For the bright end, this will allow the determination of detailed chemical abundances for up to $\sim$30 elements, including α- and neutron-capture elements, which are essential to distinguish between different progenitor systems and enrichment histories. In addition, radial velocities will allow us to refine membership and better characterize their dynamical properties. We will characterize the MDFs and explore metallicity gradient across the streams, which would provide key insights into the progenitor's internal chemical structure. Finally, for streams of globular cluster origin, we will test for multiple stellar populations and compare with inner-Galaxy clusters to trace their formation and migration history. For ex-situ progenitors, we will contrast their abundance profiles with those of known accreted halo systems, such as Gaia-Enceladus.

Single OB 20-minute exposures will be enough to achieve our science goals, but further exposures would improve the precision of the individual abundance elements. The project is also robust in terms of partial completion, as each observed star independently constrains the chemo-dynamical properties of the stream and serves as a test of the S-PLUS photometric classification. Even a small number of confirmed members will add valuable information on the inner-Galaxy transition region, whereas a larger sample would enable stronger statistical analyses and the possibility of identifying abundance gradients along the streams.

Technical justification

We request observations with the 4MOST High-Resolution Spectrograph (HRS) for a sample of 2673 stars, identified as candidate members of 9 stellar streams located in the halo and inner region of the Galaxy. 2085 out of the 2673 stars in our selection are in low-galactic latitude ($|\mathrm{GLAT}| < 20°$). These selected accreted stellar streams to be studied are 20.0-1-M18 [Mateu et al., 2018], Corvus-M18 [Mateu et al., 2018], Gaia-3-M18 [Malhan and Ibata, 2018], M30-S20 [Harris, 1996, Sollima, 2020], NGC 5053-L06 (REF), NGC 6362-S20 (REF), Palca-S18 [Shipp et al., 2018], Parallel-W18 [Sohn et al., 2016, Weiss et al., 2018] and Yangtze-Y23 [Yang et al., 2023].

All targets will be observed with a single exposure of 1200 seconds (20 minutes). As we selected objects with magnitudes between 12 and 16, that exposure time will be enough to reach the desired signal-to-noise level. The primary objective is to obtain spectra with sufficient signal-to-noise ratio (S/N) to measure chemical abundances of key elements that serve as tracers of different enrichment processes. The 4-MOST HRS wavelength coverage of the three HR arms (3926–4355 Å, 5160–5730 Å, and 6100–6790 Å) will allow (for selected targets) the chemical abundance determination of up to 30 elements tracing different nucleosynthetic processes. This includes iron-peak elements (e.g. Fe, Mn, Ni), α-elements (e.g. O, Mg, Ca), light odd-Z elements (e.g. Na, Al), and neutron-capture elements (e.g., Ba and Y for the s-process, and Eu for the r-process).

Several streams have already been analyzed in surveys such as APOGEE [Majewski et al., 2017], GALAH [De Silva et al., 2015], and DESI [DESI Collaboration et al., 2016]. However, coverage for low-latitude, high-extinction, and crowded regions is limited. In contrast, the 4MOST supplementary targets provide a unique opportunity to acquire high-quality spectra in these regions. We expect our study to offer unique information on the transition between halo, disk, and bulge, extending beyond previous studies by integrating S-PLUS photometric classification with spectroscopy. Furthermore, as previously mentioned, we now have a technique to photometrically classify accreted/unevolved versus in-situ stars, enabling a clear separation of objects within the streams.

Additionally, we will derive precise radial velocities for the selected stellar streams that currently lack this information in the literature. With these measurements, we will be able to integrate orbits, better characterize their dynamical properties, and propose refined chemo-dynamical selections for stream members.

The sky distribution of our targets is shown in Figure 1. The left panel presents the data in Galactic coordinates and is colored by the density of sources in each position, highlighting how the great majority ($\sim$ 75%) of our stars is located towards the center of our Galaxy. The right panel displays the same data, in equatorial coordinates, but in this case, members of each stream are shown in different colors/markers. In this plot, we also present the footprint of S-PLUS iDR6 as a shaded gray region in the background of the plots, highlighting the importance of its large area coverage in providing a suitable sample of stream members. S-PLUS iDR6 was made available to the members of the S-PLUS collaboration in August 2025, and the data will be publicly released in August 2026.

The magnitude distribution of our targets in Gaia's G-band is shown in the left panel of Figure 2. Most of our sample is comprised between Gmag $\sim$ 10 and $\sim$ 15. The right panel of the figure shows the right-ascension distribution. Most of our targets are concentrated around RA $\sim$ 280° due to the proximity of most of our targets to the direction of the Galactic center.

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Target selection criteria

The selection of our targets was designed to maximize the likelihood of identifying genuine stellar stream members in the Galaxy, while ensuring robust photometric and astrometric quality. The procedure involved three main steps: (i) photometric quality cuts in S-PLUS, (ii) classification of accreted or unevolved populations, and (iii) kinematical selection of possible members of known stellar streams.

We started from the S-PLUS iDR6 catalog, requiring a signal-to-noise ratio (S/N) > 3 in at least one broad band, and valid photometry in all 12 filters. Due to the necessary 4MOST signal-to-noise level we wanted to achieve, we also had to restrict our sample with a metallicity cut $12 < g < 16$.

We then cross-matched our data with Gaia DR3 (REF) to obtain the necessary kinematic parameters. After that, we used Gaia's A_G values, converting them to the S-PLUS system, to correct for the dust extinction.

We then applied our classification method (Bolutavicius et al., in prep.) select stars most likely belonging to accreted systems or unevolved stellar populations of the Milky Way. At this point, we were left with 19382 bright accreted stars.

Then, using the `galstreams` python package [Mateu, 2023], we identified candidate stream members by comparing the observed 6D phase-space information with model predictions for each star, given its principal angular component in the streams frame (ϕ_1). We chose not to use the radial velocity in the calculations, given that for most of the stars in the bulge frames, that information was missing.

Stars consistent within 8σ of the expected χ^2 distribution were retained as likely members. We chose to use a less restrictive criterion to find members because, as we had already cleaned the sample before by removing in situ stars, the contamination shouldn't go up as much. And in that case, with a larger area we can better determine the true extent of the stream after confirming the members with the 4MOST spectroscopy.

Finally, we restricted the choice of stellar streams to the ones that had more than 20 member candidates (before accounting for stream overlaps).

The final criteria can be summarized as follows:

- Initial selection from S-PLUS iDR6 with S/N > 3 in at least one broad band and complete photometry in all 12 filters and with $12 < g < 16$ mag.
- Cross-match with *Gaia* DR3 to obtain astrometry and kinematics. Also used the gaia catalog to correct for dust extinction.
- Application of our photometric classification method to identify stars likely accreted or unevolved.
- Identification of candidate stream members with `galstreams`, requiring χ^2 consistency at the $< 8\sigma$ level.
- Final restriction to streams with > 20 members.

That left us with 2673 stars, distributed in the parent streams 20.0-1-M18 [Mateu et al., 2018], Corvus-M18 [Mateu et al., 2018], Gaia-3-M18 [Malhan and Ibata, 2018], M30-S20 [Harris, 1996, Sollima, 2020], NGC 5053-L06 [Lauchner et al., 2006], NGC 6362-S20 [Harris, 1996, Sollima, 2020], Palca-S18 [Shipp et al., 2018], Parallel-W18 [Sohn et al., 2016, Weiss et al., 2018] and Yangtze-Y23 [Yang et al., 2023].

Out of the selected streams, the major part of the stars (2021 objects) are part of the 20.0-1-M18 stream, which passes behind the bulge of the Galaxy. We chose to also include the remaining 8 streams as a complement to this study, given that they also lack a complete chemo-dynamical analysis in the literature.

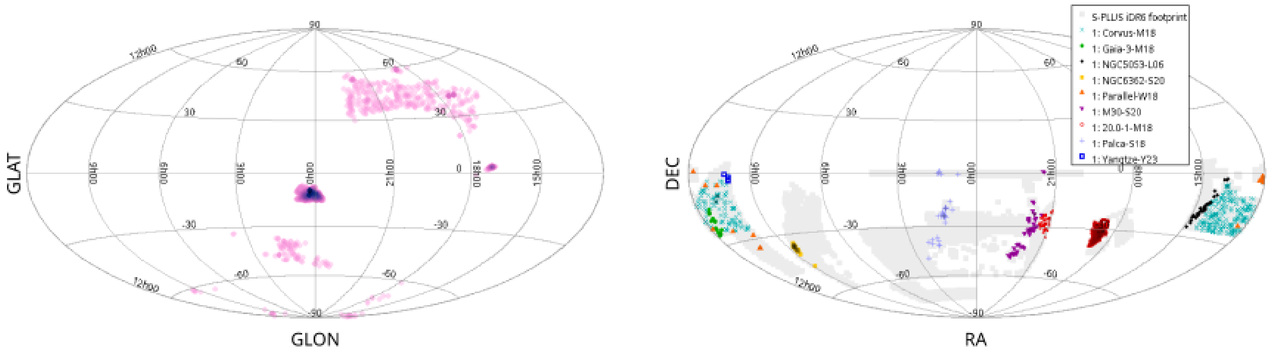

Figure 1: Left: targets distribution in Galactic coordinates colored by density. Right: target distribution in Equatorial coordinates, colored according to the assigned parental stream. The S-PLUS iDR6 is shown as a gray shaded region in the background, for reference.

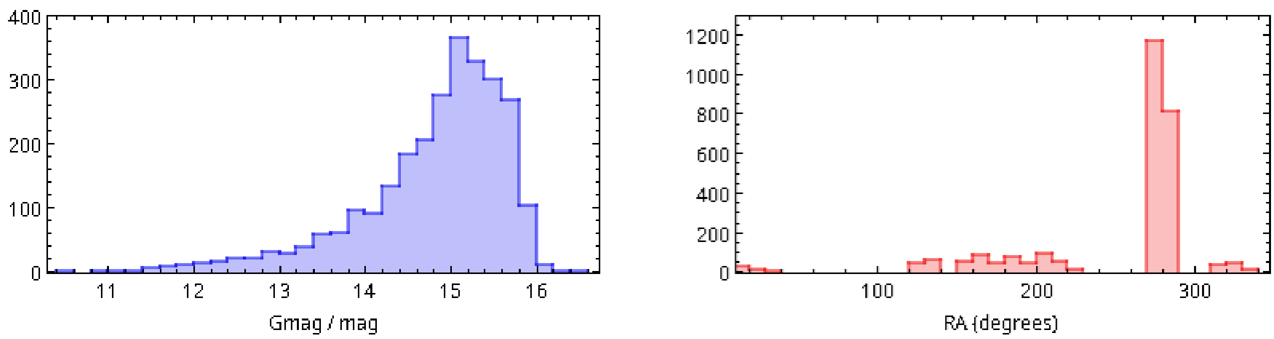

Figure 2: Left: histogram showing the magnitude distribution of the sample in G-band; right: histogram showing the number of targets as a function of RA.

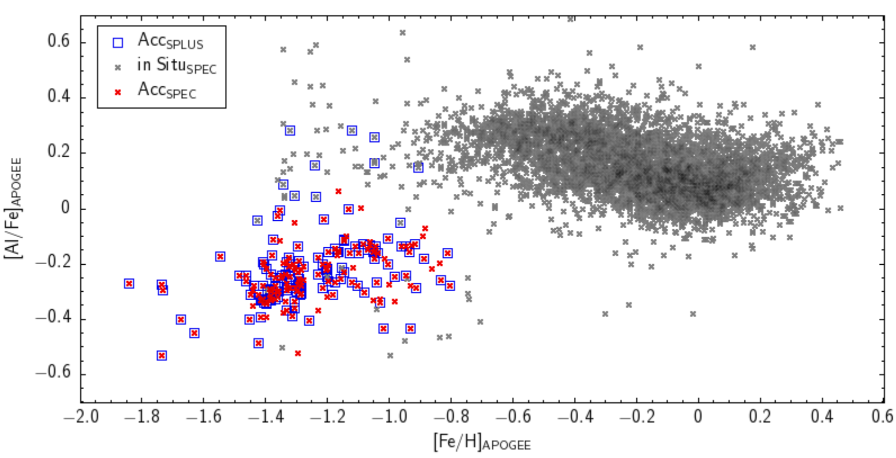

Figure 3: Performance of the accreted stars classifier based on the 12 S-PLUS bands (blue squares), compared to the APOGEE spectroscopic classification (red circles).