

## The Pristine survey

### XXV. The very metal-poor Galaxy: Chemodynamics through the follow-up of the Pristine-Gaia synthetic catalogue<sup>★</sup>

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#### ABSTRACT

**Context.** The Pristine-Gaia synthetic catalogue of reliable photometric metallicities makes use of spectrophotometric information from Gaia DR3 XP spectra to calculate metallicity-sensitive *CaHK* magnitudes, which in turn provides photometric metallicities for ~30 million FGK stars using the Pristine survey model and the survey's training sample.

**Aims.** We performed the first low- to medium-resolution spectroscopic follow-up of bright ( $G < 15$ ) and distant (upto 35 kpc) very and extremely metal-poor (V/EMP,  $[\text{Fe}/\text{H}] < -2.5$ ) red giant branch stars from this catalogue – to evaluate the quality of the photometric metallicities and study the chemodynamics of these V/EMP stars.

**Methods.** We used *Isaac Newton* Telescope/Intermediate Dispersion Spectrograph (INT/IDS) observations centred around the calcium triplet region ideal for V/EMP stars for this spectroscopic follow-up.

**Results.** We find that 76% of our stars indeed have  $[\text{Fe}/\text{H}] < -2.5$  with these inferred spectroscopic metallicities, and only 3% are outliers with  $[\text{Fe}/\text{H}] > -2.0$ . We report a success rate of 77% and 38% in finding stars with  $[\text{Fe}/\text{H}] < -2.5$  and  $-3.0$ , respectively. This is a huge improvement compared to the literature in the selection of V/EMP stars based on photometric metallicities and will allow for 10 000–20 000 homogeneously analysed EMP stars using the WEAVE survey follow-up of Pristine EMP candidates. Using kinematics, we categorised 20%, 46%, and 34% of the stars as being confined to the disc plane, or having inner and outer halo orbits, respectively. Based on their integrals-of-motion, we are able to associate these V/EMP stars with the metal-poor tail of the metallicity distribution functions of known accretion events such as the Gaia-Enceladus-Sausage, LMS-1/Wukong, Thamnos, Helmi streams, Sagittarius, Sequoia, and other retrograde mergers. For the stars that orbit close to the disc plane, we find that the prograde region with low vertical action is overdense with a significance of  $4\sigma$  compared to its retrograde counterpart. We also find three new (brightest) members of the most metal-poor stellar stream, C-19, one of which is  $50^\circ$  from the main body of the stream. This is the first member of C-19 found at positive height above the disc plane. Our measured mean metallicity, velocity dispersion, and stream width are consistent with the literature, but our results favour a slightly farther distance (~21.5 kpc) for the stream.

**Conclusions.** With this work, we publish a catalogue (and 1D spectra) of 215 V/EMP stars from this first spectroscopic follow-up of the Pristine-Gaia synthetic catalogue of photometric metallicities and showcase the power of chemokinematic analysis of bright and distant red giant stars in the V/EMP end.

**Key words.** techniques: spectroscopic – stars: Population II – stars: Population III – Galaxy: halo – Galaxy: kinematics and dynamics – Galaxy: stellar content

## 1. Introduction

The enduring presence of the most metal-poor stars within the Milky Way serves as an invaluable window to the early Universe and the pristine conditions in which these stars originated. These stellar relics are believed to have coalesced from material enriched by the initial generations of stars, offering crucial insights into the characteristics of their progenitors through their chemical compositions (Beers & Christlieb 2005;

Frebel & Norris 2015). Furthermore, by studying the dynamical properties of these ancient stars, we gain valuable insights into the early formation processes of our Galaxy.

The metal-poor halo of the Milky Way has become the heart of several accreted structures, remnants of the Galaxy's tumultuous merger history. These structures include the Gaia-Enceladus-Sausage (GES), Sequoia, Thamnos, Helmi, LMS-1/Wukong, Cetus-Palca, and Sagittarius streams (Belokurov et al. 2018; Helmi et al. 2018; Barbá et al. 2019; Myeong et al. 2019; Koppelman et al. 2019; Yuan et al. 2020; Naidu et al. 2020; Thomas & Battaglia 2022; Ibata et al. 1994), among others, each offering unique insights into past Galactic interactions. The recent discovery of numerous stellar streams further underscores the ongoing accretion events from dwarf and ultra-faint

<sup>★</sup> Based on service-mode and visitor-mode observations made with the INT/IDS operated on the island of La Palma by the *Isaac Newton* Group of Telescopes in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofísica de Canarias.

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galaxies, as well as globular clusters, enriching the Galactic halo (Li et al. 2022b; Ibata et al. 2021, 2023; Martin et al. 2022a,b; Viswanathan et al. 2023). Additionally, recent studies suggest that a significant fraction of the halo stars may have formed in situ, representing a blend of components including an  $\alpha$ -rich splashed hot thick disc and stars born in a primordial, hot, and disordered state (e.g., Bonaca et al. 2017; Haywood et al. 2018; Di Matteo et al. 2019; Belokurov et al. 2020; Belokurov & Kravtsov 2022). This comprehensive understanding of the Milky Way’s metal-poor population provides a foundation for unraveling the complex tapestry of Galactic formation and evolution.

The prevailing narrative across various cosmological simulations suggests that very metal-poor (VMP,  $[\text{Fe}/\text{H}] < -2.0$ ) stars residing within the central regions of the Milky Way, including the bulge, represent some of the oldest stars in our Galaxy. These stars serve as invaluable tracers of the early Galactic assembly, offering critical insights into its formation history (Diemand et al. 2005; Tumlinson 2010; Starkenburg et al. 2017b; El-Badry et al. 2018). On the observational front, numerous VMP stars have been scrutinised for their chemistry and kinematics, with particular emphasis on regions such as the bulge and the disc (Howes et al. 2014; Lucey et al. 2019; Arentsen et al. 2020), providing essential data for understanding their origins. The chemical characteristics of these stellar populations reveal a diverse assortment of objects that contributed to the formation of the inner Galaxy. Some stars exhibit chemical signatures indicative of formation in systems resembling ultra-faint dwarf galaxies, while others display traits consistent with birth within globular cluster-like environments (Schiavon et al. 2017). Additionally, as pointed out earlier, there is evidence pointing towards a significant presence of in situ metal-poor stars within the inner Galaxy (Conroy et al. 2019; Belokurov & Kravtsov 2022, 2023; Rix et al. 2022; Ardern-Arentsen et al. 2024). This amalgamation of observational and theoretical findings paints a picture of the early stages of Galactic evolution, underscoring the complex interplay between various stellar populations and their environments.

Finding the most metal-deficient ( $[\text{Fe}/\text{H}] < -3.0$ ) stars has long been recognised as a formidable challenge due to their exceptionally rare occurrence rate (Bond 1981). These stars are predominantly located in the Milky Way’s halo component, and the ratio of halo to disc stars in the solar neighbourhood is approximately  $10^{-3}$  (Bahcall & Soneira 1980). Moreover, the number of stars diminishes exponentially by a factor of roughly  $\sim 10$  or more for each dex decrease in metallicity (Hartwick 1976). In the solar neighbourhood, this translates to expectations of encountering one star with  $[\text{Fe}/\text{H}] = -3.0$  among every 65,000 stars, and one star with  $[\text{Fe}/\text{H}] = -3.5$  among 200 000 stars (Youakim et al. 2020). To effectively address these challenges and advance our understanding of the old halo component with sufficient statistical power, efficient selection techniques are imperative.

Over the past four decades, numerous dedicated searches have been conducted to assemble large samples of the most metal-poor stars. Various techniques have been employed to identify these stars, including the pursuit of high proper motion stars exhibiting ultraviolet excesses (Ryan & Norris 1991), the detection of objects with diminished Ca II H&K lines in extensive objective-prism surveys (Beers et al. 1985; Christlieb et al. 2008), and the utilisation of metallicity-sensitive (narrowband) photometry (Schlaufman & Casey 2014; Starkenburg et al. 2017a; Wolf et al. 2018; Cénarro et al. 2019; Almeida-Fernandes et al. 2022). Moreover, very and extremely metal-poor (V/EMP) stars have been identified in greater abundance through

large-scale spectroscopic surveys such as the Sloan Digital Sky Survey (SDSS, York et al. 2000), the Large sky Area Multi-Object fiber Spectroscopic Telescope (LAMOST, Zhao et al. 2006; Li et al. 2018), the RAdial Velocity Experiment (RAVE, Steinmetz et al. 2006), the GALactic Archaeology with HERMES spectroscopic survey (GALAH, Buder et al. 2021), and the *Gaia* Radial Velocity Spectrometer (RVS, Recio-Blanco et al. 2023; Matsuno et al. 2024; Viswanathan et al. 2024c). These photometric and spectroscopic surveys are often complemented by dedicated follow-up efforts at the VMP end (e.g. Aguado et al. 2019; Yong et al. 2021; Li et al. 2022a; Witten et al. 2022).

While astrometric data from the *Gaia* mission (Gaia Collaboration 2023) has revealed significant stellar kinematic signatures attributed to earlier accretion events, there persists a crucial requirement for precise metallicities for many stars, particularly in the extremely metal-poor regime (EMP,  $[\text{Fe}/\text{H}] < -3.0$ ). Such detailed metallicity measurements are essential for constructing a comprehensive chemodynamic framework, enabling a thorough understanding of the early structures that persist within the present Milky Way halo.

In this work, our aim is to increase the amount of chemodynamically analysed bright (and distant) metal-poor red giant branch (RGB) stars. We used the Pristine-*Gaia* synthetic catalogue of photometric metallicities to select V/EMP stars. These metallicities were estimated using the *Gaia* XP low-resolution spectrophotometry by determining the flux around the metallicity-sensitive narrowband Ca II H&K lines (hereafter *CaHK*), and running them with the Pristine survey model. We present the first results of our low- to medium-resolution follow-up spectroscopy of 215 stars in the Pristine-*Gaia* synthetic catalogue to assess the performance of the survey’s photometric pre-selection. We used *Gaia*’s astrometry, distances, radial velocities (where available) and the follow-up spectra’s radial velocities to calculate the dynamics, and we discuss their chemokinematic properties. Section 2 summarises the target selection strategy for this spectroscopic follow-up program. Section 3 presents the spectral analysis methods. Section 4 presents the success rates of the photometric metallicities and discuss the chemokinematics of the V/EMP stars. Section 5 discusses in detail the implications of disc-like V/EMP stars in the sample and new tentative members of the most metal-poor C-19 stellar stream. In Section 6, we summarise the conclusions and outlook.

## 2. Target selection

In this section, we describe how the V/EMP stars were selected using the Pristine-*Gaia* synthetic photometric metallicity catalogue. For a comprehensive overview of the Pristine survey, we refer to Starkenburg et al. (2017a). Additionally, for detailed information on the Pristine-*Gaia* synthetic catalogue and the Pristine data release 1, we refer to the work by Martin et al. (2024, hereafter MS23).

### 2.1. The Pristine survey and success rates

The Pristine survey focuses on observing the sky of the northern hemisphere using the MegaCam wide-field imager installed on the Canada France Hawaii Telescope situated on Mauna Kea. This survey employs a narrowband filter centred on the metallicity-sensitive *CaHK* in the near UV (3968.5 and 3933.7 Å). When combined with Sloan Digital Sky Survey (SDSS) *g*, *r*, *i* filters, or the *Gaia* broadband BP-RP (blue and red photometric) and *Gaia* G bands, this narrowband filter has

been demonstrated to provide very reliable estimates of stellar metallicity and an exceptional tool for identifying V/EMP stars.

The Pristine photometry, in conjunction with SDSS broadband photometry, has paved the way for medium- and high-resolution spectroscopic follow-up studies. These investigations specifically target stars with the lowest metallicity estimates derived from Pristine *CaHK* observations. Through dedicated medium- and high-resolution spectroscopic follow-up studies of Pristine-selected candidates for EMP stars, we have found strong evidence that the majority of these stars are indeed (very) metal-poor. Spectroscopic analyses of these candidates have confirmed that approximately 20% of the EMP star candidates possess  $[\text{Fe}/\text{H}] < -3.0$  and 70% of the VMP star candidates are below  $[\text{Fe}/\text{H}] < -2.0$  when carefully considering quality flags during target selection. This conclusion is supported by the work of Youakim et al. (2017), and Aguado et al. (2019) through medium-resolution follow-up and Caffau et al. (2017), Starkenburg et al. (2018), Bonifacio et al. (2019), Caffau et al. (2020), Venn et al. (2020), Kielty et al. (2021), Lardo et al. (2021), Lucchesi et al. (2022), and Caffau et al. (2023) through high-resolution follow-up studies. However, it is essential to account for potential variability in these stars and undertake thorough photometric quality cuts to ensure accurate characterisation of their metallicities (Lombardo et al. 2023).

## 2.2. Pristine-Gaia synthetic catalogue of photometric metallicities

The creation of the Pristine-Gaia synthetic catalogue is described in detail in MS23. We summarise the method here briefly. With the newest data release of *Gaia* (Gaia Collaboration 2023, DR3), the spectrophotometric BP/RP information (De Angeli et al. 2023) was used to construct a comprehensive catalogue of synthetic *CaHK* magnitudes, which emulate the narrow-band photometry employed in the Pristine survey. Several other recent works released a catalogue of metallicity estimates based on these *Gaia* XP spectra (Lukey et al. 2023; Andrae et al. 2023; Zhang et al. 2023). At the same time, the excellent *Gaia* accuracy allows us to reprocess and recalibrate the entire Pristine *CaHK* dataset comprising approximately 11,000 images obtained since 2015, resulting in an updated survey that now covers more than 6,500 square degrees.

The improved photometric catalogue exhibits enhanced accuracy, achieving a precision level of 13 millimagnitudes (mmag), a notable improvement from the estimated 40 mmag during the first year of data. As part of the updated model, the Pristine method for deriving the photometric metallicity of a star from *CaHK* magnitudes and broadband magnitudes now relies solely on *Gaia* broadband information ( $G$ ,  $G_{BP}$ ,  $G_{RP}$ ), as opposed to SDSS previously. Additionally, a more reliable iterative approach for addressing extinction correction has been implemented. This involves incorporating extinction correction on the *Gaia* broadband magnitudes and *CaHK* synthetic (or Pristine *CaHK*) narrowband magnitudes by considering the star's photometric temperature and metallicity. To mitigate the impact of photometrically variable sources, which can introduce spurious metallicities, a variability model based on the photometric uncertainties of the 1.8 billion *Gaia* sources was also implemented in the catalogue. Employing both the Pristine *CaHK* magnitudes and the BP/RP based synthetic *CaHK* magnitudes within the Pristine model, two catalogues of photometric metallicities for reliable stars were made public: the Pristine-Gaia synthetic catalogue and the Pristine data release 1 (DR1) catalogue of photometric metallicities, encompassing stars common to both Pristine and the BP/RP catalogue of *Gaia* DR3. The latter

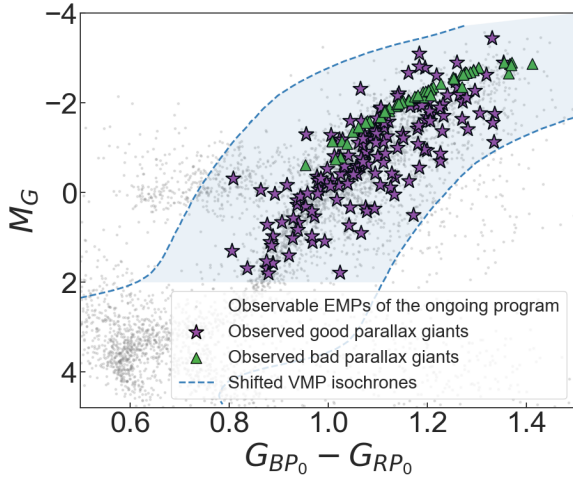
served as the first data release of the Pristine survey and provides deeper and better signal-to-noise (S/N) data for stars in common.

Both these catalogues facilitate the construction of reliable samples of metal-poor stars, with a particular emphasis on tracking V/EMP stars. The Pristine-Gaia synthetic catalogue provides photometric metallicities across a vast portion of the sky, while the Pristine BP/RP catalogue, limited to the Pristine survey's footprint, offers notably high-quality metallicities, extending to significantly fainter stars.

In this work, we use the Pristine-Gaia synthetic catalogue of photometric metallicities to select V/EMP targets that have reliable distances and are on the red giant branch (hereafter RGB) of stellar evolution for a dedicated spectroscopic follow-up. We choose to follow-up red giants as they are intrinsically bright and probe large distances out into the Galactic halo, allowing us to study the chemodynamics of the Milky Way out to large distances and down to very low metallicities. For this target selection, we use the following quality cuts on the parent sample, most of which are recommended by MS23. Because some of the cuts recommended by MS23 were introduced after this follow-up program commenced, these cuts are only implemented later in the manuscript as stricter quality cuts in Section 4.1. The quality cuts initially used for target selection are defined as follows:

- The follow-up is done from the northern hemisphere. Declination greater than  $-30$  degrees – which is the observability of the INT/IDS telescope facility used for the follow-up ( $\text{dec} > -30$ ).
- Photometric metallicity lower than  $-2.5$  dex ( $\text{FeH\_CaHKsyn} < -2.5$ ). Note that this cut was based on the first generation of photometric metallicities using the Pristine survey model on *Gaia* XP based *CaHK* magnitudes. Over the course of this work, the photometric metallicities were updated as a result of improvement in the methods. Most of the selected stars still have a V/EMP metallicity inference, also in the published catalogue (MS23). In the rest of the paper, we only ever list the final MS23 metallicities.
- Percentages of Monte Carlo iterations used to determine  $[\text{Fe}/\text{H}]$  uncertainties inside the grid is greater than 80% ( $\text{mcfrac\_CaHKsyn} > 0.8$ ).
- 84th percentile value of the probability distribution function (PDF) of the photometric metallicity is greater than  $-3.999$  ( $\text{FeH\_CaHKsyn\_84th} > -3.999$ ).
- Photometric metallicity uncertainty less than 0.5 dex ( $0.5 * (\text{FeH\_CaHKsyn\_84th} - \text{FeH\_CaHKsyn\_16th}) < 0.5$  dex).
- Extinction on B-V magnitude is less than 0.5 ( $E(B-V) < 0.5$ ).
- Brightness cut on measured *Gaia* G magnitude ( $\text{phot\_g\_mean\_mag} < 15.5$ ) to be able to observe with INT/IDS with short exposure times.
- Photometric quality cut that is defined as  $C^* < 3\sigma_{C^*}$ .  $C^*$  is *Gaia* DR3 corrected flux excess,  $C^*$ , as defined in Equation (6) of Riello et al. 2021 and  $C^*_{1\sigma}$  is normalised standard deviation of  $C^*$  for the G magnitude of this source, as defined in Equation (18) of Riello et al. 2021 ( $\text{abs}(C^*) < 3 * C^*_{1\sigma}$ ).
- Parallax cuts:
  - Good parallax giants:  $\text{parallax\_over\_error} > 5$
  - Bad parallax giants: Poorly constrained small parallax (very likely a red giant) –  $\text{parallax\_over\_error} < 5$  and  $\text{abs}(\text{parallax}) < 0.2$ .
- No star within radius  $r_{\text{max}}$  from the centre of globular clusters, with  $r_{\text{max}}$  being the rough estimate of the size of a cluster defined by Vasiliev & Baumgardt (2021).





**Fig. 1.** Colour absolute magnitude diagram (CaMD) of the INT observable targets that pass the quality cuts described in Section 2.2 in grey overplotted with the RGB stars that were observed and presented in this paper in purple and green. The purple star markers correspond to the good-quality parallax used to select the RGB stars and the green triangles correspond to the bad-quality parallax used to select the RGB stars for which the distances were derived using photometry and isochrone fitting. The blue dashed lines refer to an age 13 Gyr and metallicity  $[M/H] -2.2$  PARSEC isochrone shifted by  $\pm 0.2$  mag in  $BP_0 - RP_0$  and  $\pm 0.75$  mag in  $M_G$ . The blue polygon is the absolute magnitude limited ( $M_G < 2.0$ ) target selection area.

- Shifted VMP old isochrone (PARSEC isochrone<sup>1</sup> of age 13 Gyr and metallicity -2.2 dex, Bressan et al. 2012; Pastorelli et al. 2020) selection to remove horizontal branch stars and stars away from RGB (used to reliably select RGB stars as targets) – this selection is also limited to absolute magnitude of 2 mag and below. The magnitude-limited shifted isochrone selection is shown as the filled blue region in Figure 1.
- No overlap with literature high-resolution follow-up of VMP stars (Hansen et al. 2018; Sakari et al. 2018; Li et al. 2018, 2022a) and the Pristine survey training sample that also includes Pristine survey’s own spectroscopic follow-up programs as described in MS23. We end up having a handful of stars (14) that overlap with the SAGA database of metal-poor stars (Suda et al. 2008) (mostly from Li et al. (2022a) follow-up to avoid uncertainties due to many different follow-up methods) which we use to define the systematic uncertainty in the spectroscopic metallicity inferred in this work.

All the stars that pass the above selection criteria (using good parallax subsample) with inverted parallax as an approximation for distance ( $=1/\text{parallax}$ ) are shown in grey in Figure 1. The reliable parallax stars that were spectroscopically followed-up are shown as purple star symbols and the ones that were selected based on small parallax with large errors are shown as green triangle symbols.

Numerous studies have provided compelling evidence that relying solely on inverted parallax measurements to estimate distances can yield inaccurate results especially if the parallax measurements are imprecise ( $\varpi < 0''$  and/or  $\varpi/\sigma_\varpi > 0.2$ ). Incorporating additional priors and/or photometry has proven to enhance distance estimation (e.g., Bailer-Jones et al. 2018, 2021; Queiroz et al. 2018; Anders et al. 2022). To address these challenges, we adopted a Bayesian approach to infer distances for the

stars with bad parallax in our sample. We employed a methodology, that enables the estimation of the PDF or posterior on the distance estimates (see Sestito et al. (2019) for a full description of the method). In summary, the likelihood function is formulated as the product of Gaussian distributions from the parallax and Gaia photometry. Our prior incorporates a power-law stellar distribution for the halo that we believe to be more suited for VMP stars than the prior used in more general distance methods. Additionally, we utilised VMP ( $[M/H] = -2.5$ ) MESA/MIST isochrones<sup>2</sup> (Dotter 2016; Choi et al. 2016) to account for the age and mass characteristics of VMP stars (11–13.8 Gyr,  $< 1 M_\odot$ ) and their distribution according to an IMF-based luminosity function in the colour absolute magnitude diagram (CaMD).

This Bayesian framework, extensively employed in chemo-dynamical investigations of VMP stars (e.g. Sestito et al. 2019, 2020, 2023; Venn et al. 2020), yields distance estimates with low uncertainties even when faced with significant parallax uncertainties. Typical distance uncertainties for these stars in the sample is as low as  $\sim 8\%$ . This is achieved because the MIST isochrones restrict the potential distance solutions for a star with a given colour to two possibilities: a dwarf or a giant solution. The parallax measurement typically favours one of the two solutions, or in the case of a very poor parallax measurement, assigns different probabilities to the two peaks. This approach eliminates the possibility of intermediate distance solutions. With this method all our targets that were selected based on poorly constrained small parallax ended up having a PDF that favoured a giant solution. These are shown as green star symbols along a rough isochrone-like positioning on the CaMD in Figure 1. All the *Gaia* broadband photometry in Figure 1 and other photometry used in target selection criteria are corrected for extinction based on the iterative method described in detail in MS23 and available in their public catalogue. The on-sky distribution of the stars selected and observed with the telescope facility is shown as purple stars in Figure 2 while the grey stars in the background are all stars that satisfy the quality cuts described above (except the observability cut). The effect of *Gaia*’s scanning pattern, which has resulted in certain regions being more frequently observed, is clearly evident in the distribution of grey points in Figure 2. This pattern becomes particularly prominent as we push the limits of our observations to detect fainter stars, approaching *Gaia* XP spectra’s limiting apparent magnitude (for a more detailed visualisation of *Gaia*’s scanning pattern in the analysis of sources with XP spectra, see De Angeli et al. 2023).

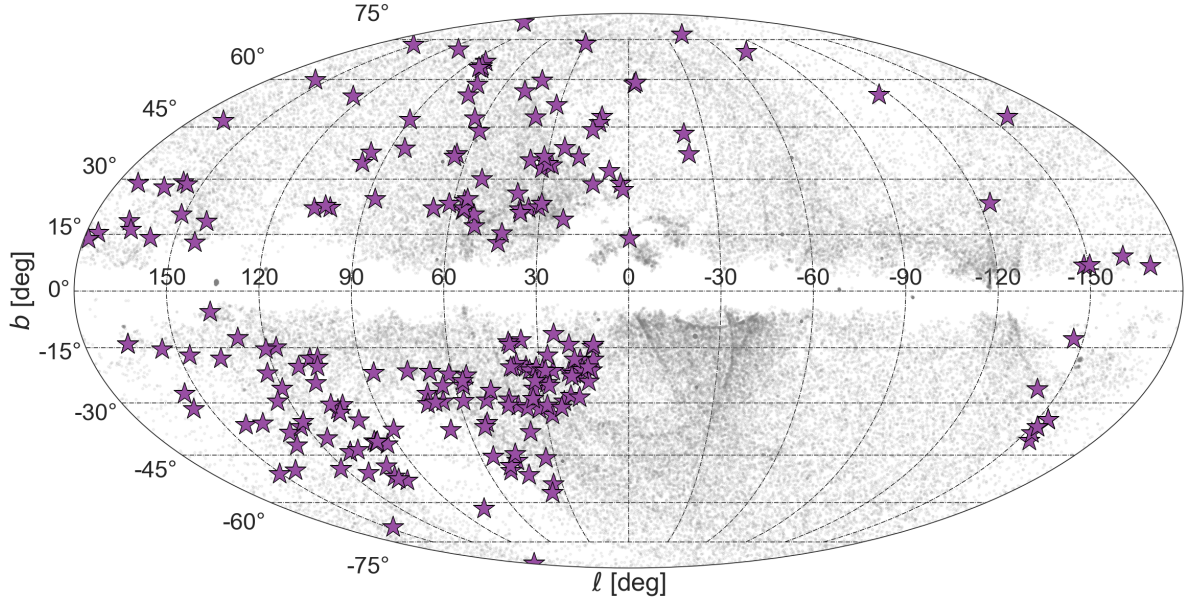
### 3. INT/IDS spectroscopic follow-up of V/EMP candidates

The spectroscopic follow-up presented in this paper stemmed from an ongoing long-term program at the *Isaac Newton* Telescope (INT) in La Palma (PI: A. Viswanathan, semesters 22B, 23A, 23B, PI: E. Starkenburg, A. Arentsen, semester 22A). We followed-up 215 stars over the course of 17 nights (along with a few other member candidates from substructures in the Milky Way). The observations include the following grey to bright nights: June 17 to June 21, 2022 (clear weather, seeing between 0.5 and 0.8), July 19 to July 21, 2022 (clear weather, seeing  $\sim 0.8$ ), 8 September to 11 September 2022 (partly cloudy, seeing  $\sim 0.9$ ) and 30 December 2022 to 3 January 2023 (partly cloudy, seeing  $\sim 1.4$ ). Our observing strategy was to go for very bright targets when the seeing is relatively bad, stay  $40^\circ$  away from the moon and away from the clouds. The results from semesters

<sup>1</sup> [stev.oapd.inaf.it/cgi-bin/cmd](http://stev.oapd.inaf.it/cgi-bin/cmd)

<sup>2</sup> [waps.cfa.harvard.edu/MIST](http://waps.cfa.harvard.edu/MIST)





**Fig. 2.** Mollweide projection of the Galactic coordinates for the V/EMP stars with  $[\text{Fe}/\text{H}] < -2.5$  in the Pristine-*Gaia* synthetic catalogue (in grey). The large-scale patterns visible in the map are mainly attributed to the scanning law of the *Gaia* satellite. The purple stars represent the subset of stars observed and analysed in this spectroscopic follow-up.

**Table 1.** Technical information of the facility used in this analysis.

Telescope	Instrument	Detector	Grating	Filter	Slit	Central $\lambda$	Range	Dispersion	Resolving power ( $\Delta\lambda$ )
2.5 m INT	IDS	Red+2	R1200R	GG495	1.37''	8500 Å	7829.5–9163.7 Å	0.51 Å px <sup>-1</sup>	8019 (0.51 Å)

23A and 23B will be published in a forthcoming paper. We used the Intermediate Dispersion Spectrograph (IDS) equipped with the RED+2 CCD. Our configuration included the R1200R grating, a 1.37'' slit width, and the GG495 order-sorting filter. This instrumental setup allowed us to achieve an effective spectral range of approximately 7850–9150 Å with a low to medium resolving power of  $\sim 8000$  (0.51 Å) over 2 pixels at the detector, specifically at 8500 Å, covering the calcium triplet region. This choice was made due to the follow-up of stellar streams (the original proposal that was changed to follow-up of EMPs in the later semesters with the use of a blue CCD).

The combination of the INT and the IDS instrument provided the necessary capabilities to achieve accurate metallicity information and radial velocities for the observed V/EMP candidates (see Table 1 for further technical details).

### 3.1. Data reduction

The spectra were processed and reduced using the Image Reduction and Analysis Facility (IRAF, Tody 1986) software package. Standard reduction techniques were applied, including bias sky subtraction, removal of telluric lines, flat fielding, spectrum extraction, sky subtraction, wavelength calibration – using CuNe+CuAr lamps and the ONEDSPEC package in IRAF, and heliocentric radial velocity correction. For wavelength calibration, we use a 10s arc per target and use the 10s and 30s arc from the beginning of the night for the calibration itself. The fringing effect, which can sometimes be a mild issue for the RED+2 CCD on the INT<sup>3</sup>, was found to have an amplitude of 2% or less for

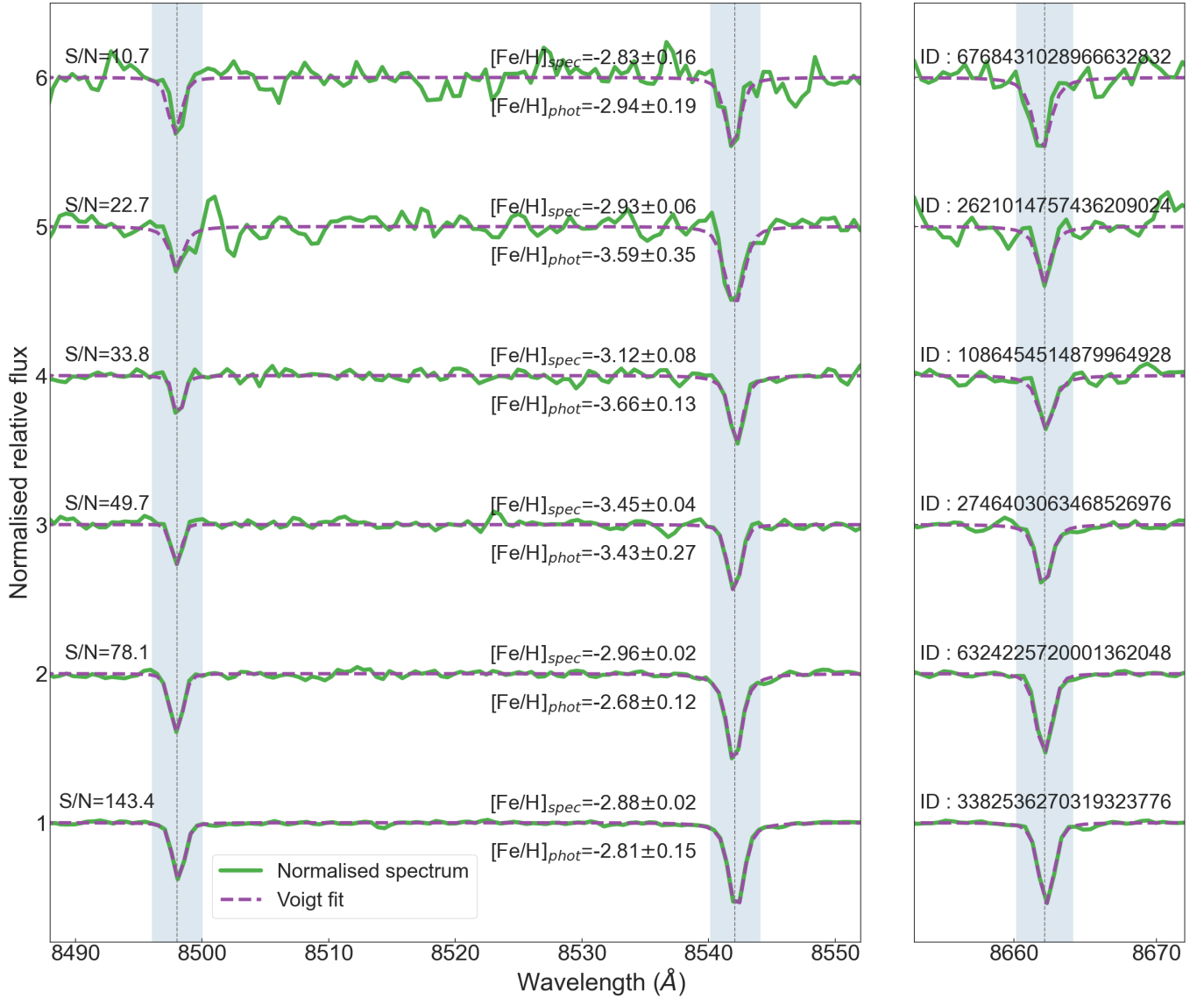
the redmost wavelengths below 9000 Å. Since the wavelength range concerned by this study is covered by the calcium II triplet from approximately 8400 Å to 8750 Å, no fringing correction was necessary.

Figure 3 illustrates spectra of six examples with varying S/N between and 10 and 140. The S/N values for each spectra are shown above each of the spectra. The S/N values calculated per pixel were computed in the calcium triplet region between line 2 (8542 Å) and line 3 (8662 Å). Due to the brightness range of the targets, (see left panel of Figure 4) we have achieved a mean S/N of 34.2 with a minimum S/N of 9.7 with an average exposure time of 10 minutes (the exposure time varies per target based on the brightness of the target and seeing conditions). We use a sophisticated MCMC pipeline to analyse the spectra to get metallicities (described in later subsections). This pipeline needs a S/N of  $\geq 3$  in the calcium triplet region to be able to statistically distinguish between the calcium triplet line with the smallest amplitude and noise (see Longeard et al. 2022). However, to achieve more robust results for our relatively bright stars, we aim for a  $\text{S/N} \geq 15$ . The aimed S/N of 15 or above was achieved for  $\sim 97\%$  of our targets while all our targets have a S/N above 3.

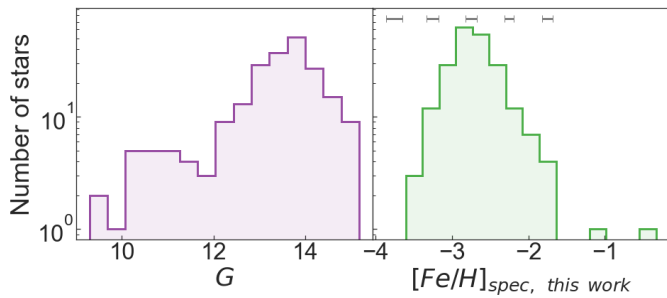
### 3.2. Radial velocities

To derive the radial velocities from calcium II triplet lines, we first cut the spectra within the wavelength range  $\lambda = [8400, 8750]$  Å, remove the cores of the calcium triplet (only to calculate the continuum) using `dispcor`, to find the continuum, and normalise the spectra using `onedspec.continuum` routine. We then run `fxcor` to obtain radial velocities through

<sup>3</sup> [https://www.ing.iac.es/astronomy/instruments/ids/ids\\_redplus2.html#4](https://www.ing.iac.es/astronomy/instruments/ids/ids_redplus2.html#4).



**Fig. 3.** INT/IDS spectra of six V/EMP subsample stars selected using photometric metallicities from the Pristine-*Gaia* synthetic catalogue, centred on the calcium triplet lines. The stars are presented and sorted based on their S/N. The normalised spectra are shown as solid green lines, while the fits, derived from our pipeline for Voigt line profiles detailed in Section 3.3, are shown as dashed purple lines. Their S/N values, the photometric metallicities used to select them, and the spectroscopic metallicities derived are also given near the corresponding spectra. For clarity, the normalised flux of each star is shifted by 0.5 and the spectra between the second and the third calcium triplet line is cut off. The calcium triplet lines are highlighted in blue and the central line is indicated by grey dashed lines. We focused on the three calcium triplet lines and removed the core between the second and third calcium triplet lines only for clarity of the spectra presented in this figure and for no scientific purpose.



**Fig. 4.** Distribution of *Gaia* G magnitudes and the derived metallicities from the Ca II triplet region for the full follow-up spectroscopic sample of 220 Pristine-*Gaia* synthetic V/EMP stars. Median uncertainties in bins of 0.5 dex in spectroscopic [Fe/H] are shown on the right.

the cross-correlation of an observed standard star<sup>4</sup> from the night with the observed V/EMP target. This is done by relative radial velocity between the observed target and the standard star and then subtracting the radial velocity of the standard star from the literature within *fxcor* module. All the routines used here are available in PyRAF and IRAF. At this stage of the analysis, the spectra has undergone several preprocessing steps including normalisation, radial velocity shift, removal of cosmic rays, subtraction of sky background, and correction for telluric absorption. Resulting spectra are shown in green with the flux of each spectrum shifted by 0.5 for better visualisation in Figure 3. Around 2 Å around each of the three calcium

<sup>4</sup> Radial velocity standards are chosen from this table: [obswww.unige.ch/udry/std/stdnew.dat](http://obswww.unige.ch/udry/std/stdnew.dat)

triplet regions are indicated within the blue filled regions with the central wavelength as black dashed lines.

### 3.3. Metallicities

To compute the (very small) additional radial velocity offset that may have been caused due to the difference in standard stars' radial velocity and equivalent widths, we use a modified version of the pipeline defined and used by [Longear et al. \(2022\)](#) and [Viswanathan et al. \(2024c\)](#). It is noteworthy that this radial velocity correction is negligible (less than 3%). The first step in our analysis is to estimate the initial radial velocity of the star. We begin by creating a smoothed spectrum for each star using a Gaussian kernel with a width corresponding to 4 elements of resolution. This smoothing helps highlight the calcium triplet (CaT) lines. We model each calcium triplet (CaT) line using a Voigt profile and determine their positions by minimising the square difference between a simulated spectrum containing only the modelled CaT lines and the observed spectrum. The Voigt profiles consider parameters such as the amplitude of the Lorentzian component, the standard deviations of both the Lorentzian (half-width at half-maximum) and Gaussian components, and the Doppler shift in wavelength linked to the radial velocity offset based on the definition in [McLean et al. \(1994\)](#).

To obtain an initial estimate of the radial velocity, we perform a cross-correlation between the simulated spectrum and the observed spectrum. This initial estimate is typically close to zero (mean of  $\sim 1$  km/s) due to previous alignment to the rest frame using a standard star. The derived radial velocity is then used as a starting point for further analysis and to improve the accuracy of the radial velocity measurement from the `fxcor` pipeline in IRAF. The mean statistical uncertainty in the inferred radial velocity is  $\sim 6.9$  km/s. The radial velocity measured from the INT spectra show good agreement with the radial velocity from *Gaia*'s Radial Velocity Spectrometer (RVS) derived radial velocity for a large majority of our sample agreeing within 25 km/s with *Gaia* RVS radial velocity, with the exception of  $\sim 6\%$  of the stars with more than a  $2\sigma$  difference between the two measurements. For 2 stars, this difference is as large as  $5\sigma$ . Such a large difference in radial velocity measurements suggests the possibility of these stars being part of a binary system. However, *Gaia* flags and astrometric quality parameters such as Renormalised unit weight error, RUWE, Total amplitude in the radial velocity time series after outlier removal, RVamp, and Radial velocity renormalised goodness of fit, RVgof do not suggest a binary origin. Some of these parameters are not available for all the stars but only for the brighter subsample ( $G < 12$ ). Due to this ambiguity, we refrain from using these members ( $2\sigma$  and above, 14 stars) in the dynamical analysis of the paper. However, the 1D spectra and inferred parameters are released for all our stars including these radial velocity mismatched stars. It is noteworthy that we do not find any systematic offset between the two radial velocities. We use the *Gaia* RVS radial velocity (where available) for the dynamical analysis of this paper with 8 stars added using INT radial velocities for which *Gaia* radial velocities are not available.

Next, we employ a Monte Carlo Markov Chain (MCMC) algorithm with a million iterations per spectrum to fit the observed spectra. Using the simulated spectrum that includes only the CaT lines shifted according to the initial radial velocity guess and the initial amplitude guess (which is set to start lower for EMP stars than normal metal-rich population in the Galaxy), we derive the final radial velocity and equivalent widths

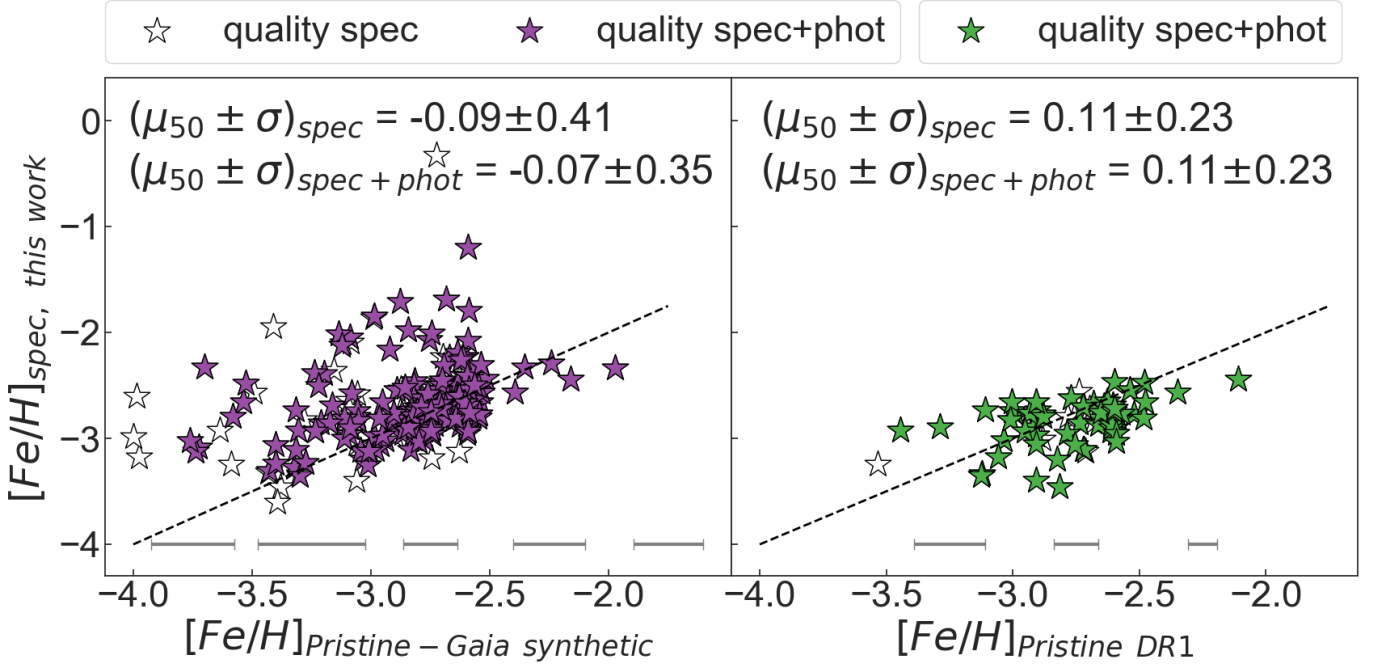
(EWs) of the lines. The step size defined to explore the parameter space to achieve the optimal acceptance ratio is set based on the S/N of the spectrum. The fitting process involves simultaneously optimising the central wavelengths, normalised fluxes, and standard deviations of each line. Constraints are applied to ensure the relative depths and widths of the lines agree with respect to each other. For example, the second CaT line is constrained to be deeper than the third one which in turn is set to be deeper than the first one. We also ensure that the first line is not narrower than the other two lines, and the third line is narrower than the second line. These constraints help maintain the expected order and shape of the CaT lines during the analysis. The MCMC analysis is performed for each star, and the parameters that maximise the likelihood are selected as the best-fit values. The central wavelengths (and therefore the radial velocities,  $v$ ), the normalised fluxes of each line  $a_1$ ,  $a_2$ , and  $a_3$  as well as their standard deviations are fitted by minimising the likelihood that is defined as:

$$\mathcal{L}_i = \frac{1}{\sigma_i \sqrt{2\pi}} \exp\left(-0.5 \frac{(s_{obs,i} - s_{sim,i})^2}{\sigma_i^2}\right) \quad (1)$$

where  $\sigma_i$  is the flux uncertainty on star  $i$ ,  $s_{obs,i}$  is the observed spectrum and  $s_{sim,i}$  is the simulated spectrum of star  $i$ , all of which are vectors. To calculate the EWs, we integrate each CaT line within a  $15 \text{ \AA}$  window centred on the line. The integration is performed on the best-fit simulated spectrum, and the resulting integrated values represent the EWs for each line. The best-fit Voigt profile for each of the six example stars of varying S/N is shown as purple dashed lines in Figure 3.

To convert the equivalent widths (EWs) of the calcium triplet lines into metallicity measurements, we employ the calibration provided by [Carrera et al. \(2013\)](#) for Voigt profile fits. This calibration is known to reliably estimate metallicities down to a value of  $-4.0$ . The inputs for this conversion include magnitudes, calcium triplet equivalent widths, and distances (inverted parallax) or height above or below the horizontal branch. Magnitudes adjusted for extinction are taken from the input photometric metallicity catalogues. Converting from *Gaia* G magnitude to Johnson-Cousins V or I magnitudes is achieved through the conversion prescribed by [Riello et al. \(2021\)](#). To determine the uncertainties associated with the metallicity measurements, we utilise a Monte Carlo procedure. In each iteration, we randomly draw values of the EWs from their PDF. We then calculate the spectroscopic metallicity for each iteration, taking into account the individual uncertainties in photometry and distances. Additionally, we incorporate the uncertainties associated with the calibration relation itself by considering the proposed uncertainties on the coefficients stated by [Carrera et al. \(2013\)](#). By performing this Monte Carlo process, we construct a PDF that captures the uncertainty in the metallicity determination for each star, considering all the relevant parameters involved in the spectroscopic metallicity derivation. The standard deviation (using a Gaussian approximation) of this distribution is taken as the uncertainty on the metallicities. The calibration for metallicities derived from the CaT equivalent width is grounded by [Carrera et al. \(2013\)](#) in empirical observations of 55 metal-poor field stars. These stars were examined at high-resolution,  $R > 20,000$ , measuring Fe I and Fe II spectral lines, which are less influenced by non-local thermodynamic equilibrium (NLTE) effects compared to the Ca II triplet lines. Consequently, the metallicities estimated through this calibration closely align with NLTE equivalents.





**Fig. 5.** Comparison of photometric and spectroscopic metallicities for the full followed-up sample of stars. The left panel shows the photometric metallicities obtained using the Pristine-*Gaia* synthetic (XP spectra) vs the spectroscopic metallicities derived from the calcium triplet equivalent widths for the entire sample. A small subset of the sample also has photometric metallicities derived from higher S/N Pristine *CaHK* magnitudes, which are shown in the right panel vs the spectroscopic follow-up metallicities. Median uncertainties in bins of 0.5 dex in photometric  $[Fe/H]$  is shown in both panels. The uncertainties increase with decreasing metallicities in general, but the first and last bins are affected by low number statistics and do not follow this trend.

The brightness range probed by the sample and the spectroscopic metallicities obtained from this analysis are shown as 1D histograms in Figure 4. Four stars that are either too hot (spectra with no distinguishable calcium triplet lines indicating blue horizontal branch contamination) or have cosmic ray on the calcium triplet lines are removed from the analysis. The spectra for these stars and inferred parameters are not released with this work due to bad quality of the spectra. Furthermore, we also remove stars that have an absolute magnitude in Johnson-Cousins I-band outside the range,  $-4 < I < 1$ , within which the established EW to metallicity relation works reliably. The spectra for these stars and inferred parameters are not released with this work due to the fact that the conversion is not robust in this regime. Stars that pass all these quality criteria in spectra and magnitudes are referred to as ‘quality spec’ in Figure 5. The median uncertainties on bins of 0.5 dex in metallicities is shown at the top of the histogram in the right panel of Figure 4. We recommend to add to the reported measurement uncertainty (only  $\sim 0.08$  in the median), a systematic uncertainty of 0.15 dex derived from comparison with high-resolution analyses of VMP stars from the SAGA database. This is based on the 14 stars in overlap between our follow-up and the SAGA database. The remaining  $\sim 200$  stars are newly discovered V/EMP stars from this work, ideal for high-resolution follow-up. The on-sky distribution of the stars colour-coded by their inferred metallicities is shown in Appendix A. We observed 225 stars as the first part of this spectroscopic campaign described in this work, and remove 4 stars due to being too hot (2 of them) or having cosmic rays on the CaT lines (2 of them), and 6 stars that have an I-band magnitude outside the range within which the EW to metallicity relation works reliably. This leaves us with a total of 215 stars. We release the 1D spectra and chemical and dynamical parameters inferred

for these 215 stars observed and analysed in this work (including the 14 stars which has a radial velocity mismatch higher than 25 km/s with *Gaia* radial velocities as we have enough evidence to trust their analysis and inferred parameters). As part of this follow-up campaign, we have also observed more than 300 stars using the blue CCD (for which we will be able to infer carbon and  $\alpha$  abundances along with metallicities), which will be analysed and released in an upcoming publication.

## 4. Results

In this section, we present the findings of our spectroscopic analysis, which encompasses both the dynamical properties and the metallicity measurements of the observed stars.

### 4.1. Performance of the Pristine-*Gaia* synthetic pre-selection

In the subsequent discussion of the results, we employ the terms “Pristine metallicities” and “photometric metallicities” interchangeably to denote the metallicity values obtained from the narrow-band synthetic *CaHK* derived from *Gaia* XP spectra combined with *Gaia* broadband BP-RP data. Conversely, we use the terms “CaT metallicities” and “spectroscopic metallicities” to refer to the metallicities derived from the analysis of spectra acquired using the INT/IDS facility in the calcium triplet region. Figure 5 shows the one-on-one comparison between the spectroscopic metallicities of the V/EMP stars observed and analysed in this work versus their photometric metallicities from the Pristine-*Gaia* synthetic catalogue in the left panel and a subsample (69) of stars that have photometric metallicities from the Pristine DR1 bright catalogue (higher S/N *CaHK* narrowband values) in the right panel. The 1:1 line and median uncertainties

**Table 2.** Evaluation of the quality of the photometric metallicities from the Pristine-*Gaia* synthetic catalogue.

	Observed with recommended quality cuts	Stricter quality cuts	$[\text{Fe}/\text{H}]_{\text{phot}} < -2.5$
Total observed	215	173	168
$[\text{Fe}/\text{H}]_{\text{phot}} < -2.5$	210	168	168
$[\text{Fe}/\text{H}]_{\text{phot}} < -3.0$	60	38	38
$[\text{Fe}/\text{H}]_{\text{spec}} < -2.5$	163	130	129
$[\text{Fe}/\text{H}]_{\text{spec}} < -3.0$	32	21	21
$[\text{Fe}/\text{H}]_{\text{spec}} > -2.0$ (outliers)	9 (4%)	6 (3%)	–
success $[\text{Fe}/\text{H}] < -2.0$	206 (96%)	166 (97%)	–
success $[\text{Fe}/\text{H}] < -2.5$	162 (77%)	129 (77%)	–
success $[\text{Fe}/\text{H}] < -3.0$	23 (38%)	14 (37%)	–

**Notes.** The number of stars with photometric metallicities from the Pristine-*Gaia* synthetic catalogue below  $-2.5$  and  $-3.0$ , the number of stars confirmed spectroscopically below those metallicity thresholds, and the corresponding success rates are provided for three distinct datasets: the entire spectroscopic sample after basic quality cuts, the sample post-application of the stricter selection criteria to increase the 1:1 agreement in photometric and spectroscopic metallicities, and the subset of stars with photometric metallicities below  $-2.5$ .

in photometric metallicities in bins of metallicities are shown in both panels. The difference between photometric and spectroscopic metallicities have a median offset of  $-0.08$  dex and  $1\sigma$  deviation of  $0.41$  dex for the Pristine-*Gaia* synthetic catalogue and a median offset of  $+0.11$  dex and  $1\sigma$  deviation of  $0.23$  dex for the Pristine survey data release 1 catalogue. The  $1\sigma$  deviation is reduced by about half with the higher S/N *CaHK* narrowband measurements from the Pristine survey DR1 data. As mentioned in Section 2.2, some of the quality cuts defined by MS23 came into effect after the start of our follow-up program. We investigate how these cuts and some other stricter cuts can improve the one-to-one agreement of photometric and spectroscopic metallicities. For the stricter quality cuts, we implement the probability of photometric variability to be less than 30% ( $\text{Pvar} < 0.3$ ), which was a quality cut established while the follow-up program was already ongoing), stricter photometric quality cut ( $\text{abs}(\text{Cstar} < \text{Cstar\_1sigma})$ ), astrometric quality cut (Renormalised Unit Weight Error  $\text{RUWE} < 1.4$ , only three stars observed have  $\text{ruwe}$  greater than 1.4 and have been removed in the dynamical analysis section of this paper because they can be non-single or otherwise problematic astrometric solutions), photometric metallicity uncertainty less than  $0.3$  dex ( $0.5 * (\text{FeH\_CaHKsyn\_84th} - \text{FeH\_CaHKsyn\_16th}) < 0.3$  dex), percentage of Monte Carlo iterations for  $[\text{Fe}/\text{H}]$  uncertainties equal to a 100% ( $\text{mcfrac\_CaHKsyn} == 1.0$ ), 16th percentile value of photometric metallicity greater than  $-3.999$  ( $\text{FeH\_CaHKsyn\_16th} > -3.999$ ), and CASU photometric data reduction flag ( $\text{flag} = -1$ , denoting very likely point-sources – only for sources with Pristine DR1 measurements). Stars that pass these extra quality cuts are referred to as “quality spec+phot” in Figure 5. The median offset and  $1\sigma$  deviation in the difference between spectroscopic and photometric metallicities reduces from  $-0.09$  dex to  $-0.07$  and  $0.41$  dex to  $0.35$  dex respectively with the stricter quality cuts in the input Pristine-*Gaia* synthetic catalogues, at the expense of losing 20% of the VMP stars followed-up. The  $1\sigma$  deviation between photometric and spectroscopic metallicities are lower ( $\sim 0.23$  dex) for Pristine DR1 photometric metallicities due to their high S/N *CaHK* measurements. It is noteworthy that regardless of the stricter quality cut, the agreement is quite good between the spectroscopic and photometric metallicities, and while the stricter quality cuts remove few outliers, they also remove few interesting VMP stars. For this reason, our conclusion is that the stricter quality cuts do not improve the selection.

Table 2 shows the number of stars present in various V/EMP photometric and spectroscopic metallicity bins for three subsamples from this spectroscopic follow-up program: A total sample of 215 stars observed with this program selected based on the recommended quality cuts and other cuts mentioned in Section 2.2, stricter quality cuts to improve the 1:1 agreement between spectroscopic and photometric metallicities as described above, and all stars with photometric metallicity estimates below  $-2.5$  dex (a subsample 168 stars). Firstly, the table outlines the number of stars within each sample that were estimated by the Pristine-*Gaia* synthetic photometric metallicities to have  $[\text{Fe}/\text{H}]$  values equal to or less than  $-2.5$  or  $-3.0$ , respectively. It also presents analogous counts based on spectroscopic  $[\text{Fe}/\text{H}]$  values and the corresponding success rates. Success rates denote the fraction of stars anticipated to have  $[\text{Fe}/\text{H}]$  values below a specified threshold by photometric metallicities, which were indeed observed to possess spectroscopic  $[\text{Fe}/\text{H}]$  values below that threshold. Outliers are stars with spectroscopic  $[\text{Fe}/\text{H}] > -2.0$ . A similar exercise was performed by Youakim et al. (2017) and Aguado et al. (2019) using the medium spectroscopic follow-up of CFHT-based Pristine survey photometric metallicities. Comparing the success rates, we find that the success rates at finding stars with  $[\text{Fe}/\text{H}] < -2.5$  and  $[\text{Fe}/\text{H}] < -3.0$  has increased from 56% and 23% to 77% and 38% respectively and the outliers ( $[\text{Fe}/\text{H}] > -2.0$ ) have gone down from 12% to 3%, with no catastrophic outliers ( $[\text{Fe}/\text{H}] > -1$ ). We refrain from making estimates for the Pristine DR1 catalogue due to limitations in the number of stars but these numbers are expected to be higher due to the higher S/N *CaHK* measurements and deeper magnitude ranges probed by the Pristine survey. The improvement in success rates are mainly due to the well-defined selection criteria weeding out catastrophic outliers due to photometry, astrometry and limitations in the photometric metallicity model. Given these new and improved success rates, we predict that the photometric metallicities from the Pristine survey and the Pristine-*Gaia* synthetic catalogues will bring more than 10 000–20 000 homogeneously analysed EMP stars from the WEAVE low-resolution ( $R \sim 5000$ ) follow-up of Pristine EMP stars (Jin et al. 2024) and allow for unprecedented statistical analyses of the metal-poor Galaxy.

#### 4.2. Chemokinematics of the V/EMP stars

To calculate the orbital properties of V/EMP stars from our follow-up program, we use right ascension, and declination in

J2016 format, proper motion in right ascension and declination from *Gaia* DR3 data, with distances based on parallax (from *Gaia* DR3) or photometry as described in Section 2.2 and radial velocities from *Gaia* RVS from DR3 when available and INT spectra based radial velocities otherwise (for 6 stars). We adjust the stars for solar motion, considering  $(U_{\odot}, V_{\odot}, W_{\odot}) = (11.1, 12.24, 7.25)$  km/s according to Schönrich et al. (2010), and for the motion of the local standard of rest (LSR) using  $v_{LSR} = 232.8$  km/s as per McMillan (2017). Both the Galactocentric cartesian and cylindrical positions and velocities of the stars are computed assuming  $R_{\odot} = 8.2$  kpc (McMillan 2017) and  $z_{\odot} = 0.014$  kpc (Binney et al. 1997). Our coordinate system is oriented such that  $x$  points towards the Galactic centre,  $y$  aligns with the direction of motion of the disc, and positive (negative)  $z$  signifies the height above (below) the disc. Angular momenta,  $L_z$  and  $L_{\perp} = \sqrt{L_x^2 + L_y^2}$ , are calculated for the stars with the sign of  $L_z$  inverted to ensure it being positive for prograde orbits. Energy,  $E$ , is determined using AGAMA (Vasiliev 2019) and the Milky Way potential from McMillan (2017). This potential, which is axisymmetric, encompasses a stellar thin and thick disc, an HI gas disc, a molecular gas disc, a bulge, and an NFW halo, which defaults to a spherical shape. The integration time is set to 1 Gyr. The output orbital parameters are the Galactocentric Cartesian coordinates  $(x, y, z)$ , the maximum distance from the Milky Way plane  $Z_{max}$ , the apocentric and pericentric distances, the eccentricity, the energy  $E$ , and the spherical actions coordinates  $(J_{\phi}, J_r, J_z)$ .

In panel b of Figure 6, we see the total energy ( $E$ ) versus the  $z$ -component of angular momentum ( $L_z$ ). We see four stars (all below  $-2.5$  in  $[\text{Fe}/\text{H}]$ ) that are unbound in our chosen gravitational potential of the Milky Way, along with 7 stars that are not associated with any known substructure region and have high apocentres. These unbound stars have a velocity of about 700 km/s at a distance of about 15 kpc which is too small to classify them as hyper velocity stars. From the literature, we see that most of the hyper velocity stars are coming from the Galactic disc. These four high-energy stars also have confined orbits ( $Z_{max} < 3.5$  kpc). However, given that their proper motions and velocities are small, it is safe to say that these stars are most likely unbound due to the measurement uncertainties. In the future, after a careful target selection of high proper motion or high-velocity stars, a large sample of stars in high-energy orbits can be used to infer the escape velocity of the Milky Way. We note that the high-energy stars are not shown in the left panels, due to their very high apocentre and  $Z_{max}$ .

It is anticipated that stars originating from the same physical structure will exhibit clustering in integrals of motion, energy and angular momentum (especially  $L_z$ ) within an axisymmetric potential, despite being widely dispersed in configuration space (Helmi et al. 2000). Since the second data release DR2 of the *Gaia* mission, phase mixed streams have been identified in kinematically selected halo stars. These structures, including the Gaia-Enceladus-Sausage, Sequoia, Thamnos, Helmi streams, LMS-1/Wukong, Heracles/Kraken/Koala, Cetus-Palca as discussed in Koppelman et al. (2019); Myeong et al. (2019); Yuan et al. (2020); Naidu et al. (2020); Lövdal et al. (2022); Ruiz-Lara et al. (2022); Malhan et al. (2022); Thomas & Battaglia (2022); Horta et al. (2023); Dodd et al. (2023), are believed to have an accreted origin primarily based on their inferred orbits, often supported further by chemical abundances where available. Nevertheless, their chemical composition, essential for determining the types of galaxies from which they originated, remains inadequately characterised, particularly at the lowest metallicities. Therefore, we associate our V/EMP stars with known

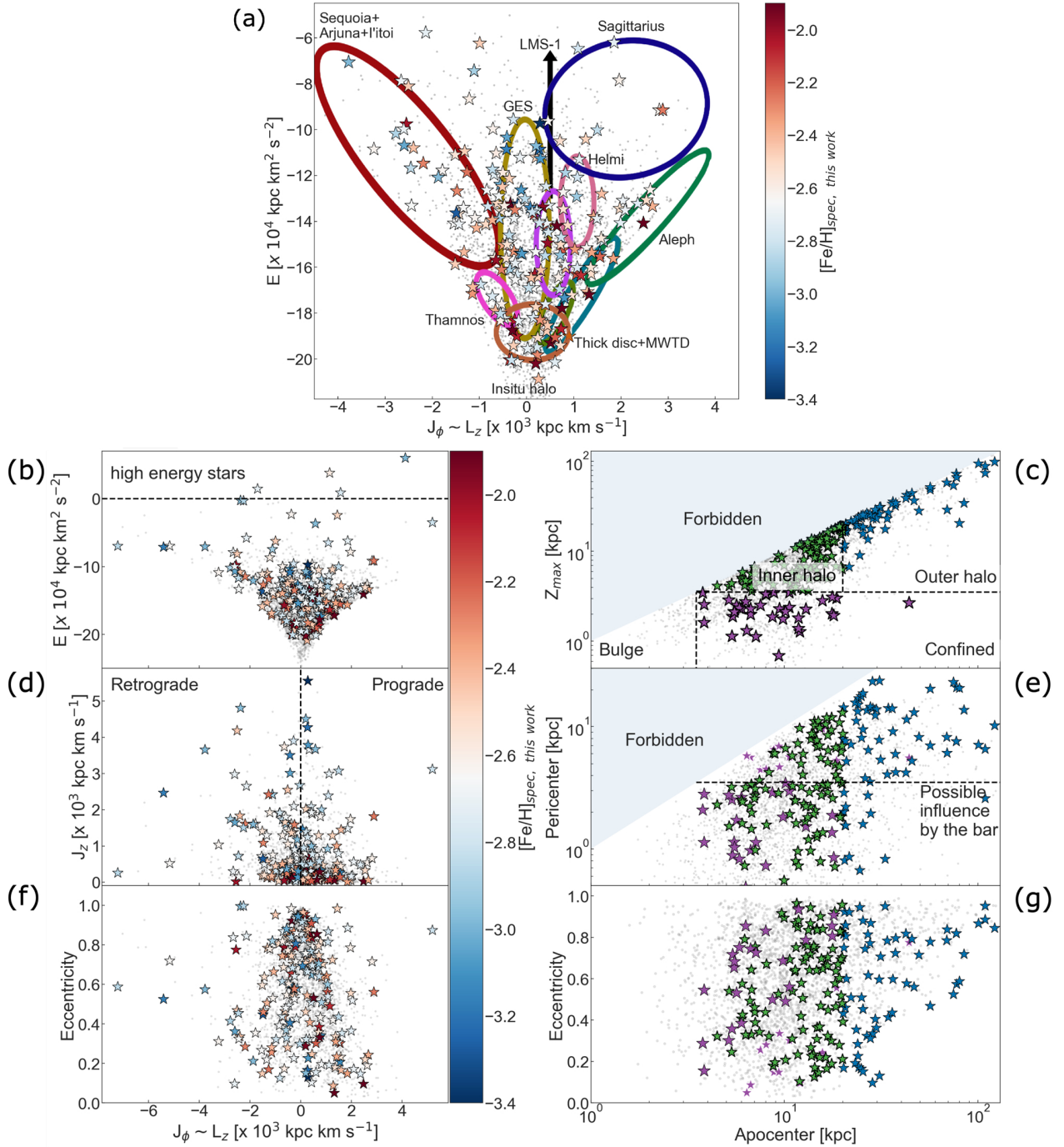
substructures with ellipses as detected using red giant stars from the H3 survey (Naidu et al. 2020) in the integral-of-motion (IOM) space (defined using the substructures in McMillan (2017) potential in Figure 23 from the same work). This is shown in panel a of Figure 6). We associate stars with a particular accretion event based on the selection criteria presented in Naidu et al. (2020). Most significantly we can associate stars with the Sequoia+Arjuna+I'toi group (23 stars with a huge spread in distance between 2–32 kpc, see also the small clump of the 3 VMP and EMP stars clustered tightly in this region and panel d), GES (total of 81 stars with  $\sim 97\%$  within 20 kpc, note the high-eccentricity stars clumped around  $L_z \sim 0$  in the left bottom panel) and the metal-poor LMS-1/Wukong (14 stars with medium eccentricity, the slightly prograde clump of stars in panel f). We associate a handful of EMP stars with the Helmi streams (6), Thamnos (11), and Sagittarius (4), with both Thamnos and the Helmi streams populating distances less than 10 kpc while Sagittarius stars all lie above 7 kpc. There are also a few stars in the thick disc and the in situ halo regions. We also find small clumps of stars with very similar metallicities that could originate from low-mass merger events or globular cluster disruptions. These groups are indicated with a group number in Table 3, which will be released electronically with this work. Due to the low number statistics and complex selection function, we refrain from defining any new substructures from this work. In the future, a more complete and large sample of V/EMP stars with dynamics and chemistry will allow us to also identify the smallest and earliest galaxies that merged into the Milky Way (Yuan et al. 2020).

In Figure 6, the three panels on the right (panels c, e, and g) illustrate the pericentric distance, eccentricity, and maximum height from the plane relative to the apocentric distance. Meanwhile, the right-hand three panels depict the energy versus the rotational component of the action (top), rotational versus vertical action (middle) and rotational action versus eccentricity (bottom). In panel d, we see stars separated into prograde and retrograde orbits. We clearly see that our sample has more prograde than retrograde stars. The sample is classified into four distinct groups based on their  $Z_{max}$  and apocentre, akin to the categorisation outlined in Sestito et al. (2023). These categories are described as follows:

- Bulge group: Stars within this group remain confined within a sphere with a radius of 3.5 kpc from the Galactic centre, i.e., apocentre  $< 3.5$  kpc. No spectroscopic follow-up has been conducted in this region.
- Confined group (purple stars): Stars within this group exhibit  $Z_{max} < 3.5$  kpc and apocentre  $> 3.5$  kpc. They are primarily restricted near the Milky Way disc, and this group comprises 41 (20%) stars that have undergone spectroscopic follow-up and presented in this work.
- Inner halo group (green stars): Comprising 101 (46%) stars, this group consists of stars with  $Z_{max} > 3.5$  kpc and apocentre  $< 20$  kpc.
- Outer halo group (blue stars): This group comprises 73 (34%) stars characterised by  $Z_{max} > 3.5$  kpc and apocentre  $> 20$  kpc.

As depicted in panel g of Figure 6, all stars, regardless of their group, show a range of eccentricities. It is noteworthy that stars in the confined group do not necessarily exhibit planar orbits. If we define planar orbits as stars with a ratio of  $Z_{max}/\text{apocentre} < 0.2$ , these constitute half of the stars in our confined group. Of these stars, about 80% are in prograde disc-like orbits. These findings are discussed in detail in the next section.





**Fig. 6.** Chemokinematics of the V/EMP stars from this work. (Panel a) Energy  $E$  vs angular momentum in  $z$  direction  $L_z$ . The substructure regions from [Naidu et al. \(2020\)](#) identified using RGB stars in the H3 survey are shown as coloured ellipses to associate V/EMP stars from this work. (Panel b) Same as top centre, but without the substructure ellipses. Stars with energy greater than 0 are high-energy and/or unbound stars in the Milky Way potential used. (Panel d) Rotational component of the action  $J_\phi$  vs vertical action  $J_z$ . (Panel f) Rotational action  $J_\phi$  vs eccentricity. (Panel c) The INT sample is divided into three dynamical groups according to their apocentre and  $Z_{\text{max}}$ . The grey shaded area denotes the forbidden region in which  $Z_{\text{max}} > \text{apocentre}$ . The vertical and horizontal lines separate the groups. (Panel e) Groups are shown in apocentre vs pericentre view. The grey shaded area denotes the forbidden region in which pericentre  $>$  apocentre. (Panel g) Groups in apocentre vs eccentricity view. All EMP stars observable by the spectroscopic follow-up program are shown in grey.

In panel e of Figure 6, we see that about 71% of the stars that are confined have small pericentre comparable to the length of the Galactic bar ( $R_b \sim 3.5 \text{ kpc}$ , [Wegg et al. 2015](#); [Lucey et al. 2023](#)). [Dillamore et al. \(2023\)](#) suggest that a possible co-rotation resonance of a centrally concentrated halo population with the rotating bar could explain why we see planar prograde stars in

the V/EMP end in the solar neighbourhood. From our sample of confined stars (of which about half of them are prograde planar), indeed the bar can play a role in the orbit of this population. However, we do see a population of confined stars (small purple symbols in panels e and g of Figure 6) that have higher pericentres and low eccentricity, more like disc orbits. The on-sky

**Table 3.** Description of the columns of the INT follow-up spectra of 215 V/EMP stars as a catalogue made available publicly in this work.

Column	Description	Unit	Type
source_id	<i>Gaia</i> DR3 Source ID	Unitless	longint
ra	<i>Gaia</i> DR3 right ascension in ICRS (J2016) format	degrees	float
dec	<i>Gaia</i> DR3 declination in ICRS (J2016) format	degrees	float
G_0	De-reddened <i>Gaia</i> G magnitude	unitless	Float
BP_0	De-reddened <i>Gaia</i> G <sub>BP</sub> magnitude	Unitless	Float
RP_0	De-reddened <i>Gaia</i> G <sub>RP</sub> magnitude	Unitless	Float
distance	Photometric distance or inverted parallax based distance derived in this work	mas	float
distance_error	Uncertainty on the photometric distance	mas	float
snr	Signal-to-noise ratio of the normalised INT CaT spectra	unitless	float
v_r	Radial velocity measured from the INT CaT spectra	km/s	float
dv_r	Uncertainty in the measured radial velocity	km/s	float
ew1	Equivalent width of the first calcium triplet line around 8498 Å	Å	float
dew1	Uncertainty on the equivalent width of the first calcium triplet line around 8498 Å	Å	float
ew2	Equivalent width of the second calcium triplet line around 8542 Å	Å	float
dew2	Uncertainty on the equivalent width of the second calcium triplet line around 8542 Å	Å	float
ew3	Equivalent width of the third calcium triplet line around 8542 Å	Å	float
dew3	Uncertainty on the equivalent width of the third calcium triplet line around 8662 Å	Å	float
feh	Spectroscopic metallicity derived in this work using INT CaT spectra	unitless	float
dfeh	Measurement uncertainty associated with the spectroscopic metallicity derived	unitless	float
E	Total energy	kpc km <sup>2</sup> /s <sup>2</sup>	float
Jphi	Rotational action vector	kpc km/s	float
Jz	Vertical action vector	kpc km/s	float
Jr	Radial action vector	kpc km/s	float
zmax	Maximum height above the plane of the orbit	kpc	float
rapo	Apocentre of the orbit	kpc	float
rperi	Pericentre of the orbit	kpc	float
ecc	Eccentricity of the orbit	unitless	float
group_number	Group number for stars that are clustered in IOM space	unitless	int

**Notes.** The reduced 1D spectra from this work is also made available publicly. All these data are available at the CDS.

distribution of the stars colour-coded by their categories (confined, inner halo, outer halo) are shown in Appendix A. Other dynamical spaces such as position distribution, velocity distribution, and IOM space for these categories of stars are shown in Appendix B.

## 5. Discussion

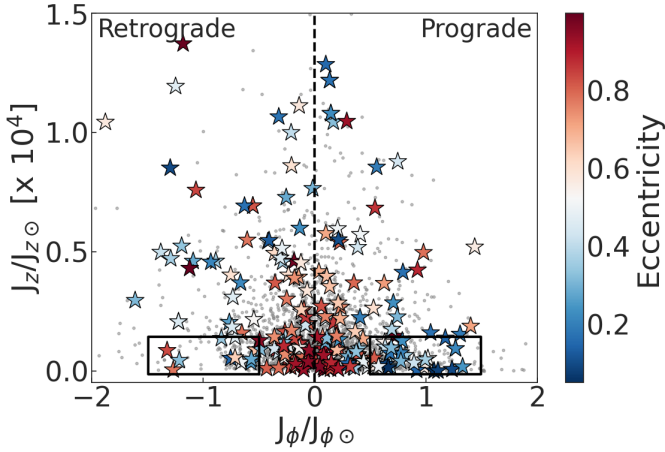
In this section, we discuss in detail the implications of planar metal-poor stars in the sample and present and discuss new members of the most metal-poor stellar stream C-19.

### 5.1. Planar metal-poor stars

The oldest and most metal-poor stars are usually found in the bulge and halo because they are relics from the era of the smallest, earliest galaxies that merged into the Milky Way halo. However, there have been recent discoveries of very, extremely and ultra-metal-poor stars in prograde, planar, and disc-like orbits confined to the plane ( $z < 3$  kpc, Sestito et al. 2019). The mechanisms for producing such stars beyond just the halo has been highly debated. Some of the proposed scenarios are as follows: (i) minor mergers that sink onto the plane before disrupting due to dynamical friction (Abadi et al. 2003; Sestito et al. 2019), (ii) stars from the building blocks of the proto-Milky Way or filaments creating a halo that is slowly rotating prograde (Sestito et al. 2019, 2020; Belokurov & Kravtsov 2022,

2023; Rix et al. 2022; Zhang et al. 2023), (iii) the in situ formation of this component of the disc at early times (Sestito et al. 2019, 2020; Di Matteo et al. 2020; Fernández-Alvar et al. 2021, 2024; Nepal et al. 2024). Regarding the feasibility of the latter scenario, in the NIHAO-UHD and FIRE simulations these stars are formed within 2–3 Gyr from the Big Bang, while the disc appears later (Sestito et al. 2021; Santistevan et al. 2021). However, disc formation in simulations cannot be evidence enough to rule out this scenario. (iv) A possible co-rotation resonance of a halo population with the bar (Dillamore et al. 2023). Yuan et al. (2024) illustrated that as a result of a rapidly decelerating bar, certain bulge stars acquire rotational motion by becoming ensnared in co-rotating regions and subsequently migrating outwards along prograde planar orbits. However, the proportion of stars influenced by this mechanism is insufficient to explain all of the metal-poor rotators identified. Consequently, their origin remains ambiguous.

Sestito et al. (2019) conducted an analysis of the kinematics and dynamics of all ultra-metal-poor (UMP,  $[\text{Fe}/\text{H}] < -4.0$ ) stars from the literature available at the time. Their findings revealed that 11 out of 42 (~26%) known UMP stars remain confined within 3 kpc of the Milky Way plane throughout their orbital lifetime. Moreover, 10 out of these 11 UMP stars exhibit prograde orbits ( $v_\phi > 0$ ). Building on this work, Sestito et al. (2020) arrived at a similar conclusion using a significantly larger dataset comprising 1027 V/EMP stars. This expanded dataset incorporated spectroscopic follow-up data from the Pristine survey



**Fig. 7.** Distribution of low-metallicity stars from the INT sample in the  $J_\phi$ – $J_z$  action space. The action quantities are scaled by the solar values (i.e.,  $J_{\phi\odot} = 2009.92$  kpc km/s,  $J_{z\odot} = 0.35$  kpc km/s). The two black boxes represent the prograde and the retrograde disc-like orbits showing an overdensity in the prograde direction. All EMP stars observable by the spectroscopic follow-up program at INT are shown in grey.

(Aguado et al. 2019) and LAMOST spectroscopy (Li et al. 2018). Their analysis revealed that approximately 31% of stars with  $|z| < 3$  kpc observed today never venture beyond 3 kpc of the disc plane. Additionally, they examined their sample in the  $J_\phi$ – $J_z$  projection of the action space. Sestito et al. (2020) observed that the number of stars in prograde disc-like orbits (characterised by high  $J_\phi$  and low  $J_z$ ) is significantly greater than the number of stars in retrograde disc-like orbits, with a statistical significance of  $5\sigma$ .

We conducted a similar orbital analysis to Sestito et al. (2019, 2020) and investigated the behavior of our V/EMP stars in the action space, as depicted in Figure 7. This figure can be directly compared to the results from Sestito et al. (2020). We see an overdensity of prograde V/EMP stars confined to the plane up to and even higher than the solar azimuthal action with low to intermediate eccentricities. Our findings indicate that the fractions of VMP and  $[\text{Fe}/\text{H}] < -2.5$  (chosen instead of EMP due to low number statistics in EMP) stars with present-day  $|z| < 3$  kpc and  $Z_{\text{max}} < 3$  kpc are 31% and 21%, respectively, which align very closely with the results of Sestito et al. (2020). In the rotation versus vertical action plane, we identified stars within the black dashed boxes representing disc-like prograde and retrograde orbits. The region corresponding to low- $Z_{\text{max}}$  corotating stars is denser by  $4\sigma$  (entire sample),  $3.5\sigma$  (VMP) and  $3.8\sigma$  ( $[\text{Fe}/\text{H}] < -2.5$ ) compared to its retrograde counterpart (using Poisson statistics), slightly lower than the findings reported by Sestito et al. (2020), but still significantly more prograde than retrograde. It is essential to note, however, that the methodologies, sample selections, and selection functions employed in these studies vary significantly. The action space distribution of these confined, confined planar (from Section 4.2) and prograde planar (disc-like) stars are shown in Appendix C.

Zhang et al. (2023) investigated this with XGBOOST derived metallicities from XP spectrophotometry and found a similar (if not higher significance) prograde to retrograde ratio of stars in the metallicity range  $-1.6 < [\text{M}/\text{H}] < -3$ . They suggest that this asymmetry can be explained by a combination of a stationary and a prograde halo (proto-MW) component in the VMP end. In a recent work by Ardern-Arentsen et al. (2024), that investigates orbits of VMP stars in the inner Galaxy ( $R < 3.5$  kpc),

they report that VMP stars are likely consisting of a mix of a prograde and a stationary halo component. The apocentre distribution shows that VMP stars are very centrally concentrated, with a steep drop towards higher apocentre (and not many with apocentre  $> 10$  kpc). The apocentre and  $Z_{\text{max}}$  distribution of our planar stars are shown in Appendix C.

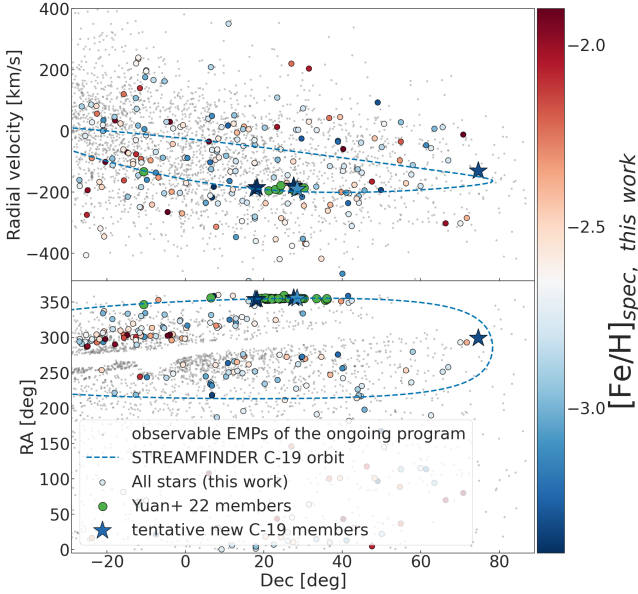
The chemical properties of these planar stars indicate that a variety of different systems contribute to the formation of this population. Dovgal et al. (2024) shows that the large scatter in  $\alpha$ -elements of the planar star might be indicative that the prograde planar stars is composed of multiple systems. Sestito et al. (2024b) shows that a planar prograde star with high eccentricity has the same chemical signatures of ultra-faint dwarf stars. Spectroscopic follow-up of some planar stars (retrograde+prograde) show that these observed stars formed in the same formation site, which look like a classical dwarf galaxy (Sestito et al. 2024a). Further investigation, incorporating age distributions and/or more extensive chemical abundance measurements along with extensive orbital analysis in the V/EMP end, is essential to definitively determine the exact metallicity threshold at which the early Milky Way disc originated (Viswanathan et al. 2024b). Stars from this spectroscopic follow-up and the ongoing follow-up will add more information in light of this problem and can be potential targets for high-resolution follow-up in the future.

## 5.2. C-19 stellar stream new members

The discovery of the most metal-poor stream C-19 by Ibata et al. (2021); Martin et al. (2022a,b) has sparked considerable interest, with its interpretation as a disrupted Globular Cluster (GC) based on several key observations. C-19 stream is the first and foremost exceptionally low-metallicity structure in the universe. Notably, its remarkably narrow metallicity dispersion and a range in Na abundances are consistent with observations of globular clusters (Martin et al. 2022b; Yuan et al. 2022), and contrasting with observations in dwarf galaxies or among the Galactic halo field stars. What sets C-19 apart is its mean metallicity ( $[\text{Fe}/\text{H}] = -3.4$ , EMP), which surpasses that of even the most metal-poor GC (Vasiliev & Baumgardt 2021) and represents the lowest metallicity structure ever found. The absence of Galactic Globular Clusters observed below a metallicity of  $-2.5$  has led to interpretations suggesting a metallicity floor beyond which GCs cannot form. The Phoenix stream (mean  $[\text{Fe}/\text{H}] = -2.7$ , Balbinot et al. 2016; Wan et al. 2020) and ED-2 stream (mean  $[\text{Fe}/\text{H}] = -2.6$ , Balbinot et al. 2023, 2024) are other streams that challenge the GC metallicity floor. However, despite chemical evidence suggesting a Globular Cluster origin, the dynamical width and velocity dispersion of C-19 resemble those of a dwarf galaxy. One hypothesis suggests that the stream may have originated from a dark matter-dominated dwarf galaxy, with the star cluster comprising most of the mass in the system, although the remnants of such a dwarf galaxy have yet to be discovered (Errani et al. 2022). Alternatively, Helmi & White (1999) demonstrated through numerical simulations that the velocity dispersion of streams can increase significantly at the turning point of their orbit, potentially explaining C-19's large velocity dispersion. However, determining whether the stream is indeed at its turning point poses a challenge due to its sensitivity to the assumed potential. Thereby, finding more members on C-19's orbit and brightest members (better suitable for high-resolution follow-up) that belong to the streams will help us constrain the origin of this ancient structure.

Figure 8 shows the right ascension versus declination in the bottom panel and radial velocity versus declination in the top

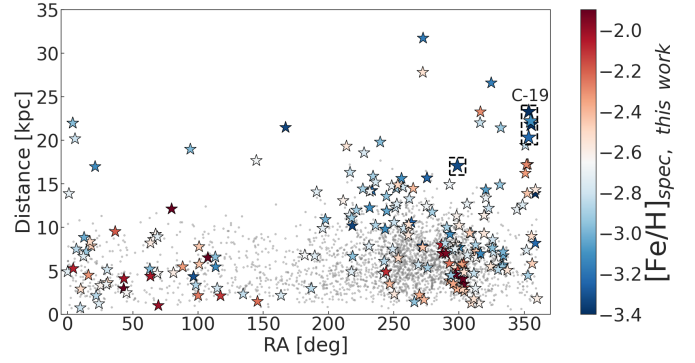




**Fig. 8.** C-19 stellar stream members from this work. The declination vs radial velocity distribution (top) and declination vs right ascension distribution (bottom) of the INT sample of V/EMP stars are colour-coded by their inferred spectroscopic metallicities with the C-19 orbit from the STREAMFINDER algorithm and the Yuan et al. (2022) identified C-19 members overlaid. The tentative C-19 members identified in this work are shown as large star markers. All EMP stars observable by the spectroscopic follow-up program at INT are shown in grey.

panel for all the stars analysed in this work, colour-coded by the inferred spectroscopic metallicity. Overlaid are the C-19 members from Yuan et al. (2022) in green, with one radial velocity member discovered  $30^\circ$  away from the main body of the stream. From the metallicities and the STREAMFINDER inferred C-19 orbit, we find five (three new, two rediscovered) C-19 members (inferred metallicities between  $-3.24$  and  $-3.6$ , all consistent with C-19 mean metallicity within  $2\sigma$  considering the measurement and systematic errors), two of which are the brightest members of the stream discovered yet at the tip of the red giant branch (RGB). One of the members discovered is  $50^\circ$  away from the main stream counterpart, above the disc plane at positive height above the plane. This is the first C-19 member discovered above the disc plane. This member increases the span of the stream on the sky. The overdensity of stars in one part of the stream could be due to the coverage in the region of the Pristine survey as it probes deeper to find C-19 members with photometric metallicities. The mean metallicity of the stream with the new members is  $-3.33 \pm 0.07$ , the stream width is  $0.39^\circ \pm 0.07^\circ$  and the velocity dispersion (excluding the member above the disc plane) is  $4.11 \pm 2.05$  km/s consistent with the literature values. We note that C-19 member stars are not associated with any of the accretion events in Figure 6, according to the literature selections. Although, Malhan et al. (2022) suggests that C-19 is mostly likely a stream associated with the LMS-1/Wukong structure. C-19 stream and LMS-1/Wukong have different orbits. Even though they are both polar, the orbital planes are separated by a large angle. A more comprehensive look at the members of C-19 all over the sky with chemistry and dynamics will be presented in the upcoming work (Yuan et al., in prep.) which will provide more insight into the progenitor and formation of the C-19 stream.

Figure 9 shows the distance versus right ascension plane of all the stars observed and analysed in this work, colour-coded



**Fig. 9.** Right ascension vs distance distribution of V/EMP stars from this work colour-coded by their spectroscopic metallicities. The identified C-19 members are shown inside black dashed boxes. All EMP stars observable by the spectroscopic follow-up program at INT are shown in grey.

by metallicity. Tentative C-19 members from this work are highlighted with a dashed black box and the members from the main body of the stream are clustered at around 21.5 kpc, while the member above the disc plane lies at 17 kpc which indicates a distance gradient across the stream. The mean distance of the stream is slightly higher than what has been reported in the literature. Ibata et al. (2021) estimated the distance to C-19 using the STREAMFINDER algorithm, which determines a most likely heliocentric distance, based on the local distribution of stars on the sky, in proper motion space, and in CMD space which is not individually precise, but for a stream as a whole, it is a good first guess. They found a distance between 16 and 22 kpc with no distance gradient along the stream. Martin et al. (2022b) estimates the distance to C-19 using 7 blue horizontal branch stars (17.5 kpc) at a favoured distance of 18 kpc to minimise the difference between the FeI and FeII iron abundances, and a distance estimate based on *Gaia* parallaxes and the best fit C-19 orbit (20.9 kpc). All these stars have bad parallax, which means that the PDF of the distance inference depends highly on the photometry, extinction, systematic offset in the method and the choice of isochrone which is most likely a bad match for  $[\text{Fe}/\text{H}] < -3$  stars. Therefore, we do not expect these stars to have distances as good as standard candles. However, Bonifacio et al. (2025), followed-up and analysed fainter sub-giant branch stars from the C-19 stream and found that an EMP isochrone fits better with 20.9 kpc distance in the subgiant branch that would match well with our estimate. Based on our analysis, we find a mean distance of 21.5 kpc, which is a slightly larger distance than the literature-reported distances.

In Figure 9, the INT observable stars are in grey. Because these are good parallax stars, we can see that the grey points end at about 10 kpc while due to the bad parallax selected giants, our sample goes up to 35 kpc in the EMP bright end, much farther than what is possible using only good parallax selections. Given the success demonstrated in this follow-up paper, we pave the way for the use of bright and distant metal-poor stars and streams from these photometric studies as invaluable guides to the early universe with a more homogeneous selection of giant stars (Viswanathan et al. 2024a).

## 6. Conclusions and outlook

Thanks to the recent *Gaia* DR3, we have spectro-photometric information from the XP spectra for  $\sim 219$  million stars. Using

these data, MS23 calculated synthetic, narrowband, metallicity-sensitive *CaHK* magnitudes that mimic the observations of the Pristine survey, and infer photometric metallicities using the narrowband *CaHK* and broadband *Gaia* magnitudes trained on the survey's training sample. In this work, we presented the first dedicated spectroscopic follow-up of V/EMP stars from this all-sky catalogue of photometric metallicities. The target selection was based on the quality cuts recommended by the catalogue paper, MS23, at the bright end (Figure 1 and 2). We used the INT/IDS instrument in La Palma for the low- to medium-resolution spectroscopic follow-up in the calcium triplet region, which is widely used to study VMP stars (Table 1). We inferred radial velocities and spectroscopic metallicities using the pipeline based on Viswanathan et al. (2024c, Figure 3). Due to the available 6D phase space information, we also took a deeper look into the dynamics of these stars in the context of Galactic archaeology. Our main results are presented as follows:

- The spectroscopic metallicities are inferred for 215 stars at a precision of 0.08 in measurement added in quadrature with 0.15 dex in systematic uncertainty down to  $\sim -3.6$  in metallicity (Figure 4).
- The photometric metallicities from the Pristine-*Gaia* synthetic catalogues agree well with the inferred spectroscopic metallicities from our follow-up with  $\sim 77\%$  and  $\sim 38\%$  success rates of having  $[\text{Fe}/\text{H}] < -2.5$  and  $-3.0$  stars, respectively. The outliers ( $[\text{Fe}/\text{H}] > -2.0$ ) are reduced to 3% with no catastrophic outliers ( $[\text{Fe}/\text{H}] > -1.0$ ). This is a huge improvement over the existing methods that search for EMP stars (Figure 5 and Table 2). With the enhanced success rates observed, we anticipate that the photometric metallicities obtained from the Pristine survey and the Pristine-*Gaia* synthetic catalogues will facilitate the identification of more than 10 000–20 000 uniformly analysed EMP stars through the WEAVE low-resolution ( $R \sim 5000$ ) follow-up of Pristine EMP stars (Jin et al. 2024). This will enable unprecedented statistical analyses of the metal-poor Galaxy.
- From the kinematics of the V/EMP stars from this work, we find 20% are in confined orbits, 46% in the inner halo, and 34% in the outer halo orbits (see panels c, e, and g of Figure 6).
- We associate V/EMP stars with several known accretion events such as GES, LMS-1/Wukong, Thamnos, Sequoia, Sagittarius, and Helmi streams, which would define the EMP end of their metallicity distribution. Some of the small and tight clumps in the  $E-L_z$  space could belong to low-mass mergers in the distant past (see panel a, and panels b, d, and f of Figure 6).
- We find that 31% of our VMP stars with  $|z| < 3$  kpc do not go beyond 3 kpc in their orbital history. Along this line, the prograde region with low vertical action (similar to disc-like orbits) is  $4\sigma$  overdense compared to the retrograde counterpart, suggesting that an important fraction of V/EMP stars reside in the disc plane (Figure 7).
- We associate five stars from our follow-up with the most metal-poor stellar stream C-19, three of which are new. One of these stars is  $50^\circ$  from the main body of the stream, and is the first star belonging to C-19 with positive height above the disc plane. Adding these bright members of C-19 helps to improve the constraints on its progenitor and orbital history. We suggest that the stream might lie farther out than has been reported in the literature (mean distance of about 21.5 kpc, compared to  $\sim 18$  kpc reported in Martin et al. 2022b), while the mean metallicity, velocity dispersion

and dynamical width are consistent with the literature values (Figures 8 and 9).

With this follow-up, we characterise the success rates of the Pristine-*Gaia* synthetic catalogue of photometric metallicities and the implications of V/EMP stars from a chemokinematics point of view. Future medium- to high-resolution follow-up with chemical abundances and large multi-object spectrographs such as WEAVE (Jin et al. 2024) and 4MOST (de Jong et al. 2019) will take the full chemodynamical analysis of V/EMP stars further, allowing us to study some of the smallest and earliest galaxies that merged into the Milky Way.

## Data availability

Table 3 released with this paper is available at the CDS via anonymous ftp to [cdsarc.cds.unistra.fr](https://cdsarc.cds.unistra.fr) (130.79.128.5) or via <https://cdsarc.cds.unistra.fr/viz-bin/cat/J/A+A/695/A112>.

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*iraf* (National Optical Astronomy Observatories 1999), *gaiadr3-zeropoint* (Lindegren et al. 2021), *JupyterLab* (Kluyver et al. 2016), and *topcat* (Taylor 2018).

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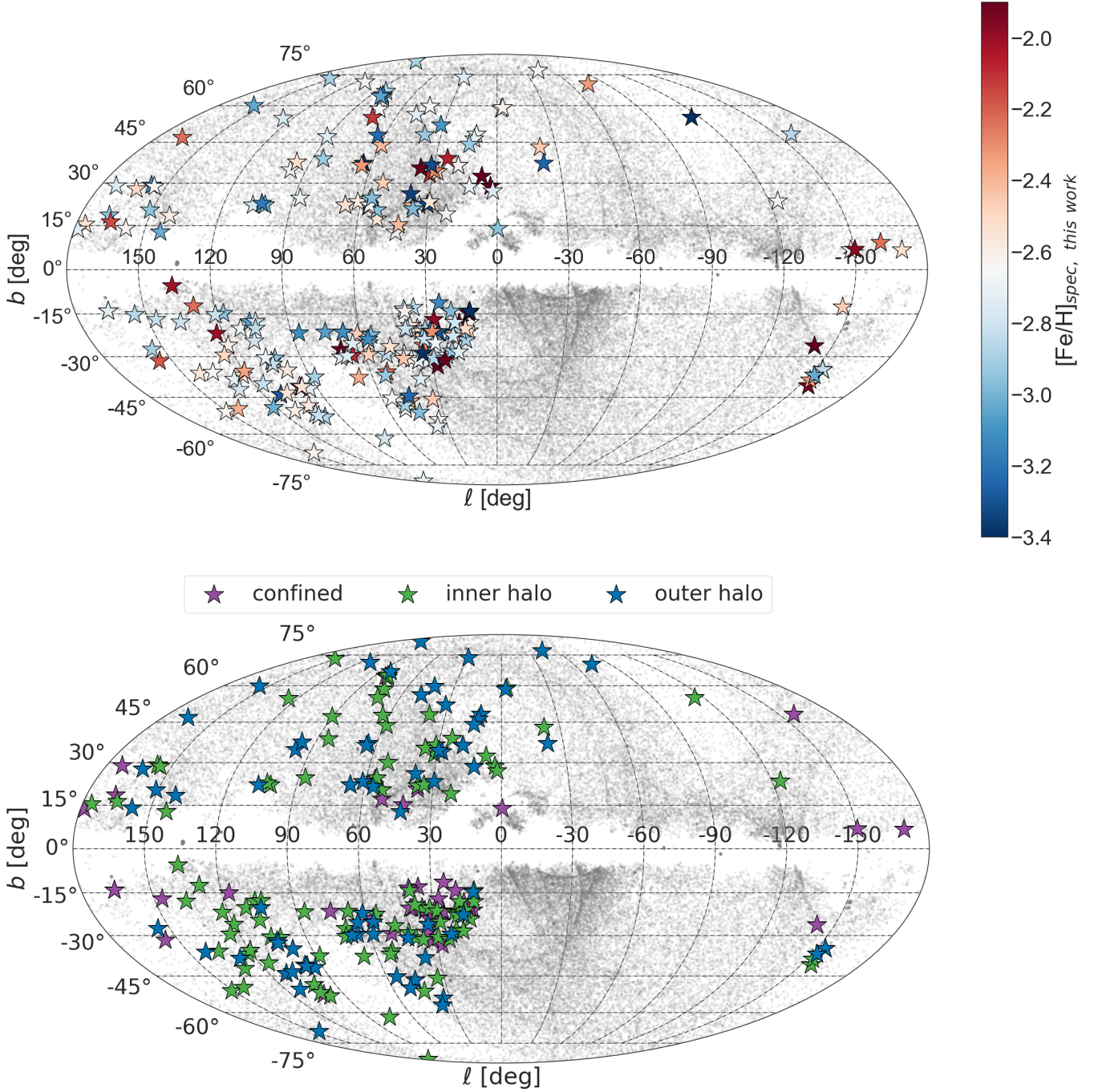
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## Appendix A: Galactic distribution of V/EMP stars

Figure A.1 top panel shows the sky distribution of stars spectroscopically followed-up in this work colour-coded by their inferred spectroscopic metallicities from this work. We do not see any striking feature or substructure(s) in this view. The distribution of both VMP and EMP stars are almost random on the sky showing that the Galactic position does not affect our inferred metallicities. The bottom panel of Figure A.1 shows the sky distribution of confined to the disc plane, inner halo and outer halo stars as defined in section 4.2 in the same colour scheme. We can see that the confined stars are almost within  $30^\circ$  of the Galactic latitude, while the inner and outer halo stars are distributed evenly over the sky.

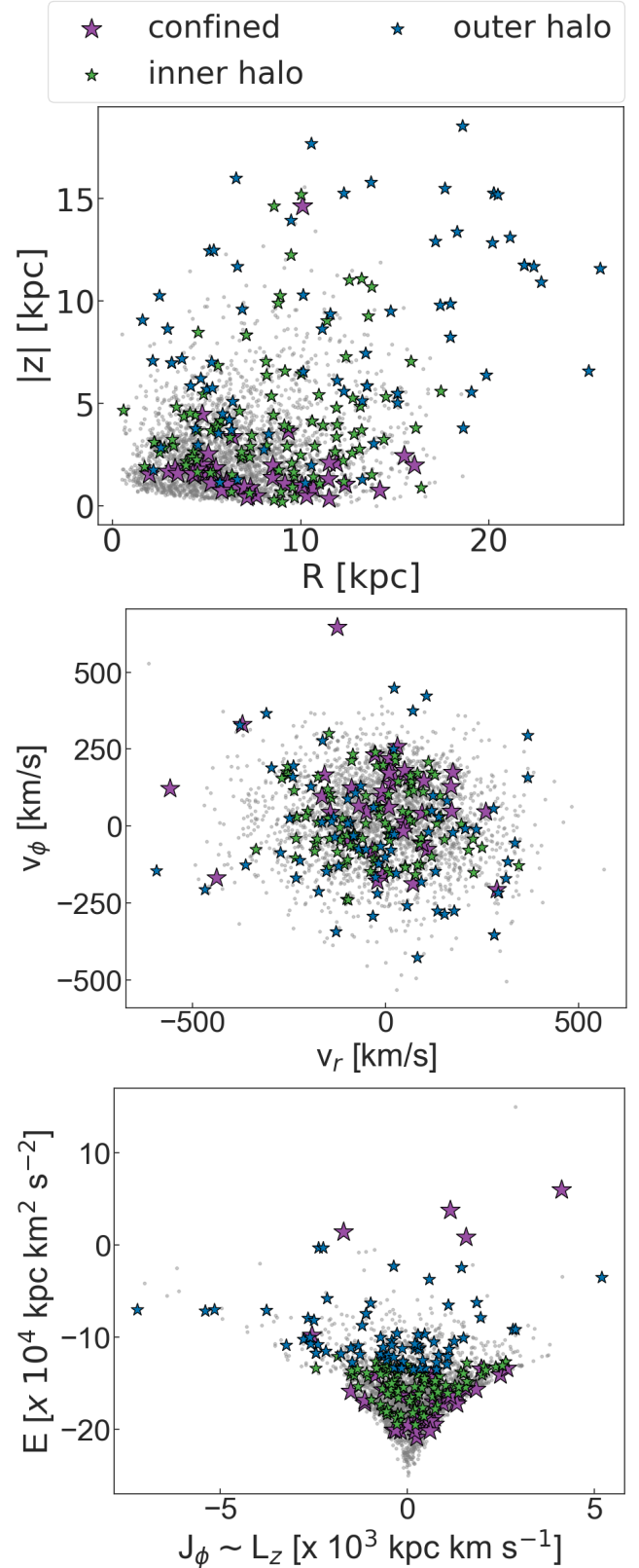


**Fig. A.1.** Mollweide projection of the Galactic coordinates for the V/EMP stars with  $[\text{Fe}/\text{H}] < -2.5$  in the Pristine-*Gaia* synthetic catalogue (in grey). The large-scale patterns visible in the map are mainly attributed to the scanning law of the *Gaia* satellite. The coloured stars represent the subset of stars observed and analysed in this spectroscopic follow-up, colour-coded by their inferred spectroscopic metallicities (top). The different coloured stars belong to confined, inner, and outer halo stars, as defined in section 4.2 (bottom).



## Appendix B: Additional chemokinematics of the V/EMP stars

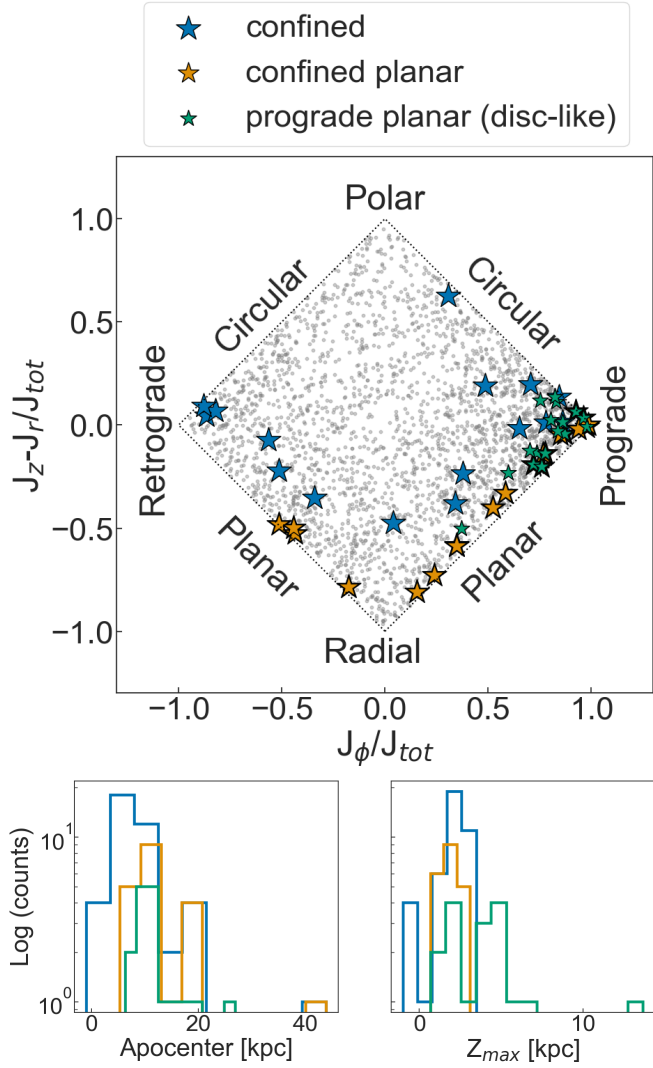
In Figure B.1, we additionally show Galactic distribution and kinematics view of the confined to the plane, inner halo and outer halo group defined in section 4.2. The top panel of Figure B.1 shows the radius ( $\sqrt{x^2 + y^2}$ ) versus absolute scale height distribution of our observed V/EMP stars. We see that most of the confined stars have a flattened distribution over the  $z$ -plane and are solar-neighbourhood stars with more stars towards the inner Galaxy, while the inner and outer halo stars go out to 15–20 kpc in radius and scale height as expected. The middle panel of Figure B.1 shows the velocity distribution in azimuth versus radial direction. The overall distribution looks quite isotropic with a small prograde rotation (about 20 km/s). The confined stars peak at around 180 km/s with the high-energy stars going out to about 600 km/s. Inner halo stars have a smaller spread in their velocities compared to outer halo, as expected. The bottom panel of Figure B.1 shows energy versus angular momentum in the  $z$ -direction (IOM space) for the confined, inner and outer halo stars. We see a clear difference in the energy distribution between inner and outer halo stars with inner halo stars sunk deeper into the potential than the outer halo stars. Confined stars have a mix of prograde and retrograde orbits. One other interesting note is that all our high-energy (unbound) stars belong to the confined plane suggesting a very high apocentre and small  $Z_{max}$ , which favours the argument that they are less likely to be hypervelocity stars but their extreme properties are more likely due to uncertainties in positions and velocities.



**Fig. B.1.** (Top) Galactocentric radius vs absolute scale height distribution of confined, inner and outer halo stars as defined in section 4.2. (Middle) Velocity distribution of these stars in  $v_\phi$  vs  $v_r$  space. (Bottom) Energy vs angular momentum in  $z$ -direction for the classified stars. All EMP stars observable by the spectroscopic follow-up program are shown in grey.

### Appendix C: Planar metal-poor stars in other kinematic spaces

immediately after, favouring the scenario that these stars could originate from a centrally concentrated, slightly prograde proto-Galaxy as shown by [Zhang et al. \(2023\)](#); [Ardern-Arentsen et al. \(2024\)](#). However, it is important to note that our sample size for this population is too small to say anything conclusive.



**Fig. C.1.** (Top) Action space diamond, the difference between the vertical and radial component of the action, vs the rotational component of the action with the axes normalised by  $J_{tot} = |J_\phi| + J_r + J_z$  for confined and confined planar stars as defined in section 4.2 and prograde planar (disc-like) stars, as defined in section 5.1. All EMP stars observable by the spectroscopic follow-up program are shown in grey (Bottom) Apocentre and  $Z_{max}$  distribution of these stars are shown in the same colour.

In Figure C.1, we show action diamond space (normalised to the sum of the three actions of motion) in the top panel and apocentre and  $Z_{max}$  distribution of confined ( $Z_{max} < 3.5$  kpc and apocentre  $> 3.5$  kpc) and confined planar (confined +  $Z_{max}$ /apocentre  $< 0.2$ ) stars from section 4.2 and prograde planar (disc-like, prograde box from Figure 7) stars from section 5.1 in the bottom panel. We can see that the confined stars are close to the plane, but are not always in the plane (few circular and radial stars), while confined planar stars are in the plane (prograde or retrograde). We see that the prograde planar (disc-like) stars is approximately around the same region of overdensity seen with metal-poor stars moving close to the plane in the action diamond (prograde and planar) from various spectroscopic surveys as shown in [Fernández-Alvar et al. \(2024\)](#). The apocentre distribution is close to the solar neighbourhood and falls off