The Prince and The Pauper: Co-evolution of the thin and thick disc in the Milky Way.

Matthew Raymond Gent\textsuperscript{1,2}, Philipp Eitner\textsuperscript{1,2}, Chervin F. P. Laporte\textsuperscript{3}, Aldo Serenelli\textsuperscript{4,5}, Sergey E. Koposov\textsuperscript{6,7}, and Maria Bergemann\textsuperscript{1,8}

\textsuperscript{1} Max-Planck Institute for Astronomy, 69117 Heidelberg, Germany
\textsuperscript{2} Ruprecht-Karls-Universität, Grabengasse 1, 69117 Heidelberg, Germany
\textsuperscript{3} Institut de Ciencies del Cosmos (ICCUB), Universitat de Barcelona (IEEC-UB), Martiri i Franques, 1, E-08028 Barcelona, Spain
\textsuperscript{4} Institute of Space Sciences (ICE, CSIC), Carrer de Can Magrans S/N, E-08193, Cerdanyola del Valles, Spain
\textsuperscript{5} Institut d’Estudis Espacials de Catalunya (IEEC), Carrer Gran Capita 2, E-08034, Barcelona, Spain
\textsuperscript{6} Instituto de Astronomía, University of Edinburgh, Royal Observatory, Blackford Hill, Edinburgh EH9 3HJ, UK
\textsuperscript{7} Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA, UK
\textsuperscript{8} Niels Bohr International Academy, Niels Bohr Institute, University of Copenhagen, Blegdamsvej 17, DK-2100 Copenhagen, Denmark

ABSTRACT

Context. One of main open questions in the evolution of the Milky Way is the origin of the chemically bi-modal structure of the Galactic disc. Is the bi-modality a manifestation of two populations with a distinct origin? Did these populations co-evolve? Or did the thick disc form before the thin disc, as contemporary chemical evolution models predict.

Aims. Our goal is to investigate in detail the chemical, temporal, and kinematical structure of the alpha-poor and alpha-rich populations in the Galactic disc.

Methods. We employ the medium-resolution spectra from the Gaia-ESO large spectroscopic survey, as well as Gaia EDR3 astrometry and photometry. The stellar parameters and chemical abundances are determined using Non-Local Thermodynamic Equilibrium (NLTE) models of synthetic spectra. Ages are computed for a large sample of subgiants using Garstec evolutionary tracks.

Results. We find a bi-modality in the [$\alpha$/Fe] distributions in the local volume. These distributions are characterised by well defined trends in the space of age- and kinematic ($V_\phi$). We present a significant detection of the metal-poor, down to [Fe/H] $\sim -1$ and [$\alpha$/Fe]-poor component with age of up $\sim 10$ Gyr. The trend is slightly different for the [$\alpha$/Fe] rich component, which also spans the entire range of ages from a few to 13 Gyr. However, it is clear that both formed coevally and evolved in parallel.

1. Introduction

Over the past decade, tremendous progress has been made in understanding the structural properties of our galaxy. A combination of data from large-scale photometric, spectroscopic, and astrometric stellar surveys, such as the Gaia-ESO, LAMOST, GALAH, APOGEE allowed robust constraints on the temporal variability of chemical enrichment across the Galactic disc, bulge, and the halo (e.g. Bland-Hawthorn & Gerhard 2016; Barbuy et al. 2018; Helmi 2020). Complemented with accurate positions and kinematics of stars from the Gaia space mission (Gaia Collaboration et al. 2016, 2018, 2020), it has become possible to constrain the detailed chemo-dynamical evolution of these stellar populations and to gain new insights into their origins.

Still, the structure and evolution of the Galactic disc remains one of the most complex problems in studies of Galaxy formation. Since the discovery of the thick disc (Gilmore & Reid 1983), much work focused on the bi-modality in the space of chemical abundances (e.g. Bensby et al. 2005; Reddy et al. 2006; Recio-Blanco et al. 2014; Duong et al. 2018). Many studies based on stars in the solar neighbourhood and beyond pointed out the existence of two populations, [$\alpha$/Fe]-rich and [$\alpha$/Fe]-poor, partly overlapping in metallicity (e.g. Fuhrmann 1998; Nidever et al. 2014), age (e.g. Bensby et al. 2014; Feuillet et al. 2019), and kinematics (e.g. et al. 2011; Lee et al. 2011; Kordopatis et al. 2011; Hayden et al. 2015). These stellar populations have been deemed as the "thin" and the "thick" disc, and their morphological parameters have since then been subject of a major interest (Bland-Hawthorn & Gerhard 2016). First, it has been shown different physical processes may influence the formation and evolution of sub-structure in the disc, including multiple infall (e.g. Chiappini et al. 1997; Spitoni et al. 2019), radial migration (e.g. Schönrich & Binney 2009a,b; Loebman et al. 2011; Minchev et al. 2013) and radial mixing caused by satellites (Quillen et al. 2009), growth induced by mergers (e.g. Villalobos & Helmi 2008; Read et al. 2008; Villalobos et al. 2010), gas-rich accretion and mergers (e.g. Brook et al. 2004; Stewart et al. 2009; Grand et al. 2018; Buck 2020), local gas instabilities associated with turbulence (Bournaud et al. 2009), dynamical interaction with cold dark matter sub-halos (Hayashi & Chiba 2006; Kazantzidis et al. 2009), galactic winds (Moster et al. 2012), and early outflows (Khoperskov et al. 2021). It has also been demonstrated that the chemical bi-modality is a relatively rare phenomenon in L$^*$ galaxy discs (Mackereith et al. 2018; Gebek & Matthee 2021). More recent studies address in more detail the spatial variability of the bi-modality (Hayden et al. 2015; Bovy et al. 2016; Nandakumar et al. 2020), finding that [$\alpha$/Fe]-rich component is more centrally concentrated, whereas the [$\alpha$/Fe]-poor component has a larger radial extent. Both stellar populations appear to be well-mixed dynamically, which implies that a robust decomposition of the two based on their phase-space is not possible. Therefore, the question of whether the populations are indeed distinct stellar components with a separate formation history still remains open.
The main difficulty in this work, so far, has been the limited observational information - not in a sense of data quantity, but in the sense of chemo-dynamical parameter coverage - combined with a complex selection function of different observational surveys (e.g. Bergemann et al. 2014; Stonkutė et al. 2016; Nandakumar et al. 2017). The observing strategy of the GALAH survey is such that the majority of stars belong to the thick disc (Duong et al. 2018), and the population statistics of objects with chemical properties of the thick disc is very incomplete. The APOGEE survey is also magnitude-limited, therefore the samples are biased to relatively metal-rich stars in the range \(-0.5 \leq [\text{Fe/H}] \leq 0.3\) (Hayden et al. 2015), also the ages are less reliable at \([\text{Fe/H}] < -0.5\) because of the paucity of metal-poor stars in the training samples (Lian et al. 2020). The LAMOST stellar survey of the Galaxy has a deeper spatial coverage compared to GALAH and APOGEE (Xiang et al. 2019), however, the accuracy of chemical composition is limited and does not allow to resolve the sub-structure in the chemical abundance plane and to identify small gradients associated with different formation scenarios and chemical enrichment sites.

In this work, we address the question of the formation and evolution of the apparently bi-modal disc through a detailed analysis of its chemical, temporal, and kinematical distribution functions with the new spectroscopic data from the Gaia-ESO large spectroscopic survey, astrometry from the Gaia early Data Release (eDR3), and stellar ages. Similar work, but based on the data from APOGEE survey, was presented by Feuillet et al. (2019) and Lian et al. (2020). However, neither of these studies performed a simultaneous analysis of stellar kinematics in the two populations. In our work, we furthermore make an attempt to quantify the temporal evolution of the \(\alpha\)-poor and \(\alpha\)-rich populations, using a large sample of subgiants with accurate age estimates.

The paper is organised as follows, in Sect. 2 we discuss the observational sample. Sect. 3 outlines the approach used for the determination of stellar parameters and chemical abundances. In Sect. 4, we briefly state how the ages are determined. The results are presented in Sect. 6, where we focus on the distributions of chemical abundances, combined with kinematics and ages. In Sect. 7 we discuss the results in the context of previous observational and theoretical findings, and we close the paper with conclusions in Sect. 8.

### 2. Observed data

In this work, we rely on targets observed within the Gaia-ESO large spectroscopic survey (Gilmore et al. 2012; Randich et al. 2013). In the latest public data release (DR4), spectra for over 10\(^7\) are available, and we use all spectra taken with the HR10 setting of Giraffe spectrograph\(^1\). The HR10 data are available for 55,761 stars. The signal-to-noise (SNR) distribution of the sample is very broad and ranges from 2 to a few 100 per pixel.

Fig. 1 shows the targets in the photometric colour-magnitude (CMD), \(J\) versus \(J - K_s\), plane, where \(J\) and \(K_s\) are VISTA photometric filters (McMahon et al. 2013). The apparent regular distribution is caused by the photometric selection of targets in the input Gaia-ESO catalogue. For the Giraffe catalogue, the following basic selection scheme was used: \(0.00 \leq (J - K_s) \leq 0.45\) and \(14.0 \leq J \leq 17.5\) for the blue box, and \(0.40 \leq (J - K_s) \leq 0.70\) and \(12.5 \leq J \leq 15.0\) for the red box. The boxes were defined to maximise the probability of observing targets in all Galactic components, the discs and the halo, therefore the target densities vary drastically, and to account for this effect, the boxes were slightly extended in order to optimise the fiber occupancy in each field. In particular, in the fields, where number of targets exceeded the number of fibers - as in low latitude fields - additional selection criteria were used, such as shifting the boxes by the mean value of extinction in a given field 0.5 E(B - V). This procedure leads to a characteristic spread of the distribution along the x-axis, as seen in Fig. 1. The relative distribution is such that the majority of targets (80\%) are in the blue box, whereas stars in the red box account for about 20\% of the sample. The blue box targets include main-sequence, turnoff, and subgiant stars, and the red box was optimised for red clump stars, however because of the extension of the boxes a certain overlap exists. For the detailed description of the selection, we refer to Stonkutė et al. (2016). This selection implies that most targets in the Gaia-ESO HR10 sample are rather faint, \(14 \leq G_{\text{mag}} \leq 17\), compared to other surveys such as RAVE, APOGEE, or GALAH.

We complement these data with the proper motions, photometry, and extinction from the EDR3 Gaia catalogue (Gaia Collaboration et al. 2020). The cross-match between every Gaia-ESO spectrum and Gaia ED3 catalogue was performed on grounds of angular position within a 1.0 arcsec tolerance (cone search). Distances and their uncertainties were adopted from Bailes-Jones et al. (2021). The spatial distribution of the sample is shown in Fig. 2. Most of these objects are confined closer to the plane with altitudes of up to 2 kpc and they probe a range of Galactocentric radii from ~5 to 12 kpc. The 3D space velocities\(^2\) for the sample are calculated using the Python package ’astropy’ (Astropy Collaboration et al. 2013; Price-Whelan et al. 2018). The accuracy of the astrometric information is high enough to yield the velocities with the uncertainty of \(\lesssim 5\) km s\(^{-1}\).

### 3. Stellar parameters

The homogeneity, accuracy, and precision of stellar parameters is essential given by the scientific goals of this study. However, our analysis of the Gaia-ESO sixth internal data release (iDR6)\(^3\) (Gilmore et al. 2012; Randich et al. 2013) show artificial ridges

---

\(^1\) The NLTE grids employed in this work cover the corresponding wavelength regime

\(^2\) In this work, we use galactocentric cylindrical coordinate system. So that \(V_r, V_\phi, V_z\) are the components of the full 3D space velocity pointing towards Galactic center \(R\), in the direction of rotation \(\phi\), and vertically relative to the disc mid-plane, respectively.

\(^3\) https://www.gaia-eso.eu/
and bifurcations in the space of stellar parameters and their uncertainties. It suffers from some loss of precision owing to the complex homogenisation and cross-calibration procedure employed. Therefore, this does not allow for a robust analysis of the distribution functions in the space of astrophysical parameters and ages.

4. Stellar ages

One important component of this study is the availability of ages. Ages are derived using the Bayesian pipeline BeSPP presented in Serenelli et al. (2013), which was also applied to the analysis of the first Gaia-ESO data release in Bergemann et al. (2014). The code relies on the GARSTEC grid of stellar evolutionary tracks (Weiss & Schlattl 2008) (also used in SAPP) that covers the mass range from 0.6 to 5.0 $M_\odot$ with a step of 0.02 $M_\odot$ and metallicity from $-2.50$ to $+0.60$ with a step of 0.05 dex. The resulting precision of ages is approximately 30%.

The analysis of ages is limited to subgiants and upper main-sequence stars (including turn-off), because of the strong degeneracy typically identified between tracks of different ages and metallicities for the lower MS and RGB phases. This selection is made by limiting the effective temperature and surface gravity to: 4700 - 6700 K, 3.5 - 4.5 dex for subgiants and turn-off stars, and 5400 - 6700 K, 3.5 - 4.2 dex for the upper main-sequence. We also include the stars with accurate abundances and ages analysed in Bergemann et al. (2014). These stars are part of the Gaia-ESO sample. The uncertainties of stellar parameters are small enough to ensure that our selection retains most of the subgiants in the sample and it minimises the contamination by lower main-sequence stars. Our final stellar sample with ages thus contains 4,406 stars, all of have a complete kinematic characterisation.

5. Selection function

In order to assess the influence of the survey selection function on our data set, we followed the methodology of Bergemann et al. (2014). To ensure self-consistency in the analysis, the same

---

Fig. 2: Spatial distribution of the observed sample. The vertical axis represents the height above the disc plane in kpc and the horizontal represents the Galacto-centric radius in kpc. The colour scale shows normalised density from 0.07% (dark blue) to 100% (dark red).

Fig. 3: The distribution of the observed sample in the $T_{\text{eff}}$-$\log g$ plane. The targets enclosed within the red box represent the sample used for the analysis of ages.

---
evolutionary tracks were used (Sect. 4). Firstly, a complete population of stars has been generated assuming the Salpeter initial mass function (IMF), a constant star formation rate (SFR), and a uniform and age-independent metallicity \( [\text{Fe}/\text{H}] \) distribution. The distribution exhibits a trend, which reflects simply the initial mass function (IMF), a constant star formation rate (SFR), and a uniform and age-independent metallicity \( [\text{Fe}/\text{H}] \) distribution. The distribution exhibits a trend, which reflects simply the IMF and the stellar evolution lifetime, that is shorter at lower metallicity. In case of no bias, the completeness fraction is unity 1.

Based on Fig. 4, it can be concluded that the distribution of stars in the age-metallicity plane suffers from a strong and systematic bias, which is primarily caused by the rigid colour cuts adopted in the Gaia-ESO survey. These cuts lead to a very pronounced depletion in the fraction of young stars with ages between 0 and ~6 Gyr, although the effect slightly depends on metallicity. The red box additionally skews the distribution towards old metal-rich stars, whereas the blue box is primarily sensitive to old metal-poor stars. This situation is rather similar to the completeness for the Gaia-ESO UVES sample described by Bergemann et al. (2014), although the UVES selection appears to be less restrictive in the age-metallicity plane.

We conclude that the distribution of our Gaia-ESO HR10 sample is thus preferentially skewed towards older populations with slightly sub-solar metallicities. This effect will be discussed in the context of our results in Sect. 6.5.

### 6. Results

#### 6.1. Chemical abundances

The \([\text{Mg}/\text{Fe}]\) abundance ratios of our sample against metallicity are shown in Fig. 5. Here we limit the analysis to the abundance of Mg, because no particular sub-structure is visible in the distribution of Ti or Mn abundance ratios.

We find a clear bi-modality in the \([\text{Mg}/\text{Fe}]\) abundance ratio, which is seen as two over-densities separated at \([\text{Mg}/\text{Fe}] = +0.15\) dex across the entire metallicity range, \(-1.5 \approx [\text{Fe}/\text{H}] \approx -0.2\) dex. The low-\(\alpha\) component peaks at \([\text{Mg}/\text{Fe}] \approx +0.05\) dex and the high-\(\alpha\) component at \([\text{Mg}/\text{Fe}] \approx +0.24\) dex. It shall be stressed that no component of the analysis, neither the (spatial distribution) observed data nor the grid (models), have any known non-linear dependence that could lead to this discontinuity in the space of Mg and Fe abundances. In particular, in the spectroscopic grid used in the chemical abundance analysis, all elemental abundances have a random uniform distribution. Therefore, it appears to be plausible that the chemical discontinuity is real. In agreement with the visible over-densities, we choose to assign stars to the \(\alpha\)-rich population, if their associated \([\text{Mg}/\text{Fe}]\) abundance is above 0.13 dex, and to the \(\alpha\)-poor disc otherwise. Throughout the text, we will proceed to call these two sets of stars “\(\alpha\)-rich” and “\(\alpha\)-poor” populations.

Comparing our distributions with literature, we find an overall satisfactory agreement, although it should be noted that owing to a combination of factors, including vastly different spatial-photometric coverage of observational surveys, their observational strategy, and incomplete volume sampling, certain differences arise that render a one-to-one comparison of chemical abundances in a given volume of the Galaxy impossible. Nonetheless, it appears that our distributions are consistent with the distributions seen in the previous DRs of the Gaia-ESO (e.g.,...
6.2. Kinematics and abundances

Figure 6 shows the distribution of our complete sample in the V_r - V_phi plane. The upper and lower rows of the panel correspond the distributions for the alpha-poor and alpha-rich populations, respectively. The sample is split in different [Fe/H] bins from -2.5 to +0.5 to highlight the metallicity dependence of the kinematical substructure. The majority of stars from both alpha-rich and alpha-poor populations are centred with V_r ≈ 0 kms^{-1} and V_phi ≈ 220 kms^{-1}. Consistent with the expectations for the Galactic disc (et al. 2011; Navarro et al. 2011; Bensby et al. 2014). With decreasing metallicity, the velocity dispersion in the radial direction increases significantly, and the mean rotation of stars decreases and a counter-rotating component appears at [Fe/H] ≈ −0.6, in line with previous studies (Fuhmann 2004; Chiba & Beers 2000; Deason et al. 2017). In the most metal-poor bin, [Fe/H] ≤ −1 dex, low-V_phi stars with large radial velocities |V_r| ≥ 200 kms appear. In Belokurov et al. (2018), these stars were identified as a population with very radial orbits associated with a massive merger event around 8 to 11 Gyr ago. Helmi et al. (2018) coined this merger as the Gaia-Enceladus event.

Combining Gaia DR2 with APOGEE, Di Matteo et al. (2019) found that the accreted halo component is characterised by the V_phi ≈ 0 kms^{-1} and is approximately Gaussian distributed in V_r, with the corresponding velocity dispersion of ≈ 120 kms^{-1} (Lancaster et al. 2019). For highly prograde velocities, V_phi > 100 kms^{-1} (Di Matteo et al. 2019, their Fig. 10) however, the contribution of the accreted halo population is of the order of a few percent.
6.3. Halo contamination

We estimate the contamination by the halo stars in our sample following the multi-Gaussian decomposition approach by Belokurov et al. (2018). The model estimates are performed separately for the α-poor and the α-rich populations. In short, we select all stars with $V_\phi < 0$ and any $V_r$ value and model the bivariate distribution of $V_\phi$ and $V_r$ by a Gaussian that is centered on $V_\phi = 0$. This resulting bivariate Gaussian function is then assumed to represent the halo component of the entire stellar sample. Then, the resulting contamination fraction is calculated as the ratio of the number of stars in this Gaussian to the total number of stars above a given $V_\phi$ value (Tab. 1).

Table 1: Contamination of the observed sample by halo stars in %. See text.

| Disc population | $V_\phi \geq 110$ km s$^{-1}$ | $V_\phi \geq 180$ km s$^{-1}$ |
|-----------------|-------------------------------|-------------------------------|
| α-poor          |                               |                               |
| $-2.5 < [\text{Fe/H}] < -1.0$ | 3.5                           | 0.1                           |
| $-1.0 < [\text{Fe/H}] < -0.6$ | 0.2                           | 0.0                           |
| $-0.6 < [\text{Fe/H}] < -0.2$ | 0.0                           | 0.0                           |
| $-0.2 < [\text{Fe/H}] < 0.5$ | 0.0                           | 0.0                           |
| α-rich          |                               |                               |
| $-2.5 < [\text{Fe/H}] < -1.0$ | 68.9                          | 58.3                          |
| $-1.0 < [\text{Fe/H}] < -0.6$ | 3.3                           | 1.9                           |
| $-0.6 < [\text{Fe/H}] < -0.2$ | 0.7                           | 0.3                           |
| $-0.2 < [\text{Fe/H}] < 0.5$ | 0.0                           | 0.0                           |

In Table 1, we show the resulting expected fractions of the contamination of our sample by halo stars, as predicted by our model for both α populations. Similar to Di Matteo et al. (2019), we find the lowest value of this range to be ~110 km s$^{-1}$ (Fig. 6). For $V_\phi$ above this limit, the contamination by the halo is expected to be at the level of <1% for the α-poor population, as long as $[\text{Fe/H}] \geq -1$. For the most metal-poor bin, $[\text{Fe/H}] \leq -1$, the contamination is ~12%. In the α-rich population, the fractions are not too different in the metallicity bins $[\text{Fe/H}] \geq -1$. However, as expected, the halo component becomes dominant over disc for the most metal-poor α-rich bin.

In addition, we compute the halo contamination through a slightly different model independent procedure described in detail the Appendix A, where instead of fitting the $V_\phi$ distribution, we calculate the contamination at $V_\phi$ velocities in individual $[\text{Fe/H}]$ bins by reflecting the $V_\phi$ distribution across $V_\phi = 0$. The results of this calculation (Fig. A.1) confirm the decomposition based on Belokurov et al. (2018), suggesting that above $[\text{Fe/H}] \geq -1$ the observed stellar sample is primarily represented by stars with disc-like kinematics, and the contribution of accreted halo stars is marginal (see also et al. 2011). It is therefore safe to assume that stars above this metallicity with $V_\phi \geq 110$ km s$^{-1}$ are representative of the Galactic disc. We use this working definition of the kinematic disc in the next section to investigate its evolutionary properties, by combining the chemo-kinematical distributions with the ages of stars.

6.4. Age-metallicity relationship

Here, we investigate the age-metallicity relationship in the context of how complete our sample is. Figure 7 shows the density of the Chronos sample in the $[\text{Fe/H}]$ vs Age plane with percentage completeness contours calculated as described in Sect. 5 (see Fig. 4). The red and blue contours associate with the photometric selection boxes described in Sect. 2.

It is clear that the blue selection box dominates the structure of the observed age-metallicity distribution. The majority of our stars are older than 5 Gyrs, and the distribution is heavily skewed to older ages. In addition, owing to the red box selection, we also observe a strong suppression of stars at $[\text{Fe/H}] \sim -1$ dex for all ages. This distribution is fully confirmed by the completeness decreasing for younger stars, reflecting what is seen in the simulated Gaia-ESO selection function (Sect. ref) and in independent studies (e.g. Thompson et al. 2018). As the highest density of oldest stars around $\geq 10$ Gyrs coincides within iso-completeness contours and is consistent between the red and blue photometric cuts, we determine that the selection function does not significantly impact our conclusions with respect to older populations. Also, and more importantly, the selection function does not distort the chemical parameter space, so that the relative fractions of $[\alpha/\text{Fe}]$-poor and $[\alpha/\text{Fe}]$-rich stars of a given age are expected to be robust at a given metallicity.

6.5. Ages, abundances, and kinematics

In this section, we investigate the distribution of $[\alpha/\text{Fe}]$ with respect to age for the Galactic disc using the kinematic decomposition discussed in Sect. 6.2. Figure 8 (top panel) shows the relationship between stellar ages and $[\alpha/\text{Fe}]$ abundance ratios for different metallicity bins. In the bottom panel of Fig. 8, we additionally show the distributions in the $[\text{Fe/H}] - [\alpha/\text{Fe}]$ plane split in age bins.

The bi-modal distribution defining the α-rich and α-poor populations clearly shows a strong evolution with age and metallicity. Most stars in the α-rich population, with the mean $[\alpha/\text{Fe}] \approx 0.24$ dex, have the age of $\sim 8$ to $12$ Gyrs, in line with the results by Xiang & Rix (2022). In contrast, the α-poor population, mean $[\alpha/\text{Fe}] \approx 0.03$ dex, is characterised by a much wider distribution of ages from a few to $10$ Gyrs. In the inter-
mediate range of ages, $7 \lesssim \tau \lesssim 11$ Gyr, both $\alpha$-poor and $\alpha$-rich components overlap in age, which suggests their co-evolution over this limited period of time.

As seen in the bottom panel of Fig. 8, there is also a difference in terms of metallicity evolution of both populations. At a given age the $\alpha$-rich population is somewhat more metal-poor, by $\sim 0.2$ dex, compared to the $\alpha$-poor population. The $\alpha$-rich population dominates in the metallicity range $-1 \lesssim [\text{Fe/H}] \lesssim -0.4$ and gradually vanishes at higher $[\text{Fe/H}]$. The $\alpha$-poor population becomes dominant at solar and super-solar metallicities. We remind that the owing to the photometric selection function of the survey, the younger part of the distribution is incomplete and there is a bias against metal-poor stars, $[\text{Fe/H}] < -1$ dex (Sect. 5).

The presence of old $\alpha$-poor stars with a broad range of metallicities, up to $[\text{Fe/H}] \sim +0.4$ dex, is intriguing although not fully unexpected. Among the earlier studies, Hayden et al. (2017) remarked on the significant temporal and chemical ($[\text{Fe/H}]$) overlap of the $\alpha$-rich and $\alpha$-poor components of the Galactic disc, studying the properties of TO and subgiant stars in the AMBRE.HAPRS survey. Silva Aguirre et al. (2018) identified a population of old $\alpha$-poor stars through asteroseismic age dating of APOGEE targets in the Kepler field. They report an overlap in age from 8 - 14 Gyrs between the $\alpha$-poor and $\alpha$-rich components. A non-negligible fraction of $\alpha$-poor metal-rich stars with ages up to 9 Gyr is also evident in the results by Xiang & Rix (2022). Similar distributions are seen in the results based on the APOGEE data by Cucă et al. (2021) and Beraldino et al. (2021), who find $\alpha$-poor stars with ages up to $\sim 12$ Gyr spanning the entire range of metallicity, $-0.7 \lesssim [\text{Fe/H}] \lesssim +0.4$, in the solar neighbourhood. The study by Beraldino et al. (2021) is relevant in the context of our work, as the spatial coverage is similar, $R_{\text{Gal}} \sim 2$ kpc, and the targeted stellar population (subgiants and the lower part of the RGB branch) overlaps with the properties of our observed Gaia-ESO sample. Feuillet et al. (2019) find rather tight age-$[\alpha/\text{Fe}]$ relationships, with some evidence for the presence of old $\alpha$-poor stars. However, they do not report stellar densities in each bin in the age-$[\alpha/\text{Fe}]$ plane (e.g. their Fig 6), whereas this would be necessary to confirm whether an age-$[\alpha/\text{Fe}]$ bimodality exists in their distributions.

7. Discussion
The main finding of our work is that the $[\alpha/\text{Fe}]$-poor and $[\alpha/\text{Fe}]$-rich stellar populations with disc-like kinematics, often referred to as the thick and the thin discs - , co-existed during a non-negligible period of their evolution.

The rather limited temporal extent of the thick ($[\alpha/\text{Fe}]$)-rich disc appears to be well-established (Bensby et al. 2005; Haywood et al. 2013; Hayden et al. 2017), and our results reinforce the evidence for an extended star formation in this population spanning several Gyrs. More interesting is the age distribution of the $[\alpha/\text{Fe}]$-poor disc population, which extends out to $\tau > 10$ Gyr and spans a broad range of metallicities $-0.7 \lesssim [\text{Fe/H}] \lesssim +0.4$. It cannot be ruled at this stage that the temporal distributions seen in the data are related to the uncertainties of stellar ages. However, the fact that these distributions are confirmed by different age dating methods and different observational samples (Hayden et al. 2017; Ciucă et al. 2021; Beraldino et al. 2021), lends support to the interpretation that the thick and thin disc are possibly coeval.

This analysis is not the first to highlight the possibility of the parallel formation of the Galactic discs. This scenario has also received support from studies based on other tracers, including the analyses of properties of $\alpha$-poor RR Lyrae in the disc (Prudil et al. 2020) and high-latitude stellar overdensities (e.g. Laporte et al. 2020). The latter study, in particular, showed that for the Anticenter Stream (ACS), a coherent stream-like outer disc structure with $[\text{Fe/H}] \sim -0.6$ and no enhancement of $\alpha$ elements, the cumulative age distribution is consistent a high fraction of old stars $\tau > 10$ Gyr and an abrupt dearth of young stars. The Monoceros Ring (Newberg et al. 2002) shows more steady star formation through the presence of a more extended distribution stars with ages from $\sim 5$ to $\sim 10$ Gyr (Laporte et al. 2020).

At face value, this implies that the Milky Way galaxy already had an $[\alpha/\text{Fe}]$-poor disc in place before $z \sim 2$, around the peak of the cosmic star formation rate density (Madau & Dickinson 2014). The size of the early disc cannot be reliably estimated in this work, because our sample probes a rather limited spatial volume, about few kpc from the Sun. However, we find that even the oldest stars in the alpha-poor disc are not preferentially confined to the inner disc, but are rather broadly distributed over the entire range of Galactocentric radii probed by the observed sam-
ple. While such an extended disc size would make the Galaxy seem like an outlier to the general size-evolutionary trend for MW-like galaxies (van Dokkum et al. 2013), we note that the stars in the ACS most probably started out with smaller guiding radii and were later excited to larger ones following interactions with a massive satellite (see Laporte et al. 2019, for an N-body study on the formation of ACS-like structures). Laporte et al. (2022) argued that estimated time at which the ACS decoupling from the disc is similar to the timescale of the merger via the Gaia-Sausage-Enceladus event (Naidu et al. 2021). This is also consistent with the Beraldo e Silva et al. (2021) interpretation that a significant (30 to 50%) fraction of the local old α-poor stars are migrants from the inner disc.

Several scenarios have been invoked to explain the formation of the thick and thin disc, but only several of them predict a co-evolution of the discs. In cosmological simulations of galaxy formation (e.g. Brook et al. 2004; Buck 2020; Agertz et al. 2021), the old alpha-poor stellar population originates as a result of star formation following a merger that brings pristine (H-rich) metal-free gas from the circumgalactic medium, thus drastically reducing the metallicity of the ISM at a constant (low) [α/Fe] ratio. These stars are expected to be about 7 to 10 Gyr old, although this depends on the time of the merger. Nonetheless, the main prediction of this scenario is the presence of both alpha-poor and alpha-rich populations at a given metallicity, whereby the alpha-poor population is about 2 Gyr younger. There are also controlled hydrodynamical simulations of clump formation in the primordial disc (Bournaud et al. 2009; Clarke et al. 2019) that follow the evolution of self-enriching high star formation density clumps similar to those seen in high-z galaxies (e.g. Elmegreen & Elmegreen 2005). In these simulations, the formation of the thin disc sequence is accompanied by that of the thick disc (a-rich) sequence, the latter emerging from gas-rich self-enriching clumps in the early a-poor disc. Whereas this scenario is favoured by Beraldo e Silva et al. (2021), whose conclusions on the bimodal age-α[Fe] structure of the disc are very similar to ours, Ciucă et al. (2021) interpret their findings in the hybrid framework, involving rapid central enrichment, cold gas accretion (or merger), and radial evolution of the disc (Grand et al. 2018). That is, the signature of gradual chemical enrichment in the disc, with the old part of the thick disc component forming from turbulent well-mixed inner regions owing to a merger or metal-poor gas accretion, and the thin (inner and outer disc) forming at later stages over a continuous period of time fuelled by hot gas accretion from the halo.

In summary, our results disfavour strictly sequential formation scenarios for the thin and thick discs and are in line with recent observational studies (Silva Aguirre et al. 2018; Beraldo e Silva et al. 2021; Ciucă et al. 2021). Instead, our data can be best interpreted in the context of the parallel formation scenario of the discs. However, the precision and accuracy of ages is not yet fully sufficient to disentangle between the clumpy formation (as in Clarke et al. 2019) and gradual enrichment involving a metal-poor gas accretion and mergers (as in Grand et al. 2018), that is the two disc formation scenarios that predict that the disc components grew in parallel, at least during a limited period of time, in the early Galaxy.

8. Conclusion

In this work, we study the enrichment properties of Galactic disc using the observed abundances, ages, and kinematics of stars observed by the Gaia-ESO survey. We have used spectra from the fourth public data release (DR4) of the Gaia-ESO survey, to derive stellar parameters and non-LTE abundances for stars within a ~ 2 kpc volume about the Sun, with majority of stars spanning 6 < R < 10 kpc in Galactocentric radius and [Z] < 2 kpc in vertical distance from the plane. We further determine ages for a fraction of stars in the sample, primarily focusing on main-sequence and turn-off stars, and investigate the influence of the survey selection function on the age-metallicity distributions.

We find that the two chemically-defined components of the Galactic disc, [α/Fe]-poor and [α/Fe]-rich, show a significant temporal overlap of about 2 to 3 Gyr. Both populations are old. The α-rich disc extend out to ages τ > 12 Gyr, and the α-poor component with −0.7 ≤ [Fe/H] ≤ +0.4 is present already as early as 10 Gyr ago. The overlap thus refers to the limited period from τ ~ 7 to ~ 11 Gyr, which is when both disc components are clearly visible in the age-α diagram.

Our results favour the parallel formation of the disc components, challenging the classical sequential scenarios, such as the two-infall model with a star-formation hiatus (Chiappini et al. 1997) or the in-situ formation of the thin disc from the thick disc (Bird et al. 2013). Rather, we suggest that the growth of the α-poor and α-rich components accompanied each other during a significant period of time of several Gyr. The two possible options are the formation of the α-rich component from the primordial thin disc, i.e. the clumpy formation (Clarke et al. 2019) or gradual formation of the two populations primarily associated with the differential evolution of the inner and outer discs (Grand et al. 2018; Ciucă et al. 2021). There is tentative evidence for the latter, since in our data the α-rich disc component is on average older and more metal-poor than the α-poor component. However, we do find some stars in the α-poor population that are as old as those in the α-rich population. Since in the clumpy and distributed star formation scenario, the gas-rich fragments have a high star formation rate density, the paucity of primordial thin disc stars (compared to thick disc stars) in our observations can in principle also be understood in the framework of the clumpy disc formation model. Future surveys with better coverage and higher quality data such 4MOST, and WEAVE, will allow to provide a better spatial and temporal coverage of the disc allowing to distinguish between the two scenarios.

Acknowledgements

This research made use of Astropy, a community-developed core Python package for Astronomy (Astropy Collaboration et al. 2013; Price-Whelan et al. 2018). MB is supported through the Lise Meitner grant from the Max Planck Society. We acknowledge support by the Collaborative Research centre SFB 881 (projects A5, A10), Heidelberg University, of the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation). This project has received funding from the European Research Council (ERC) under the European Union’s Horizon 2020 research and innovation programme (Grant agreement No. 949173).

For the purpose of open access, the author has applied a Creative Commons Attribution (CC BY) licence to any Author Accepted Manuscript version arising from this submission.

References

G. R., Fulbright, J. P., Wyse, R. F. G., et al. 2011, ApJ, 737, 9
Adibekyan, V. Z., Figueira, P., Santos, N. C., et al. 2013, A&A, 554, A44
Agertz, O., Renaud, F., Feltzing, S., et al. 2021, MNRAS, 503, 5826

7 http://www.astropy.org
Appendix A: Halo contamination

Figure A.1 shows the determination of halo contamination in the thick and thin disc for varying [Fe/H] bins as an alternative method. Similarly described in Sec. 6.2, we analyse stars with $V_\phi < 0$ Kms$^{-1}$, assume symmetry in $V_\phi$ distribution with respect to $V_\phi = 0$ and therefore determine the number of halo stars with positive circular velocities. The contamination is determined by inspecting the number of stars with $V_\phi > 110$ Kms$^{-1}$ and comparing that to the number of stars in total above the velocity cut. This is determined for each bin of [Fe/H] and so a running average is calculated as opposed to fitting a velocity ellipsoid. This allows us to determine how contamination depends on metallicity and therefore informs the [Fe/H] limit for each alpha-population. Assuming a cut at [Fe/H] = -1, the average halo contamination is less than 10%.

Fig. A.1: Running average of halo contamination in the disc in variable [Fe/H] bins with $V_\phi > 110$ Kms$^{-1}$. The red dotted line represents high $\alpha$ and the blue dotted line represents low $\alpha$. 