From metal-poor to metal-rich: new insights on MW disc history with machine learning and Gaia

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In collaboration with:
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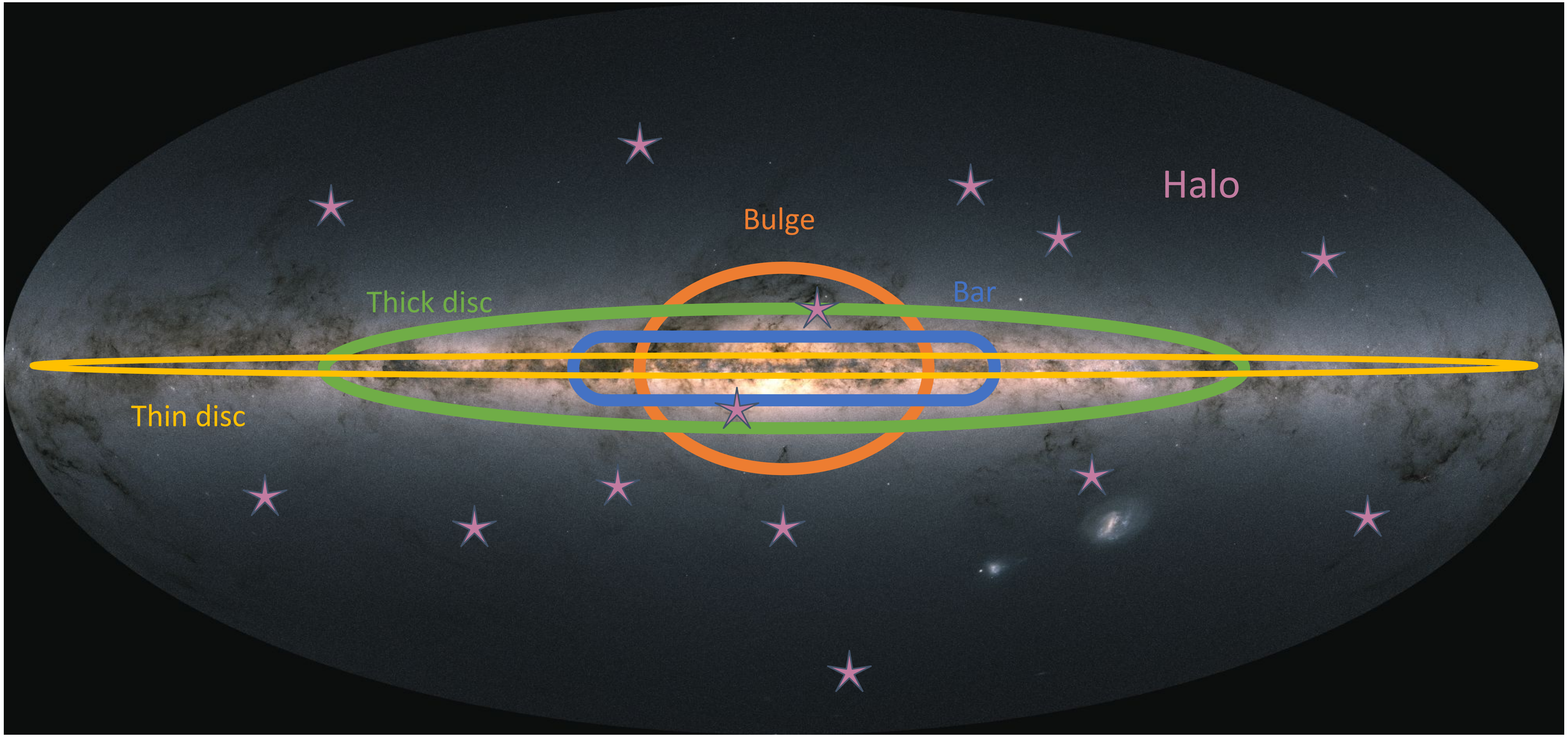
Josefina Montalbán(UB), Andrea Miglio(UB),
Friedrich Anders (ICCB), Arman Khalatyan(AIP),
Angeles Pérez-Villegas(UNA), and others

The Milky Way Assembly Tale, Bologna, Italy
Date: 27-31 May 2024

The classical view of the Milky Way:



How do we trace Milky Way's history ?

gaia

Things we need:

- ***Chemical Composition, Ages, Positions and Kinematics*** of a large number of stars are necessary for the complete picture.
- Atmospheric parameters and chemical abundances for the stars (multiple species).
  Large Spectroscopic Surveys like 4MOST, WEAVE, LAMOST, SDSS-V, GALAH, Gaia RVS, etc.
- 6D phase space information.
  Gaia Mission & RVs from spectroscopy
- Accurate distances, extinction and ages for these stars necessary.
  e.g. StarHorse code with atmospherics params, parallax and photometry as input

The **heavy** data:

- The RVS-CNN Catalog (Guiglion, Nepal et al. 2024 A&A):
  Teff, log(g), [M/H], [Alpha/M] and [Fe/H] for >840,000 stars. (Catalog is public)
  >12,000 metal-poor ([Fe/H]<-1.0) and ~19,000 super-metal-rich ([Fe/H]>0.2)

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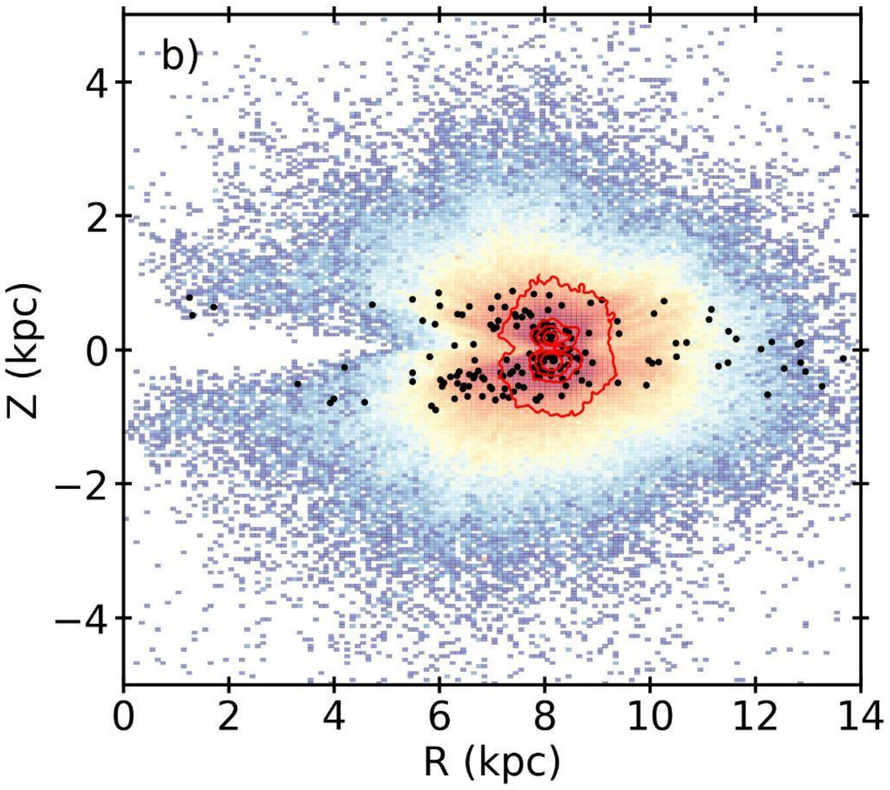
- 6D phase-space + StarHorse distance → Velocities and orbits using Astropy & Galpy

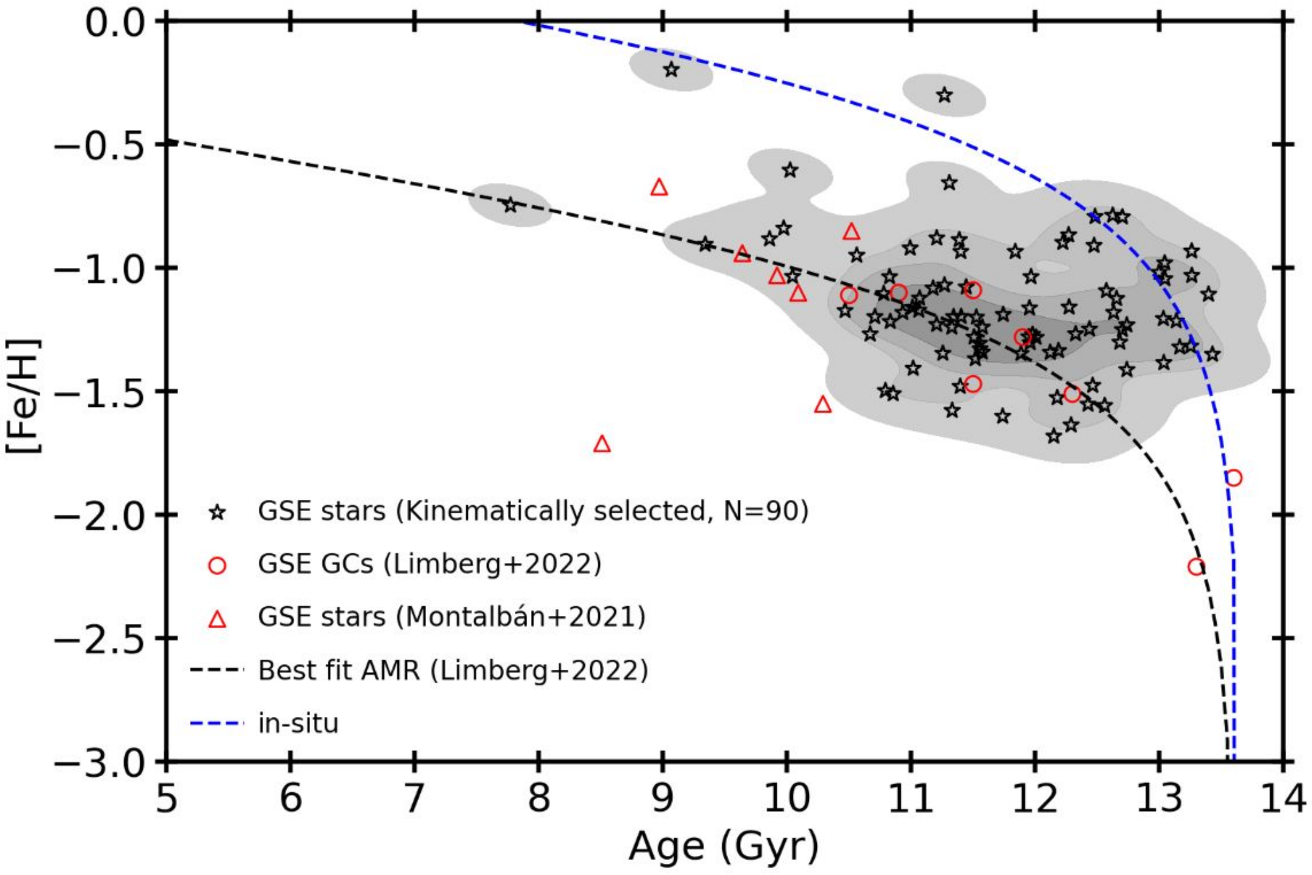
  (McMillan 2017 potential).

The heavy data: High quality sample from the RVS-CNN

- >565,000 stars with mean distance uncertainty of 2%.
- > 200,000 MSTO+SGB stars with mean uncertainty of 12% for age and 1% for distance.



Validating ages: AMR for confirmed GSE members



Nepal et al. 2024b (in press)

We recover the age-[Fe/H] relation for the GSE candidates confirmed with the GSE globular clusters and member stars with asteroseismic ages.

Two science cases:

- Old thin disc
- Young bar

The oldest thin disc of Milky Way: (Nepal et al. 2024b in press)

- At high-redshift ($z > 4$) there have been recent observations of cold disc galaxies with ALMA and JWST.
  Rizzo+2020,2021; Tsukui & Iguchi 2021, Lelli+2023; Roman-Oliveira+2023; Ferreira+2022; Kartaltepe+2023; Robertson+2023

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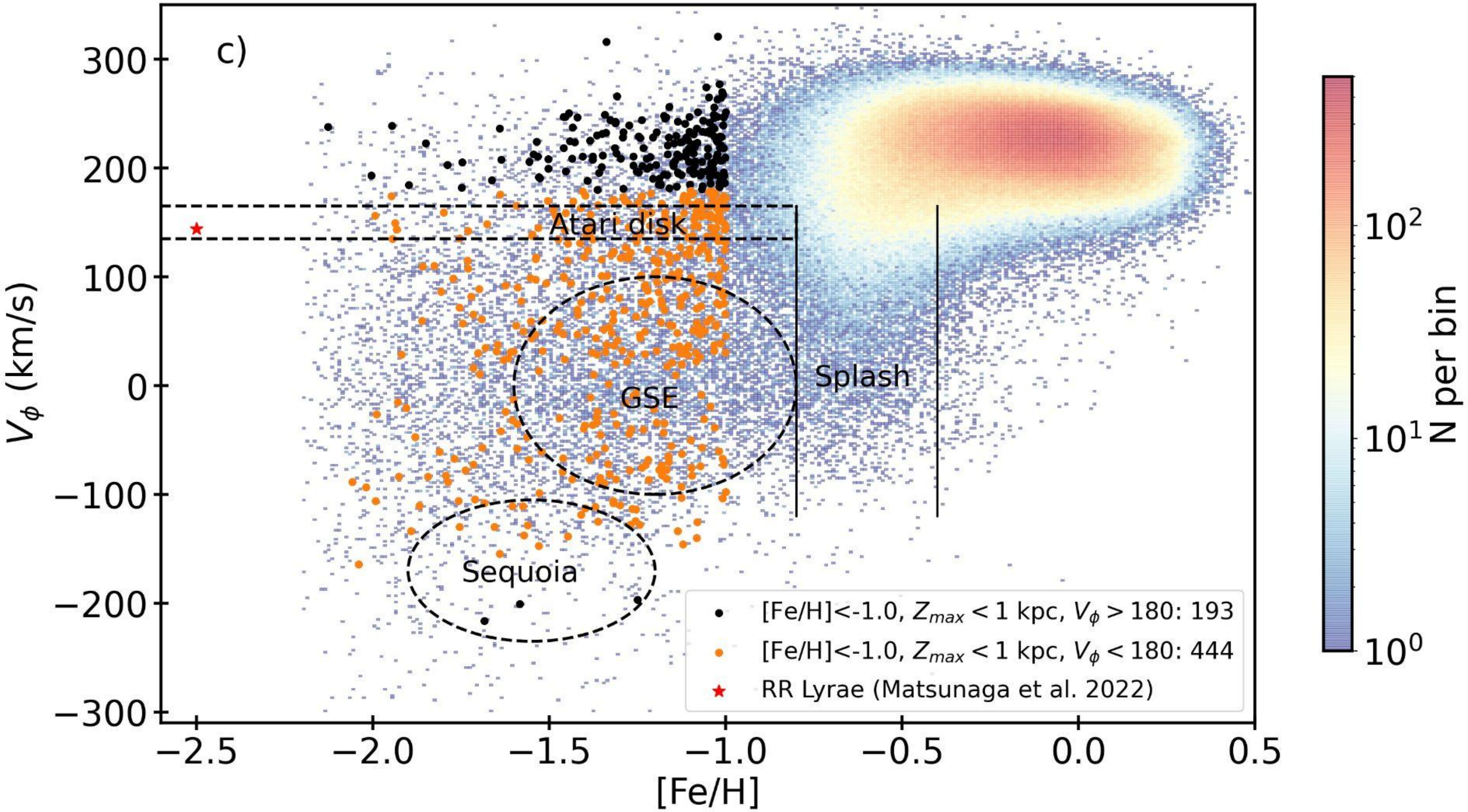
- Does Milky Way have an ancient disc?

- When did this MW disc form and did it begin as thin disc or the thick disc?

The metal-poor thin disc: (Nepal et al. 2024b in press)



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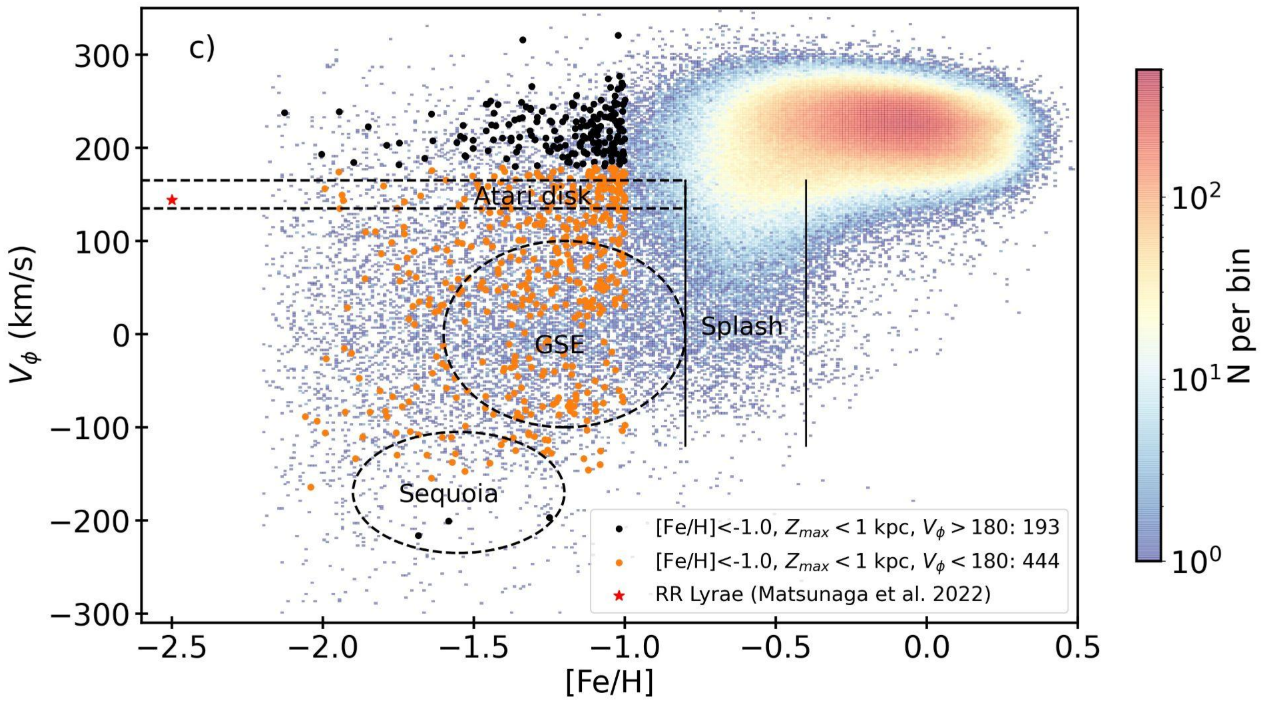

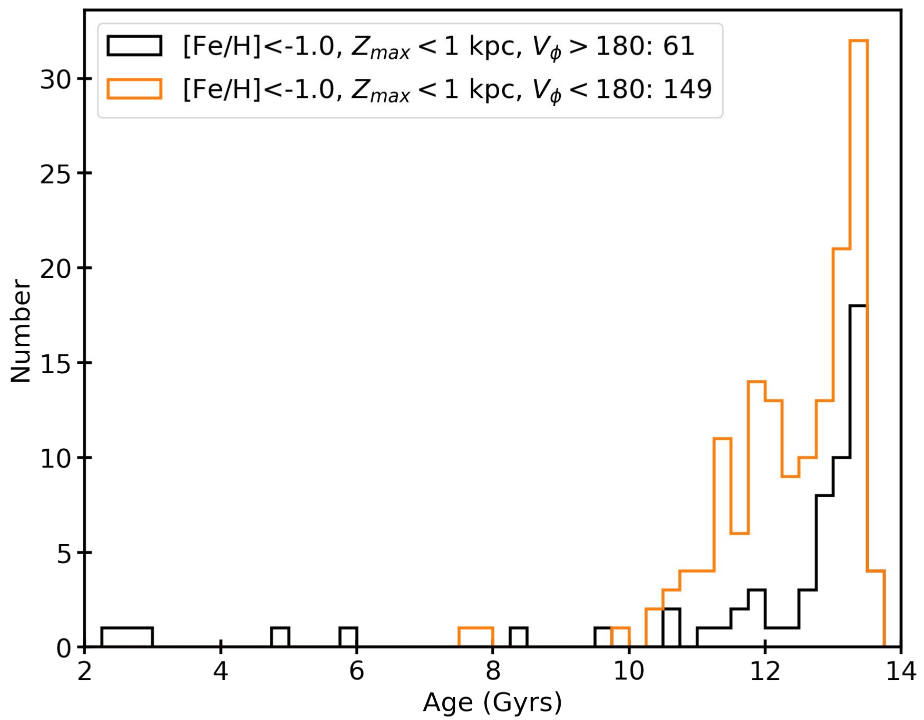

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- significant % of kinematically hotter MP stars < 13 Gyr

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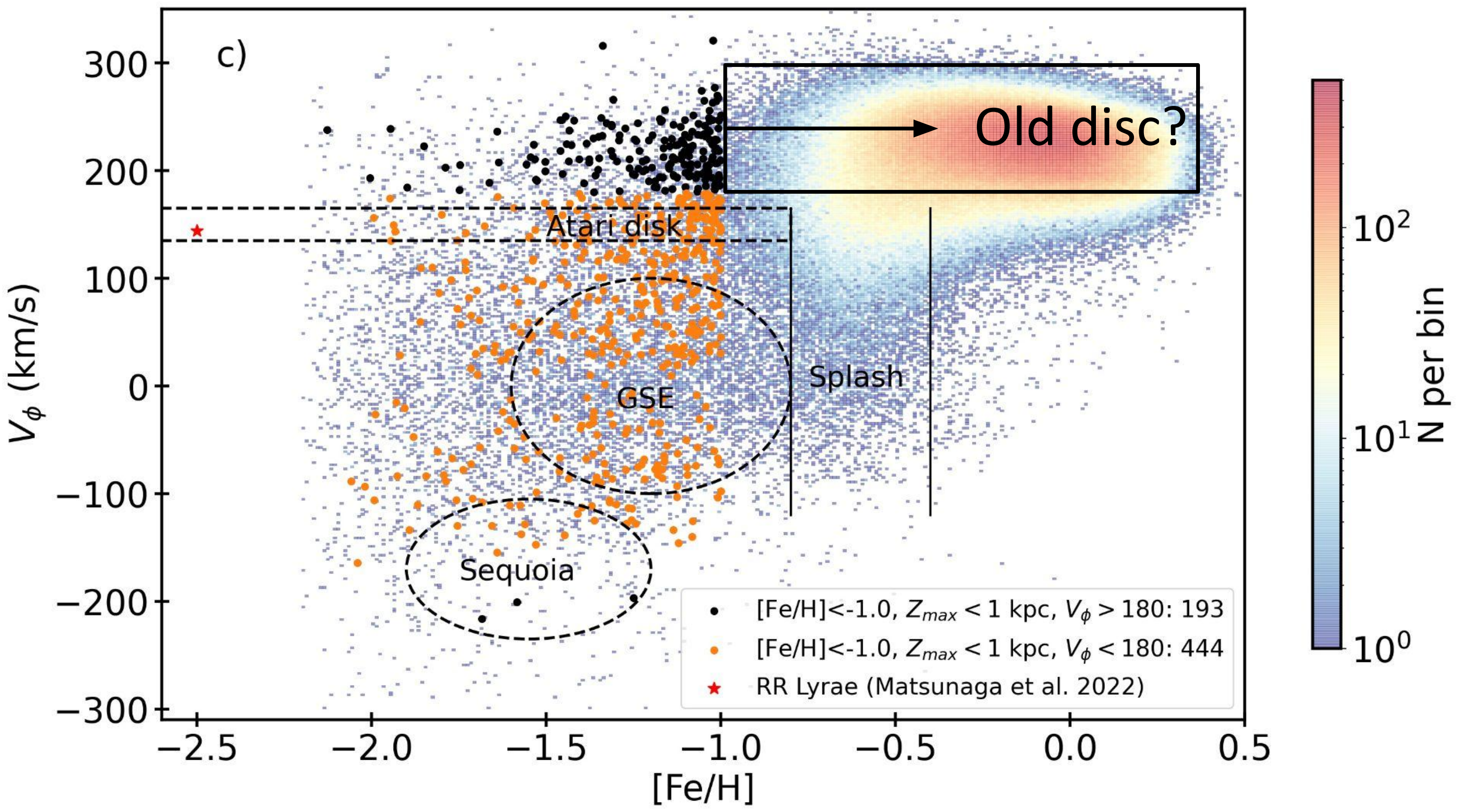
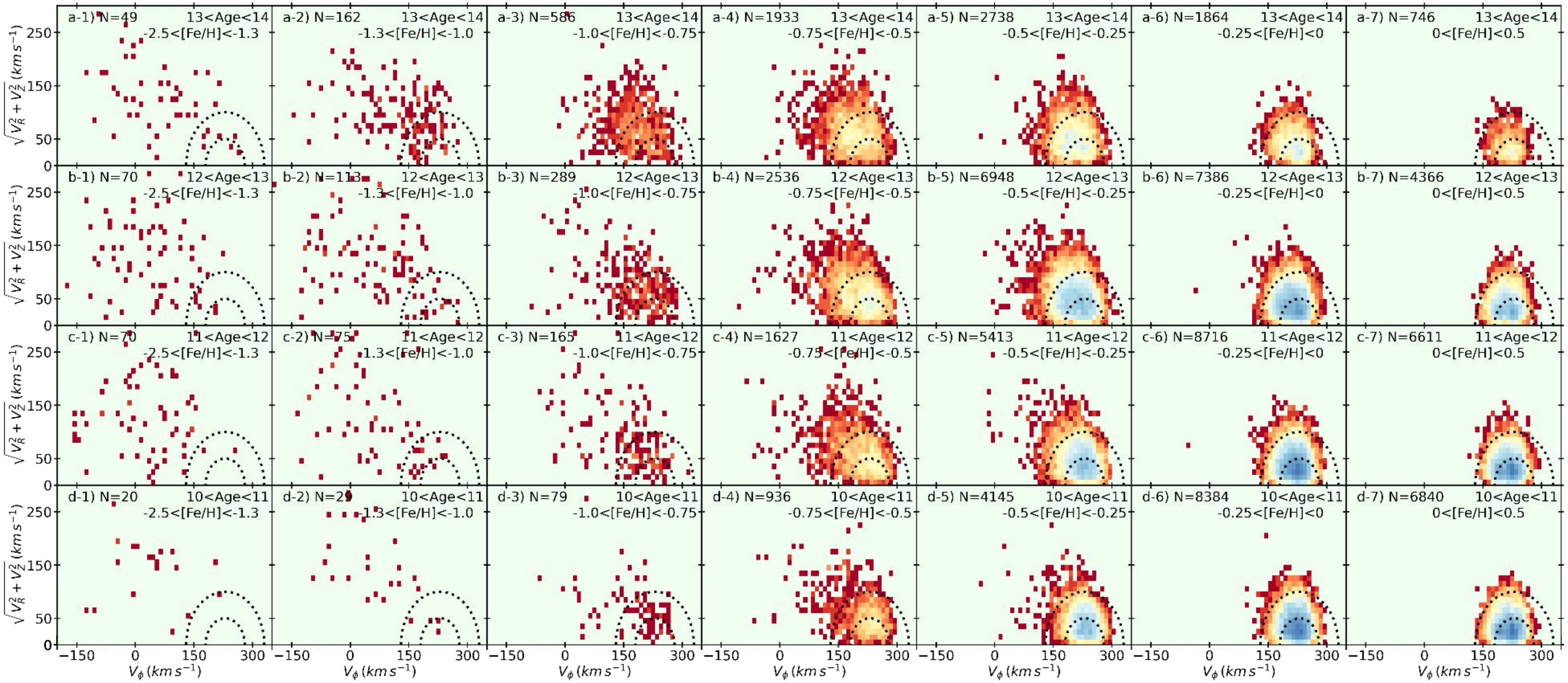


The oldest thin disc of MW: (Nepal et al. 2024b in press)

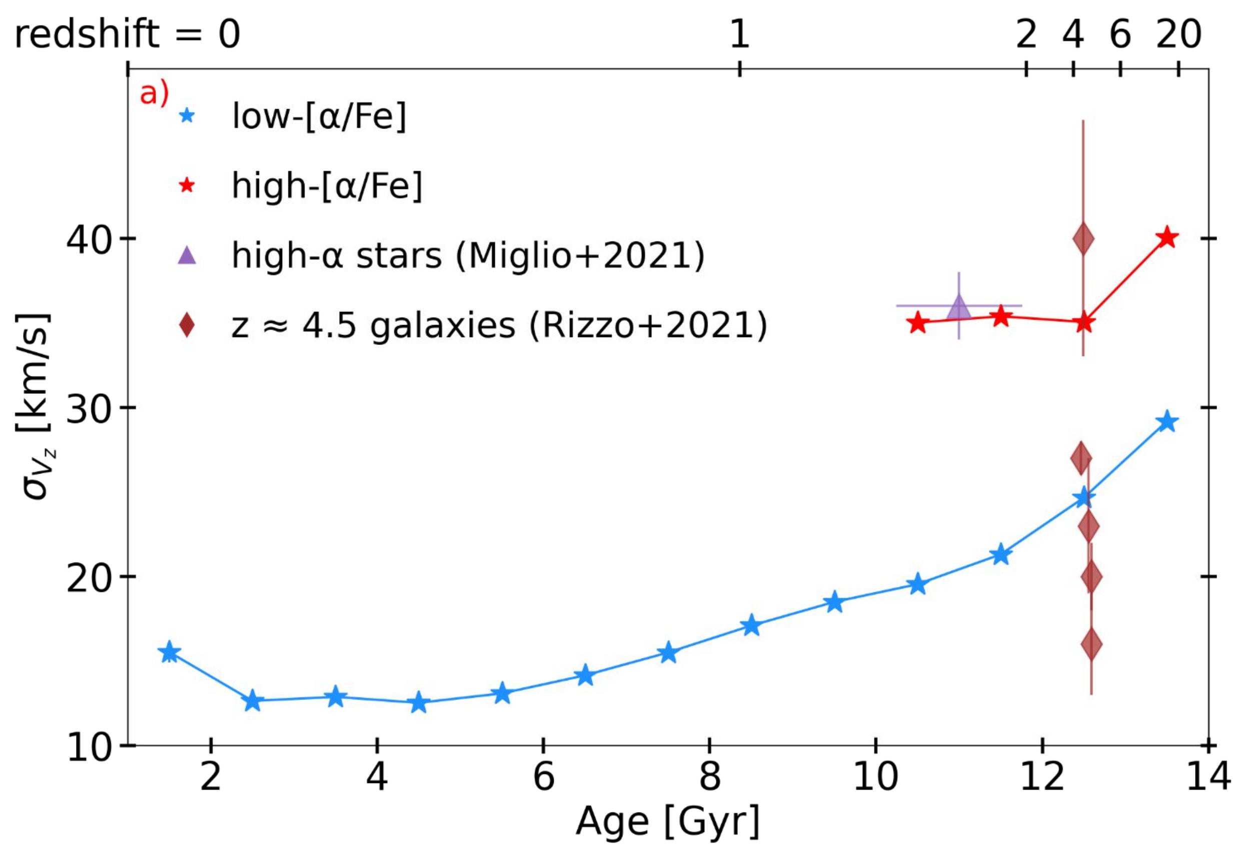
Old
to
Young



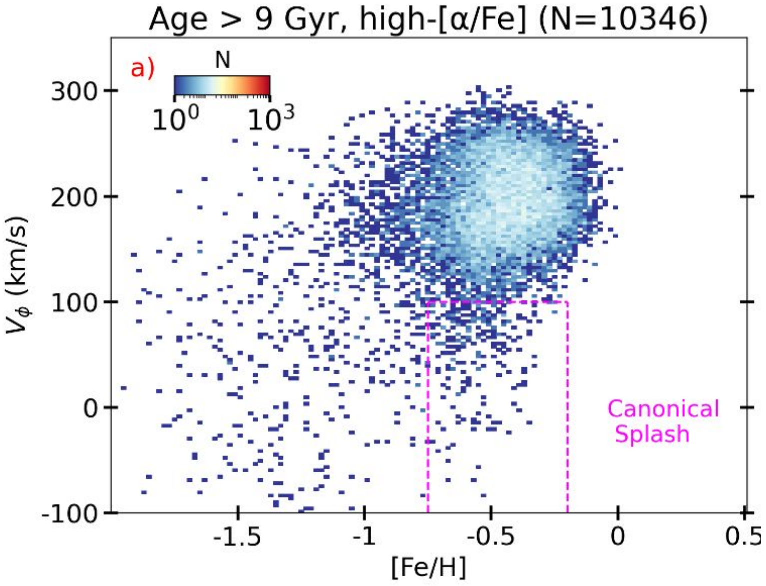
Metal-poor to Metal-rich

Significant fraction of old stars with wide [Fe/H] range already in thin/thick disc orbits at the oldest ages.

high-z discs of MW: (Nepal et al. 2024b in press)



Splashing the old thin and thick discs: (Nepal et al. 2024b in press)



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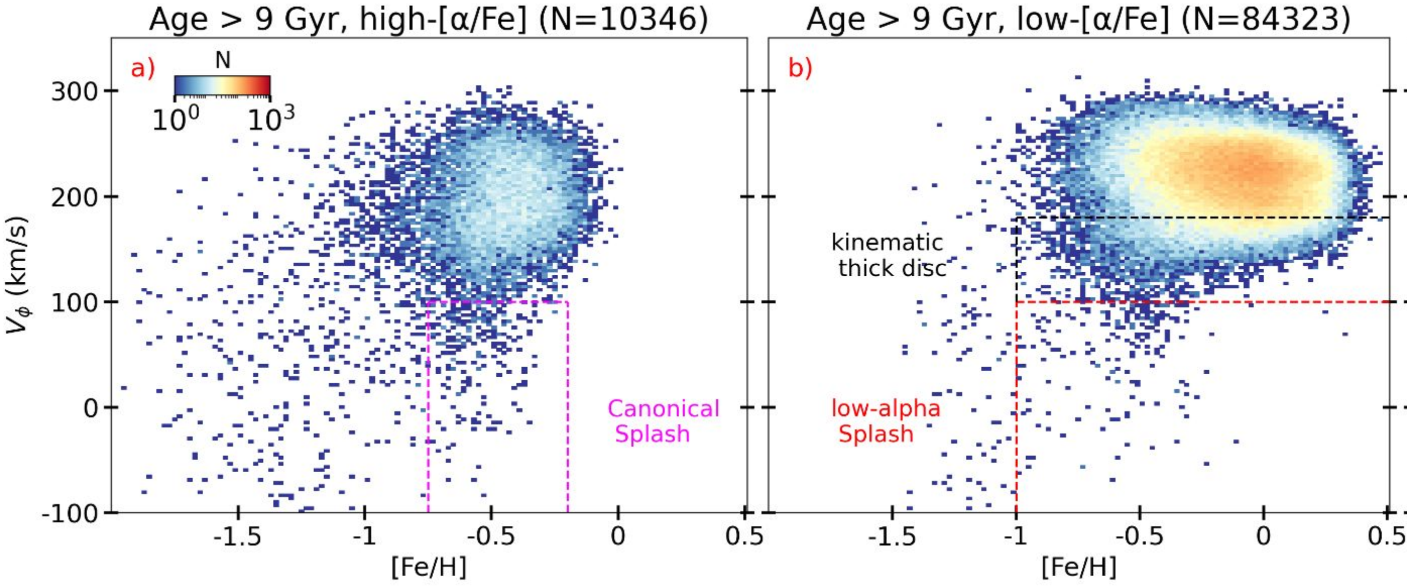

≈ 10% old low-α stars with thick disc velocities
(Note: higher fraction expected in the inner disc)

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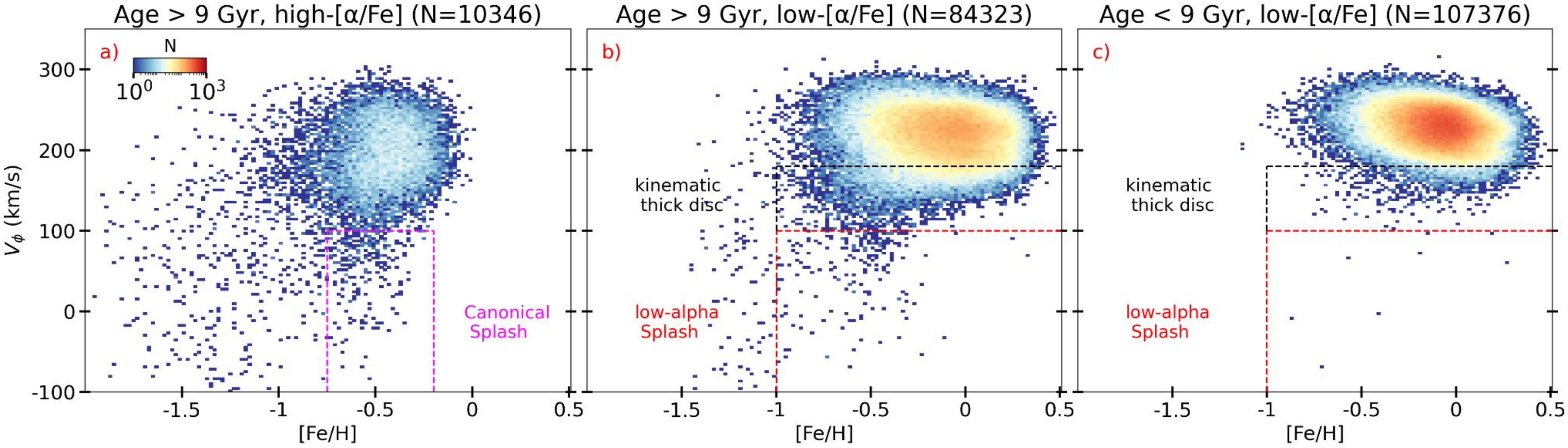

≈ 1.5%

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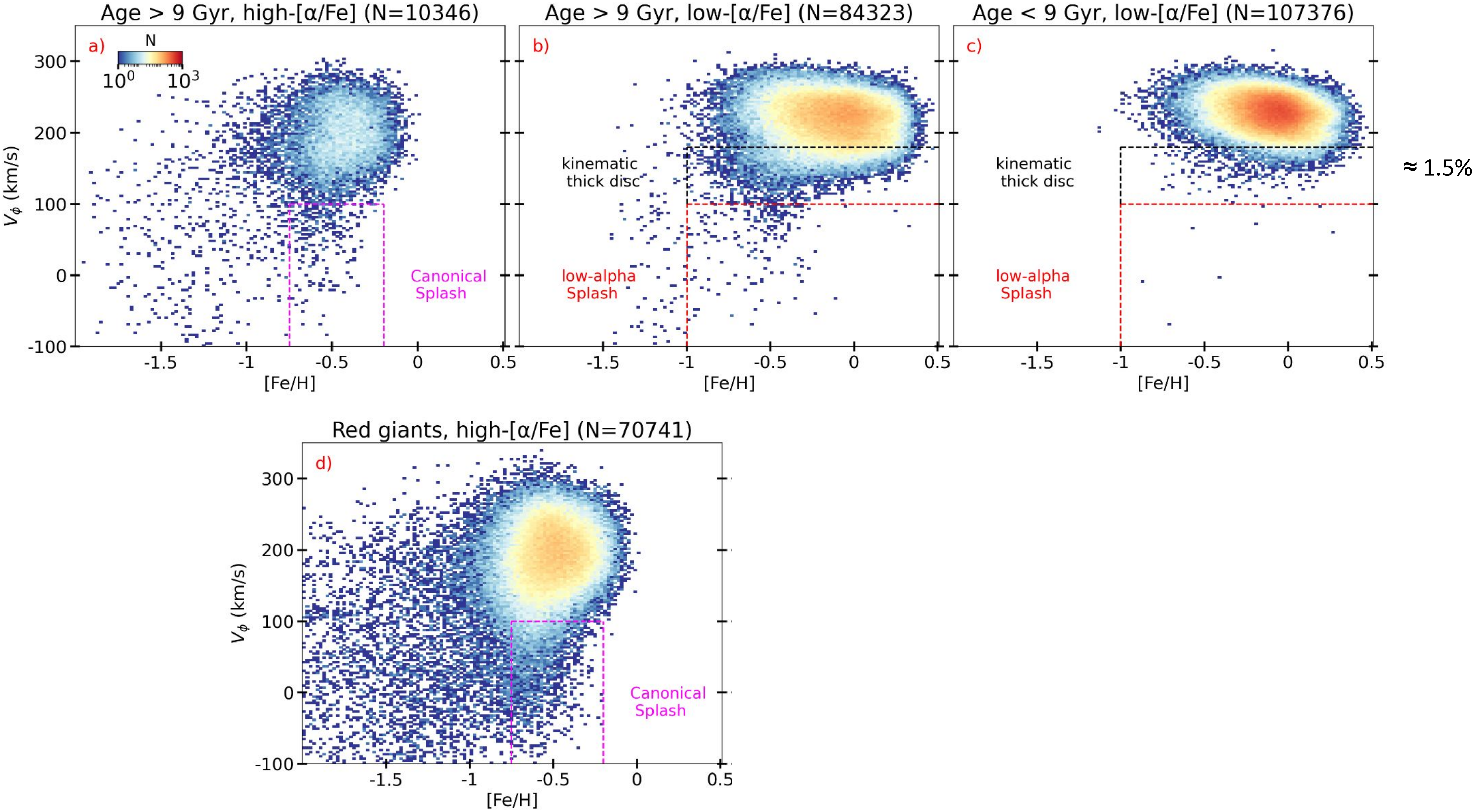

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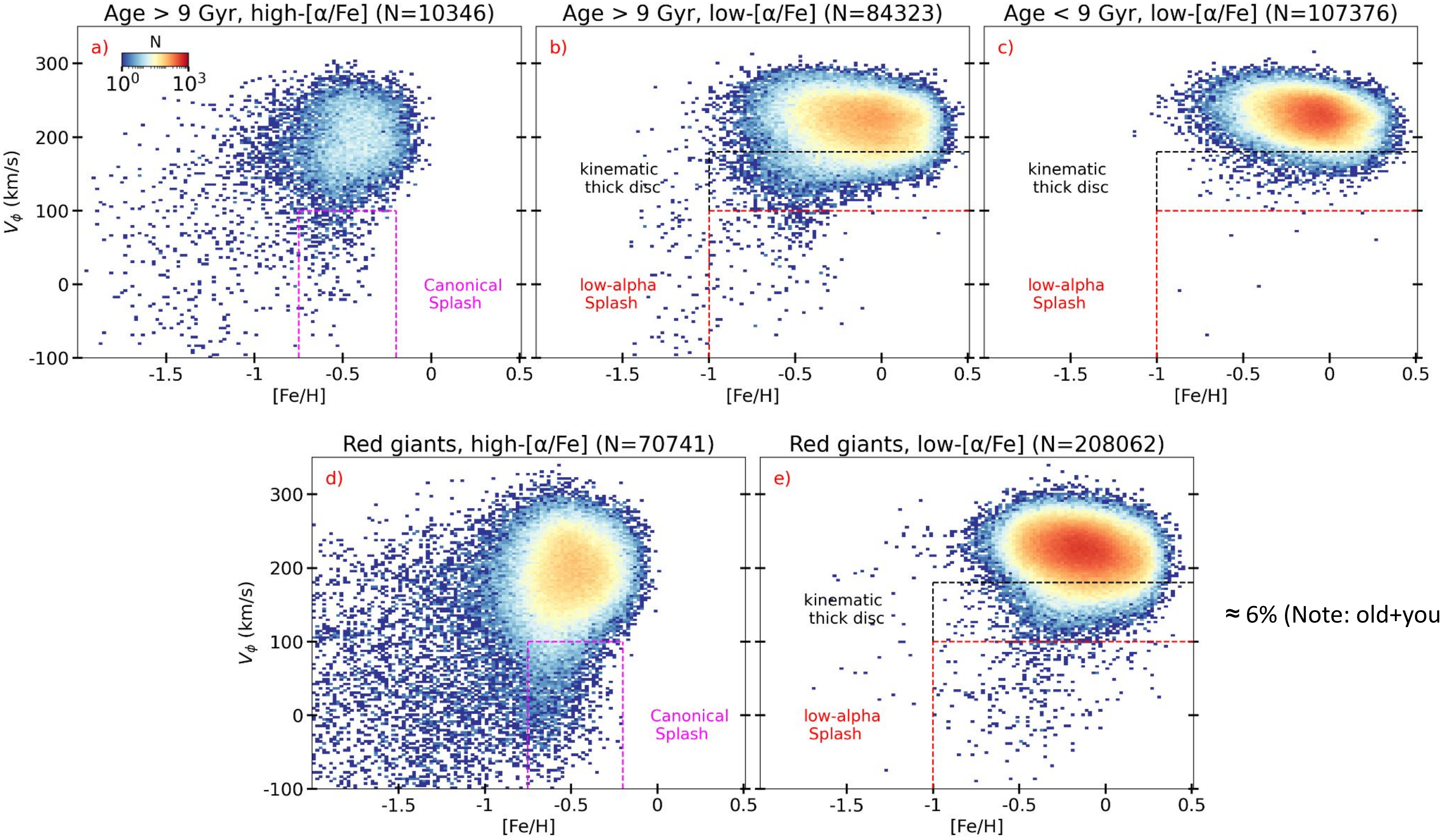


≈ 6% (Note: old+young)

Insights from super-metal-rich stars: (Nepal A&A 681, L8 2024)

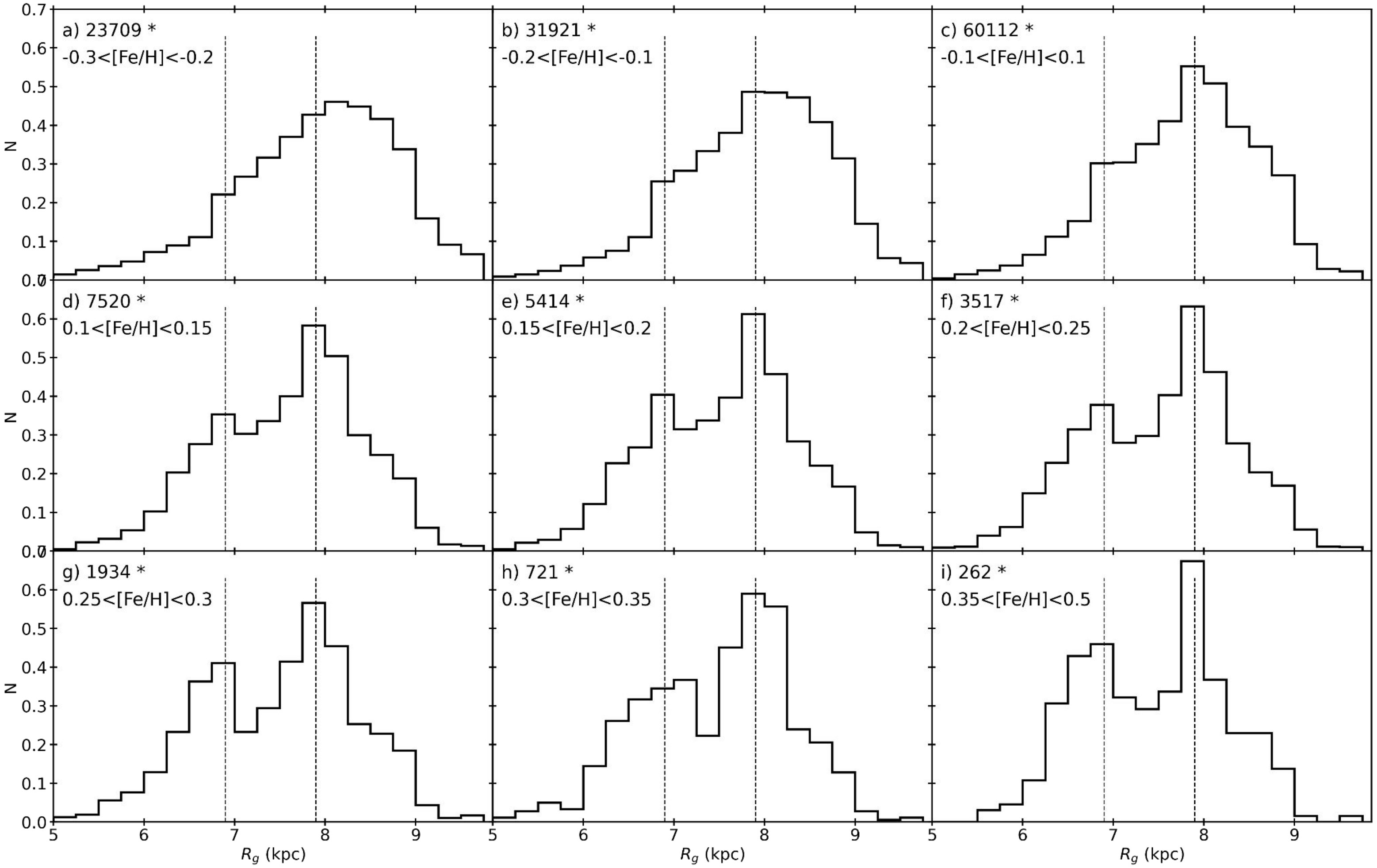
- Super-metal-rich (SMR) stars are expected to be formed only in the inner regions of our Galaxy.

- Can SMR stars currently in the Solar Neighbourhood inform us about their migration?

- Bars are one of the main drivers of galaxy evolution and can significantly rearrange stars within the Galaxy.

Super-metal-rich stars as tracers of bar activity: (Nepal A&A 681, L8 2024)

- A clear bimodality in the distribution of Rg appears as we move from sub-solar [Fe/H] to SMR stars.
- The peaks at 6.9 and 7.9 kpc correspond to bar resonances.



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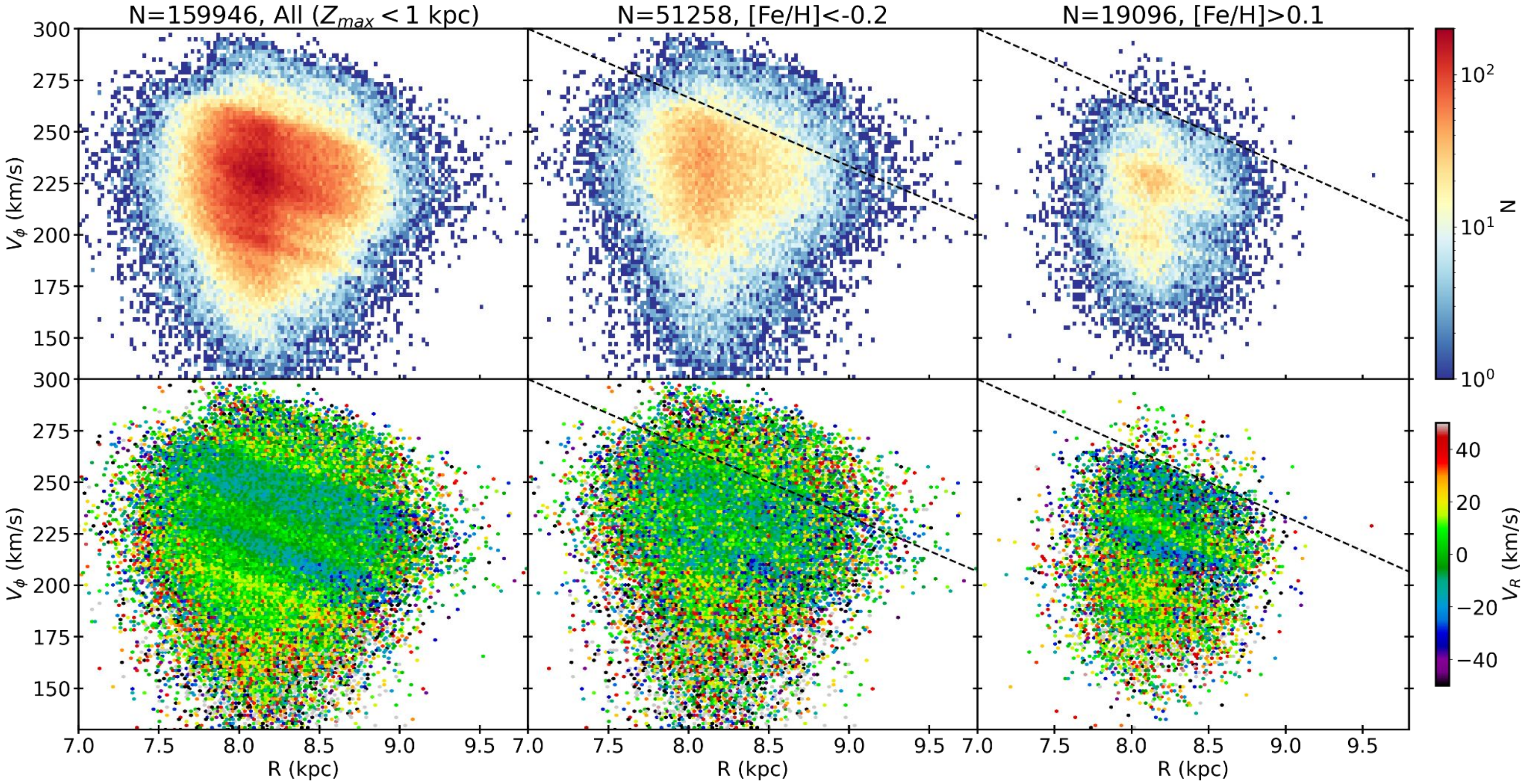
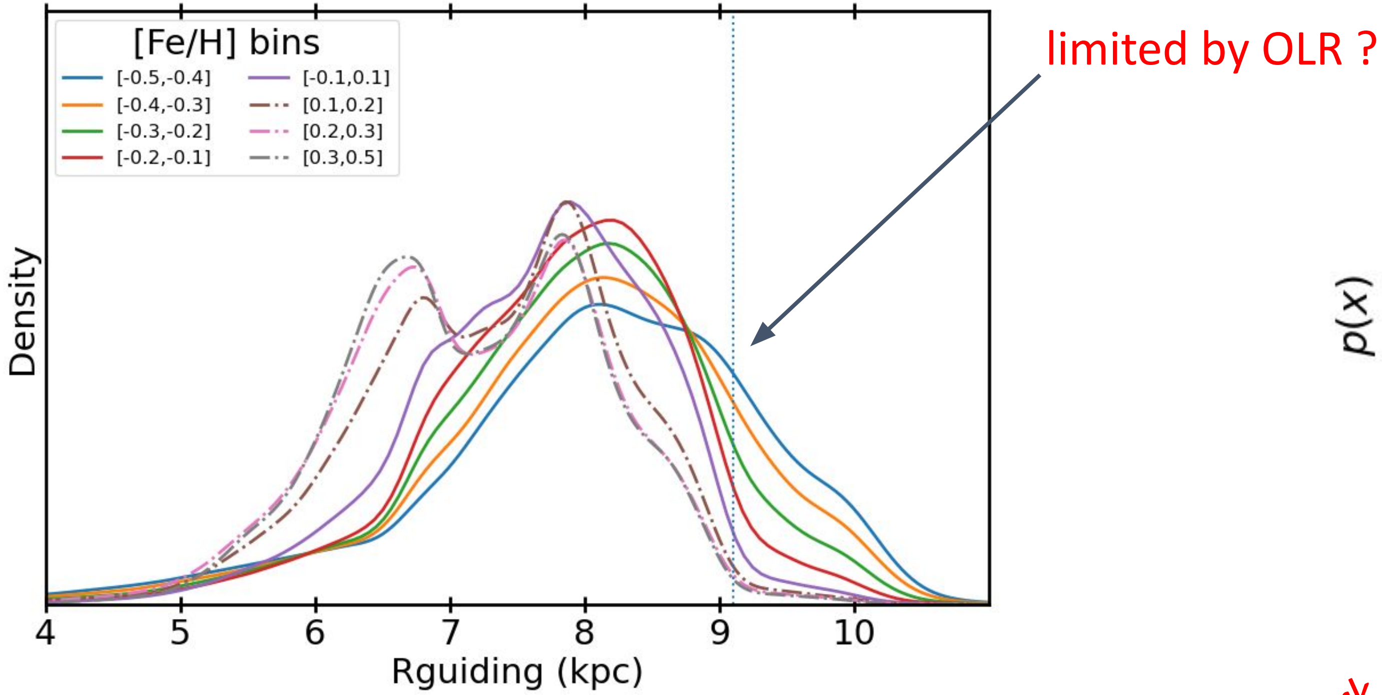
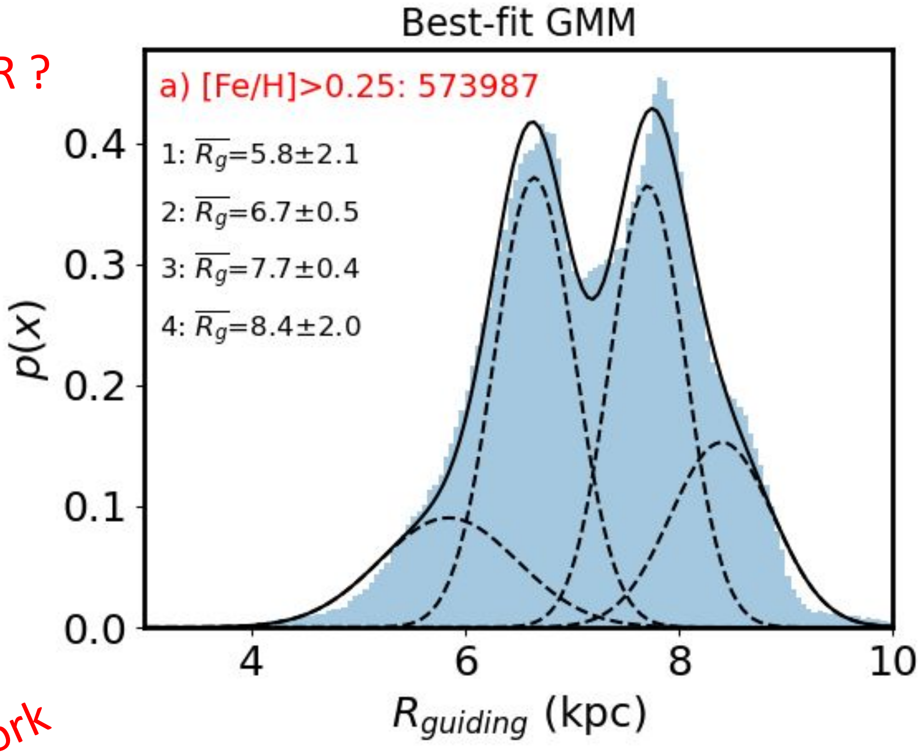


Super-metal-rich stars as tracers of bar activity:

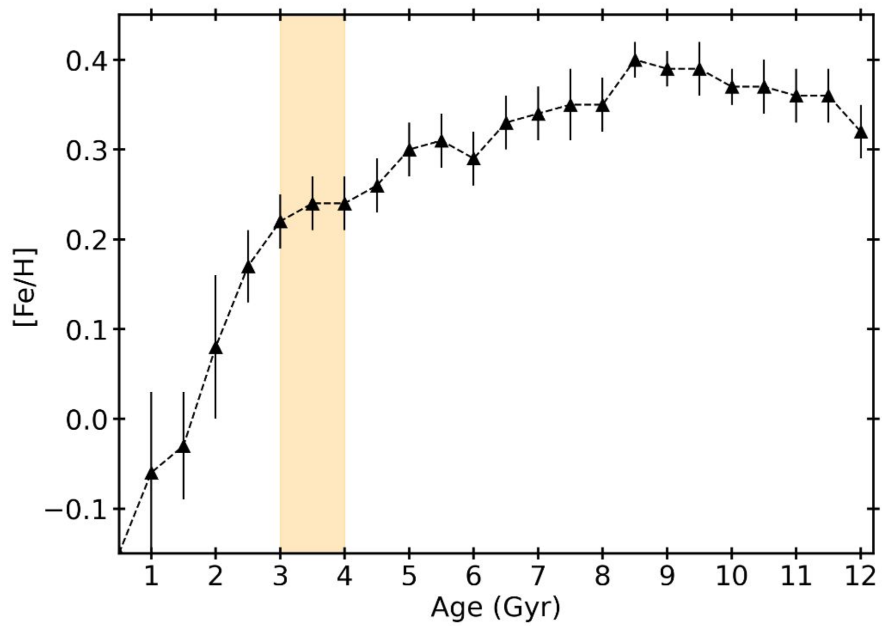
- Confirmation with a large dataset of > 7 Million stars with radial velocities with Gaia XP Spectra using SHBoost. (Anders et al. 2024 to be submitted soon…..)





Preliminary work

Ages of SMR stars tell some tale:



- A steep decline in [Fe/H] for stars younger than 3 Gyrs.
- Absence of local SMR stars hints to a cease in main mechanism that brings SMR stars to Solar vicinity.

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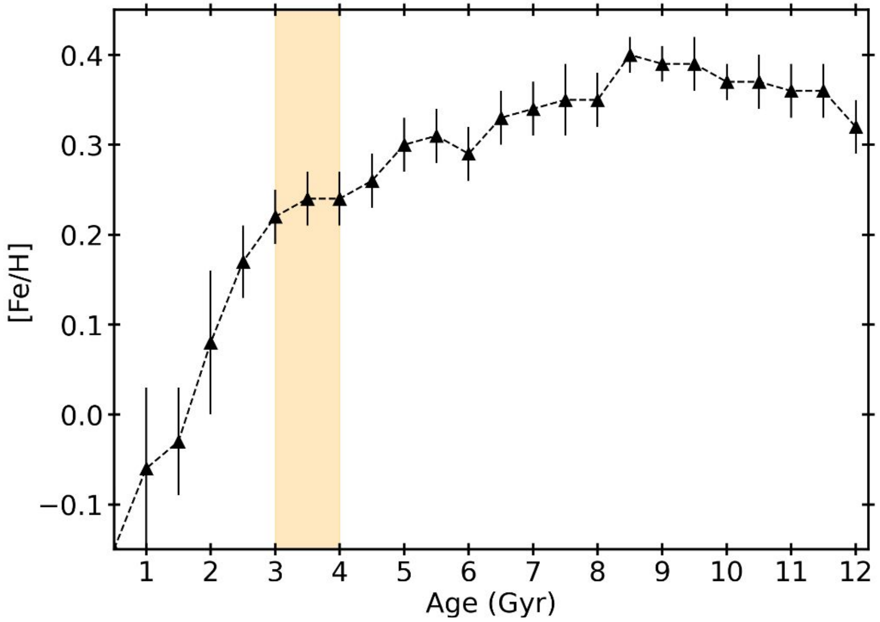
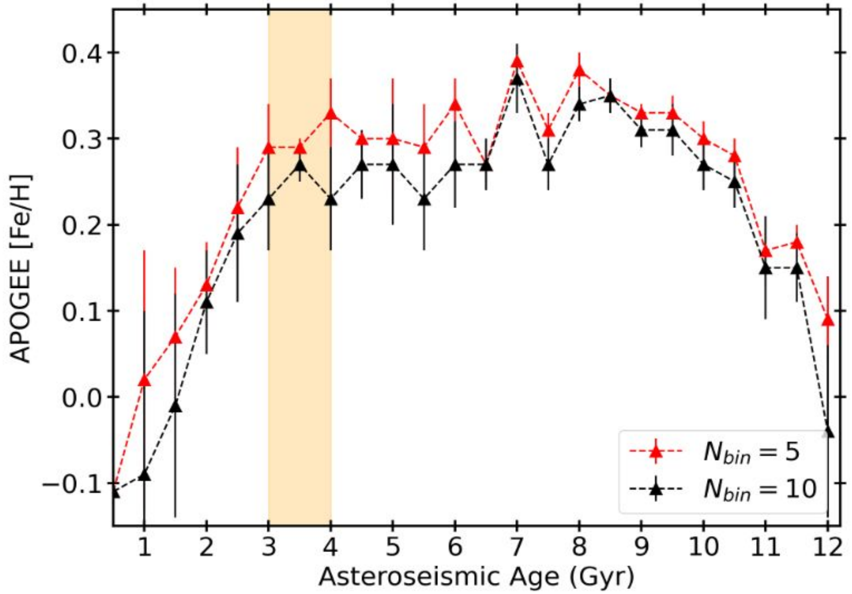
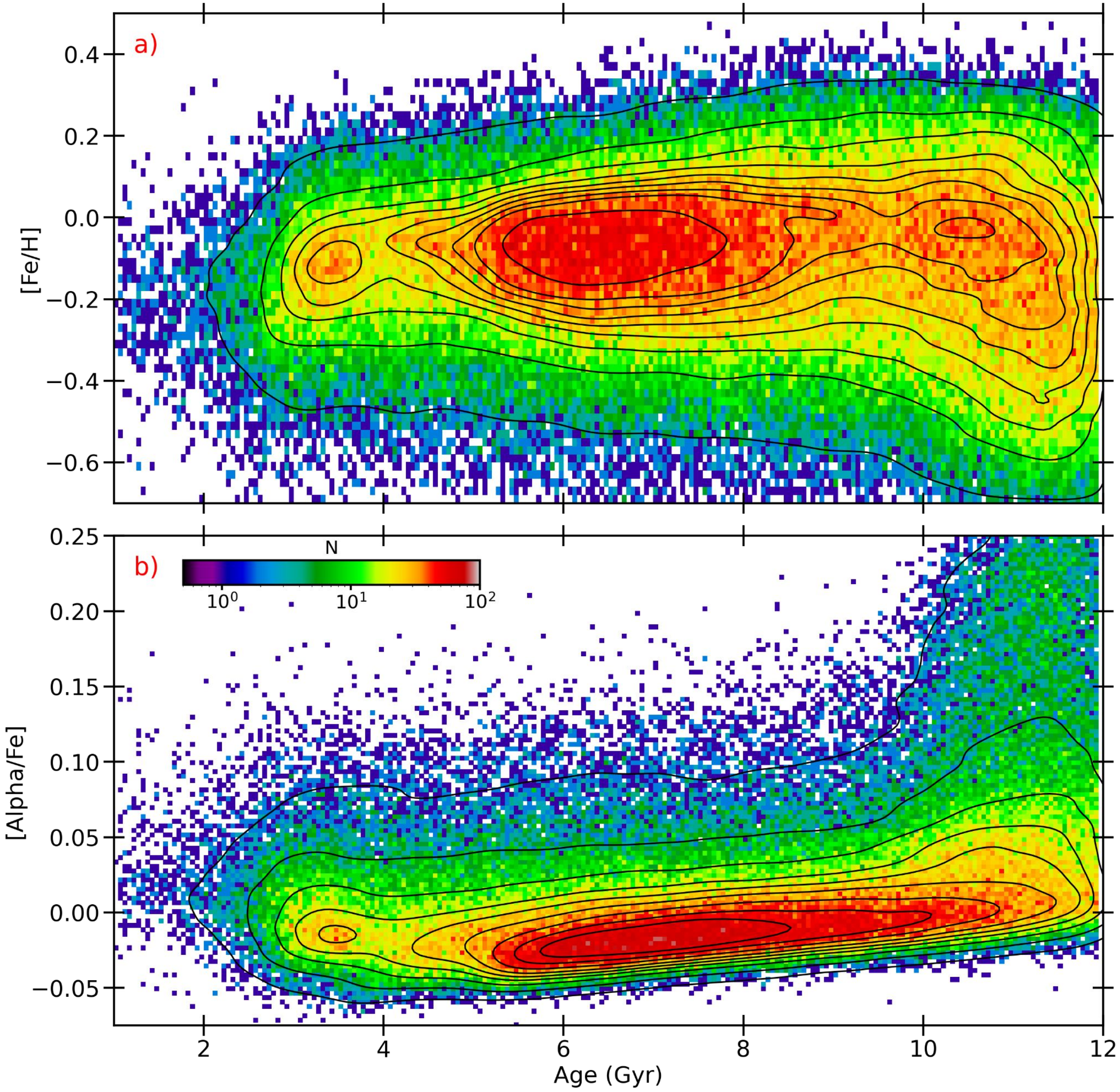


Similar trend seen with the asteroseismic sample of Miglio+2021



Star Formation in the disc triggered by bar?

- Age-metallicity relationship shows a SF peak, between 4 to 3 Gyr corresponding to high bar activity.
- Mixing and strong gas inflow due to bar lowers the [Fe/H] while [α/Fe] increase due to intense SF.



Main Conclusions:

The old thin disc: **(Nepal et al. 2024b in press)**

- MW has an old metal-poor disc (with over 50% being older than 13 Gyr).
- MW thin disc starts forming within the first Billion year with metal-poor to super-solar [Fe/H].
- high-[α/Fe] thick disc σ_{Vz} as 35 km/s, the low-[α/Fe] disc at same age range has a σ_{Vz} lower by 10 to 15 km/s. Our old thin disc appears similar to those estimated for the high-z disc galaxies.
- Using StarHorse ages, we extend the [Y/Mg] chemical clock to the oldest ages.
- The Splash includes both old (> 9 Gyr) high-and low-[α/Fe] populations and extends to a wider [Fe/H] range reaching super-solar [Fe/H].

The young bar: **(Nepal et al. 2024b in press)**

- The super-metal-rich stars arrange themselves in guiding radius space and are good traces of bar resonances.
- After the high peak of ~0.4 dex at ~10 Gyr, a sharp drop at ~3 Gyr in seen in [Fe/H] envelope. Bar mechanism bringing SMR stars from inner Galaxy to solar neighbourhood en masse has ceased.
- A SF burst triggered by high bar activity 4–3 Gyr at sub-solar [Fe/H] and enhanced [α/Fe].

Extra Slides

The oldest thin disc of Milky Way: (Nepal et al. 2024b in press)

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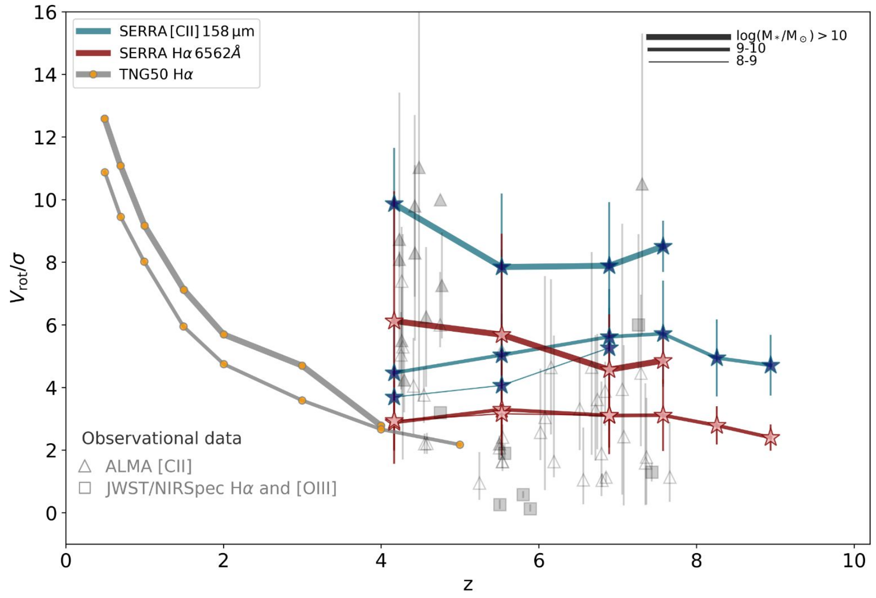
Early disc formation is still considered a challenge in cosmological simulations !!

(e.g. See Hopkins+2023)

But progress is being made



Kohandel et al 2023 (SERRA)
(see also e.g. Tamfal+2022, Kretschmer+2022)

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THE ASTROPHYSICAL JOURNAL, 928:106 (15pp), 2022 April 1 Tamfal et al.

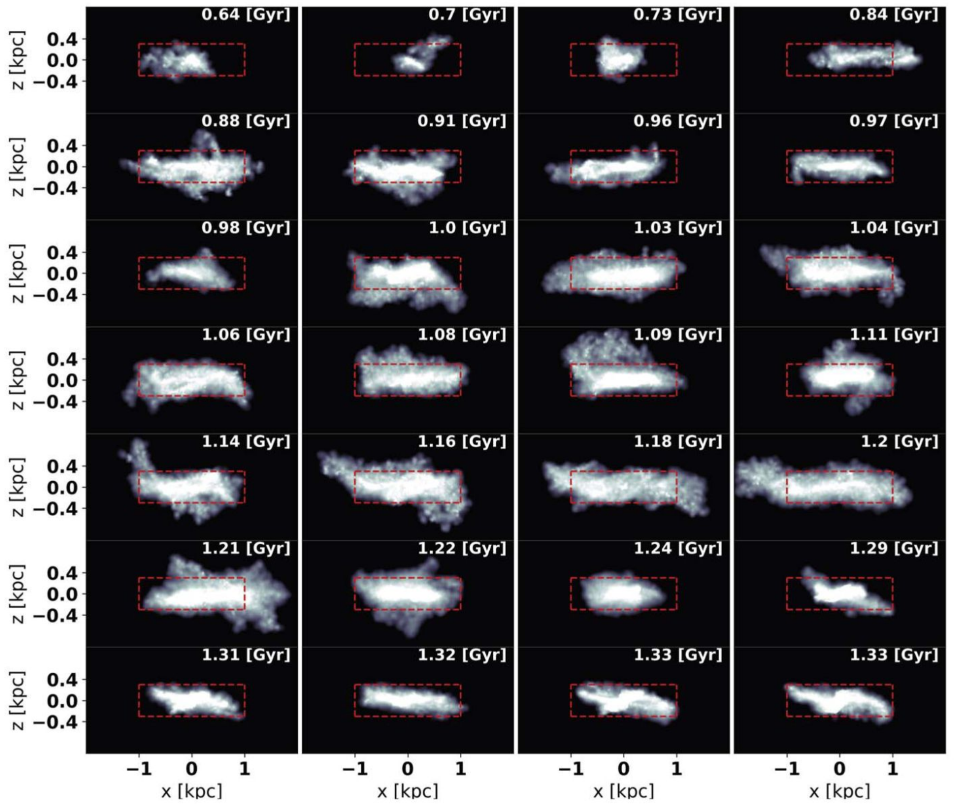
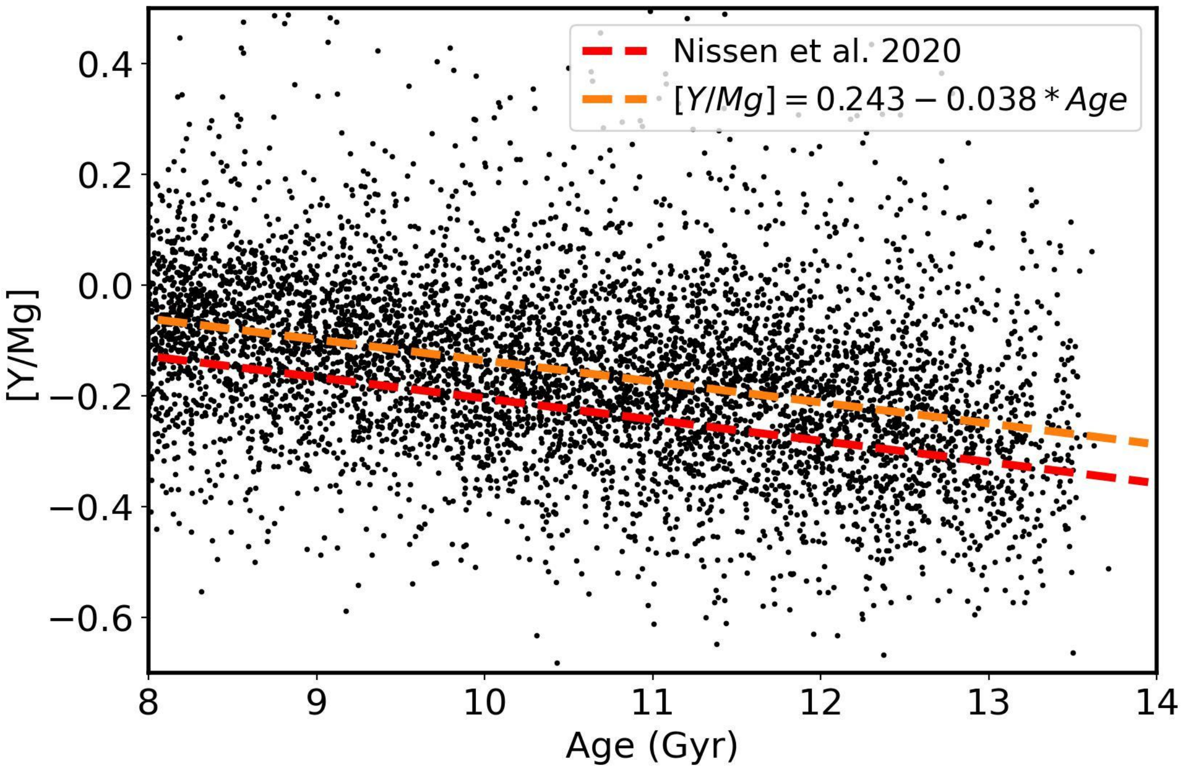


Figure 11. Surface density of the newly born stars (edge on) of the main GIGAERIS galaxy as a time sequence. The thin disk appears to exist in every snapshot, although we can observe a slight warp in some cases. The red box indicates a height of 600 pc and a width of 2 kpc.

Tamfal+2022
(see also e.g. Kretschmer+2022)

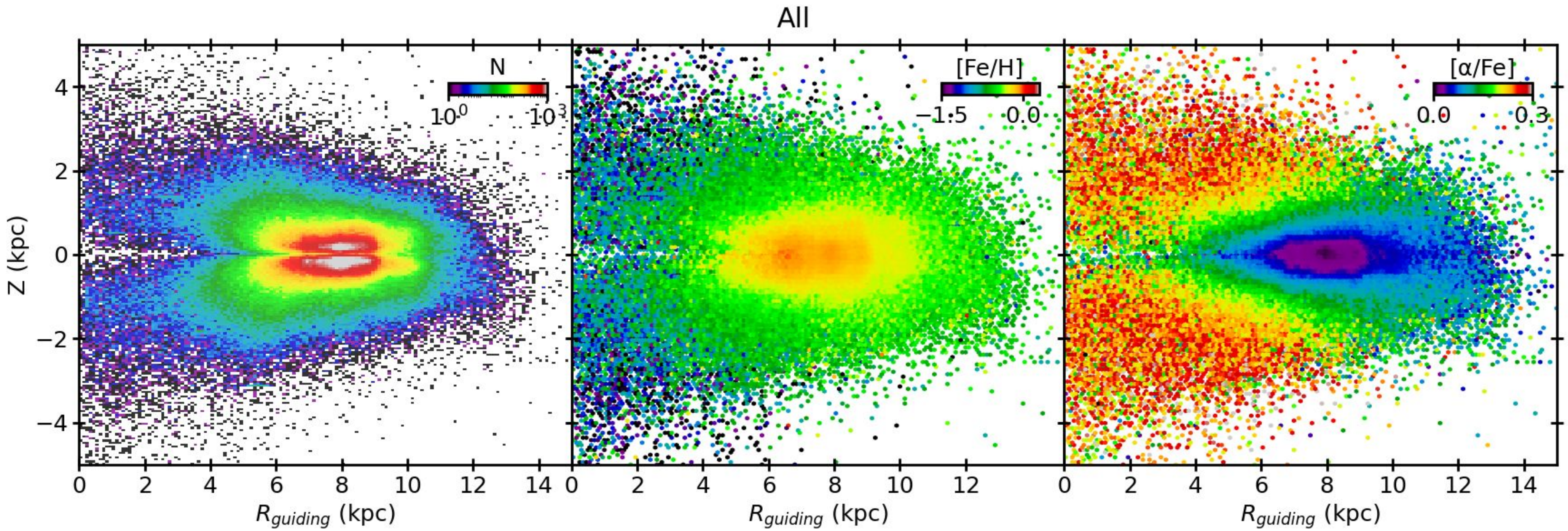
Validating ages: Chemical clock relation



Nepal et al. 2024b (in press)

We extend [Y/Mg] chemical clock to oldest ages.

The data:


All
N
10^0
10^3
[Fe/H]
−1.5
0.0
[α/Fe]
0.0
0.3
Z (kpc)
4
2
0
−2
−4
0
2
4
6
8
10
12
14
$R_{guiding}$ (kpc)
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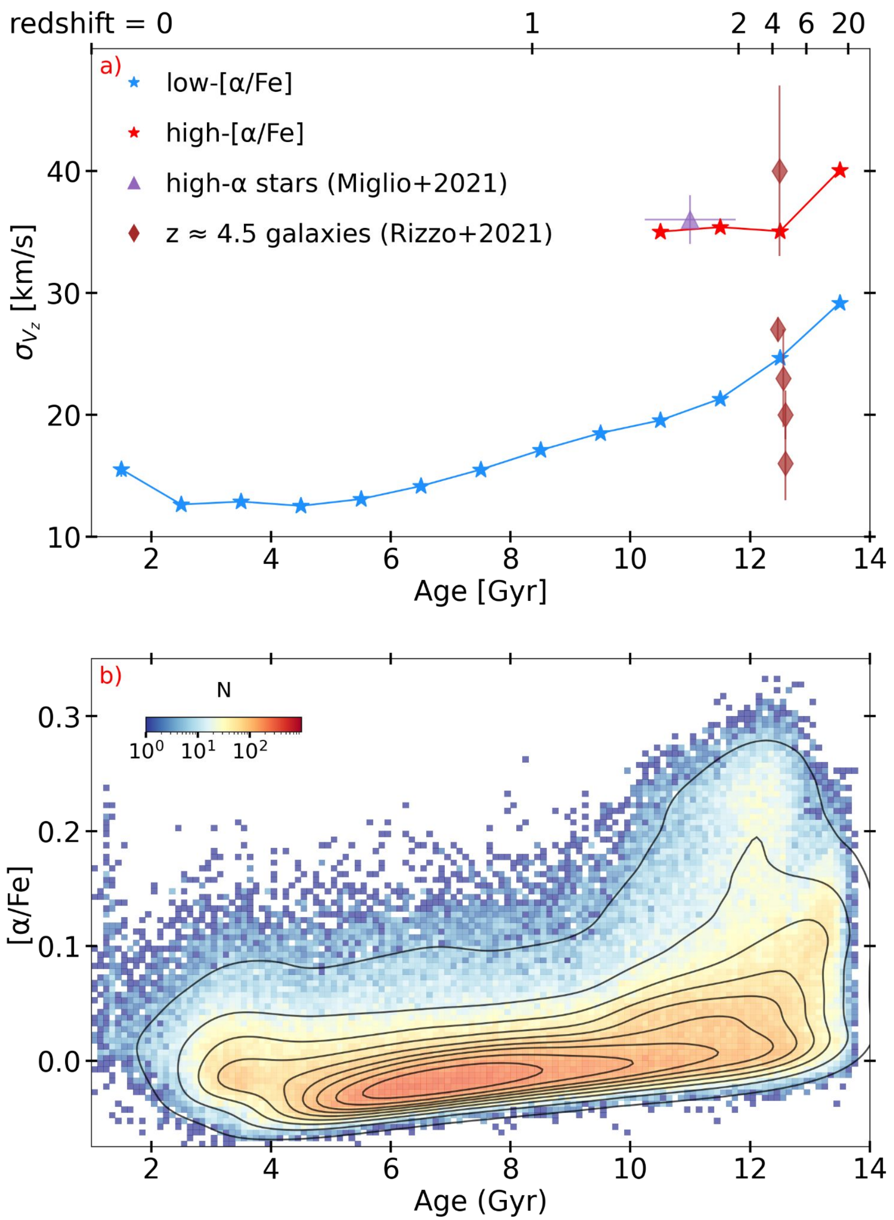
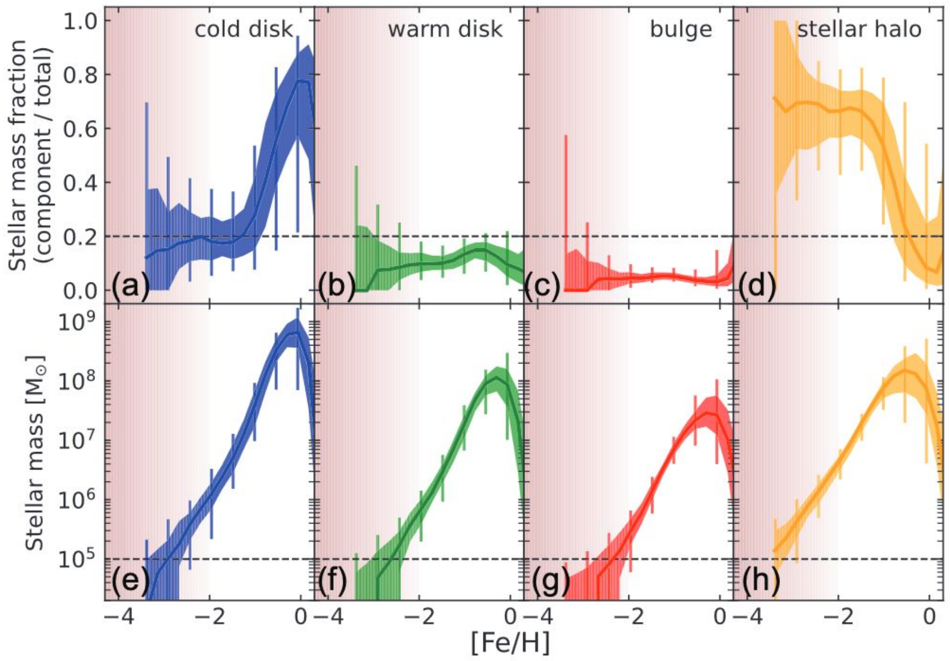
high-z discs of MW: (Nepal et al. 2024b in press)

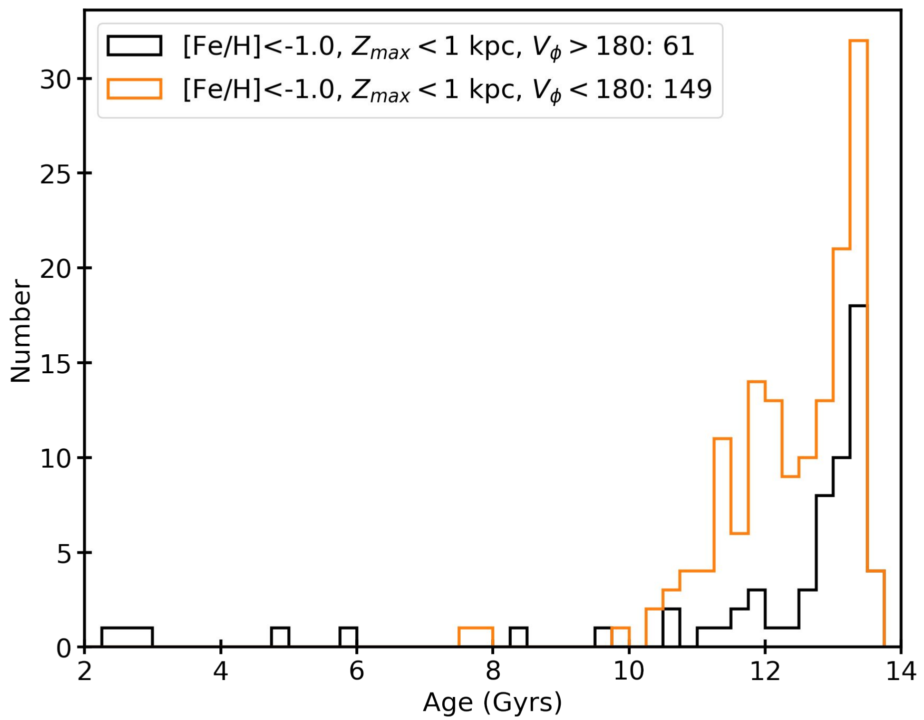


The metal-poor thin disc:



Sotillo-Ramos+2023

~20% of the VMP stars belong to the disc & ~50% are older than 12.5 Gyr



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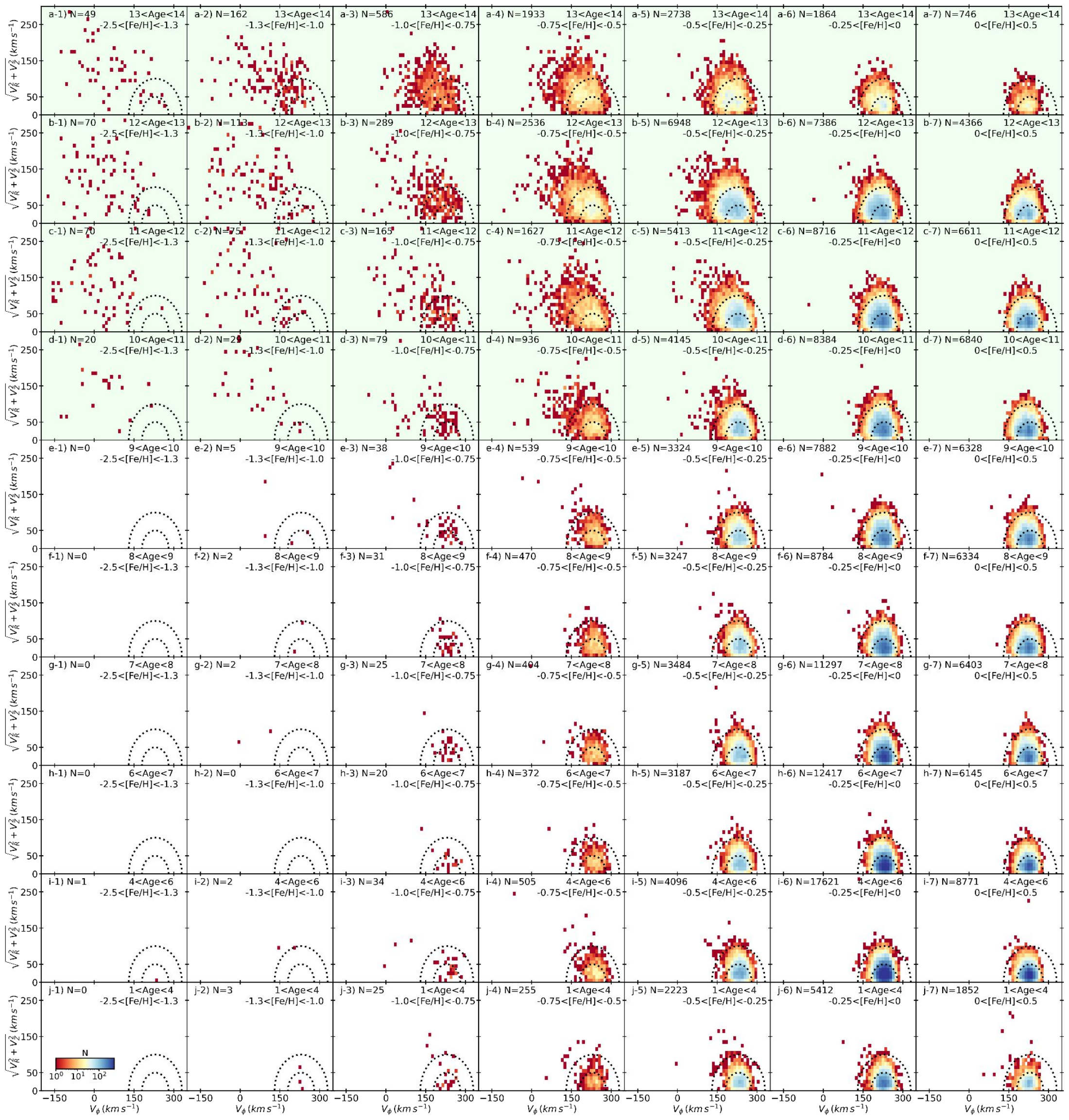


Metal-poor to Metal-rich

Efforts in high-z for disc thickness:

The Astrophysical Journal Letters, 960:L10 (7pp), 2024 January 10 Lian & Luo

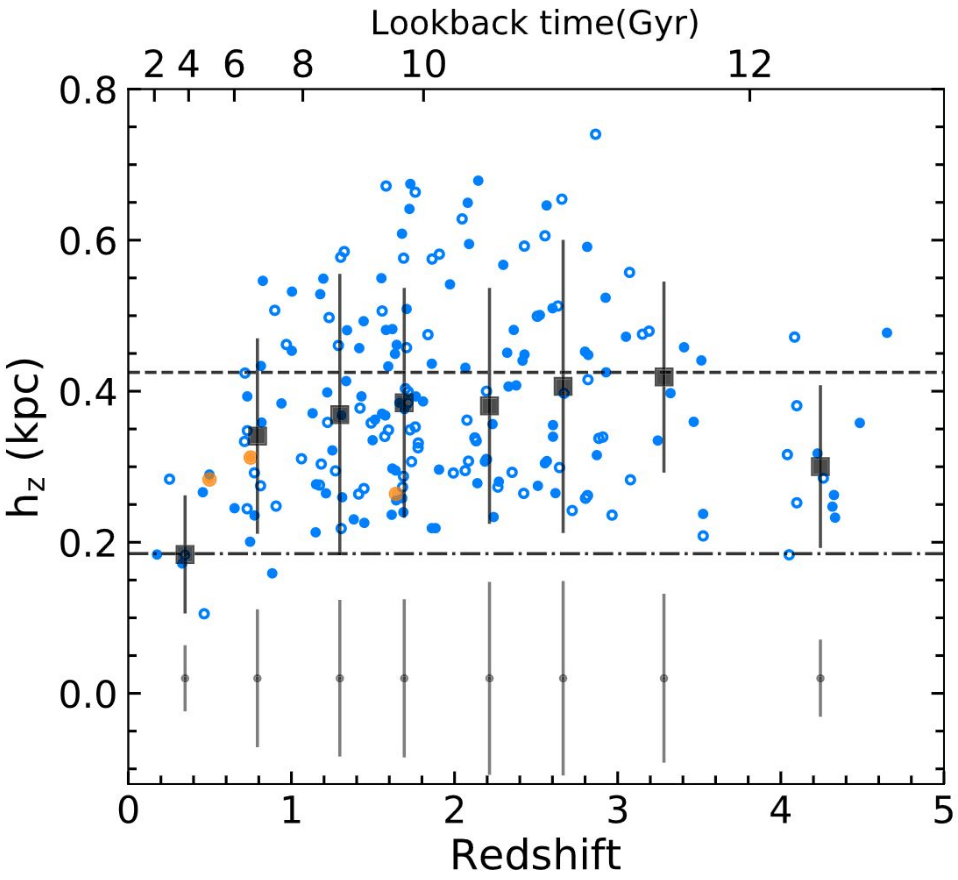
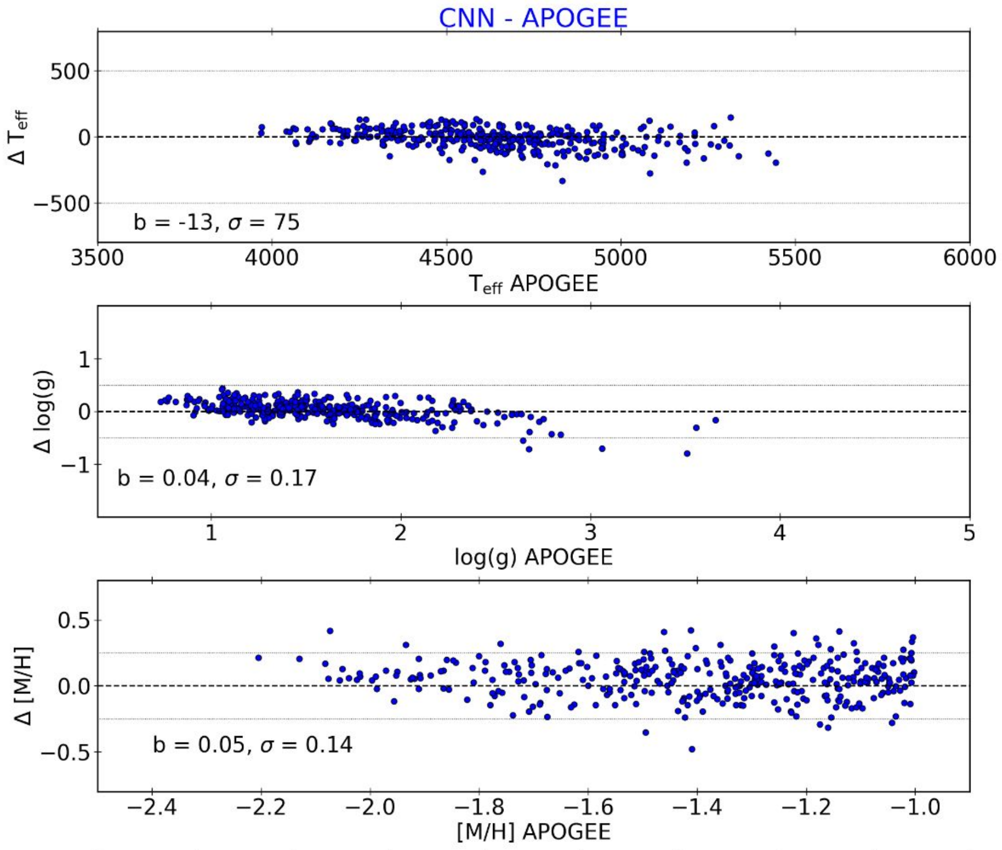


Figure 4. Redshift evolution of galaxy disk thickness. Small blue circles indicate the sech^2 scale height measurements of individual edge-on galaxies with only a photometric redshift estimate and orange circles for those with spectroscopic redshift. Filled circles are the galaxies with a valid uncertainty estimate and empty circles are those without. The level of uncertainties is shown at the bottom in gray. Enlarged black squares and error bars show the median scale length and 1σ scatter at each redshift bin with a bin width of 0.5 at $z < 3$ and a bin width of 1 at $z > 3$. The converted sech^2 scale height of the Milky Way's thick and thin disks are denoted by the dashed and dashed–dotted lines, respectively.

Thick or thin disc first?

Improving Performance of Spectroscopic Surveys with Machine Learning

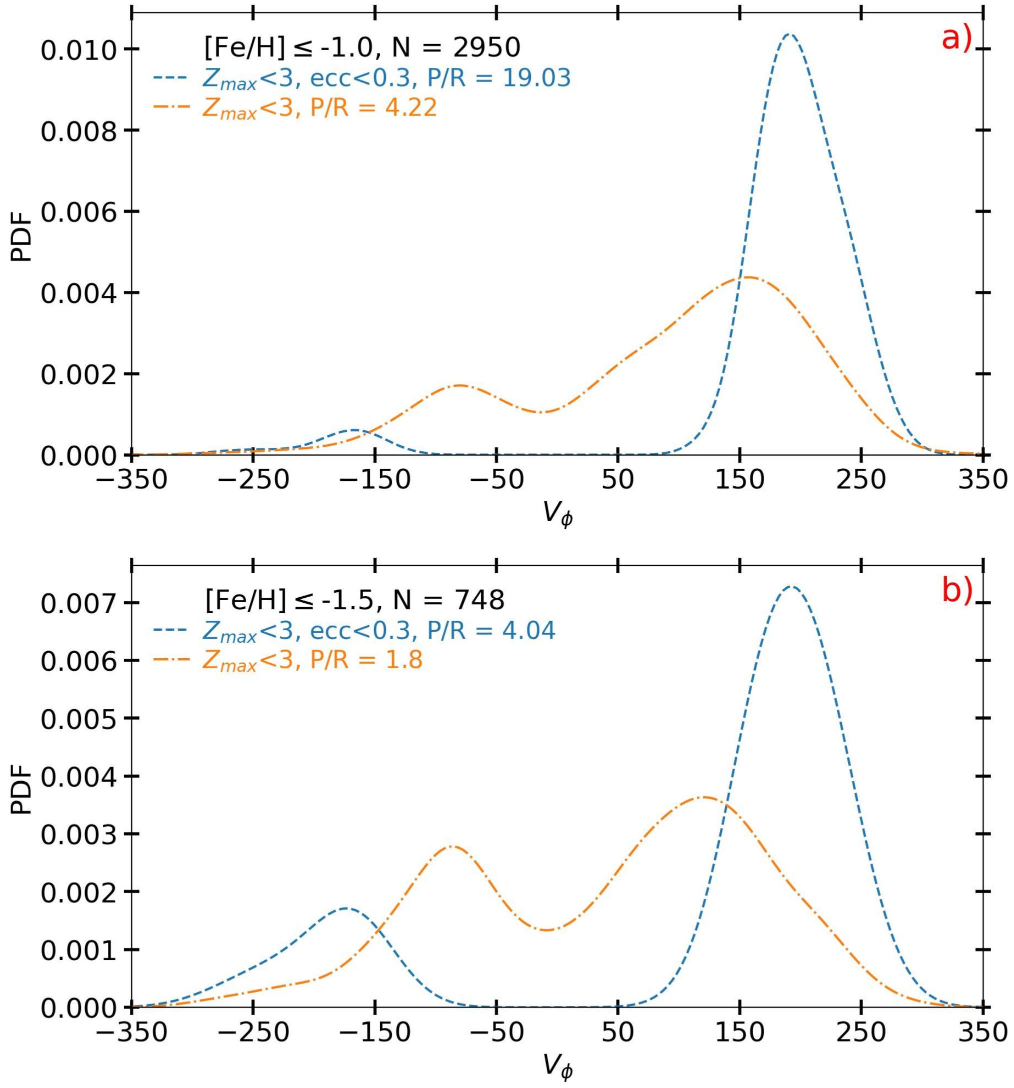


Guiglion et al. 2024

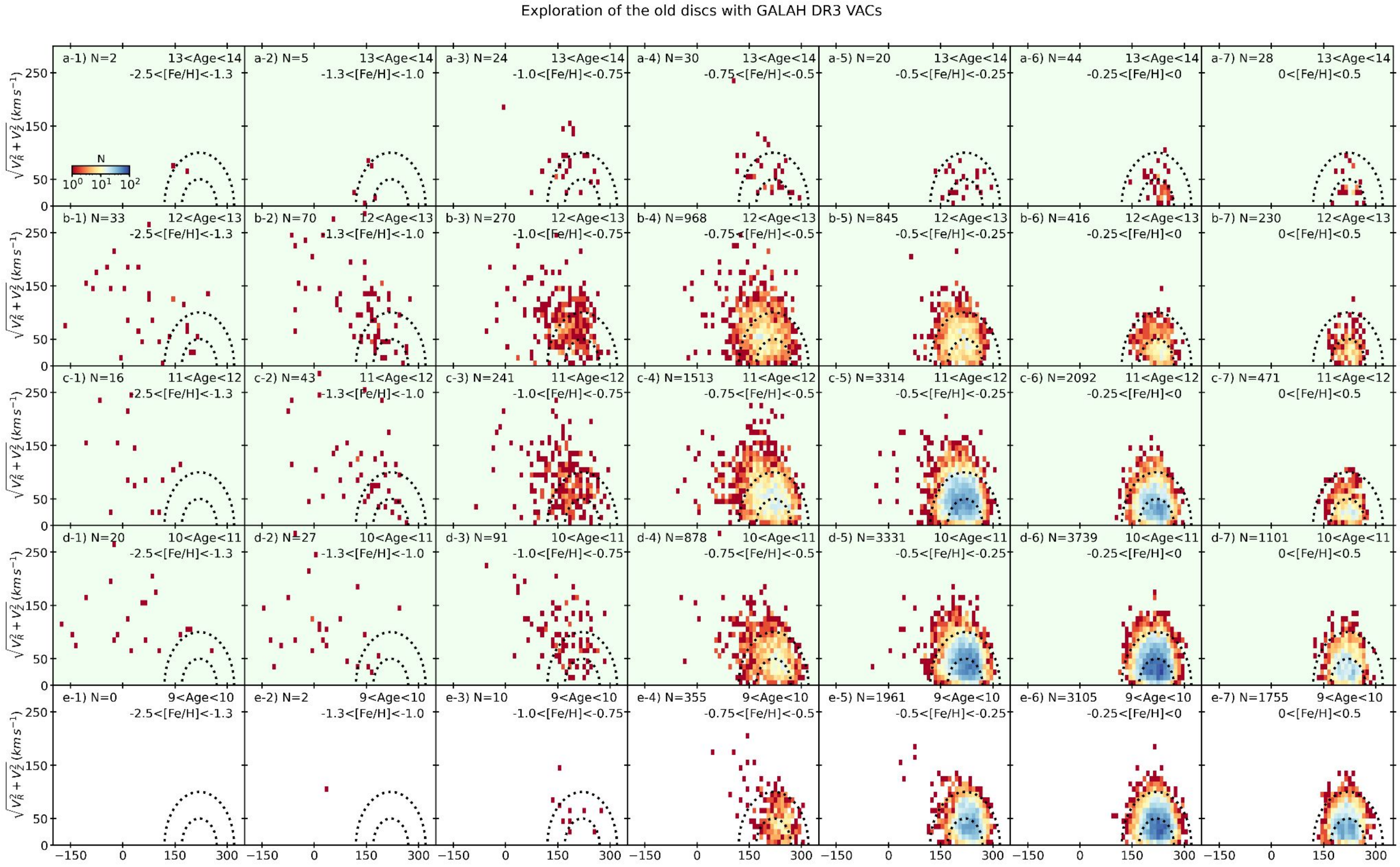
Robust results in the low S/N and [Fe/H] regime!

15 < S/N < 25 & [Fe/H]<-1.0

Appendix plots:



Appendix plots:



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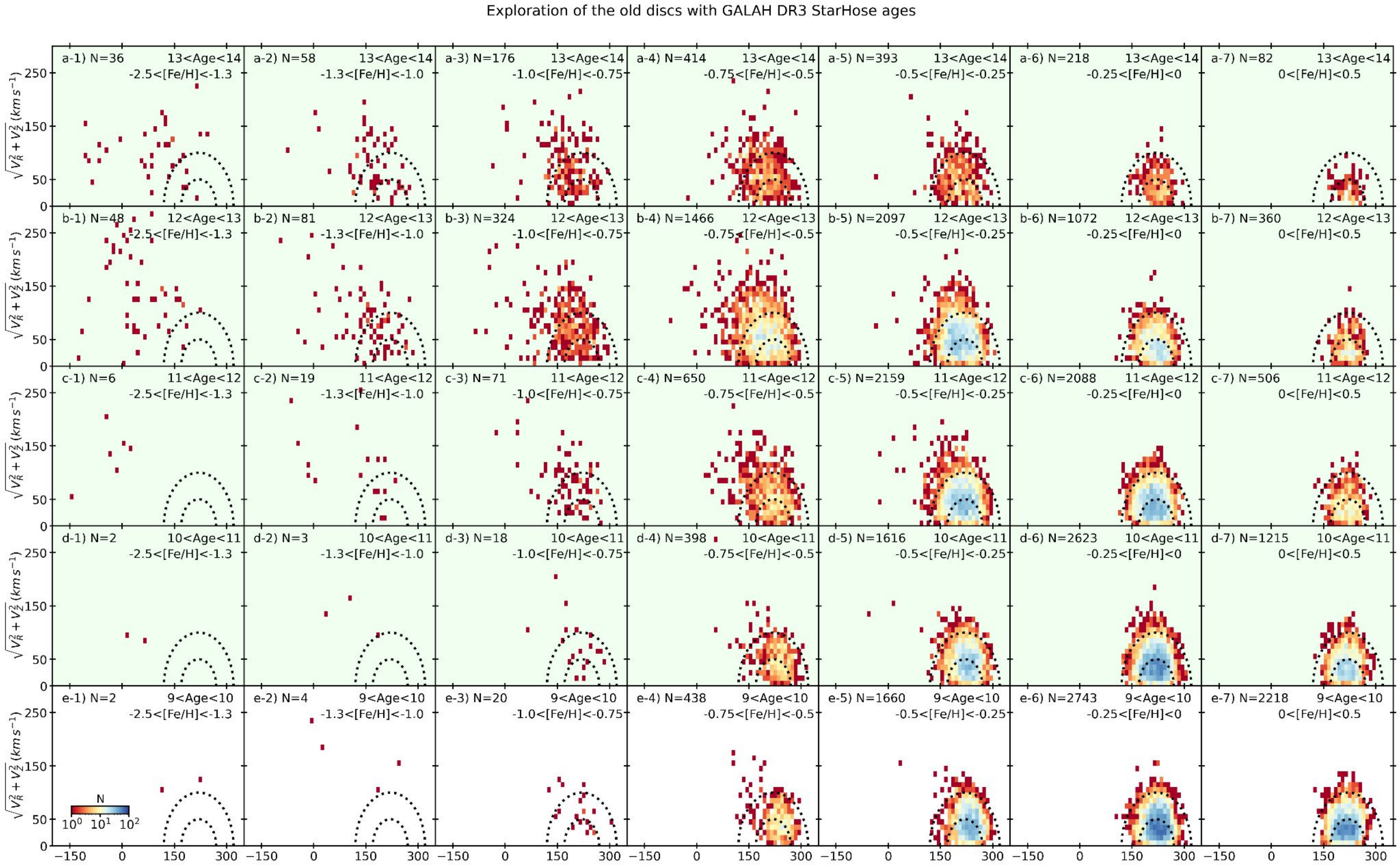
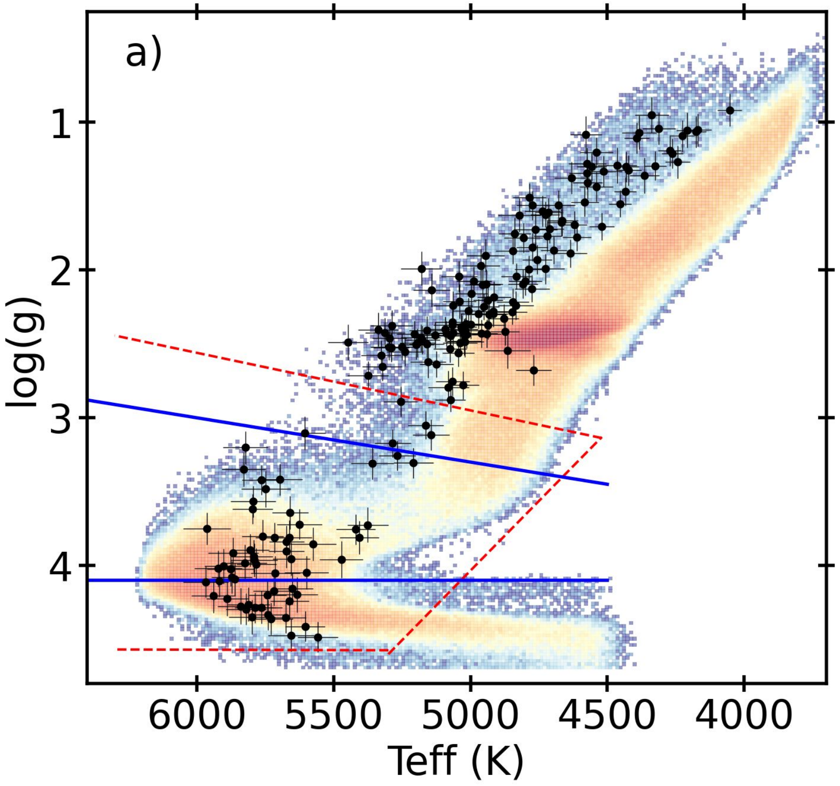


Old discs with strict selection:



Sample is reduced by half to about 100,000