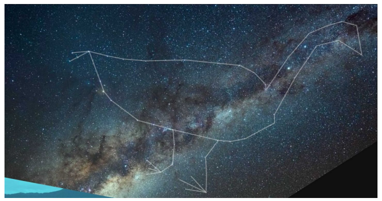
From metal-poor to metal-rich: new insights on MW disc history with machine learning and gaia

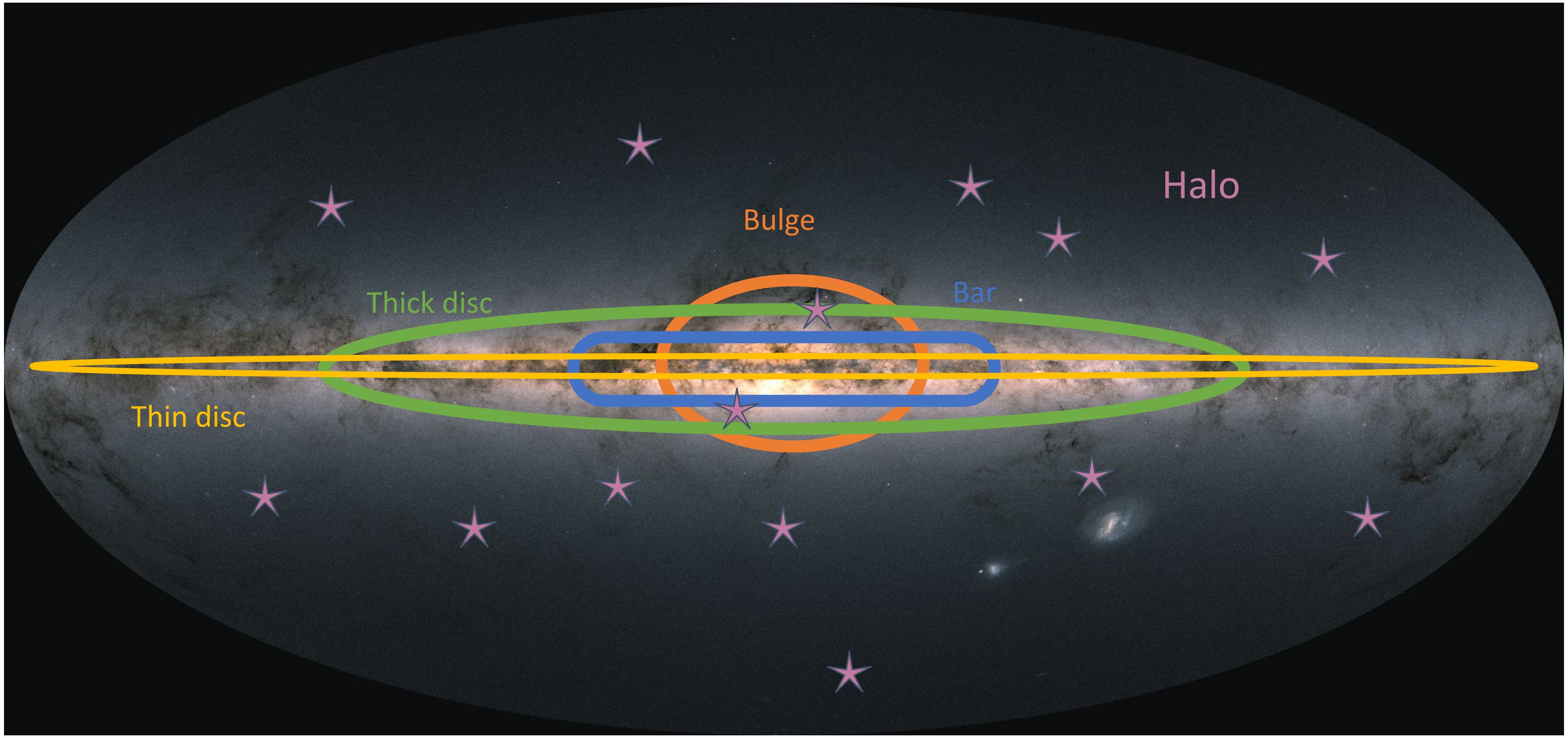
Samir Nepal (PhD Student)

In collaboration with:
Cristina Chiappini (AIP), Matthias Steinmetz (AIP), Guillaume Guiglion(ZAH/LSW), Anna Queiroz(IAC), Josefina Montalbán(UB), Andrea Miglio(UB), Friedrich Anders (ICCB), Arman Khalatyan(AIP), Angeles Pérez-Villegas(UNA), and others



IAUS395 – Stellar Populations, Paraty, Brazil
Date: 19 November, 2024

The classical view of the Milky Way:



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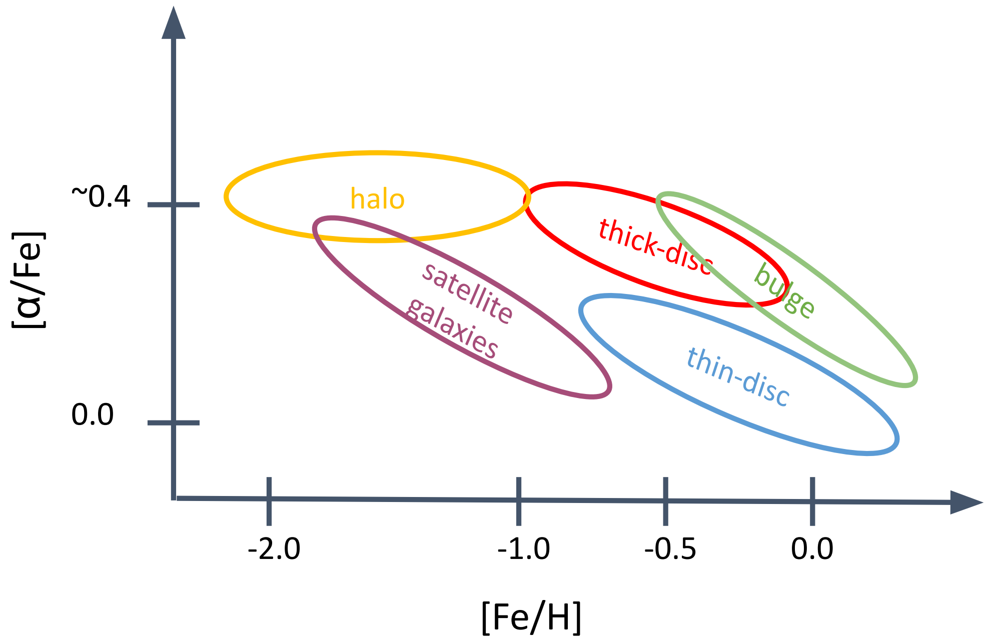
What is the formation mechanism, relation between the various components and origin epoch?

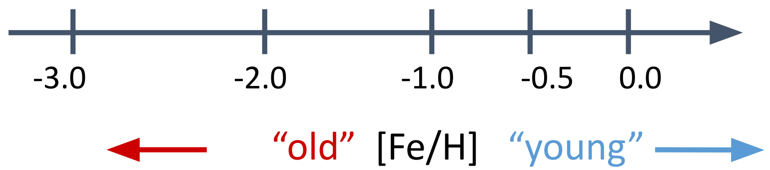
How do we trace Milky Way's history ?



- Stars are luminous story tellers of our Galactic Saga.
- Chemical abundances of a Star's outer layers is preserved from birth (almost).
  (Photospheric chemistry = ISM composition at T_{birth})
- Different stellar populations also retain their formation history in their motions.
- Relative abundances of different populations inform us about star-formation in various parts of our Galaxy. (e.g. Matteucci and Brocato 1990)

How do we trace Milky Way's history ?

Metallicity as proxy for age



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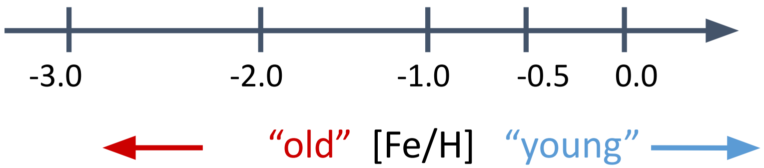
How do we trace Milky Way's history ?

Are only the metal-poor stars
exclusively old?
or
Is it always metal-poor ⟶ old &
metal-rich ⟶ young ?



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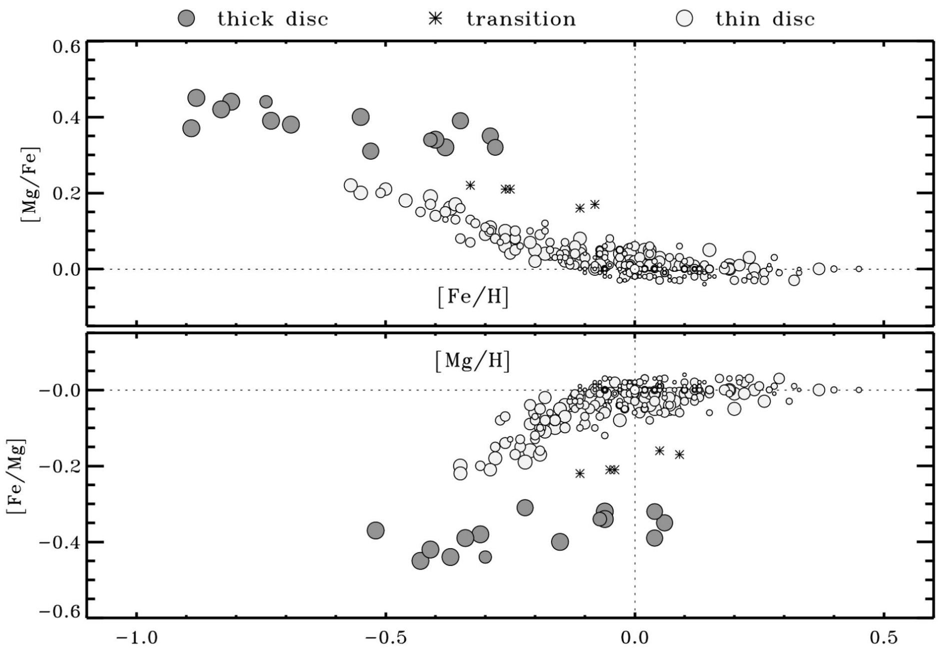
How do we trace Milky Way's history ?

Diversity in our local neighbourhood (25pc)



Klaus Fuhrmann, 2011

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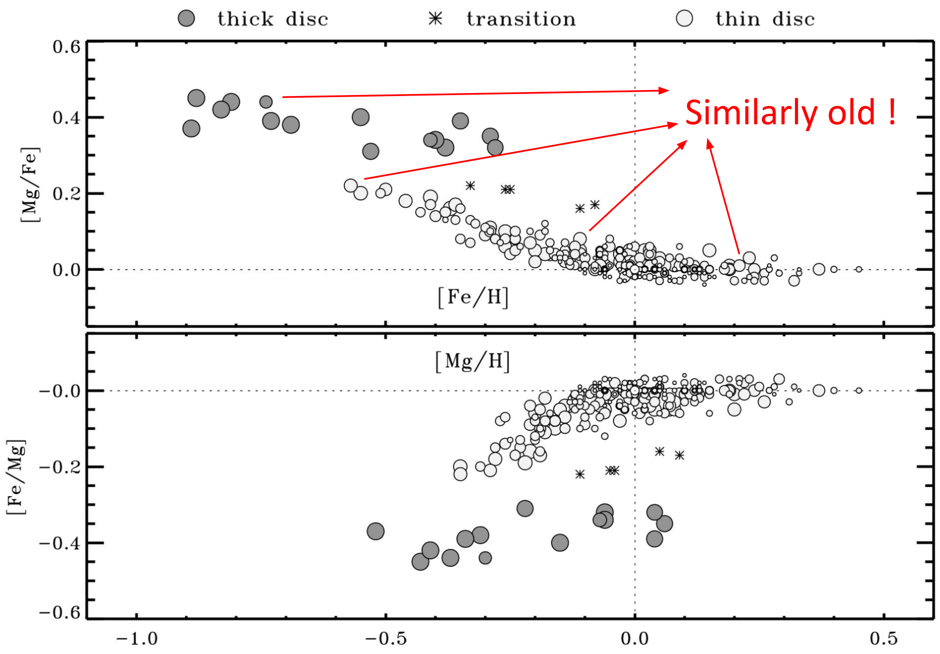

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  (there could be significant overlap in chemistry and/or kinematics)

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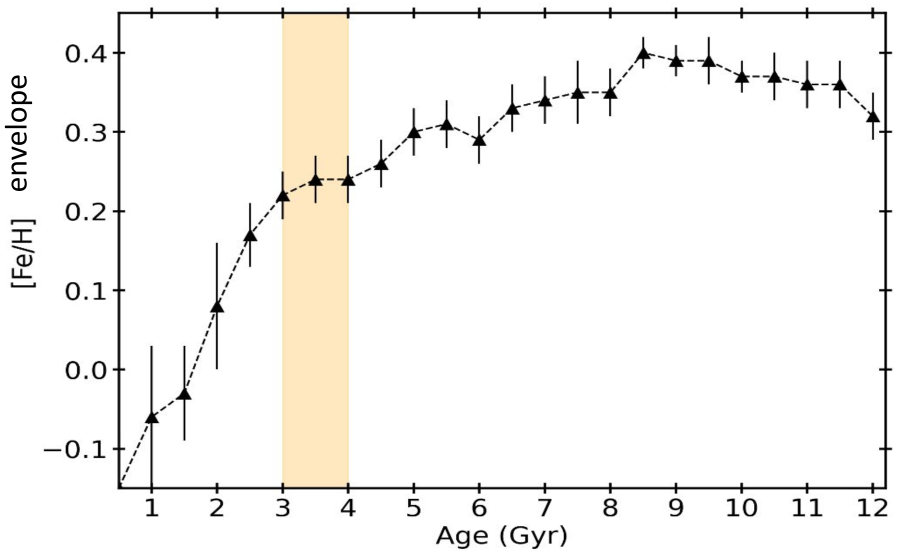

Nepal et al. 2024a

Stars in solar neighbourhood (~1 kpc) show the peak metallicity reached already at ~9-10 Gyrs ago.
See also: e.g. Miglio+2021, Dantas+2023

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How do we trace Milky Way's history ?

Things we need:

Chemical Composition
+
Positions and Kinematics
+
Ages

for a large number of stars (>10^6) are necessary for the complete picture.

How do we trace Milky Way's history ?
- The big data

More by Guillaume in session 6.

- 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)
  Note: Only possible with novel machine learning technique esp. low S/N spectra

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- StarHorse: a bayesian isochrone fitting tool to estimate distances, extinctions, stellar ages etc. for individual stars (e.g. Anders et al. 2019,2022, Queiroz et al. 2018,2020,2021,2023)

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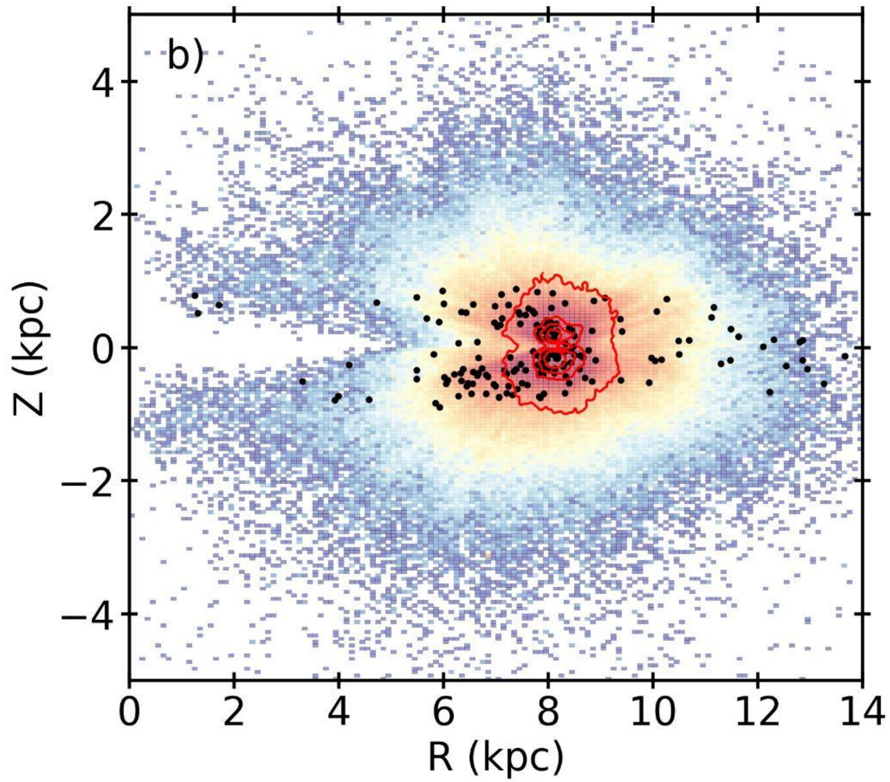
- 6D phase-space + StarHorse distance → Velocities and orbits using Astropy & Galpy
  (McMillan 2017 potential).

The big 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.



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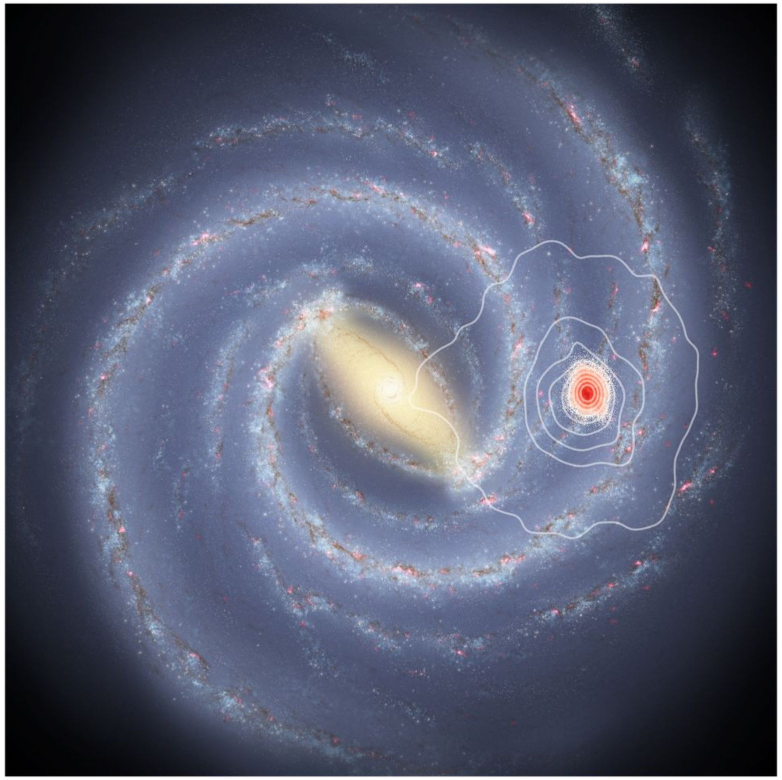
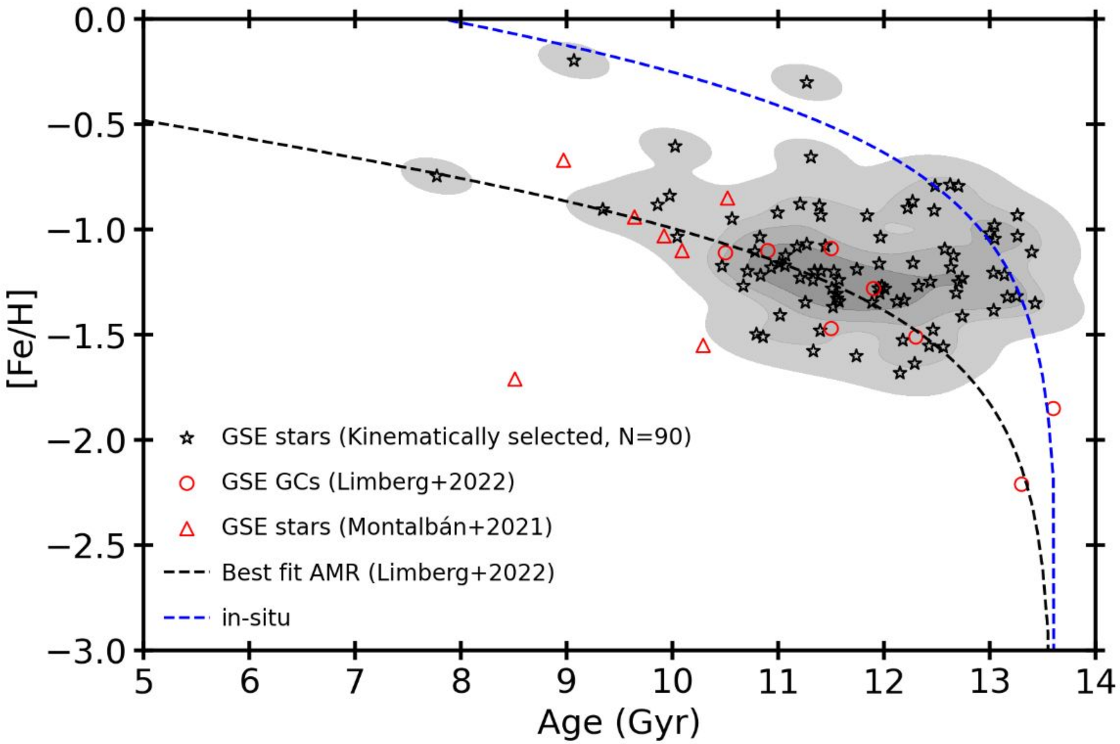


Validating ages: AMR for confirmed GSE members

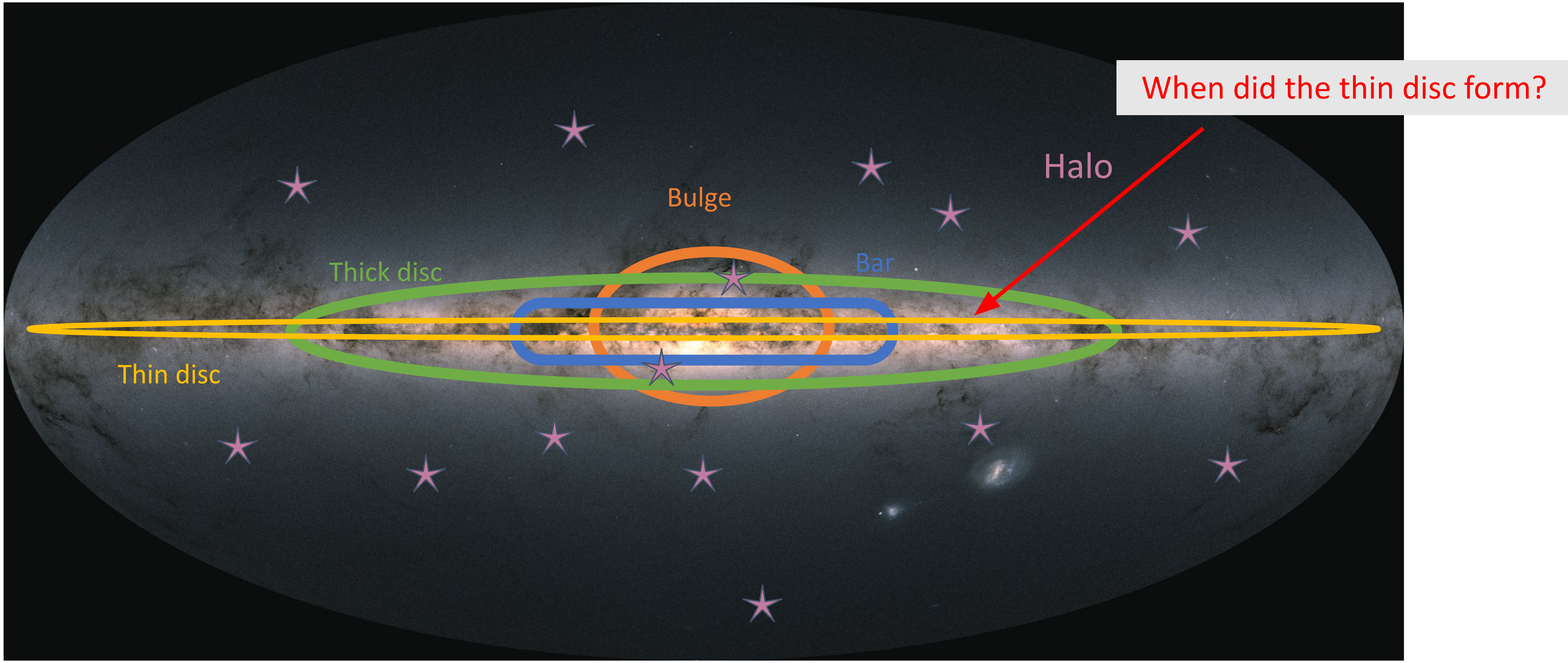


Nepal et al. 2024b

We recover the age-[Fe/H] relation for the GSE candidates confirmed with the GSE globular clusters and member stars with asteroseismic ages. (selected in Lz vs E space)

Also yesterday's talks by Davide, Angeles and Stefano on GC age-metallicity relation.

The classical view of the Milky Way:



ESA/Gaia/DPAC; CC BY-SA 3.0 IGO. Acknowledgement: A. Moitinho.

What is the formation mechanism, relation between the various components and origin epoch?

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

- 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

Rowland et al. 2024

Discovery of a dynamically cold disc at z = 7.3 13

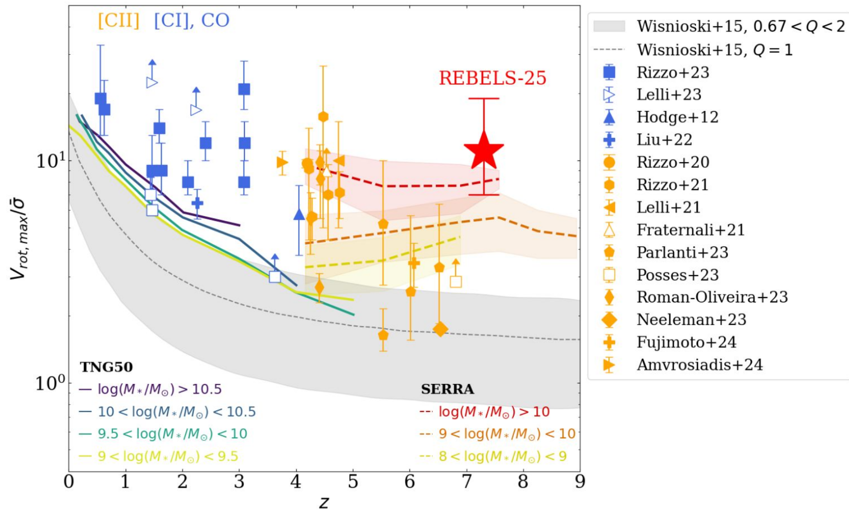


Figure 9. As with Figure 8, but instead the ratio of ordered to random motion (the ratio of the maximum rotational velocity to the average velocity dispersion) is plotted as a function of redshift.

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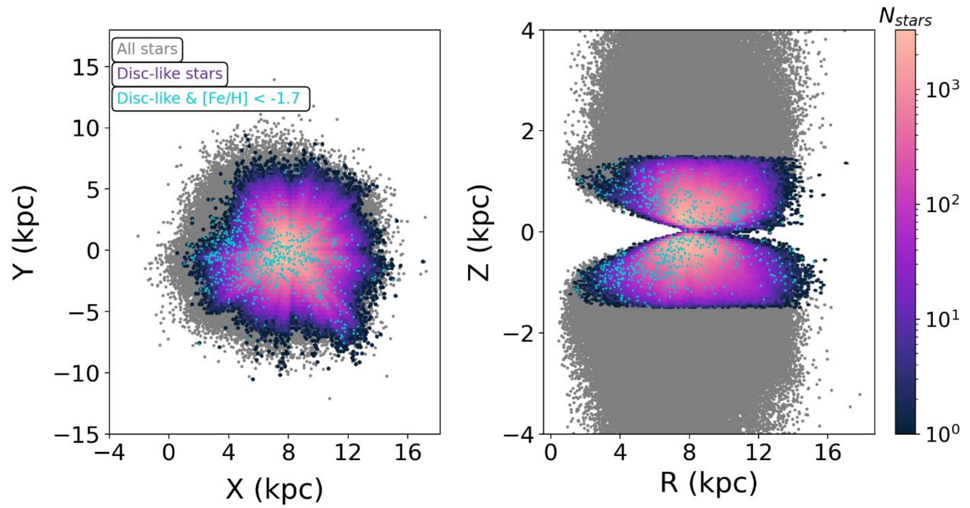
- In the MW, several recent studies show presence of metal-poor stars in disc orbits.
  Sestito et al. 2019, 2020; Fernández-Alvar et al. 2021; Mardini et al. 2022; Matsunaga et al. 2022; Carollo et al. 2023; Bellazzini et al. 2024; Fernández-Alvar et al. 2024; Re Fiorentin et al. 2024;

  But see Zhang et al. 2024



González Rivera+24

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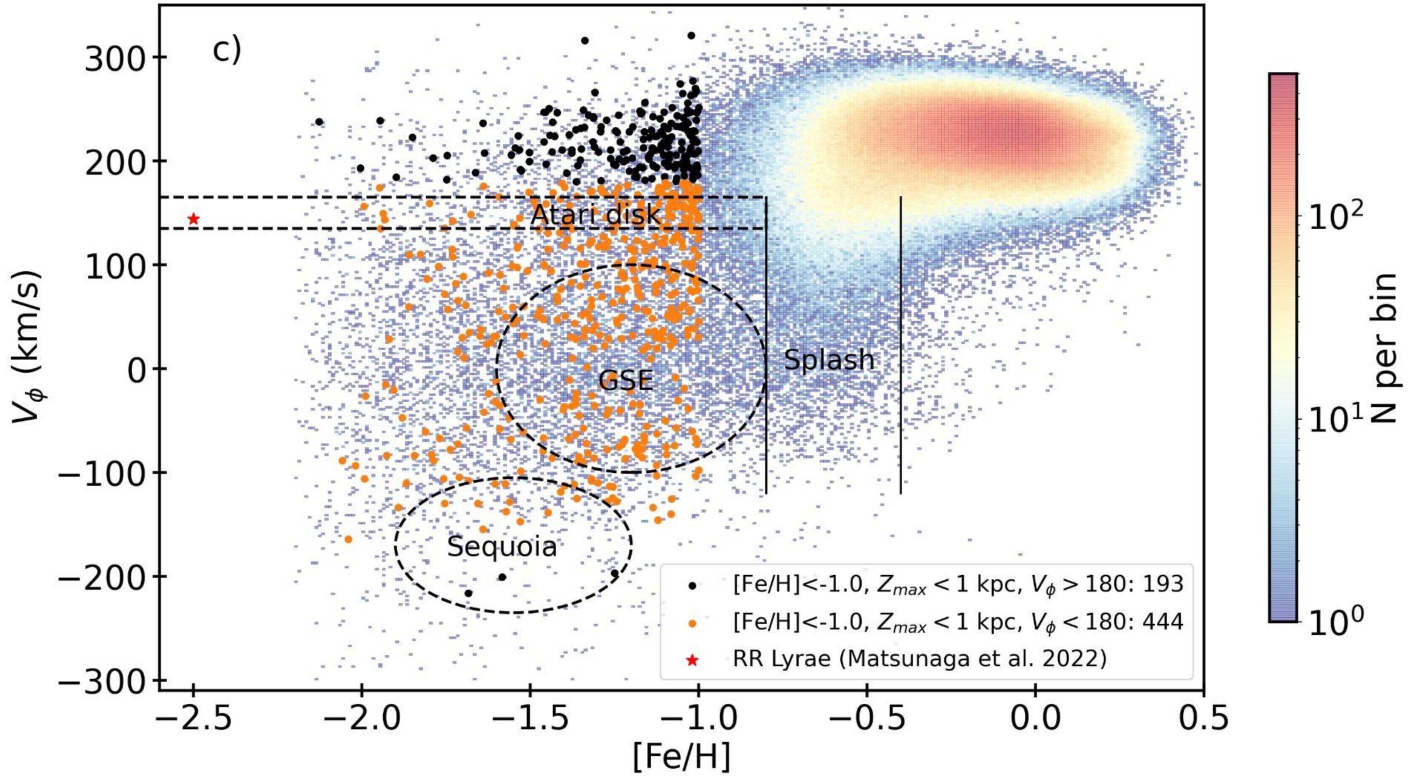
  But see Zhang et al. 2024

Key questions:

- Does Milky Way have an ancient disc?

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

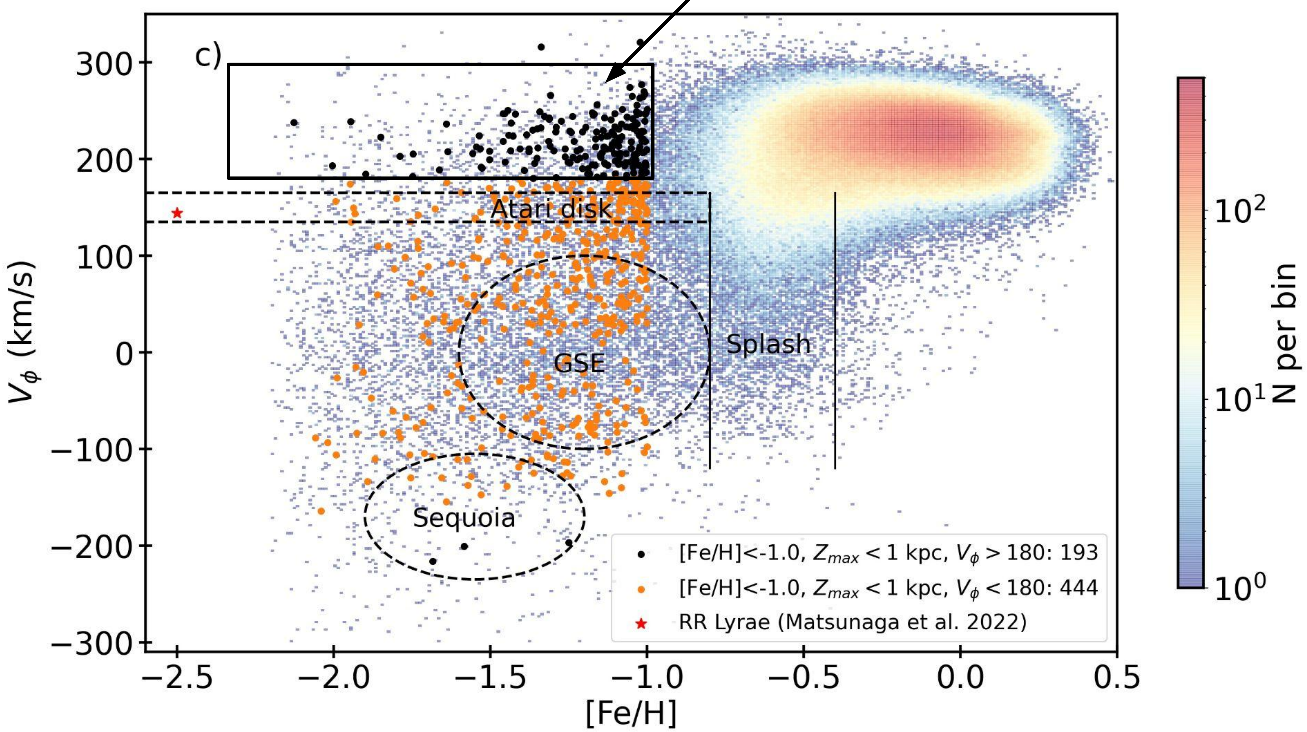
The metal-poor thin disc: (Nepal et al. 2024b)



We kinematically selected metal-poor stars to find large number of them in thin disc orbits.
(See also Fernández-Alvar et al. 2024)

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

Just edge of the velocity distribution?



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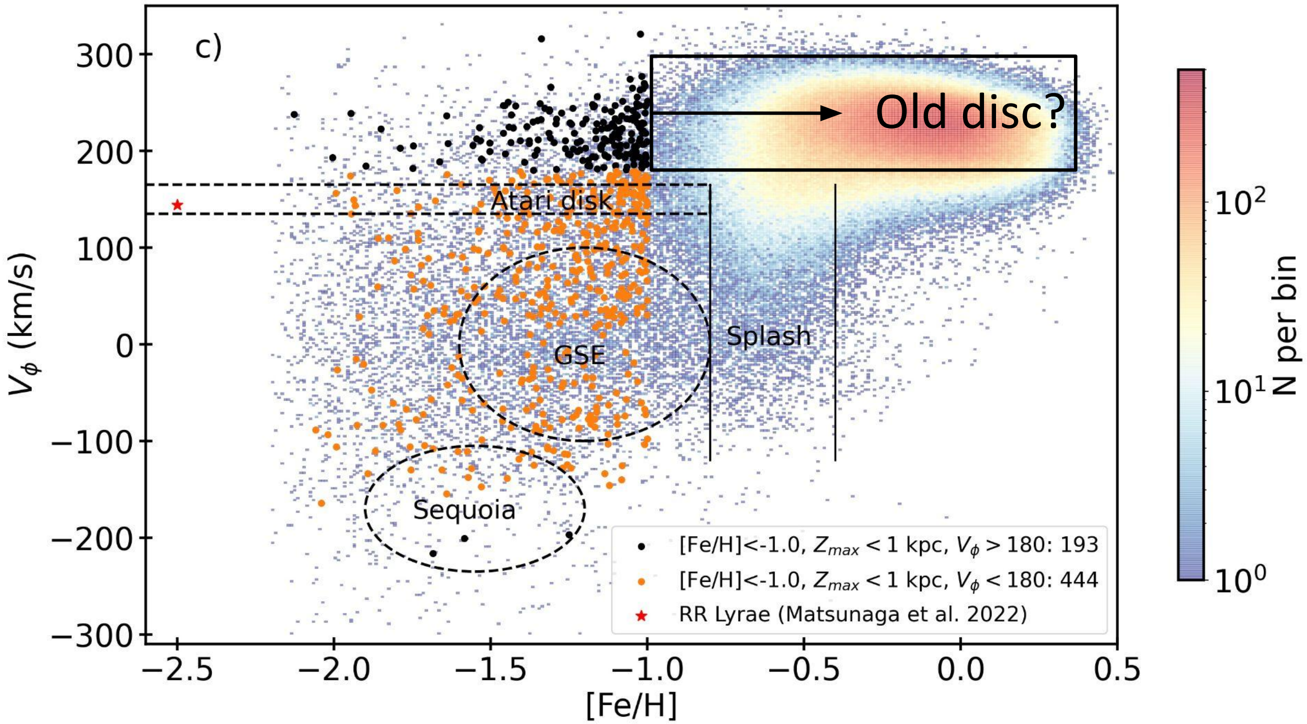
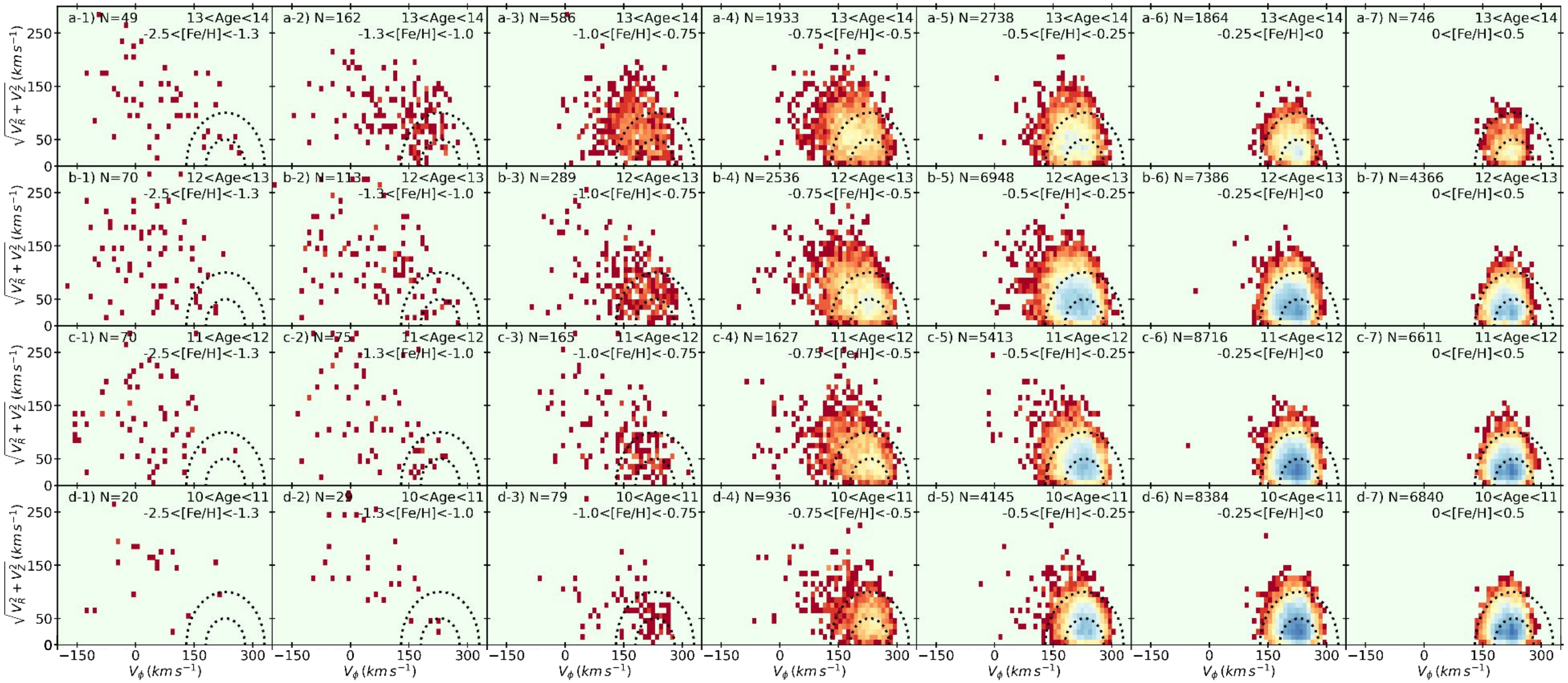


The oldest thin disc of MW: (Nepal et al. 2024b)



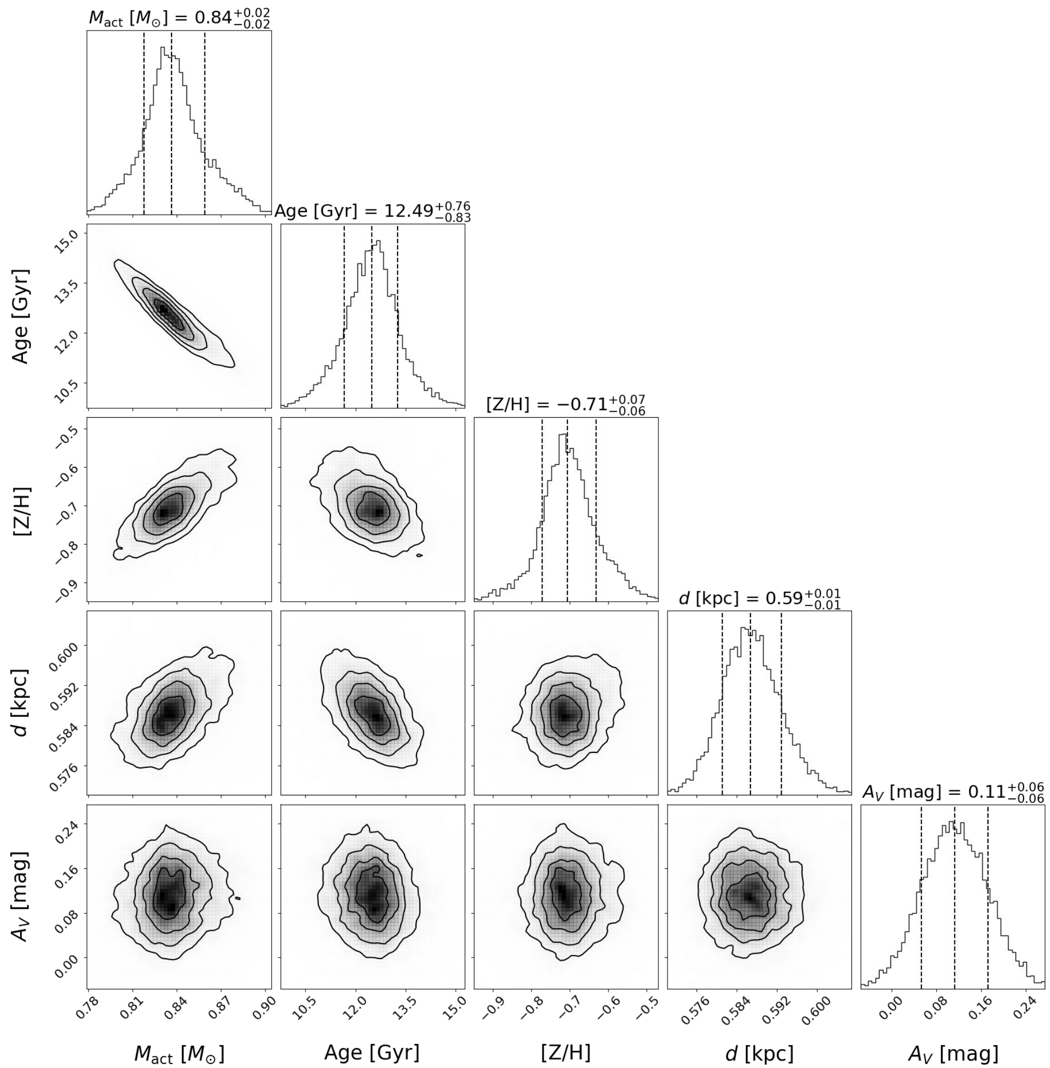
Old
to
Young

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.

Validating ages: Beautiful pdfs!

Nepal et al. in preparation
StarHorse catalog with age, distance, extinction, etc. coming soon…



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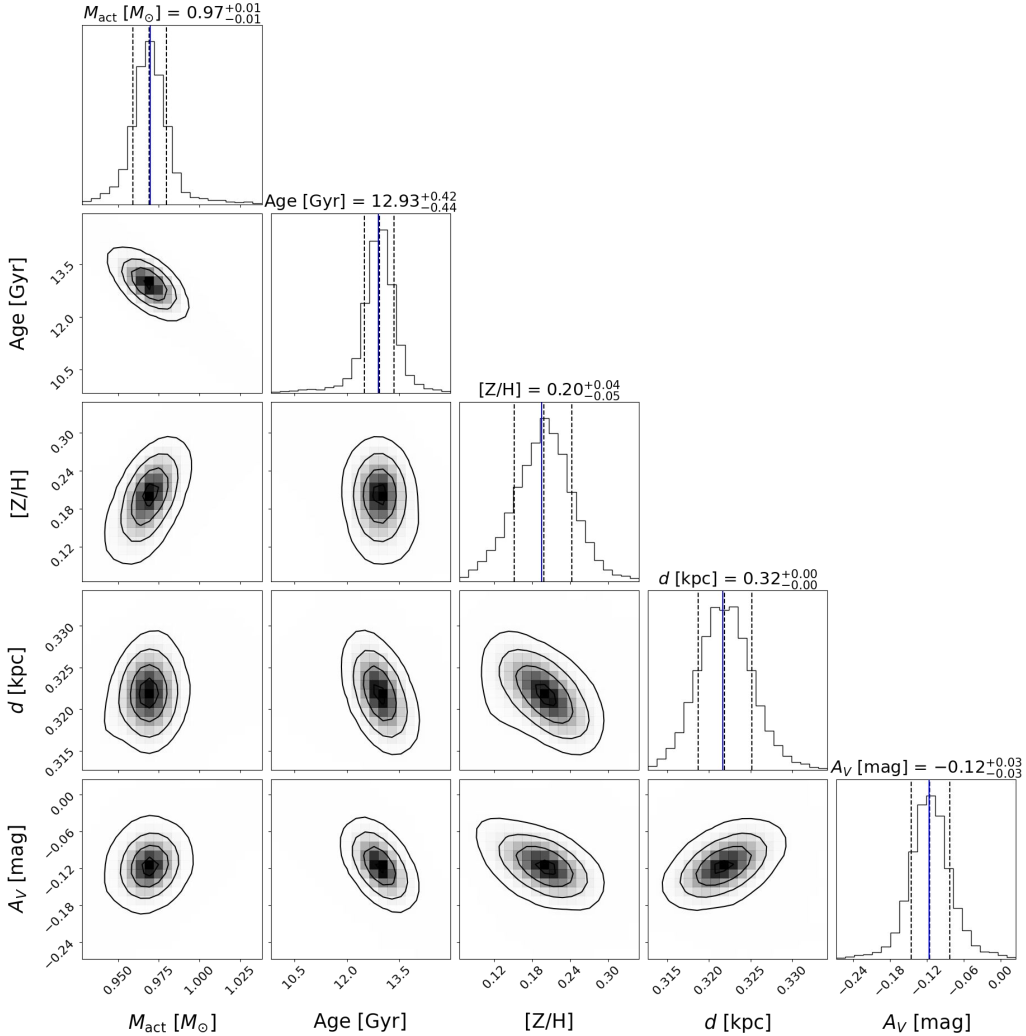

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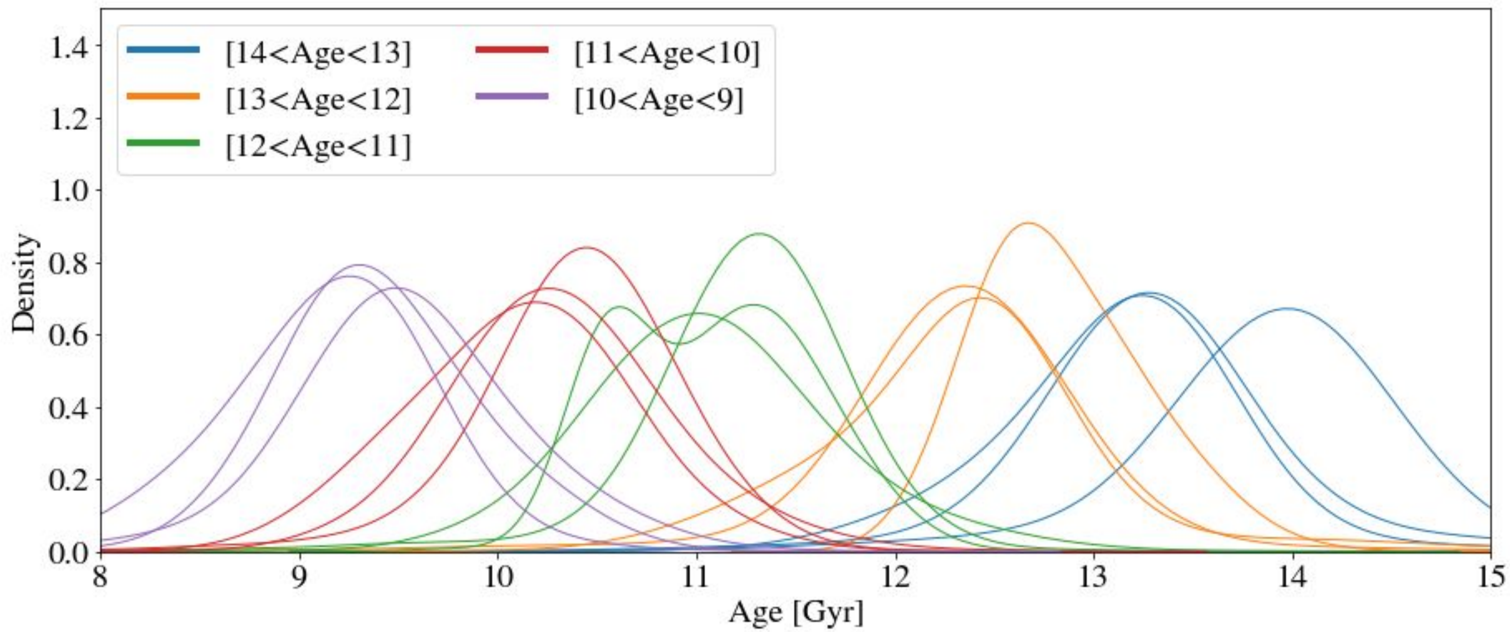
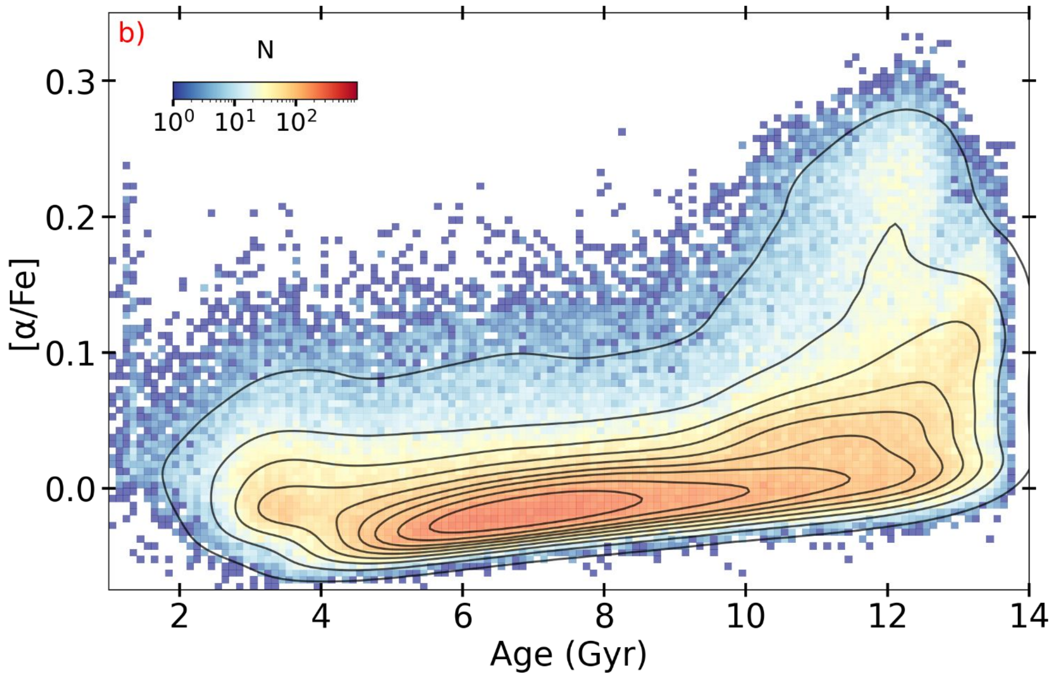


Ages are precise enough to differentiate between e.g. 10–11 Gyr and 11–12 Gyr!

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



high and low-[α/Fe] populations overlap in ages and show coeval thin and thick discs.

More work needed with detailed chemical abundances!

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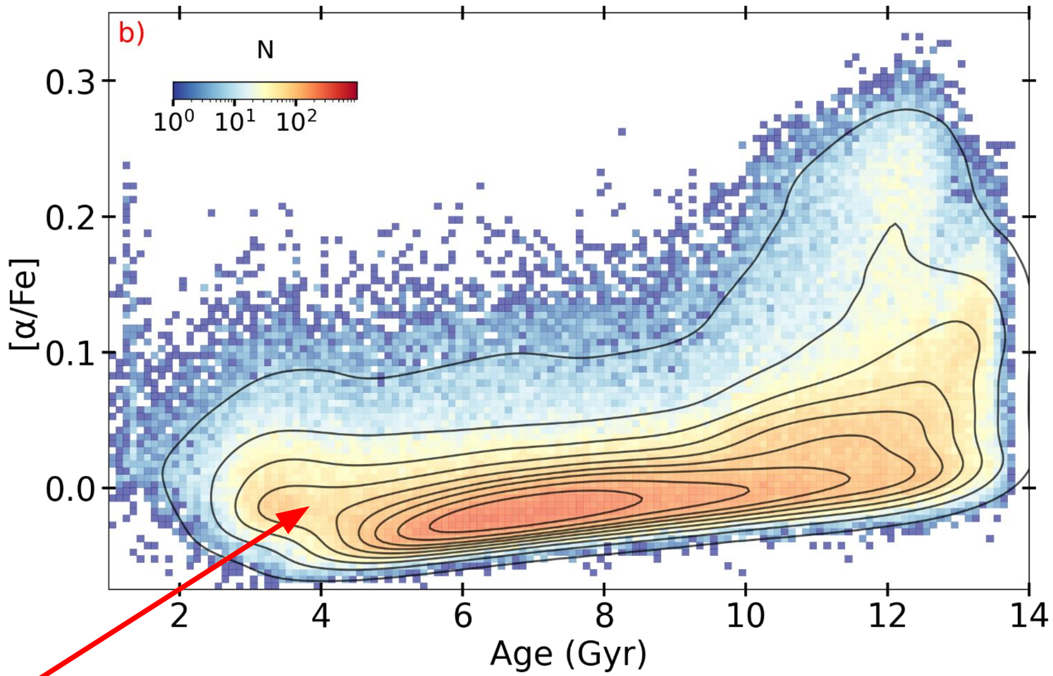

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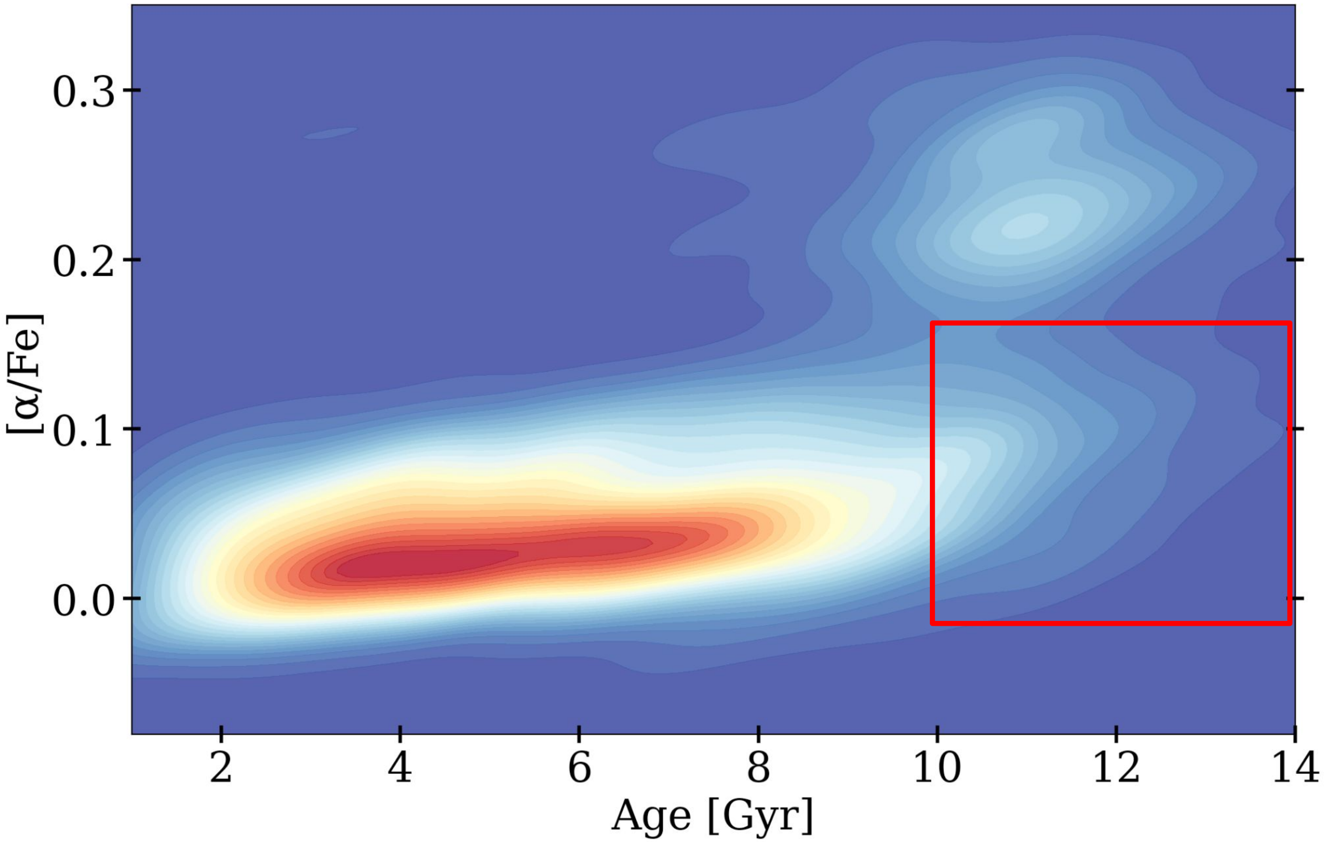
Hints of a young bar (Nepal et al. 2024a)

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



low-[α/Fe] thin disc stars with asteroseismic ages at ~10% precision.

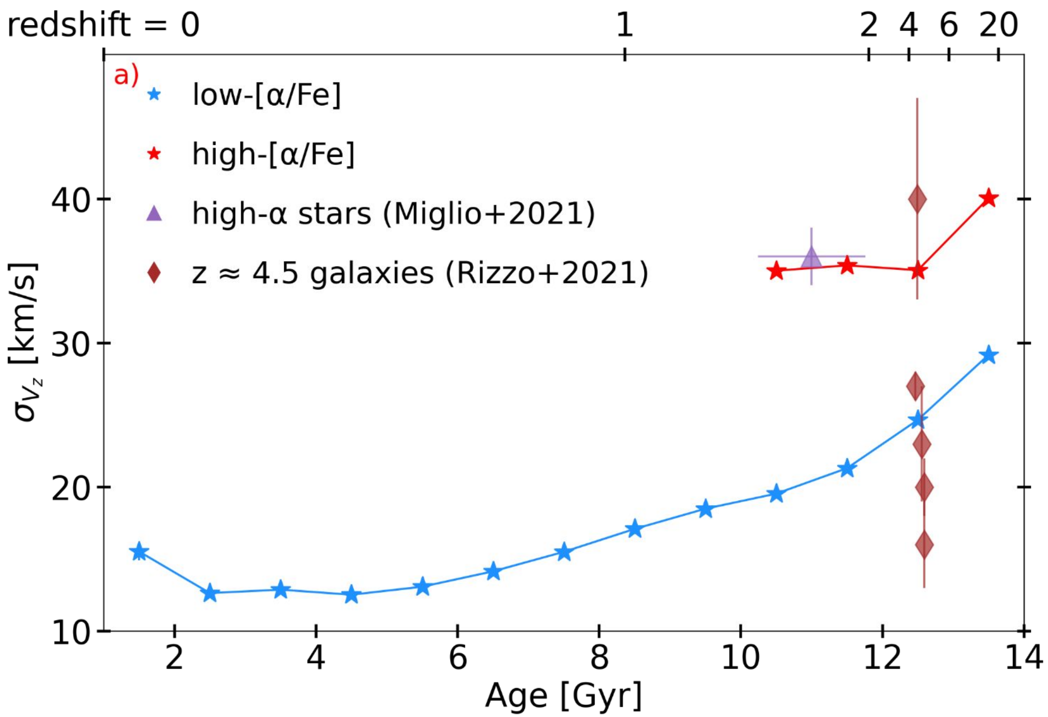
Montalbán et al. (in preparation)

See also:
Beraldo e Silva+2021 with APOGEE

Ghent+2024 with Gaia-ESO

D'Orazi et al. 2024 with metal-rich RR Lyraes

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



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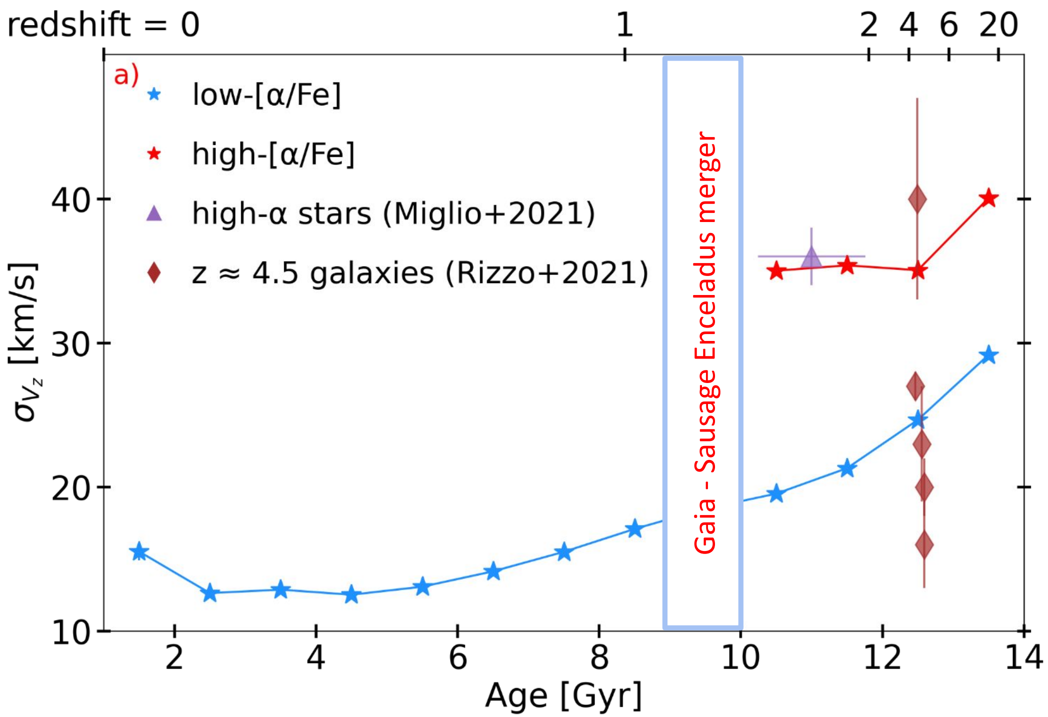


We identify GSE merger at ~9-10 Gyr ago leads to splashing of both old thick and thin discs.

→ Kinematic selection of GSE and Splash should find both old high & low-[α/Fe] in-situ stars.

Simulations of high-z galactic discs:

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

(e.g. See Hopkins+2023)

But progress is being made

Simulations of high-z galactic discs:

The Astrophysical Journal, 928:106 (15pp), 2022 April 1 https://doi.org/10.3847/1538-4357/ac558e

The Dawn of Disk Formation in a Milky Way-sized Galaxy Halo: Thin Stellar Disks at $z > 4$

Tomas Tamfal[1], Lucio Mayer[1], Thomas R. Quinn[2], Arif Babul[3], Piero Madau[4], Pedro R. Capelo[1], Sijing Shen[5], and Marius Staub[6]
[1] Center for Theoretical Astrophysics and Cosmology, Institute for Computational Science, University of Zurich, Winterthurerstrasse 190, CH-8057 Zürich, Switzerland; tomas.tamfal@uzh.ch
[2] Astronomy Department, University of Washington, Seattle, WA 98195, USA
[3] Department of Physics & Astronomy, University of Victoria, BC, V8X 4M6, Canada
[4] Department of Astronomy & Astrophysics, University of California, 1156 High Street, Santa Cruz, CA 95064, USA
[5] Institute of Theoretical Astrophysics, University of Oslo, Postboks 1029, NO-0315 Oslo, Norway
[6] Institute for Particle Physics and Astrophysics, Eidgenössische Technische Hochschule, Wolfgang-Pauli-Strasse 27, 8049 Zürich, Switzerland

Exploring the fate of primordial discs in Milky Way-sized galaxies with the GigaEris simulation

Floor van Donkelaar,[1★] Lucio Mayer,[1] Pedro R. Capelo[1] and Piero Madau[2,3]
[1] *Department of Astrophysics, University of Zurich, Winterthurerstrasse 190, CH-8057 Zürich, Switzerland*
[2] *Department of Astronomy and Astrophysics, University of California, 1156 High Street, Santa Cruz, CA 95064, USA*
[3] *Dipartimento di Fisica "G. Occhialini", Università degli Studi di Milano-Bicocca, P.za della Scienza 3, I-20126 Milano, Italy*

Monthly Notices of the Royal Astronomical Society
MNRAS **525**, L105–L111 (2023) https://doi.org/10.1093/mnrasl/slad103
Advance Access publication 2023 July 27

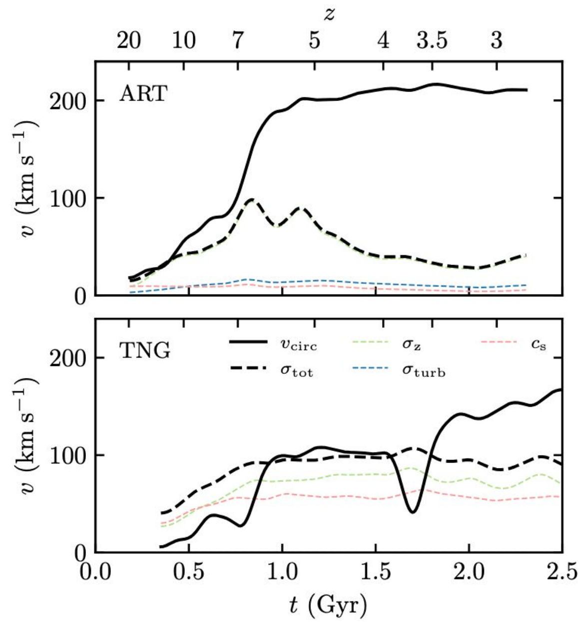
On the likelihoods of finding very metal-poor (and old) stars in the Milky Way's disc, bulge, and halo

Diego Sotillo-Ramos,[1★] Maria Bergemann,[1★] Jennifer K.S. Friske[2] and Annalisa Pillepich[1]
[1] *Max-Planck-Institut für Astronomie, Königstuhl 17, D-69117 Heidelberg, Germany*
[2] *Mullard Space Science Laboratory, University College London, Holmbury St. Mary, Dorking, Surrey RH5 6NT, UK*

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

How Early Could the Milky Way's Disk Form?

Vadim A. Semenov,[1,*] Charlie Conroy,[1] Aaron Smith,[2] Ewald Puchwein,[3] and Lars Hernquist[1]
[1] *Center for Astrophysics | Harvard & Smithsonian, 60 Garden St, Cambridge, MA 02138, USA*
[2] *Department of Physics, The University of Texas at Dallas, Richardson, Texas 75080, USA*
[3] *Leibniz-Institut für Astrophysik Potsdam, An der Sternwarte 16, 14482 Potsdam, Germany*



Took a TNG50 simulation and re-simulated with detailed modeling of cold interstellar medium (ISM) formation, coupled with on-the-fly UV radiative transfer, turbulence-regulated star formation, and stellar feedback.

Main Conclusions:

- *We can leverage Machine Learning (and AI in the near future) to the improve scientific output of large surveys like Gaia. (for example: Guiglion, Nepal et al. 2024)* → *Guillaume's Talk in Session 6*

- *Stellar ages crucial for Galactic Archaeology, stellar metallicity as a proxy for a Galactic clock is unreliable!!*

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- *Stellar ages crucial for Galactic Archaeology, stellar metallicity as a proxy for a Galactic clock is unreliable!!!*

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

- MW thin disc starts forming within the first Billion year with metal-poor to super-solar [Fe/H].
- Thin and thick discs appear coeval with significant overlap at the oldest ages (14 – 10 Gyrs ago).
- 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.
- 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].