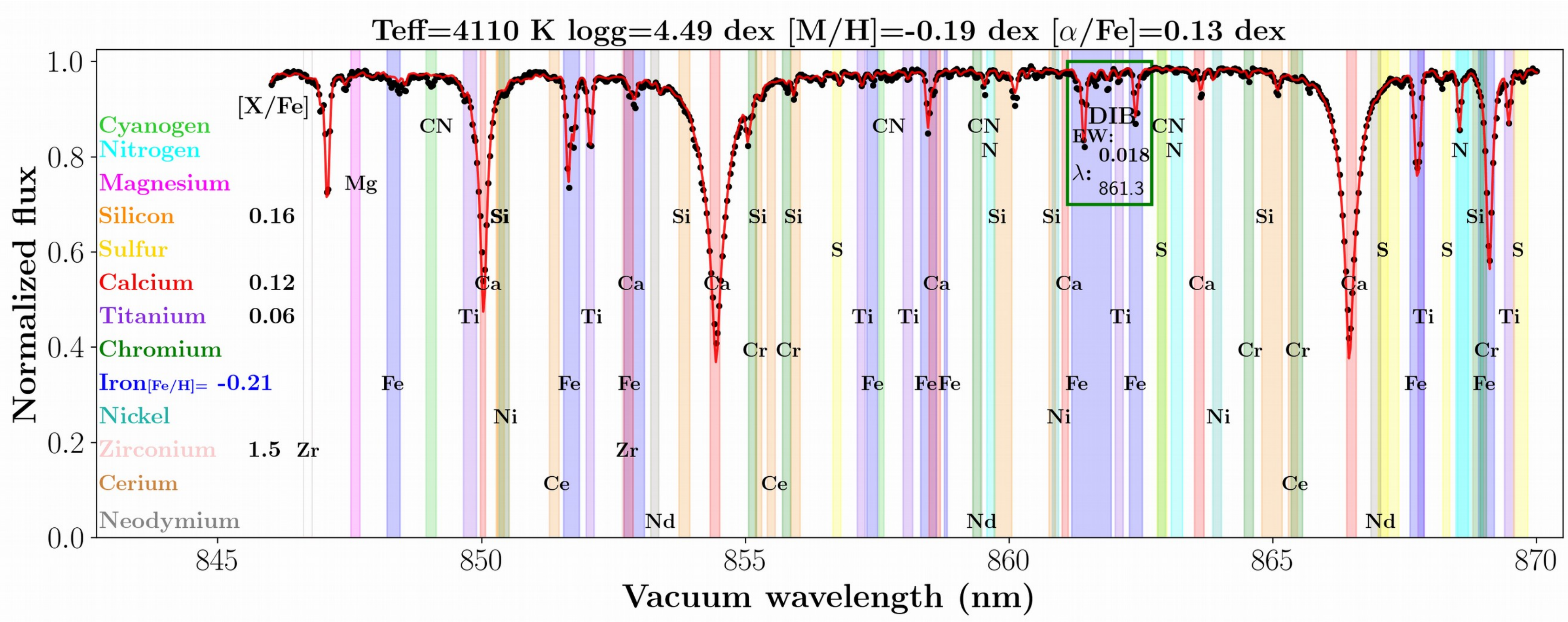
UNIVERSIDAD COMPLUTENSE DE MADRID

Precise abundances of Mg and neutron-capture elements in the Milky Way: chemodynamical relations using Gaia data and chemical evolution models



ESA/Gaia/DPAC-CU8, Recio-Blanco and the GSP-Spec team

Pablo Santos-Peral

Alejandra Recio-Blanco (OCA), Georges Kordopatis (OCA), Pedro Alonso-Palicio (OCA), Emma Fernández-Alvar (IAC), Marco Palla (U. Trieste/U. Ghent), Patrick de Laverny (OCA)

Outline:

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Automatic spectral synthesis code GAUGUIN for deriving abundances

The AMBRE observational data sample

Results

I. [Mg/Fe] in the Galactic disc

Precise [Mg/Fe] vs [Fe/H] (Santos-Peral et al. 2020)

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II. [Eu/Fe] & [Sr/Fe] in Milky Way disc and halo

- Heavy elements Eu/Sr as signatures of accreted populations (Santos-Peral et al., will be submitted soon)

Conclusions

Galactic Archaeology ➡ **history of the Milky Way analyzing fossil signatures**

I. Chemical abundances	II. Dynamics (orbits)	III. Kinematics (velocities)	IV. Ages

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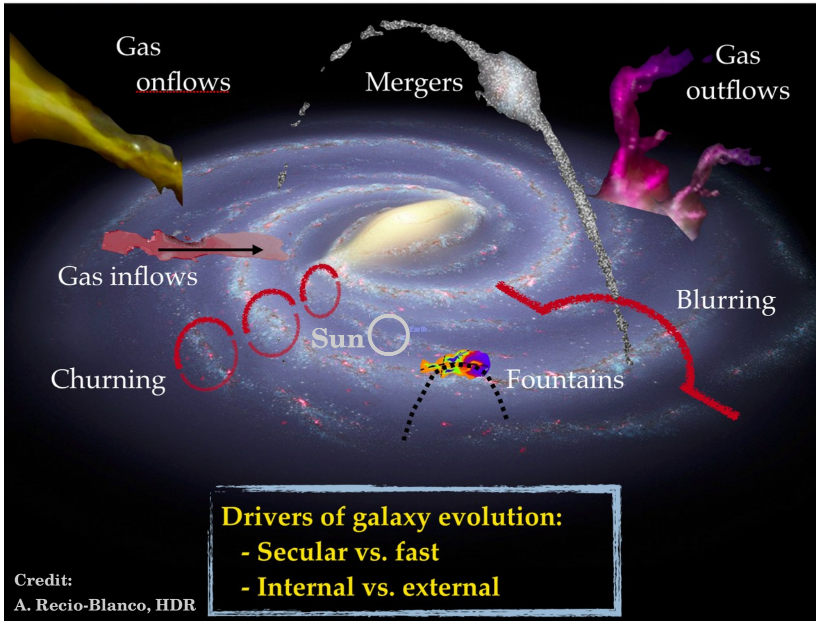
<u>Temporal evolution of chemodynamical correlations:</u>

→ constraints on the physical processes of the Galactic formation



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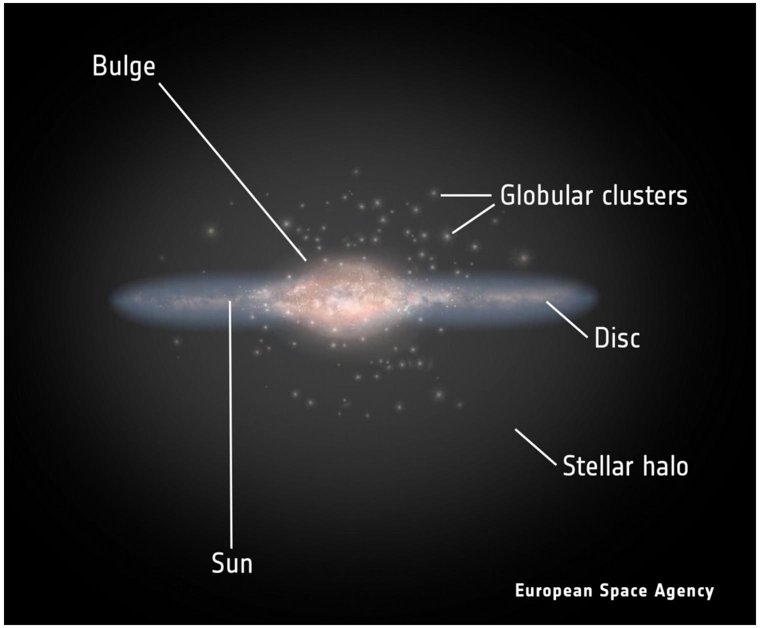

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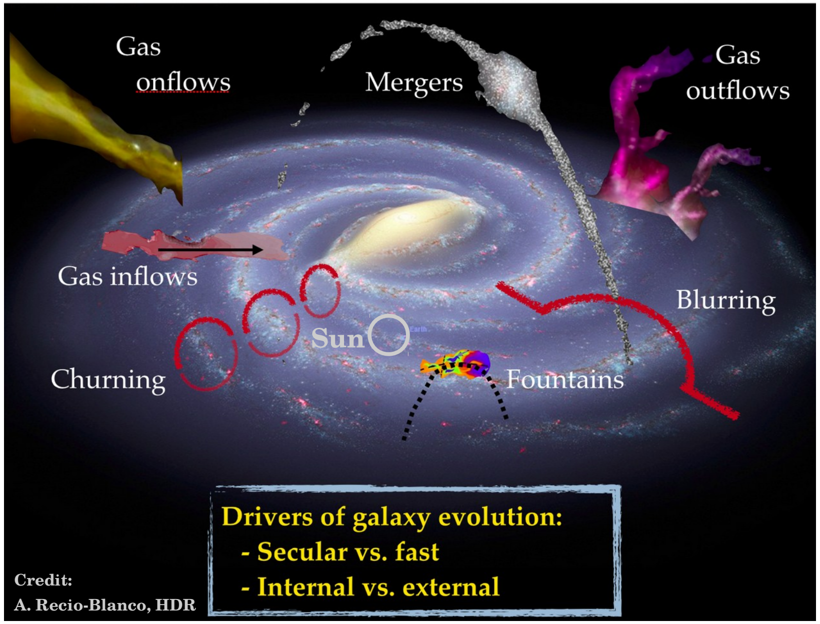

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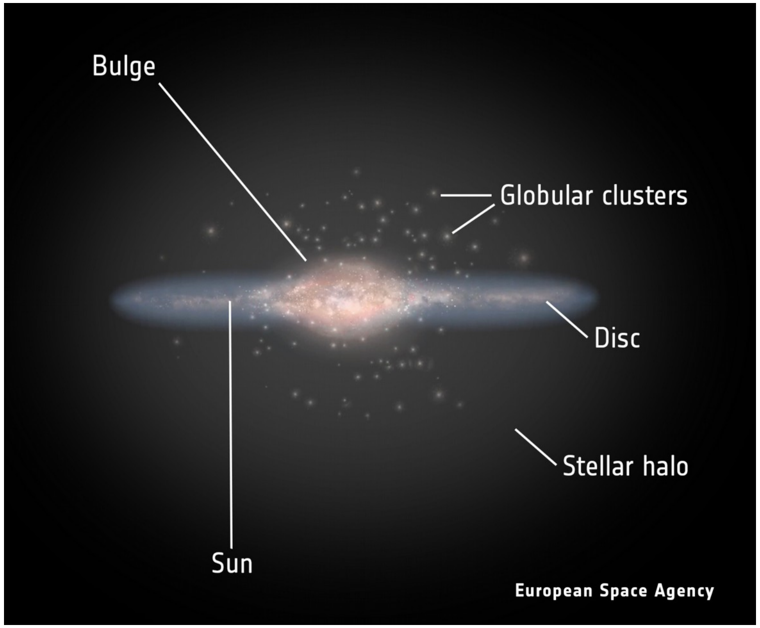


-External: interaction with satellites, gas/stellar accretion, mergers...

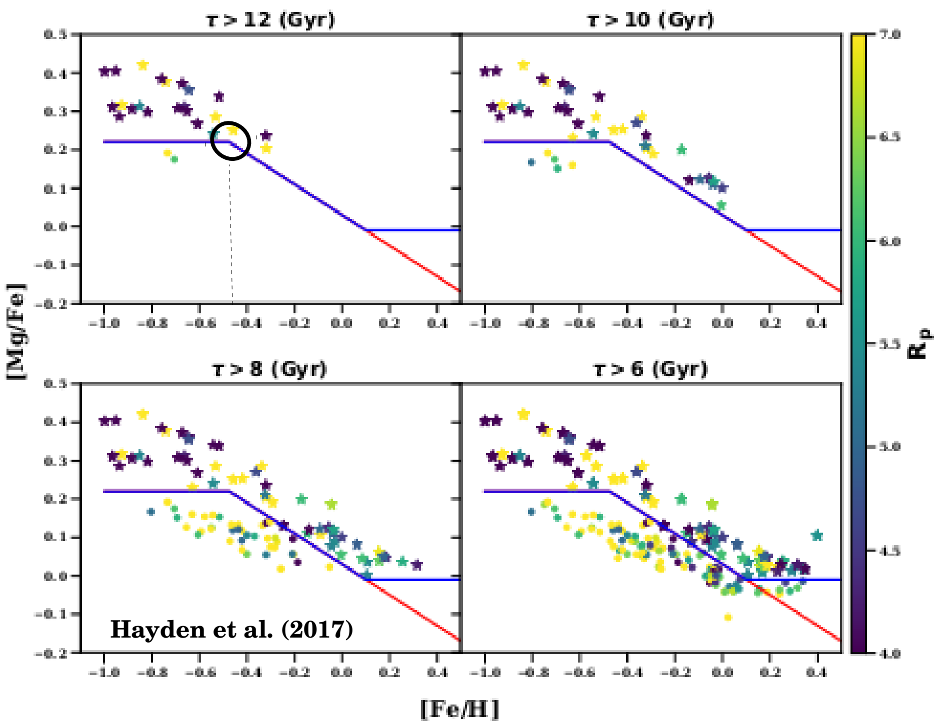
-Internal: radial migration (gas + stars), SN feedback...

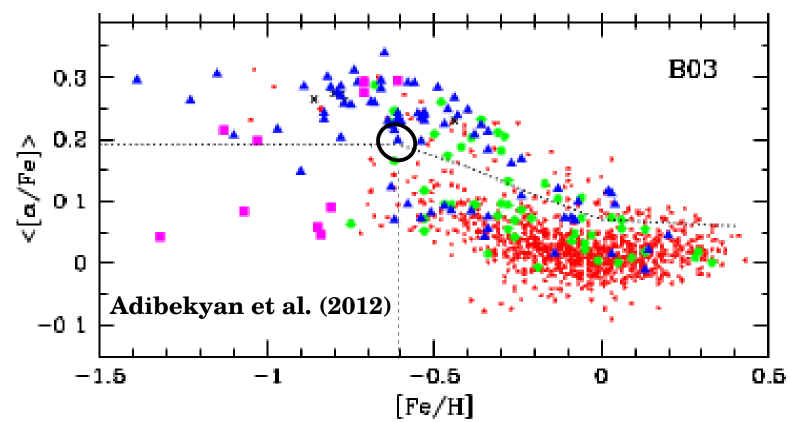
α – elements (O, Mg, Si, S, Ca, Ti), relative to iron ([α/Fe]), to trace the chemical evolution of the disc:

I. Type II SN $\rightarrow$ α – elements
(collapse of massive stars – *short timescale*)

II. Type Ia SN $\rightarrow$ Fe-peak elements
(collapse of white dwarfs – *long timescale*)

[α/Fe] ≈ [Mg/Fe]





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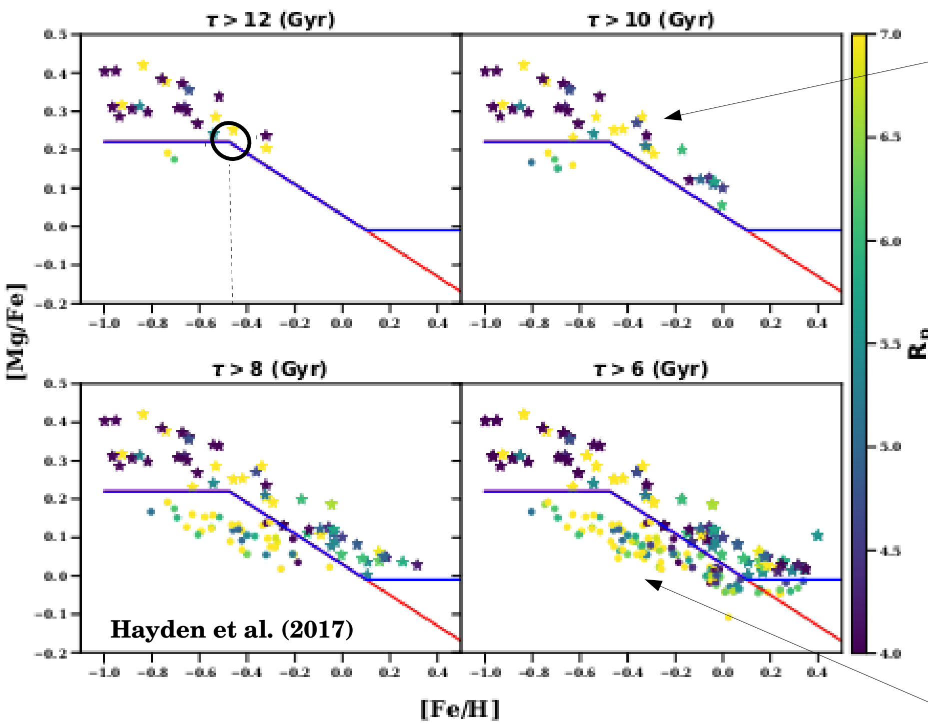
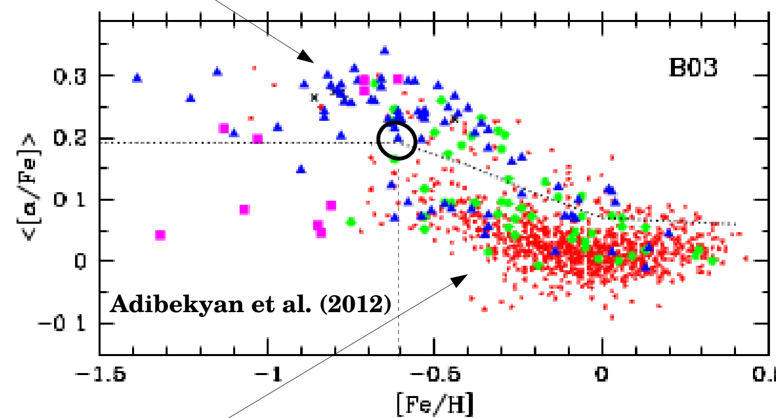


Thick disc:

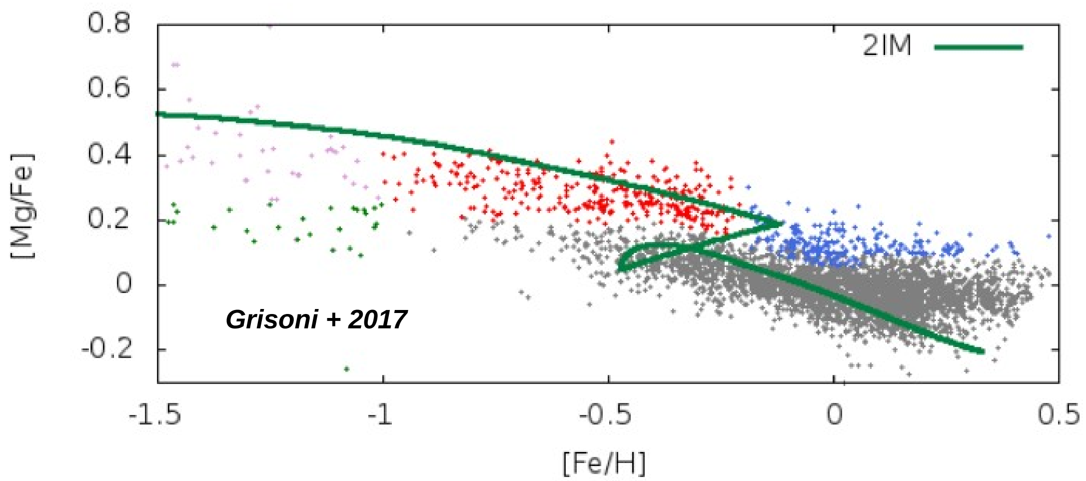
- appears to be old (> 8-10 Gyr)
- moderately metal-poor
- kinematically hotter, lower rotation
- [α/Fe]-enhanced
- scale height ~ 750 pc
- scale length ~ 3.5 kpc

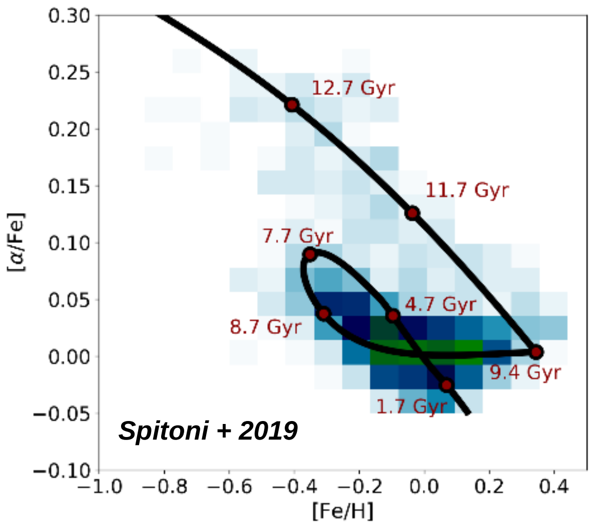


Thin disc:

- relatively younger (< ~10 Gyr)
- moderately metal-rich
- more rotationally supported
- low-[α/Fe] sequence
- scale height ~ 300 pc
- scale length ~ 2.8 kpc

- **Galactic disc formation:** **two different epochs of star formation?**





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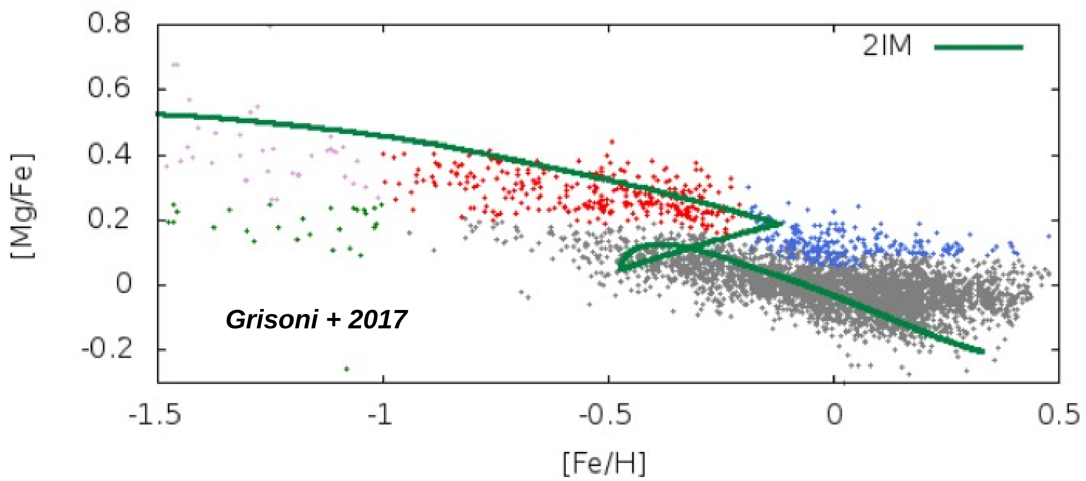

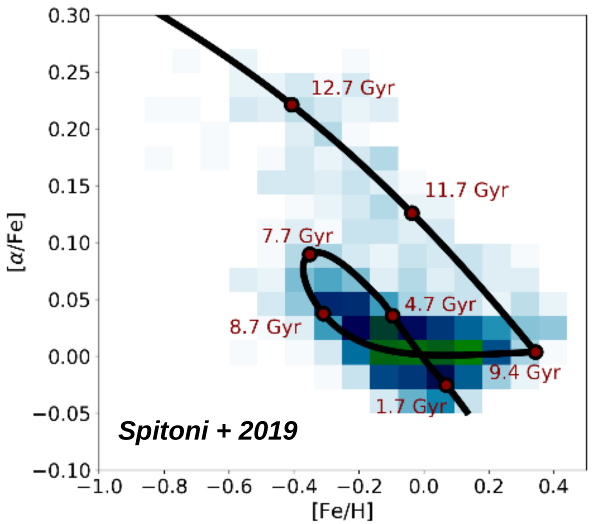

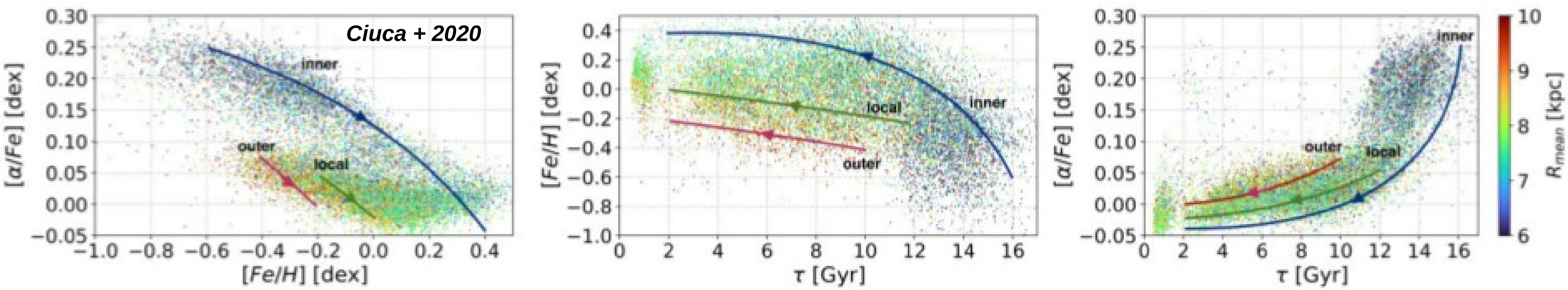

- **Galactic disc formation:** two different epochs of star formation?

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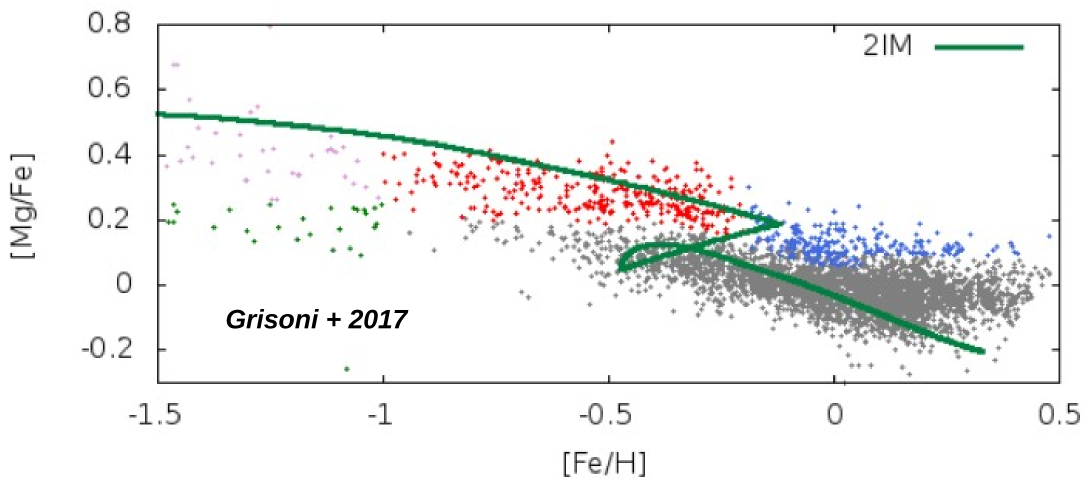
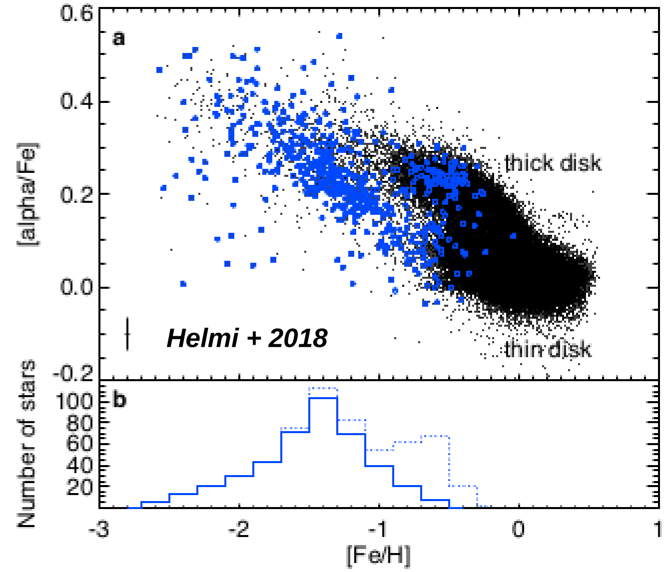
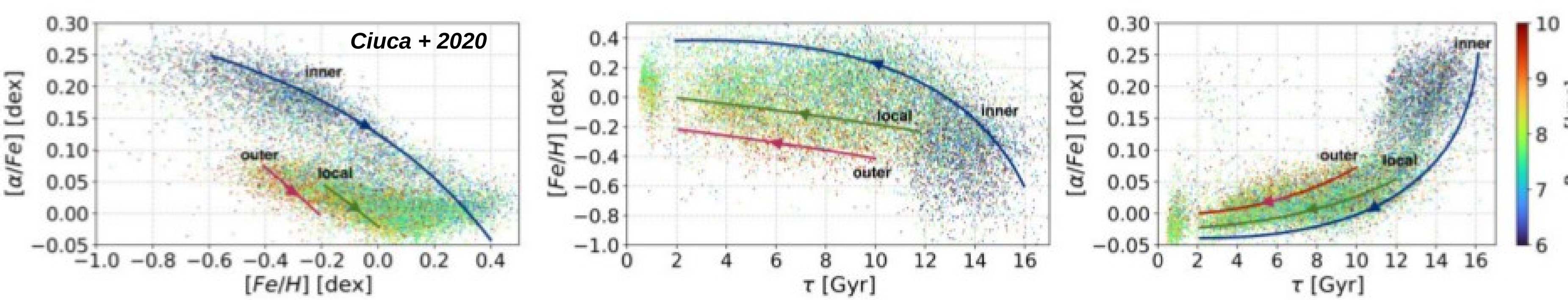
  major accretion event by a massive satellite (e.g. *Gaia*-Enceladus)? (~10 Gyr ago)







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1. Stellar spectroscopic sample:

- AMBRE Project (*Teff, log g, [M/H], [alpha/Fe], Vrad*) (de Laverny et al. 2013 ; De Pascale et al. 2014)
- HARPS ESO spectrograph (R ~ 115000)
- Solar neighbourhood stars

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(Bijaoui et al. 2012; Guiglion et al. 2016)

Developed for RVS → **Gaia DR3**
(Gaia Radial Velocity Spectrograph)

Optimisation of the spectral normalisation procedure for each stellar type and spectral line

Mg I (Å):	**5167.3**	**5172.7**	**5183.6**	**5528.4**	**4730.04**	**5711.09**	**6318.7**	**6319.24**	**6319.49**
	Strong saturated lines				**Non-saturated lines**				

Data & Methodology: I. [Mg/Fe] in the Galactic disc

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2. Gaia DR2: photometry, astrometry and distances

Cross-math with AMBRE:HARPS catalogue by Emma Fernández-Alvar

- Ages

Isochrone fitting method developed by Georges Kordopatis

→ Santos-Peral et al. 2021

- Kinematic and orbital properties (ecc, z_{max}, R_{apo}, R_{per}, R_g)

Integration of the orbits by Emma Fernández-Alvar

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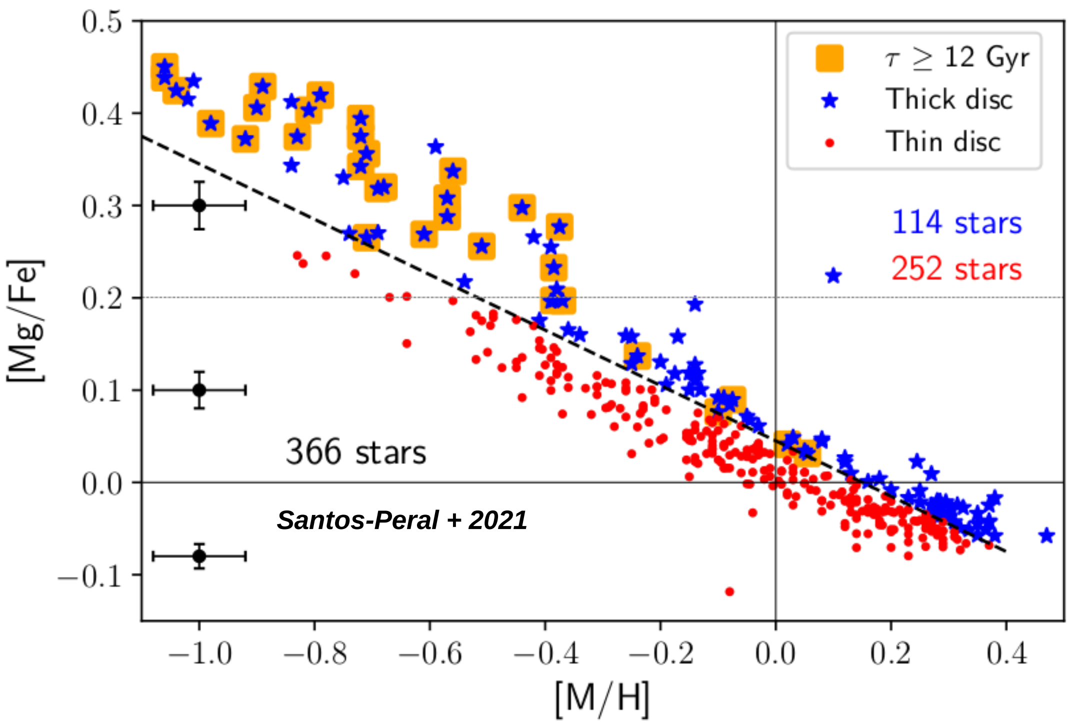
➢ Results (I): Chemical definition of the thin disc

Santos-Peral et al. 2021 → chemodynamical analysis of Galactic disc evolution

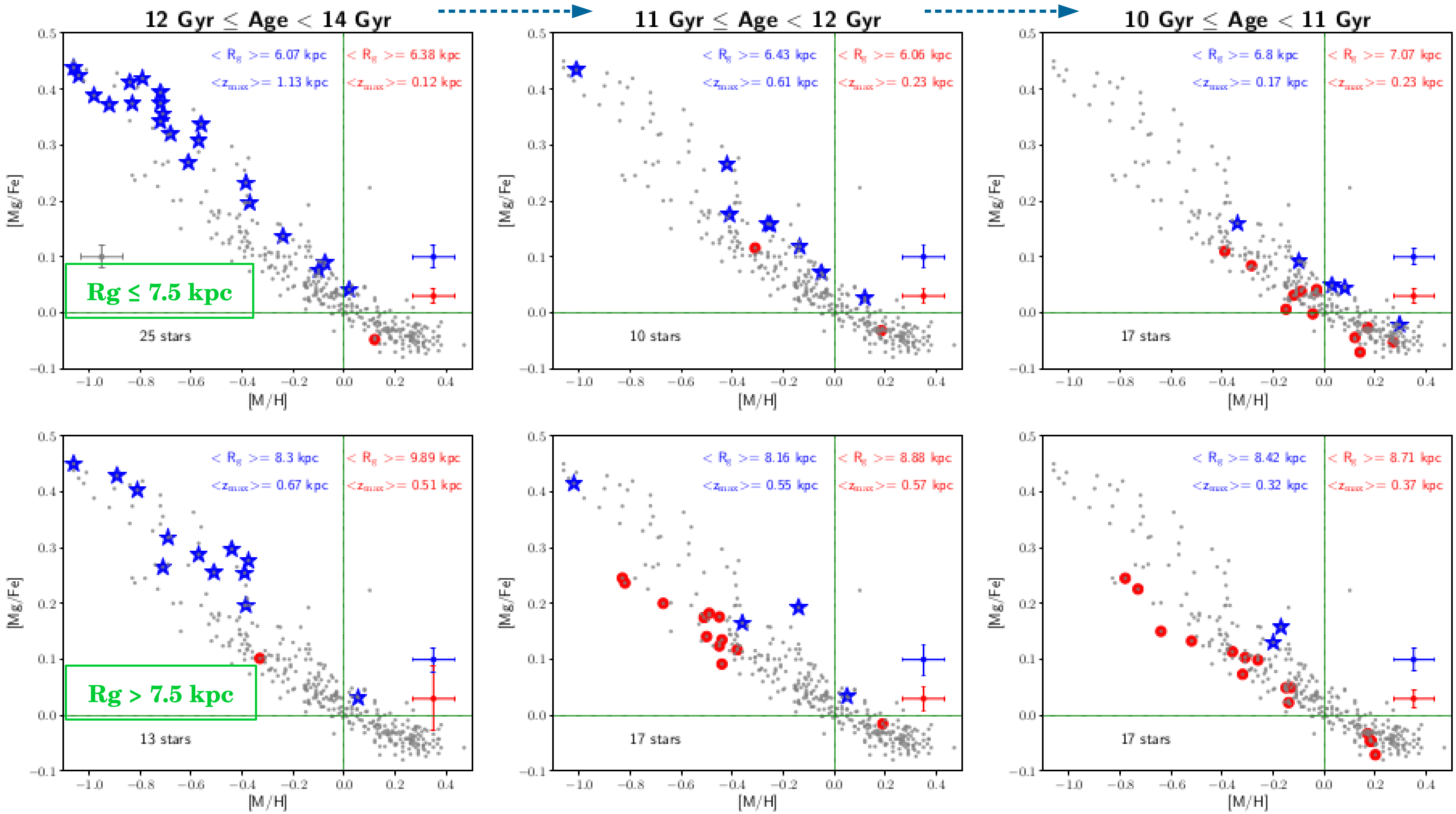
- Sample identical to Hayden+2017 (**494 MSTO stars,** Gaia DR1 + Mikolaitis+2017 [Mg/Fe] abundances)

- **Local Galactic disc:** d < 300 pc ; |z| < 1 kpc

- Stars $\tau \geq 12$ Gyr → old (thick ; high-[Mg/Fe]) disc population



Temporal evolution in the [Mg/Fe] – [M/H] plane :



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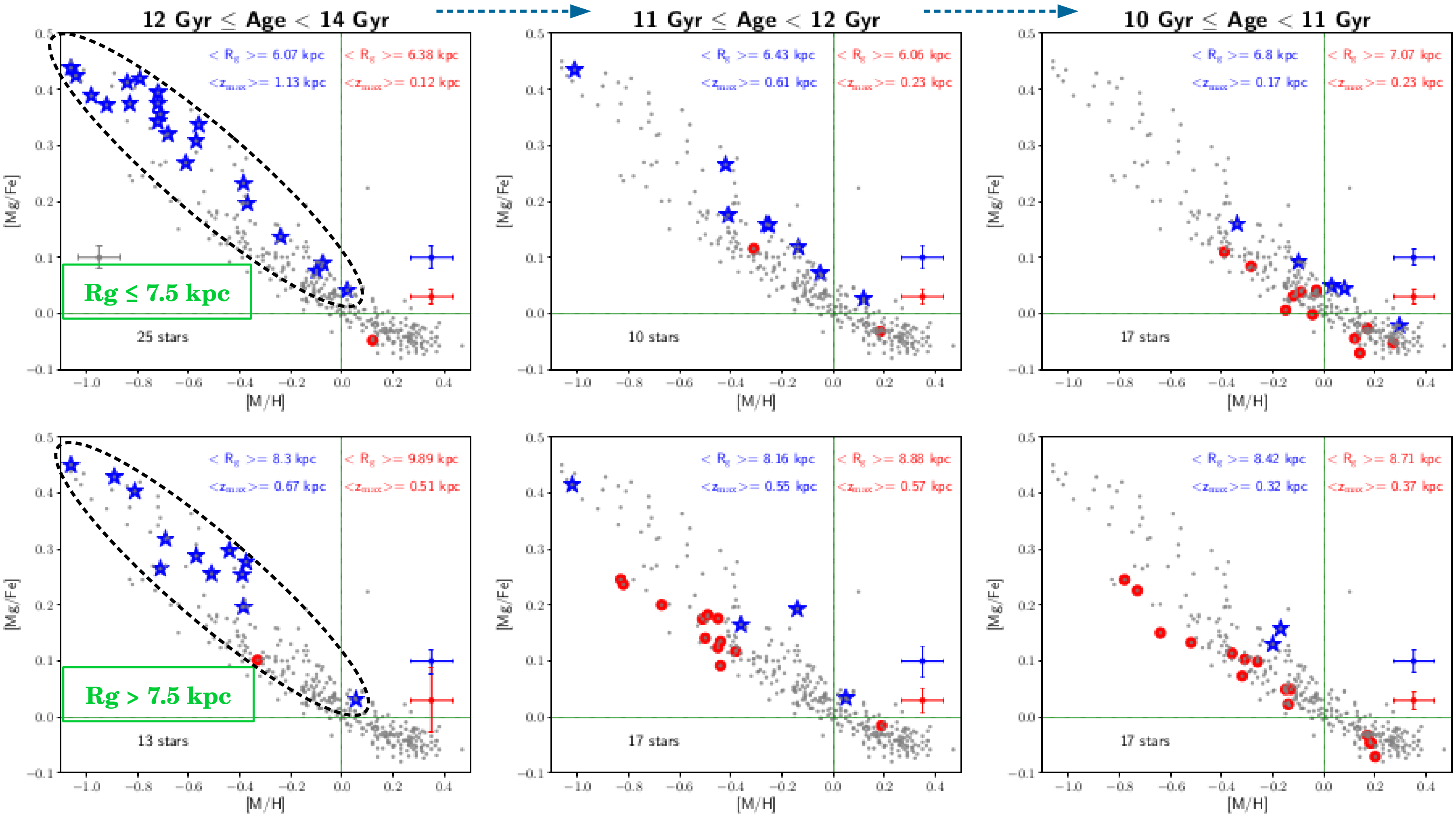

Stars τ ≥ 12 Gyr (high-[Mg/Fe] sequence), rapid chemical enrichment reaching ~ solar abundances

➢ Results (I): Global disc evolution

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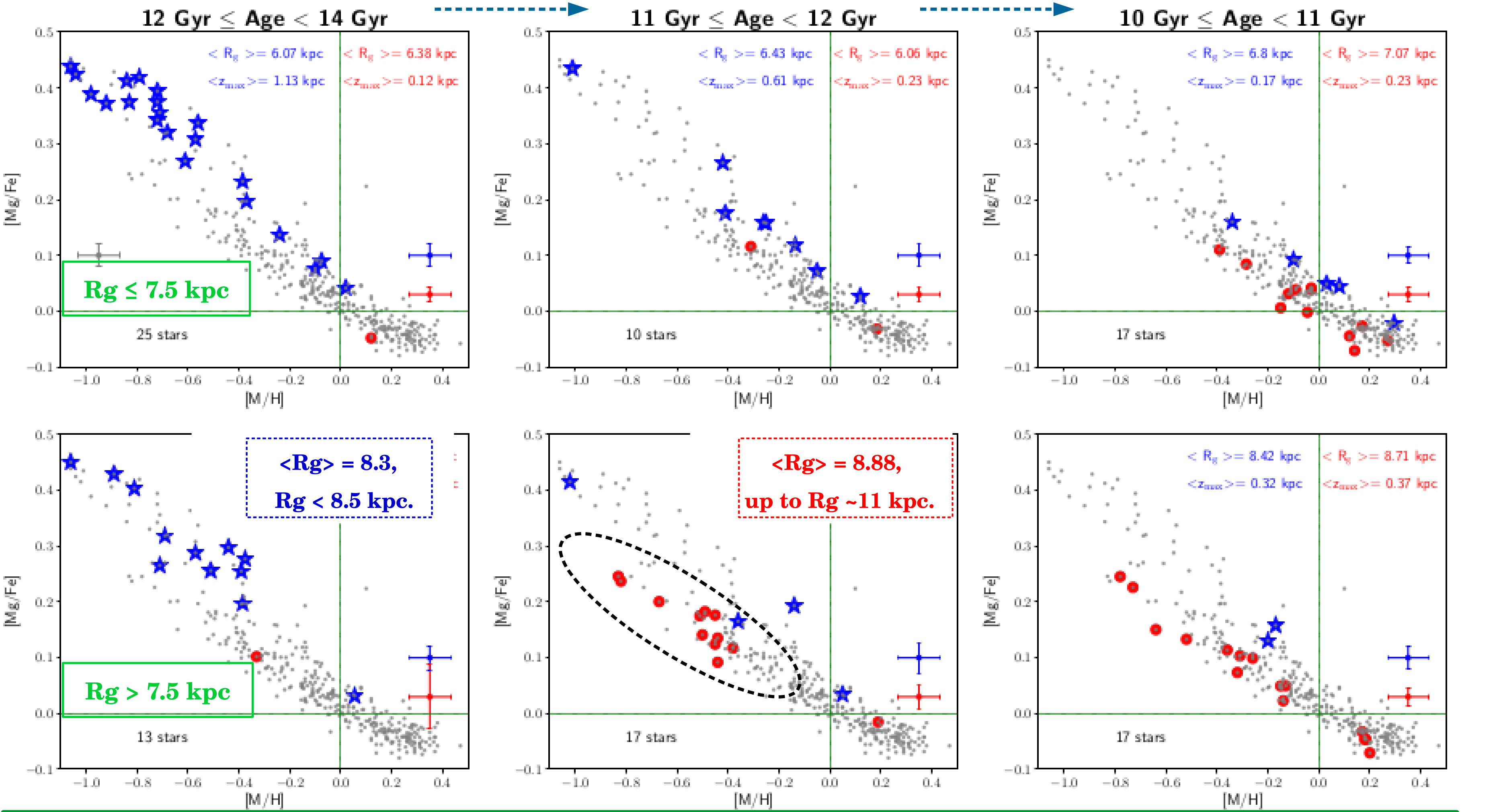

At 10-12 Gyr, stars populating the metal-poor ([M/H]<-0.4) low-[Mg/Fe] tail in the outer regions → leading to a chemical discontinuity in the Galactic disc

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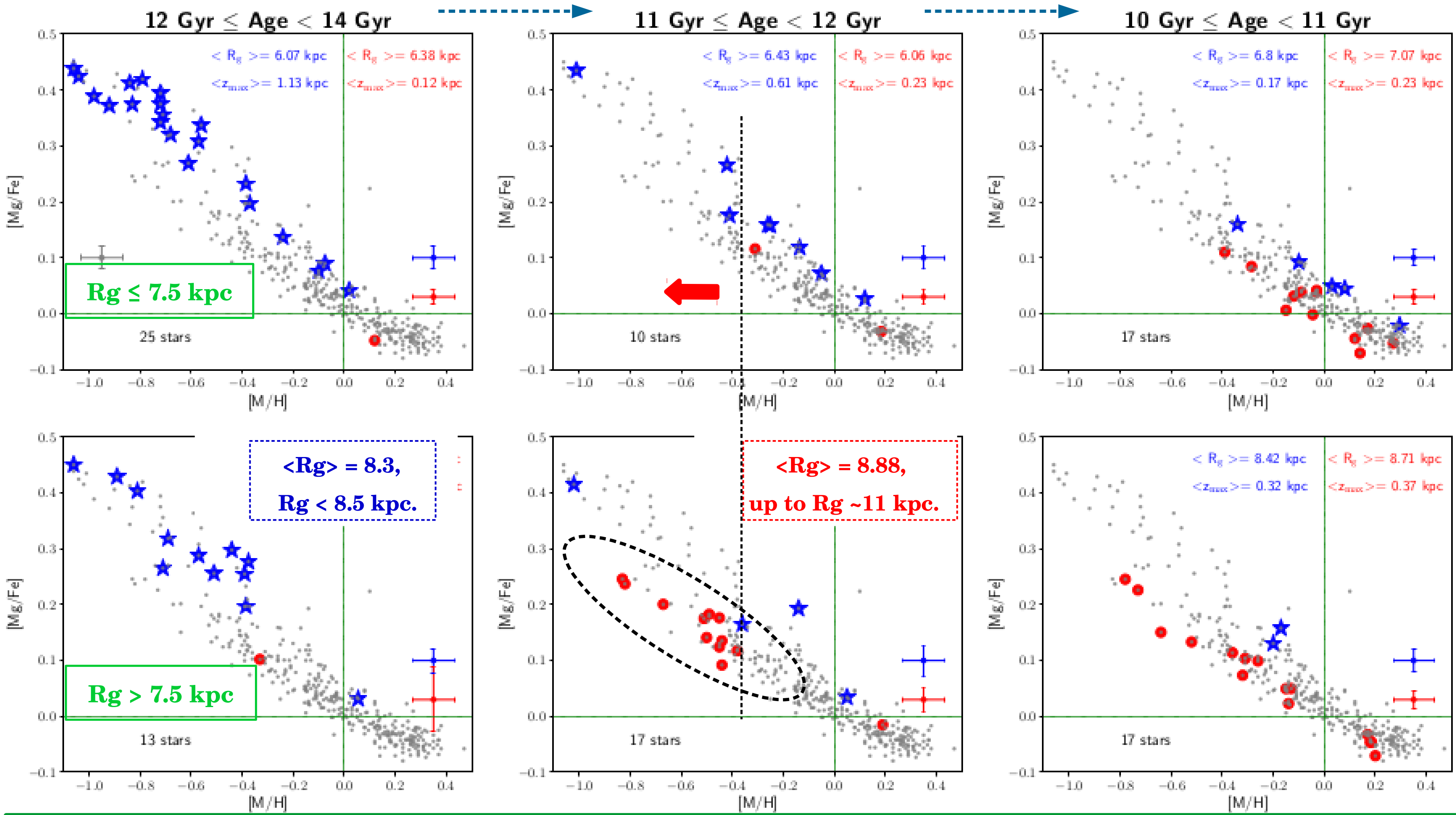

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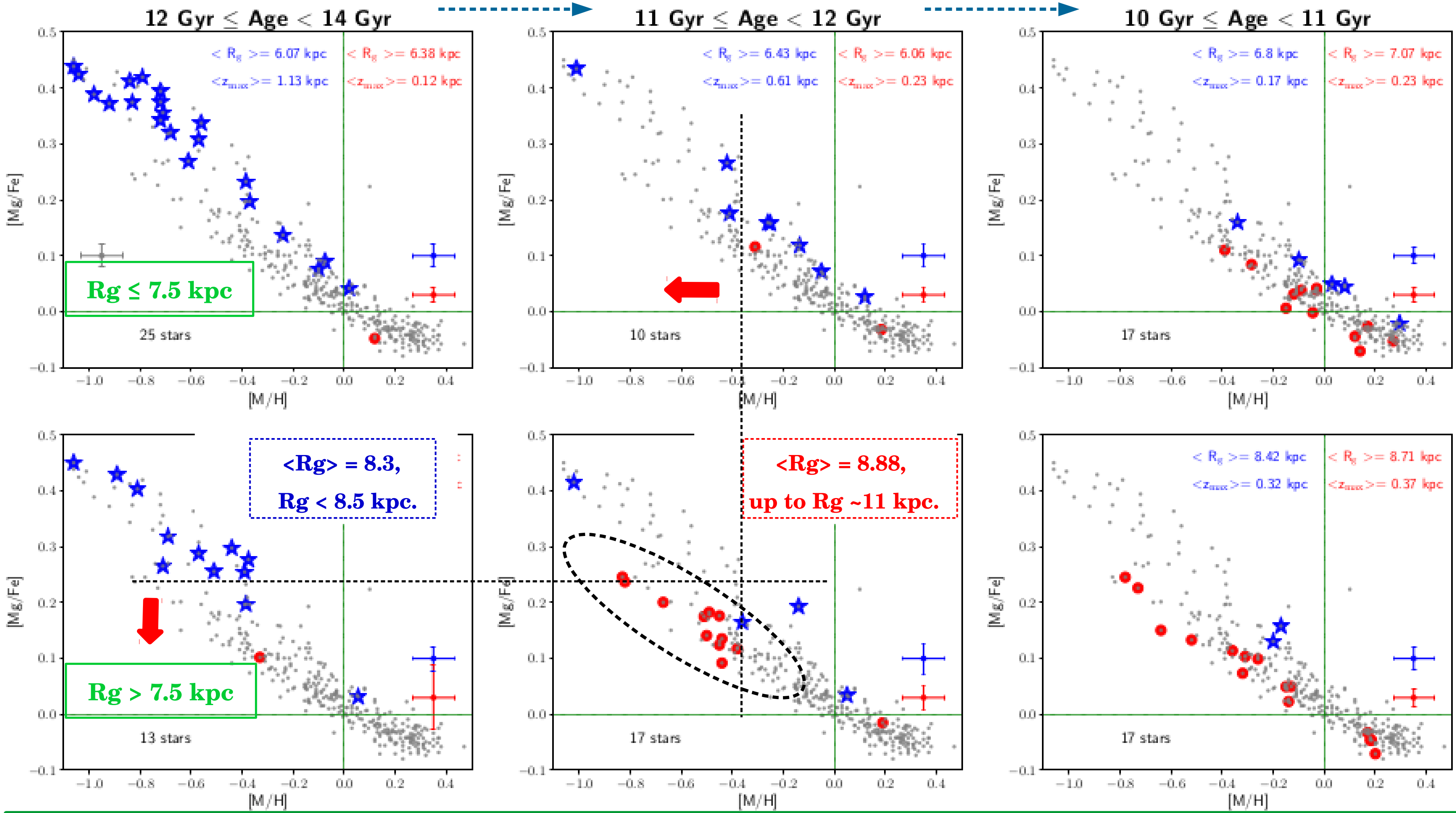

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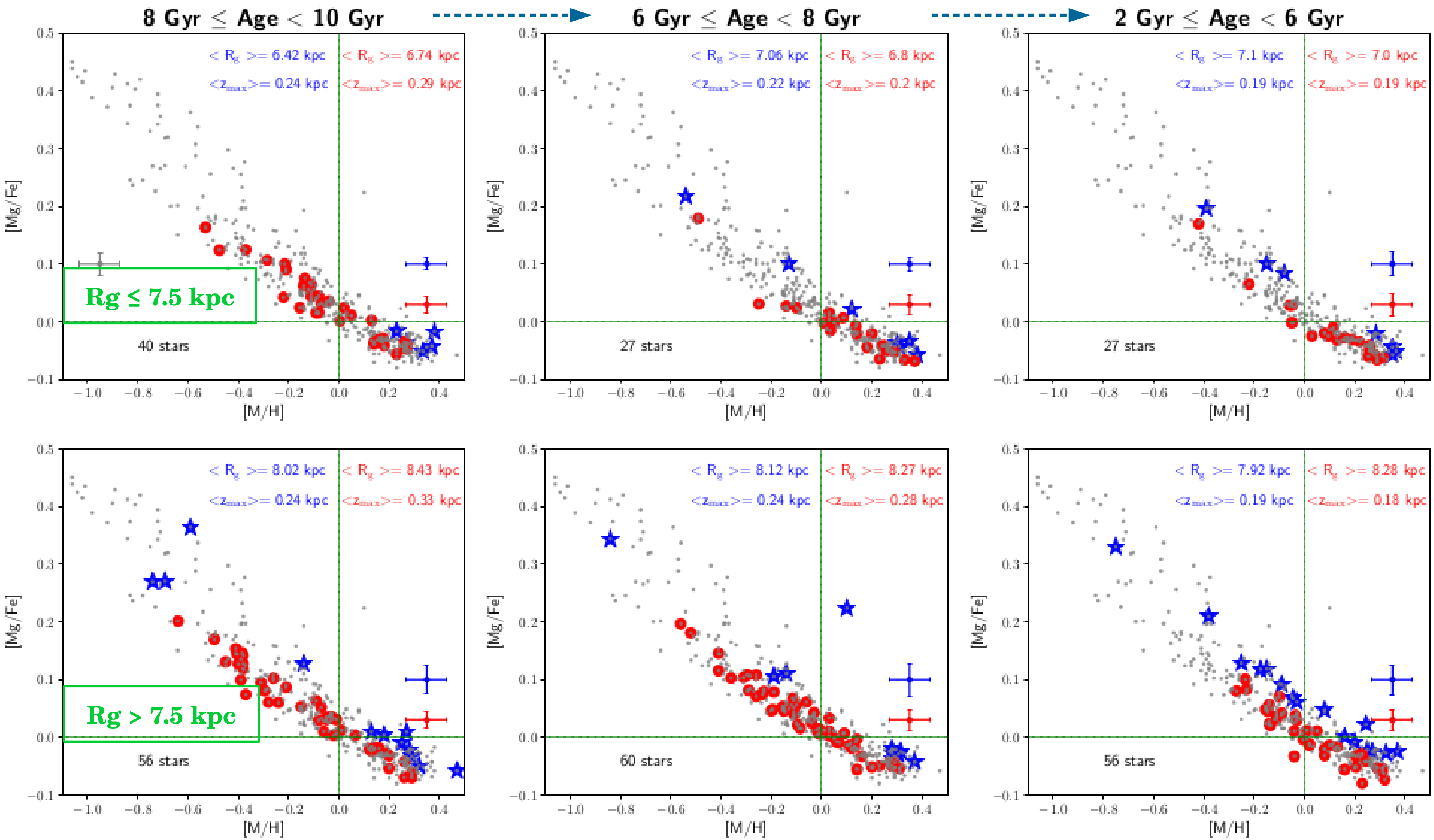

Slower and continuous chemical evolution in the last 10 Gyr

➢ Results (I): Global disc evolution: summary

Observational analysis :

I. **Old high-[Mg/Fe] population** (formed earlier and faster) **pre-enriched the ISM**

II. **Chemical discontinuity (~ 10 Gyr ago):**

Arrival of **pristine gas (infall/gas rich merger**)

→ **formation of the second [Mg/Fe] sequence on longer timescales**

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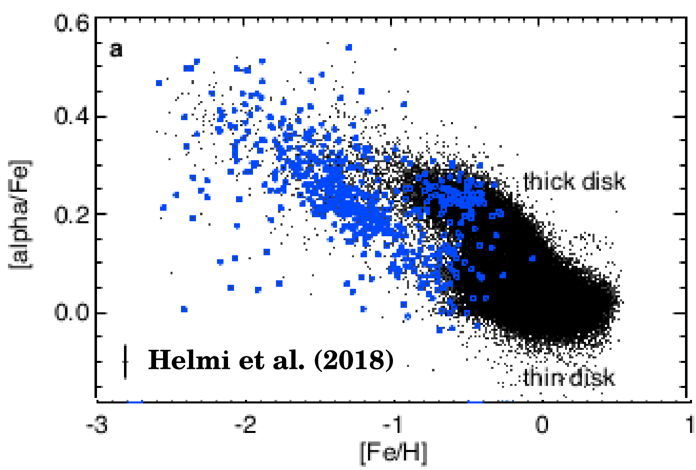
Overlap in time (~ 10 Gyr) and chemical similarities between the Gaia-Enceladus more metal-rich tail and the outer metal-poor low-[Mg/Fe] disc



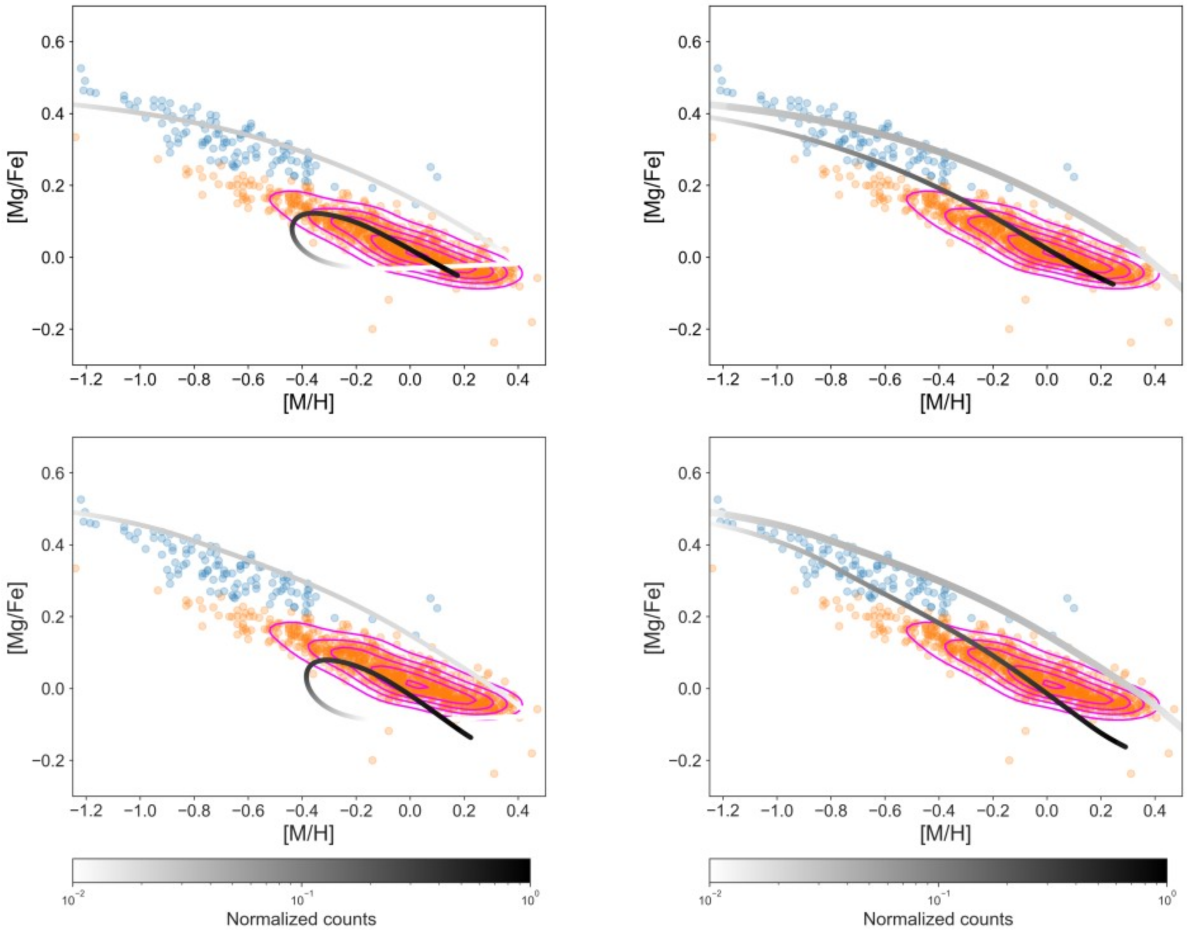
➢ Results (I): Comparison with Chemical Evolution Models

Palla et al. 2022 → chemical evolution scenarios directly compared to [Mg/Fe] abundances

- Delayed two-infall and parallel models, including radial migration prescriptions
- Comparison with the whole analysed AMBRE:HARPS sample (1066 stars)

Palla et al. 2022 → chemical evolution scenarios directly compared to [Mg/Fe] abundances

- Both delayed two-infall and parallel scenarios reproduce the bulk of the data



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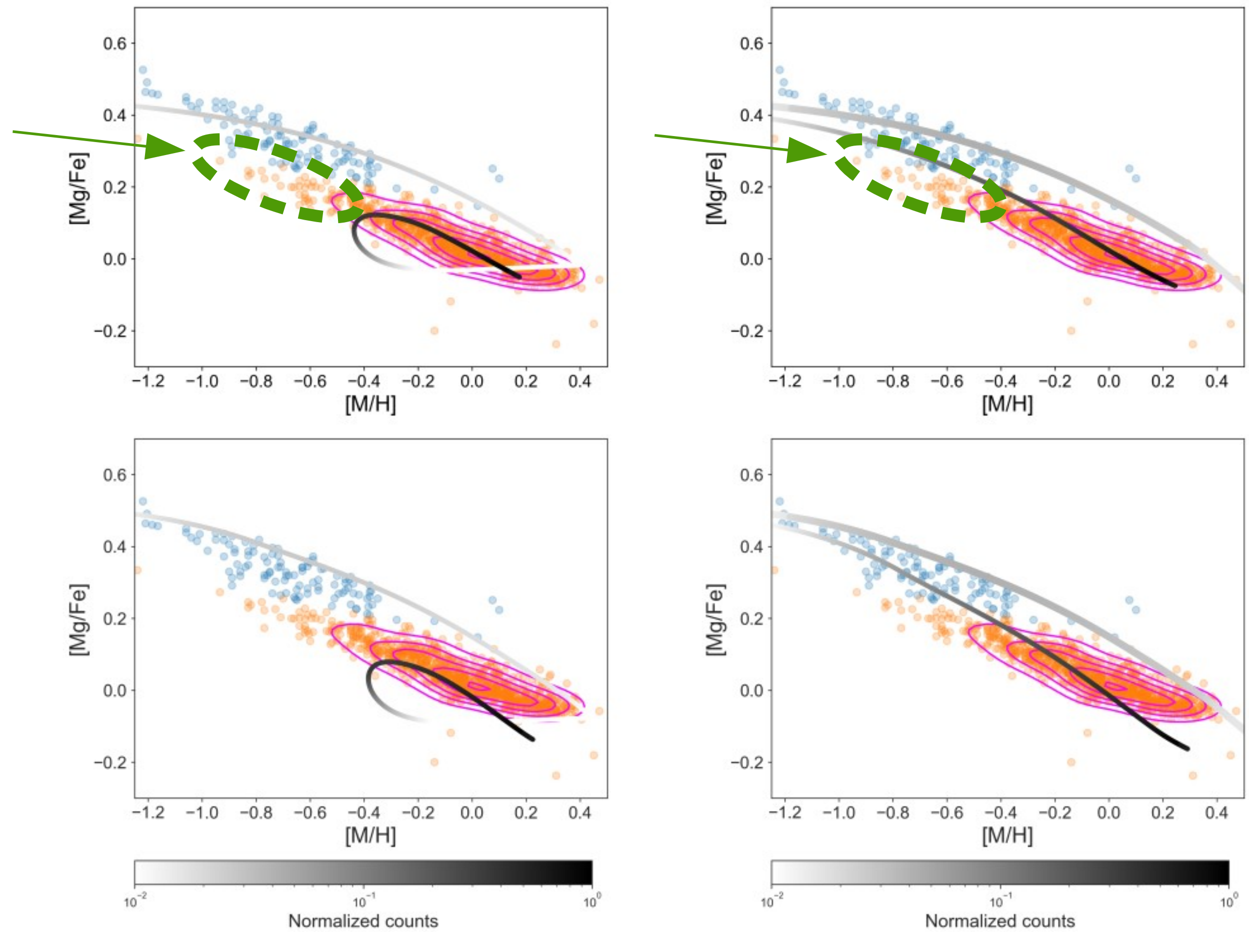

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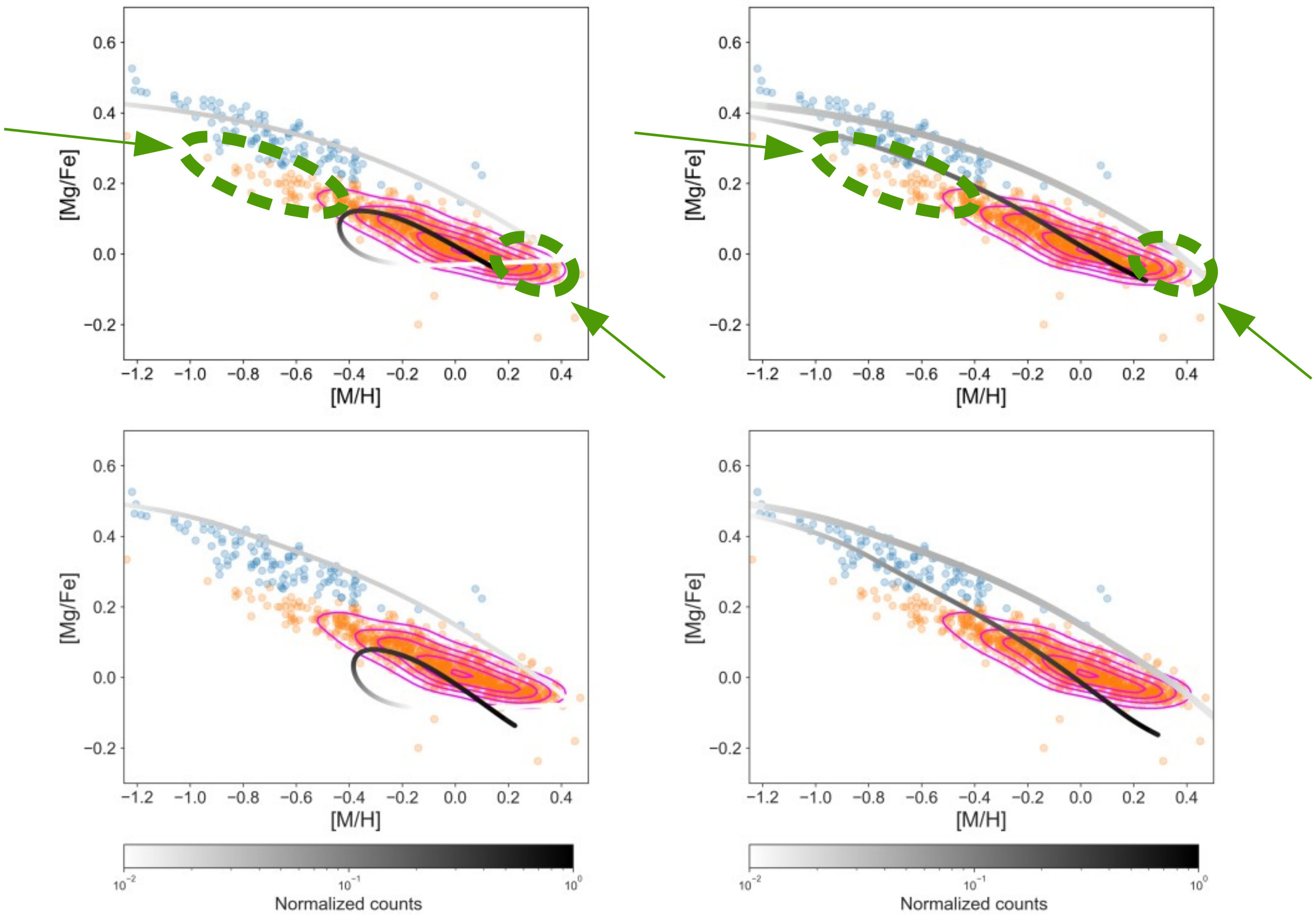

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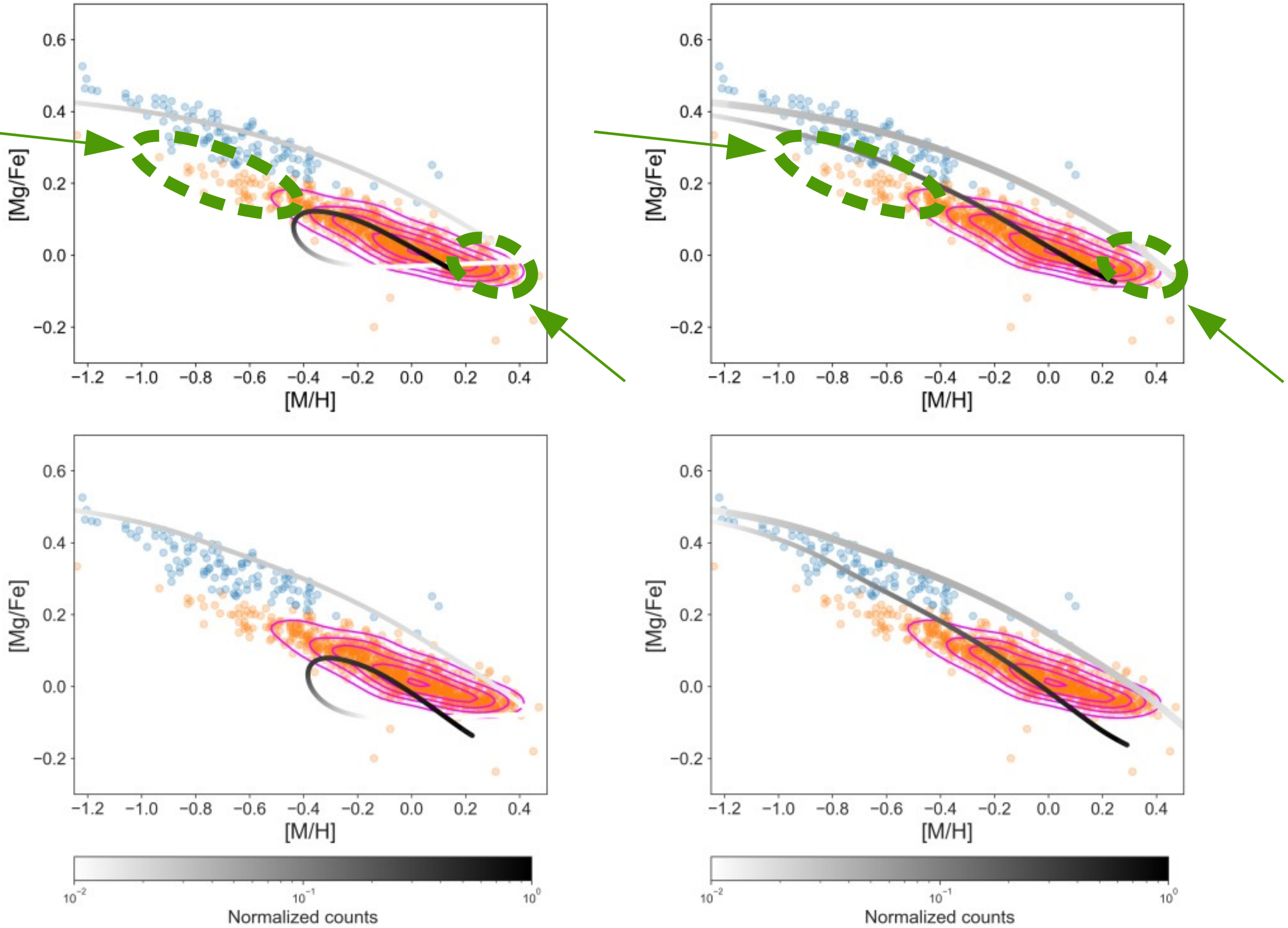

- Problems in explaining the most metal-poor of the low-α sequence… and the metal-rich tail
- Explained in light of radial migration from outer and inner disc regions, respectively

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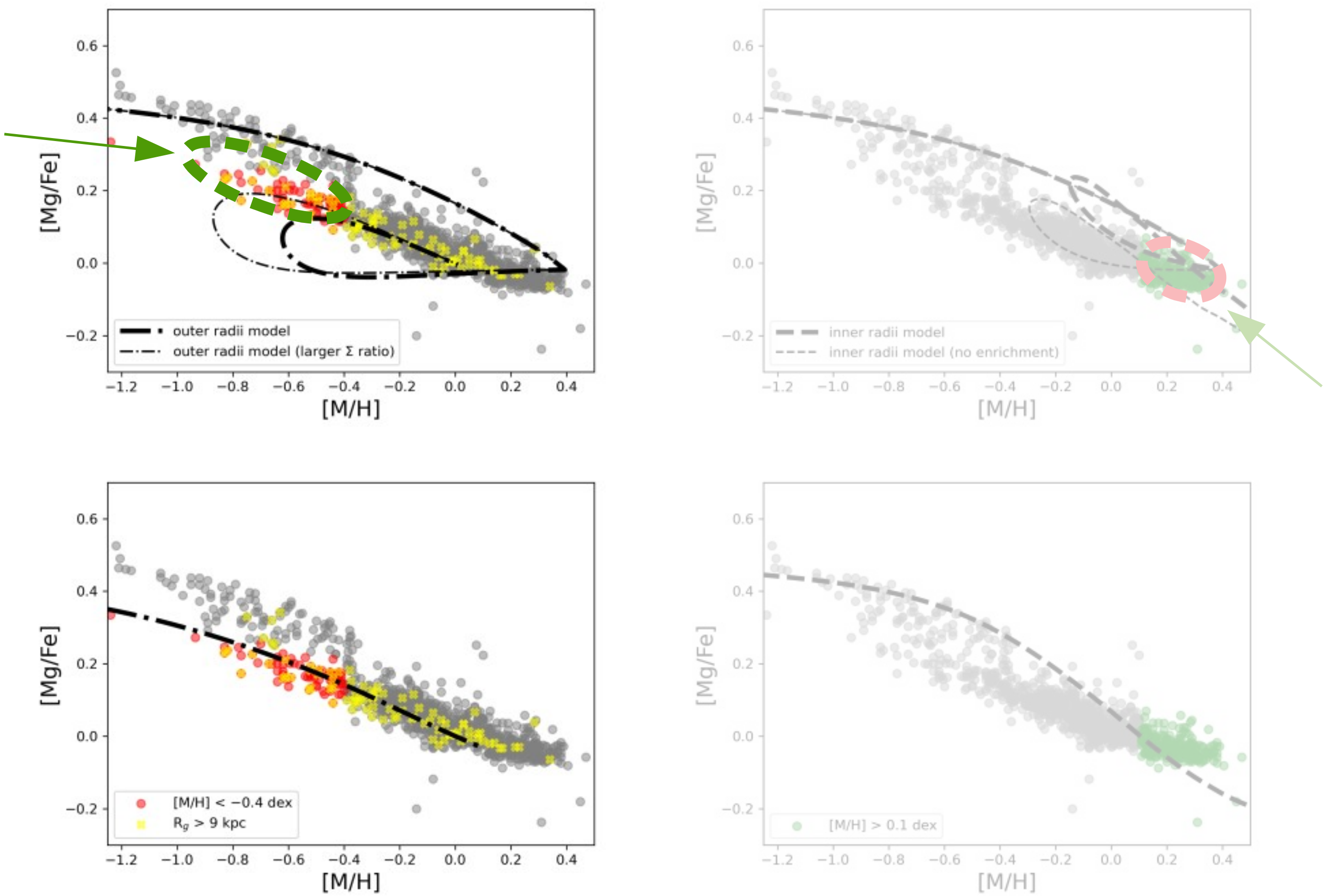

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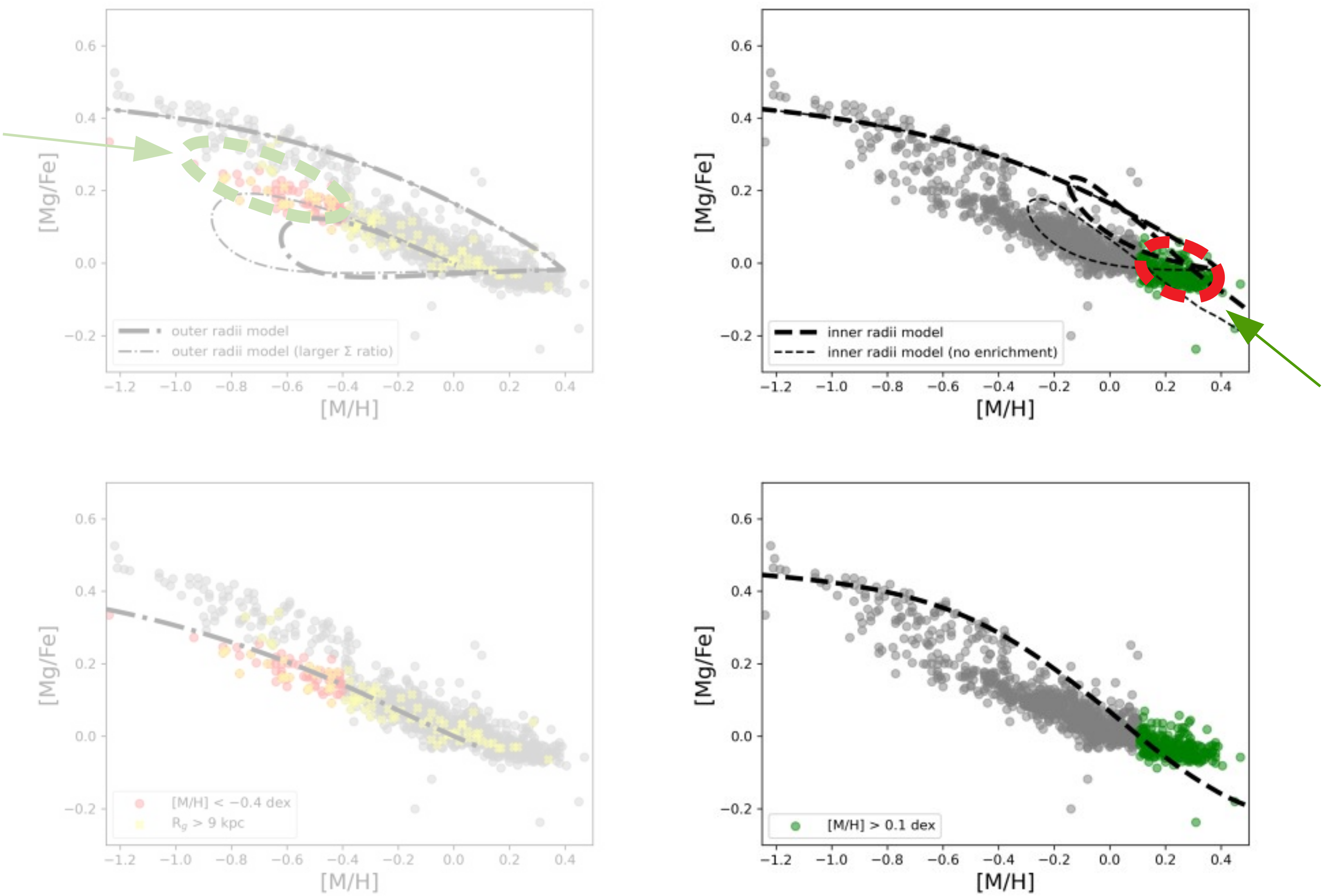

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- **Low-α super-metal-rich stars:** two-infall model for inner radii, with enrichment in the second gas accretion episode. Without pre-enrichment or one-infall model, predict low [α/Fe] for a given metallicity.

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➢ Introduction: Galactic Archaeology of the Milky Way - r/s-process

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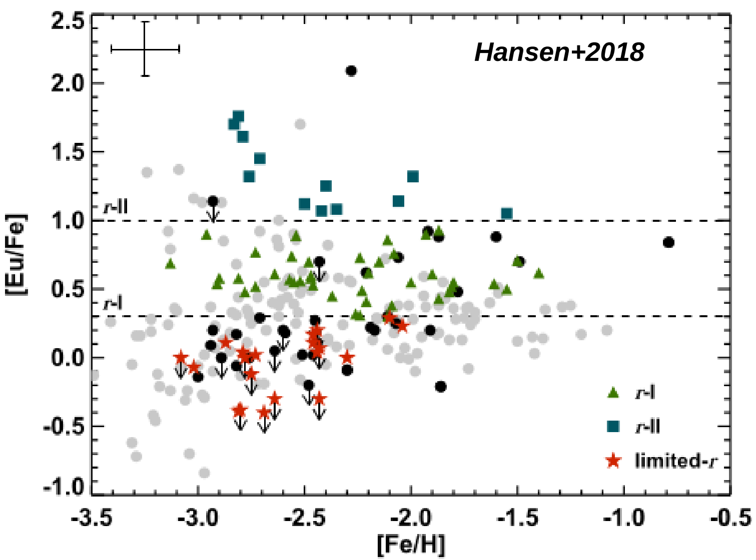
(Beers & Christlieb 2005 ; Frebel 2018)



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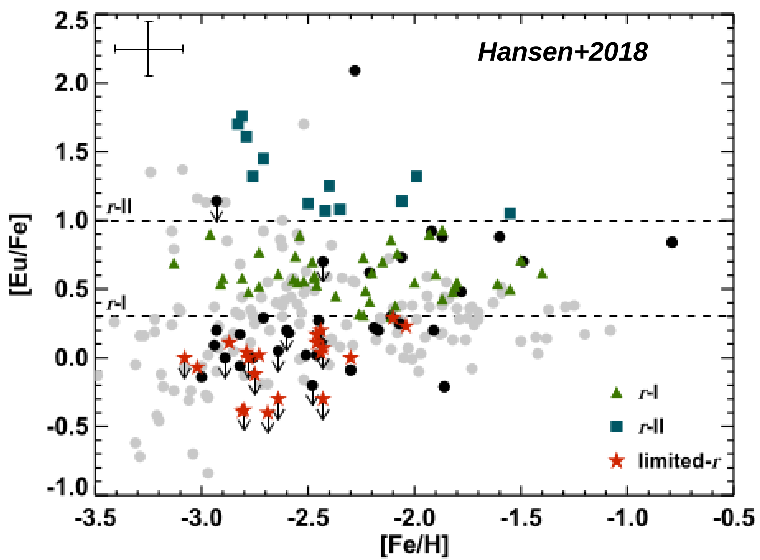
- **Sr** mostly **s-process** neutron-capture element (low/intermediate-mass AGB stars)



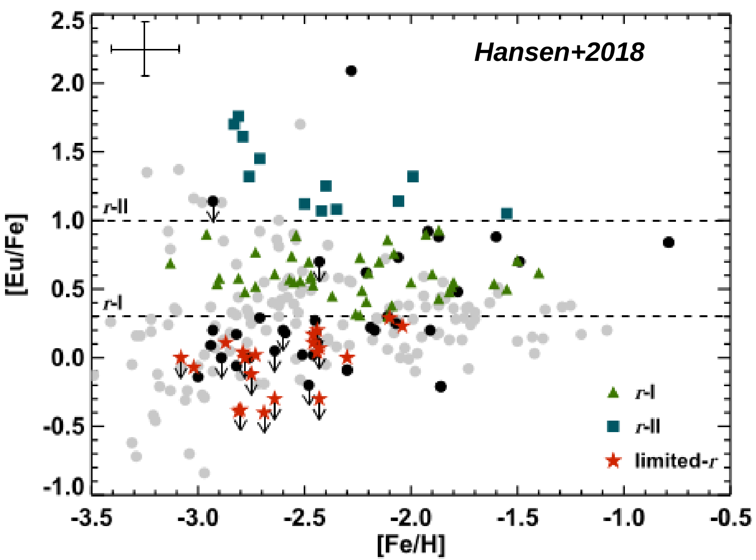
Neutron-capture elements (Z > 30, e.g. Eu, Sr, Ba): early stages of the formation and evolution of the Galaxy

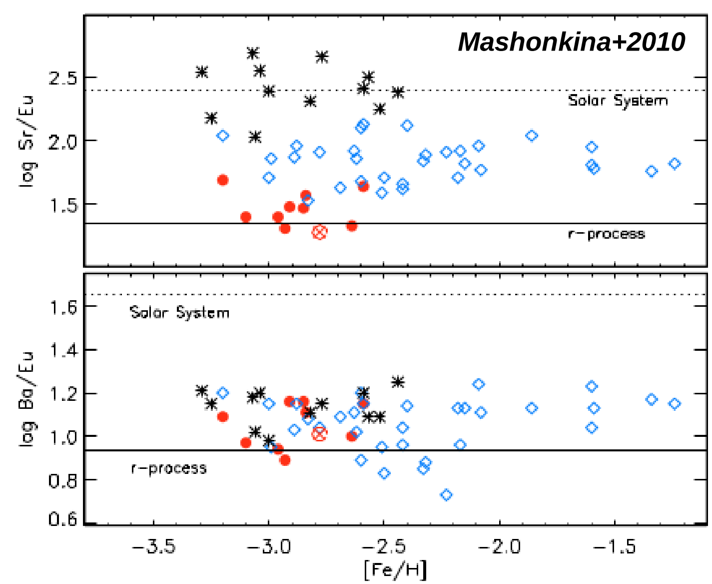
- **Eu** considered **"pure" r-process** neutron-capture element (Type-II SNe, neutron star mergers…)
  1. Strongly enhanced r-II → [Eu/Fe] > +1.0 dex
  2. Moderately enhanced r-I → +0.3 ≤ [Eu/Fe] ≤ +1.0 dex

  (Beers & Christlieb 2005 ; Frebel 2018)

- **Sr** mostly **s-process** neutron-capture element (low/intermediate-mass AGB stars)

[Eu/Fe], [Sr/Fe], [Eu/Sr], [Sr/alpha]…
→ ideal to identify different progenitors and chemical enrichment histories





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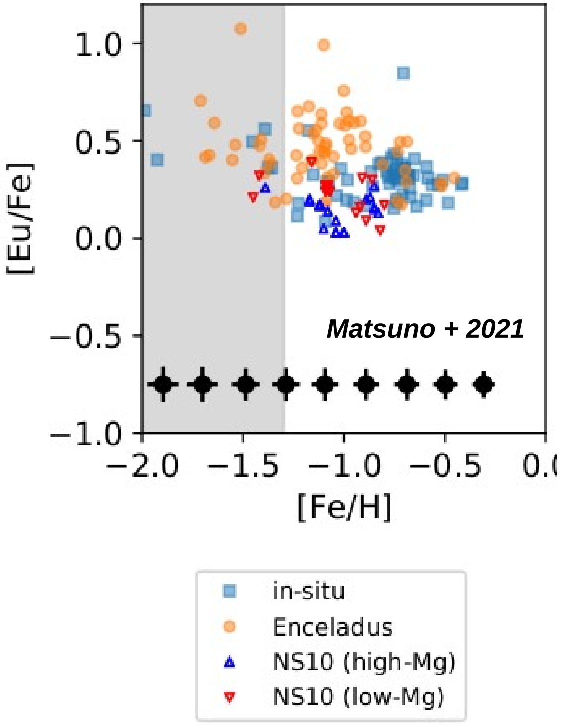
[Eu/Fe] → higher in accreted populations



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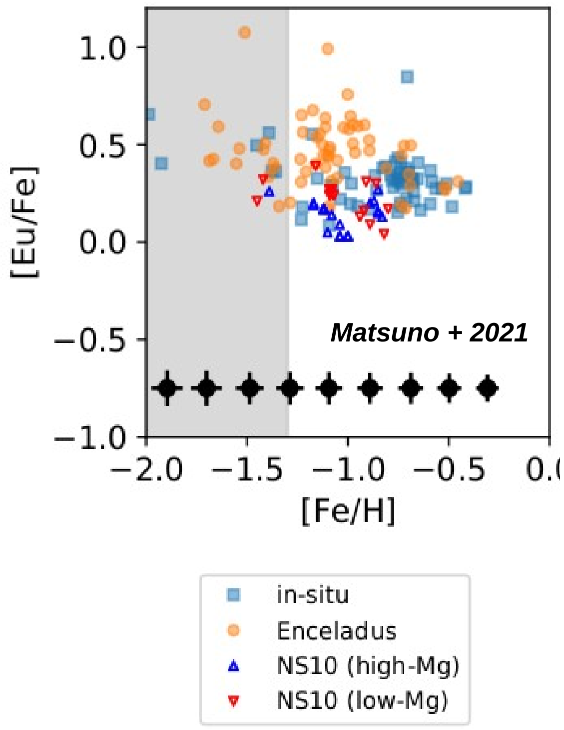
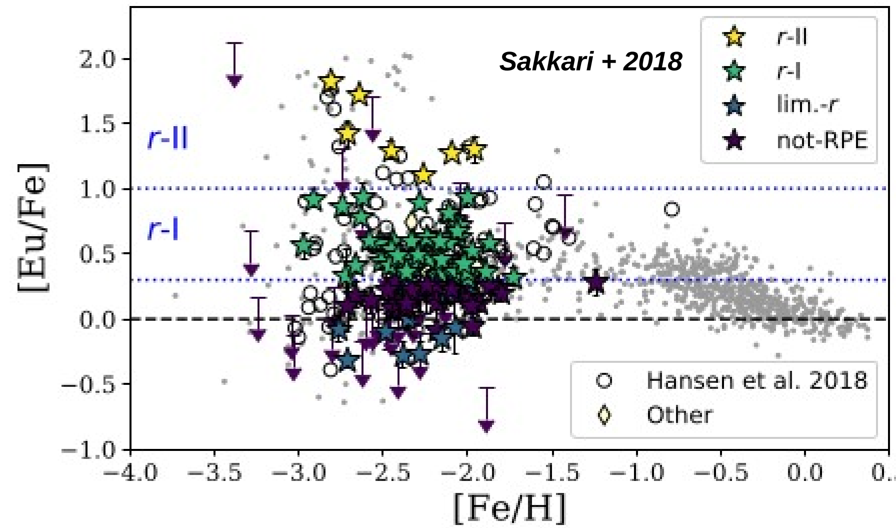
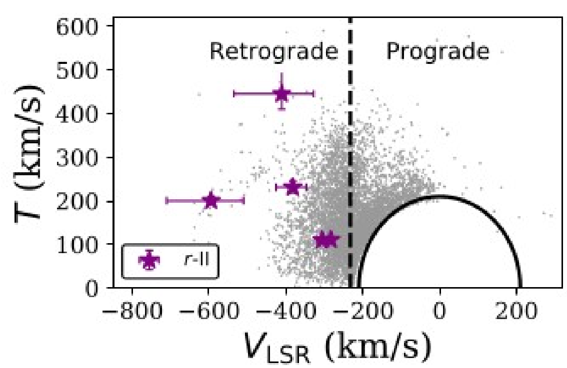
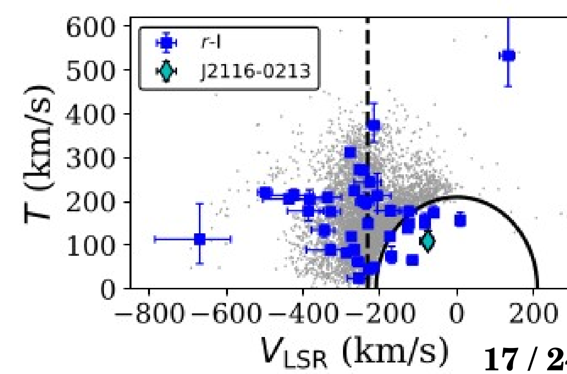


Enhanced [Eu/Fe] → retrograde orbits (Lz>0)







- Complete table AMBRE – Selection of potential accreted population

> FEROS (R = 48000)
(Worley et al. 2012)

> HARPS (R ~ 115000)
(De Pascale et al. 2014)

> UVES (R ~ 47000)
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Lz > -1 [10^3 kpc km s^{-1}] & **Eorb > 0** **(Helmi + 2018 , Naidu + 2020)**

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370 "accreted" stars:
- **25 HARPS**
- **256 UVES**
- **89 FEROS**

Selection "in-situ" with similar parameters:
- Teff ± 100 K; logg ± 0.1; [M/H] ± 0.1; [alpha/Fe] ± 0.1
- SNR > 100
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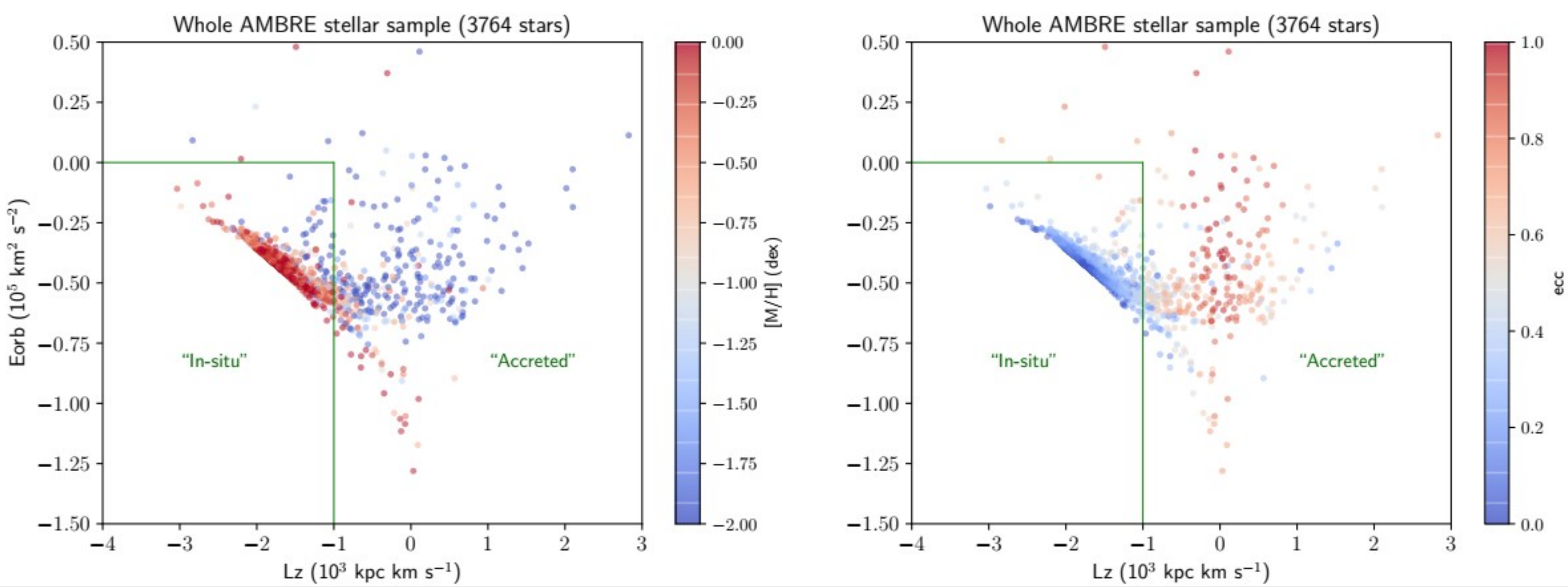

➢ Results (II): Neutron-capture elements Eu/Sr

- **Line selection:** **Eu II (Å):** 4129.72 6645.13 **Sr II (Å):** 4215.52

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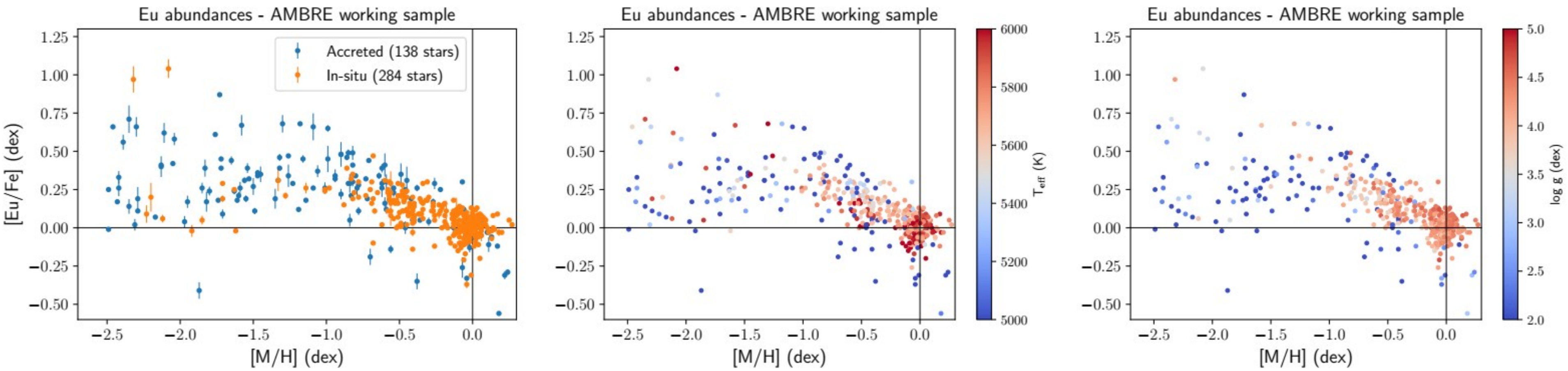

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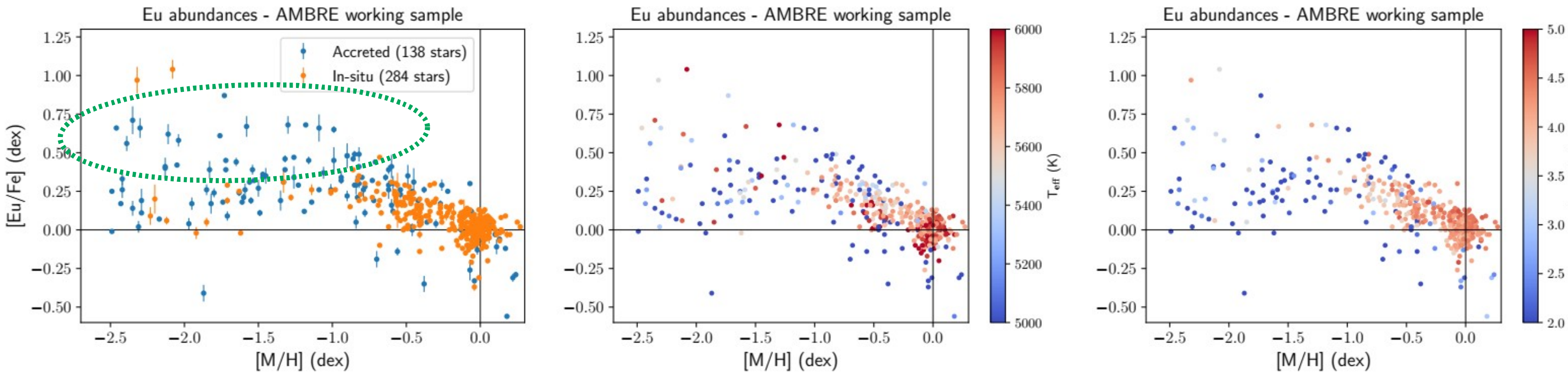

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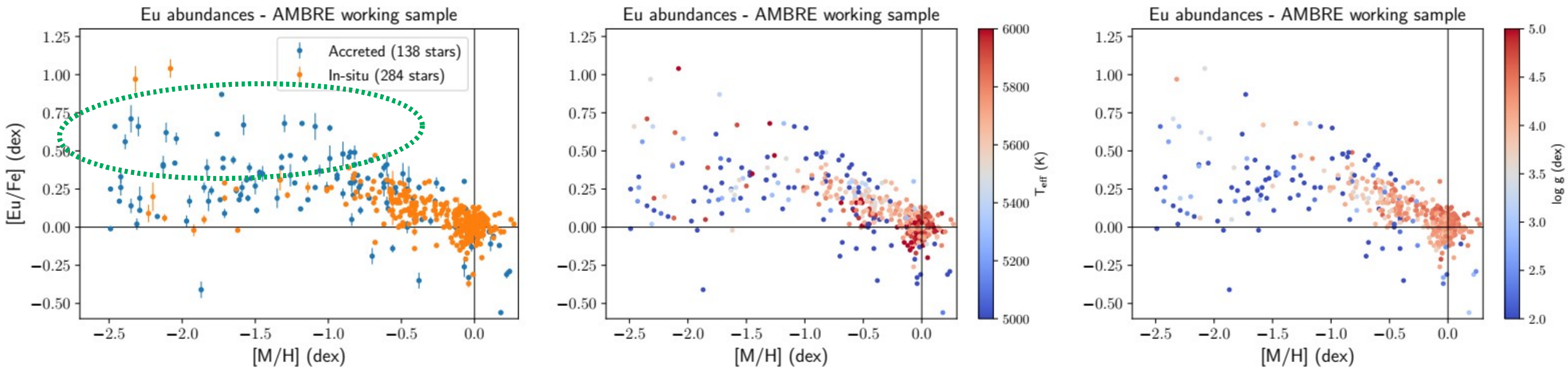

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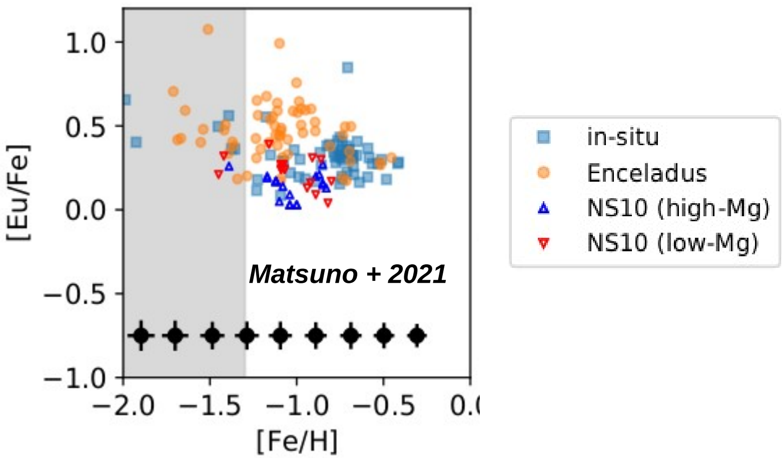

Good agreement with results from the GALAH DR3 survey

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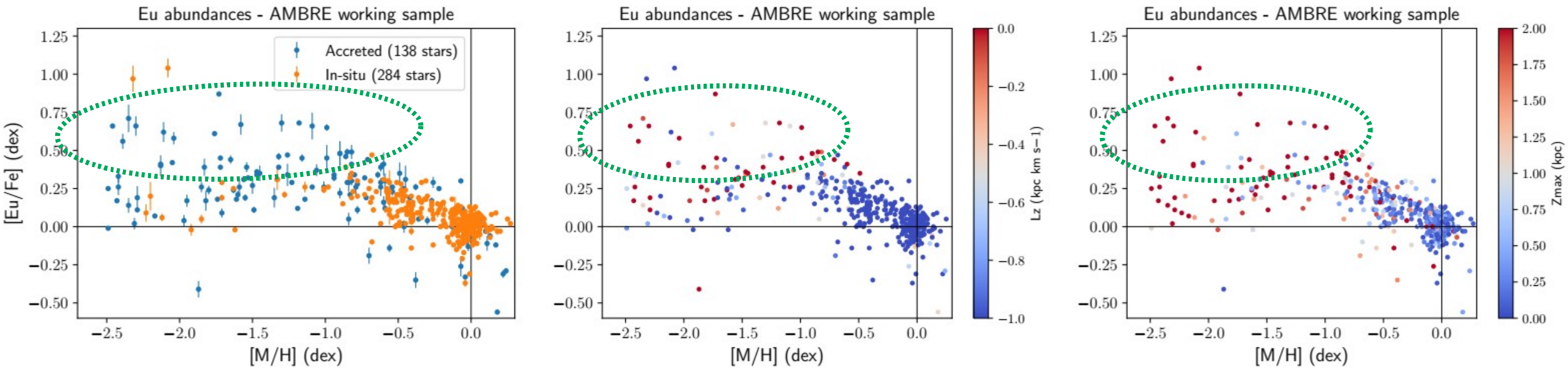

Possible correlation of [Eu/Fe] with Lz, and higher Zmax

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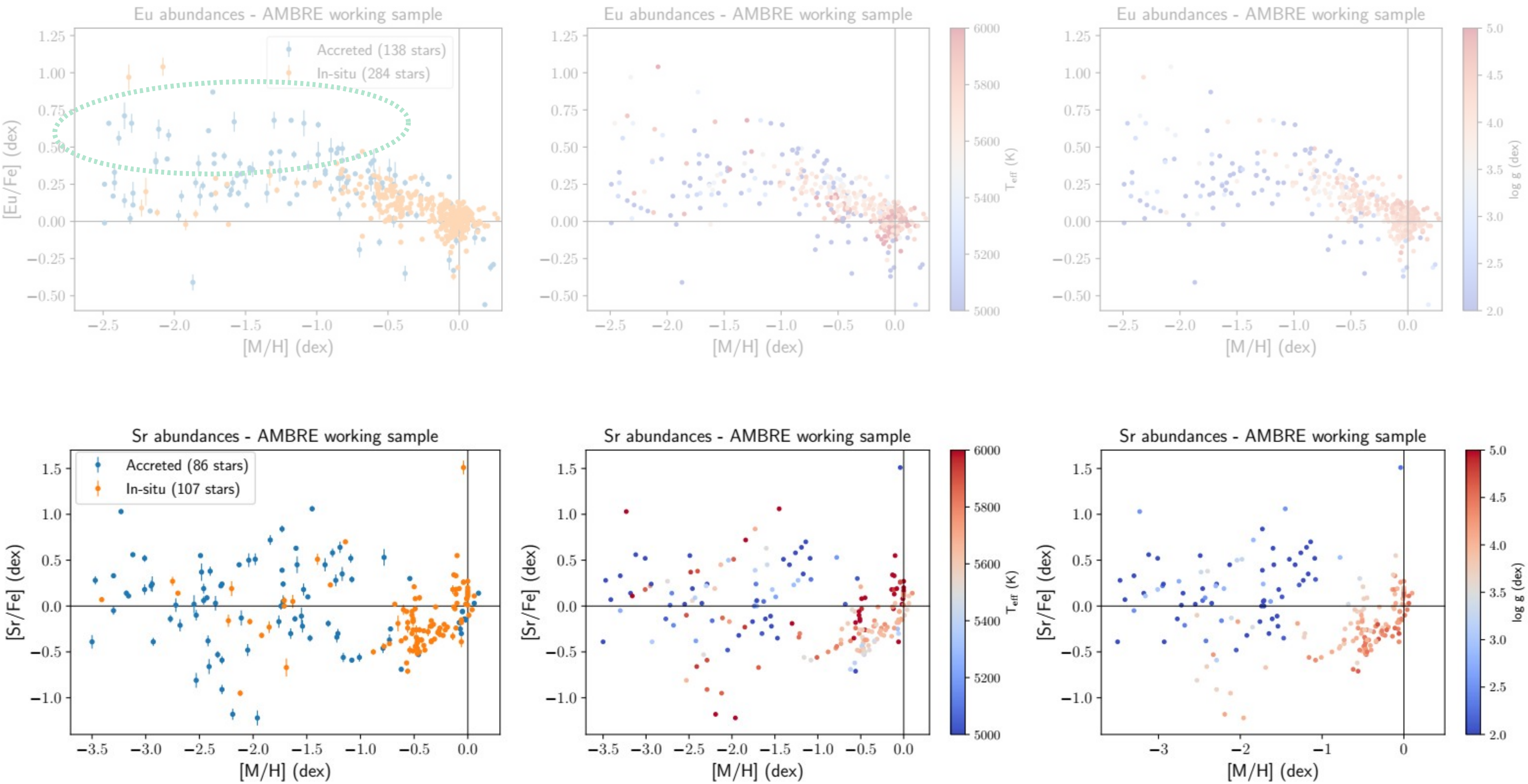

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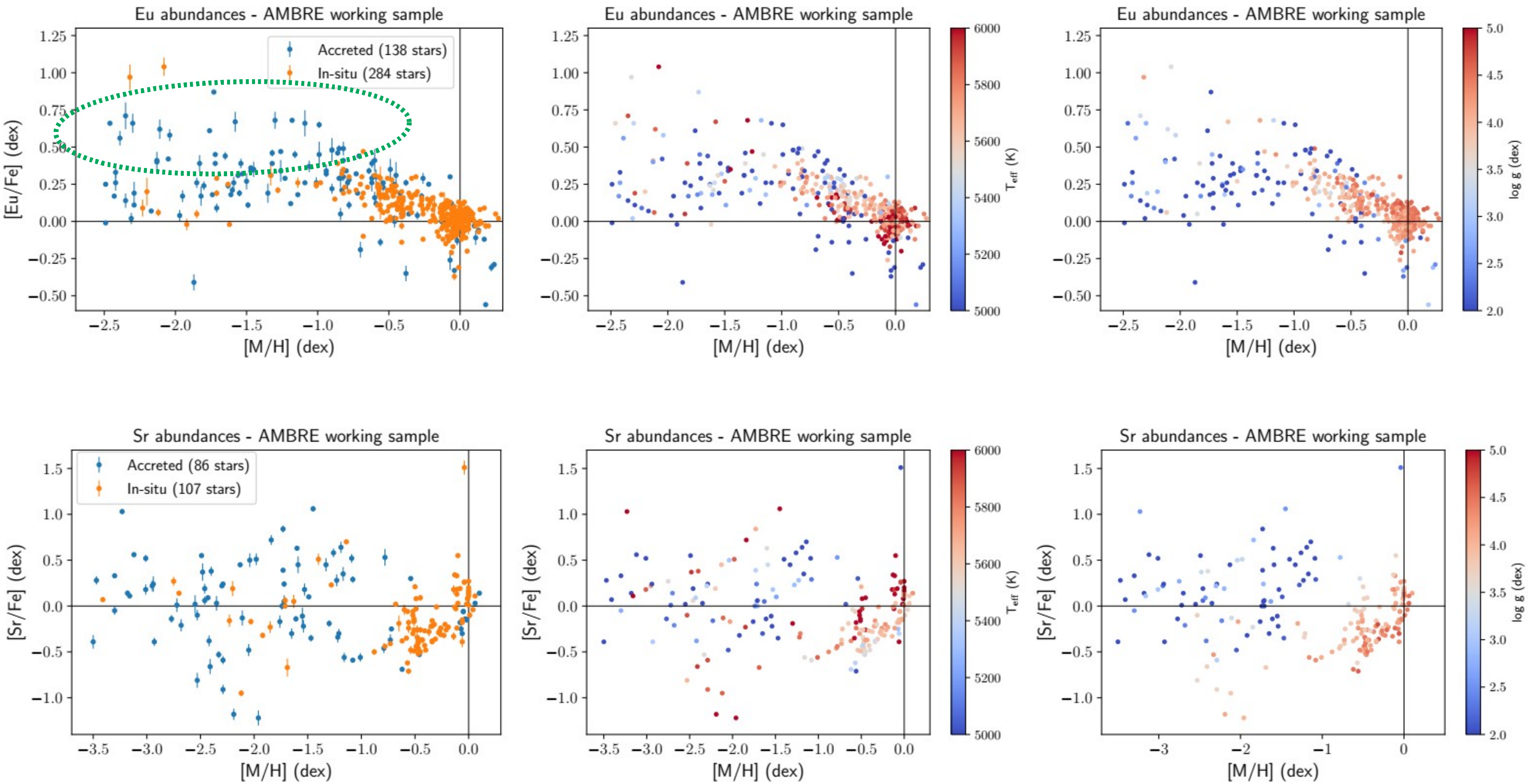

- Comparison with chemical evolution models of Marta Molero (work in progress, see Molero et al. 2021, 2023)

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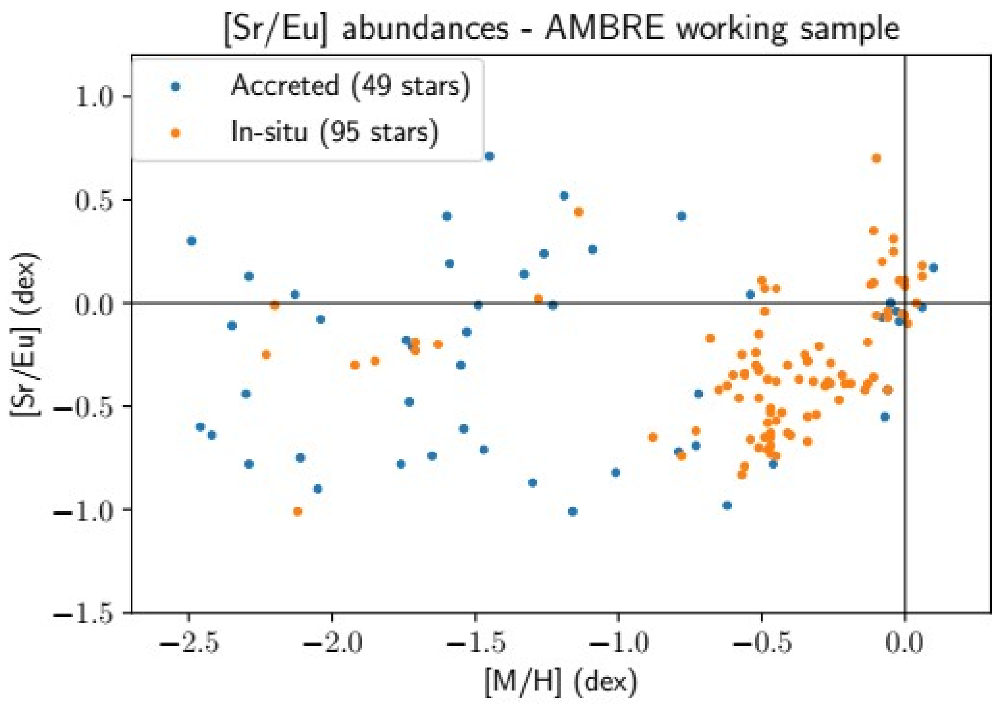

We do not observe that the s- and r-process ratio, [Sr/Eu], provide any remarkable insight into the chemical evolution histories of the different samples

No clear differences between the accreted vs. in-situ populations

Outline:

Introduction

Data & Methodology

- Automatic spectral synthesis code GAUGUIN for deriving abundances
- The AMBRE observational data sample
- Gaia DR2+EDR3+DR3: photometry, astrometry and distances → Stellar ages and orbital properties

Results

I. [Mg/Fe] in the Galactic disc

- Precise [Mg/Fe] vs [Fe/H] (Santos-Peral et al. 2020)
- Chemical structure of the Galactic disc → formation and evolution
- Chemodynamical trends: age-abundance relations, radial gradients
  (Santos-Peral et al. 2021)
- Comparison with Chemical Evolution Models (Palla et al. 2022)

II. [Eu/Fe] & [Sr/Fe] in Milky Way disc and halo

- Heavy elements Eu/Sr as signatures of accreted populations (Santos-Peral et al., will be submitted soon)

Conclusions

➢ Conclusions:

I. Santos-Peral et. al. 2020

Analysis of [Mg/Fe] abundance estimate from observed spectra from ESO:HARPS (R = 115000), AMBRE Project

- **Optimisation of the continuum normalisation for each stellar type and spectral line**
- **Decreasing trend of [Mg/Fe] even at supersolar metallicities ([M/H] > 0).**

  Solving discrepancies between observations and chemical evolution models (CEM) (e.g. Palla et al. 2020)

II. Santos-Peral et. al. 2021

Exploration of observed chemodynamical relations over 366 MSTO stars with Gaia DR2 data and ages

- **Steeper [Mg/Fe] radial gradient in the disc compared to the literature.**
- **Appearance of the thin disc sequence (low-[Mg/Fe]) in the external regions, 10-12 Gyr ago with [M/H] < -0.4, probably linked to external metal-poor gas accretion.**

III. Palla et. al. 2022

Comparison with two-infall and parallel Chemical Evolution Models

- **Metal-poor low-Mg** stars from **outer regions**
- **Super Metal-rich** stars from **inner parts**
- **Larger proportion of gas in the second infall could explain the low-Mg metal-poor sequence**