The origins of stellar populations in the Milky Way halo revealed by precise chemical abundances

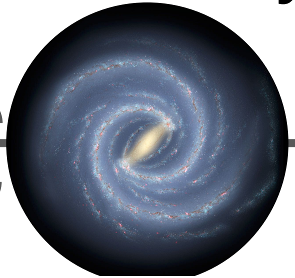
Tadafumi Matsuno*
(ARI/ZAH, Universität Heidelberg)

In collaboration with Dodd, E., Helmi, A. (Kapteyn Institute), Amarsi, A. (Uppsala), Aoki, W., Ishigaki, M. N. (NAOJ), Li, H.-N., Zhang, R.-Z. (NAOC) et al.

*Gliese fellow

Kinematic substructures in the Milky Way

Big Bang | Thick disk | Thin disk | Present day



-13.8 Gyr

~ -10 Gyr
z ~ 2

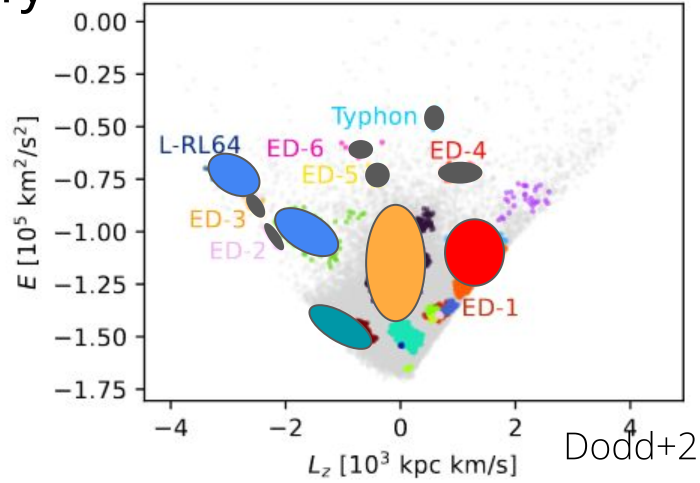
Quiet history

Gaia-Enceladus
The last major merger

Thamnos   Sequoia   Helmi Streams
Accretion remnants

ED streams, typhon, LMS-1, C-19, etc.
Accretion remnants or disrupted globular clusters

Ruiz-Lara+22



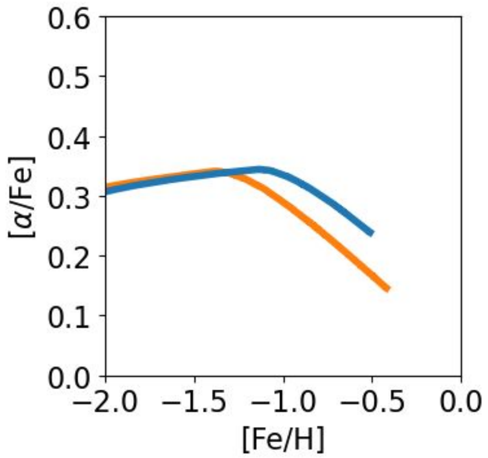
Dodd+23

Chemical abundance of stars

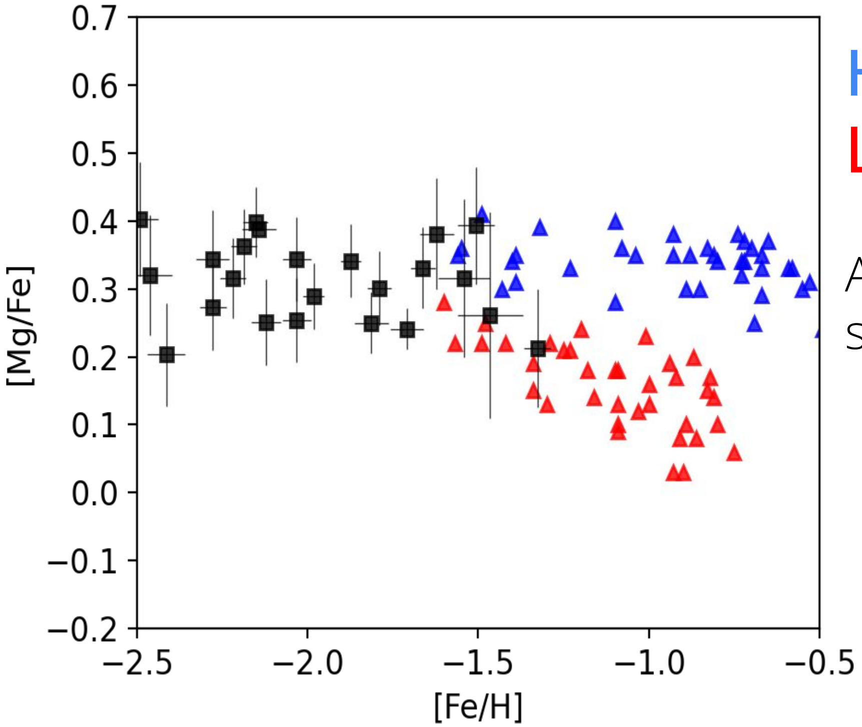
A more massive galaxy forming stars efficiently
A less massive galaxy

Chemical abundances reflect galaxies’ star formation histories

- Does each substructure correspond to and contain a single accreted galaxy?
- What is the star formation history of the accreted galaxies?



Chemical abundance of major substructures



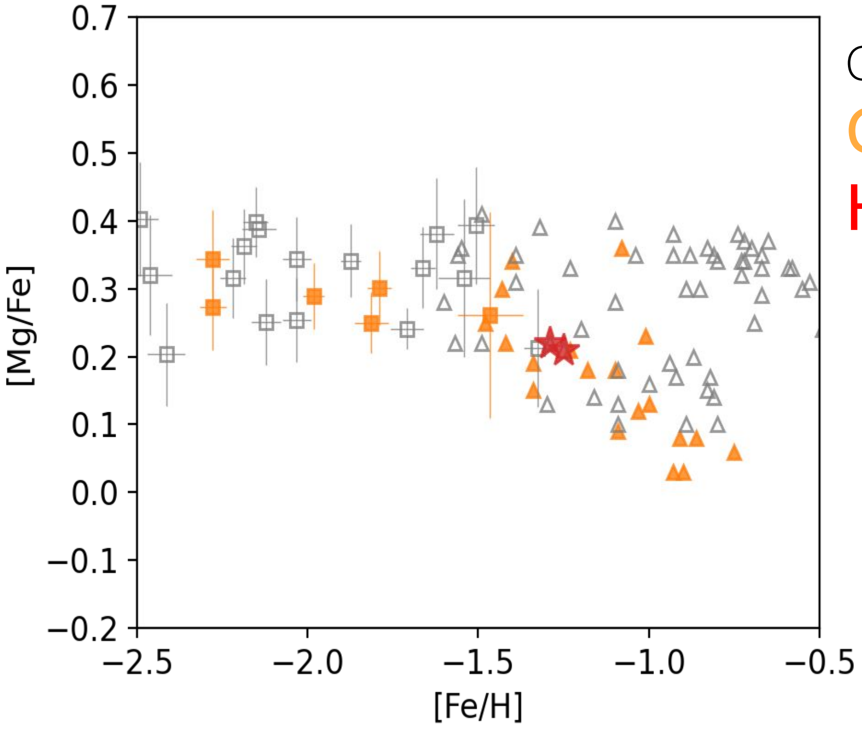
High-α: in-situ stars

Low-α: accreted stars

A larger contribution from type Ia supernovae are seen among low-α stars

Data from Nissen & Schuster (2010) & Reggiani et al. (2017)

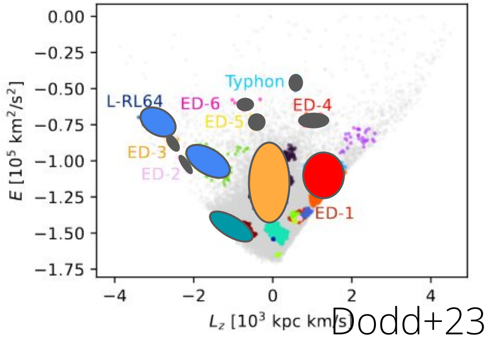
Chemical abundance of major substructures



Classification based on kinematics

Gaia-Enceladus

Helmi streams



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Matsuno et al. (2022a, b)

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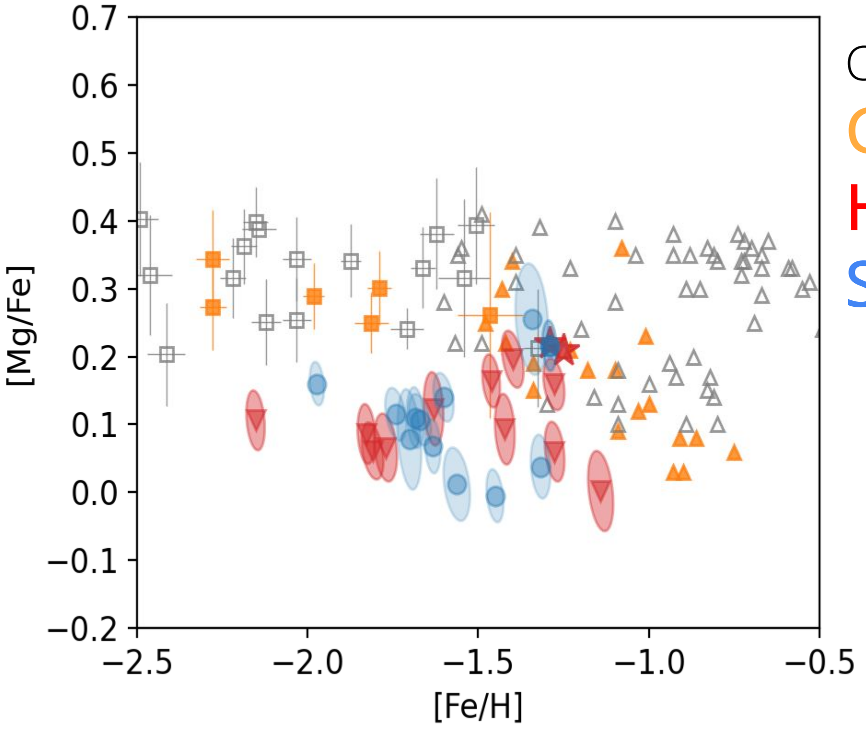

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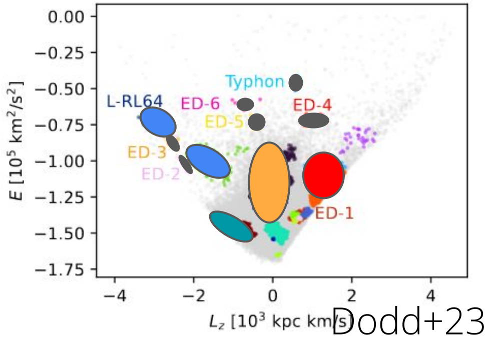

Dodd+23

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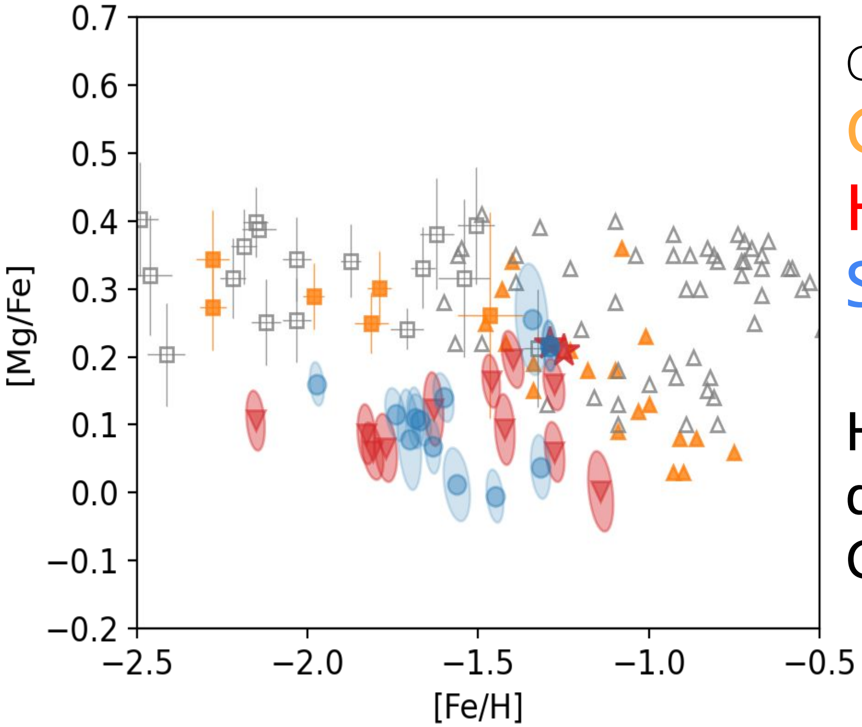


Classification based on kinematics

Gaia-Enceladus

Helmi streams

Sequoia

Helmi streams & Sequoia have distinct abundance patterns than Gaia-Enceladus or other MW stars

Data from Nissen & Schuster (2010) & Reggiani et al. (2017), Matsuno et al. (2022a, b)

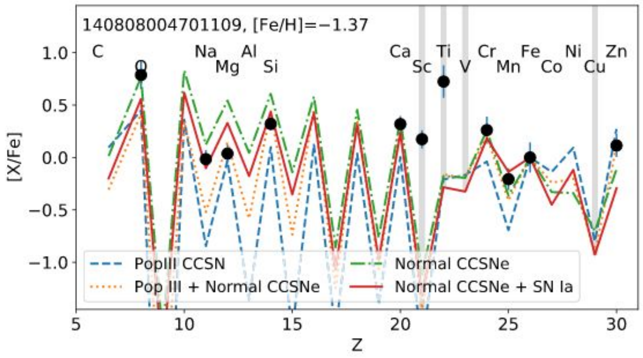
Chemical abundance of major substructures

We fit abundance patterns of individual objects (see Ishigaki+21)

<u>Parameters</u>

- α (slope in IMF)
- Z_{CC}(Representative metallicity of CCSNe)
- **N_{Ia}/N_{CC}**

The number ratios between SNIa and SNII



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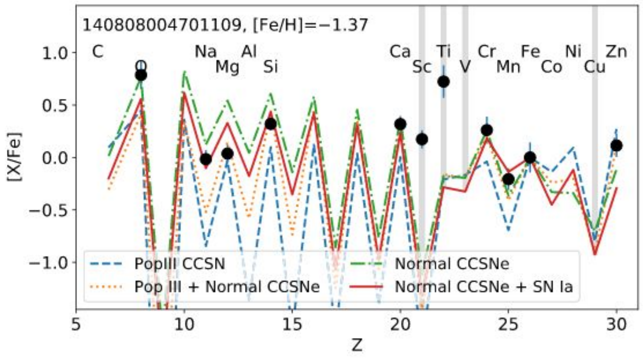
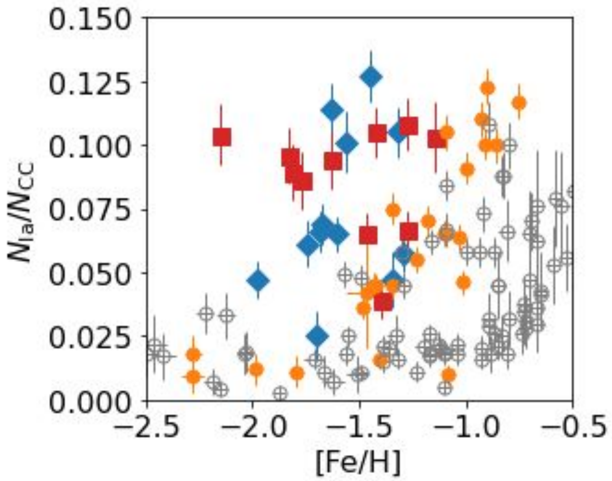


Gaia-Enceladus Sequoia
Helmi Streams Other halo stars



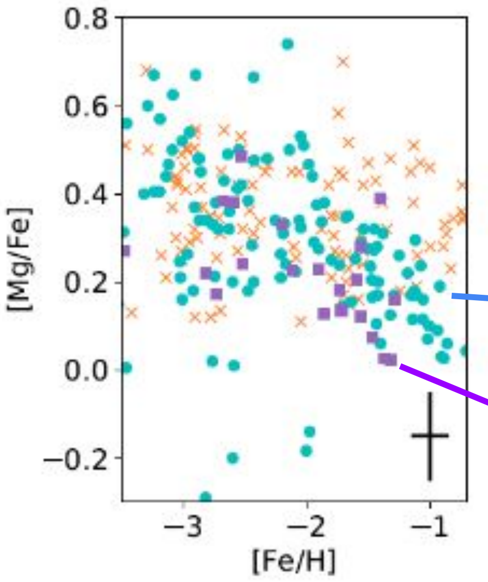
Large type Ia contributions in Sequoia and Helmi streams

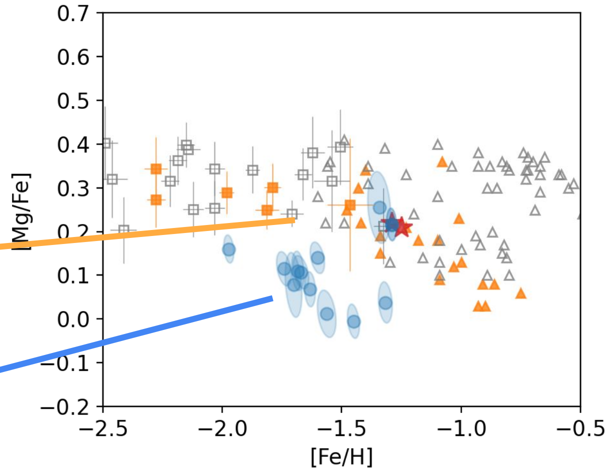
Matsuno et al. (2022a, b)

Precise abundance is the key

Matsuno+19

This study (Matsuno+22a)



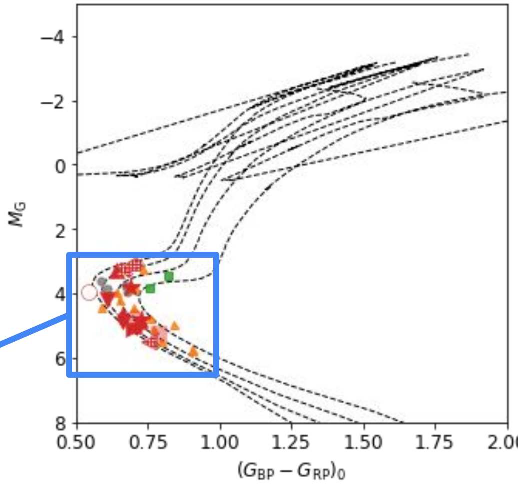


Gaia-Enceladus

Sequoia

Data from the SAGA database

Matsuno+22a, b

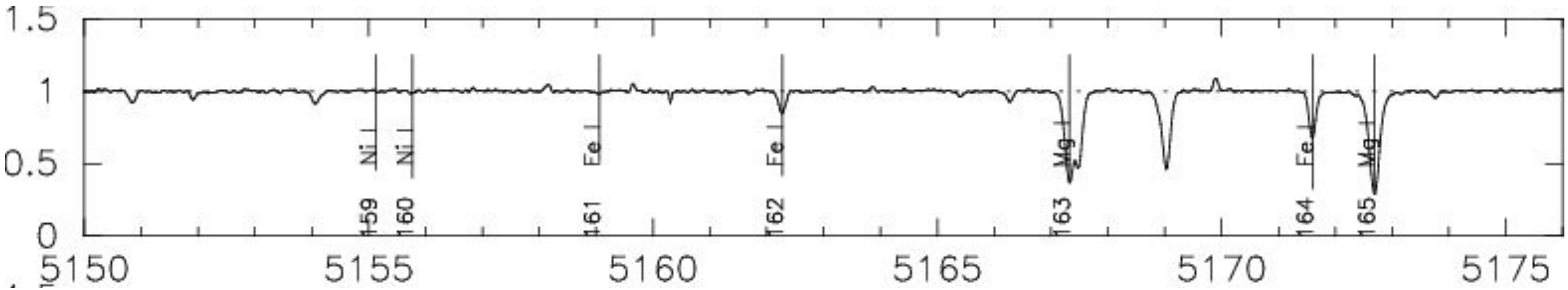


To achieve high-precision

- ★ High-S/N, high-resolution spectra

  R ~ 80,000, S/N (per pix) > 100

- ★ Narrow stellar parameter range
- ★ Differential abundance analysis to minimize the effect of input data
- ★ Reanalysis of the literature sample



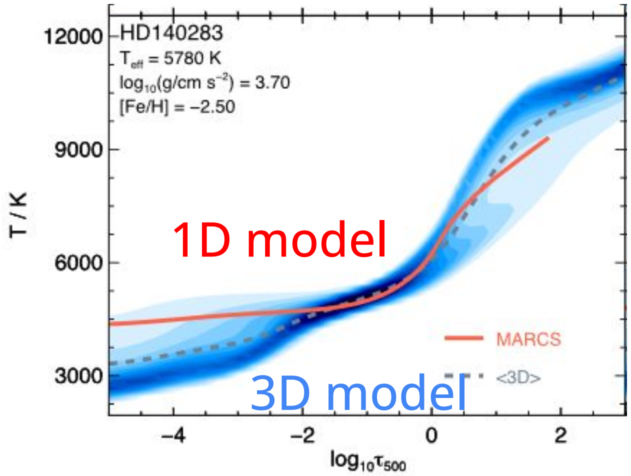
More realistic abundance measurement

★ Local thermodynamic equilibrium (LTE)

➡ non-LTE

★ 1D model of stellar atmosphere

➡ 3D models

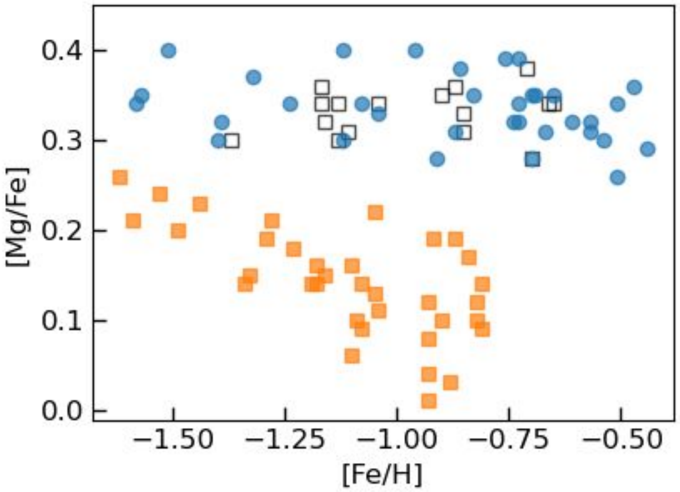


What do we gain by going to 3D/non-LTE analysis?

Matsuno, Amarsi et al. (2024)

3D non-LTE Mg abundance of halo stars

1D LTE

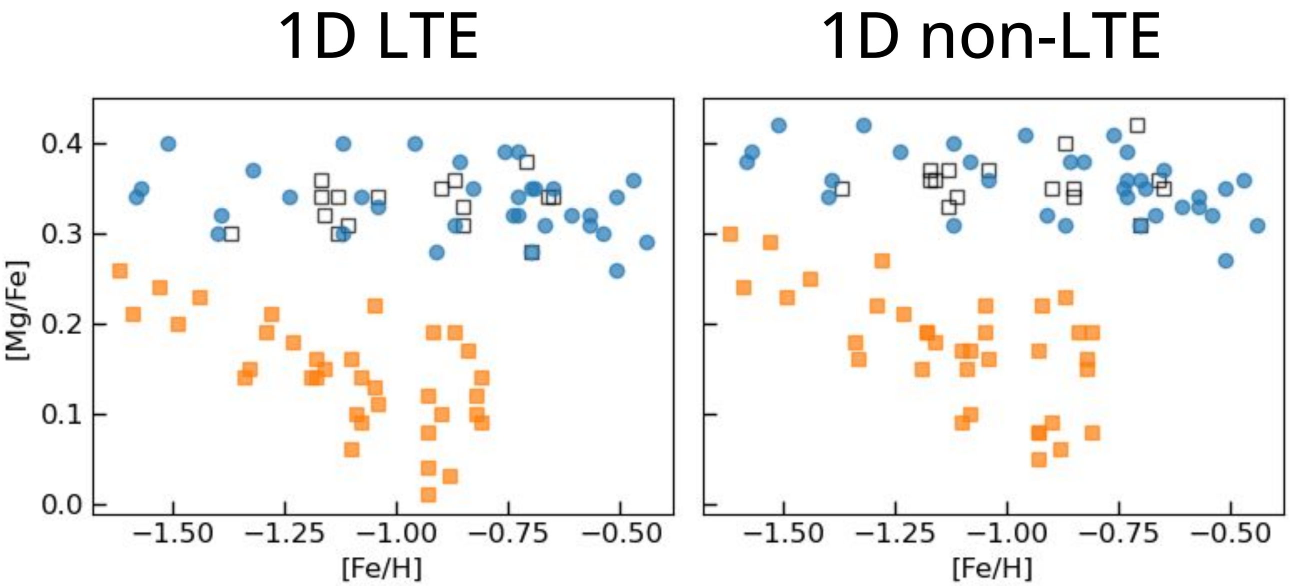


High-α+thick disk: in-situ stars
Low-α: accreted stars

Sample from Nissen & Schuster (2010)

Matsuno, Amarsi et al. (2024)

3D non-LTE Mg abundance of halo stars



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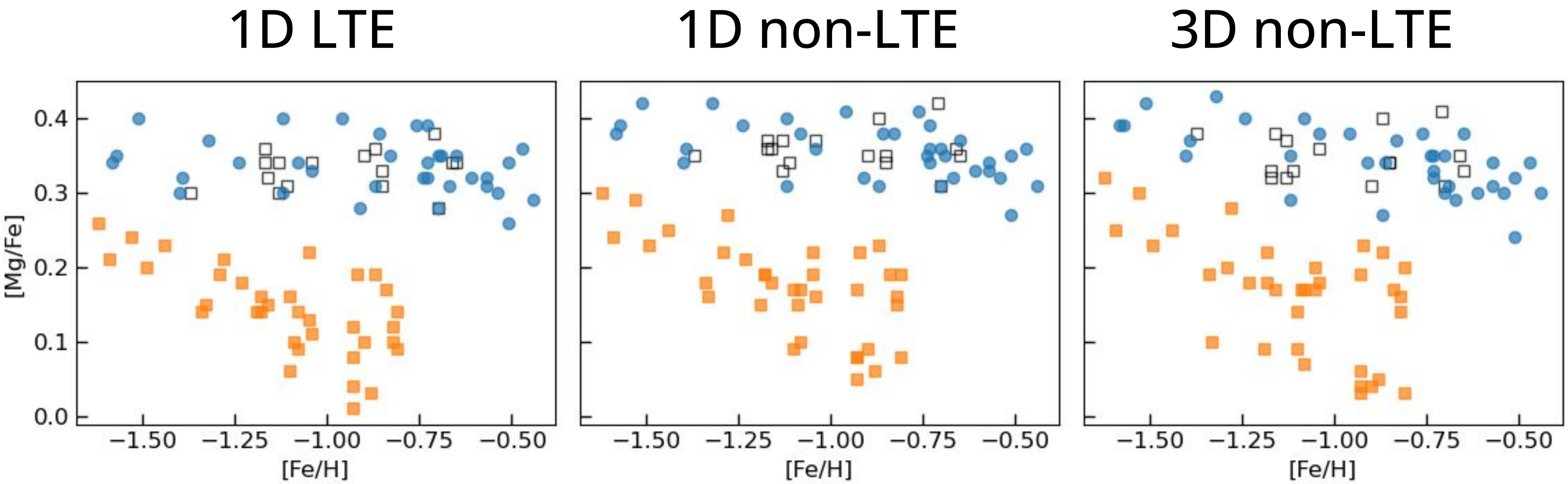

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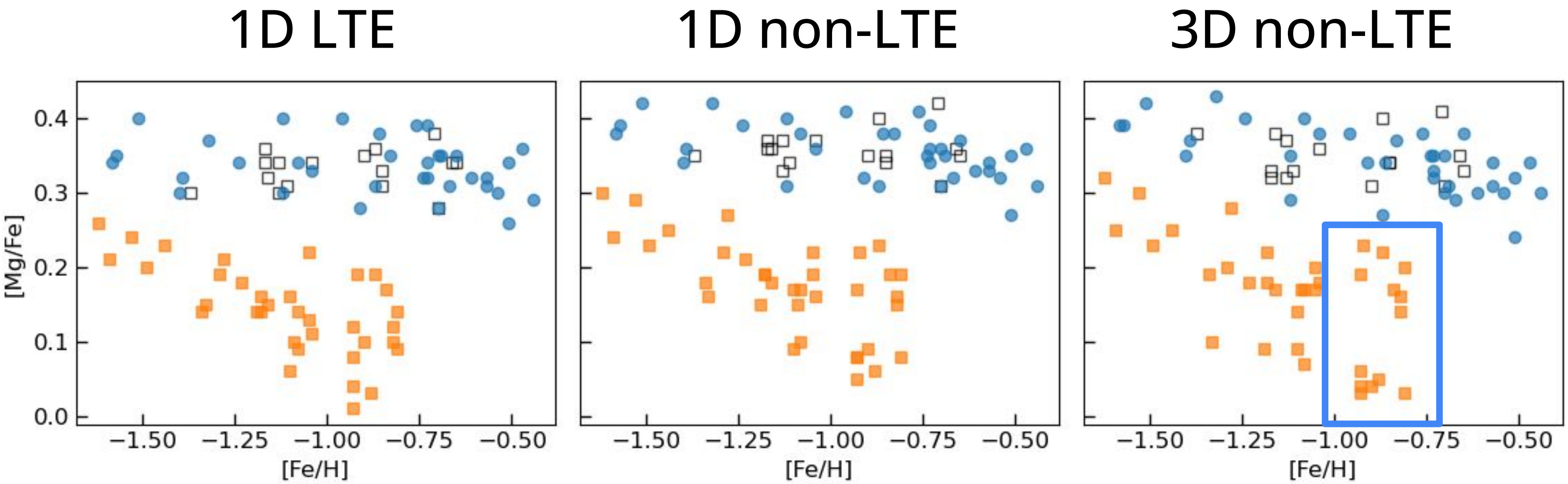

The metal-rich end of low-α stars splits into two

Sample from Nissen & Schuster (2010)

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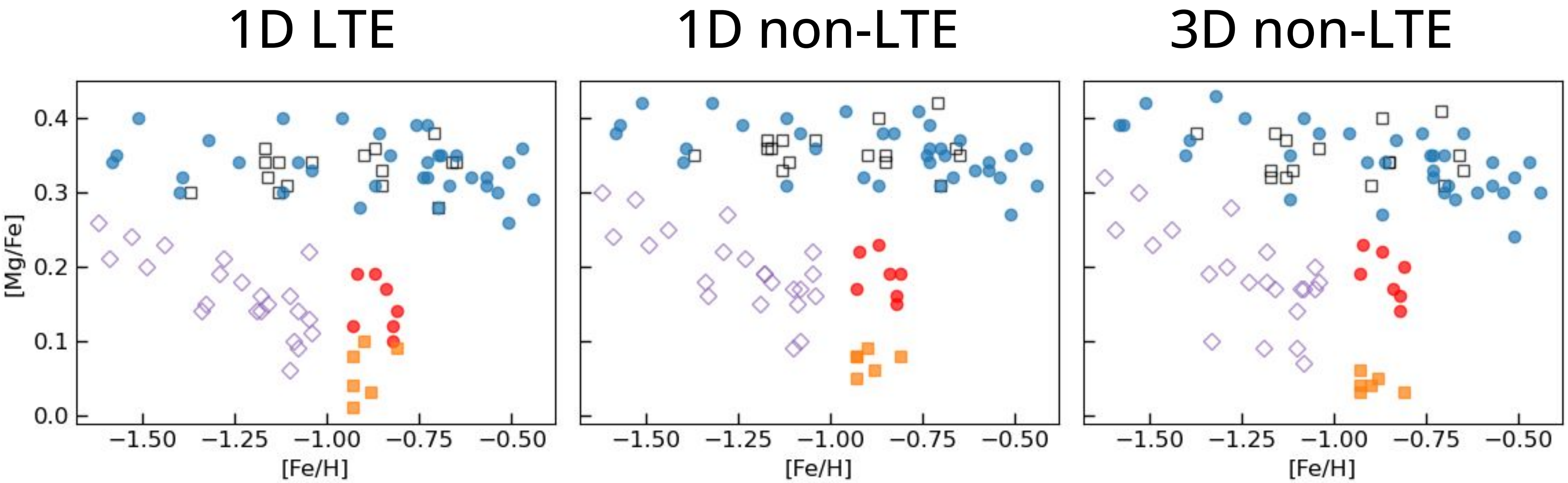
A new population revealed from 3D non-LTE analysis



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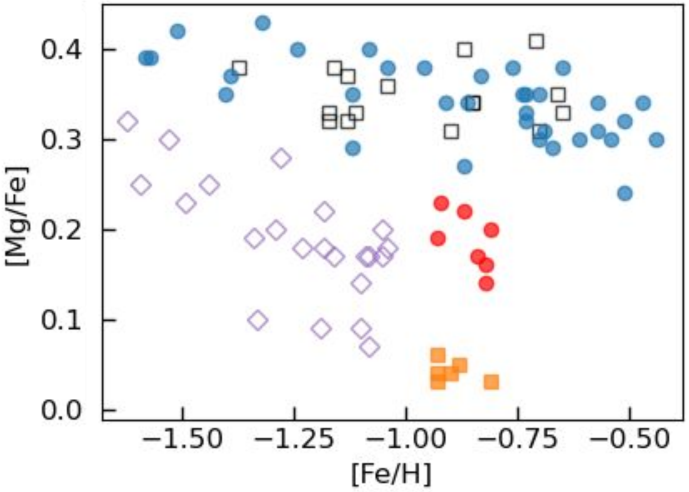
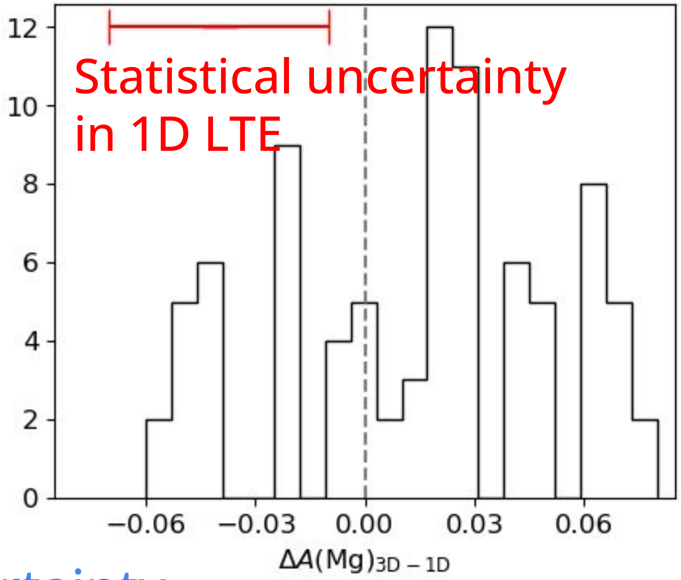
Why has the separation been hidden?

3D non-LTE



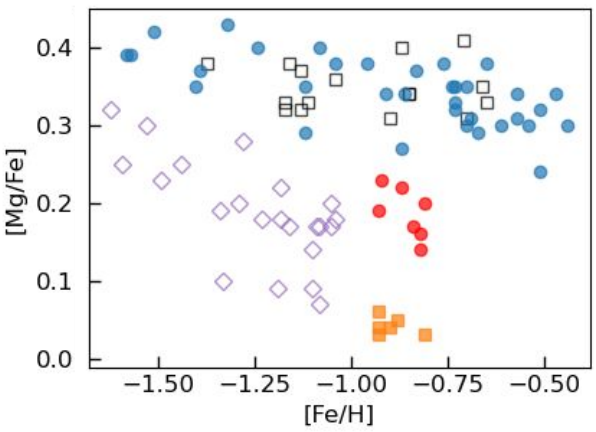
The amplitude of 3D non-LTE — 1D LTE correction



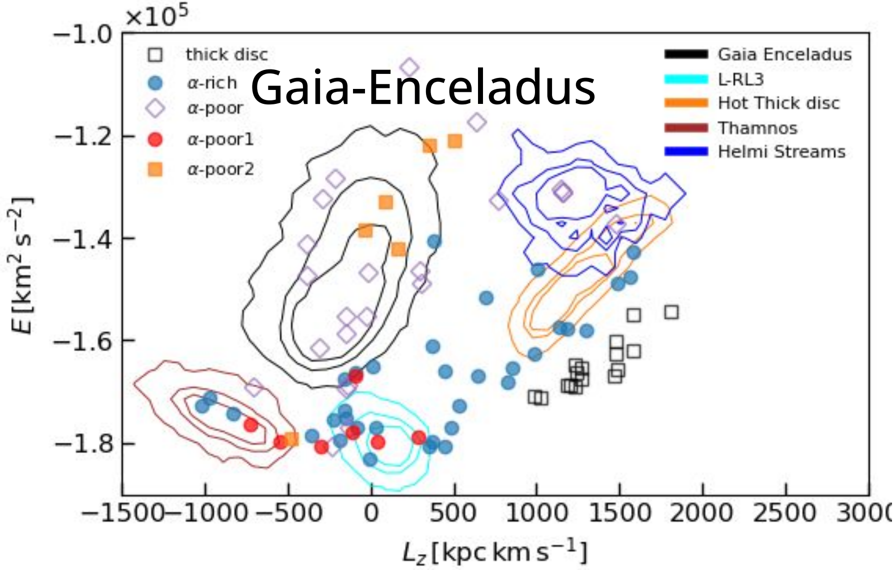
3D non-LTE correction ~ statistical uncertainty

The origin of the new populations

[Mg/Fe]



Kinematics



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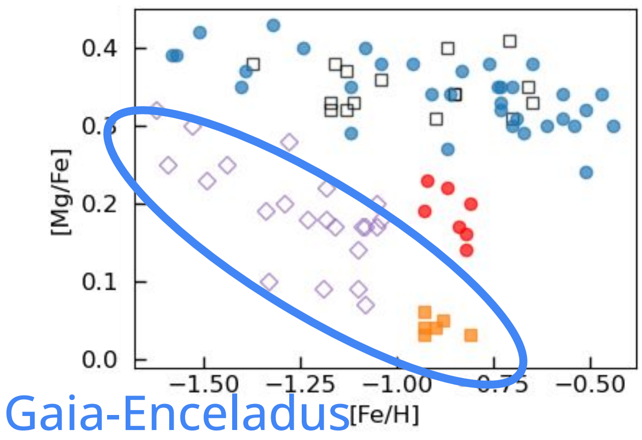

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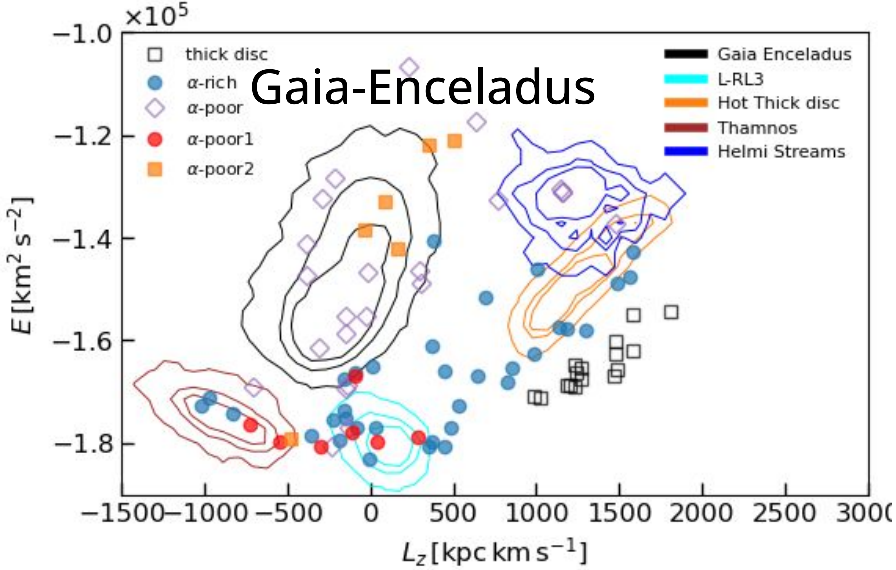


The lowest-Mg population is part of Gaia-Enceladus

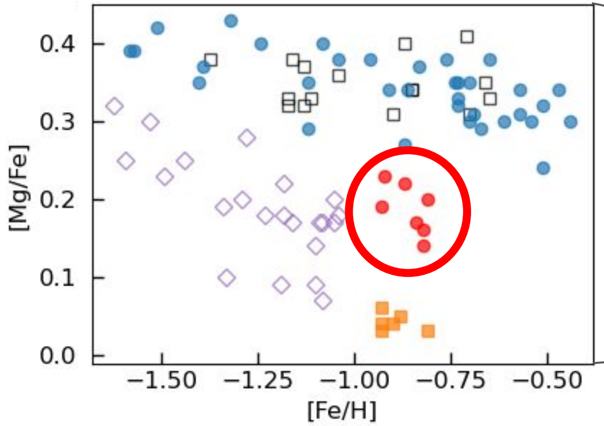
Matsuno, Amarsi et al. (2024)

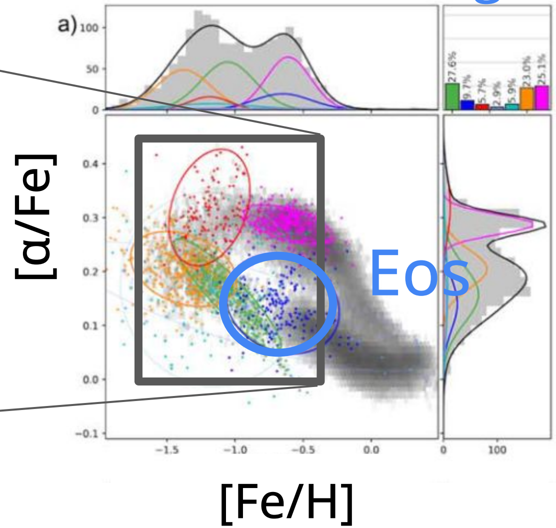
The origin of the new populations

Our work

Myeong et al. (2022), see also Ortigoza-Urdaneta+23

APOGEE + clustering analysis in multi-dimension





★ Eos resembles our intermediate-Mg population in abundance

Matsuno, Amarsi et al. (2024)

The origin of the new populations

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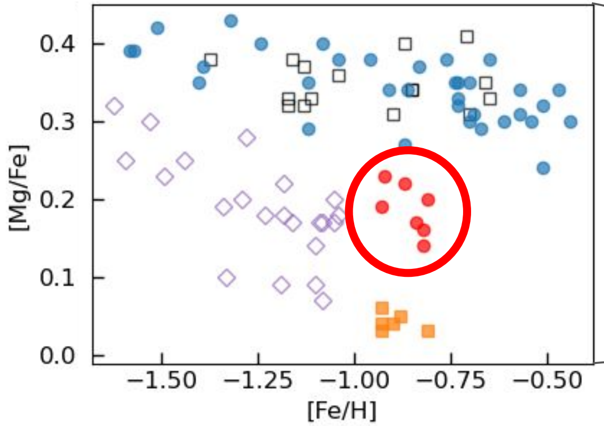

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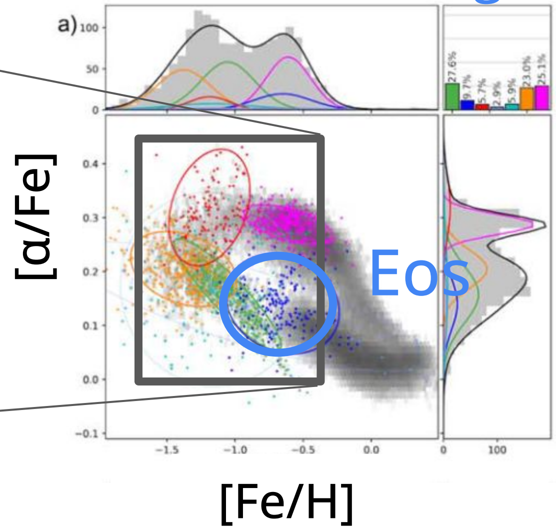
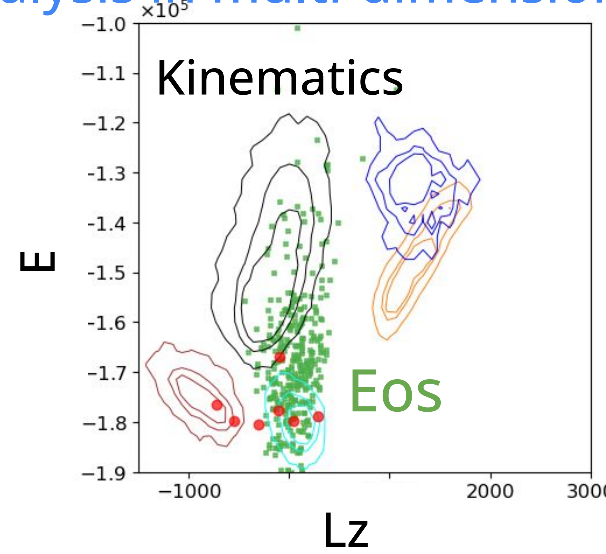




- ★ Eos resembles our intermediate-Mg population in abundance
- ★ Overlap in kinematics, but there are statistically significant differences

A larger sample with precise and accurate abundances are needed

What is missing?

★ **Heavy elements**

e.g., Y, Eu

★ **Larger sample from surveys**

GALAH, APOGEE + 4MOST, WEAVE

★ **Lower metallicity**

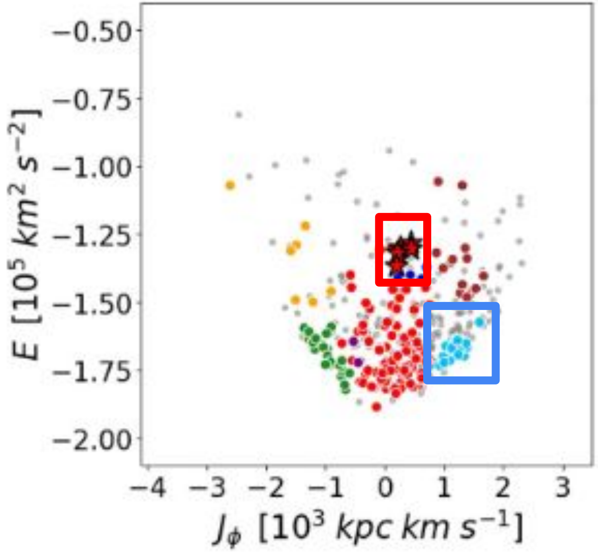
Tracer of smaller building blocks

Zhang, Matsuno et al. (2024)

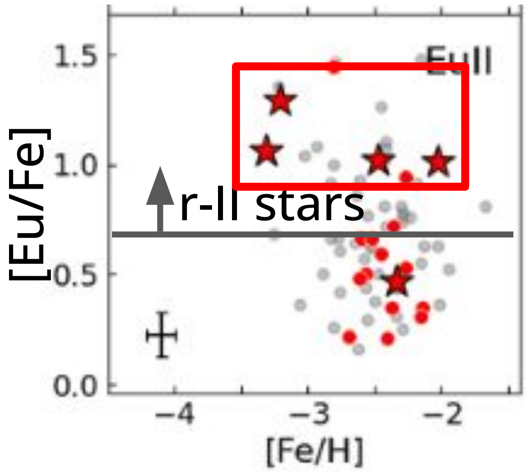
The low-metallicity end of the Galactic building blocks

Kinematic analysis of 385 VMP stars ([Fe/H] < -2)

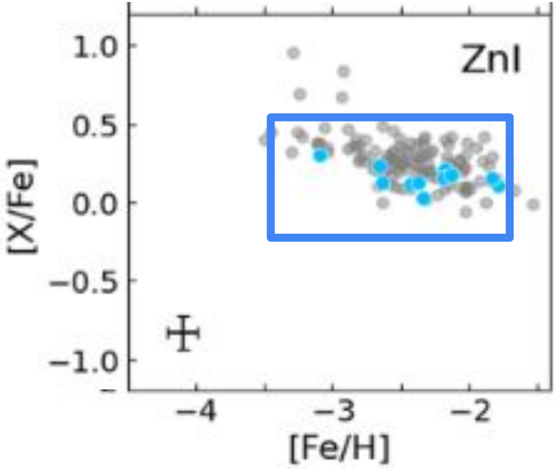
Kinematics



R-rich subgroup in GES



Slightly low-Zn abundance of VMPD



Matsuno et al. (2022a, b)
Matsuno, Amarsi et al. (2024)
Zhang, Matsuno et al. (2024)

Summary

★ Major kinematic substructures show distinct chemical abundances

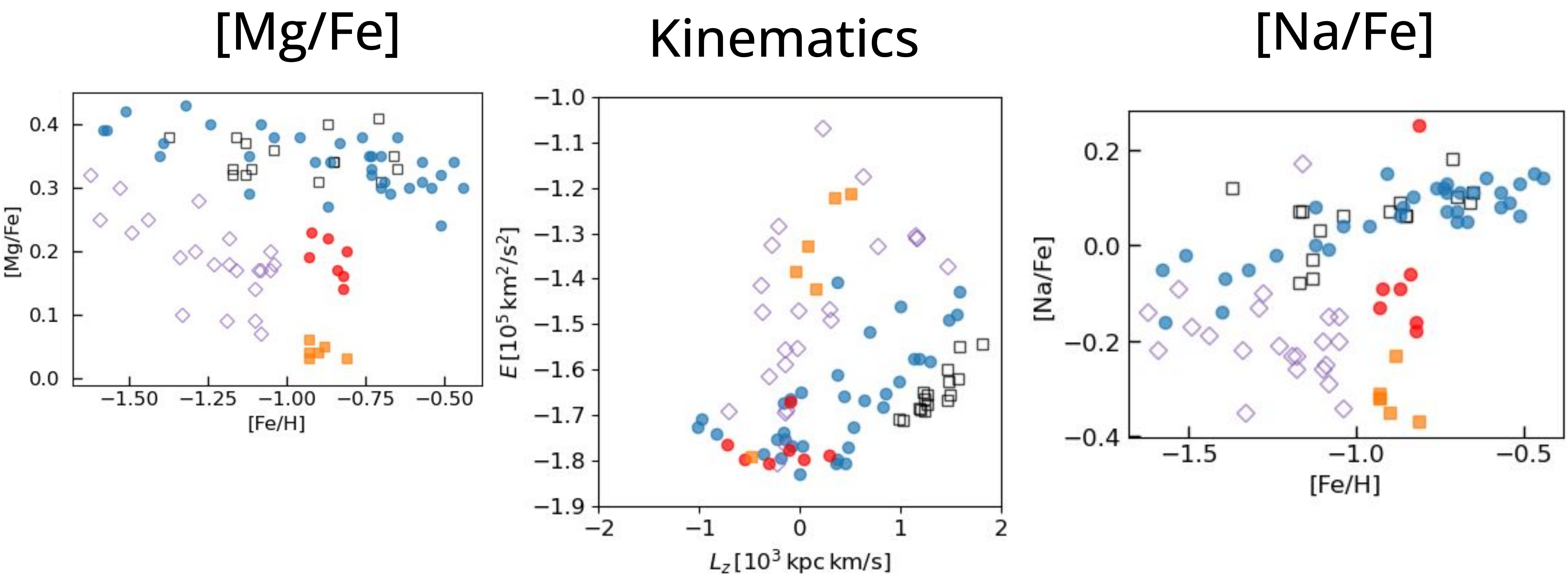
★ Abundance needs to be precisely measured

★ 3D non-LTE analysis allows us to achieve even higher precision and to detect hidden populations

★ There are still a lot to explore – n-capture elements, very meta-poor regime, larger samples

Matsuno, Amarsi et al. (2024)

A new population revealed from 3D non-LTE analysis



The two subpopulations differ in kinematics as well as [Na/Fe]

Matsuno, Amarsi et al. (2024)

The origin of the new populations

Our work

Ortigoza-Urdaneta+23

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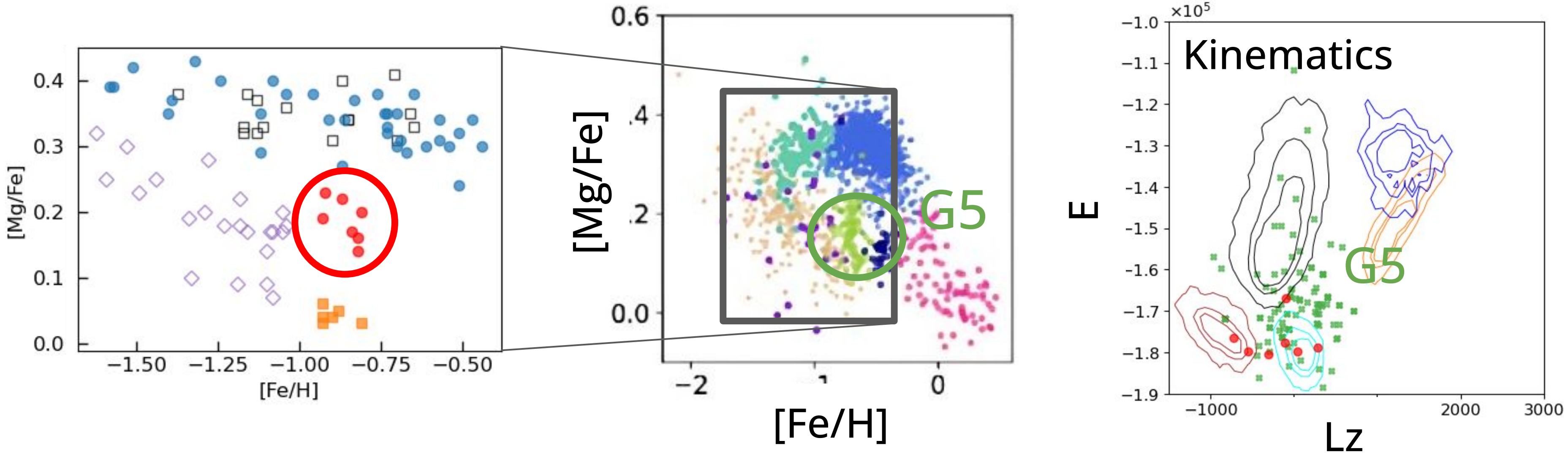
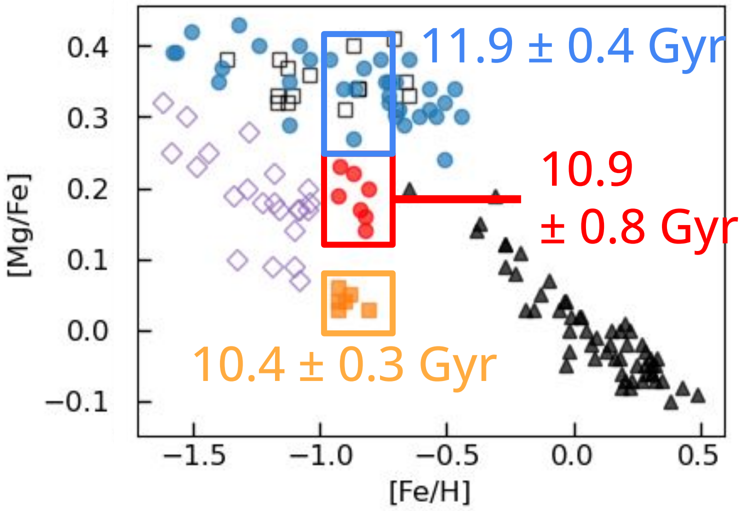


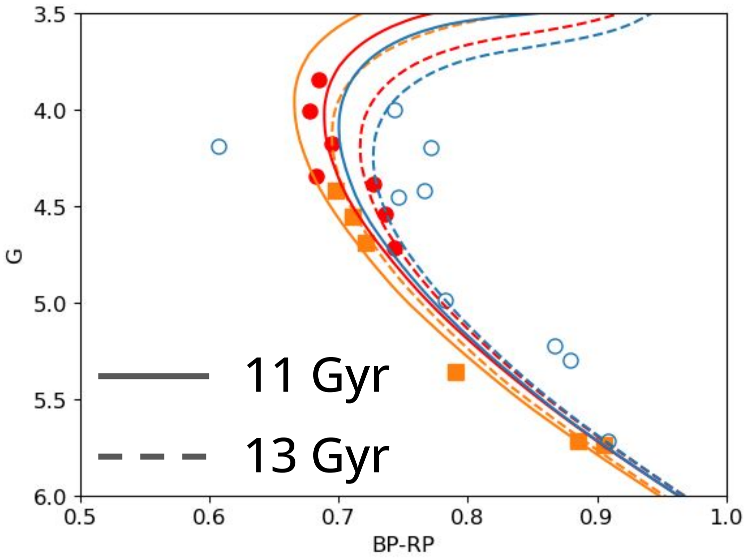
★ G5 resembles our intermediate-Mg population in abundance

★ Overlap in kinematics, but there are statistically significant differences

A larger sample with precise and accurate abundances are needed

Ages of the stars





*Age is from Schuster+12