kapteyn astronomical institute

Chemical evolution of disrupted dwarf galaxies in the Milky Way

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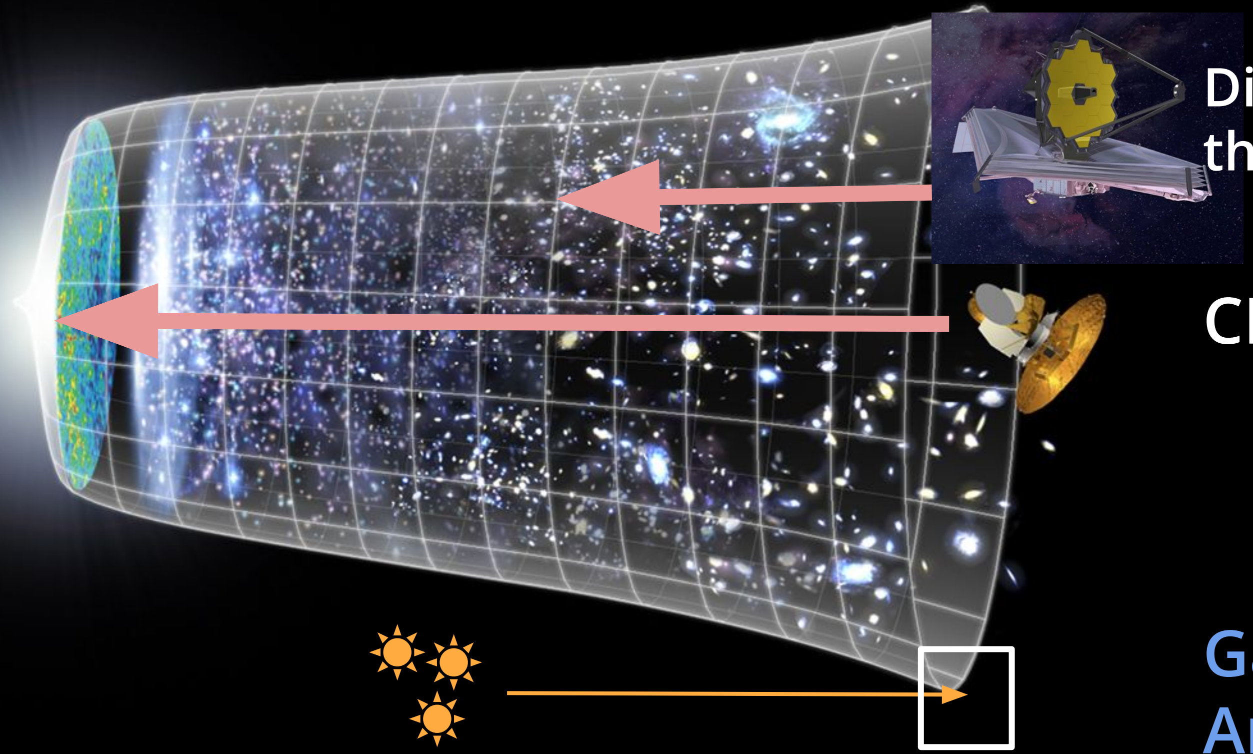


Direct observation of the high-z Universe

CMB

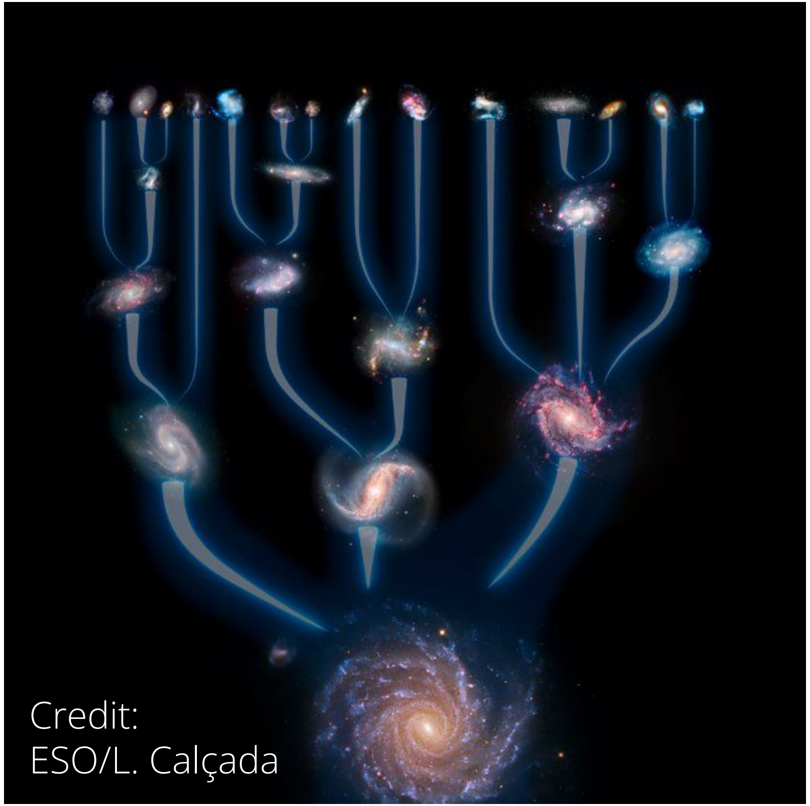
Galactic Archaeology

Low mass stars formed in the early Universe

Local universe (Milky Way)

Credit: NASA/WMAP

Galaxies evolve hierarchically



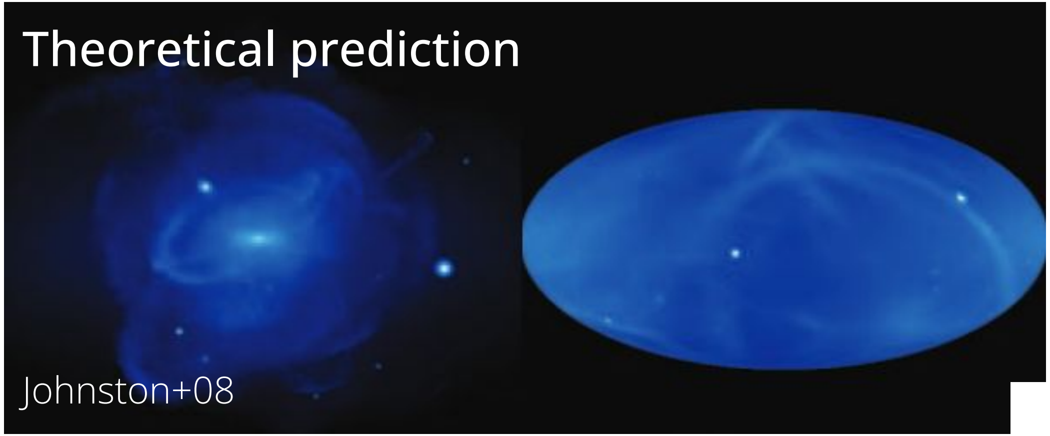
Mergers/accretions are a fundamental process in galaxy evolution

They bring materials, trigger star formation, and heat up the galaxy's disk

Can we constrain the accretion history of the Milky Way? How do we find signatures of past accretion events?

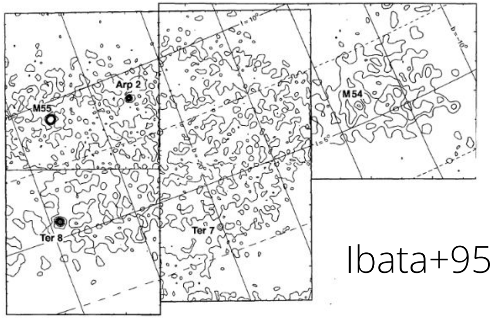
Evidence of galaxy accretions: stellar streams

One of the predicted features of galaxy accretions

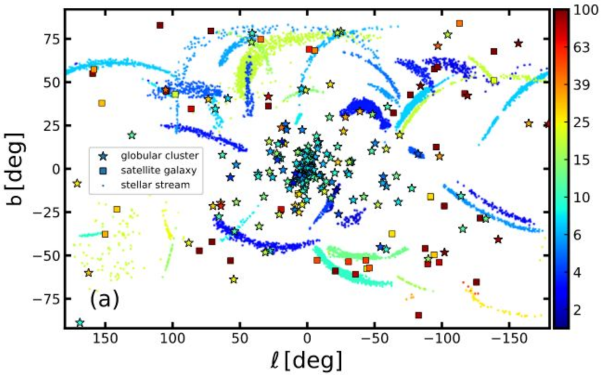


However, these features quickly go away in the inner part of the Galaxy

Observations



Ibata+95

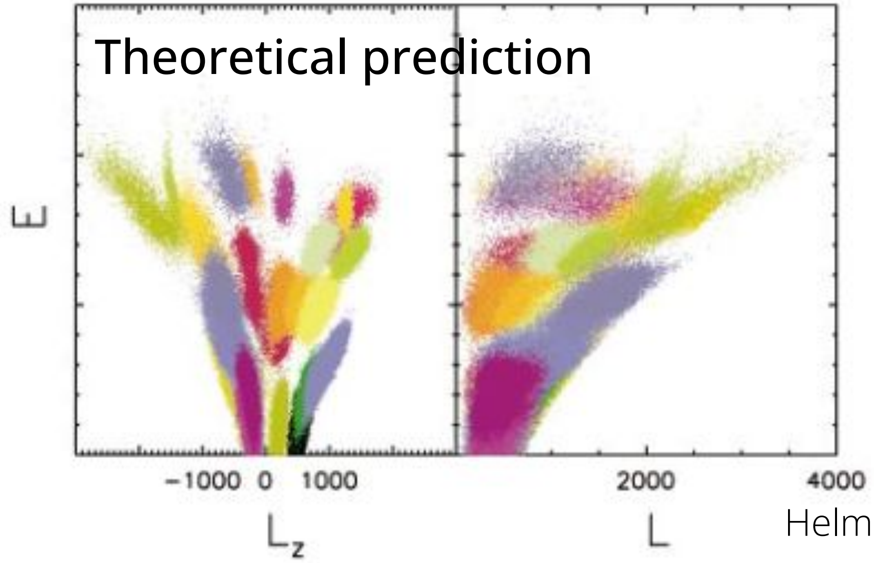


Malhan+22

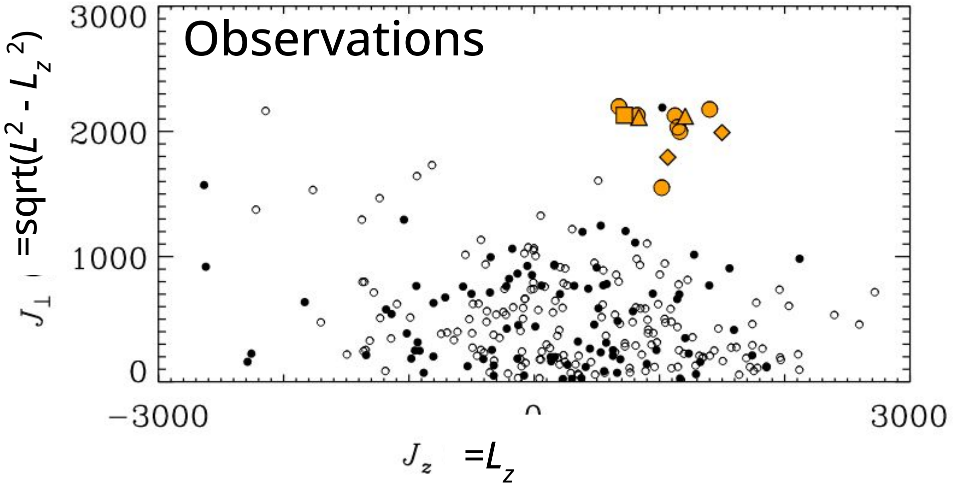
Evidence of galaxy accretions: kinematics

Disk galaxies are ~axisymmetric

L_z and E (+total L) are roughly conserved

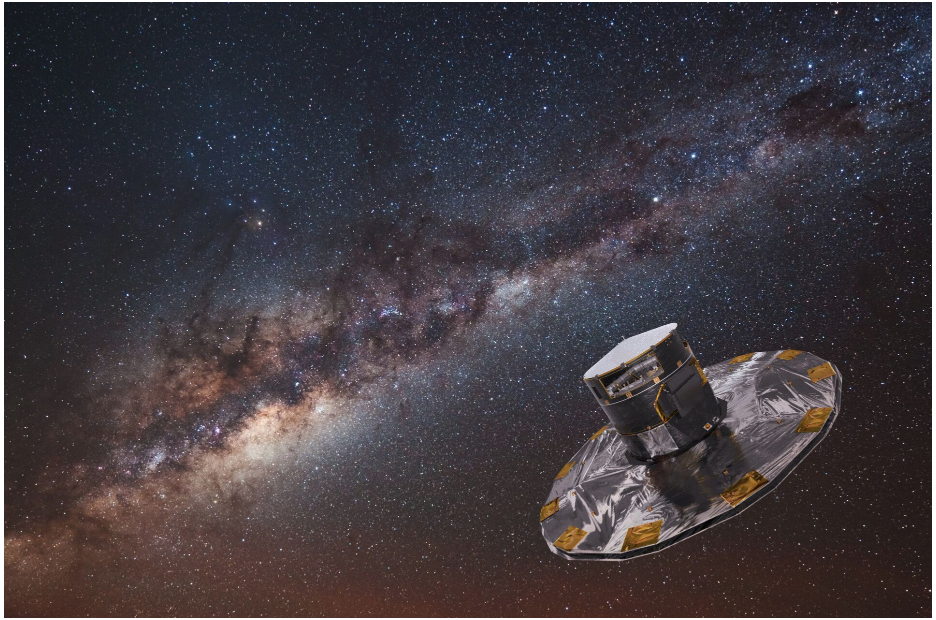


Helmi+00



Helmi+99

The revolution brought by the Gaia mission (2013-)



ESA/ATG medialab; background: ESO/S. Brunier

Astrometry (~1.5 B stars)
Position, proper motion, parallax (distance)

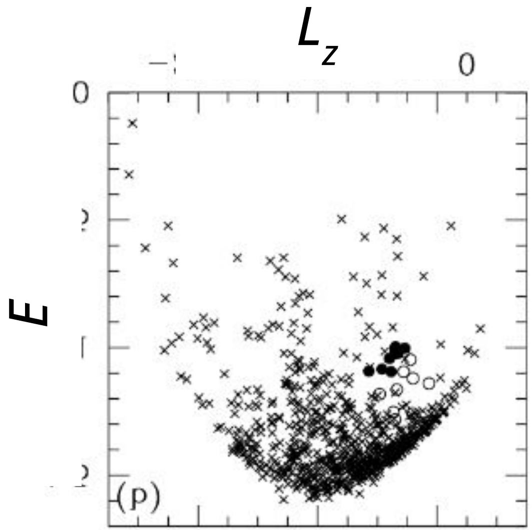
Radial Velocity (~33 M stars)

Stellar characterization
SED, temperature, distance, metallicity, etc.

The numbers are for DR3 (2022. June)

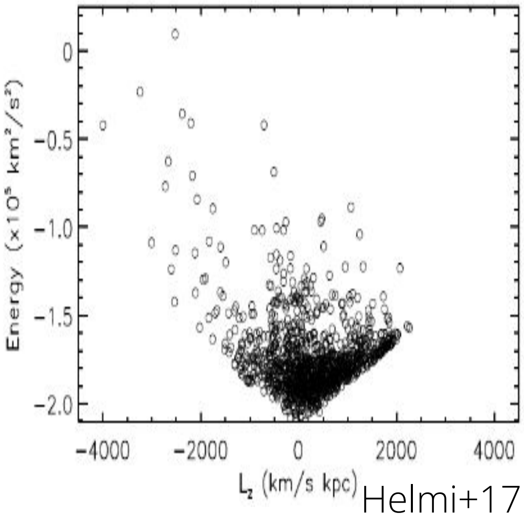
The revolution brought by the Gaia mission

Pre-Gaia
(Hipparcos and ground based observation)



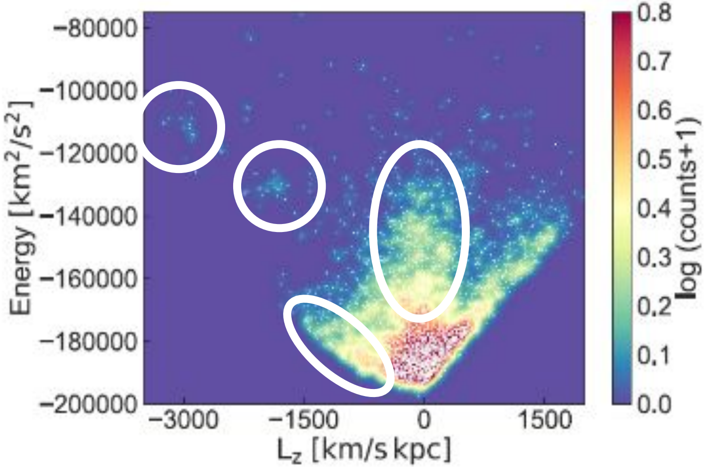
Chiba & Beers 00

Gaia DR1 (2016)
(Hipparcos and Gaia)



Helmi+17

Gaia DR2 (2018)
(full-Gaia)



Koppelman+18

Data-driven identification of substructures

Lövdal+22, Ruiz-Lara+22, Dodd+22

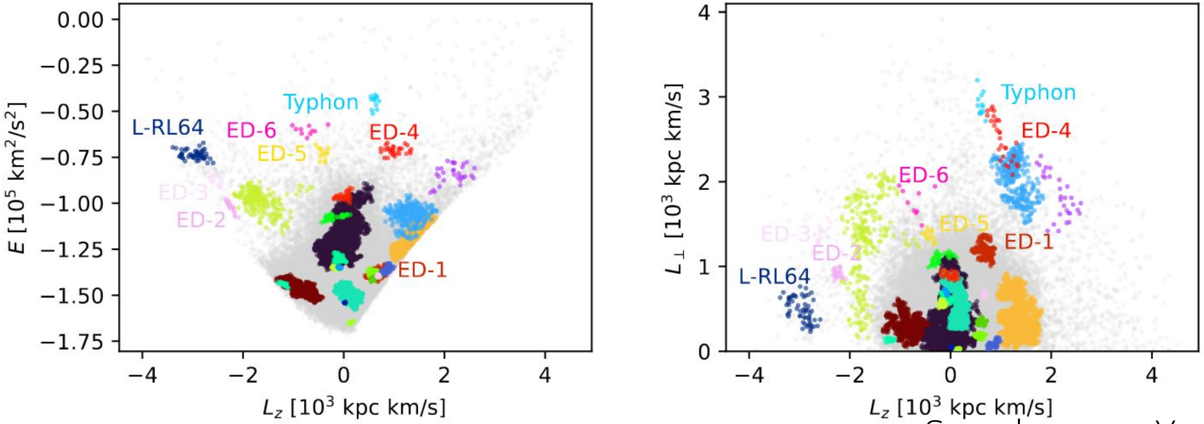
1. **Cluster-identification**

   Single-linkage algorithm in the (L_z, L_{perp}, En) space

   \+ Significance estimates with artificial "smooth" halos

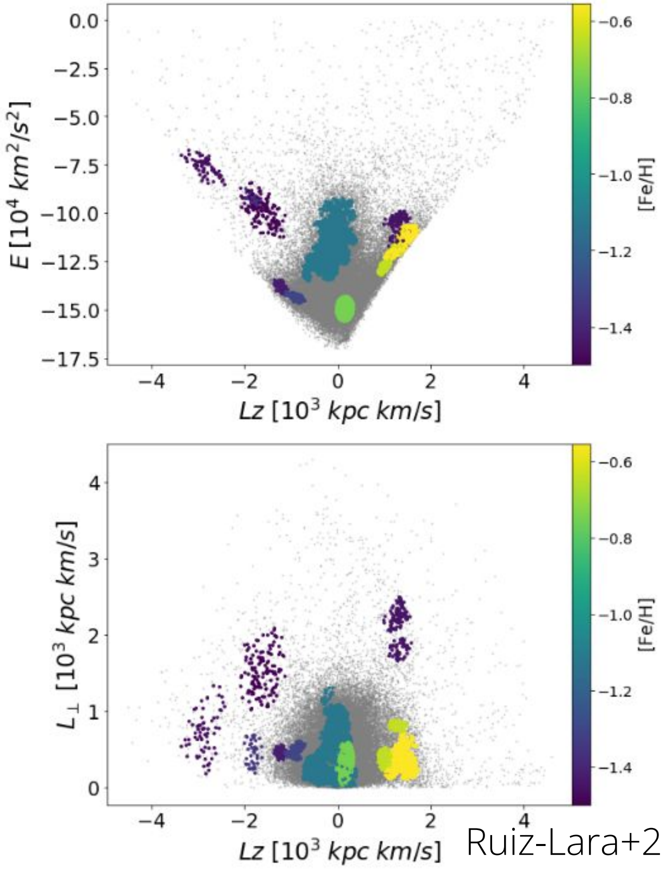
2. **Substructure-identification**

   Merge "clusters" to form substructures based on kinematics and metallicity



See also, e.g., Yuan+20 for another data-driven approach

Chemical characterization of substructures



Ruiz-Lara+22

Metallicity

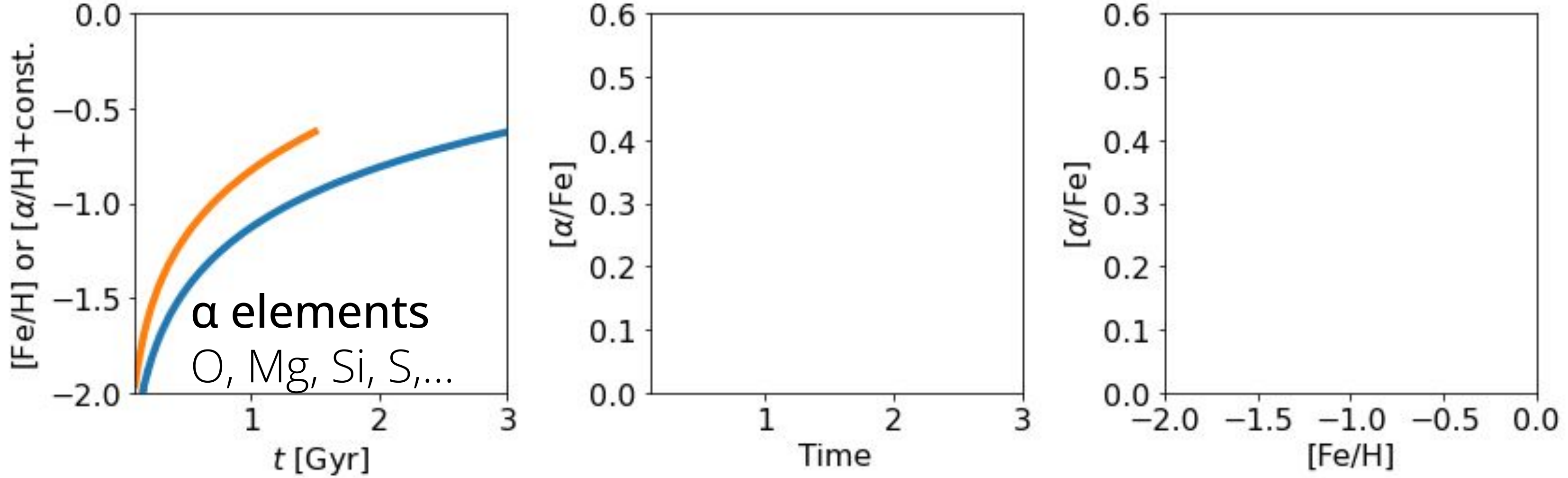
Provides some insights through mass-metallicity relation

Detailed elemental abundance ratios

- Are two subst.s independent?
- Chemo-dynamical membership?
- Progenitor galaxy's property
- Nucleosynthesis processes

Example: [α/Fe] ratio

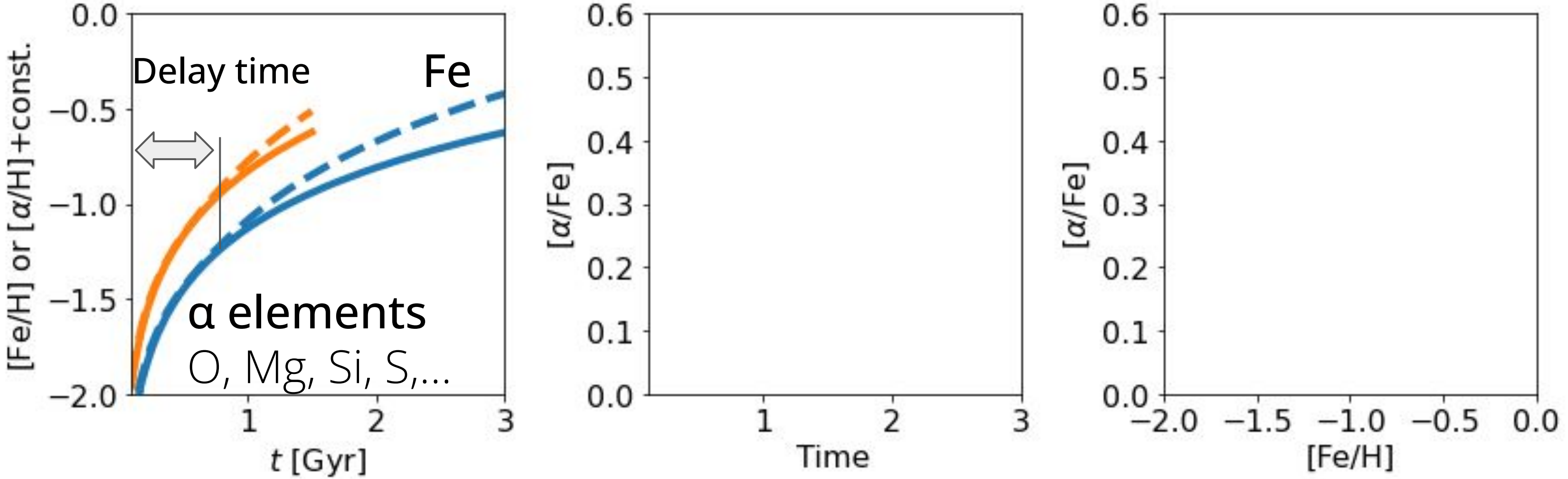
Enrichments by CCSNe



A more massive galaxy forming stars efficiently
A less massive galaxy

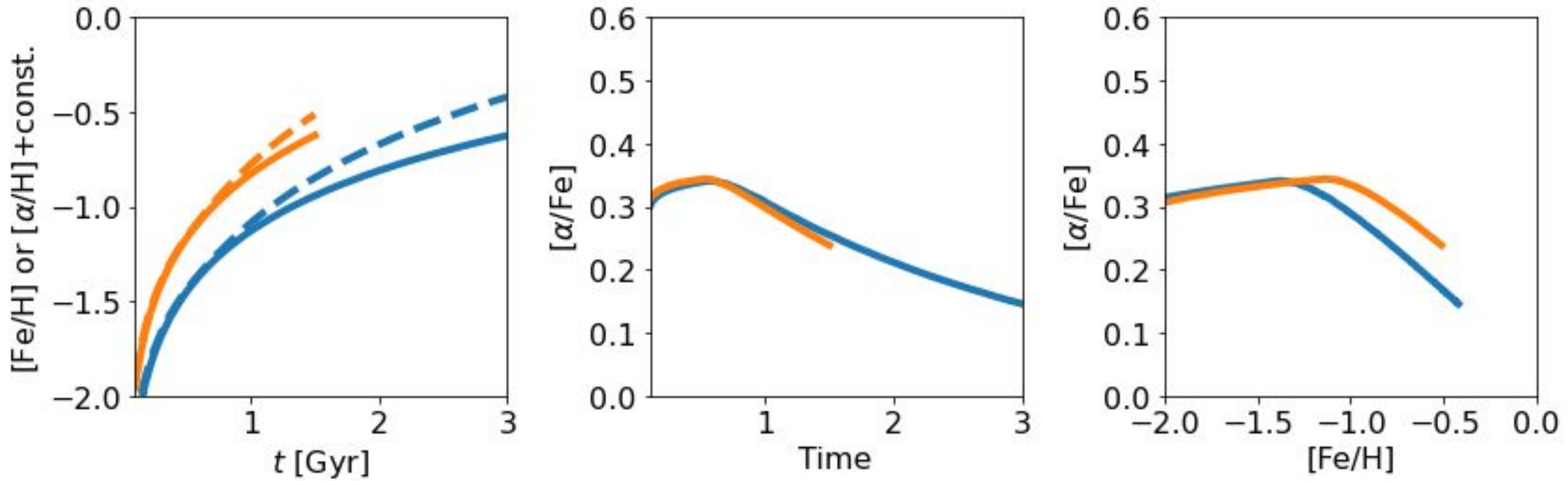
Example: [α/Fe] ratio

Enrichments by Type Ia SNe



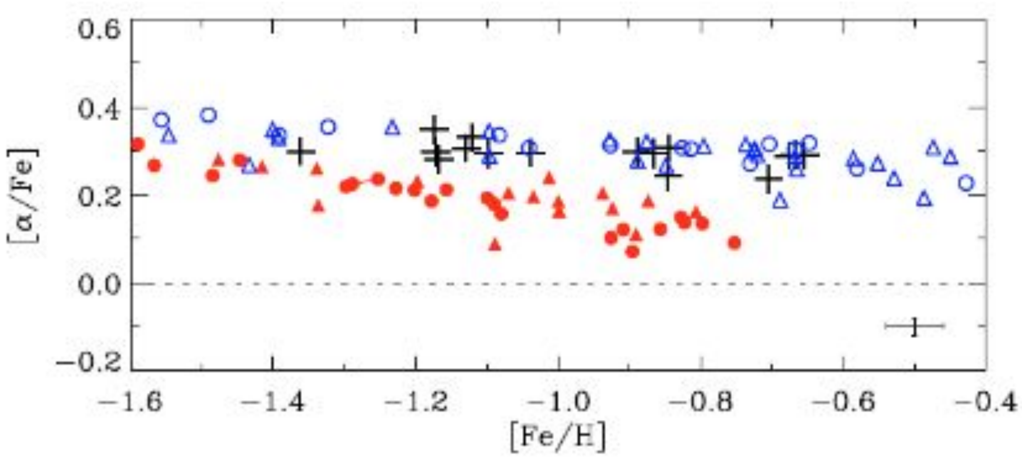
A more massive galaxy forming stars efficiently
A less massive galaxy

Example: [α/Fe] ratio



A more massive galaxy forming stars efficiently
A less massive galaxy

Example: two distinct populations among halo stars



Nissen & Schuster 10

High-α stars

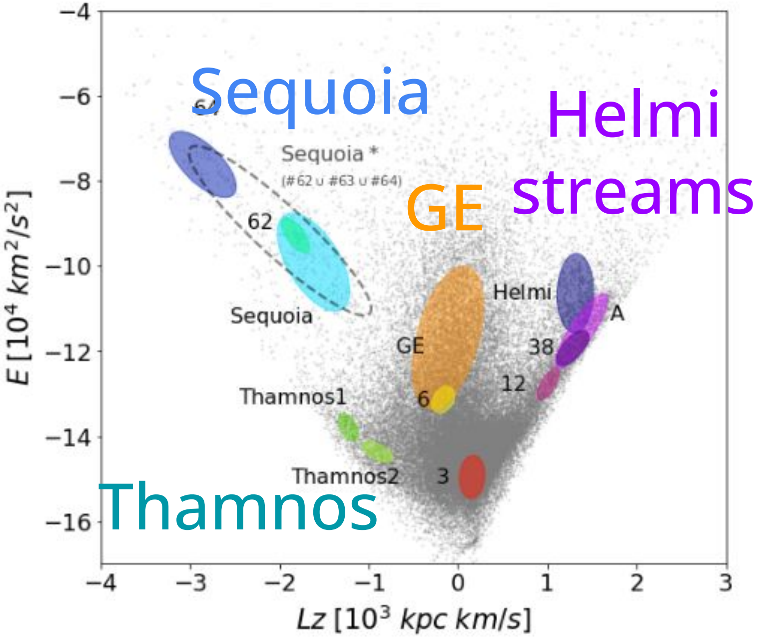
Formed in a more massive galaxy, **Milky Way**

Low-α stars

Formed in a less massive galaxy, **accreted dwarf galaxy**

If we understand the origins of elements, we can use them to constrain the property of galaxies

Properties of the prominent substructures



Ruiz-Lara+22

Gaia-Enceladus (GE)

- This is the most prominent structure and dominates the local stellar halo
- The last major merger
- Known to correspond to the low-α sequence

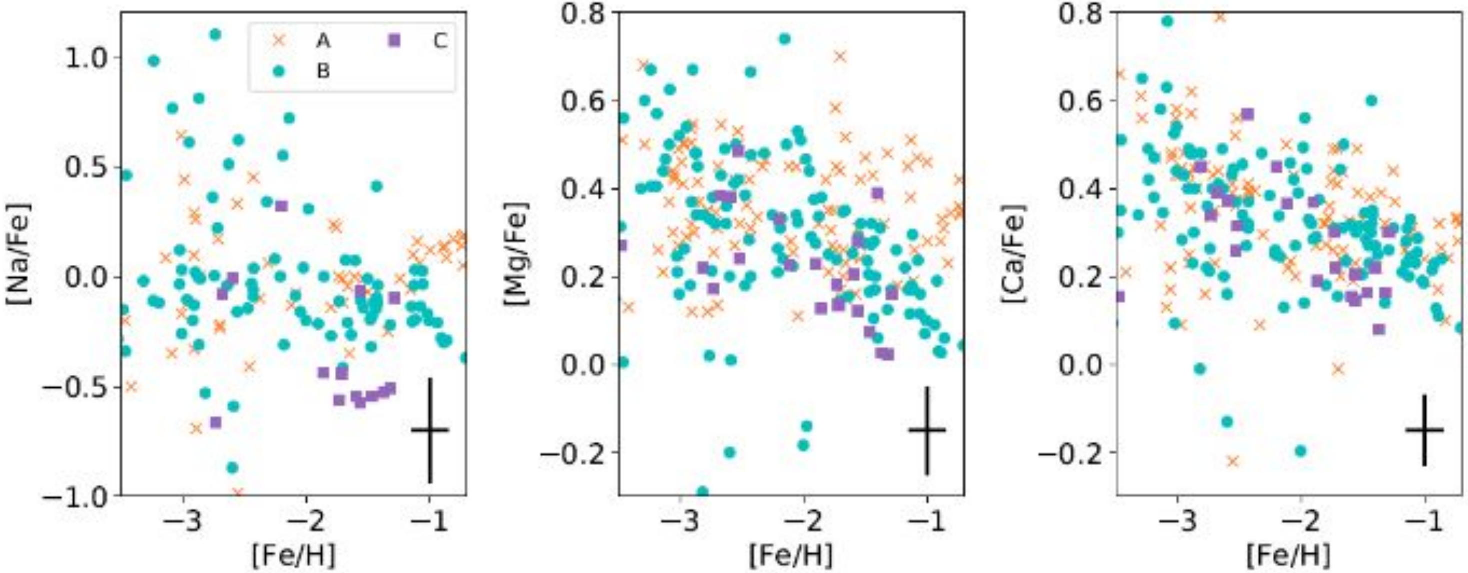
Sequoia, Thamnos, Helmi streams

- Minor to GE, lower mean metallicity
- But not much on the abundance ratio

A hint of chemical distinctness

Matsuno+19

Data: a database of past chemical abundance measurements (SAGA db)



MW
GE
Sequoia

Sequoia seem to have lower [Na, Mg, Ca/Fe] abundances
but the interpretation is limited by systematic uncertainty

Observing campaign with the Subaru telescope

Matsuno+22a, b

Goal

To study if chemical abundances are distinct among substructures

To constrain the chemical property of substructures

Targets

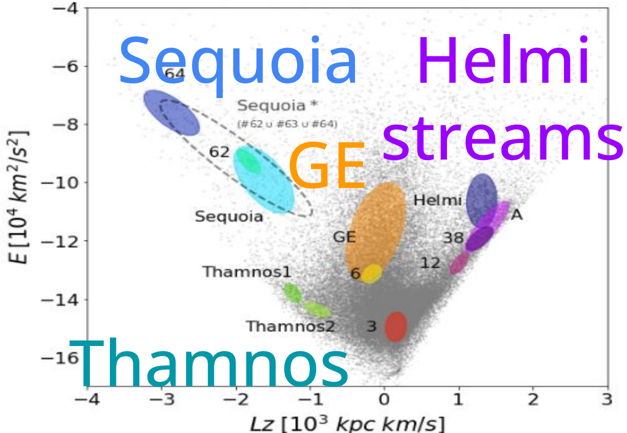
Stars in the three prominent substructures

Sequoia, Helmi streams, and Thamnos

Observations

HDS on the Subaru telescope (PI: T. Matsuno)

~ 6 nights in total



To achieve high-precision

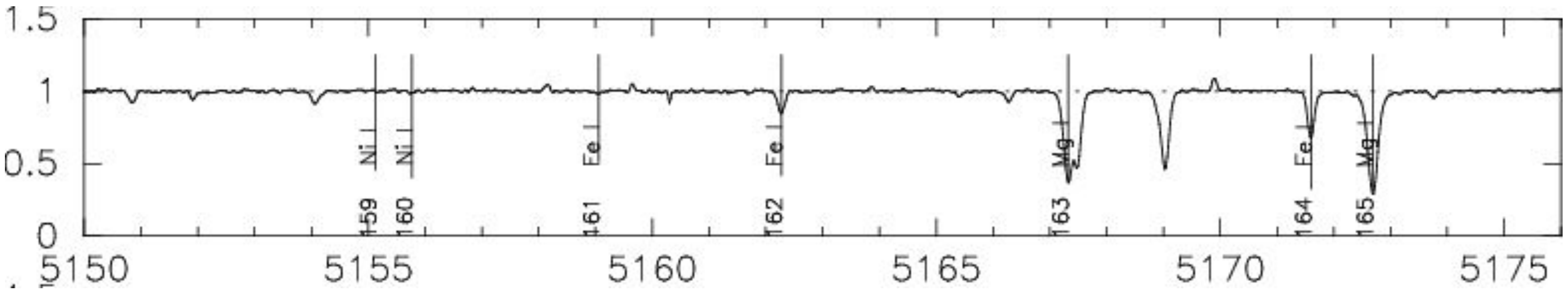
Matsuno+22a, b

★ High-S/N, high-resolution spectra

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

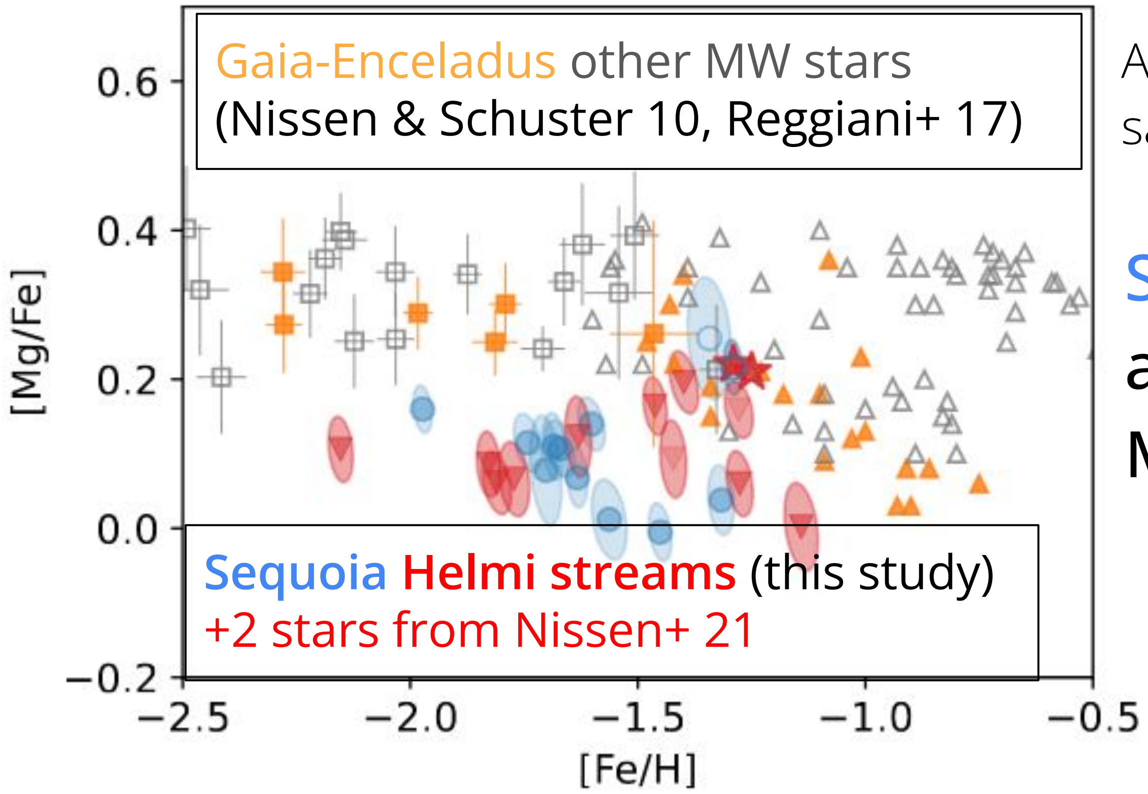
★ Suppressing systematic uncertainty due to different stellar types. We focus on main-sequence turn–off stars

★ Differential abundance analysis to minimize the effect of input data



Results: Mg abundance, one of the α-elements

Matsuno+22a, b



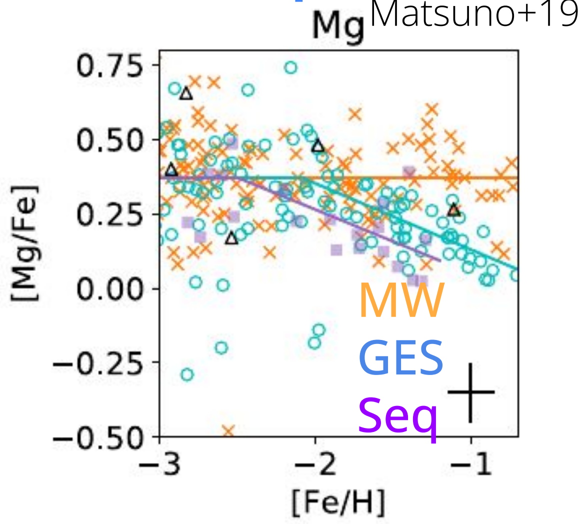
All the abundances are on the same scale

Seq. and HS have distinct and lower [Mg/Fe] than MW and GE

Matsuno+22a, b

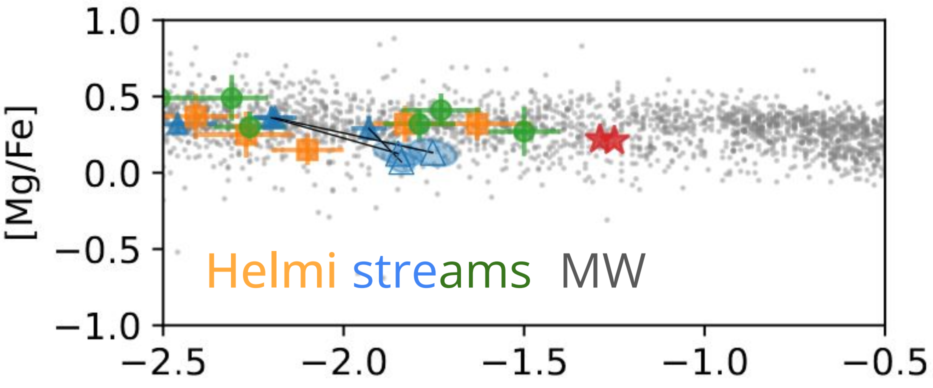
Comparison with the literature data

Sequoia



SAGA database (Suda+08)

Helmi streams



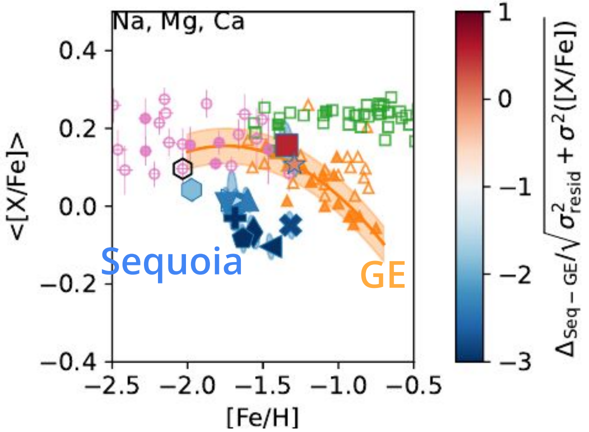
SAGA db, Roederer+10
Aguado+21, Nissen+21, Gull+21

Chemical distinctness has not always been there

✓Homogeneous abundance

✓High precision from high S/N data

What precision do we need to see the "distinctness"?

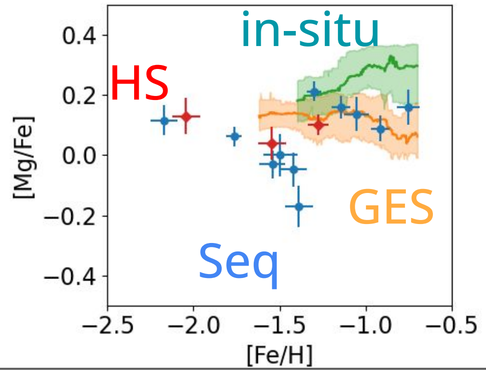


Δ[X/Fe] between GE and Seq: ~ 0.20 dex
σ ([X/Fe]) among GE stars : ~ 0.07 dex

The measurement uncertainty needs to be
σ([X/Fe]) < 0.07 dex
to separate Seq from GE by >2σ.

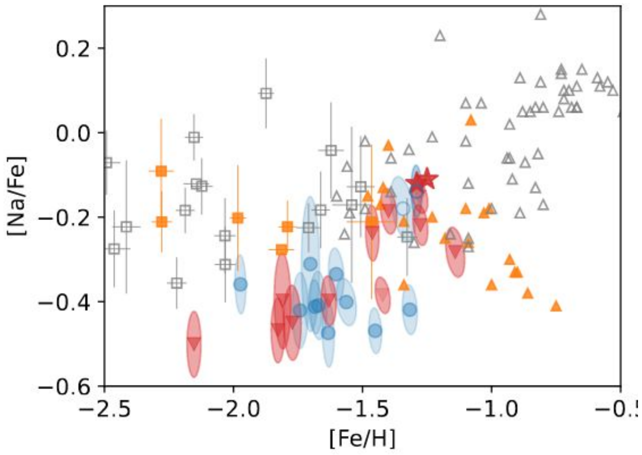
e.g., Horta+23 confirms our finding with APOGEE data

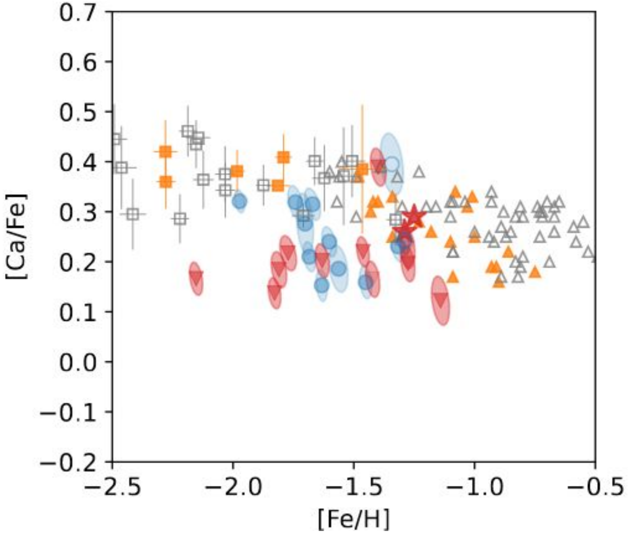
We also confirmed this with GALAH stars with σ < 0.07

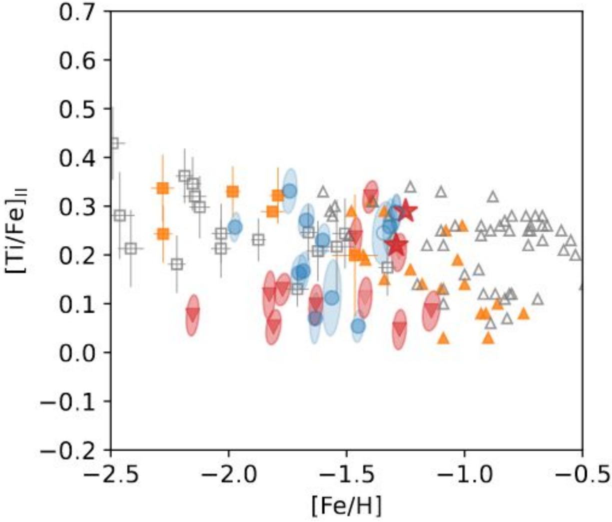


The origin of low [Mg/Fe]

The natural interpretation is large type Ia supernovae contribution
The detailed abundance pattern is the key





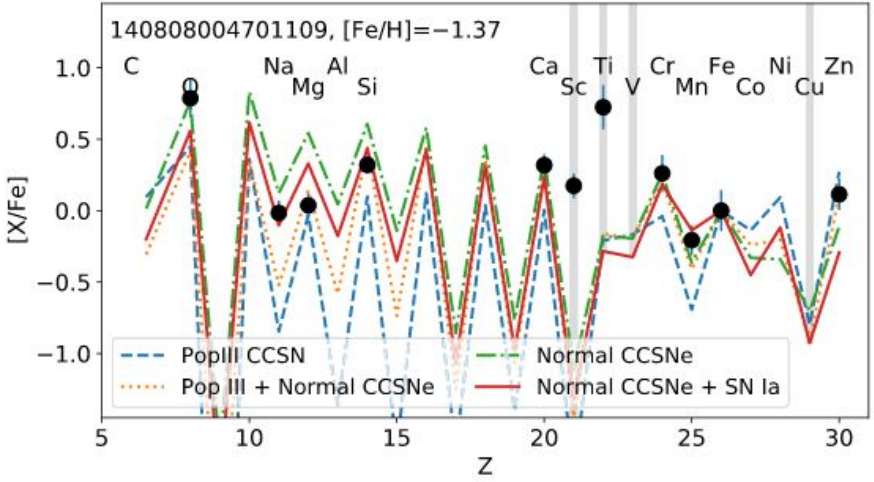


The origin of low [Mg/Fe]

We fit abundance patterns of individual objects

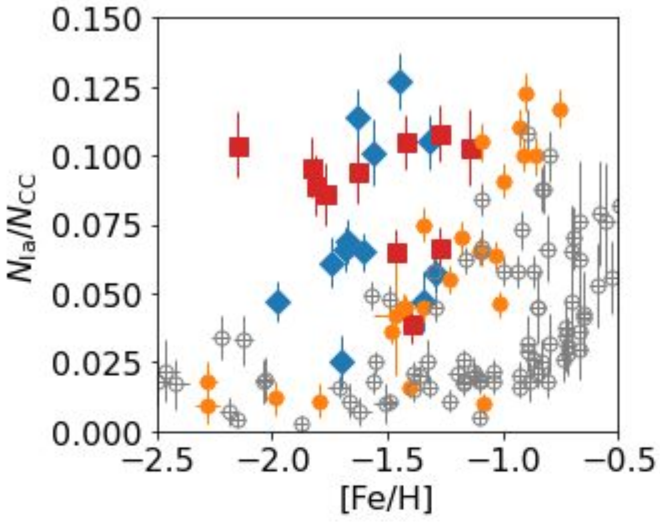
Parameters

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



Ishigaki+21

The origin of low [Mg/Fe] *(preliminary)*

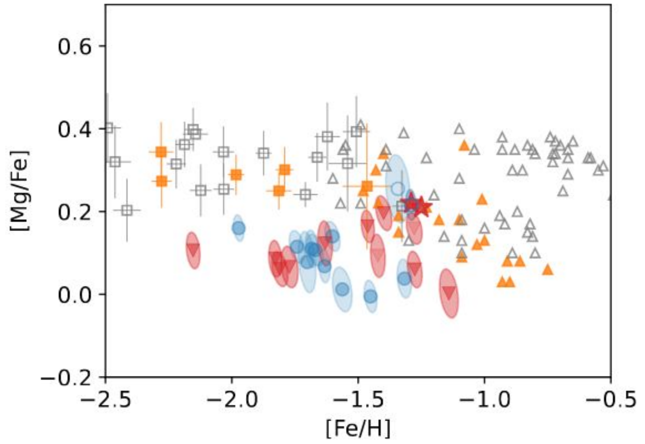


Gaia-Enceladus
Sequoia
Helmi Streams
Other halo stars

The abundance patterns of Seq. and HS are very well explained by large contributions from type Ia SNe

Matsuno+22a, b

Summary of interpretation



The distinct abundance of Seq. and HS

Seq. and HS have independent origins from GE

The lower [Mg/Fe] of Seq. and HS than MW and GE

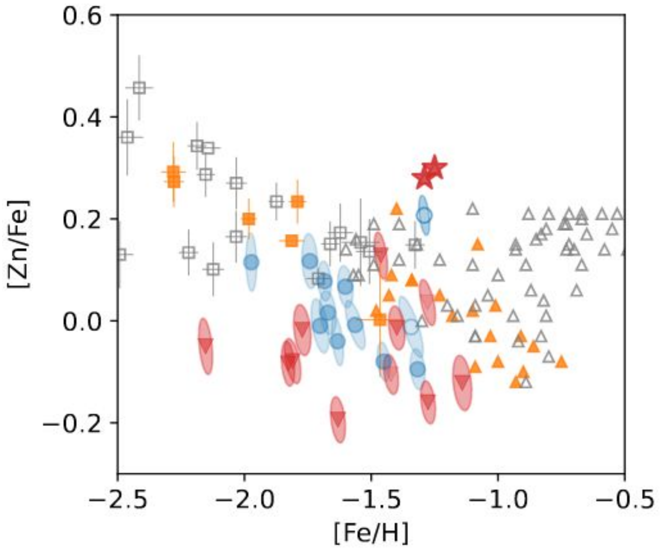
Type Ia contribution seems larger in Seq. and HS

[Mg/Fe] might have started decreasing at lower [Fe/H].

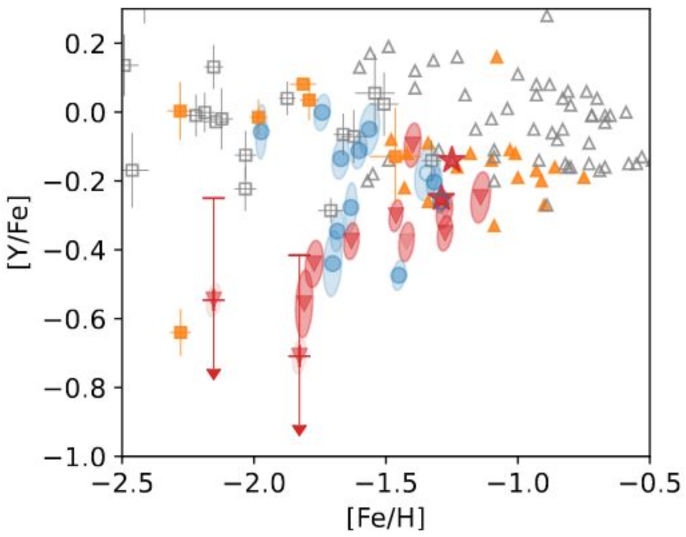
Suggestive of lower progenitor mass

Matsuno+22a, b

More elements show diversity, but...



Large variation in [Zn/Fe] in Helmi streams (driven by 2 stars from Nissen+21)

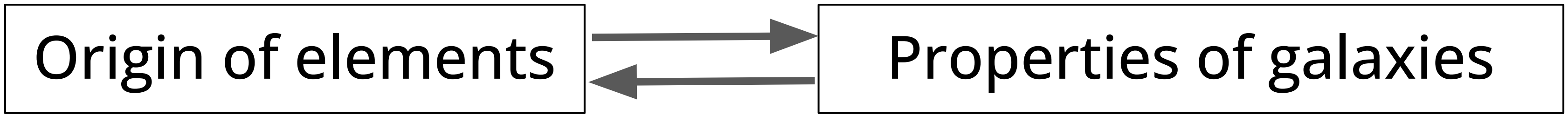


Helmi streams' extremely low abundance of Y
(see also Aguado+21 on Sr)

we don't know much about their origin yet.

Kinematic substructures also improve our understandings of nucleosynthesis

Constraining nucleosynthesis with substructures



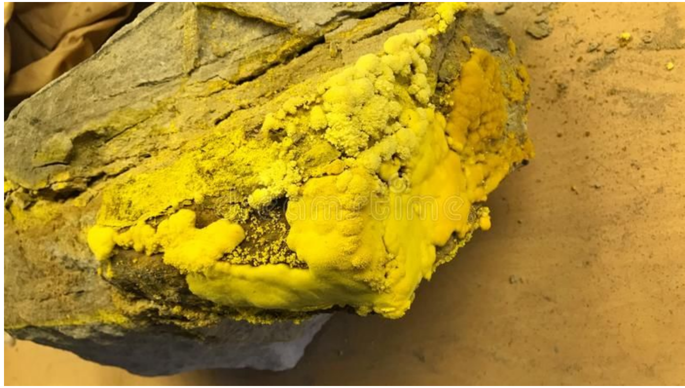
Kinematic substructures

- They were once dwarf galaxies, having undergone their own chemical enrichments
- Their stars are now orbiting around the Milky Way. Some are in the solar neighbourhood and very suitable for detailed study

A new opportunity to constrain the origin of elements

R-process elements

About half of elements heavier than Fe are produced by so-called rapid neutron-capture process



Their formation requires very high neutron density,
and **the site is still debated**

A promising site for R-process nucleosynthesis

The most promising site is NSMs

- observations of the afterglow of GW170817 (e.g., Tanaka+17)
- numerical simulations of the nucleosynthesis (e.g., Wanajo+14)

But there should be a "delay time" in NSMs

They require two NSs to merge

Is this consistent with observation?

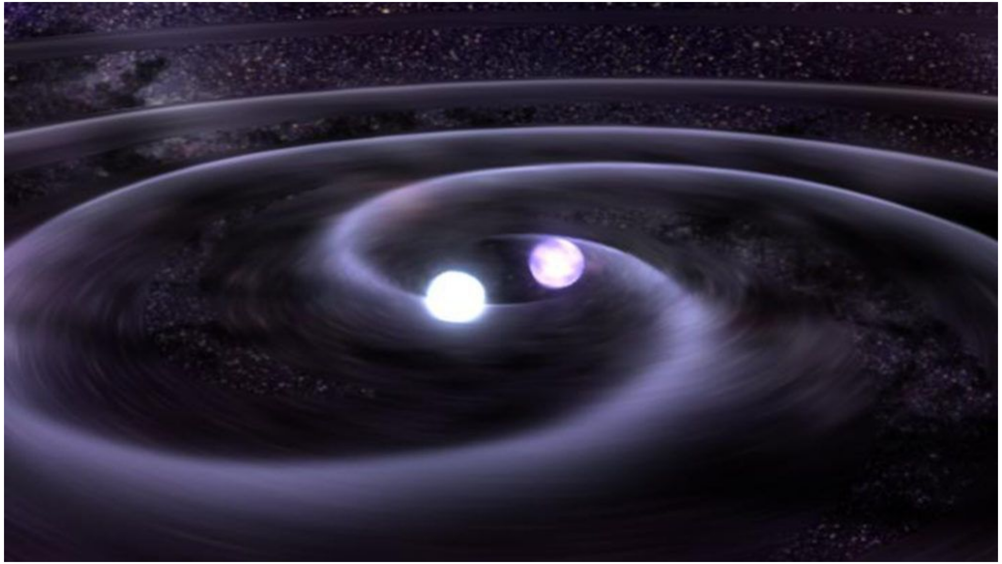


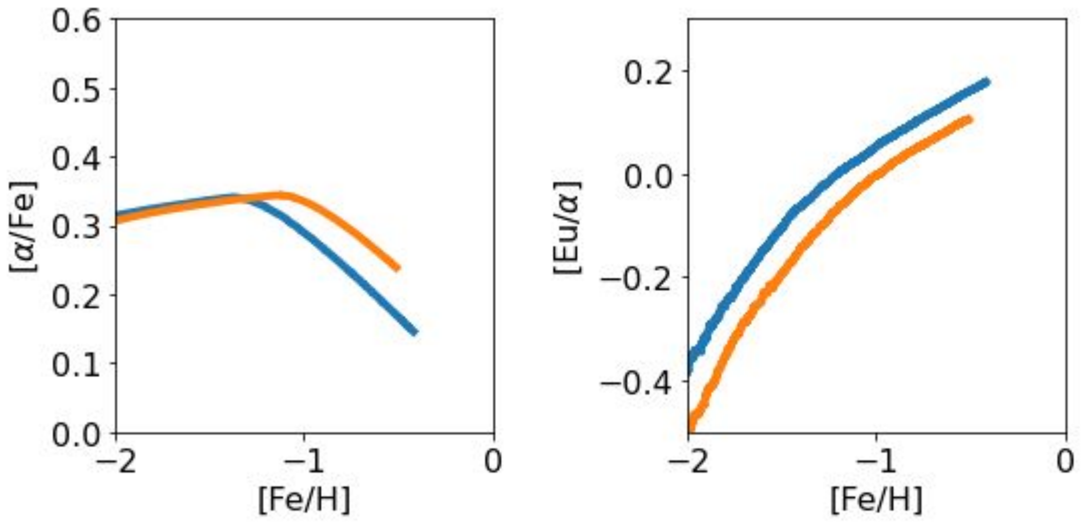
Image credit: Goddard Space Flight Center/NASA

An opportunity to provide a new constraint

Similarly to [α/Fe], [Eu/α] should depend on the star formation efficiency

We expect high [Eu/α] for stars from dwarf galaxies

(including those in kinematic substructures)



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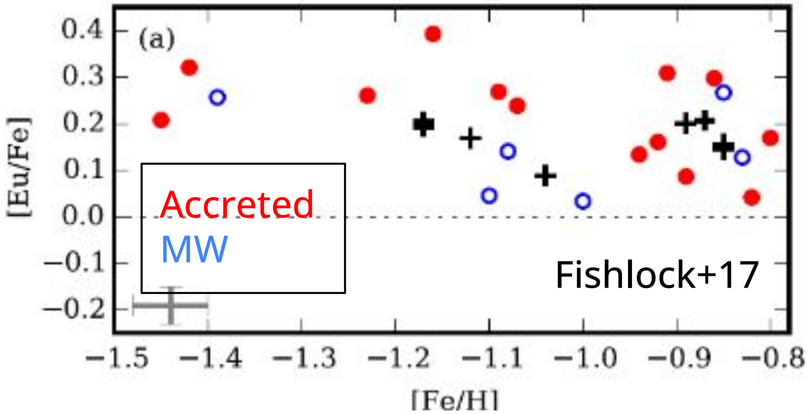
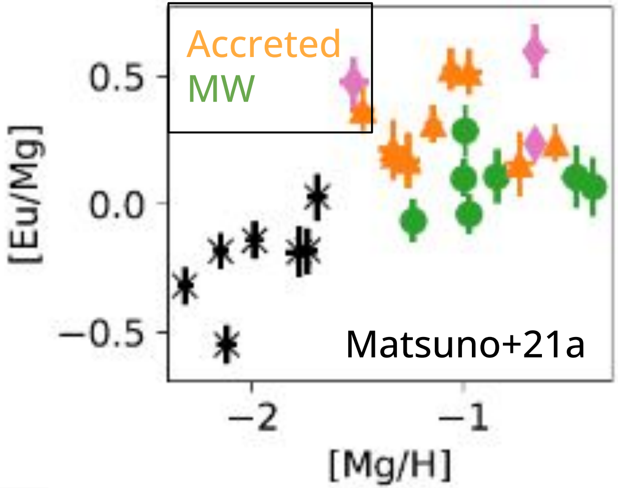
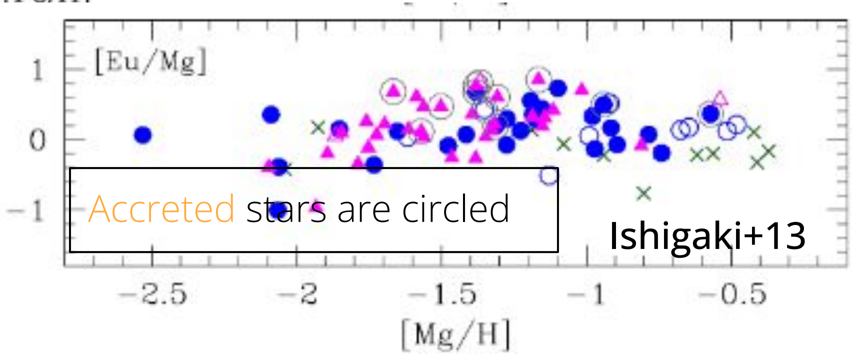
Hints in the literature

Accreted stars seem to show high Eu

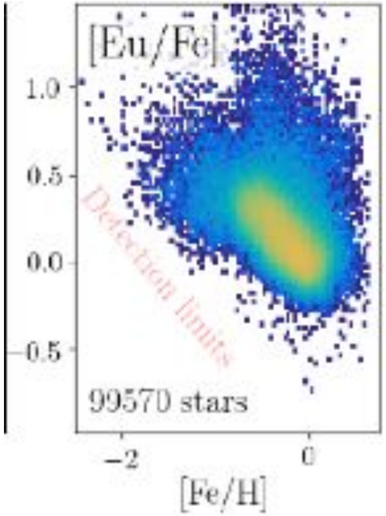




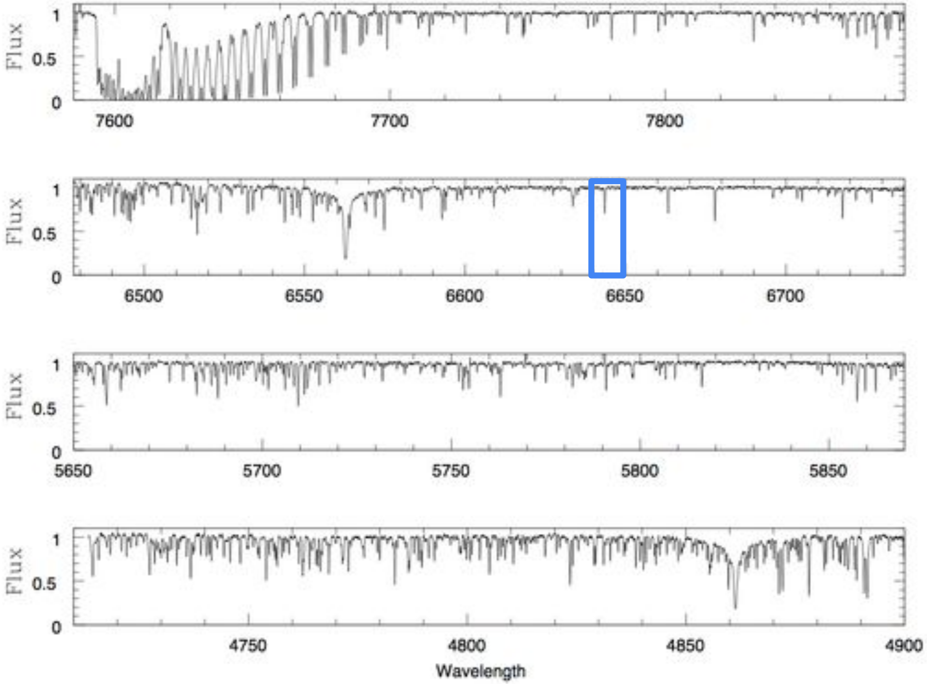


The largest sample of Eu abundance from GALAH

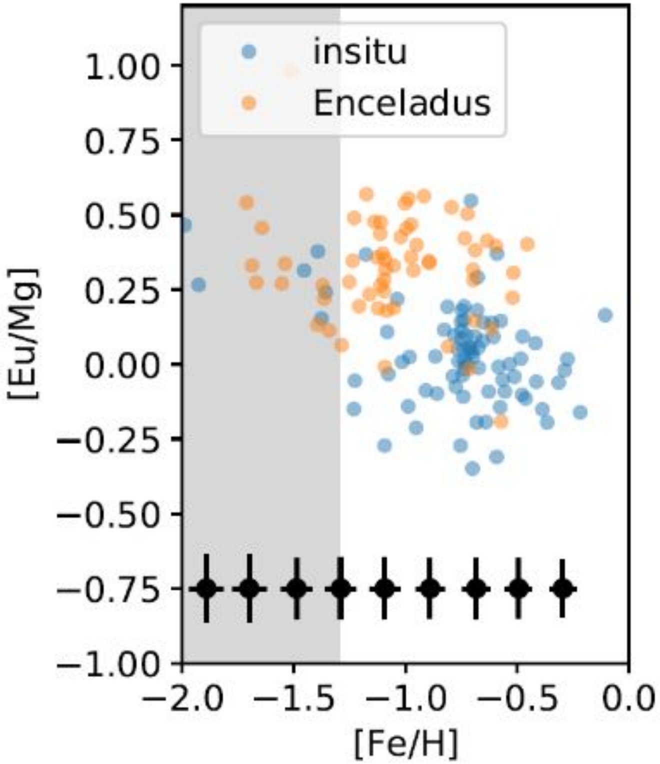
An optical high-resolution spectroscopic survey with a multi-object spectrograph



Buder+21

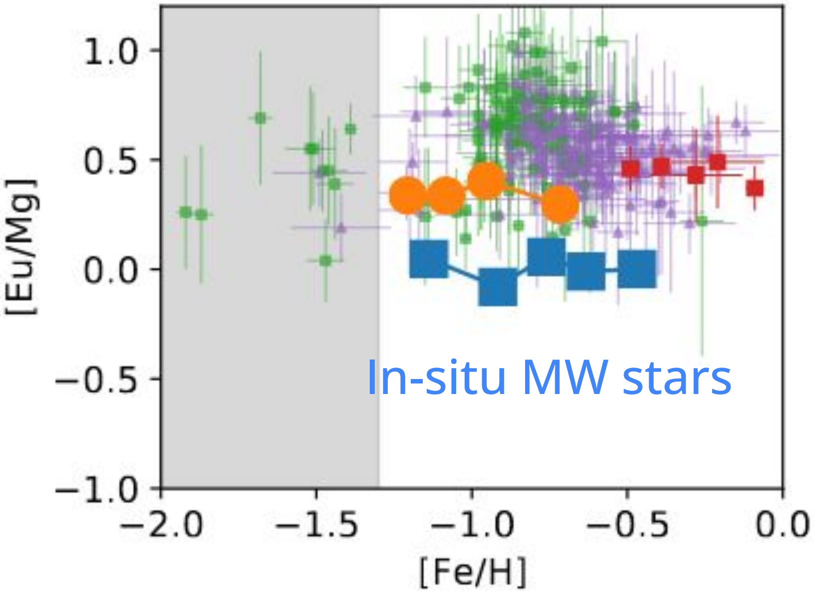


Eu abundance in the Milky Way and Gaia-Enceladus



[Eu/Mg] is clearly higher in stars formed in Gaia-Enceladus than those formed in-situ

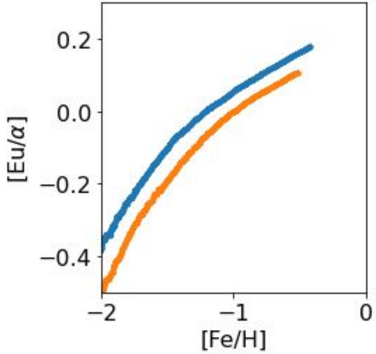
High [Eu/Mg] in dwarf galaxies (GE, Sgr, LMC, Fornax)



Enceladus
LMC
Sagittarius
Fornax

Data for LMC, Sgr, Fornax are from
Van der Swaelmen+13, Bonifaccio+00,
McWilliam+13, Latarte+10, Lemasle+14

This is expected if there is a delay in r-process enrichments



A more massive galaxy forming stars efficiently
A less massive galaxy

Summary

Gaia revolutionized the field of reconstructing the accretion history of the Milky Way

- **Data-driven identification of substructures = accretion remnants**
- **Spectroscopic follow-up for their chemical characterization**
  - Both Sequoia and Helmi streams show distinct abundances
  - They have signatures of large type Ia SN contribution
- **Constraining nucleosynthesis process using a substructure**
  - R-process abundance is high in Gaia-Enceladus
  - Consistent with r-process enrichment with delay time