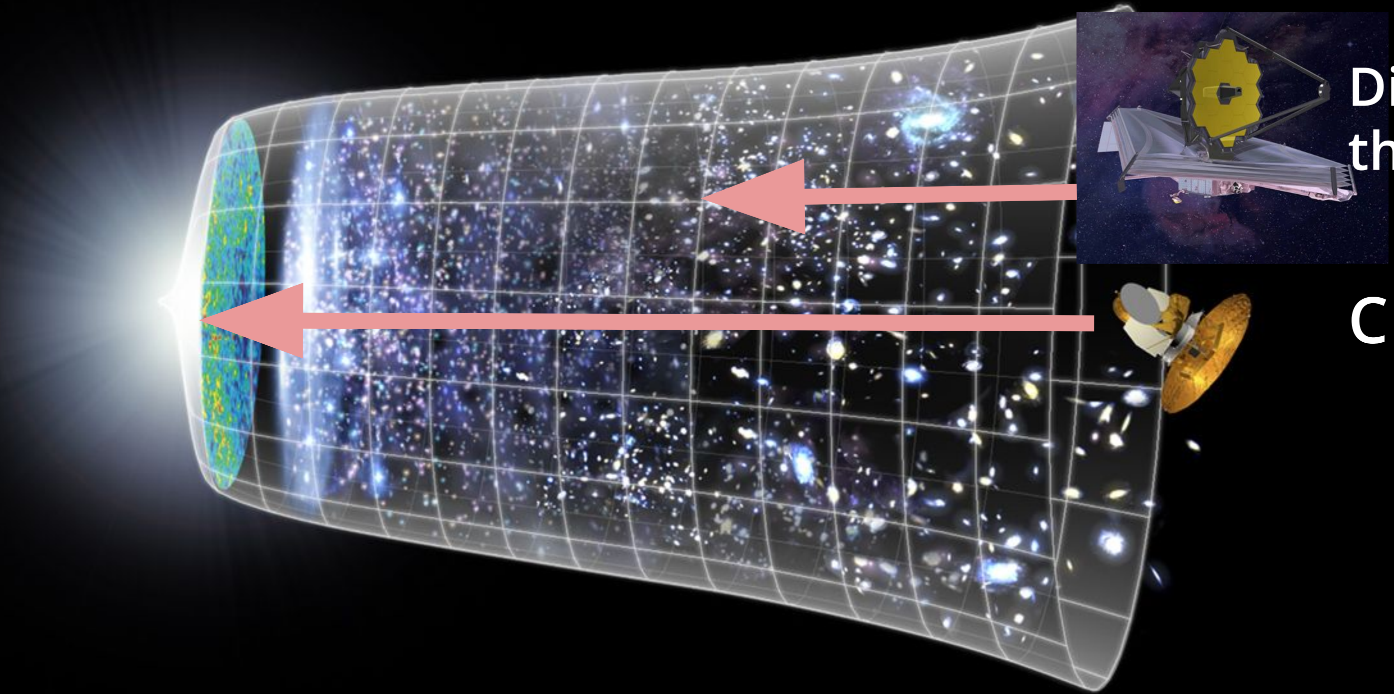
kapteyn astronomical
institute

# Building blocks of the Milky Way revealed from the chemodynamics of halo stars

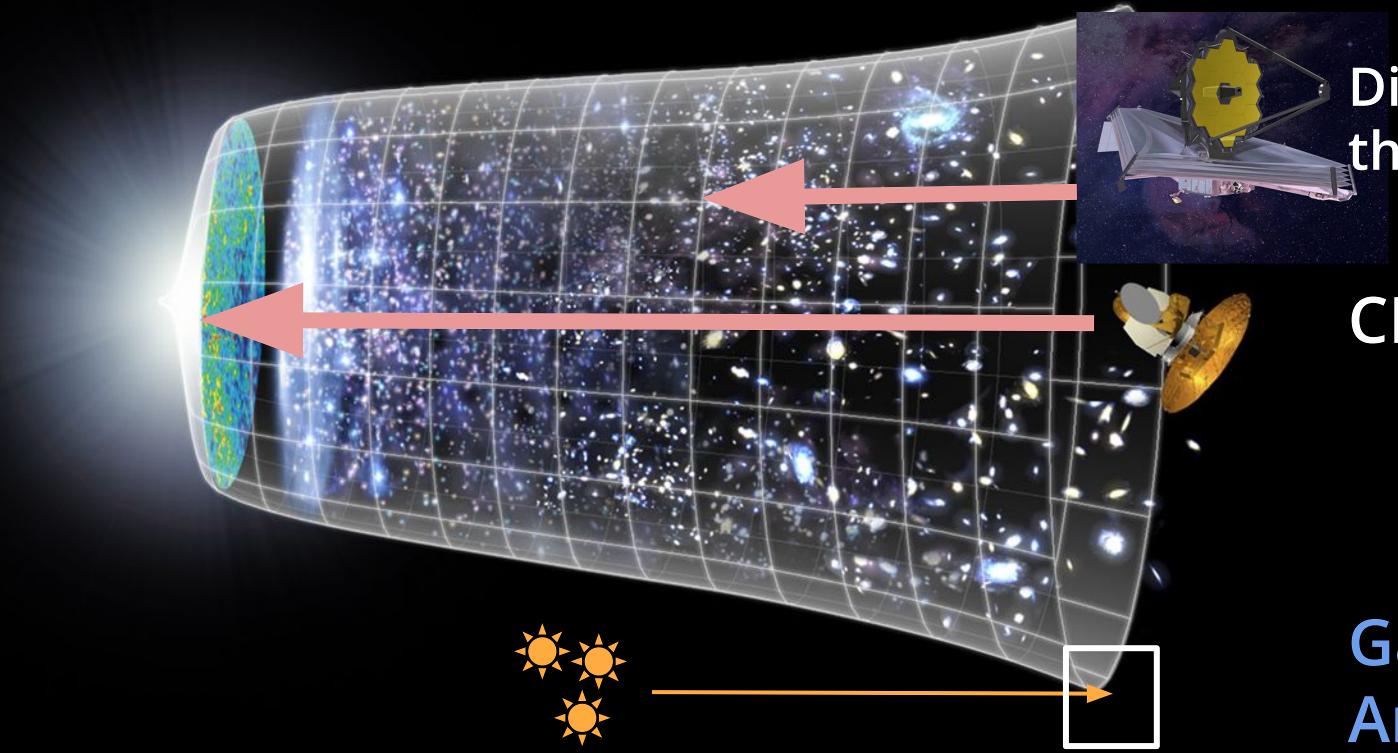
Tadafumi Matsuno
(Gliese fellow, ARI/ZAH, Universität Heidelberg)
In collaboration with Dodd, E., Amarsi, A. Koppelman, H. H., Helmi, A., Aoki, W., Zhao, J.K., Yuan, Z., Hattori, K., Suda, T., Lövdal, S.S., Callingham, T., Ruiz-Lara,T., Balbinot, E. et al.



Direct observation of the high-$z$ Universe

CMB

Credit: NASA/WMAP



Direct observation of the high-$z$ Universe

CMB

## Galactic Archaeology

Galaxy evolution,
star formation,
nucleosynthesis etc.

Low mass stars formed
in the early Universe

Local universe
(Milky Way)

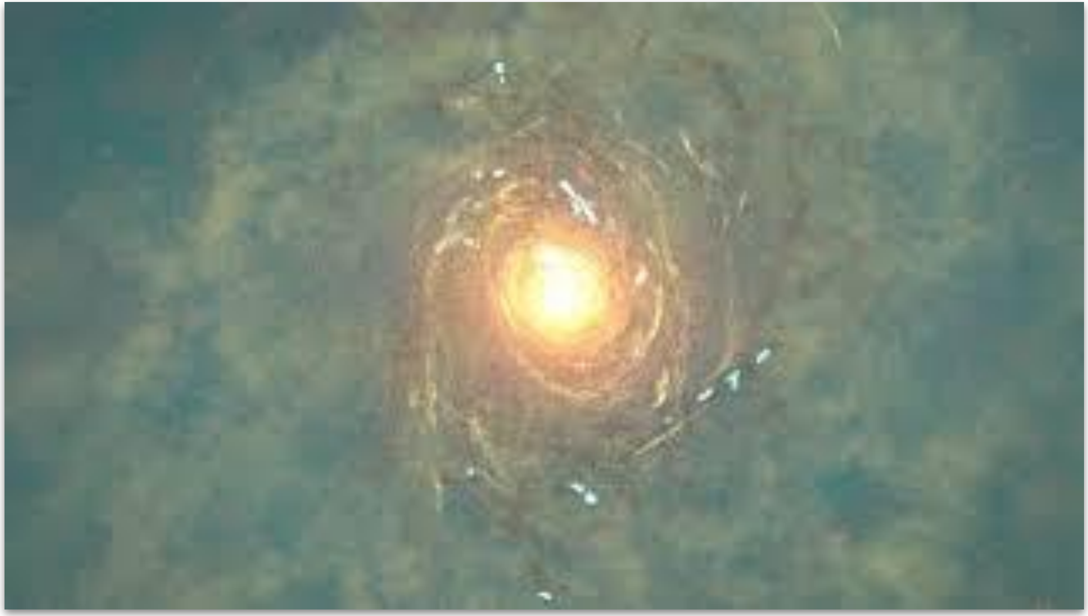
Credit: NASA/WMAP

Galaxies grow through mergers and accretions

➡ Accretion remnants in the Milky Way (building blocks)

## A way to study more than "a galaxy"

- Galaxy interactions
- Chemical evolutions
- Nucleosynthesis processes



Credit: Takayuki Saitoh

# Satellite accretions to the Milky Way

Present day

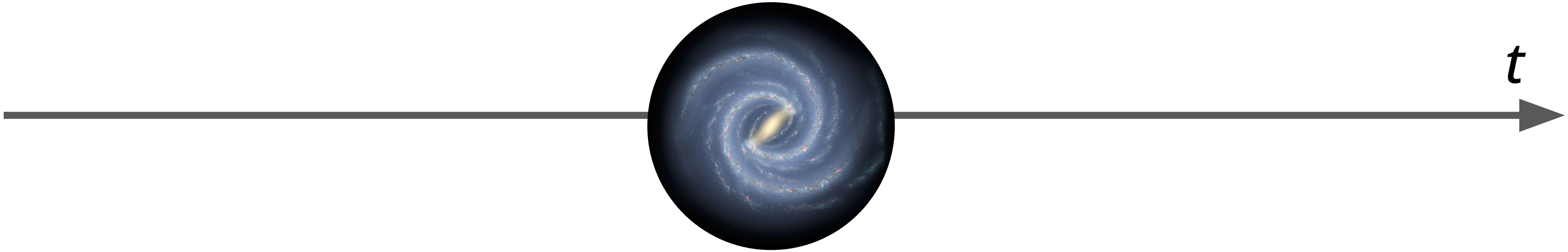
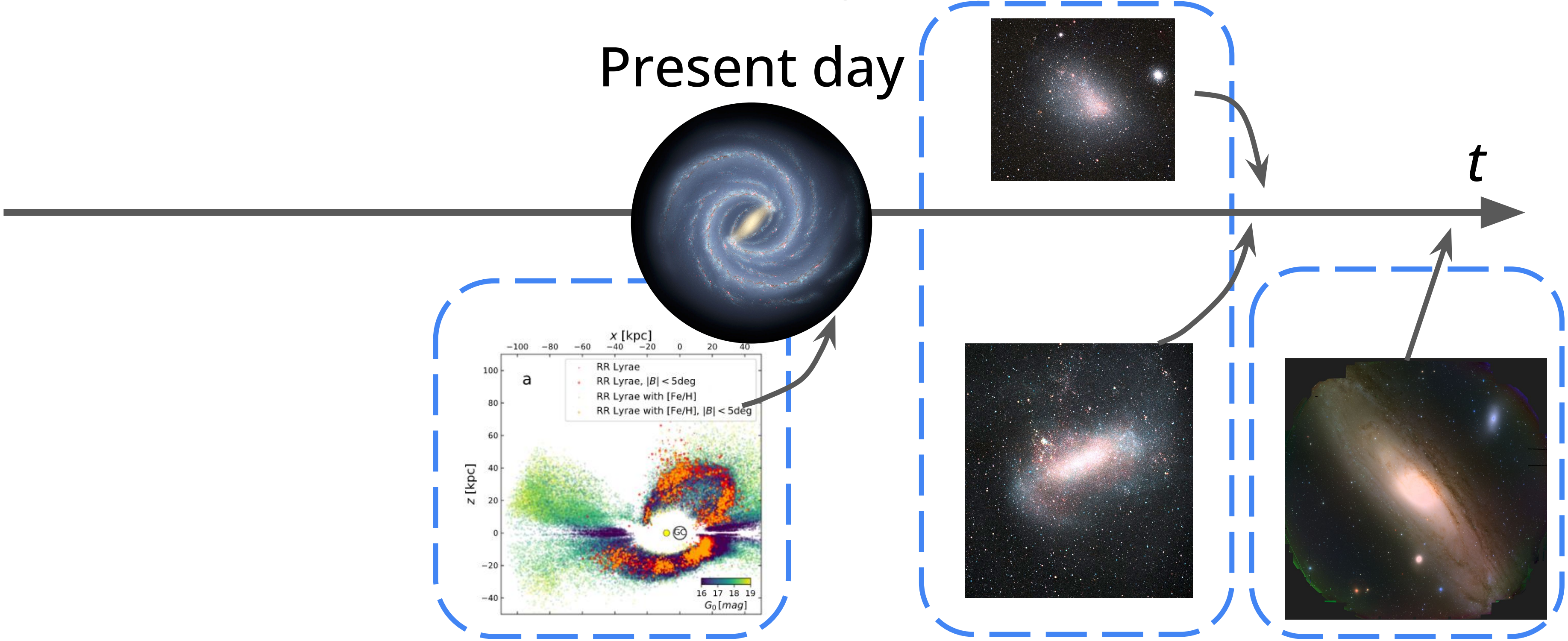


Image credits: NASA/JPL-Caltech/ESO/R. Hurt,
Ibata et al. (2020), ESO/VMC Survey,

# Satellite accretions to the Milky Way



Present day

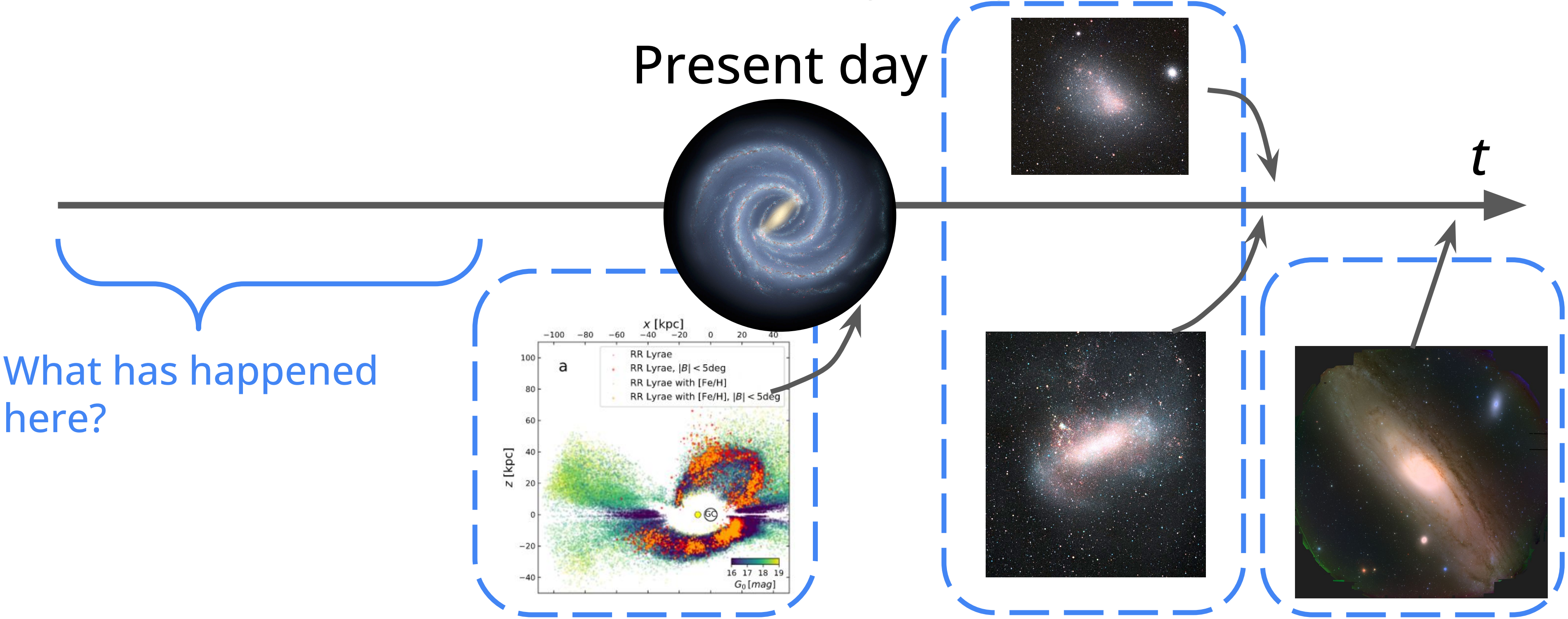
Satellite galaxies

Streams

Image credits: NASA/JPL-Caltech/ESO/R. Hurt, Ibata et al. (2020), ESO/VMC Survey,

# Satellite accretions to the Milky Way

Satellite galaxies



Present day

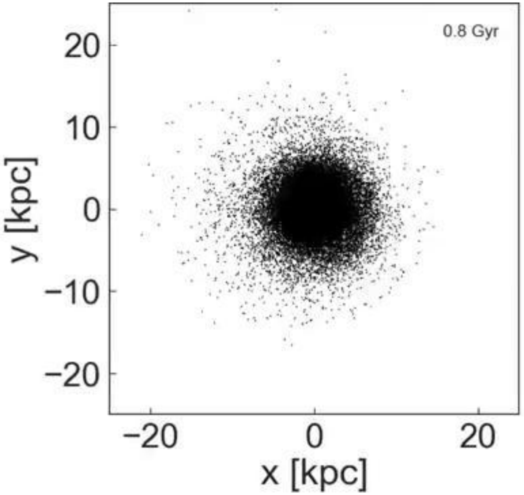
What has happened here?

Streams

Image credits: NASA/JPL-Caltech/ESO/R. Hurt, Ibata et al. (2020), ESO/VMC Survey,

# Accretion remnants in kinematics of stars

## Spatial coherence quickly disappears

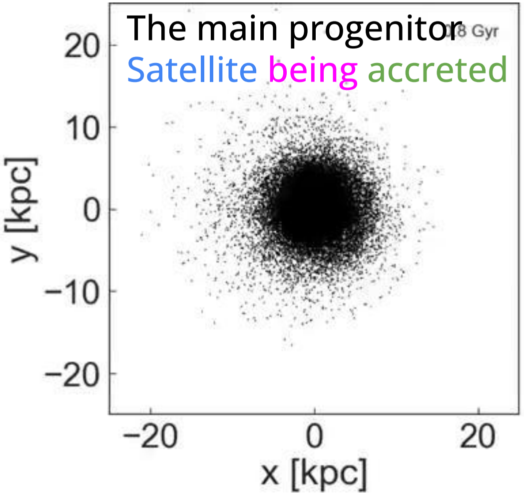


Koppelman et al. (2020)

The main progenitor
Satellite being accreted

# Accretion remnants in kinematics of stars

## Spatial coherence quickly disappears

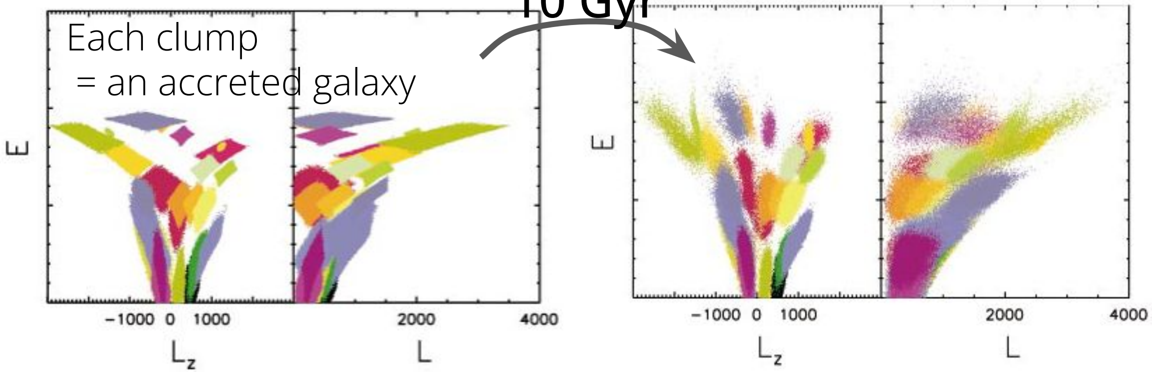


The main progenitor

Satellite being accreted

Koppelman et al. (2020)

## Energy-Angular momentum



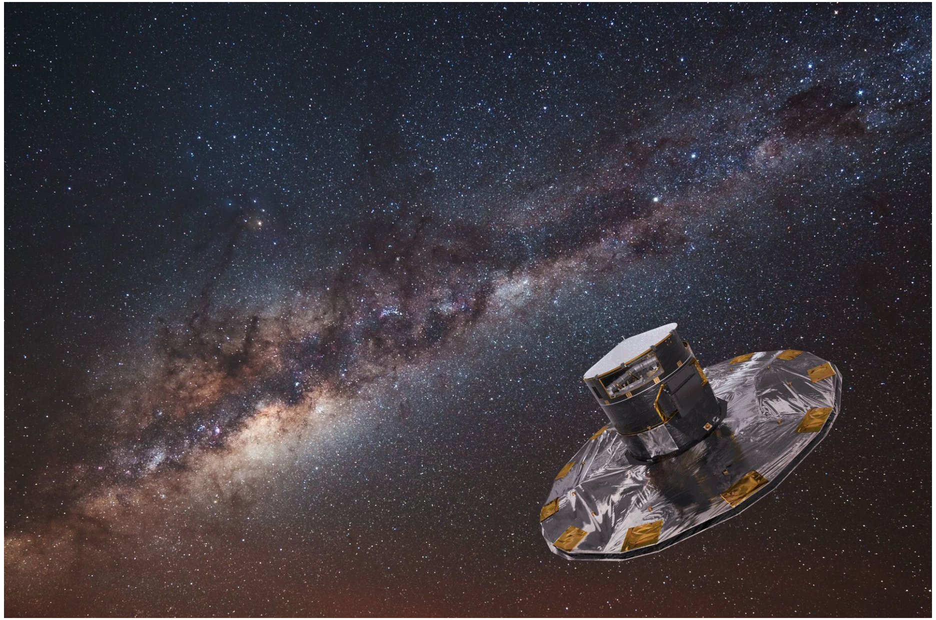
10 Gyr

Each clump = an accreted galaxy

Helmi+00

Accreted galaxies are expected to appear as over-densities = kinematic substructures

# Gaia observations (2013-)



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

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

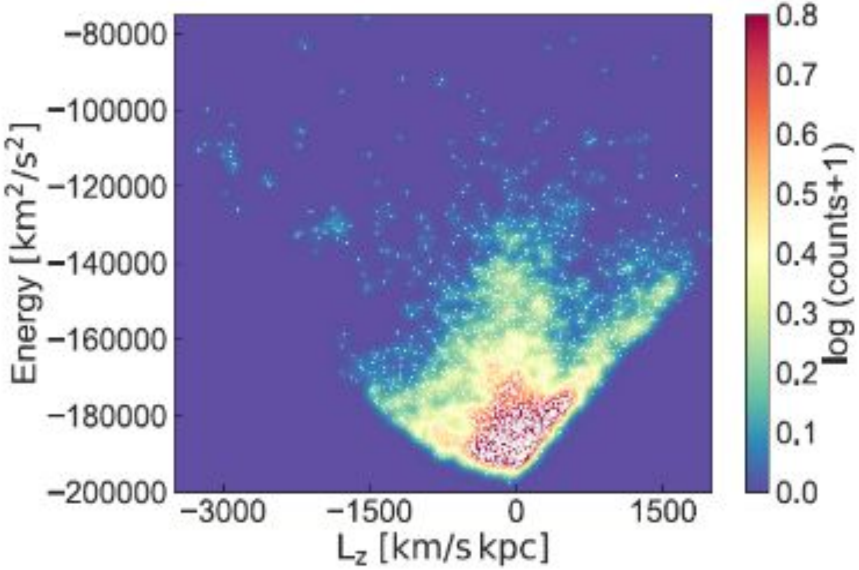
Radial Velocity **(~33 M stars)**

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

The numbers are for DR3 (2022. June)

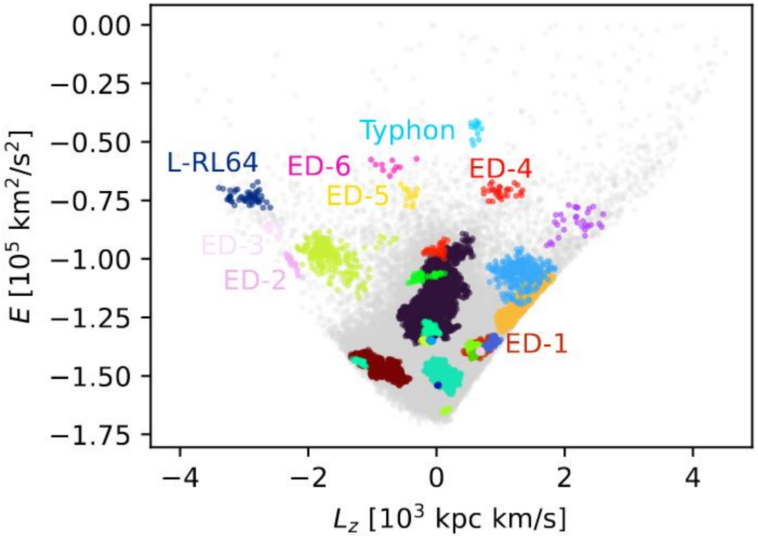
# Data-driven identification of substructures

Lövdal+22, Ruiz-Lara+22, Dodd+22



Koppelman+18

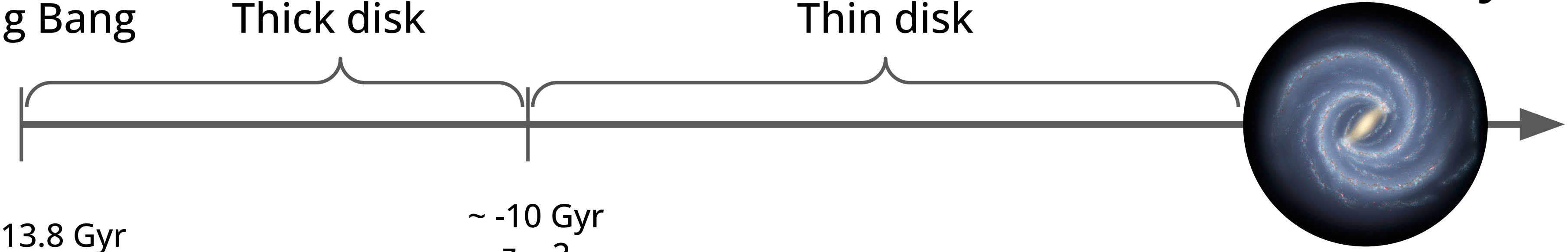
Clustering analysis



Dodd+23

See also, e.g., Yuan+20

# The formation history of the Milky Way



Present day

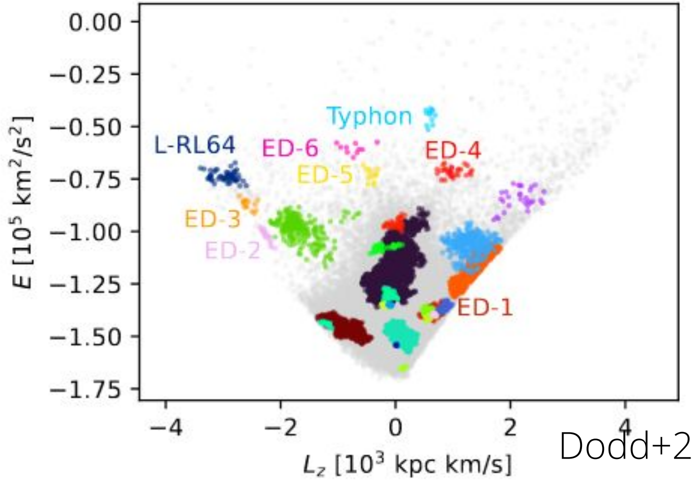
Big Bang

Thick disk

Thin disk

-13.8 Gyr

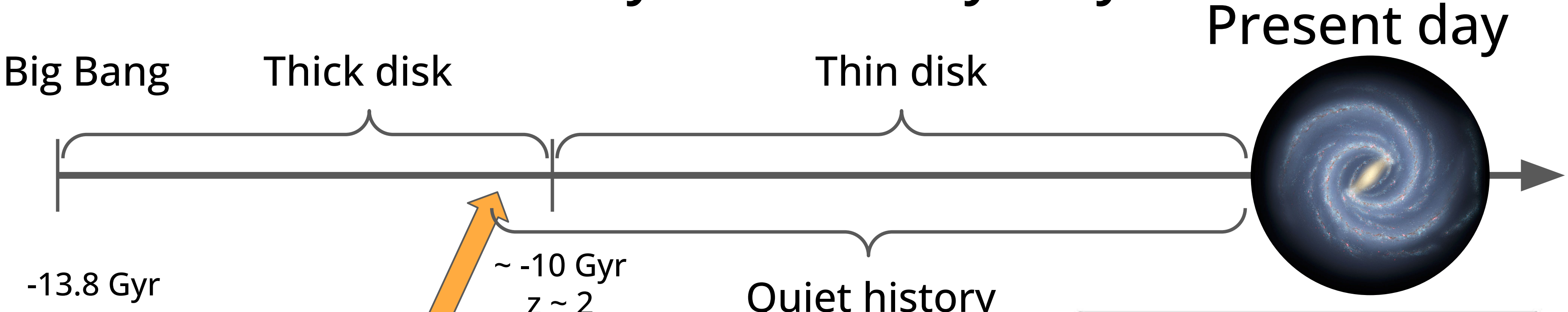
~ -10 Gyr
z ~ 2



Dodd+23

Ruiz-Lara+22

# The formation history of the Milky Way



Present day

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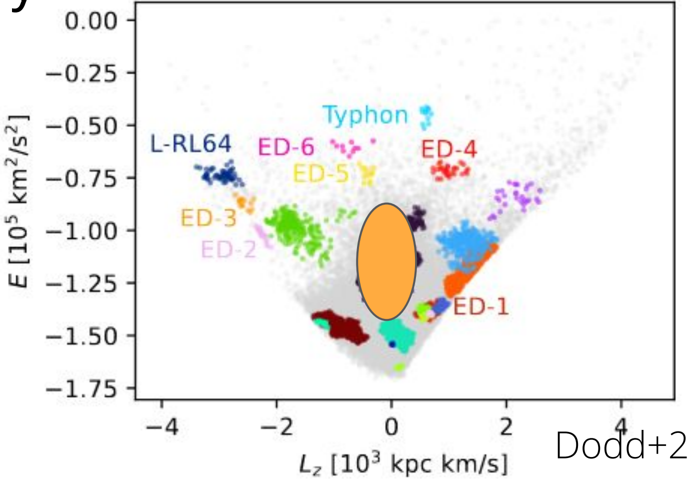
-13.8 Gyr

~ -10 Gyr
z ~ 2

Quiet history

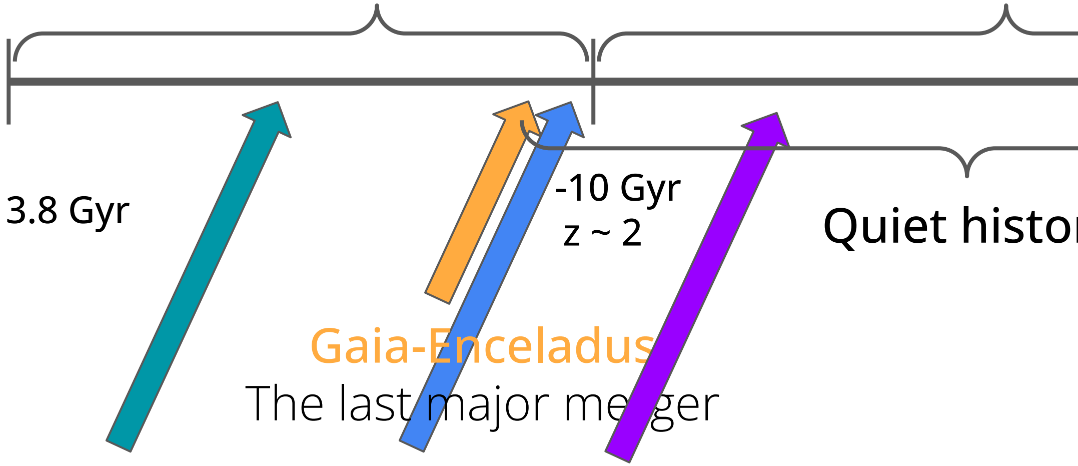
**Gaia-Enceladus**
The last major merger



Dodd+23

Ruiz-Lara+22

# The formation history of the Milky Way



Big Bang

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Quiet history

Gaia-Enceladus
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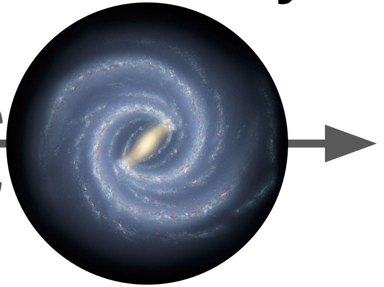
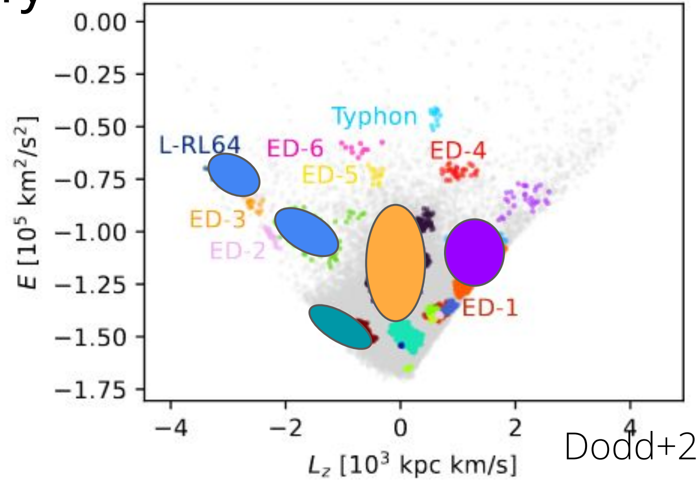
Thamnos Sequoia Helmi Streams
Accretion remnants

Ruiz-Lara+22

Present day





Dodd+23

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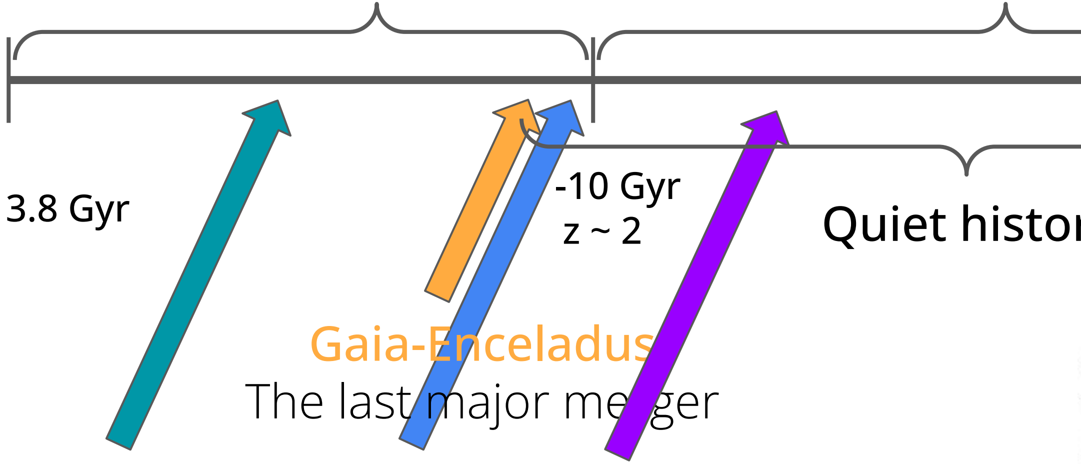
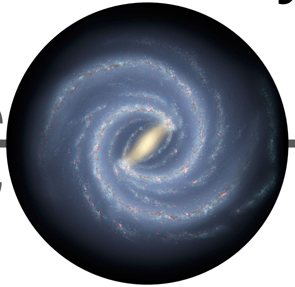


Big Bang

Thick disk

Thin disk

Present day



-13.8 Gyr

-10 Gyr
z ~ 2

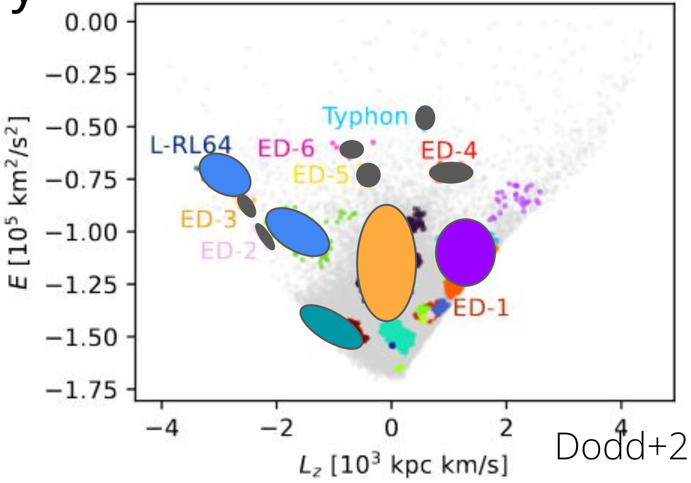
Quiet history

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

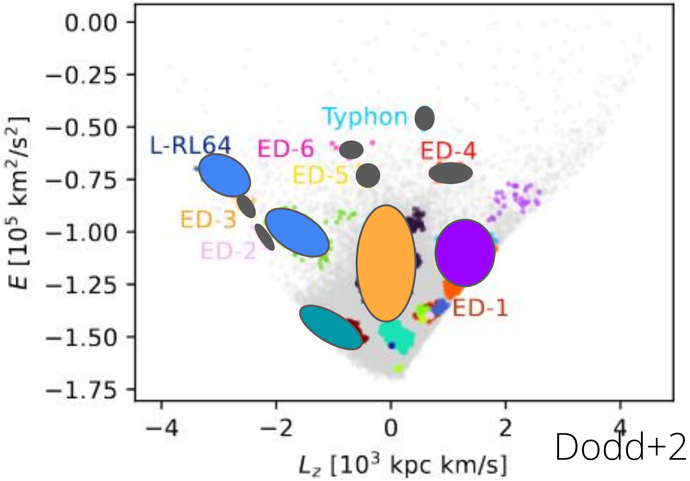


Dodd+23

# Chemical abundance

## Properties of the substructures

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



Dodd+23

## Constraining astrophysical processes

- Is star formation in these accreted galaxies similar to that in MW?
- Is chemical enrichment different?

# Chemical characterization of substructures

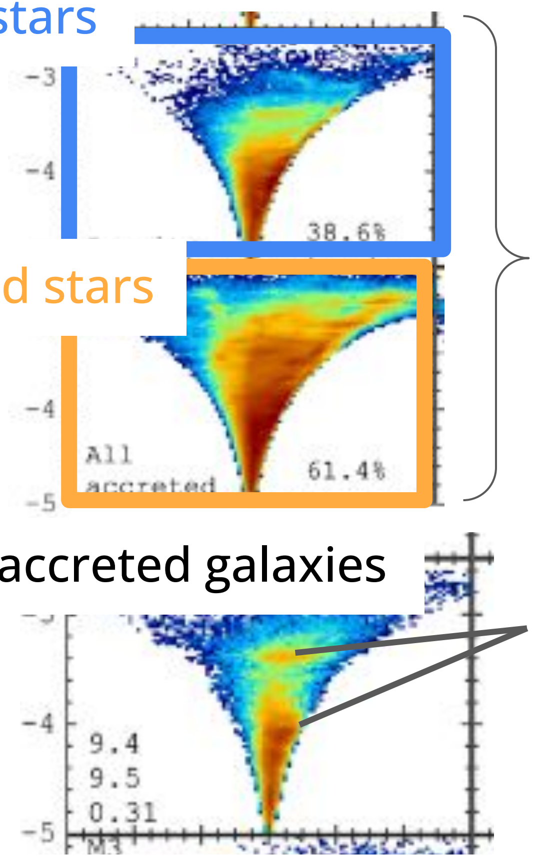
Khoperskov+23

**A better membership**

Stars with different origins can overlap

**Associating substructures**

A single accretion can form more than one substructures



In-situ stars

Accreted stars

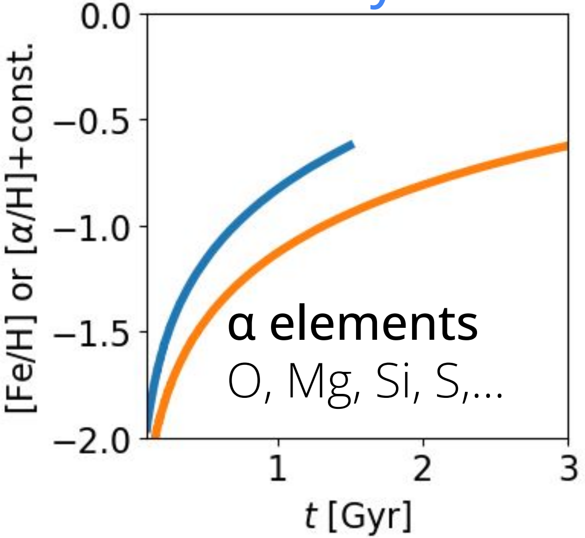
Significant overlap

One of accreted galaxies

Multiple substructures

# Example: [α/Fe] ratio

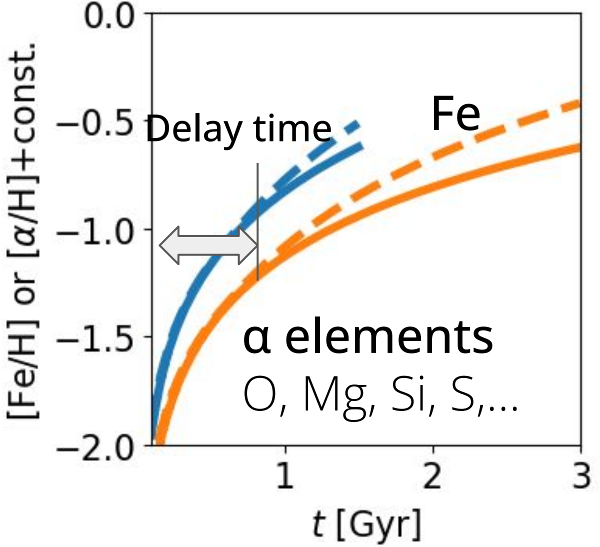
Enrichments by CCSNe



A more massive galaxy forming stars efficiently
A less massive galaxy

# Example: [α/Fe] ratio

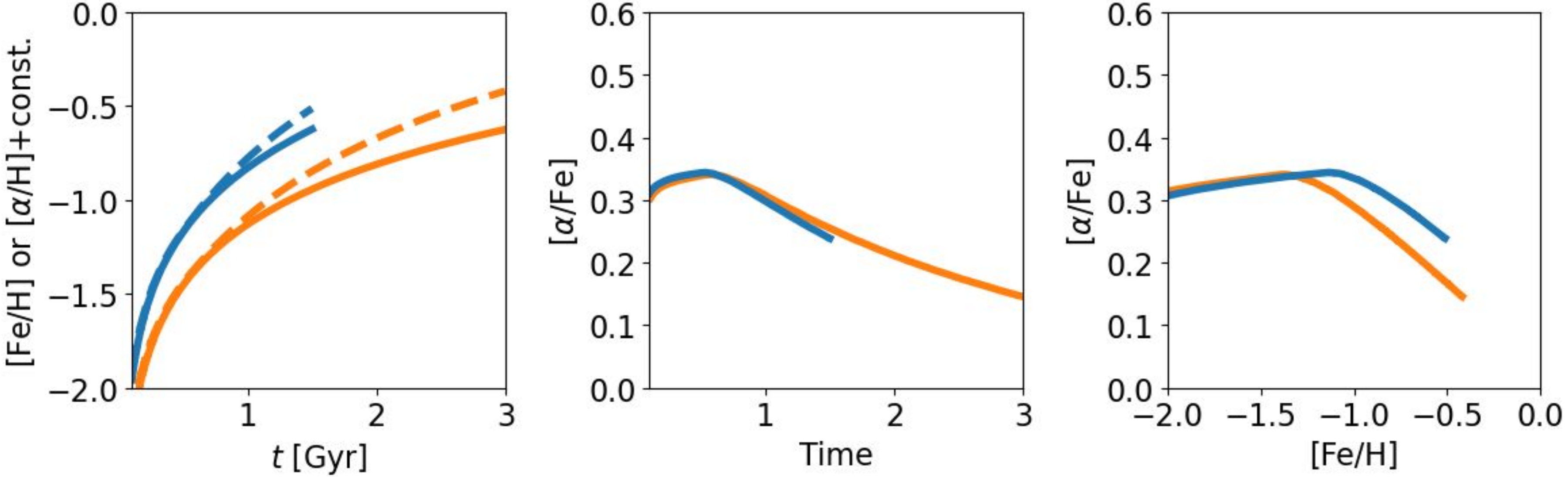
Enrichments by Type Ia SNe



A more massive galaxy forming stars efficiently
A less massive galaxy

# Example: [α/Fe] ratio

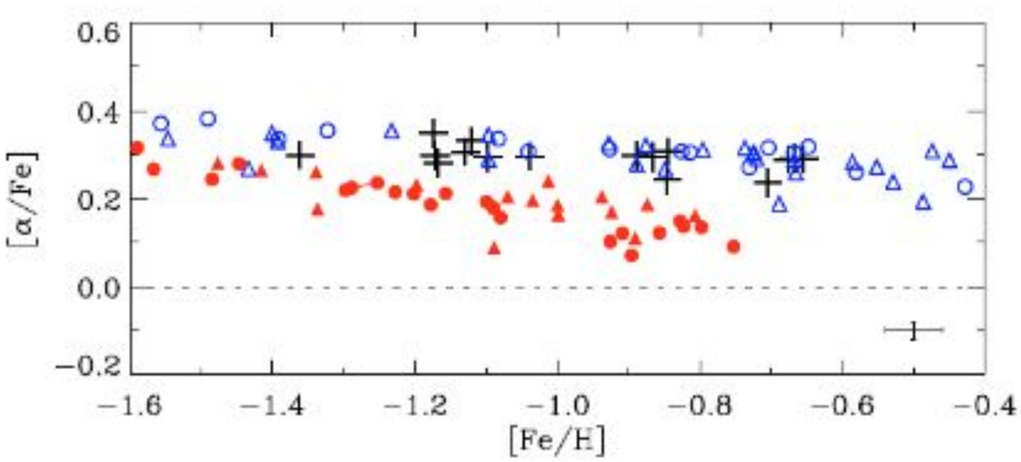
More massive galaxies have [α/Fe] at high [Fe/H]



A more massive galaxy forming stars efficiently

A less massive galaxy

# Example: two distinct populations among halo stars



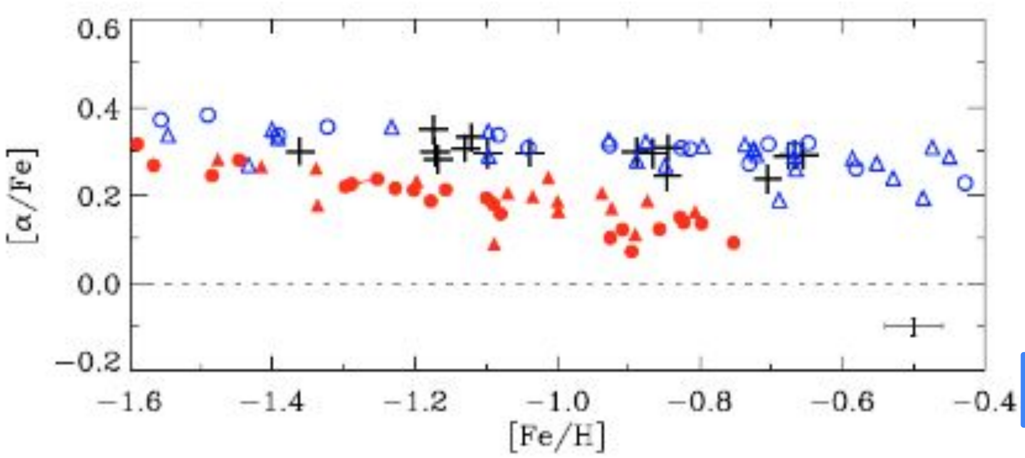
Nissen & Schuster 10

High-α stars
Formed in a more massive galaxy, **Milky Way**

Low-α stars
Formed in less massive galaxies, **accreted dwarf galaxies**

We can learn about formation of stellar populations using elements with known origins

# Example: two distinct populations among halo stars



Nissen & Schuster 10

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

Low-α stars

Formed in less massive galaxies, **accreted dwarf galaxies**

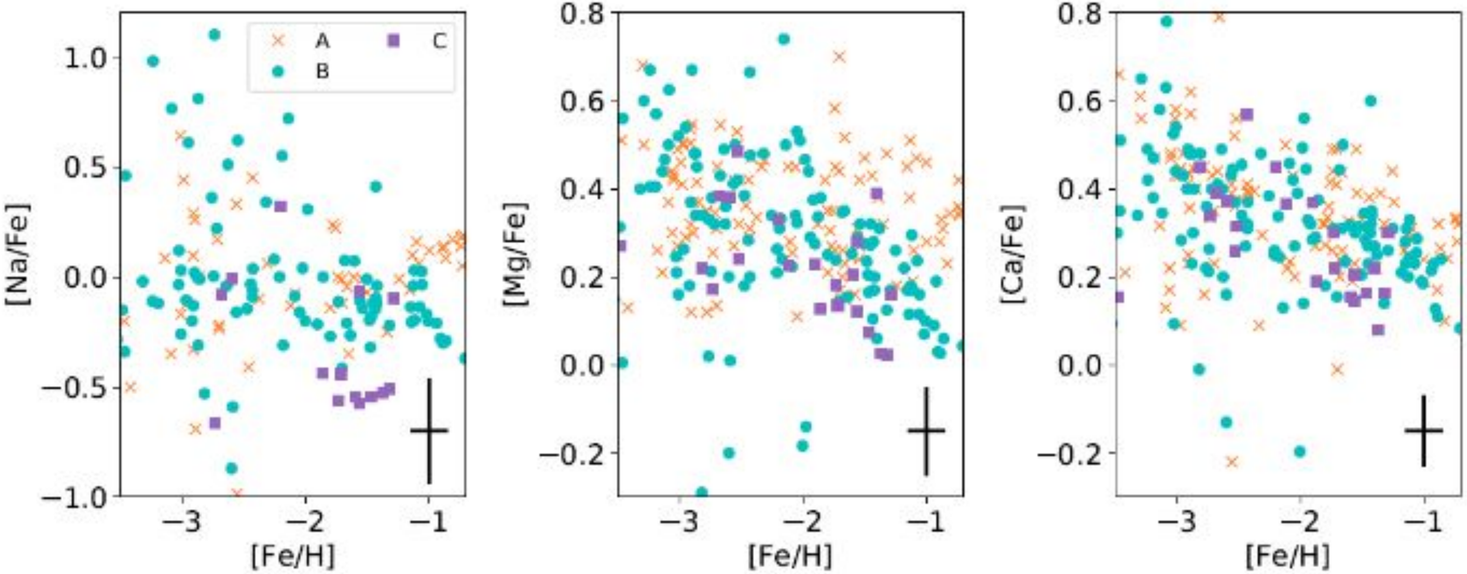
Differences among them?

We can learn about formation of stellar populations using elements with known origins

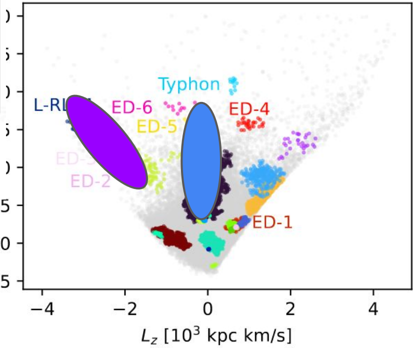
# A hint of chemical difference

Matsuno+19

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



MW in-situ
Gaia-Enceladus
Sequoia

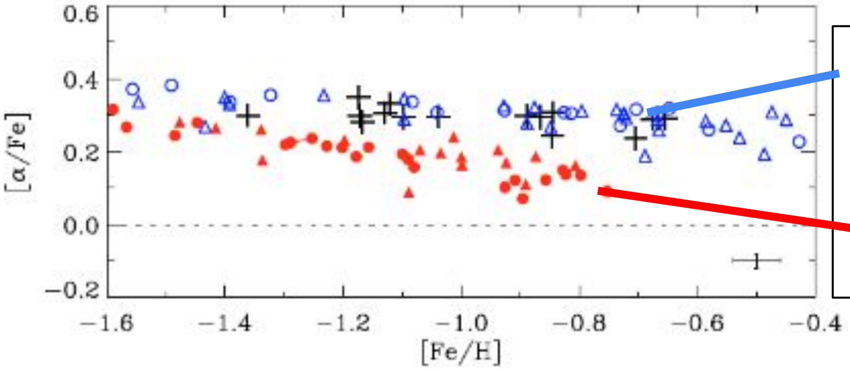


Sequoia seems to have lower [Na, Mg, Ca/Fe] abundances

# High-precision to clarify "chemical distinctness"

High-precision

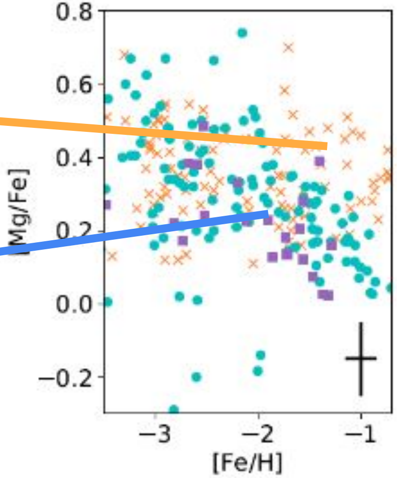
Moderate-precision



Nissen & Schuster 10

MW in-situ

Gaia-Enceladus



Matsuno+19

High-precision is necessary to clearly detect separations

# 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

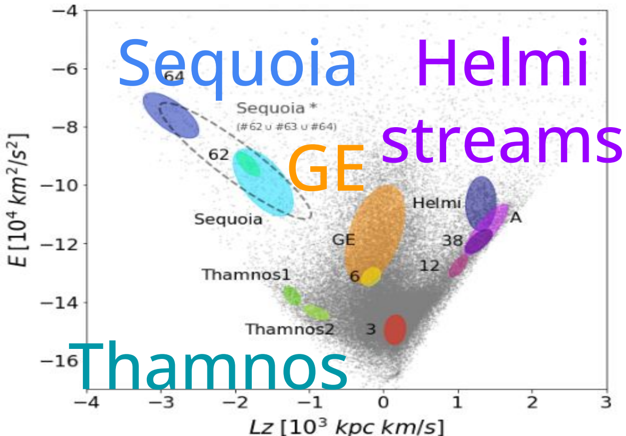
Stars in the three prominent substructures

<u>Sequoia, Helmi streams</u>, and Thamnos

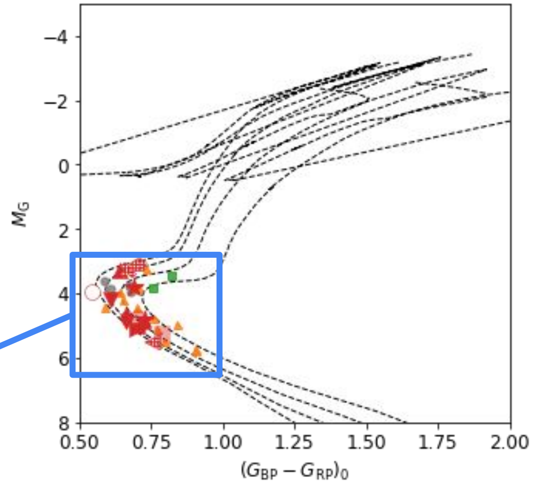
## Observations

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

~ 6 nights in total



Matsuno+22a, b



# To achieve high-precision

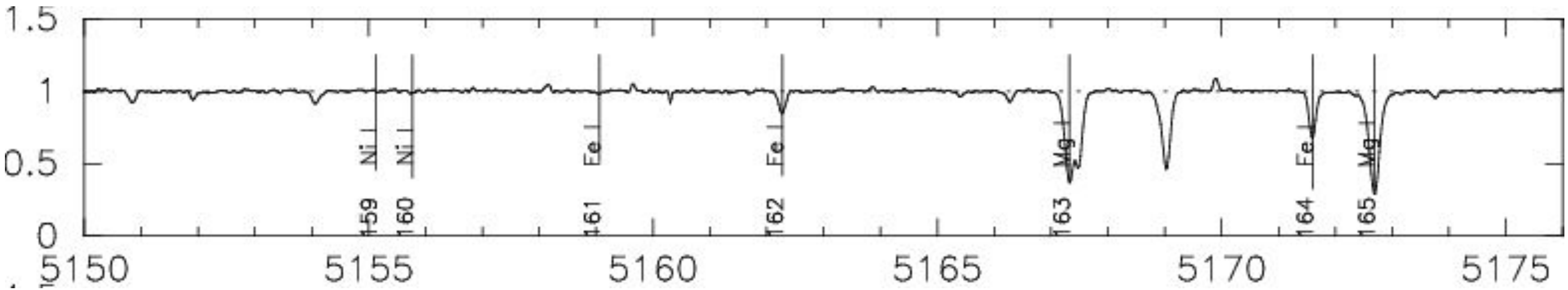
★ High-S/N, high-resolution spectra

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

★ Narrow stellar parameter range

★ Differential abundance analysis to minimize the effect of input data

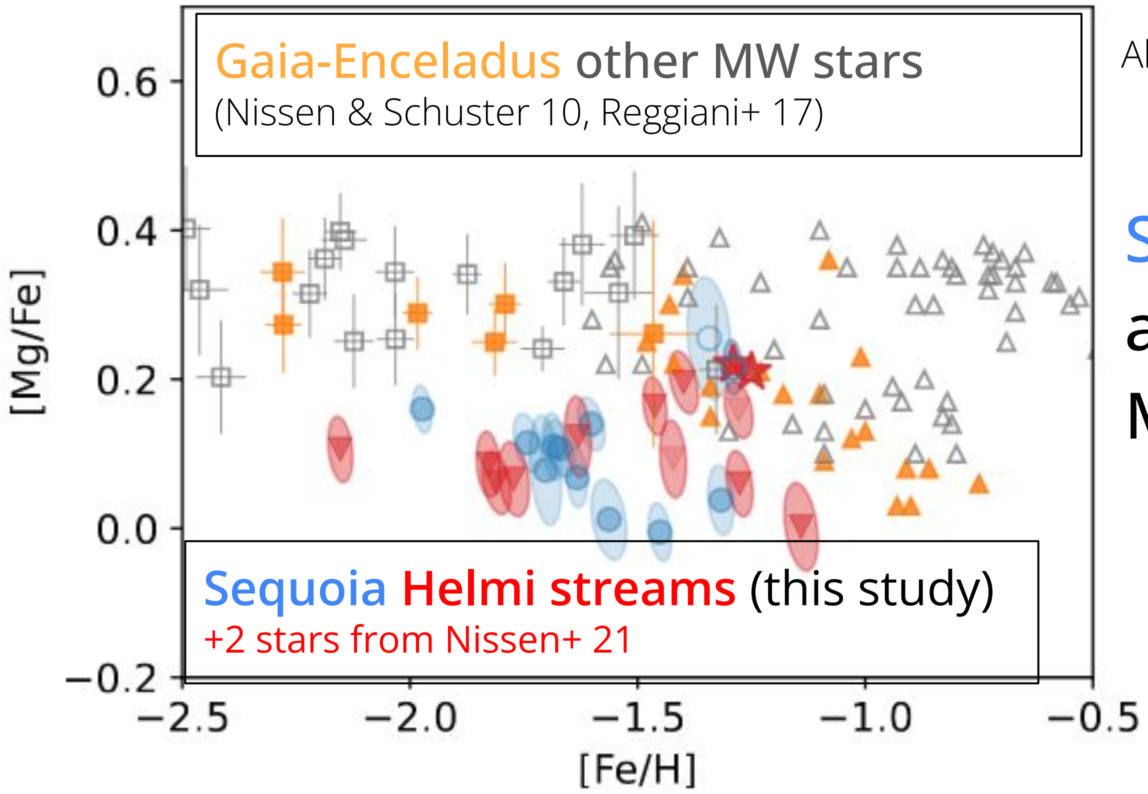
★ Reanalysis of the literature sample



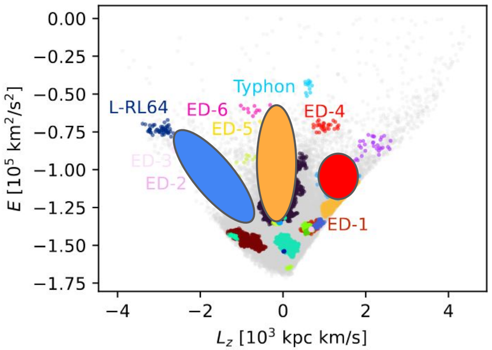
# Results: Mg abundance, one of the α-elements

Matsuno+22a, b

All the abundances are on the same scale



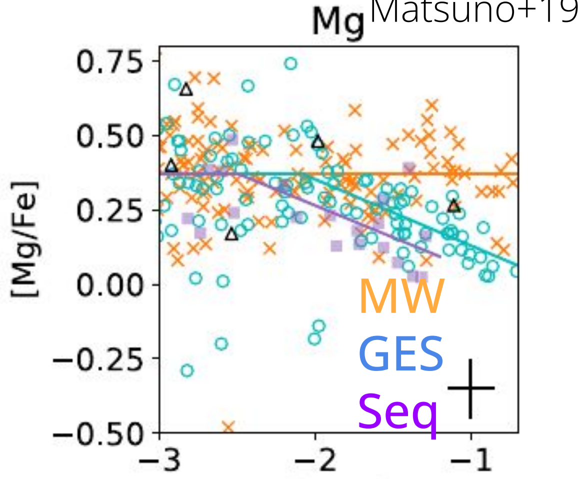
Seq. and HS have distinct and lower [Mg/Fe] than MW and GE



Matsuno+22a, b

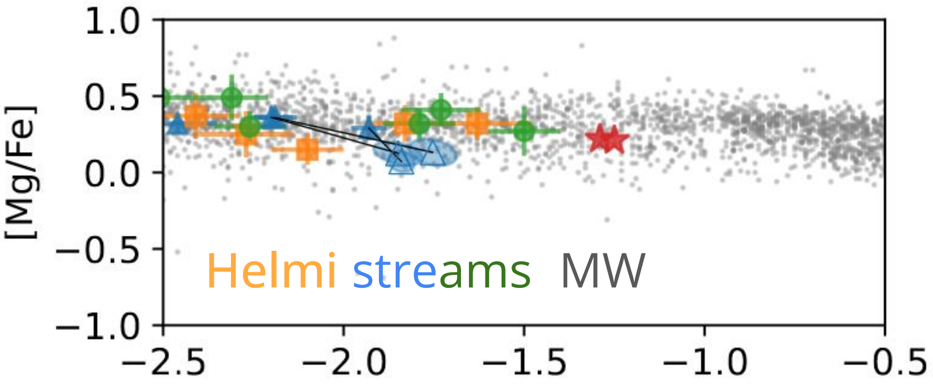
# Comparison with the literature data

## Sequoia



SAGA database (Suda+08)

## Helmi streams



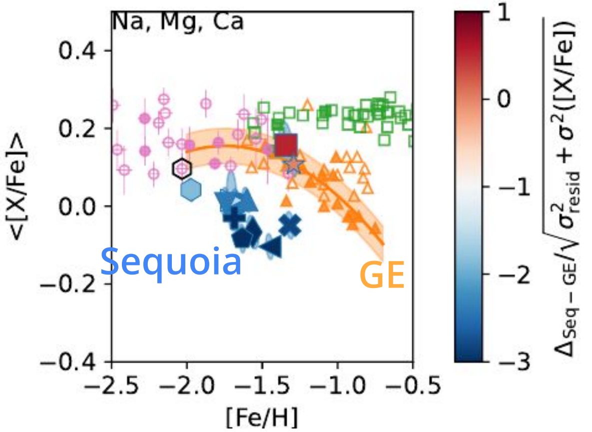
SAGA db, Roederer+10
Aguado+21, Nissen+21, Gull+21

## The differences are hard to see in the literature data

✓Homogeneous abundance from the literature reanalysis
✓High precision from differential analysis of high S/N data

Matsuno+22a, b

# What precision do we need to see the differences?



Δ[X/Fe] between GE and Seq: ~ 0.20 dex

σ ([X/Fe]) among GE stars : ~ 0.07 dex

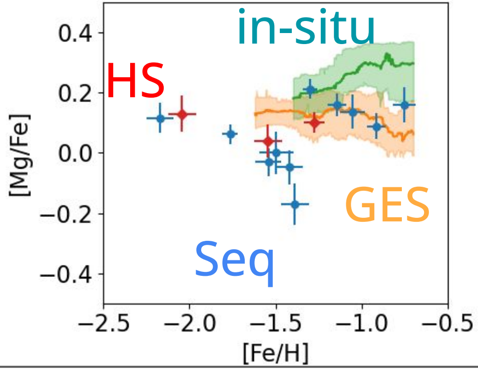
**The measurement uncertainty needs to be**

**σ([X/Fe]) < 0.07 dex**

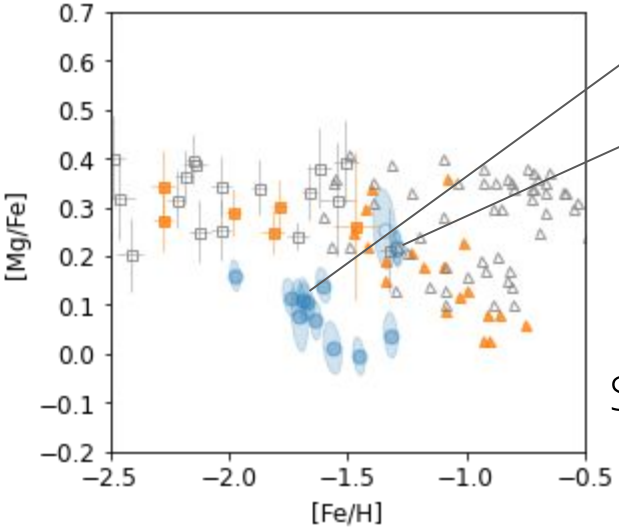
**to separate Seq from GE by >2σ.**

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

We also confirmed this with GALAH stars with σ < 0.07



# What does the different abundance indicate?

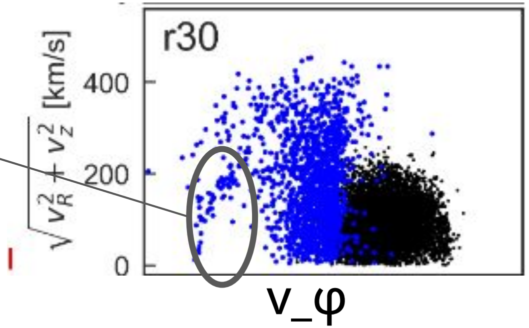


The majority are different from Gaia-Enceladu

Two stars are on the Gaia-Enceladus path

Gaia-Enceladus like
merger simulation

Sequoia-like orbits

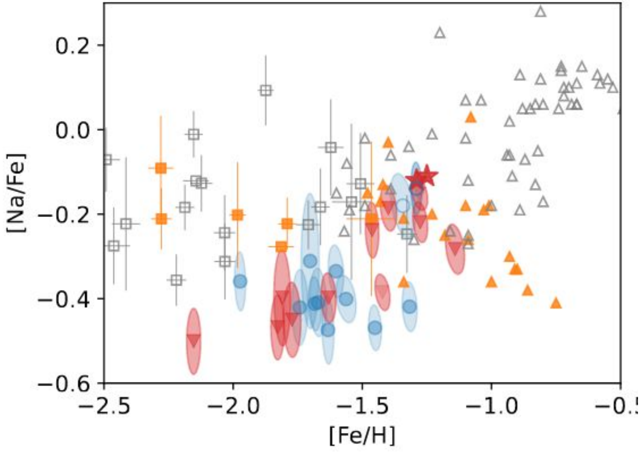


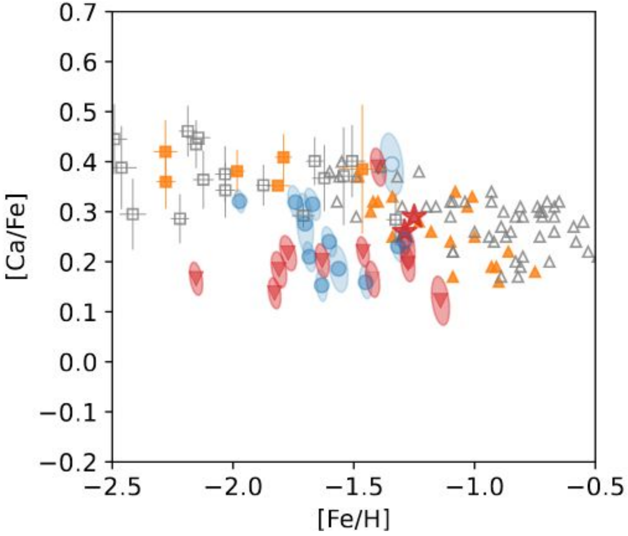
Koppelman et al. (2020)

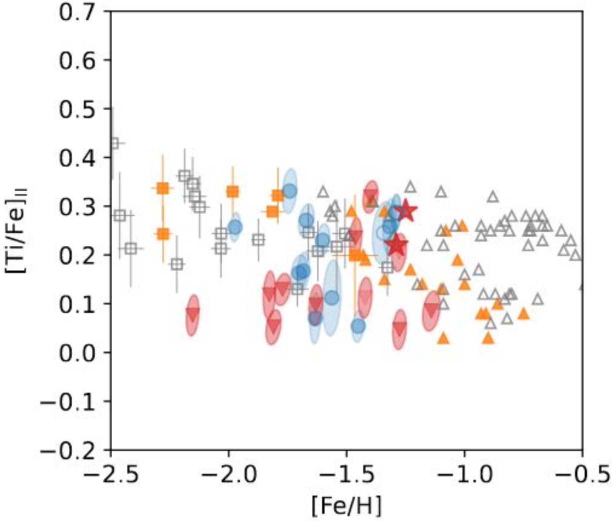
Sequoia = an accreted galaxy + ~20% Gaia-Enceladus

# The astrophysical origin of low [Mg/Fe]

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





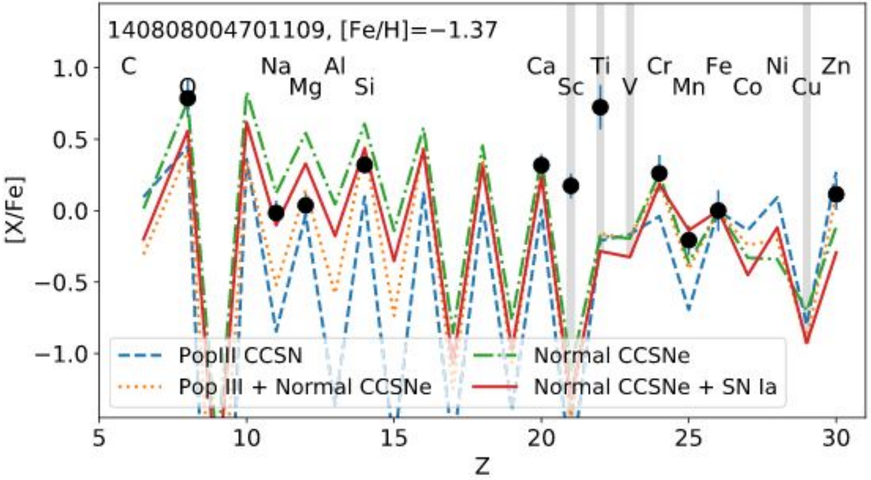


# The astrophysical origin of low [Mg/Fe]

We fit abundance patterns of individual objects

Parameters

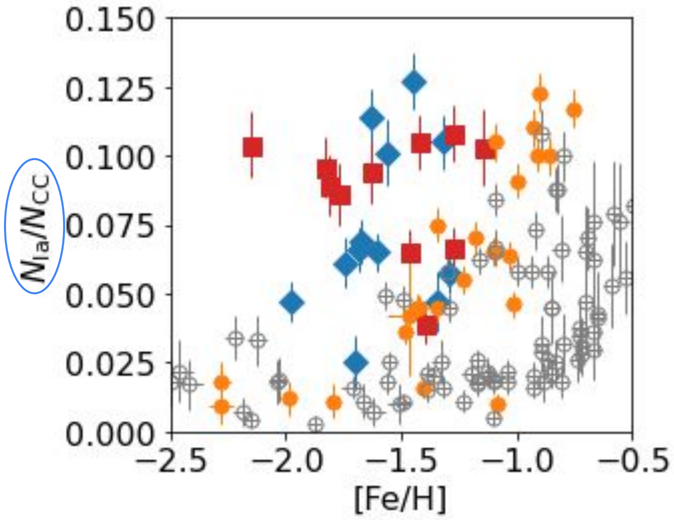
- α (slope in IMF)
- $Z_{CC}$(Representative metallicity of CCSNe)
- $N_{Ia}/N_{CC}$



Ishigaki+21

# The astrophysical origin of low [Mg/Fe]

The number ratios between SNIa and SNII



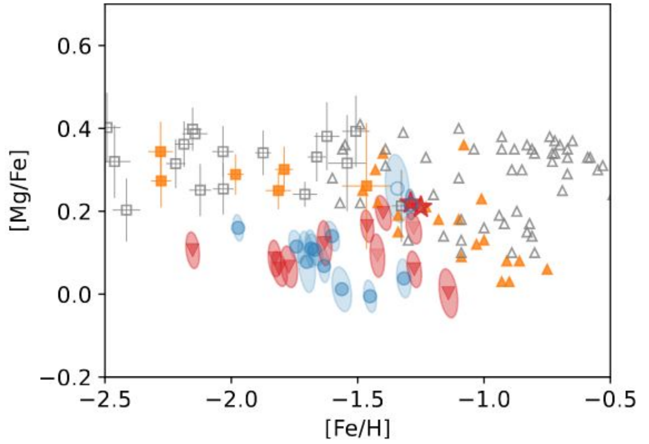
Gaia-Enceladus
Sequoia
Helmi Streams
Other halo stars

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

**Suggestive of slower chemical evolution, lower stellar mass**

Matsuno+22a, b

# Summary of interpretation



## The distinct abundance of Seq. and HS

Both substructures need their own progenitors

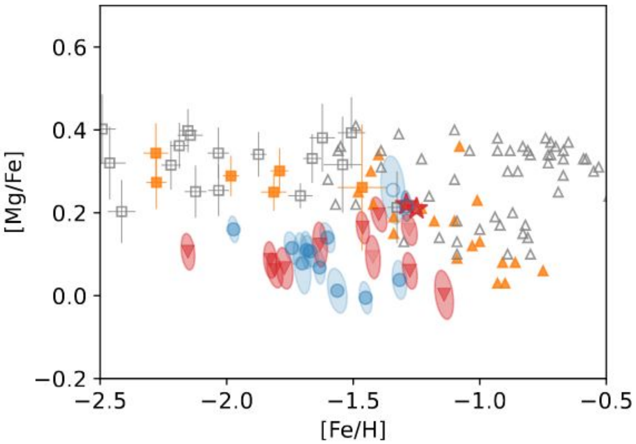
## The lower [Mg/Fe] of Seq. and HS than MW and GE

Type Ia contributions are larger in Seq. and HS than in GE

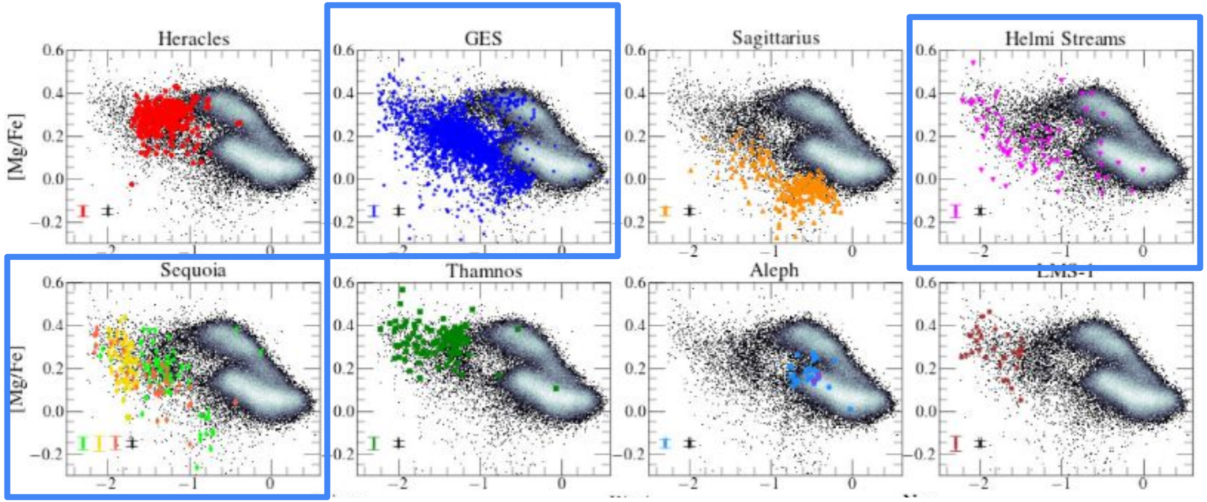
Suggestive of lower progenitor mass (consistent with the number of stars)

# In the context of large surveys...

Matsuno+22a, b



Horta+23



These are complementary

- **High-precision for a small sample**

  e.g., chemical membership, evaluating contamination
- **Moderate precision for a large sample**

  e.g., chemical evolution trend, global picture

# What are the current limitations?

Major assumptions in most of abundance analysis

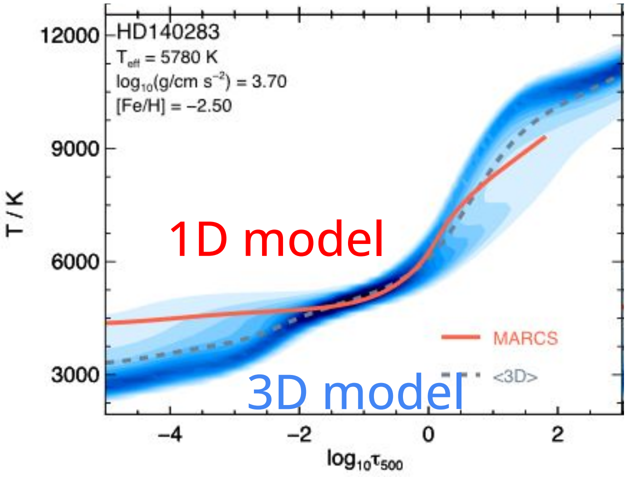
Amarsi+16

★ Local thermodynamic equilibrium (LTE)

→ non-LTE

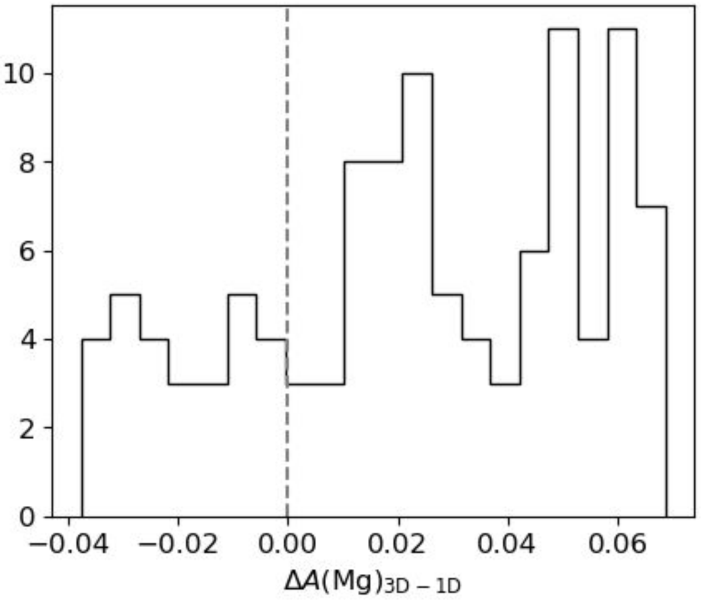
★ 1D model of stellar atmosphere

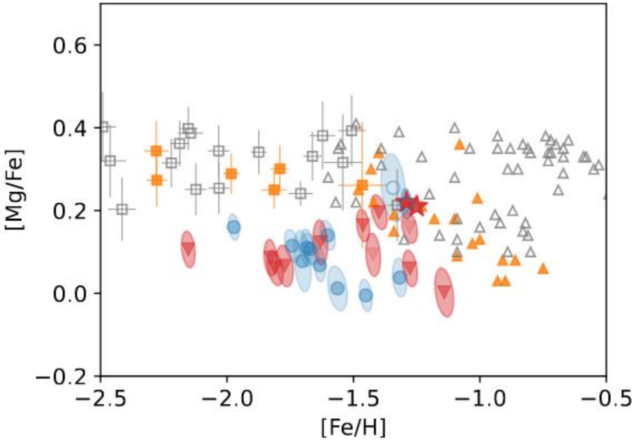
→ 3D models



What do we gain by more sophisticated analysis?

# The amplitude of 3D corrections





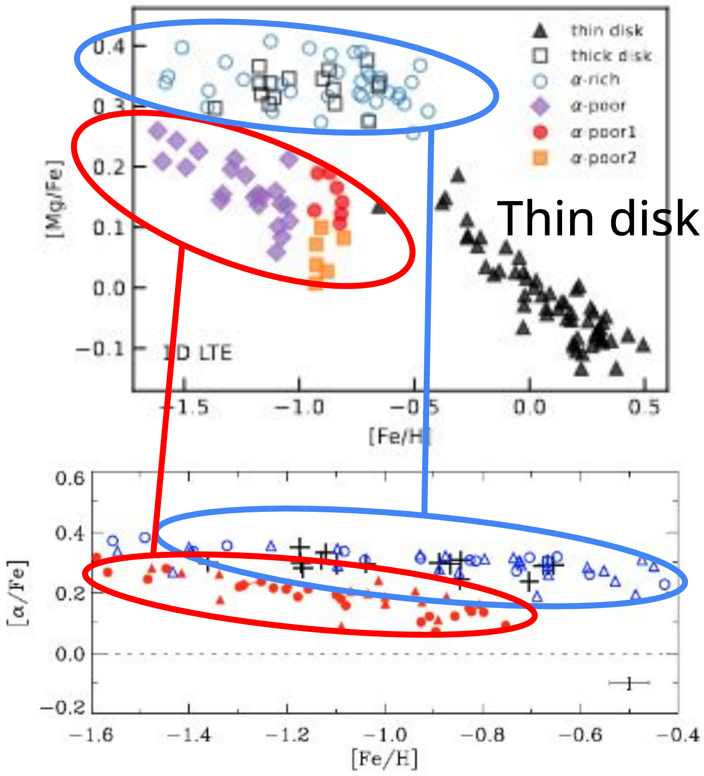
Matsuno, Amarsi (2024, in prep.)

The range of the corrections is larger than measurement uncertainty
The current limitation is the use of 1D LTE analysis

# A new population revealed in 3D non-LTE analysis

Matsuno, Amarsi  (2024, in prep.)

1D LTE



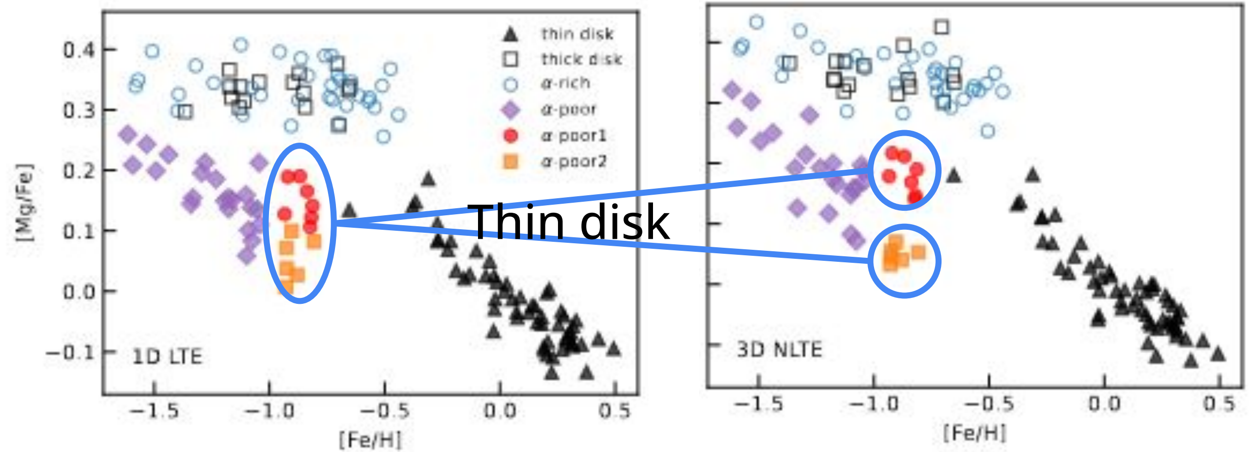
Thin disk

# A new population revealed in 3D non-LTE analysis

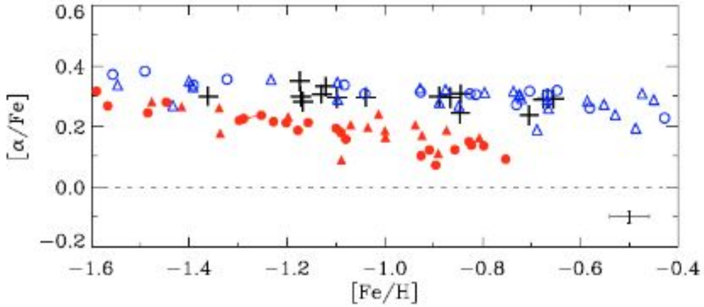
Matsuno, Amarsi  (2024, in prep.)

## 1D LTE

## 3D non-LTE



Thin disk



High metallicity end of the accreted population split into two

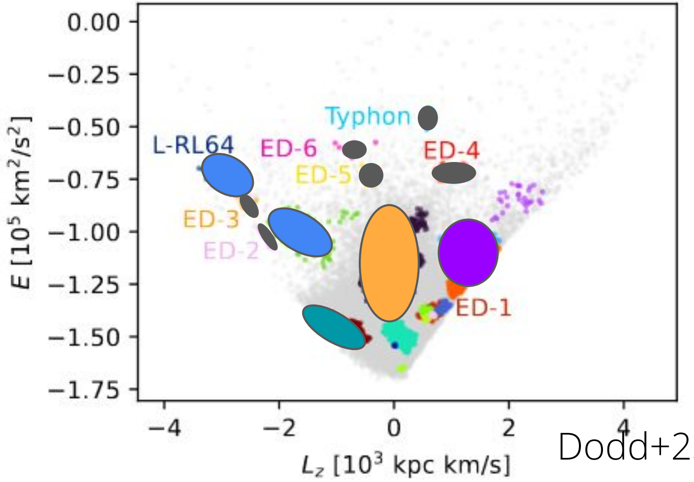
# Chemical abundance

## Properties of the substructures

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

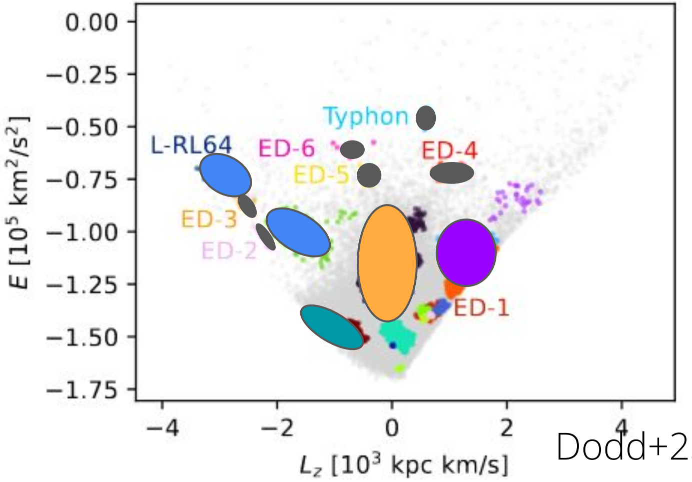
## Constraining astrophysical processes

- Is star formation in these accreted galaxies similar to that in MW?
- Is chemical enrichment different?



Dodd+23

# Chemical abundance



Dodd+23

## Properties of the substructures

- Does each substructure correspond to and contain a single accreted galaxy?
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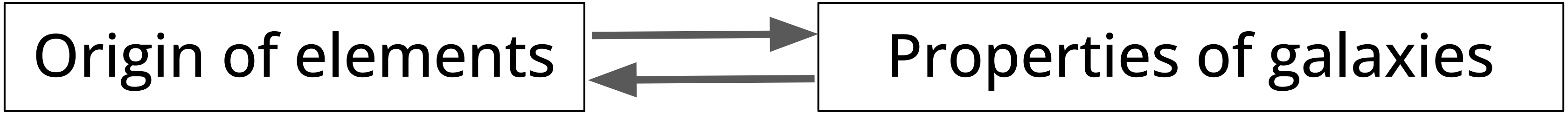
## Constraining astrophysical processes

- Is star formation in these accreted galaxies similar to that in MW?
- **Is chemical enrichment different?** → **Nucleosynthesis process**

# Constraining nucleosynthesis with substructures



Origin of elements

Properties of galaxies

## 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.

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?

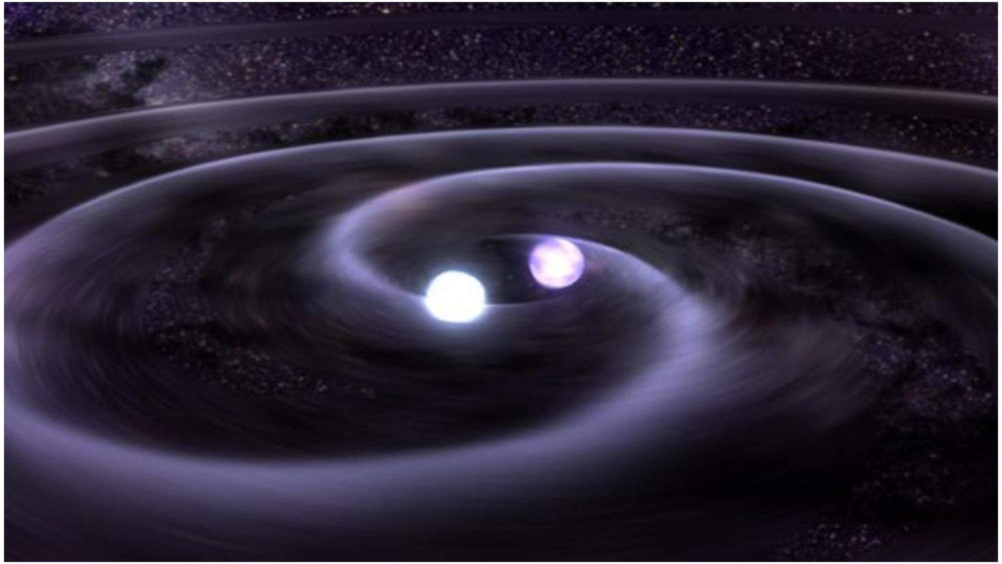


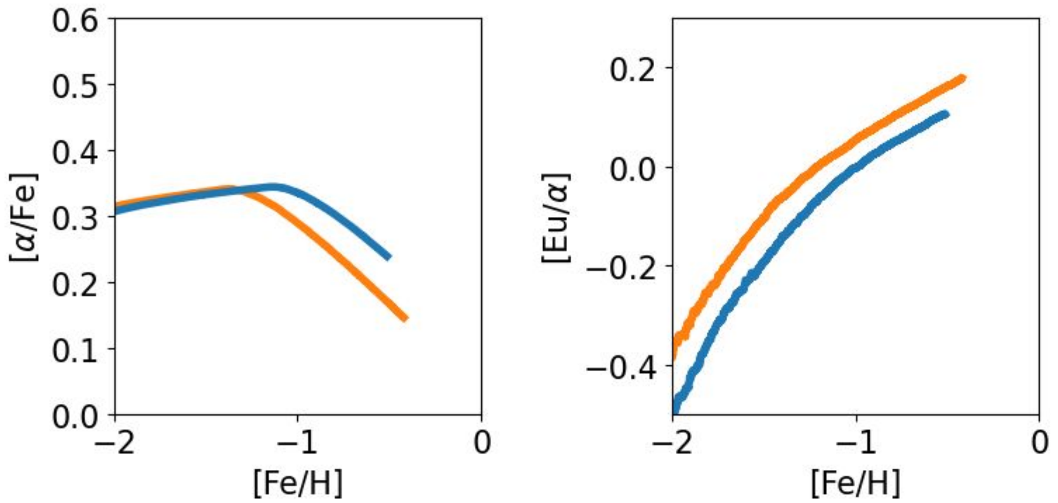
Image credit: Goddard Space Flight Center/NASA

# 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)

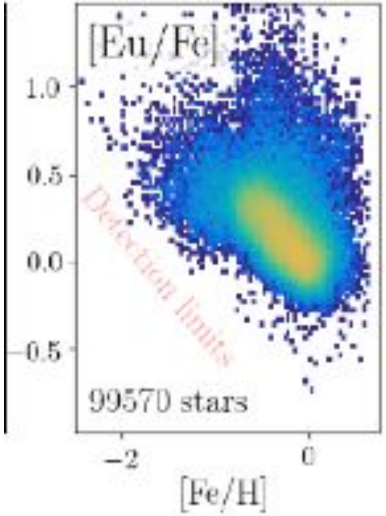


A more massive galaxy forming stars efficiently

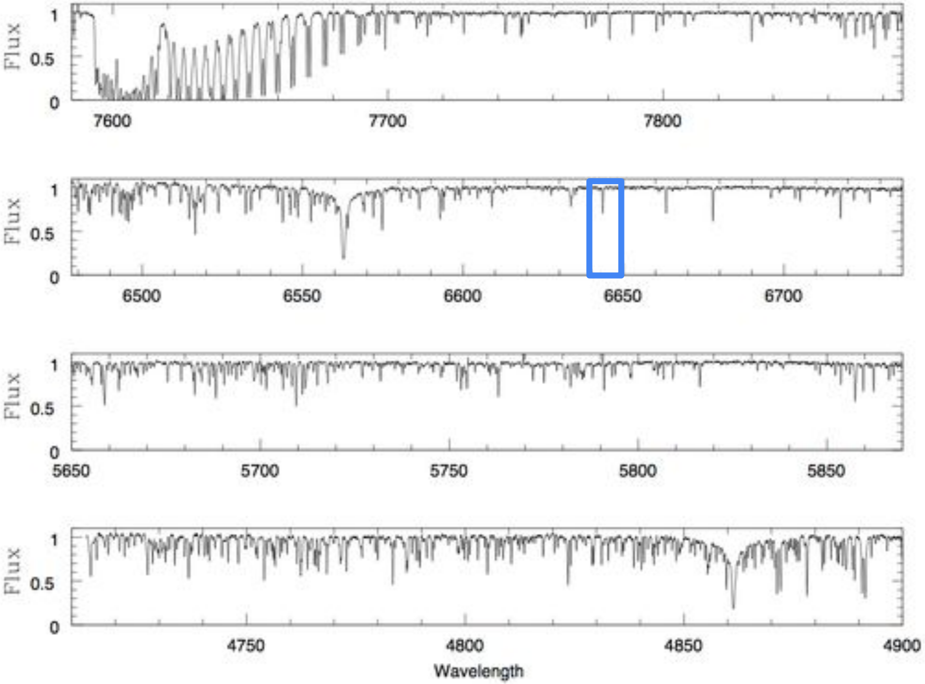
A less massive galaxy

# The largest sample of Eu abundance from GALAH

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

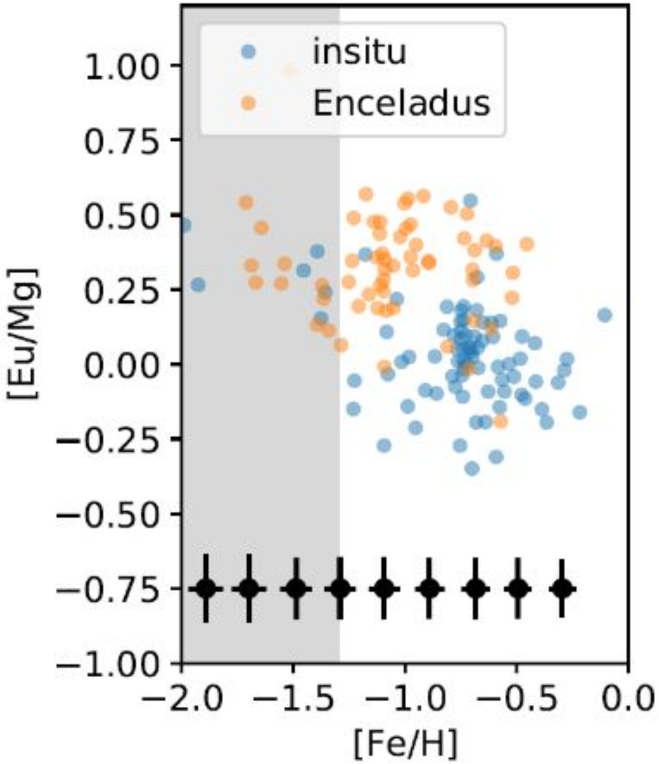


Buder+21



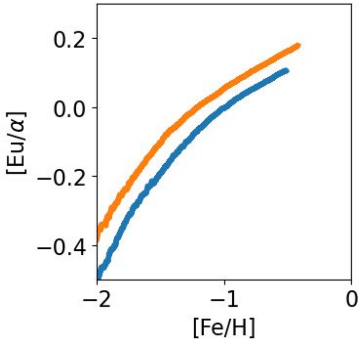
Matsuno+21b

# Eu abundance in the Milky Way and Gaia-Enceladus



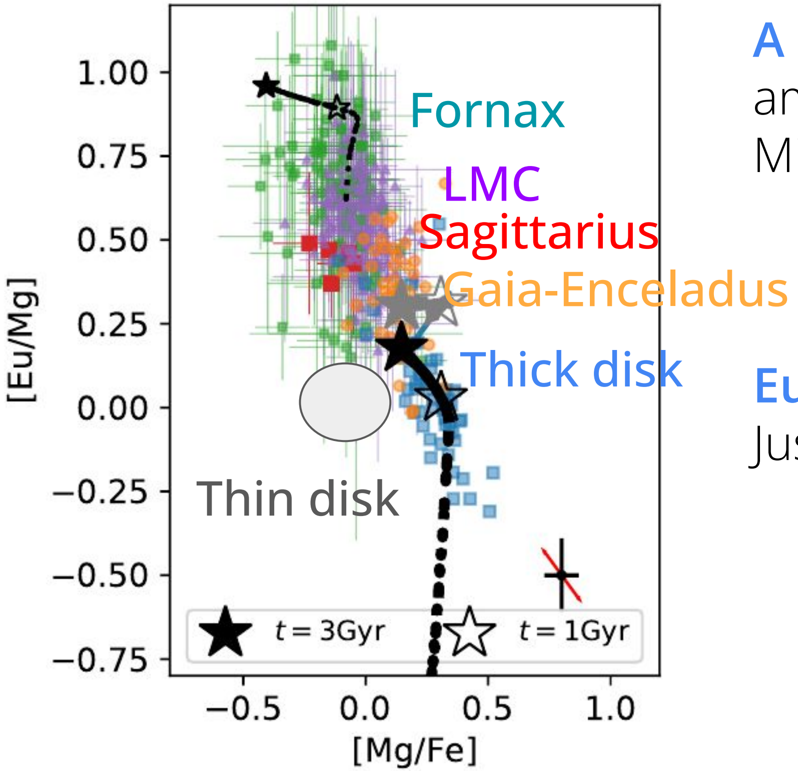
[Eu/Mg] is clearly higher in stars formed in Gaia-Enceladus than those formed in-situ

Exactly what we would expect if Eu is produced by NSMs



A more massive galaxy forming stars efficiently
A less massive galaxy

# Eu enrichments in MW and in dwarf galaxies



**A clear sequence between [Eu/Mg] and [Mg/Fe]**
among old stellar populations in and around the Milky Way

**Eu production with a delay by NSM**
Just like Fe production with a delay by SNe Ia

# Future prospects

## One-by-one observation

SUBARU TELESCOPE
National Astronomical Observatory of Japan

- Contamination rates
- Origin of elements

## Surveys

ongoing APOGEE GALAH

soon WEAVE 4MOST

~2035 WST

Comprehensive view of the merging history of the Milky Way

# Summary

- Kinematic substructures are promising candidates for accreted galaxies in the Milky Way
- **Precise chemical abundance** allows us to detect abundance differences among substructures and characterize their progenitors
- **3D non-LTE analysis** enables even more precise abundance study
- Accreted galaxies offer opportunities to study **nucleosynthesis**

**These knowledge complements what we get from upcoming surveys**