Identification of low-mass accreted galaxies with metal-poor stars

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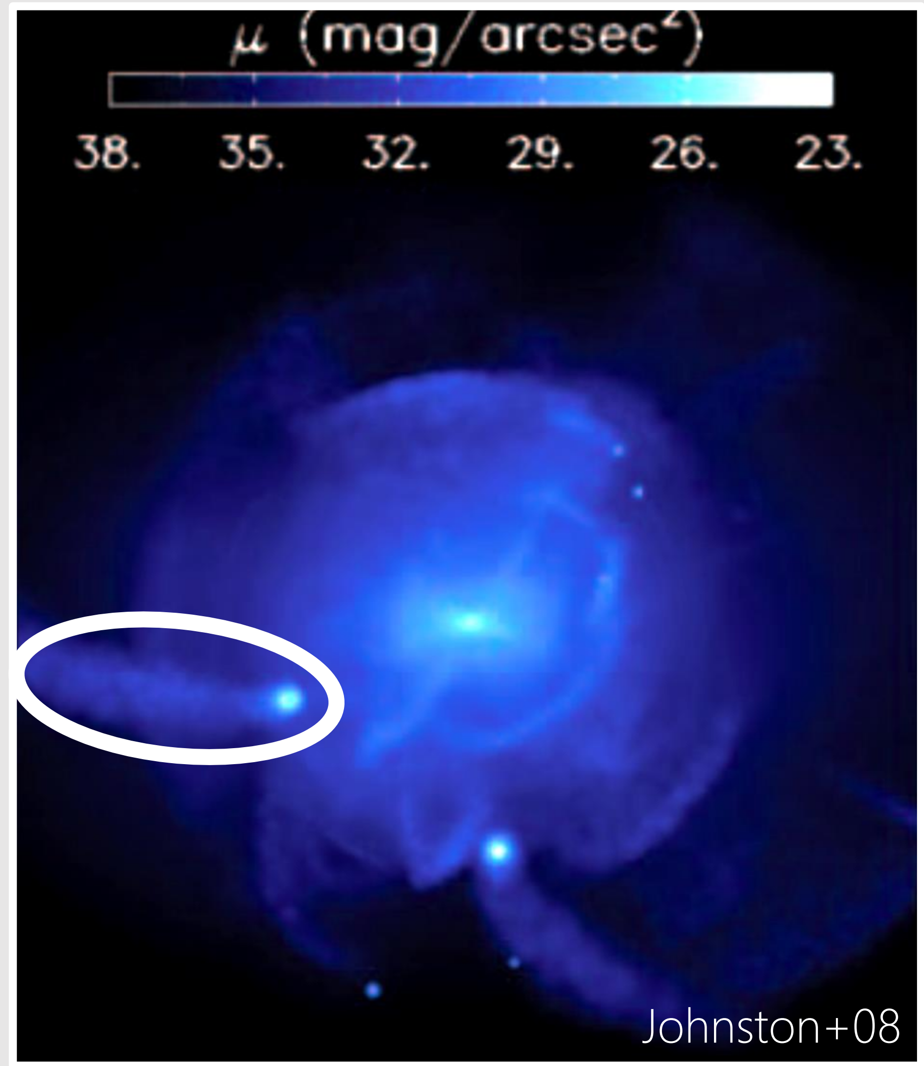
Galaxy formation in ΛCDM models

Galaxies form through **accretions/mergers of galaxies**

Signatures are left in the outskirt of galaxies (halo)

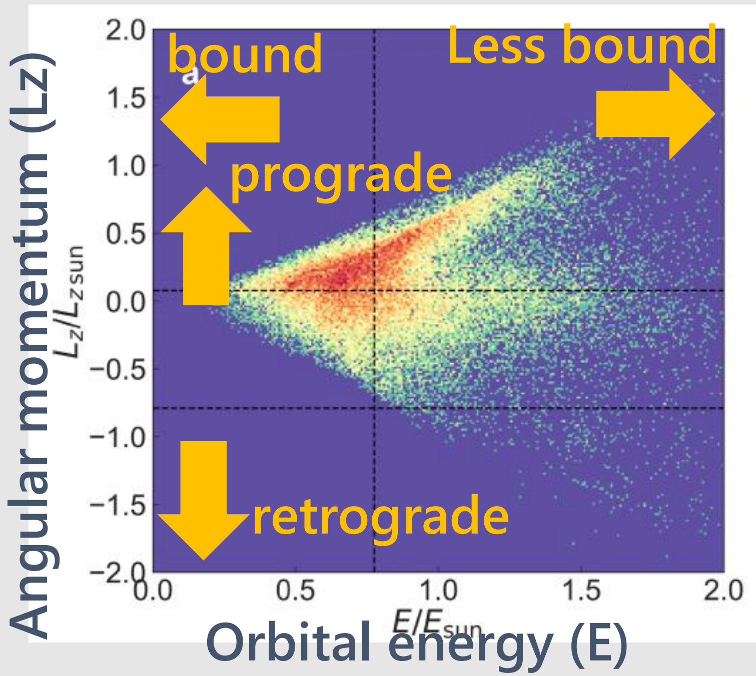
- What are the properties of progenitors?
- How was our Galaxy specifically formed?



Past accretion of a massive galaxy

From Gaia results Helmi+18 (see also Belokurov+18 etc.)

Kinematics



Lz and E are conserved in a static axisymmetric potential

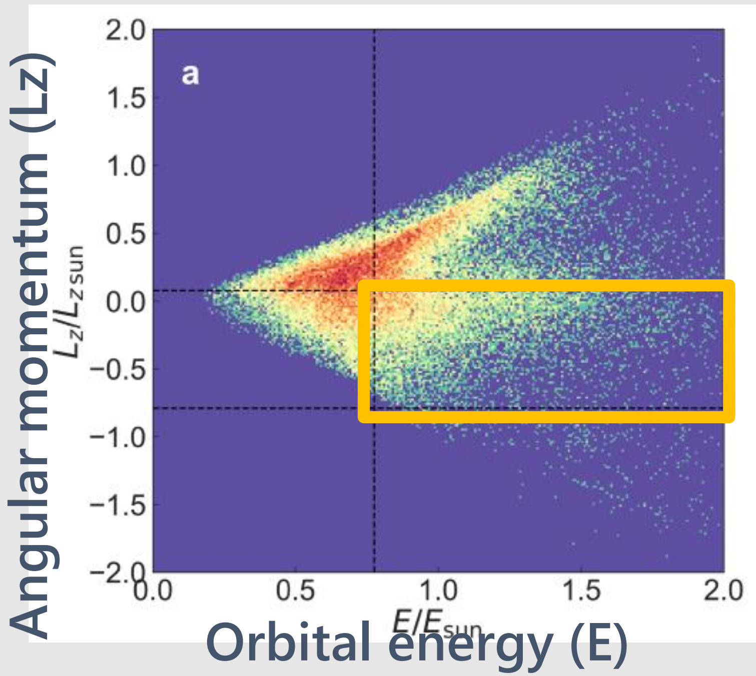
Lz-E plane is suited to search for accretion signatures

Past accretion of a massive galaxy

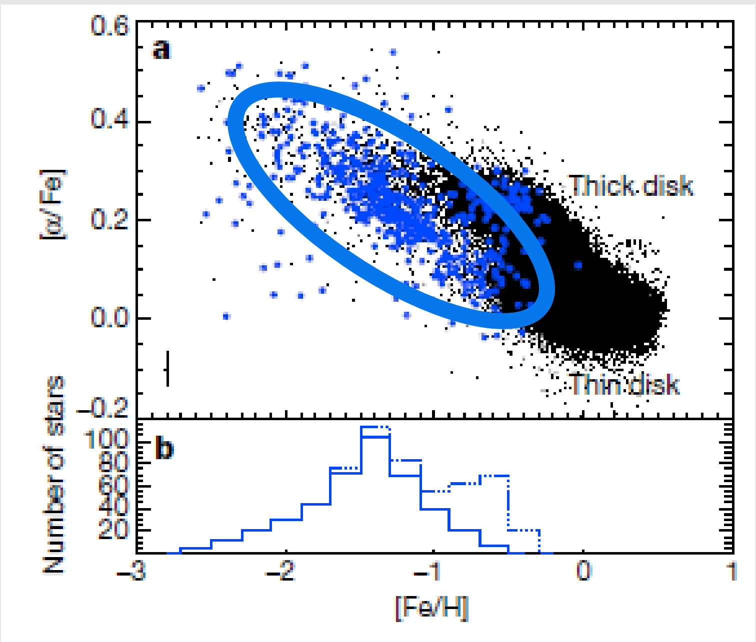
Helmi+18

(see also Belokurov+18, Haywood+18, Myeong+18 etc.)

Kinematics



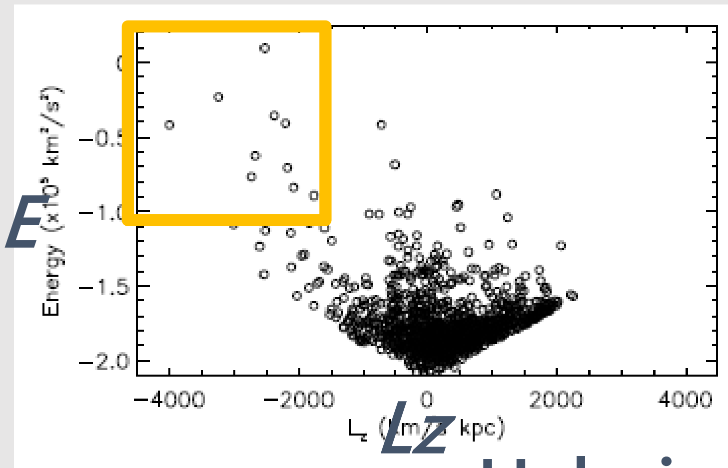
Abundances



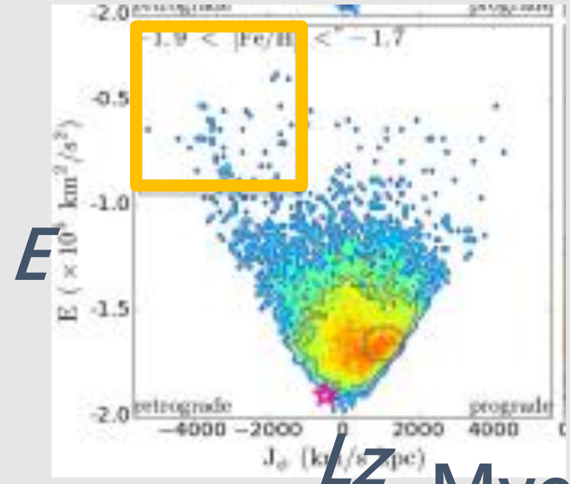
Clear evidence of past accretion of a massive dwarf galaxy, Gaia Enceladus (aka Gaia sausage)

Suggestion of other components

Excess of retrograde stars at high energy

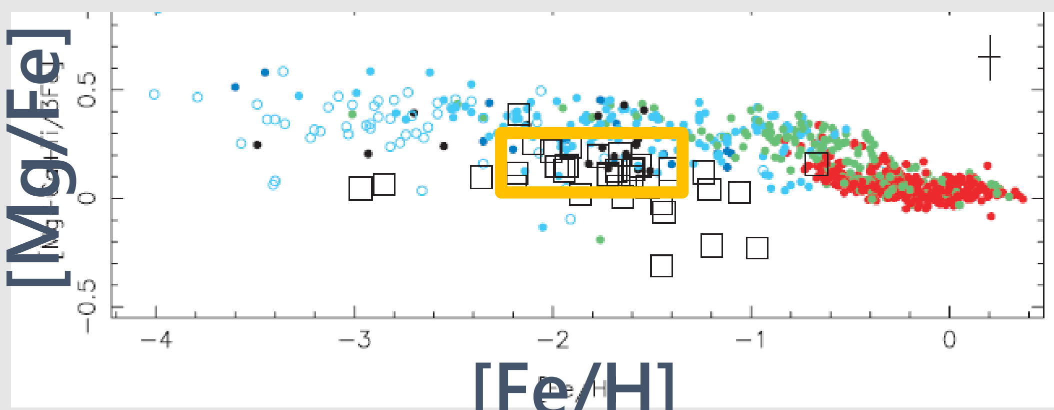


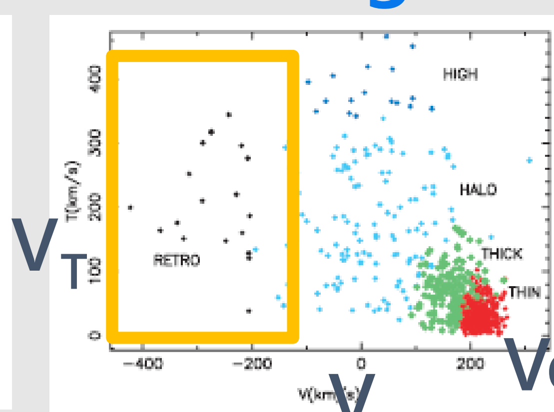
Helmi+17



Myeong+18

Low α-elements abundances of retrograde stars





Venn+04

Getting chemical abundances

Stellar chemical abundances

Need expensive observations

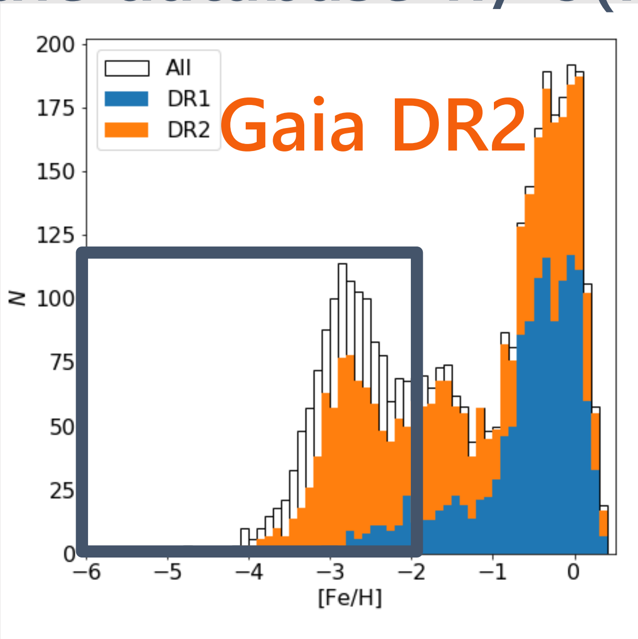
SAGA database Suda et al. (2008, 2011, 2017) Yamada et al. (2013)

Stellar Abundances for Galactic Archaeology Database

- **>1300 very metal-poor stars** in >300 literatures

MDF of stars in the database w/ $\sigma(\pi)/\pi<0.2$

VMP Stars ~608

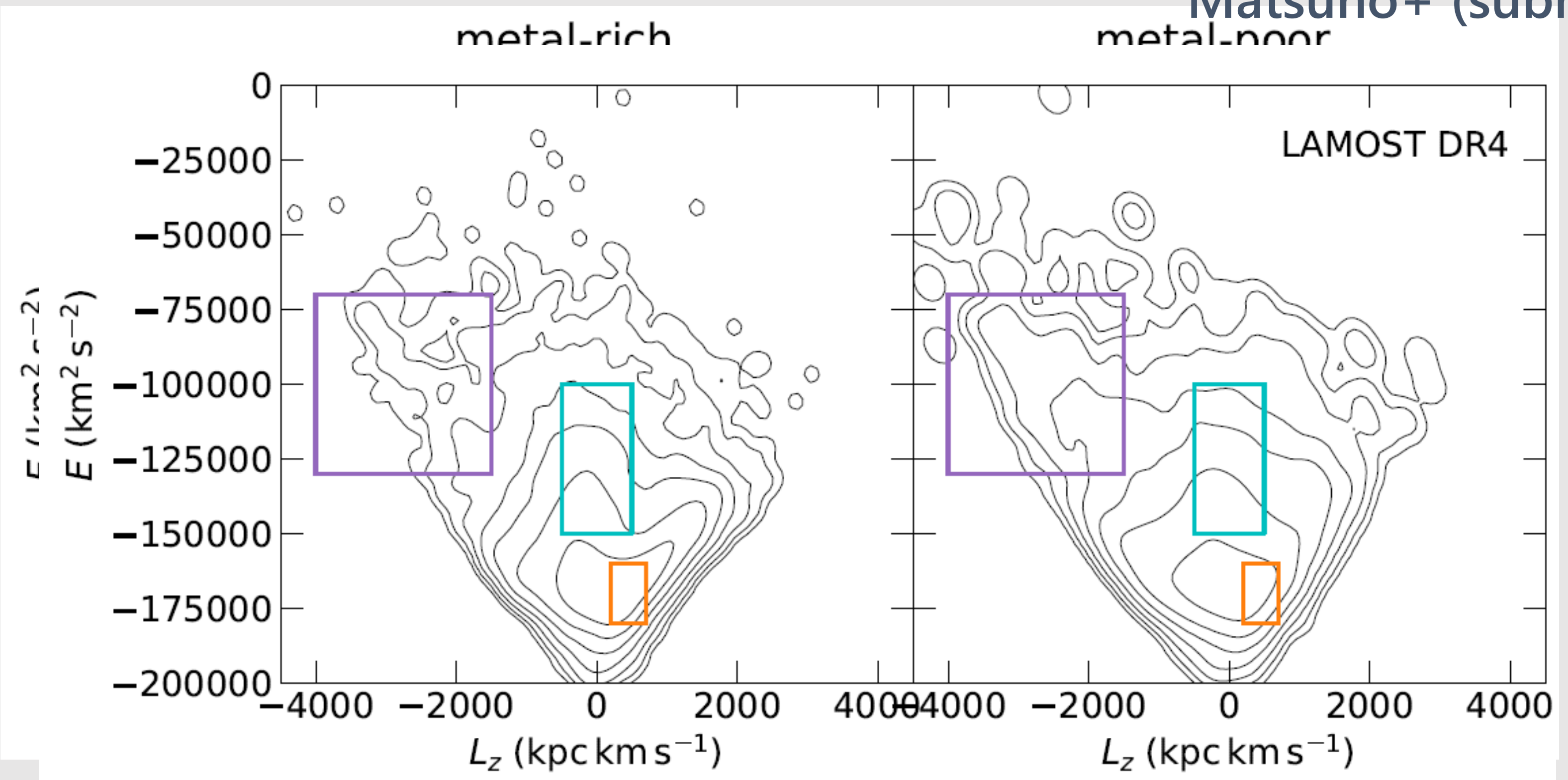


Gaia DR1

Binaries are excluded

Kinematics of stars in the database

Matsuno+ (submitted)

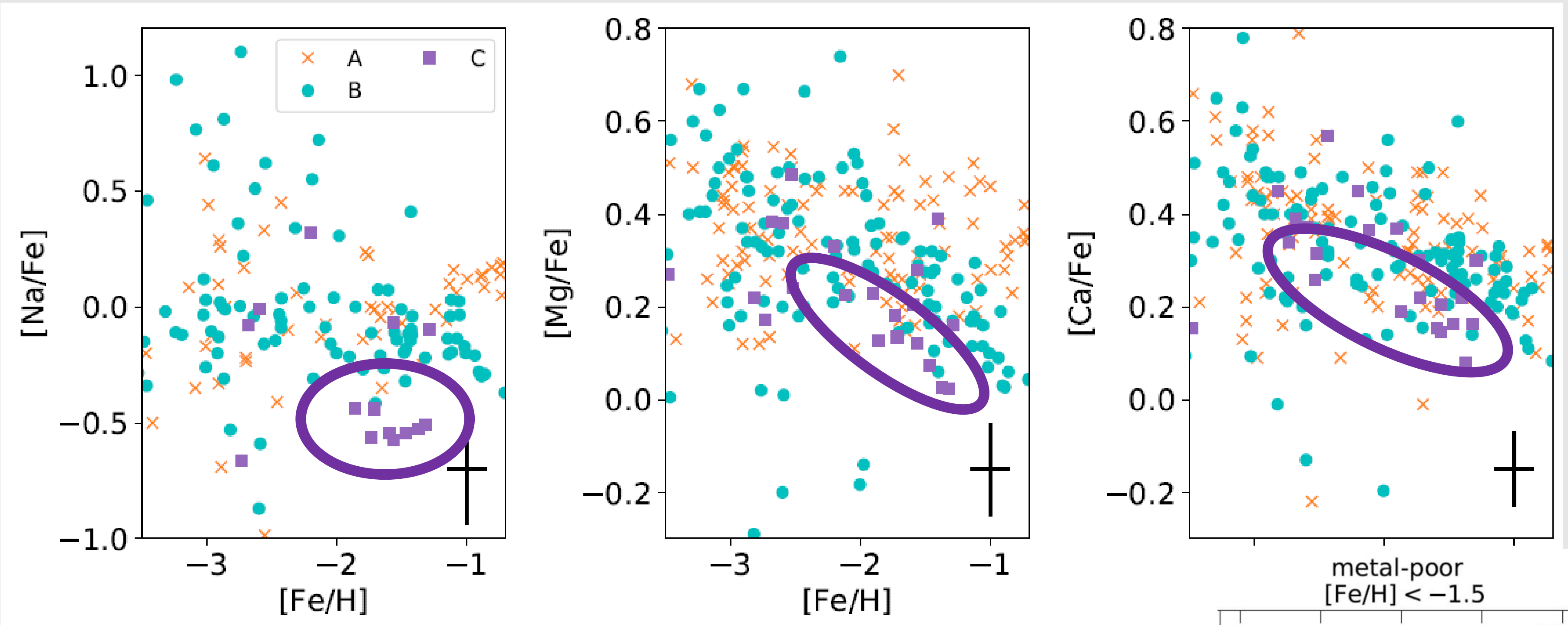


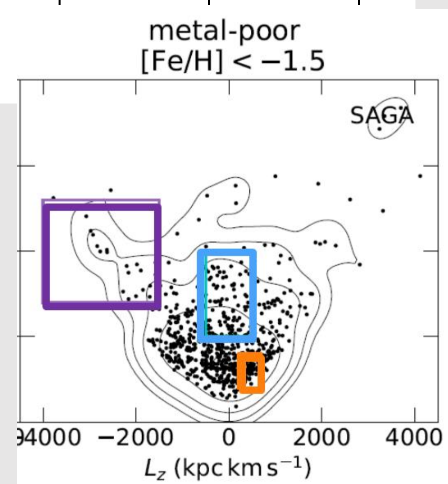
Clear enhancement of high-energy retrograde stars at low metallicity (see Myeong+18)

Hereafter, we compare abundances of region **A** (low-*E*, prograde), **B** (Gaia Enceladus), and **C** (high-*E*, retrograde)

Detailed abundance pattern

Matsuno+ (submitted)

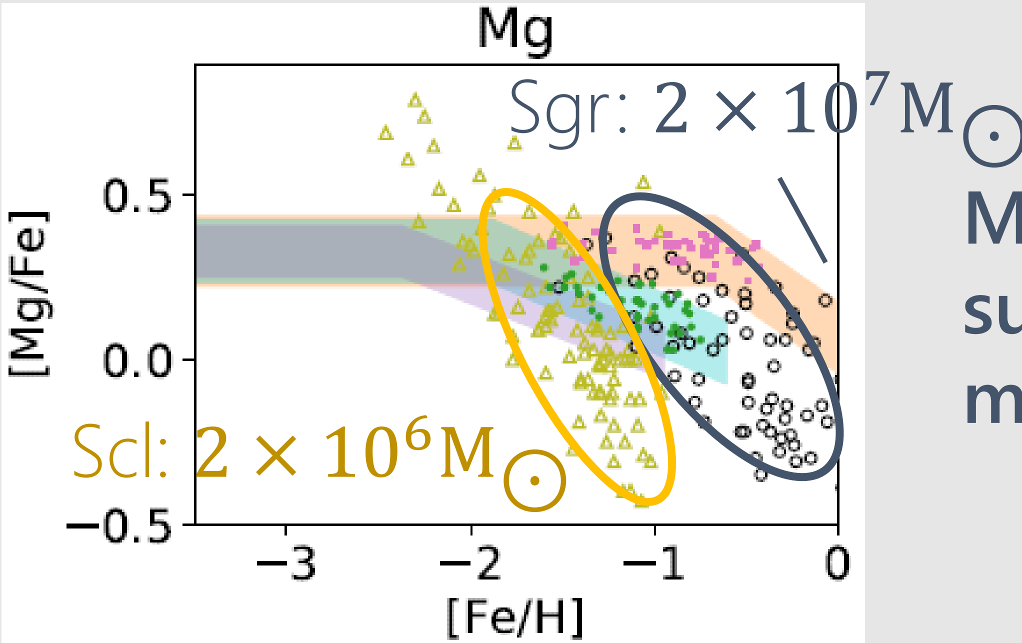




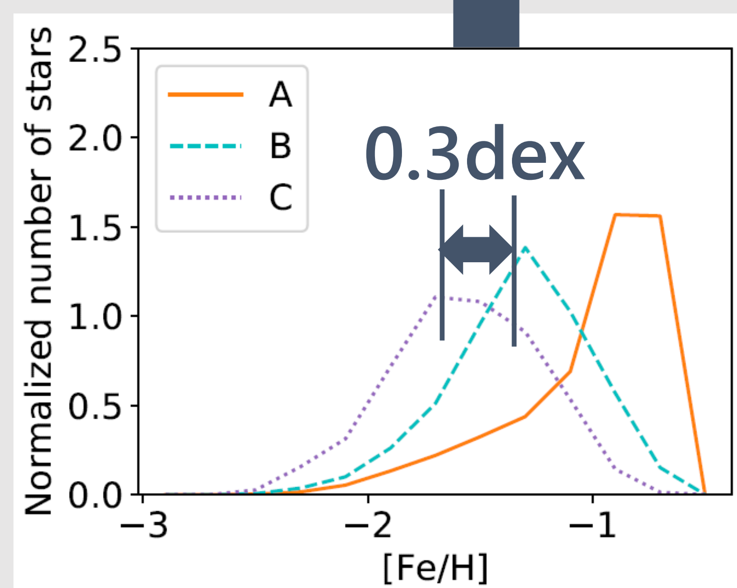
Chemical abundances of high-E retrograde stars are different from the rest

(Very rough) Mass estimates

Matsuno+ (submitted)



Mass-metallicity relation suggests a factor of ~10 mass difference



Made from LAMOST DR4 data

The progenitor seems to have been 1/10 times as massive as Gaia Enceladus

High-E Retrograde Stars

We can relate recent discoveries of the excess of high-E retrograde stars to the very low-α population using the SAGA database

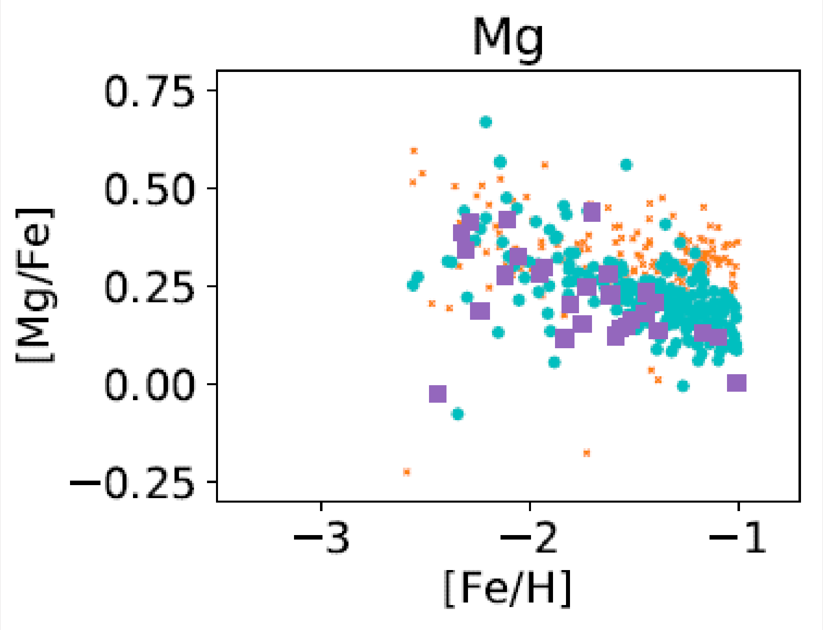
Matsuno, Aoki, & Suda (submitted)

Can we study them with more homogeneous sample of abundances? APOGEE, GALAH, etc.

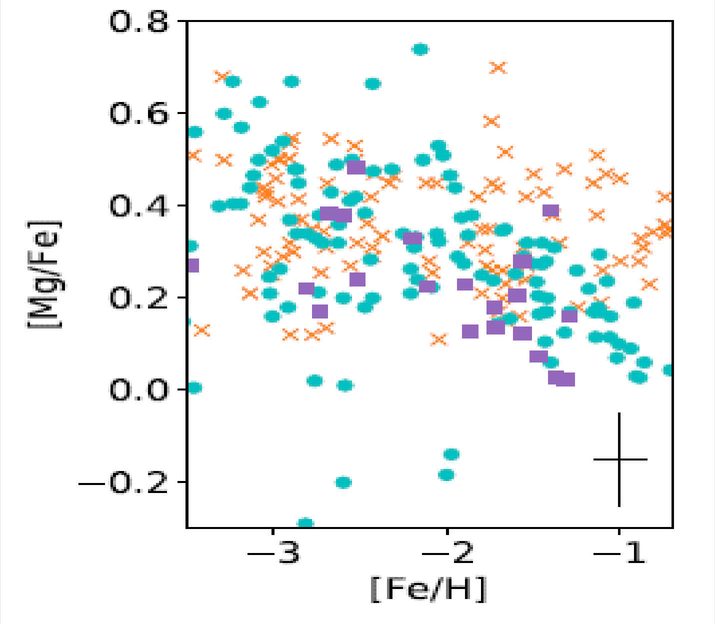
High-E retrograde stars in APOGEE

Can we study them with more homogeneous sample of abundances? APOGEE -> yes!

APOGEE



SAGA



GALAH DR2 seems to have problems with metal-poor stars

Correlation between abundance and kinematics

If there are accreted stars in the halo, we expect them to cluster in both kinematic and chemical space

Correlation?

kinematics

Lz — E (— I_3)

action

Abundance

[Fe/H]

α-elements

n-captures

Distance correlation

Székely et al. 2007

Distance correlation $R(\boldsymbol{X},\boldsymbol{Y})$

- n points
- i th point has $\boldsymbol{X_i}$ and $\boldsymbol{Y_i}$

$$R(\boldsymbol{X},\boldsymbol{Y}) = \frac{\nu^2(\boldsymbol{X},\boldsymbol{Y})}{\sqrt{\nu^2(\boldsymbol{X},\boldsymbol{X})\nu^2(\boldsymbol{Y},\boldsymbol{Y})}}$$

where,

$$a_{ij} \equiv \left|\left|\overrightarrow{X_i} - \overrightarrow{X_j}\right|\right|,$$

$$A_{ij} \equiv a_{ij} - \frac{\Sigma_{k=1}^{n} a_{kj}}{n} - \frac{\Sigma_{l=1}^{n} a_{il}}{n} + \frac{\Sigma_{k,l=1}^{n} a_{kl}}{n^2}$$ (similarly, B_{ij} for Y)

$\nu^2(\boldsymbol{X},\boldsymbol{Y}) \equiv \Sigma_{k,l=1}^{n} A_{kl}B_{kl}/n^2$ (similarly, $\nu^2(\boldsymbol{X},\boldsymbol{X}), \nu^2(\boldsymbol{Y},\boldsymbol{Y})$)

X, Y can be in arbitrary dimension

$0 \leq R \leq 1 (Y = a + bXC,)$

C: an orthogonal matrix

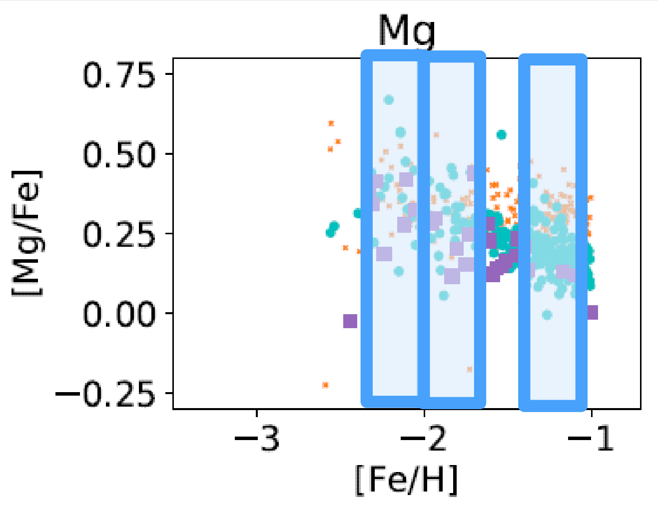
Distance correlation: metallicity effect

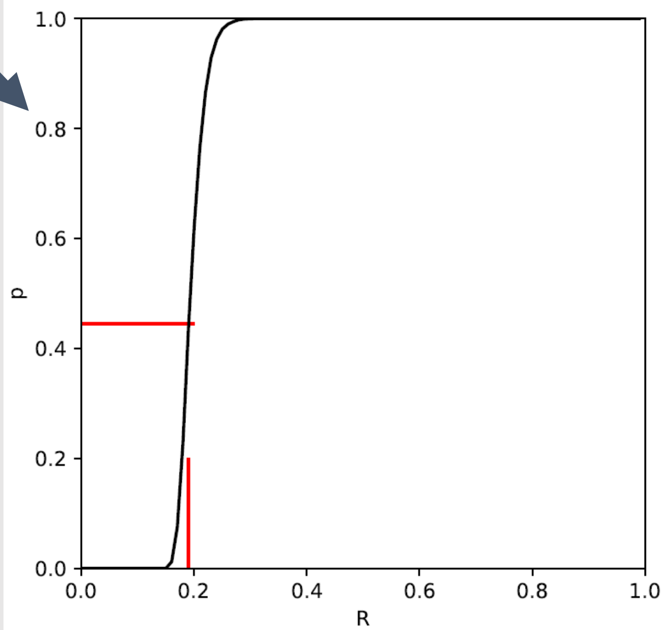
Distance correlation $R(\boldsymbol{X}, \boldsymbol{Y})$

$X = (L_z, E)$: kinematics

Y =([Fe/H], [Mg/Fe]): abundances

[Fe/H]		*R*	*p(>R)*
[-2.3..-2.0]	No correlation is expected	0.19	0.56
[-2.0..-1.7]	Effects of high-E retrograde stars	0.20	0.01
[-1.3..-1.0]	Effects of GE	0.40	<0.01





Distance correlation

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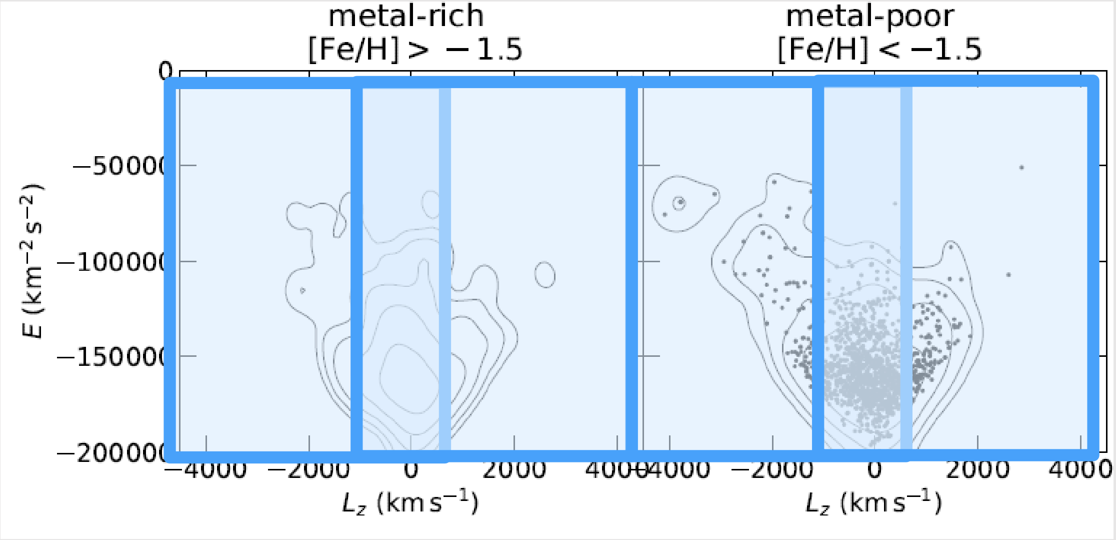

	R	*p(>R)*
all	0.20	0.01
Lz>-1000	0.17	0.39
Lz<1000	0.20	0.02

Summary

The recently discovered high-E retrograde halo stars have very low-α abundances (SAGA database)

- The progenitor seems ~1/10 times as massive as Gaia Enceladus

There is a significant correlation between kinematics and chemical abundances due to the high-E retrograde halo stars (APOGEE)