A chemo-kinematic glimpse of the most ancient Milky Way

Our Galaxy was a hot mess before it became a disk

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From dawn till disc: Milky Way's turbulent youth revealed by the APOGEE+*Gaia* data

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Unsolved questions related to this talk

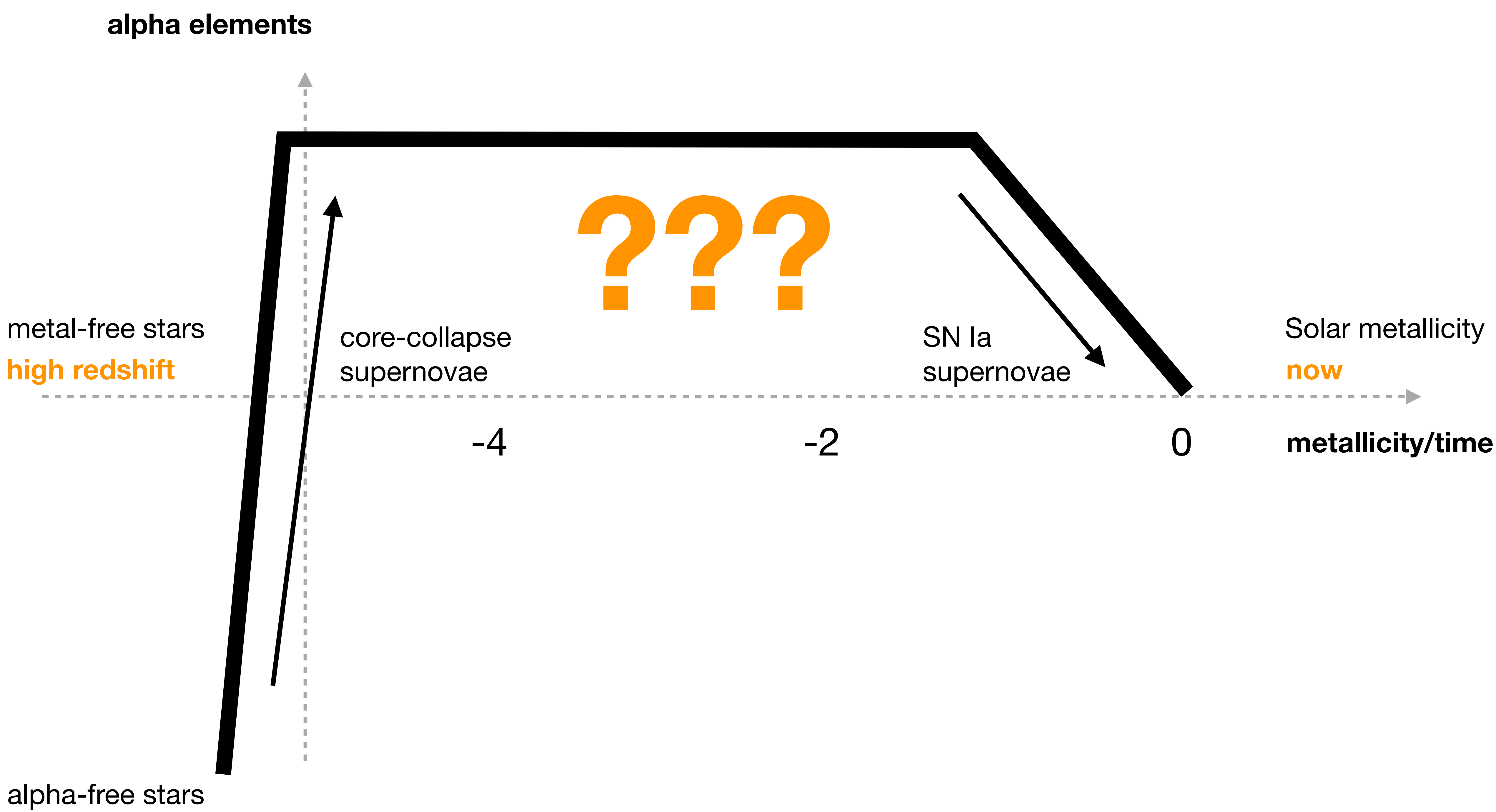
- When and how do galactic disks emerge?
- Exact yields of CC SN, SN Ia and NS-NS events?
- Role of Globular Clusters in high-z galaxy formation?

A brief history of the Galaxy

- 11 Gyr ago: high-alpha disk is actively forming
- 7-11 Gyr ago: merger with a relatively massive dwarf galaxy, the *GS/E* progenitor
- MW-*GS/E* interaction triggers a response - heating of the pre-existing high-alpha disk and formation of the *Splash,* metal-rich in-situ halo component

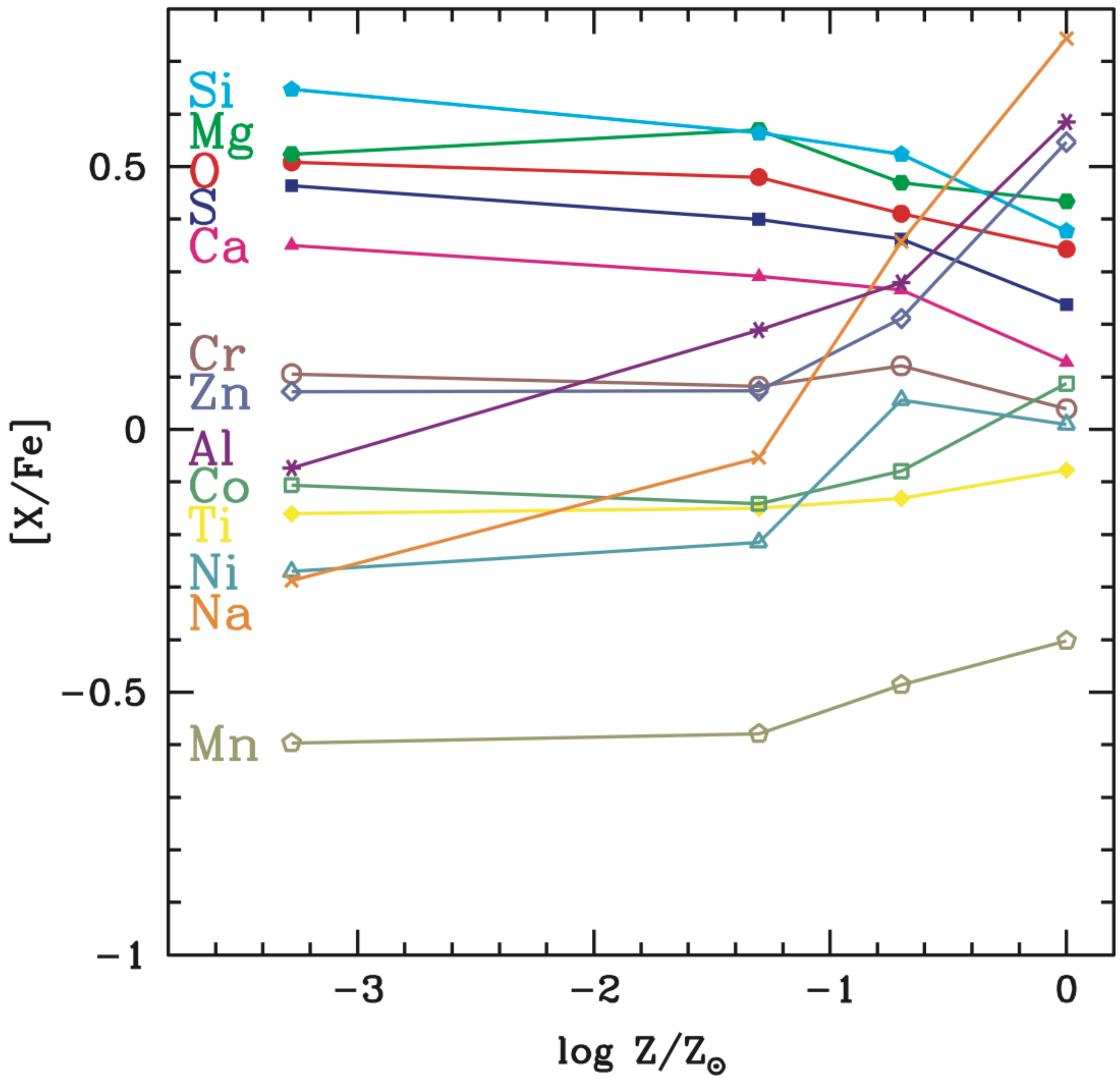
But how did the Milky Way look before all of this happened?

Searching for a chemical fingerprint of early star formation



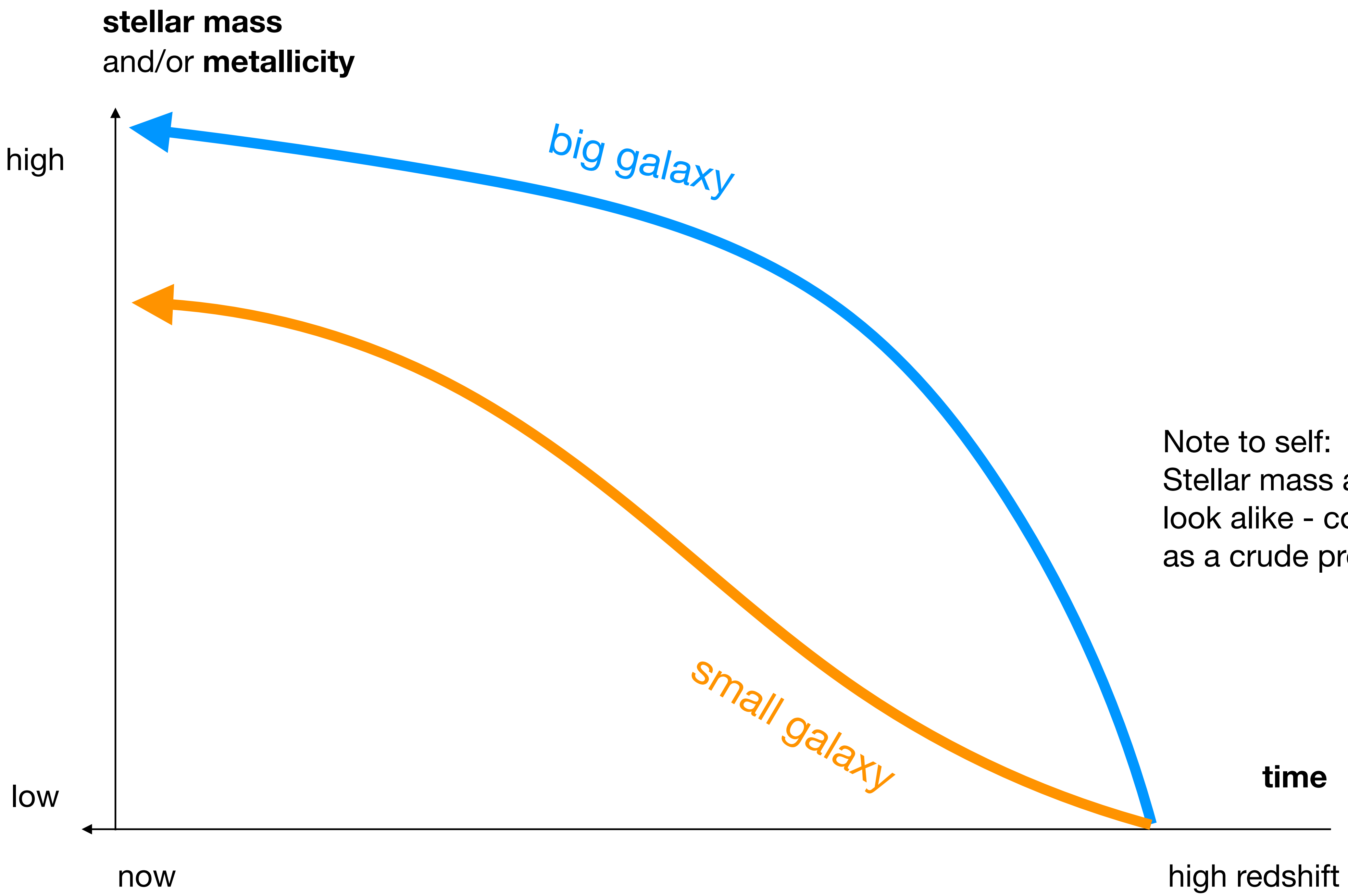
Al and Na are special

metallicity dependence of yields



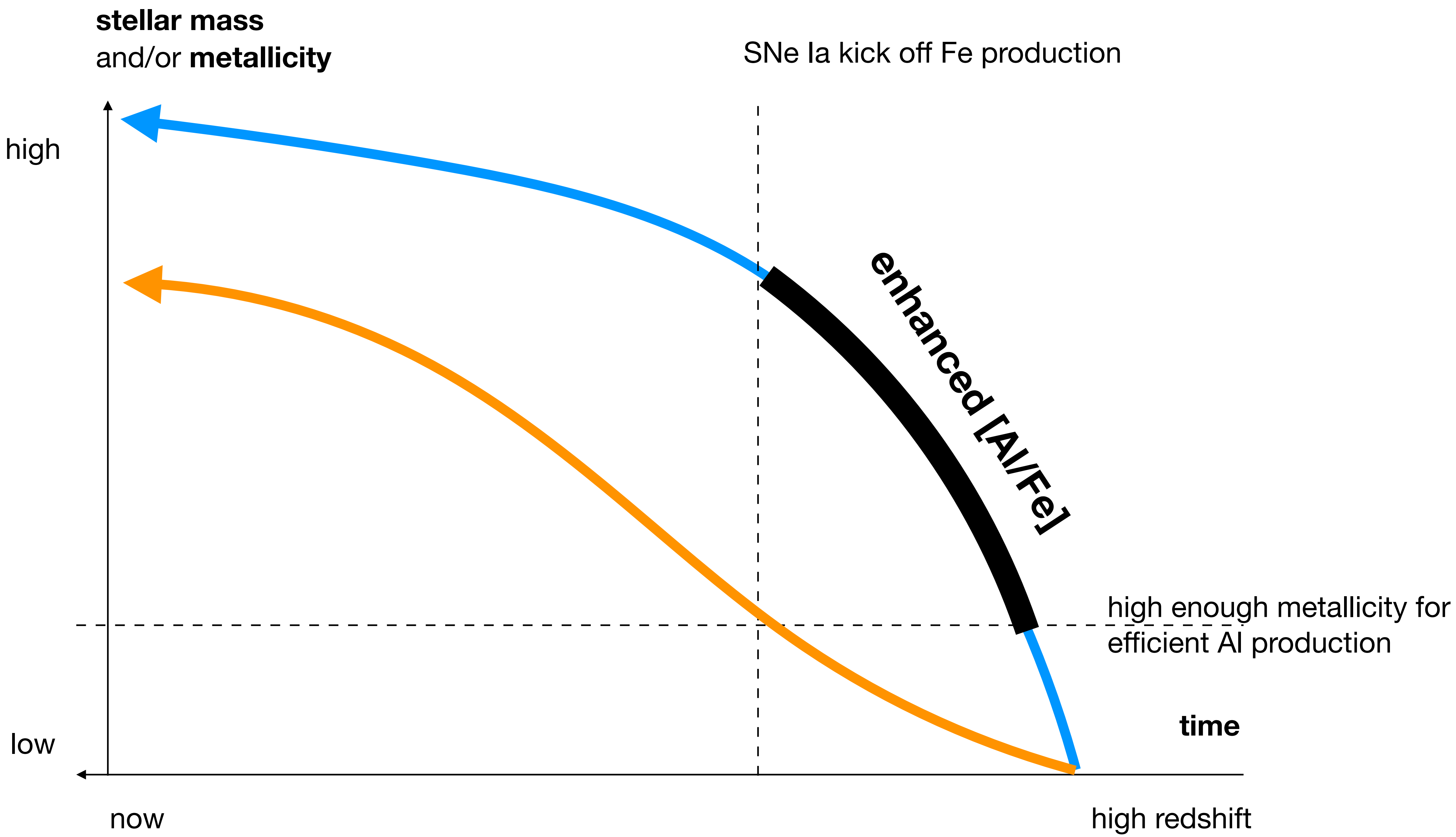
Kobayashi et al 2006

Star-formation and chemical history

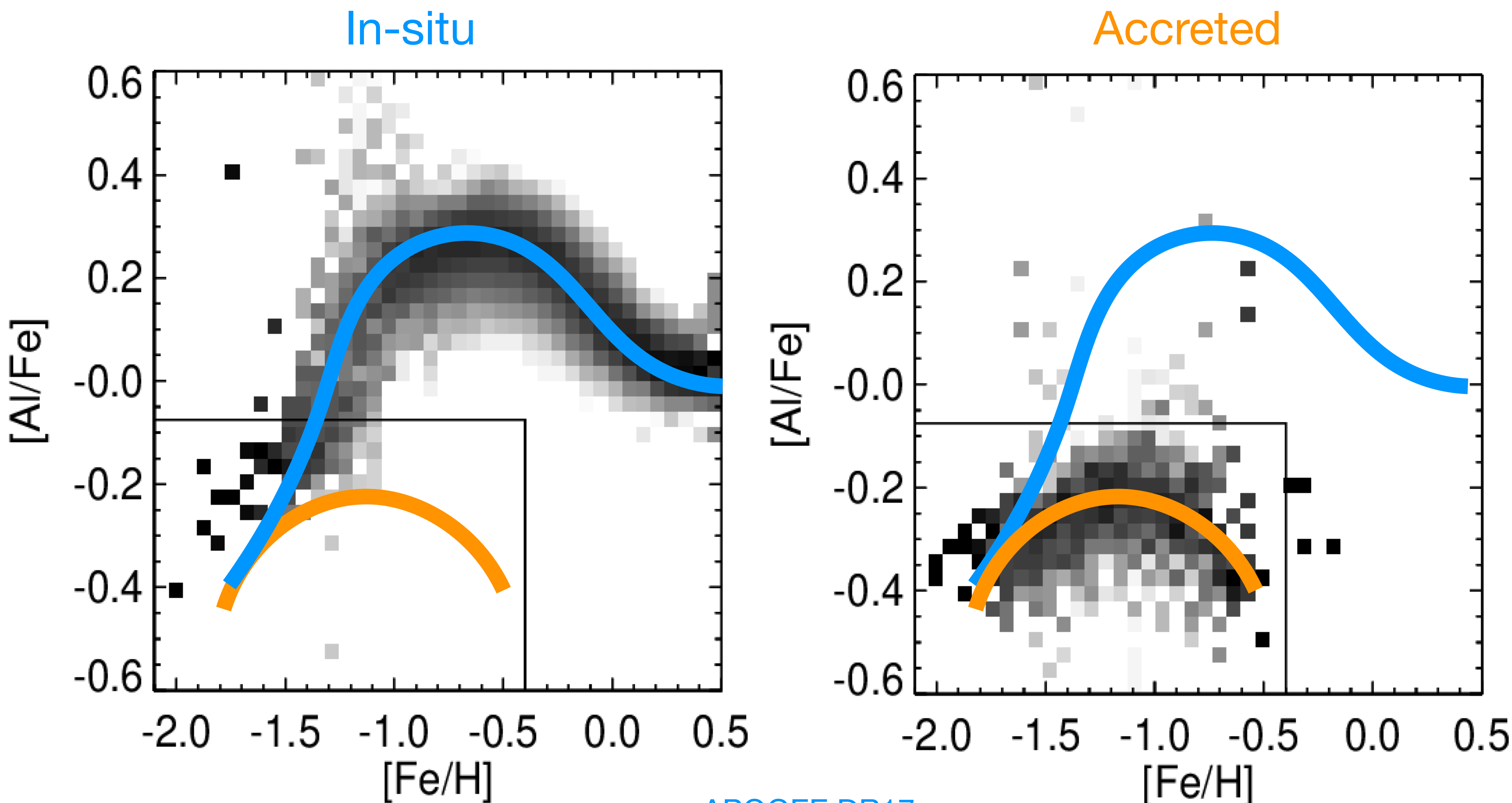


Note to self:
Stellar mass and metallicity curves look alike - could use metallicity as a crude proxy for time

Al/Fe balance



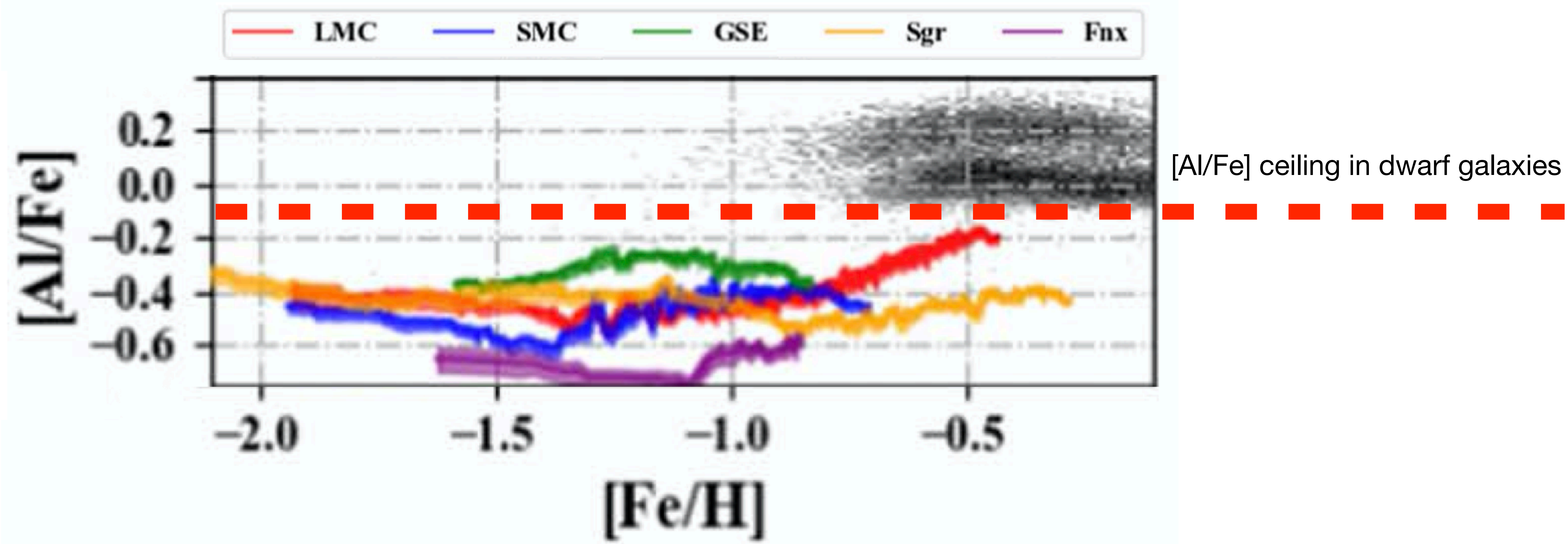
Al/Fe balance



APOGEE DR17

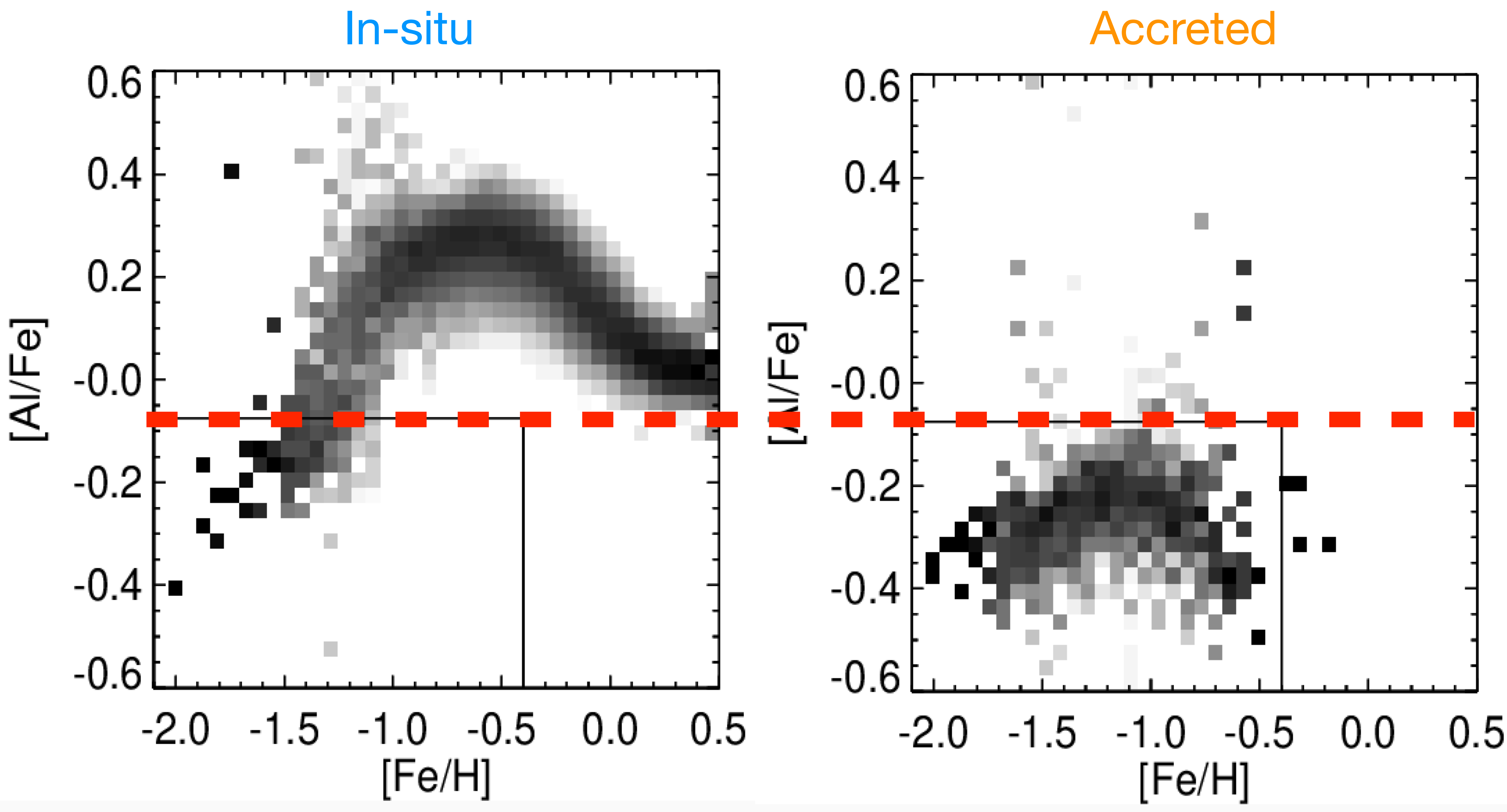
Al/Fe balance in Galactic dwarfs

APOGEE DR17 observations

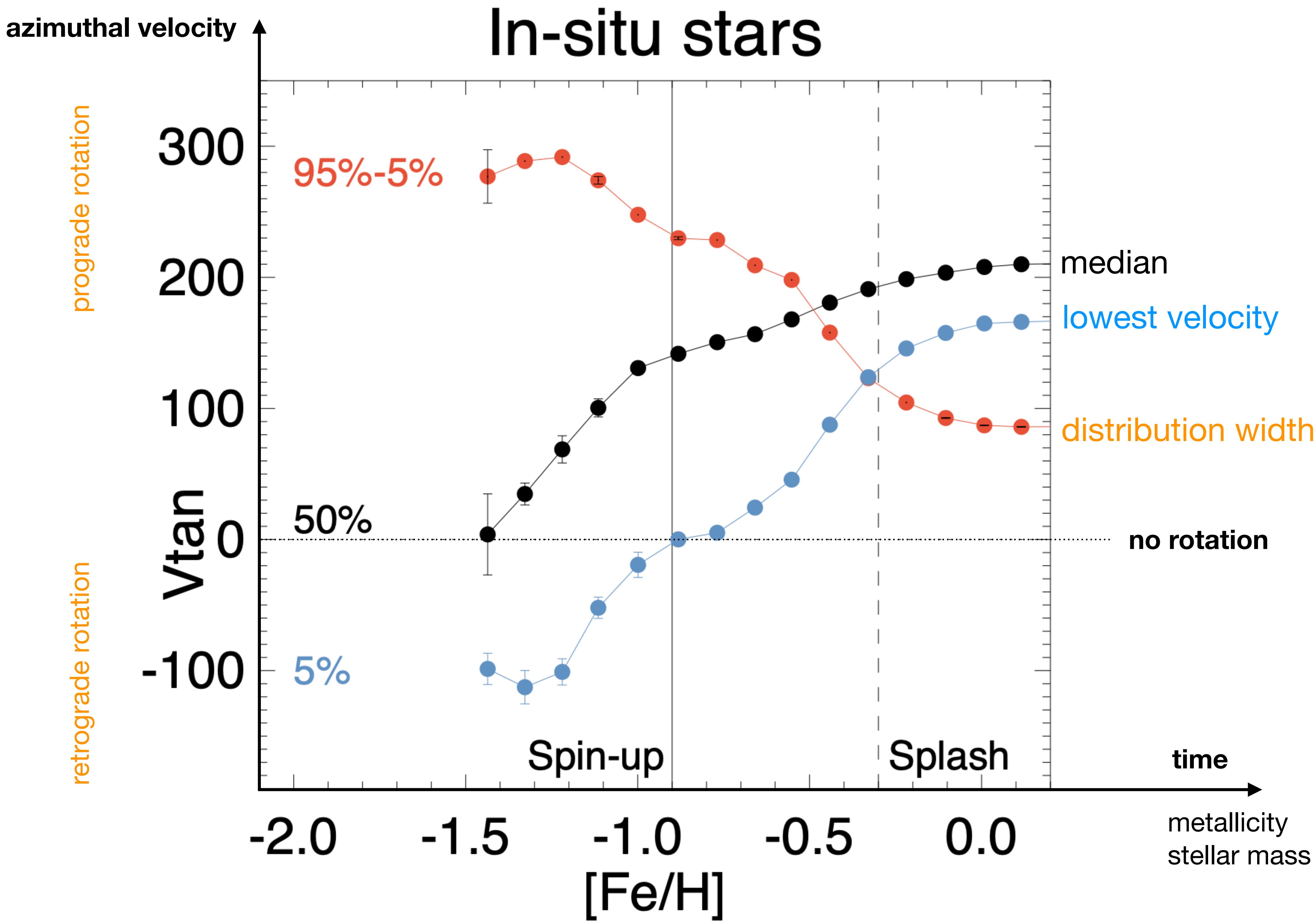


Hasselquist et al 2021

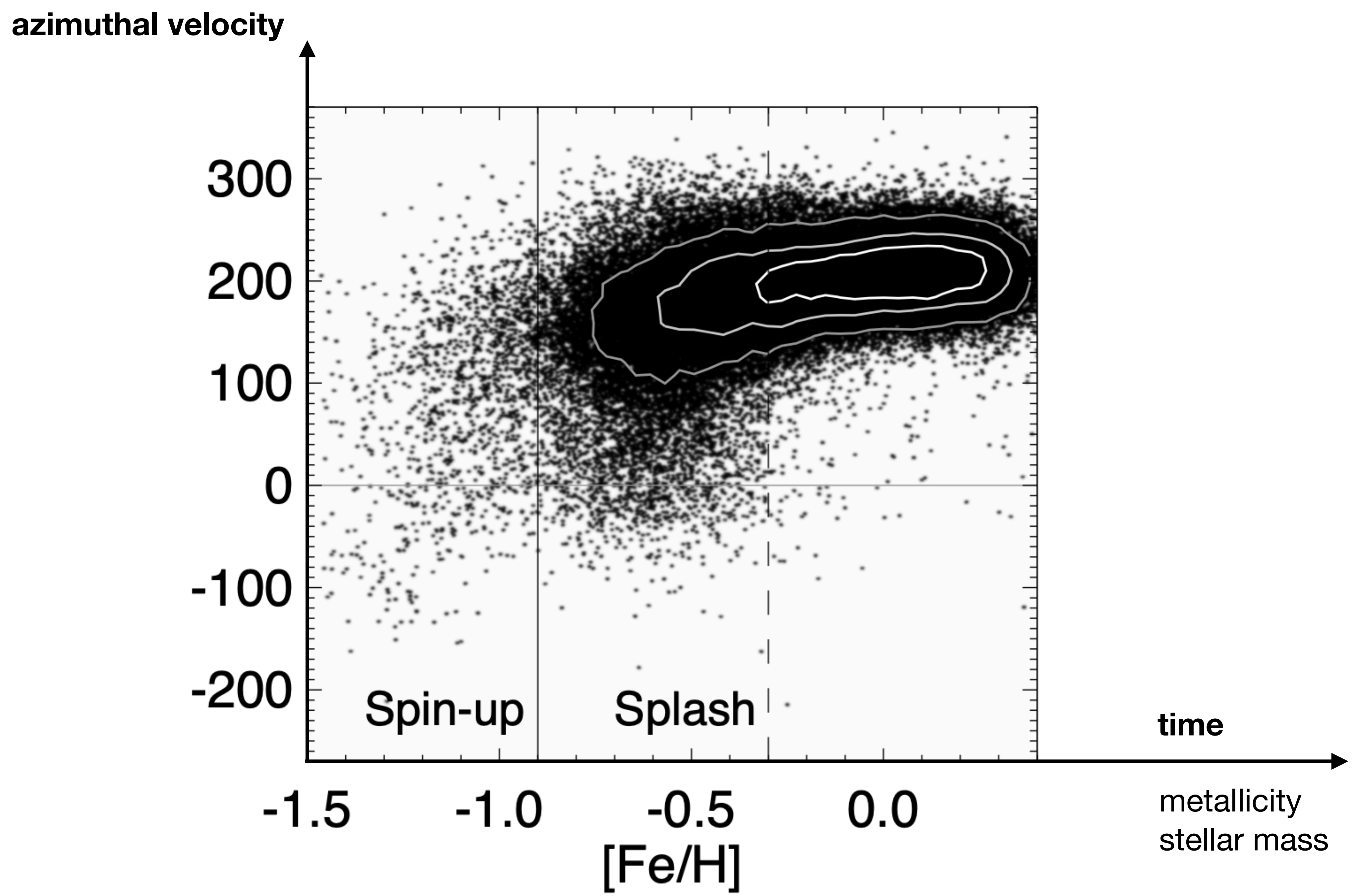
Selecting in-situ population



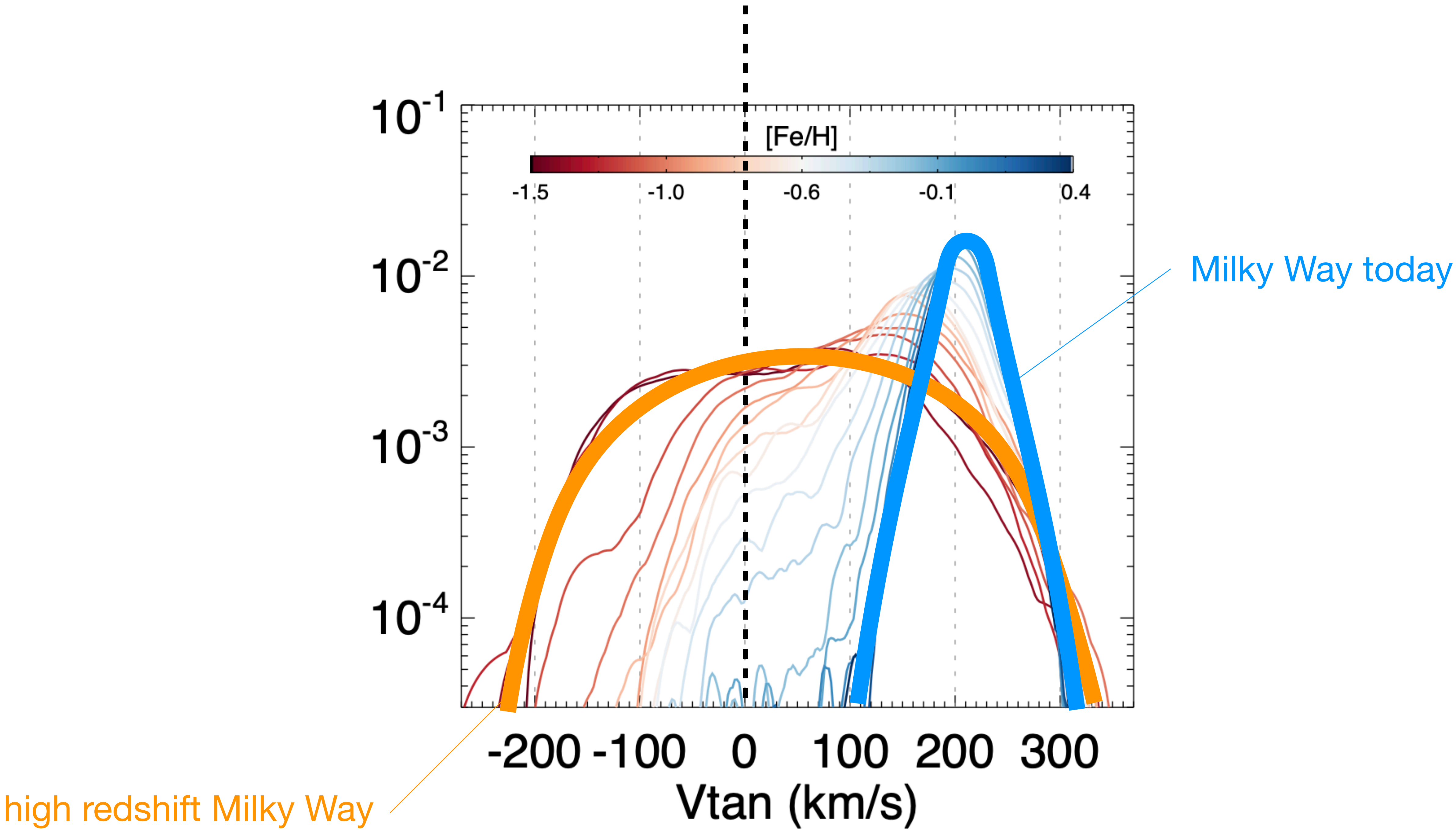
Kinematic history of the Galaxy



Azimuthal velocity distribution

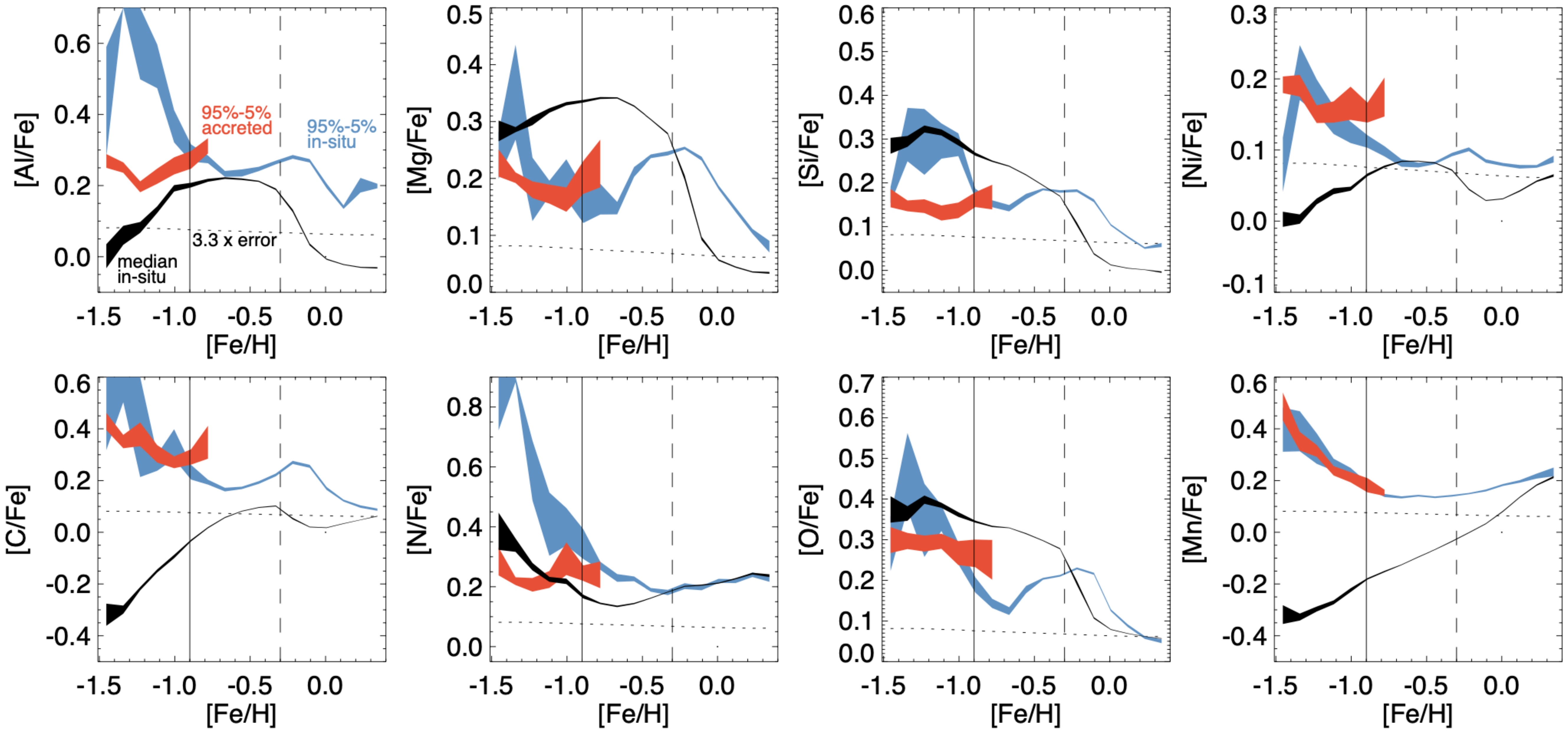


Azimuthal velocity distribution

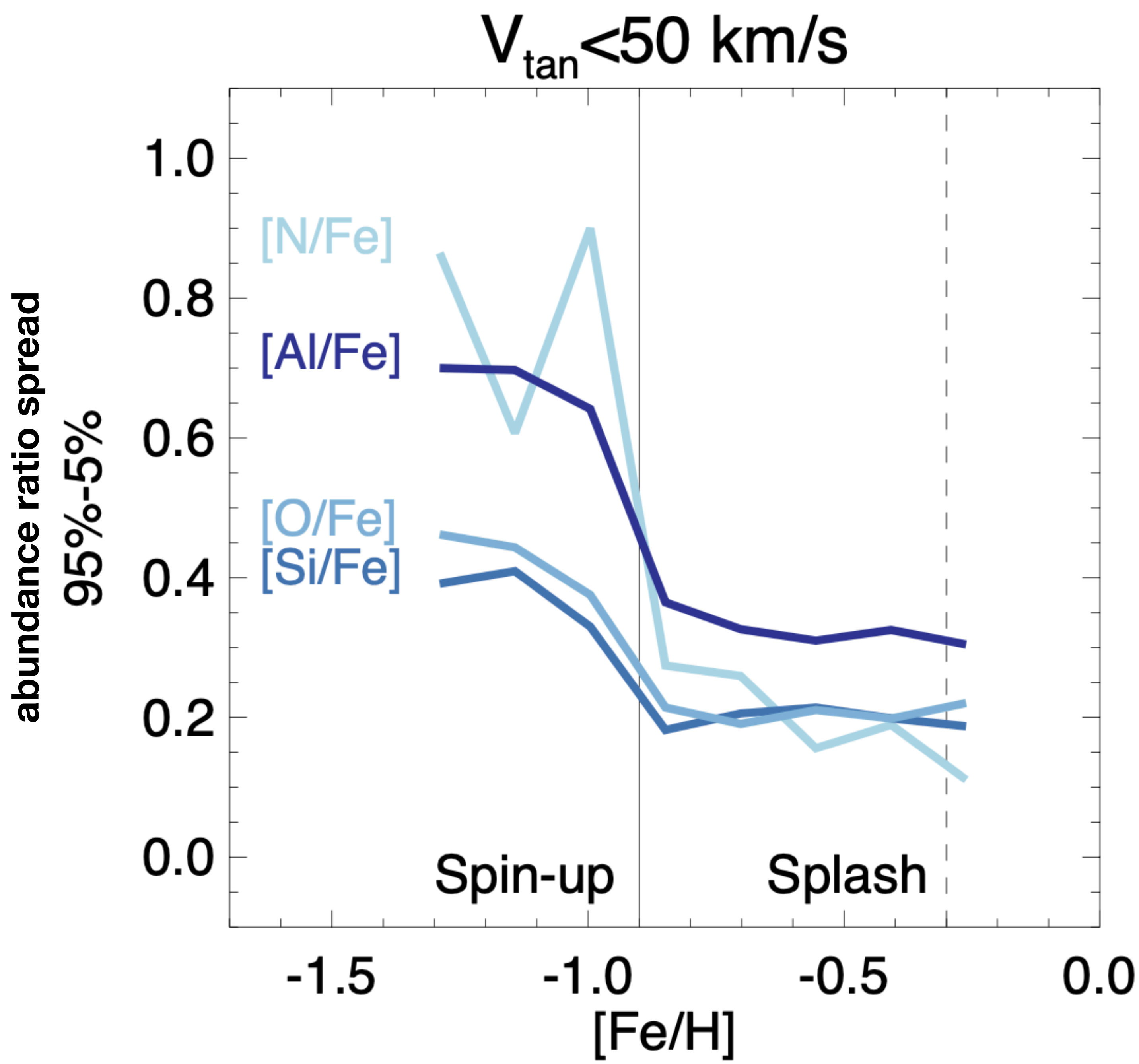


Chemistry

Chemical trends with [Fe/H]



Chemical trends with [Fe/H]



Previously, similarly large spreads in abundance ratios of these elements were **detected only in the Globular Clusters** (GCs)

Abundance spreads in Galactic GCs also show a very **similar dependence on [Fe/H]**

GC abundance spreads are a function of GC mass with the **largest spreads observed in the most massive clusters**

Aside 1/2

- Recent additional pieces of evidence for Aurora

BIRTH OF THE GALACTIC DISK REVEALED BY THE H3 SURVEY

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Submitted to ApJ

ABSTRACT

We use chemistry ([α/Fe] and [Fe/H]), main sequence turnoff ages, and kine
spectroscopy and *Gaia* astrometry to identify the birth of the Galactic disk
stars on the basis of angular momenta and eccentricities. The sequence of
to at least [Fe/H] ≈ -2.5 and shows unexpected non-monotonic behavior: w
ulation first declines in [α/Fe], then increases over the range $-1.3 \lesssim$ [Fe/H
at higher metallicities. The number of stars in the in-situ population rapi
The average kinematics of these stars are hot and independent of metallicit
increasingly cold and disk-like at higher metallicities. The ages of the in-sit
old (≈ 13 Gyr) at [Fe/H] $\lesssim -1.3$, and span a wider range ($8-12$ Gyr) at
the chemistry with a simple chemical evolution model suggests that the n
significant increase in star formation efficiency, which began ≈ 13 Gyr ago.
which the first ≈ 1 Gyr of the Galaxy was characterized by a "simmering
efficiency was low and the kinematics had substantial disorder with some net
a dramatic transformation to a "boiling phase", in which the star formation
the kinematics became disk-like, and the number of stars formed increased
mation as the birth of the Galactic disk at $z \approx 4$. The physical origin of this
not seem to be reproduced in current galaxy formation models.

The Poor Old Heart of the Milky Way

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ABSTRACT

Massive disk galaxies like our Milky Way should host an ancient, metal-poor, and centrally concentrated stellar population. This population reflects the star formation and enrichment in the few most massive progenitor components that coalesced at high redshift to form the *proto-Galaxy*. While metal-poor stars are known to reside in the inner few kiloparsecs of our Galaxy, current data do not yet provide a comprehensive picture of such a metal-poor "heart" of the Milky Way. We use information from Gaia DR3, especially the XP spectra, to construct a sample of 2 million bright ($G_{\rm BP} < 15.5$ mag) giant stars within 30° of the Galactic Center with robust [M/H] estimates, δ[M/H] $\lesssim 0.1$. For most sample members we can calculate orbits based on Gaia RVS velocities and astrometry. This sample reveals an extensive, ancient, and metal-poor population that includes $\sim 18,000$ stars with $-2.7 <$ [M/H] < -1.5, representing a stellar mass of $\gtrsim 5 \times 10^7\,{\rm M}_\odot$. The spatial distribution of these [M/H] < -1.5 stars has a Gaussian extent of only $\sigma_{\rm R_{GC}} \sim 2.7$ kpc around the Galactic center, with most of these orbits being confined to the inner Galaxy. At high orbital eccentricities, there is clear evidence for *accreted* halo stars in their pericentral orbit phase. Stars with [M/H] < -2 show no net rotation, whereas those with [M/H] ~ -1 are rotation dominated. Most of the tightly bound stars show [α/Fe]-enhancement and [Al/Fe]–[Mn/Fe] abundance patterns expected for an origin in the more massive portions of the proto-Galaxy. These central, metal-poor stars most likely predate the oldest part of the disk ($\tau_{\rm age} \approx 12.5$ Gyrs), which implies that they formed at $z \gtrsim 5$, forging the proto-Milky Way.

Aside 2/2

- Evidence against the so-called “metal-weak disk”
- Evidence against Kraken/Heracles/Koala - an ancient massive merger

Conclusions 1/2

- Pure in-situ sample thanks to precise chemistry from APOGEE (combine with unprecedented kinematics from Gaia)

- At metallicities [Fe/H]<-1.3 the Galaxy is kinematically hot, with approximately isotropic velocity ellipsoid and modest net spin (Aurora)

- Median azimuthal velocity increases sharply with metallicity (Spin-up) and by [Fe/H]=-0.9, the Milky Way settles into a coherent, rotating disk

Conclusions 2/2

- In the pre-disk Aurora state the Galaxy exhibits a large scatter in all elemental abundances

- This is likely caused by the increased stochasticity in metallicity at early times driven by strong variations in gas accretion and gas outflow rates and associated burstiness of star formation

- Additional anomalous scatter in Al, Si, N and O similar to that observed in globular clusters - **massive stellar clumps** played an important role in the young Milky Way

Future Prospects

- Studying stars (spatial and kinematics distributions) in Aurora and during Spin-up will shed light on the disk emergence in relatively low-mass DM halos

- Aurora stars probe faster early SF timescales and provide a new channel to disentangle CCSN and NS-NS yields

- Through chemical abundance correlations unique to GC enrichment patterns reconstruct the fraction of stellar mass in clusters at high redshift

Thanks!