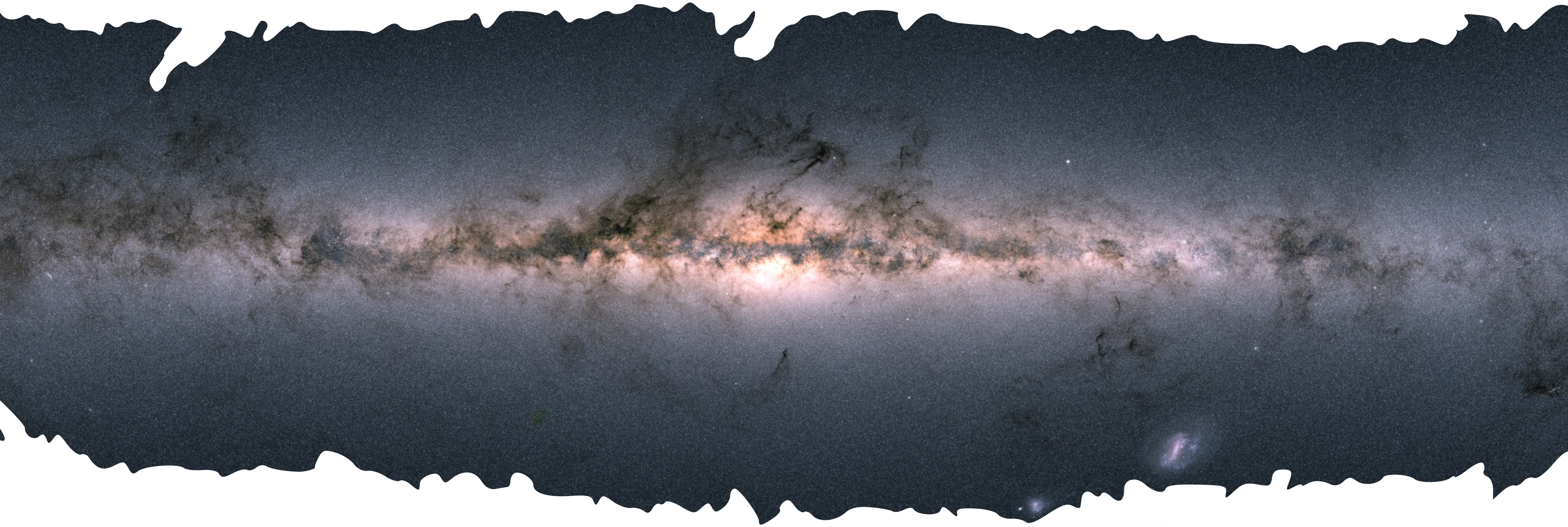
Unravelling the assembly of the Milky Way with Galactic surveys and numerical simulations

Ted Mackereth, *University of Birmingham*

w/ Jo Bovy, Ricardo Schiavon, Rob Crain, Andrea Miglio, APOGEE Team



@ted_mackereth

jmackereth.github.io

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ASTERO CHRONOMETRY

To get the most out of ‘Galactic archaeology’ we need to deeply understand the *context* of the Milky Way

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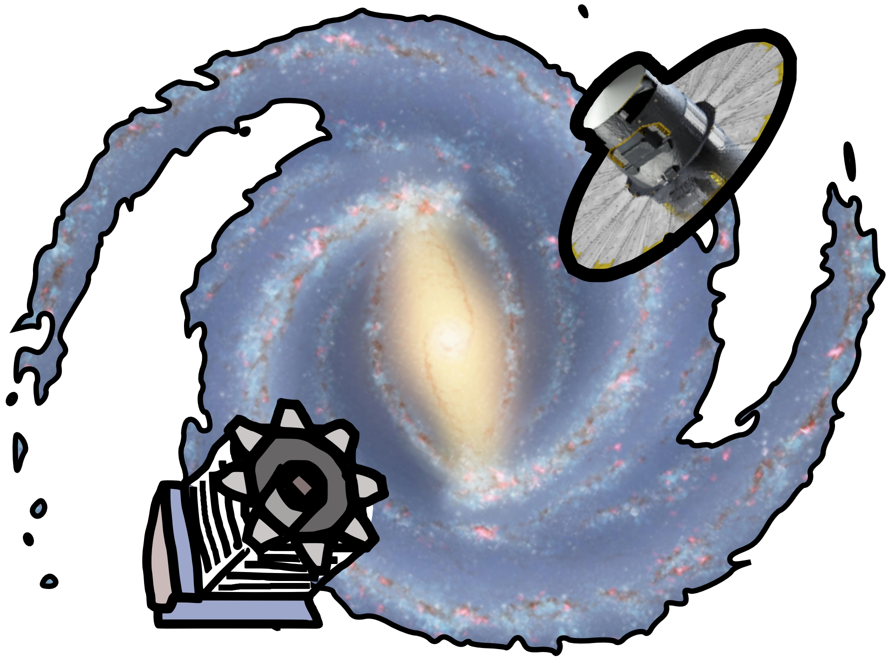

***Constraints* - Study the present day structure of the Galaxy**

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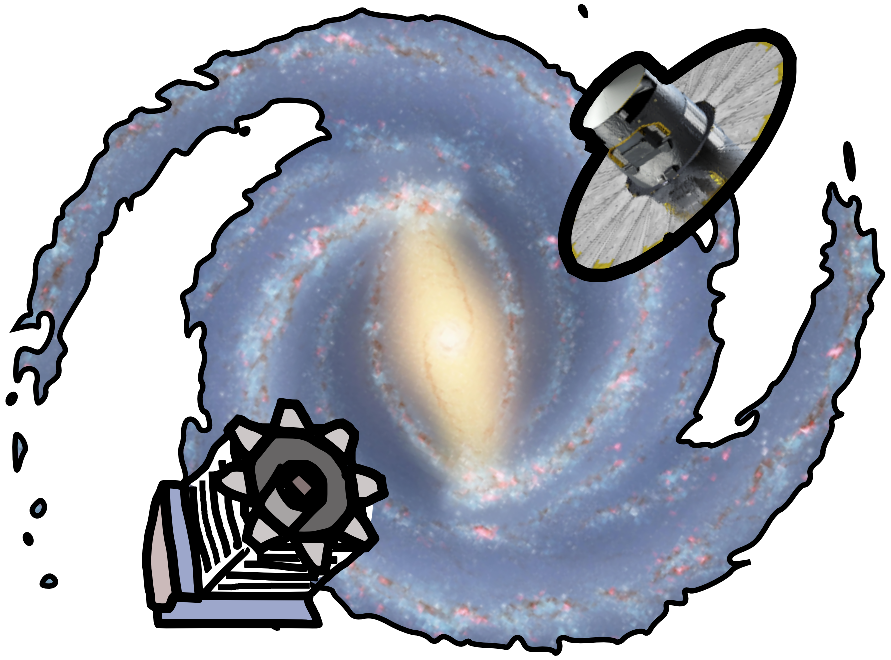

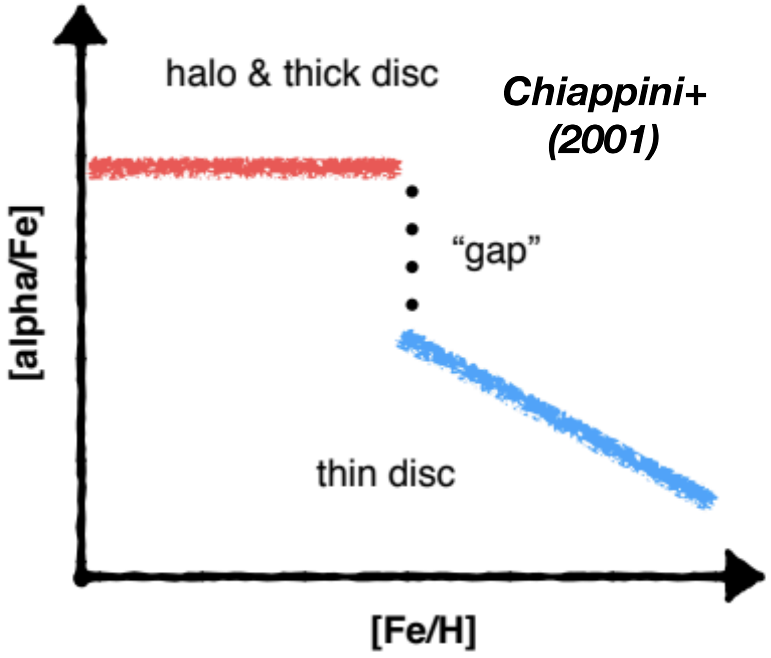

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Predictions **- make models that meet the constraints and make new predictions**

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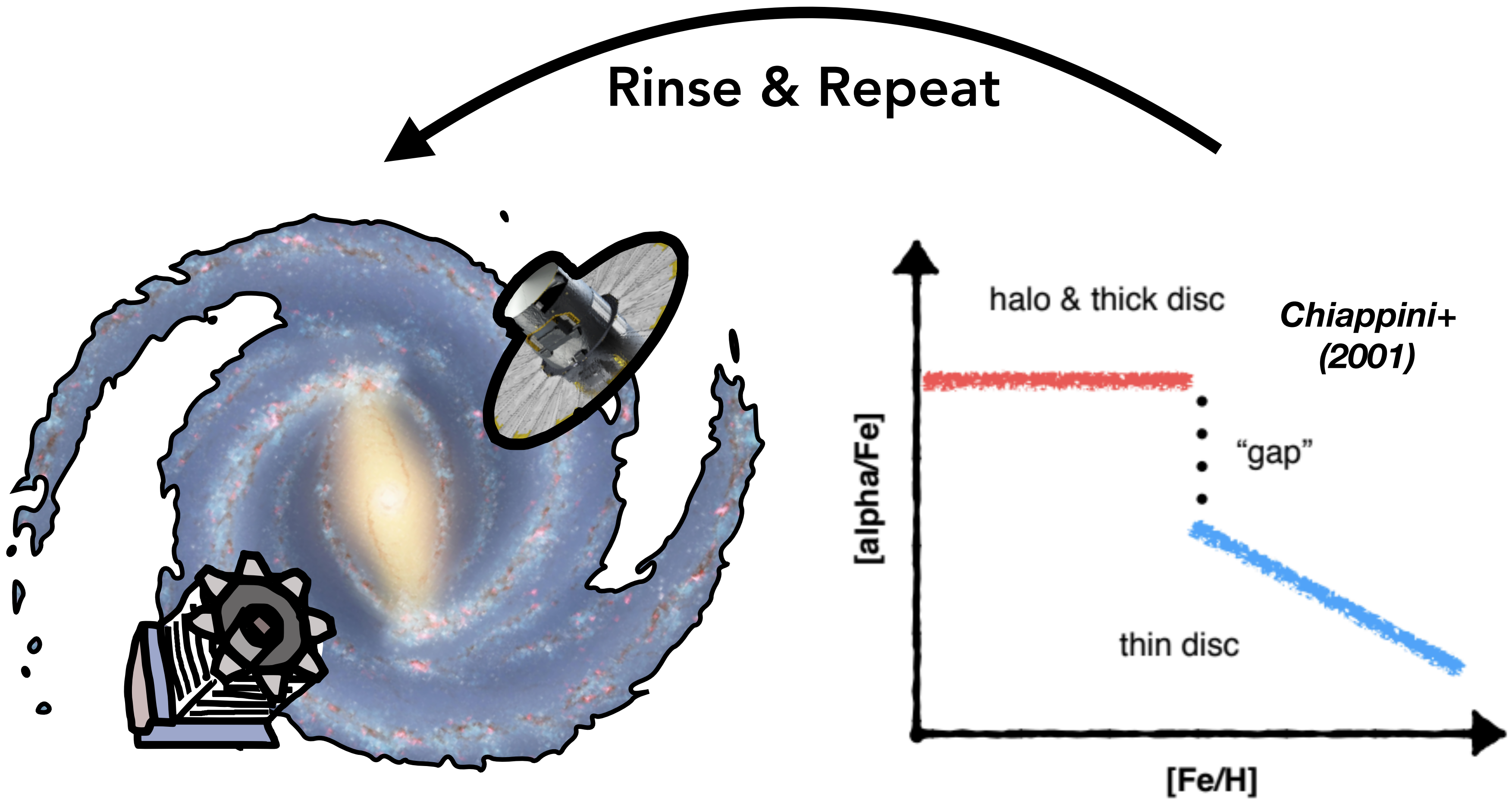

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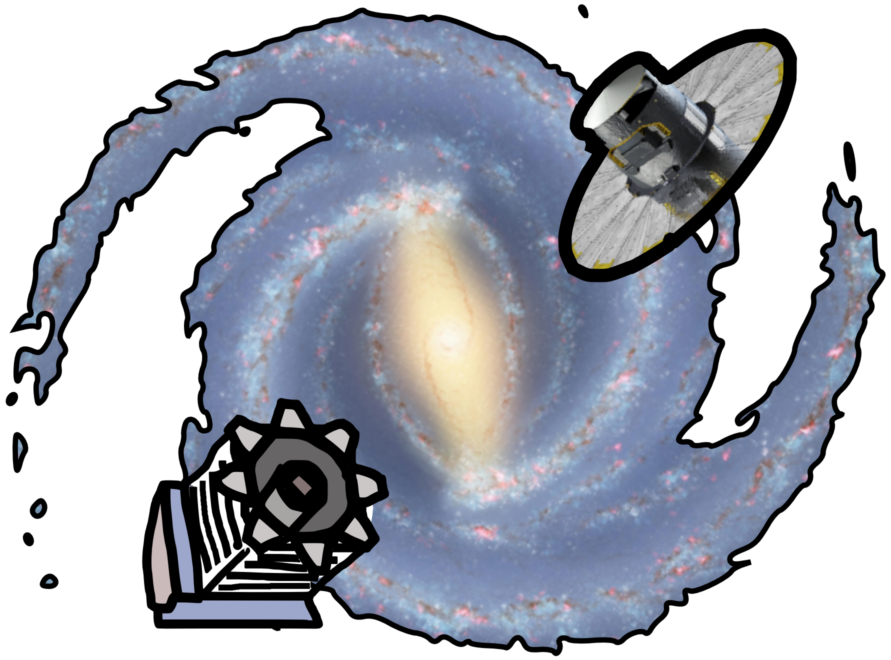
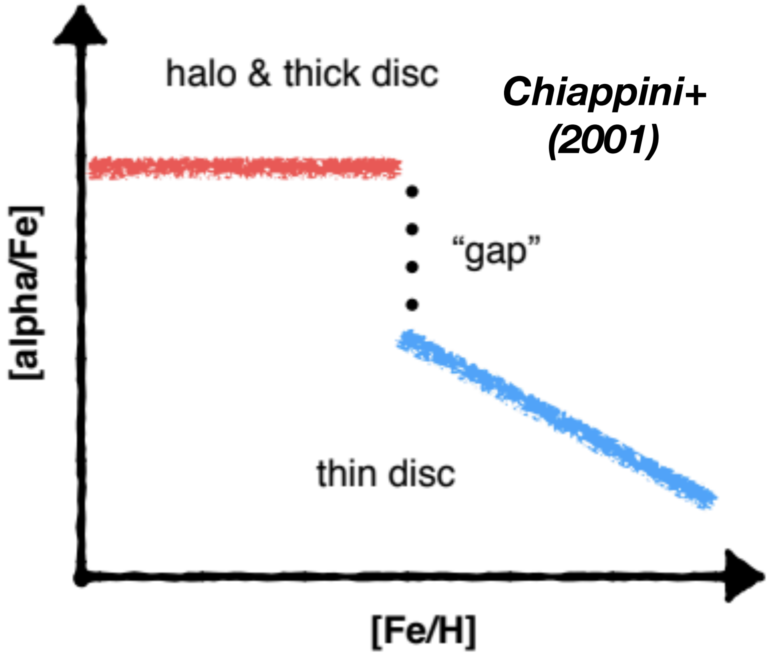
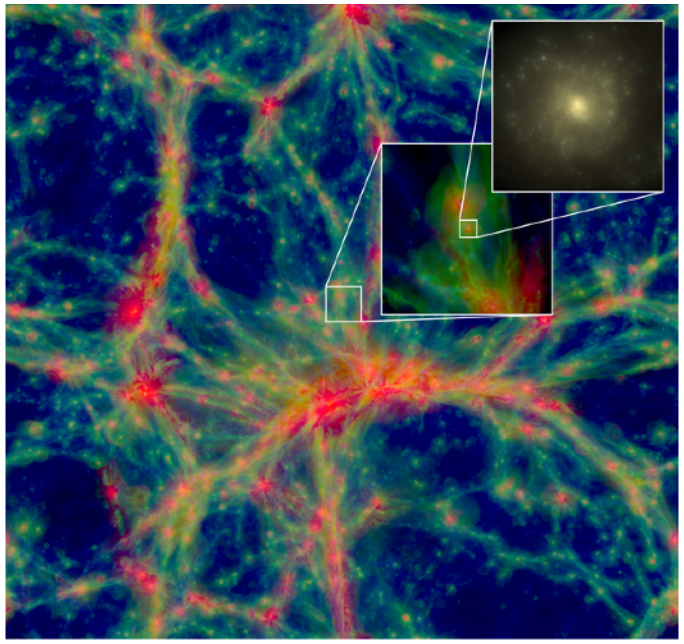
Rinse & Repeat





Chiappini+ (2001)

Schaye+ (2015), Crain+ (2015)



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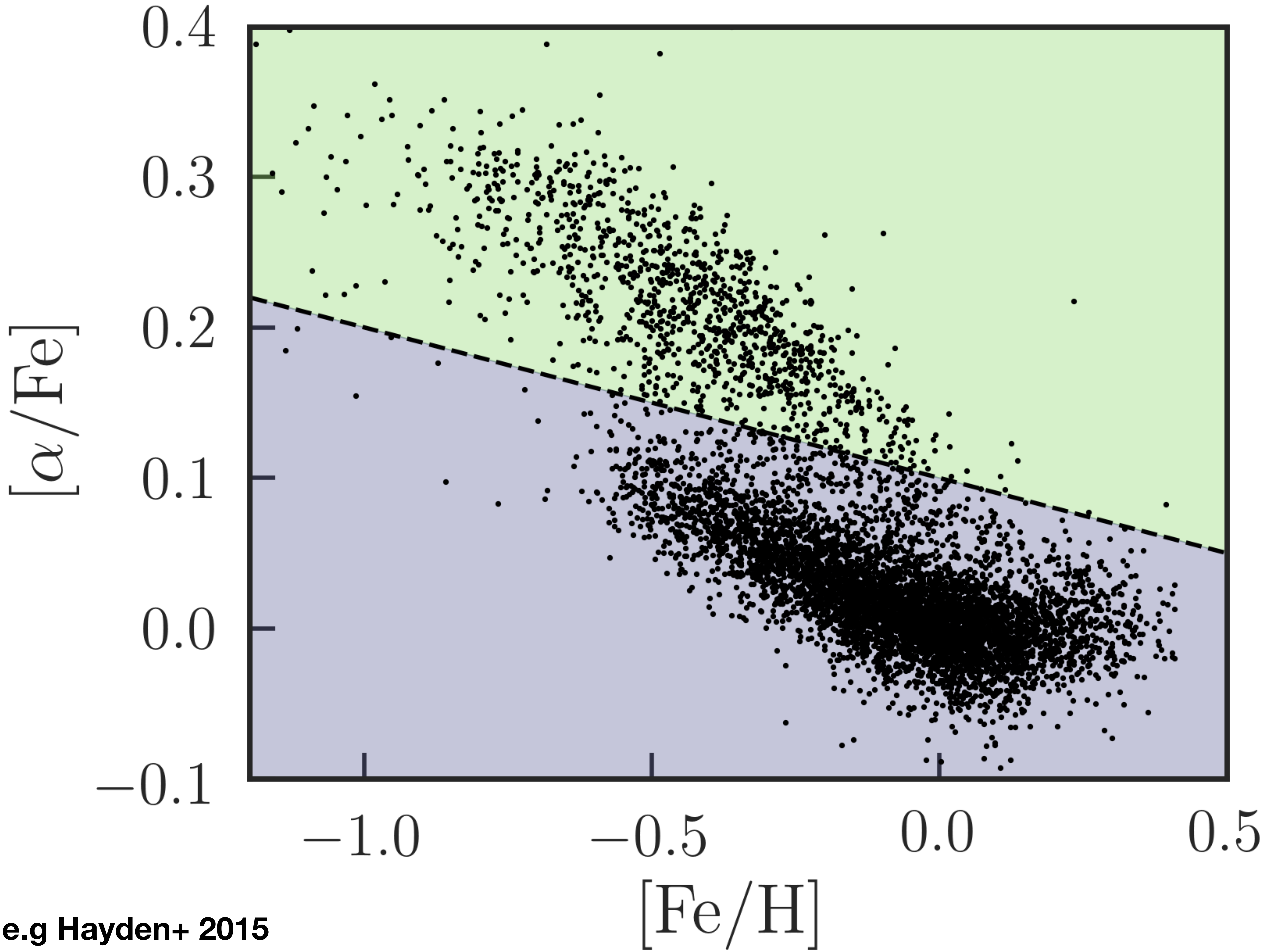
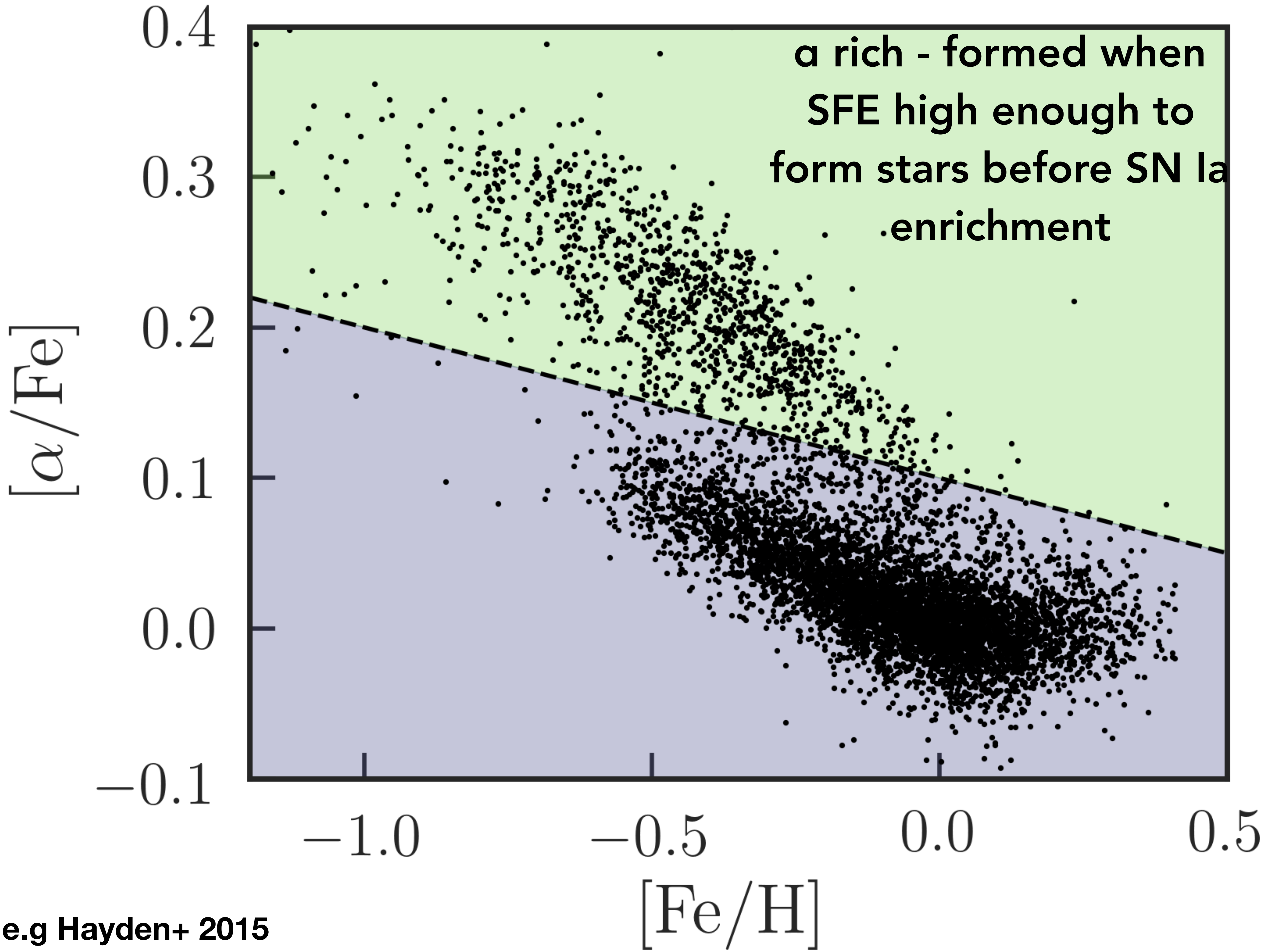
Predictions - make models that meet the constraints and make new predictions

Implications - what does it all *mean* for galaxy evolution



e.g Hayden+ 2015



a rich - formed when SFE high enough to form stars before SN Ia enrichment

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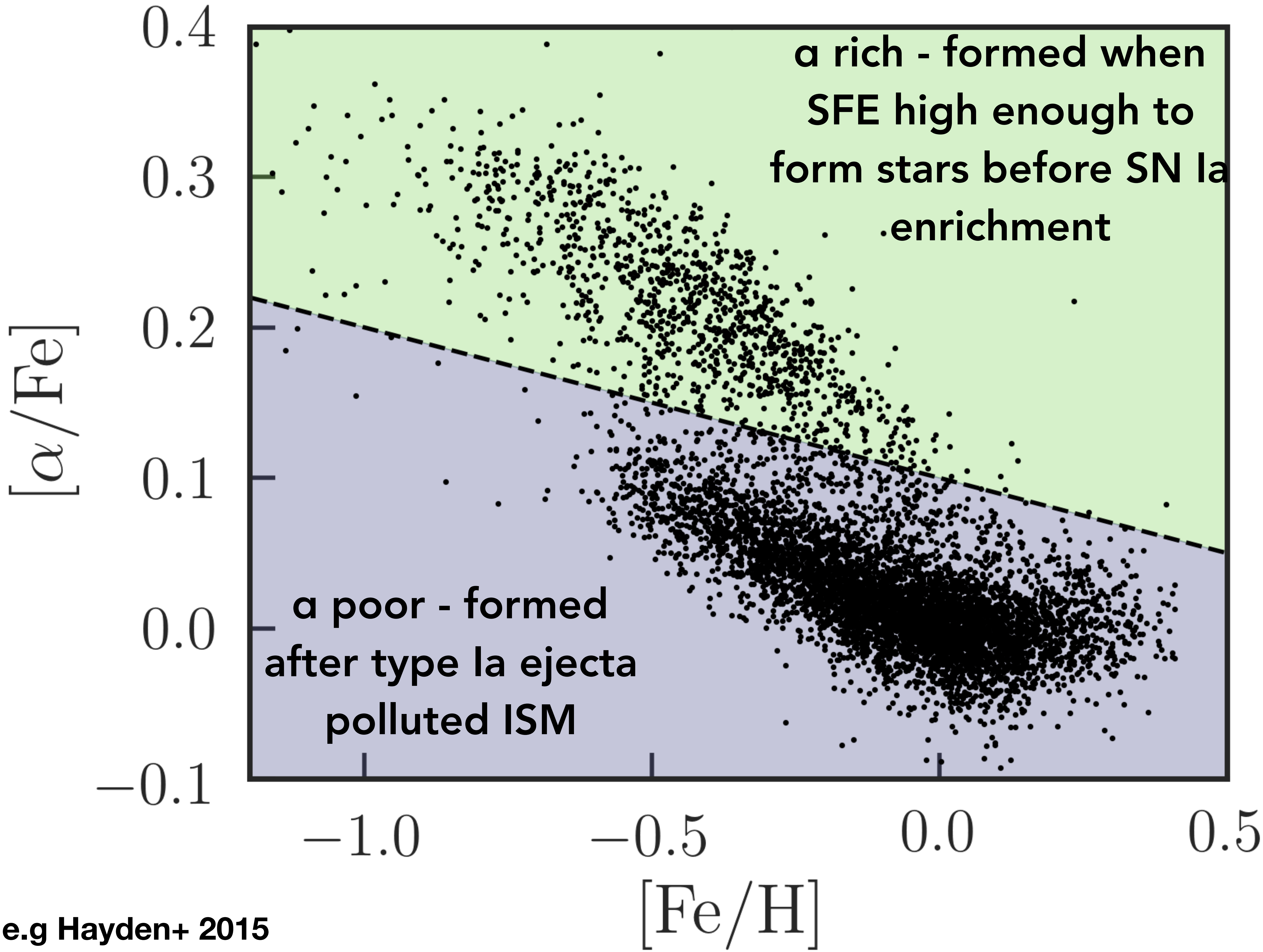
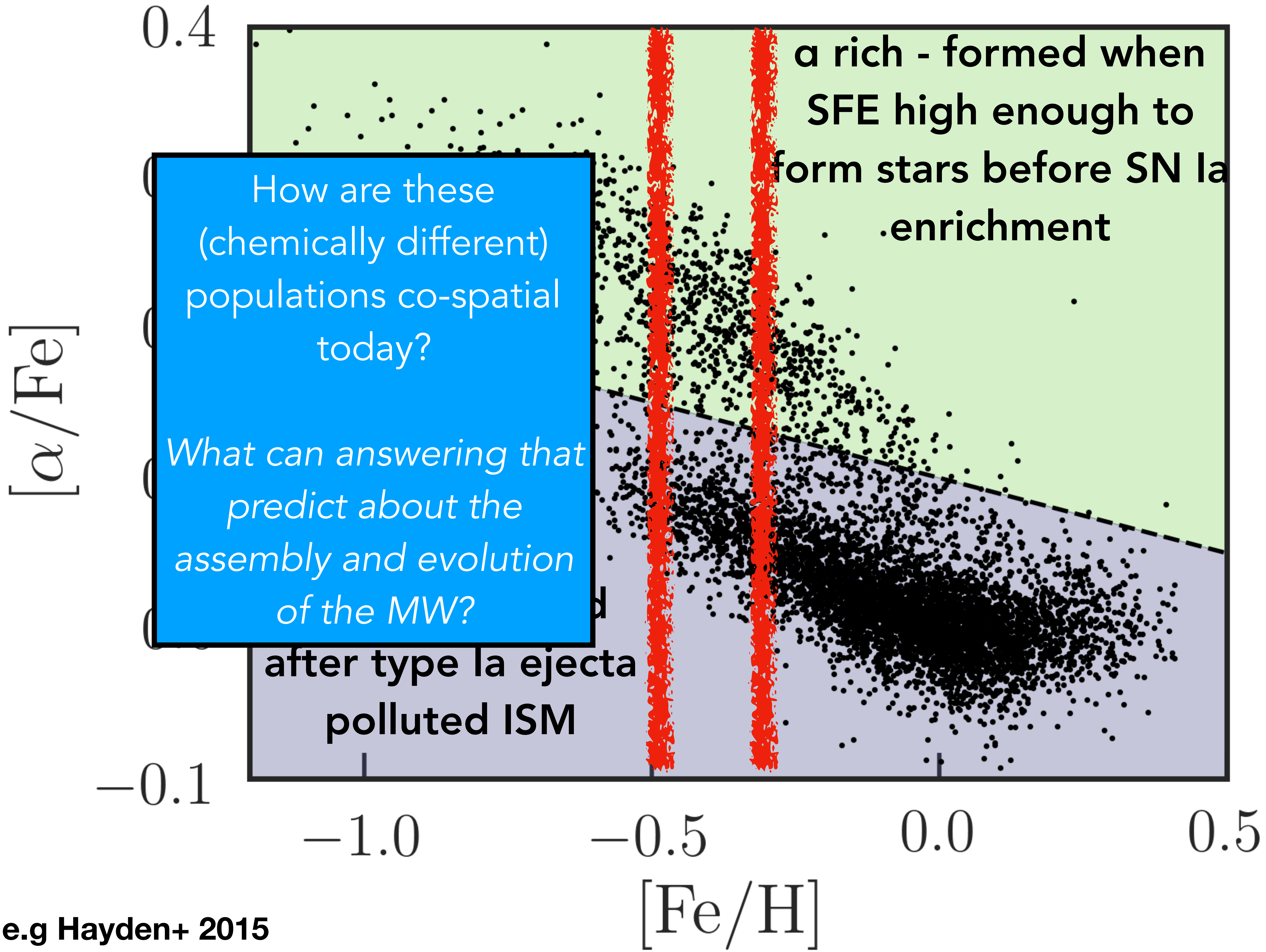


a rich - formed when SFE high enough to form stars before SN Ia enrichment

a poor - formed after type Ia ejecta polluted ISM

e.g Hayden+ 2015



a rich - formed when SFE high enough to form stars before SN Ia enrichment

How are these (chemically different) populations co-spatial today?

What can answering that predict about the assembly and evolution of the MW?

d after type Ia ejecta polluted ISM

e.g Hayden+ 2015

Galactic chemical evolution models can be used to reproduce [α/Fe] bimodality

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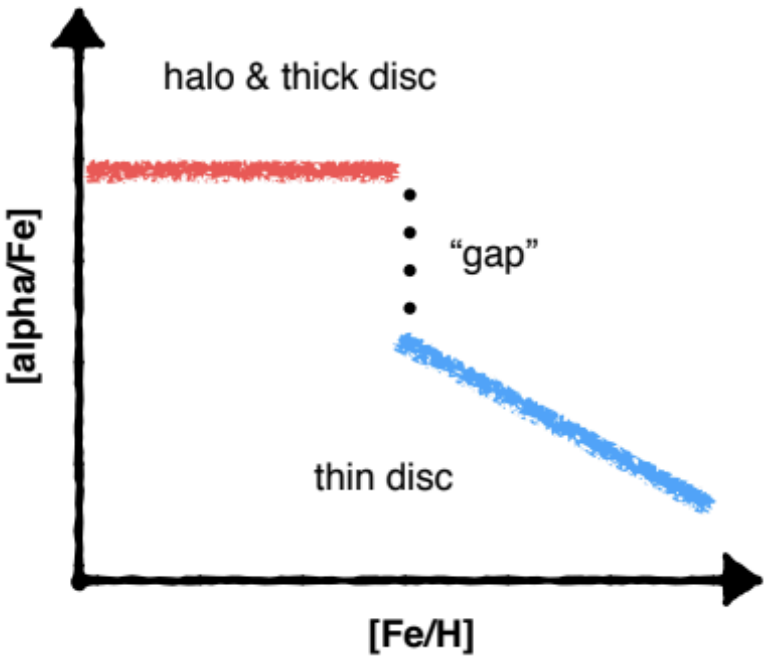
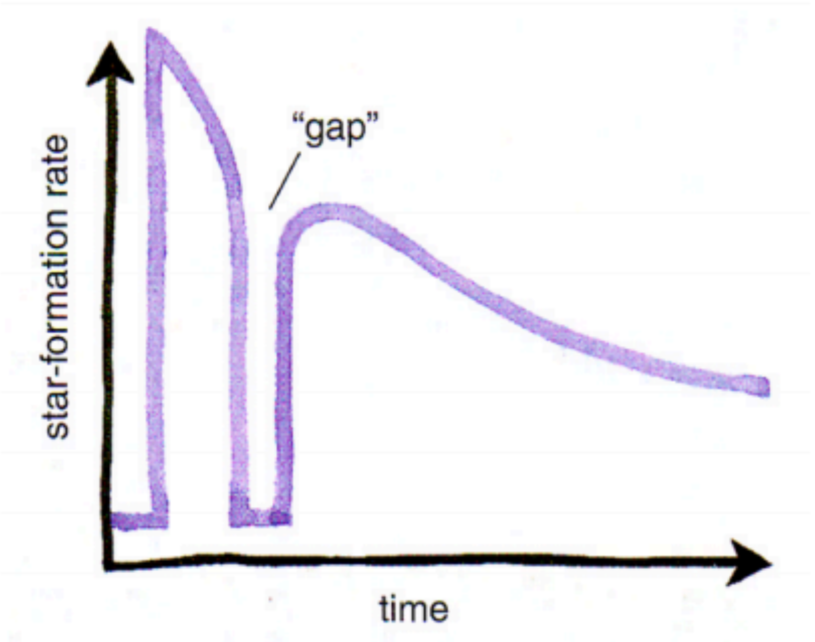
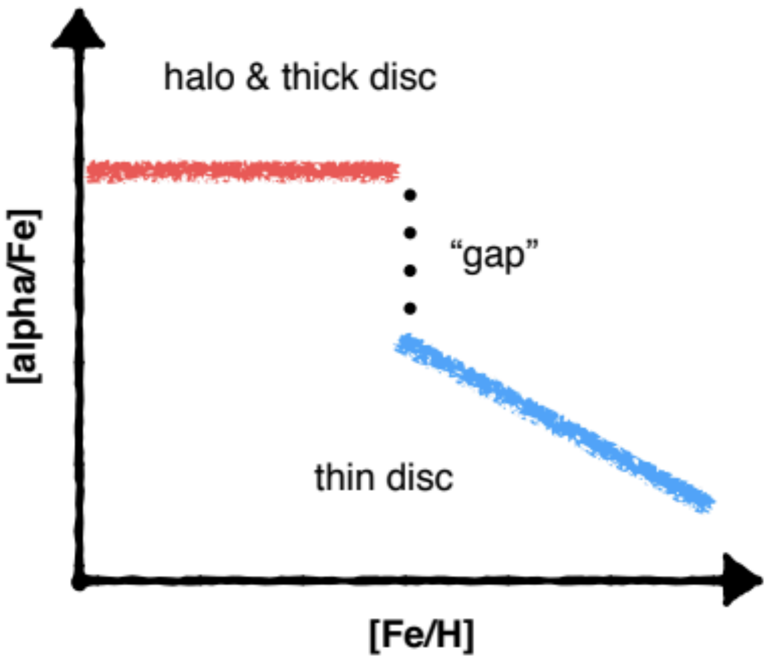


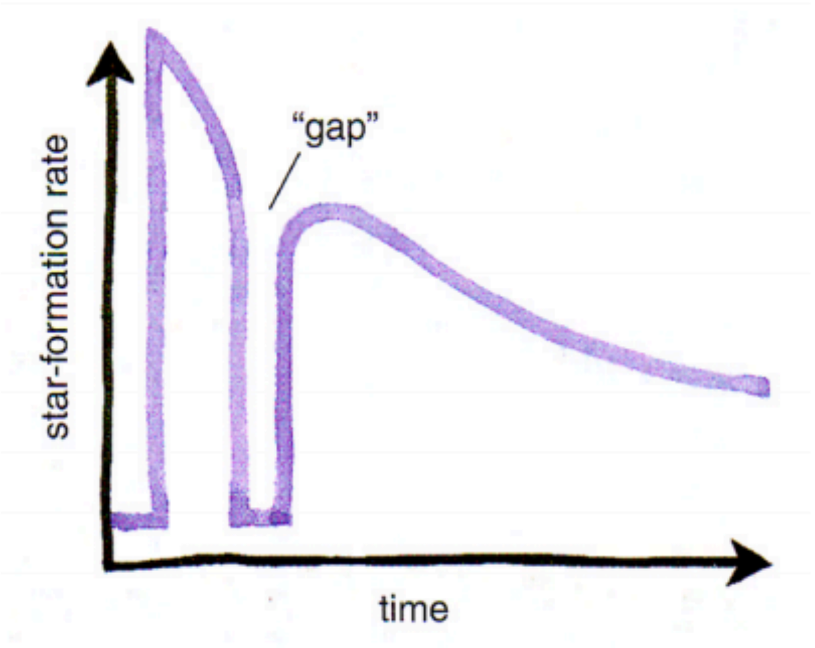


the 'two-infall' model - Chiappini et al. 1997, 2001

Since refined: Spitoni et al. 2018 and many others

Galactic chemical evolution models can be used to reproduce [α/Fe] bimodality





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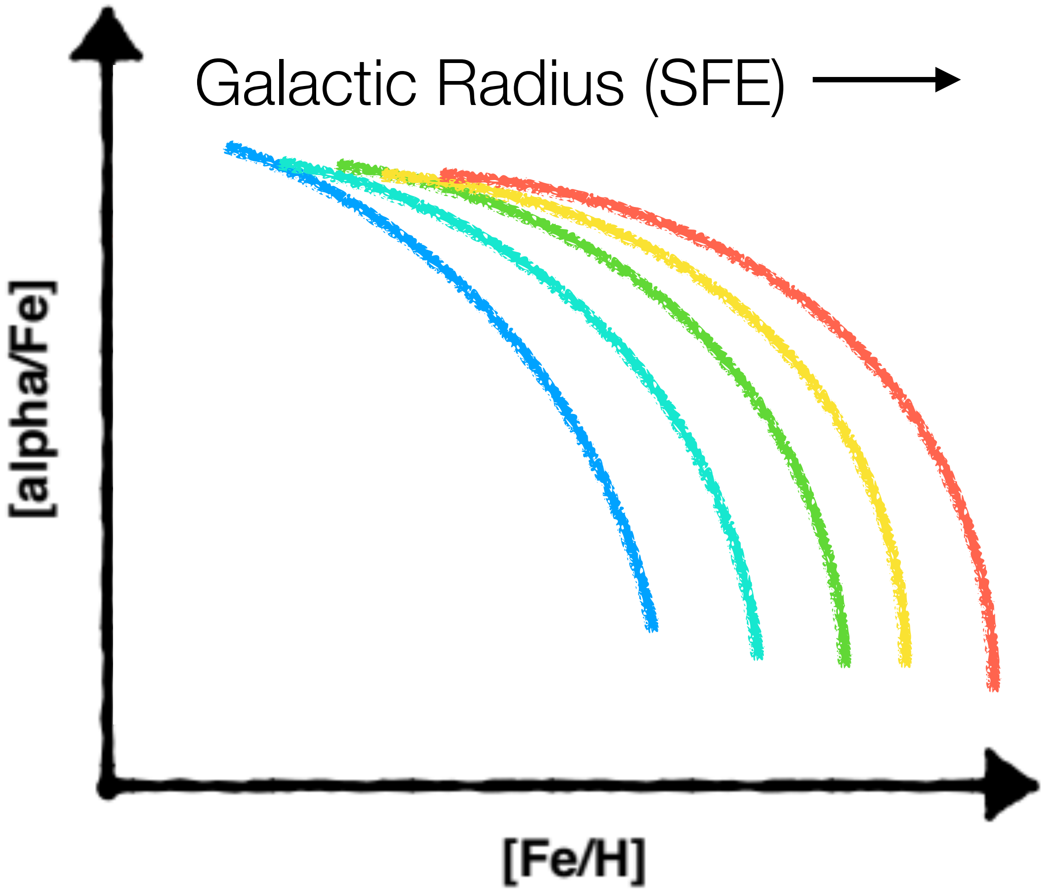
Since refined: Spitoni et al. 2018 and many others

'radial migration' model - Schoenrich and Binney (2009)

Studied in context of numerical sims in Aumer et al. (2016)



Analytic models can reproduce the data by having freedom to adapt and `reverse engineer' the data

Need to produce a Milky Way-like [α/Fe] plane *ab initio* to make orthogonal *predictions* for the Milky Way and understand its *context*

➡ *Forward Model:*
use Cosmological Simulations

EAGLE Simulations

(Schaye+ 2015, Crain+ 2015, McAlpine+ 2015)

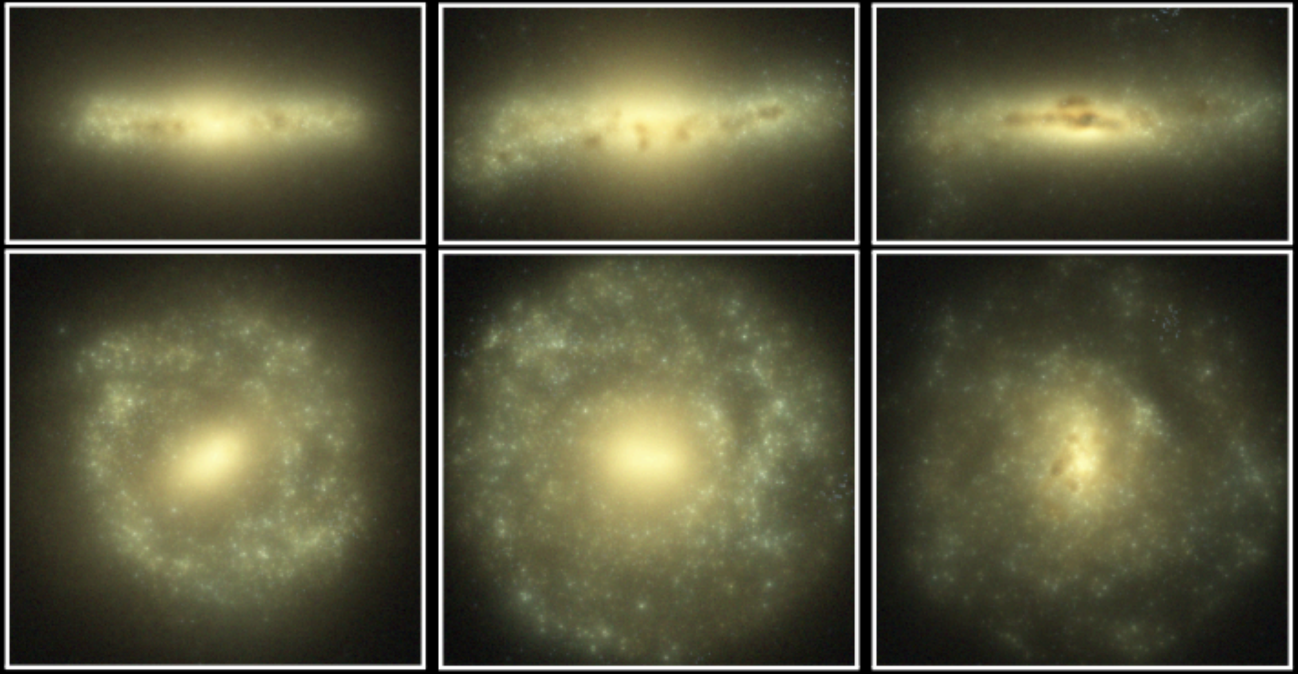
133 Milky Way-like galaxies

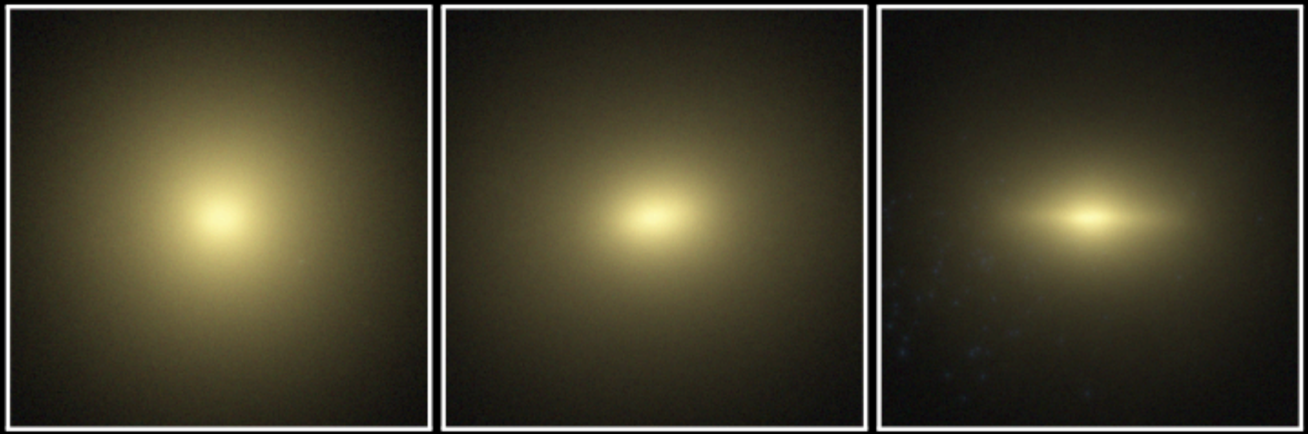
$$5 < M_* < 7 \times 10^{10} \mathrm{M}_\odot$$

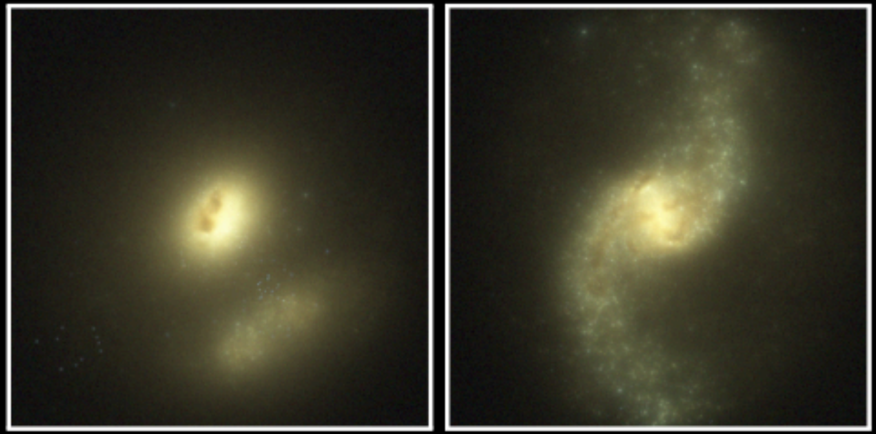
Disk Dominated

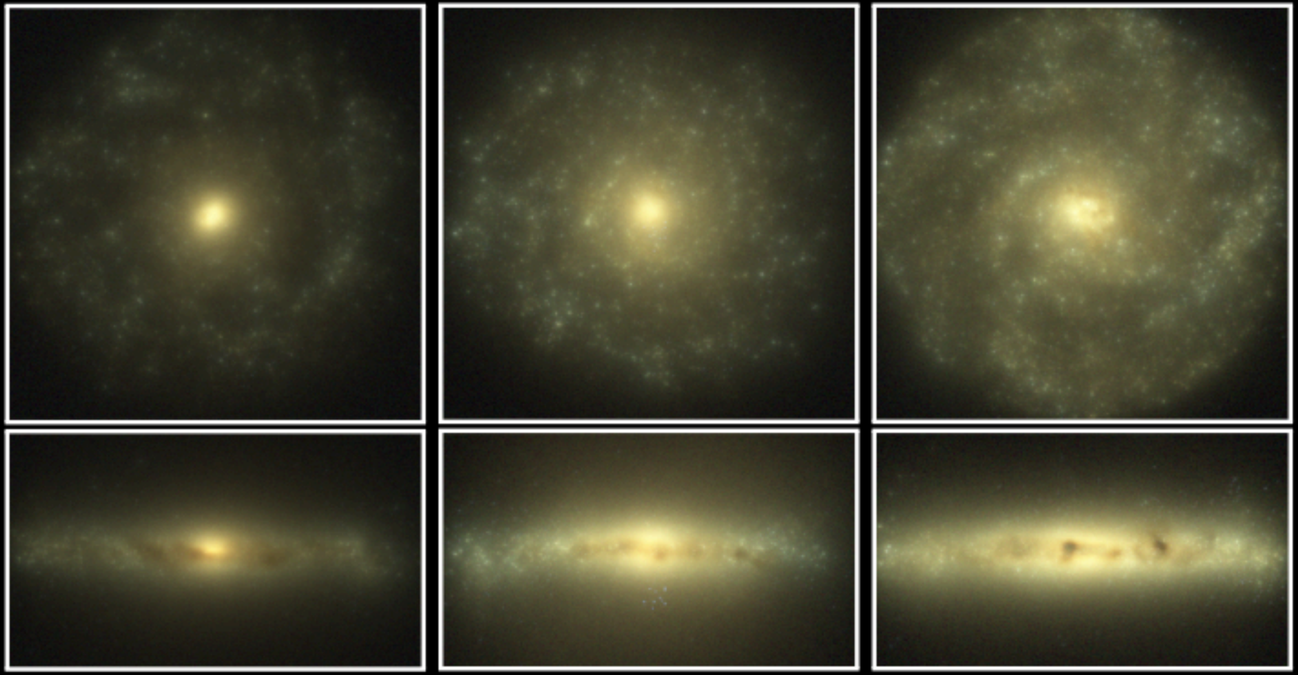
100 Mpc simulated self-consistently in a cosmological context

11 elements (inc. α) tracked for radiative cooling calculations

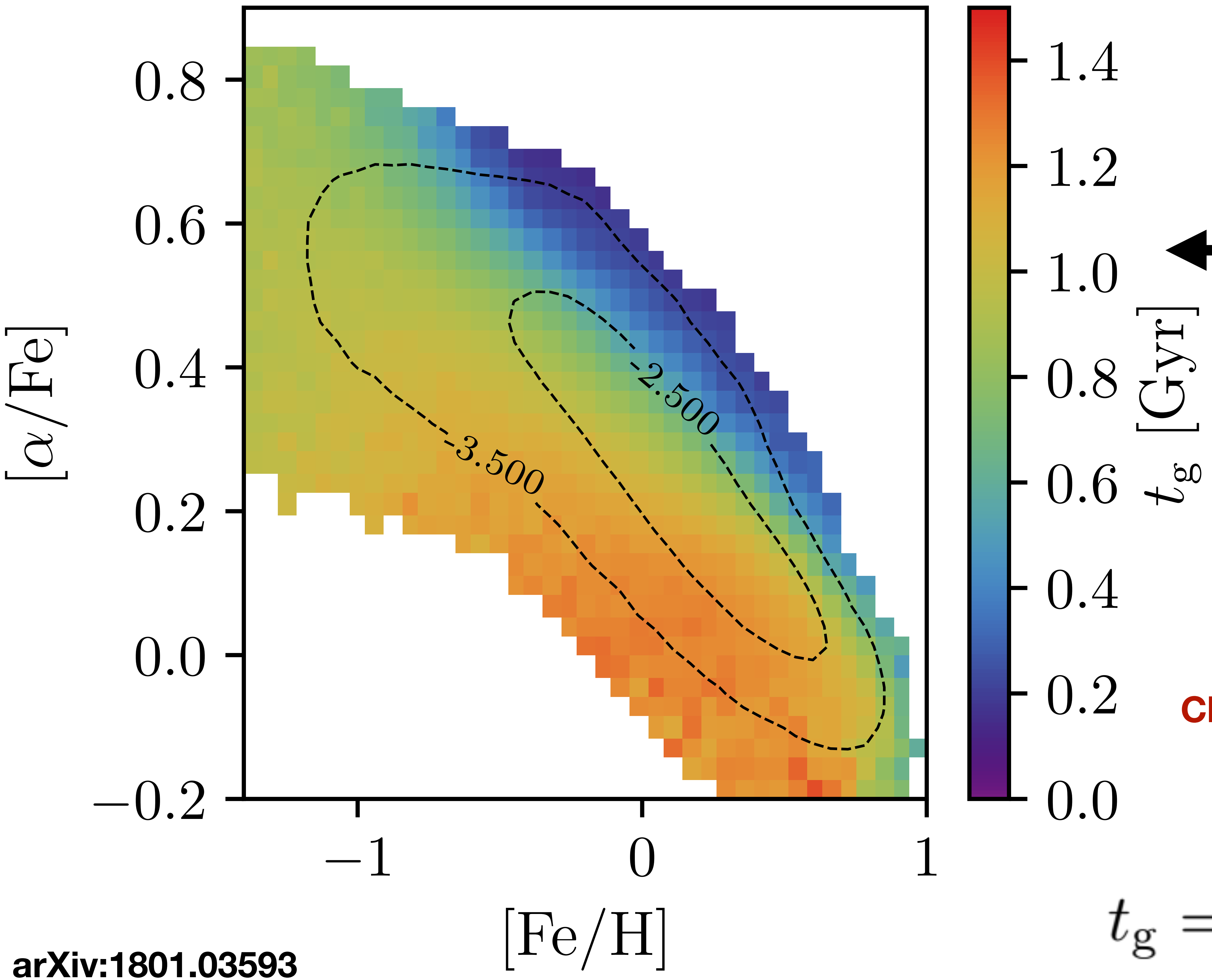








[α/Fe] in EAGLE correlates with star formation timescales



half-life for SNIa

See also Clarke et al. 2019

$$t_g = \Sigma_g / \dot{\Sigma}_\star$$

arXiv:1801.03593

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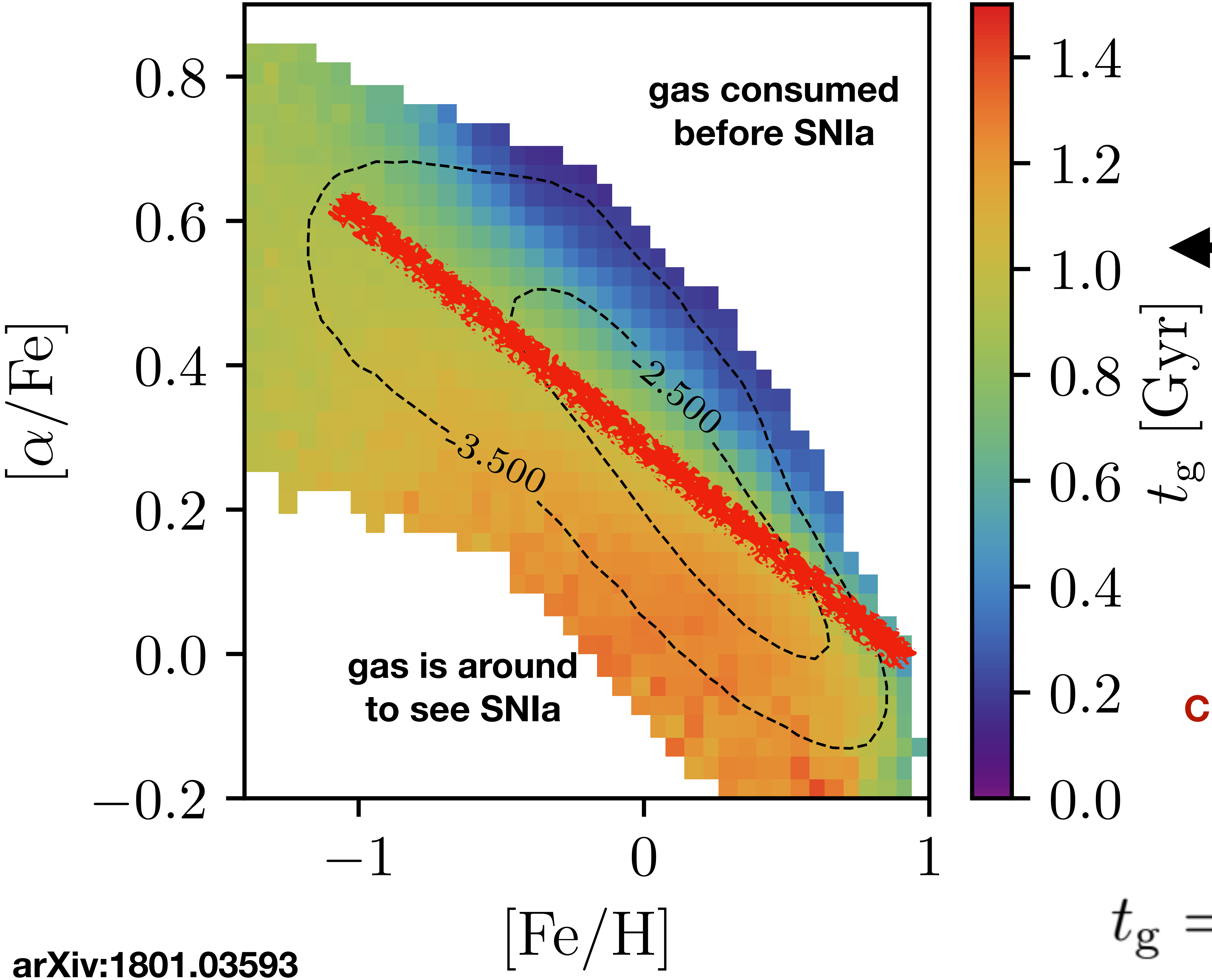

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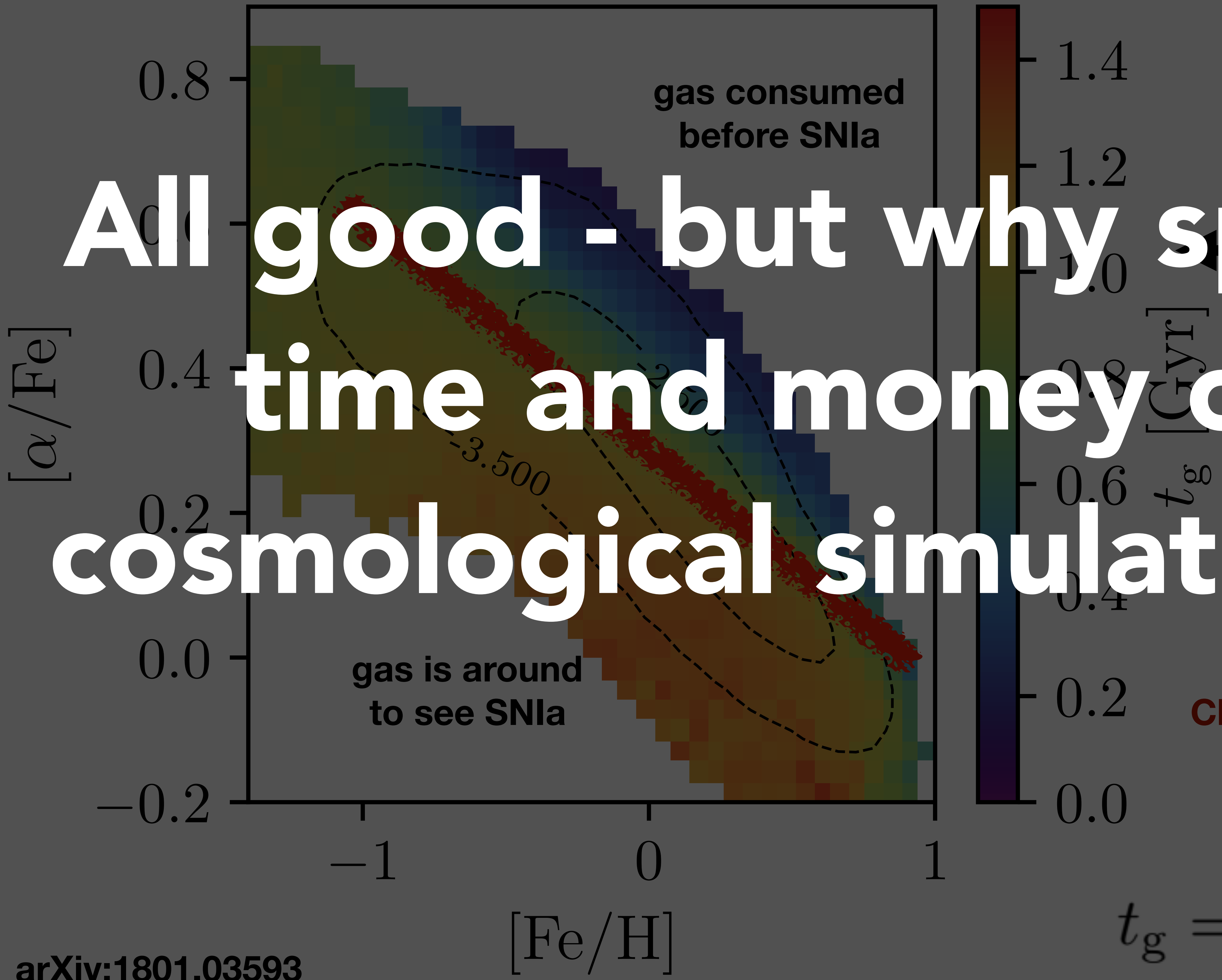

All good - but why spend time and money on cosmological simulations?

See also Clarke et al. 2019

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Diversity in α-element enrichment

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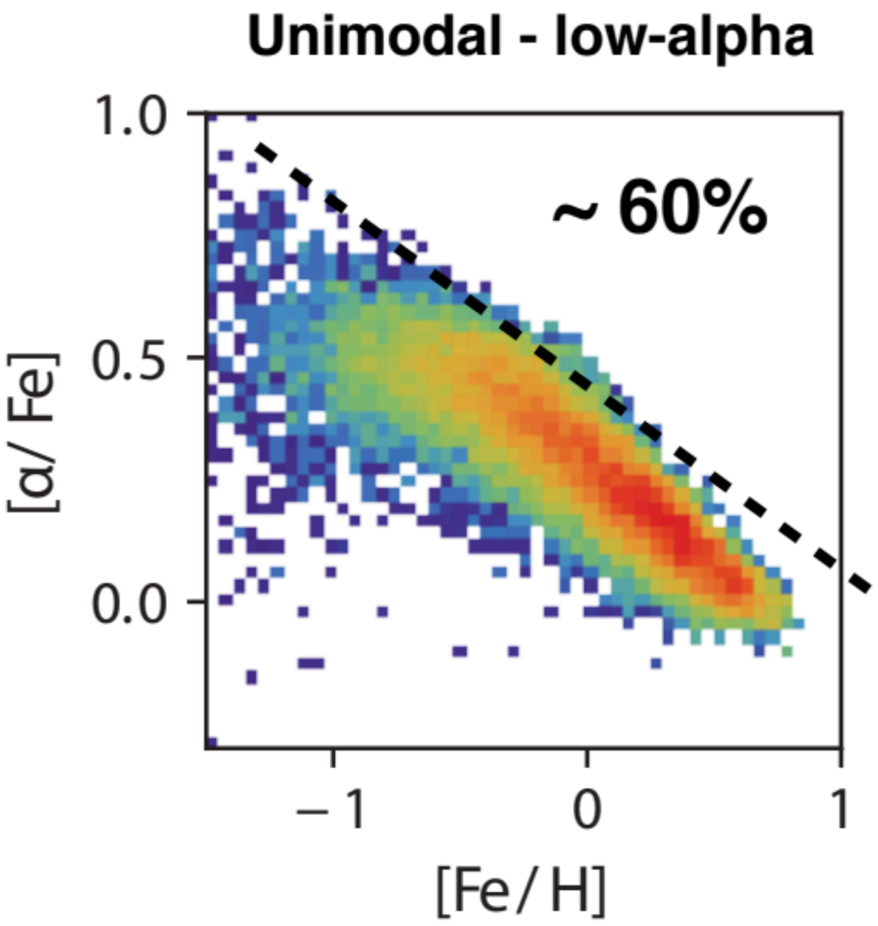

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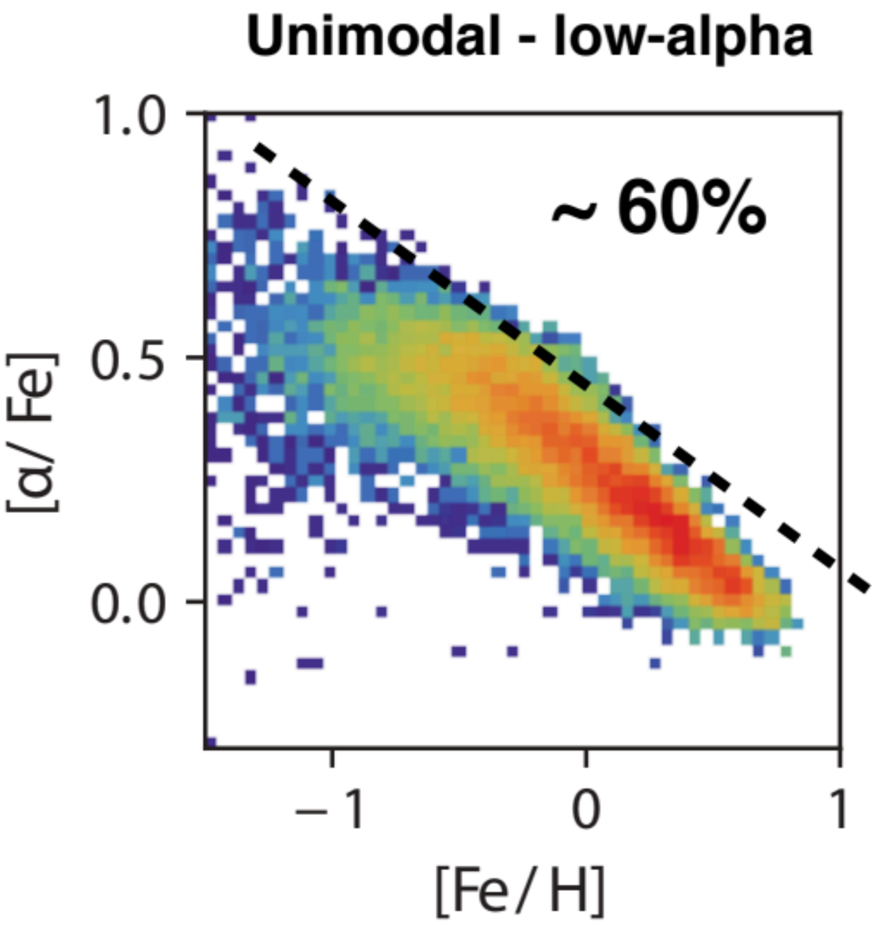

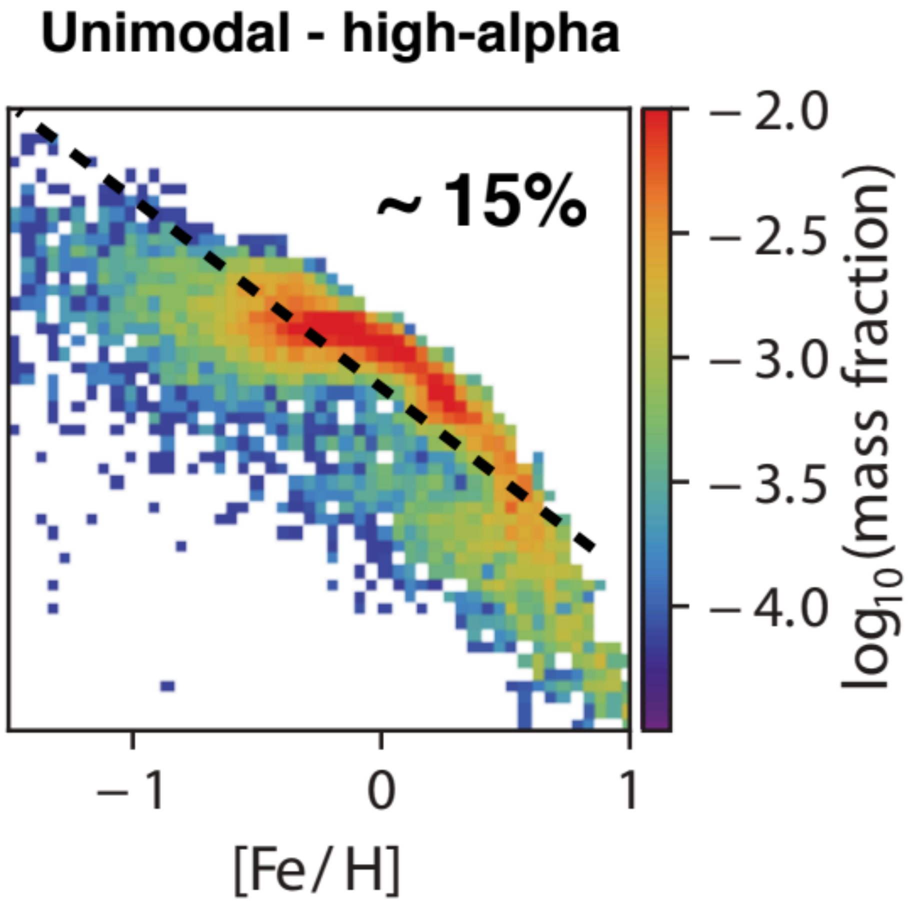

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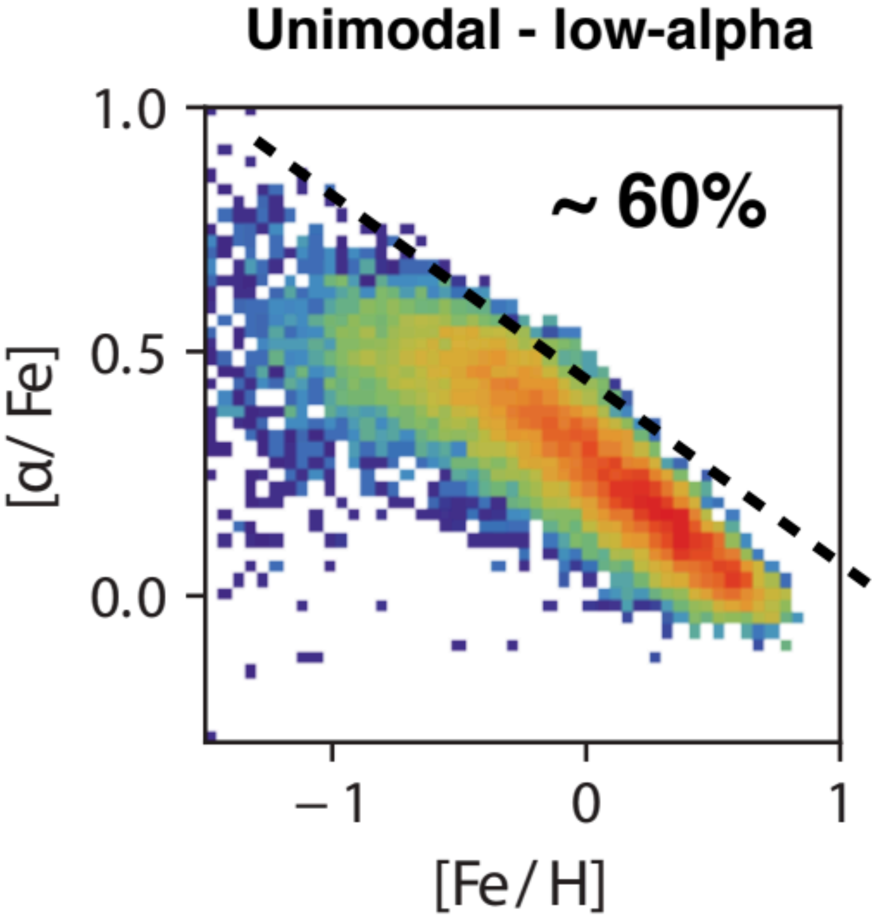

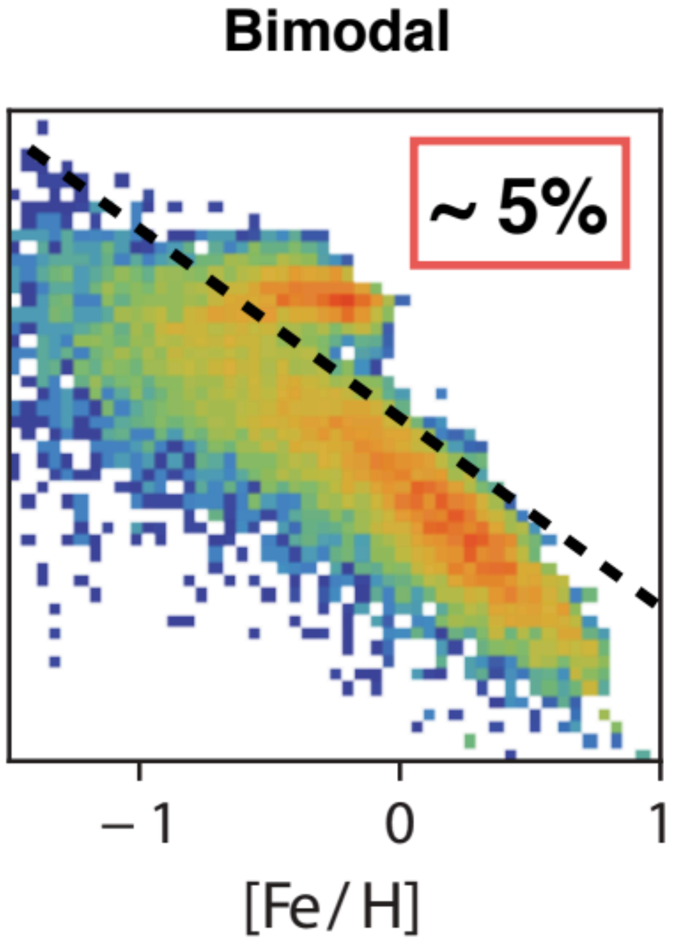

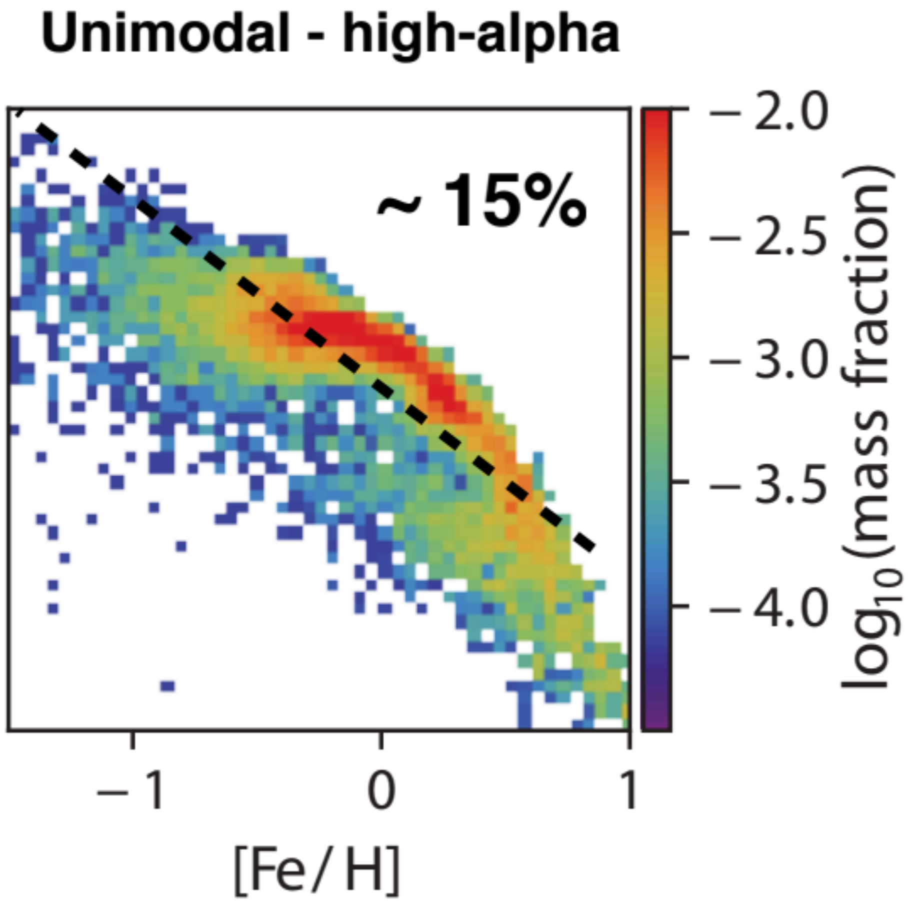

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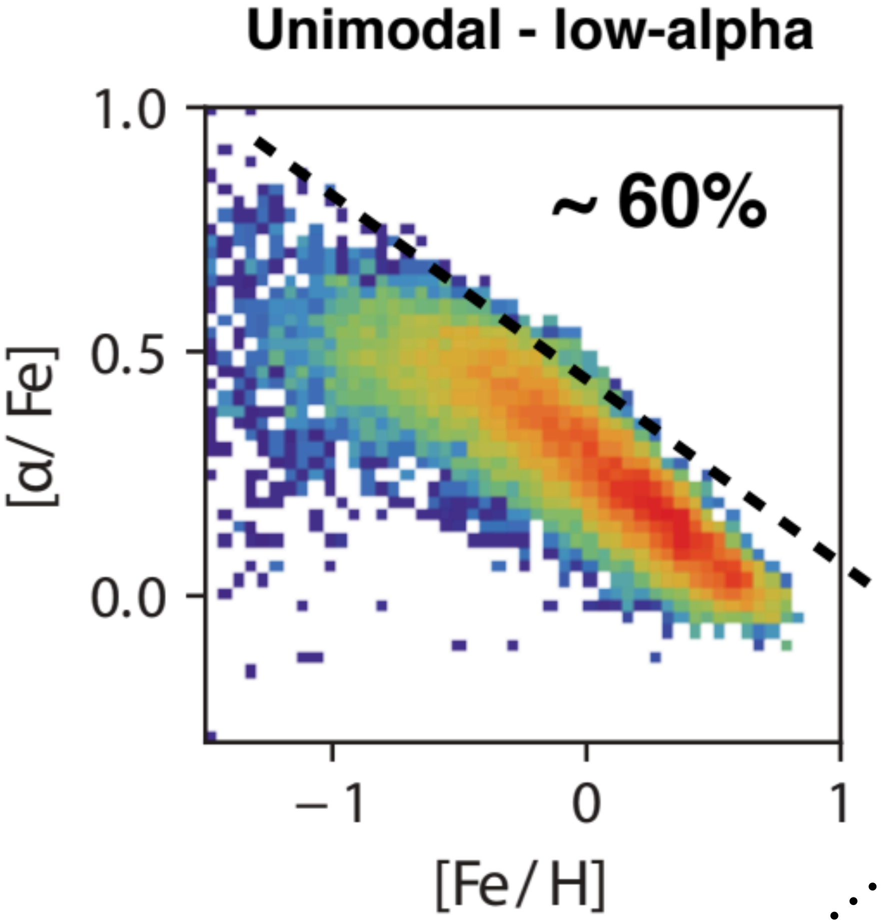

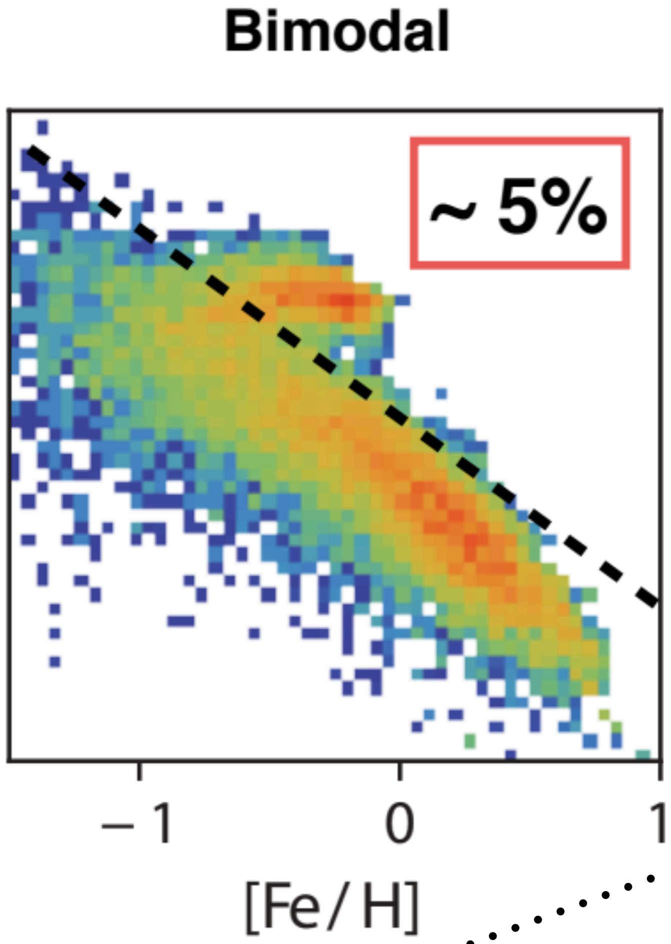

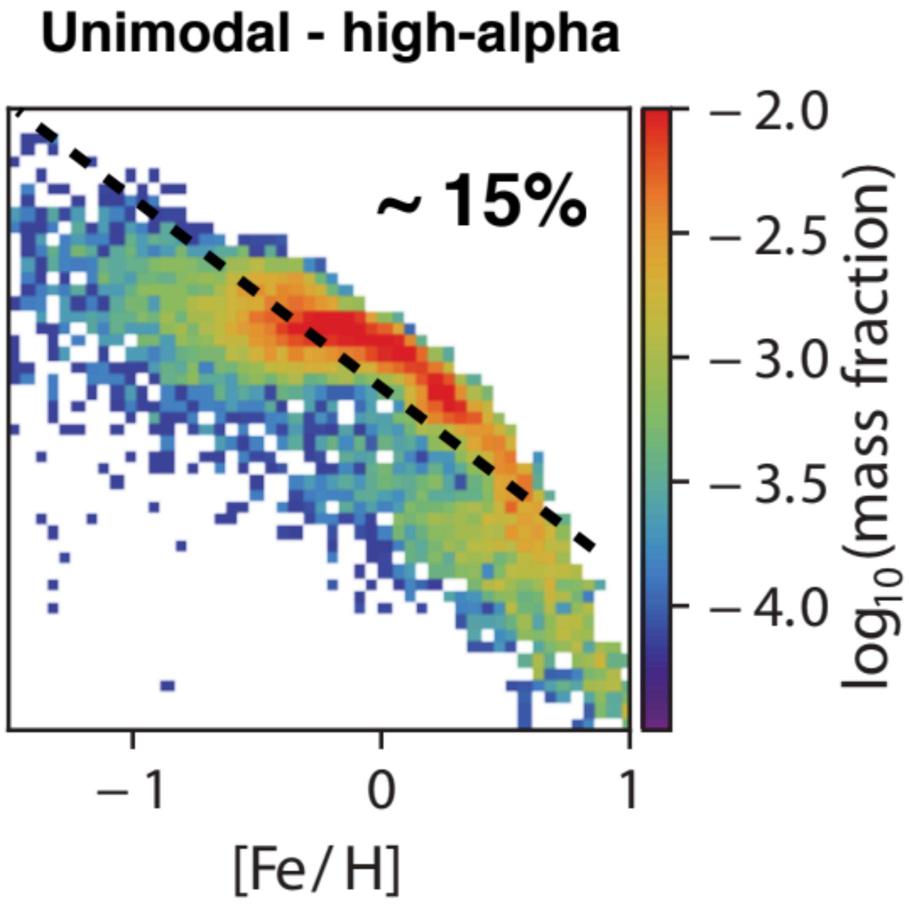

[α/Fe] bimodality (at fixed [Fe/H]) *rarely* seen at the MW stellar mass range

Now seeing bimodality in many zooms!
- e.g. AURIGA (Grand+ 2018), FIRE (Wetzel), Clarke+ 2019

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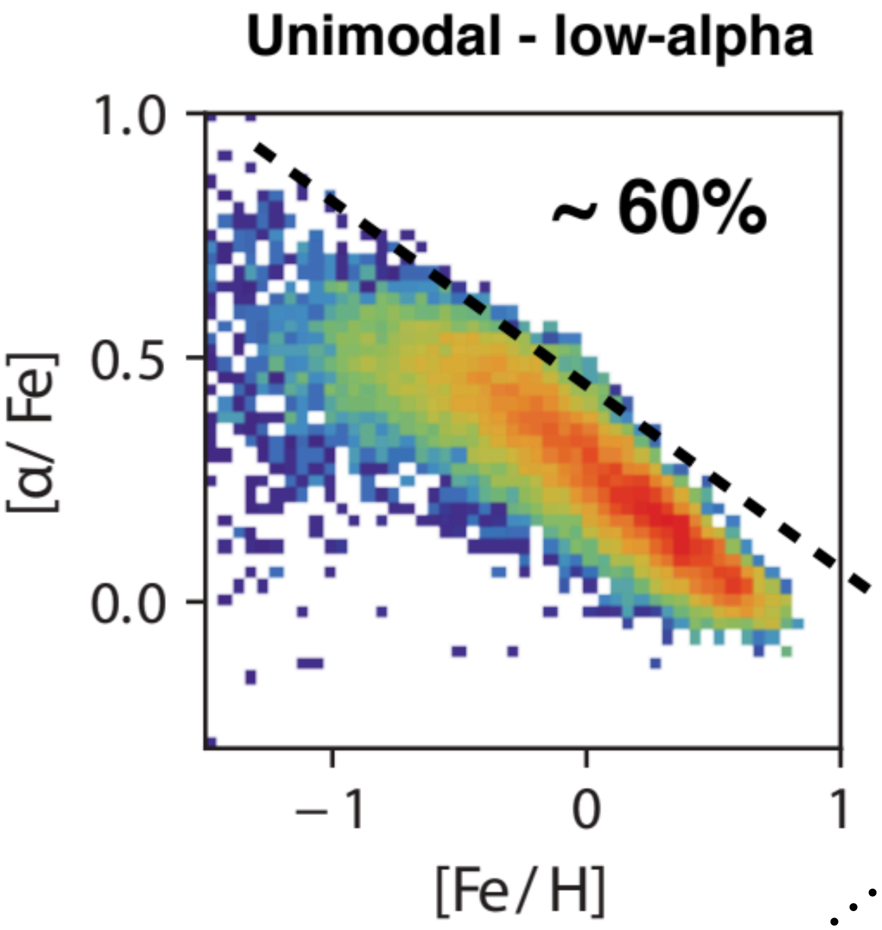
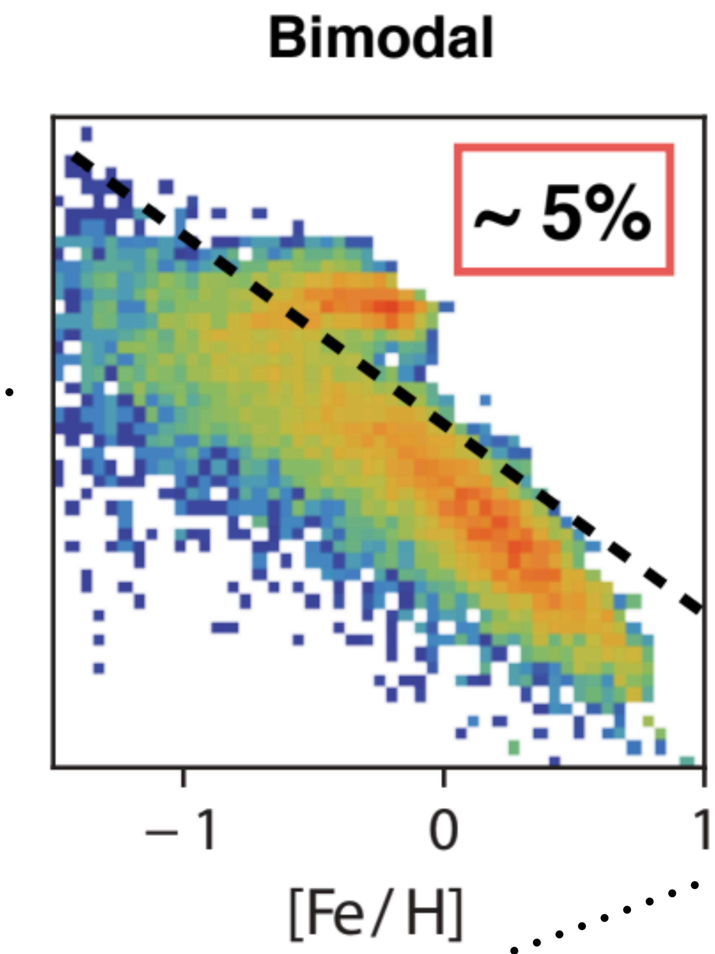
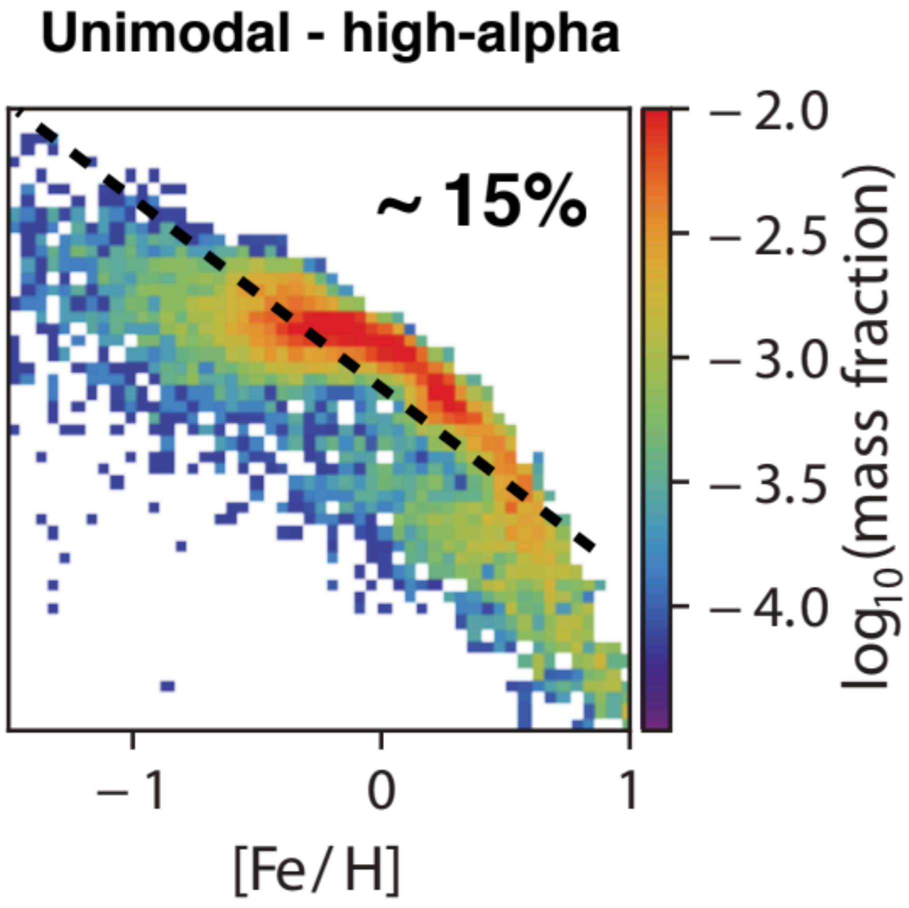




+20% ambiguous!



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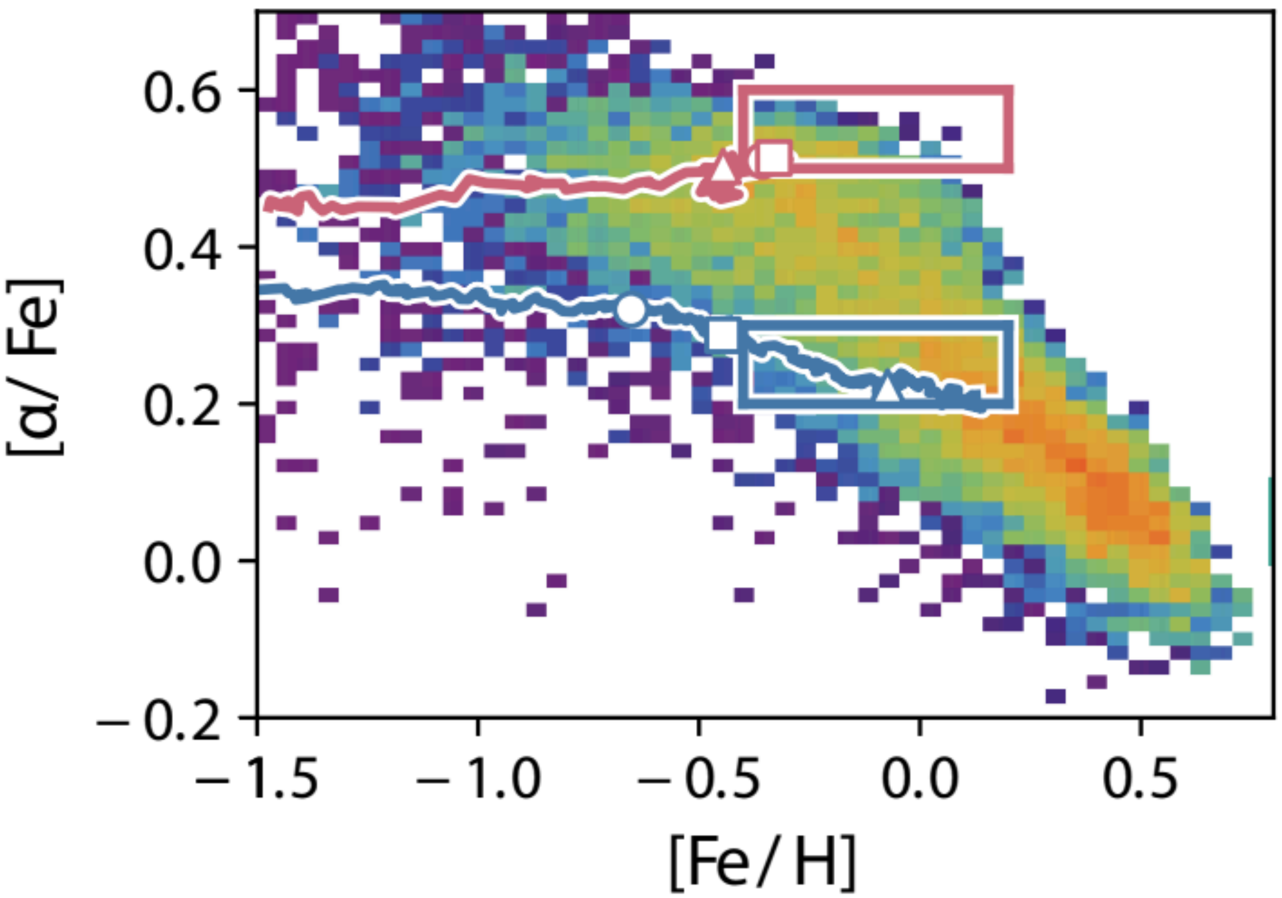

[α/Fe] bimodality is *linked* to infall, SFH and radial migration

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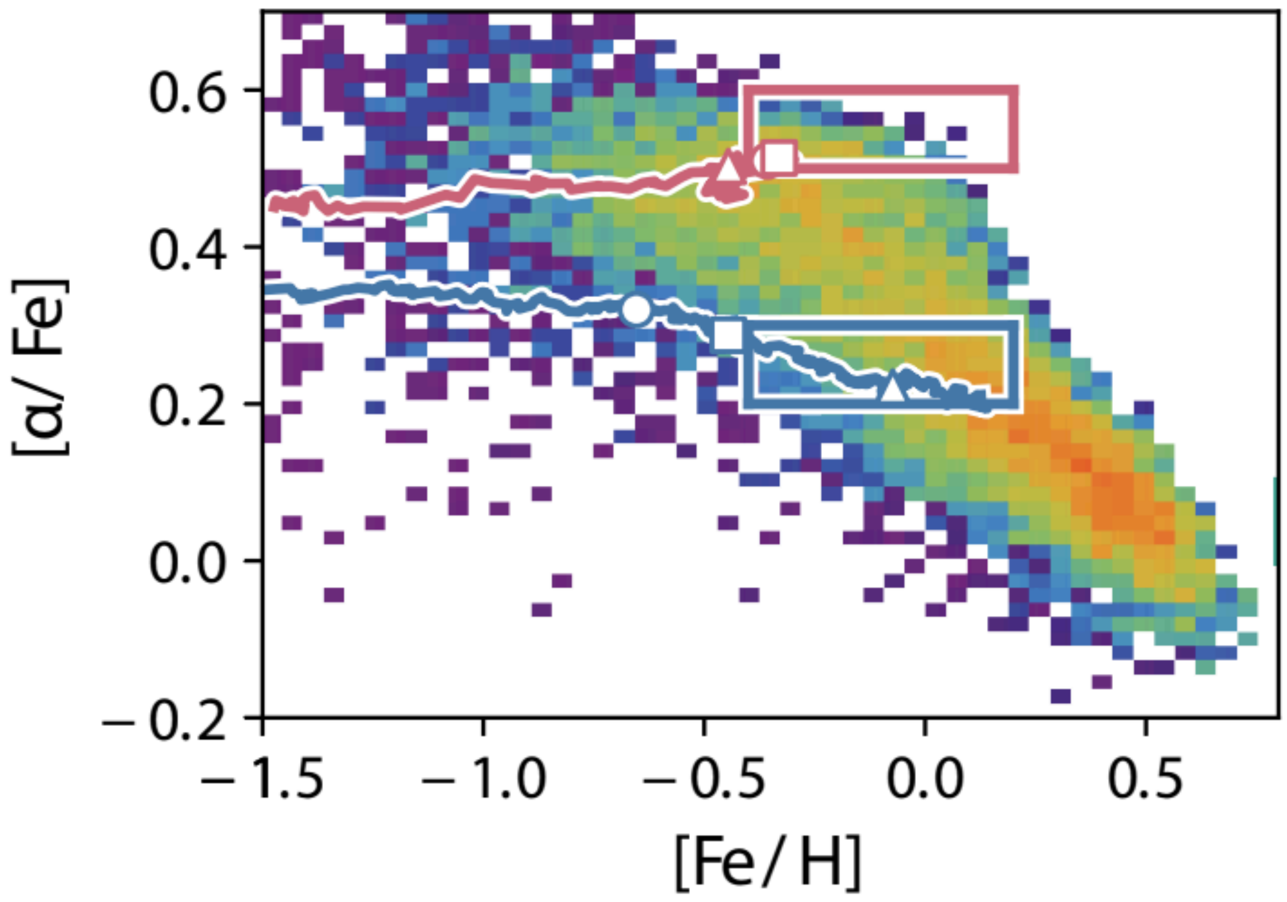

Gas evolves along different tracks in abundance space as it forms the two populations

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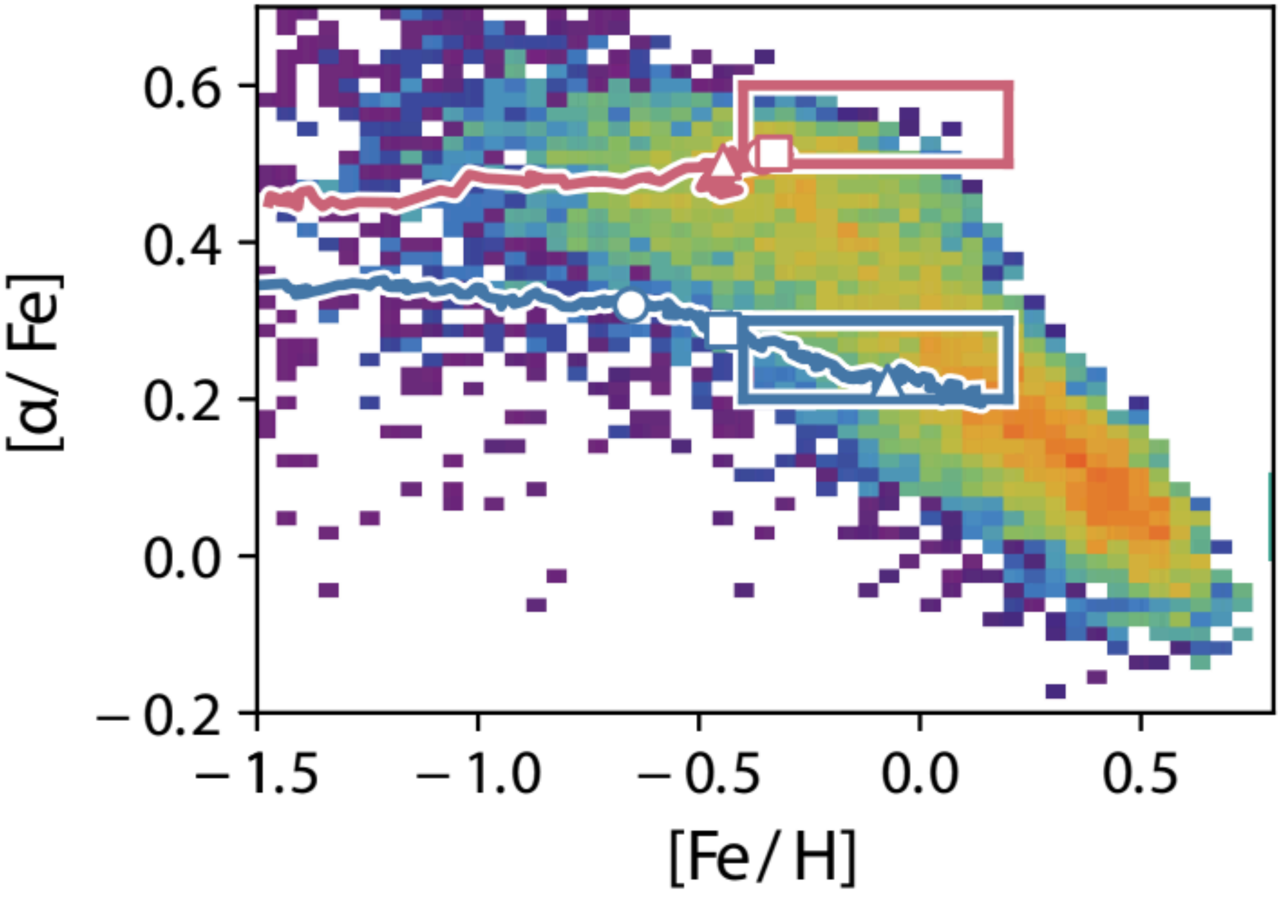

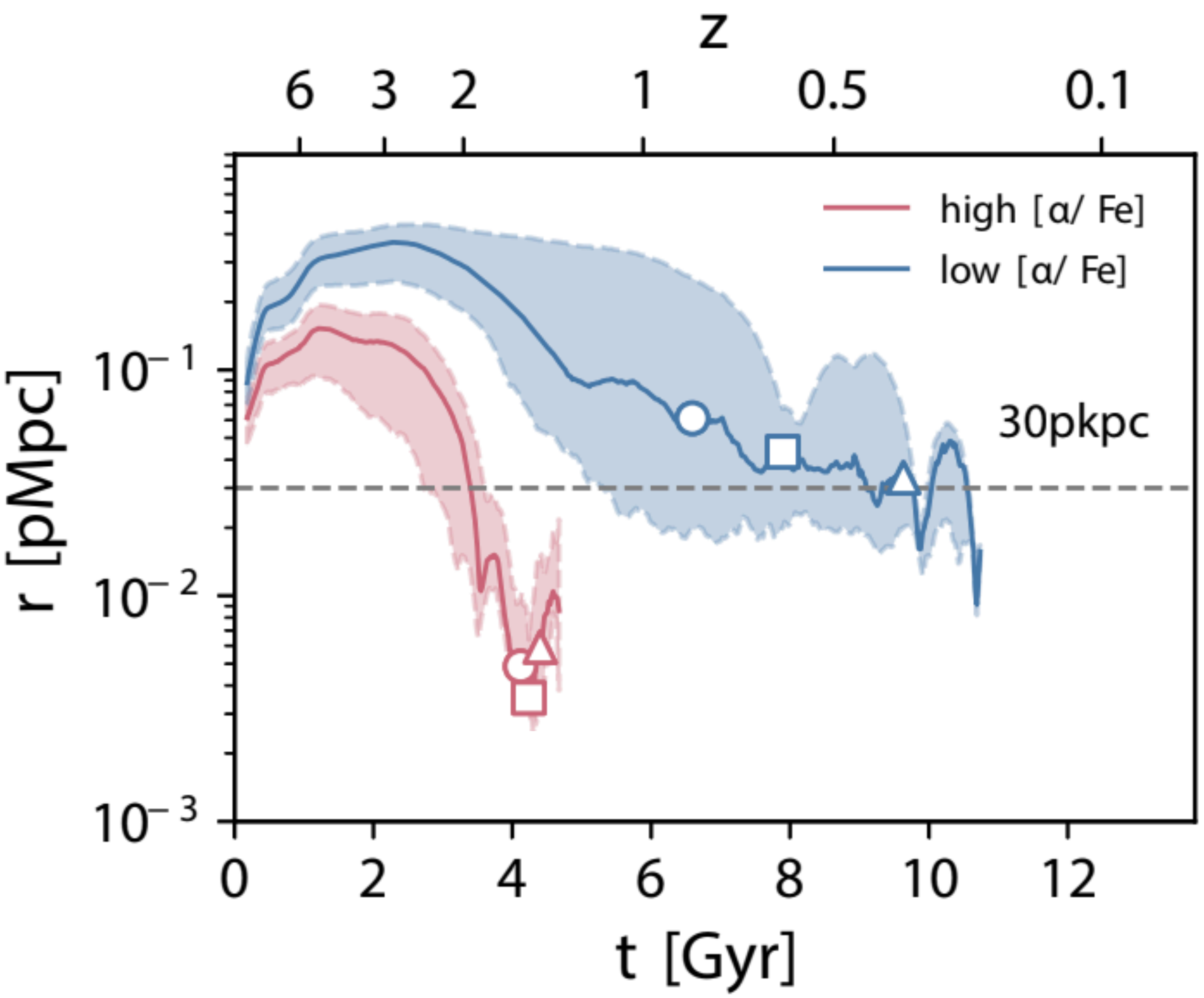

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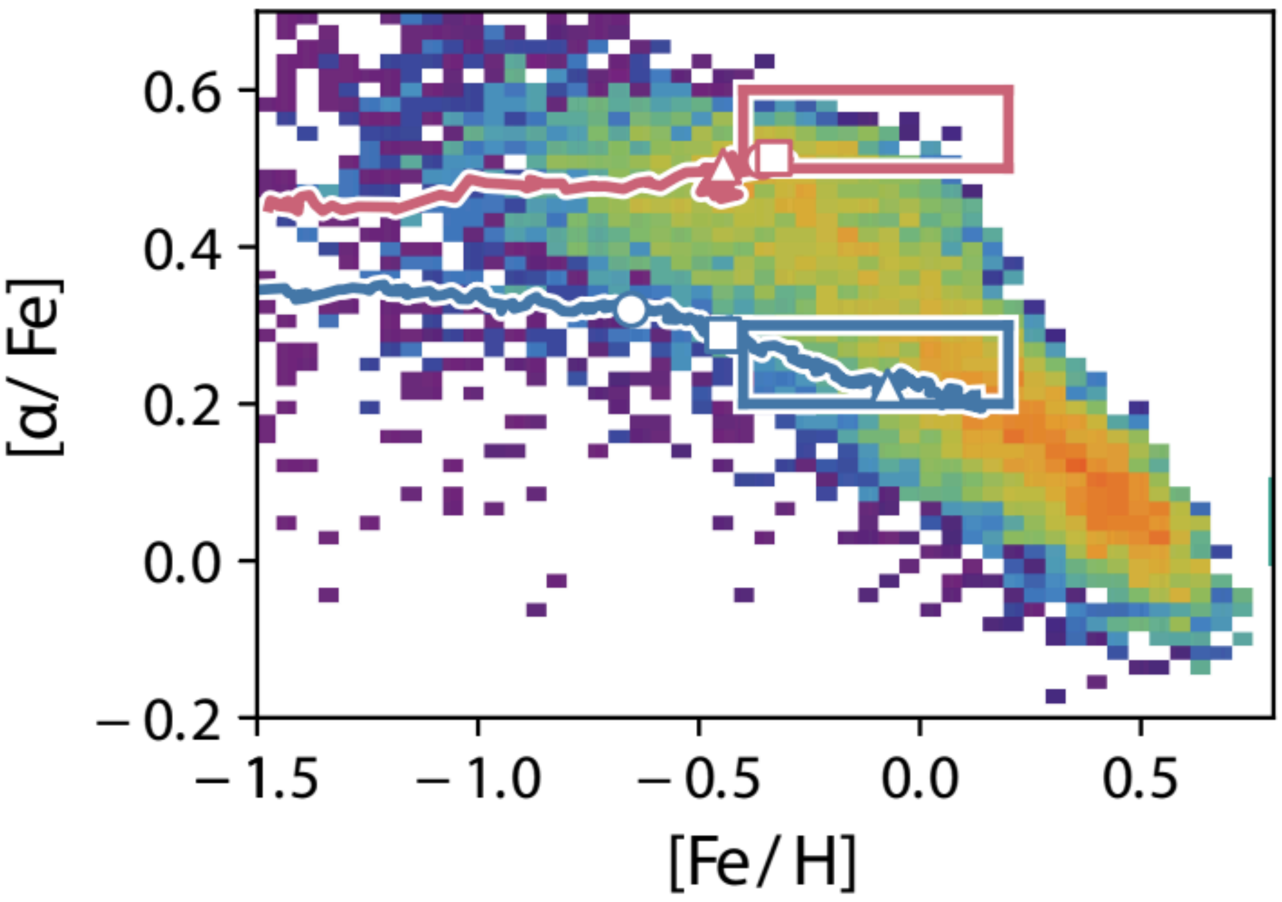

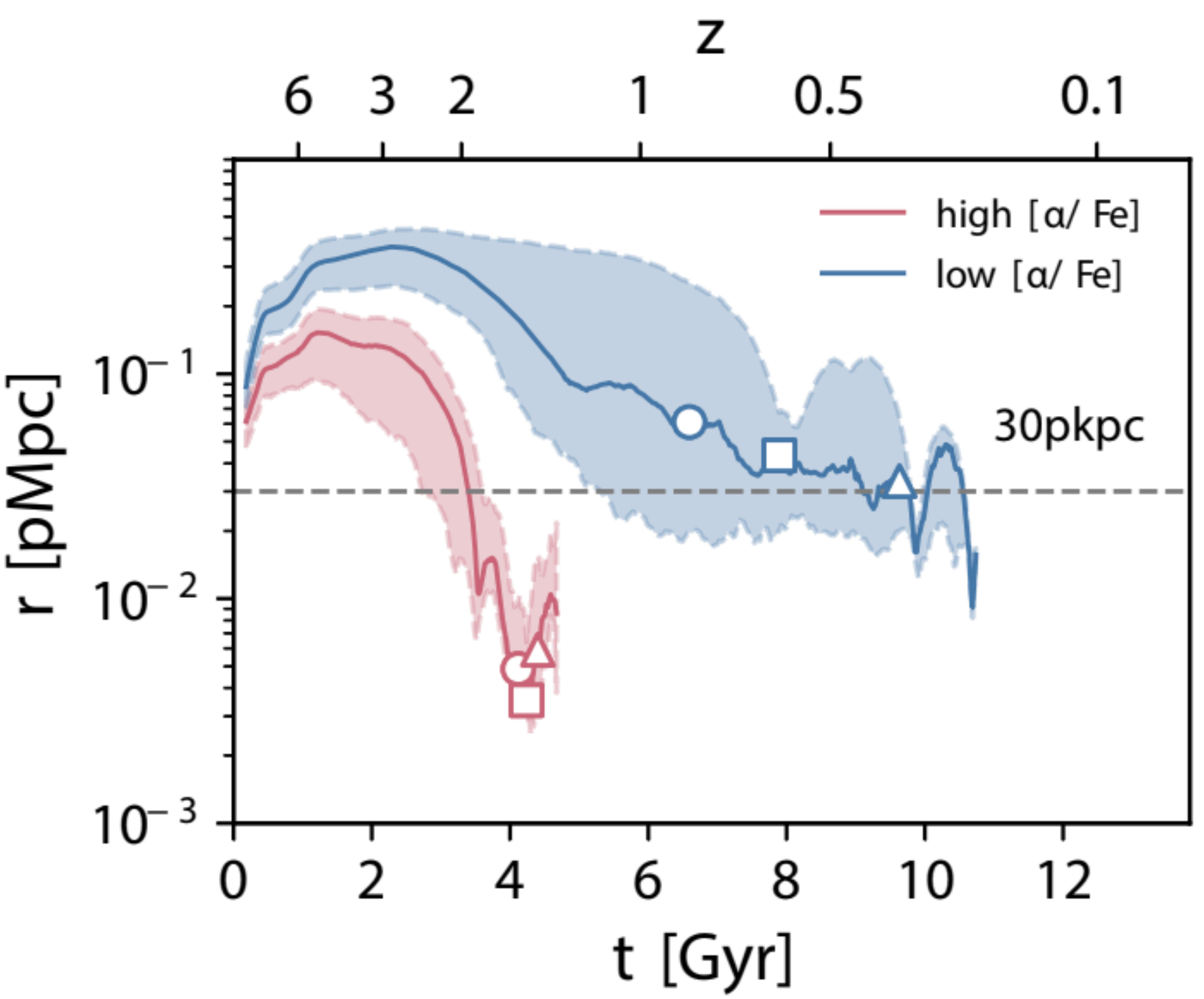

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gas accretion occurs in distinct episodes, at different times, and in different ways

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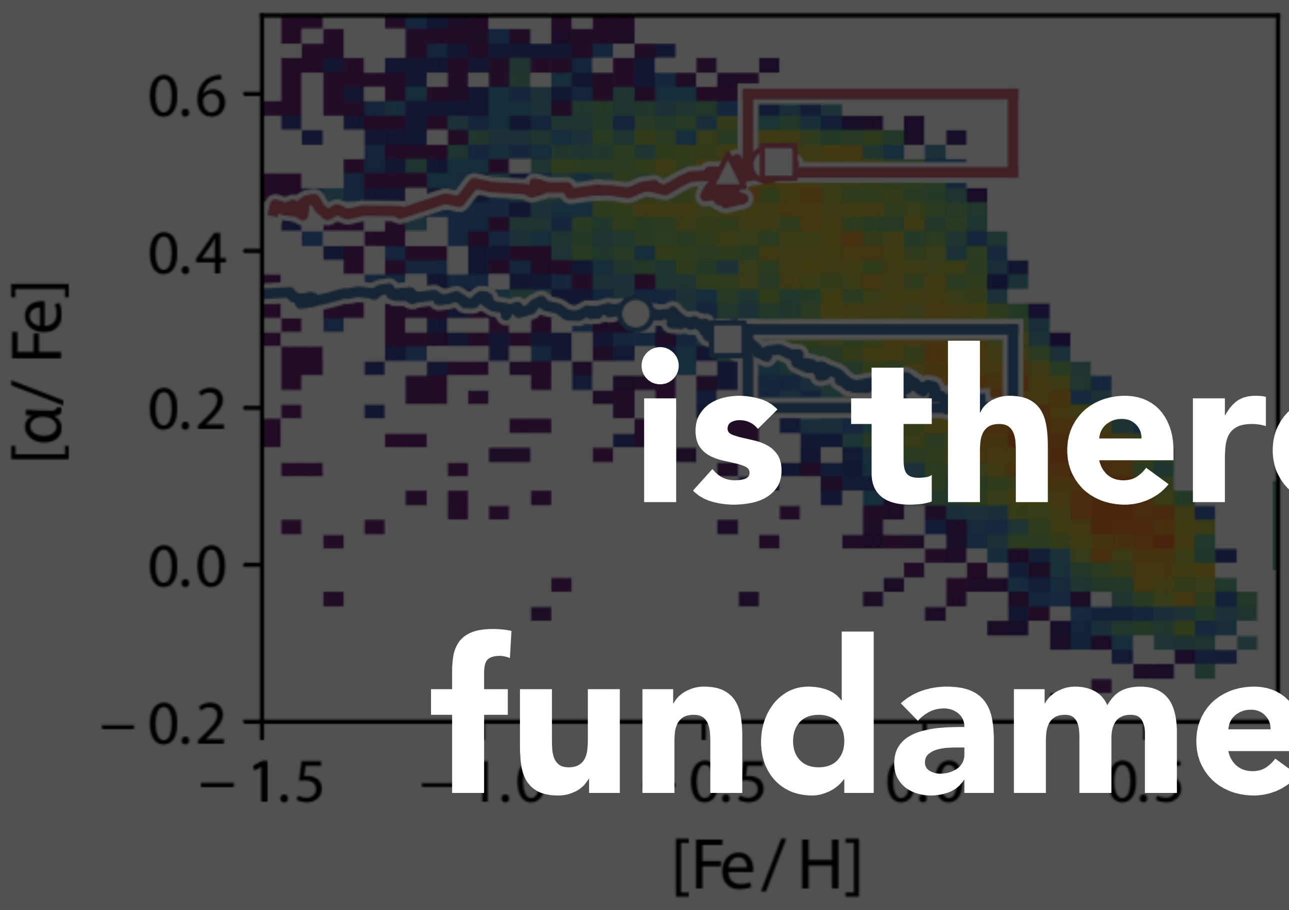

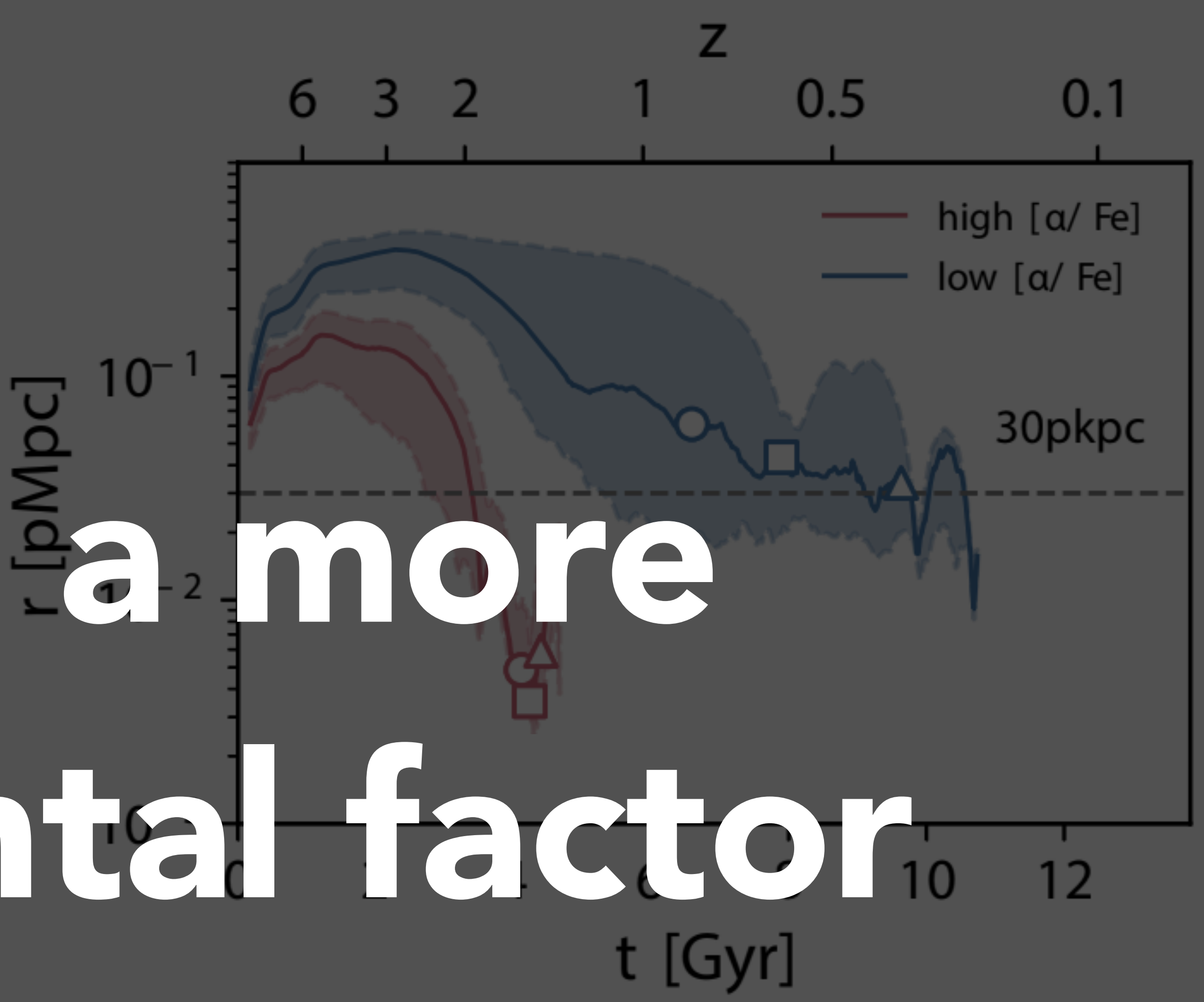

is there a more fundamental factor driving bimodality?

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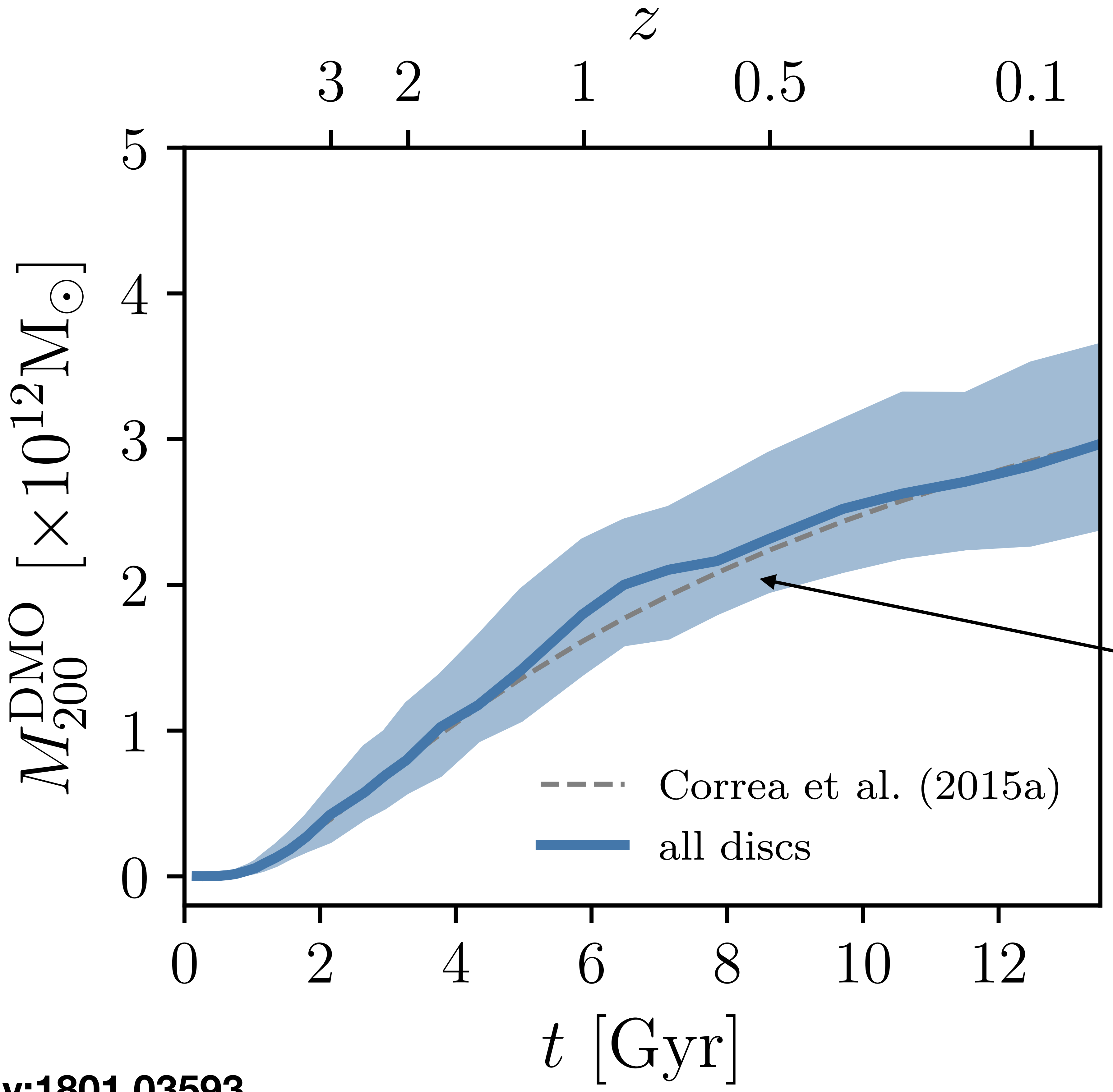
Galaxy [α/Fe] bimodality correlates with mass accretion history



median accretion history of all 133 MW stellar mass discs

analytic estimate for the median z=0 halo mass

Matched Haloes from Dark Matter only simulation!

arXiv:1801.03593

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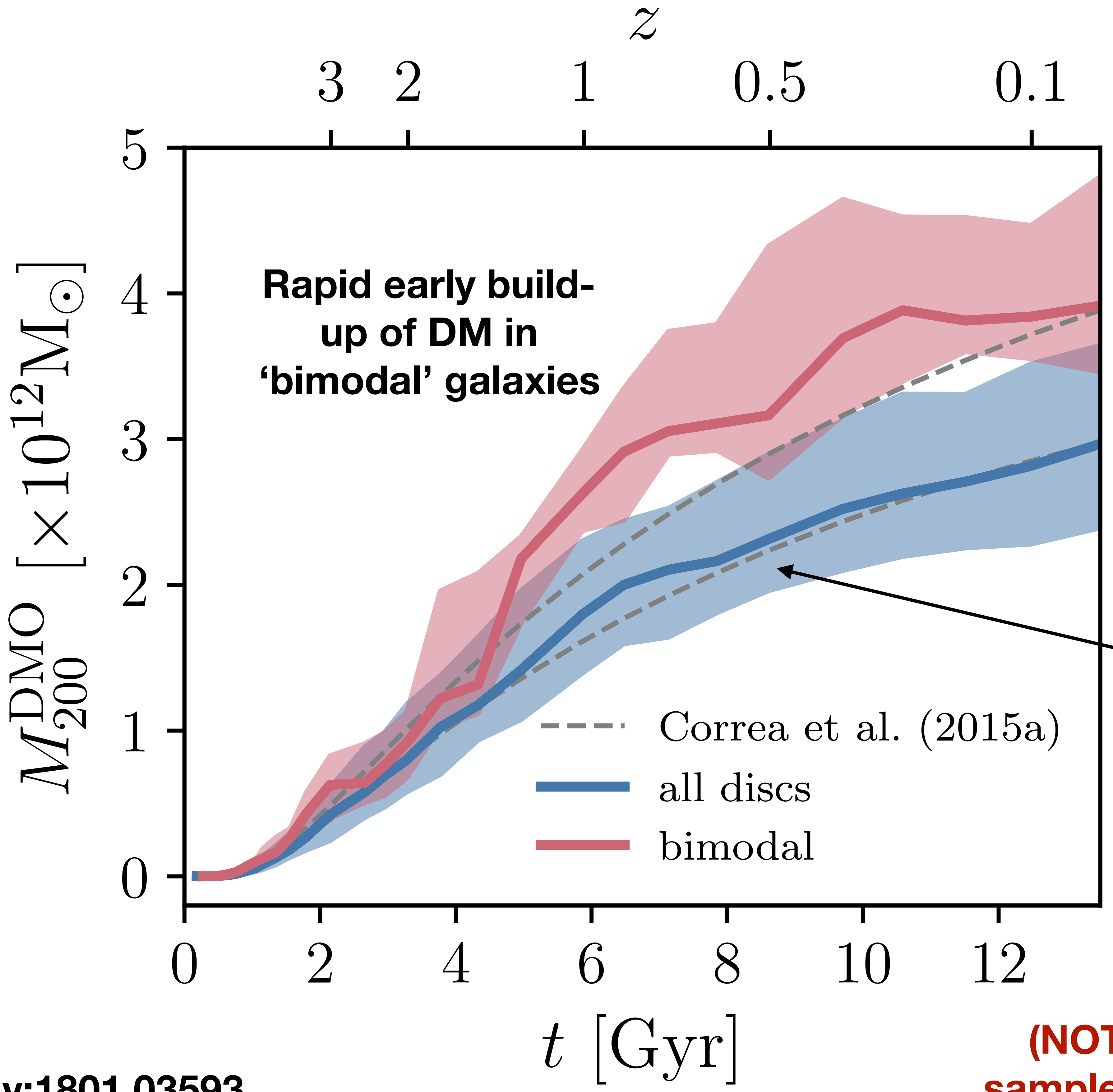

Rapid early build-up of DM in 'bimodal' galaxies

bimodal galaxies live in more massive haloes

median accretion history of all 133 MW stellar mass discs

analytic estimate for the median z=0 halo mass

(NOTE: halo mass matched sample shows similar deviation)

arXiv:1801.03593

EAGLE presents predictions for the Milky Way as a galaxy

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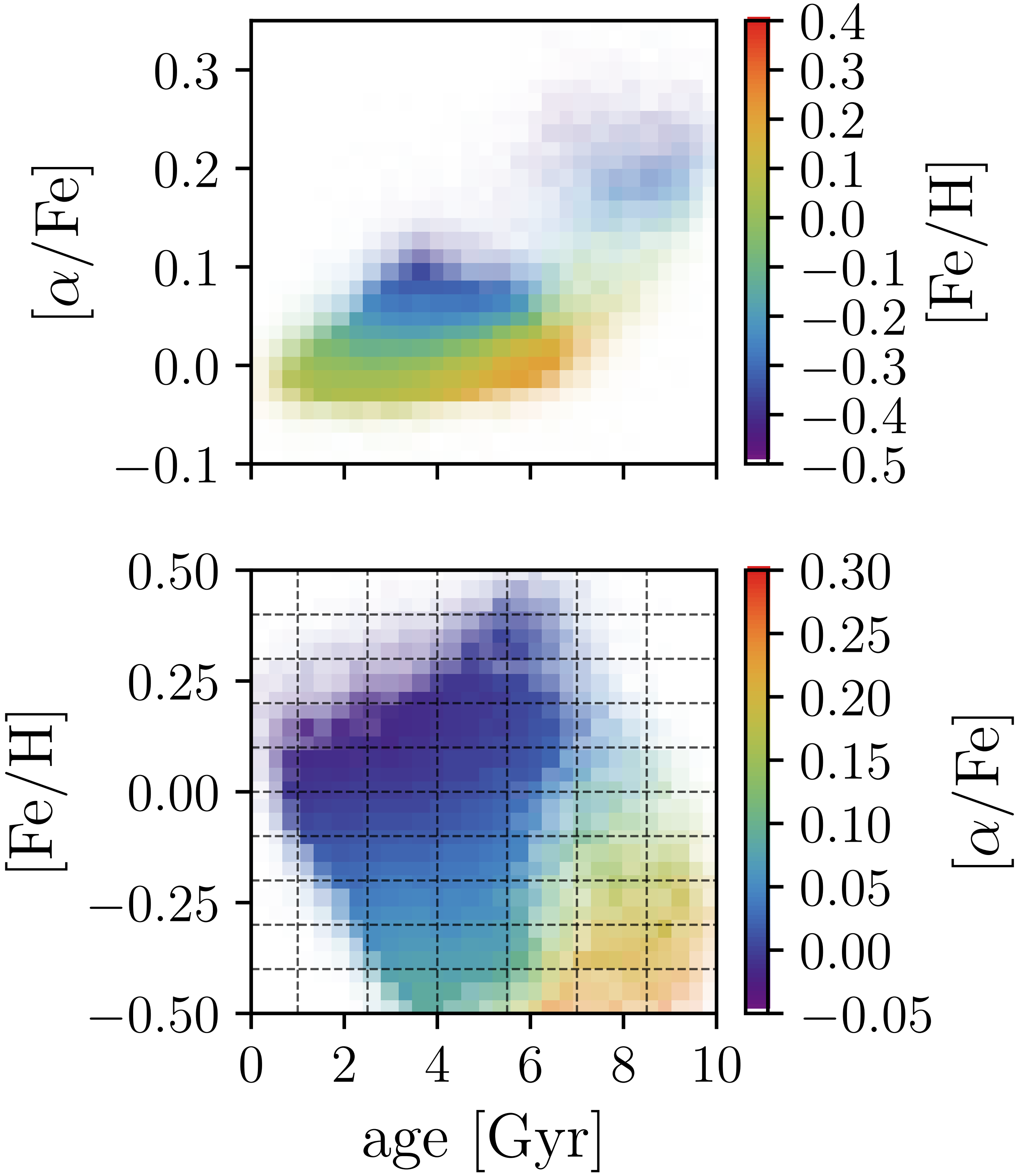
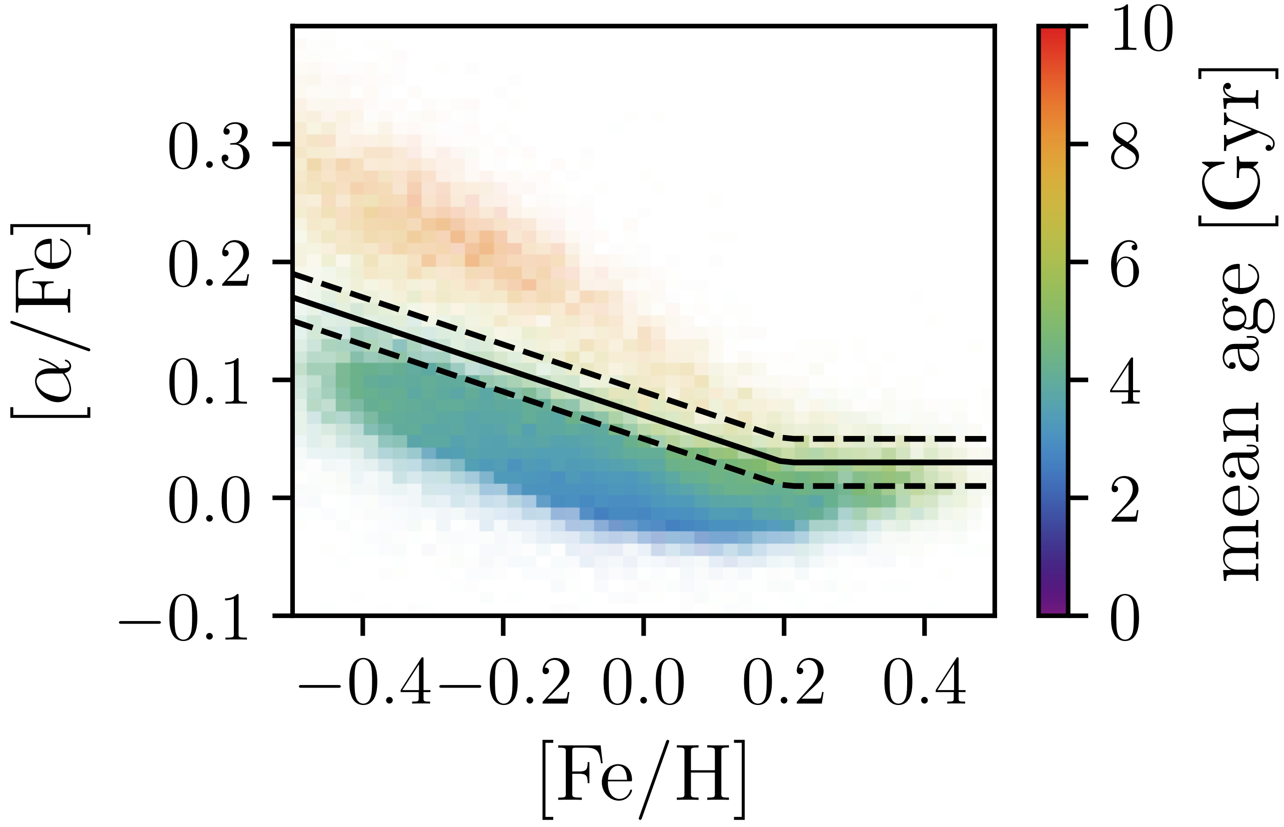
Mono-age, mono-[Fe/H] populations can disentangle processes of the Milky Way's formation



- extrapolate asteroseismic ages onto spectroscopic samples using Bayesian Neural Network

(implemented using astroNN, Leung & Bovy 2019a,b)

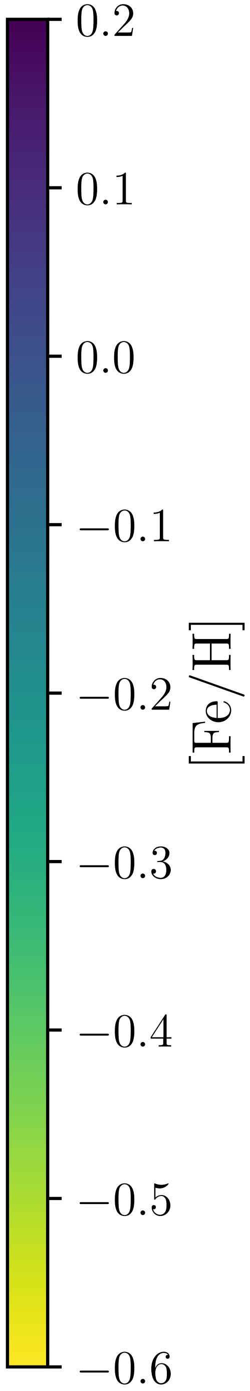
- unprecedented, *multi-dimensional* data-set



(low-[α/Fe])

`The Milky Way disk is made up of donuts’

Mackereth+ (2017)
arXiv: 1706.00018



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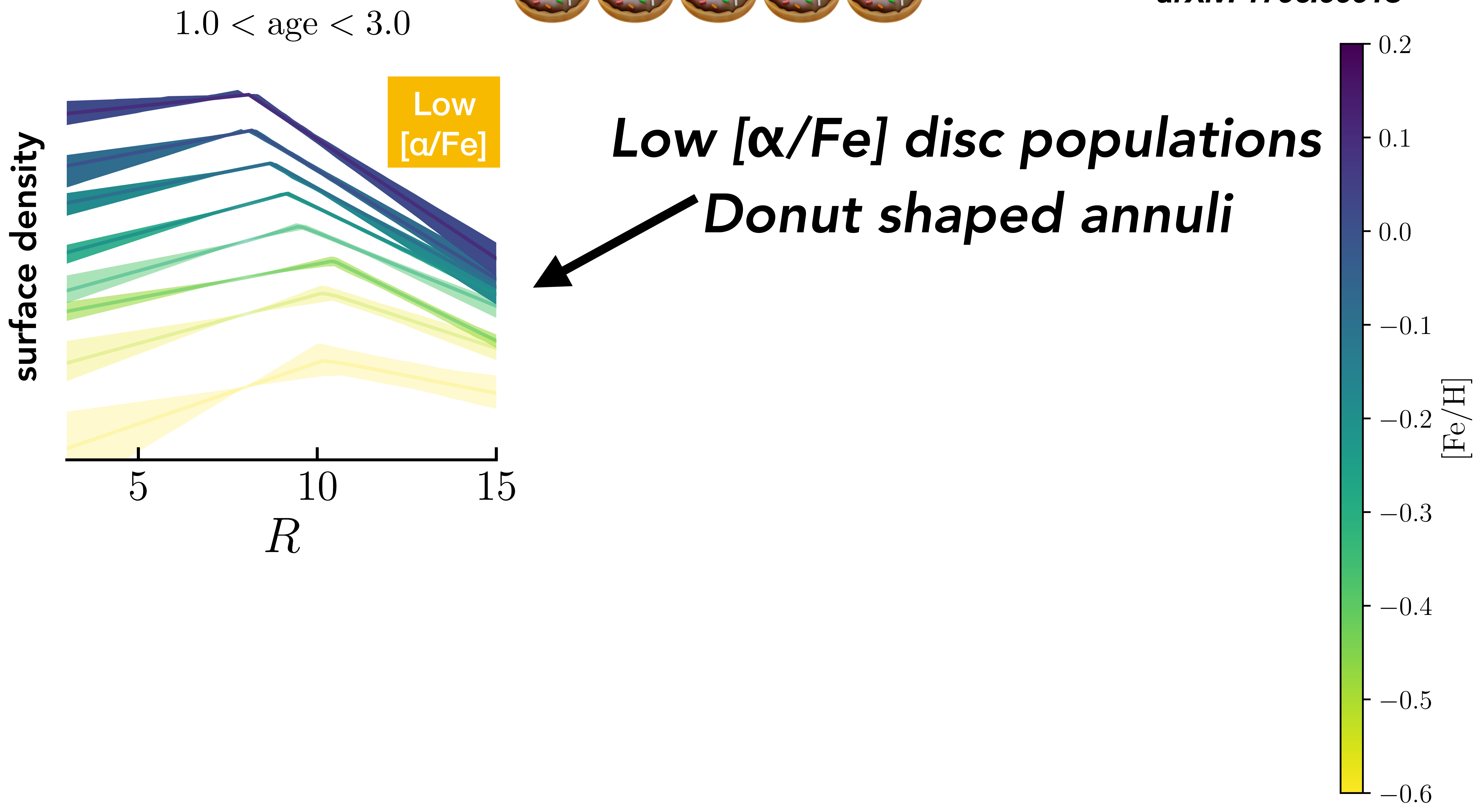

Low [α/Fe] disc populations
Donut shaped annuli

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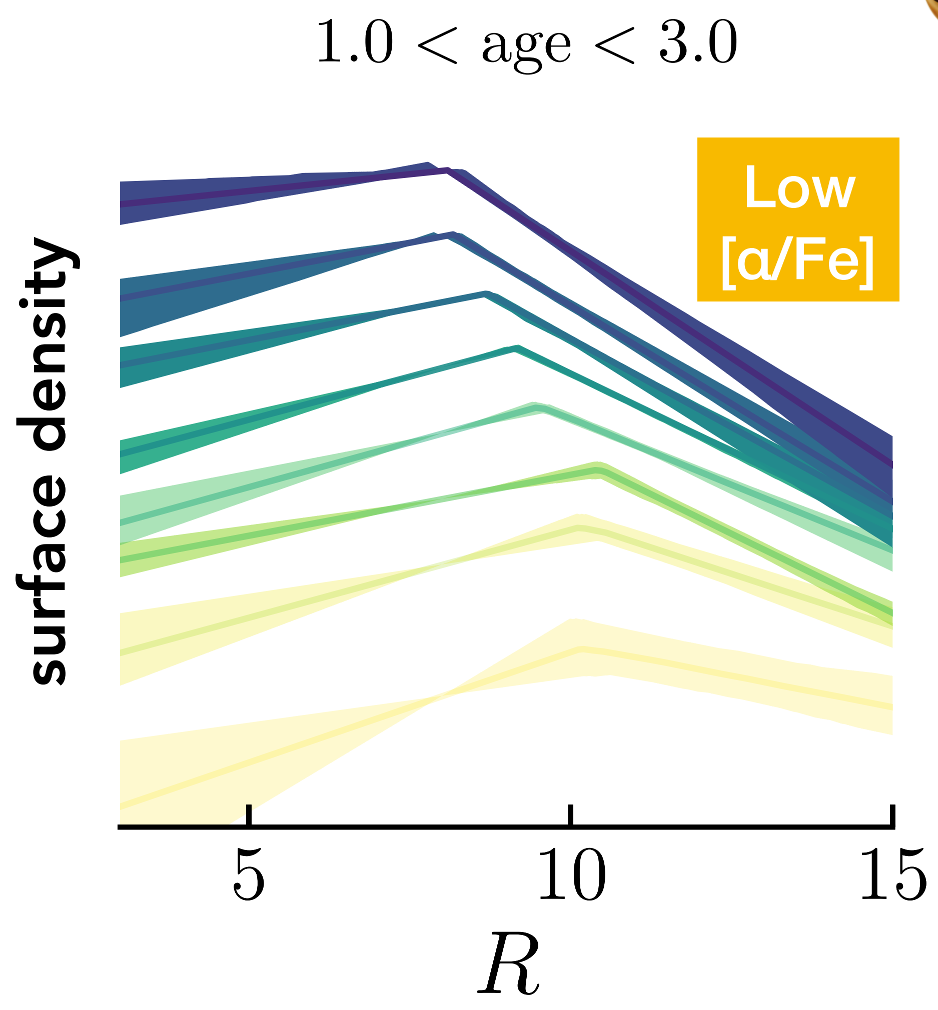

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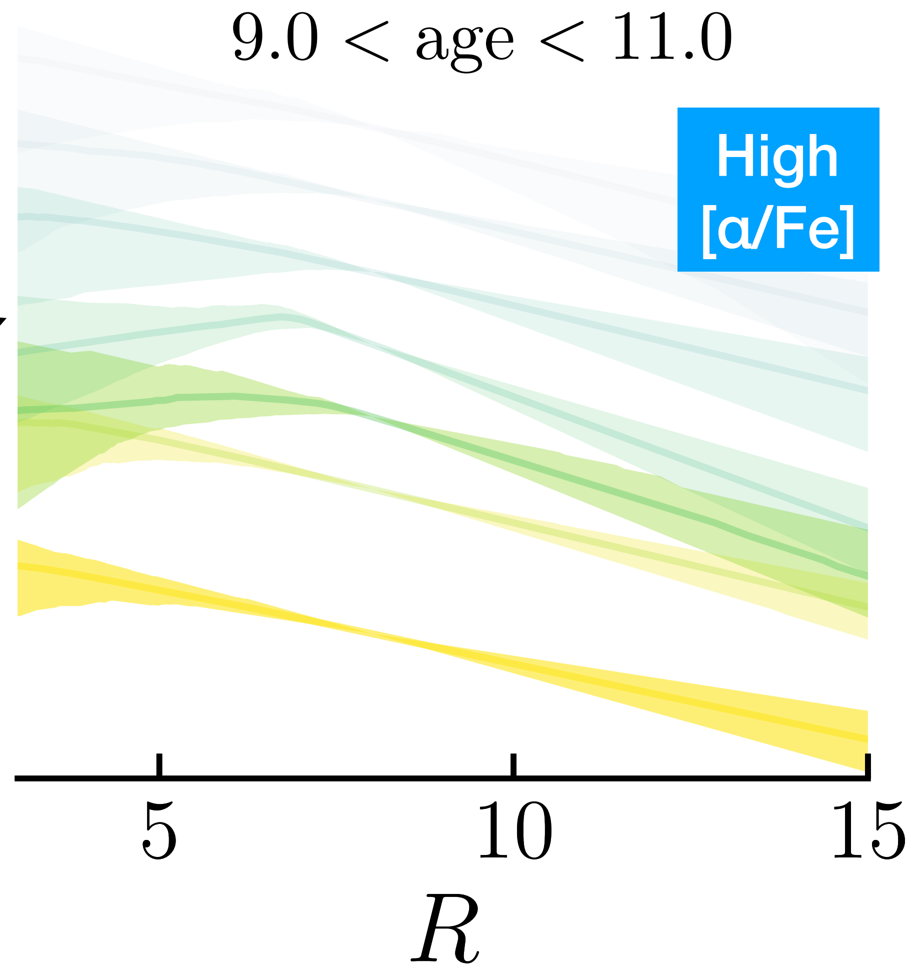

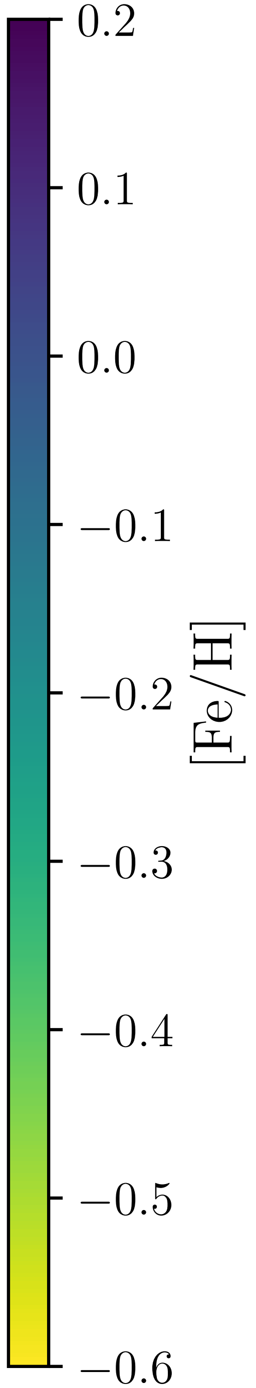

High [α/Fe] disc populations

No Donuts! Centrally concentrated....

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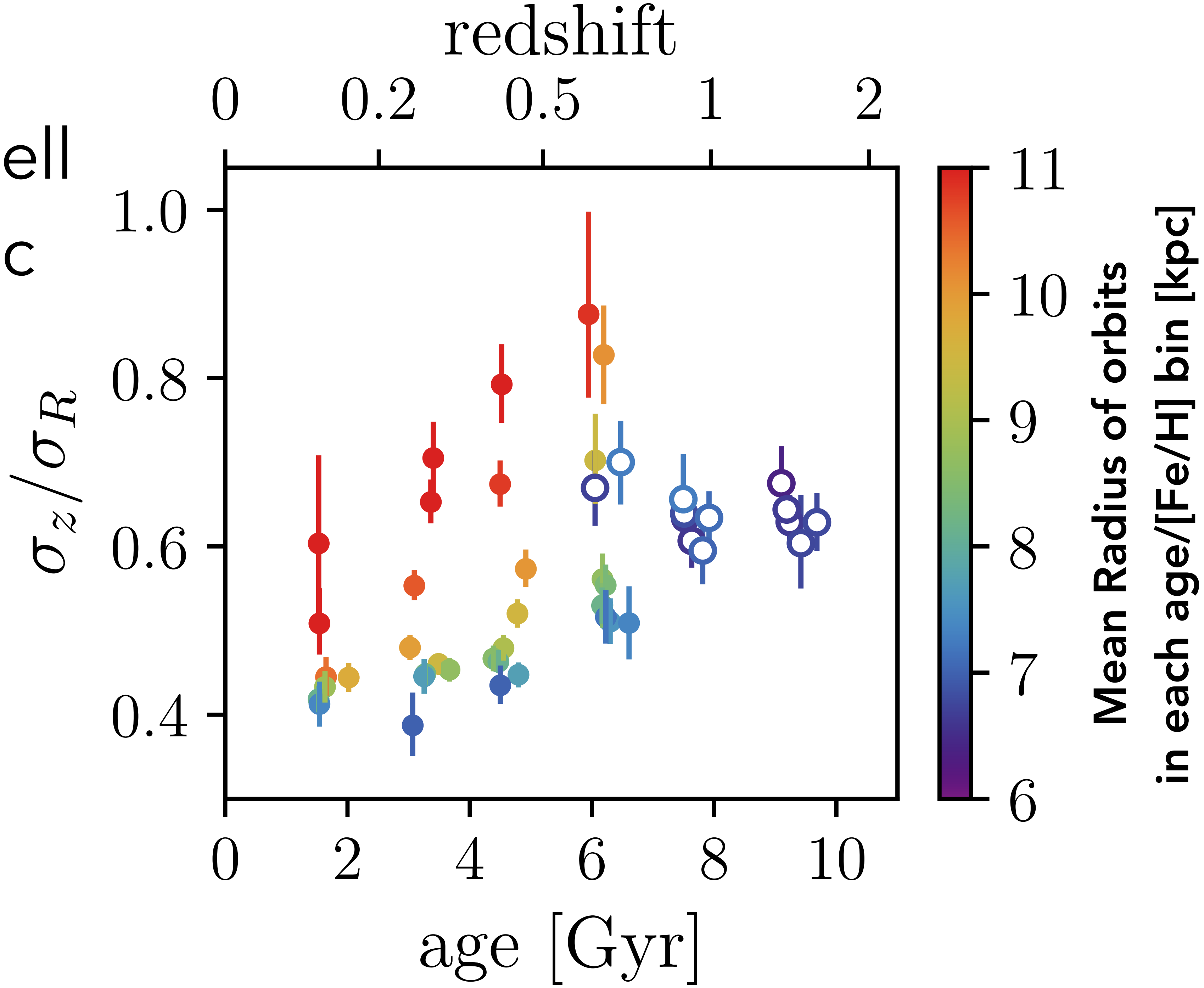
The kinematics of high and low [α/Fe] populations tell the story of the disc

Ratio of vertical to radial `heat'



Mackereth+ (2019b, submitted) arXiv: 1901.04502

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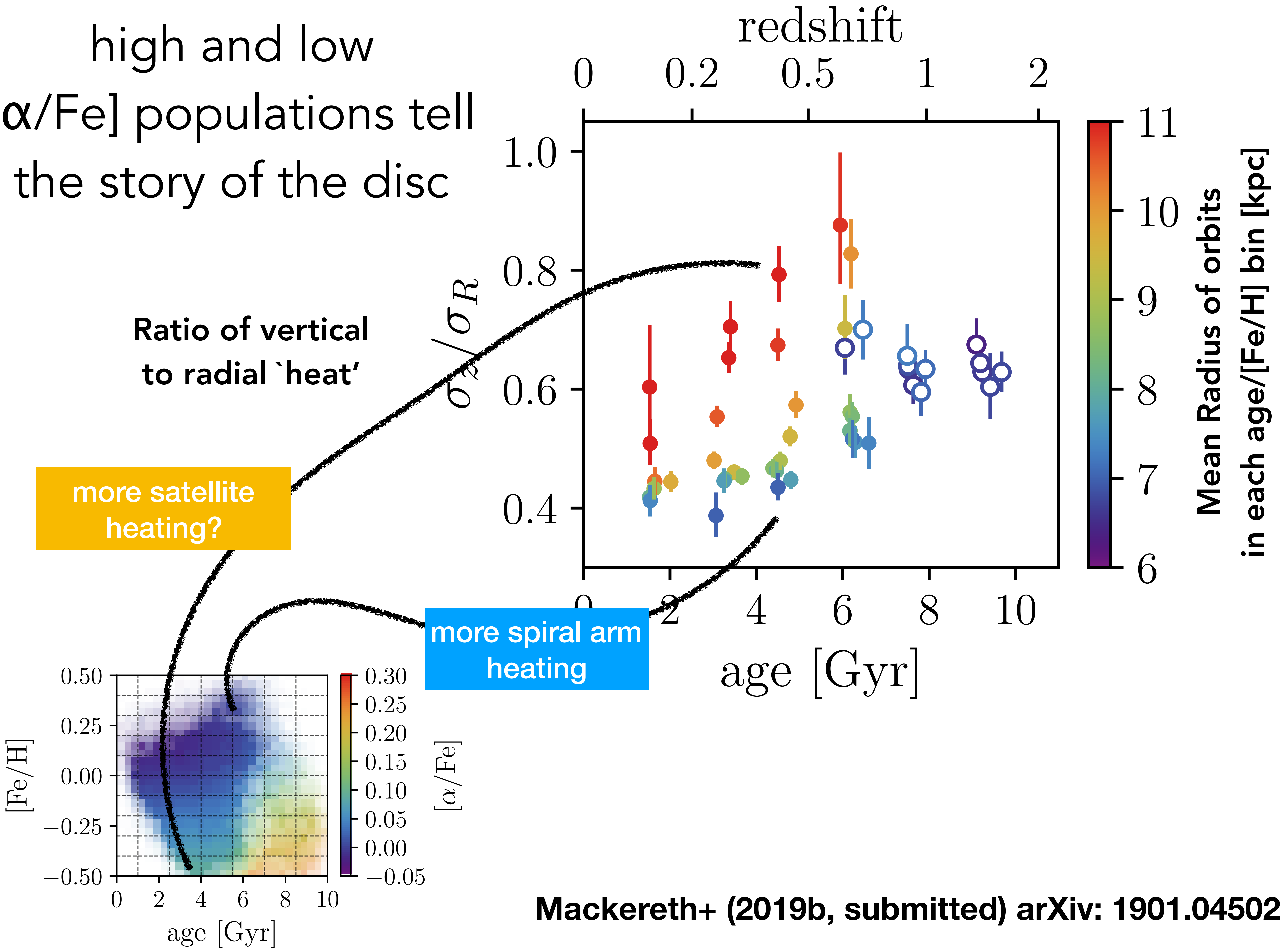

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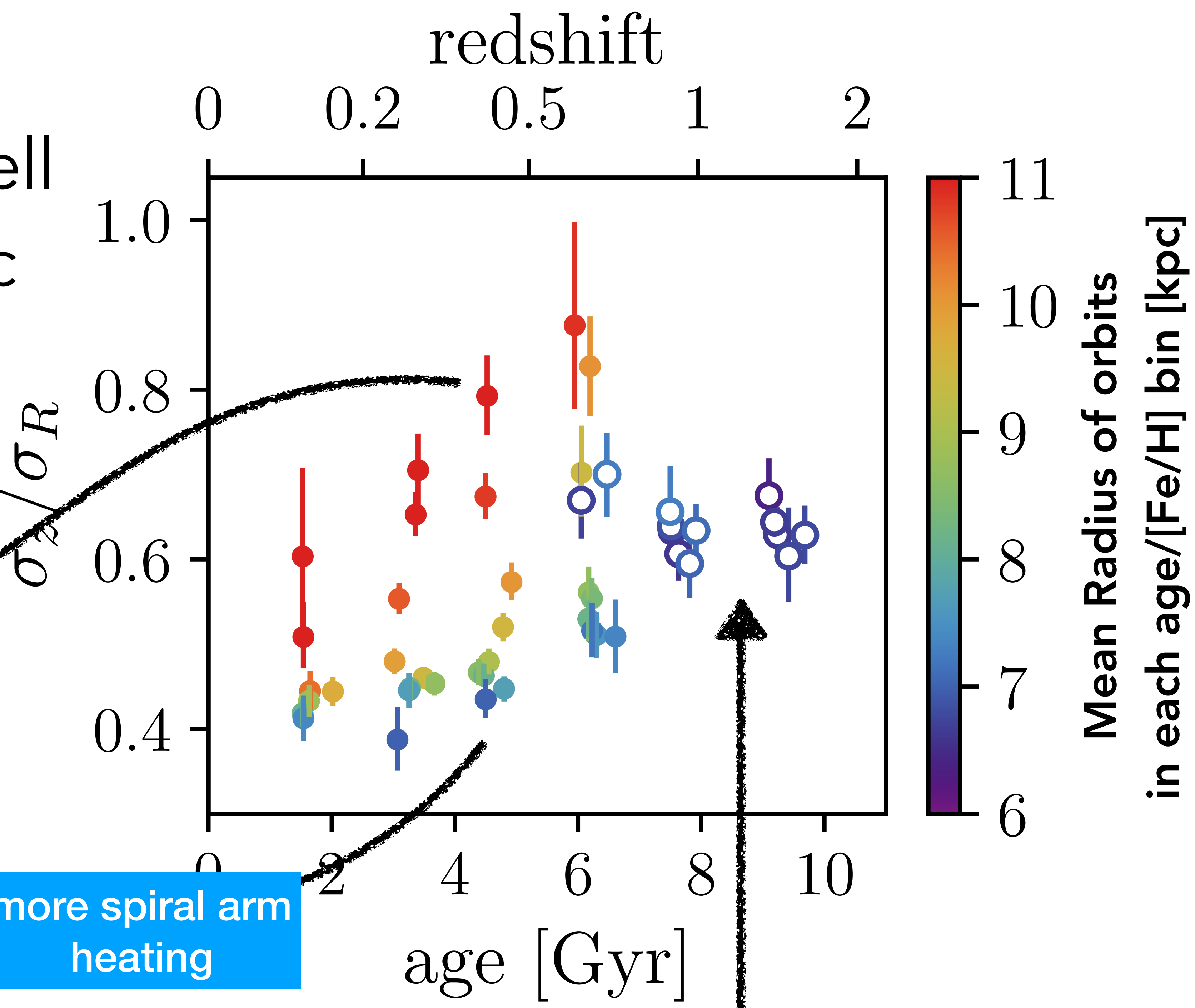

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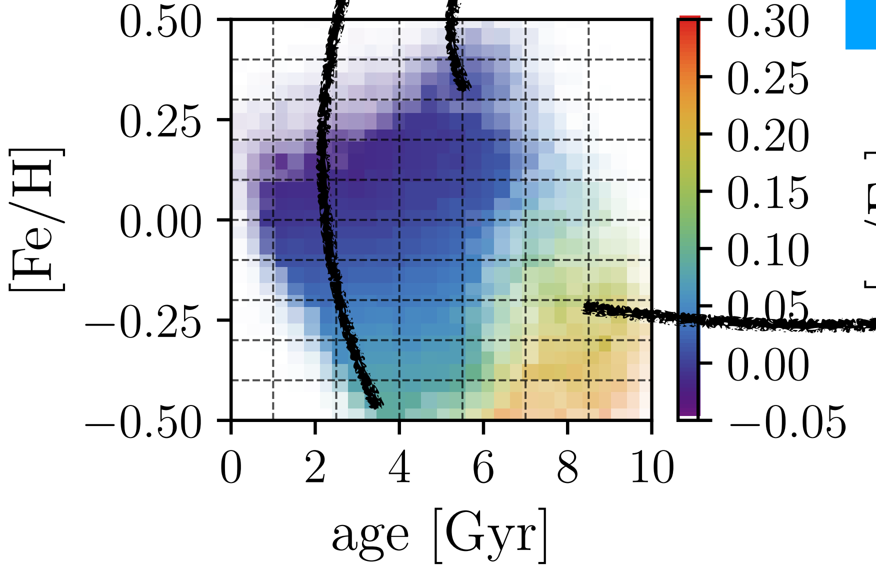
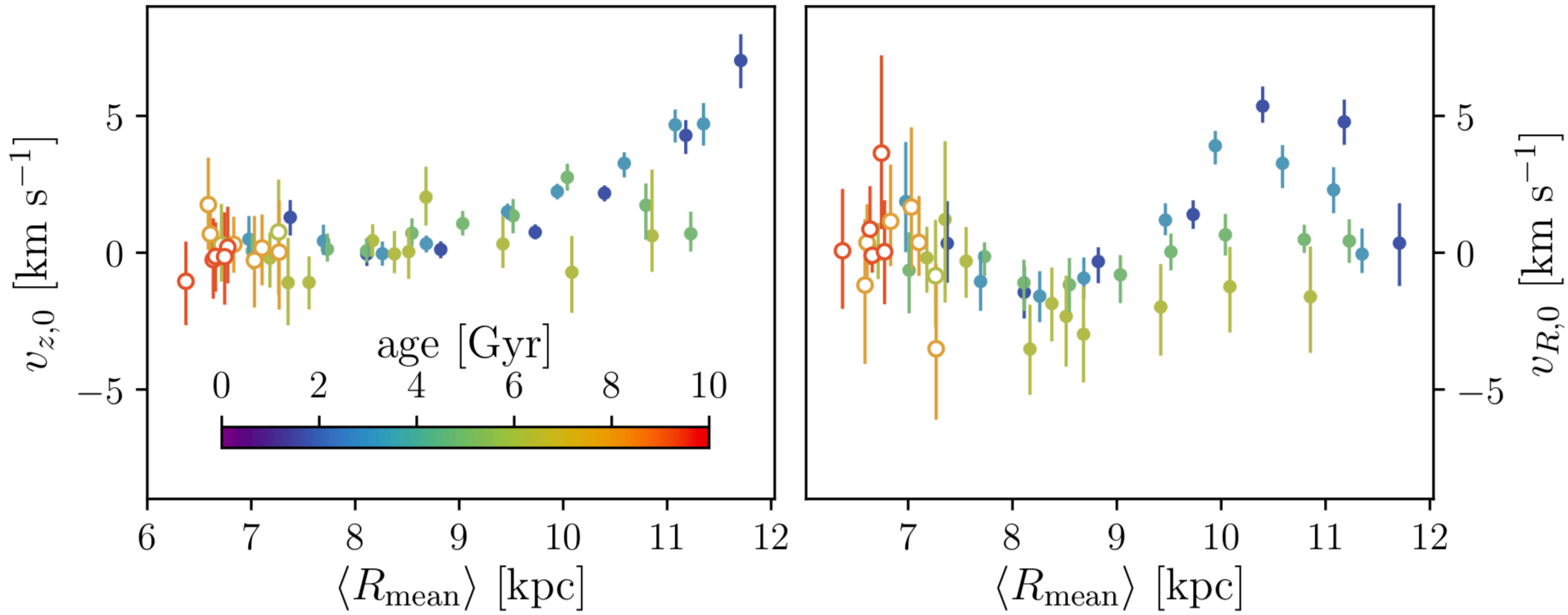


*High [**α**/Fe] population - different again!*

Mackereth+ (2019b, submitted) arXiv: 1901.04502

See also Laporte talk (and refs within!)



The low [α/Fe] population is warped

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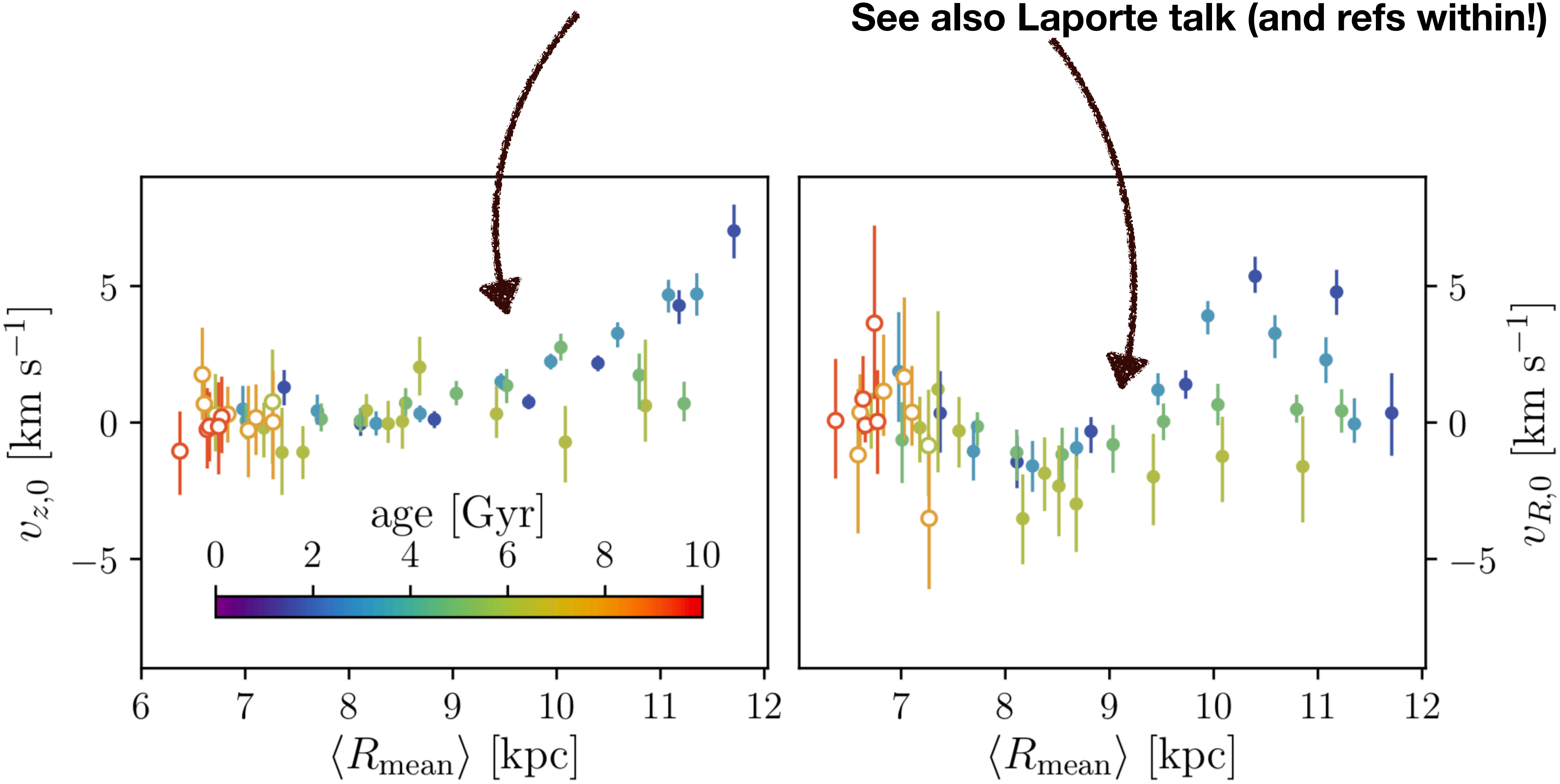

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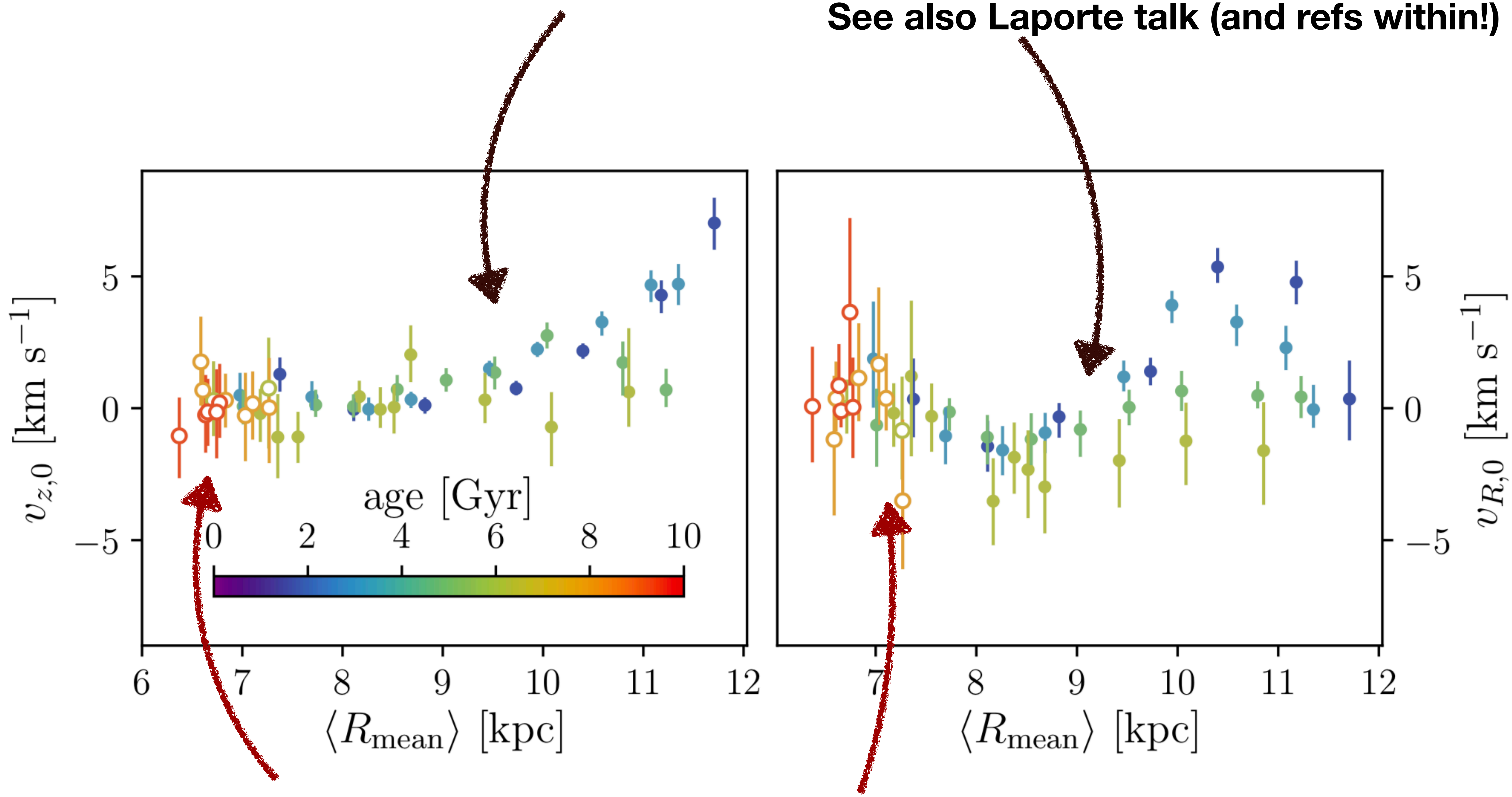

High [α/Fe] stars are clumped at a single mean velocity and radius

EAGLE presents predictions for the Milky Way as a galaxy

Galaxies that are chemically similar to the MW should be rare at its stellar mass

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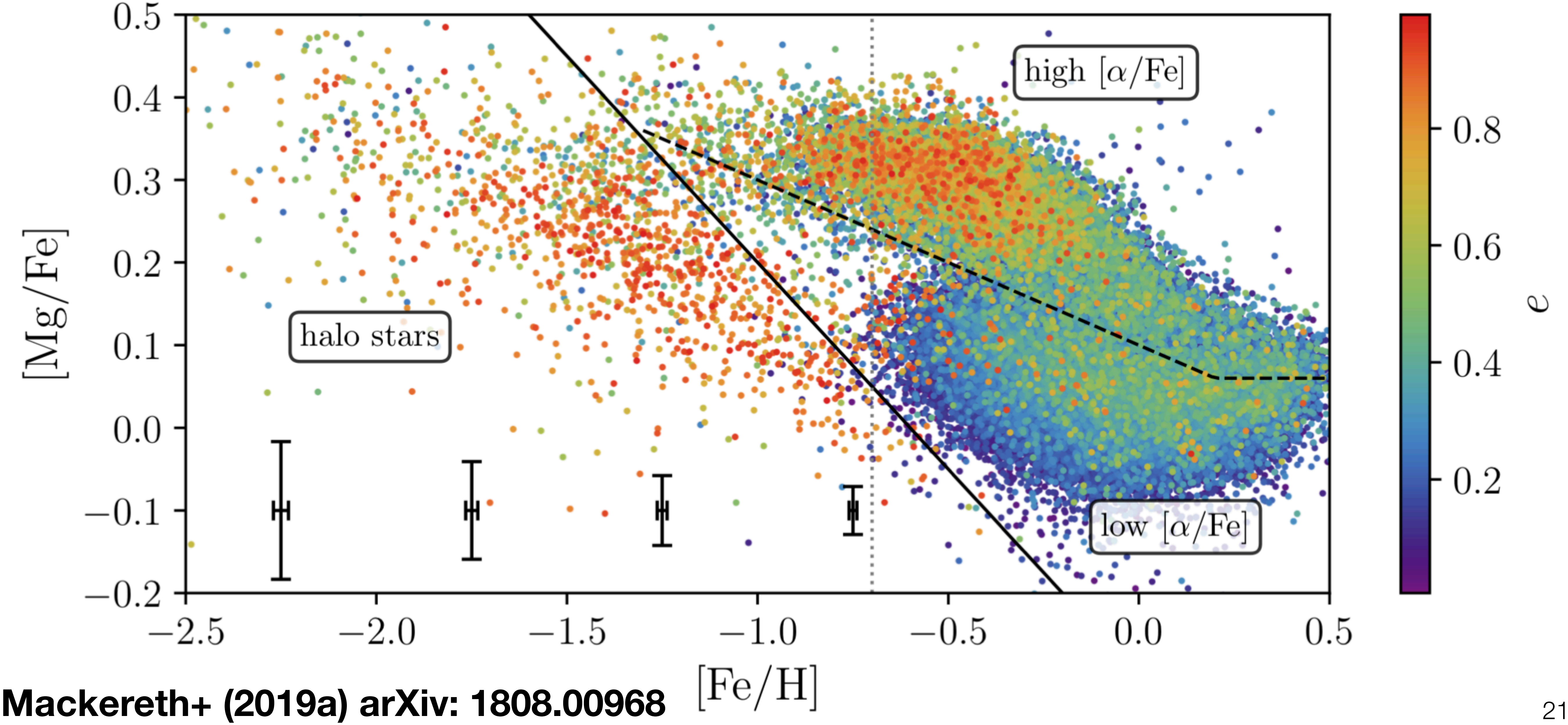
Element abundances reveal the remnants of the assembly of the Galaxy



Mackereth+ (2019a) arXiv: 1808.00968

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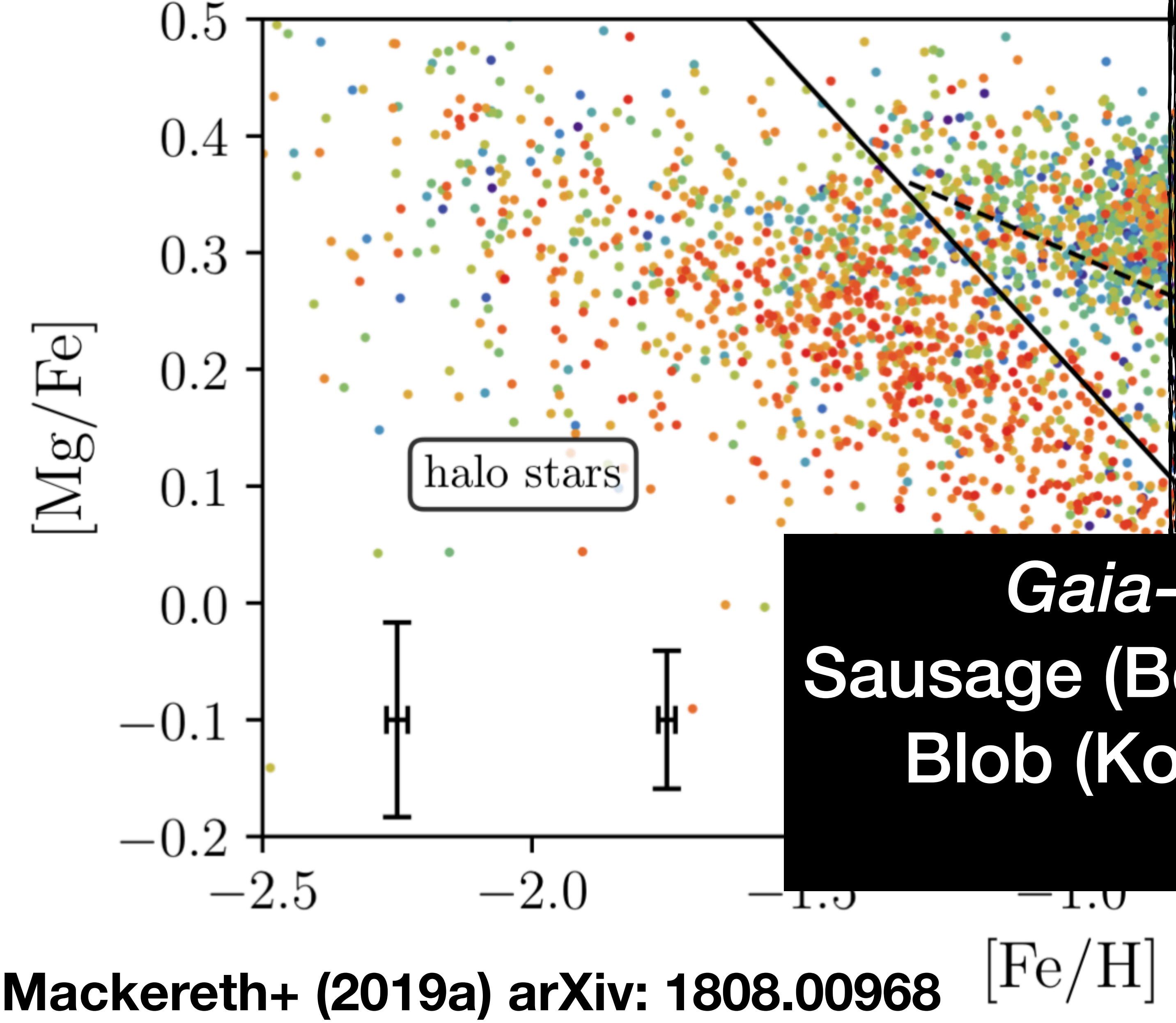
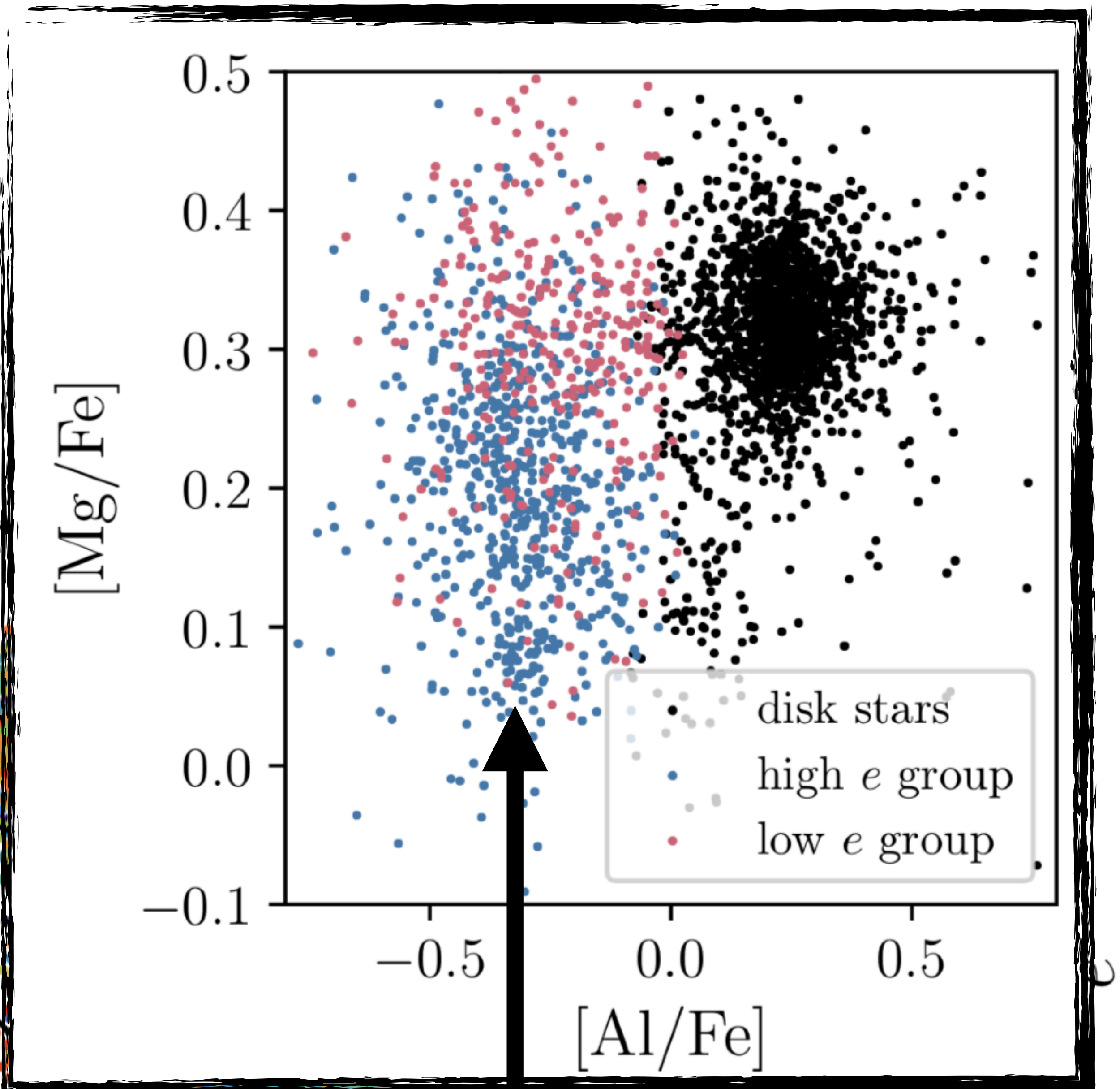


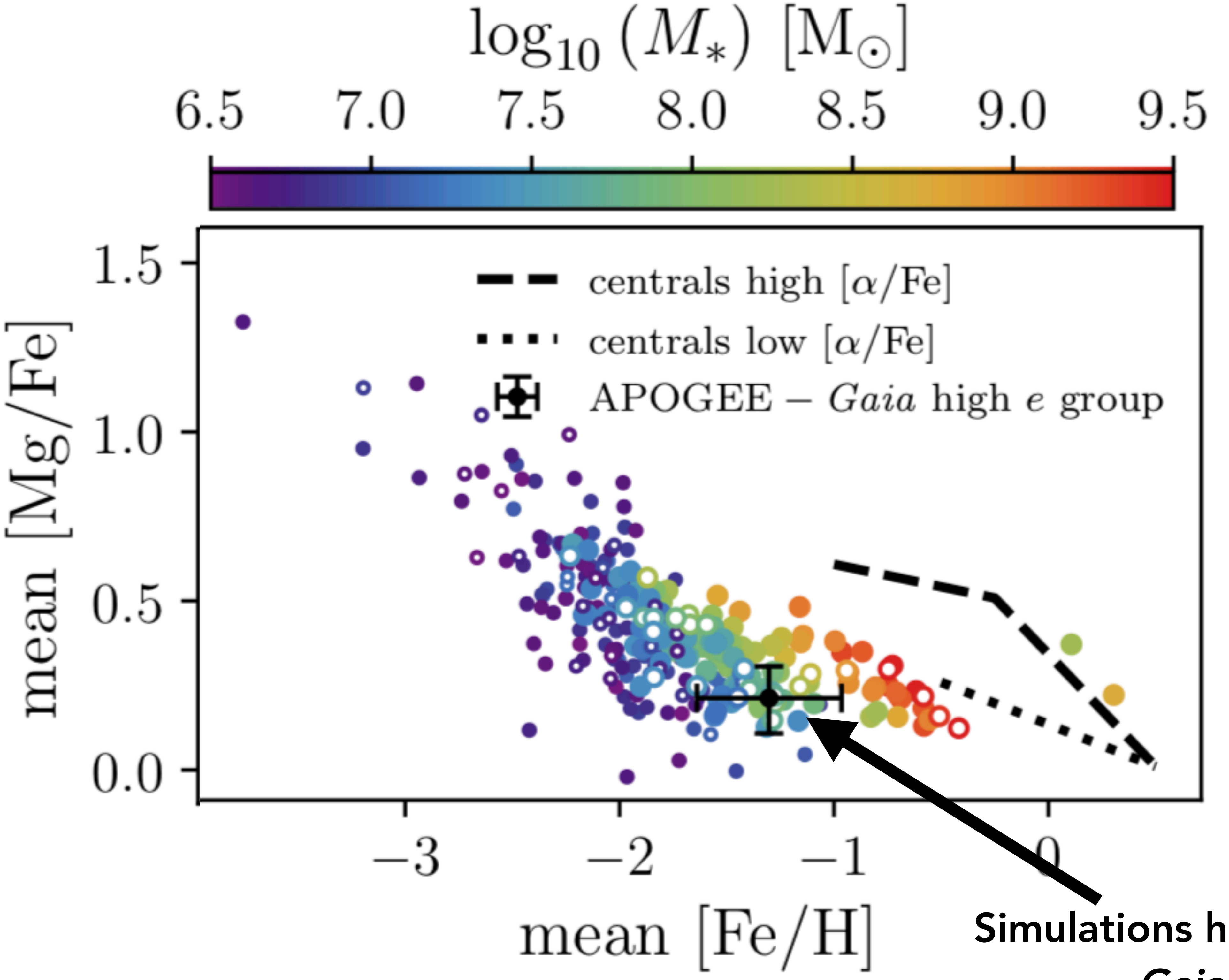
division in useful abundance plane from Hawkins+ (2015)



Gaia-Enceladus (Helmi+ 2018),
Sausage (Belokurov+ 2018, Myeong+2018),
Blob (Koppelman+ 2018, Das+ 2019),
Jeff?

Mackereth+ (2019a) arXiv: 1808.00968

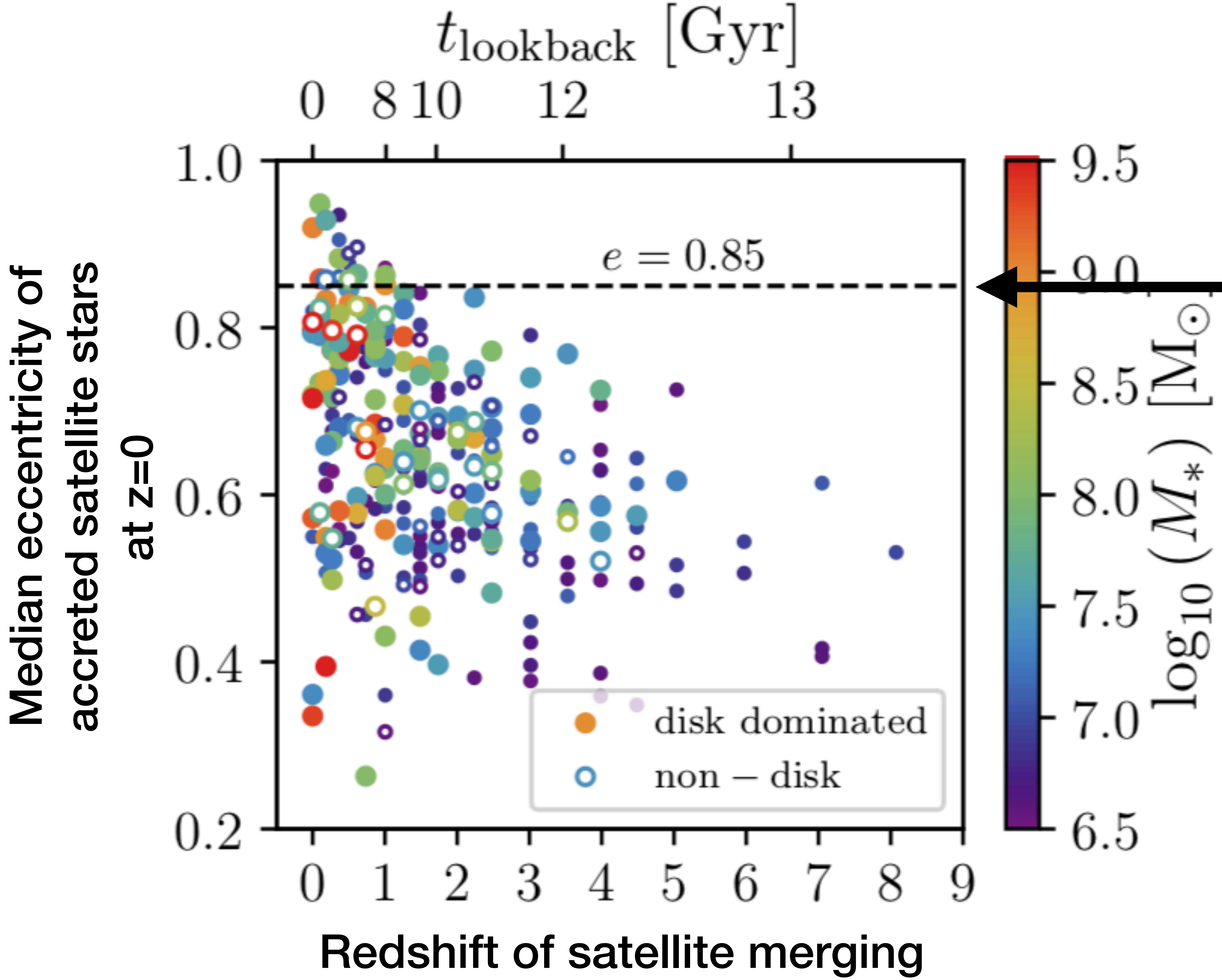
Element abundances of EAGLE satellites match those seen in the Milky Way



Simulations help predict mass of *Gaia*-Enceladus

arXiv: 1808.00968

High-eccentricity satellite debris is *rare* in EAGLE



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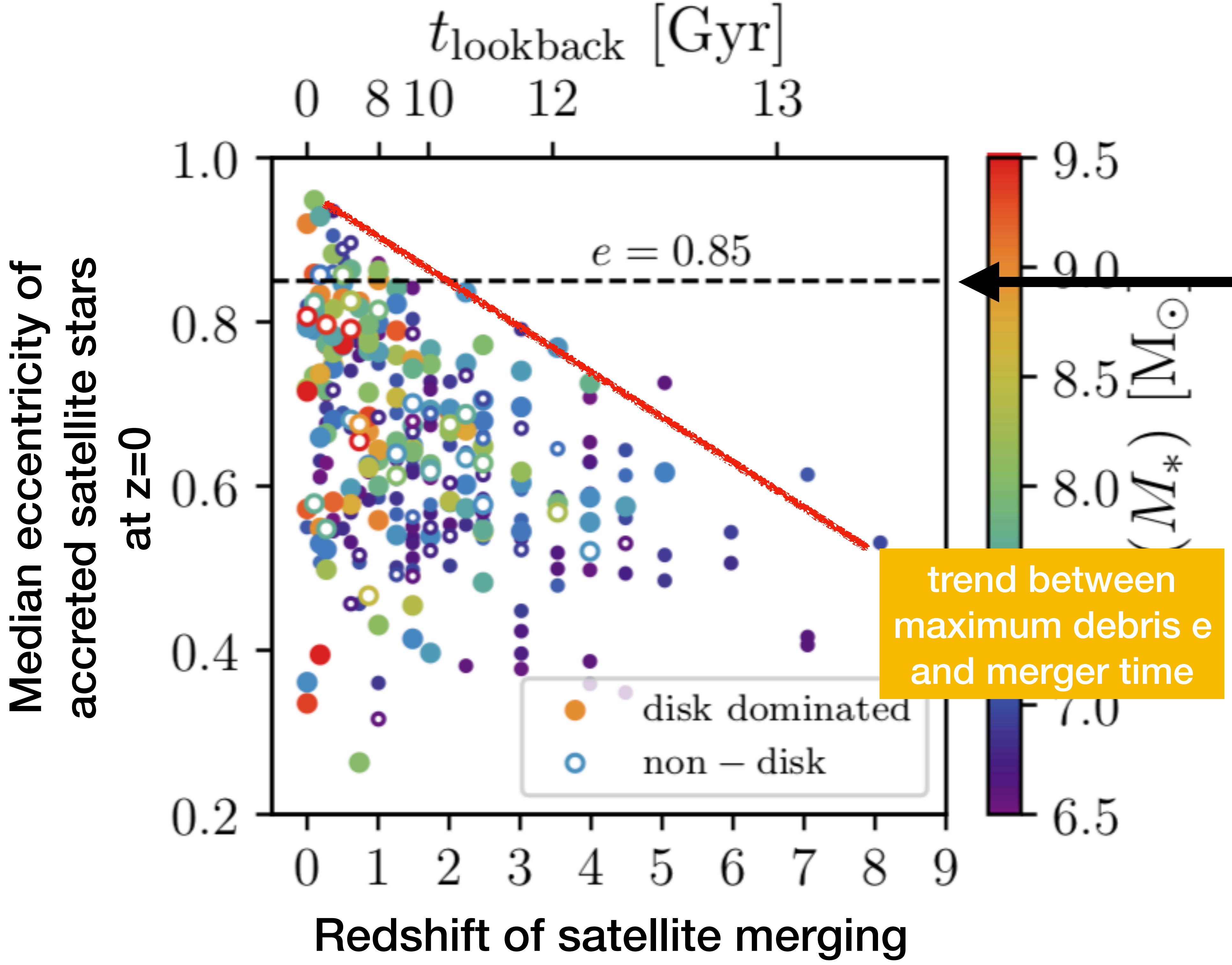

Gaia-Enceladus Eccentricity

trend between maximum debris e and merger time

arXiv: 1808.00968

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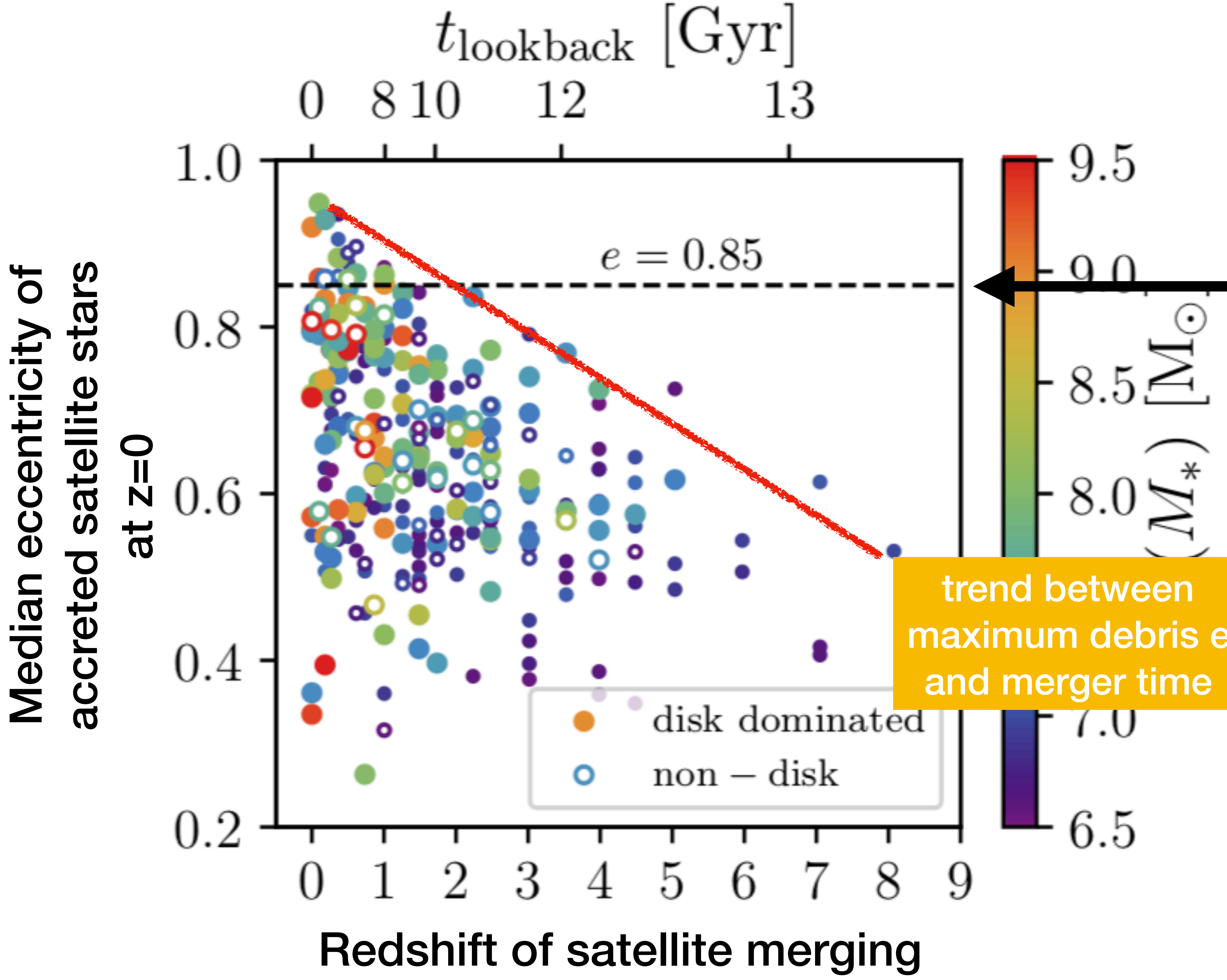

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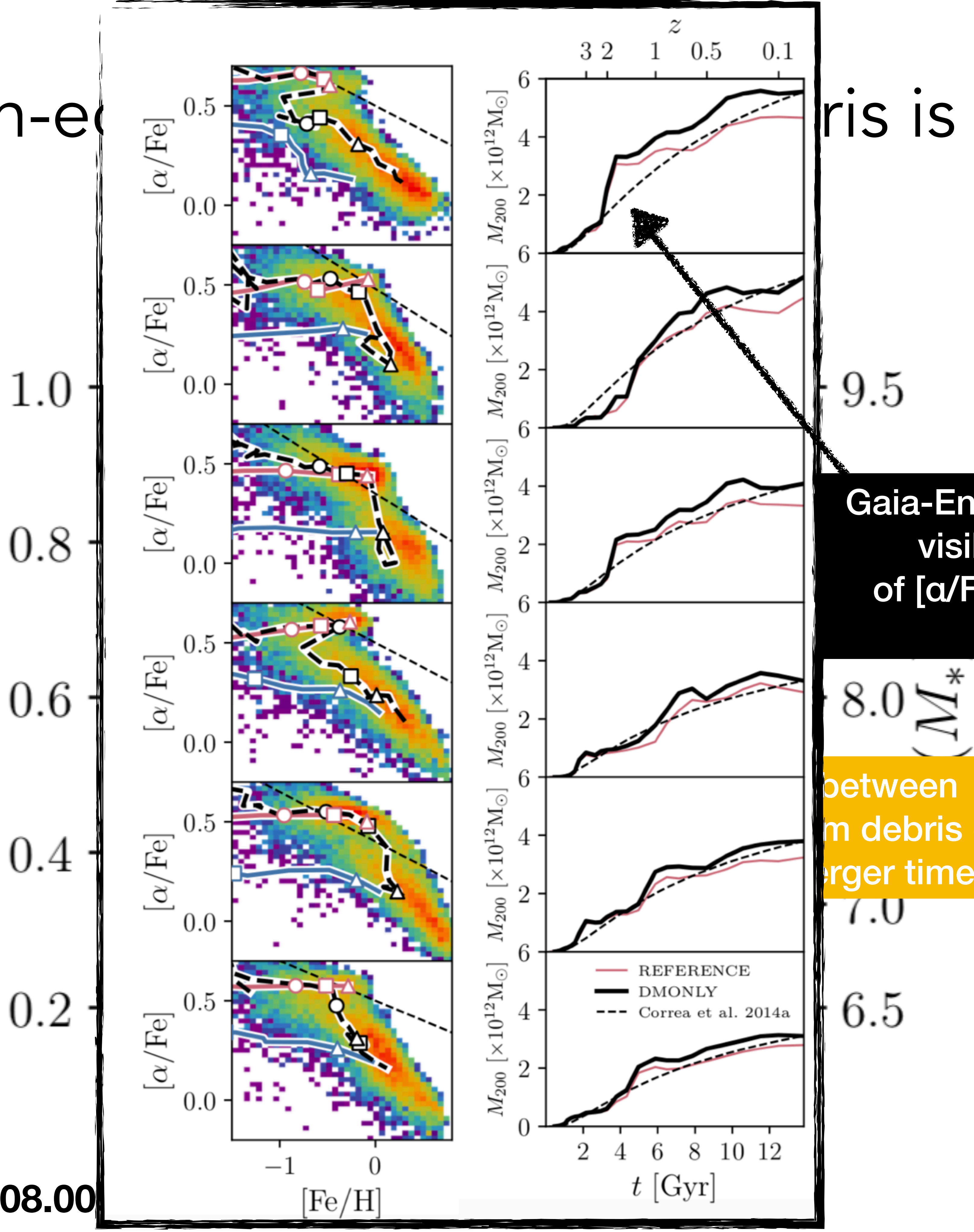
Halo growth dictates the maximum eccentricity of accreted debris?

arXiv: 1808.00968

High-ec ris is *rare* in EAGLE



Gaia-Enceladus-esque Mergers visible in DM accretion of [α/Fe] bimodal galaxies in EAGLE?

between
m debris e
erger time

Halo growth dictates the maximum eccentricity of accreted debris?

arXiv: 1808.00

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Simulations present a model for [α/Fe] bimodality *at fixed [Fe/H]* that suggests the Milky Way had a **more intense early history** than its similar mass disc galaxy counterparts

The (qualitative) prediction of this model is that the high [α/Fe] component should be very different in structure and kinematics and this is **consistent with observations**

If this model of the Milky Way is correct, then it had an **atypically rapid build up of dark matter at early times**

Gaia is beginning to reveal that this may be the case - but how can we ***extend the predictions to the extra-galactic?***

EAGLE [α/Fe] origins: 1801.03593
APOGEE disk structure: 1706.00018
APOGEE disk kinematics: 1901.04502
***Gaia*-Enceladus in APOGEE/EAGLE: 1808.00968**

Thank you!

@ted_mackereth