



APOGEE

Ricardo Schiavon
IAUS 395, Paraty, 20/11/2024

© 2MASS, IPAC/Caltech & U Mass
© 2000, Axel Mellinger

IAU Angra dos Reis, 1991



APACHE POINT OBSERVATORY GALACTIC EVOLUTION EXPERIMENT

2.5 m SDSS telescope at
Apache Point Observatory



2.5 m du Pont telescope at
Las Campanas Observatory

A dual hemisphere spectroscopic survey of Milky Way stellar populations
PI: Steve Majewski

APOGEE SCIENTIFIC FOOTPRINT

- Galactic Archaeology (MW, Local Group)
- Stellar clusters (globular and open)
- Stars (single and binary)
- Interstellar medium
- Substellar components
- Spectral analysis

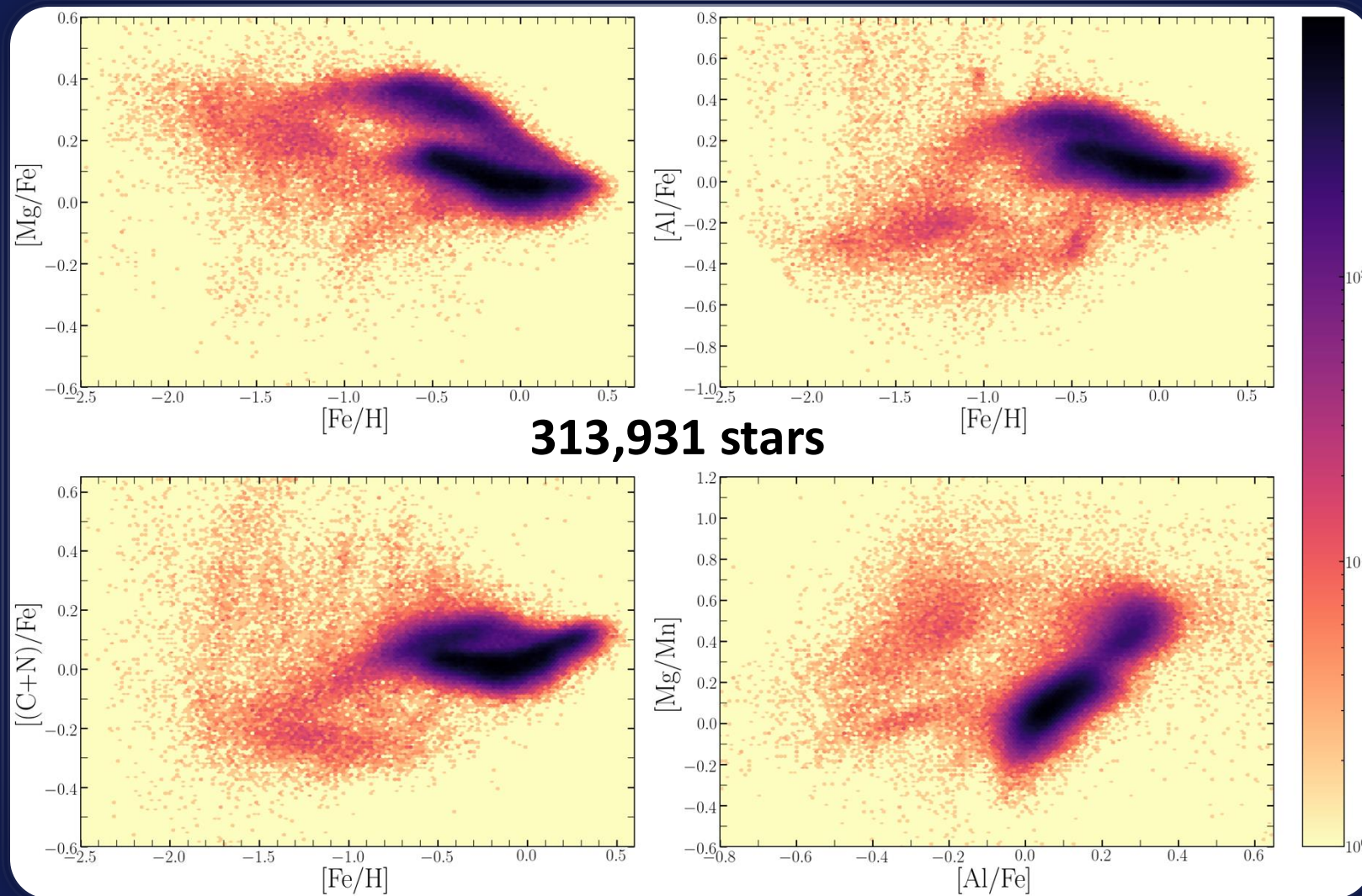
APOGEE SCIENTIFIC FOOTPRINT

- Galactic Archaeology (MW, Local Group)
- Stellar clusters (globular)
- Stars (single and binary)
- Interstellar medium
- Substellar components
- Spectral analysis

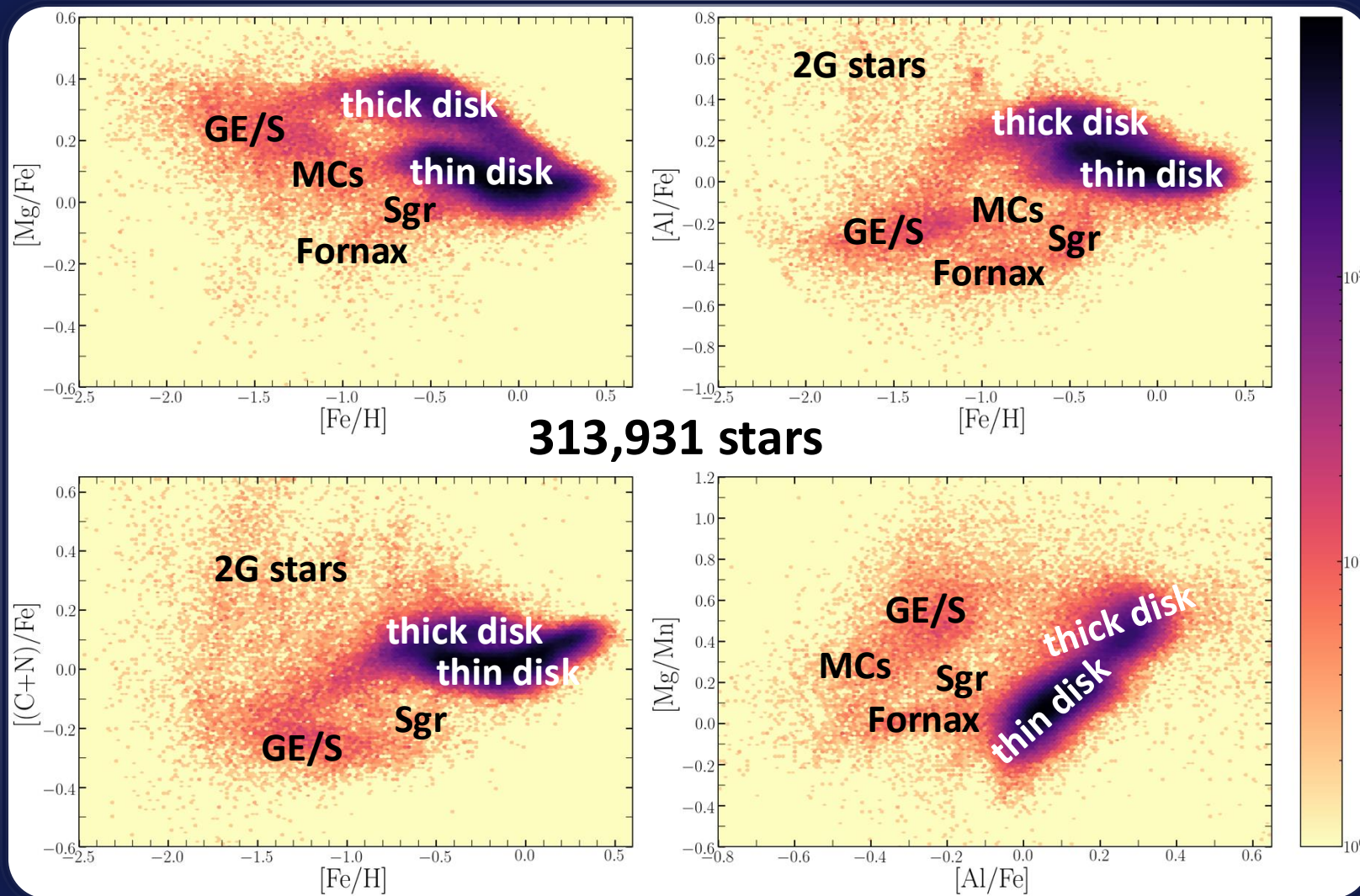
WHY APOGEE STANDS OUT

- R = 23,000, high S/N
- Near Infrared & Dual hemisphere
 - 500,000 giants

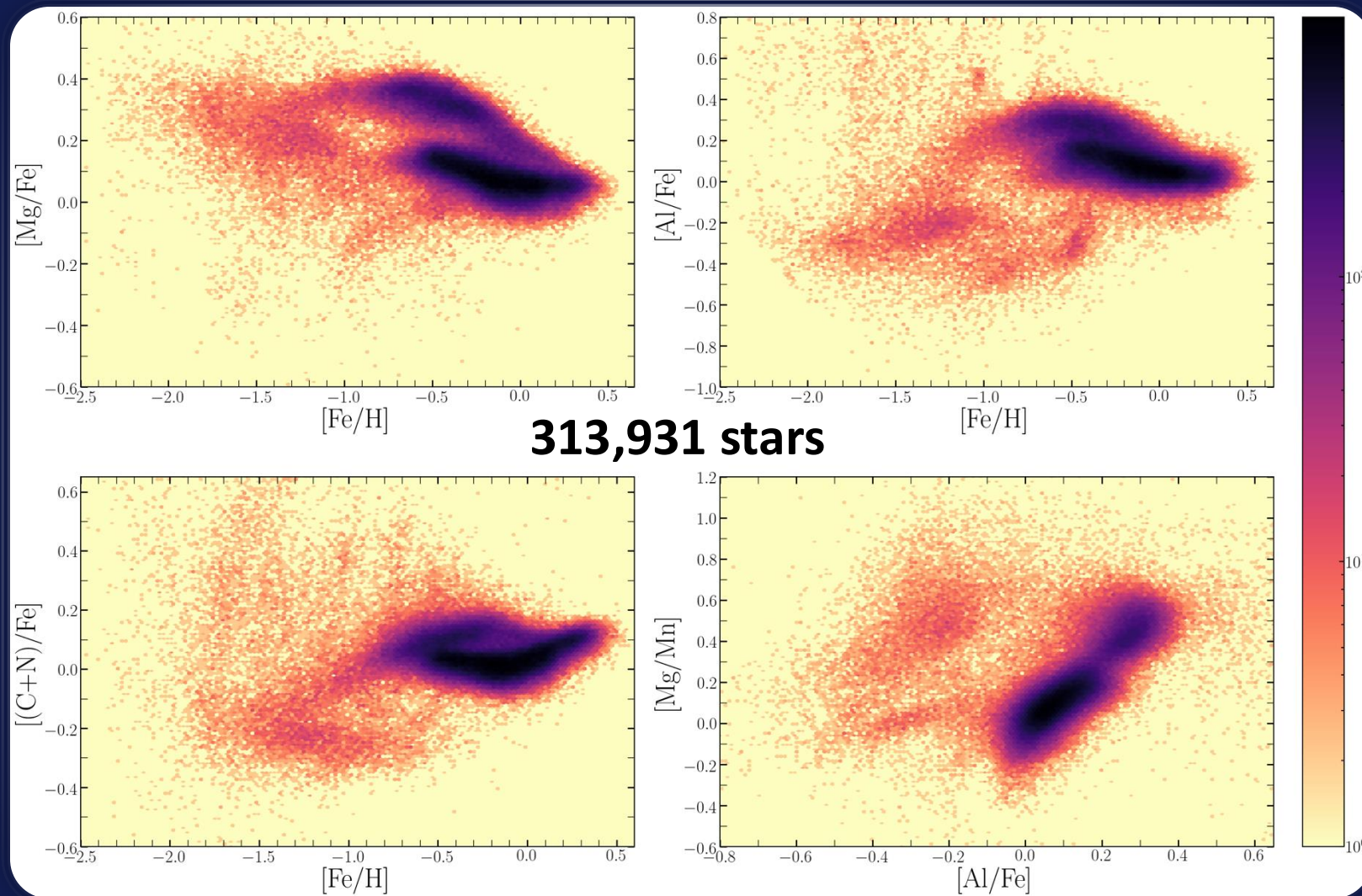
PRECISION ABUNDANCES



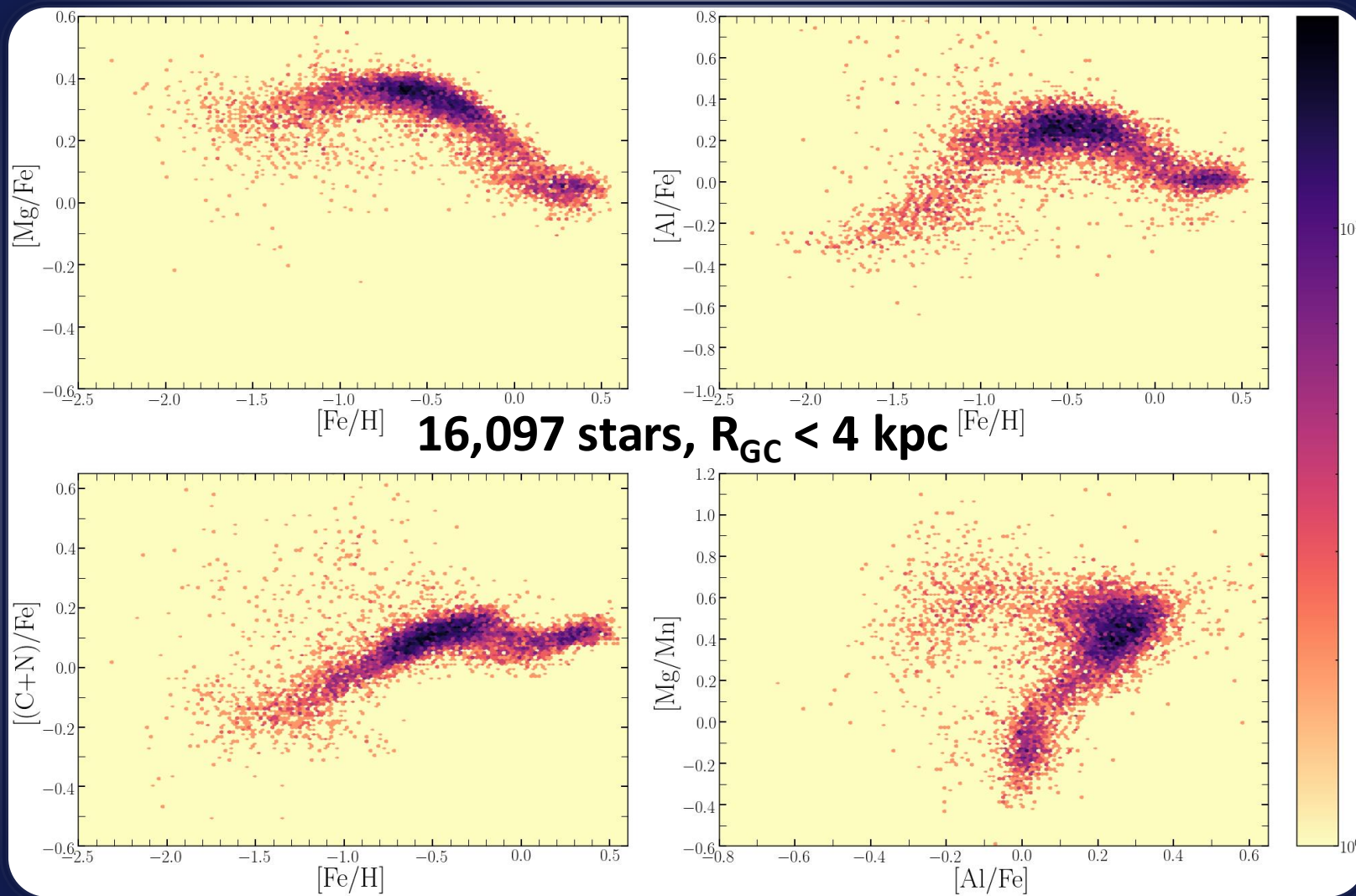
PRECISION ABUNDANCES



PRECISION ABUNDANCES



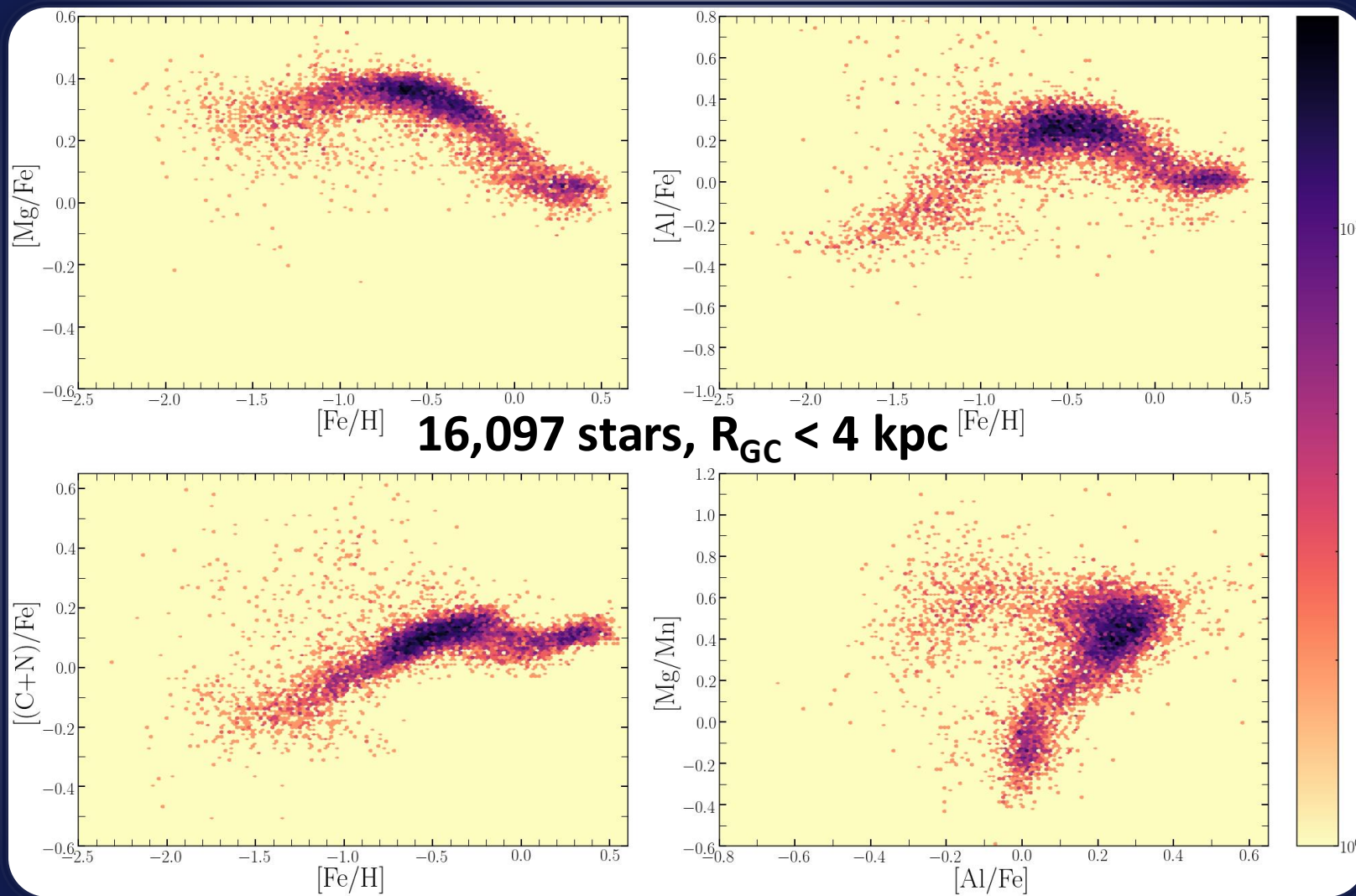
PRECISION ABUNDANCES



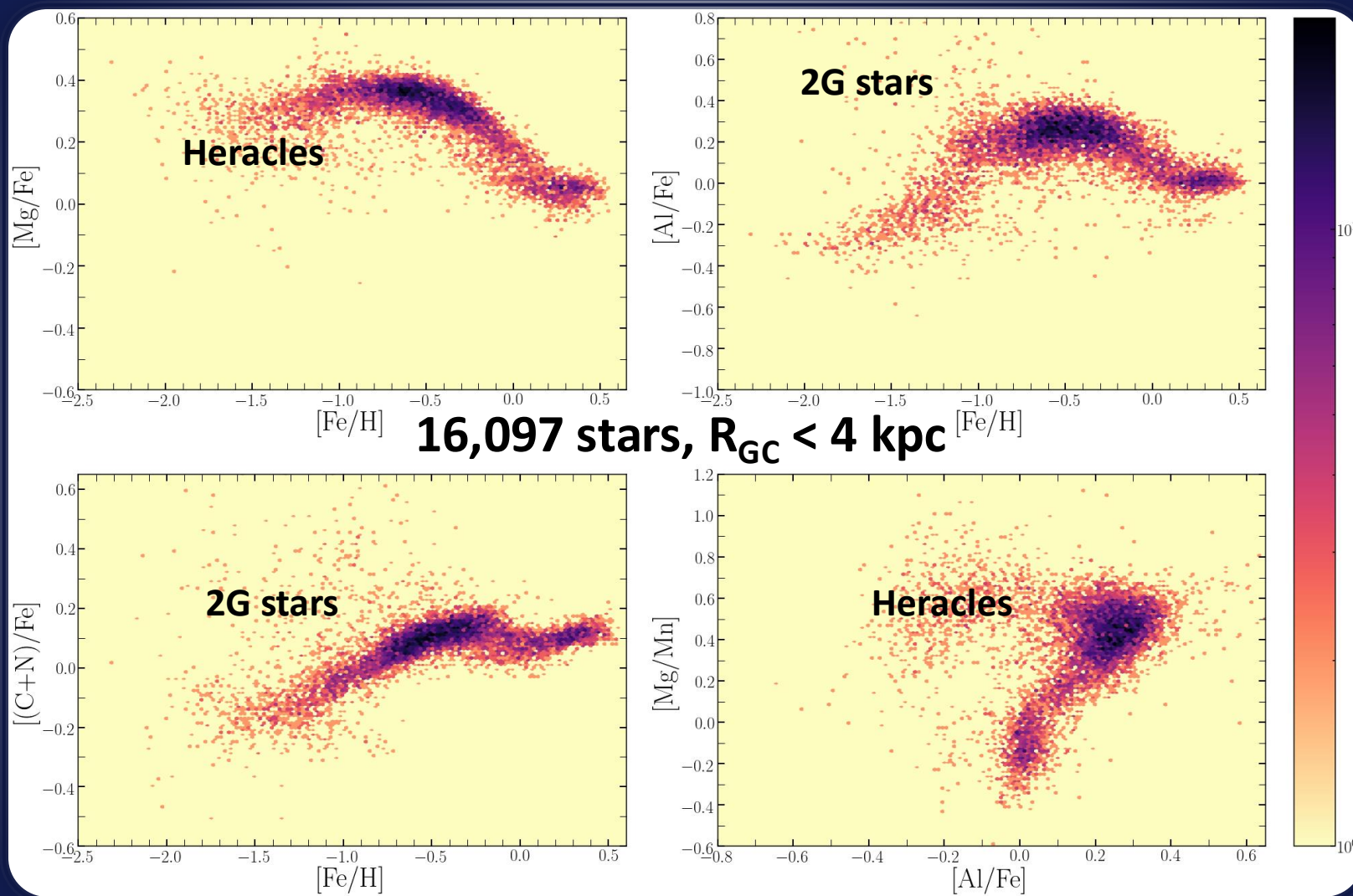
IN THE INNER GALAXY

- *For the first time*: precision detailed chemistry for 10^4 stars

PRECISION ABUNDANCES



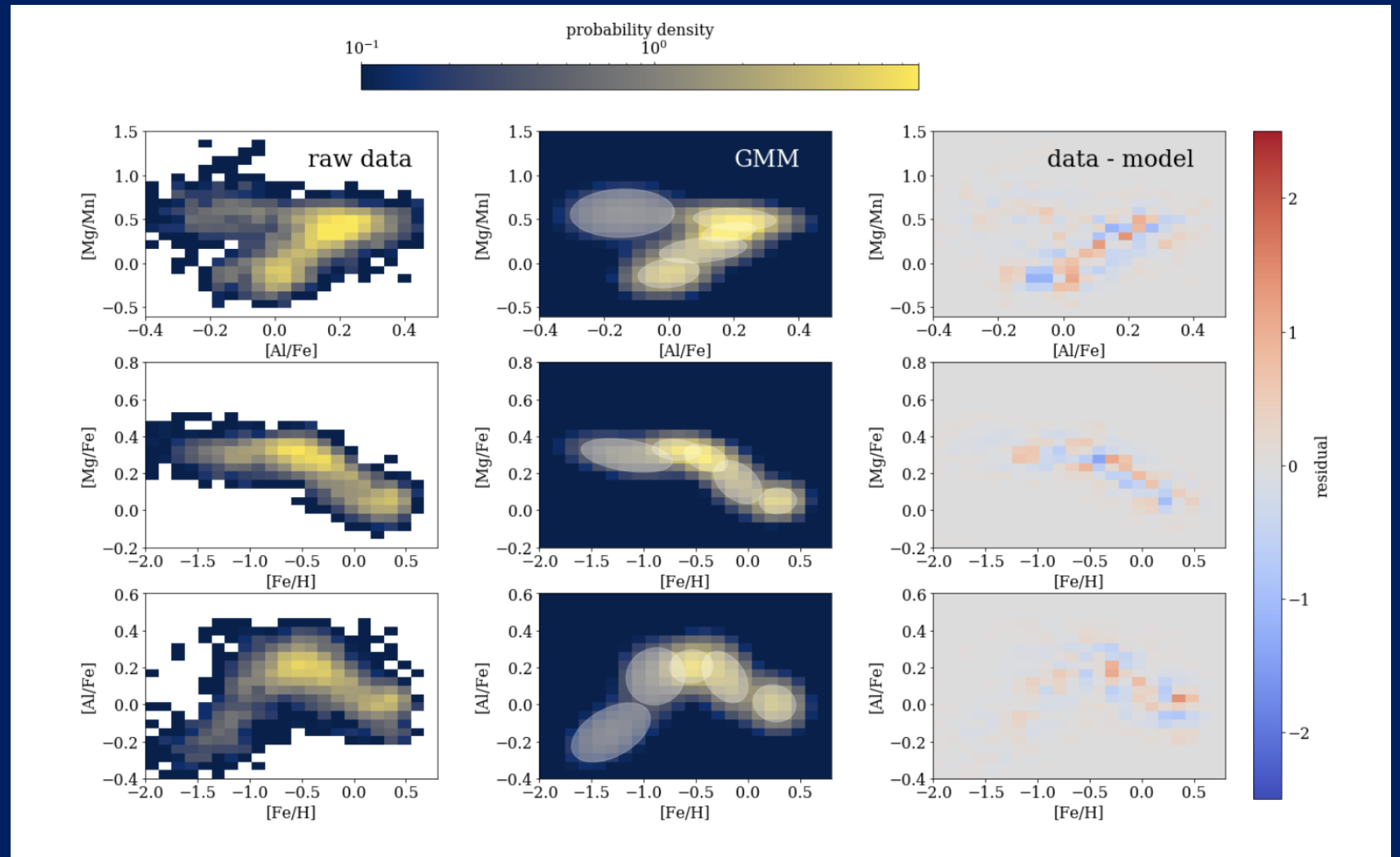
PRECISION ABUNDANCES



GALACTIC BULGE

See talk by Anna Queiroz

- Going beyond metallicity and α/Fe
- Going beyond MDFs
- Breaking degeneracies brings multiple components to sharp relief

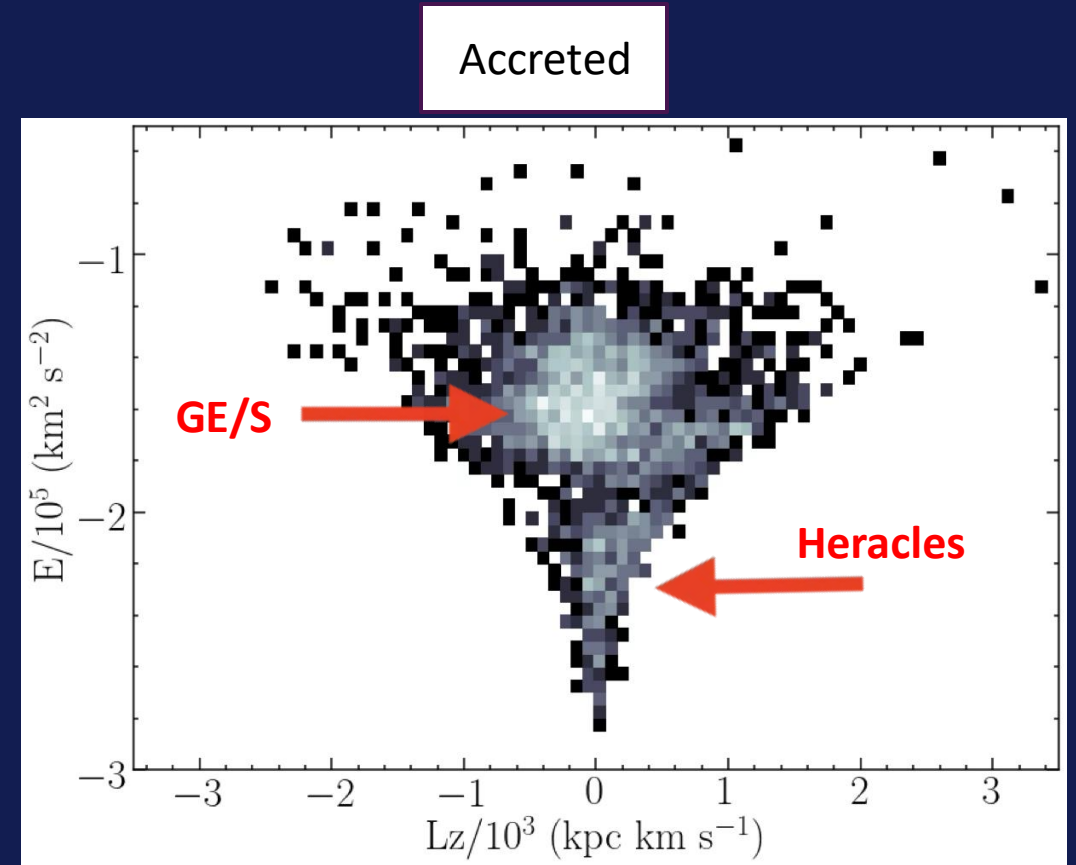
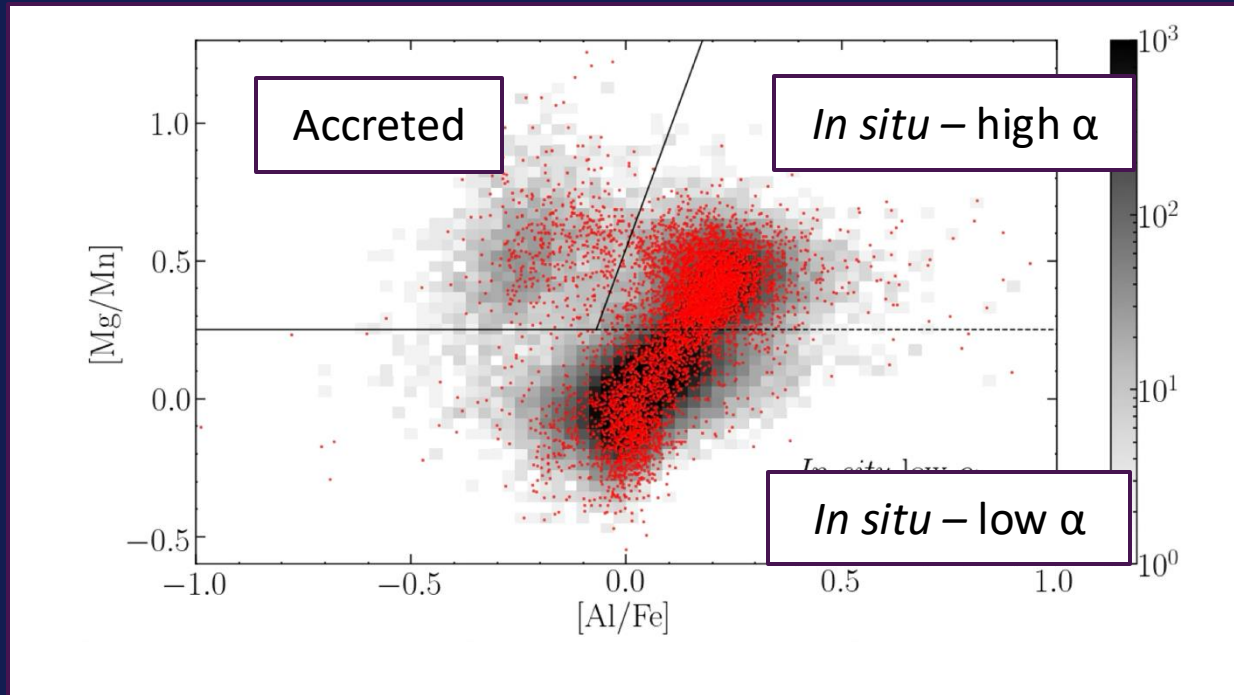


Horta+2021

THE MILKY WAY ACCRETION HISTORY

Heracles

Horta+2021, Horta & RPS 2024

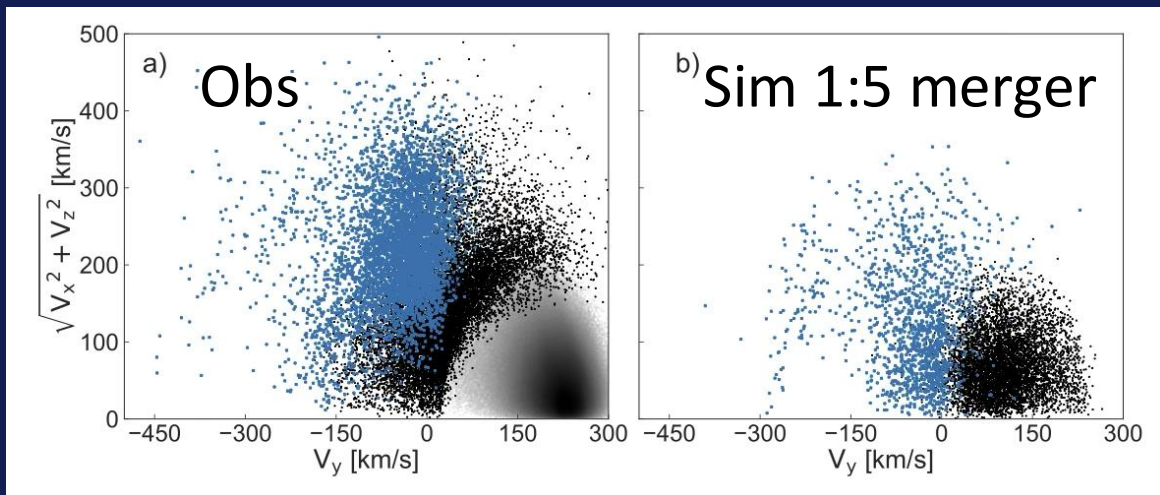


- Massive accretion event ($M_* \approx 5 \times 10^8 M_\odot$)
- Maybe associated with the Kraken (Kruijssen+2020)
- Higher $[\alpha/\text{Fe}]$

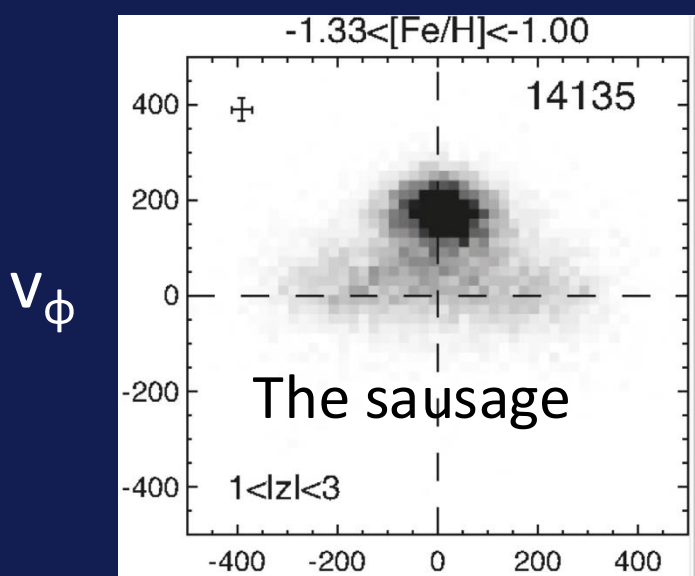
THE MILKY WAY ACCRETION HISTORY

Gaia Enceladus / Sausage

Helmi+2018, Belokurov+2018, Haywood+2018,
Gaia Collab+Babusiaux+2018, Mackereth+2019

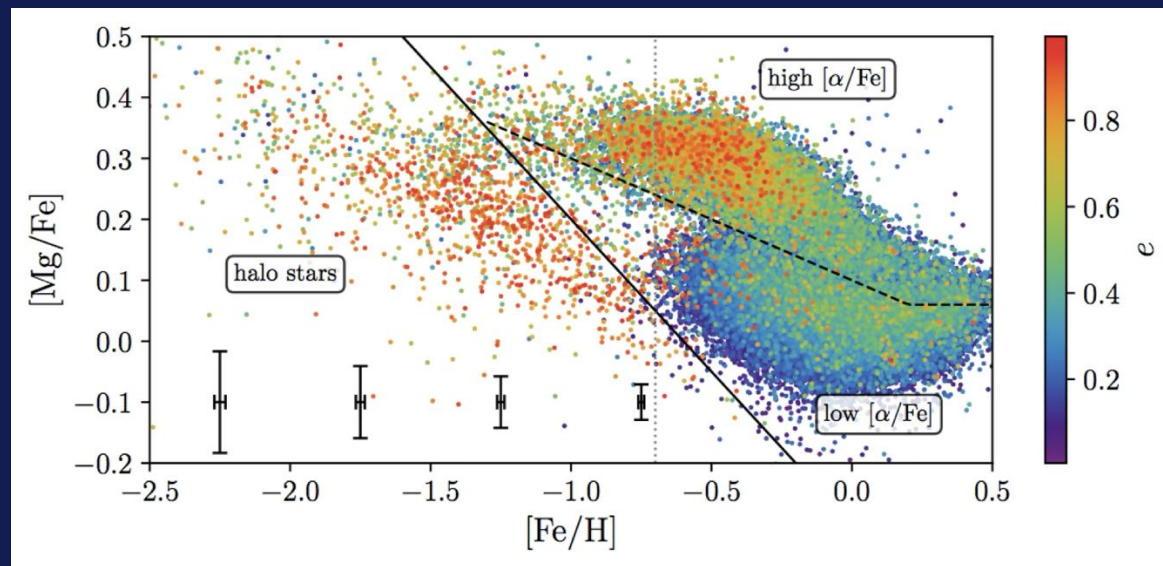


Massive accretion event ($M_* \approx 3 \times 10^8 M_\odot$)
Approximately 9 Gyr ago
Low $[\alpha/\text{Fe}]$



Helmi+2018

Belokurov+2018

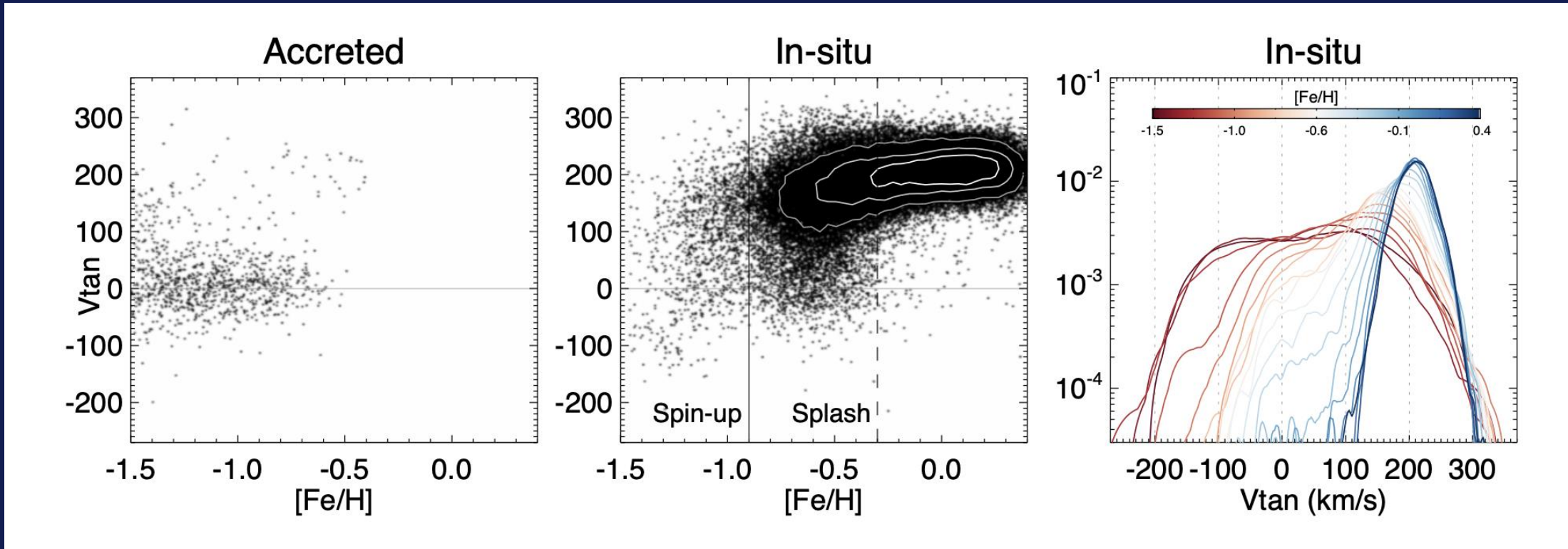


Mackereth+2019

THE EARLY MILKY WAY HALO

Aurora & MW Poor Old Heart

Belokurov & Kravtsov 2022, Rix+2022

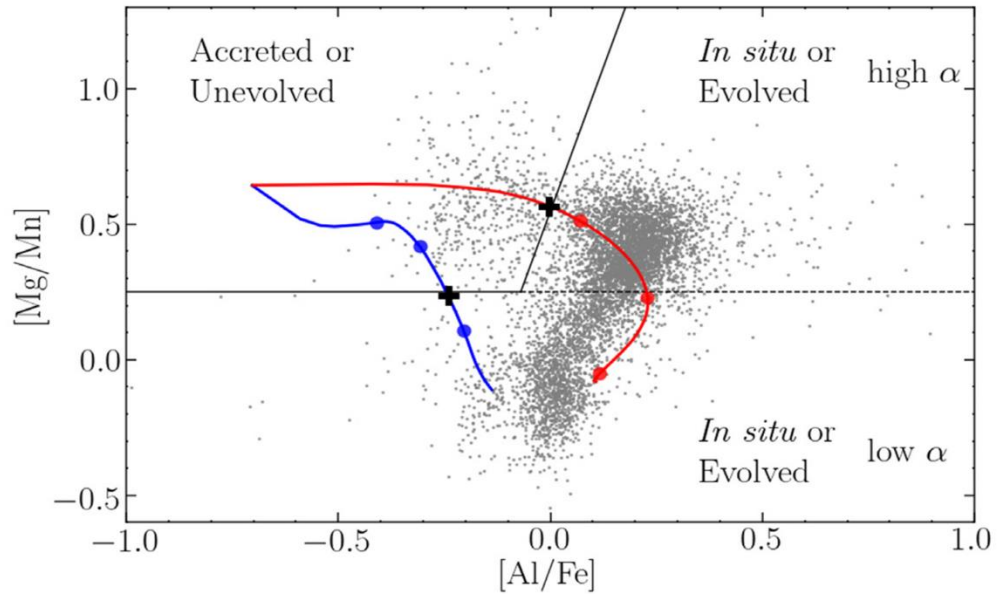


- Detection of the early in situ Milky Way population
- Turbulent, kinematically hot, pre formation of the disk (Spin up phase)
- No need for an accreted component in the inner Galaxy

THE MILKY WAY ACCRETION HISTORY

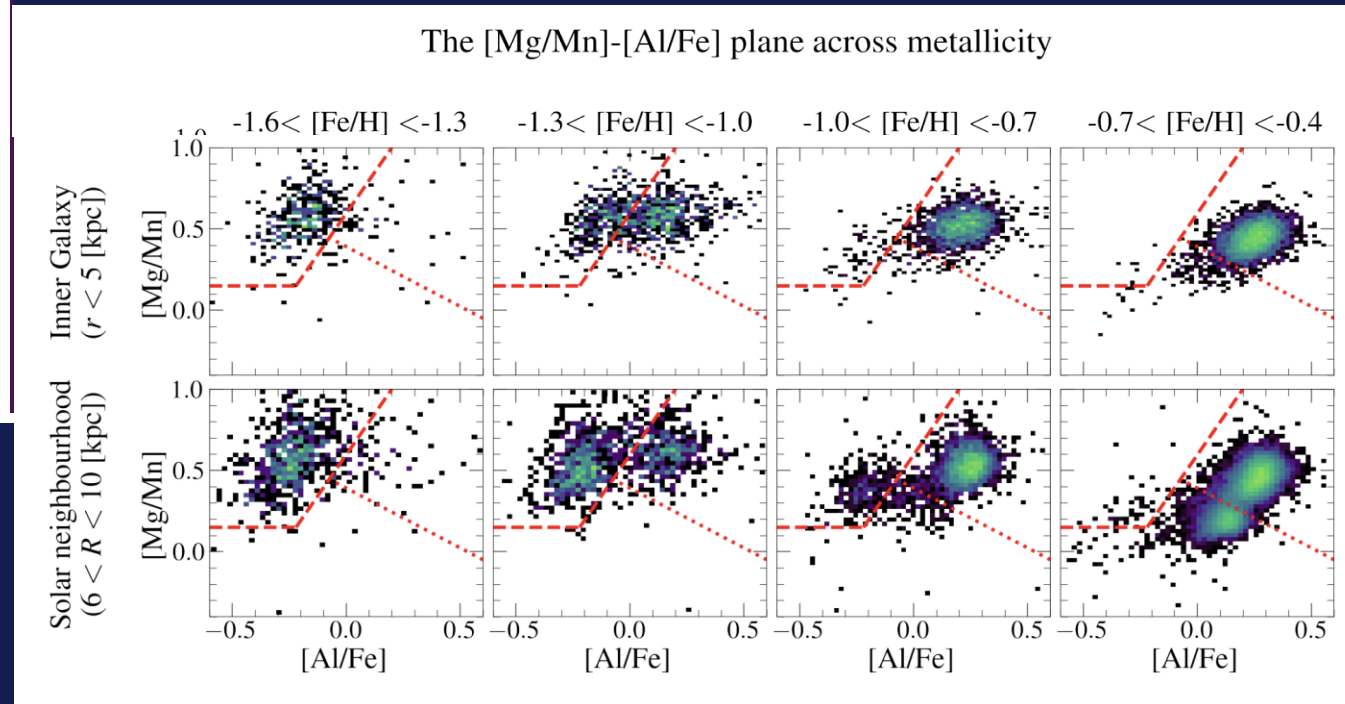
Heracles

Horta+2021, Horta & RPS 2024



Horta+2021

- Star formation efficiency can help distinguish in situ (Aurora) from accreted (Heracles) populations

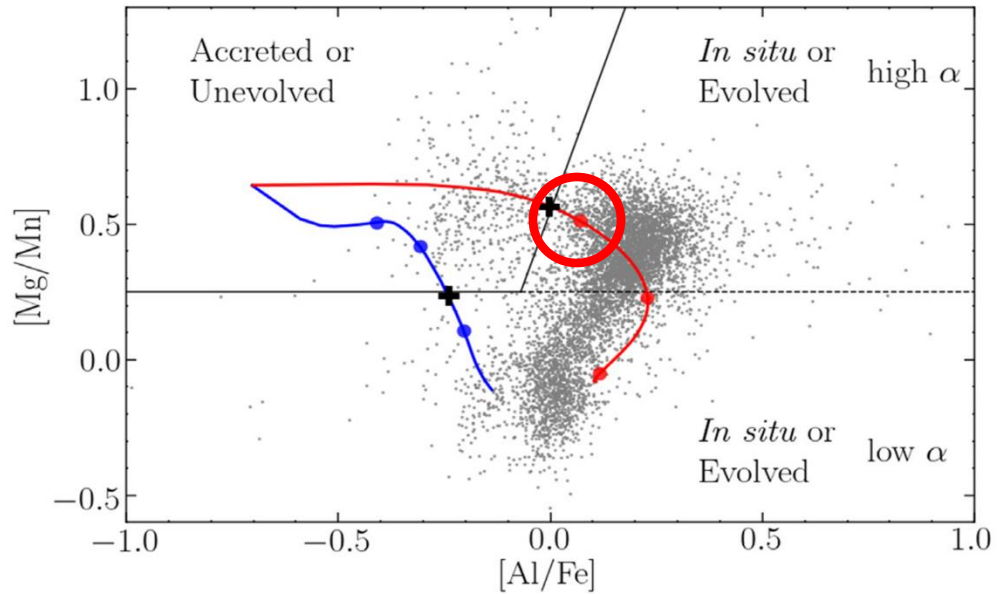


Horta & RPS 2024

THE MILKY WAY ACCRETION HISTORY

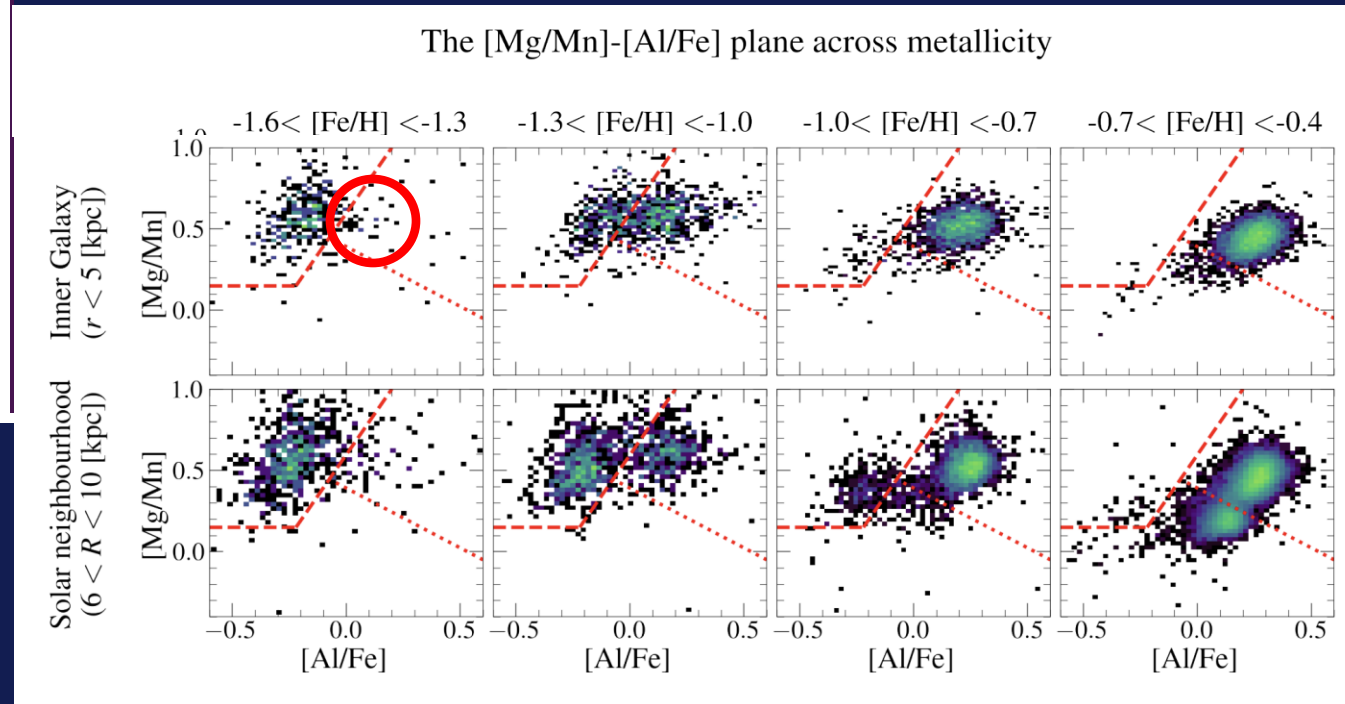
Heracles

Horta+2021, Horta & RPS 2024



Horta+2021

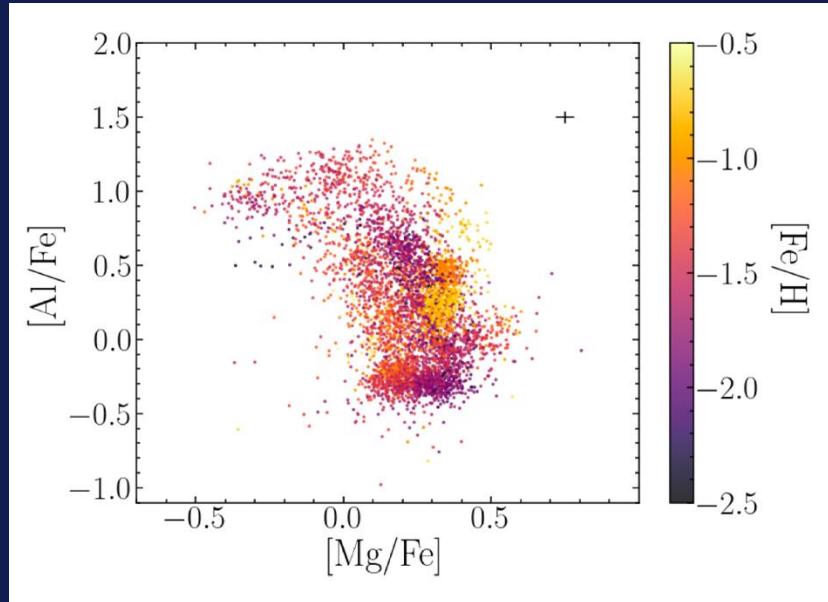
- Star formation efficiency can help distinguish in situ (Aurora) from accreted (Heracles) populations



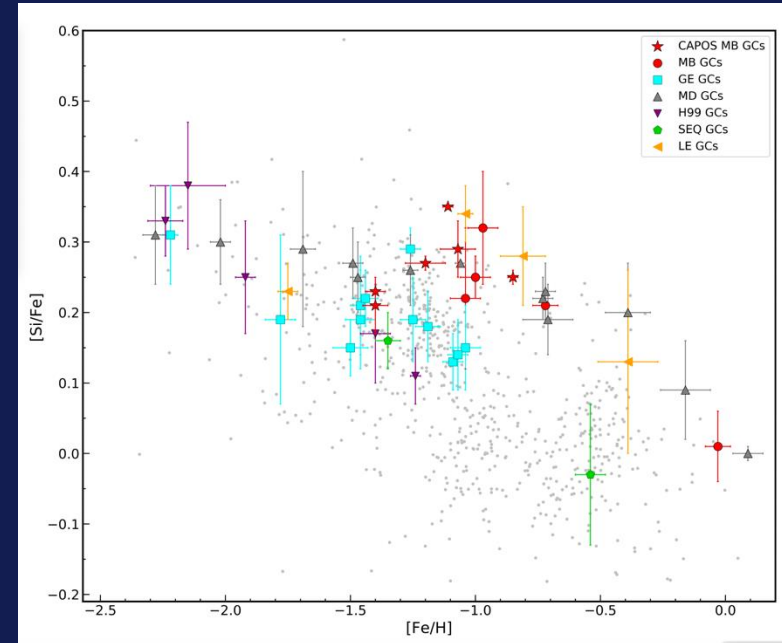
Horta & RPS 2024

GLOBULAR CLUSTERS

Mészáros+2015,2020,2021, Schiavon+2017, Masseron+2019,
Nataf+2019, Horta+2021, Geisler+2024, Schiavon+2024



Schiavon+2024

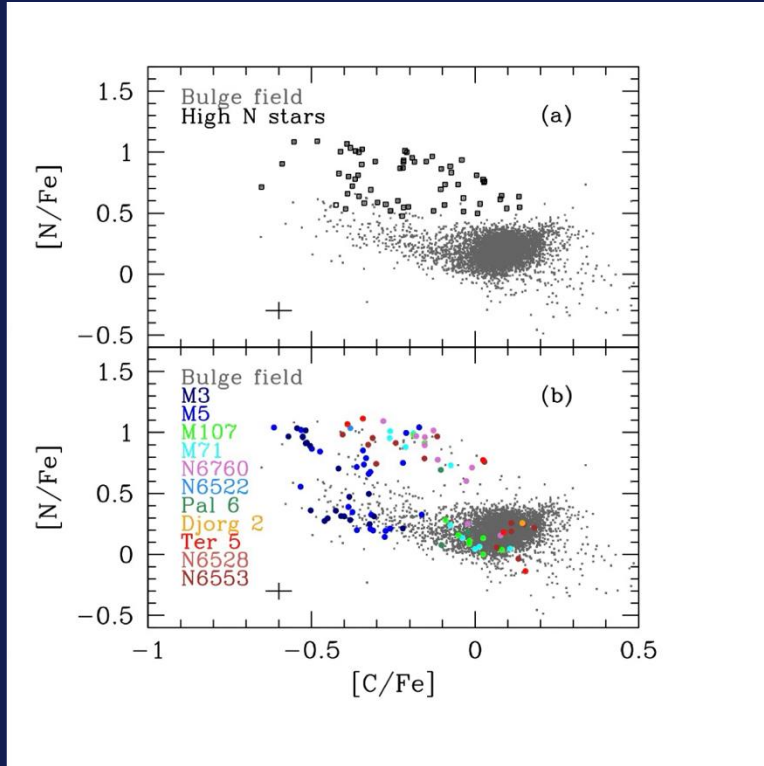


Geisler+2024

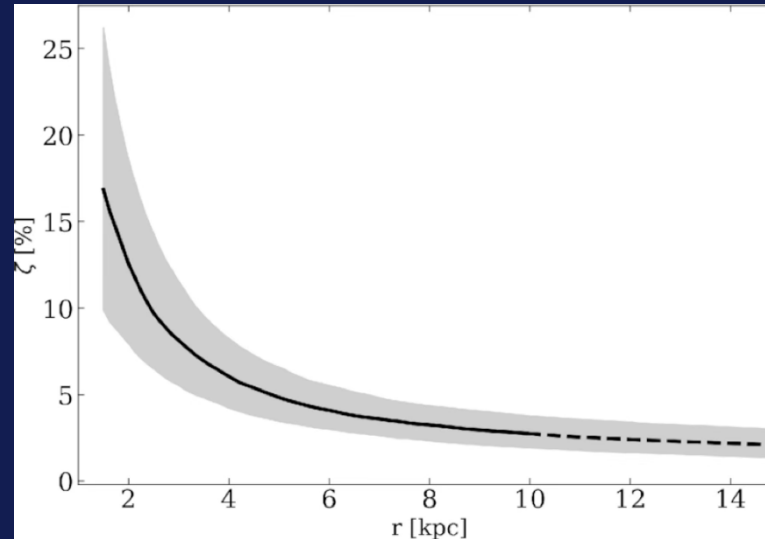
- Value Added Catalog of GC member stars (6400+ stars, 72 GCs), including data from the CAPOS project (Geisler+2024)
- Multiple populations phenomenon
- Accretion history of the MW halo

GLOBULAR CLUSTER DESTRUCTION

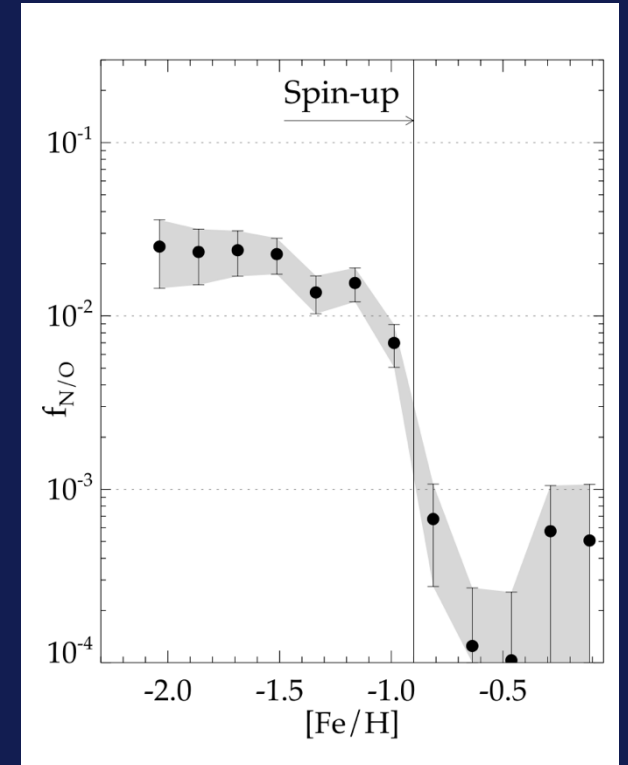
Schiavon+2017, Martell+2016, Fernández-Trincado+2017,2022, Kisku+2021, Horta+2021, Belokurov & Kravtsov 2023



Schiavon+2017



Horta+2021b



Belokurov+Kravtsov 2022

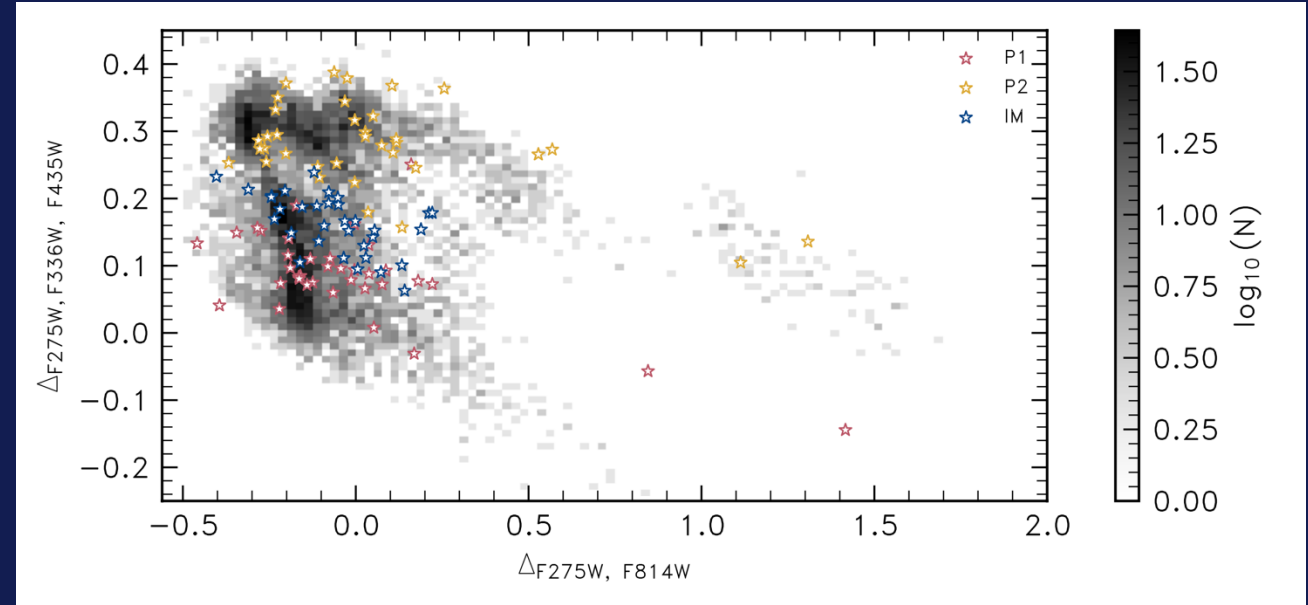
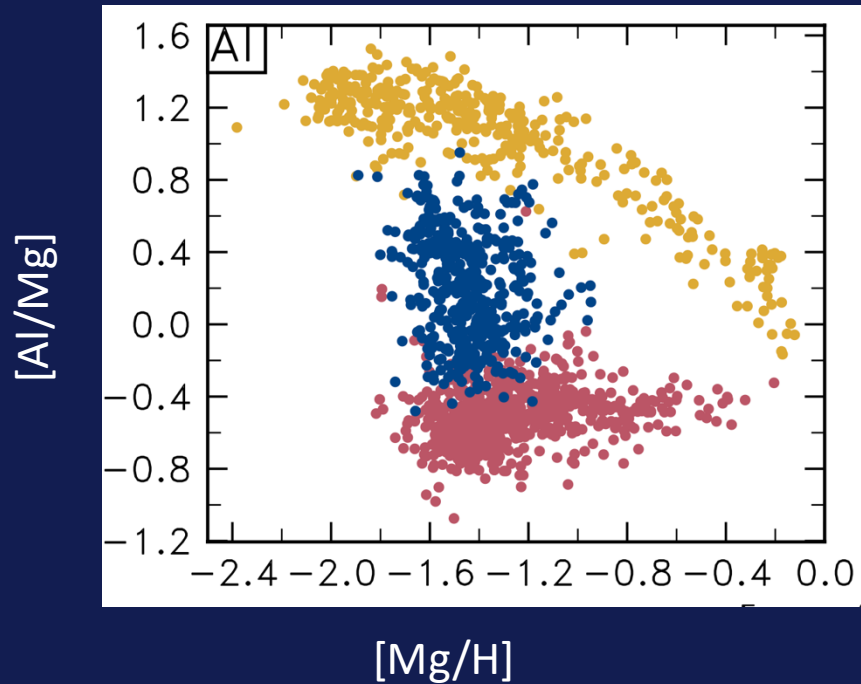
- Approx $10^8 M_{\odot}$ in destroyed GCs within few kpc of MW centre
- Strongly concentrated
- Accreted or in situ?

NUCLEAR STAR CLUSTERS

Mészáros+2021, Álvarez Garay+2024, Mason+2024

Mason+2024

APOGEE DR17

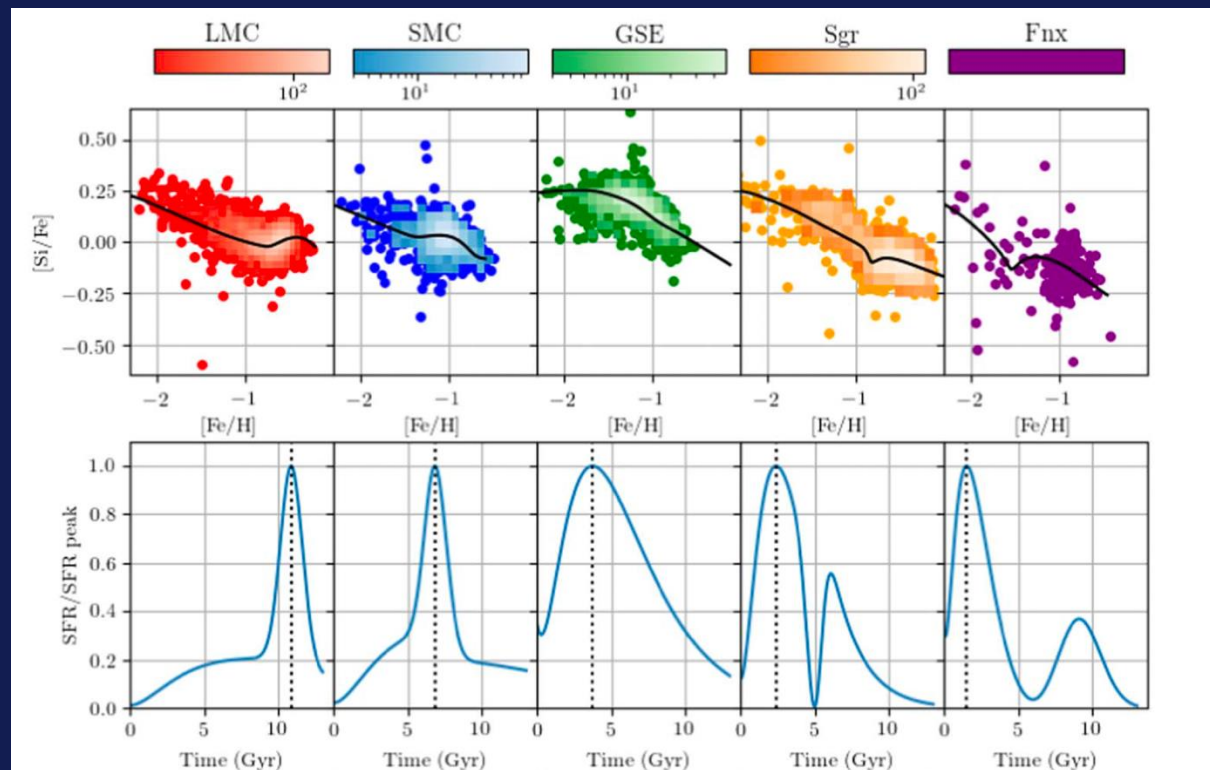


Cross-match with OmegaCAT (Nitschai+2023,Häberle+2024)

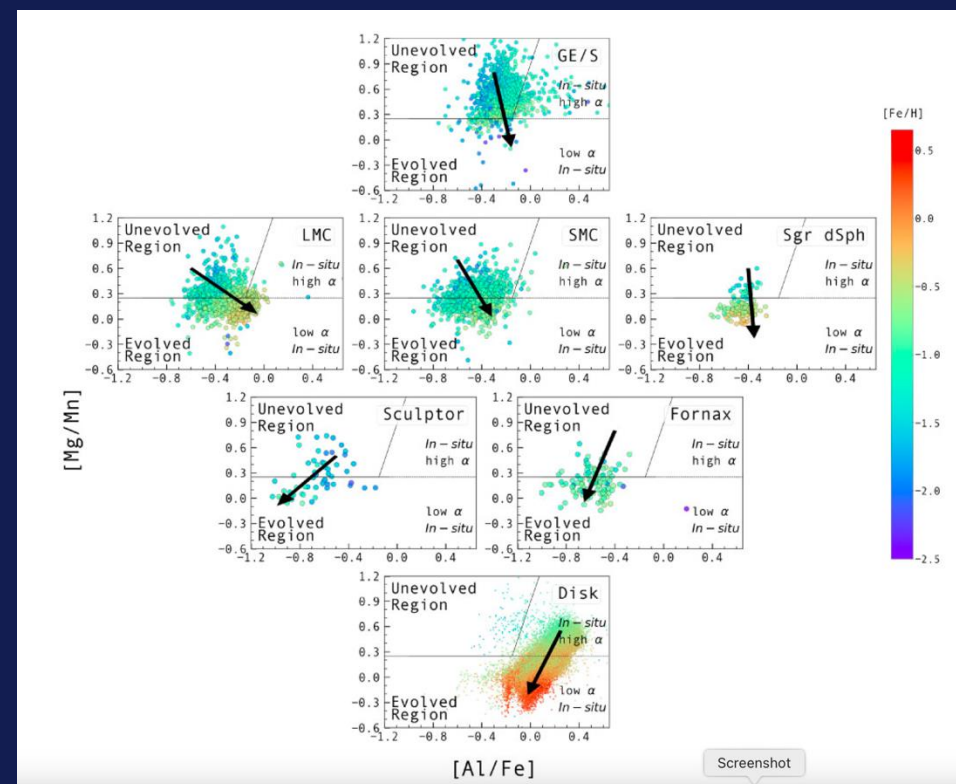
- History of star formation and chemical enrichment of NSCs
- Constraints on the MP phenomenon
- See also Michael O'Connor's poster on M54 (P48)

MILKY WAY SATELLITES

Hayes+2018,2020, Hasselquist+2021,2024,
Nidever+2020, Fernandes+2023



Hasselquist+2021

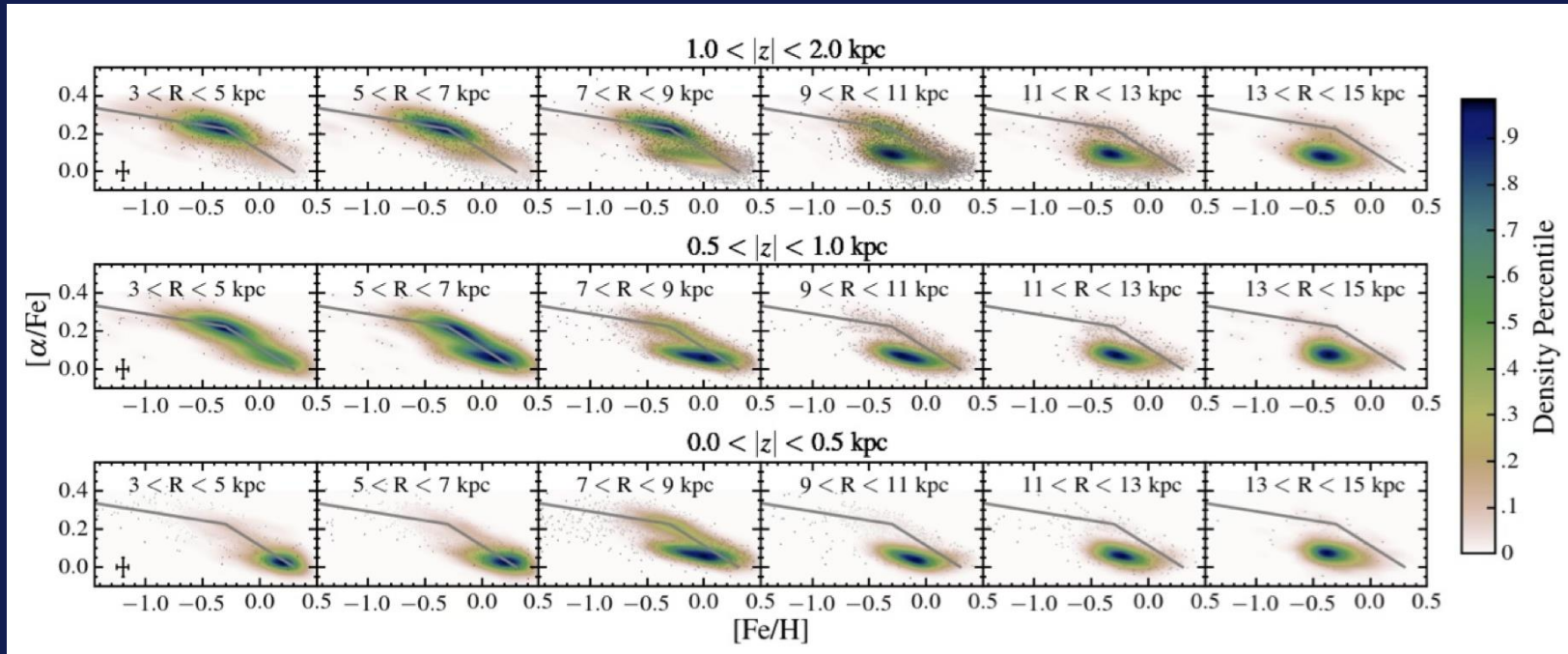


Fernandes+2023

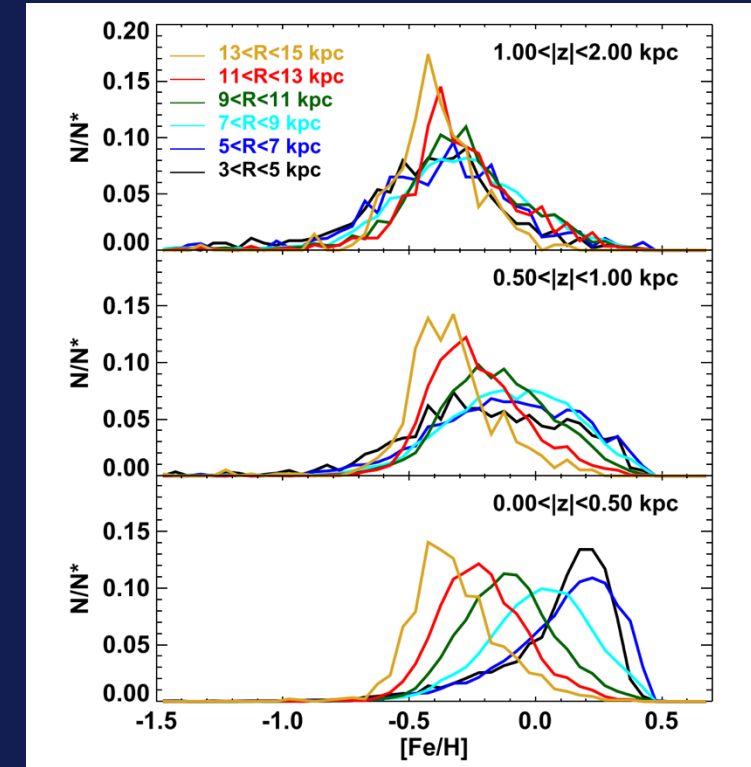
- Star formation histories of Milky Way satellites of all masses
- Dependence on mass and (possibly) environment

CHEMICAL CARTOGRAPHY OF THE DISK

Nidever+2014, Hayden+2015, Mackereth+2017, Weinberg+2019,2022



Hayden+2015

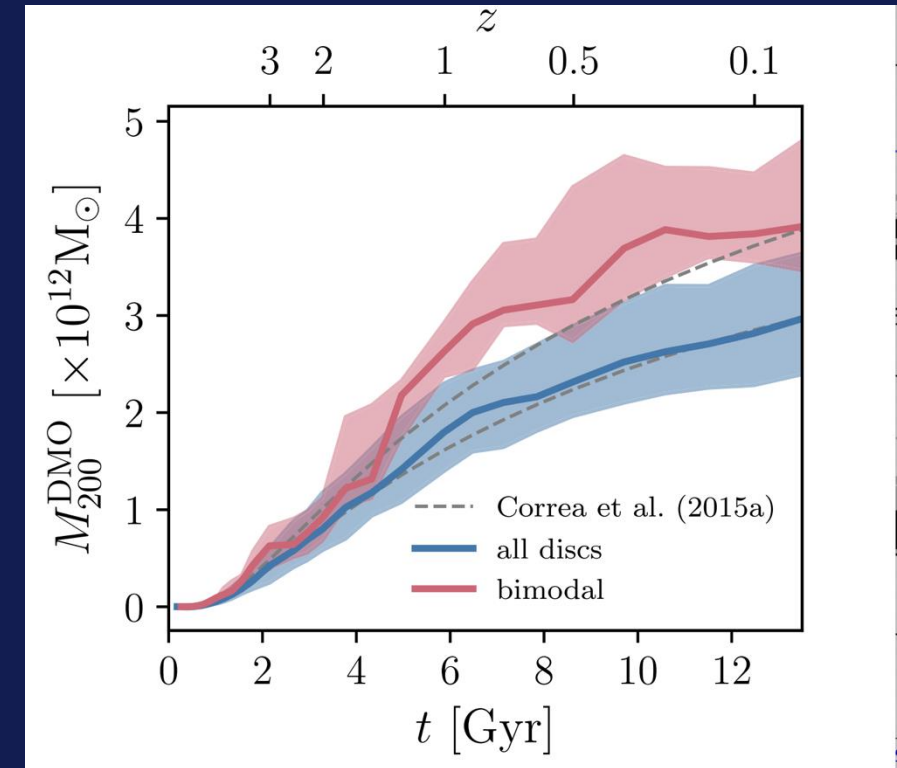
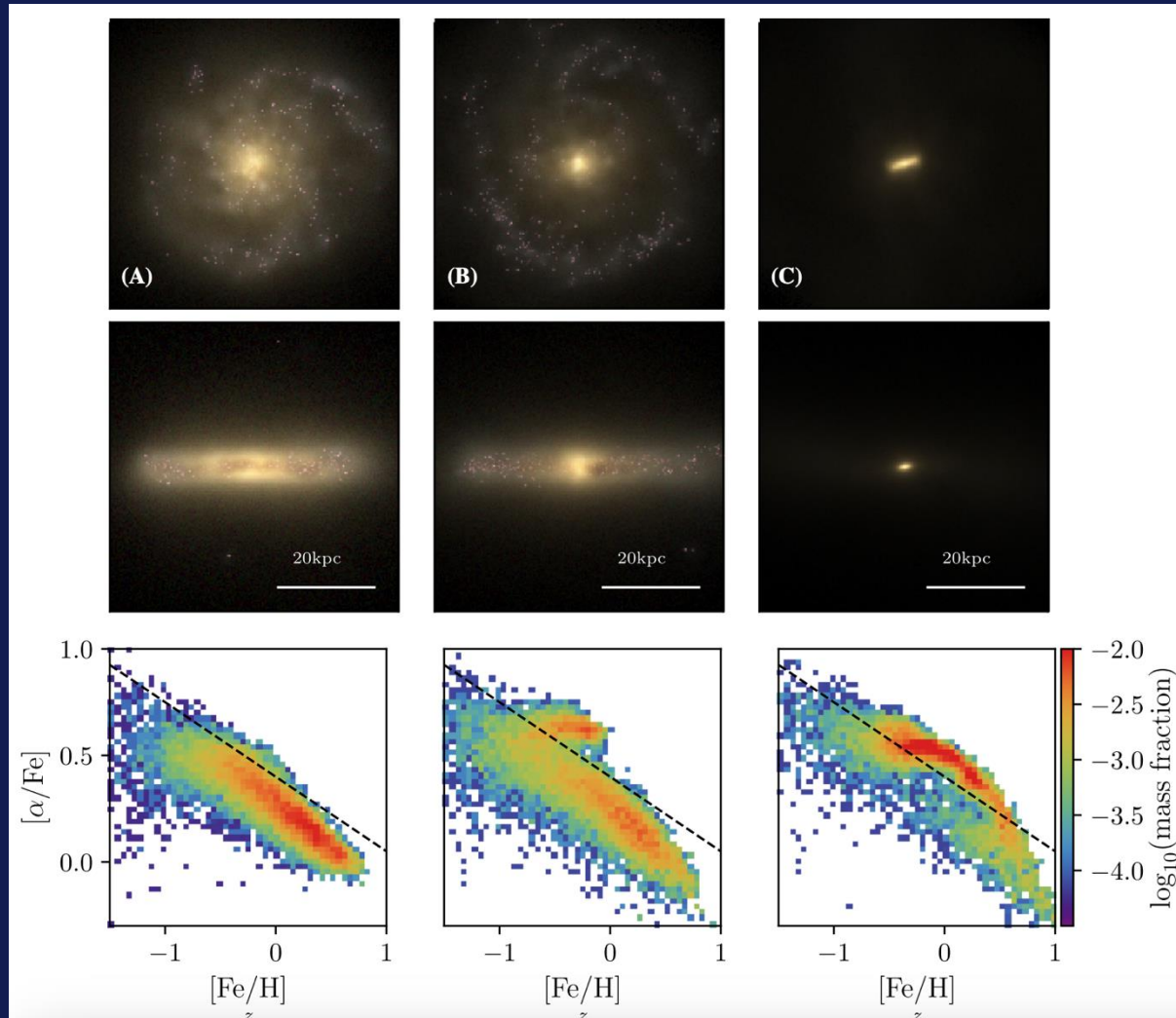


Hayden+2015

- The first large scale assessment of the detailed chemistry of the disk
- Radial mixing spotted?
- Is the Galaxy a common galaxy? (Mackereth+2018, Grand+2018, Clarke+2019, Buck+2021)

THE DISK ALPHA BIMODALITY IN COSMOLOGICAL SIMULATIONS

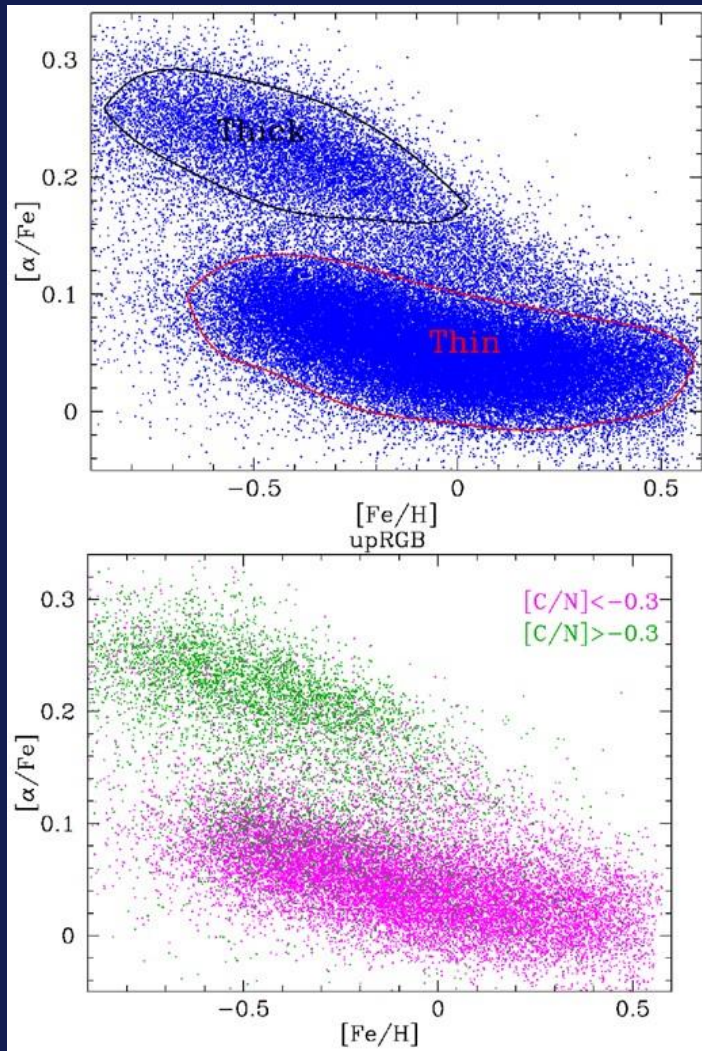
Mackereth+2018



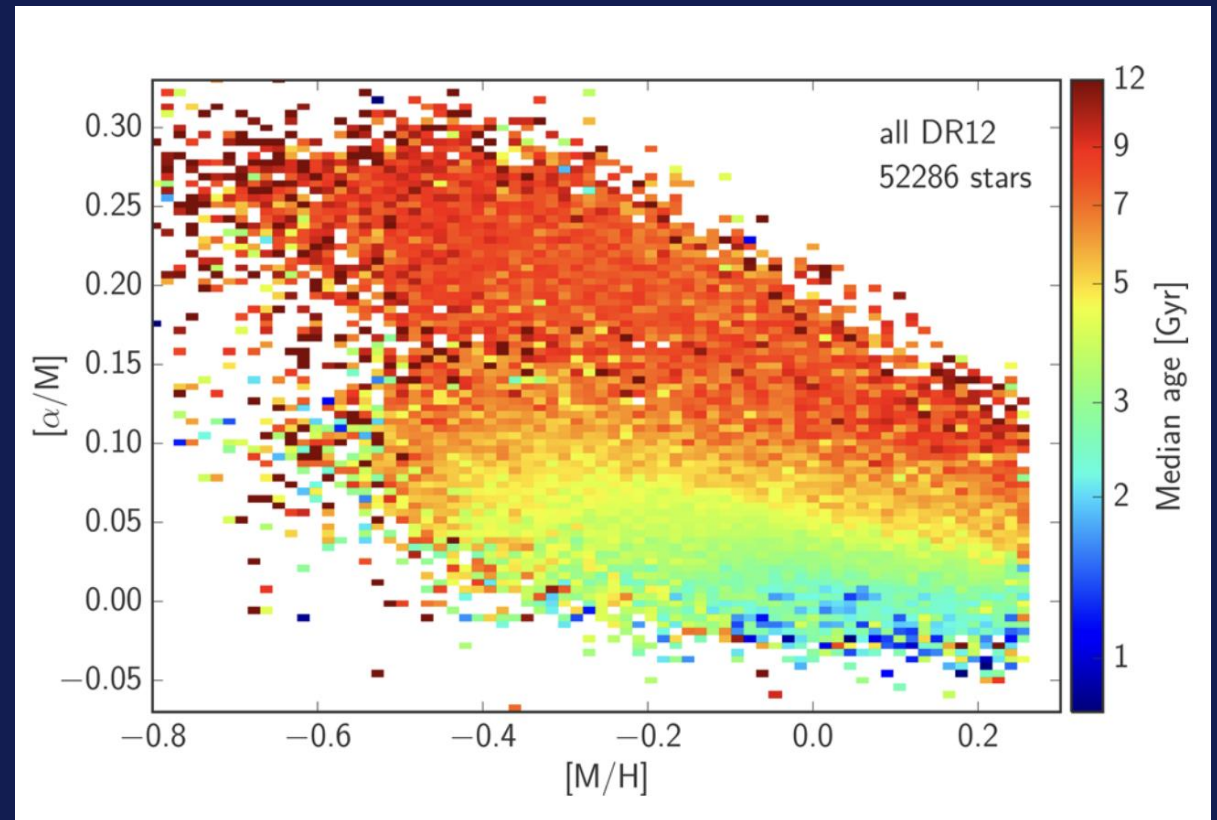
- Only 5% of MW-like galaxies have bimodality in EAGLE universe
- Bulk of accretion occurred early

STELLAR AGES

Masseron+Gilmore 2015 , Feuillet+2015, Martig+2016, Ness+2016, Schultheis+2017



Masseron+Gilmore 2015



Martig+2016

- Dependence of C/N on giant star mass
- Calibrated against Kepler/Corot asteroseismology

APOGEE SCIENCE IMPACT

The screenshot shows the ADS (Astrophysical Data Service) search interface. At the top left is the ADS logo. On the top right, there are links for 'Feedback' and 'ORCID'. Below the logo, there is a search bar with a dropdown menu for 'QUICK FIELD:' containing options: 'Author', 'First Author', 'Abstract', and 'All Search Terms'. The search query entered is 'pubdate:[2007-01 TO 9999-12] title:(apogee)'. To the left of the search bar is a button 'Start New Search' with a left arrow. To the right of the search bar is a search button with a magnifying glass icon. Below the search bar, it states 'Your search returned 281 results with 19,228 total citations'. At the bottom, there are two filter tags: 'Collection +astronomy' and 'Property +refereed AND article', both with close buttons. To the right of these tags is a sorting button with a downward arrow and the text 'Citation Count'.

From ADS, including only refereed articles

BARBUY SCIENCE IMPACT

The screenshot shows the top navigation bar of the ADS website with the logo on the left and 'Feedback' and 'ORCID' links on the right. Below the navigation bar is a search interface with a 'QUICK FIELD:' dropdown menu set to 'All Search Terms'. The search input field contains the query 'author:(\"barbuy, b.\")'. To the left of the search field is a 'Start New Search' button, and to the right is a search button with a magnifying glass icon. Below the search field, a message states: 'Your search returned **327** results with **19,505** total citations'. At the bottom of the search interface, there are two filter tags: 'Collection +astronomy' and 'Property +refereed AND article', each with a close button. To the right of these tags is a sorting menu with a downward arrow icon and the text 'Citation Count'.

Beatriz beats us!

LESSONS LEARNED

- **Push the envelope:** the NIR frontier, automatic abundance analysis
- **“Simple Instrument”:** stable, single mode, no moving parts, made engineering, calibration, data reduction, simpler
- **Target selection:** focus on giants. Abundance pipeline simpler, results more homogeneous, higher precision
- **Legacy nature:** high S/N, high resolution spectra have lots of information. Can be extracted with improved future tools
- **Always ask:** do I need this much data? Are the data good enough?
- **Empower the young:** ECRs in leading roles, both technical and scientific