Tracing Chemical Evolution over the Extent of the Milky Way's Disk with APOGEE Red Giant Stars

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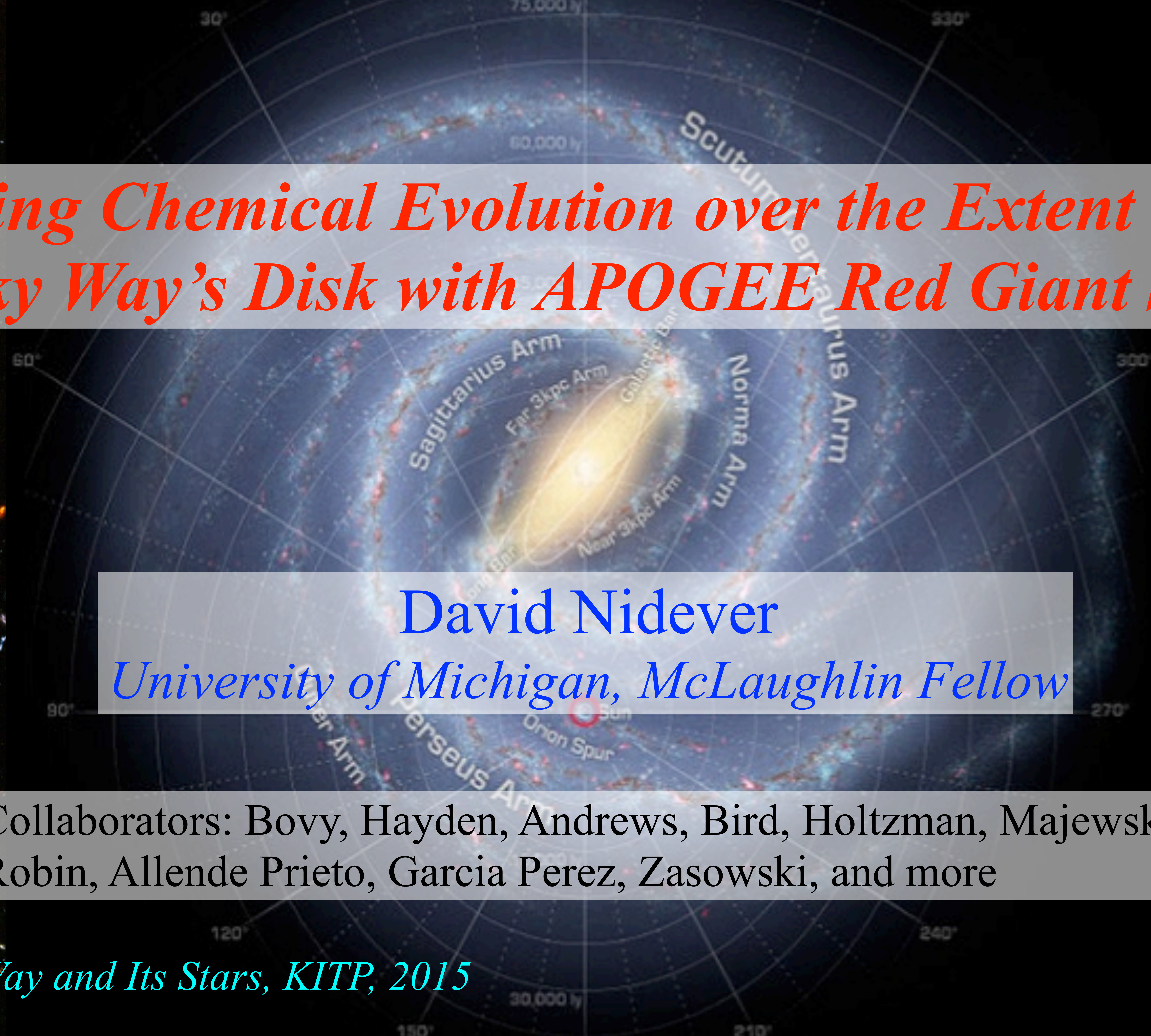


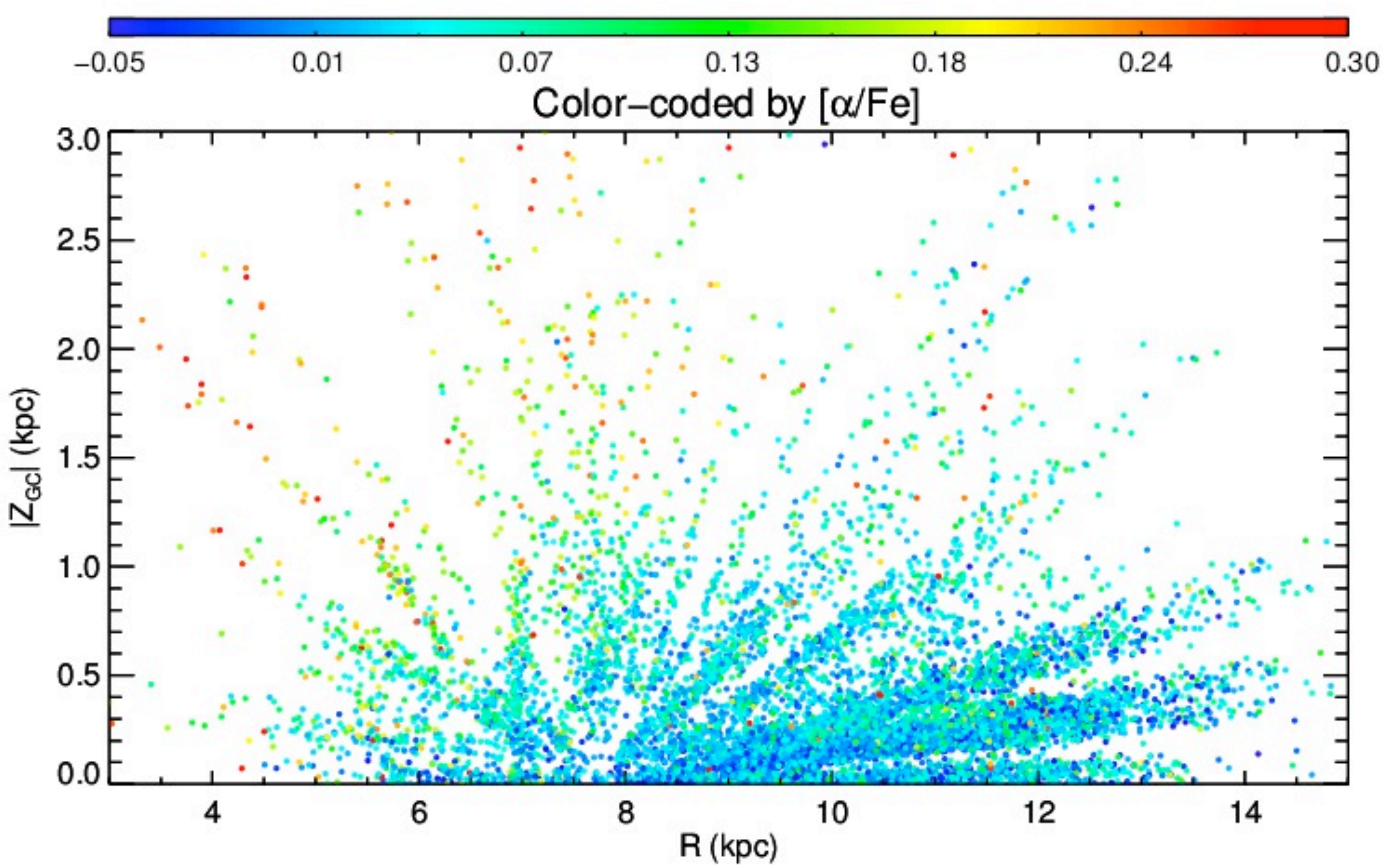
Collaborators: Bovy, Hayden, Andrews, Bird, Holtzman, Majewski, Robin, Allende Prieto, Garcia Perez, Zasowski, and more

The Milky Way and Its Stars, KITP, 2015

Brief Disk Background

- Classically two disk components:
  - Thick disk: older, high [α/Fe] , larger h_z, high σ_z
  - Thin disk: younger, low [α/Fe] small h_z, low σ_z
- But they might not be so "distinct" (e.g. Bovy et al. 2012b)
- Origin of disk variation unclear
  - Major merger puffing older stars up
  - Disk formed "hot" and settled/cooled over time

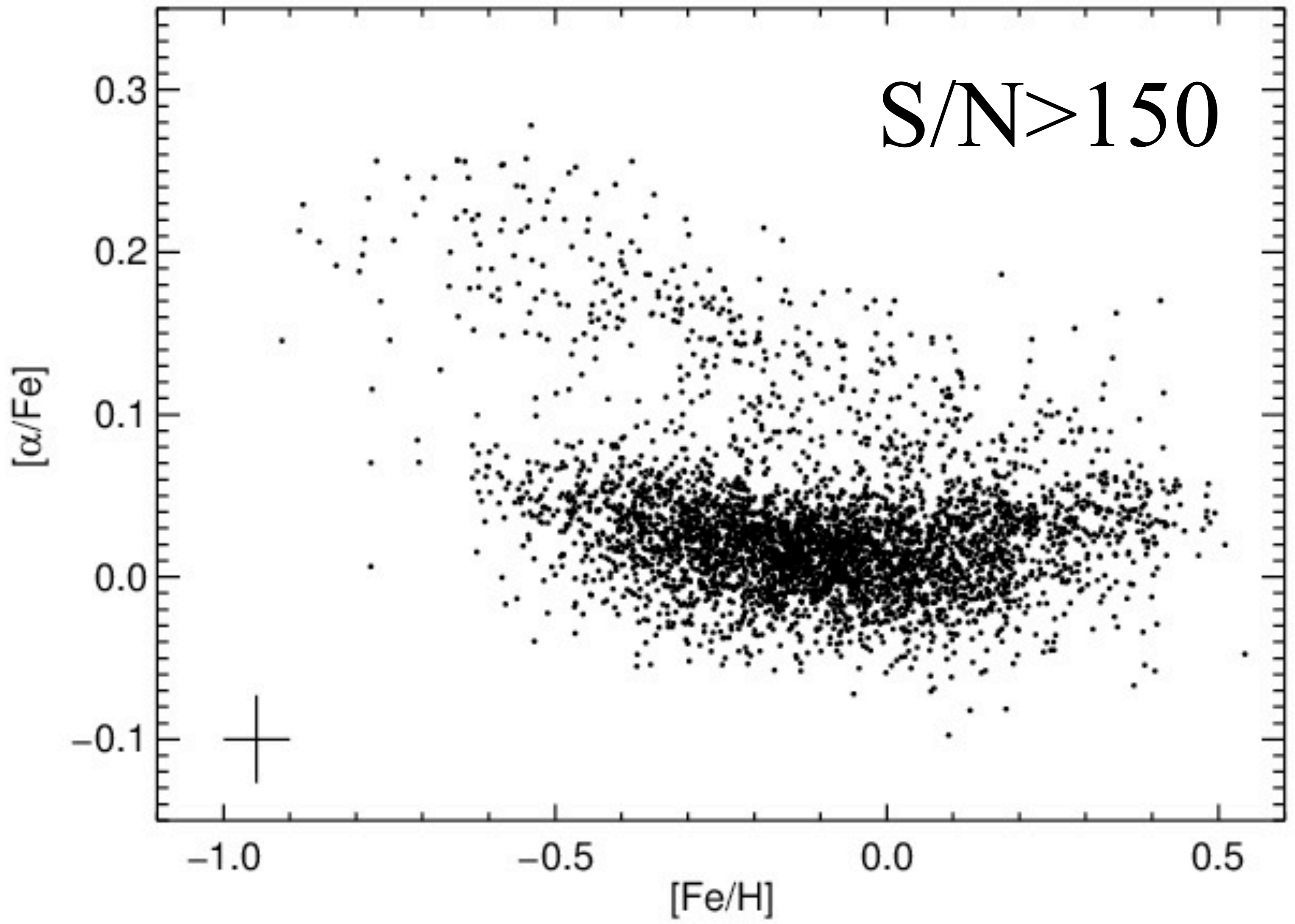
APOGEE Red Clump Stars

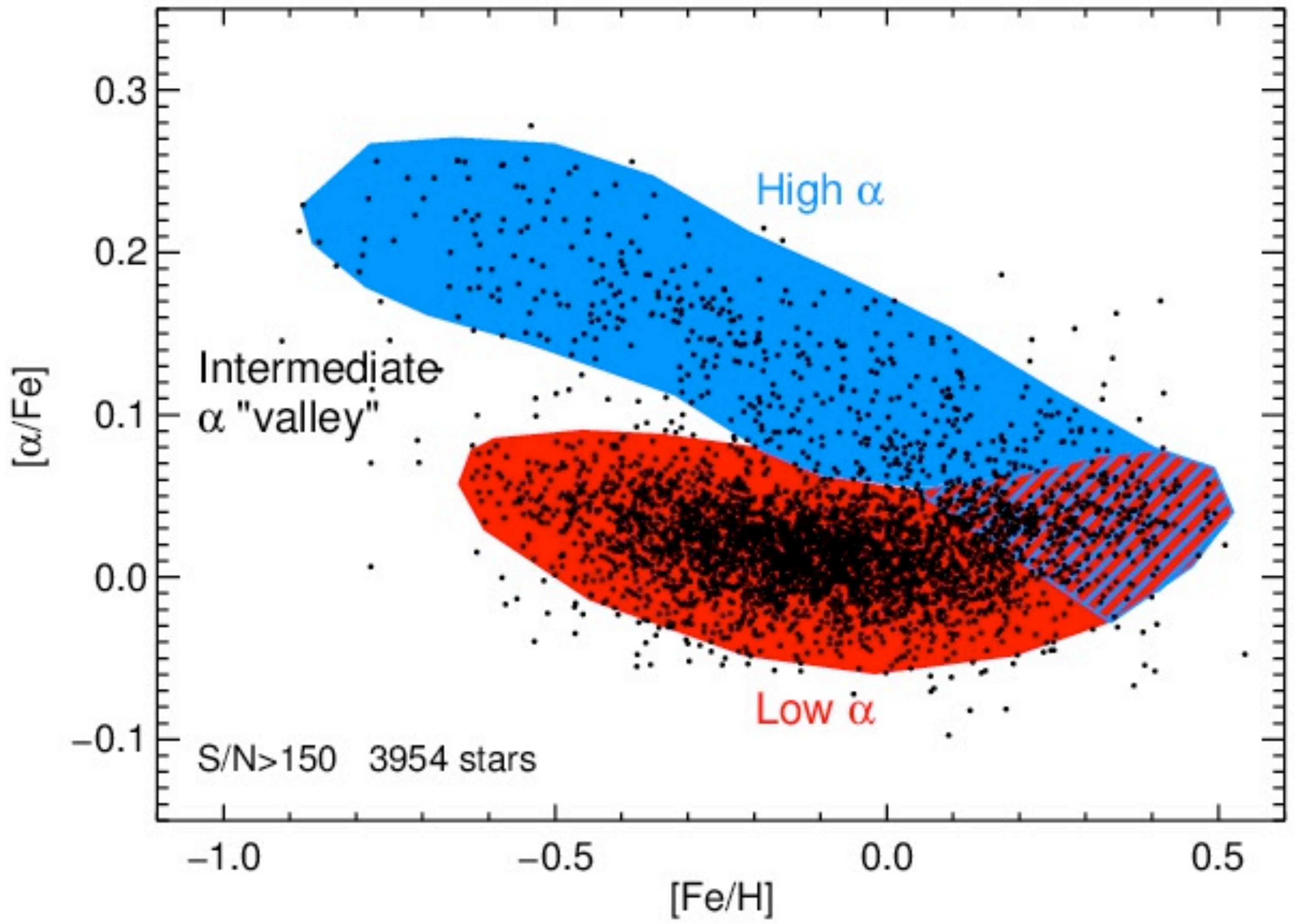


- Use α-element abundances of the red clump catalog (Bovy, Nidever et al. 2014)
- ~10,000 RC stars (~20,000 in DR12)
- Standard candles, accurate distances (~5%)
- Most stars within ~4 kpc of the sun

Use APOGEE to explore chemical abundances through the MW disk

Abundance Features



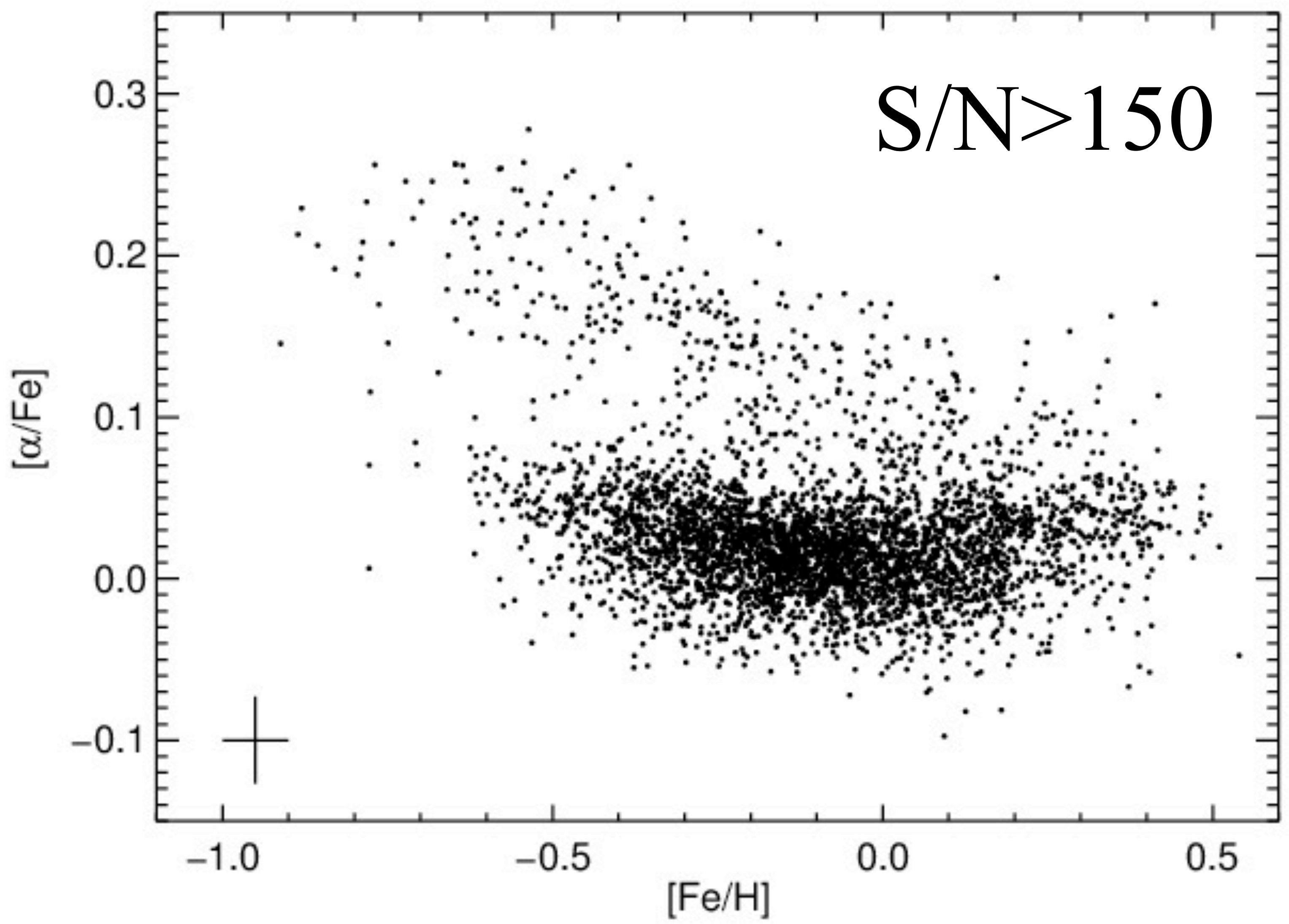


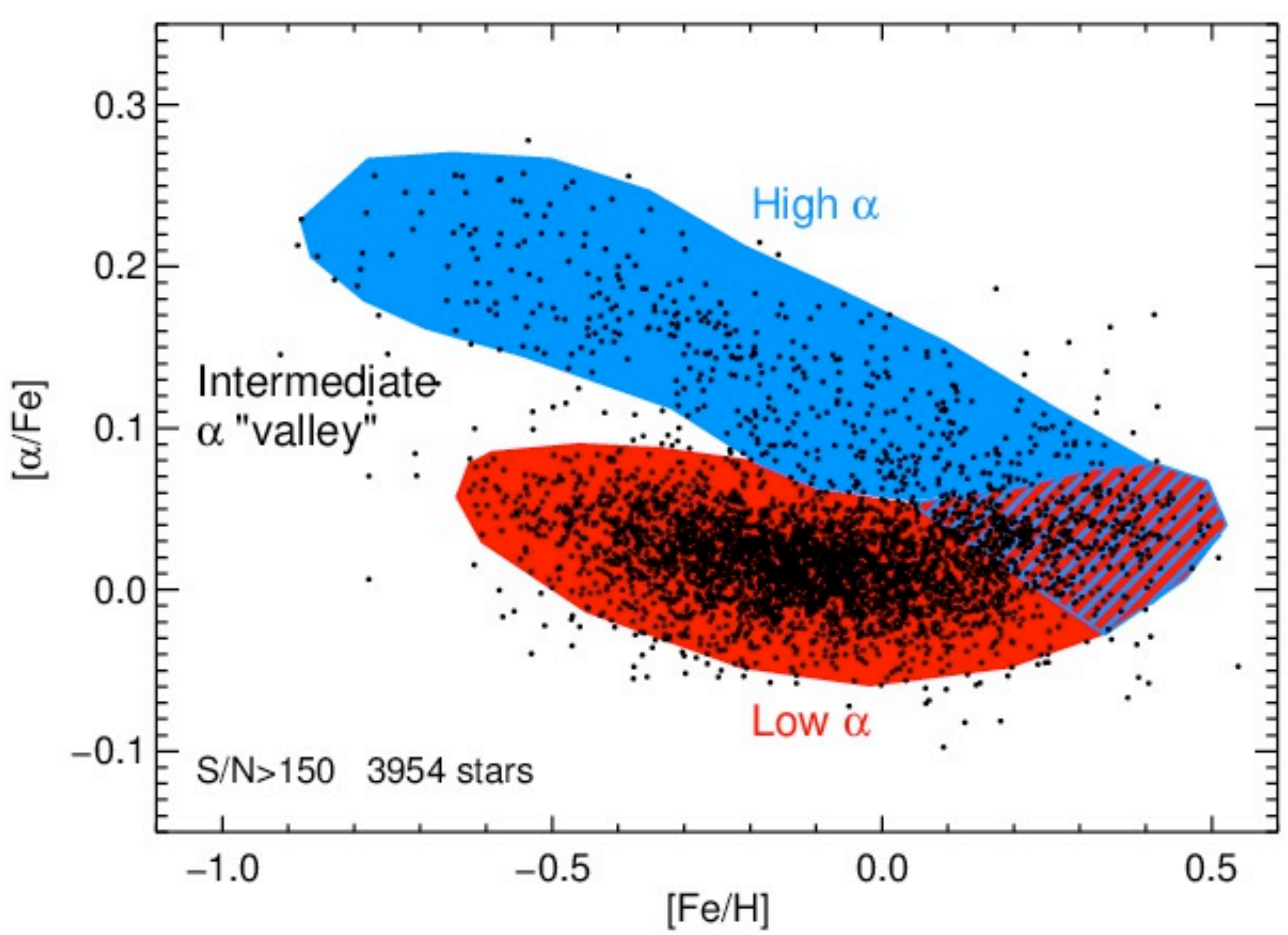
Qualitative Features

1. α-bimodality at intermediate metallicity
2. Merging of two α groups at [Fe/H]~+0.2
3. Valley between groups not empty

Nidever et al. (2014)

Abundance Features





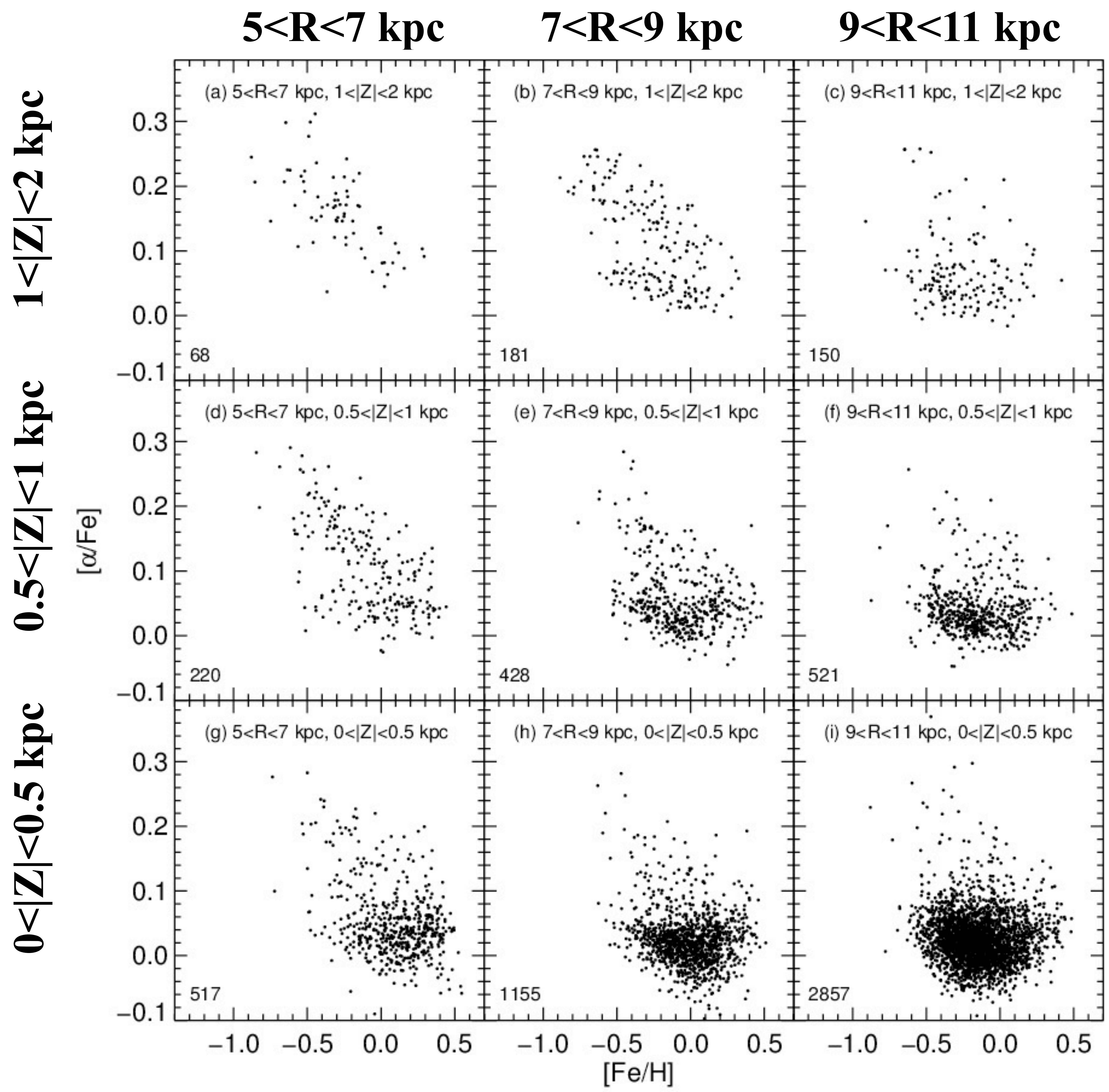
Qualitative Features

1. α-bimodality at intermediate metallicity
2. Merging of two α groups at [Fe/H]~+0.2
3. Valley between groups not empty

- Selection effects have little impact on overall abundance *patterns*

Nidever et al. (2014)

Chemical Cartography



- Chemical cartography
- Look at abundance patterns across the MW disk

Nidever et al. (2014)

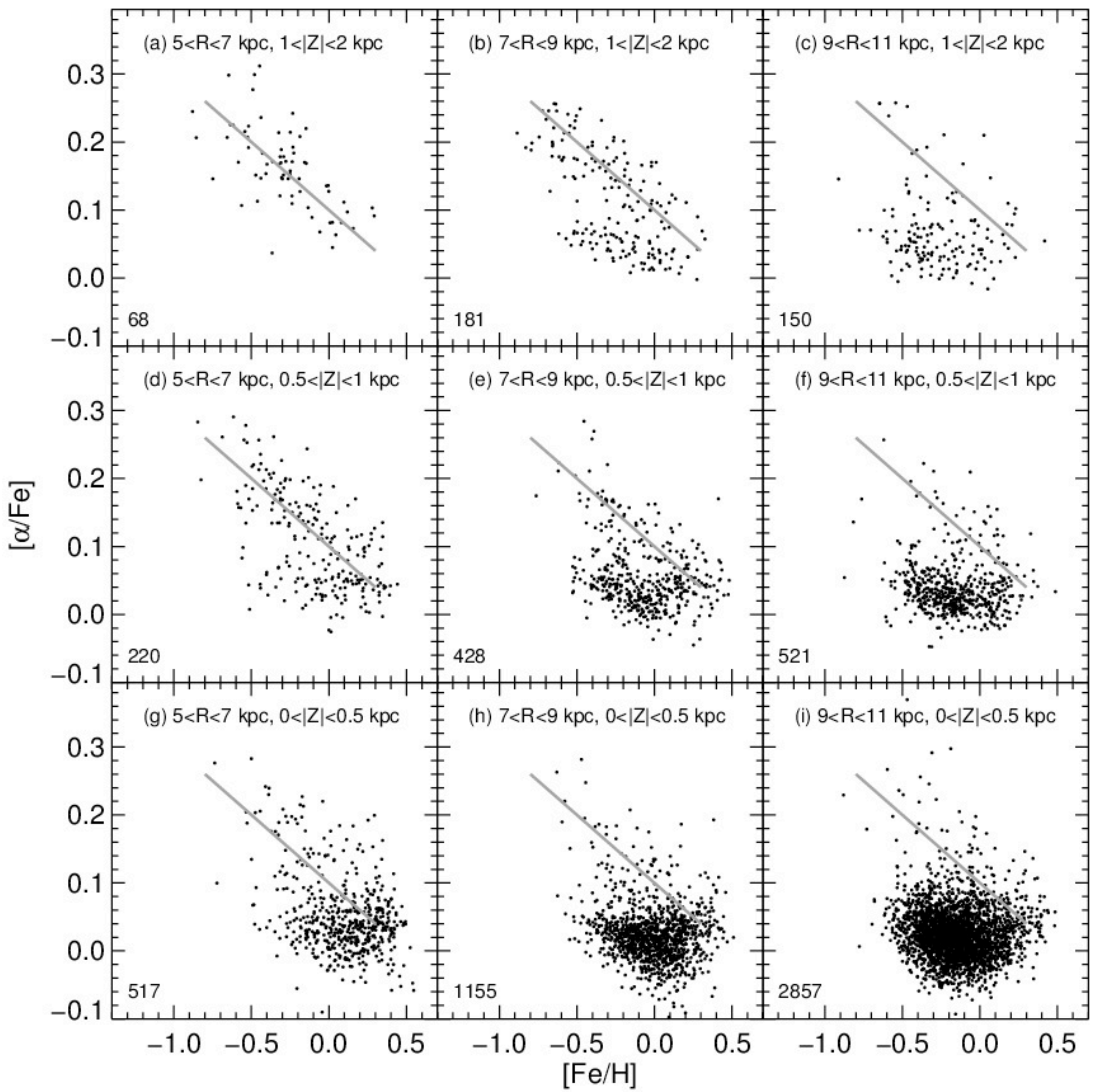
Chemical Cartography

5<R<7 kpc | 7<R<9 kpc | 9<R<11 kpc

1<|Z|<2 kpc

0.5<|Z|<1 kpc

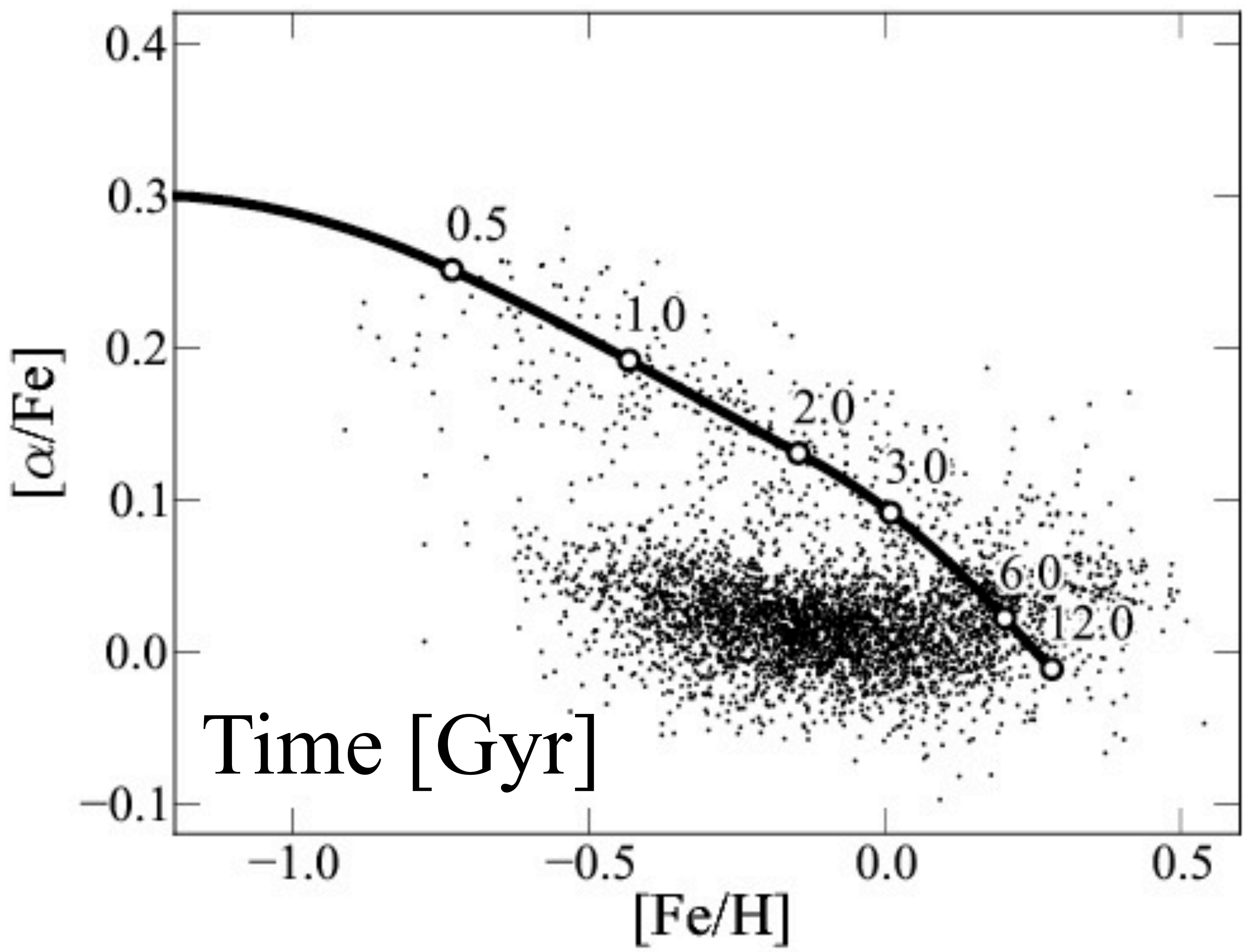
0<|Z|<0.5 kpc

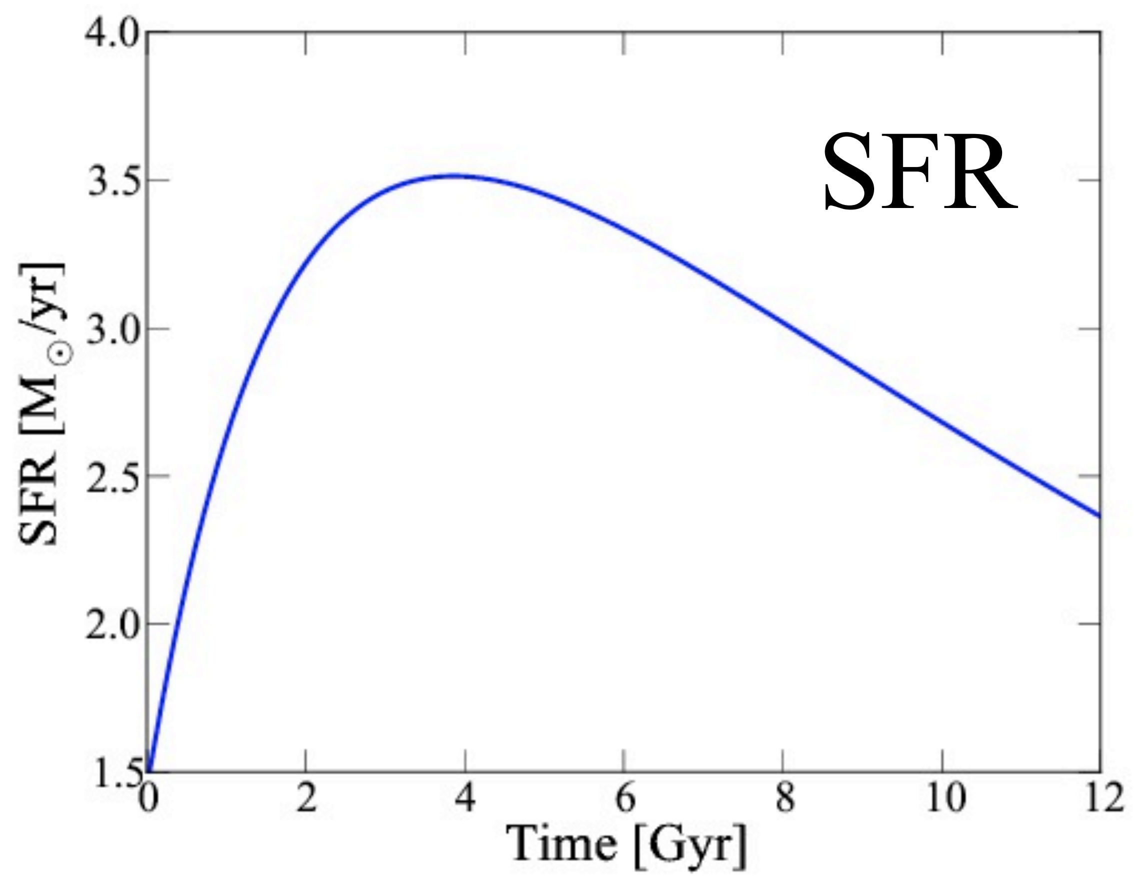


- Chemical cartography
- Look at abundance patterns across the MW disk
- Shape of the high-α stars similar in all panels
- Only varies ~10% spatially across the Galaxy

Nidever et al. (2014)

Chemical Evolution Models

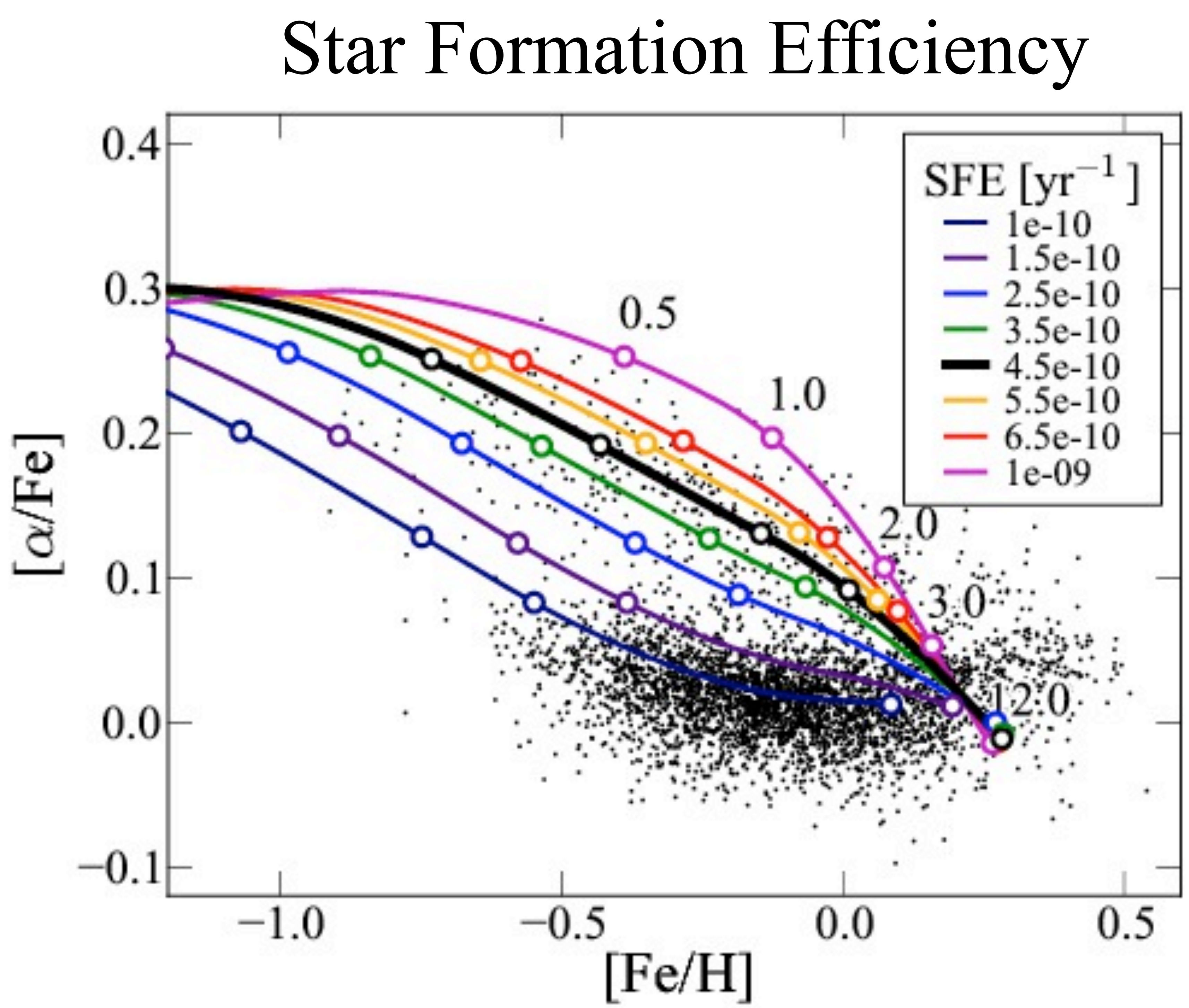


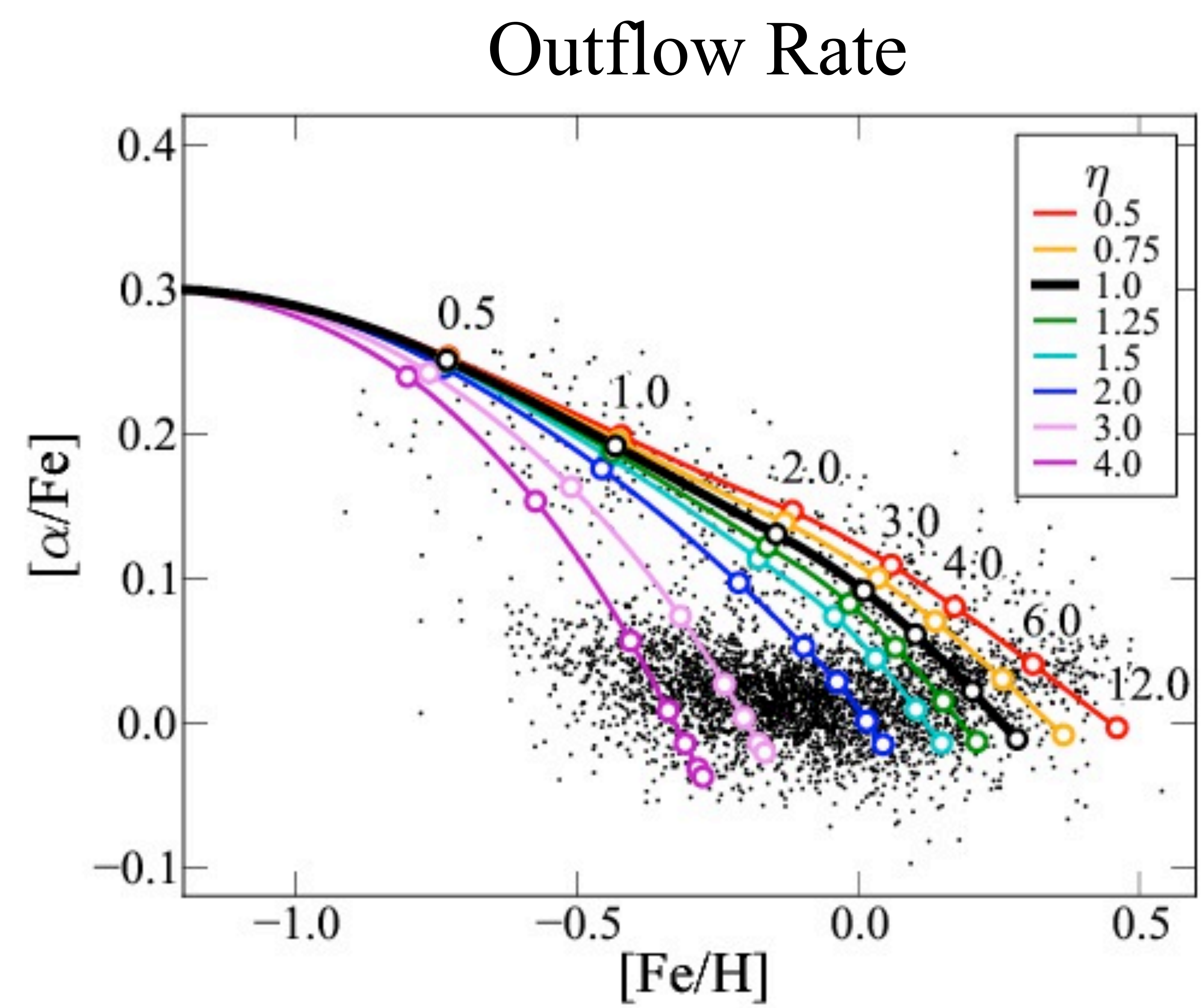


- Simple, one-zone chemical evolution model (Andrews et al. 2015, in prep.)
- SFR = SFE x M_{gas}
- Outflow = η x SFR
- Inflow exponential with e-folding time of 14 Gyr

Nidever et al. (2014)

Chemical Evolution Models

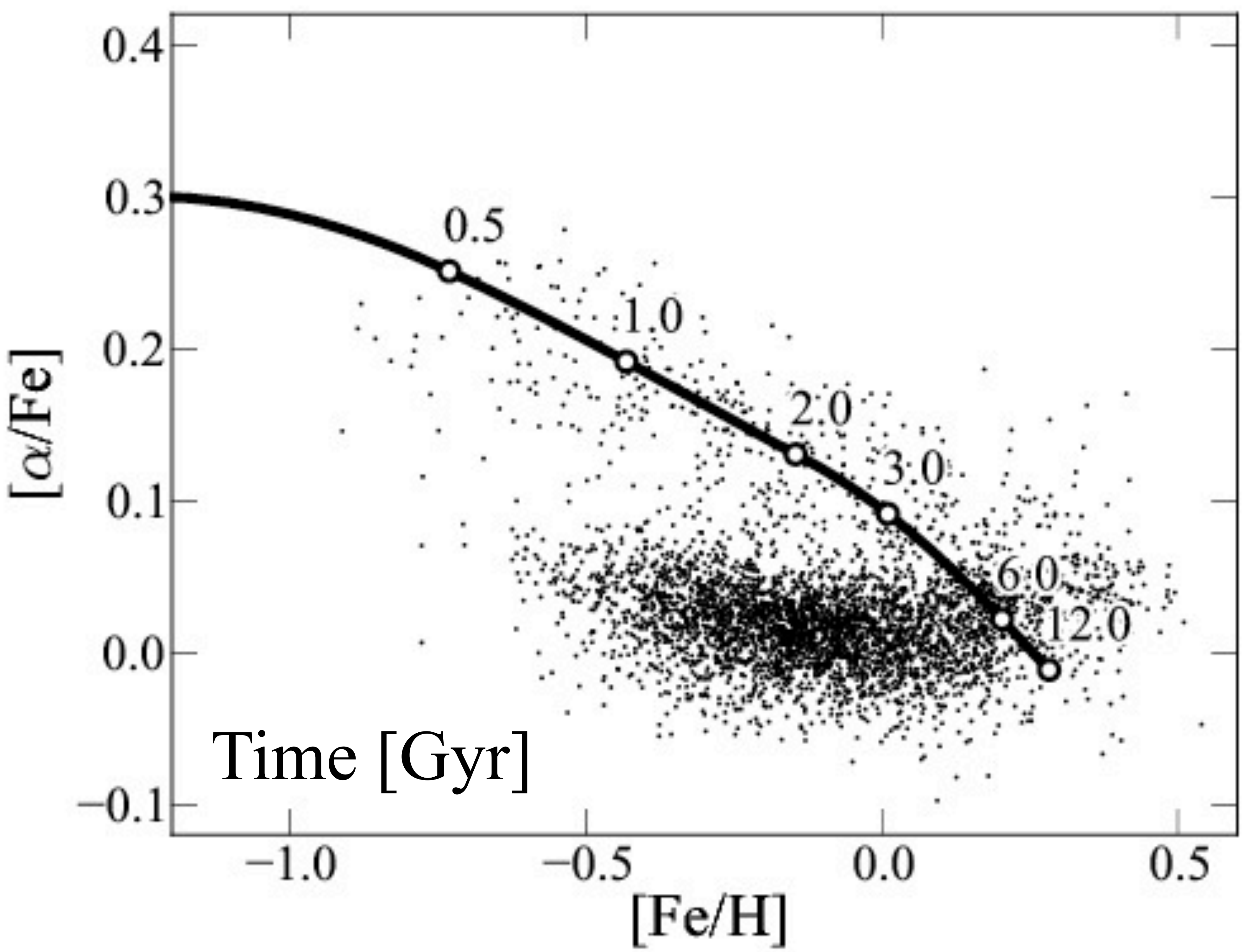




- SFE mainly affects "knee" metallicity
- Outflow rate mainly affects final metallicity
- Data can constrain outflow rate and SFE

Nidever et al. (2014)

High-α Sequence

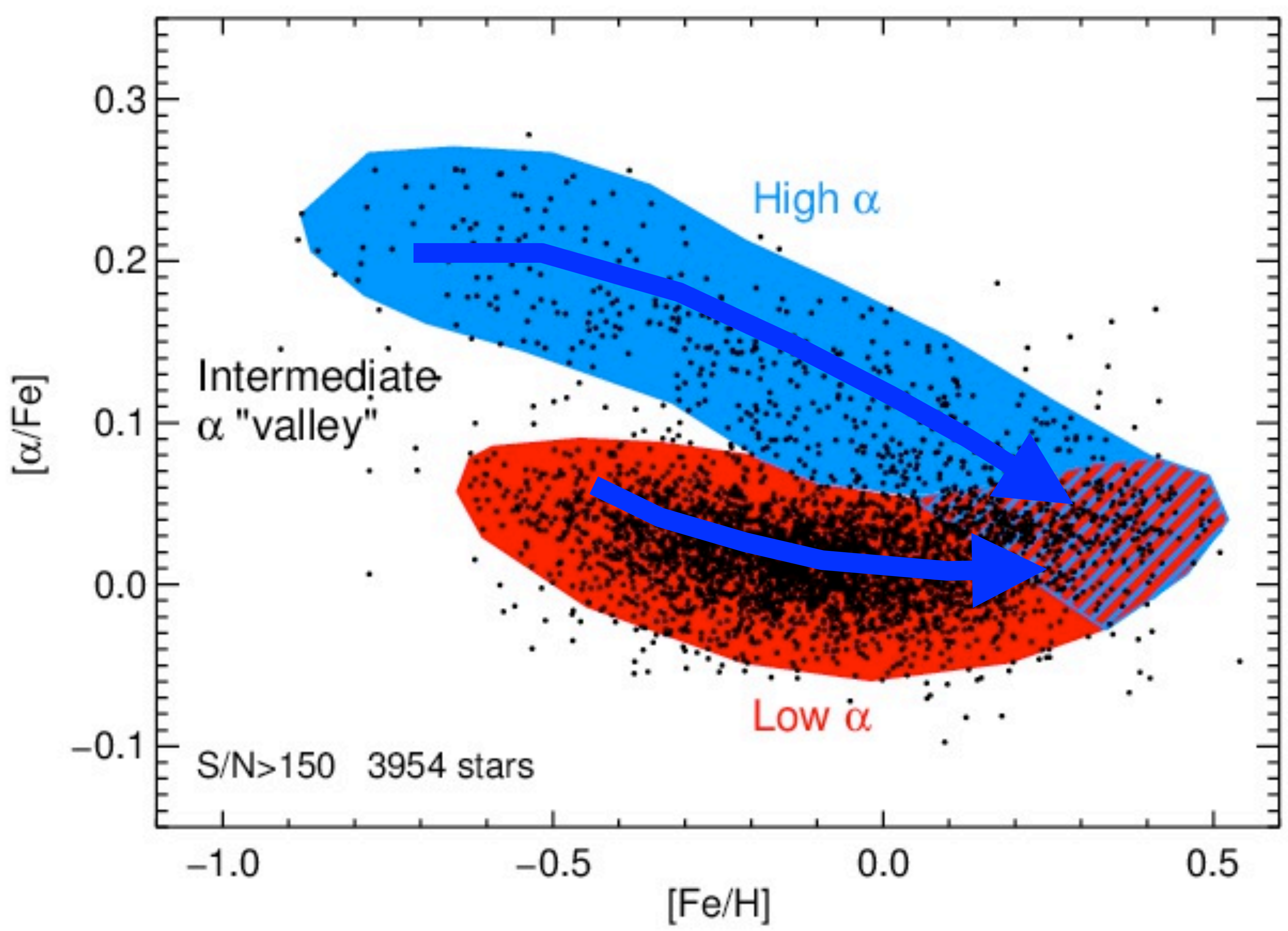


- Fit to the high-α sequence
- **SFE=4.5x10^{-10} yr^{-1}, η=1.0**
- Gas consumption timescale **~2 Gyr** (SFE^{-1})
- Only ~10% spatial variation of SFE
- Uniform, high-SFE in the early MW
- Contradicts simple expectation of higher SFE in inner Galaxy where densities are higher
- *Uniform SFE suggests star formation in well-mixed, turbulent ISM*

Nidever et al. (2014)

SFE Transition

Two Sequences



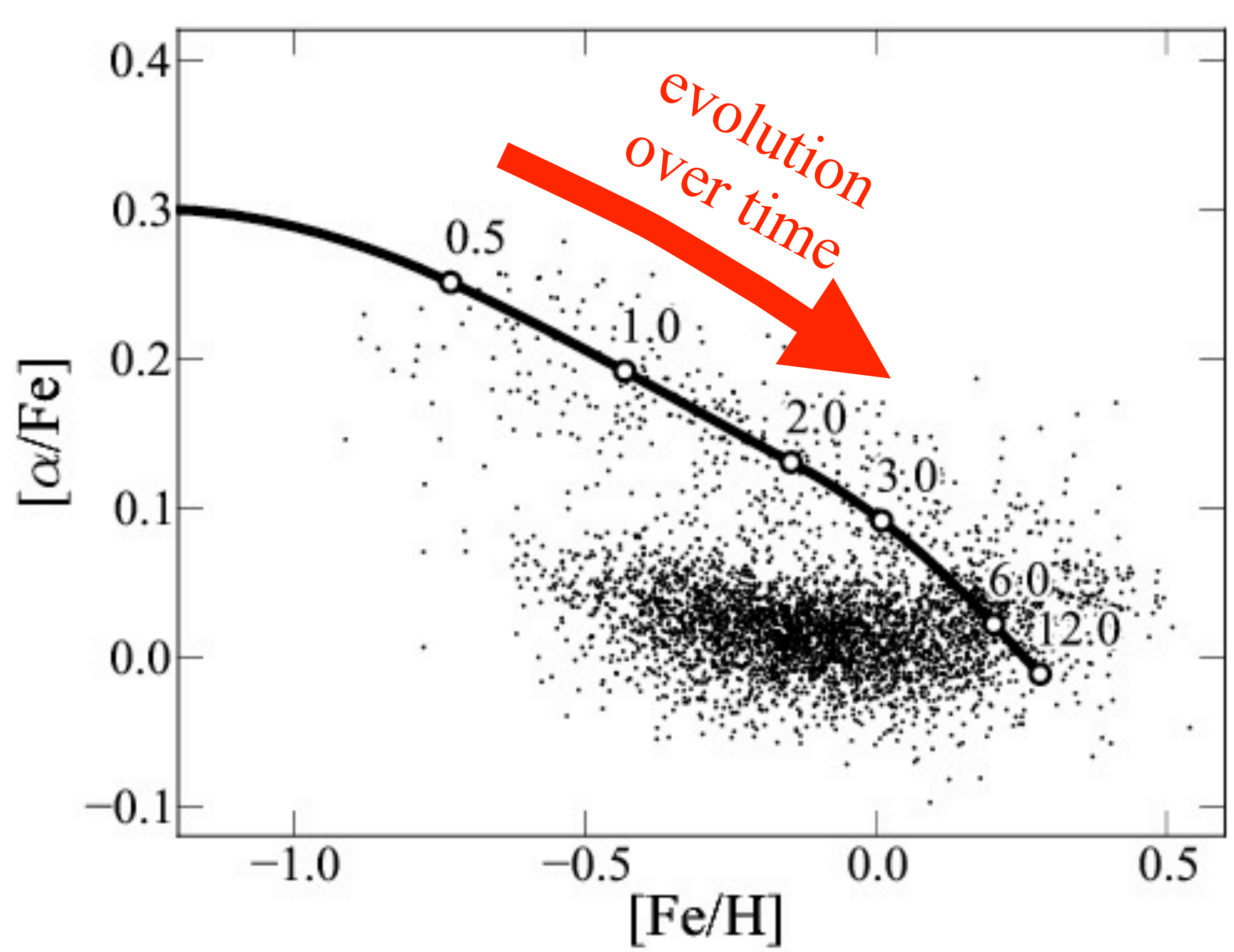
- Two α-sequences are two separate *evolutionary sequences* with different SFE:
  1. High-α ➞ High-SFE
  2. Low-α ➞ Low-SFE

Nidever et al. (2014)

SFE Transition

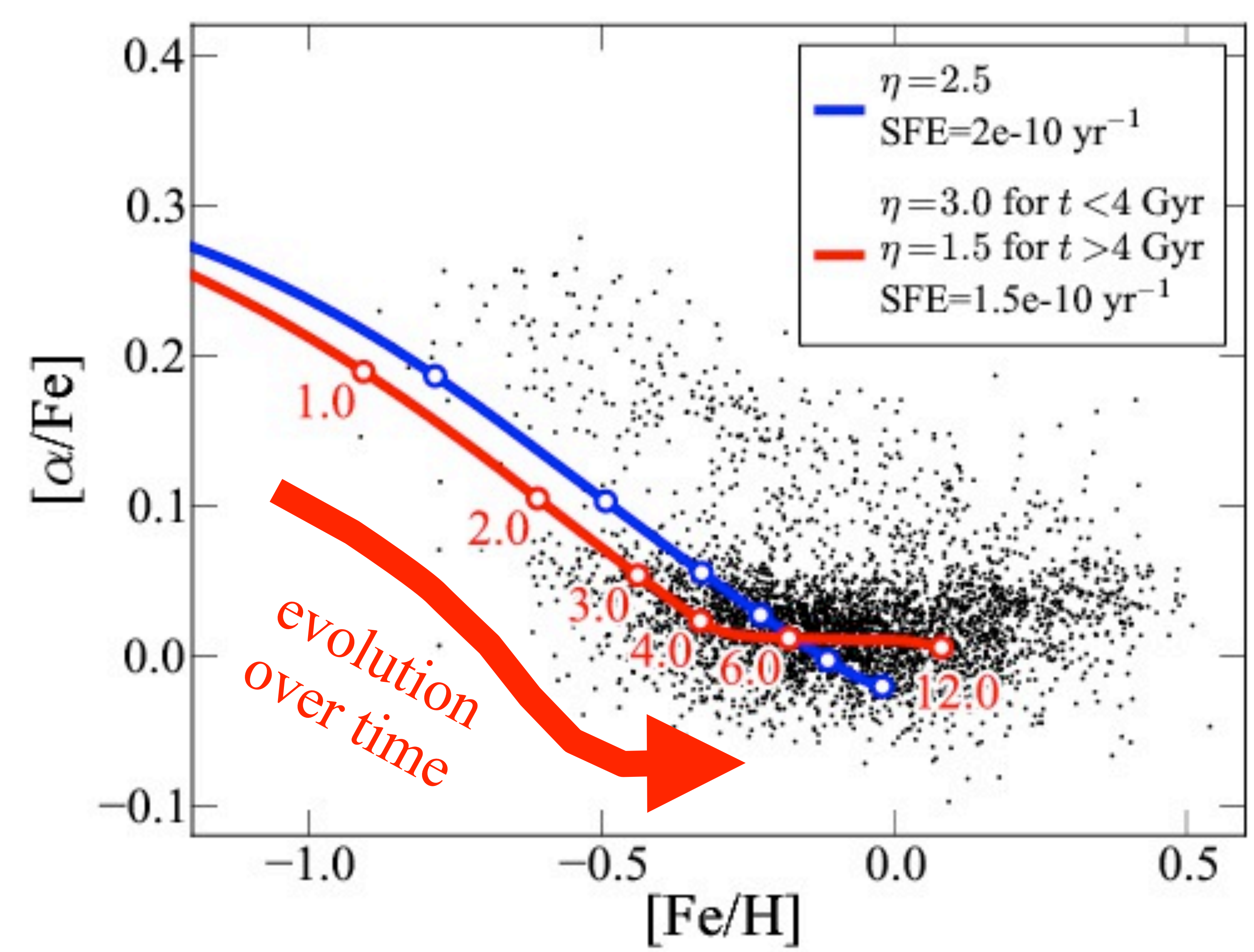
Two Evolutionary Sequences

High-α



High-SFE, 4.5x10^{-10}

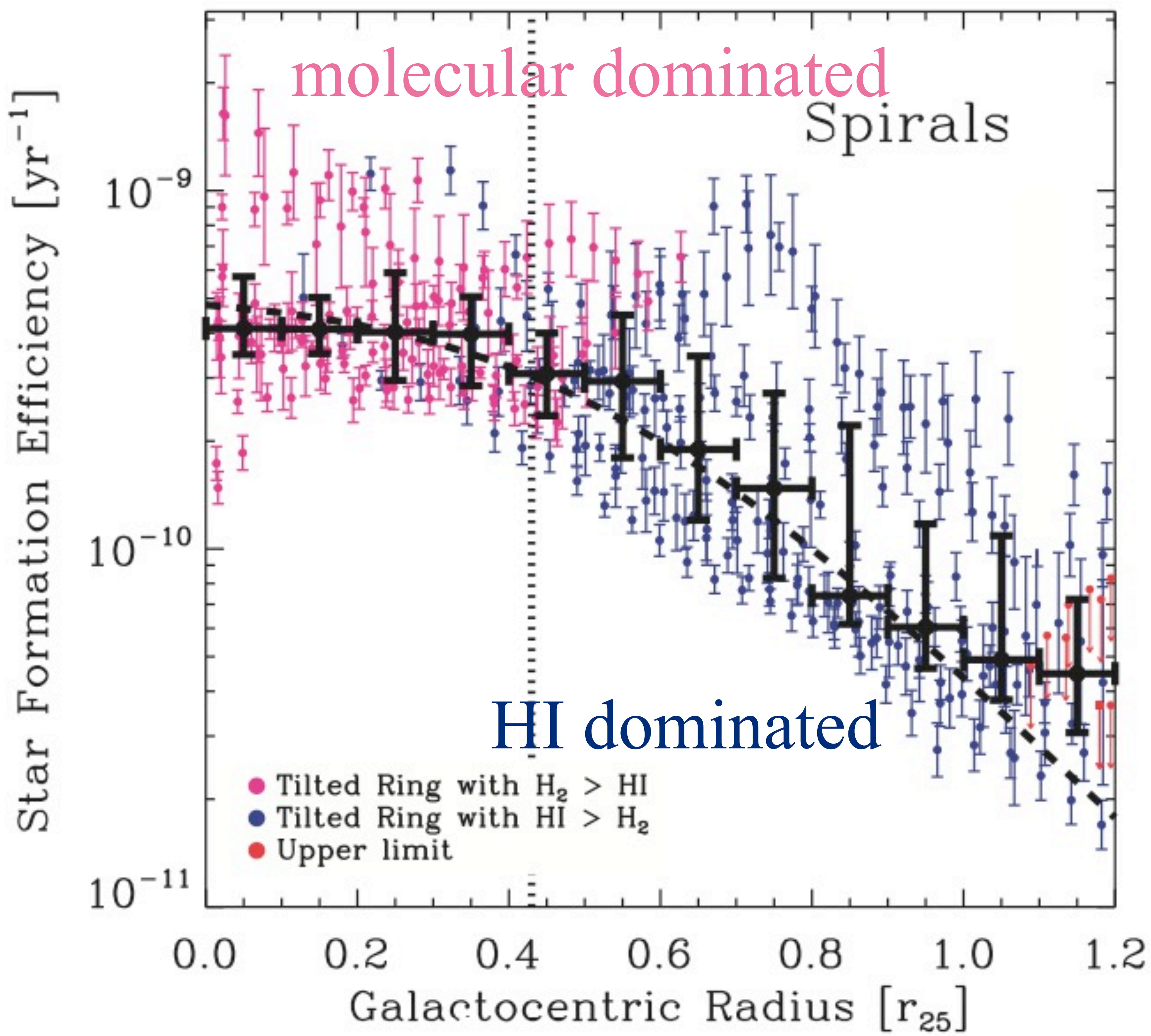
Low-α



Low-SFE, ~1.5x10^{-10}

Nidever et al. (2014)

SFE Transition



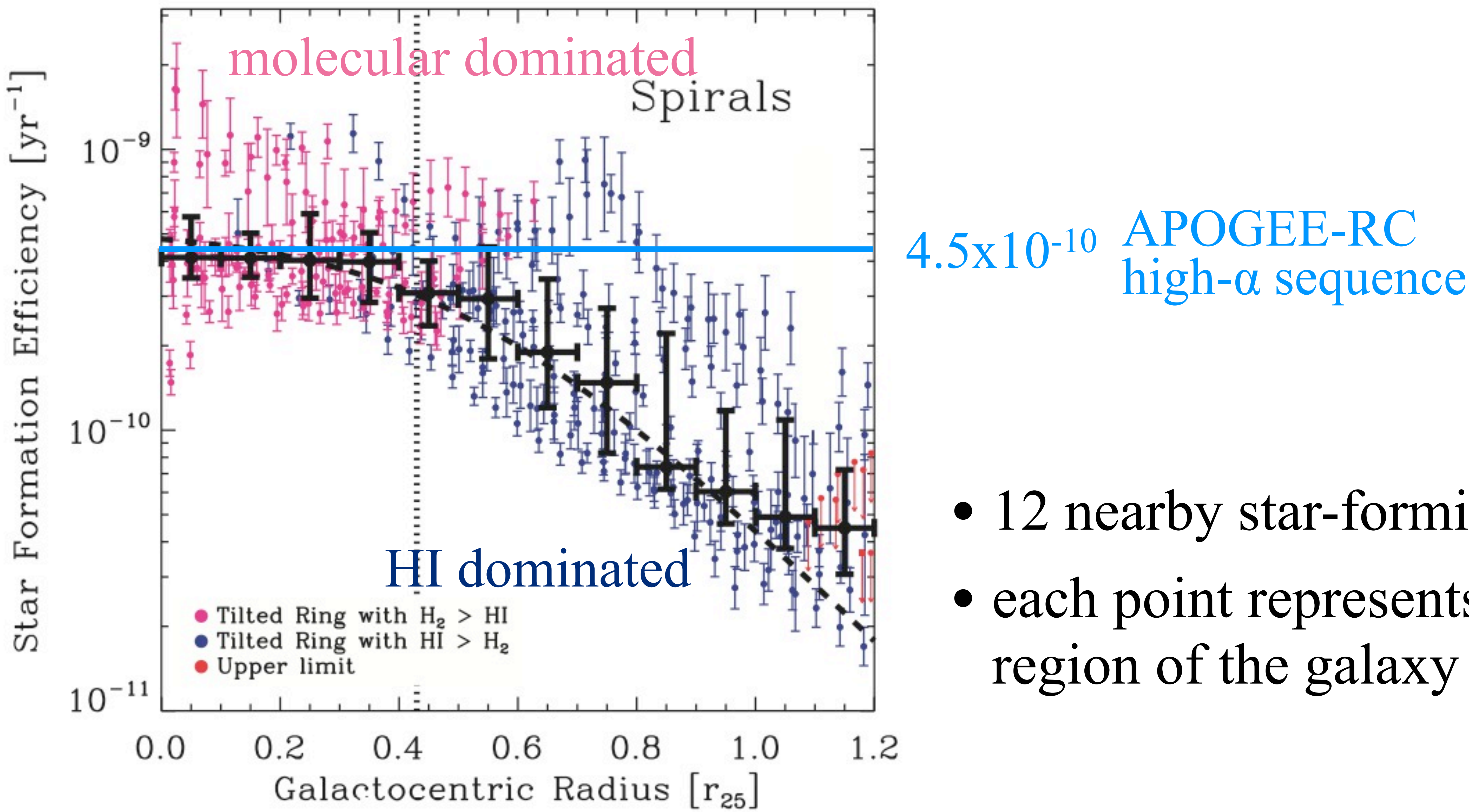
Leroy et al. (2008)

- 12 nearby star-forming spirals
- each point represents a 800pc x 800pc region of the galaxy

Nidever et al. (2014)

SFE Transition

- High-α sequence SFE very close to the nearly-constant SFE in molecular-dominated regions of nearly galaxies (inner regions)



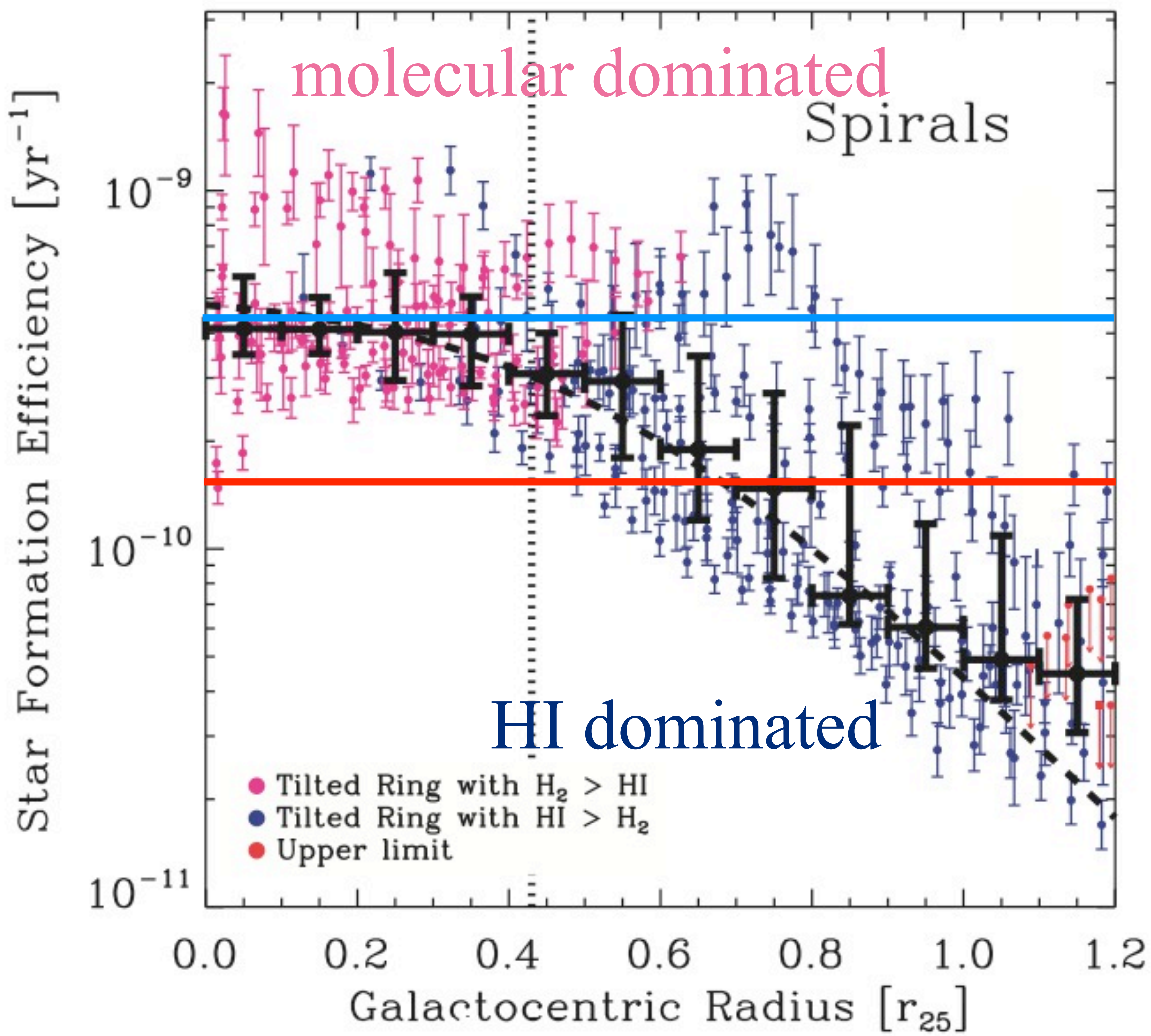
- 12 nearby star-forming spirals
- each point represents a 800pc x 800pc region of the galaxy

Leroy et al. (2008)

Nidever et al. (2014)

SFE Transition

- Low-α sequence SFE in middle of HI-dominated region, varies with radius, outer regions



4.5×10^{-10} APOGEE-RC high-α sequence

1.5×10^{-10} APOGEE-RC low-α sequence

- 12 nearby star-forming spirals
- each point represents a 800pc x 800pc region of the galaxy

Leroy et al. (2008)

Nidever et al. (2014)

SFE Transition

Two sequences

1. High-α sequence
   - High-SFE
   - Inner Galaxy
   - *Molecular-dominated*

2. Low-α sequence
   - Low-SFE
   - Outer Galaxy
   - *HI-dominated*

Leroy et al. (2008)

Nidever et al. (2014)

SFE Transition

Two sequences

1. High-α sequence
   - High-SFE
   - Inner Galaxy
   - *Molecular-dominated*
   - *Older, ~8-12 Gyr*

2. Low-α sequence
   - Low-SFE
   - Outer Galaxy
   - *HI-dominated*
   - *Younger, ~1-8 Gyr*

Leroy et al. (2008)

Haywood et al. (2013)

Nidever et al. (2014)

SFE Transition

Two sequences

1. High-α sequence
   - High-SFE
   - Inner Galaxy
   - *Molecular-dominated*
   - *Older, ~8-12 Gyr*

2. Low-α sequence
   - Low-SFE
   - Outer Galaxy
   - *HI-dominated*
   - *Younger, ~1-8 Gyr*

Leroy et al. (2008)

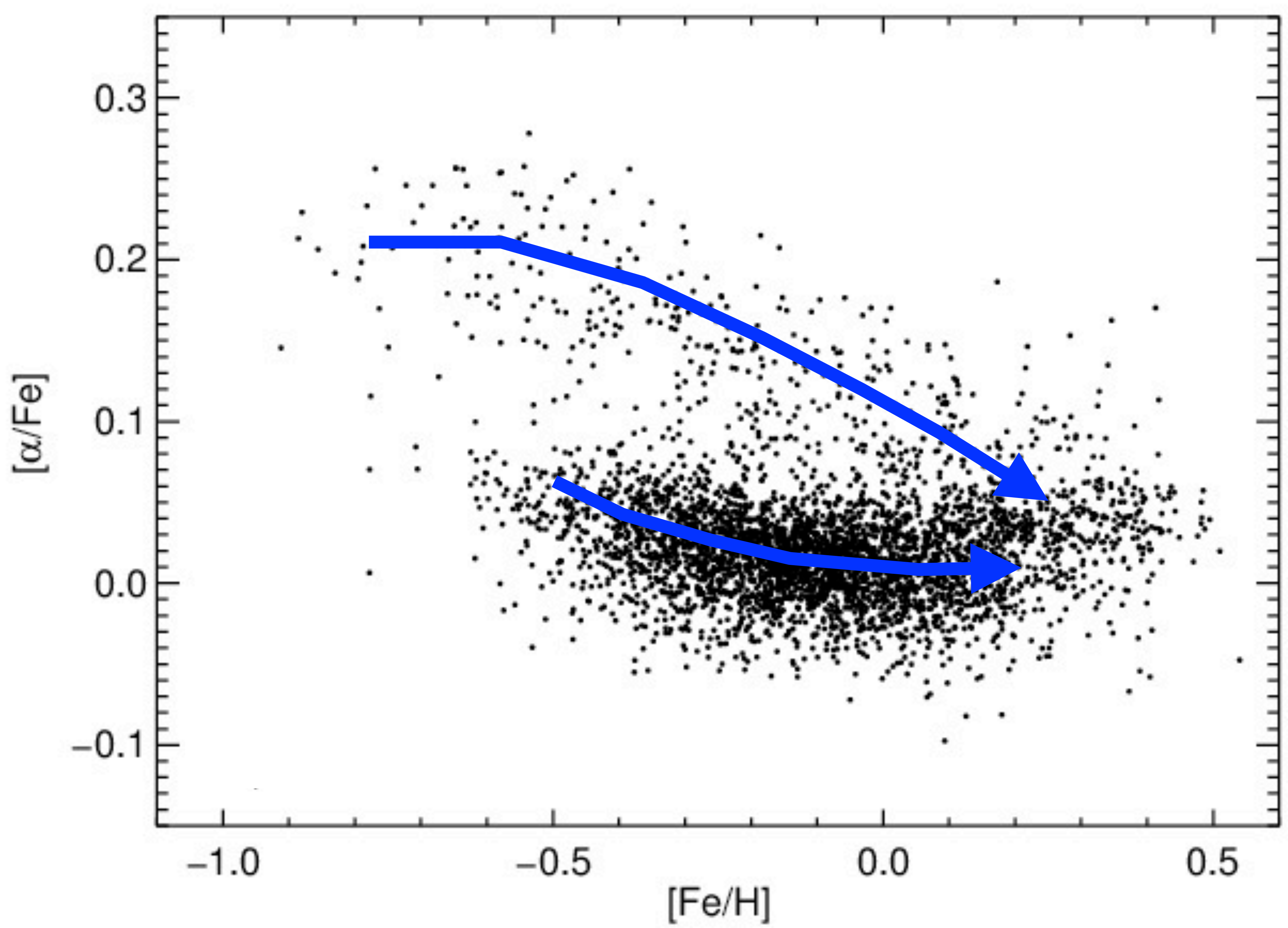
Haywood et al. (2013)

➡**SFE transition**, ~8 Gyr ago (but position dependent?)
molecular-dominated → HI-dominated SF

Nidever et al. (2014)

SFE Transition

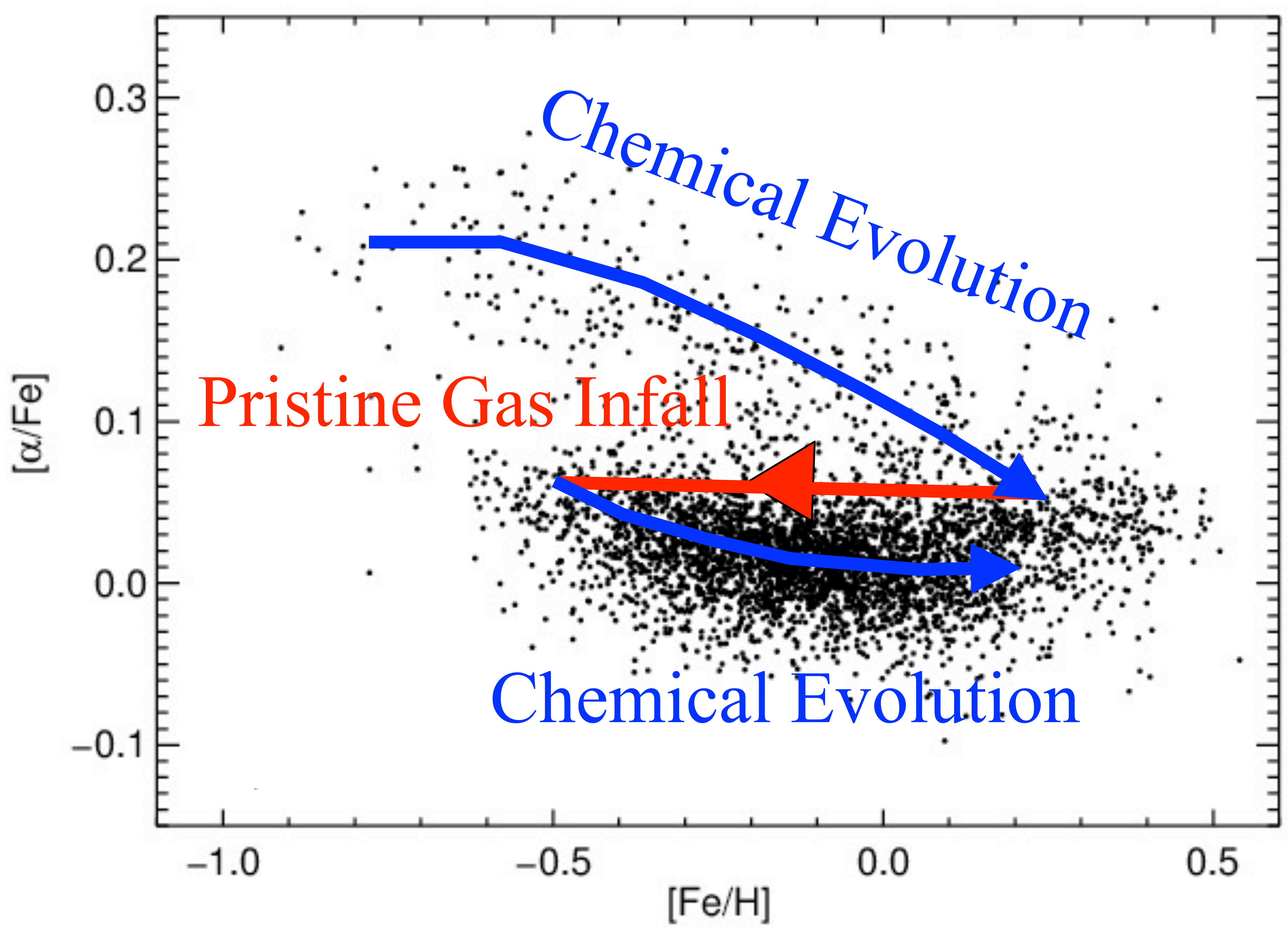
- To also match the chemistry, need gas infall at SFE transition



Nidever et al. (2014)

SFE Transition

- To also match the chemistry, need gas infall at SFE transition
- Infall of pristine gas, lower [Fe/H], [α/Fe] constant
- Low SFE and SNIa from older "High-α" population keep α low

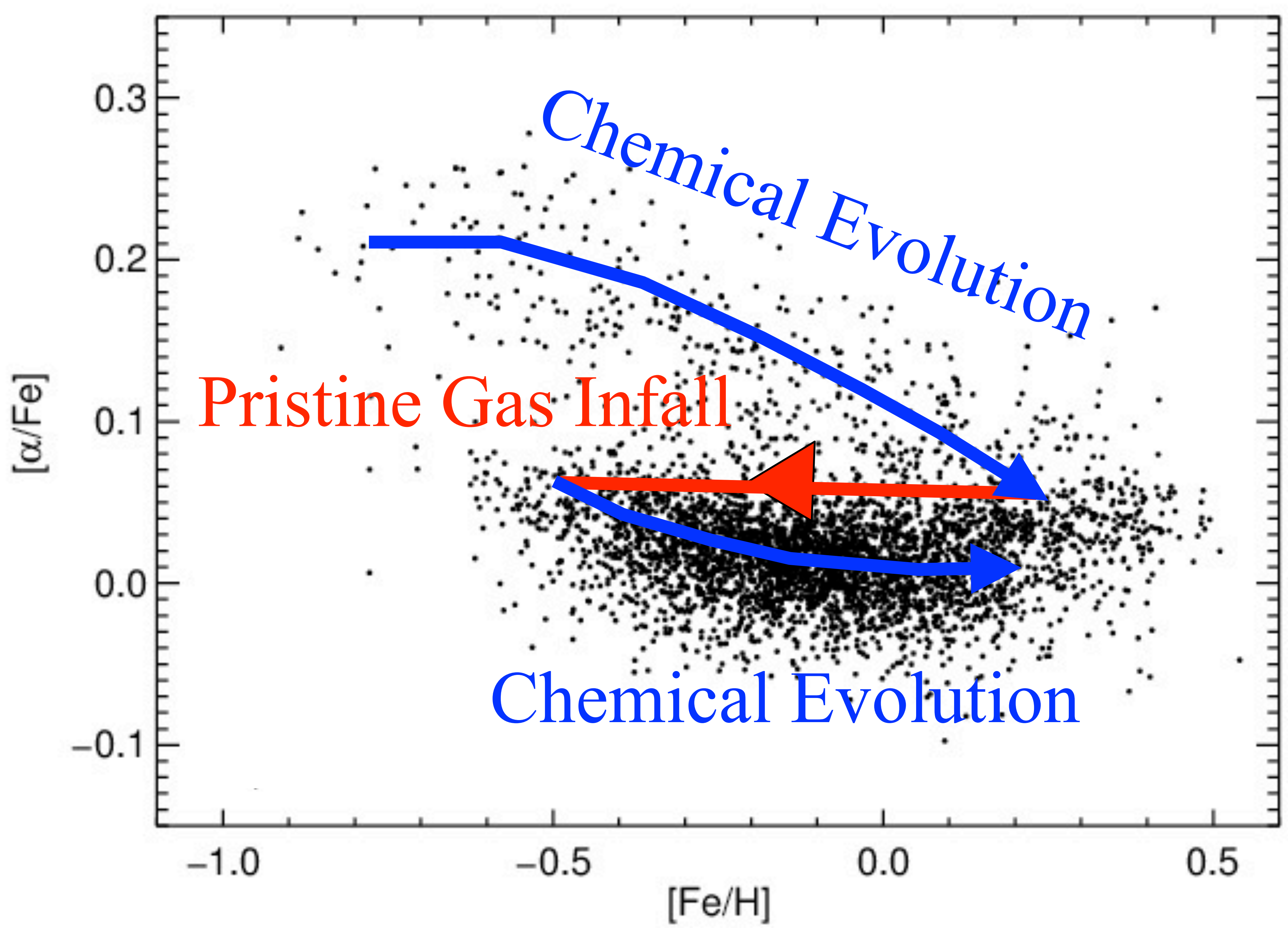


- Infall of pristine gas ~8 Gyr ago

Nidever et al. (2014)

SFE Transition

- Infall of pristine gas combined with gas depletion from early rapid SF could have triggered the transition
  (also suggested by Chiappini et al. 2009, two-infall model)

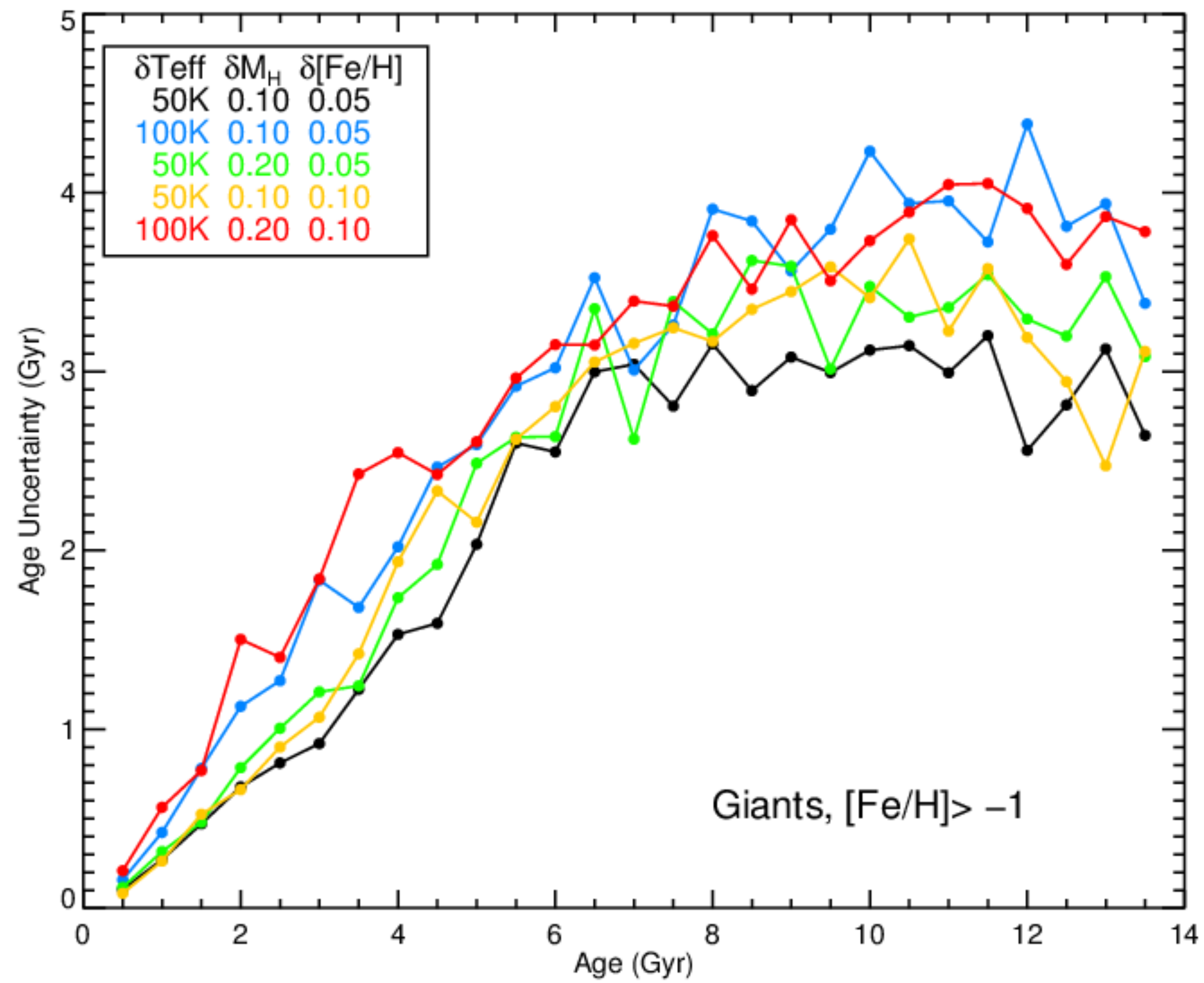


- Infall of pristine gas ~8 Gyr ago

Nidever et al. (2014)

Ages with Gaia

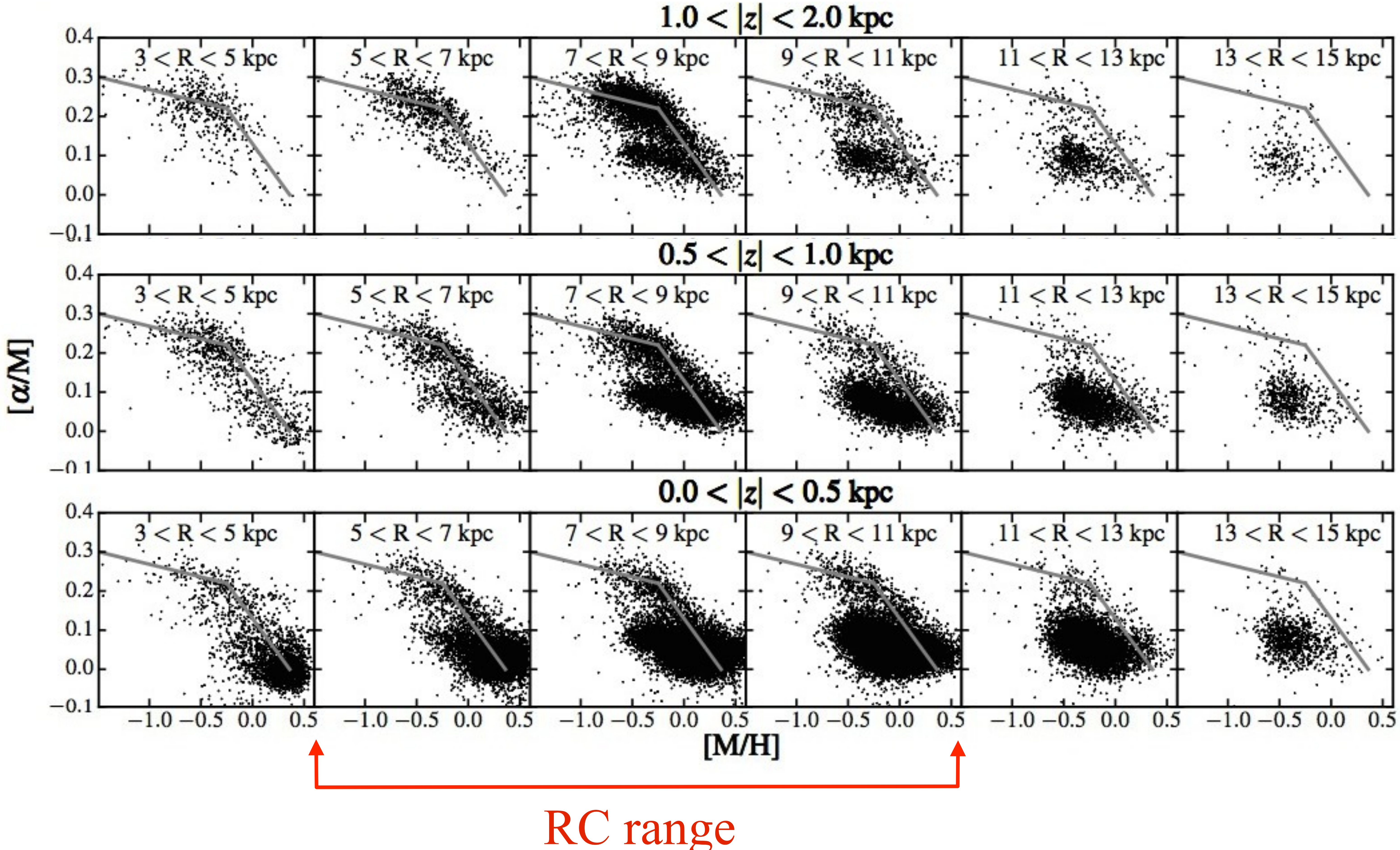
APOGEE RGB Age Uncertainties



Ages from Teff, logg, [Fe/H], distance, photometry and isochrones

RGB Chemical Pattern

- Extending the reach with ~70,000 RGB stars, 3<R<15 kpc

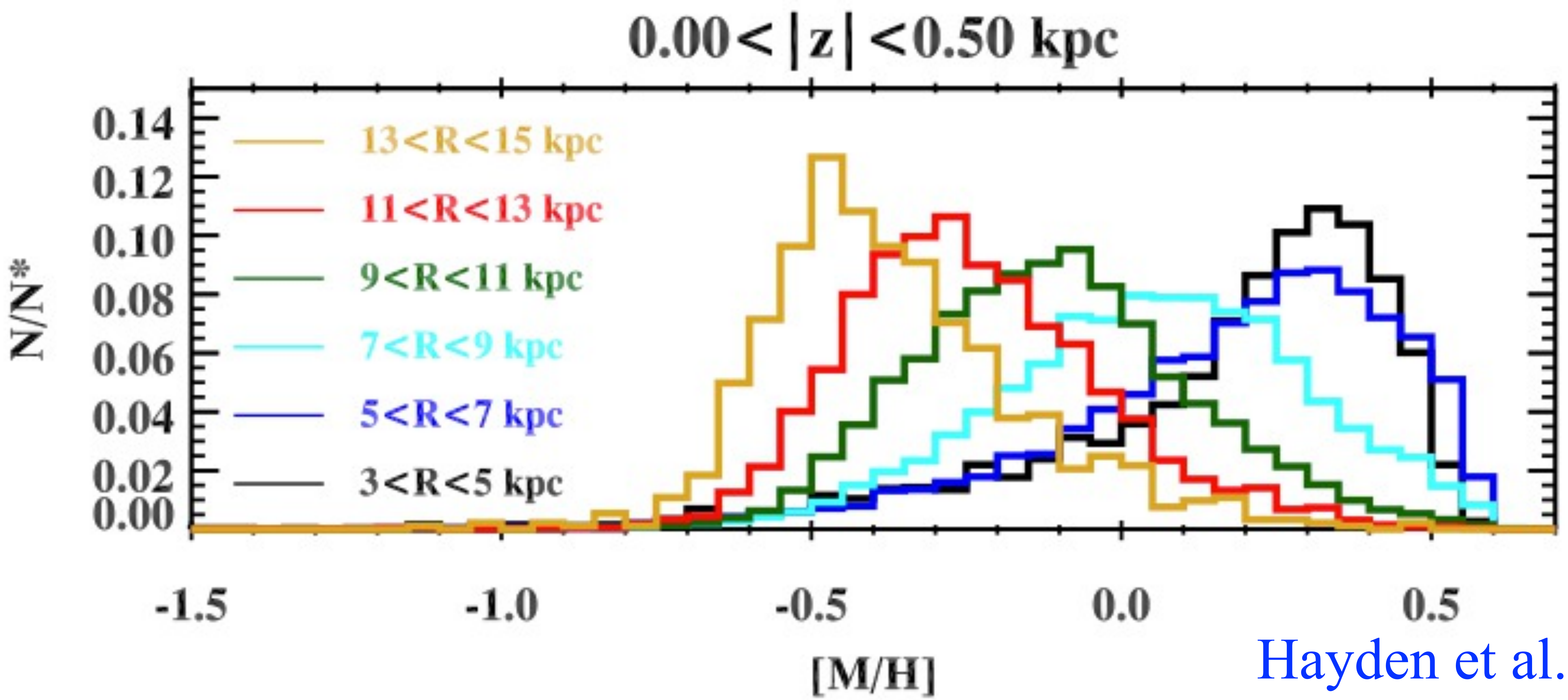


Hayden et al. (2015), in prep.

Metallicity Distribution Functions

MDF shape change with radius

- Skew-negative in inner galaxy
- Roughly Gaussian at solar circle
- Skew-positive in outer galaxy

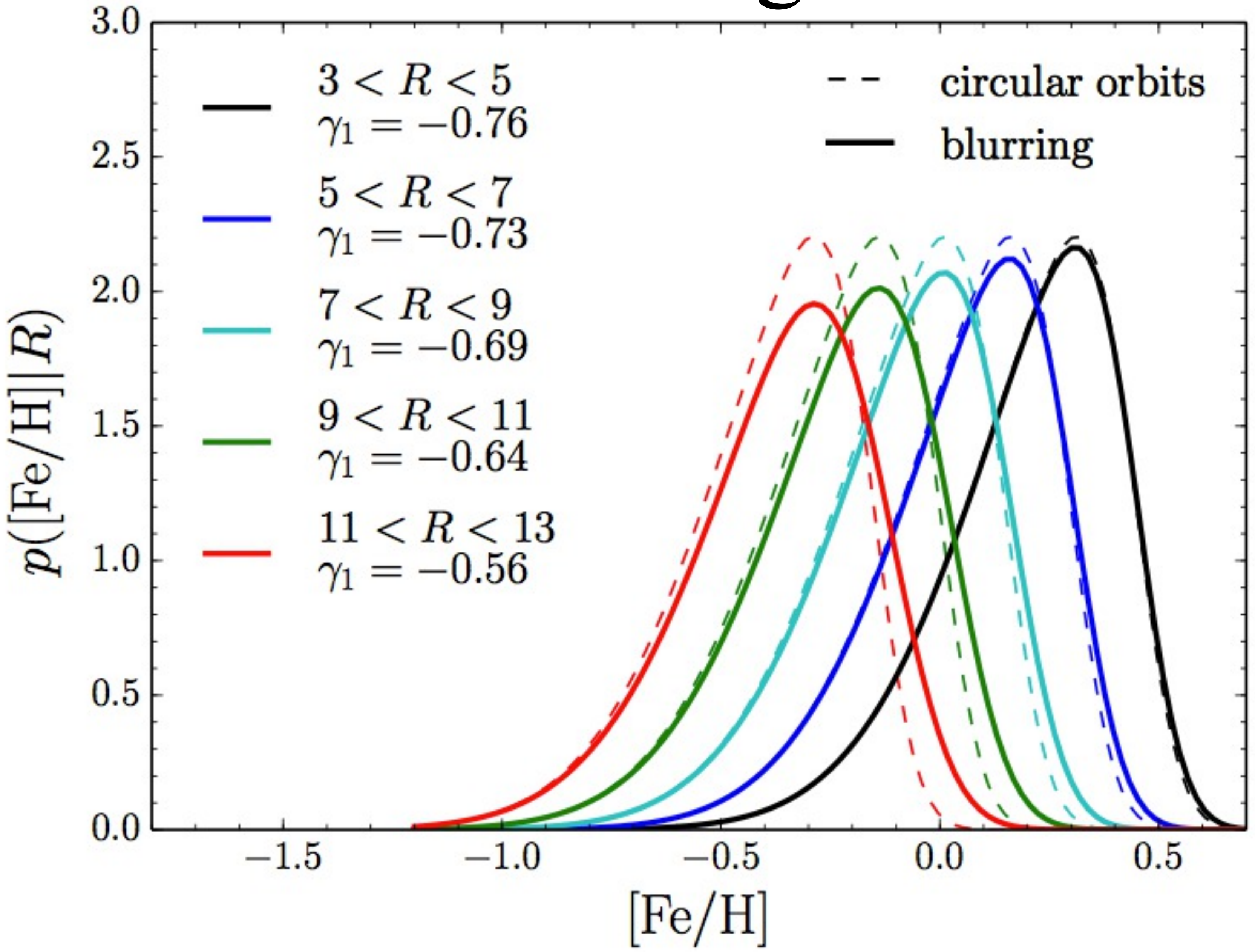


Hayden et al. (2015), in prep.

Metallicity Distribution Functions

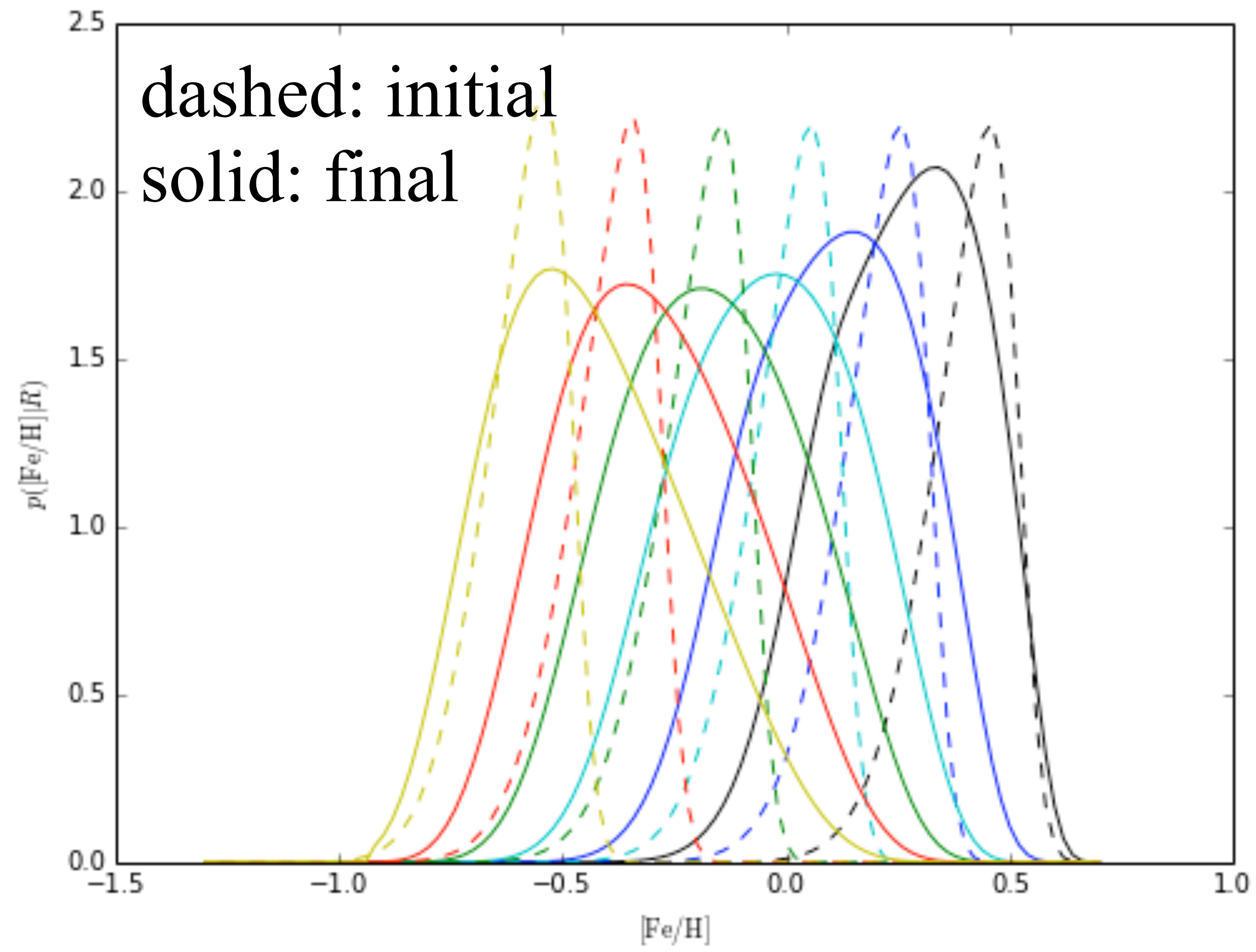
- Blurring (asymmetric drift) does *not* work
- Churning (radial migration) *reproduces* the observed behavior

Blurring



blurring with 30 km/s velocity dispersion

Churning



analysis by J. Bovy

Hayden et al. (2015), in prep.

Conclusions

- α bimodality at intermediate metallicity, throughout MW
- Little spatial variation of high-α sequence chemical pattern (~10%)
- Suggests early MW stellar evolution was in well-mixed, turbulent, molecular-dominated environment
- Can explain low/high-α sequences SFE-transition from high to low SFE ~8 Gyr ago
- MDFs skewness change with radius, inner-negative, outer-positive
- Evidence for radial migration

Nidever et al. (2014)   Hayden et al. (2015), in prep.

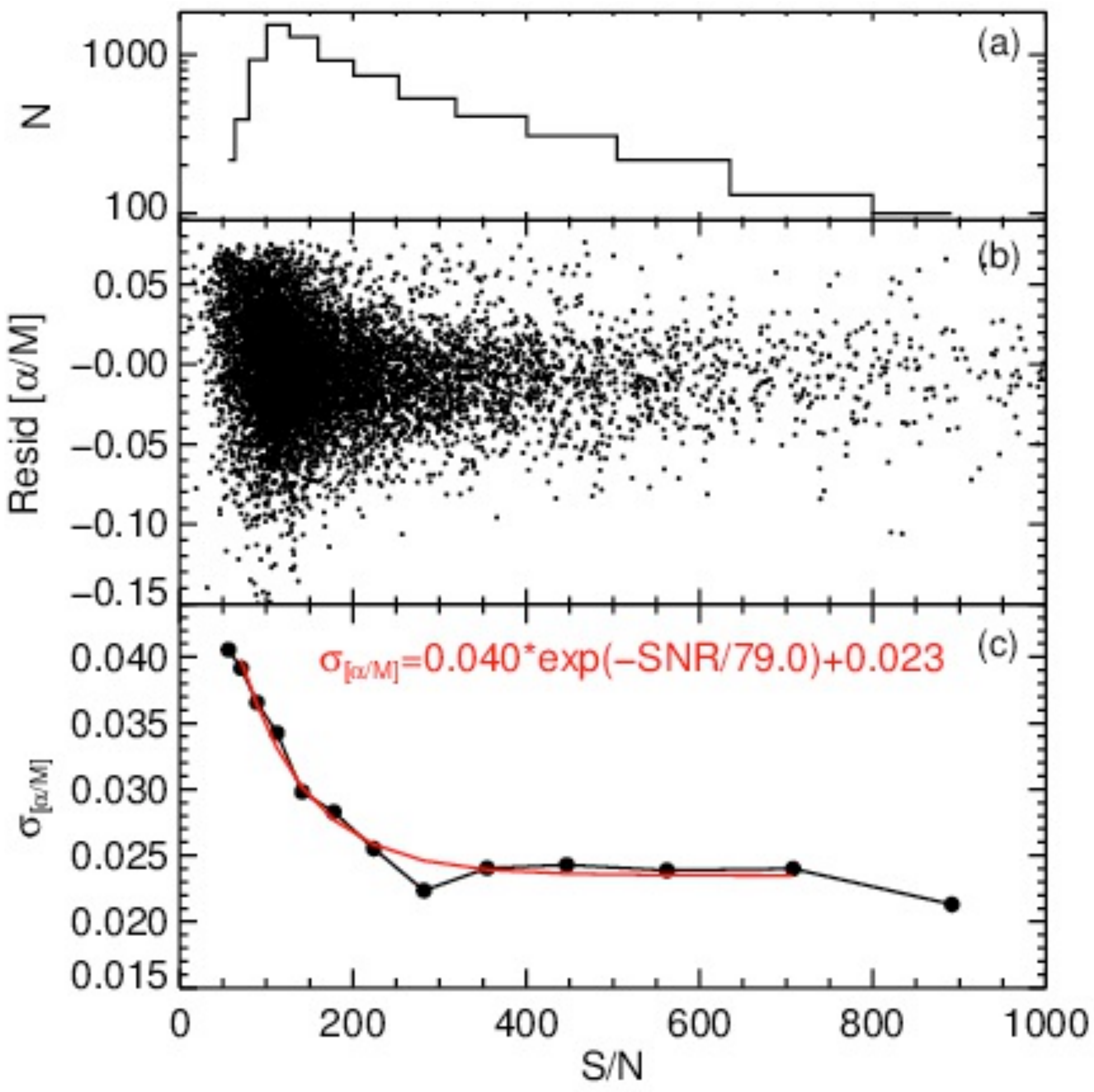
The End

APOGEE

SDSSIII

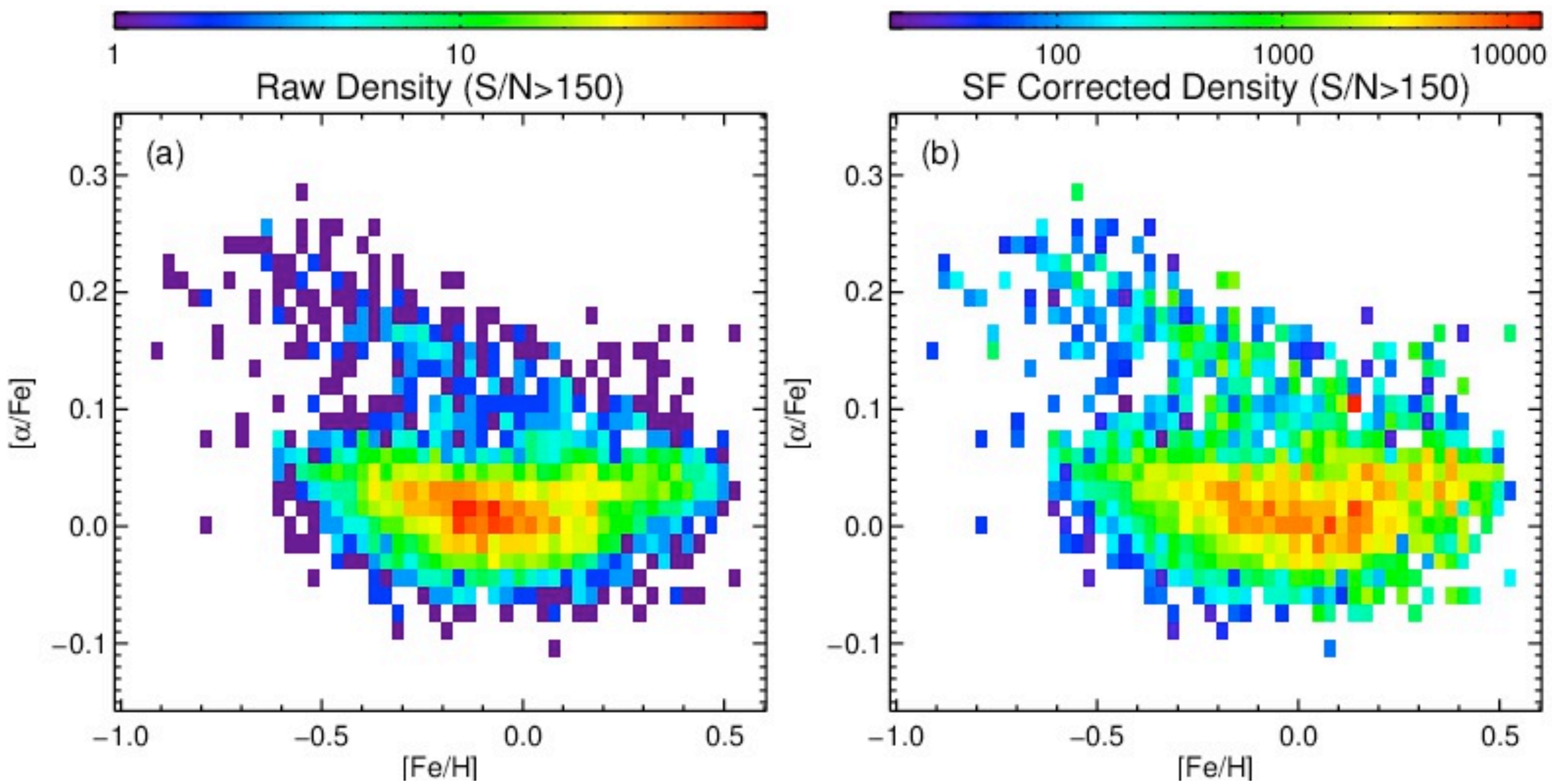
Backup Slides

α Abundance Precision



- Abundance precision by looking at scatter in low-alpha sequence
- Most stars have $\sigma_{[\alpha/M]}$~0.035 dex
- This precision important for studying abundance patterns

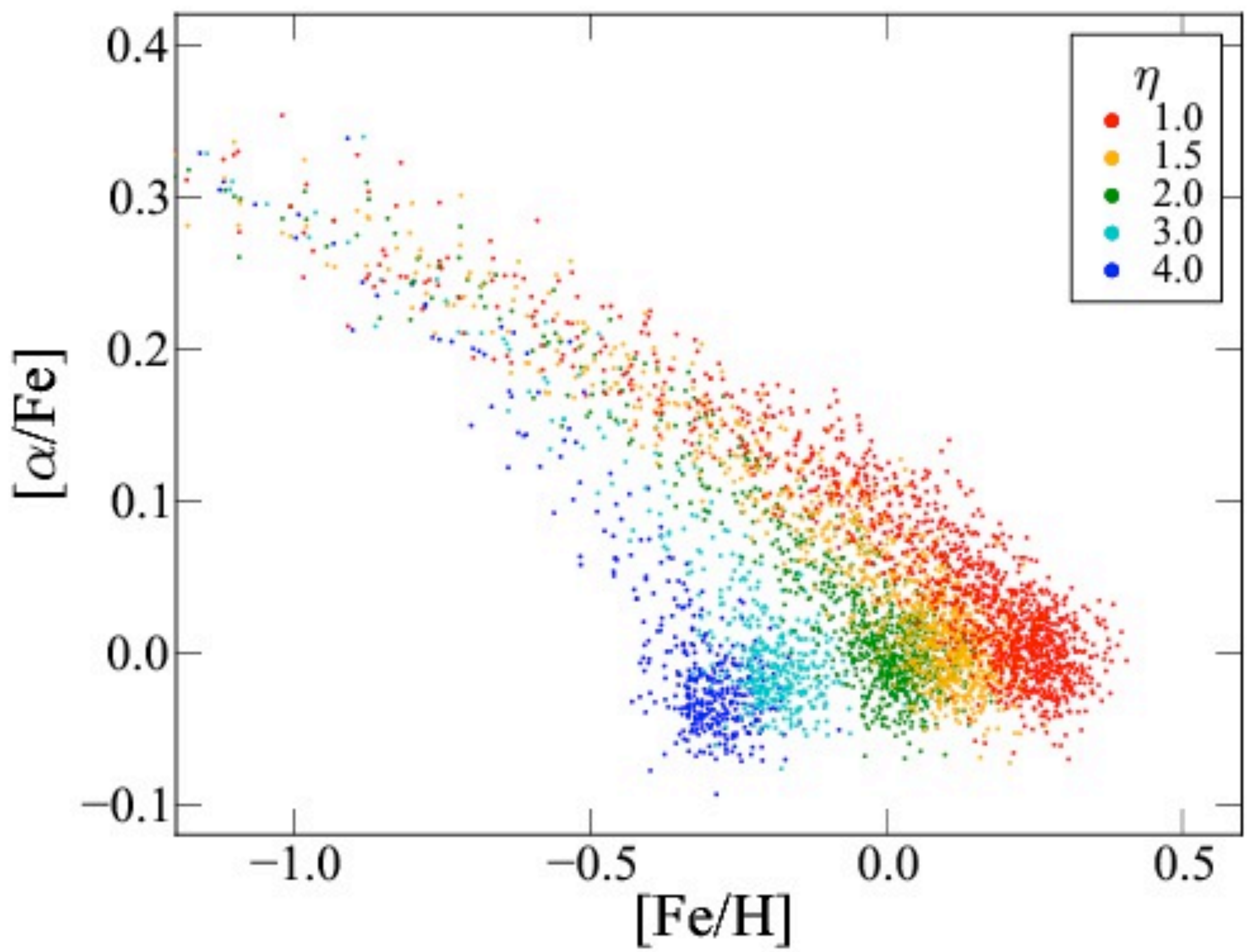
Selection Function



Selection Function Effects

- Correcting for the selection function does not change the qualitative behavior in the α-metallicity plane
- Will work with raw numbers from here on

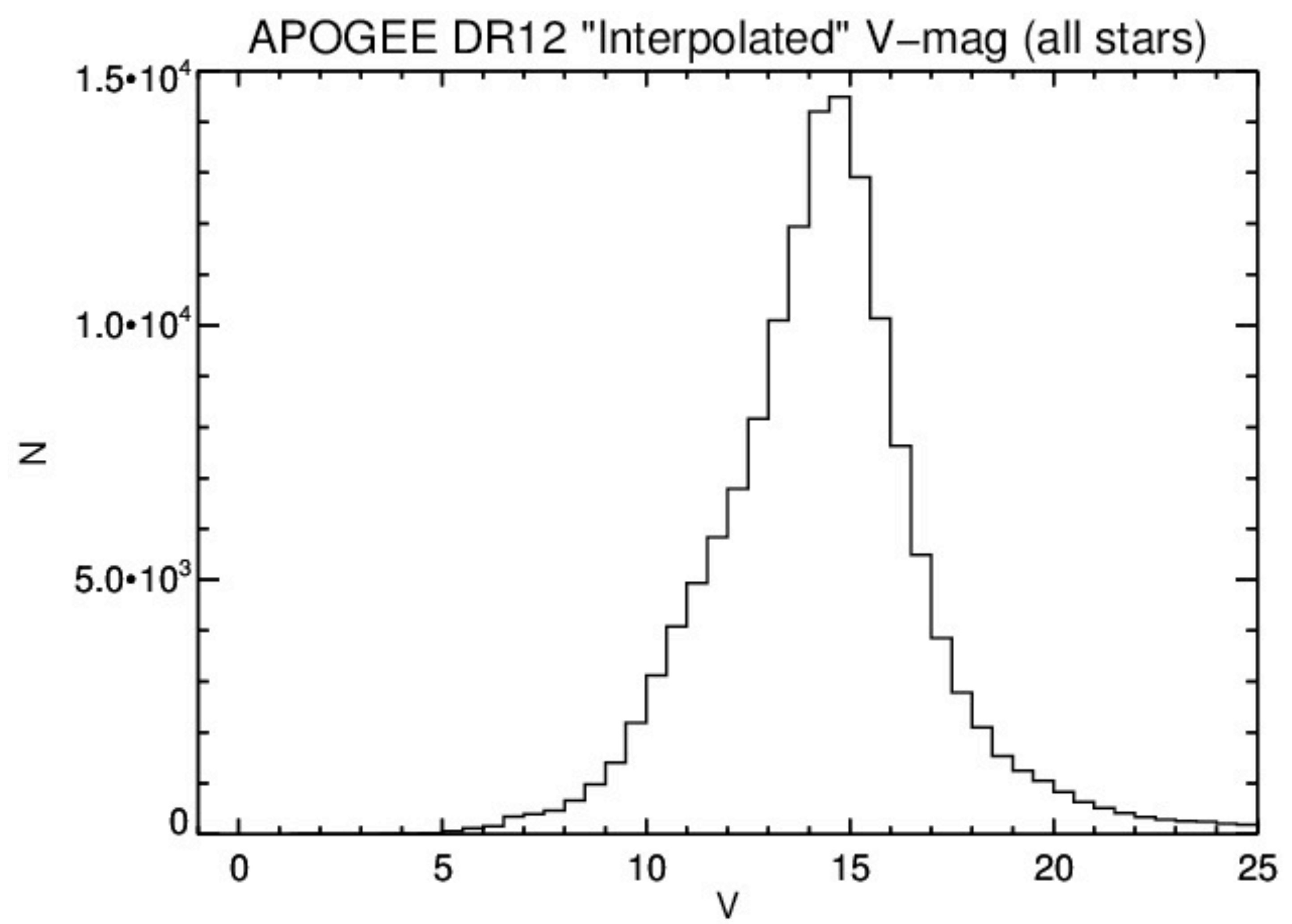
Superposition of multiple populations

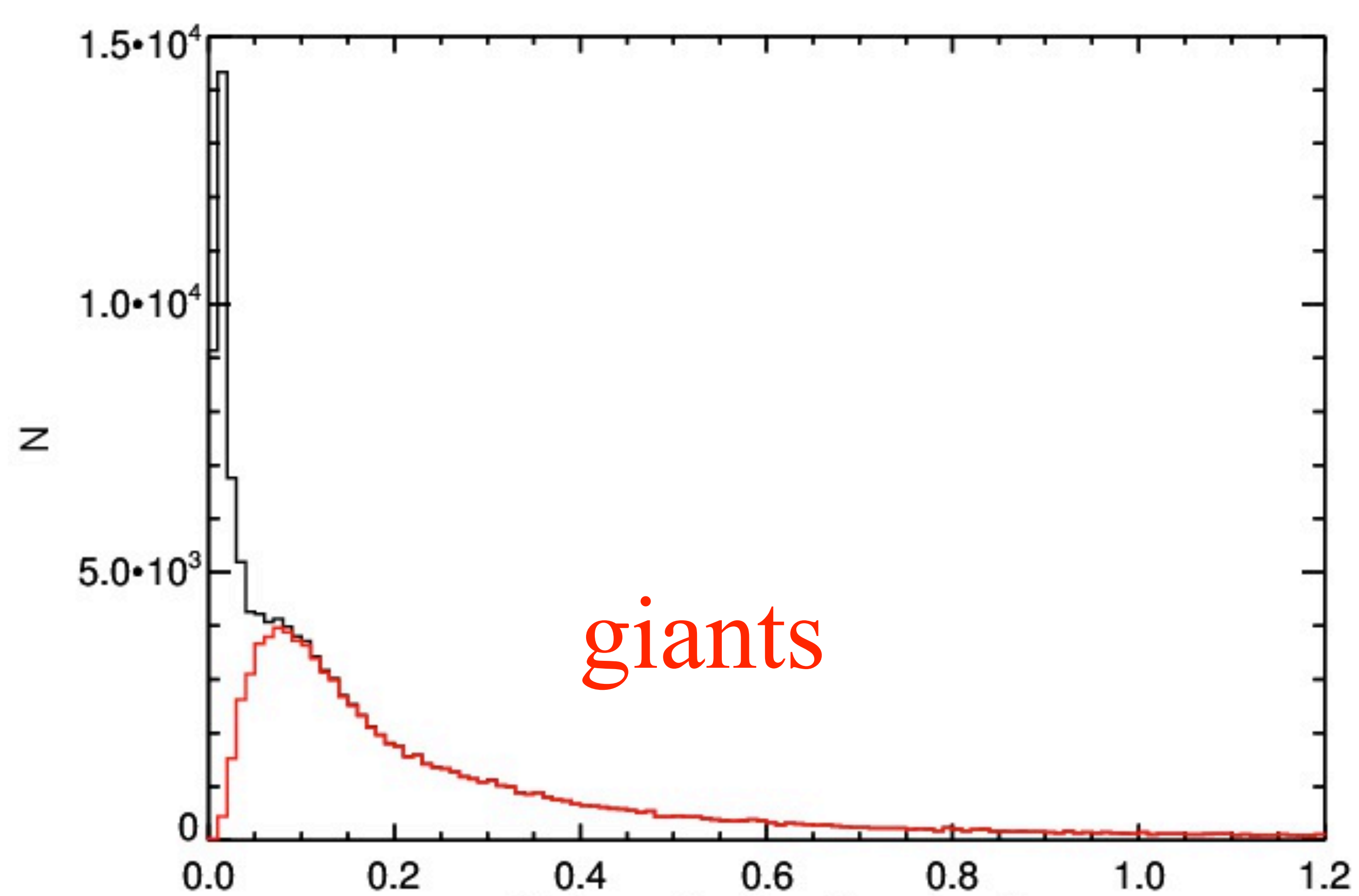


Stars drawn randomly from 5 models

- Low-α group ***not*** an evolutionary sequence, but
- Superposition of multiple populations with different star formation and enrichment histories
- Each population has different outflow rate
- SFR exp. decline (η=1-2), constant (η=3,4)
- Radially mixed
- If outflow rate increases with radius then can *reproduce the metallicity gradient*
- Similar to Schönrich & Binney (2009a)
- Mostly reproduces the data qualitatively

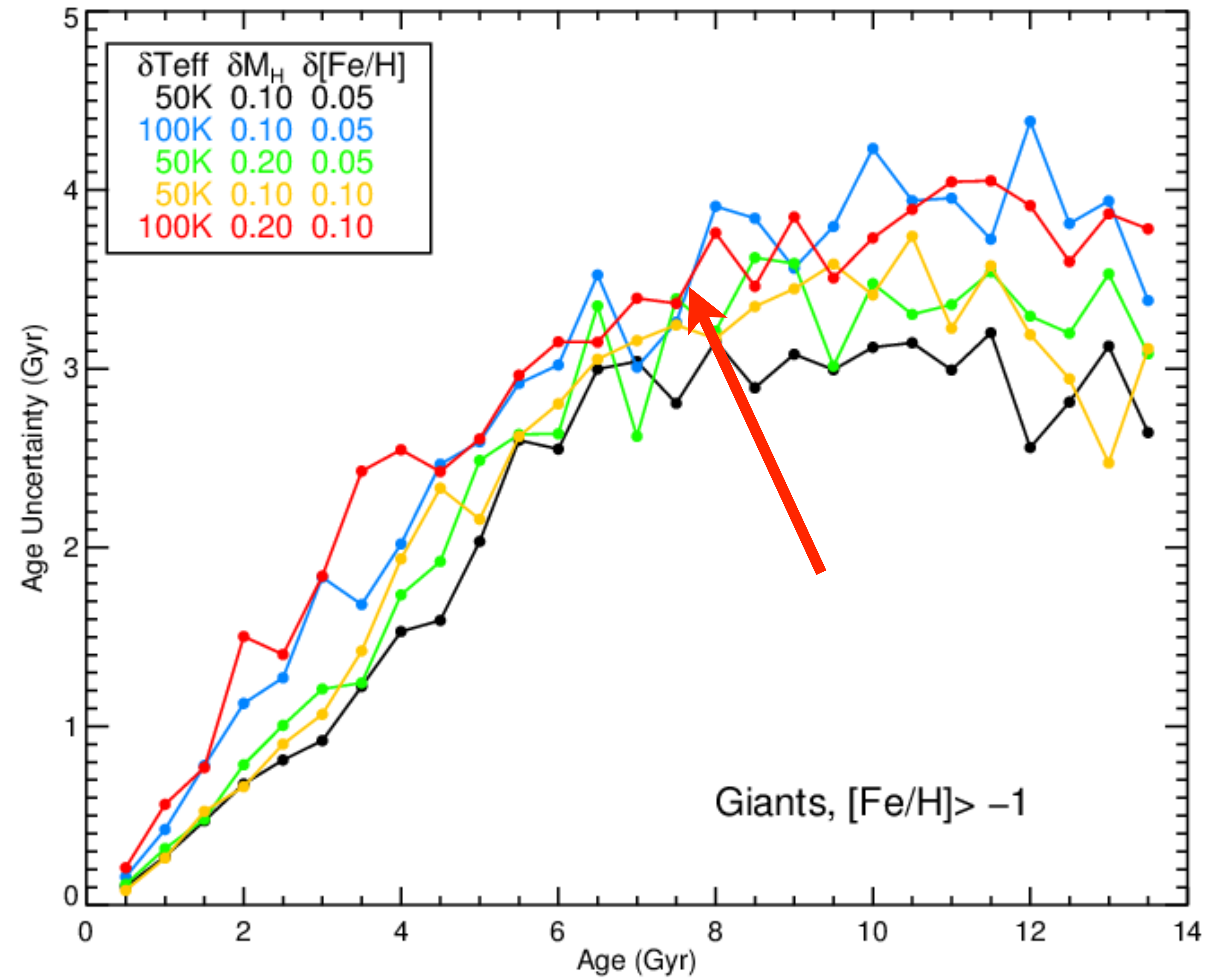
Ages with Gaia





Distance Modulus error (mag)

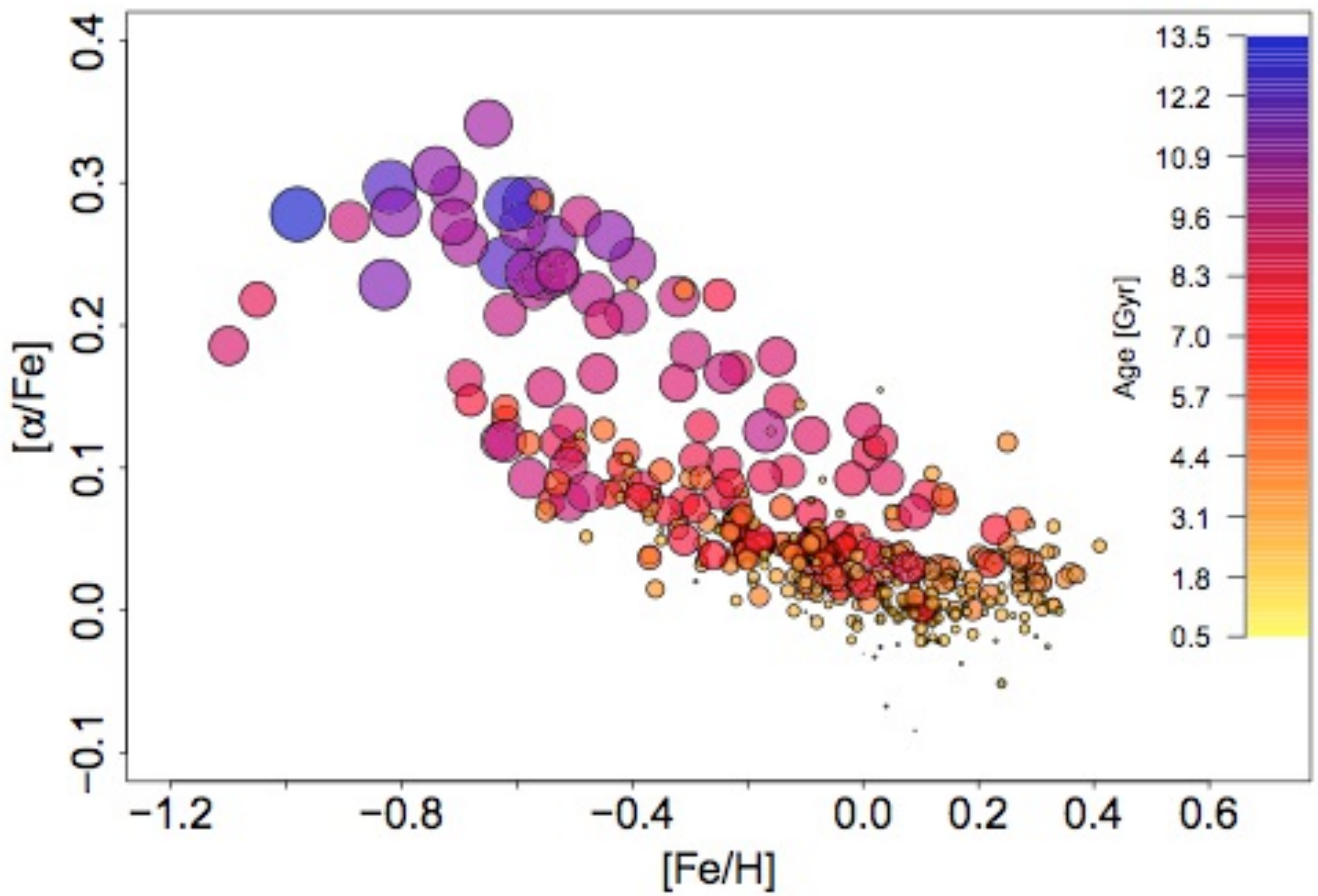
Age Uncertainties



Ages from Teff, logg, [Fe/H], distance, photometry and isochrones

Ages

Color/size indicates age

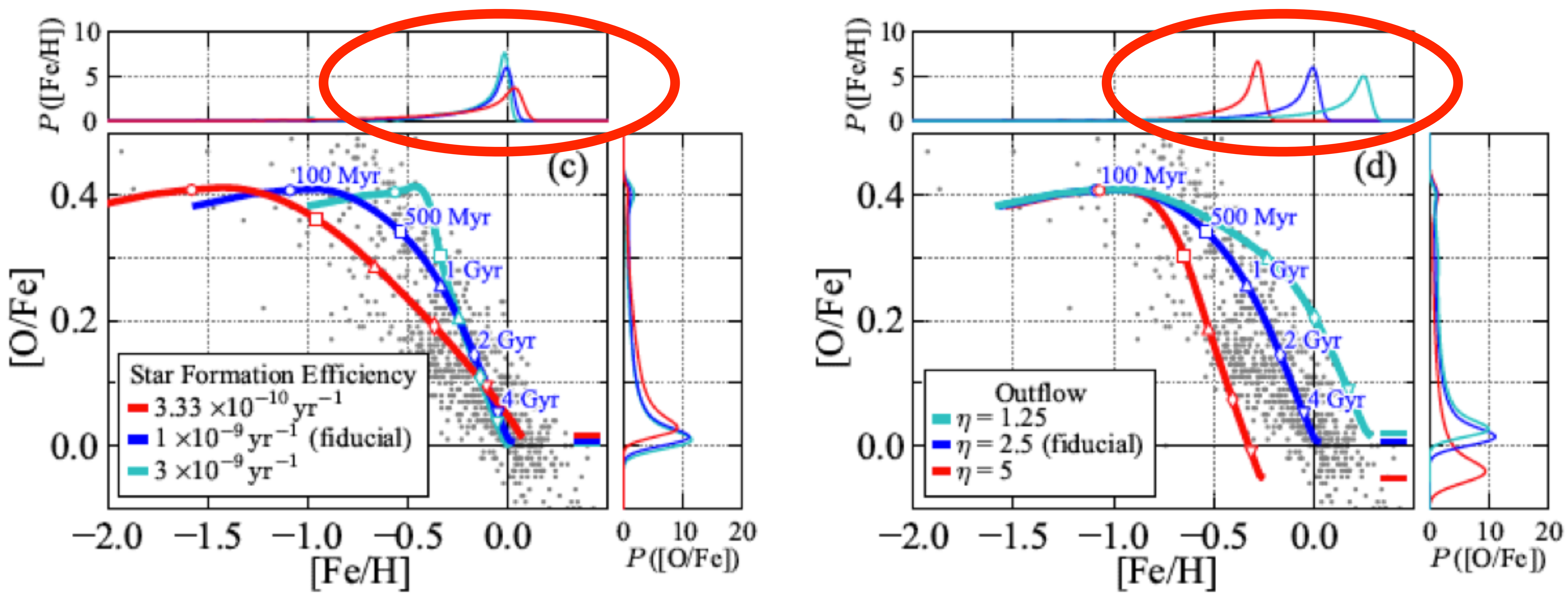


Haywood et al. (2013)

- Haywood et al. (2013) derived ages for the Adibekyan sample
- Solar neighborhood turnoff stars
- Fairly tight age-[α/Fe] sequence (combined and separate)
- Metal-poor low-α and metal-rich high-α overlap slightly in age

Metallicity Distribution Functions

- Chemical evolution models produce skew-negative MDFs, not skew-positive
- How did the outer galaxy get a skew-positive MDF?



Andrews et al. (2015)

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