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

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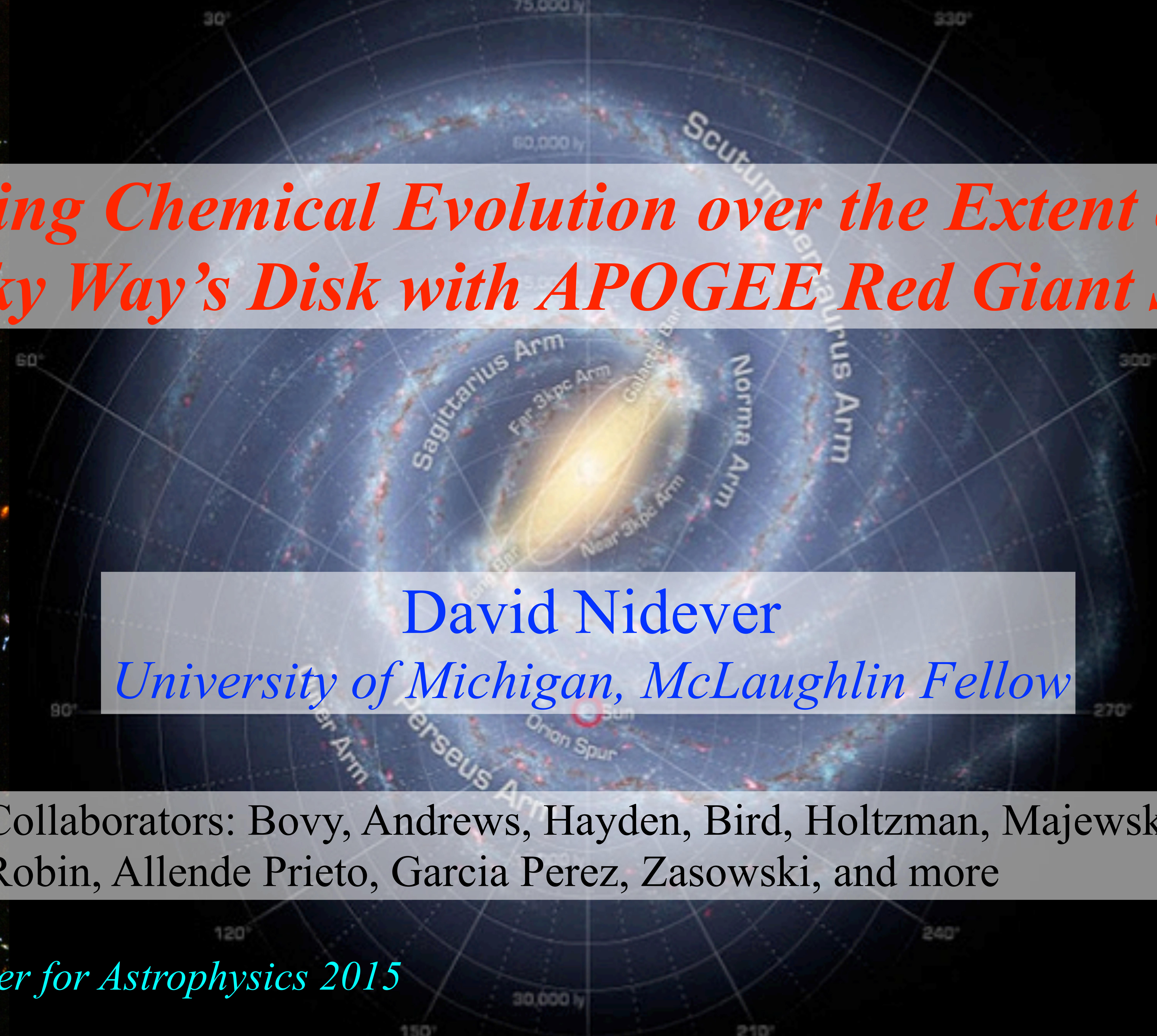
Collaborators: Bovy, Andrews, Hayden, Bird, Holtzman, Majewski, Robin, Allende Prieto, Garcia Perez, Zasowski, and more

Sexten Center for Astrophysics 2015



Evolution of the Milky Way

- Use MW as prototype to understand galaxy formation and evolution, can study in great detail
- Study the chemistry and kinematics throughout the disk
- Outstanding questions:
  - How did our Galaxy form?
  - What is the MW's star formation history?
  - Chemical and dynamical evolution?
- Most past samples very local
- APOGEE allows us to probe most of the galaxy, see through dust
- Constrain chemical/dynamical evolution models

Galactic Archaeology

Heyday for Galactic chemistry and archaeology studies

Current (*R*>20,000)

Name	Years	Nstars	λ	Depth	Telescope	N/S
APOGEE	2011-14 2014-19	10^5 $\sim 4 \times 10^5$	NIR	H<12.5	APO APO/LCO	N N/S
Gaia-ESO	2011-16	10^5	optical	V<19	VLT	S
GALAH	2014-17?	10^6	optical	V<14	AAT	S

Future (*R*>20,000)

WEAVE	2018	5×10^4	optical	V<18	VHT	N
MOONS	2019	$\sim 2 \times 10^6$	NIR	H<15.5	VLT	S
4MOST	2019	2×10^6	optical	V<16	VISTA	S
MSE	2024	$\sim 2 \times 10^6$	optical	V<19	CFHT	S

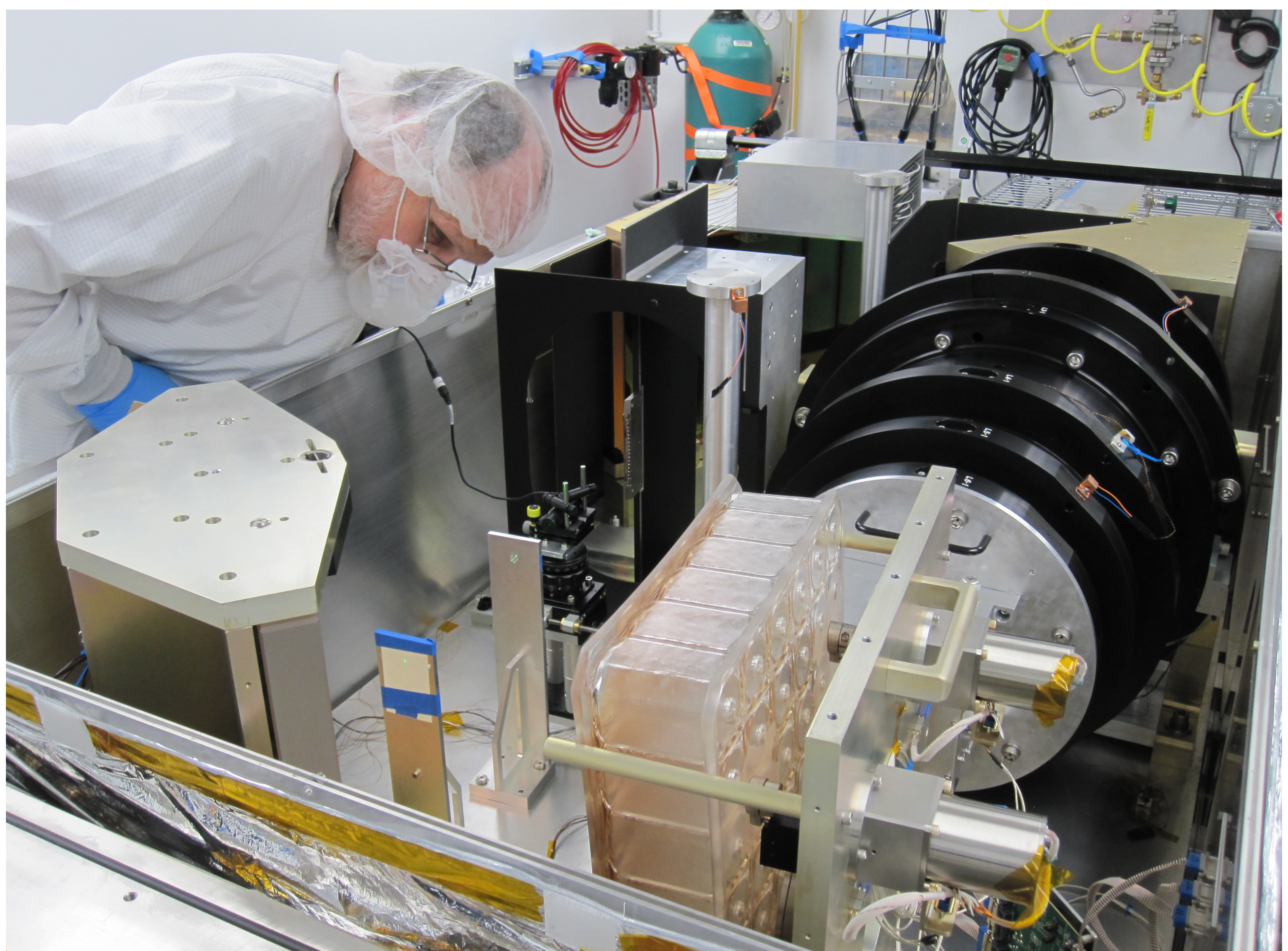
APOGEE Overview

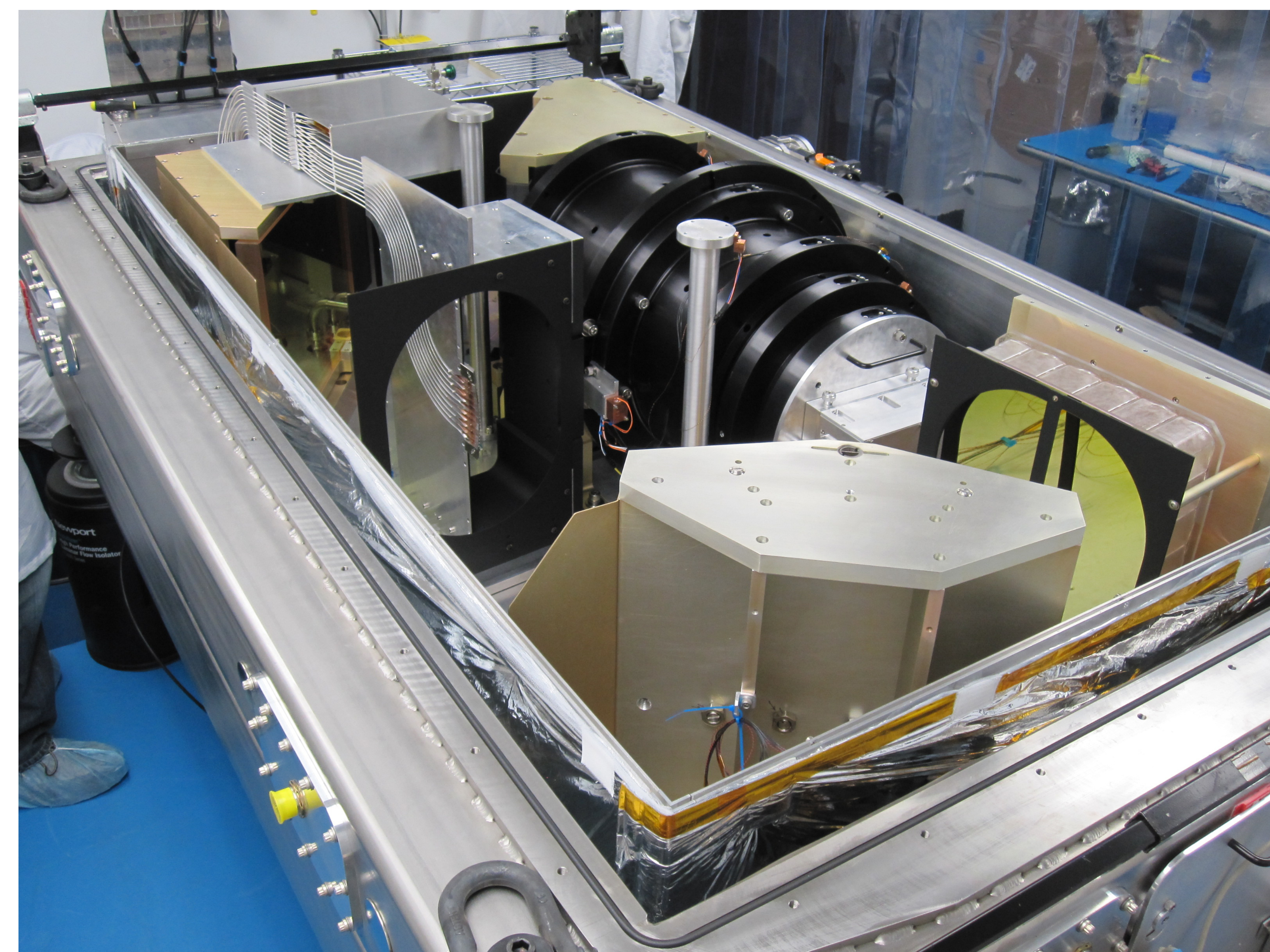
Large, uniform, systematic survey of MW chemistry and kinematics

- Part of Sloan Digital Sky Survey (SDSS)-III
- 300 fiber, $R \geq 22{,}500$, cryogenic spectrograph
- NIR H-band ($A_H / A_V \sim 1/6$)
- $S/N = 100$/pixel
- 0.1 dex precision abundances for ~15 chemical elements
- 100,000+ 2MASS-selected giant stars across all Galactic populations

The APOGEE Instrument

- Built at the University of Virginia with private industry and other SDSS-III collaborators.
- The APOGEE instrument employs a number of novel technologies to achieve 300-fiber multiplexing / high resolution / infrared.





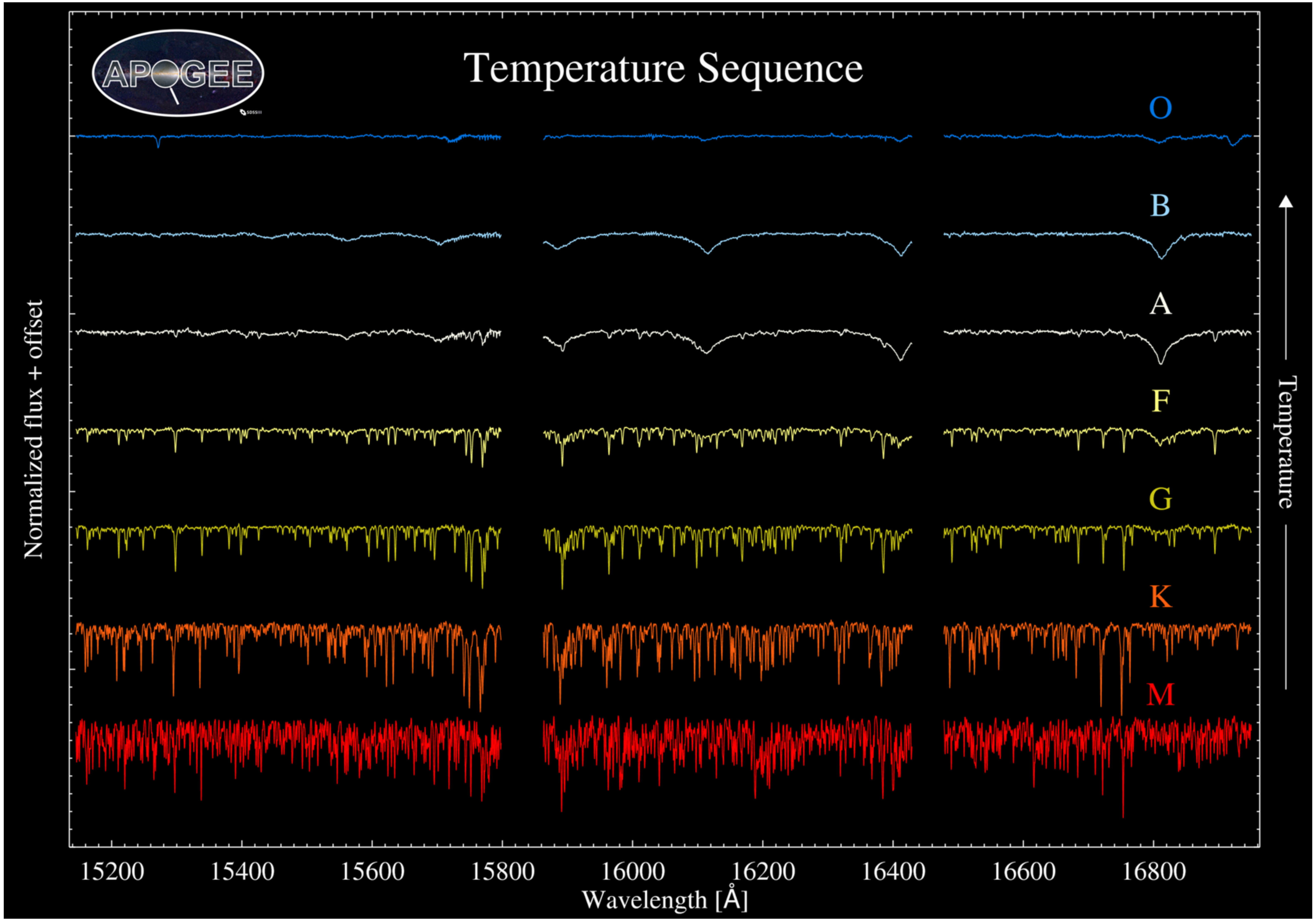
Photos by S.R. Majewski

APOGEE First Light

Below: First APOGEE+Sloan 2.5-m observations of Galactic bulge (May 2011)
(in full moon, at 2 airmasses, and towards lights of El Paso).

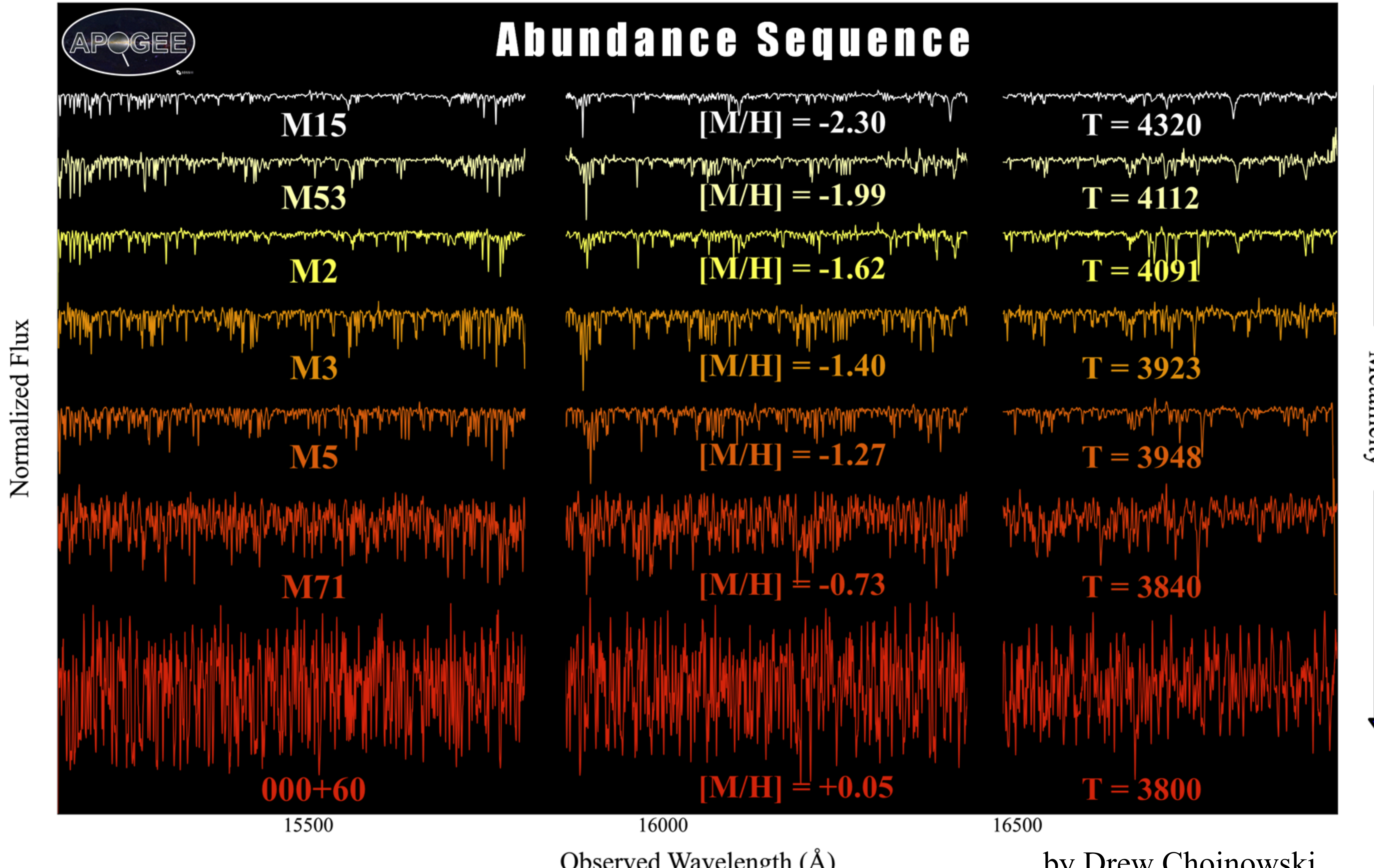
Photo by S.R. Majewski

Example Spectra



by Drew Chojnowski

Example Spectra

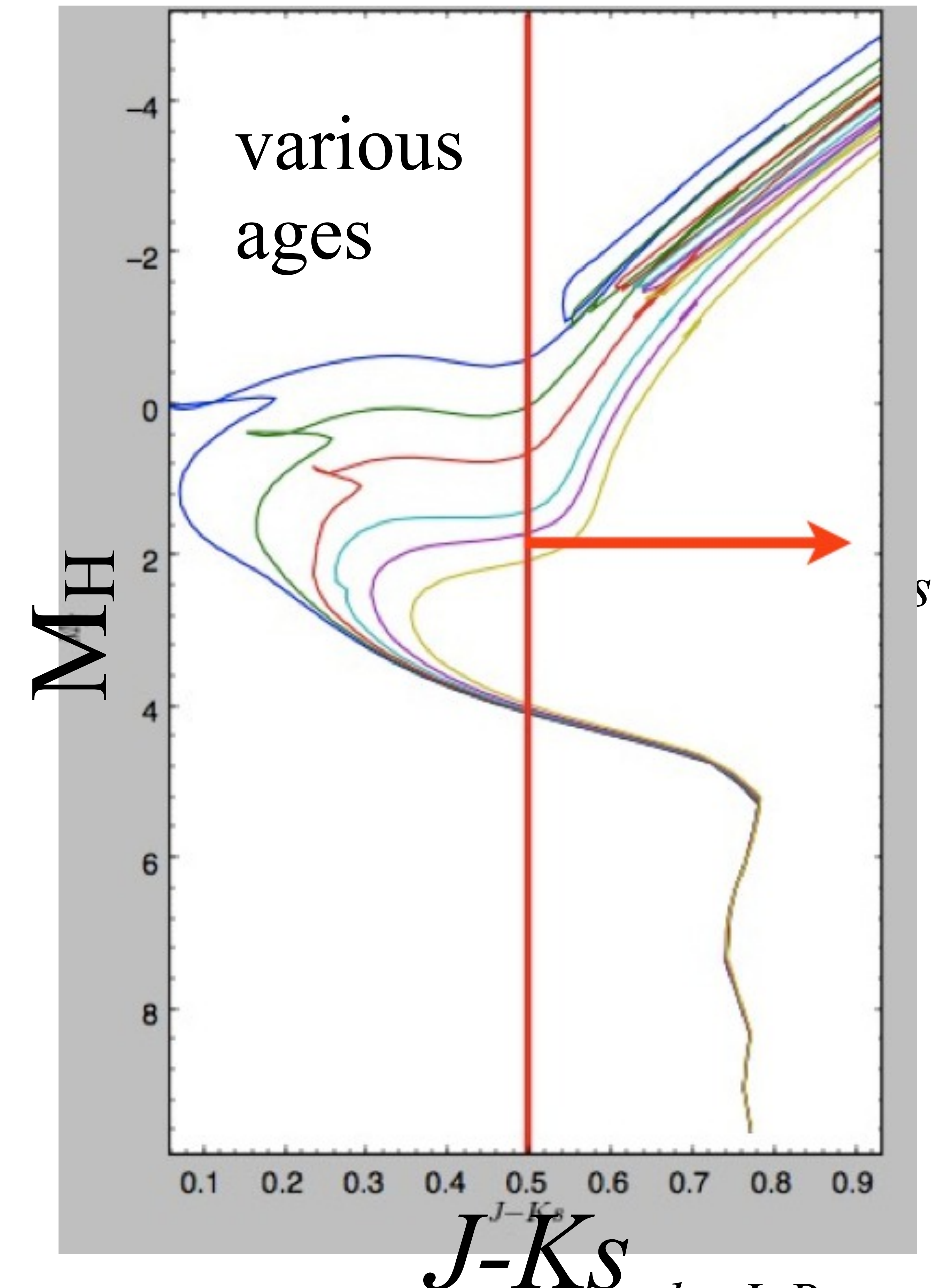


by Drew Chojnowski

APOGEE Target Selection

Colors & Magnitudes

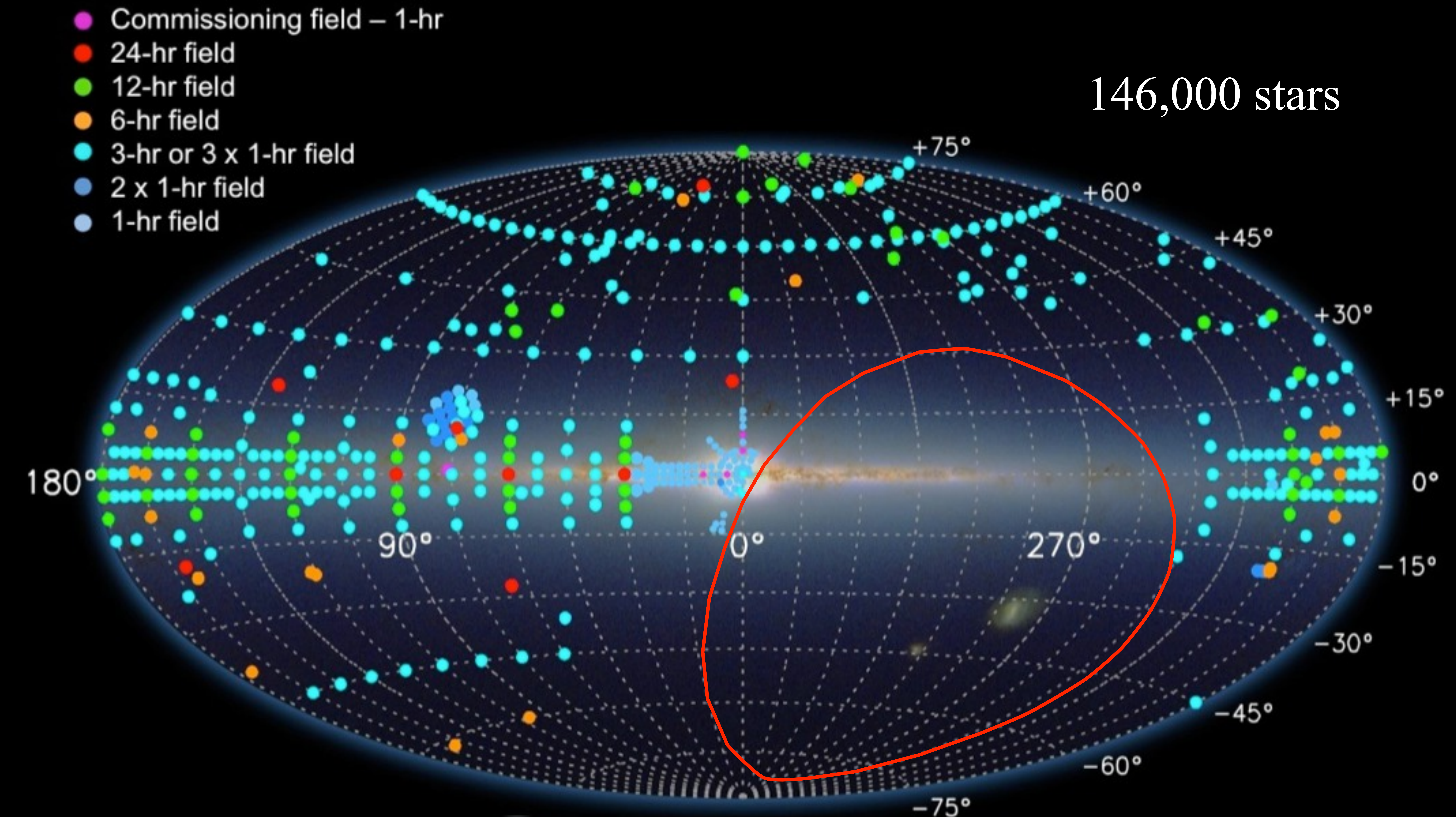
- Science targets
  - –Use NIR/MIR RJCE method to deredden (Majewski, Zasowski & Nidever 2011)
  - –Simple color-cut: $(J\text{-}K_s)_0 \geq 0.5$
  - –Variable magnitude limits (H < 11-14) for both shallow and deeper probes of MW
  - –Mainly luminous K and M giants (RC and RGB)
  - –About ~20% "contamination" by dwarfs



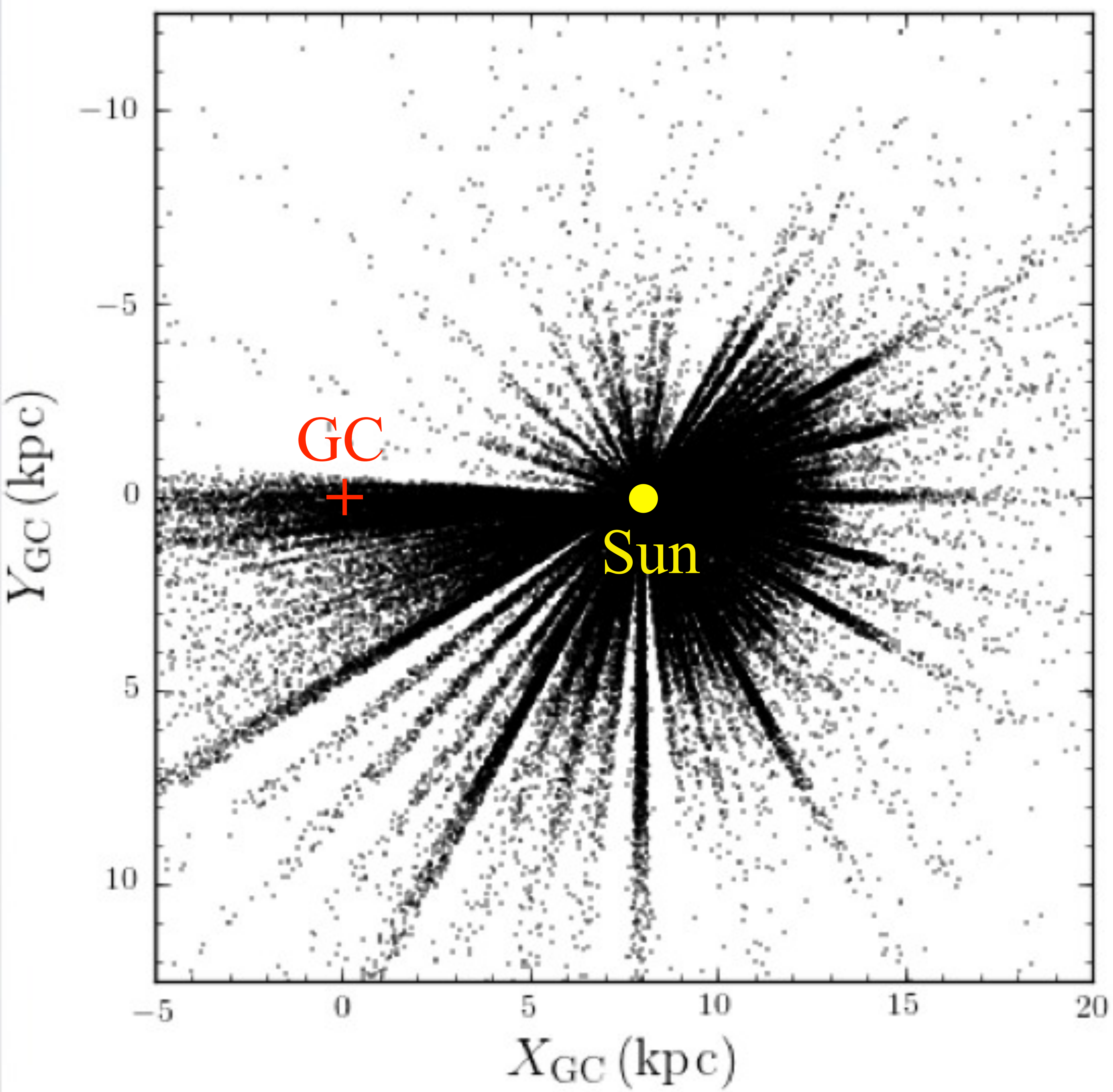
by J. Bovy

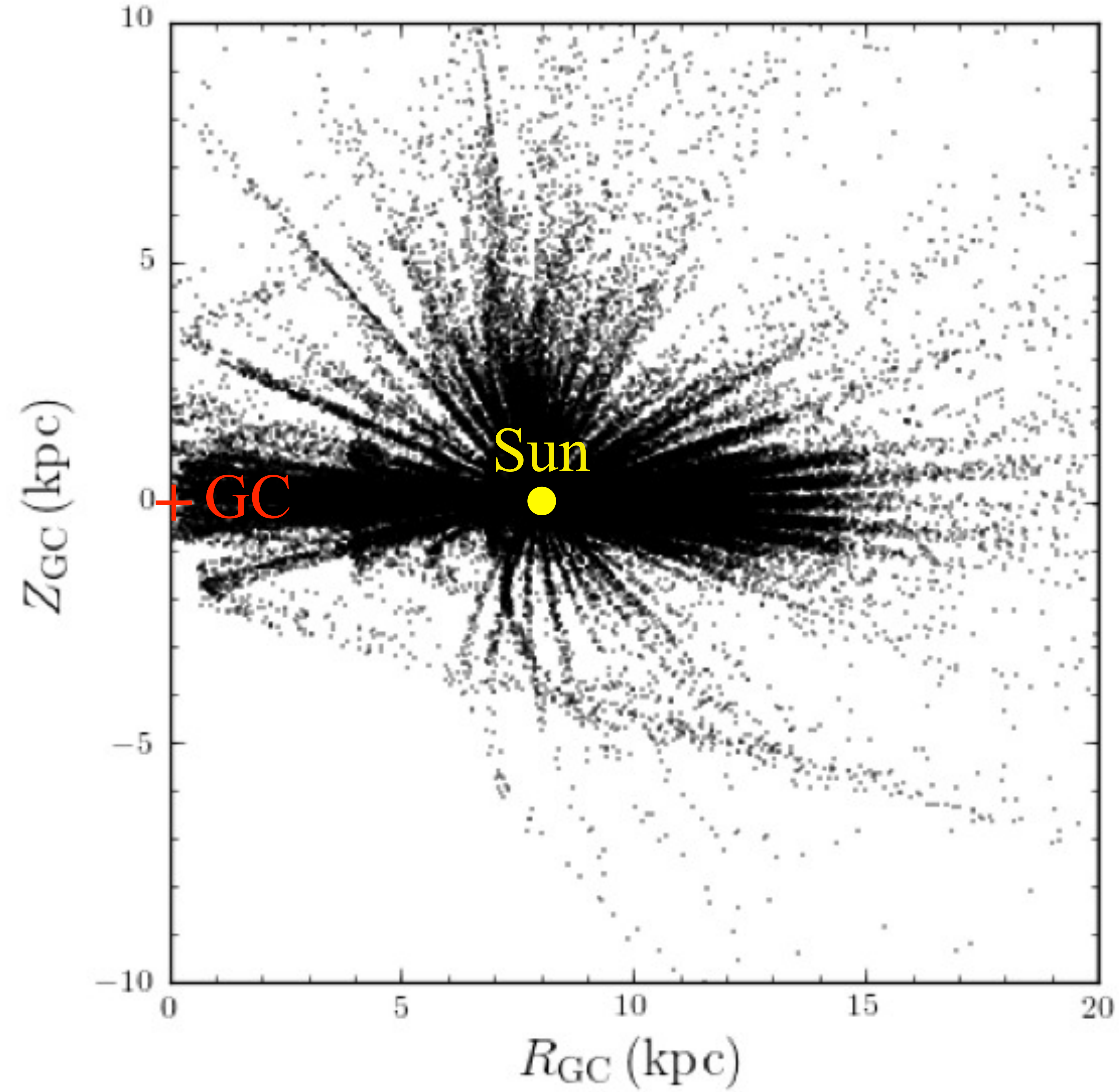
Zasowski et al. (2013)

APOGEE DR12 Coverage - Observed Survey Plan

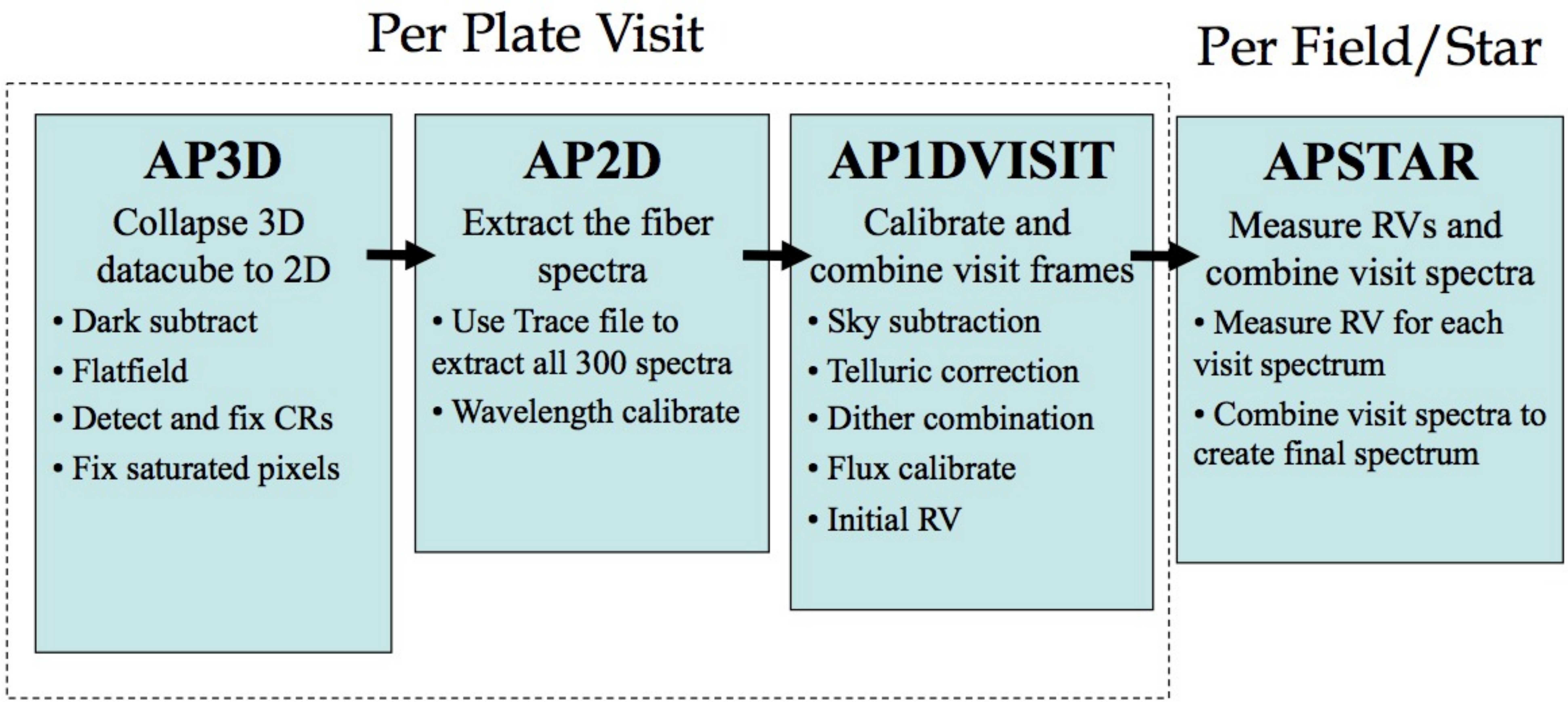


APOGEE Spatial Coverage





Reduction Pipeline



Nidever et al. (2015), submitted

Velocity Uncertainties

Velocity Uncertainty

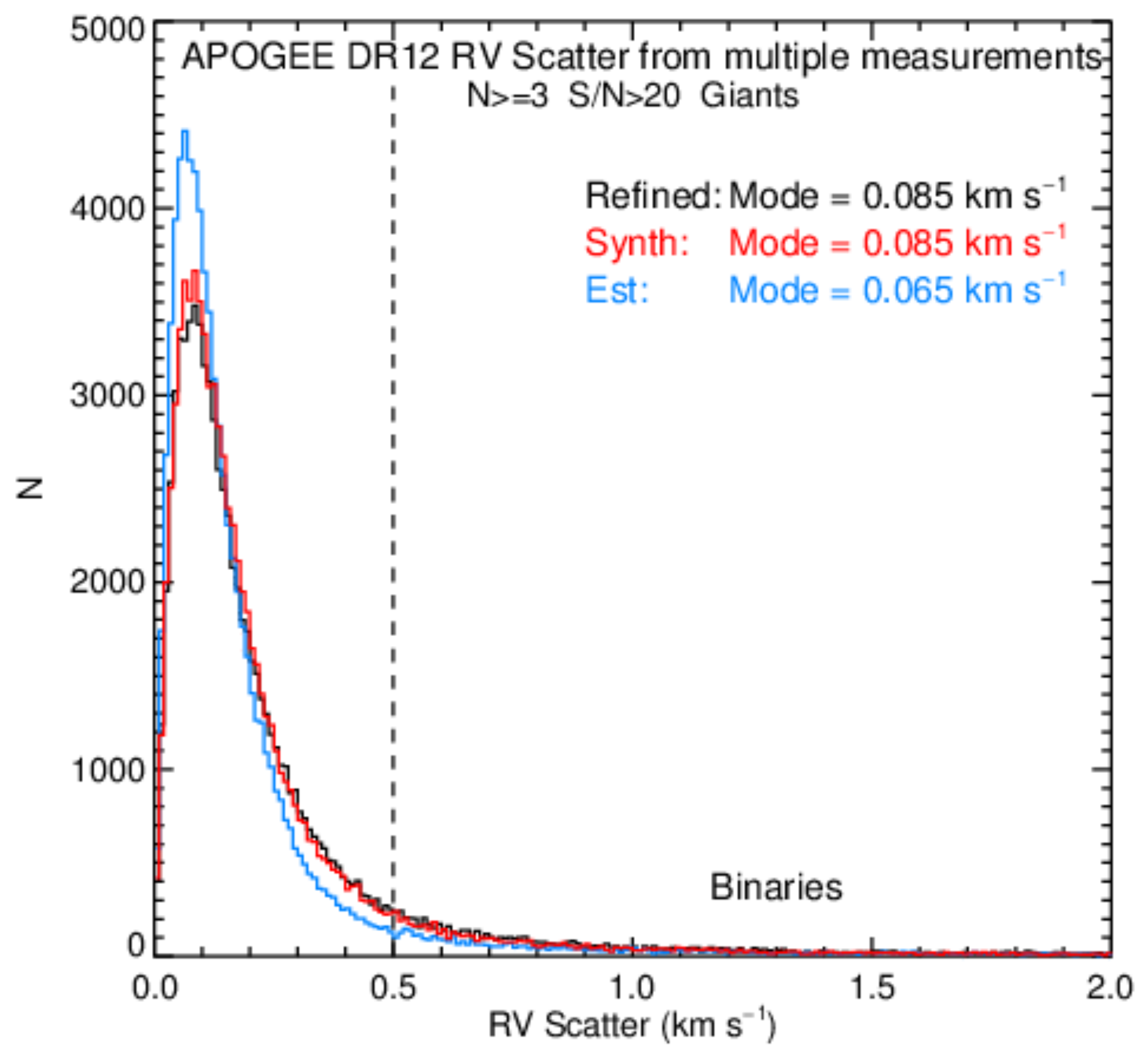
- Scatter from multiple measurements
- Peak RV scatter = ~0.08 km/s

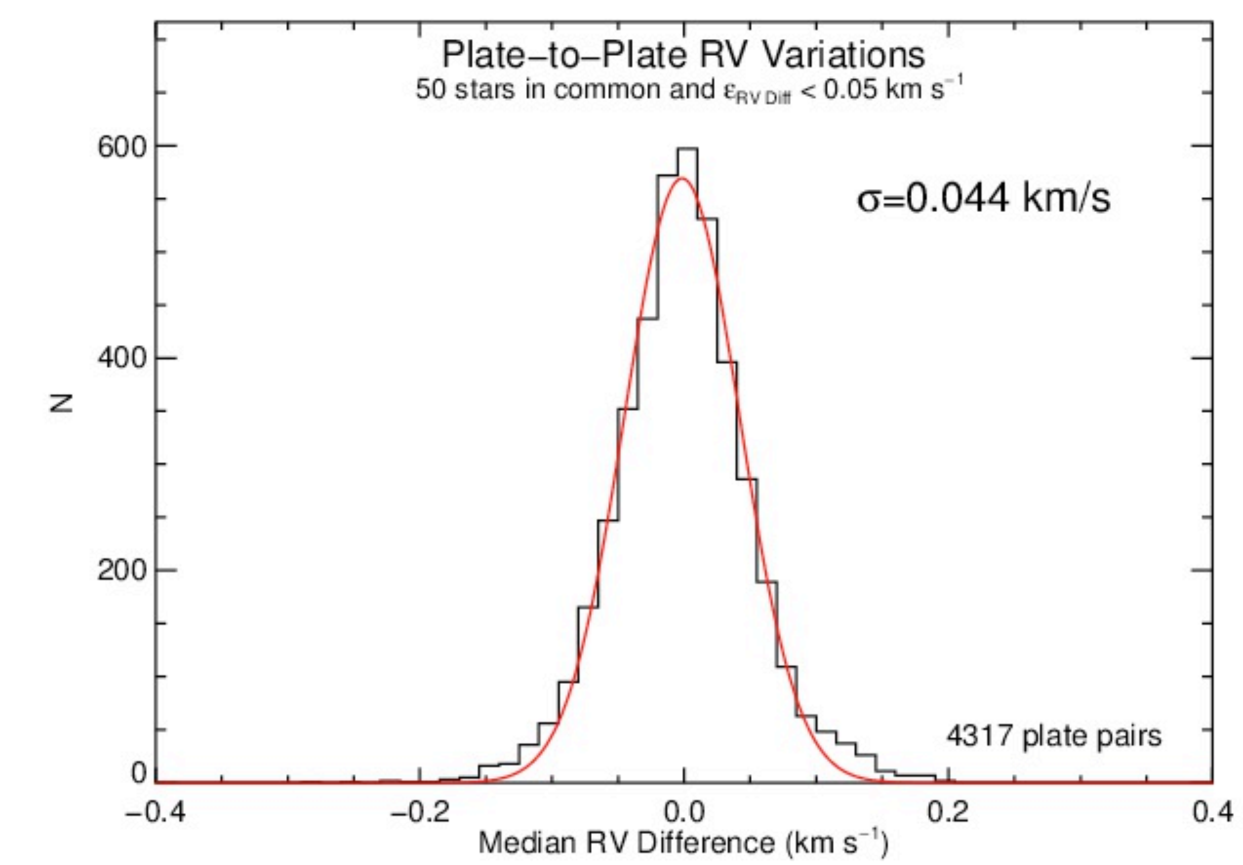
Velocity Zeropoint

- Comparison to 41 RV stable stars from Nidever et al. (2002) and Chubak & Marcy (2012)
- RV Offset (Lit - APG) = -0.36 +/- 0.03 km/s

Velocity Drift

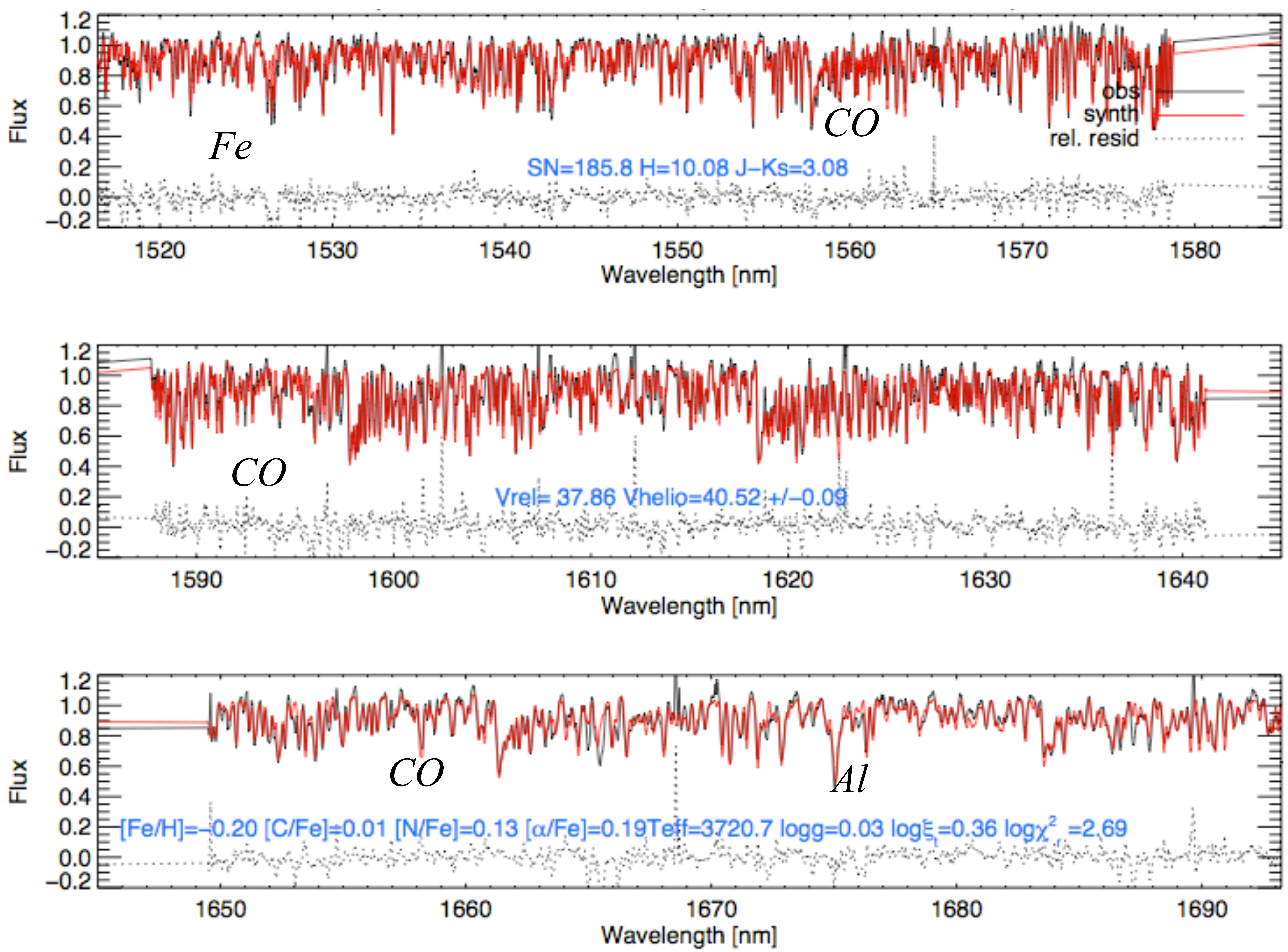
- Plate-to-plate mean RV offset errors = 0.044 km/s





Chemical Abundance Determination

Bulge [Fe/H]~-0.2



Abundance Pipeline

- χ^2 optimization against large library of synthetic spectra
- First find stellar parameters (Teff, logg, [Fe/H], micro, ...)
- Then find individual abundances (15)

DR12 Data Products

- APOGEE DR12 data release includes:
  - Target selection information
    - –Sufficient to reconstruct sampling functions
  - Spectra across full APOGEE spectral window (1.51-1.69 μm)
    - –Reduced, calibrated 1-D spectra with error, pixel flag, LSF vectors
    - –*S/N* > 100 per pixel (Nyquist limit)
  - Velocity data (~80 m/s precision)
    - –Radial velocities, variability information (multiple epochs), errors
  - Stellar atmospheric parameters from matches to synthetic libraries
    - –Via simultaneous 7-D optimization of $T_{\rm eff}$, log g, [Fe/H], [C-N-O/Fe], ξ
    - –Uncertainties, covariances
  - Chemical abundances (≤ 0.1 dex internal accuracy)
    - –C, N, O, Na, Mg, Al, Si, S, K, Ca, Mn, Co, Ni, (Ti, V)
- For 163,000 unique stars; ~650,000 spectra

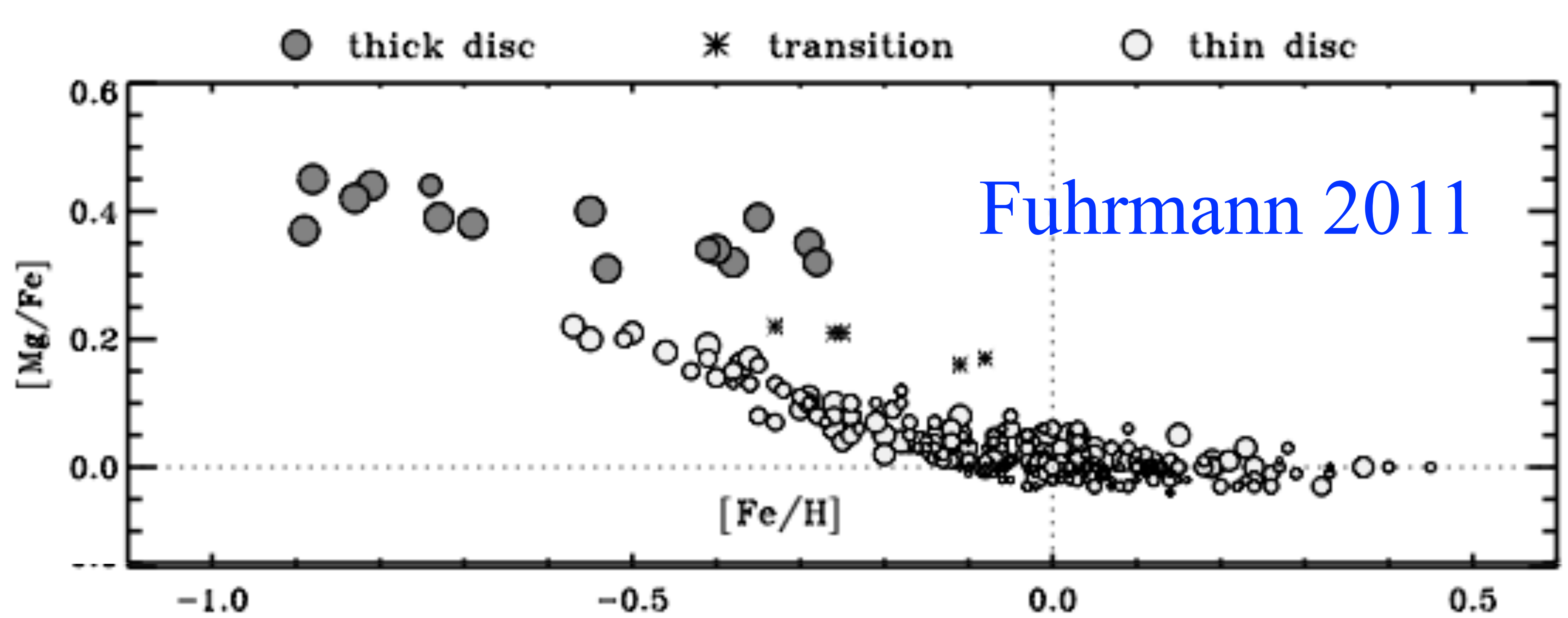
http://www.sdss.org/dr12/ Holtzman et al. (2015), submitted

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

Nidever et al. (2014)

Brief Disk Background

- MW vertical stellar density profile decomposed into “thin” and “thick” components (Gilmore & Reid 1983)
- From solar neighborhood samples (e.g., Fuhrmann 98, Bensby+05):
  - Thin disk, low vertical velocity dispersion, low [α/Fe], younger
  - Thick disk, high vertical velocity dispersion, high [α/Fe], older



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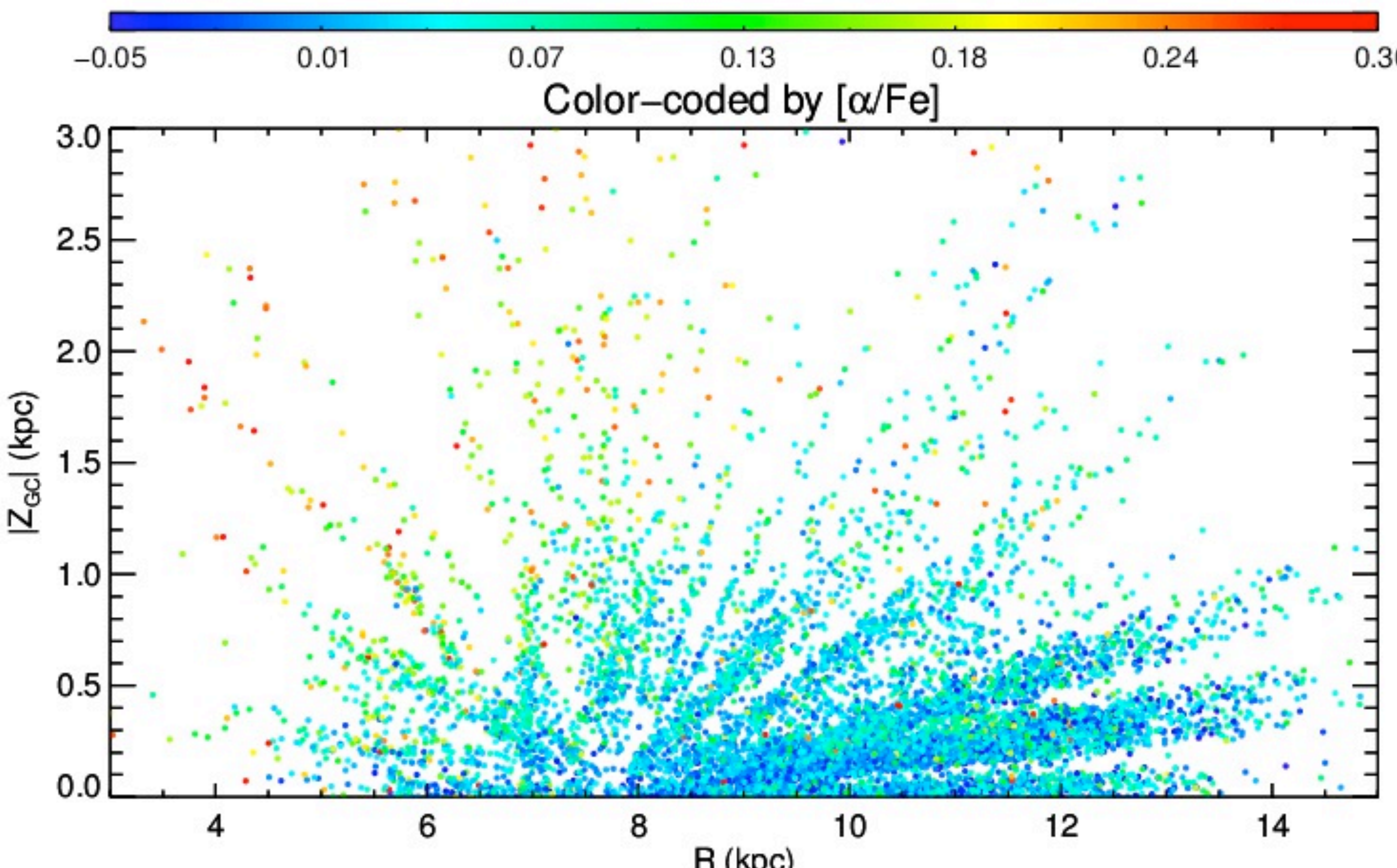
  - Thick disk, high vertical velocity dispersion, high [α/Fe], older
- But they might not be so “distinct” (e.g. Bovy et al. 2012b)
- Thick disk formed in high-SFR (Snaith et al. 2014)
- Origin of disk variation unclear. Could be:
  - Major merger puffing older stars up
  - Disk formed “hot” and settled/cooled over time

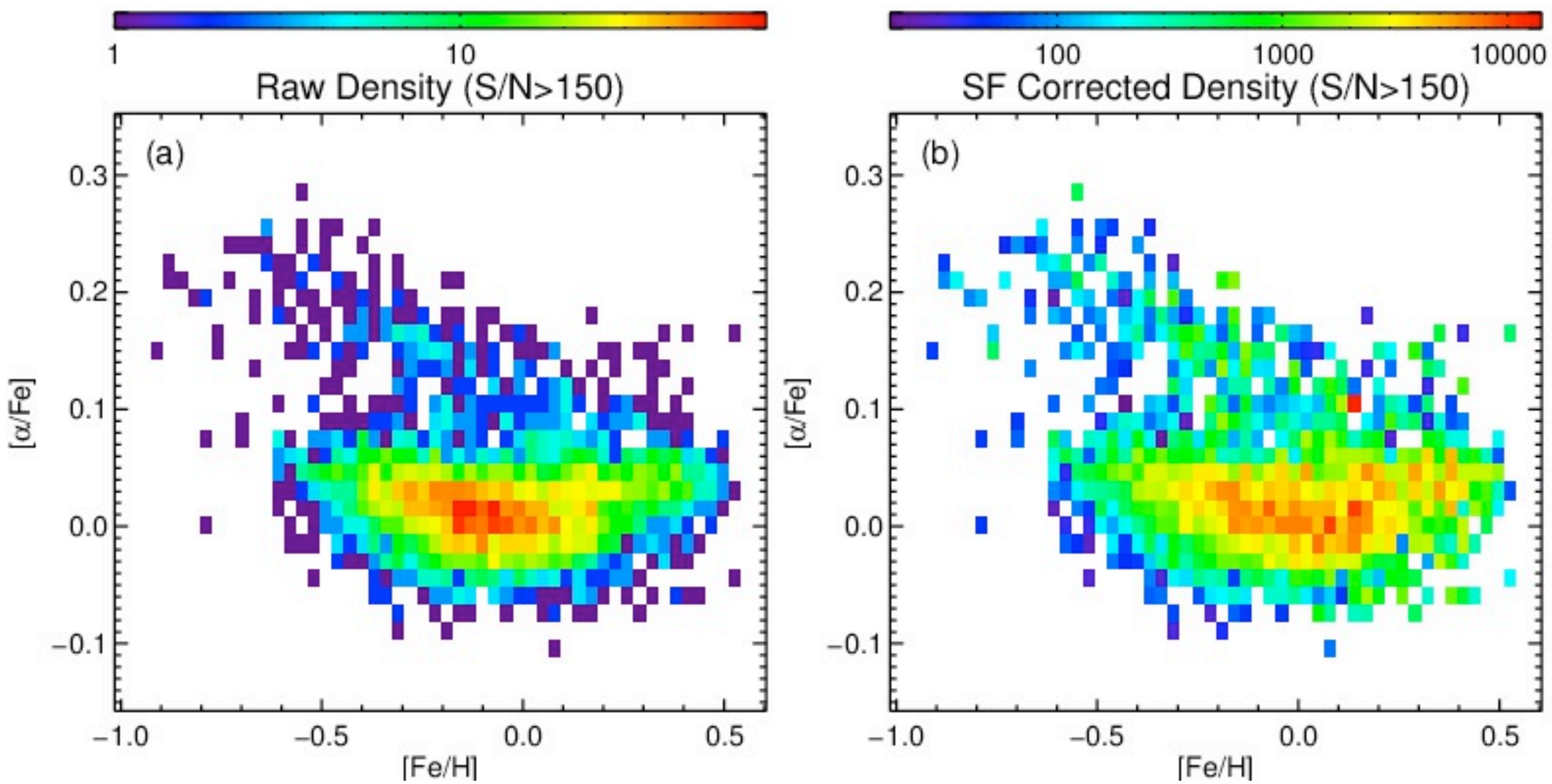
APOGEE Red Clump Stars

- Trace chemical abundance patterns over the MW disk
- Use α-element abundances of the red clump catalog (Bovy, Nidever et al. 2014)
- ~10,000 RC stars
- Standard candles, accurate distances (~5%)
- [Fe/H]>-0.9 because of APOGEE targeting $(J\text{-}K_s)_o>0.5$ color cut
- Most stars within ~4 kpc of the sun

RC Abundances



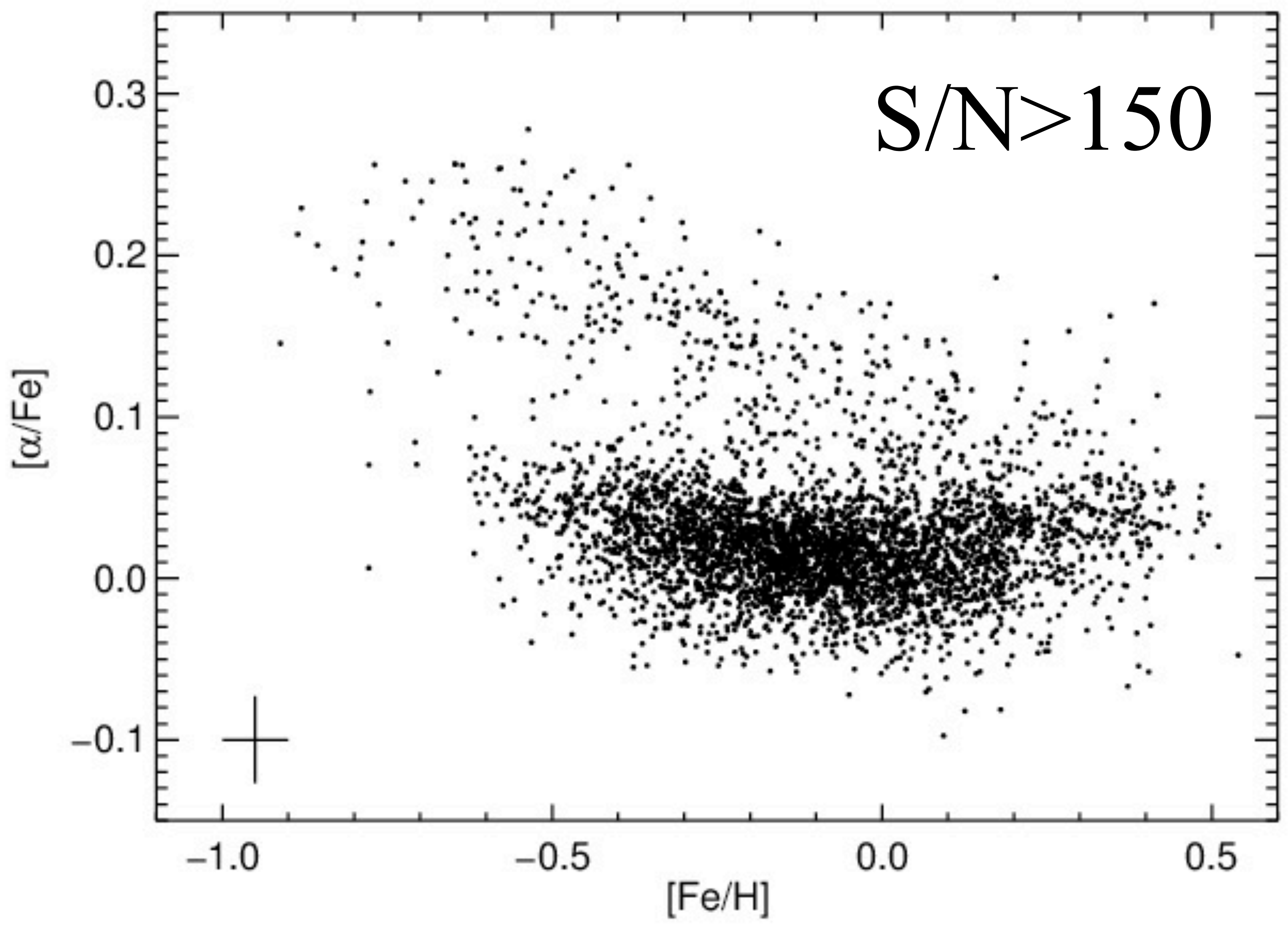
Selection Function

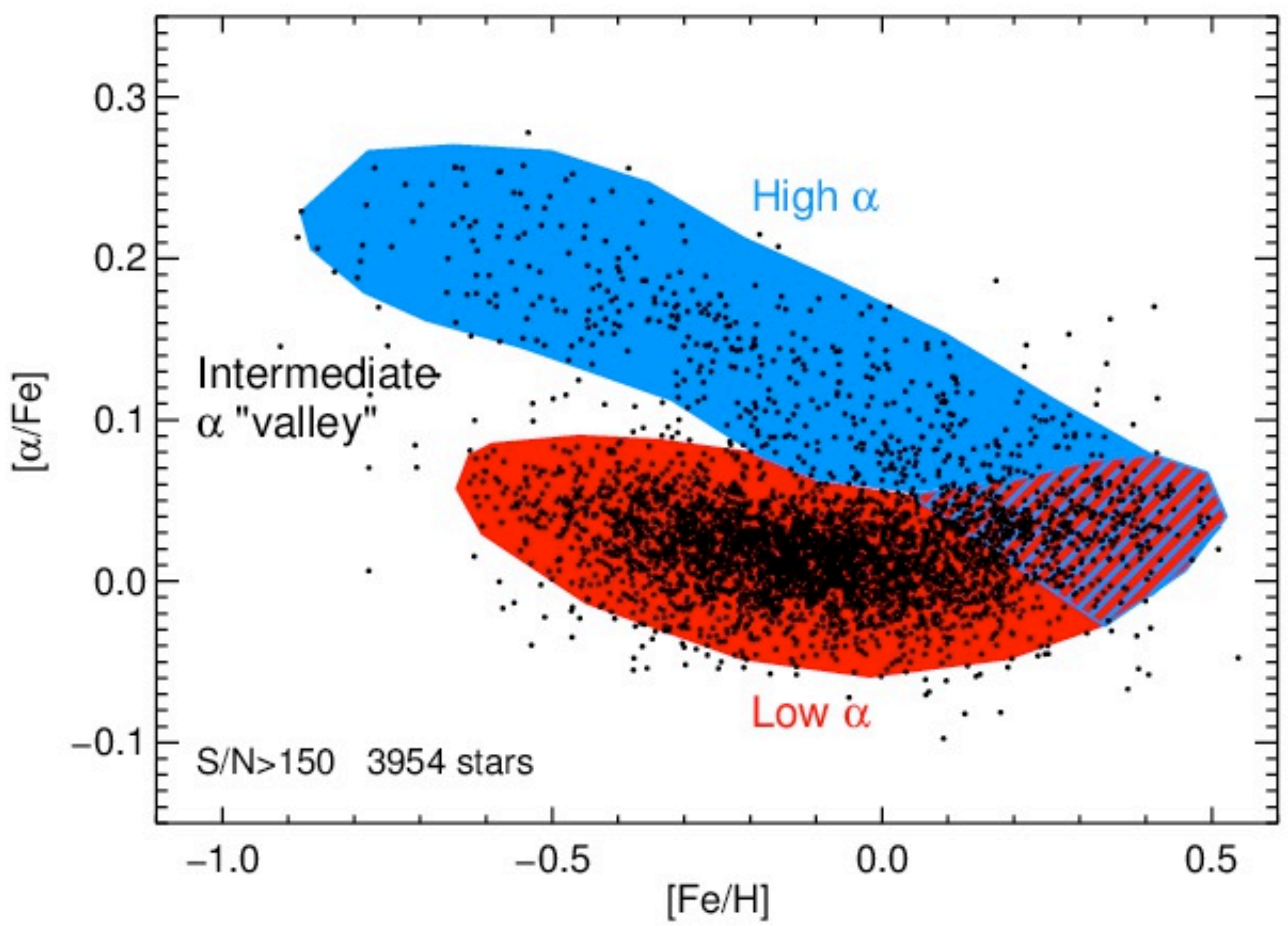


Selection Function Effects

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

Abundance Features

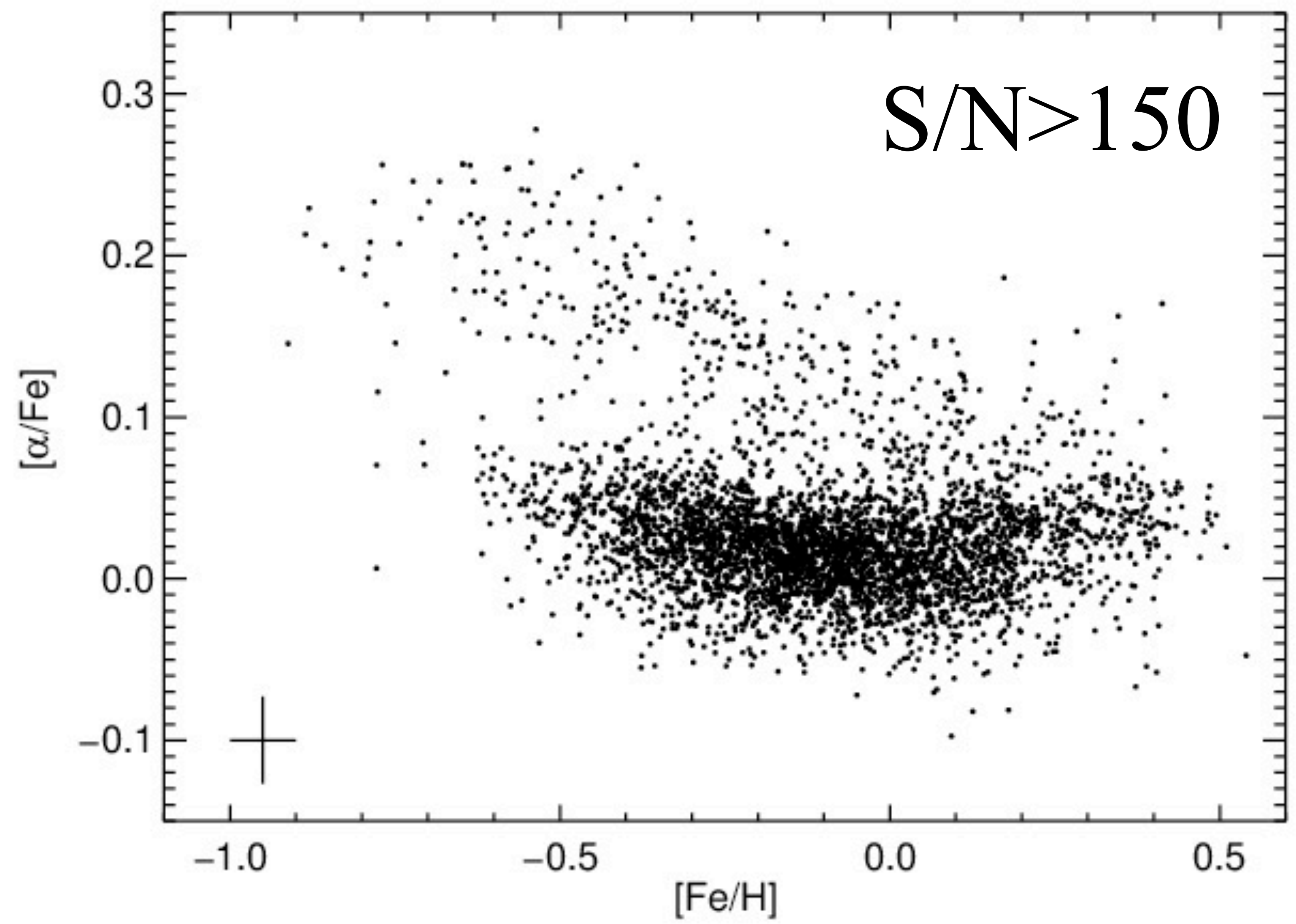


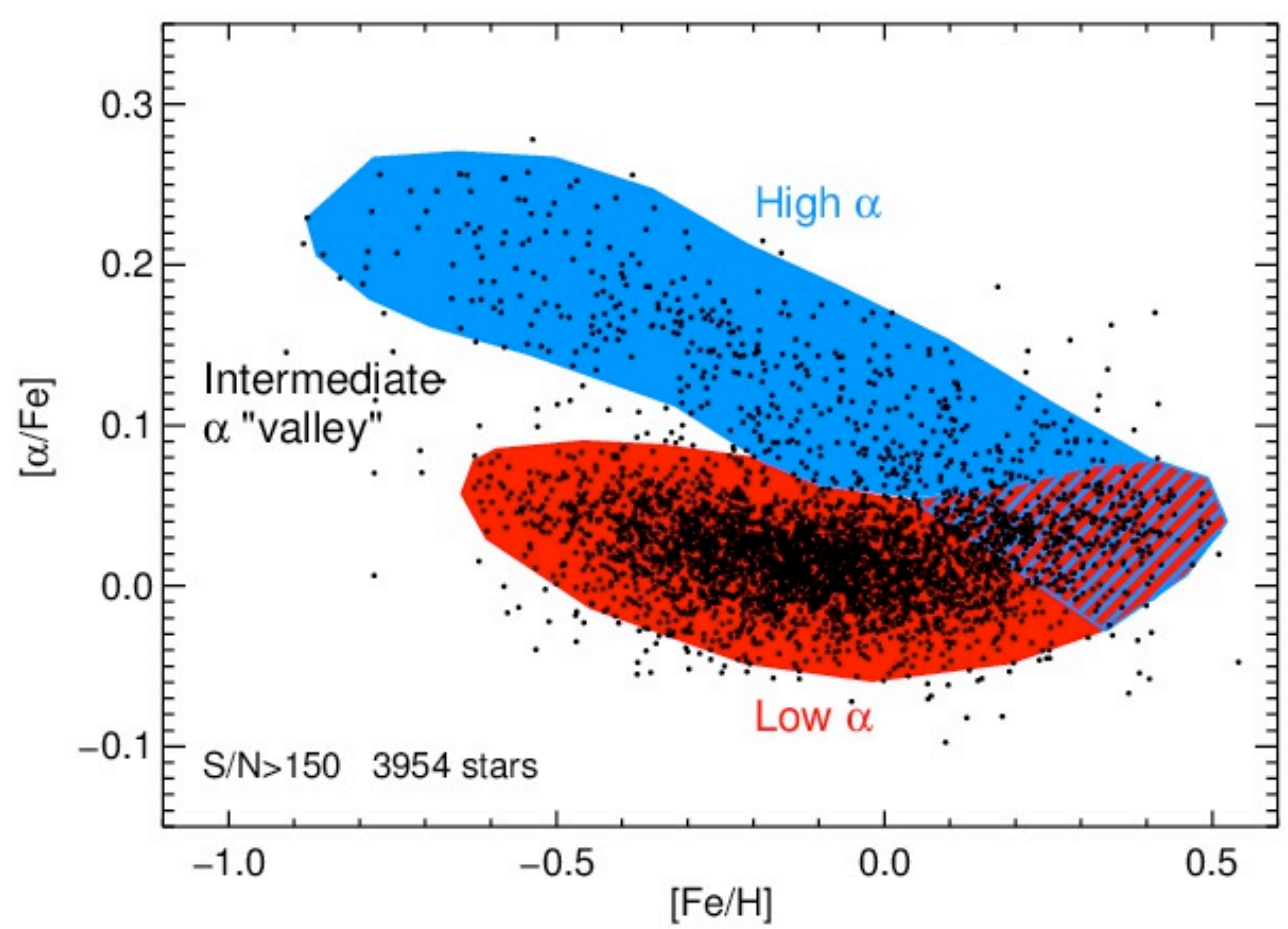


Qualitative Features

1. α-bimodality at intermediate metallicity

Abundance Features

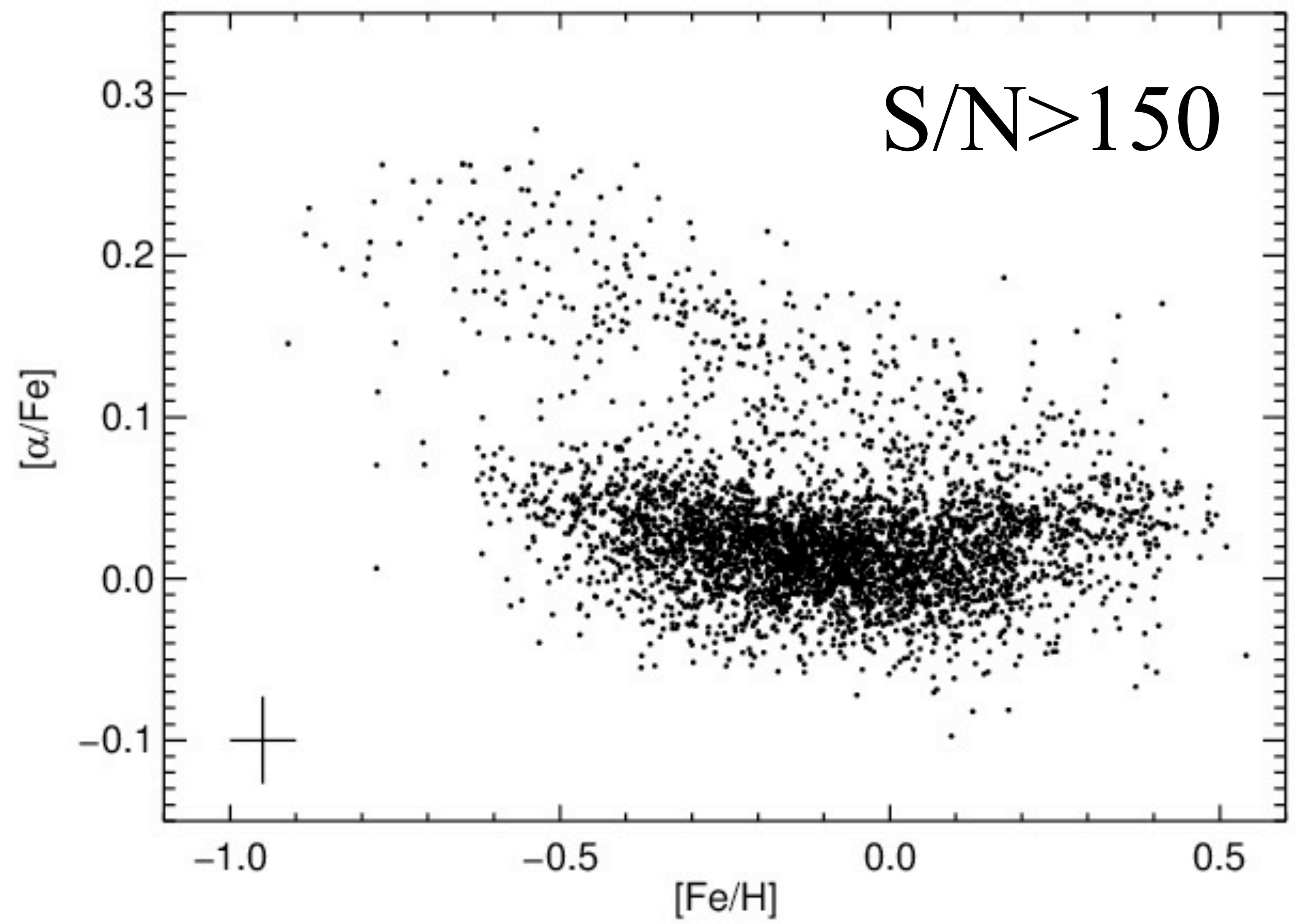


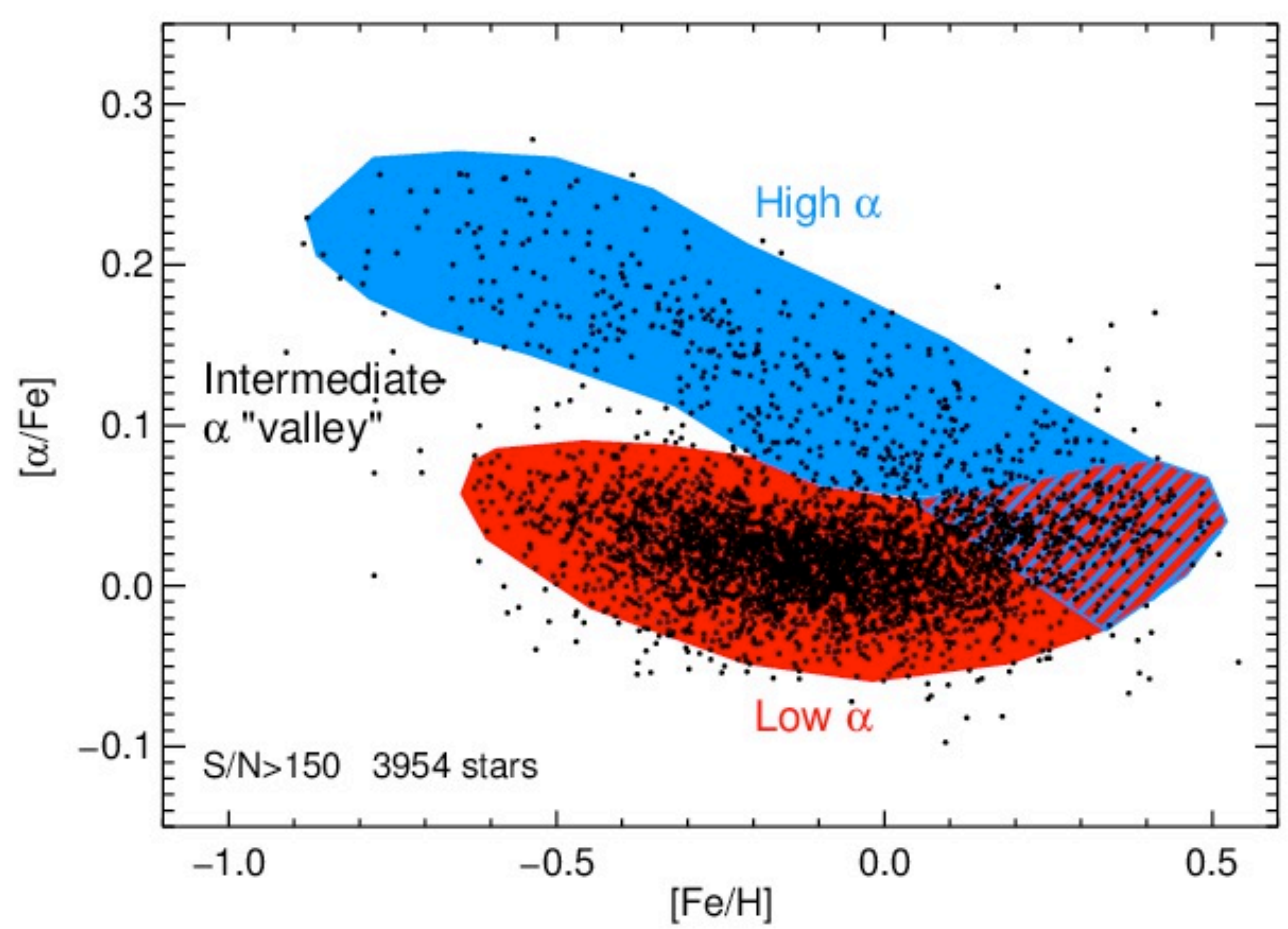


Qualitative Features

1. α-bimodality at intermediate metallicity
2. Merging of two α groups at [Fe/H]~+0.2

Abundance Features

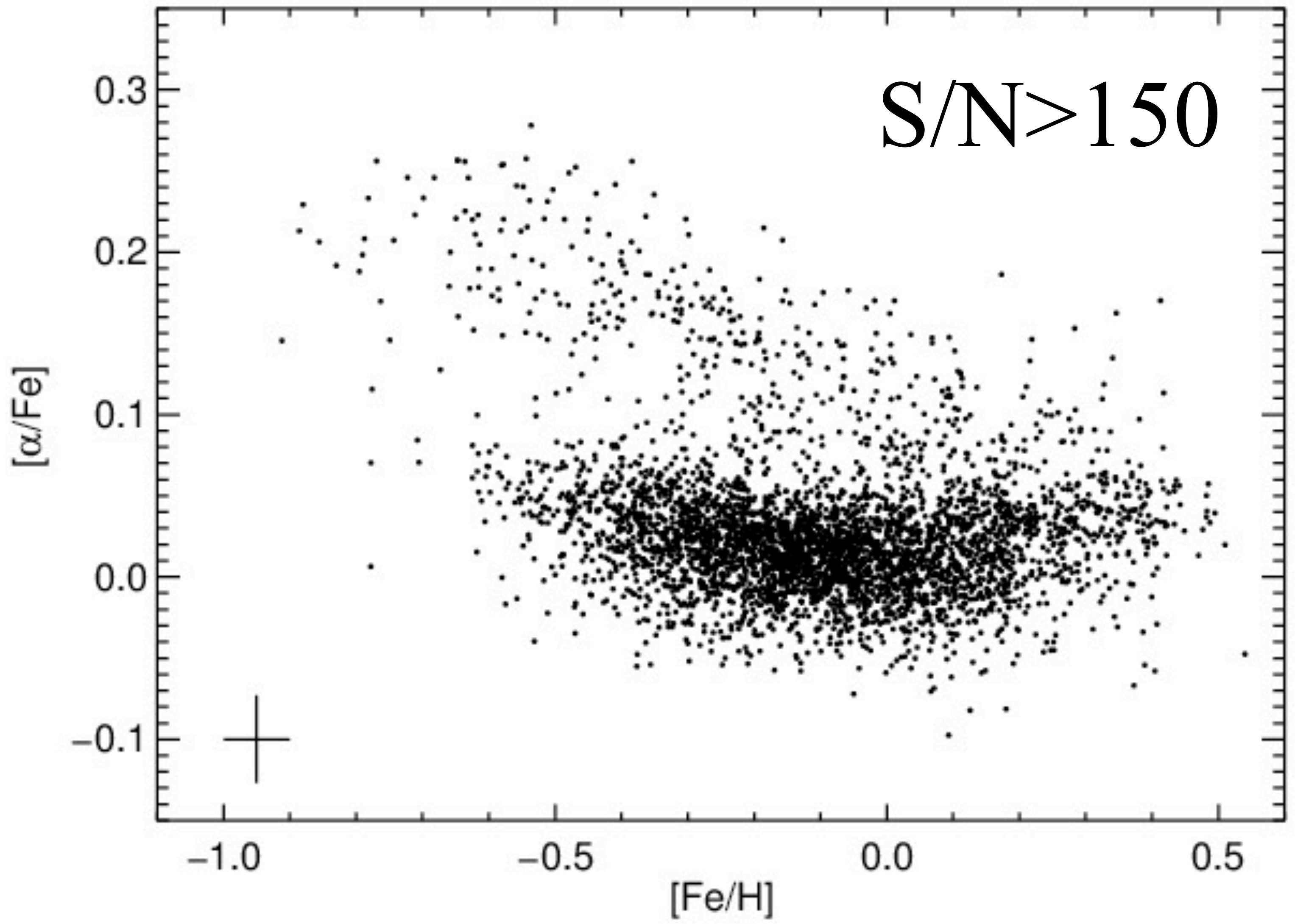


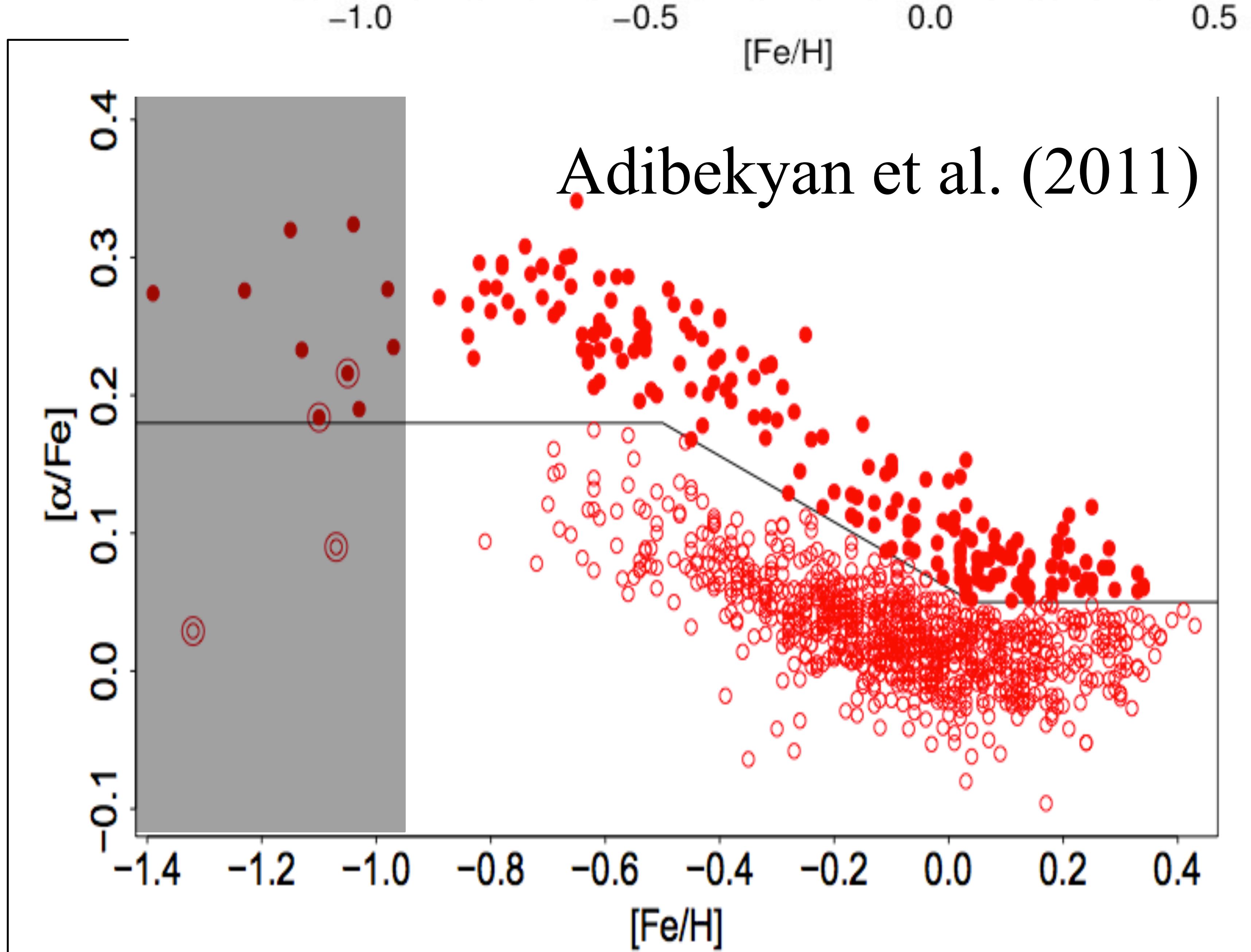


Qualitative Features

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

Abundance Features



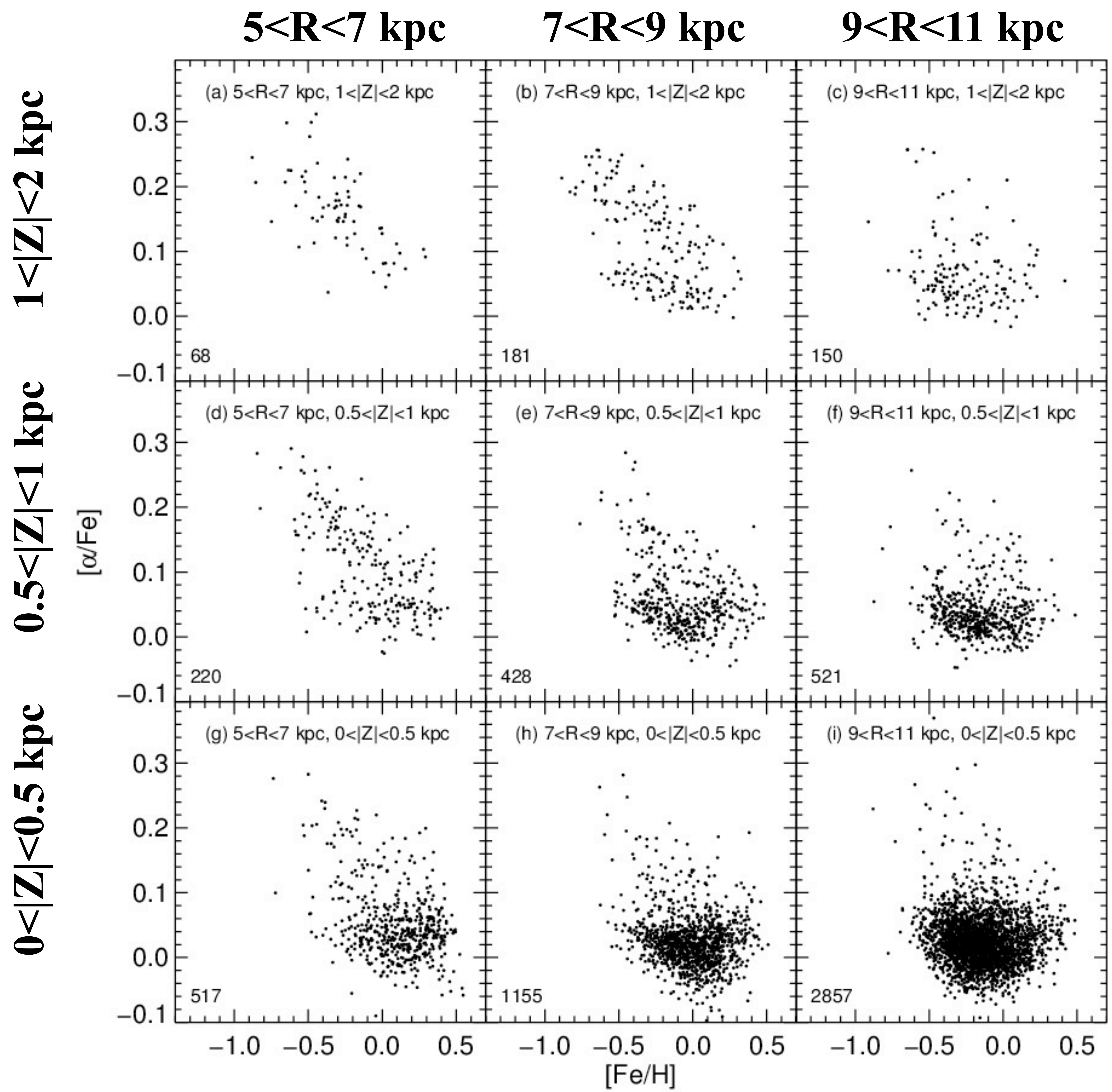


Qualitative Features

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

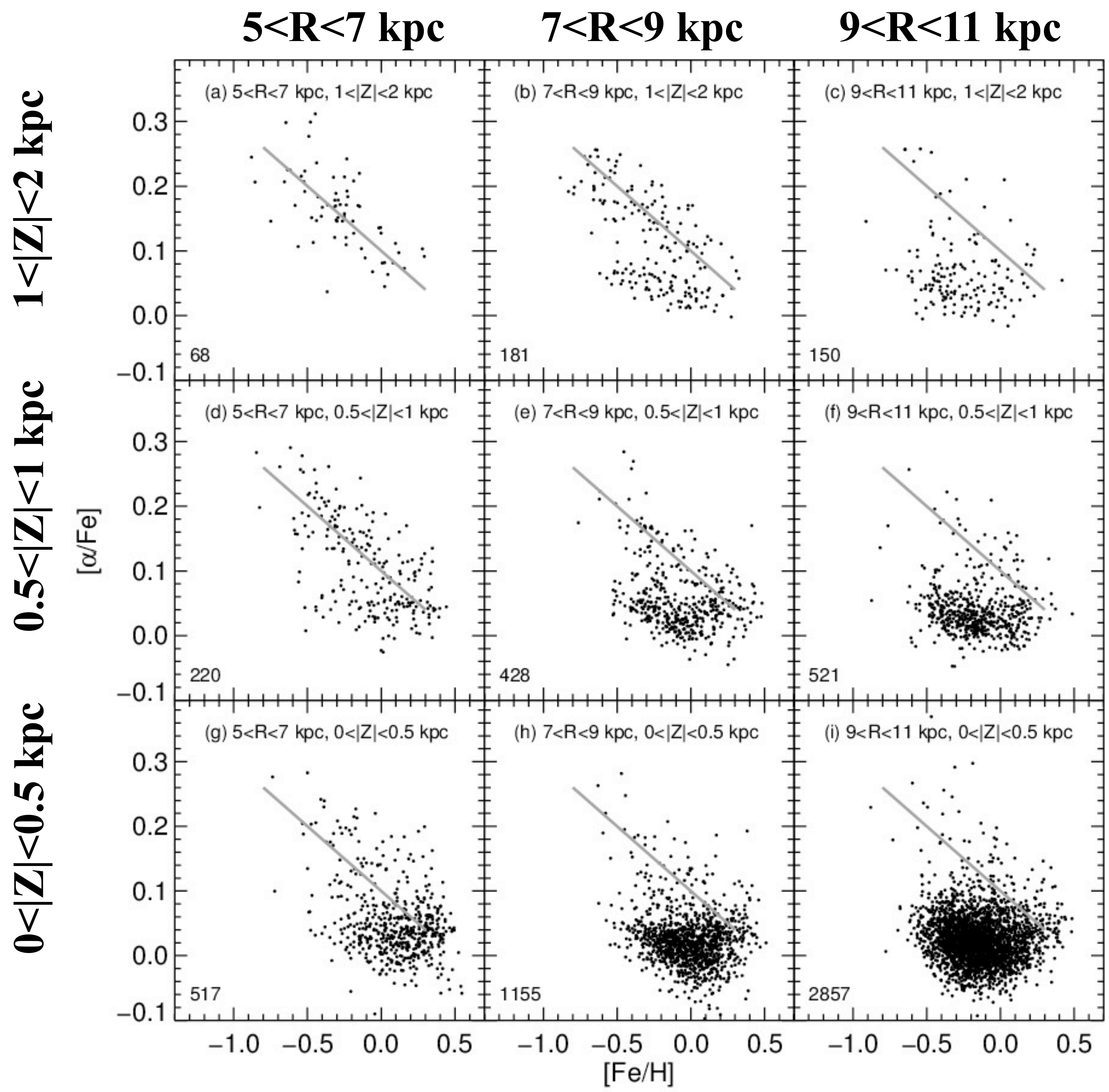
- Very similar to the local sample (~45 pc) of Adibekyan et al. (2011)

Chemical Cartography



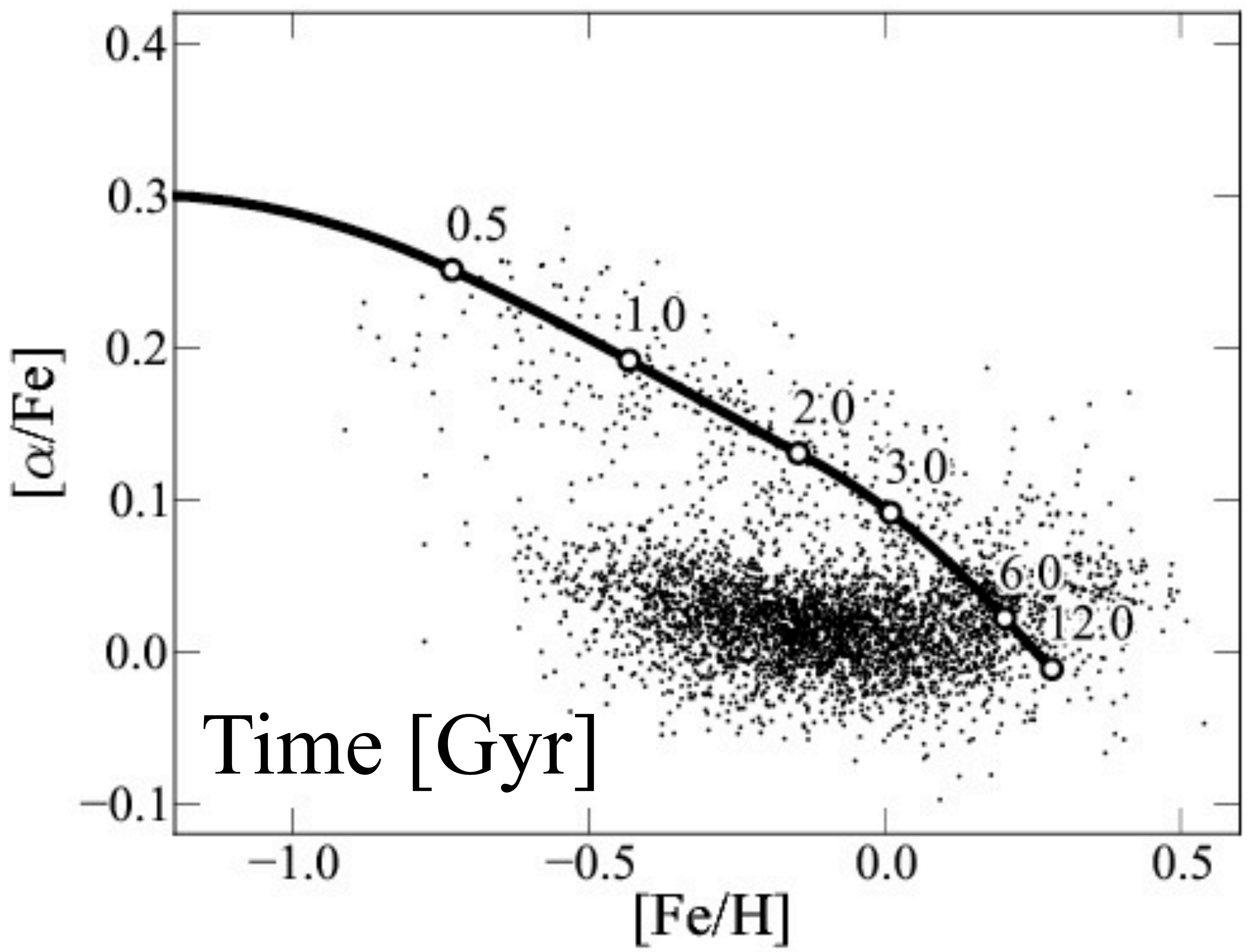
- Chemical cartography
- Look at abundance patterns across the MW disk

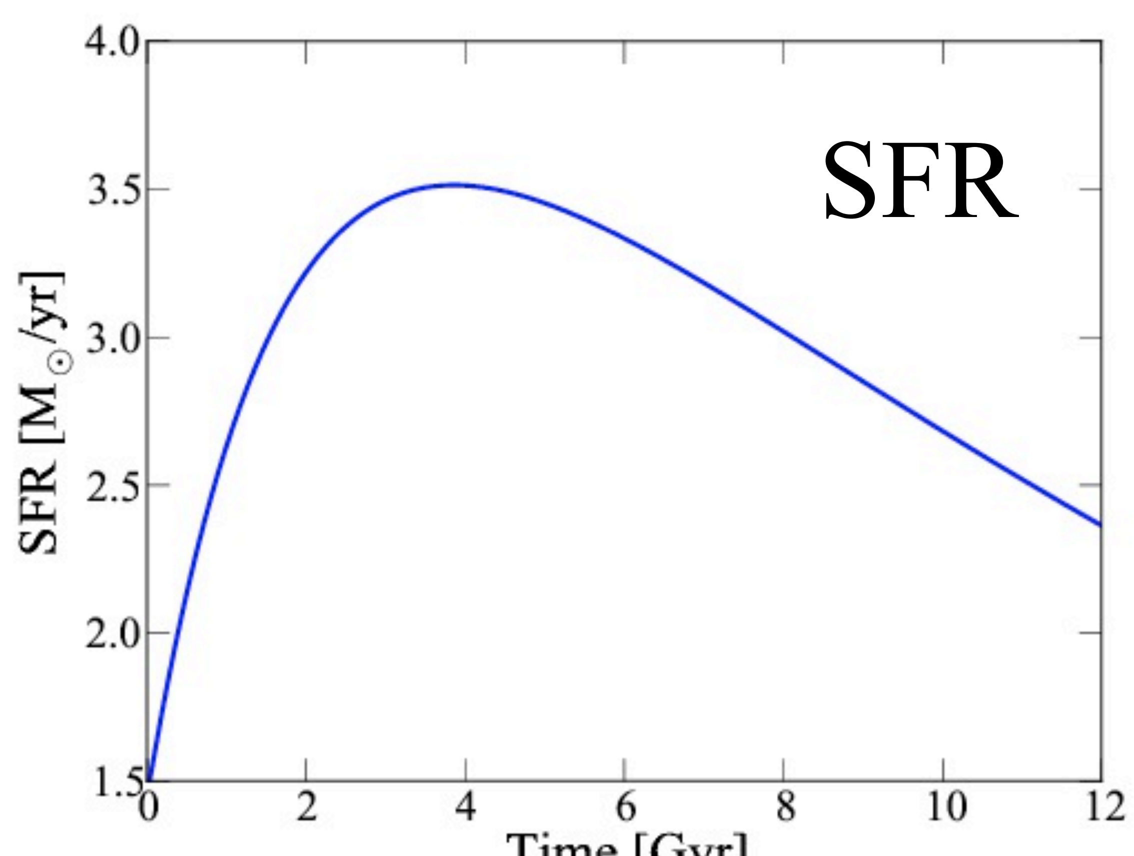
Chemical Cartography



- 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

Chemical Evolution Models

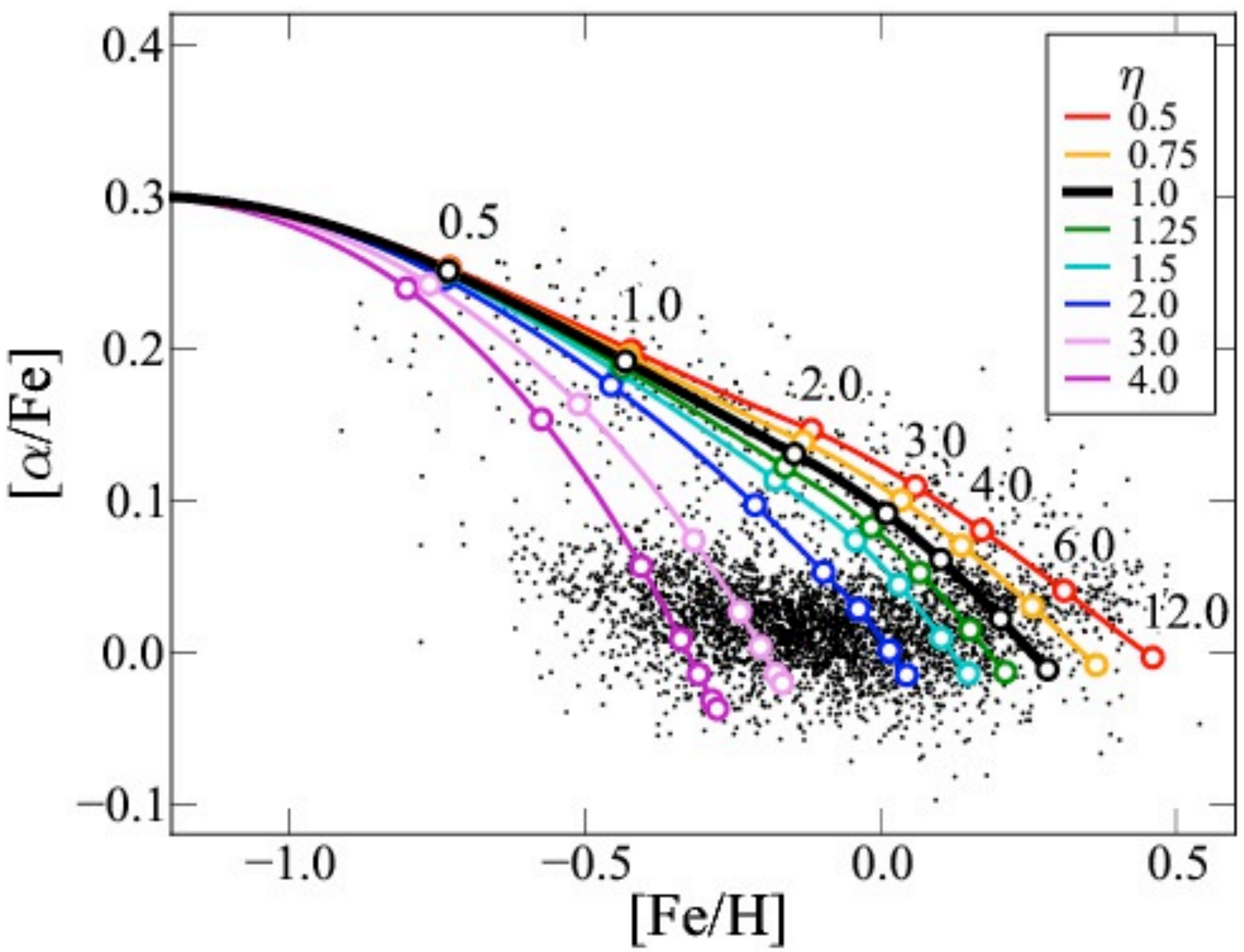




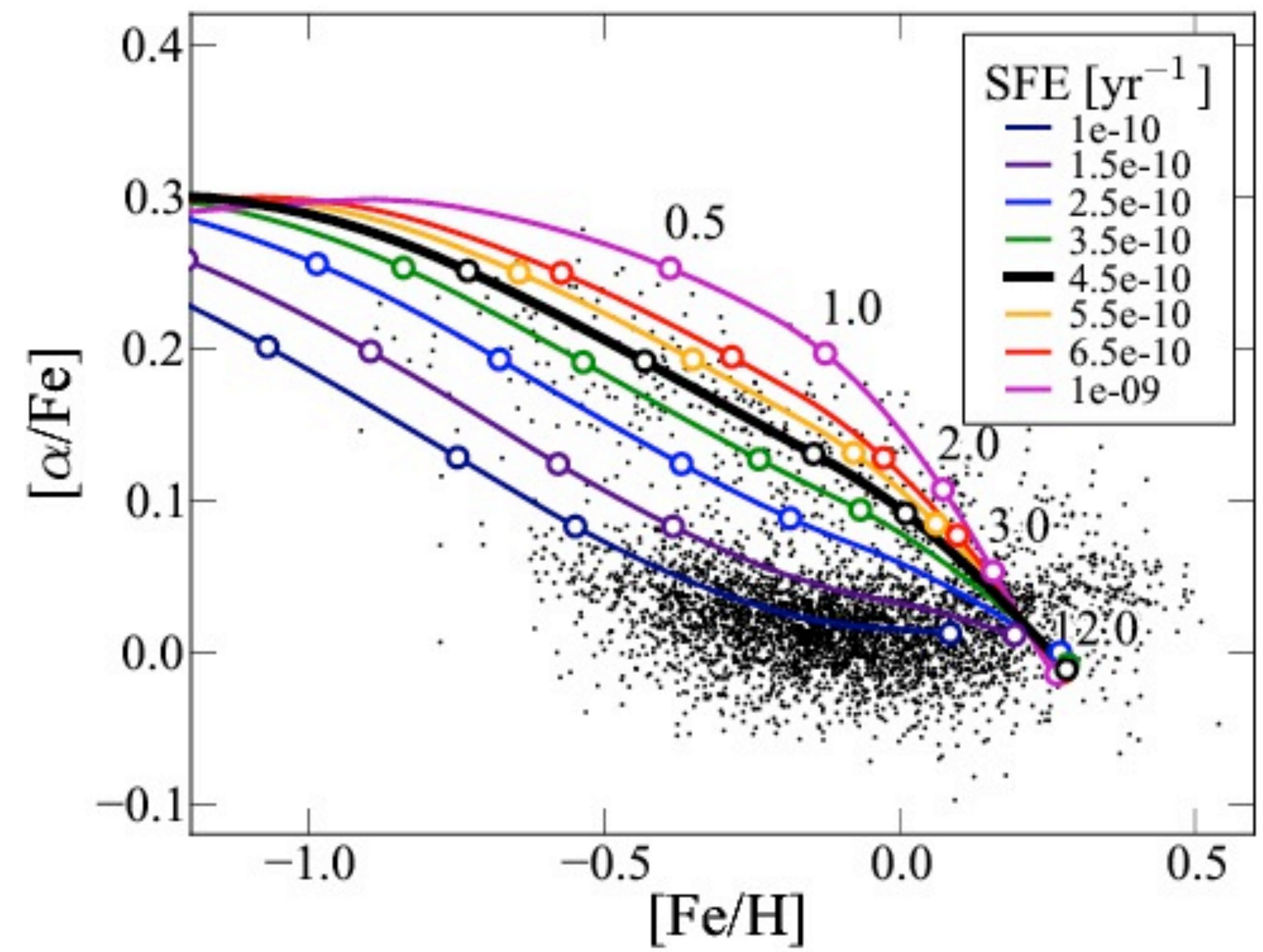
- Simple, one-zone chemical evolution model (Brett Andrews)
- SFR = SFE x M_{gas}
- Outflow = η x SFR
- Inflow exponential with e-folding time of 14 Gyr

Chemical Evolution Models

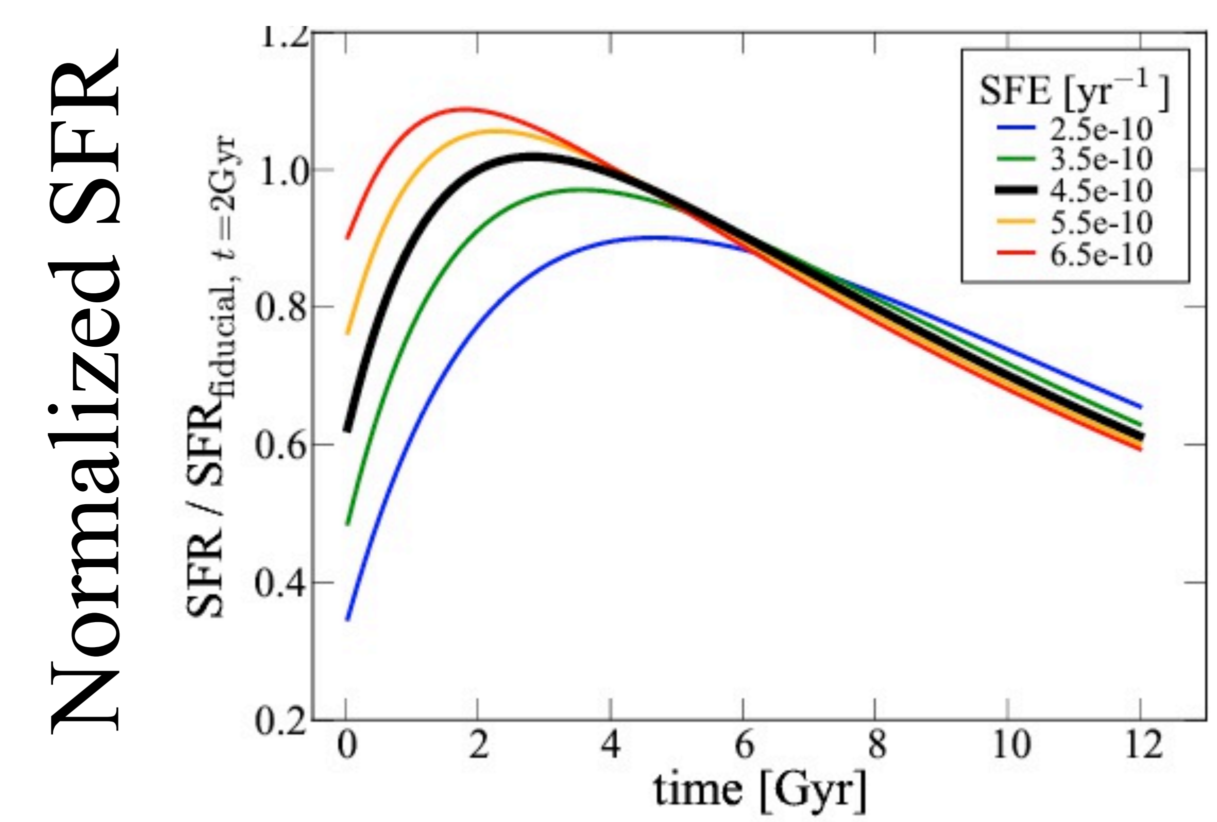
Outflow Rate



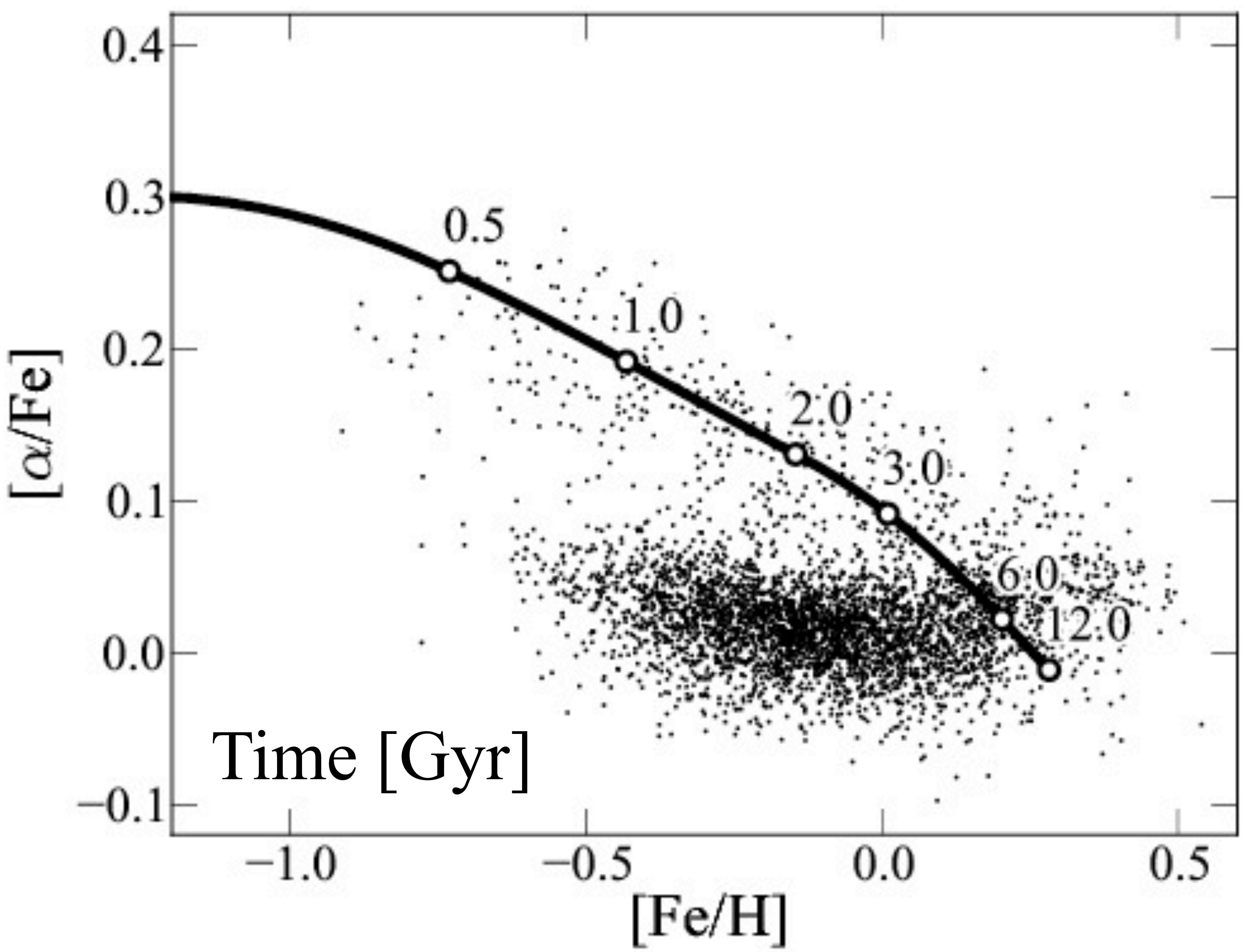
Star Formation Efficiency



- Vary the two main parameters
  - SFR = SFE x M_{gas}
  - Outflow = η x SFR
- evolved for 12 Gyr



High-α Sequence



- Fit to the high-α sequence
- SFE=4.5×10^{-10} yr^{-1}, η=1.0
- Gas consumption timescale ~2 Gyr (SFE^{-1})
- 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*

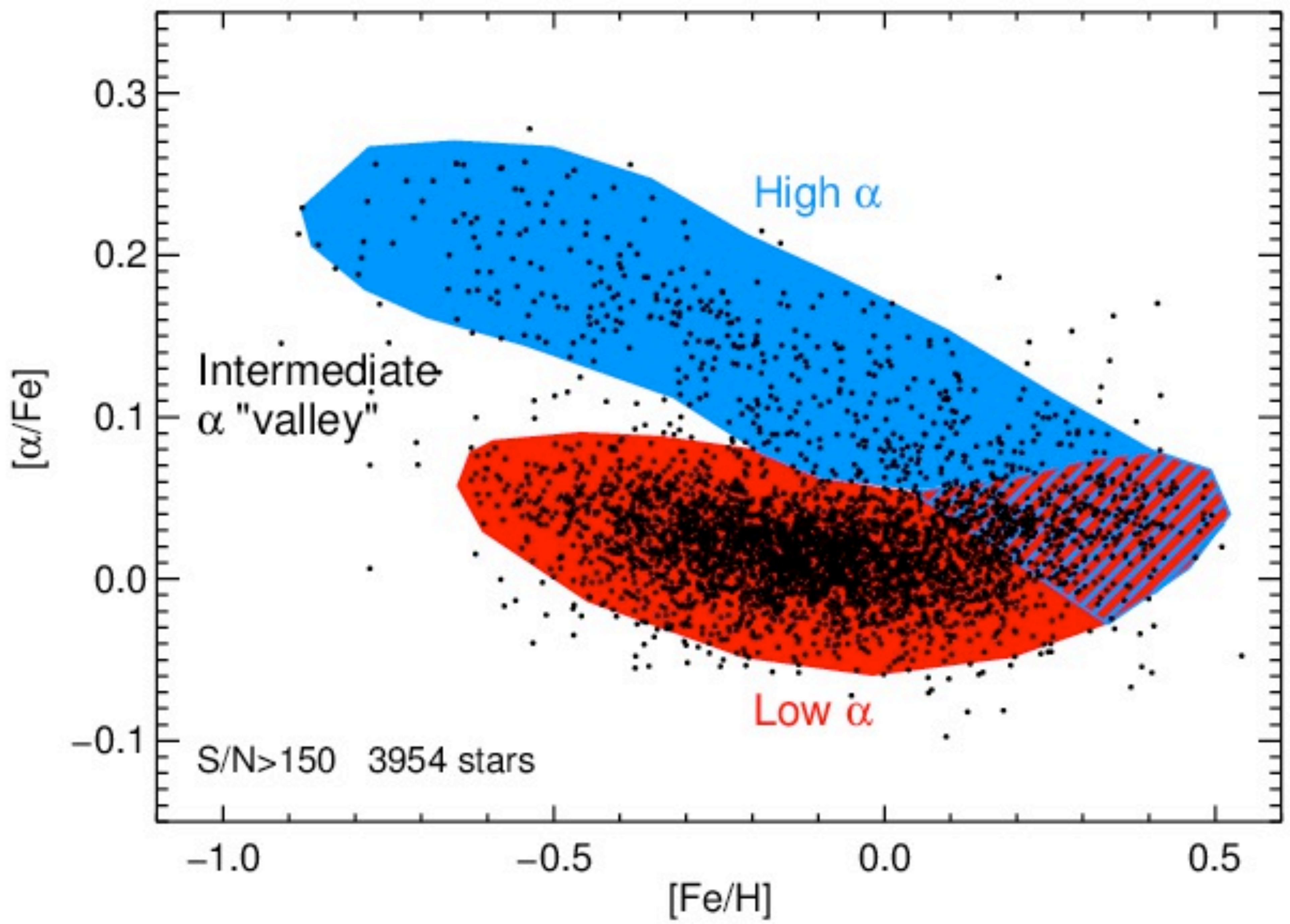
Two Scenarios

Two scenarios to explain these chemical abundance patterns:

1. SFE transition
2. Superposition of multiple populations

SFE Transition

Two Sequences

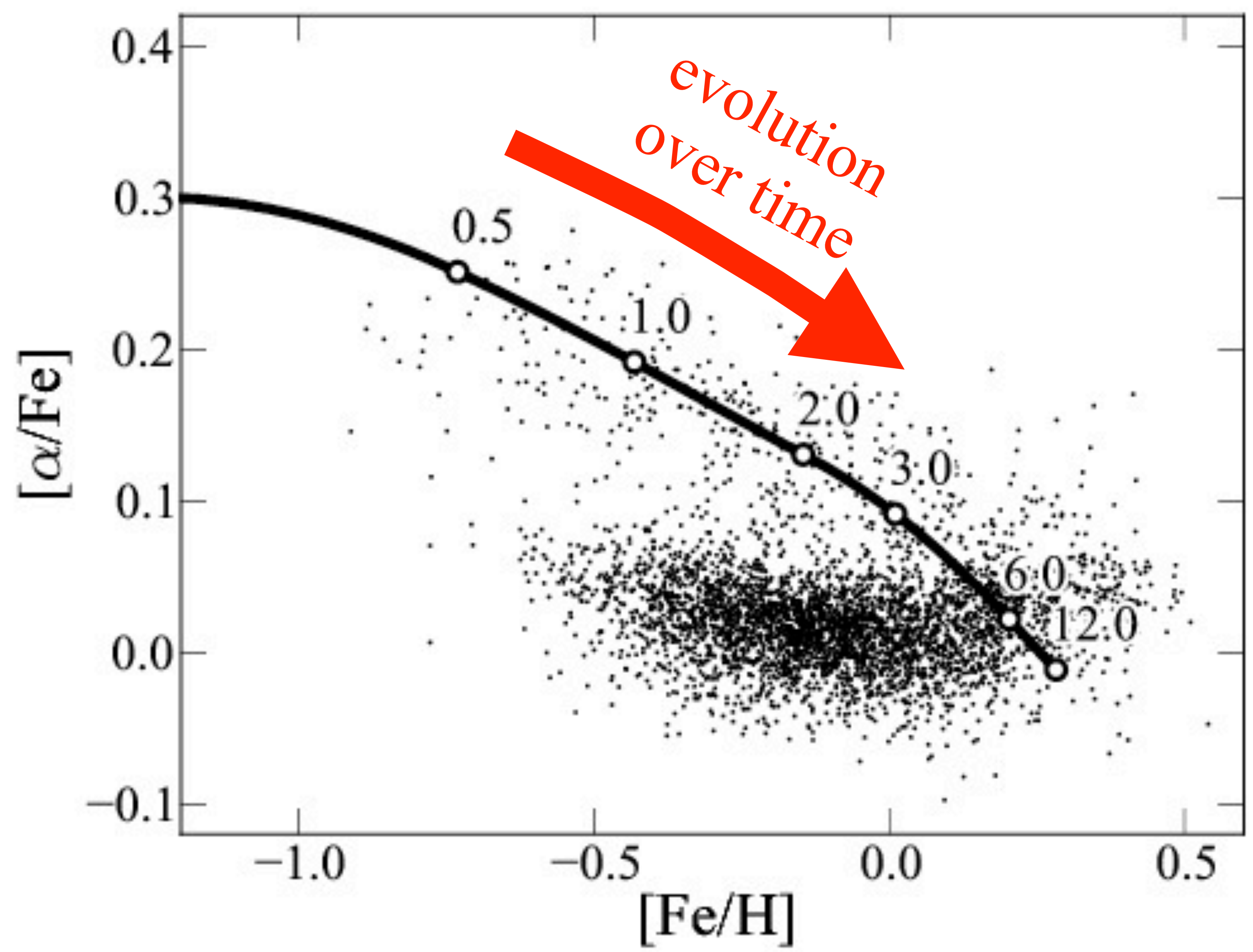


- Think of the two α-sequences as two separate evolutionary sequences with different SFE:
  1. High-α ➞ High-SFE
  2. Low-α ➞ Low-SFE

SFE Transition

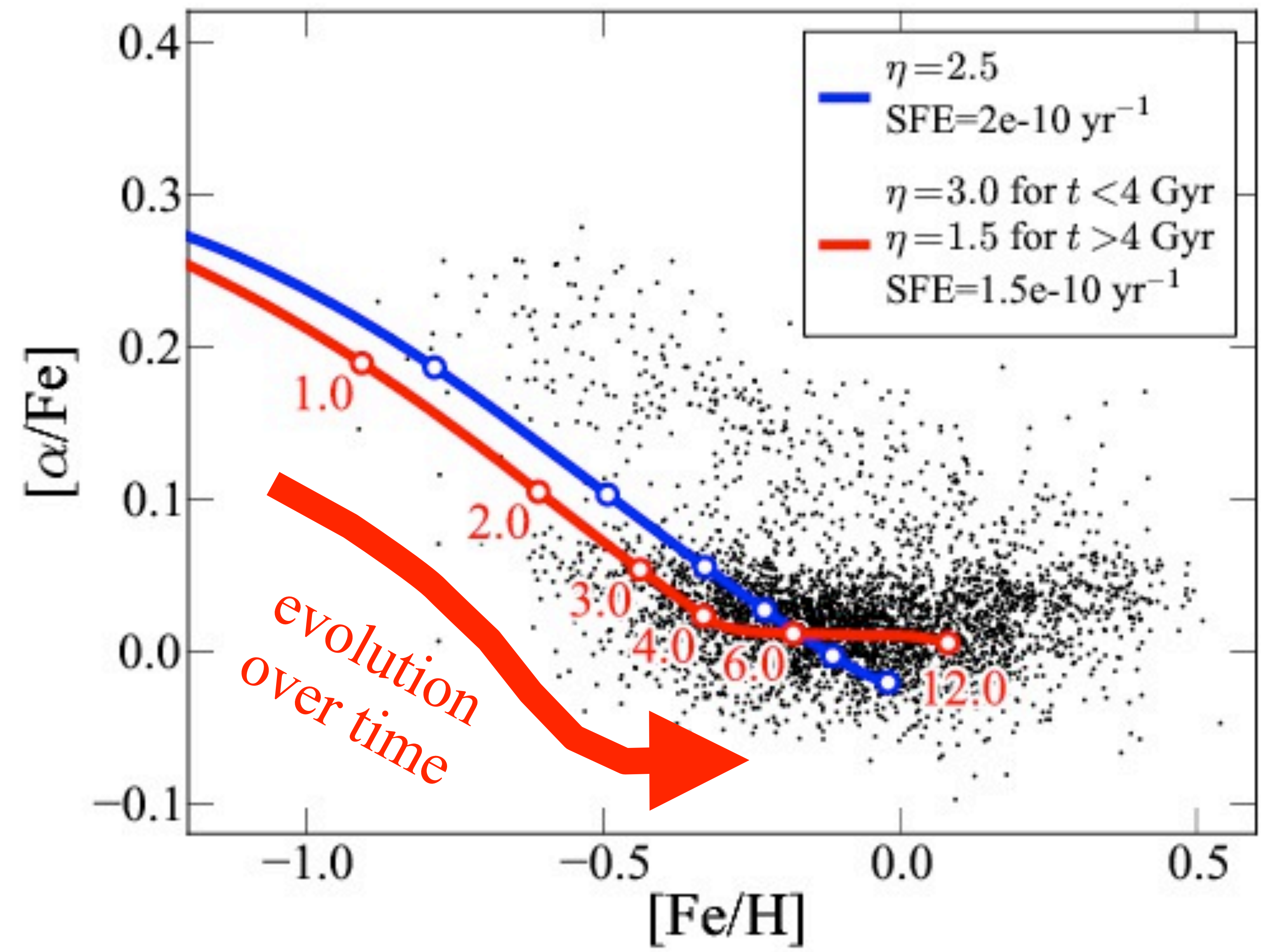
Two Evolutionary Sequences

High-α



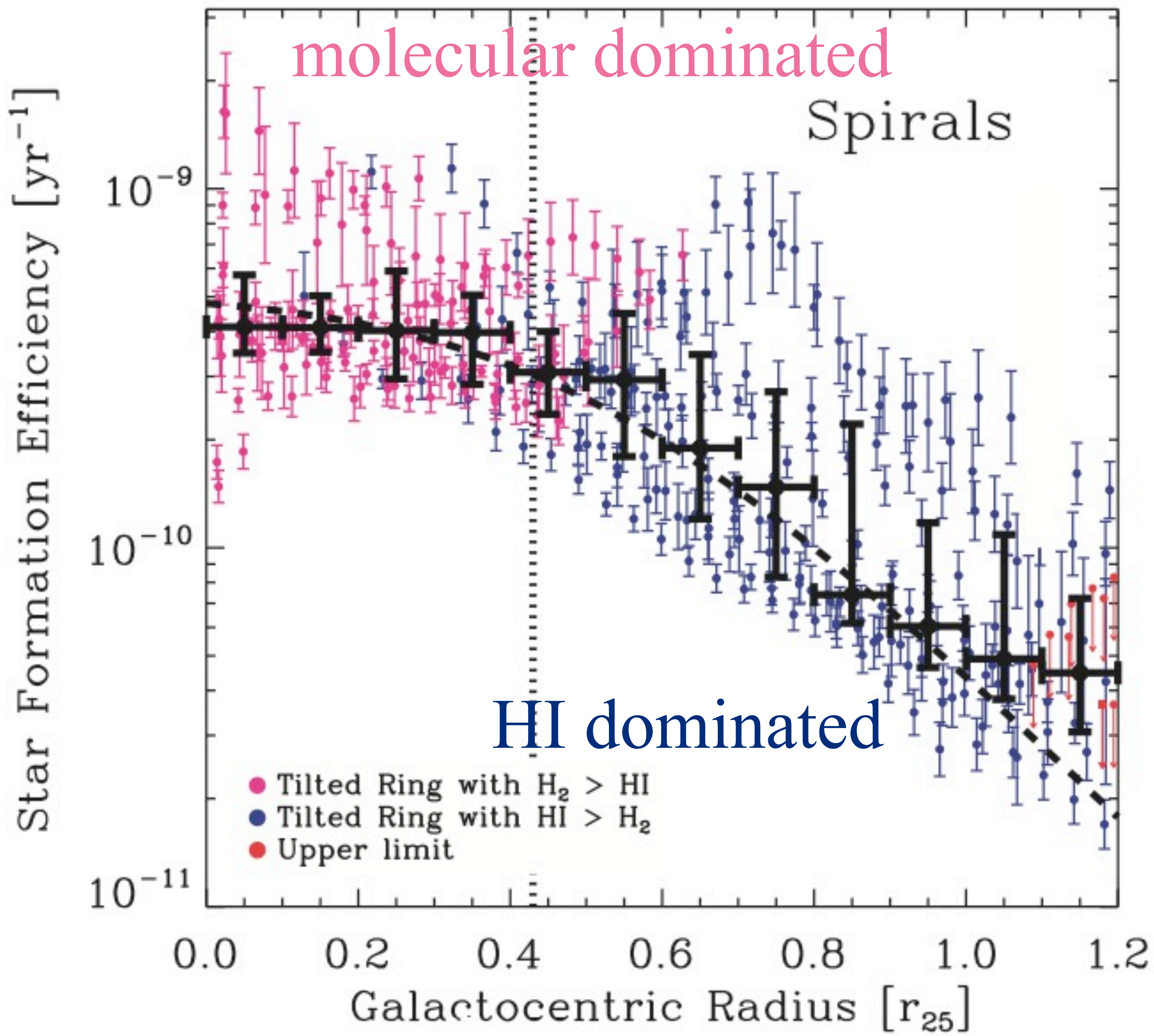
High-SFE, 4.5×10^{-10}

Low-α



Low-SFE, $\sim 1.5 \times 10^{-10}$

SFE Transition

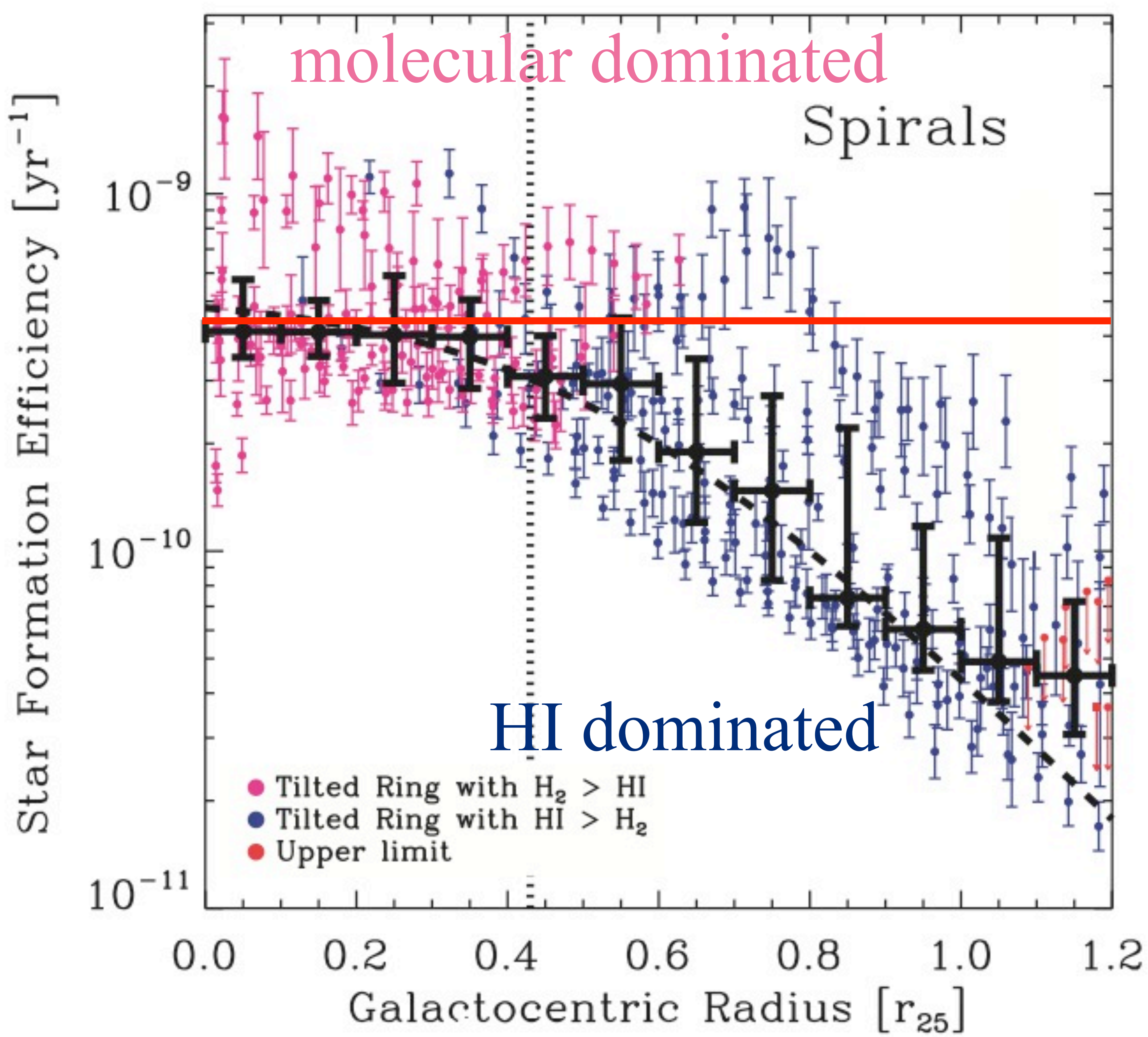


- 12 nearby star-forming spirals
- each point represents a 800pc x 800pc region of the galaxy

Leroy et al. (2008)

SFE Transition

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



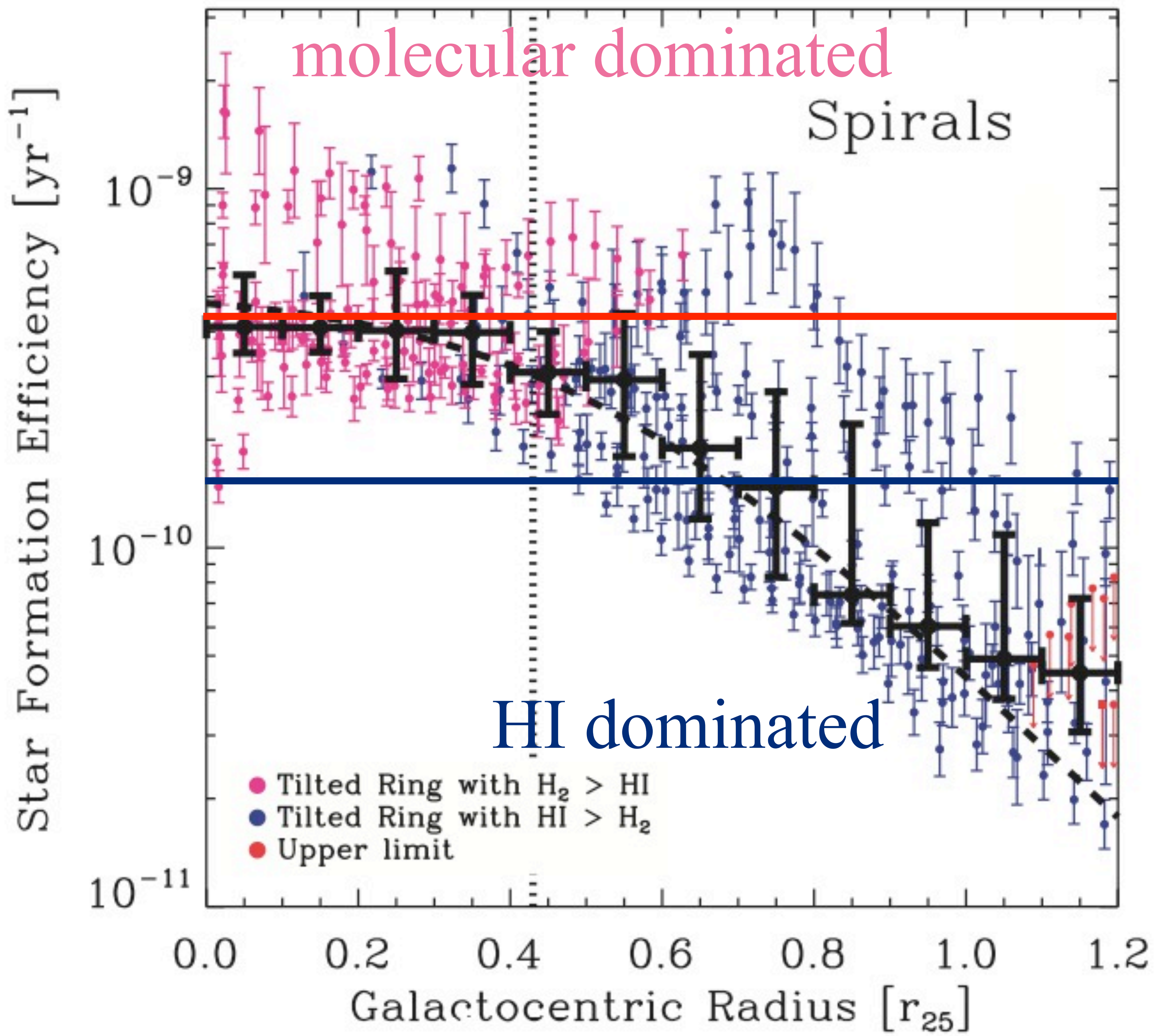
4.5×10^{-10} APOGEE-RC high-α sequence

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

Leroy et al. (2008)

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)

SFE Transition

- Two sequences:
- High-α sequence, high-SFE, molecular-dominated, concentrated in inner Galaxy
- Low-α sequence, low-SFE, HI-dominated, concentrated in outer Galaxy

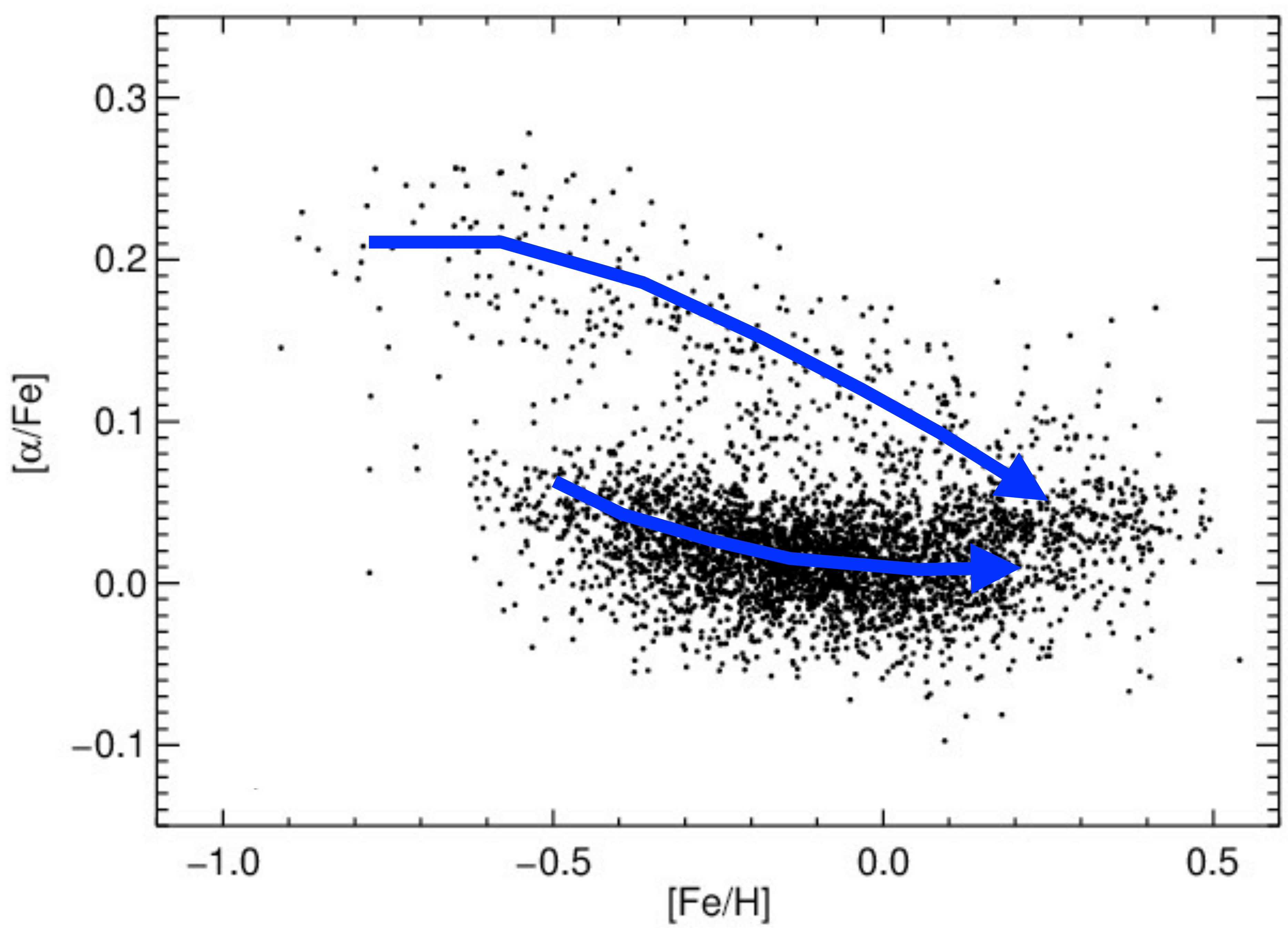
SFE Transition

- Two sequences:
- High-α sequence, high-SFE, molecular-dominated, concentrated in inner Galaxy, older
- Low-α sequence, low-SFE, HI-dominated, concentrated in outer Galaxy, younger

- SFE transition, ~8 Gyr ago (but position dependent), between molecular-dominated to HI-dominated SF

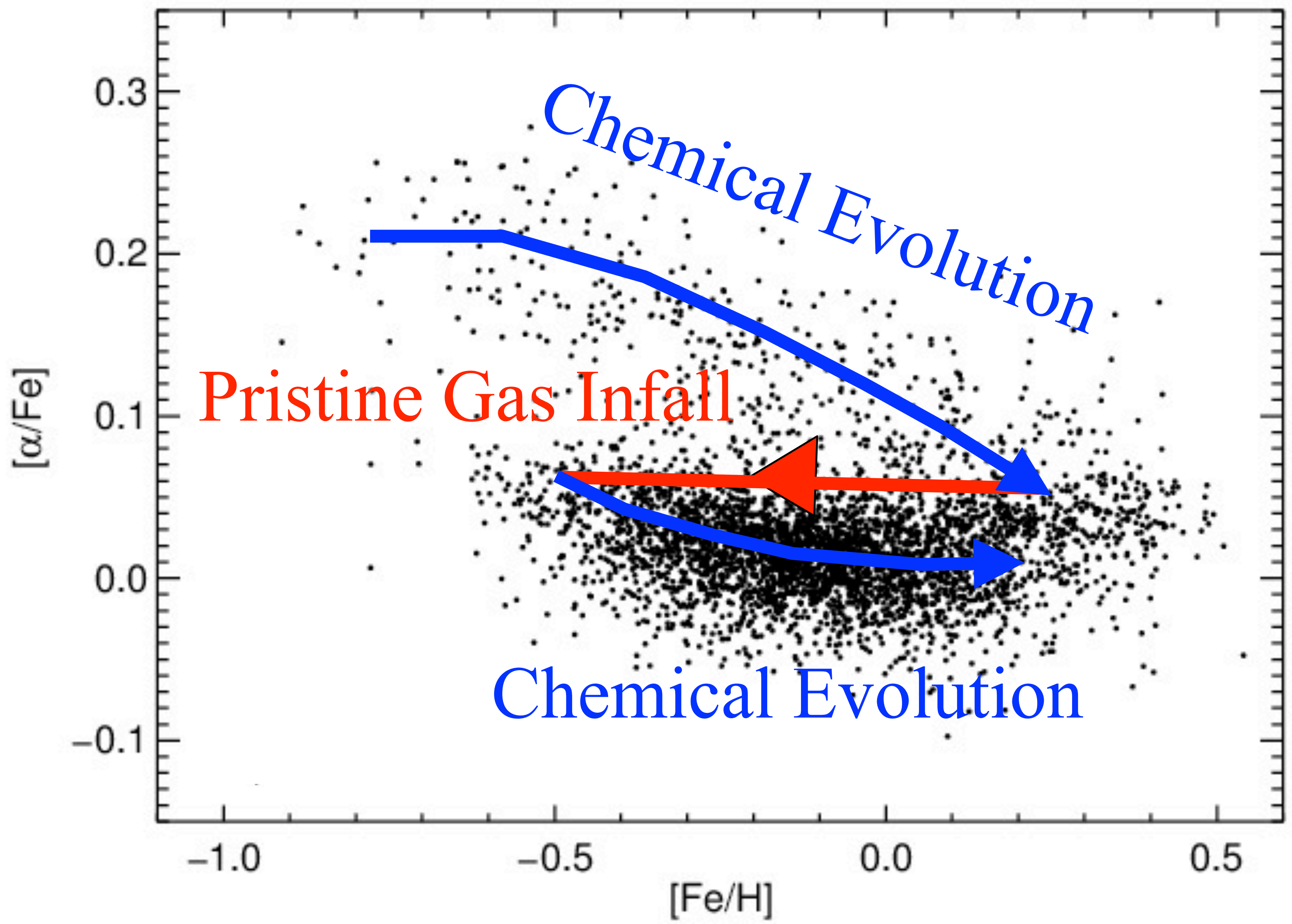
SFE Transition

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



SFE Transition

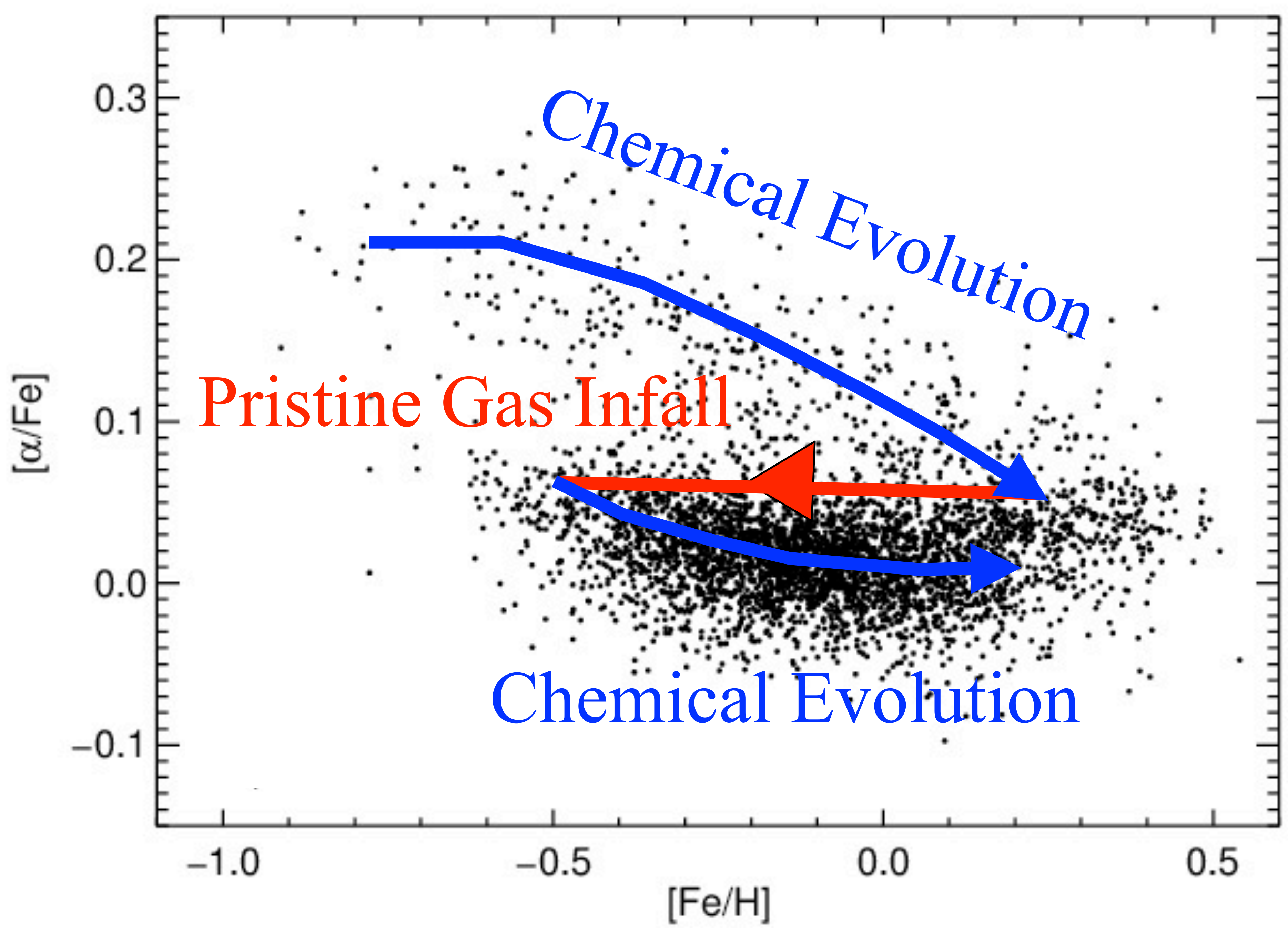
- To also match the chemistry, need gas infall at SFE transition
- Infall of pristine gas, lower [Fe/H], [α/Fe] constant
- Low SFE and SNIa from older “High-α” population keep α low



- Infall of pristine gas ~8 Gyr ago

SFE Transition

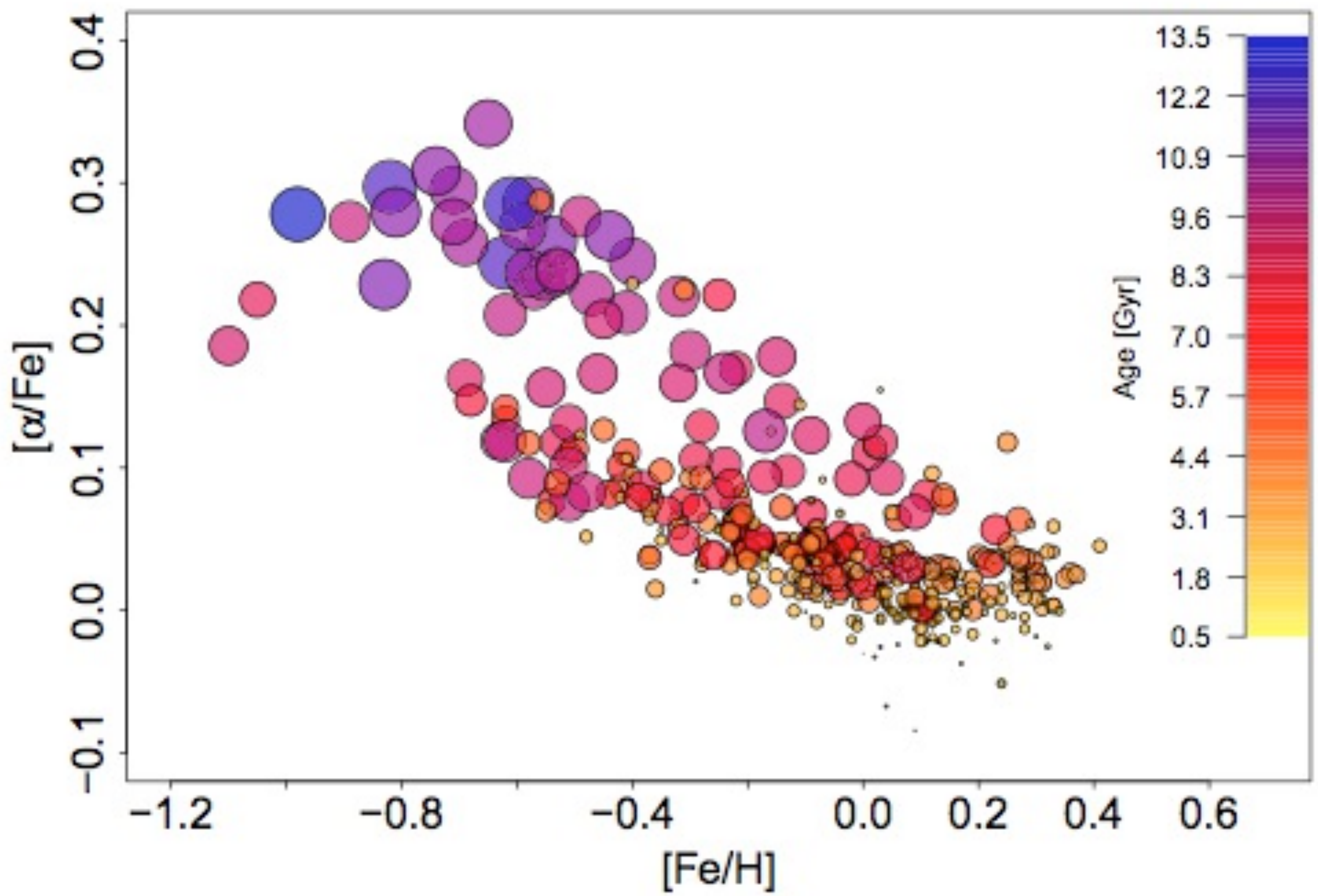
- Infall of significant pristine gas combined with gas depletion from early rapid SF could have triggered the transition (also suggested by Chiappini et al. 2009)



- Infall of pristine gas ~8 Gyr ago

Ages

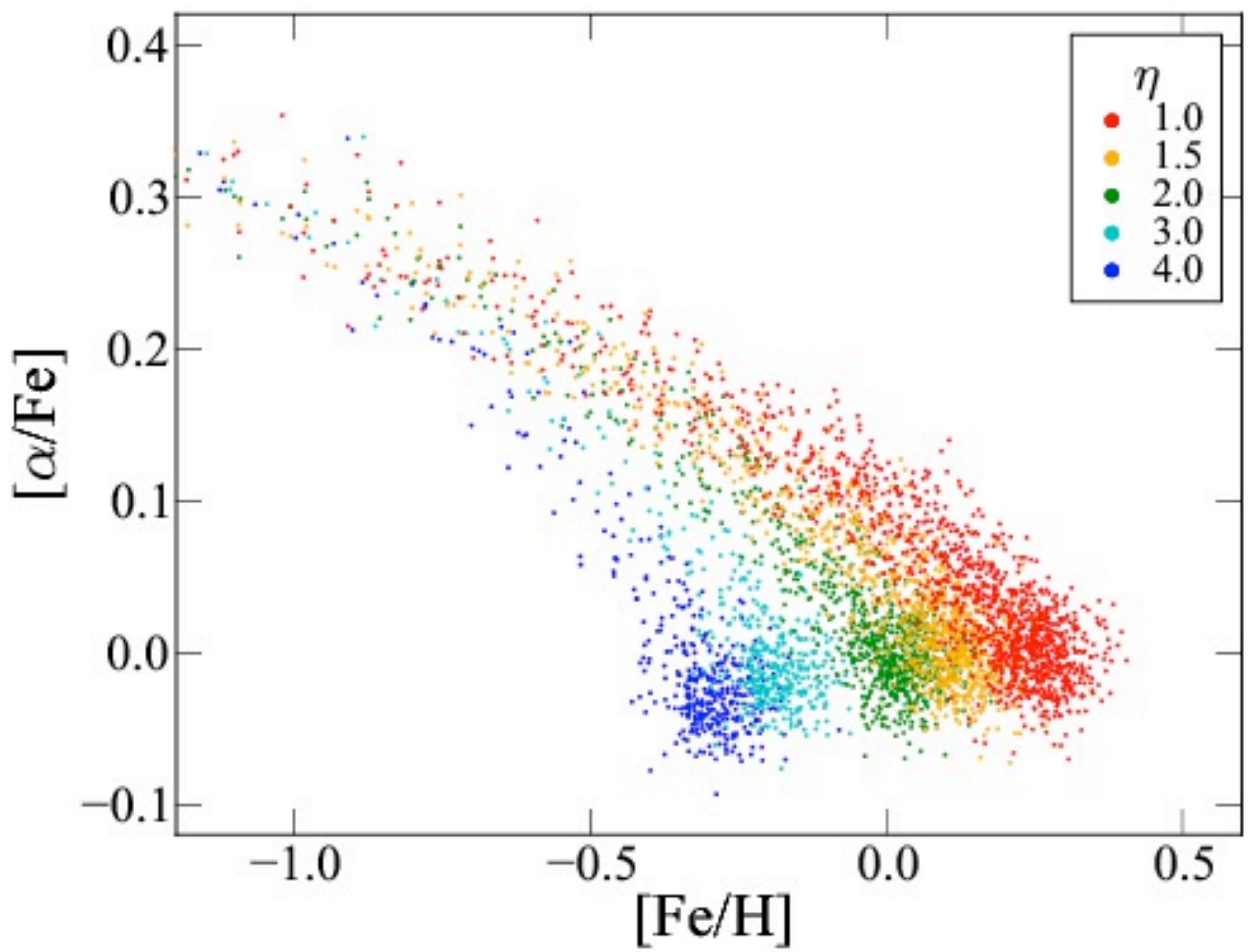
Color/size indicates age



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

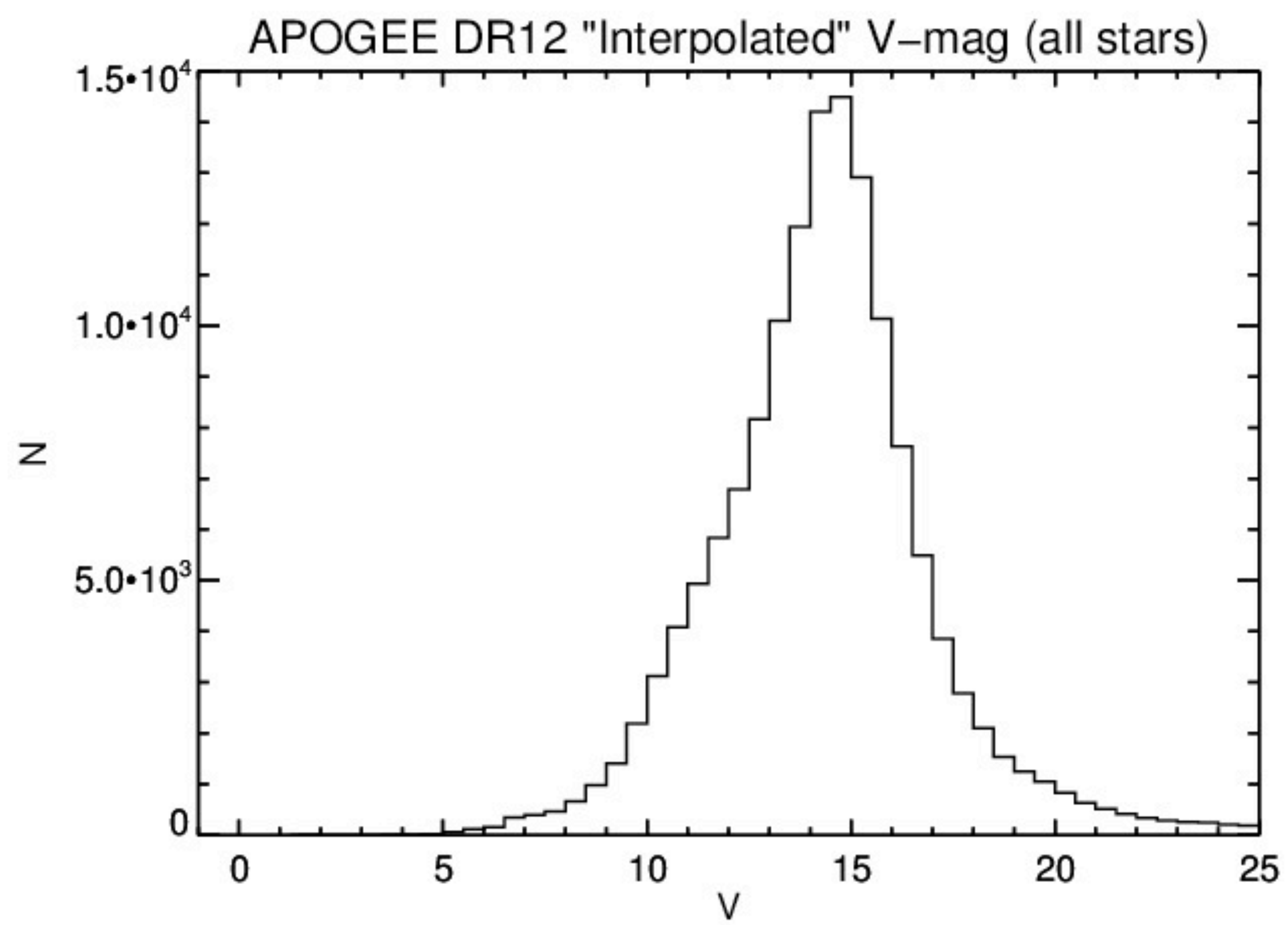
Superposition of multiple populations

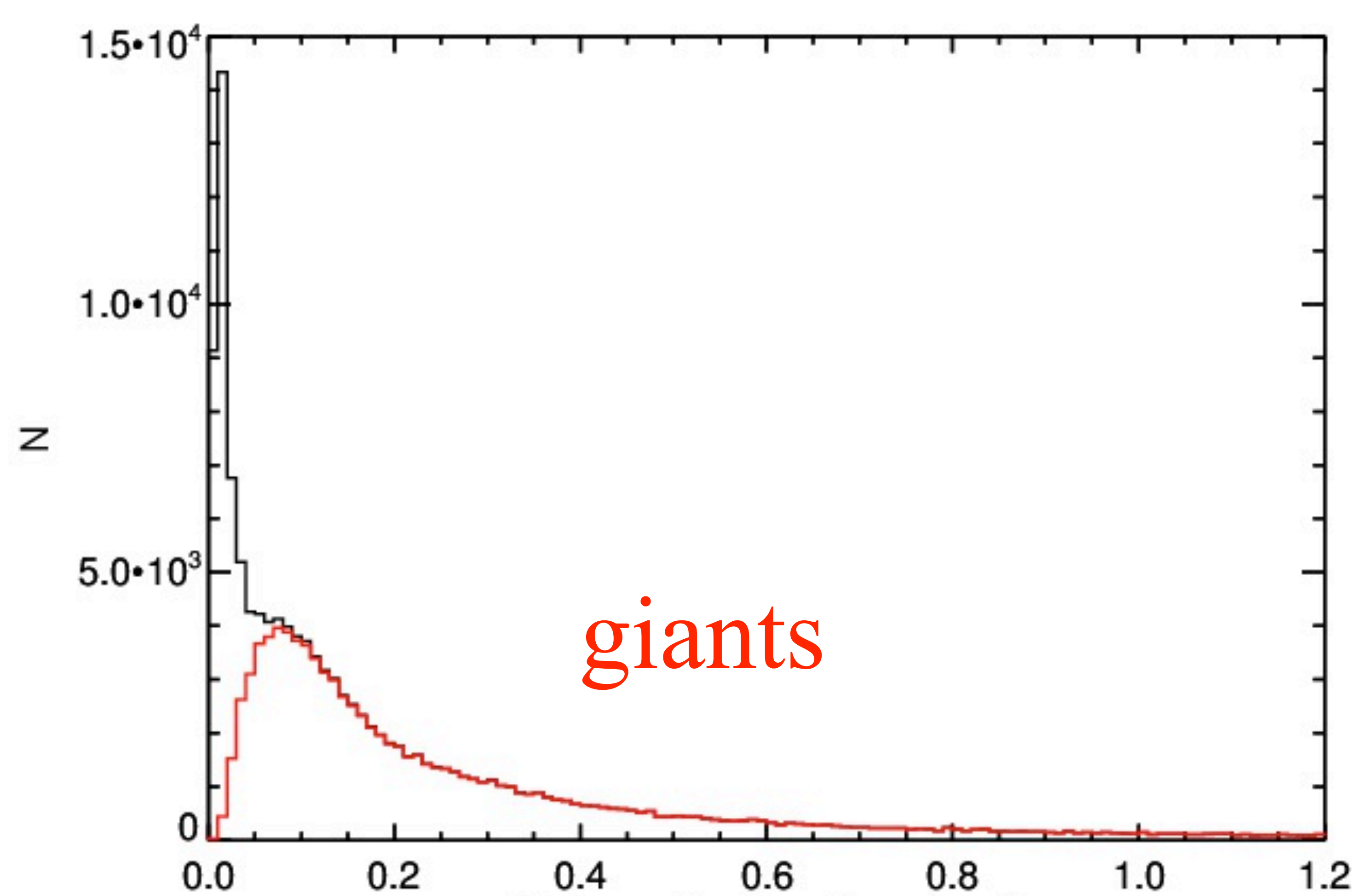


Stars drawn randomly from 5 models

- 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

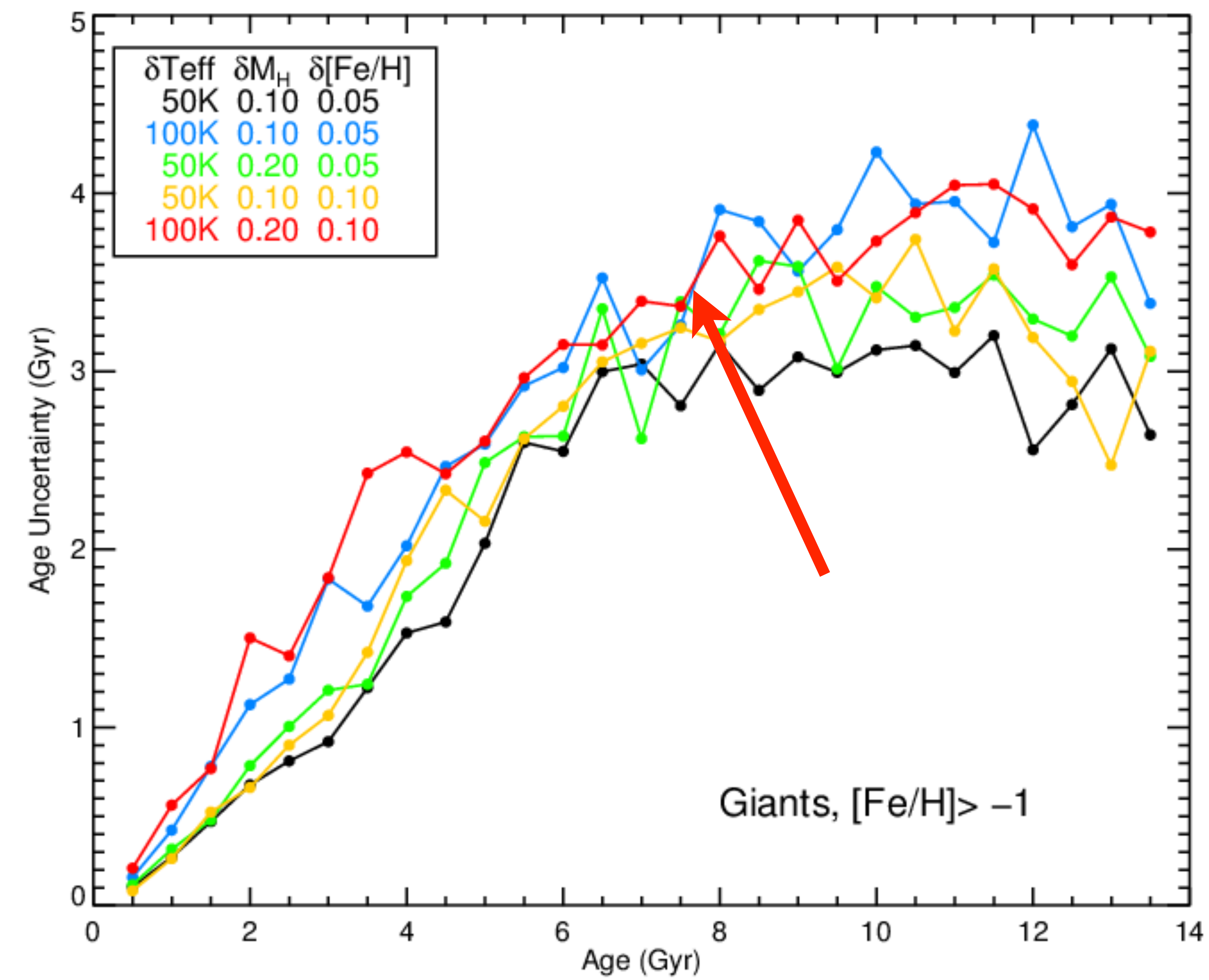
Ages with Gaia





Distance Modulus error (mag)

Age Uncertainties



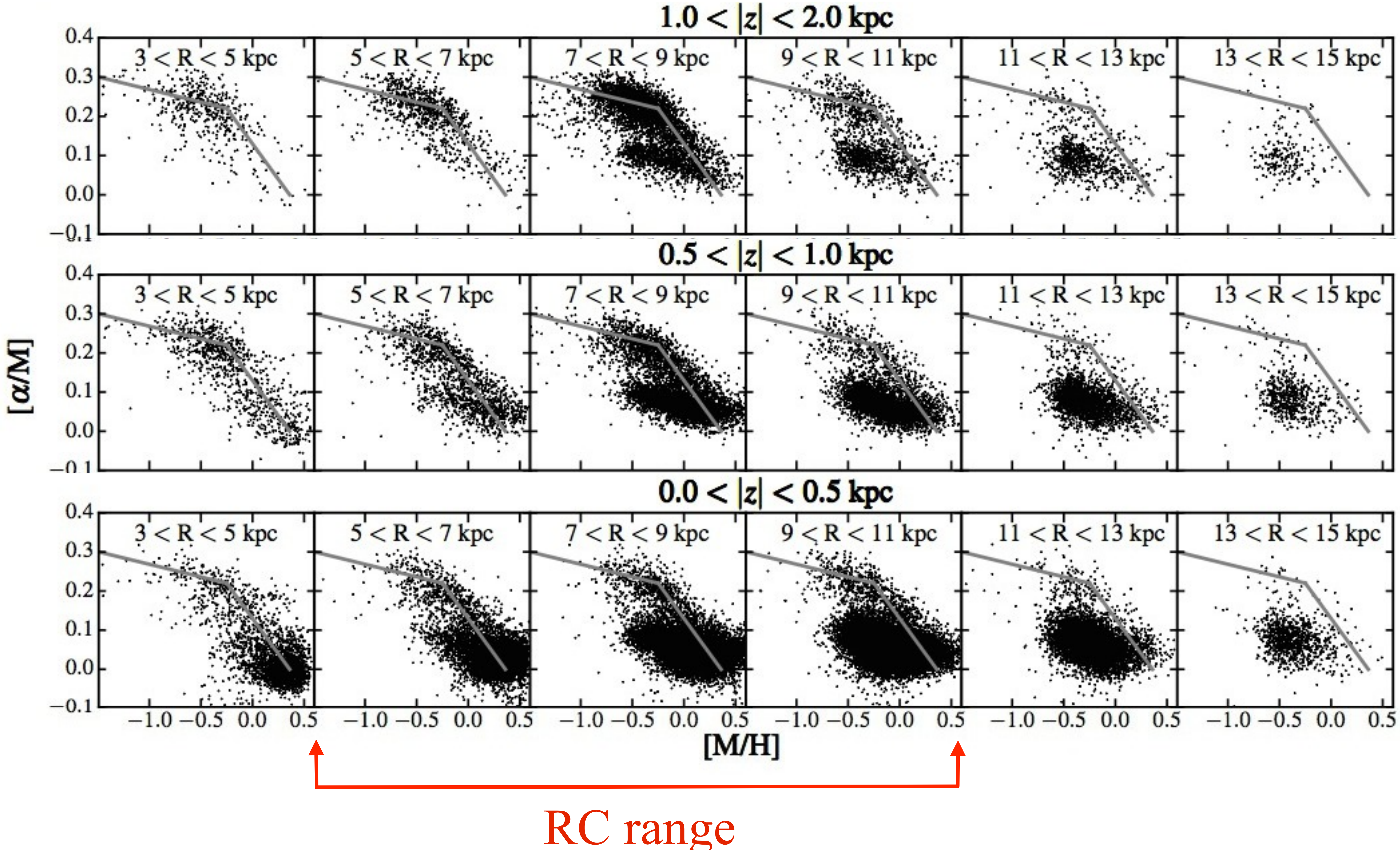
Ages from Teff, logg, [Fe/H], distance, photometry and isochrones

Chemical Cartography with APOGEE II: Metallicity Distribution Functions and the Chemical Structure of the Milky Way Disk

Hayden et al. (2015), in preparation

RGB Chemical Pattern

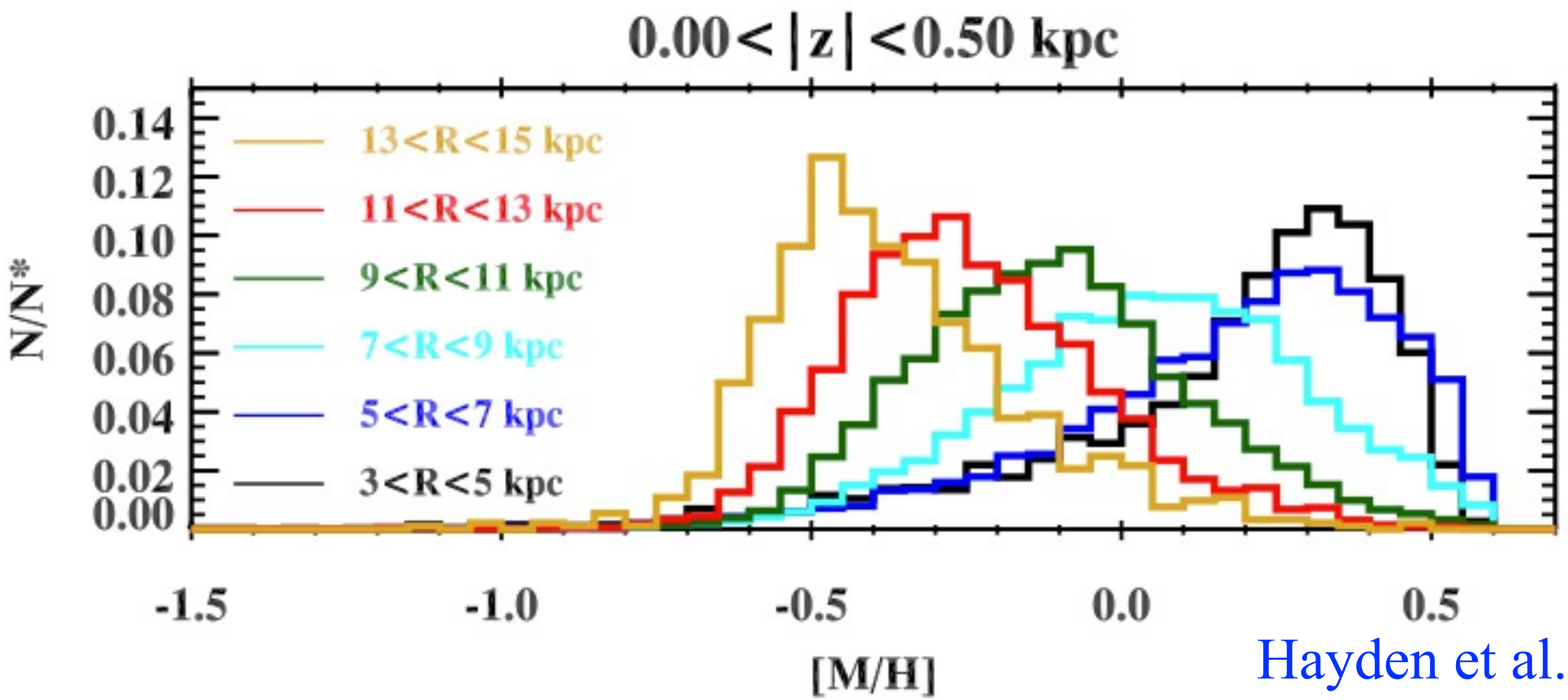
- Extending the reach with ~70,000 RGB stars, 3<R<15 kpc



Hayden et al. (2015), in prep.

Metallicity Distribution Functions

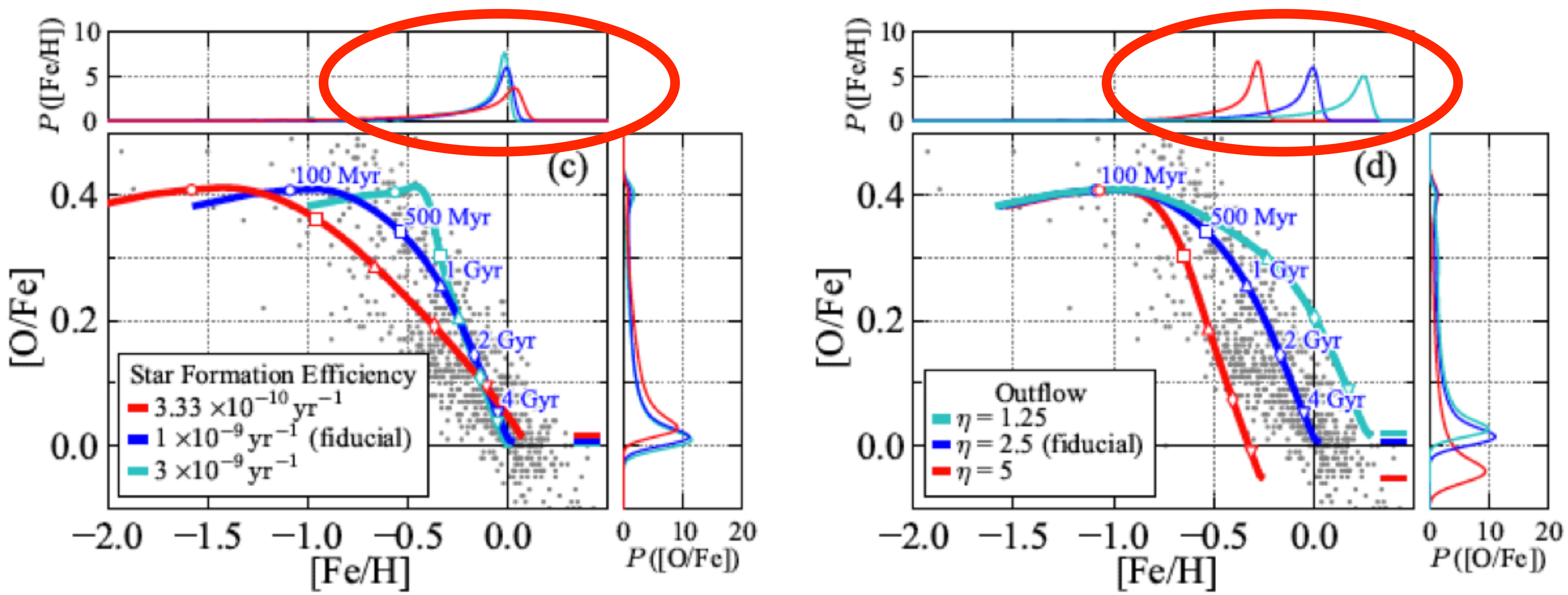
- MDF shape change with radius
  - Skew-negative in inner galaxy
  - Approximately Gaussian near solar circle
  - Skew-positive in outer galaxy



Hayden et al. (2015), in prep.

Metallicity Distribution Functions

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

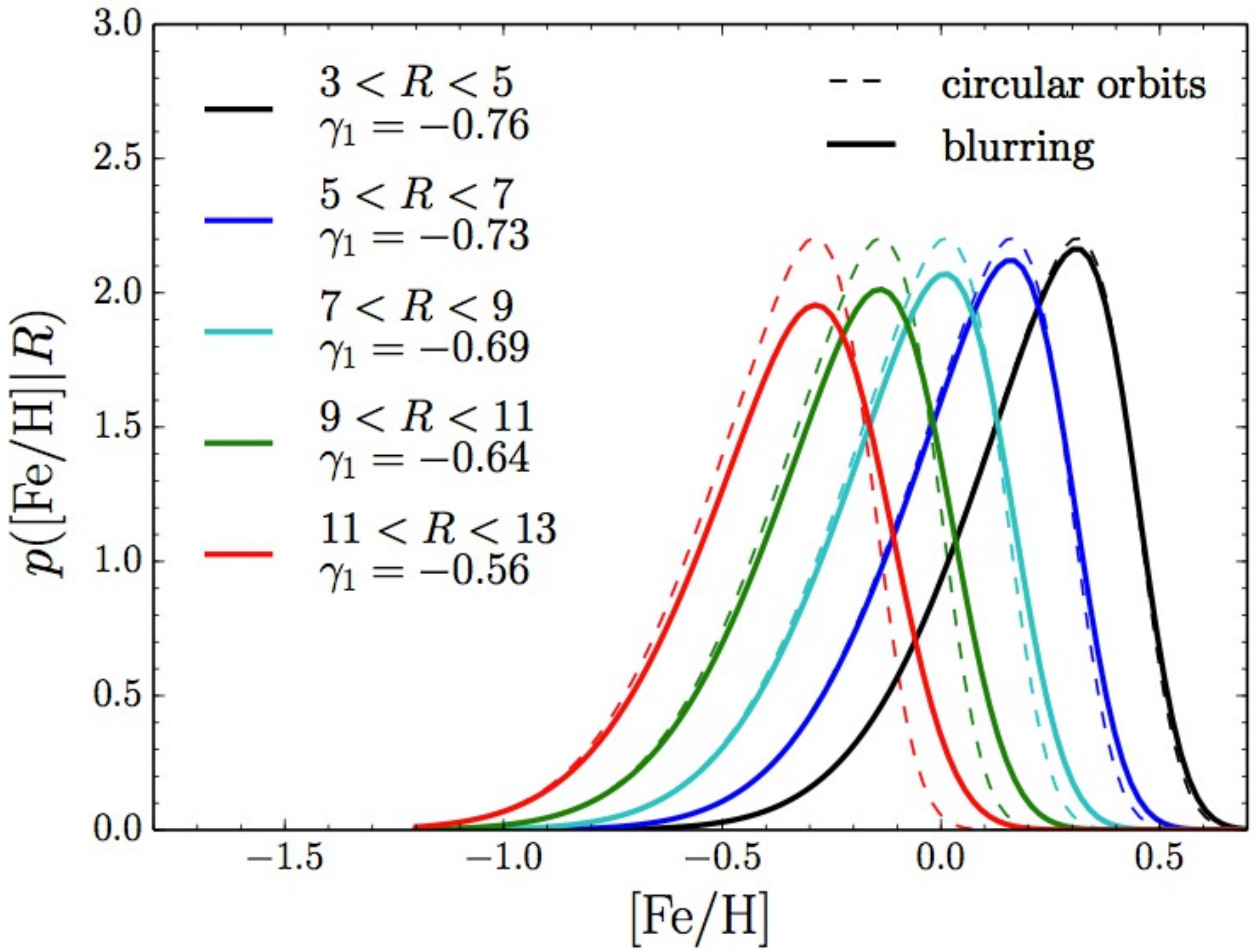


Andrews et al. (2015)

Hayden et al. (2015), in prep.

Metallicity Distribution Functions

- Blurring model (no ang. mom. change) does not work



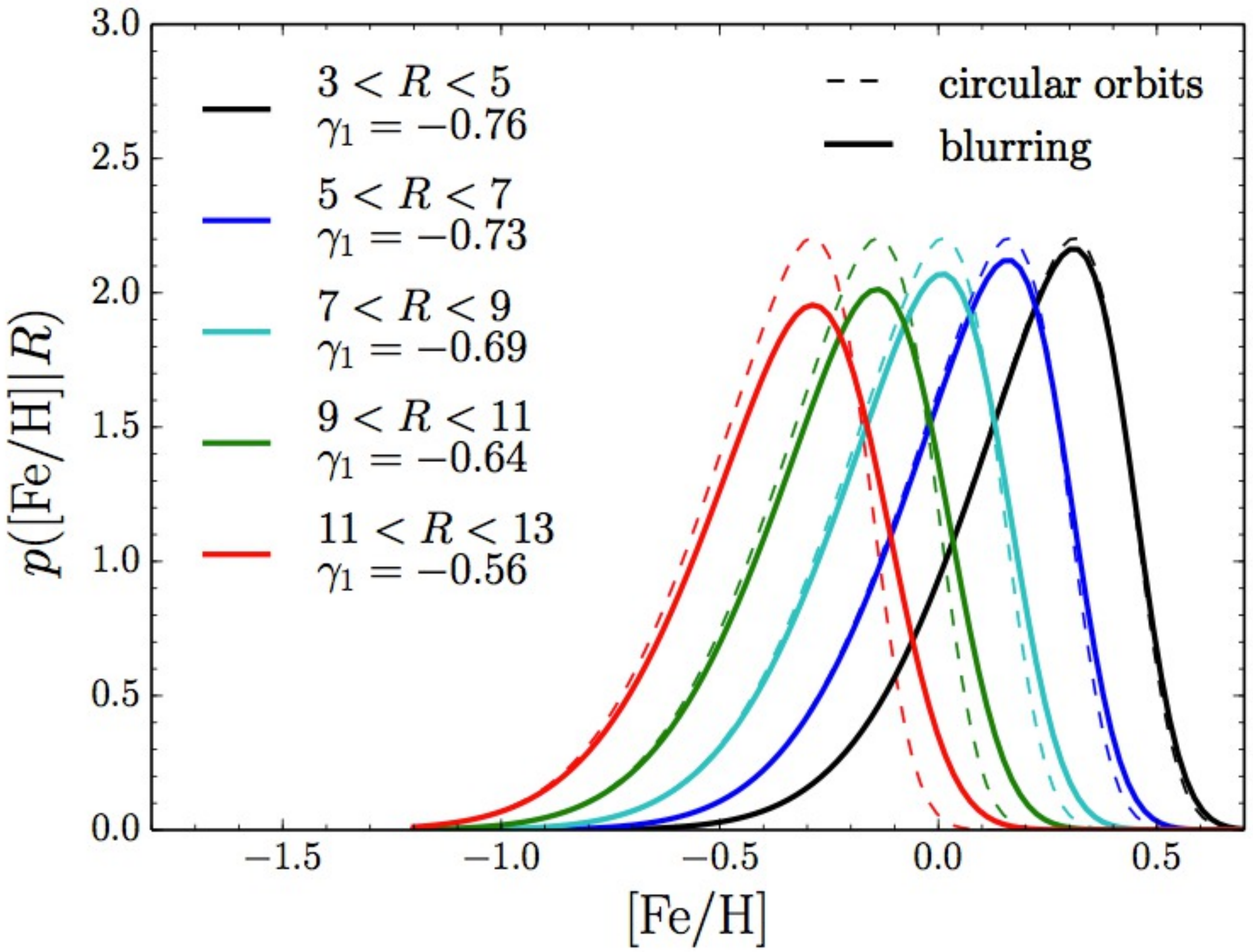
blurring with 30 km/s
velocity dispersion

analysis by J. Bovy

Hayden et al. (2015), in prep.

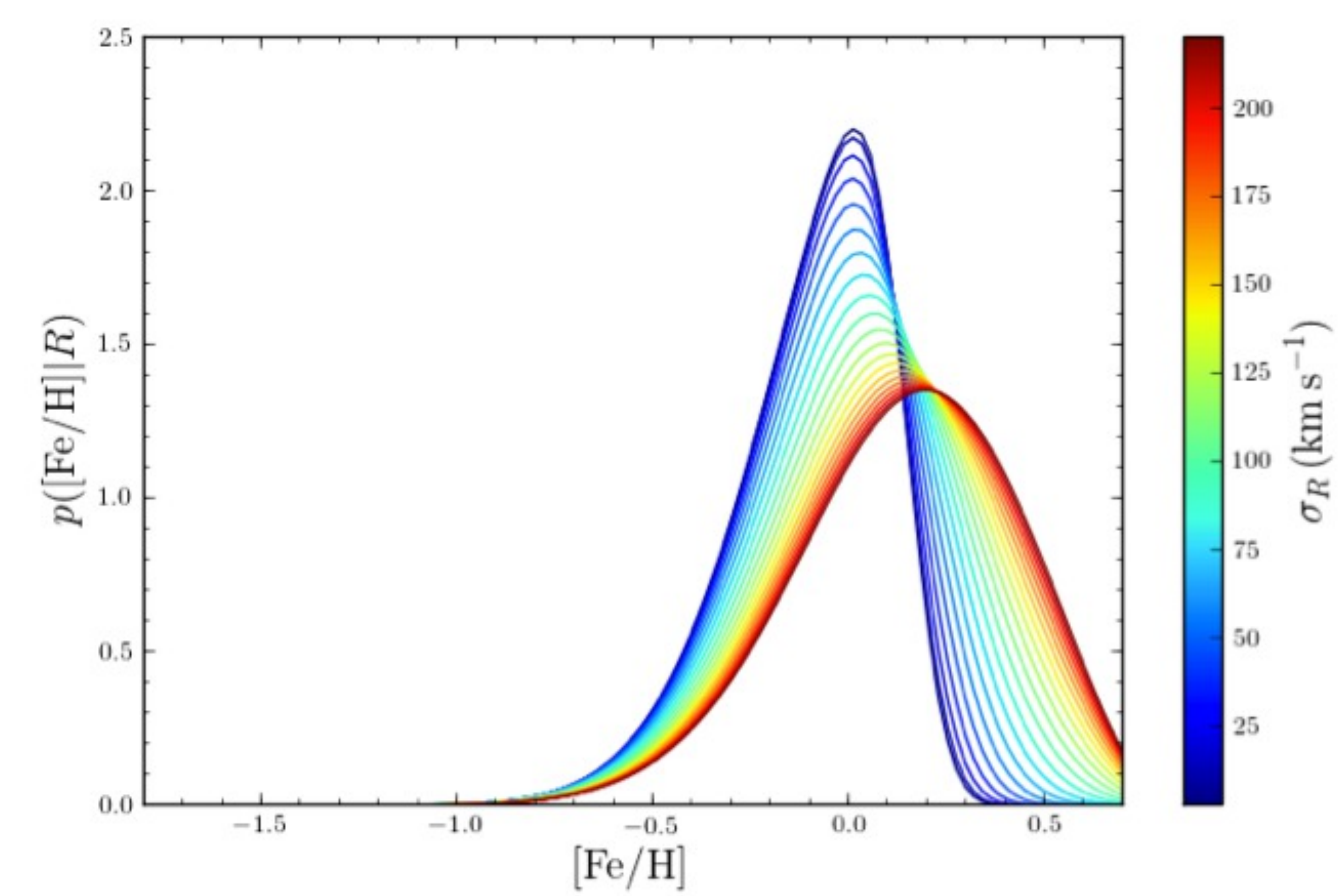
Metallicity Distribution Functions

- Blurring model (no ang. mom. change) does not work
- Need dispersion of 100s of km/s to have any real effect



blurring with 30 km/s velocity dispersion

Skewness Change with Dispersion

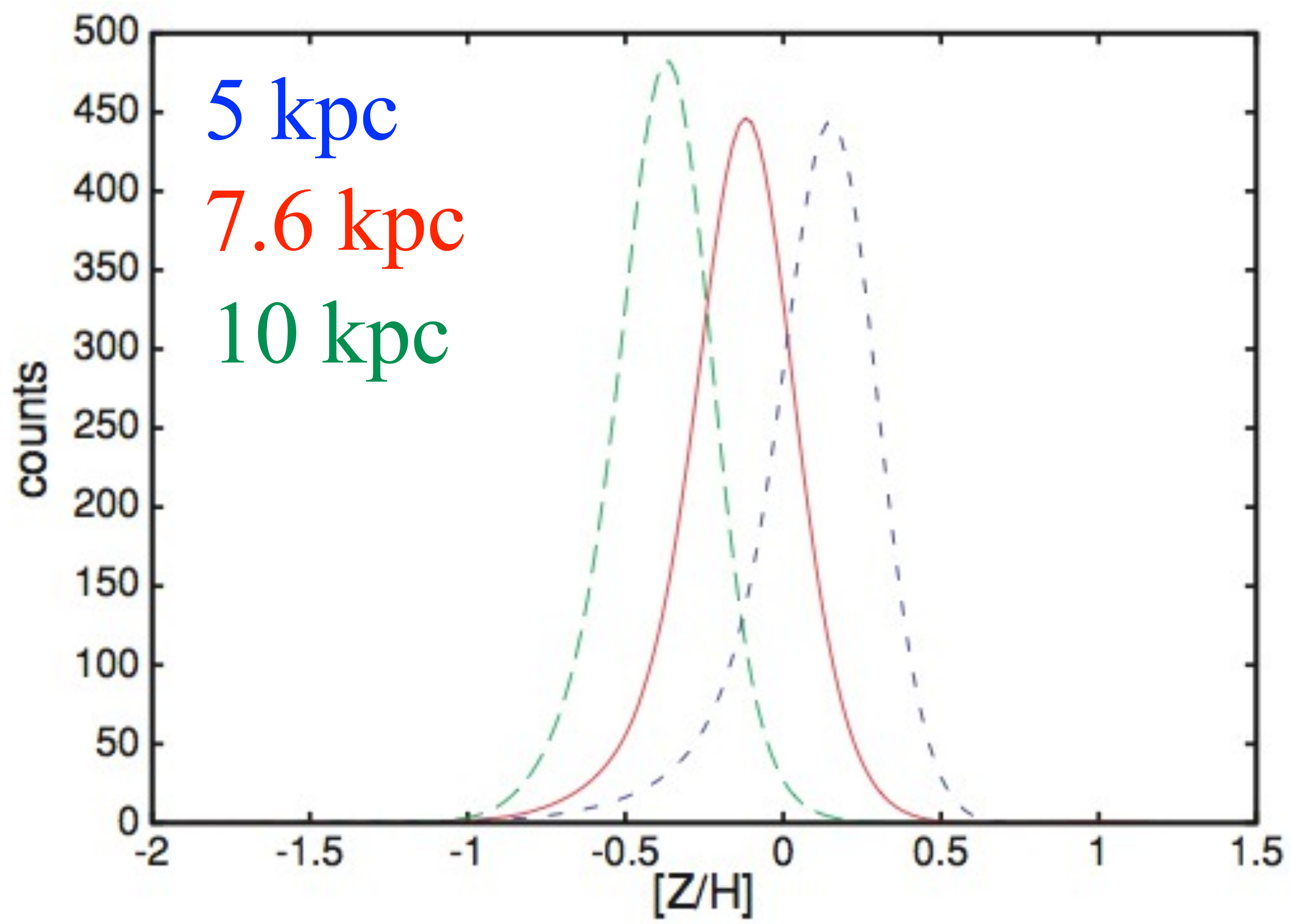


analysis by J. Bovy

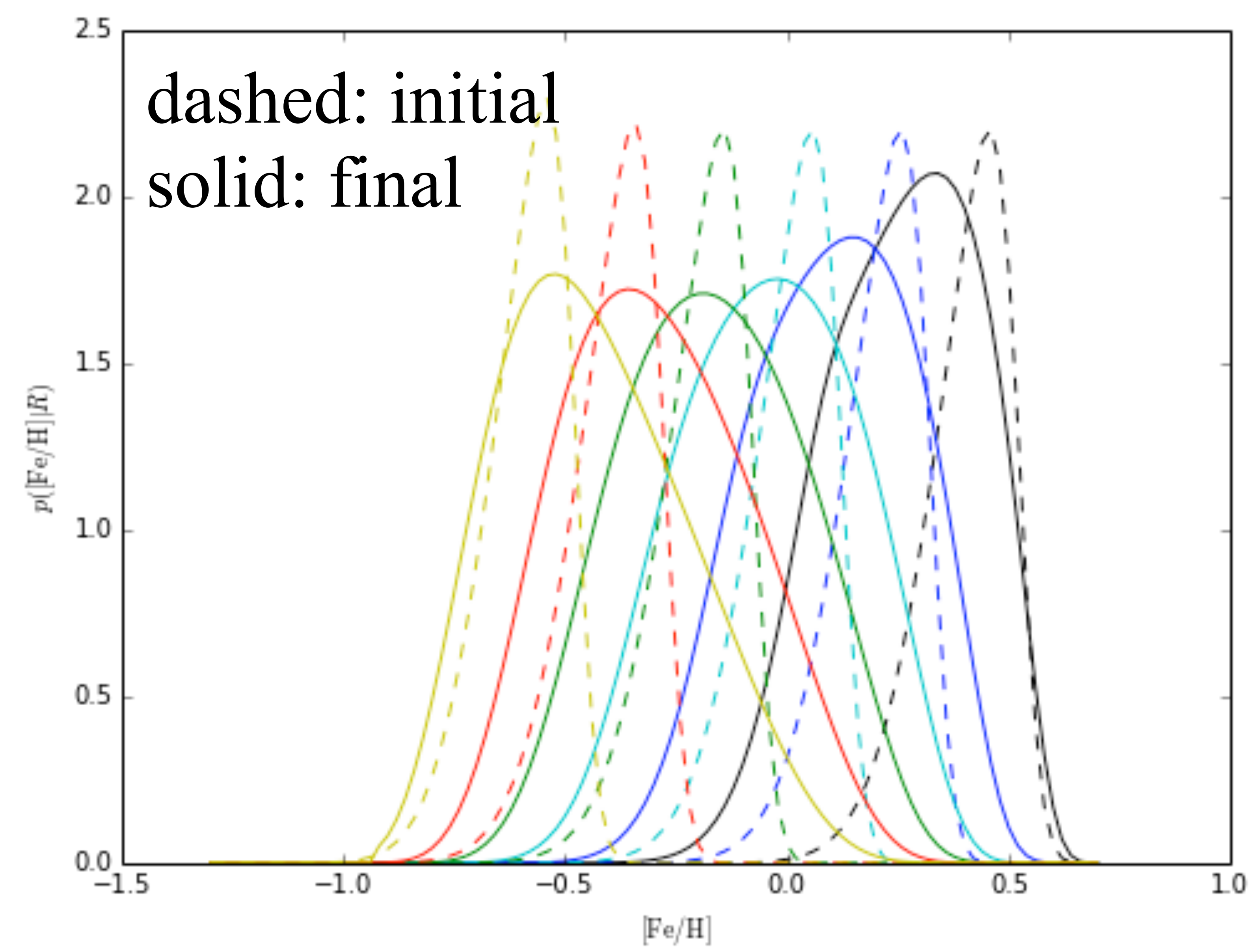
Hayden et al. (2015), in prep.

Metallicity Distribution Functions

- Churning (radial migration) reproduces the observed behavior



Schoenrich & Binney (2009a)



analysis by J. Bovy

Hayden et al. (2015), in prep.

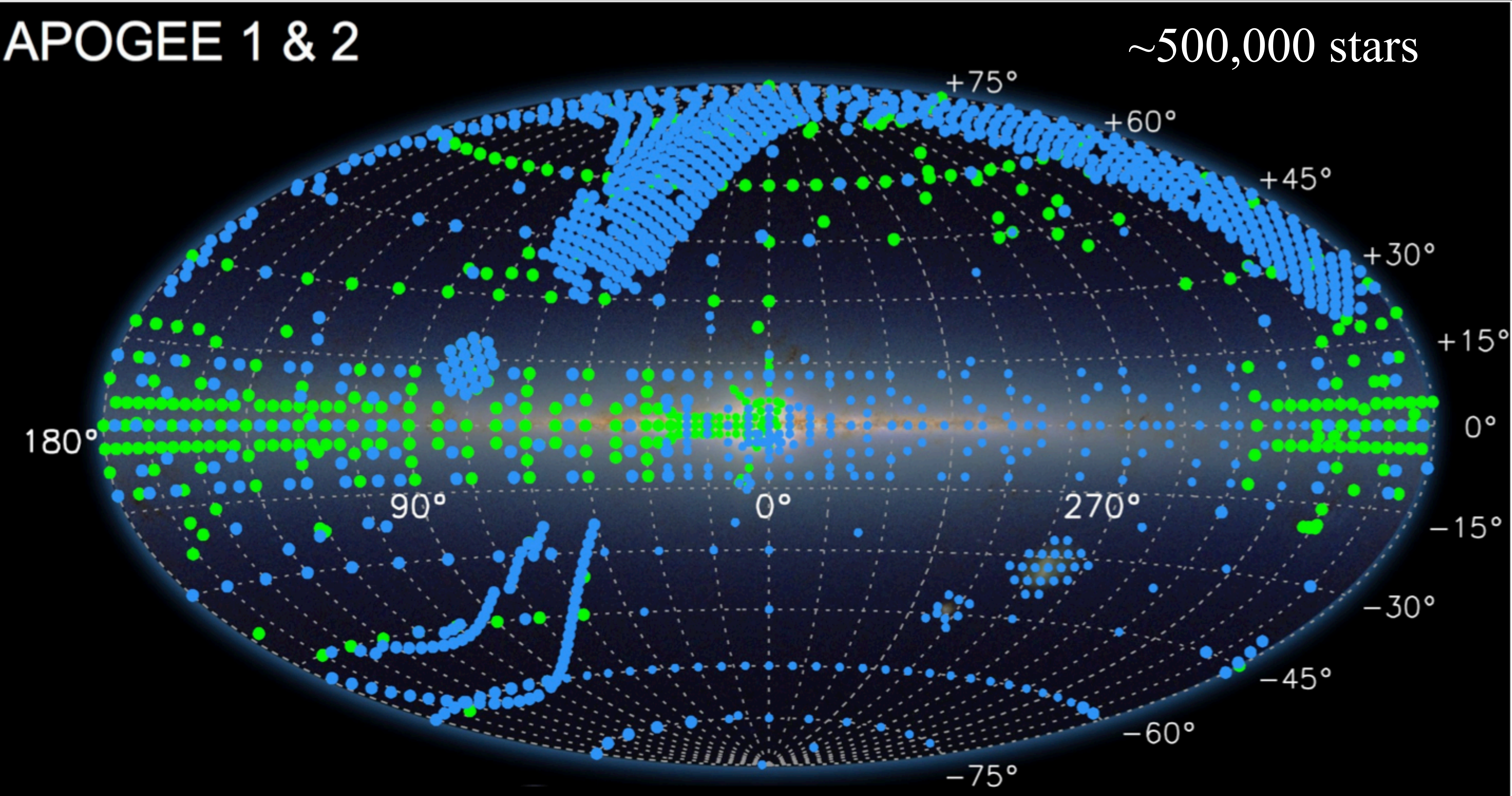
Metallicity Distribution Functions

- Blurring model (no ang. mom. change) does not work
- Churning (radial migration) reproduces the observed behavior

- **We can use the chemical distributions to constrain the disk dynamics!**

Hayden et al. (2015), in prep.

APOGEE-2



Conclusions

- APOGEE-1 mapped the MW with ~150,000 stars, DR12
- RC/RGB show α bimodality at intermediate metallicity, throughout MW
- Selection function does not affect abundance *patterns*
- Little spatial variation of high-α sequence chemical pattern (~10%)
- Suggests early MW stellar evolution was in well-mixed, turbulent, molecular-dominated environment
- Two scenarios to explain low/high-α sequences:
  1. SFE-transition from high to low SFE ~8 Gyr ago
  2. Superposition of multiple stellar populations
- Need ages to tell the two apart, w/ Gaia in 2017
- MDFs skewness change with radius, inner-negative, outer-positive
- Radial migration

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

The End

APOGEE

SDSSIII