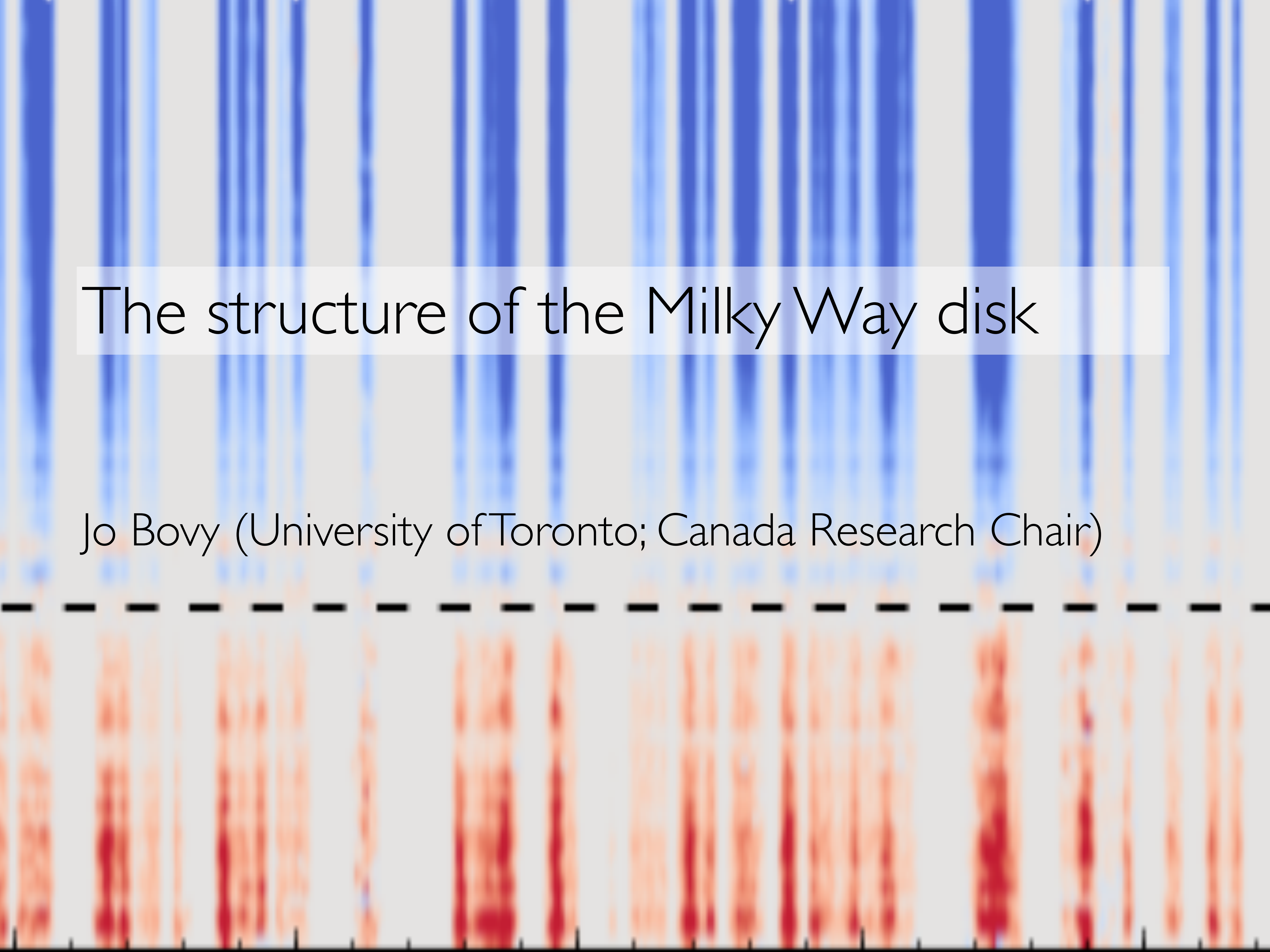
The structure of the Milky Way disk



Jo Bovy (University of Toronto; Canada Research Chair)

Credit: *Composite Image Data* - Subaru Telescope (NAOJ), Hubble Legacy Archive, Michael Joner, David Laney (West Mountain Observatory, BYU); *Processing* - Robert Gendler

WHY THE MILKY WAY?

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- Detailed measurements of position, velocity, age, abundances [X/H] of *individual stars*

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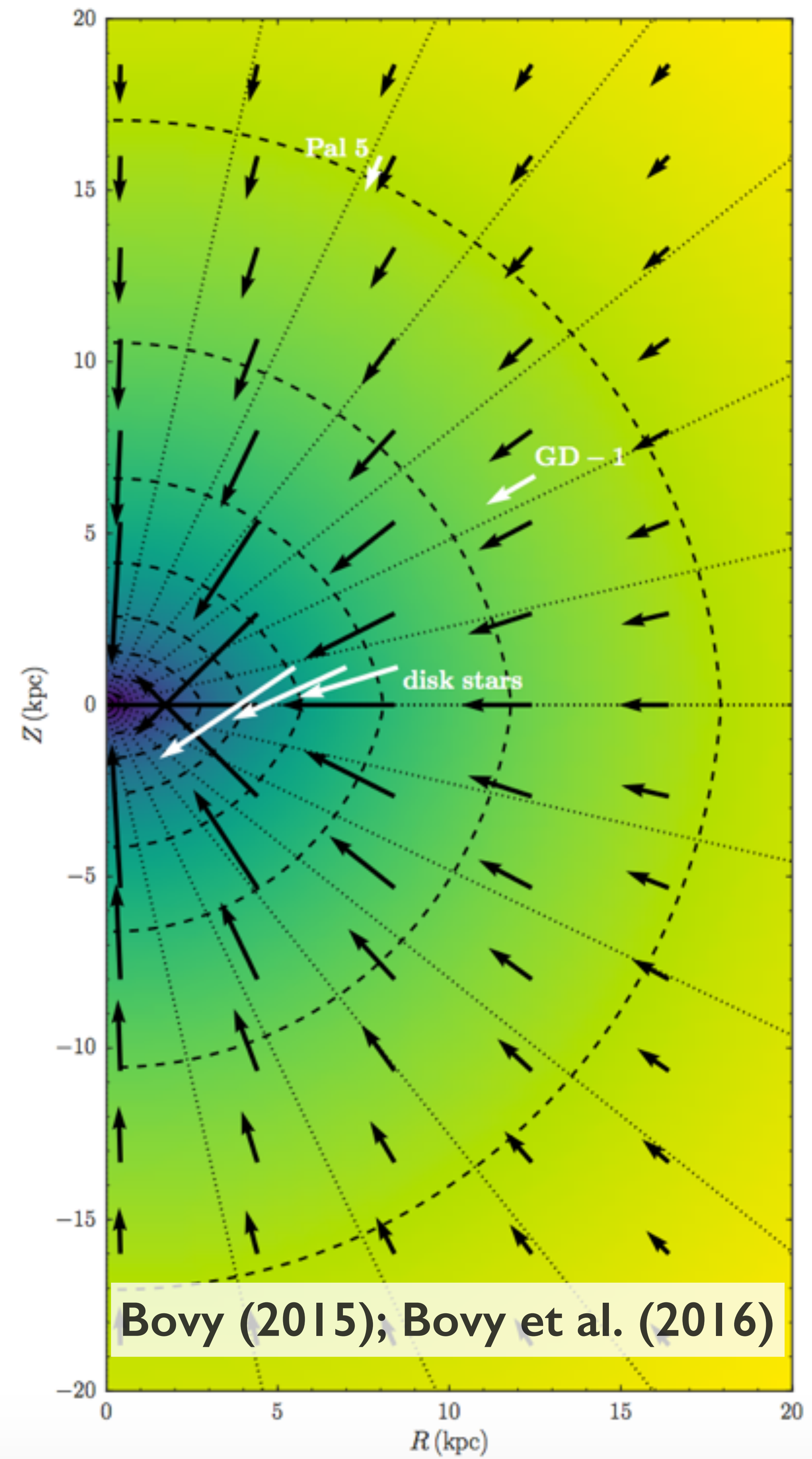
- Detailed dynamical modeling: 3D distribution of mass (stars, dark matter), importance of non-axisymmetric flows, resonances, …

MILKY WAY DISK CONTEXT

- Double-exponential-ish with $h_Z \sim 350$ pc, $h_R \sim 2$ - 3 kpc (e.g., Juric et al. 2008, Bovy & Rix 2013)



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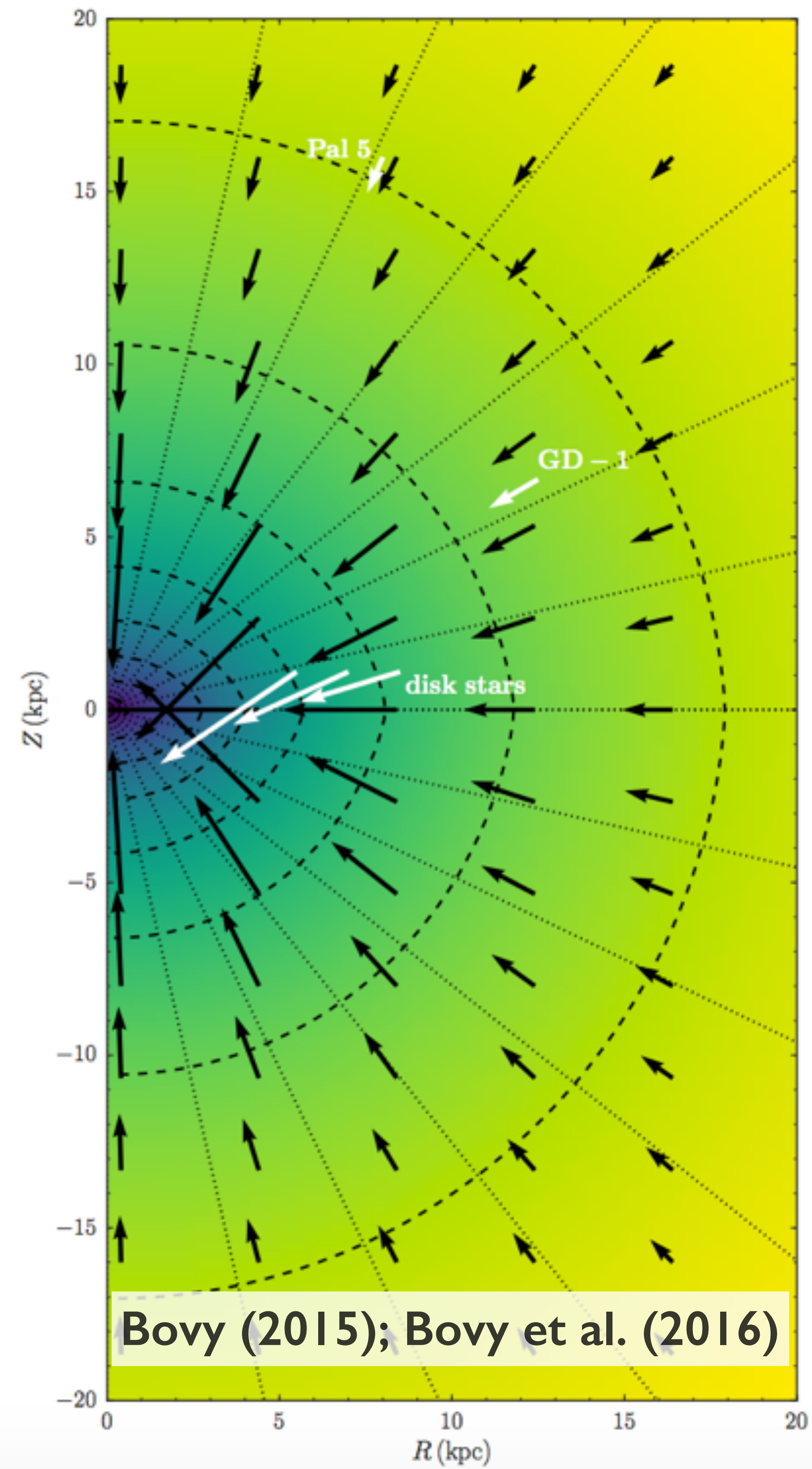

Bovy (2015); Bovy et al. (2016)

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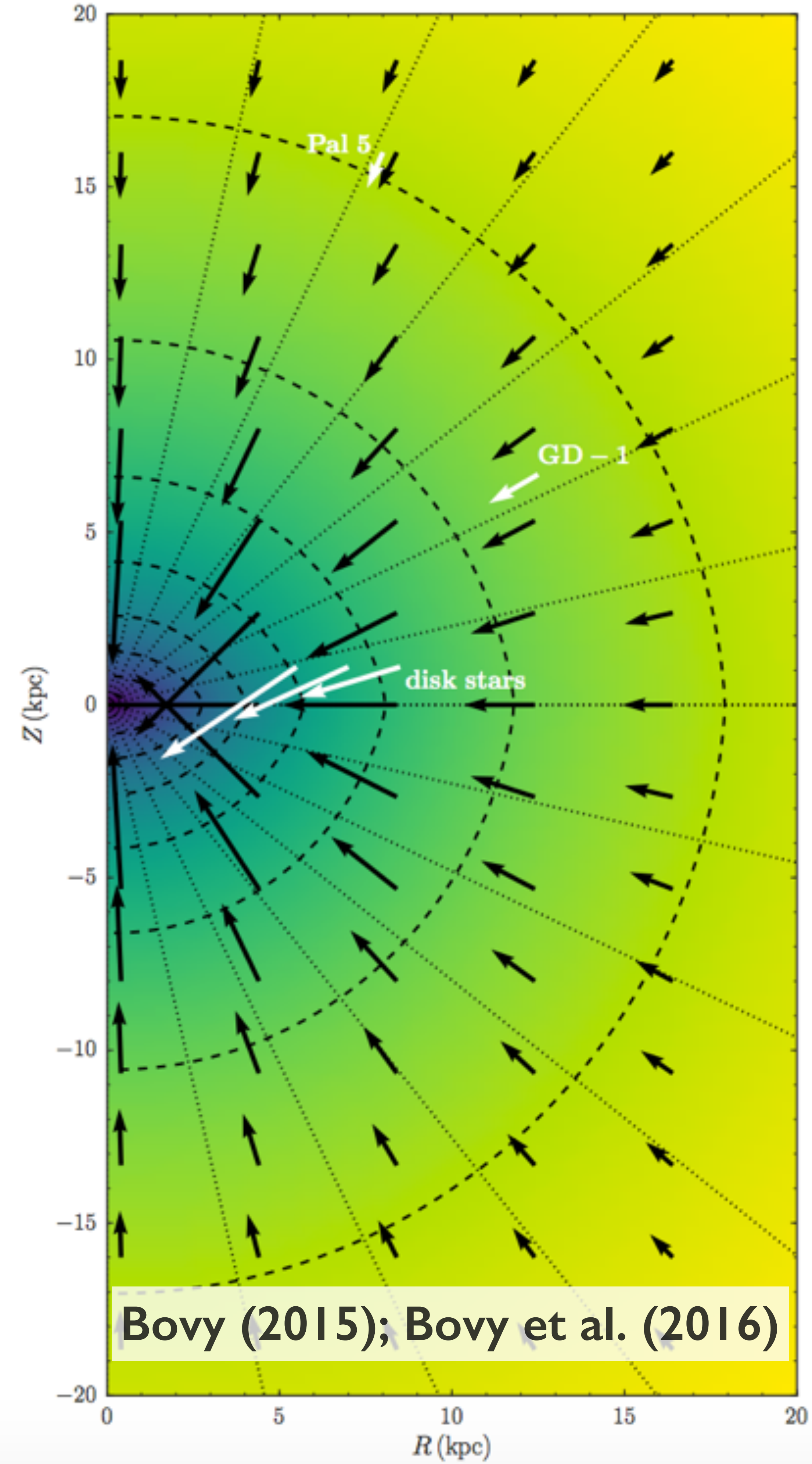
- See Bland-Hawthorn & Gerhard (2016, ARAA) for most up-to-date Galactic parameters

The Galaxy in Context: Structural, Kinematic & Integrated Properties

Joss Bland-Hawthorn[1], Ortwin Gerhard[2]

[1]Sydney Institute for Astronomy, School of Physics A28, University of Sydney, NSW 2006, Australia; email: jbh@physics.usyd.edu.au
[2]Max Planck Institute for extraterrestrial Physics, PO Box 1312, Giessenbachstr., 85741 Garching, Germany; email: gerhard@mpe.mpg.de



Bovy (2015); Bovy et al. (2016)

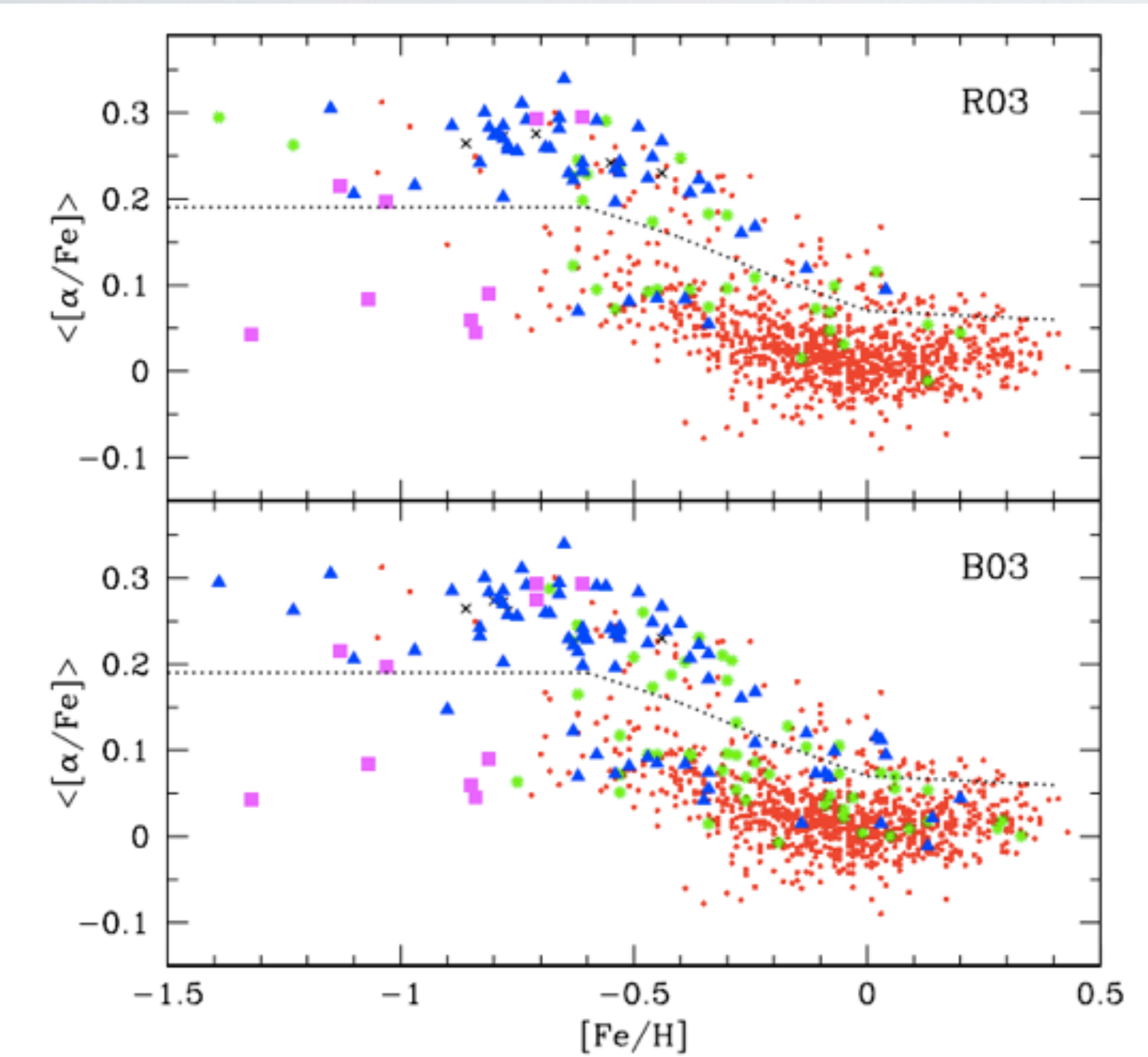
Table 1 Description of Galactic parameters[a].

R_0	Distance of Sun from the Galactic Centre (§3.2)
z_0	Distance of Sun from the Galactic Plane (§3.3)
Θ_0, Ω_0	Circular speed, angular velocity at Sun with respect to Galactic Centre (§3.4, §6.4.2)
$U_\odot, V_\odot, W_\odot$	U, V, W component of solar motion with respect to LSR (§5.3.3)
$\mathbf{v}_\odot$	Solar motion with respect to LSR (§5.3.3)
V_{LSR}	Possible LSR streaming motion with respect to Θ_0 (§5.3.3, §6.4.2)
A, B	Oort's constants (§6.4.2)
r_{vir}	Galactic virial radius (§6.3)
M_{vir}, $M_{\mathrm{vir,timing}}$	Galactic virial mass, virial timing mass (§6.3)
$M_\star$, $\dot{m}_\star$	Galactic stellar mass, global star formation rate (§2.2)
M_{bary}, $f_{\mathrm{bary}}{}^b$	Galactic baryon mass, baryon fraction (§6.2, §6.4.3)
$M_{\mathrm{b}}^{\mathrm{dyn}}$, M_{b}^*, $M_{\mathrm{clb}}/M_{\mathrm{b}}^*$	Bulge dynamical mass and stellar mass, classical bulge fraction (§4.2.4)
$\sigma_x^b, \sigma_y^b, \sigma_z^b, \sigma_{\mathrm{rms}}^b$	Half-mass bulge velocity dispersions in (x, y, z) and rms (§4.2.3)
ϕ_{bp}, $(b/a)_{\mathrm{bp}}$	b/p-bulge orientation and axis ratio from top (§4.2.1)
h_{bp}, $(c/a)_{\mathrm{bp}}$	Central vertical scale-height and edge-on axis ratio of b/p-bulge (§4.2.1)
x_X	Radius of maximum X (§4.2.1)
M_{tlb}, M_{slb}	Stellar masses of thin and superthin long bar (§4.3)
ϕ_{lb}, R_{lb}	Long bar orientation and half-length (§4.3)
h_{tlb}, h_{slb}	Vertical scale heights of thin and superthin long bar (§4.3)
Ω_b, R_{CR}	Bar pattern speed and corotation radius (§4.4)
$M_\bullet$, r_{infl}	Mass and dynamical influence radius of supermassive black hole (§3.4)
M_{NSC}, M_{NSD}	Masses of nuclear star cluster and nuclear stellar disk (§4.1)
r_{NSC}, $(c/a)_{\mathrm{NSC}}$	Nuclear star cluster half-mass radius and axis ratio (§4.1)
r_{NSD}, h_{NSD}	Nuclear stellar disk break radius and vertical scale-height (§4.1)
M_{hot}	Coronal (hot) halo mass (§6.2)
M_{s}, M_{sub}	Stellar halo mass and substructure mass (§6.1.2)
α_{in}, α_{out}, r_{s}	Stellar halo inner, outer density slope, break radius (§6.1.1)
q_{in}, q_{out}	Inner and outer mean flattening (§6.1.1)
σ_r^{s}, $\sigma_\theta^{\mathrm{s}}$, σ_ϕ^{s}	Stellar halo velocity dispersions in r, θ, ϕ near the Sun (§6.1.3)
$\overline{v}_\phi^{\mathrm{s}}$	Local halo rotation velocity (§6.1.3)
M^{t}, M^{T}	Thin, thick disk stellar masses (§5.1.3, §5.2.2)
R^{t}, R^{T}	Thin, thick disk exponential scalelength in R (§5.1.3, §5.2.2)
z^{t}, z^{T}	Thin, thick disk exponential scaleheight in z (§5.1.3)
f_ρ, f_Σ	Thick disk fraction in local density, in integrated column density (§5.1.3)
σ_R^{t}, σ_z^{t}	Old thin disk velocity dispersion in R, z at 10 Gyr (§5.4)
σ_R^{T}, σ_z^{T}	Thick disk velocity dispersion in R, z (§5.4)
Σ_{tot}, ρ_{tot}, ϵ_{tot}	Local mass surface density, mass density, dark matter energy density (§5.4.2)

Bland-Hawthorn & Gerhard (2016)

CHEMICAL EVOLUTION IN THE MILKY WAY

THE ABUNDANCE PLANE IN THE SOLAR NEIGHBORHOOD

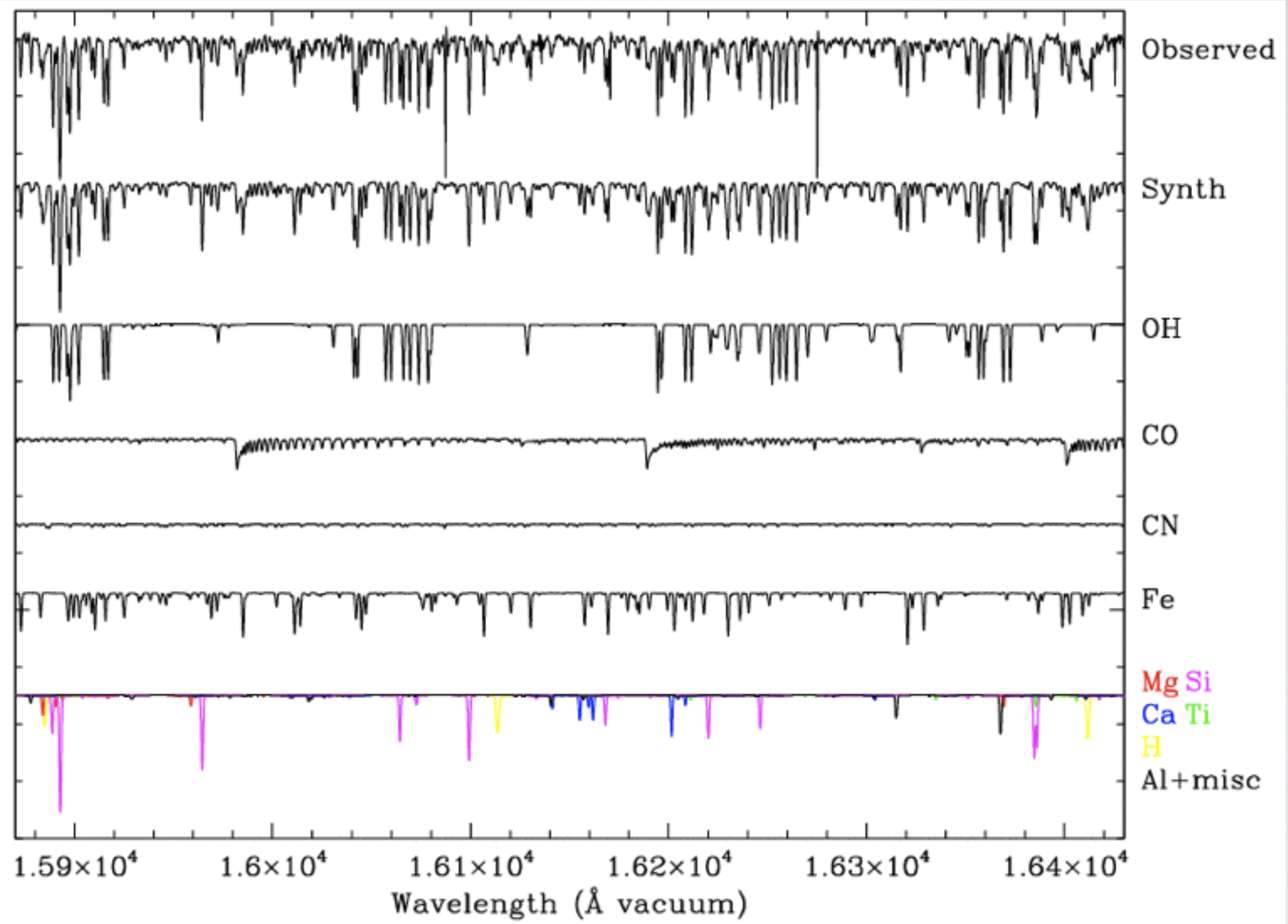


Adibeykan et al. (2012)

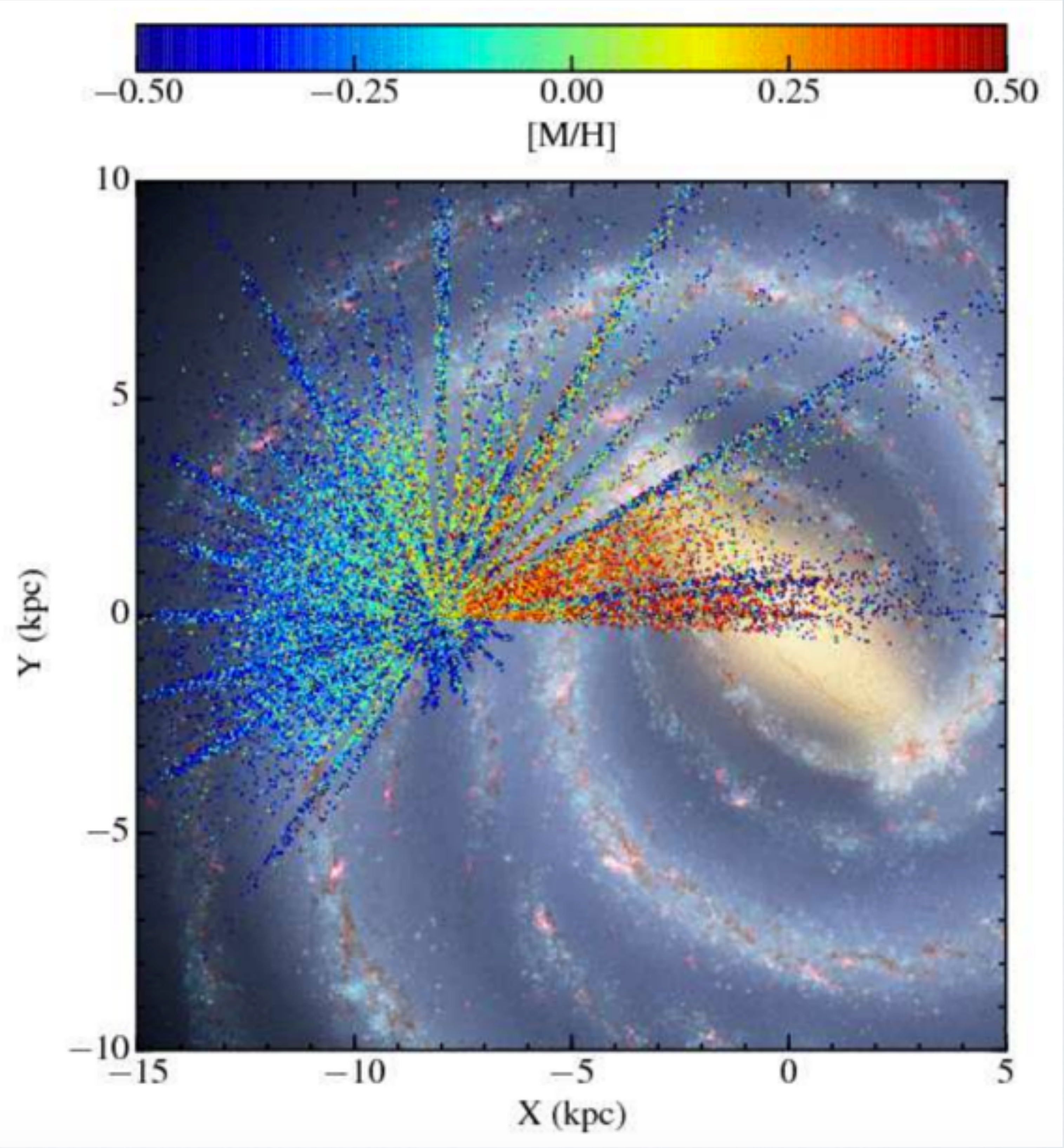
- Kinematically- and (~)metallicity unbiased sample of ~1,000 stars within ~50 pc from the Sun
- Improves on abundant earlier work by Fuhrmann, Prochaska, Reddy, Bensby, et al.
- Blue: high-velocity stars
Red: low-velocity stars


APOGEE
SDSSIII

APOGEE HI-RES BEYOND THE SOLAR NEIGHBORHOOD



- Infrared *H*-band spectrograph
- high resolution (R ~ 22,500)
- S/N > 100 / pixel
- $(J\text{-}Ks)_0 > 0.5$, H <~ 13.8
- v_{los}, logg, Teff, + 15 abundances (C,N,O,Na,Mg,Al,Si,S,K,Ca,Ti,V,Mn,Fe,Ni)
- APOGEE-1 survey complete: 500k high-res spectra for ~150,000 stars
- PI: Steve Majewski, + many people

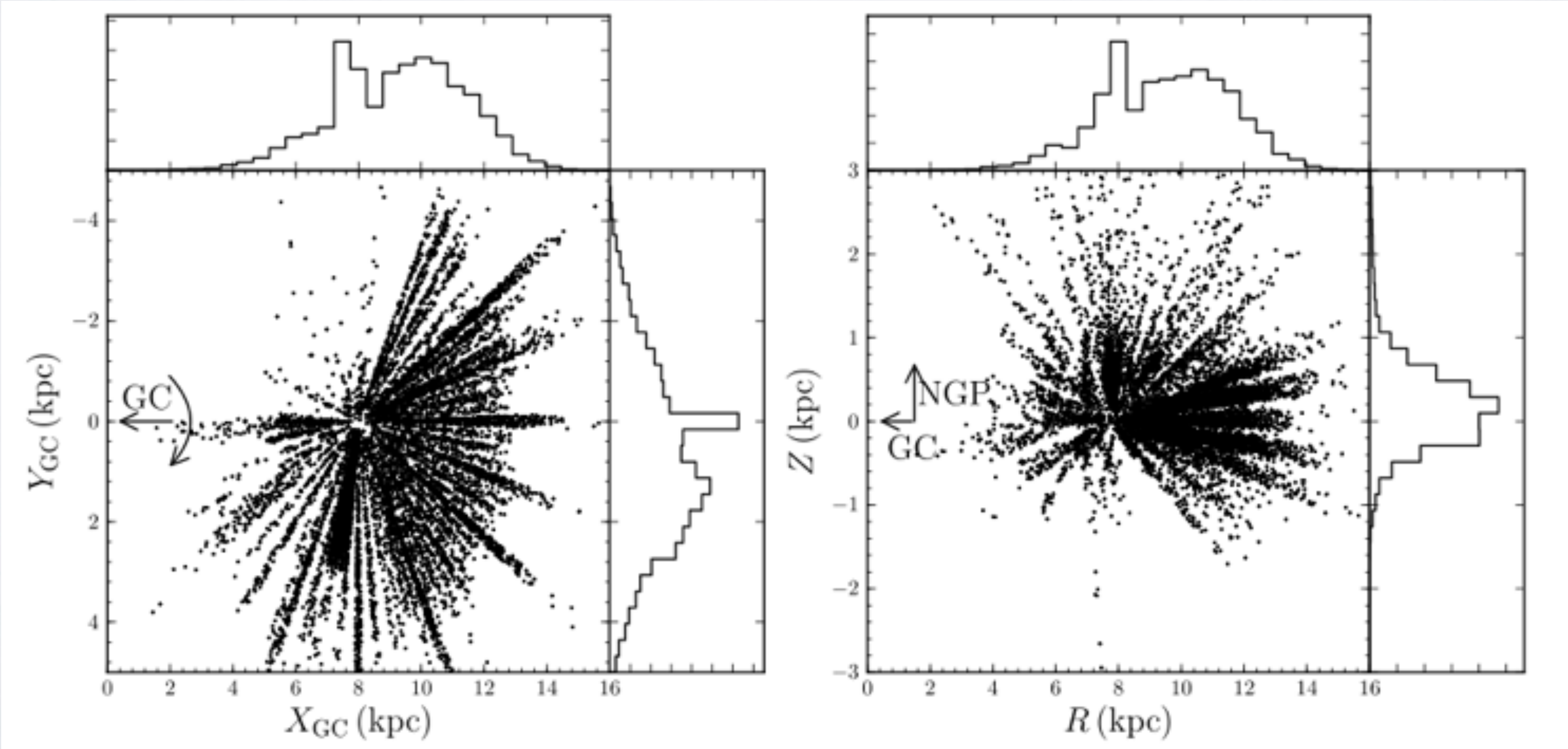


Majewski et al. (2016)
Credit: Michael Hayden,
Background: R. Hurt, JPL-Caltech, NASA

APOGEE RED-CLUMP CATALOG

Bovy et al. (2014)

- High-resolution spec. data allows us to select pure samples of RC stars (purity ~ 95%); calibrated w/ asteroseismology
- RC distances precise to ~5%, unbiased to ~2%, now ~20k stars; valuable for *Gaia* DR1

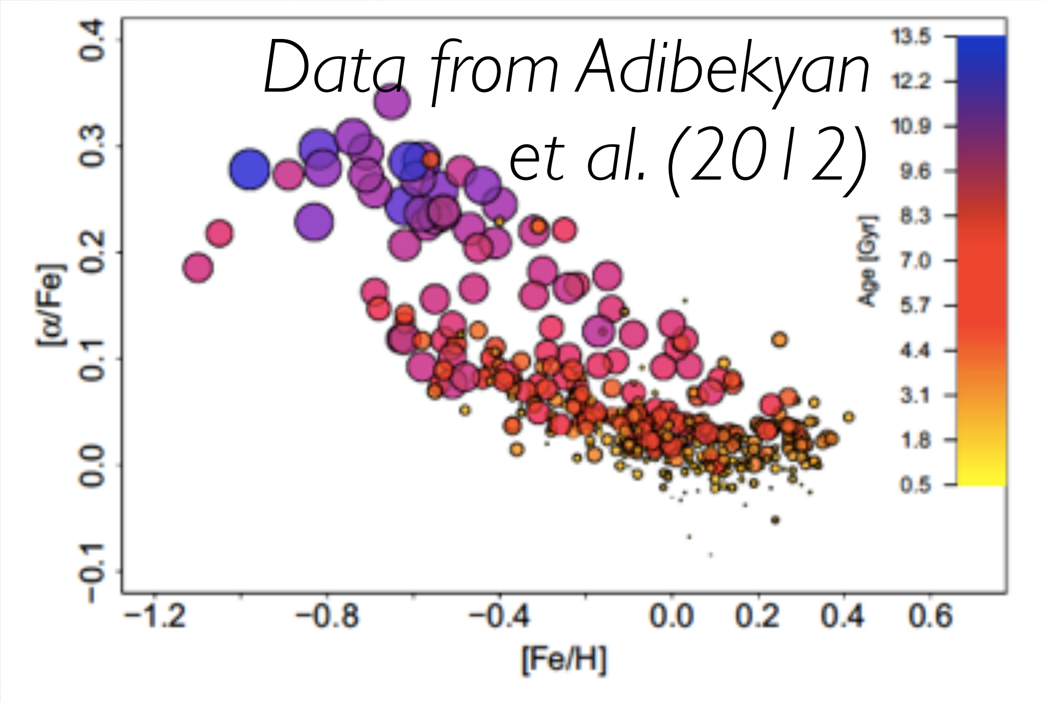


ABUNDANCE DISTRIBUTION

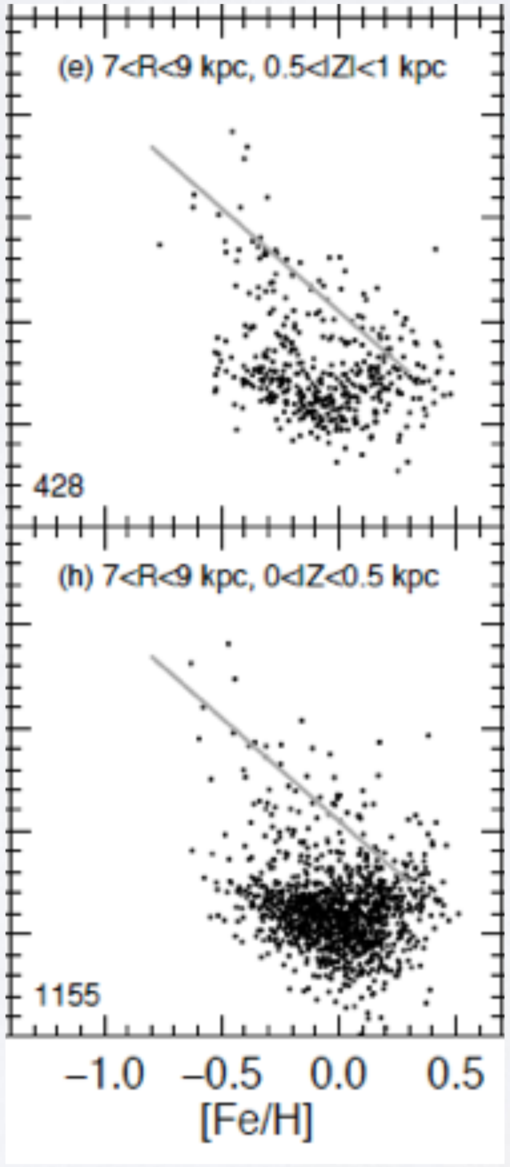
Nidever, Bovy et al. (2014)

- Solar neighborhood [α/Fe] vs. [Fe/H] similar to previous high-resolution studies, e.g., HARPS sample (Adibekyan et al. 2012)

<~ 50 pc



Haywood et al. (2013)



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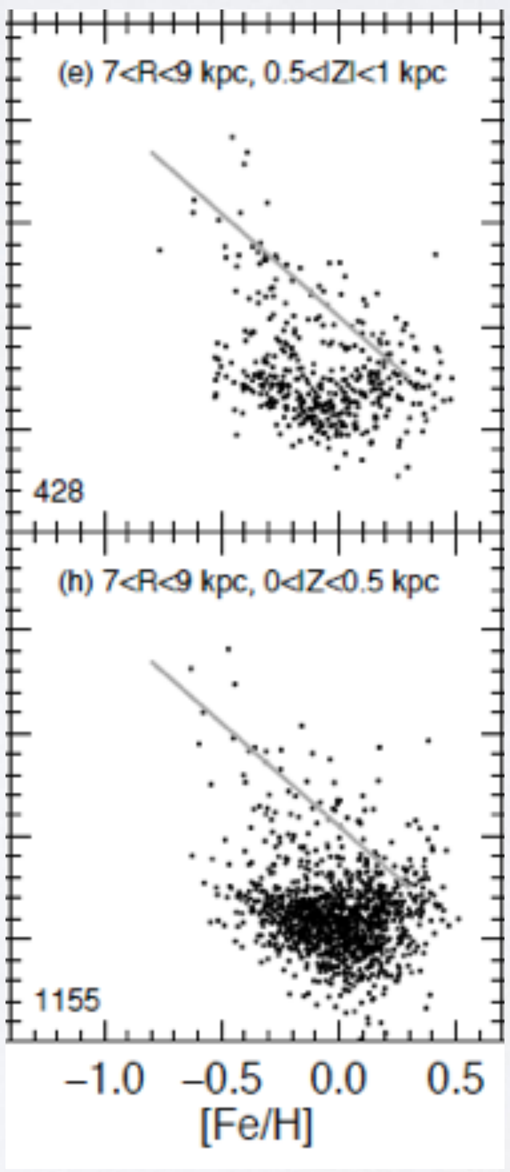

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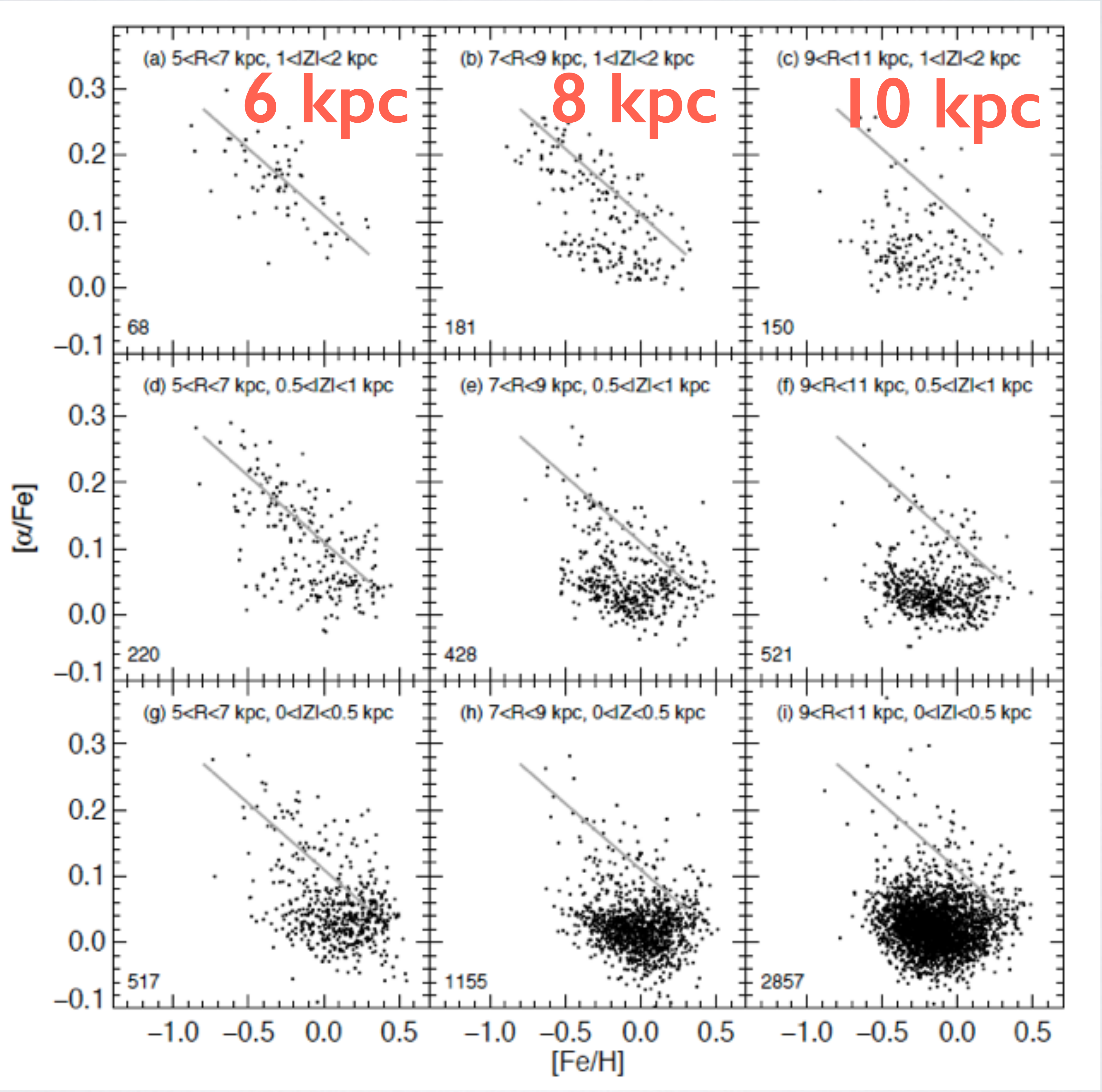
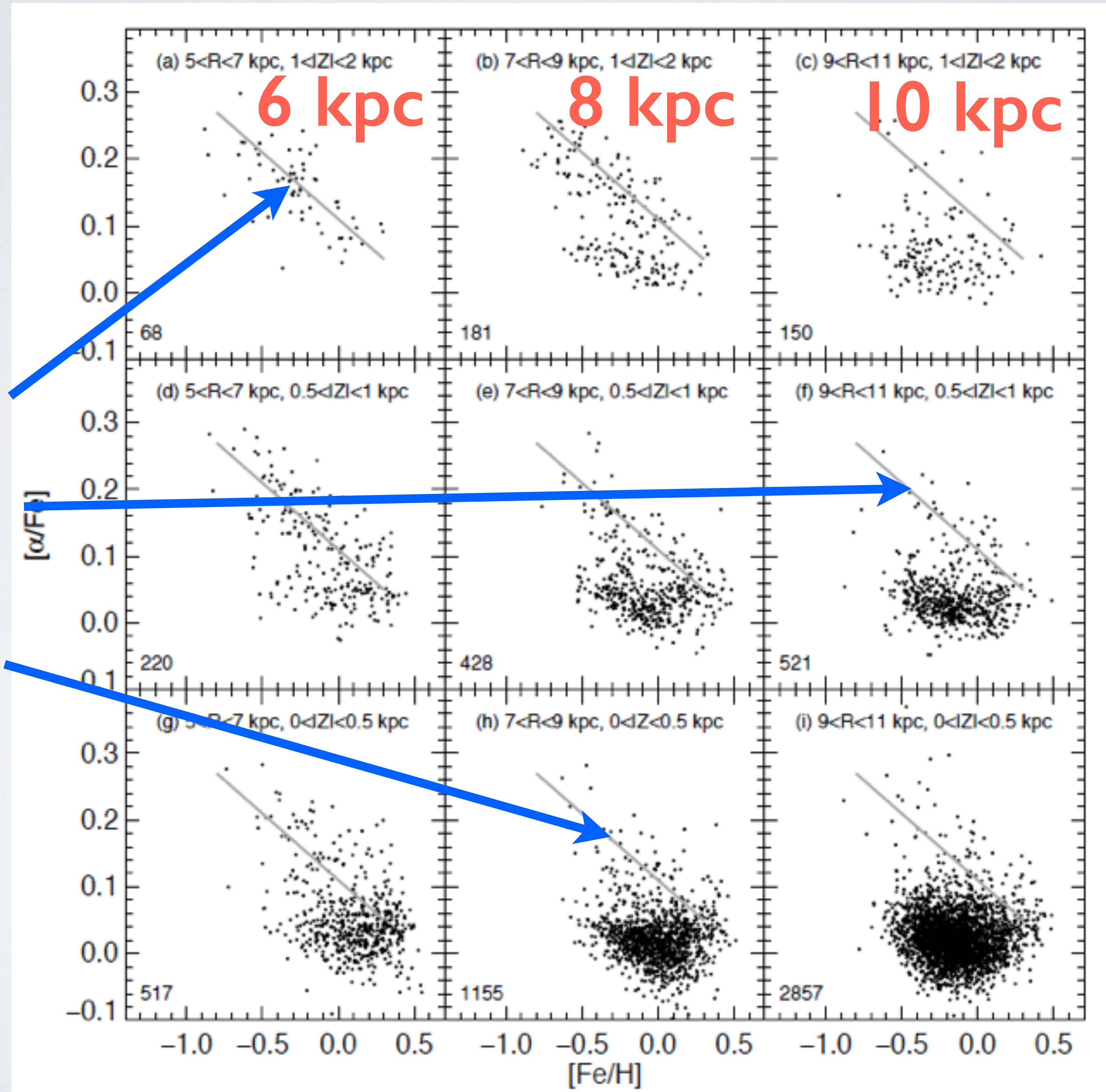
Nidever, Bovy et al. (2014)



ABUNDANCE DISTRIBUTION

Nidever, Bovy et al. (2014)

High-[α/Fe] sequence remarkably uniform throughout the Galaxy



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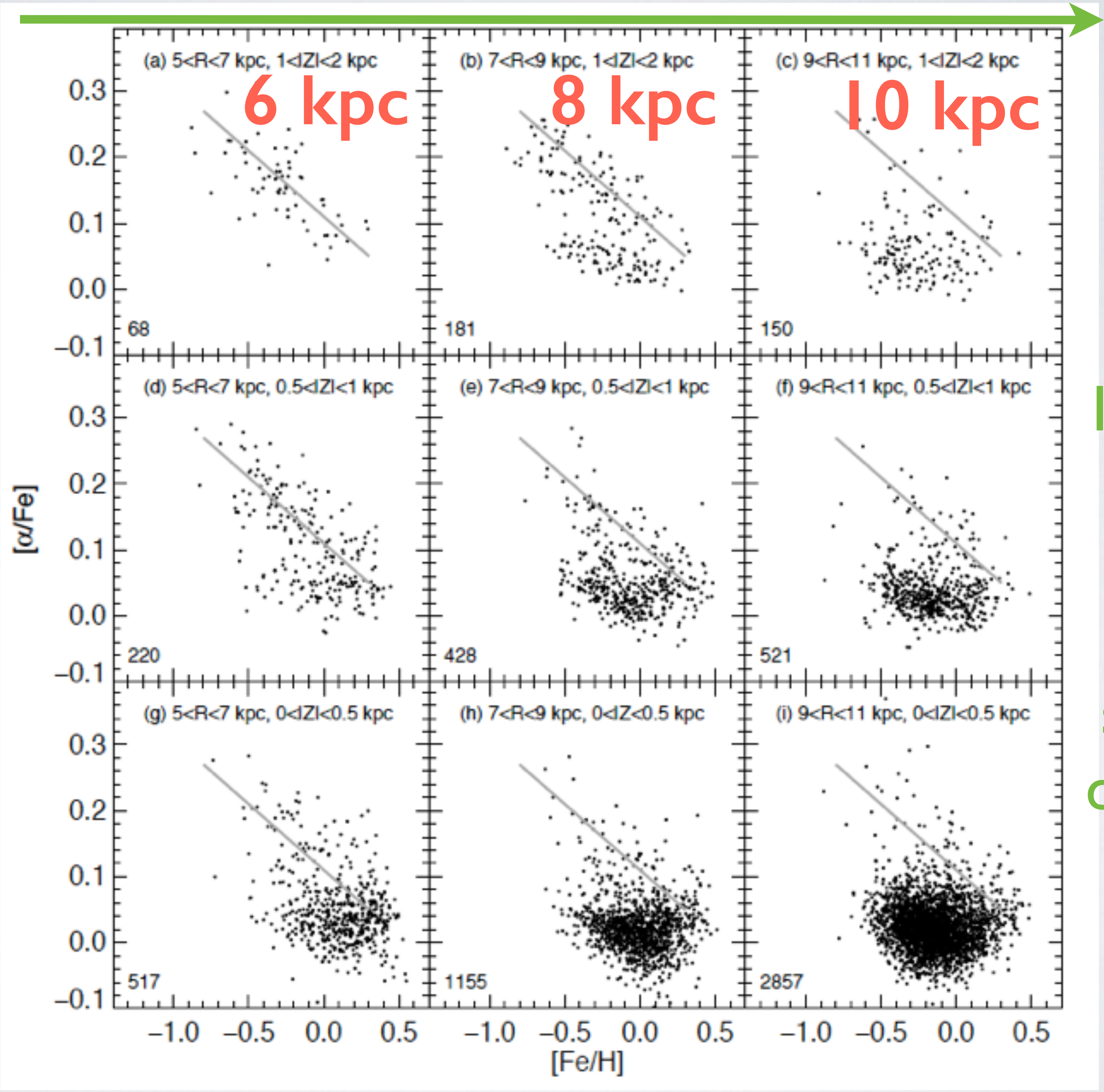
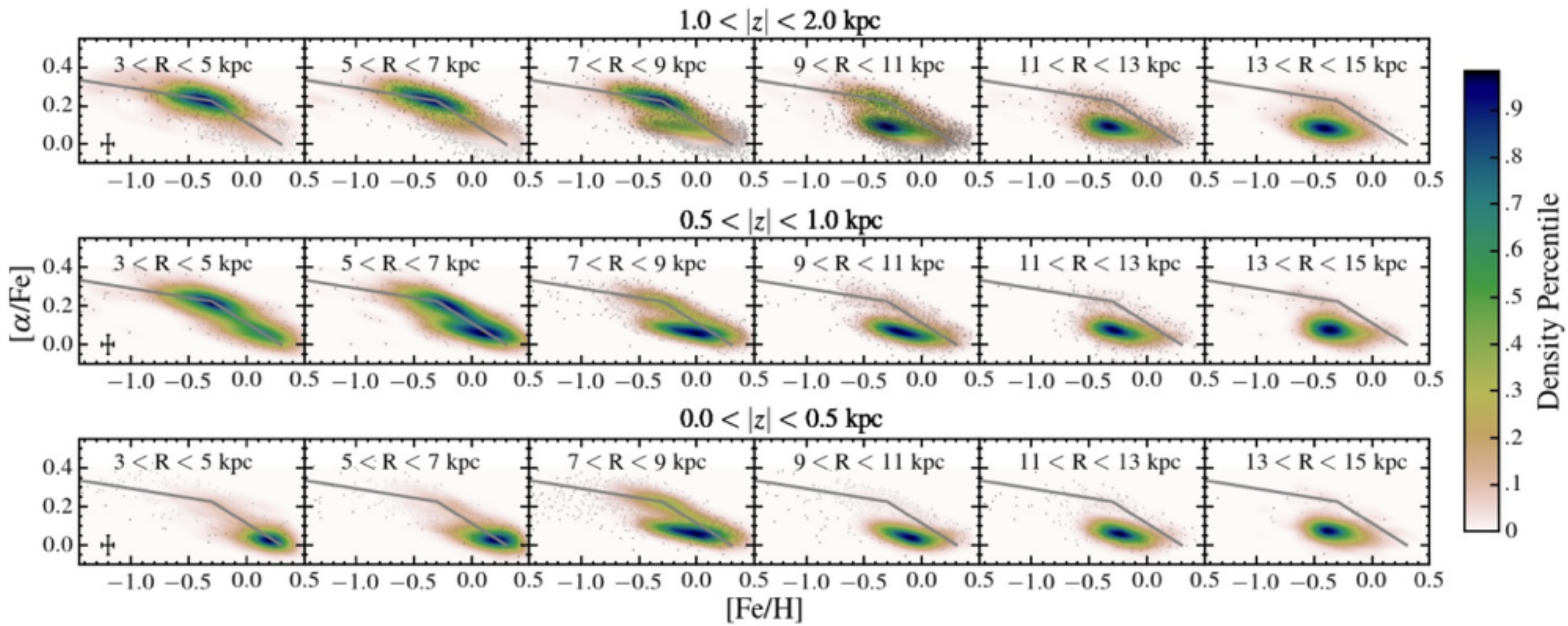


Increasing radii = high-[α/Fe] sequence disappears

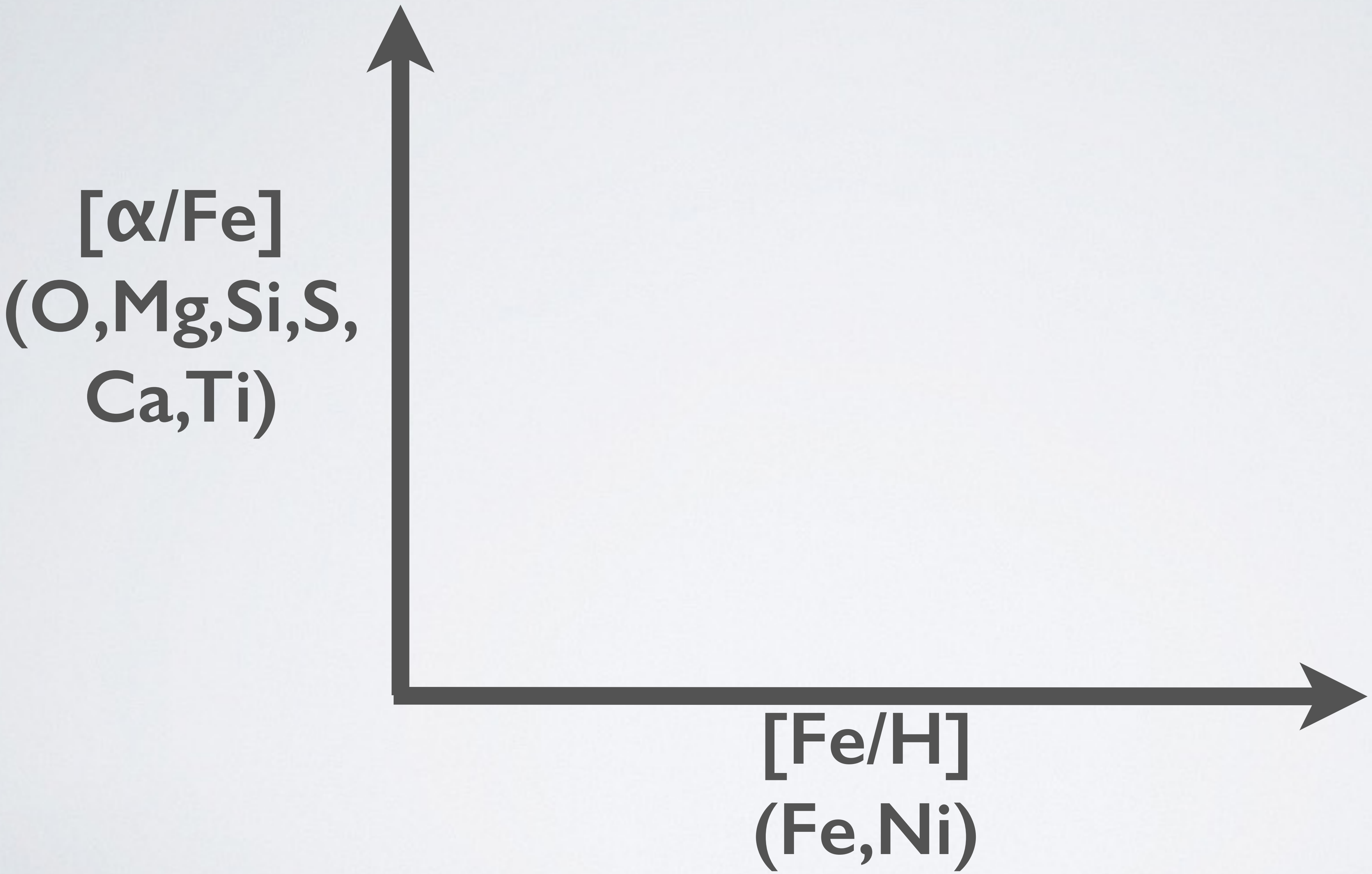
LARGER-SCALE ABUNDANCE DISTRIBUTION

Hayden, Bovy, et al. (2015)

~whole disk!



CHEMICAL EVOLUTION



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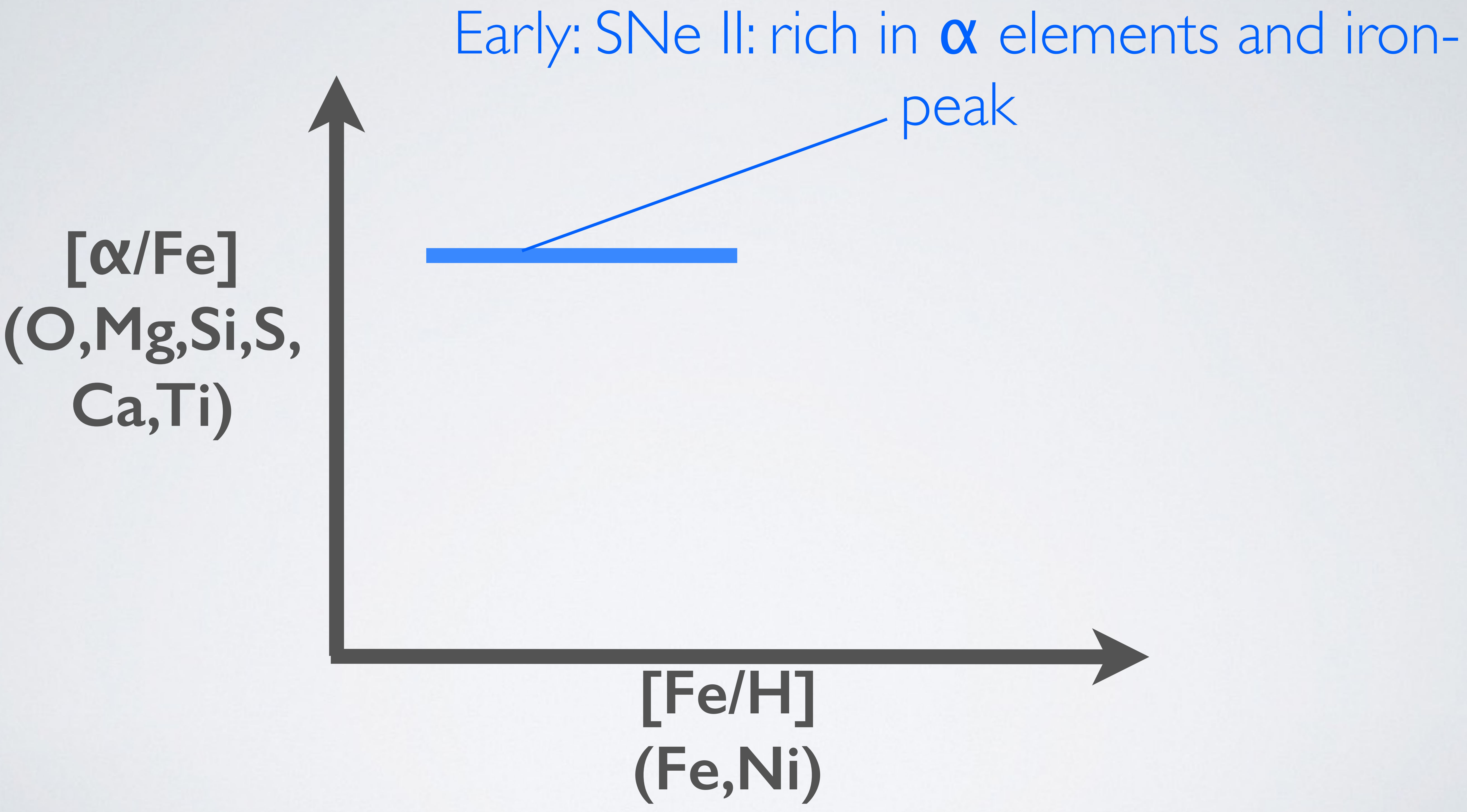

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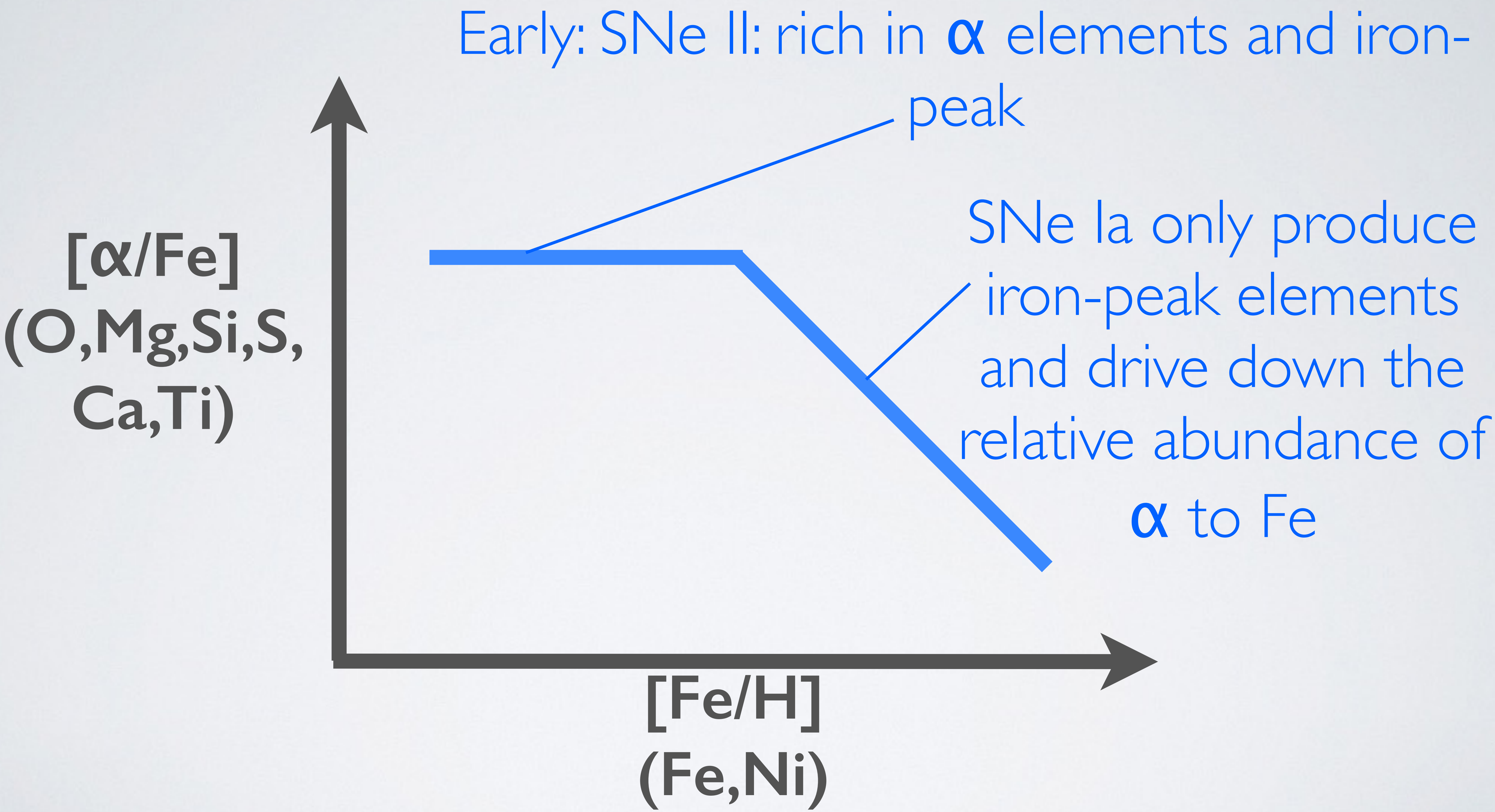

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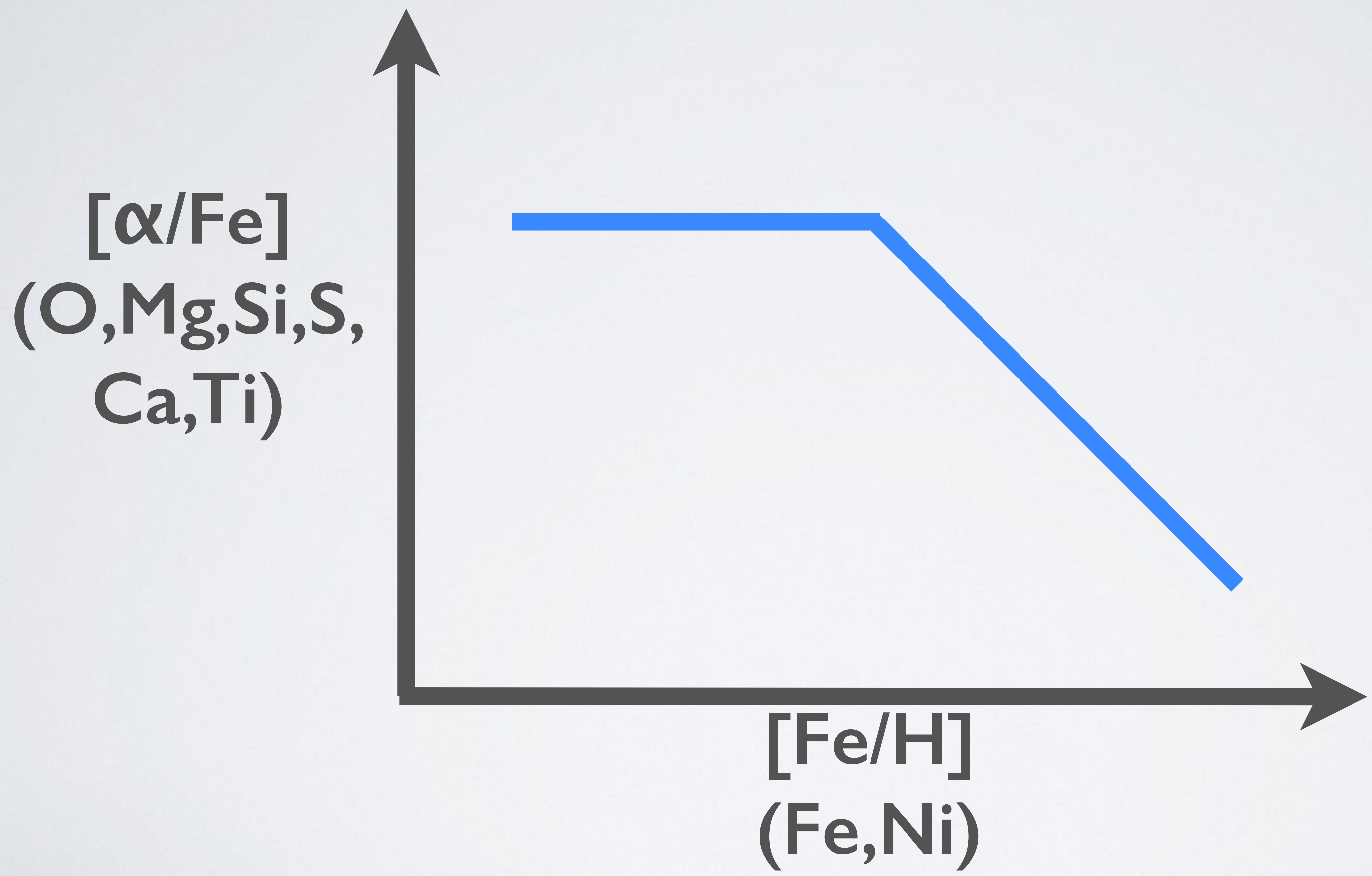

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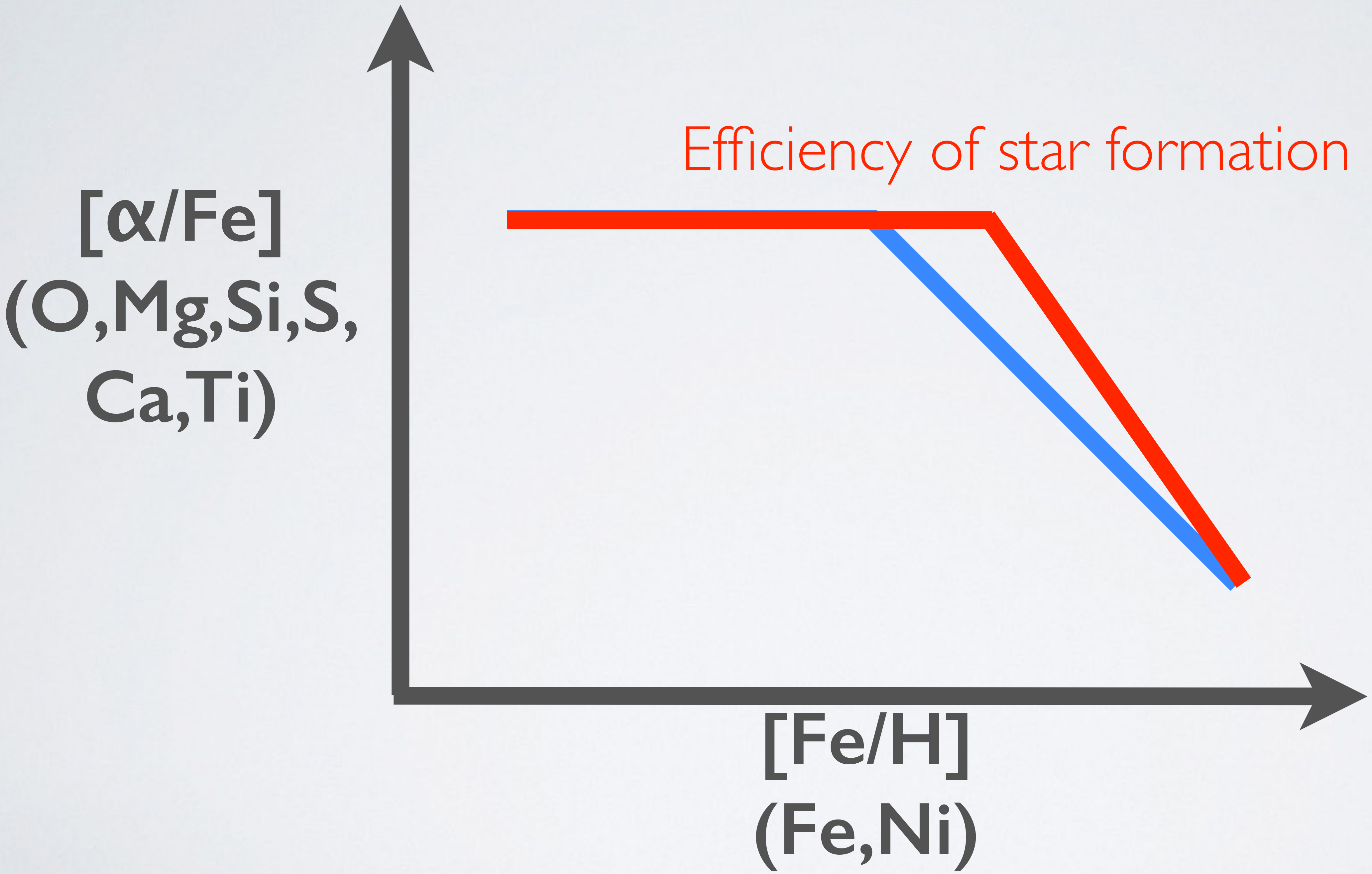

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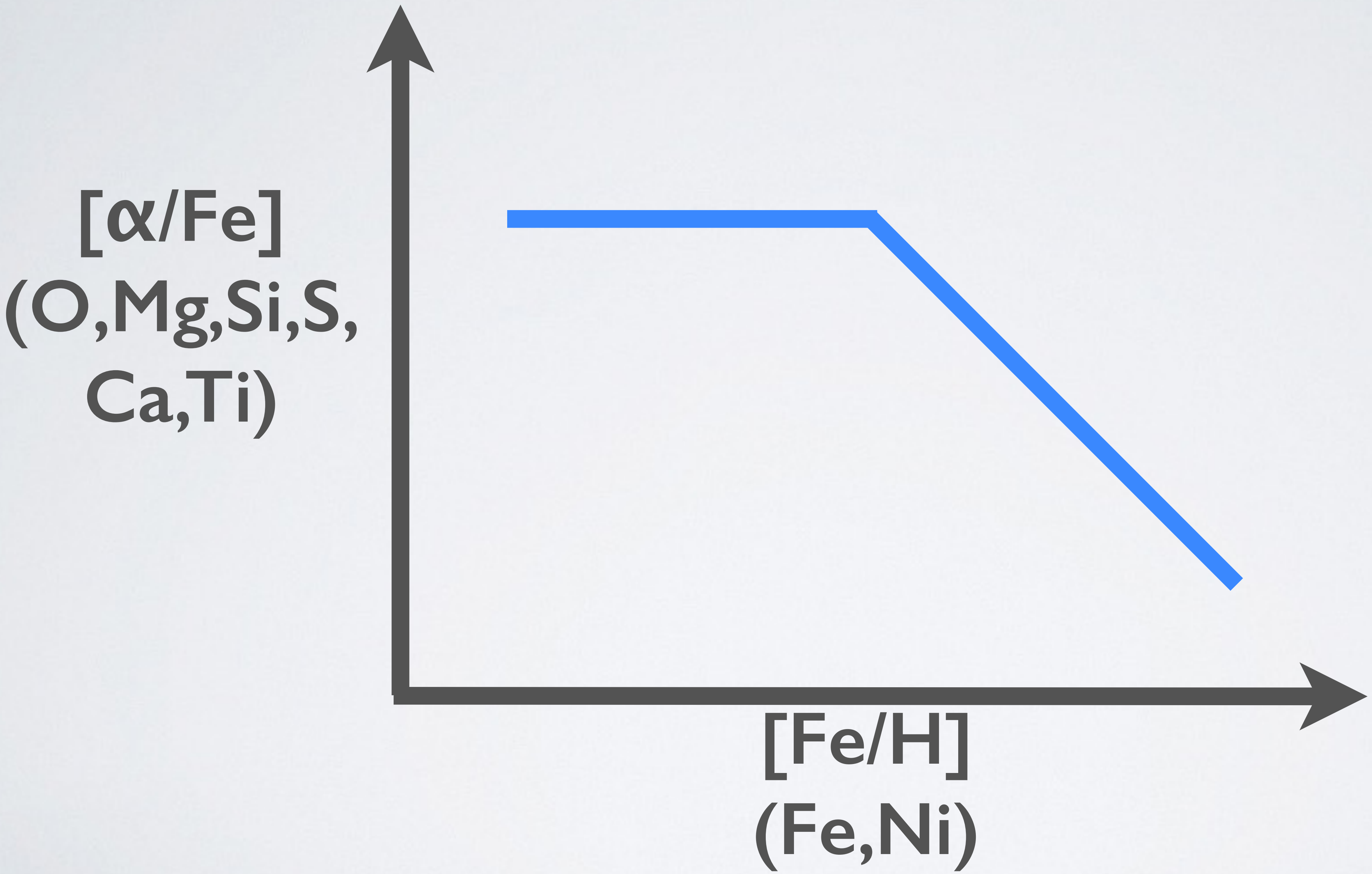

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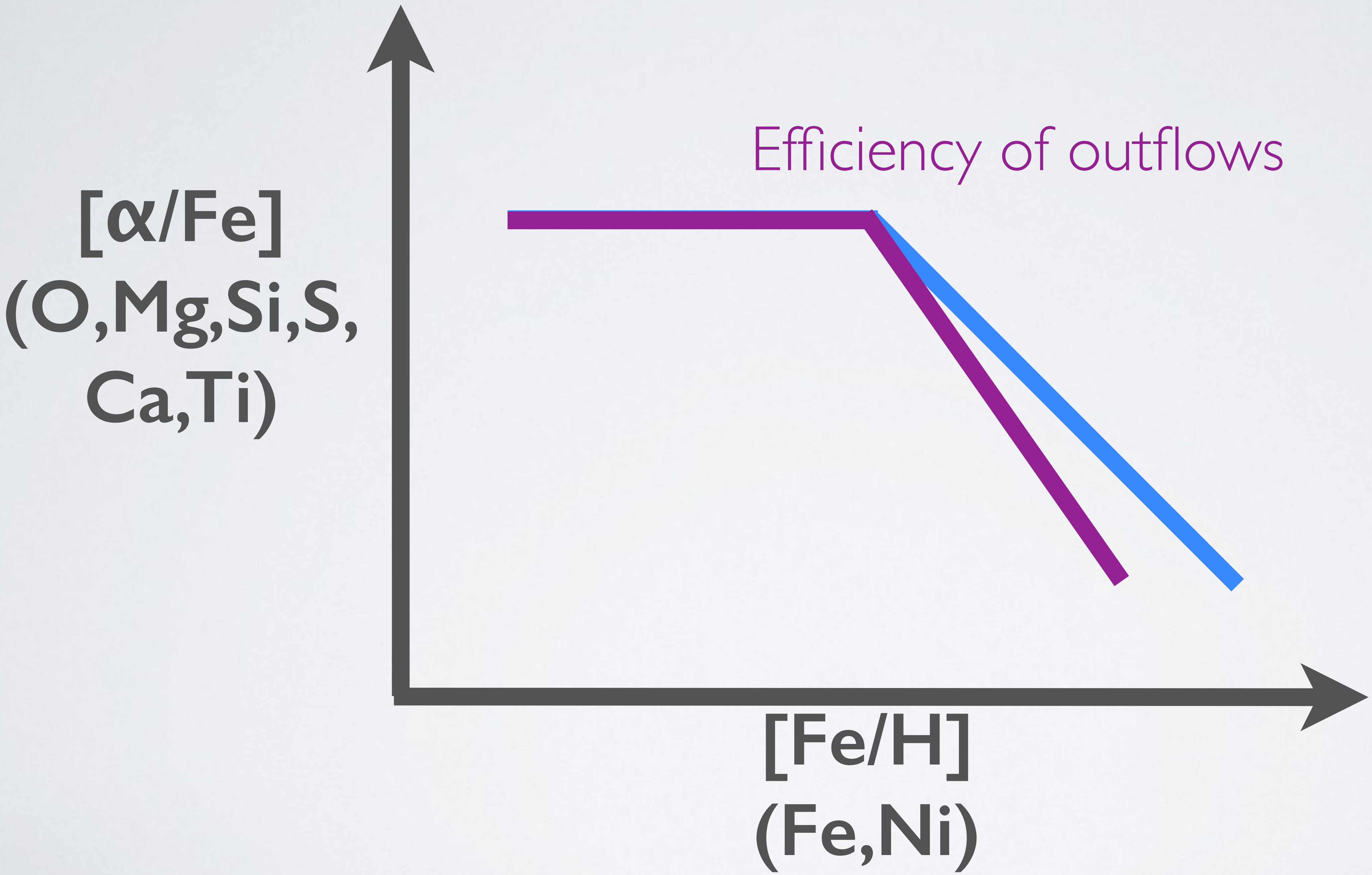

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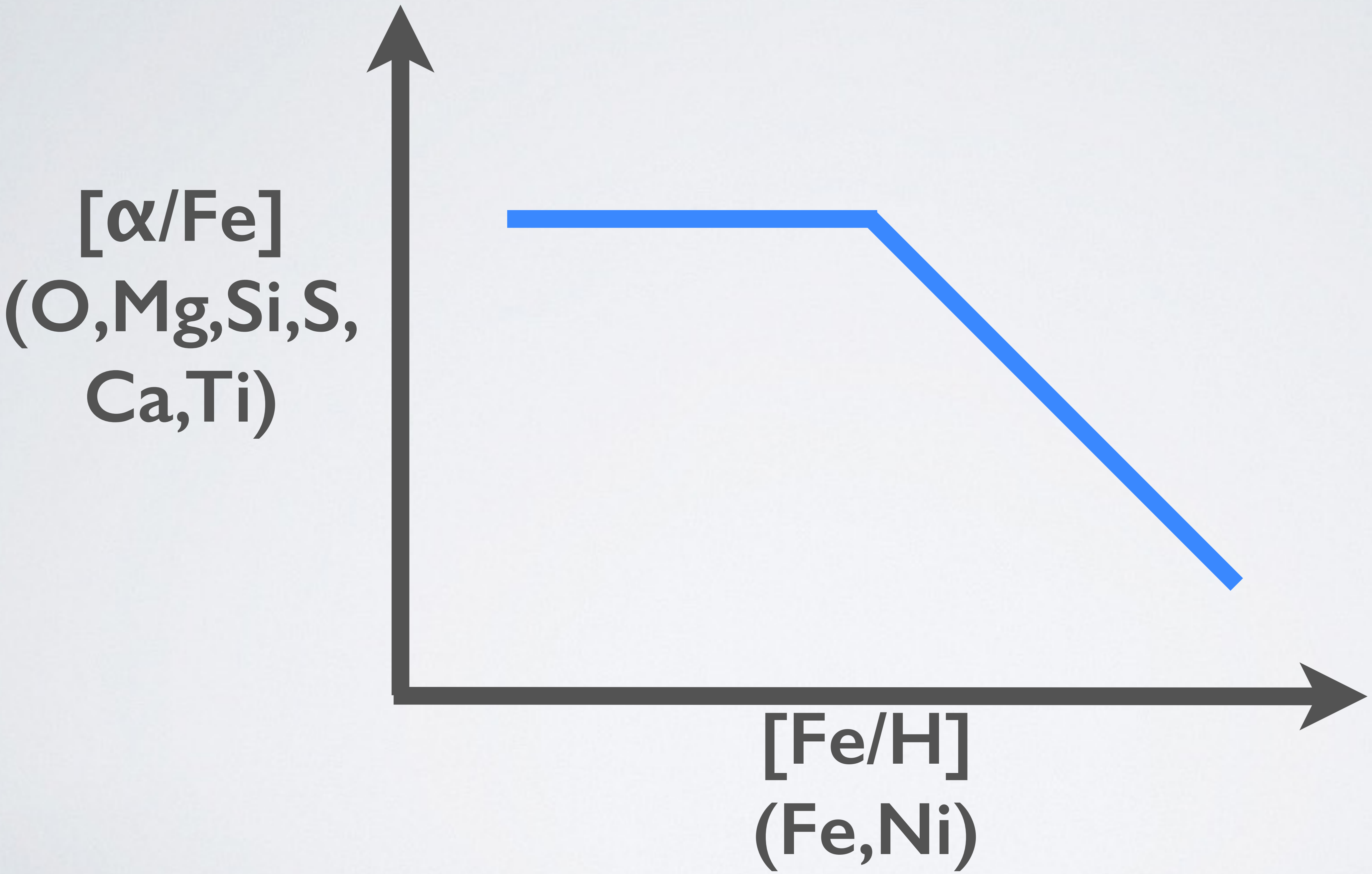
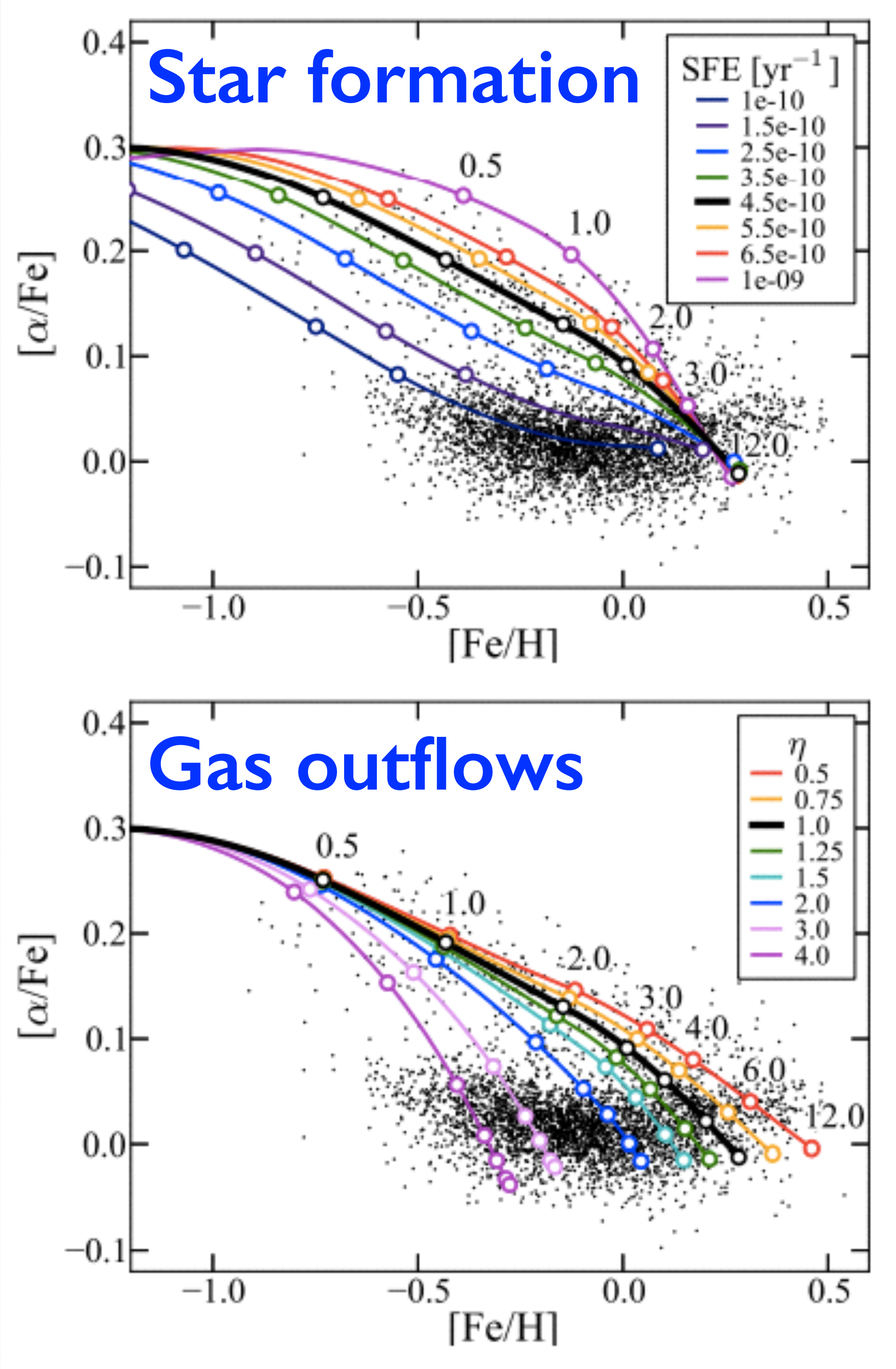


HIGH-ALPHA SEQUENCE

Nidever, Bovy et al. (2014)

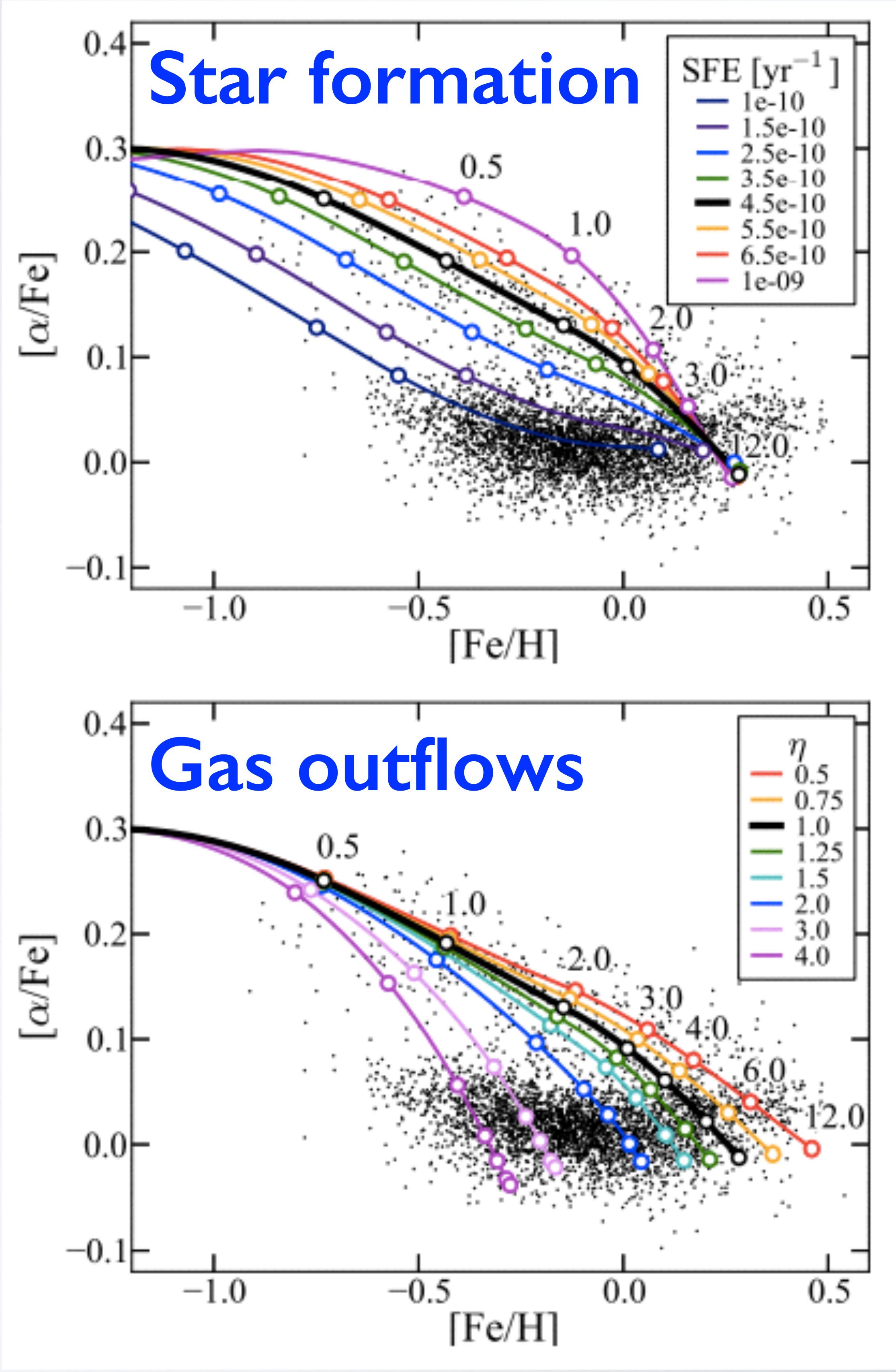
- Early evolution of the Disk



HIGH-ALPHA SEQUENCE

Nidever, Bovy et al. (2014)

- Early evolution of the Disk
- Star formation and gas in/outflow must have been very similar everywhere at R < 10 kpc within the first ~4 Gyr of the Disk's existence



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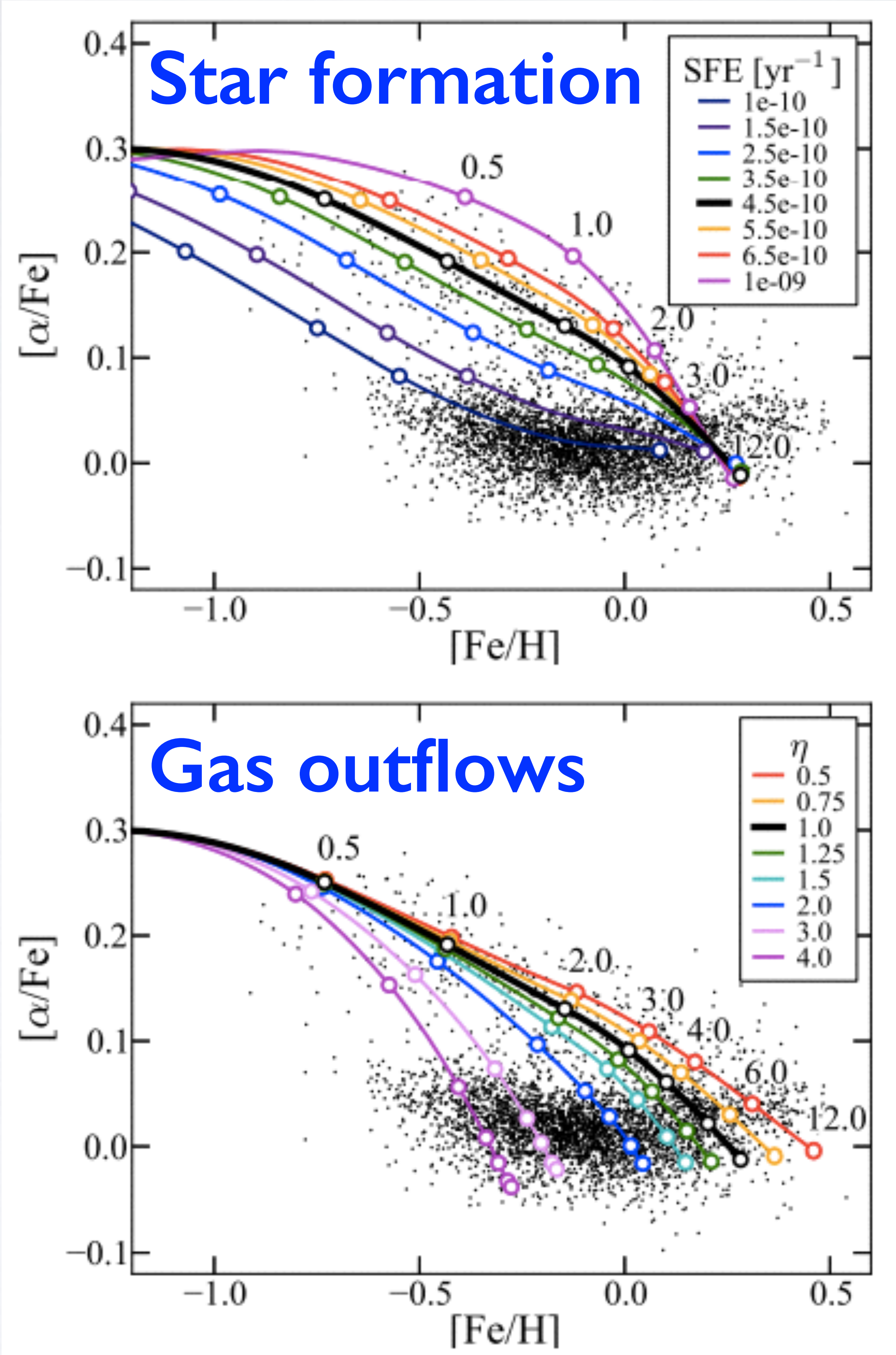
- SFR constant to within ~15%



DISSECTING THE MILKY WAY'S STELLAR POPULATIONS

IDENTIFYING DISK POPULATIONS

- (currently) impossible to identify single-stellar populations, but would like to get as close to that as possible
- Previously, *populations* were typically defined based on position or velocity (bad!)
- Even integrals of the motion likely change significantly over the lifetime of a star
- Surface abundance of stars don't change* over the stellar lifetime and uniform for SSPs
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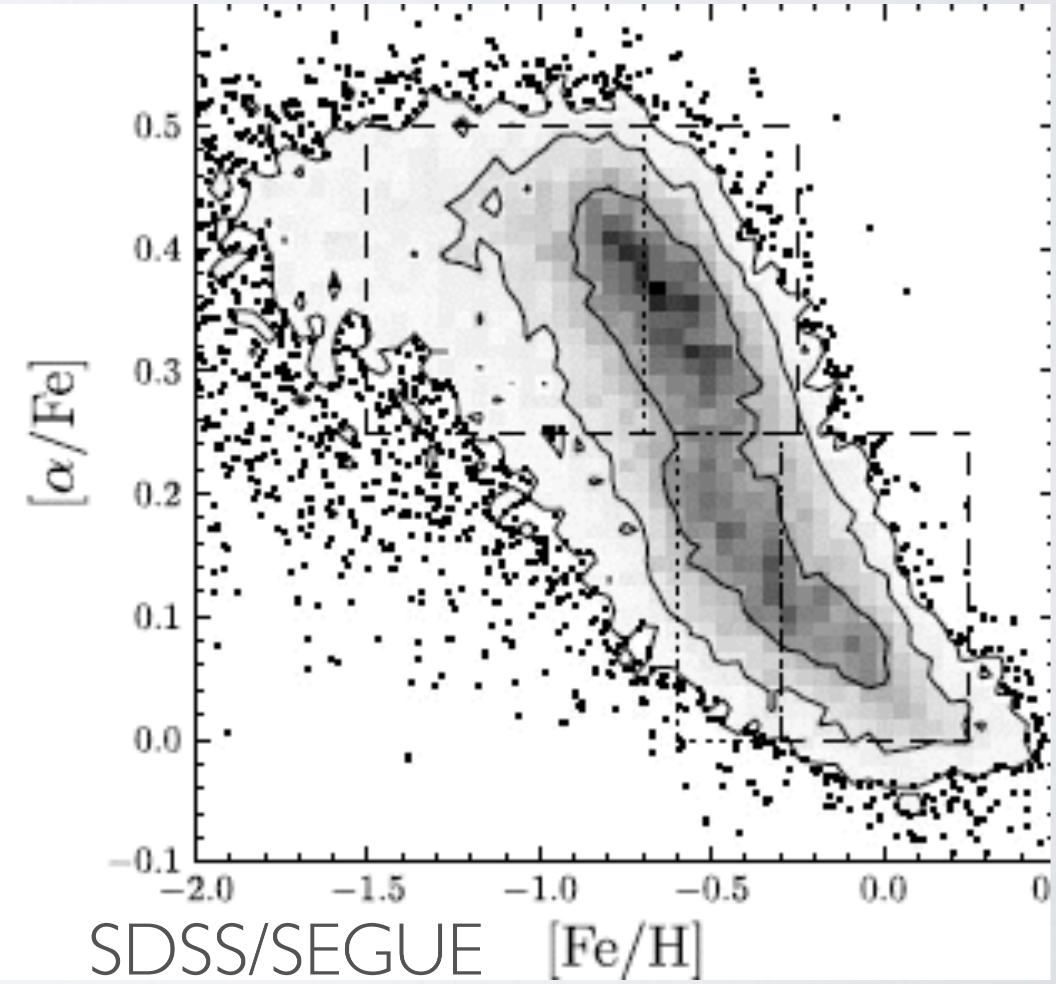

SDSS/SEGUE

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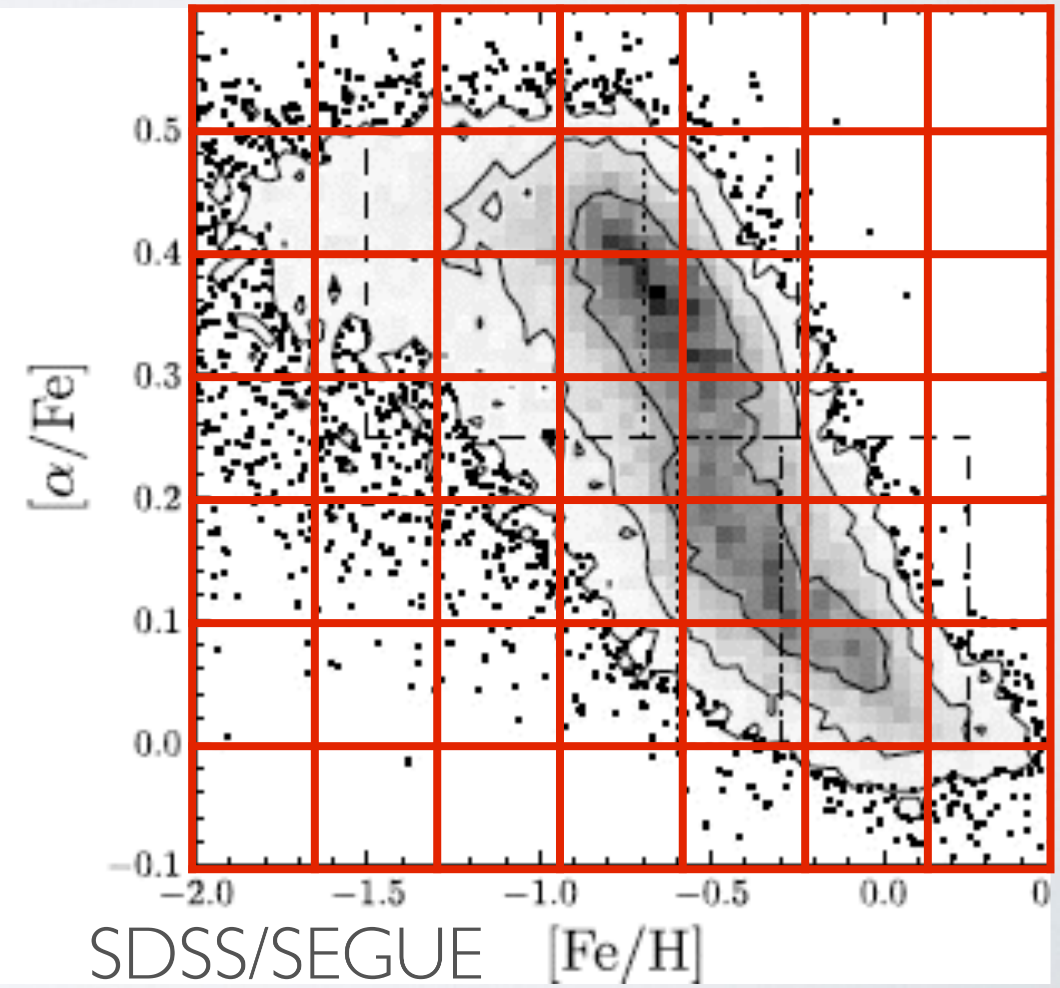
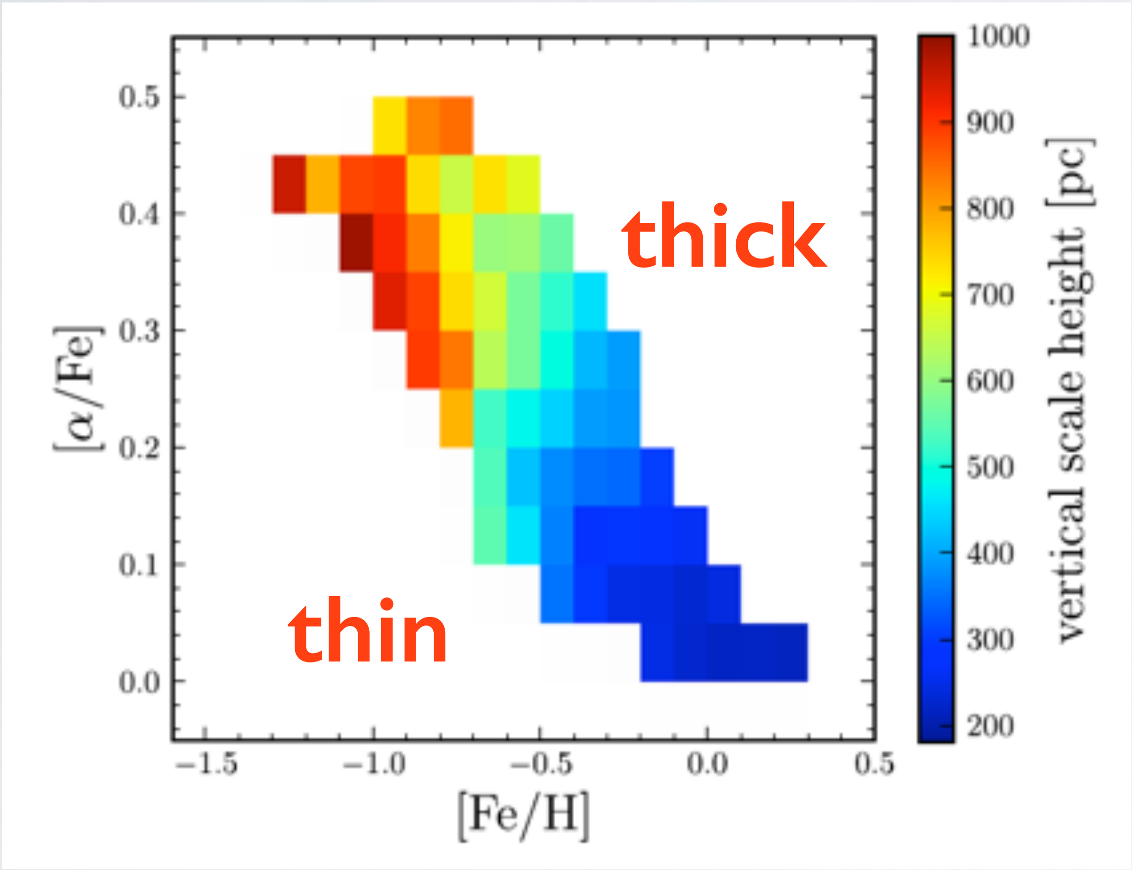
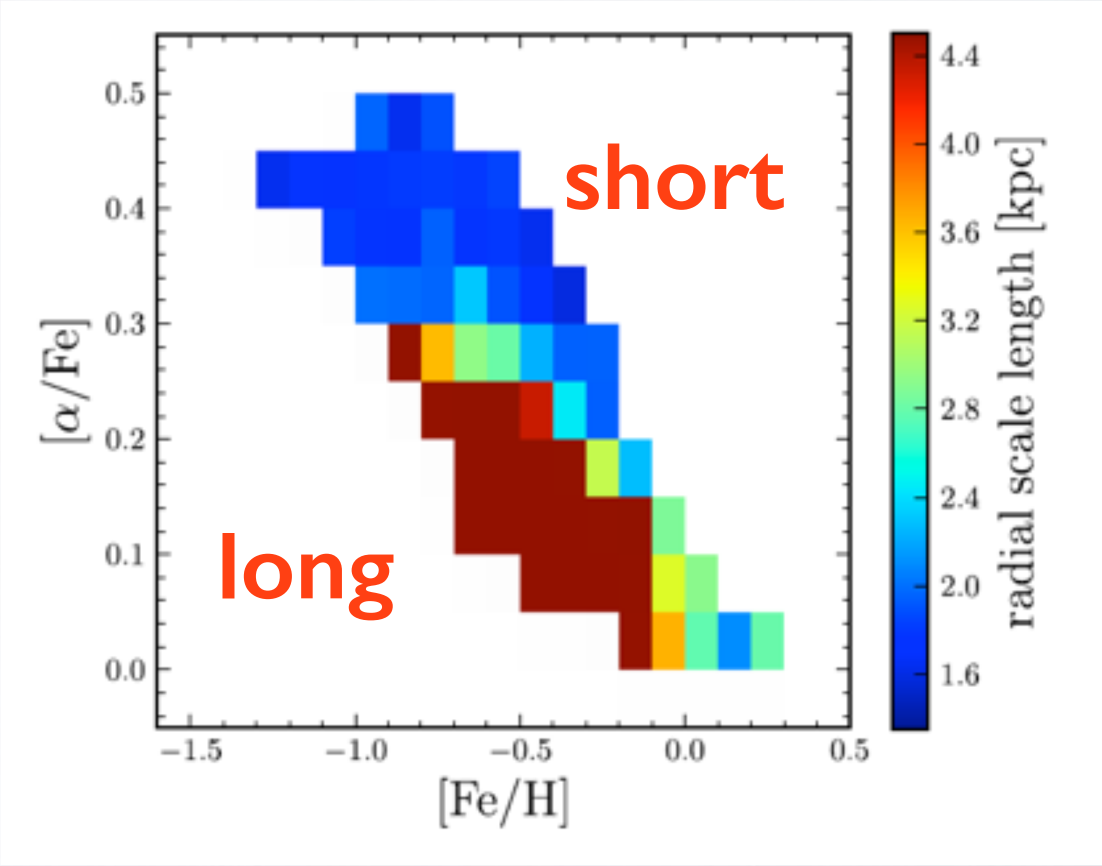


MONO-ABUNDANCE POPULATIONS

vertical profile: scale height



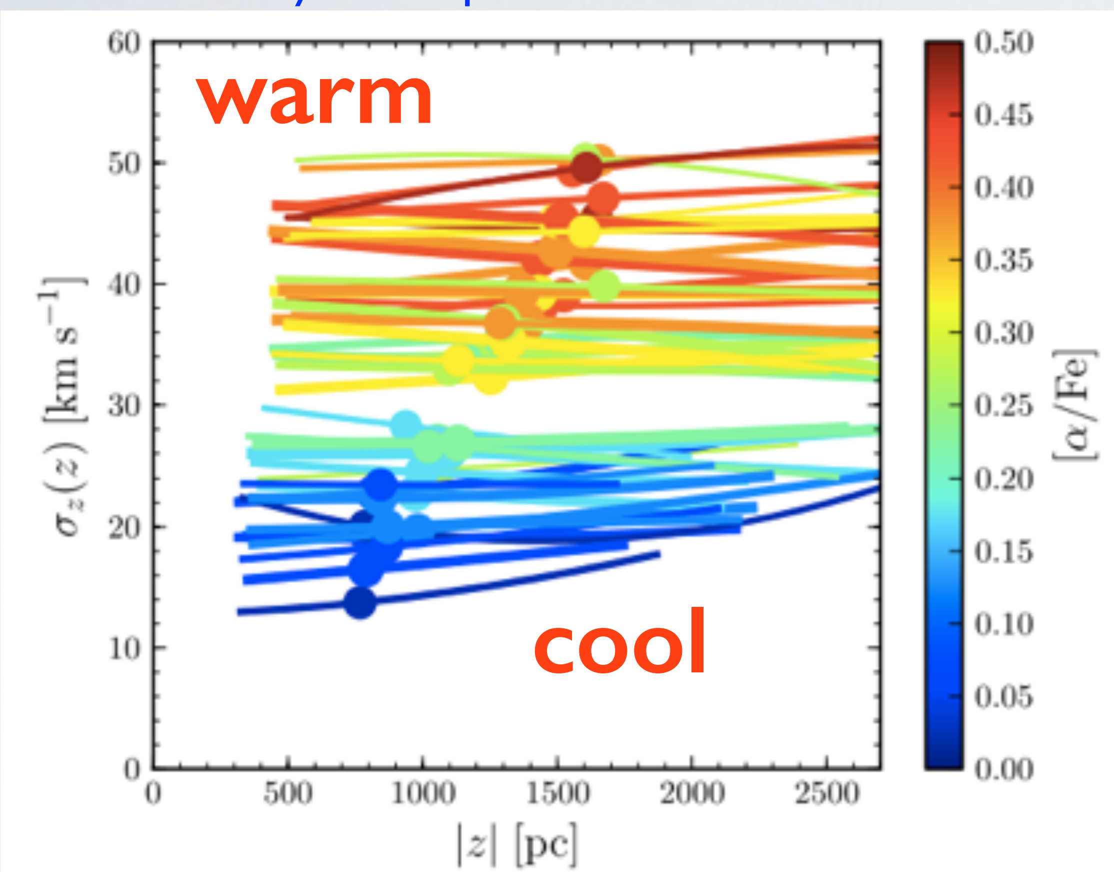
radial profile: scale length



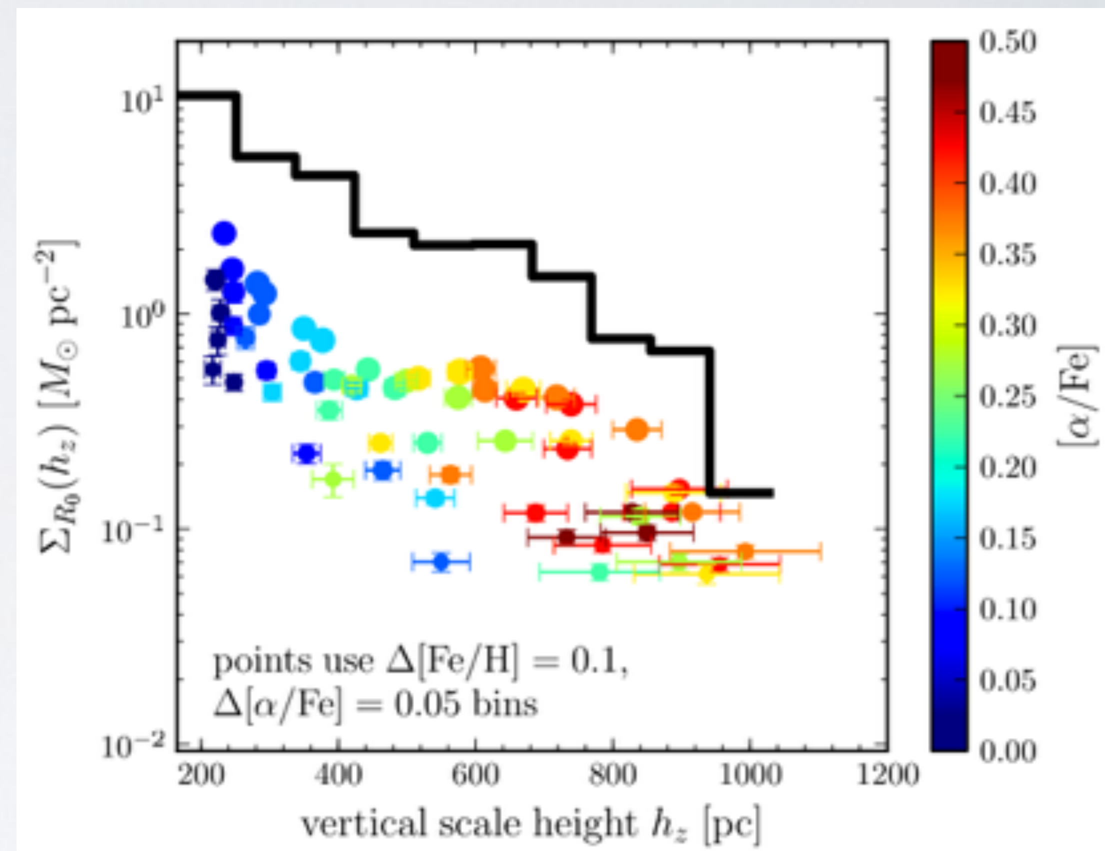
Bovy et al. (2012abc) using SDSS/SEGUE data

MONO-ABUNDANCE POPULATIONS

velocity dispersion: vertical



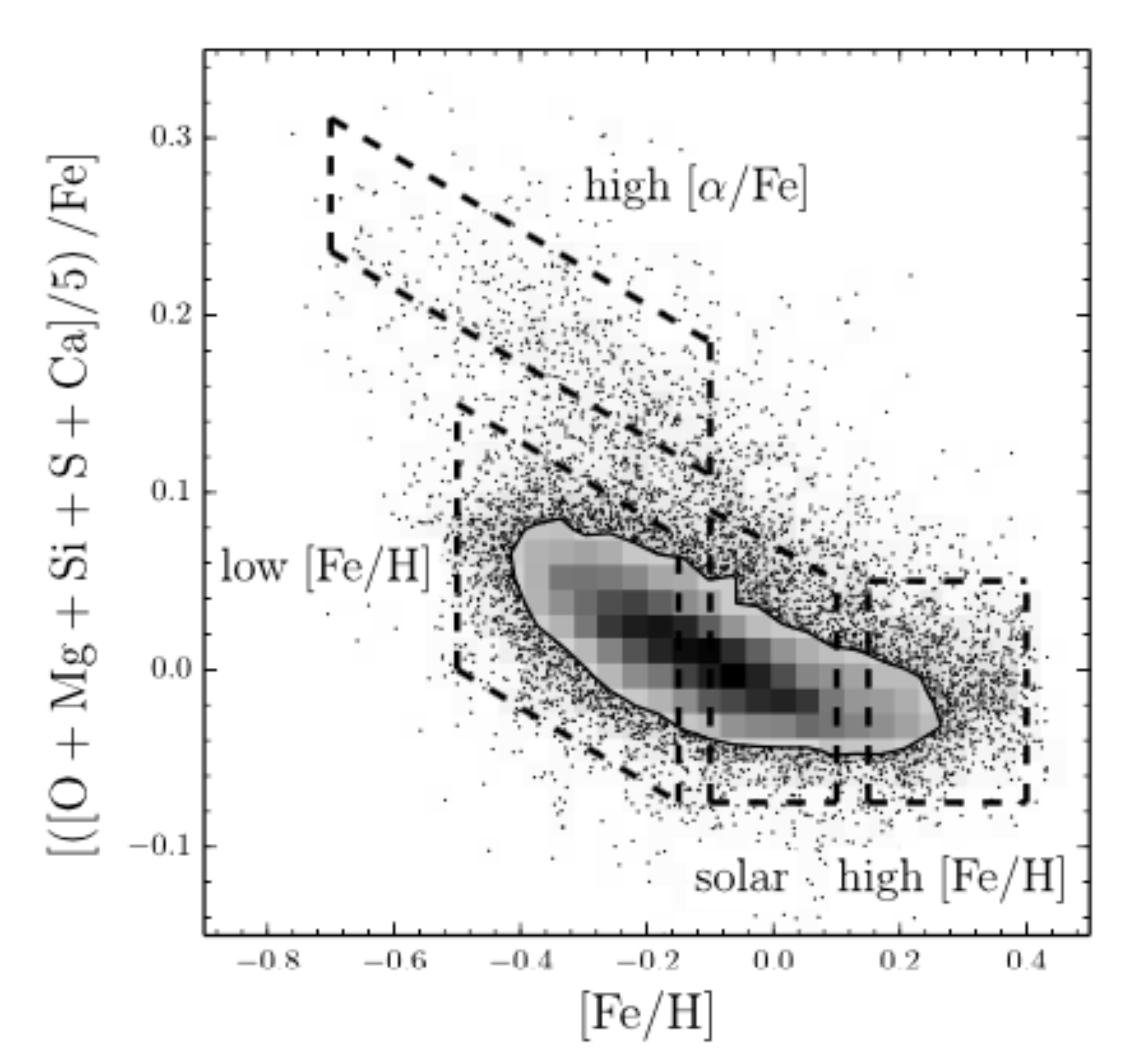
vertical profile: detailed distribution of mass



Bovy et al. (2012abc) using SDSS/SEGUE data

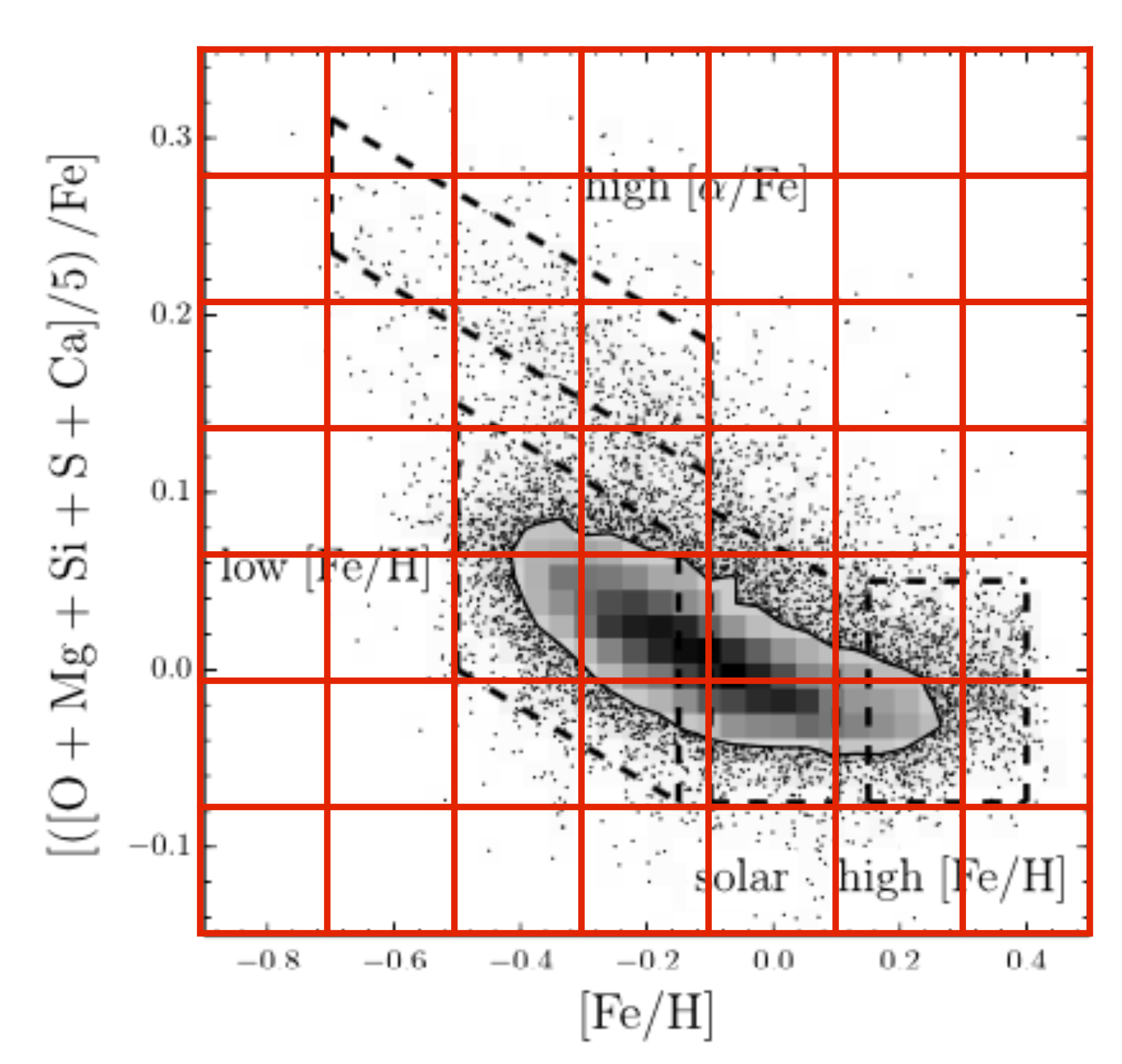
APOGEE MAPS

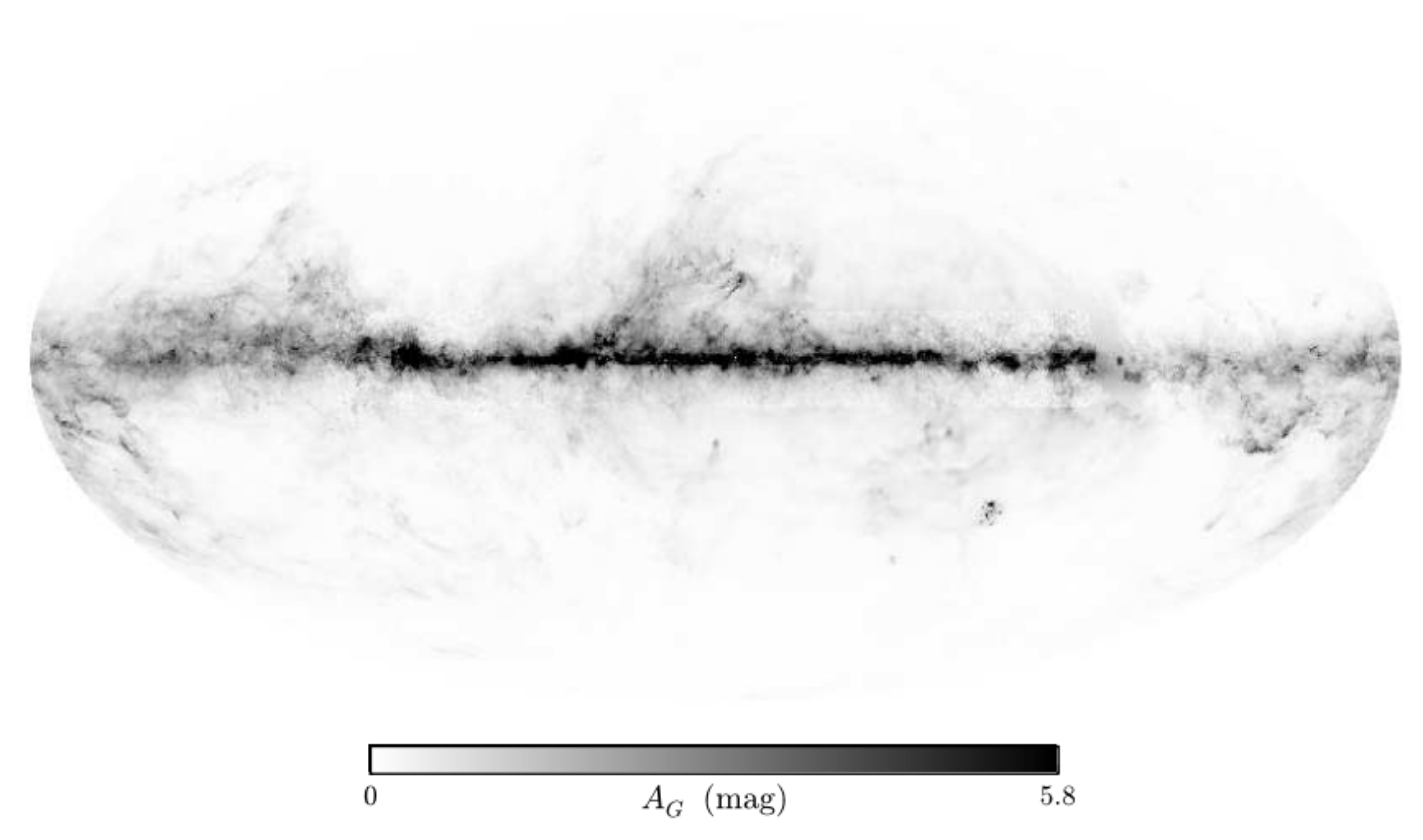
Bovy et al. (2016a)



APOGEE MAPS

Bovy et al. (2016a)

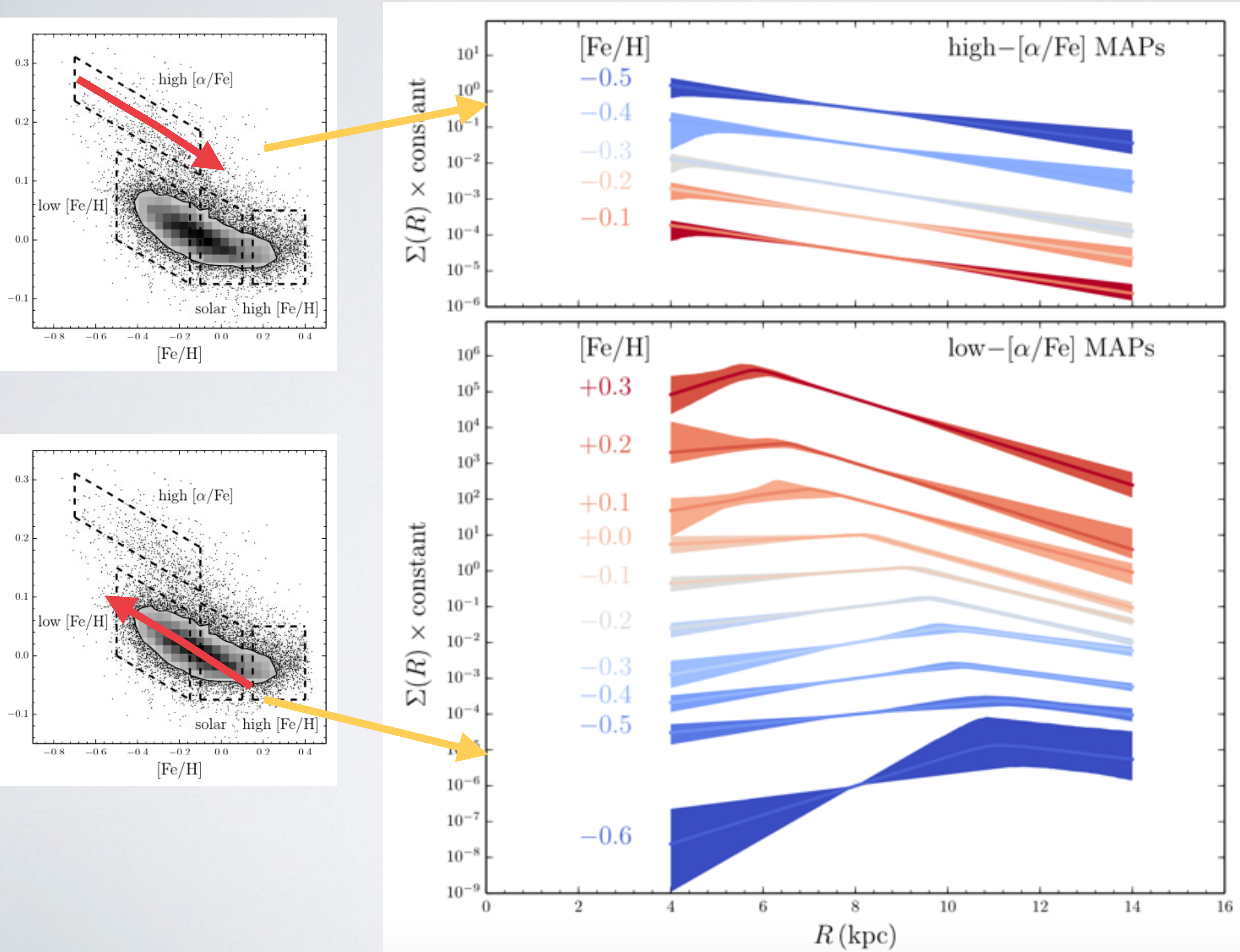




Combination of Green et al. (2015), Marshall et al. (2006), Drimmel et al. (2003)
see Bovy et al. (2016b)

APOGEE MAPS: RADIAL PROFILE

Bovy et al. (2016a)

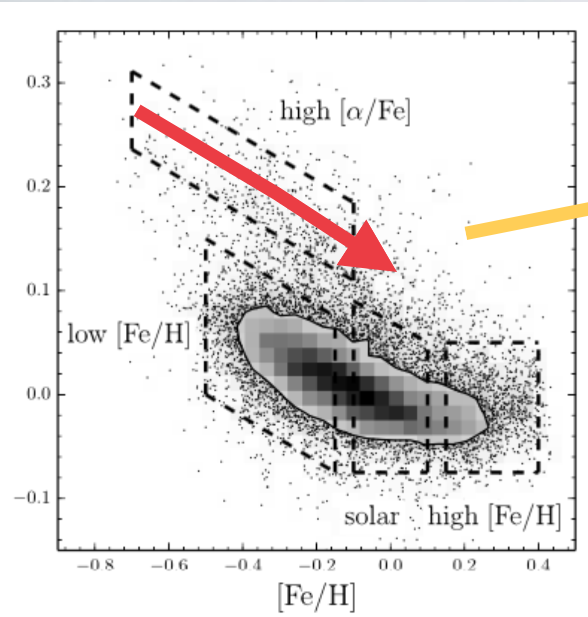


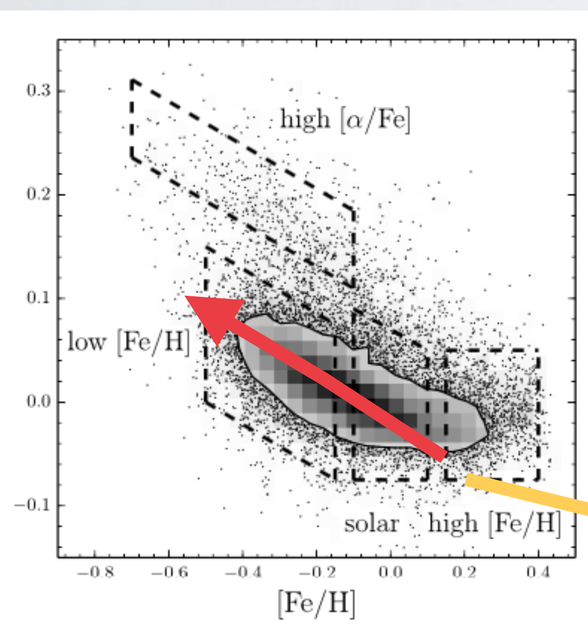
old

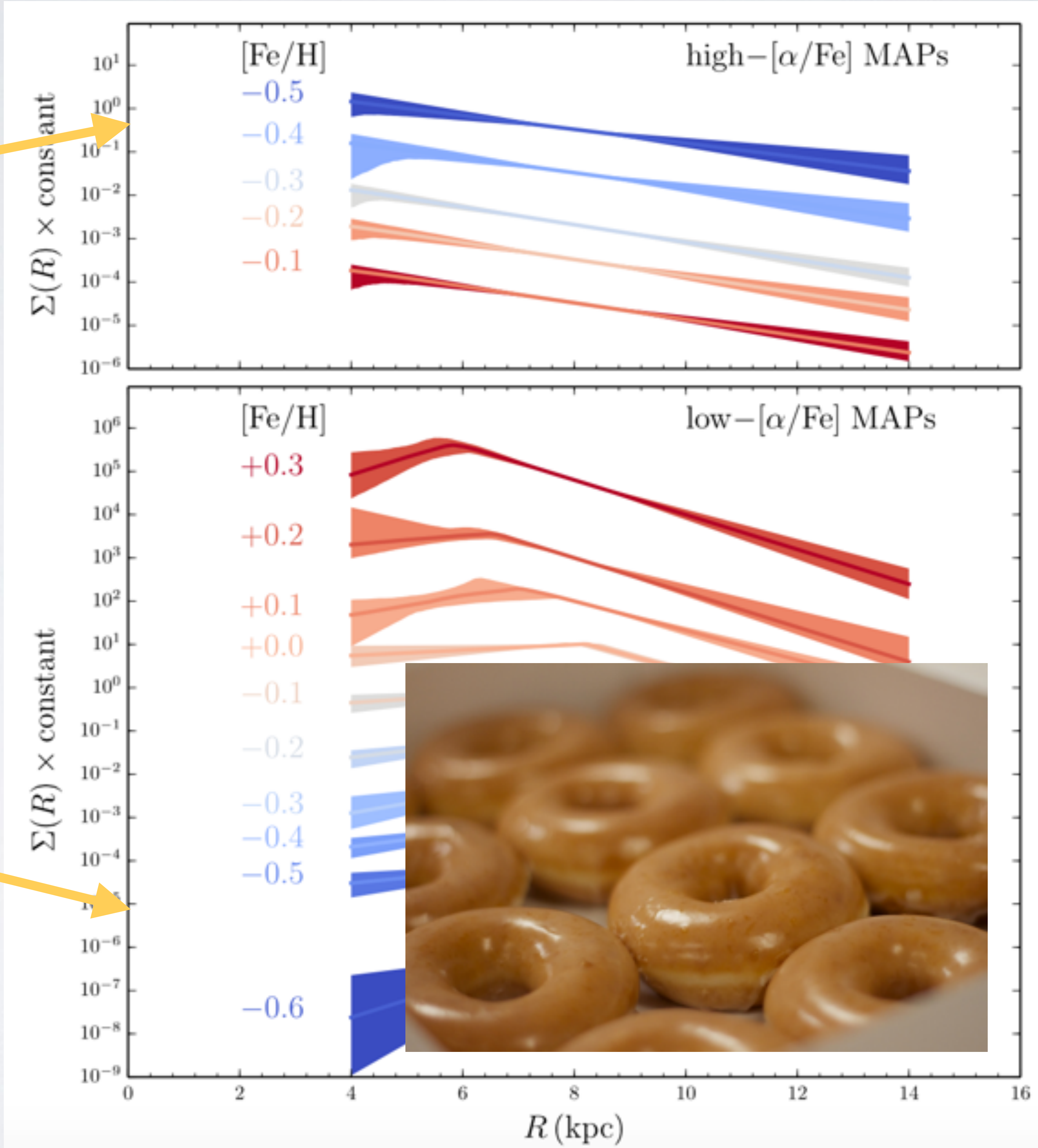
younger

APOGEE MAPS: RADIAL PROFILE

Bovy et al. (2016a)





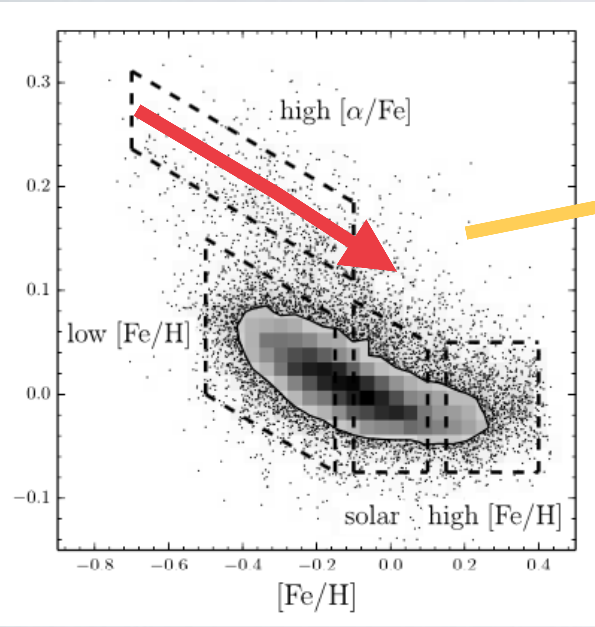


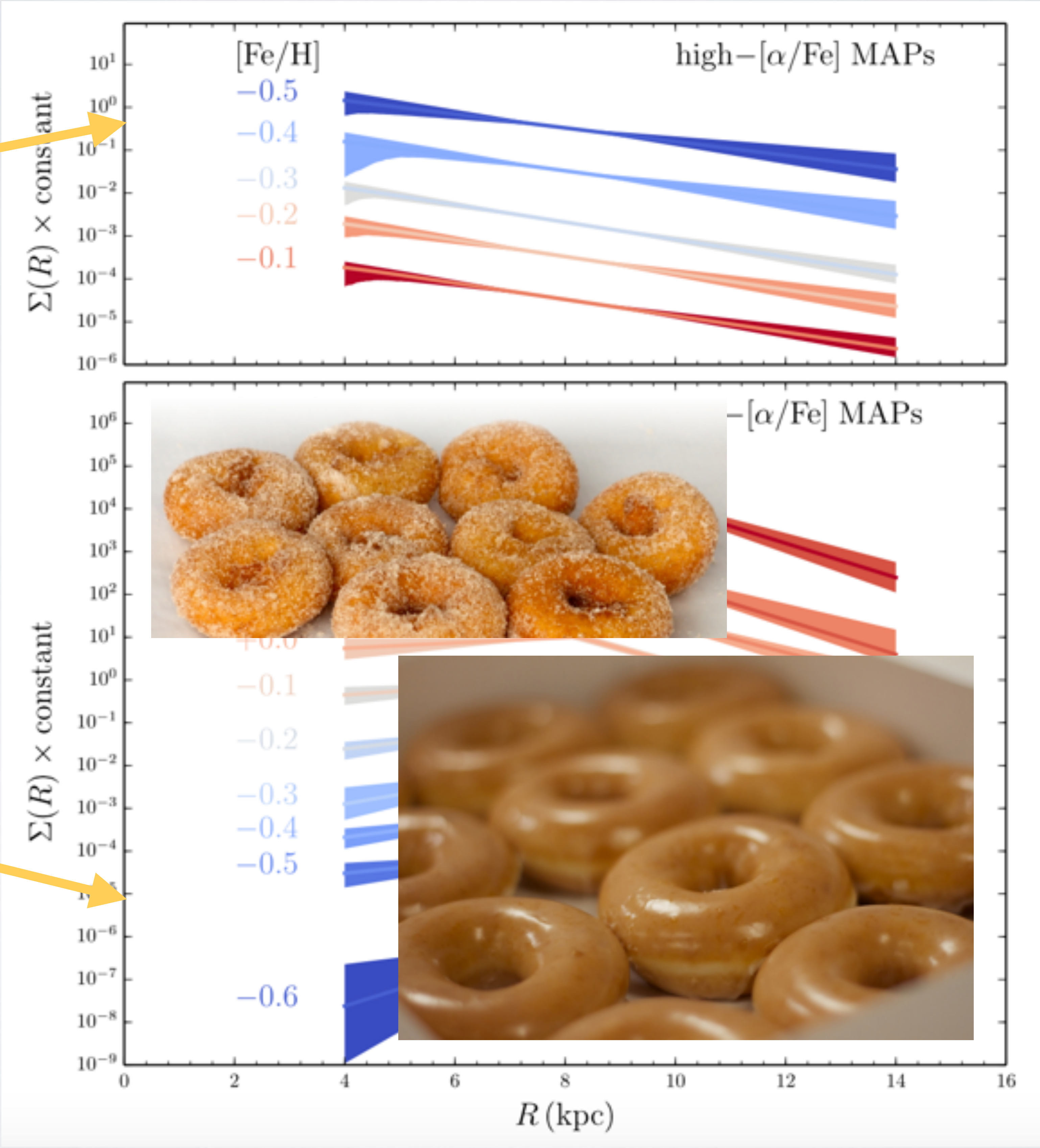
old

younger

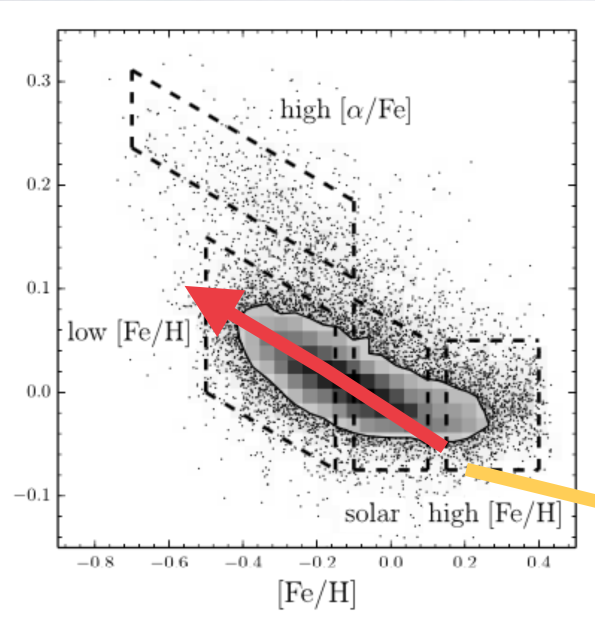
APOGEE MAPS: RADIAL PROFILE

Bovy et al. (2016a)





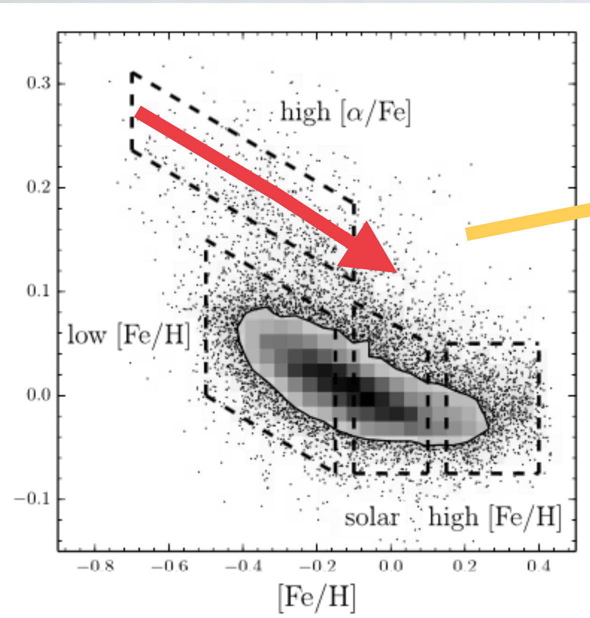
old

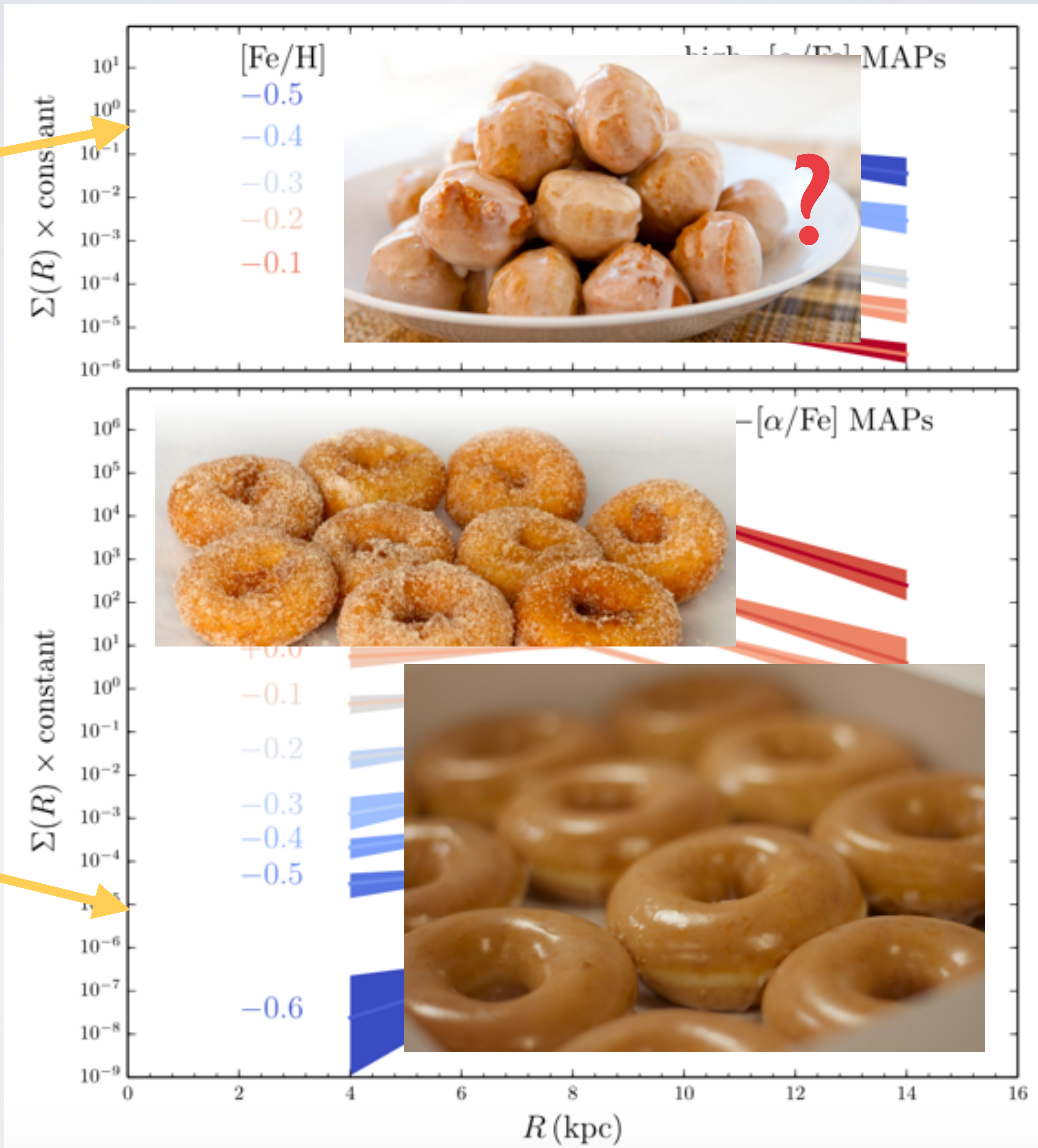


younger

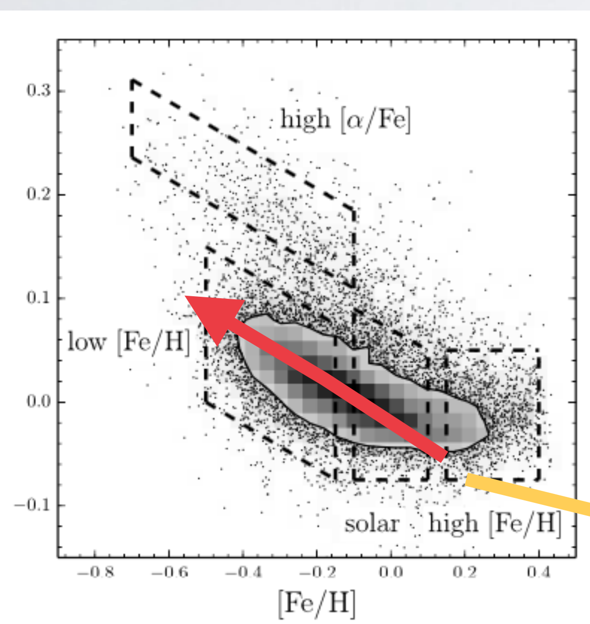
APOGEE MAPS: RADIAL PROFILE

Bovy et al. (2016a)





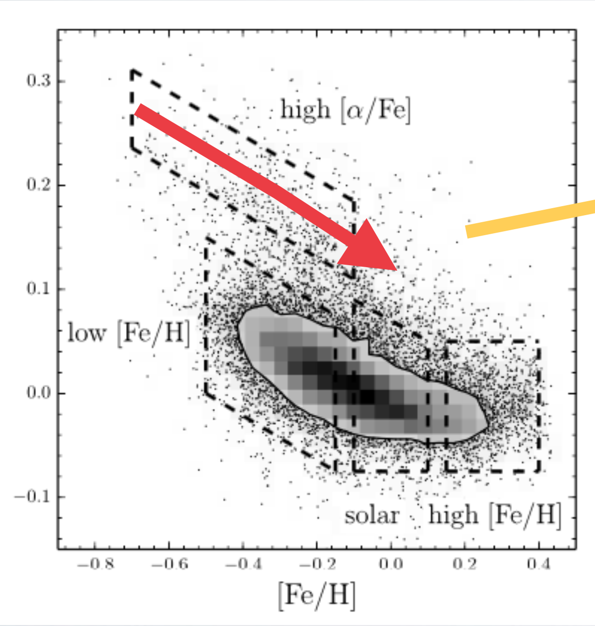
old

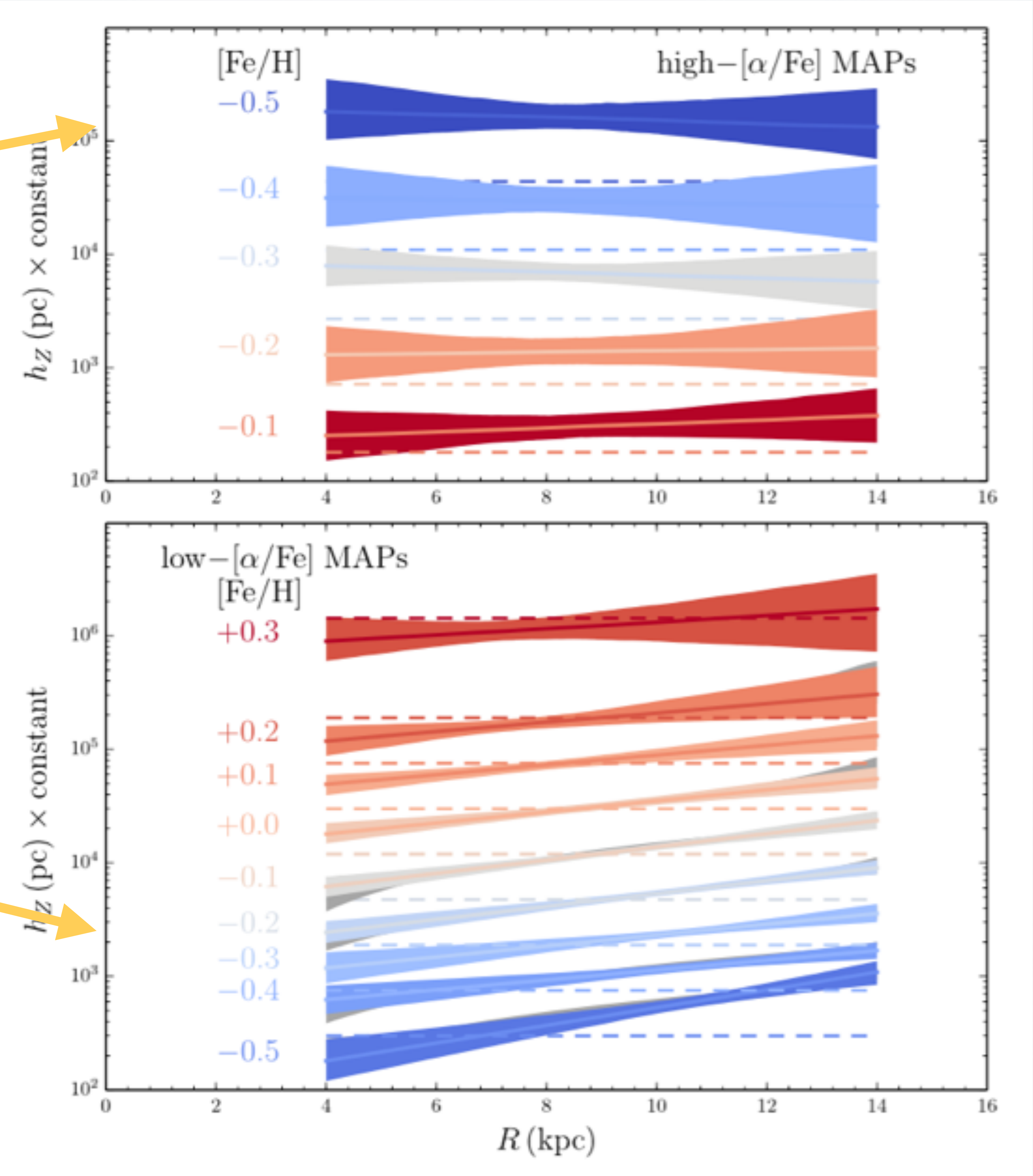


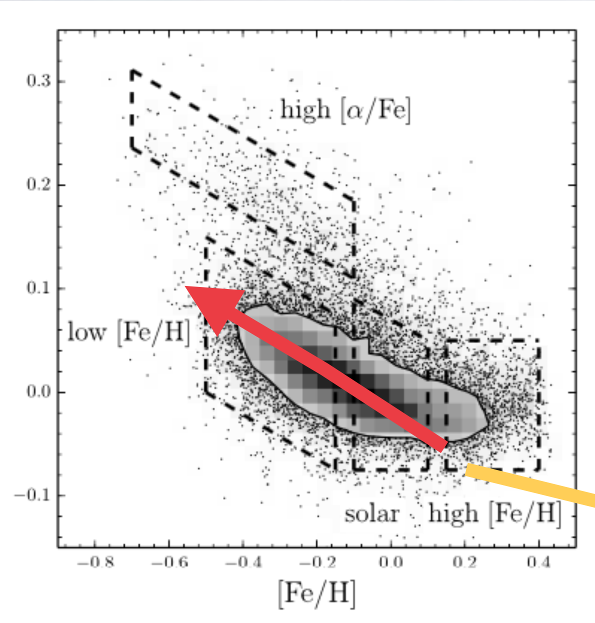
younger

APOGEE MAPS: VERTICAL PROFILE

Bovy et al. (2016a)







old

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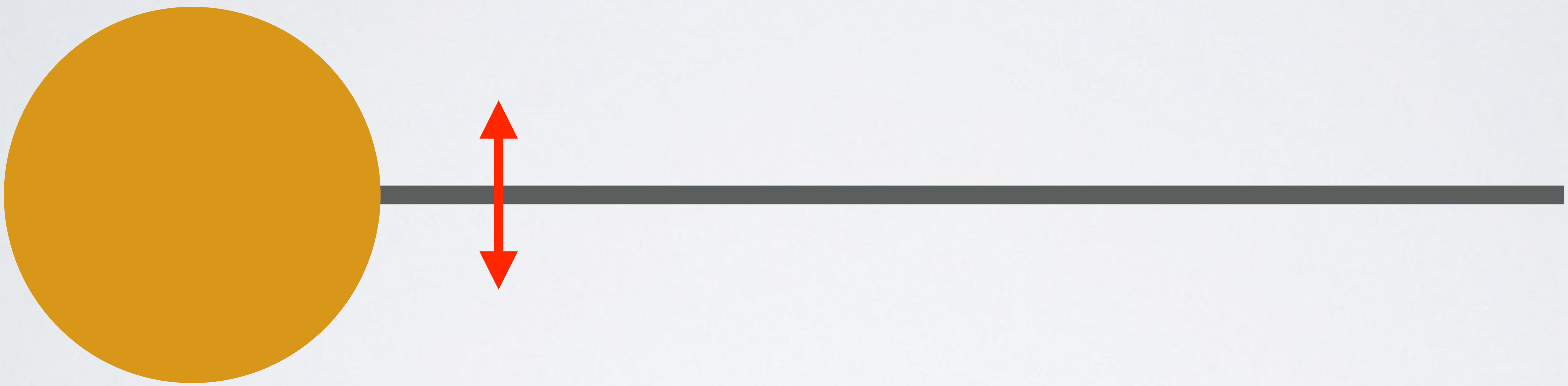
RADIAL MIGRATION AND DISK FLARING



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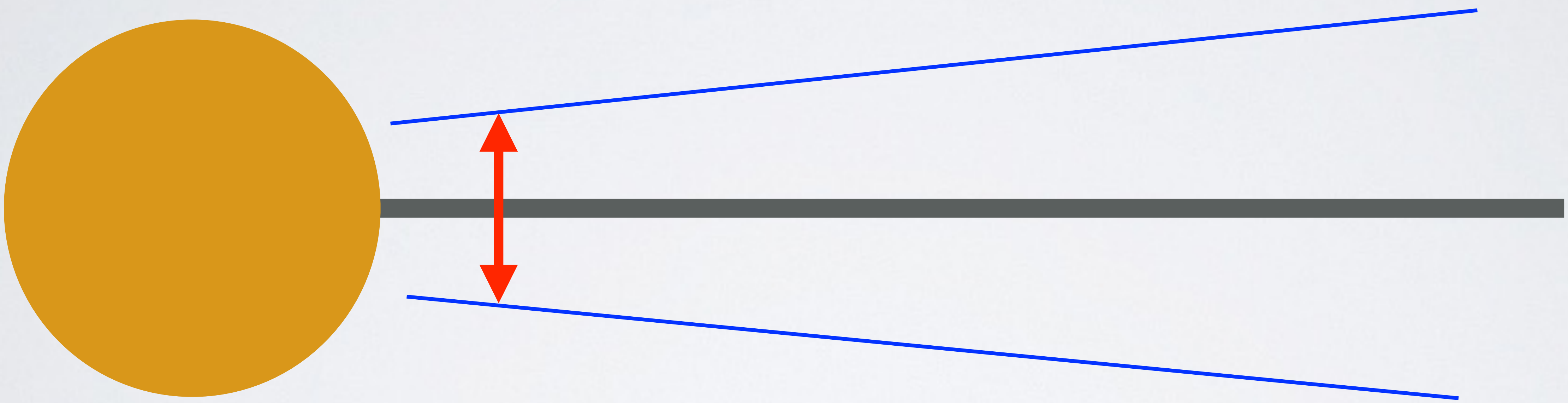

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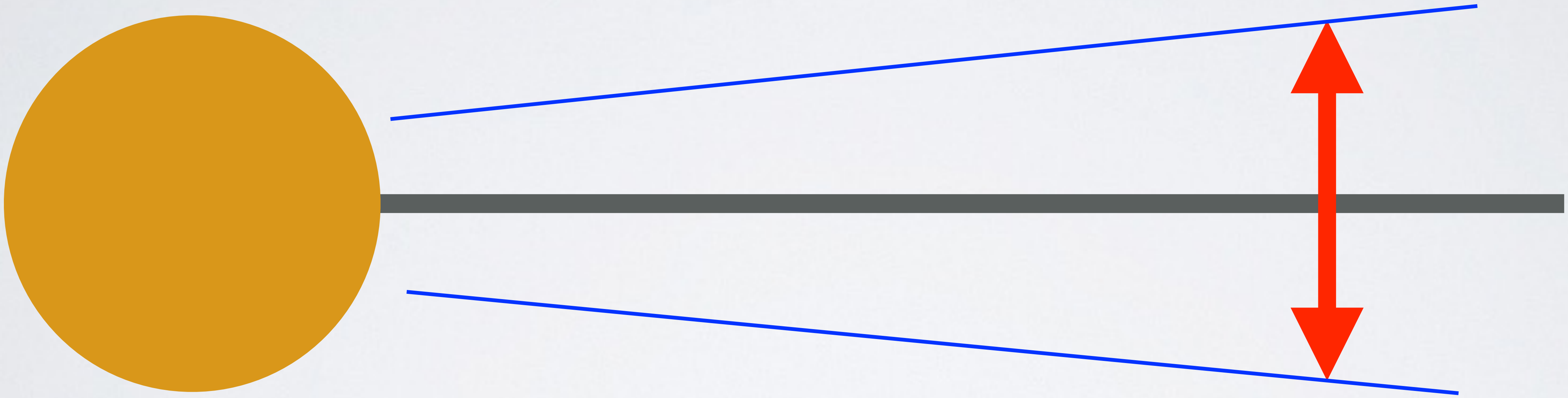

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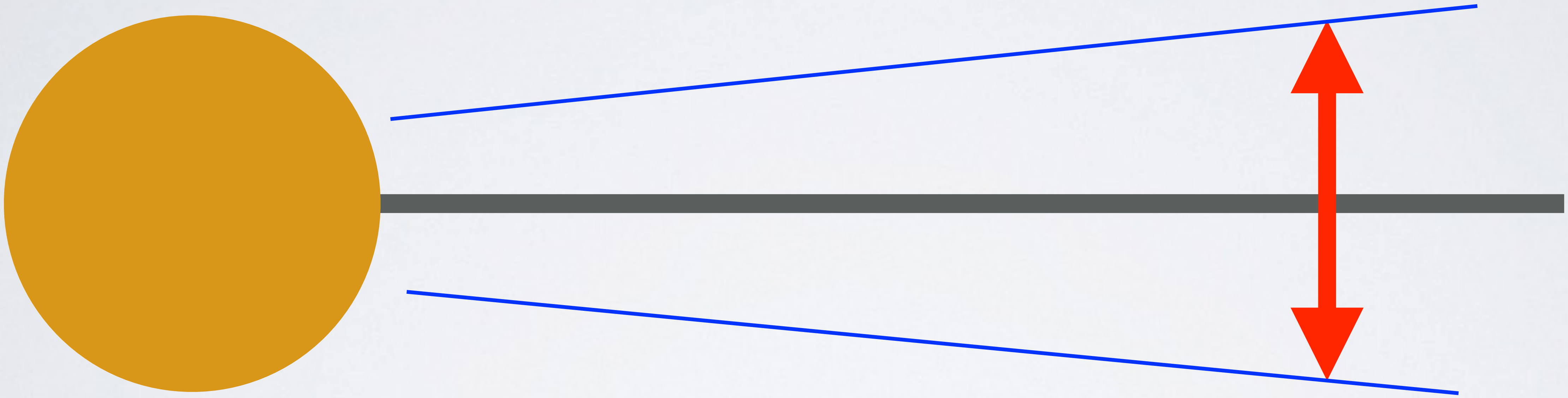
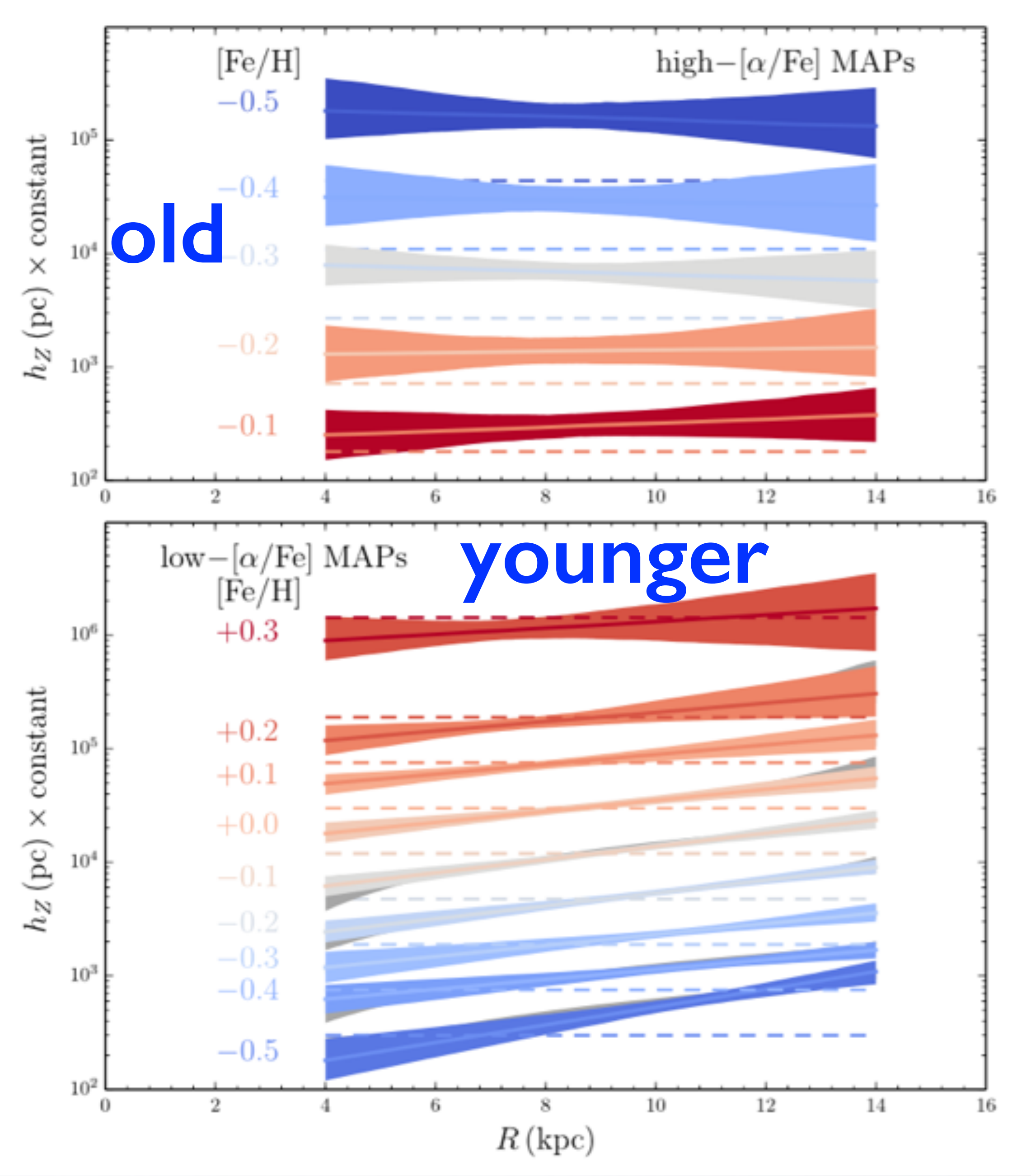


- *Requires: approx. J_z conservation, no “provenance bias” (Vera-Ciro et al. 2015,2016)

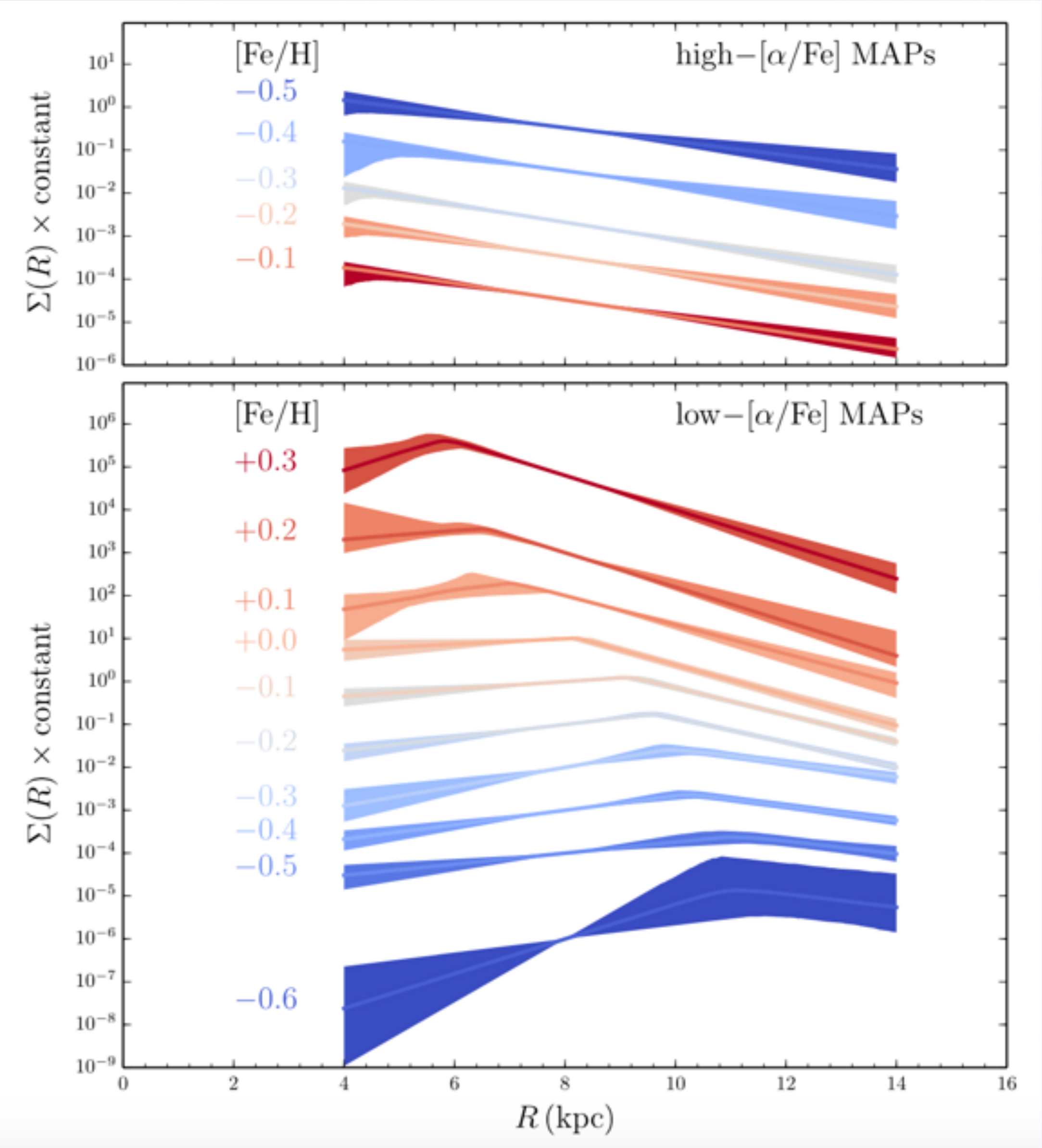
APOGEE MAPS: VERTICAL PROFILE

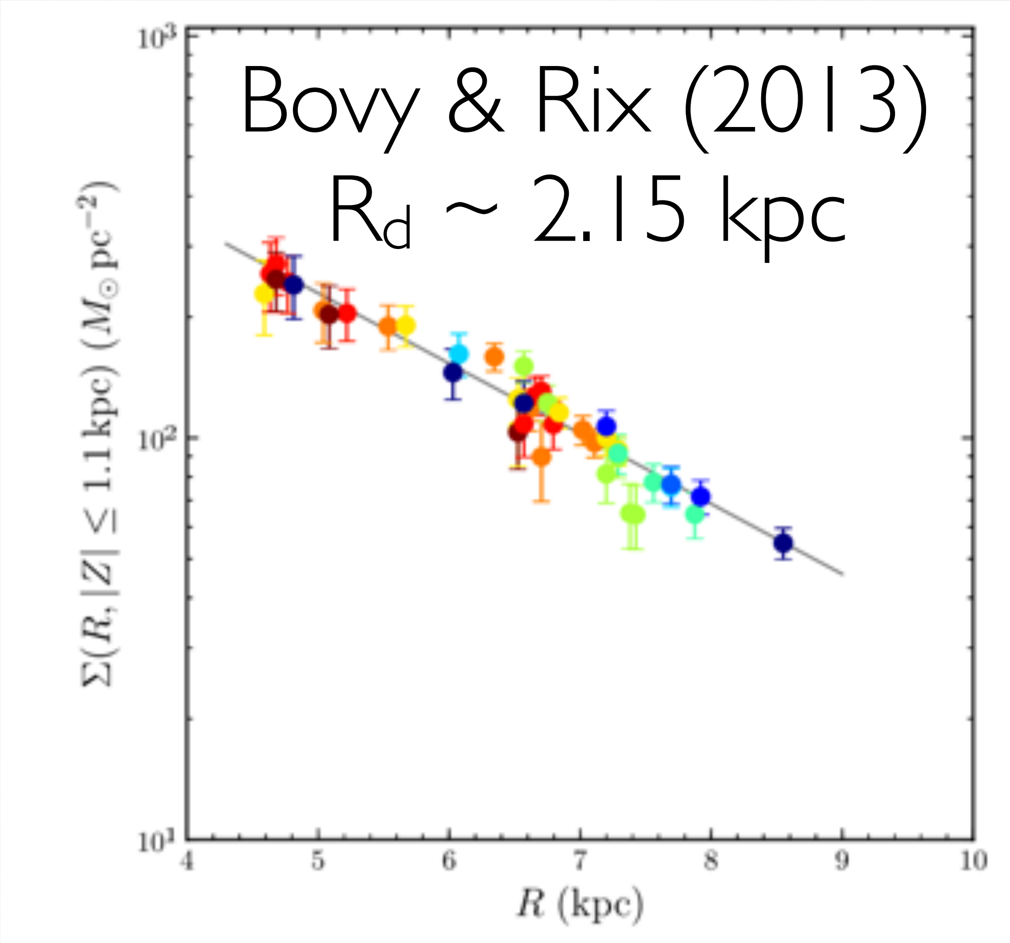
Bovy et al. (2016)

- IF flaring due to radial migration:
  - low-alpha (young): no strong provenance bias, J_z conservation, plausible for massive MW disk?
  - high-alpha (old): probably strong provenance bias
  - Difficult to imagine how to make the 'thick disk' through migration w/o flaring



MAPS AND THE OVERALL DISK





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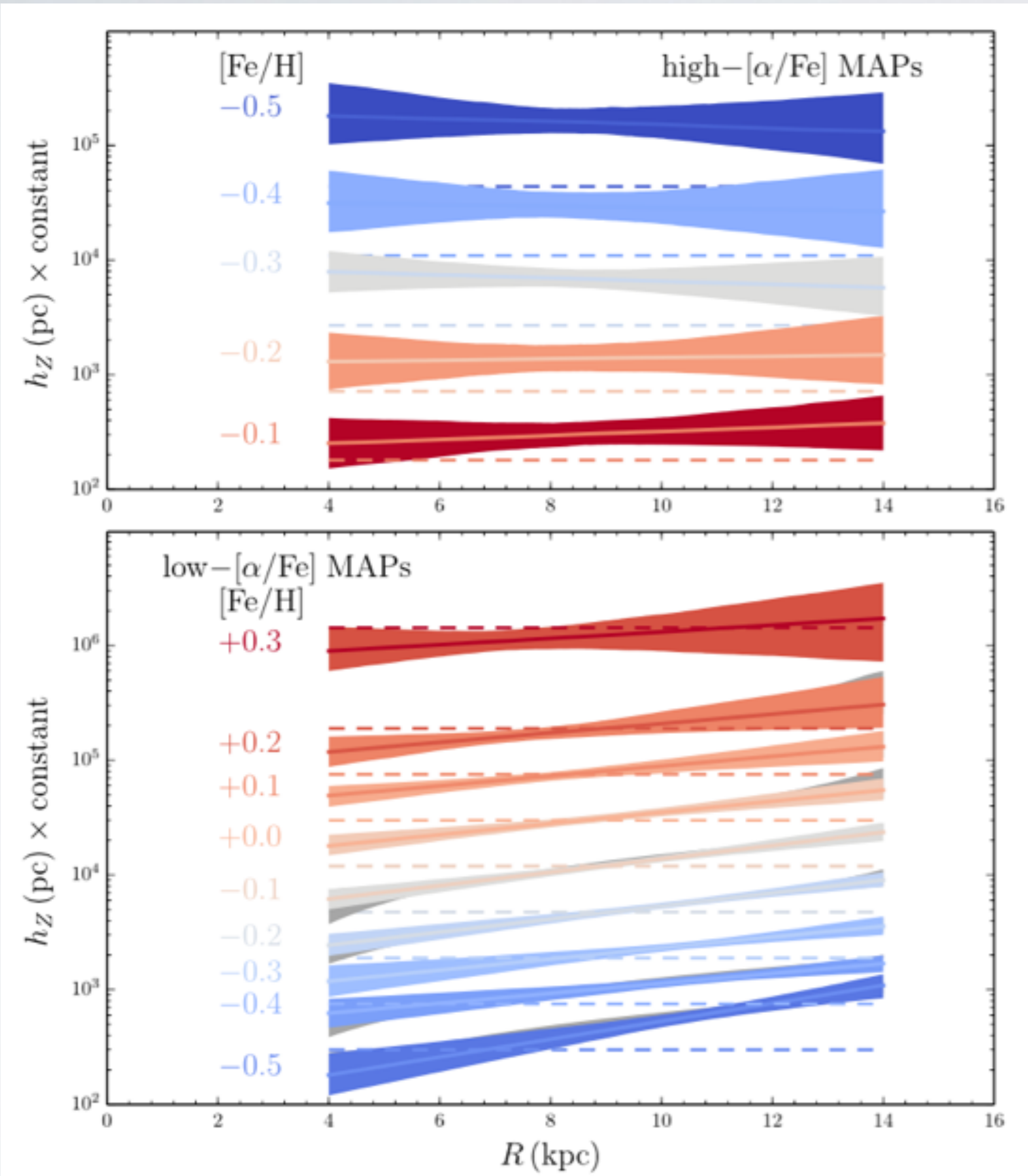

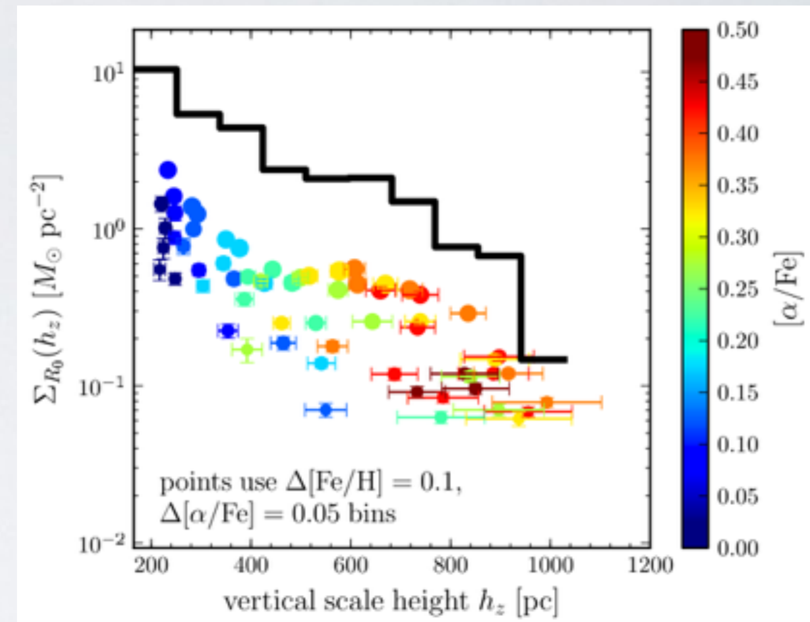

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- Flaring of low-alpha, cool populations —> consistent with radial migration
- No flaring of **high-alpha populations** —> **likely formed thick** in turbulent ISM (cf. high-z studies)

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- But no coherent picture has yet emerged that ties everything together

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- Stream—dark-matter sub-halo encounters: Sanders, Bovy, & Erkal (2016), Bovy (2016b); Bovy et al. (2016a) —> Find **CDM-like population down to 3×10^6 M_{sun} —> DM cold**

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