Precision measurements of the Milky Way's disk's structure and dynamics

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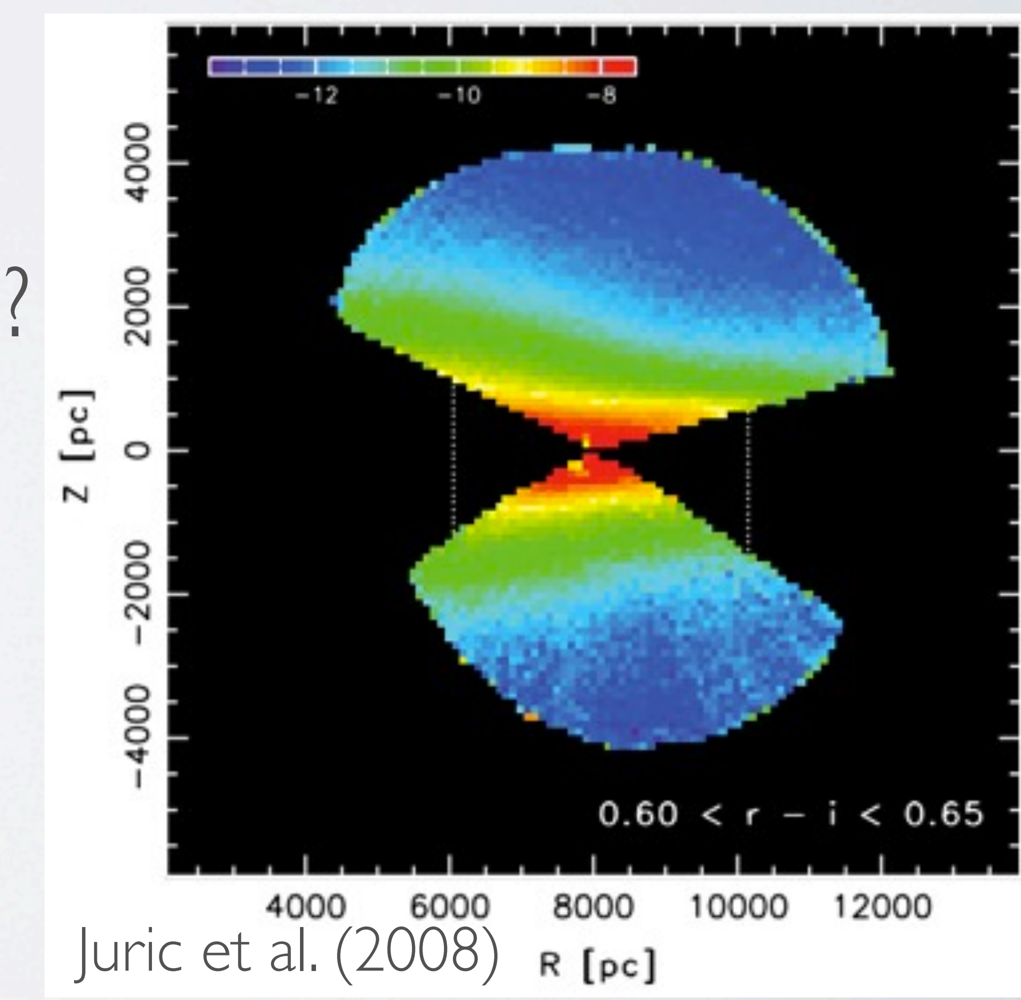
2MASS/J. Carpenter, T. H. Jarrett, & R. Hurt

DISK FORMATION AND EVOLUTION

- forming realistic disks *ab initio* remains difficult
- current structure: formation or evolution?
- internal and external evolution: what information about formation is retained?
- many stars in z=0 Universe live in the disk of MW-size galaxies



Juric et al. (2008)

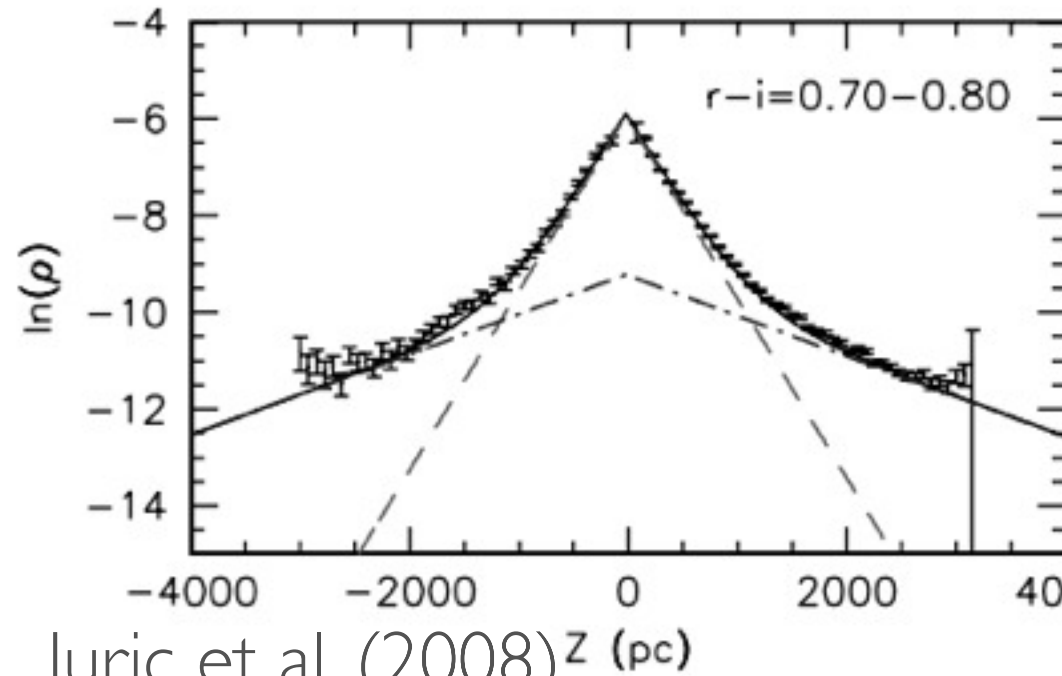
OVERVIEW

- Introduction: disk formation and evolution
- Spatial distribution of abundance-selected sub-populations
- Kinematics of abundance-selected sub-populations
- Discussion of abundance-selected sub-populations
- New measurement of Milky Way's rotation curve 4 <~ R <~ 14 kpc (if time)

DISK FORMATION AND EVOLUTION

- Galactic disks are thought to form from the inside-out, but little direct observational evidence
- Subsequent evolution erases formation signatures in present-day MW disk
- Can we 'tag' the building blocks of the disk?
- Simplest picture, thin + thick disk, correct?

THICK DISK COMPONENTS

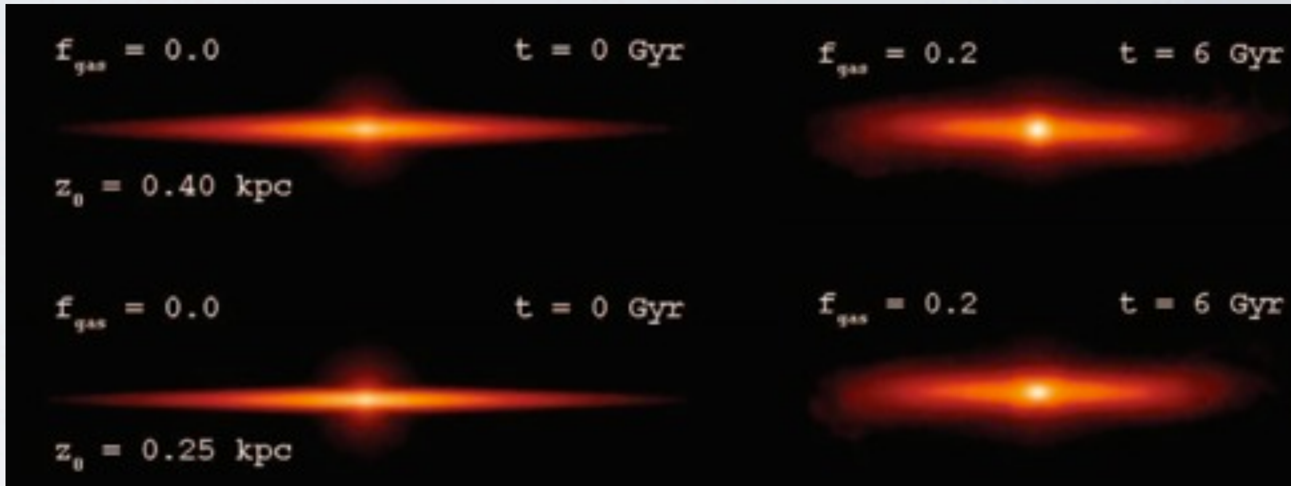


Juric et al. (2008)

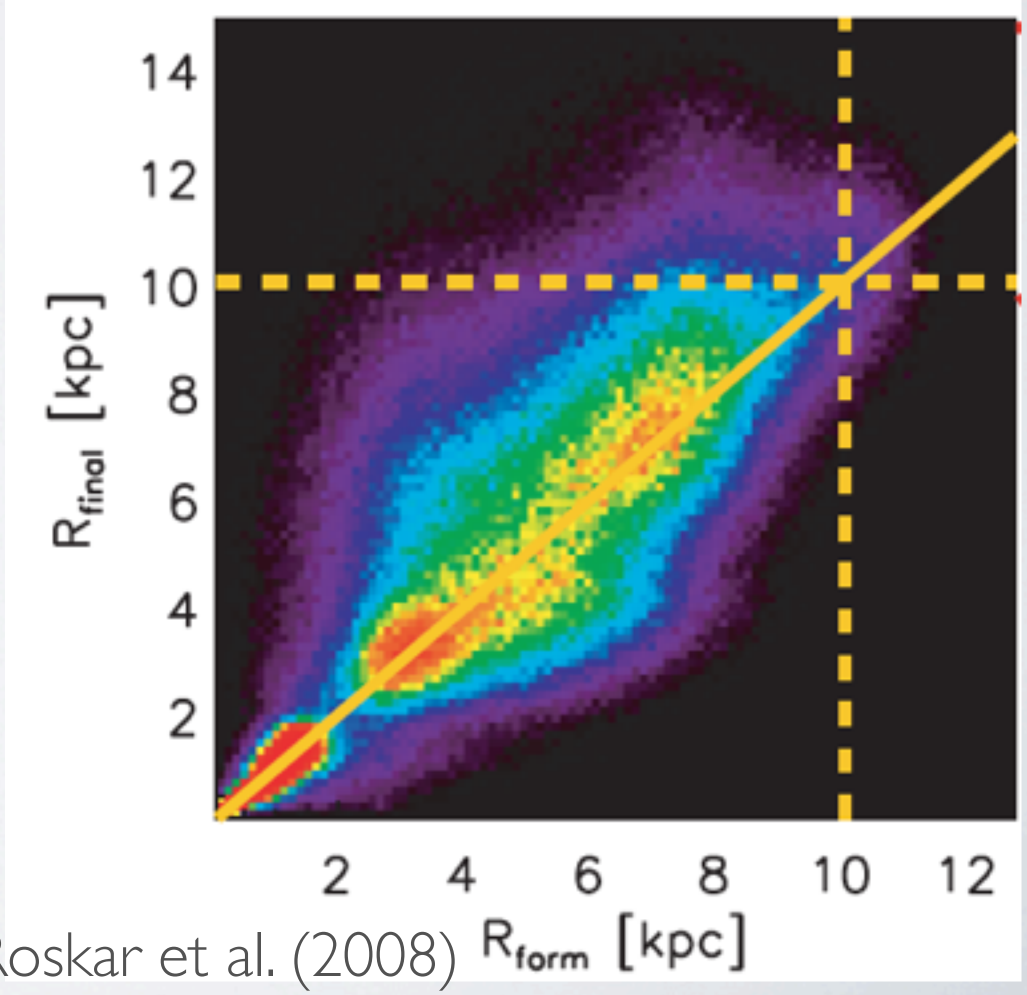
- "Thick" == large-scale height (~ 1 kpc)
- Too thick to have been formed by "regular" heating
- old, metal-poor, enriched in alpha elements, kinematically warm (Bensby et al. 2005; Yoachim & Dalcanton 2008; Chiba & Beers 2000; Soubiran et al. 2003; Gilmore et al. 2002; Yoachim & Dalcanton 2005; Fuhrmann 1998; Prochaska et al. 2000; Tautvaiˇsien˙e et al. 2001; Feltzing et al. 2003; Mishenina et al. 2004; Bensby et al. 2003, 2005; Reddy et al. 2006; Haywood 2008)
- could result from formation or evolution of the disk
- unclear whether really distinct components

DISK EVOLUTION

- external: minor mergers can lead to *accretion* of satellite stars or *heating* of the existing disk (Abadi et al. 2003; Quinn et al. 1993)
- internal: *wet merger* can induce rapid star formation, bar/spiral ams lead to *radial migration* (Brook et al. 2004; Schoenrich & Binney 2008)
- Or, the disk may have *formed* hot due to disk instabilities at higher redshift (Bournaud et al. 2009, Stinson, Bovy, et al., in prep)



Moster et al. (2010)



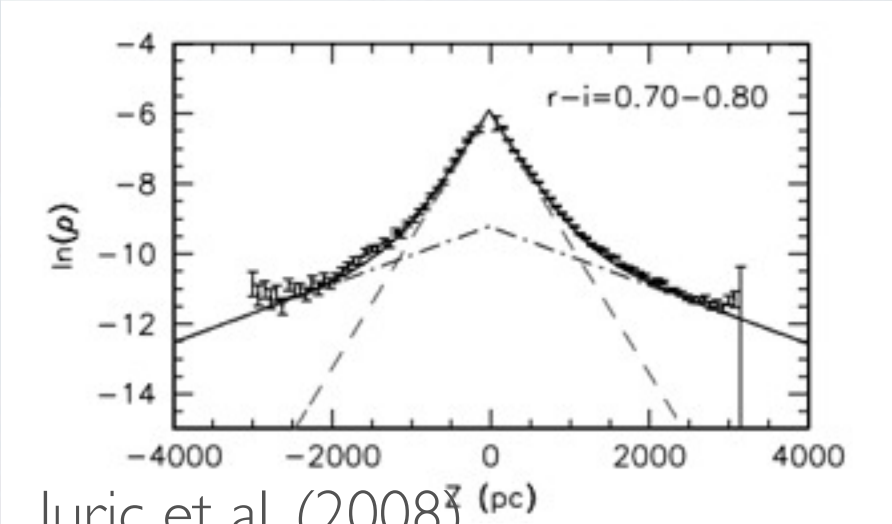
Roskar et al. (2008)

GALACTIC PARAMETERS

- Circular velocity curve V_c (R): flat? To what degree?
- V_c (R_0): 220 km/s or 250 km/s? (IAU versus radio astronomy)
- Sun's phase-space position: R_0, $V_{\varphi,\odot}$, $V_{R,\odot}$
- Total mass of the Milky Way: $<$ or $>$ 10^{12} $M_\odot$?
- What kind of galaxy do we simulate to match the Milky Way?

GALACTIC STRUCTURE

- Thin disk scale length and height:
  $h_Z \approx 200$ to 400 pc
  $h_R \approx 2$ to 4 kpc
- Same for all populations? Mass-weighted?
- "Thick disk": scale height / scale length?
- What is the relation between the "structural thick disk" and the "chemical thick disk"?



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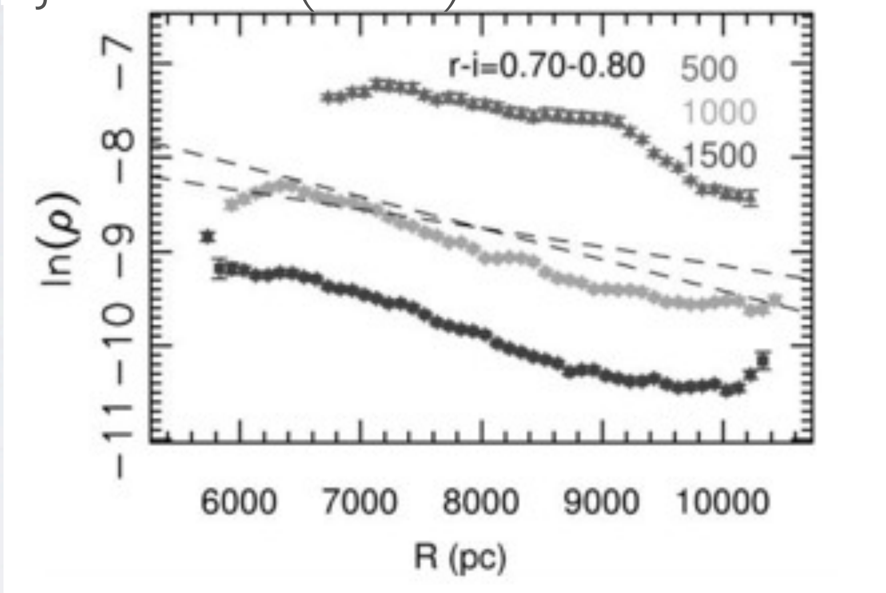
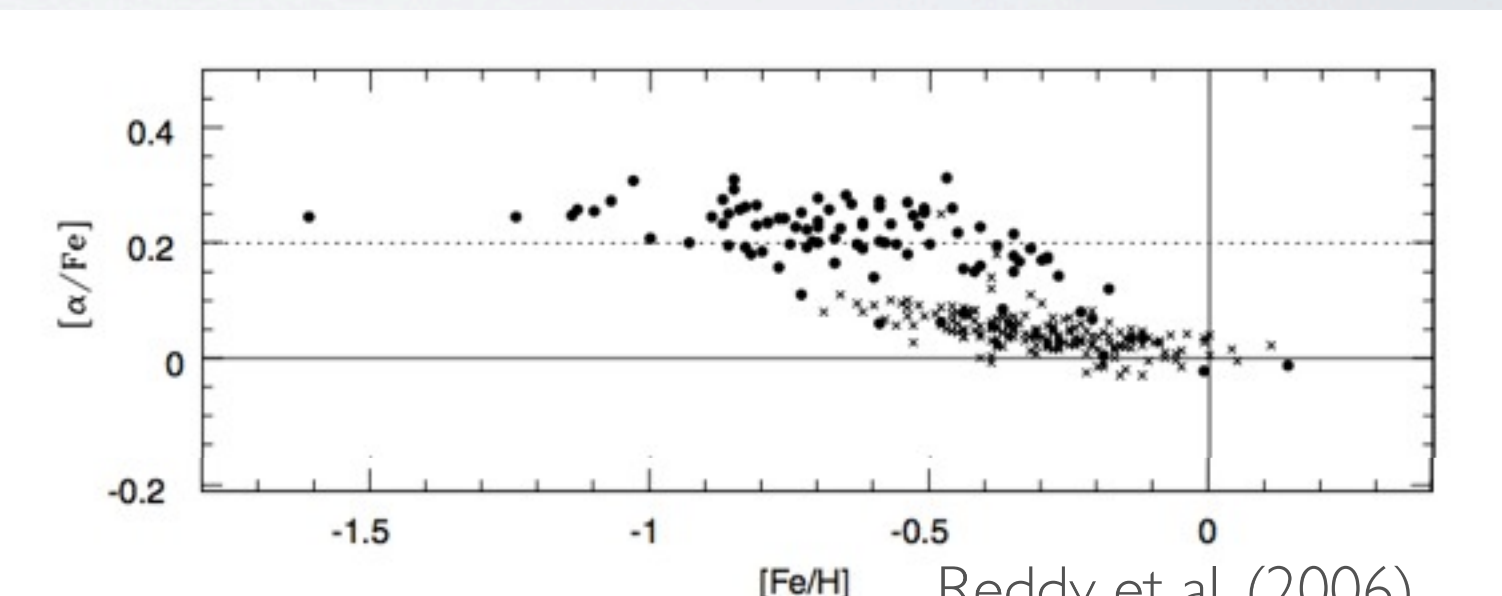




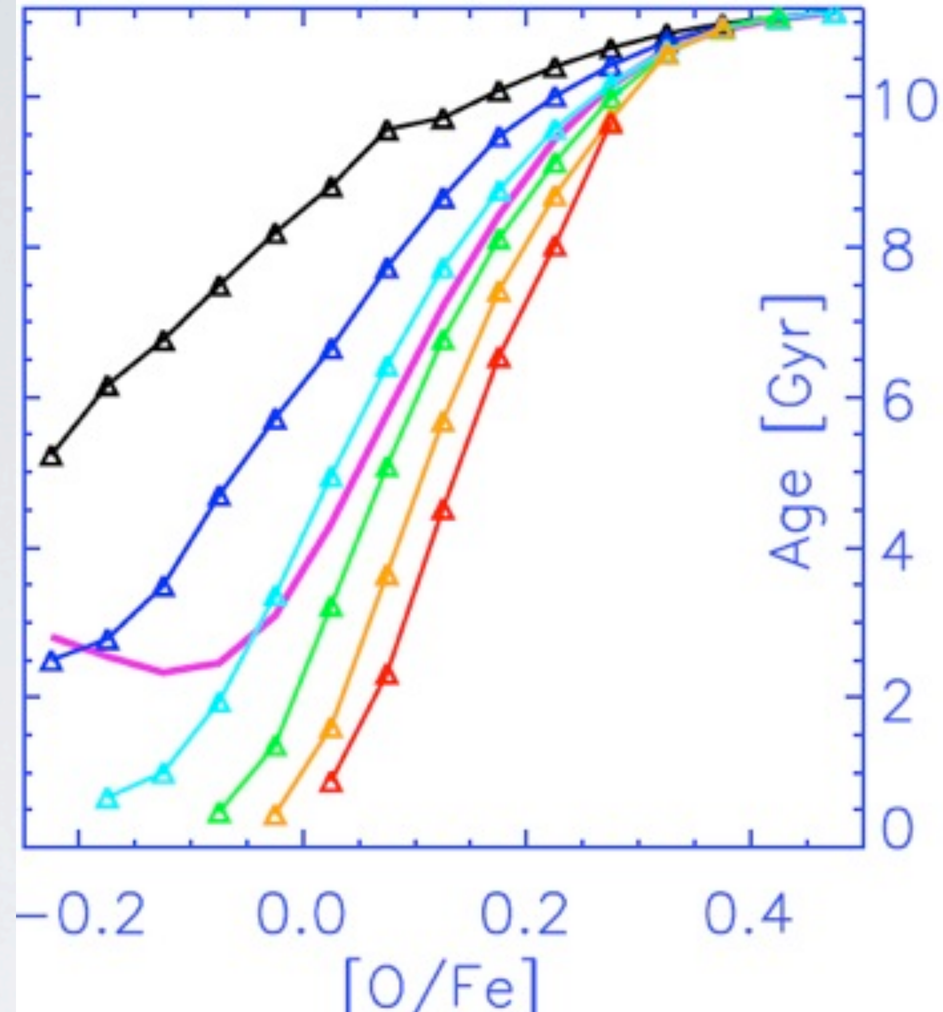
Reddy et al. (2006)

‘TAGGING’ DISK POPULATIONS

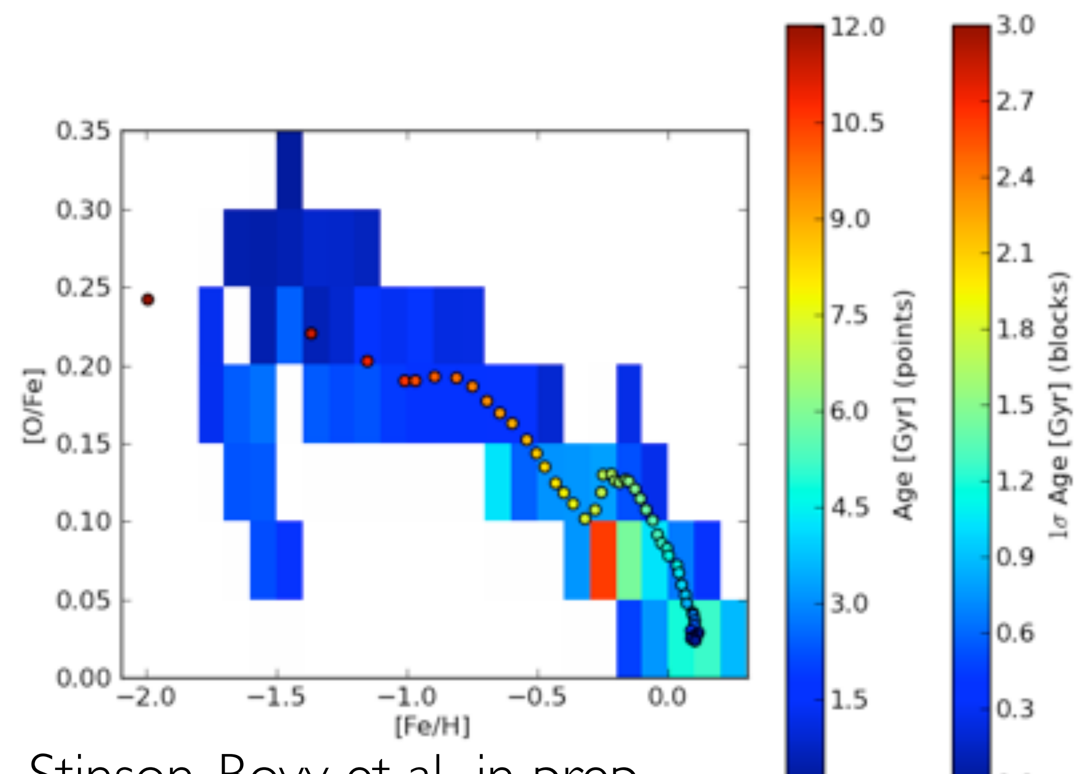
- Clear that position is bad tag:
  - function of evolution
  - large overlap between components
- Velocities: similarly problematic
- Elemental abundances ([Fe/H], [α/Fe],...):
  - constant over lifetime of star
  - requires chemical-evolution models for interpretation, but basic interpretation robust:
    - with time, evolution toward more ‘Solar’ abundances

'ABUNDANCE' AGES

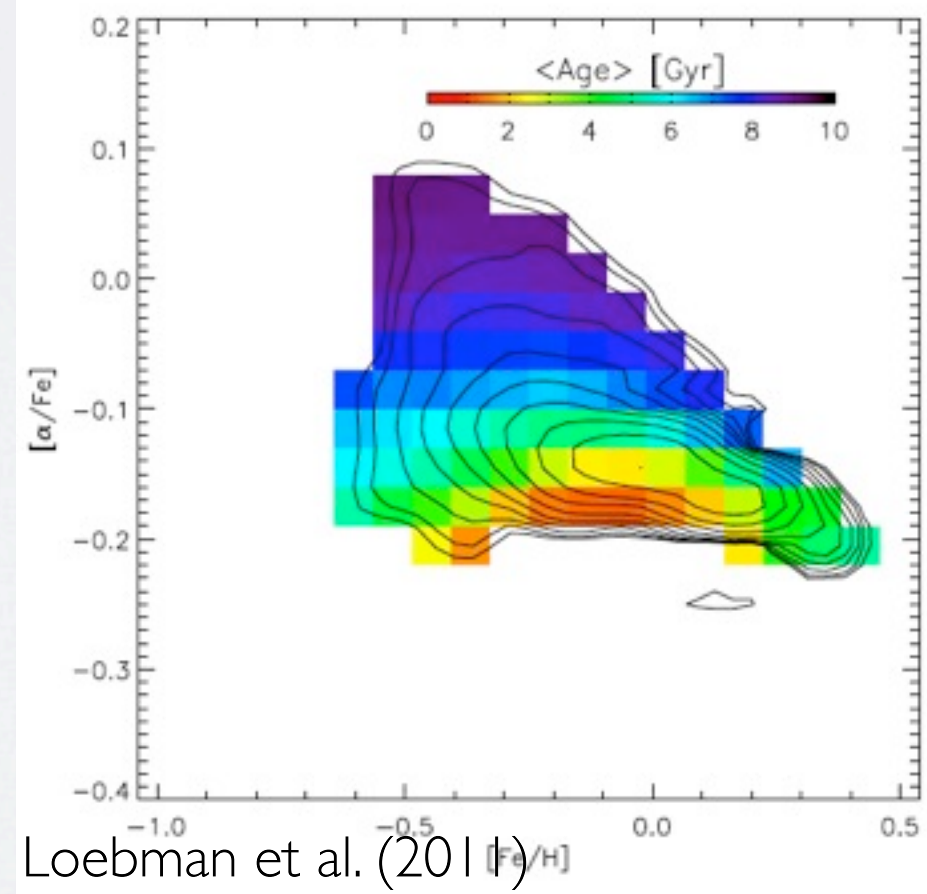
- Expect [α/Fe] to be relative age indicator
- Makes sense, but not much observational support
- Tests in near future (*APOGEE/ Kepler*)



Minchev, Chiappini, & Martig (2012)



Stinson, Bovy, et al., in prep.



Loebman et al. (2011)

$$f(\vec{x}, \vec{v} | [\mathrm{Fe/H}], [\alpha/\mathrm{Fe}])$$

$$f(\vec{x}|[\mathrm{Fe/H}], [\alpha/\mathrm{Fe}])$$

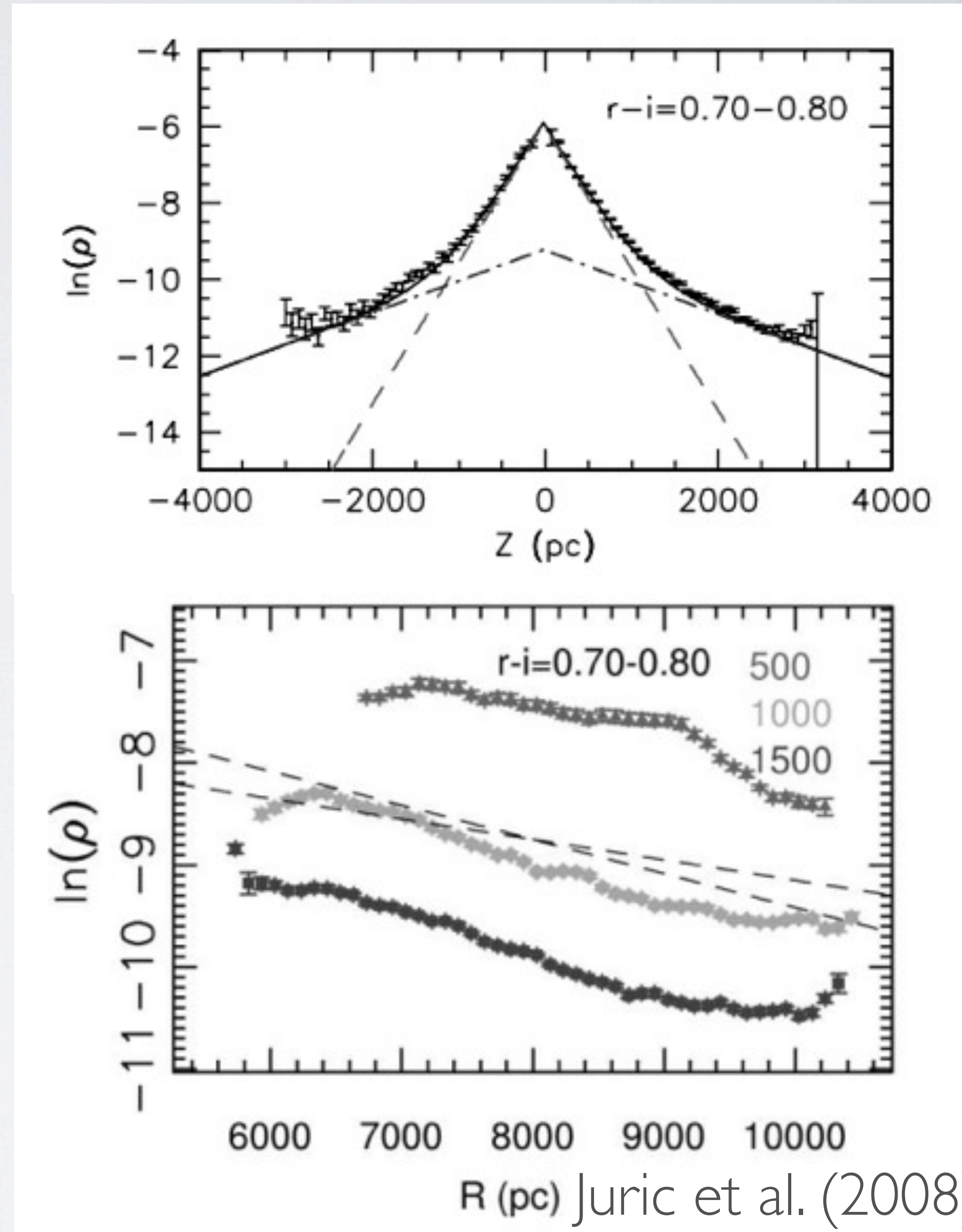
GEOMETRIC THICK–THIN DECOMPOSITIONS

- 2 component fits

- thin disk
  $h_Z \approx$ 300 pc
  $h_R \approx$ 2.5 kpc

- thick disk
  $h_Z \approx$ 900 pc
  $h_R \approx$ 3.5 kpc

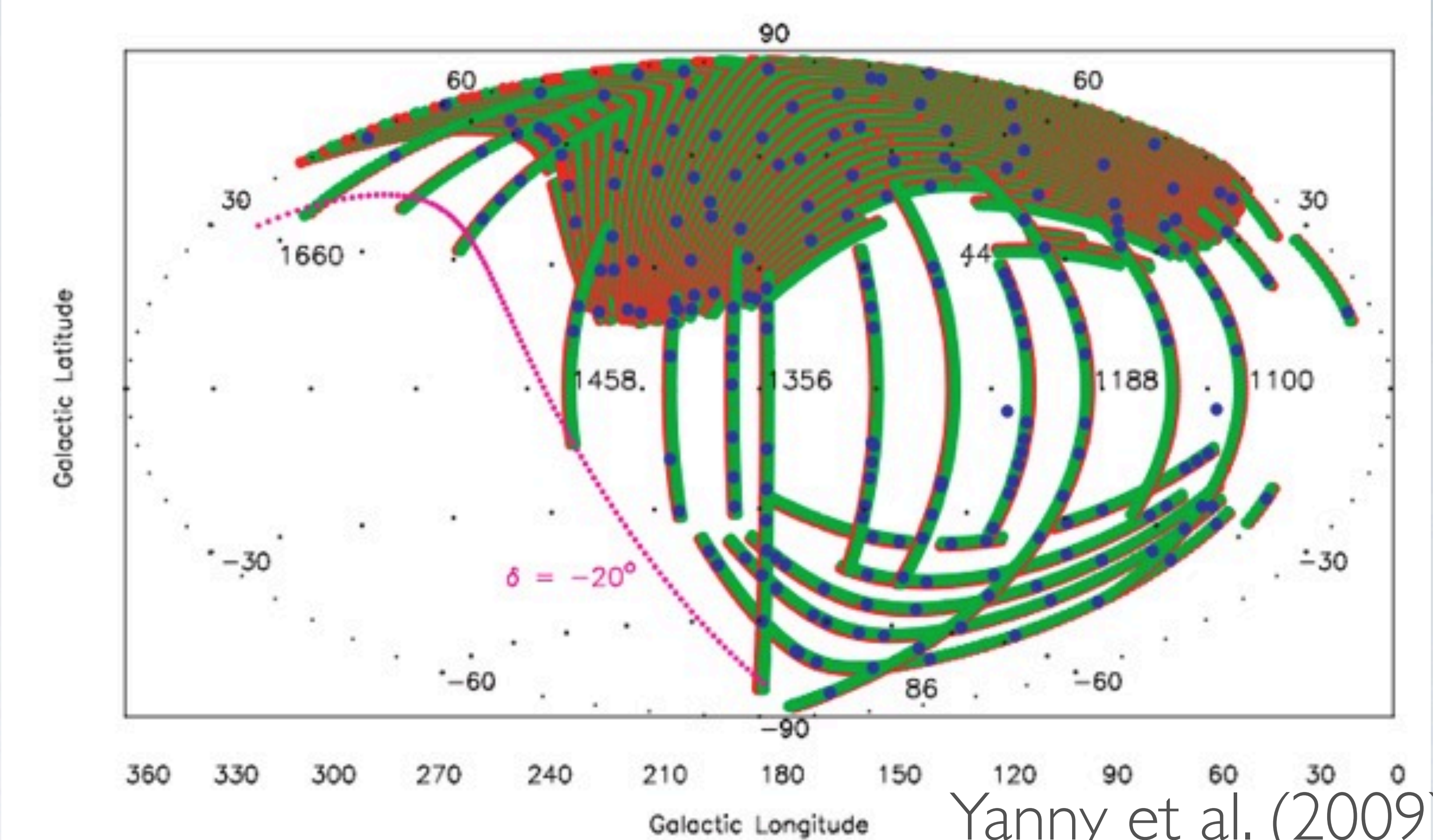
- similar in external galaxies



Juric et al. (2008)

SEGUE

- spectra for 240,000 stars
- R ≈ 1800
- 14 < r < 20

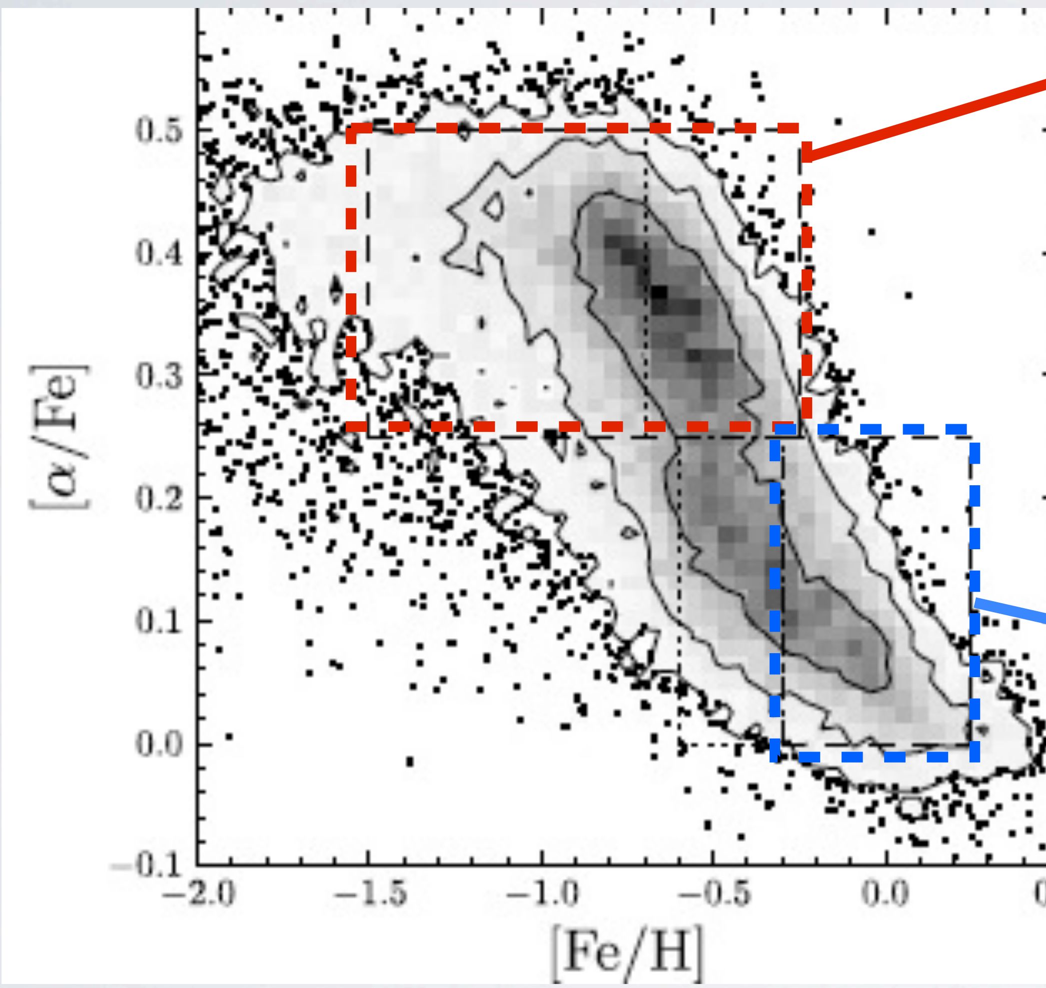


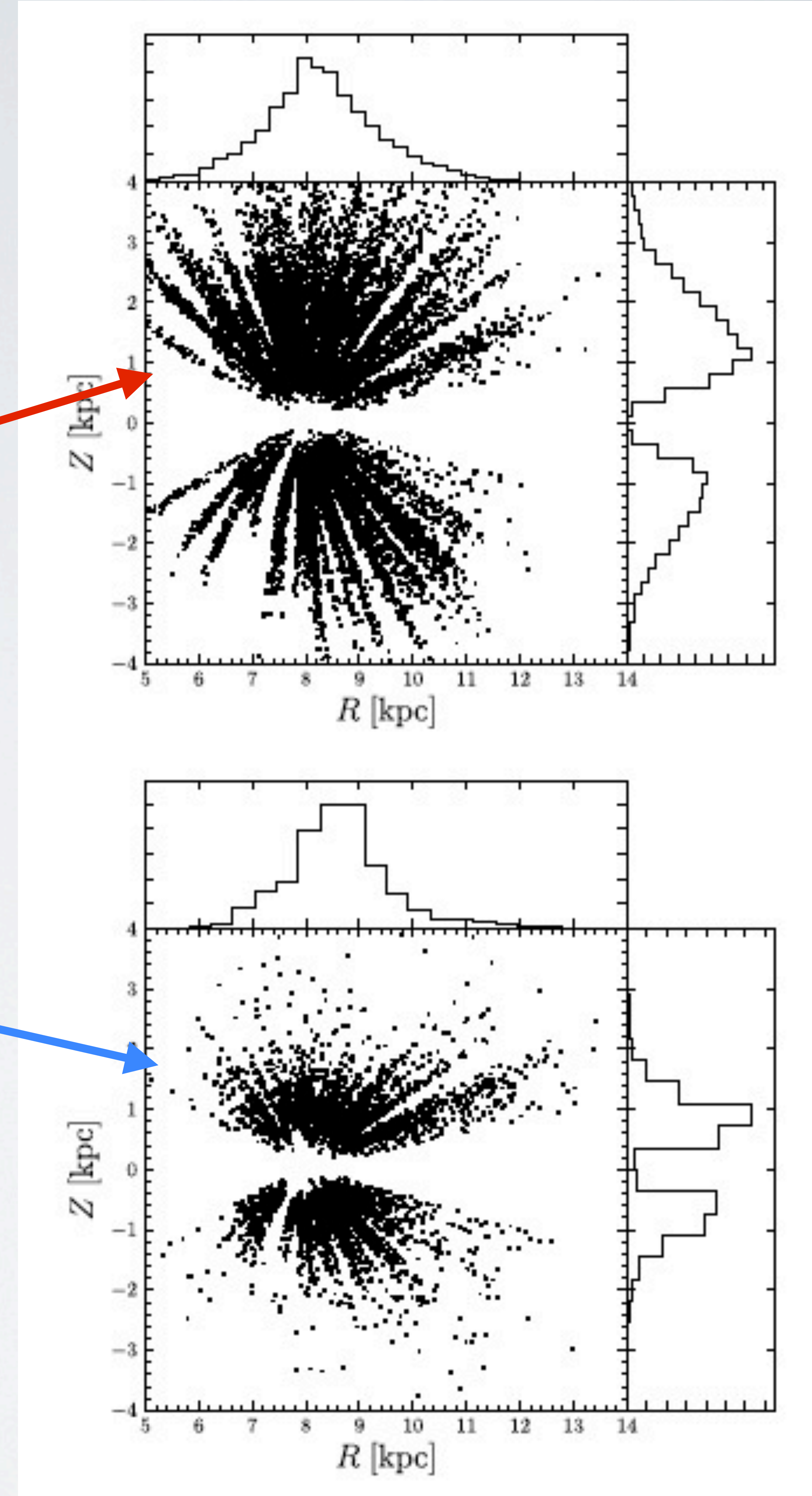
Yanny et al. (2009)

- T_{eff}, log g, [Fe/H] (±0.15 dex), [α/Fe] (±0.1 dex)
- photometric distances ≈ 10%
- δv_{los} ≈ 7 km/s, $\delta\mu$ ≈ 3.5 mas/yr ≈ 12 km/s
- *relatively* simple selection

SEGUE G STARS

- G dwarf sample: $0.48 \leq g\text{-}r \leq 0.55$, $14.5 \leq r \leq 20.2$, $\log g > 4.2$, SN > 15, —*30,000 stars*

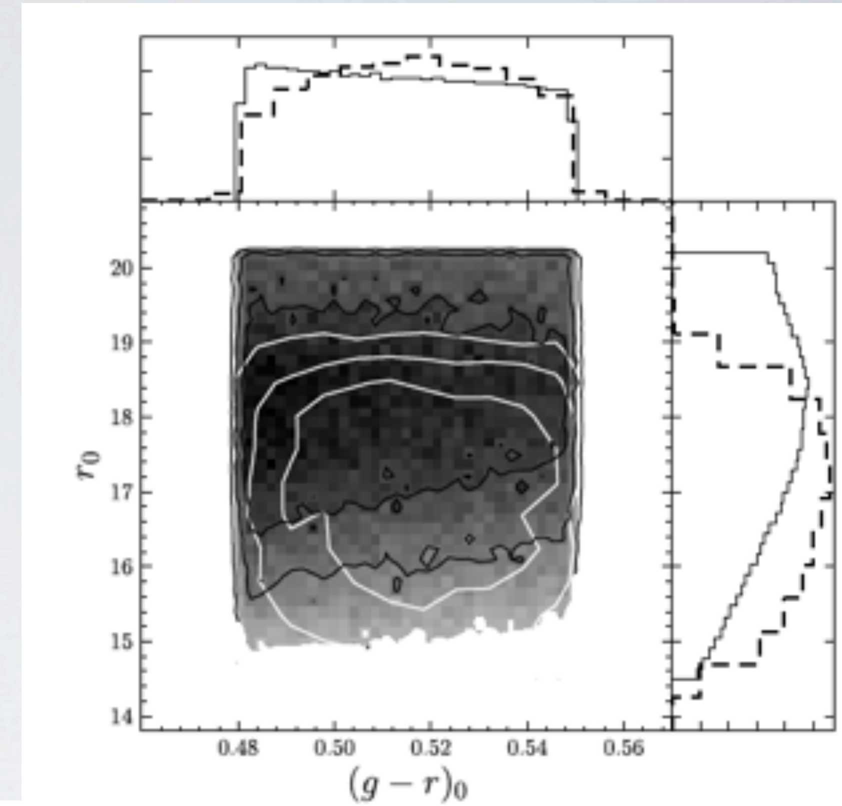


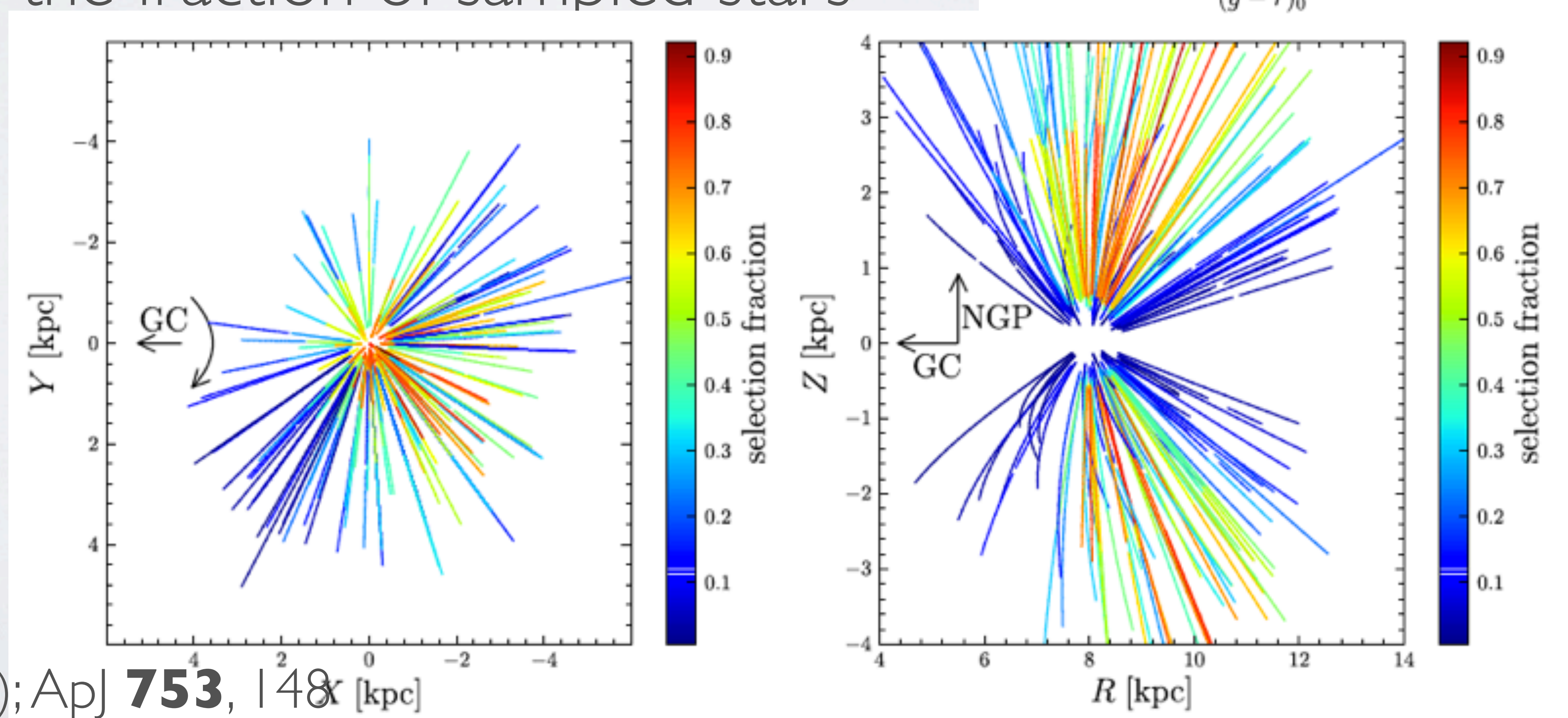


Bovy et al. (2012b); ApJ **753**, 148

SEGUE SELECTION FUNCTION

- SEGUE samples each line-of-sight uniformly down to r = 20.2 mag
- SN cut induces brighter cut-off
- for each plate we empirically determine the cut-off and the fraction of sampled stars





Bovy et al. (2012b); ApJ **753**, 148

LIKELIHOOD-BASED DENSITY FITS

- proper model is a *Poisson process*
- observed density of stars λ(l,b,d,r,g-r,[Fe/H]):

$$\lambda(l, b, d, r, g-r, [\mathrm{Fe/H}]) = \rho(r, g-r, [\mathrm{Fe/H}]|R, Z, \phi) \times \nu_*(R, Z, \phi) \times |J(R, Z, \phi; l, b, d)| \times S(\mathrm{plate}, r, g-r)$$

- log likelihood:

$$\ln \mathcal{L} = \sum_i \{\ln \lambda(\{l, b, d, r, g-r, [\mathrm{Fe/H}]\}_i|\theta)\} - \int \mathrm{d}l\, \mathrm{d}b\, \mathrm{d}d\, \mathrm{d}r\, \mathrm{d}(g-r)\, \mathrm{d}[\mathrm{Fe/H}]\, \lambda(l, b, d, r, g-r, [\mathrm{Fe/H}]|\theta)$$

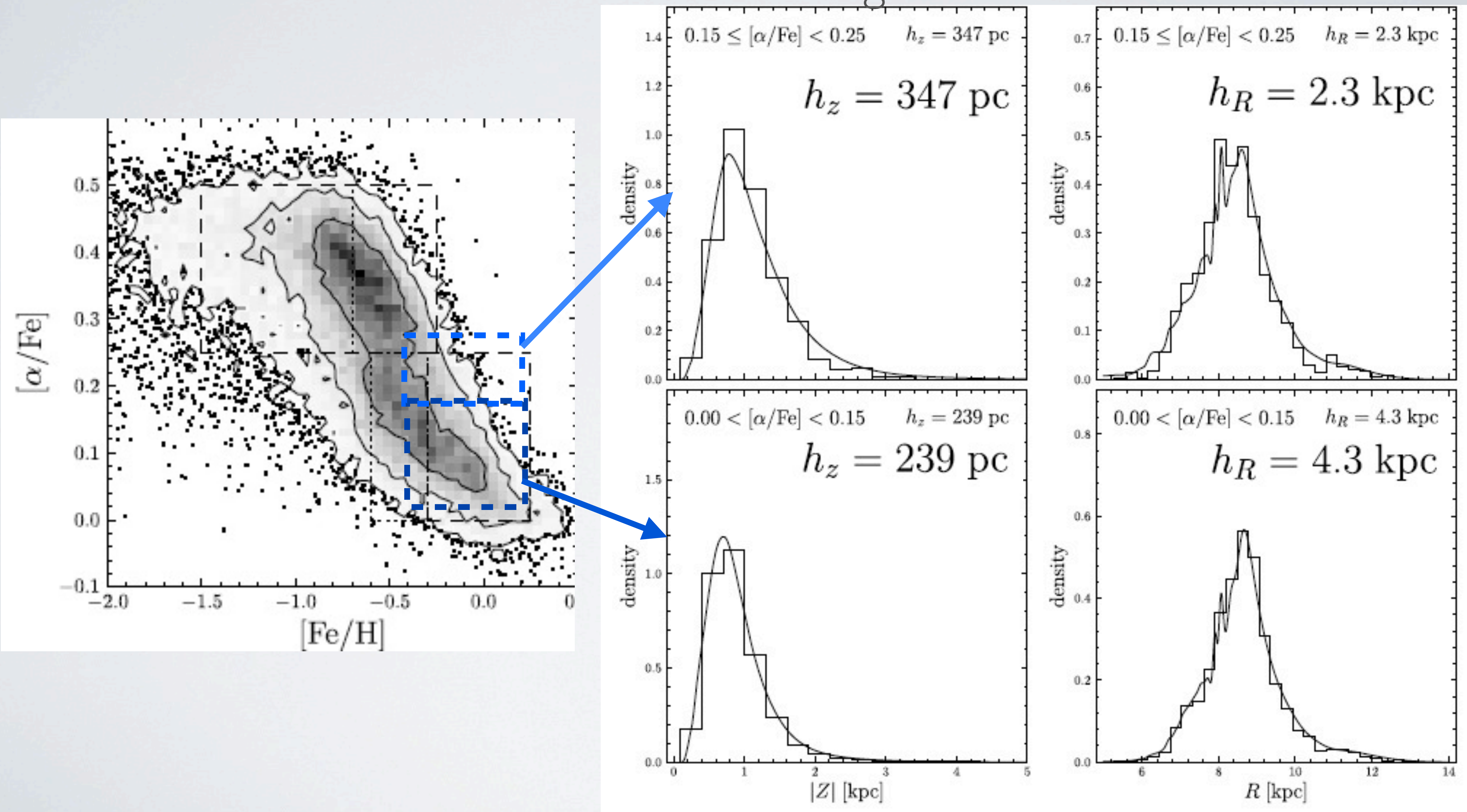
- marginalize over amplitude:

$$\ln\mathcal{L} = \sum_i \left\{\ln \nu_*(R, z|\{l, b, d\}_i, \theta) - \ln \int \mathrm{d}l\, \mathrm{d}b\, \mathrm{d}d\, \mathrm{d}r\, \mathrm{d}(g-r)\, \mathrm{d}[\mathrm{Fe/H}]\, \lambda(l, b, d, r, g-r, [\mathrm{Fe/H}]|\theta)\right\}$$

Bovy et al. (2012b); ApJ **753**, 148

BROAD BINS IN ABUNDANCE

Vertical height Galactocentric radius



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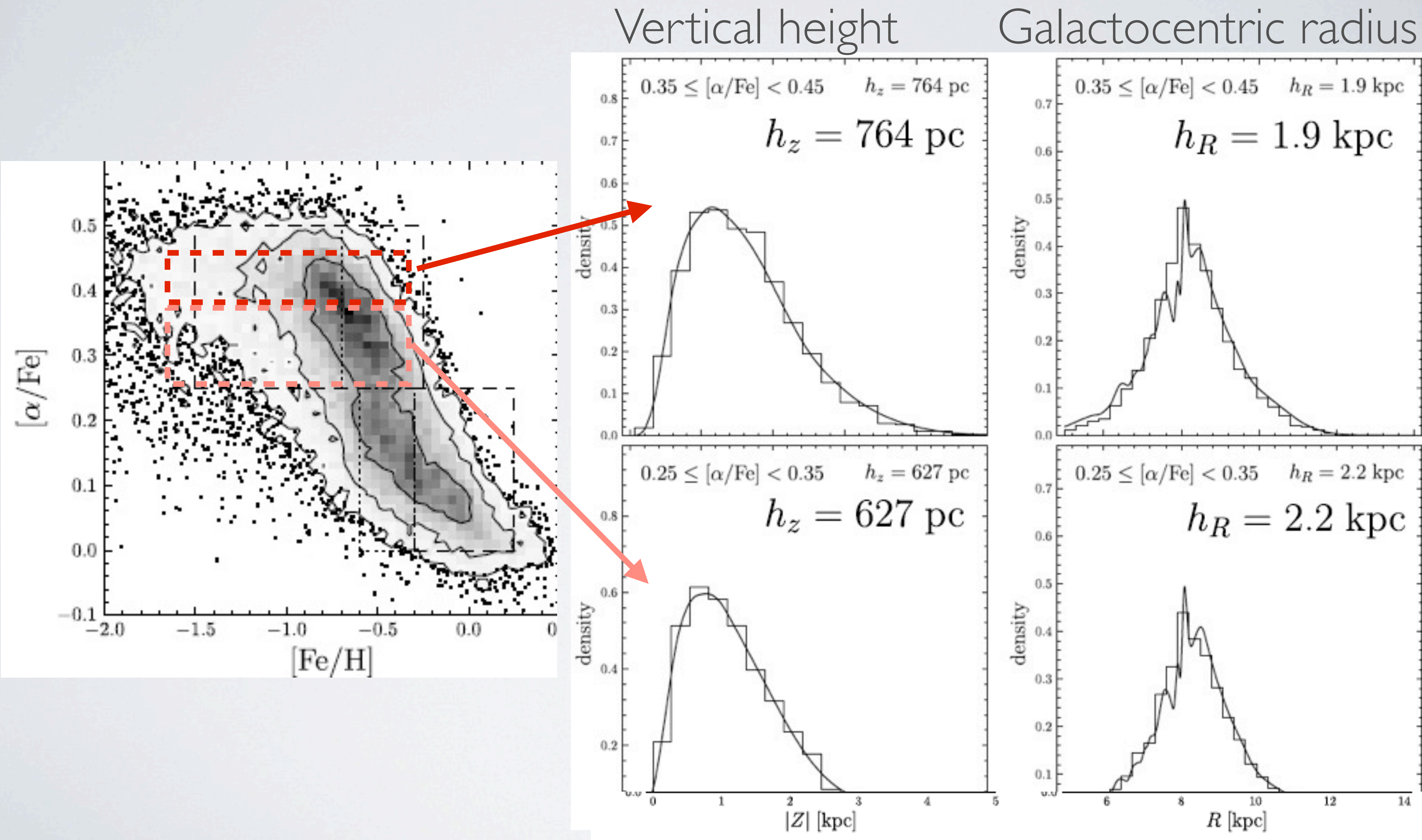
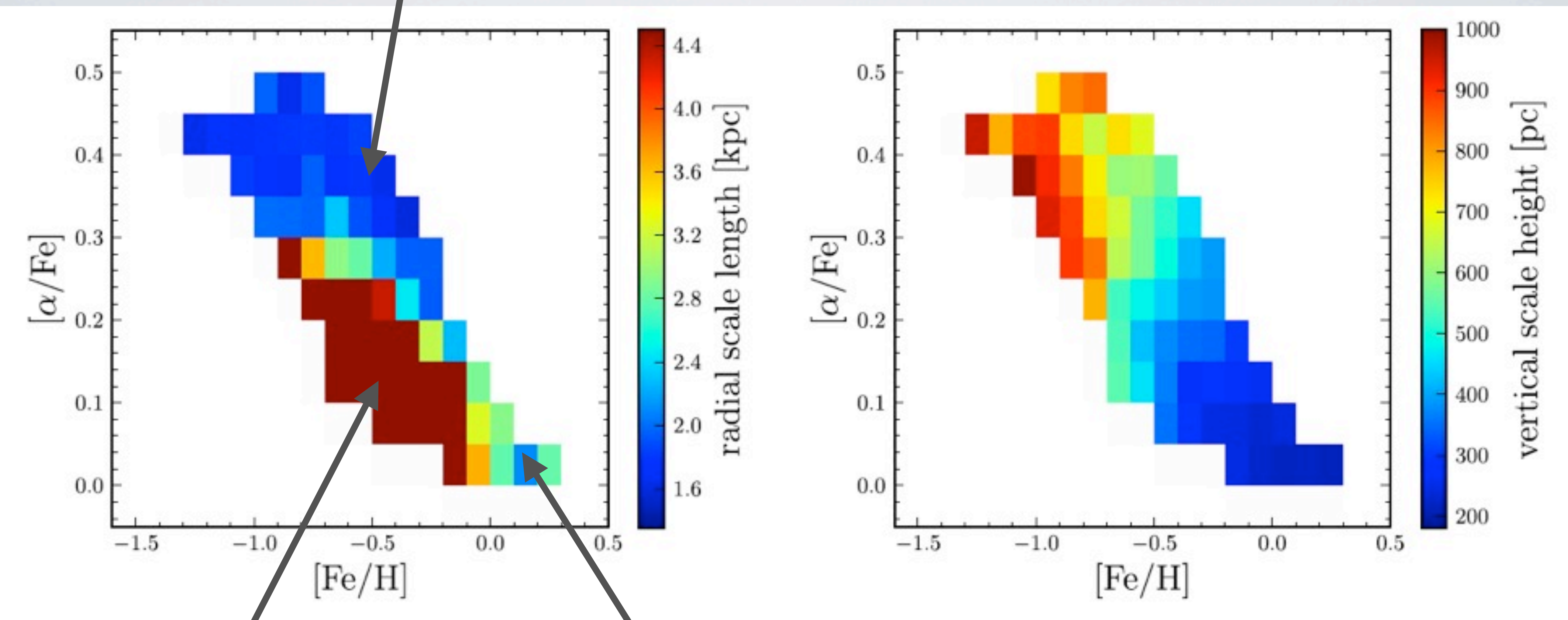


Bovy et al. (2012b); ApJ **753**, 148

ABUNDANCE-RESOLVED SPATIAL STRUCTURE

Short thick disk scale length

Smoothly increasing scale heights



Very long scale length

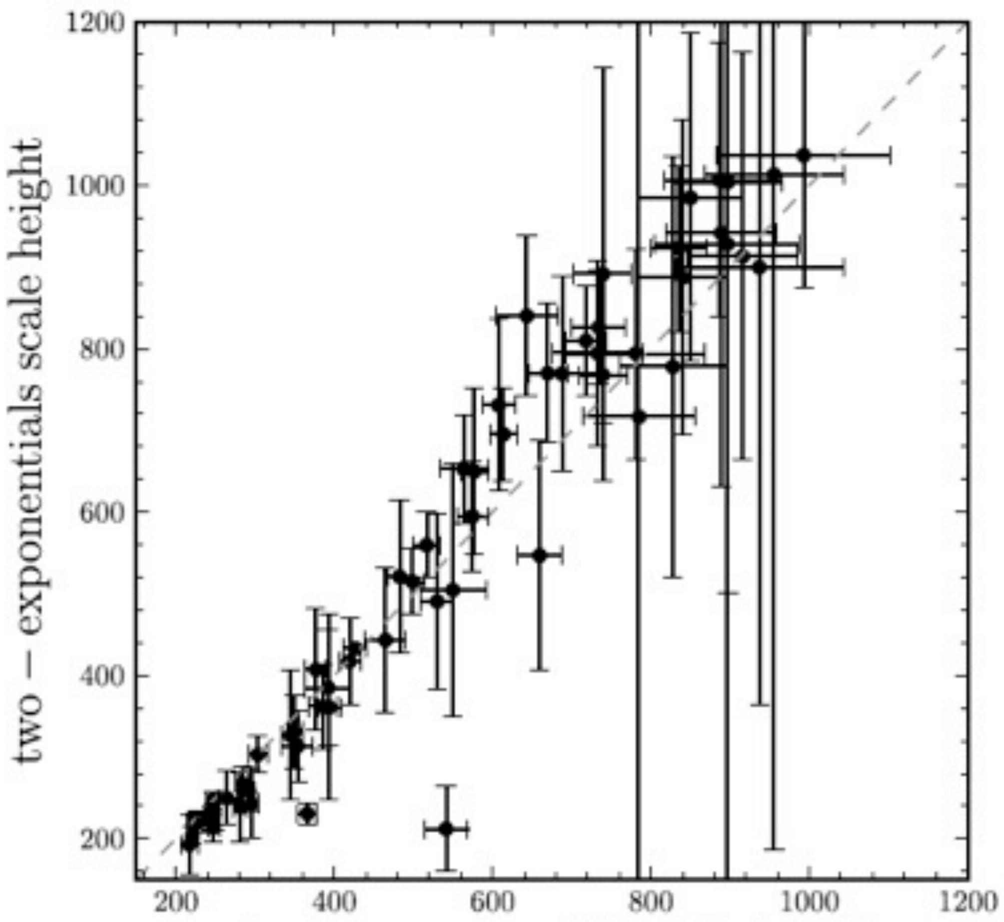
Longer thin disk scale length

Inside-out disk formation

Bovy et al. (2012b); ApJ **753**, 148

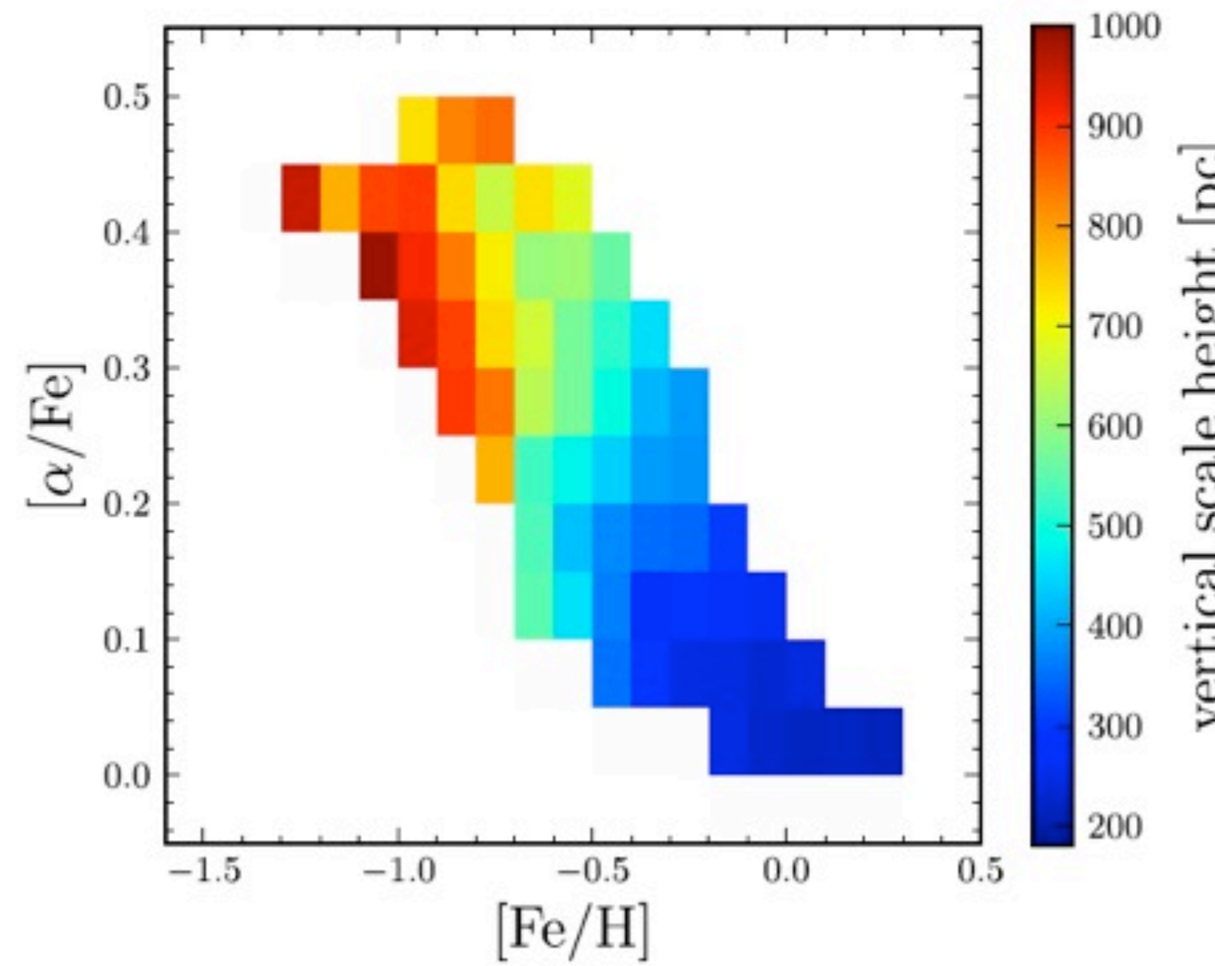
ABUNDANCE-RESOLVED SPATIAL STRUCTURE

two component fit scale height



one component fit scale height

Smoothly increasing scale heights



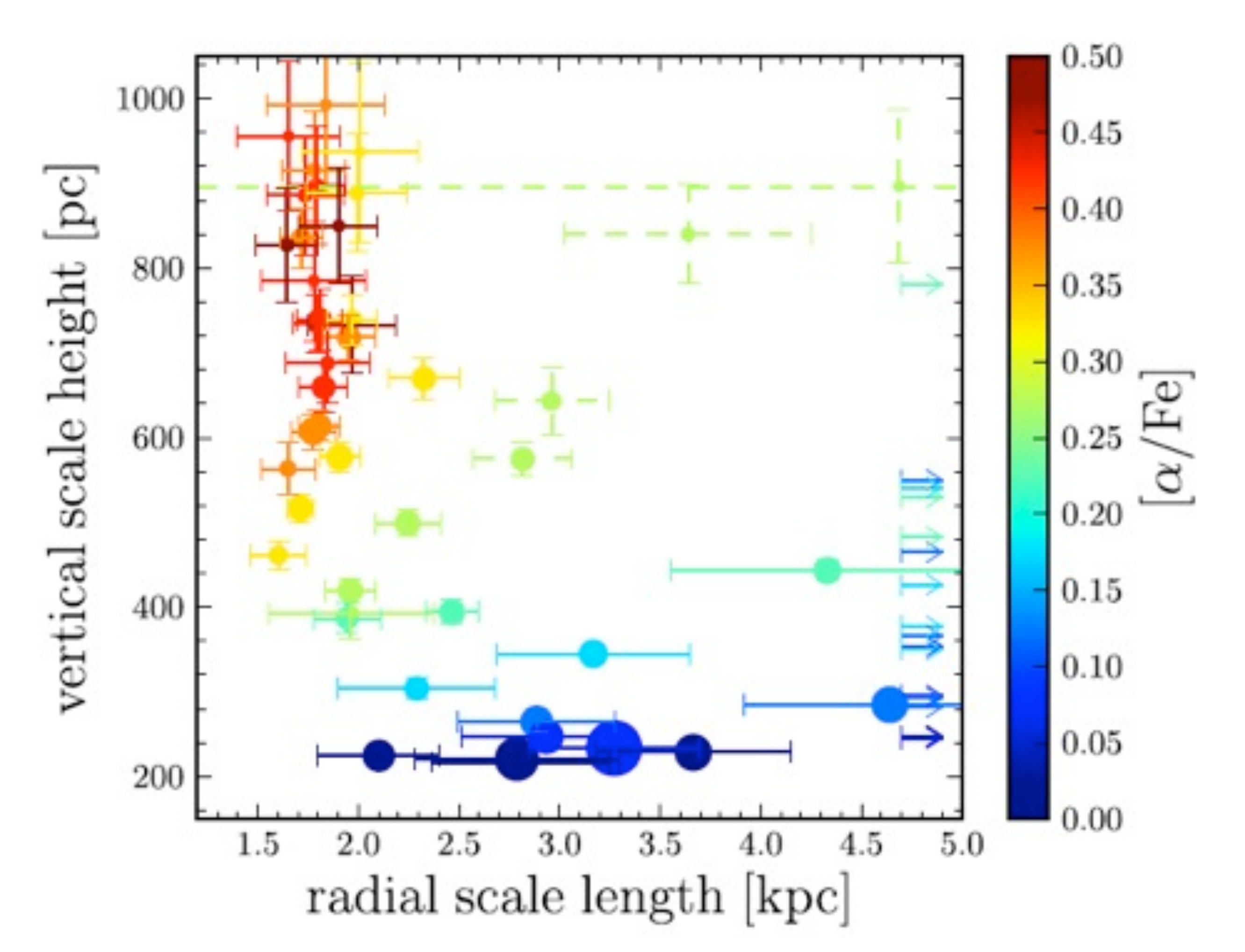
Each population best fit as a single exponential

Bovy et al. (2012b); ApJ **753**, 148

ABUNDANCE-RESOLVED SPATIAL STRUCTURE

Scale length and scale height are anti-correlated

Structure set both by [α/Fe] (~age) and [Fe/H] (~birth radius)



Smooth internal evolution

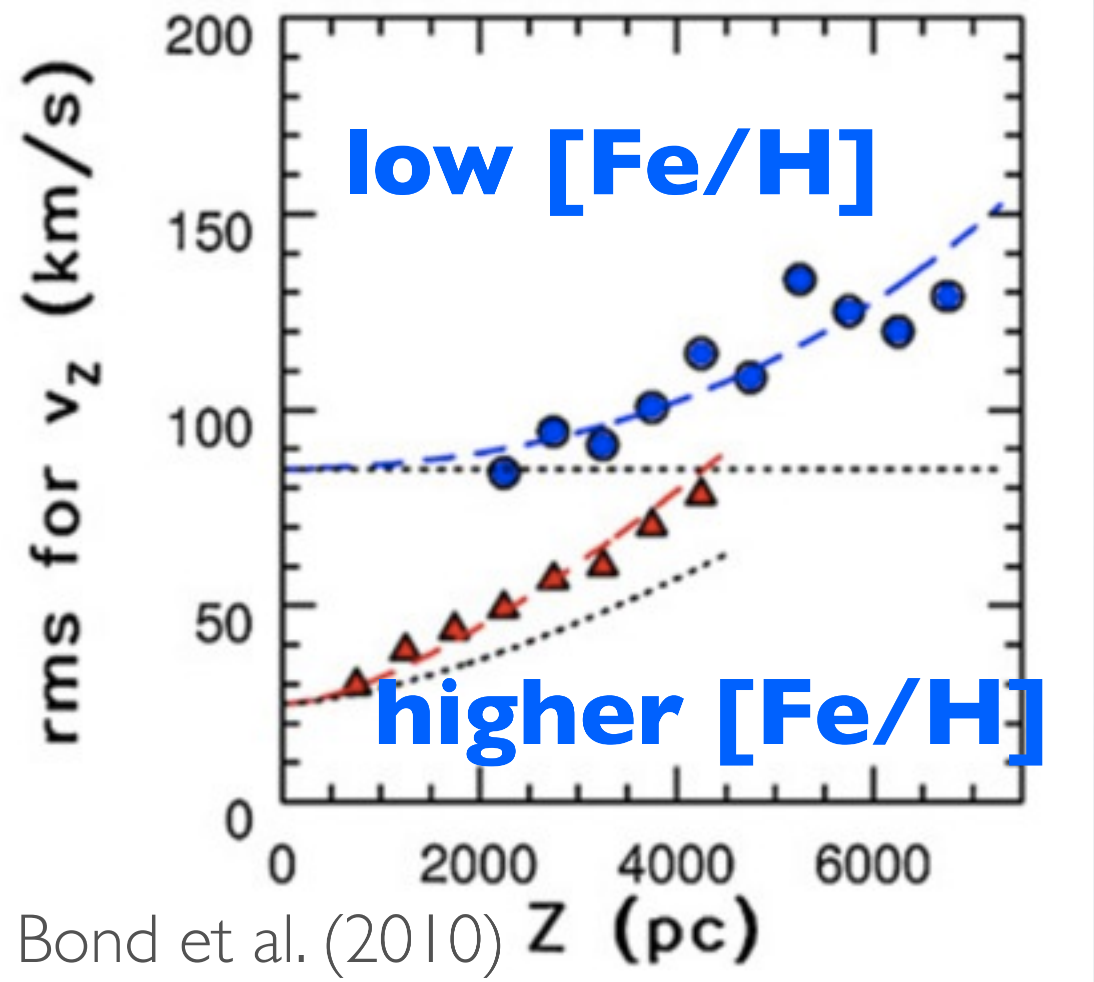
Bovy et al. (2012b); ApJ **753**, 148

$$f(\vec{v}|[\mathrm{Fe/H}], [\alpha/\mathrm{Fe}], \vec{x})$$

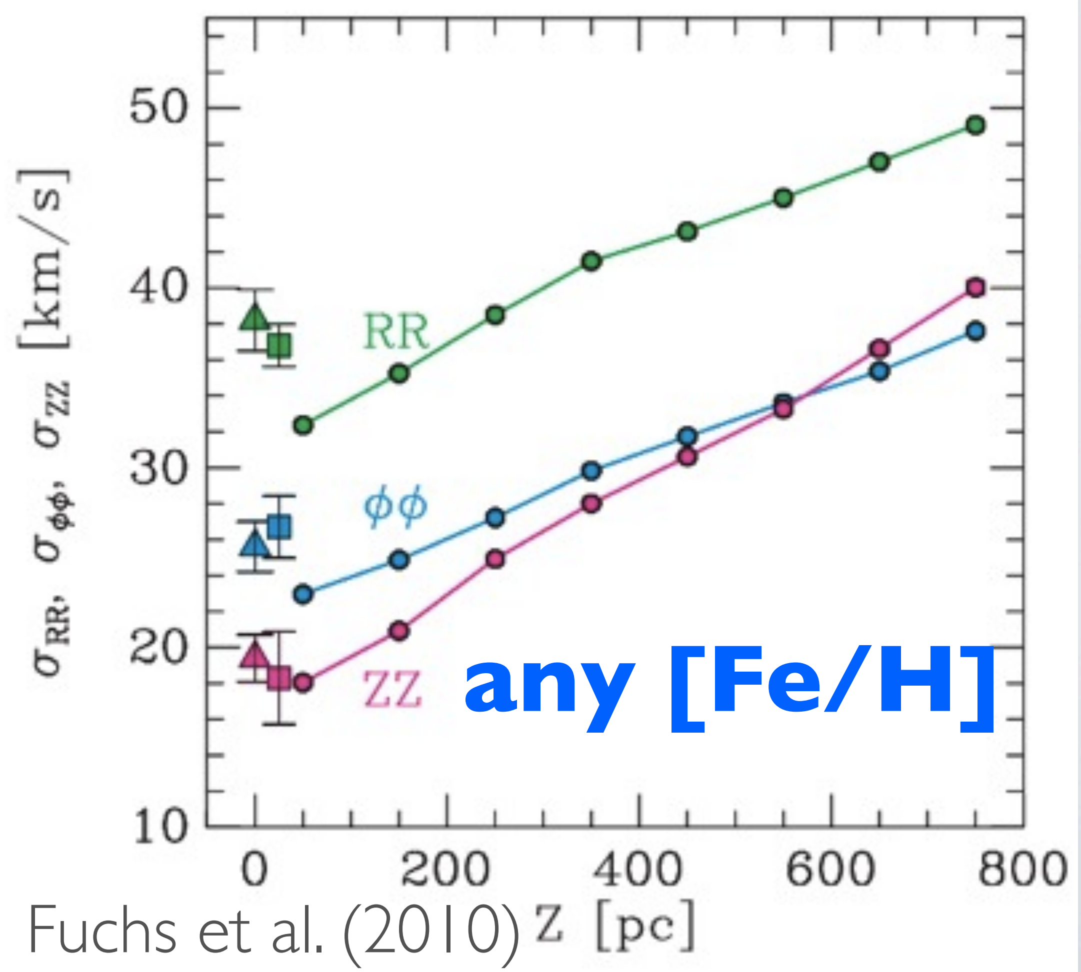
VERTICAL KINEMATICS

- Previous determinations find increasing vertical velocity dispersion with distance from the plane (e.g., Fuchs et al. 2009, Bond et al. 2010)

- Increase within component, or changes between components?

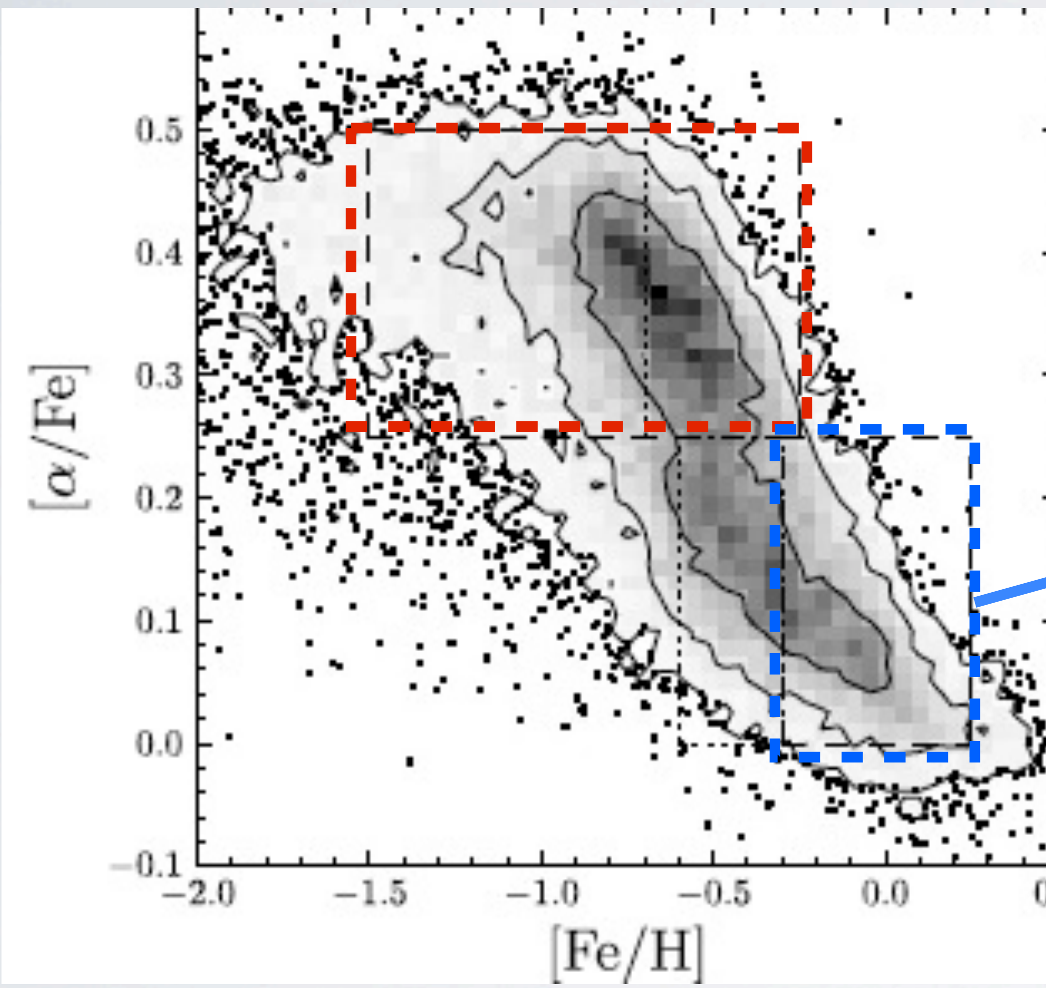


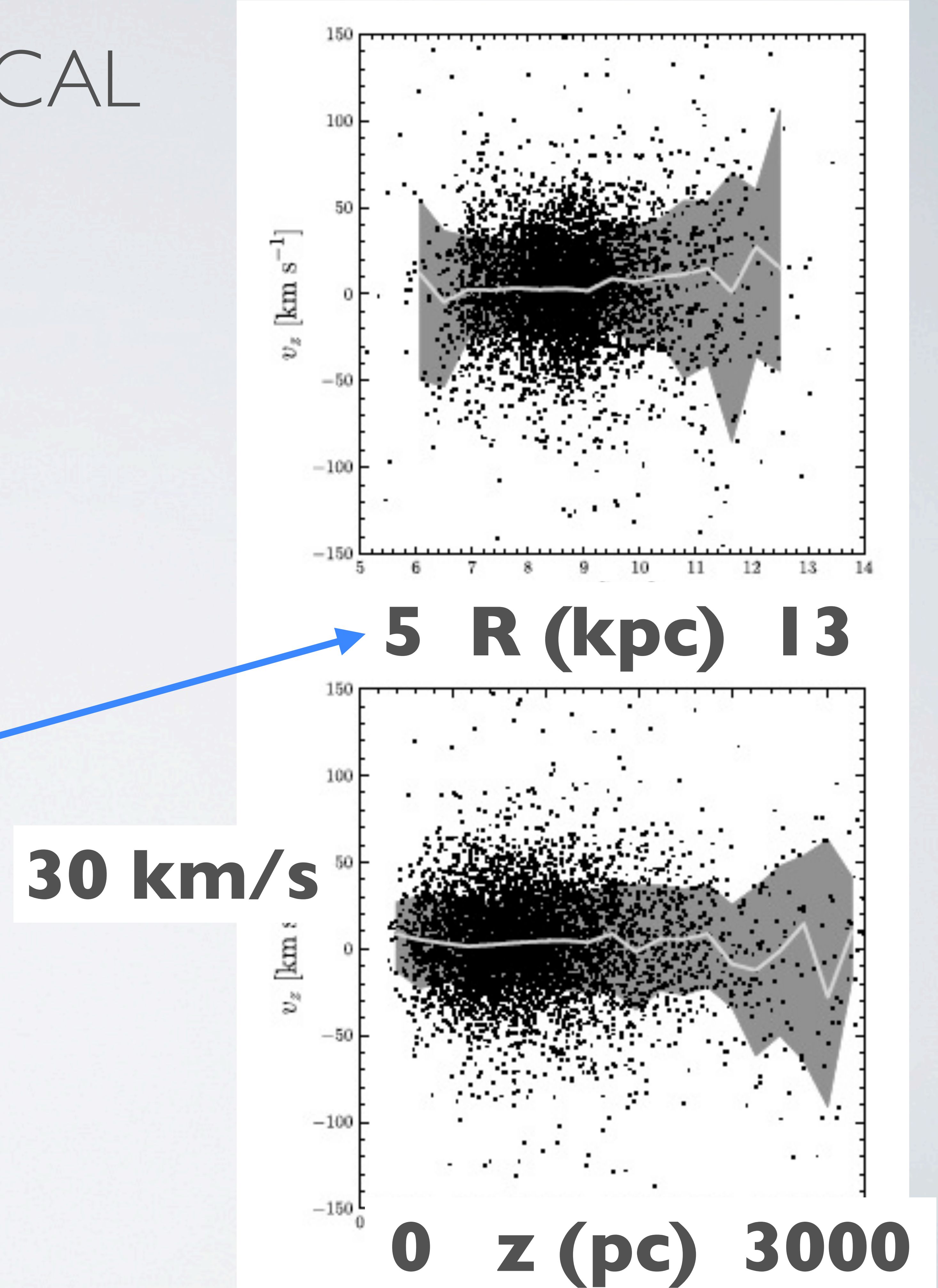
Bond et al. (2010)



Fuchs et al. (2010)

SEGUE G STARS: VERTICAL VELOCITIES





Bovy et al. (2012c); ApJ **755**, 115

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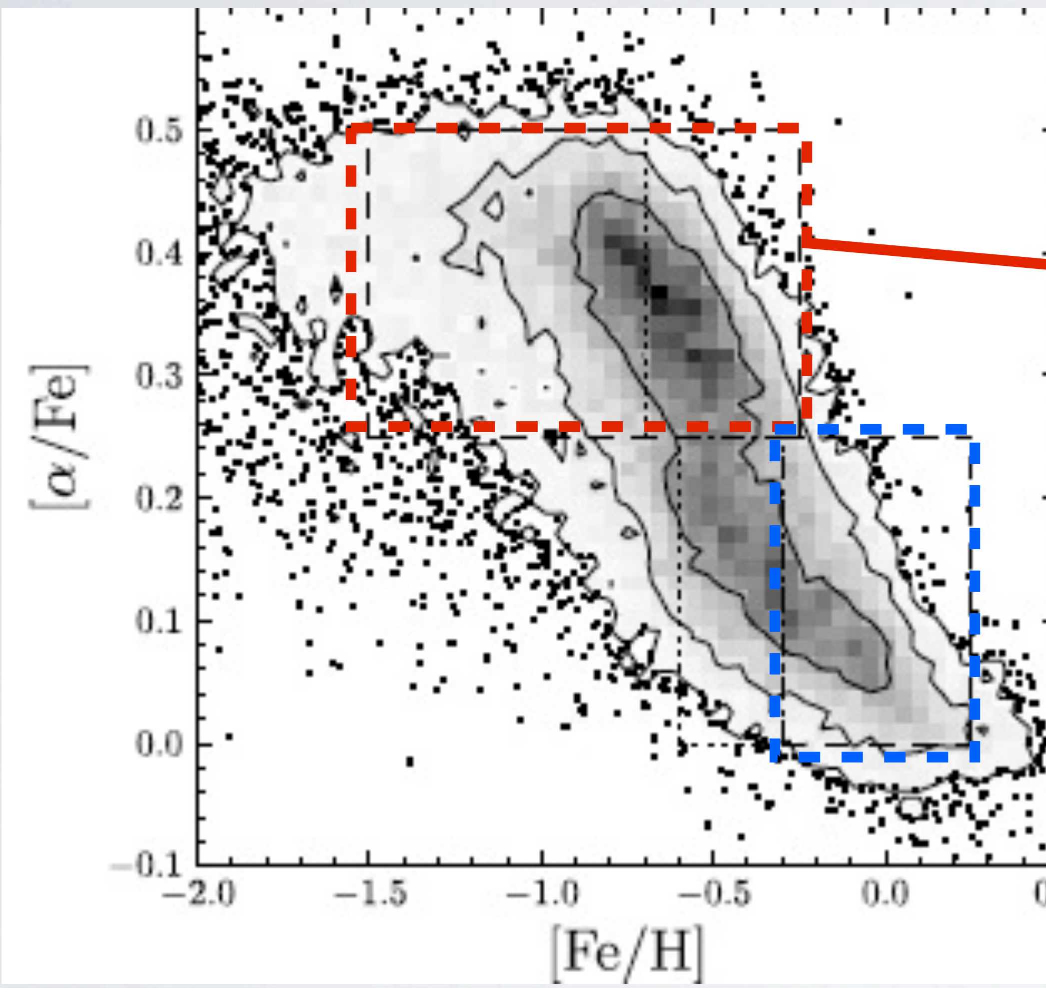
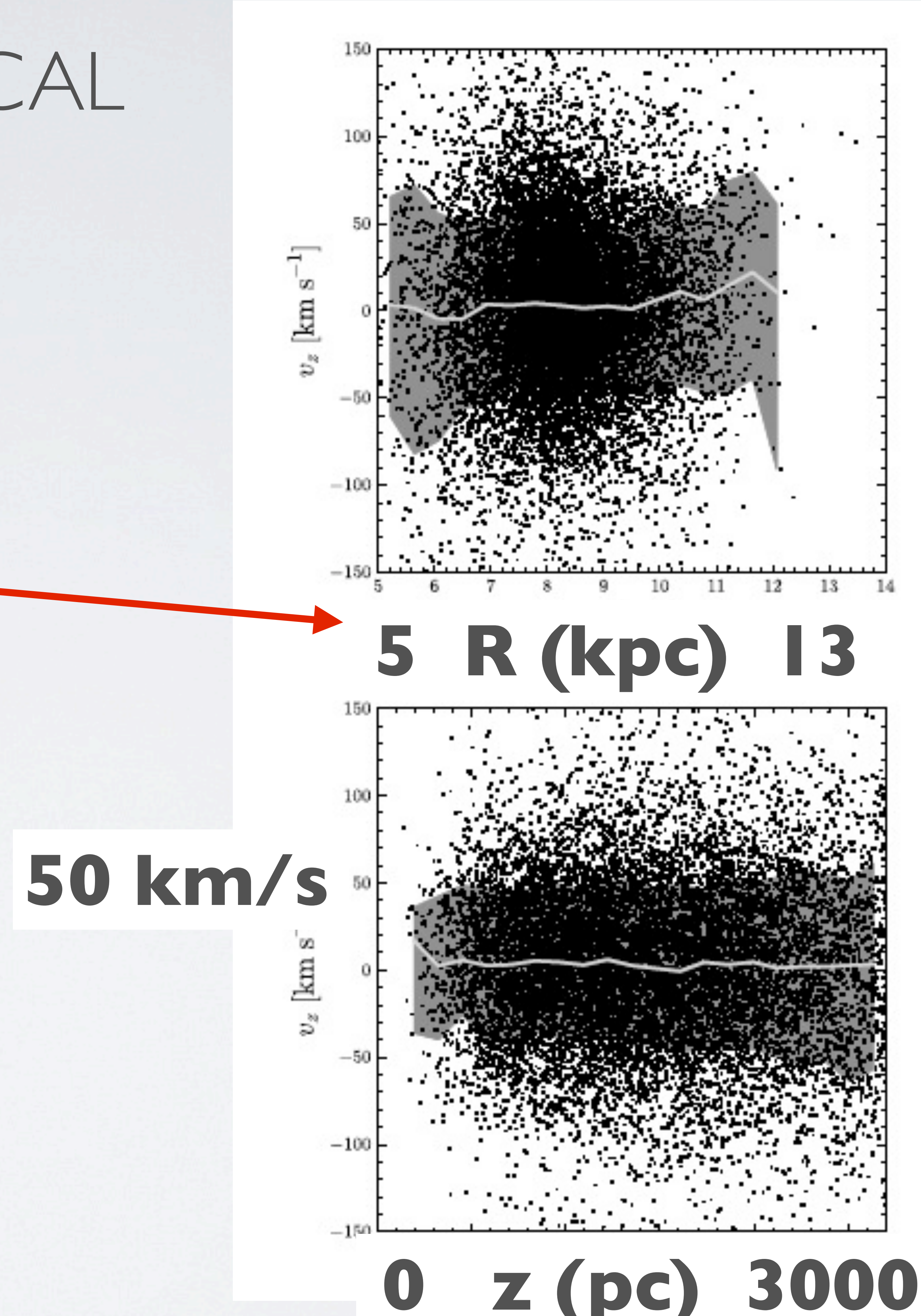




Bovy et al. (2012c); ApJ **755**, 115

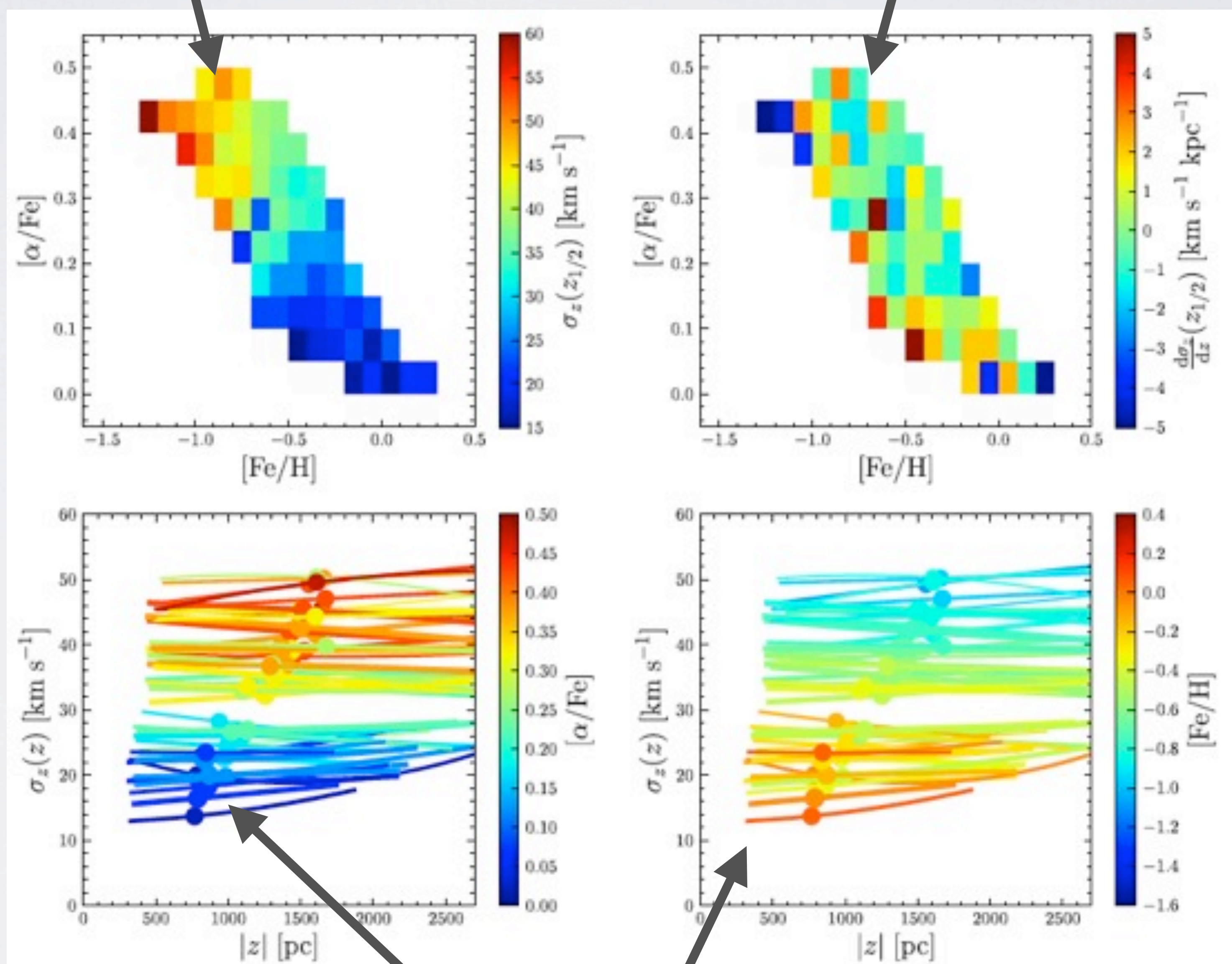
ABUNDANCE-RESOLVED VERTICAL KINEMATICS

$$\sigma_z(z,R) = (\sigma_z(0,R_0) + p_1 z + p_2 z^2)\,\exp\left(-\frac{R-R_0}{h_\sigma}\right)$$

Vertical dispersion

p1: slope

Smoothly increasing dispersion



Approximately isothermal

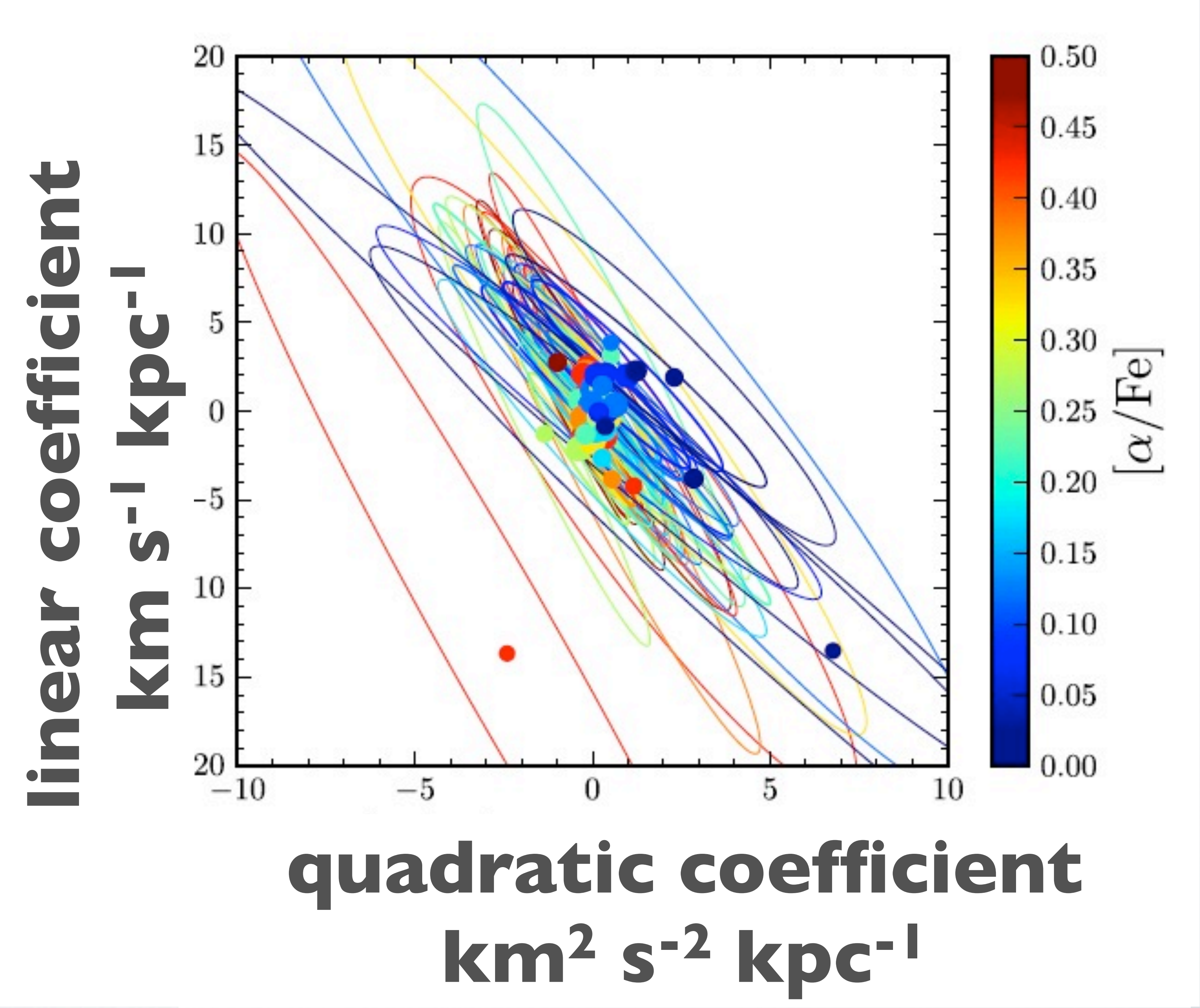
[α/Fe] (age) sets dispersion

Vertical dispersion profile

Bovy et al. (2012c); ApJ **755**, 115

ABUNDANCE-RESOLVED VERTICAL KINEMATICS: ISOTHERMALITY

- slope < 1 km/s/kpc
- mono-abundance populations consistent with isothermal over multiple kpc



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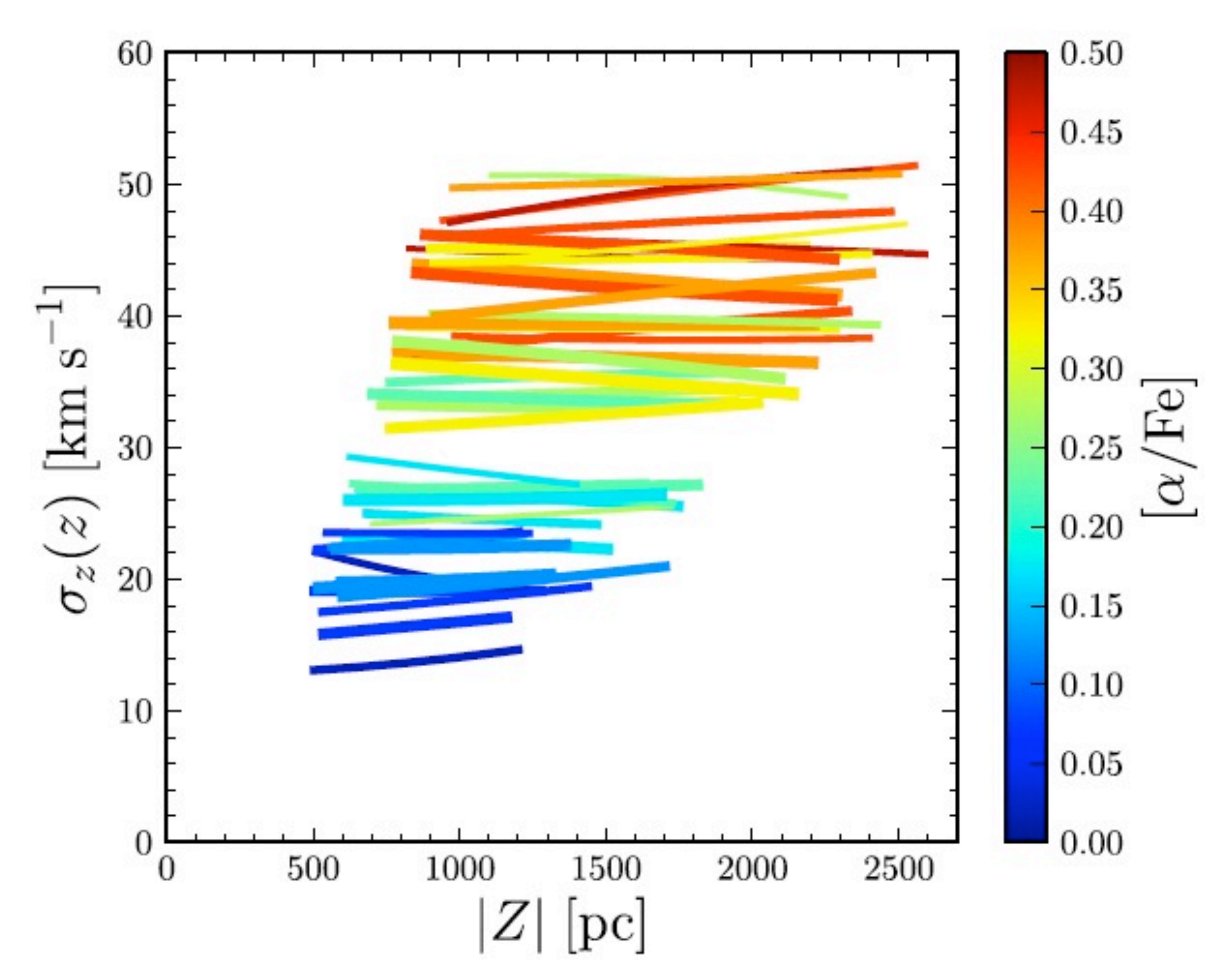


Bovy et al. (2012c); ApJ **755**, 115

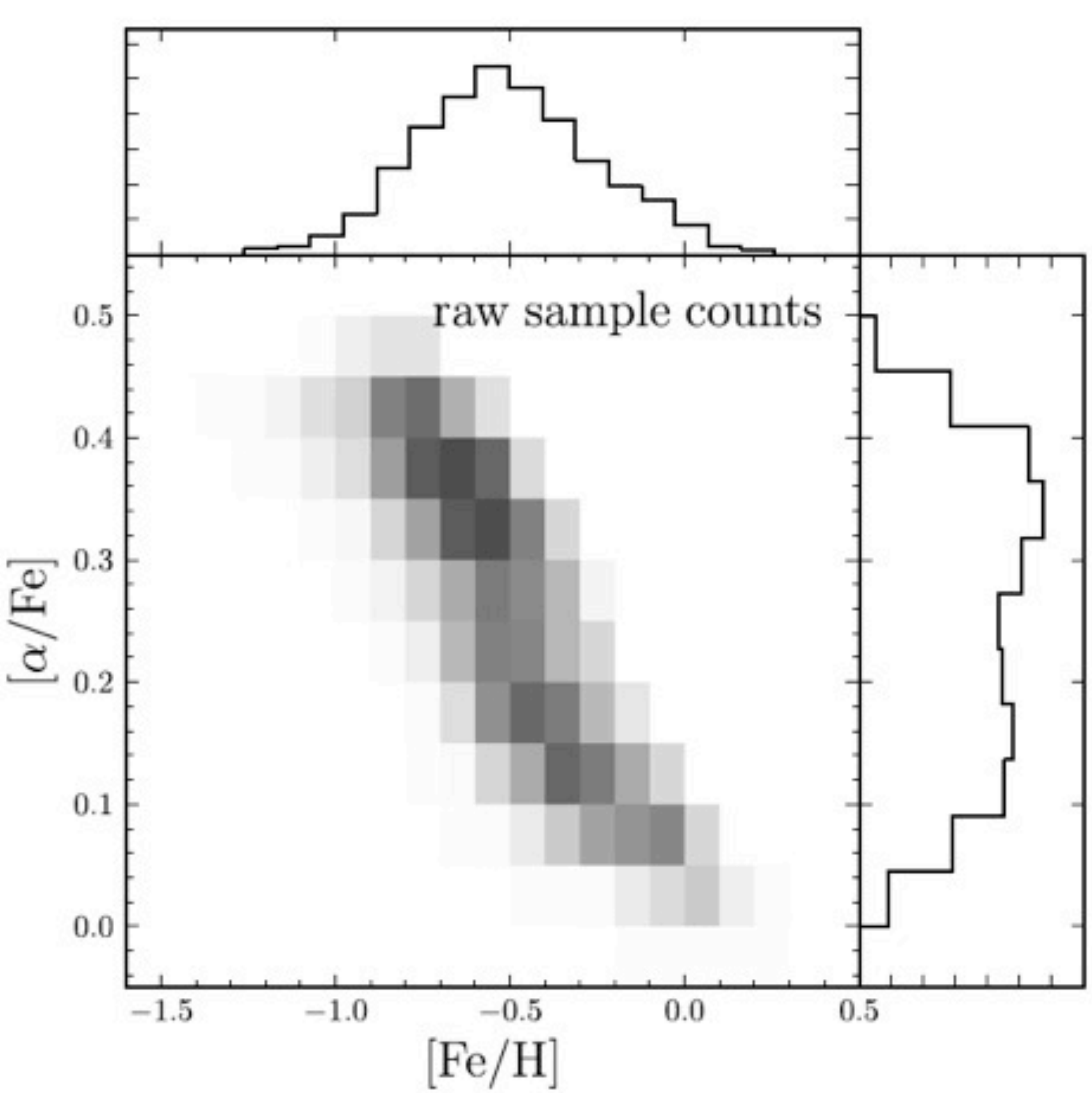
DOES THE MILKY WAY HAVE A THICK DISK?

- traditional evidence for thick disk based on two-component vertically-exponential density fits
- two component fits find two components!
- our mono-abundance fits show a large number of components with scale heights 200 - 1000 pc, dispersions between 20 and 50 km/s
- chemical bi-modality (alpha-enhanced thick disk) strongly depends on spectroscopic targeting
- what is the mass-weighted distribution of elemental abundances and scale heights?

Bovy et al. (2012a); ApJ **751**, 131

DOES THE MILKY WAY HAVE A THICK DISK?

CHEMICAL BI-MODALITY?



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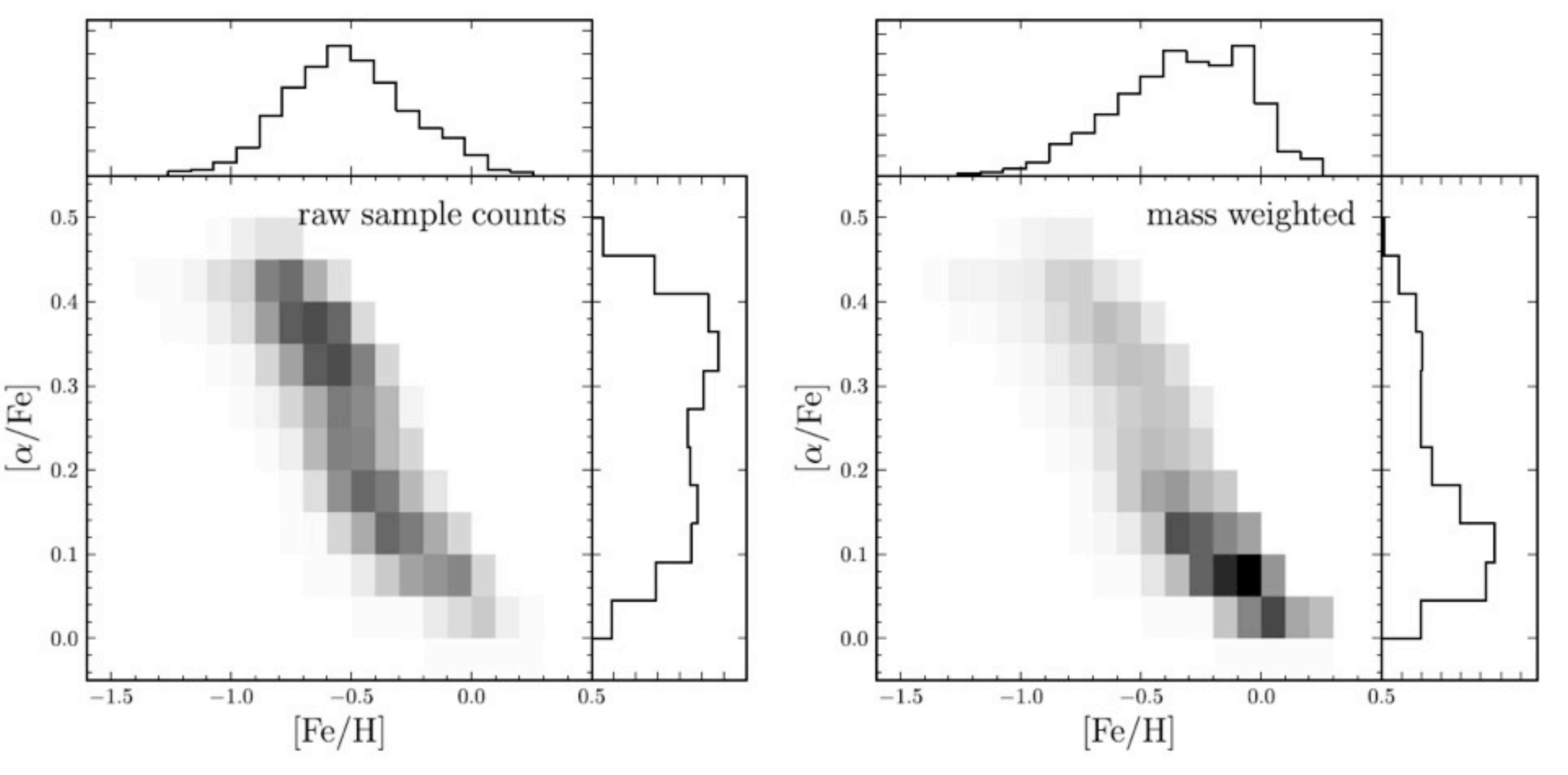
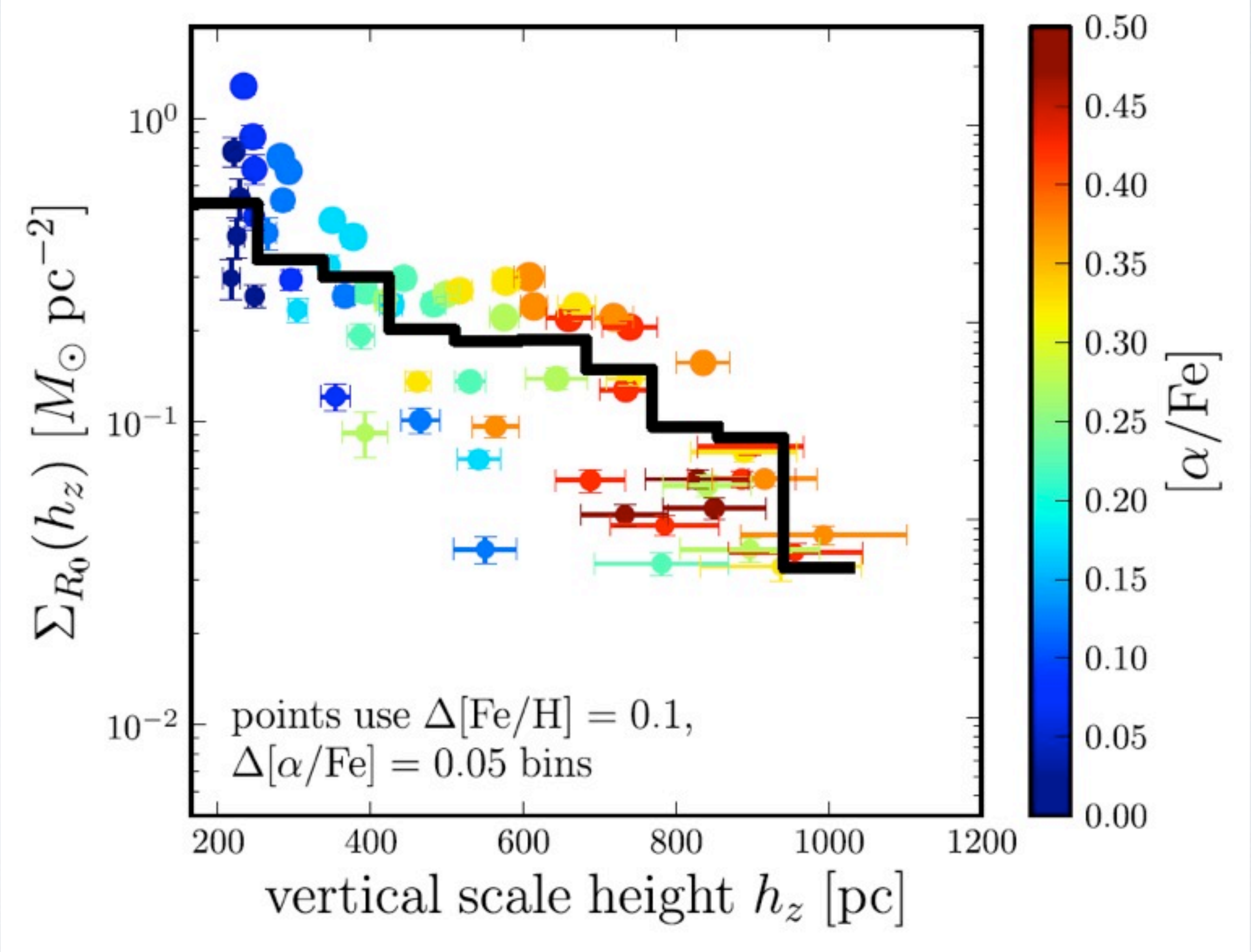
DOES THE MILKY WAY HAVE A THICK DISK?
CHEMICAL BI-MODALITY?



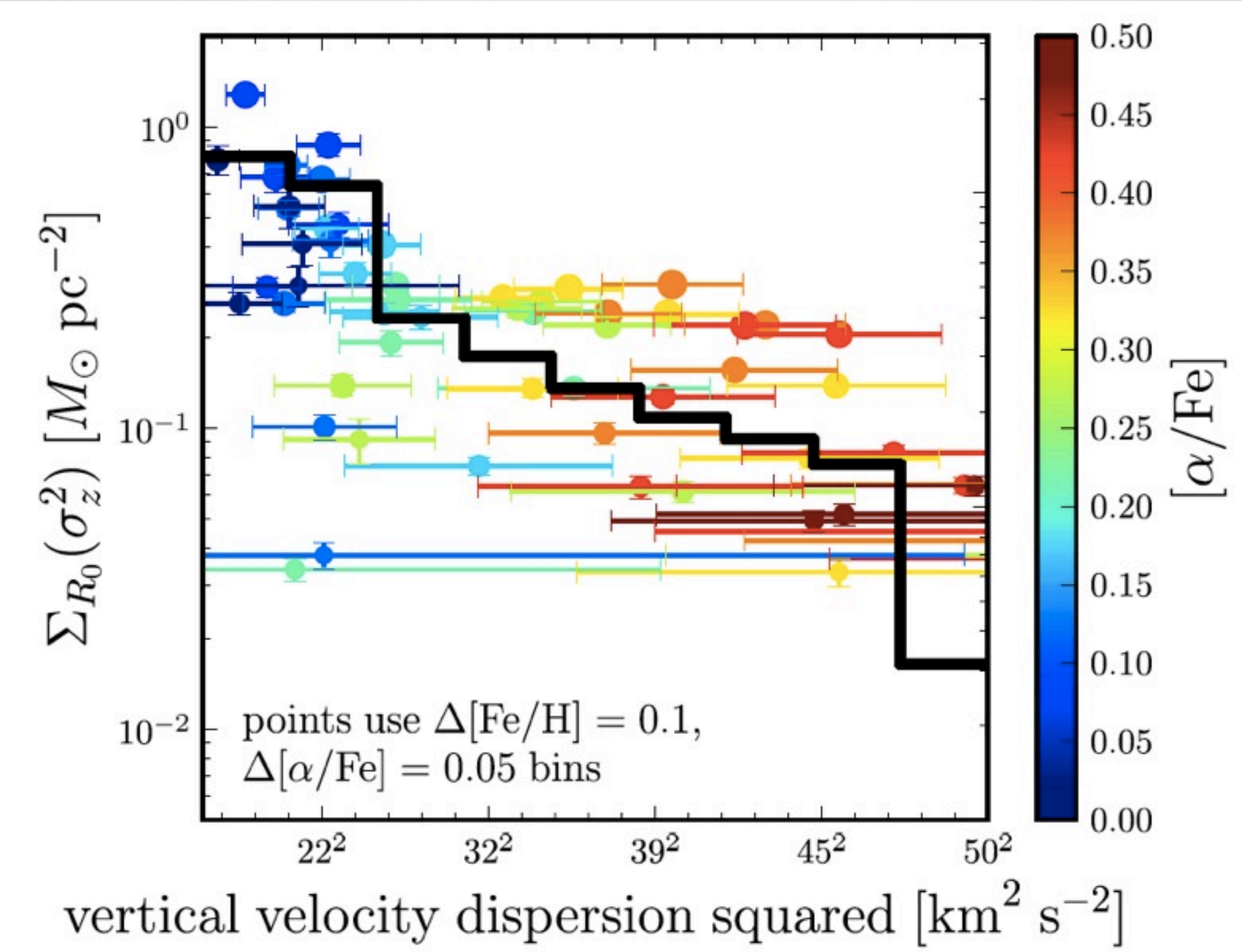
Bovy et al. (2012a); ApJ **751**, 131

DOES THE MILKY WAY HAVE A THICK DISK?
SCALE-HEIGHT BI-MODALITY?



Bovy et al. (2012a); ApJ **751**, 131

DOES THE MILKY WAY HAVE A THICK DISK?
KINEMATICS BI-MODALITY?



Bovy et al. (2012c); ApJ **755**, 115

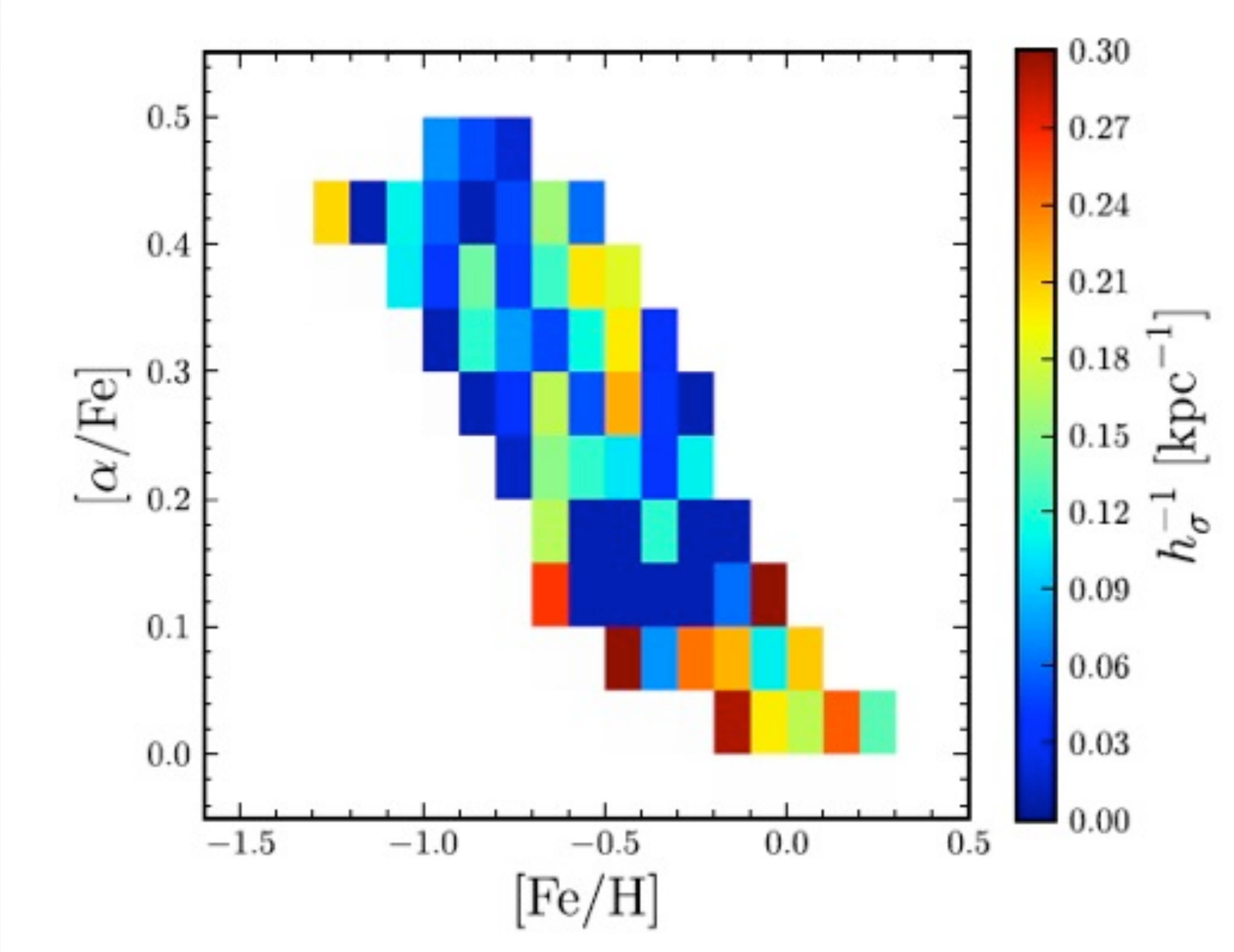
MONO-ABUNDANCE DYNAMICS

- All mono-abundance populations feel the same potential

- should be reflected in a common relationship between their vertical density and velocity profiles (e.g., Jeans equation)

- Simple estimate has the total disk surface-mass density

$$\Sigma \propto \frac{\sigma_z^2}{h_z}$$



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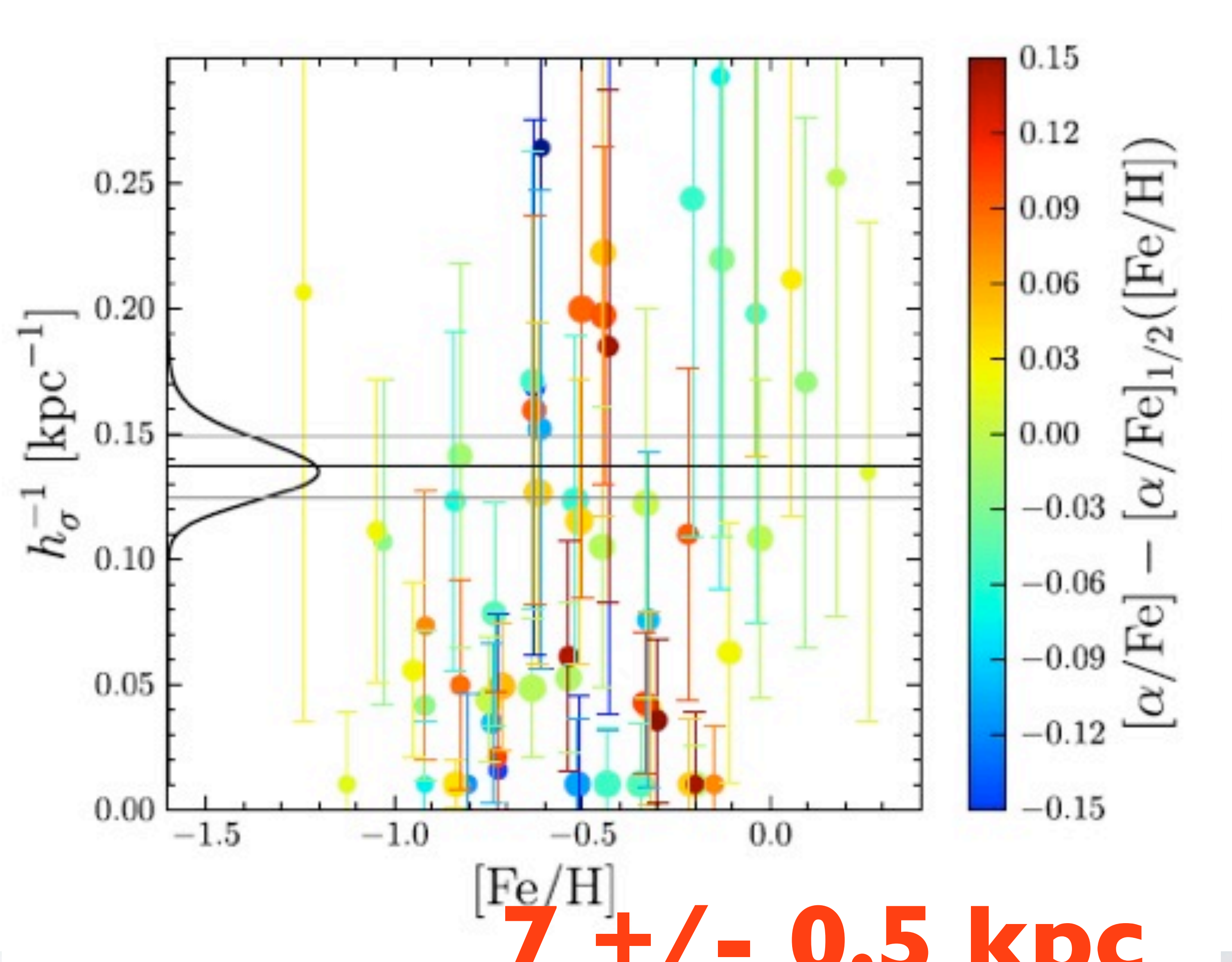


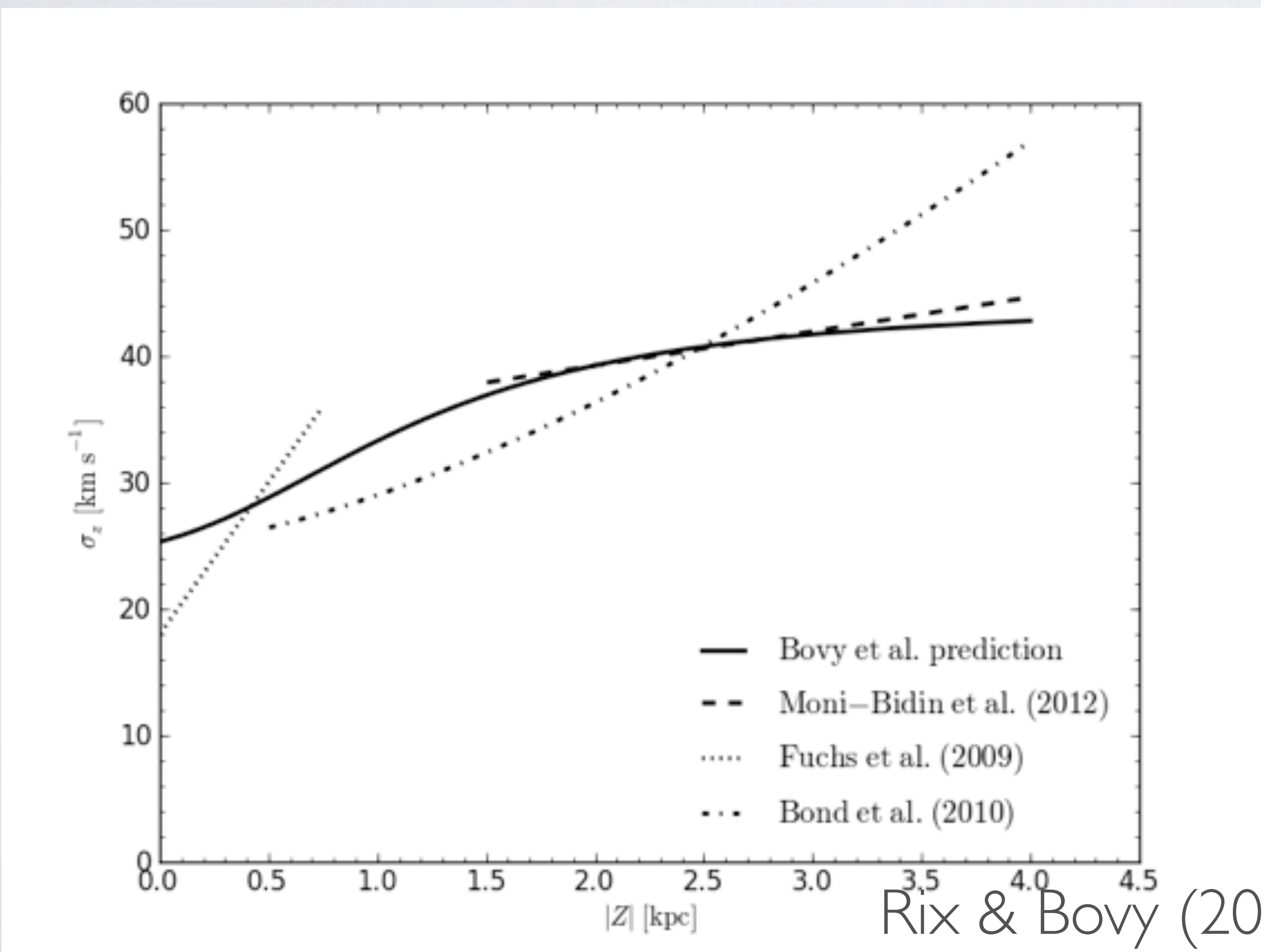
7 +/- 0.5 kpc

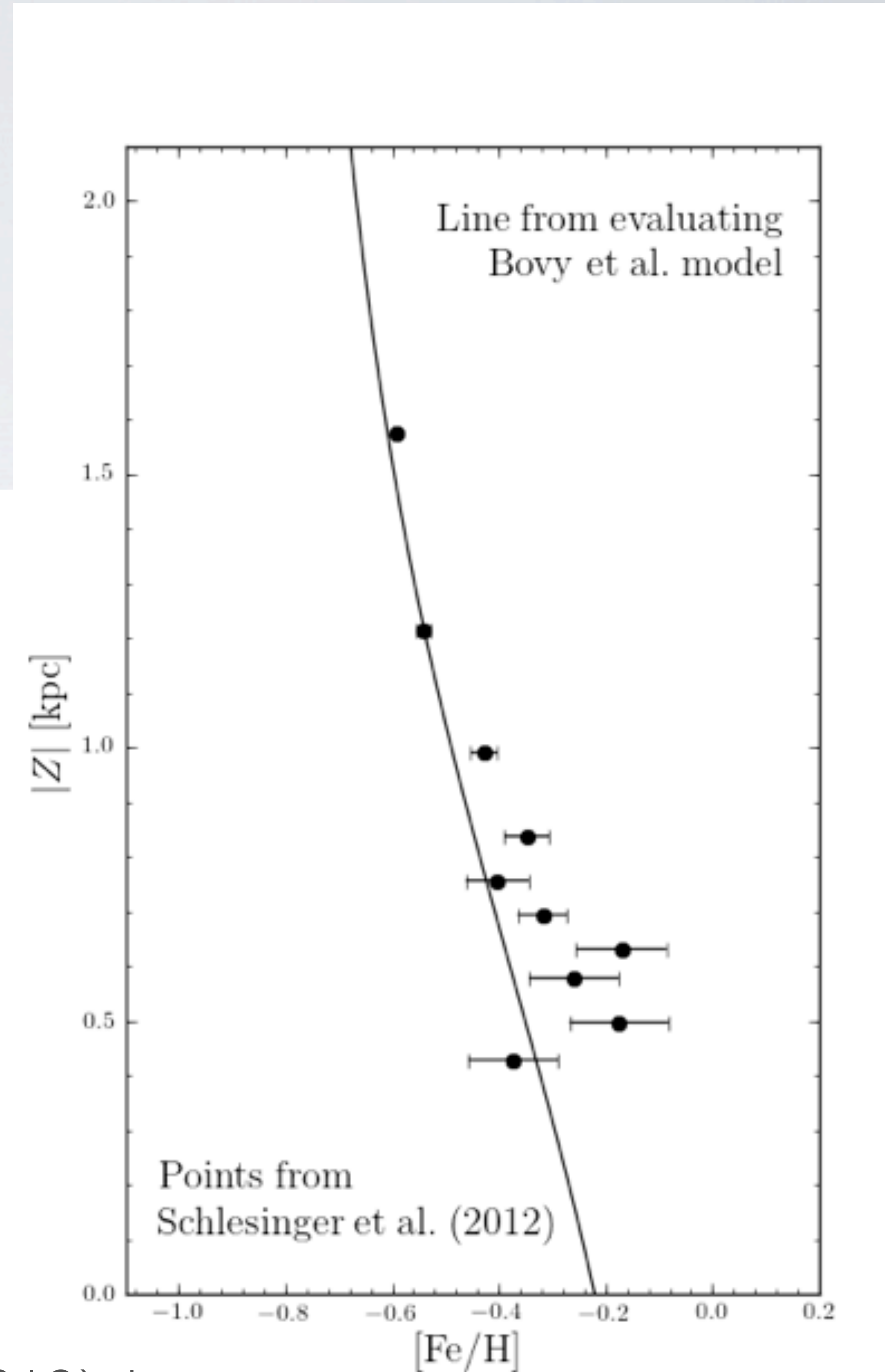
A NEW VIEW OF THE MILKY WAY I

- mono-abundance components are about as simple as it gets:
  - exponential profiles in R and |Z|
  - isothermal with |Z|, expected drop-off with R
- vertical gradients: changes in population with |Z| rather than changes within population
- theoretical models need to explain
  - why the populations are simple
  - their distribution of h_R, h_z, σ_z ([Fe/H],[α/Fe])

A NEW VIEW OF THE MILKY WAY II

- Abundance and σ_z gradients due to different mixes of populations at different (R,Z)

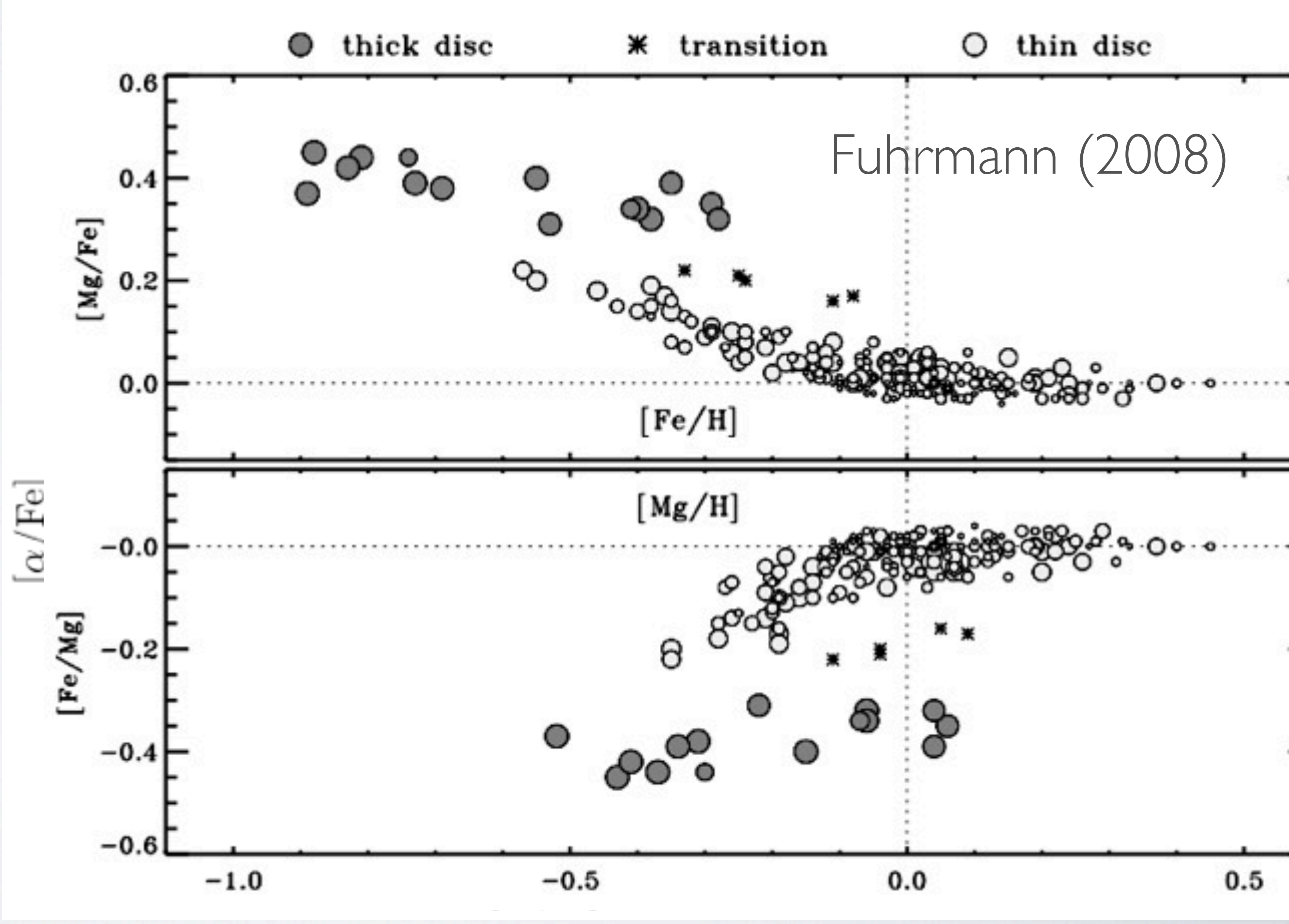




Rix & Bovy (2012), in prep.

COMPARISON WITH HIGH-RES WORK

- high-resolution abundances out to ~50 pc
- Much kinematic selection, creates structure in abundance-space
- We predict the |Z| =~ 0 [Fe/H] -- [α/Fe] distribution



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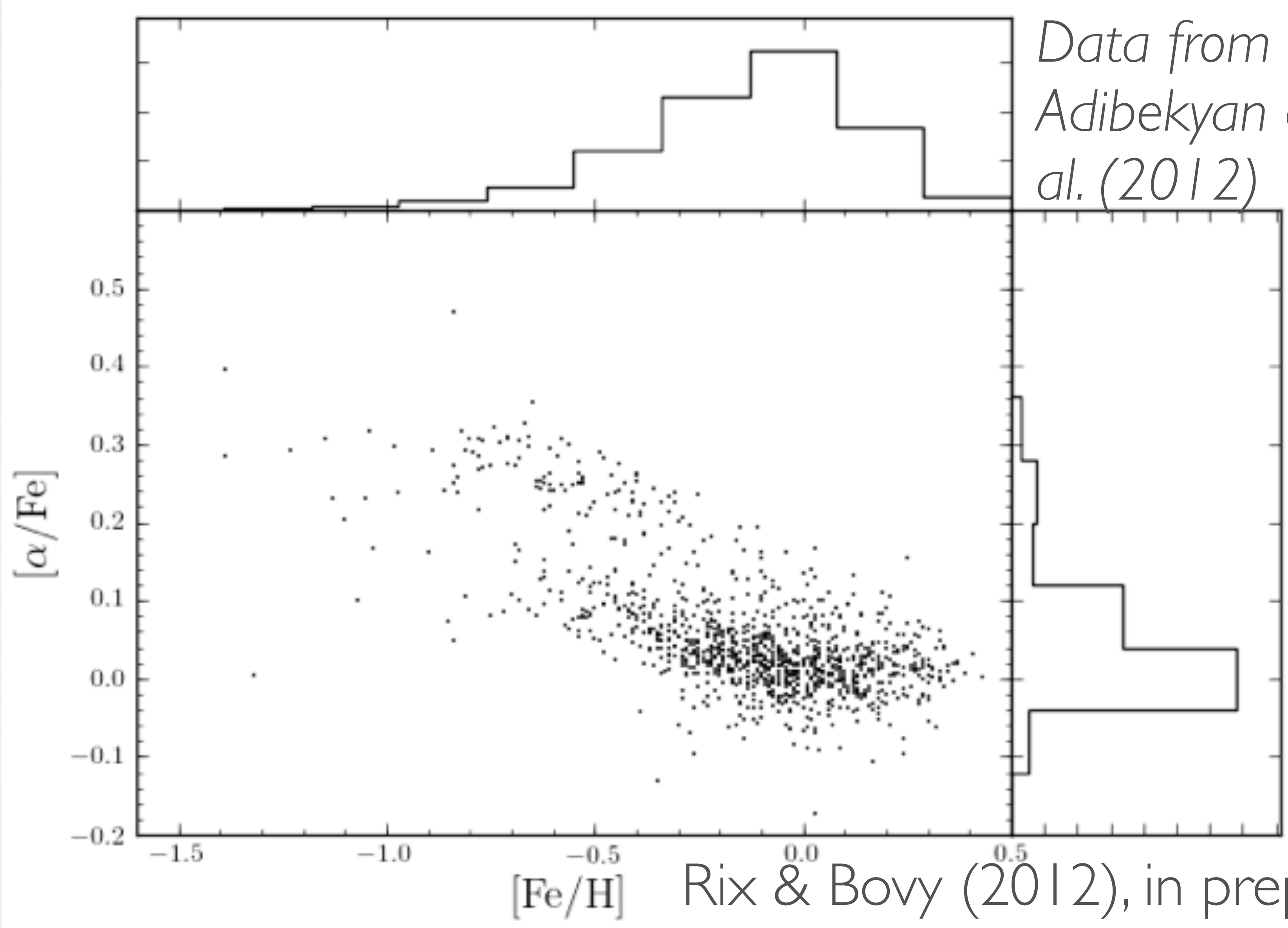

Data from Adibekyan et al. (2012)

Rix & Bovy (2012), in prep.

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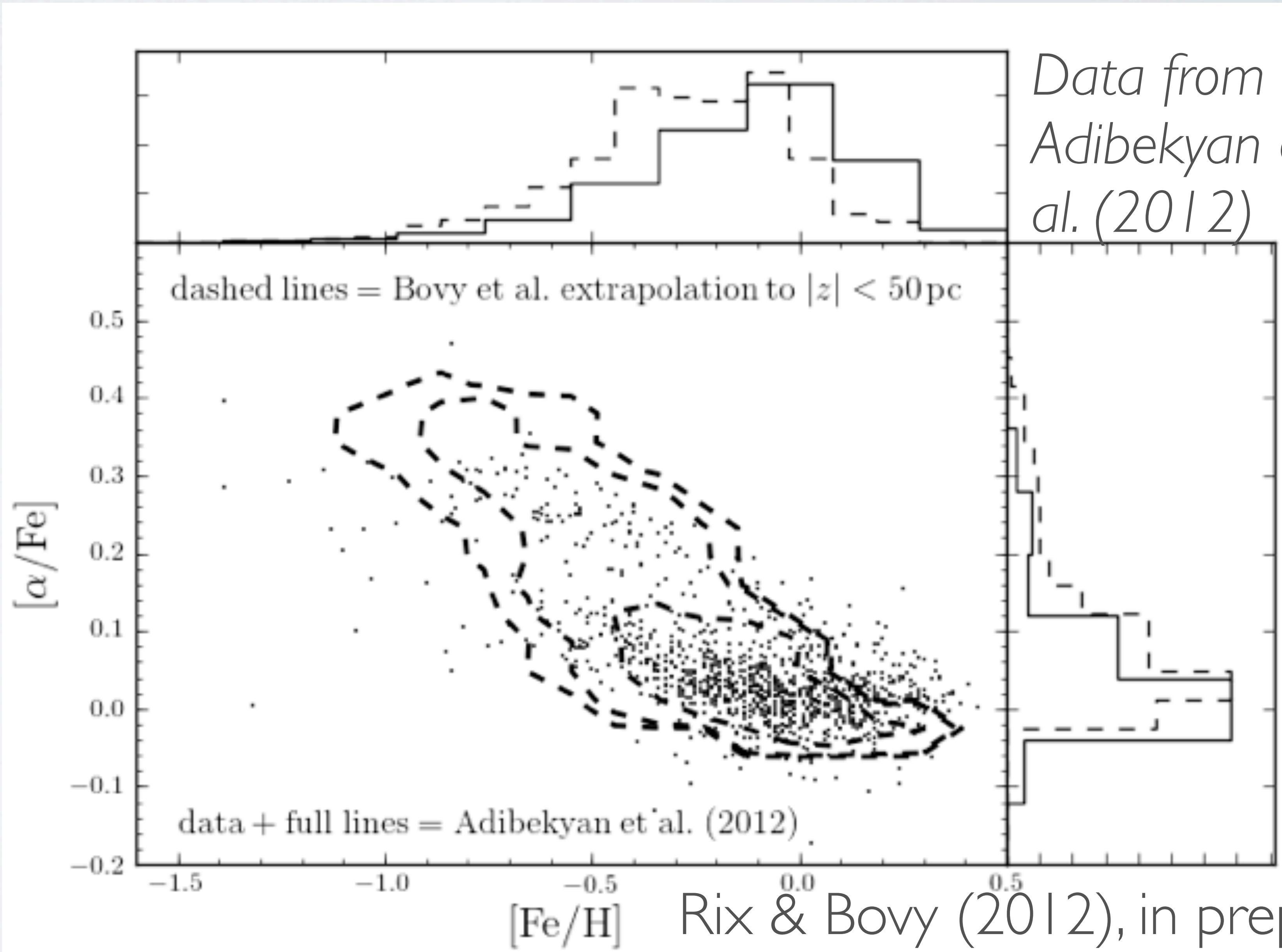


Data from Adibekyan et al. (2012)

Rix & Bovy (2012), in prep.

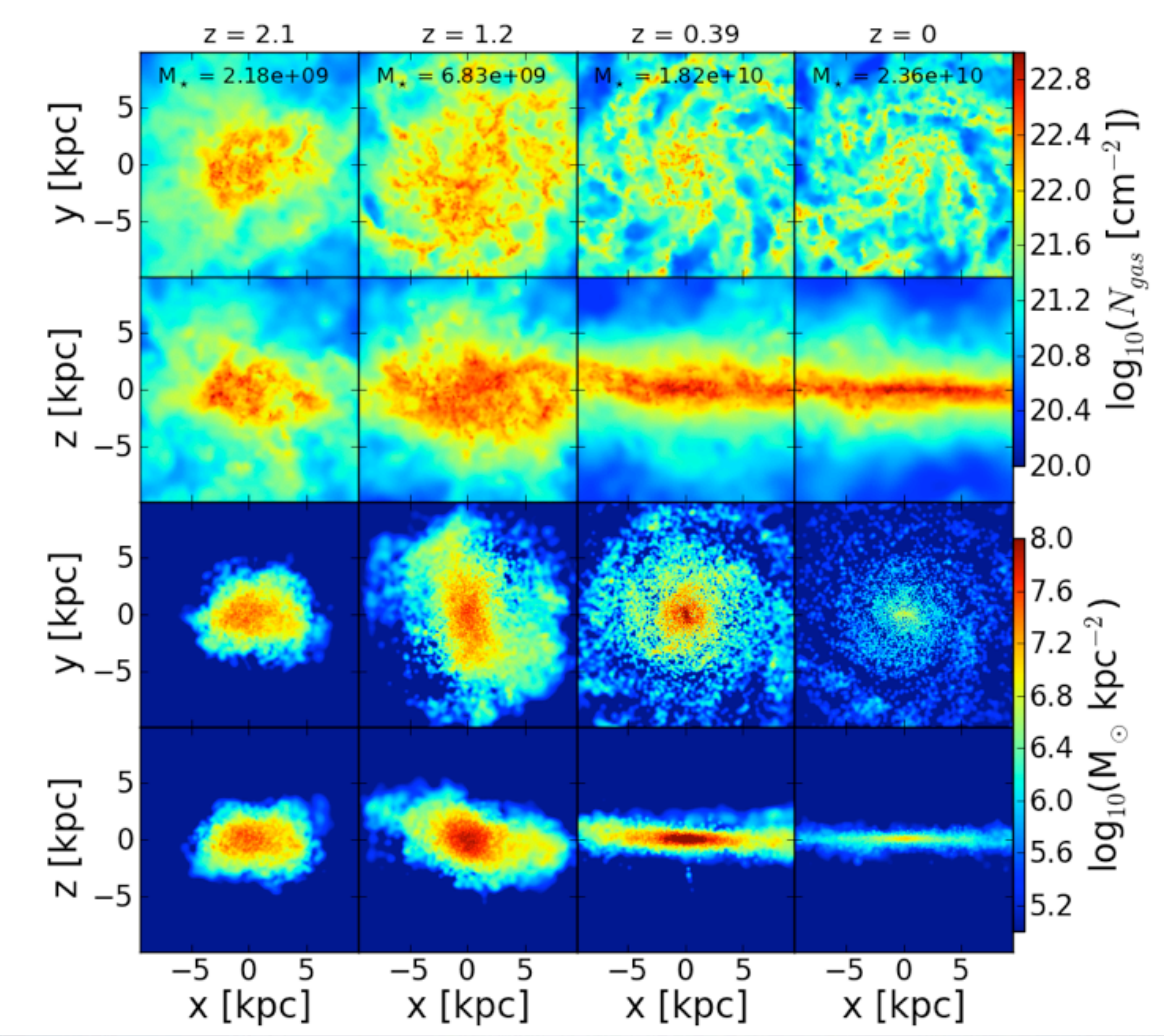
MODEL COMPARISONS

- Many models for (MW) disk formation are being compared to these results (Minchev, et al. 2012, Brook et al. 2012, Stinson, Bovy, et al., in prep, Roskar et al., in prep, Bird et al., in prep, Guedes et al., in prep)

- Preliminary results are that they can reproduce some observed features, unclear whether all trends are matched by any simulation

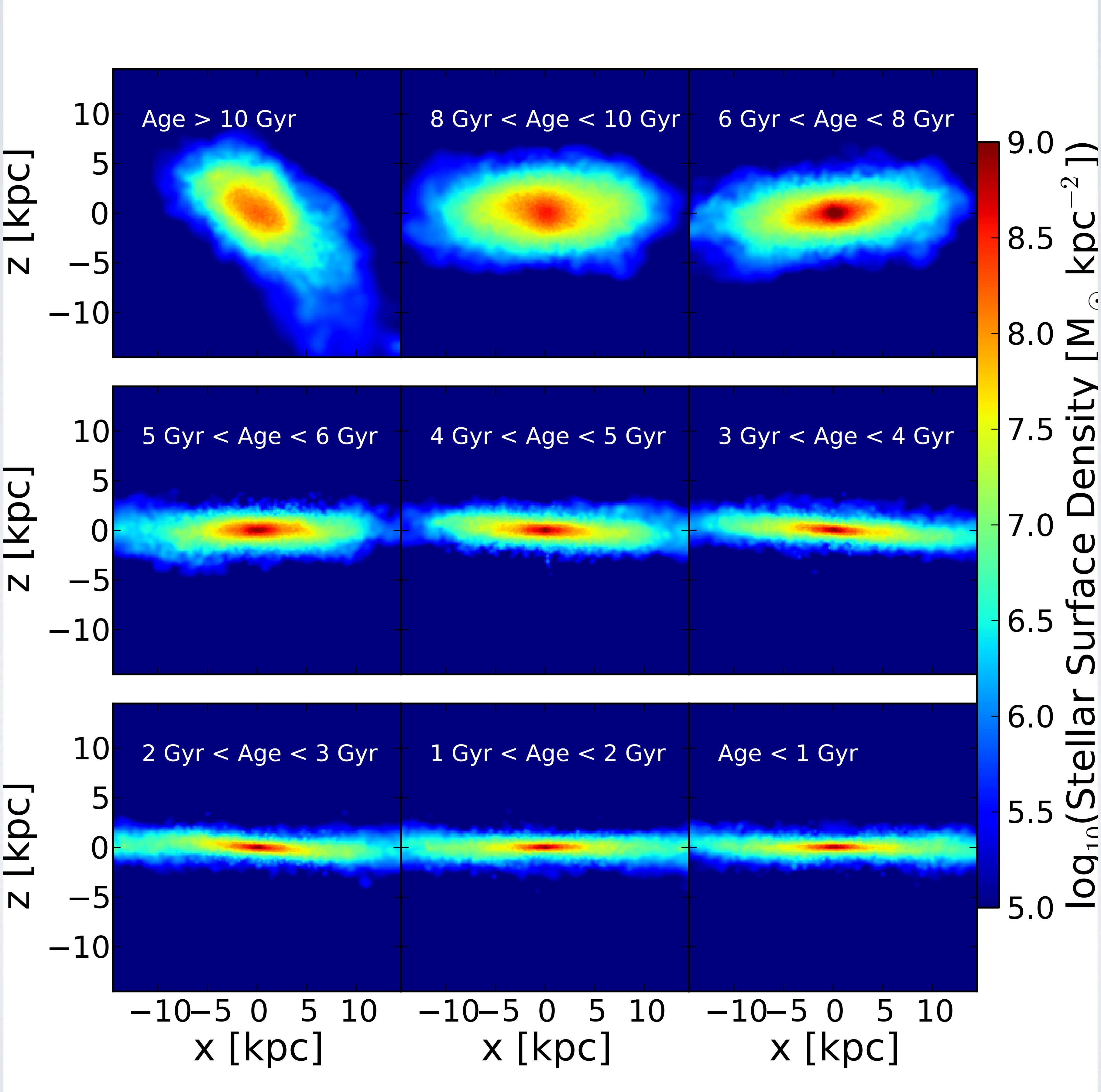
- Caution against choosing some trends and ignoring others, quantitative/qualitative

MODEL COMPARISONS



Stinson, Bovy, et al. (in prep)

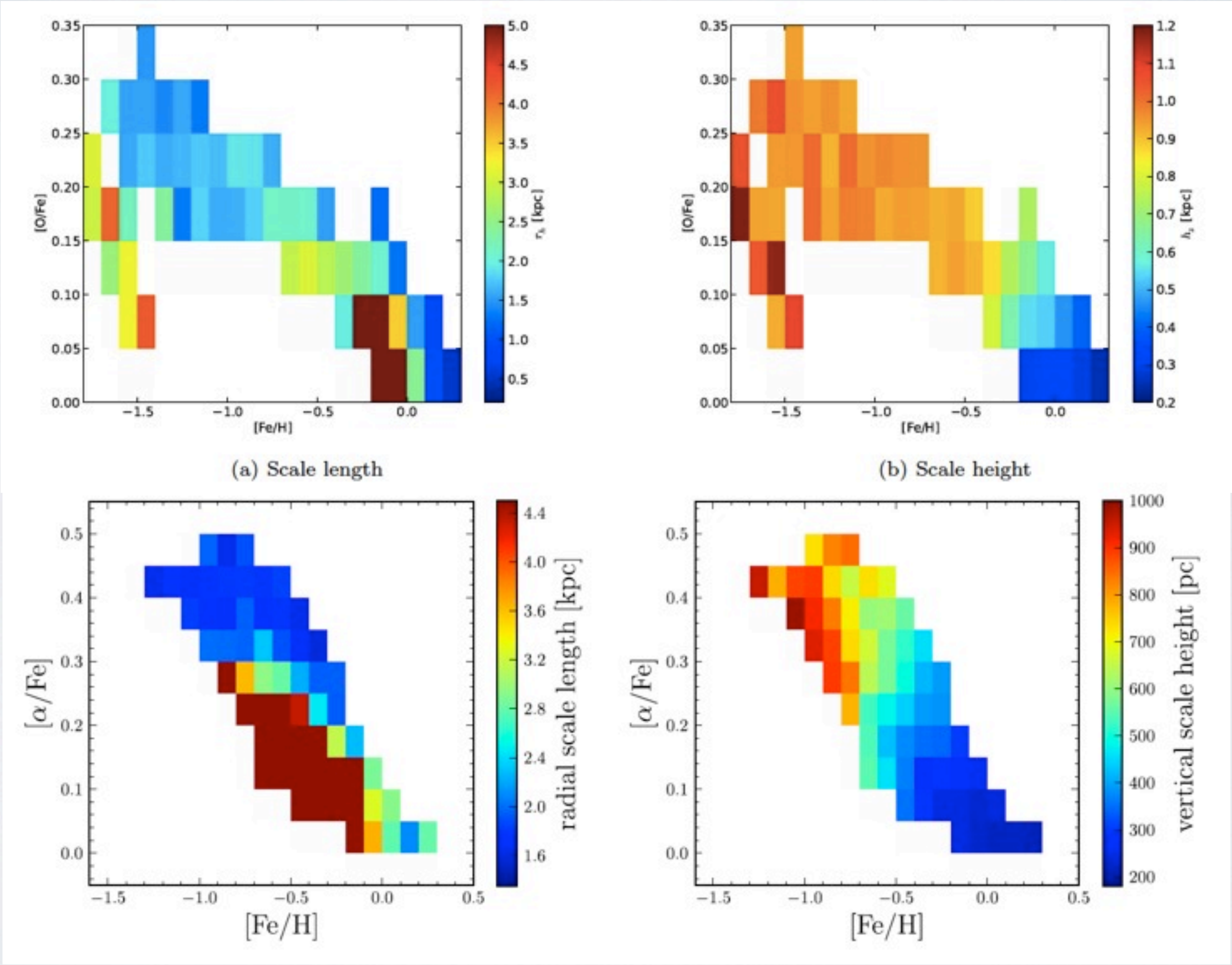
MODEL COMPARISONS



Stinson, Bovy, et al. (in prep)

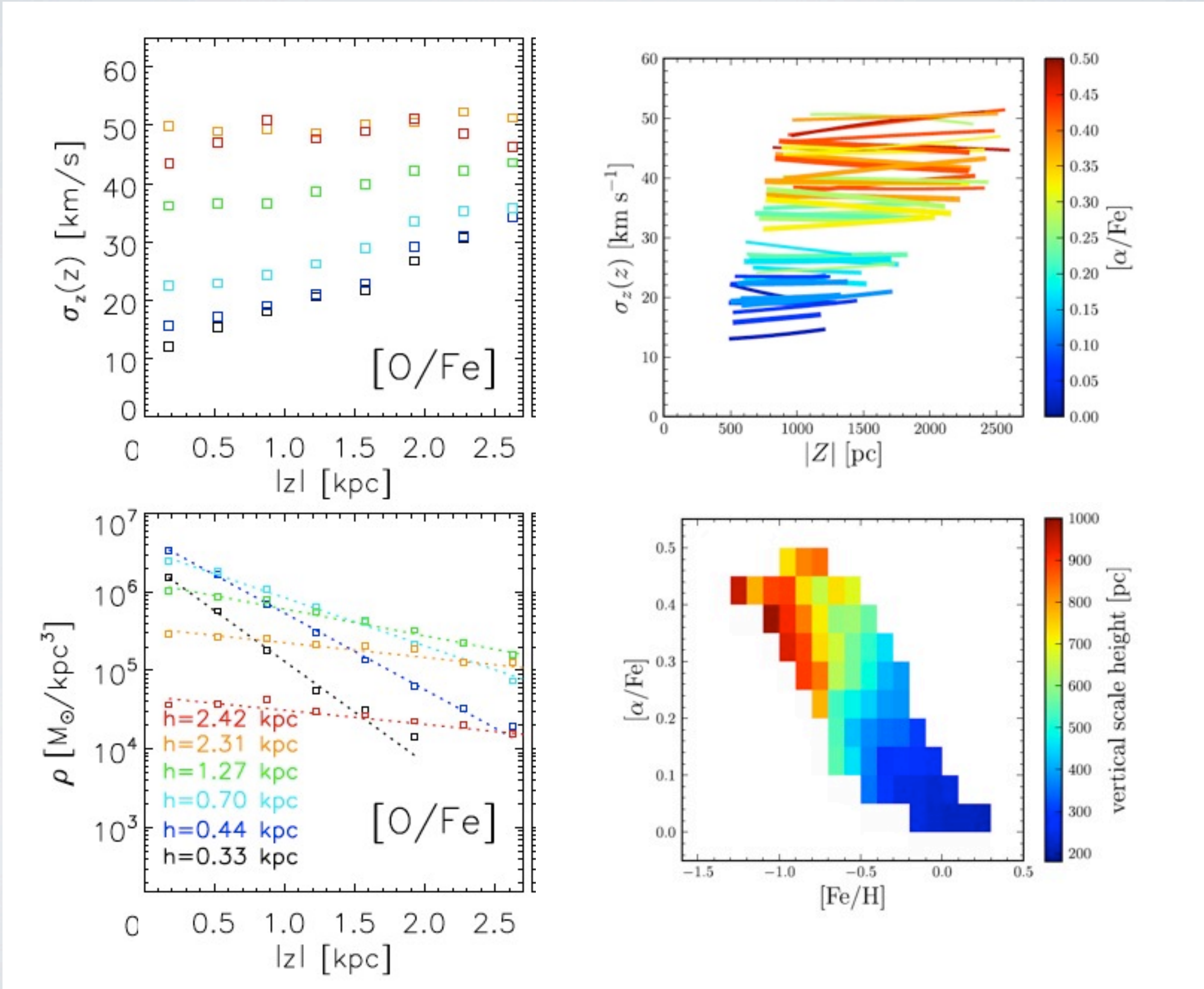
MODEL COMPARISONS

Stinson, Bovy, et al. (in prep)



MODEL COMPARISONS

Minchev, Chiappini, & Martig (2012)



CONCLUSIONS

- first real constraint on thick-disk component's scale length shows that it is short ≈ 2 kpc

- assuming that [α/Fe] is a proxy for age, our results show that old components are more centrally concentrated than young components → inside-out disk formation

- smooth increase in scale height and dispersion that is anti-correlated with scale length → internal evolution played a large role in the evolution of the disk

- scale heights and vertical dispersion increases smoothly from thin to thick → no clear thick/thin disk break; mass-weighted vertical height and kinematics distribution shows no bimodality → no thick disk