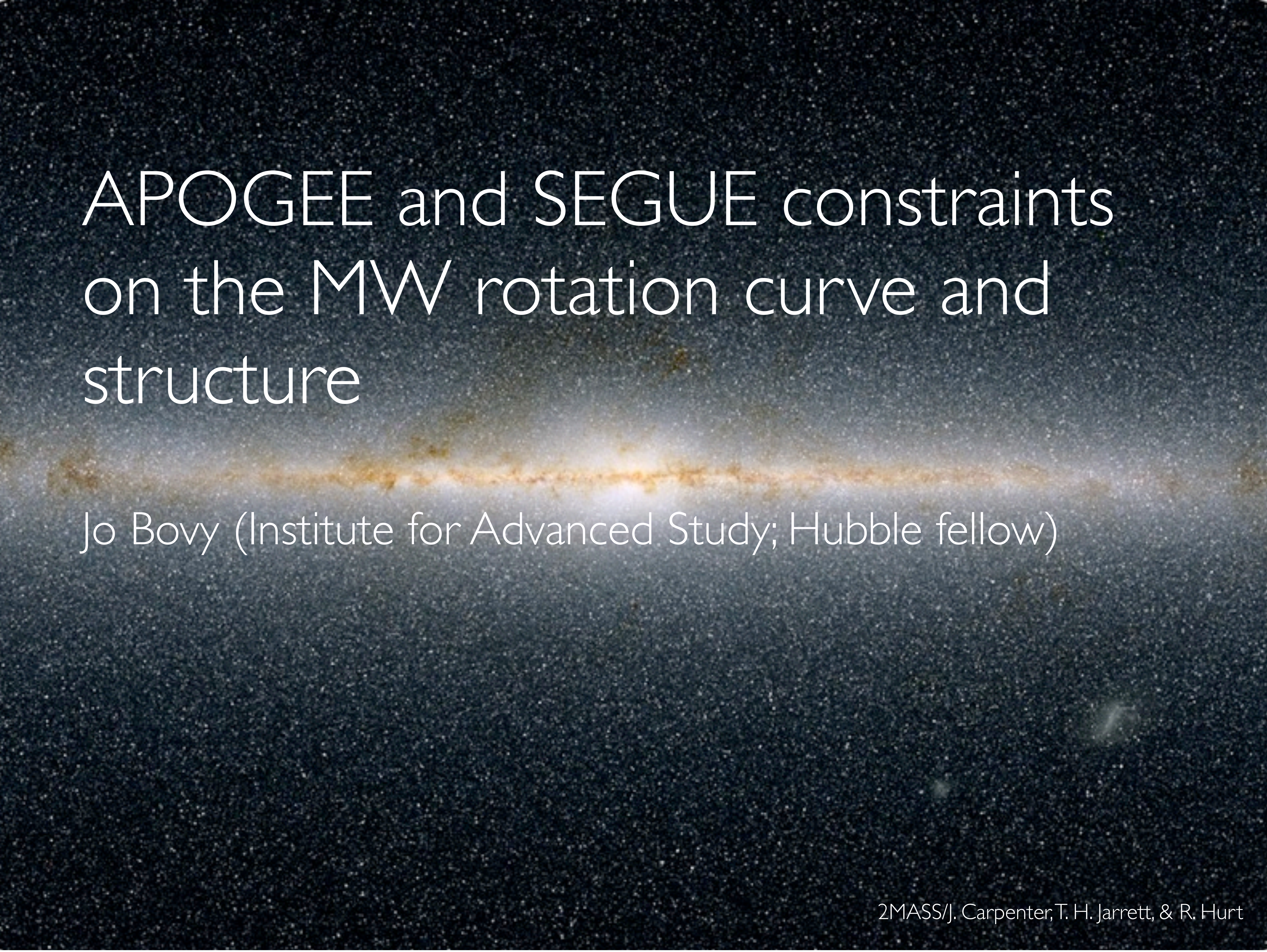
# APOGEE and SEGUE constraints on the MW rotation curve and structure

Jo Bovy (Institute for Advanced Study; Hubble fellow)

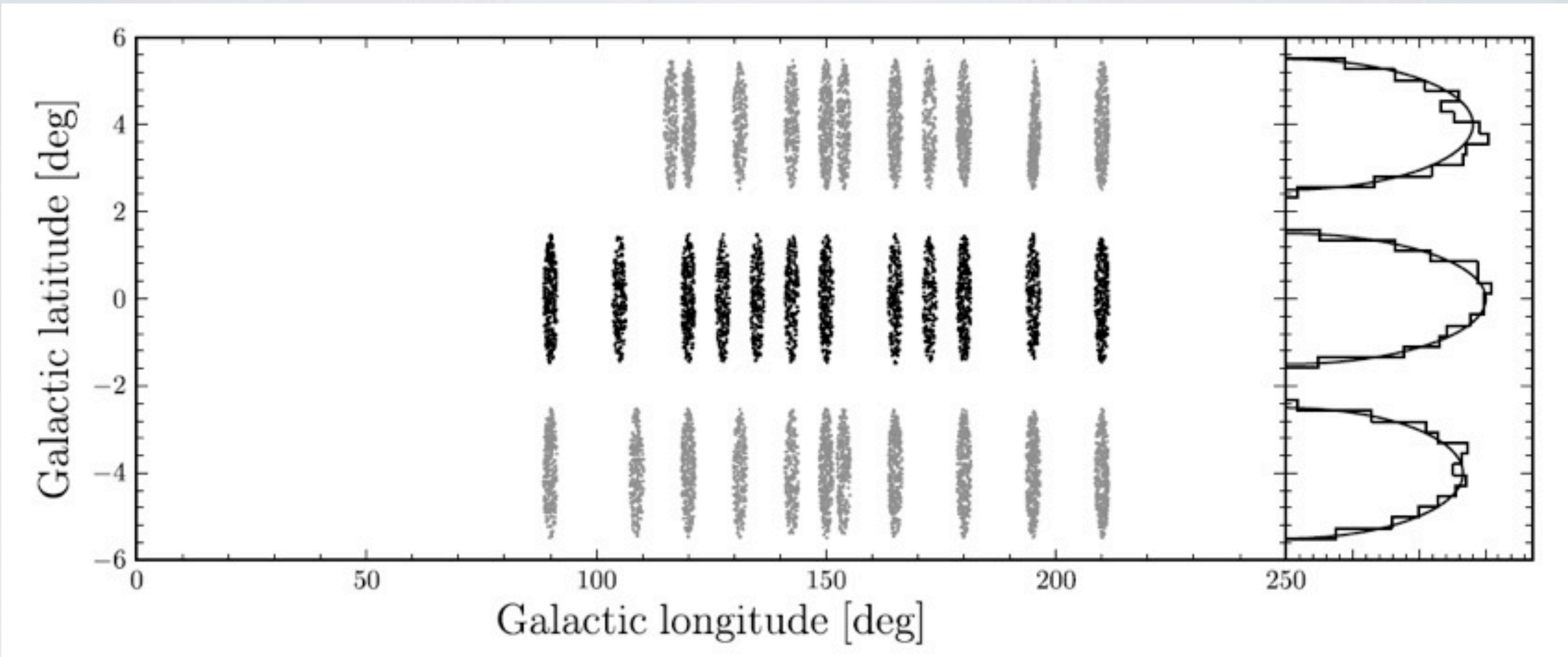


2MASS/J. Carpenter, T. H. Jarrett, & R. Hurt

# SDSS-III/APOGEE

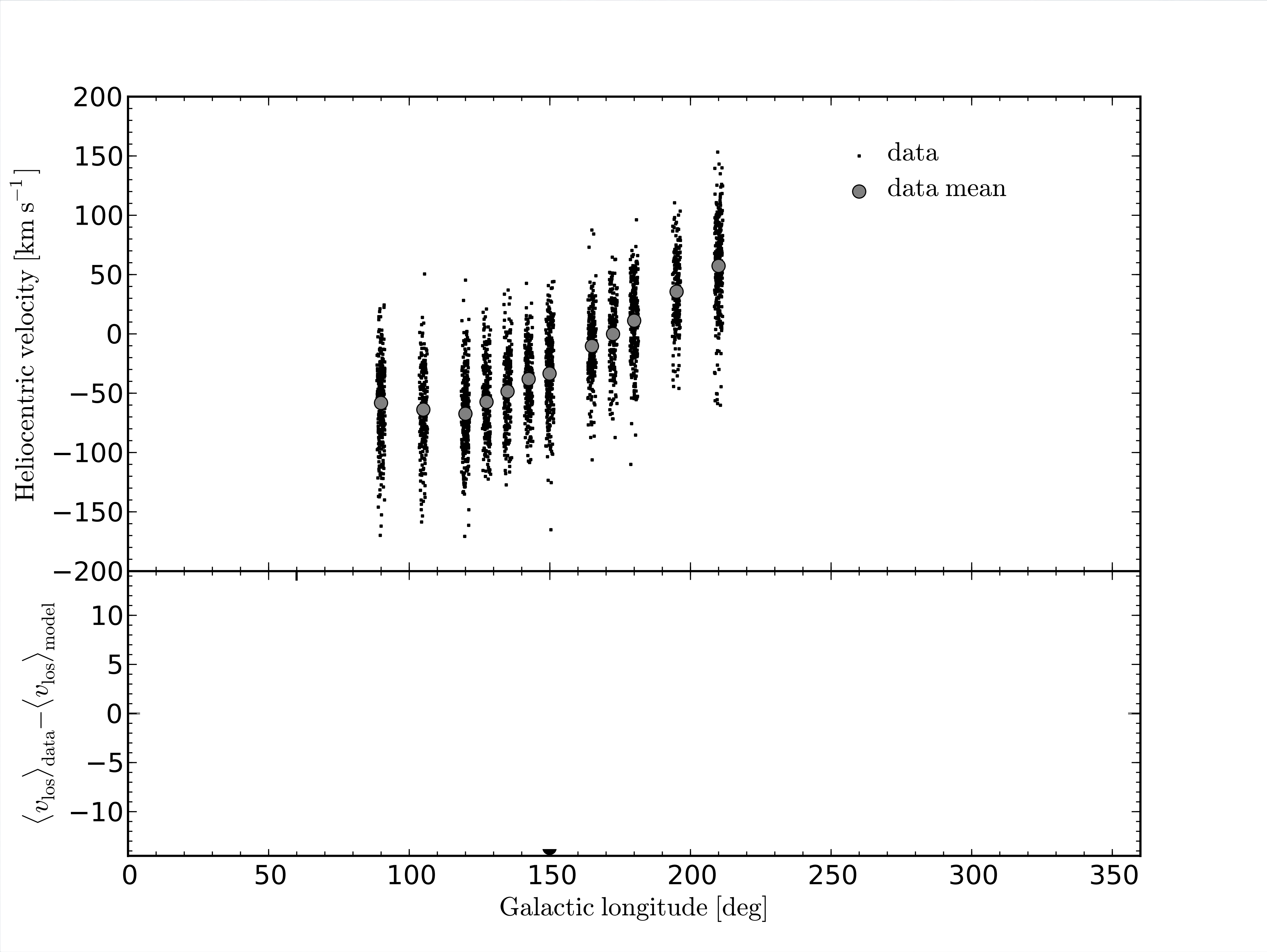
- Infrared *H*-band spectra for 100k stars in disk, bulge, and halo
- high resolution (R ~ 22,500)
- S/N > 100 / pixel
- $(J-Ks)_0 > 0.5$, H <~ 13.8
- now: $v_{los}$ , working on [Fe/H], logg, Teff, + other abundances
- after < 1 yr: ~20,000 stars, 4,000 disk stars
- PI: Majewski, + many people

# DISK SAMPLE



Galactic latitude [deg]
Galactic longitude [deg]
6
4
2
0
−2
−4
−6
0
50
100
150
200
250

# "RAW" DATA



data
data mean
Heliocentric velocity [km s$^{-1}$]
200
150
100
50
0
−50
−100
−150
−200
$\langle v_{los} \rangle_{data} - \langle v_{los} \rangle_{model}$
10
5
0
−5
−10
0
50
100
150
200
250
300
350
Galactic longitude [deg]

# MODEL INGREDIENTS

$$p(v_{\rm los}|l, b, (J-Ks)_0, H_0, v_c(R), R_0, v_\odot^{\rm gal}, {\rm DF}, {\rm iso})$$
$$= \sum_{\rm dwarf/giant} P({\rm dwarf/giant}) \int {\rm d}d\, p(v_{\rm los}|d, l, b, v_c(R), R_0, v_\odot^{\rm gal}, {\rm DF})$$
$$\times\, p(d|l, b, (J-Ks)_0, H_0, {\rm DF}, {\rm iso}, {\rm dwarf/giant}).$$

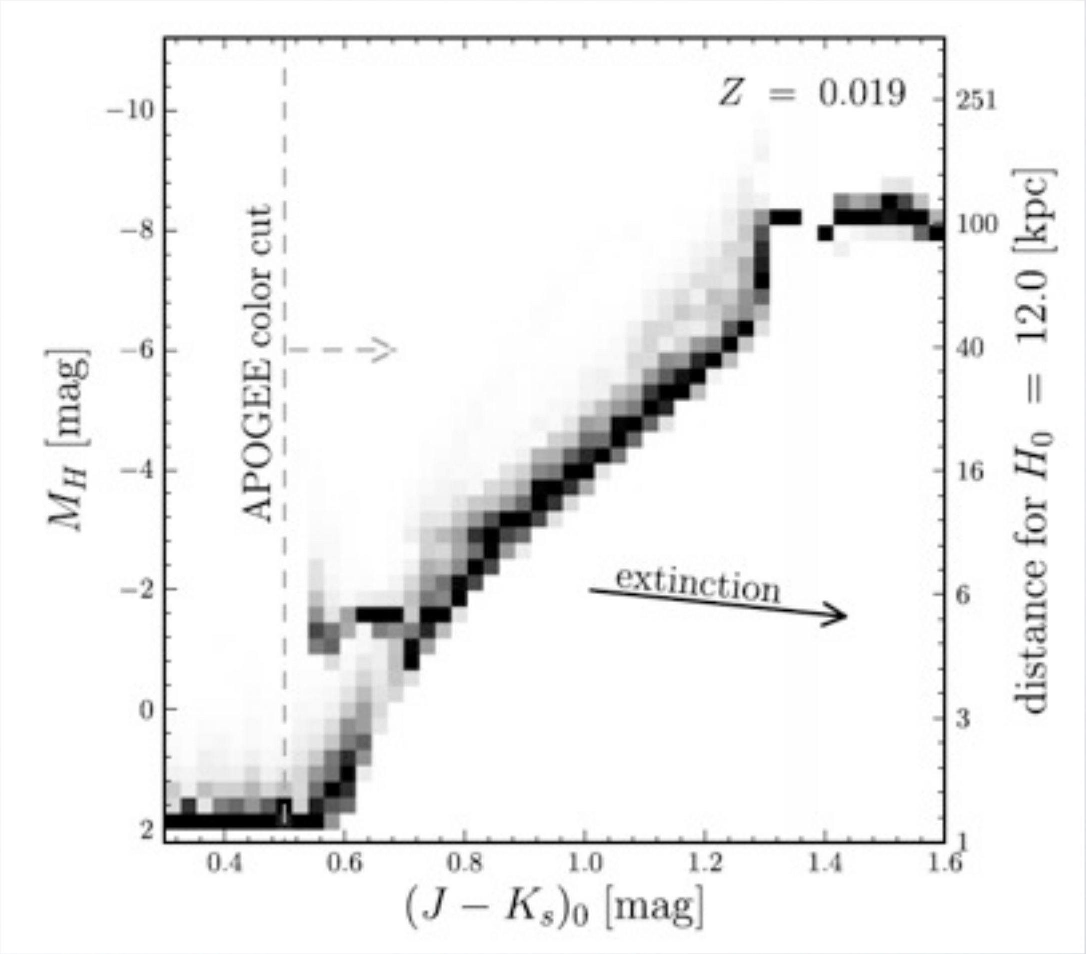
- "no" distances! Marginalize over distance
- no logg yet! Marginalize over dwarf/giant (expect 10 - 20% dwarfs)
- Model:
  - rotation curve
  - DF: at least velocity dispersion, scale length
  - Solar position and velocity
  - ...

# MODEL INGREDIENTS

$$p(v_{\rm los}|l, b, (J-Ks)_0, H_0, v_c(R), R_0, v_\odot^{\rm gal}, {\rm DF}, {\rm iso}) = \sum_{\rm dwarf/giant} P({\rm dwarf/giant}) \int {\rm d}d\, p(v_{\rm los}|d, l, b, v_c(R), R_0, v_\odot^{\rm gal}, {\rm DF}) \times p(d|l, b, (J-Ks)_0, H_0, {\rm DF}, {\rm iso}, {\rm dwarf/giant}).$$

$$p(d|l, b, J-Ks, H, {\rm DF}, {\rm iso}) \propto p((J-Ks)_0, H_0|d, {\rm iso})\, p(d, l, b|{\rm DF}) = {\rm iso}(H_0 - \mu(d), (J-Ks)_0)\, \nu_*(R, z|{\rm DF})\, d^2 \cos b$$

- Giants: Average isochrones for constant SFR, Chabrier IMF, solar metallicity
- Dwarfs: Must be local, $\delta(d)$



# MODEL INGREDIENTS

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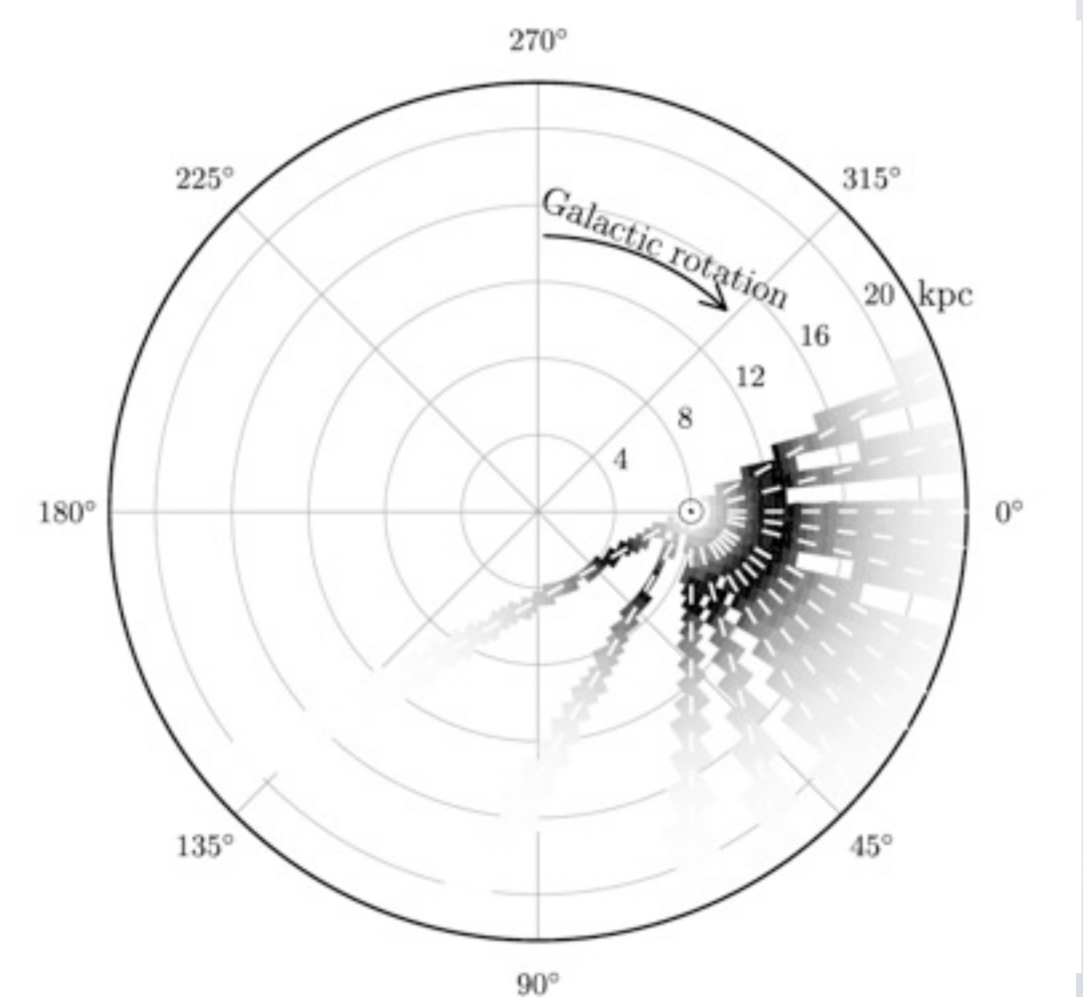

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$$p(v_{\rm los}|l, b, (J-Ks)_0, H_0, v_c(R), R_0, v_\odot^{\rm gal}, {\rm DF}, {\rm iso})$$
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$$\times\, p(d|l, b, (J-Ks)_0, H_0, {\rm DF}, {\rm iso}, {\rm dwarf/giant}).$$

$$v_{\rm los}^{\rm gal} = v_{\rm los}^{\rm helio} - \cos l\, v_{R,\odot} + \sin l\, \Omega_\odot\, R_0$$

- Approximate DF with Gaussian:

mean $(v_c(R) - v_a(R;\sigma, h_R, h_\sigma))\sin(\phi + l)$ and variance $\sigma_R^2\,(1 + \sin^2(\phi + l)\,(X^2 - 1))$.

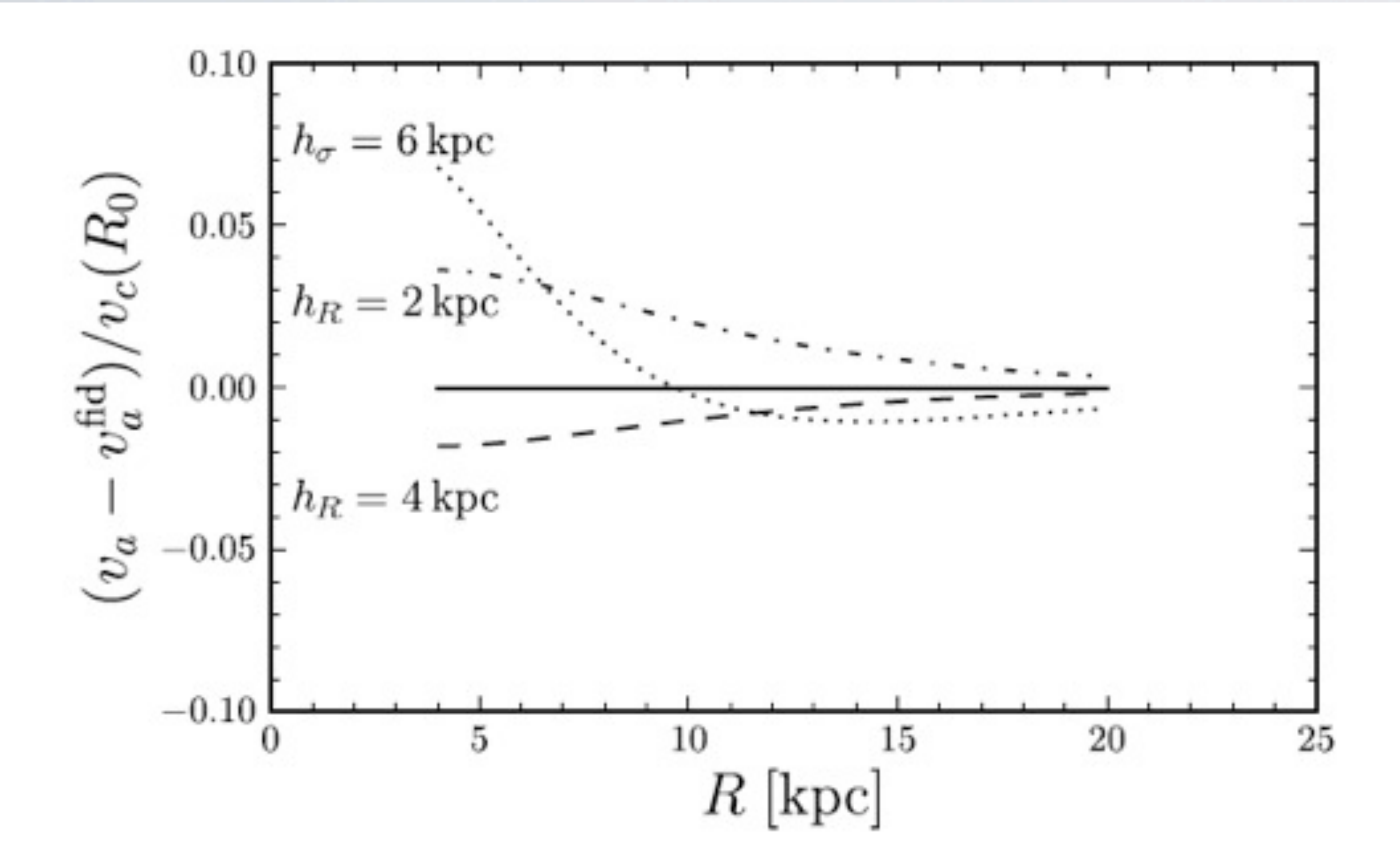
- mean azimuthal velocity calculated using asymmetric drift:

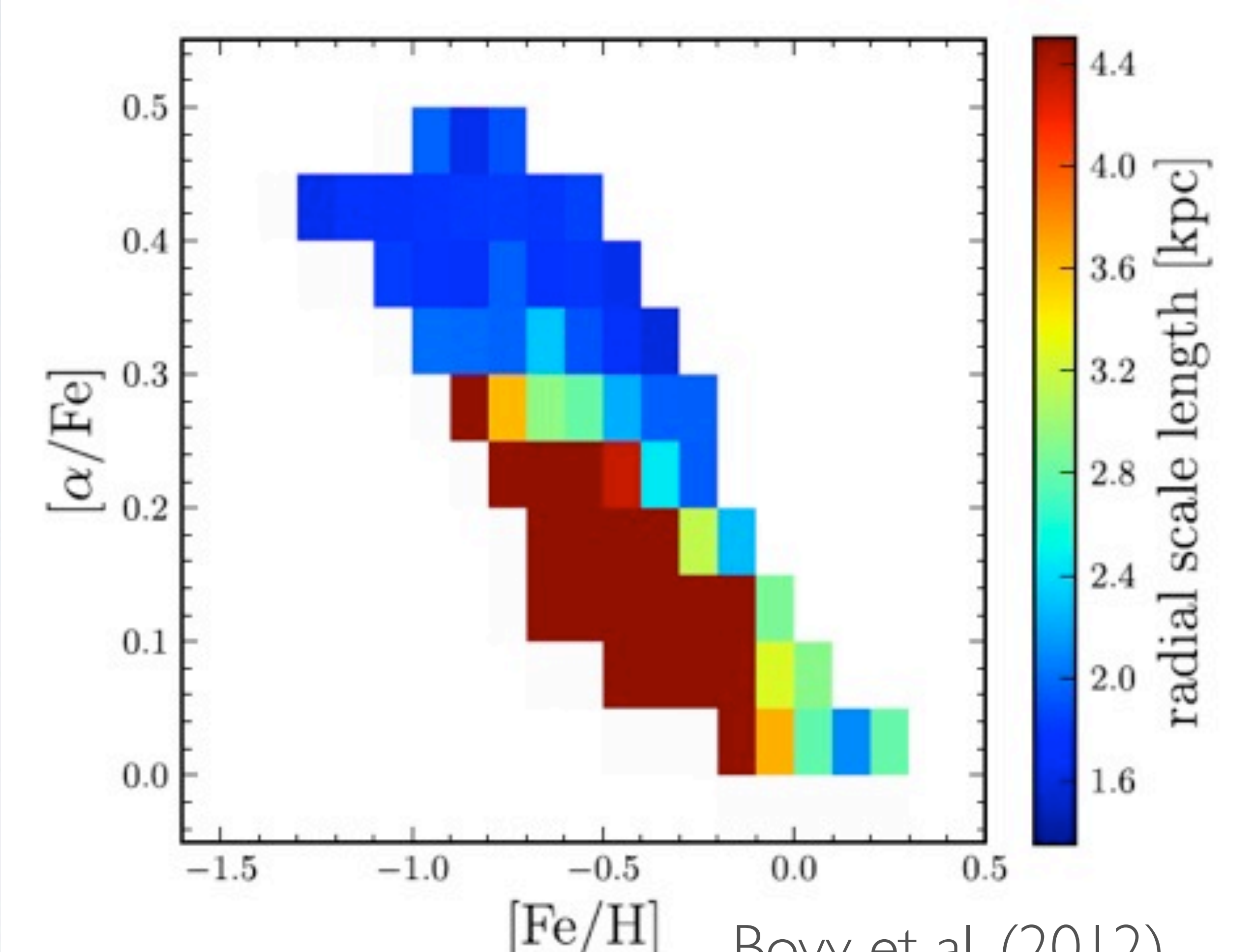
$$\frac{v_c(R) v_a(R)}{\sigma_R^2(R)} = \frac{1}{2}\left[X^2 - 1 + R\left(\frac{1}{h_R} + \frac{2}{h_\sigma}\right)\right]$$

- Marginalize over tangential velocity

# SYSTEMATICS

Asymmetric drift:



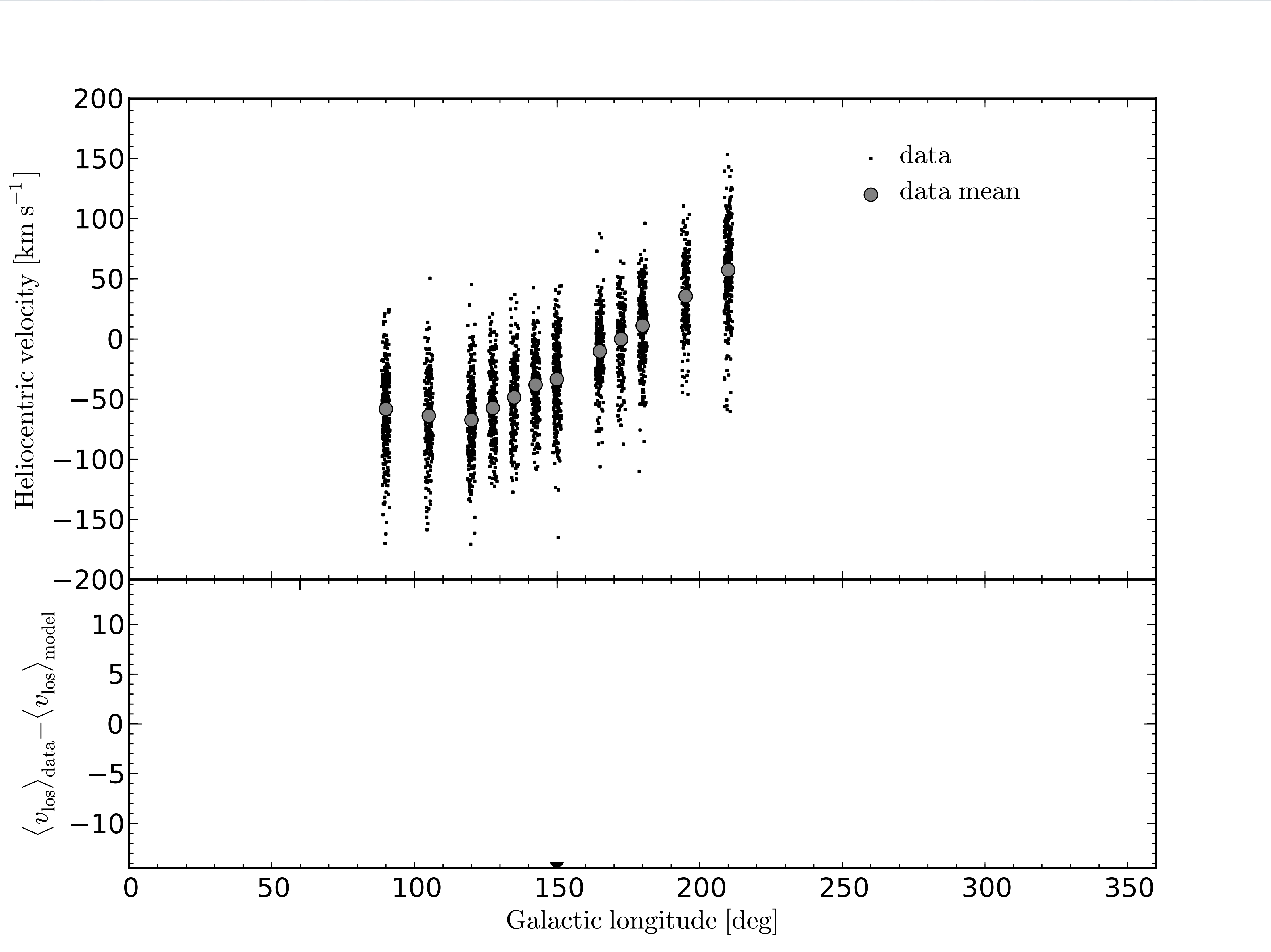

Bovy et al. (2012)

Multiple populations

Isochrones, metallicity, extinction

Using a Gaussian rather than f(**J**)

...



data
data mean
Heliocentric velocity [km s$^{-1}$]
200
150
100
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−200
10
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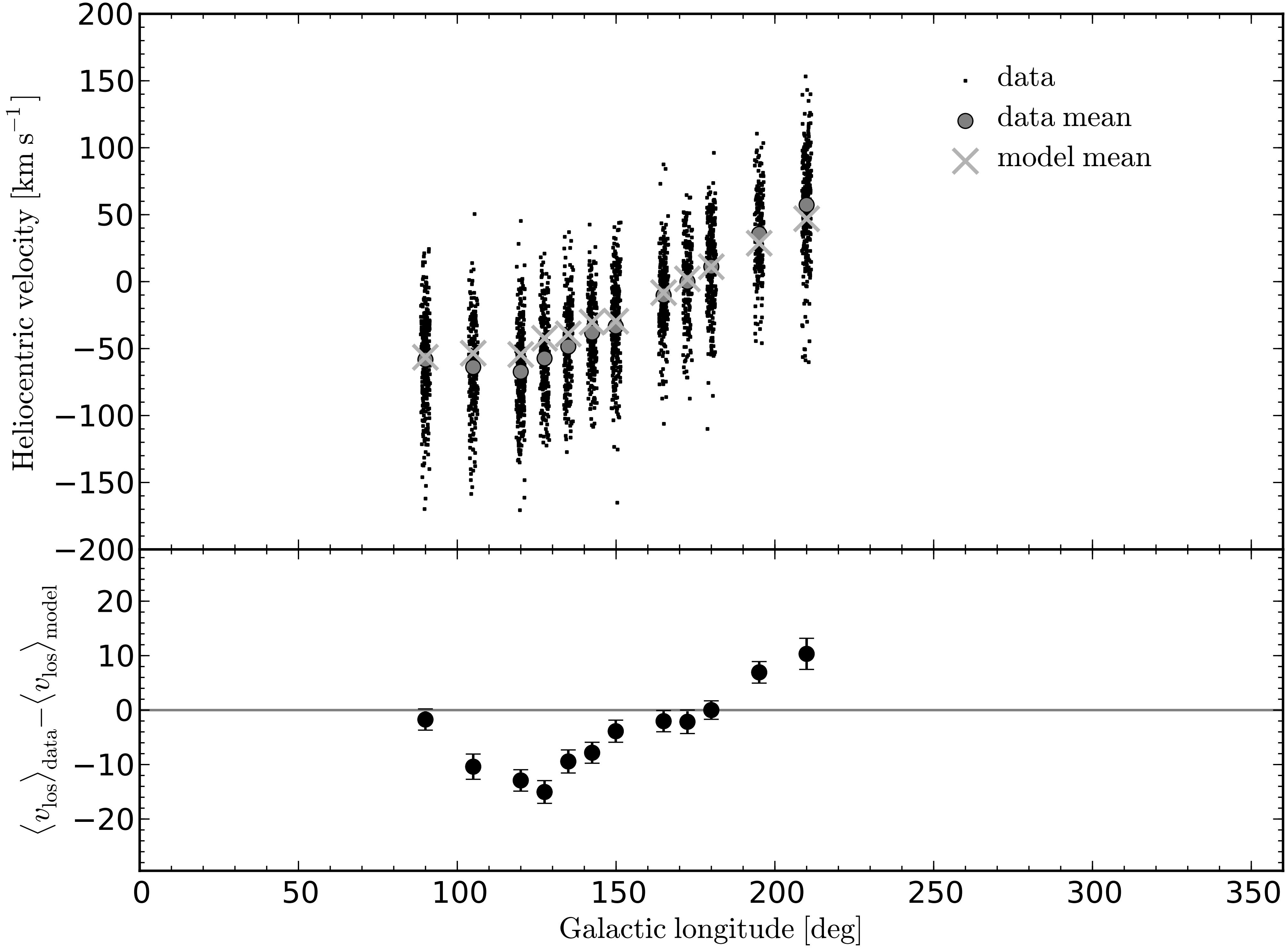
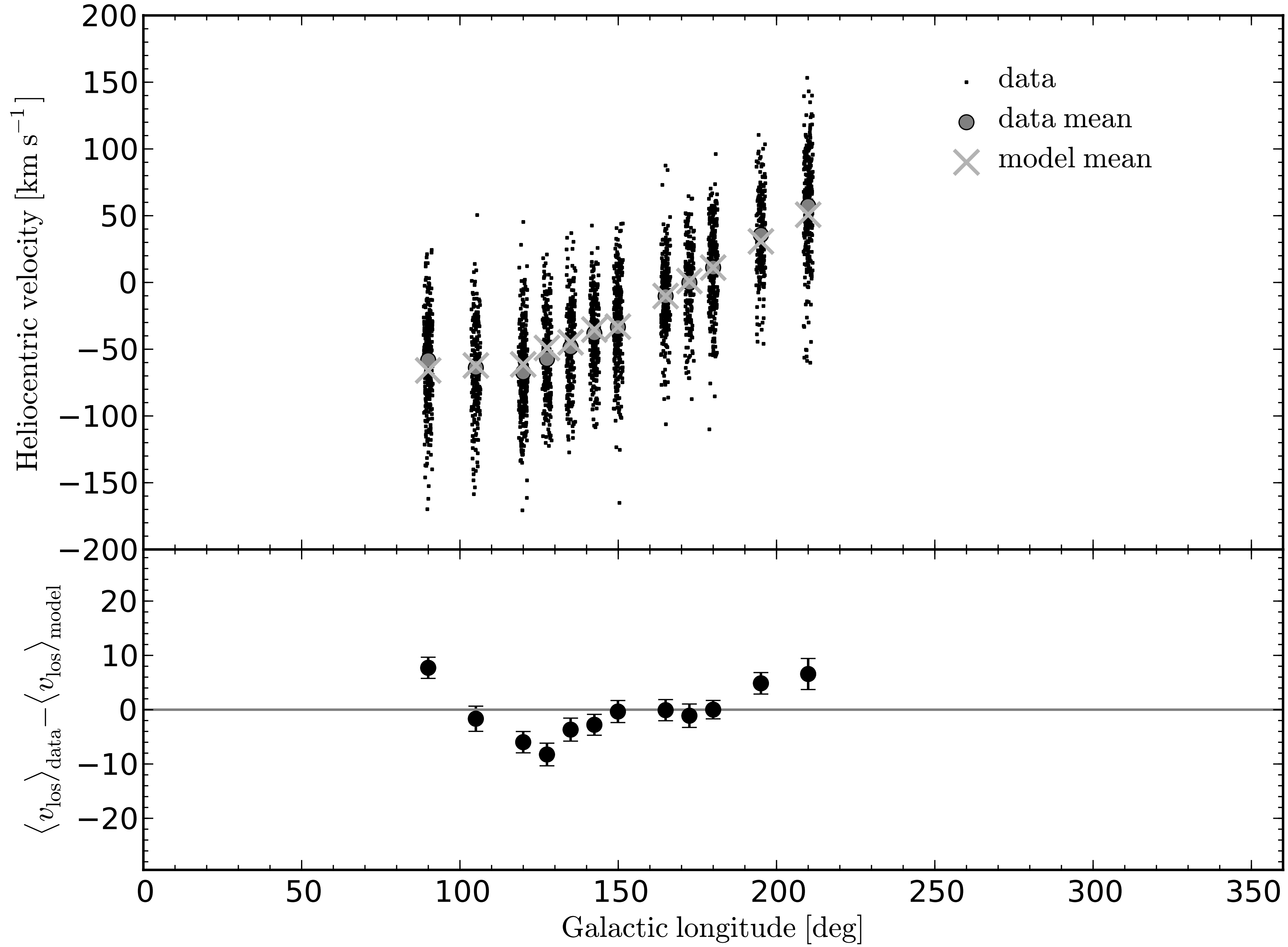
−5
−10
$\langle v_{\rm los}\rangle_{\rm data} - \langle v_{\rm los}\rangle_{\rm model}$
0
50
100
150
200
250
300
350
Galactic longitude [deg]



data
data mean
model mean
Heliocentric velocity [km s$^{-1}$]
$\langle v_{\rm los}\rangle_{\rm data} - \langle v_{\rm los}\rangle_{\rm model}$
Galactic longitude [deg]



data
data mean
model mean
Heliocentric velocity [km s$^{-1}$]
$\langle v_{\rm los}\rangle_{\rm data} - \langle v_{\rm los}\rangle_{\rm model}$
Galactic longitude [deg]
200
150
100
50
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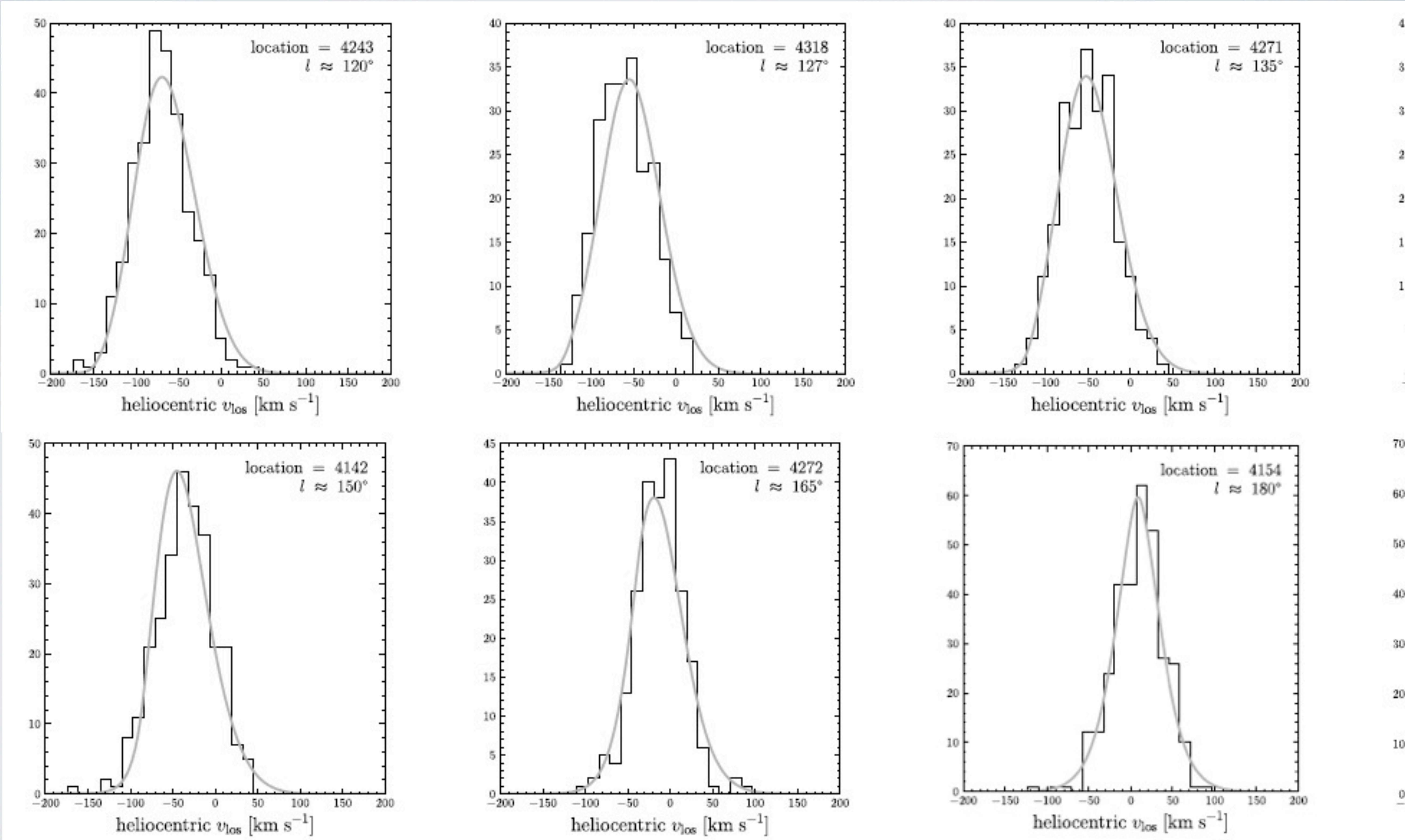
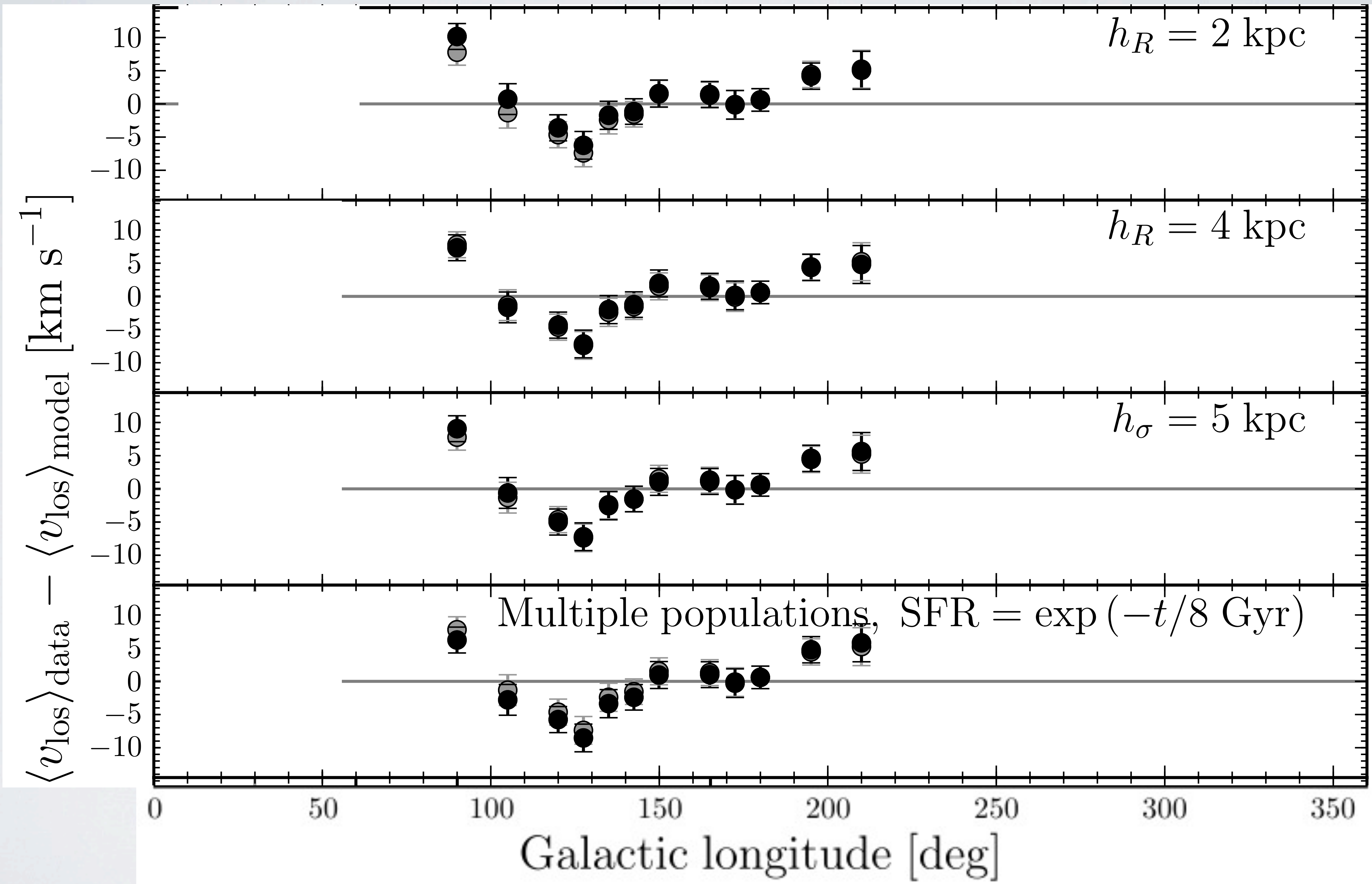
50
100
150
200
250
300
350

# MOST FIELDS ARE BORING



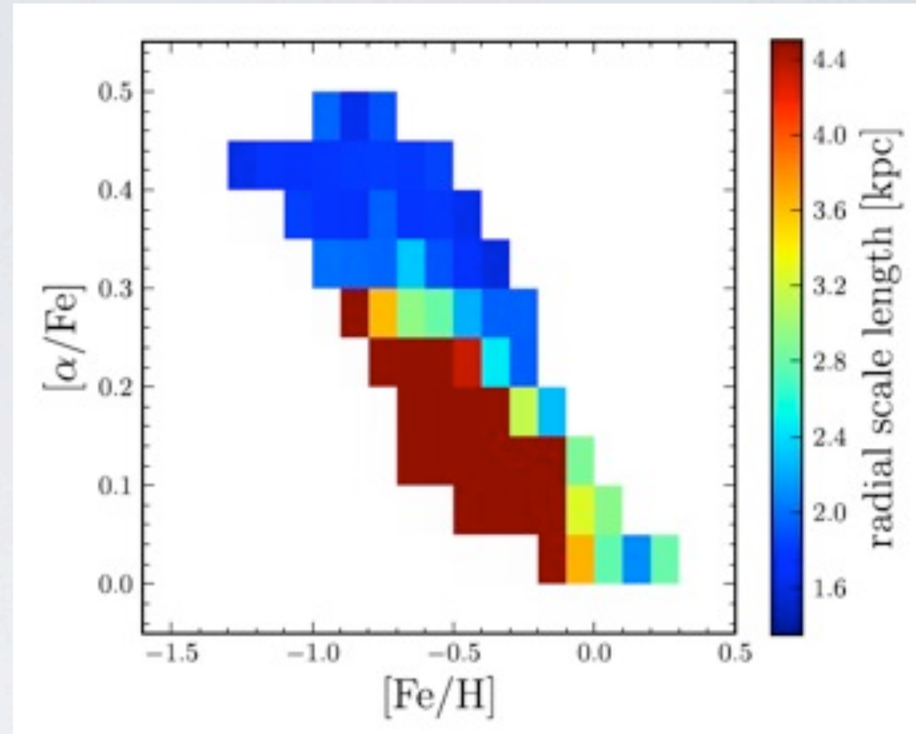
# SYSTEMATICS II

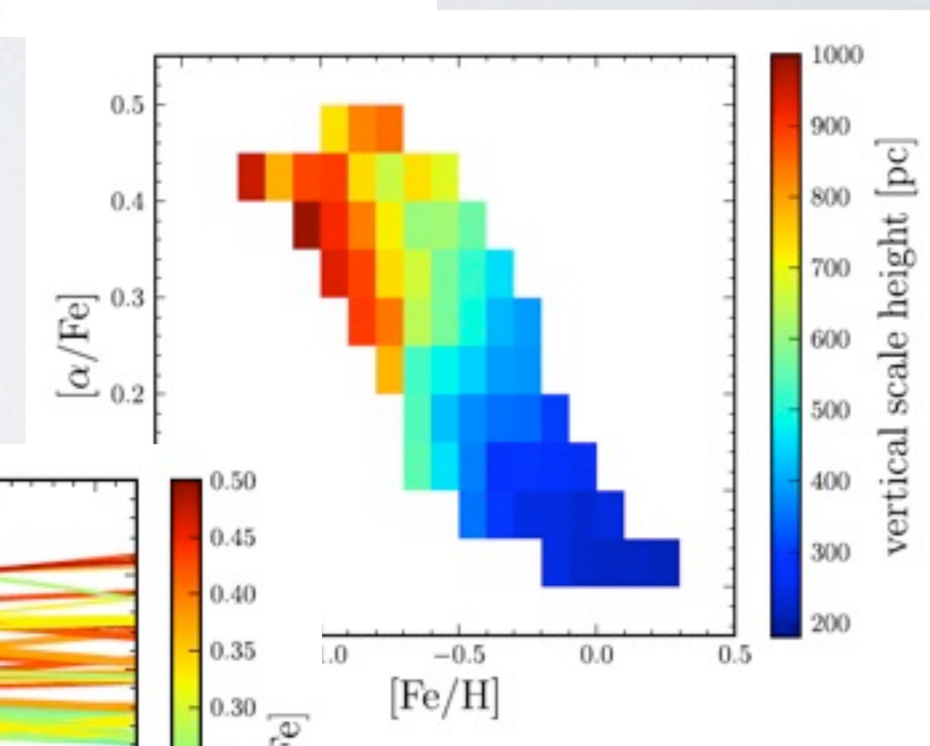


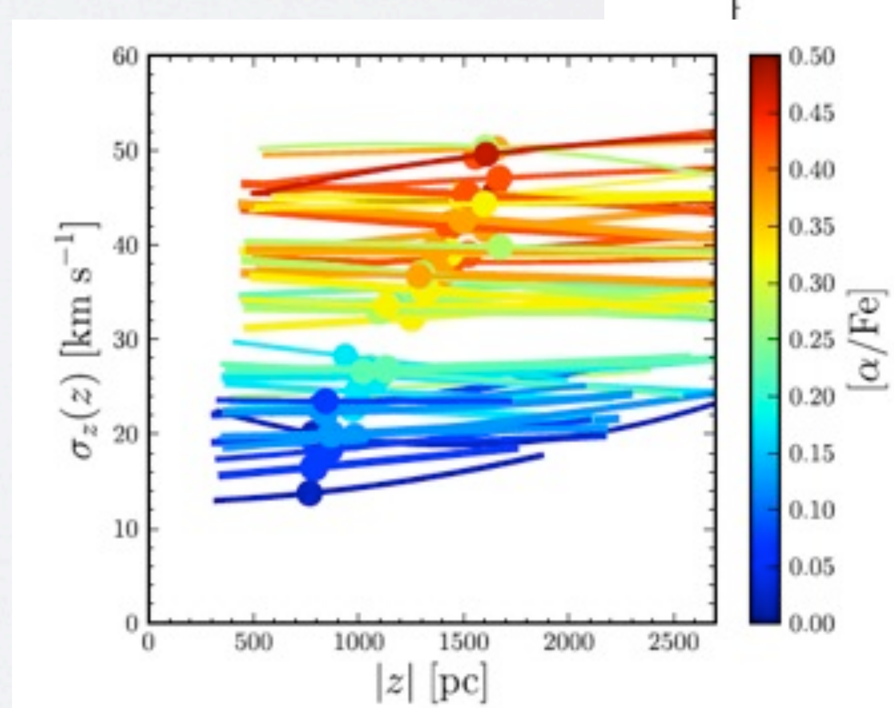
# IS THE THICK DISK A DISTINCT COMPONENT?

# LOOKING AT THE DISK WITH "MONO-ABUNDANCE" GLASSES: RECAP

- SEGUE measures [Fe/H], [a/Fe] for ~30,000 stars between 300 pc <~ |Z| <~ 3 kpc, 5 <~ R <~ 13 kpc
- We fit density and kinematics in narrow Δ[Fe/H] = 0.1 dex, Δ[a/Fe] = 0.05 dex
- Result: each abundance-bin=simple exponential in R and |Z|, isothermal $\sigma_z(z)$



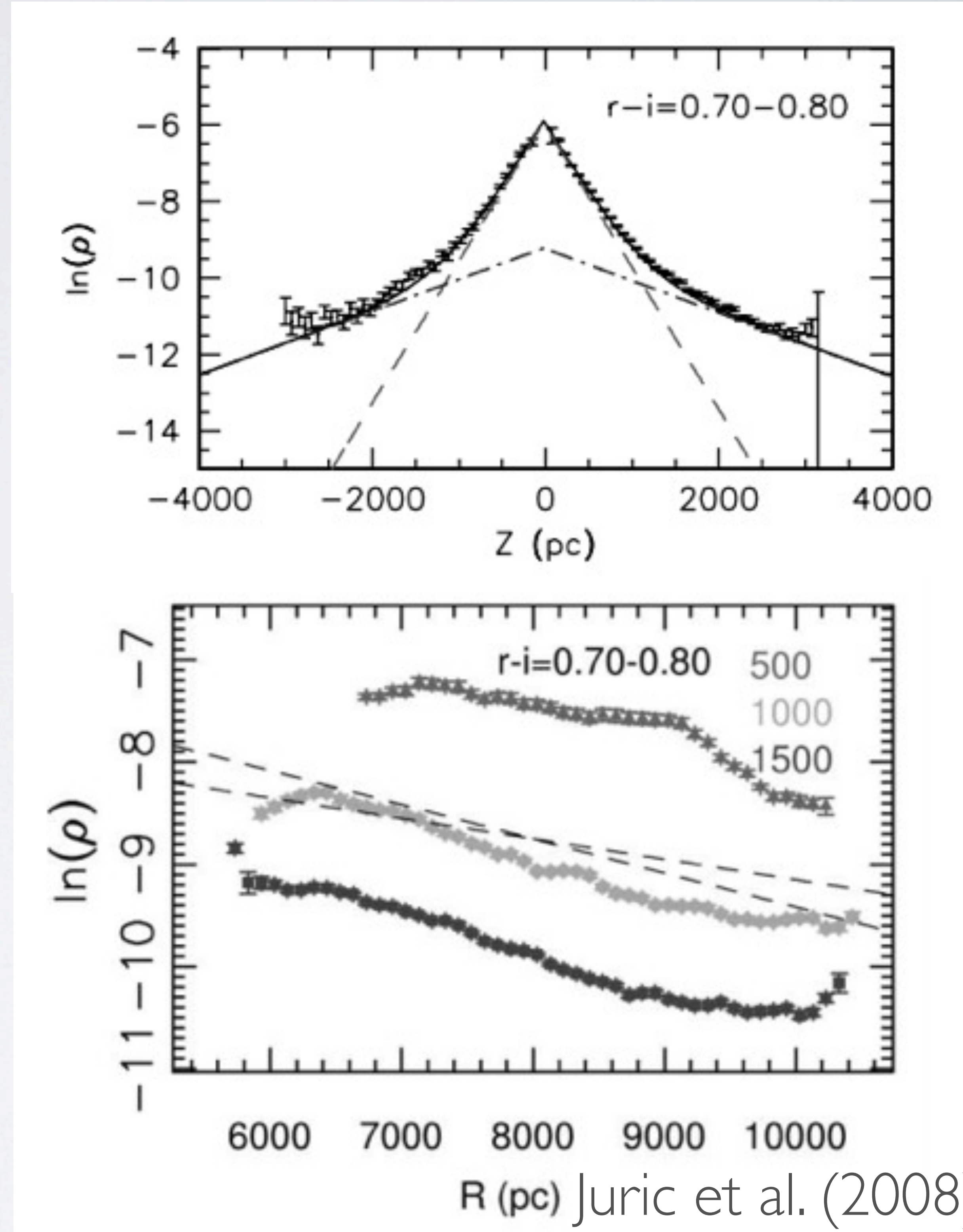
# IS THE THICK DISK A DISTINCT COMPONENT?

- Two-exponential fits to stellar density: fitting function that cannot distinguish between 2 and many components

- There is more than 1 exponential component

- But there is no reason to think that the disk would be a simple exponential

- Abundances....



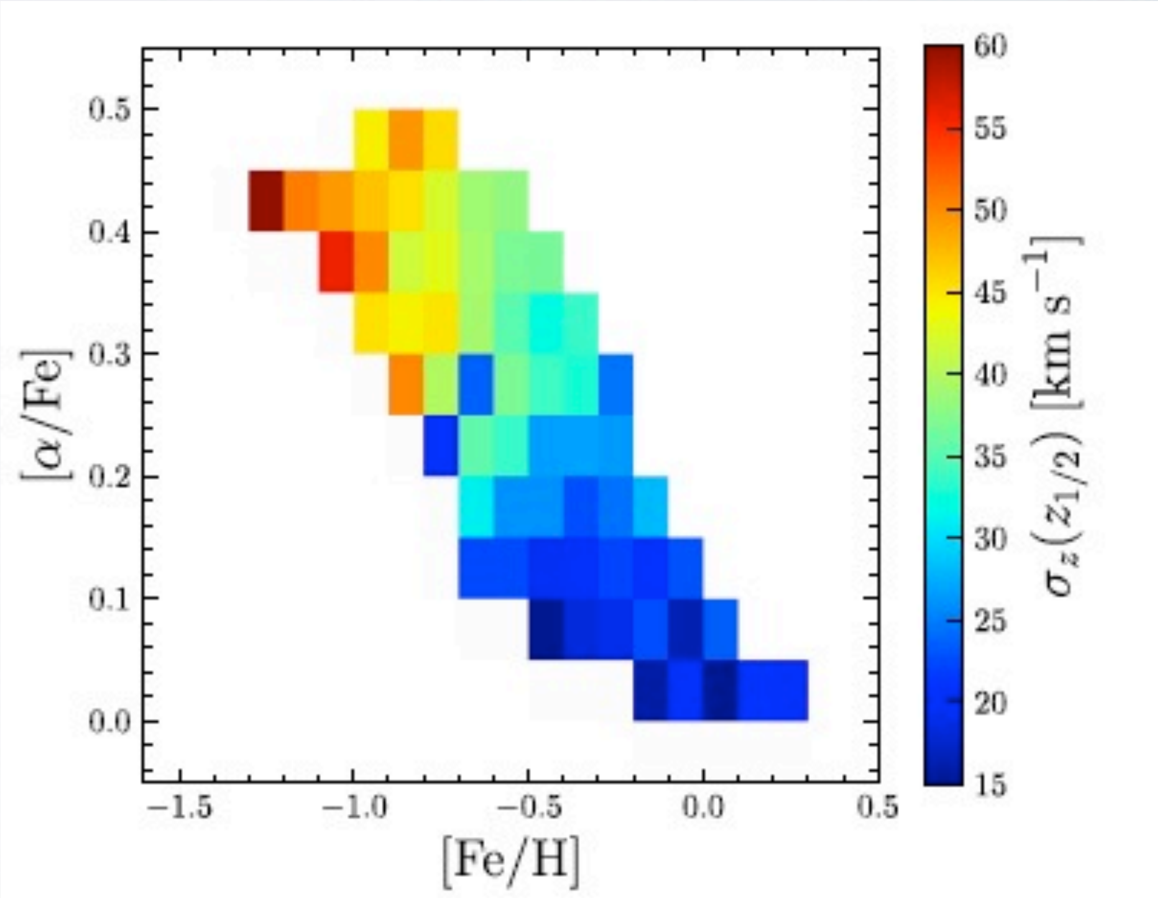

Juric et al. (2008)

# ABUNDANCES ARE EXPENSIVE

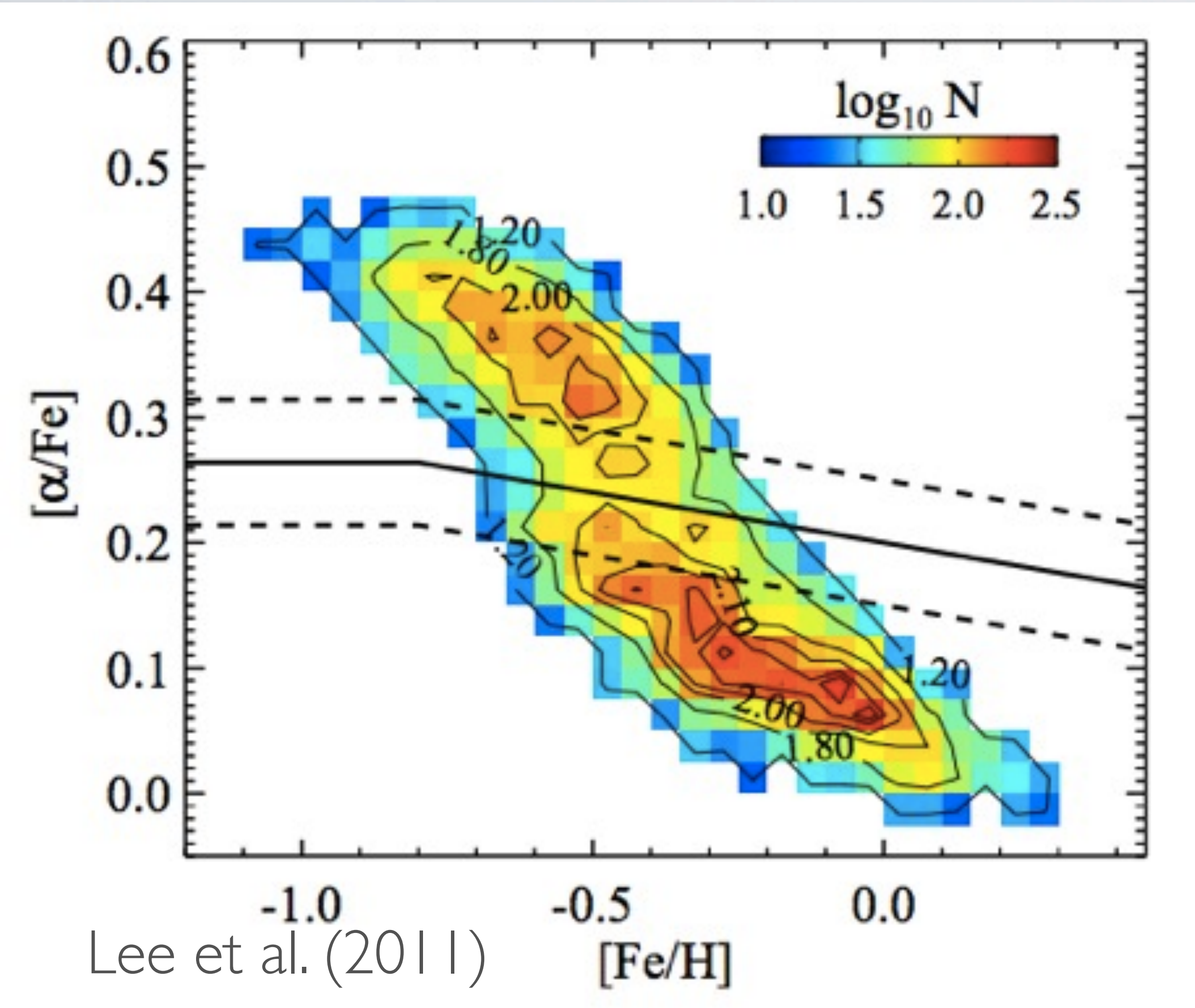
- High-resolution samples are small, local, and heterogeneous:

- Fuhrmann's volume-complete sample: out to 25 pc, only 15 "thick disk" stars, some included outside of sample bounds!

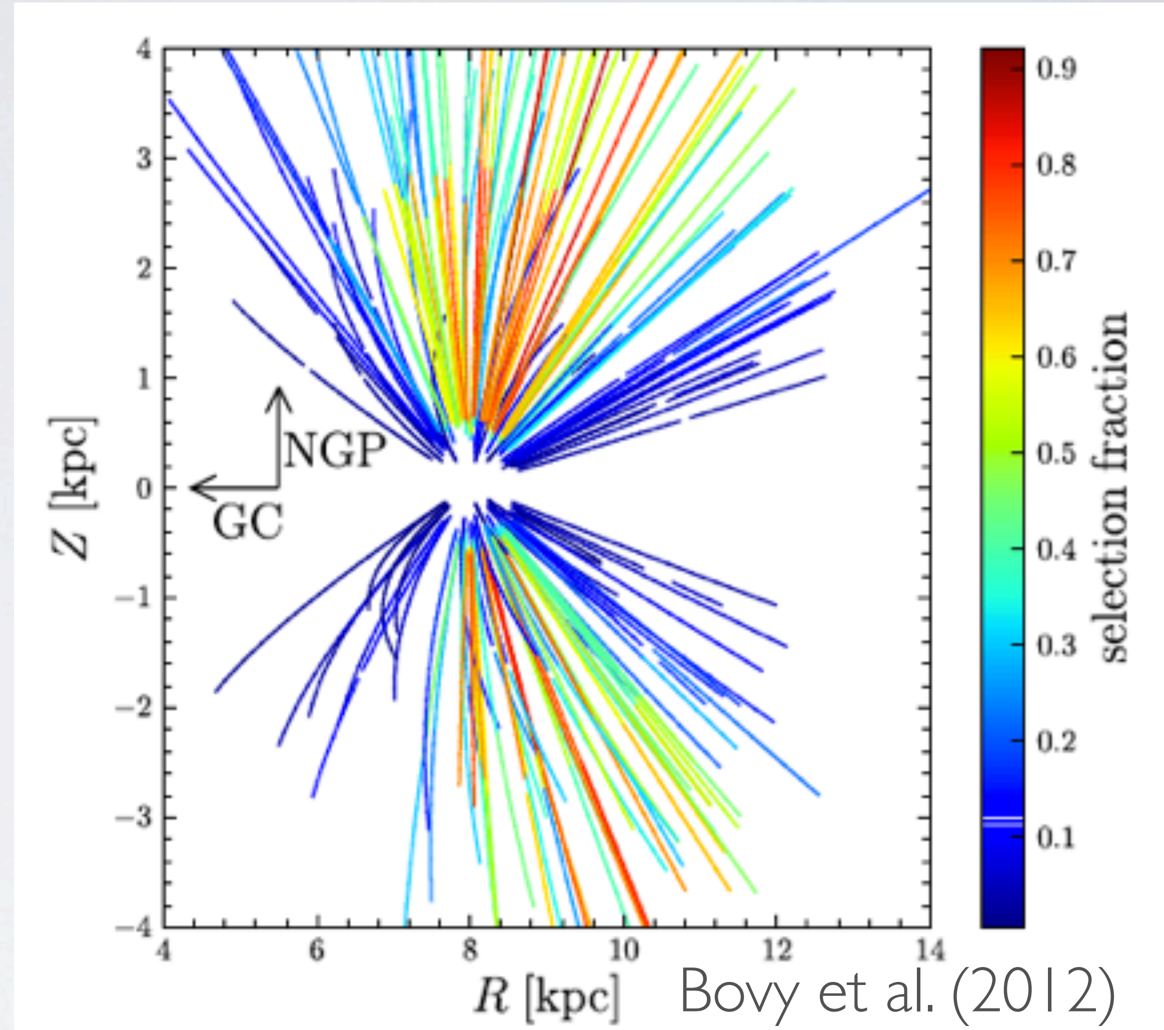
- Other high-resolution samples (e.g., Reddy et al., Navarro et al.): kinematic selection that emphasizes high-[a/Fe] stars, selection effects hard to correct for



# SPECTROSCOPIC SELECTION EFFECTS ARE SEVERE



Lee et al. (2011)

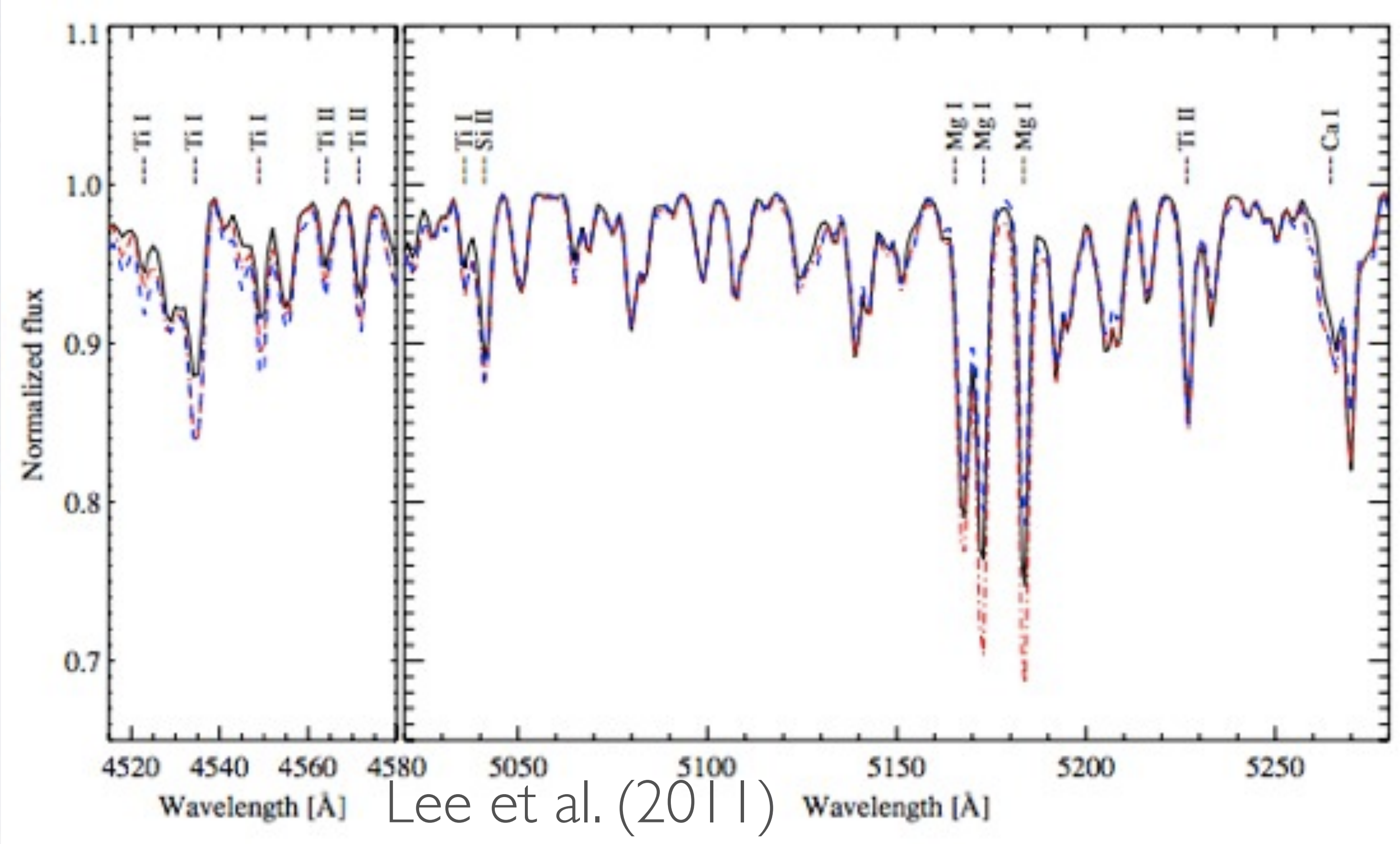


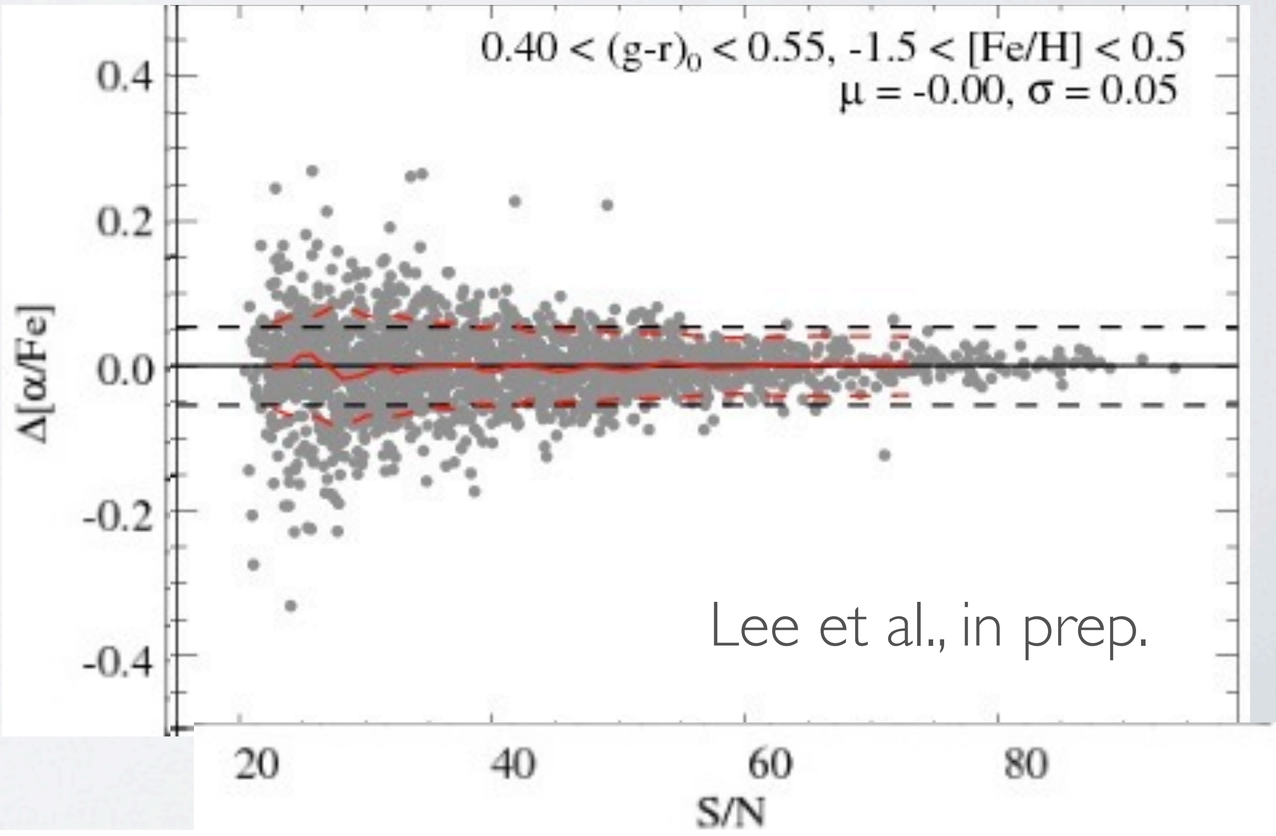
Bovy et al. (2012)

- SEGUE has a relatively simple color-magnitude selection, but the sample is high-latitude, weighted toward the faint end, and weighted toward more low-mass, metal-poor stars
- Impossible to draw conclusions from the figure on the left!

# MEDIUM-RESOLUTION [A/FE]

- Many [a/Fe] lines in SEGUE spectral window
- Comparison with high-resolution shows that procedure works at high S/N
- Repeated observations show internal consistency at low S/N



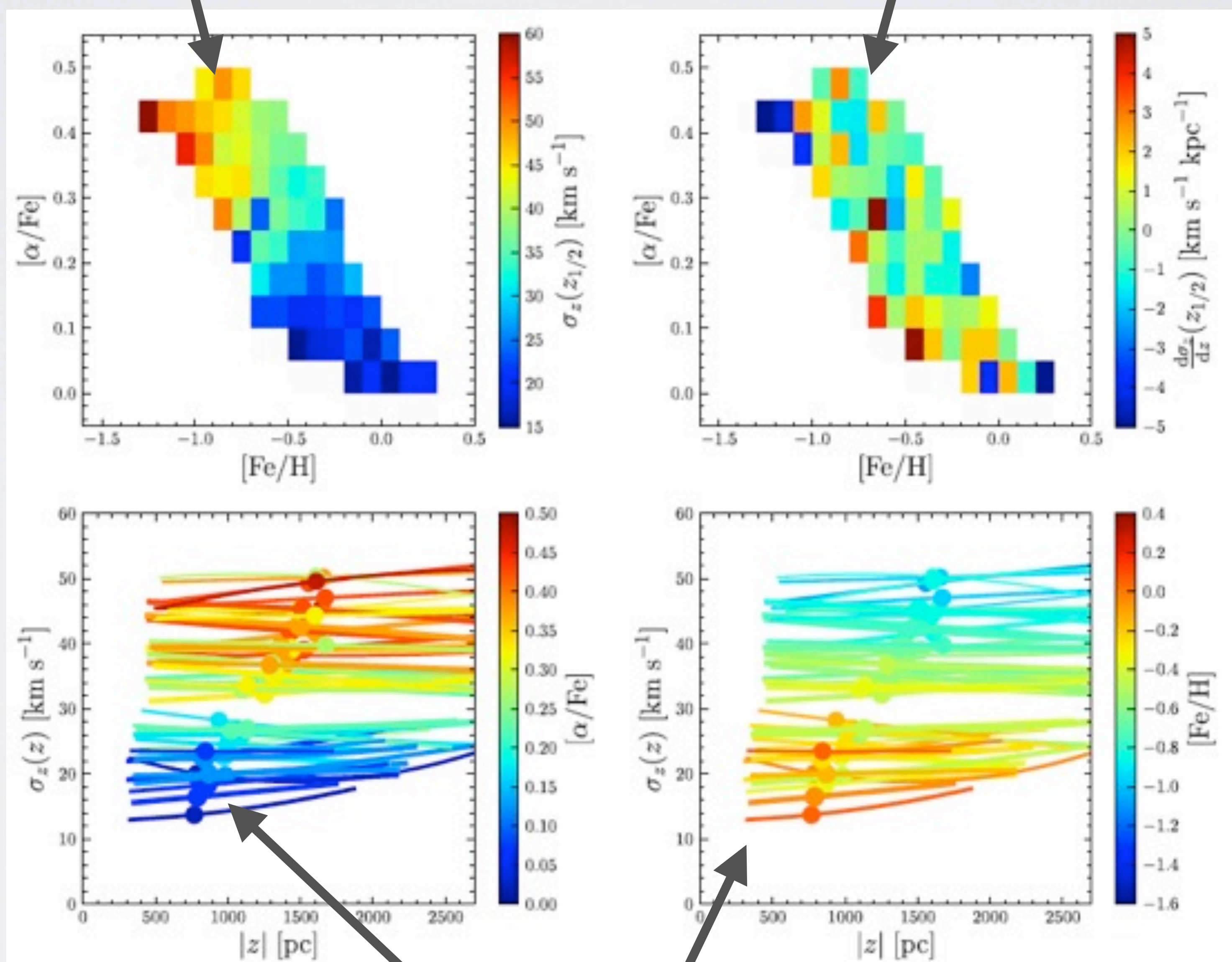
# MEDIUM-RESOLUTION [A/FE]: SCIENCE VERIFICATION

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

Vertical dispersion    p1: slope

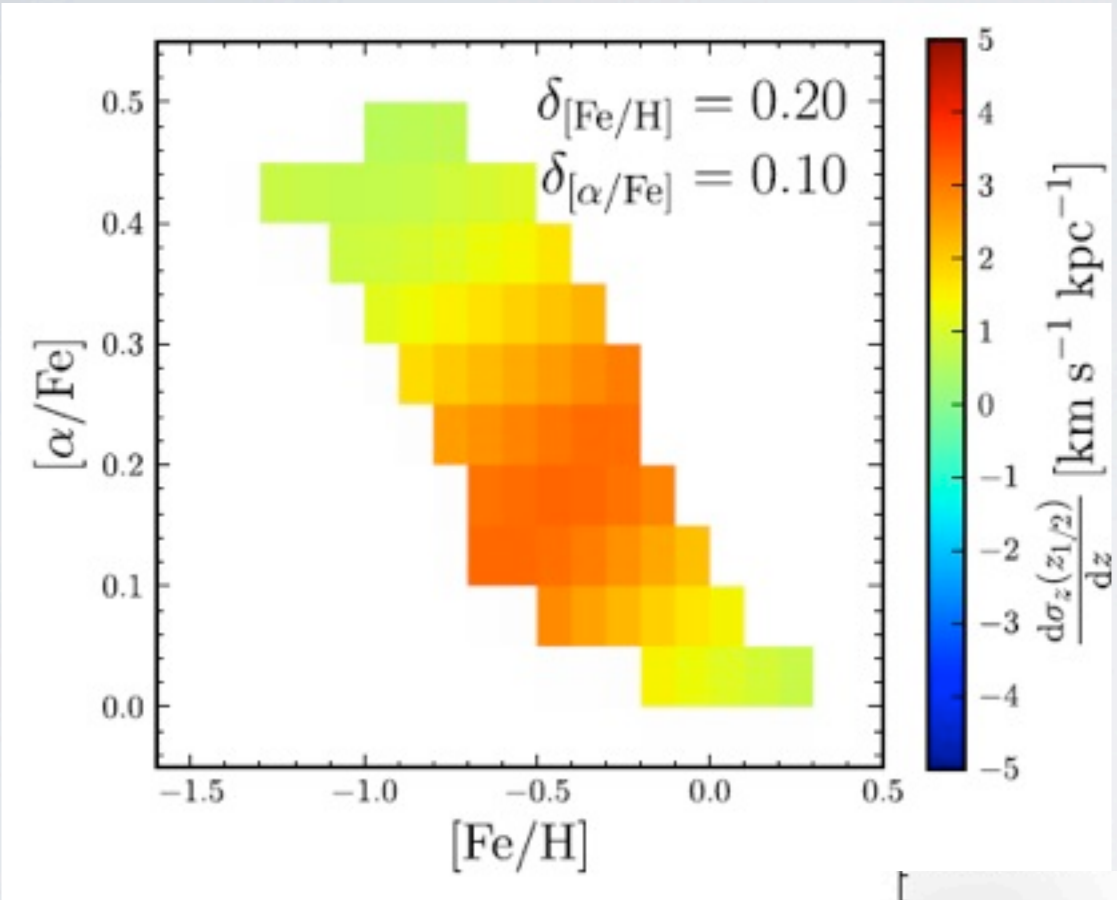
Smoothly increasing dispersion

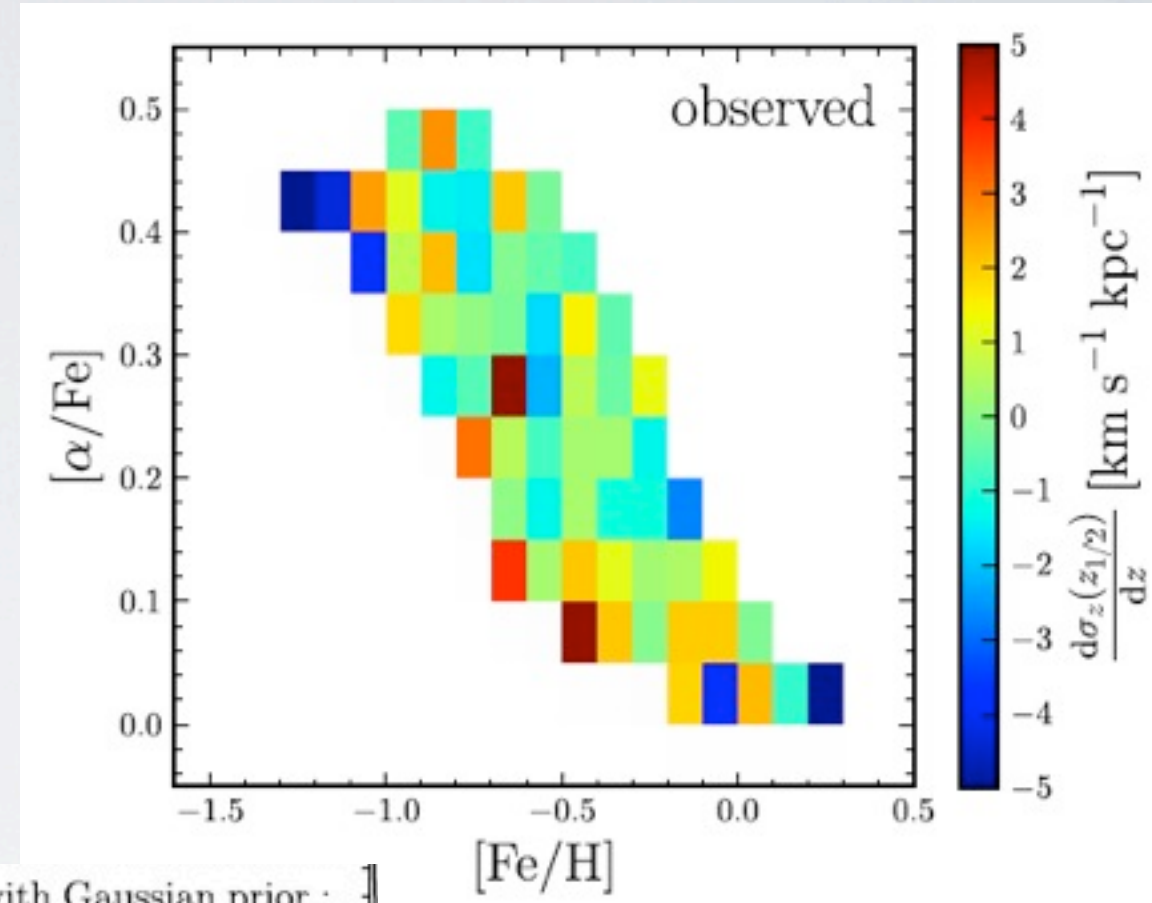
Approximately isothermal

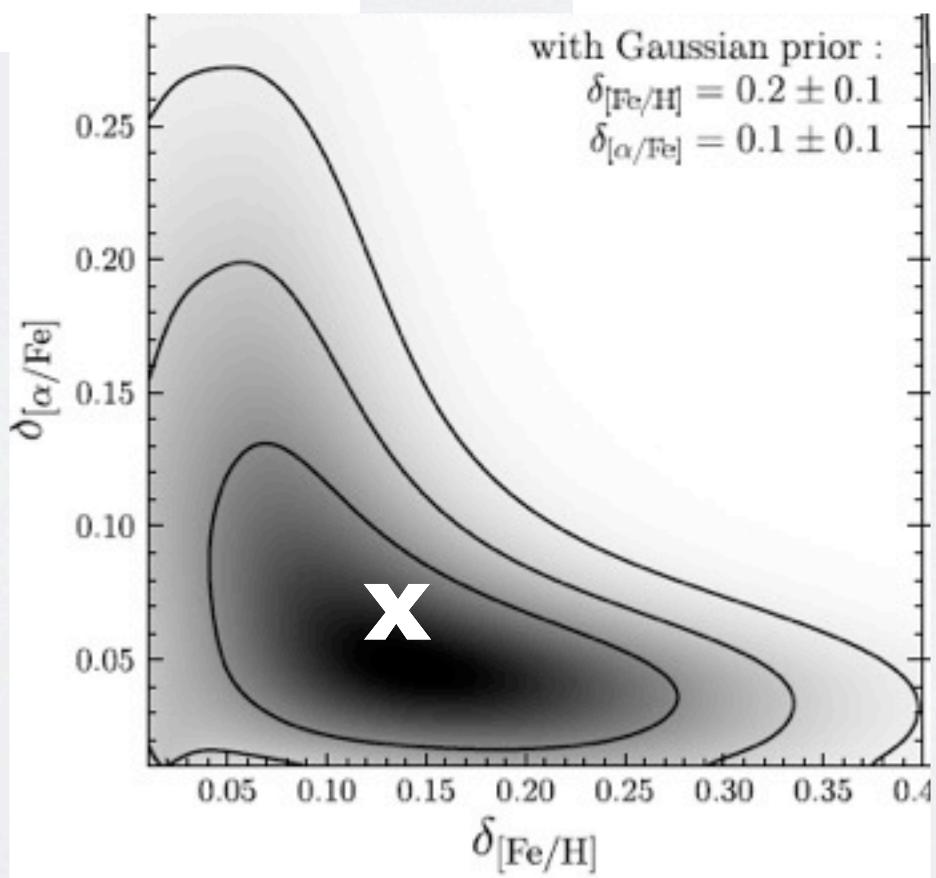



Vertical dispersion profile

# MEDIUM-RESOLUTION [A/FE]: SCIENCE VERIFICATION



# 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:

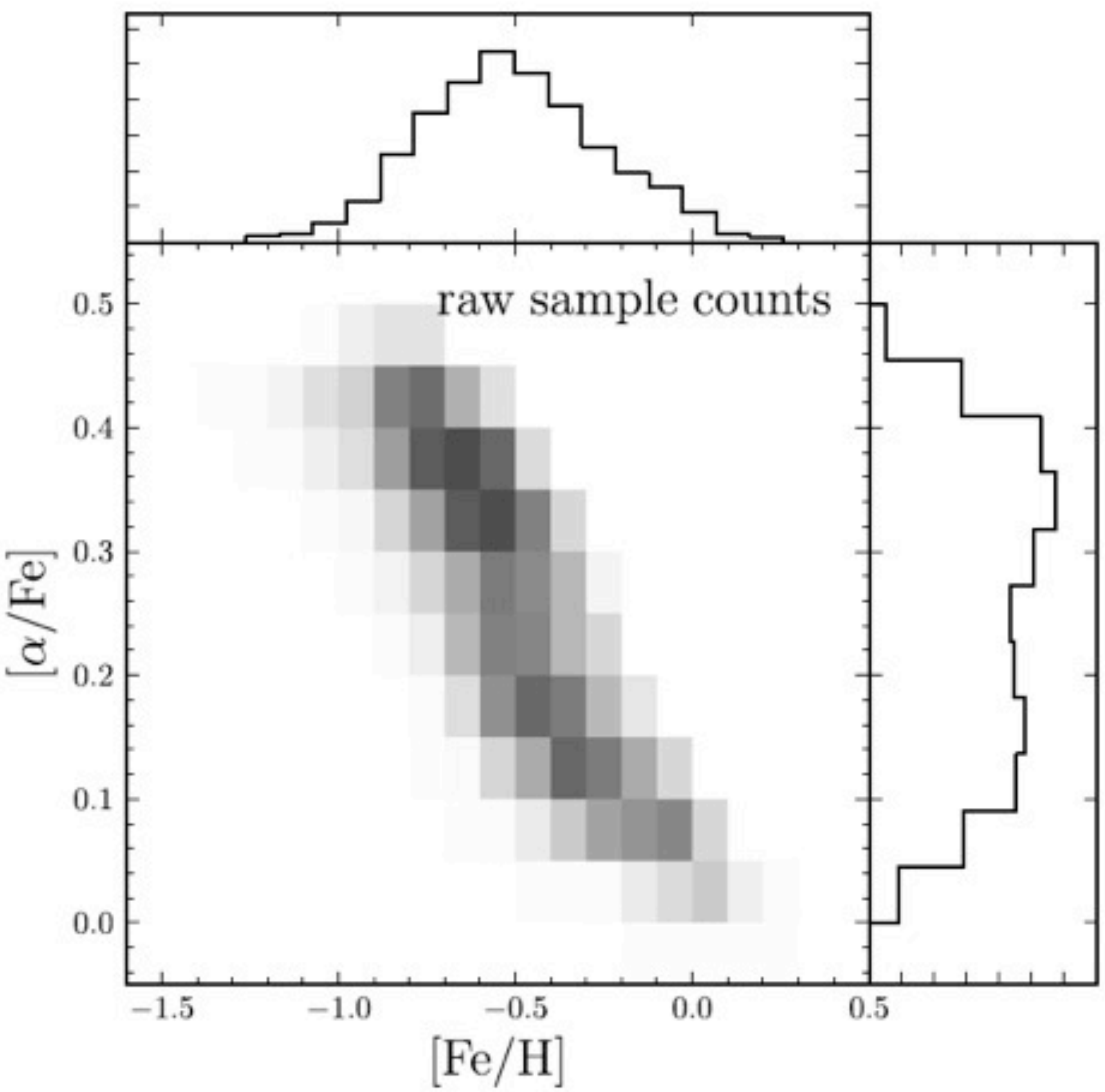
$$\ln \mathcal{L} = \sum_i \{\ln \lambda(\{l, b, d, r, \; g - r, [\mathrm{Fe/H}]\}_i | \theta)\} - \int \mathrm{d}l \, \mathrm{d}b \, \mathrm{d}d \, \mathrm{d}r \, \mathrm{d}(g - r) \, \mathrm{d}[\mathrm{Fe/H}] \, \lambda(l, b, d, r, g - r, [\mathrm{Fe/H}] | \theta)$$

- allows us to derive the number normalization factor

Bovy et al. (2012); arXiv:1111.1724

# DOES THE MILKY WAY HAVE A THICK DISK?

## CHEMICAL BI-MODALITY?




Bovy, Rix, & Hogg (2012), ApJ, in press, arXiv:1111.6585

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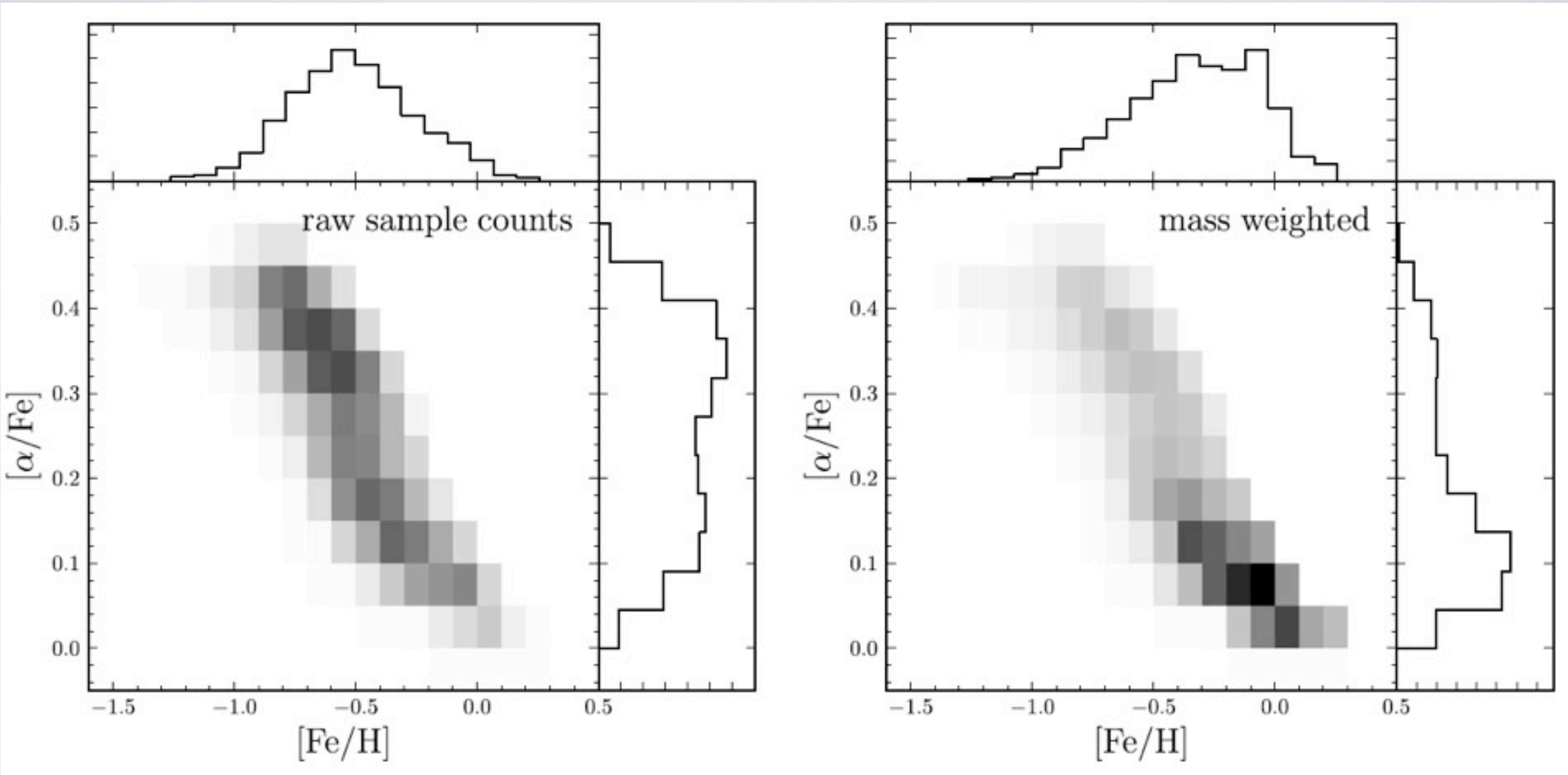


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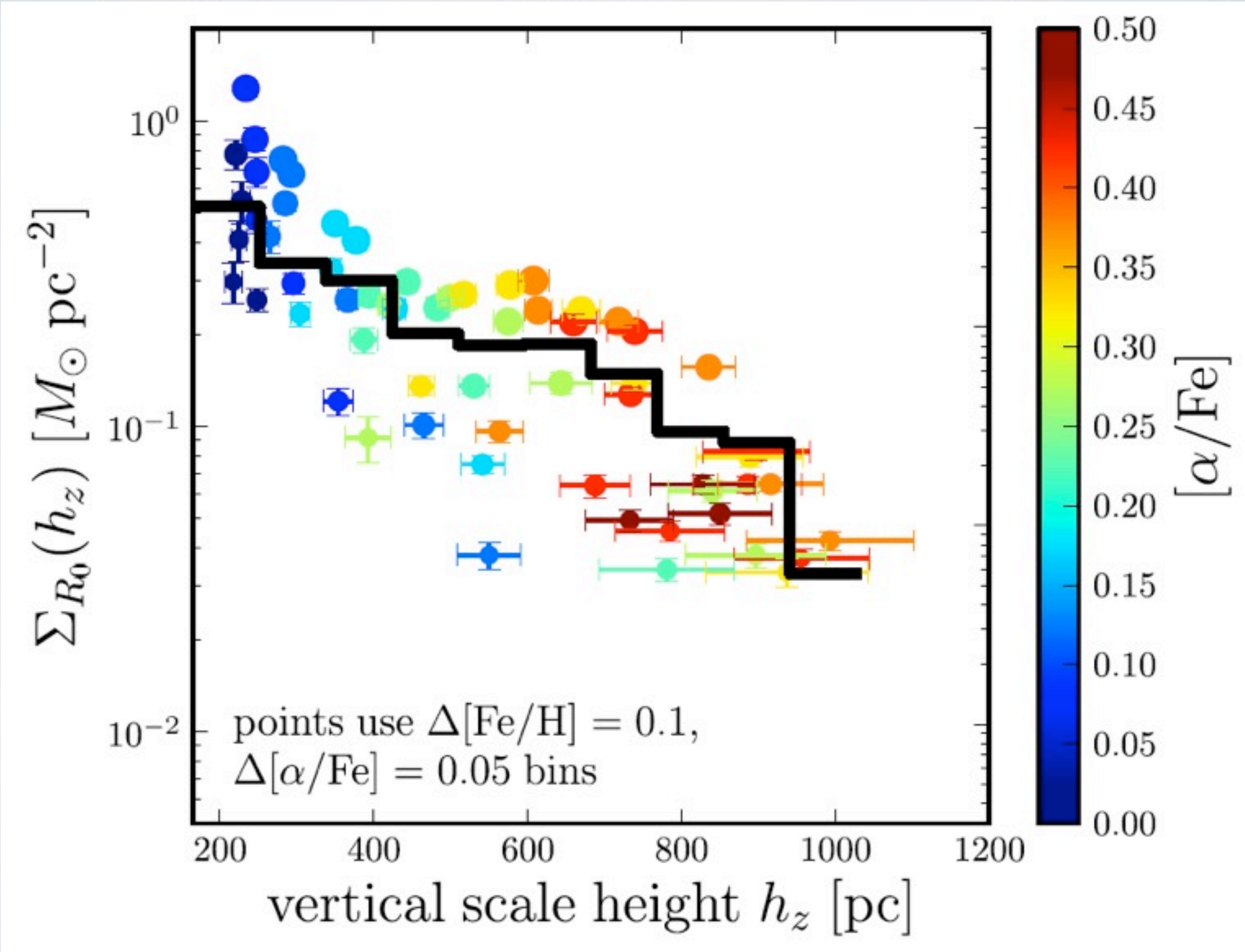
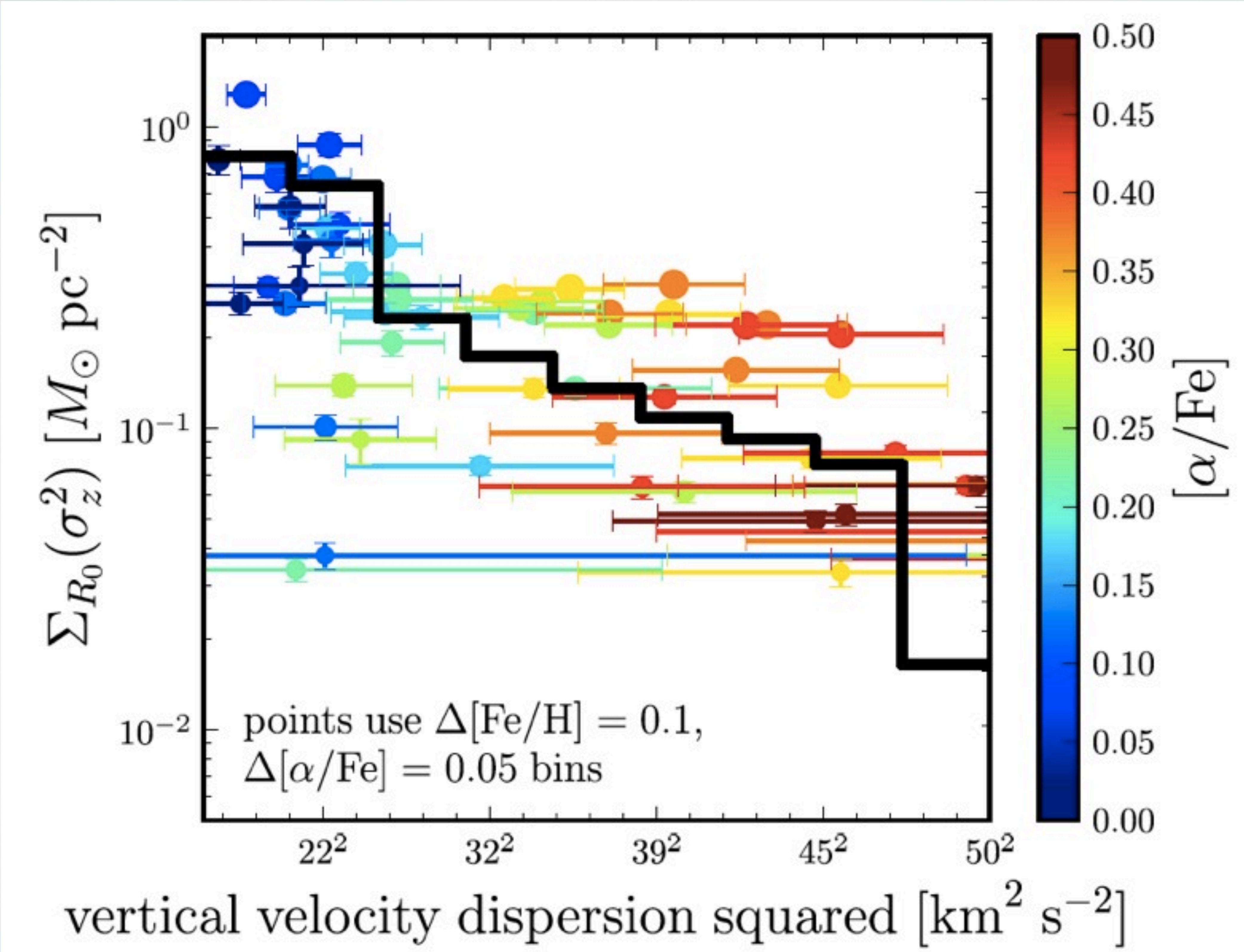
# DOES THE MILKY WAY HAVE A THICK DISK?
## SCALE-HEIGHT BI-MODALITY?




Bovy, Rix, & Hogg (2012), ApJ, in press, arXiv:1111.6585

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




Bovy, Rix, et al. (2012), arXiv:1202.2819

# CONCLUSIONS

- On our way to constrain MW rotation curve with APOGEE
- APOGEE data prefers low value of circular velocity
- Analysis of SEGUE data implies no break between "thin" and "thick" disk components