The Milky Way's stellar and dark mass distributions

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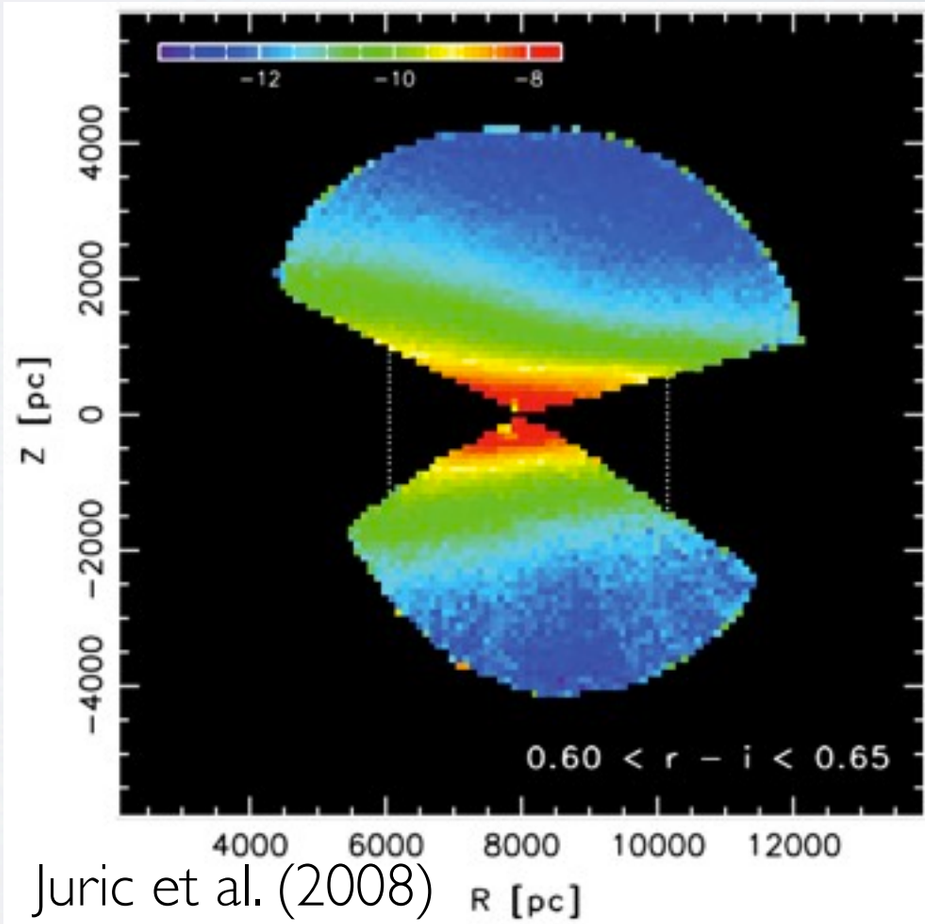
THE MILKY WAY

- MW: fairly typical example of large disk galaxy
- MW provides unique detailed view of the distribution of baryonic and dark matter in a large disk galaxy
- This talk: new measurements of the MW's stellar density distribution and gravitational potential

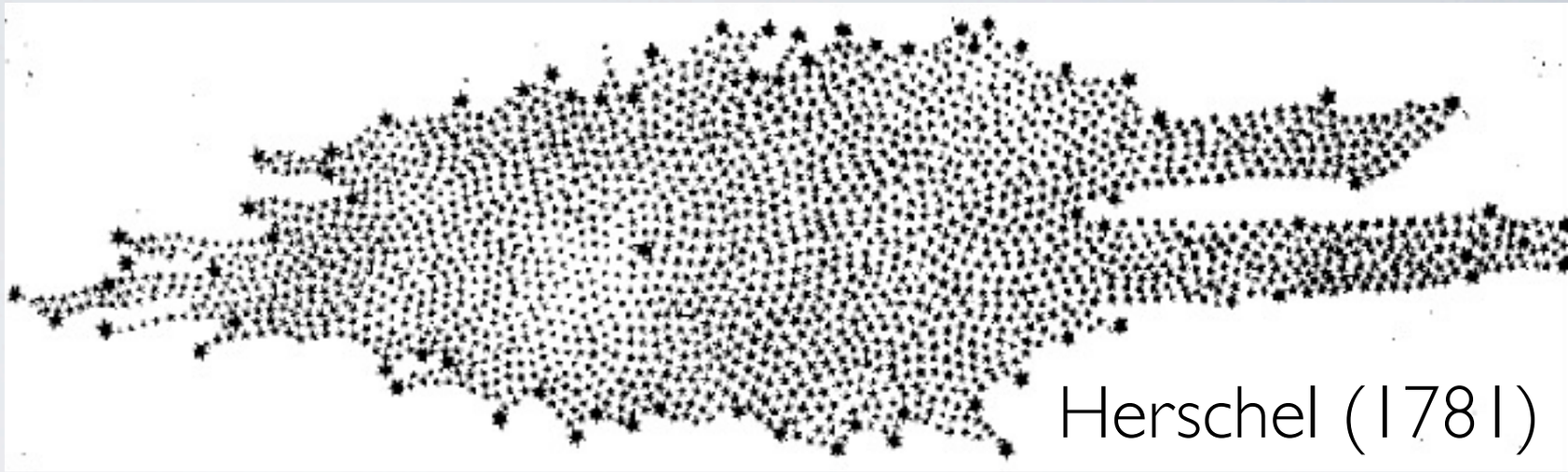


Juric et al. (2008)

STELLAR AND DARK MASS IN THE INNER MILKY WAY

- What is the overall structure of the disk and how did it change over time? Did the disk grow "inside-out"?
- What is the Milky Way's circular velocity?
- What is the relative importance of baryonic and dark matter:
  - Is the Milky Way's disk maximal? That is, does it have as much baryonic matter as possible without a central hole in the dark halo?
  - How much dark matter is there near the Sun?
- What is the radial profile of the halo? Is the halo contracted?
- What is the total stellar mass of the Milky Way? Is this normal for a galaxy with the MW's circular velocity?
- Is all of the dynamical mass accounted for by baryonic matter + ~spherical DM?

STAR COUNTS



Phenomenological:

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

Dynamical:

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

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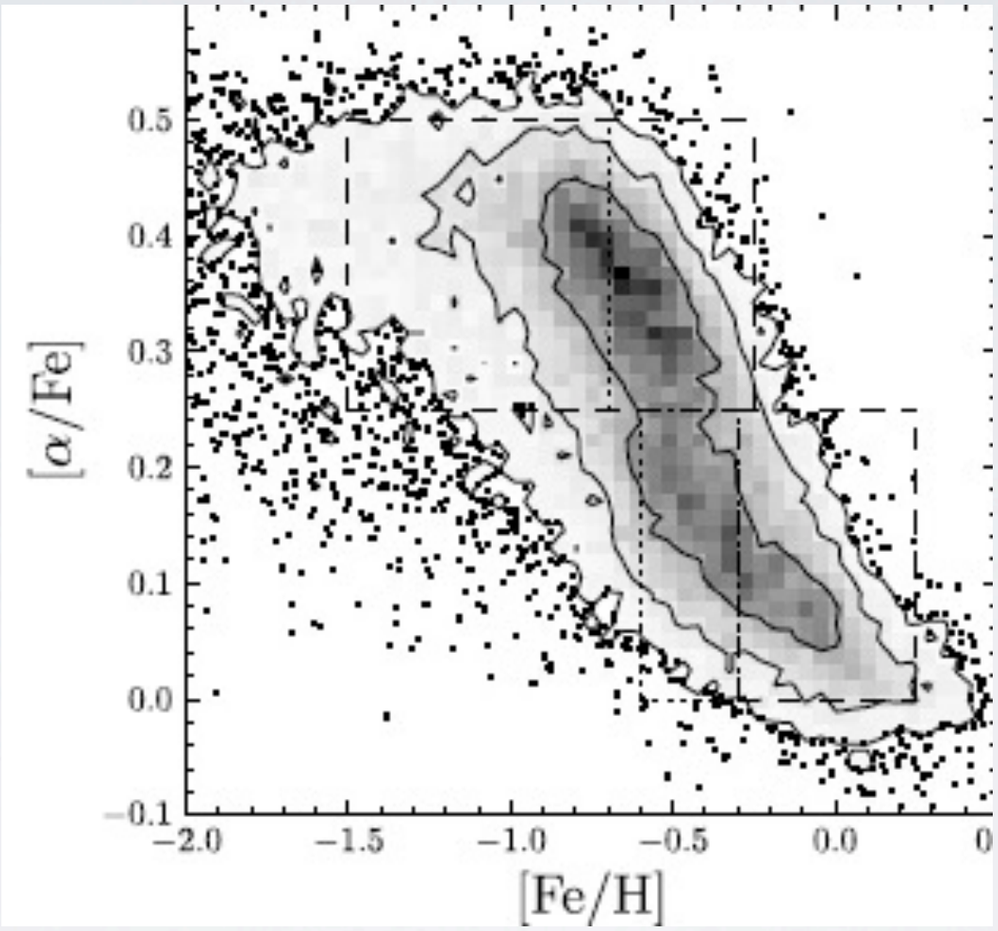
MAPS: MONO-ABUNDANCE POPULATIONS



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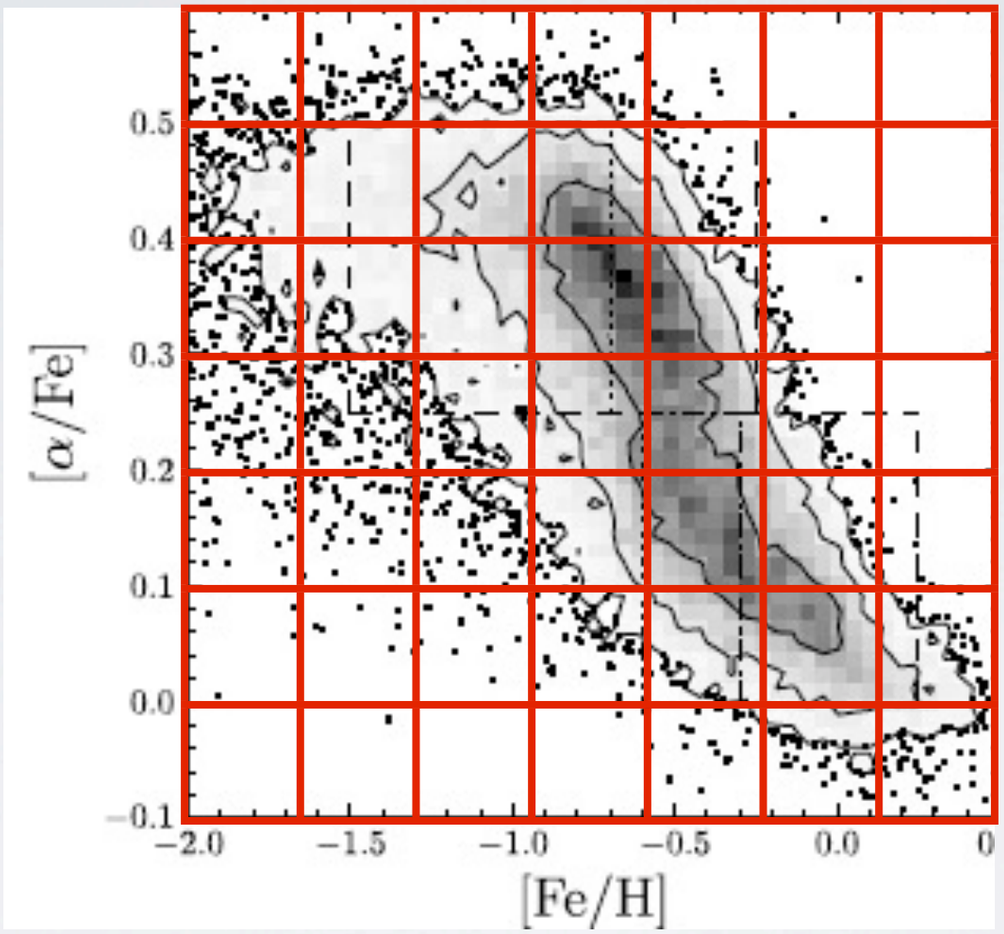

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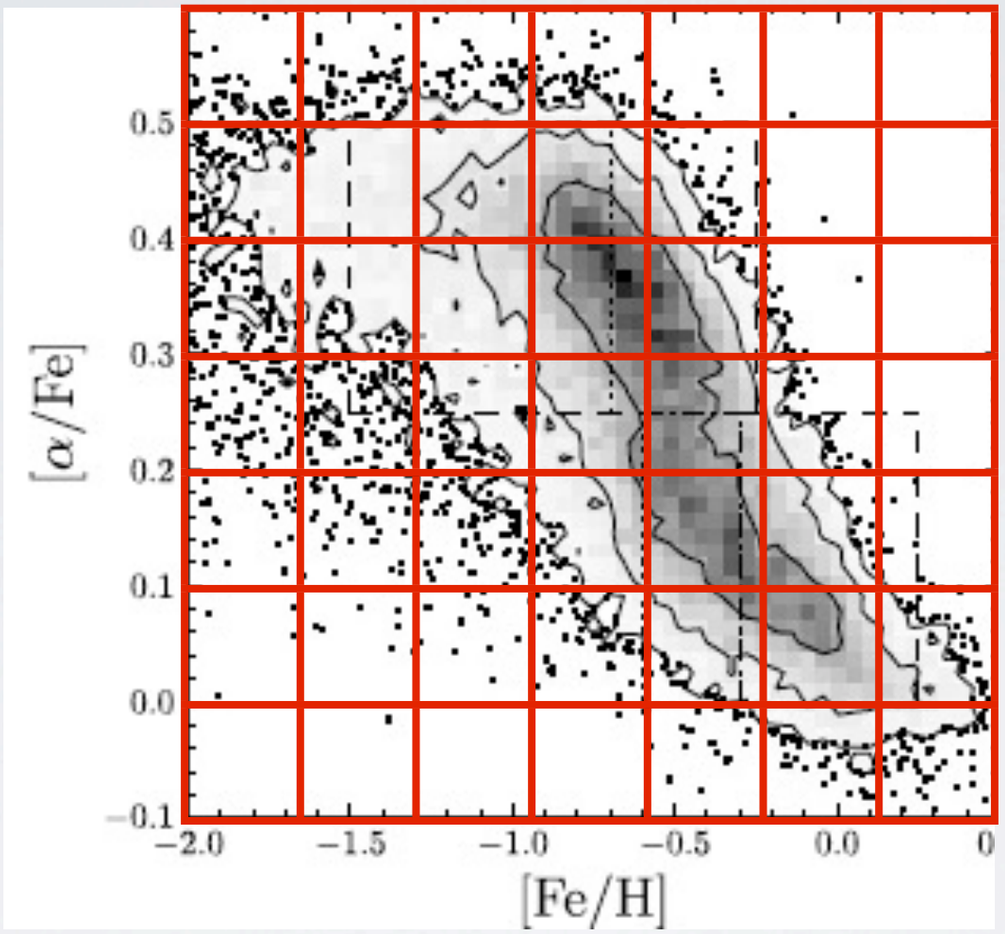
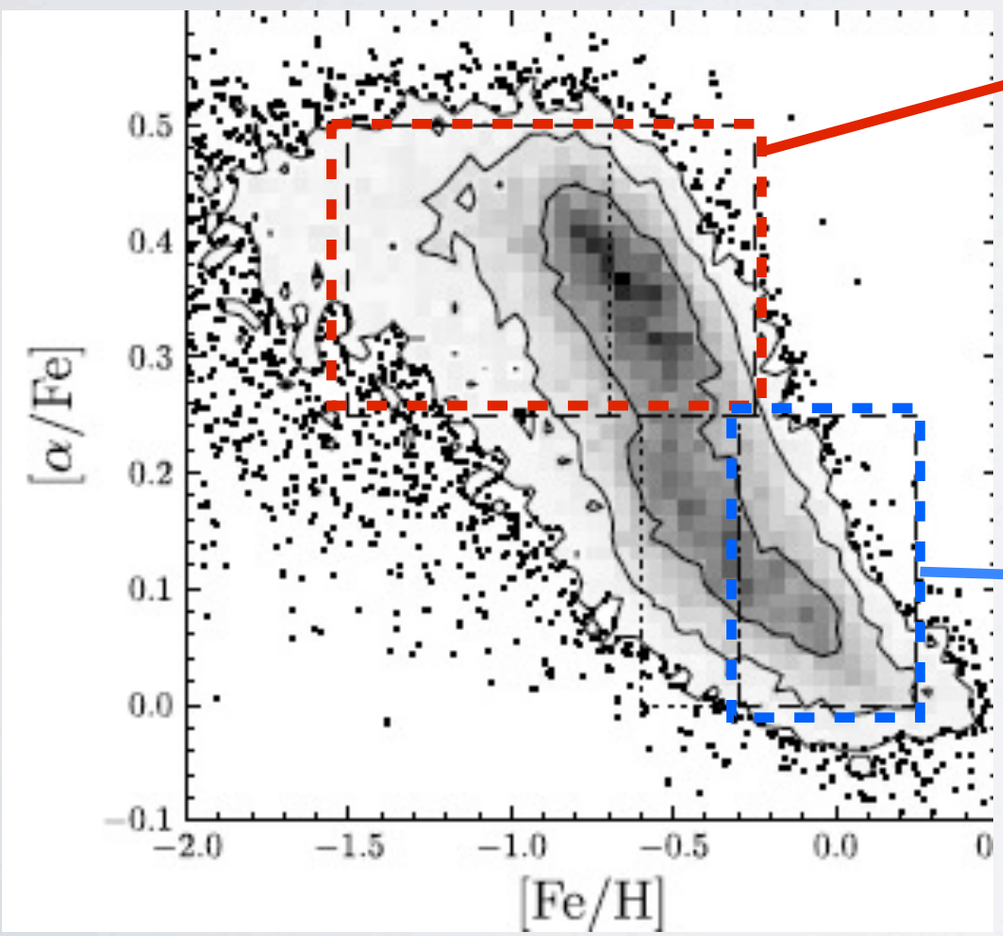


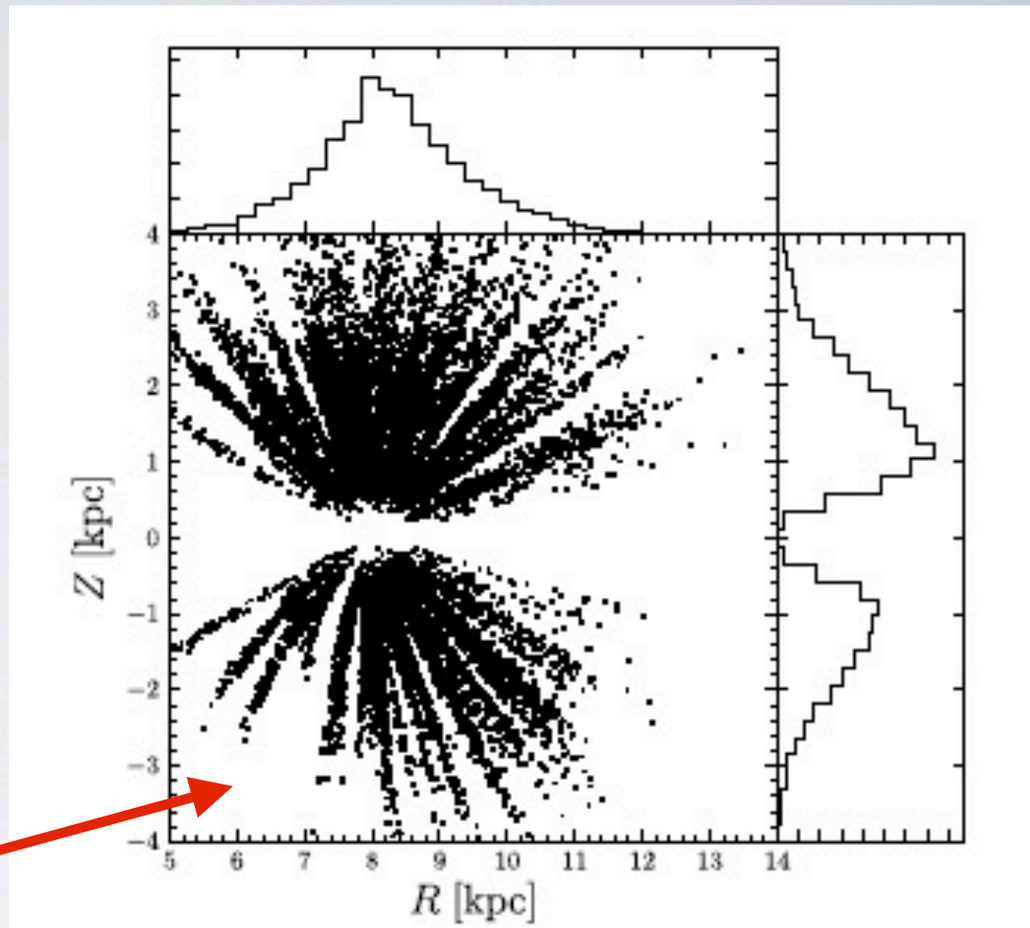
- What is the spatial and kinematic structure of each MAP?
- What does this tell us about the global structure of the disk?

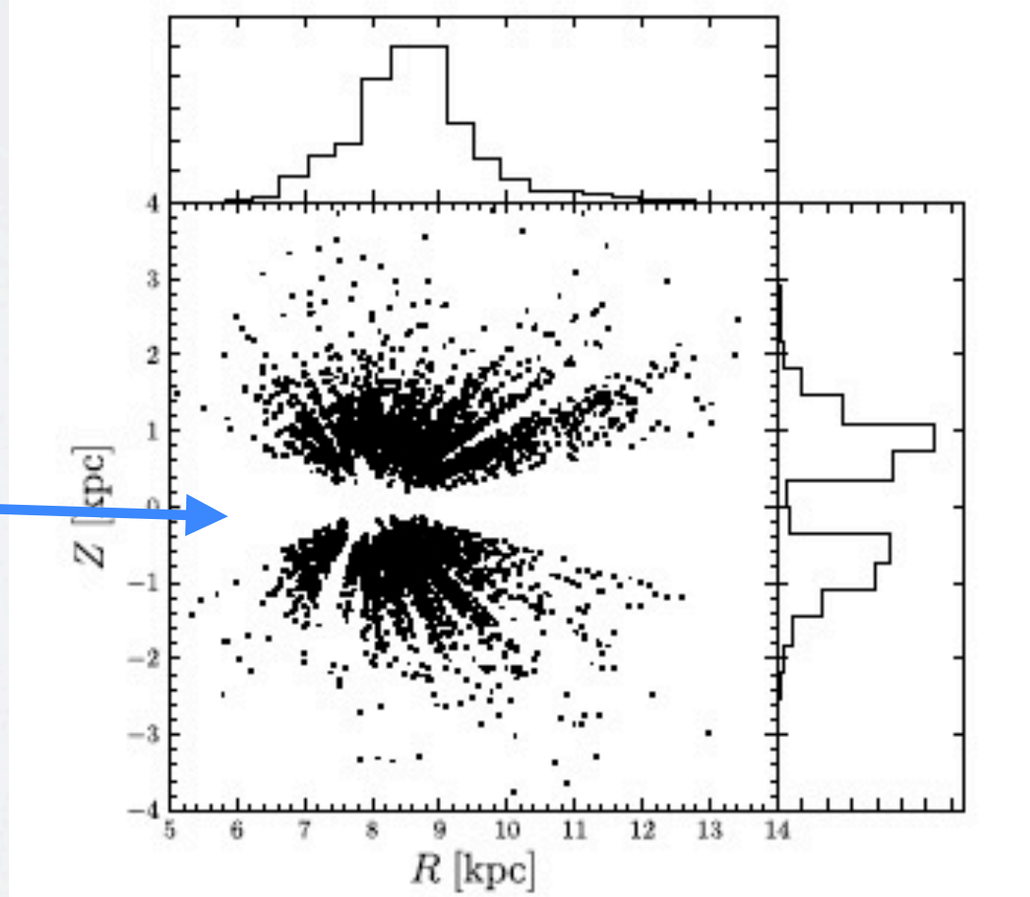
SEGUE G STARS

- G dwarf sample: 0.48 ≤ g-r ≤ 0.55, 14.5 ≤ r ≤ 20.2, log g > 4.2, SN > 15, —*30,000 stars*

- Narrow range of Teff → relative ranking of [Fe/H] and [α/Fe] good







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

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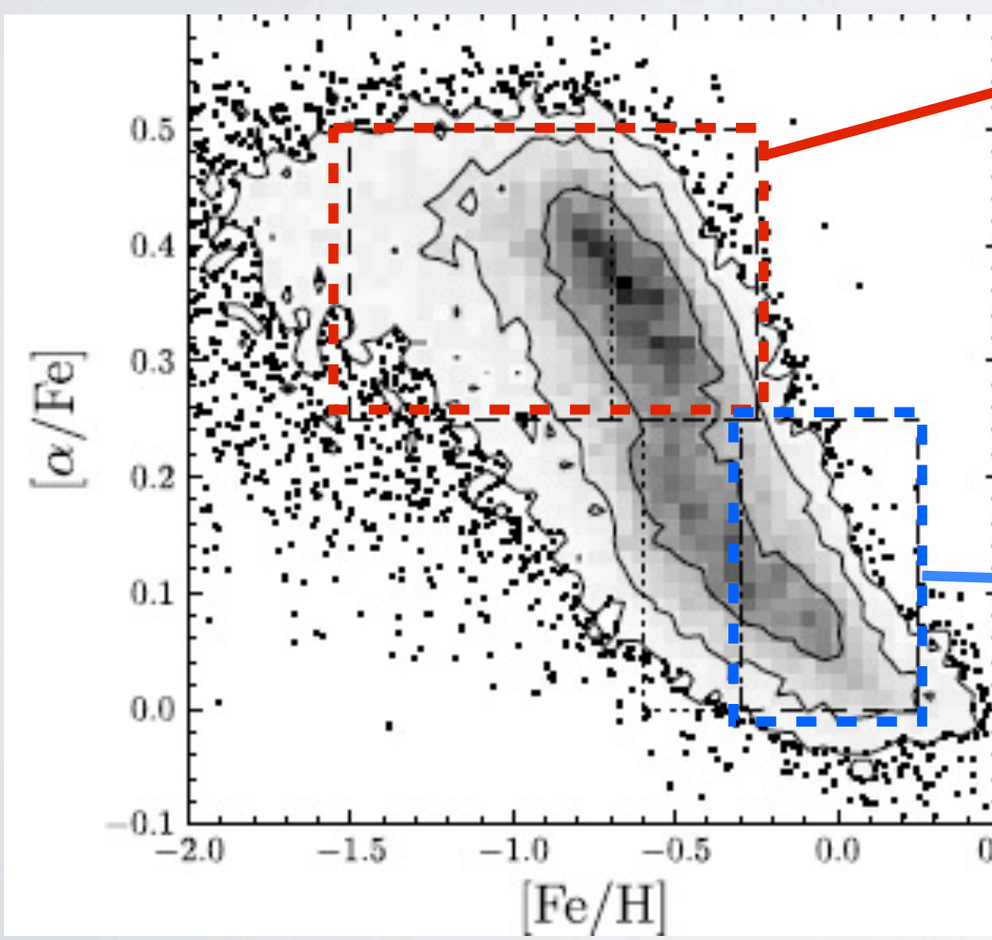

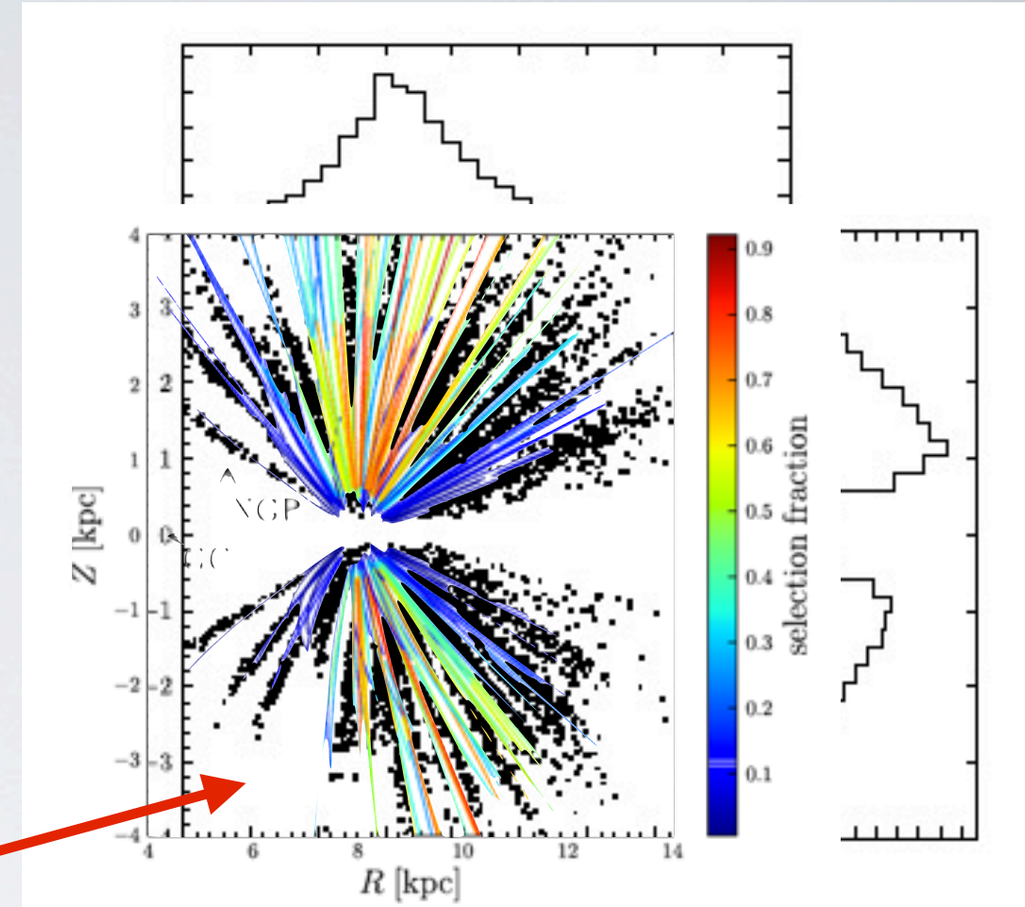

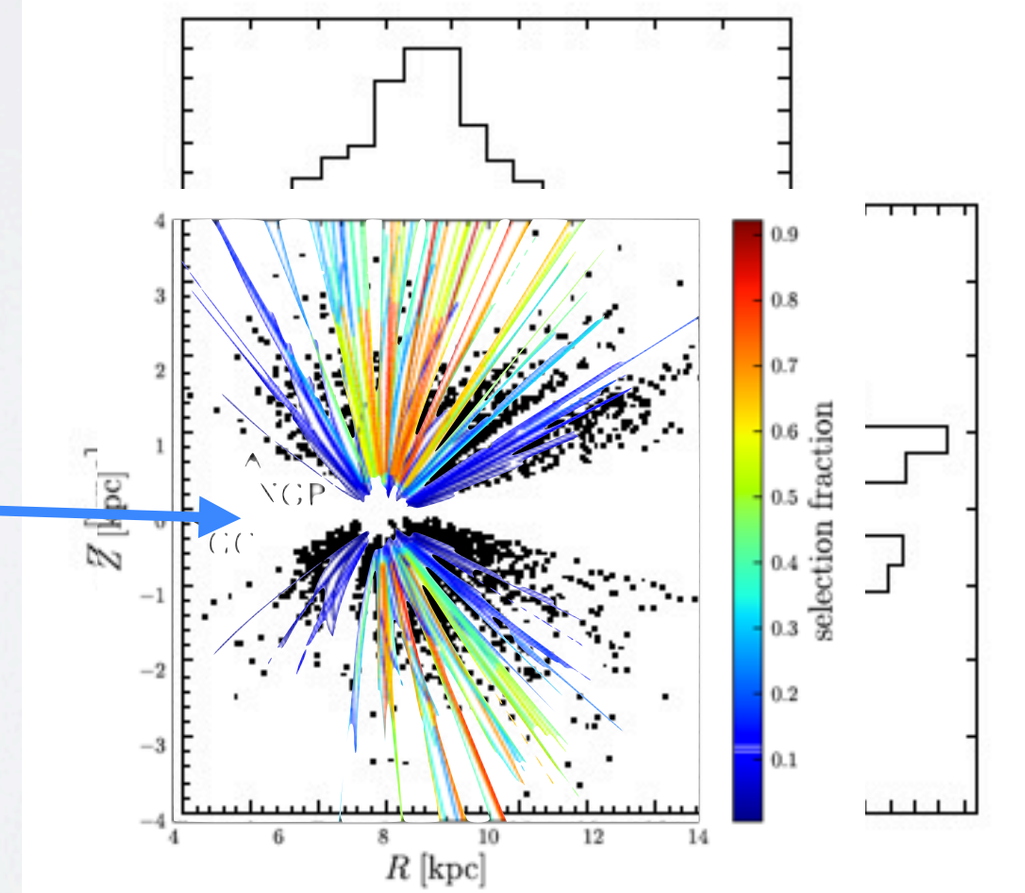

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LIKELIHOOD-BASED DENSITY FITS

- proper model is a *Poisson process*
- observed density of stars $\boldsymbol{\lambda}$(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:

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

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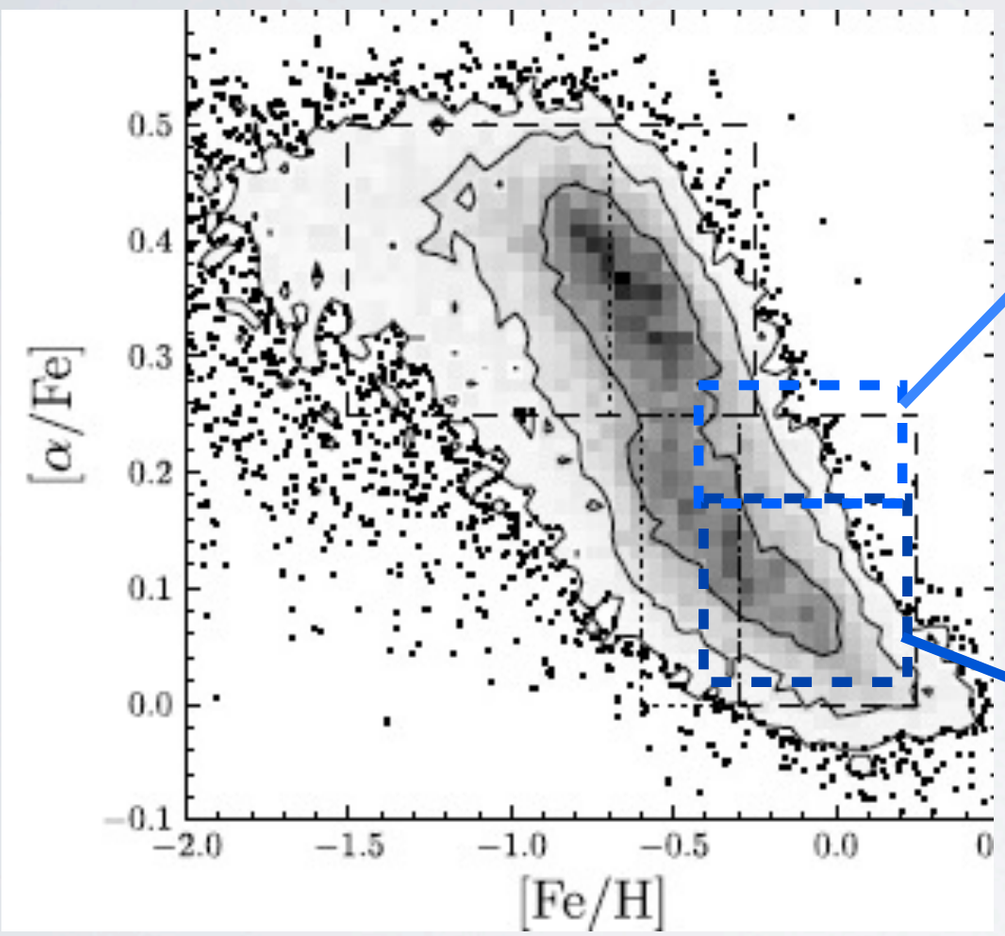
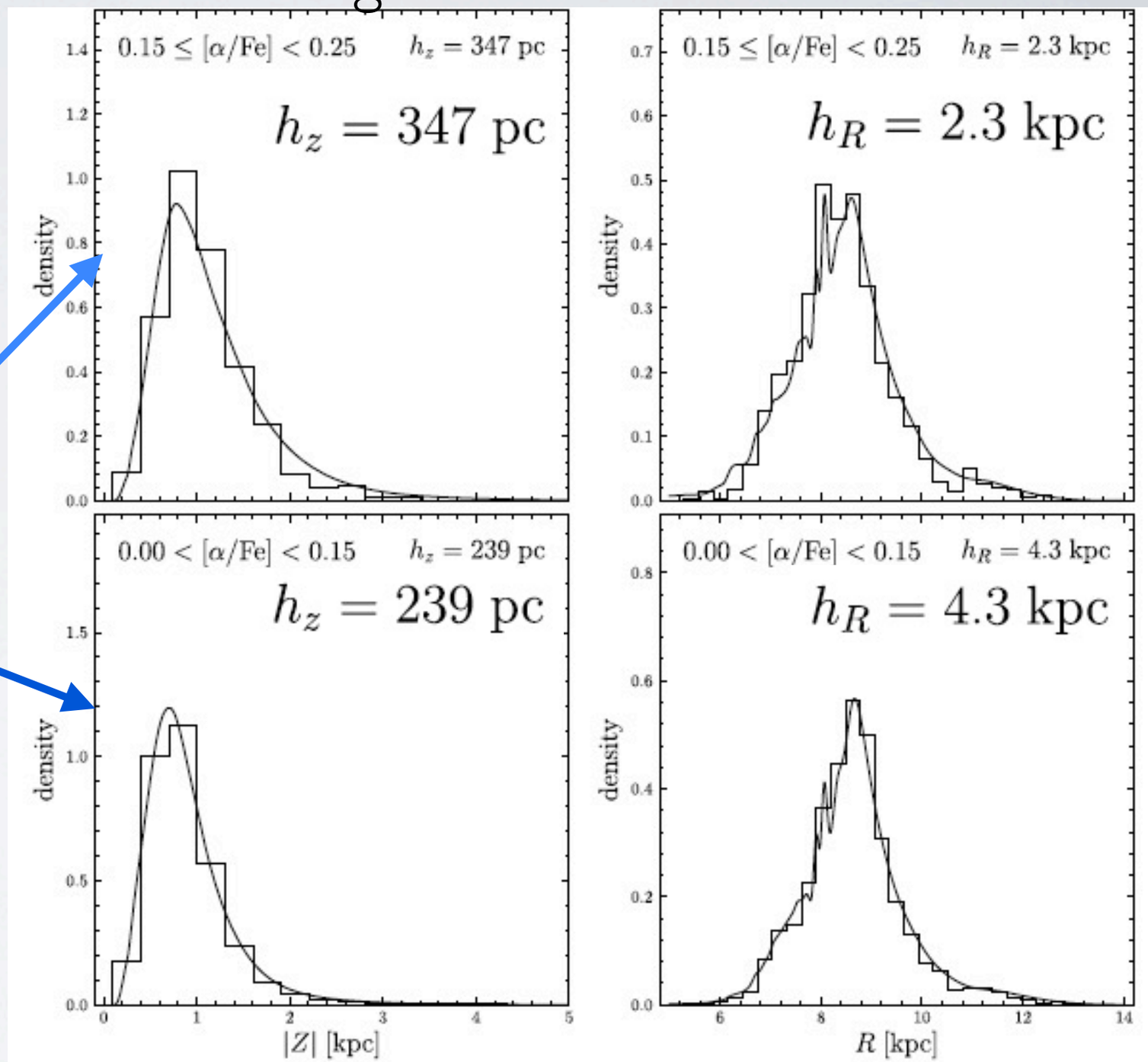
FIT EXAMPLES IN BROAD BINS IN ABUNDANCE



Vertical height

Galactocentric radius



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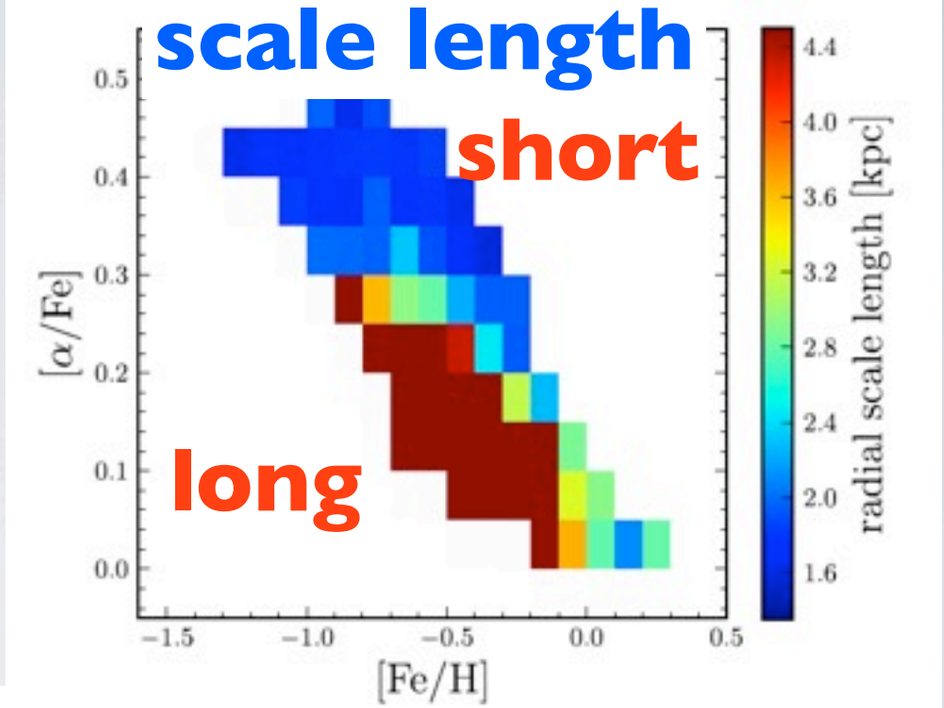

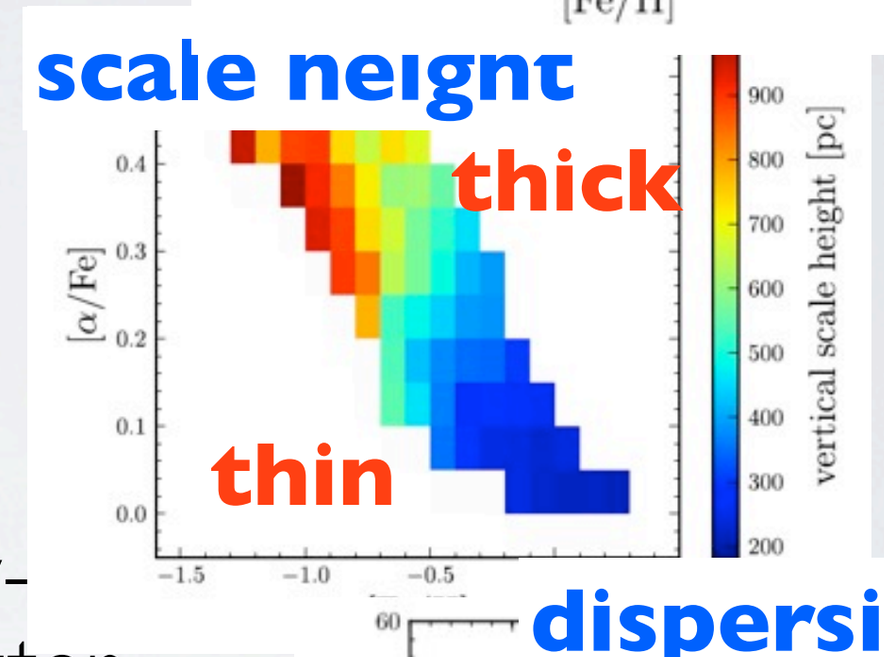

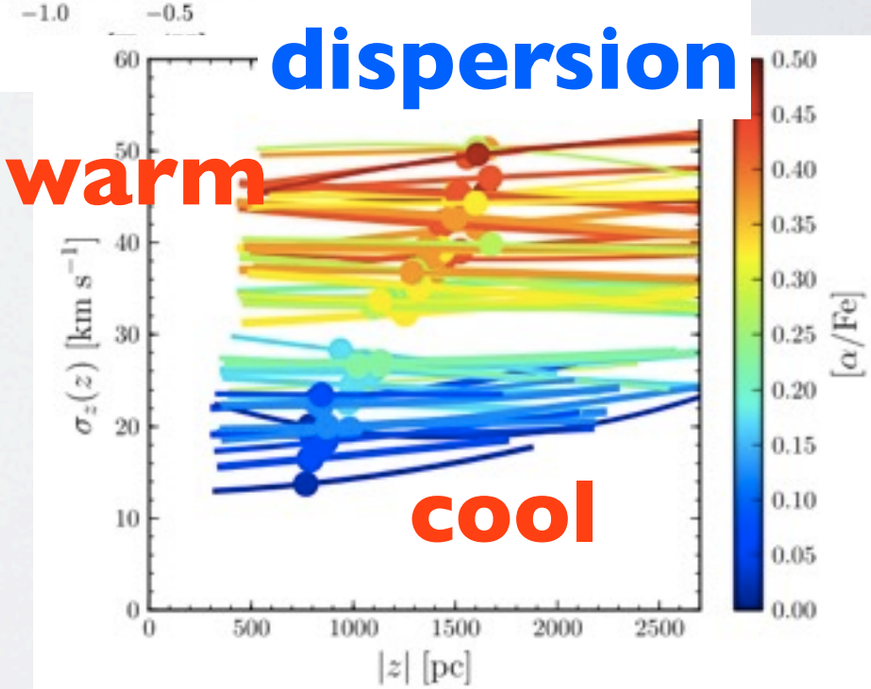

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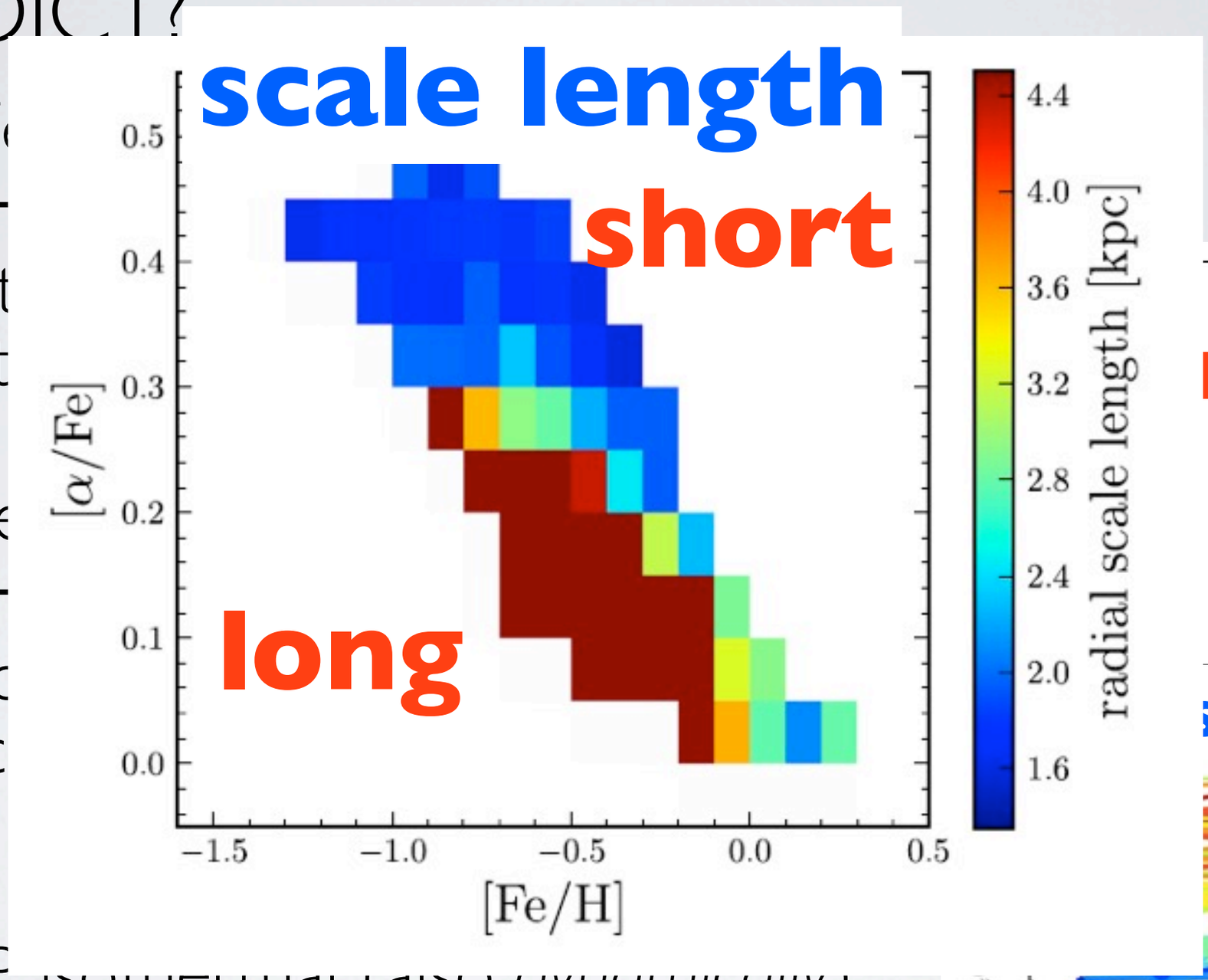

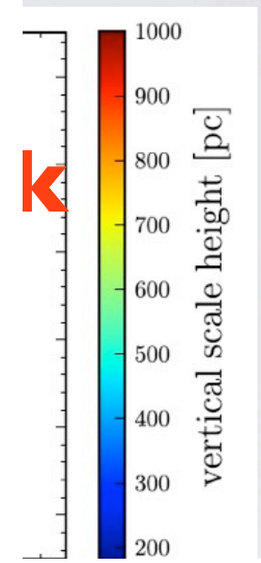

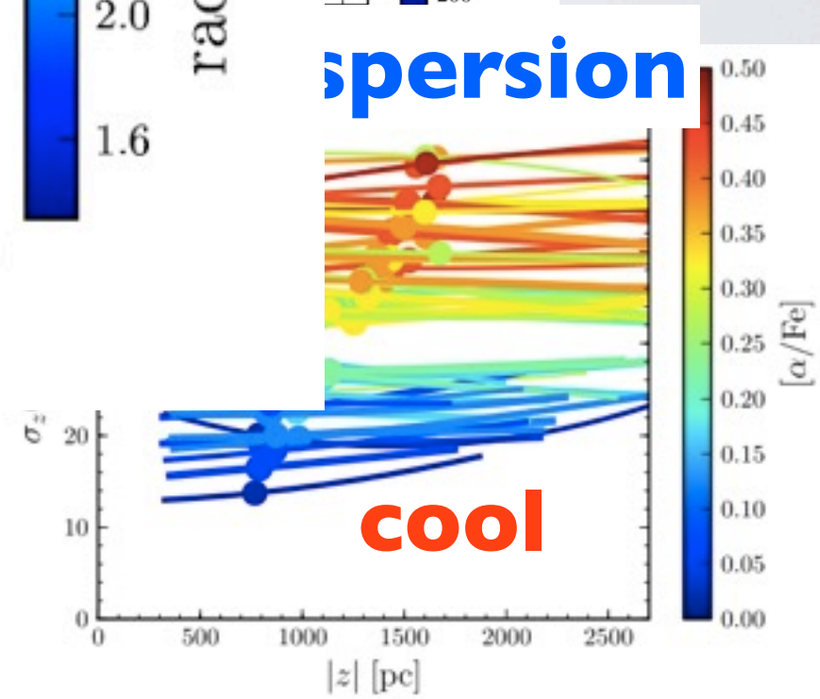

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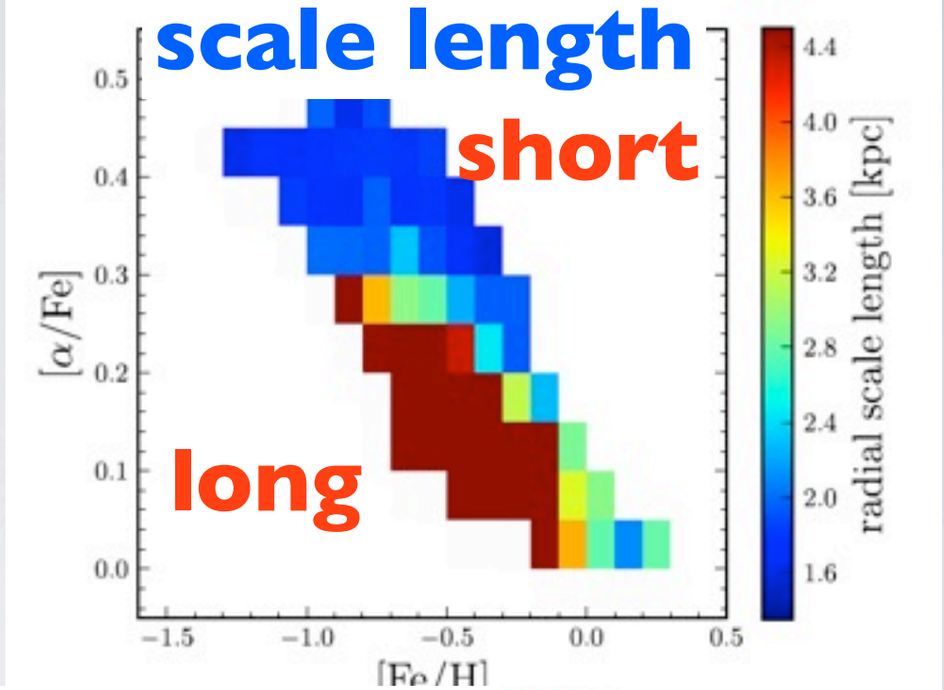

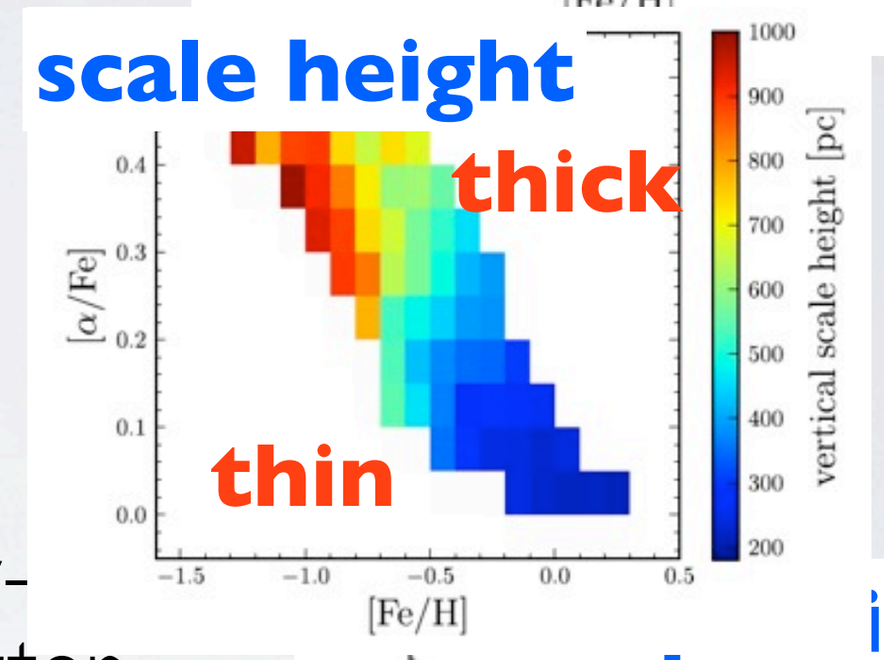

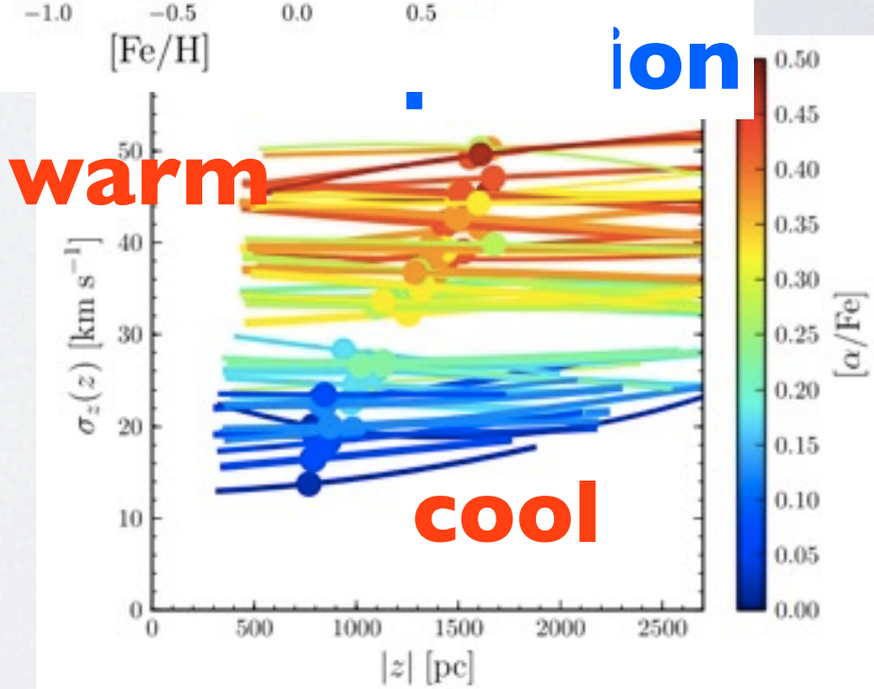

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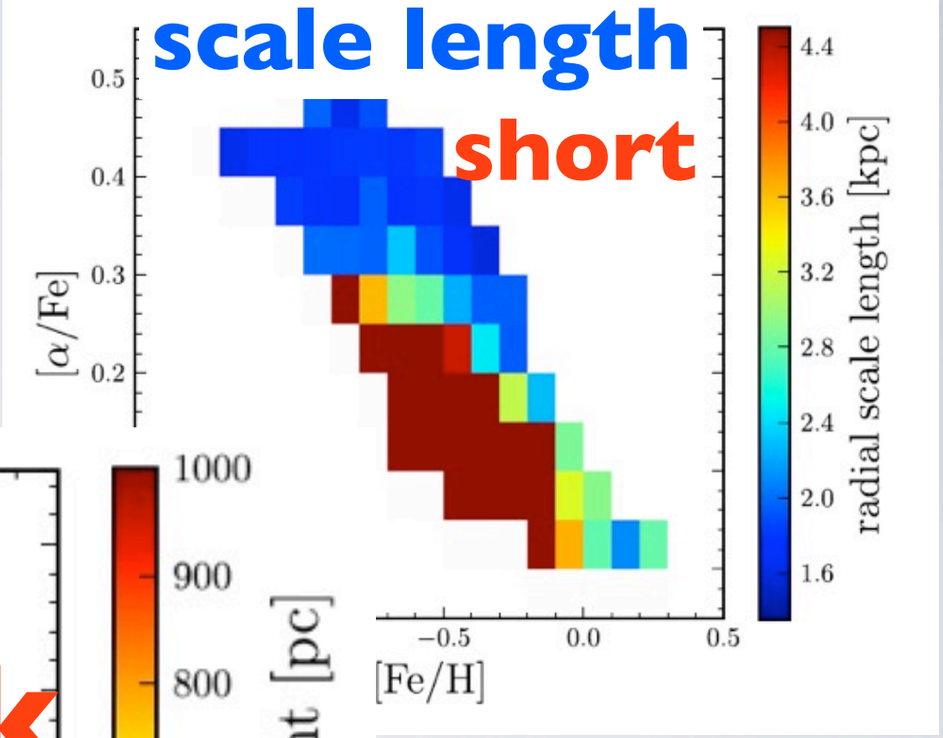

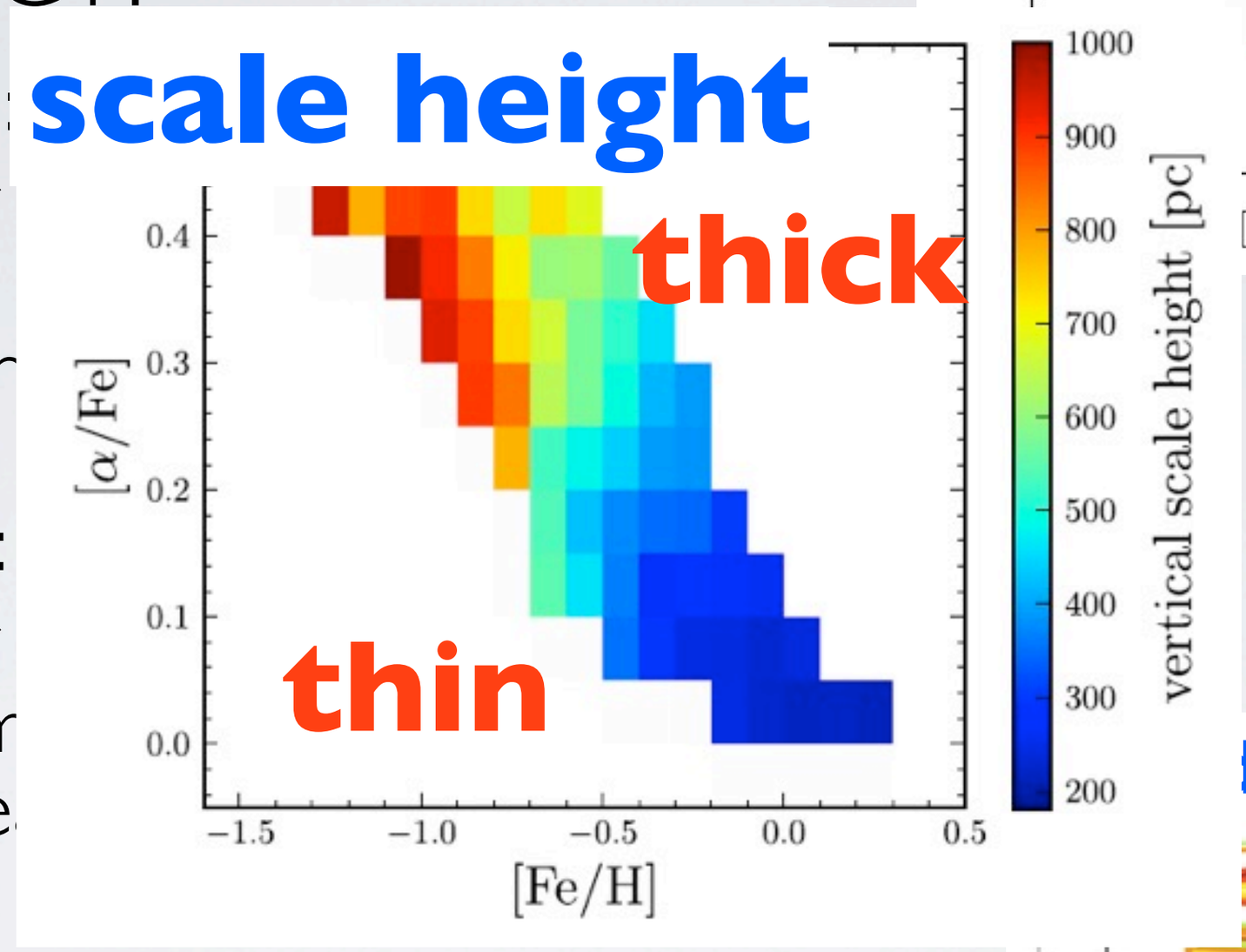

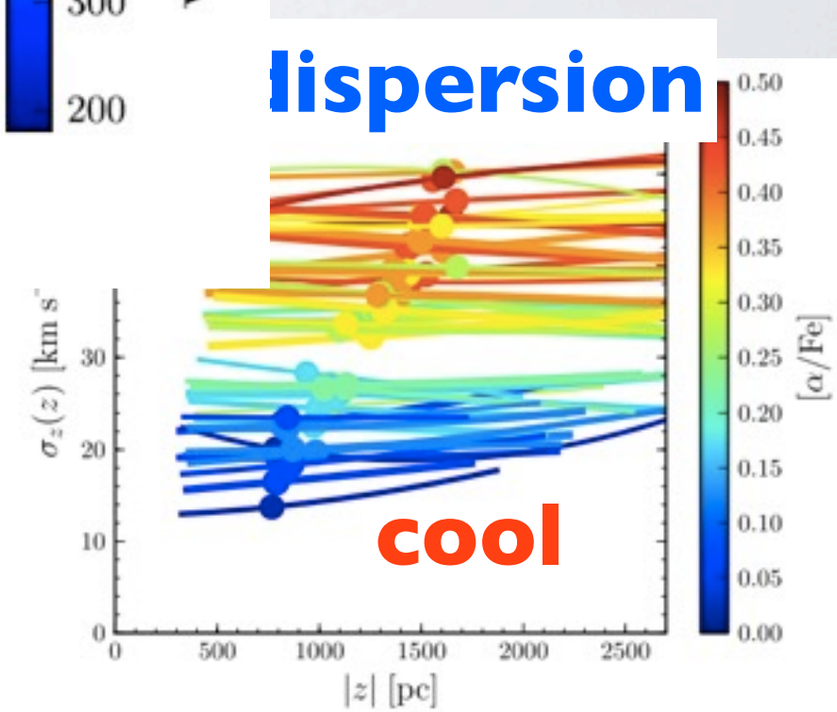

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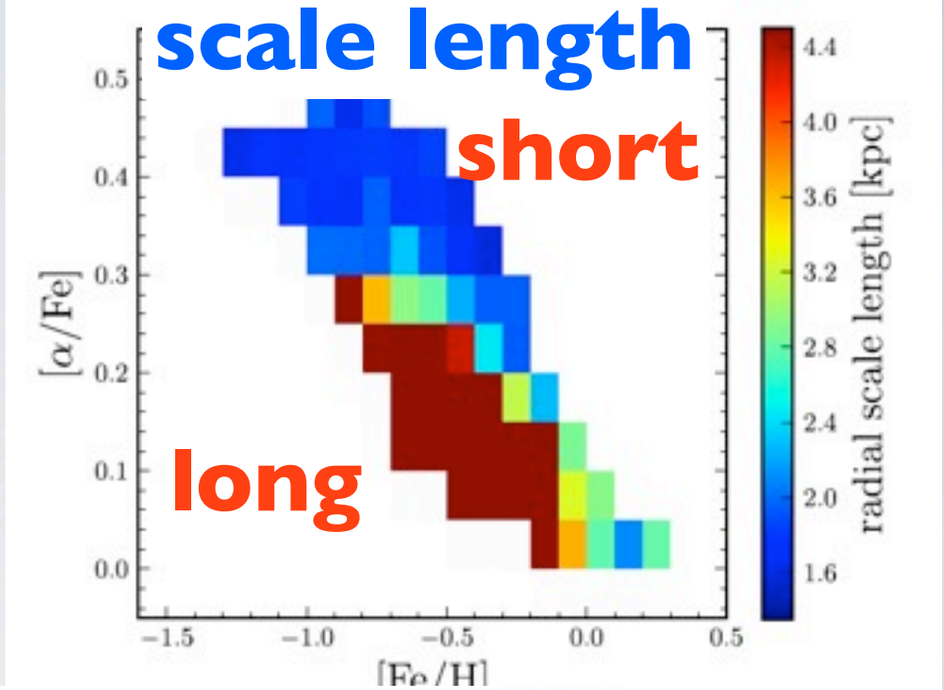

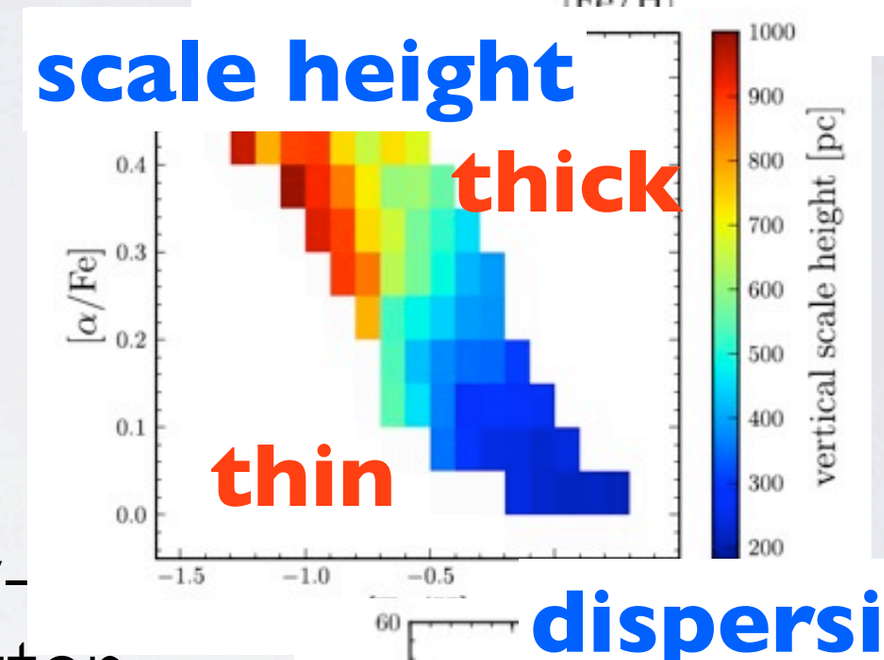

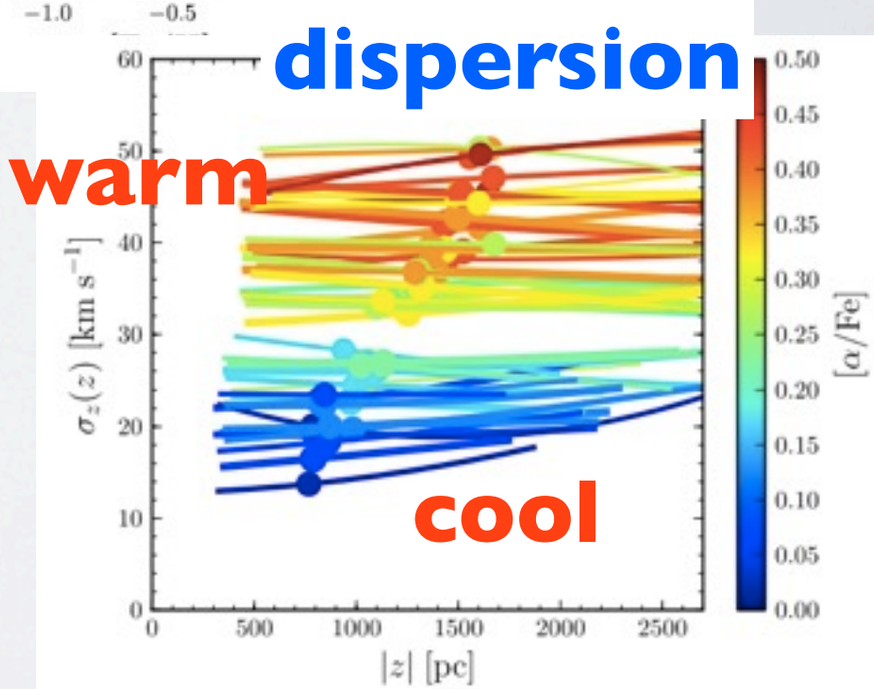

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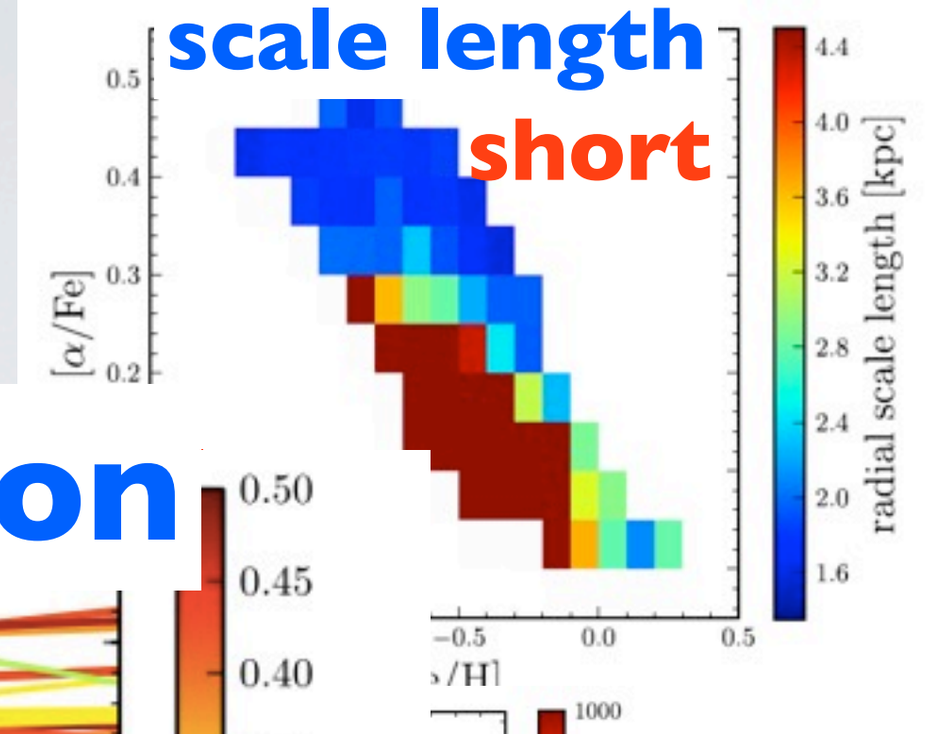

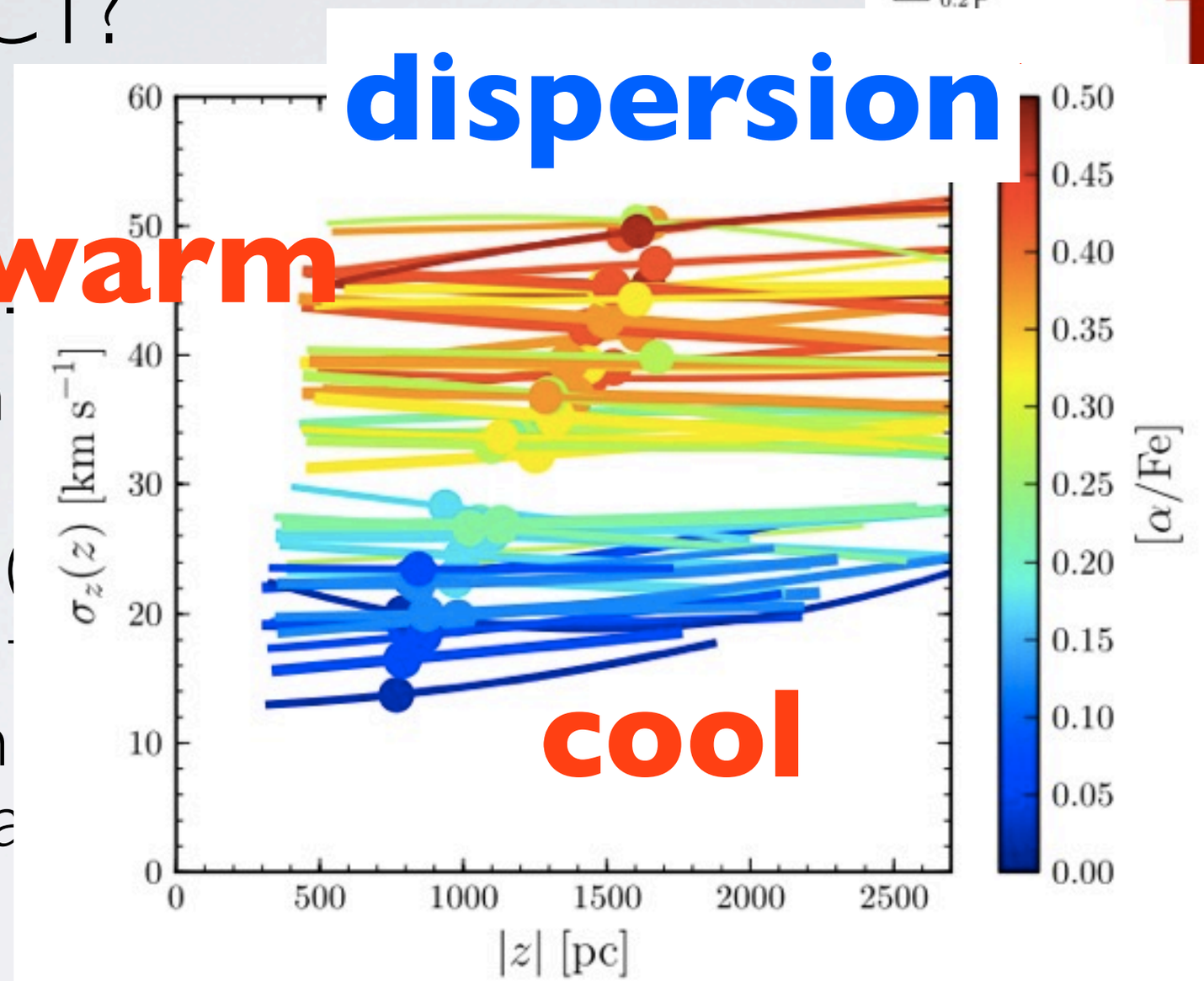

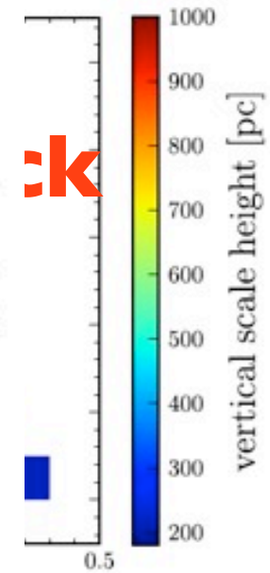

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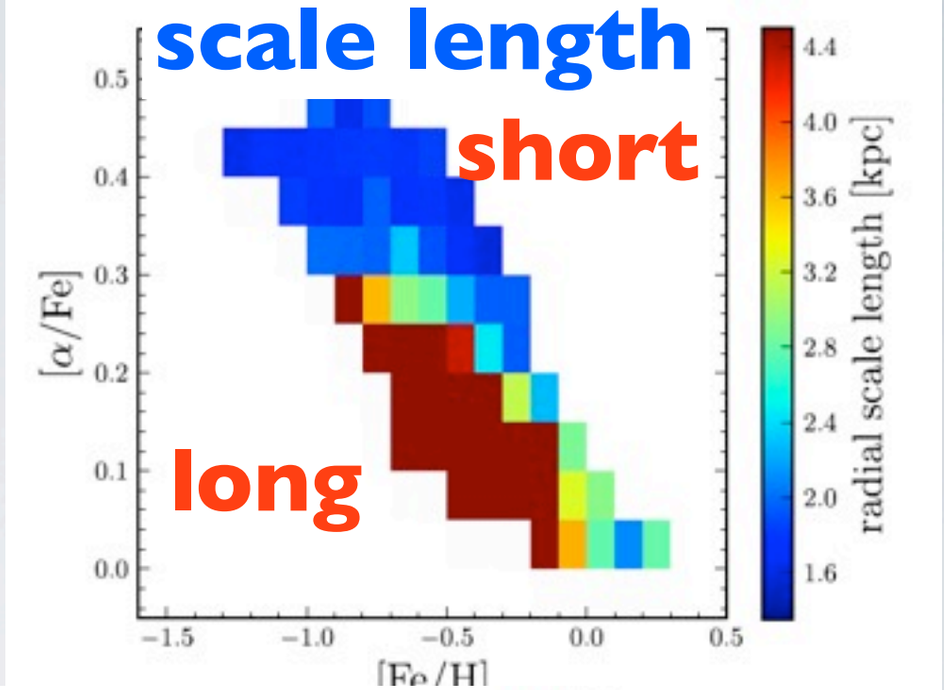
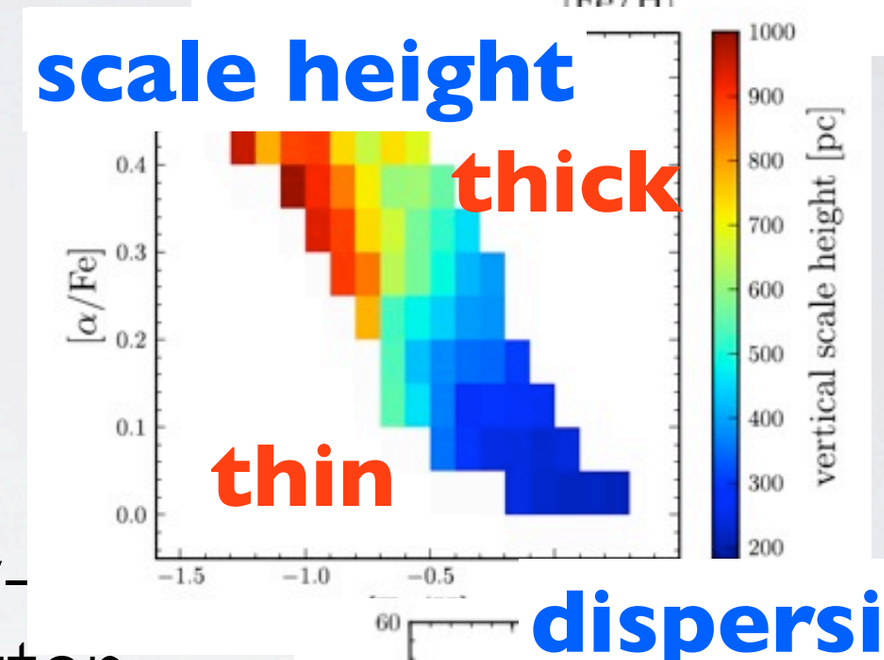
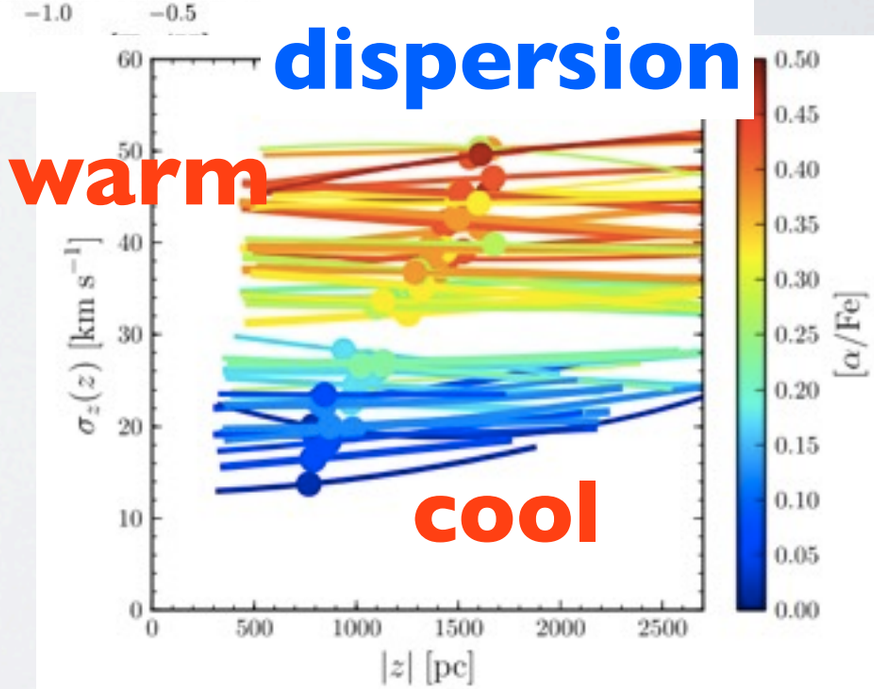
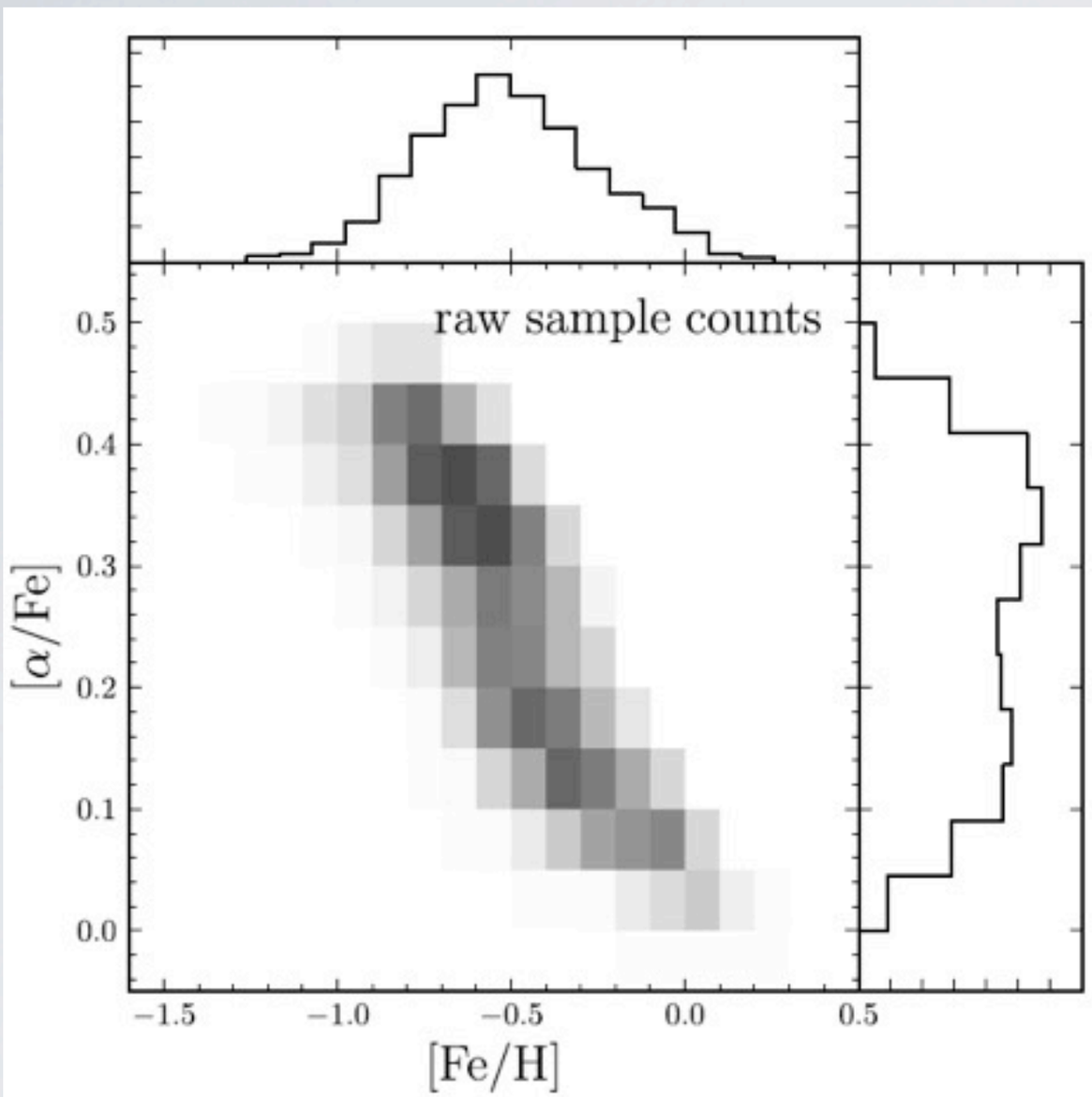
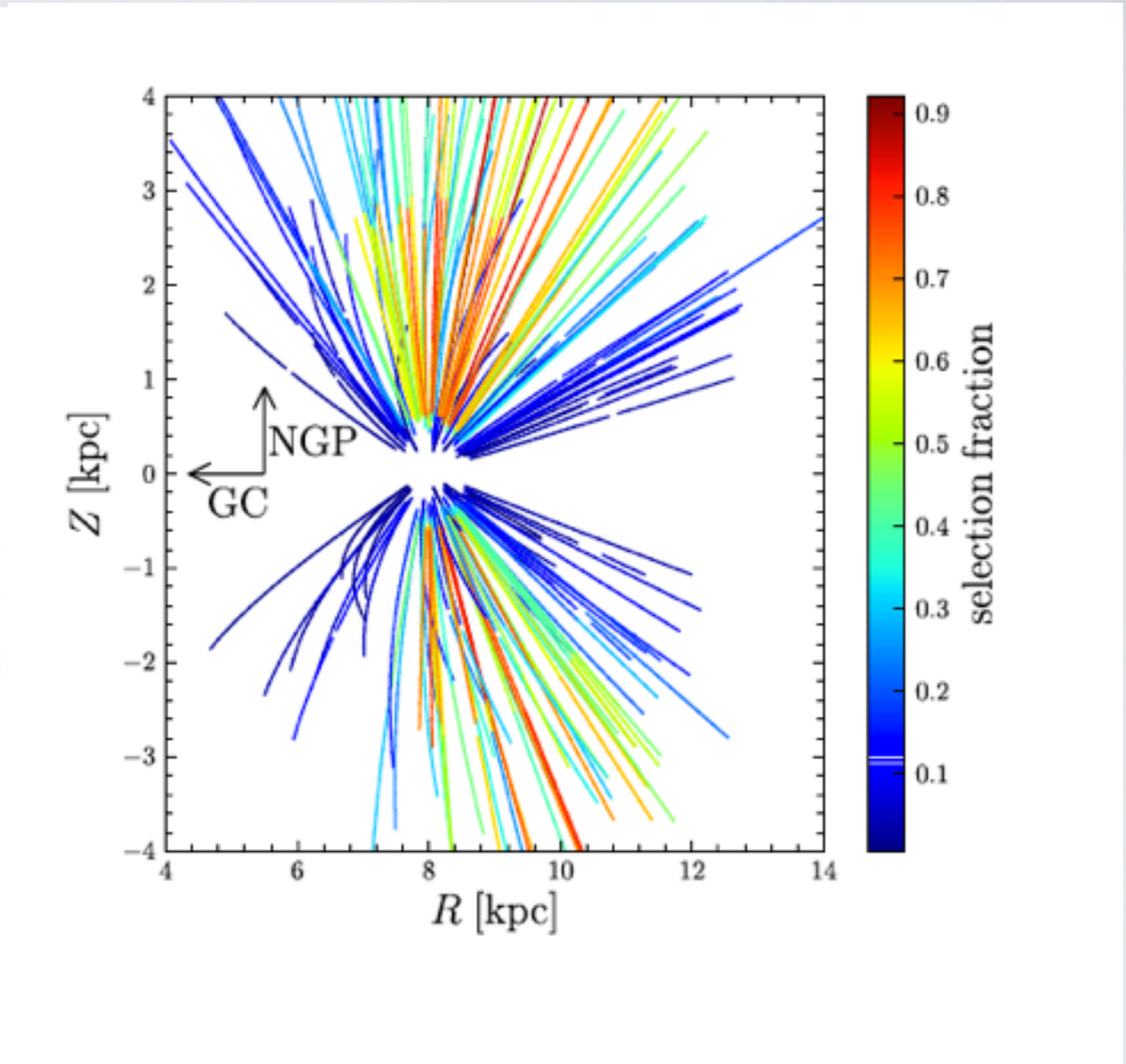






DOES THE MILKY WAY HAVE A THICK DISK?
CHEMICAL BI-MODALITY?





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- Impossible to draw conclusions from the figure on the left!

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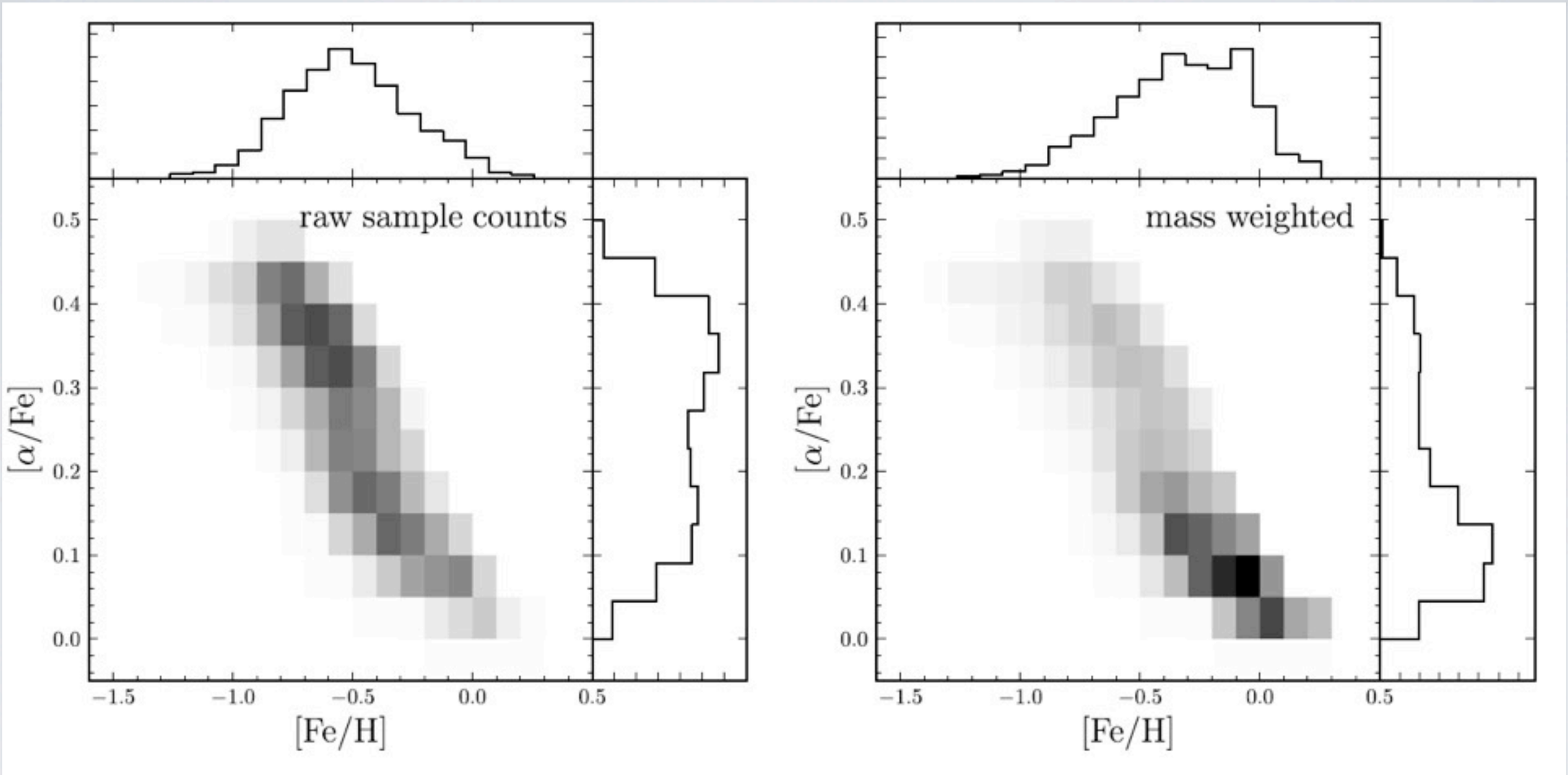

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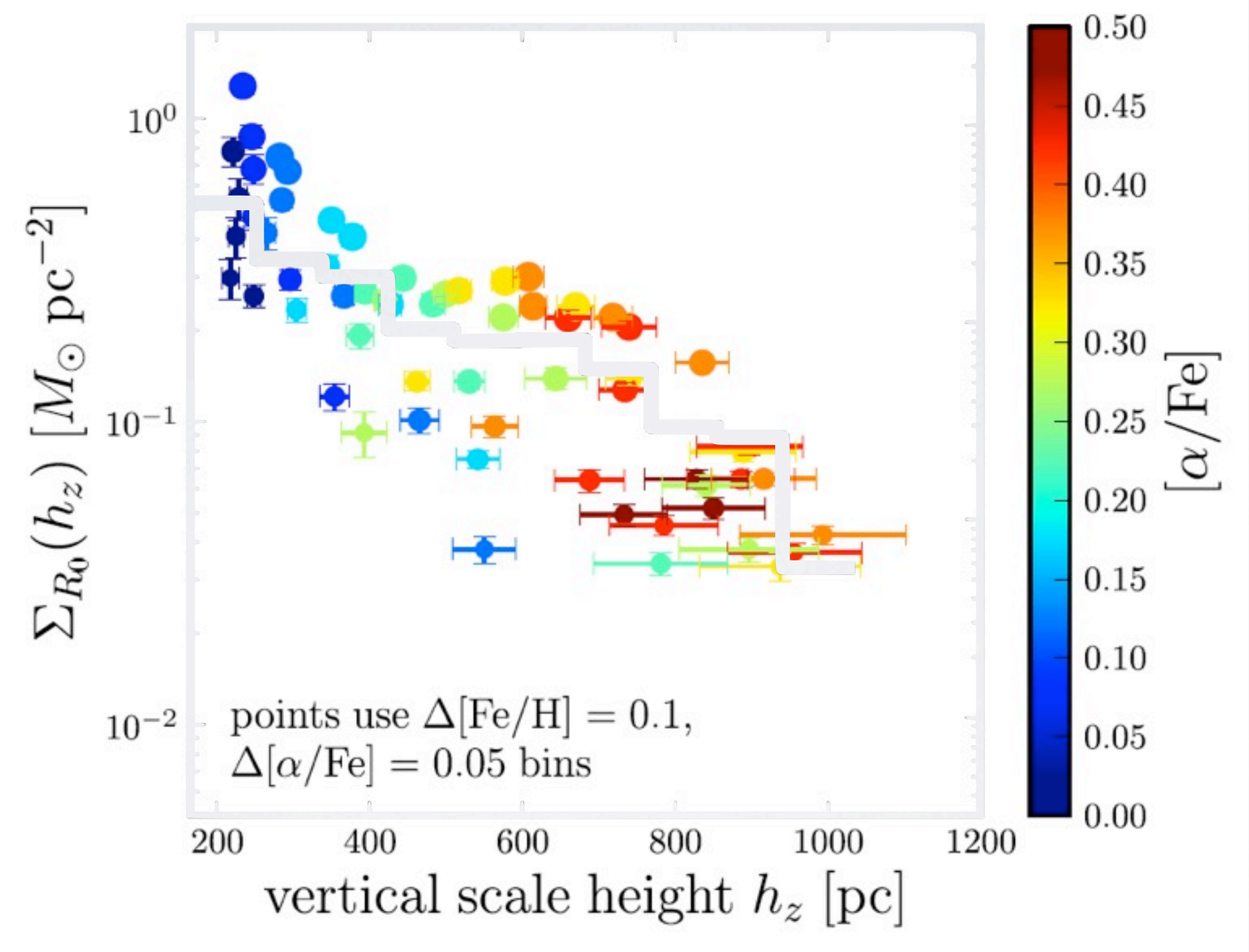
SCALE-HEIGHT BI-MODALITY?



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

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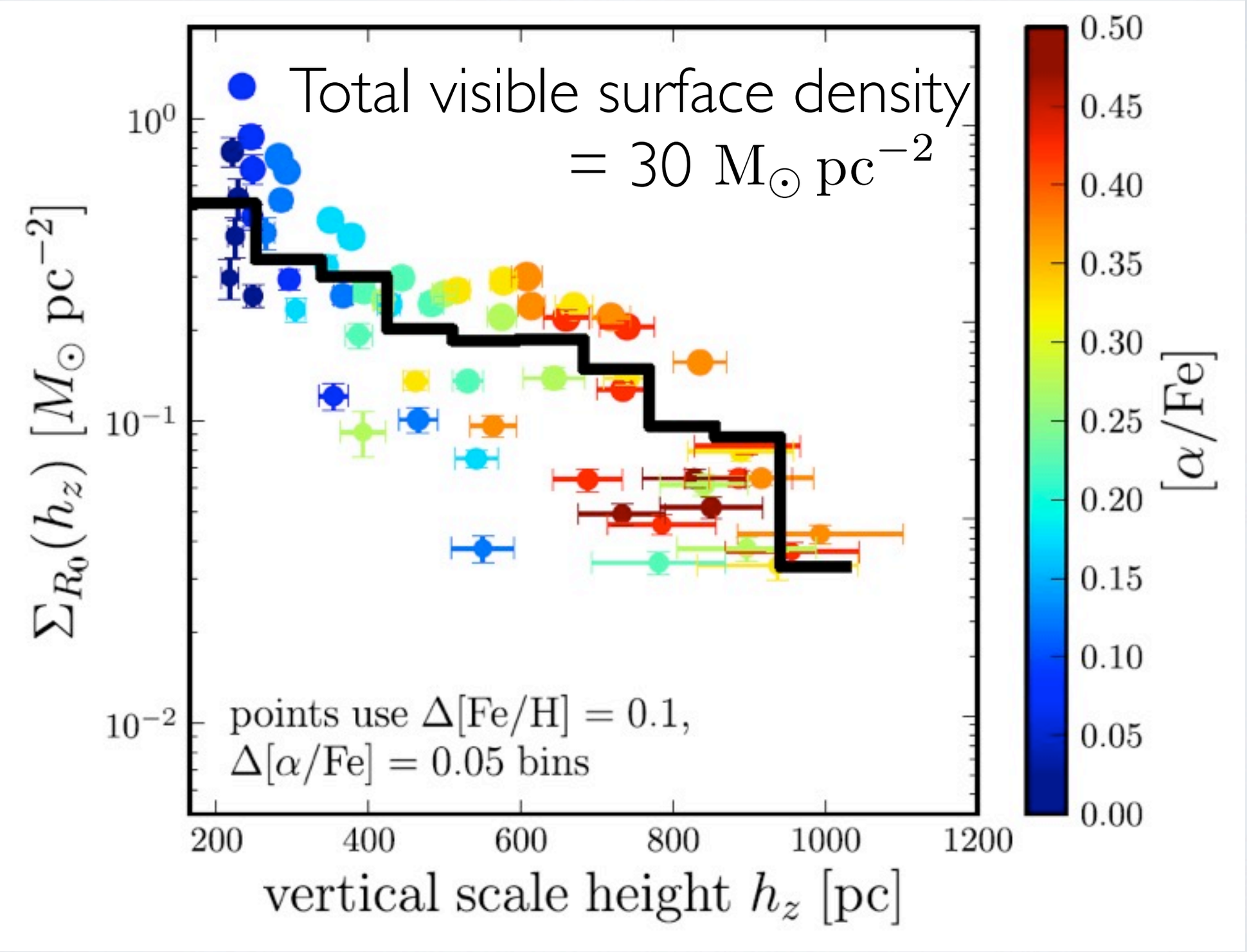

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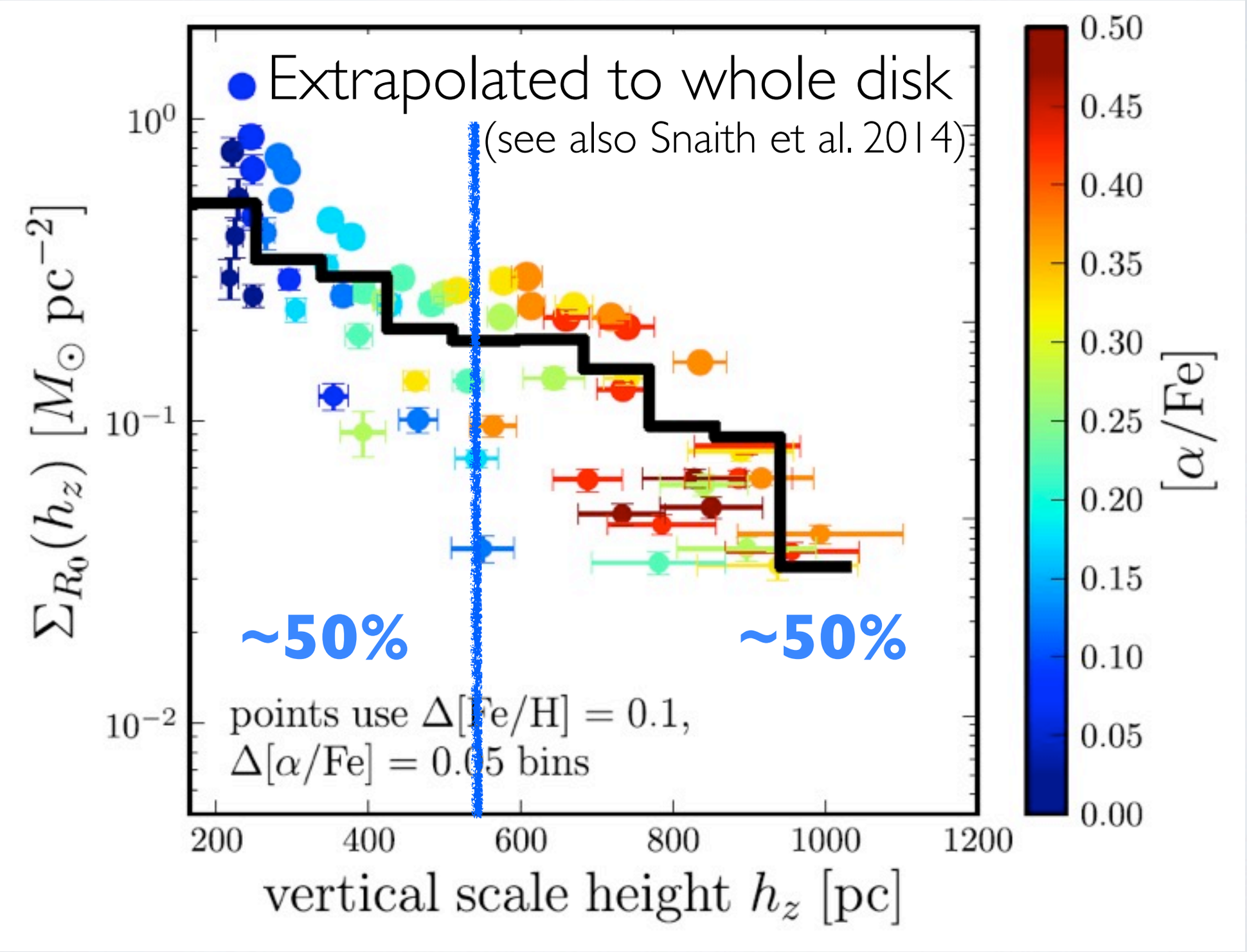

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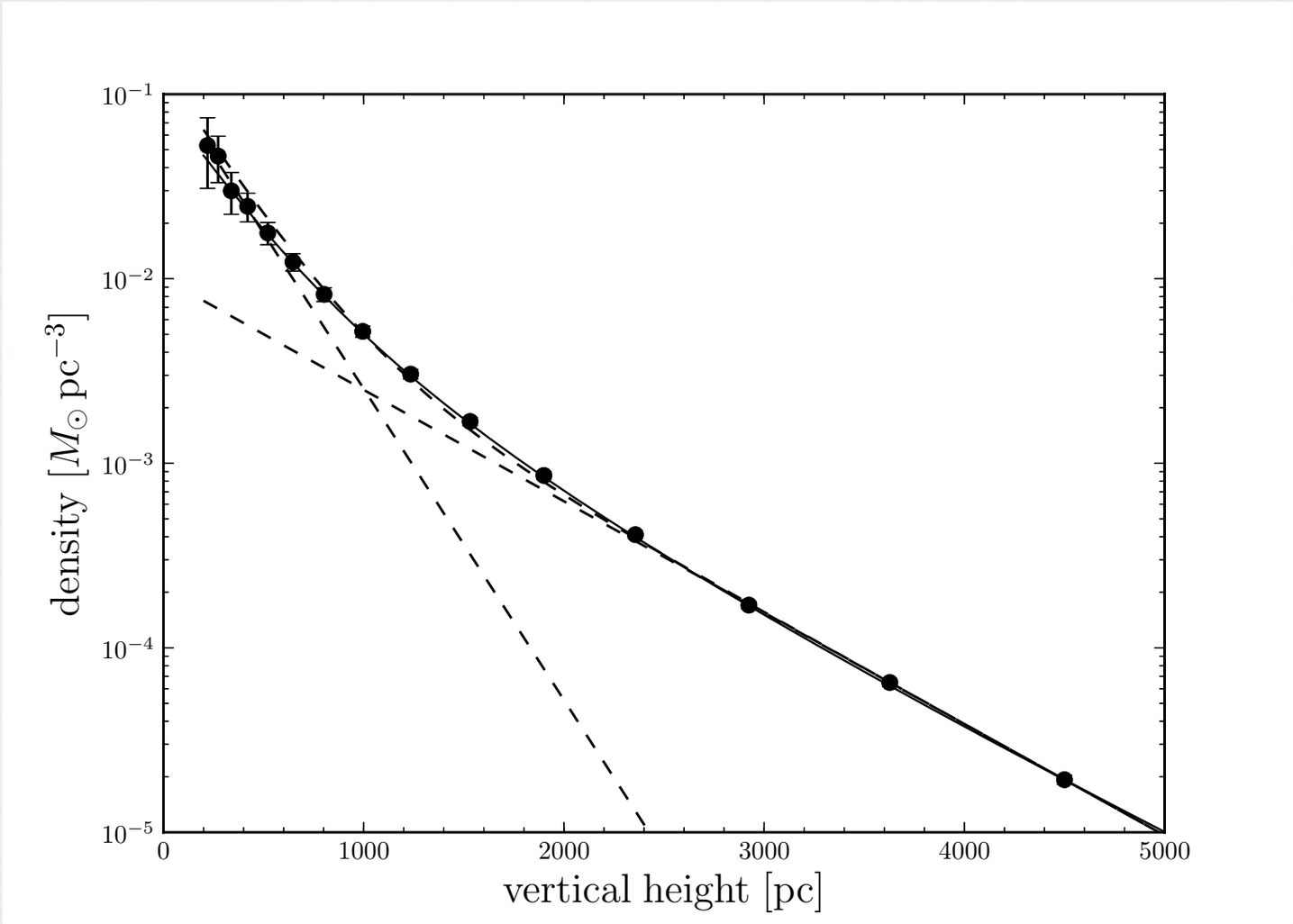
WHAT ABOUT THE VERTICAL PROFILE?

- Total vertical profile looks like two exponentials with a ratio of scale heights 3:1



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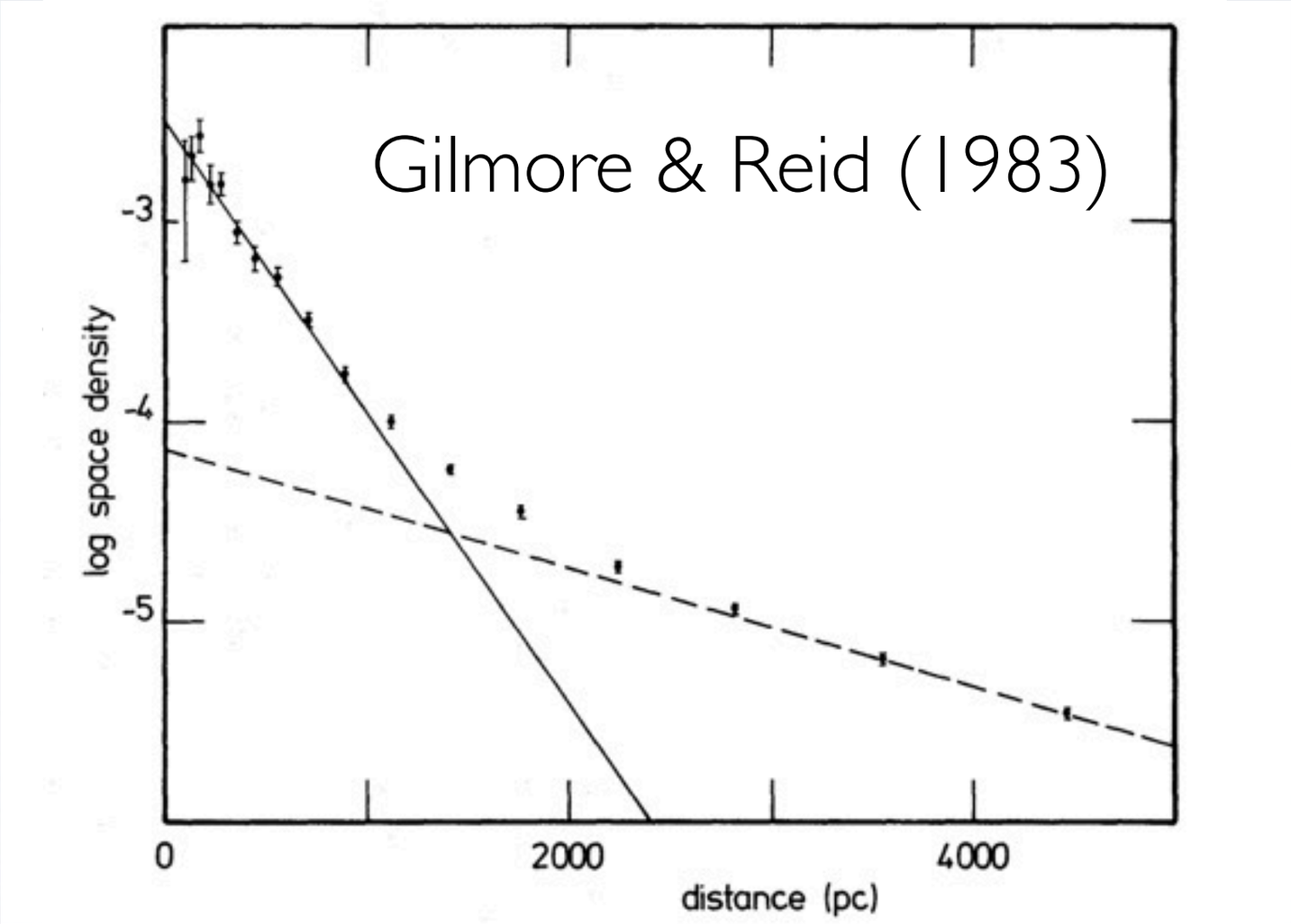

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STELLAR MASS DISTRIBUTION

- 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*

- 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*

- Smooth structure and large amount of mass in large scale-height components difficult to reconcile with impact of (few) mergers → *internal processes dominate evolution*

DYNAMICS

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

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

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

VERTICAL KINEMATICS: JEANS+POISSON EQUATIONS

- Jeans Eqns.: Moments of collisionless Boltzmann equation that describes the steady state

$$F_R(R,Z) = -\frac{\partial \Phi(R,Z)}{\partial R} = \frac{1}{\nu}\frac{\partial\left(\nu\sigma_U^2\right)}{\partial R} + \frac{1}{\nu}\frac{\partial\left(\nu\sigma_{UW}^2\right)}{\partial Z} + \frac{\sigma_U^2 - \sigma_V^2 - \bar{V}^2}{R},$$

$$F_Z(R,Z) = -\frac{\partial \Phi(R,Z)}{\partial Z} = \frac{1}{\nu}\frac{\partial(\nu\sigma_W^2)}{\partial Z} + \frac{1}{R\nu}\frac{\partial\left(R\nu\sigma_{UW}^2\right)}{\partial R}.$$

$$\Sigma(R,Z) = -\frac{1}{2\pi G}\left[\int_0^Z \mathrm{d}z\,\frac{1}{R}\frac{\partial(RF_R)}{\partial R} + F_Z(R,Z)\right]$$

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1D

Tilt =~ 0

$$\Sigma(R,Z) = -\frac{1}{2\pi G}\left[\int_0^Z \mathrm{d}z\,\frac{1}{R}\frac{\partial(RF_R)}{\partial R} + F_Z(R,Z)\right]$$

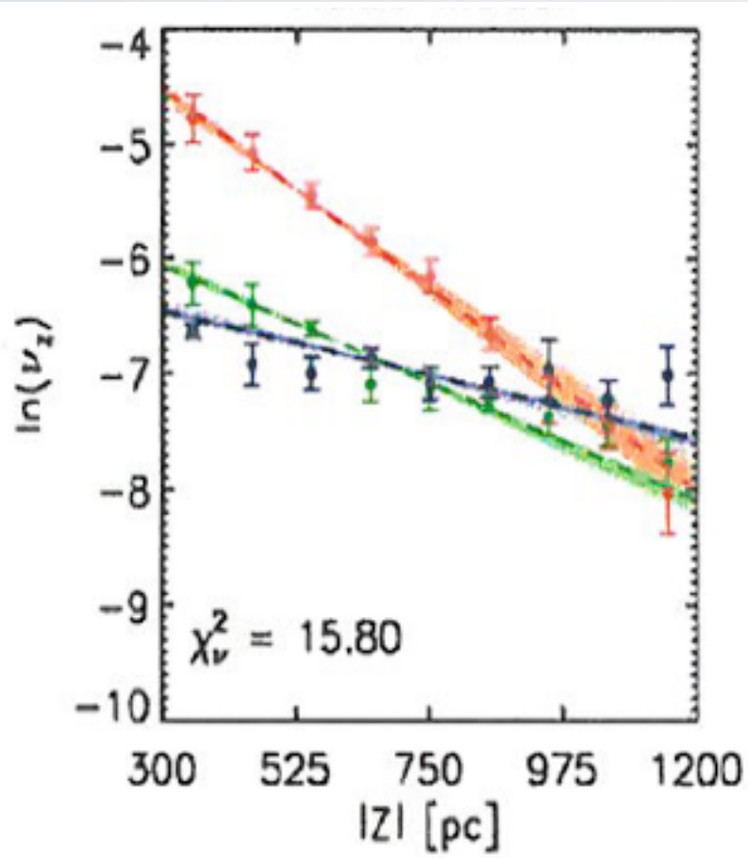
slope of rotation curve =~ 0

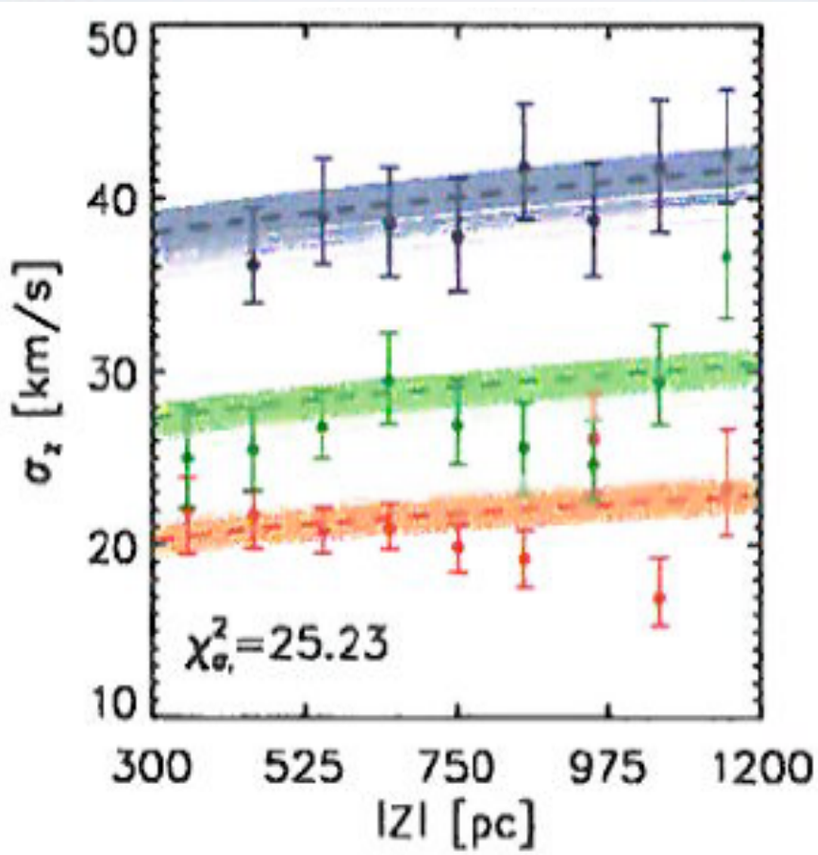
MONO-ABUNDANCE DYNAMICS: VERTICAL

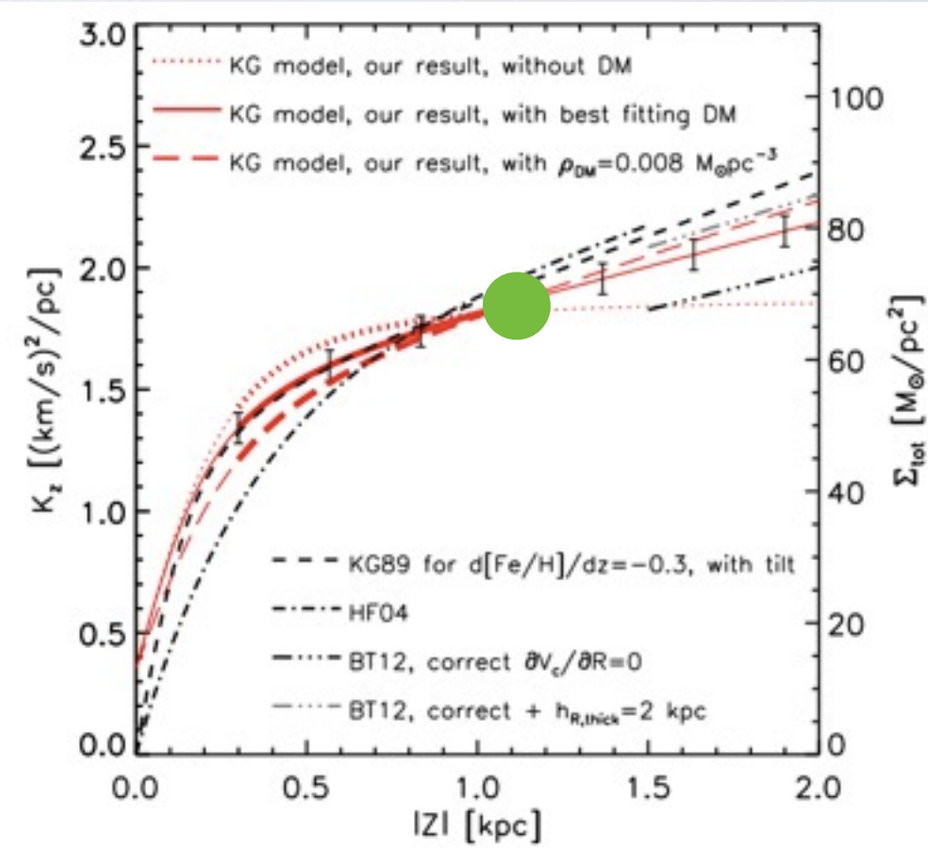
- All mono-abundance populations feel the same potential

$$F_Z(R,Z) = -\frac{\partial \Phi(R,Z)}{\partial Z} = \frac{1}{\nu}\frac{\partial(\nu\sigma_W^2)}{\partial Z} + \frac{1}{R\nu}\frac{\partial\left(R\nu\sigma_{UW}^2\right)}{\partial R}.$$

Spatial density + kinematics = vertical force







Zhang, Rix, van de Ven, Bovy, et al. (2012), ApJ, **772**, 108

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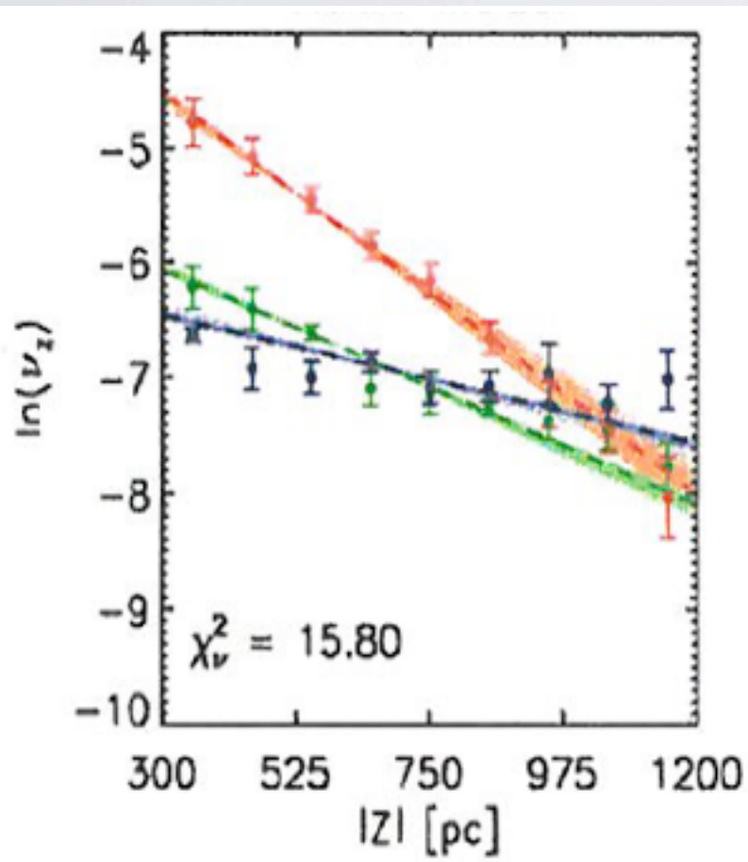

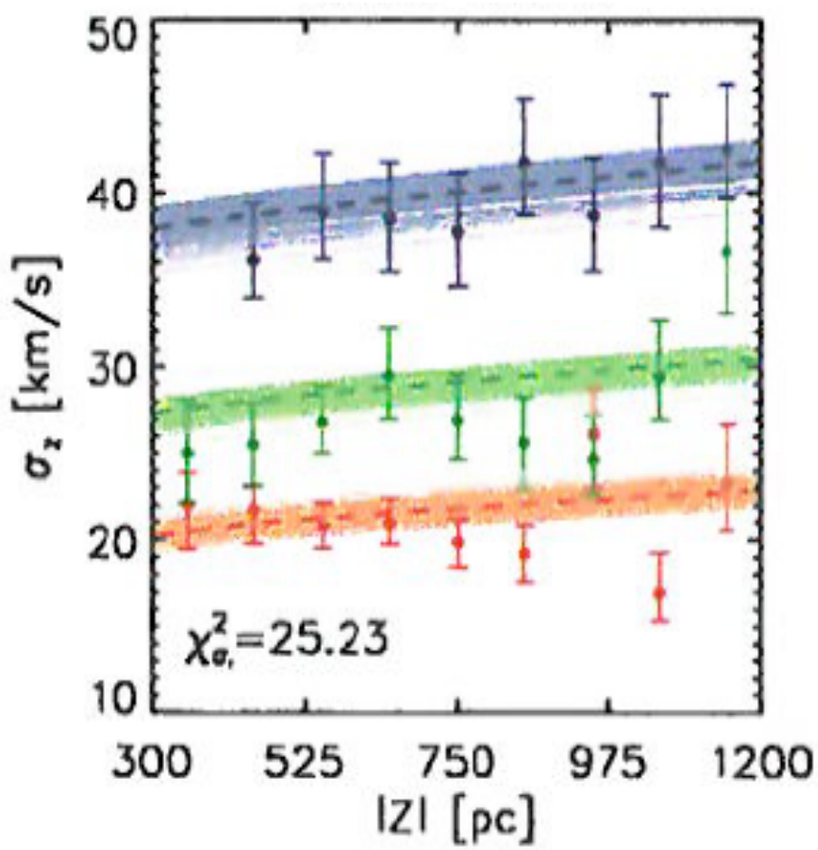

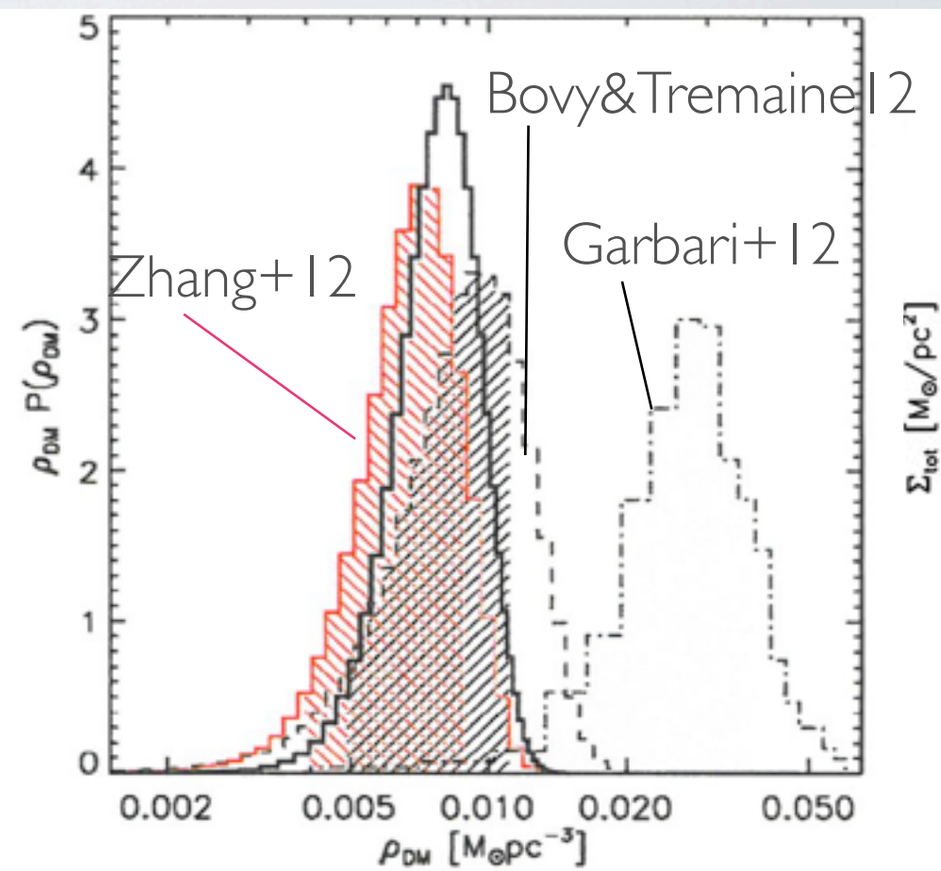

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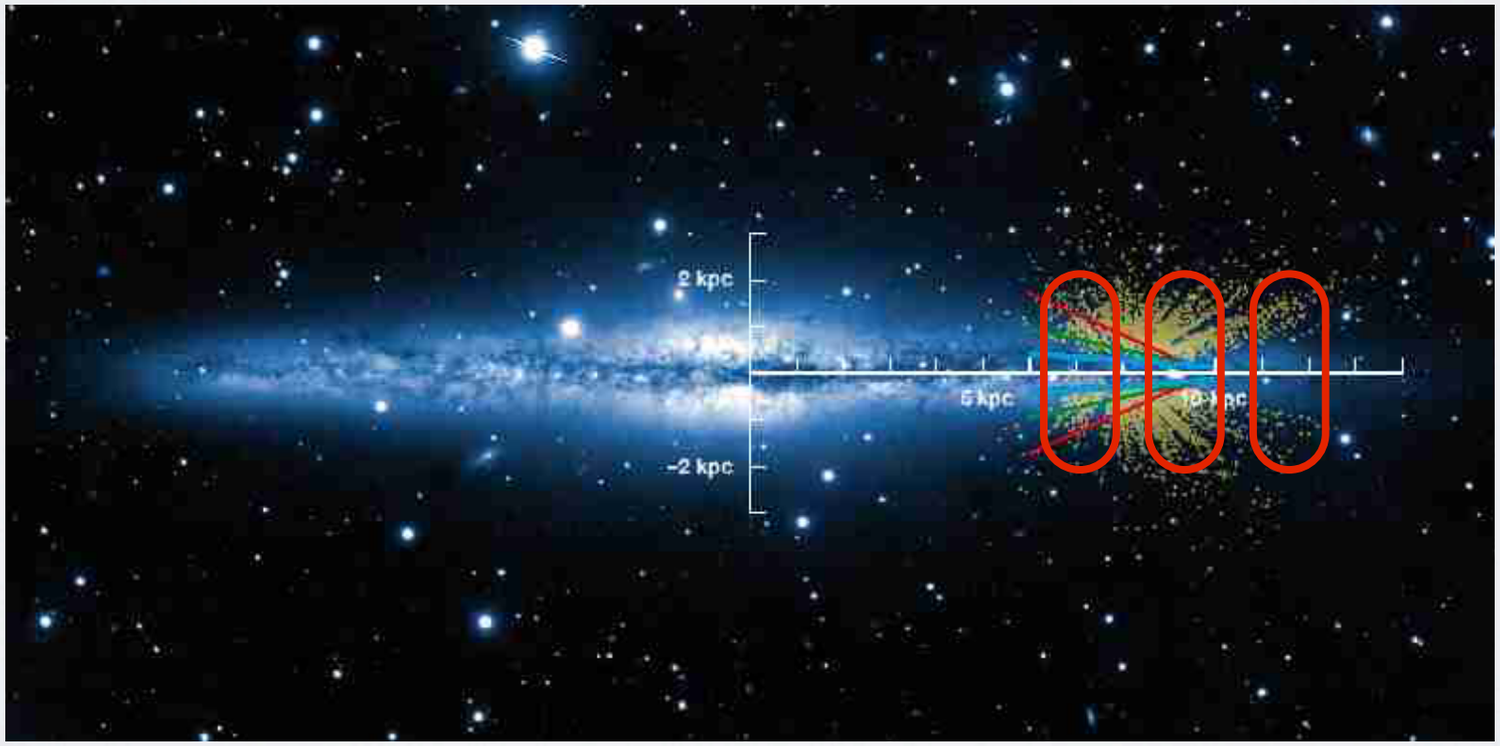
RADIAL DISK AND HALO PROFILES

- Existing and future data (e.g., *Gaia*) allow us to perform the previous analysis at R =/= R_0 => $\Sigma(R)$ and $\rho(R)$

- This allows us to measure the disk profile (scale length) and infer the halo profile



ACTION MODELING OF THE DISK

- Going beyond the Jeans equation is necessary at large heights and for larger distances from the Sun
- Can use Jeans theorem: distribution function can only be a function of integrals of the motion
- Full modeling of the disk has been held back by difficulty in calculating the third integral ($\sigma_R \neq \sigma_z$)
- Typical approximation: $I_3 = E_z \sim$ Oort limit and analysis
- Binney (2010) introduced action-based *quasi-isothermal* DF and modeled the solar neighborhood as a superposition of such DFs in a fixed potential
- Binney (2012): Uses Staeckel fudge to get actions and modeled the solar neighborhood again

DISTRIBUTION FUNCTION MODELING

$$p(\mathbf{x}, \mathbf{v}|\mathrm{model}) = \frac{DF(\mathbf{x}, \mathbf{v})}{\int \mathrm{d}\mathbf{x}\mathrm{d}\mathbf{v} DF(\mathbf{x}, \mathbf{v})}$$

- Model the distribution function of stars in x,v as being in a steady state:

$$p(\mathbf{x}, \mathbf{v}|\mathrm{model}) = \frac{DF(\mathbf{J}(\mathbf{x}, \mathbf{v}))}{\int \mathrm{d}\mathbf{x}\mathrm{d}\mathbf{v} DF(\mathbf{J}(\mathbf{x}, \mathbf{v}))}$$

- With selection function:

$$p(\mathbf{x}, \mathbf{v}|\mathrm{model}) = \frac{DF(\mathbf{J}(\mathbf{x}, \mathbf{v}))}{\int \mathrm{d}\mathbf{x}\mathrm{d}\mathbf{v} DF(\mathbf{J}(\mathbf{x}, \mathbf{v}))S(\mathbf{x})}$$

- With errors/missing data:

$$p(\mathbf{x}_{\mathrm{obs}}, \mathbf{v}_{\mathrm{obs}}|\mathrm{model}) = \int \mathrm{d}\mathbf{x}'\mathrm{d}\mathbf{v}'\, p(\mathbf{x}_{\mathrm{obs}}, \mathbf{v}_{\mathrm{obs}}|\mathbf{x}', \mathbf{v}')p(\mathbf{x}', \mathbf{v}'|\mathrm{model})$$

DISK DISTRIBUTION FUNCTION MODELING

Binney (2010), Binney & McMillan (2011)

$$f(J_r, L_z, J_z) = f_{\sigma_r}(J_r, L_z) \times \frac{\nu_z}{2\pi\sigma_z^2} \mathrm{e}^{-\nu_z J_z/\sigma_z^2},$$

where

$$f_{\sigma_r}(J_r, L_z) \equiv \left.\frac{\Omega\Sigma}{\pi\sigma_r^2\kappa}\right|_{R_c} [1 + \tanh(L_z/L_0)]\mathrm{e}^{-\kappa J_r/\sigma_r^2}.$$

- In four component model for Milky Way potential (2 exponential disks, bulge, halo)
- Properties of DF:

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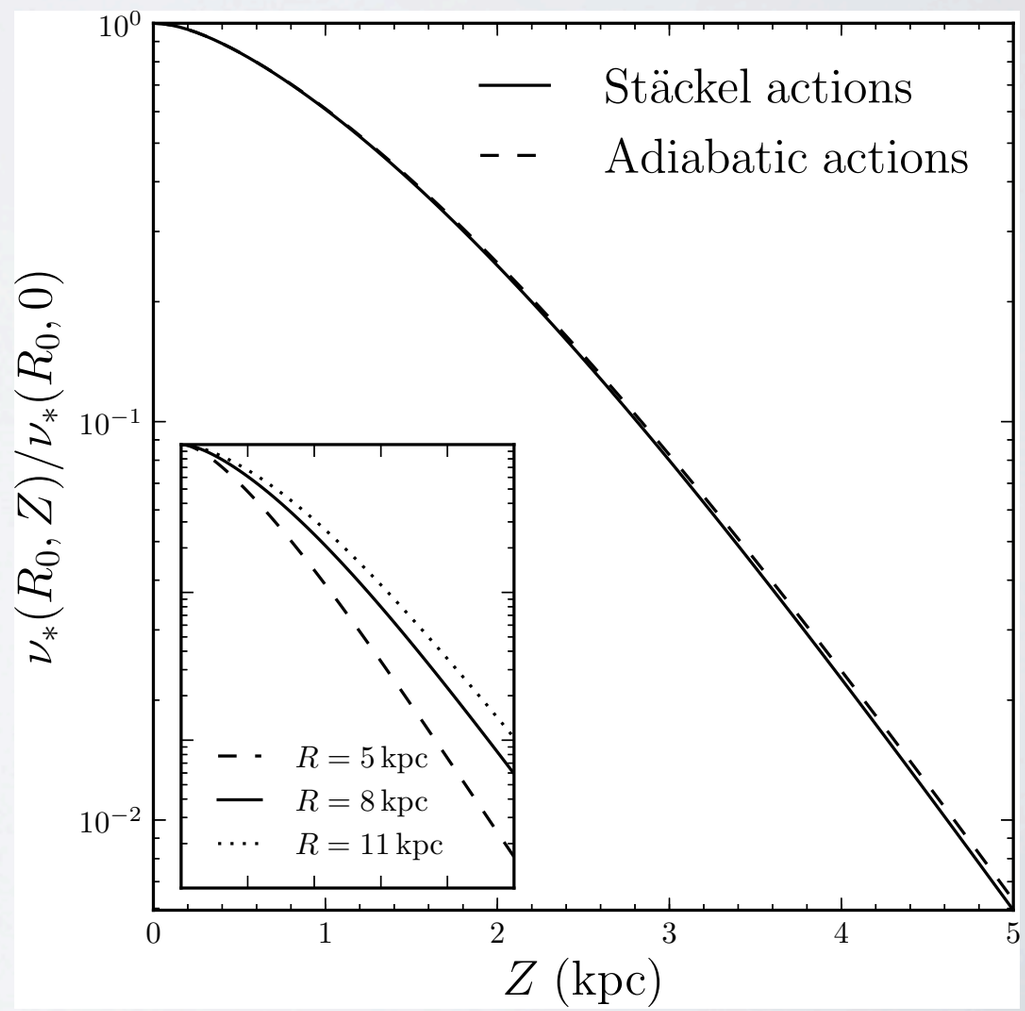

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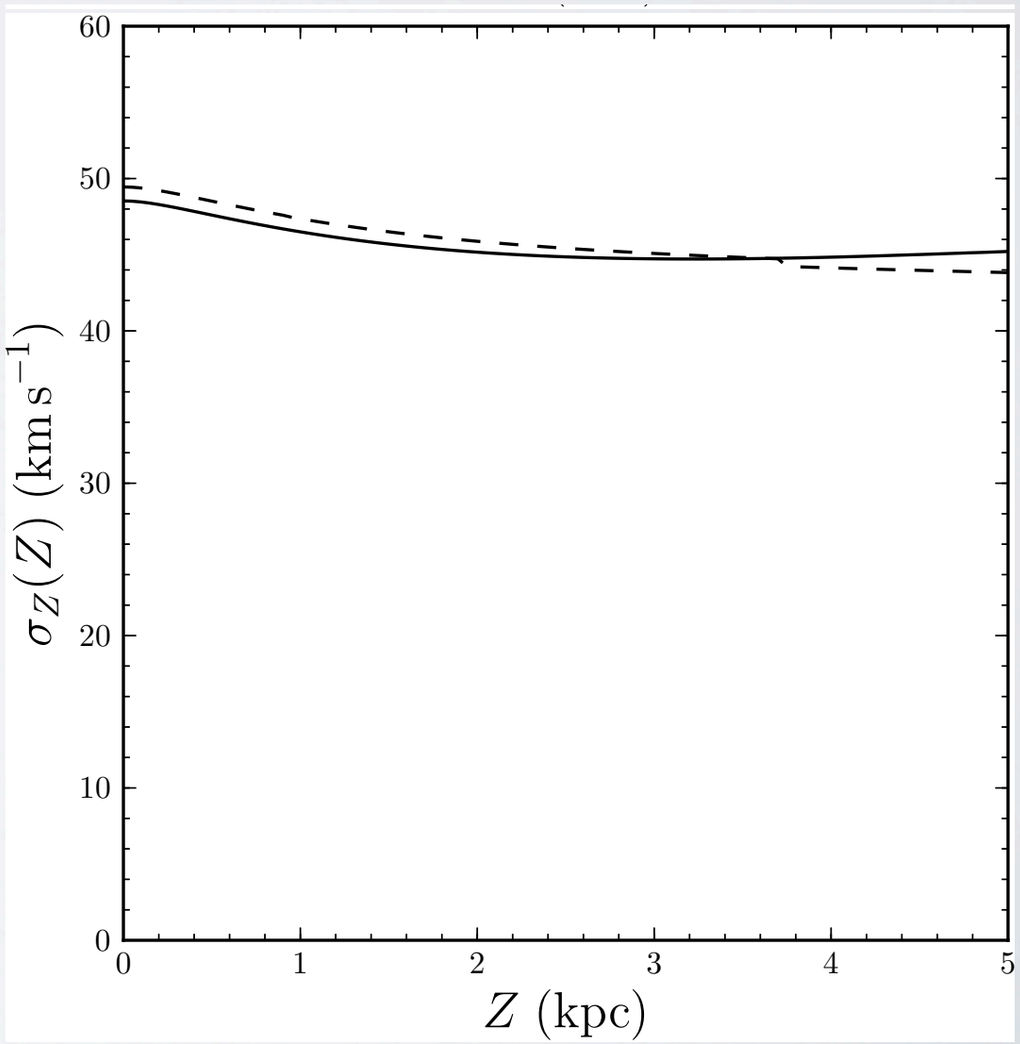

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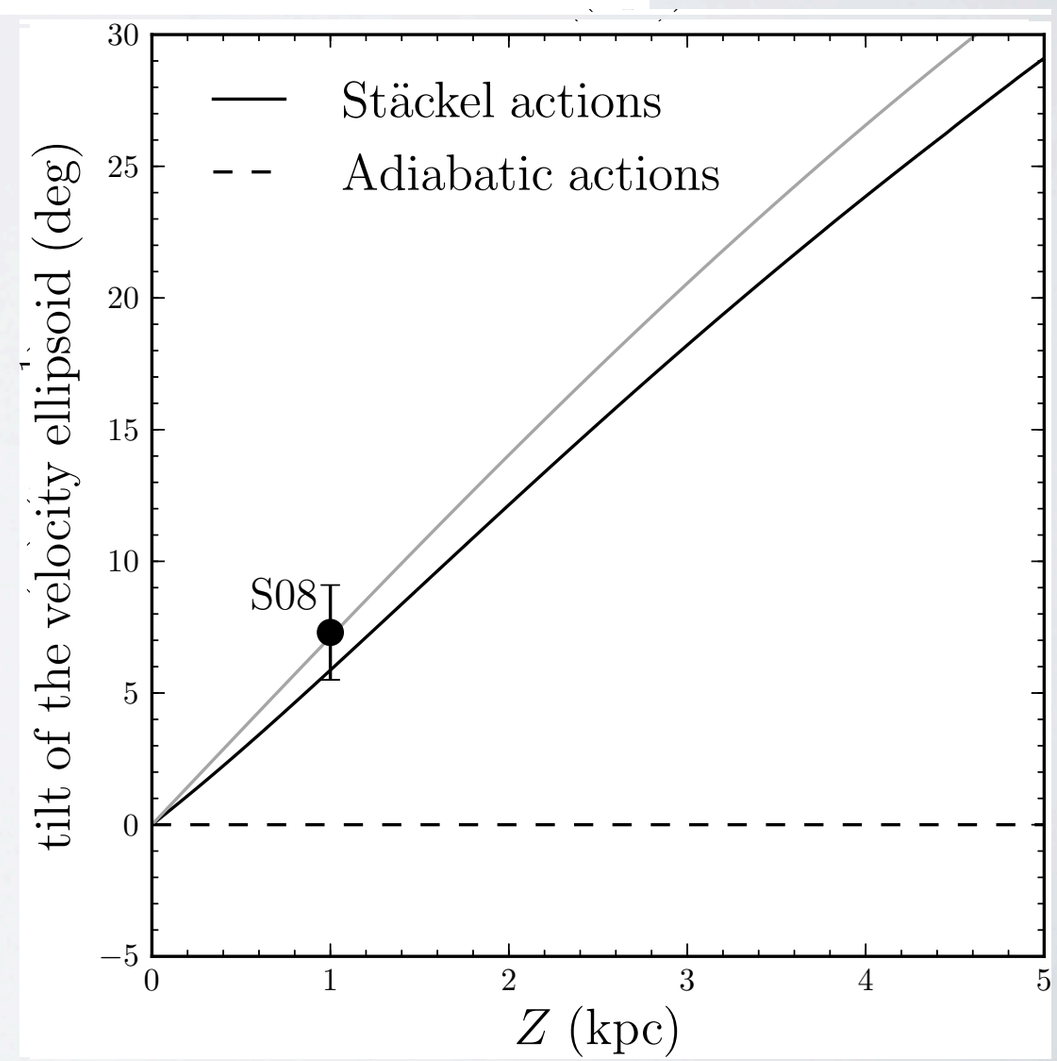
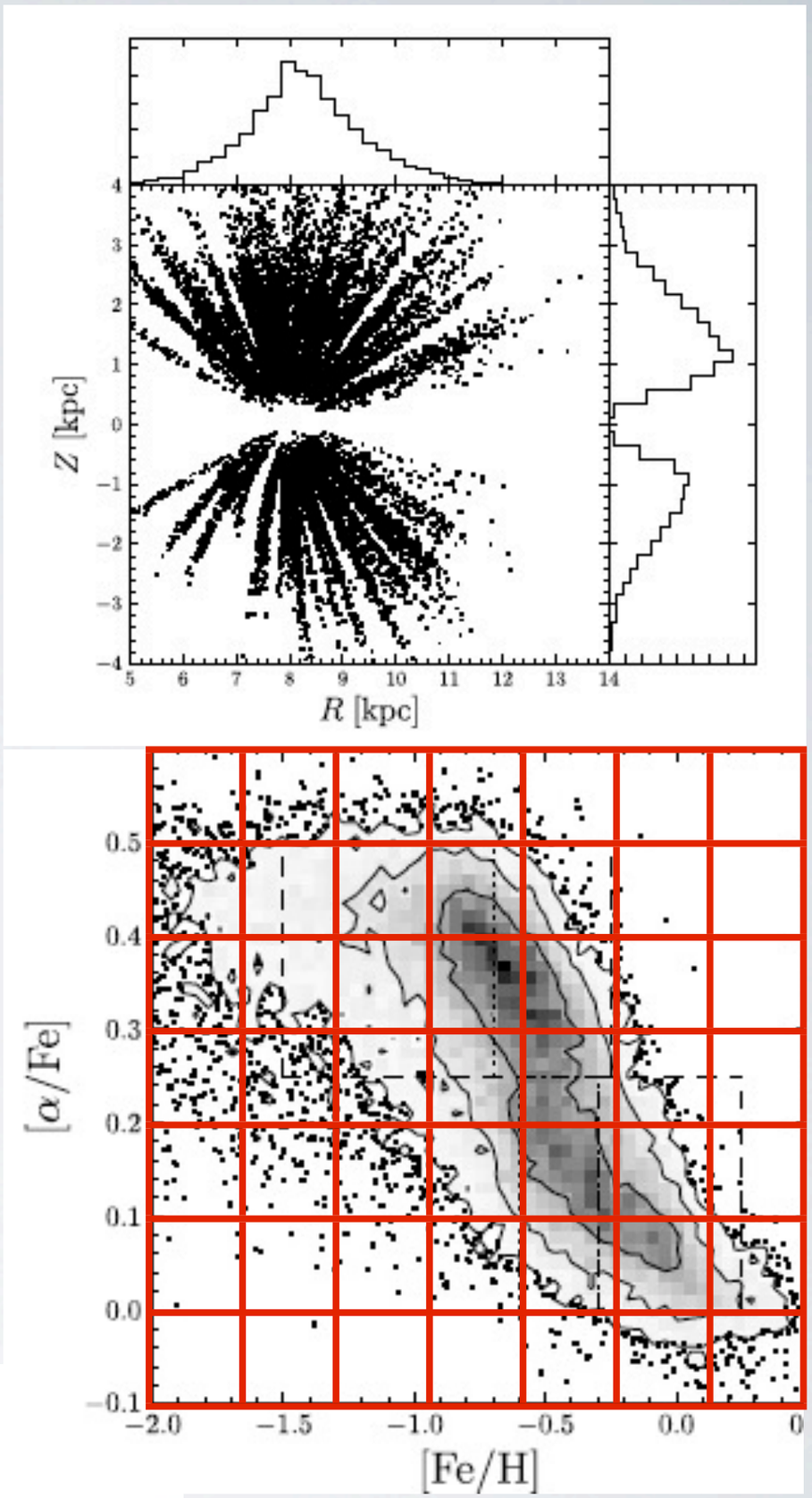


APPLICATION TO SEGUE

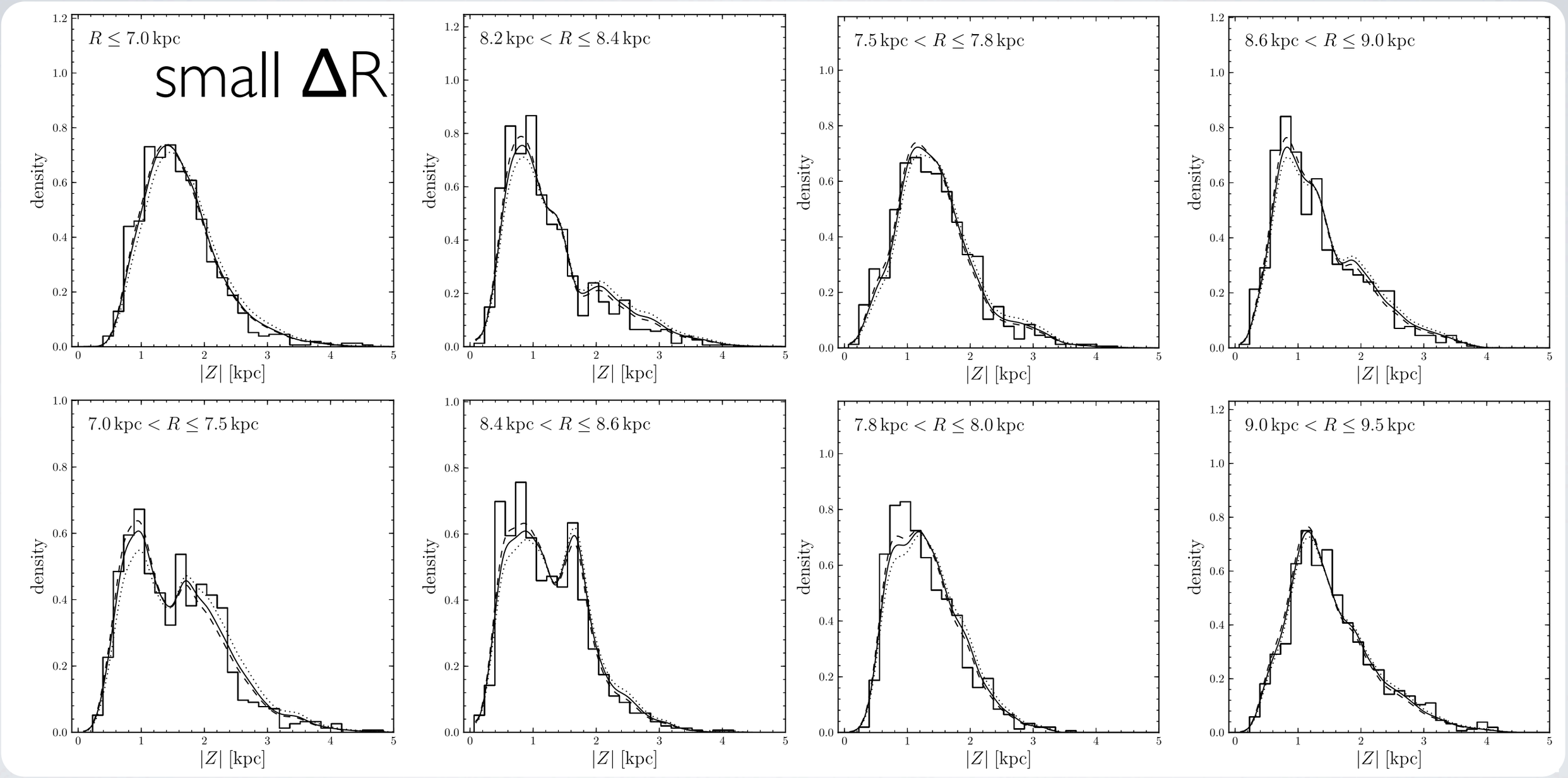
Bovy & Rix (2013), ApJ, **779**, 115

- SEGUE: 6D data set extending to multiple kpc from the Sun at high latitude
- Separate stars by chemical abundance and model each population as a quasi-isothermal DF
- Marginalizing over DF parameters and simple potential model, use each population to constrain $F_z(z=1.1\ \mathrm{kpc})$ at a certain radius



$$\ln \mathcal{L} = \sum_i \left[\ln \sum_j f(\mathbf{J}[\mathbf{x}_i^j, \mathbf{v}_i^j]) | \mathbf{p}_\Phi, \mathbf{p}_{\mathrm{DF}}) - \ln \int \mathrm{d}l\, \mathrm{d}b\, \mathrm{d}d\, \mathrm{d}\mathbf{v}\, \mathrm{d}r\, \mathrm{d}(g-r)\, \mathrm{d}[\mathrm{Fe/H}]\, \lambda(l, b, d, \mathbf{v}, r, g-r, [\mathrm{Fe/H}] | \mathbf{p}_\Phi, \mathbf{p}_{\mathrm{DF}}) \right]$$

SPATIAL FITS USING DYNAMICAL MODEL



Data distribution in distance from plane

Bovy & Rix (2013), ApJ, **779**, 115

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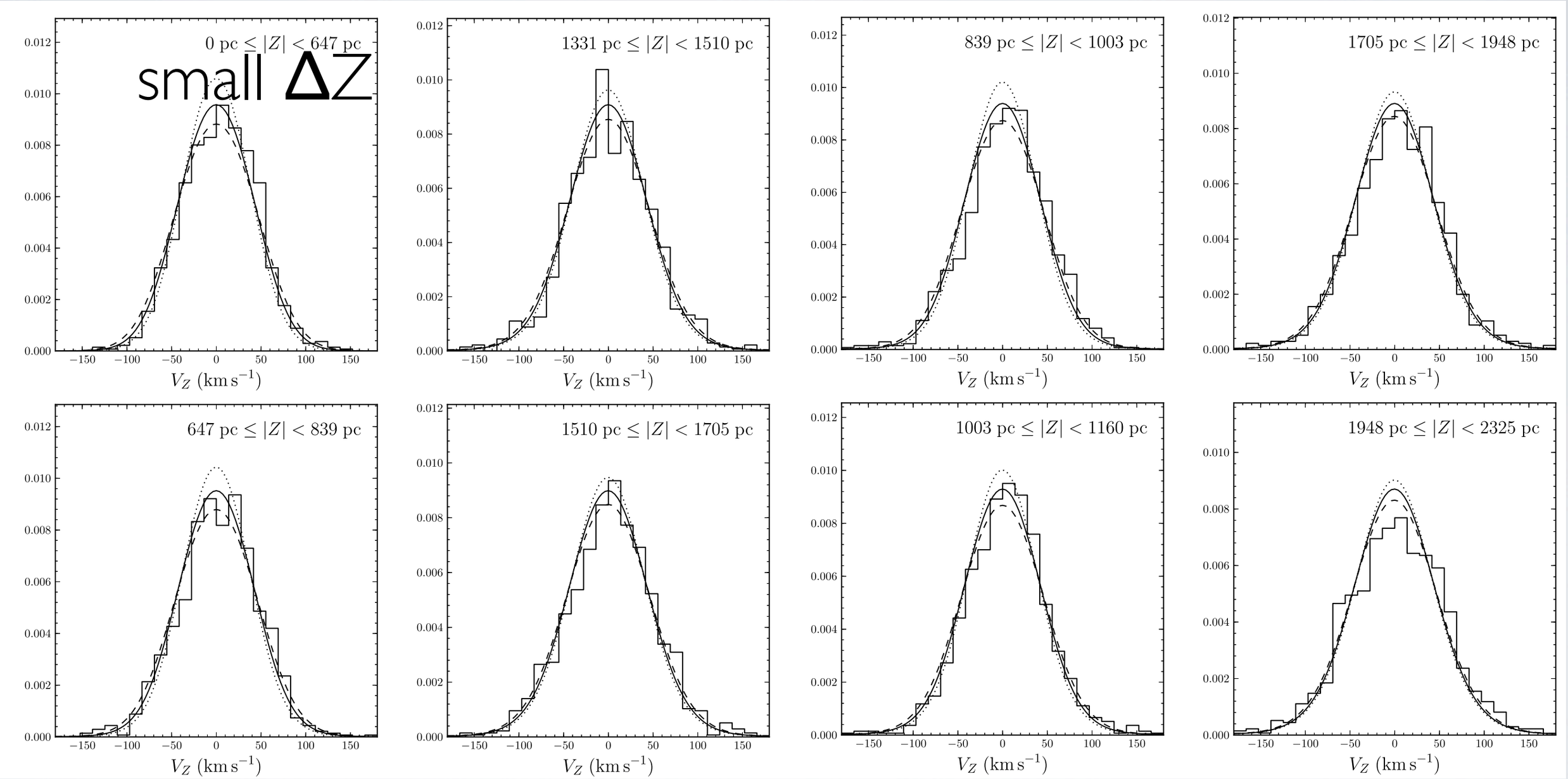
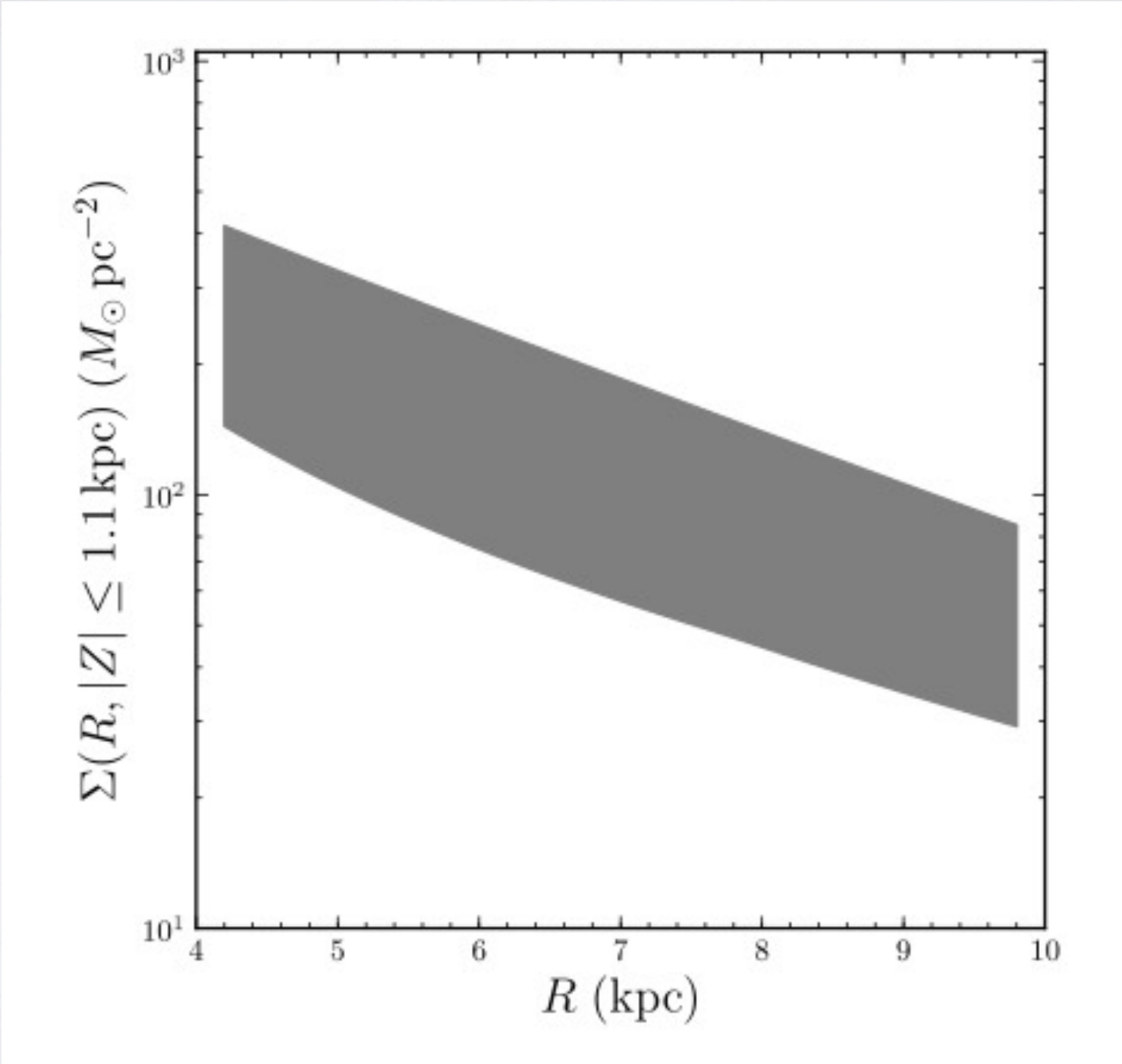


Data distribution in vertical velocity

Bovy & Rix (2013), ApJ, **779**, 115

SURFACE-DENSITY PROFILE



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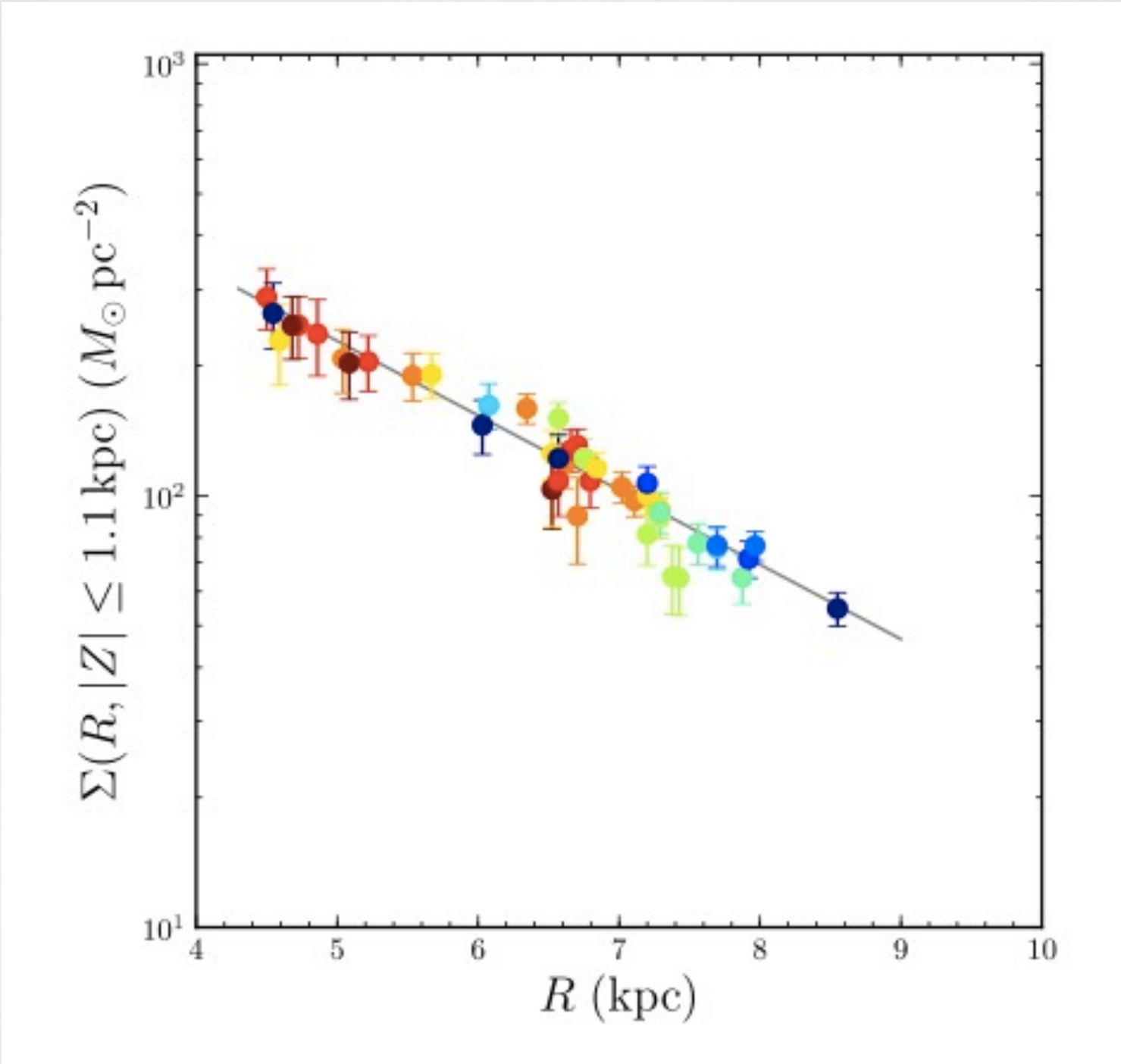
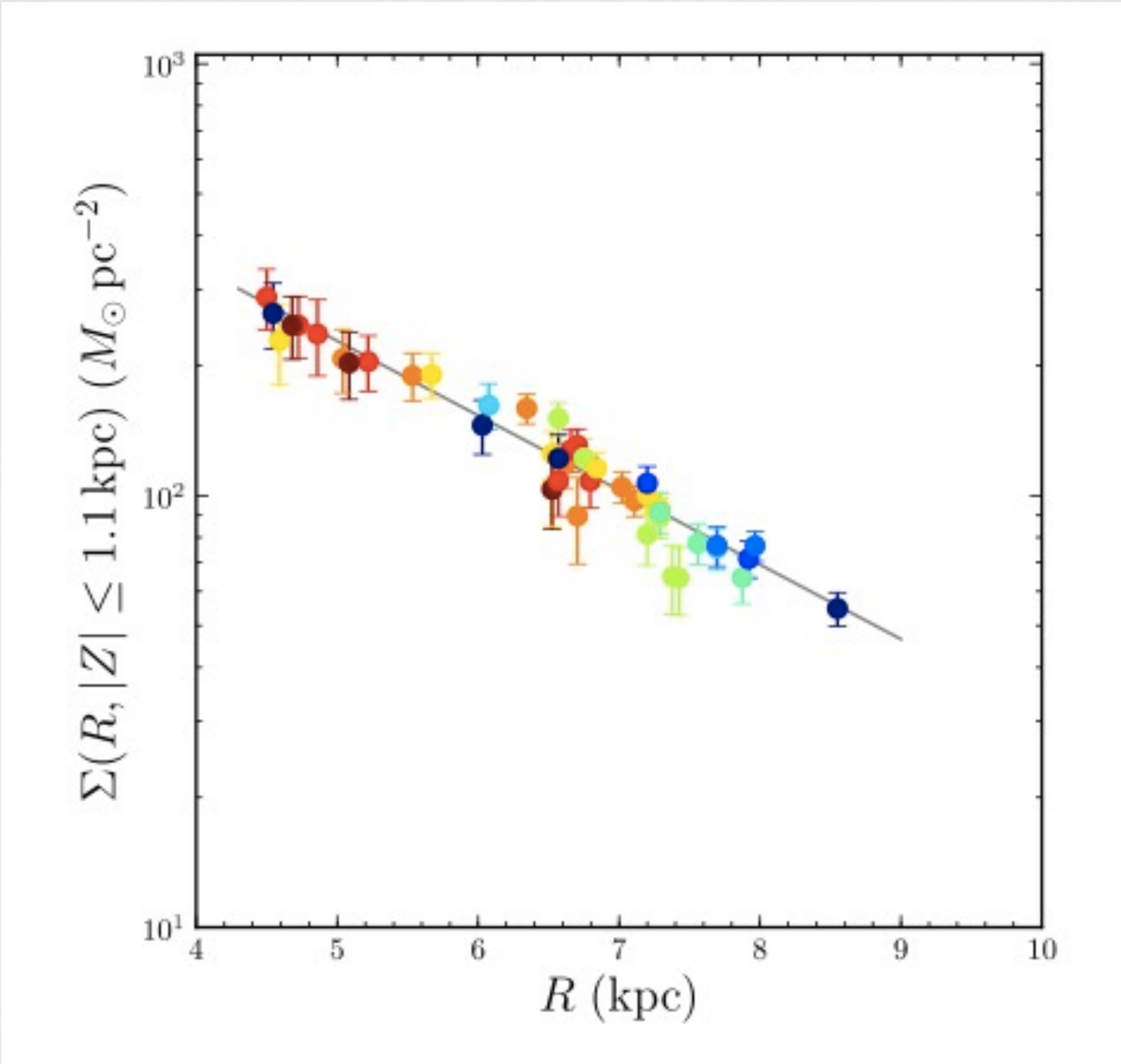


Bovy & Rix (2013), ApJ, **779**, 115

SURFACE-DENSITY PROFILE

$$\Sigma(R, |Z| \leq 1.1\,\mathrm{kpc}) = 69\,M_\odot\,\mathrm{pc}^{-2}\,\exp\left[-\frac{R - R_0}{2.5\,\mathrm{kpc}}\right]$$



Bovy & Rix (2013), ApJ, **779**, 115

43 MEASUREMENTS OF VERTICAL FORCE THAT CAN BE USED FOR CONSTRAINING THE MASS DISTRIBUTION

TABLE 3
Measured surface density and vertical force at different Galactocentric radii

[Fe/H] (dex)	[α/Fe] (dex)	R (kpc)	$\Sigma_{1.1}(R)$ ($M_\odot$ pc^{-2})	$\delta\Sigma_{1.1}(R)$ ($M_\odot$ pc^{-2})	$R_0 - R$ (kpc)	$K_{Z,1.1}(R)$ ($2\pi G\, M_\odot$ pc^{-2})	$\delta K_{Z,1.1}(R)$ ($2\pi G\, M_\odot$ pc^{-2})
-1.25	0.425	4.63	256.0	50.4	3.37	217.6	41.5
-1.15	0.425	4.68	270.9	44.3	3.32	230.6	36.8
-1.05	0.375	6.71	89.7	20.3	1.29	84.2	18.5
-1.05	0.425	4.77	244.2	40.1	3.23	209.0	33.2
-0.95	0.325	4.59	228.4	48.3	3.41	194.7	38.6
-0.95	0.375	5.04	207.6	34.9	2.96	180.5	29.2
-0.95	0.425	5.22	204.3	30.1	2.78	179.0	25.6
-0.95	0.475	4.68	247.9	41.3	3.32	211.4	33.7
-0.85	0.275	7.38	65.0	11.9	0.62	62.2	11.2
-0.85	0.325	6.53	104.9	19.8	1.47	97.5	18.0
-0.85	0.375	6.62	118.1	14.0	1.38	109.8	12.9
-0.85	0.425	6.66	127.6	14.0	1.34	119.0	12.9
-0.85	0.475	5.08	202.8	35.9	2.92	176.8	30.1
-0.75	0.275	7.42	64.4	11.6	0.58	61.7	11.0
-0.75	0.325	6.53	125.0	16.2	1.47	115.9	14.8
-0.75	0.375	7.11	97.3	8.0	0.89	92.0	7.5
-0.75	0.425	6.71	130.6	11.8	1.29	121.9	10.9
-0.75	0.475	6.53	103.3	19.8	1.47	96.1	18.0
-0.65	0.275	7.20	81.4	12.6	0.80	77.3	11.8
-0.65	0.325	7.20	100.2	9.9	0.80	95.2	9.3
-0.65	0.375	6.34	159.2	12.7	1.66	146.3	11.5
-0.65	0.425	6.79	108.0	14.5	1.21	101.2	13.4
-0.55	0.275	7.29	89.2	9.6	0.71	84.9	9.1
-0.55	0.325	7.29	93.1	7.8	0.71	88.5	7.4
-0.55	0.375	7.02	104.7	8.7	0.98	98.7	8.2

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-0.55	0.425	6.57	108.3	18.7	1.43	100.8	17.1
-0.45	0.225	7.56	77.6	8.5	0.44	74.5	8.1
-0.45	0.275	6.75	122.4	12.6	1.25	114.3	11.7
-0.45	0.325	6.84	115.7	10.1	1.16	108.4	9.4
-0.45	0.375	5.54	189.6	24.1	2.46	168.6	20.9
-0.35	0.225	7.29	91.5	10.2	0.71	87.2	9.6
-0.35	0.275	6.57	150.9	13.5	1.43	140.1	12.4
-0.35	0.325	5.67	190.6	22.3	2.33	170.6	19.5
-0.25	0.175	7.70	75.6	8.4	0.30	72.8	8.0
-0.25	0.225	7.88	64.6	8.5	0.12	62.4	8.2
-0.15	0.125	7.70	76.7	8.1	0.30	73.9	7.8
-0.15	0.175	6.08	161.8	19.8	1.92	147.4	17.7
-0.05	0.025	6.57	121.9	16.4	1.43	113.2	14.9
-0.05	0.075	7.92	71.4	7.0	0.08	69.2	6.8
0.05	0.025	8.55	54.7	4.9	-0.55	53.4	4.7
0.05	0.075	7.20	106.8	10.0	0.80	101.3	9.4
0.15	0.025	6.03	145.4	20.9	1.97	132.4	18.8
0.25	0.025	4.82	240.3	42.9	3.18	206.2	35.7

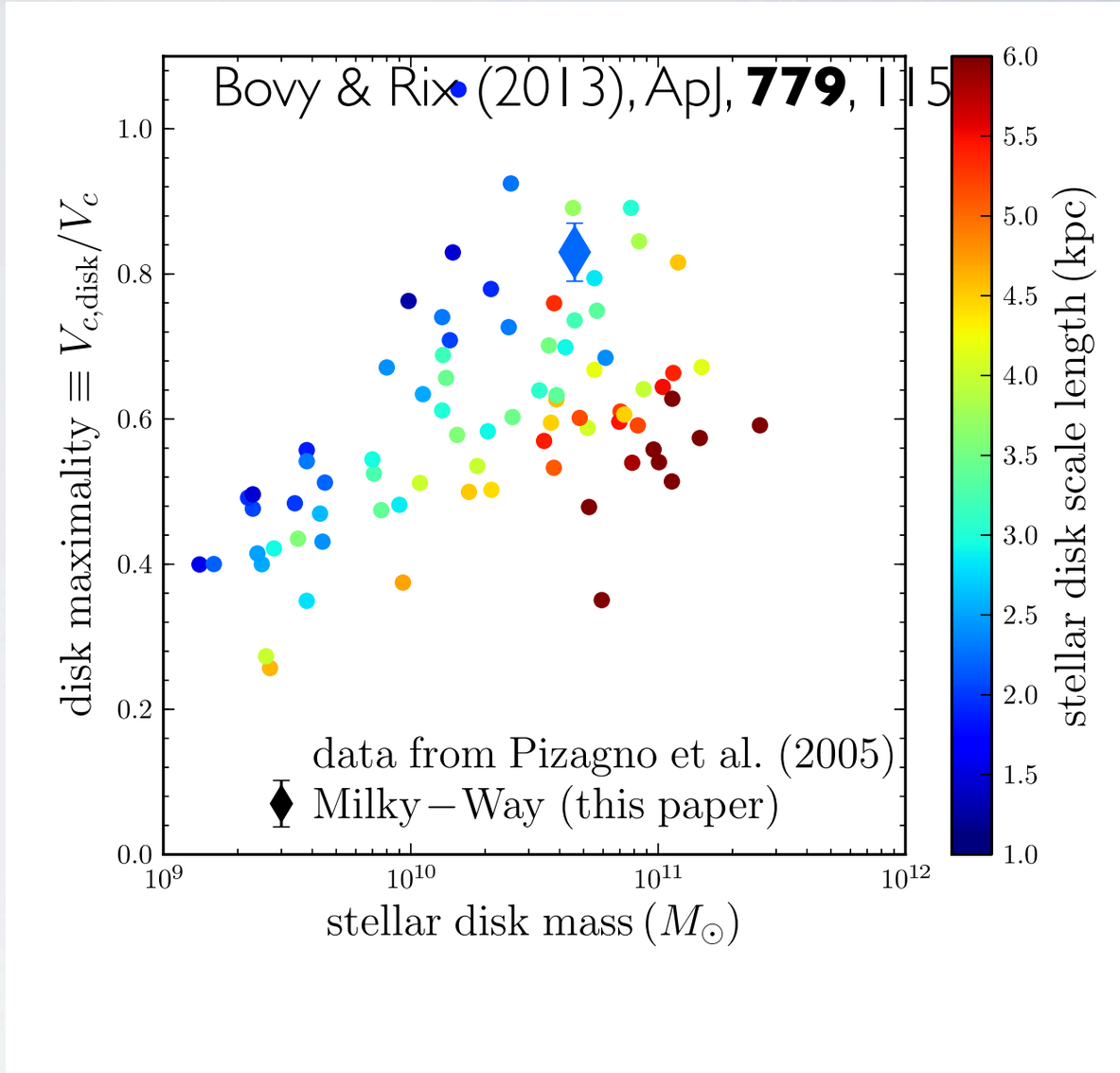
SUMMARY OF RESULTS

- Disk scale length: 2.15+/-0.15 kpc

$$M_* = 4.6 \pm 0.3 \times 10^{10}\, M_\odot$$

$$\left.\frac{V_{c,*}}{V_c}\right|_{2.2\,R_d} = 0.83 \pm 0.04$$

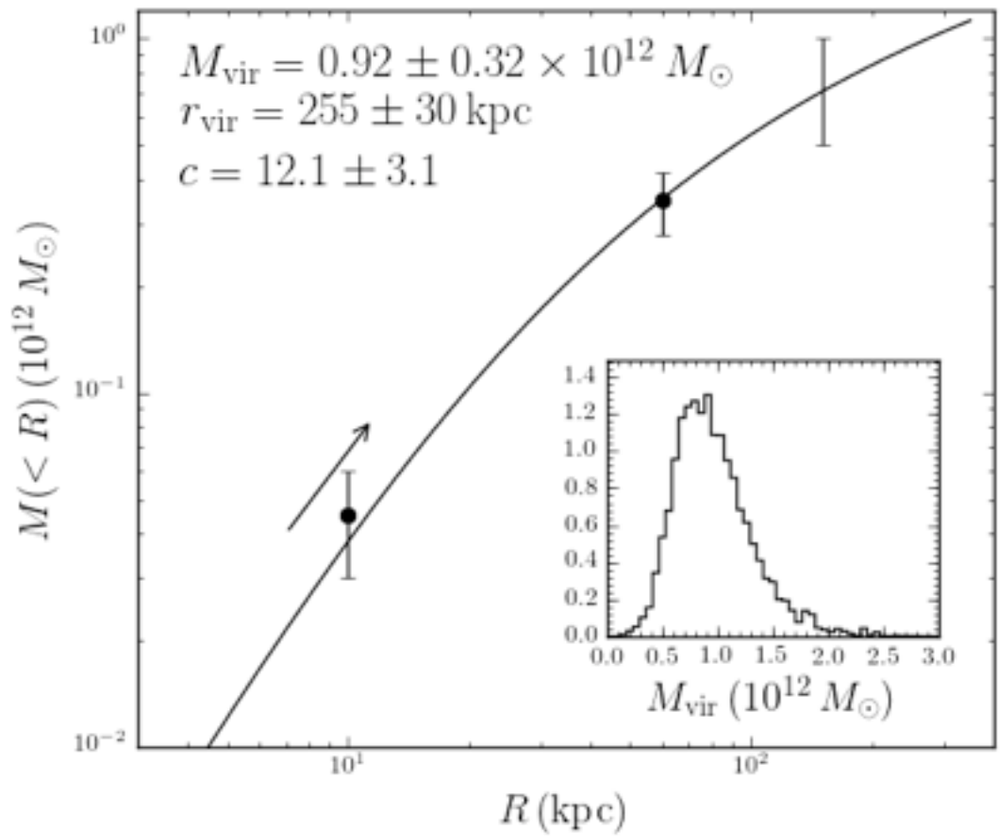
- Halo contributes little to rotation curve and surface density at R < 10 kpc



- M_{halo}(R < 10 kpc) = 4.5 +/-1.5 x 10^{10} M_{sun}
- First breaking of disk-halo degeneracy in the Milky Way:
  - Disk is maximal
  - Halo density relatively low, radially compatible with NFW

SUMMARY OF RESULTS

Bovy & Rix (2013), ApJ, **779**, 115



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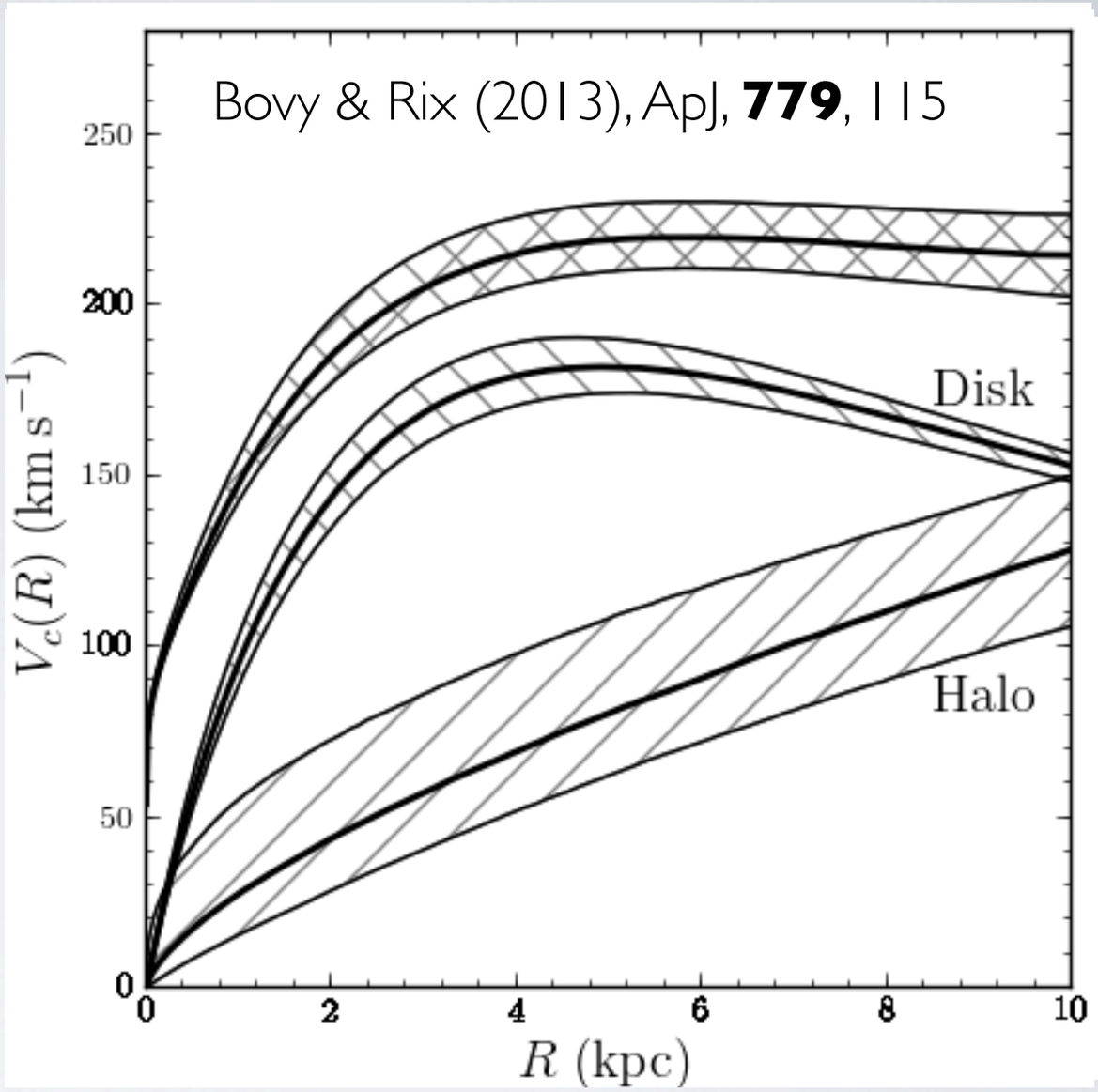


- Disk scale length: 2.15+/-0.15 kpc

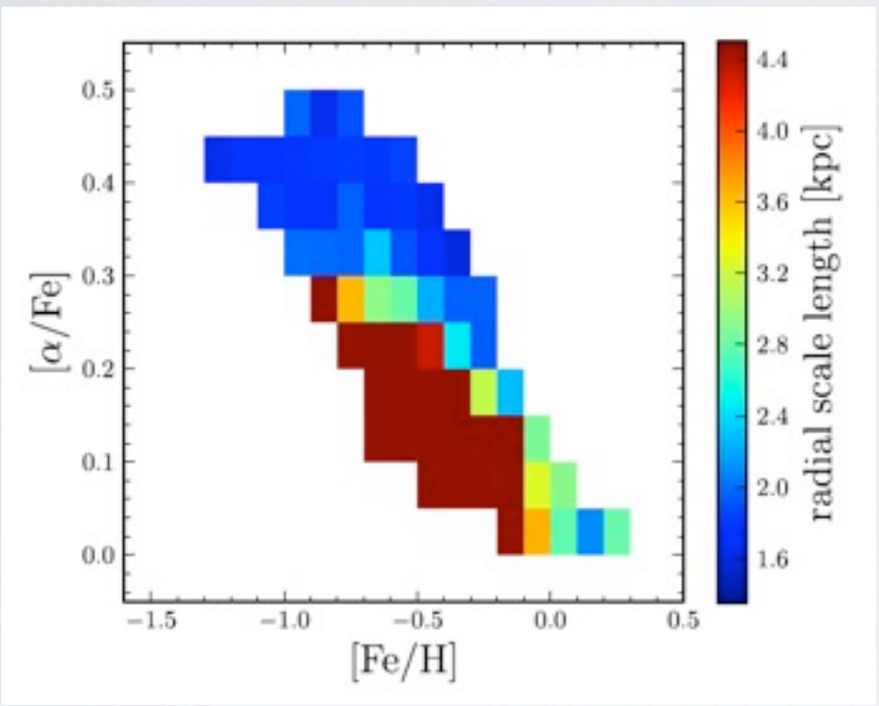
$$M_* = 4.6 \pm 0.3 \times 10^{10}\, M_\odot$$

$$\left.\frac{V_{c,*}}{V_c}\right|_{2.2\,R_d} = 0.83 \pm 0.04$$

- Halo contributes little to rotation curve and surface density at R < 10 kpc
- M_{halo}(R < 10 kpc) = 4.5 +/-1.5 x 10^{10} M_{sun}
- First breaking of disk-halo degeneracy in the Milky Way:
  - Disk is maximal
  - Halo density relatively low, radially compatible with NFW

COMPARISON WITH STAR COUNTS

- MAP decomposition allows one to predict the scale length as a function of radius



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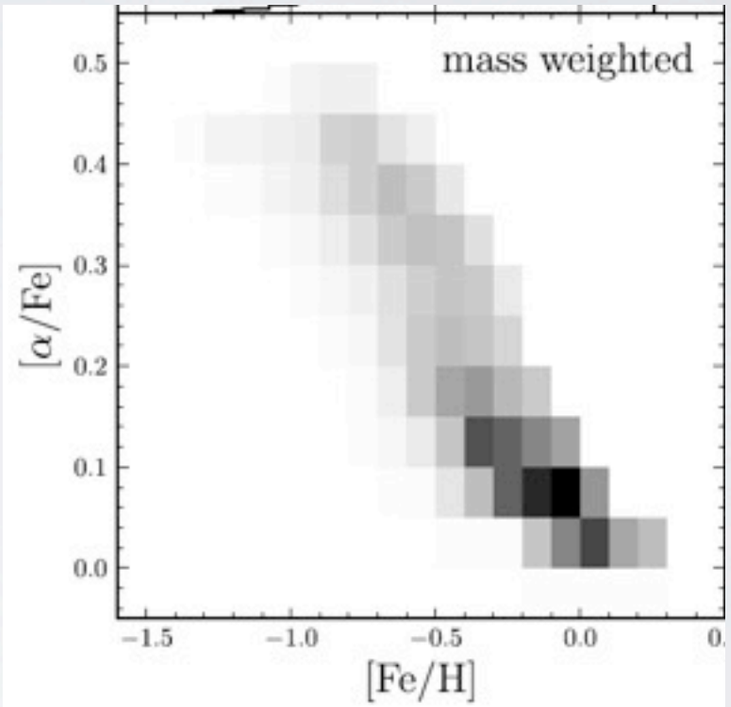

Bovy & Rix (2013), ApJ, **779**, 115

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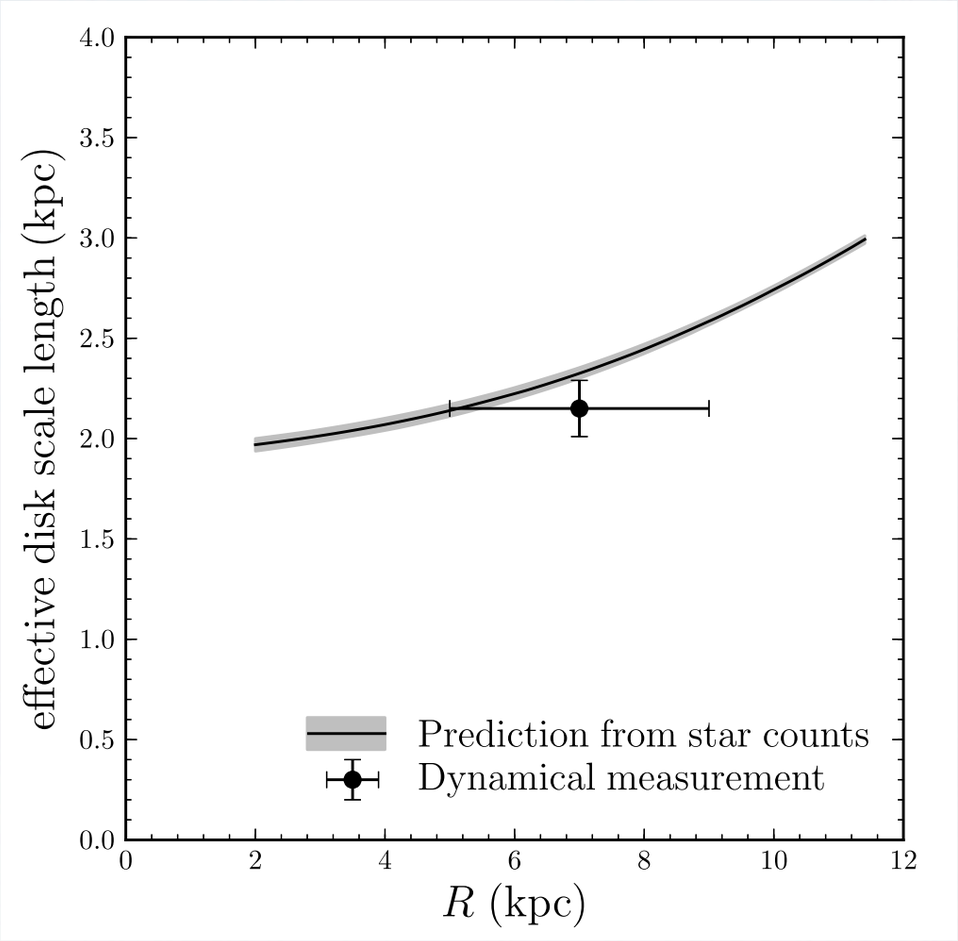

- Similar results for the mass scale height vs. stellar scale height

- We understand the stellar disk incredibly well!

Bovy & Rix (2013), ApJ, **779**, 115

THE MW ROTATION CURVE

ROTATION CURVE FROM STELLAR KINEMATICS

$$F_R(R,Z) = -\frac{\partial \Phi(R,Z)}{\partial R} = \frac{1}{\nu}\frac{\partial\left(\nu\sigma_U^2\right)}{\partial R} + \frac{1}{\nu}\frac{\partial\left(\nu\sigma_{UW}^2\right)}{\partial Z} + \frac{\sigma_U^2 - \sigma_V^2 - \bar{V}^2}{R},$$

- Radial Jeans equation in the mid-plane (Z=0) gives relation between mean rotational velocity ($\bar{V}$) and V_c, given measurements of the density profile (nu), and the velocity dispersion (radial $\boldsymbol{\sigma}_U$ and tangential $\boldsymbol{\sigma}_V$)
- APOGEE: large sample of red giants in the mid-plane of the MW (b=0) out to 10 kpc
- We can model the kinematics of these stars using the model above
- Essentially we measure $\bar{V}$(R) and use the Jeans equation to correct this to V_c

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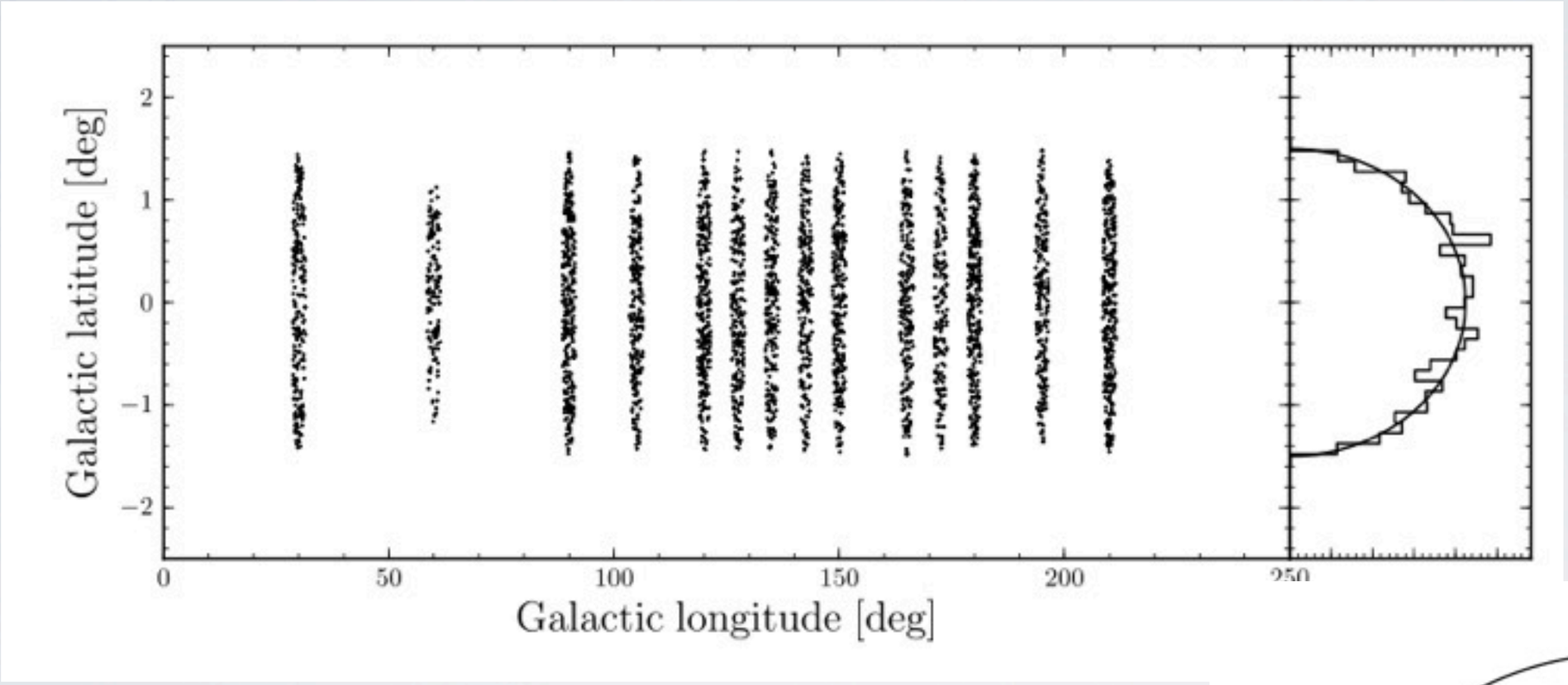
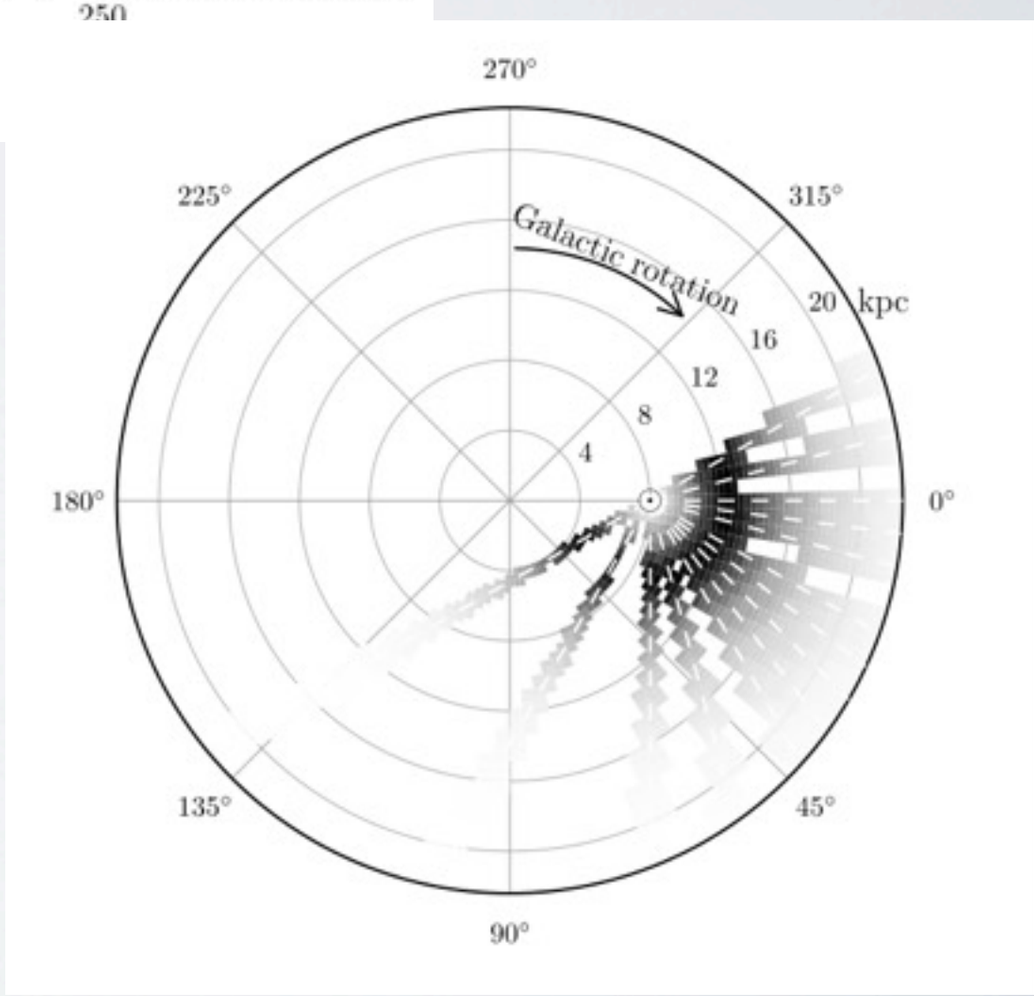
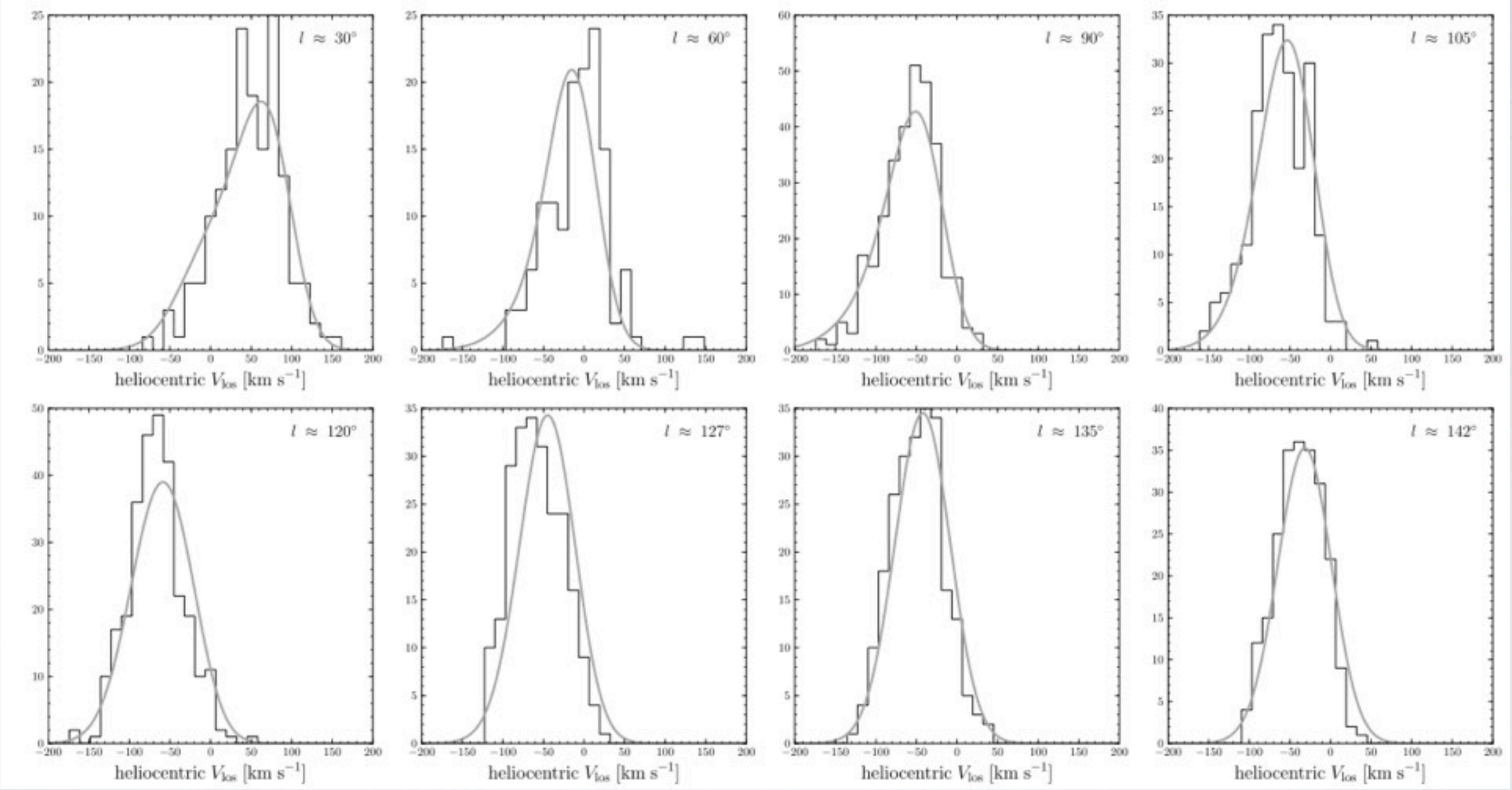
APOGEE YEAR 1 DATA





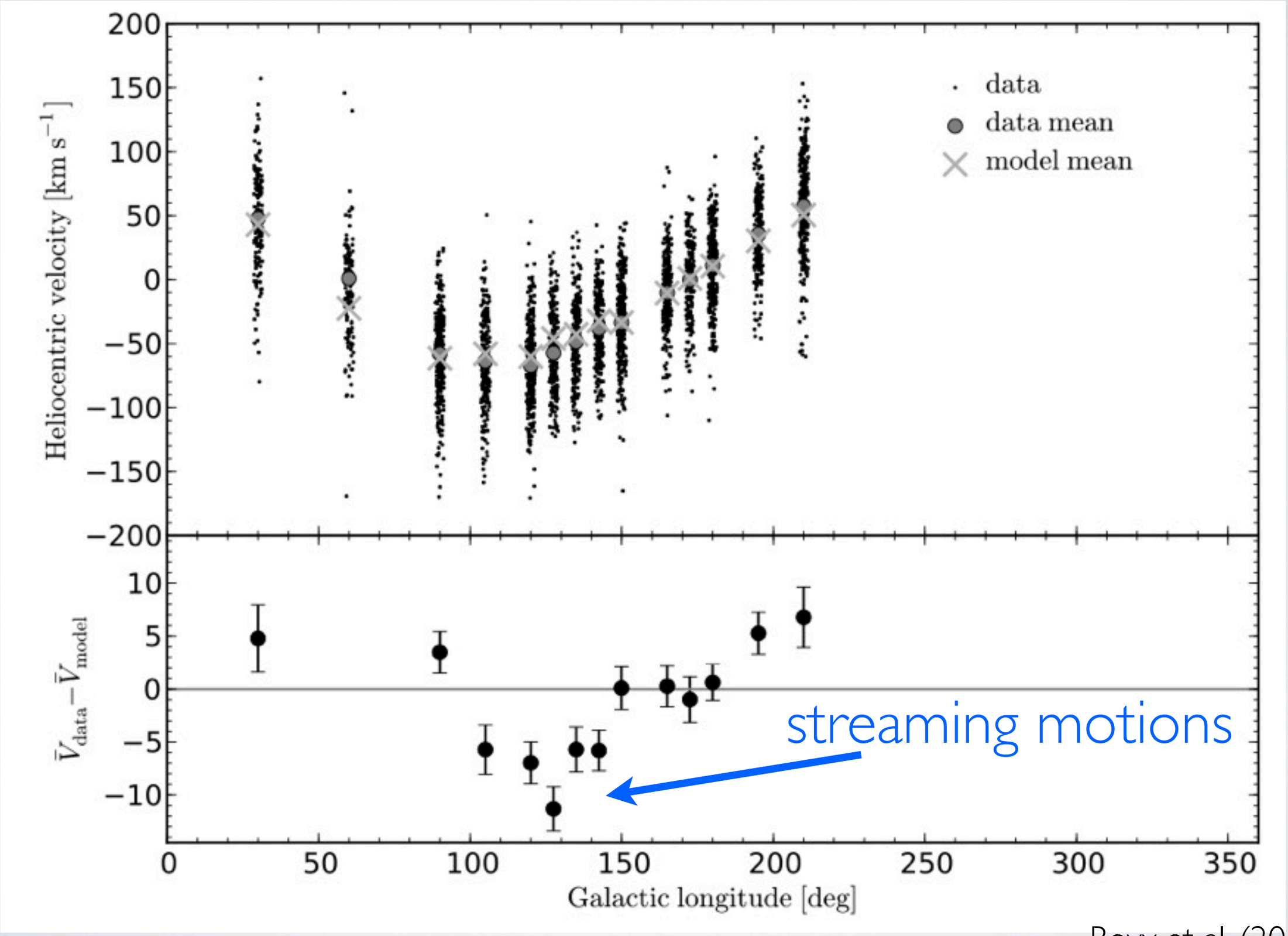
- Δl =~ 180° at b=0°
- distances up to 10 kpc, but low precision photometric distances that we need to marginalize over
- Model: Gaussian velocity distribution with model dispersion and $\bar{V}$ from Jeans

RESULTS



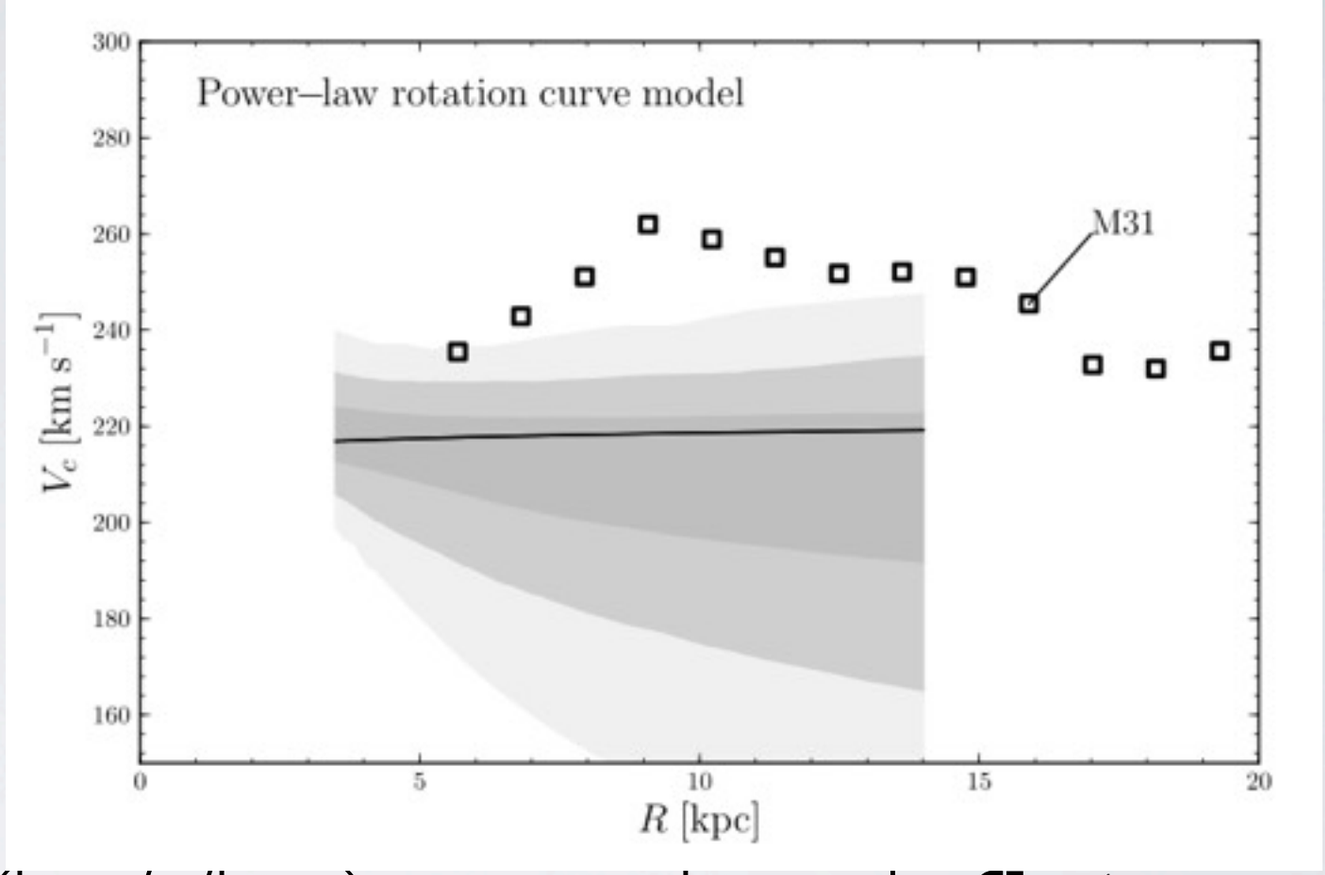
Bovy et al. (2012)

RESULTS

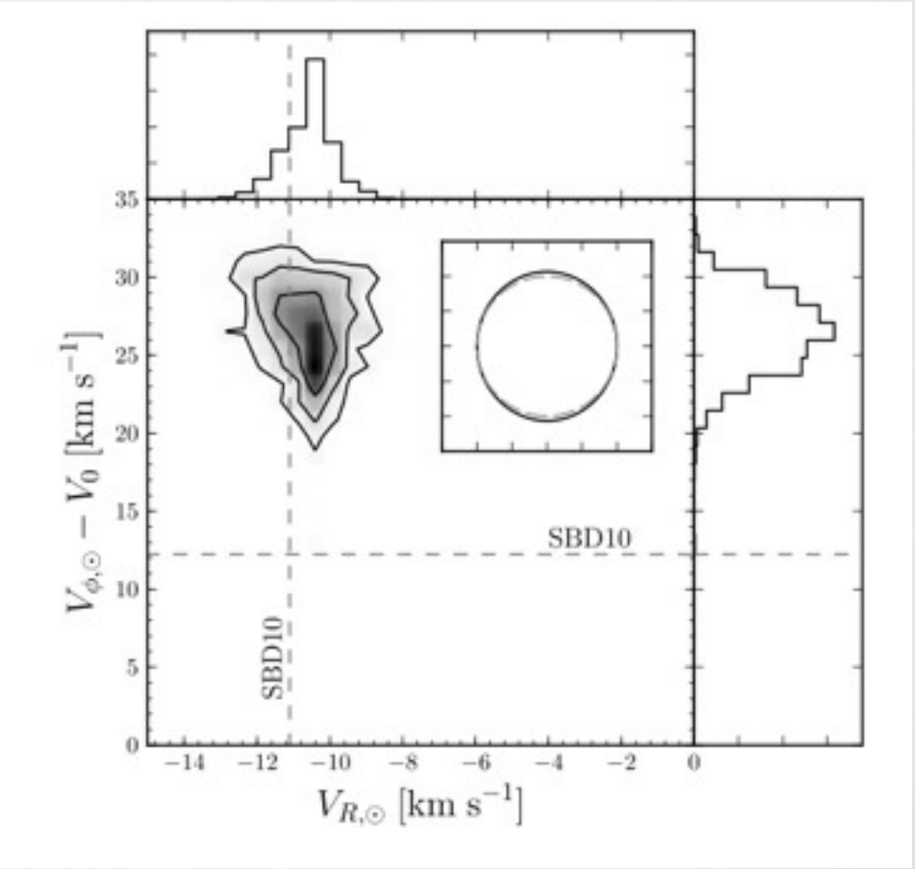


Bovy et al. (2012)

RESULTS



- V_c (R_0) = **218** +/- 6 km/s
- 8 < R_0 < 9 (kpc)
- -3 < d V_c / d R (R_0) < 0.5 (km/s/kpc): approximately **flat**
- 240 <~ $V_{\varphi,\odot}$ <~ 250 (km/s) or
  5.6 < $\mu_{Sgr\,A*}$ < 6.4 (mas/yr)
- **Solar motion =~ 25 km/s**
  (compared with SBD =~ 12 km/s)
- Systematics < few km/s;
  V_c (R_0) < 235 km/s (99% confidence)



Bovy et al. (2012)

SIMPLE MODEL

galpy https://github.com/jobovy/galpy

Galactic Dynamics in python Bovy (2015)

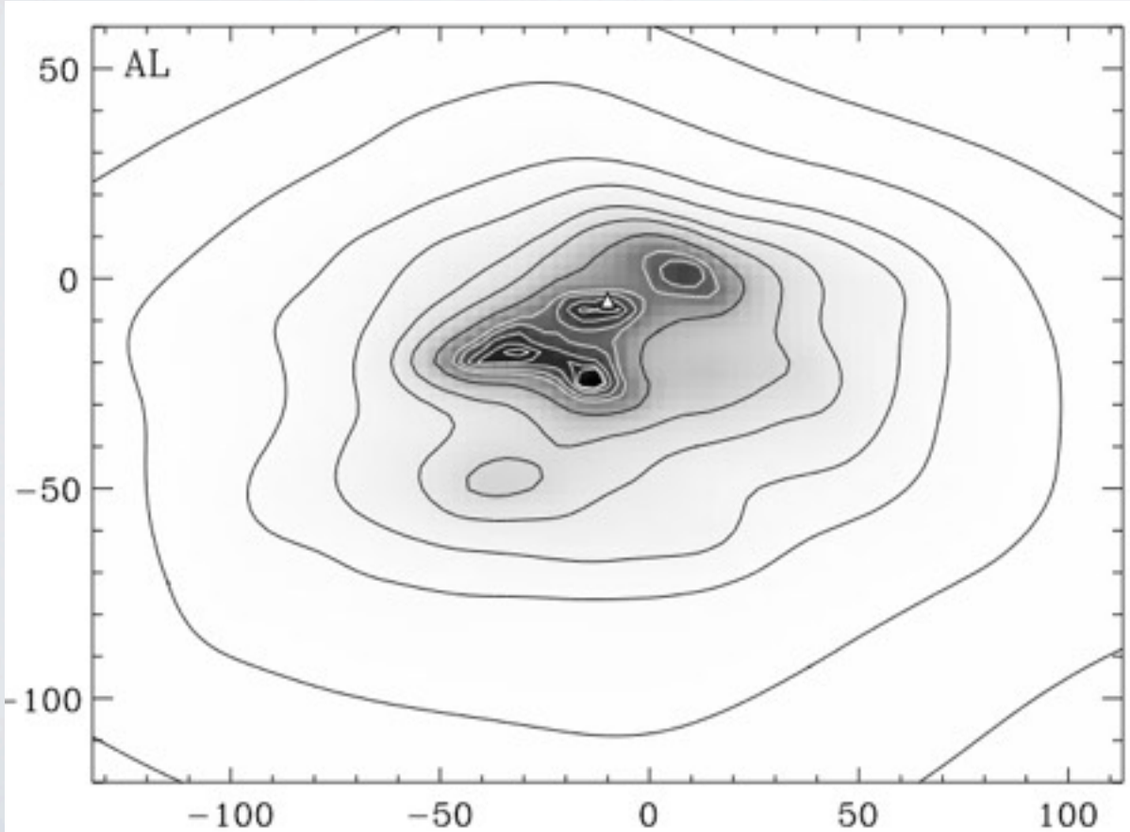
build passing | coverage 100% | C coverage 99% | Docs latest | pypi v0.1 | license New BSD

- A simple model for the Milky Way's potential is included in my *galpy* code as `galpy.potential.MWPotential2014`
- This model is a Miyamoto-Nagai disk, spherical NFW halo, power-law bulge w/ exp. cut that allows for fast orbit integration etc.
- In detail this model agrees with:
  - Velocity dispersion in the bulge (Baade's window)
  - Vertical force at the Solar radius and the baryonic surface density (Zhang et al. 2013); Vertical force measurements as a function of radius from before
  - Terminal velocity curve
  - Local mid-plane density (Holmberg & Flynn 2000)
  - Rotation curve from APOGEE (Bovy et al. 2012)
  - Total mass within 60 kpc from Xue et al. (2008)

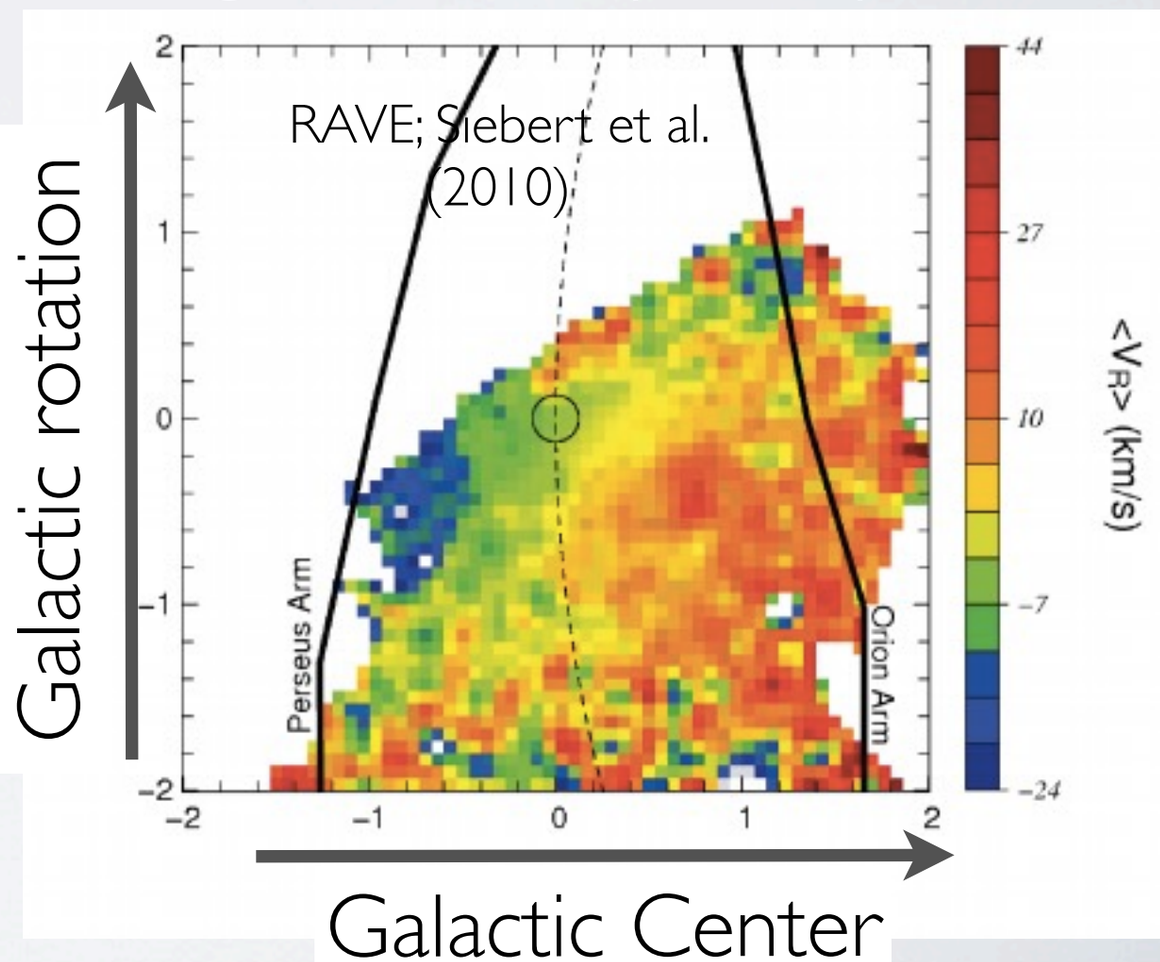
NON-AXISYMMETRY

SEARCHING FOR NON-AXISYMMETRY

- Radial distribution of gas and stars driven by non-axisymmetric perturbations should leave imprints in the distribution of stellar orbits today
- Can search for dynamical effect of perturbations (bar, spirals, ...)
- E.g., velocity DF (*Hipparcos*), streaming motions (RAVE)



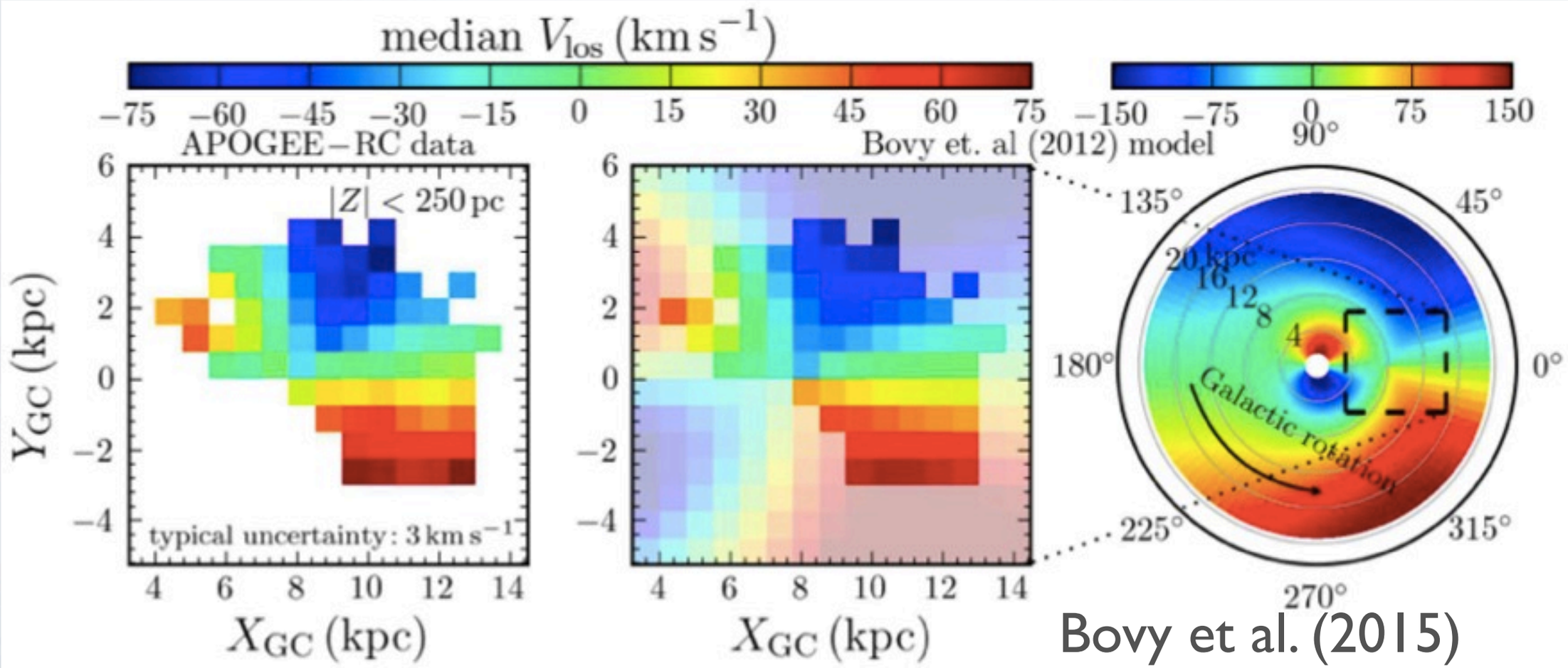
Dehnen et al. (1998)



GALACTIC DYNAMICS WITH RED CLUMP STARS

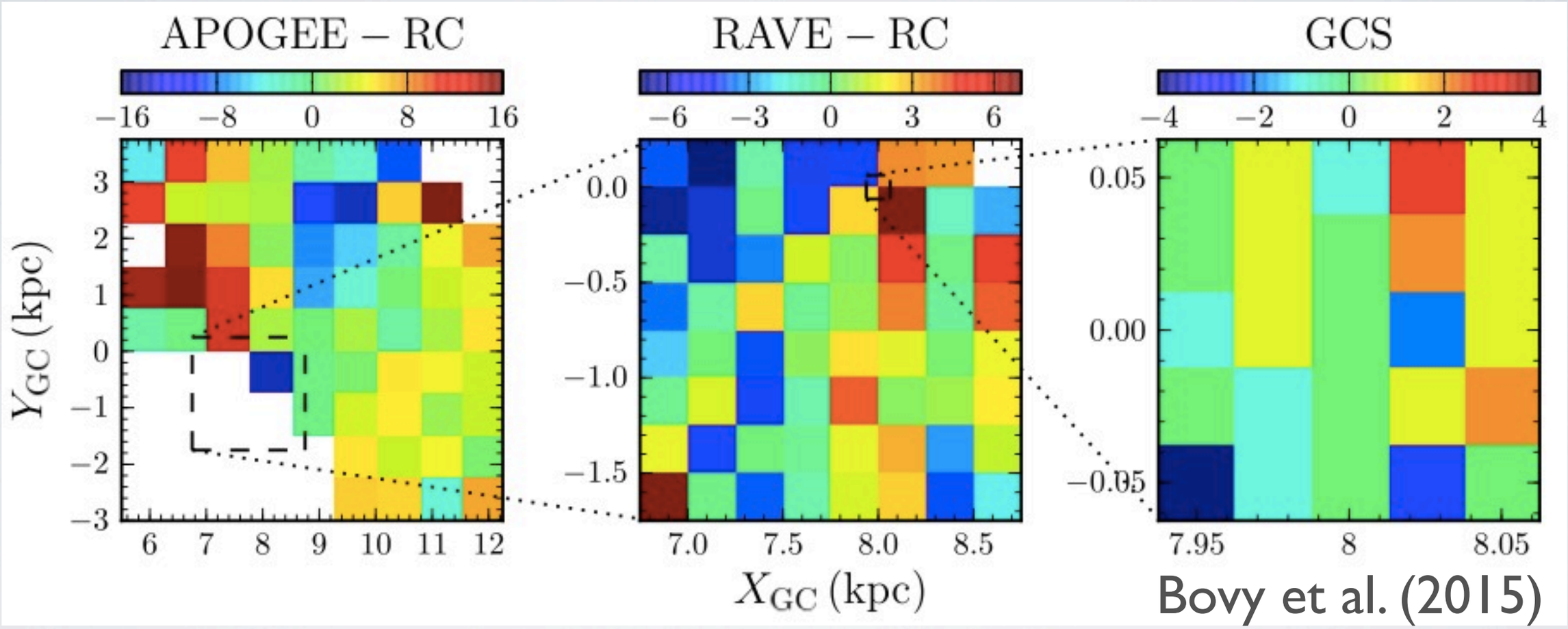
- Wide disk coverage and rotation-curve+DF fits from Bovy et al. (2012) allow us to look at deviations from axisymmetric rotation

- Main contribution from Sun's motion wrt Vc, can determine this



Bovy et al. (2015)

GALACTIC DYNAMICS WITH RED CLUMP STARS

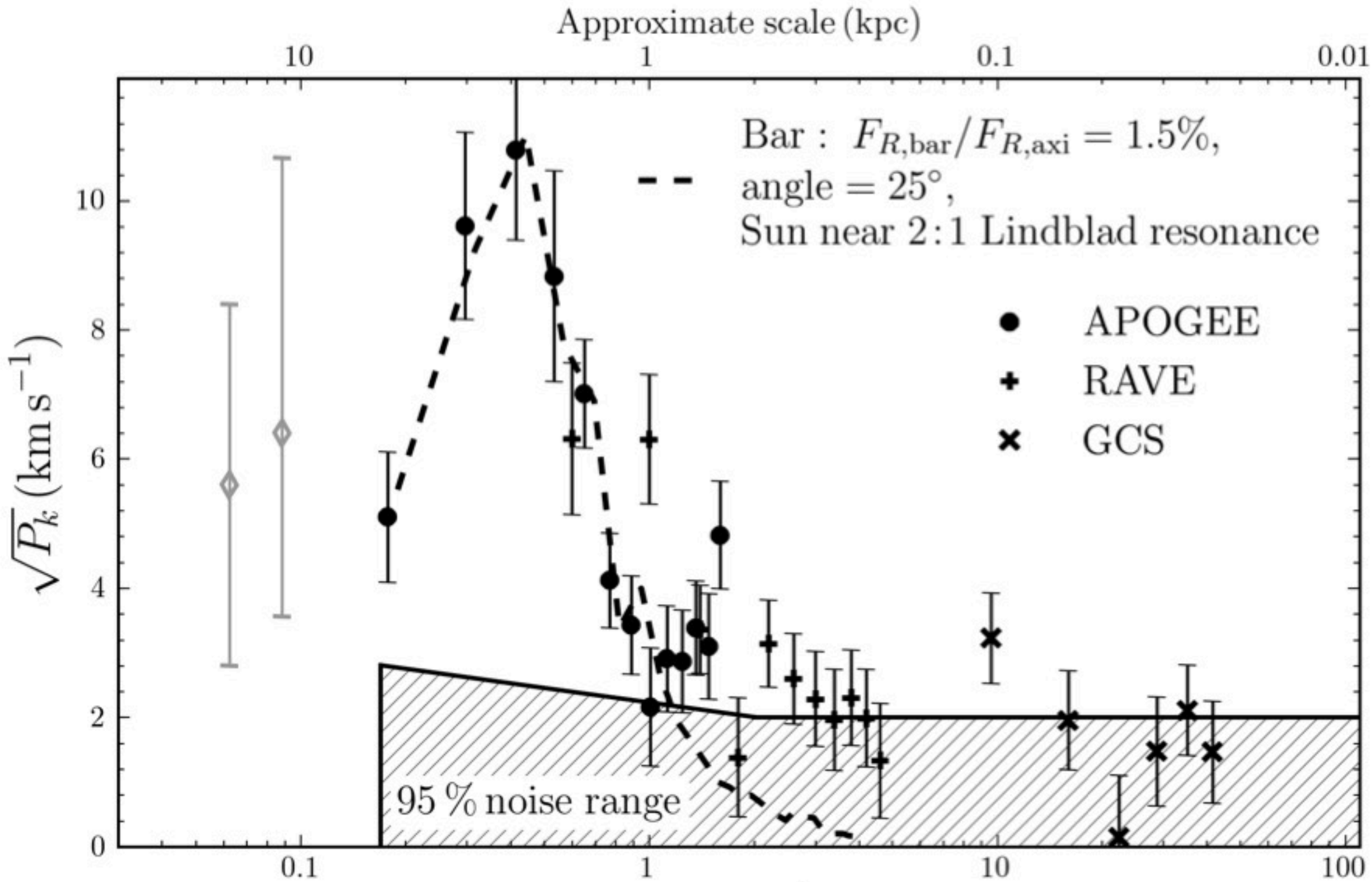


- After subtracting smooth axisymmetric rotation, can look at peculiar velocities

- New interpretation tool: power spectrum

GALACTIC DYNAMICS WITH RED CLUMP STARS

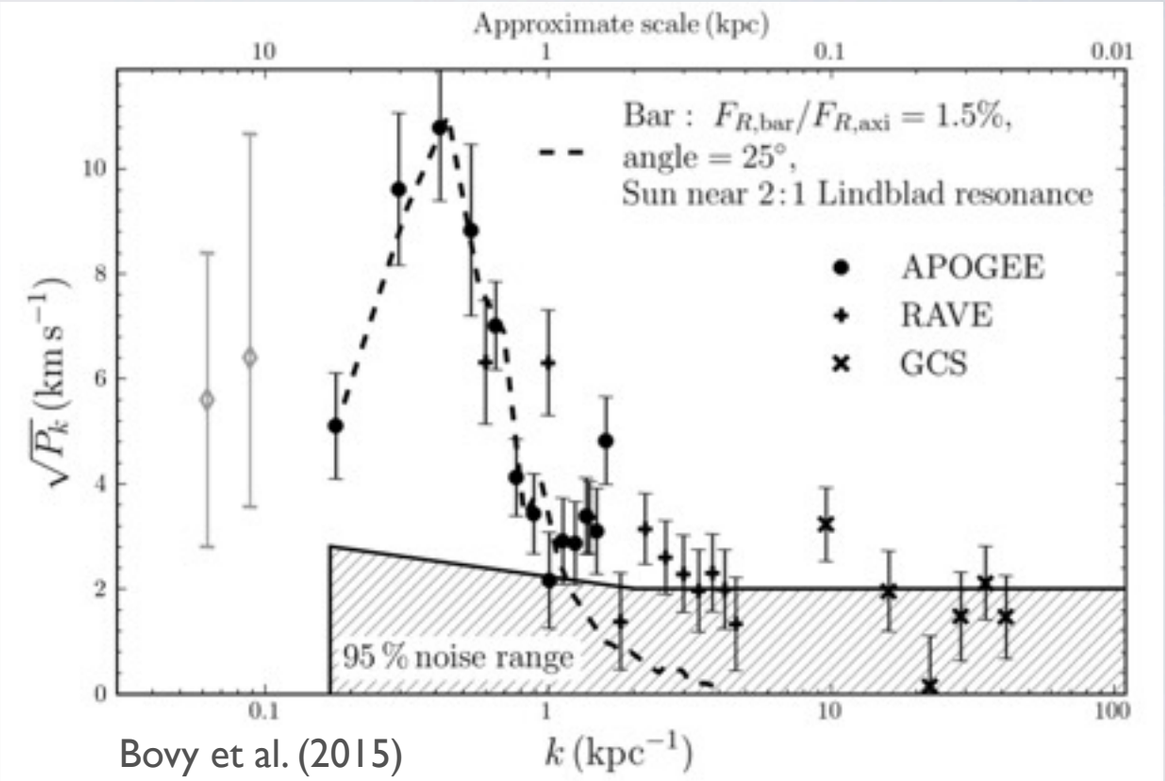
- F
  f
  a
- S
- C
- I
  c
  s
- V



Bovy et al. (2015)

GALACTIC DYNAMICS WITH RED CLUMP STARS

- Power spectrum demonstrates that fluctuations affect the large scales around 3 kpc mostly
- Surprising turn-over on the largest scales
- Can be fit well with standard MW bar,
- Inconsistent with steady spirals, but consistent w/ transient, co-rotating spiral structure (Grand, Bovy, Kawata,+ in prep.)
- $V_{sun} = 24 \pm 1$ km s^{-1}



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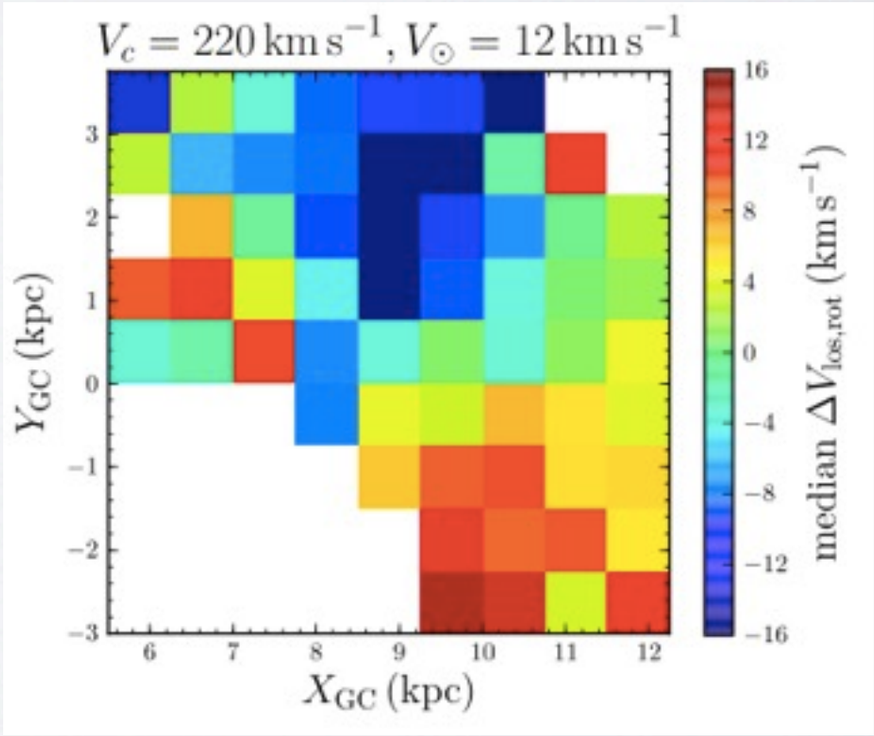
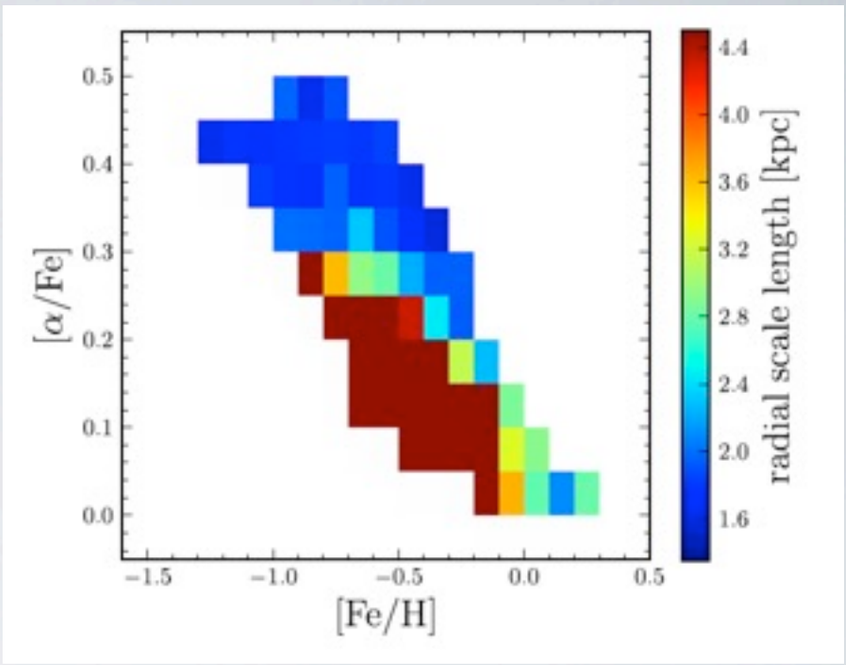
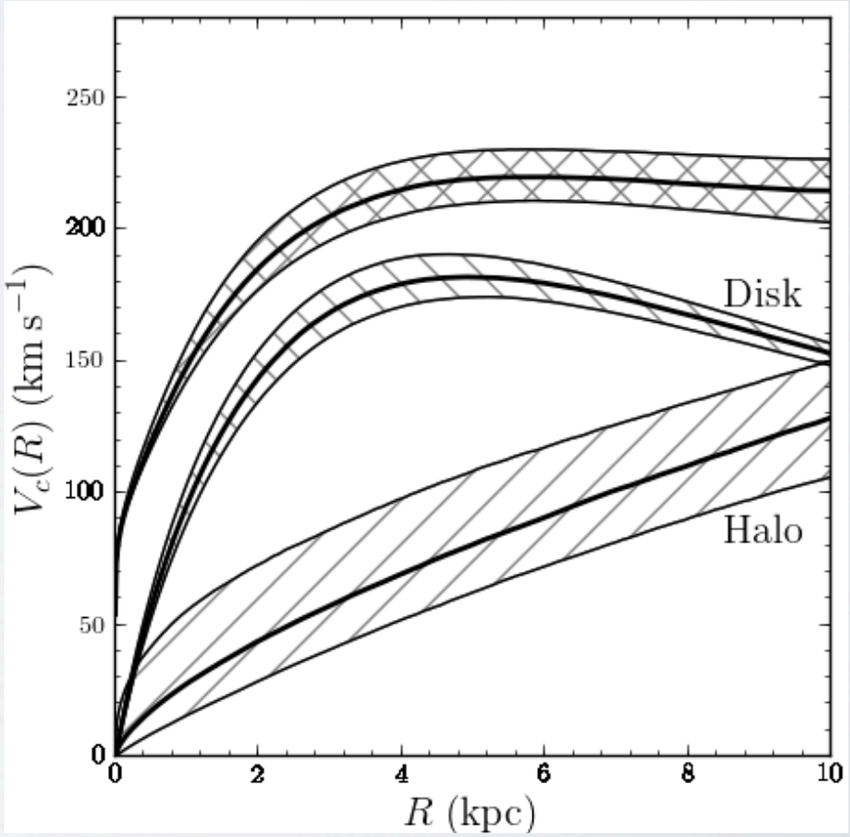


CONCLUSIONS

- Complete re-assessment of the structure of the stellar disk from SEGUE data:
  - "thick disk": centrally-concentrated, fits smoothly on the "thin disk" component, accounts for ~50% of the mass
  - Large number of components revealed through their elemental abundances with range in scale length, scale height, and kinematics
  - Smoothness of disk difficult to reconcile with large influence of mergers on disk
- Abundance-selected populations → robust dynamical inferences:
  - MAPs consistent with living in same potential
  - MW disk is maximal (Vrot mainly from stars, not DM)
  - "Dynamical" scale length agrees with star counts → consistency and !MOND
- Future will bring *Gaia* and better spec. surveys