New measurements of the local density of dark matter

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INTRODUCTION

- Local density and density profile important for dark matter detection
- Direct detection: $\rho_{\rm DM}(R_0)$
- Indirect detection: e.g., Galactic center $\rho_{\rm DM}(r)$

TWO METHODS

- Global fits: Use *all* available dynamical information and optimize simple potential model (e.g., Catena & Ullio 2010, McMillan 2011)
    - Strongly influenced by assumption about scale length (see later) or halo kinematics of r ~ 50 kpc
    - Often combine mutually-inconsistent measurements
- Local fits (*this talk*): use local stellar kinematics to measure the amount of dark matter near the Sun

CURRENT CONSTRAINTS (PRE 2012)

- $\rho_{\rm DM}(R_0)$ =~ zero not strongly excluded
- Local measurement (≲100 pc) of density leaves 0.01+/- 0.01 $\mathrm{M}_{\odot}\,\mathrm{pc}^{-3}$ unaccounted by visible matter; no real prospect for improving this
  e.g., Crézé et al. (1998), Holmberg & Flynn (2000)
- Dynamical measurements of the total column density within 1 kpc require ~ 20+/-10 $\mathrm{M}_{\odot}\,\mathrm{pc}^{-2}$ of dark matter within 1 kpc --> ~ 0.01 $\mathrm{M}_{\odot}\,\mathrm{pc}^{-3}$
  e.g., Kuijken & Gilmore (1989,1991), Siebert et al. (2003) , Holmberg & Flynn (2004)

BASIC IDEA OF LOCAL MEASUREMENT

- Throw a ball up with a known velocity v and measure its maximum height h_z

$$g = \frac{v^2}{2\,h_z}$$

- For stars we can statistically measure their velocities and the heights they reach above the plane:
  - Velocity distribution: $f(v_z|z)$ characterized by dispersion σ_z
  - Density: $\rho(z)$ ~ exponential with scale height h_z
- Assuming that the stars are in a steady state, we can relate these to the gravitational potential

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

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

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

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KINEMATICAL AND CHEMICAL VERTICAL STRUCTURE OF THE GALACTIC THICK DISK. II. A LACK OF DARK MATTER IN THE SOLAR NEIGHBORHOOD*,†

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ABSTRACT

We estimated the dynamical surface mass density Σ at the solar position between $Z = 1.5$ and 4 kpc from the Galactic plane, as inferred from the kinematics of thick disk stars. The formulation is exact within the limit of validity of a few basic assumptions. The resulting trend of $\Sigma(Z)$ matches the expectations of visible mass alone, and no dark component is required to account for the observations. We extrapolate a dark matter (DM) density in the solar neighborhood of $0 \pm 1\, mM_\odot$ pc^{-3}, and all the current models of a spherical DM halo are excluded at a confidence level higher than 4σ. A detailed analysis reveals that a small amount of DM is allowed in the volume under study by the change of some input parameter or hypothesis, but not enough to match the expectations of the models, except under an exotic combination of non-standard assumptions. Identical results are obtained when repeating the calculation with kinematical measurements available in the literature. We demonstrate that a DM halo would be detected by our method, and therefore the results have no straightforward interpretation. Only the presence of a highly prolate (flattening $q > 2$) DM halo can be reconciled with the observations, but this is highly unlikely in ΛCDM models. The results challenge the current understanding of the spatial distribution and nature of the Galactic DM. In particular, our results may indicate that any direct DM detection experiment is doomed to fail if the local density of the target particles is negligible.

JEANS + POISSON EQUATIONS

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

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

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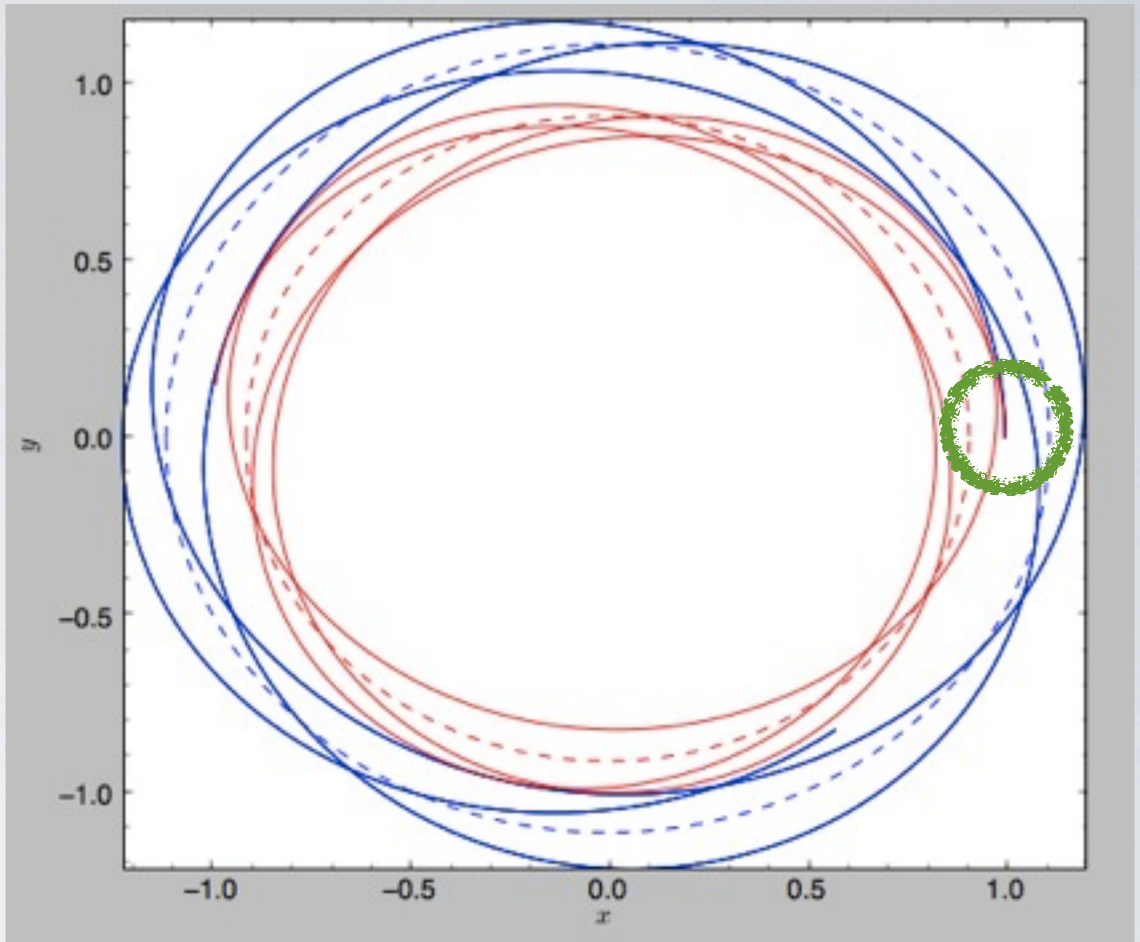
MONI-BIDIN ET AL. (2012)

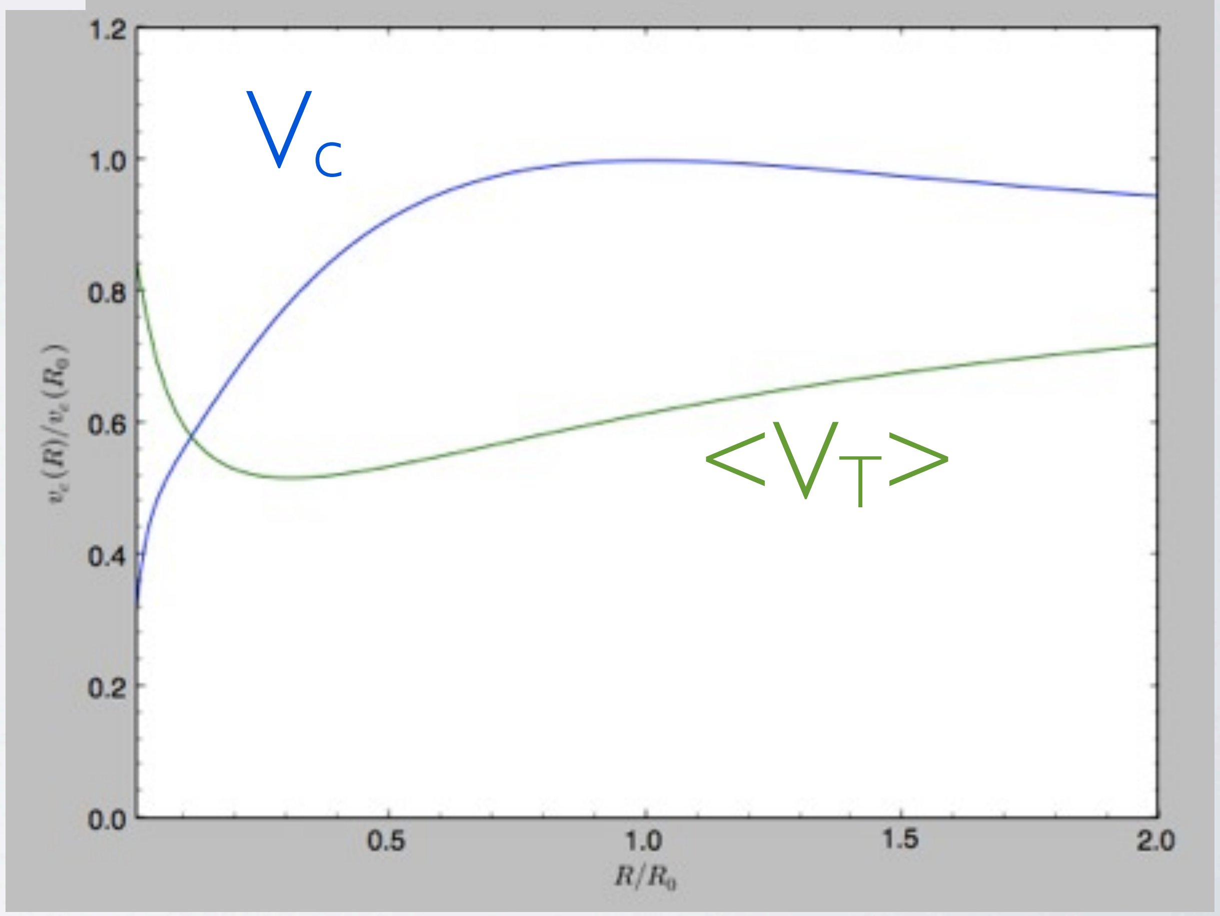
- Requires $\frac{\partial \bar{V}}{\partial R}$ but their sample has a very small range in R
- MB12: Assumption 8) "The rotation curve is locally flat in the volume under study": $\frac{\partial \bar{V}}{\partial R}$ = 0 at all Z,
- However, $\bar{V} \neq V_c$, because of the asymmetric drift

Bovy & Tremaine (2012)

ASYMMETRIC DRIFT

- Galaxy disks have decreasing density and dispersion profiles with radius
- Therefore, there are more stars coming from the inner Galaxy than from the outer Galaxy
- Because of conservation of L, inner-Galaxy stars move slower than V_c in the solar neighborhood
- The mean V_T is therefore < V_c
- This effect is bigger for larger dispersions





ASYMMETRIC DRIFT

- We can use the radial Jeans equation to calculate the asymmetric drift ...

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

- ....
- For Moni Bidin stars: $\frac{\partial\bar{V}}{\partial R}$ =~ 21 km/s/kpc at Z=2.5 kpc
- "However, ∂V /∂R = 10 km $s^{-1}kpc^{-1}$ is required to match the minimum DM density deduced by the Galactic rotation curve (MIN model), and ∂V /∂R = 16.5 km $s^{-1}kpc^{-1}$to match the SHM. Such steep rotation curves are excluded by observations." (Moni Bidin et al. 2012)

WHAT DO THE MB12 DATA TELL US?

- Using the 1D approximation:

$$\Sigma(Z) = -\frac{1}{2\pi G}\left[-\frac{1}{h_Z}\sigma_W^2 + \frac{\partial \sigma_W^2}{\partial Z} + \sigma_{UW}^2\left(\frac{1}{R} - \frac{1}{h_R} - \frac{1}{h_\sigma}\right)\right]$$

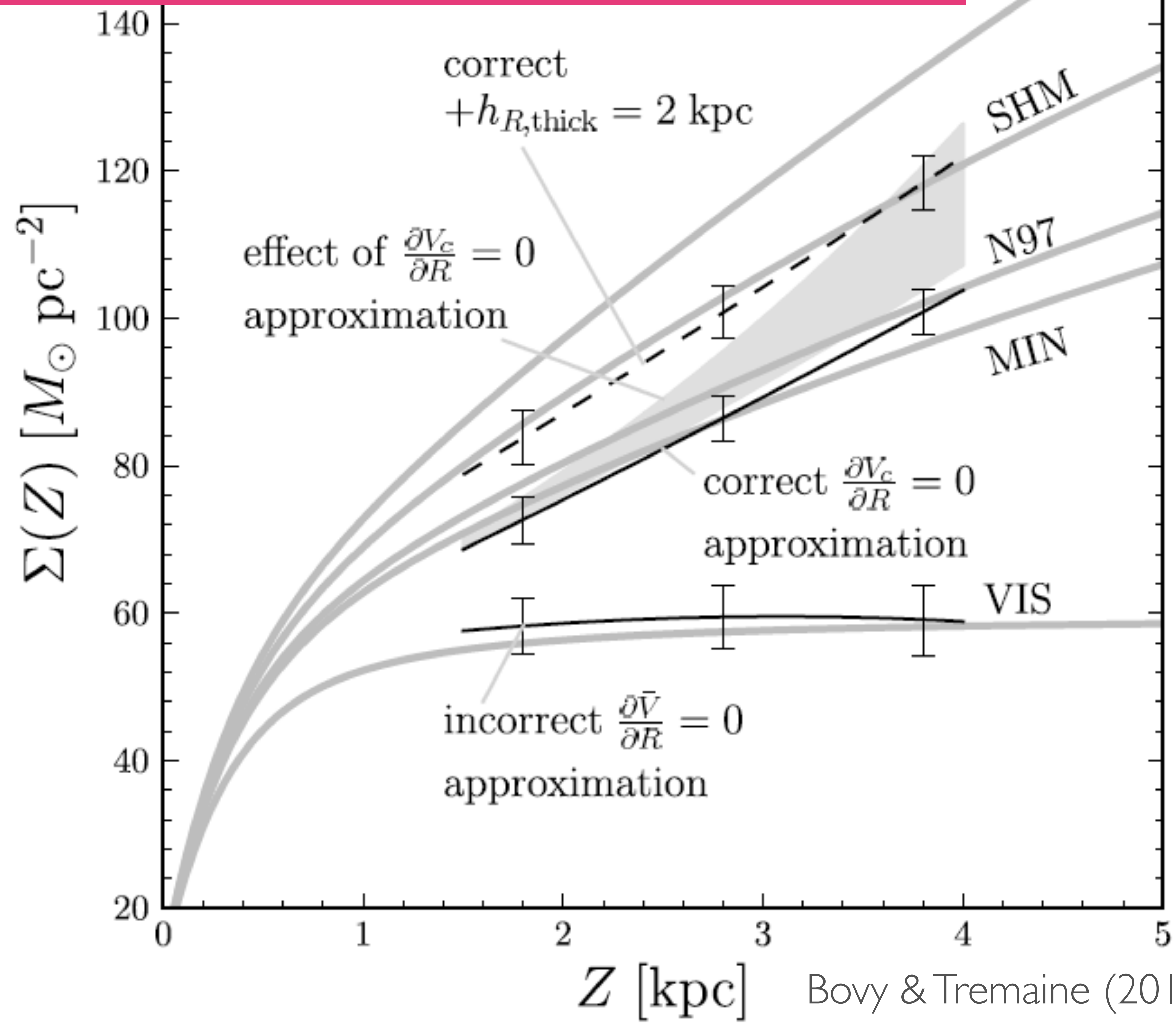
- Plug in measured values

$$\sigma_U(R_0, Z) = (82.9 \pm 3.2) + (6.3 \pm 1.1)\cdot(|Z|/\mathrm{kpc} - 2.5)\ \mathrm{km\ s^{-1}}$$
$$\sigma_V(R_0, Z) = (62.2 \pm 3.1) + (4.1 \pm 1.0)\cdot(|Z|/\mathrm{kpc} - 2.5)\ \mathrm{km\ s^{-1}}$$
$$\sigma_W(R_0, Z) = (40.6 \pm 0.8) + (2.7 \pm 0.3)\cdot(|Z|/\mathrm{kpc} - 2.5)\ \mathrm{km\ s^{-1}}$$

and that for σ_{UW}^2 from MB12

$$\sigma_{UW}^2(R_0, Z) = (1522 \pm 100) + (366 \pm 30)\cdot(|Z|/\mathrm{kpc} - 2.5)\ \mathrm{km^2\ s^{-2}}\,.$$

$$\rho_{\rm DM} = 0.008 \pm 0.003\, M_\odot\,{\rm pc}^{-3} = 0.3 \pm 0.1\,{\rm GeV\ cm}^{-3}$$



Bovy & Tremaine (2012)

SEGUE ANALYSIS OF MULTIPLE POPULATIONS

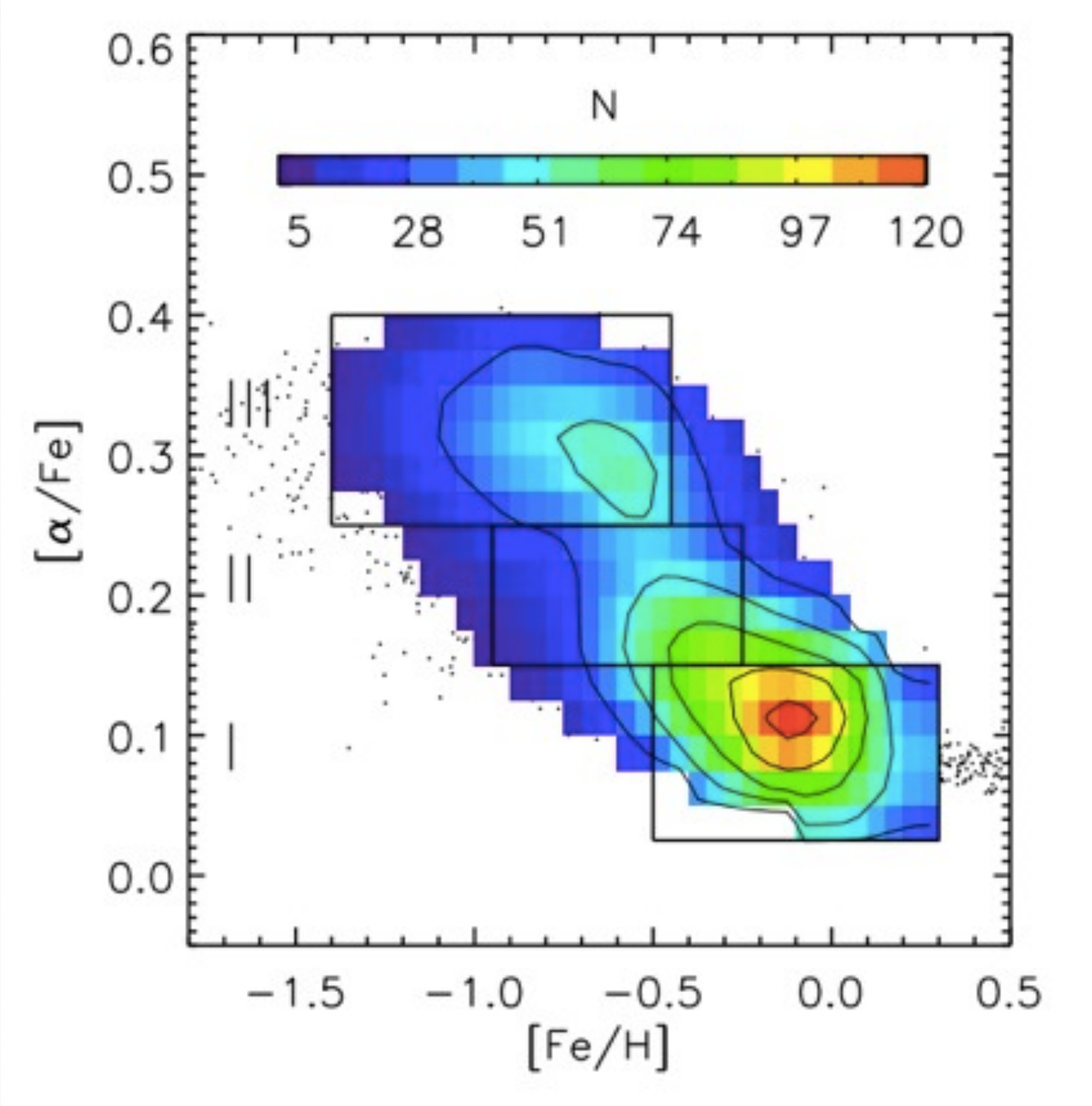
- Like in dwarf galaxies, the Milky Way disk has many different populations of stars

- SDSS/SEGUE: 6D positions and velocities / metallicities and alpha-element abundances for 10k stars

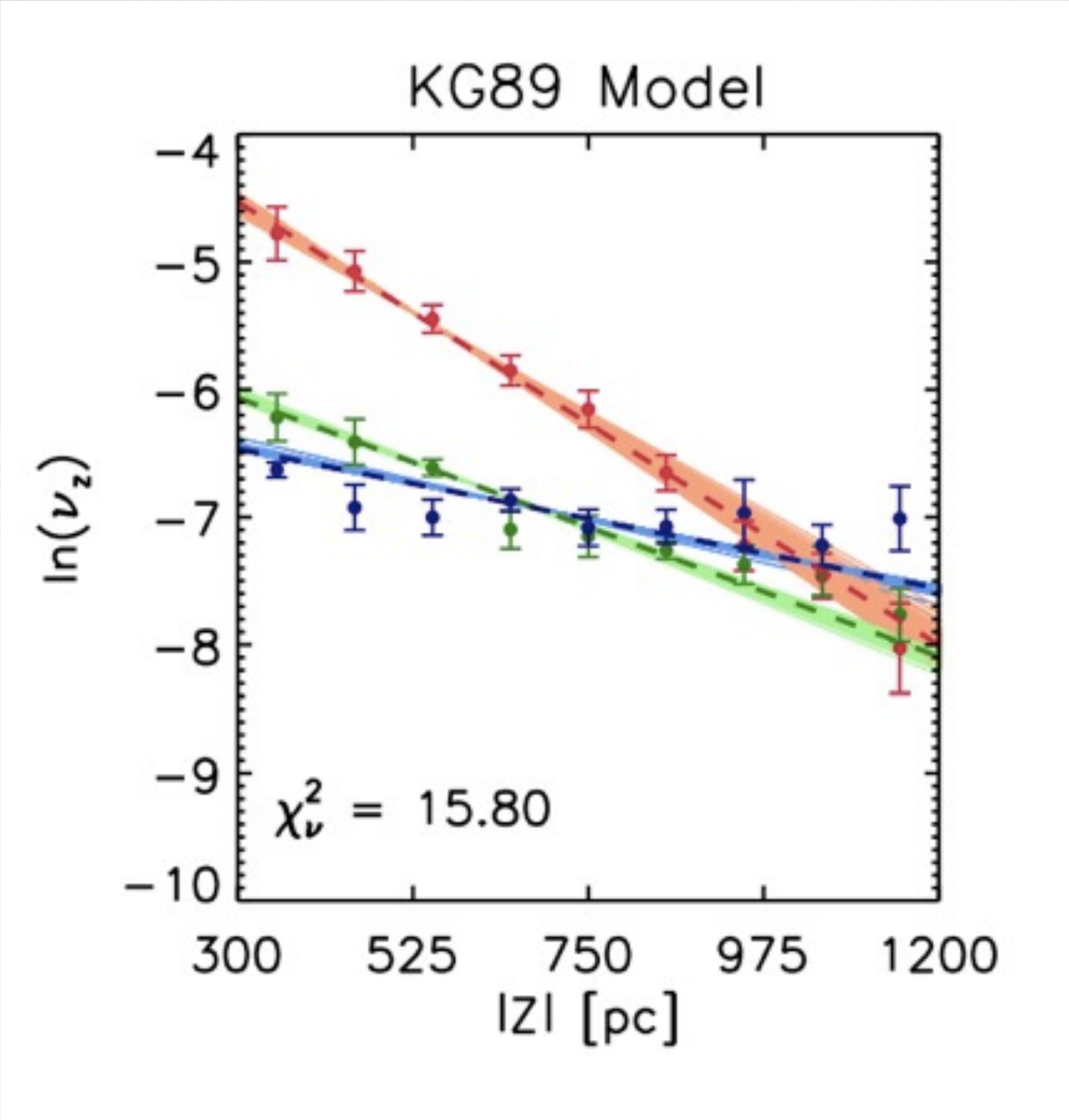
- Main-sequence stars with precise distances

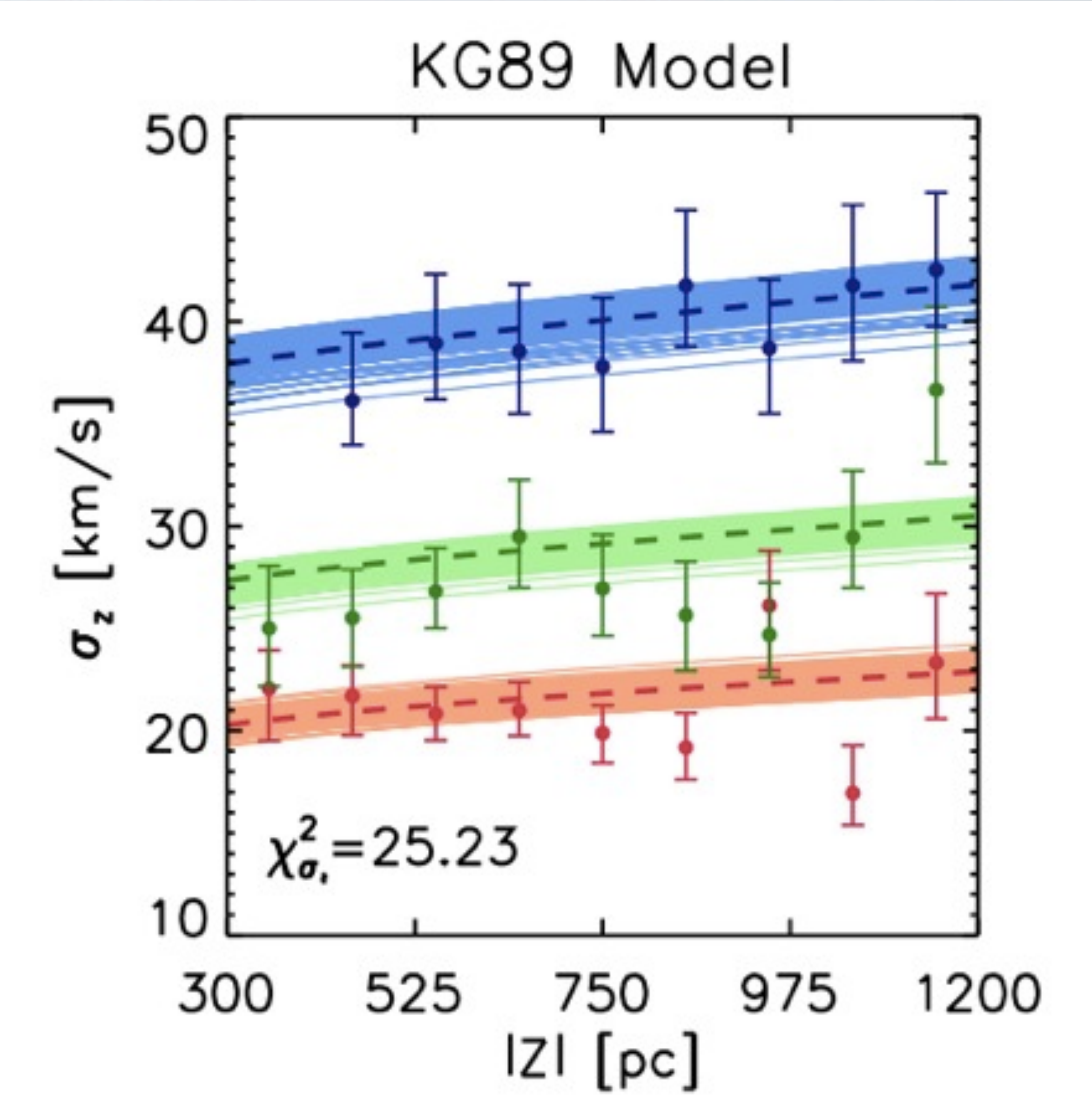
- 200 pc < |Z| < 1.5 kpc

Zhang, Rix, van de Ven, Bovy, et al. (2012)



DIFFERENT POPULATIONS HAVE VERY DIFFERENT SPATIAL AND KINEMATIC PROFILES

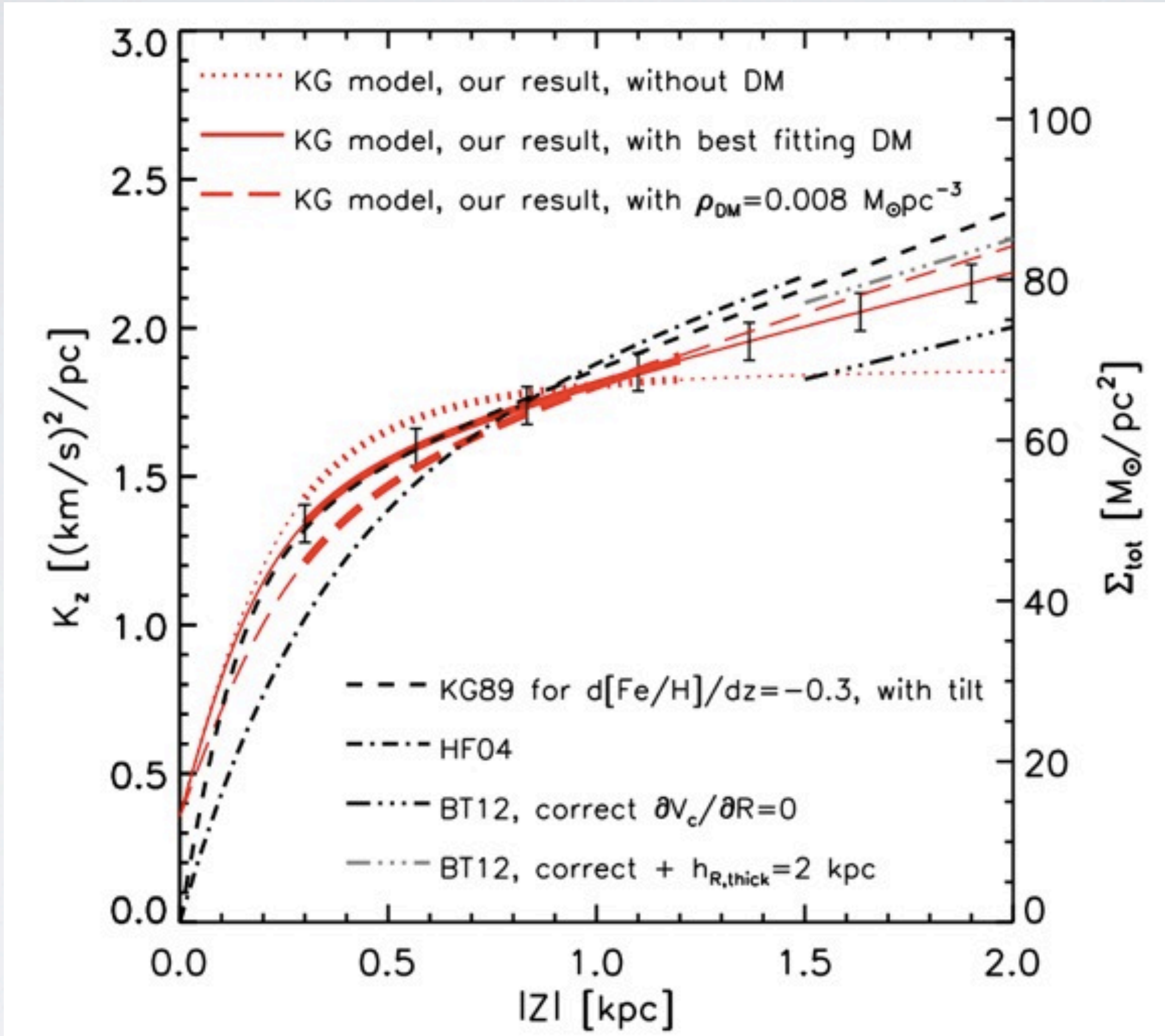




These should all give the same gravitational potential

Zhang, Rix, van de Ven, Bovy, et al. (2012)

RESULTS FROM JOINT FIT



Zhang, Rix, van de Ven, Bovy, et al. (2012)

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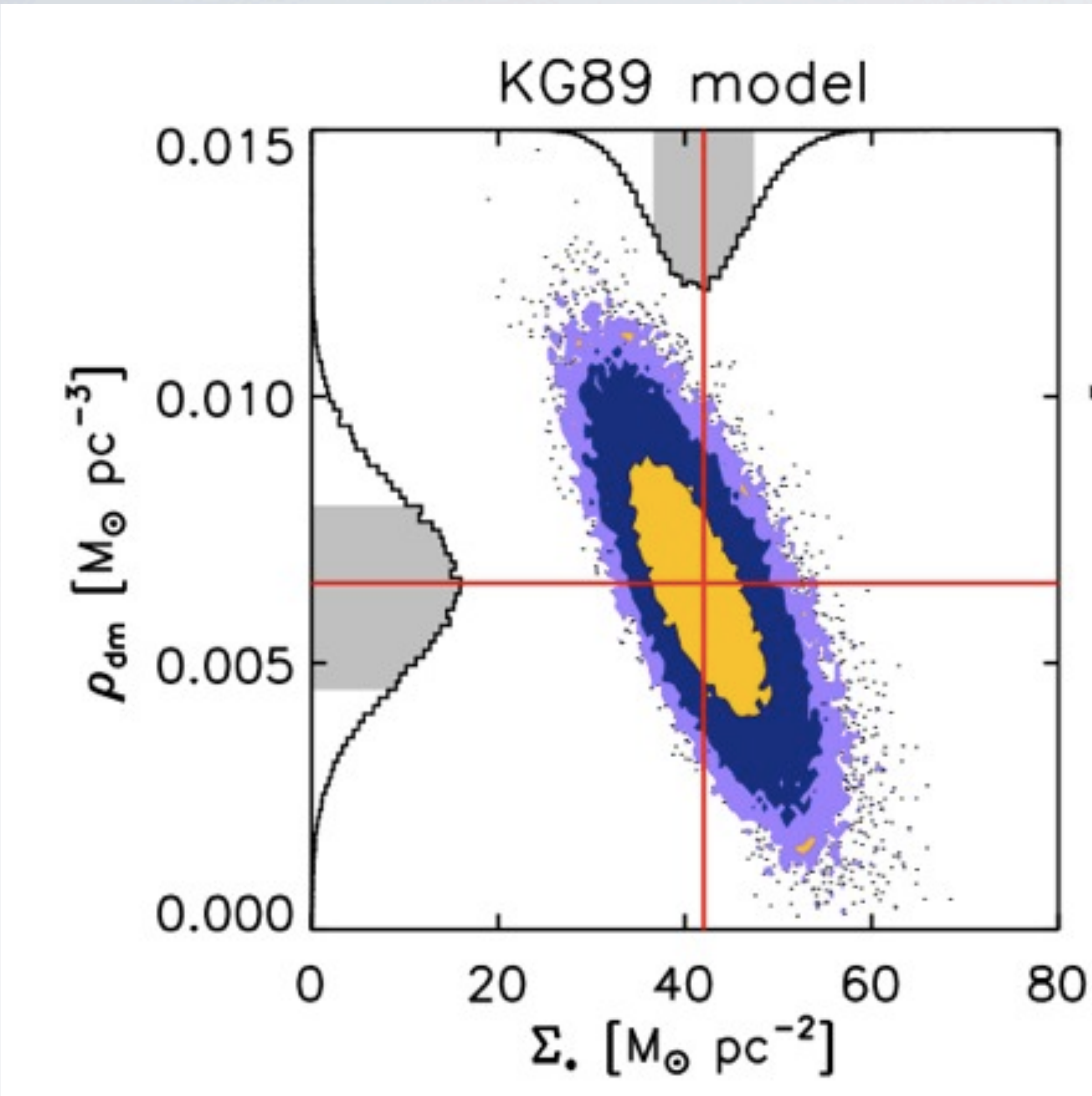
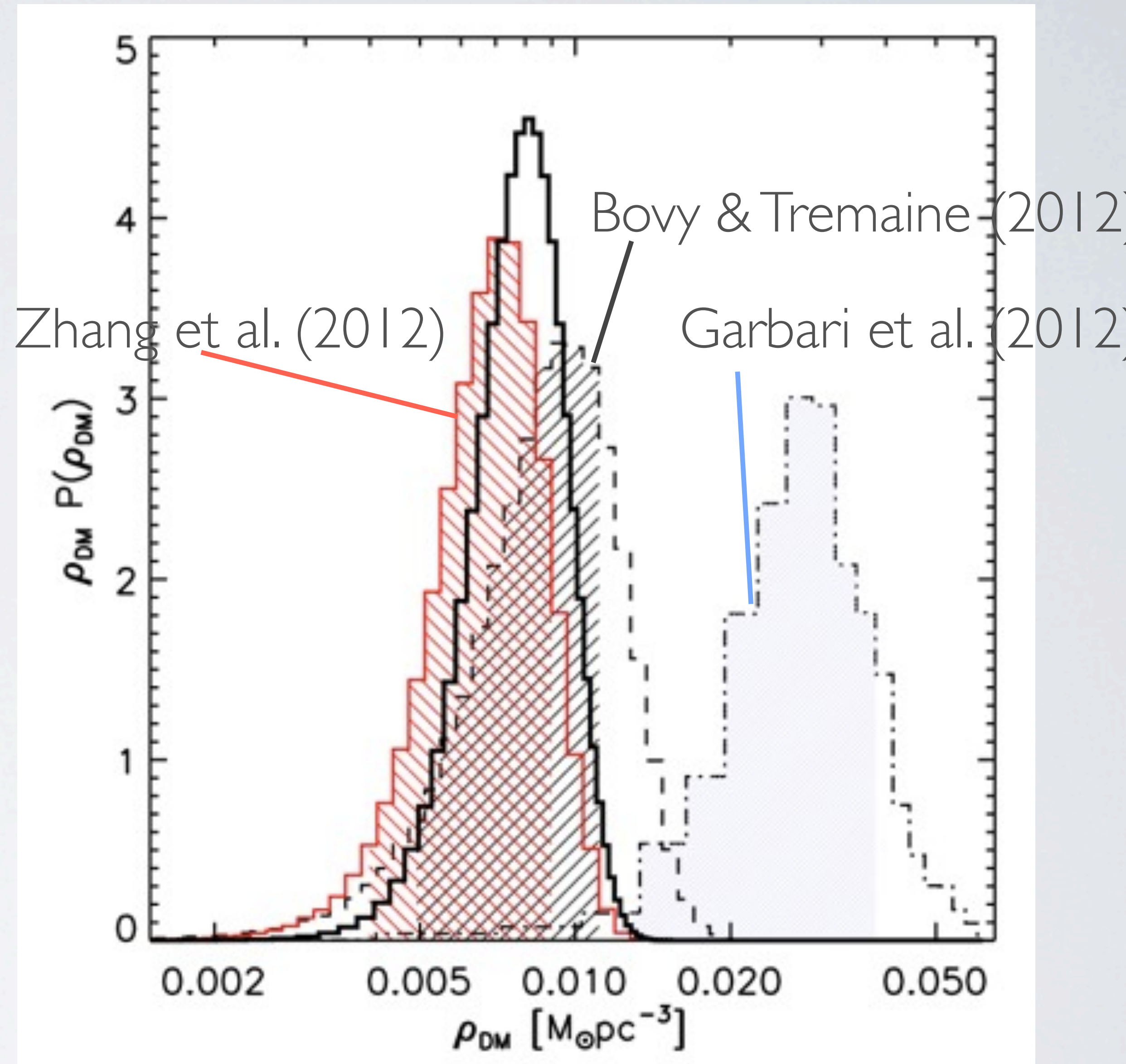




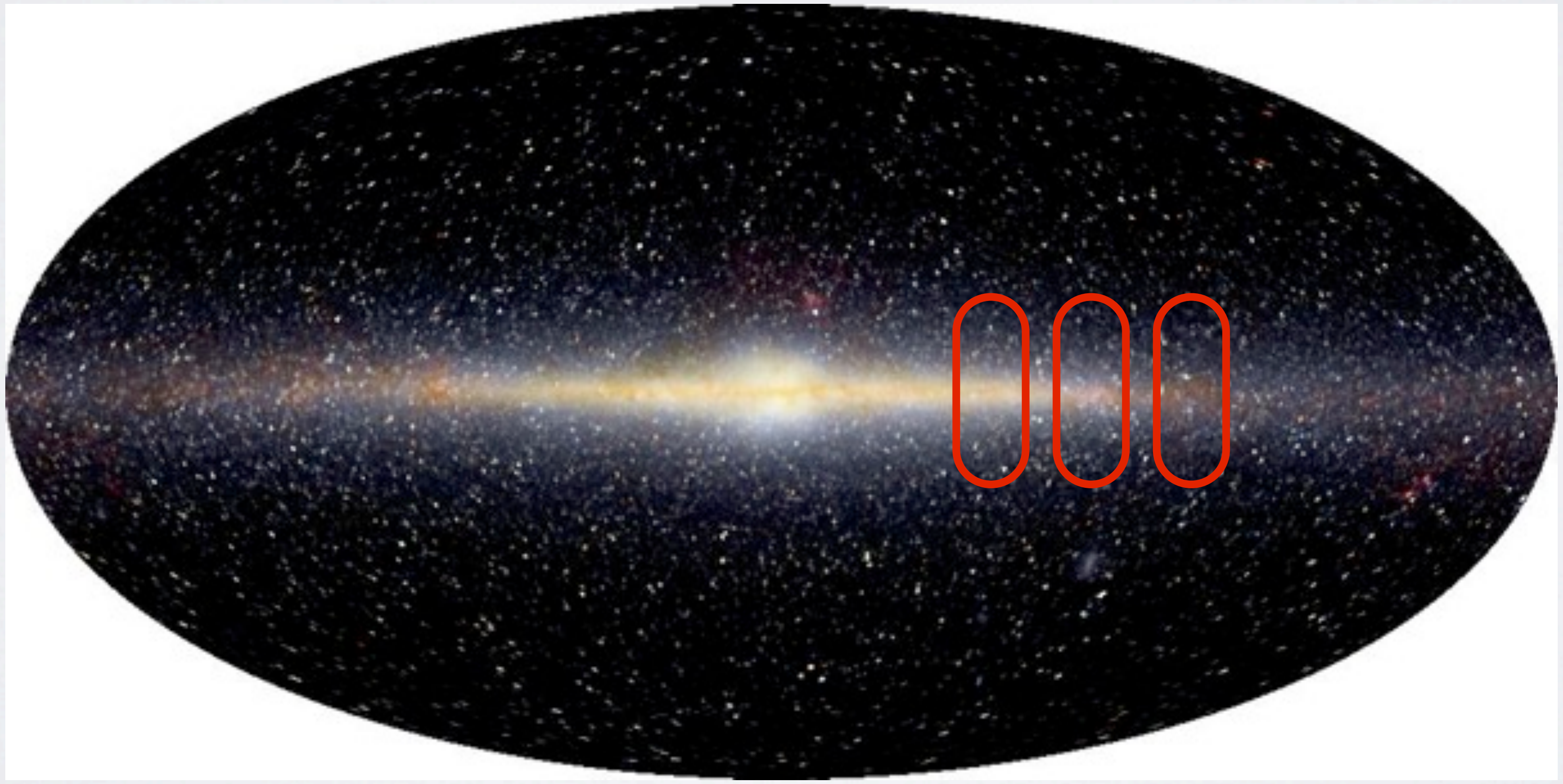
Zhang, Rix, van de Ven, Bovy, et al. (2012)

$$\rho_{\rm DM}(R_0) = 0.0075 \pm 0.0021 \text{ M}\odot \text{ pc}^{-3}$$

$$(0.28 \pm 0.08 \text{ GeV cm}^{-3})$$

NEXT 1: RADIAL DISK AND HALO PROFILES

- Future data (e.g., *Gaia*) will allow us to perform the previous analysis at R =/= R_0 => Σ(R) and ρ(R)
- This will allow us to measure the disk profile (scale length)



DISK SCALE LENGTH IS MAIN UNKNOWN FOR INNER DARK MATTER PROFILE

2.7 The potential of our Galaxy 113

Table 2.3 Parameters of Galaxy models

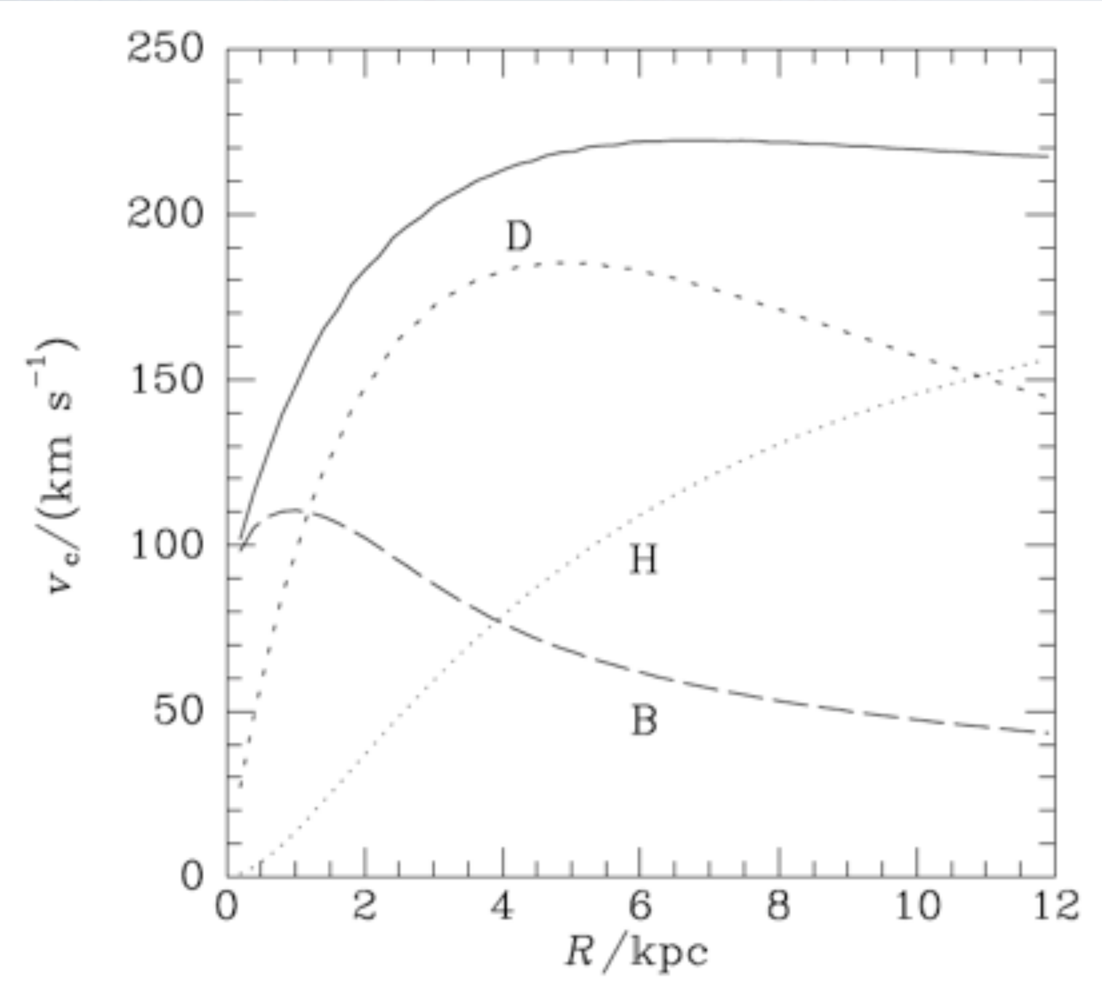
Parameter	Model I	Model II
R_d/kpc	2	3.2
$(\Sigma_d + \Sigma_g)/\mathcal{M}_\odot\,\mathrm{pc}^{-2}$	1905	536
$\rho_{b0}/\mathcal{M}_\odot\,\mathrm{pc}^{-3}$	0.427	0.3
$\rho_{h0}/\mathcal{M}_\odot\,\mathrm{pc}^{-3}$	0.711	0.266
α_h	−2	1.63
β_h	2.96	2.17
a_h/kpc	3.83	1.90
$M_d/10^{10}\,\mathcal{M}_\odot$	5.13	4.16
$M_b/10^{10}\,\mathcal{M}_\odot$	0.518	0.364
$M_{h,<10\,\mathrm{kpc}}/10^{10}\,\mathcal{M}_\odot$	2.81	5.23
$M_{h,<100\,\mathrm{kpc}}/10^{10}\,\mathcal{M}_\odot$	60.0	55.9
$v_e(R_0)/\mathrm{km\,s^{-1}}$	520	494
f_b	0.05	0.04
f_d	0.60	0.33
f_h	0.35	0.63

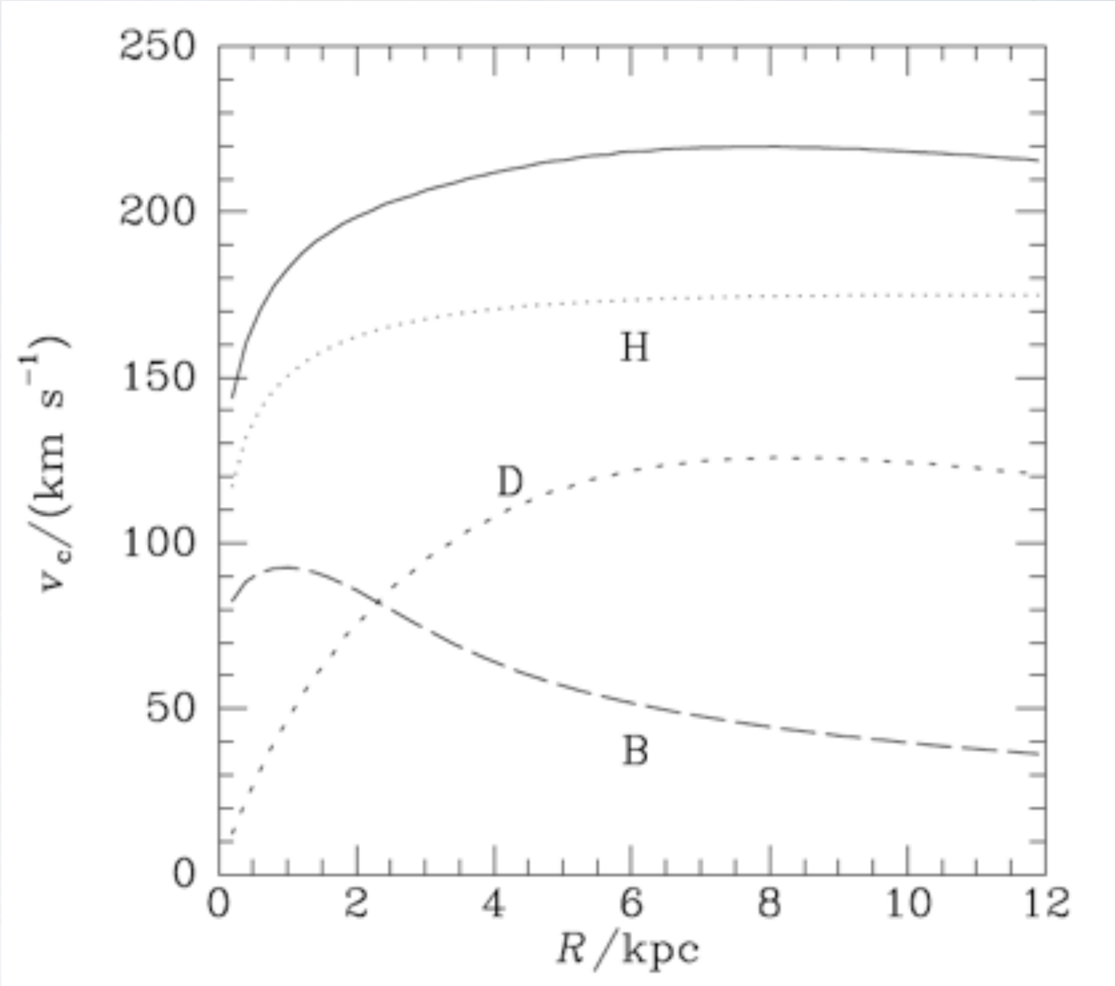
halo profile

local halo density

Binney & Tremaine (2008)

DISK SCALE LENGTH IS MAIN UNKNOWN FOR INNER DARK MATTER PROFILE





Binney & Tremaine (2008)

NEXT 2: FULL 3D, 3-INTEGRAL DYNAMICAL MODELS

- Precise dynamical inference requires consistent density-potential models and 3D modeling (e.g, tilt)
- Disk dynamics requires 3 integrals of motion to describe the stellar distribution function
- Elemental abundances can be used to separate *simple populations*

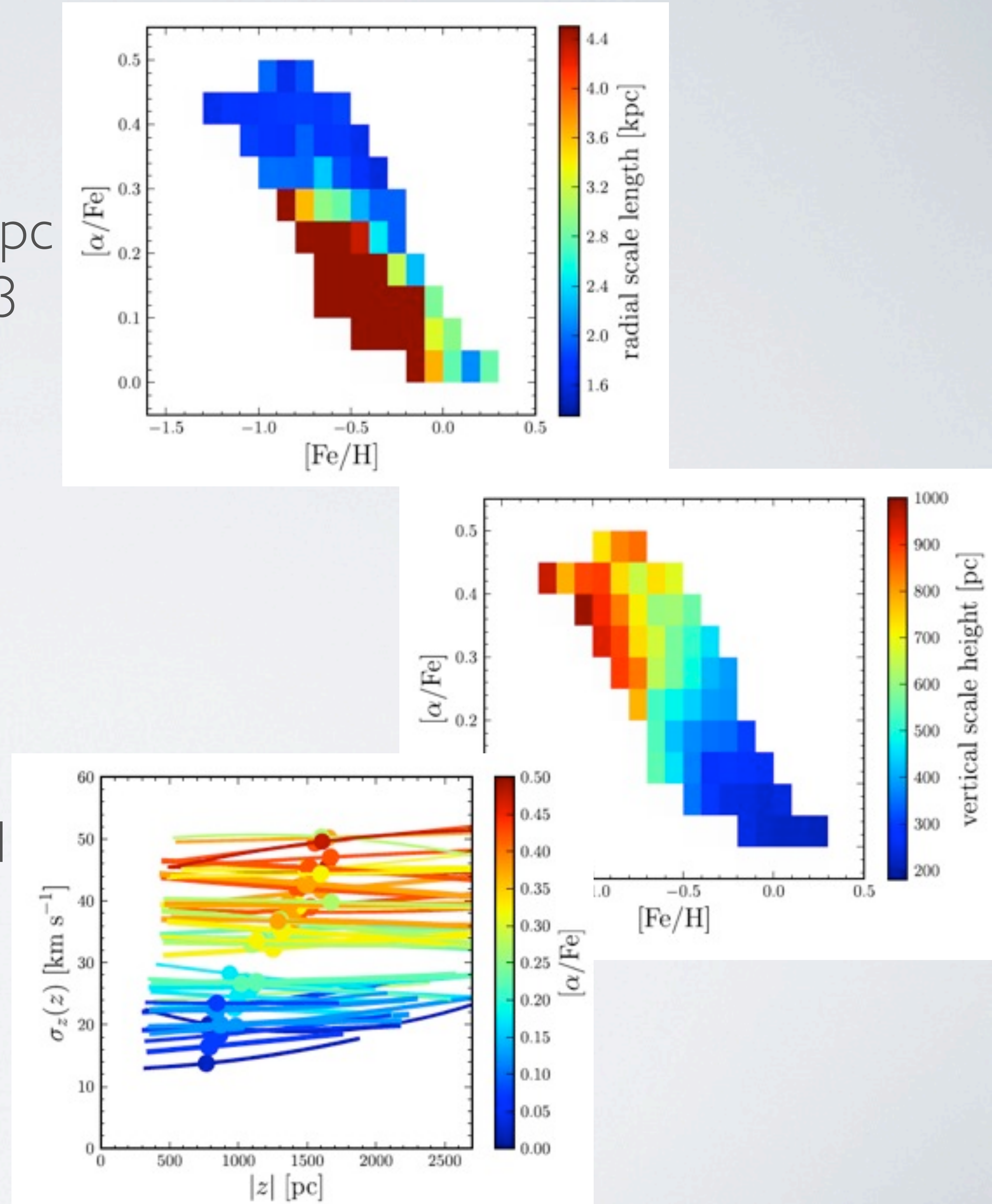
LOOKING AT THE DISK WITH "MONO-ABUNDANCE" GLASSES (BOVY + 2012)

- 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 $\sigma_z(z)$

- Each pop can be described by simple action-based distribution function



MONO-ABUNDANCE POPULATIONS CAN BE DESCRIBED BY A QUASI-ISOTHERMAL DF

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

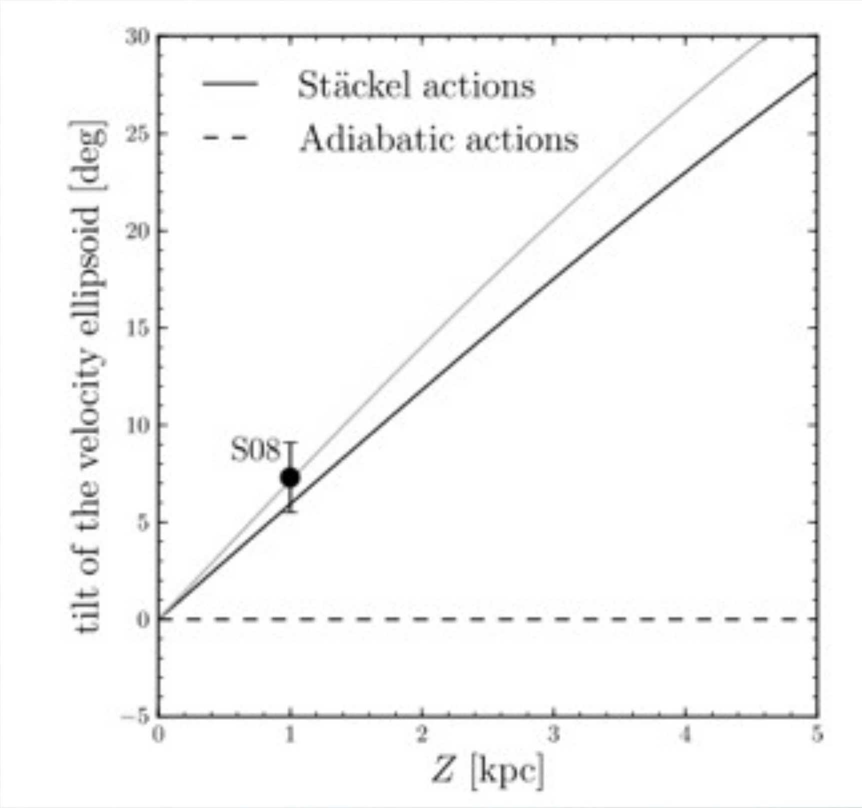
where

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

- Distribution function in terms of orbital actions (Binney 2010; Binney & McMillan 2011)
- Likelihood:

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

- Requires fast action evaluations and fast computation of the "effective survey volume"

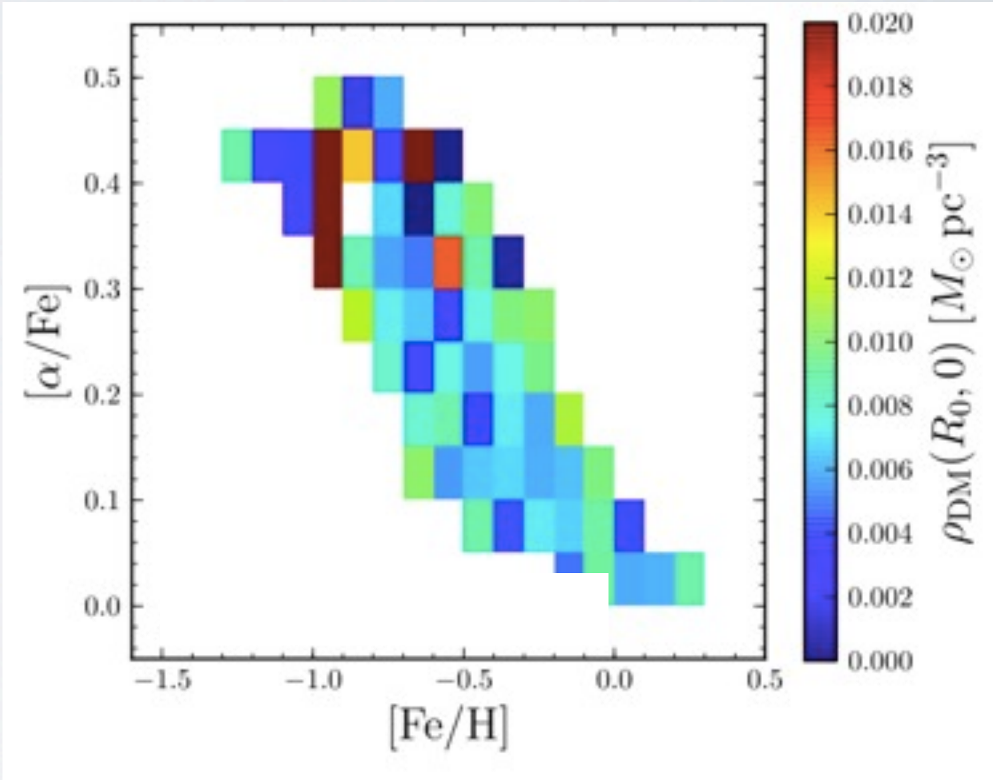


TECHNICAL CHALLENGES MOSTLY SOLVED

- Precise action calculation at 10^4 to 10^5 actions / s
- Precise enough calculation of the effective survey volume
- Fast evaluation of any axisymmetric density distribution's gravitational potential
- Fit 92 populations independently
- But very slow...

PROJECTED PERFORMANCE

- Expect to measure ρ_{DM} to 0.0005 $\mathrm{M_\odot\ pc^{-3}}$ (0.02 Gev cm^{-3}; ~20σ for standard ρ_{DM})
- R_d to 100 pc, z_h to 10 pc
- Local halo power-law index to 0.1 or R_0/r_s to 20%
- Determine whether the Milky Way disk is maximal or not
- But systematics may be important...



Mock data

CONCLUSION

$$\rho_{\rm DM}(R_0) = 0.0075 \pm 0.0021\ M_\odot\ \mathrm{pc}^{-3}$$
$$(0.28 \pm 0.08\ \mathrm{GeV\ cm}^{-3})$$