Dark matter in the Milky Way

Jo Bovy (Institute for Advanced Study; Hubble fellow)

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

INTRODUCTION

- Milky Way provides up-close look of distribution of dark matter (DM) in a large disk galaxy

- Local density and density profile important for dark matter detection
- Direct detection: local density and velocity distribution
- Indirect detection: e.g., Galactic center
- DM content intimately linked with formation and evolution of large disk galaxies like the Milky Way
- This lecture: overview of dynamical measurements of DM in the Milky Way

OVERVIEW

- Basics of dynamical modeling in the MW
- The Milky Way rotation curve
- Local determinations of the DM density
- The radial profile of DM near the center of the MW
- The large-scale distribution of DM in the halo
- Future developments

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$$\vec{F} = m\vec{a}$$

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- Gravitational potential only affects accelerations; positions and velocities are initial conditions
- We can only measure x,v for all but a few stars in the MW
- Need to make assumptions about the distribution function DF(x,v) of dynamical tracers: e.g.,
  - tracers are on circular orbits: DF(x,v) = δ(circ. orb.) f(L_z)
  - tracers are in dynamical equilibrium: DF(x,v) = DF(integrals) (cf., virial theorem)
  - tracers originate from common phase-space point (e.g., streams, timing argument)

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GALAXY ROTATION CURVES

- For spherical mass distribution, from Newton's laws we know that

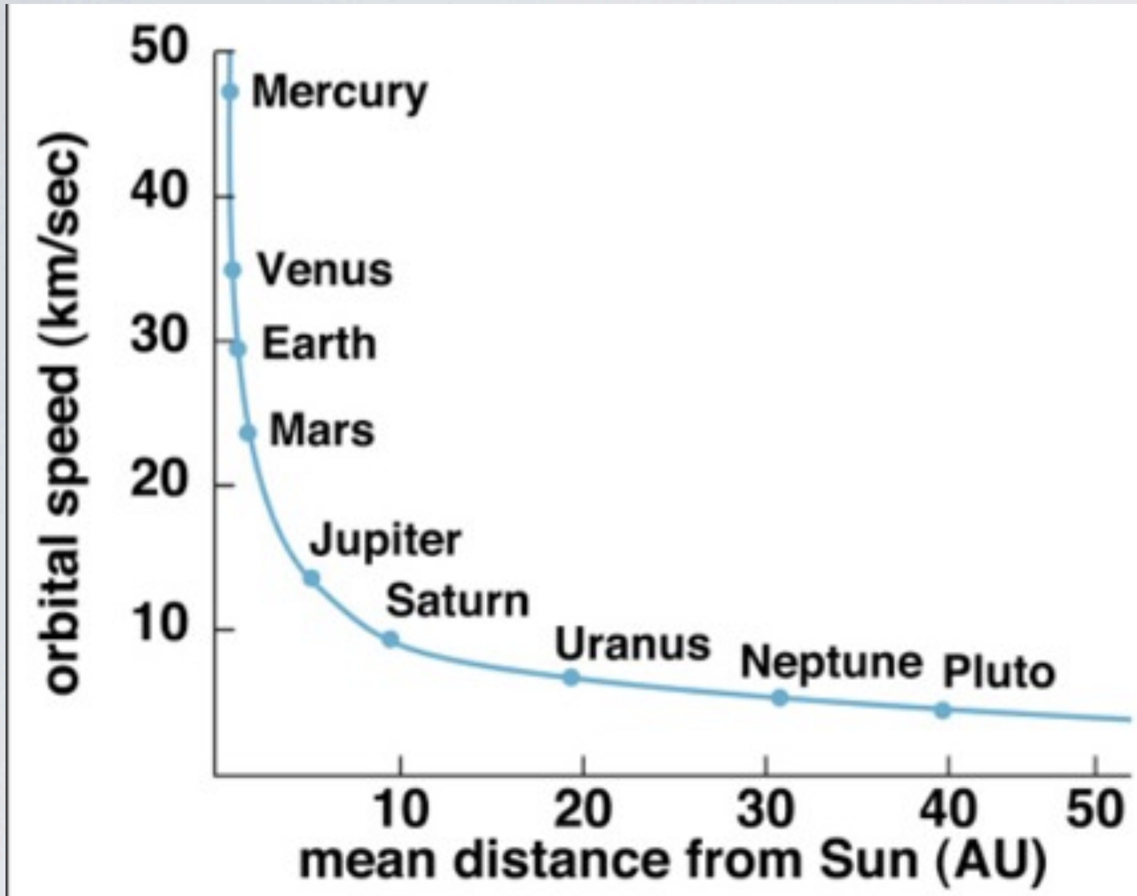
$$V_c^2 \sim \frac{GM(< R)}{R}$$

- (does not quite hold for non-spherical distributions, but close)

- As such, the rotation curve mainly measures the *total enclosed mass*

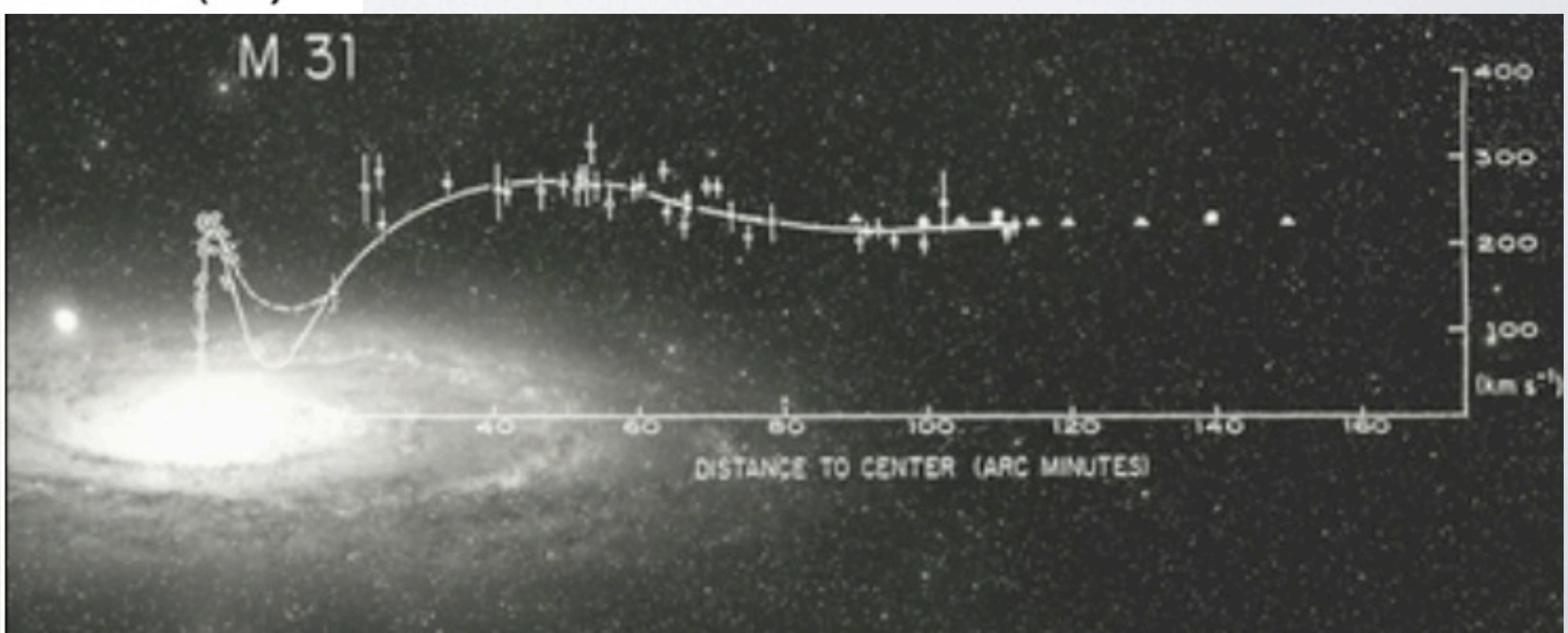
- It does *not* distinguish clearly between roughly spherical mass distributions (~DM halo) and flattened distributions (~stellar or gas disk)

ROTATION CURVES AT LARGE DISTANCES: DISCOVERY OF DARK MATTER



$$V_c^2 \sim \frac{GM(< R)}{R}$$

For a flat V_c, $M \sim R$, $\rho \sim R^{-2}$



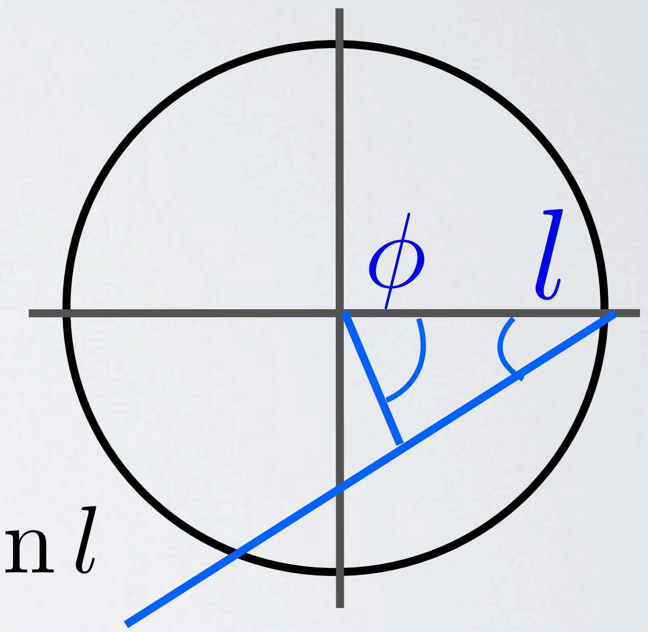
Rubin+ (1970)

MEASURING THE MILKY WAY'S ROTATION CURVE

- Determining the rotation curve in external galaxies is relatively straightforward: measure motion of gas from Doppler shifts of emission lines

- In the Milky Way this is complicated by the fact that the Sun is (approximately) co-rotating with the gas

- Traditional method of measuring the MW rotation curve: terminal velocity curve:



$$V_{\rm los} = V_c(R)\sin(\phi + l) - V_c(R_0)\sin l$$

- (assuming the Sun is moving with the circular velocity, 2nd term)

- Max. $V_{\rm los}$ when $(\phi + l) = 90°$ (only in inner MW)

MEASURING THE MILKY WAY'S ROTATION CURVE

- Therefore, gas bunches up at $(\phi + l) = 90°$, where V_{los} has a maximum; this can be measured from 21cm gas emission (hyperfine structure)
- From geometry: $$\frac{R_0}{\sin(\phi + l)} = \frac{R}{\sin l}$$
- So we have that
$$V_{\mathrm{los}} = \sin l \left[V_c(R) \frac{R_0}{R} - V_c(R_0) \right]$$
- This equation can be solved to give $V_c(R)$, but it is invariant under
$$V_c(R) \rightarrow V_c(R) + \Omega R$$
- This means that we cannot measure both solid-body rotation (ΩR) and $V_c(R_0)$

MEASURING THE MILKY WAY'S ROTATION CURVE

- So, measure $V_c(R_0)$ another way and use terminal-velocity curve for $V_c(R)$
- Other issues:
  - Doesn't work in outer MW (no tangent-point, ϕ+l > 90°)
  - Only measure $V_c(R)$ at one l, or ϕ (non-axisymmetry)

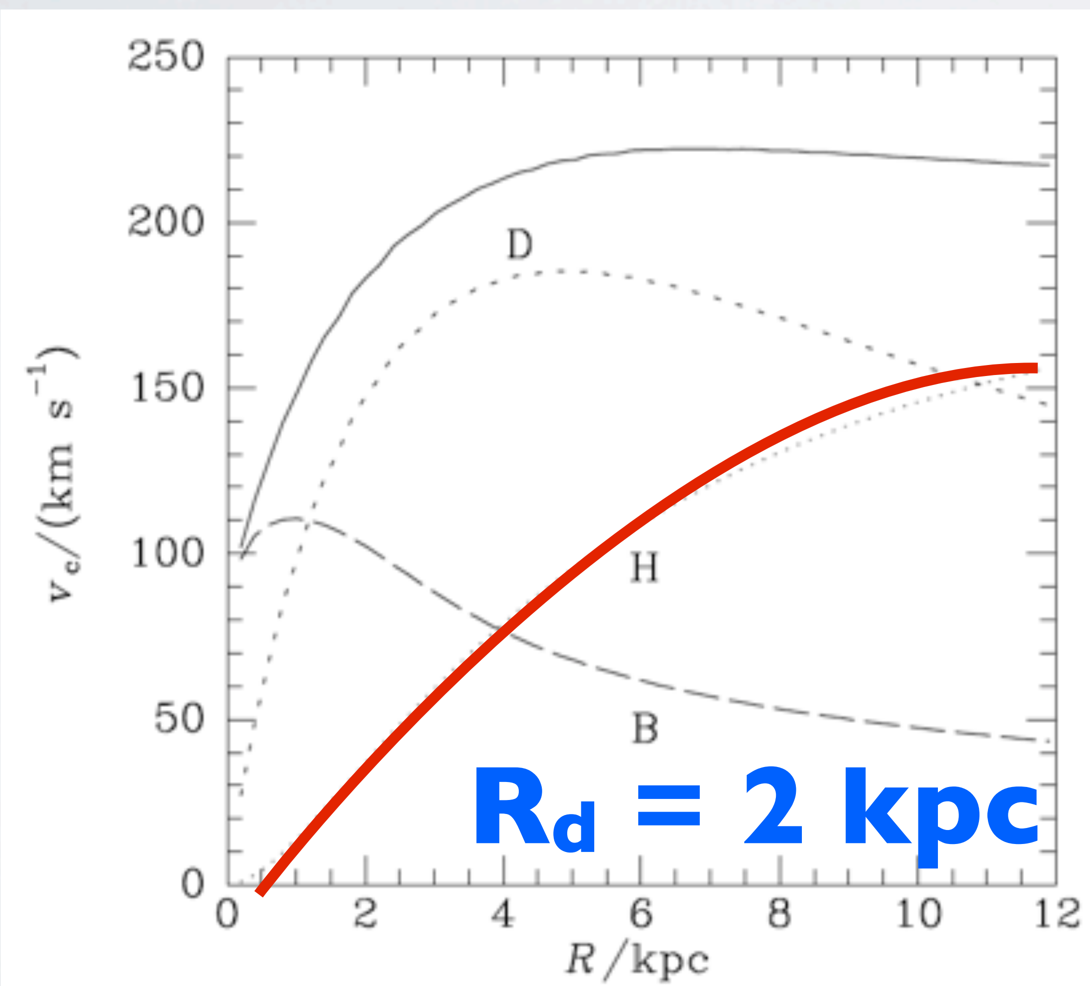
MEASURING THE MILKY WAY'S ROTATION CURVE

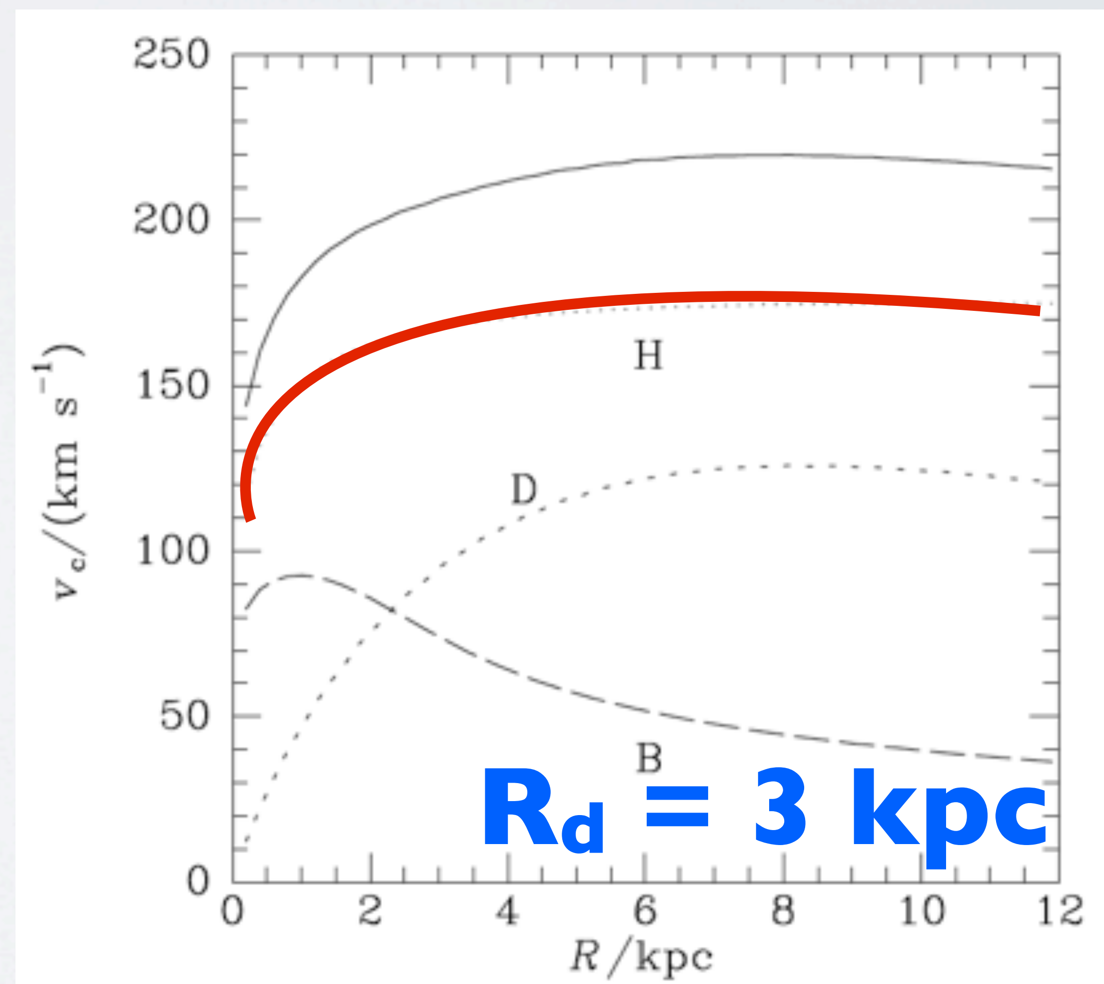
- Solutions:
  - Many other ways to measure $V_c(R_0)$, all controversial
  - Use gas proper motions (masers; Reid et al. 2009, 2014)
  - Use stellar disk kinematics (local: Feast & Whitelock1997; global: Bovy et al. 2012)
  - Measure Sun's motion wrt population assumed to be at rest (halo globular clusters, halo stars, the black hole at the center); uncertain bc of unknown Solar motion
- Current best-knowledge: $V_c(R_0) = 220$ to 240 km/s, rotation curve very close to flat over $4 < R/\mathrm{kpc} < 16$

MILKY WAY ROTATION CURVE IS AMBIGUOUS

- Even with perfect measurements of the rotation curve, disentangling the contributions from stars and dark matter is impossible

- "Disk-halo degeneracy"





Binney & Tremaine (2008)

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VERTICAL MASS DISTRIBUTION

- Rotation curve measurements are getting better, but they cannot tell to what extent the mass is flattened (i.e., what the relative contribution of baryonic and dark matter is)

- Measurements of the vertical mass distribution directly measure how concentrated the mass is around the Galactic mid-plane

BASIC IDEA OF VERTICAL MASS 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

$$K_Z \approx \frac{\sigma_Z^2}{h_Z}$$

JEANS+POISSON EQUATIONS

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

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

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

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stellar density profile

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radial velocity dispersion

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

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rotational velocity dispersion

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mean rotational velocity

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vertical velocity dispersion

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radial-vertical covariance

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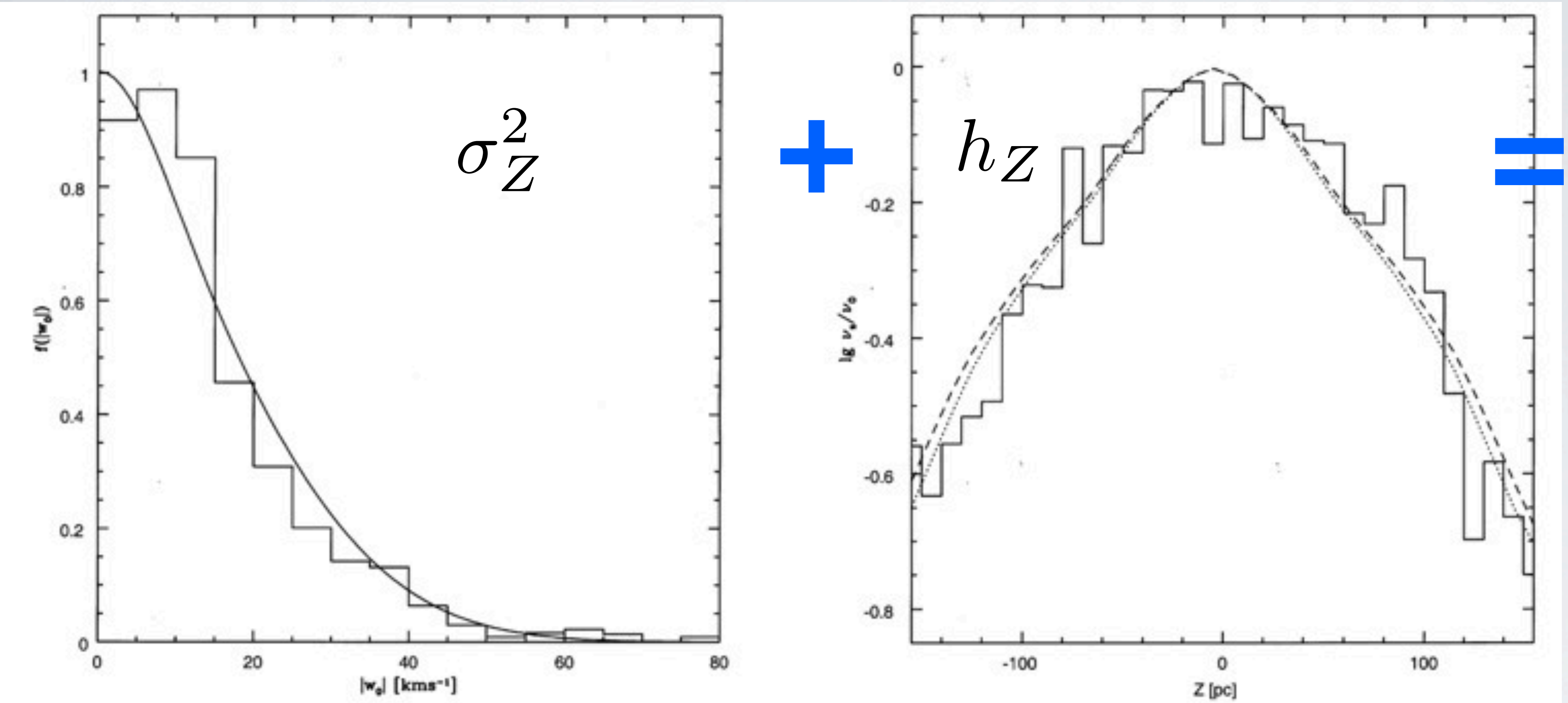
1D

Tilt =~ 0

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

slope of rotation curve =~ 0

LOCAL DENSITY MEASUREMENTS (OORT 1932)



σ_Z^2 **+** h_Z **=** $\rho_{\rm total}(R_0, Z=0)$

- Holmberg & Flynn (2000; and many earlier analyses): Model equilibrium distribution of A&F stars to measure the local mass density

- $\rho_{\rm total}(R_0, Z=0)$ = 0.1 +/- 0.01 $\mathrm{M}_\odot\,\mathrm{pc}^{-3}$; no sign of dark matter (not expected), but strong constraint on scale height of disk dark matter

LOCAL DENSITY MEASUREMENTS ARE VERY ROBUST

Table 2. Local density estimates.

Density ρ_0 ($M_\odot\,pc^{-3}$)	Error ($M_\odot\,pc^{-3}$)	Reference
0.185	0.020	Bahcall (1984b)
0.210	0.090	Bahcall (1984c)
0.105	0.015	Bienaymé, Robin & Crézé (1987)
0.260	0.150	Bahcall, et al. (1992)
0.110	0.010	Pham (1997)
0.076	0.015	Crézé et al. (1998)
0.102	0.010	This paper
0.150	0.026	Straight average
0.108	0.011	Variance-weighted average

Holmberg & Flynn (2000)

SURFACE DENSITY MEASUREMENTS

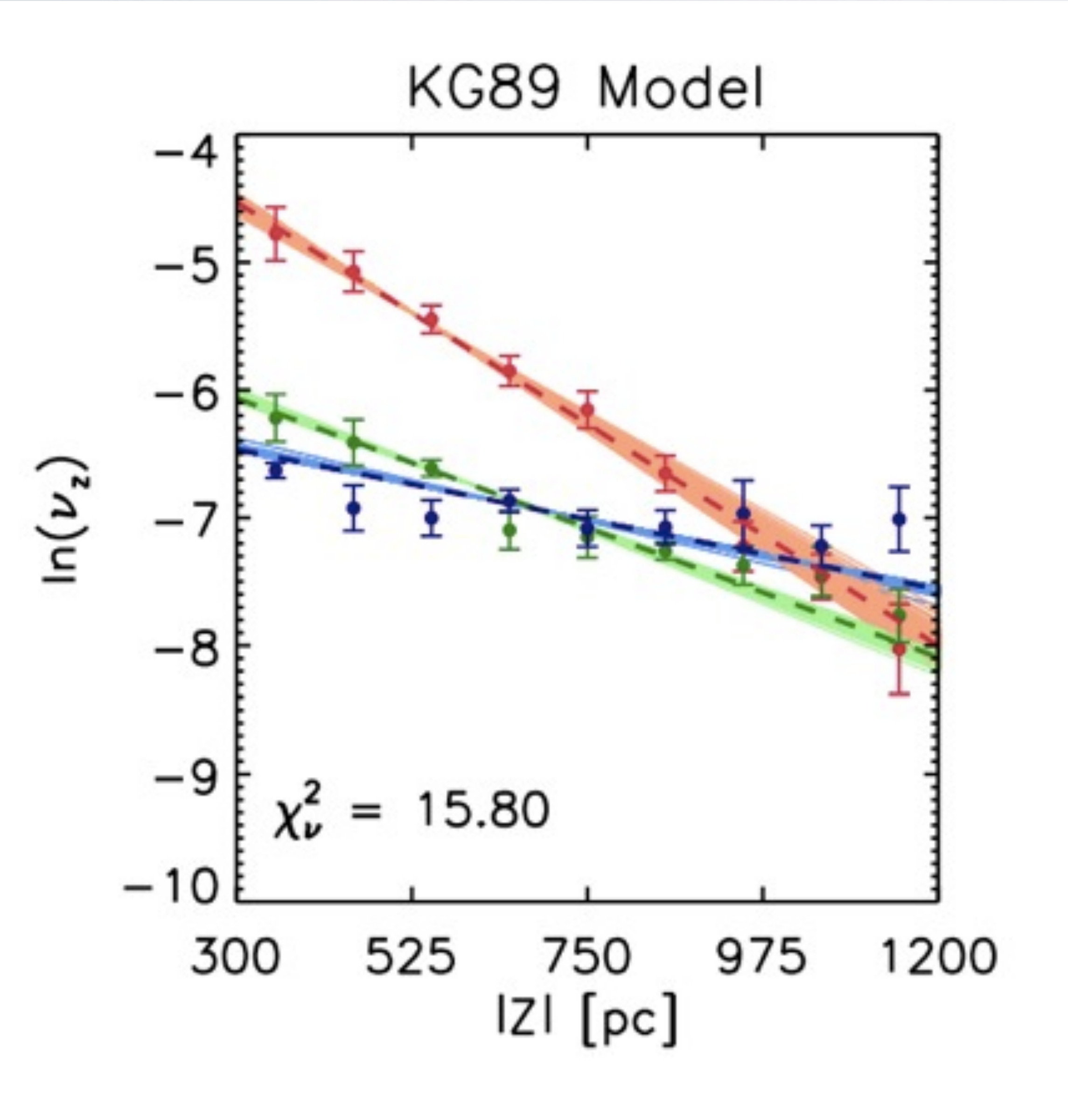
- Similar data as used in Holmberg & Flynn (2000) at larger heights measure the surface density at large heights
- Small, noisy data samples require forward modeling (e.g., Kuijken & Gilmore 1989)
- First modern measurement of Kuijken & Gilmore (1989): star counts and velocities for ~1,000 stars, measures total surface density at 1.1 kpc = 72 +/- 6 $\mathrm{M}_\odot\,\mathrm{pc}^{-2}$
- Recent measurements of the vertical dependence of the surface density allow baryons and DM contributions to be separated
- On their own: $\rho_{\mathrm{total}} = \Sigma_{\mathrm{total}}/2h_Z$ --> h_z ~ 360 pc

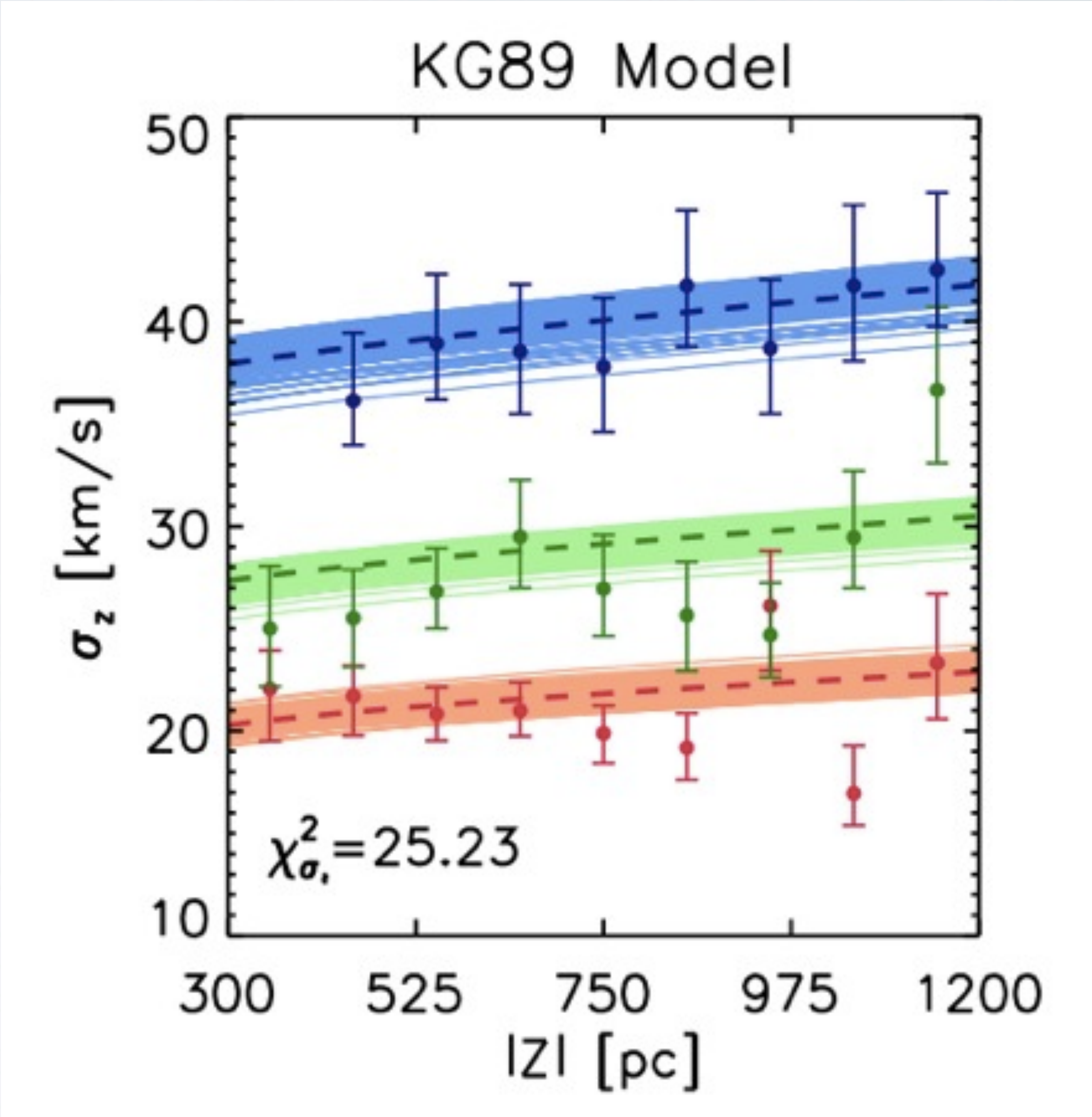
RECENT SURFACE DENSITY MEASUREMENTS

- Recently, new data have allowed the surface-density of matter around 1kpc above the mid-plane to be measured more precisely and with some Z dependence
  - Larger samples with good distances and velocity, and understood selection effects (for determining the stellar profile)
  - Improved understanding of MW disk populations
  - Improved dynamical modeling methods (beyond the Jeans equations)

ONE RECENT ANALYSIS: ZHANG ET AL. (2013)

- Jeans analysis w/ three different populations of stars: young, intermediate-age, old

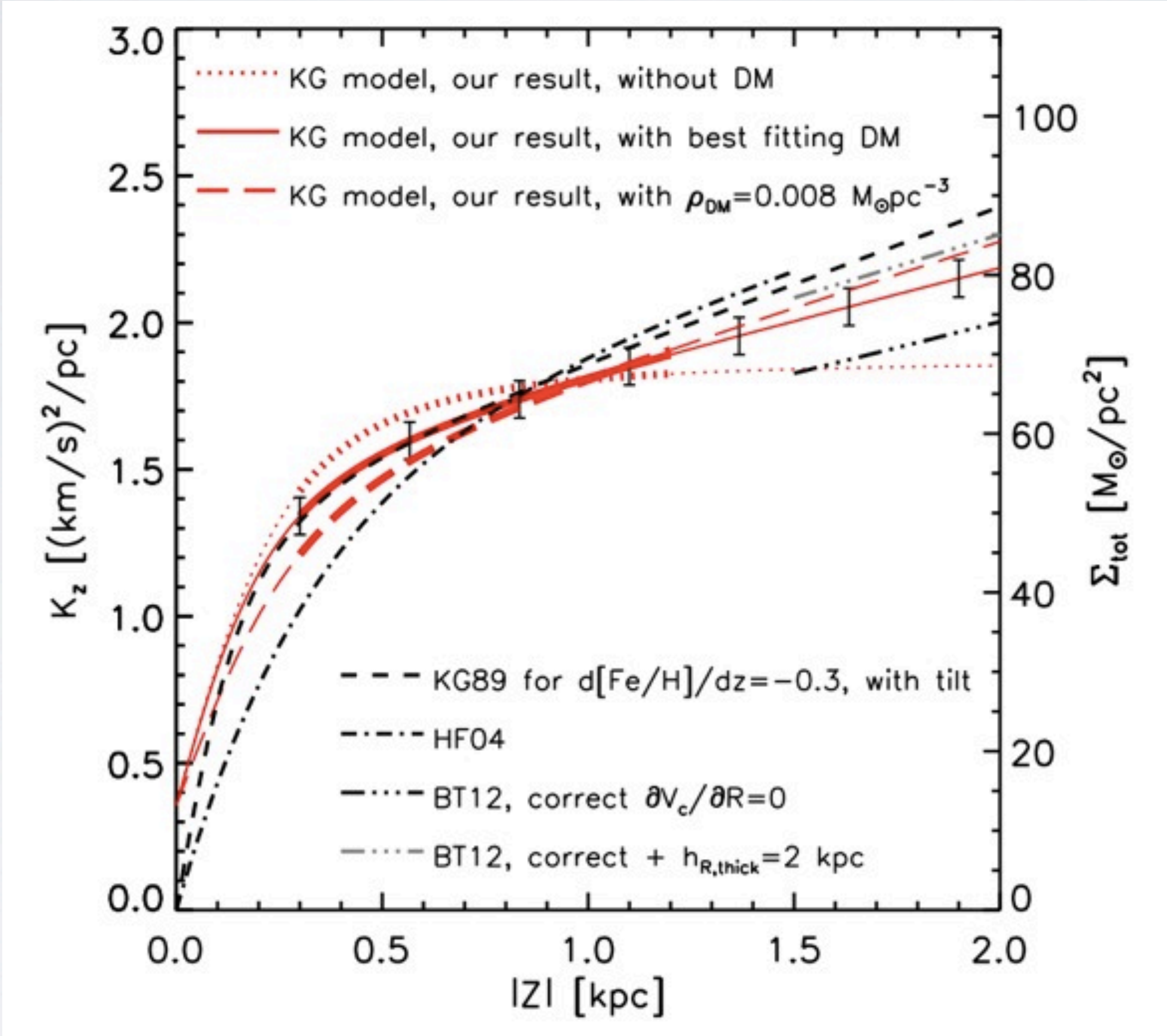




- These should all give the same gravitational potential

Zhang, Rix, van de Ven, Bovy, et al. (2013)

RESULTS FROM JOINT FIT



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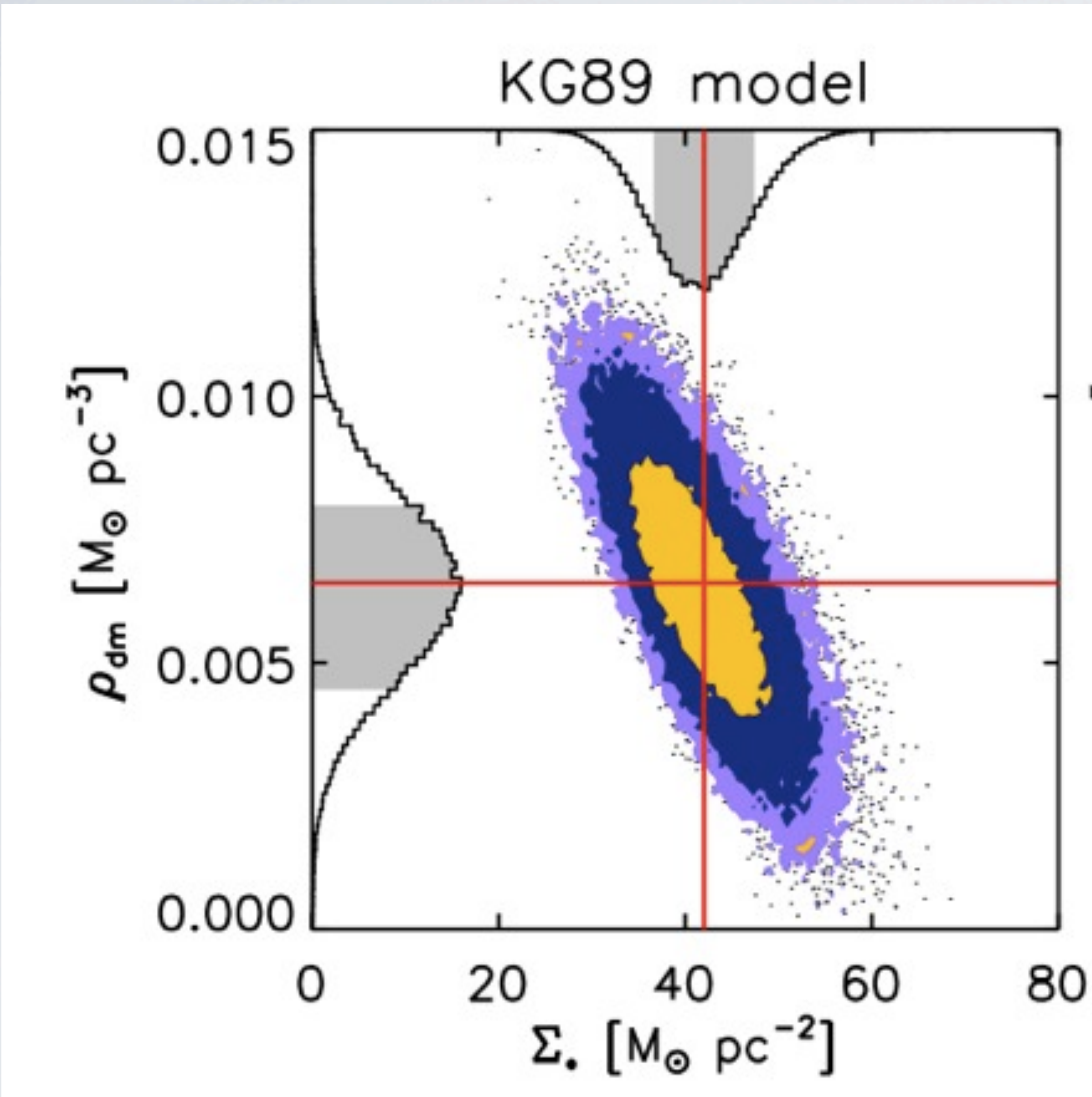
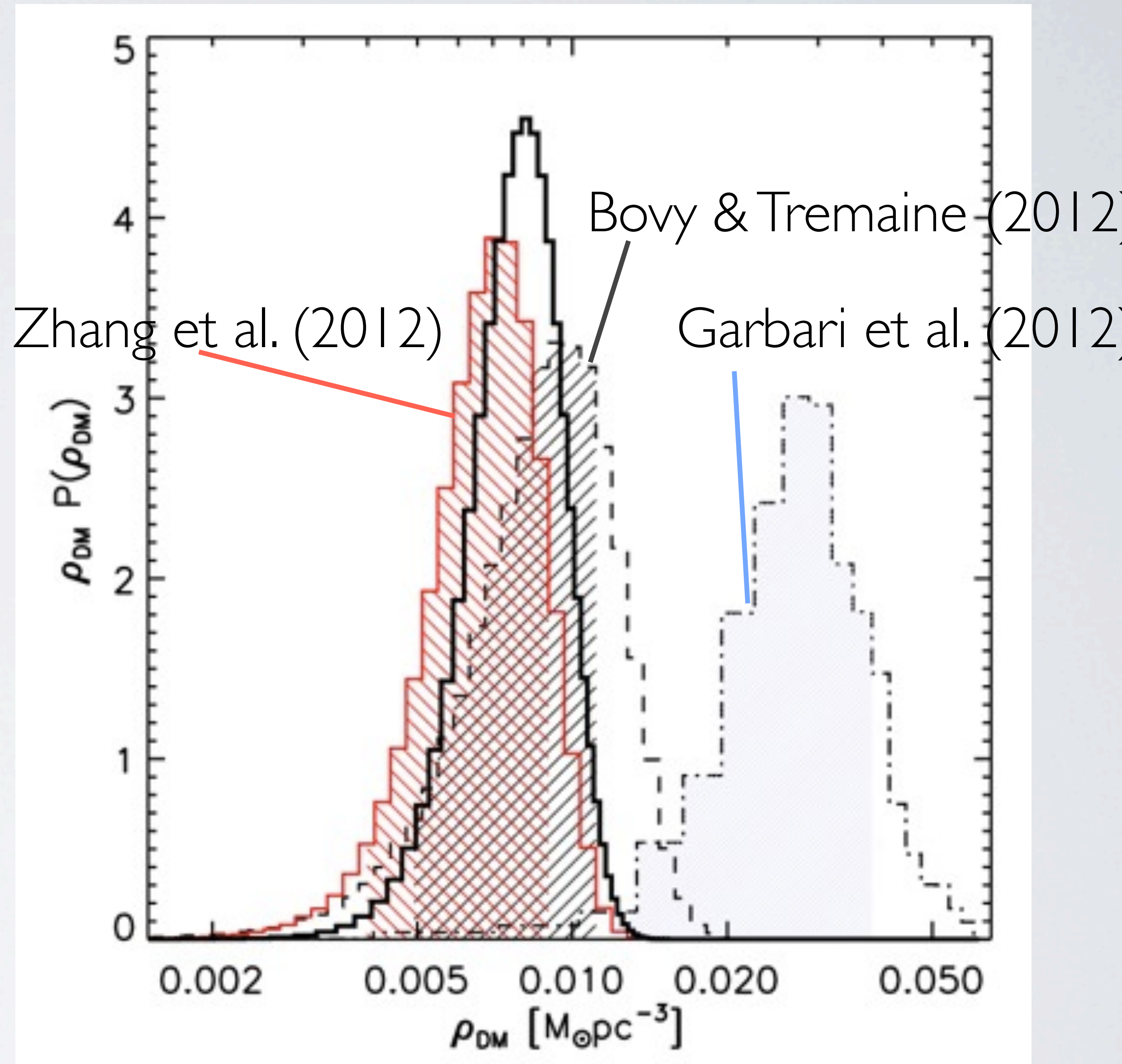


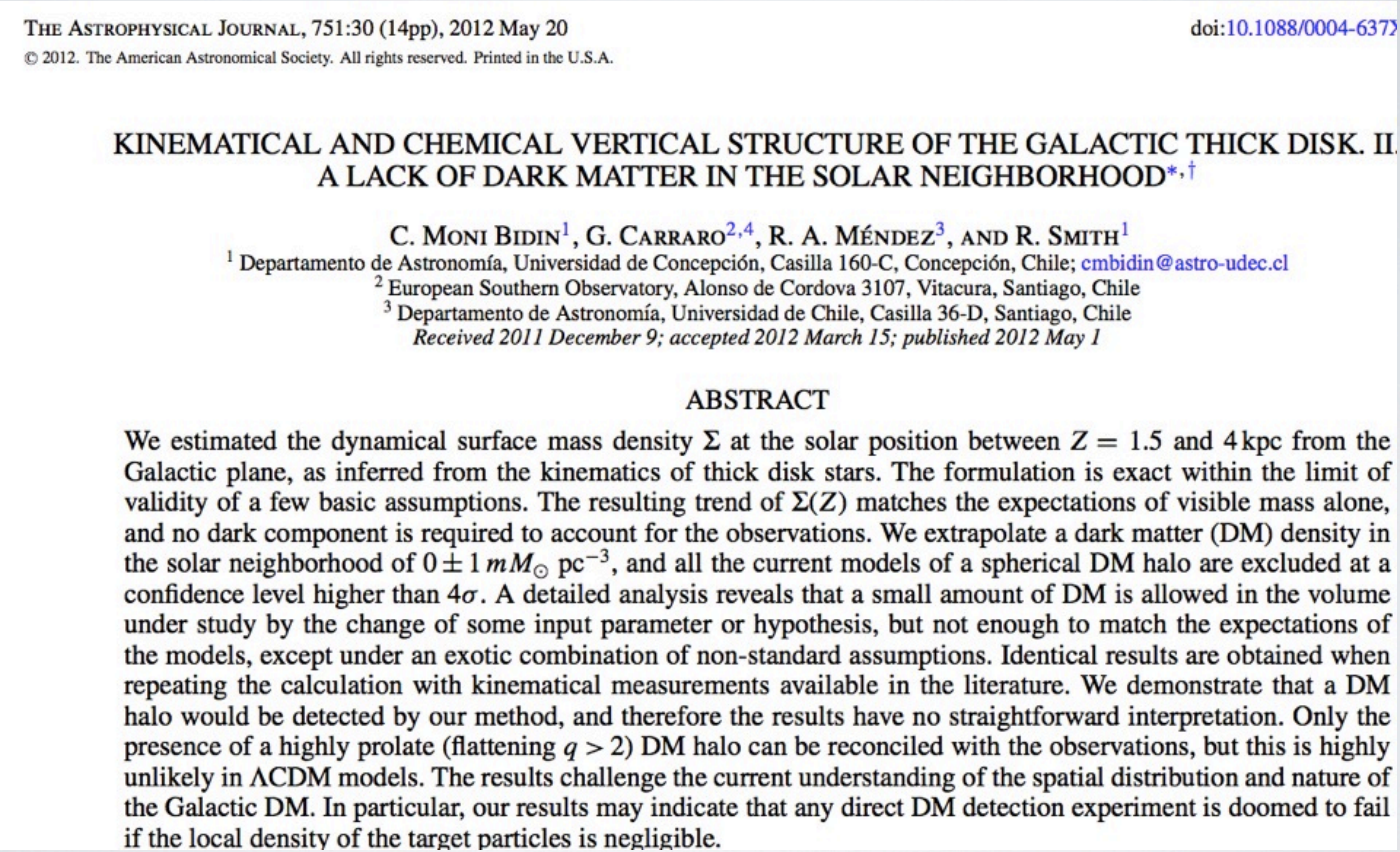


Zhang, Rix, van de Ven, Bovy, et al. (2012)

$$\Sigma(R_0, |Z| \leq 1.1\,\mathrm{kpc}) = 69 \pm 6\, M_\odot\, \mathrm{pc}^{-2}$$

+ measurements of DM density and disk surface density

A CAUTIONARY TALE


The Astrophysical Journal, 751:30 (14pp), 2012 May 20 doi:10.1088/0004-637X

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 $0 \pm 1\, mM_\odot\ \mathrm{pc}^{-3}$, 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

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

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

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

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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

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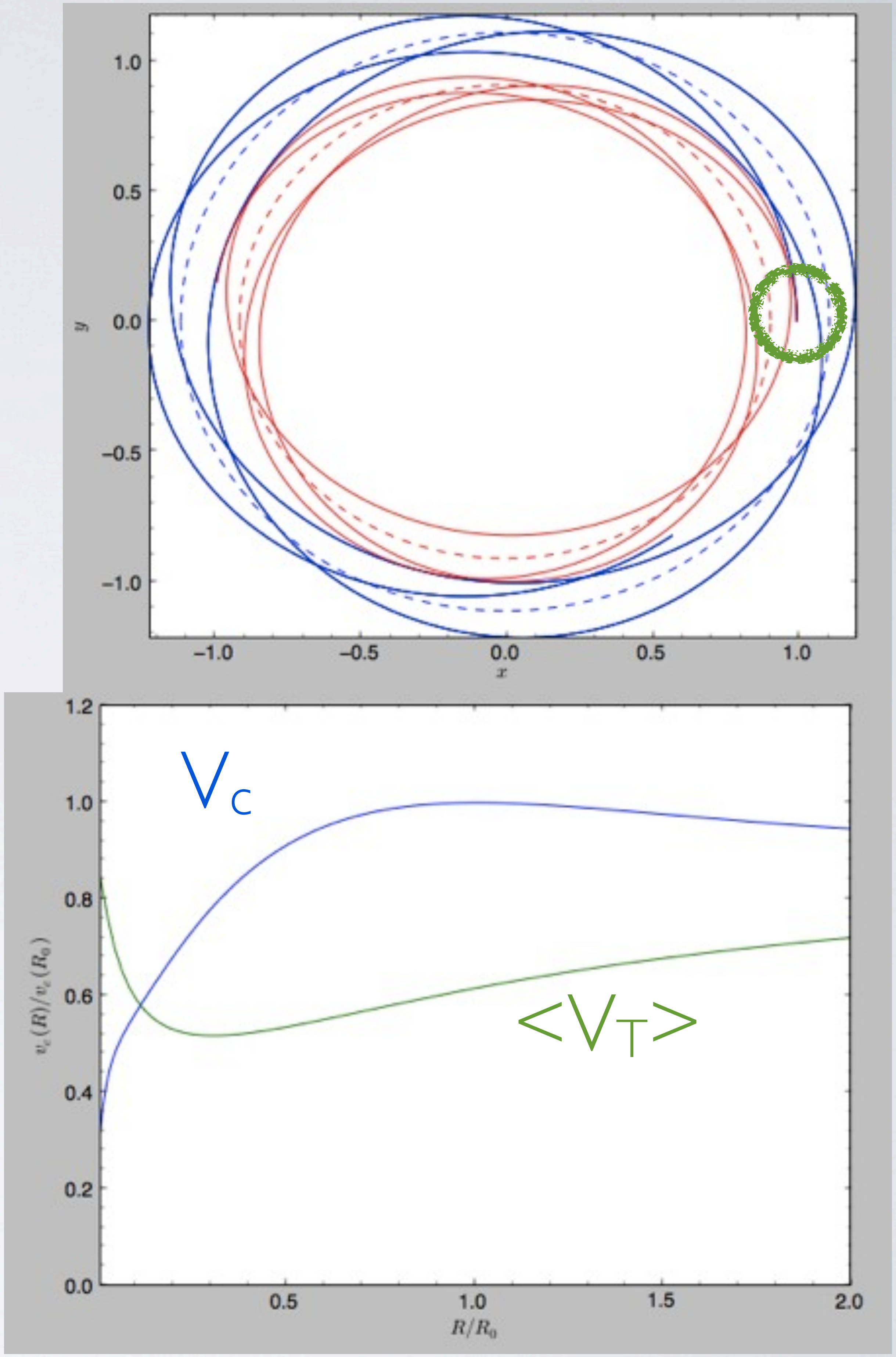
MONI-BIDIN ET AL. (2012)

- 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, $\partial V / \partial R = 10$ km $s^{-1}kpc^{-1}$ is required to match the minimum DM density deduced by the Galactic rotation curve (MIN model), and $\partial V / \partial R = 16.5$ 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:

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

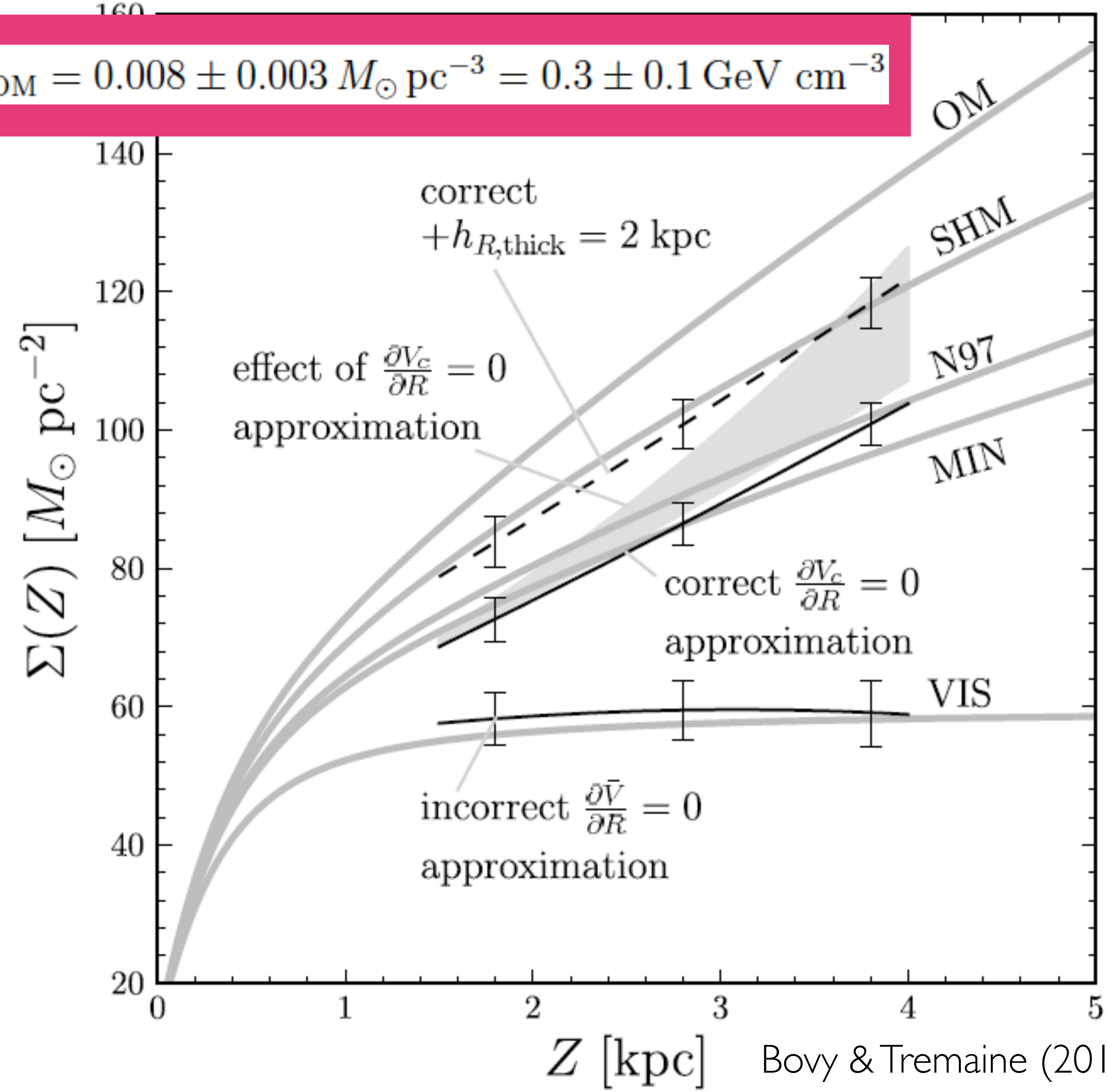
- Plug in measured values

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

and that for σ_{UW}^2 from MB12

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

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



Bovy & Tremaine (2012)

LOCAL MASS BUDGET e.g., Holmberg & Flynn (2000)

- ISM:
  - $\sim 3\,\mathrm{M_\odot\,pc^{-2}}$ in molecular gas
  - $\sim 8\,\mathrm{M_\odot\,pc^{-2}}$ in HI
  - $\sim 2\,\mathrm{M_\odot\,pc^{-2}}$ in ionized gas
  - scale height ~ 100 pc
  - Total uncertainty of a few $\mathrm{M_\odot\,pc^{-2}}$
- Stars:
  - Different populations with different scale heights
  - ~38 +/- a few $\mathrm{M_\odot\,pc^{-2}}$ in stars and stellar remnants
- Dark matter: the rest (72 - 38 - 13) / 2 / 110 pc ≈ 0.01$\mathrm{M_\odot\,pc^{-3}}$

LOCAL MASS BUDGET, CTD

- ISM + stellar disk:
  - From direct counts: ~50 $\mathrm{M_\odot\,pc^{-2}}$
  - Dynamical estimate: 51 $\mathrm{M_\odot\,pc^{-2}}$
- Dark disk: conservatively $< 10\,\mathrm{M_\odot\,pc^{-2}}$
- DDDM: < 1% of dark matter in this sector, scale height must be > 300 pc (otherwise conflict with local density measurement)

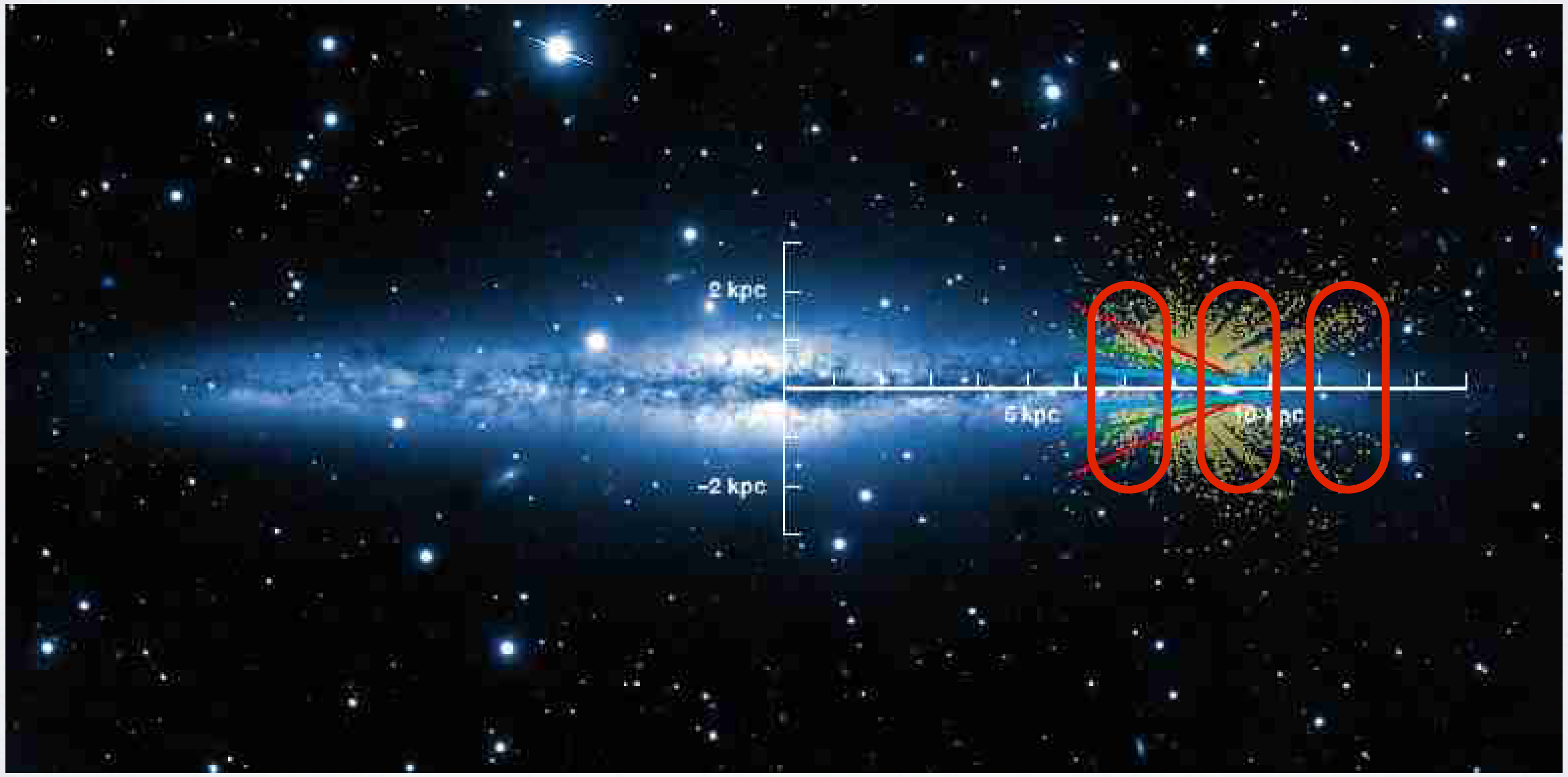
OVERVIEW

- Basics of dynamical modeling in the MW
- The Milky Way rotation curve
- Local determinations of the DM density
- **The radial profile of DM near the center of the MW**
- The large-scale distribution of DM in the halo
- Future developments

RADIAL DISK AND HALO PROFILES

- We can perform the vertical-force analysis at R =/= R_0 => $\boldsymbol{\Sigma}(R)$ and $\boldsymbol{\rho}(R)$

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



BEYOND THE JEANS EQUATIONS

- Jeans equations are great: no strong assumptions beyond equilibrium, can measure all ingredients in the Milky Way (in principle)

- In practice applying the Jeans equations is hard:

  - Radial gradients are difficult to measure

  - *gradients* in general are difficult to measure

  - Uncertainties and selection effects not gracefully included

- Using *Jeans theorem* instead (DF[x,v] == DF[integrals]) helps with these problems, but need to carefully choose a general enough family of DFs

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:

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

STATE-OF-THE-ART: ACTIONS AS ARGUMENTS

- Jeans theorem: can use any integrals of the motion as the arguments of the DF; often use E,L_z

- Orbital actions are natural integrals to use:

  - Part of canonical (action,angle)=(J,θ) variables where dynamics is *very* simple

  - Jacobian determinant of $(x,v) \rightarrow (J,\theta)$ is unity

  - Adiabatic invariants: natural coordinates to compare orbits in different potentials

  - Simple bounds and simple interpretation: radial and vertical action range from 0 (closed orbits) to infinity (unbound orbits), give extent of radial and vertical excursions

WHAT ARE ACTION-ANGLE COORDINATES?

- In position-velocity space, dynamics follows from Hamilton's equations: $$\dot{\mathbf{x}} = \mathbf{v};\ \dot{\mathbf{v}} = -\mathrm{d}\Phi/\mathrm{d}\mathbf{x}$$
- However, we can express dynamics in any other set of canonical coordinates, using a generating function S(**x**,**J**):
$$\theta = \frac{\partial S}{\partial \mathbf{J}},\ \mathbf{v} = \frac{\partial S}{\partial \mathbf{x}}$$
- Then $H \equiv H\left(\mathbf{x}, \frac{\partial S}{\partial \mathbf{x}}(\mathbf{x}, \mathbf{J})\right)$ and we can solve the Hamilton-Jacobi equation for S
$$H\left(\mathbf{x}, \frac{\partial S}{\partial \mathbf{x}}(\mathbf{x}, \mathbf{J})\right) = E$$
- As a PDE this is hard to solve and explicit solutions are rare

WHAT ARE ACTION-ANGLE COORDINATES?

- Hamilton's equations for action-angle coordinates:

$$\dot{\mathbf{J}} = -\frac{\partial H}{\partial \theta} = 0; \; \dot{\theta} = \frac{\partial H}{\partial \mathbf{J}} = \mathbf{\Omega}(\mathbf{J}) = \mathrm{constant}$$

- Dynamics is extremely simple:
  - Actions are conserved along orbit
  - Angles increase linearly in time

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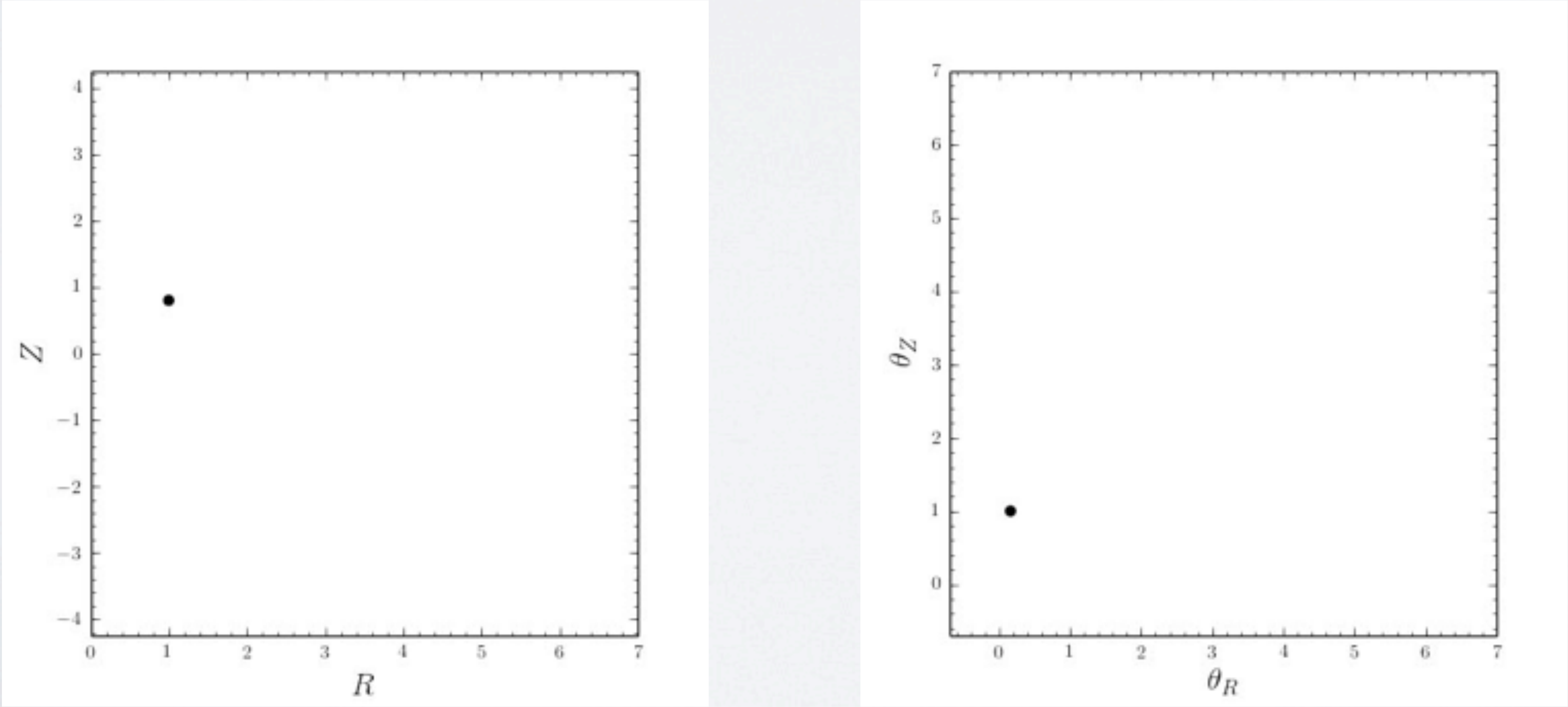

ACTION-ANGLE COORDINATES: SOME SOLUTIONS

- Only analytic case: isochrone potential (incl. Kepler and harmonic oscillator)

- Spherical: $J_\phi=L_z$, $J_z=L-|L_z|$, J_r = integral, frequencies and angles can be calculated as integrals (one frequency is zero)

- Axisymmetric: L_z, no general expressions for J_r and J_z (~ third-integral problem)

- Staeckel potentials: integral expressions for class of potential, incl. triaxial, but realistic galactic potentials are not of this form

- For orbits in and near the galactic plane, can approximate vertical and planar motion as decoupled, allows action-angle coordinates to be calculated (e.g., Binney 2010), or approximate potential as Staeckel potential (Binney 2012)

- General solutions for time-independent potentials now available (Bovy 2014, Sanders & Binney 2014)

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

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

- Actions calculated using Staeckel fudge (Binney 2012) in four component model for Milky Way potential (2 exponential disks, bulge, halo)
- Properties of DF:

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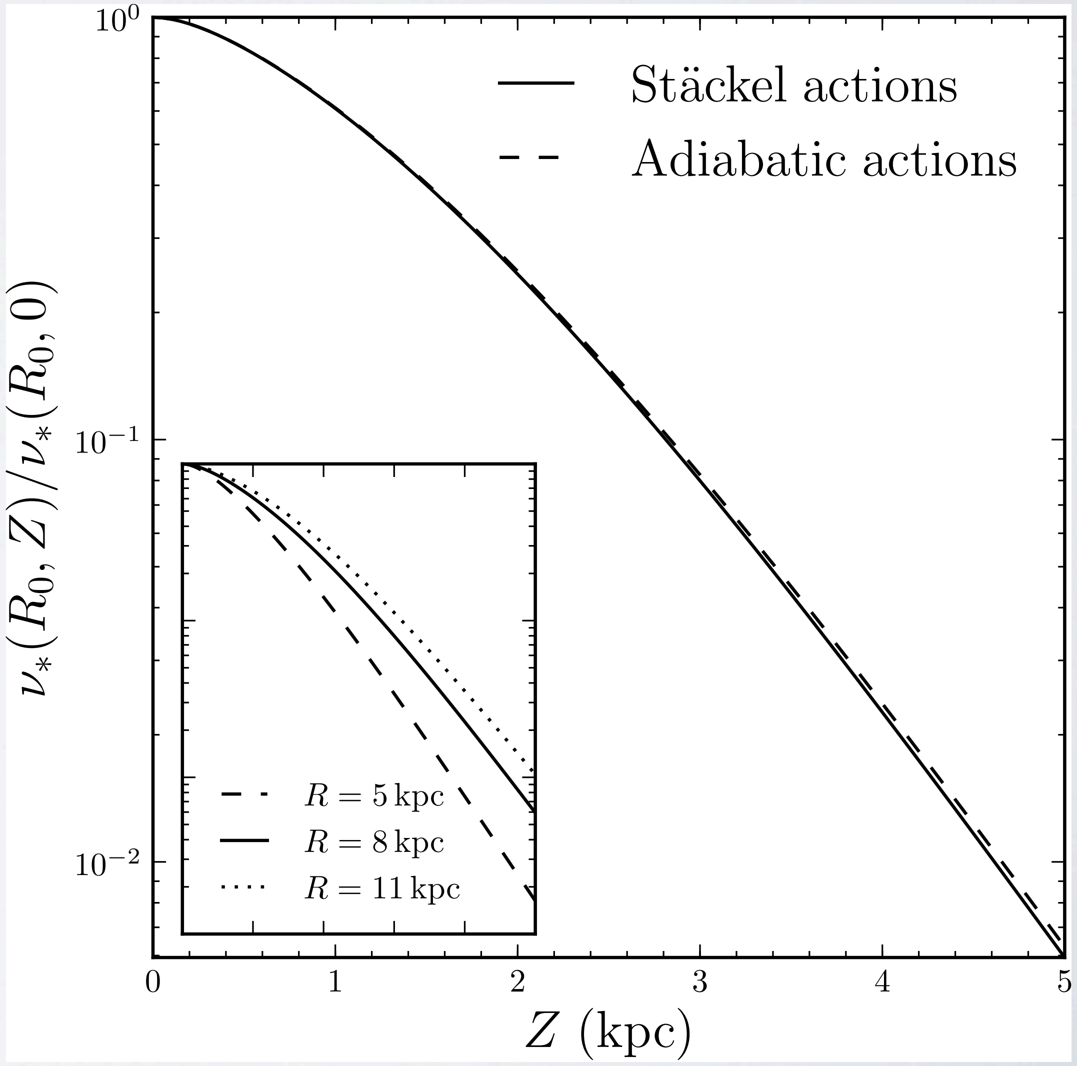

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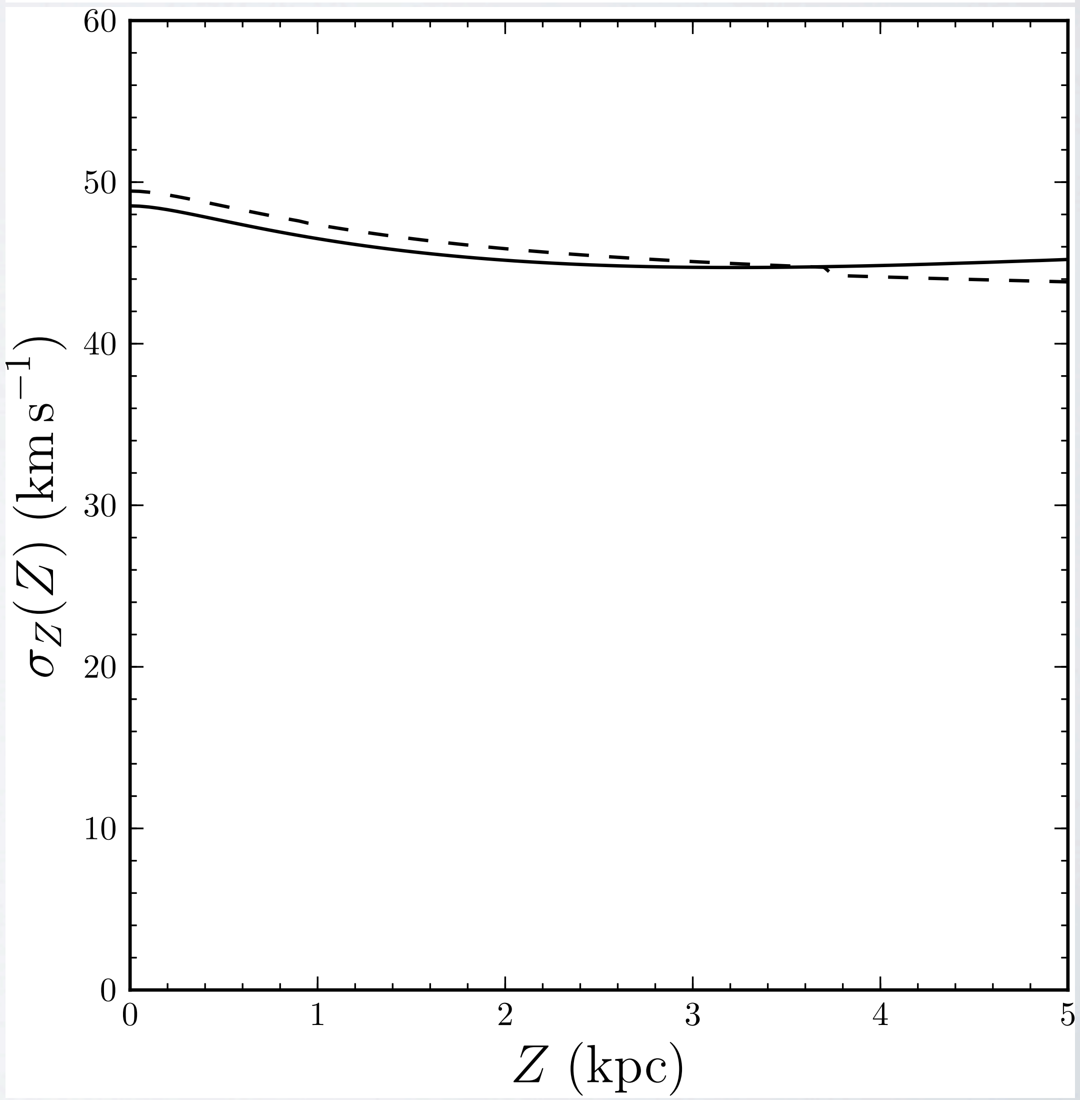

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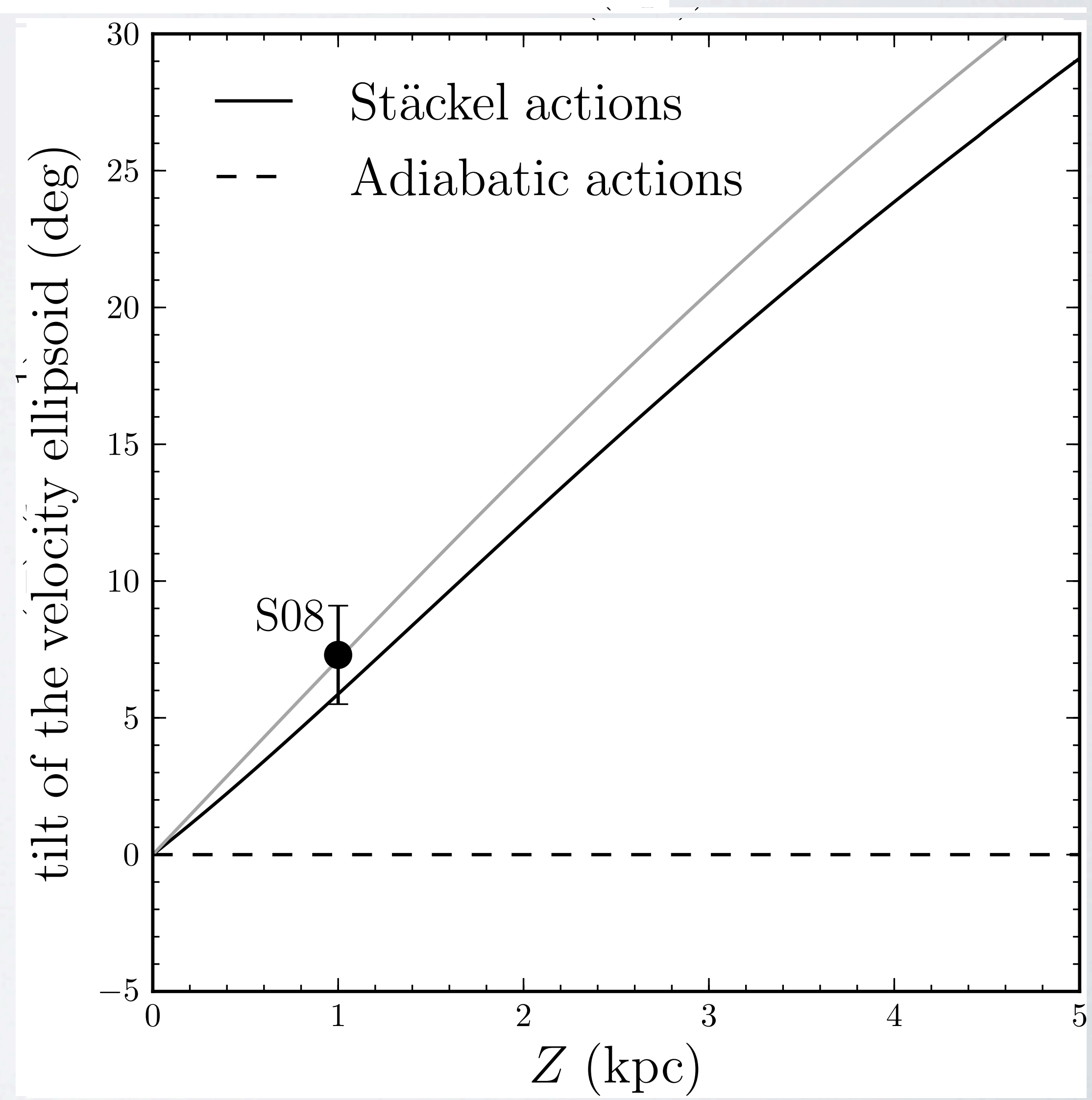


RECENT WORK MAKING USE OF THIS

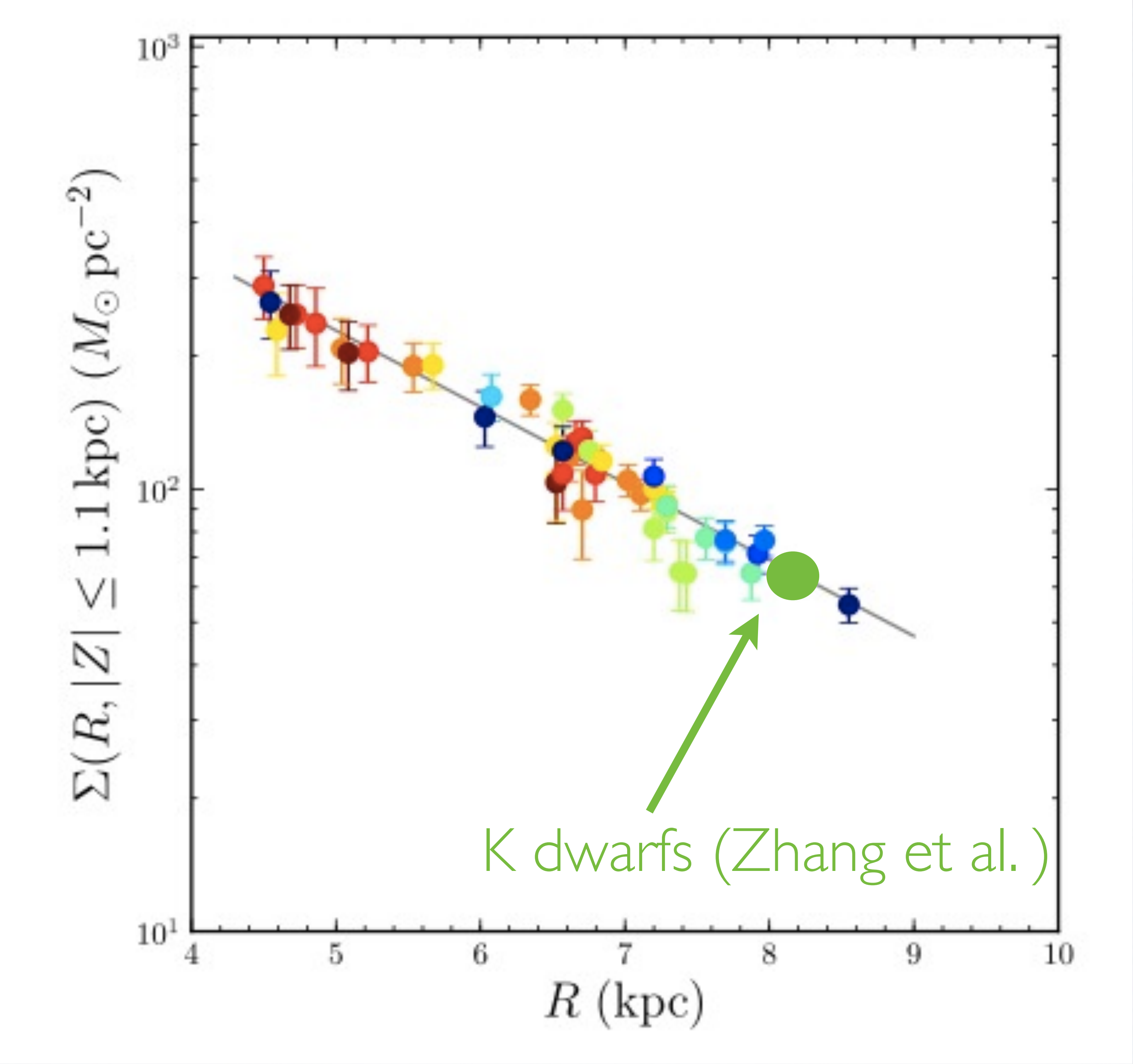
- Modeling the kinematics of the Solar neighborhood: Binney (2010, 2012): In fixed potential, fit a mixture of these basic DFs to the kinematics of stars near the Sun

- Piffl et al. (RAVE; 2014): Modeling the kinematics of ~200,000 stars within about 1.5 kpc from the Sun to constrain the local potential. Tight constraint on the dark matter density: $\rho_{DM}(R_0)$ = 0.48±0.05 GeV/cc

- Bovy & Rix (2013): Modeling the kinematics of ~16,000 SEGUE stars out to ~5 kpc to constrain the potential

SURFACE-DENSITY PROFILE

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

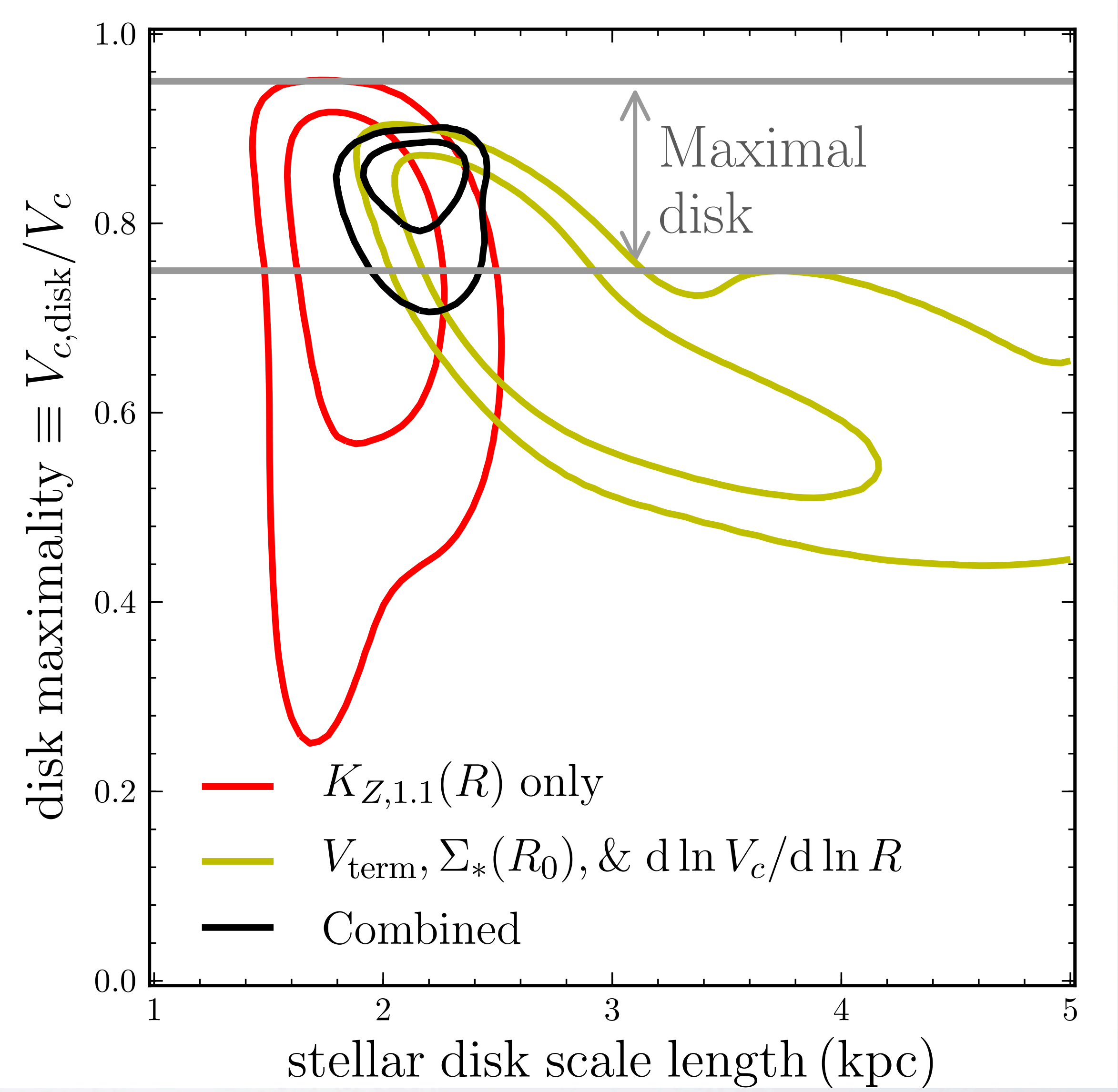


Bovy & Rix (2013), ApJ, 779, 115

CONSTRAINTS ON THE DISK

$$\begin{aligned} \text{stellar disk scale length} &= 2.15 \pm 0.14\,\mathrm{kpc}\,, \\ \Sigma_*(R_0) &= 38 \pm 4\,M_\odot\,\mathrm{pc}^{-2}\,, \\ \Sigma_{\mathrm{disk}}(R_0) &= 51 \pm 4\,M_\odot\,\mathrm{pc}^{-2}\,, \\ M_* &= 4.6 \pm 0.3 \times 10^{10}\,M_\odot\,, \\ M_{\mathrm{disk}} &= 5.3 \pm 0.3 \times 10^{10}\,M_\odot\,, \\ M_{\mathrm{baryonic}} &= 6.3 \pm 0.3 \times 10^{10}\,M_\odot\,. \end{aligned}$$

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



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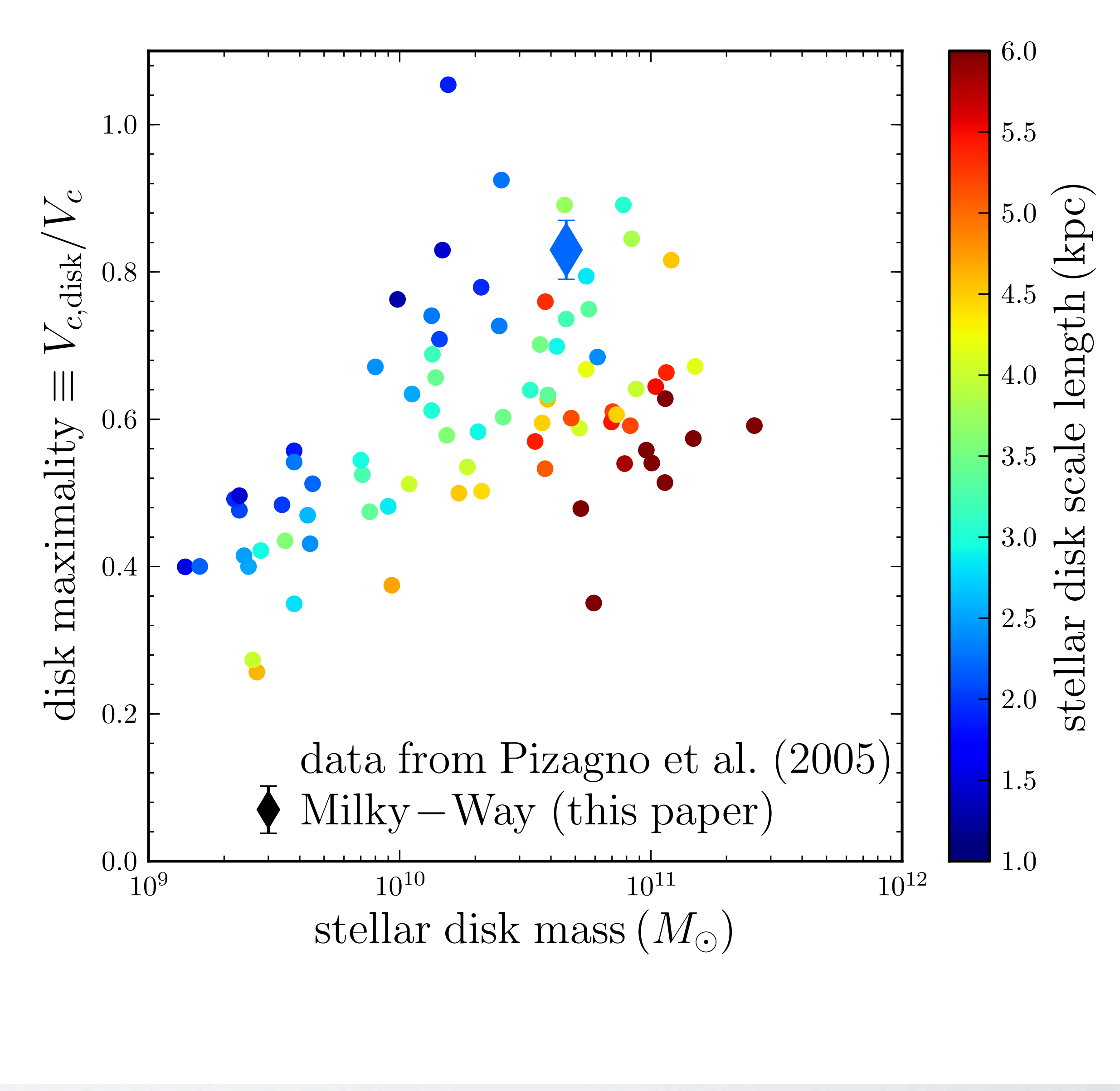
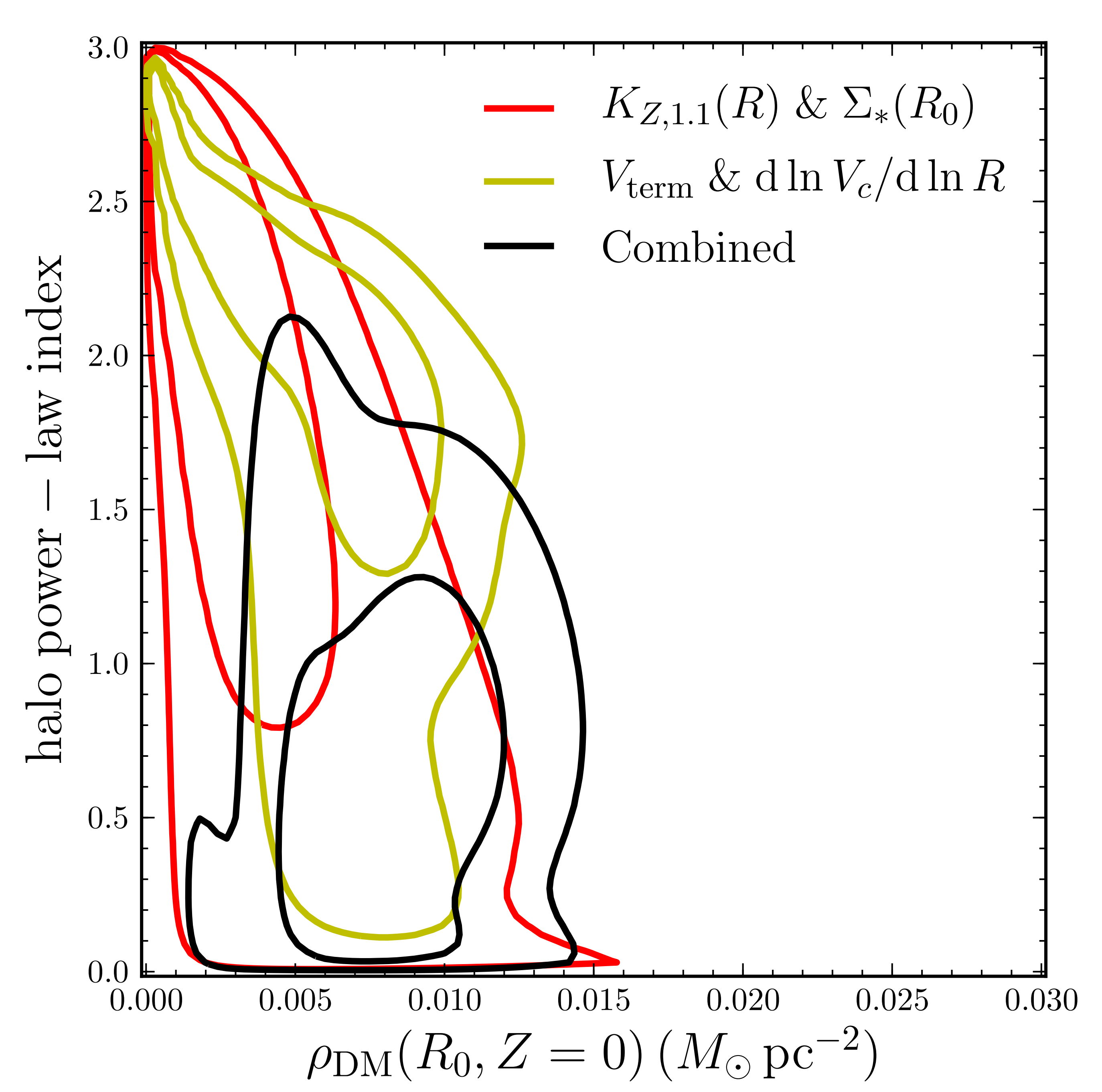


Bovy & Rix (2013), ApJ, 779, 115

CONSTRAINTS ON THE HALO

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

- $\alpha \leq 1.53 \quad (95\,\%\ \text{confidence})$



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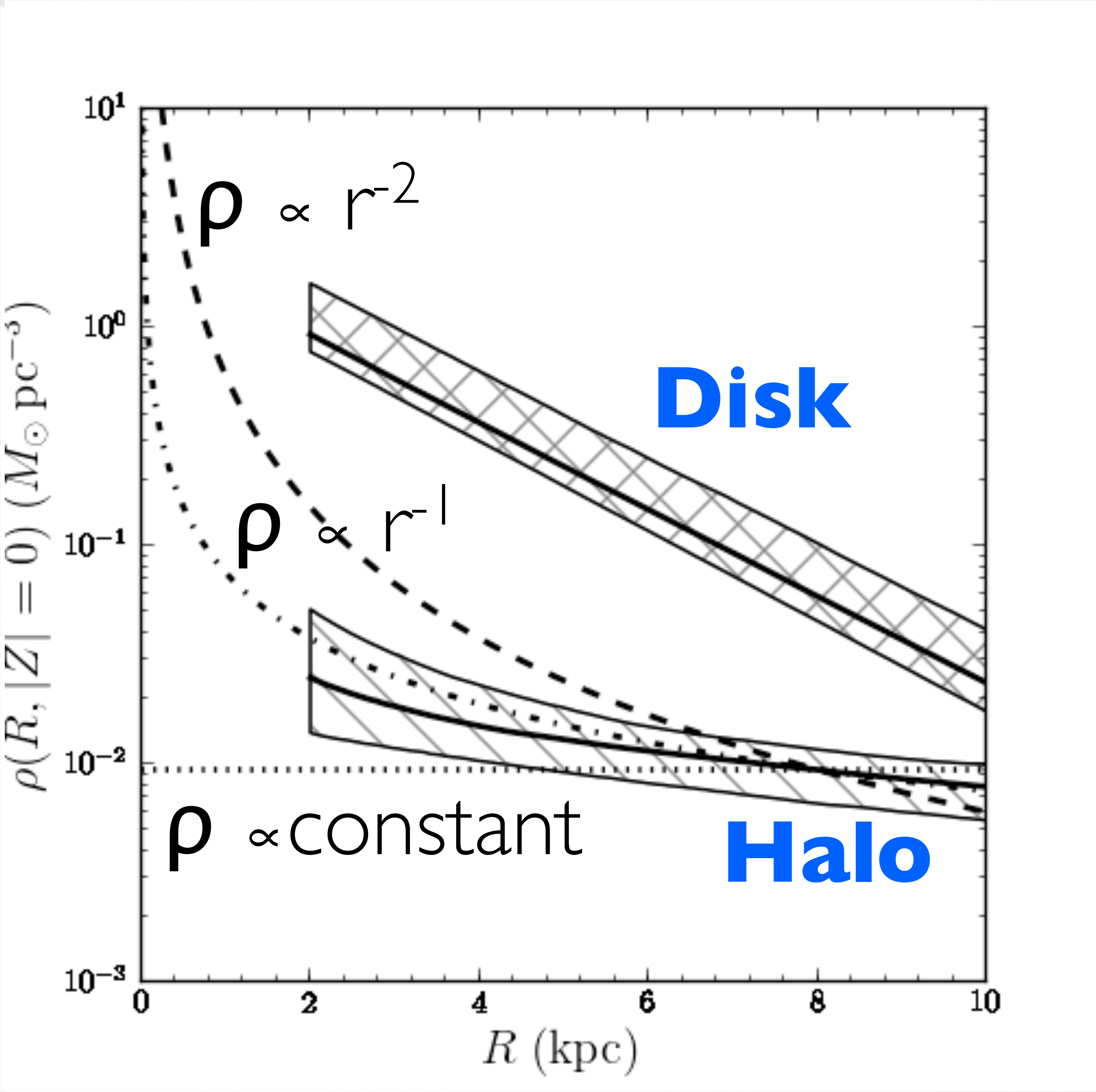

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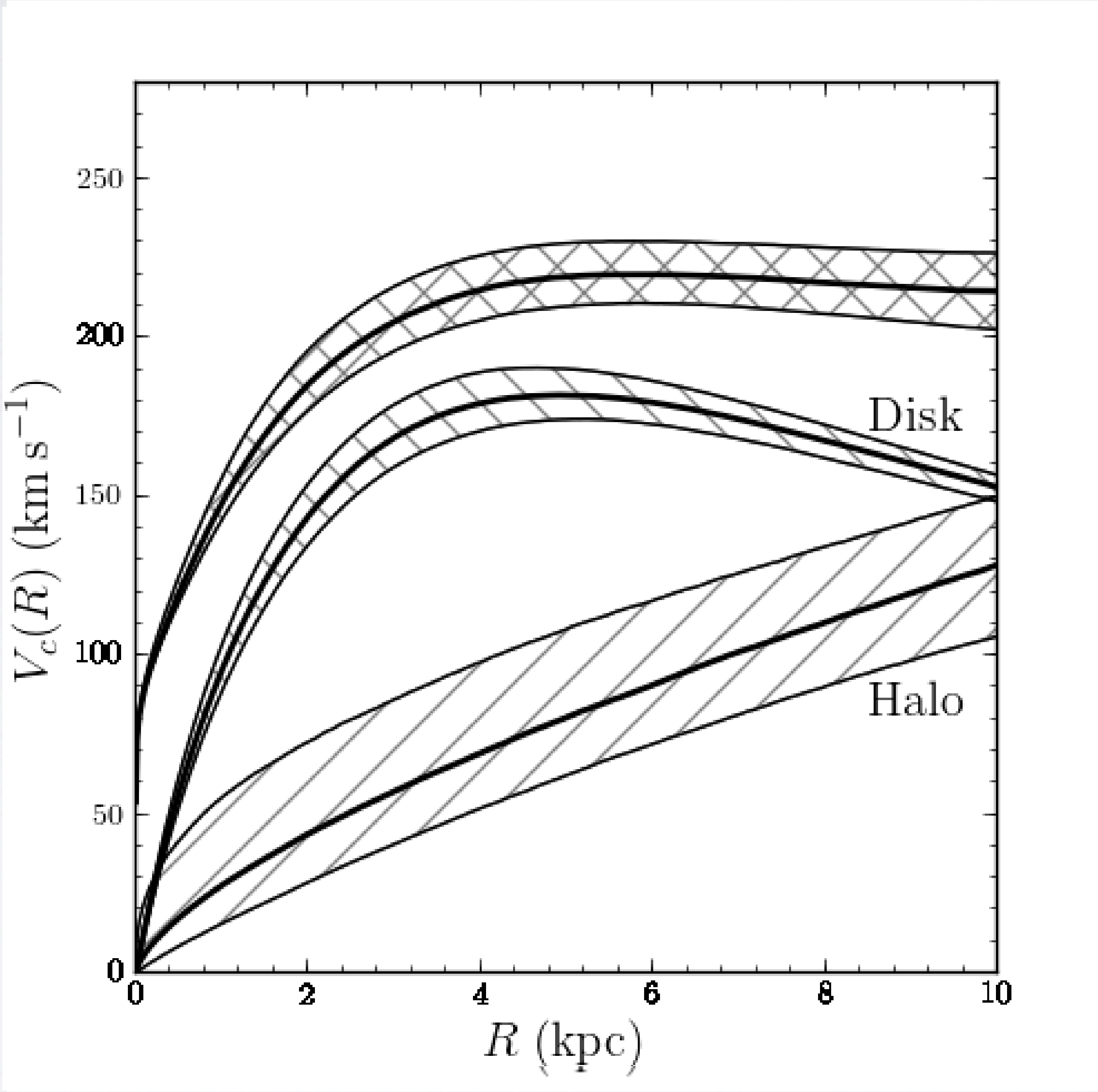

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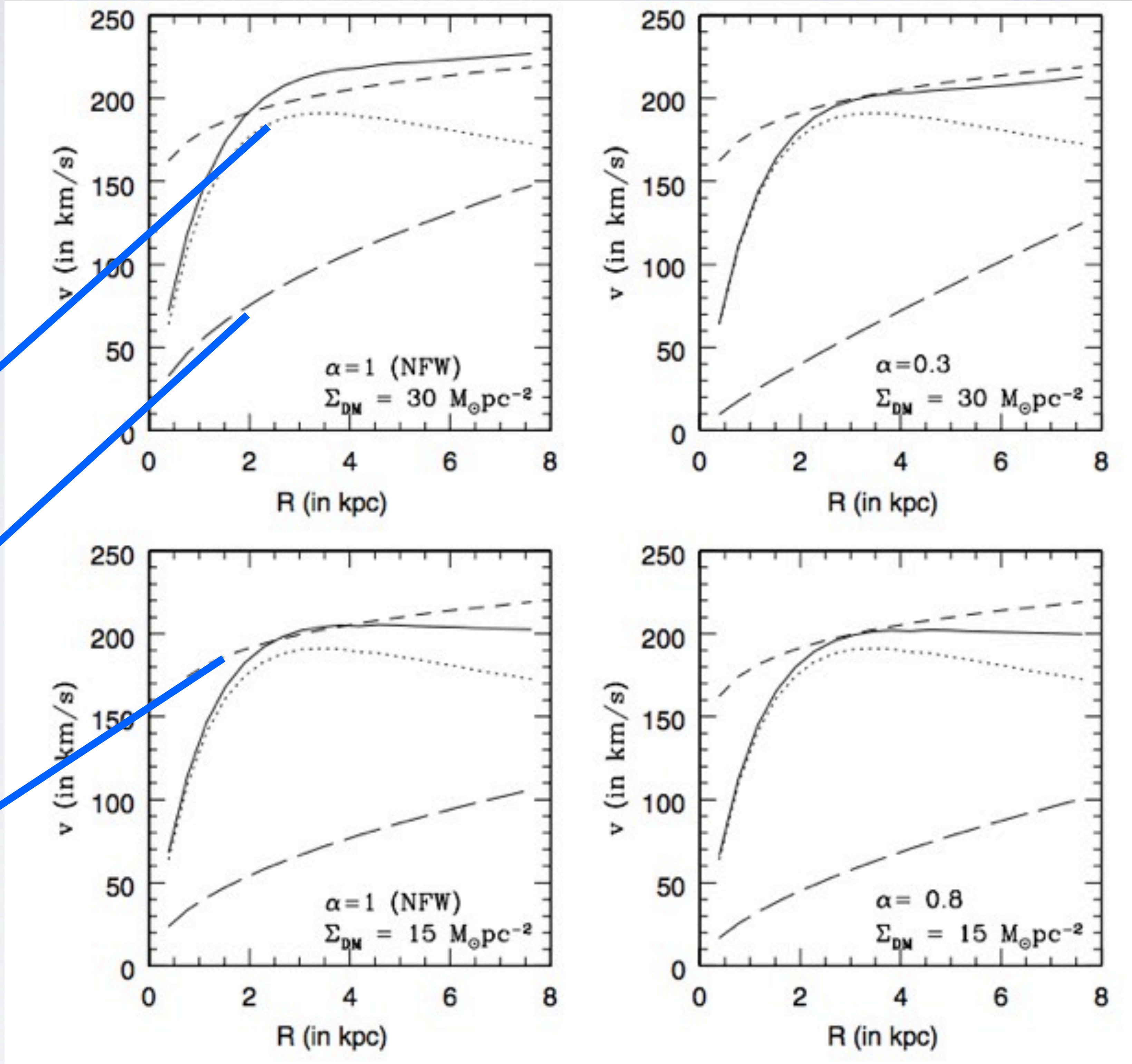
CONSTRAINTS FROM MICROLENSING

- Construct model of inner Galaxy w/ gas and stellar content constrained by optical depth to microlensing

- How much DM is allowed to remain below the observed rotation curve?



Binney & Evans (2001)

Recent updates in the optical depth to microlensing and proper modeling of baryonic components should be taken into account (see Iocco et al. 2011)

OVERVIEW

- Basics of dynamical modeling in the MW
- The Milky Way rotation curve
- Local determinations of the DM density
- The radial profile of DM near the center of the MW
- **The large-scale distribution of DM in the halo**
- Future developments

DARK MATTER HALO

- Topic for another whole lecture...
- Techniques:
  - Jeans equations: similar to local DM Jeans equations earlier, but for spherical potential (e.g., Xue et al. 2008)
  - stellar DF modeling: DF(E,L_z) (e.g., Deason et al. 2011)
  - Streams: e.g., Sagittarius: many conflicting results
  - Satellite kinematics (Is Leo I bound?)
- Virial masses between 0.8 and 2×10^{12} M_{sun} are commonly reported; some measurements of the slope of the density profile (concentration)

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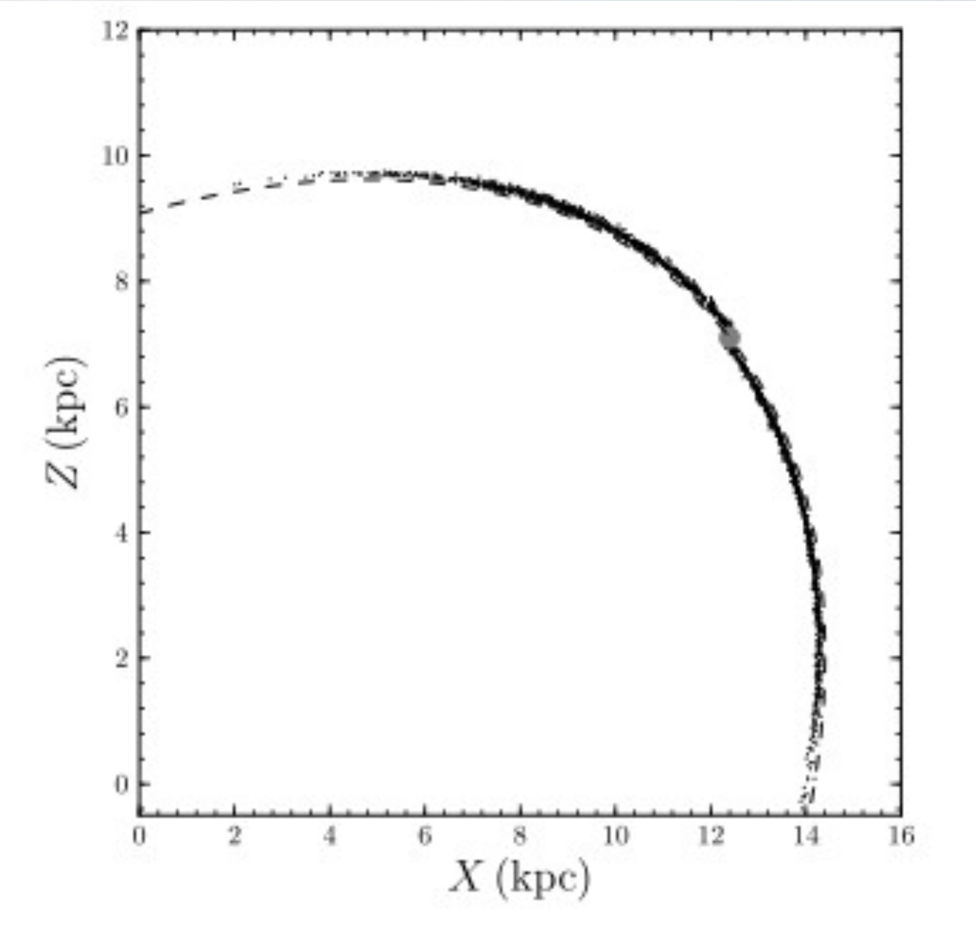
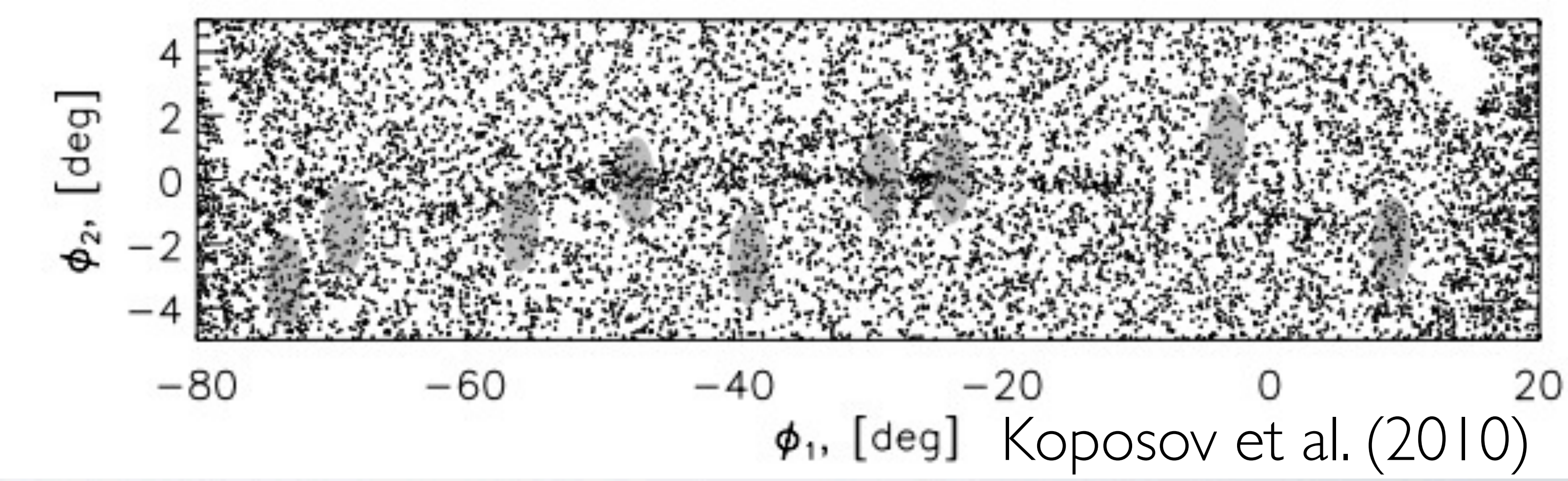
FUTURE IMPROVEMENTS AND CHALLENGES: GAIA

- Astrometric space mission:
  - parallaxes and proper motions for 1 billion stars out to 10 kpc and beyond, full 6D motions for up 100 million stars
  - Study of stellar populations over large volume of the disk (+spectroscopic surveys)
- Much improved stellar rotation curve with proper motions
- $\mathbf{\Sigma}(R,Z)$ at $2 < R < 16$ kpc

FUTURE IMPROVEMENTS AND CHALLENGES: TIDAL STREAMS

- Tidal streams show us part of an "orbit" --> strong probe of the acceleration field
- Some already known near the disk, Gaia will find many more
- Largely on non-disk orbits: complementary to studies of disk dynamics
- Much work on removing the quotation marks....

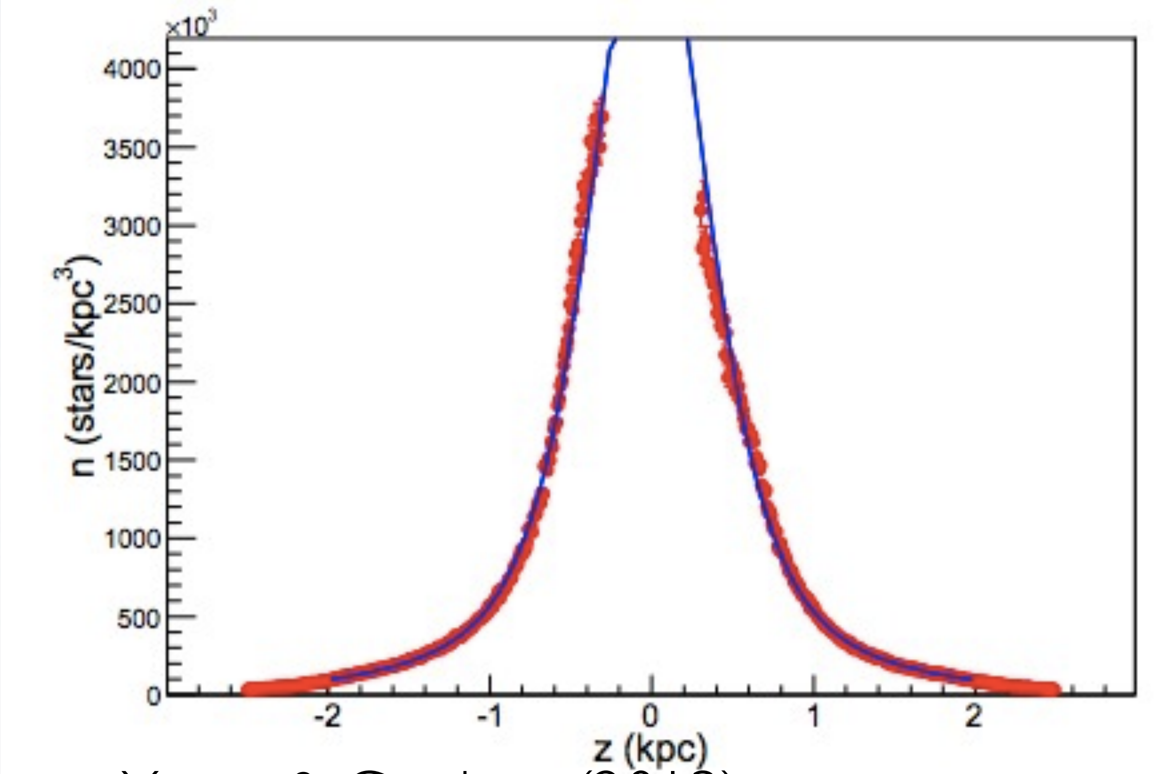




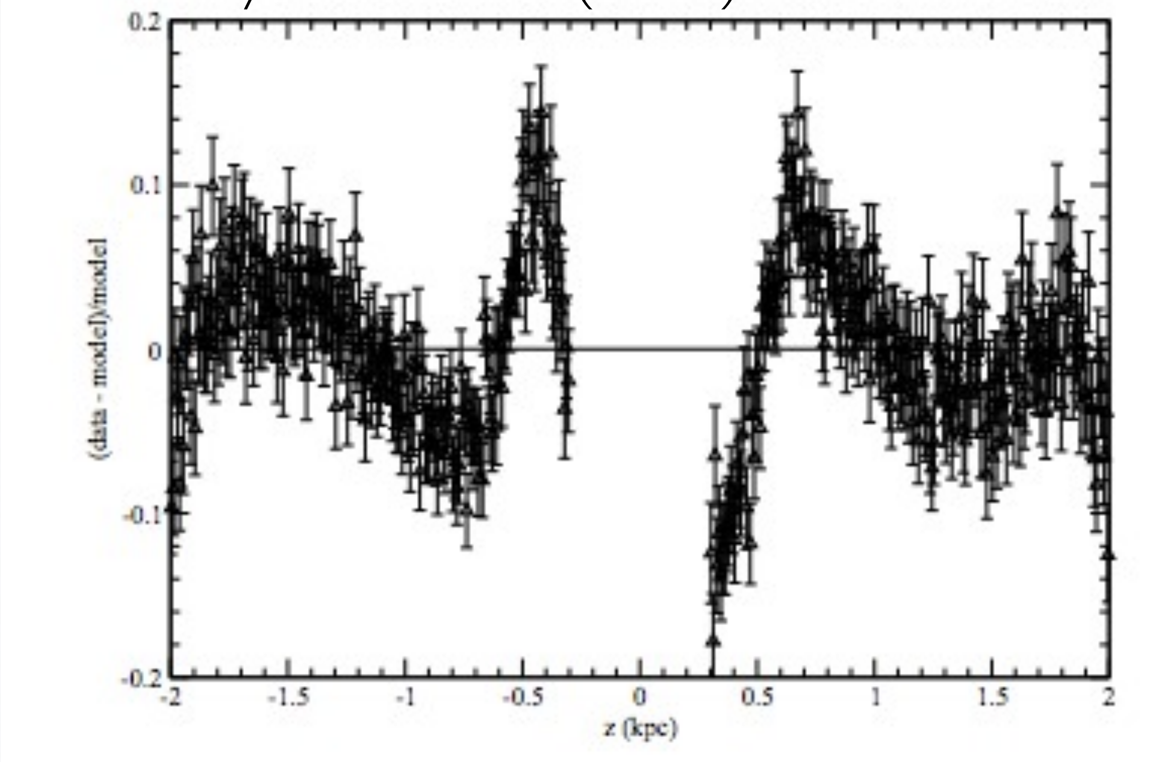
Koposov et al. (2010)

FUTURE IMPROVEMENTS AND CHALLENGES: ASYMMETRIES AND STREAMING MOTIONS

- Recent work on density and velocities fields within a few kpc of the Sun find asymmetries and streaming motions
- Challenge to incorporate these into dynamical modeling and avoid being systematics-limited



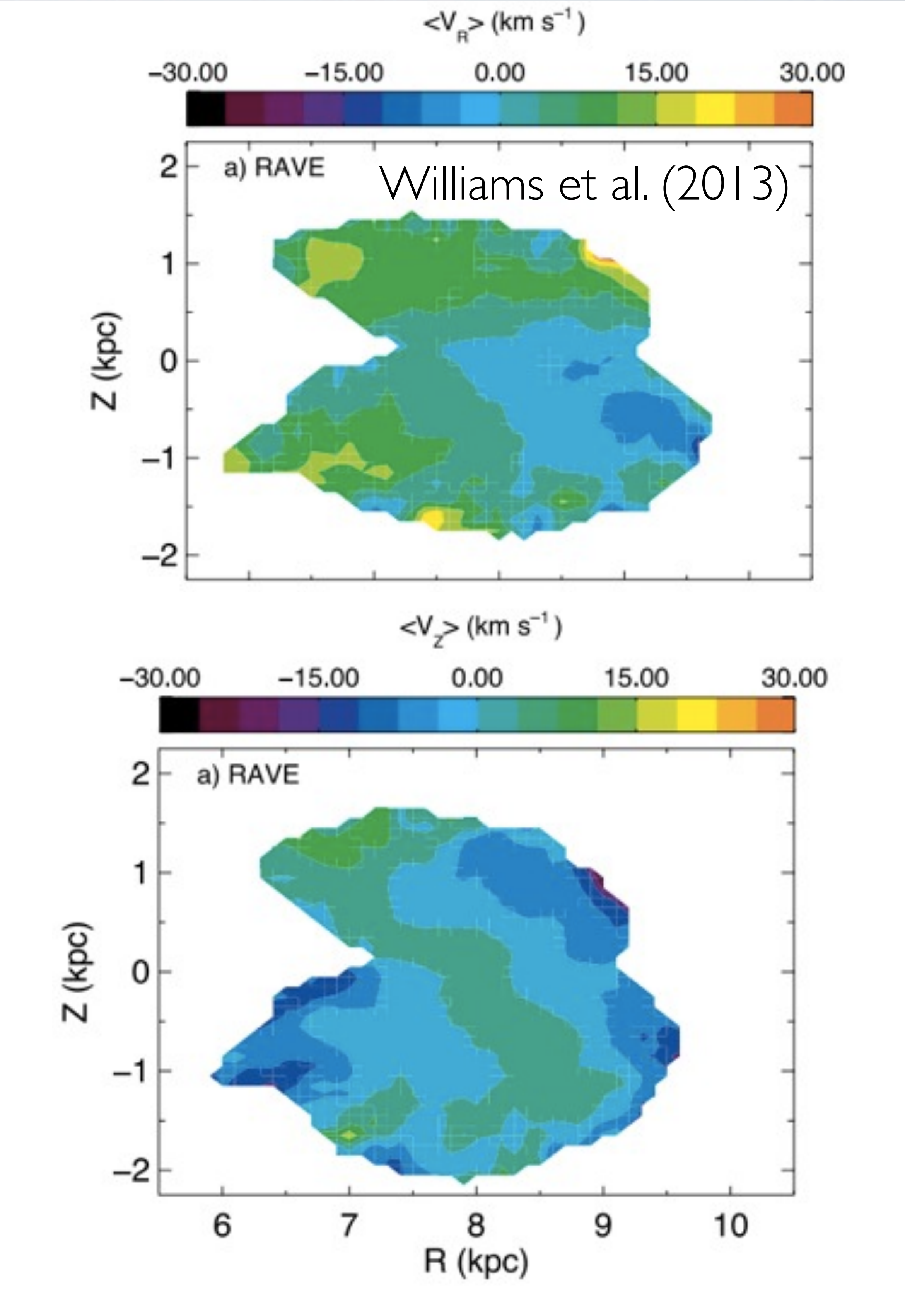
Yanny & Gardner (2013)



FUTURE IMPROVEMENTS AND CHALLENGES: ASYMMETRIES AND STREAMING MOTIONS

- Recent work on density and velocities fields within a few kpc of the Sun find asymmetries and streaming motions

- Challenge to incorporate these into dynamical modeling and avoid being systematics-limited



galpy

Galactic Dynamics in python

build passing | coverage 87% | pypi 0.1

https://github.com/jobovy/galpy

jobovy / galpy

Unwatch 4 | Unstar 12 | Fork 4

developed on Github

Galactic Dynamics in python http://galpy.readthedocs.org/ — Edit

2,667 commits | 3 branches | 1 release | 2 contributors

Code | Issues 34 | Pull Requests 0 | Wiki | Pulse | Graphs

branch: master | galpy / +

mv interpolation test

jobovy authored 17 hours ago | latest commit c09cb45535

doc	fix mistake in the documentation	7 days ago
galpy	interpolate x and y instead of R and phi for orbit, fixes #187	17 hours ago

Welcome to galpy's documentation

galpy is a python package for galactic dynamics. It supports orbit integration in a variety of potentials, evaluating and sampling various distribution functions, and the calculation of action-angle coordinates for all static potentials.

Quick-start guide

w/ extensive docs

- Installation
  - Advanced installation
- Introduction
  - Rotation curves
  - Units in galpy
  - Orbit integration
  - Escape velocity curves

- Properties of large variety of potentials (rotation curves, etc.)
- Numerical orbit integration w/ 8 integrators
- Action-angle calculations
- Various distribution functions

SOME REFERENCES:

- *The* book: *Galactic Dynamics*, J. Binney & S. Tremaine, 2nd edition (2008) Princeton University Press

- Some recent reviews:

  - *Dynamics for Galactic Archeology*, J. Binney (2013), *New Astronomy Reviews 57, 29*: Overview of dynamics concepts useful for studying the MW disk (http://arxiv.org/abs/1309.2794)

  - *The local dark matter density*, J. Read (2014), *J. Phys. G.* 41, 063101: Overview of techniques for measuring the local DM density and overview of recent measurements (http://arxiv.org/abs/1404.1938)

  - *The Milky Way's stellar disk*, H.-W. Rix & J. Bovy (2013), *Astron. Astrophys. Rev.* 21, 61: Overview of methods for learning about MW disk stellar populations and of recent progress (http://arxiv.org/abs/1301.3168)

SOME REFERENCES: CIRCULAR VELOCITY CURVE

- van den Hulst, H.C., Muller, C.A., & Oort, J.H. 1954, BAN 12, 117: Original paper with terminal velocity measurements of rotation curve

- Gunn, J.E., Knapp, G.R., & Tremaine, S. 1979, AJ 84, 1181: Good terminal-velocity reference

- Kerr, F.J. & Lynden-Bell, D. 1986, MNRAS 221, 1023: IAU standard $V_c(R_0)$ = 220 km/s

- Feast, M. & Whitelock, P. 1998, MNRAS 291, 683: Measurement of the Oort constants (combination of $V_c(R_0)/R_0$ and its derivative) from *Hipparcos* data

SOME REFERENCES: CIRCULAR VELOCITY CURVE: RECENT PROGRESS

- Reid, M.J. et al. 2009, ApJ 700, 137 and update 2014, ApJ 783, 130: Measurement of $V_c(R_0)$ and $V_c(R)$ from the kinematics of masers in the MW disk; some residual dependence on Sun's motion wrt $V_c(R_0)$ (http://arxiv.org/abs/1401.5377)

- Bovy, J. et al. 2012, ApJ 759, 131: Measurement of $V_c(R_0)$ and $V_c(R)$ from the kinematics of intermediate-age stars in the MW disk, *first measurement that is independent of the unknown value of the Sun's velocity wrt $V_c(R_0)$*: $V_c(R_0) = 218 \pm 6$ km/s (http://arxiv.org/abs/1209.0759)

SOME REFERENCES: LOCAL DARK MATTER

- Bovy, J. & Tremaine, S. 2012, ApJ 756, 89: at large heights above the plane, so largely unaffected by uncertainty in baryonic mass distribution, first 3σ detection; finds $\rho_{DM}(R_0)$ = 0.3±0.1 GeV/cc (http://arxiv.org/abs/1205.4033)

- Zhang, L., Rix, H.-W., van de Ven, G., Bovy, J., Liu, C., & Zhao, G. 2013, ApJ 772, 108: Measurement based on SEGUE K dwarfs between 300 pc and 1.5 kpc; finds $\rho_{DM}(R_0)$ = 0.28±0.08 GeV/cc (http://arxiv.org/abs/1209.0256)

- Piffl, T. et al. (RAVE) 2014, MNRAS, submitted: Most recent measurement using 200,000 stars from the RAVE survey up to 1.5 kpc from the plane, finds $\rho_{DM}(R_0)$ = 0.48±0.05 GeV/cc (http://arxiv.org/abs/1406.4130)

SOME REFERENCES: DARK MATTER PROFILE

- Microlensing+rotation curve bound on dark-matter profile:
  - Binney, J. & Evans, N. W. 2001, MNRAS 327, 27: original paper pointing out that the optical depth of microlensing toward the bulge does not leave much room for DM to not exceed the observed rotation curve (http://arxiv.org/abs/astro-ph/0108505)
  - Iocco, F., Pato, M., Bertone, G., & Jetzer, P. 2011, JCAP 11, 029: recent re-analysis with updated microlensing constraints; NFW now consistent (http://arxiv.org/abs/1107.5810)
- Direct measurement of the disk mass profile and first dynamical bound on radial profile of dark matter near the Sun:
  - Bovy, J. & Rix, H.-W. 2013, ApJ 779, 115 (http://arxiv.org/abs/1309.0809)

SOME REFERENCES: DARK MATTER HALO

- Wilkinson, M.I. & Evans, N.W. 1999, MNRAS 310, 645: Mass within 50 kpc from kinematics of globular clusters and satellites: $M(r<50\text{kpc}) = 5.4^{+0.2}_{-3.6} \times 10^{11}\ M_{sun}$(http://arxiv.org/abs/astro-ph/9906197)

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- Xue, X.X. et al. 2008, ApJ 684, 1143: Mass within about 60 kpc from the kinematics of 2,400 BHB stars; $M(r<60\text{kpc}) = 4.0\pm0.7 \times 10^{11}\ M_{sun}$ (http://arxiv.org/abs/0801.1232)

SOME REFERENCES: DARK MATTER HALO CTD

- Smith, M.C. et al. 2007, MNRAS 379, 755 and recent update Piffl, T. et al. 2014, A&A 562, A91: Virial mass from measuring the local potential-well depth using the escape velocity: M_{vir} =~ 1.5±0.5 x 10^{12} M_{sun} (http://arxiv.org/abs/astro-ph/0611671 and http://arxiv.org/abs/1309.4293)

- Deason, A.J., Belokurov, V., Evans, N.W., & An, J. 2012, MNRAS 424, L44 and Deason, A.J. et al. 2012, MNRAS 425, 2840: Milky Way mass out to 50 and 100 kpc from BHB stars and other stellar tracers; M(r<50kpc) =~ 4 x 10^{11} M_{sun} and M(r<150kpc) =~ 5 to 10 x 10^{11} M_{sun} (http://arxiv.org/abs/1204.5189 and http://arxiv.org/abs/1205.6203)