Does the outer Milky Way lack Dark Matter?

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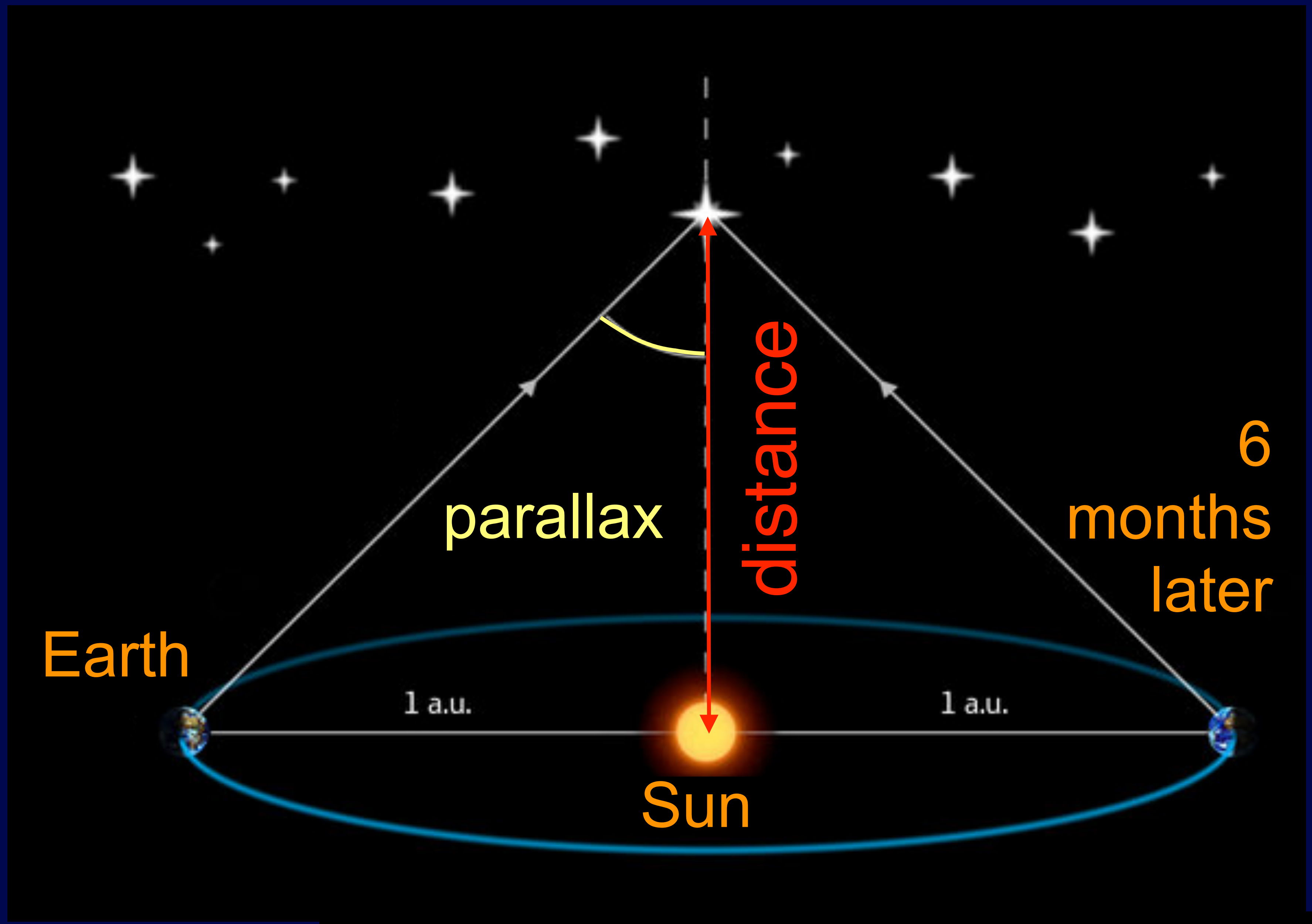
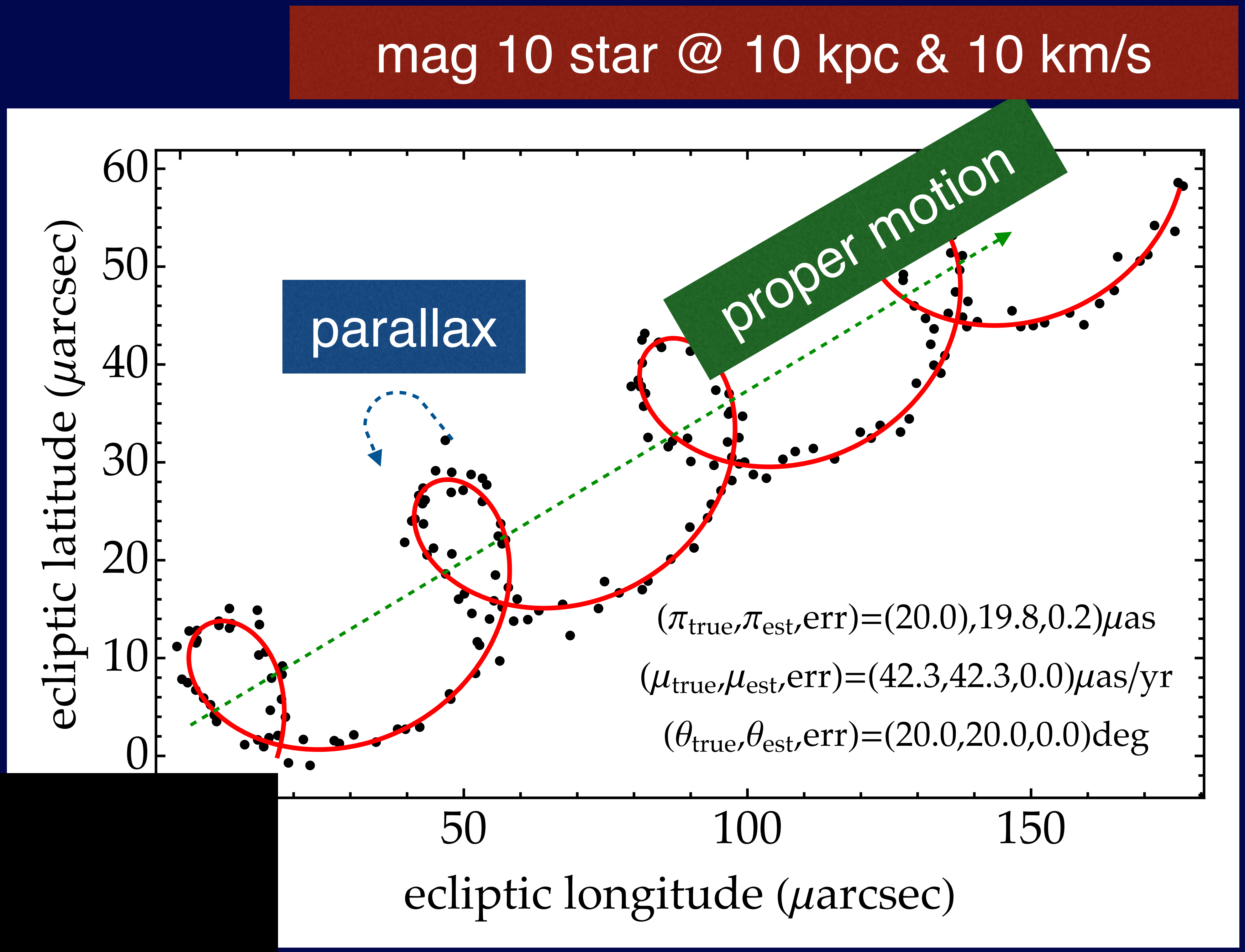
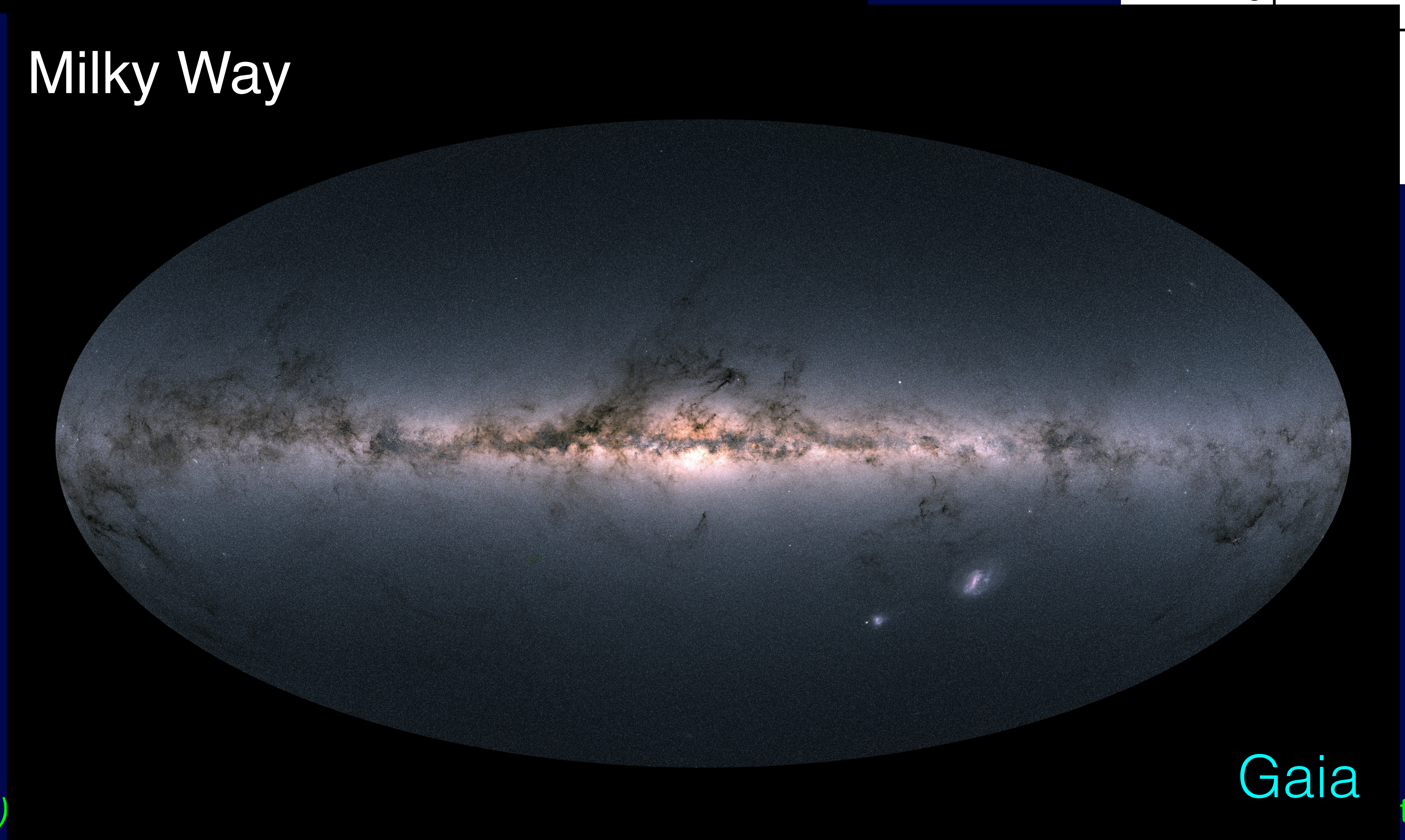
Gaia: All-sky survey of Parallaxes & Proper Motions

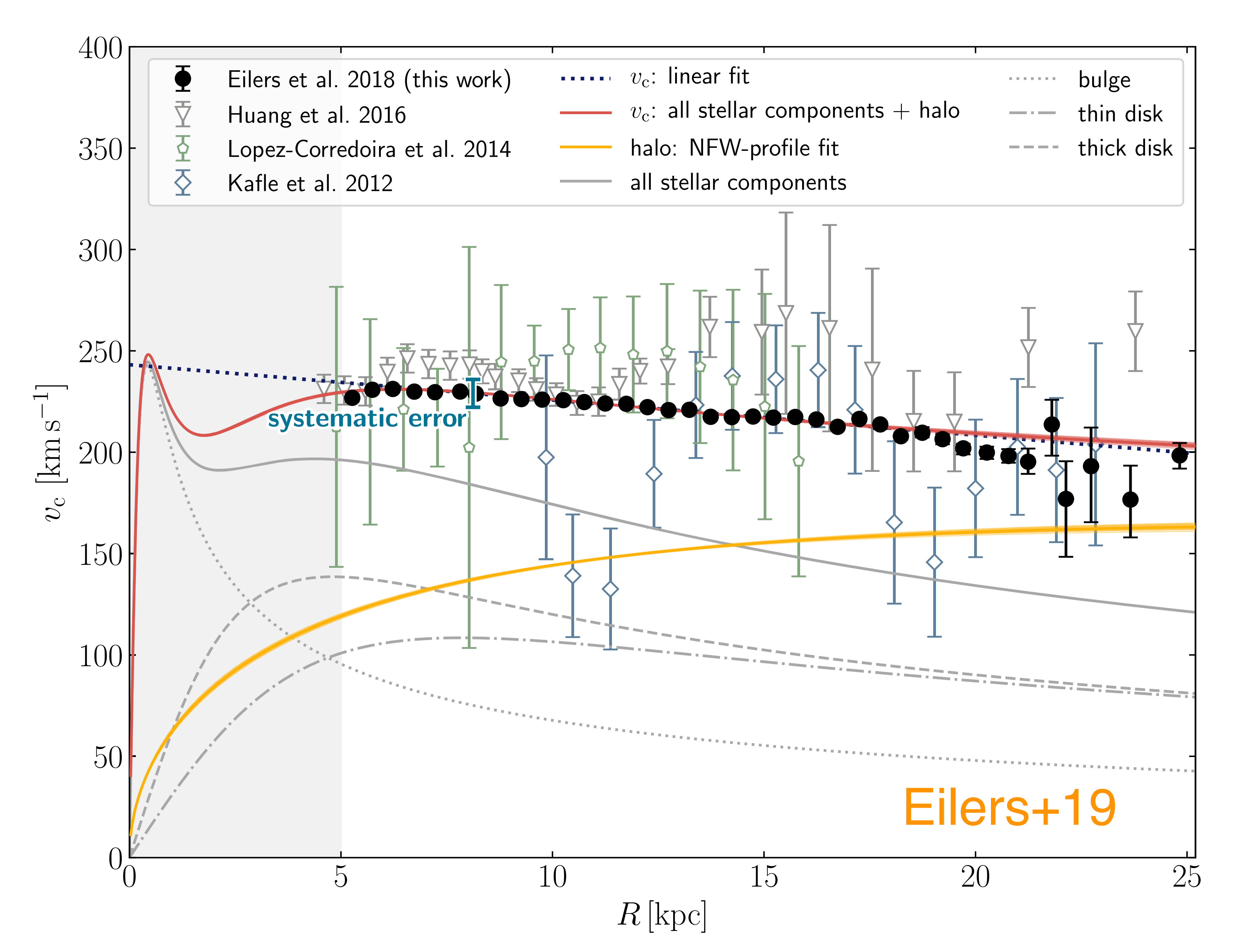


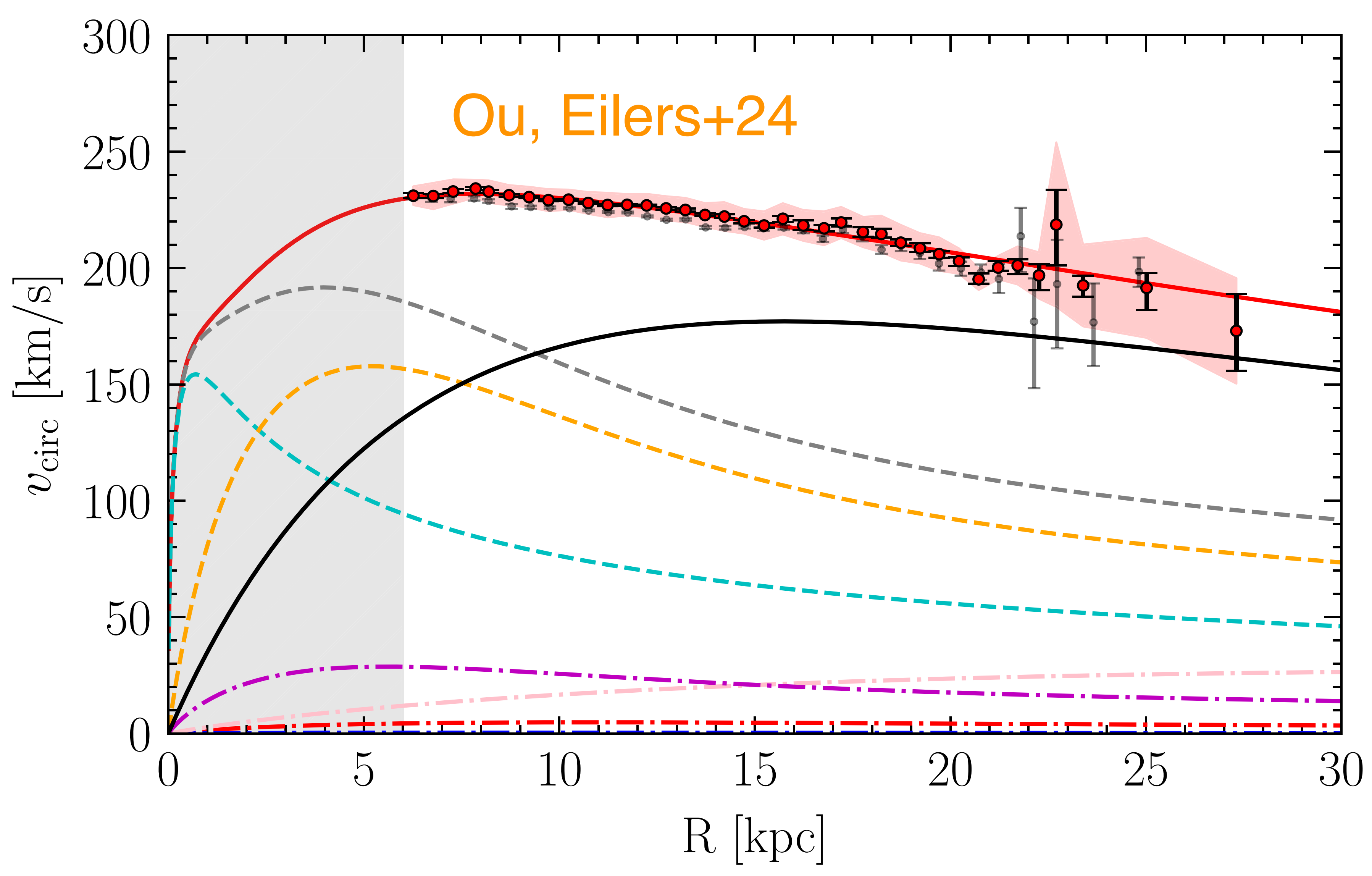


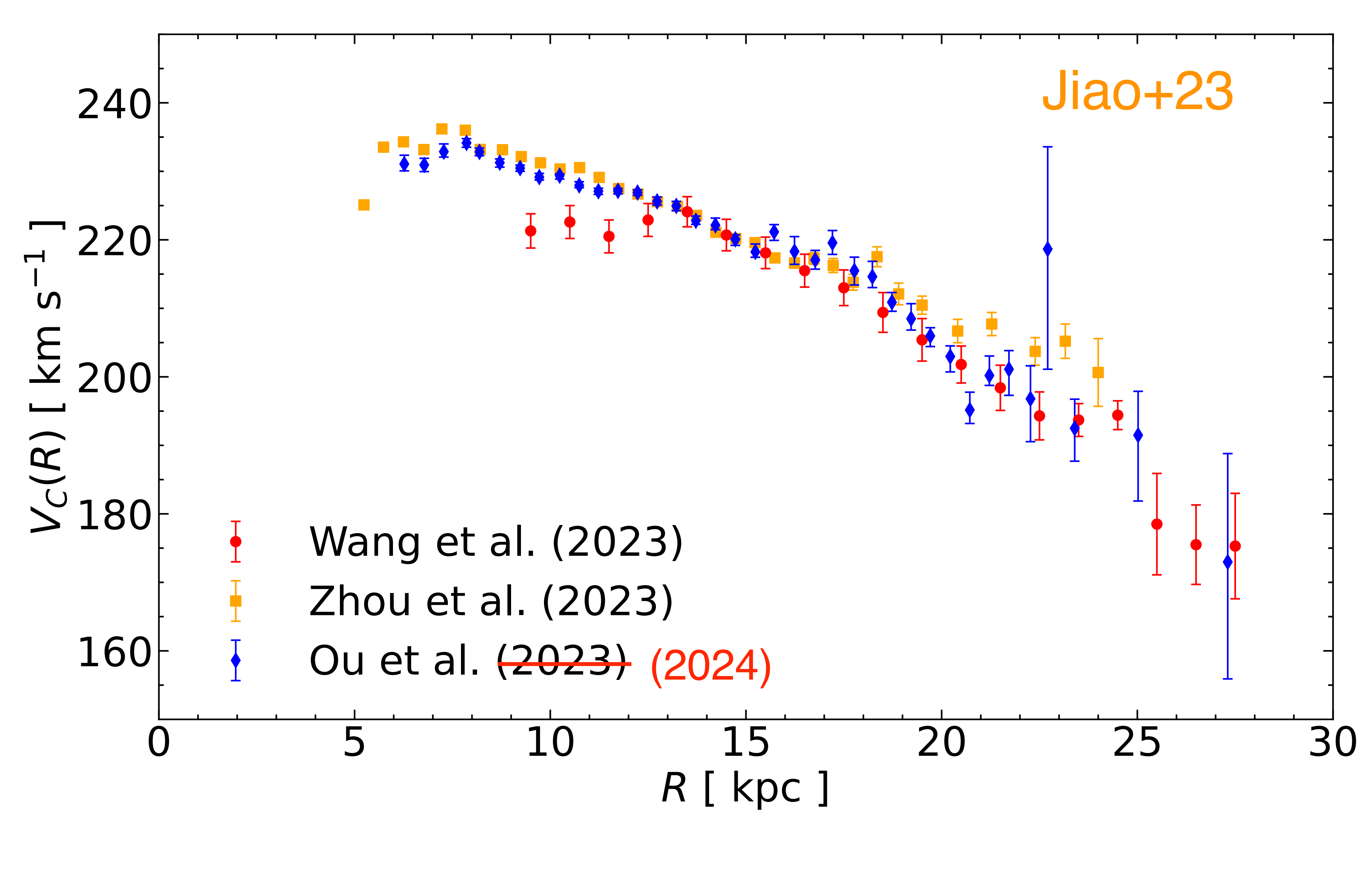


→ 6D view of much of the Milky Way

Previous results on rotation curves of MW







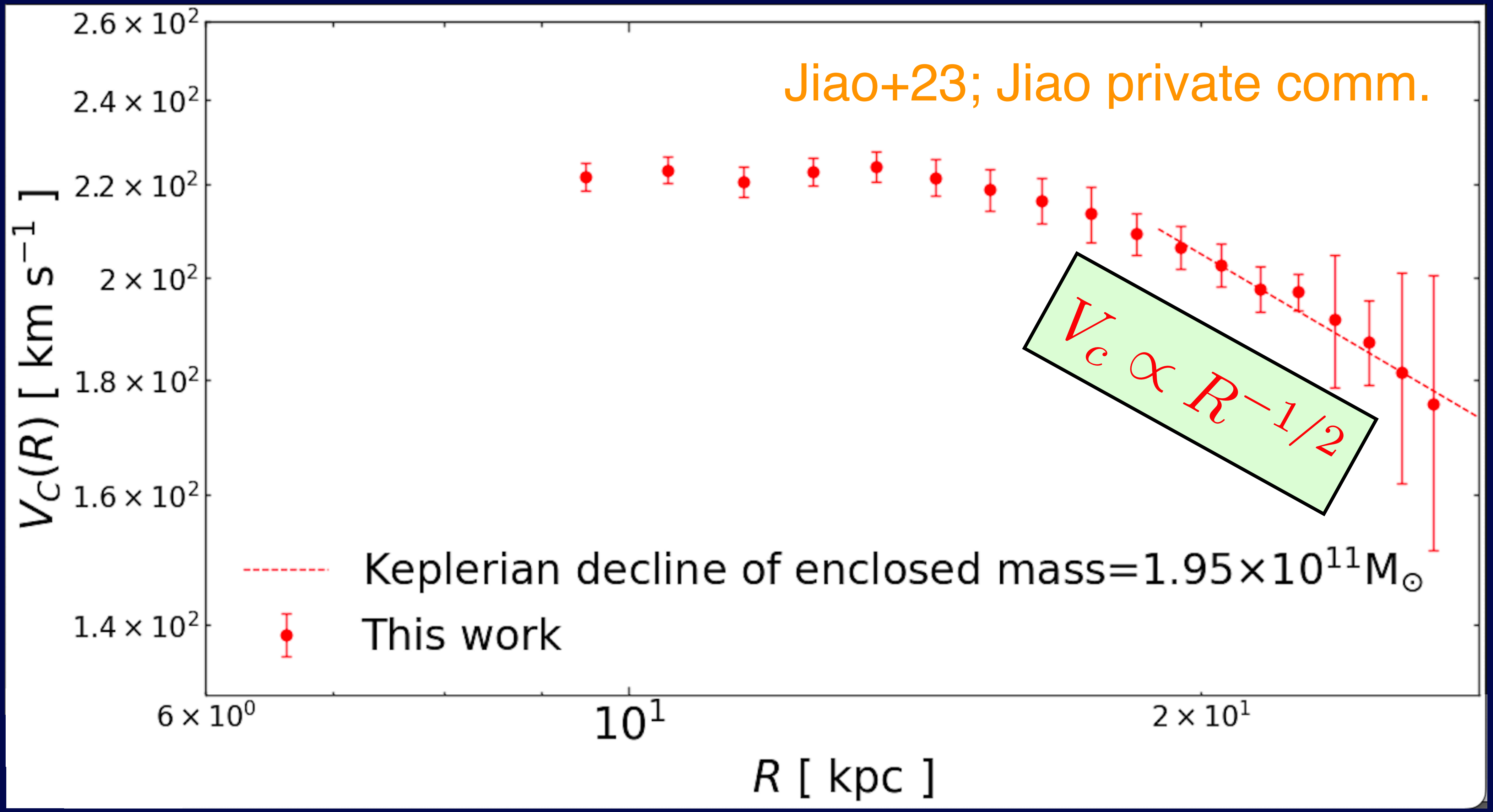
Keplerian decline of MW rotation curve

A&A 678, A208 (2023)
https://doi.org/10.1051/0004-6361/202347513

Astronomy & Astrophysics

Detection of the Keplerian decline in the Milky Way rotation curve

Yongjun Jiao[1], François Hammer[1], Haifeng Wang[2], Jianling Wang[1,3], Philippe Amram[4], Laurent Chemin[5], and Yanbin Yang[1]



Outline

Jeans equation of local dynamical equilibrium

Analysis of pseudo Milky Way galaxies in cosmological hydrodynamical simulation

Reanalysis of Milky Way data

PRELIMINARY

- Catalog
- Distances to stars
- Galactocentric frame: data and errors
- Analysis in radial bins
- Bayesian star-by-star analysis

From phase space to local space

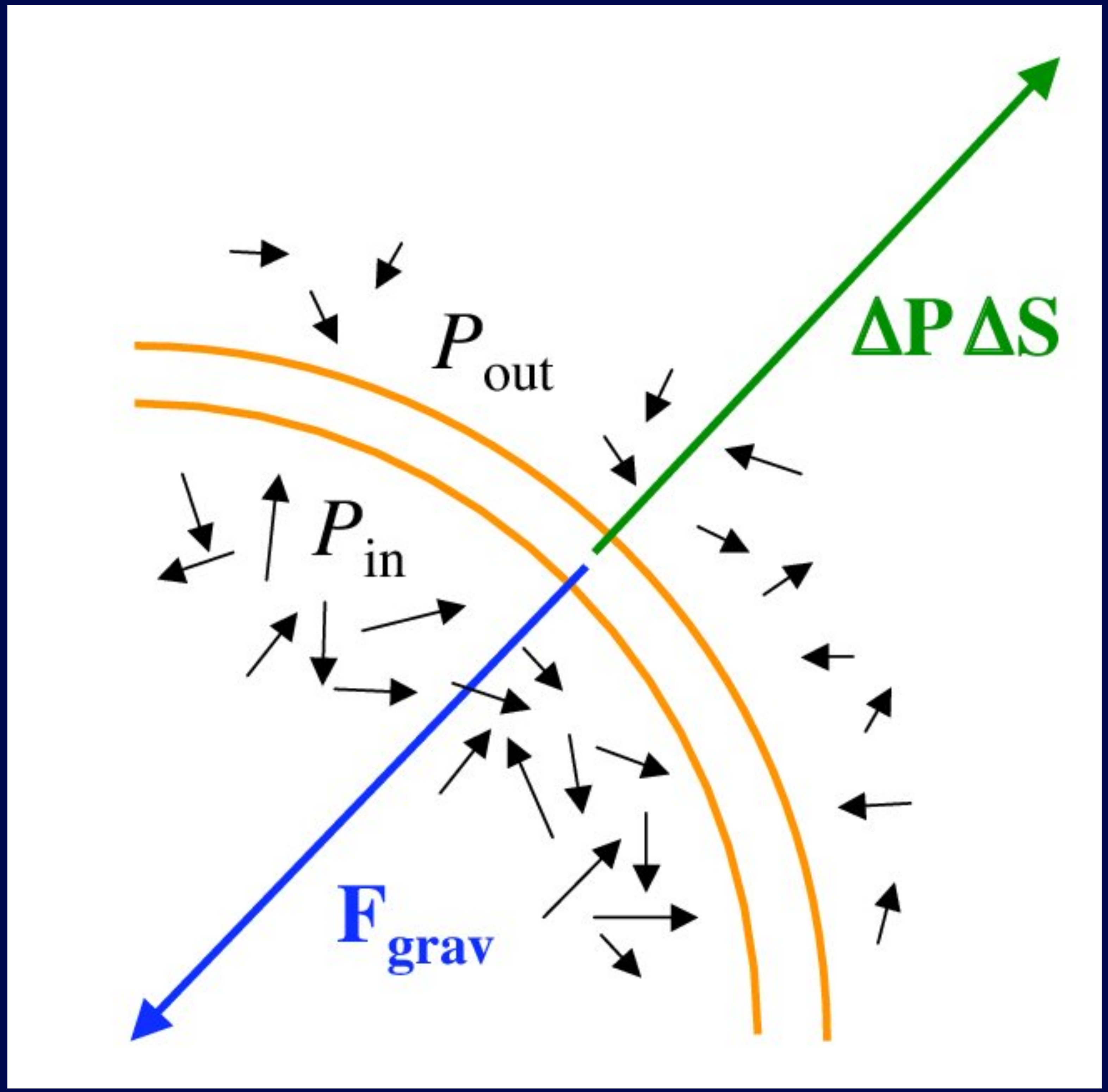
$f = f(r,v) \equiv$ distribution function = 6D phase space density

Collisionless Boltzmann Equation

incompressible 6D fluid

$$\frac{\partial f}{\partial t} + \mathbf{v}\cdot\nabla f - \nabla\Phi\cdot\frac{\partial f}{\partial \mathbf{v}} = 0$$

$$\int v_j \,\mathrm{CBE}\, d^3\mathbf{v}$$

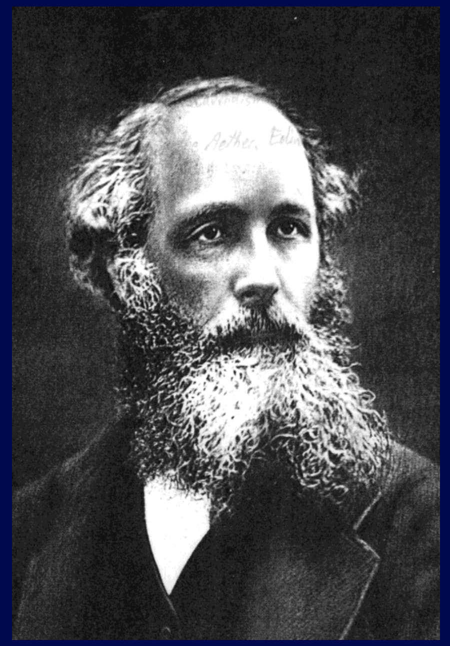


$$\nabla \cdot \boldsymbol{P} = -\nu\, \nabla\Phi$$

Jeans Equation

tracer density

$$\boldsymbol{P} = \nu\, \boldsymbol{\sigma}_v^2$$



Maxwell

Jeans

Stationary axisymmetric Jeans equation

applied to stars in disk with scale length *h*(*R*) & scale height *H*(*R*)

non-exp'l disk

flaring

$$V_c^2(R) = R\,\frac{\partial \Phi}{\partial R}\bigg|_{z\approx 0}$$

$$= \left\langle V_\phi \right\rangle^2 + \sigma_\phi^2 - \left\langle V_R^2 \right\rangle - \frac{R}{\nu}\,\frac{\partial\left(\nu\left\langle V_R^2\right\rangle\right)}{\partial R} - \frac{R}{\nu}\,\frac{\partial\left(\nu\left\langle V_R V_Z\right\rangle\right)}{\partial Z}$$

$$= \left\langle V_\phi \right\rangle^2 + \sigma_\phi^2 - \left(1 + \frac{\partial \ln \nu}{\partial \ln R} + \frac{\partial \ln \left\langle V_R^2\right\rangle}{\partial \ln R}\right)\left\langle V_R^2\right\rangle - \frac{R}{\nu}\,\frac{\partial\left(\nu\left\langle V_R V_Z\right\rangle\right)}{\partial Z}$$

$$= \left\langle V_\phi \right\rangle^2 + \sigma_\phi^2 - \left[1 - \frac{R}{h(R)} + \left(\frac{R}{h(R)}\right)^2 h'(R)\right]\left\langle V_R^2\right\rangle - R\,\frac{\partial\left\langle V_R^2\right\rangle}{\partial R} - R\,\frac{\partial\left\langle V_R V_Z\right\rangle}{\partial Z} + \mathrm{sgn}(Z)\frac{R}{H(R)}\left\langle V_R V_Z\right\rangle$$

$$= \left\langle V_\phi \right\rangle^2 + \sigma_\phi^2 - \left[1 - \frac{R}{h(R)} + \left(\frac{R}{h(R)}\right)^2 h'(R) + \frac{\partial \ln \left\langle V_R^2\right\rangle}{\partial \ln R}\right]\left\langle V_R^2\right\rangle + R\left[\frac{\mathrm{sgn}(Z)}{H(R)} - \mathrm{sgn}\left(\left\langle V_R V_Z\right\rangle\right)\frac{\partial \ln\left(\left|\left\langle V_R V_Z\right\rangle\right|\right)}{\partial Z}\right]\left\langle V_R V_Z\right\rangle$$

exponential disk approximation

no ×-term approximation

The exponential disk approximation followed by all previous studies (with too large *h*)!!

The neglect of the x-term followed by all previous studies except Koop+24!

Consequences on Dark Matter

Dark Matter mass profile analysis of 2 datasets:
TW = “This work” of Jiao+23
O23 = Ou, Eilers et al. (2024)

Einasto *scale* | Einasto *index* (low=steep outer)

Baryon model (bulge, disk)	M_{bar} [10^{11} $M_\odot$]	M_{dyn} [10^{11} $M_\odot$]		M_0 [10^{11} $M_\odot$] (Jiao+23)		h [kpc]		n	
		TW	O23	TW	O23	TW	O23	TW	O23
B2	0.616	$2.05^{+0.08}_{-0.06}$	$2.19^{+0.17}_{-0.12}$	$3.72^{+0.45}_{-0.70}$	$1.23^{+0.63}_{-0.58}$	$11.41^{+1.15}_{-1.62}$	$5.5^{+1.46}_{-1.56}$	$0.43^{+0.12}_{-0.09}$	$0.87^{+0.20}_{-0.15}$
E dJ	0.607	$1.97^{+0.09}_{-0.06}$	$2.07^{+0.15}_{-0.11}$	$3.72^{+0.36}_{-0.63}$	$1.82^{+0.64}_{-0.72}$	$12.30^{+1.10}_{-1.63}$	$7.3^{+1.46}_{-1.74}$	$0.40^{+0.13}_{-0.09}$	$0.73^{+0.18}_{-0.14}$
E J	0.603	$1.97^{+0.09}_{-0.06}$	$2.08^{+0.16}_{-0.11}$	$3.72^{+0.36}_{-0.70}$	$1.70^{+0.65}_{-0.72}$	$12.21^{+1.12}_{-1.68}$	$7.03^{+1.49}_{-1.79}$	$0.40^{+0.13}_{-0.09}$	$0.76^{+0.19}_{-0.14}$
E CM	0.589	$1.97^{+0.09}_{-0.06}$	$2.10^{+0.17}_{-0.12}$	$3.55^{+0.43}_{-0.73}$	$1.26^{+0.69}_{-0.61}$	$11.63^{+1.20}_{-1.77}$	$5.81^{+1.58}_{-1.71}$	$0.43^{+0.14}_{-0.10}$	$0.85^{+0.21}_{-0.16}$
G dJ	0.575	$1.98^{+0.09}_{-0.07}$	$2.14^{+0.17}_{-0.12}$	$3.47^{+0.51}_{-0.78}$	$1.02^{+0.64}_{-0.52}$	$11.34^{+1.28}_{-1.86}$	$4.99^{+1.52}_{-1.54}$	$0.45^{+0.15}_{-0.10}$	$0.94^{+0.21}_{-0.17}$
G J	0.571	$1.98^{+0.09}_{-0.06}$	$2.15^{+0.19}_{-0.13}$	$3.39^{+0.50}_{-0.76}$	$0.89^{+0.62}_{-0.51}$	$11.29^{+1.26}_{-1.82}$	$4.72^{+1.60}_{-1.64}$	$0.45^{+0.14}_{-0.10}$	$0.97^{+0.24}_{-0.18}$
G CM	0.557	$1.99^{+0.10}_{-0.07}$	$2.16^{+0.18}_{-0.13}$	$3.31^{+0.58}_{-0.91}$	$0.64^{+0.56}_{-0.38}$	$10.63^{+1.40}_{-2.01}$	$3.85^{+1.52}_{-1.35}$	$0.49^{+0.16}_{-0.11}$	$1.06^{+0.23}_{-0.19}$

Jiao+23 dataset → faster than Gaussian cutoff of DM density profile!

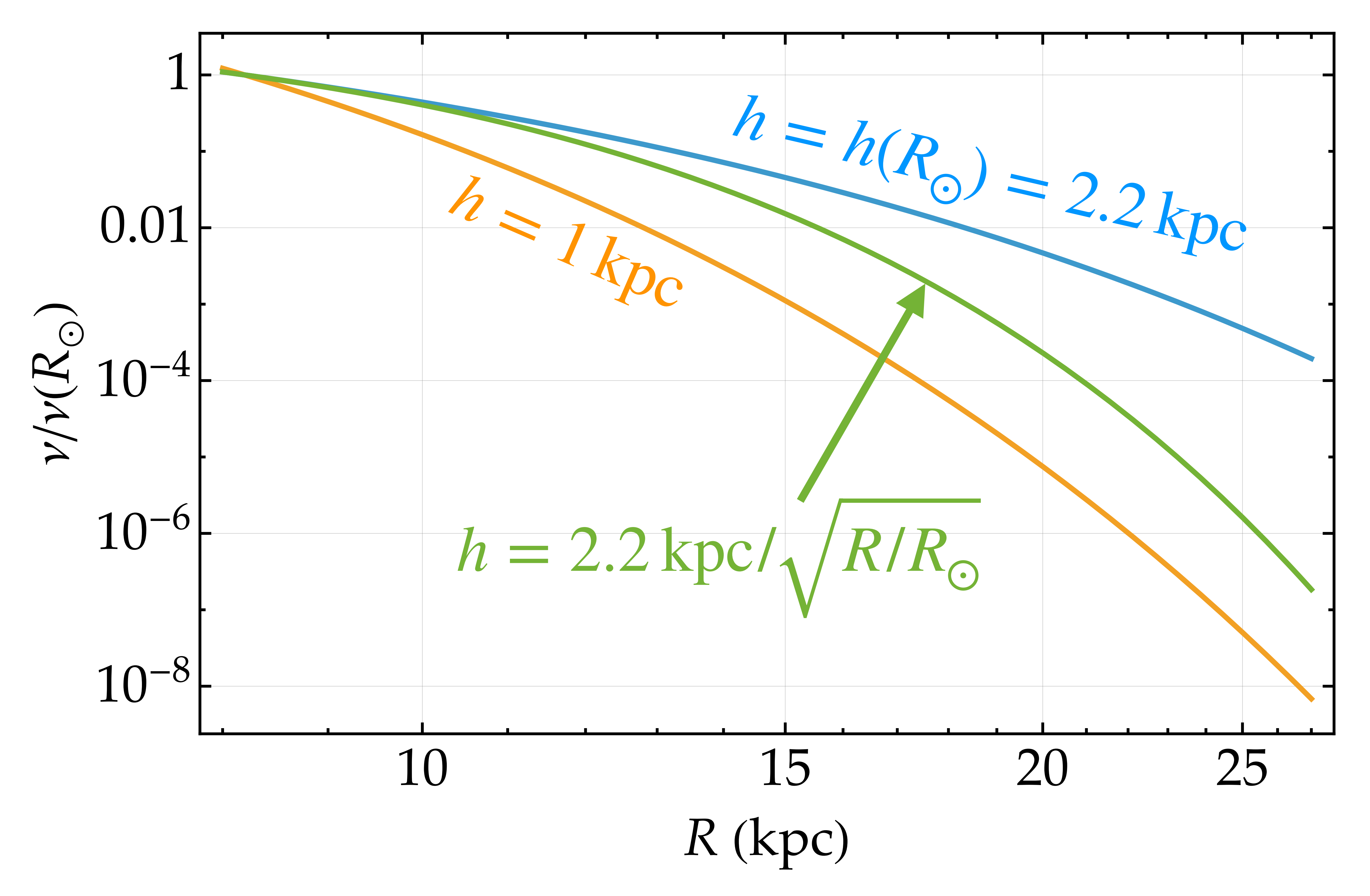
Ou+24 dataset → ~exp’l cutoff of DM density profile, w much smaller Einasto scale

back to Jeans equation

$$V_c^2(R) = \left\langle V_\phi \right\rangle^2 + \sigma_\phi^2 - \left(1 + \frac{\partial \ln \nu}{\partial \ln R} + \frac{\partial \ln \left\langle V_R^2 \right\rangle}{\partial \ln R}\right) \left\langle V_R^2 \right\rangle - \frac{R}{\nu} \frac{\partial \left(\nu \left\langle V_R V_Z \right\rangle\right)}{\partial Z}$$

$h(R) < h_{\rm ref}$ & decreases with $R \Rightarrow \dfrac{\partial \ln \nu}{\partial \ln R}$ more negative than for exponential disk

$\Rightarrow$ rotation curve decreases less rapidly than for $h(R) = h_{\rm ref}$



Explanations of keplerian outer rotation curve

Dark Matter does not exist — contradicts CMB power spectrum — Planck mission

Dark Matter is rare in massive galaxies — contradicts MW mass profile from globular clusters, streams — Watkins+19 Ibata+24

The Milky Way is special:
Tidal truncation of its outer Dark Matter
from encounter with object more massive AND very concentrated

Systematic errors in the analysis of Gaia data

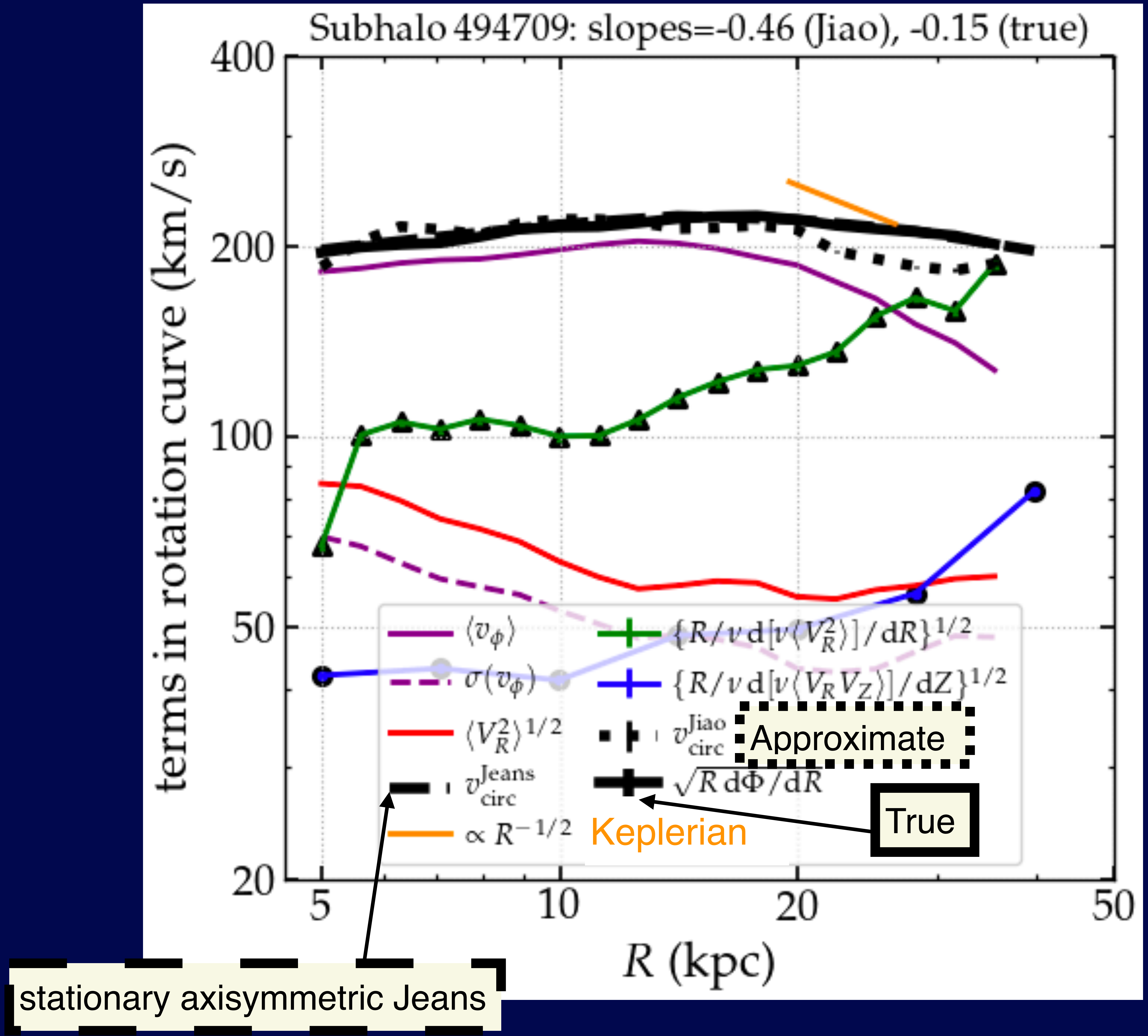
Test using cosmological hydrodynamical simulations

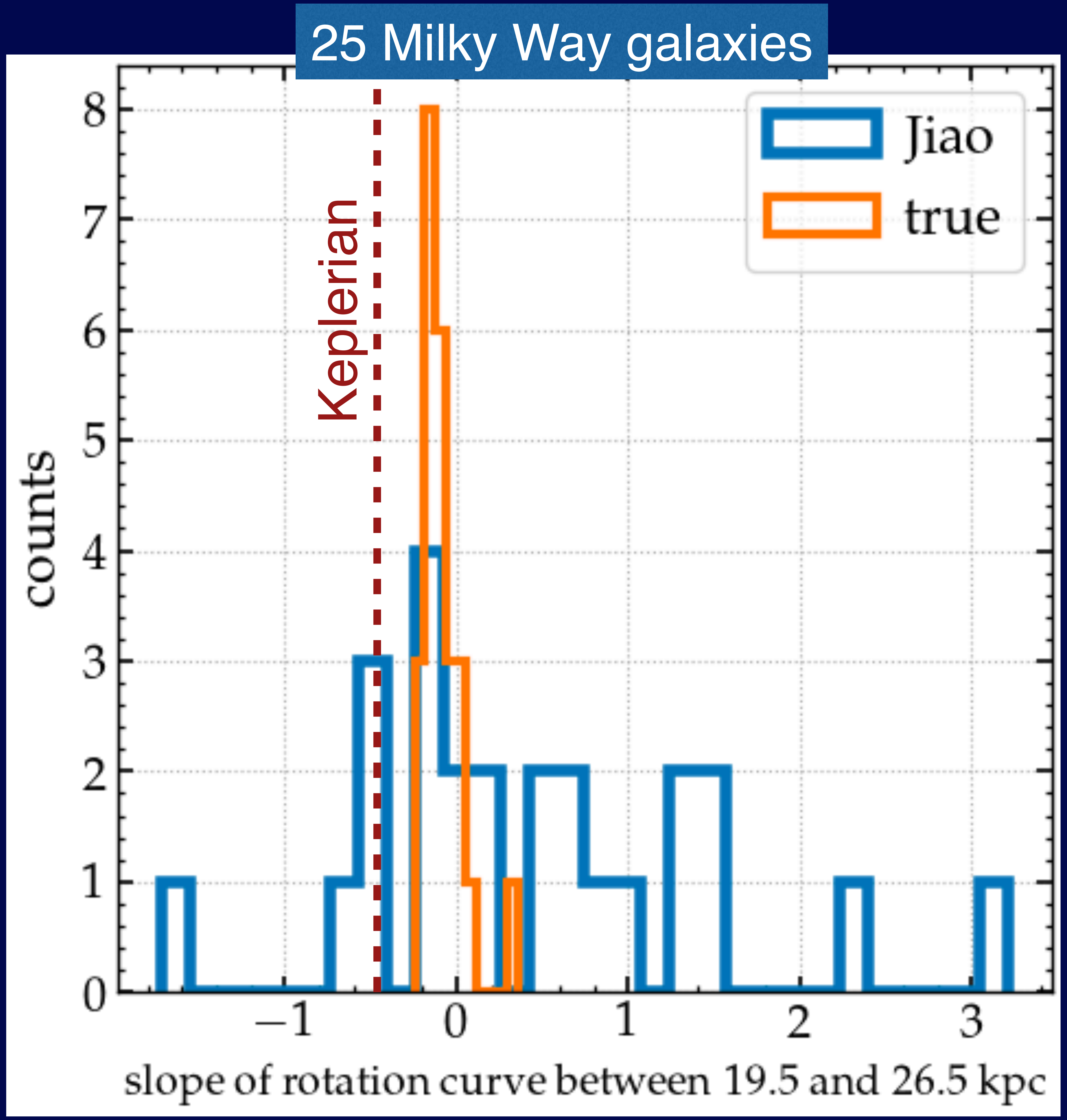
TNG50:
box size L=51 Mpc
gas resolution 70 pc
star & DM resolution 300 pc

Milky Way analogs:
$10.4 < \log(M_\star/\mathrm{M}_\odot) < 11.2$
disky: $c/a < 0.45$
central galaxies
with > 85% of halo mass

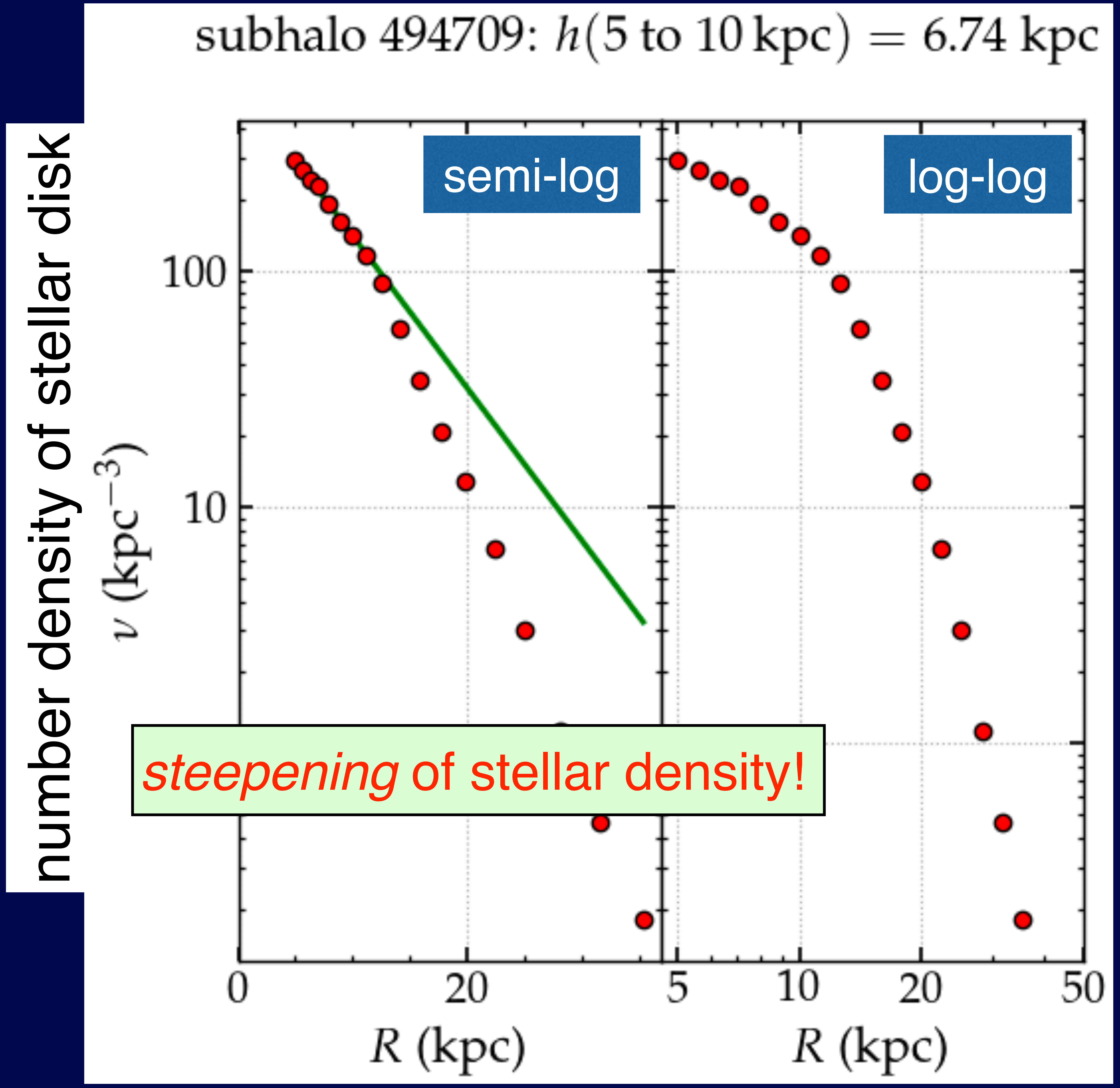
→ 129 galaxies
→ analyzed 25

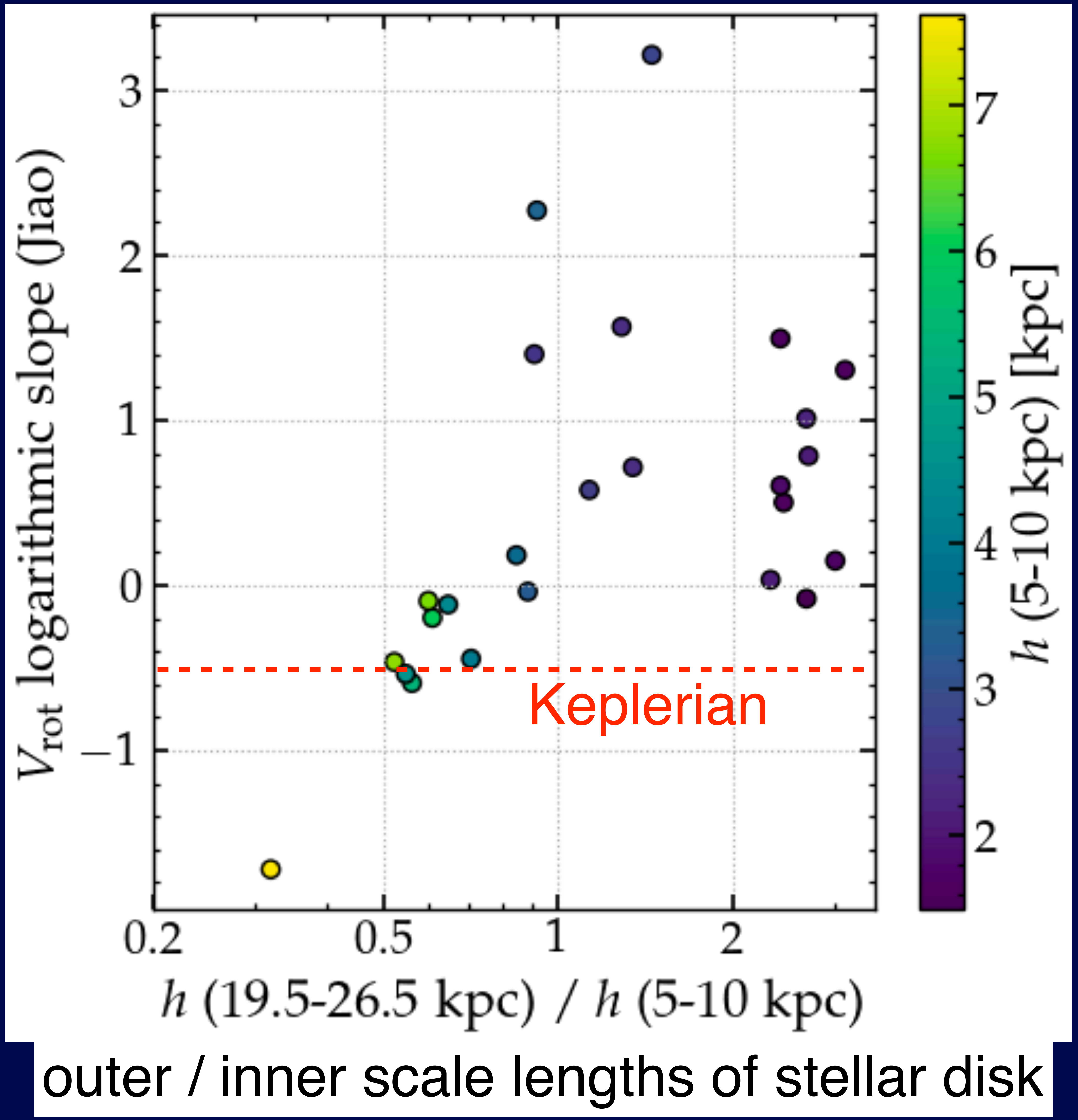
Keplerian slope in TNG50 MWs?





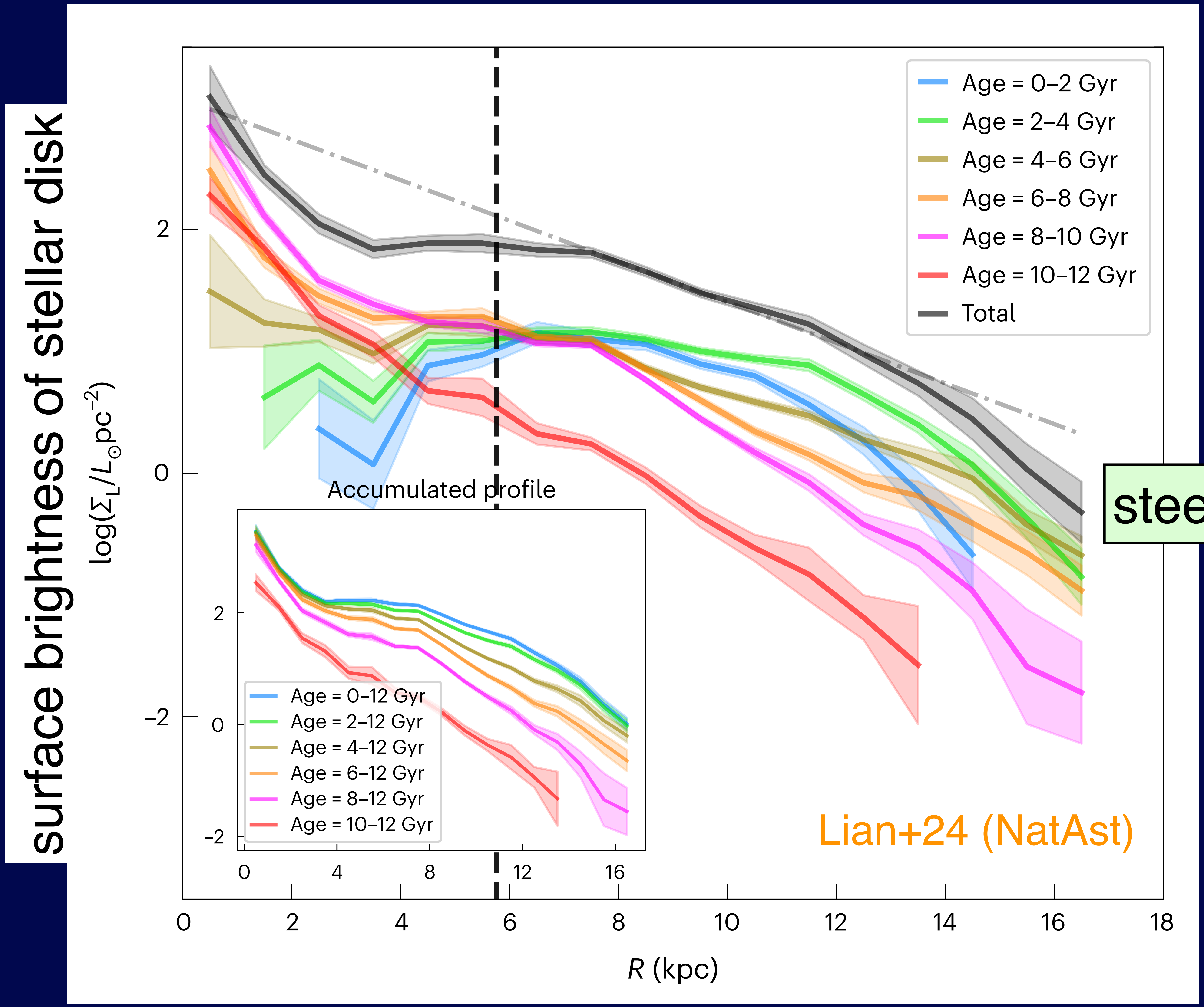
Stellar Density profiles





correlation of $V_{\rm rot}$ slope with change of slope of stellar density profile

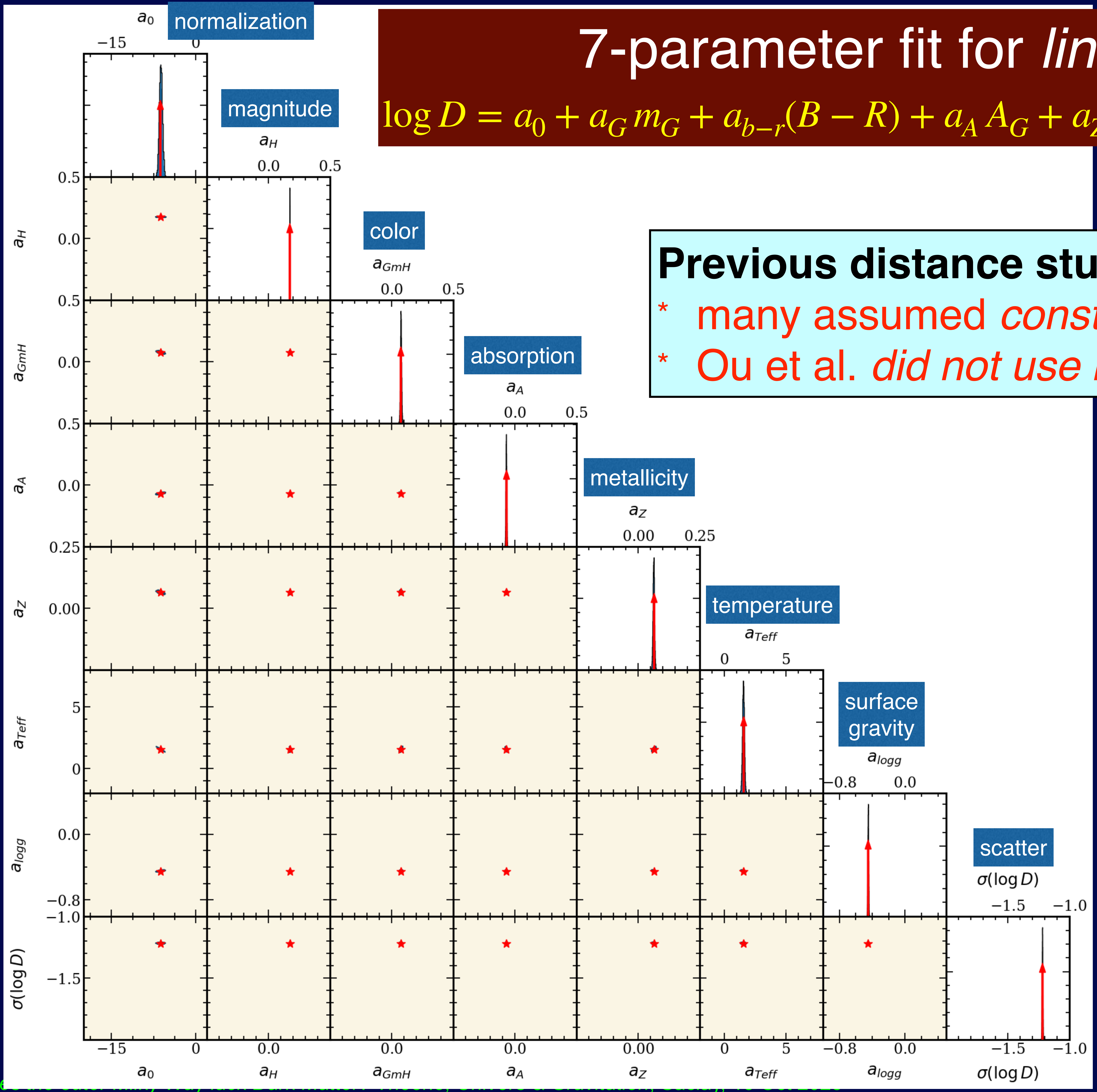
Observational evidence of steepening of exponential disk



steeper at large R!

7-parameter fit for *linear* model

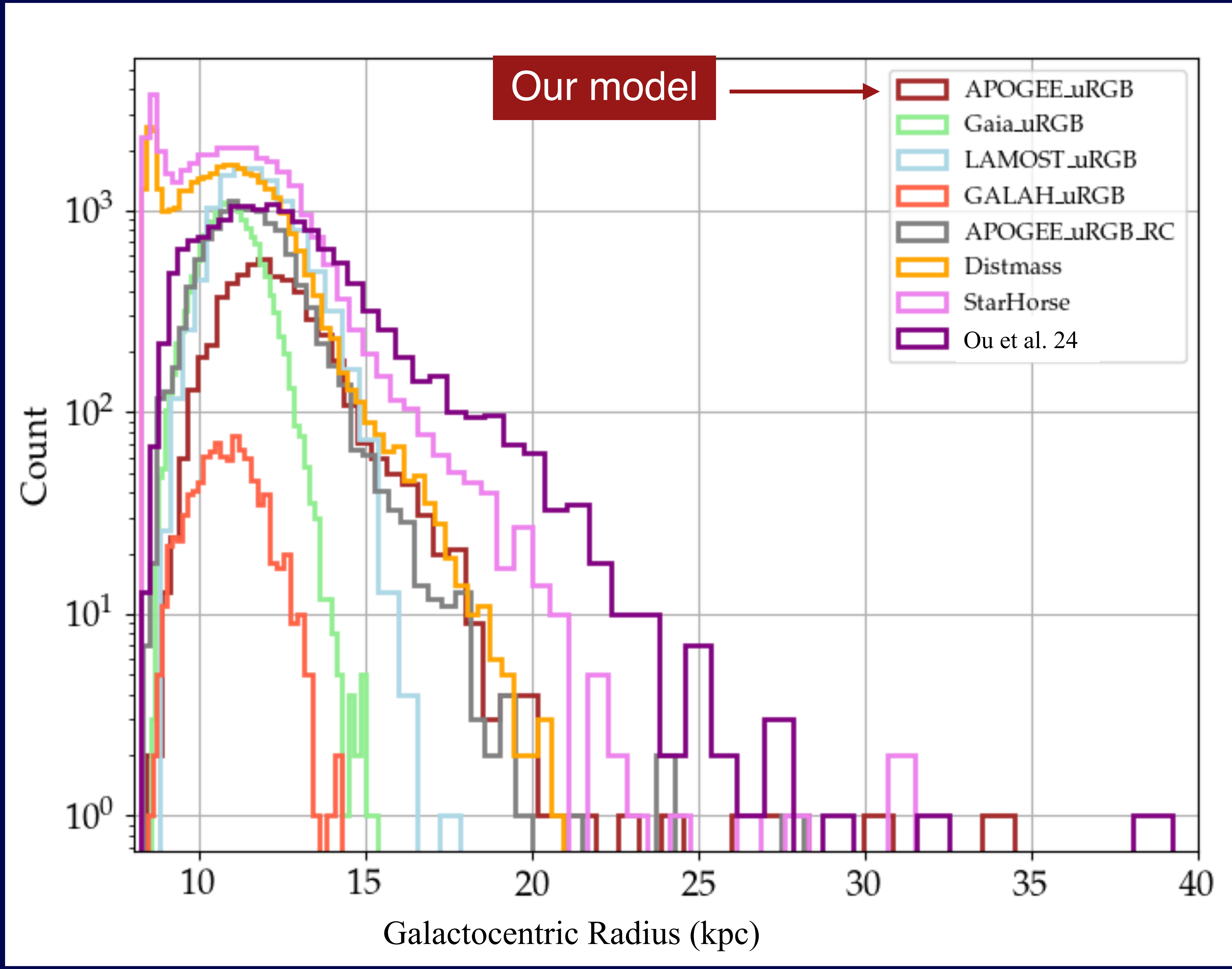
$$\log D = a_0 + a_G\, m_G + a_{b-r}(B-R) + a_A\, A_G + a_Z\,[\mathrm{M/H}] + a_T\, \log T + a_g \log g$$

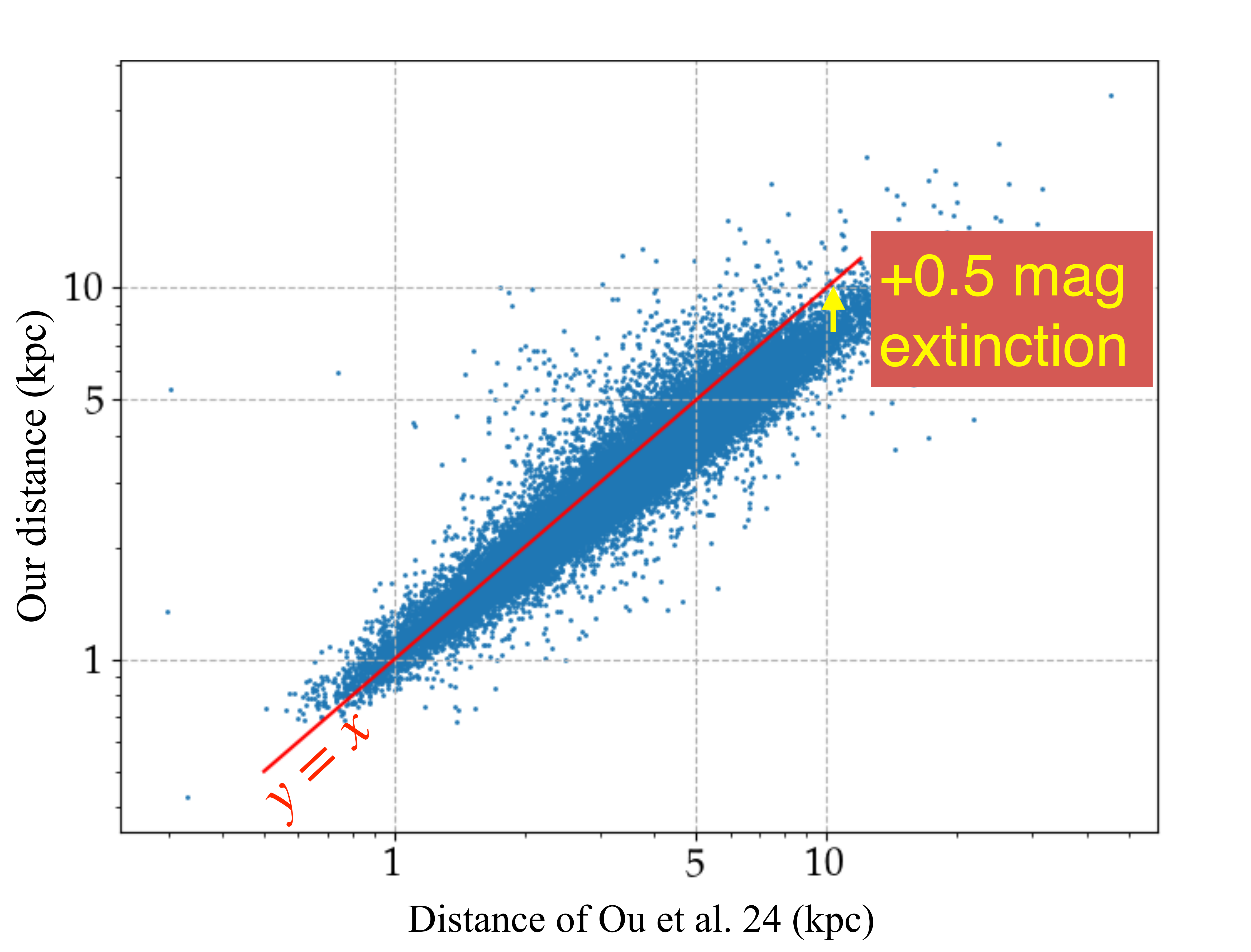


Previous distance studies:

- * many assumed *constant disk scale length*
- * Ou et al. *did not use best absorption model*

Distribution of star distances





Wide range in number of outer stars

Data	Distance model	Comments	Parallax bias correction	Dust model	Number in 19.5 - 26.5 kpc
Ou et al.	Hogg+19	On 7000+ spectral elements; all parallaxes (even < 0)	+0.017 mas	Intrinsic	**311**
APOGEE	StarHorse Anders+22	Assume exponential disk	5-parameter model Lindegren+21		**70**
APOGEE	DistMass Stone-Martinez+24	machine learning	0		**9**
APOGEE	Ours		0.017 mas	DustMap Green+18	**25**
APOGEE	Ours		5-parameter model Lindegren+21	DustMap Green+18	**25**

Equatorial → Galactocentric frame

$$P(V_R, V_\phi, V_Z) = \int \mathrm{d}^3\mathbf{V}_{\mathbf{true}} \frac{1}{(2\pi)^{3/2}\sqrt{|\mathrm{C_{GC}}|}} \exp\left[-\frac{1}{2}(\mathbf{V}-\mathbf{V}_{\mathbf{true}})^T \cdot \mathrm{C}_{\mathrm{GC}}^{-1} \cdot (\mathbf{V}-\mathbf{V}_{\mathbf{true}})\right] \exp\left[-\frac{1}{2}(\mathbf{V}_{\mathbf{true}}-\overline{\mathbf{V}}_{\mathbf{true}})^{\mathrm{T}} \cdot C_\sigma^{-1} \cdot (\mathbf{V}_{\mathbf{true}}-\overline{\mathbf{V}}_{\mathbf{true}})\right]$$

$$= \frac{1}{(2\pi)^{3/2}\sqrt{|\mathrm{C_{GC}}+\mathrm{C}_\sigma|}} \exp\left\{-\frac{1}{2}\left[(\mathbf{V}-\overline{\mathbf{V}})^T \cdot \left(\mathrm{C_{GC}}+\mathrm{C}_\sigma\right)^{-1} \cdot (\mathbf{V}-\overline{\mathbf{V}})\right]\right\}$$

$\mathrm{C_{GC}}$ = *covariance matrix* of errors in galactocentric frame

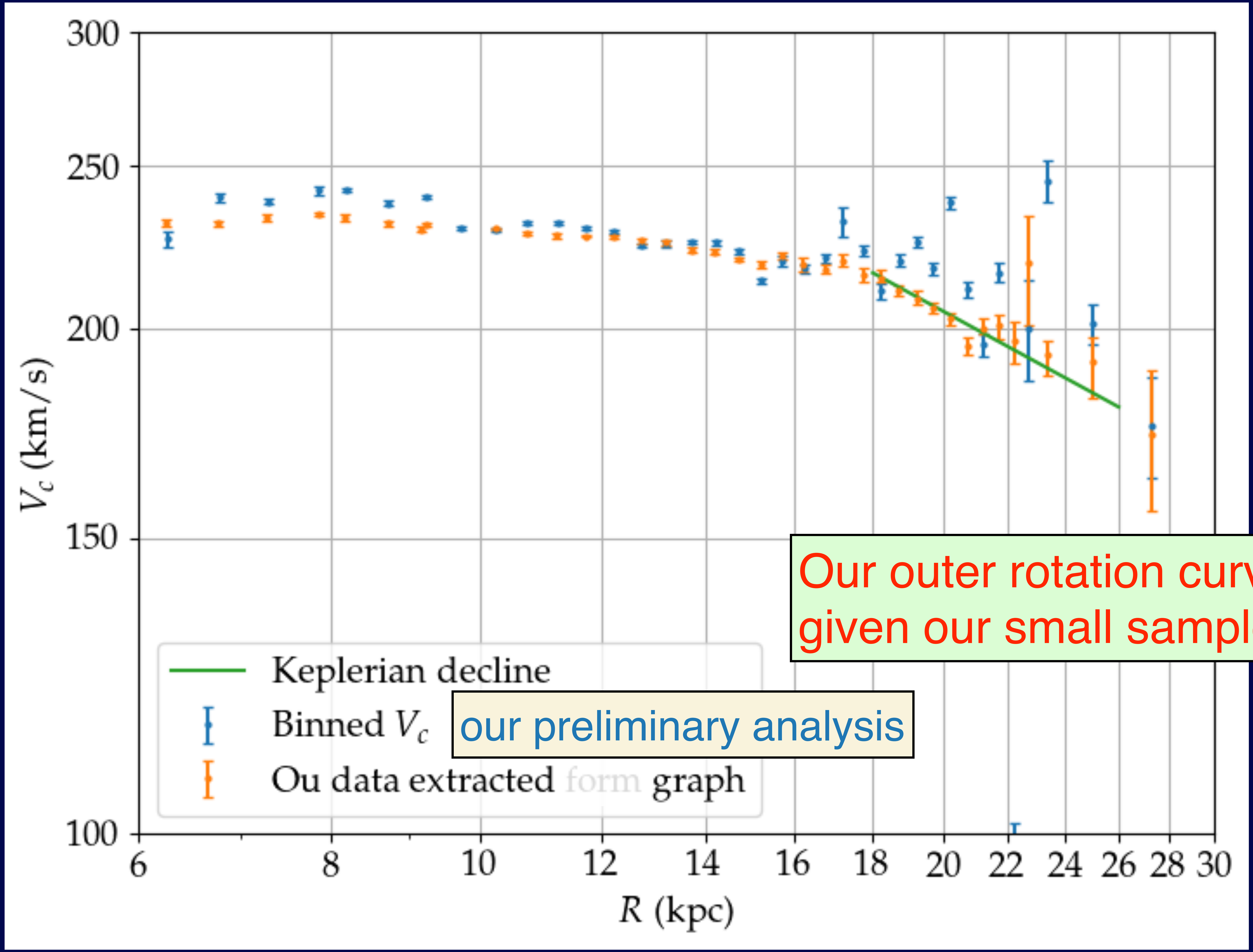
$$\mathrm{C_{GC}} = \mathrm{J}_{\mathrm{gal}\to\mathrm{GC}} \cdot \mathrm{J}_{\mathrm{eq}\to\mathrm{gal}} \cdot \mathrm{C_{eq}} \cdot \mathrm{J}^T_{\mathrm{eq}\to\mathrm{gal}} \cdot \mathrm{J}^T_{\mathrm{gal}\to\mathrm{GC}}$$

$$\mathrm{C_{eq}} = \begin{pmatrix} \epsilon^2_{\mu\alpha*} & \rho\,\epsilon_{\mu\alpha*}\,\epsilon_{\mu\delta} & 0 \\ \rho\,\epsilon_{\mu\alpha*}\,\epsilon_{\mu\delta} & \epsilon^2_{\mu\delta} & 0 \\ 0 & 0 & \epsilon^2_{\mathrm{los}} \end{pmatrix}$$

C_σ = *covariance matrix* of velocity moments

$$\mathrm{C}_\sigma = \begin{pmatrix} \sigma_R^2 & 0 & \sigma_{RZ} \\ 0 & \sigma_\phi^2 & 0 \\ \sigma_{RZ} & 0 & \sigma_Z^2 \end{pmatrix}$$

Binned rotation curve



our preliminary analysis

Our outer rotation curve is noisy, given our small sample of 25 outer stars

Conclusions

Previous analyses of Gaia data → rapidly decreasing outer rotation curve (perhaps Keplerian)
⇒ exponential or gaussian truncation of Dark Matter density profile!

Analysis of outer rotation of curves of Milky Way - like galaxies in cosm'l hydro simulation TNG50
→ Keplerian behaviour when solving Jeans eq. by fixing scale length of exponential disk,
while scale length is lower at large radii

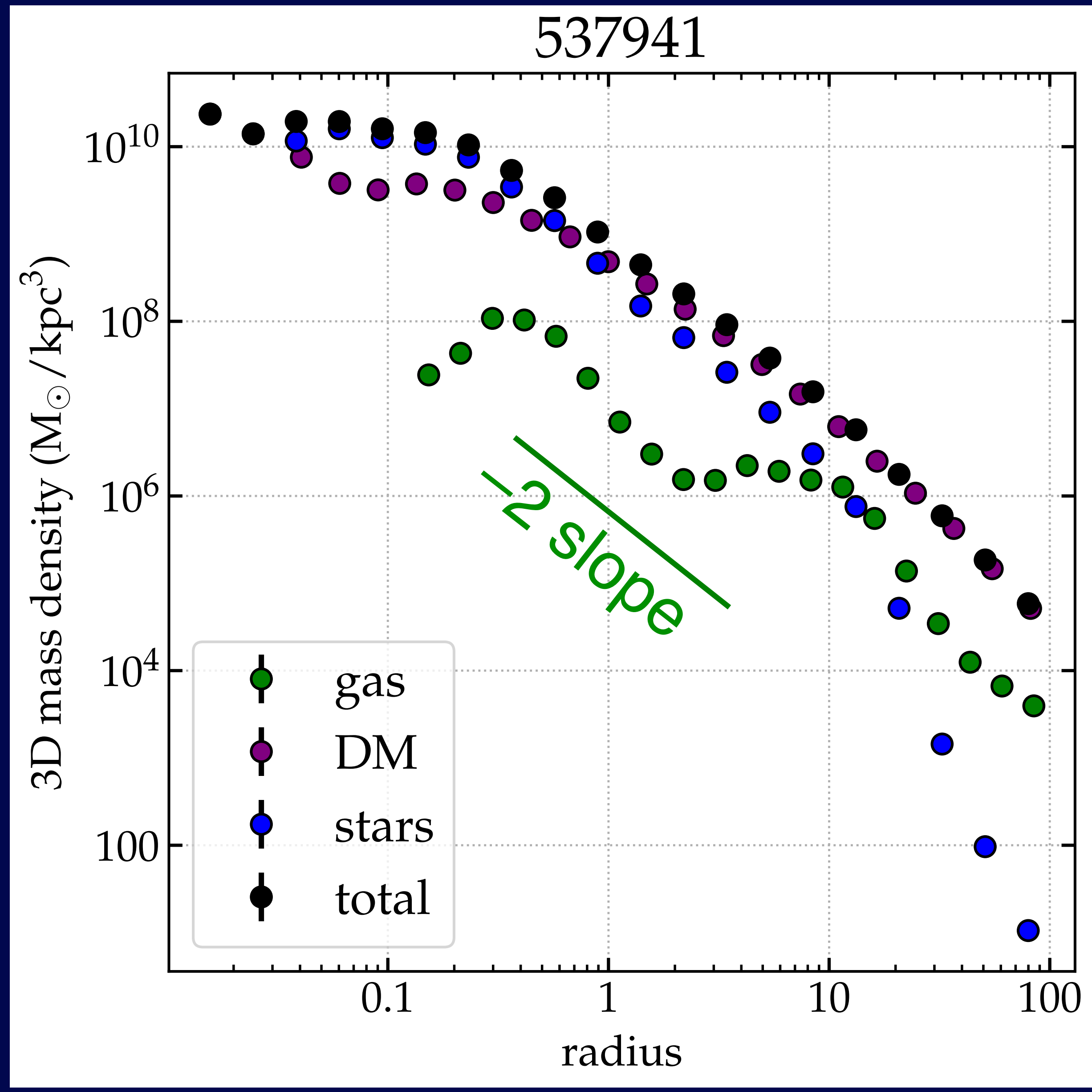
Besides stellar density profile of disk, issues are:

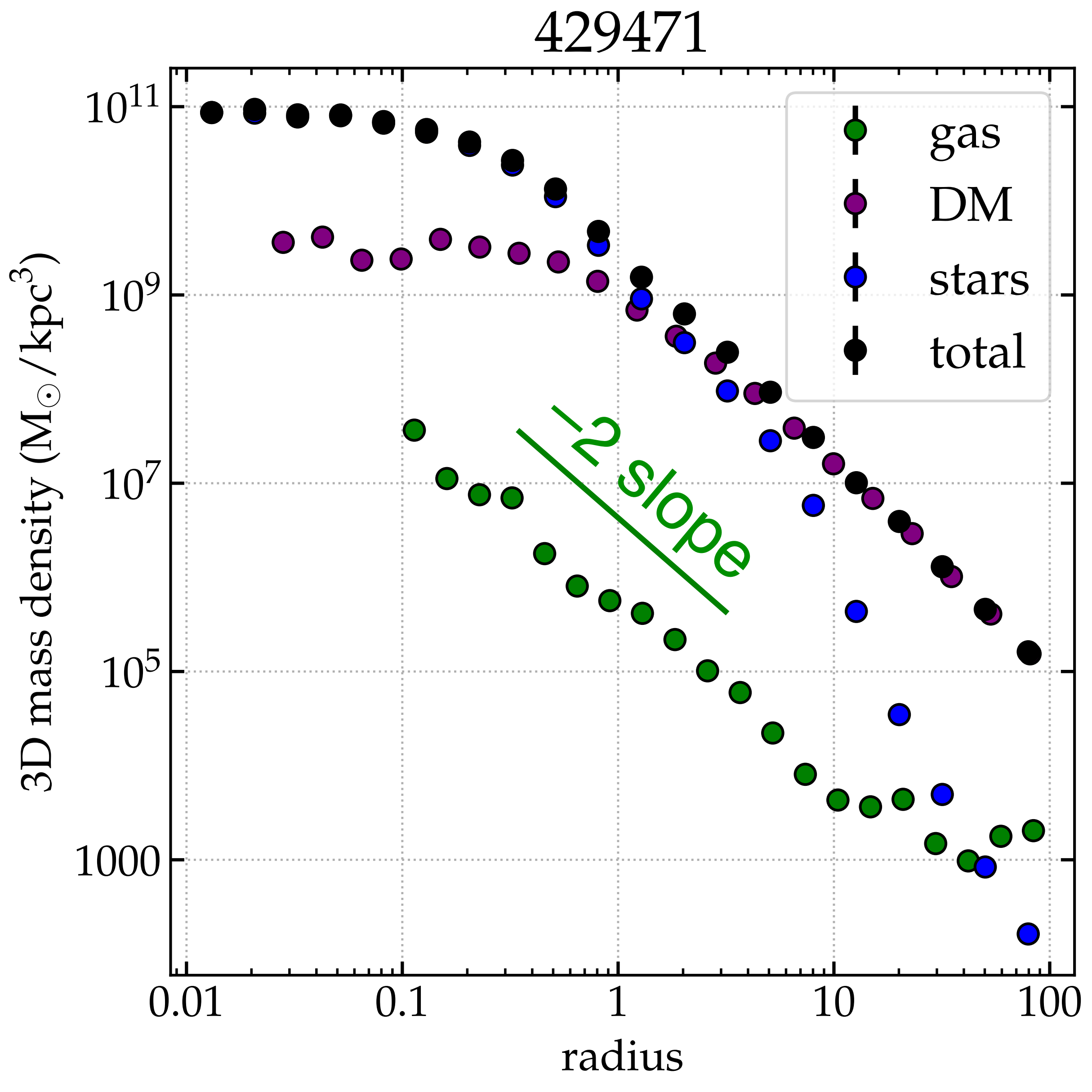
* very ≠ distances to stars between teams (modeling & *dust extinction* to stars)
  → 9 to 311 stars in range of galactocentric radii
* uncertain *bias* in Gaia astrometric parallaxes (used for refined distance modeling)
* possible *warp* in disk: increasing warp inclination ⇒ steeper outer rotation curve

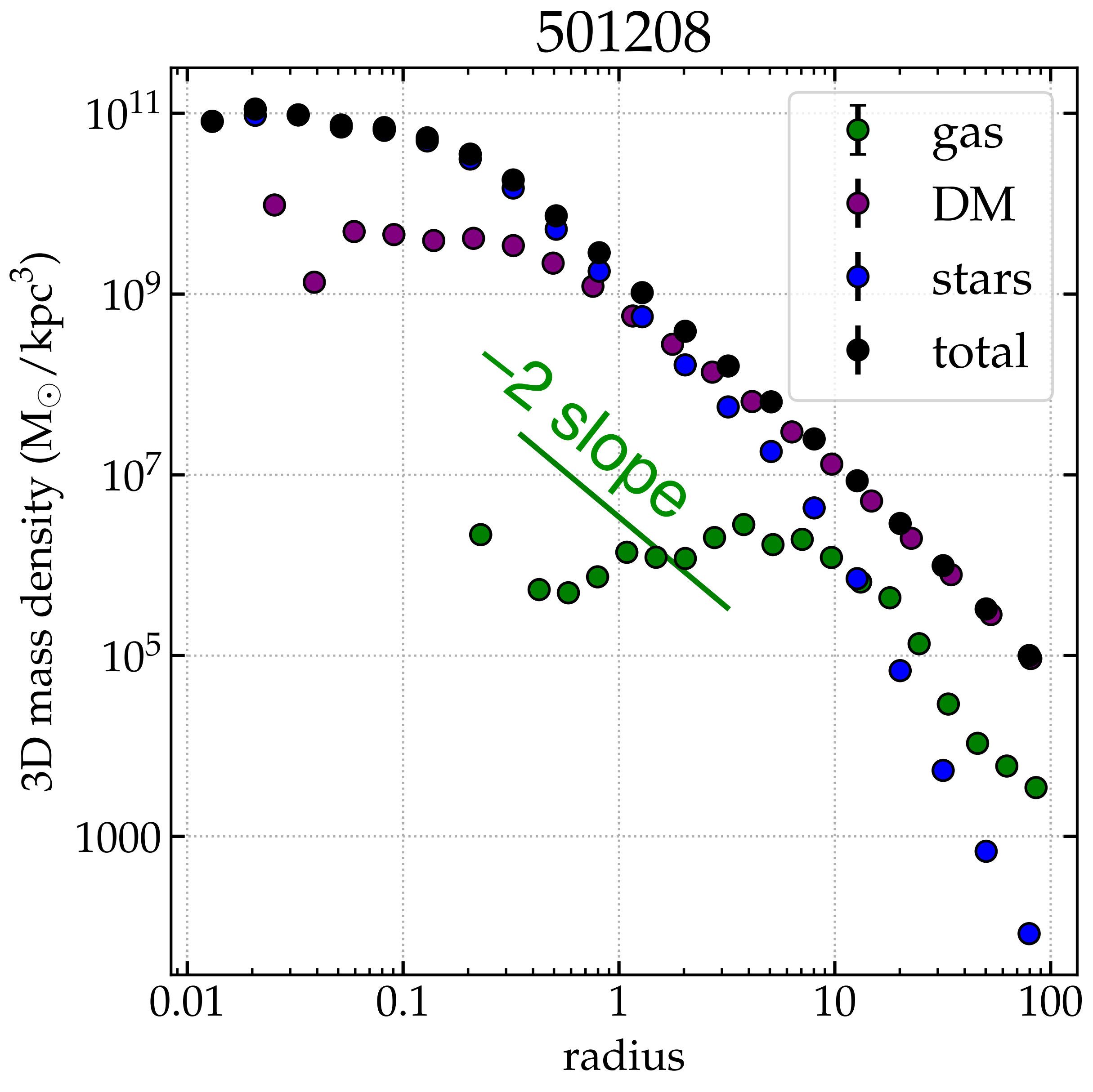
Too early to lose sleep over Dark Matter!

Extra slides

Keplerian outer rotation curves?

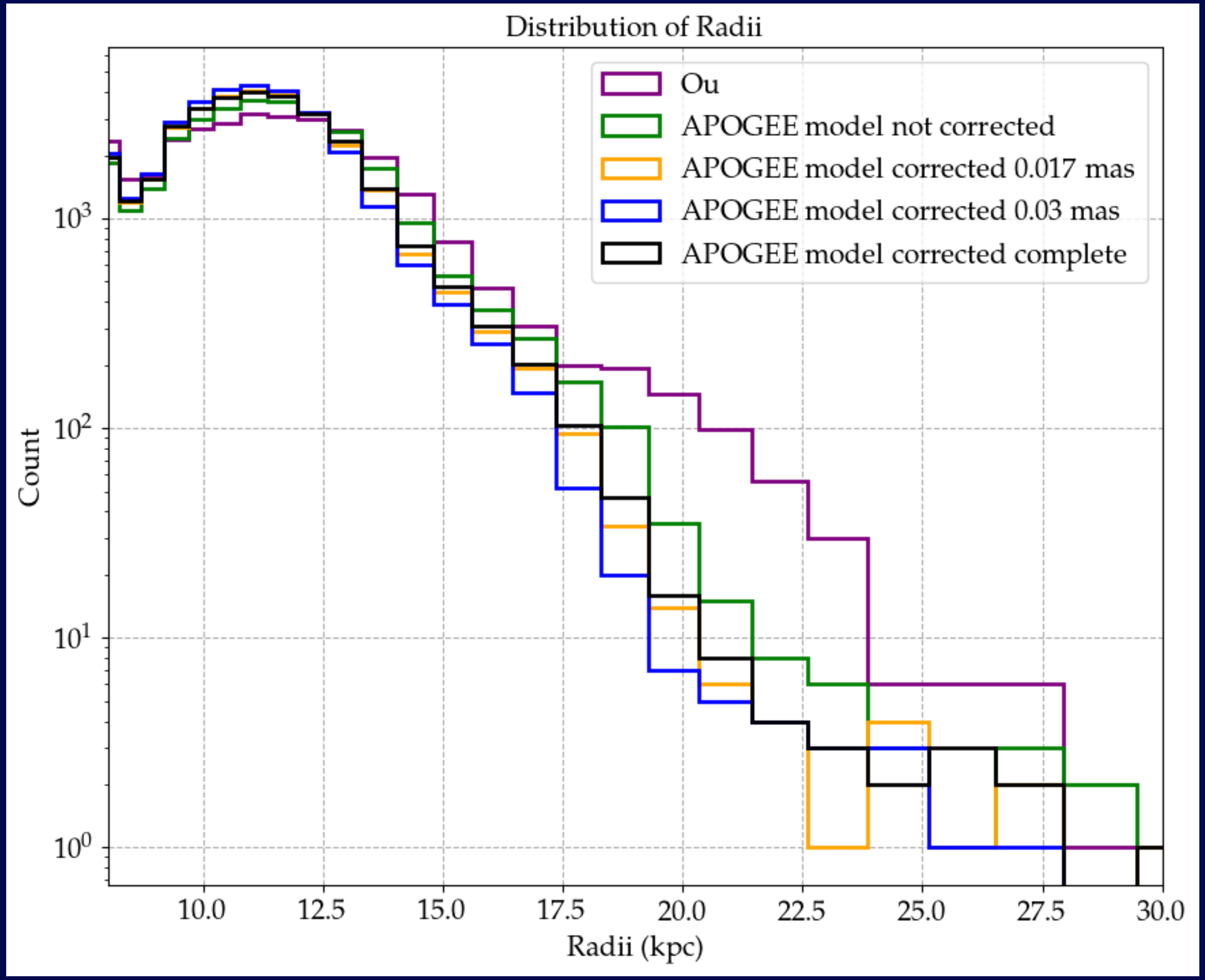


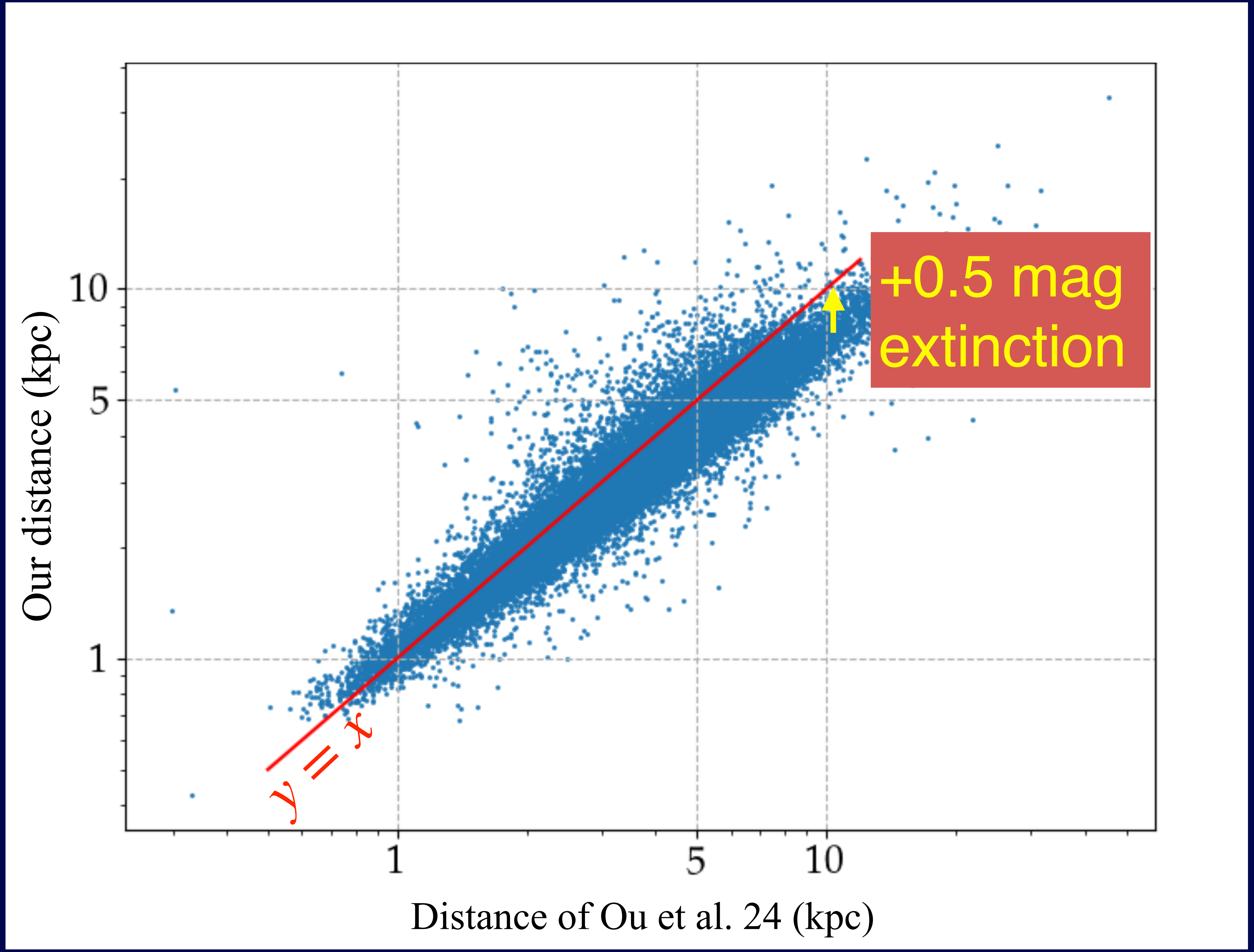




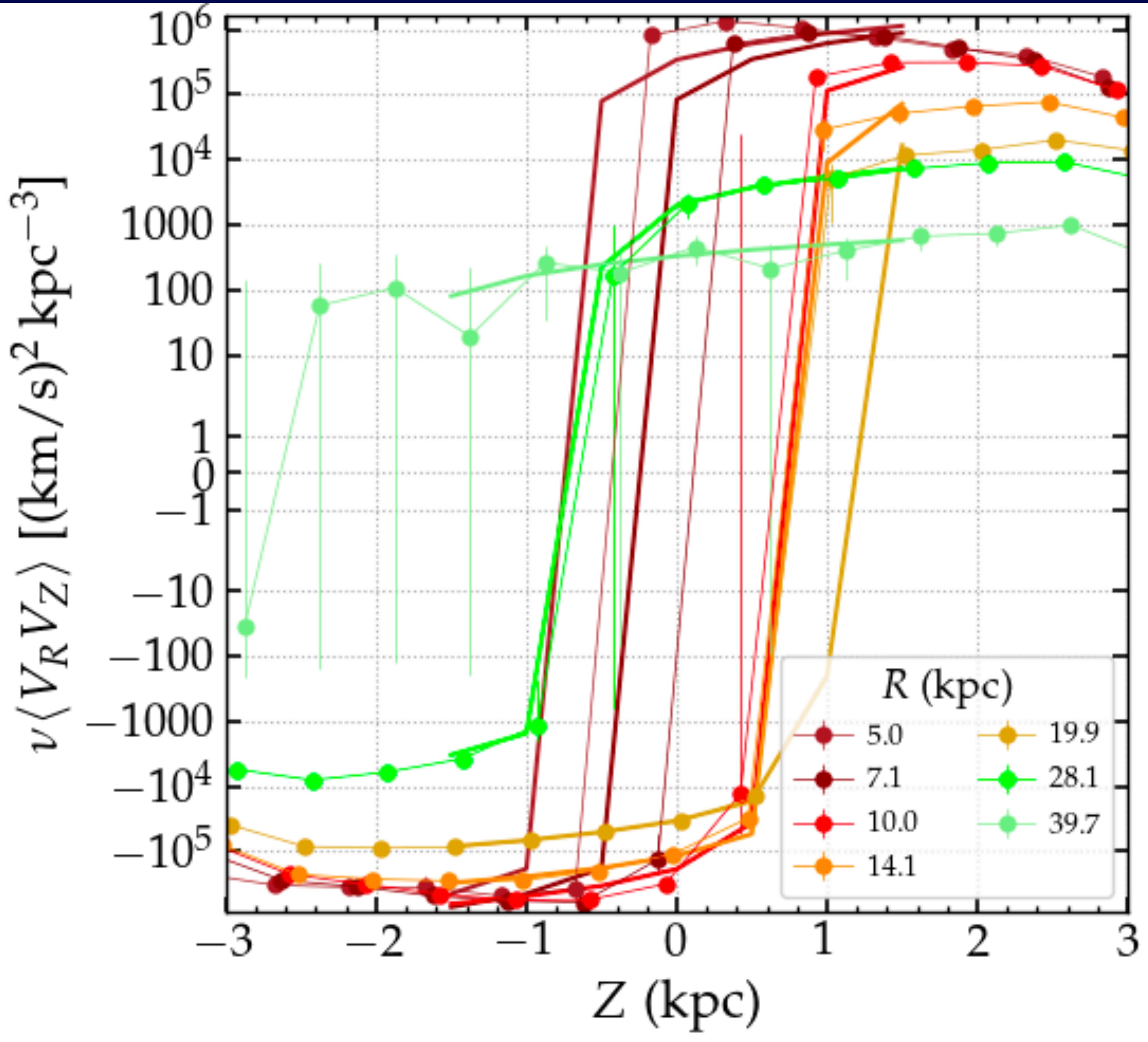
simulated MWs: –2 slope 3D density profiles in very wide range of radii encompassing where MW rotation curve appears to be keplerian

Distribution of star distances



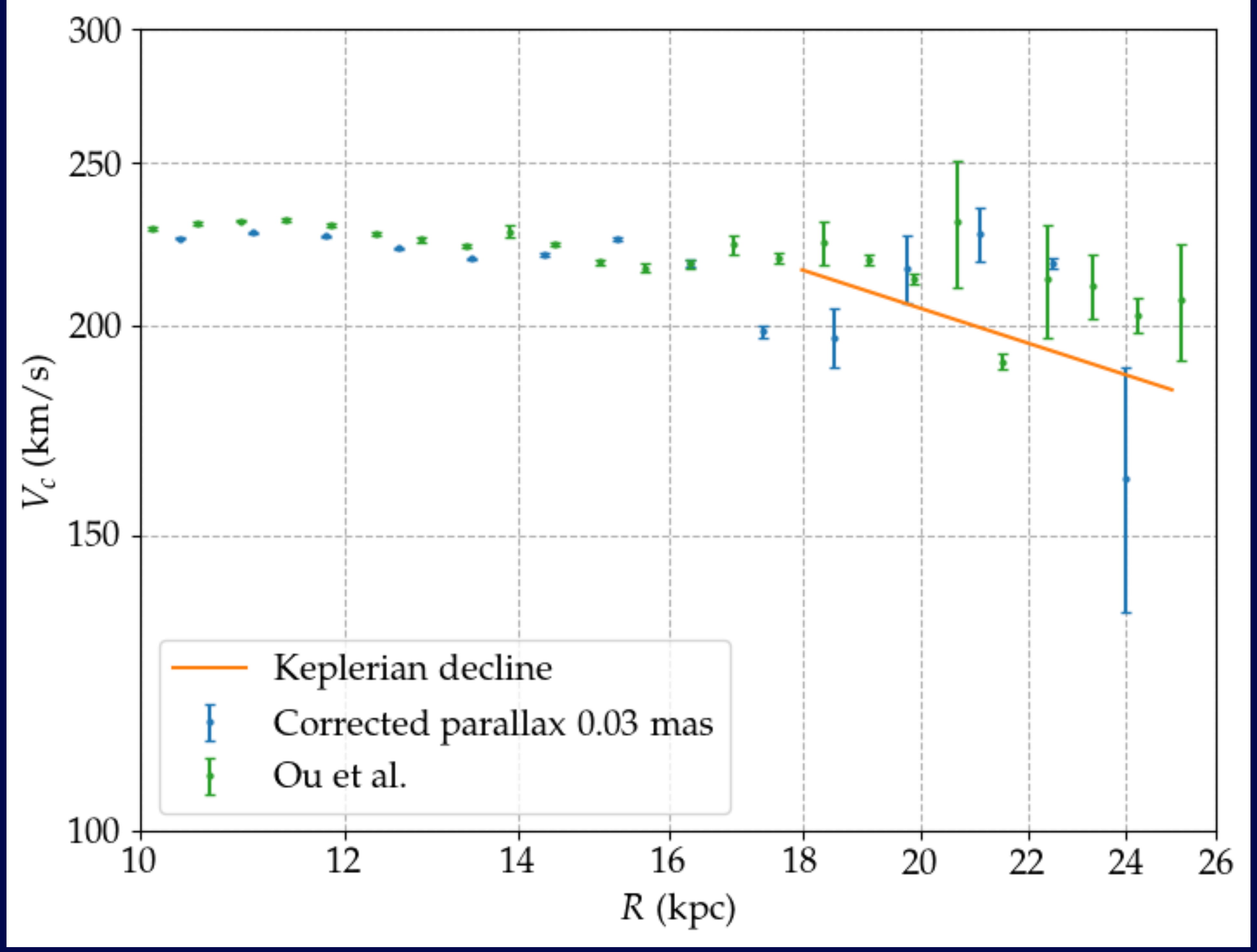


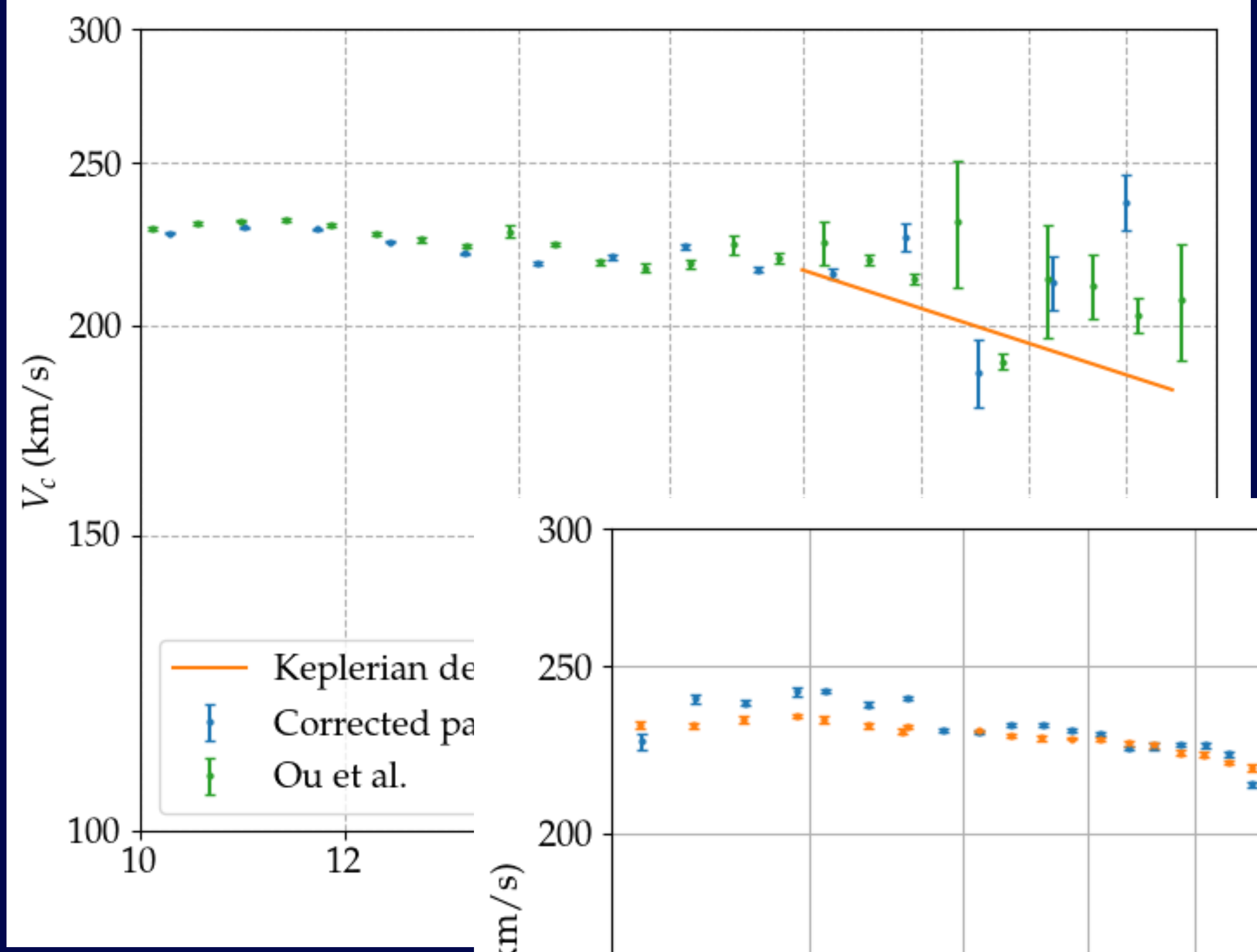
Cross term

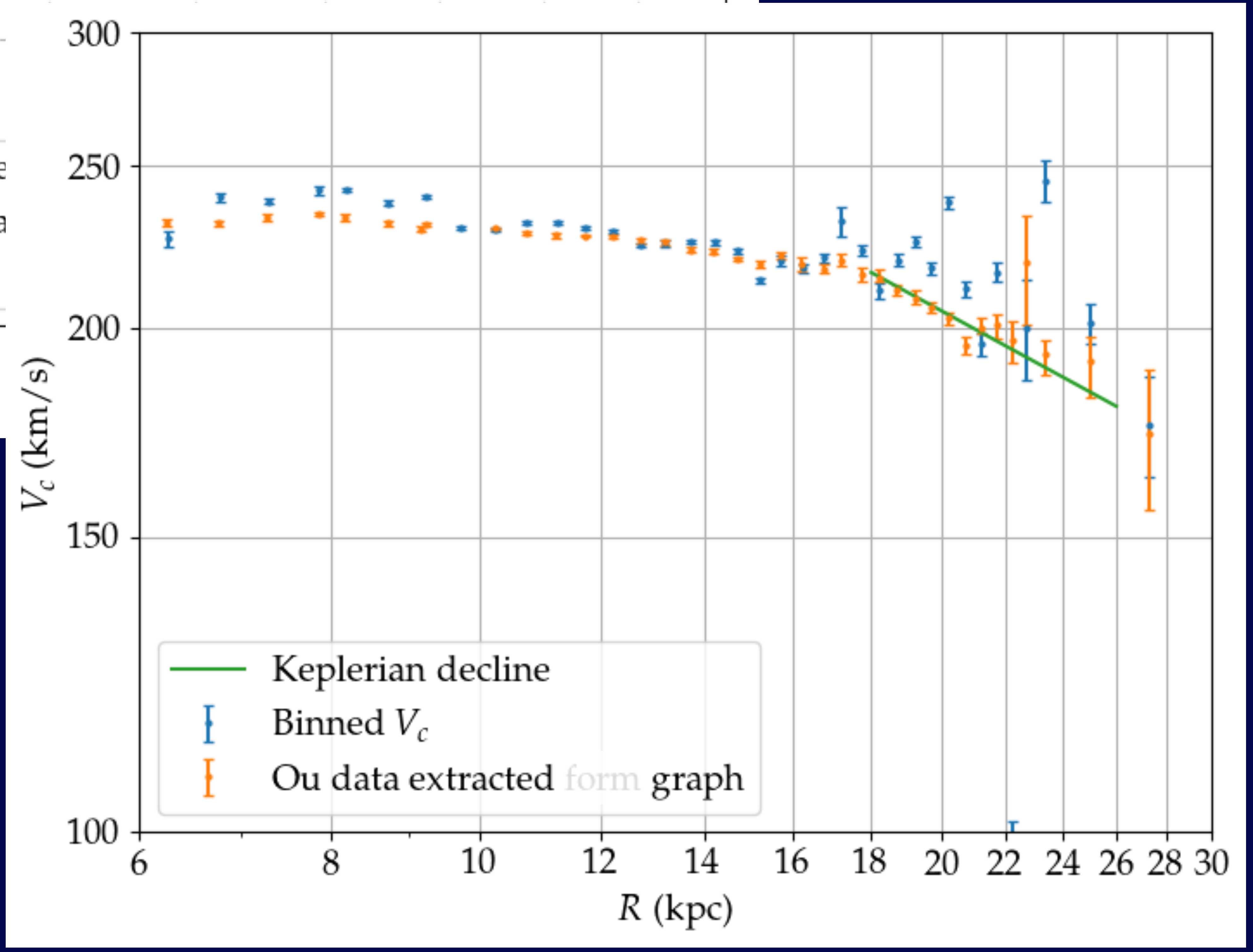


non-zero *Z*-derivative, but could be small

Robustness to parallax bias







Bayesian analysis

with possible improvements following what Giacomo wrote

Posterior — Likelihood — Priors

$$\mathcal{P}(\mathrm{Model}\,|\,\mathrm{Data}) = \mathcal{L}(\mathrm{Data}|\mathrm{Moments},\mathrm{Scales}) \times \pi(\mathrm{Moments}\,|\,R)\,\pi(\mathrm{Scales}\,|\,R)\,\pi(V_\mathrm{c}\,|\,R) \times p(R\,|\,D_\mathrm{obs})$$

Gaussians

Power-Laws

Moments: velocity moments: $\sigma_R, \sigma_\phi, \sigma_Z, \sigma_{RZ}$

Scales:
disk scale length: $h(R)$
disk scale height: $H(R)$

$$\mathscr{L} = \prod_i p(\mathrm{Data}_i\,|\,\mathrm{Model})$$

$$\Rightarrow -\ln \mathscr{L} = -\sum_i \ln p(\mathrm{Data}_i\,|\,\mathrm{Model})$$

Markov Chain Monte Carlo (MCMC):
posterior from jumps in parameter space according to $\ln \mathscr{L}(\mathbf{M}_i) - \ln \mathscr{L}(\mathbf{M}_{i-1})$