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Detection of the Keplerian decline in the Milky Way rotation curve

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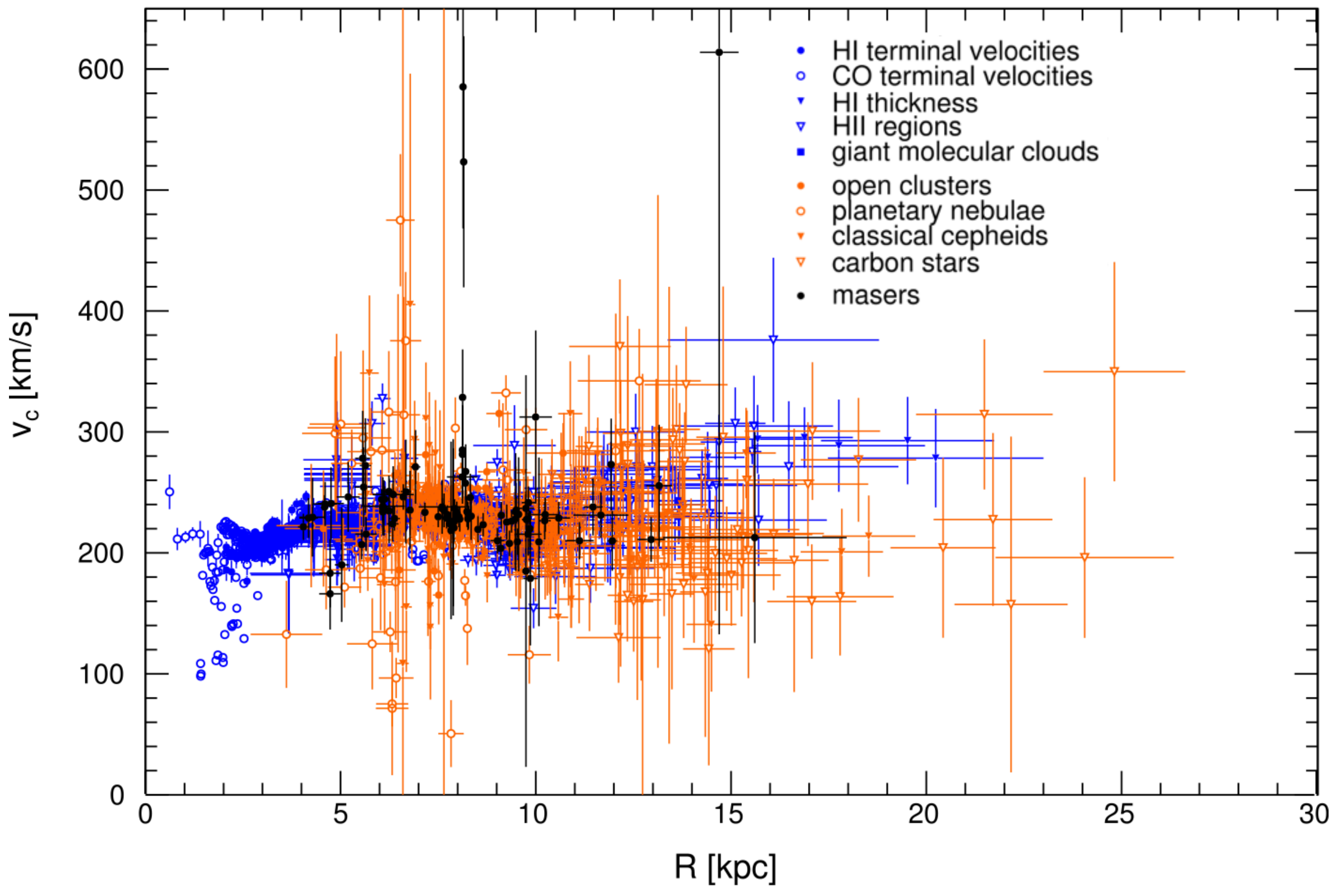
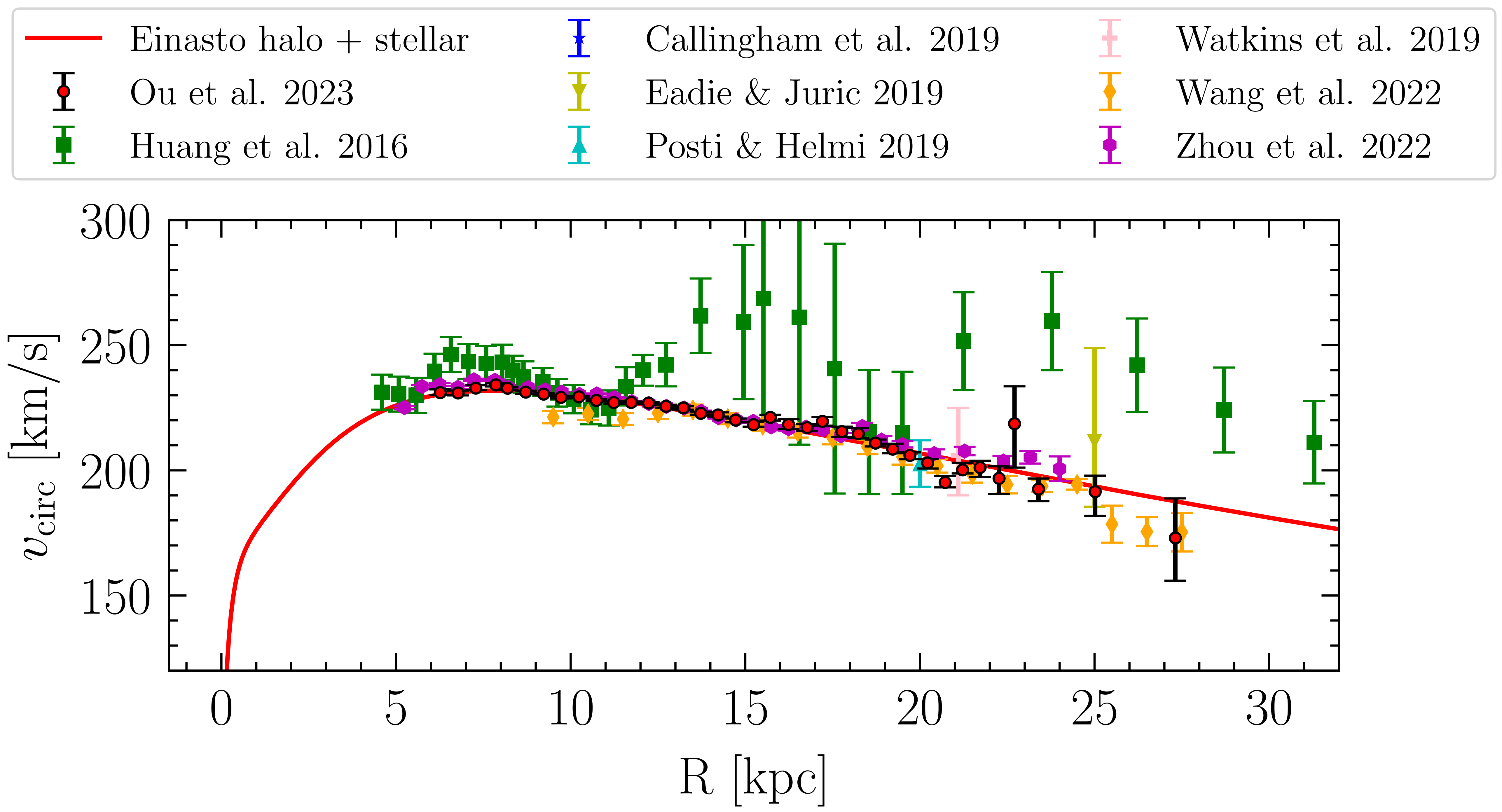
The revolution of Gaia

Comparison of Milky Way (MW) rotation curve (RC) before and after *Gaia*



MW RCs using different tracers (Pato et al. 2016)



Comparison of MW RCs from *Gaia* (Ou et al. 2023)

The *Gaia* mission provides us with the **6D coordinates** of stars with unprecedented precision.

- 3D Positions
  - Sky coordinate
  - Distance (*Gaia* parallax)
- 3D Velocities
  - Proper motion (*Gaia* proper motion)
  - Line-of-sight velocity (*Gaia* Radial Velocity Spectrometer)

From *Gaia* DR 2 to DR 3

- The number of stars (down to $G_{\mathrm{RVS}} = 14$ mag) that have combined radial velocities increases 7 224 631 -> 33 812 183
- Proper motion uncertainty is divided by ~2
- Parallax uncertainty is divided by ~1.3

Three measurements of the rotation curve based on Gaia DR3

Correction of the **asymmetric drift** (AD) to obtain V_C from V_ϕ for an **axisymmetric** and **equilibrium** disk using **Jeans equation**:

$$\frac{\partial \nu \langle V_R \rangle}{\partial t} + \frac{\partial \nu \langle V_R^2 \rangle}{\partial R} + \frac{\partial \nu \langle V_R V_z \rangle}{\partial z} + \nu \left(\frac{\langle V_R^2 \rangle - \langle V_\phi^2 \rangle}{R} + \frac{\partial \phi}{\partial R} \right) = 0$$

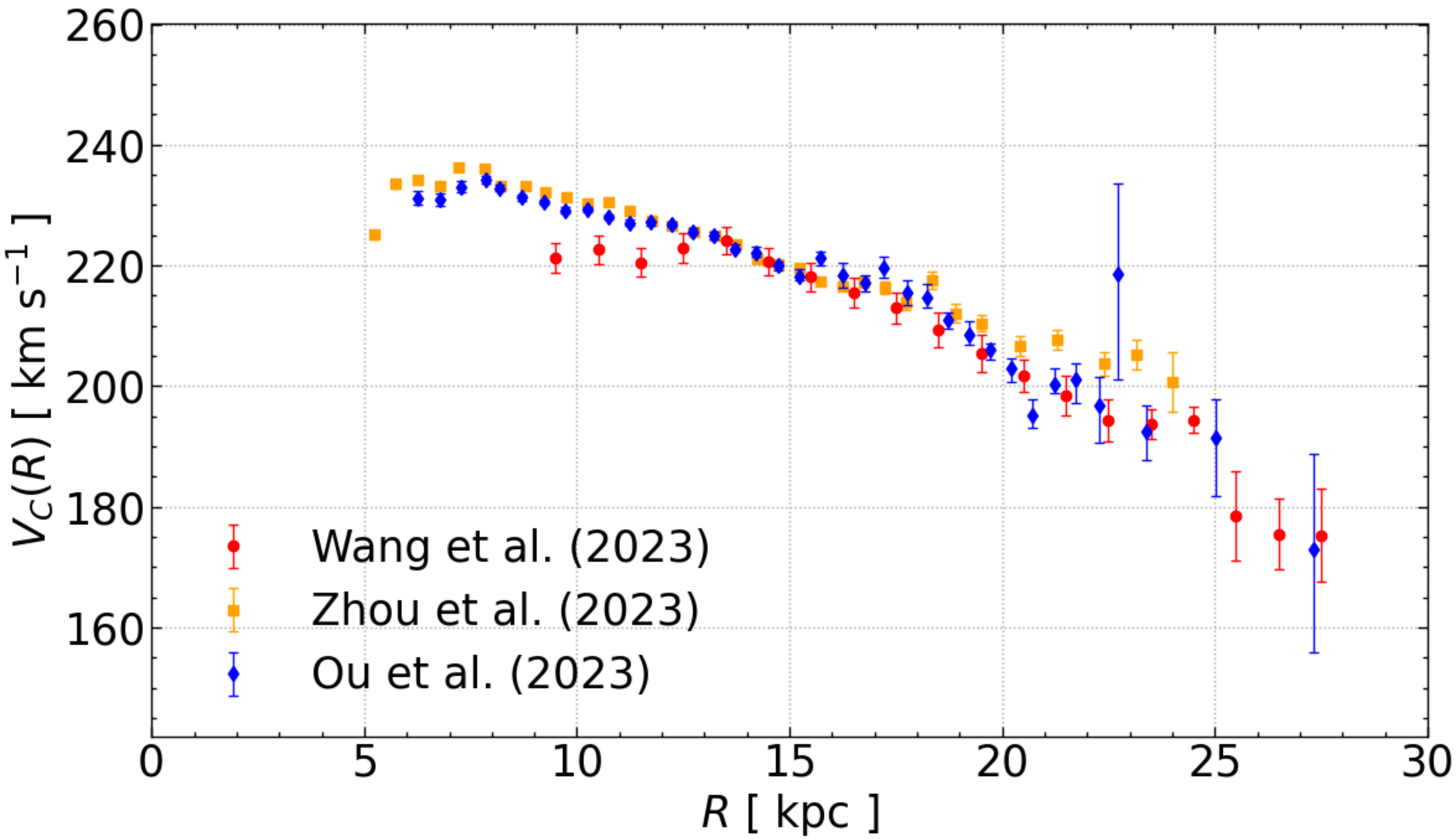
Assumptions in previous works:

- Time-independent
  $\partial \nu \langle V_R \rangle / \partial t = 0$
- Exponential radial density profile of tracers (disk)
  $\nu(R) \propto \exp(-R/R_{\rm exp})$
- Neglect vertical gradient of cross-term $\langle V_R V_z \rangle$

The **circular velocity** V_C is derived:

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

V_ϕ: azimuthal velocity V_z: vertical velocity
V_R: radial velocity ν: density distribution

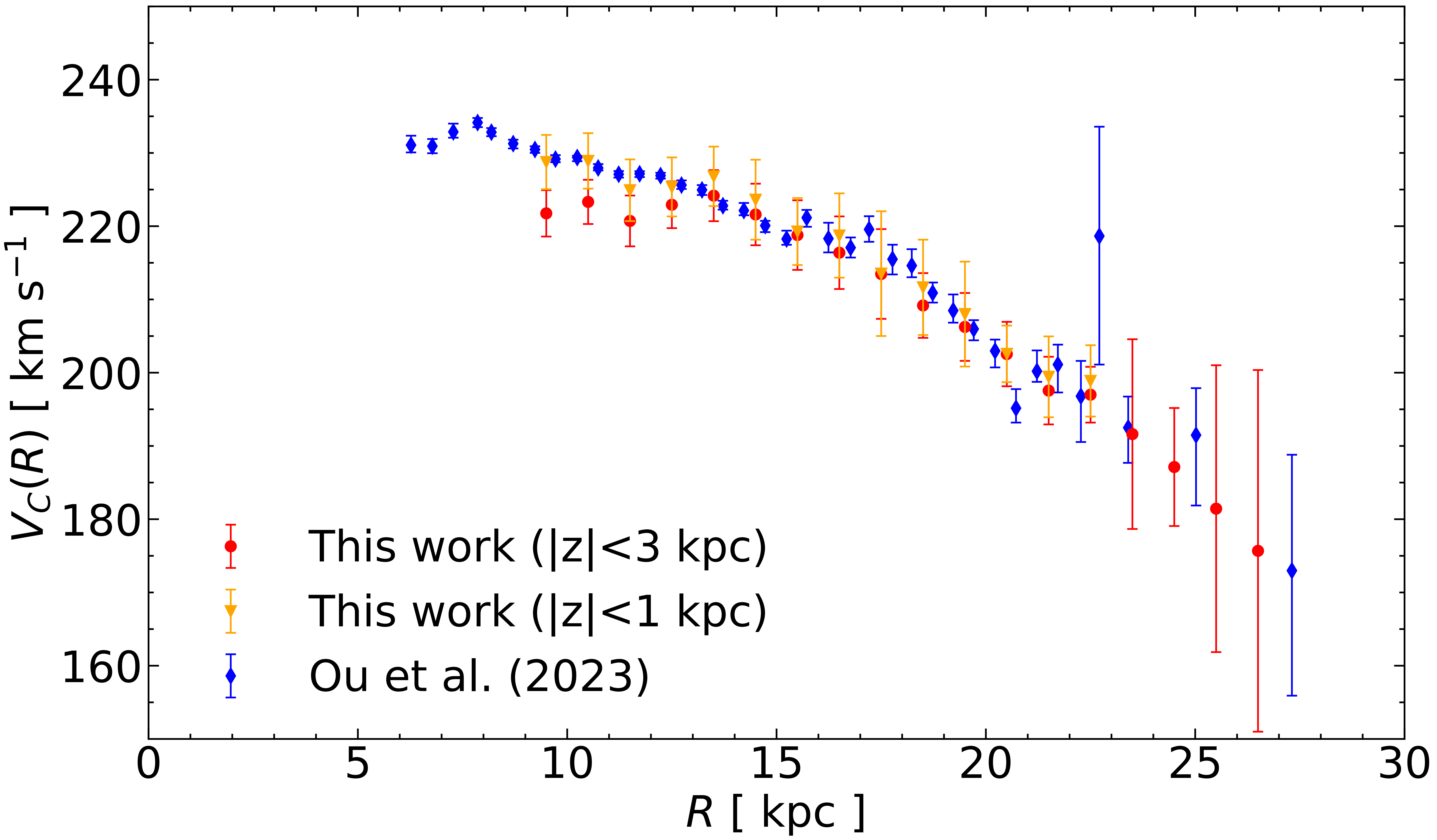


Wang et al. (2023): Lucy's Inversion Method (LIM) -full *Gaia* DR3 sample
Distance from *Gaia* parallaxes

Ou et al. (2023): 33 335 luminous red giant branch (LRGB) stars
Distance from spectrophotometric parallaxes

Zhou et al. (2023): 53 409 LRGB stars
Distance from a data-driven method

Milky Way rotation curve



The underestimated circular velocities at small radii are due to the height of the data sample.
But the measurements of RC are consistent at large radii.

Further analysis of systematic uncertainties (Jiao et al. 2023)

Analysis of **systematic uncertainties** based on Wang et al. (2023):

- **Neglected cross-term**

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

- **Disk scale length**

$$R_{\rm exp} = 2.5 \pm 1 \text{ kpc}$$

- **Disk radial density profile**

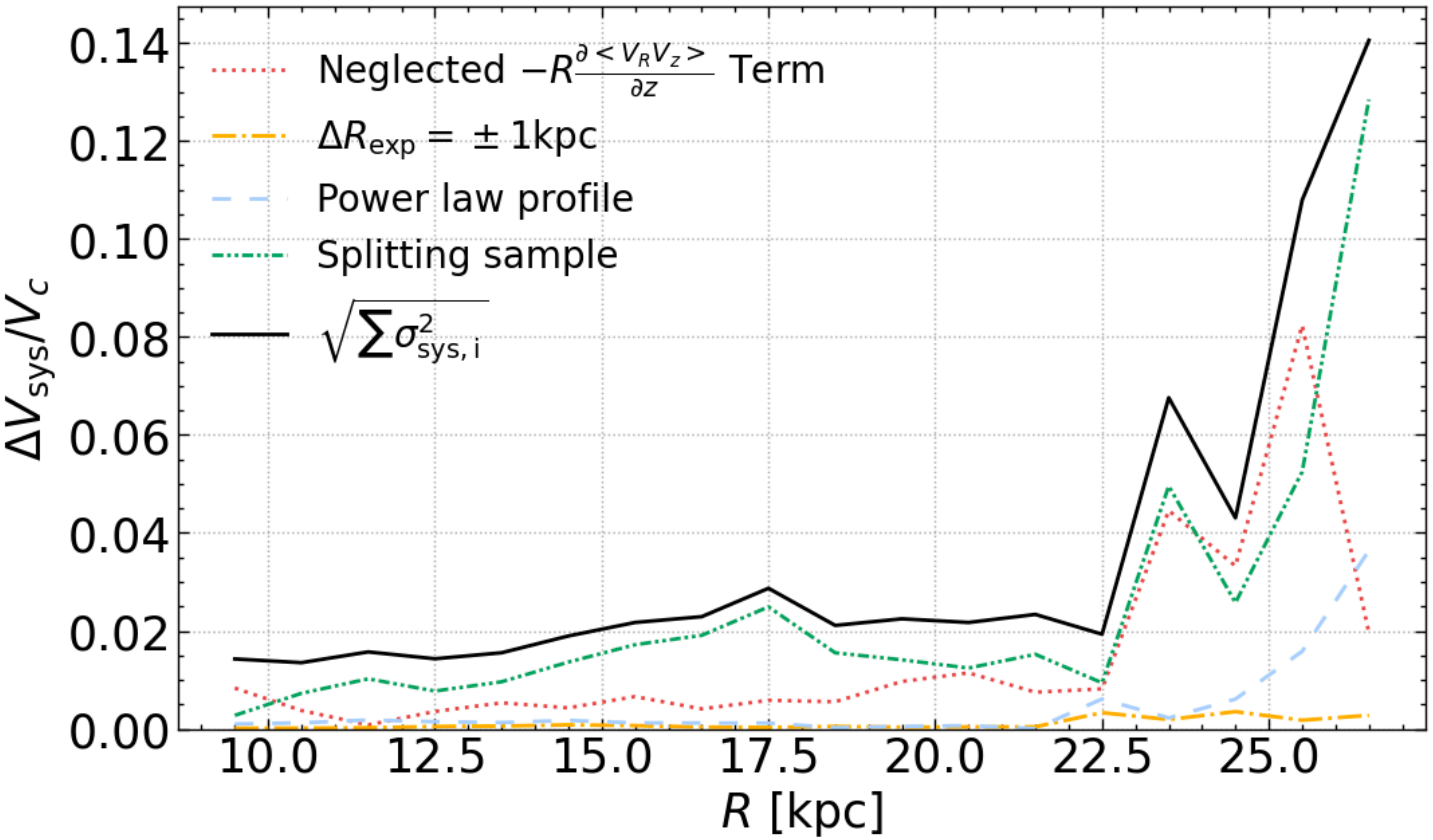
$$\nu(R) \propto \exp(-R/R_{\rm exp}) \quad \Rightarrow \quad \nu(R) \propto (R/R_{\rm exp})^{-\alpha}$$

where $\alpha = 2.25$

- **Splitting data sample**

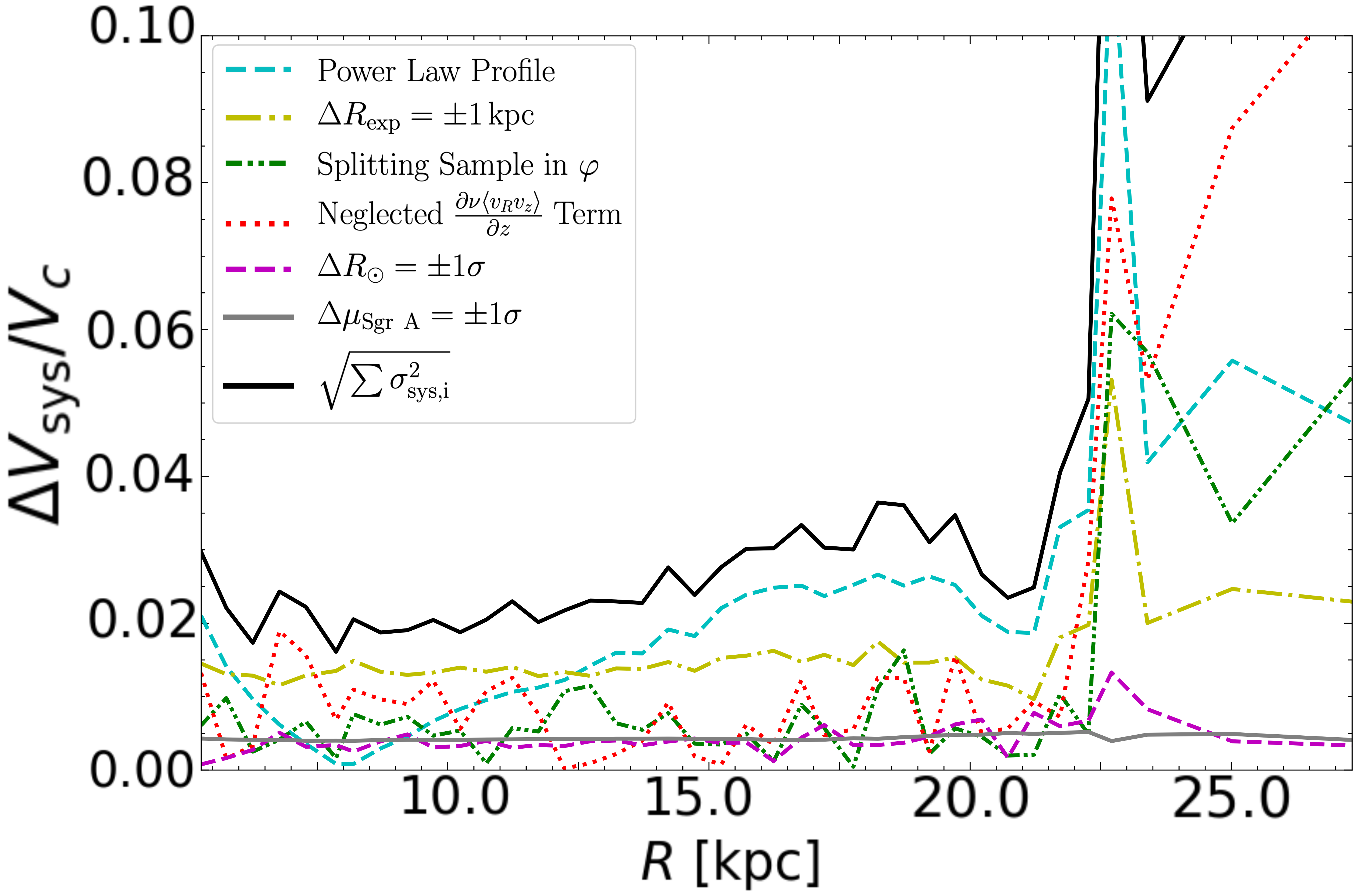
data sample in the Galactic anticenter region (l: Galactic longitude):

$160^\circ < l < 200^\circ \quad \Rightarrow \quad 160^\circ < l < 180^\circ$ and $180^\circ < l < 200^\circ$

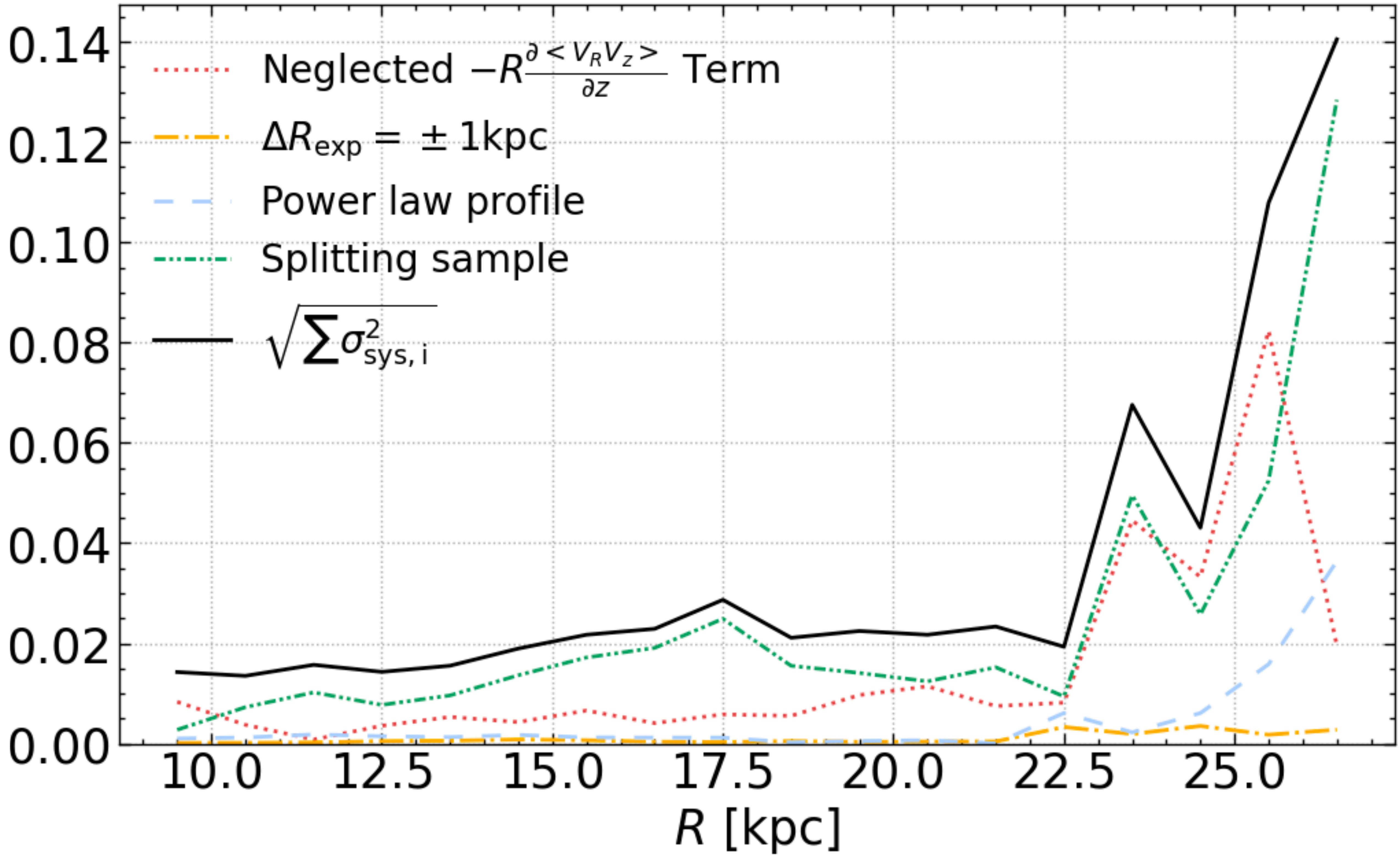


Comparison of the systematic analysis

Systematic uncertainties of Ou et al. (2023)



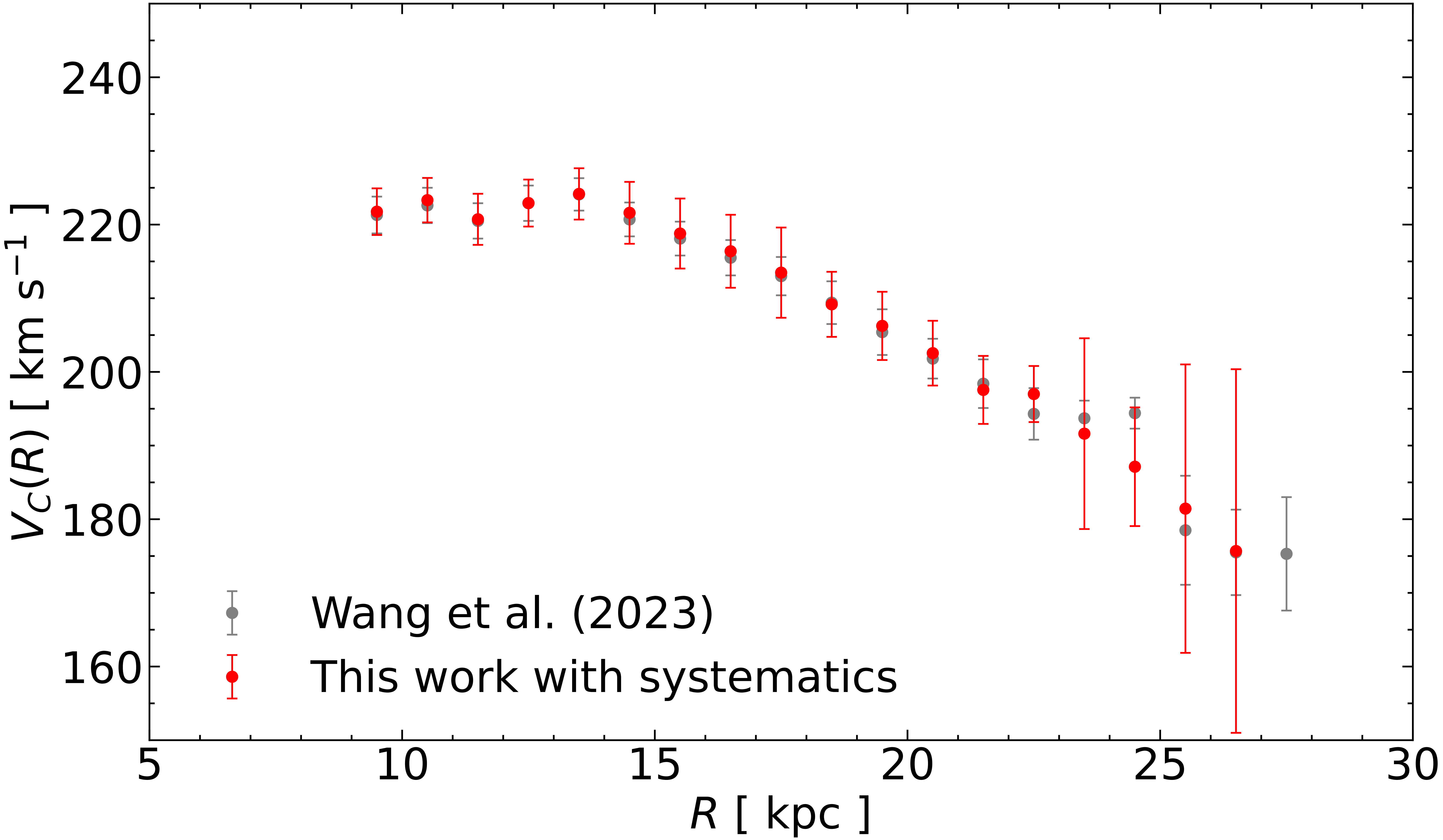
This work (Jiao et al. 2023)



The systematics of Ou et al. (2023) are slightly larger than our estimation but still consistent.

Milky Way rotation curve

Comparison of Jiao et al. (2023, this work) and previous measurements without systematics by Wang et al. (2023)



Method to derive Milky Way mass: adopted model

Baryonic model (Iocco et al. 2015, de Salas et al. 2019, Misiriotis et al. 2006):

$$M_{\rm disk} = 3.65 - 4.11 \times 10^{10}\ M_\odot$$
$$M_{\rm bulge} = 1.55 - 2.41 \times 10^{10}\ M_\odot$$
$$M_{\rm gas} = 9.5 \times 10^{9}\ M_\odot$$
$$M_{\rm dust} = 7.02 \times 10^{7}\ M_\odot$$

Dark matter model:

Einasto dark matter (DM) density profile (Einasto 1965; Retana-Montenegro et al. 2012):

$$\rho(r) = \rho_0 \exp\left[-\left(\frac{r}{h}\right)^{1/n}\right]$$

ρ_0: the central density
n: the Einasto index
h: the scale length

Note that we do not consider the NFW (Navarro et al. 1997) profile because it does not fit the significant declining rotation curve. (Chemin et al. 2011, Jiao et al. 2021, Sylos Labini et al. 2023, Ou et al. 2023).

Markov chain Monte Carlo (MCMC) method to estimate MW mass

Einasto profile:

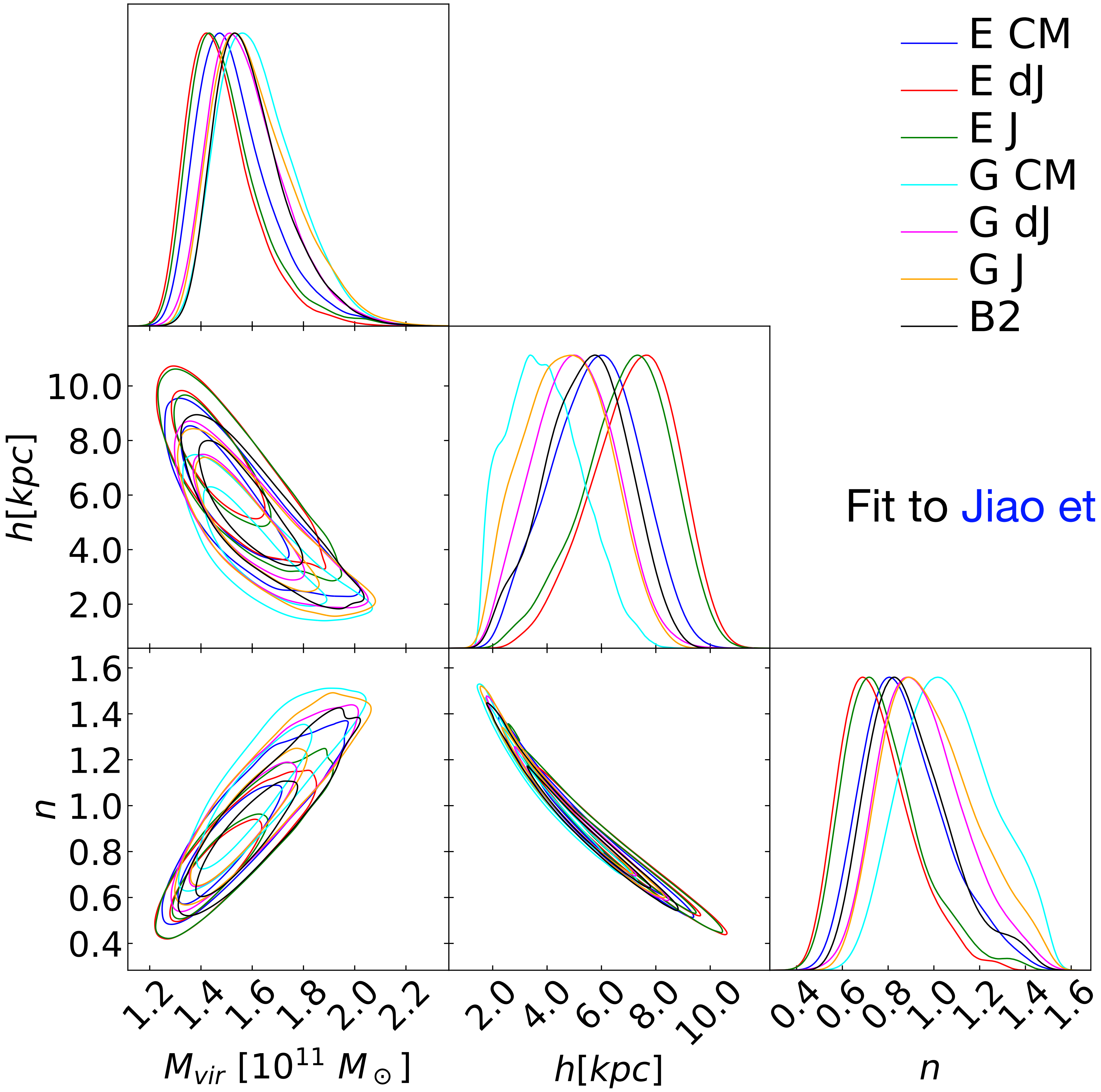
$$\rho(r) = \rho_0 \exp\left[-\left(\frac{r}{h}\right)^{1/n}\right]$$

Prior:

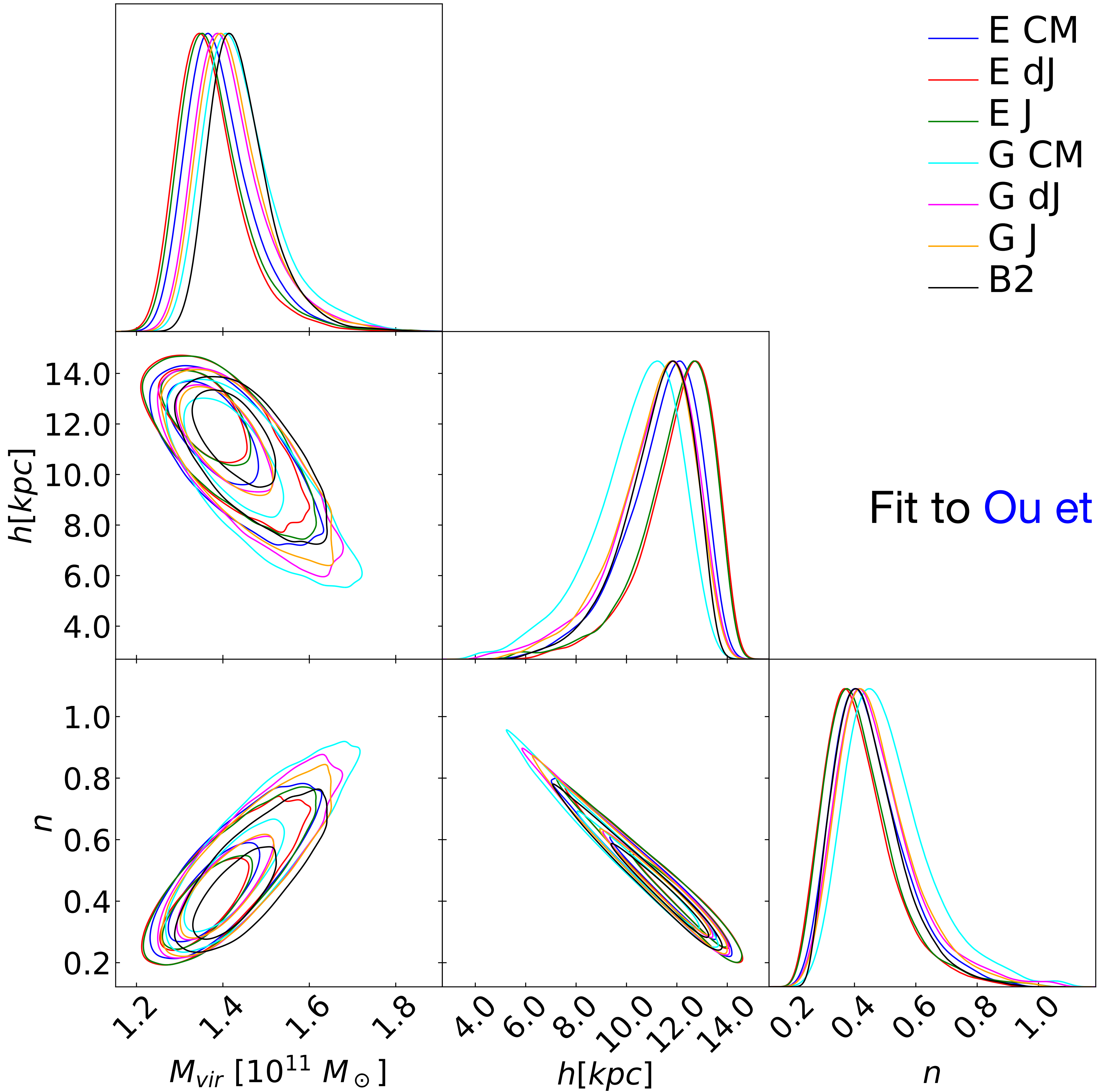
$$M_0 = 4\pi\rho_0 h^3 \quad : \quad 10^{10} < M_0 < 10^{14}\, M_\odot$$
$$\alpha = \frac{1}{n} \quad : \quad 0 < \alpha < 5$$
$$h = r_s \quad : \quad 0 < r_s < 20 \quad \text{kpc}$$

Likelihood:

$$\ln \mathcal{L} = -\frac{1}{2}\sum_i \left(\frac{v_{\mathrm{mod},i} - v_{\mathrm{obs},i}}{\sigma_i}\right)^2$$

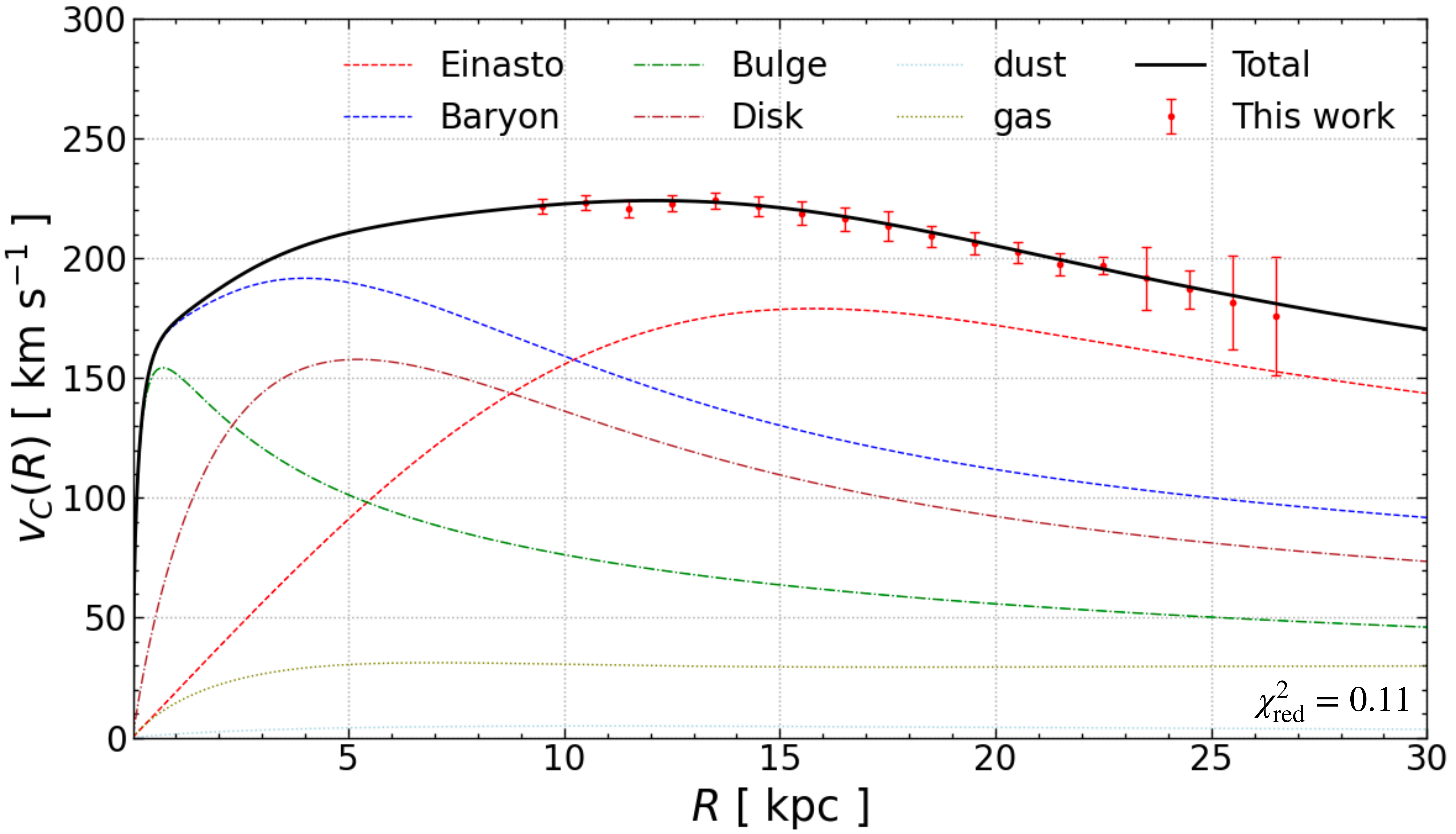


Fit to Jiao et al. (2023)



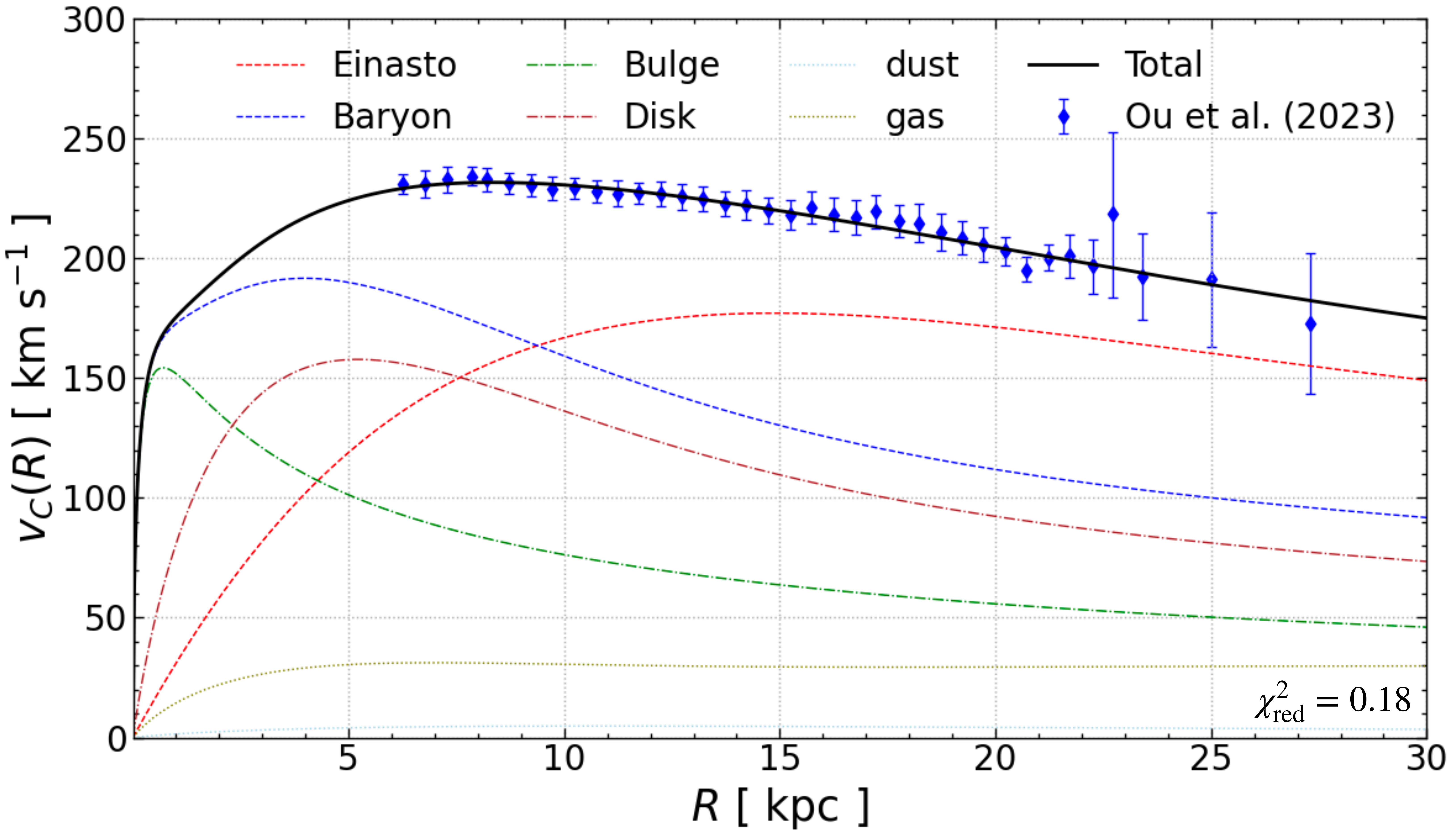
Fit to Ou et al. (2023)

Milky Way model fit to the rotation curve



By applying Markov Chain Monte Carlo (MCMC) method, we estimated the MW dynamical mass $M_{\rm dyn} = 1.99^{+0.09}_{-0.06} \times 10^{11} M_\odot$ at $R = 121.03^{+1.80}_{-1.23}$ kpc.

Milky Way model fit to the rotation curve



For the RC of Ou et al. (2023) with systematics, we used the same method and estimated the MW dynamical mass $M_{\rm dyn} = 2.13^{+0.17}_{-0.12} \times 10^{11} M_\odot$ at $R = 123.80^{+3.21}_{-2.37}$ kpc.

The estimated MW mass is $1.99^{+0.09}_{-0.06} \times 10^{11} M_\odot$ with the RC of Jiao et al. (2023) and $2.13^{+0.17}_{-0.12} \times 10^{11} M_\odot$ with the RC of Ou et al. (2023).

By combining the two measurements, the estimated MW mass would be $2.06^{+0.24}_{-0.13} \times 10^{11} M_\odot$

Detection of the **Keplerian decline** in the Milky Way rotation curve

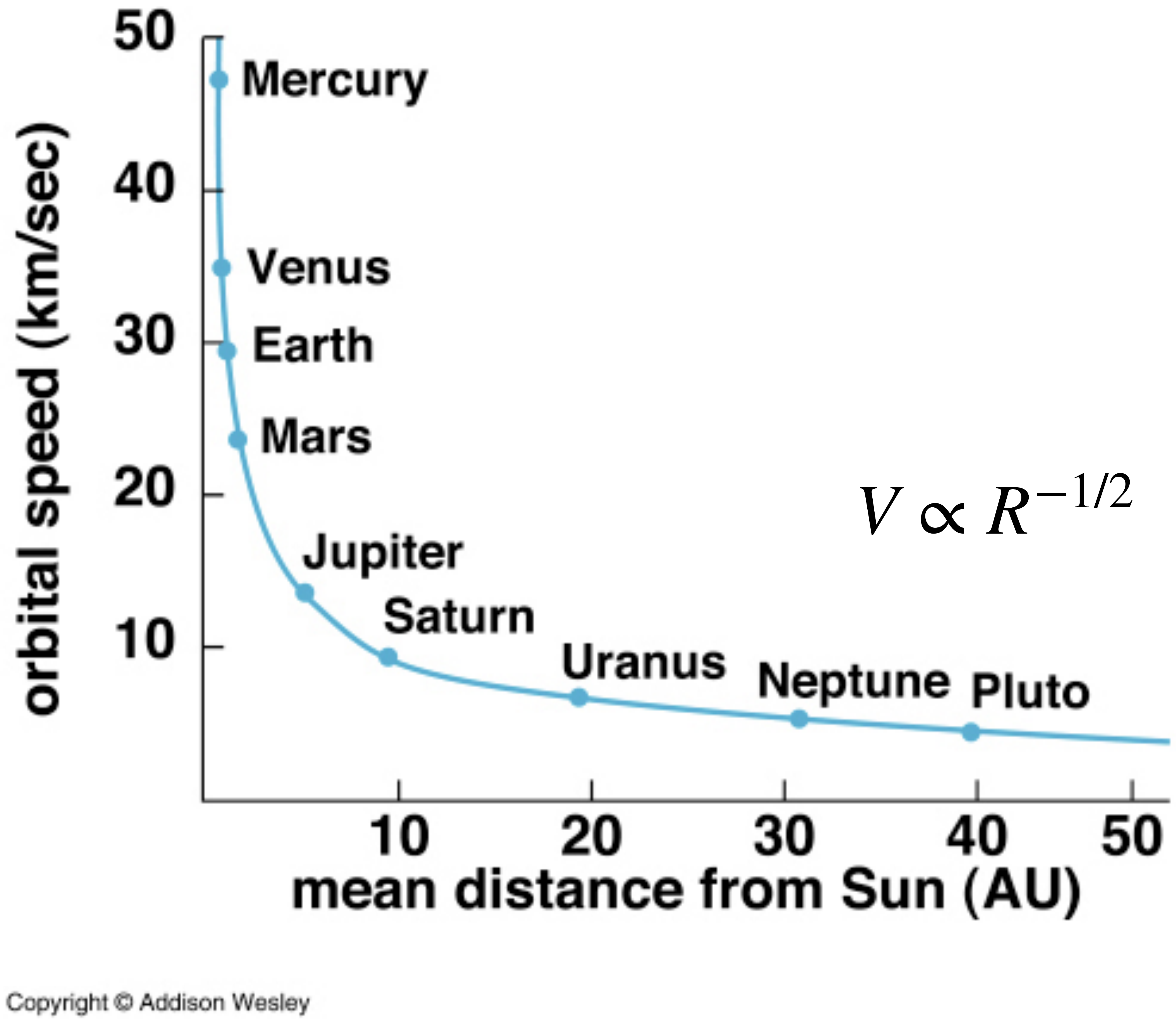
Keplerian decline of planetary system

In the solar system, the Sun comprises more than 99% of all the mass. So we could think of the Sun as a point mass. Then from Newton's law of universal gravitation:

$$\frac{GM_{\odot}m}{R^2} = \frac{mV^2}{R}$$

We could derive:

$$V = \sqrt{\frac{GM_{\odot}}{R}}$$



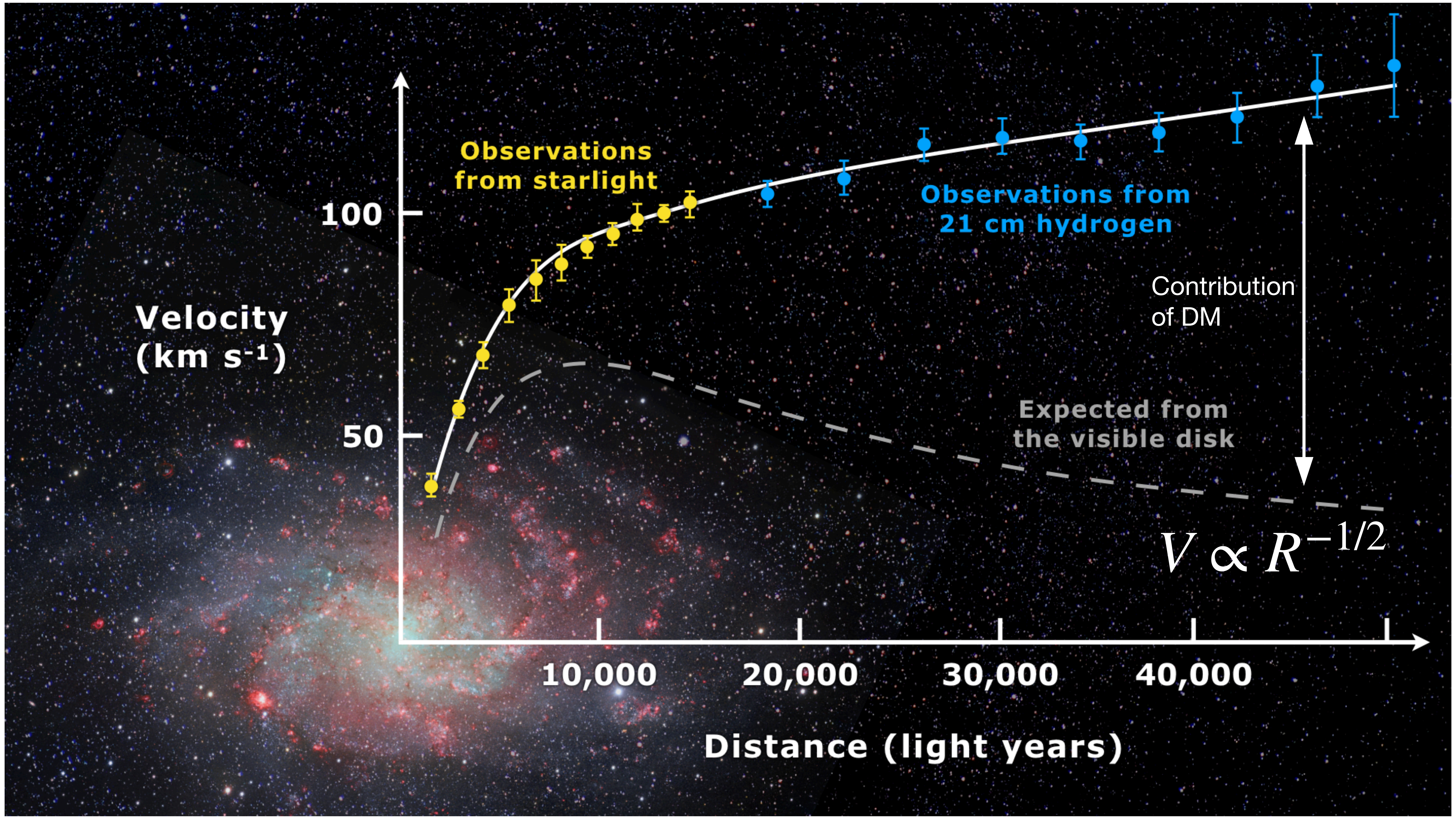
RC of the solar system
https://ircamera.as.arizona.edu/NatSci102/NatSci/lectures/darkmatter.htm

What about spiral galaxies?

Lundmark (1925) was the first to identify the flat RC of disc galaxies.

Babcock (1939, then Mayall 1951) reported that the RC of M31 shows no decrease up to 20 kpc from optical spectroscopy.

Rubin et al. (1978) and Bosma (1978, HI) found that several spiral galaxies have a flat RC.



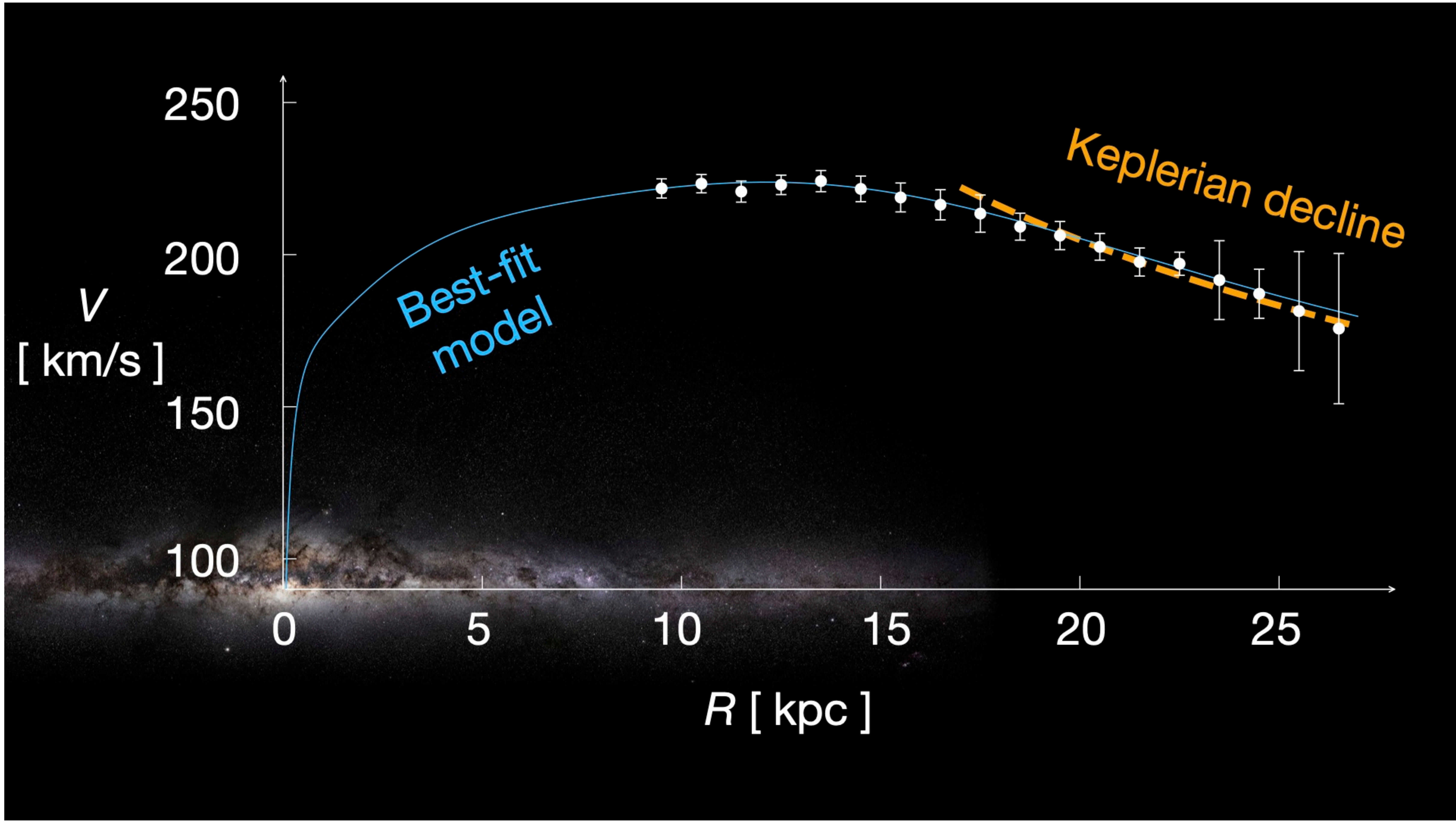
RC of M33

https://en.wikipedia.org/wiki/Galaxy_rotation_curve#/media/File:Rotation_curve_of_spiral_galaxy_Messier_33_(Triangulum).png

Keplerian decline in the MW rotation curve

We find a sharply decreasing MW RC, the decrease in velocity between 19.5 and 26.5 kpc is approximately 30 km/s.

We identify a **Keplerian decline** of the RC, starting at the edge of the Galaxy disc.



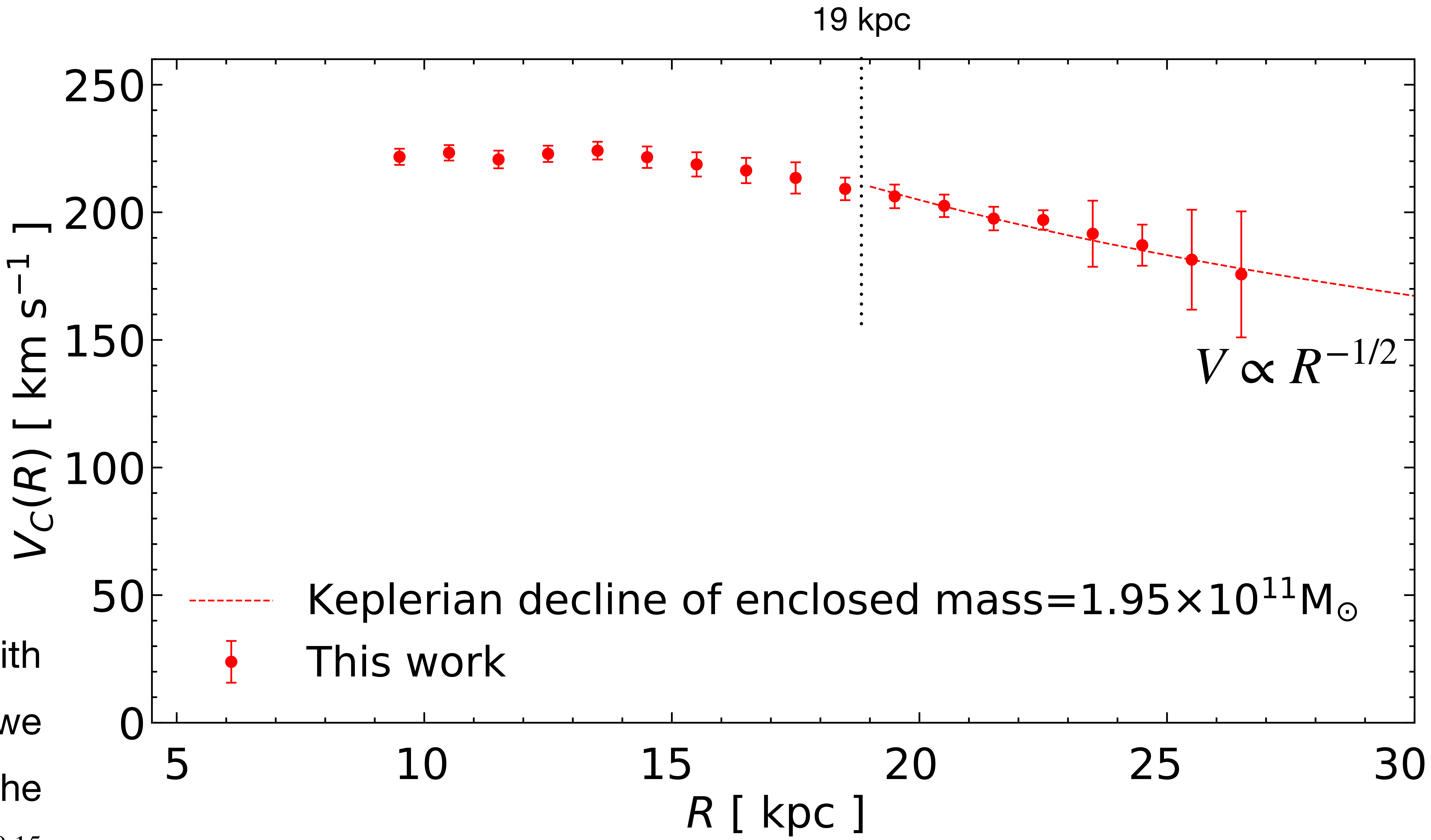
The Milky Way rotation curve (Jiao et al. 2023)

Keplerian decline in the MW rotation curve

We assumed a circular velocity profile beyond 19 kpc:

$$V(R) = AR^{\gamma}$$

To test the Keplerian decline with the RC of Jiao et al. (2023) we applied an MCMC exercise and the result is $\partial \ln V(R) / \partial \ln R = -0.47^{+0.15}_{-0.15}$ beyond 19 kpc.



Rotation curve of Jiao et al. (2023) with the best fit Keplerian decline

MCMC method to test the Keplerian decline

Assumed a circular velocity profile:
$V(R) = AR^{\gamma}$

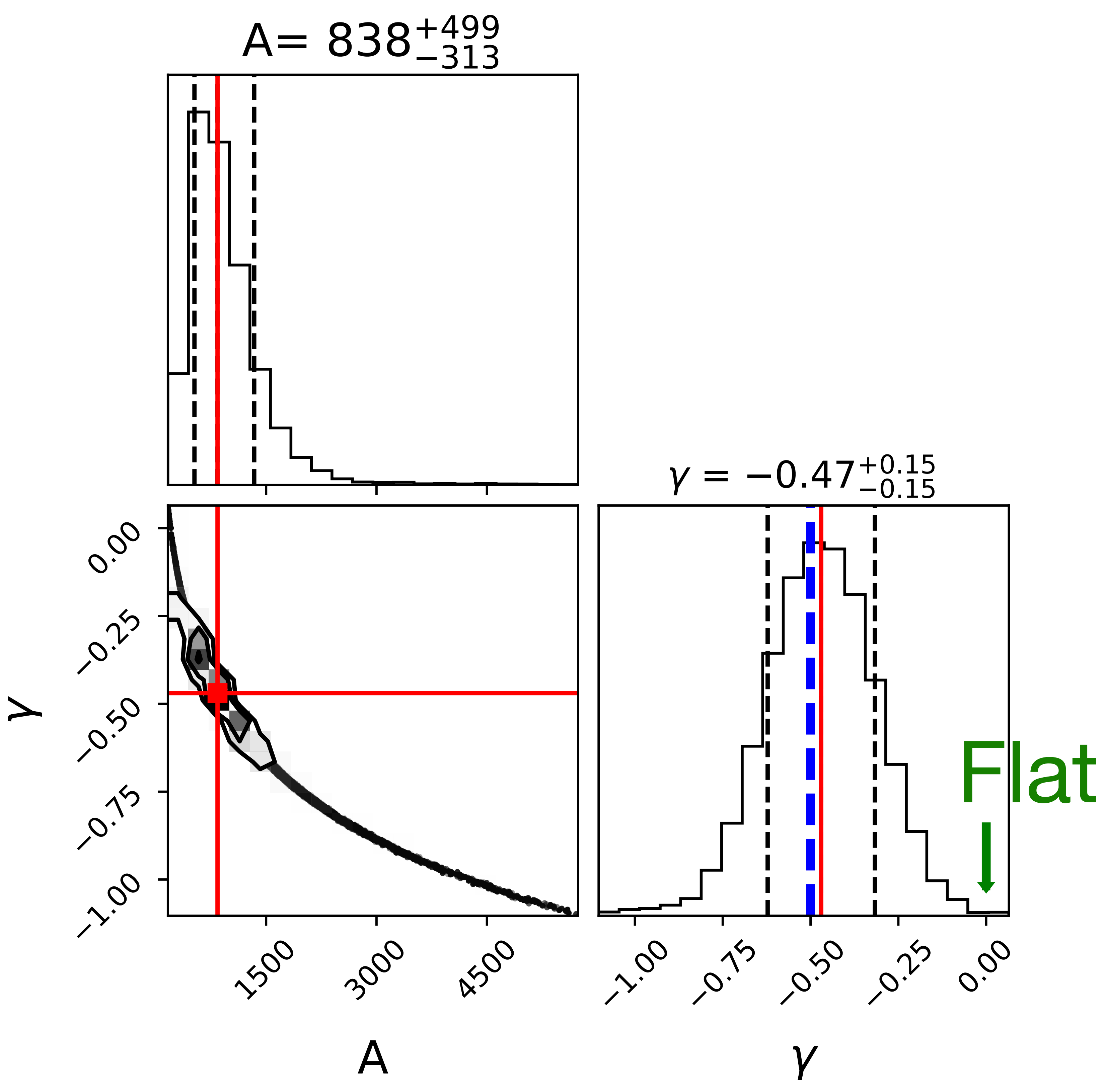
Prior:

Amplitude : $0 < A < 10000$
γ : $-10 < \gamma < 5$

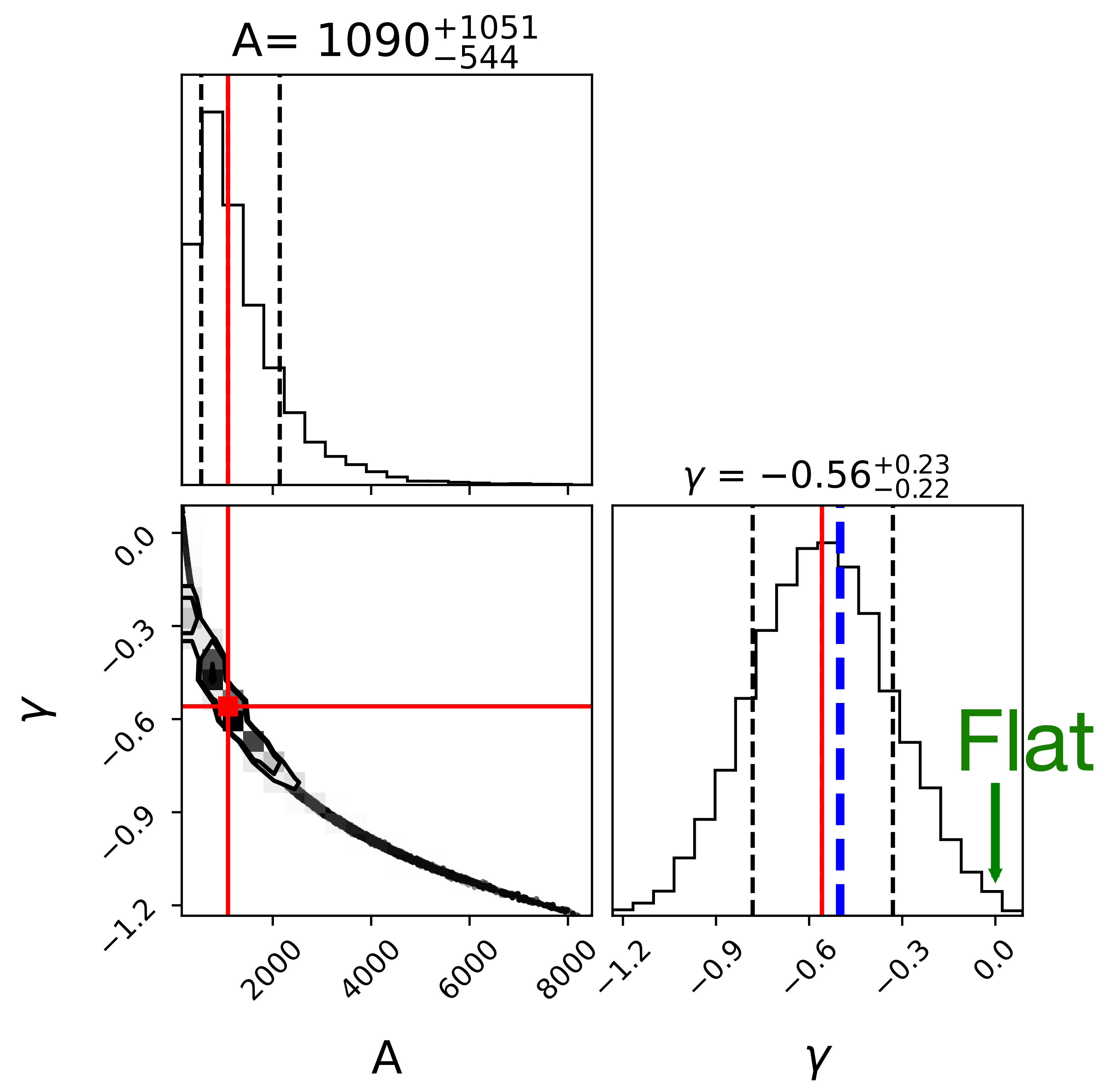
Likelihood:

$$\ln \mathscr{L} = -\frac{1}{2}\sum_i \left(\frac{v_{\mathrm{mod},i} - v_{\mathrm{obs},i}}{\sigma_i}\right)^2$$

Fit to this work beyond 19 kpc



Fit to Ou et al. (2023) beyond 19 kpc

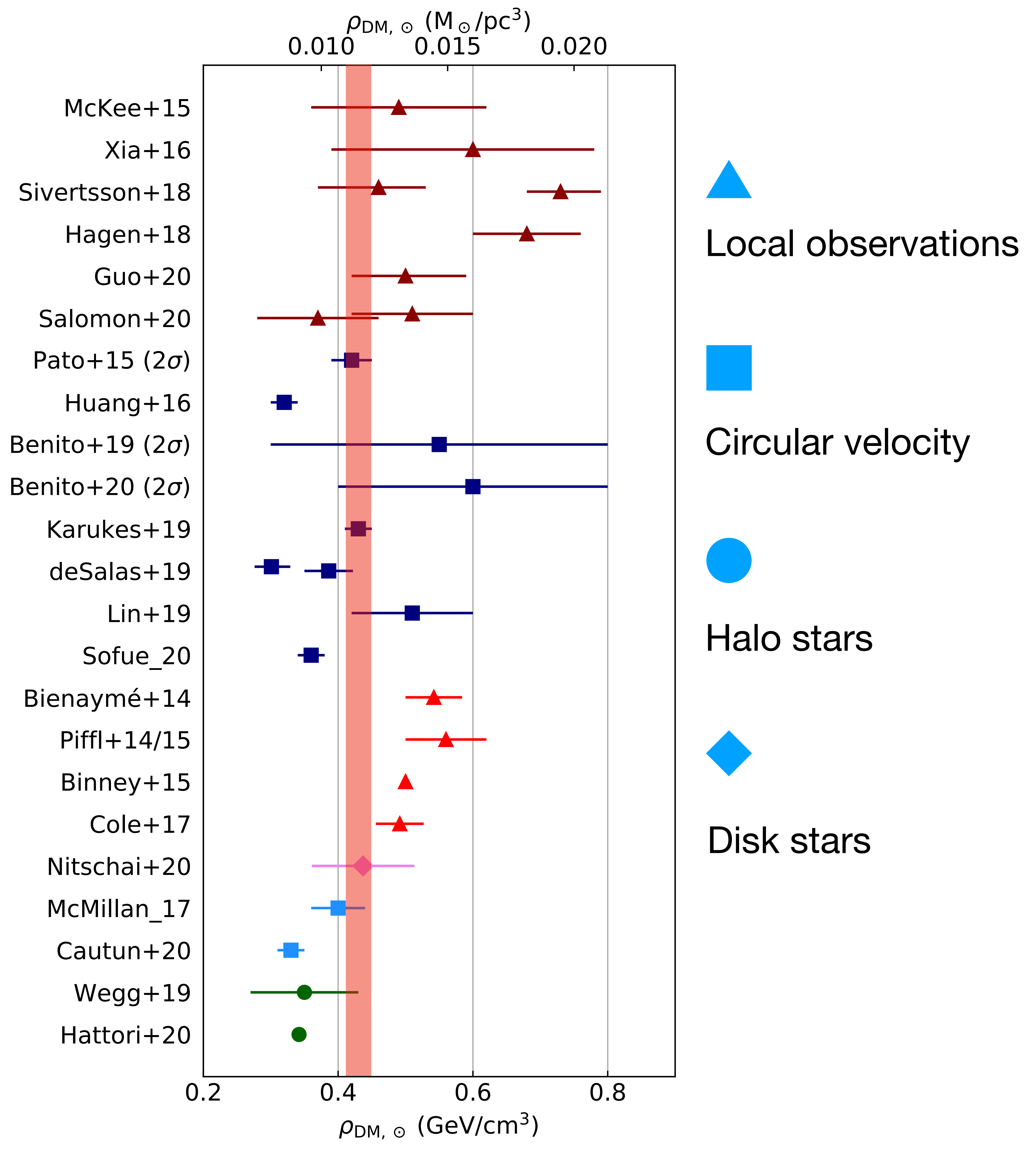


Local dark matter density

The estimation of local DM density is 0.011-0.012 $M_{\odot}/\mathrm{pc}^3$ (0.417-0.456 $\mathrm{GeV/cm}^3$), consistent with previous studies. The Keplerian decline DO NOT change this estimation:

- The circular velocity at the location of the sun is relatively robust.
- The MW baryon mass is well estimated if we do not consider additional components (e.g. ionised gas)
- The local DM density is relatively model-independent (e.g. no core-cusp problem).

But it will significantly change the estimation of MW mass, thus the structure of the MW, and the behaviour of halo members (e.g. Magellanic Clouds, Globular Clusters, Dwarf galaxies).

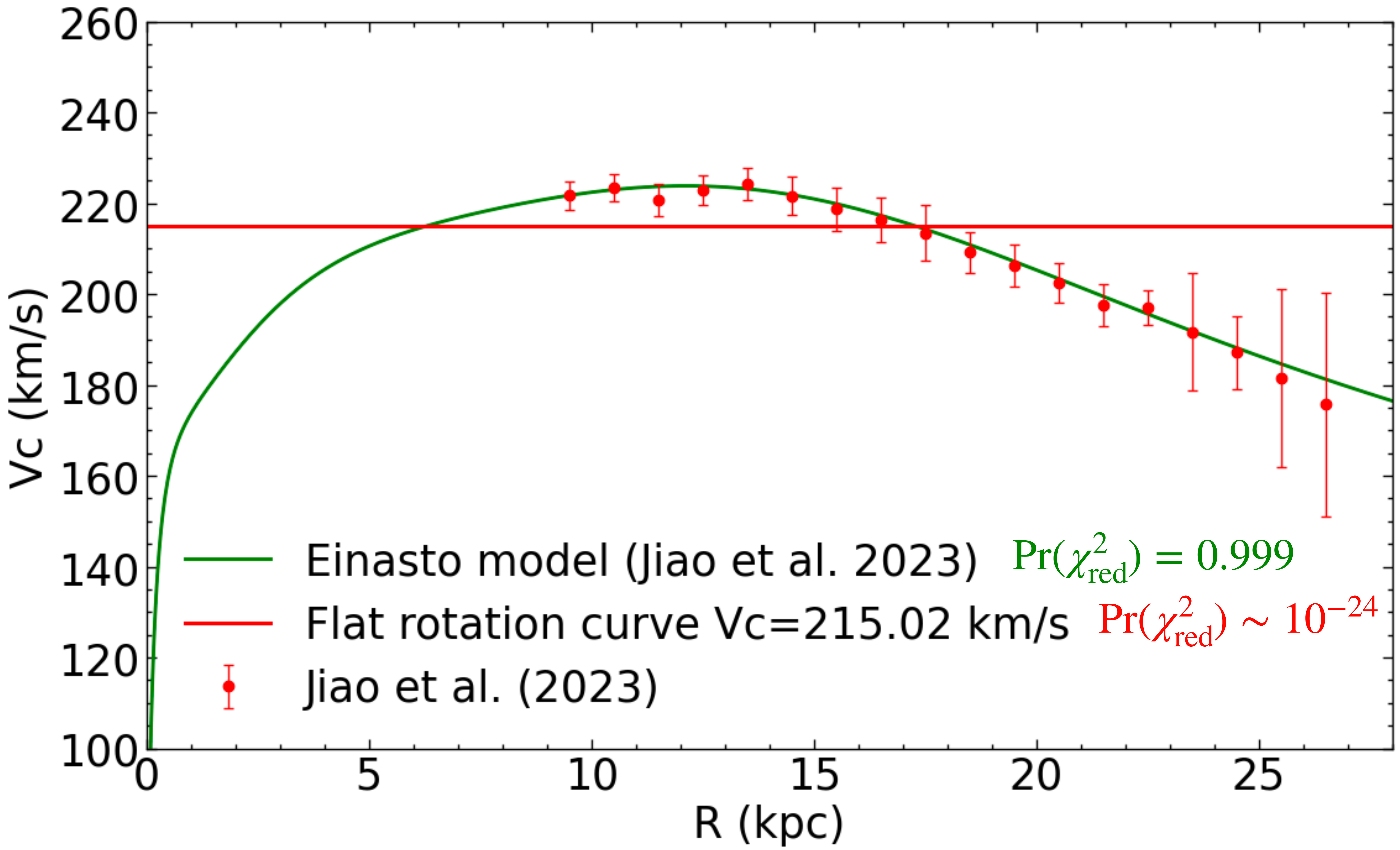


Summary from de Salas and Widmark (2021)

Λ*CDM*

In the MW, $M_{\rm Baryon} \sim 0.6 \times 10^{11} M_\odot$ and $M_{\rm Dyn} \sim 2.1 \times 10^{11} M_\odot$, the mass ratio of DM to the baryon is $\sim 2 - 2.5$, which is smaller than the universal estimate of ~6 (Planck Collaboration et al. 2020).

- Flat rotation curve can be tested and its associated probability is very low

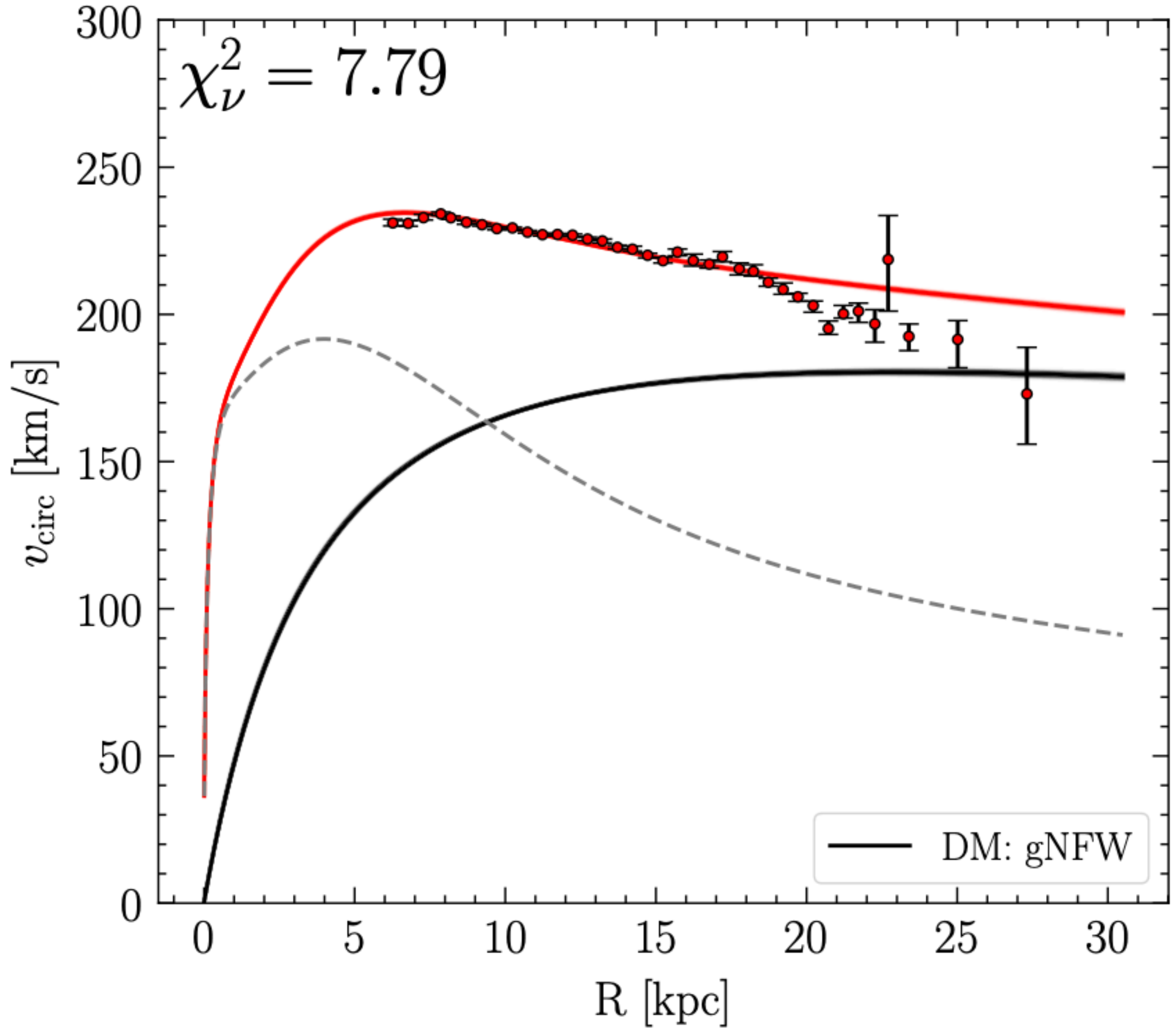


Consequences

ΛCDM

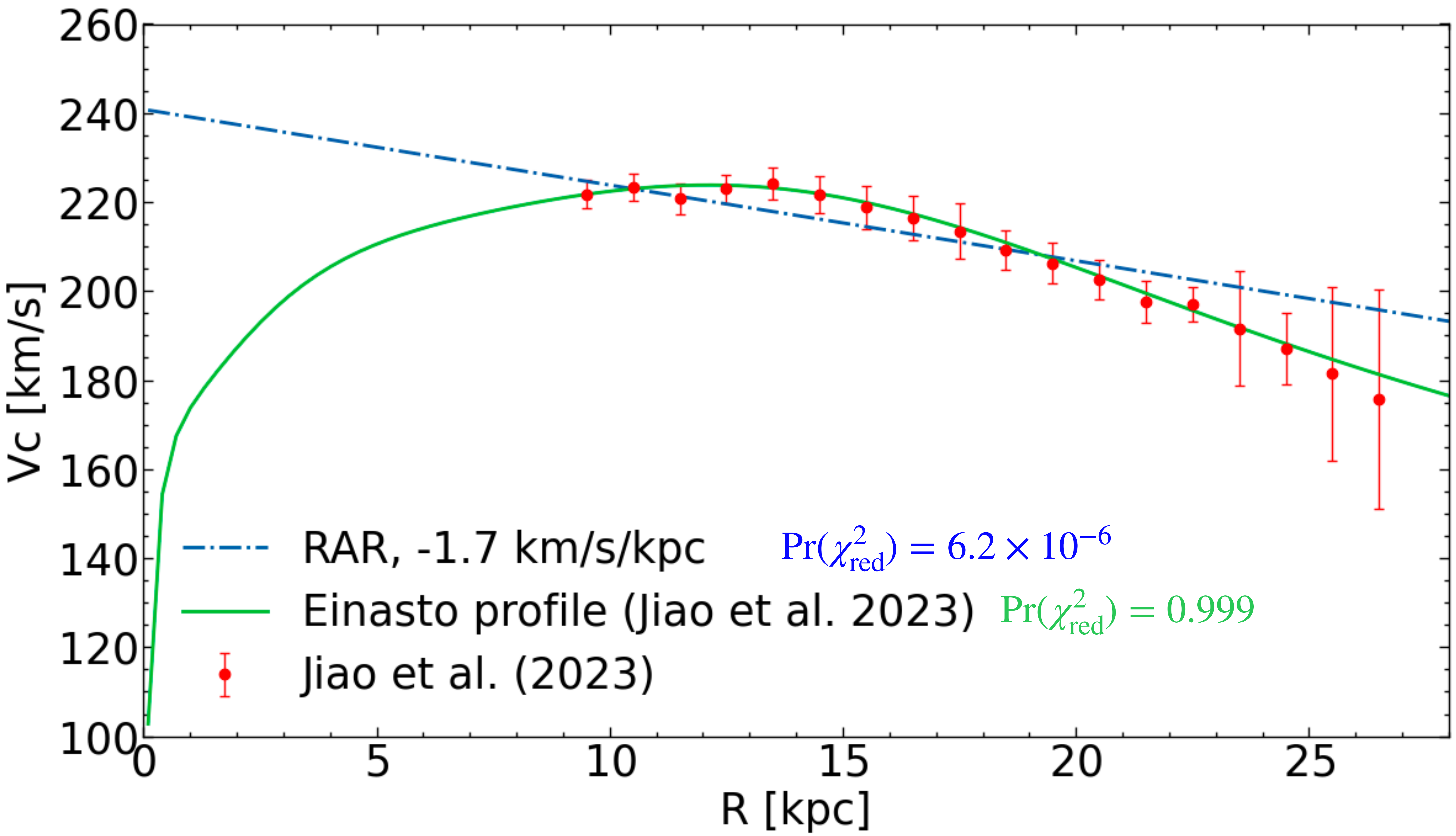
In the MW, $M_{\rm Baryon} \sim 0.6 \times 10^{11} M_\odot$ and $M_{\rm Dyn} \sim 2.1 \times 10^{11} M_\odot$, the mass ratio of DM to the baryon is $\sim 2 - 2.5$, which is smaller than the universal estimate of ~6 (Planck Collaboration et al. 2020).

- generalised NFW profile is also unlikely (Ou et al. 2023, Fig. 7)



Modified Newtonian dynamics (MOND)

Radial Acceleration Relation (RAR) predict a slope of -1.7 km/s/kpc at large radii (McGaugh 2019)



Why the Milky Way RC shows a Keplerian decline, while no external spiral galaxies do?

1- Is MW an **exceptional** galaxy compared to other spiral galaxies?

- MW halo is particularly poor and its disk angular momentum is exceptionally small (Hammer et al. 2007)
- Its last major merger, *Gaia-Sausage-Enceladus* (GSE), occurred 9-10 Gyr ago (Haywood et al. 2018, Belokurov et al 2018, Helmi et al. 2018), which underlines the fact that even the very edge of the MW disk is sufficiently at equilibrium to have circular velocities (radial and vertical velocities are found very small by *Gaia* DR3) and experienced at least 6 orbits at 26.5 kpc.
- While most spiral galaxies experienced it 6 Gyr ago on average (Hammer et al. 2009; Hopkins et al. 2010)

Why the Milky Way RC shows a Keplerian decline, while no external spiral galaxies do?

2- **Methodological** problem**?**

- *Gaia* provides us with the 3D spatial + 3D velocity coordinates (phase diagram) for disk stars, constraining, e.g., orbit circularity and stability
- For external spiral galaxies, the best RCs at large radii are from the neutral gas (HI), i.e., based on only 2 spatial and one (los) velocity coordinates
- Moreover, the stability of outer material in the external galaxy disks can be affected by non-equilibrium motions.

➔ To further study external galaxies' RC, we will try to determine their past history and use hydrodynamical simulation to test whether or not the gas component at large radii is in equilibrium (Jiao et al. in preparation)

Conclusions

- Our measurement of the rotation curve and the estimation of systematics uncertainty are consistent with other *Gaia* DR3 studies.

- By fitting the Einasto profile to the rotation curve with various baryonic models, the Milky Way dynamical mass is $M_{\rm dyn} = 2.06^{+0.24}_{-0.13} \times 10^{11} M_{\odot}$.

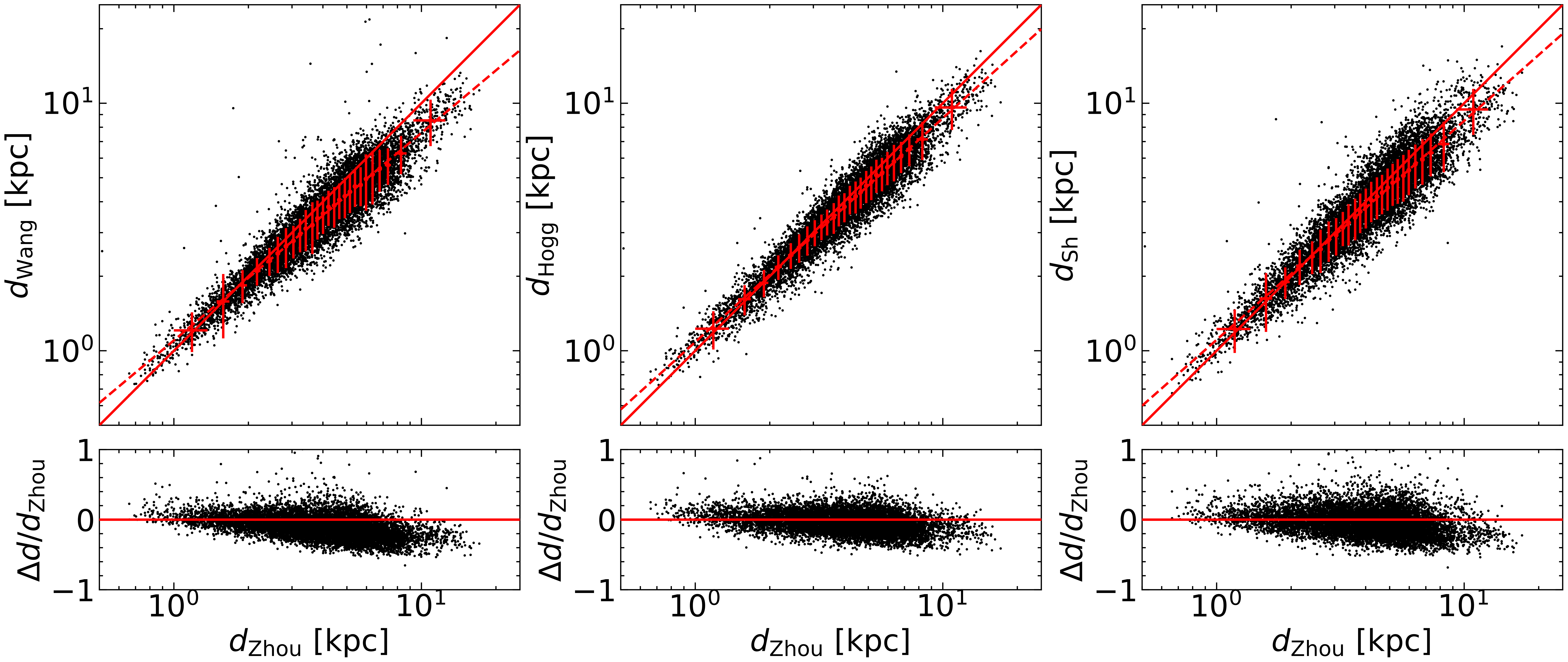
- The rotation curve follows a Keplerian decline beyond *R*>19 kpc.

- It needs to be confirmed by *Gaia* DR4 (or further data release) with smaller uncertainty.

Thank you

Milky Way rotation curve

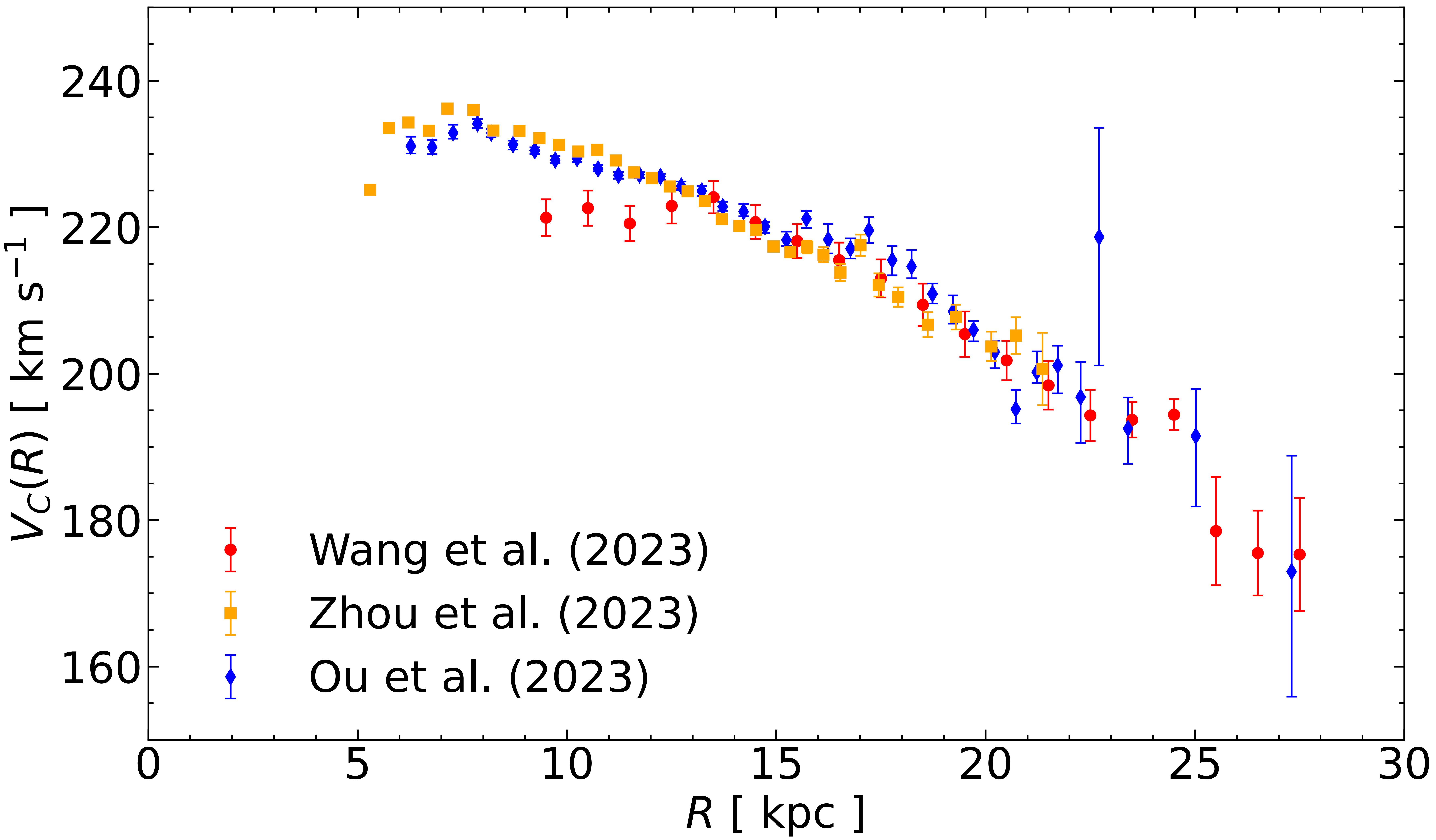
Problem on the distance measurement of Zhou et al. (2023)



Comparison of distance estimates made by Zhou et al. (2023) to those made by Wang et al. (2016), Hogg et al. (2019), and StarHorse (Queiroz et al. 2023) in the top panels, respectively.

Milky Way rotation curve

Modify the distance of Zhou et al. (2023) by Hogg et al. (2019)

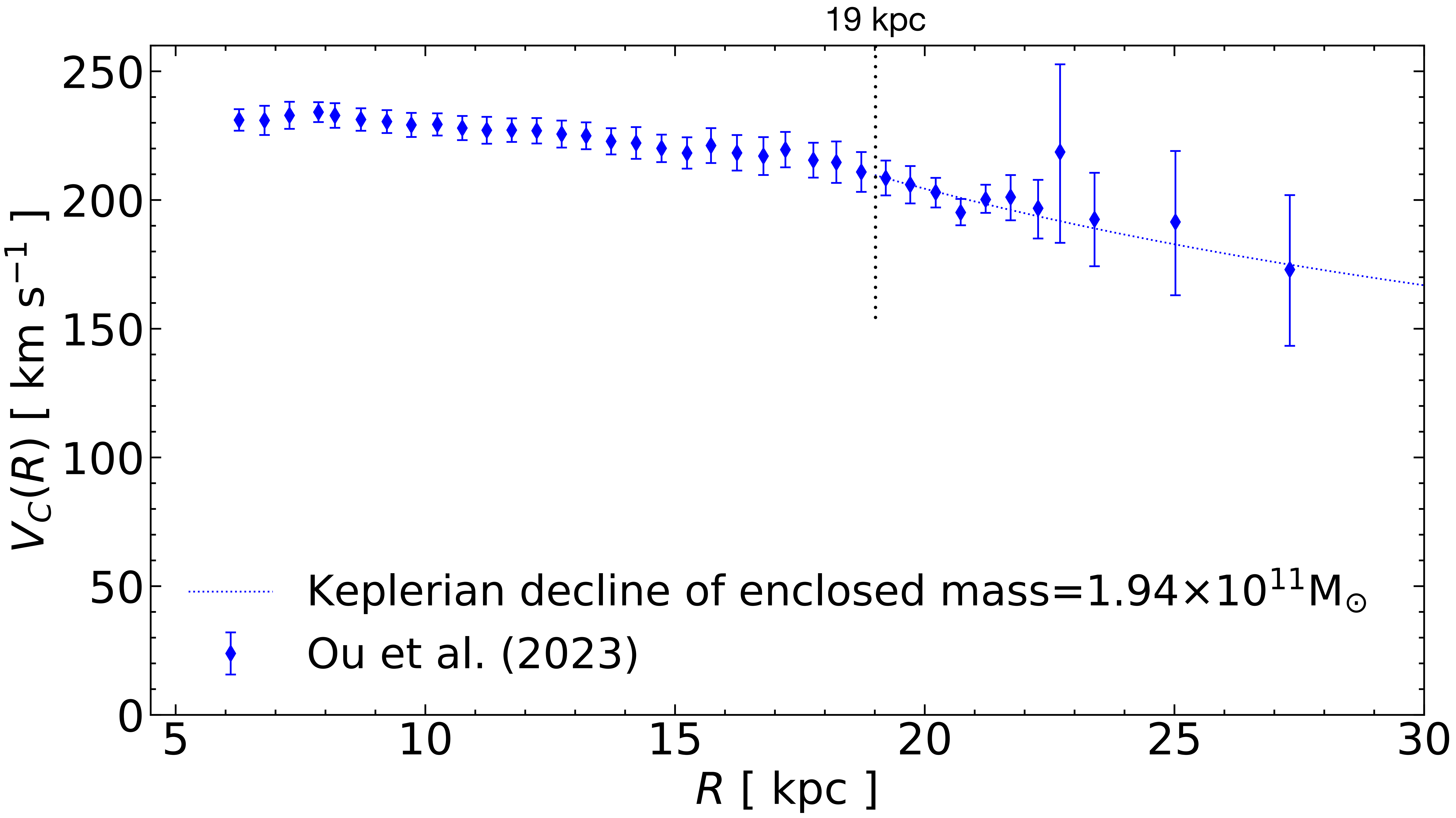


A Keplerian decrease in the MW rotation curve

We assumed a circular velocity profile beyond 19 kpc:

$$V(R) = AR^{\gamma}$$

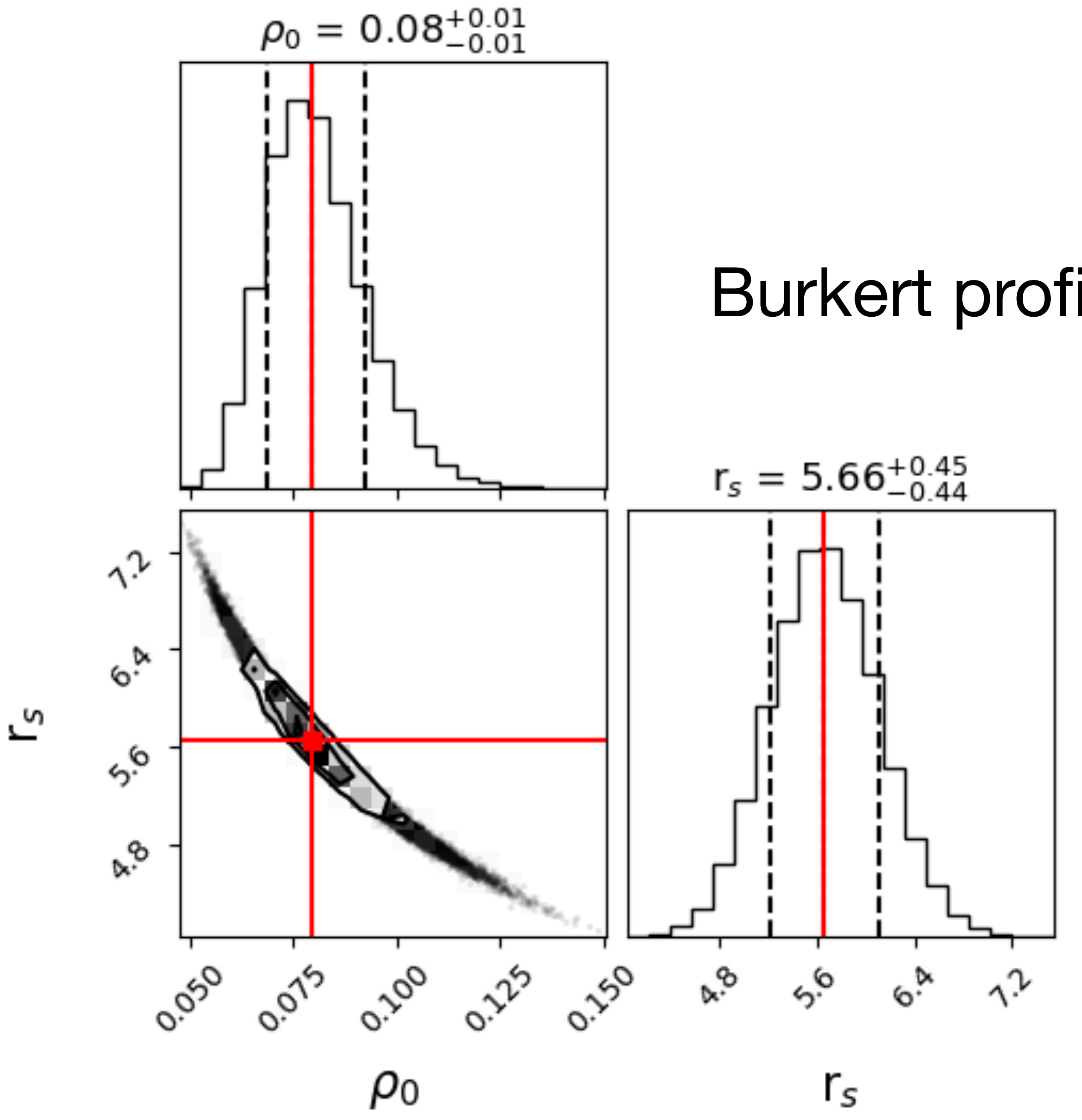
To test the Keplerian decline with the RC of Ou et al. (2023). The MCMC exercise gives $\partial \ln V(R)/\partial \ln R = -0.56^{+0.23}_{-0.22}$ beyond 19 kpc.



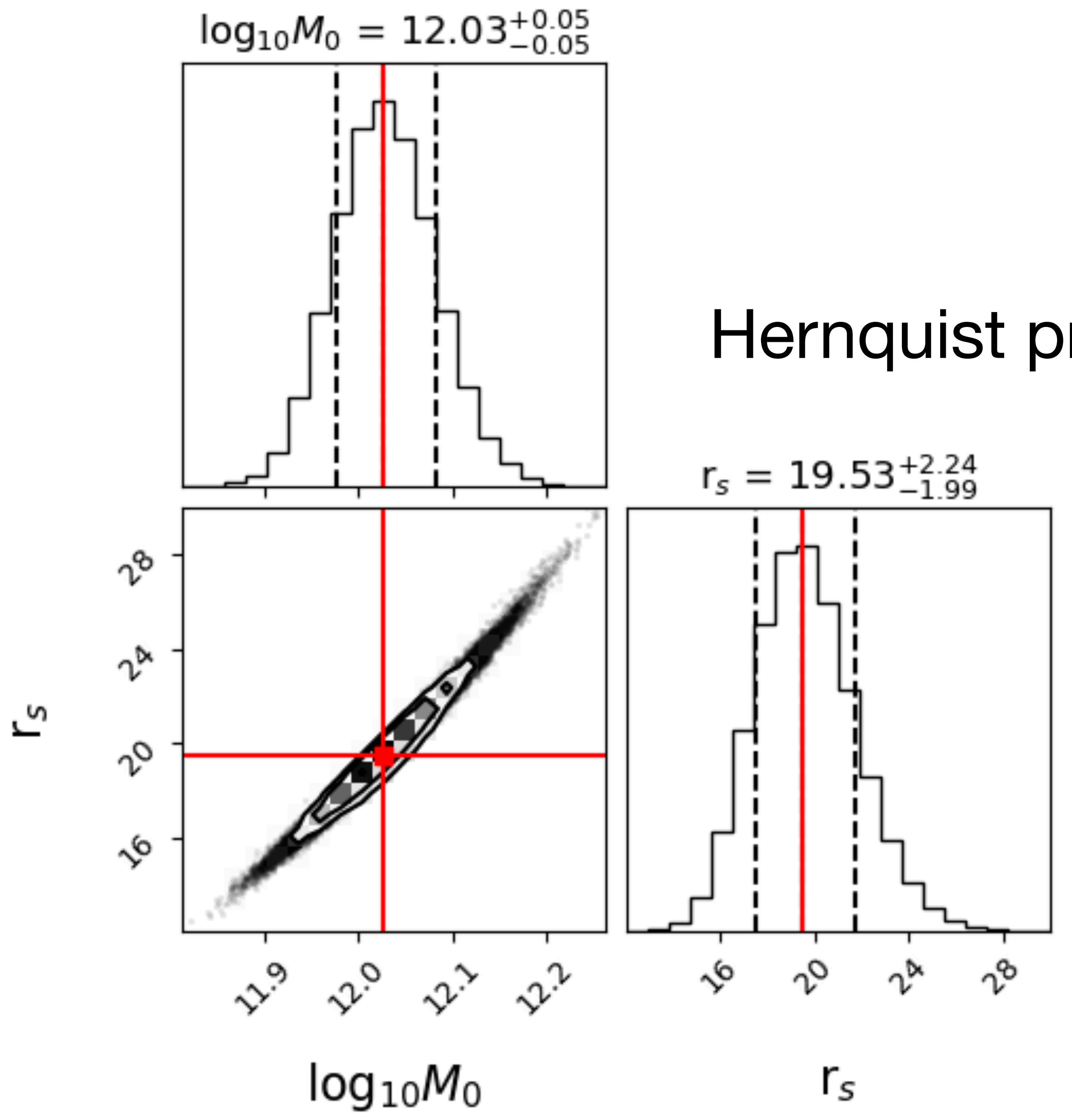
Rotation curve of Ou et al. (2023) with the best fit Keplerian decrease

Test of other DM density profiles

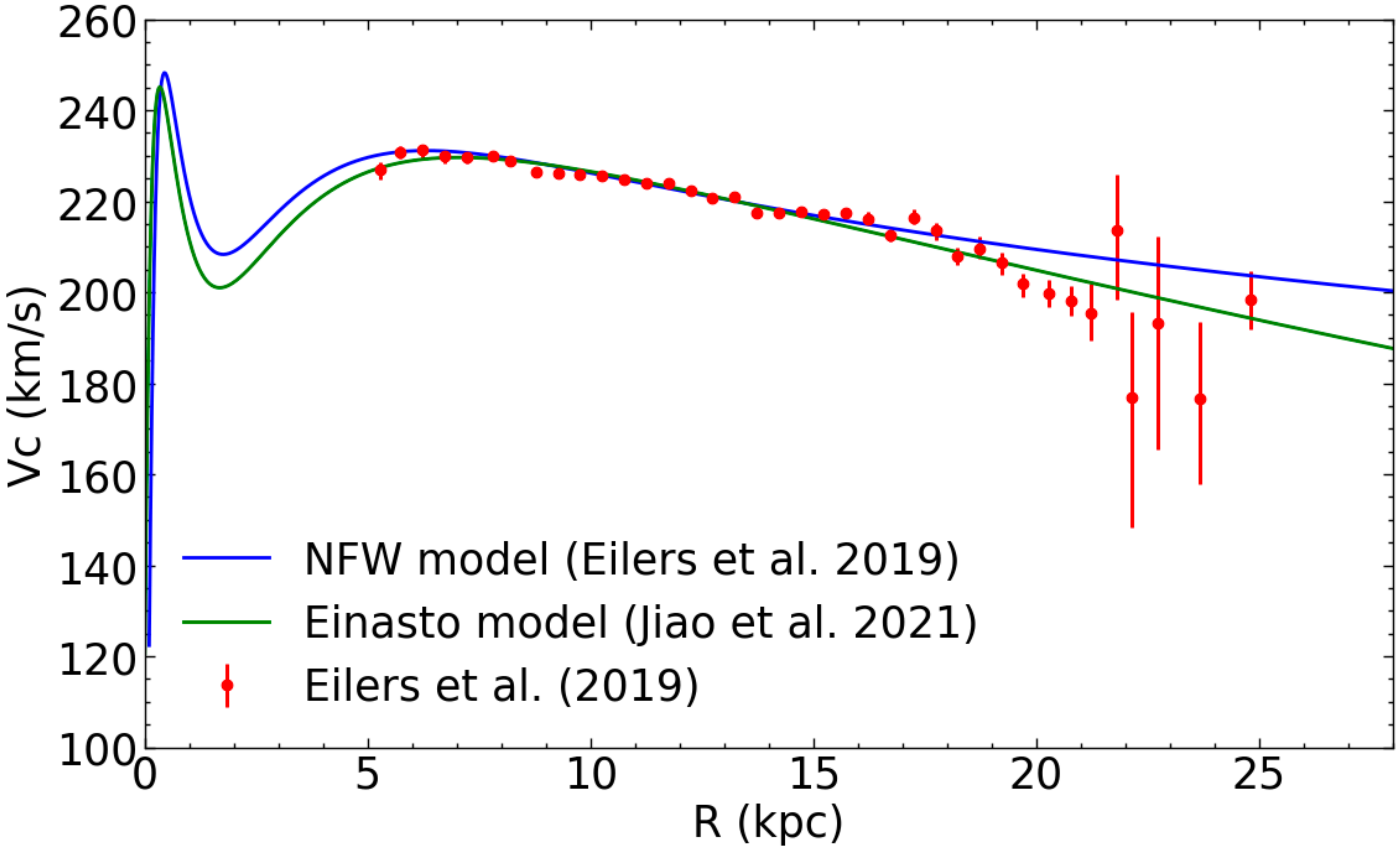
		Burkert	Hernquist
Virial radius	kpc	161^{+4}_{-5}	155^{+6}_{-5}
DM halo mass	10^11 Msun	$4.73^{+0.31}_{-0.50}$	$4.22^{+0.44}_{-0.40}$
Local DM density	Msun/pc^3	$0.0107^{+0.0001}_{-0.0004}$	$0.0097^{+0.0001}_{-0.0001}$
	Gev/cm^3	$0.4062^{+0.0038}_{-0.0152}$	$0.3682^{+0.0038}_{-0.0038}$



Burkert profile

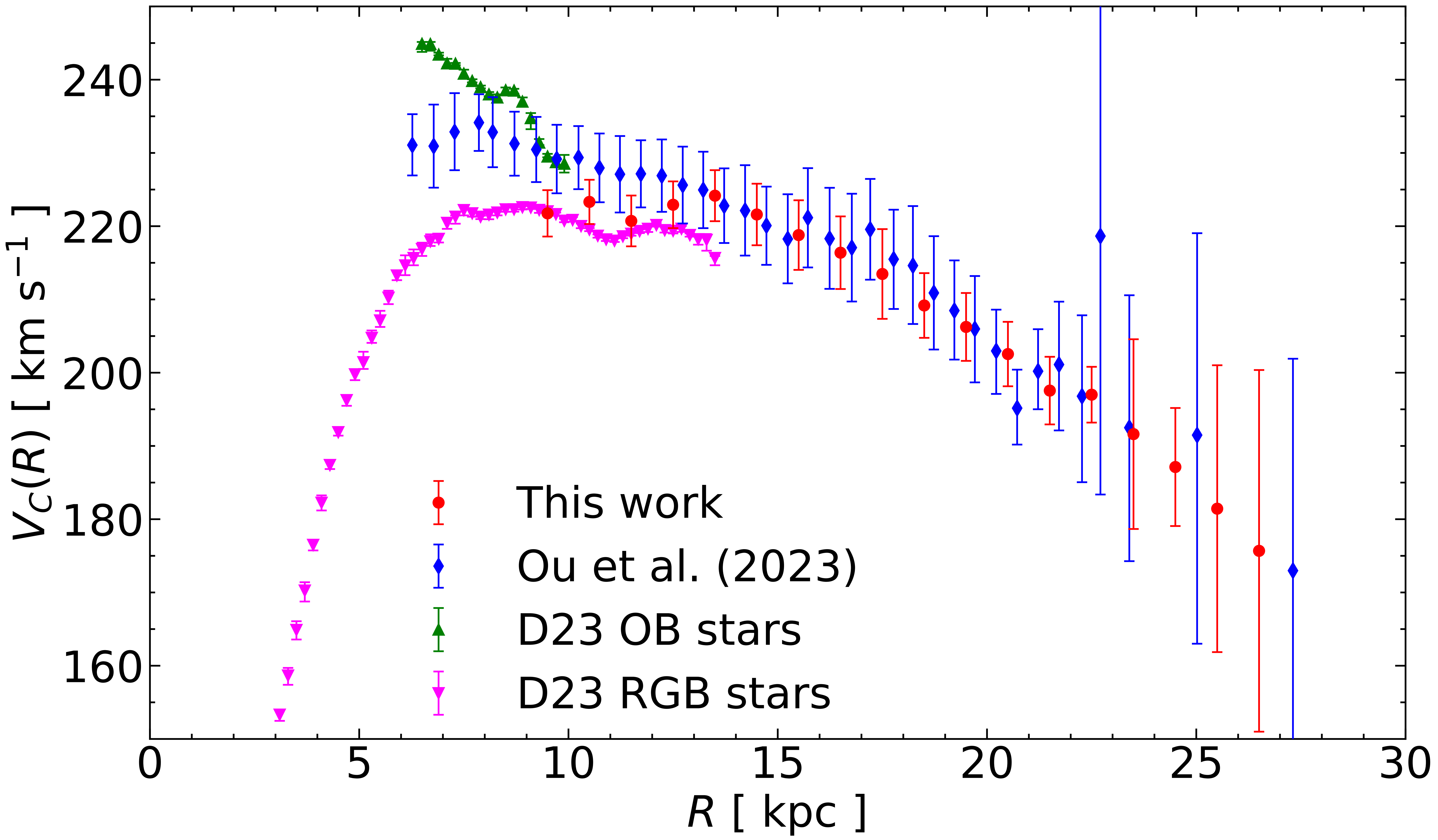


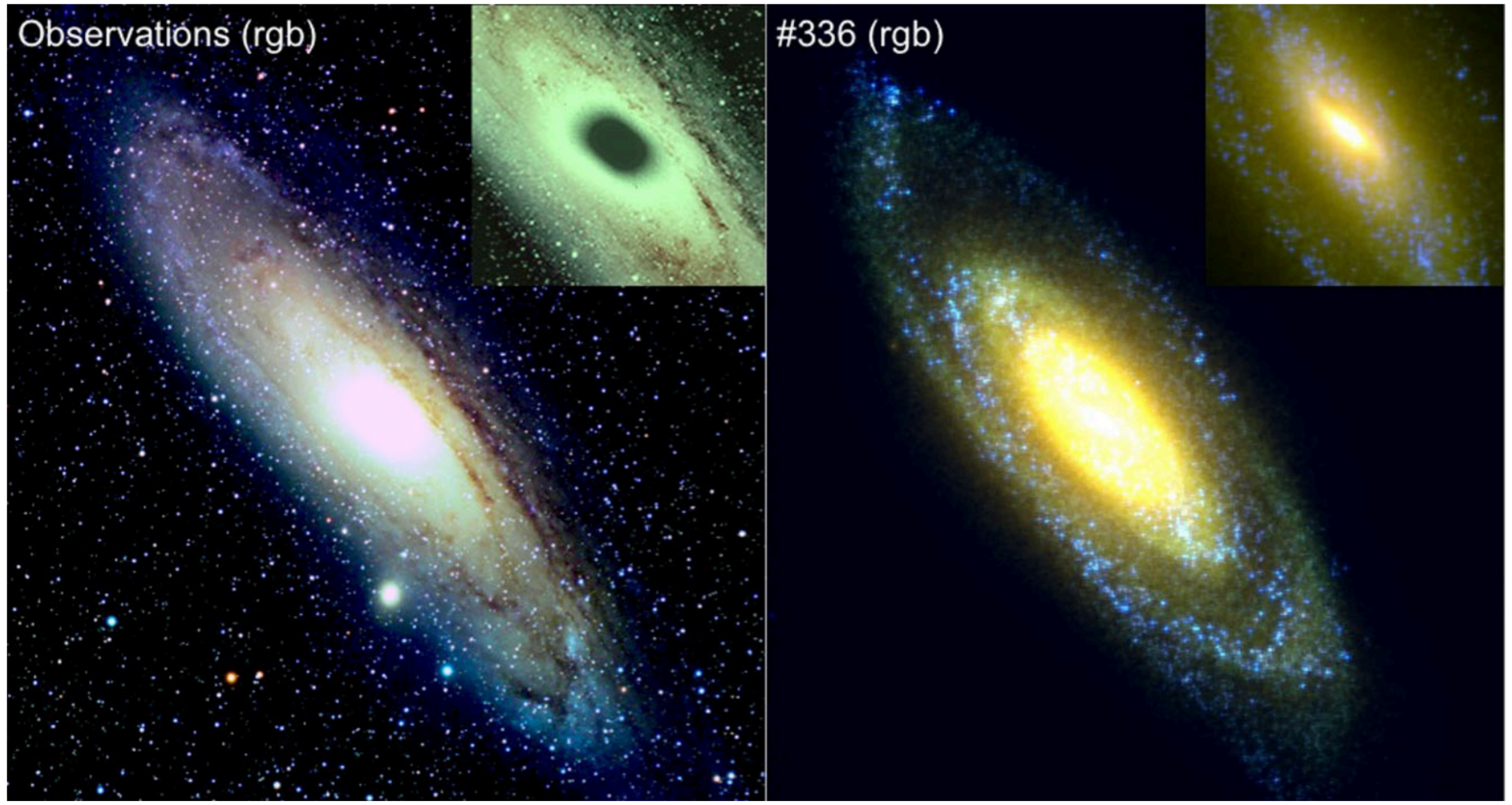
Hernquist profile

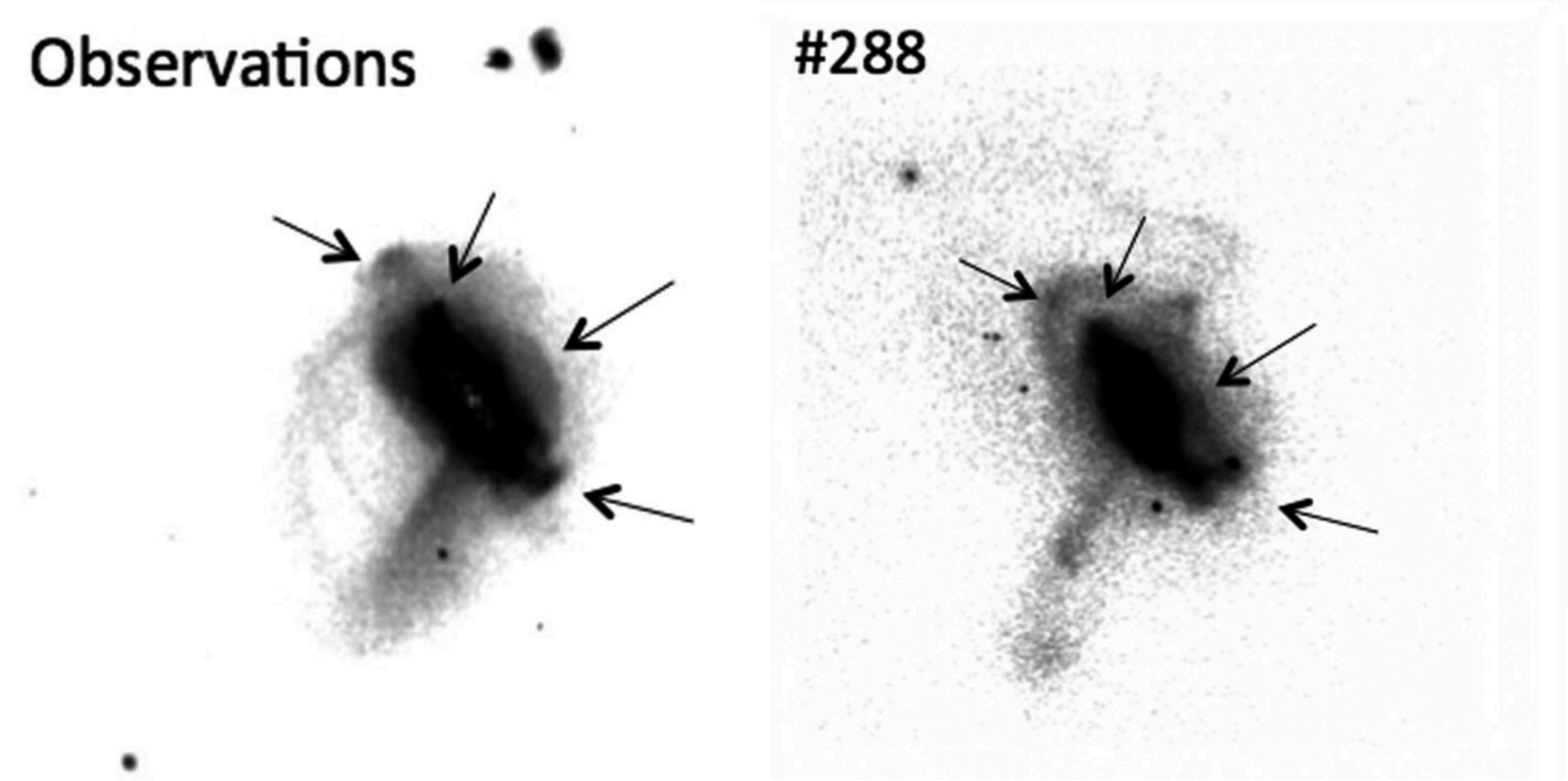


With *Gaia* DR2, our estimate of MW mass is $2.77 \times 10^{11} M_{\odot}$ with the Einasto profile

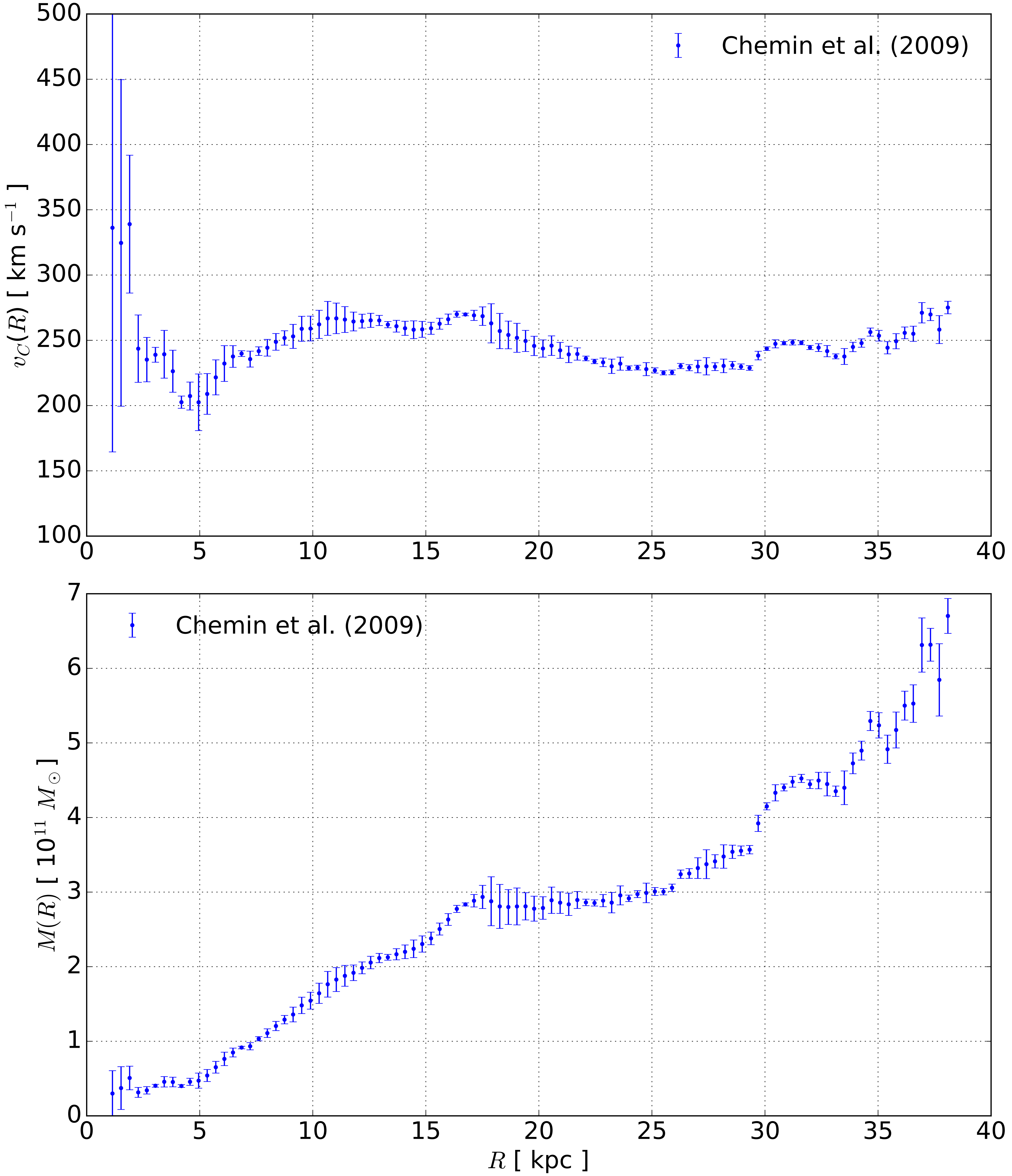
Milky Way rotation curve







For example, in M31 (Andromeda galaxy), there was a major merger ~**2-3 Gyr** ago, which could have a serious impact on the outskirts of M31 RC (Hammer et al 2018).



M31 RC and its dynamical mass profile