Dark Halos of M31 and the Milky Way

-- Their Dynamical Similarity –

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2015 03 24 @ MW2015, U.Tokyo

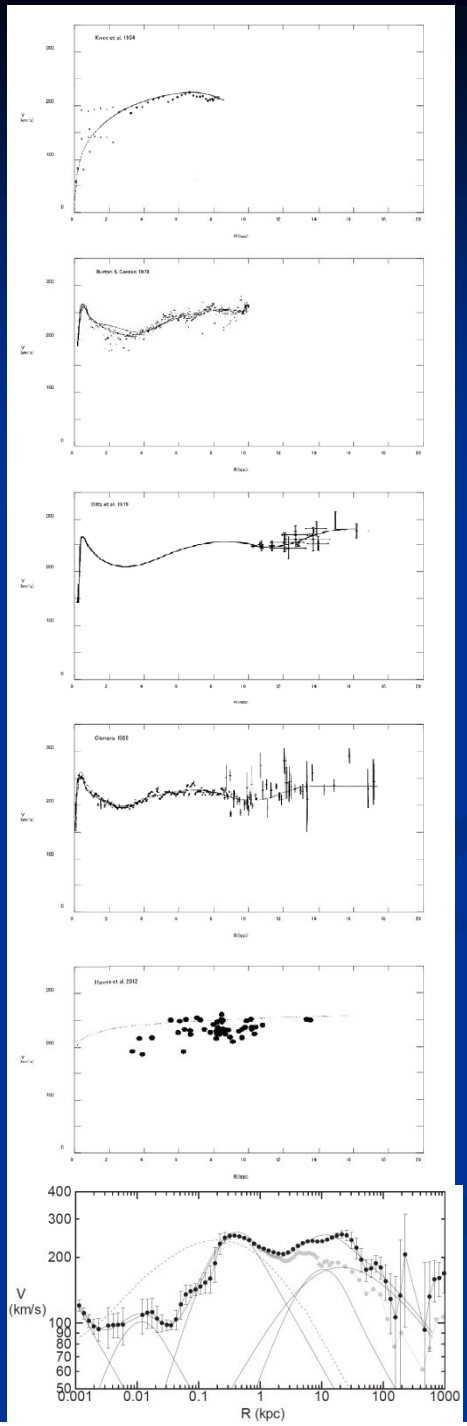
1. Introduction

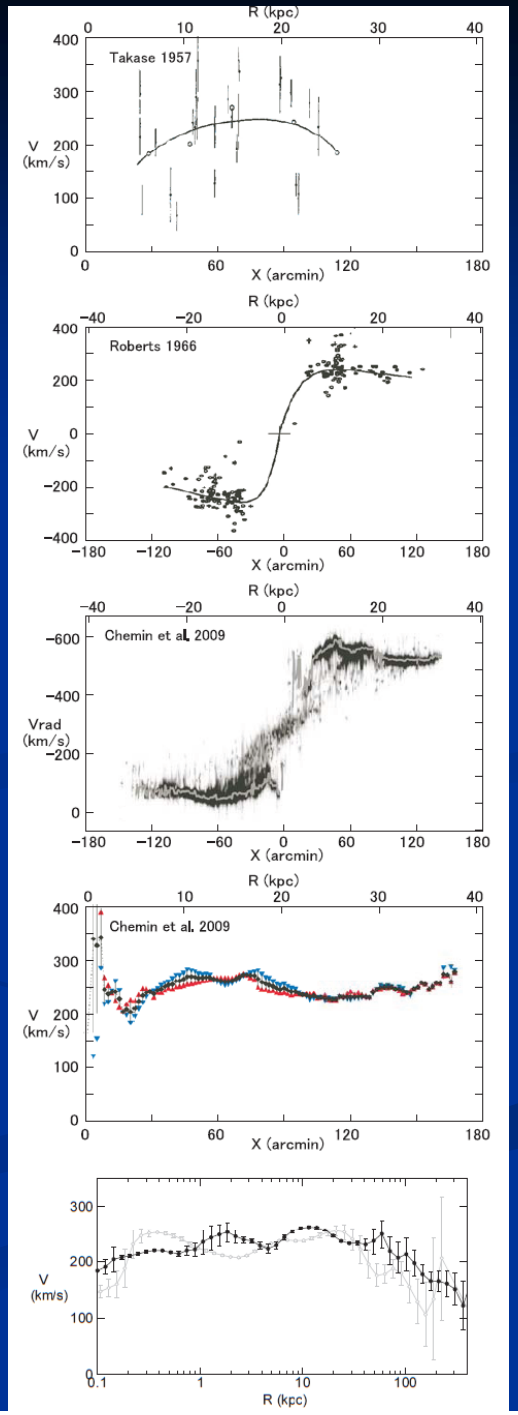
Progress in RC 1950's to 2015

MW
Kwee (1954) ~ VERA

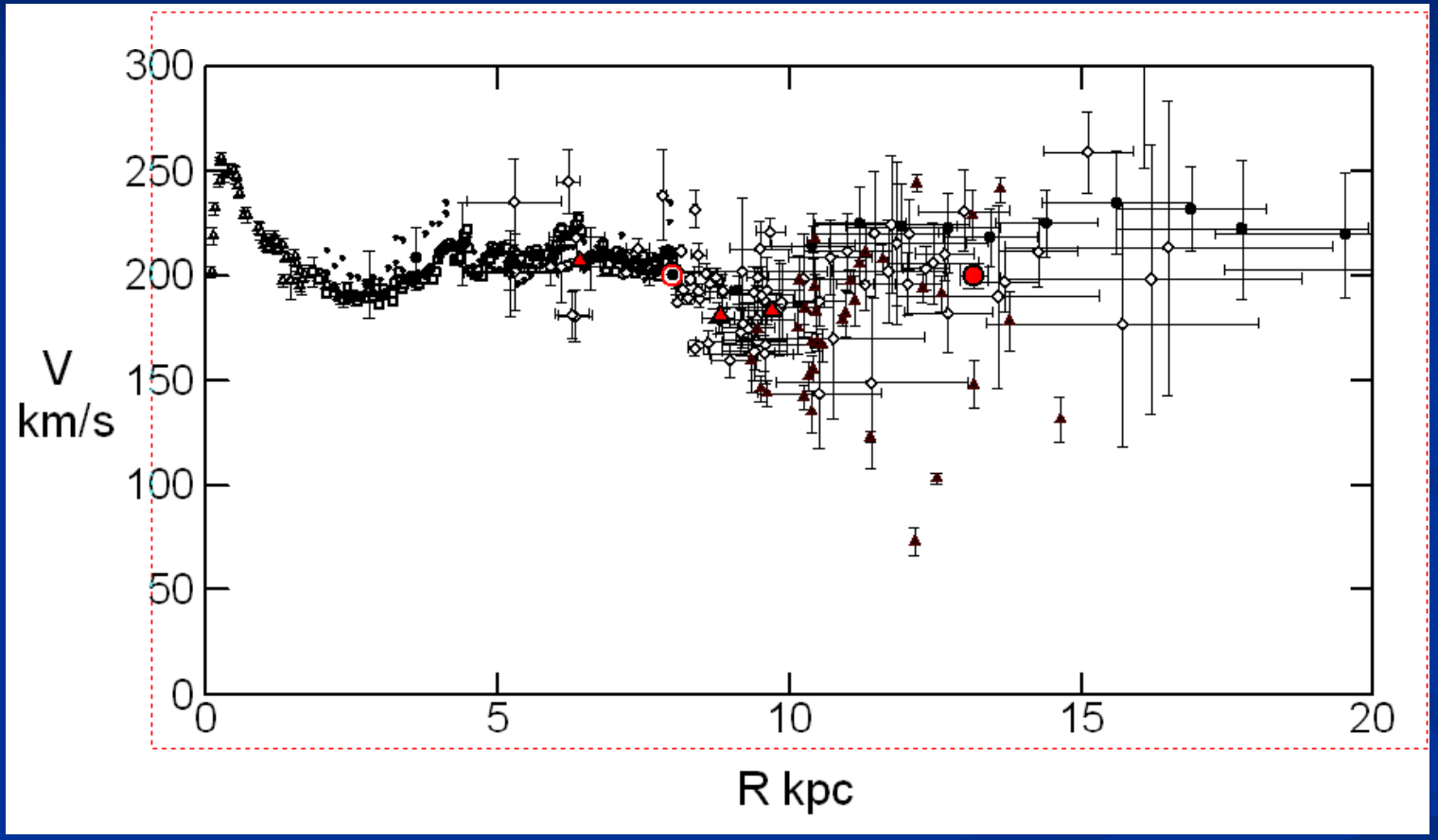
vs

M31
Takase (1957) ~



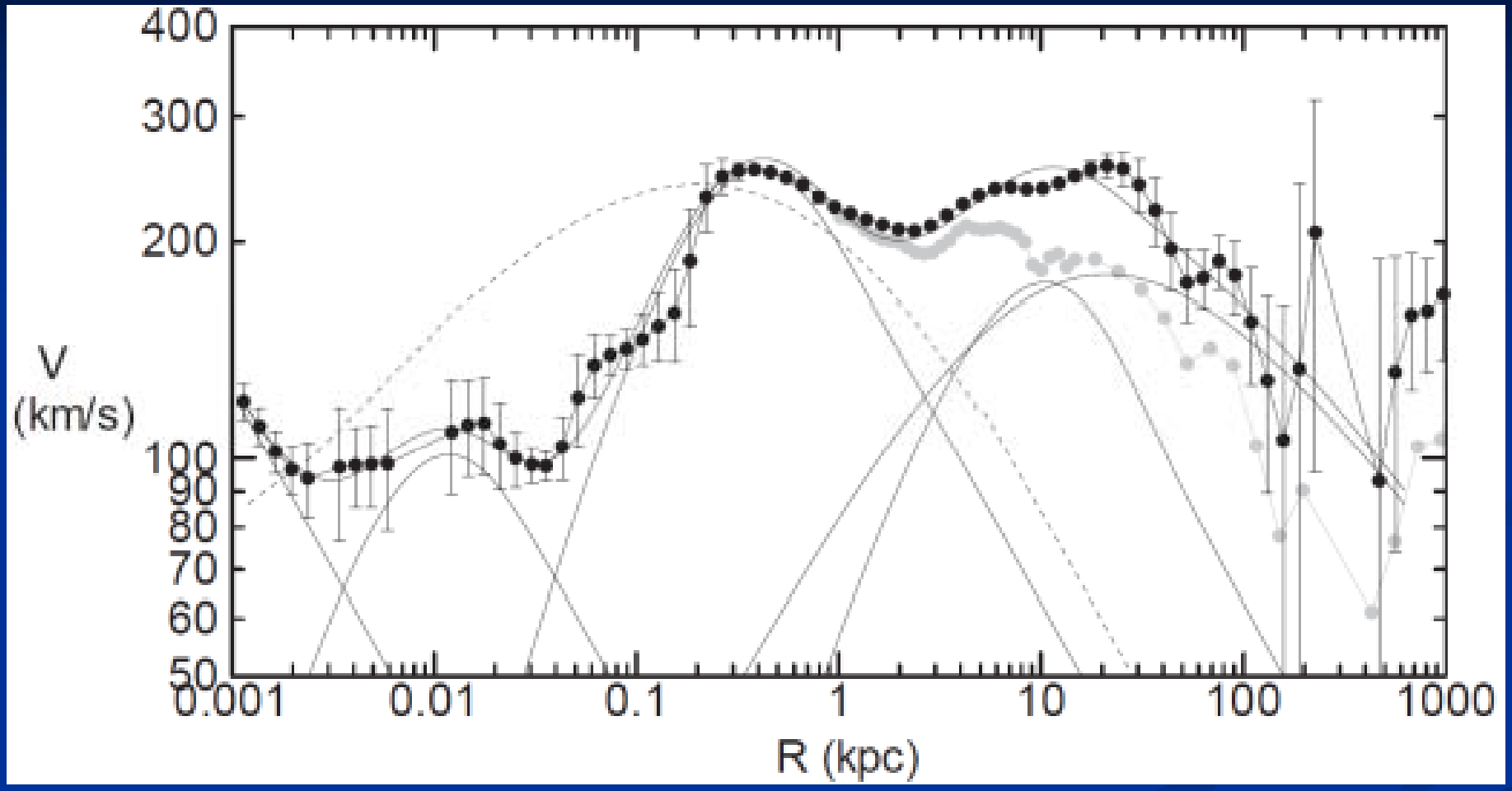


今までの
Rotation Curve

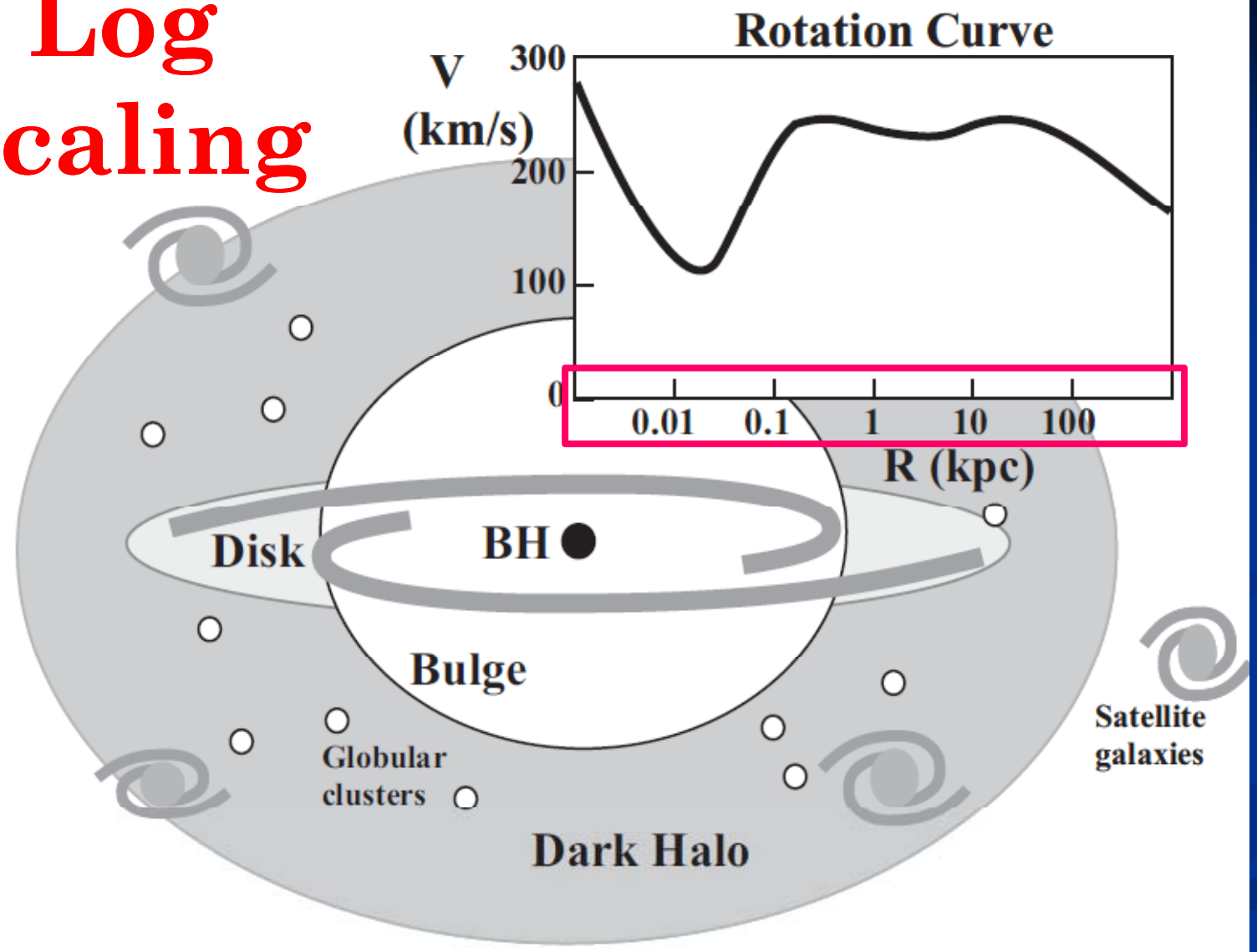


Sofue, Honma, Omodaka 2007

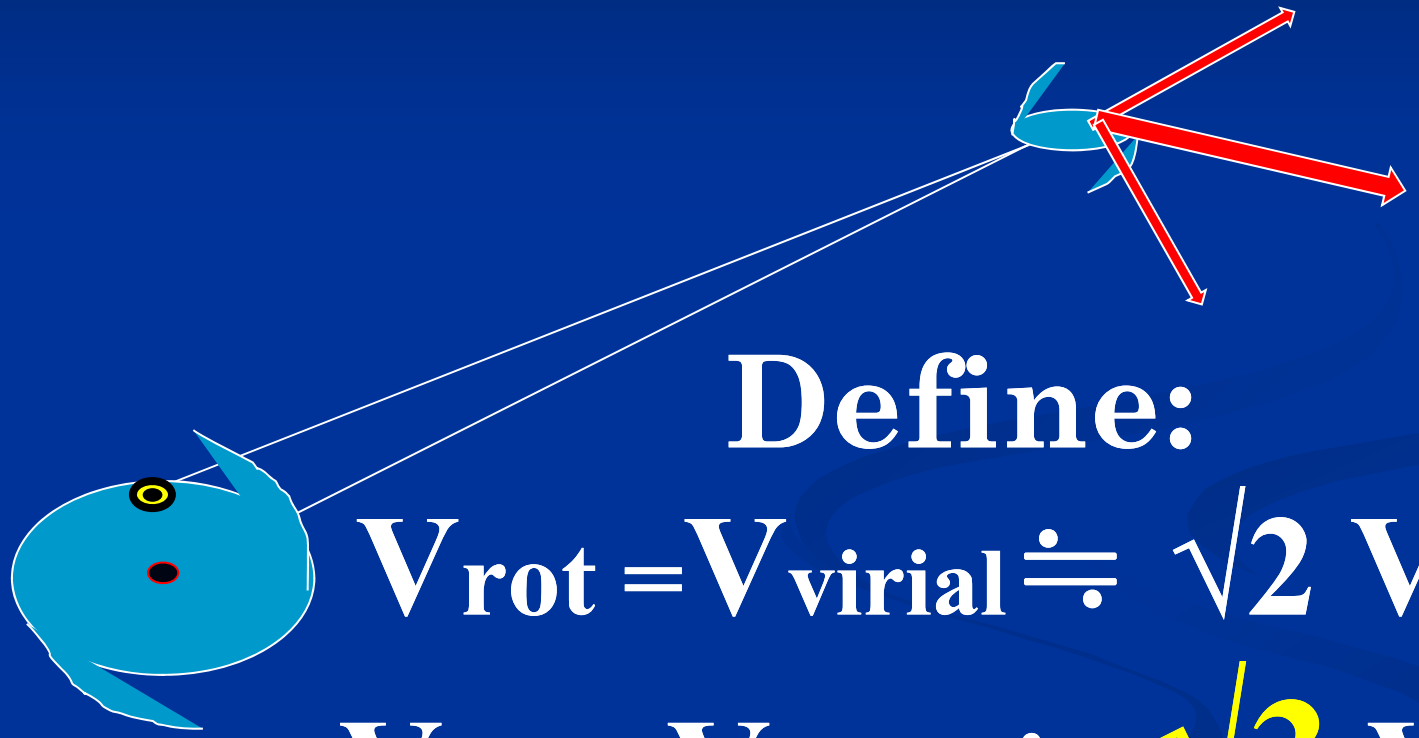
これからのLog Grand RC



Log Scaling


Rotation Curve
V
(km/s)
300
200
100
0
0.01
0.1
1
10
100
R (kpc)
Disk
BH
Bulge
Globular
clusters
Dark Halo
Satellite
galaxies

R>30 kpc
Globular clusters and satellite galaxies



Define:

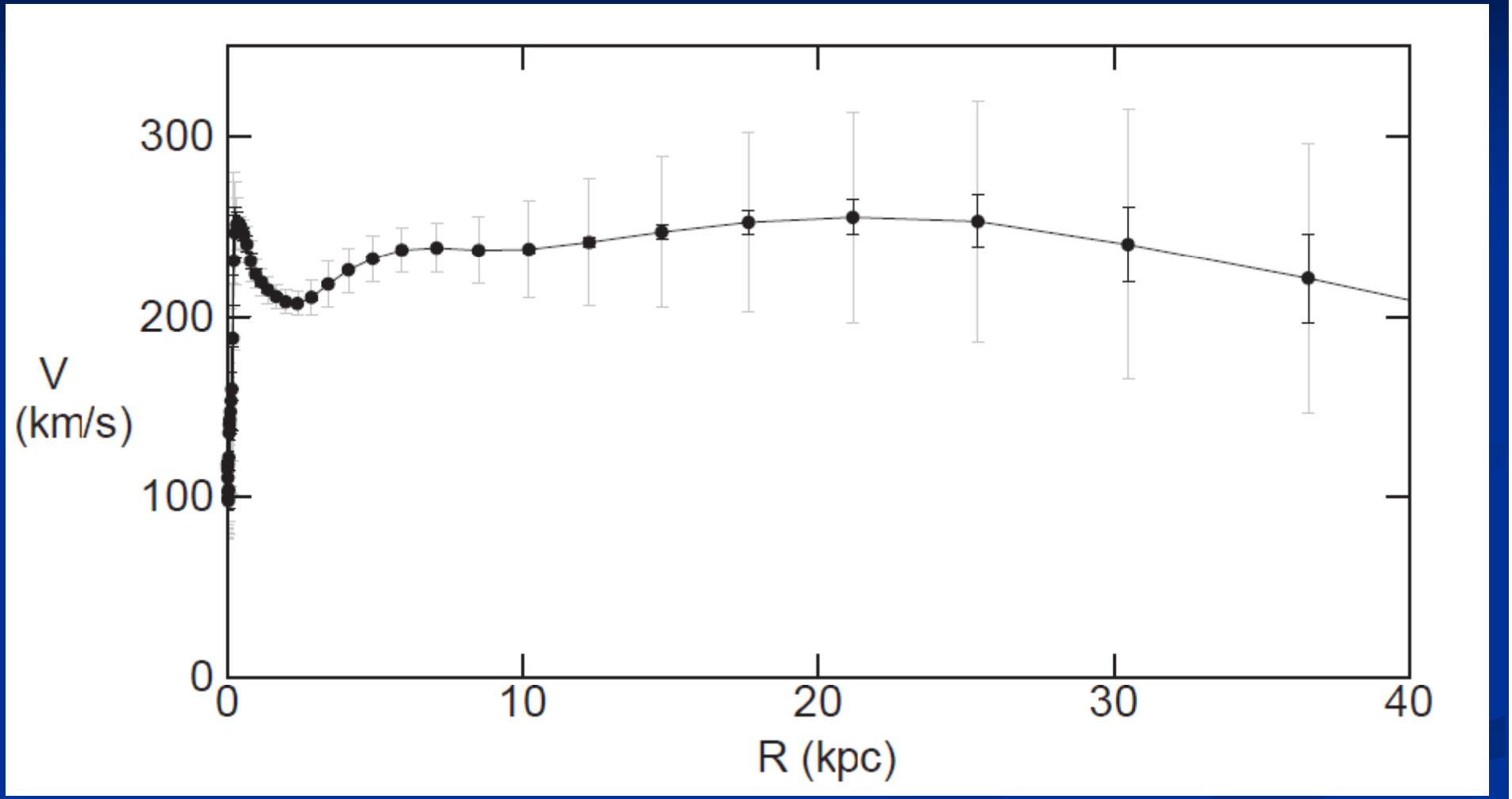
$$V_{rot} = V_{virial} \doteqdot \sqrt{2}\, V_{GC}$$

$$V_{rot} = V_{virial} \doteqdot \sqrt{3}\, V_{GC}$$

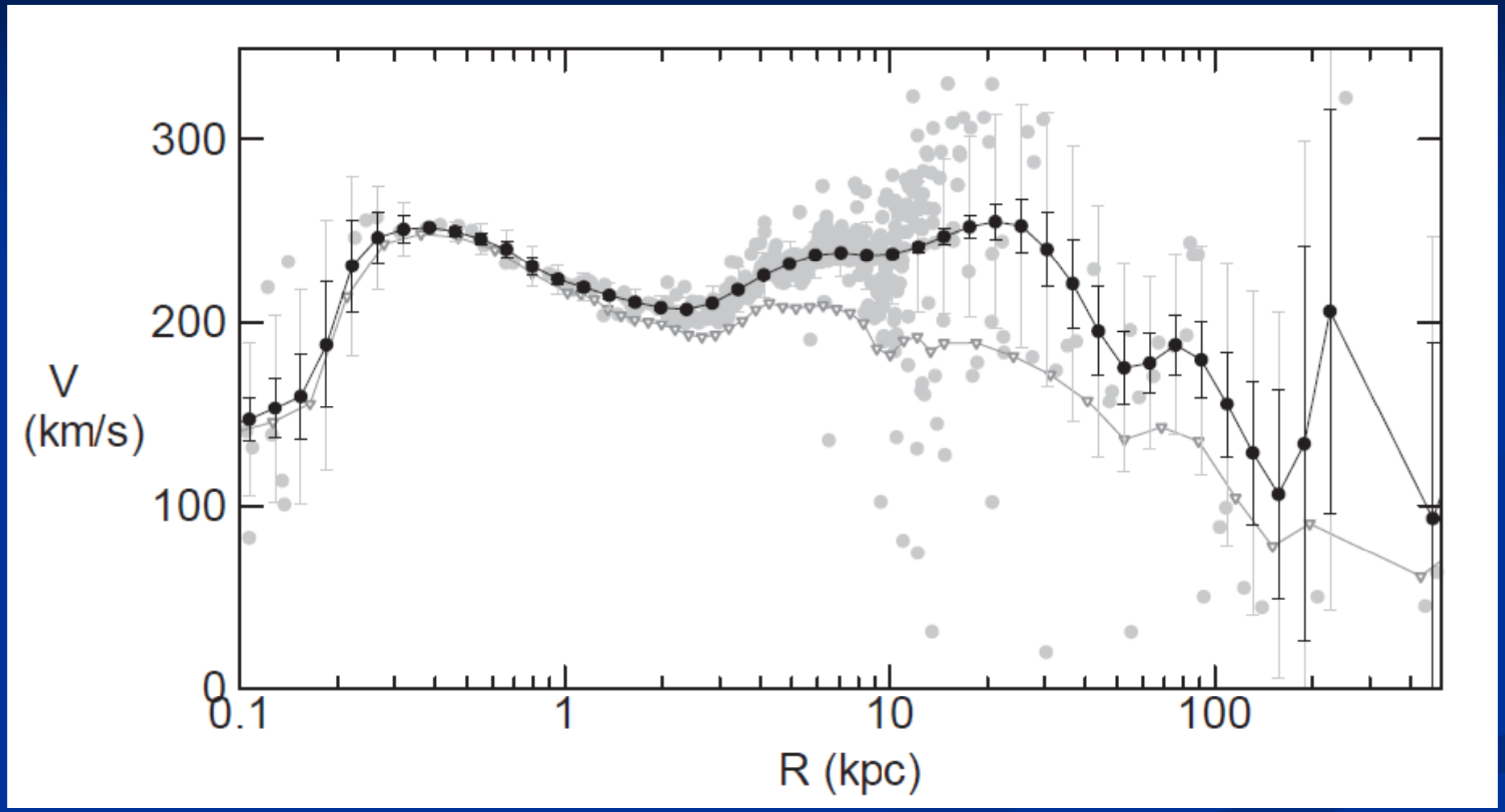
2. Log. Grand Rotation Curve

Milky Way

(8 kpc, 238 km/s)



GRC (8 kpc, 238 km/s)

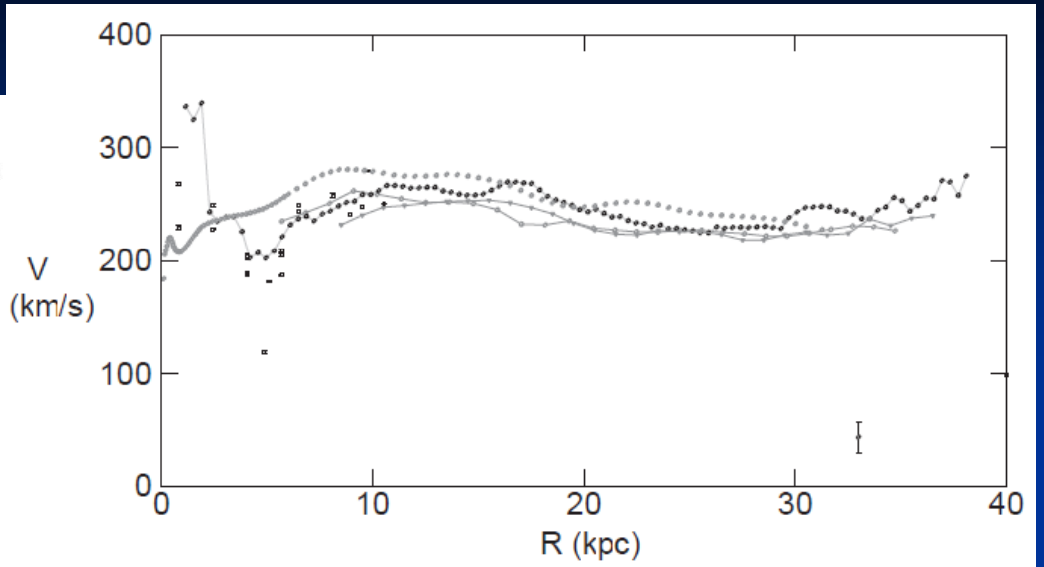


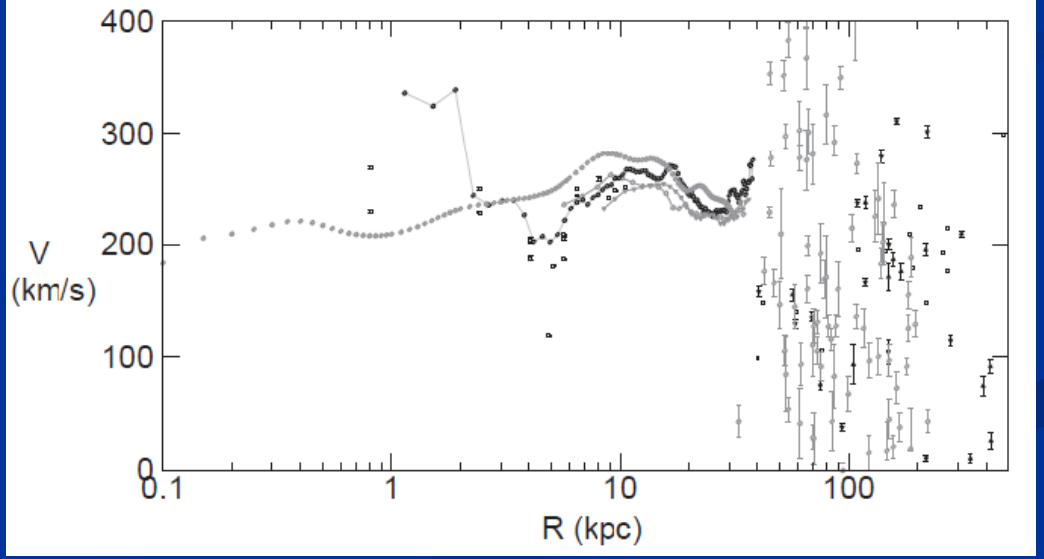
M31

M31

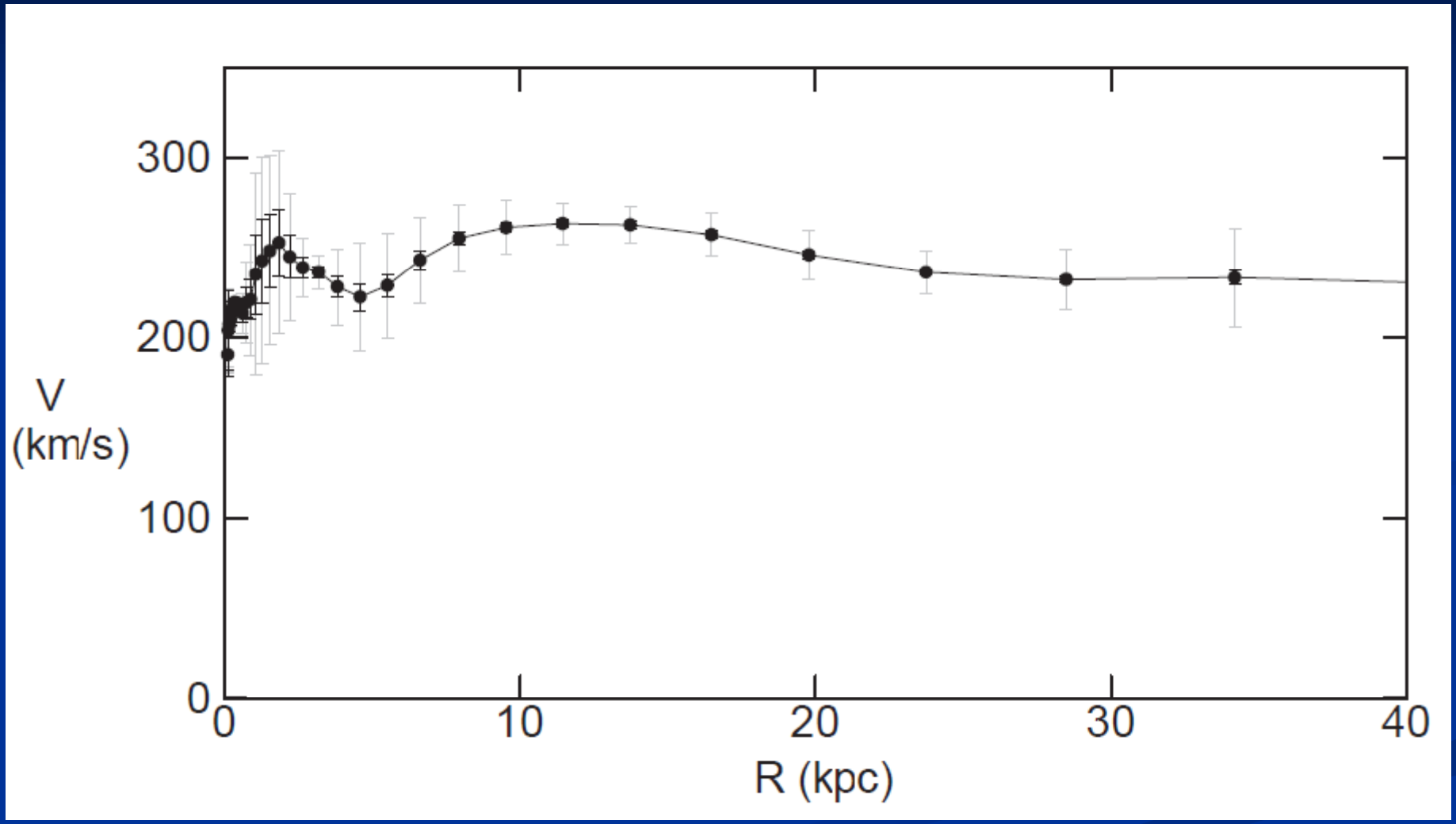
Table 1. References to the data in figure 1

Rectangles at $R < 10$ kpc	Disk RC (CO)	Loinard et al. (1995)
Grey circles at $R < 32$ kpc	ibid (combi: HI, CO, opt)	Sofue et al. (1981, 1999)
Grey open circles linked by line	ibid (HI)	Carignan et al. (2006)
Black-grey circles linked by line	ibid (HI, CO)	Chemin et al. (2009)
Grey reverse triangles linked by line	ibid (HI)	Corbelli et al. (2010)
Rectangles at $R > 40$ kpc	galaxies around M31	Metz et al. (2007)
Triangles with bars	ibid	van der Marel et al. (2008)
Reverse triangle at $R > 40$ kpc	ibid	Tollerud et al. (2012)
Open circles with bars	Globular clusters	Veljanovski et al. (2014)

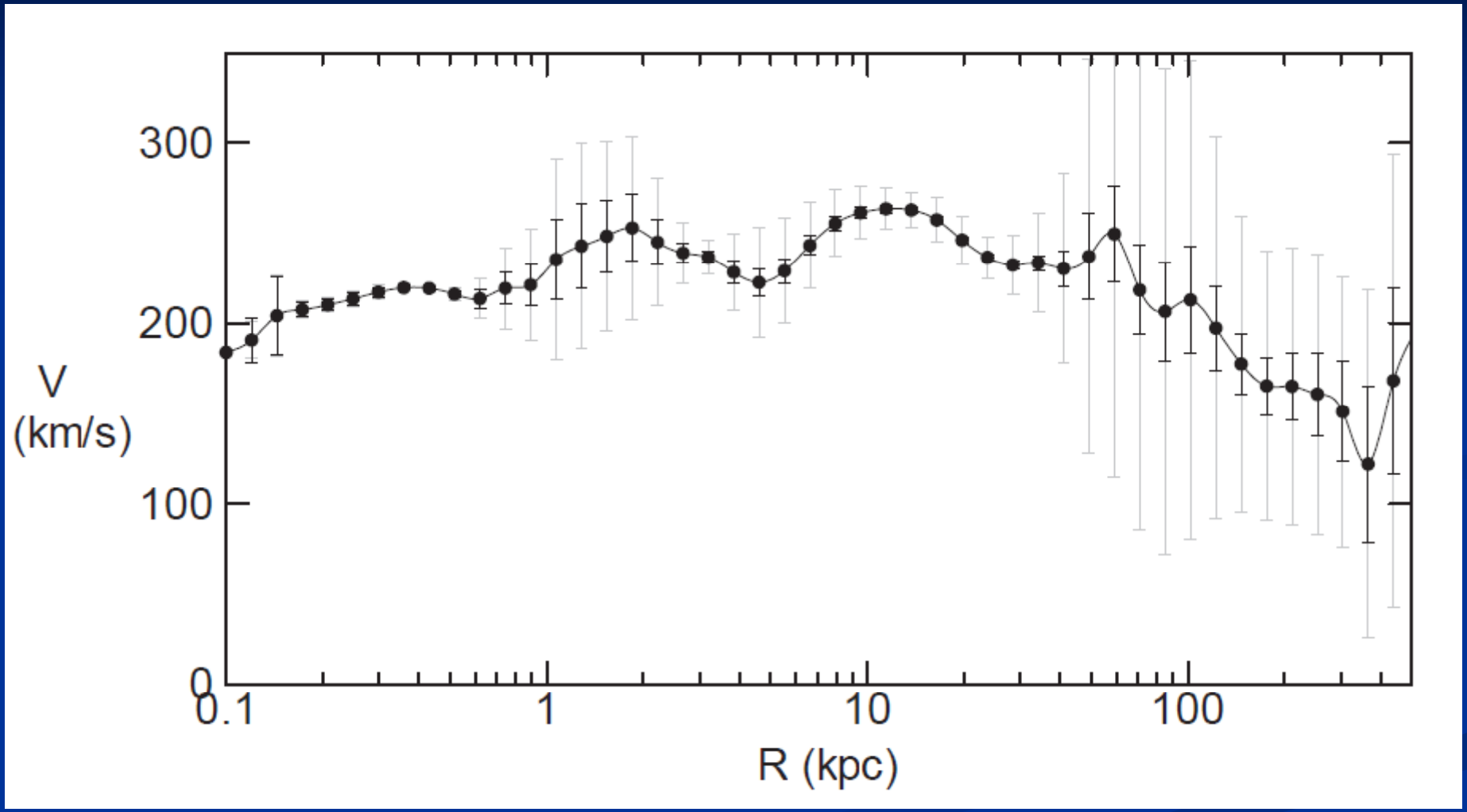




Grand Rotation Curve



Grand Rotation Curve



3. Deconvolution into Bulge,Disk, & Dark Halo

(1) Bulge de Vaucouleurs:

$$\Sigma_b(r) = \lambda_b B_b(r) = \Sigma_{be} \exp\left[-\kappa\left(\left(\frac{r}{R_b}\right)^{1/4} - 1\right)\right]$$

$$\rho(r) = \frac{1}{\pi}\int_r^\infty \frac{d\Sigma_b(x)}{dx}\frac{1}{\sqrt{x^2 - r^2}}dx$$

$$M_b(R) = 4\pi \int_0^R r^2 \rho(r) dr. \qquad M_{\rm b} = 22.665 a_{\rm b}^2 \Sigma_{\rm be}$$

$$V_b(R) = \sqrt{\frac{GM_b(R)}{R}}.$$

(2) Disk: Exponential

$$V_{\rm d}(R) = \sqrt{\frac{GM_{\rm d}}{a_{\rm d}}}\mathscr{D}(X),$$

where $X = R/a_{\rm d}$, and

$$\mathscr{D}(X) = (X/\sqrt{2}) \times$$

$$\times \left[\{I_0(X/2)K_0(X/2) - I_1(X/2)K_1(X/2)\}\right]^{1/2}$$

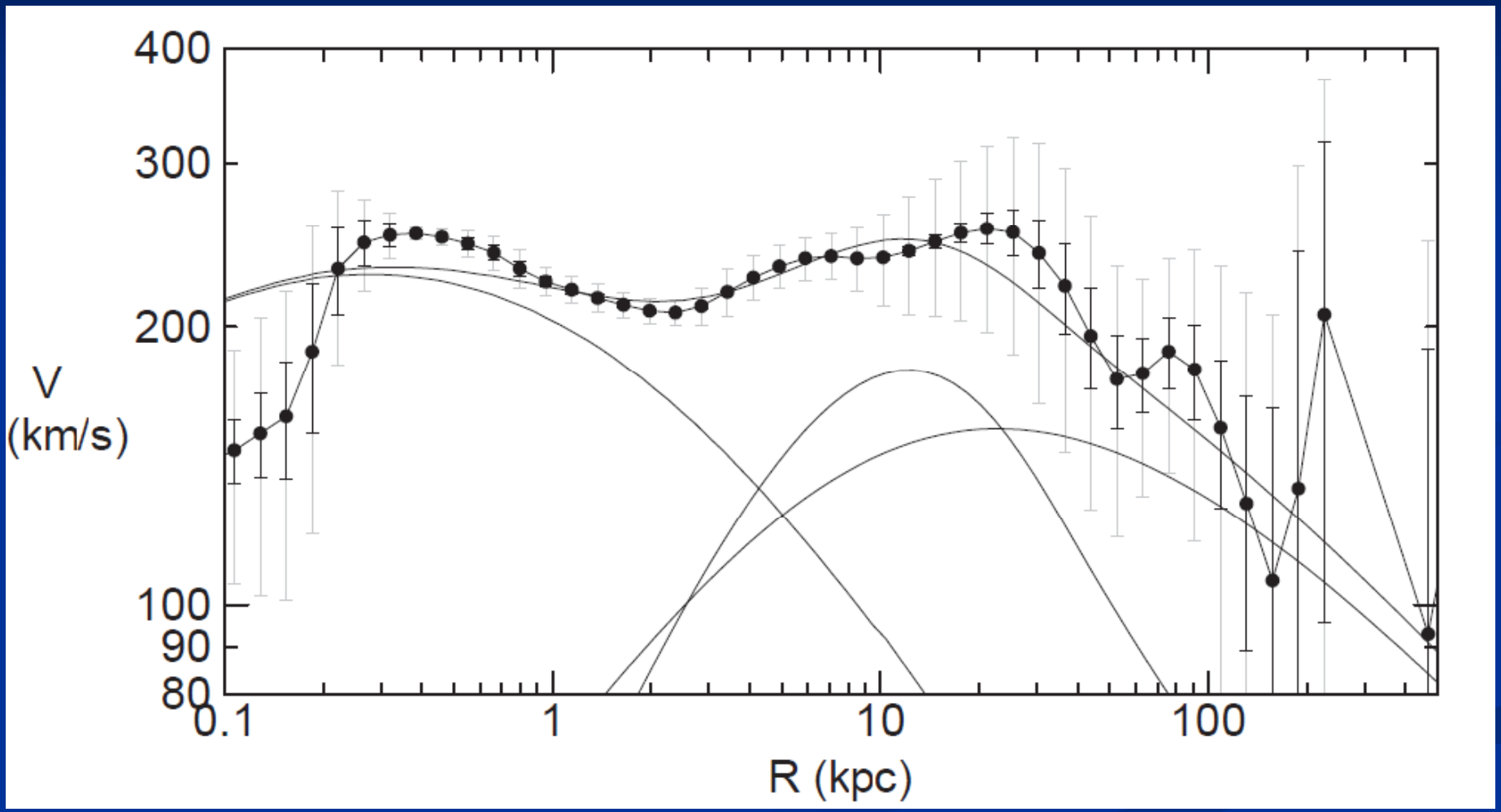
(3) Dark Halo
Navarro-Frenk-White (1996)
Density Profile

$$X = R/h$$

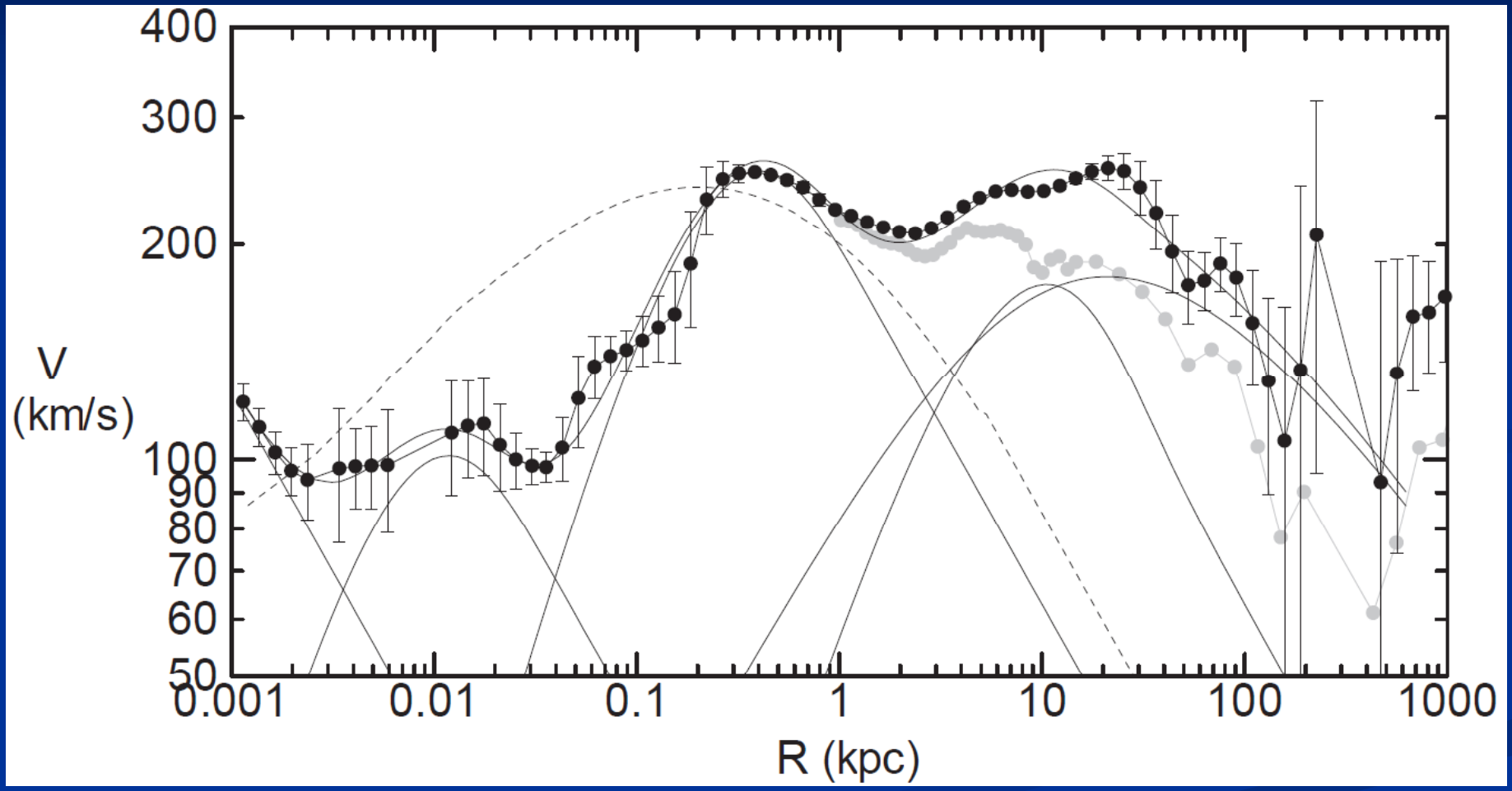
$$\rho(R) = \frac{\rho_0}{X\,(1+X)^2},$$

$$M_{\rm h}(R) = 4\pi\rho_0 h^3 \left\{ \ln(1+X) - \frac{X}{1+X} \right\}.$$

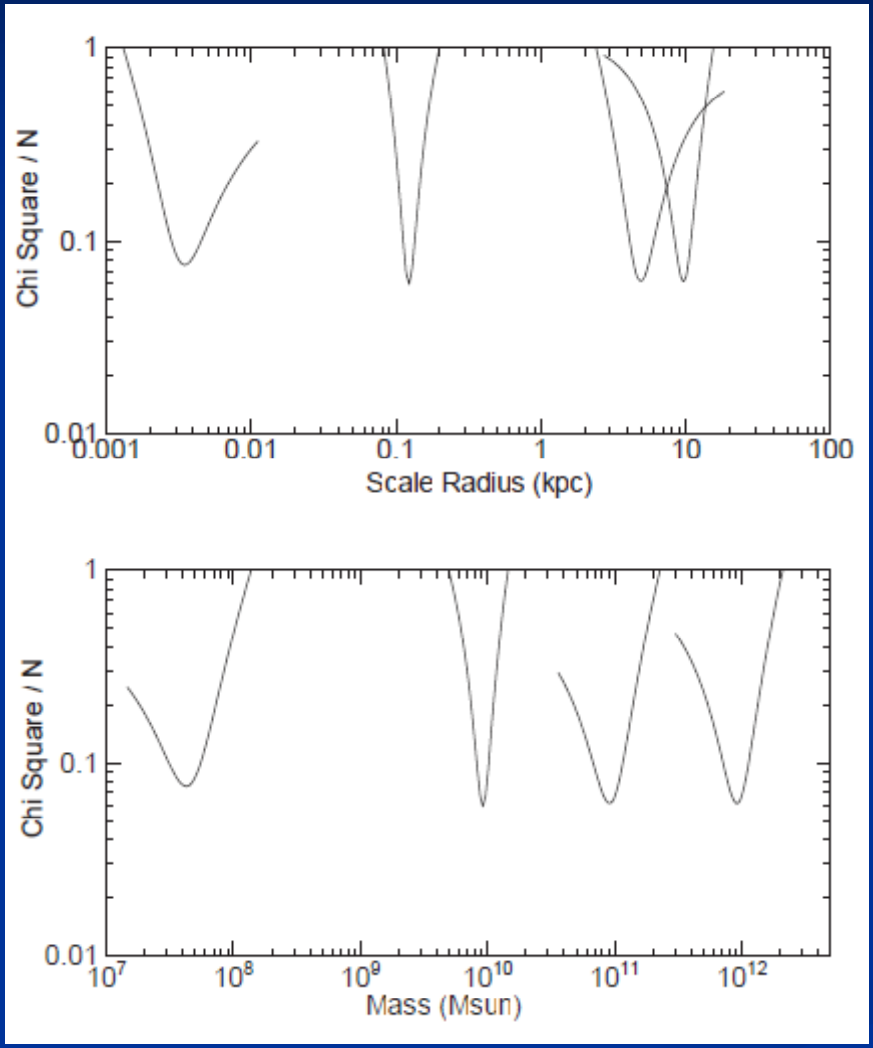
MW GRC Decomposition

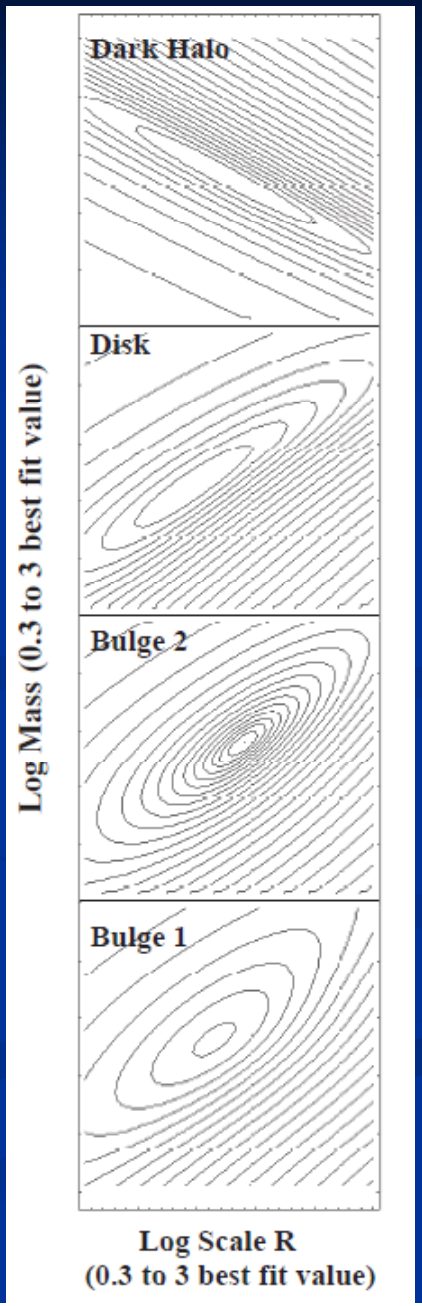


Two-Expo. Bulge Decomposition

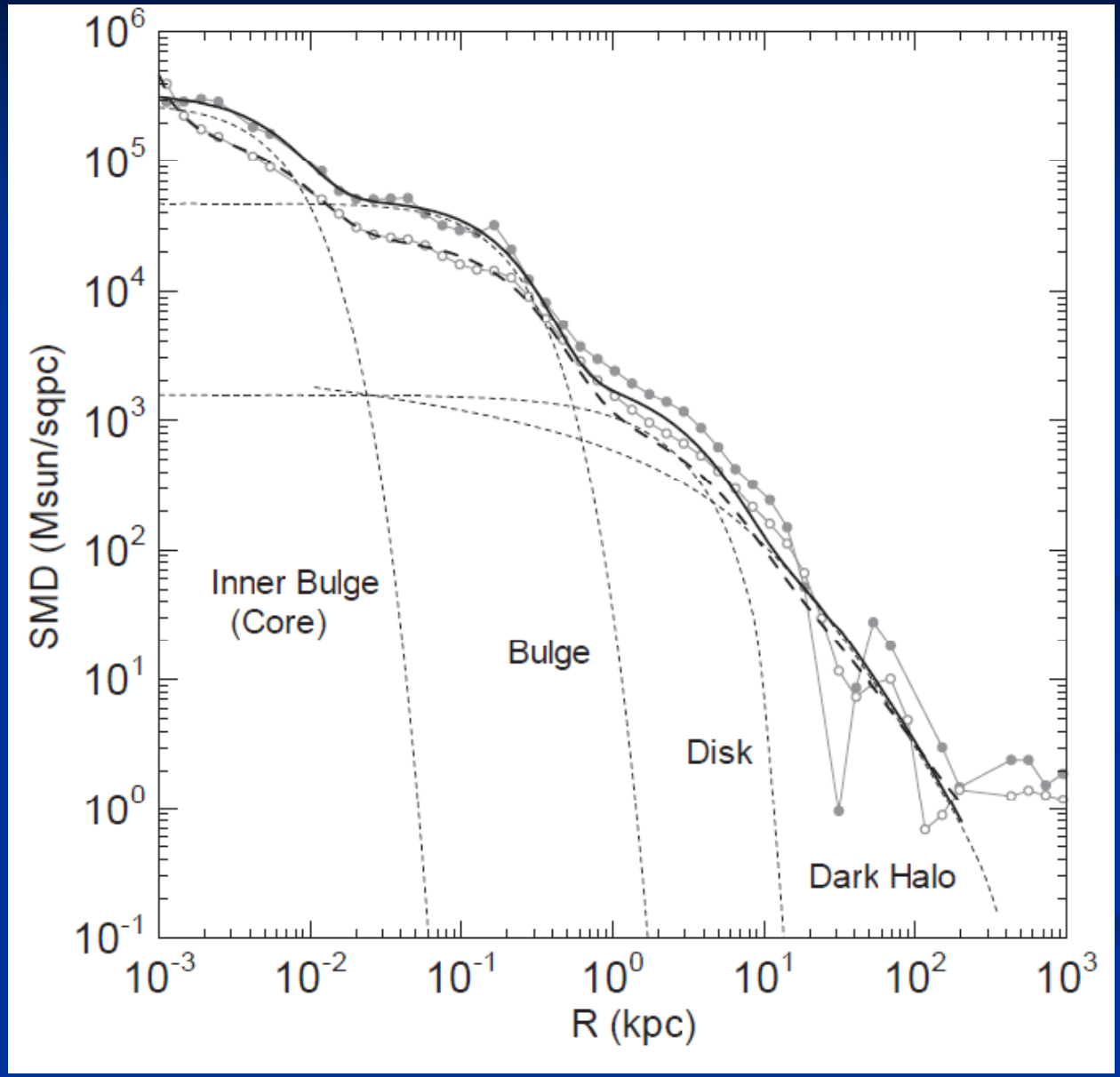


Chi-Square Fitting

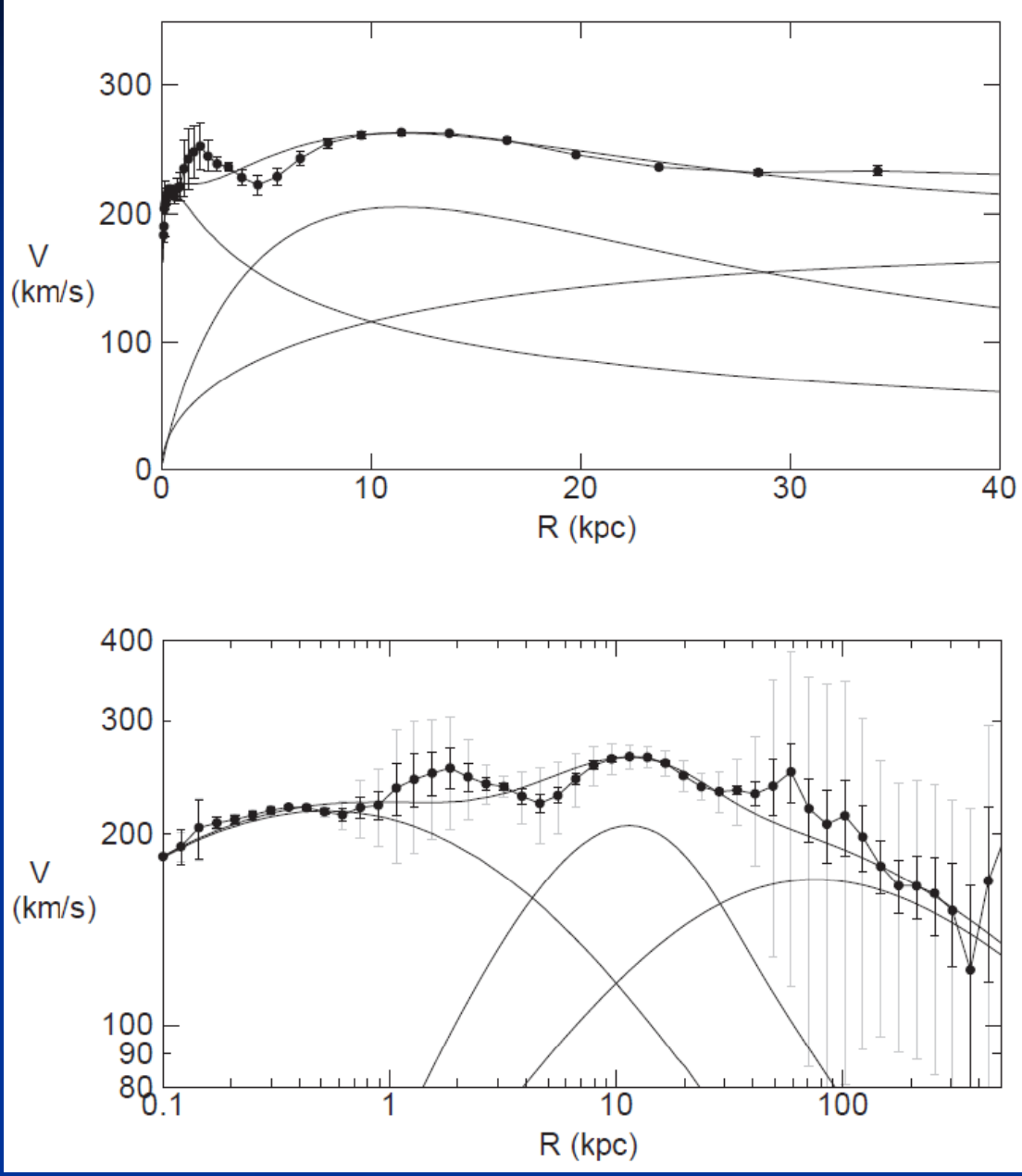




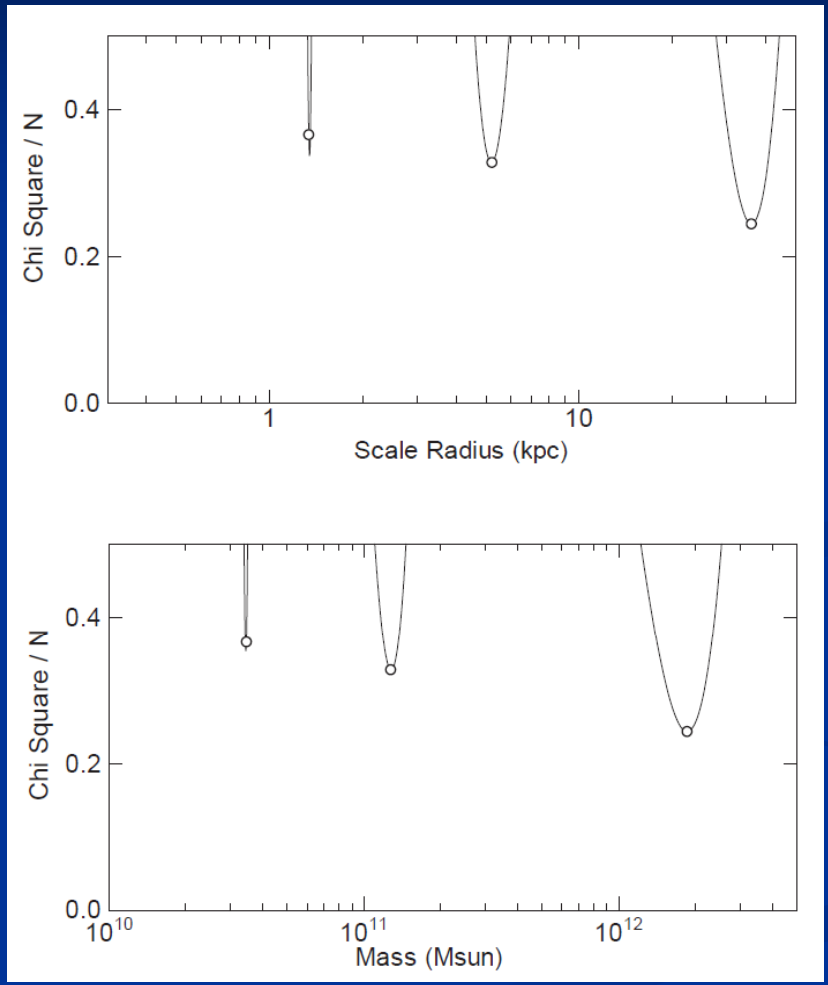
SMD : Obs vs Model



M31 Fitting

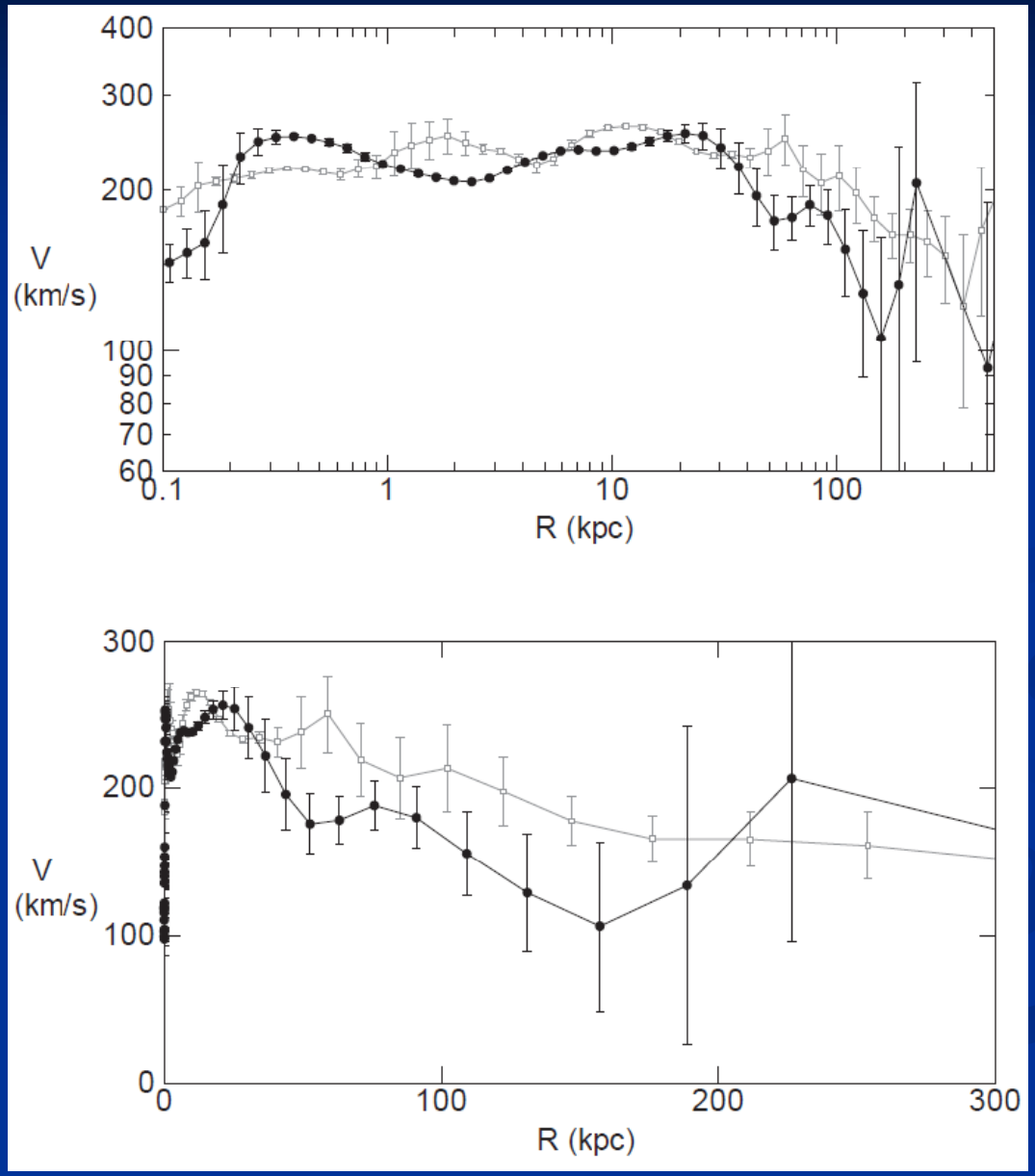

300
200
100
0
V
(km/s)
0
10
20
30
40
R (kpc)
400
300
200
100
90
80
V
(km/s)
0.1
1
10
100
R (kpc)

Chi square map

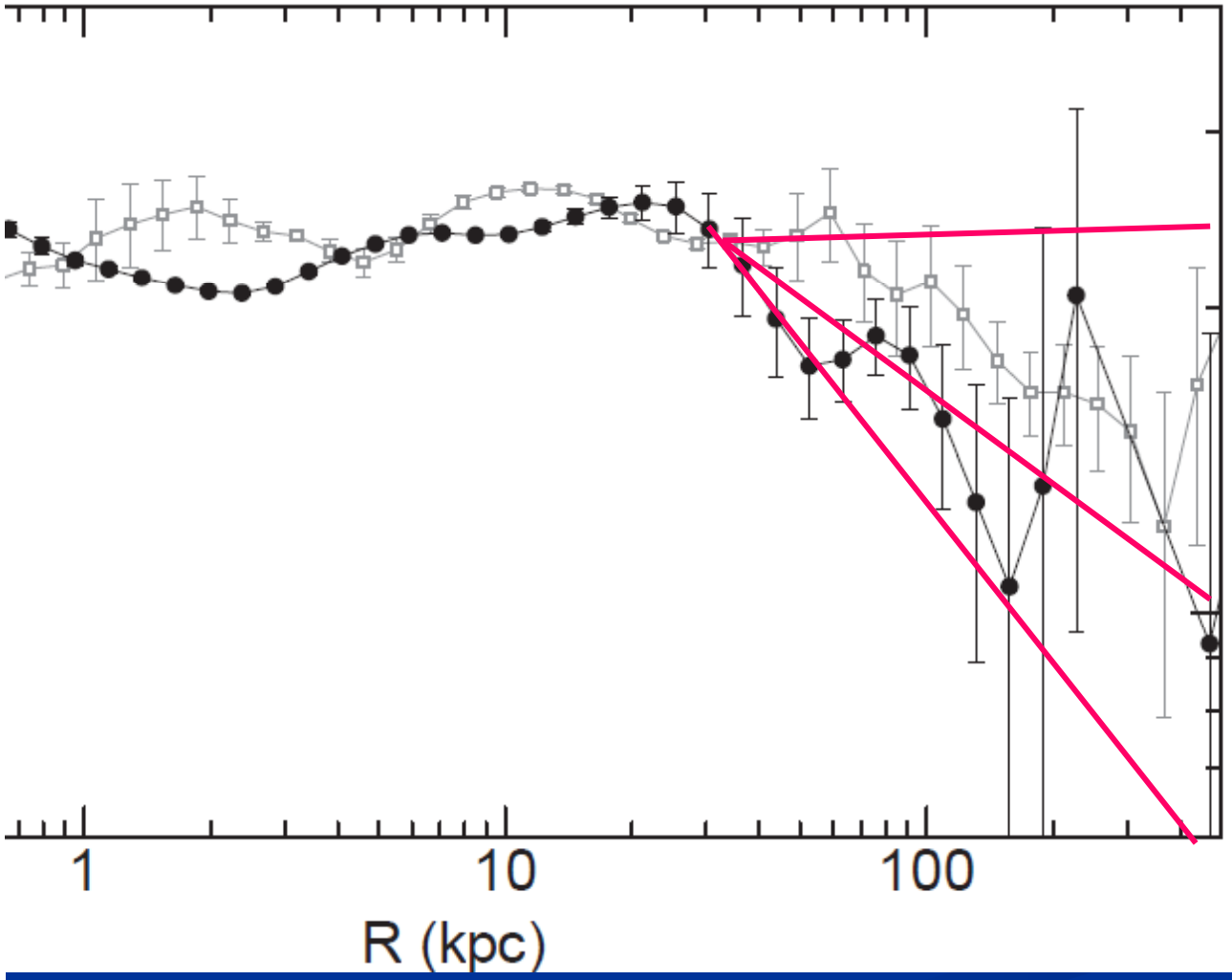


5. Dark Halo Similarity in MW and M31

Log RC: MW / M31 Dark Halos



Universal Dark Halo RC

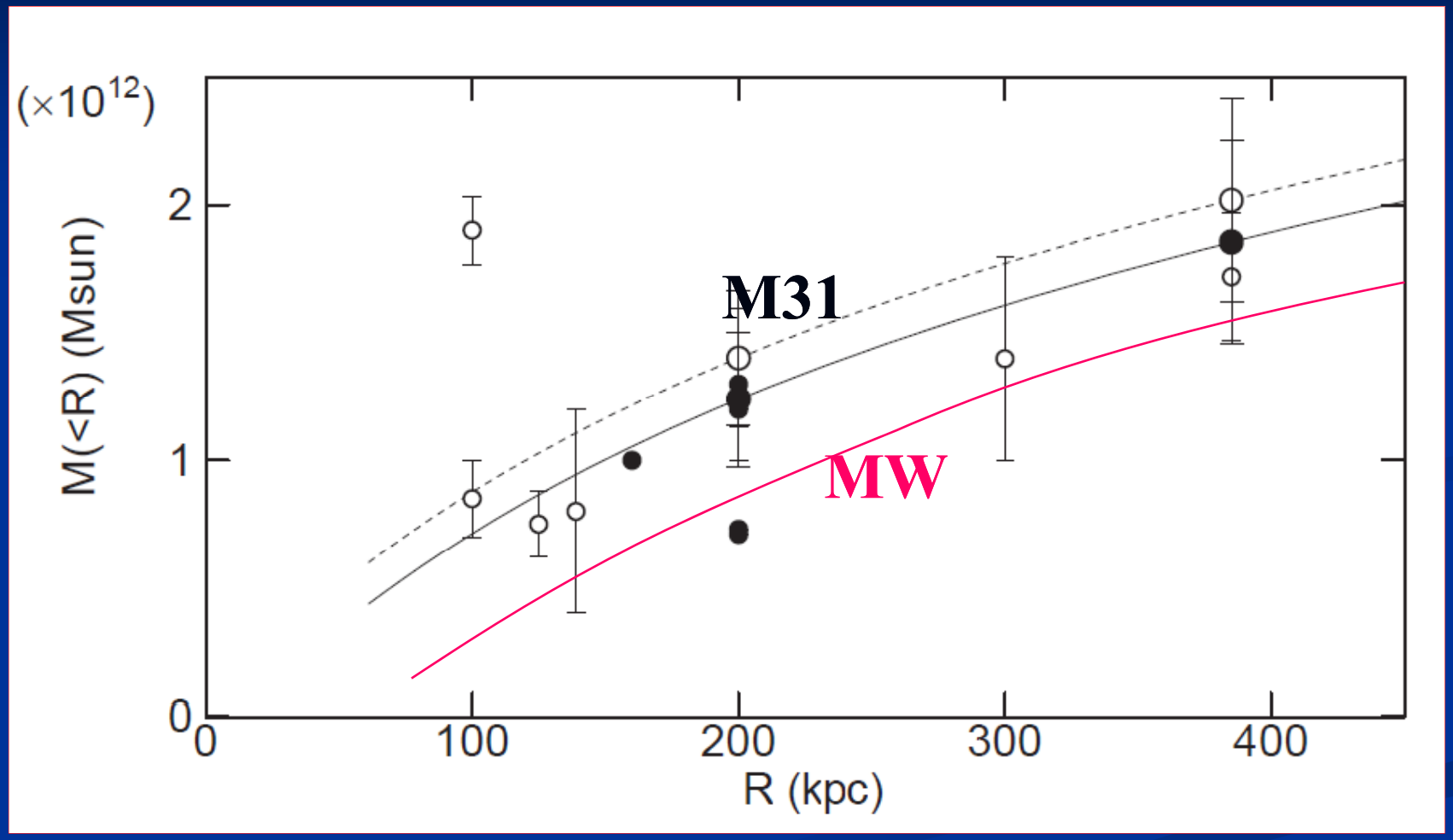


Isotherma

NFW

Kepler

DH Mass: M31 vs MW



Best Fit Parameters

Table 2. The best fit dynamical parameters for M31 and the Galaxy†

Component	Parameter	M31	Milky Way
Bulge	$a_{\rm b}$ (kpc)	1.34 ± 0.02	0.72 ± 0.07
	$M_{\rm b}(10^{11} M_{\odot})$	0.35 ± 0.00	0.20 ± 0.02
Disk	$a_{\rm d}$ (kpc)	5.23 ± 0.32	5.68 ± 1.21
	$M_{\rm d}(10^{11} M_{\odot})$	1.27 ± 0.08	1.10 ± 0.40
NFW Halo	h (kpc)	36.01 ± 2.20	10.56 ± 2.86
	$\rho_0(10^{-3} M_{\odot} {\rm pc}^{-3})$	2.05 ± 0.23	18.46 ± 7.55
	$\rho_{8\ {\rm kpc}}(10^{-3} M_{\odot} {\rm pc}^{-3})$	6.17 ± 0.68	7.89 ± 3.22
	–(GeV cm^{-3})	0.23 ± 0.03	0.30 ± 0.12
	$M_{\rm h:200}(10^{11} M_{\odot})$	12.40 ± 2.65	5.58 ± 5.07
	$M_{\rm h:385}(10^{11} M_{\odot})$	18.55 ± 3.96	7.24 ± 6.58
Total Mass	$M_{\rm tot:200}(10^{11} M_{\odot})$	14.02 ± 2.65	6.88 ± 5.09
	$M_{\rm tot:385}(10^{11} M_{\odot})$	20.17 ± 3.96	8.54 ± 6.59

Conclusion and Implication

1. GRC MW similar to M31.
2. NFW is a good model.
   (vs Isothermal, Plummer)

3. Assume NFW universal.
4. Determine DH in ~100 galaxies.
5. Statistics: Baryonic Bulge, Disk,
   vs Dark Halo.

For references, visit

http://www.ioa.s.u-tokyo.ac.jp/~sofue/h-rot.htm