Grand Rotation Curves & Galactic Roche Lobes in the Galaxy and M31

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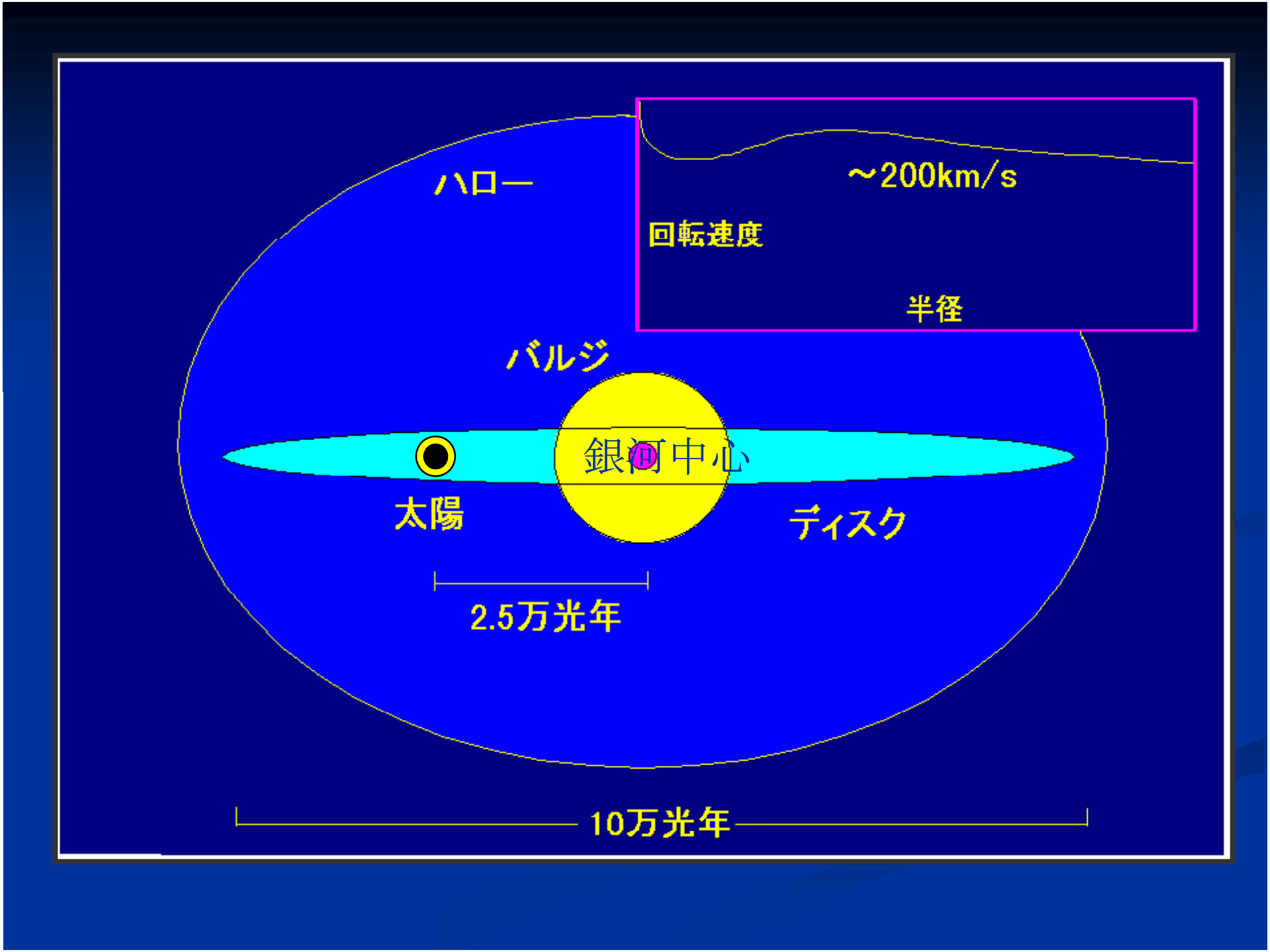
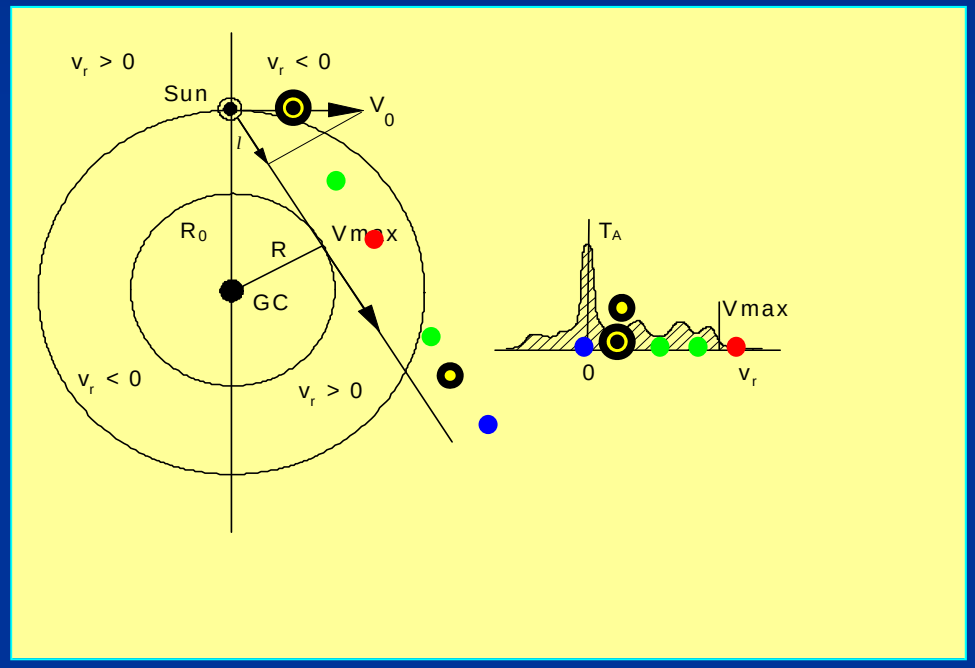
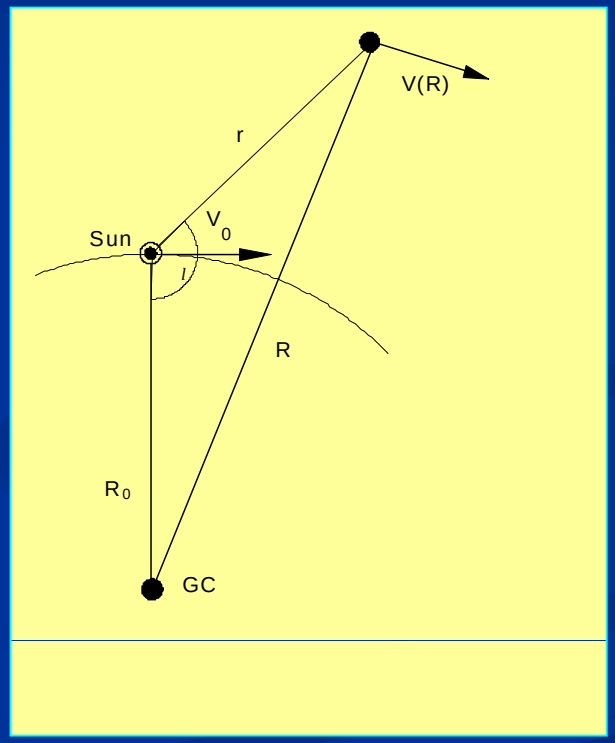
Contents

1. Rotation Curve


ハロー
～200km/s
回転速度
半径
バルジ
銀河中心
太陽
ディスク
2.5万光年
10万光年

Rotation velocities inside/outside Solar Circle



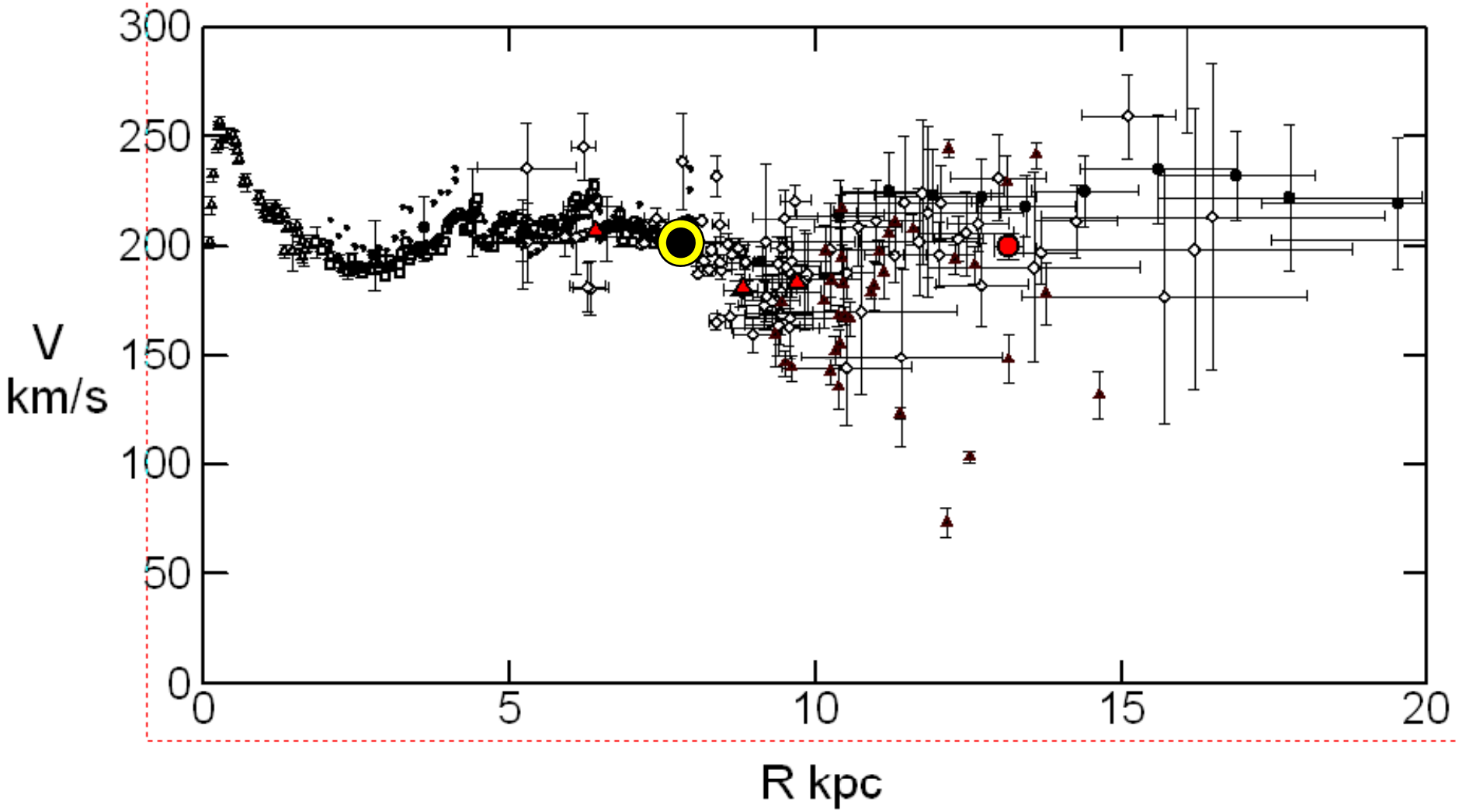


Rotation curve at R>30 kpc assuming random motion of satellite galaxies

Define:

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

Solar Circular Velocity V_0=200 km/s @ R_0=8kpc



2. Mass Model

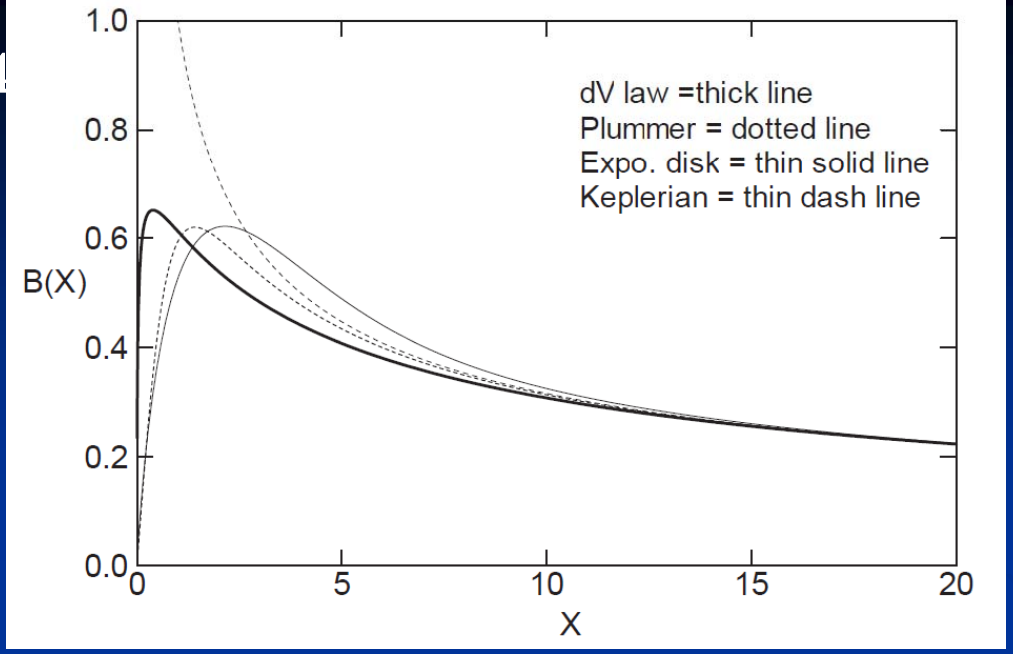
RC Fitting by

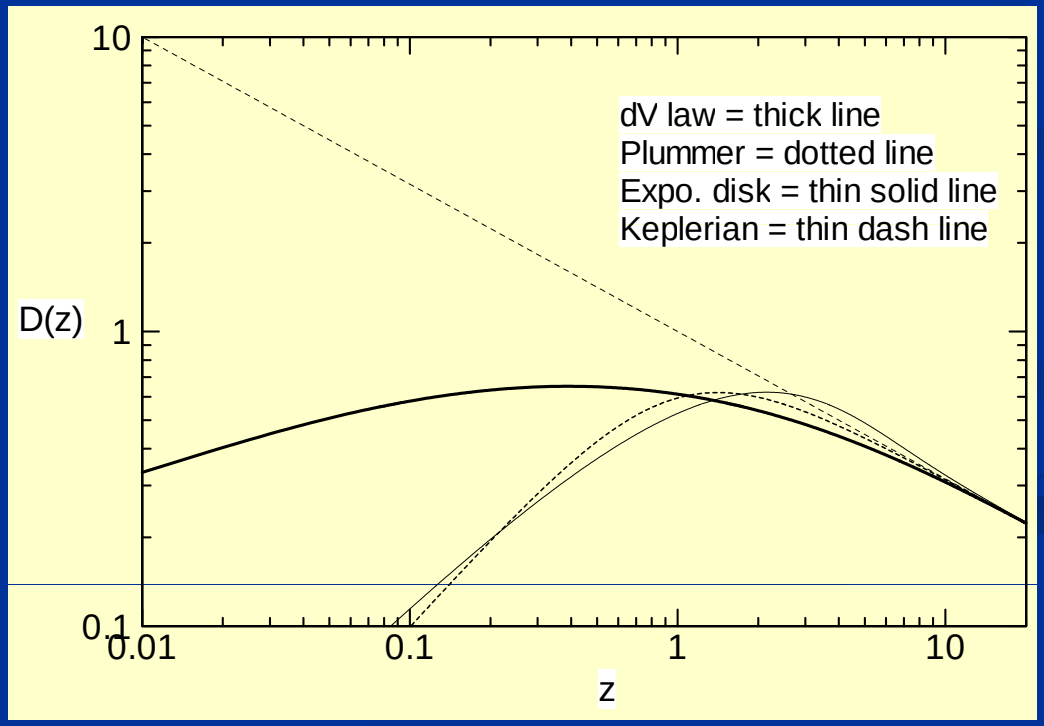
(1) Bulge: de Vaucouleurs Law

(2) Disk: Exponential

(3) Dark Halo: NFW

de V ∝ exp(-r$^{1/4}$)
Expo.
Plummer
Kepler





(1) Bulge de Vaucouleurs: $\exp(-r^{1/4})$

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

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

$$M_b(R) = 4\pi \int_0^R r^2 \rho(r) dr.$$

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

Mass models: Bulge: de Vaucouleurs ($r^{1/4}$)

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

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

$$\mathscr{B}(X) = \left[\frac{1}{X}\int_0^X y^2 \int_y^\infty \frac{\frac{d}{dx}\left\{e^{-\kappa(x^{1/4}-1)}\right\}}{\sqrt{x^2-1}} dx dy\right]^{1/2}$$

(2) Exponential Disk +Arm/Ring

$$\Sigma_d(r) = \Sigma_{dc}\exp(-r/R_d) + \Delta,$$

$$f(R) = G\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\frac{\Sigma_d(r)(R-x)}{s^3}dxdy,$$

$$s = \sqrt{(R-x)^2 + y^2},$$

$$V_d(R) = \sqrt{fR}.$$

(If Δ=0, V(R)=written by modified Bessel functions)

Disk: Exponential

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

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

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

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

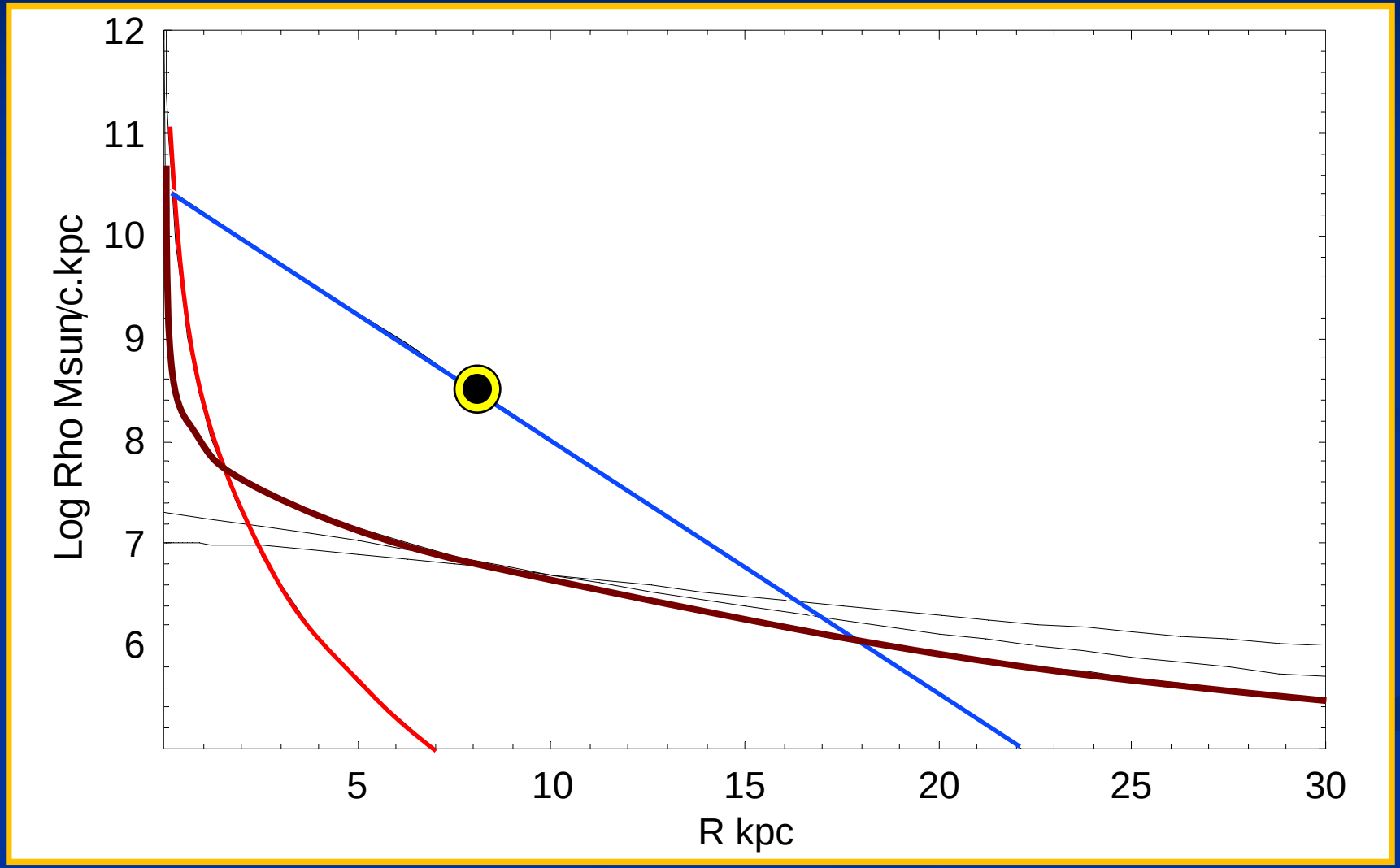
(3) Dark Halo Density Profile
NFW Profile
(Navaro-Frenk-White 1994)

$$X = R/h$$

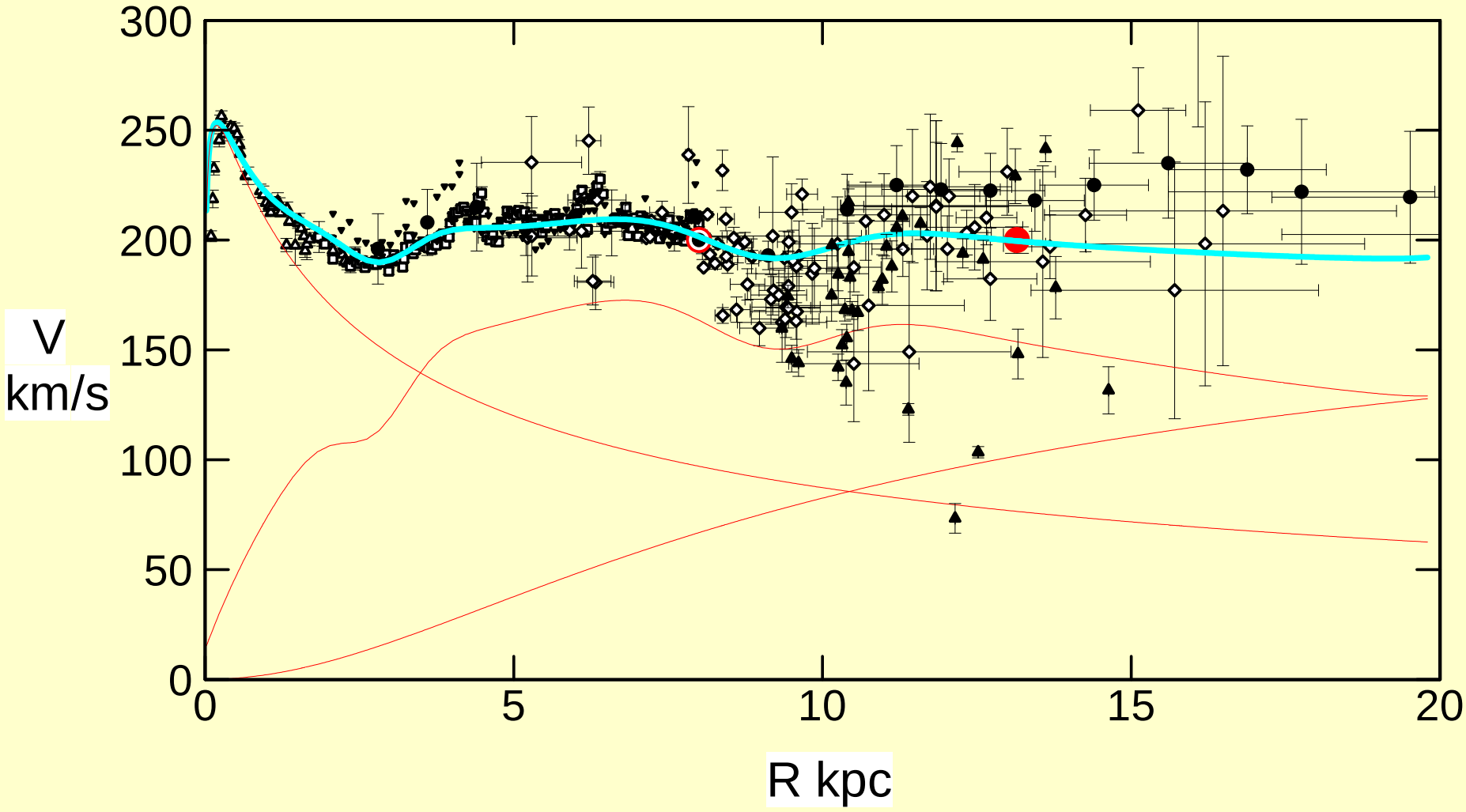
$$\rho(R) = \frac{\rho_0}{X\,(1+X)^2},$$

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

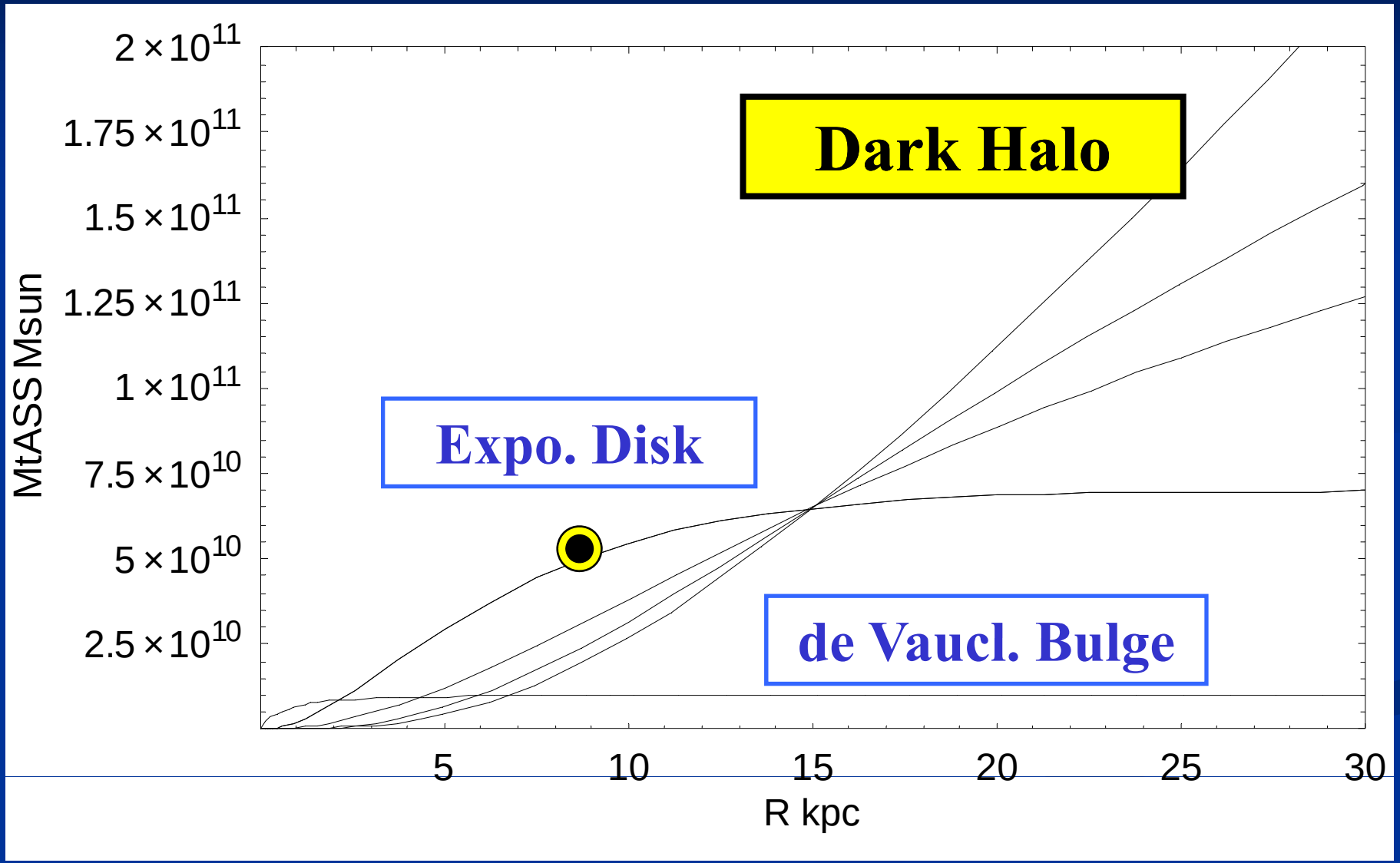
Volume Densities for Bulge, Disk, and Halo (Isoth, NFW, Burkert)



Sofue, Honma, Omodaka 2009



Total Masses



3. Grand Rotation Curve

Dark Halo Density Profiles

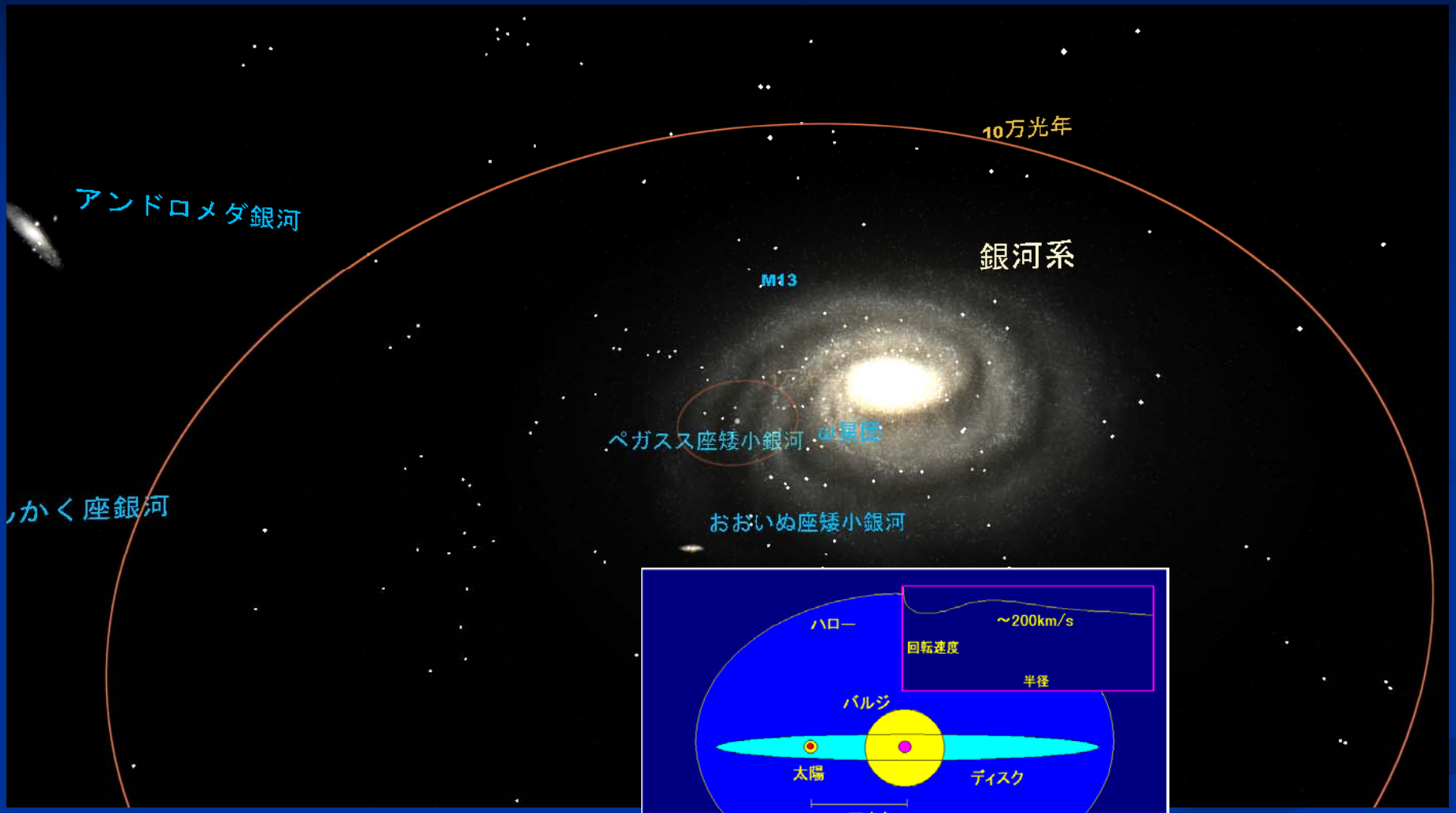
(X=R/h)

NFW density $\propto 1/X(1+X)^2$

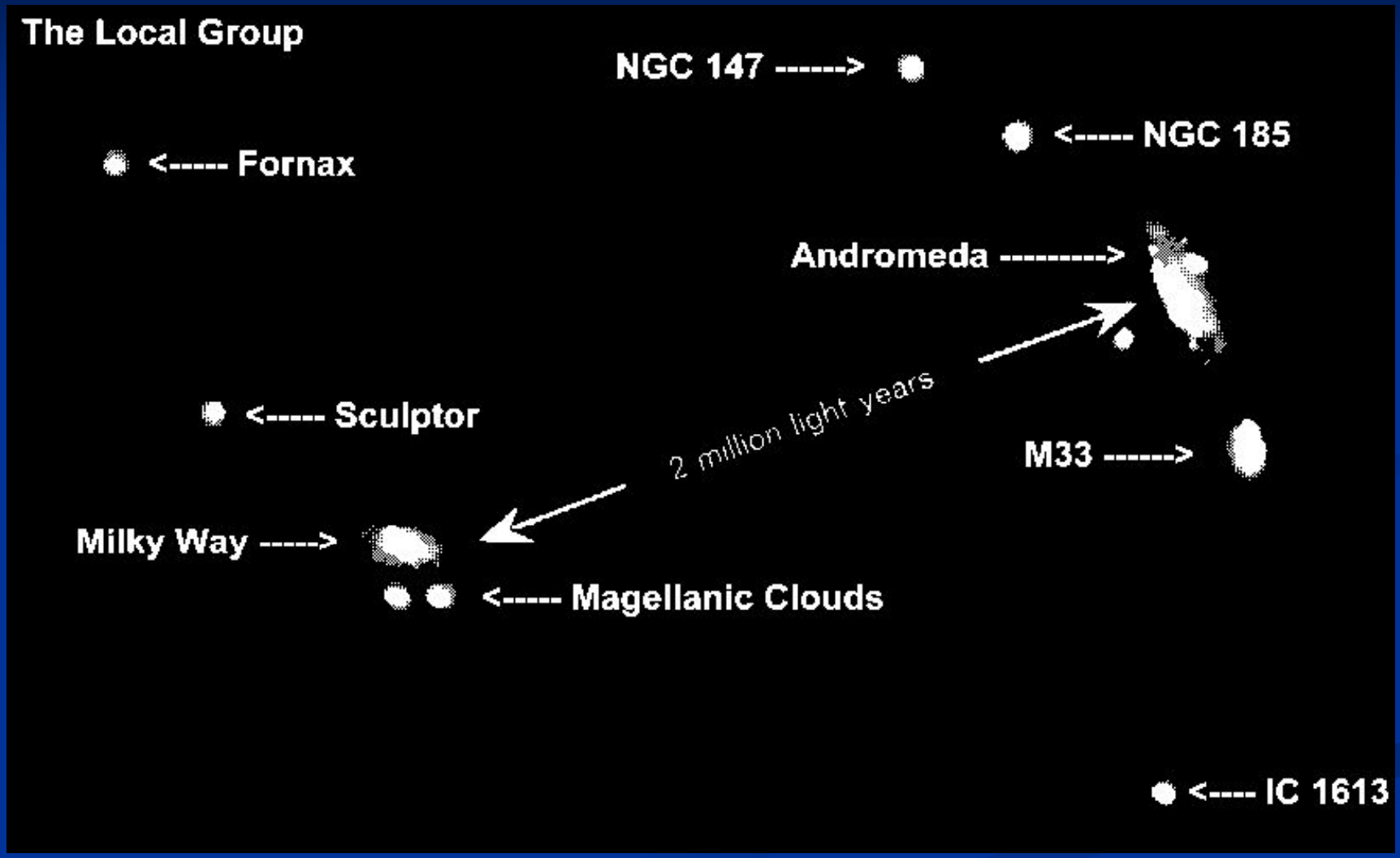
(Navaro-Frenk-White 1994)

Burkert $\propto 1/(1+X)(1+X^2)$

Isothermal $\propto 1/(1+X^2) \Rightarrow X^{-2}$


10万光年
アンドロメダ銀河
銀河系
M13
ペガスス座矮小銀河
α星団
おおいぬ座矮小銀河
ハロー
～200km/s
回転速度
半径
バルジ
太陽
ディスク
2.5万光年
10万光年

Local Group of Galaxies

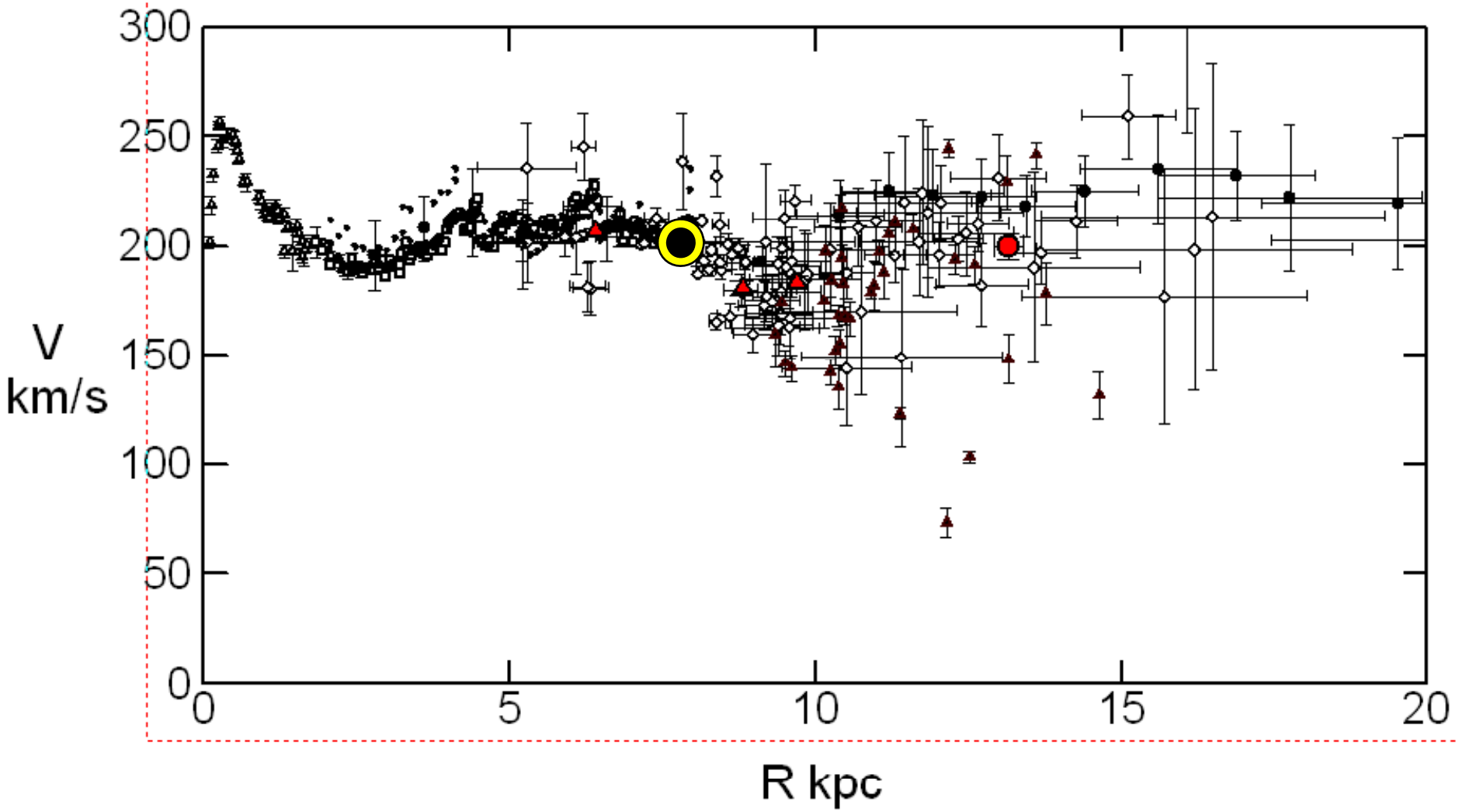


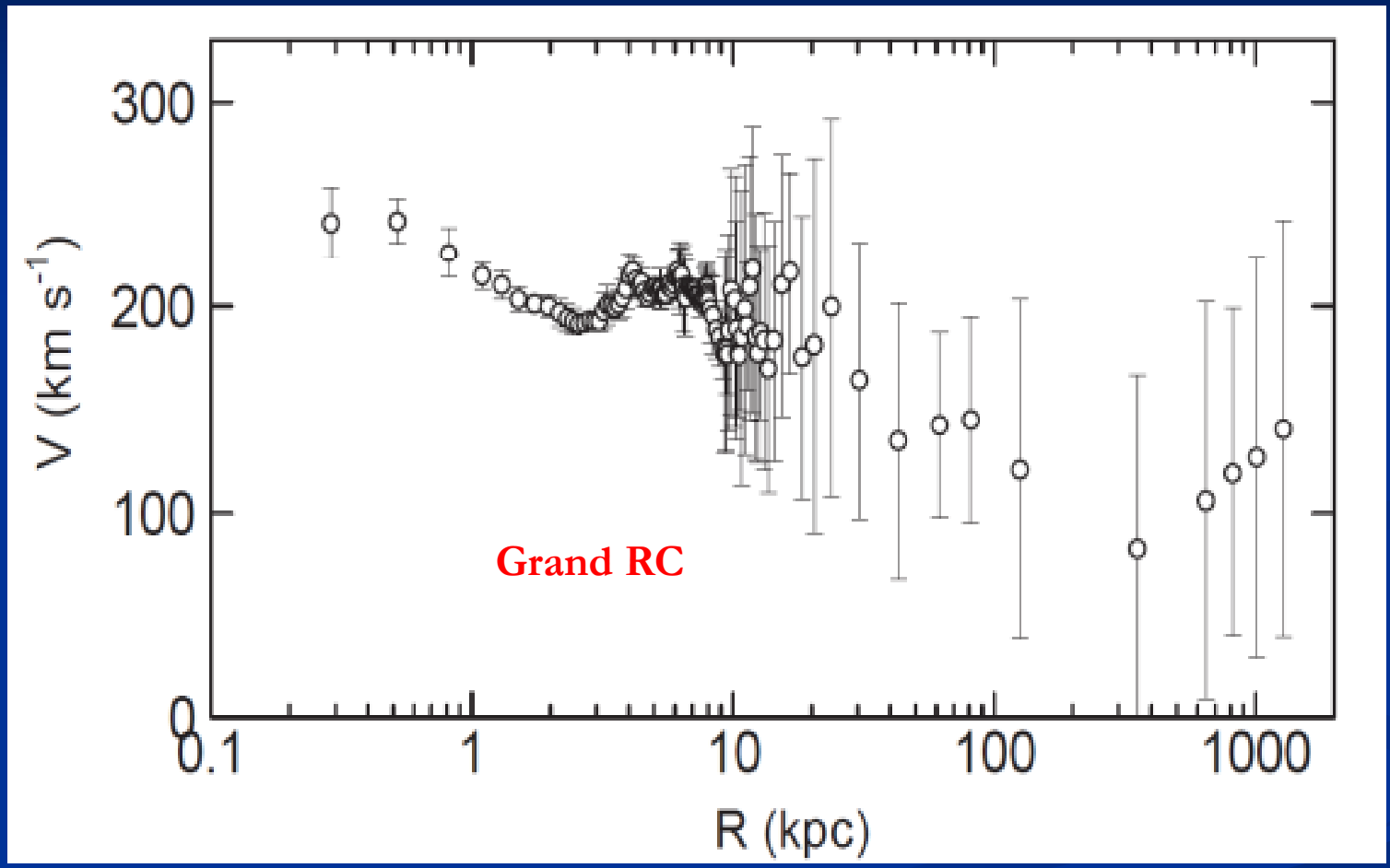
Grand Rotation Curve

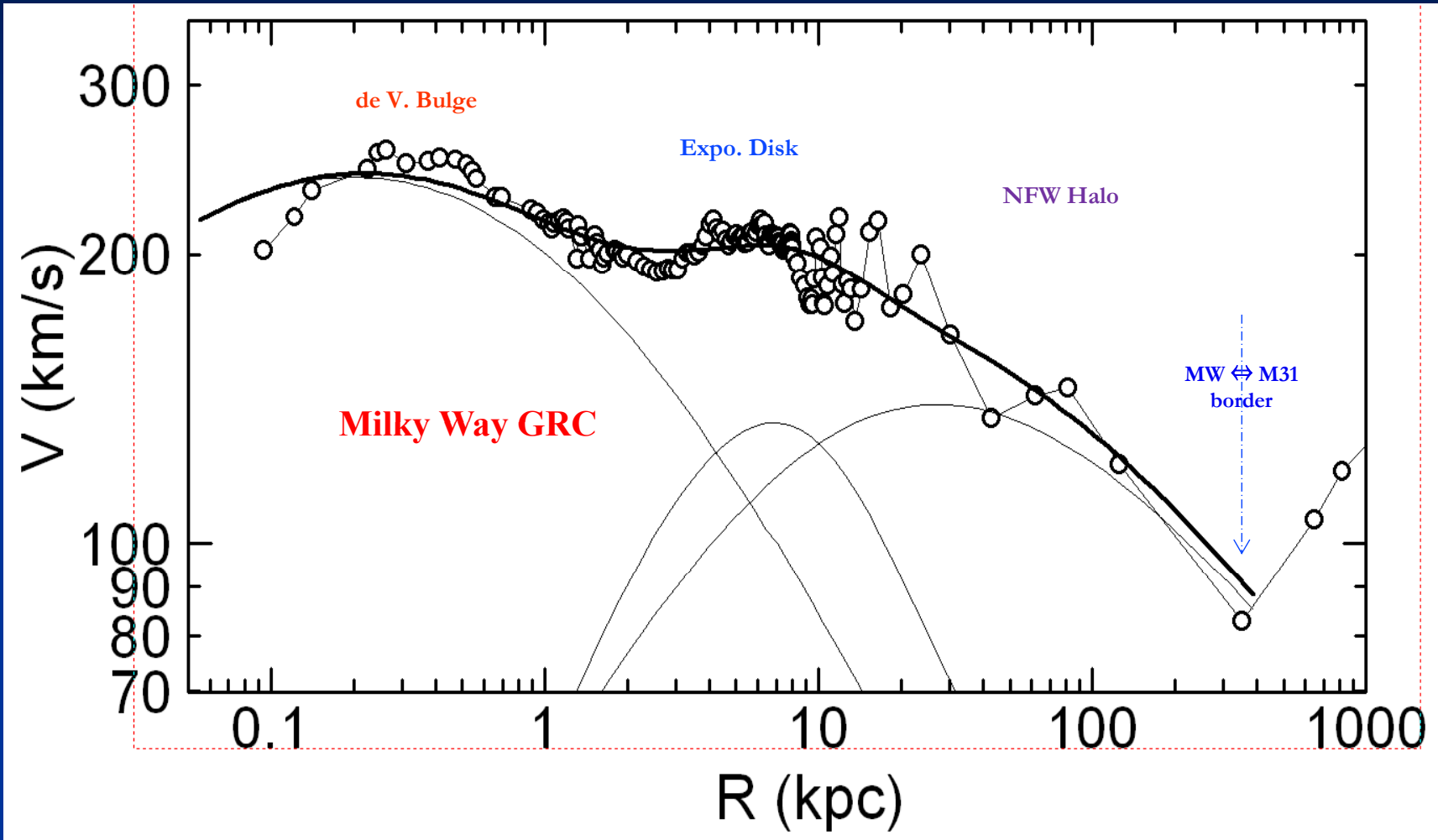
Sattelite's velocity
=>Virial Mass

$$V(R)=\sqrt{2}\,Vr$$

Solar Circular Velocity V_0=200 km/s @ R_0=8kpc

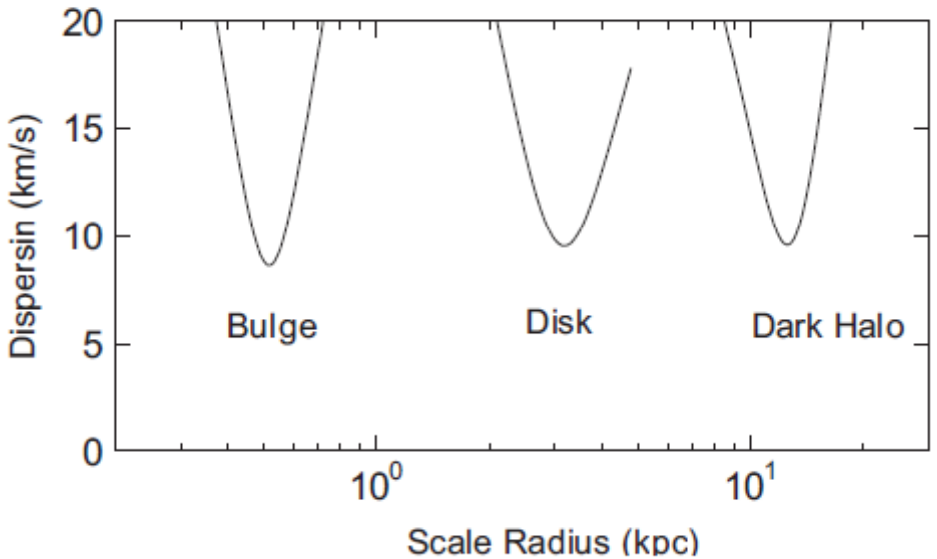



300
200
100
0
V (km s-1)
0.1
1
10
100
1000
R (kpc)
Grand RC


de V. Bulge
Expo. Disk
NFW Halo
MW ⇔ M31
border
Milky Way GRC
V (km/s)
300
200
100
90
80
70
0.1
1
10
100
1000
R (kpc)

4. Galaxy Parameters & Locad DM Density

Dispersion Scale radius fit



Dispersion Mass fit

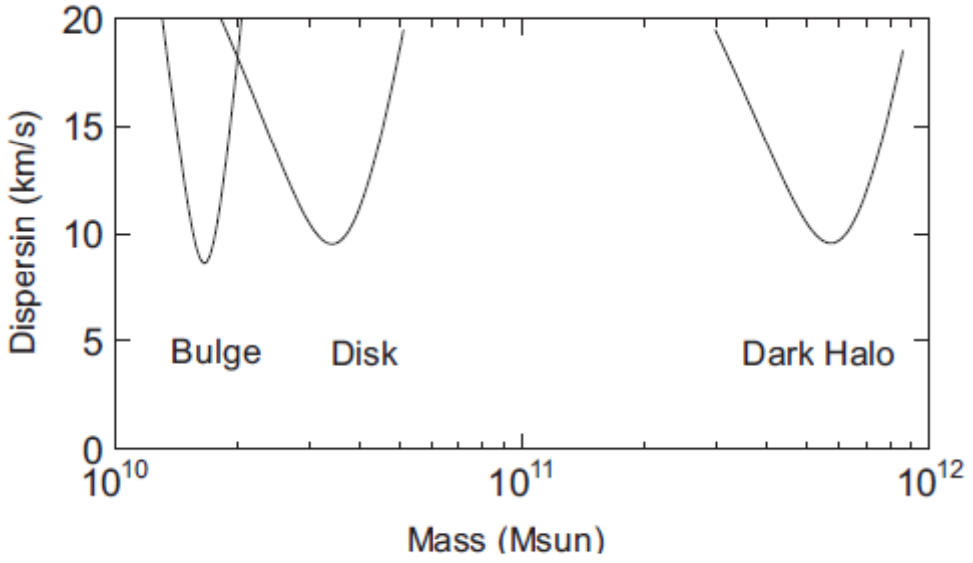


Table 1. Best-fit parameters for the mass components of the Galaxy

Mass component	Mass; Density	Scale Radius
Bulge param.	$M_{\rm b} = (1.652 \pm 0.083) \times 10^{10} M_\odot$	$a_{\rm b} = 0.522 \pm 0.037$ kpc
Disk param.	$M_{\rm d} = (3.41 \pm 0.41) \times 10^{10} M_\odot$	$a_{\rm d} = 3.19 \pm 0.35$ kpc
B+D Mass	$M_{\rm b+d} = (5.06 \pm 0.97) \times 10^{10} M_\odot$	
B/D ratio	$M_{\rm b}/M_{\rm d} = 0.48 \pm 0.09$	
DH param.	$\rho_0 = (1.06 \pm 0.14) \times 10^{-2} M_\odot {\rm pc}^{-3}$	$h = 12.53 \pm 0.88$ kpc
	$= 0.403 \pm 0.051$ GeV cm^{-3}	
Local DM dens.	$\rho_0^\odot = (6.12 \pm 0.80) \times 10^{-3} M_\odot {\rm pc}^{-3}$	
at $R_0 = 8$ kpc	$= 0.235 \pm 0.030$ GeV cm^{-3}	
DH Mass[‡]	$M_{\rm h}(R \leq 8{\rm kpc}) = (2.71 \pm 0.42) \times 10^{10} M_\odot$	
	$M_{\rm h}^*(\leq h) = (5.05 \pm 0.78) \times 10^{10} M_\odot$	
	$M_{\rm h}(\leq 20{\rm kpc}) = (8.87 \pm 1.37) \times 10^{10} M_\odot$	
	$M_{\rm h}(\leq 385{\rm kpc}) = (6.52 \pm 1.01) \times 10^{11} M_\odot$	
Galaxy Mass	$M_{\rm b+d+h} = (7.03 \pm 1.01) \times 10^{11} M_\odot$	$(R \leq 385$ kpc$)$
Baryon Fraction	$M_{\rm b+d}/(M_{\rm b+d+h}) =$ **0.072 ± 0.018**	

The Local Dark Matter Density @ Sun

$$\rho_{\odot} = 0.235 \pm 0.030$$

$$\text{GeV cm}^{-3}$$

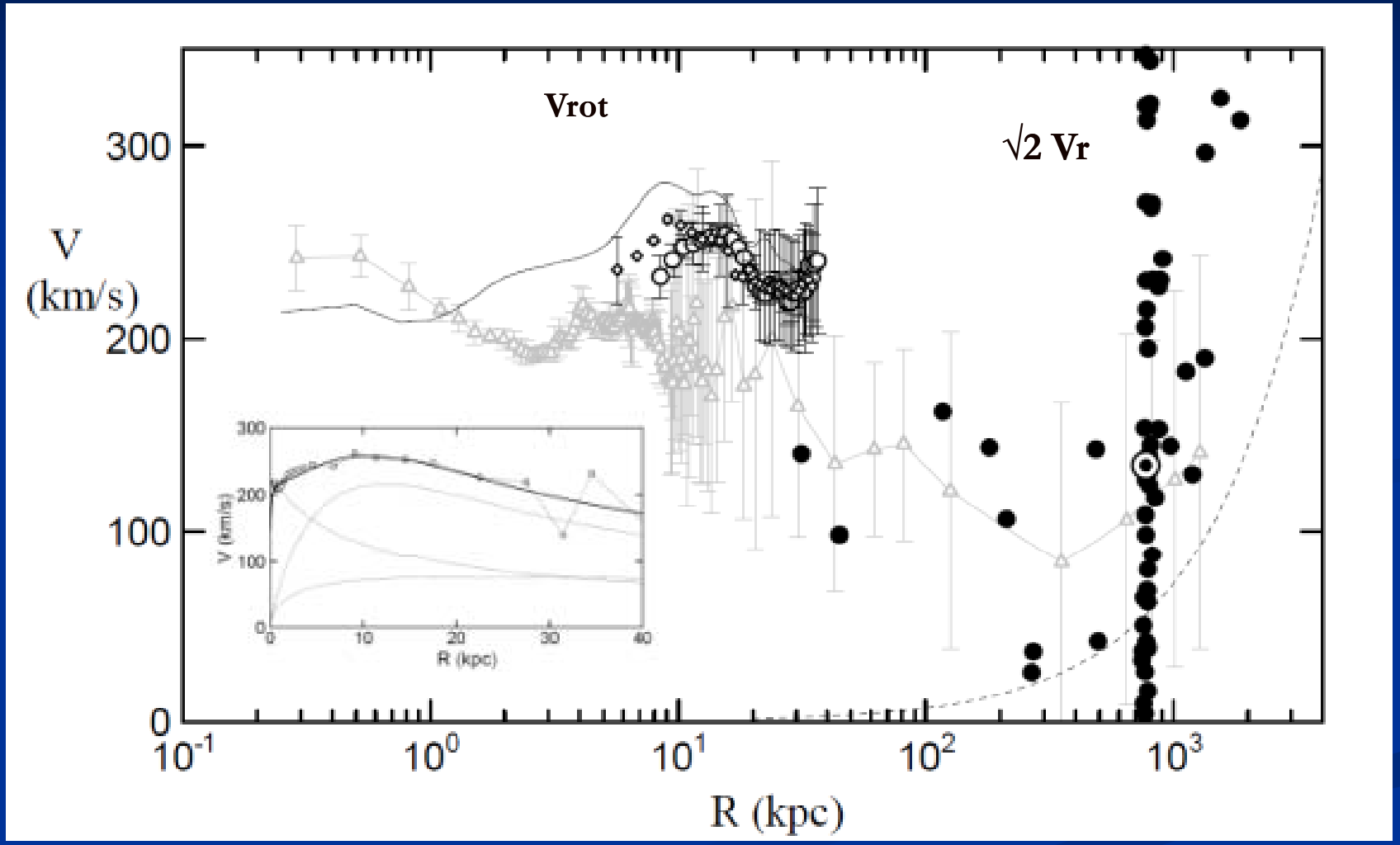
$$M \sim RV^2/G \Rightarrow \rho_0 \sim M/R^3 \sim (V/R)^2 \sim \Omega^2$$

$V_0/R_0=\Omega_0$ (km s^{-1} kpc^{-1})	ρ_0 (GeV cm^{-3})
Sofue (2012)	
200/8.0 ＝25.0	0.235±0.030
(248/8.2 ＝ 30.3	0.34 ± 0.04)
Salucci, et al. (2011)≒Honma et al (2012)	
248/8.2 ＝ 30.3	0.43 ± 0.11
(200/8.0 ＝ 25.0	0.29 ± 0.07)
Weber and de Boer (2010)	
	0.2 ~ 0.4

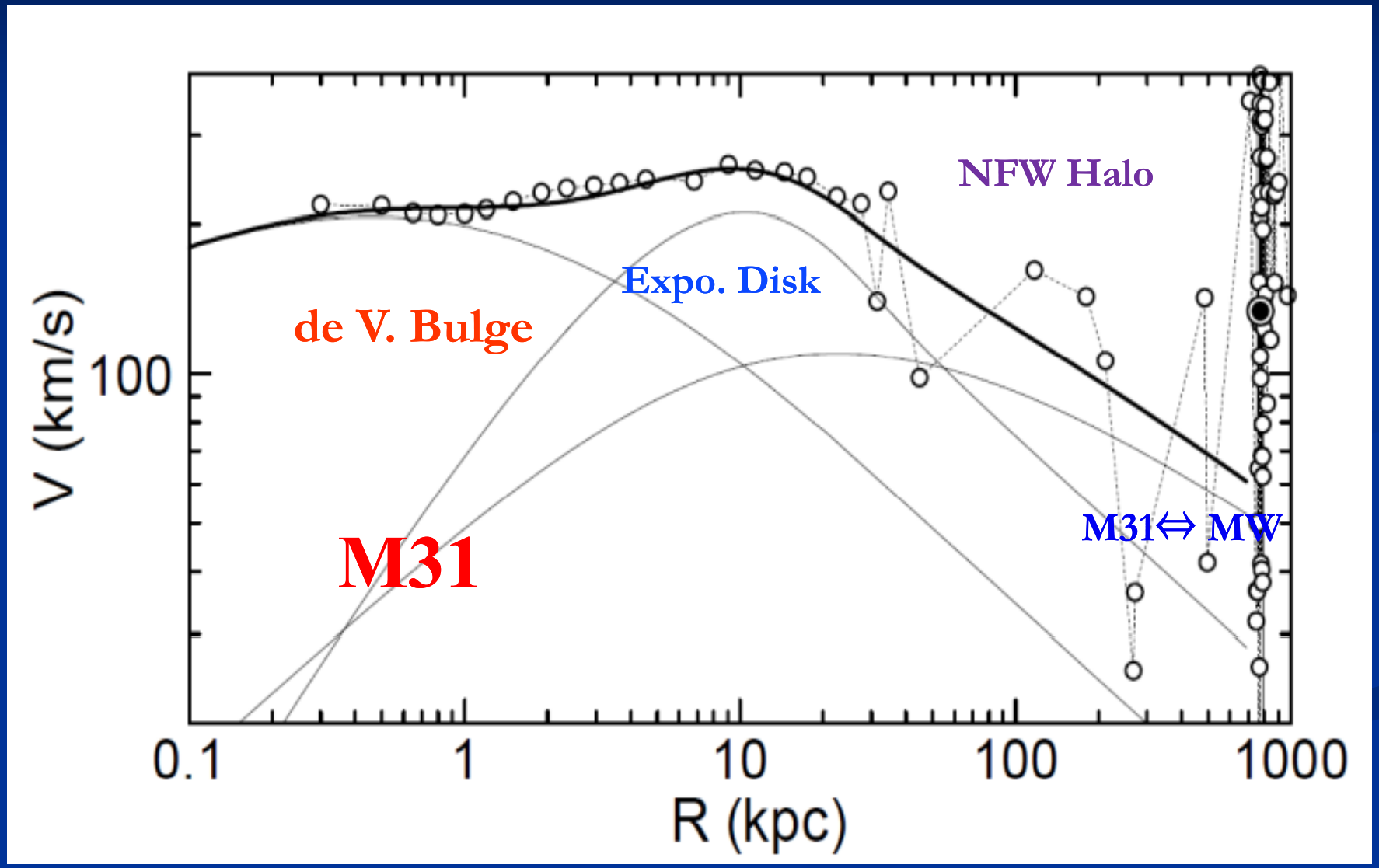
6. Galactic Roche Lobe

- Territory problem –

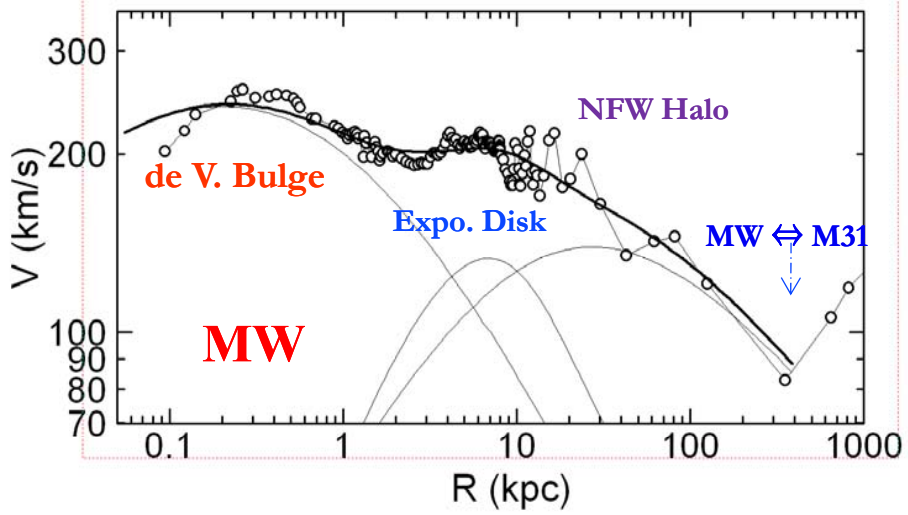
Grand RC of M31

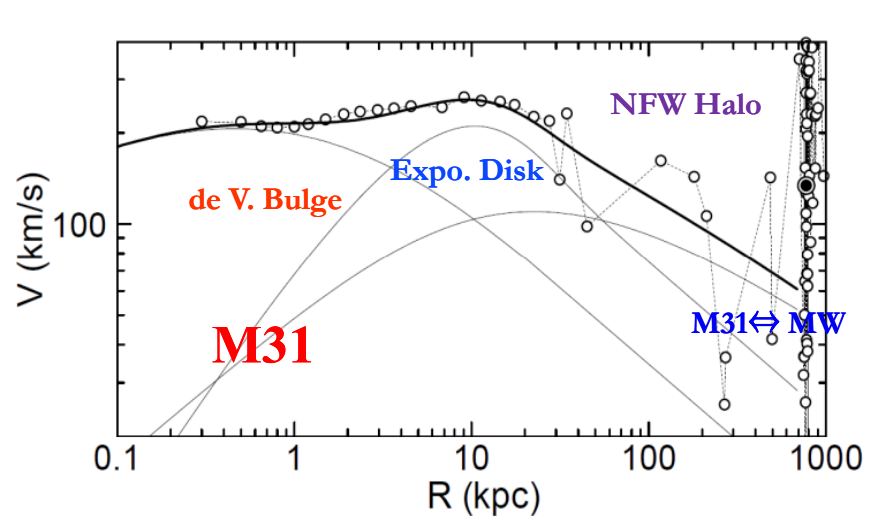


GRC of M31


NFW Halo
Expo. Disk
de V. Bulge
M31
M31⇔ MW
V (km/s)
100
0.1
1
10
100
1000
R (kpc)

Grand RC of M31 ≒ Galaxy

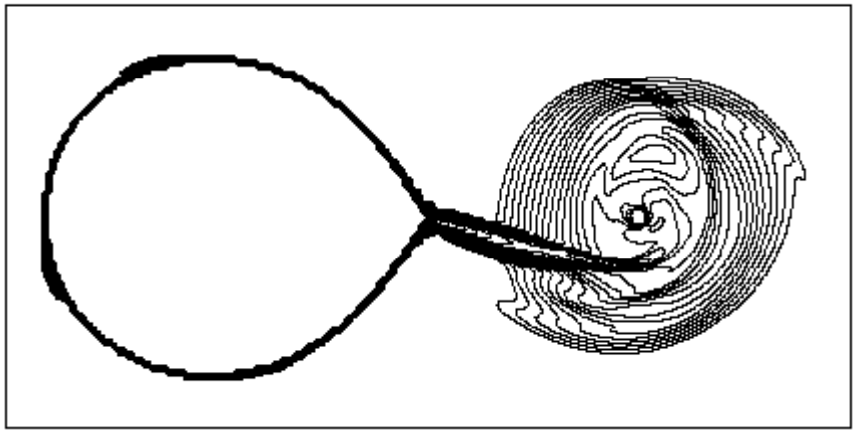


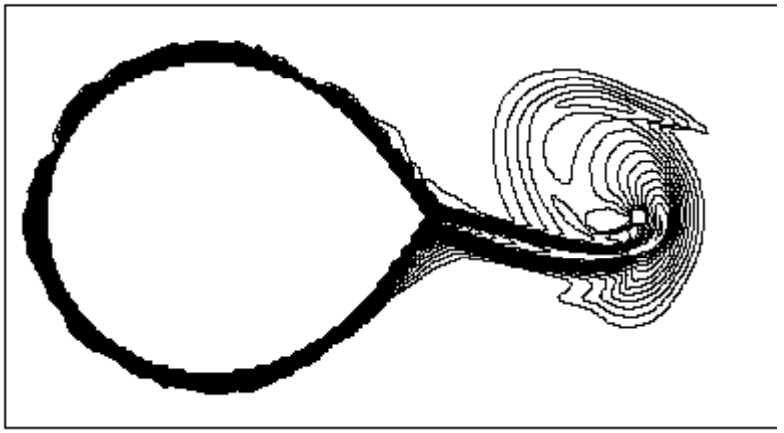


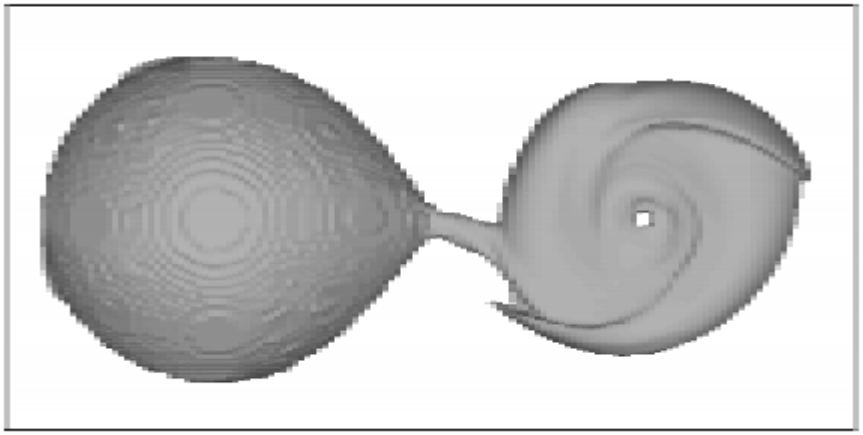
M31 ≒ Galaxy>> M33, dwarfs

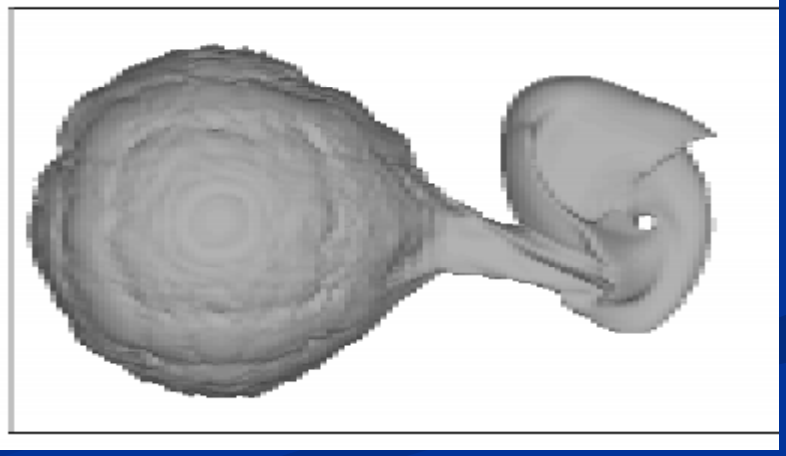
MW+M31≒Binary

2D Matsuda et al. 2000

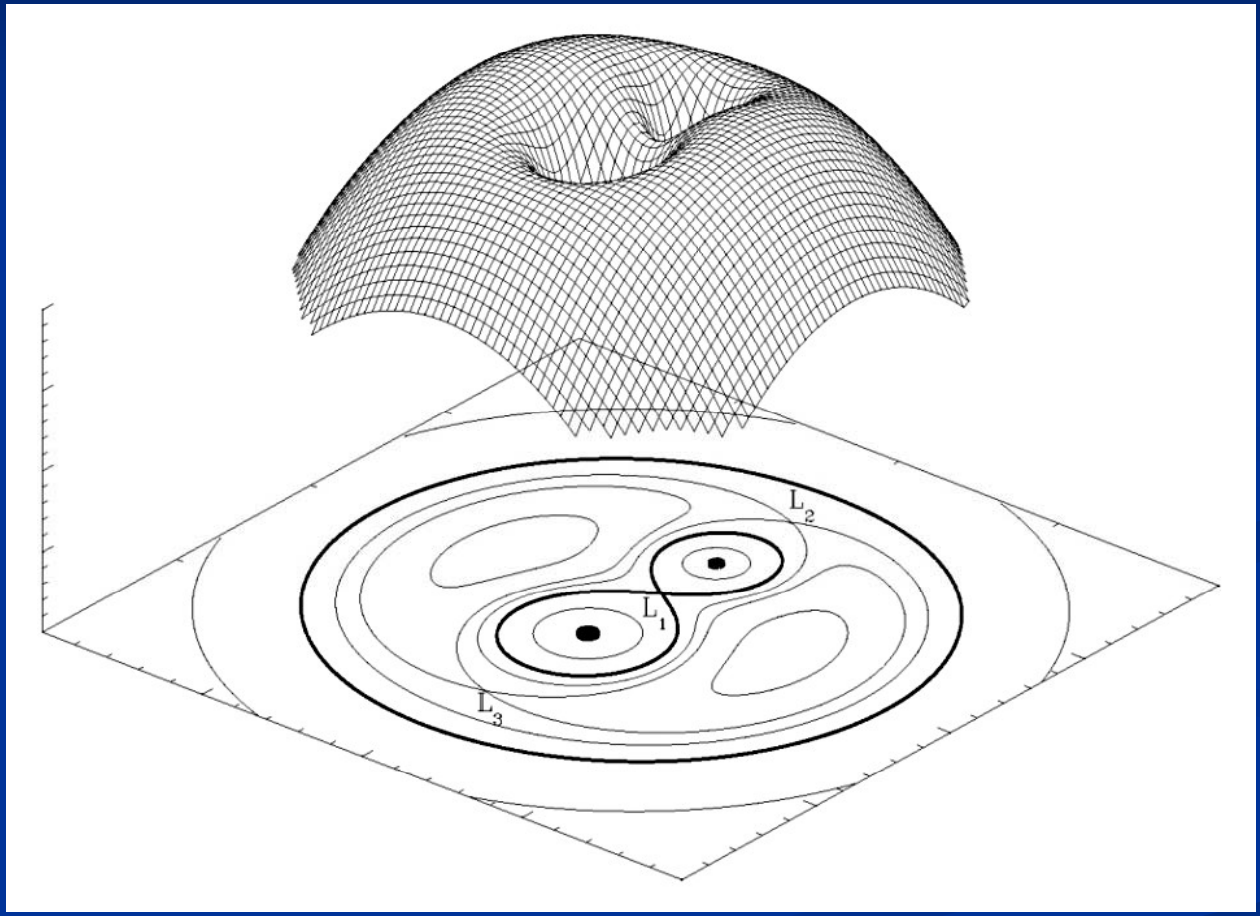








Binary (2 point masses) Roche Lobes



Galactic Roche Lobe

$$\Phi = \Phi_G + \Phi_{M31} + \Phi_{\Omega\ Rigid\ rot\ coordi.}$$

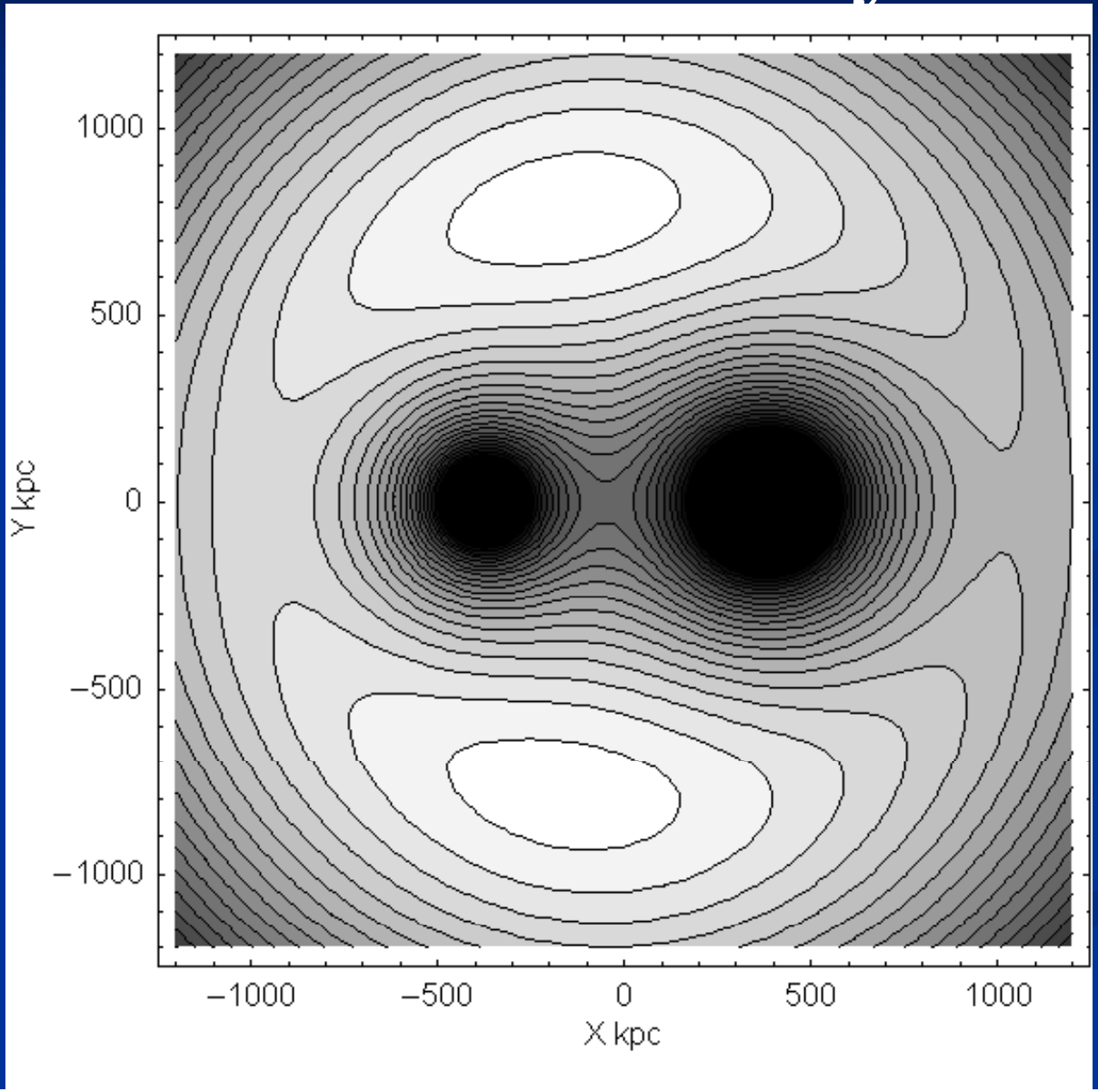
$$= -GM_1/r_1 - GM_2/r_2 - (1/2)\Omega^2 r^2$$

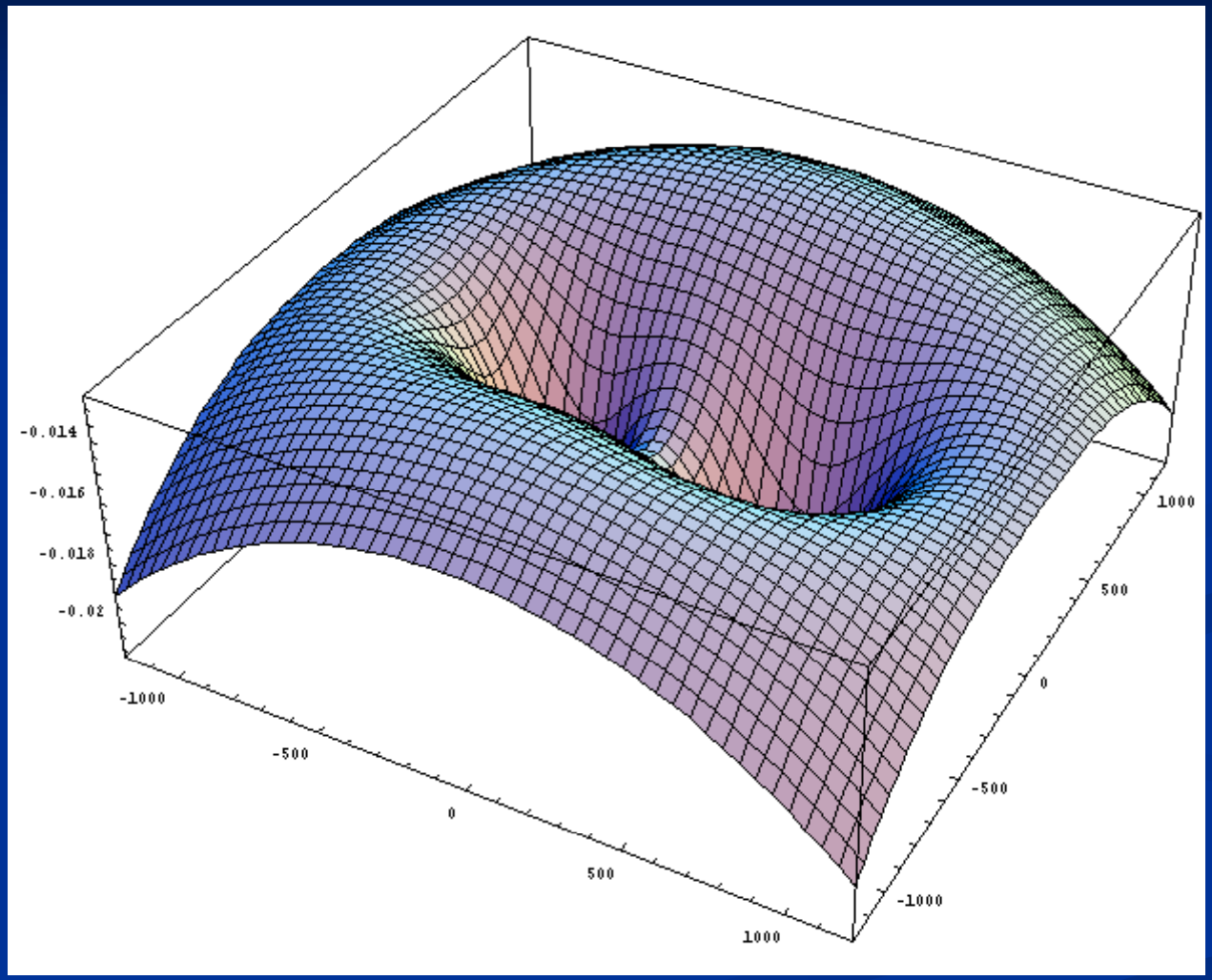
NFW Roche Lobe

$$M_h(R) = 4\pi\rho_0 h^3\{\ln(1+X)-X/(1+X)\}$$

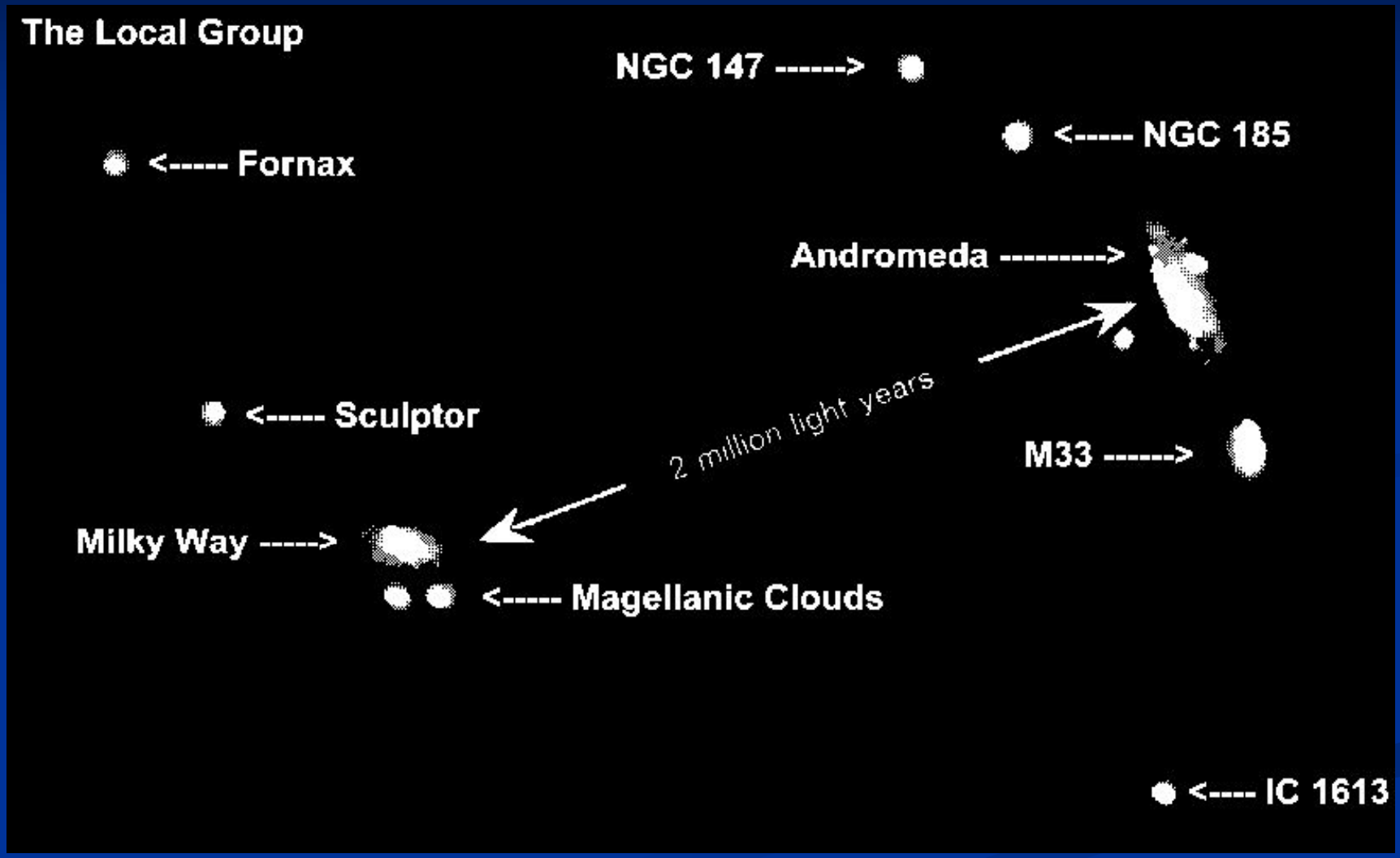
$$X=R/h$$

Galactic DM Roche Lobe
MW-M31 Binary

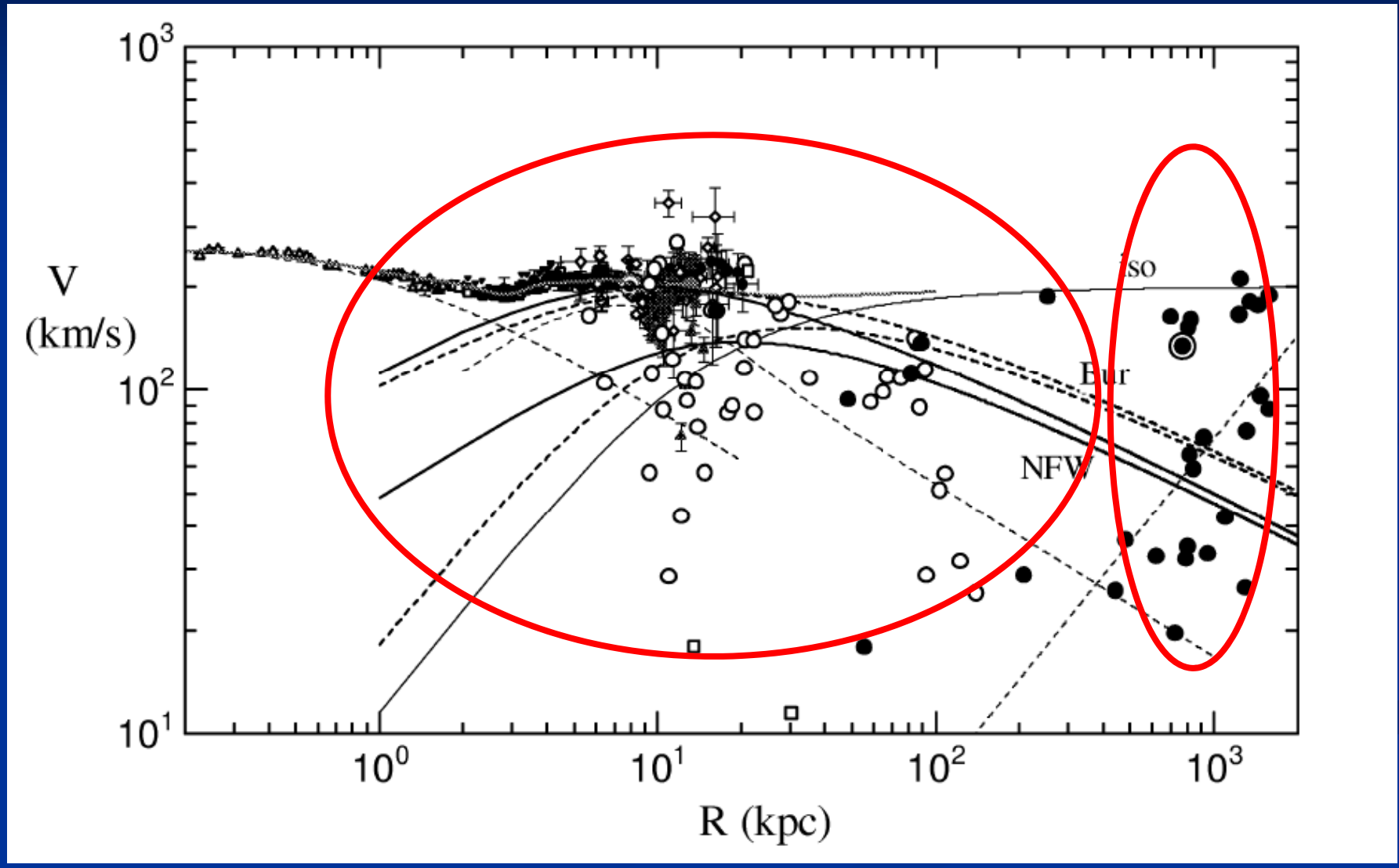



-0.014
-0.016
-0.018
-0.02
-1000
-500
0
500
1000
1000
500
0
-500
-1000

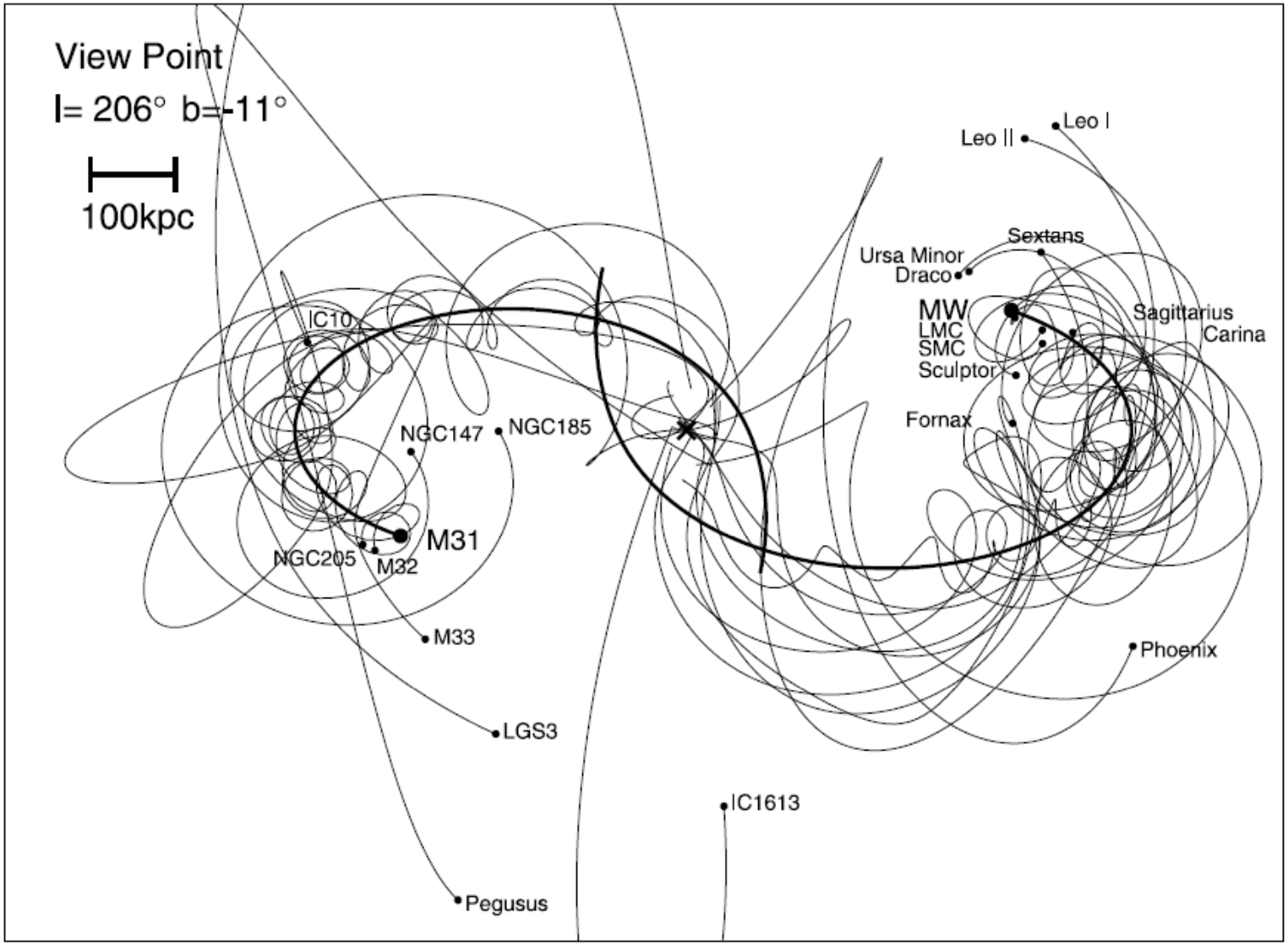
Local Group of Galaxies



Galaxy + M31 ＝＞What in future ?



Galaxy – M31


View Point
l= 206° b=-11°
100kpc
Leo II
Leo I
Sextans
Ursa Minor
Draco
MW
LMC
SMC
Sculptor
Sagittarius
Carina
Fornax
IC10
NGC147
NGC185
M31
NGC205
M32
M33
LGS3
Phoenix
IC1613
Pegusus

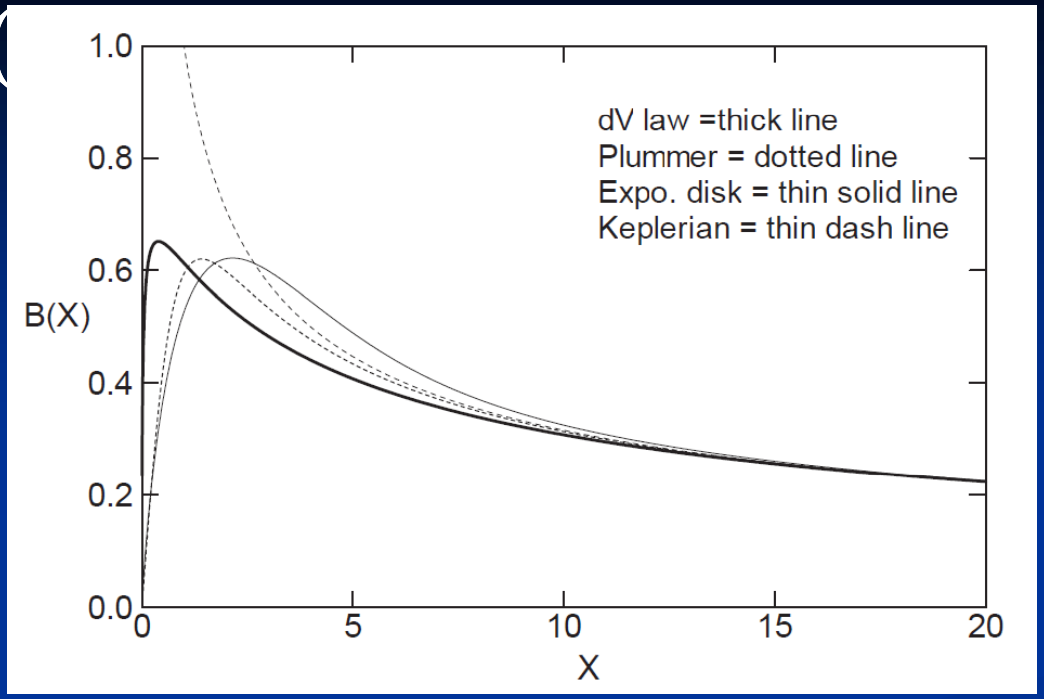
Summary

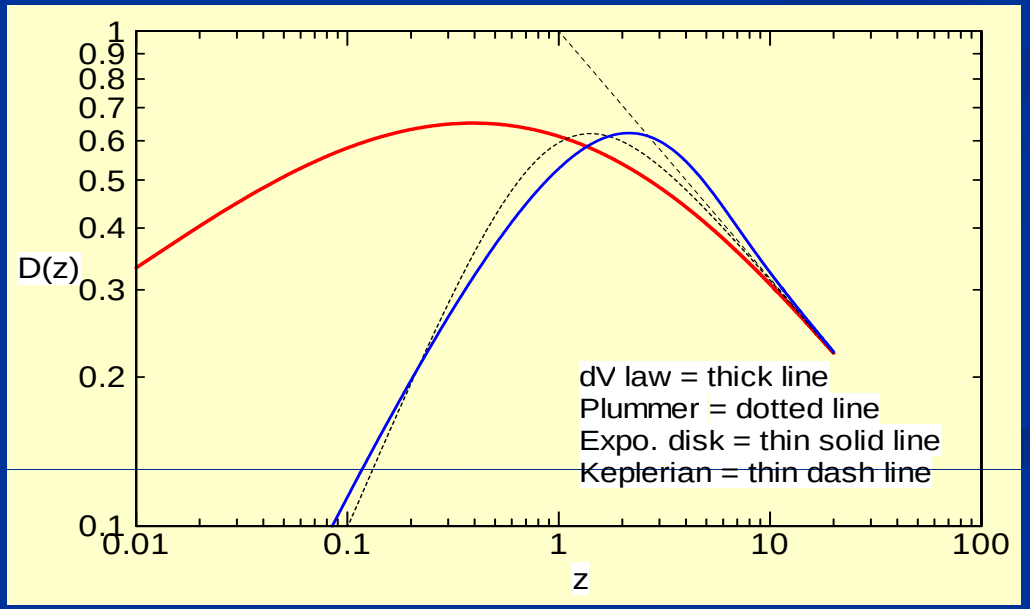
1. Rotation Curve
2. Mass models
3. Grand RC (Log RC)
4. Local DM Density & G-parameters
5. Roche Lobe
   - Galactic Territory MW vs M31

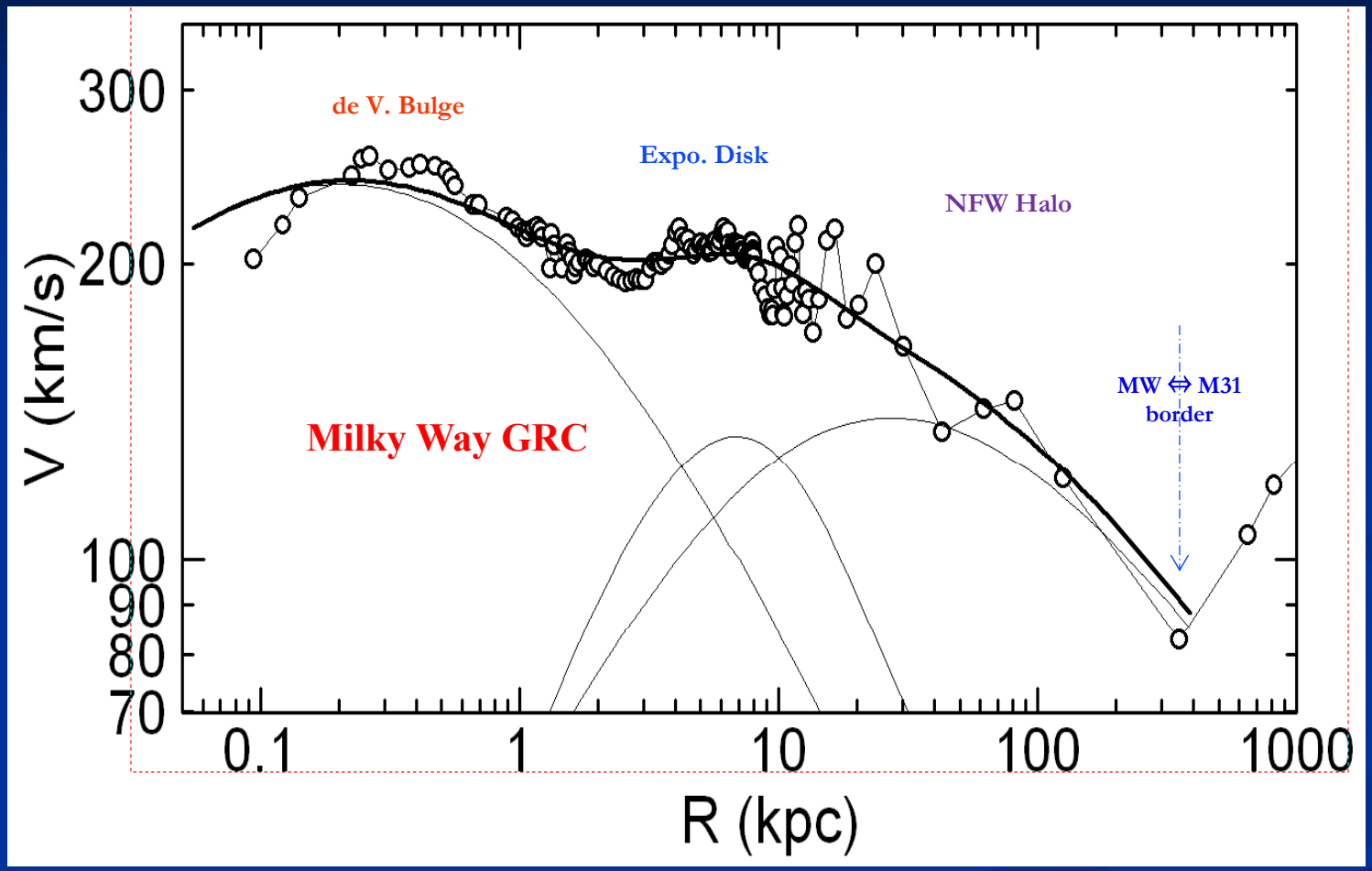
7. Grand RC (Log RC) for the Galactic Center

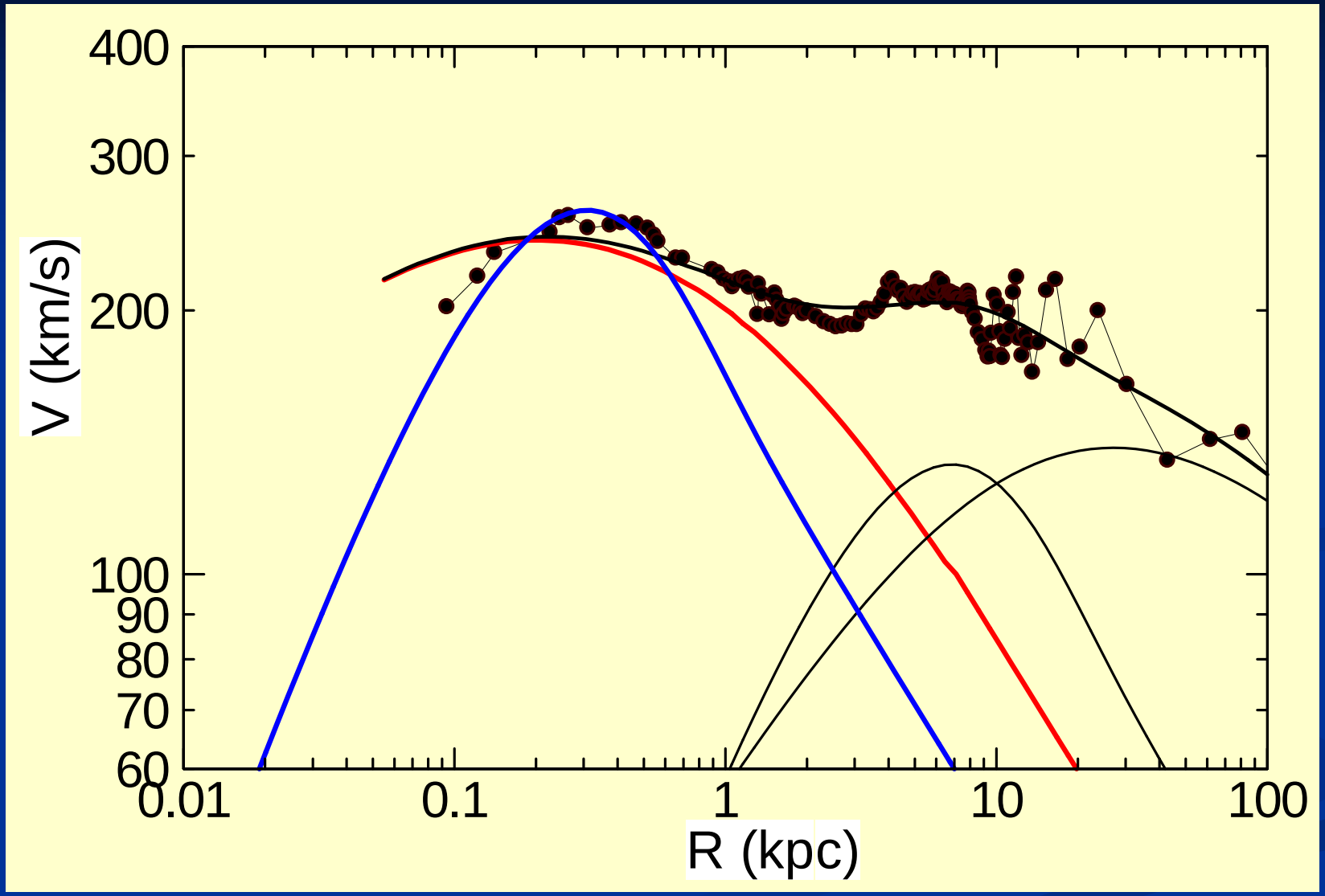
Bulge is in between de Vaucouleurs and Exponential

de V ∝ exp(
Expo.
Plummer
Kepler






de V. Bulge
Expo. Disk
NFW Halo
MW ⇔ M31
border
Milky Way GRC
V (km/s)
R (kpc)
300
200
100
90
80
70
0.1
1
10
100
1000


400
300
200
100
90
80
70
60
V (km/s)
0.01
0.1
1
10
100
R (kpc)