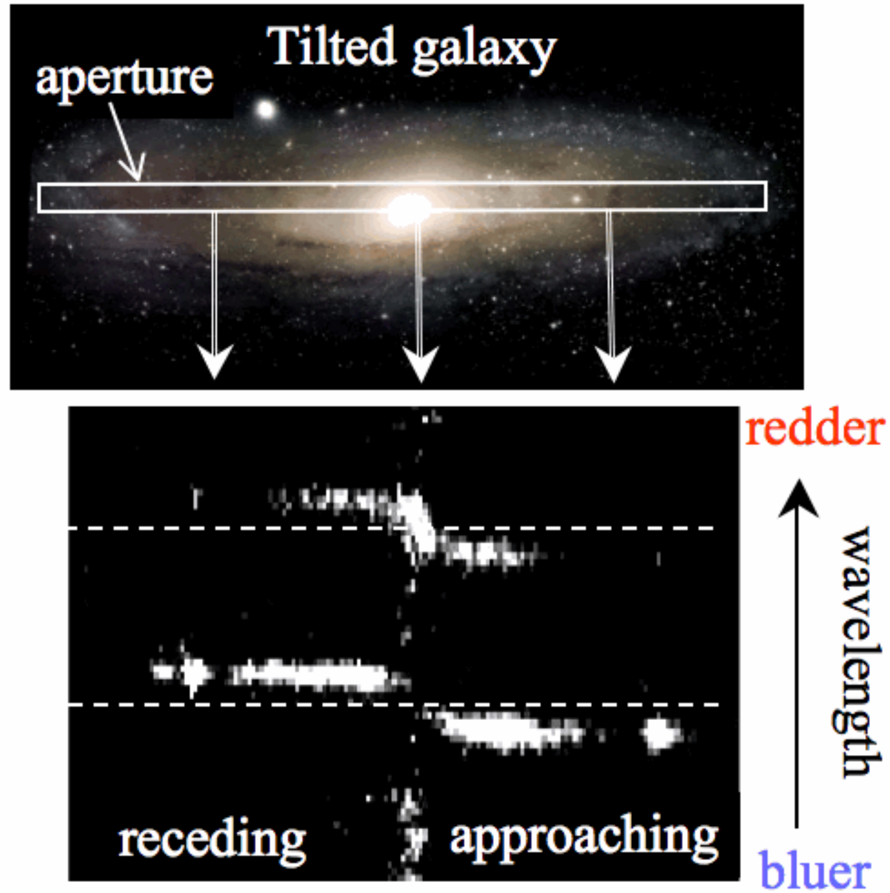
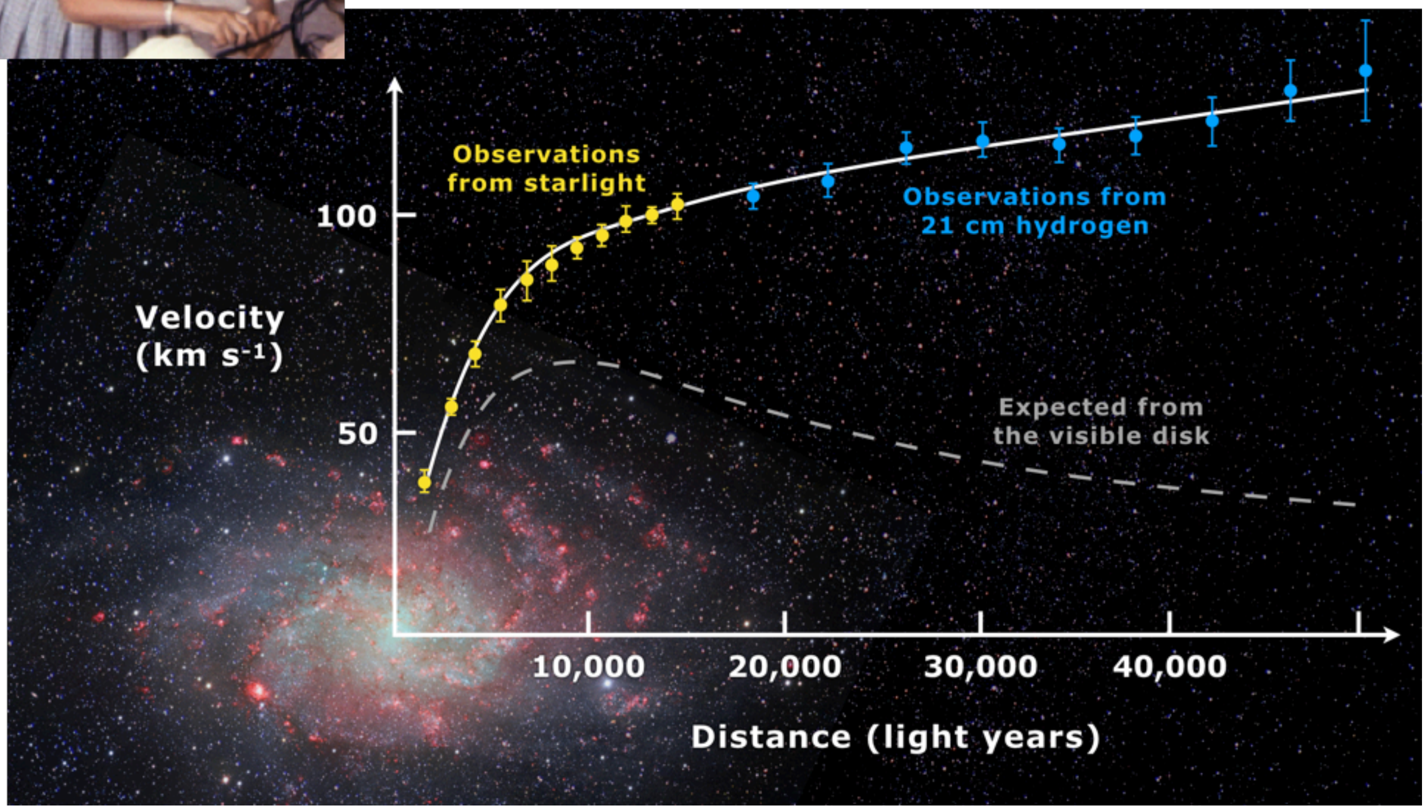
Vera Rubin measuring galaxy rotation curves (~1970)



Resulting spectrum of light within aperture

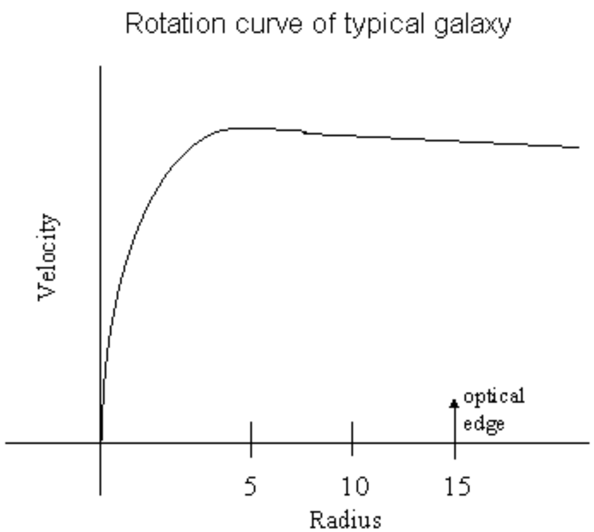
Vera Rubin measured that stars in galaxies are moving faster than they should be, inferring the existence of an unseen mass we call "dark matter"



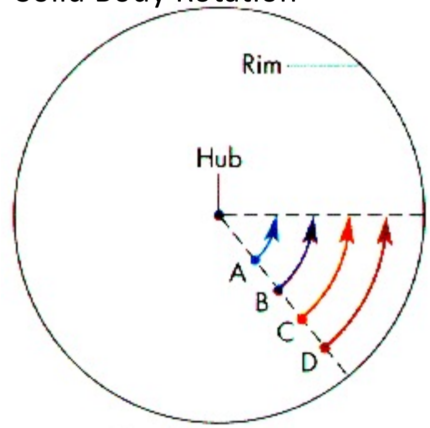
$$GMm/R^2 = mV^2/R$$

$$M(< R) \propto V^2 R$$

$$v_c(R) = \sqrt{GM(< R)/R}$$

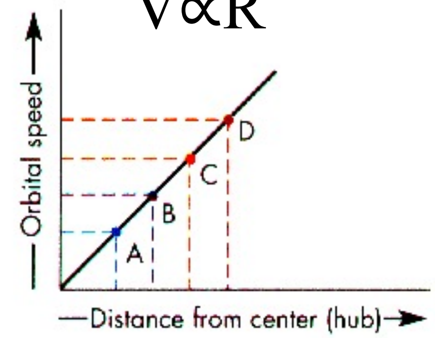


Solid Body Rotation



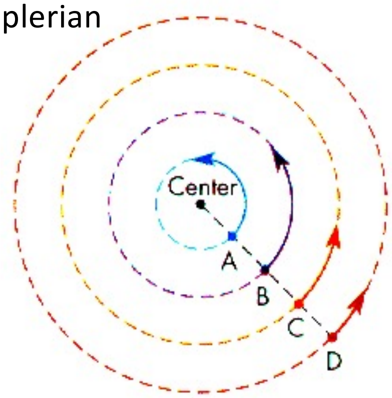
Wheel-like rotation

$V \propto R$



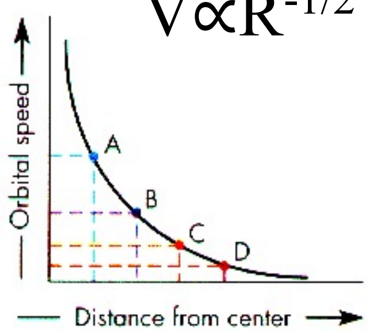
Rotation curve for wheel-like rotation

Keplerian



Planet-like rotation

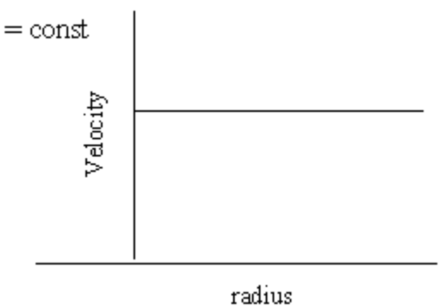
$V \propto R^{-1/2}$

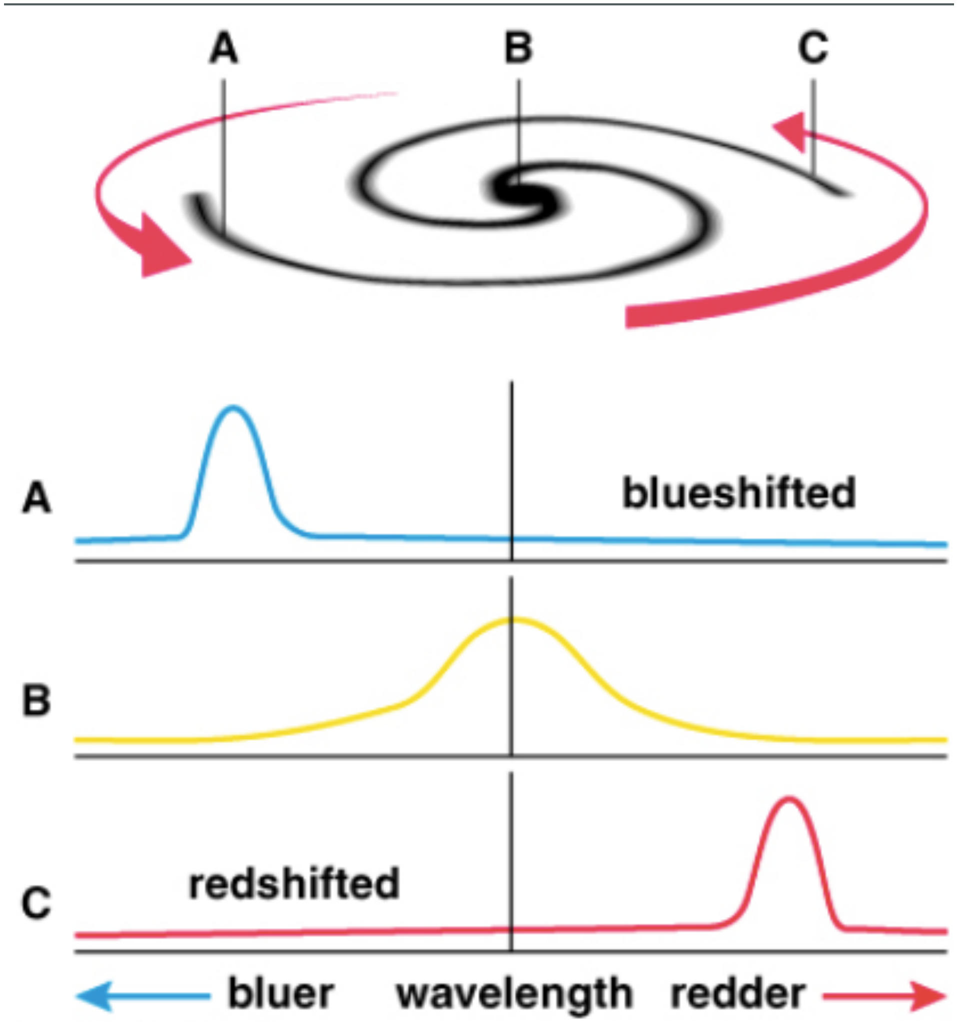


Rotation curve for planet-like rotation

Flat Rotation Curve

$V = \text{const}$




A
B
C
A
blueshifted
B
C
redshifted
bluer
wavelength
redder

Milky Way Rotation Curve (updates since book)

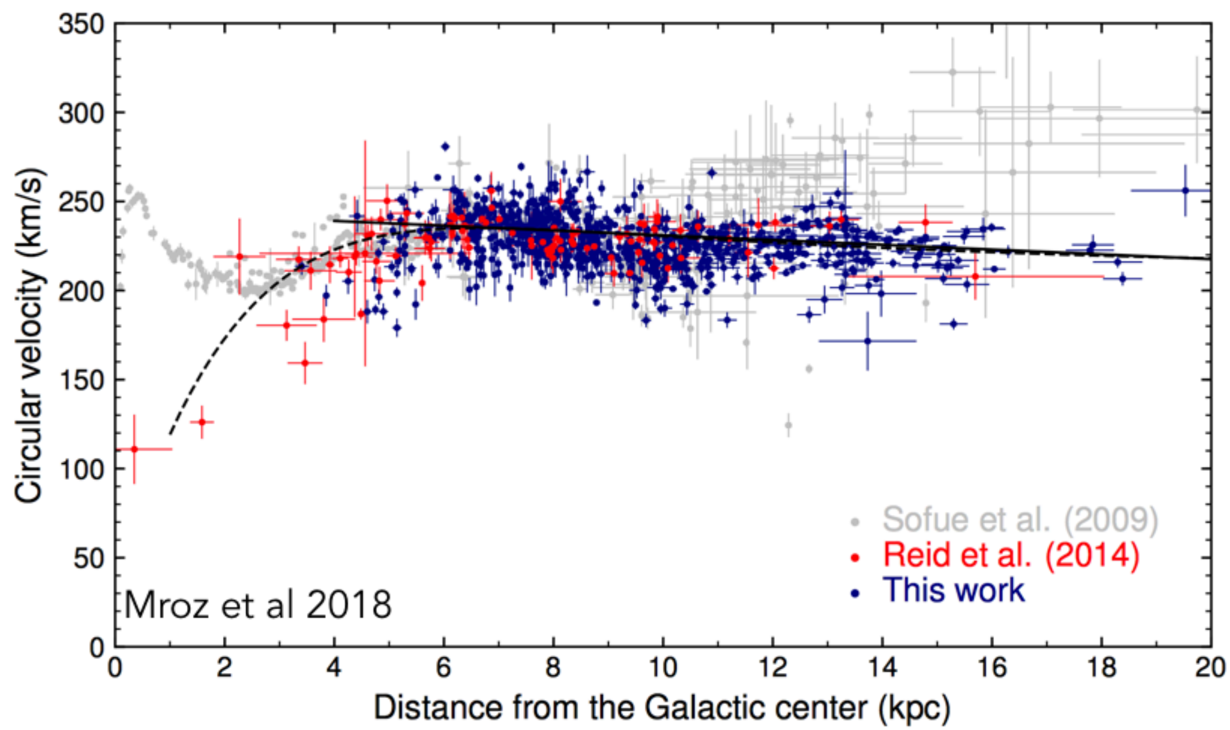
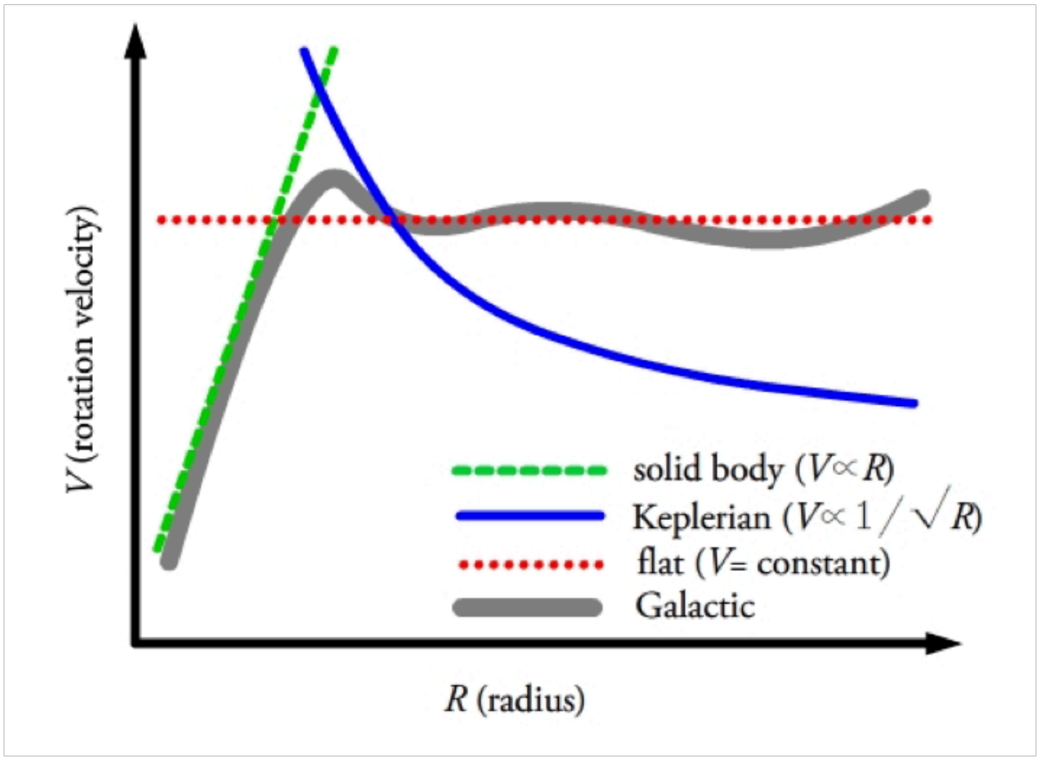


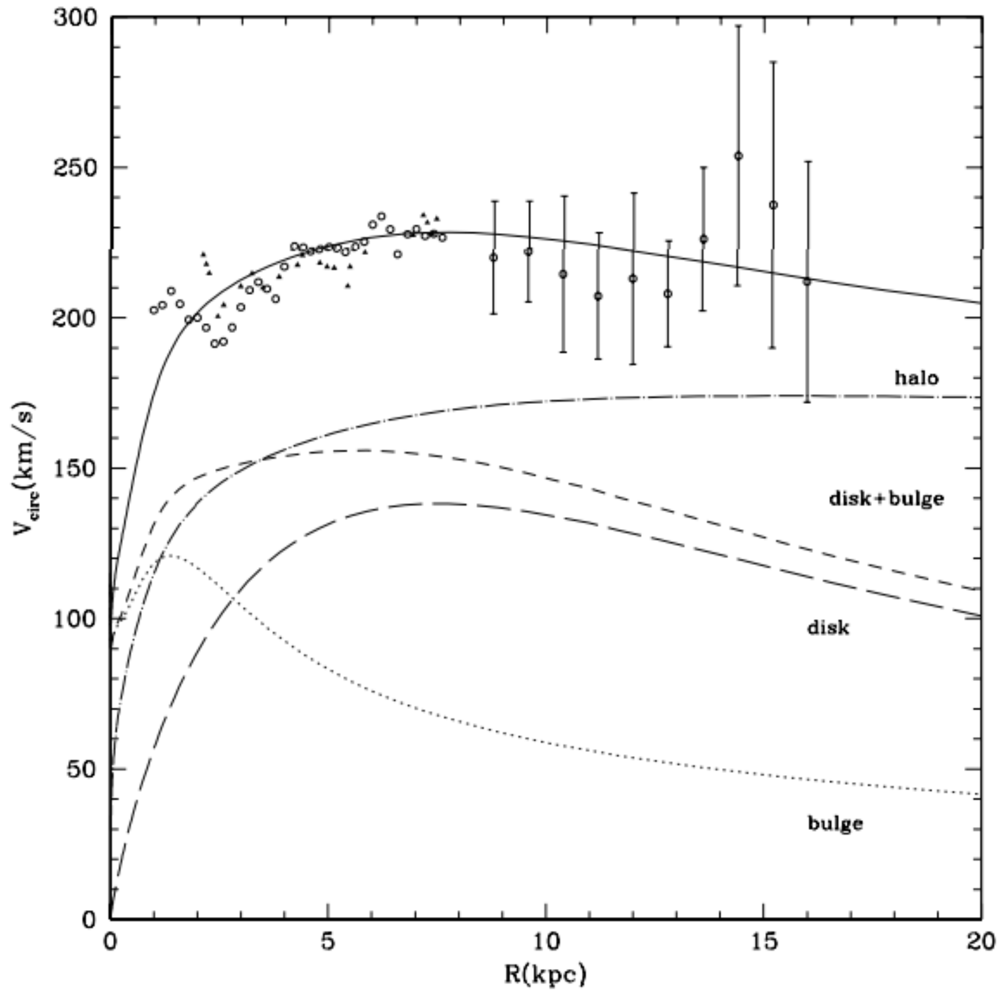
FIG. 2.— Rotation curve of the Milky Way for Cepheids assuming $R_0 = 8.09\,\mathrm{kpc}$ and $\Theta_0 = 233.6\,\mathrm{km\,s^{-1}}$ (model 2). Red data points represent high mass star forming regions (Reid et al. 2014). Grey data points are taken from Sofue et al. (2009) and were rescaled to new (R_0, Θ_0) using formula $V_{\mathrm{new}} = V_{\mathrm{old}} + \frac{R}{8.0}(\Theta_0 - 200)$. Solid and dashed lines show the best-fitting models (linear and universal, respectively).

Rotation curve and the dark matter



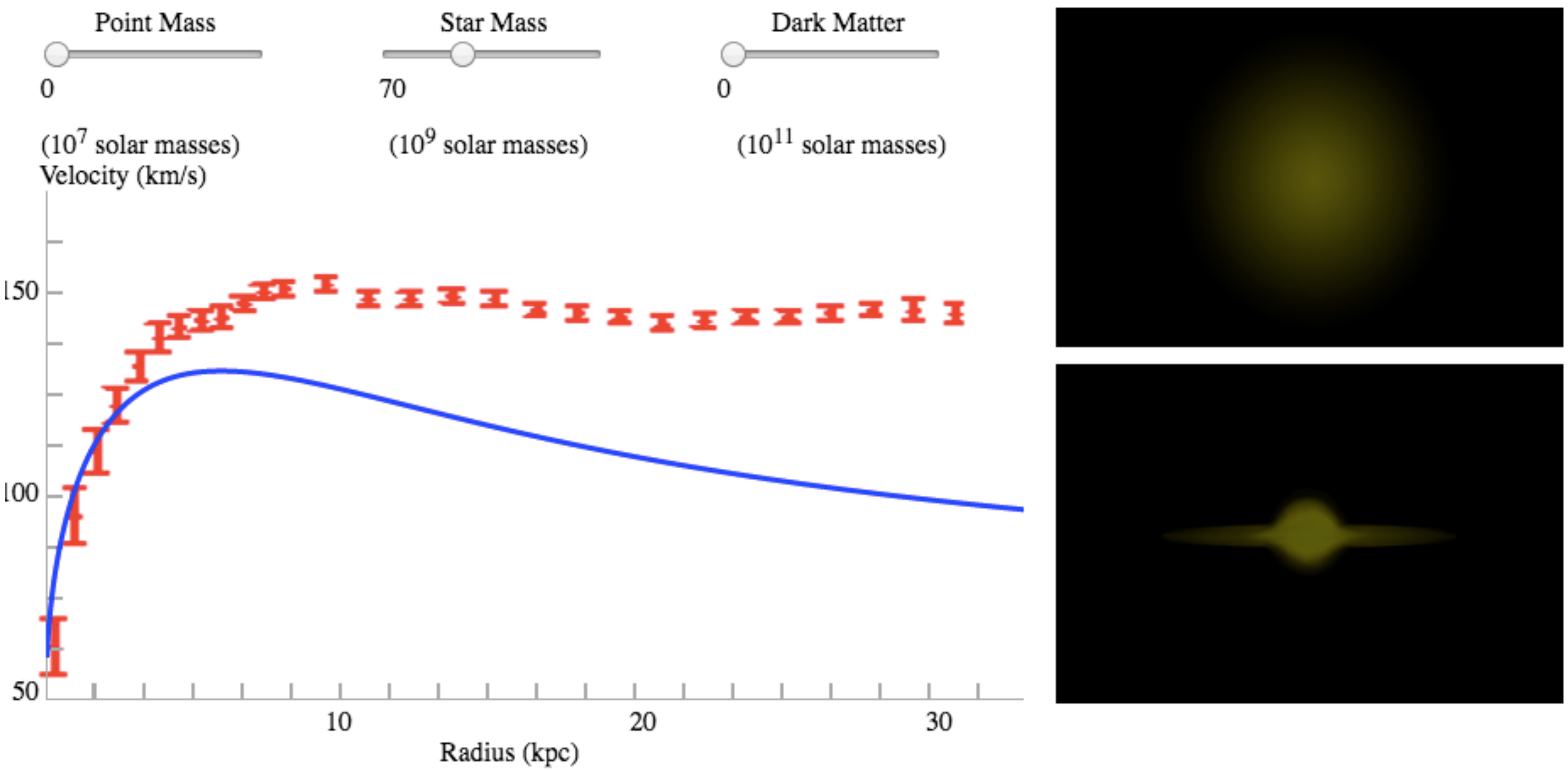
https://en.wikipedia.org/wiki/Oort_constants

Klypin+2002
Data needs to be Scaled to account for new R0

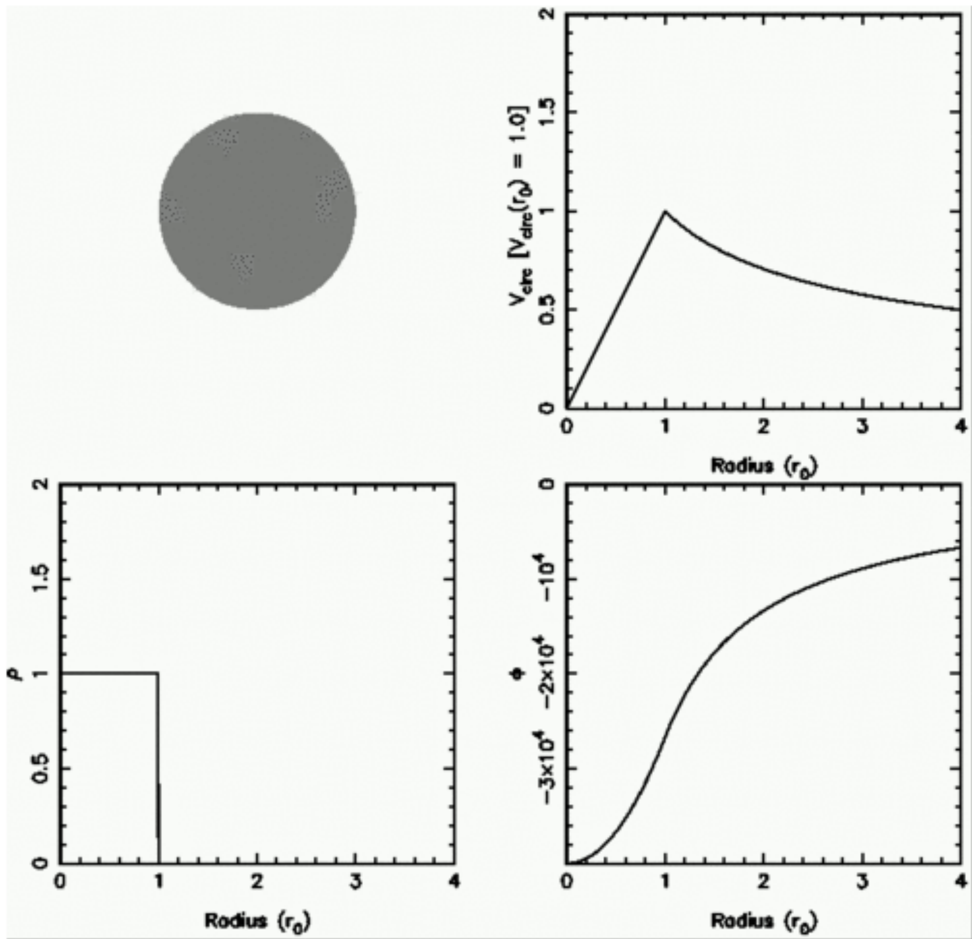


Try for yourself:

http://wittman.physics.ucdavis.edu/Animations/RotationCurve/GalacticRotation.html



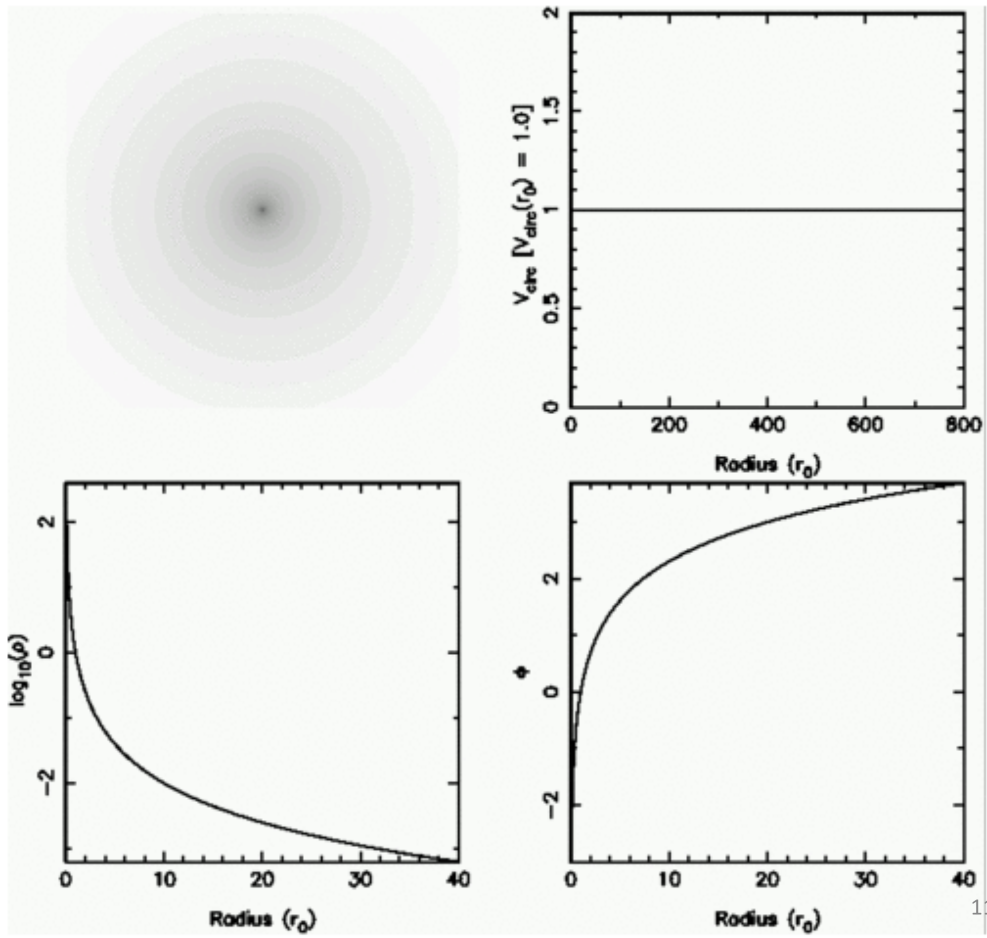
Uniform Sphere



$$\rho(r) = \frac{V_o^2}{4\pi G r^2}$$

$$\Phi(r) = 4\pi G\rho_o ln(r) = V_o^2 ln(r)$$

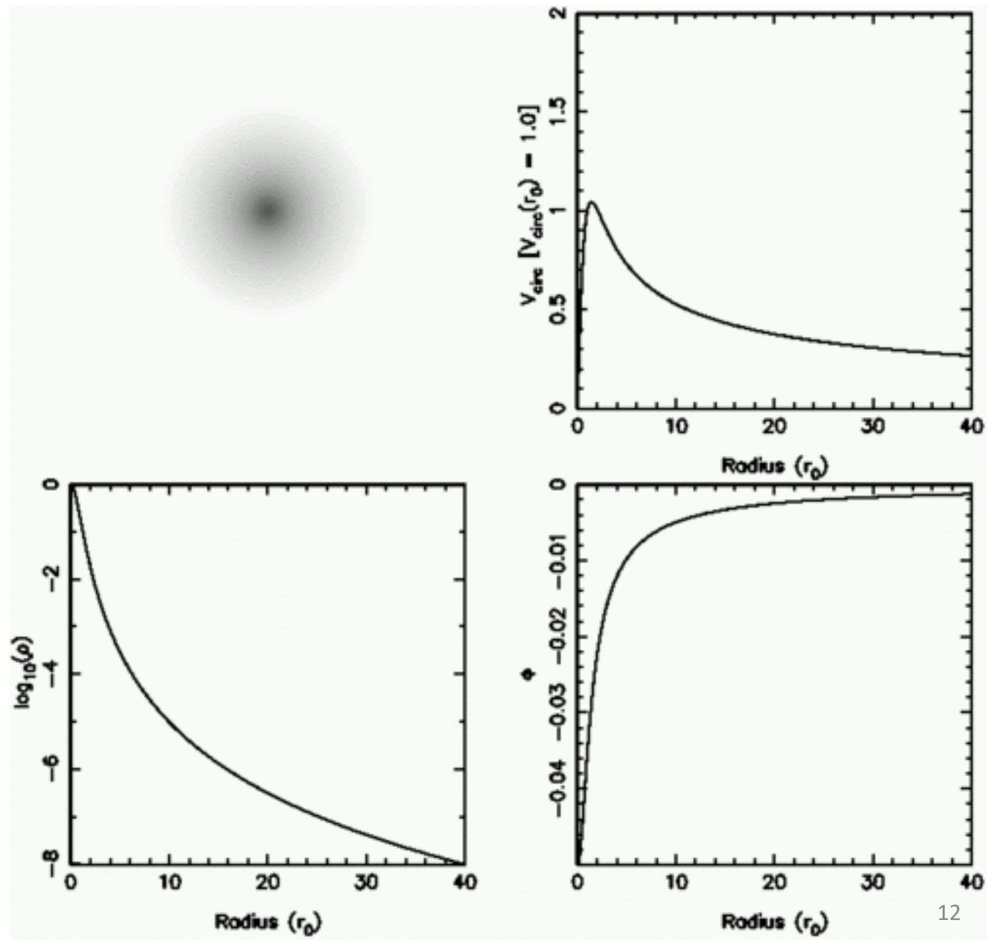
Isothermal Sphere

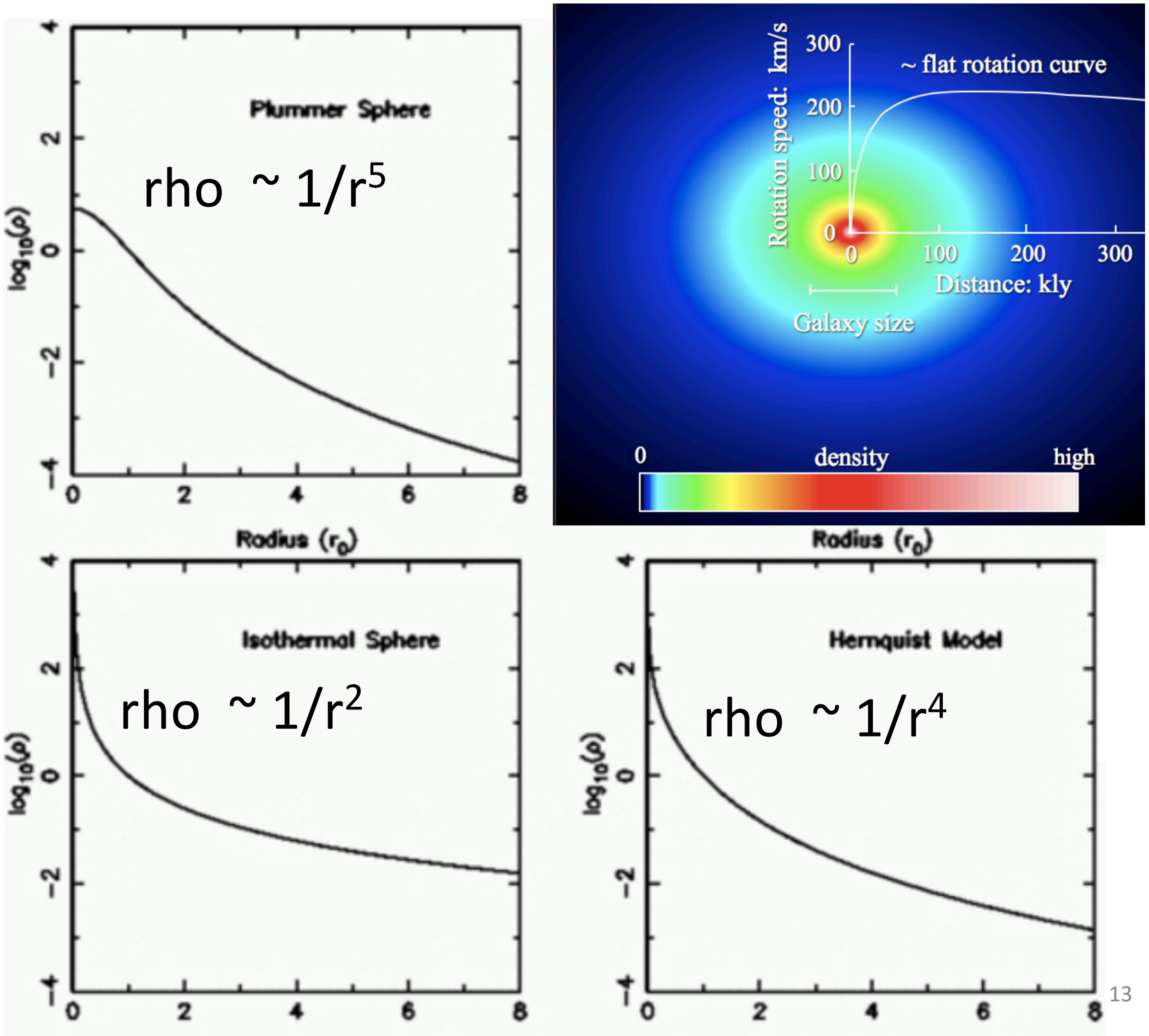


$$\rho(r) = \frac{M}{4/3\pi a^3}(1.0 + r^2/a^2)^{-5/2}$$

$$\Phi(r) = -GM/\sqrt{r^2 + a^2}$$

Plummer model





Hernquist 1990 Profile

$$\rho(r) = (M/2\pi)\frac{a}{(r(r+a)^3)}$$

$$\Phi(r) = -GM/(r+a)$$

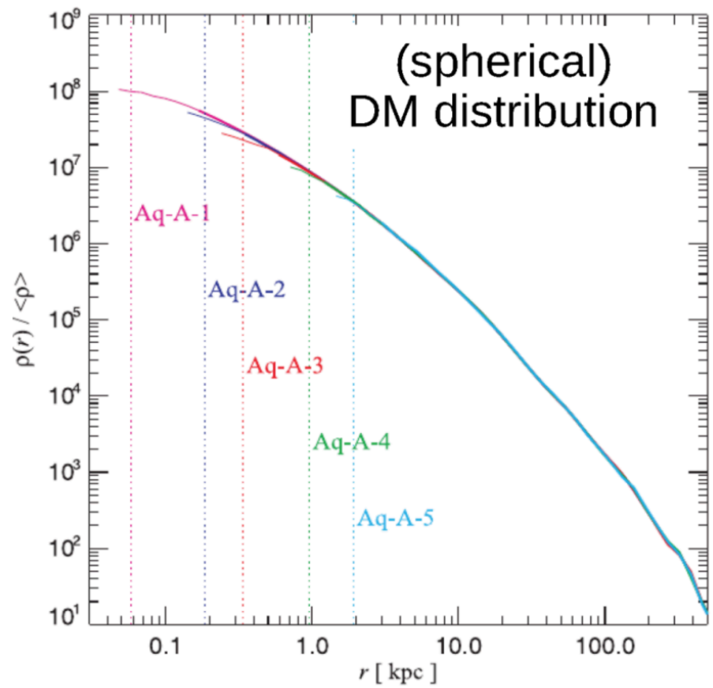
NFW

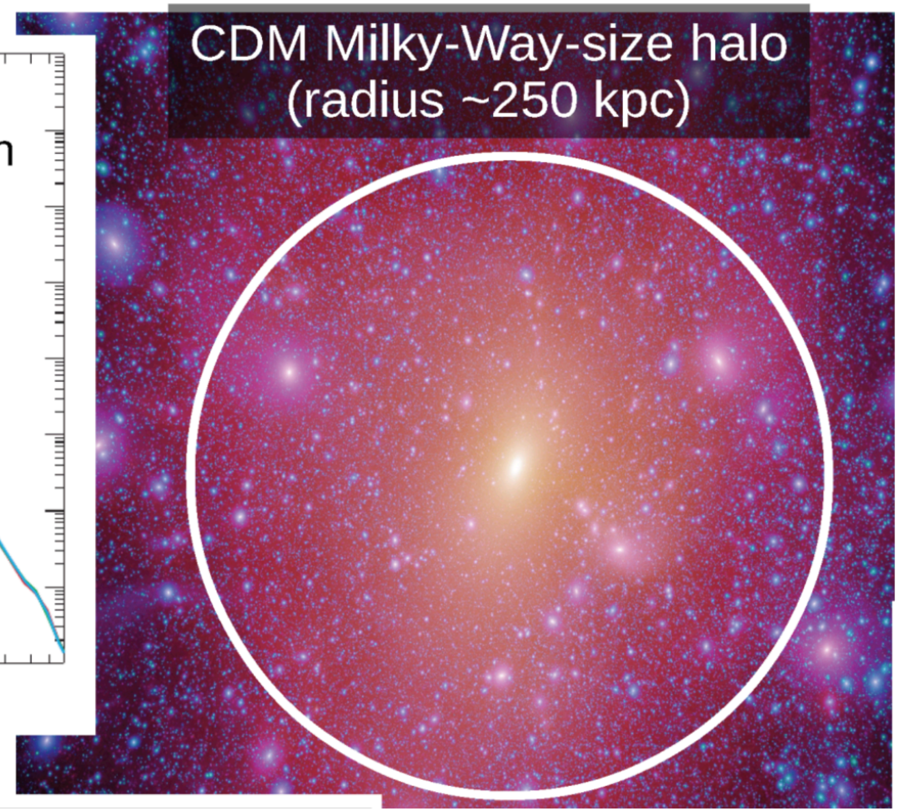
rho ~ $1/r^3$

$$\rho(r) = \frac{\rho_o}{r/r_s(1+r/r_s)^2}$$

$$\Phi_{\rm NFW}(r) = -\sigma_N^2 \frac{\ln(1+{\rm r}/{\rm r_s})}{r/r_s}$$

$$\sigma_N = 4\pi G\rho_o r_s^2$$





Zavala & Frenk 2019 Review

complications ….

Cores vs. Cusps

McGaugh & dBlok (2002)

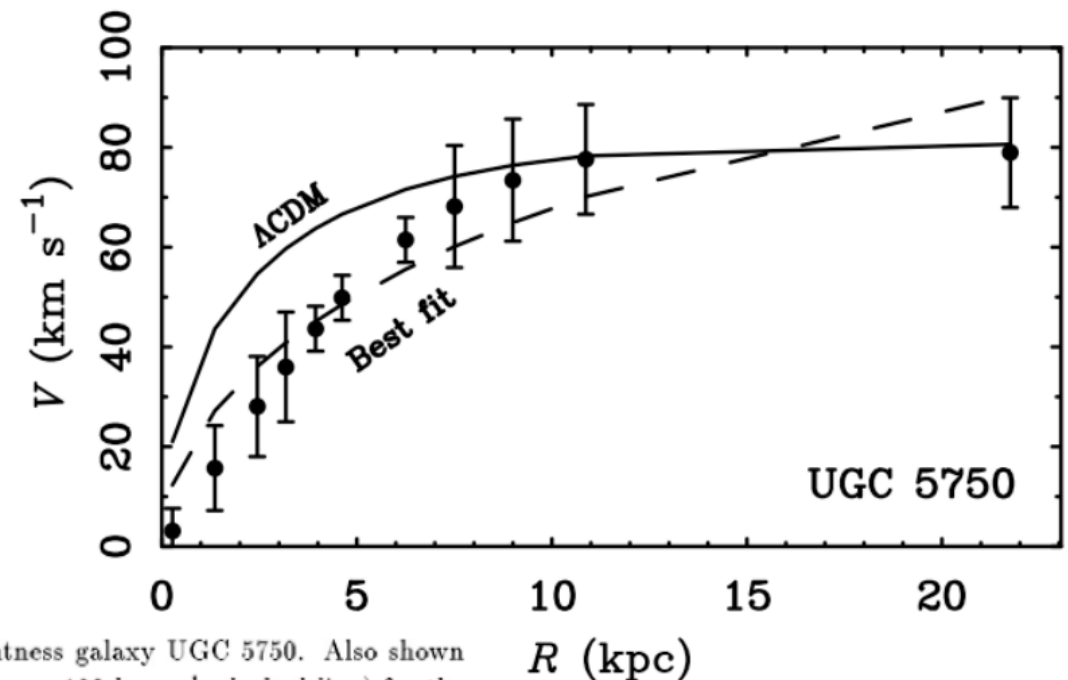
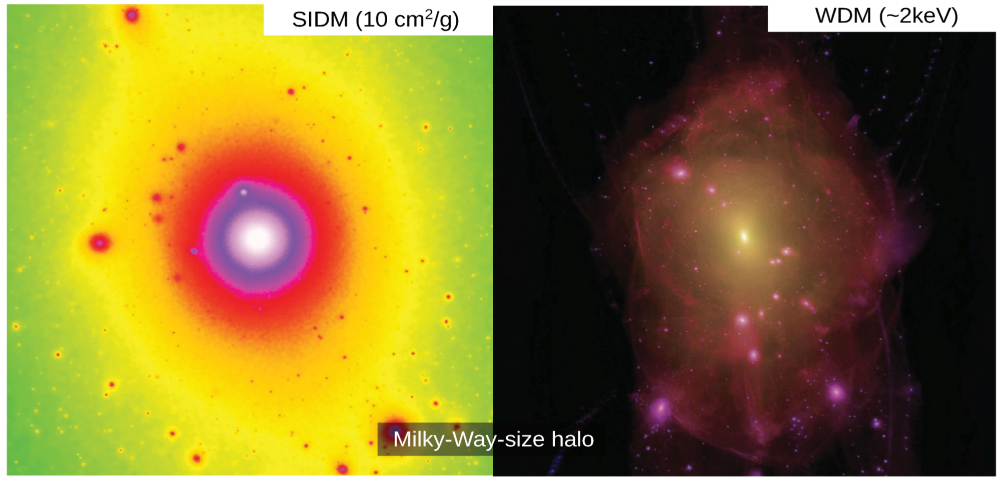
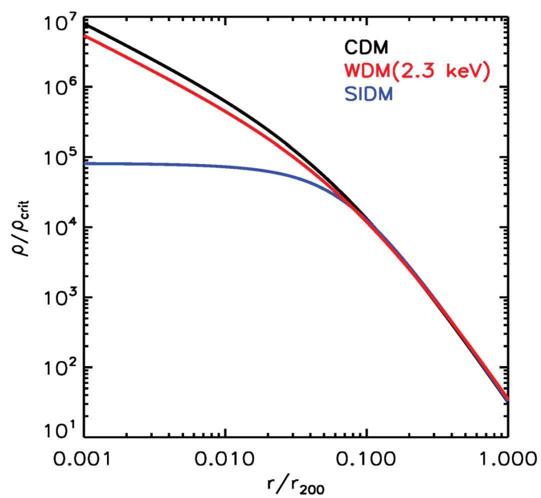
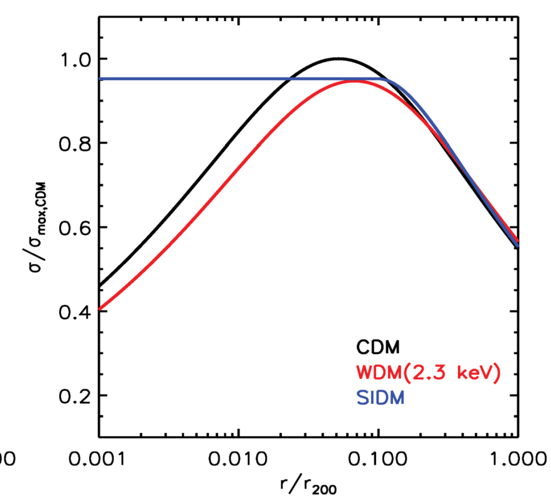


Fig. 1.— The rotation curve of the low surface brightness galaxy UGC 5750. Also shown are the best fitting NFW halo parameters ($c = 2.6$, $V_{200} = 123$ km s^{-1}: dashed line) for the limiting case of a zero mass (minimum) disk, and what the NFW halo should look like for a galaxy of this rotation velocity in the standard ΛCDM cosmology ($c = 10$, $V_{200} = 67$ km s^{-1}: solid line). The excess of the solid line over the data illustrates the cuspy halo problem. Though an NFW fit can be made (dashed line), it is a poor description of the data, and requires a very low concentration ($c = 2.6$ does not occur in any plausible cosmology). These problems become more severe as allowance is made for stars (BMR; BB).

More complications ….







Zavala & Frenk 2019 Review