Nonlinear density waves in galactic dynamics

Can the nonlinearity overcome missing mass?

Observations

Theoretical models

Nonlinearity working in the galaxy

Restoring the flat rotation curve

Future research

Miroslava Vukcevic

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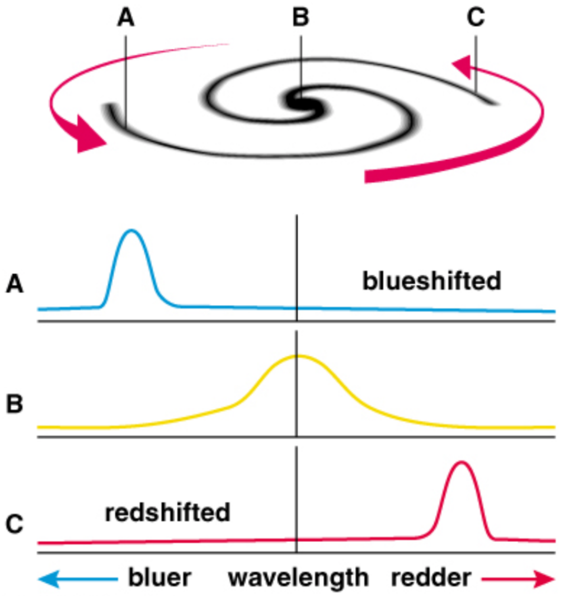
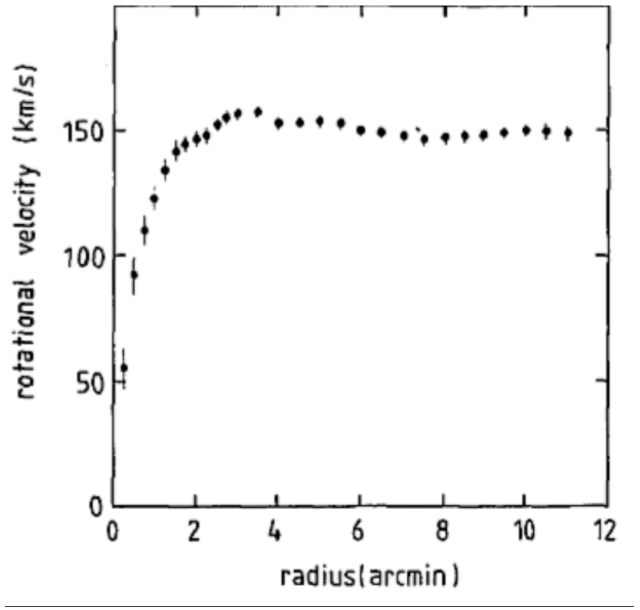
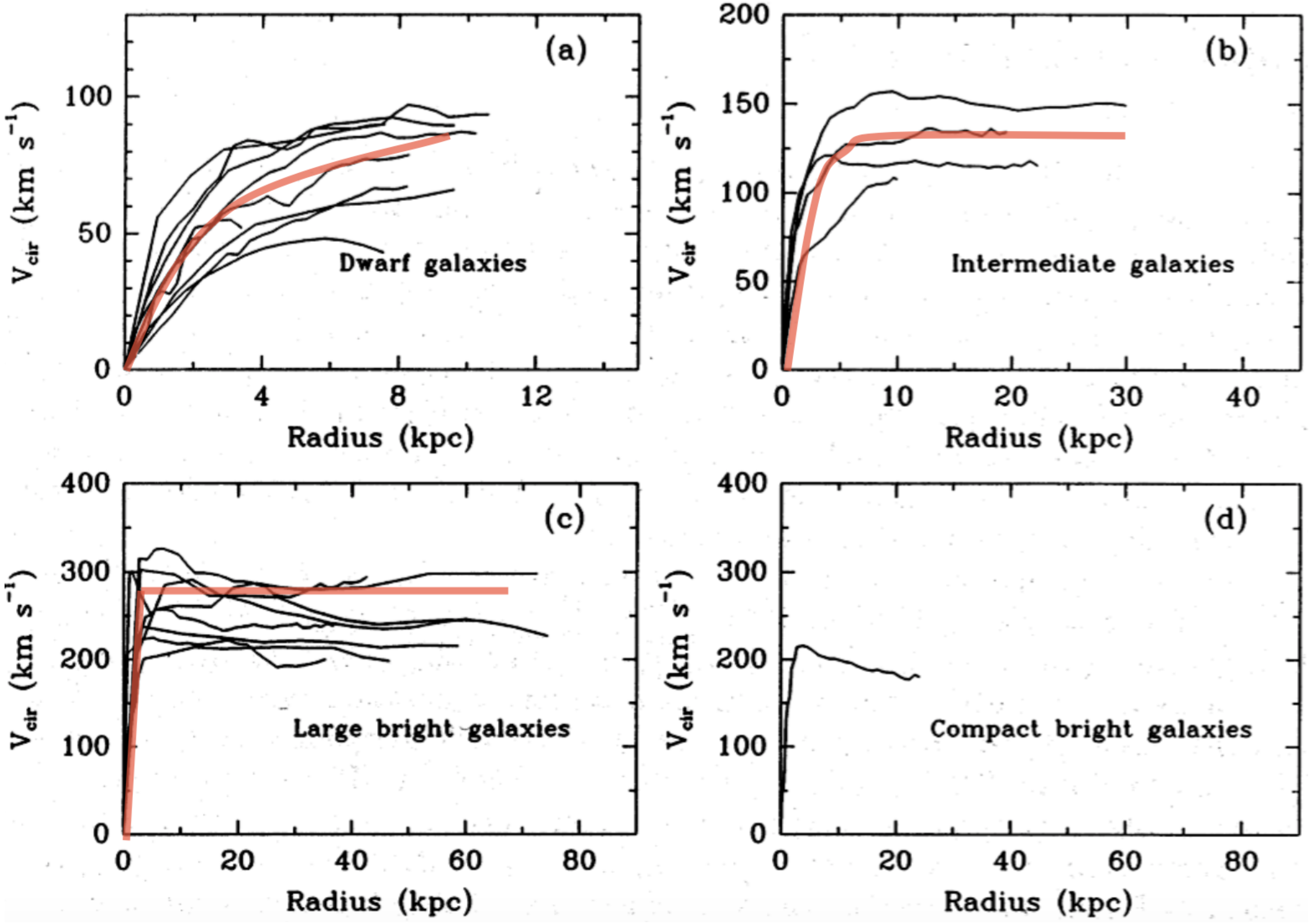
Observations

Rotational velocity curve of spiral galaxies







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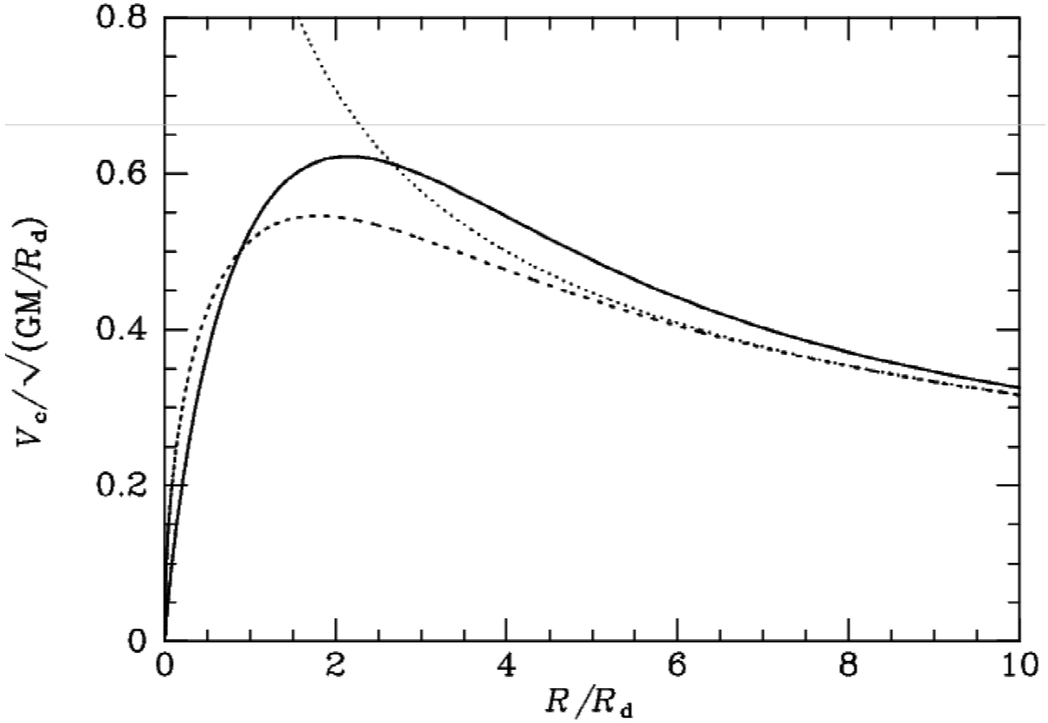
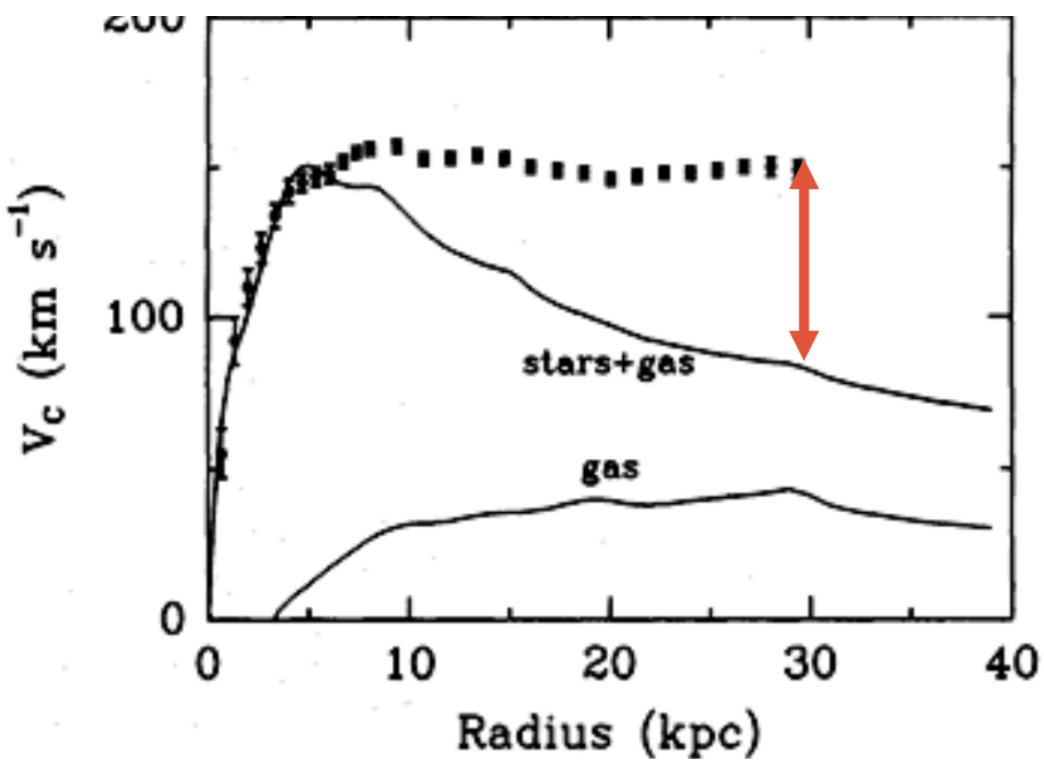
Theoretical models



Circular velocity for: an exponential disk (solid);

a spherical body with the same mass (dashed);

a point mass (dotted)



NGC 3198

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Nonlinearity working in the galaxy

Infinitesimaly thin disk approximation

$$\frac{\partial \phi(r, z=0)}{\partial r} = \pm 2\pi \mathrm{i} G \sigma$$

Lin&Shu 1964

Linearized →dispersive waves → winding dilemma

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Fluid description based on Lin & Shu but with nonlinear terms

Reductive perturbation method (Jaffrey& Taniuti 1964)

Equlibrium + stretched coordinates + variable expansion

Linear dispersion relation → marginal stability of the disk

Frequency goes to zero → group velocity tends to infinity (Watanabe 1969)

$$i\frac{\partial}{\partial\eta}\rho^{1,1} + P\frac{\partial^2}{\partial\xi^2}\rho^{1,1} + Q\left|\rho^{1,1}\right|^2\rho^{1,1} = 0.$$

$$\rho^{1,1}(\xi,\eta) = \rho_a\frac{e^{i\psi}}{ch(\sqrt{\frac{Q}{P}}\rho_a(\xi - P\eta))}.$$

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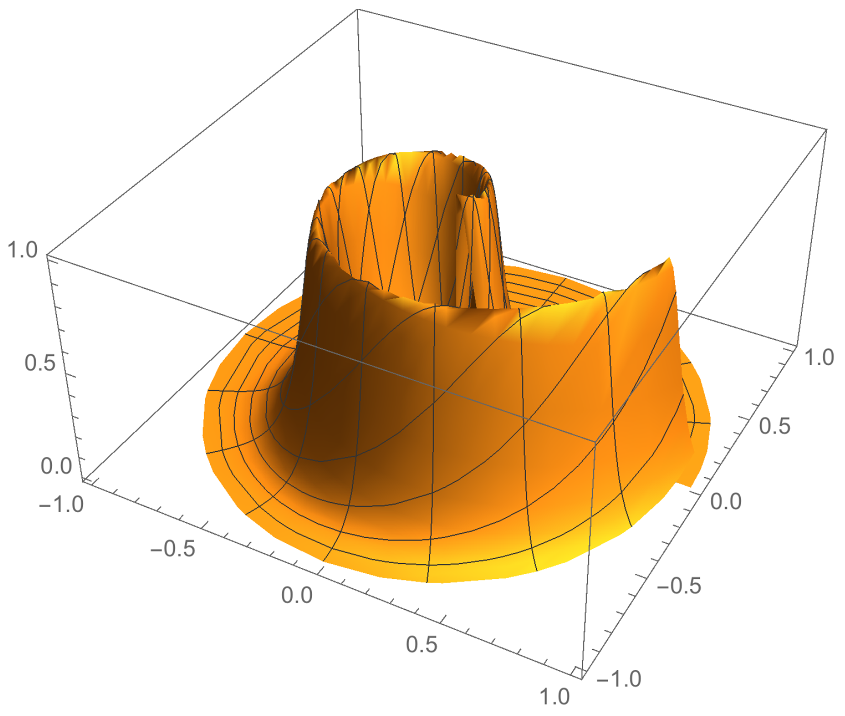
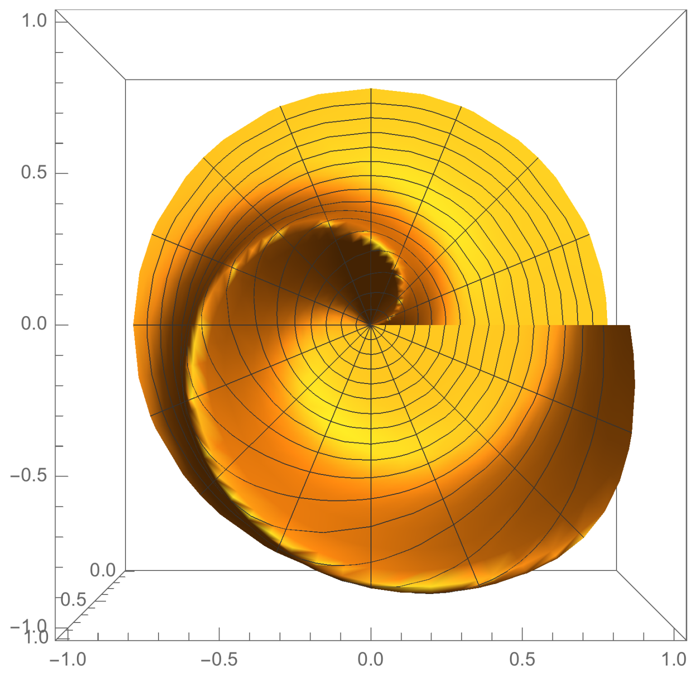
Soliton → constant amplitude and group velocity due to balance in dispersion and nonlinearity

One-dimensional curved wave → moving along the spiral





Vukcevic 2014, MNRAS

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Back to the Rotation Curve of the galaxy (P. Jovanovic and E. Bon)

$$V^2(r) = r\frac{\partial \phi}{\partial r}.$$

$$\frac{\partial \phi}{\partial r} = r\Omega^2 + \sum_{\infty}^{n=1} \sum_{m=-\infty}^{\infty} 2\pi G \epsilon^n \Re(\rho^{(n,m)}(\xi,\eta) e^{i(kr-\omega\tau)}),$$

$$\rho^{1,1}(\xi,\eta) = \rho_a \frac{e^{i\psi}}{ch(\sqrt{\frac{Q}{P}}\rho_a(\xi - P\eta))}.$$

$$V(r) = \sqrt{\Omega^2 r^2 + \frac{ar}{\cosh b(T - cr)}}.$$

$$a = 2\pi G \rho_0 \rho_a [km/s^2]$$

$$b = \kappa \rho_a [1/s]$$

$$c = 1/V_g [s/km]$$

$$V_g = \pi G \rho_0 / \kappa \sim 200 km/s$$

$$(\kappa \sim 10^{-15} 1/s,\ \rho_0 \sim (4-6) \times 10^{-2} g/cm^2 = (200-300) M_\odot/pc^2).$$

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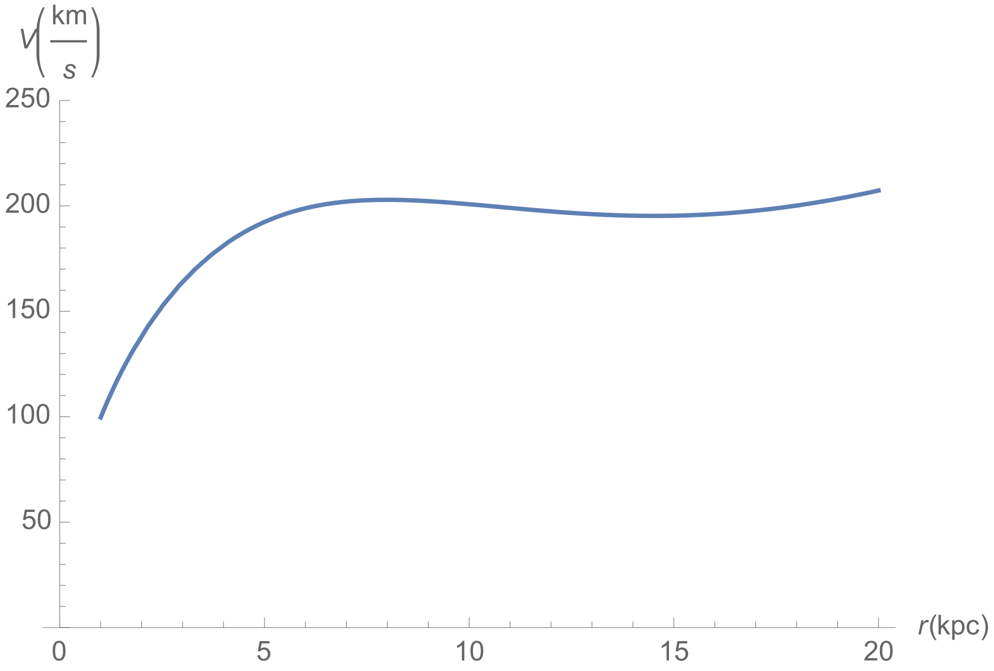
Restoring the flat rotation curve

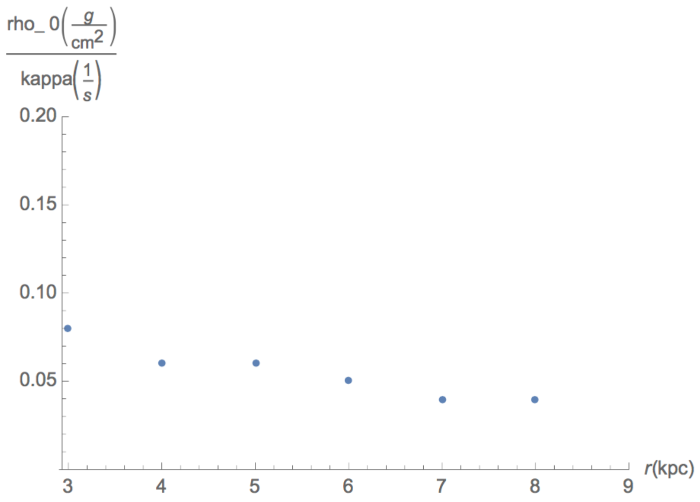


Surface mass density ρ_0=0.045g/cm^2=200M$_\odot$/pc^2

Angular velocity $\Omega \sim 30 \times 10^{-16} 1/s$ (Luna et al. 2006)

V_g=200km/s

Ω^2=90 [km/(s kpc)]^2 a=6x10^3 b=4.5x10^{-16} c=4x10^{14}



$\Omega=\Omega(r)$ $\rho_0=\rho_0(r)$ $\kappa=\kappa(r)=\sqrt{2}\Omega$

a,b, V_g ~ ρ_0/κ=const!

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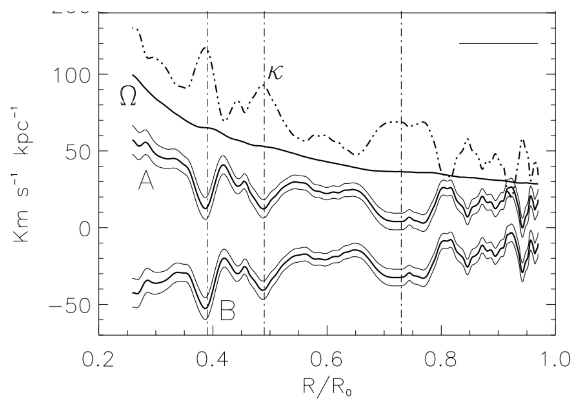
Corrections:



FICH, BLITZ, AND STARK

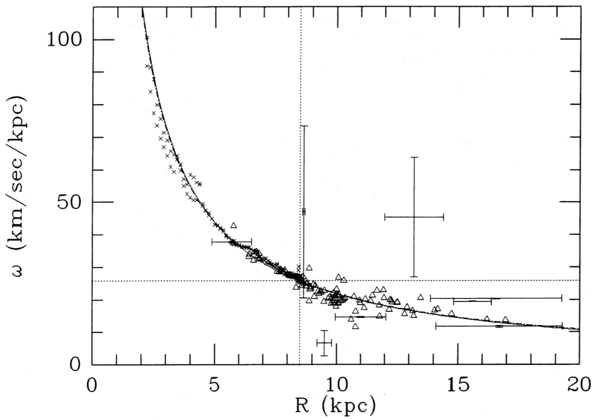
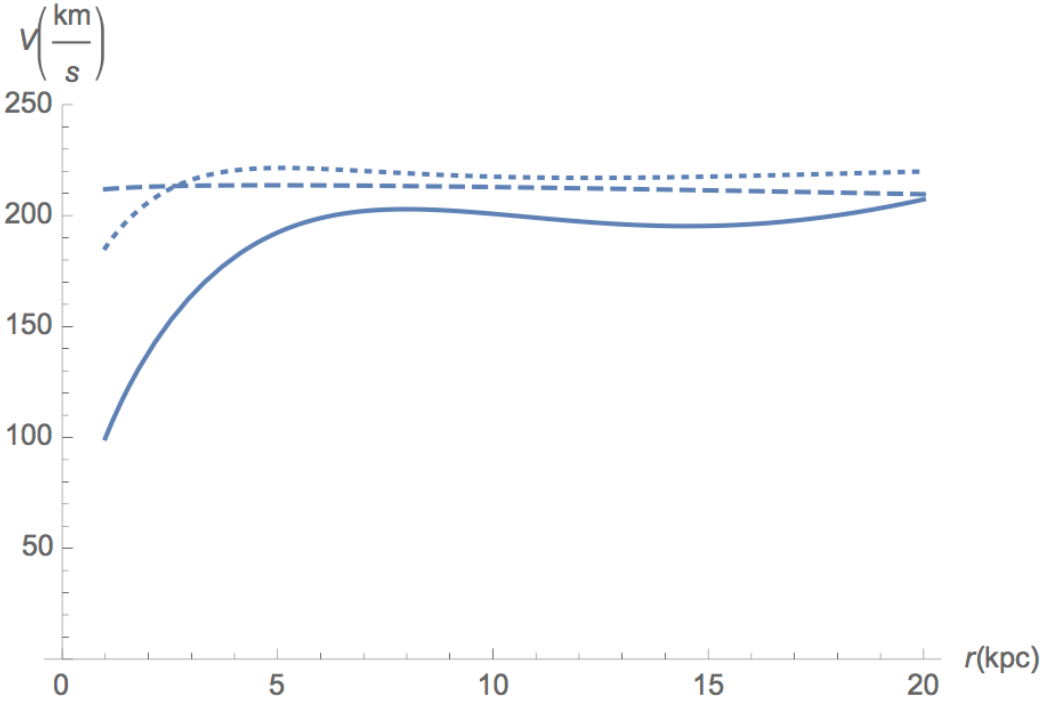
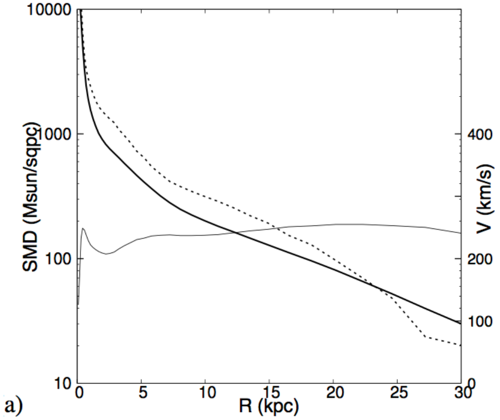
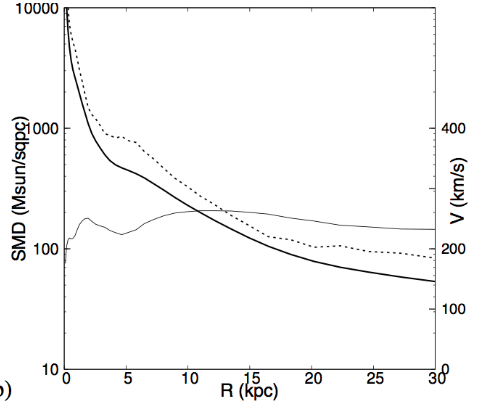


FIG. 2a





a)



b)

Figure 1. Rotational velocity curve for $\Omega = const.$ presented by solid line. Dotted line is rotational velocity curve for power-law fit given by Eq. (22) in Fich et al. (Fich et al. 1989), namely $\Omega(r) \sim r^{-0.9}$, while dashed line is result obtained from Eq. (6) taking all variables r dependent ($\rho(r) \sim r^{(-0.7)}$; power-law for SMD is approximated according to result obtained by Sofue for Milky Way and M31 (Sofue 2018), and $\Omega(r) \sim r^{-0.9}$).

Vukcevic 2021, AJ

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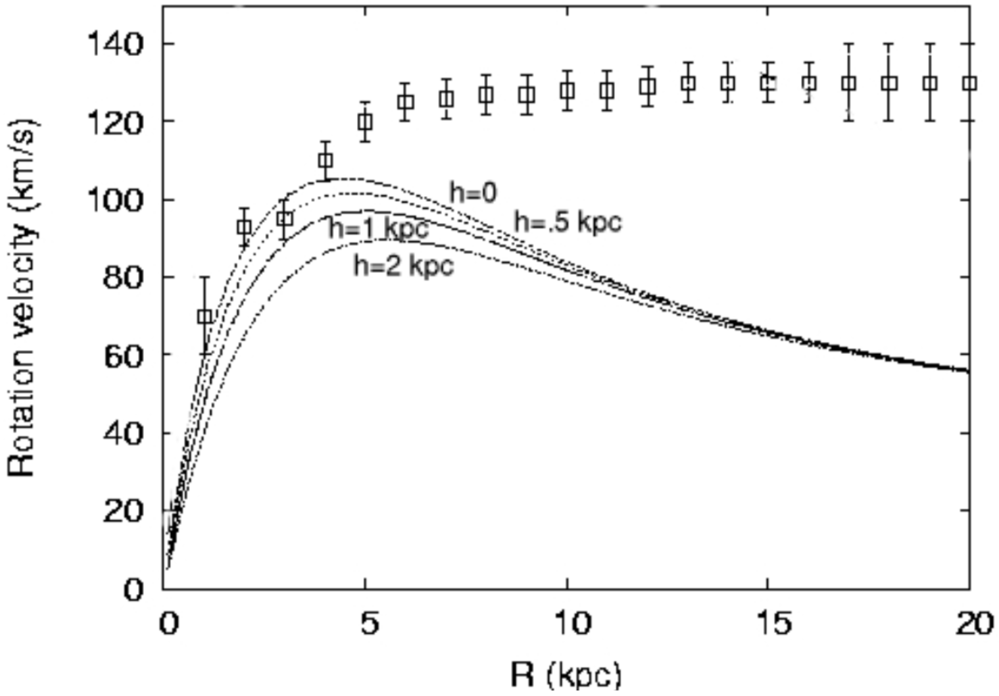
Thickness effects:



V_g overestimated due to infinitesimally thin disk approximation

but it can be compensated by neglected gas contribution

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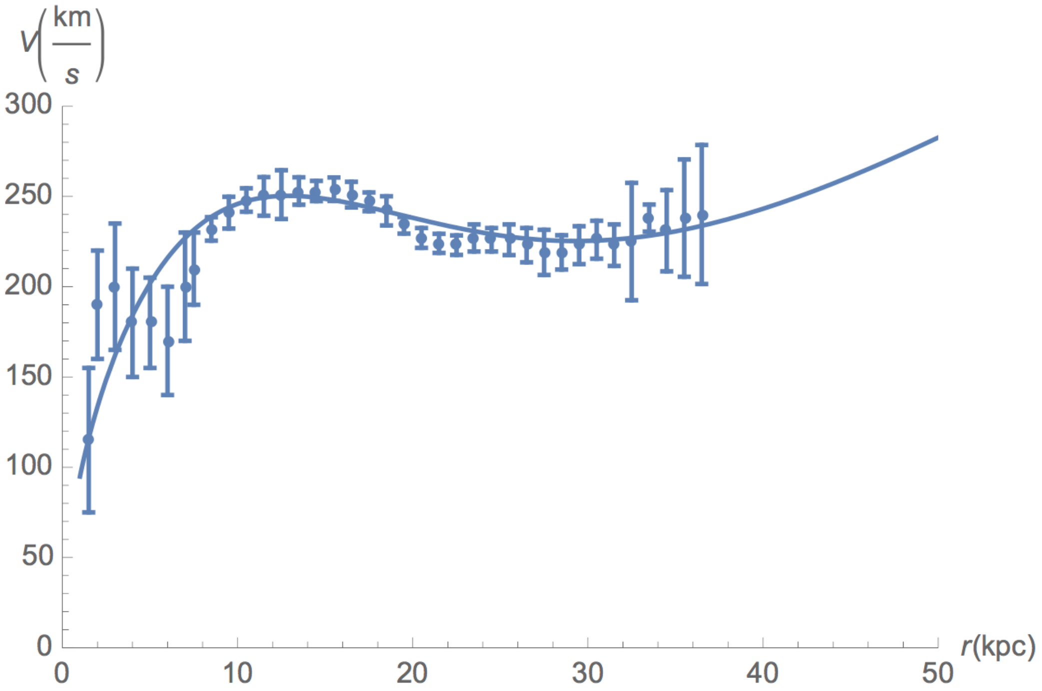


Figure 6. The rotational velocity curve for the galaxy M31. Dots are observed data [45], and the solid curve is the result of Equation (9) for the following parameters: $a = 8 \times 10^3$, $b = 0.03$, $c = 3.5$.

Vukcevic 2022, Universe

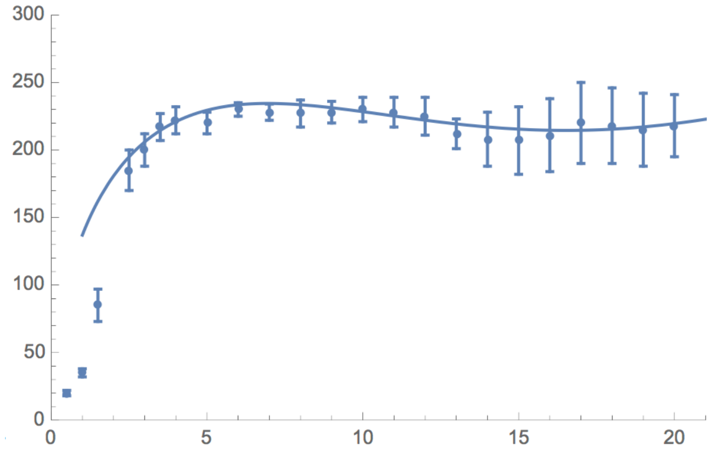
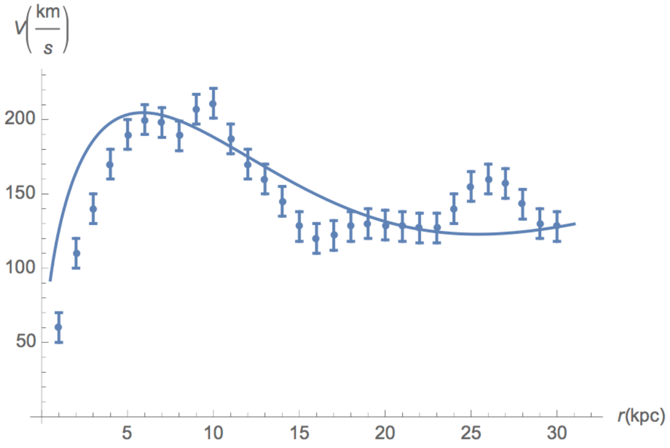


Fig. 7: RC NGC 3521. dots observations (de Blok et al. 2008); solid line: Ω^2=80, a=6.5x10^3, b=4.2x10^{-16}, c=3.8x10^{14}, for observed values Ω=28x10^{-16}, ρ_0=4.3x10^{-2}g/cm^2, V_g=220km/s



Peculiar NGC 157
Ω=7x10^{-16}1/s, ρ_0=2.4x10^{-2} g/cm^2, V_g=180km/s
Ω^2=15, a=6x10^3, b=3.8x10^{-16}, c=3.6x10^{14}

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Further research

Numerical simulations: N-body simulations V. Zekovic & M. Radeta (Vukcevic et al. 2021, AN)

Indication that spirals evolve into ring → implication on the galaxy evolution

Gas contribution: implication on the accretion disk dynamics and dwarf gas reach galaxies

Analysis of elliptical galaxies dynamics

Baryonic Tully-Fisher relation by fitting as many as possible spiral galaxies: Dj. Savic

Larger scale nonlinearity contribution – galaxy clusters

Before involving some exotic undetectable matter it is always useful to reinvestigate assumptions done in theoretical models (if observations are trustful)

Thank you for your attention!

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