Milky Way-like Rotation Curves in f(R) Gravity

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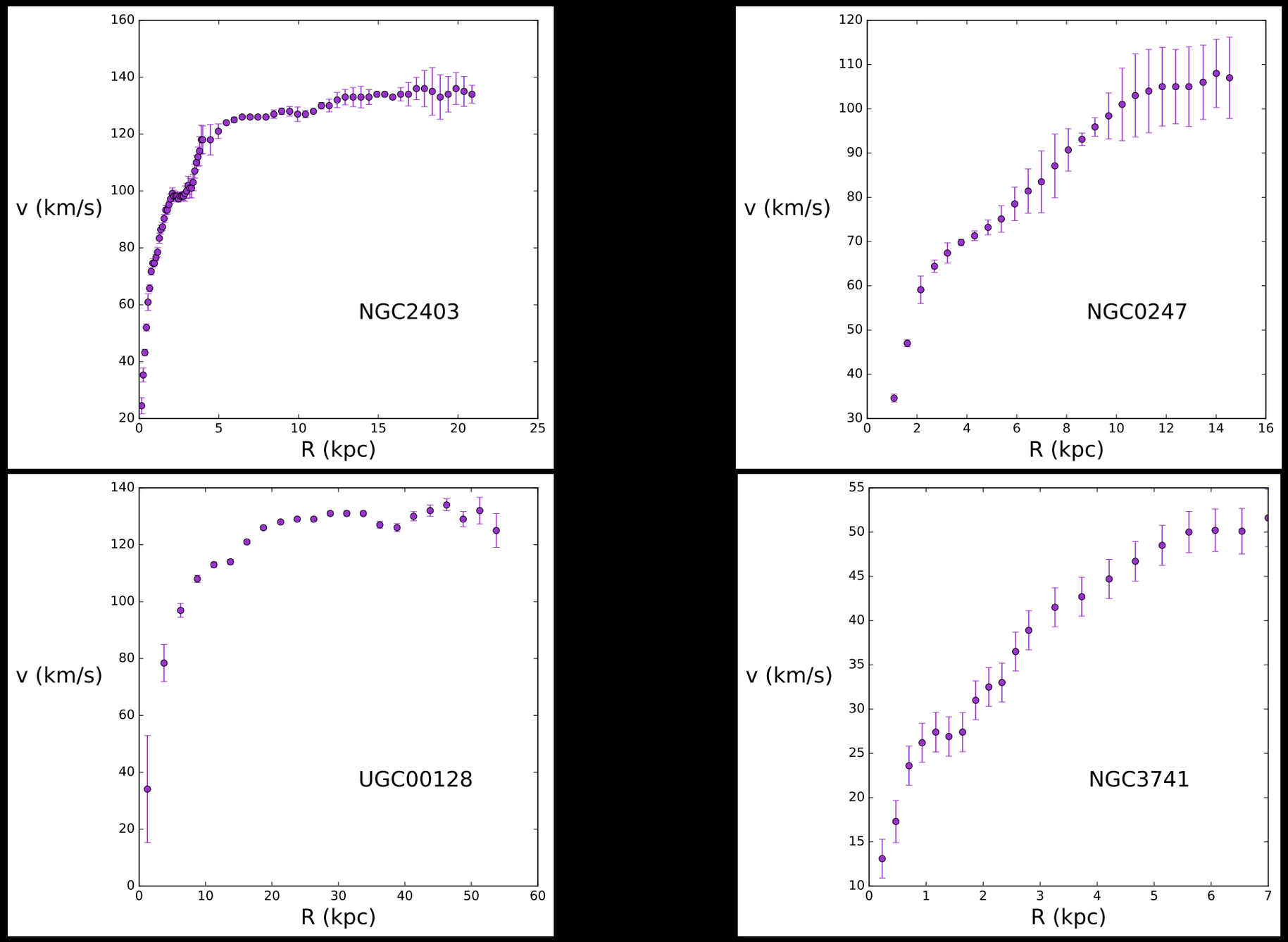
Observed Rotation Curves

Credit: Lelli *et al.* (2016)



Take home: Galaxy rotation curves show upturns!

Governing Equations

$$\left(f_R \equiv \frac{df}{dR}\right)$$

$$\nabla^2 f_R = \frac{1}{3}\left(\delta R - 8\pi G \delta\rho\right)$$

$$\nabla^2 \Phi = \frac{16\pi G}{3}\delta\rho - \frac{1}{6}\delta R$$

Take home: f_R is our scalar field:
choice of f(R) = choice of potential

Fifth Force

$$\ddot{\boldsymbol{x}} + \boldsymbol{\nabla}\Phi_{Newton} = \frac{c^2}{2}\boldsymbol{\nabla} f_R$$

Take home: Fifth force is proportional to field gradient;
can screen it by suitably choosing f(R)

Hu-Sawicki f(R)

$$f(R) = -m^2 \frac{c_1 \left(\frac{R}{m^2}\right)^n}{1 + c_2 \left(\frac{R}{m^2}\right)^n}$$

$$(m^2 \equiv H_0^2 \Omega_m)$$

Hu-Sawicki f(R)

$$\frac{c_1}{c_2} = 6\frac{\Omega_\Lambda}{\Omega_m}$$

Hu-Sawicki f(R)

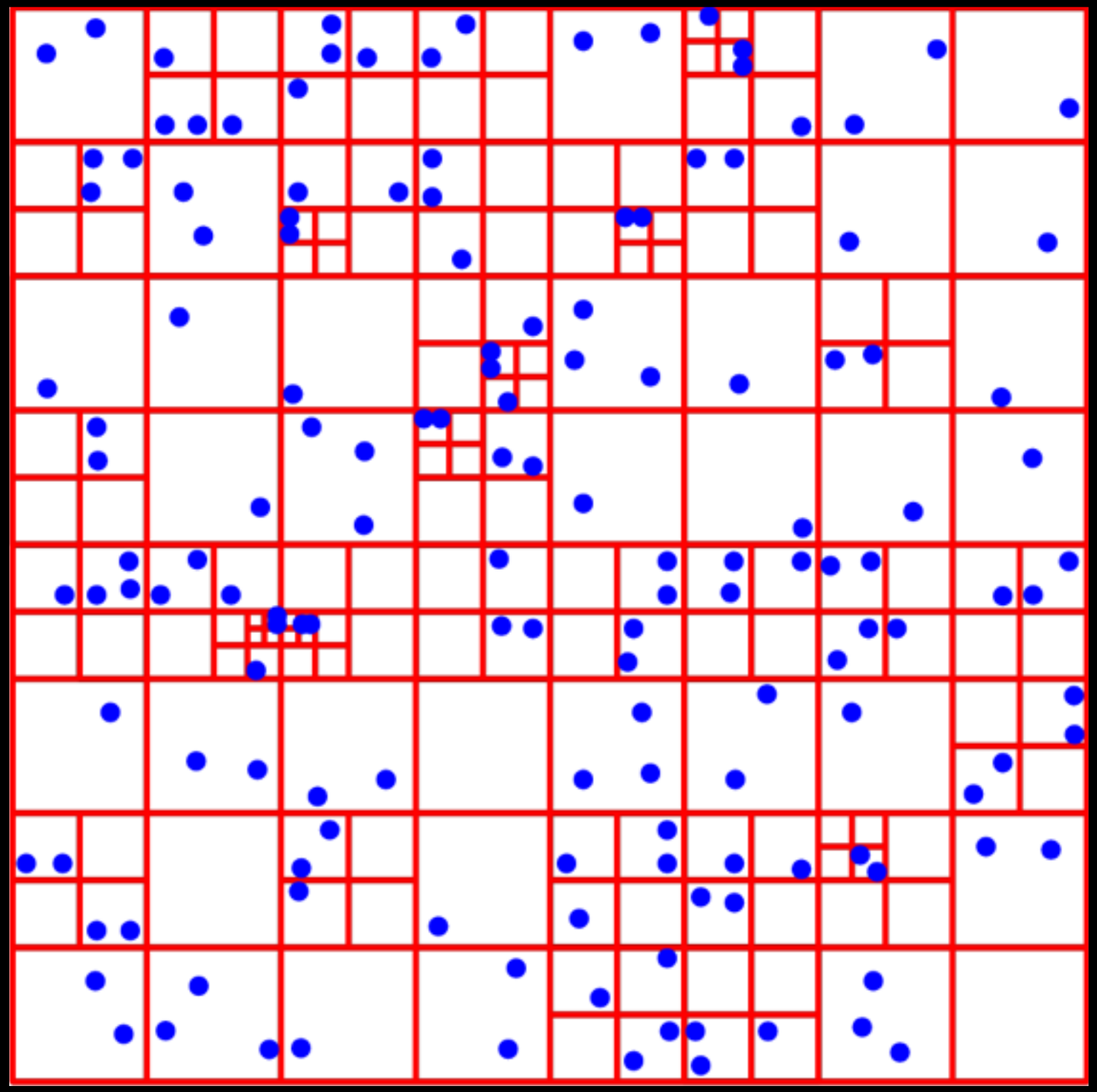
$$\bar{f}_{R0} = -\frac{2\Omega_\Lambda \Omega_m}{3\left(\Omega_m + 4\Omega_\Lambda\right)} \frac{1}{c_2}$$

$$\bar{f}_{R0} \to 0, \quad f(R) \to -2\Lambda$$

Take home: We're fitting one extra parameter: f_{R0}

MG-GADGET

Credit: Puchwein *et al*. (2013)



MG-GADGET

$$\bar{f}_R(a) = a^6 \bar{f}_{R0} \left(\frac{1 + 4\frac{\Omega_\Lambda}{\Omega_m}}{1 + 4\frac{\Omega_\Lambda a^3}{\Omega_m}} \right)^2$$

$$\delta R = \bar{R}(a) \left(\sqrt{\frac{\bar{f}_R(a)}{f_R}} - 1 \right)$$

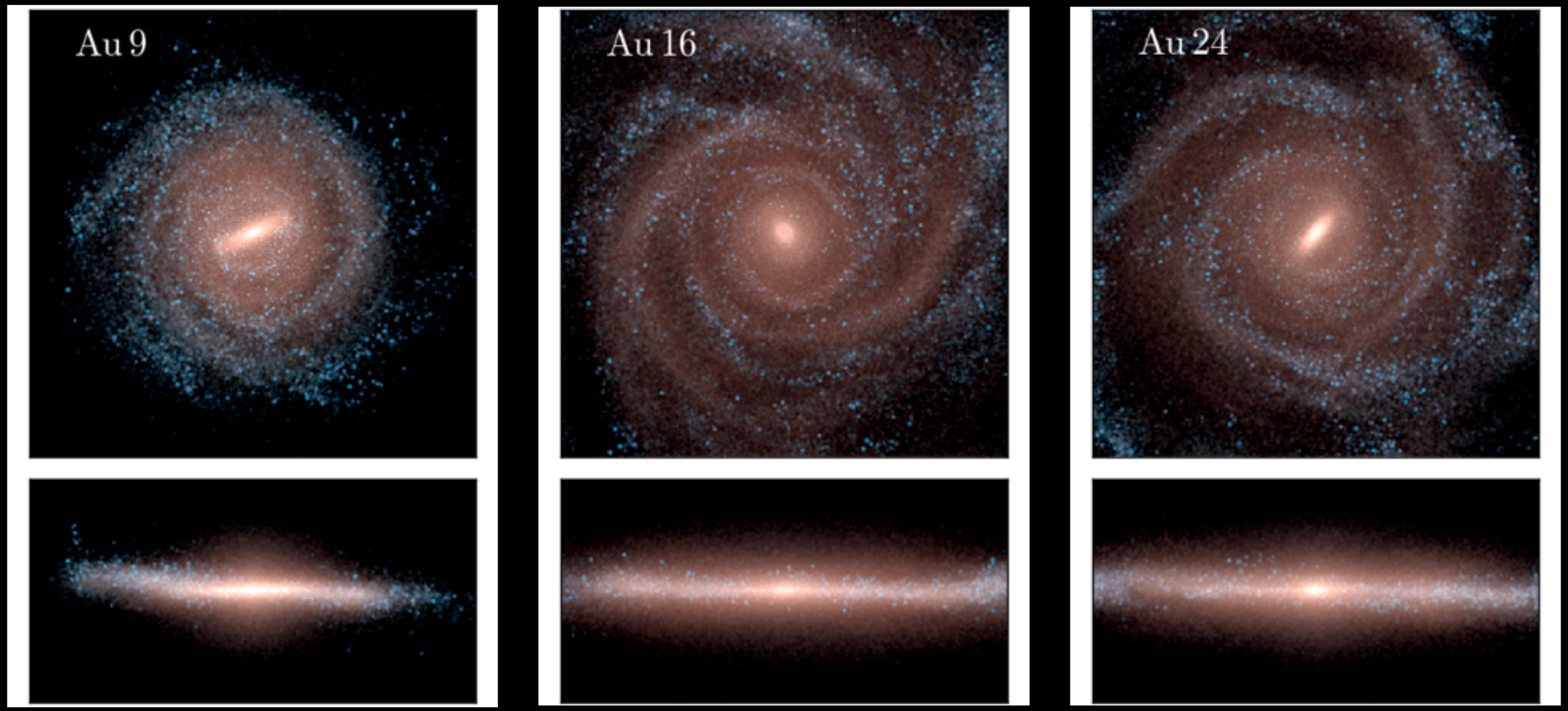
$$\nabla^2 f_R = \frac{1}{3} \left(\delta R - 8\pi G \delta\rho \right)$$

$$\nabla^2 \Phi = \frac{16\pi G}{3} \delta\rho - \frac{1}{6} \delta R$$

Take home: Equations are non-linear;
have to solve in post-processing!

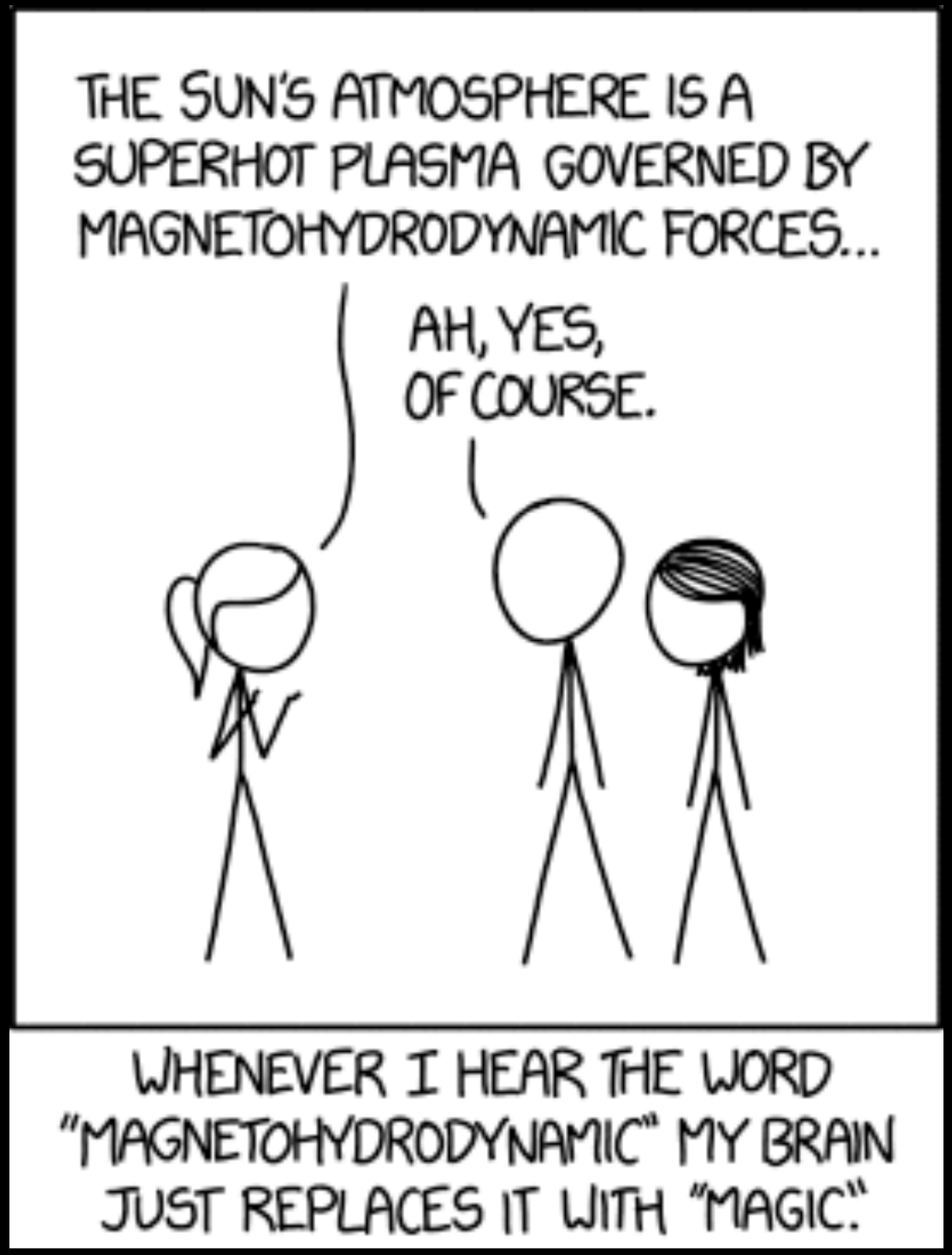
Auriga Galaxies

Credit: Grand *et al.* (2017)



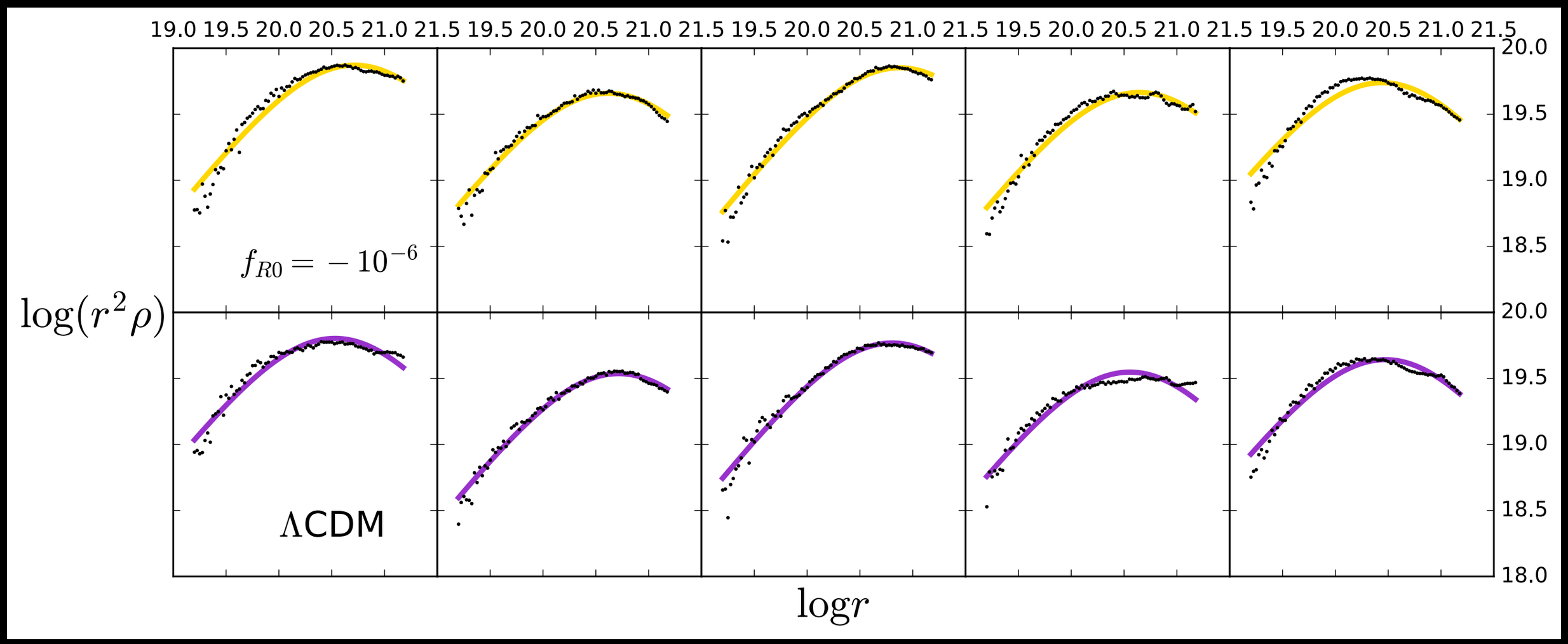
Take home: State of the art galaxy simulations, but ΛCDM

Source: xkcd.com



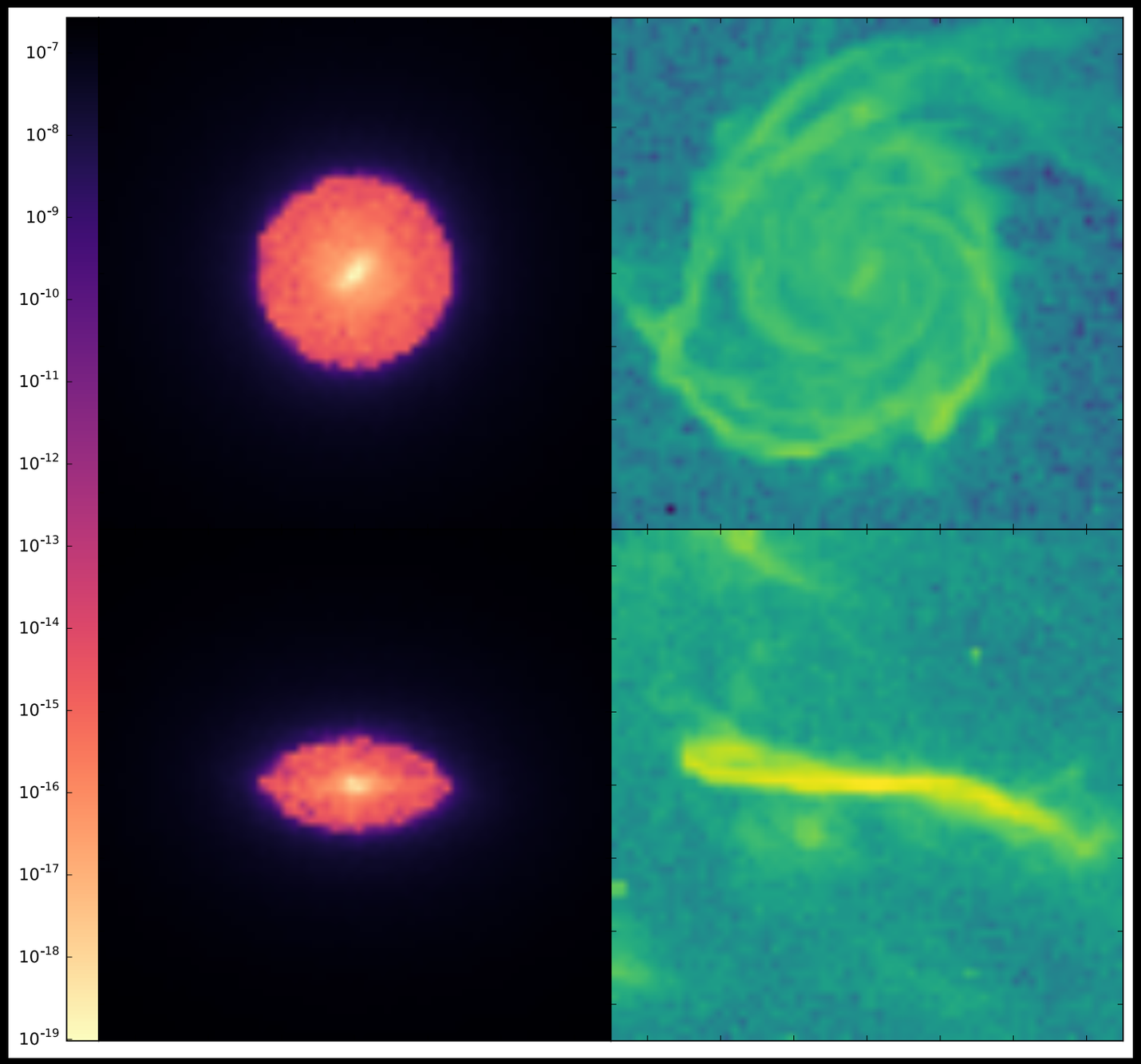
NFW Fits

Credit: Arnold *et al*. (2016)



Take home: NFW equally good for f(R) haloes as for ΛCDM

Field Profiles

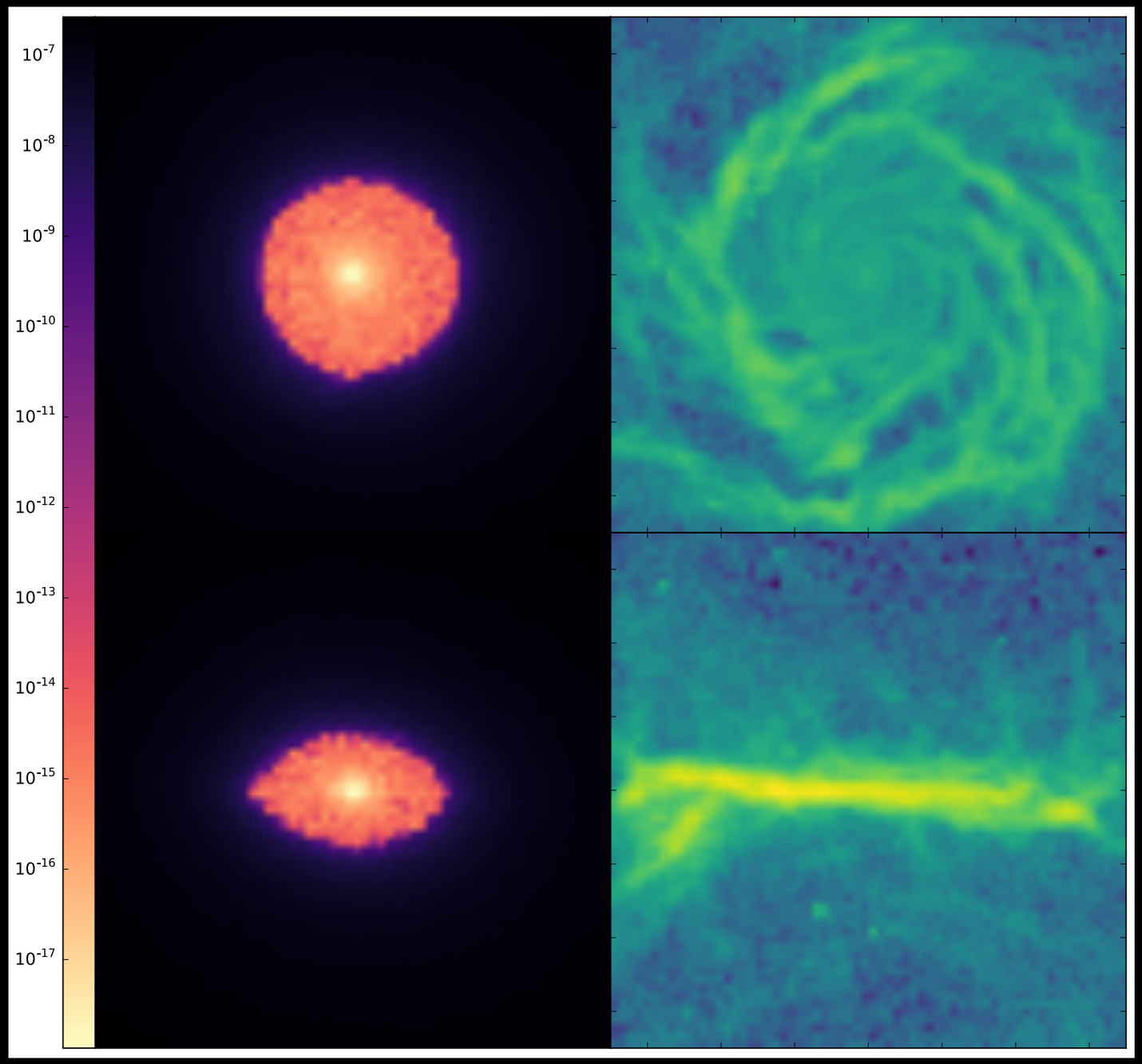


Galaxy 24

$f_{R0} = -8 \times 10^{-7}$

Take home: Galaxies display a discoid screening profile

Field Profiles

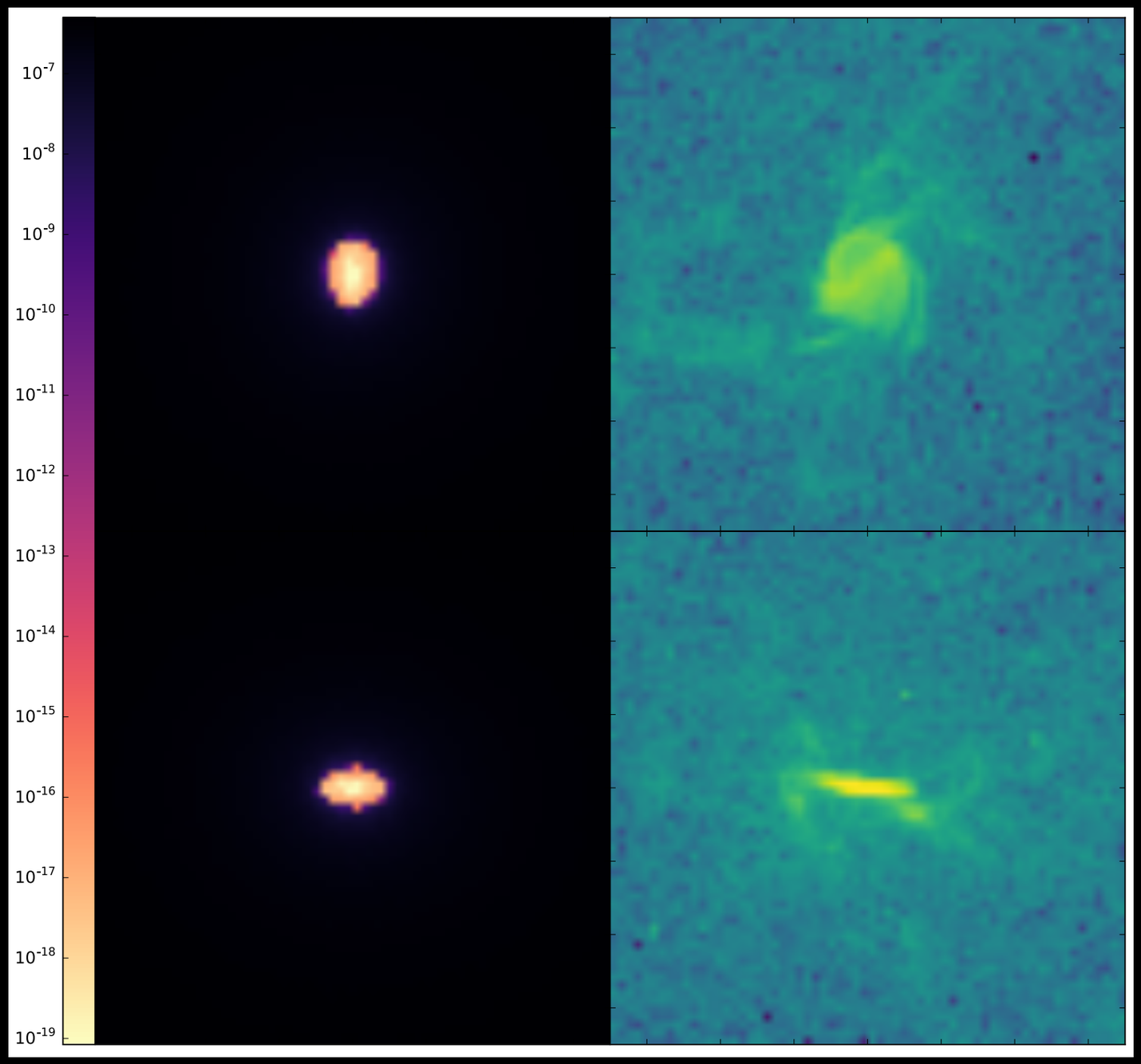


Galaxy 16

$f_{R0} = -8 \times 10^{-7}$

Take home: Galaxies display a discoid screening profile

Field Profiles

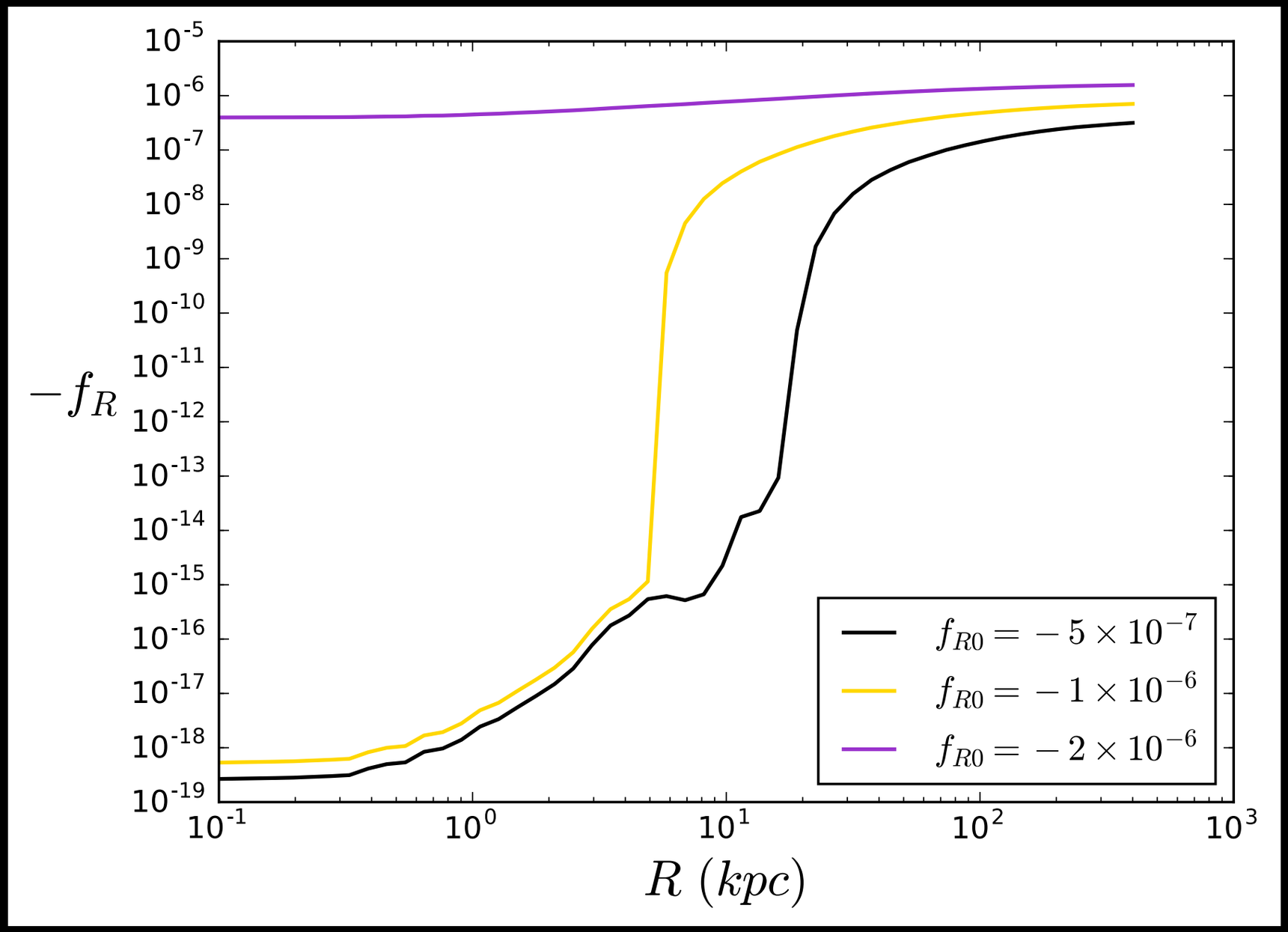


Galaxy 9

$f_{R0} = -8 \times 10^{-7}$

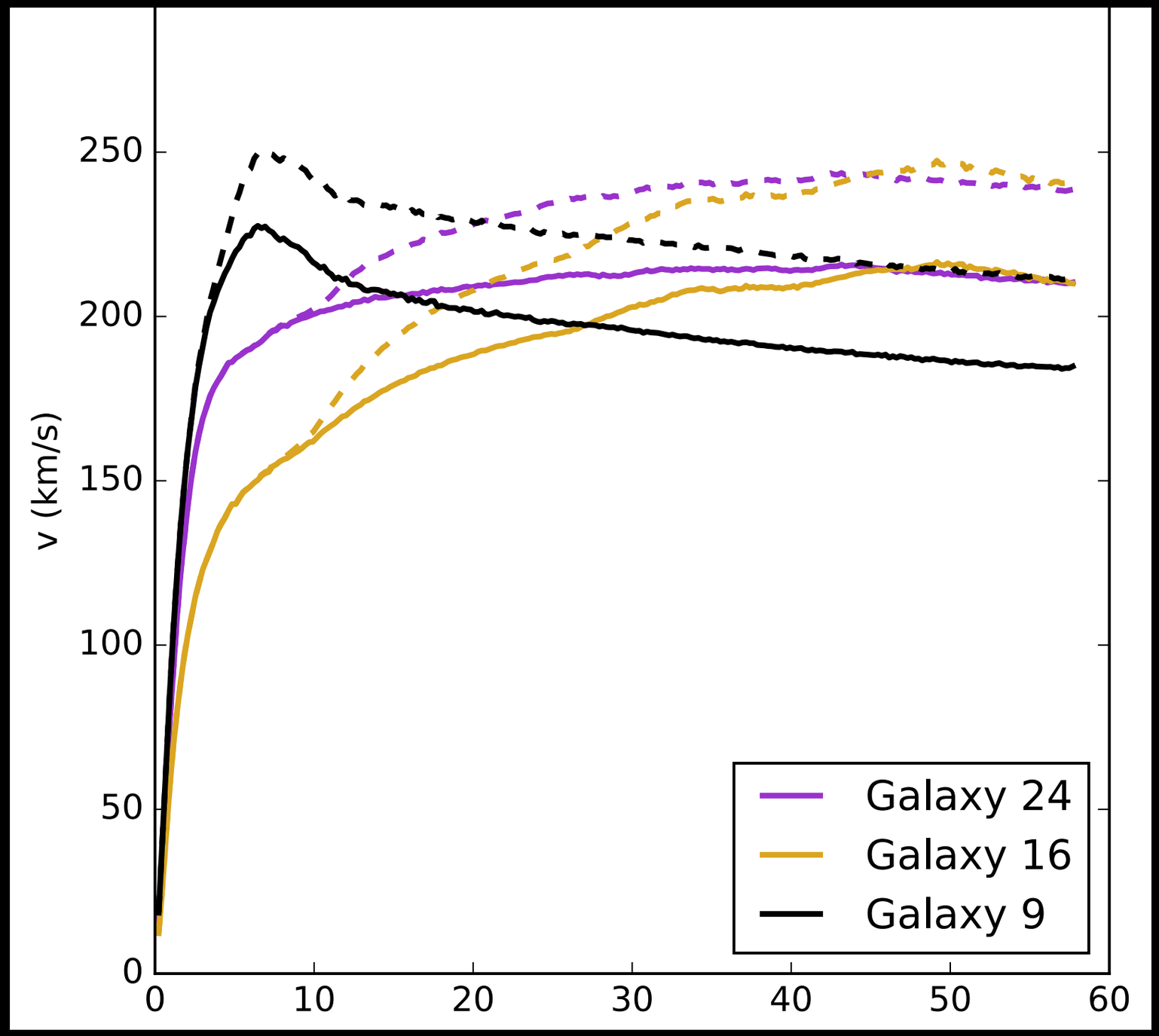
Take home: Galaxies display a discoid screening profile

Field Profiles



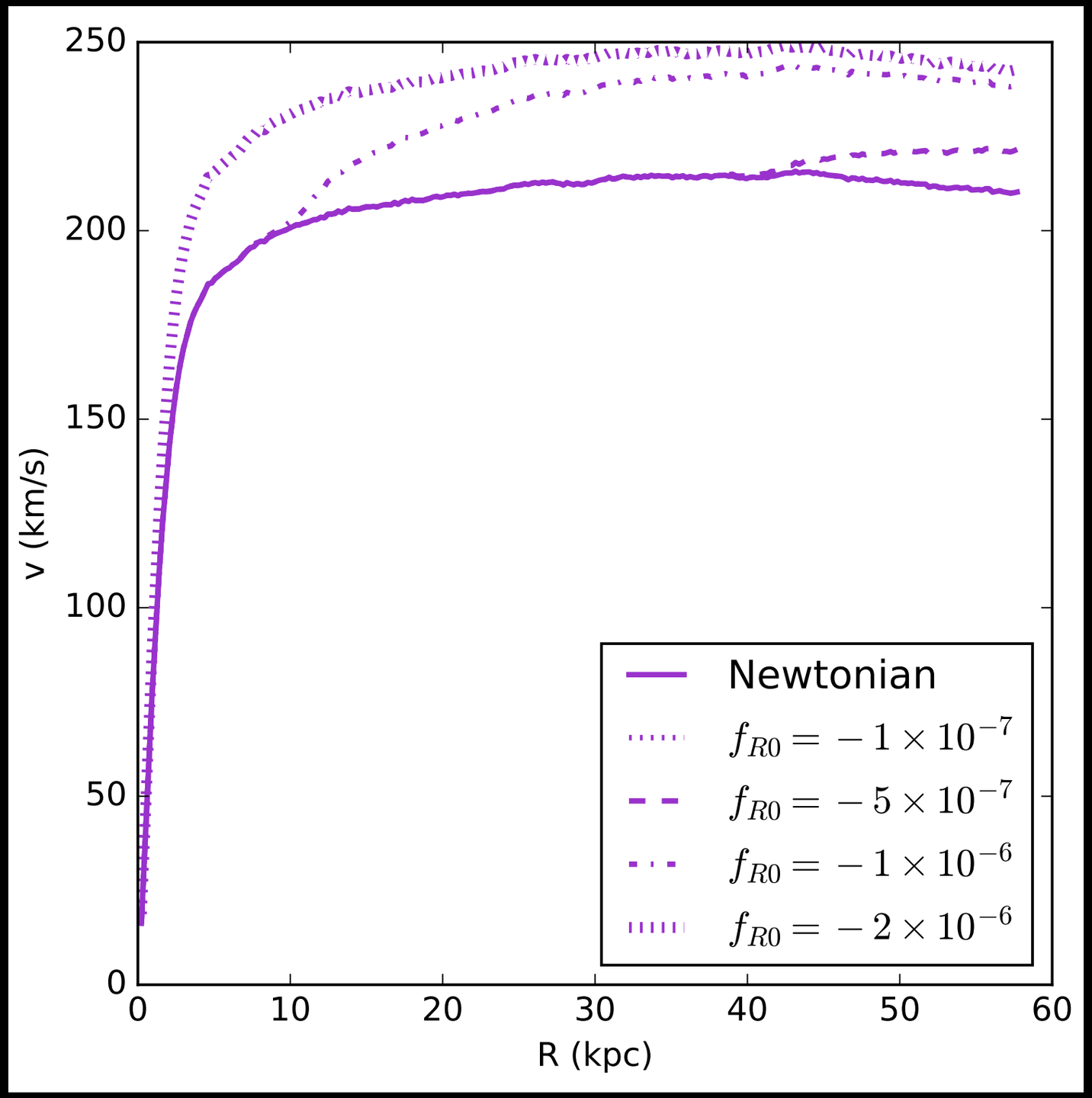
Take home: Changing f_{R0} changes the screening radius, or stops the screening altogether!

Rotation Curves



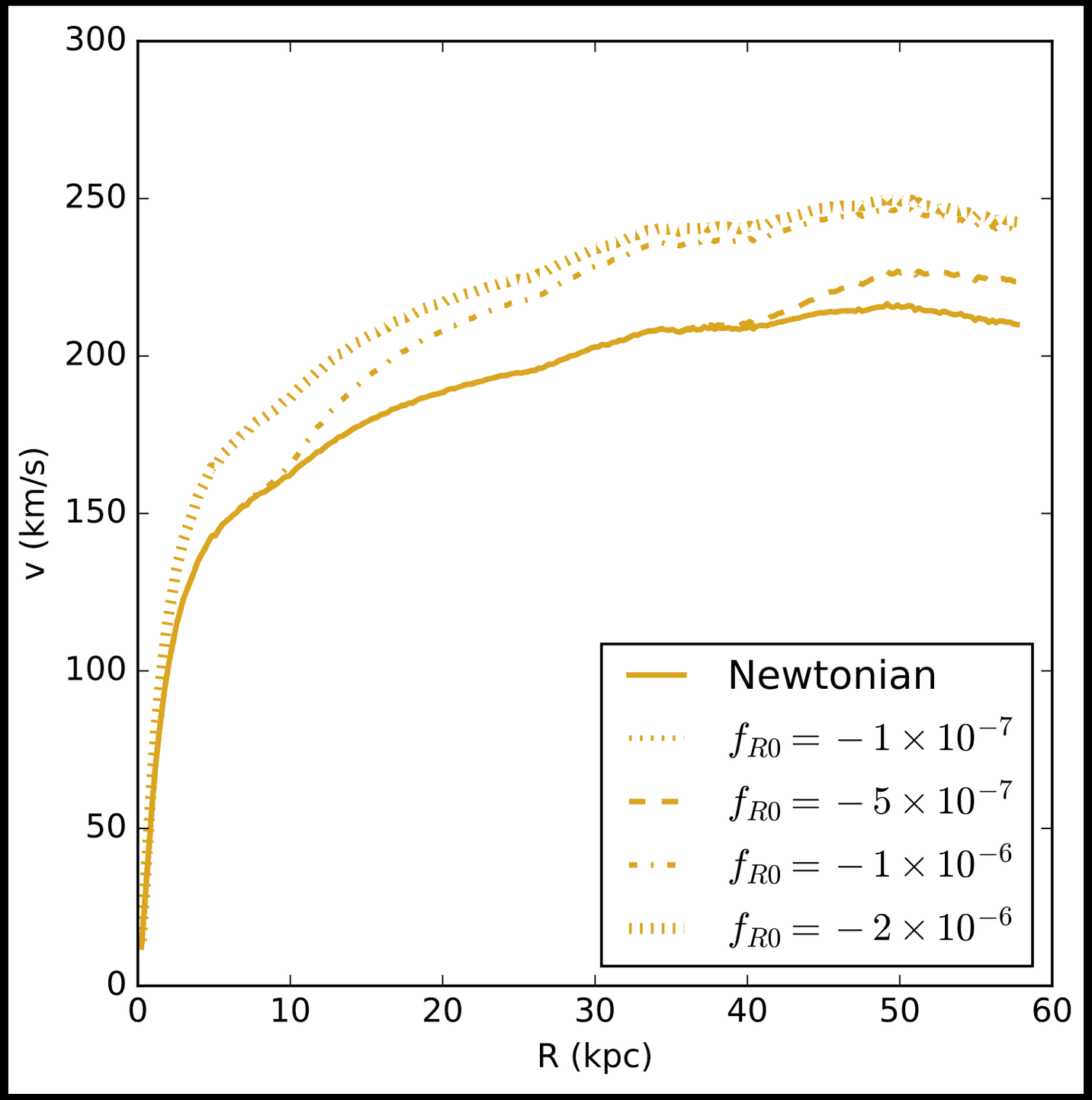
Take home: Rotation curves show upturns at screening radii!

Rotation Curves



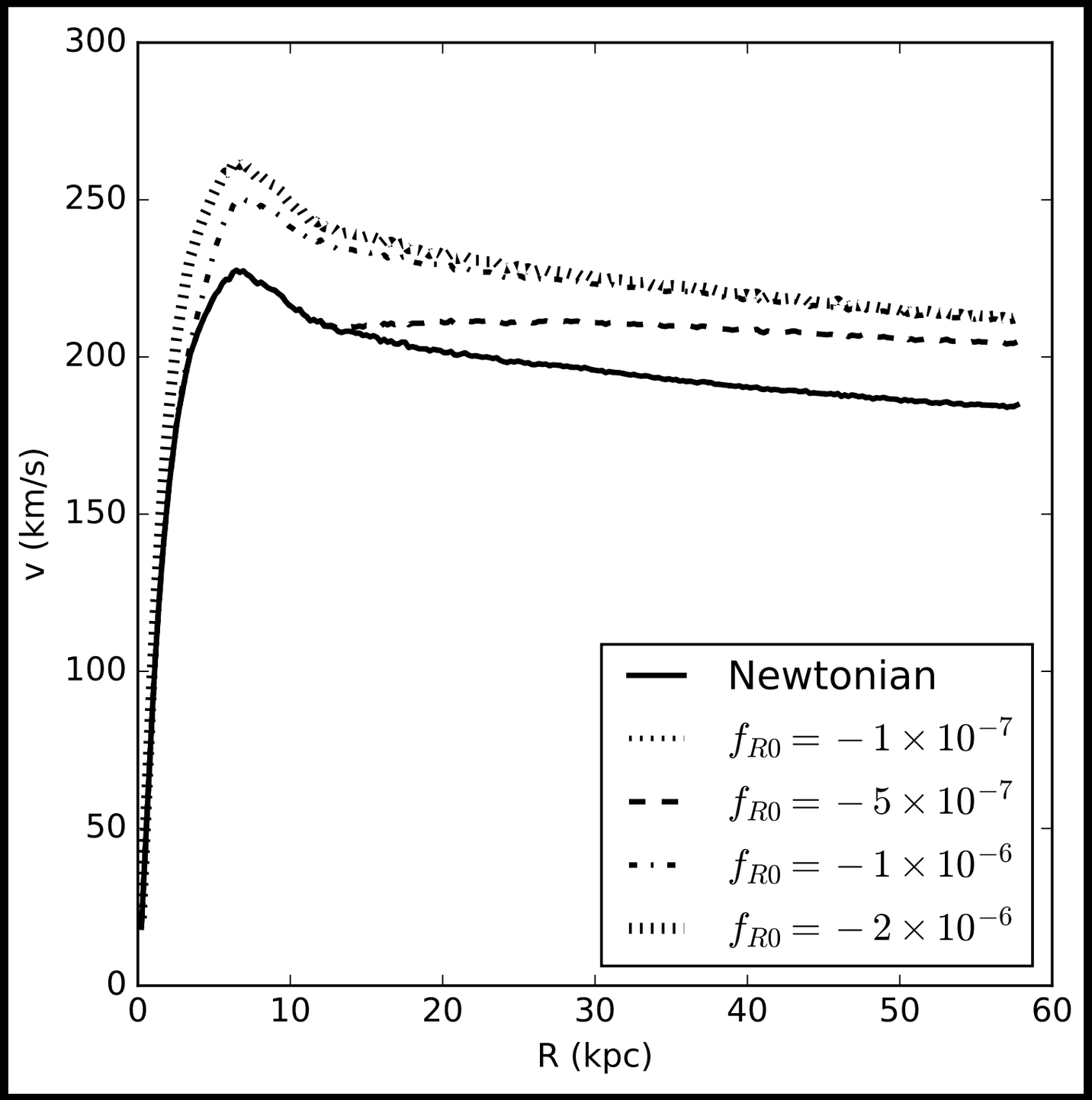
Galaxy 24

Rotation Curves



Galaxy 16

Rotation Curves

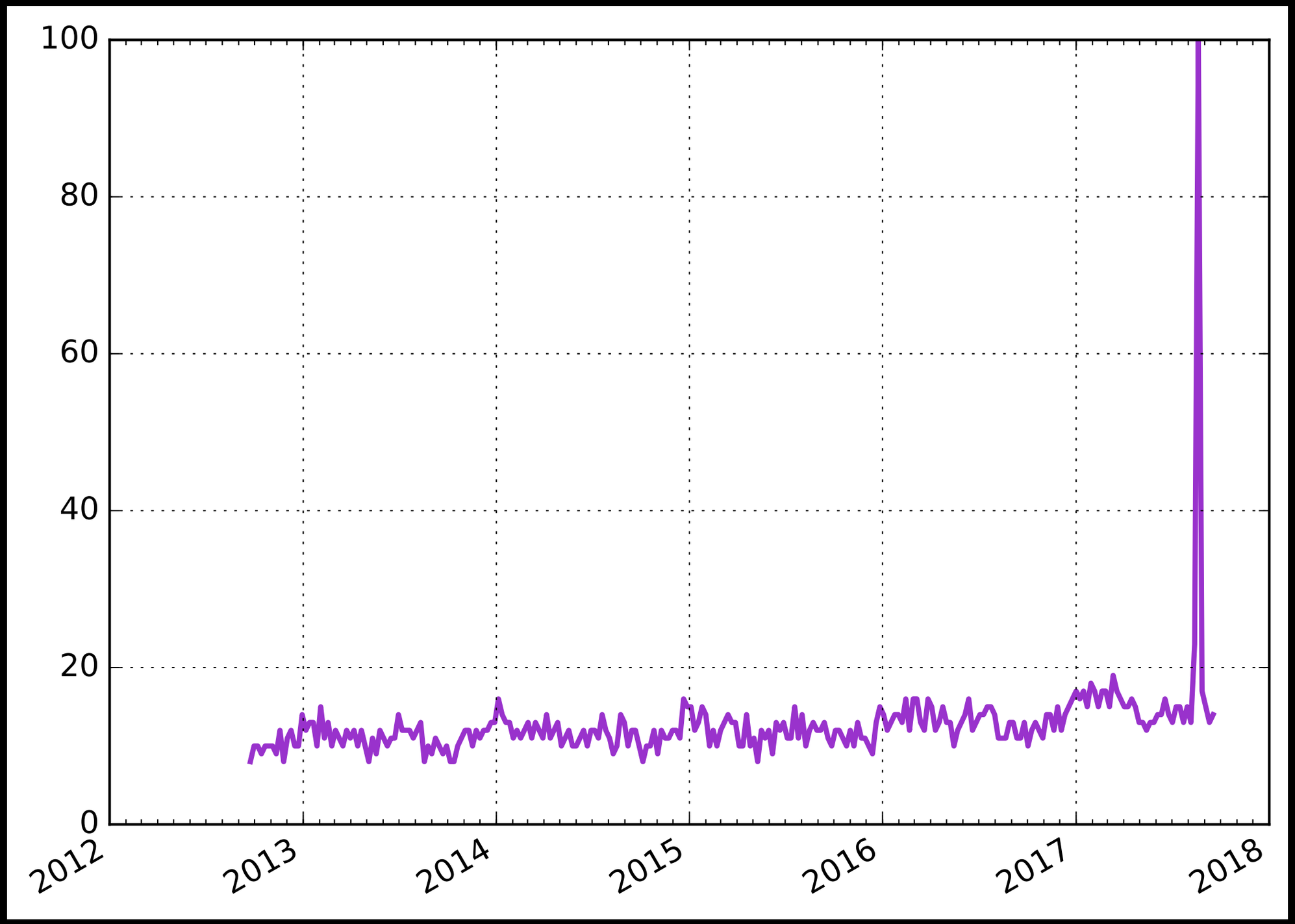


Galaxy 9

Conclusions

- Observed galaxy rotation curves show upturns
- For plausible values of f_{R0}, we have shown that realistic Milky-Way type galaxies would also exhibit upturns in chameleon f(R) gravity
- To fit observed rotation curves, we will be fitting the dark matter profiles with NFW - this was shown to be as reasonable an approximation in f(R) gravity as in ΛCDM.
- An analytic/semi-analytic model would speed up parameter fit, but spherical model doesn't work

“my eyes hurt”



Source: google.co.uk/trends

Thanks for listening!