The masses of Local Group galaxies and the baryonic Tully-Fisher relation

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McGaugh+ 2021, AJ, 162, 202

Empirical Laws of Galactic Rotation

- Flat rotation curves
- Baryonic Tully-Fisher relation (BTFR)

$$M_b = AV_f^4$$

- Radial acceleration relation (RAR)

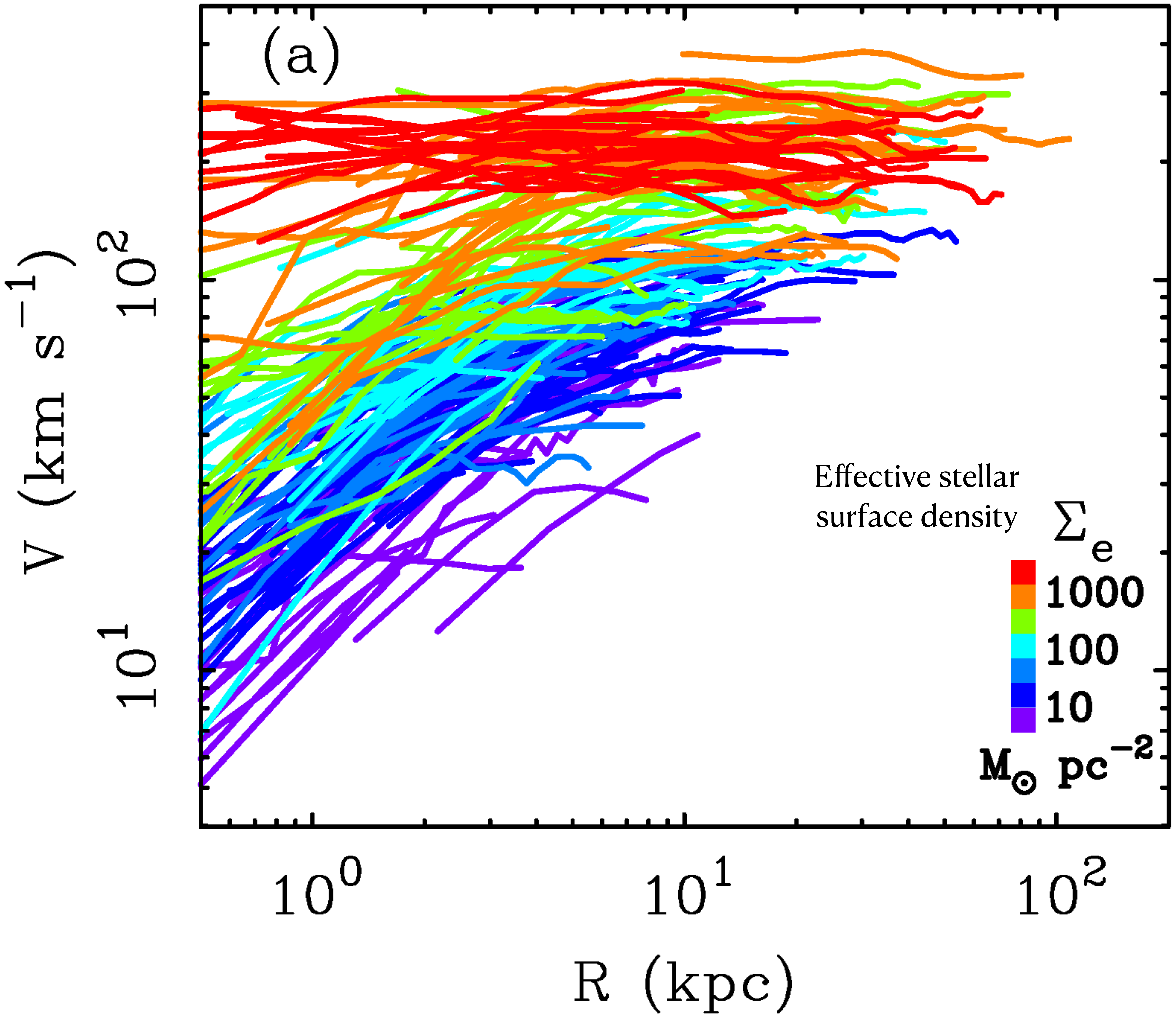
$$g_{obs} = \mathscr{F}(g_{bar})$$

Note that

$M_b = AV_f^4$ is not $M_{dyn} = RV^2/G$

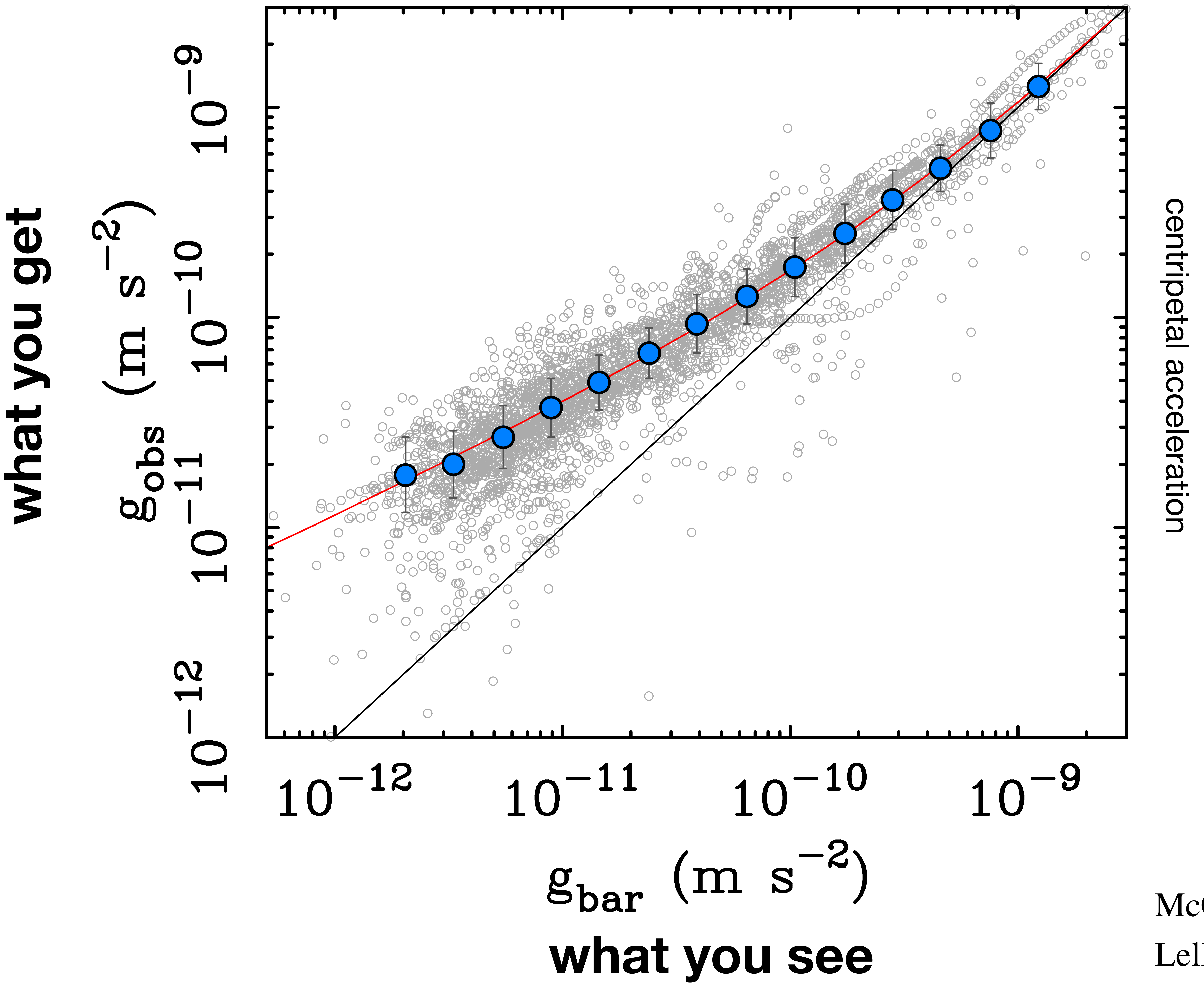
though presumably they must be related.

McGaugh+ 2019 (IAU 353; 1909.02011)



The Radial Acceleration Relation (RAR)

A scaling relation observed in spiral galaxies



$$g_{obs} = \mathscr{F}(g_{bar})$$

$$g_{obs} = \frac{g_{bar}}{1 - e^{-\sqrt{g_{bar}/g_{\dagger}}}}$$

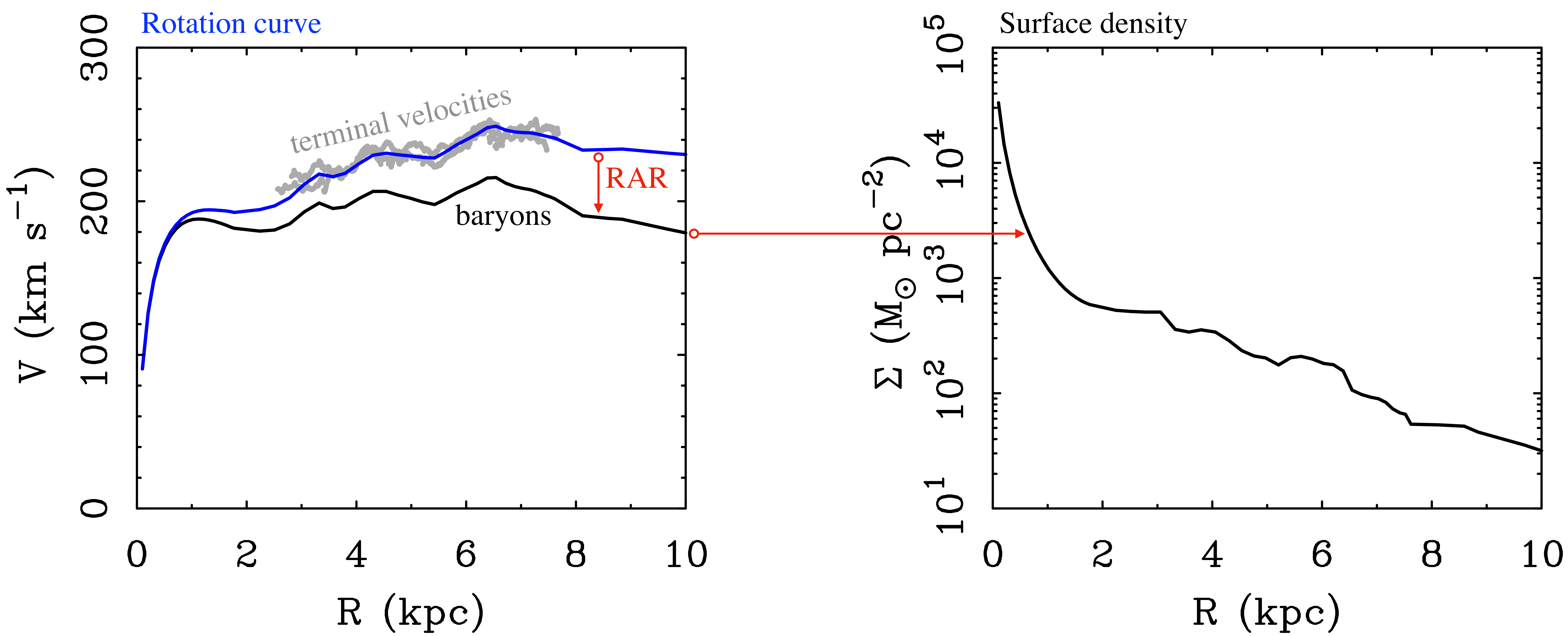
$$g_{\dagger} = 1.2 \times 10^{-10}\,\mathrm{m\,s^{-2}}$$
$$\pm 0.02\ (\mathrm{stat}) \pm 0.24\ (\mathrm{sys})$$

McGaugh+ 2016, PRL, 117, 201101

Lelli+ 2017, ApJ, 836, 152

Presumably the Empirical Laws hold for galaxies in the Local Group

- Starting with the observed terminal velocities (HI from McClure-Griffiths shown), one can
- Apply the RAR to find the corresponding distribution of stars.



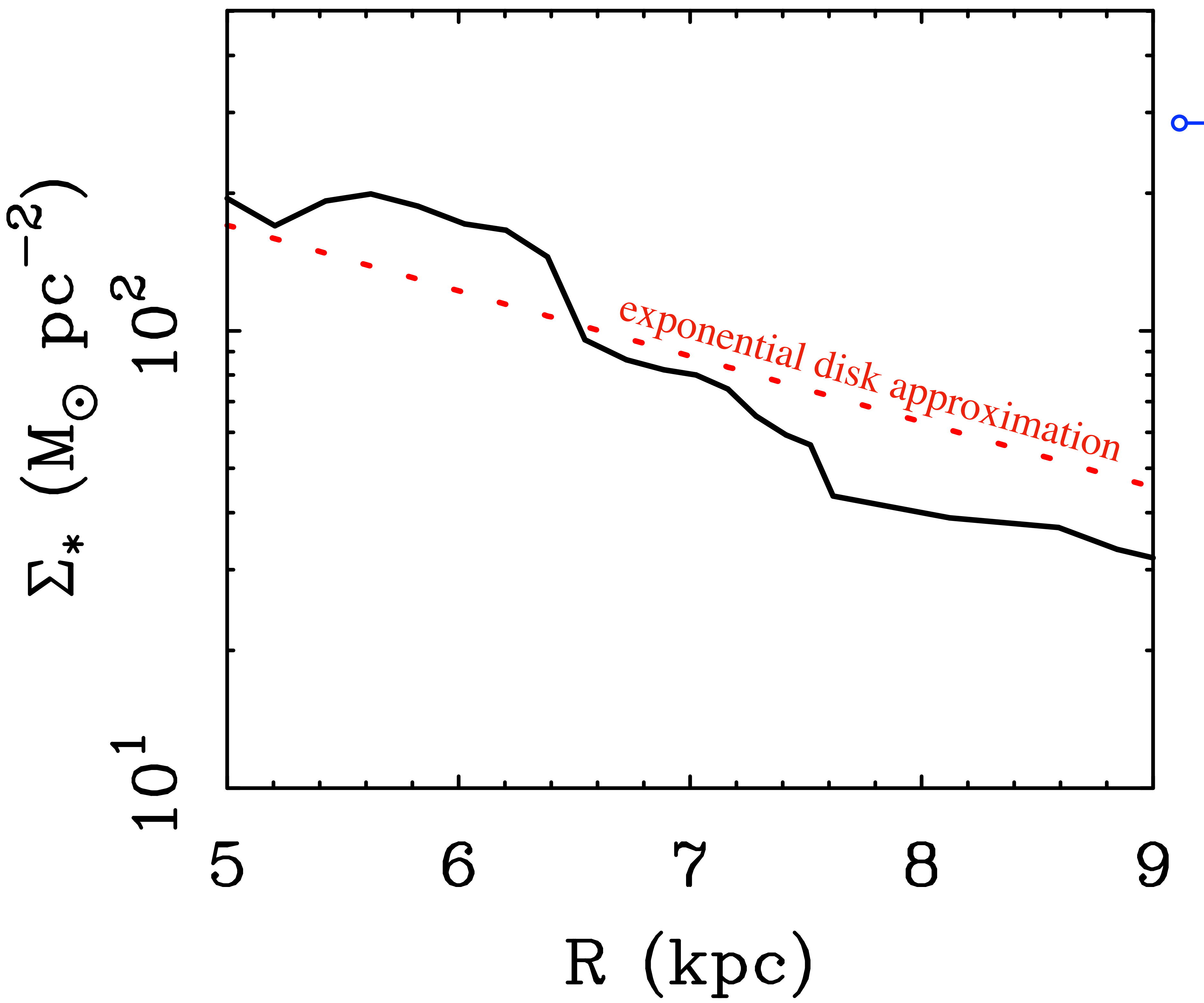
- The resulting surface density profile has features corresponding to observed spiral arms

McGaugh 2016, ApJ, 816, 42

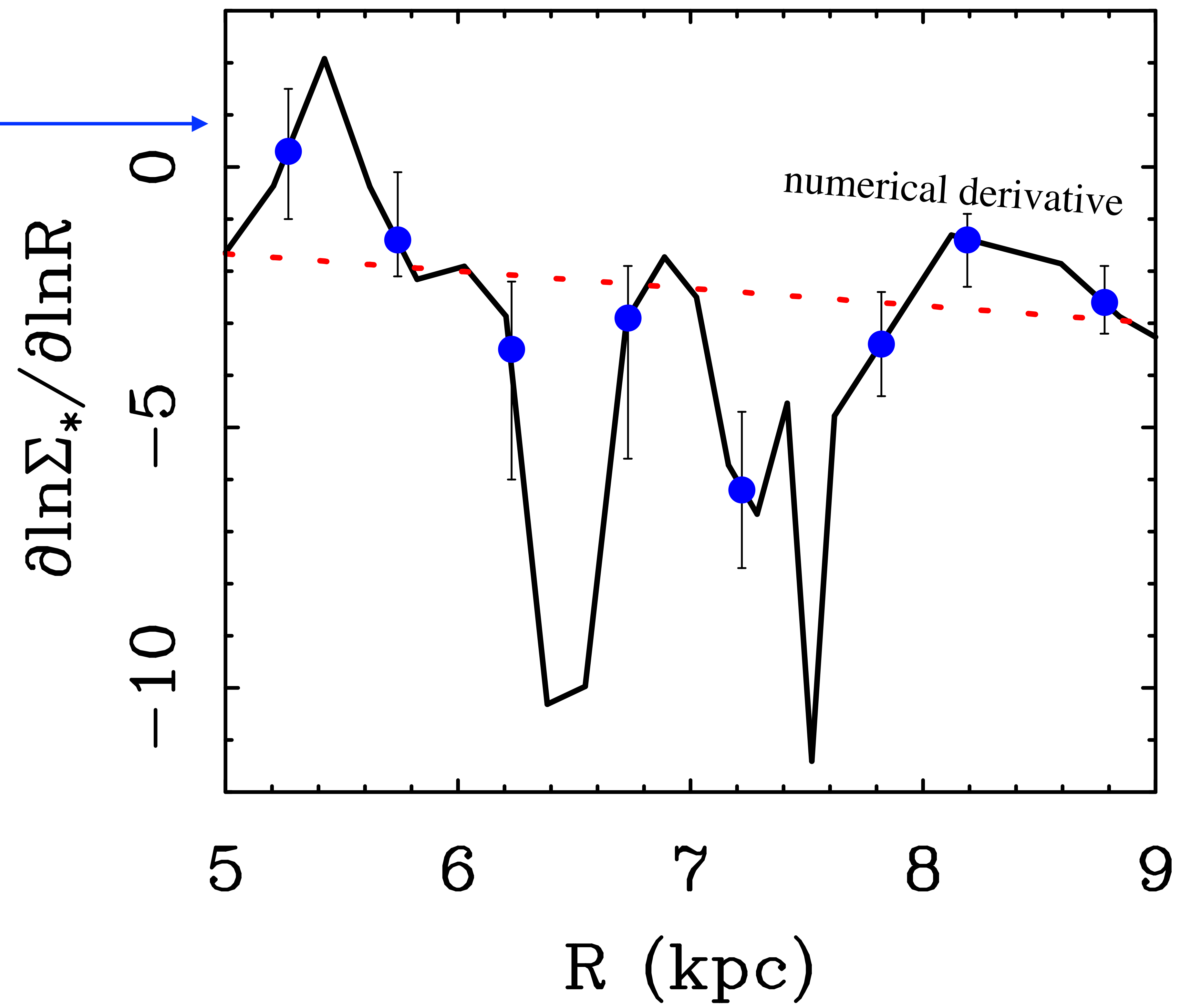
Can improve on the exponential disk approximation in the Jeans equation:

$$V_c^2(R) = \langle v_\phi^2 \rangle - \langle v_R^2 \rangle \left(1 + \frac{\partial \ln \Sigma}{\partial \ln R} + \frac{\partial \ln \langle v_R^2 \rangle}{\partial \ln R} \right)$$

Surface density



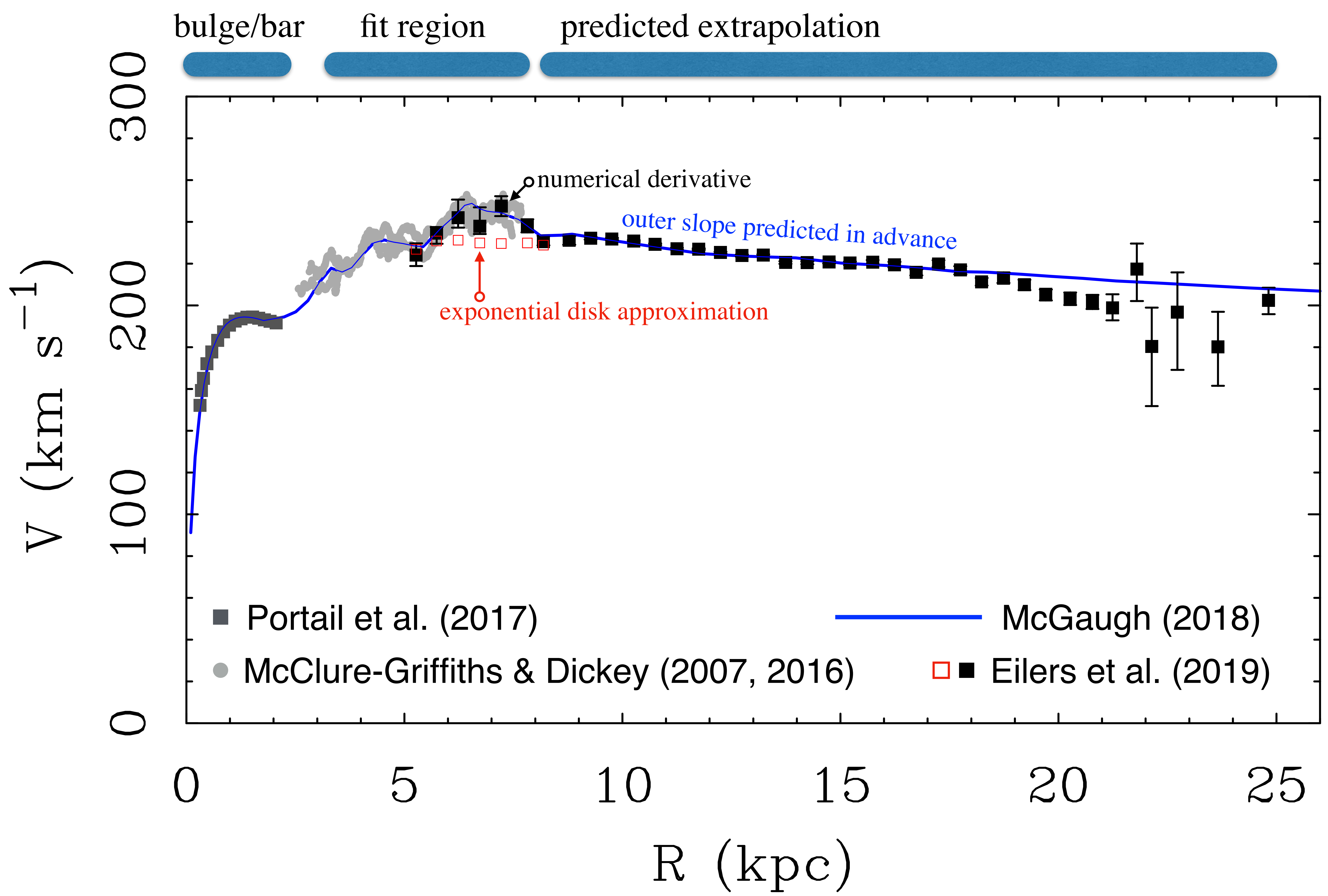
Logarithmic density derivative



Using the numerical derivative in the Jeans equation resolves the tension between the Gaia rotation curve and that from terminal velocity observations of the ISM.

McGaugh 2019, ApJ, 885, 87

Milky Way Rotation Curve



Milky Way Parameters

$R_0 = 8.122$ kpc

$\Theta_0 = 233.3\ \mathrm{km\,s^{-1}}$

$M_* = 6.16 \times 10^{10}\ \mathrm{M_\odot}$

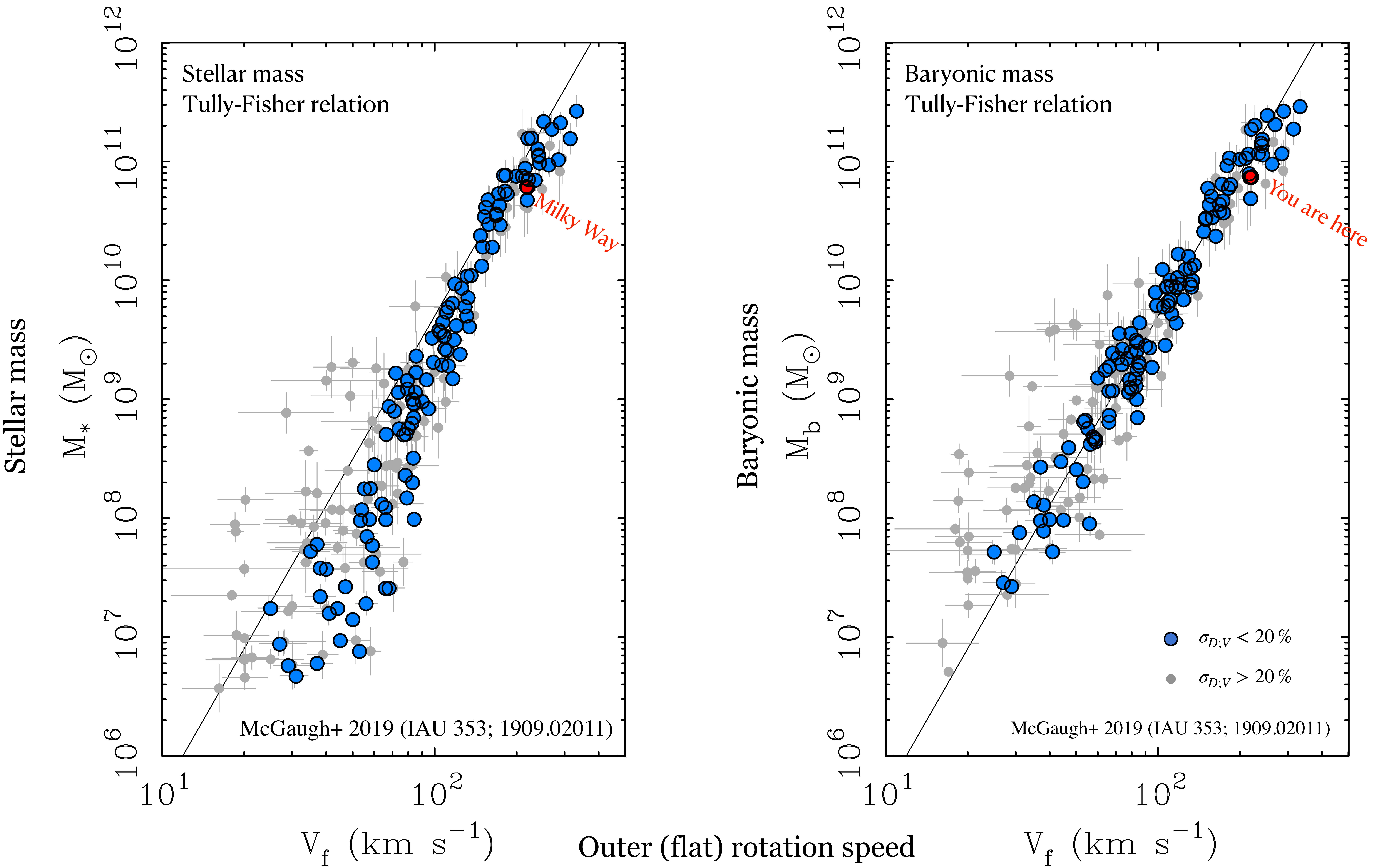
$M_g = 1.22 \times 10^{10}\ \mathrm{M_\odot}$

$M_{200} \approx 1.39 \times 10^{12}\ \mathrm{M_\odot}$

$\rho_{DM}(R_0) \approx 0.00676\ \mathrm{M_\odot\ pc^{-3}}$

Using the numerical derivative in the Jeans equation resolves the tension between the Gaia rotation curve and that from terminal velocity observations of the ISM.

McGaugh 2019, ApJ, 885, 87



Stellar mass
Tully-Fisher relation
Milky Way
McGaugh+ 2019 (IAU 353; 1909.02011)
Stellar mass
M* (M☉)
Vf (km s−1)
Baryonic mass
Tully-Fisher relation
You are here
σD;V < 20 %
σD;V > 20 %
McGaugh+ 2019 (IAU 353; 1909.02011)
Baryonic mass
Mb (M☉)
Vf (km s−1)
Outer (flat) rotation speed

BTFR calibration

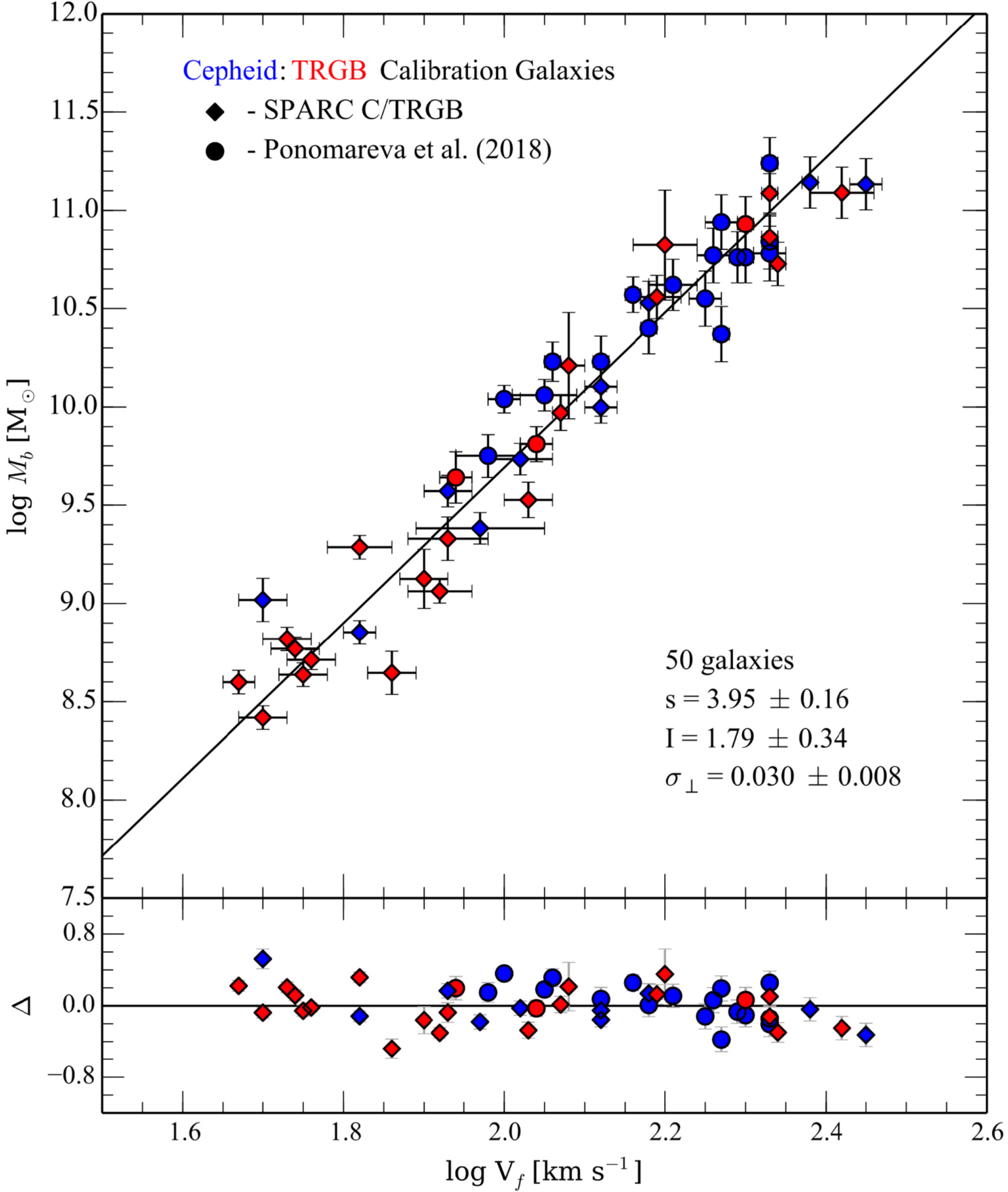
50 galaxies

with well-resolved HI data cubes, Spitzer [3.6] luminosities, and accurate distances from

27 Cepheids

23 TRGB

No tension between Cepheid and TRGB calibrators



$M_b = A\,V_f^4$

$A = 48.5\ M_\odot\,\mathrm{km}^{-4}\,\mathrm{s}^4$

Consistent with previous estimates $45 \leq A \leq 50$.

$H_0 = 75.1 \pm 2.3\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$

$H_0 < 70.5$ excluded at 95% c.l.

Schombert+ 2020, AJ, 160, 71

Local Group galaxies follow BTFR defined by external galaxies

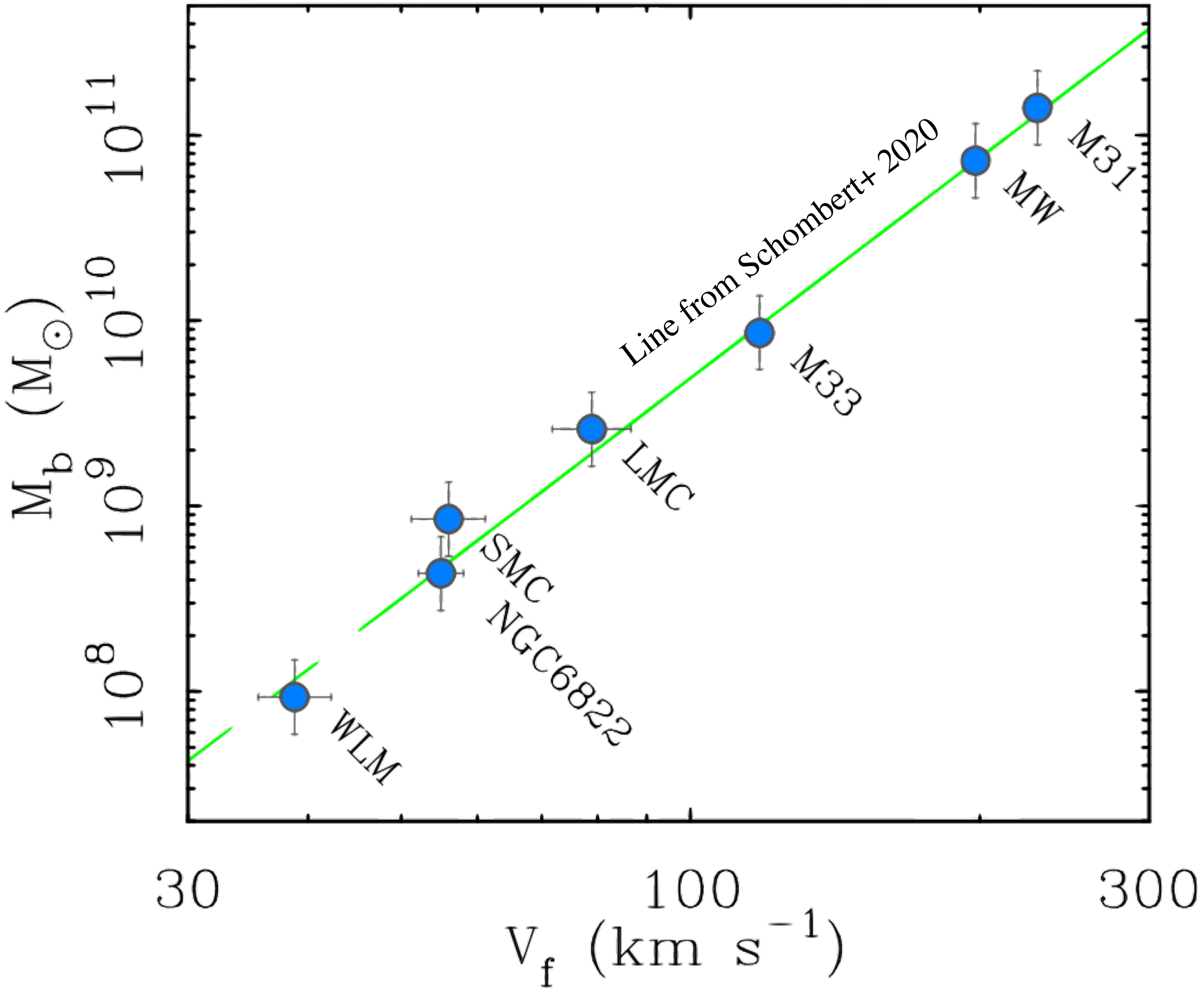


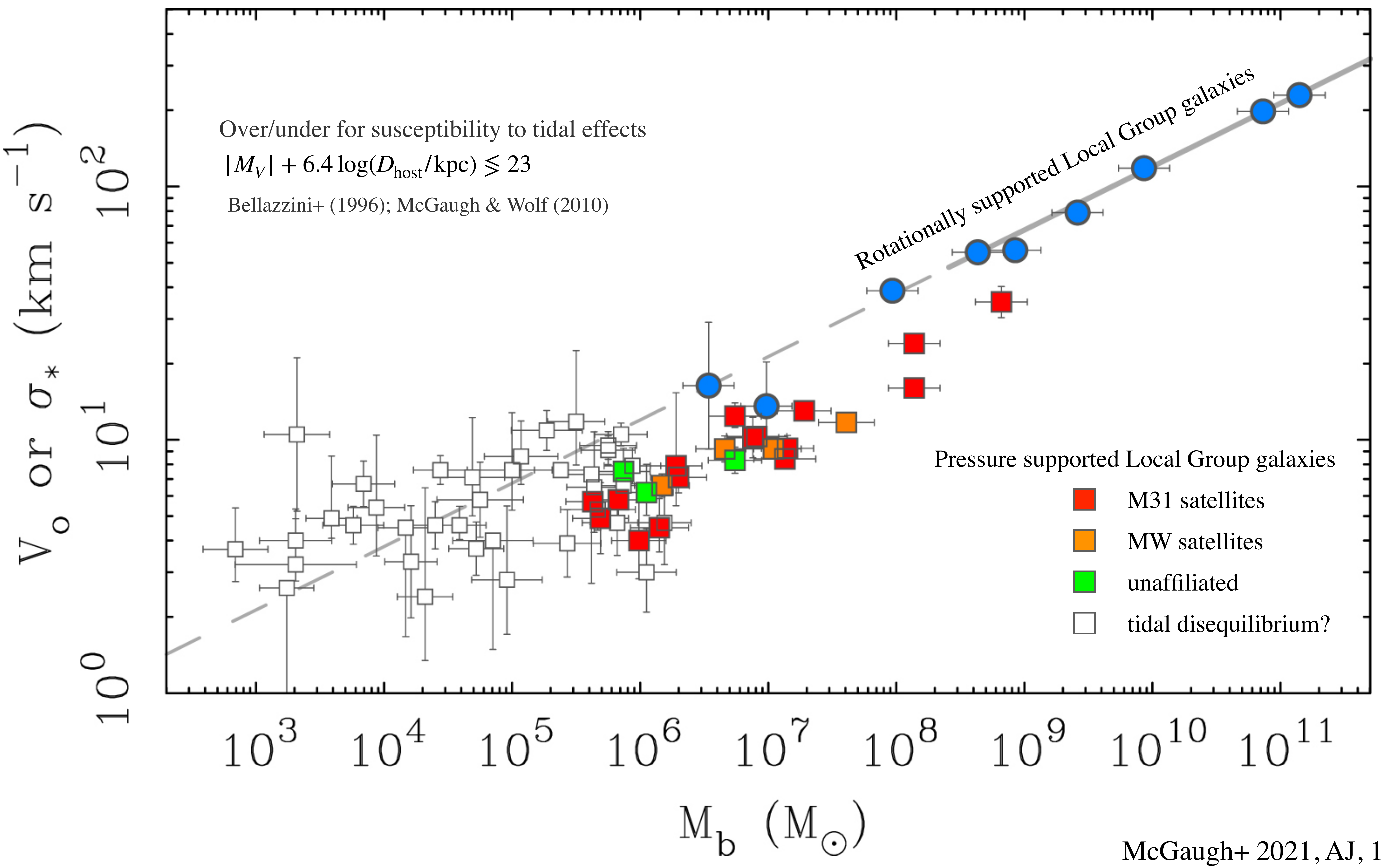
Table 1
Rotationally-supported Local Group Galaxies

Galaxy	M_* (10^9 $M_\odot$)	M_g	V_o (km s^{-1})	References
M31	135.	5.46	229.5 ± 2.2	1
MW	60.8	12.2	197.9 ± 1.9	2, 3, 4
M33	5.5	3.1	118.0 ± 1.1	5
LMC	2.0	0.60	78.9 ± 7.5	6, 7, 8
SMC	0.31	0.54	56 ± 5	6, 7, 9
NGC 6822	0.234	0.20	55 ± 3	10
WLM	0.0163	0.077	38.7 ± 3.4	11, 12
DDO 216	0.0152	0.00816	13.6 ± 5.5	11, 12
DDO 210	0.00068	0.00274	16.4 ± 9.5	11, 12

References. (1) Chemin et al. (2009), (2) Licquia & Newman (2015), (3) Olling & Merrifield (2001), (4) Eilers et al. (2019), (5) Kam et al. (2017), (6) Skibba et al. (2012), (7) Brüns et al. (2005), (8) van der Marel & Sahlmann (2016), (9) Di Teodoro et al. (2019), (10) Weldrake et al. (2003), (11) Zhang et al. (2012), (12) Iorio et al. (2017).

McGaugh+ 2021, AJ, 162, 202

Can we find an empirical factor β_c that relates the measured velocity dispersion of dwarf spheroidal to the outer rotation speed?



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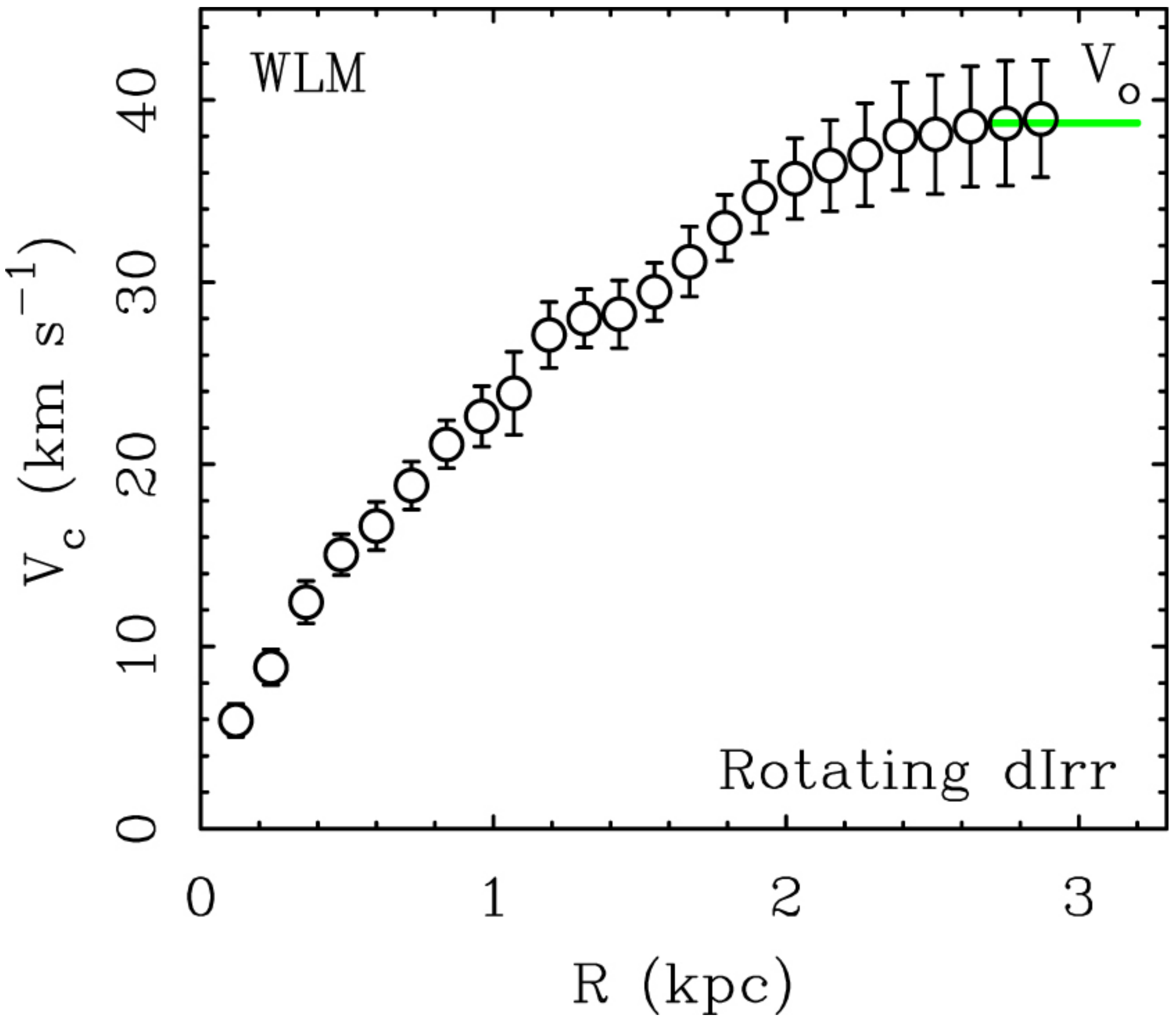
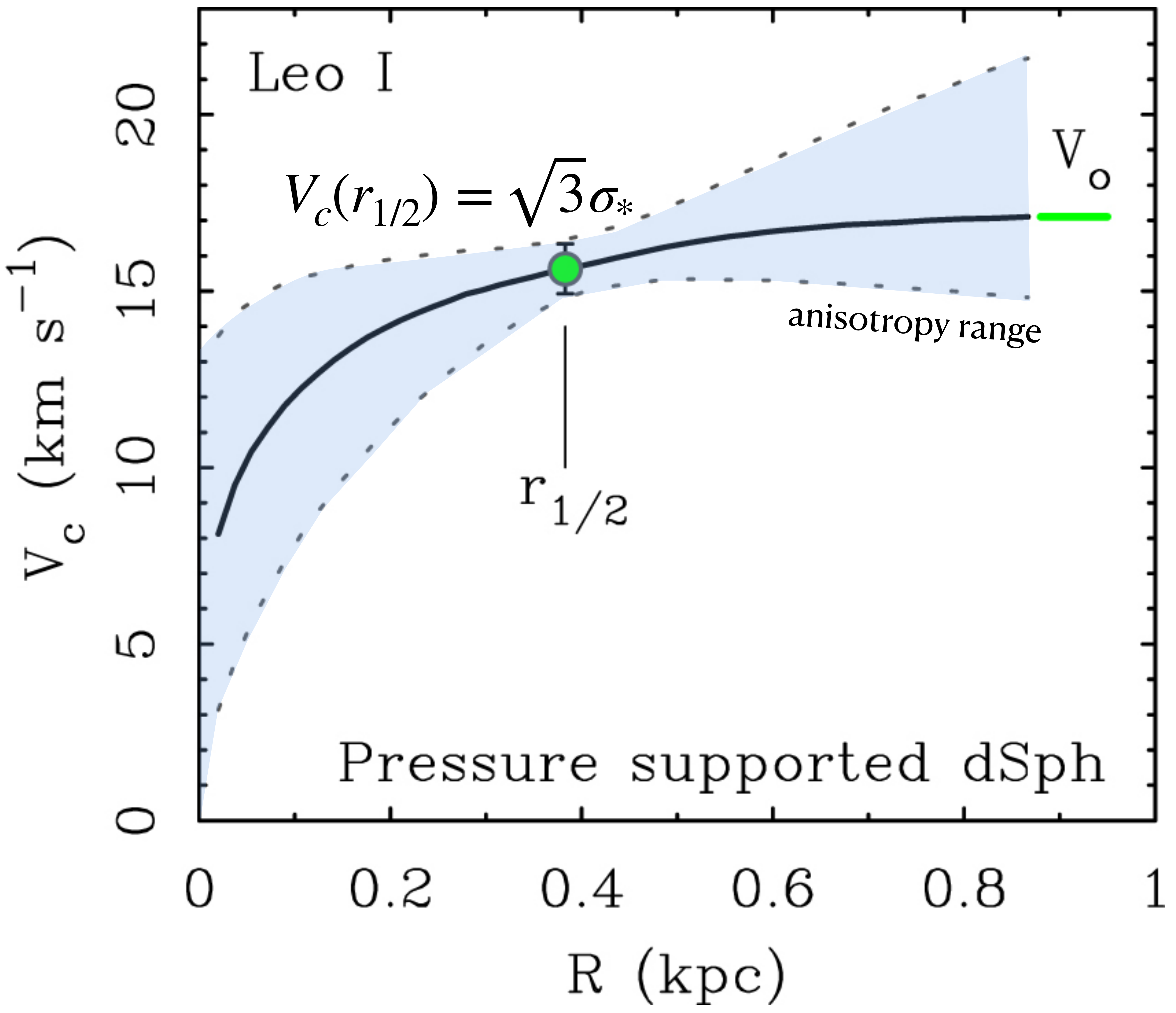
Can we find an empirical factor β_c that relates the measured velocity dispersion of dwarf spheroidal to the outer rotation speed?

$$V_o = \beta_c \sigma_*$$





McGaugh+ 2021, AJ, 162, 202

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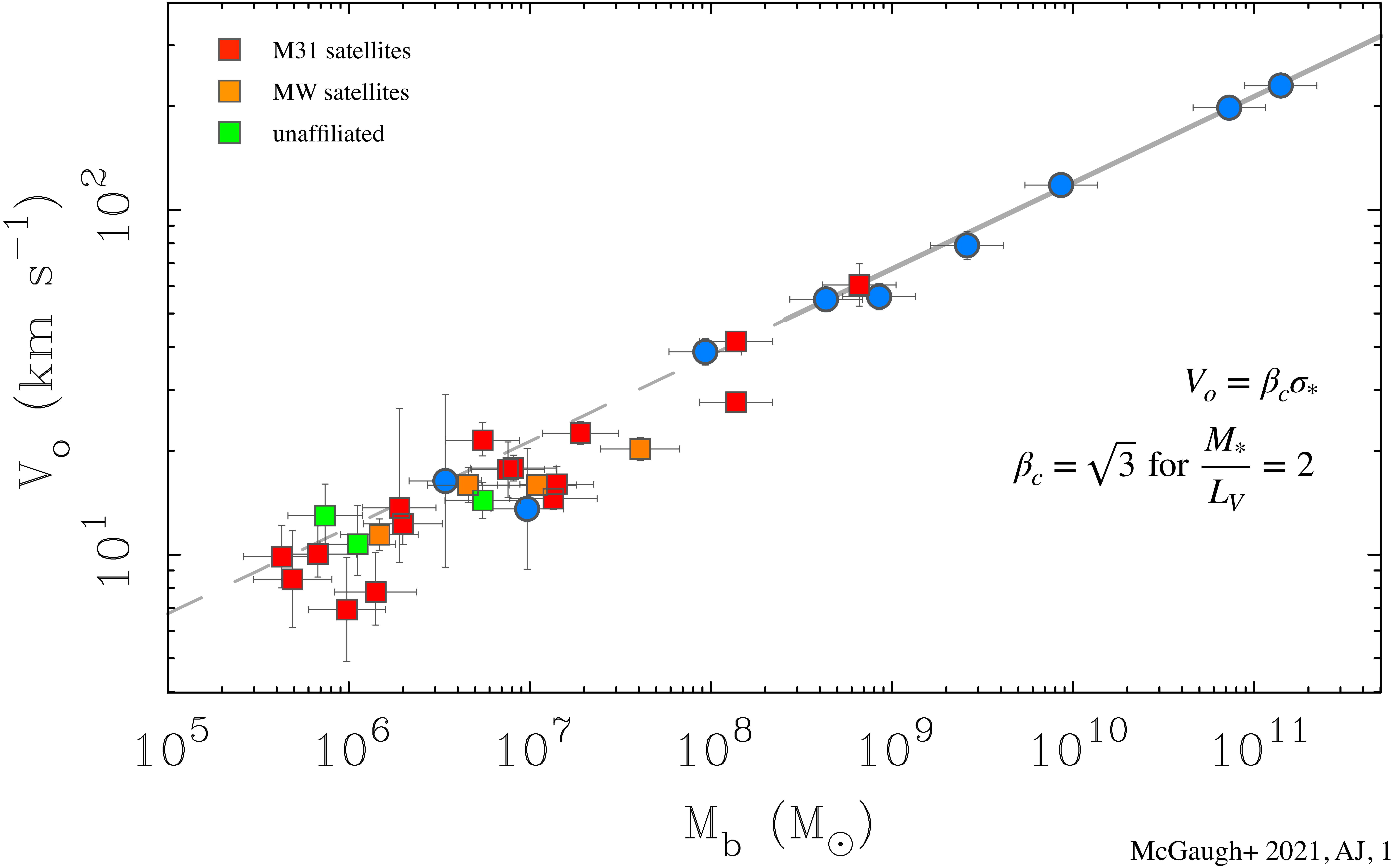

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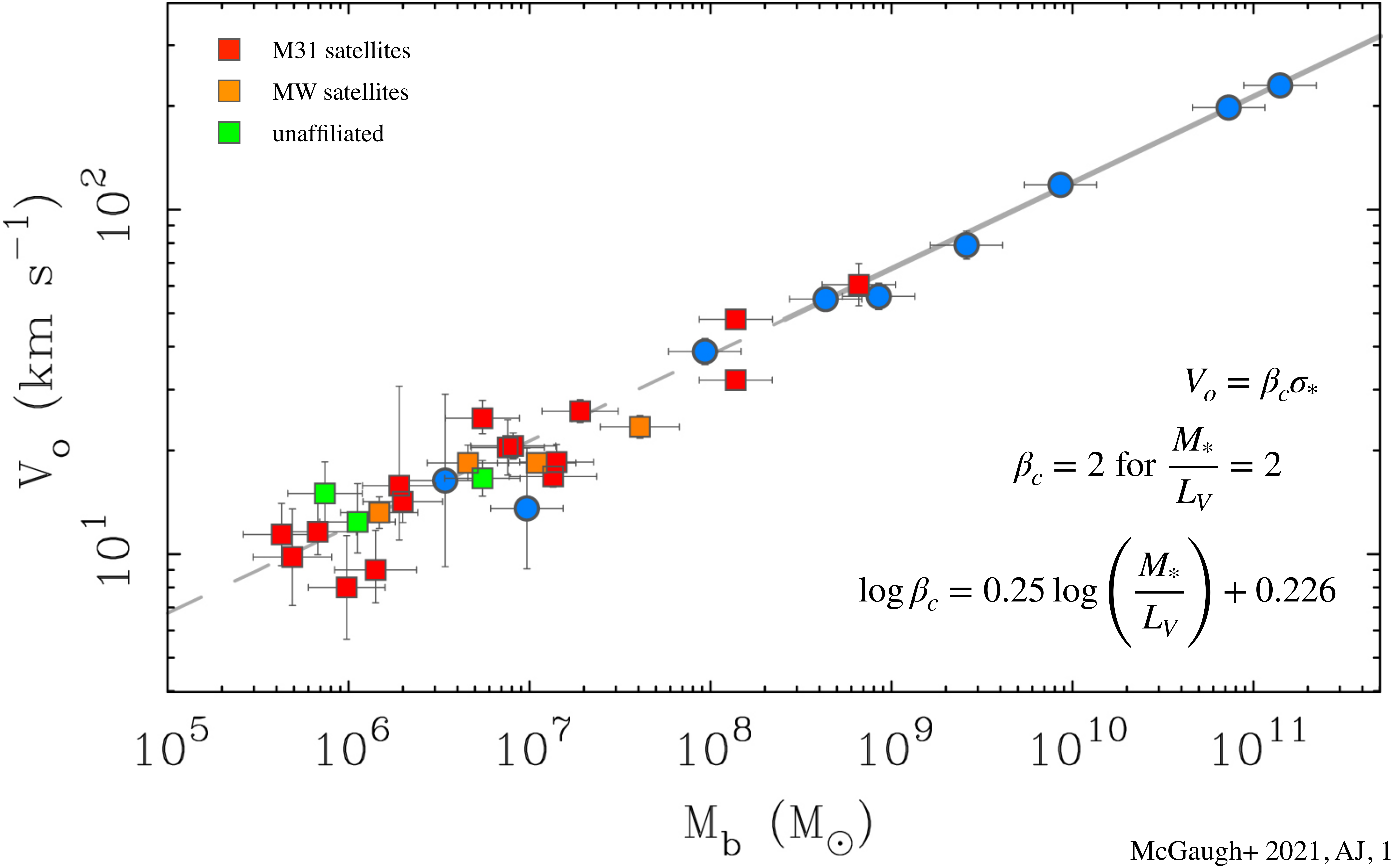


McGaugh+ 2021, AJ, 162, 202

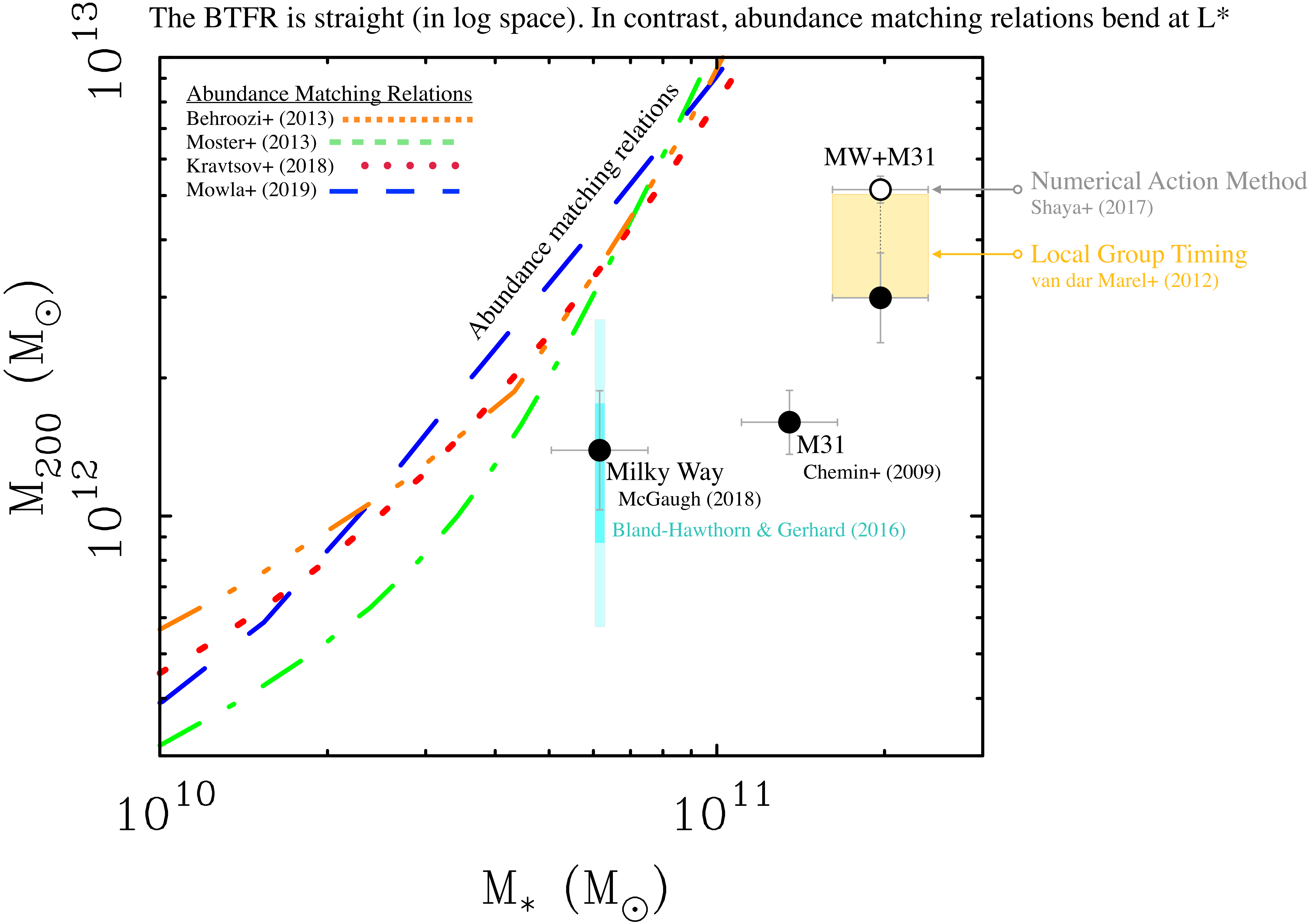
The BTFR is straight (in log space). In contrast, abundance matching relations bend at L*

$$M_{dyn} = RV^2/G$$

What about dynamical mass?

There is a mismatch between dynamical masses and those from abundance matching for bright spiral galaxies (L > L*).

Abundance matching predicts a halo mass for the Milky Way of $M_{200} \approx 4 \times 10^{12}$ $M_\odot$.



McGaugh & van Dokkum 2021, RNAAS, 5, 23

Conclusions

- Local Group galaxies follow the same RAR, BTFR as other spiral galaxies
- Accounting for deviations from a pure exponential disk reconciles the stellar rotation curve from Gaia with ISM terminal velocities
- The equivalent TF circular velocity of dwarf spheroidals is $V_o \approx 2\sigma_*(r_{1/2})$
- Dynamical masses deviate from abundance matching for bright spirals
- The total dynamical mass $M_{dyn} \sim R\,V^2$ does not relate trivially to the observed BTFR $M_b \sim V^4$

McGaugh+ 2021, AJ, 162, 202