Maryland Center for Fundamental Physics & Joint Space-Science Institute 26-28 May 2010

Advances in Theoretical and Observational Cosmology

Dark Matter in Dwarf Galaxies

Stacy McGaugh

University of Maryland

Advances in Theoretical and Observational Cosmology

Collaborators

Rachel Kuzio de Naray (UCI)
David Stark (UNC)
Joe Wolf (UCI)
Matthew Zagursky (Hawaii)
Clemens Trachternach (R-U Bochum)
Matt Walker (Cambridge)
Rob Swaters (NOAO)
Erwin de Blok (Cape Town)
Jim Schombert (Oregon)
Thijs van der Hulst (Groningen)
Mario Mateo (Michigan)
Ed Olzewski (Arizona)
Bob Sanders (Groningen)
R-J Dettmar (R-U Bochum)

Advances in Theoretical and Observational Cosmology

Outline

- Dark Matter Distribution in Spirals and Dwarfs
- Baryonic Tully Fisher Relation (BTFR) & Halo Baryons
- Correlated Deviations from the BTFR among ultrafaints

David St. Hubbins: “It's such a fine line between stupid, and clever.”

UGC 2885

100 kpc

$V_c = 300$

NGC 2403

10 kpc

$V_c = 134$

Leo I

500 pc

$\sigma_0 = 9$

NGC 1560

5 kpc

$V_c = 72$

WLM

2 kpc

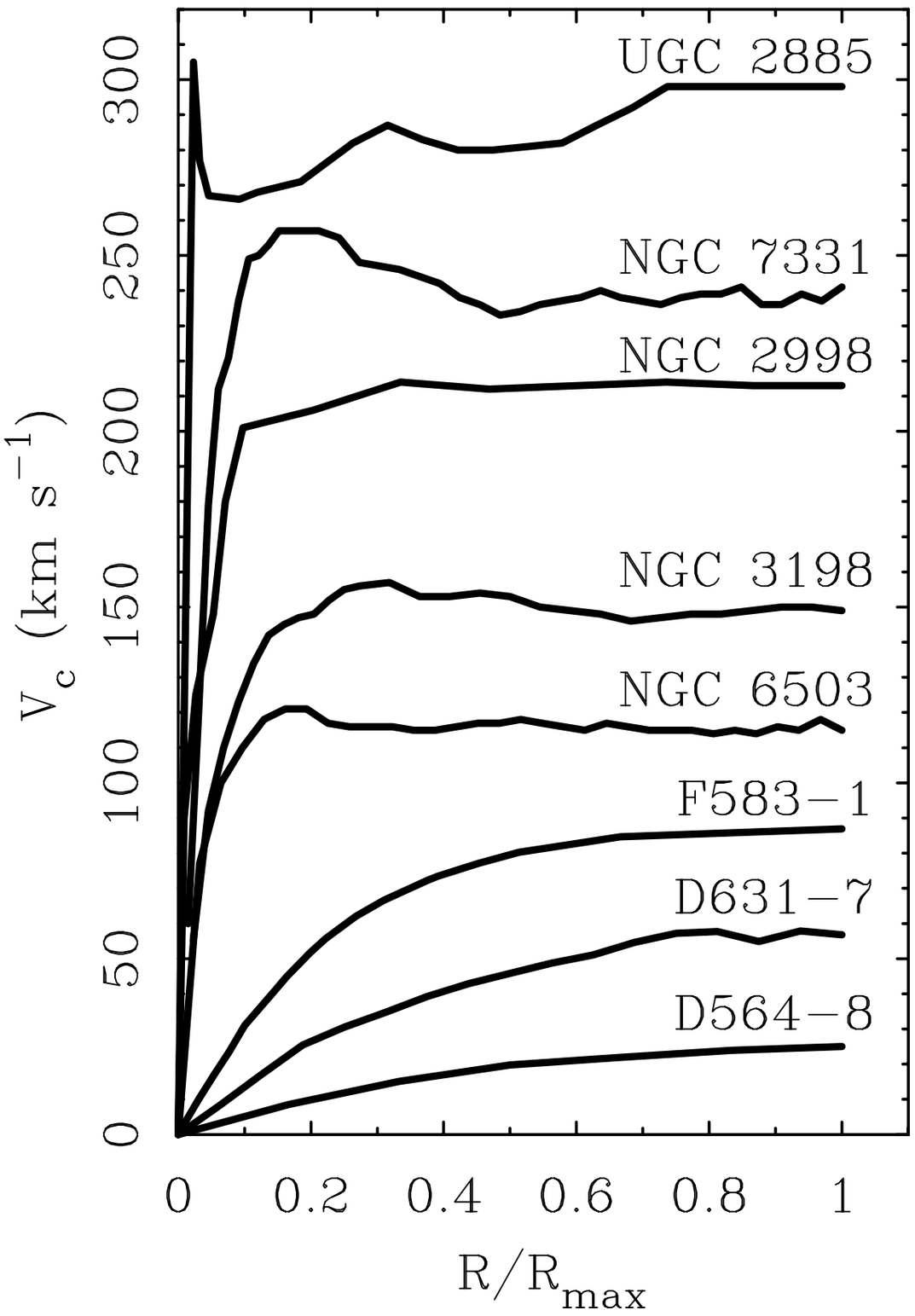
$V_c = 38$

M13

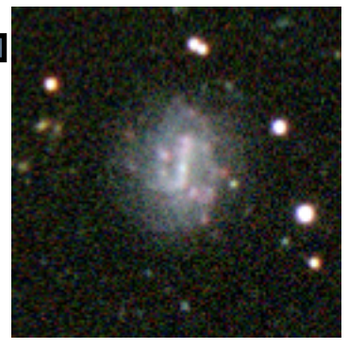
20 pc

$\sigma_0 = 6$

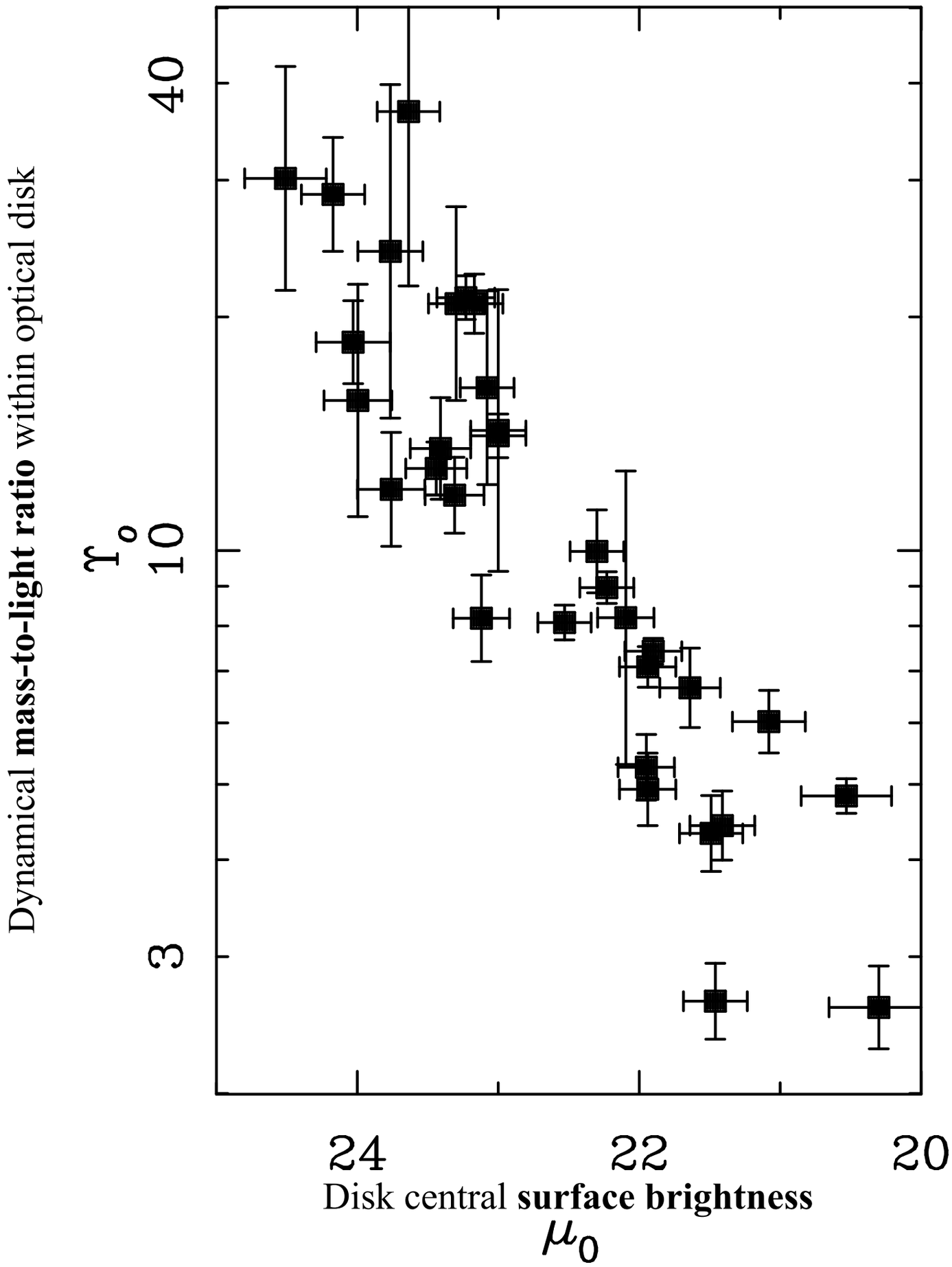
Rotation curves of spirals



Rotation curves and late type disks (Sd, Sm, Irr)



Kuzio de Naray et al. (2006, 2008, 2009); Trachternach et al. (2009)



M/L increases as the characteristic system surface brightness decreases. McGaugh & de Blok (1998)

There is a critical scale at which the mass discrepancy appears:

$$\Sigma_\dagger \approx 1000\ \mathrm{M}_\odot\ \mathrm{pc}^{-2}$$

McGaugh (2004)

NGC 2403

HSB

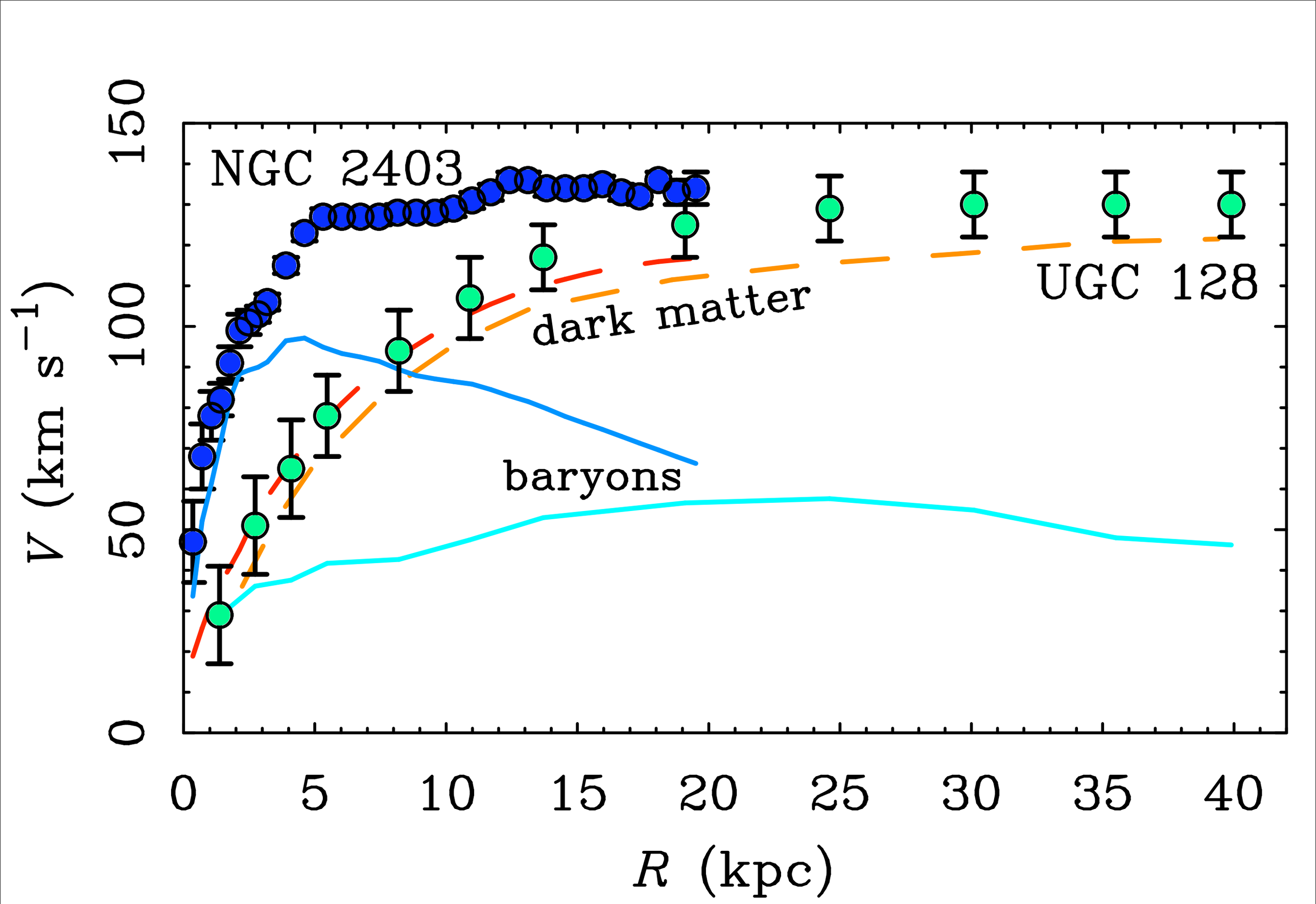
UGC 128

LSB

Same global M_b, V

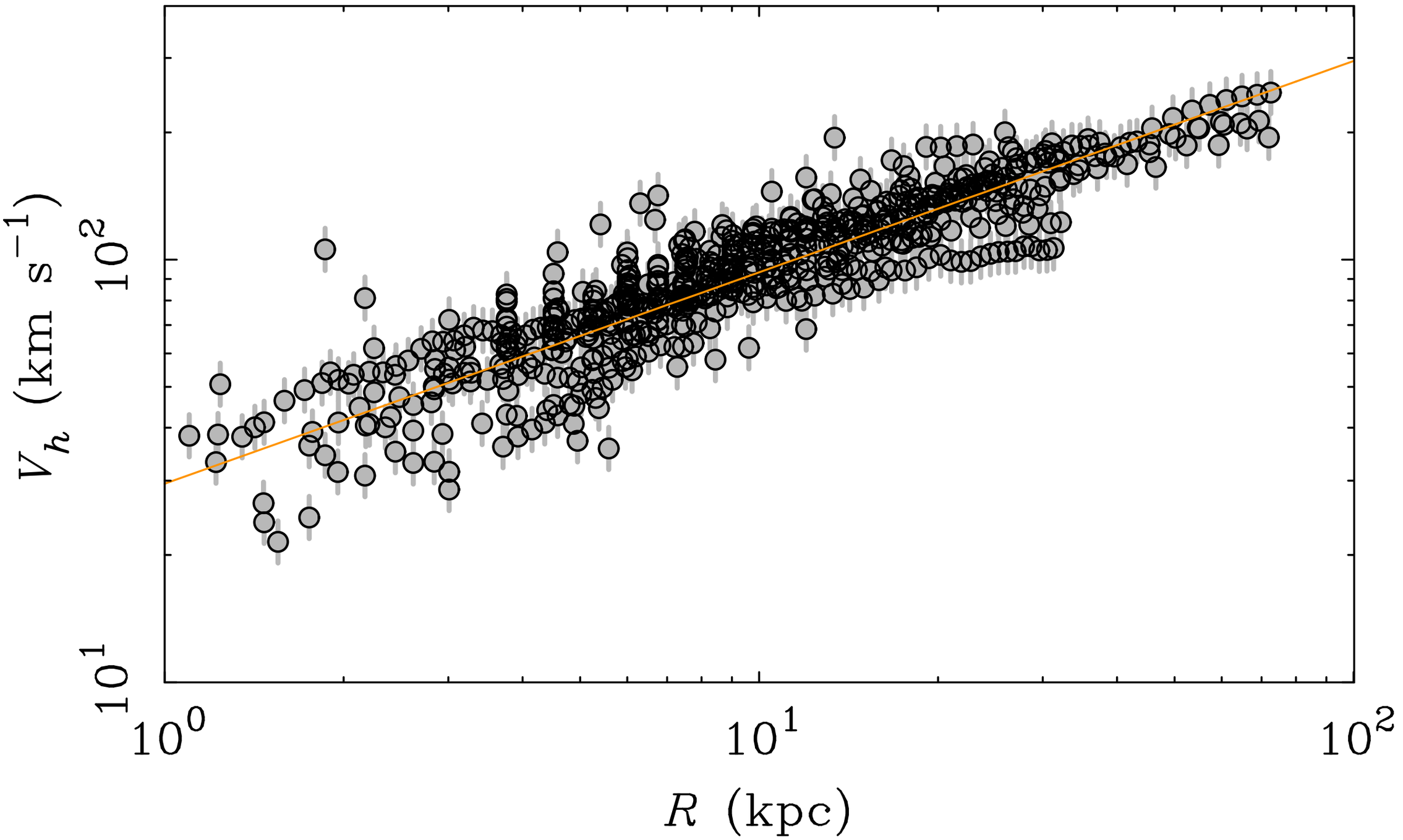
Very different mass distributions

de Blok & McGaugh (1996)
Tully & Verheijen (1997)


NGC 2403
UGC 128
dark matter
baryons
V (km s^{-1})
0
50
100
150
0
5
10
15
20
25
30
35
40
R (kpc)

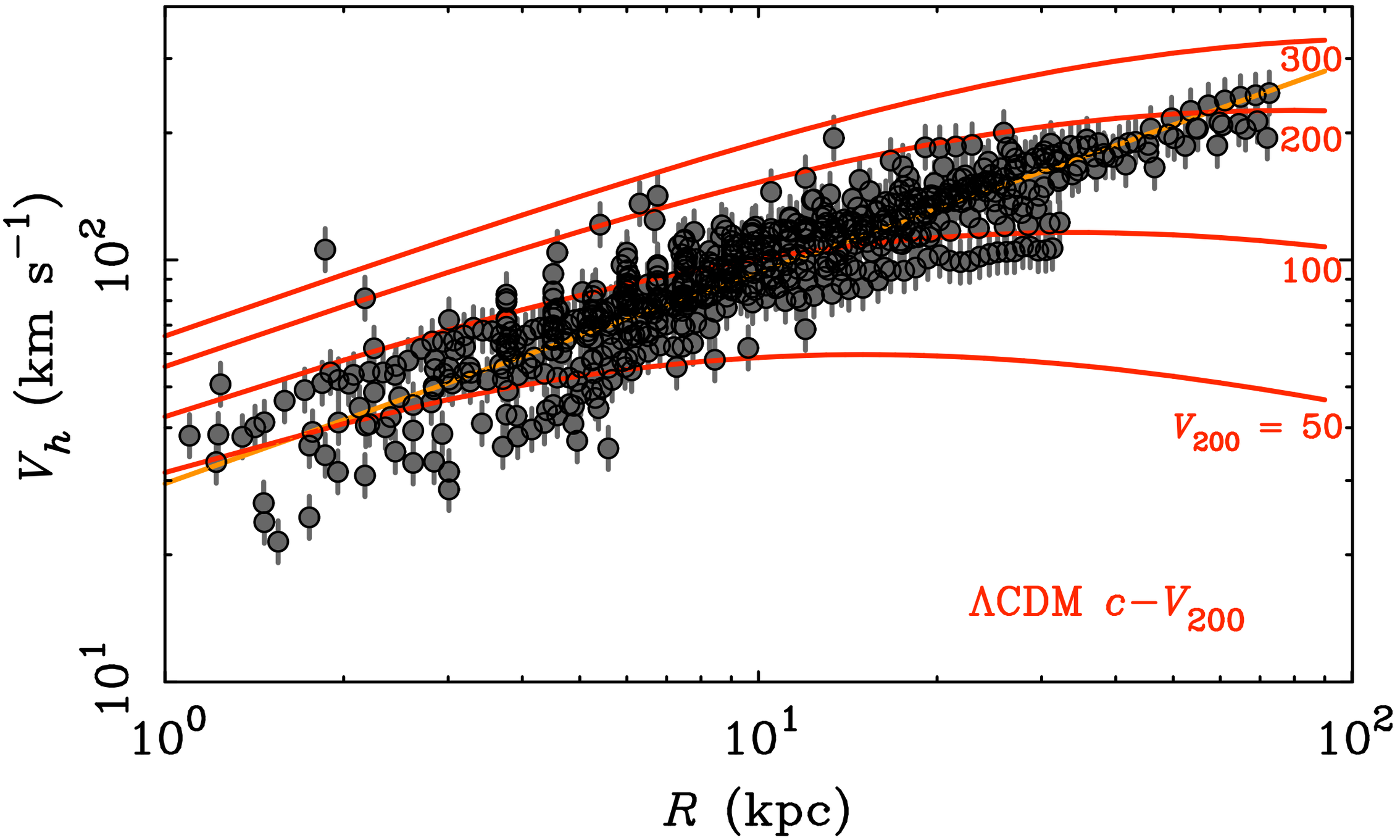
The **halo-only** rotation curves of all spirals are strikingly similar (McGaugh et al. 2007)
~600 resolved points from 60 galaxies with $\sigma_V/V < 5\%$ & $R > 1$ kpc.

$$\log V_h = \frac{1}{2}\log R + 1.47^{+0.15}_{-0.19} \quad \Rightarrow \quad \rho = \frac{0.032}{R}\frac{\mathrm{M}_\odot}{\mathrm{pc}^3} = \frac{1.27}{R}\frac{\mathrm{GeV}}{\mathrm{cm}^3}$$



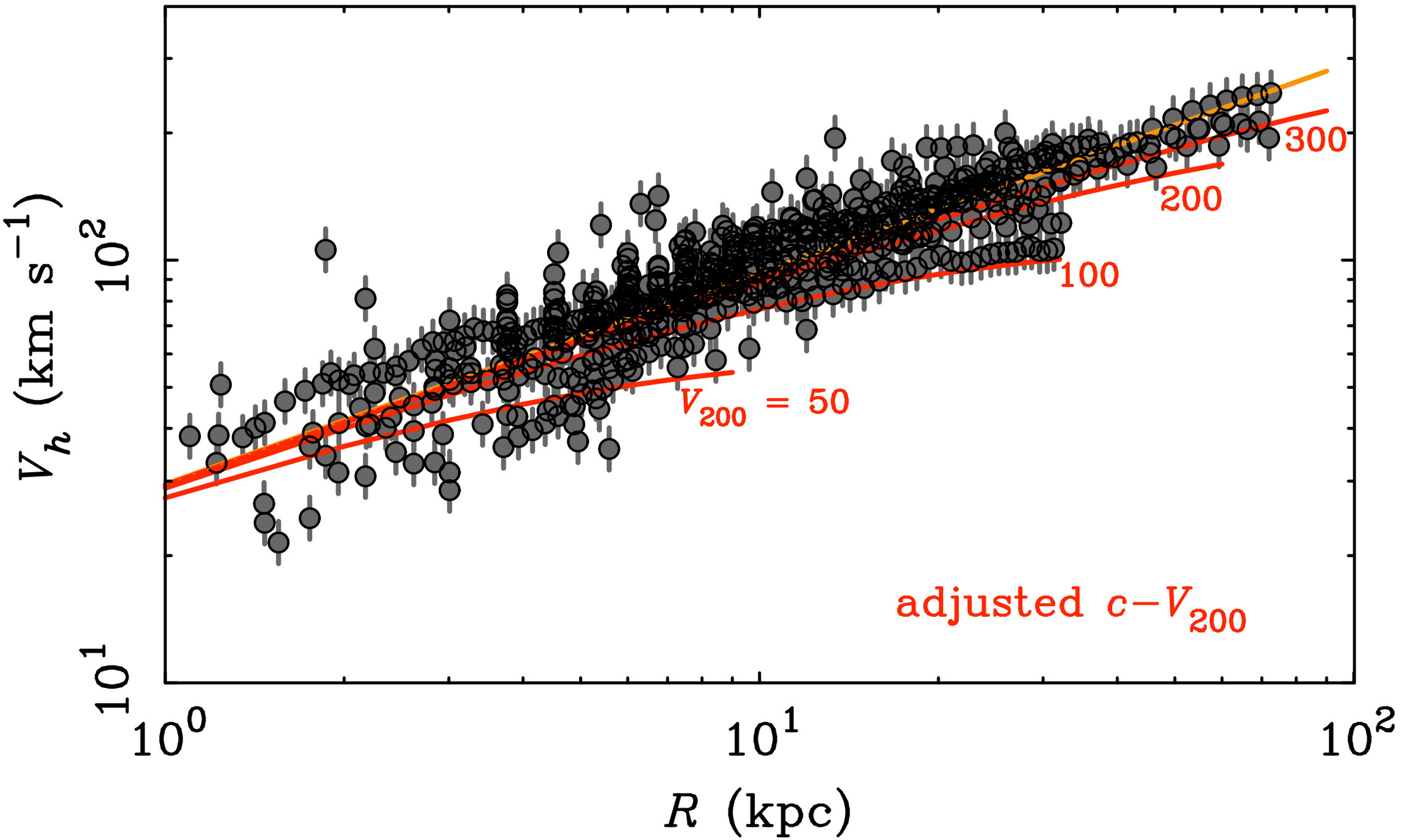
The **halo-only** rotation curves of all spirals are strikingly similar (McGaugh et al. 2007)
~600 resolved points from 60 galaxies with $\sigma_V/V < 5\%$ & $R > 1$ kpc.

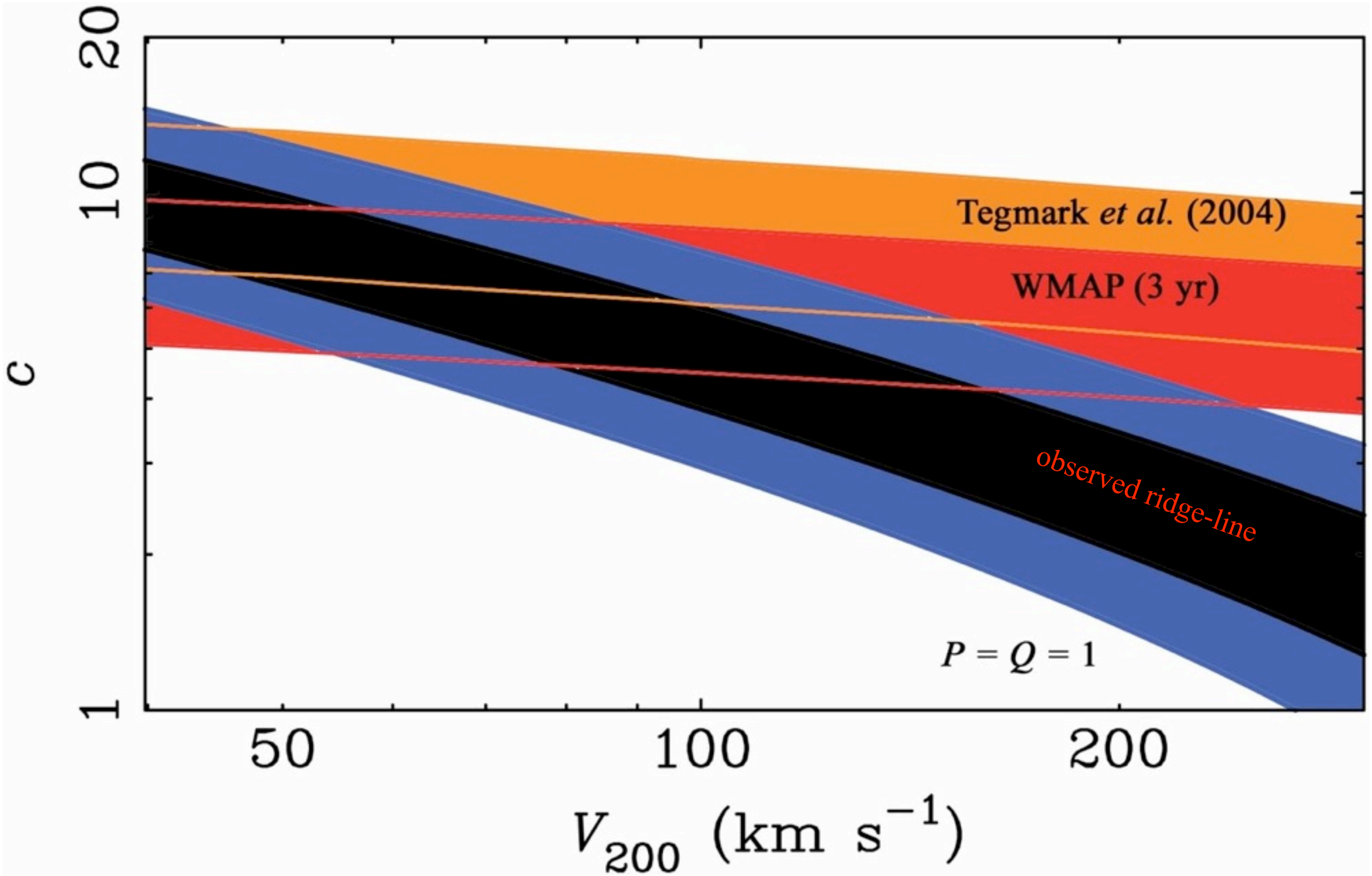
$$\log V_h = \frac{1}{2}\log R + 1.47^{+0.15}_{-0.19} \quad \Rightarrow \quad \rho = \frac{0.032}{R}\frac{\mathrm{M}_\odot}{\mathrm{pc}^3} = \frac{1.27}{R}\frac{\mathrm{GeV}}{\mathrm{cm}^3}$$



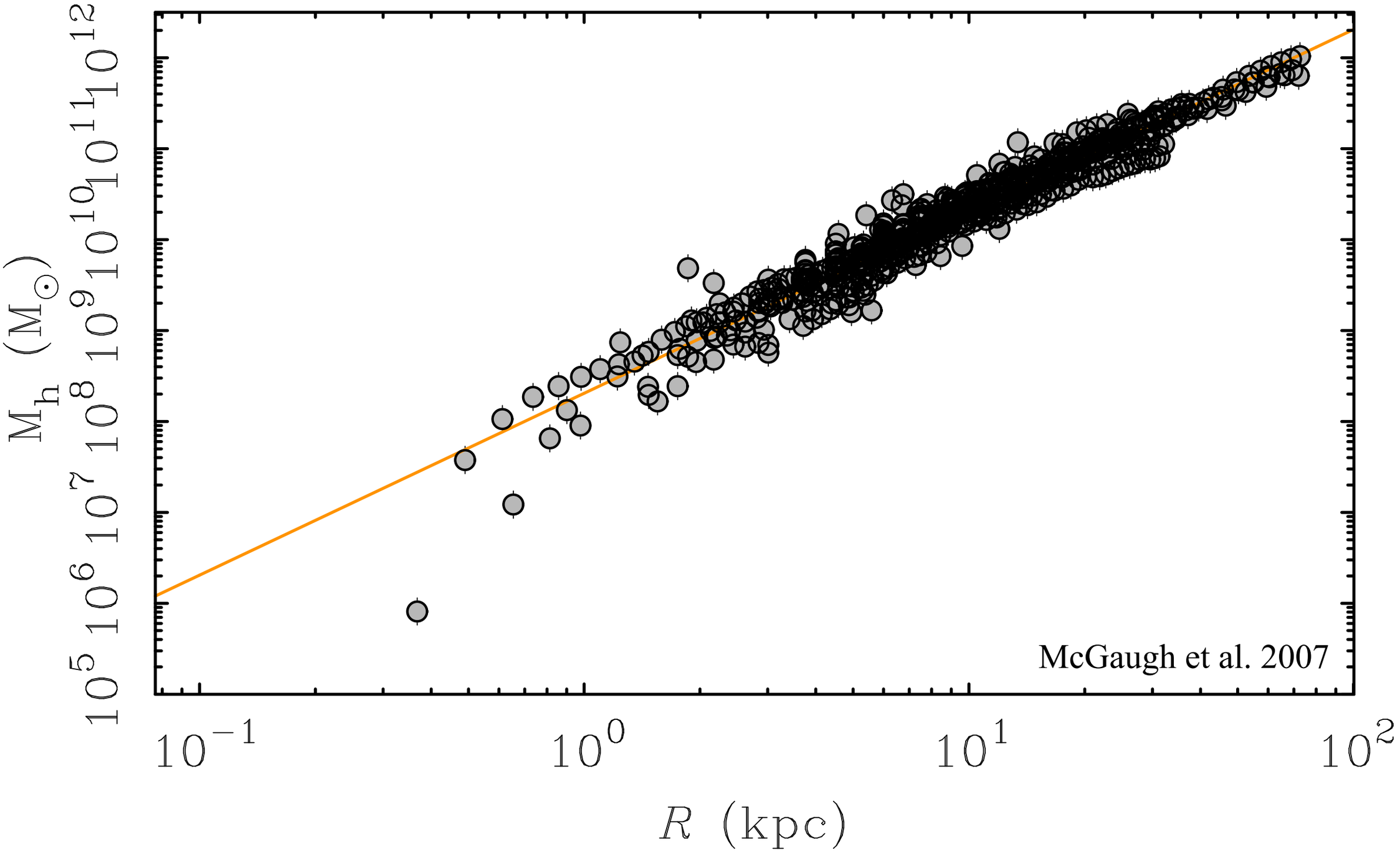
The **halo-only** rotation curves of all spirals are strikingly similar (McGaugh et al. 2007)
~600 resolved points from 60 galaxies with $\sigma_V/V < 5\%$ & $R > 1$ kpc.

$$\log V_h = \frac{1}{2}\log R + 1.47^{+0.15}_{-0.19} \quad \Rightarrow \quad \rho = \frac{0.032}{R}\frac{\mathrm{M}_\odot}{\mathrm{pc}^3} = \frac{1.27}{R}\frac{\mathrm{GeV}}{\mathrm{cm}^3}$$



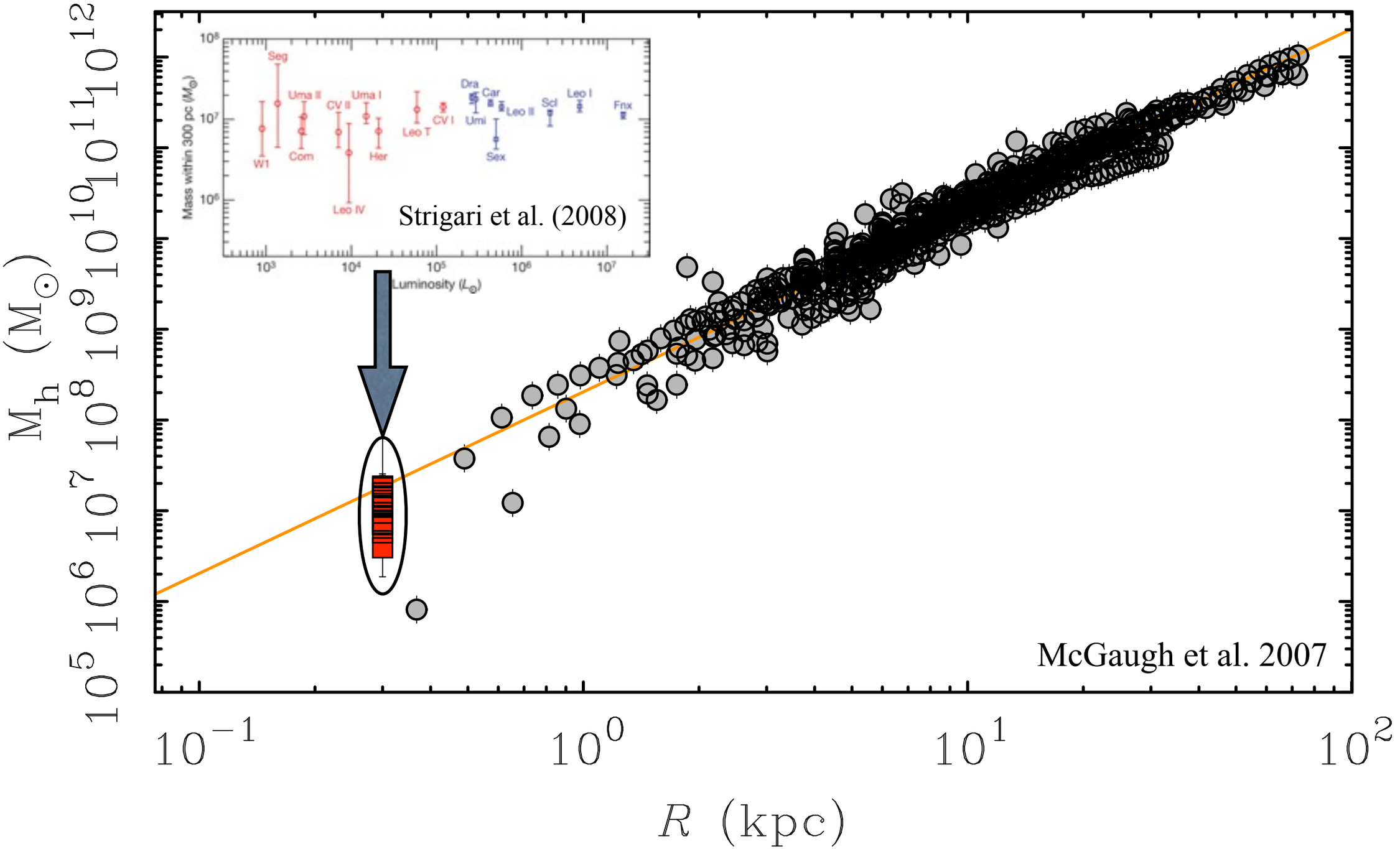

20
10
1
c
Tegmark et al. (2004)
WMAP (3 yr)
observed ridge-line
P = Q = 1
50
100
200
V200 (km s−1)

Enclosed halo mass $\mathrm{M} = (200\ \mathrm{M}_\odot\ \mathrm{pc}^{-2})R^2$

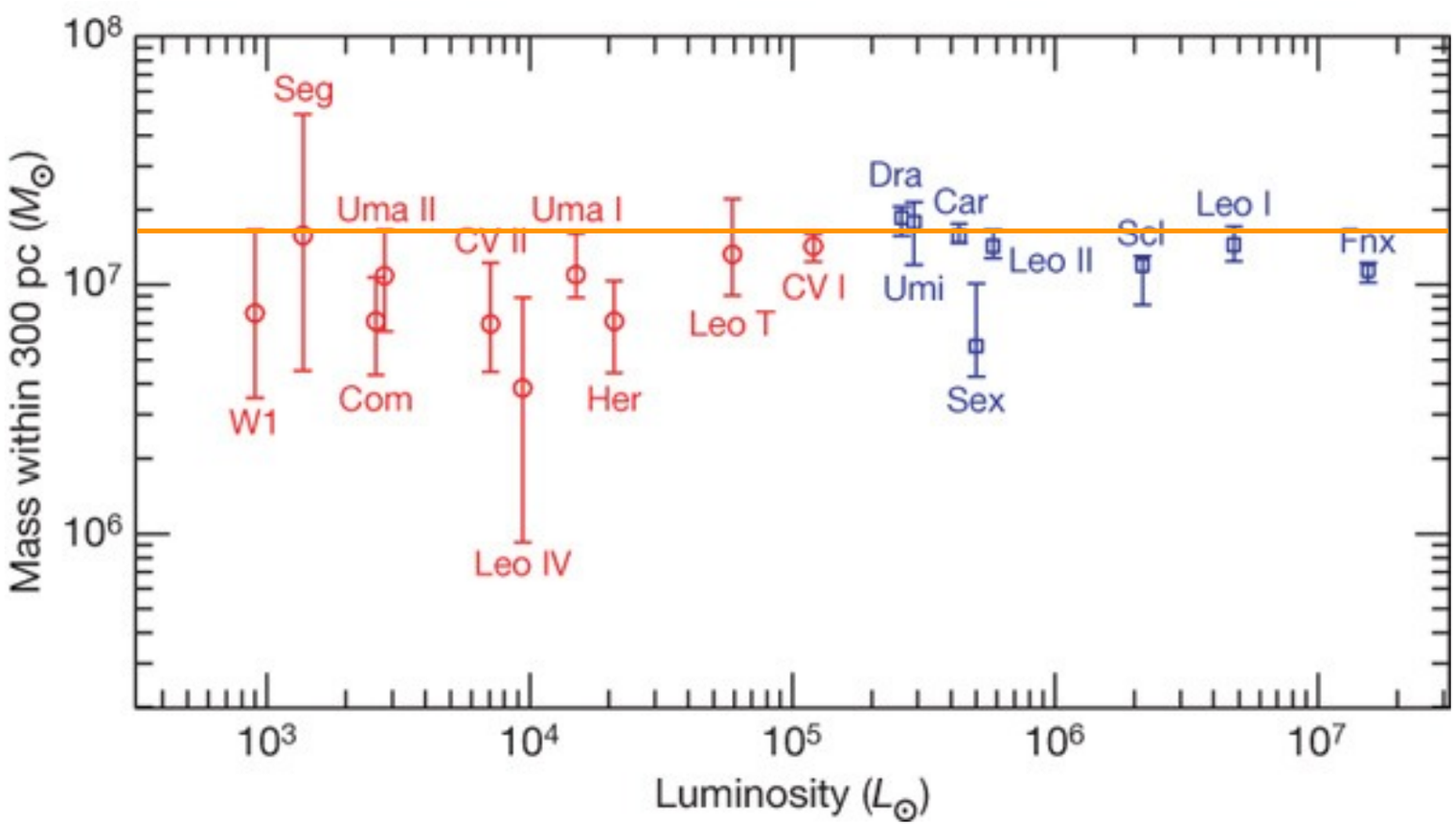


Enclosed halo mass $\mathrm{M} = (200\ \mathrm{M}_\odot\ \mathrm{pc}^{-2})R^2$

Data are consistent with a [nearly] universal halo.



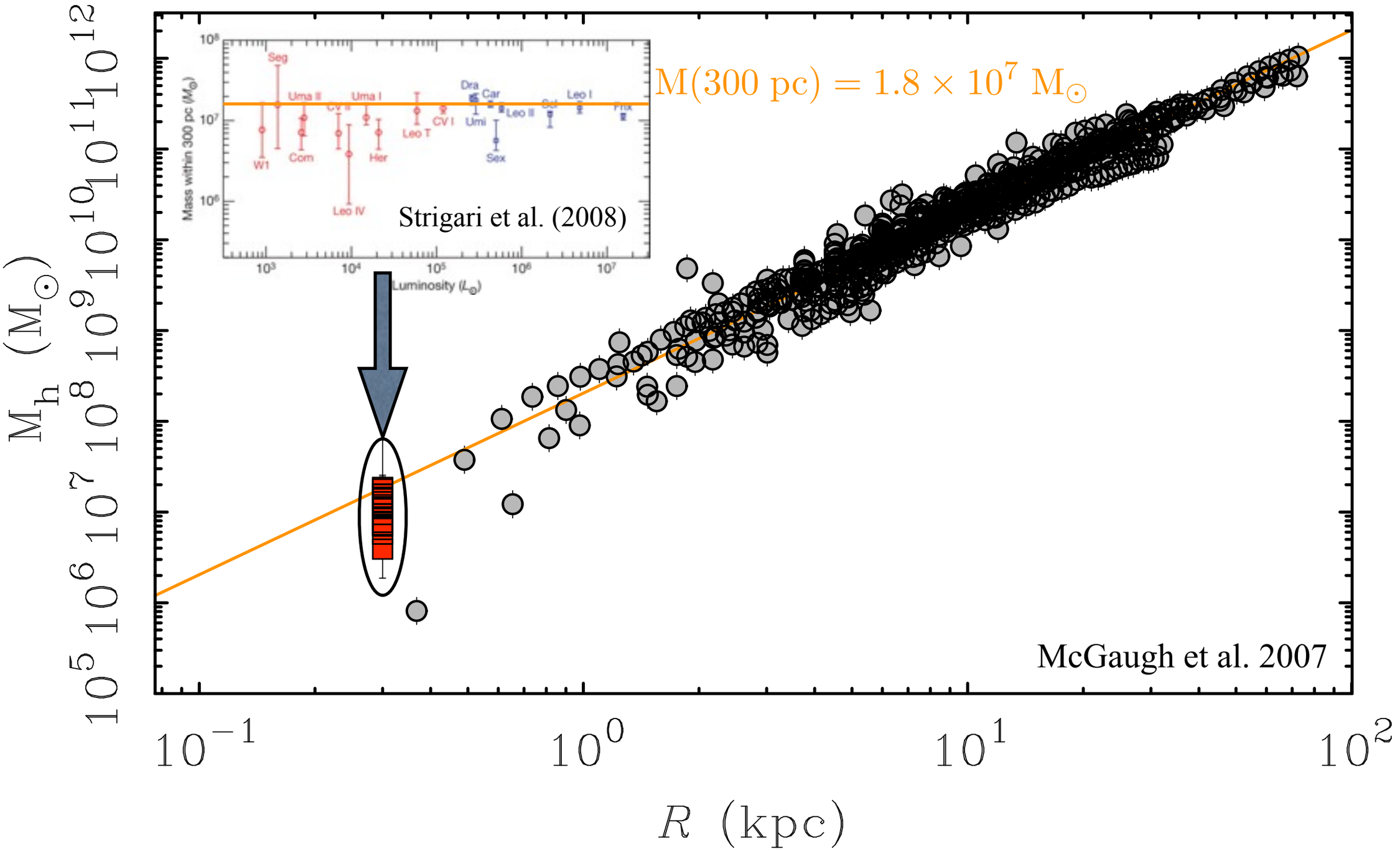
Strigari et al. (2008)



$$\mathrm{M}(300\ \mathrm{pc}) = 1.8 \times 10^7\ \mathrm{M}_\odot$$

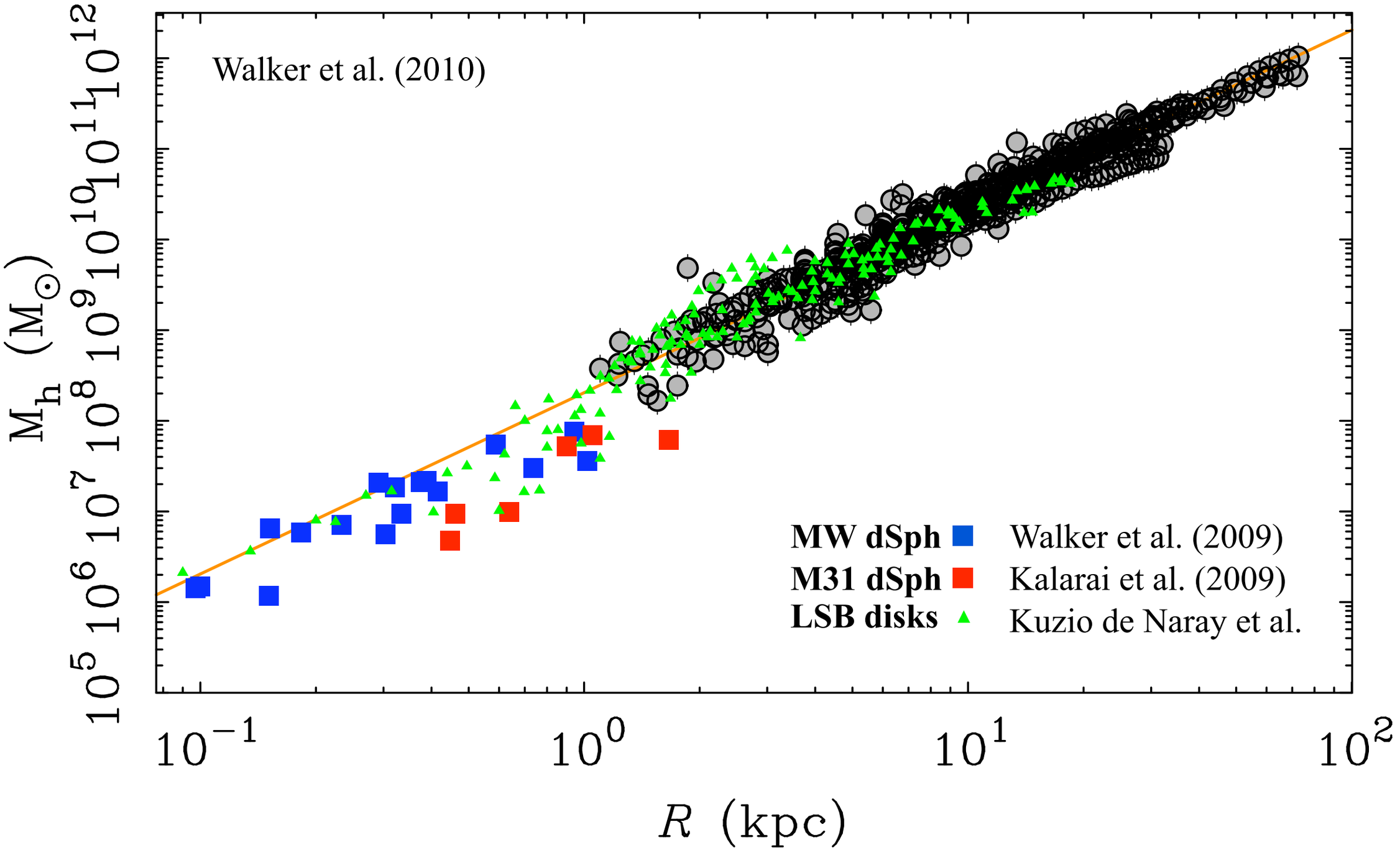
Enclosed halo mass $\mathrm{M} = (200\ \mathrm{M}_\odot\ \mathrm{pc}^{-2})R^2$

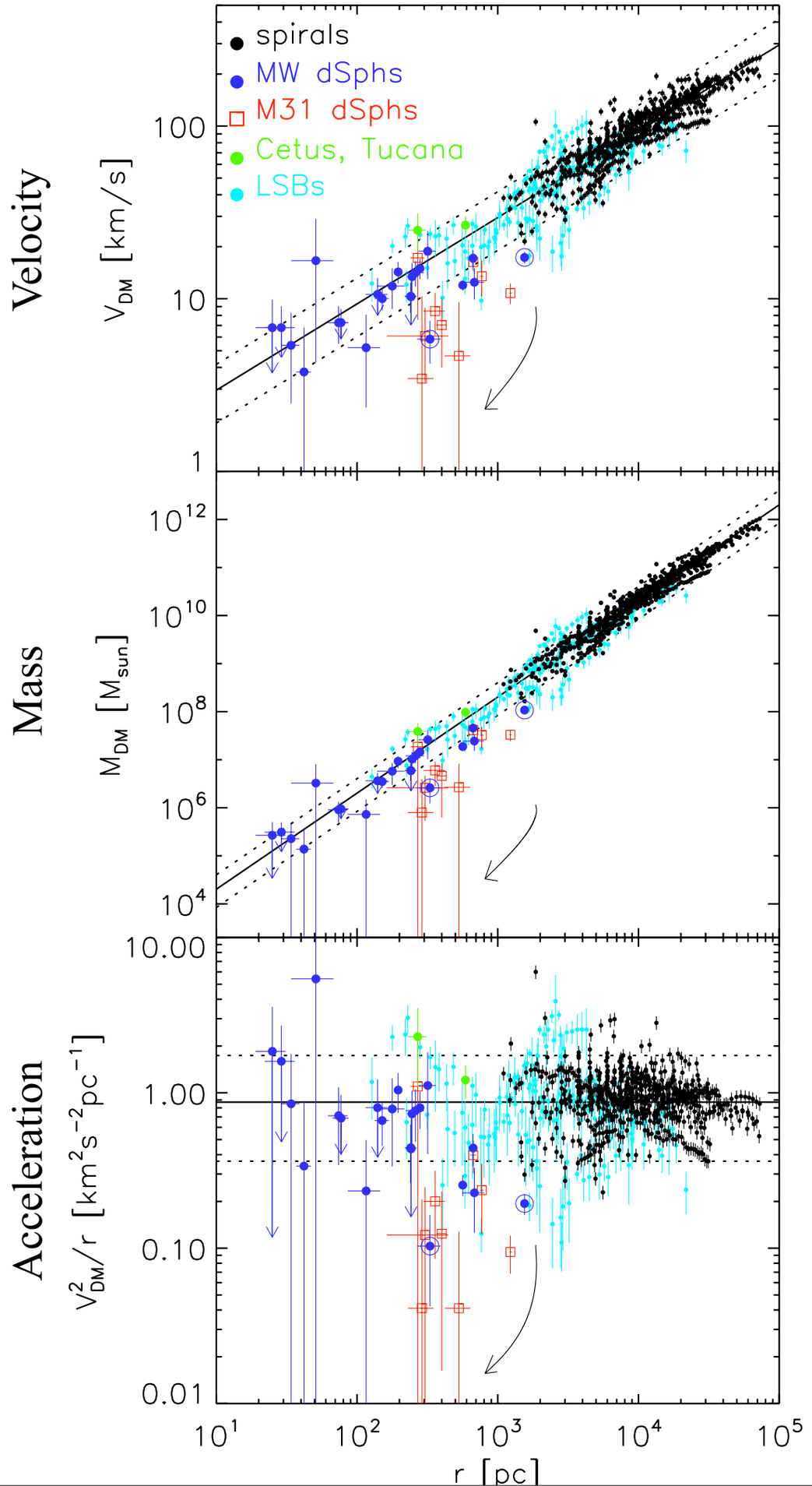
Data are consistent with a [nearly] universal halo.



Enclosed halo mass $\mathrm{M} = (200\ \mathrm{M}_\odot\ \mathrm{pc}^{-2})R^2$

Data are consistent with a [nearly] universal halo.





Walker et al. (2010)

$$\log V_h = \frac{1}{2}\log R + 1.47^{+0.15}_{-0.19}$$

$$\mathrm{M} = (200\ \mathrm{M}_\odot\ \mathrm{pc}^{-2})R^2$$

$$g_h \approx 1\ \mathrm{km}^2\,\mathrm{s}^{-2}\,\mathrm{pc}^{-1}$$

Advances in Theoretical and Observational Cosmology

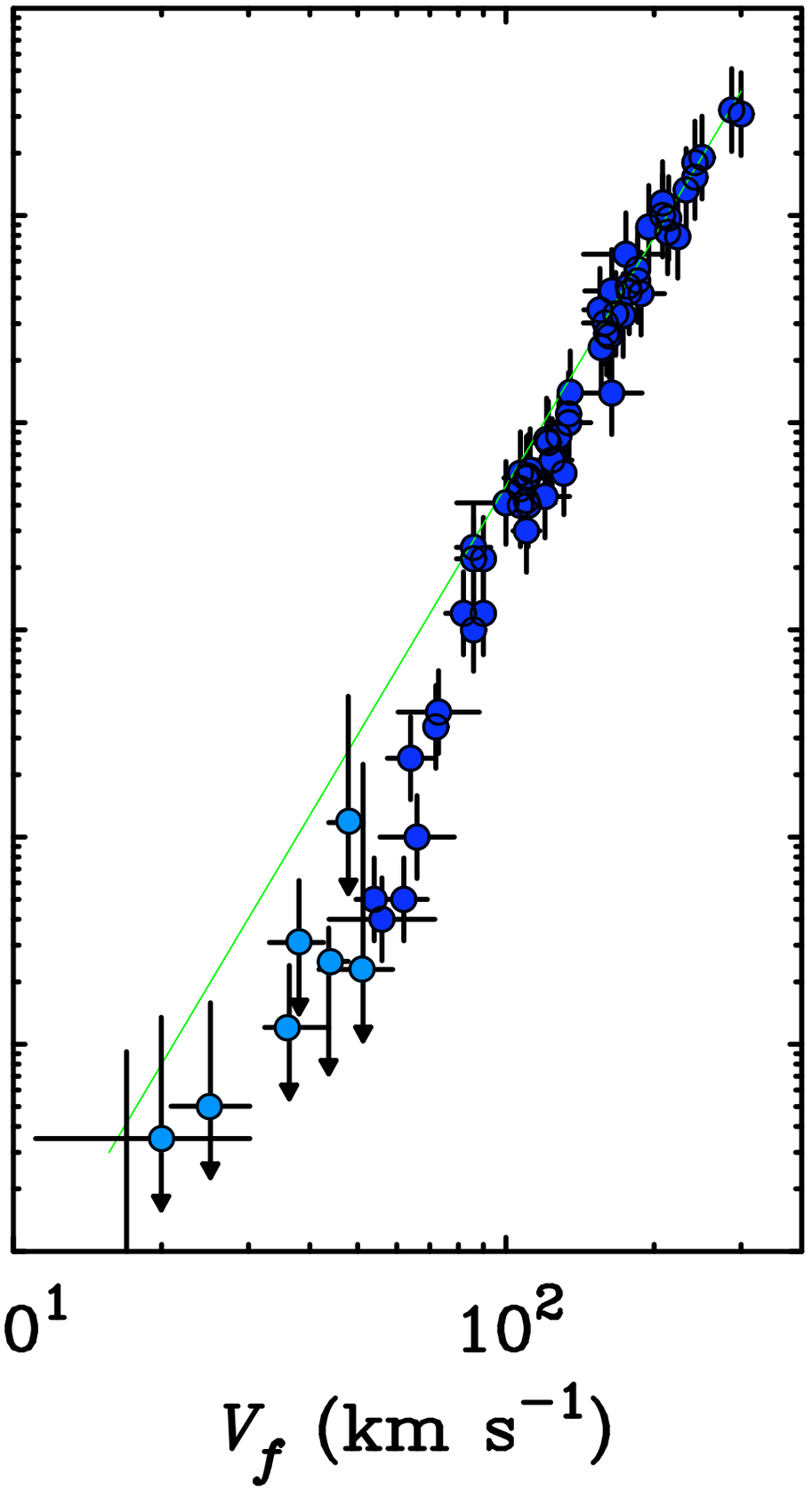
- Dark Matter Distribution in Spirals and Dwarfs
  - Data are consistent with quasi-universal halo

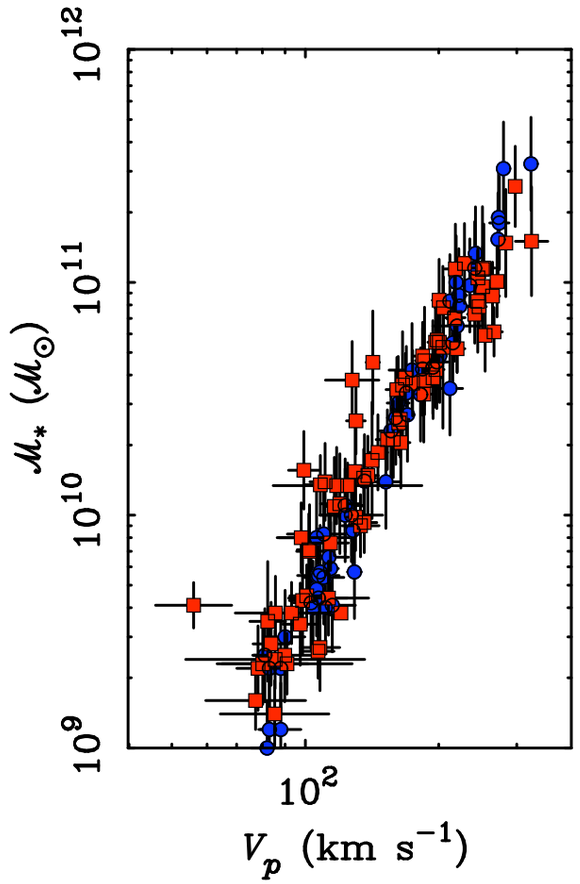
    Unifies results of Strigari et al. (2008),
    Donato et al. (2009), & Gentile et al. (2009).
    All implicitly contained in McGaugh et al. (2007).
- Baryonic Tully Fisher Relation (BTFR) & Halo Baryons

Global Relation: Tully-Fisher Relation

Stars only

$M_\star = \Upsilon_\star L$



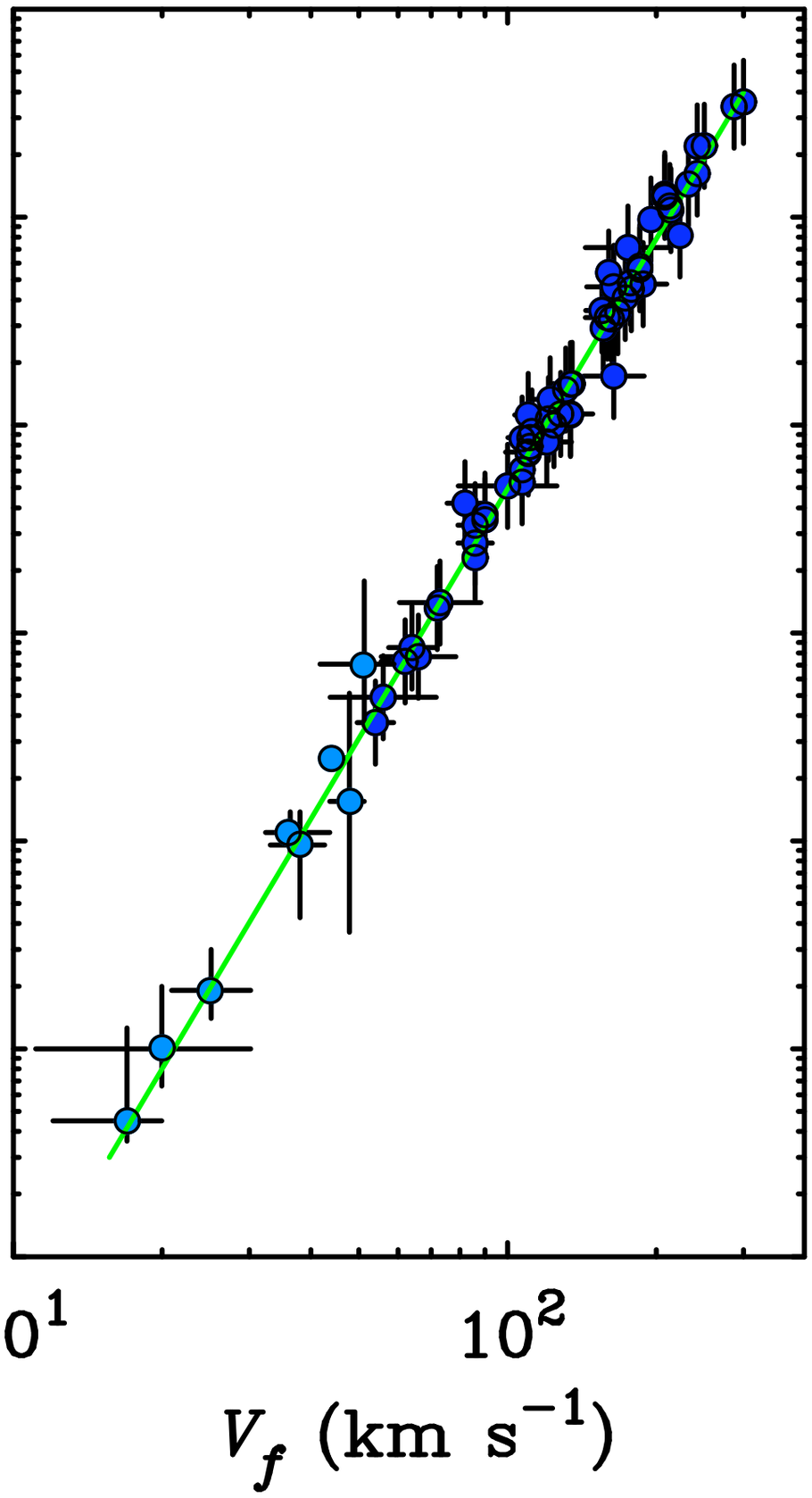


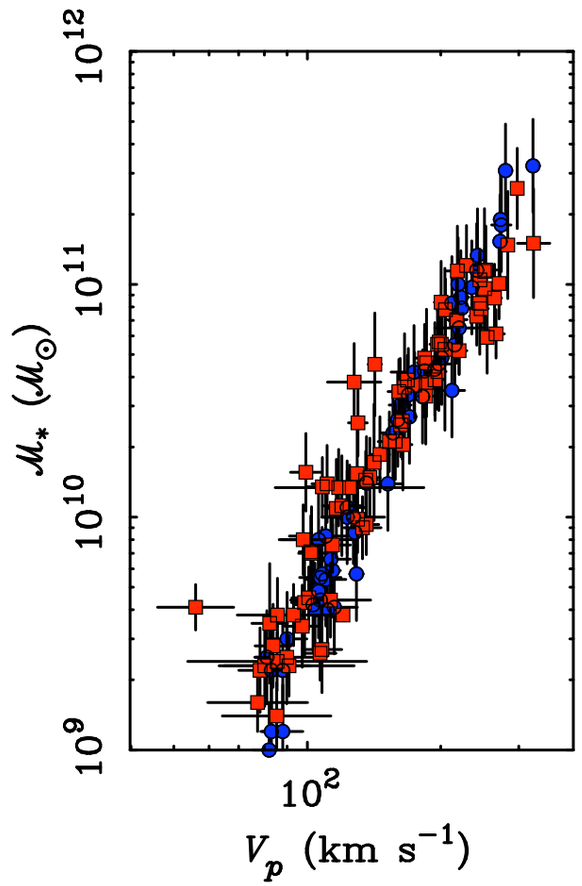
- McGaugh (2005)
- Pizagno *et al.*

Global Relation: Baryonic Tully-Fisher

Stars plus gas

$M_b = M_\star + M_{gas}$





line:

$$\log M_b = 4 \log V_f + 1.7$$

(McGaugh 2005)

Implies no other substantial reservoirs of baryonic mass.

Line-widths

M_b $(M_\odot)$

10^6 10^7 10^8 10^9 10^{10} 10^{11} 10^{12}

100 200 300

10^{11}

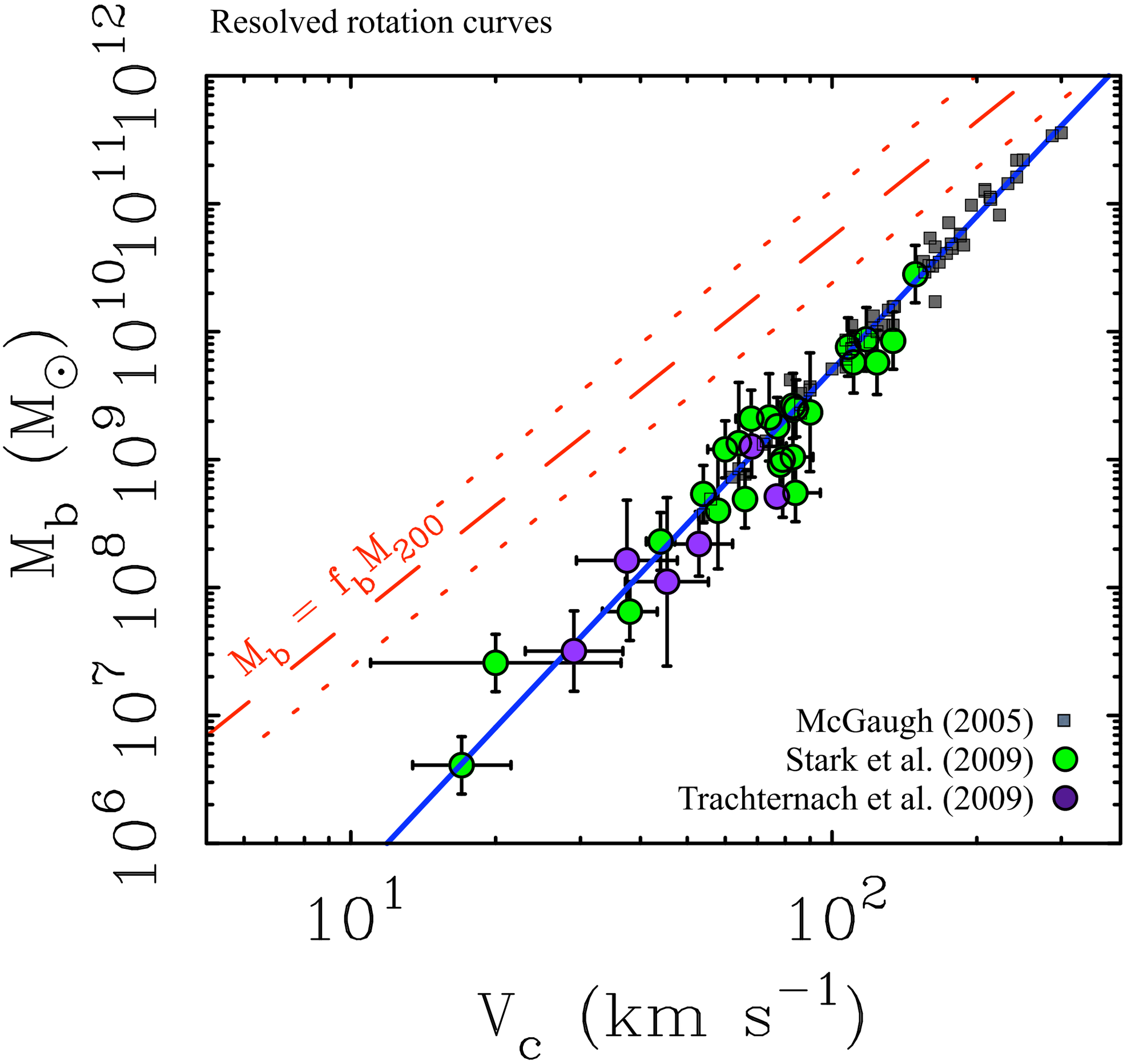
10^{10}

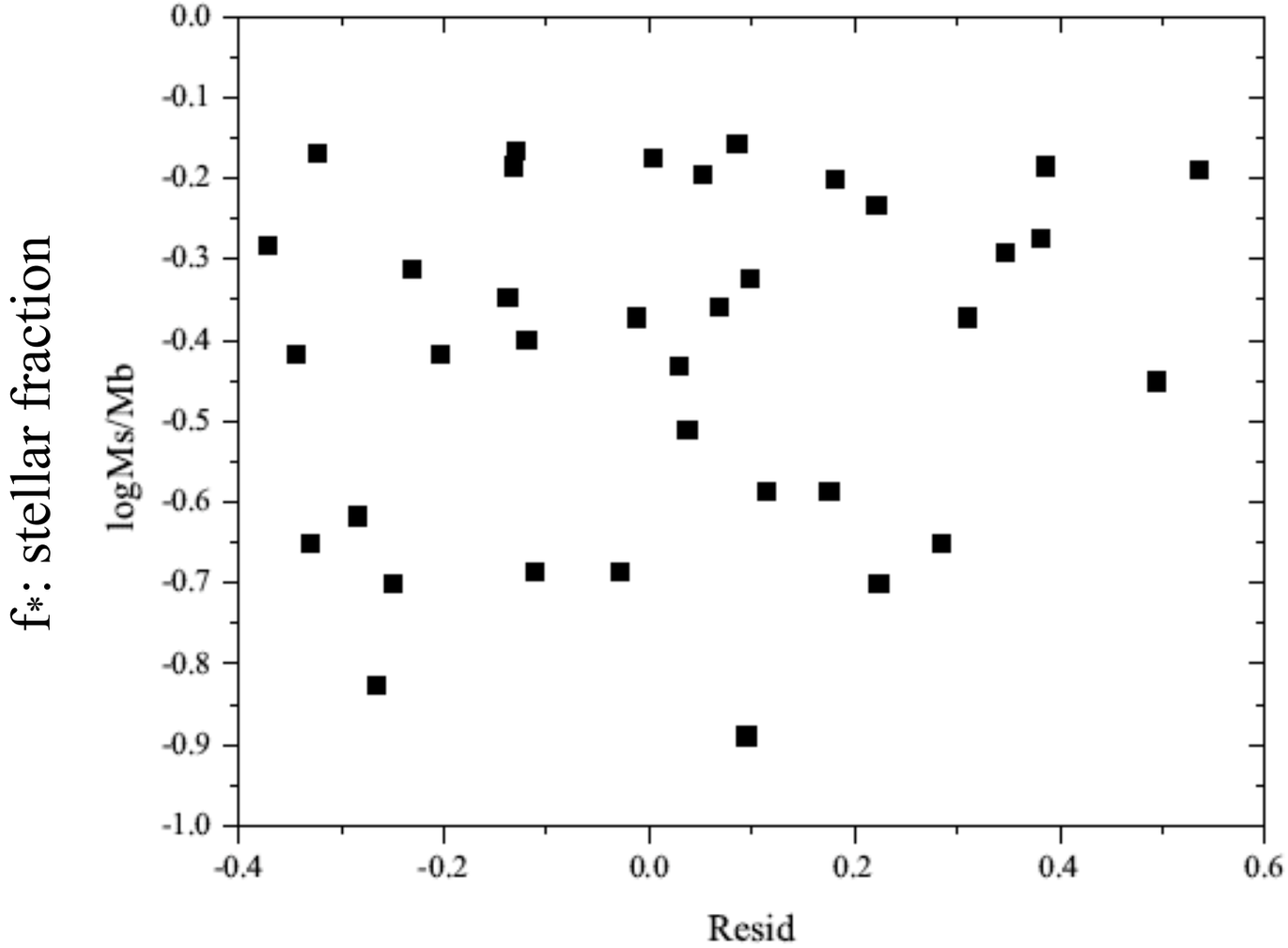
Bothun et al. (1985)
Sakai et al. (2000)
McGaugh et al. (2000)
Gurovich et al. (2010)
Trachternach et al. (2009)

10^1 10^2

$\frac{1}{2}W_{20}$ (km s^{-1})

Resolved rotation curves

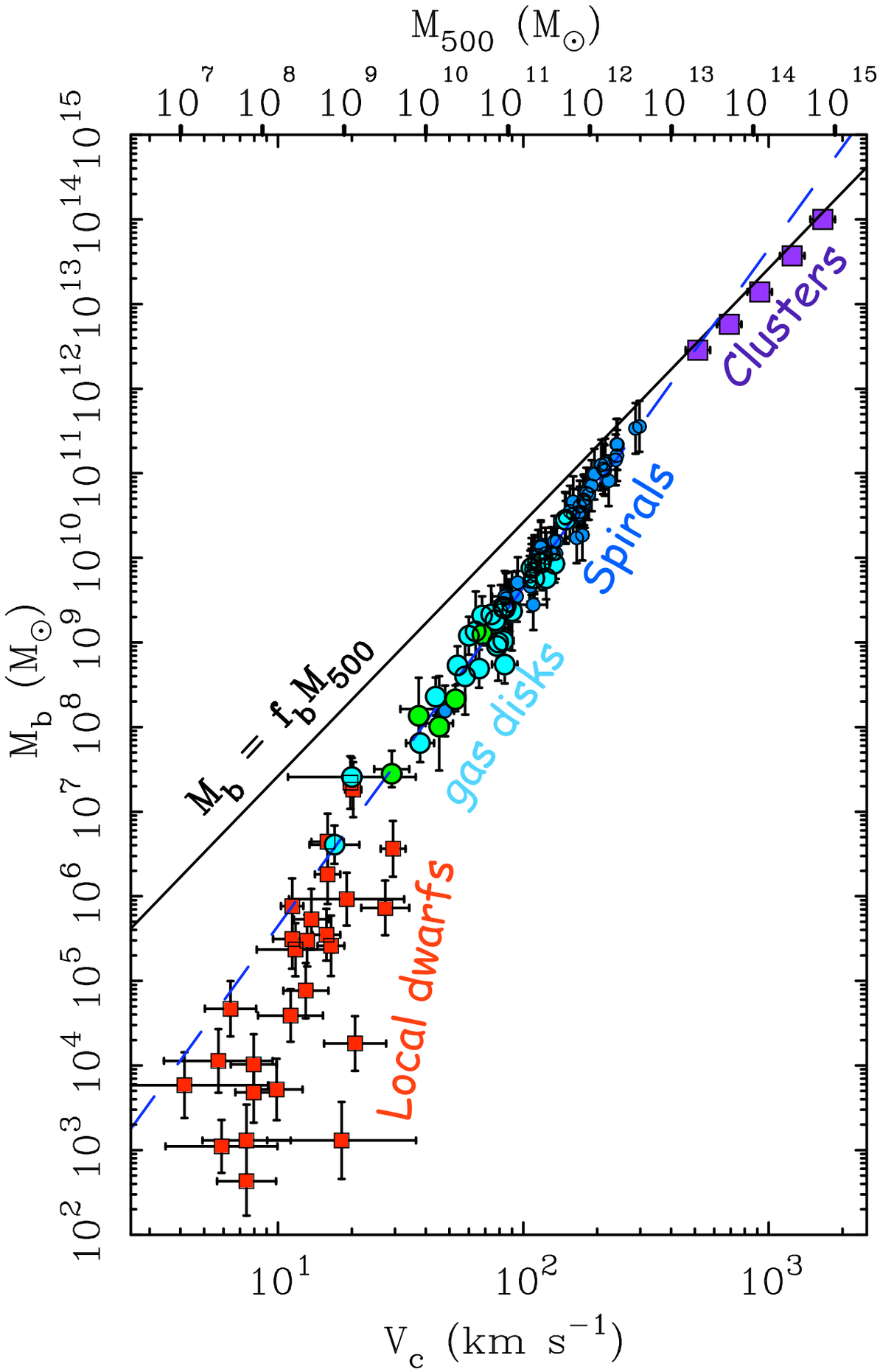




residual form BTFR

Fig. 3.— Comparison of galaxy residuals about the baryonic Tully-Fisher relation as a function of their stellar mass fraction for the gas-dominated sample of Stark et al. (2009). For several of these galaxies, the stars comprise less than 25% of the baryons, yet they have the same baryon fraction as the more star-rich galaxies. As discussed in section 6, we conclude that supernovae from the stars in these galaxies are not responsible for ejecting most of the missing baryons from the galaxies.

Anderson & Bregman (2010)



BTFR: $M_b = AV_c^4$

$A = 45 \pm 10\ \mathrm{M}_\odot\ \mathrm{km}^{-4}\ \mathrm{s}^4$

Cluster data: Giodini et al. (2009)

$M_\Delta = B_\Delta V_\Delta^3$

$B_{500} = 1.5 \times 10^5\ \mathrm{M}_\odot\ \mathrm{km}^{-3}\ \mathrm{s}^3$

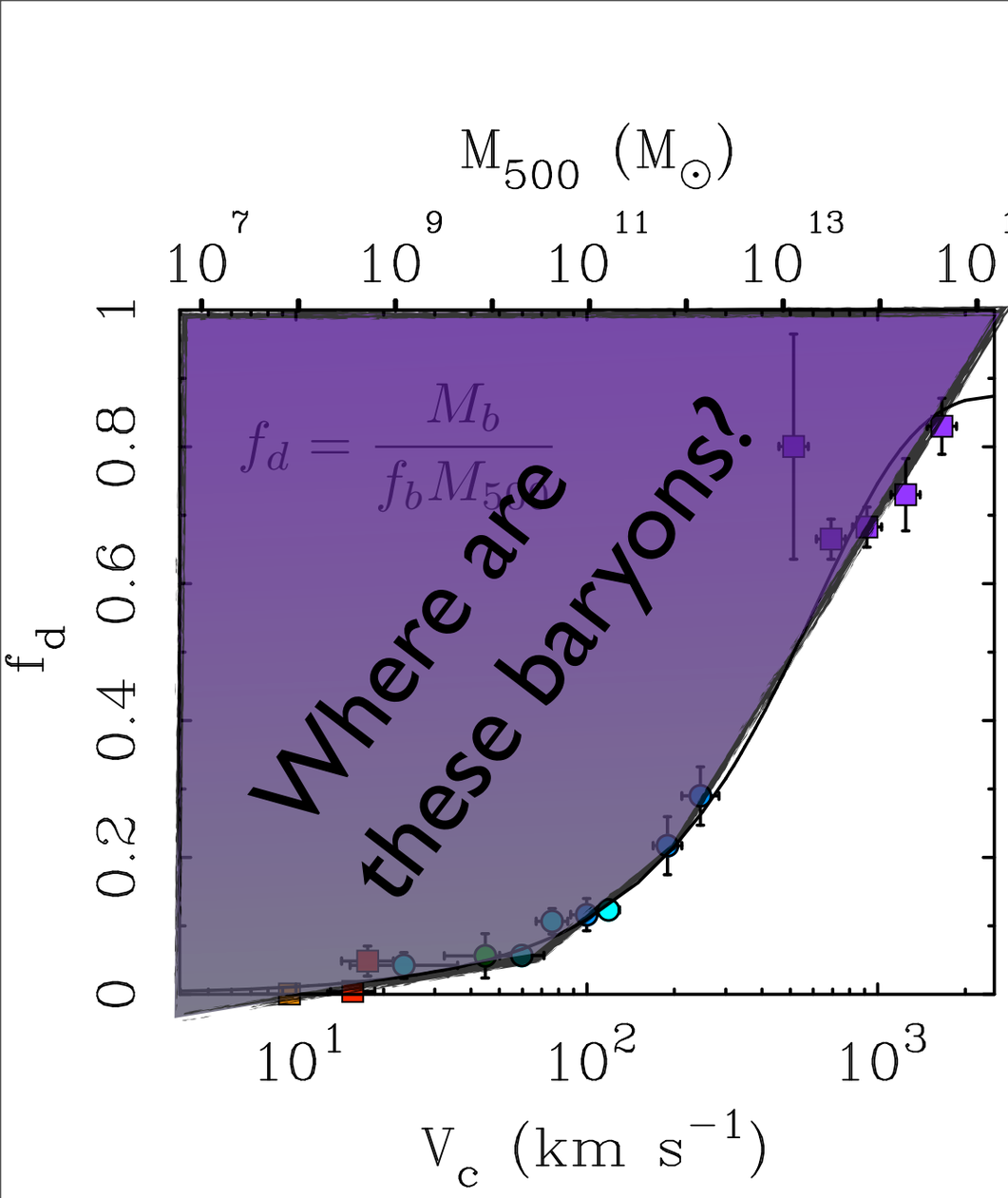
Spiral data: McGaugh et al. (2005)

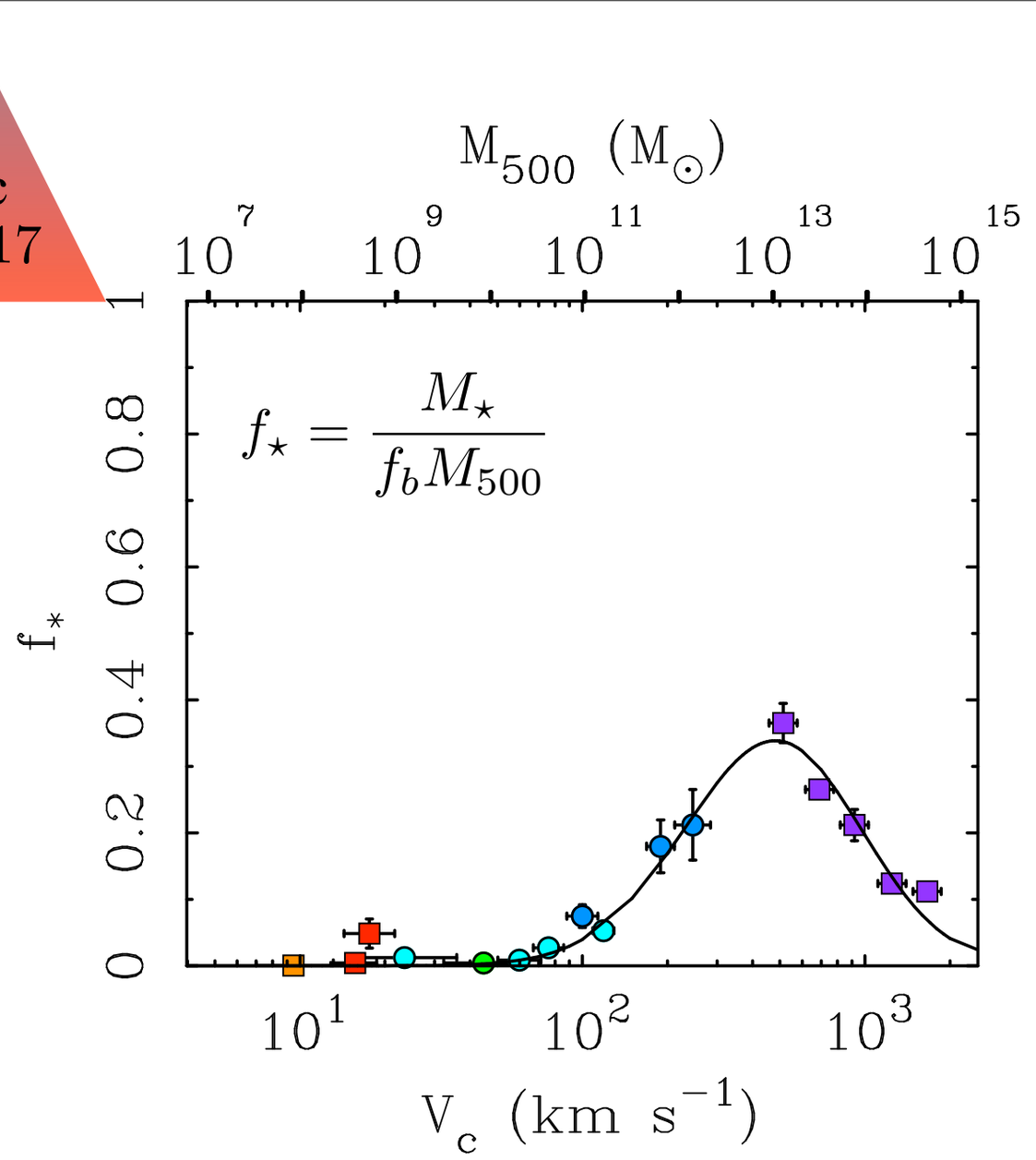
Gas dominated disks:
Stark et al. (2009)
Trachternach et al. (2009)

Local dwarf data: Walker et al. (2009)
M∗/L as per Mateo et al. (1998)

$V_c = \sqrt{3}\sigma$

McGaugh et al. (2010)





Detected baryon fraction increases monotonically with mass

Star formation peak conversion efficiency $\sim 10^{13}$ $M_\odot$

$$M_\Delta = \frac{4\pi}{3}\Delta\rho_{crit}R_\Delta^3$$

$$M_{500} = 2 \times 10^5 V_{500}^3 \text{ for } H_0 = 72$$

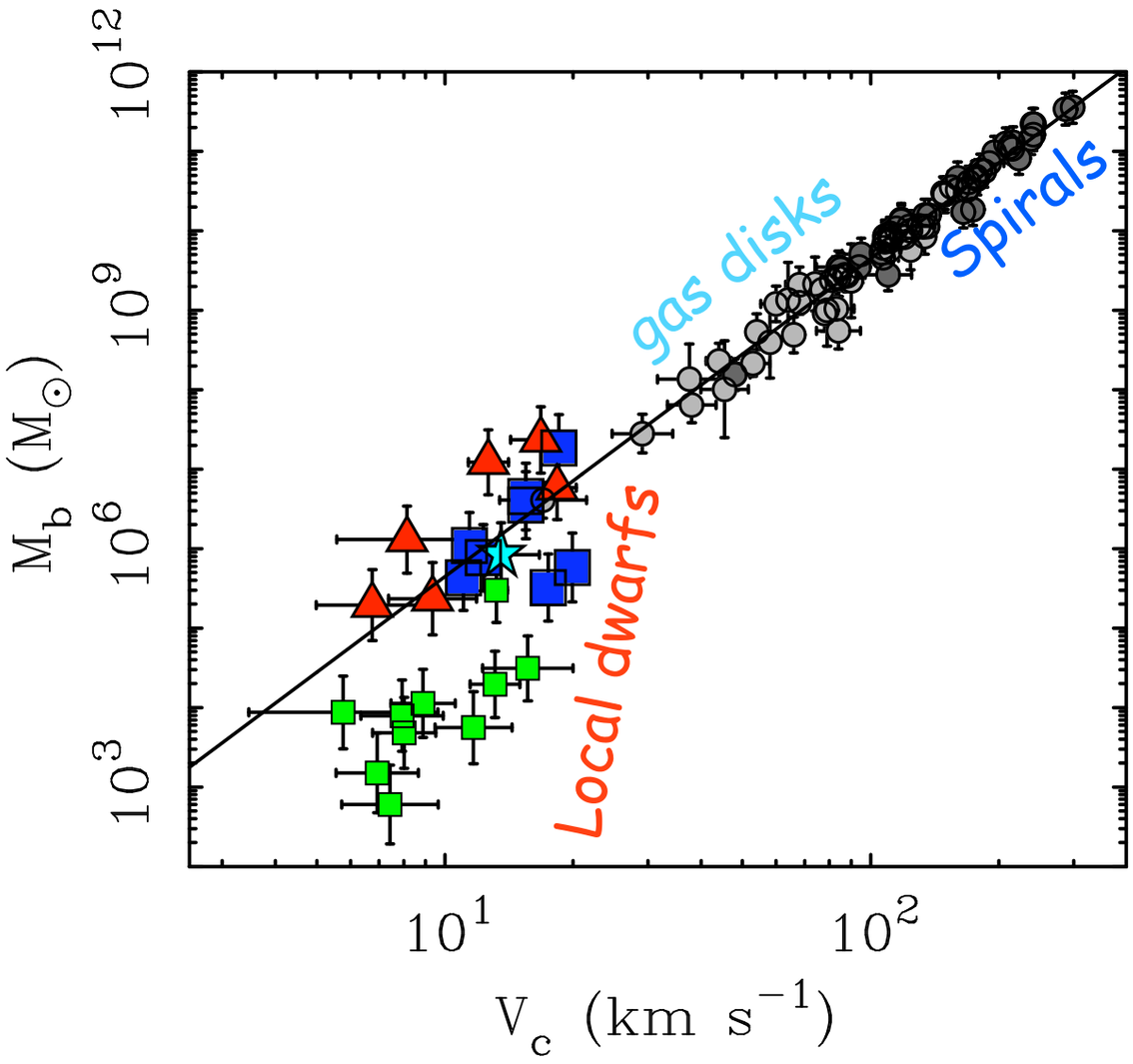
$$V_c = f_V V_{500};\ \text{assume } f_V = 1.1$$

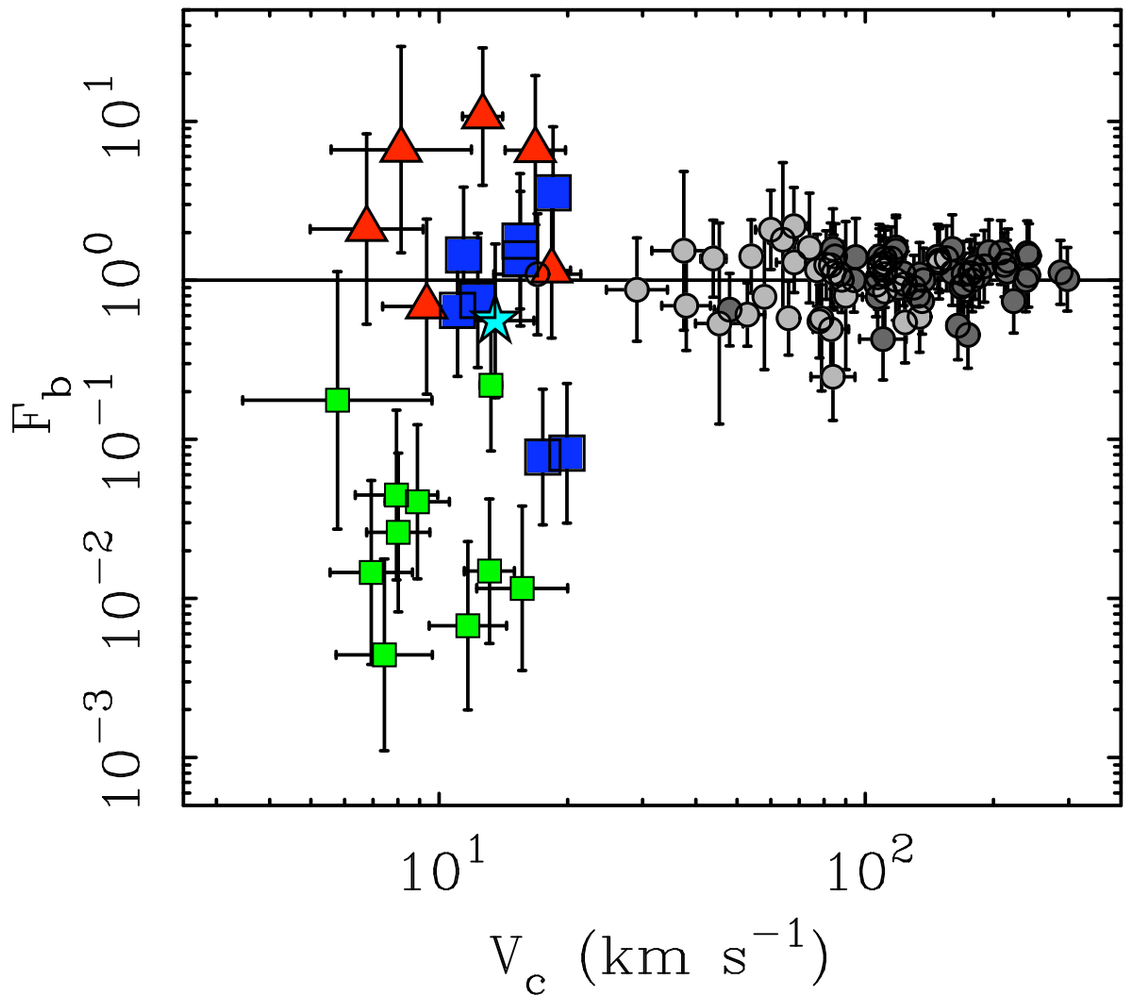
McGaugh et al. (2010)

Advances in Theoretical and Observational Cosmology

- Baryonic Tully Fisher Relation (BTFR) & Halo Baryons
  - Disks obey BTFR with $\mathrm{M_b} = AV_c^4$
  - Most halo baryons are missing
- Correlated Deviations from the BTFR among ultrafaints

Residuals of dwarf Spheroidals from Baryonic Tully-Fisher Relation
McGaugh & Wolf (2010)





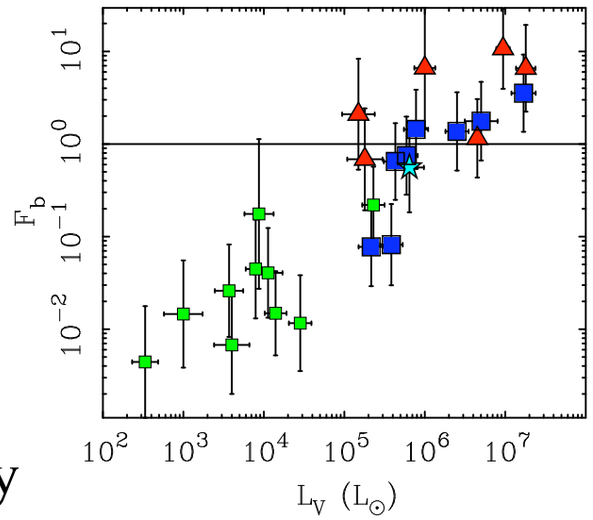
- Classical dwarfs
- Ultrafaint dwarfs
- M31 dwarfs
- Leo T (contains gas)

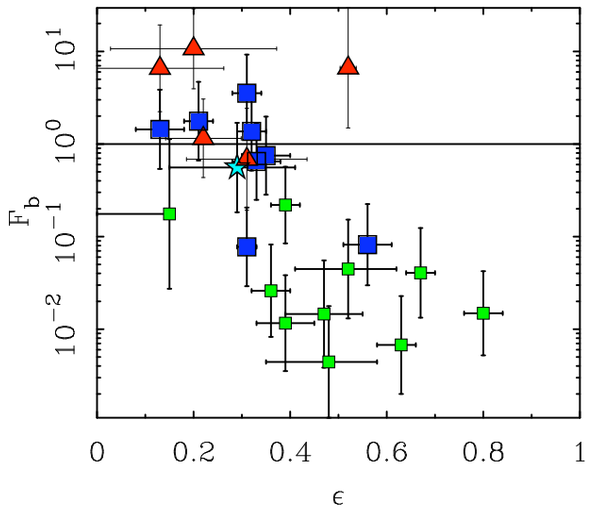
Local dwarf data: Wolf et al. (2010)
Kalirai et al. (2009; M31)
M∗/L as per Mateo et al. (1998)
& Martin et al. (2008)

$$F_b = \frac{M_b}{AV_c^4}$$

dSph BTFR residuals correlate with

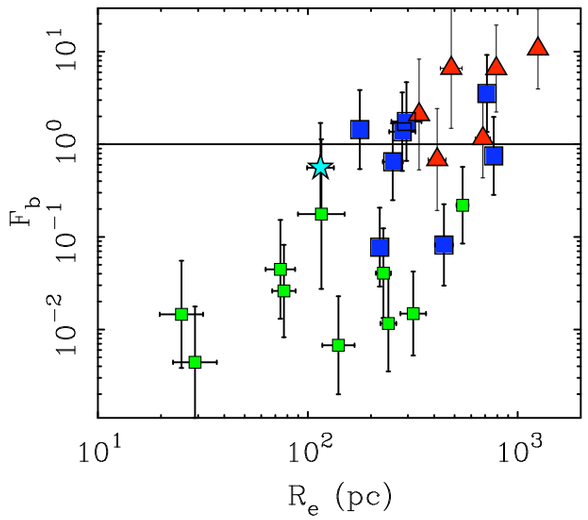
Luminosity

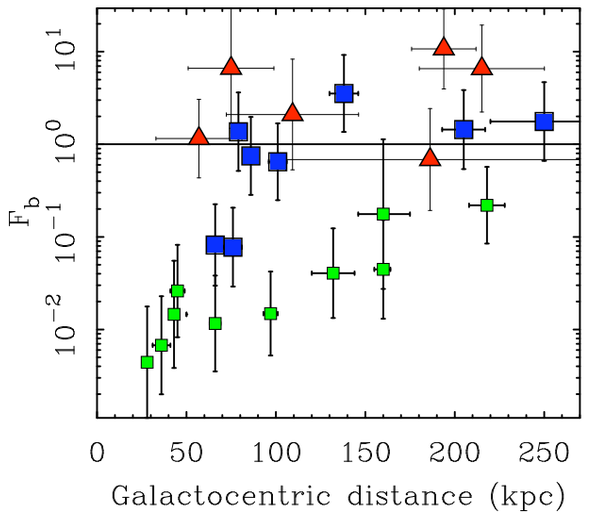




Shape

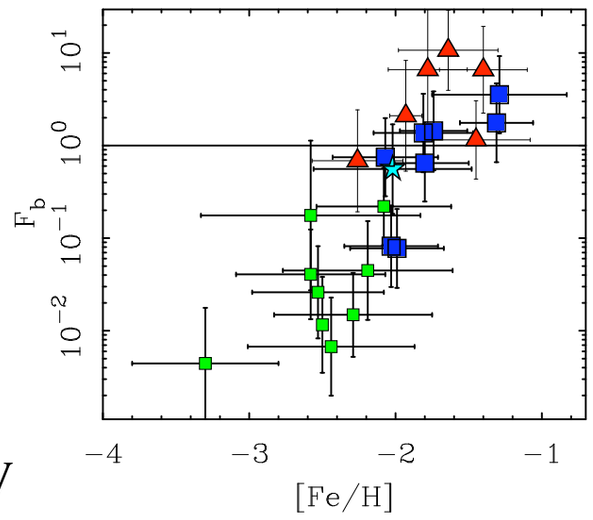
Size

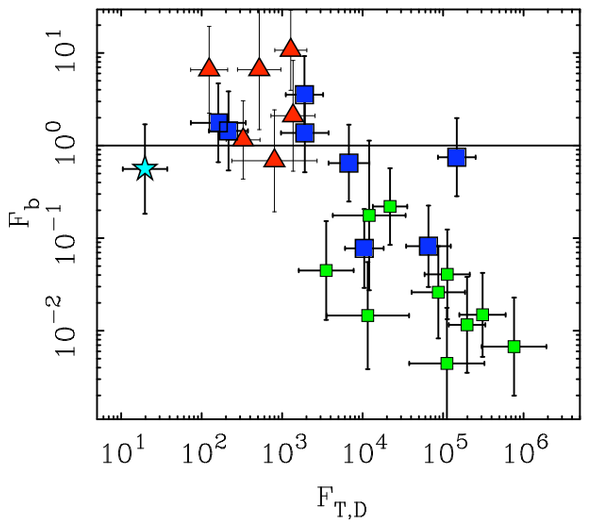




Distance

Metallicity

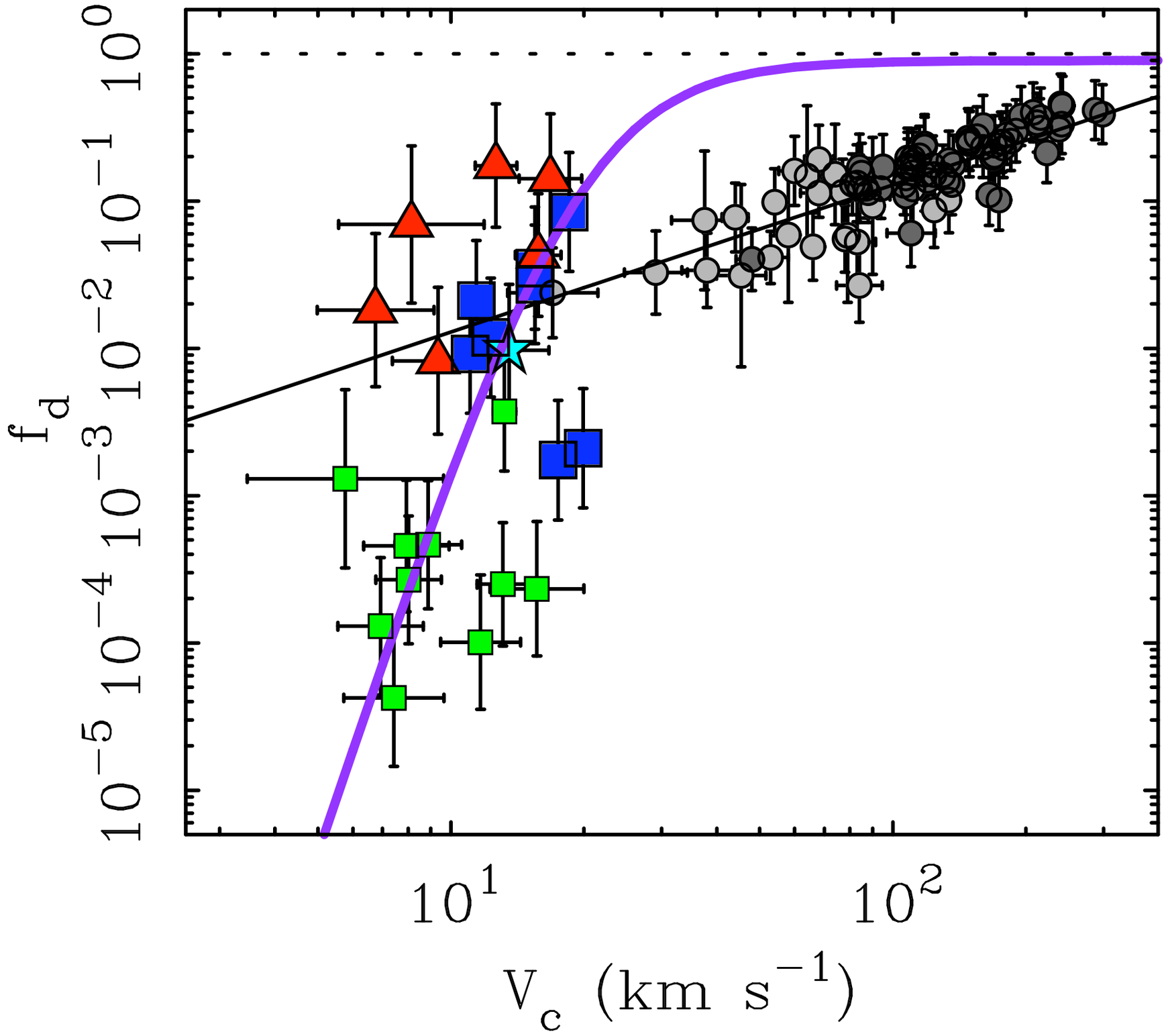


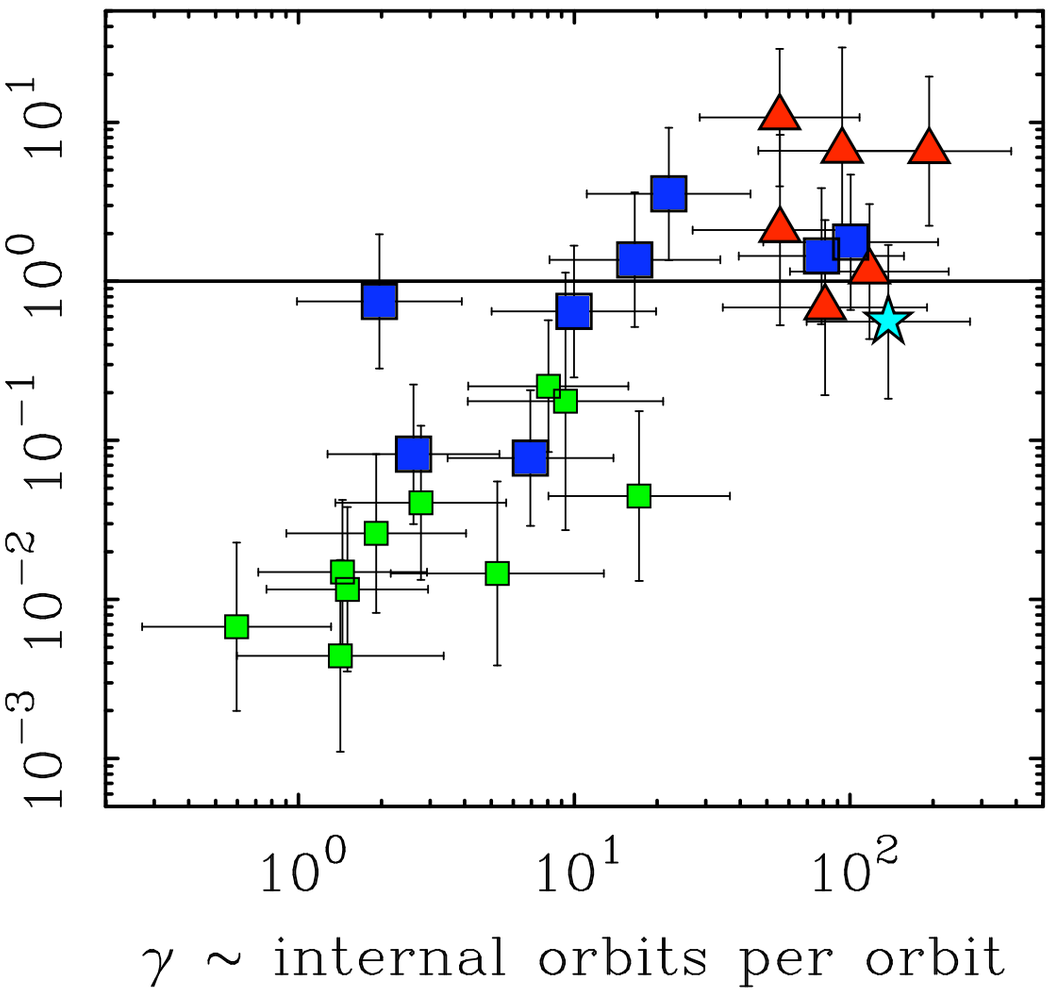


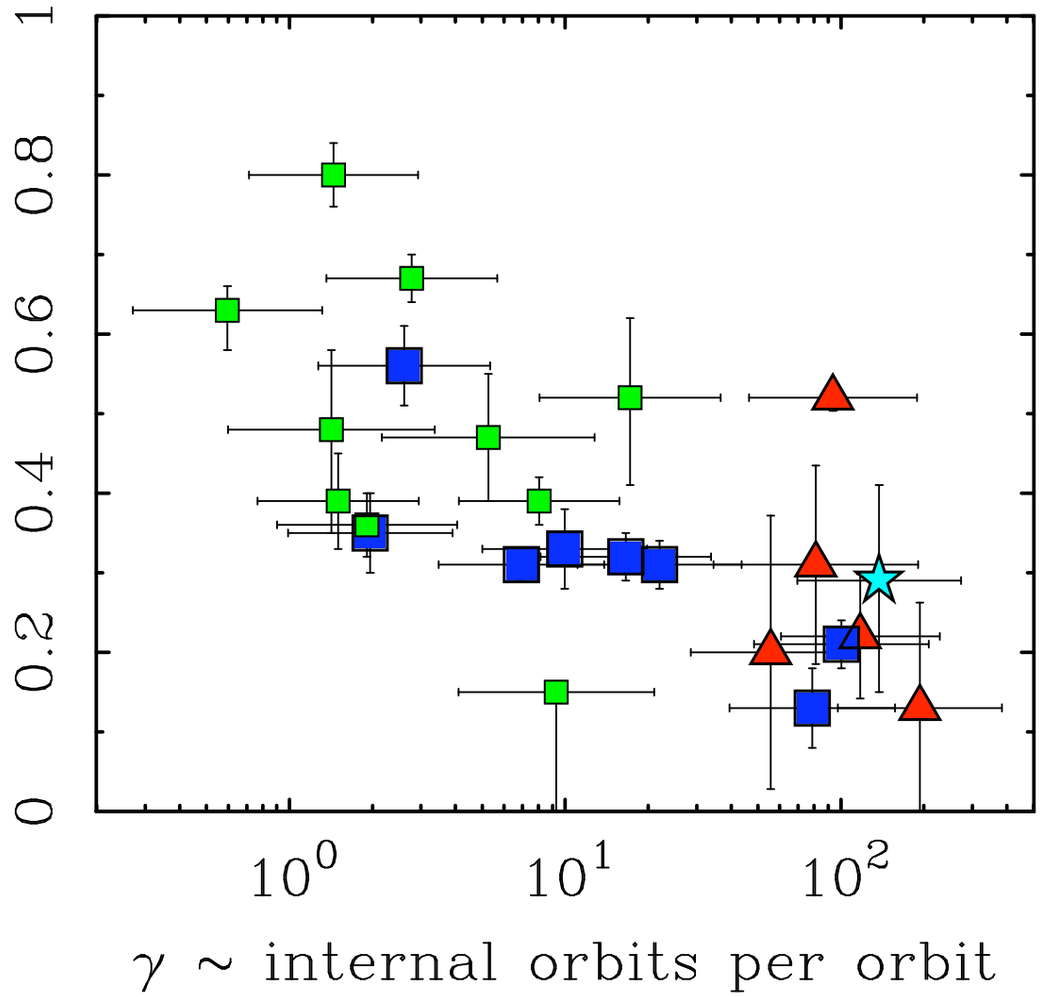
$$F_{T,D} = \frac{M}{m}\left(\frac{r}{D}\right)^3$$

Tidal Susceptibility

Reinoization Does not simultaneously explain spirals
Does not explain correlations of BTFR residuals







Dwarfs whose stars have little time to adjust to changes in the potential suffer the largest deviations and have more elliptical shapes.

Suggests a role for tides.

Advances in Theoretical and Observational Cosmology

- Correlated Deviations from the BTFR among ultrafaints

- Deviations correlate with luminosity, size, [Fe/H], shape, distance, and tidal susceptibility

- Disfavors stochastic models - probably not just a cut-off from reionization or feedback

- Tides appear to play some role.