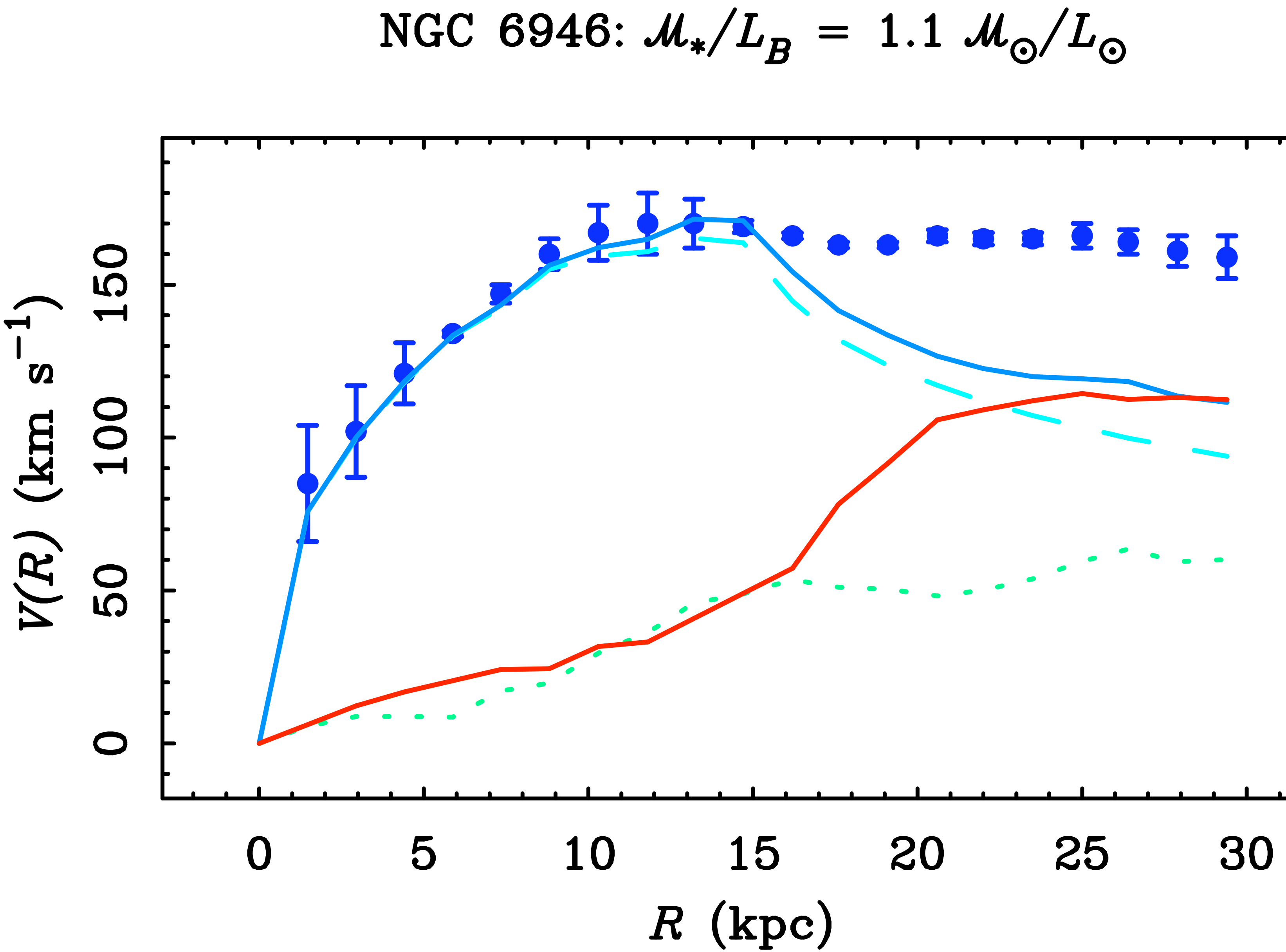
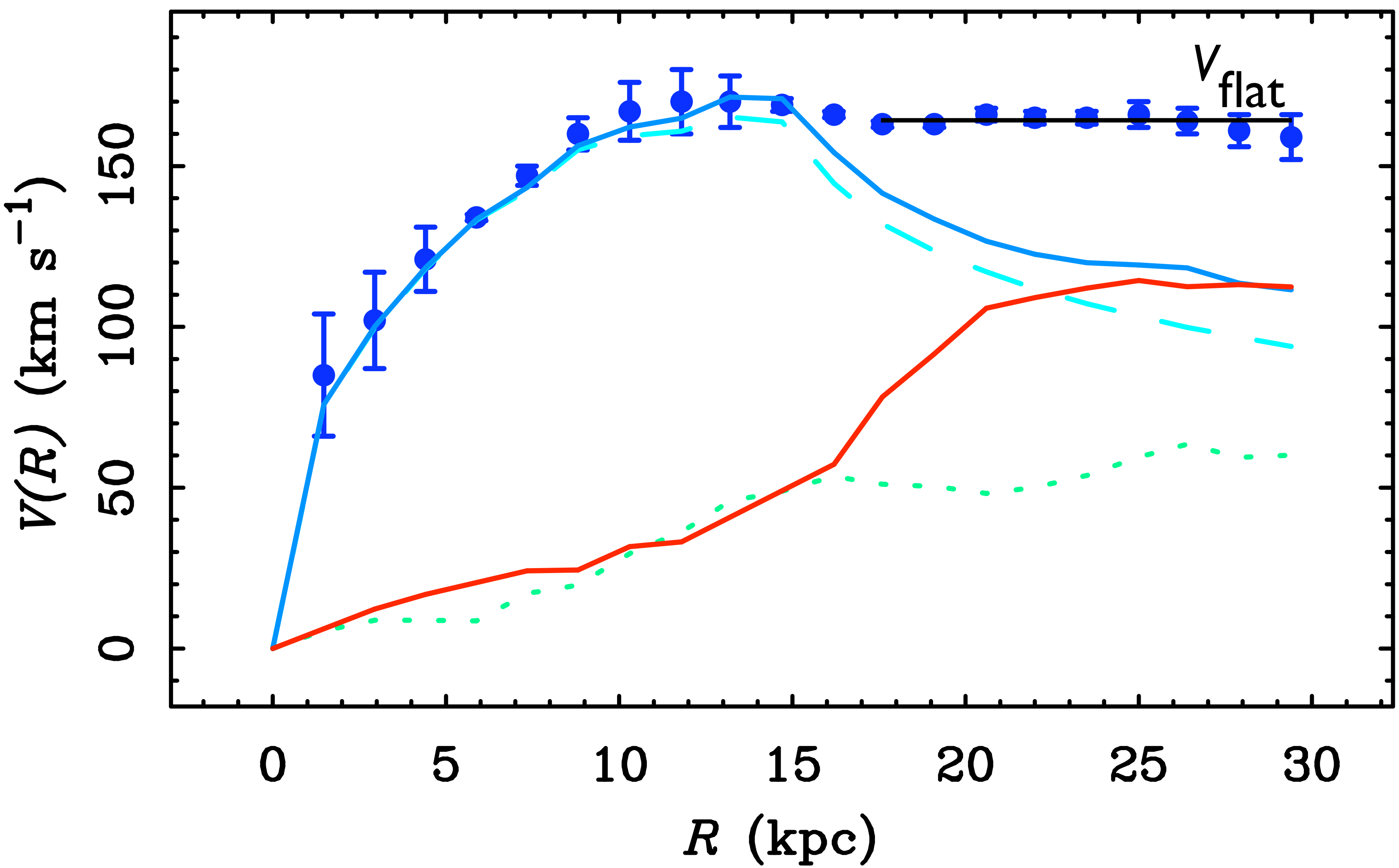
KITP, UCSB, 5 October 2006

The Balance of Dark and Luminous Mass in Rotating Galaxies

Stacy McGaugh
University of Maryland


NGC 6946: $\mathcal{M}_*/L_B$ = 1.1 $\mathcal{M}_\odot/L_\odot$
$V(R)$ (km s^{-1})
0
50
100
150
0
5
10
15
20
25
30
R (kpc)

NGC 6946: $\mathcal{M}_*/L_B = 1.1\ \mathcal{M}_\odot/L_\odot$



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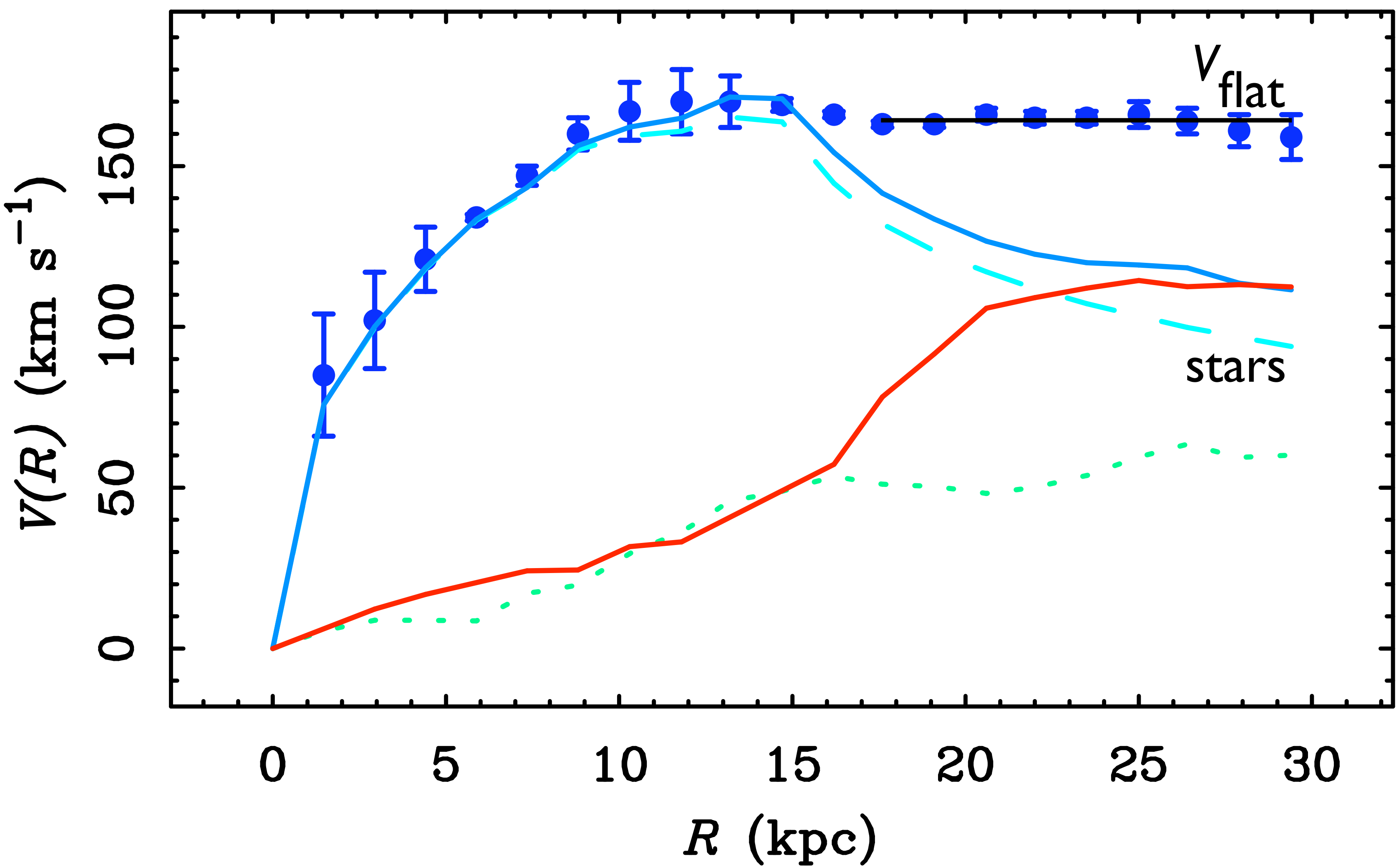

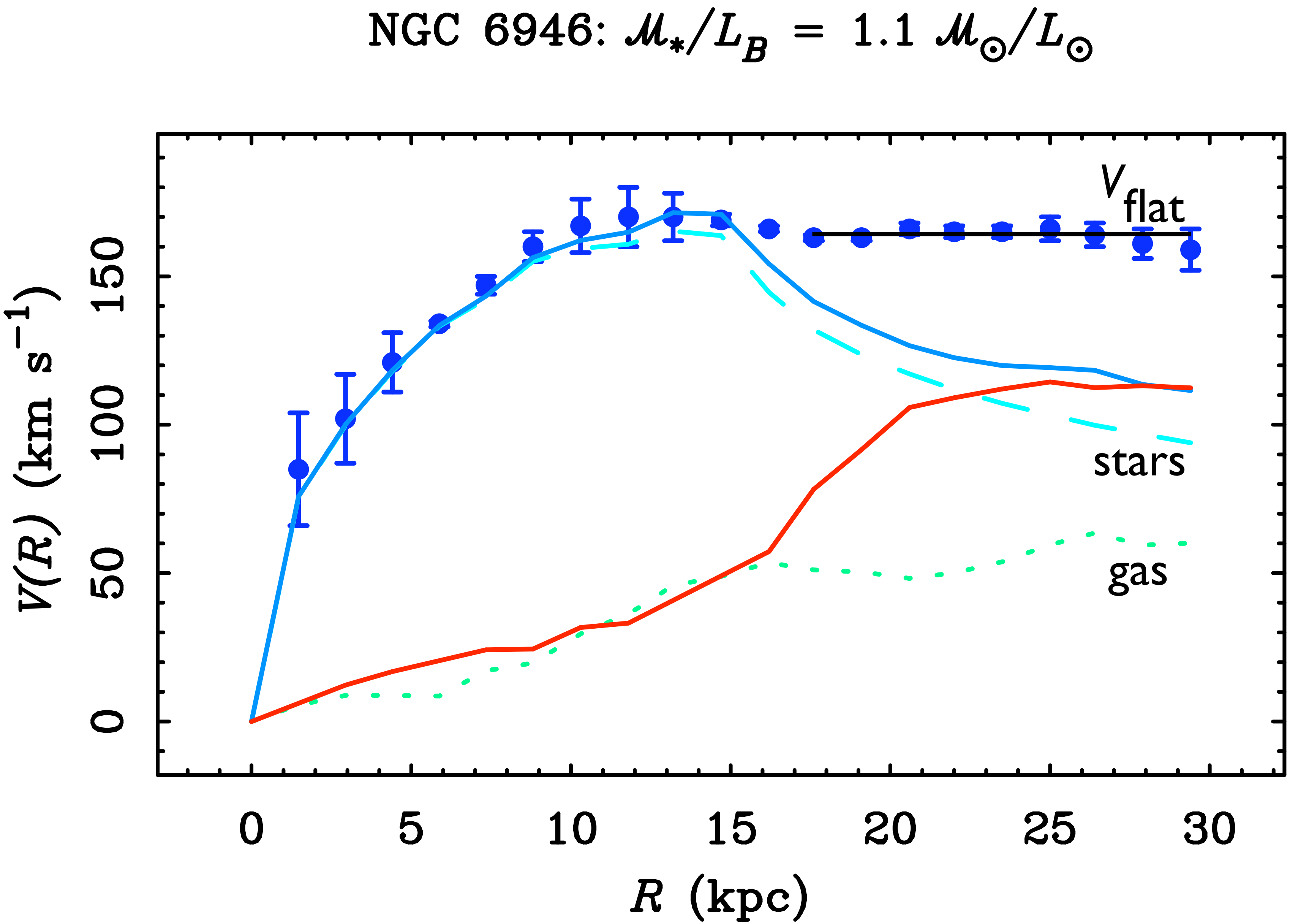

NGC 6946: $\mathcal{M}_*/L_B = 1.1\ \mathcal{M}_\odot/L_\odot$
V_{flat}
stars
gas
$V(R)$ (km s^{-1})
0
50
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5
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25
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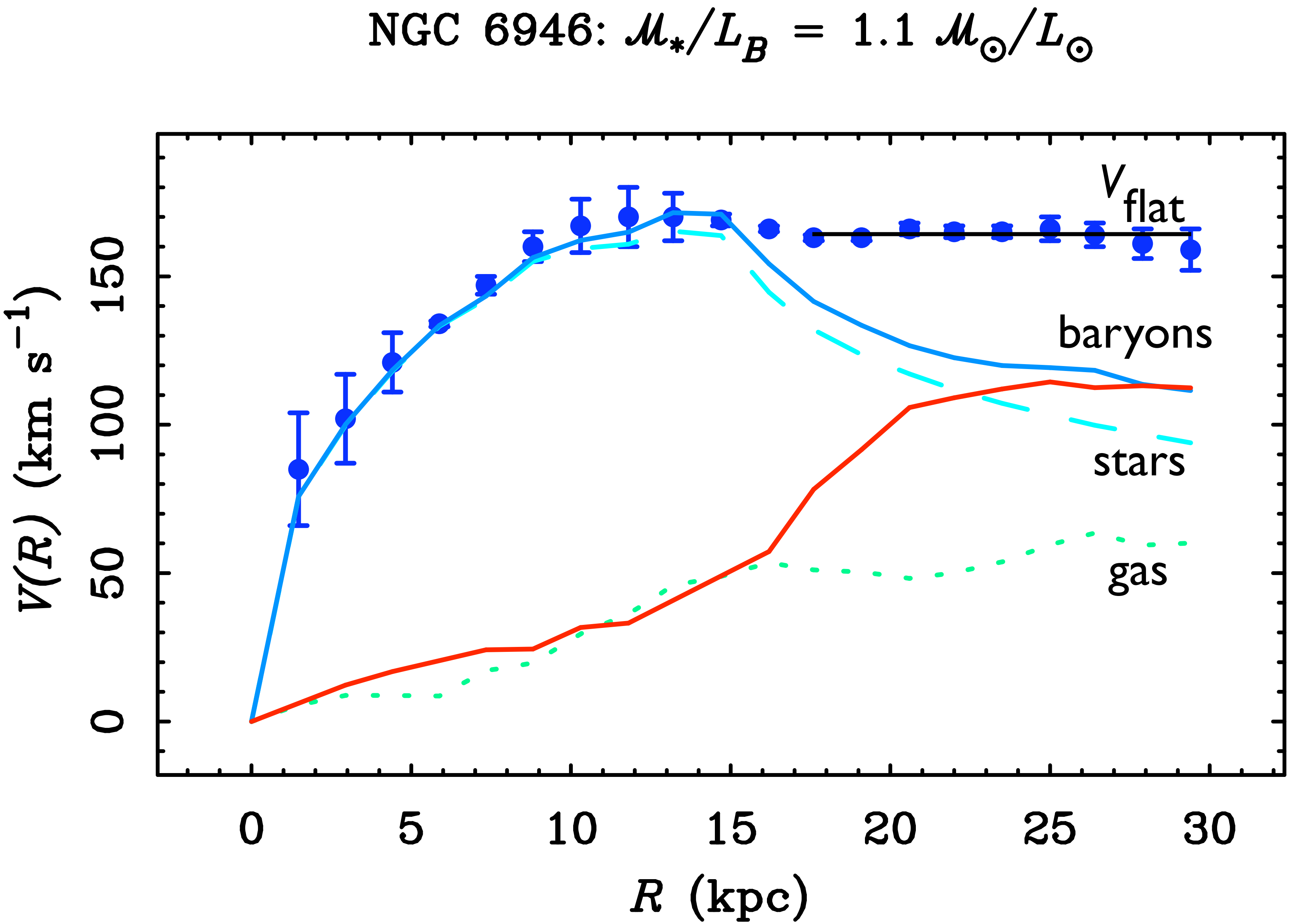
R (kpc)



NGC 6946: $\mathcal{M}_*/L_B = 1.1\ \mathcal{M}_\odot/L_\odot$
V_{flat}
baryons
stars
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$V(R)$ (km s^{-1})
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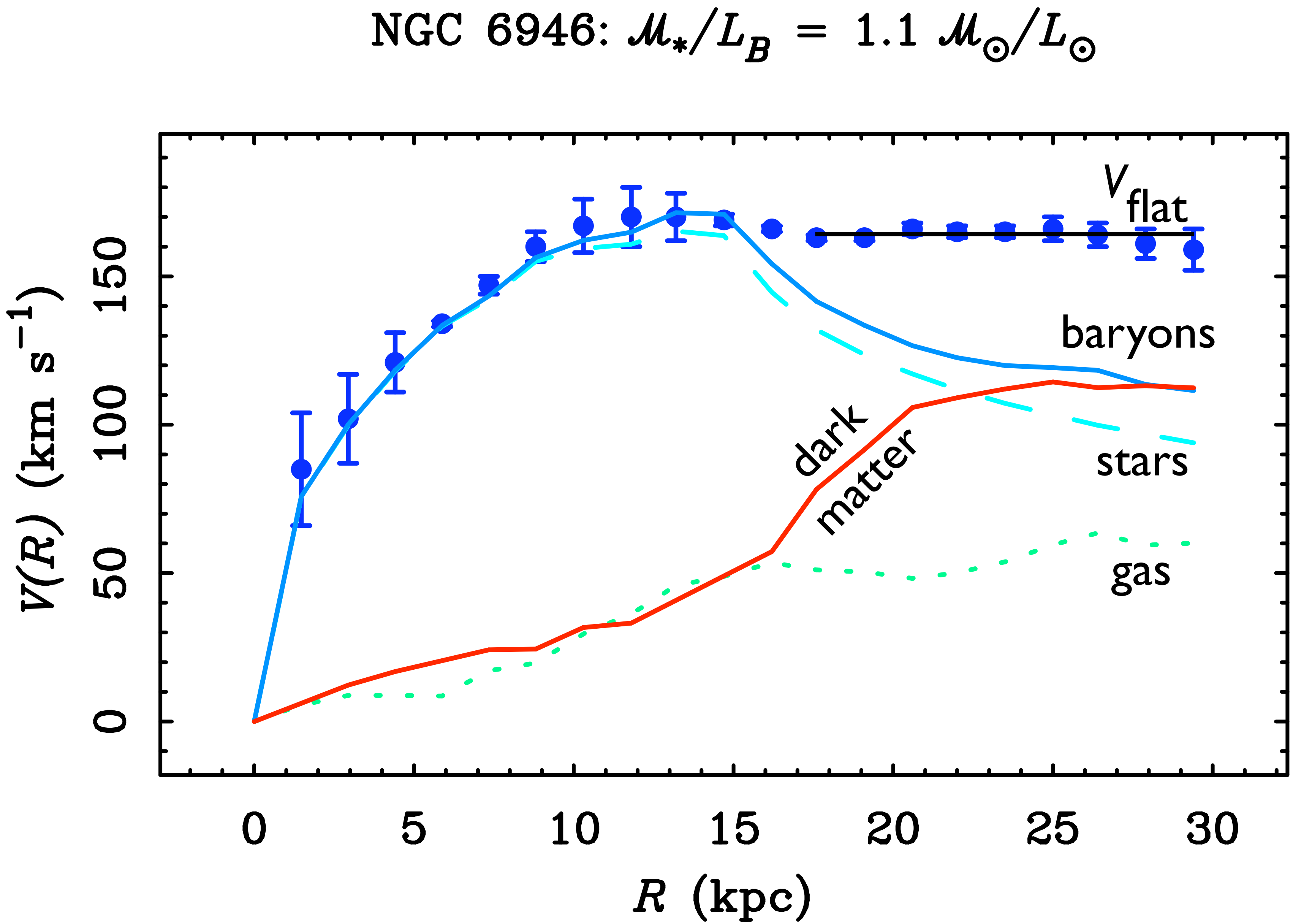

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V_{flat}
baryons
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matter
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50
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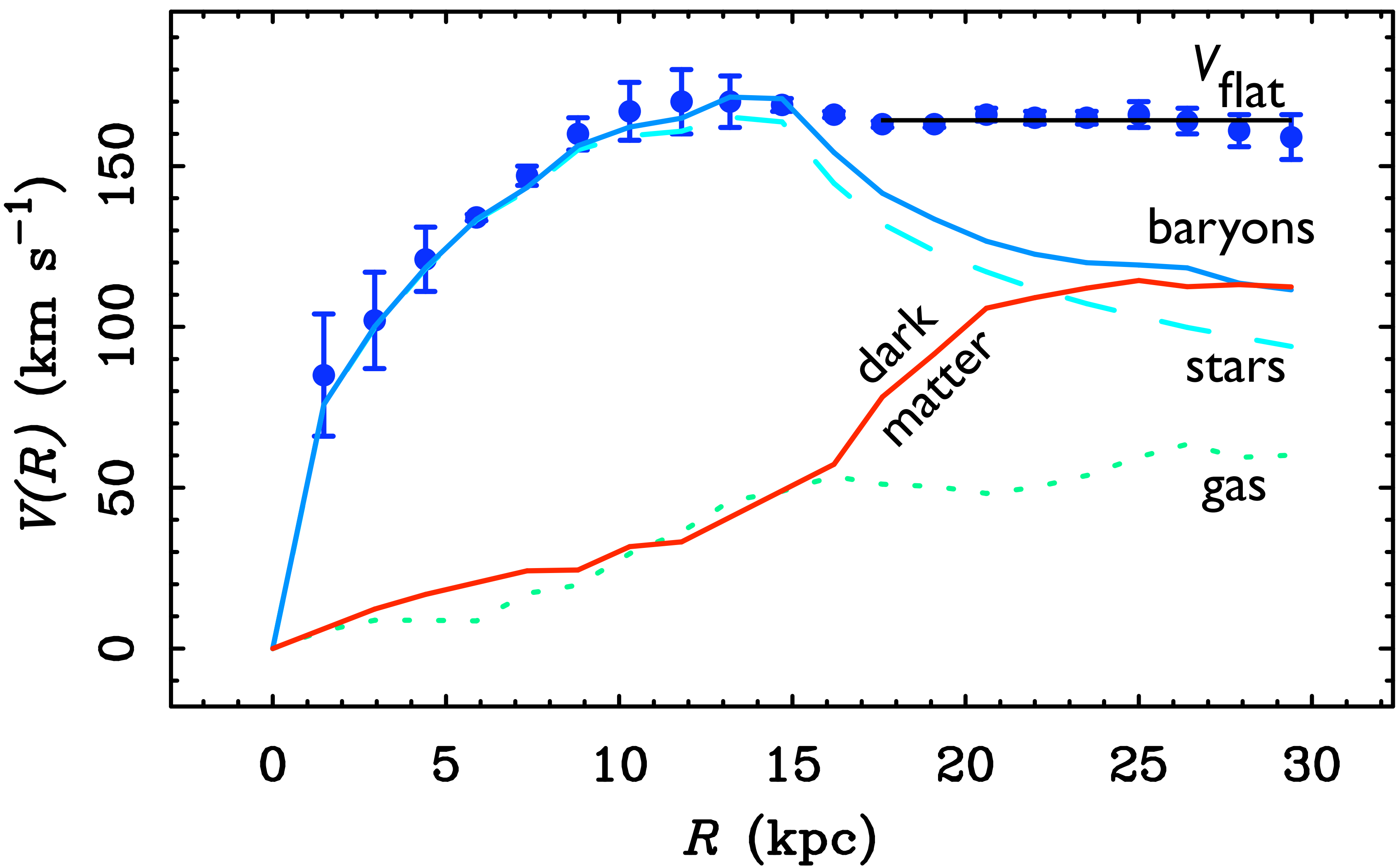


sum of DM + baryons conspire to give isothermal potential interpretations differ...

Primary Sample

74 galaxies with detailed mass models
60 have high precision velocity data $(\sigma_V/V < 0.05)$
All have extended rotation curves from 21 cm velocity fields
Galaxies span all disk Hubble Types Sa to Irr (mostly later types)
Span wide range of physical parameters:

Rotation velocity: $54 \leq V_f < 300\ \mathrm{km\,s^{-1}}$

Baryonic Mass: $3 \times 10^8 < M_d < 3 \times 10^{11}\ M_\odot$

Disk Scale Length: $0.5 \leq R_d \leq 13\ \mathrm{kpc}$

Central Surface Brightness: $19.6 \leq \mu_0 \leq 24.2\ B\ \mathrm{mag\,arcsec^{-2}}$

Data have many sources:

compilations - Sanders (1996); McGaugh & de Blok (1998); Sanders & McGaugh (2002); McGaugh (2005, 2006)

original sources -

Begeman (1987)
Broeils (1992)
de Blok (1997)
Verheijen (1997)

Jobin & Carignan (1990)
Begeman, Broeils, & Sanders (1991)
de Blok, McGaugh, & van der Hulst (1996)
Sanders & Verheijen (1998)
McGaugh, de Blok, & Rubin (2001)
Verheijen (2001)

and many others...

Supplemented by Extreme Dwarf Sample

8 galaxies with resolved, extended HI rotation curves
Very low mass & velocity:

Rotation velocity: $17 \leq V_f \leq 51\,\mathrm{km\,s^{-1}}$

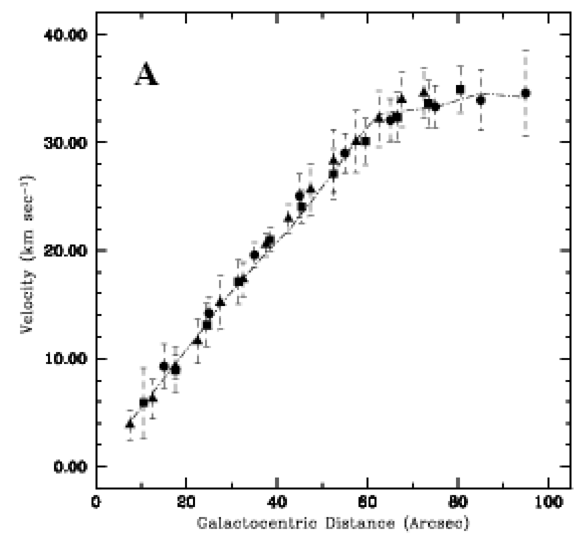
Baryonic Mass: $4 \times 10^6 < M_d < 8 \times 10^8\ M_\odot$

TABLE 5
EXTREME DWARF GALAXY DATA

Galaxy	V_f (km s^{-1})	$\mathcal{M}_\star$ ($10^6\ \mathcal{M}_\odot$)	$\mathcal{M}_g$ ($10^6\ \mathcal{M}_\odot$)	References
ESO215–G?009	51^{+8}_{-9}	23	714	1
UGC 11583[a]	48^{+3}_{-4}	119	36	2, 3
NGC 3741	44^{+4}_{-2}	25	224	4
WLM	38^{+5}_{-5}	31	65	5
KK98 251	36^{+8}_{-4}	12	98	3
GR 8	25^{+5}_{-4}	5	14	6
Cam B	20^{+10}_{-13}	3.5	6.6	7
DDO 210	17^{+3}_{-5}	0.9	3.6	8

[a] UGC 11583 is KK98 250.

REFERENCES.—(1) Warren et al. 2004; (2) McGaugh et al. 2001; (3) Begum & Chengalur 2004a; (4) Begum et al. 2005; (5) Jackson et al. 2004; (6) Begum & Chengalur 2003; (7) Begum et al. 2003; (8) Begum & Chengalur 2004b.



(McGaugh 2005)

TF Relation

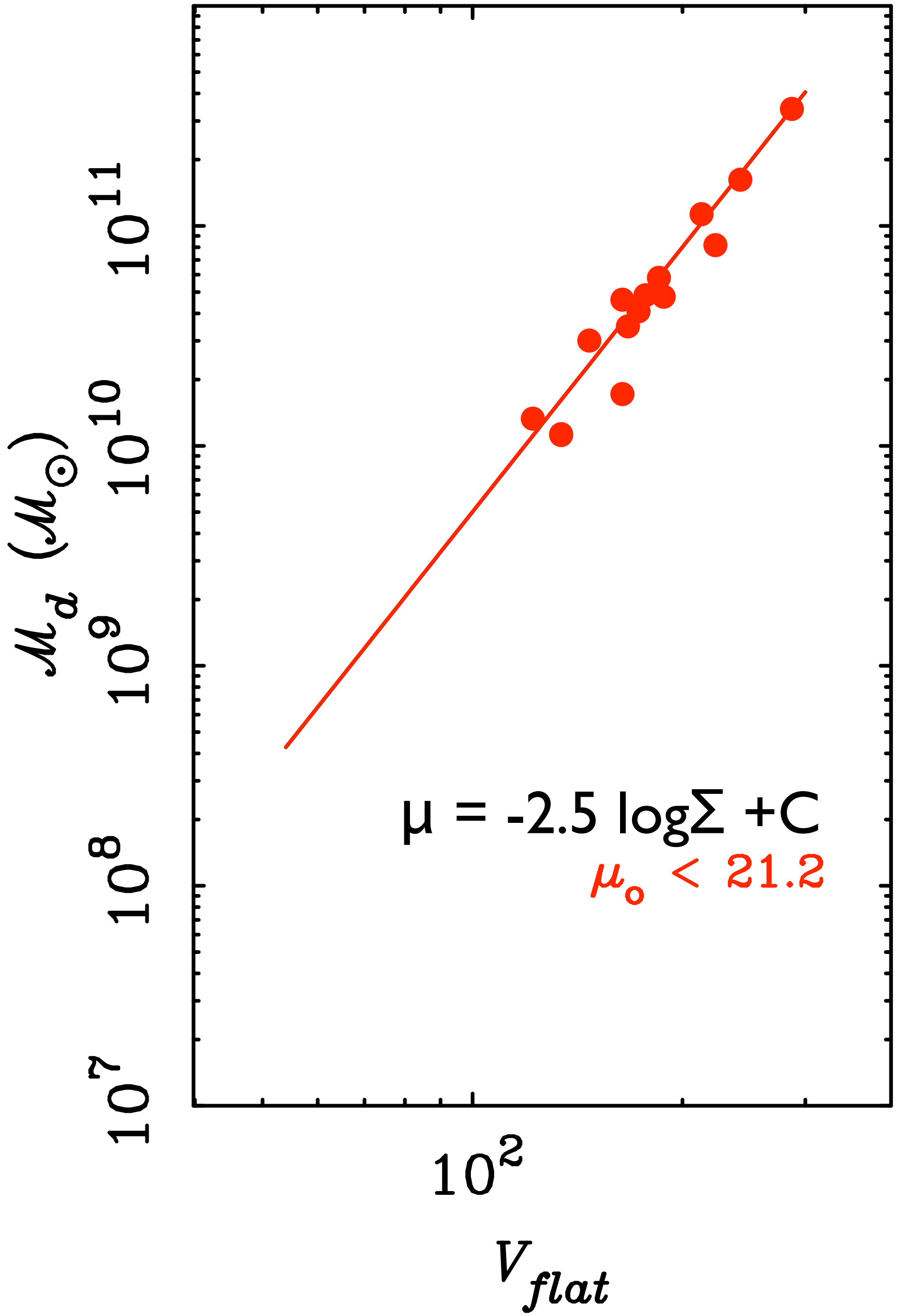
<u>Newton says</u>

$V^2 = GM/R.$

Equivalently,

$\Sigma = M/R^2$

$V^4 = G^2 M \Sigma$



<u>Tully Fisher residuals</u>

Zwaan et al. (1995)
Sprayberry et al. (1995)
Tully & Verheijen (1997)
McGaugh & de Blok (1998)
Courteau & Rix (1999)
McGaugh (2005)
Pizagno et al. (2005)
Dutton et al. (2006)
Gnedin et al. (2006)

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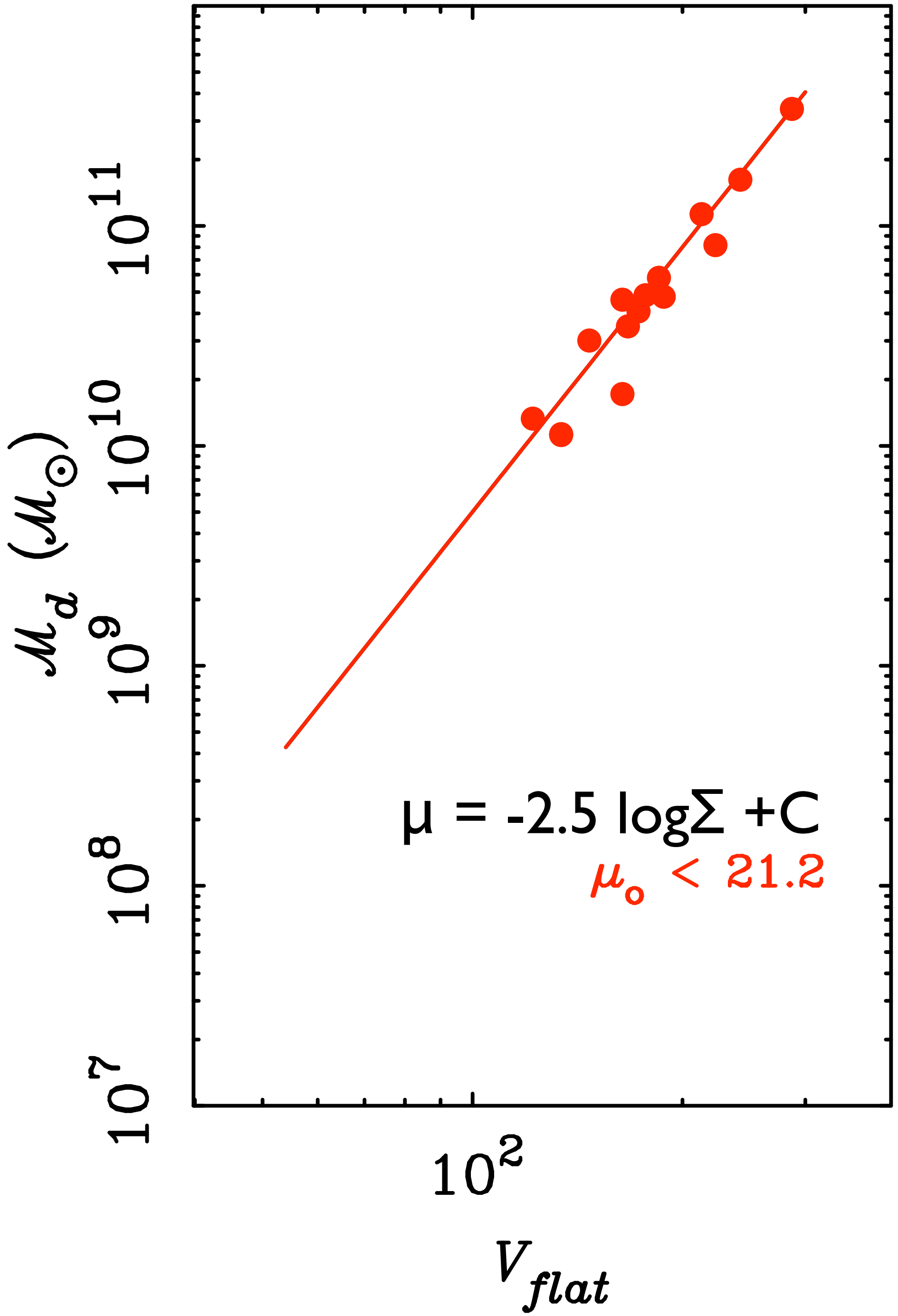

Therefore

Different Σ *should* mean different TF normalization.

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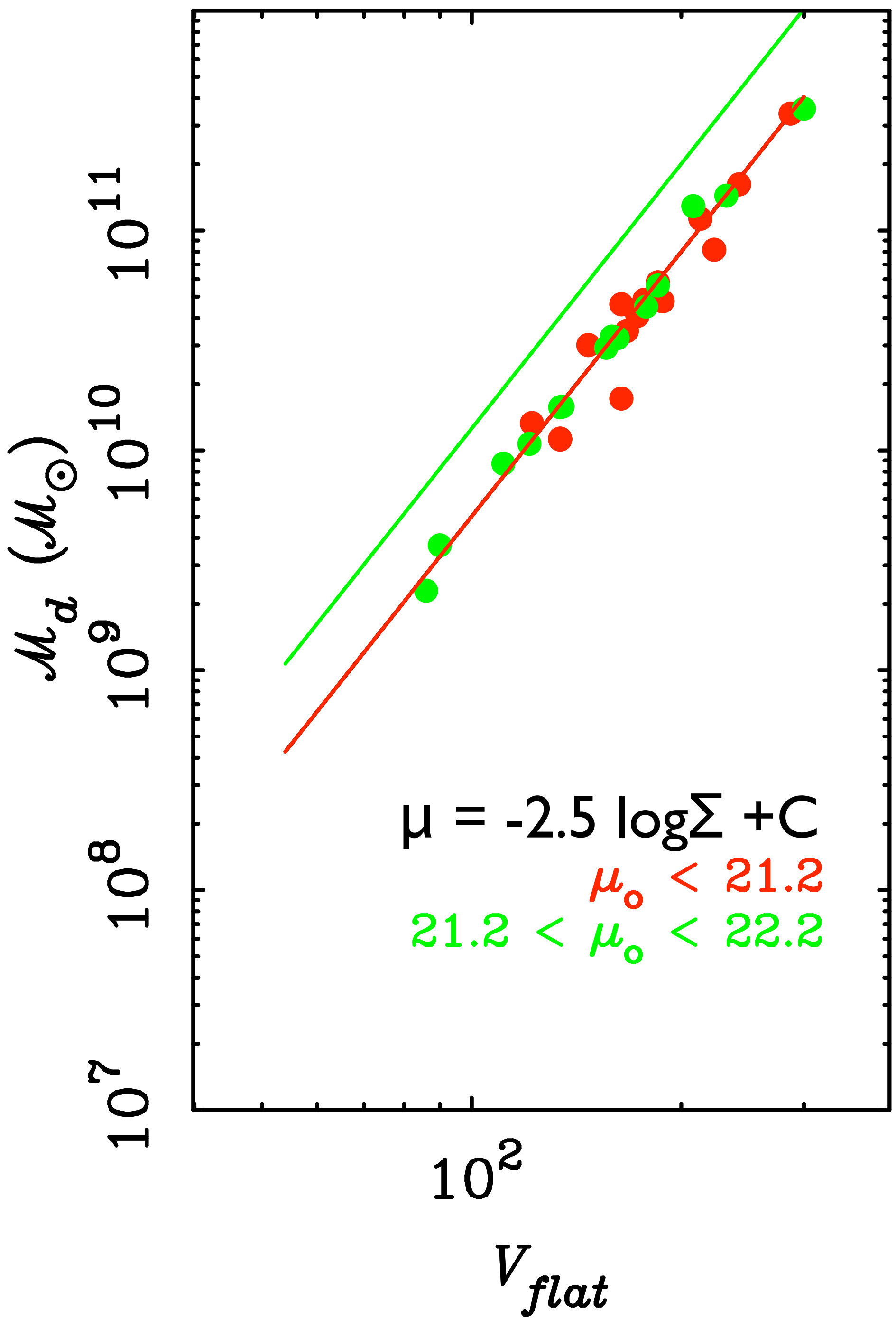

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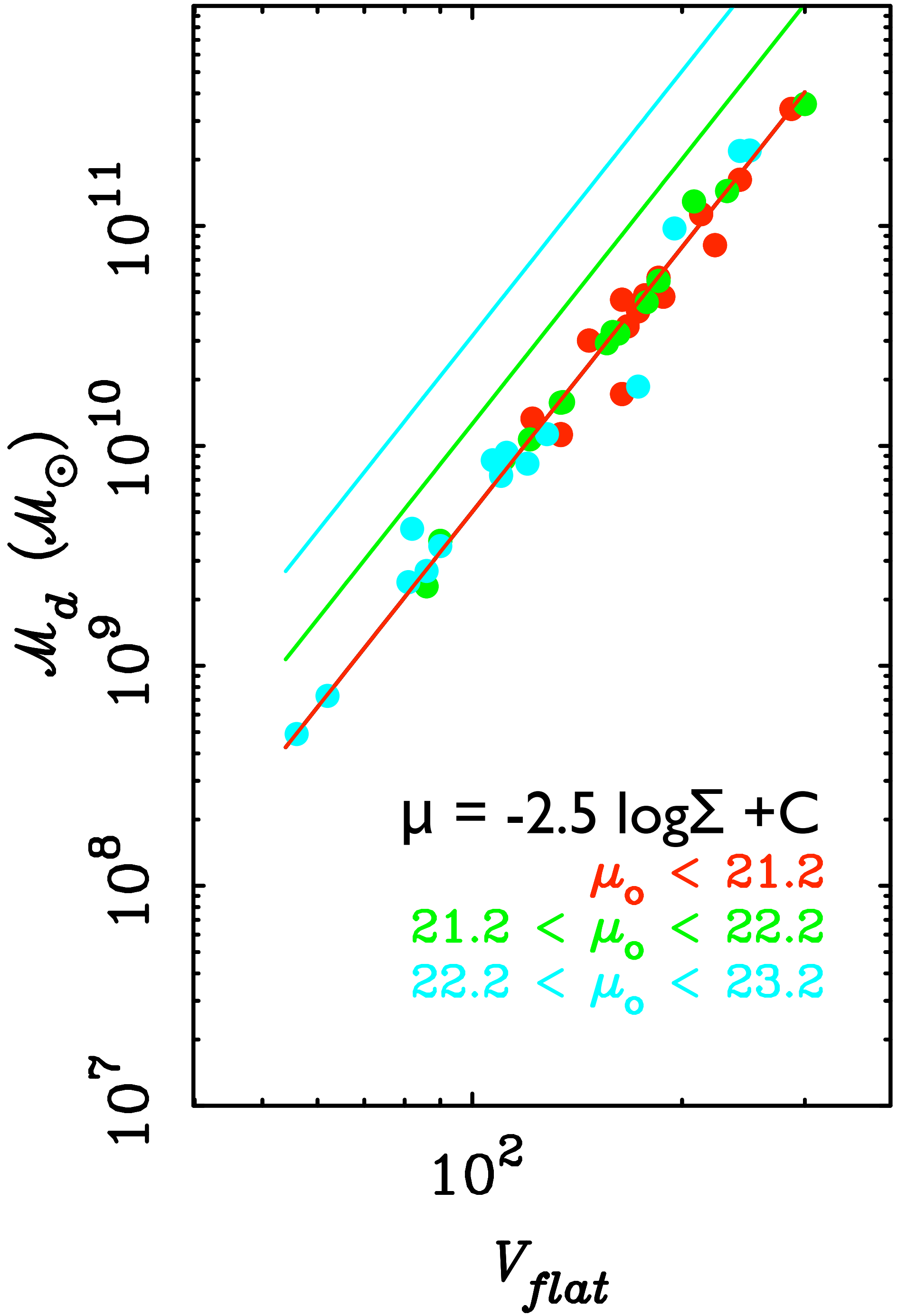

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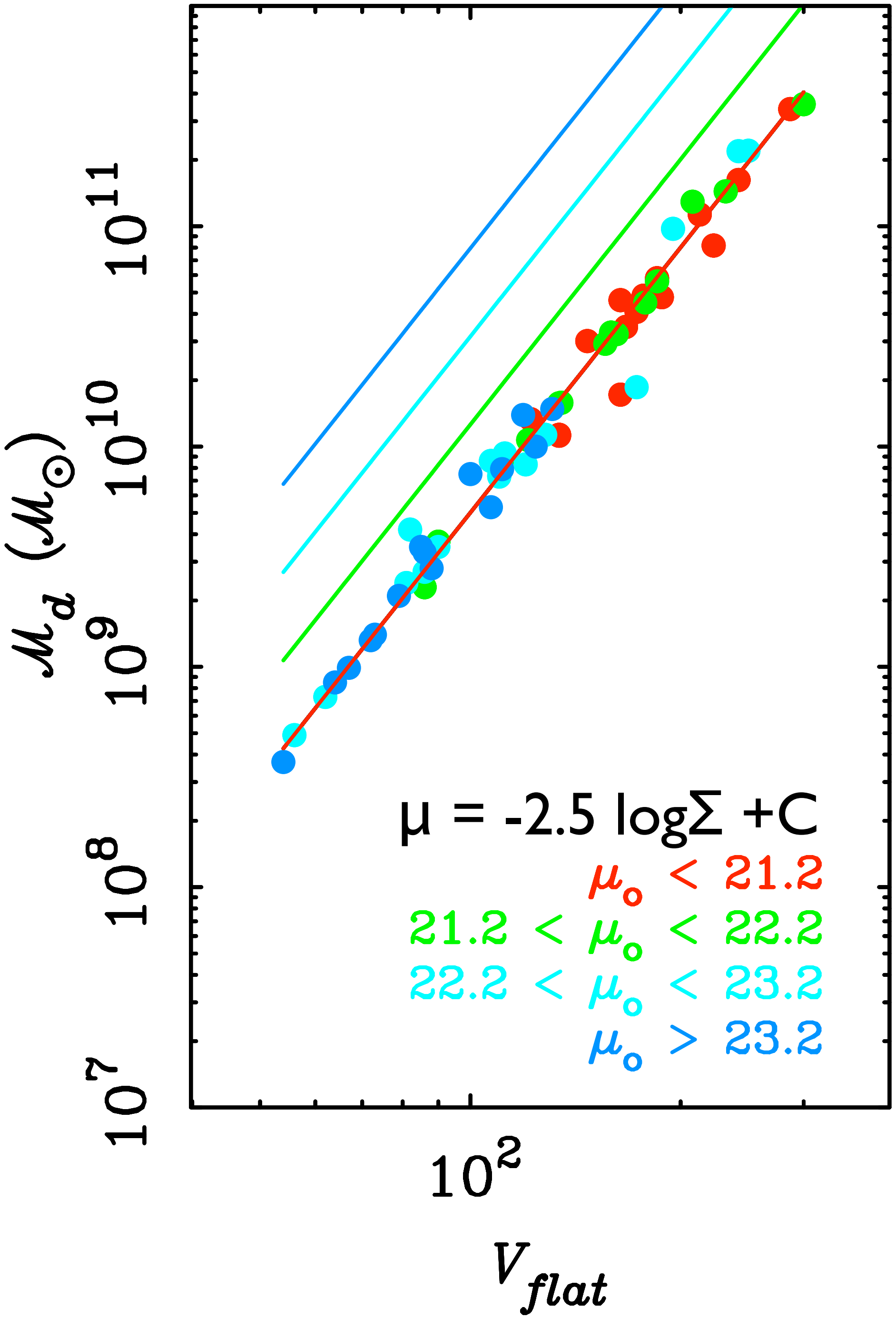

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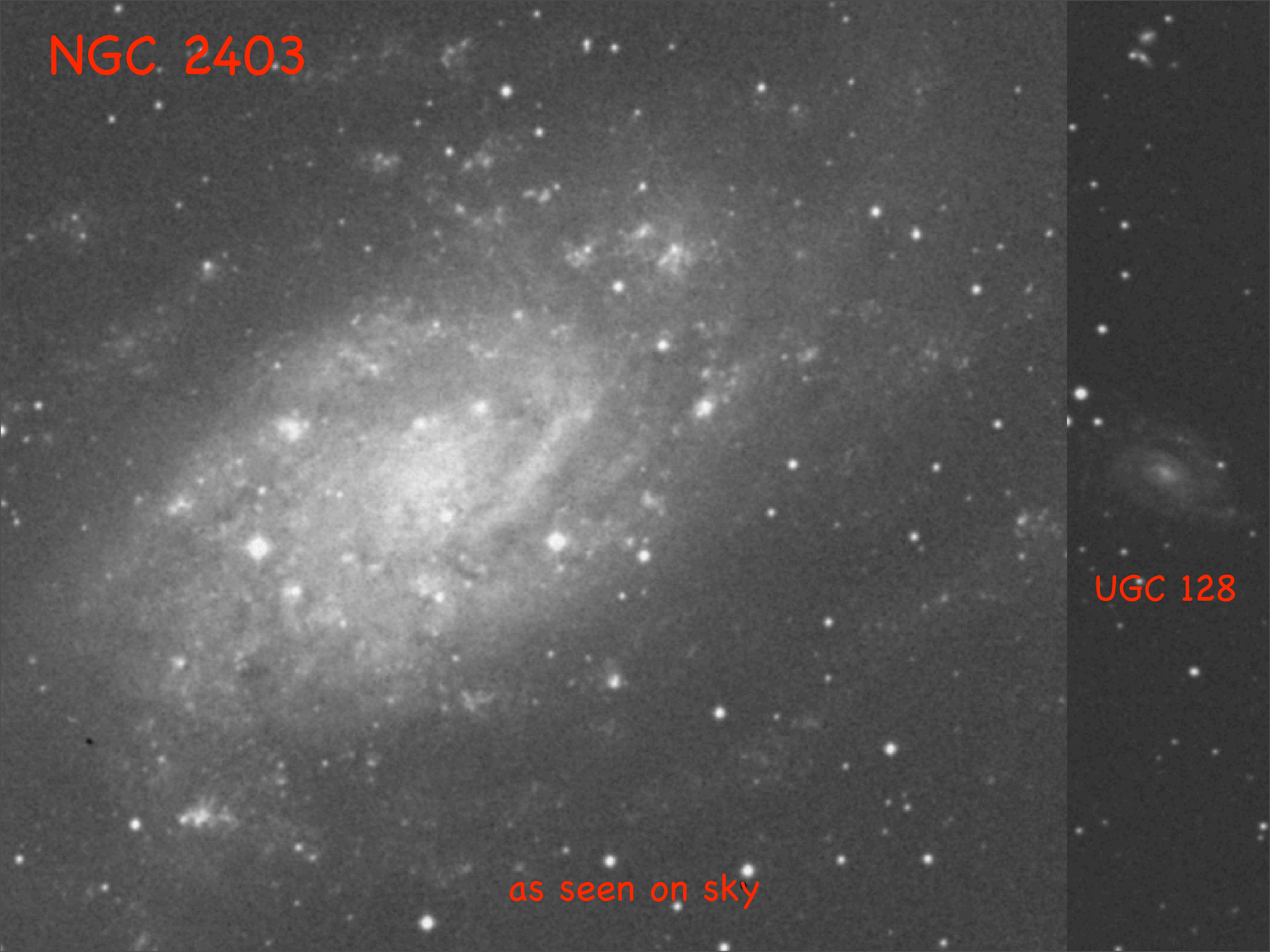
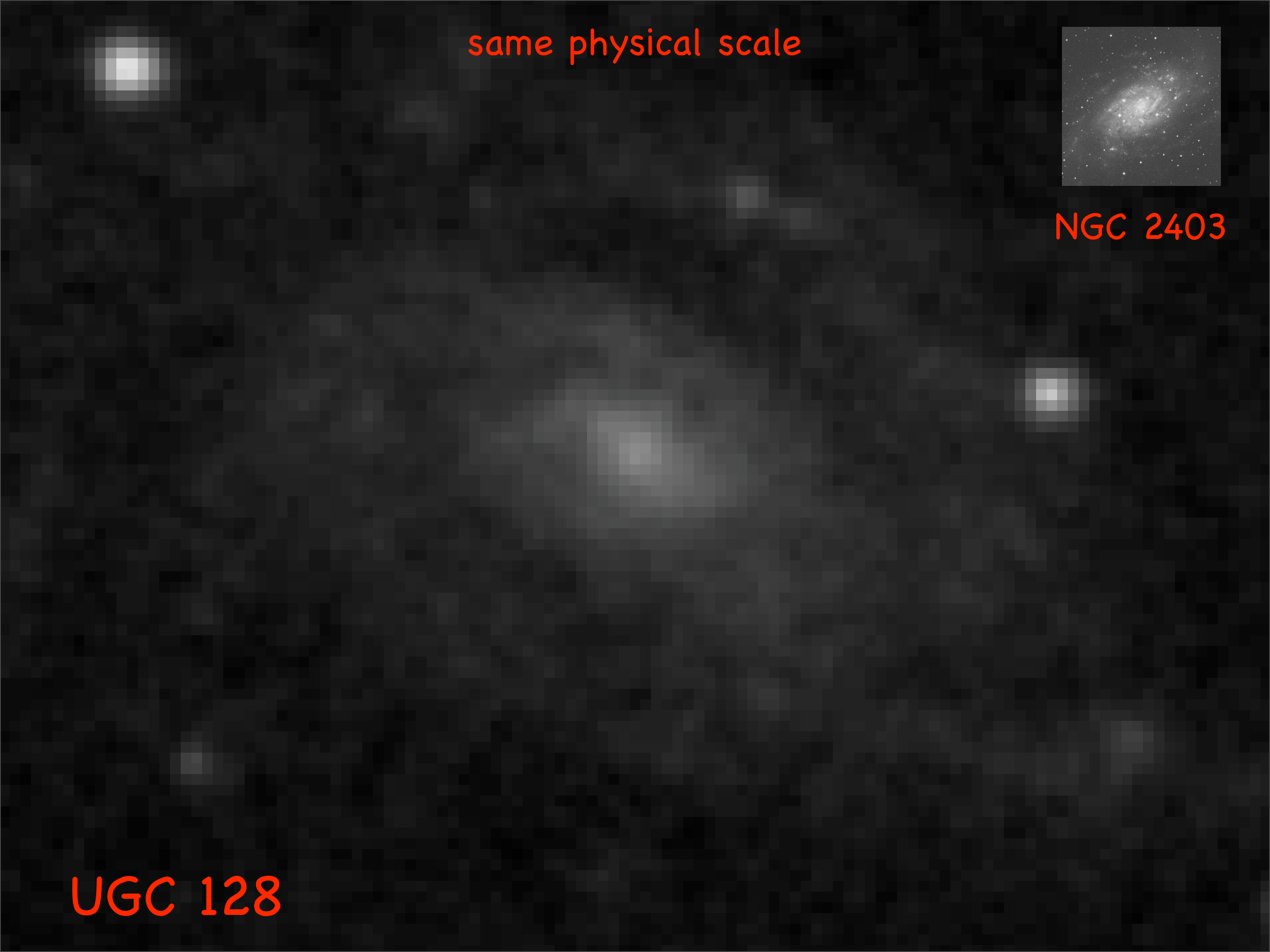
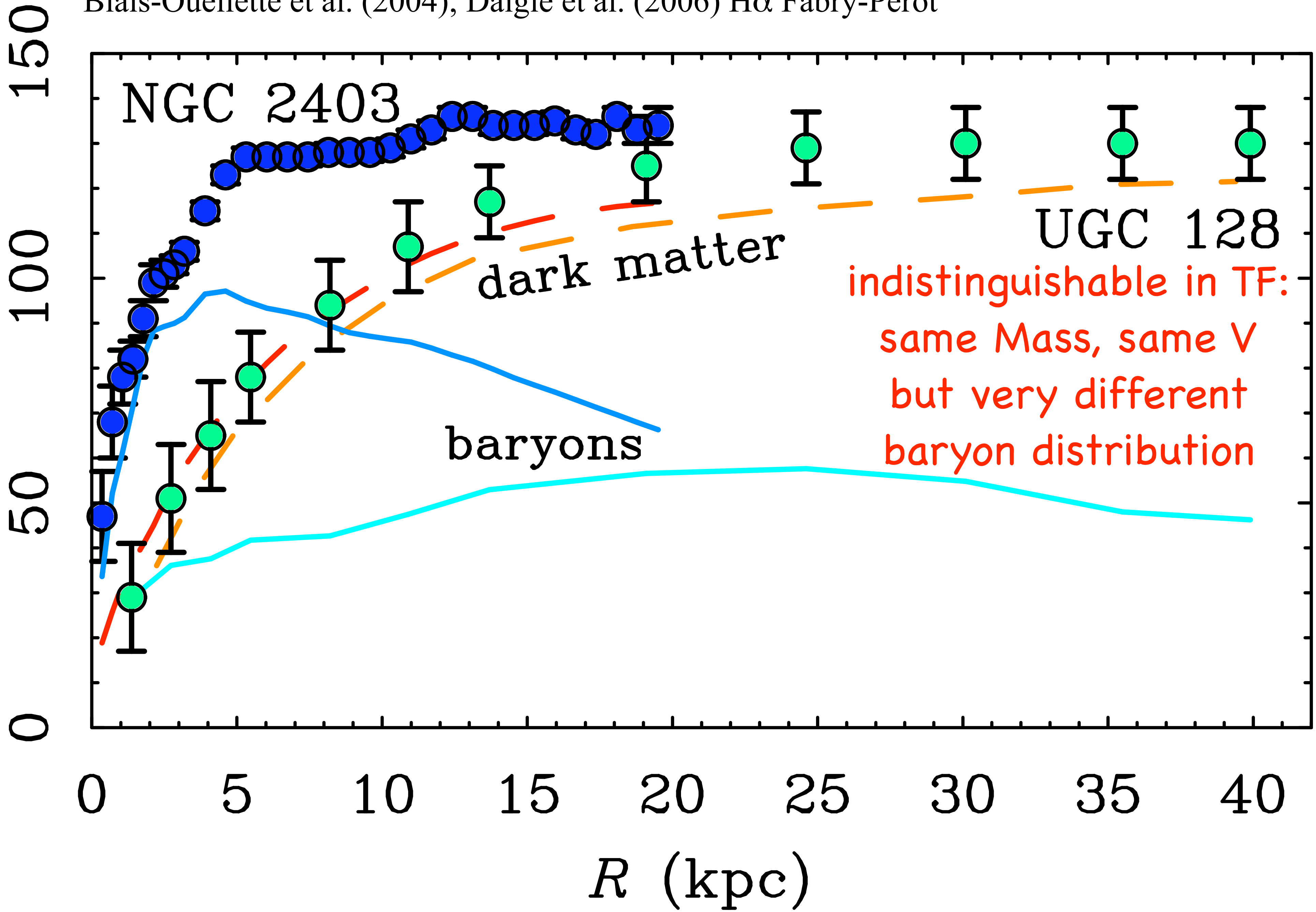

NGC 2403
UGC 128
as seen on sky


same physical scale
NGC 2403
UGC 128

NGC 2403: Begeman (1987); Fraternali et al. (2001) : HI data
Blais-Ouellette et al. (2004); Daigle et al. (2006) Hα Fabry-Perot



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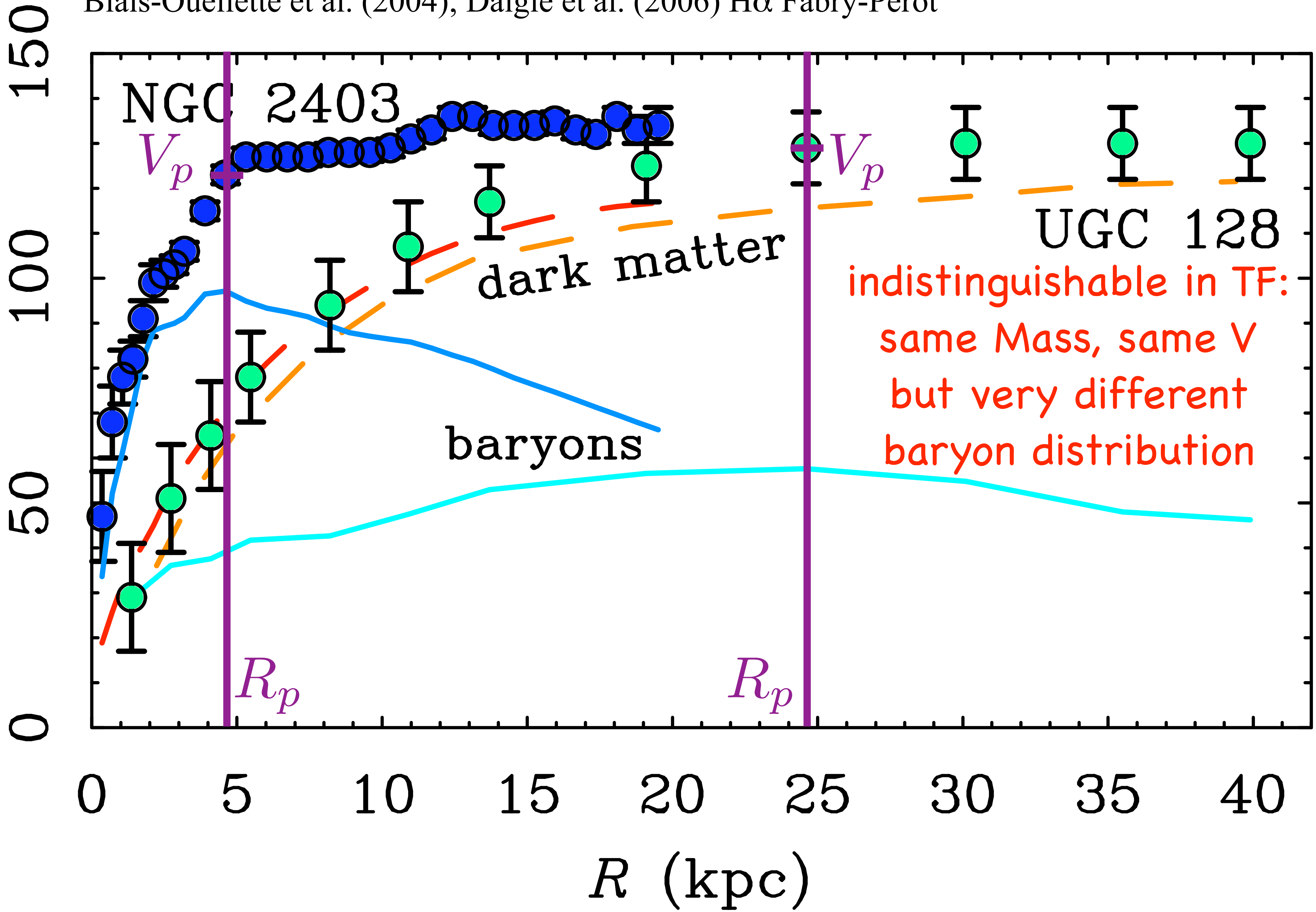

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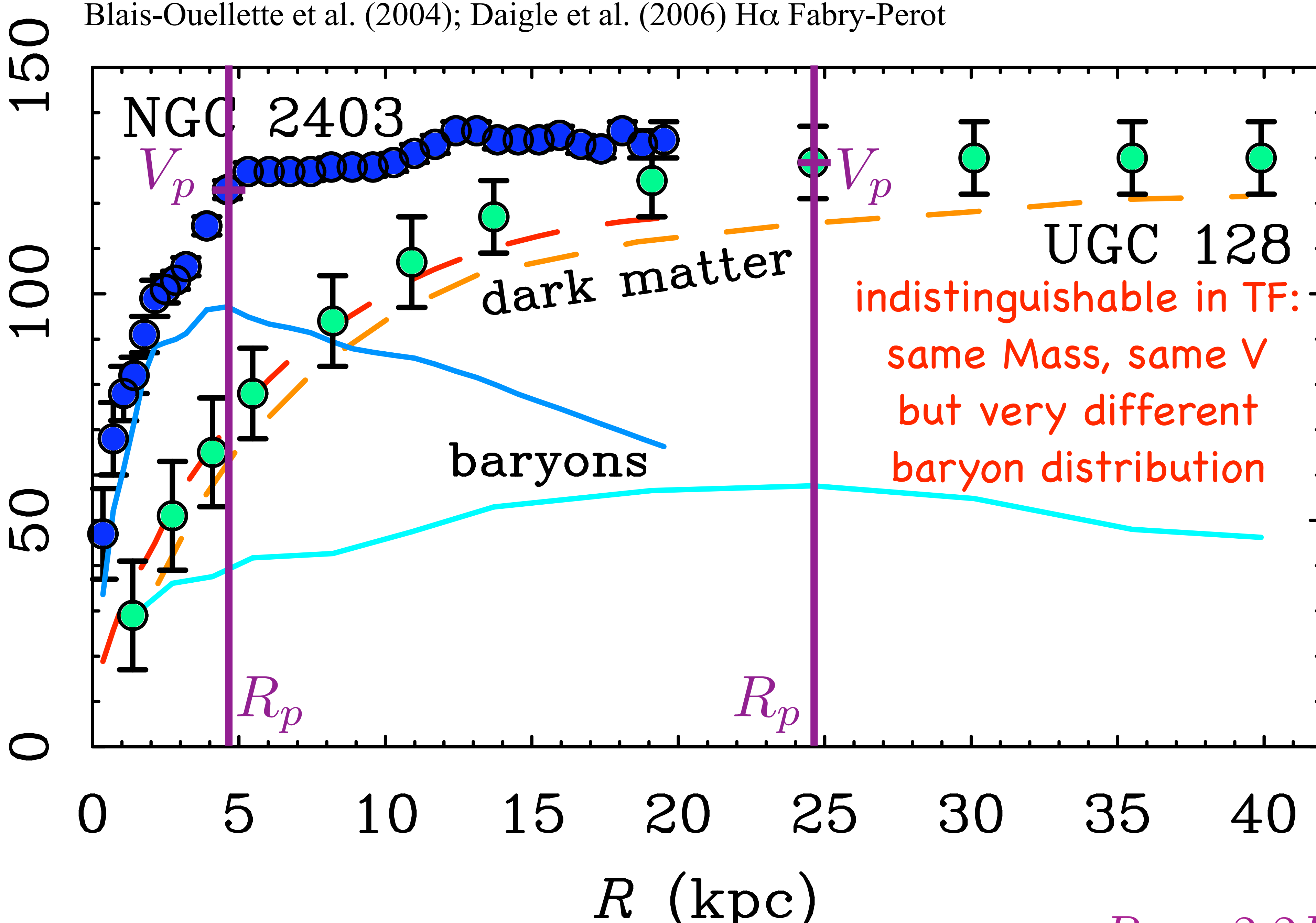

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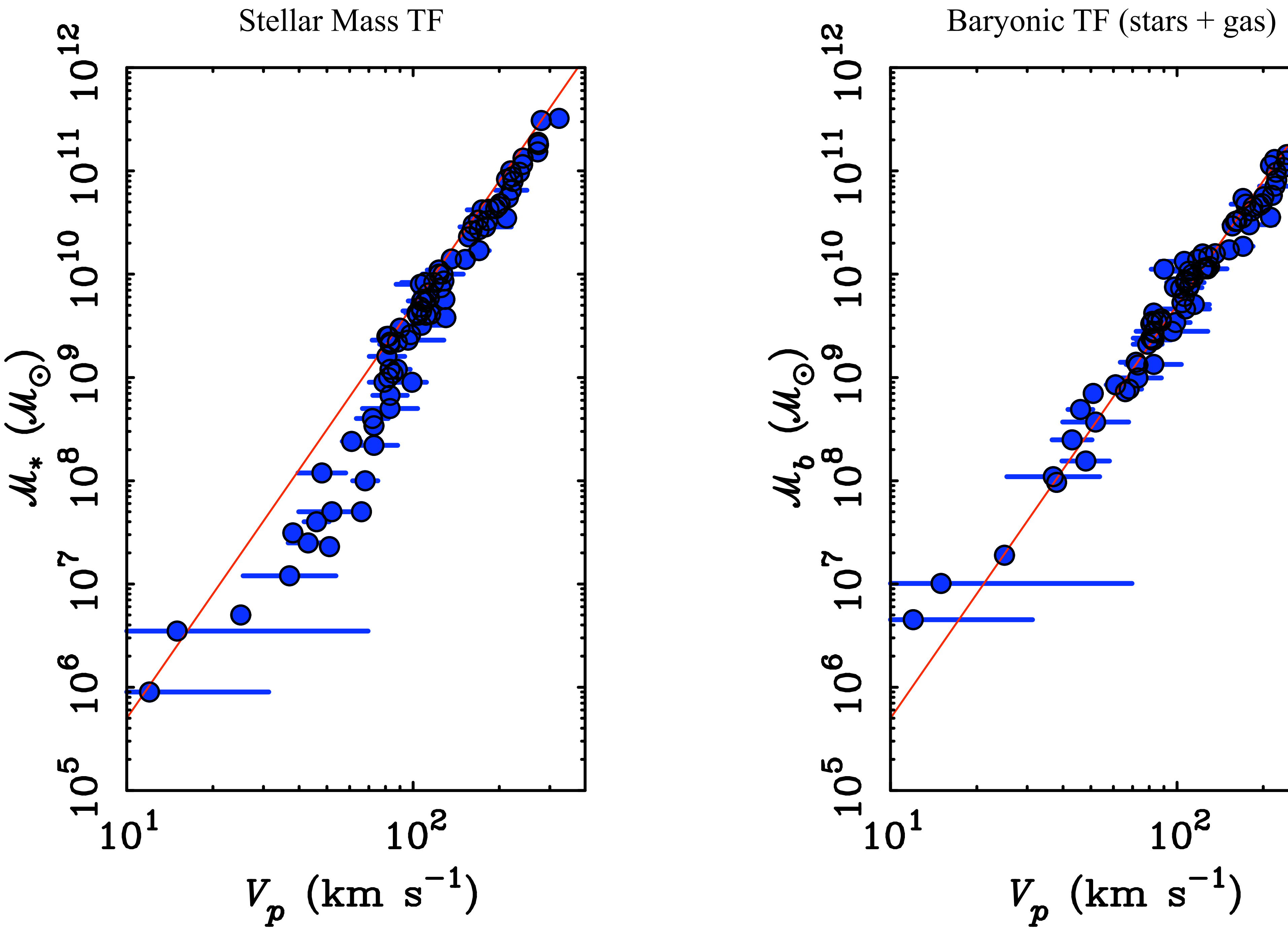
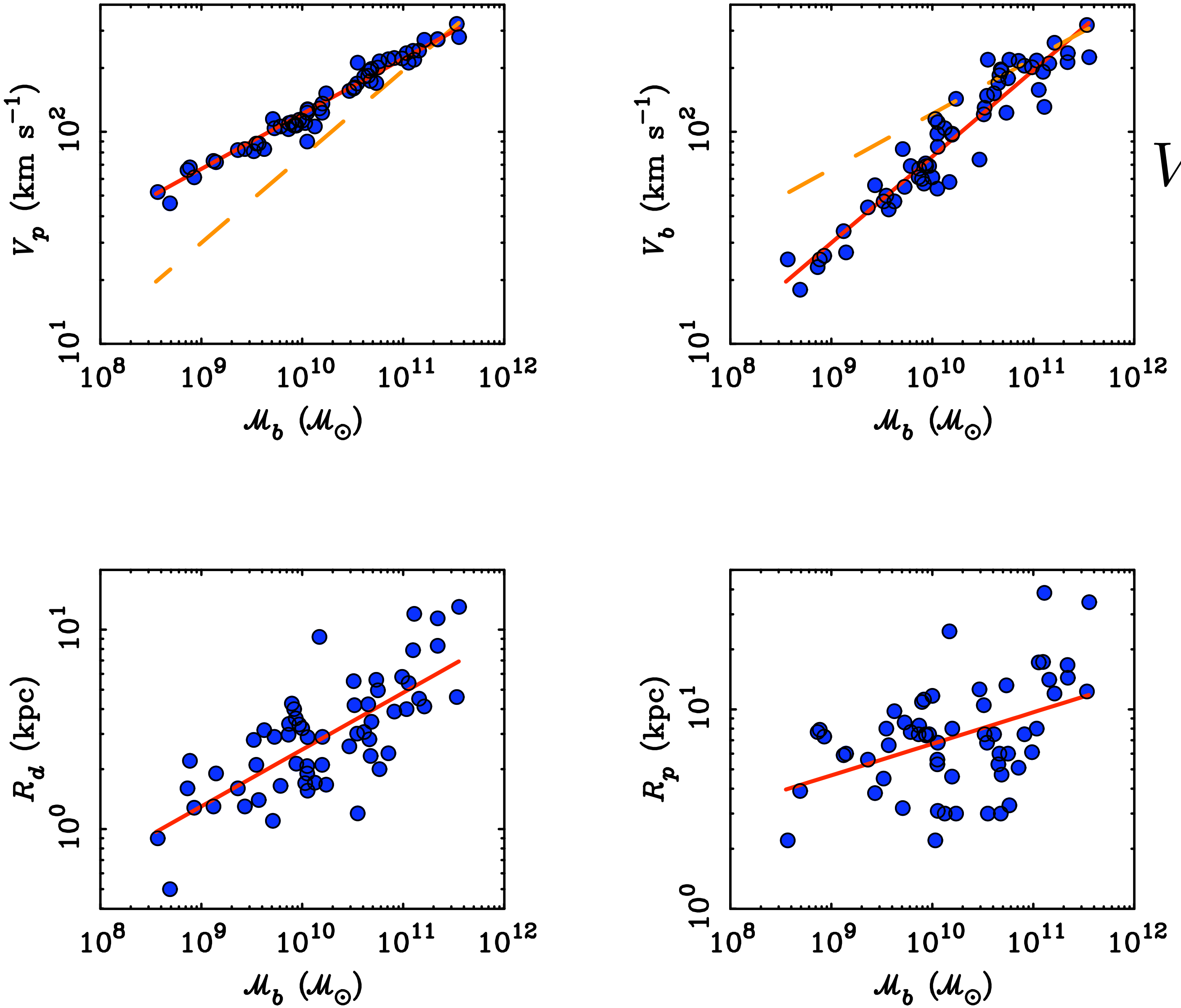
Kuzio de Naray et al. (in prep.) Hα IFU

$R_p \approx 2.2 R_d$



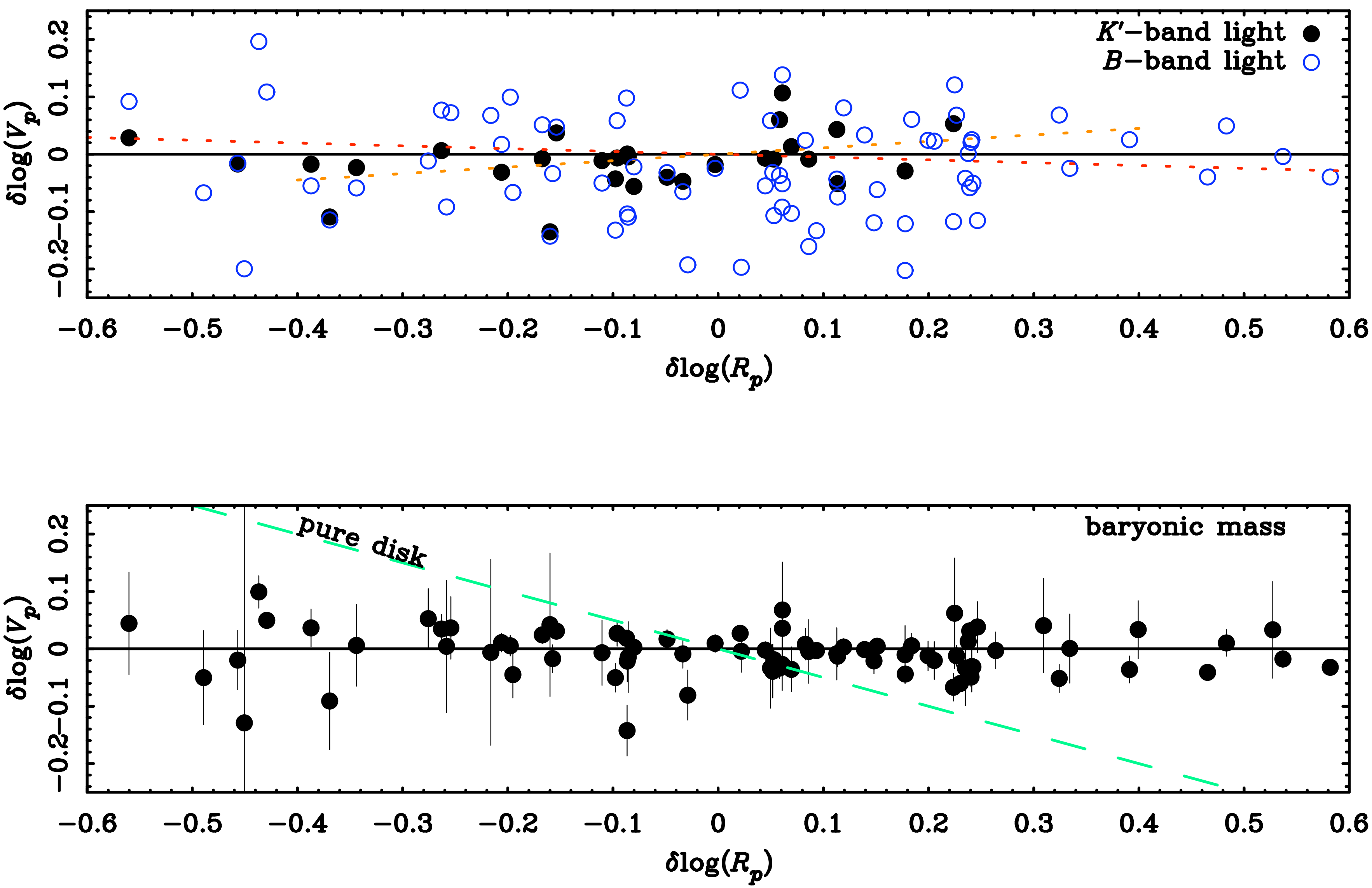
Stellar Mass TF
Baryonic TF (stars + gas)
$\mathcal{M}_*$ ($\mathcal{M}_\odot$)
$\mathcal{M}_b$ ($\mathcal{M}_\odot$)
10^5 10^6 10^7 10^8 10^9 10^{10} 10^{11} 10^{12}
10^1 10^2
V_p (km s^{-1})



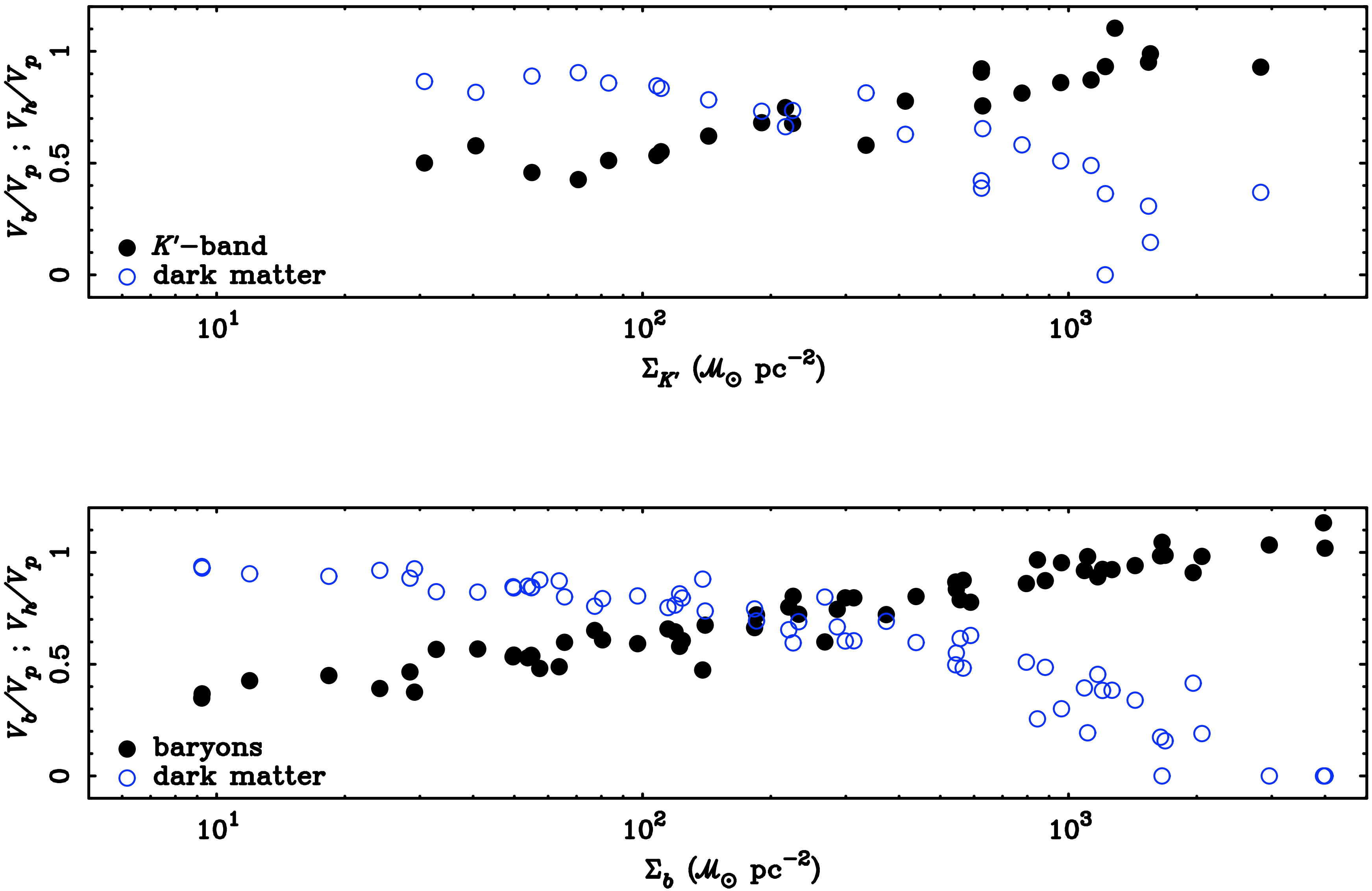
$$V_b^2|_{R_p} \propto \Sigma_b$$

Search for signature of disk in TF residuals:
velocity residuals as a fcn of scale length residuals

No Residuals from TF rel'n



Requires fine balance between dark & baryonic mass



McGaugh (2005) Phys. Rev. Lett. 95, 171302

Renzo’s Rule:

“For any feature in the luminosity profile there is a corresponding feature in the rotation curve and vice versa.”

(Sancisi 2004, IAU 220, 233)

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The distribution of mass is coupled to the distribution of light.

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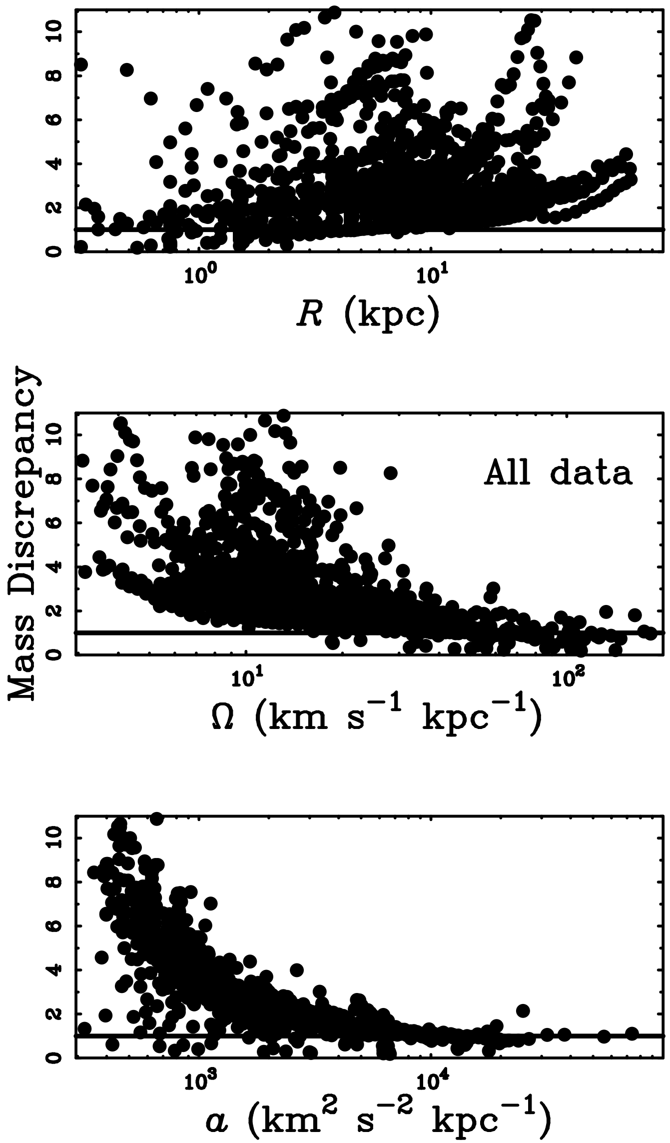
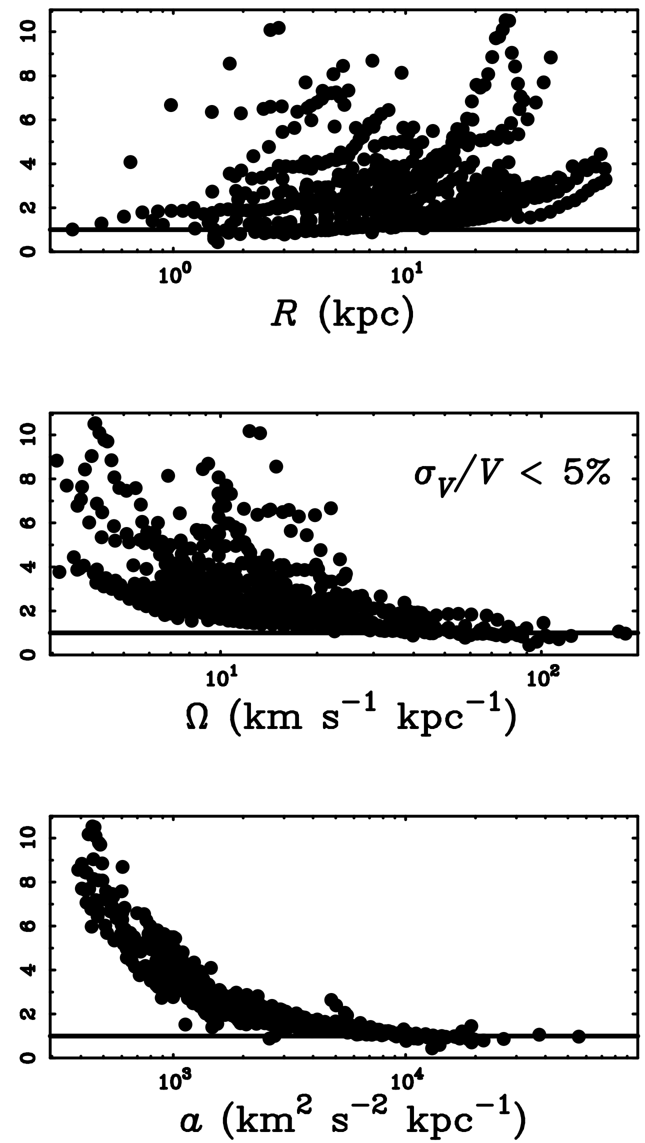
(Sancisi 2004, IAU 220, 233)

The distribution of mass is coupled to the distribution of light.

Quantify by defining the Mass Discrepancy:

$$\mathcal{D} = \frac{V^2}{V_b^2} = \frac{V^2}{\Upsilon_\star v_\star^2 + V_g^2}$$





radius

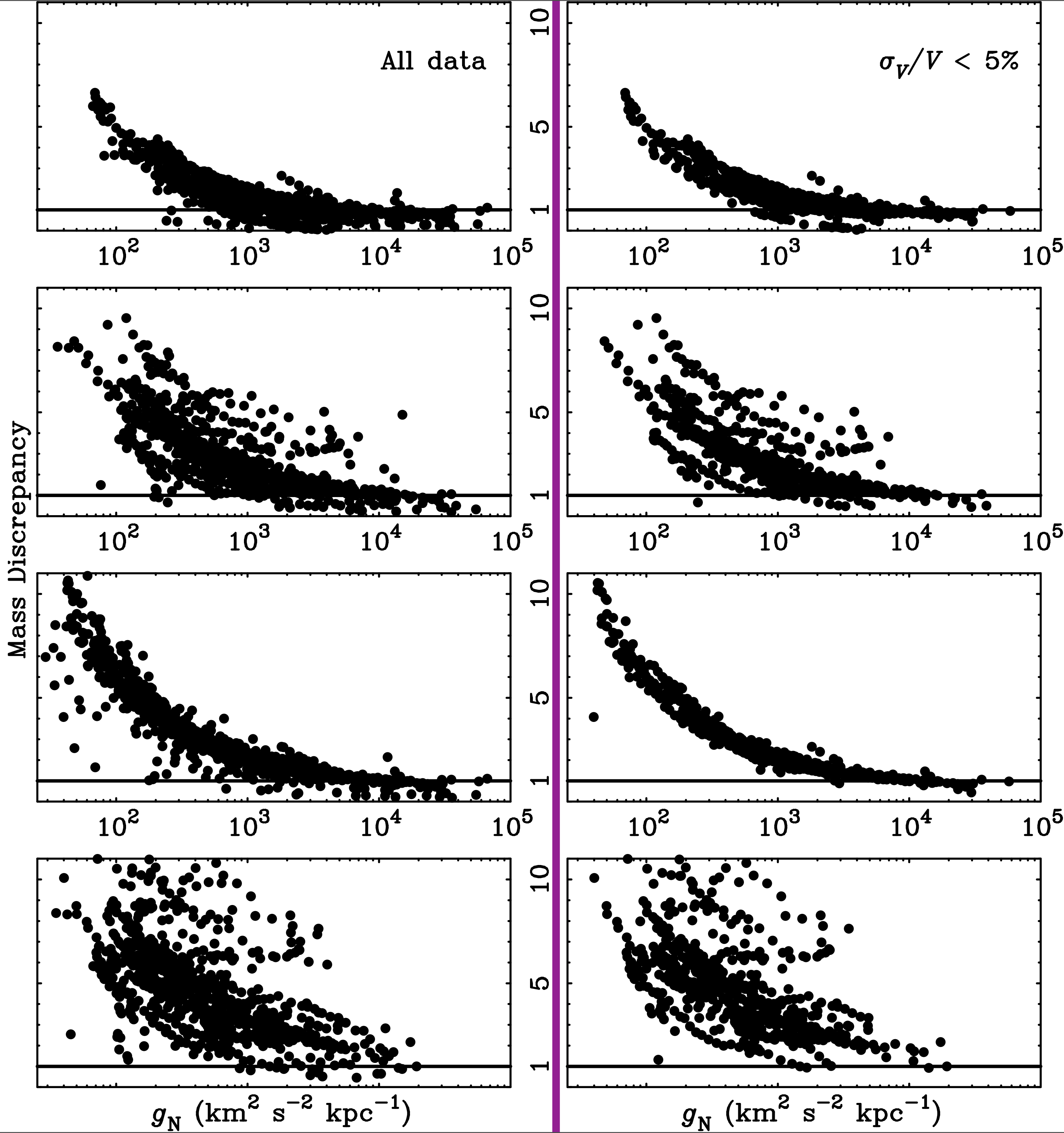
orbital frequency

acceleration

74 galaxies
> 1000 points
(all data)

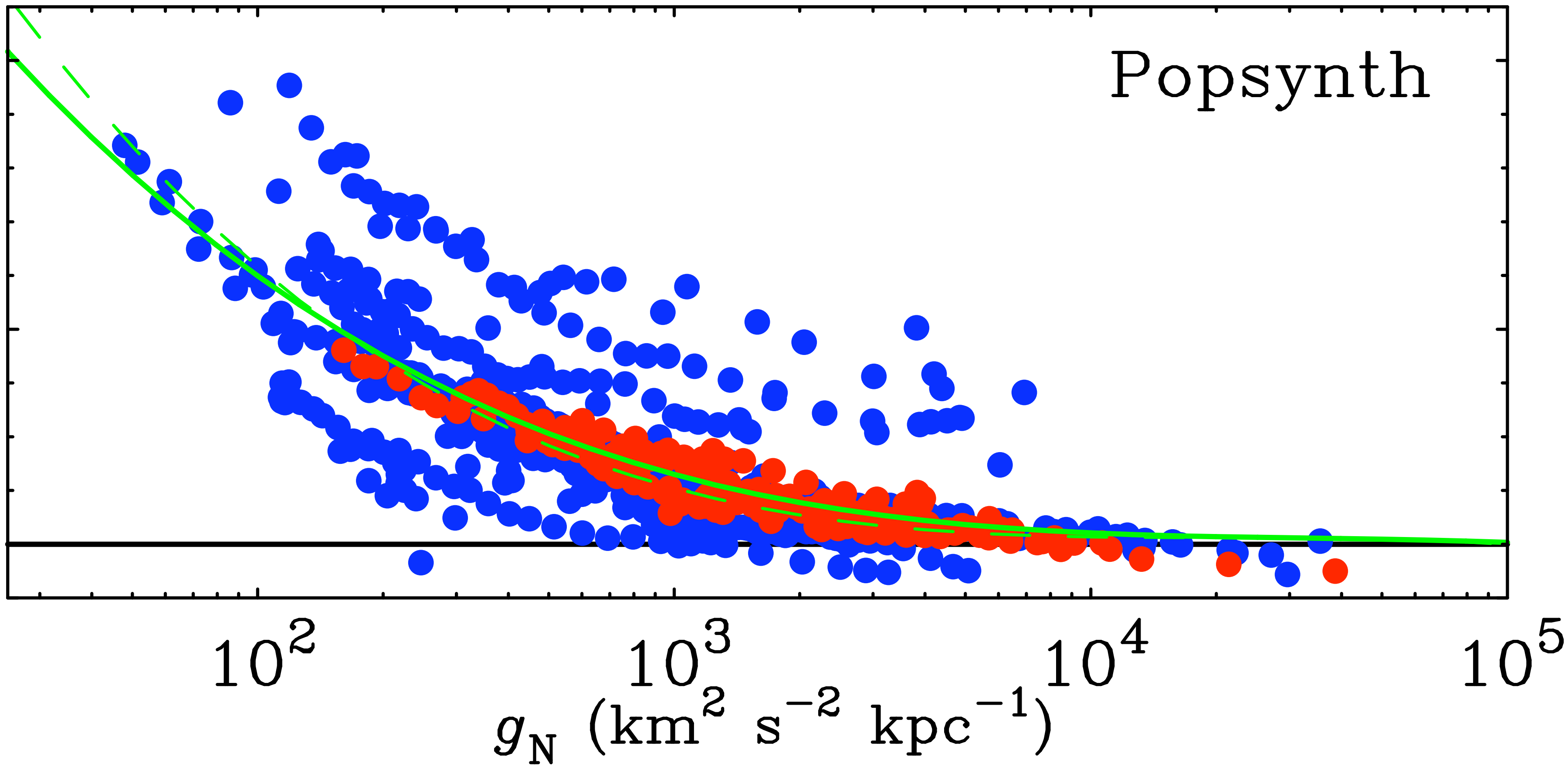
60 galaxies
> 600 points
(errors < 5%)

Different choices of Stellar Mass-to-Light Ratio



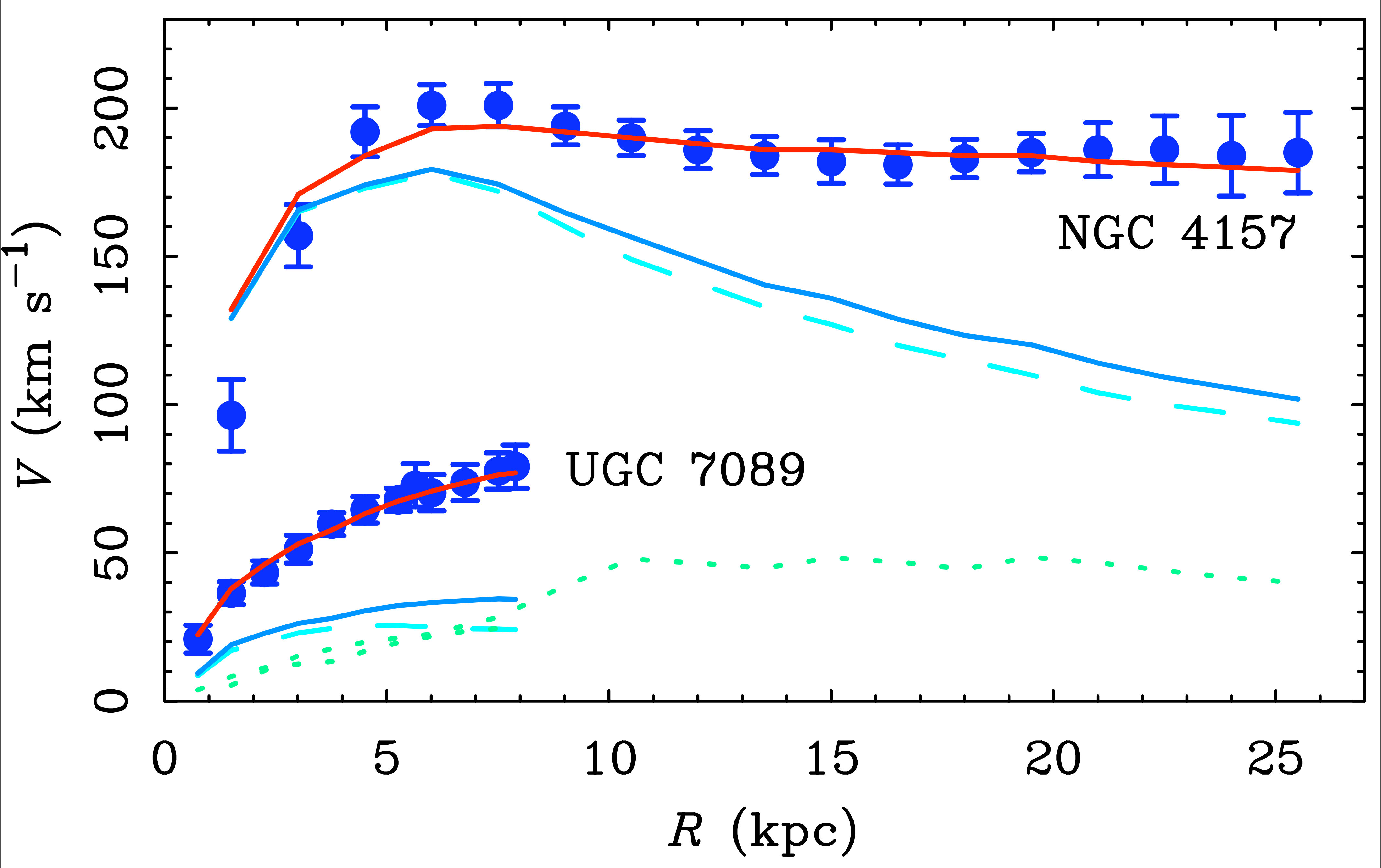
The mass discrepancy - acceleration relation

$$\mathcal{D}(g_N) = \frac{V^2}{\Upsilon_\star v_\star^2 + V_g^2}$$

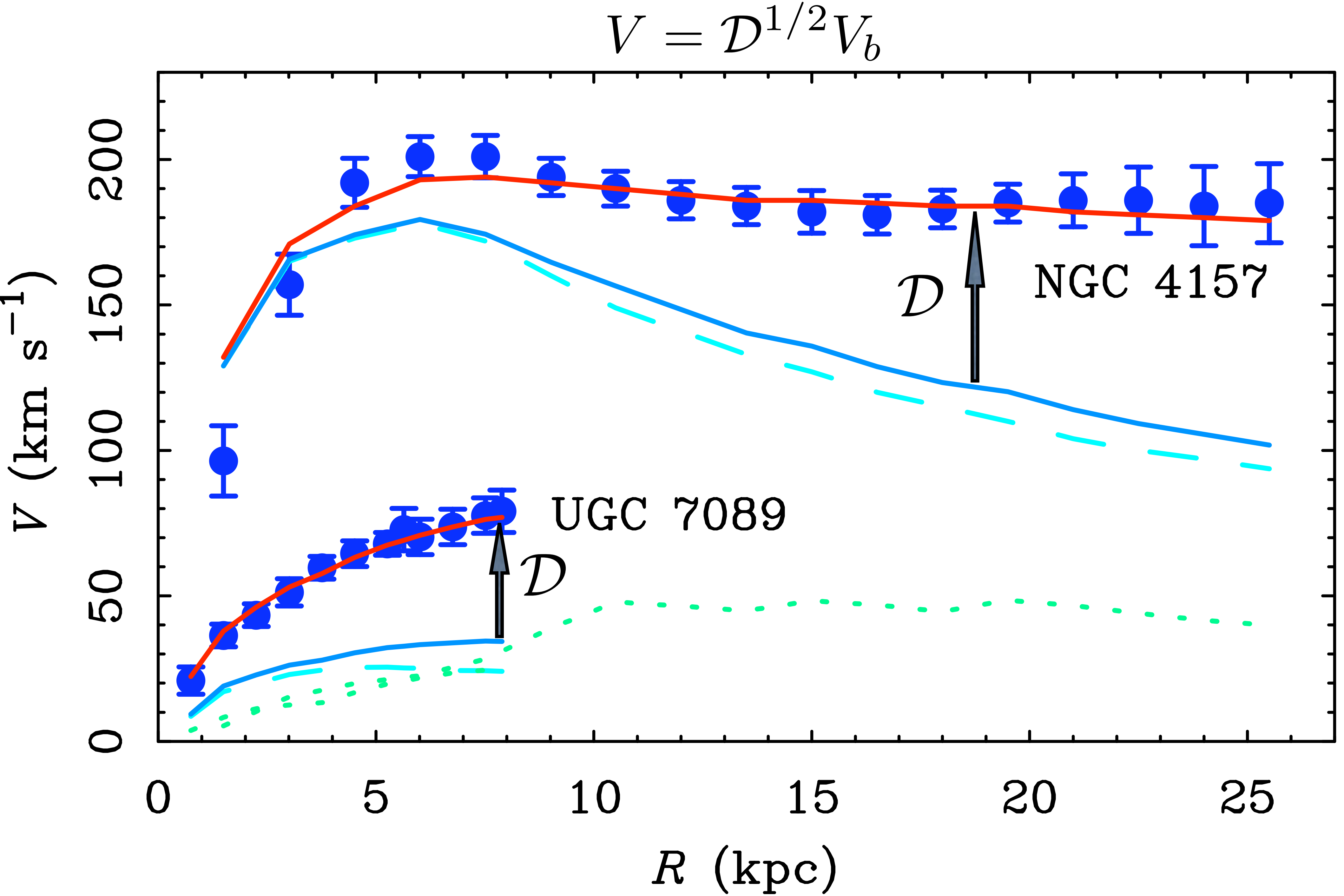


$$g_N \propto \Sigma$$

McGaugh 2004, ApJ, 609, 652



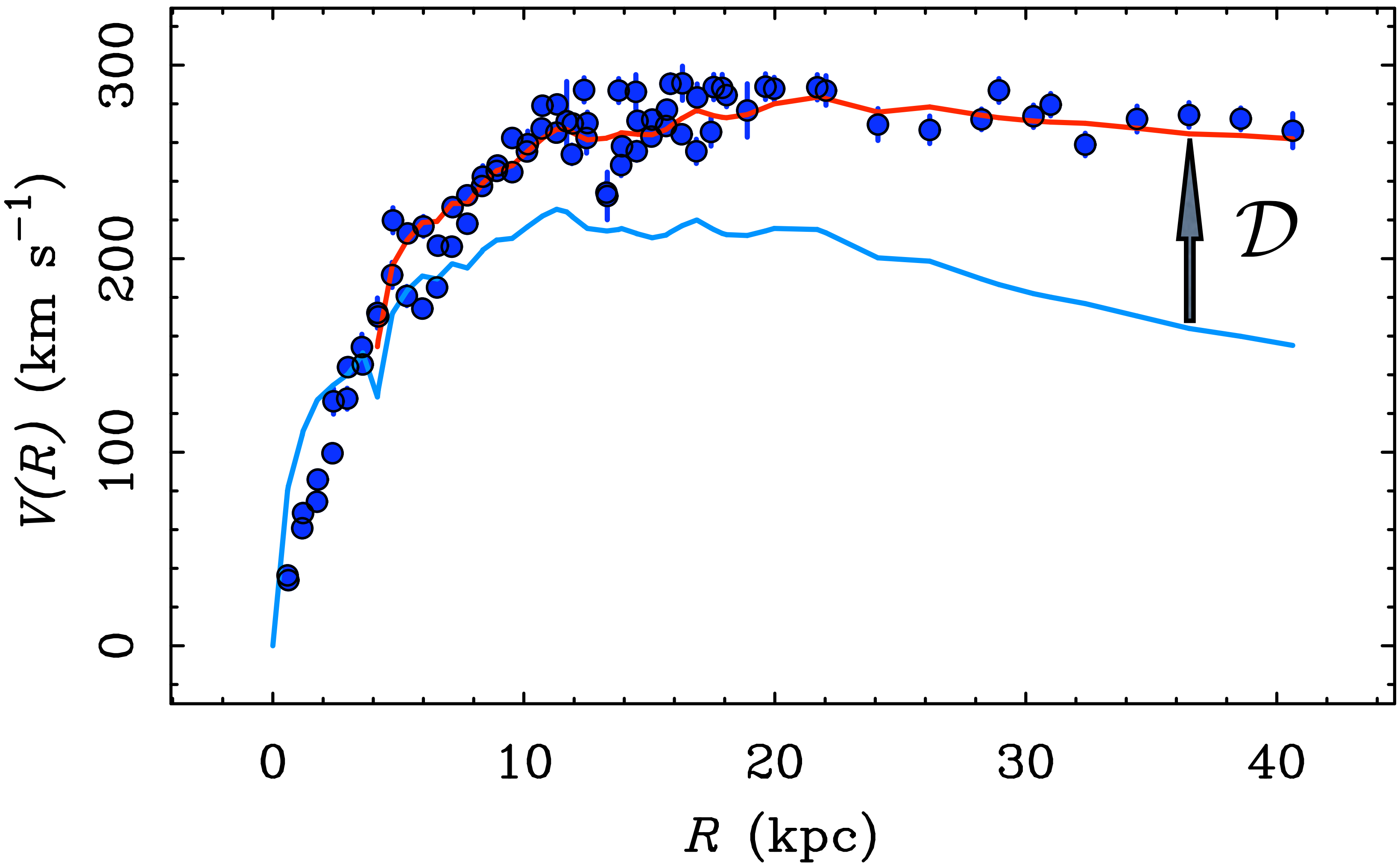
NGC 4157
UGC 7089
0
50
100
150
200
V (km s^{-1})
0
5
10
15
20
25
R (kpc)



$V = \mathcal{D}^{1/2} V_b$
V (km s^{-1})
R (kpc)
NGC 4157
UGC 7089
$\mathcal{D}$
$\mathcal{D}$
0
50
100
150
200
0
5
10
15
20
25

UGC 11455: Spekkens & Giovanelli (2006): HI + Hα data

Independent from calibrating data



$$\Upsilon_\star^I = 1.1\ M_\odot / L_\odot$$

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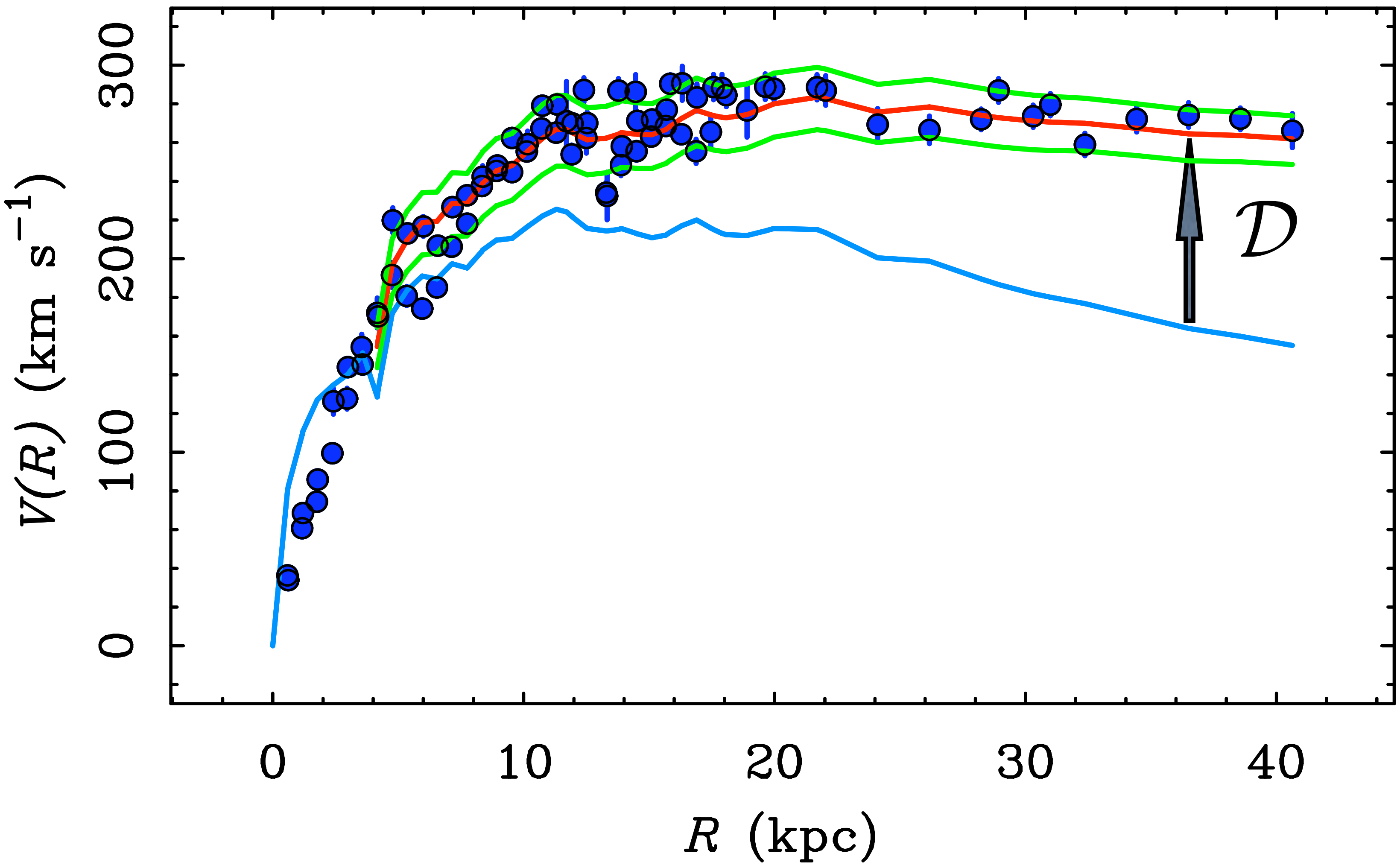
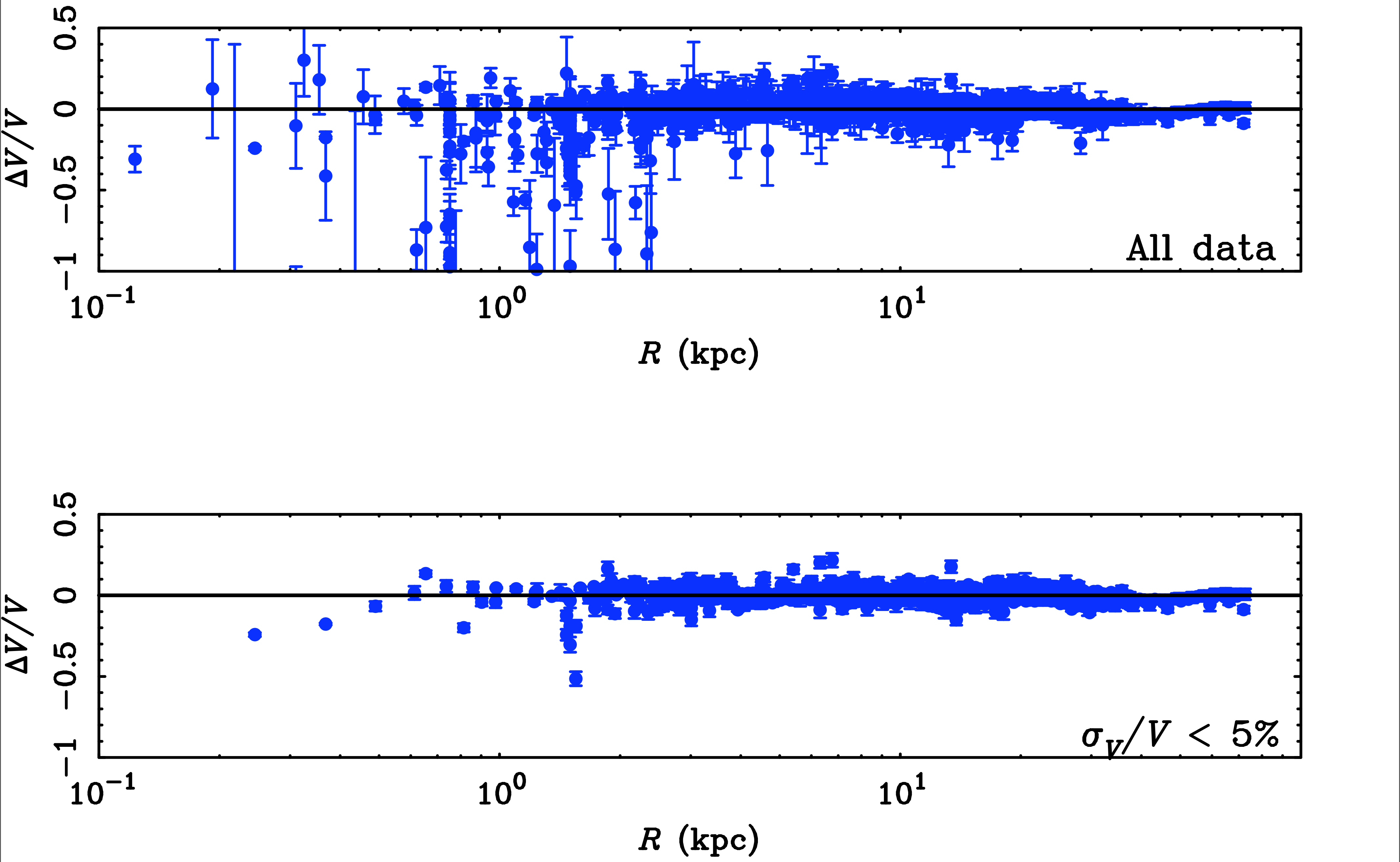
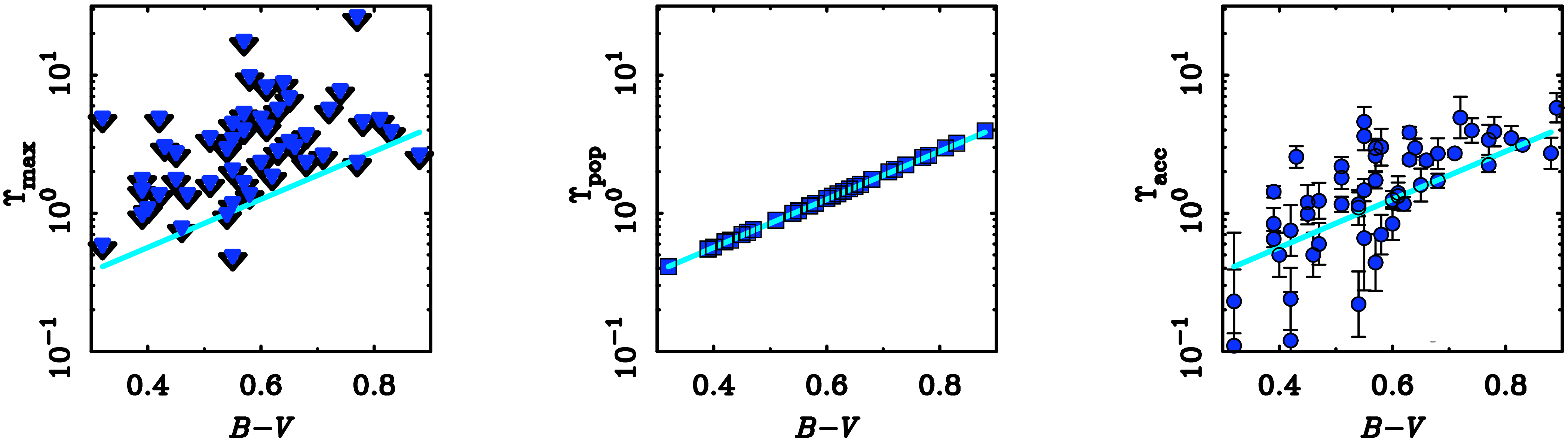


$$\Upsilon_\star^I = 1.1\ M_\odot / L_\odot \ \ \pm 0.2$$

Residuals

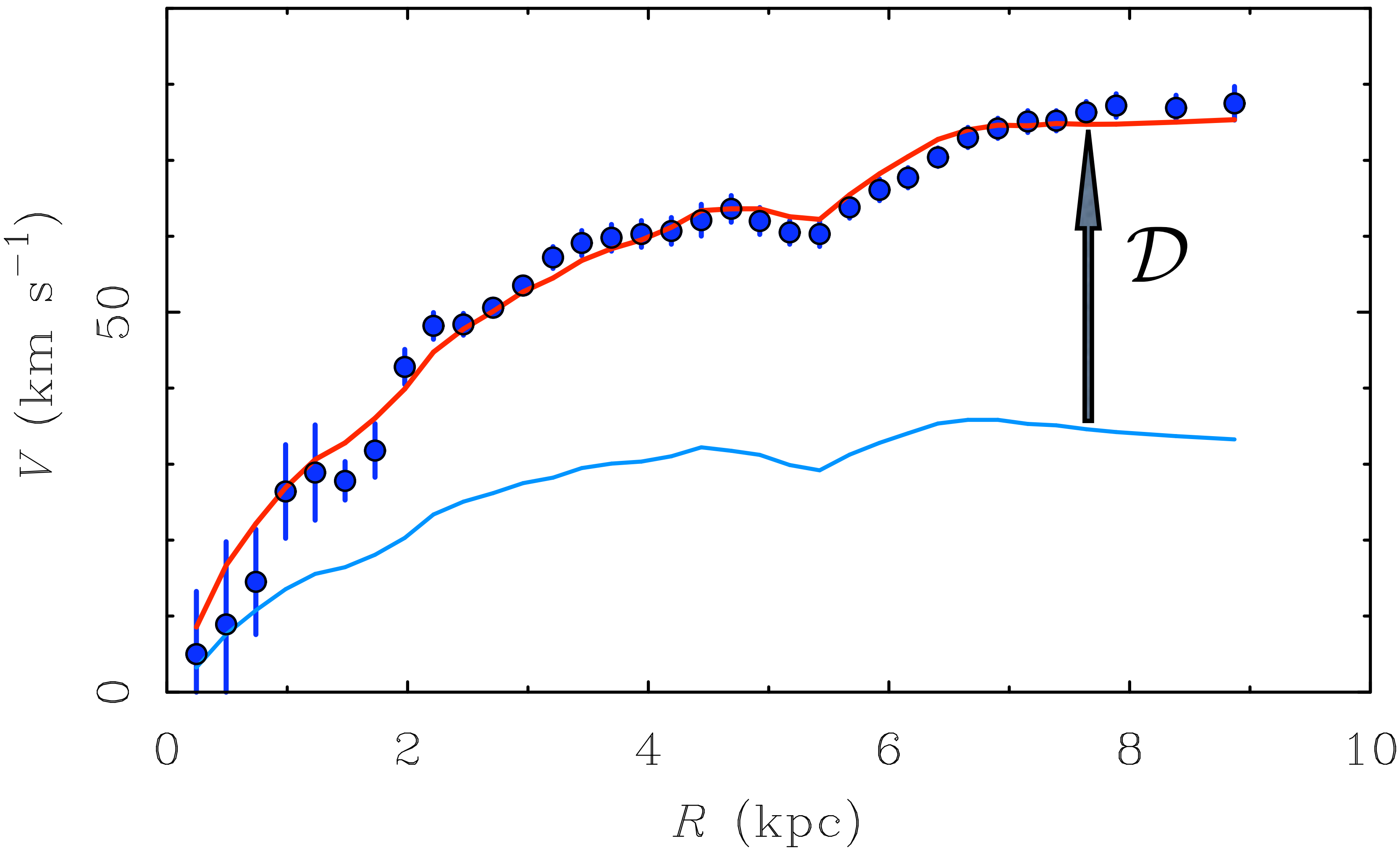


ΔV/V
0.5
0
−0.5
−1
All data
10^−1
10^0
10^1
R (kpc)
ΔV/V
0.5
0
−0.5
−1
σ_V/V < 5%
10^−1
10^0
10^1
R (kpc)



Line: Bell et al. (2003)

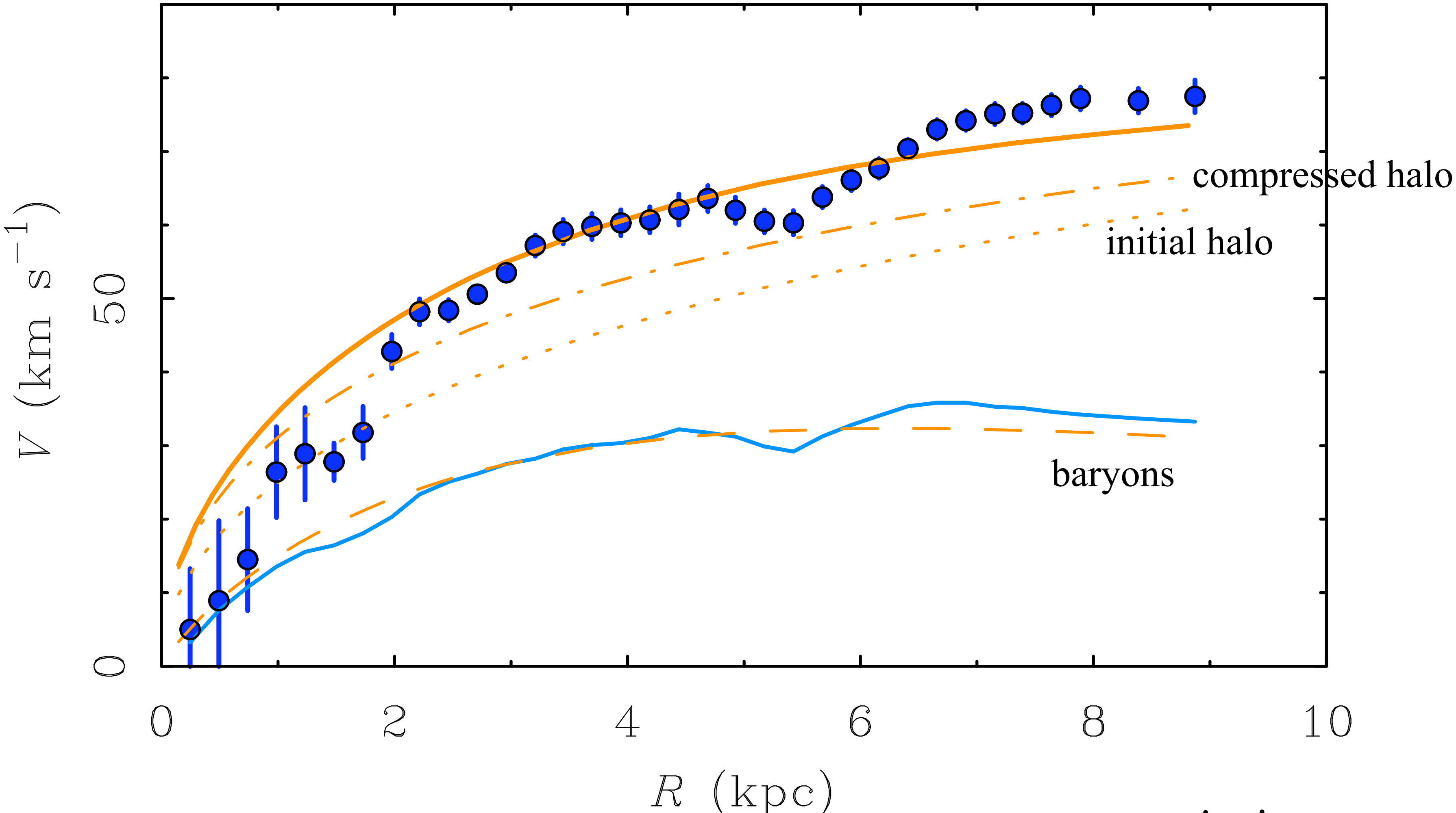
Renzo’s rule works even for LSBs! - e.g., NGC 1560:



initial halo

$c = 4.9$

$V_{200} = 80$



halo compression

$m_d = 0.01$

$\frac{R_d}{R_s} = 0.12$

Sellwood & McGaugh 2005, ApJ, 634, 70

Conclusions

It's all about the baryons!

One universal fcn + one free parameter per galaxy (M^*/L)
is more efficacious than multi-parameter disk-halo fits.

i.e., there is a single effective force law in disk galaxies.
What does this?

CDM: doesn't fall out naturally. Feedback? Scatter?
Why does the baryonic tail wag the dark matter dog?

MOND: most natural interpretation of rotation curves.
TeVeS, BSTV: can test with gravitational lensing.

Other forms of DM?
SIDM, WDM... ignore baryons!
(Just making a core is not good enough.)
Other ideas...

Piazza & Marinoni (2003) PRL
Blanchet (2006) gr-qc/0609121