Galaxies in the Cosmic Web

Empirical Constraints on Halo Profiles from Rotation Curves

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1. Global Correlations: Tully-Fisher
2. Intermediate radii: dark matter density
3. Small radii: cusp/core

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); Sanders & McGaugh (2002); McGaugh (2005, 2006)

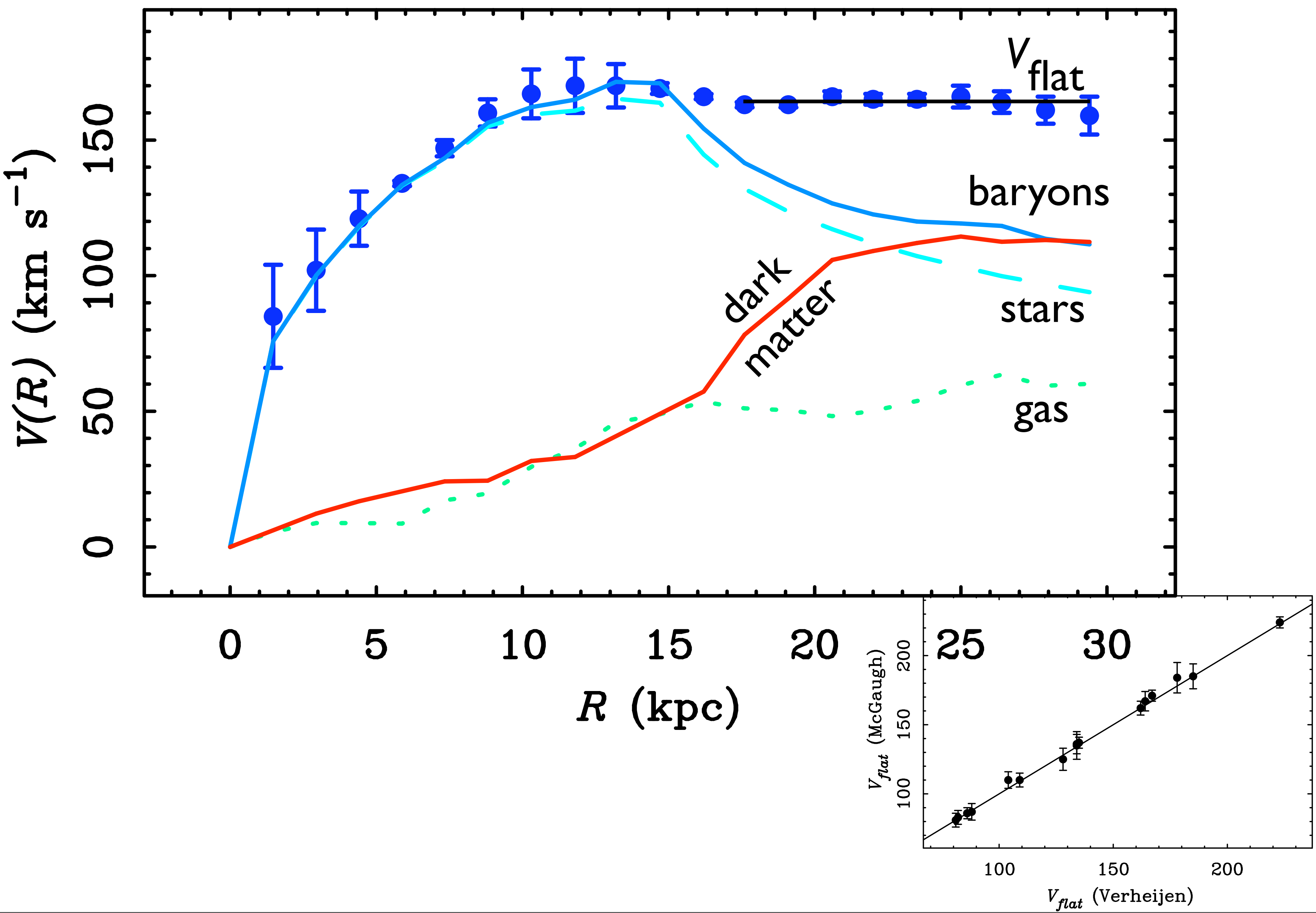
original sources -

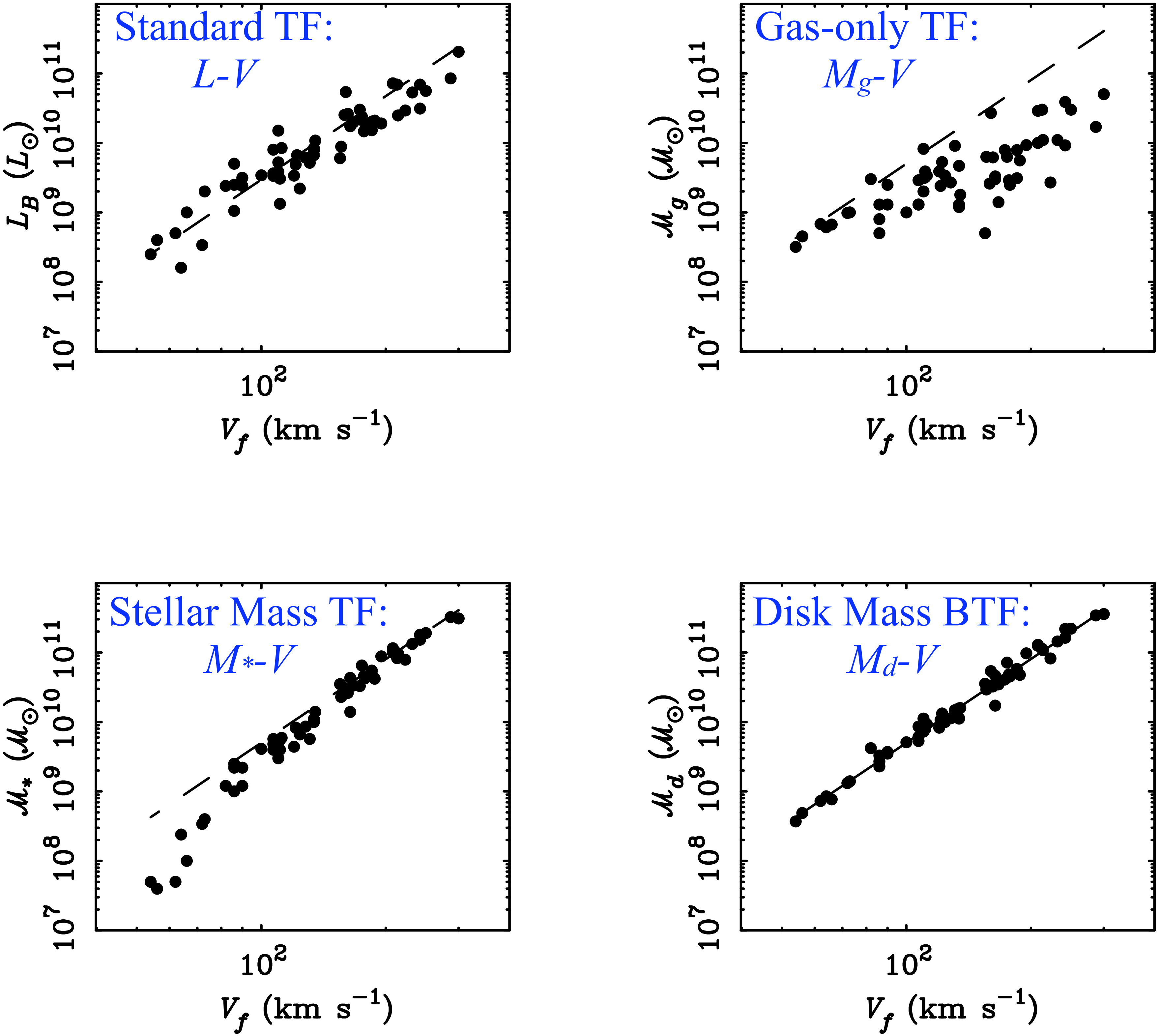
Begeman (1987)
Broeils (1992)
de Blok (1997)
Verheijen (1997)

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...

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





Standard TF:
L-V
Gas-only TF:
Mg-V
Stellar Mass TF:
M*-V
Disk Mass BTF:
Md-V
L_B ($L_\odot$)
$\mathcal{M}_g$ ($\mathcal{M}_\odot$)
$\mathcal{M}_*$ ($\mathcal{M}_\odot$)
$\mathcal{M}_d$ ($\mathcal{M}_\odot$)
V_f (km s^{-1})
10^2
10^7
10^8
10^9
10^{10}
10^{11}

Test various prescriptions for estimating $\Upsilon_\star$

$\Upsilon_\star = \Gamma \Upsilon_{max}$ fraction of maximum disk

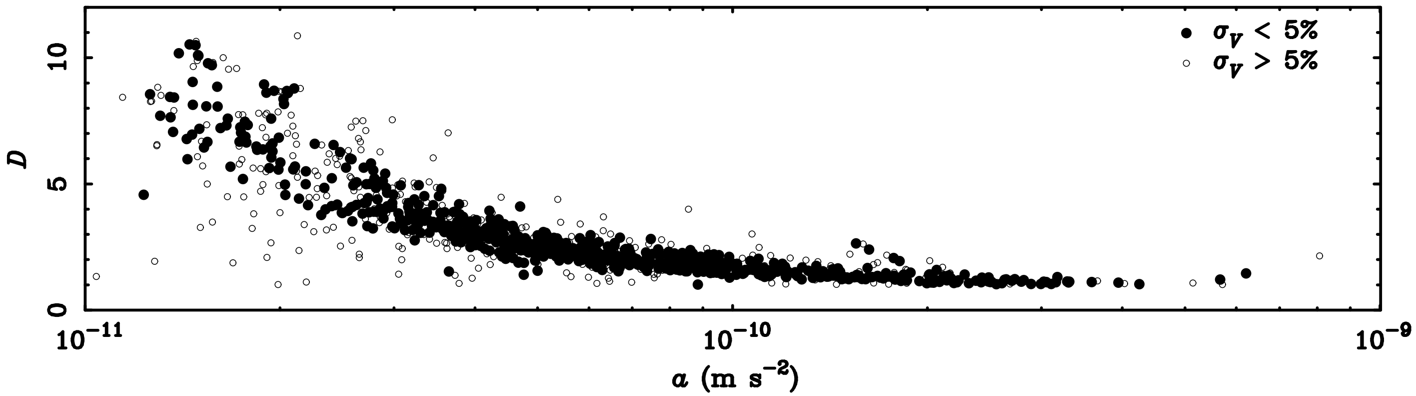
$\Upsilon_\star = \mathcal{P} \Upsilon_{pop}$ relative to popsynth model

(Bell *et al.* 2003, Portinari *et al.* 2004)

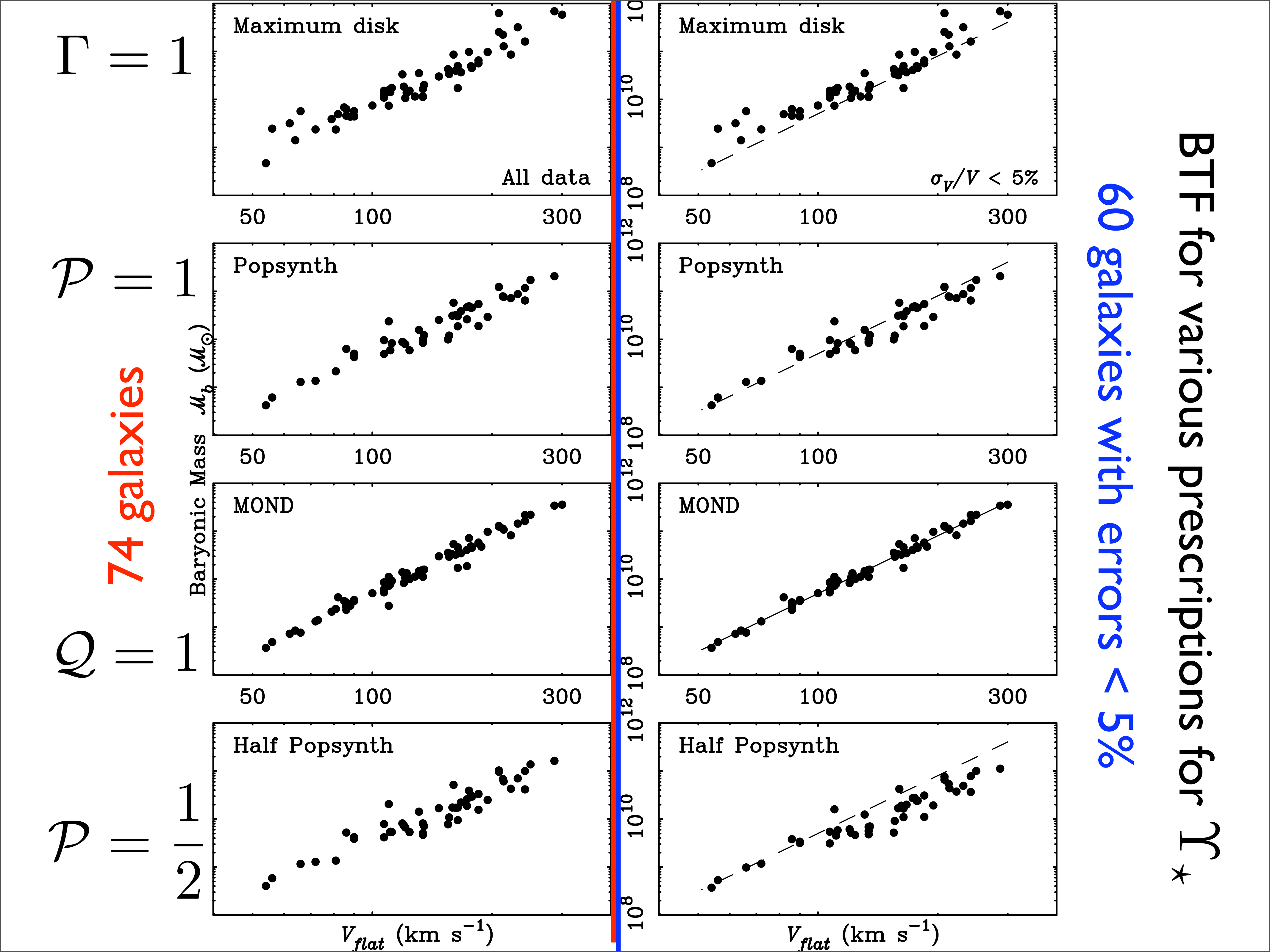
$\Upsilon_\star = \mathcal{Q} \Upsilon_{MOND}$ relative to MOND fit

(Sanders & McGaugh 2002)

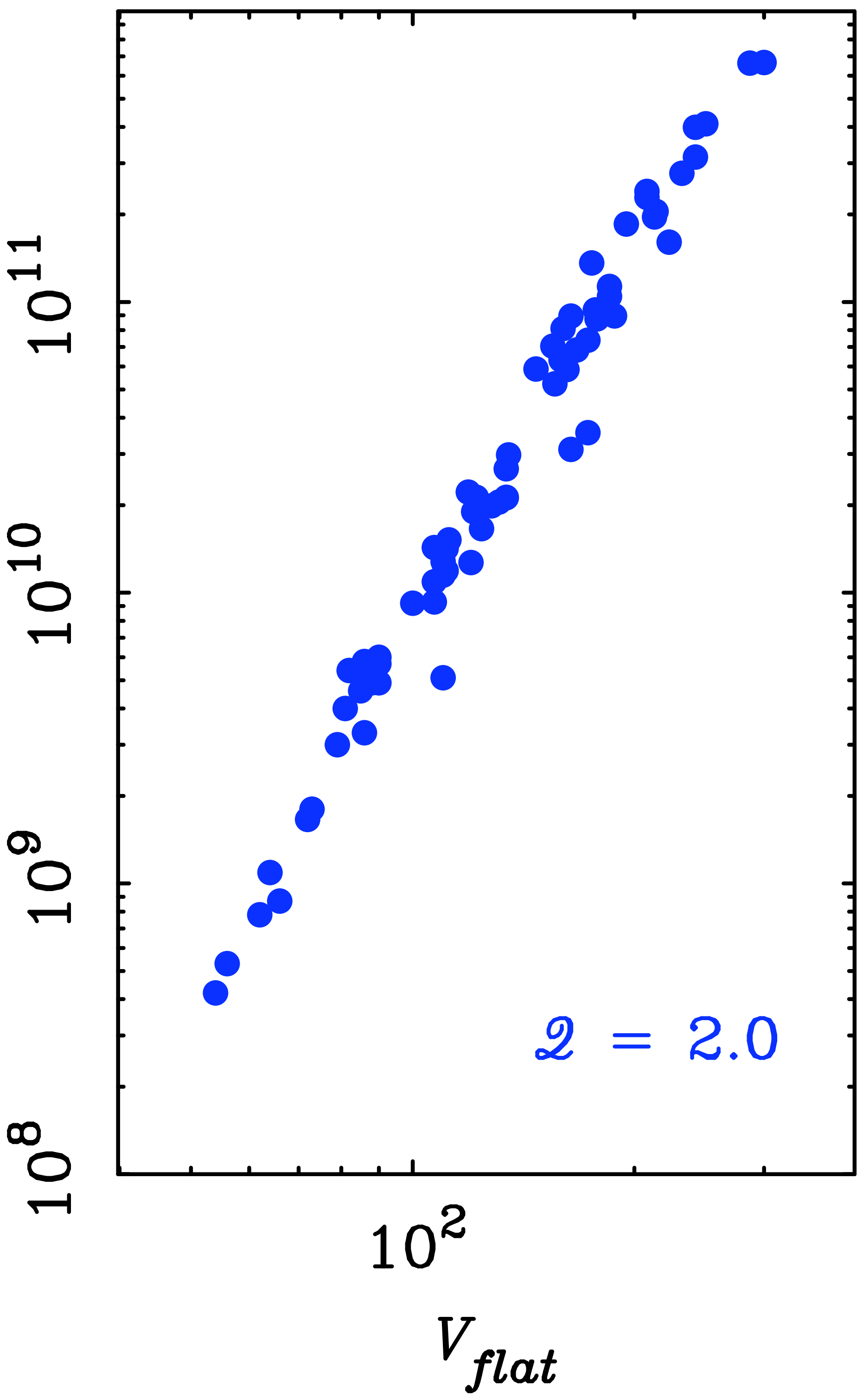
MOND can be re-cast as a purely empirical correlation



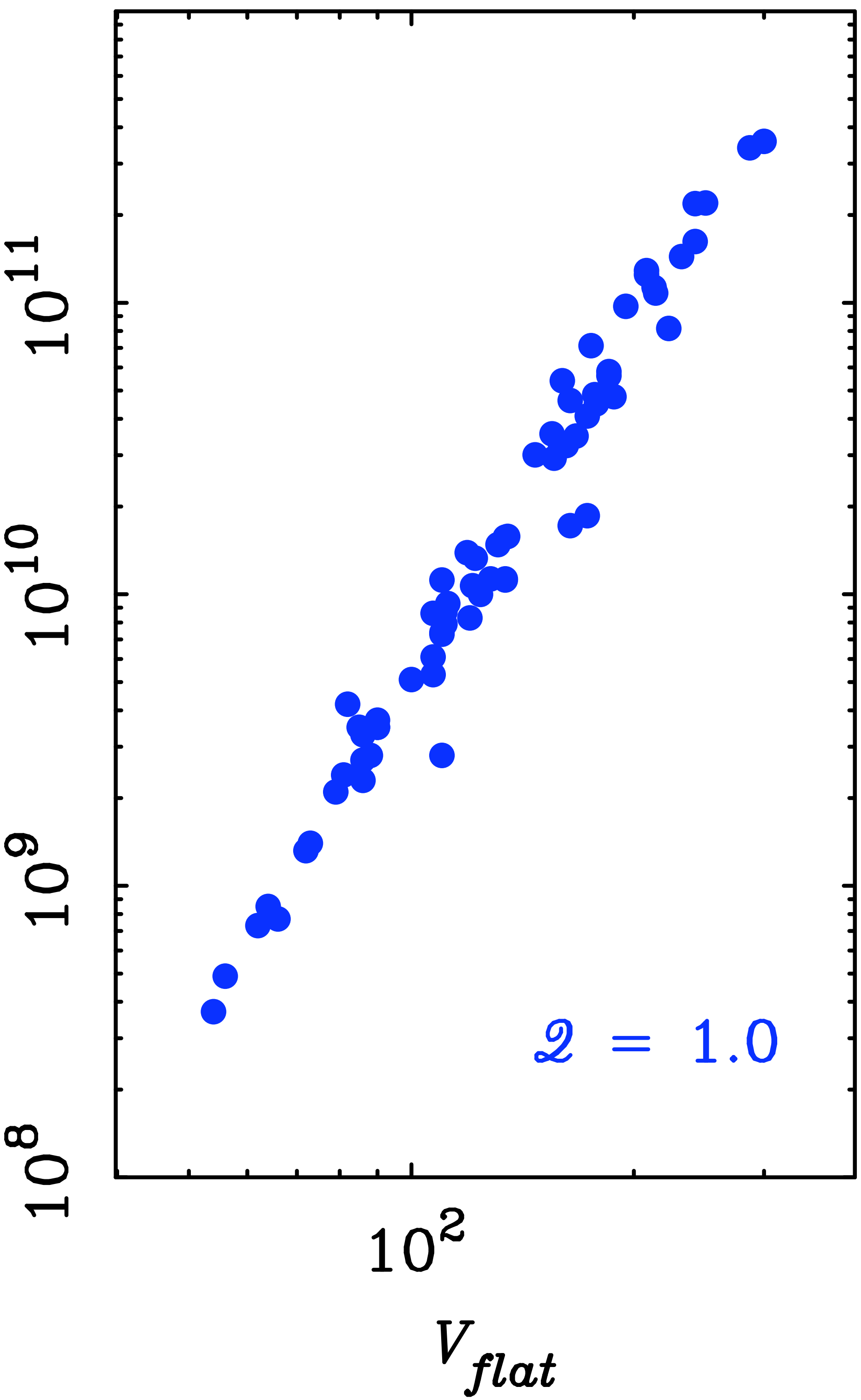
(McGaugh 2004)



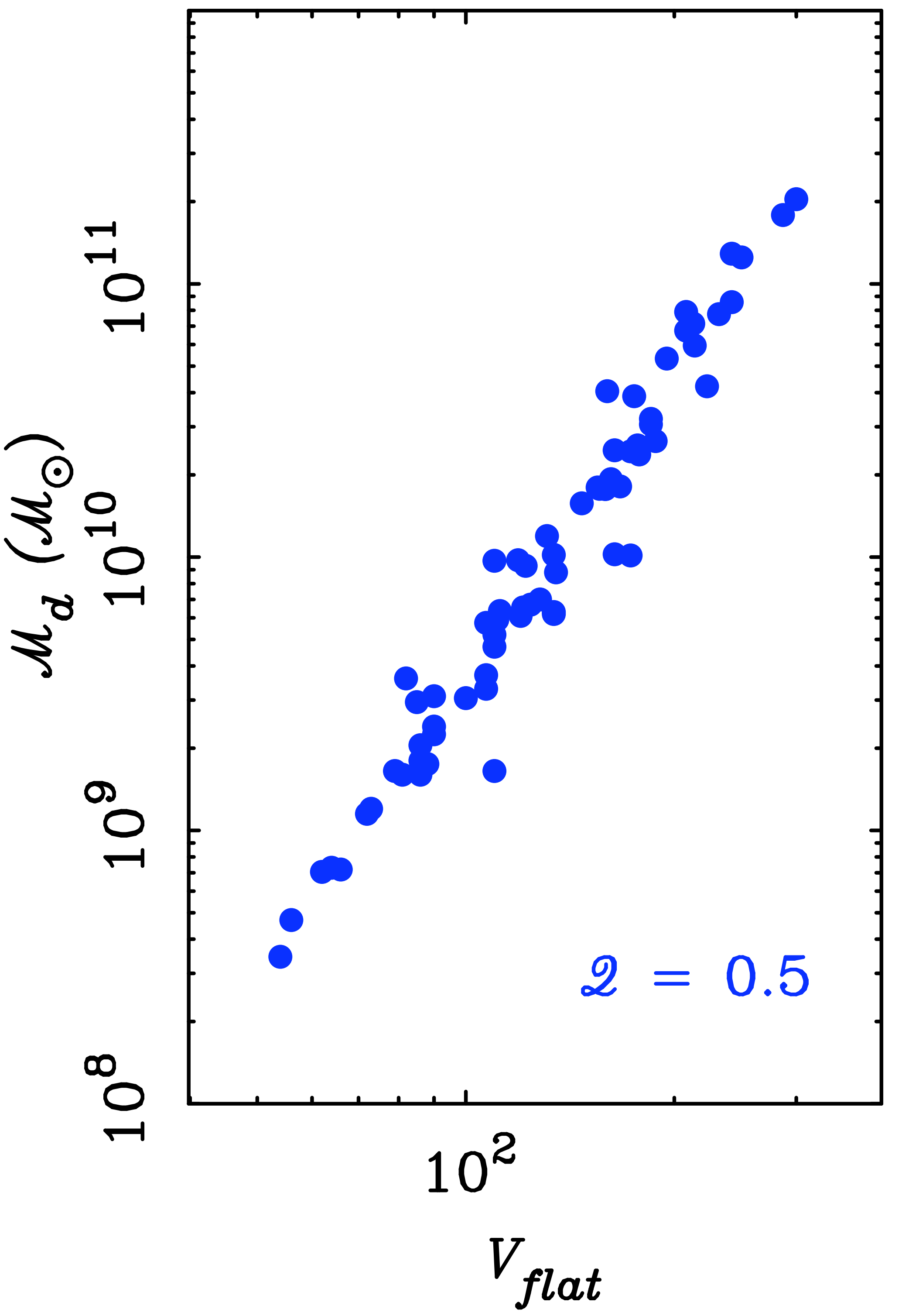
Γ = 1
P = 1
Q = 1
P = 1/2
74 galaxies
60 galaxies with errors < 5%
BTF for various prescriptions for Υ⋆
Maximum disk
All data
σ_V/V < 5%
Popsynth
MOND
Half Popsynth
Baryonic Mass M_b (M_⊙)
V_flat (km s^-1)
50
100
300
10^8
10^10
10^12



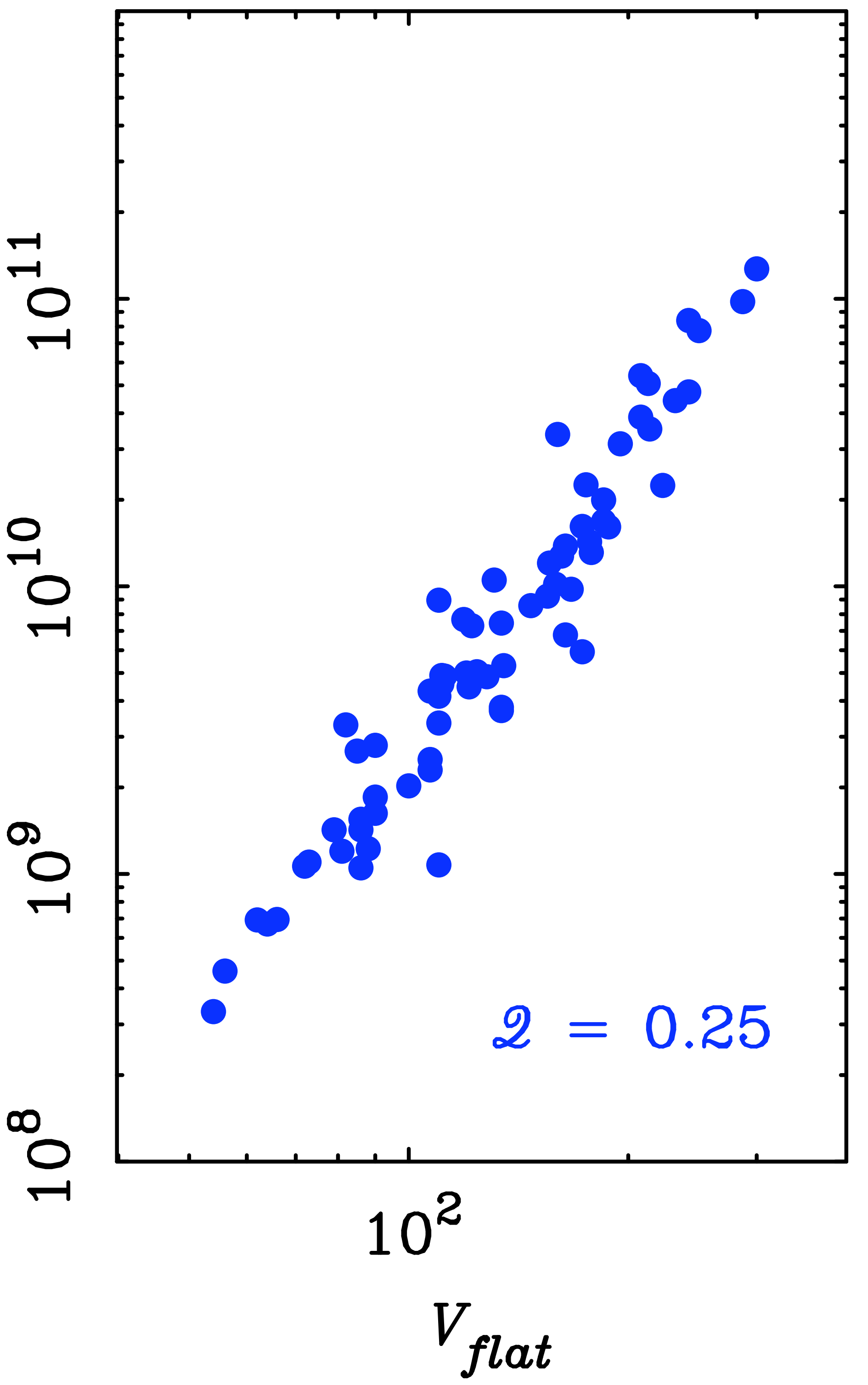
$\mathcal{M}_d$ ($\mathcal{M}_\odot$)
10^8
10^9
10^{10}
10^{11}
10^2
V_{flat}
$\mathcal{Q}$ = 2.0



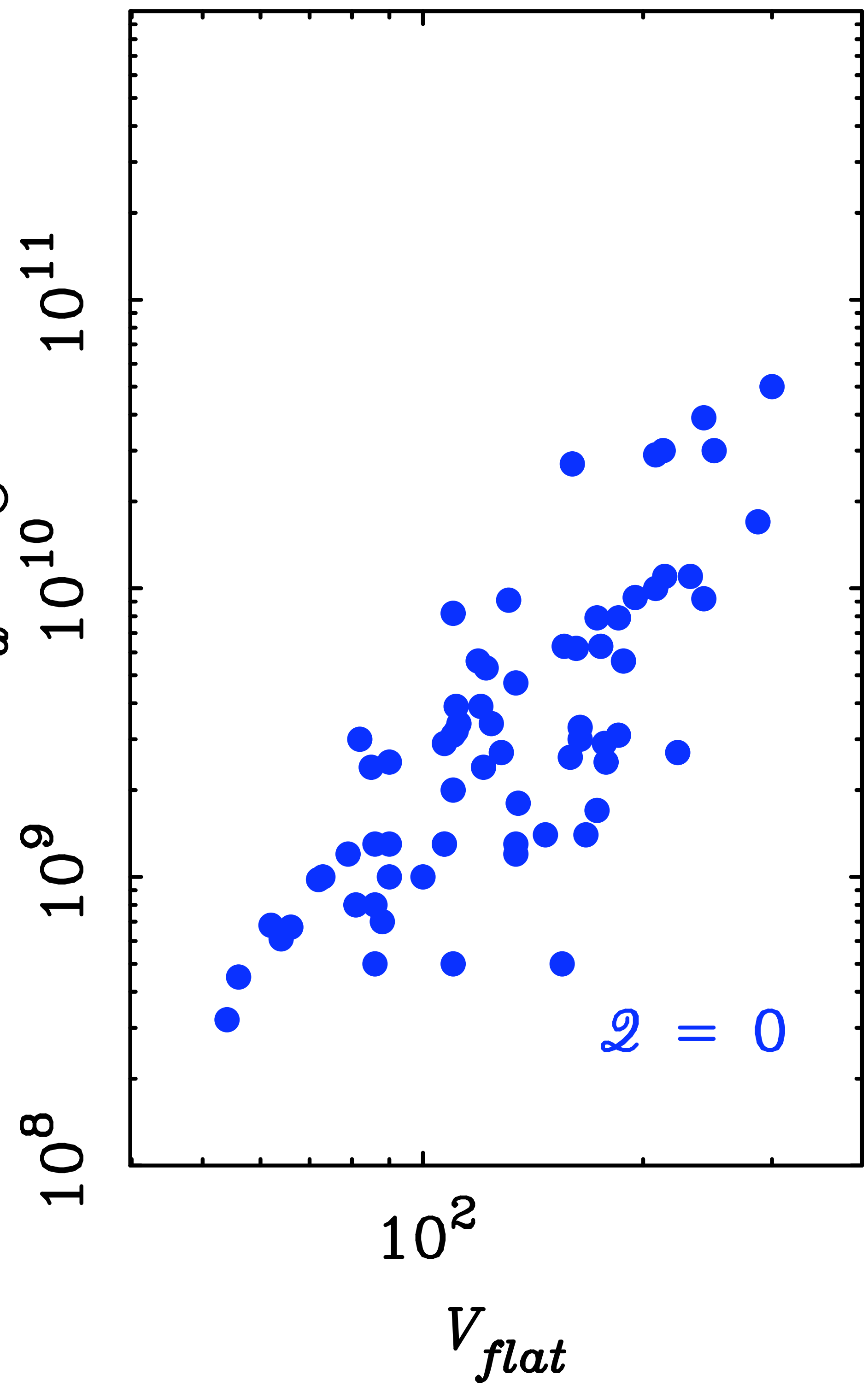
10^8
10^9
10^{10}
10^{11}
$\mathcal{M}_d$ ($\mathcal{M}_\odot$)
10^2
V_{flat}
$\mathcal{Q}$ = 1.0



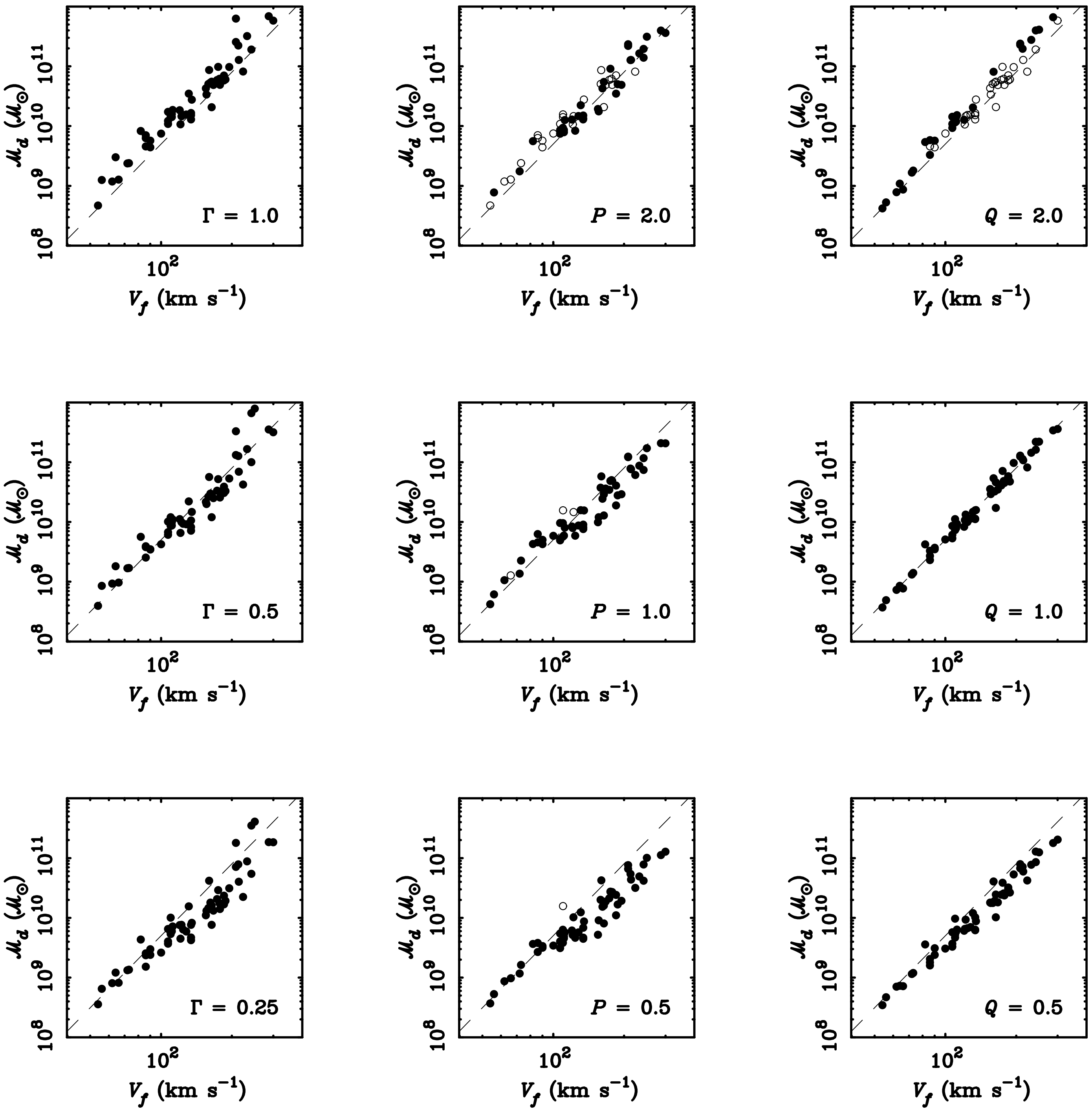
$\mathcal{M}_d$ ($\mathcal{M}_\odot$)
10^{11}
10^{10}
10^{9}
10^{8}
10^{2}
V_{flat}
$\mathcal{Q}$ = 0.5



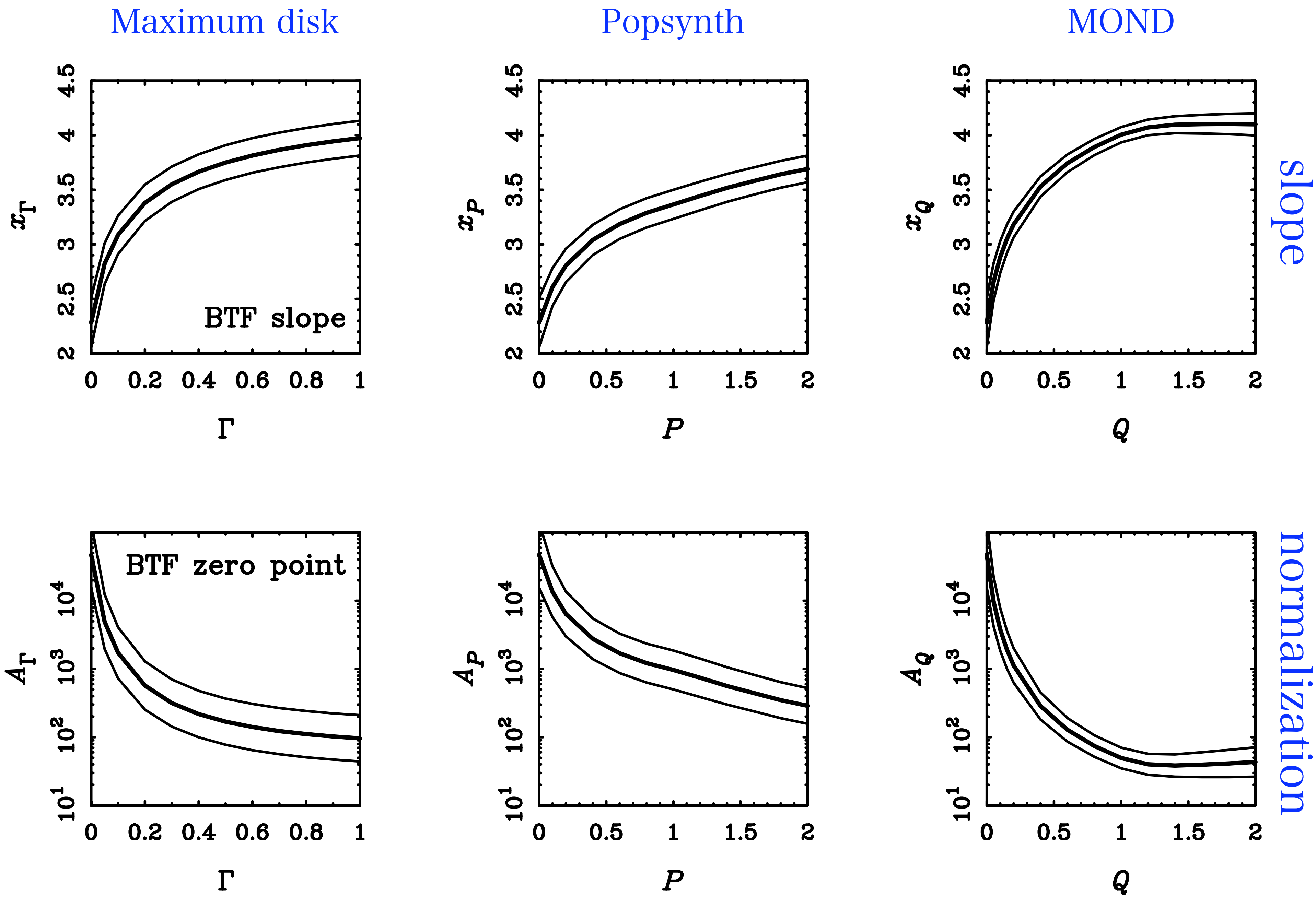
$\mathcal{M}_d$ ($\mathcal{M}_\odot$)
10^{11}
10^{10}
10^9
10^8
10^2
V_{flat}
$\mathcal{Q}$ = 0.25



10^{8}
10^{9}
10^{10}
10^{11}
$\mathcal{M}_d\ (\mathcal{M}_\odot)$
10^{2}
V_{flat}
$\mathcal{Q} = 0$

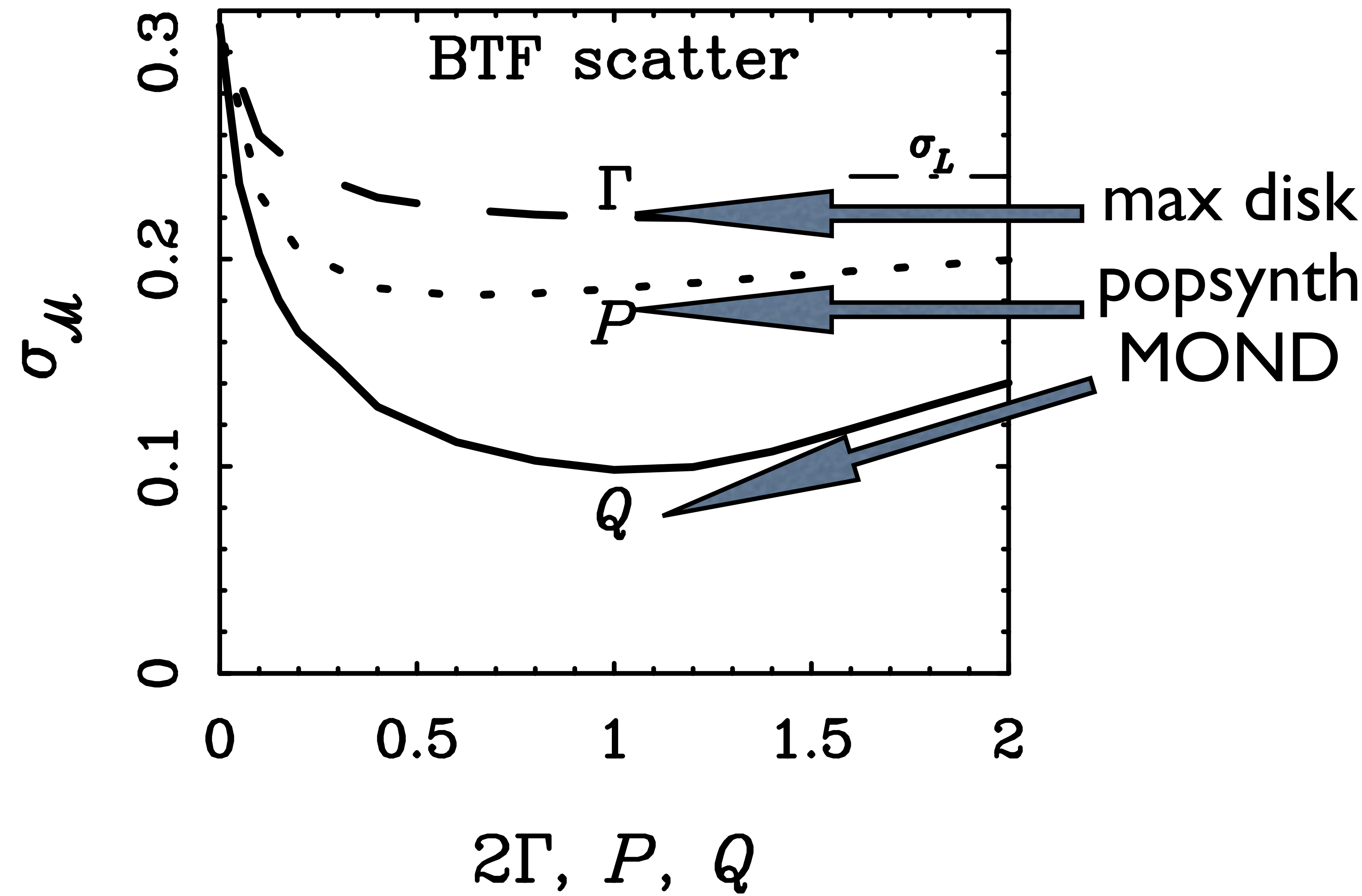


Maximum disk Popsynth MOND



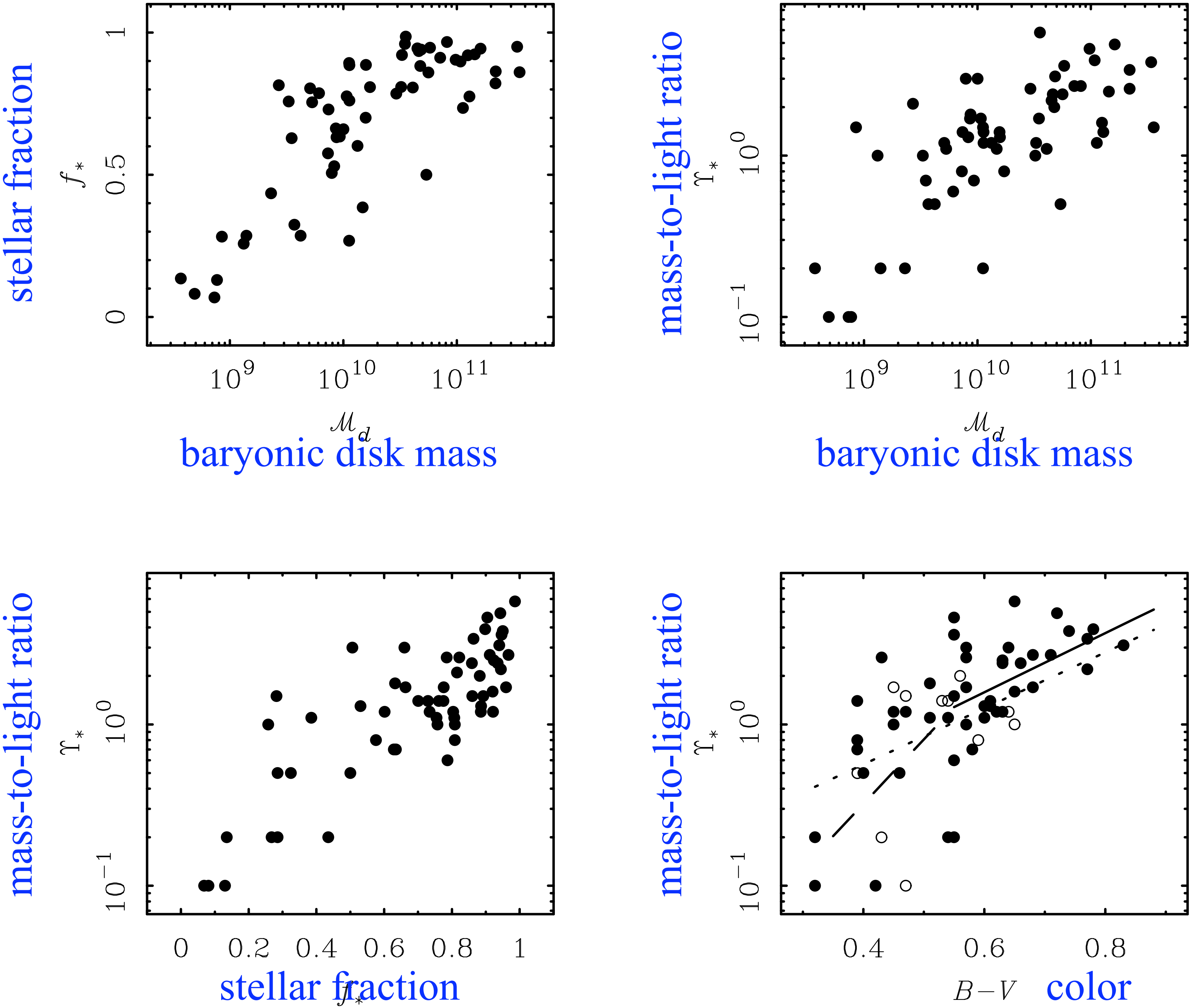
Fits to BTF: $\mathcal{M}_d = \mathcal{A} V_f^x$

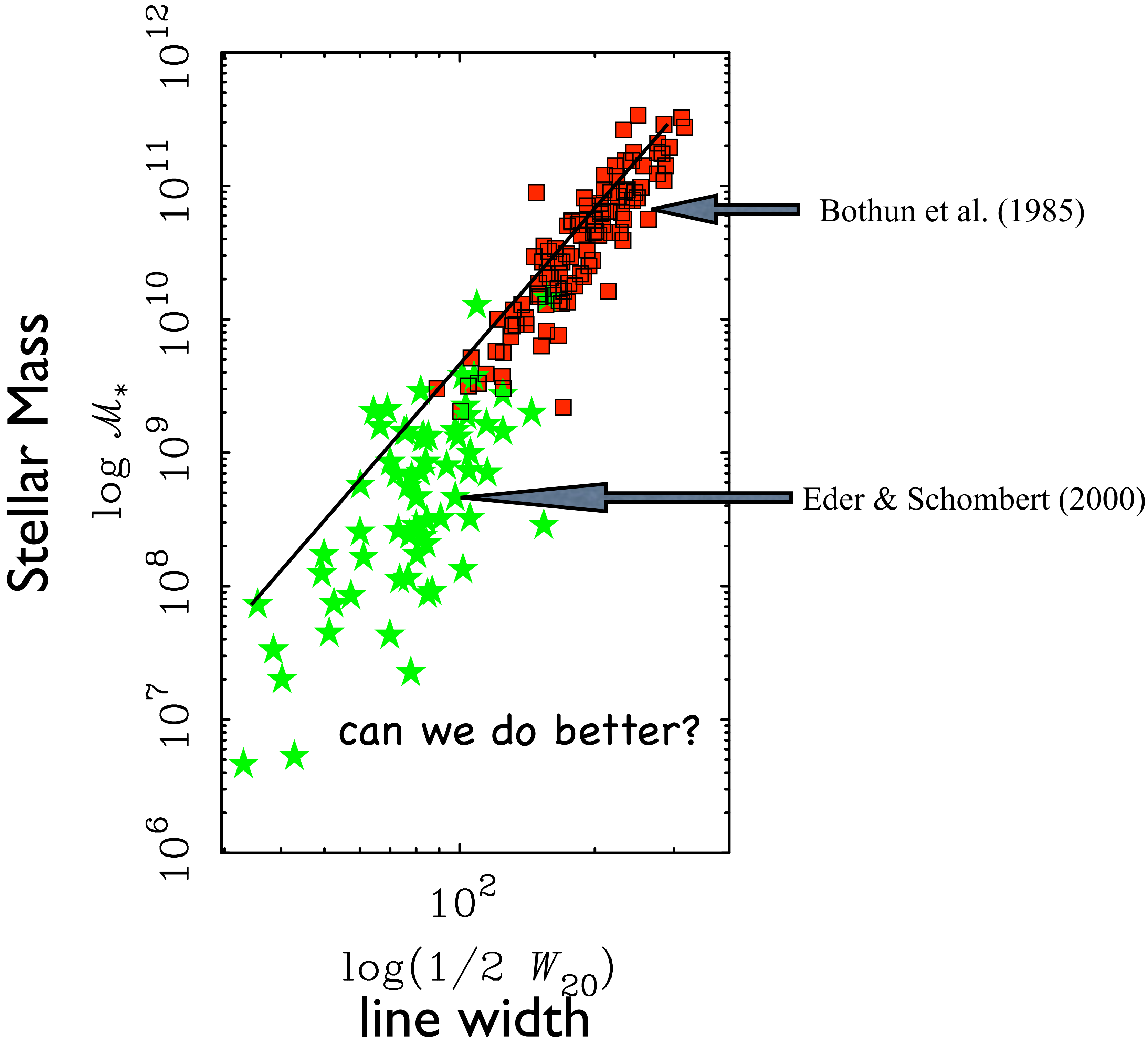
table of fits - choose your favorite prescription, get BTF (McGaugh 2005)



Best fit BTF: $\mathcal{M}_d = 50\, V_f^4$

down-sizing at z=0





Stellar Mass
log $\mathcal{M}_*$
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{2}
log(1/2 W_{20})
line width
Bothun et al. (1985)
Eder & Schombert (2000)
can we do better?

Extreme Dwarf Sample

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

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

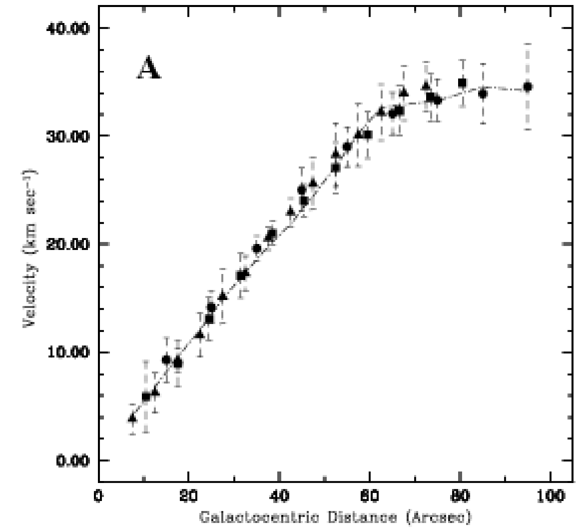
Baryonic Mass: $4 \times 10^6 < M_d < 8 \times 10^8 \; M_\odot$

Extends dynamics range of BTF to 5 decades in mass; tests slope.

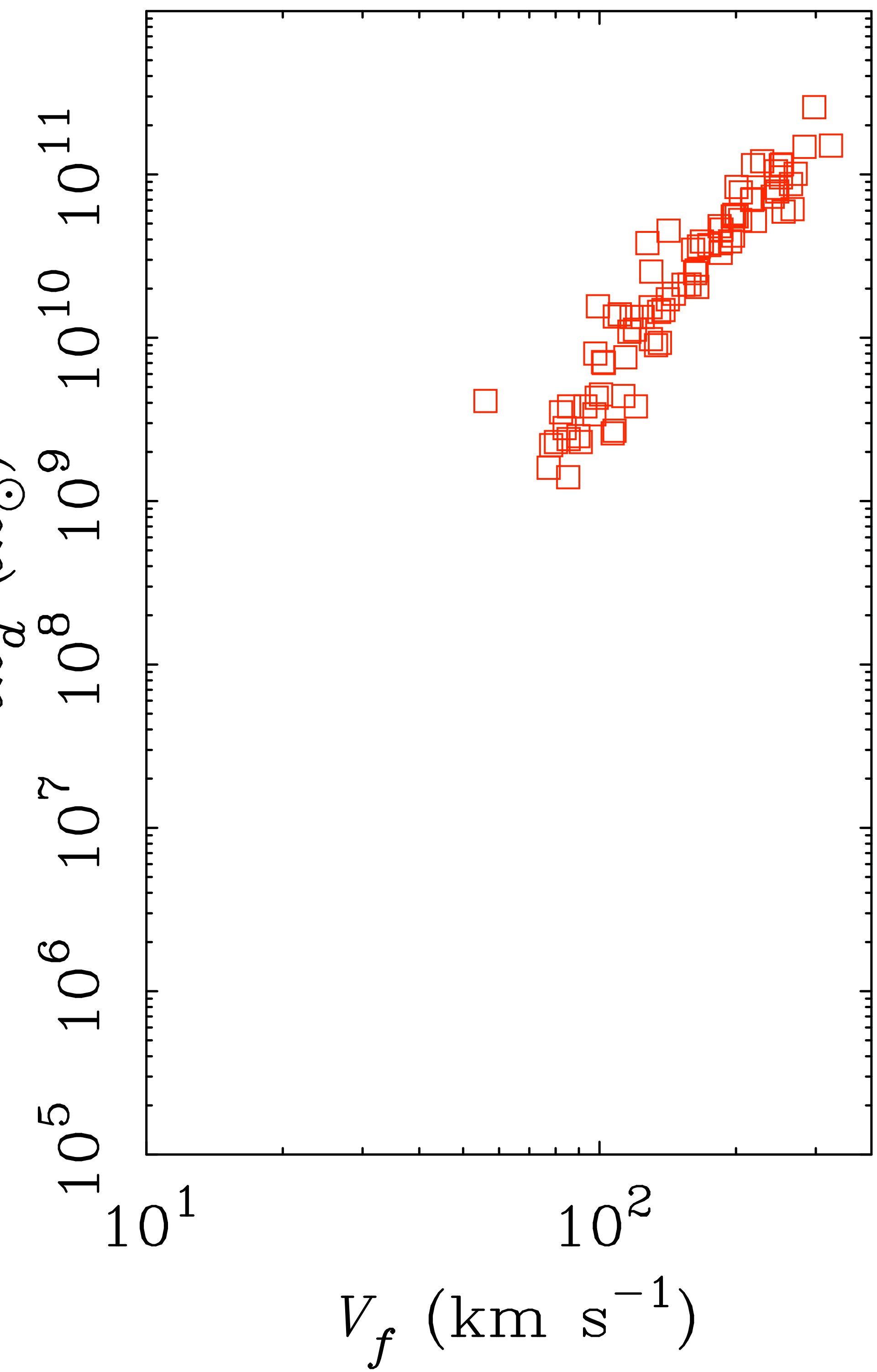
TABLE 5
EXTREME DWARF GALAXY DATA

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.

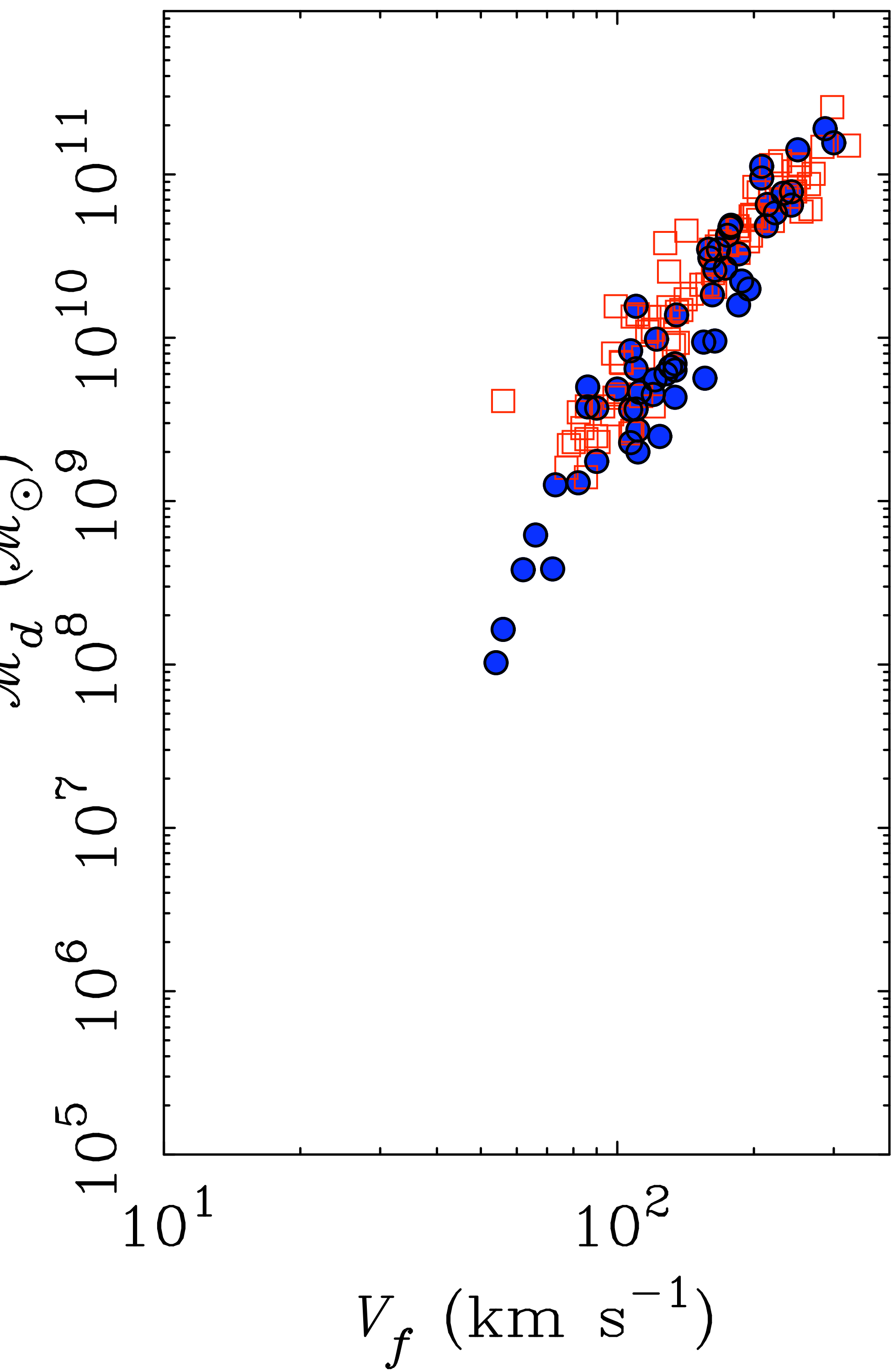


(McGaugh 2005)



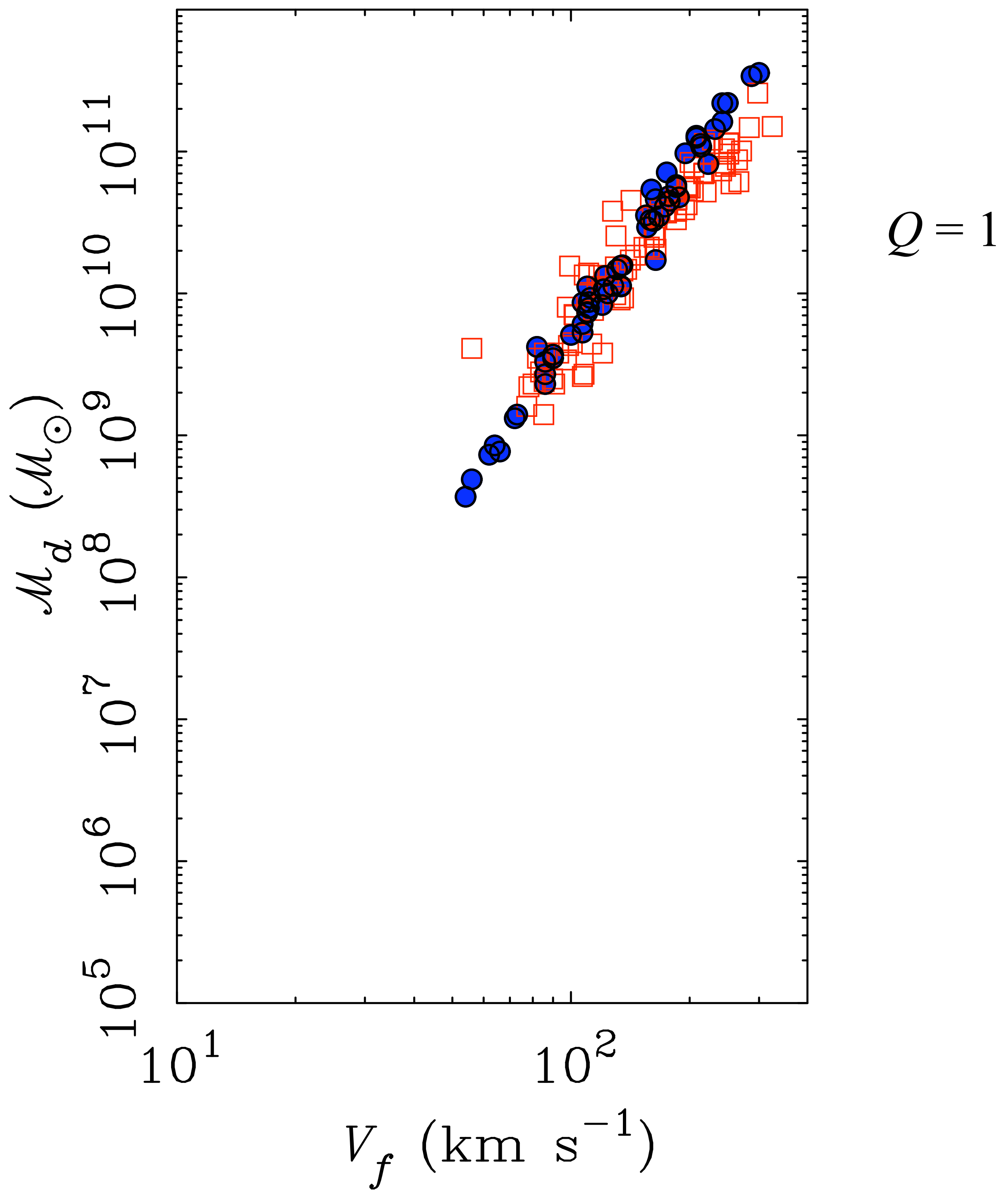
Pizagno et al. (2005)

$P = 1$

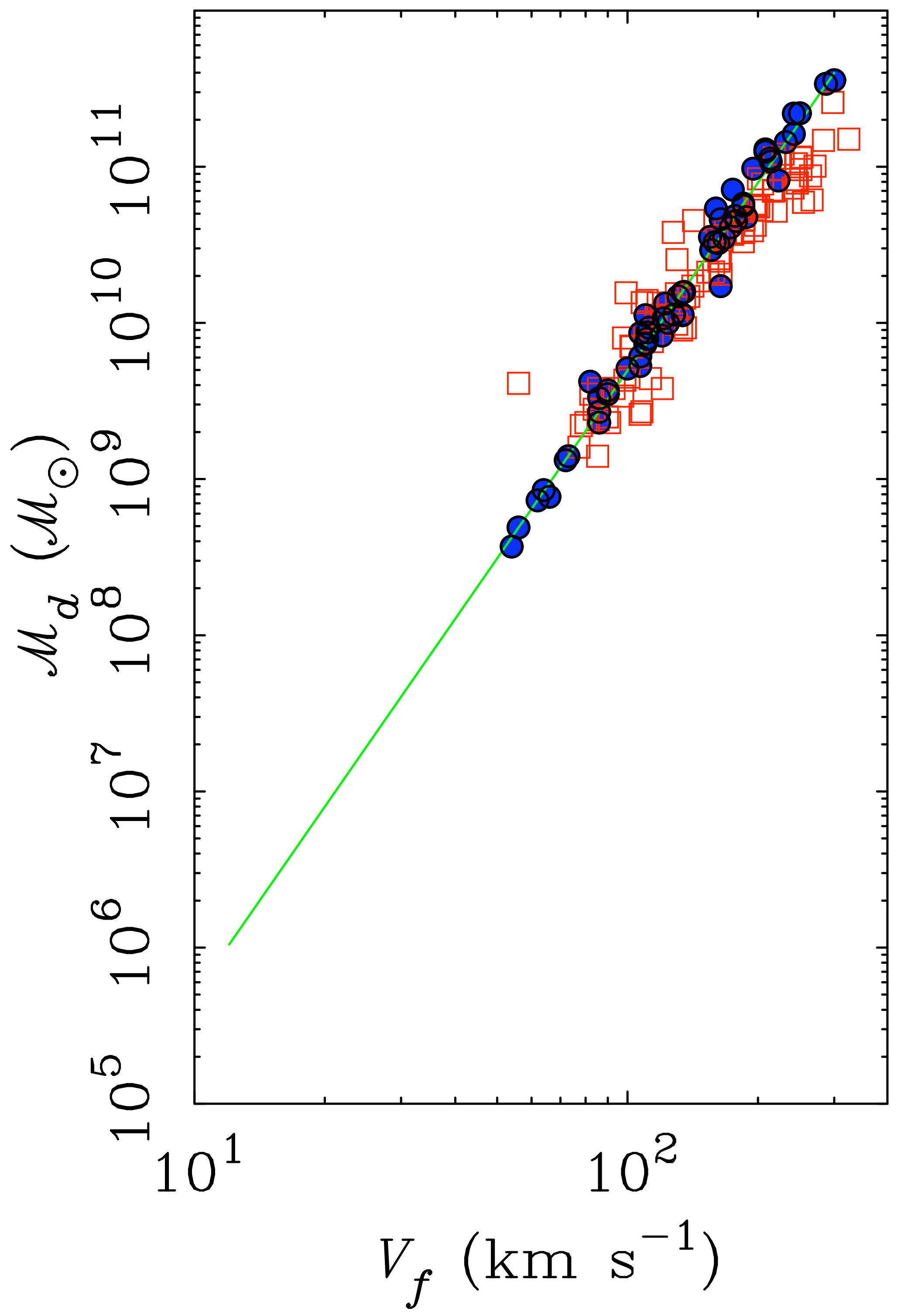


10^5
10^6
10^7
10^8
10^9
10^{10}
10^{11}
$\mathcal{M}_d$ ($\mathcal{M}_\odot$)
10^1
10^2
V_f (km s^{-1})

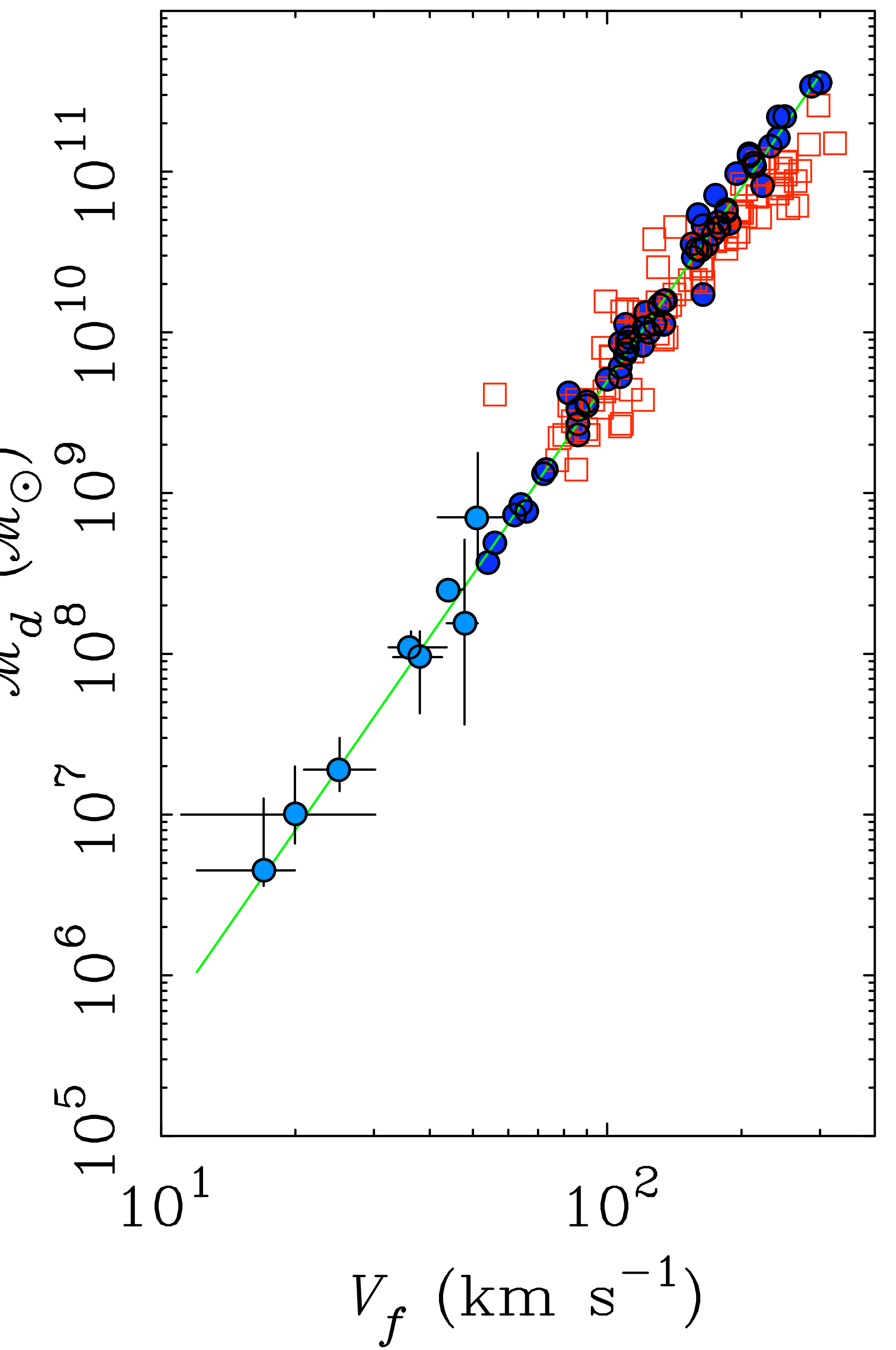
$P = 1$



$\mathcal{M}_d$ ($\mathcal{M}_\odot$)
10^5
10^6
10^7
10^8
10^9
10^{10}
10^{11}
10^1
10^2
V_f (km s^{-1})
$Q = 1$



$\mathcal{M}_d$ ($\mathcal{M}_\odot$)
10^5
10^6
10^7
10^8
10^9
10^{10}
10^{11}
10^1
10^2
V_f (km s^{-1})



$\mathcal{M}_d$ ($\mathcal{M}_\odot$)
10^5
10^6
10^7
10^8
10^9
10^{10}
10^{11}
10^1
10^2
V_f (km s^{-1})

BTF Summary

Best fit $\mathcal{M}_d = 50 V_f^4$

does an excellent job in predicting BTF locations of low mass, gas rich galaxies where M/L indicator unimportant.

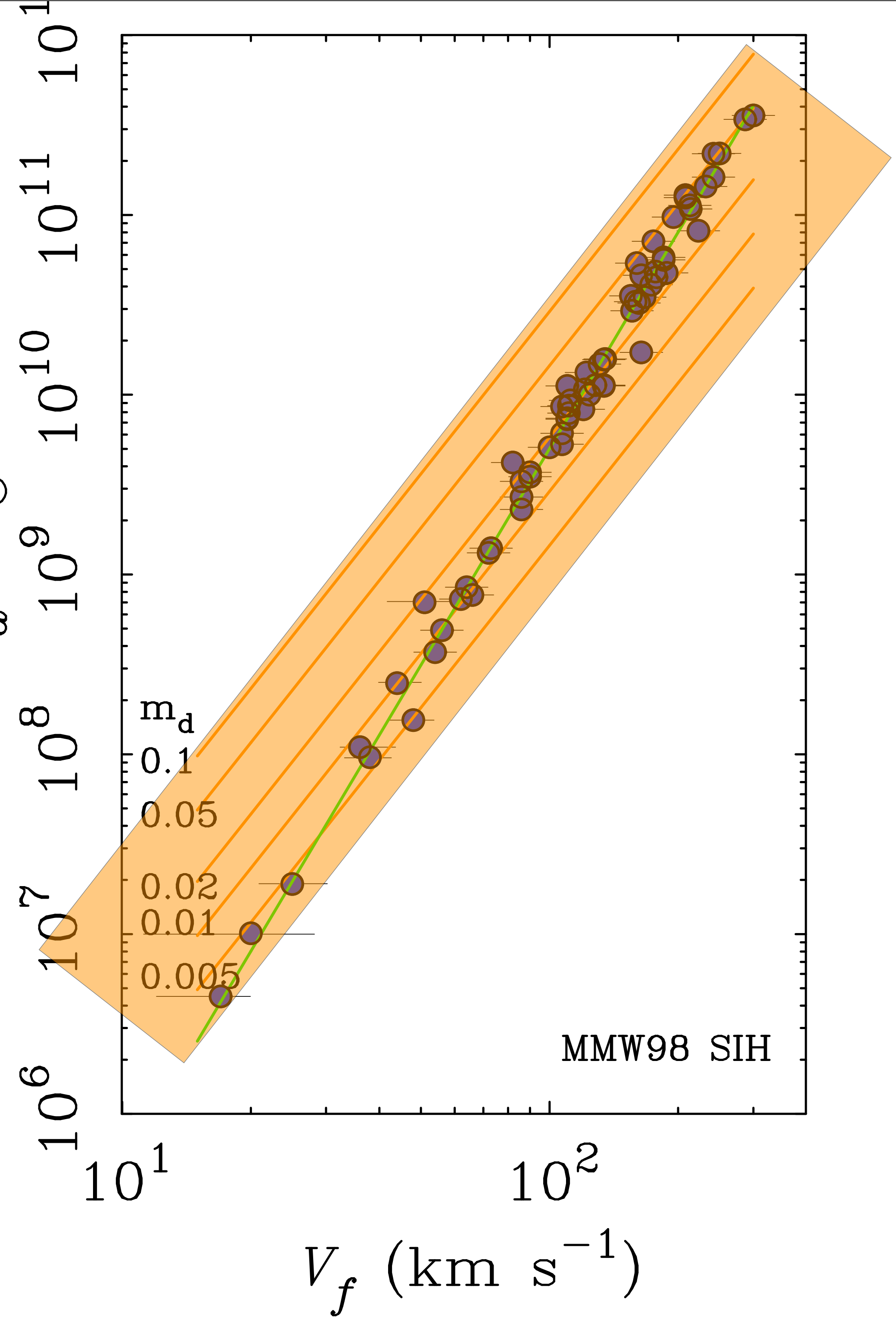
Really need extended dynamical range to constrain slope and normalization. Can get anything from $V_f > 100\,\mathrm{km\,s^{-1}}$

Constrains IMF: 0.5 < P < 1.3 (conservative)

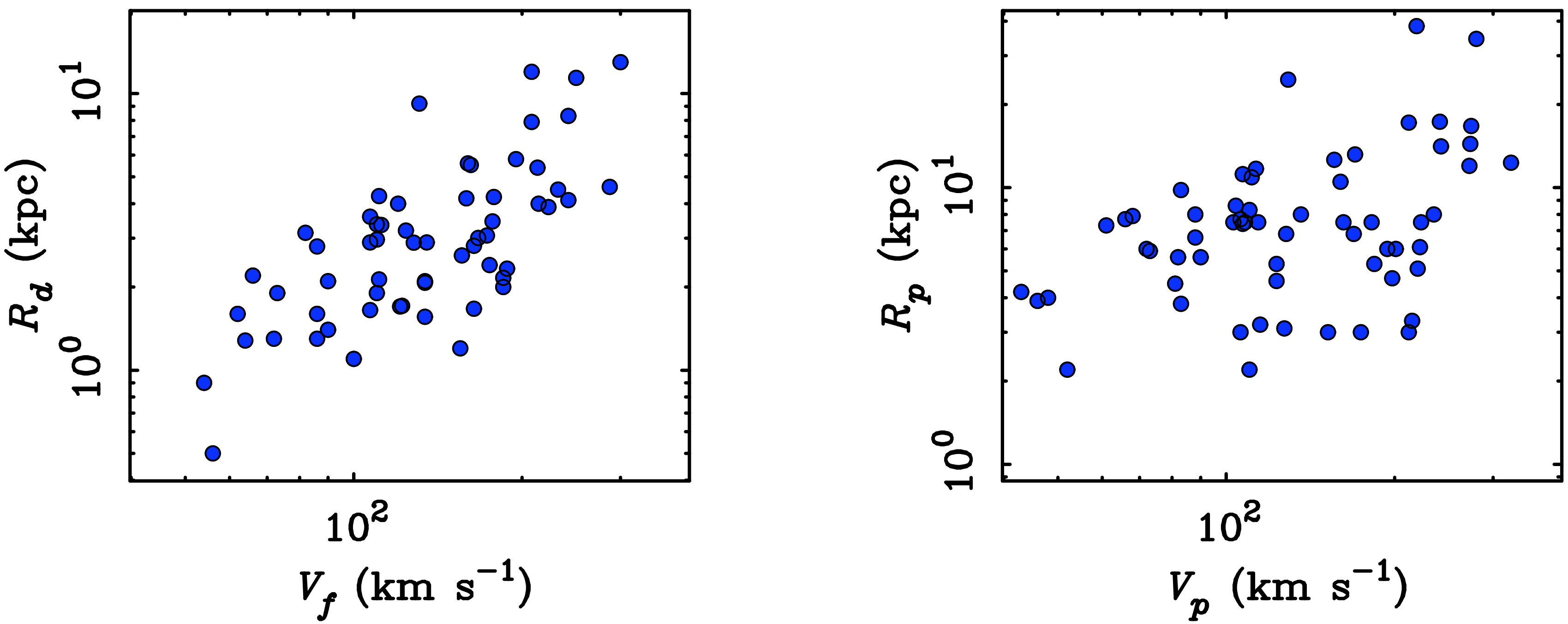
Steep slope implies disk fraction varies as $m_d \propto V_f$

$$m_d = \frac{\mathcal{M}_{disk}}{\mathcal{M}_{tot}}$$

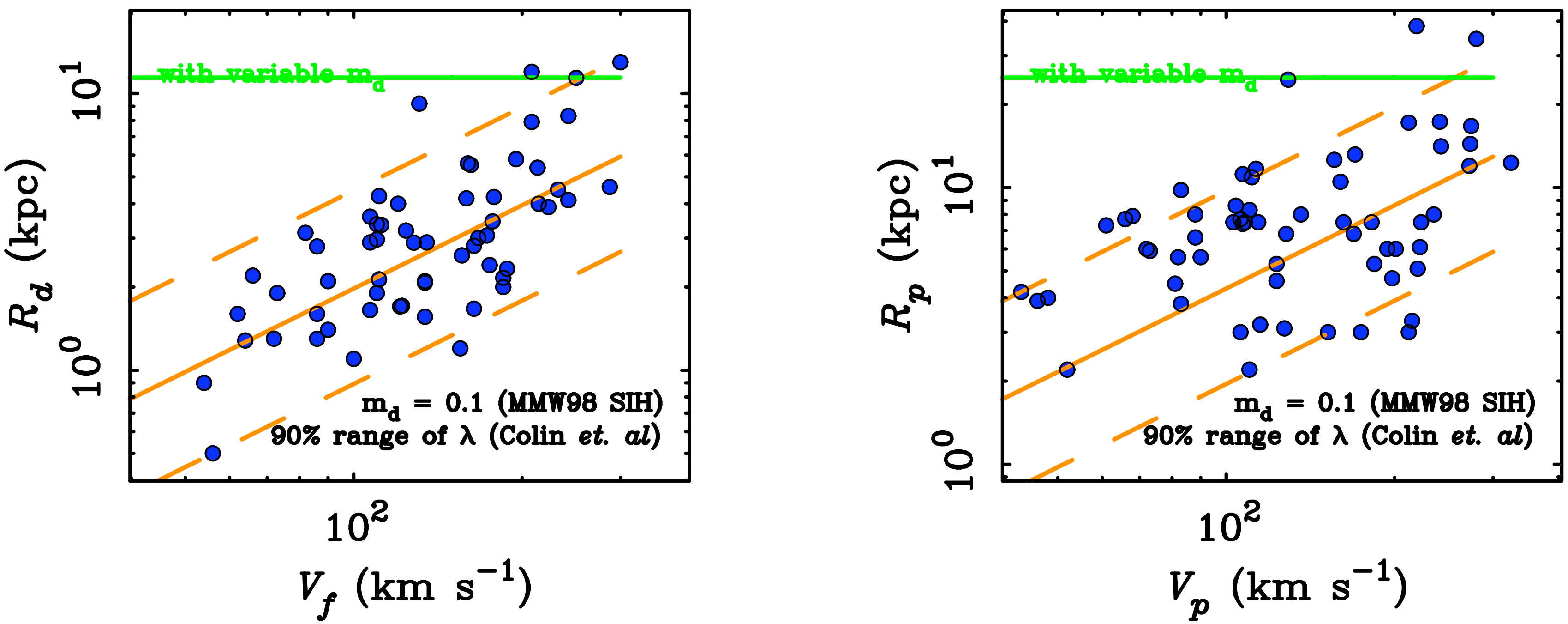
$$(m_d \leq f_b)$$



$$m_d \propto V_f$$



10^1
10^0
R_d (kpc)
10^2
V_f (km s^{-1})
10^1
10^0
R_p (kpc)
10^2
V_p (km s^{-1})



with variable m_d
m_d = 0.1 (MMW98 SIH)
90% range of λ (Colin et. al)
R_d (kpc)
V_f (km s^-1)
with variable m_d
m_d = 0.1 (MMW98 SIH)
90% range of λ (Colin et. al)
R_p (kpc)
V_p (km s^-1)

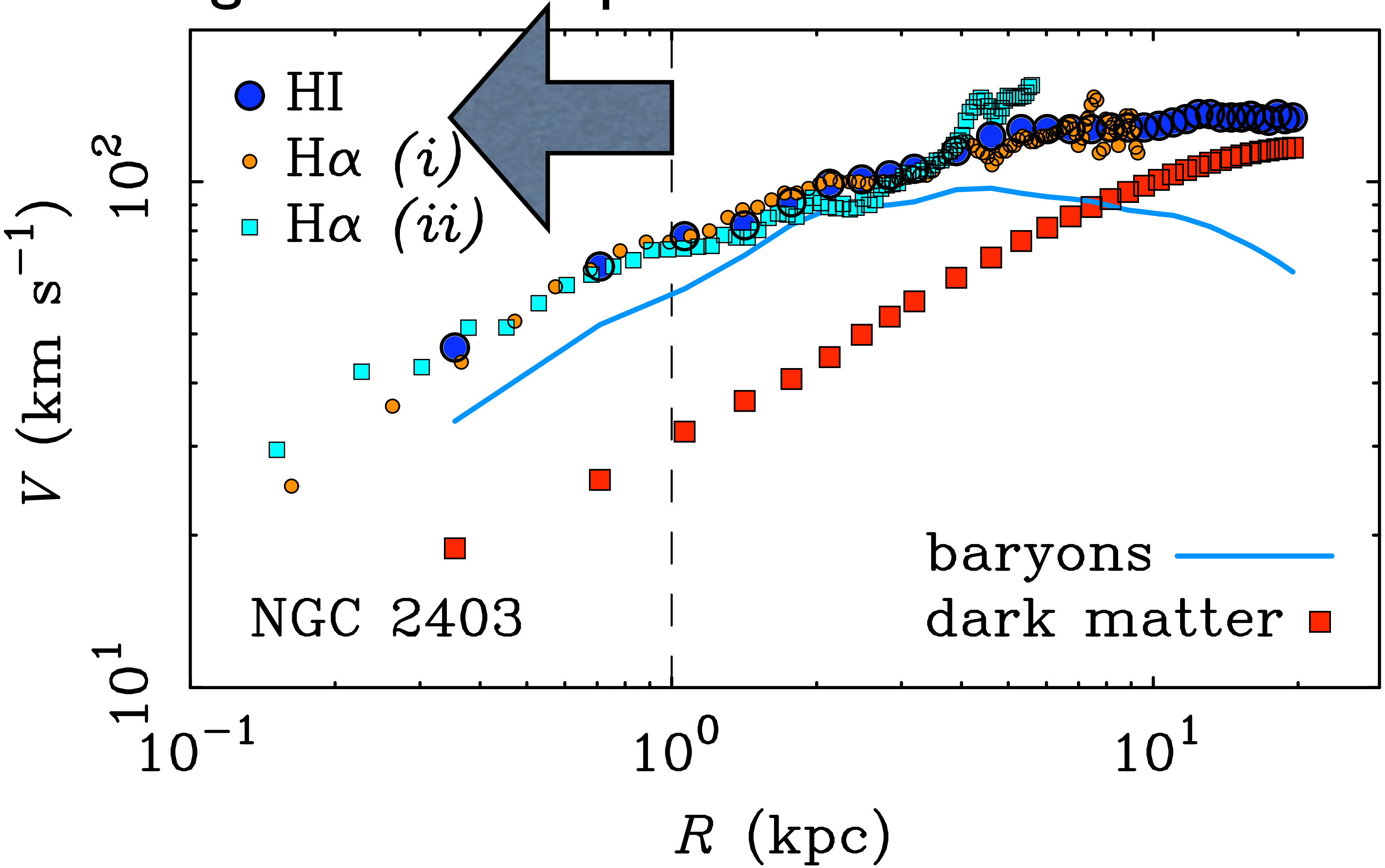
Intermediate radii

High precision sample of 60 galaxies

Ignore inner 1 kpc where systematics might affect cusp

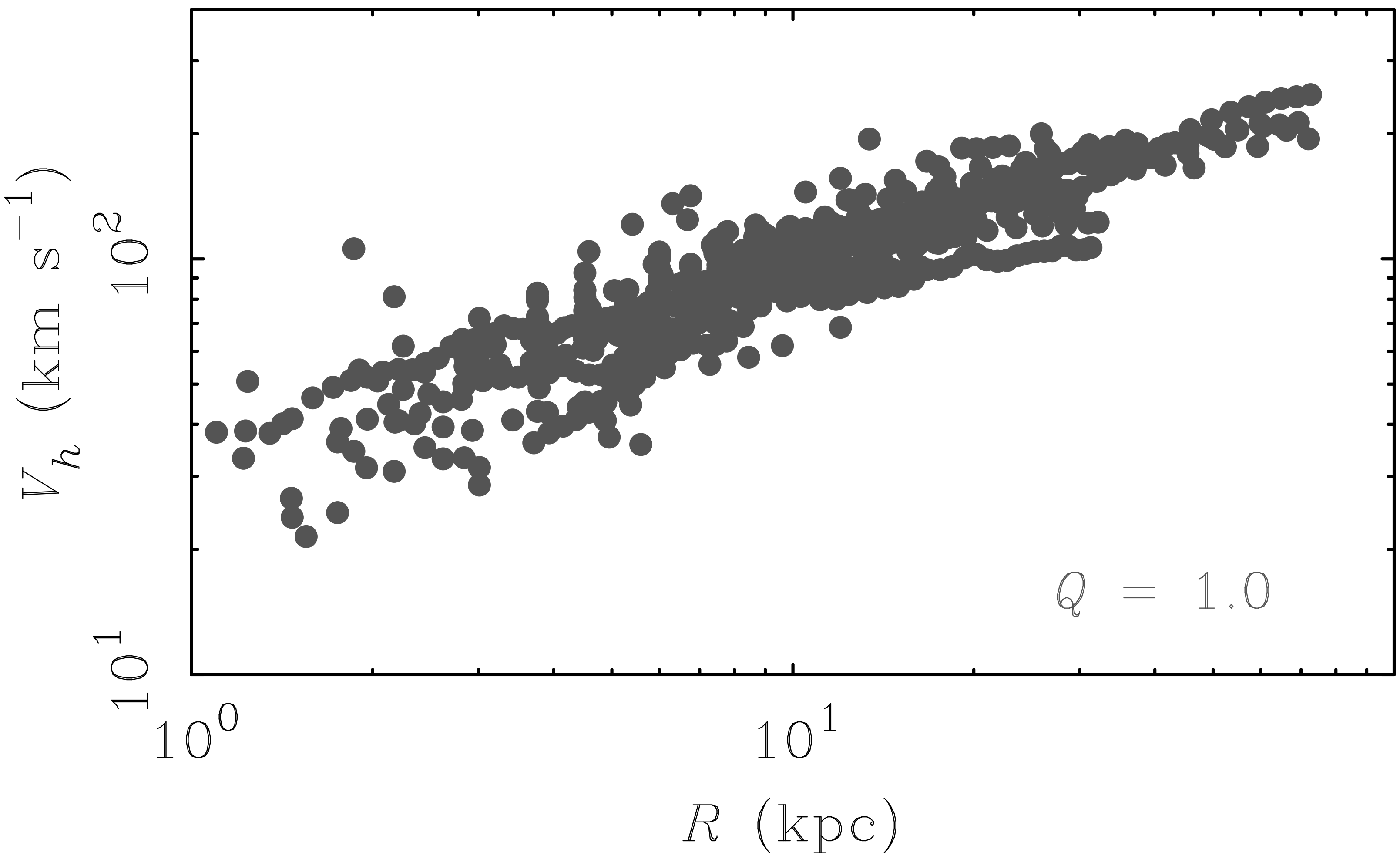
Constrain concentration in model independent fashion -
no individual fits, just amplitude of dark halo V(R)

let's ignore inner kpc



- Begeman (1987): HI data
- Blais-Ouellette et al. (2004) Hα Fabry-Perot
- Daigle et al. (2006) Hα Fabry-Perot

dark matter-only V(R) for 60 galaxies



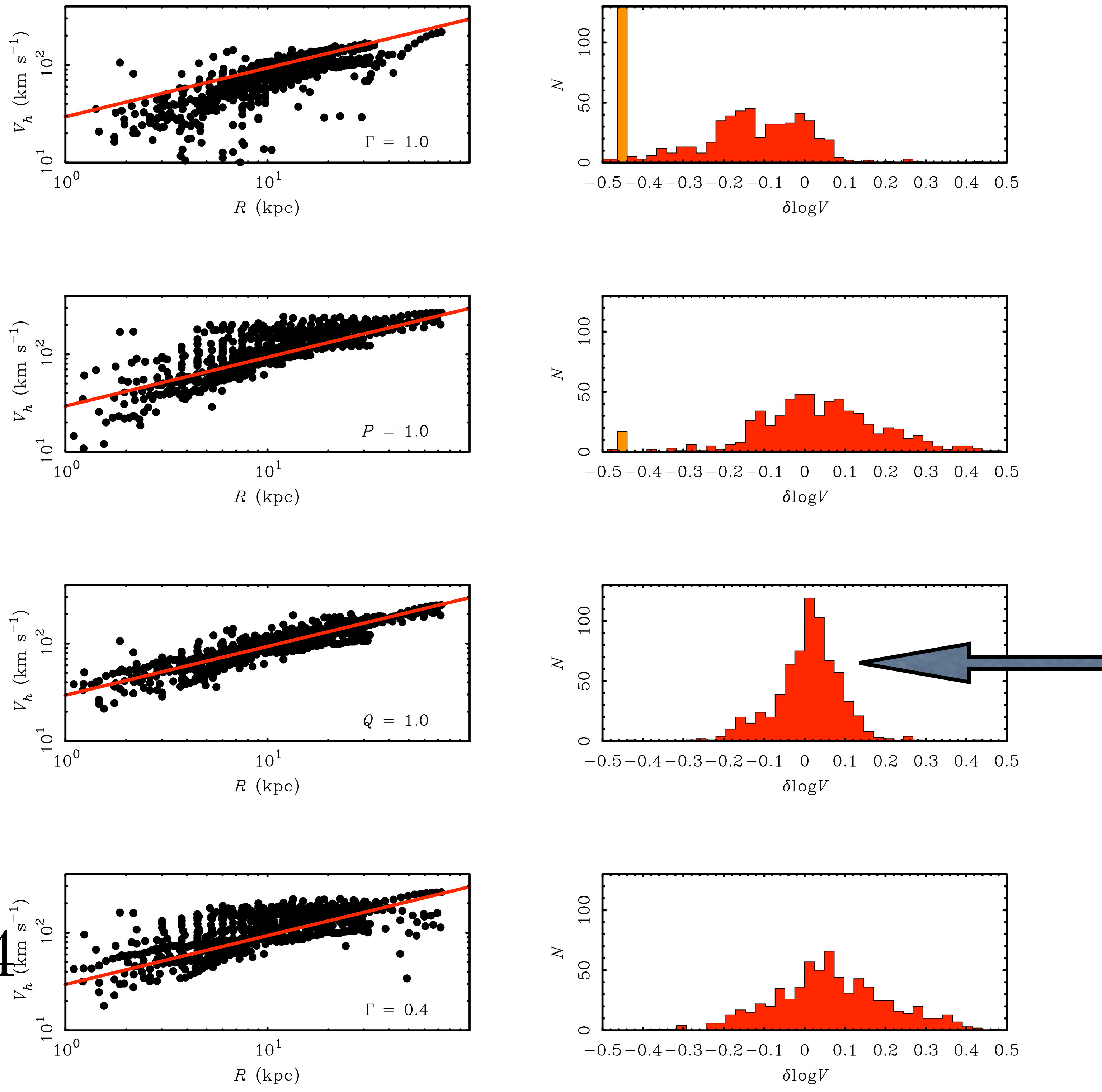
R > 1 kpc: logV-logR slope = 0.49
indistinguishable from NFW inner slope

$\Gamma = 1$

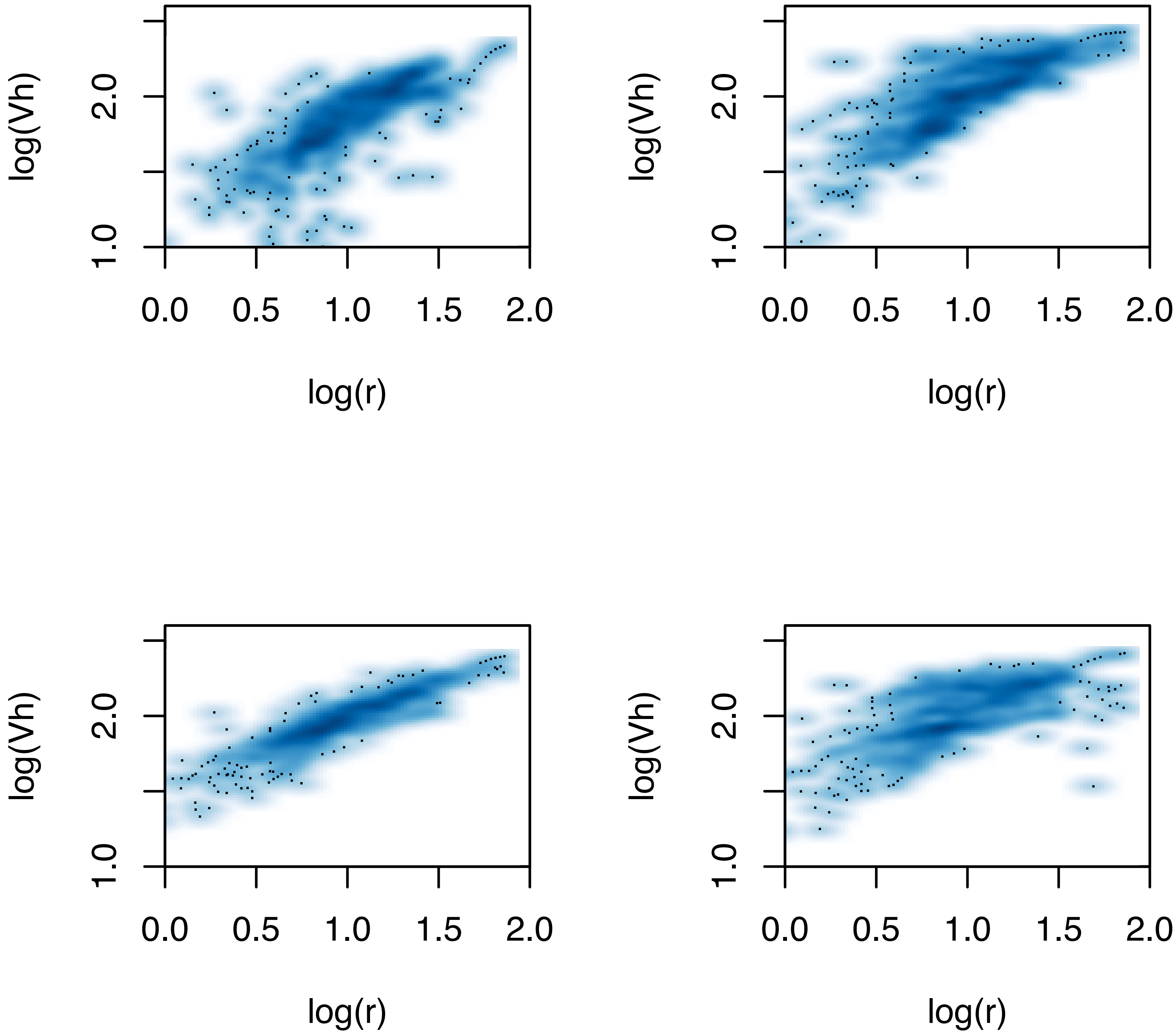
$\mathcal{P} = 1$

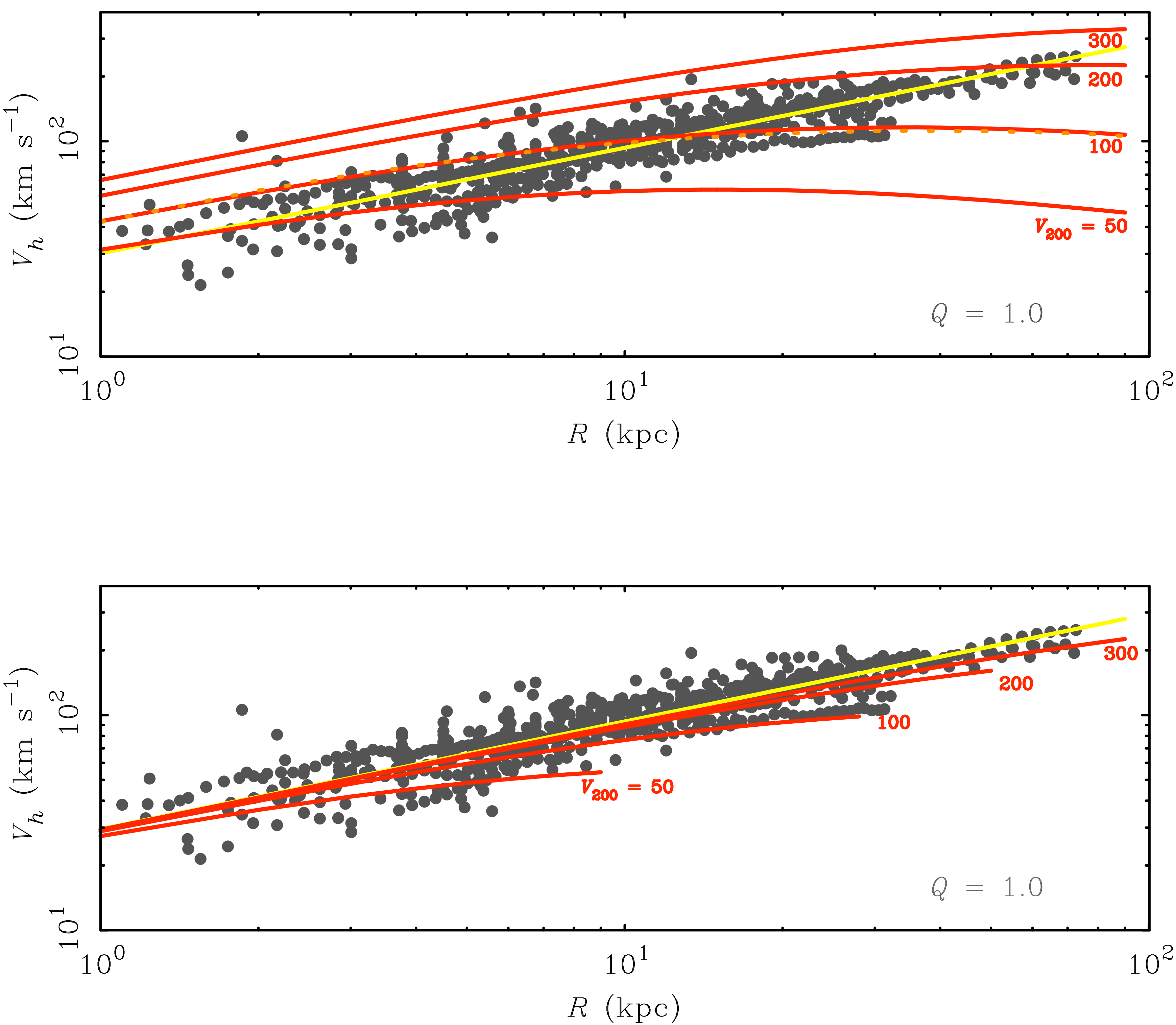
$\mathcal{Q} = 1$

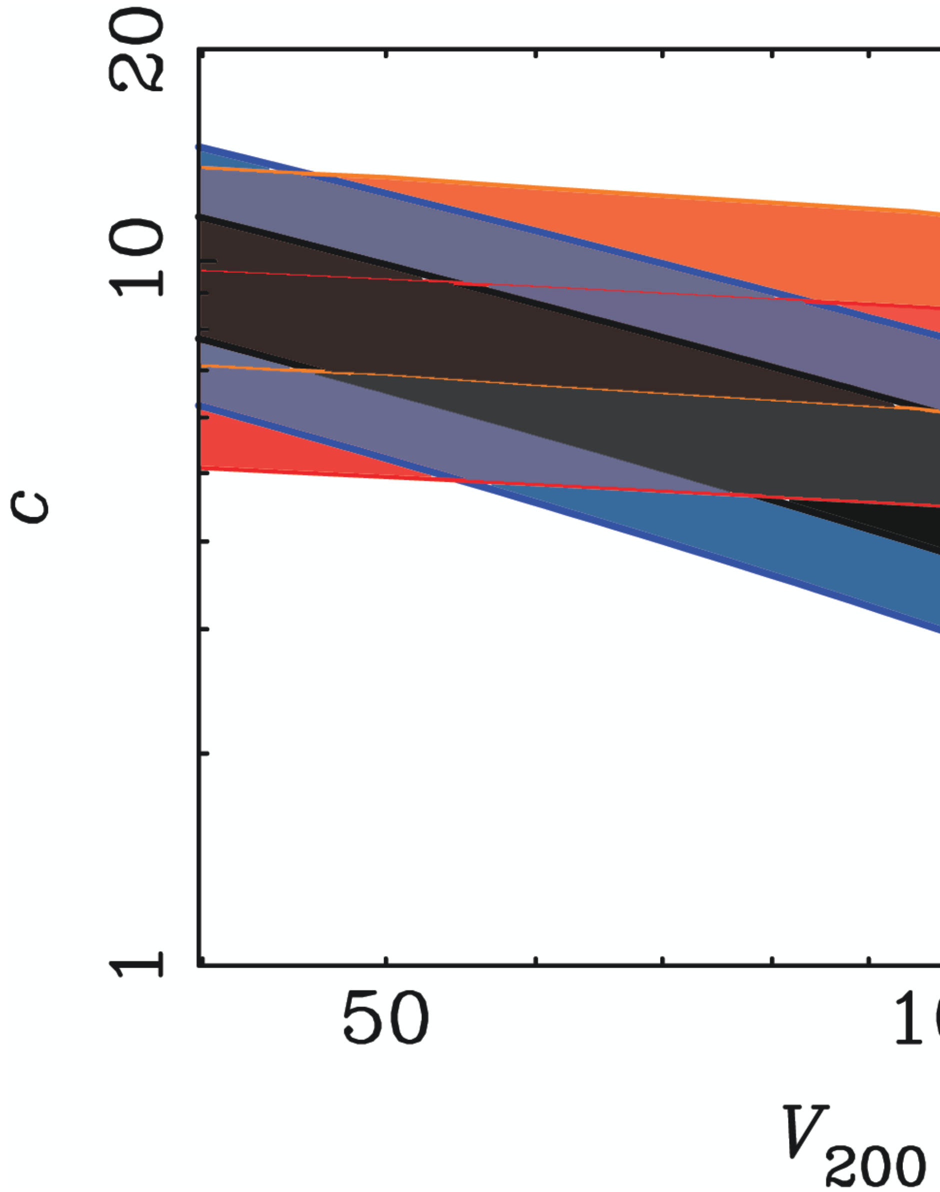
$\Gamma = 0.4$



$\mathcal{Q} = 1$ also minimizes scatter in dark matter!

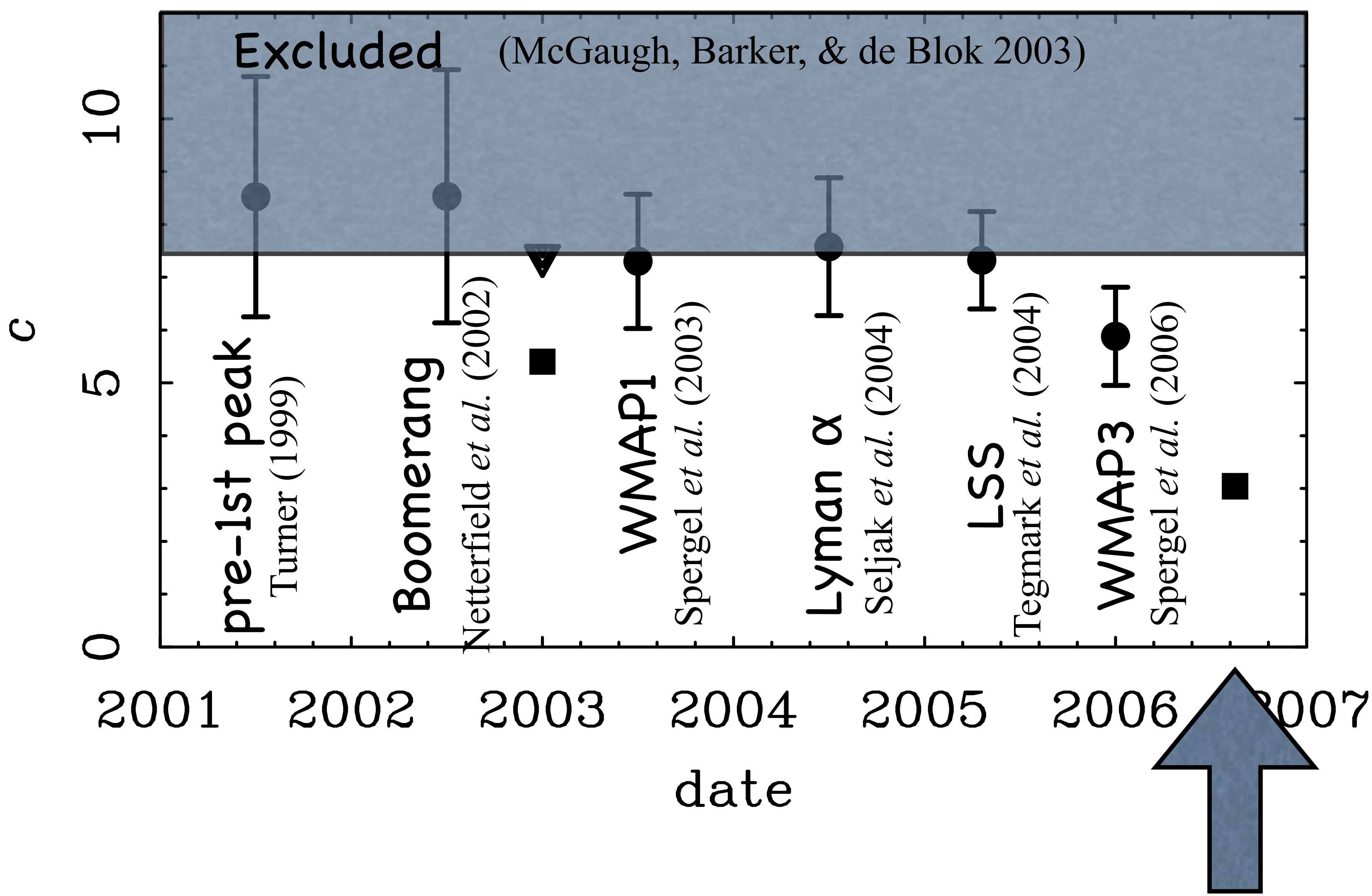

log(Vh)
1.0
2.0
0.0
0.5
1.0
1.5
2.0
log(r)
log(Vh)
1.0
2.0
0.0
0.5
1.0
1.5
2.0
log(r)
log(Vh)
1.0
2.0
0.0
0.5
1.0
1.5
2.0
log(r)
log(Vh)
1.0
2.0
0.0
0.5
1.0
1.5
2.0
log(r)


300
200
100
V_{200} = 50
Q = 1.0
V_h (km s^{-1})
R (kpc)
10^1
10^2
10^0
10^1
10^2
300
200
100
V_{200} = 50
Q = 1.0
V_h (km s^{-1})
R (kpc)
10^1
10^2
10^0
10^1
10^2



$$\Gamma_{0.6} = \Omega_m^{0.6} h e^{-(\Omega_b + \sqrt{2h}\frac{\Omega_b}{\Omega_m})}$$

$$c = 1.88 + 23.9\sigma_8\Gamma_{0.6}$$



$10^{12}\ M_{\odot}$ halos require $\sigma_8 \approx 0.3$ or $\Omega_m \approx 0.05$

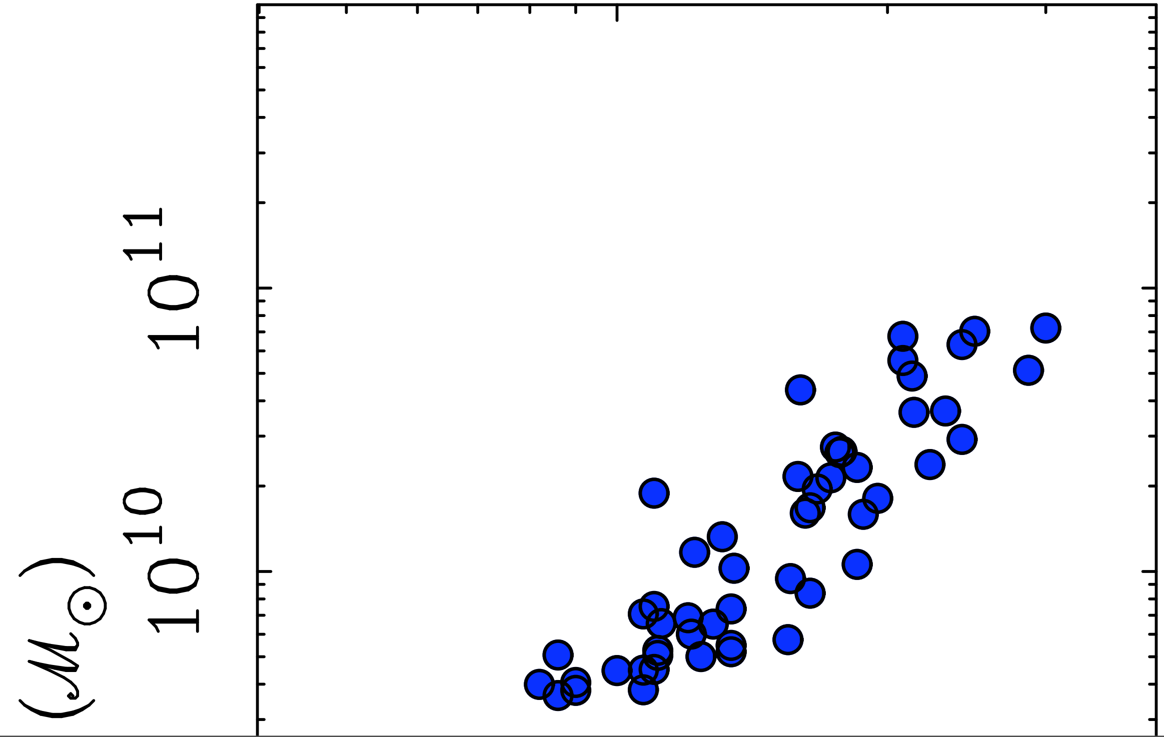
dark matter density summary

WMAP3 catching up with rotation curves -
concentrations are low.

OK now for low mass galaxies, but a problem for big ones.

Observed c-V_{200} relation too steep;
need IMF to become systematically lighter with increasing halo mass

BUT this screws up BTF:



Central Profile: high resolution velocity fields

Thesis project of Rachel Kuzio de Naray (astro-ph/0604576)

(Kuzio de Naray, McGaugh, de Blok, & Bosma, ApJS, in press)

Observed 28 dwarf and/or LSB galaxies with Densepak IFU

- 12 from LSB "clean" sample with well resolved long slit data

- 16 dwarfs selected from Nearby Galaxies Catalog to have

$$V_f \approx \frac{W_{20}}{2} < 100\,\mathrm{km\,s^{-1}}$$

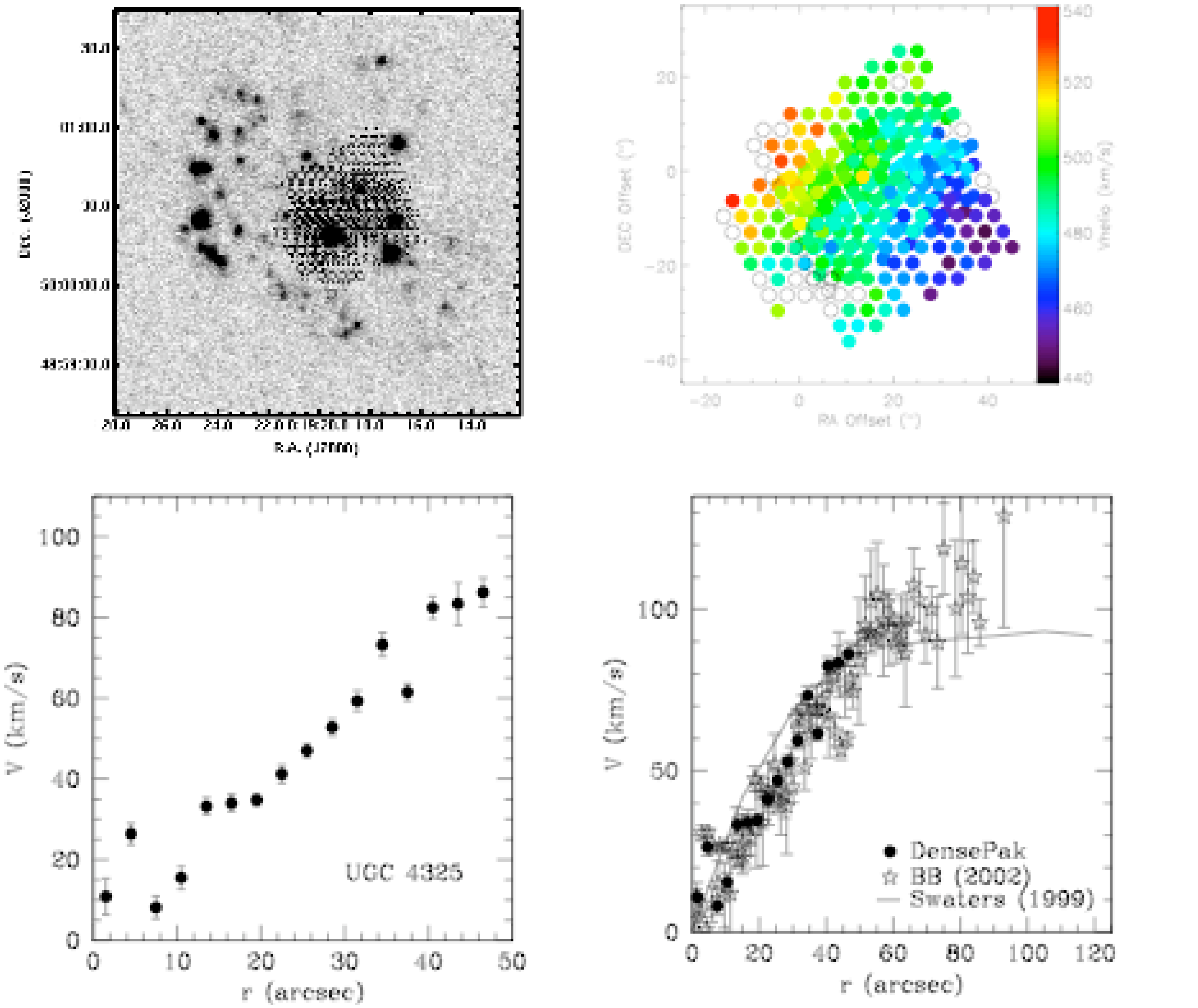


Fig. 1.— Results for UGC 4325: *(Upper left)* Position of DensePak array on the Hα image

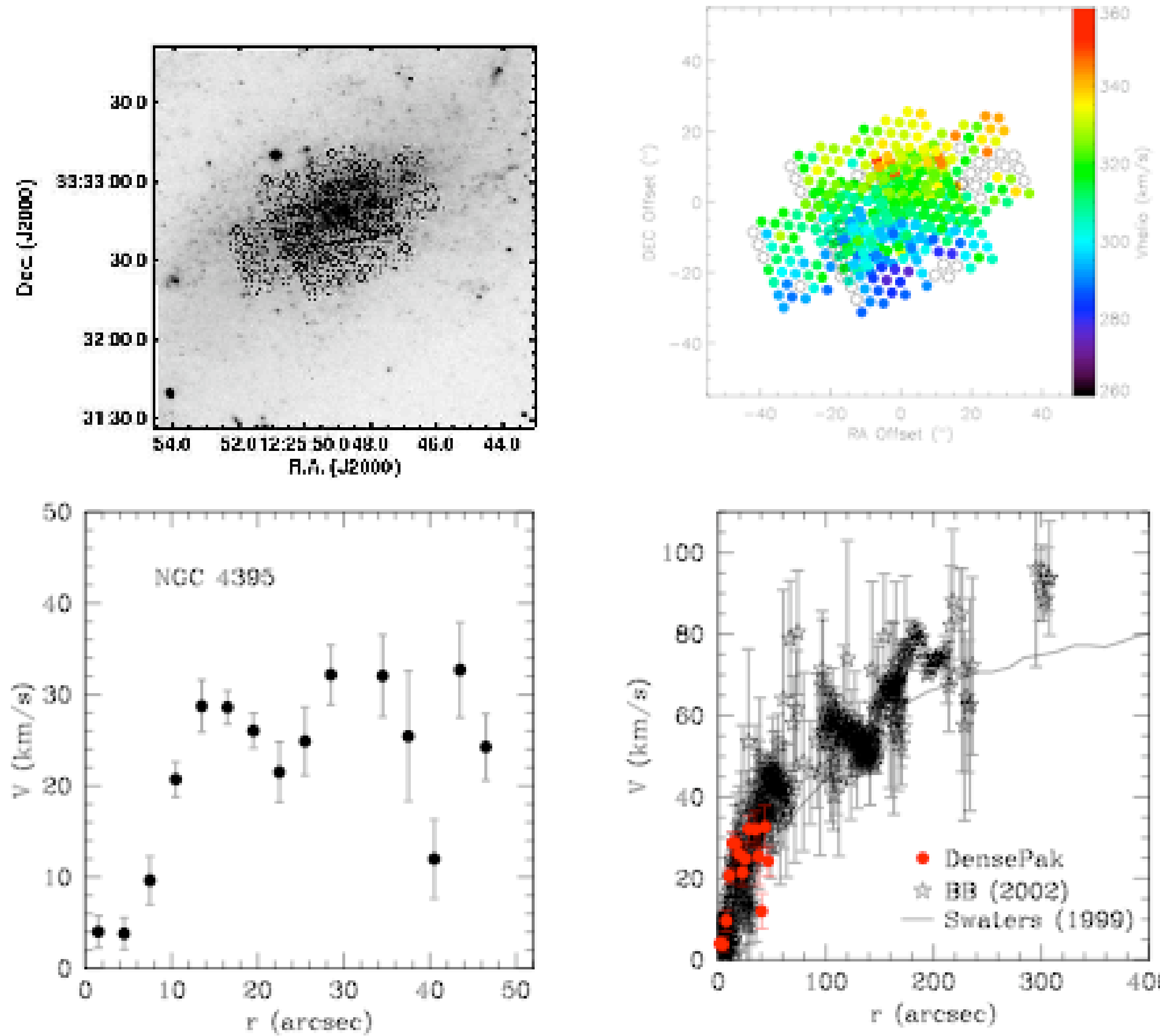
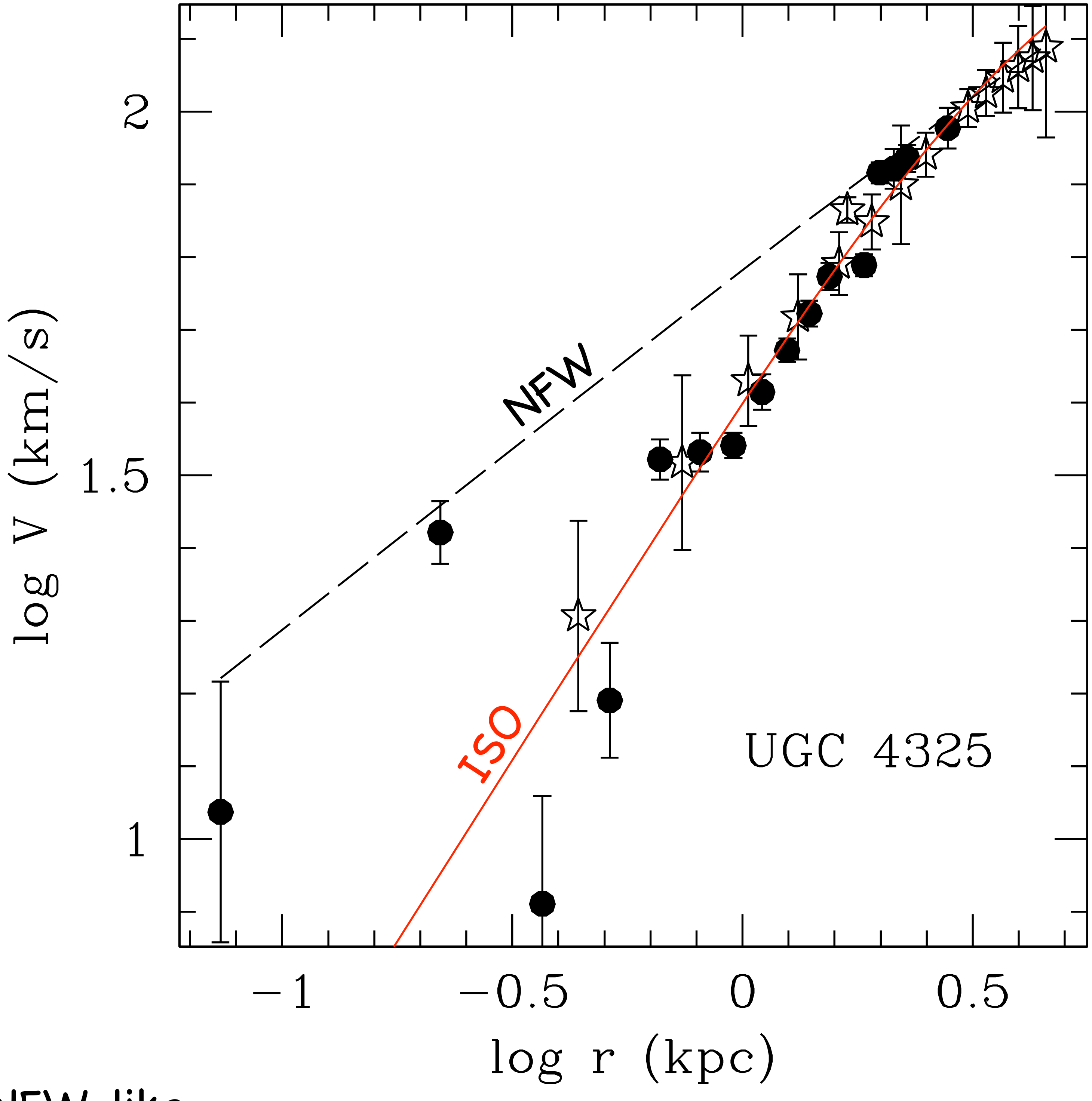
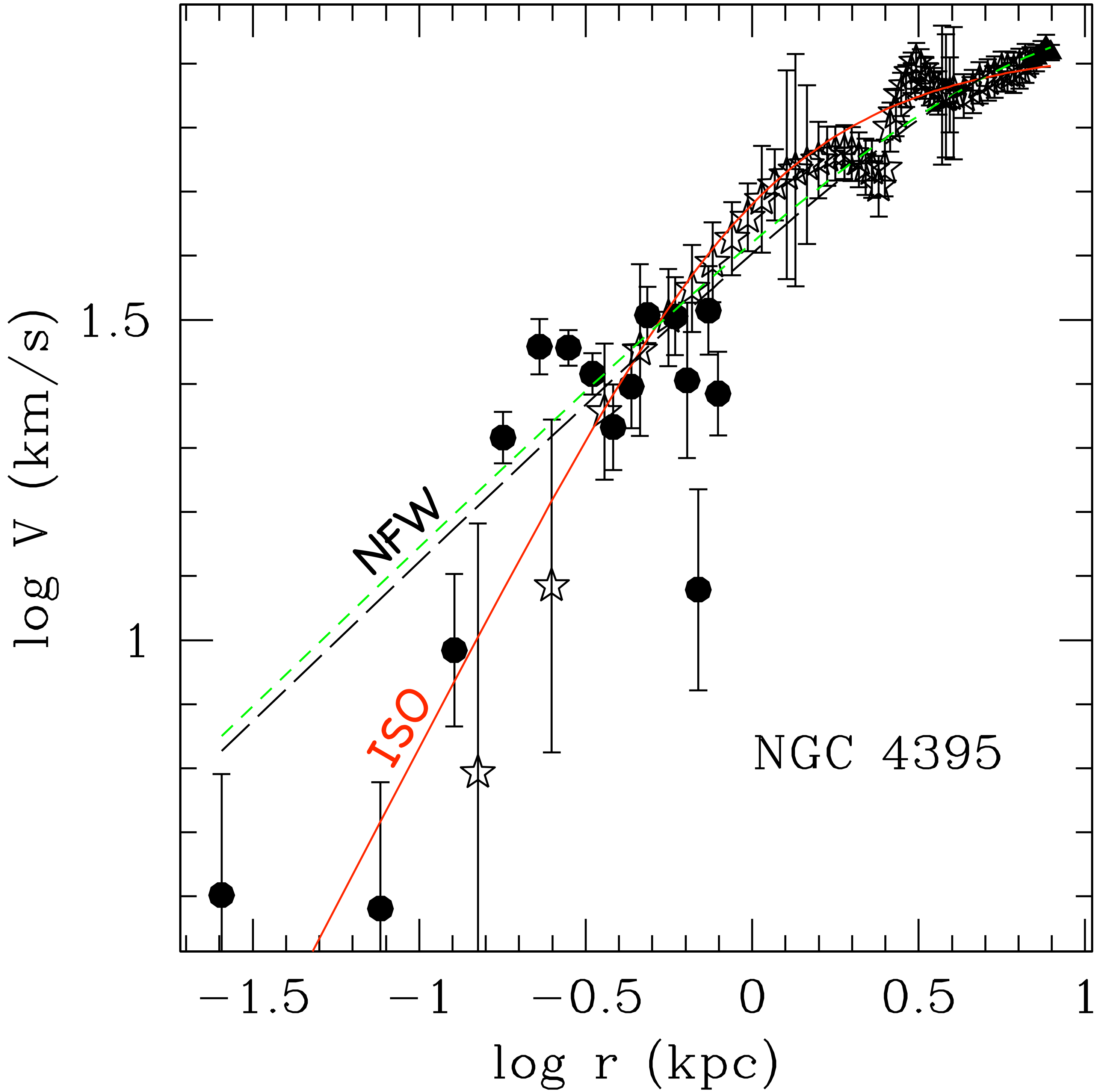


Fig. 7.— Results for NGC 4395: *(Upper left)* Position of DensePak array on an R-band



least NFW-like



most NFW-like

Central Profile Summary

2D velocity fields give same answer as long slit data

Of 11 dwarf/LSB galaxies with decent 2D velocity fields

7 prefer ISO

1 prefers NFW

3 indistinguishable

in limit of zero disk. Baryonic mass non-negligible at small radii, even in LSBs. This is the most important systematic effect!

velocity dispersions modest -- 7 - 10 km/s

no room for concentrated potential to hide

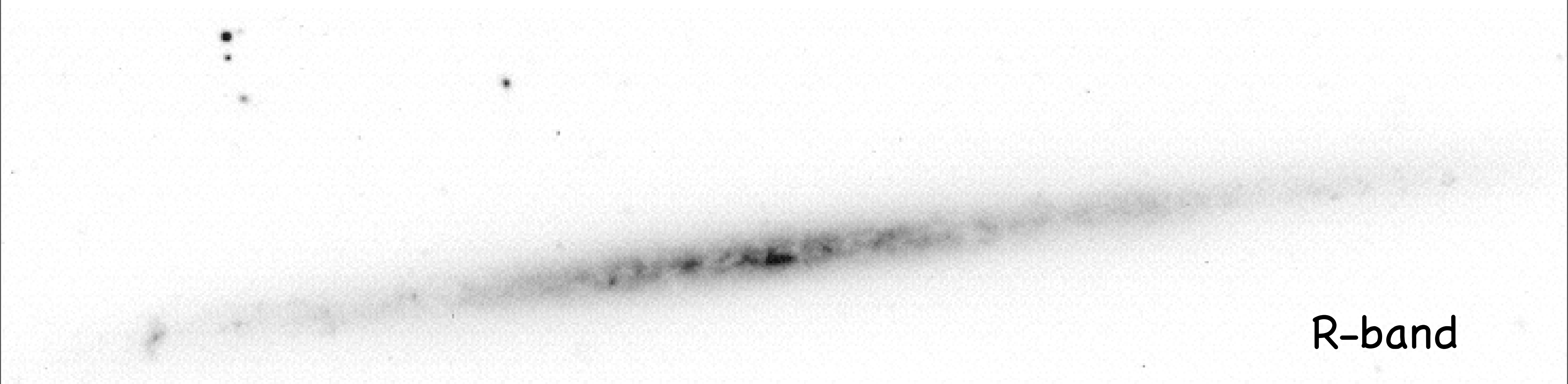
UGC 7321

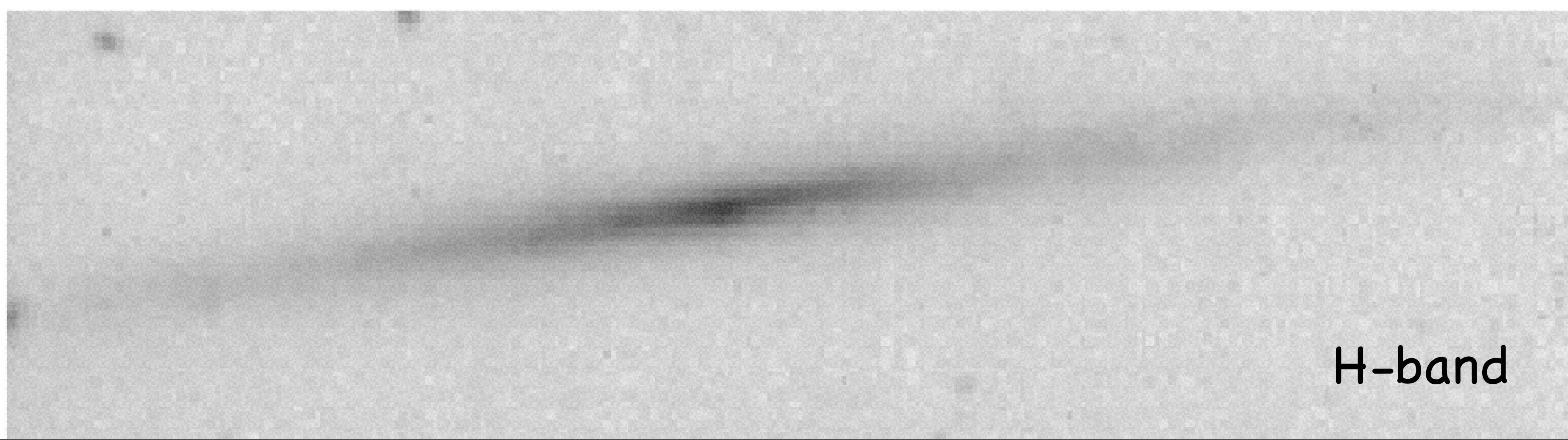
(Matthews, Gallagher, & van Driel 1999)

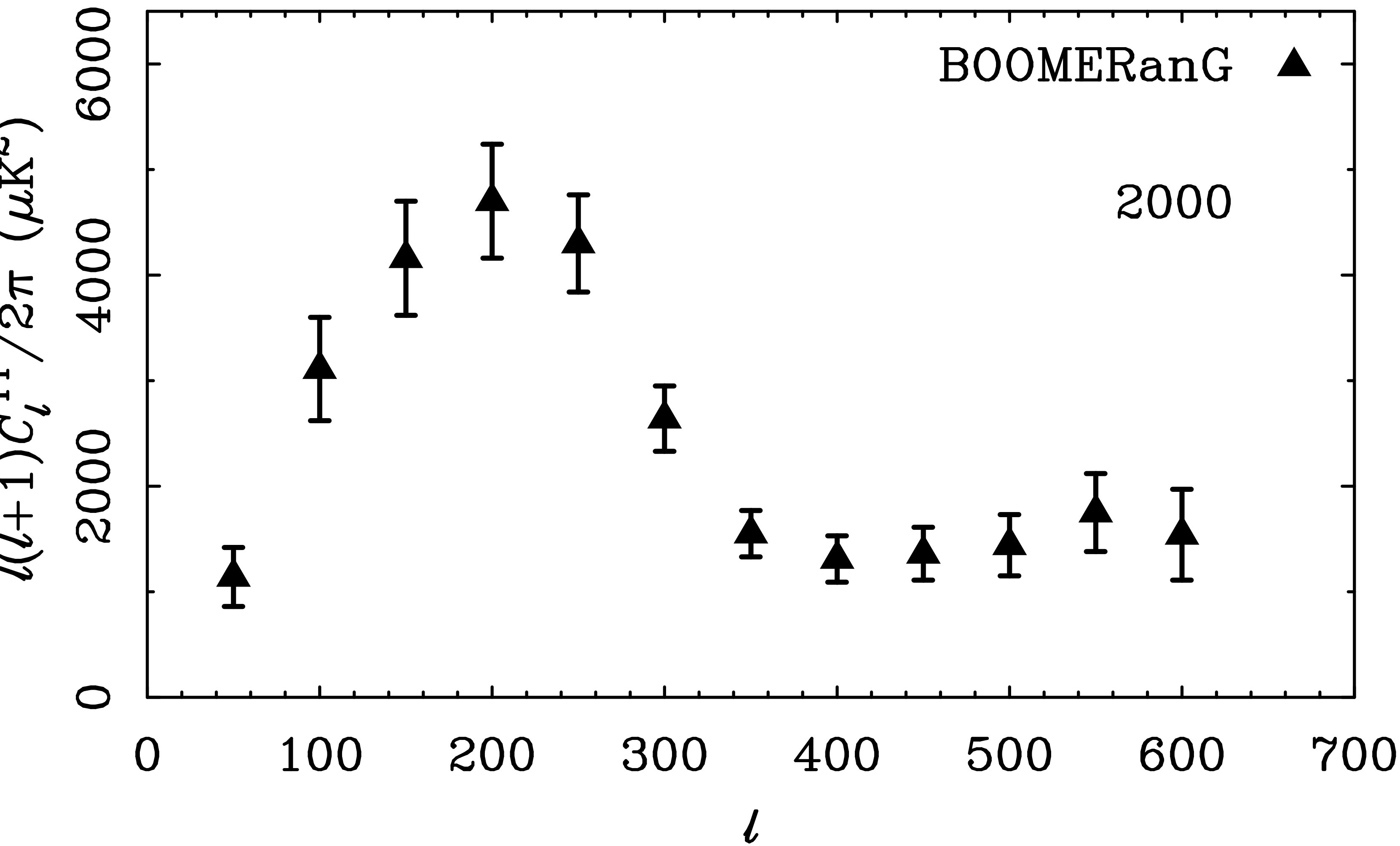
$$h_z = 140 \text{ pc}$$

$$\frac{h_r}{h_z} = 14$$

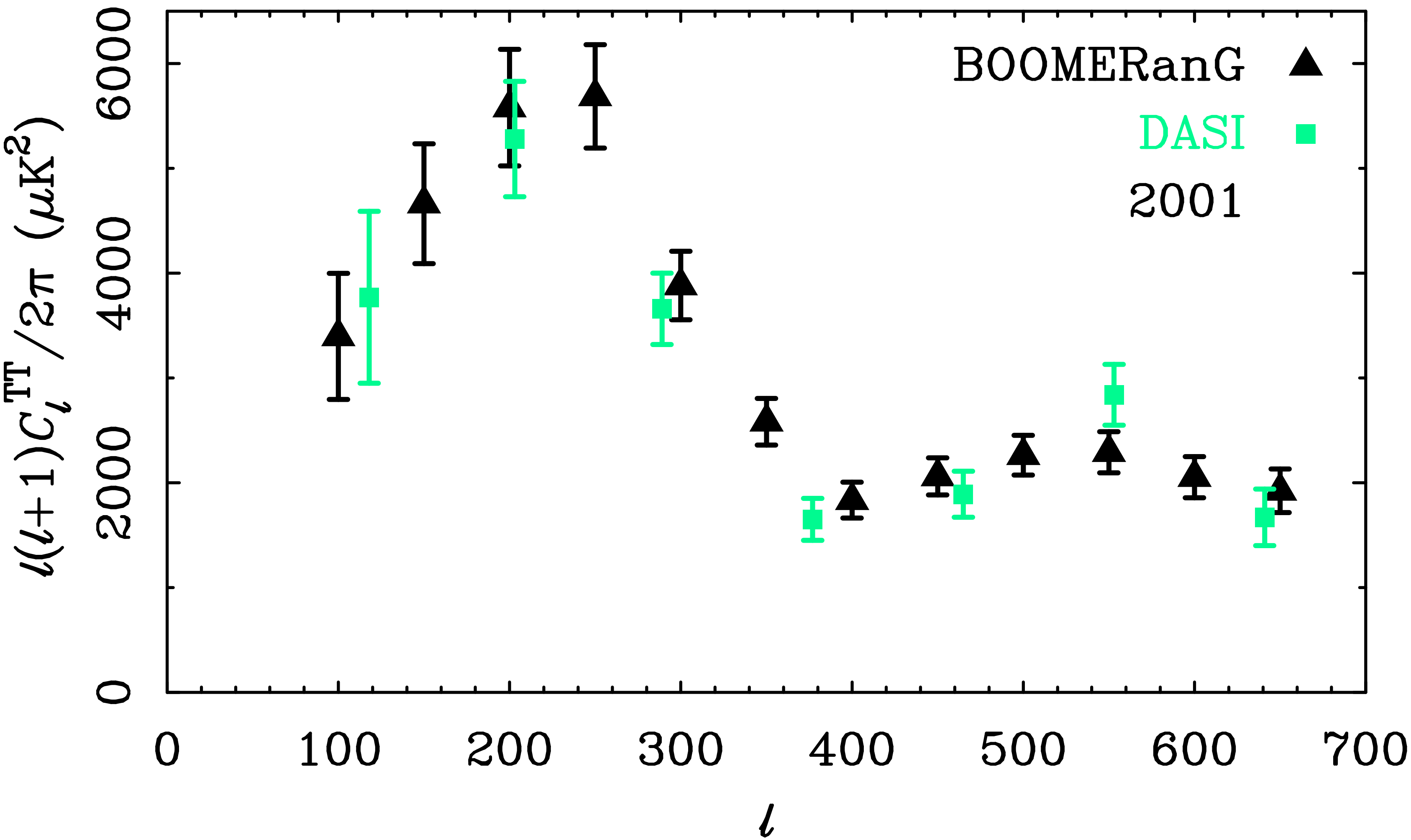
What is the velocity ellipsoid of this beast?



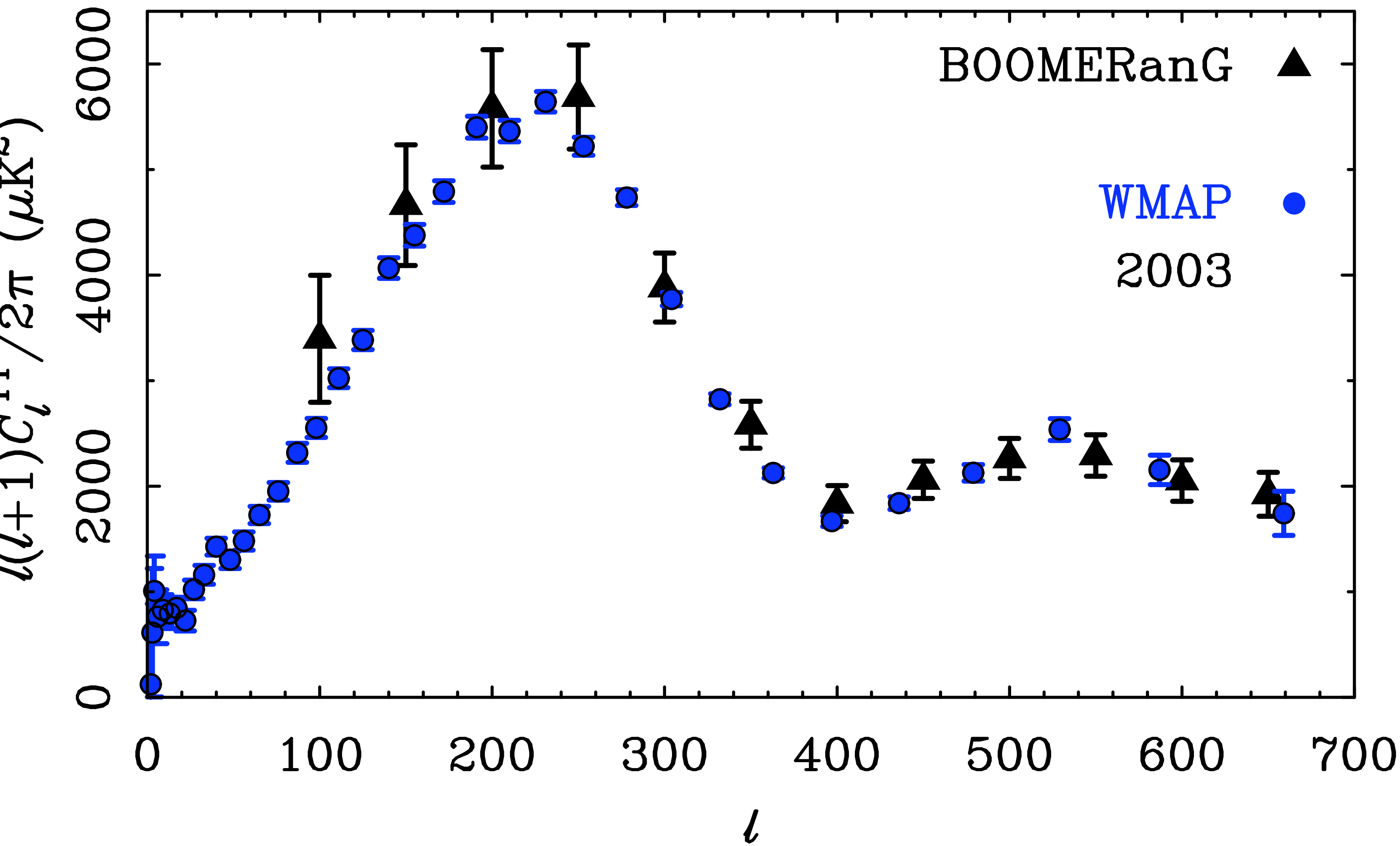




BOOMERanG
2000
$\ell(\ell+1)C_\ell^{TT}/2\pi\ (\mu K^2)$
0
2000
4000
6000
0
100
200
300
400
500
600
700
ℓ

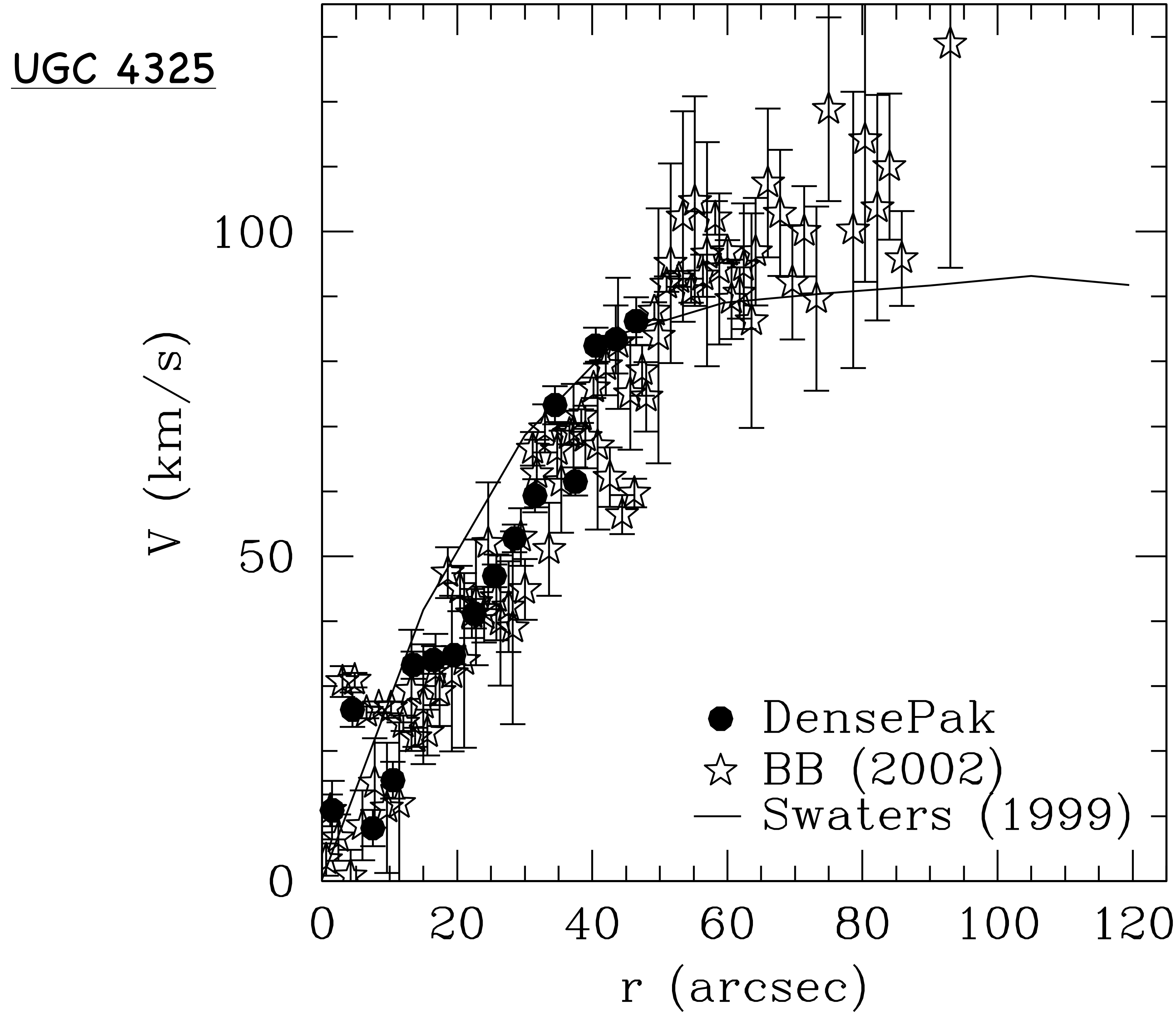


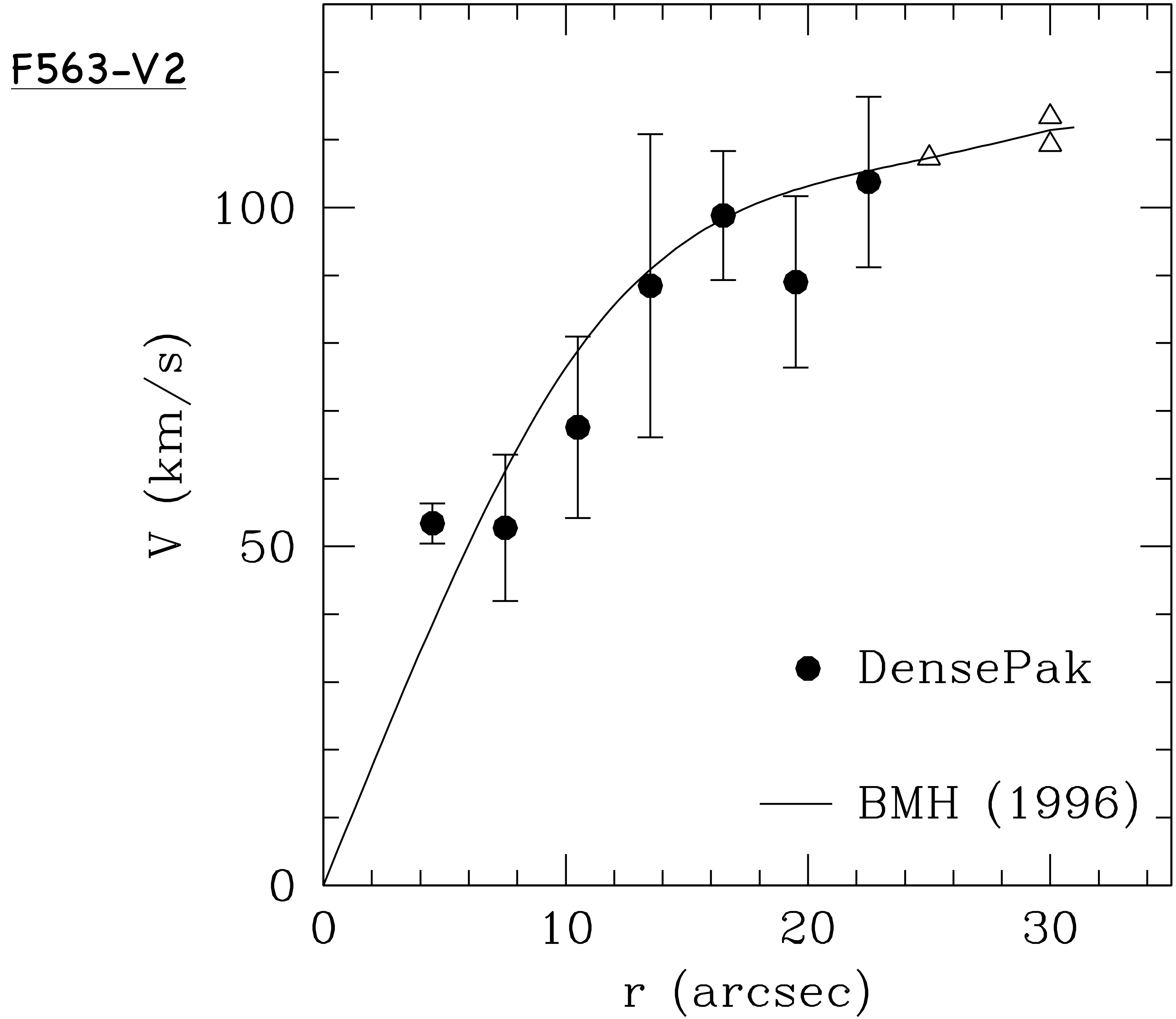
BOOMERanG
DASI
2001
0
2000
4000
6000
0
100
200
300
400
500
600
700
$\ell(\ell+1)C_\ell^{TT}/2\pi$ (μK^2)
ℓ

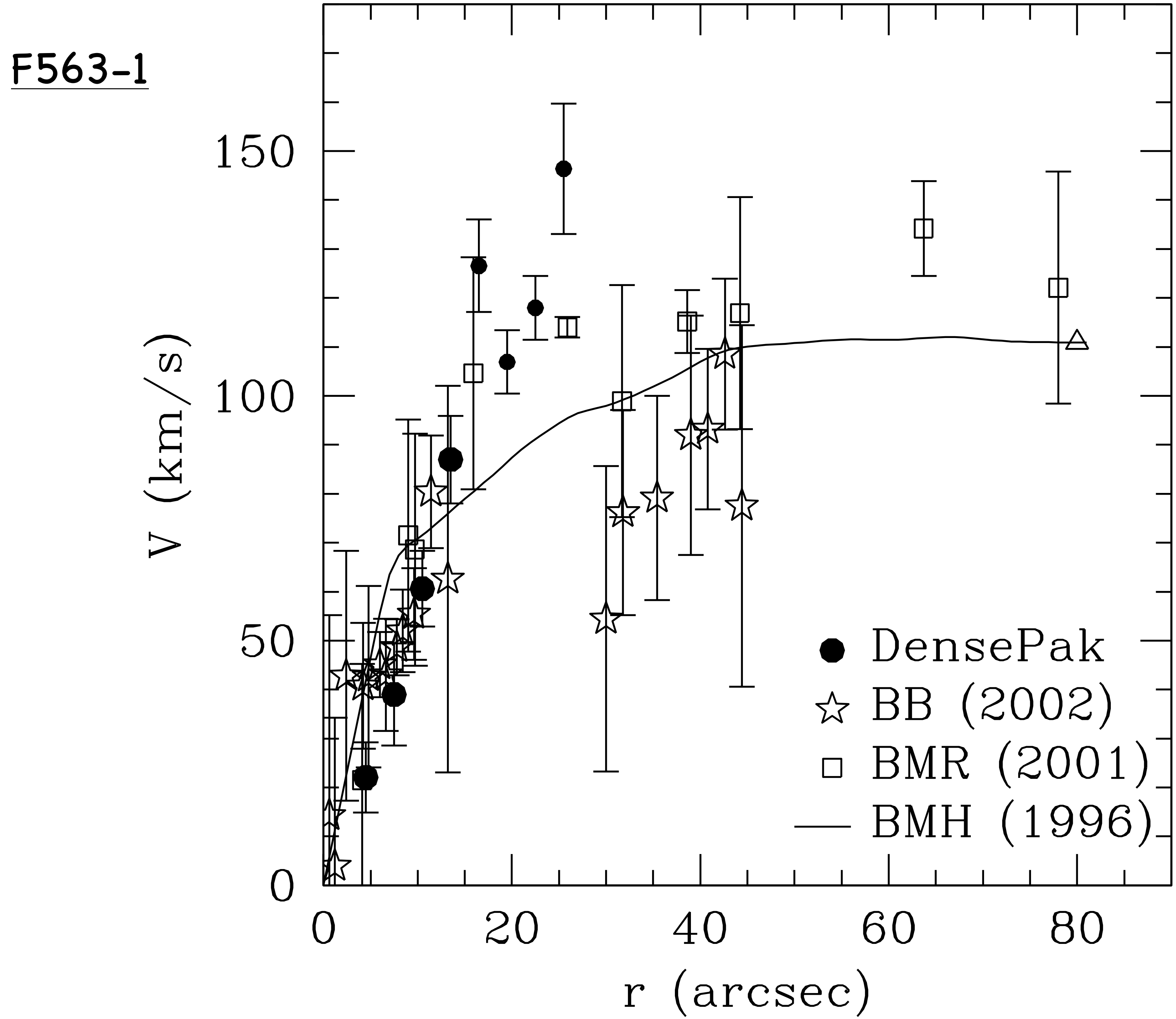


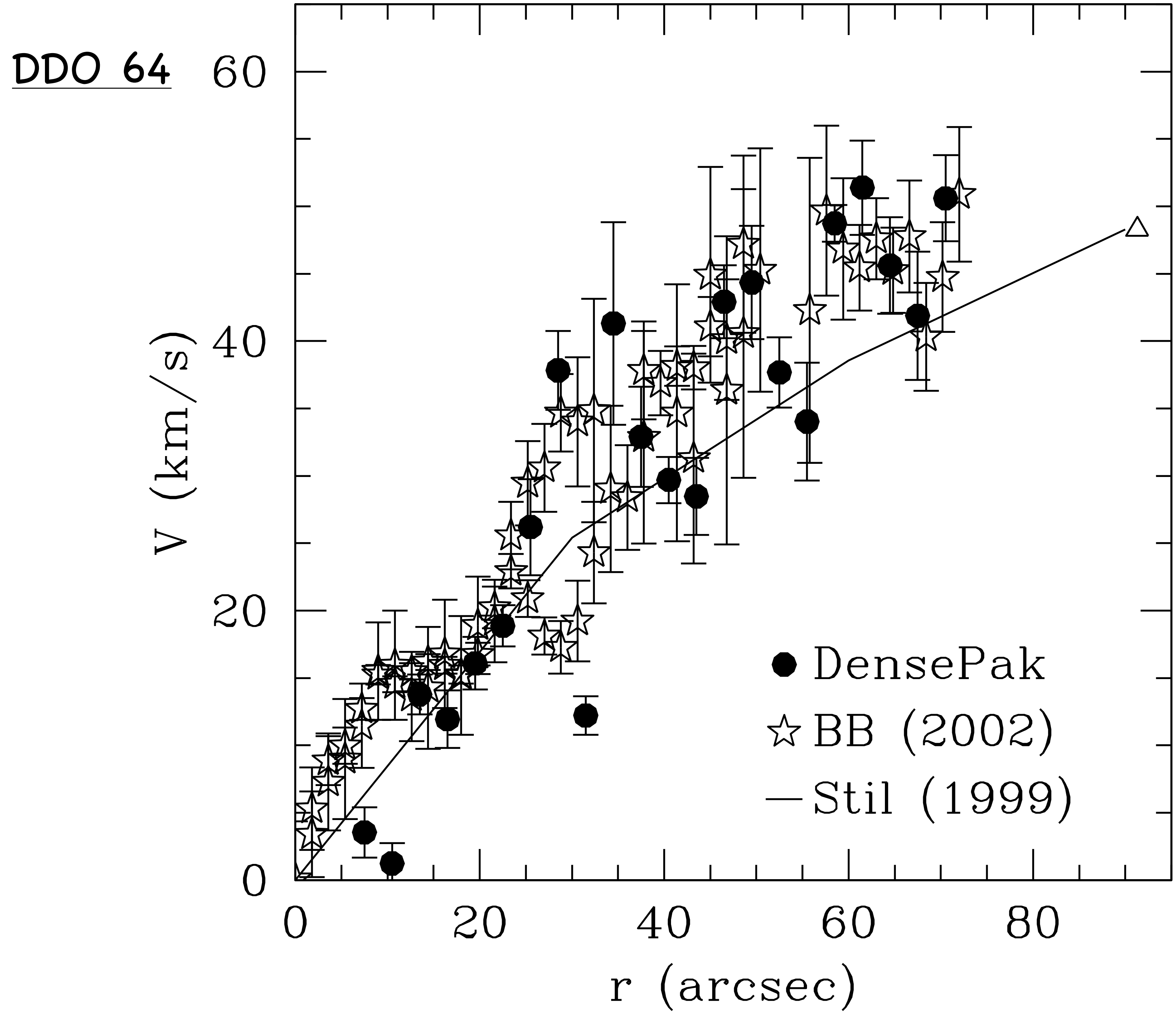
Data improve with time.

Details often change, usually not basic answer

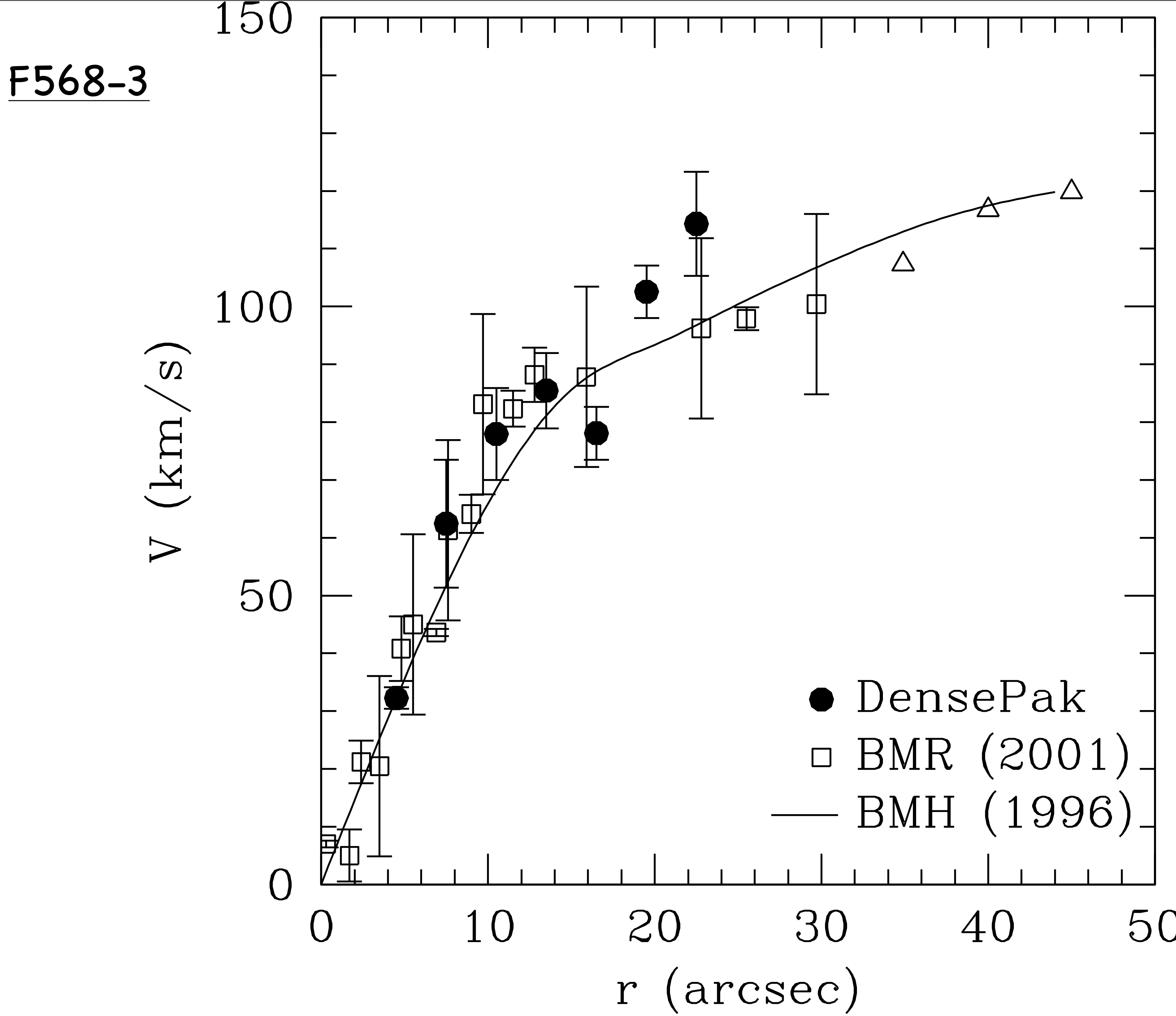

UGC 4325
V (km/s)
r (arcsec)
0
50
100
0
20
40
60
80
100
120
DensePak
BB (2002)
Swaters (1999)


F563-V2
V (km/s)
0
50
100
0
10
20
30
r (arcsec)
DensePak
BMH (1996)

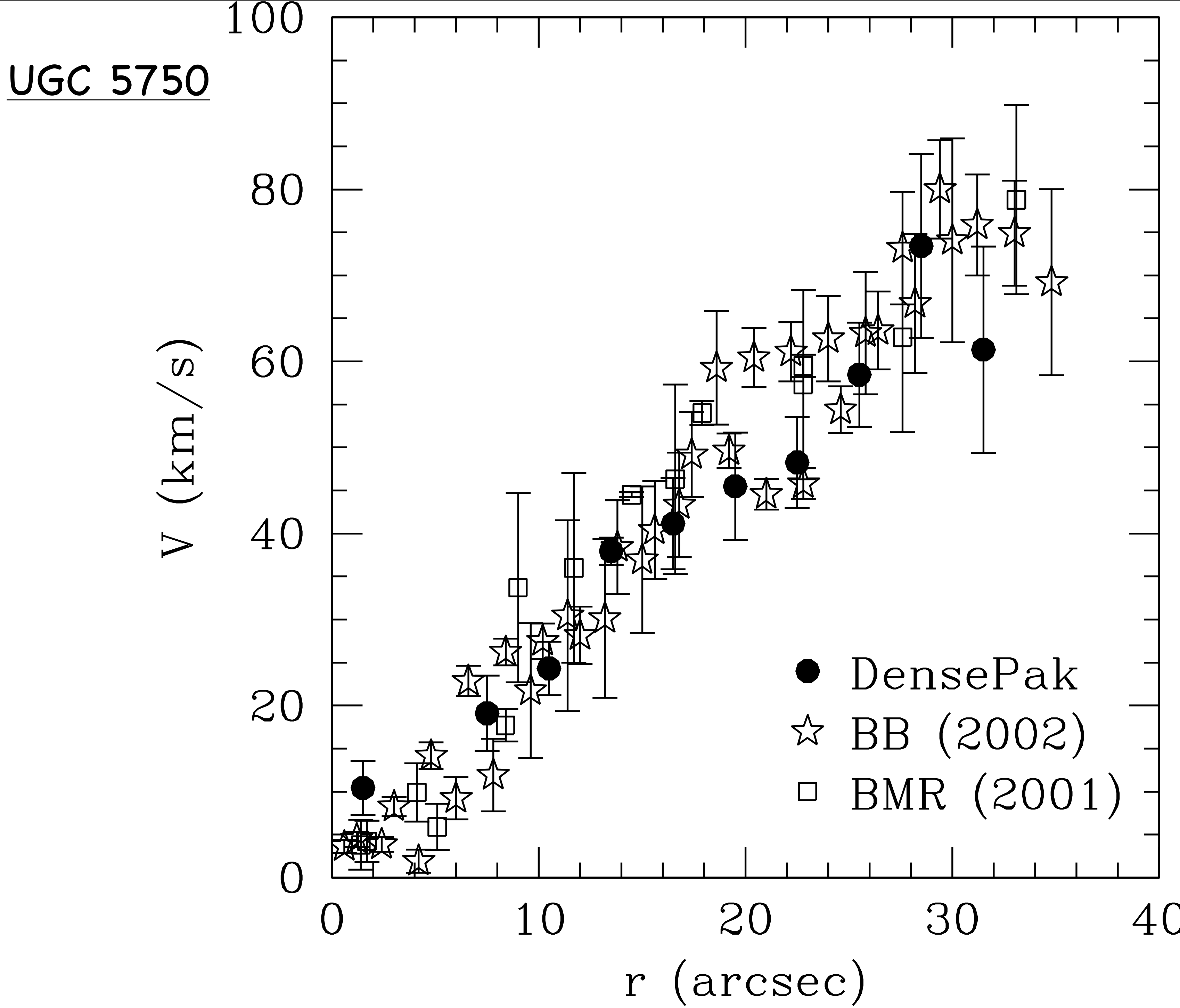

F563-1
V (km/s)
r (arcsec)
0
50
100
150
0
20
40
60
80
DensePak
BB (2002)
BMR (2001)
BMH (1996)

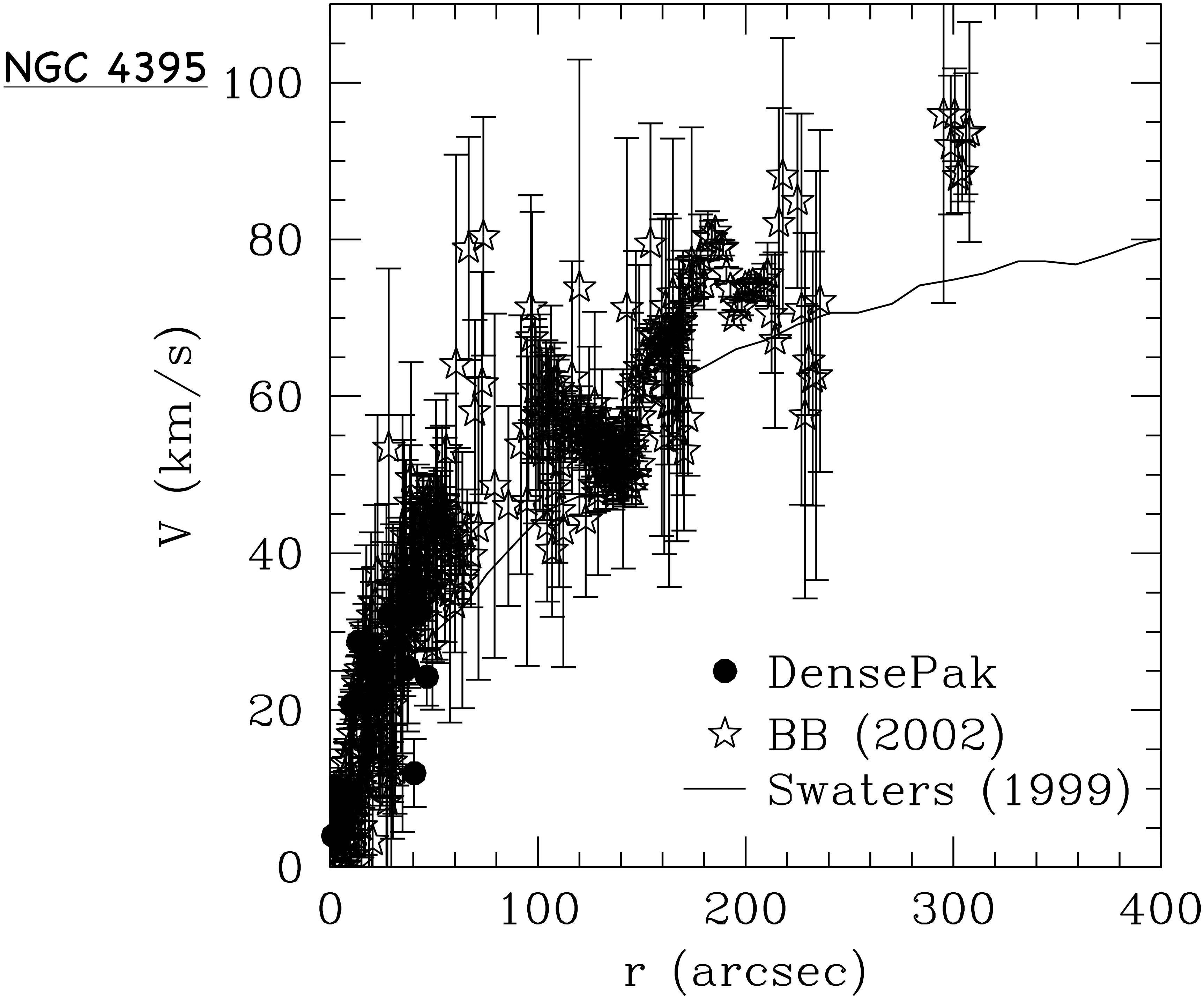


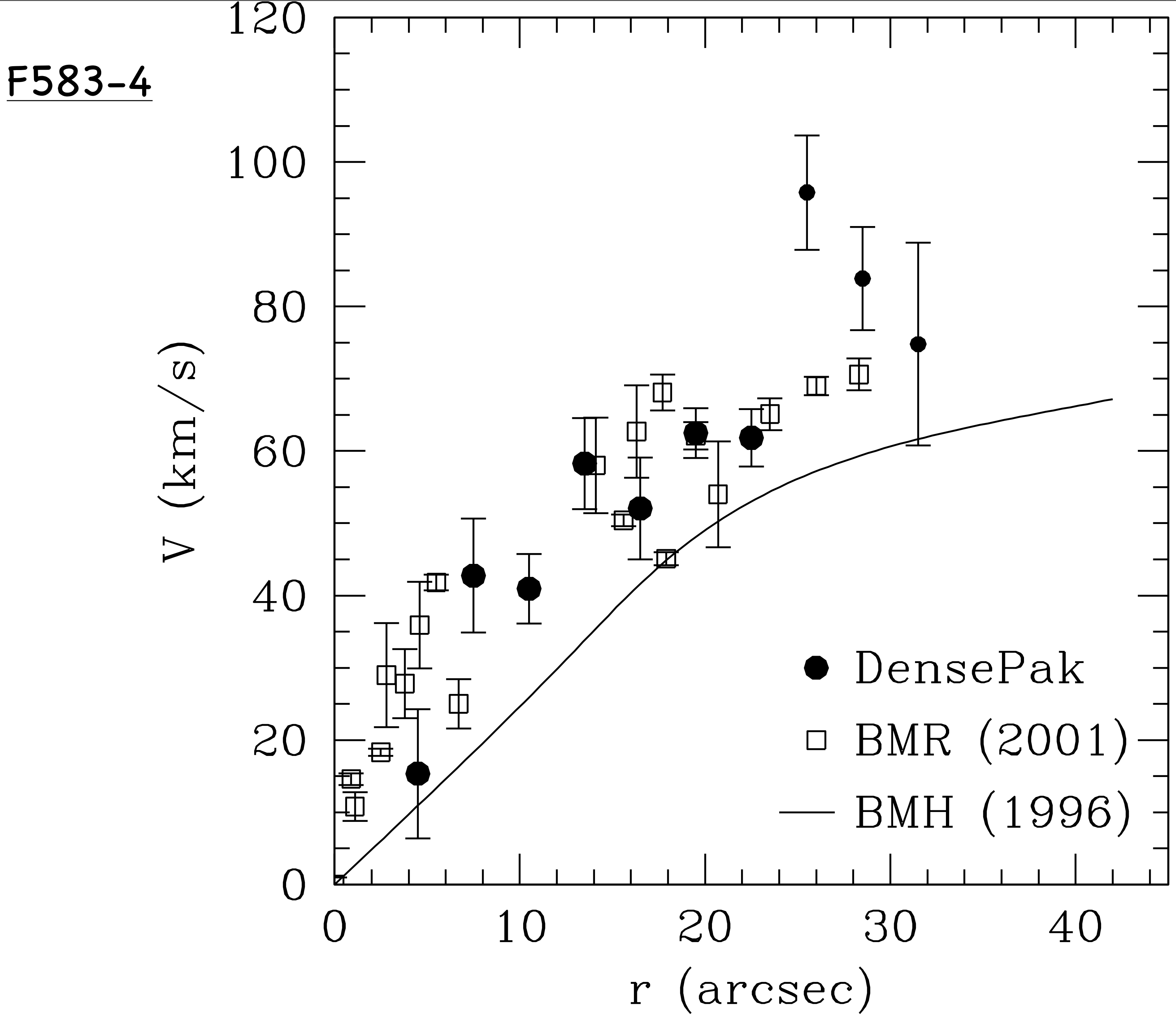
DDO 64
60
40
20
0
V (km/s)
0
20
40
60
80
r (arcsec)
DensePak
BB (2002)
Stil (1999)



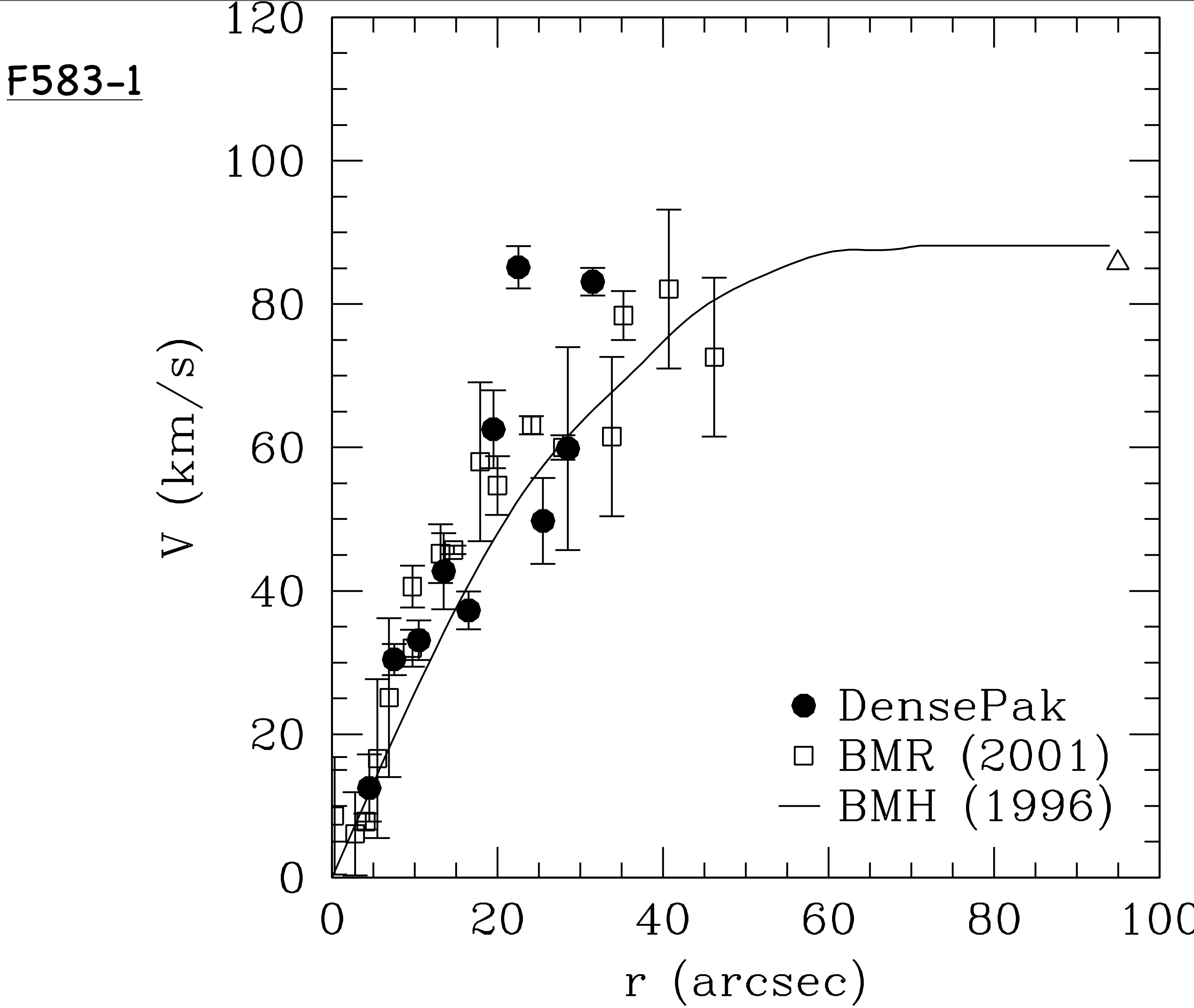
F568-3
150
100
50
0
V (km/s)
0
10
20
30
40
50
r (arcsec)
DensePak
BMR (2001)
BMH (1996)


UGC 5750
V (km/s)
r (arcsec)
0
20
40
60
80
100
0
10
20
30
40
DensePak
BB (2002)
BMR (2001)

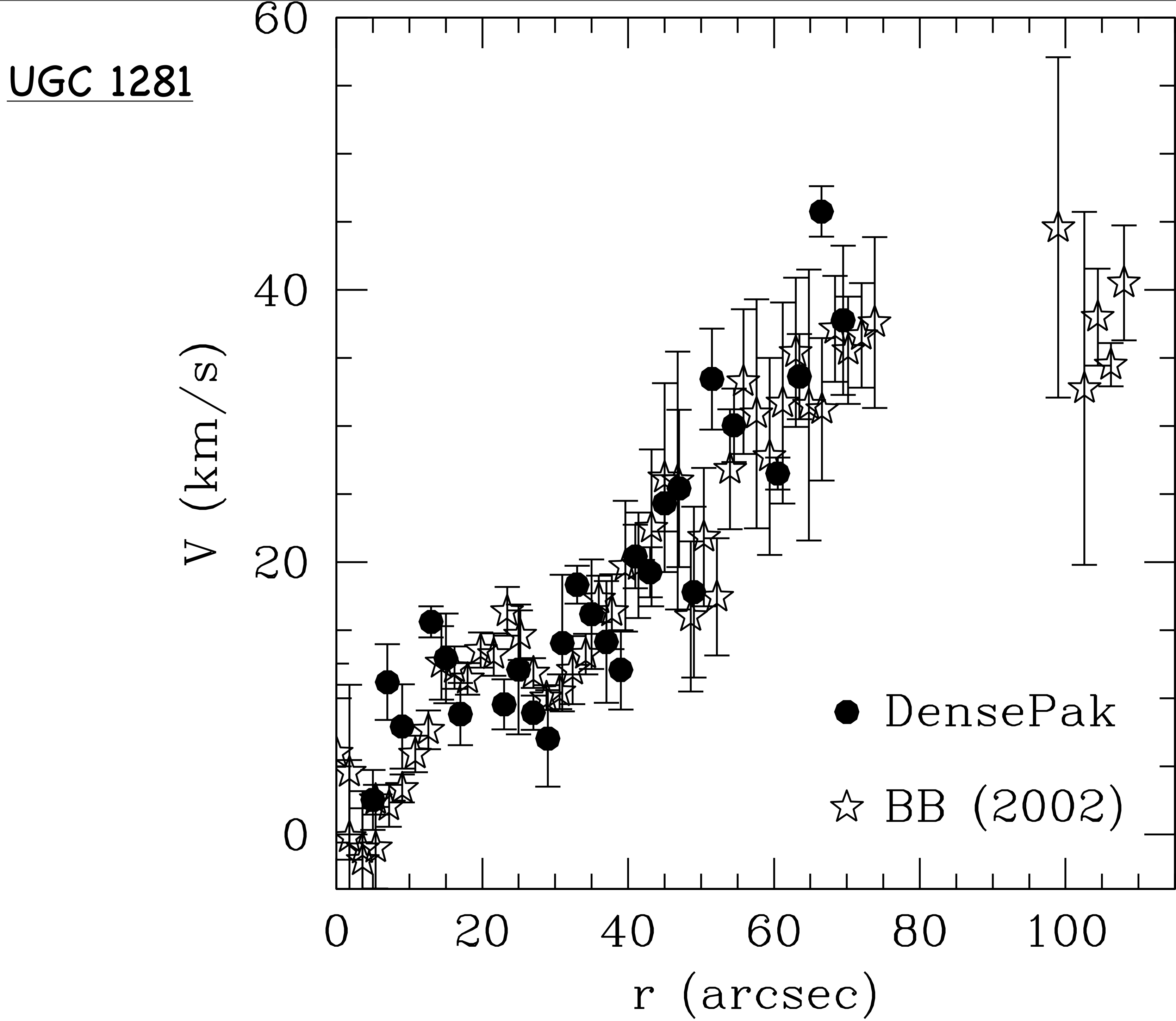

NGC 4395
V (km/s)
r (arcsec)
0
20
40
60
80
100
0
100
200
300
400
DensePak
BB (2002)
Swaters (1999)



F583-4
V (km/s)
r (arcsec)
0
20
40
60
80
100
120
0
10
20
30
40
DensePak
BMR (2001)
BMH (1996)



F583-1
V (km/s)
r (arcsec)
0
20
40
60
80
100
120
DensePak
BMR (2001)
BMH (1996)


UGC 1281
V (km/s)
r (arcsec)
DensePak
BB (2002)
0
20
40
60
0
20
40
60
80
100