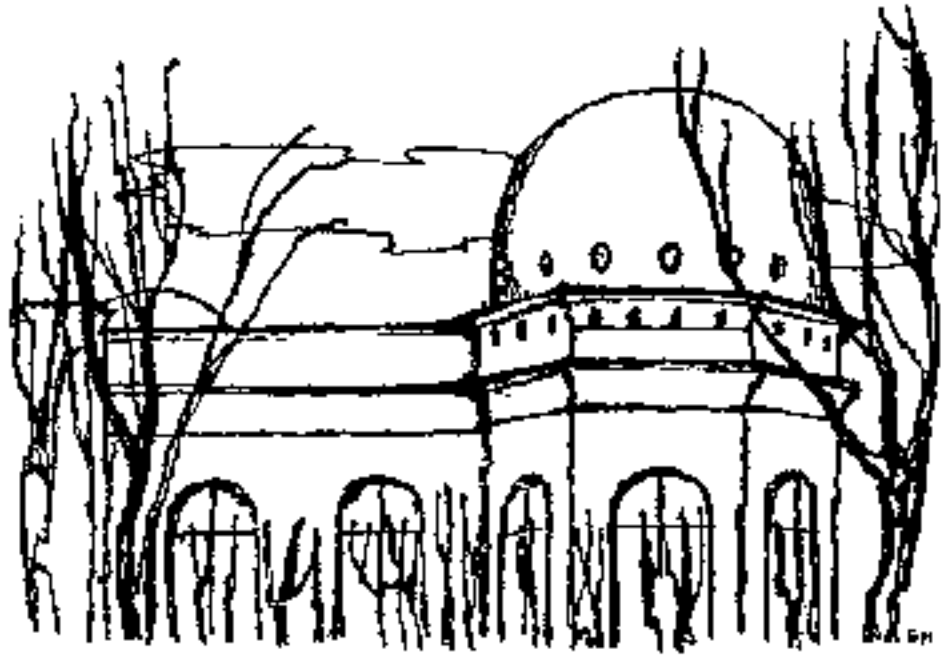
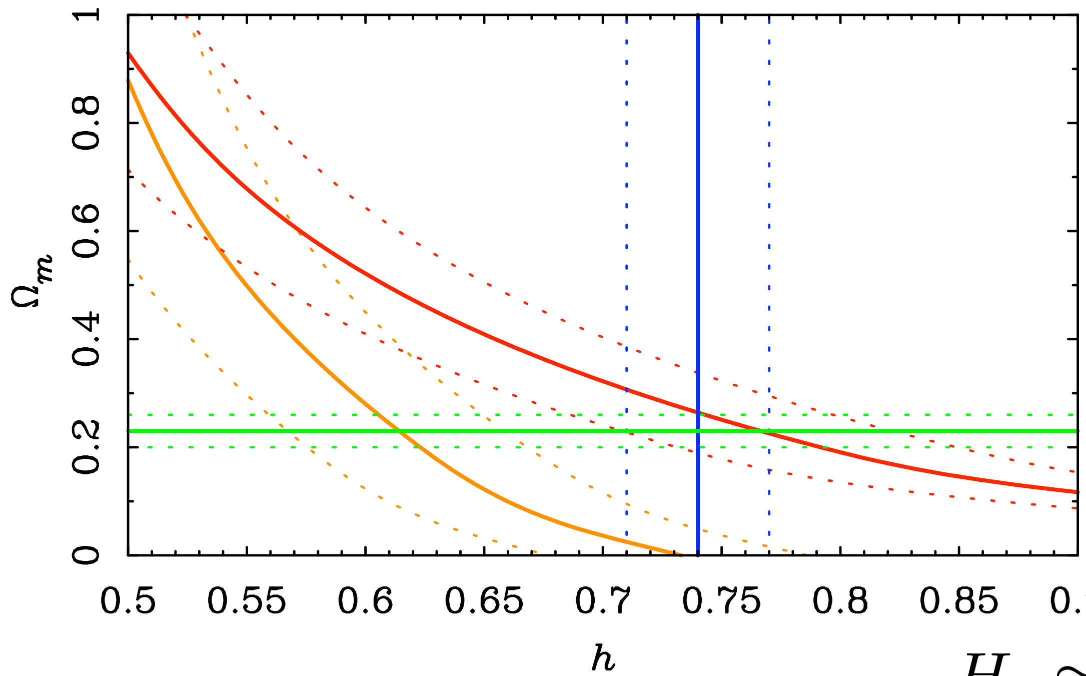
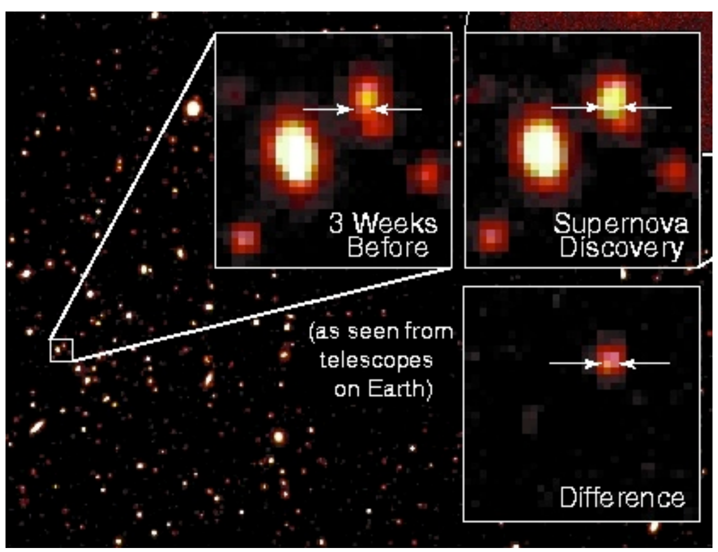


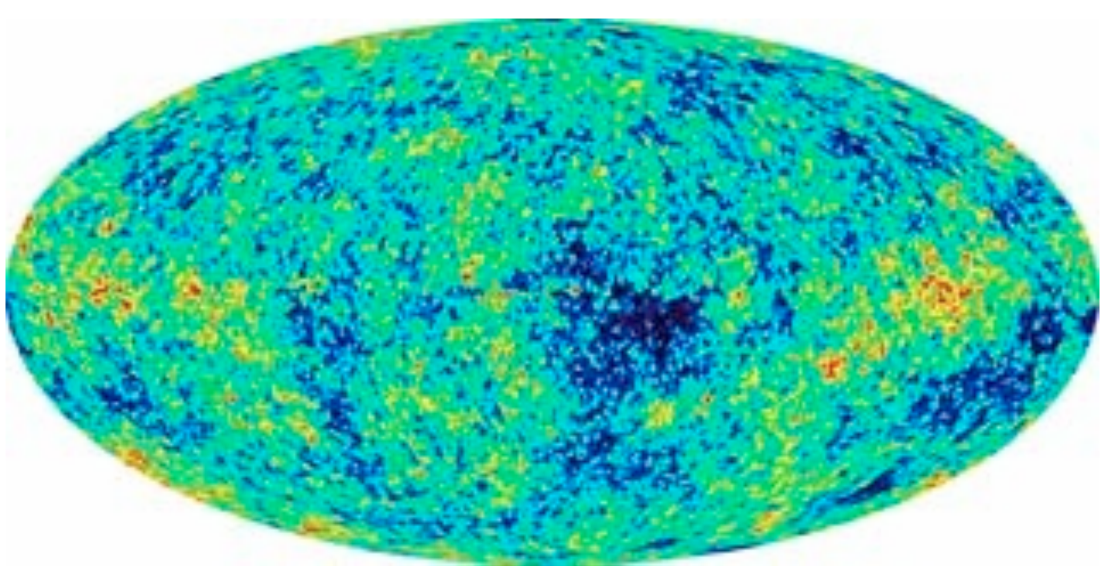
The Baryon Content of Cosmic Structures

Stacy McGaugh

University of Maryland







$$H_0 \approx 72$$

$$\text{Age} \approx 13$$

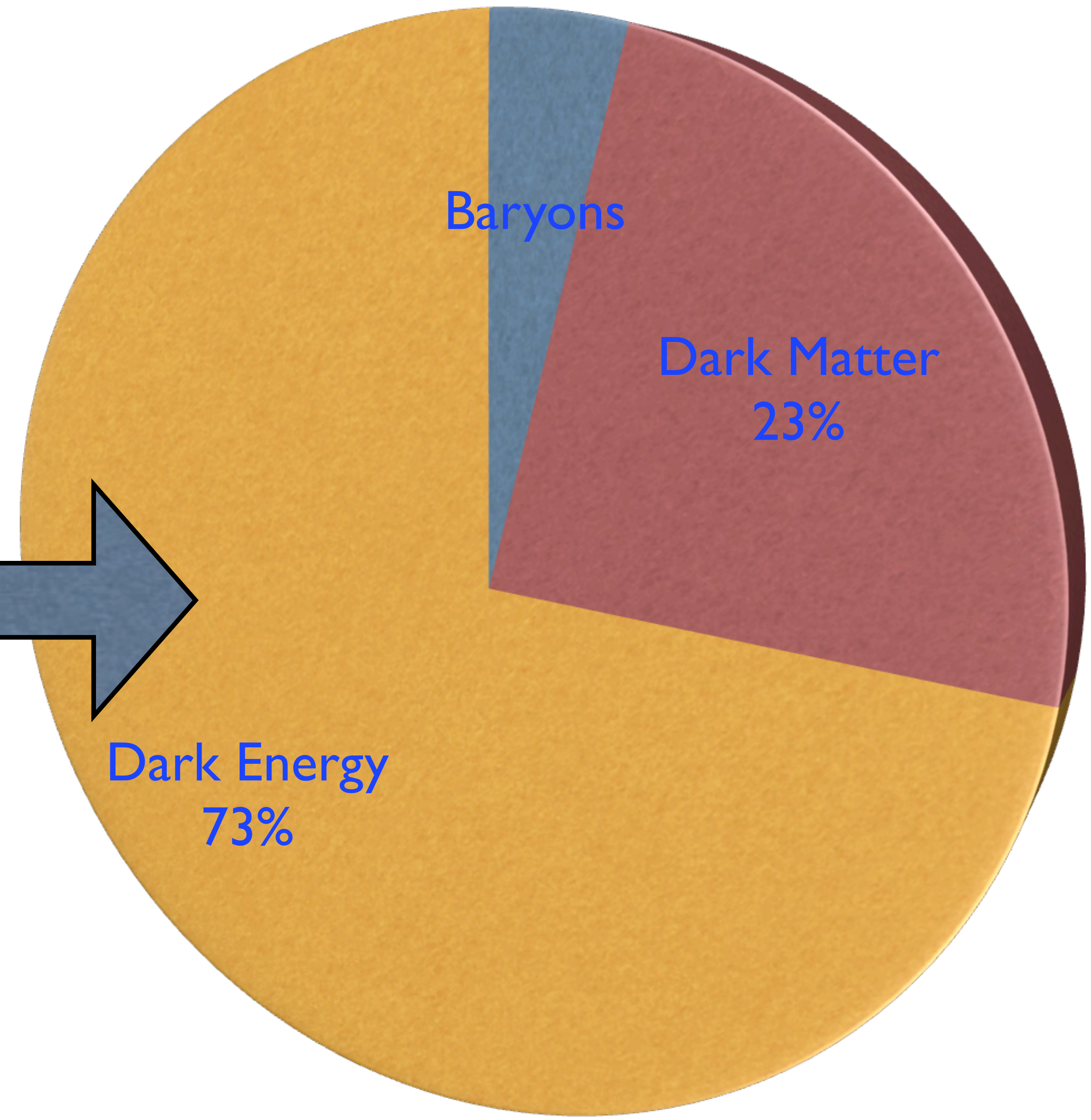
$$\Omega_m \approx 1/4$$

$$q_0 \leq 0$$

$$\Omega_k \approx 0$$

$$\Omega_m + \Omega_\Lambda = 1$$

ΛCDM



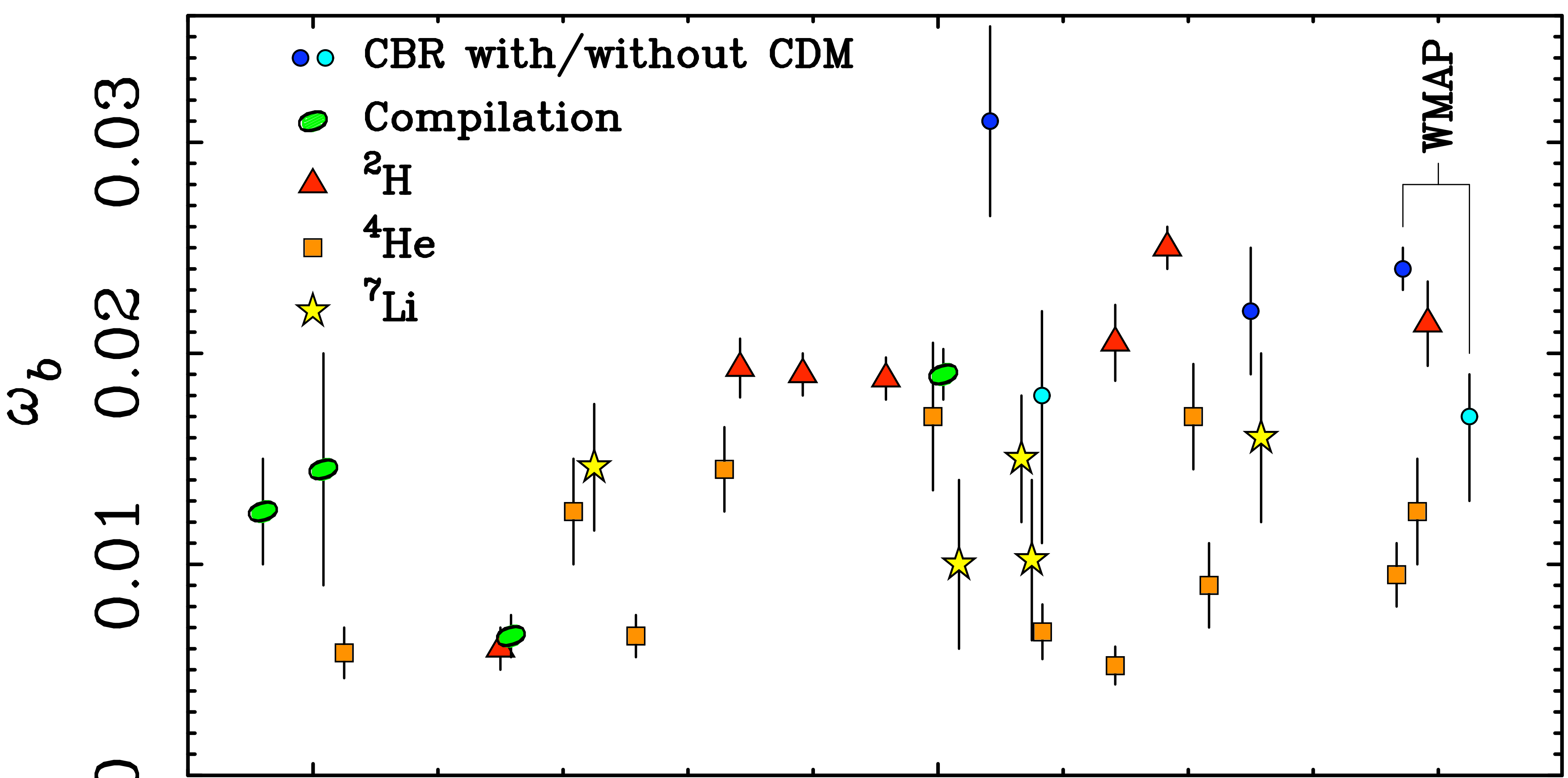
Cosmic Baryon Fraction:

BBN & $\Omega_b = 0.042$

matter density $\Omega_m = 0.25$

$$\left.\begin{matrix}\Omega_b = 0.042 \\ \Omega_m = 0.25\end{matrix}\right\} \quad f_b = \frac{\Omega_b}{\Omega_m} = 0.17 \pm 0.01$$

combined give numbers similar to CMB fits



Big Bang Nucleosynthesis

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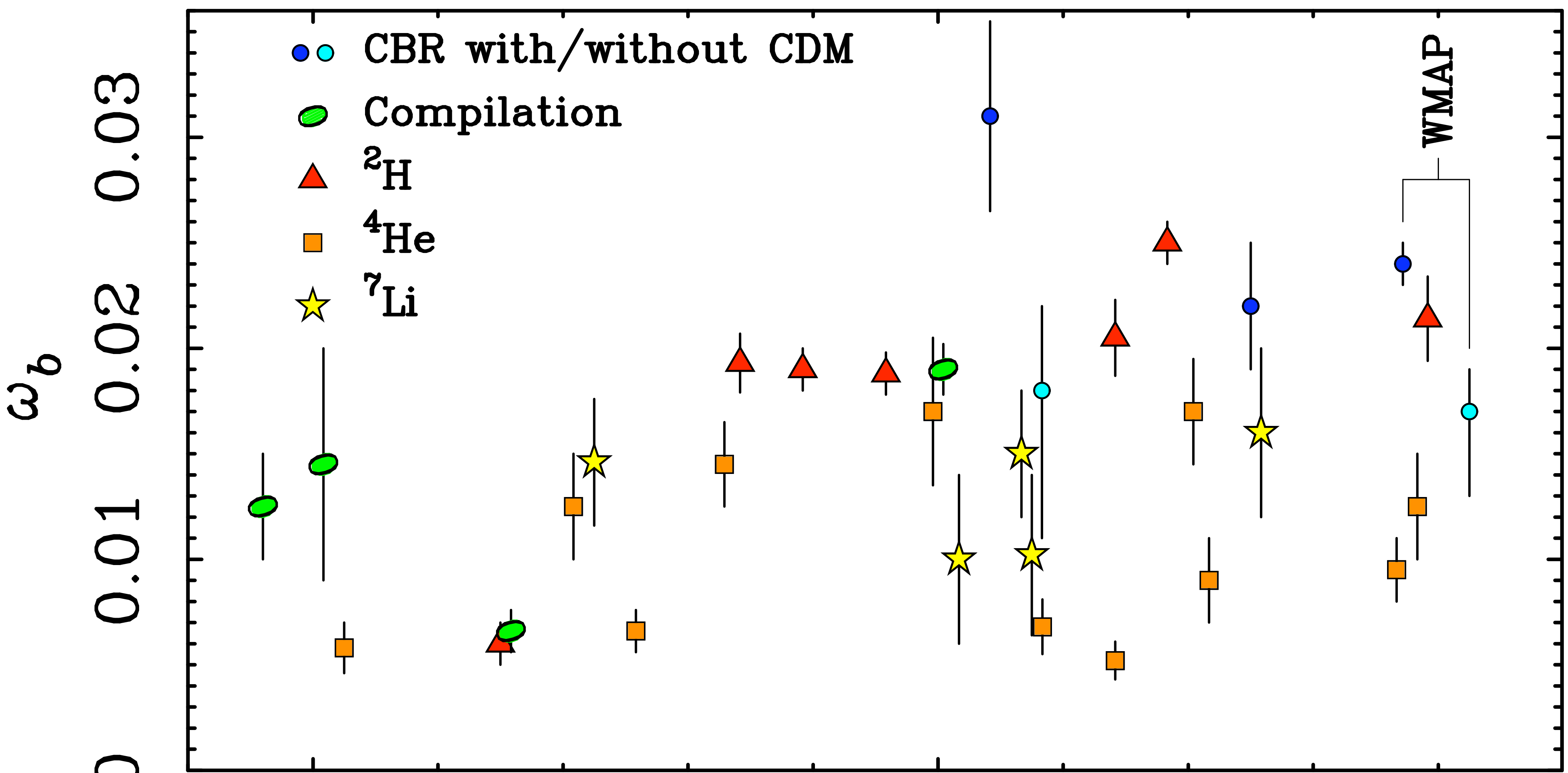
combined give numbers similar to CMB fits

This is the cosmic average.

What about individual structures?



Big Bang Nucleosynthesis

f_b = 0.17 is the cosmic average.
What about individual structures?

$$f_b = \frac{M_b}{M_\Delta}$$

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

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

f_b = 0.17 is the cosmic average.
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molecular (H_2)
ionized (HII)
etc...

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$$= (\Delta/2)^{-1/2}(GH_0)^{-1}\, V_\Delta^3 = B_\Delta V_\Delta^3$$

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$$= (\Delta/2)^{-1/2}(GH_0)^{-1}\, V_\Delta^3 = B_\Delta V_\Delta^3$$

for $\Delta = 500$, $\quad M_{500} = B_{500}V_{500}^3$

$$B_{500} = 2\times 10^5\ \mathrm{km}^{-3}\,\mathrm{s}^3\,\mathrm{M}_\odot$$

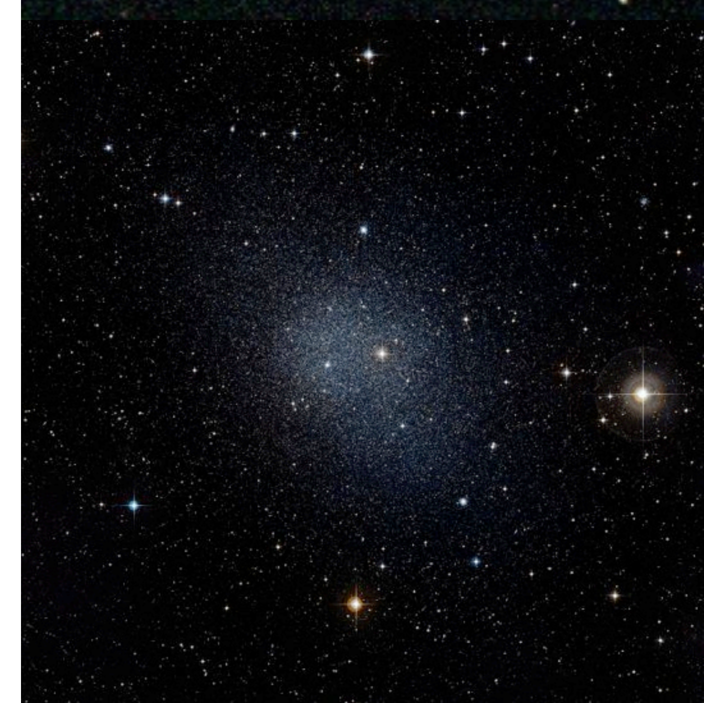
clusters

spirals

groups

gas rich
late types

ellipticals



dSph
satellites

McGaugh et al. (2010)

clusters

spirals

dominant baryonic component

HII gas

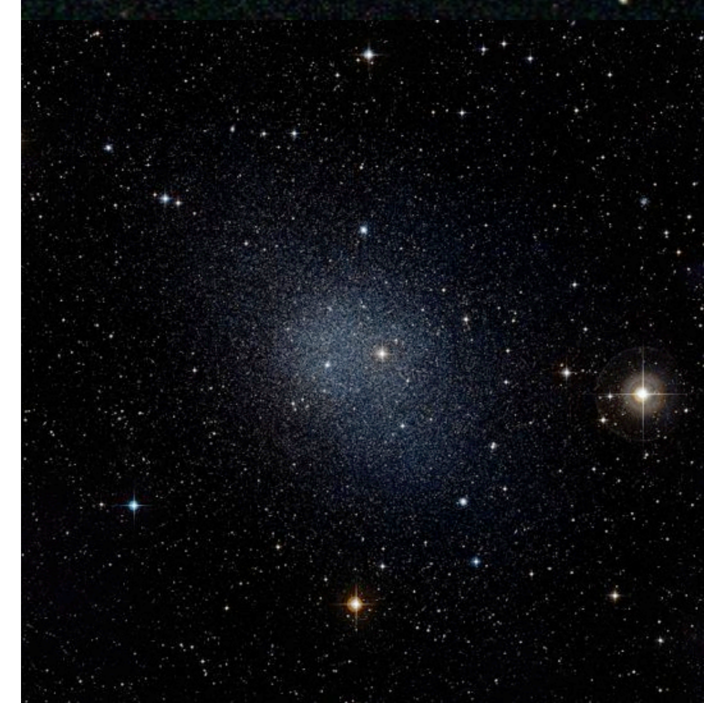
stars

groups

gas rich late types

stars?

HI gas



ellipticals

dSph satellites

stars

stars

McGaugh et al. (2010)

clusters — spirals

<u>dominant baryonic component</u>

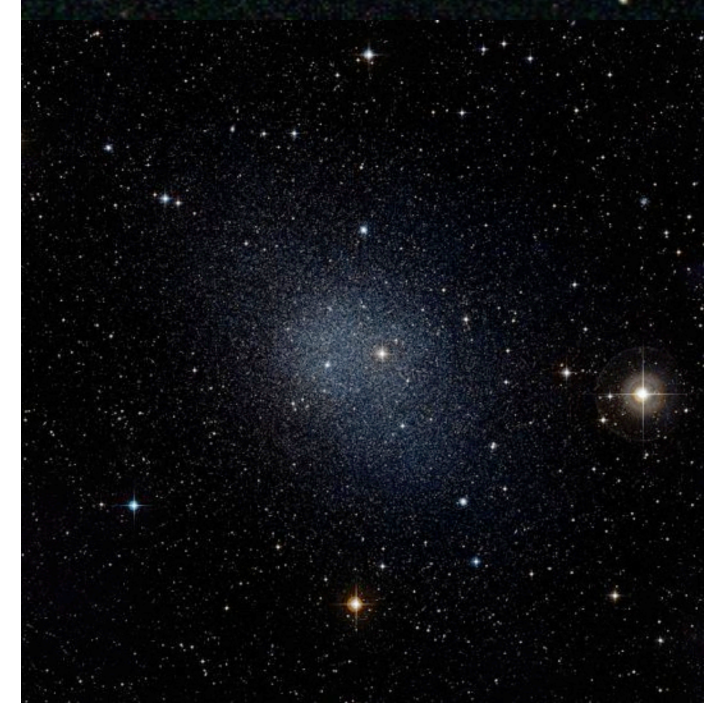
HII gas — stars

$\sim 10^{14}\ M_\odot$ — <u>typical M_{500}</u> — $\sim 10^{12}\ M_\odot$

groups — gas rich late types

stars? — HI gas

$\sim 10^{13}\ M_\odot$ — $\sim 10^{10}\ M_\odot$



ellipticals — dSph satellites

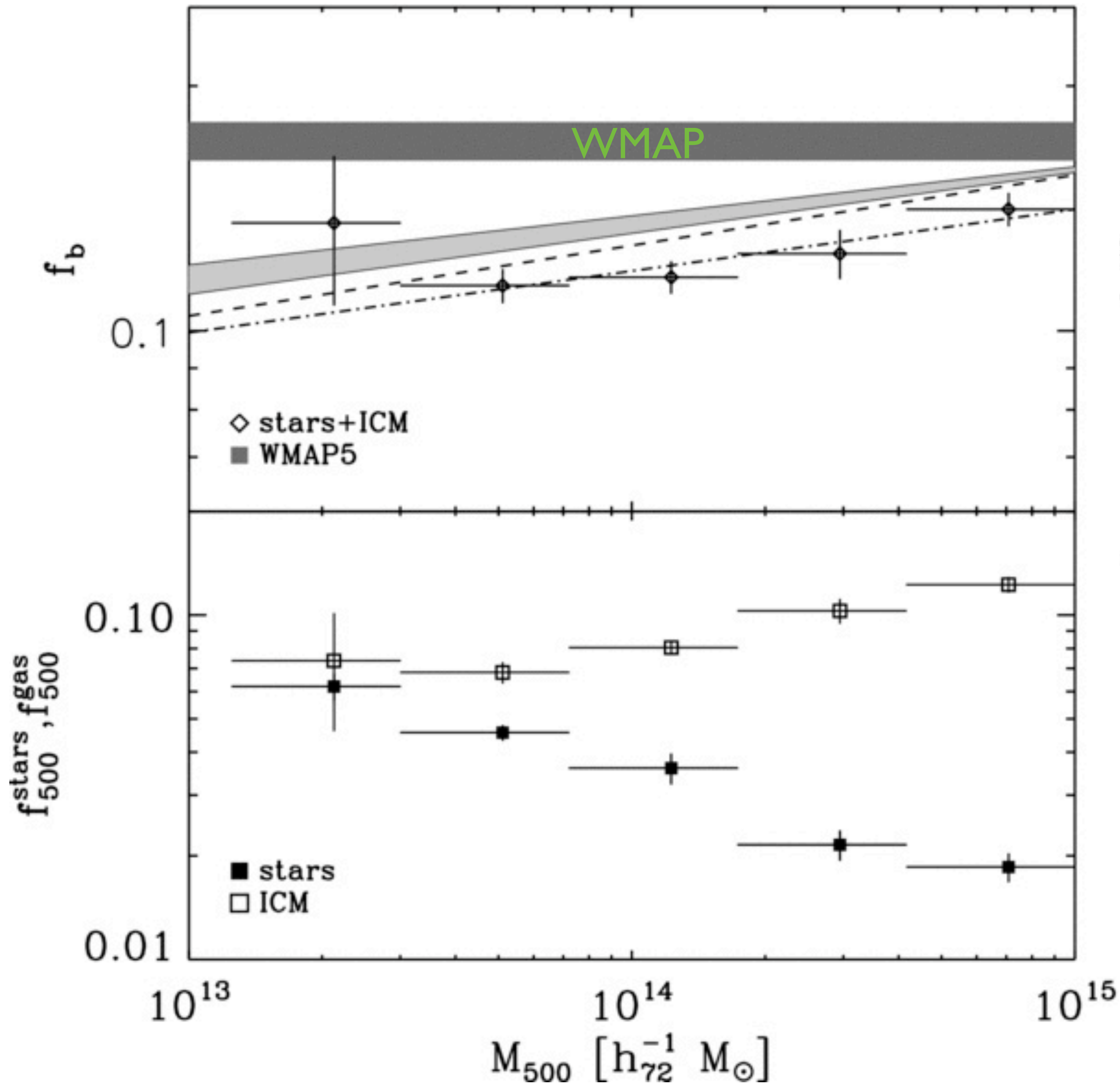
stars — stars

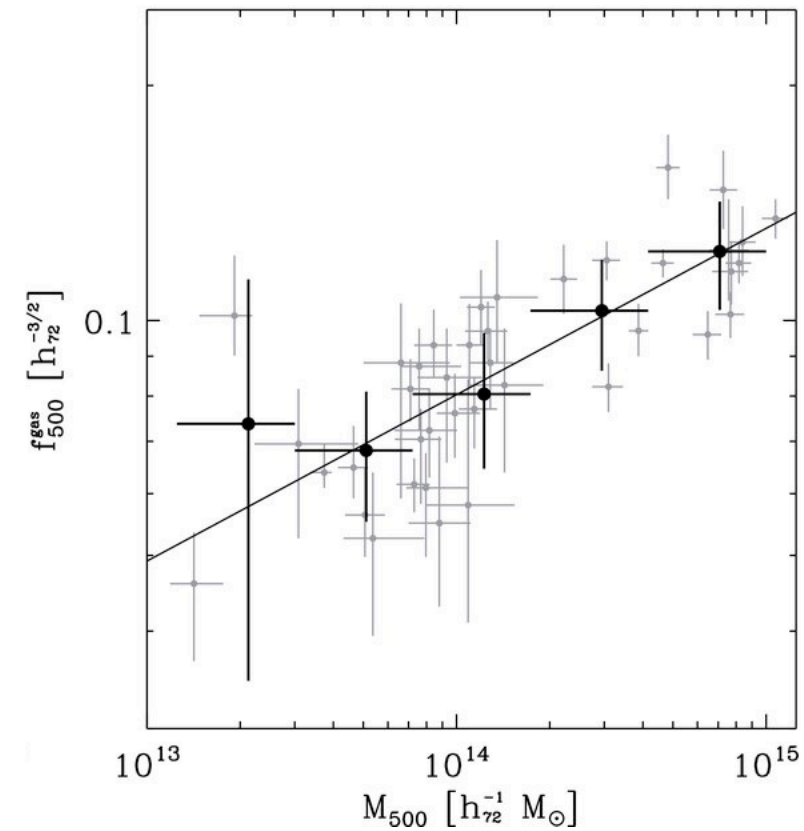
$\sim 10^{13}\ M_\odot$ — $\sim 10^{8}\ M_\odot$

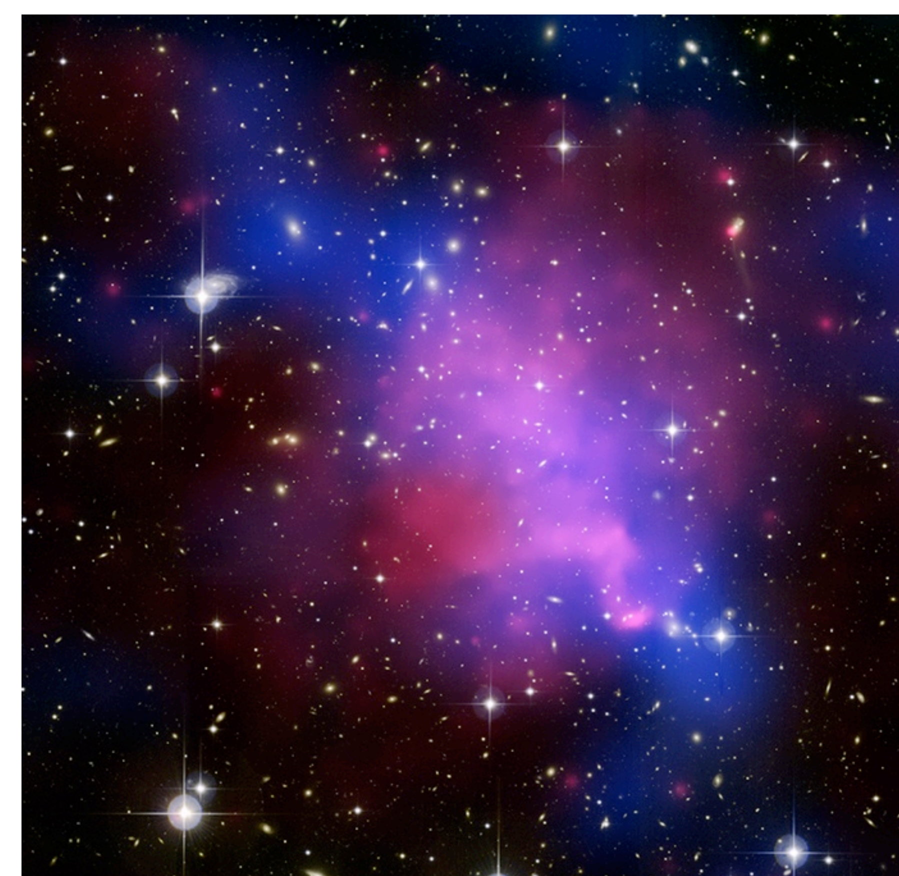
McGaugh et al. (2010)

clusters

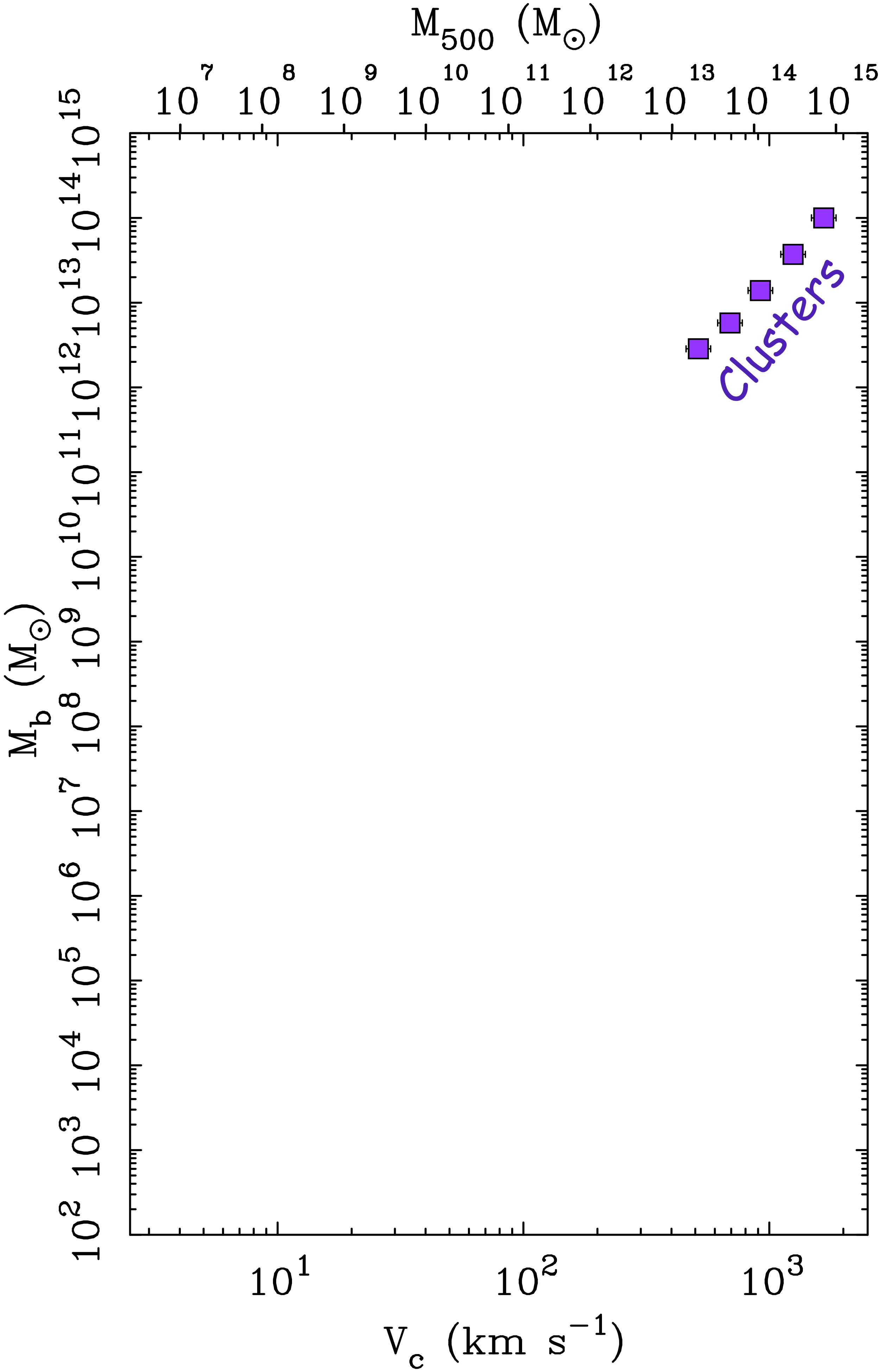
Clusters:
Giodini et al. (2009)







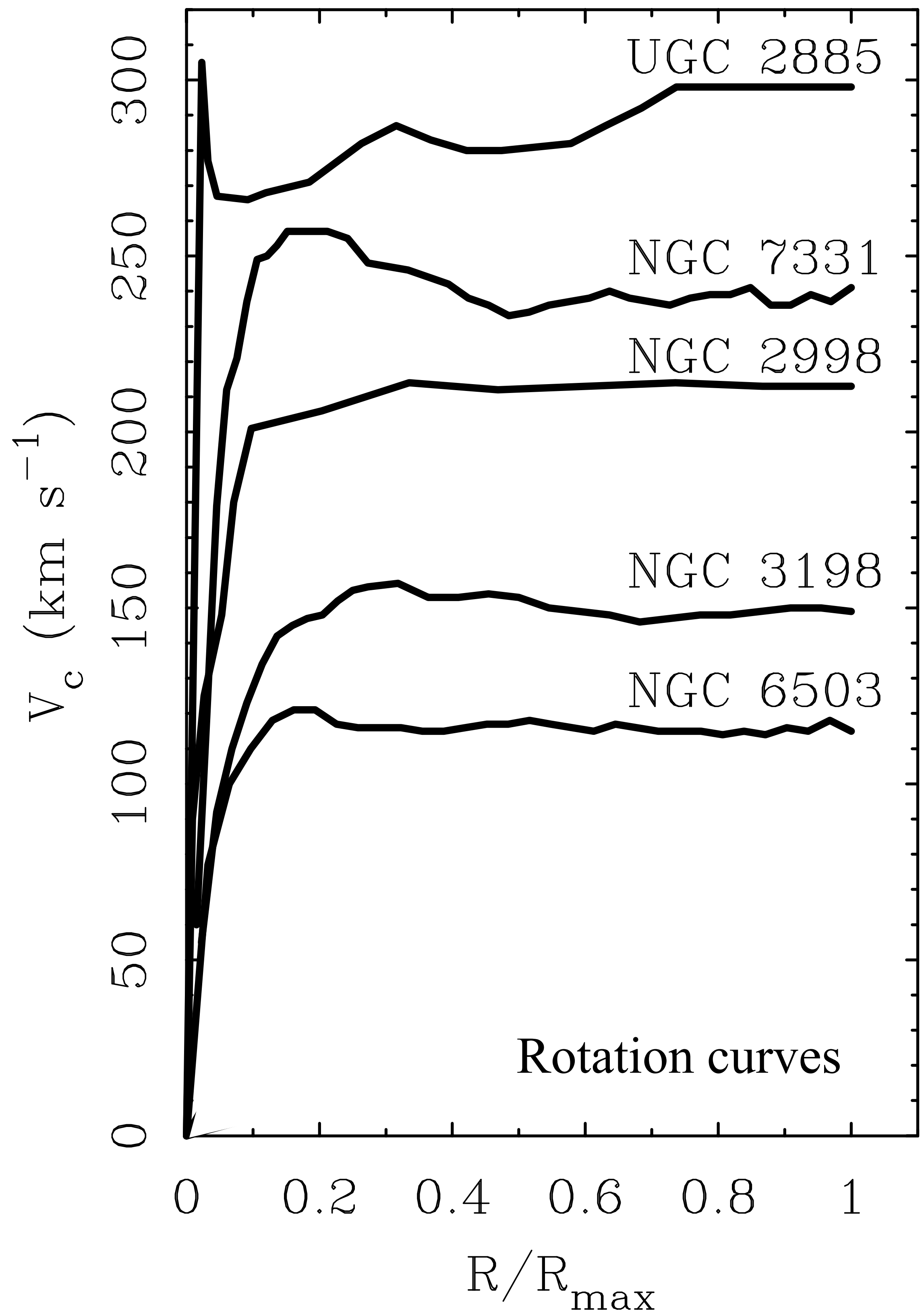
M_b-V_c Relation



Cluster data: Giodini et al. (2009)

assume $V_c = f_v V_{500}$

Spirals



Baryonic mass:
stars
atomic gas
molecular gas

$$M_b = M_\star + M_{HI} + M_{H_2}$$

Total mass:

$$M_{500} = B_{500} V_{500}^3$$

$$V_c = f_v V_{500}$$

assume $f_v = 1.1$

Measuring M_b

Stars:

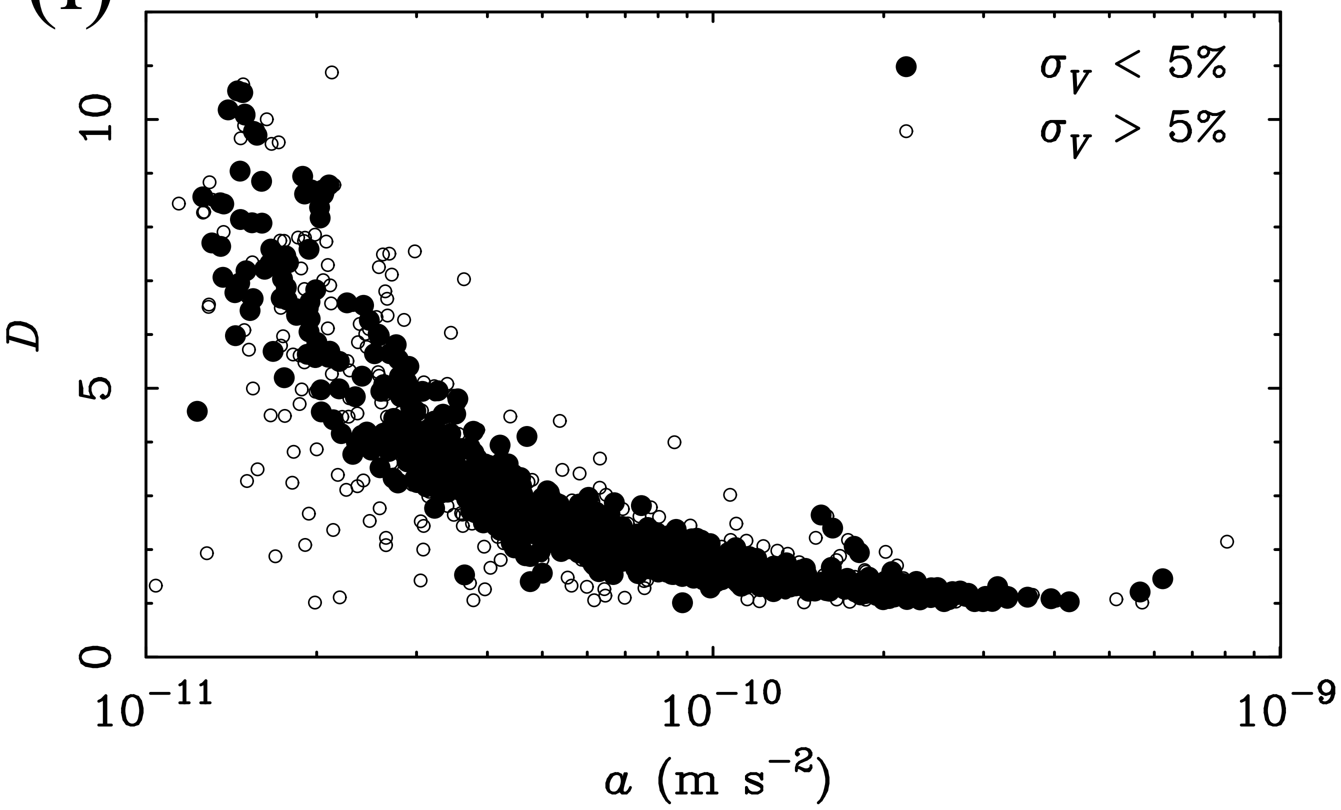
$$M_\star = \Upsilon_\star L$$

Mass-to-light ratio $\Upsilon_\star$ from

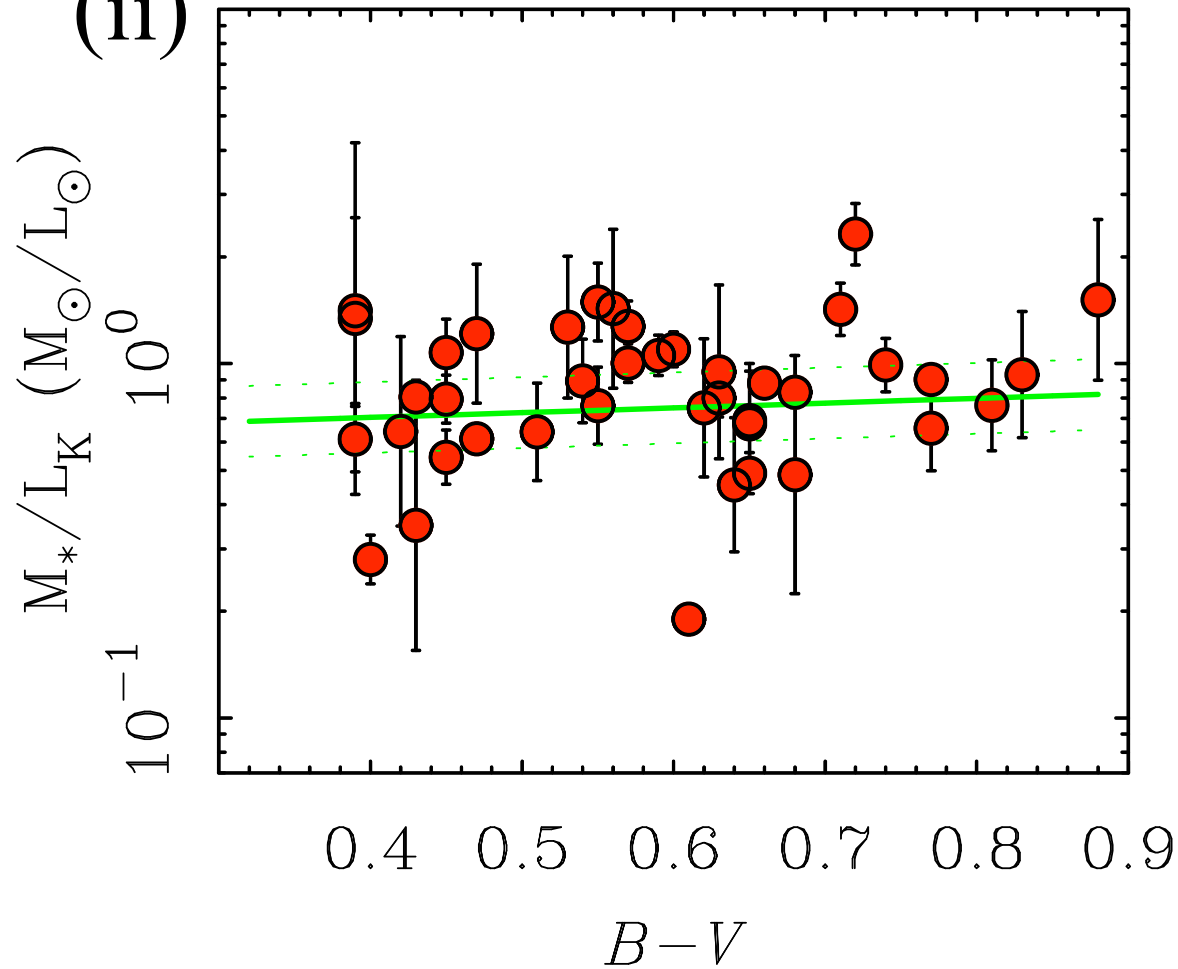
(i) mass discrepancy-acceleration relation

(ii) population synthesis models

(i)



(ii)



Measuring M_b

Gas:

$$M_{gas} = M_{HI} + M_{H_2}$$

HI mass follows directly from 21 cm luminosity. Molecular gas trickier; taken from scaling relation

Young & Knezek (1989); McGaugh & de Blok (1997)

$$M_{gas} = \eta M_{HI}$$

$$\eta = \frac{1}{X}\left(1 + \frac{M_{H_2}}{M_{HI}}\right)$$

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Cosmic Hydrogen fraction:

$$X = \frac{3}{4}$$

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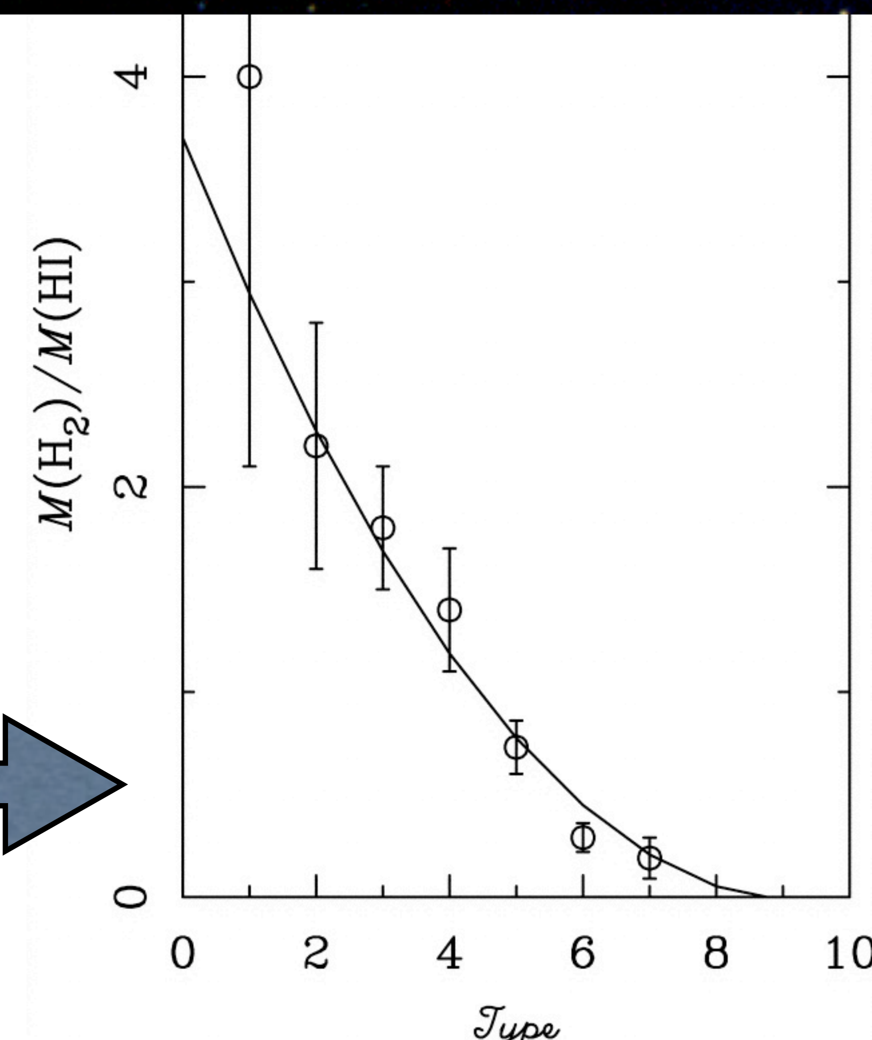
$$\frac{M_{H_2}}{M_{HI}} = 3.7 - 0.8T + 0.043T^2$$



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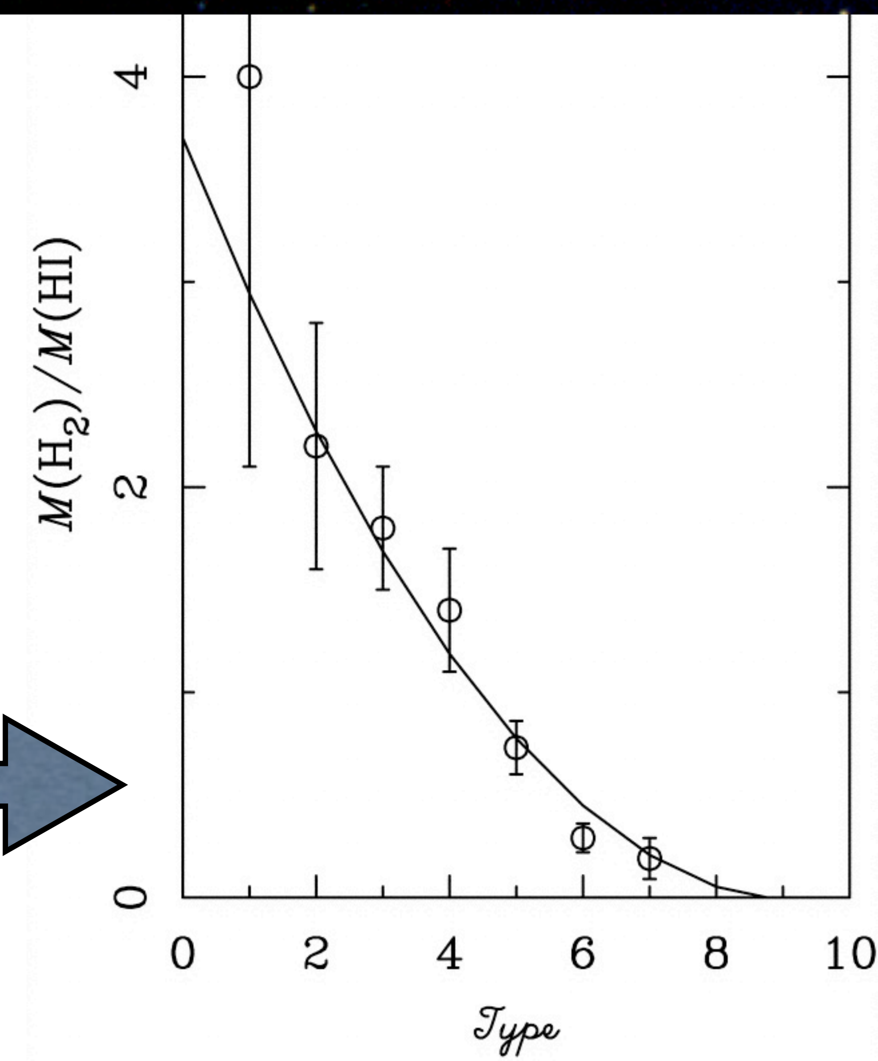
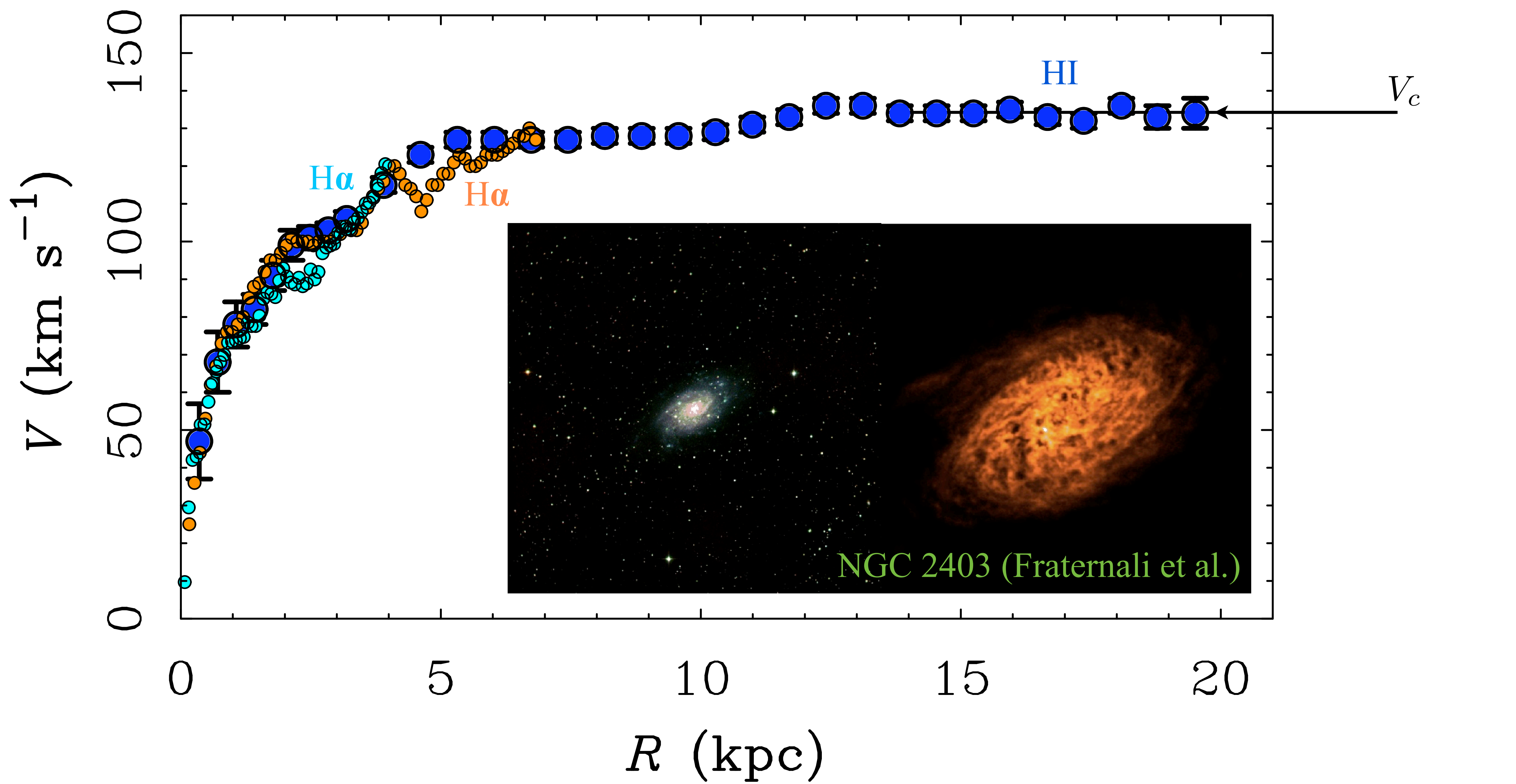


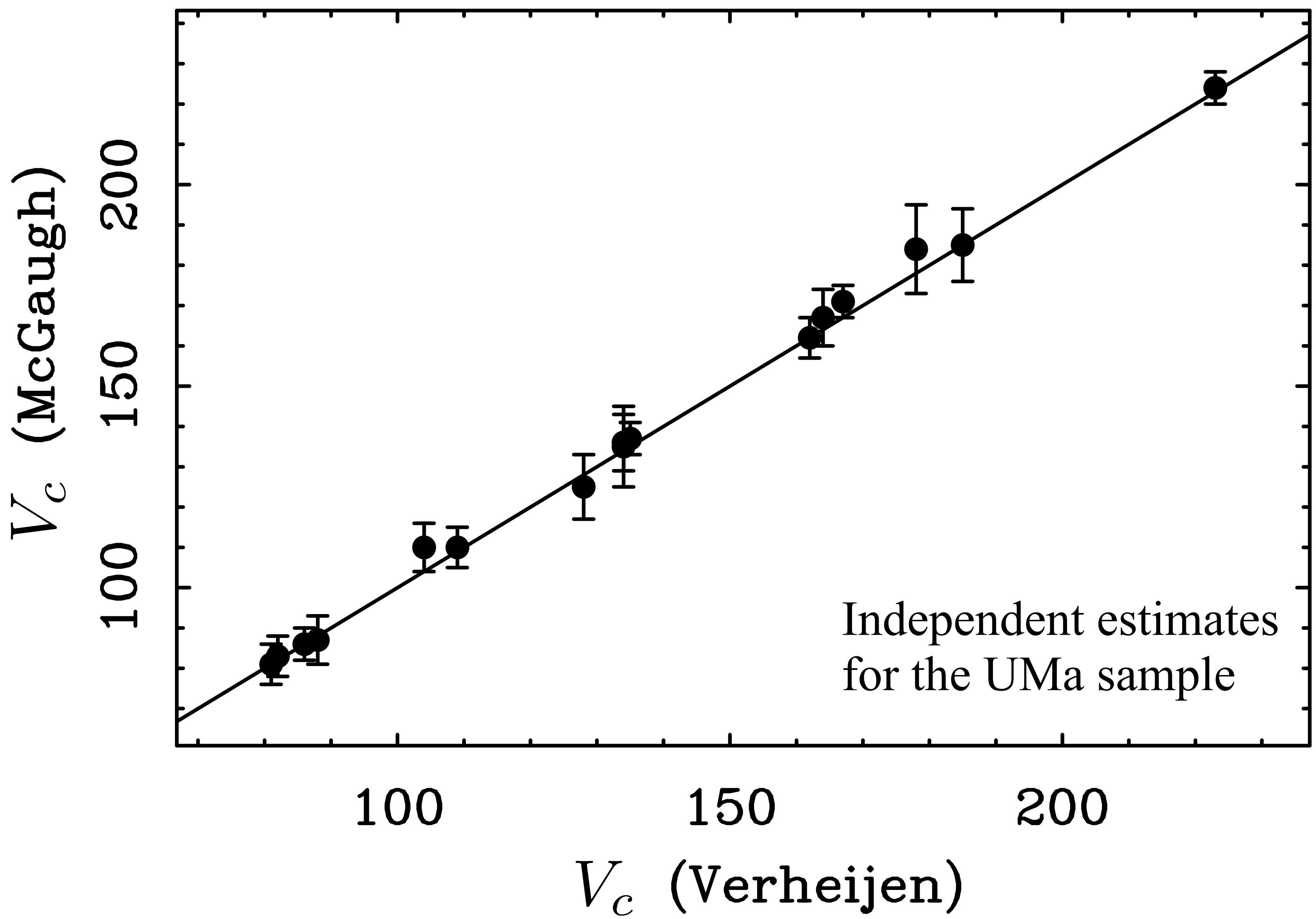
Typically, $M_\star > M_{HI} > M_{H_2}$

Measuring V_c



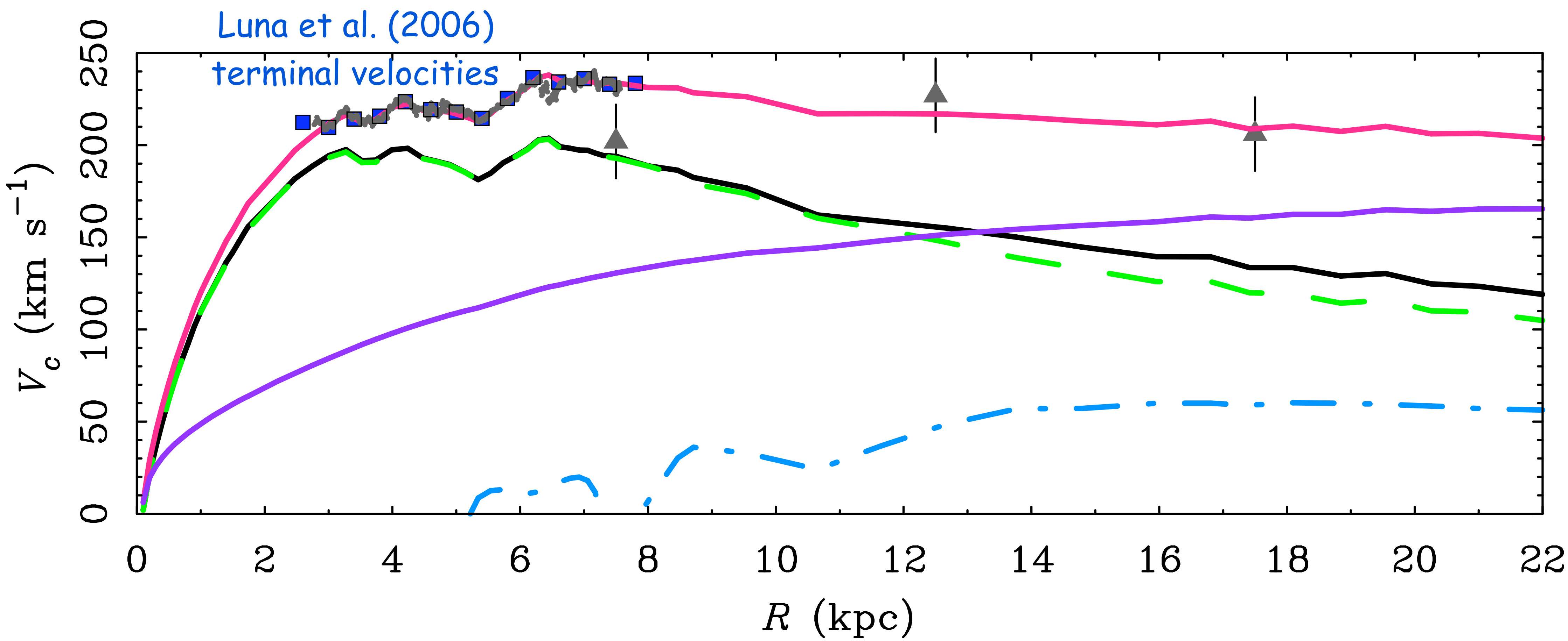
It is straightforward to derive consistent measures of Vc from extended HI rotation curves; most have $\left|\frac{\partial \log V}{\partial \log R}\right| < 0.1$

It can also be done with Hα data or single dish 21 cm line-widths, at the expense of greater scatter.



Having M_b and V_c, need to estimate f_V to relate V_c to V_{500}

Milky Way:



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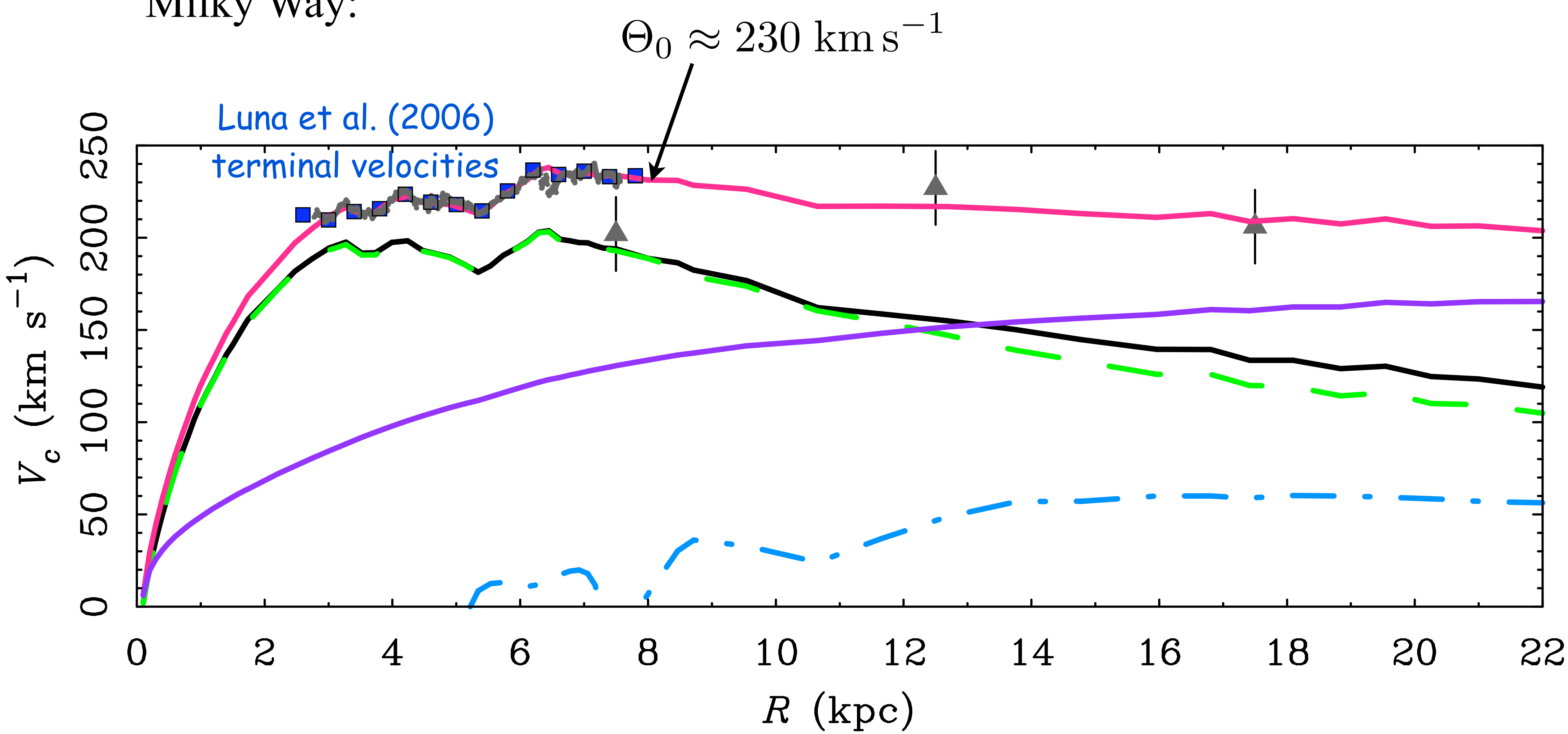

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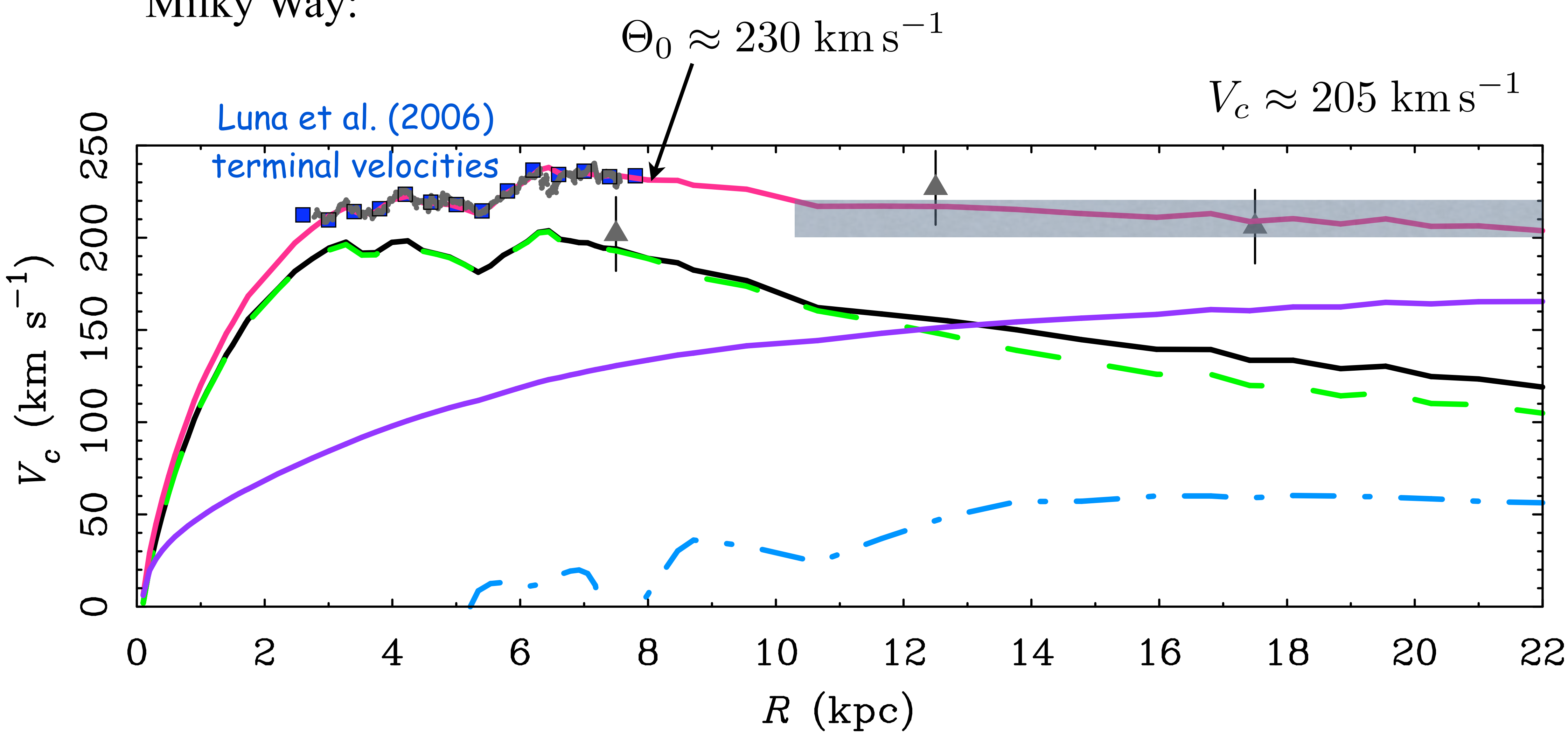
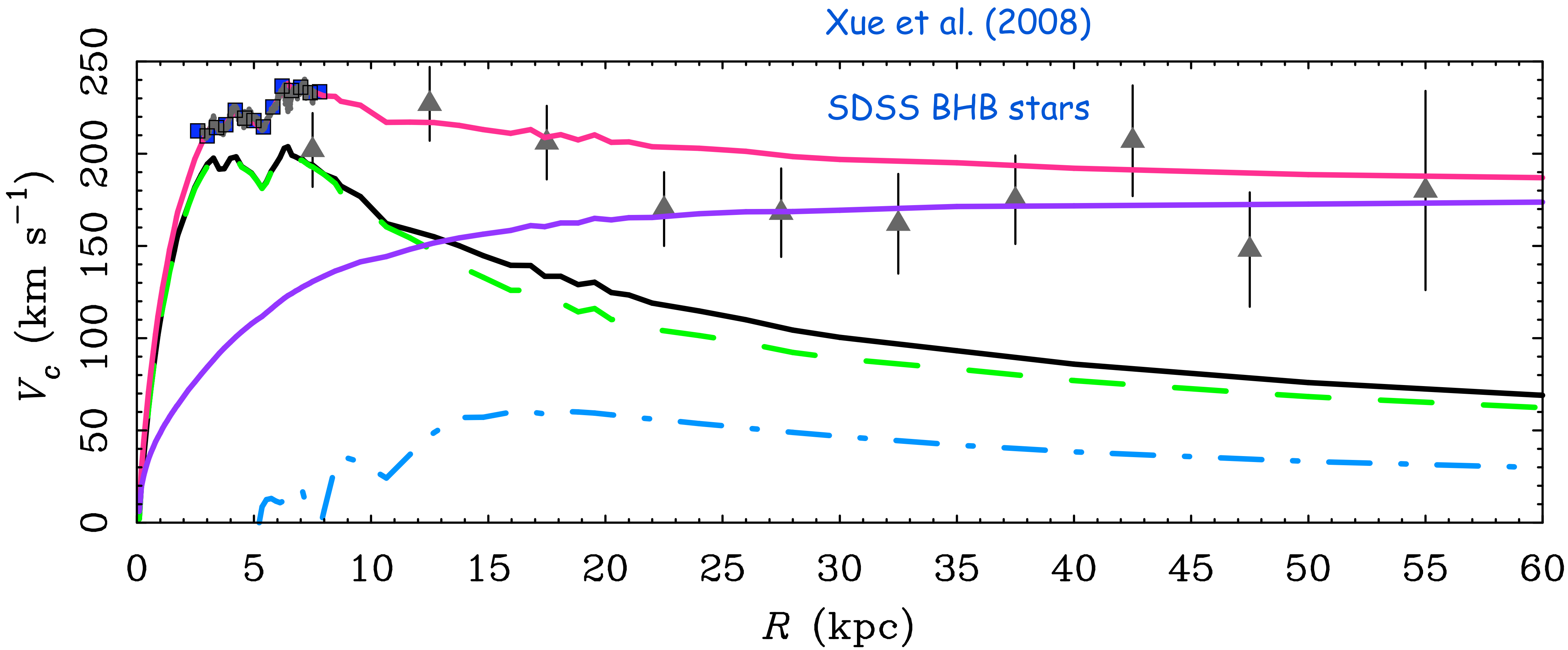


Estimating f_V

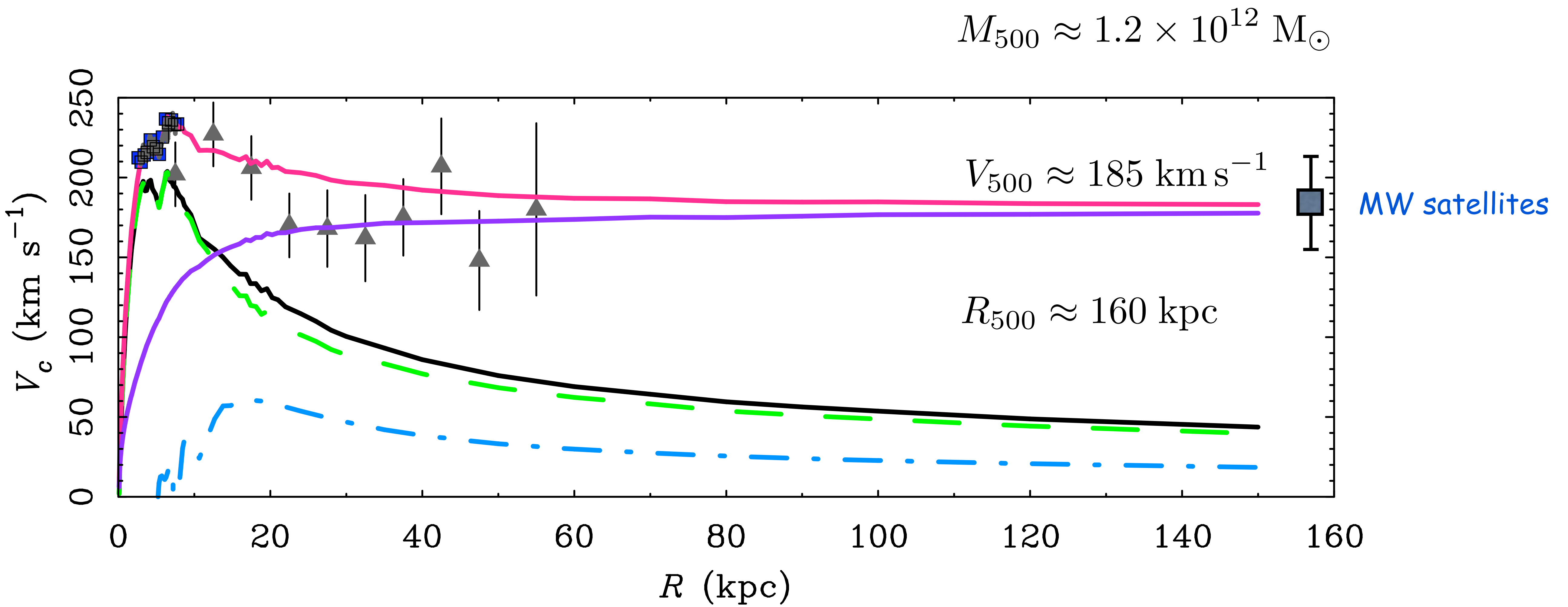
Milky Way:



Estimating f_V

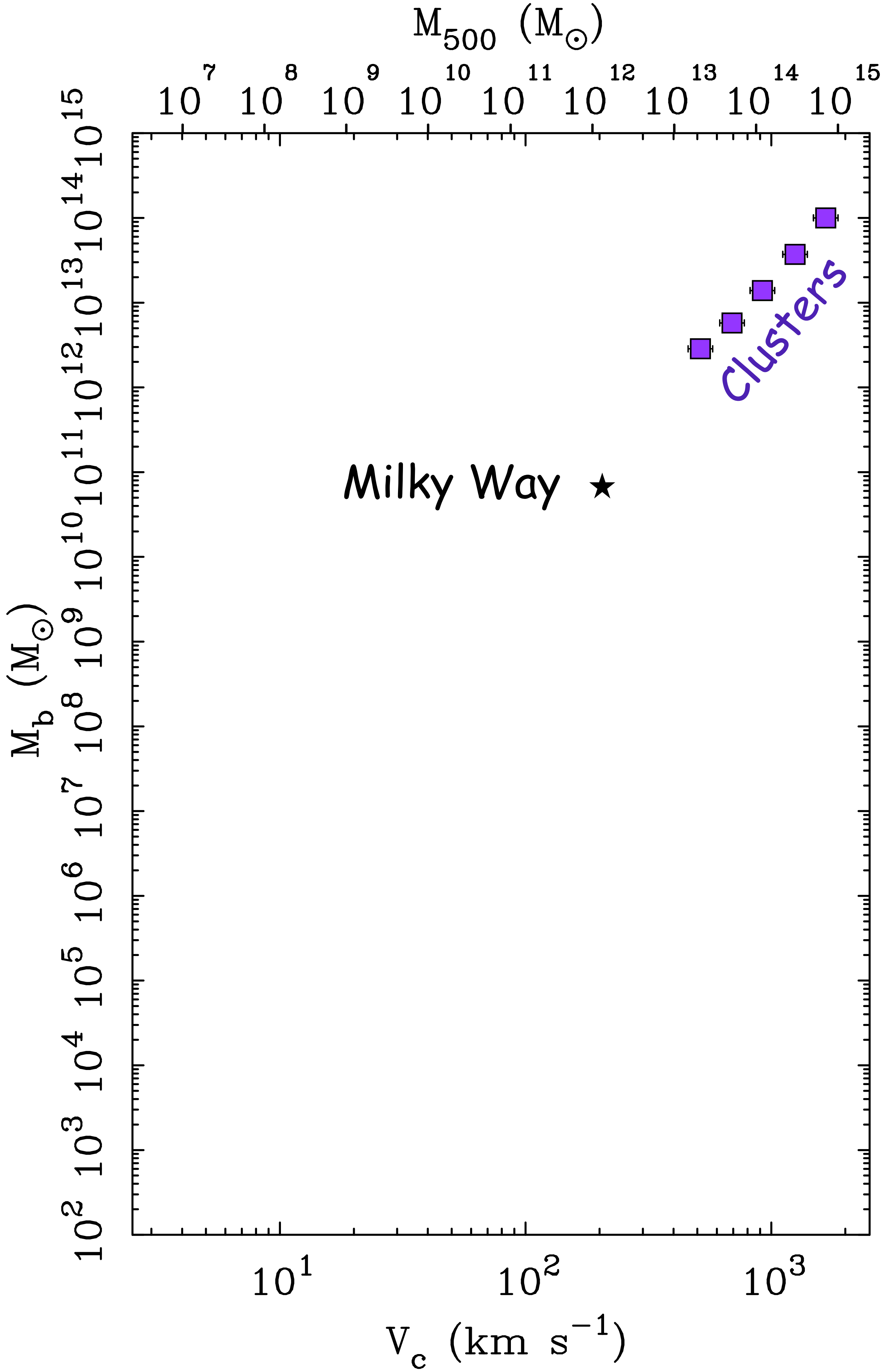
adopt $f_V = \dfrac{V_c}{V_{500}} = 1.1$

Milky Way:



Looking at other galaxies (Sellwood & McGaugh 2005), $1.0 < f_V < 1.5$ with $f_V < 1.3$ in most cases. Nonetheless, f_V is rather uncertain.

M_b-V_c Relation



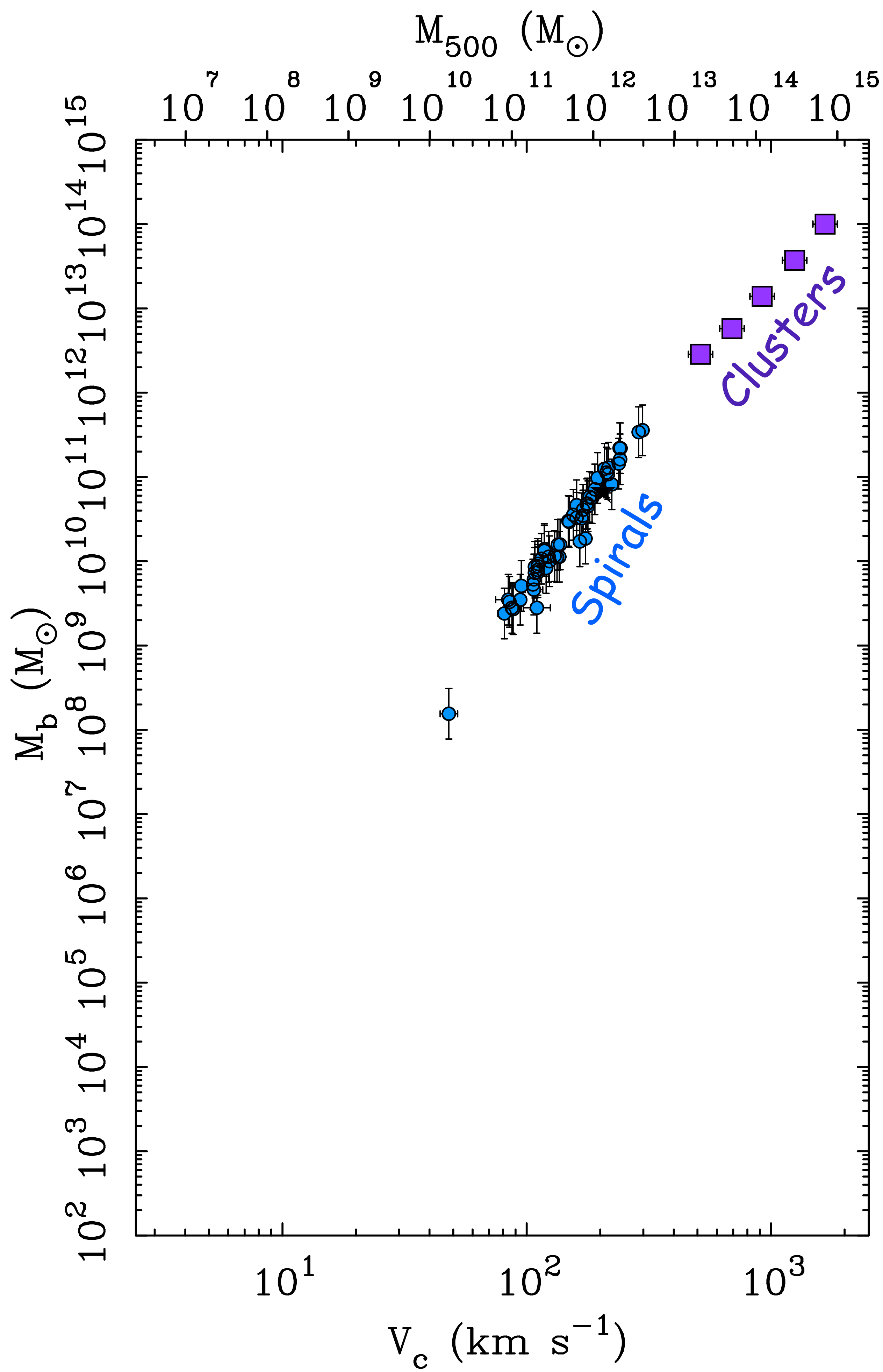
Cluster data: Giodini et al. (2009)

assume $V_c = 1.1 V_{500}$

Milky Way: McGaugh (2008; unpublished)

COBE Milky Way

M_b-V_c Relation



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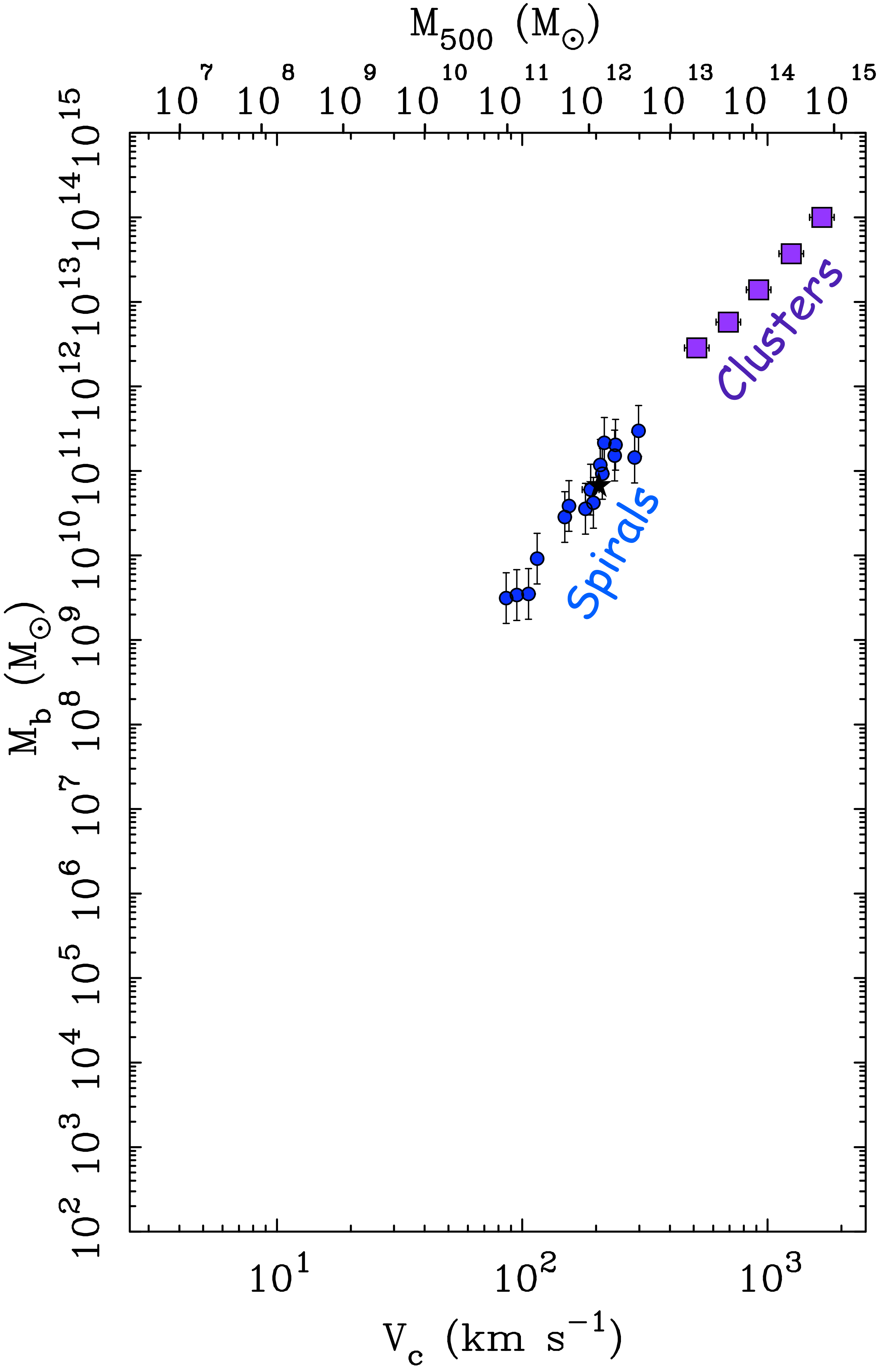
assume $V_c = 1.1V_{500}$

Spirals: McGaugh (2004; 2005)
M_*/L from mass discrepancy-acceleration relation

M_b-V_c Relation

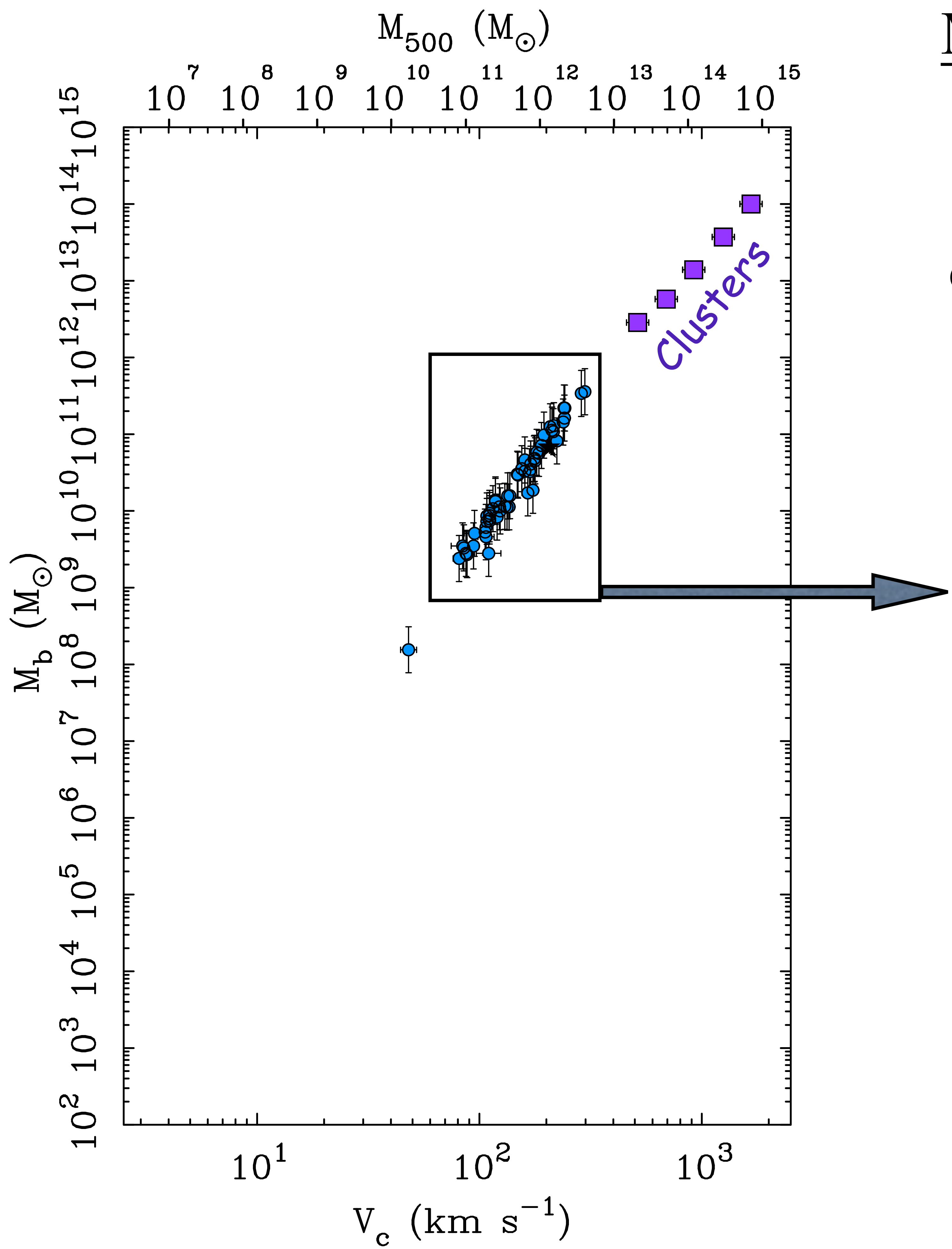


Cluster data: Giodini et al. (2009)

assume $V_c = 1.1 V_{500}$

Spirals: Zakursky et al. (in prep.)
M*/L from K-band luminosities
and population synthesis models.

M_b-V_c Relation



Cluster data: Giodini et al. (2009)

assume $V_c = 1.1 V_{500}$

Spirals: McGaugh (2004; 2005)
M*/L from mass discrepancy-acceleration relation

Tully-Fisher relation

also known as the
Baryonic Tully-Fisher relation
when including gas mass as well as stars.

clusters ✓

spirals ✓

groups

Stellar mass obvious;
gas hard to detect.
Similar to Ellipticals if we ignore gas.

ellipticals

Most of the baryonic mass is in stars.
The hard part here is V_c / M_{500}.

clusters ✓

spirals ✓

groups

✗ Stellar mass obvious;
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ellipticals

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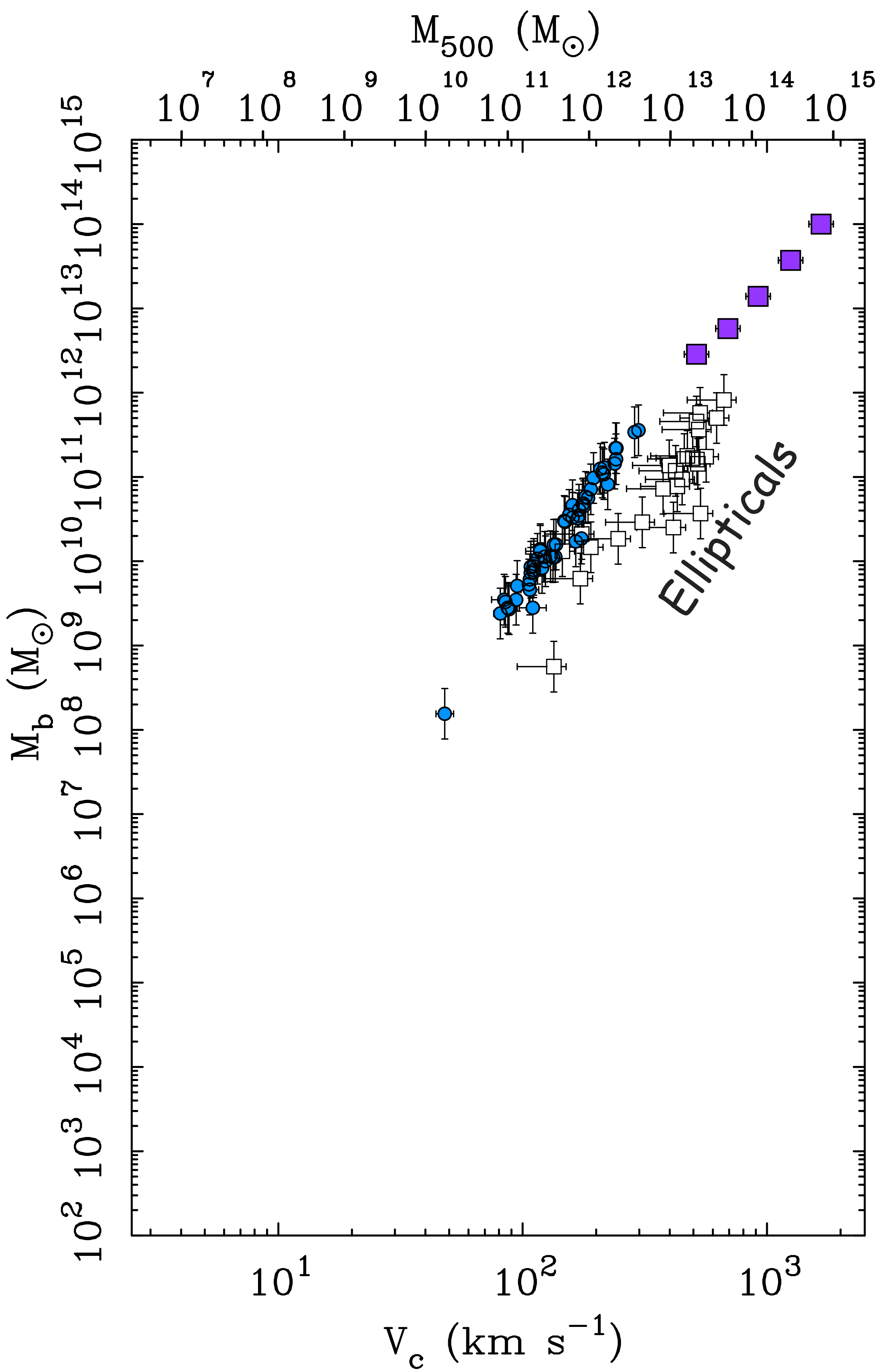


M_b-V_c Relation

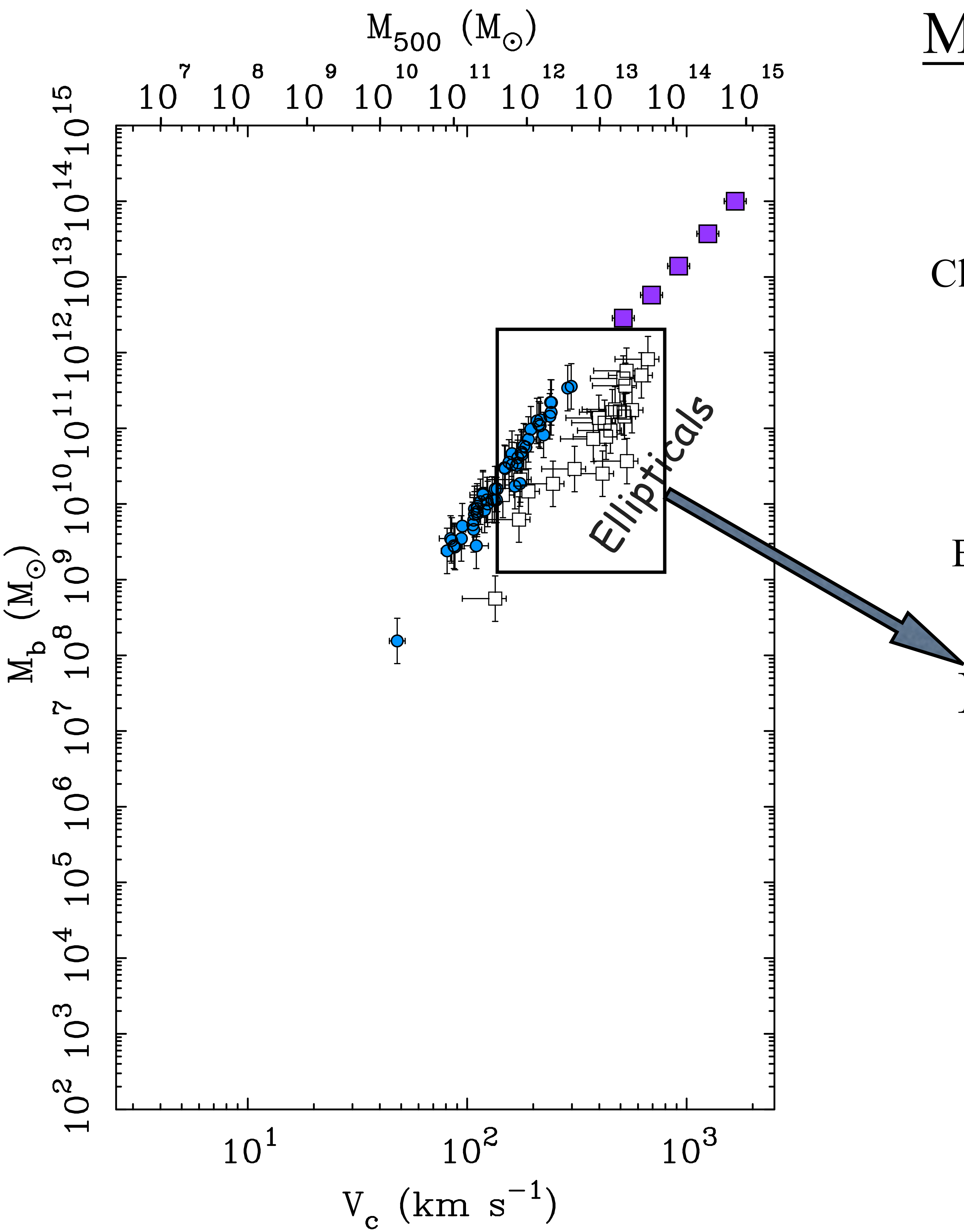
Cluster data: Giodini et al. (2009)

assume $V_c = 1.1V_{500}$

Spirals: McGaugh (2004; 2005)

Ellipticals: Cappalleri et al. (2006)
[SAURON]

M_b-V_c Relation



Cluster data: Giodini et al. (2009)

assume $V_c = 1.1 V_{500}$

Spirals: McGaugh (2004; 2005)

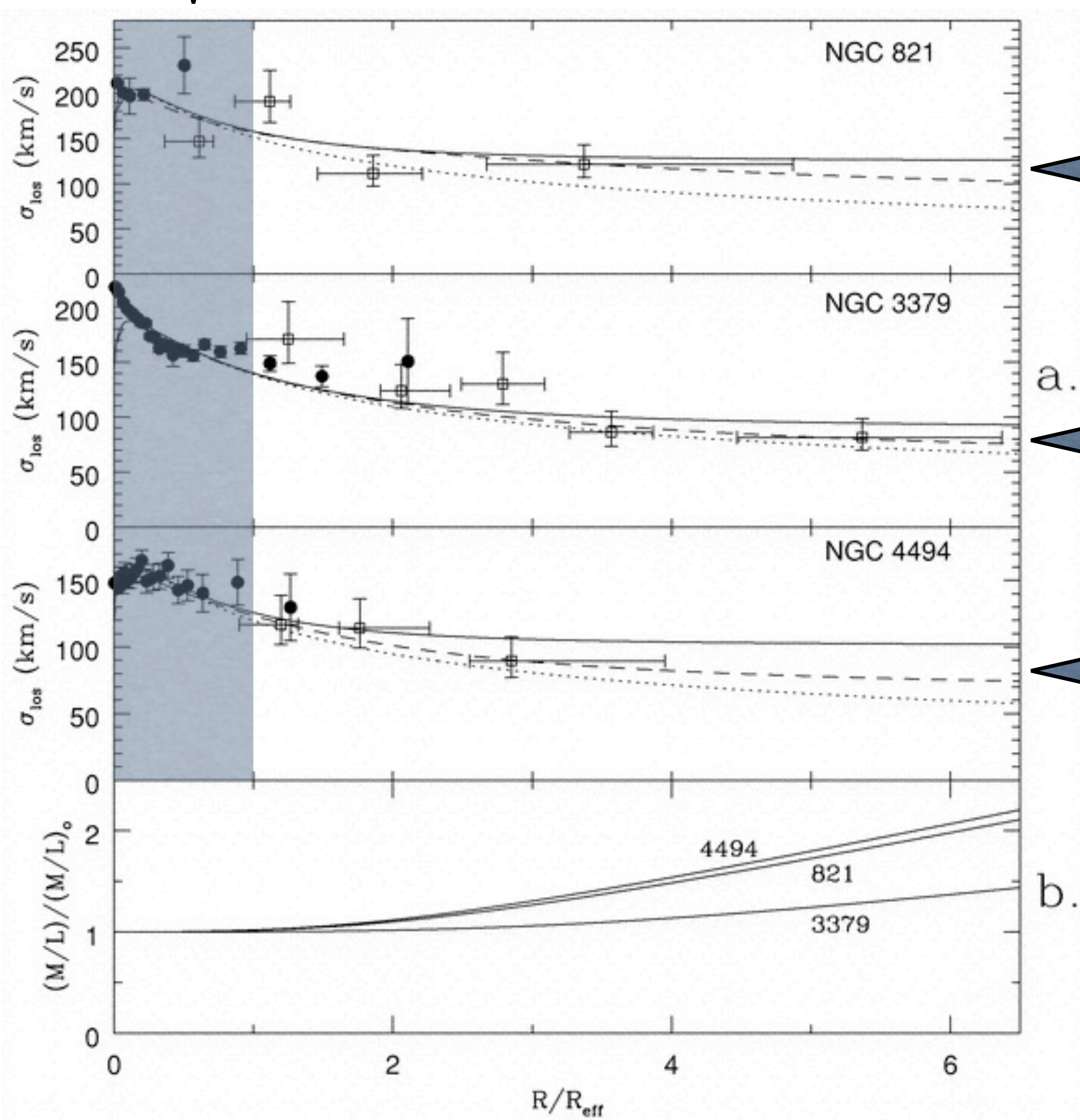
Ellipticals: Cappalleri et al. (2006) [SAURON]

Faber-Jackson relation

$$V_c = \sqrt{3}\sigma_{los}$$

V_c typically measured at small radii but $V_c(r)$ declines substantially for most Elliptical galaxy mass models.

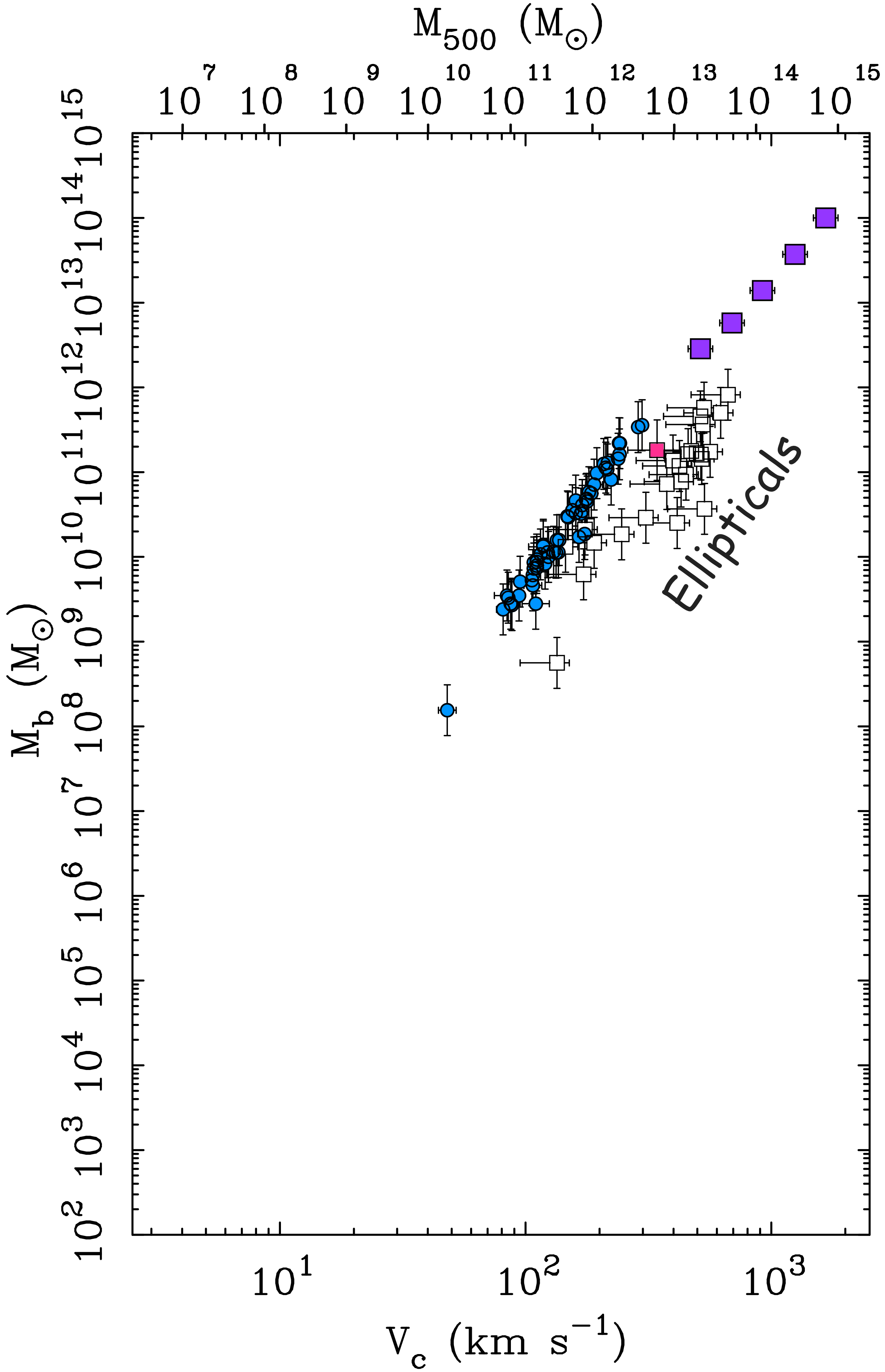
Circular velocity overestimated.
[f_v large and uncertain.]



$$V_c > V_{500}$$

Romanowsky et al. (2003)

M_b-V_c Relation



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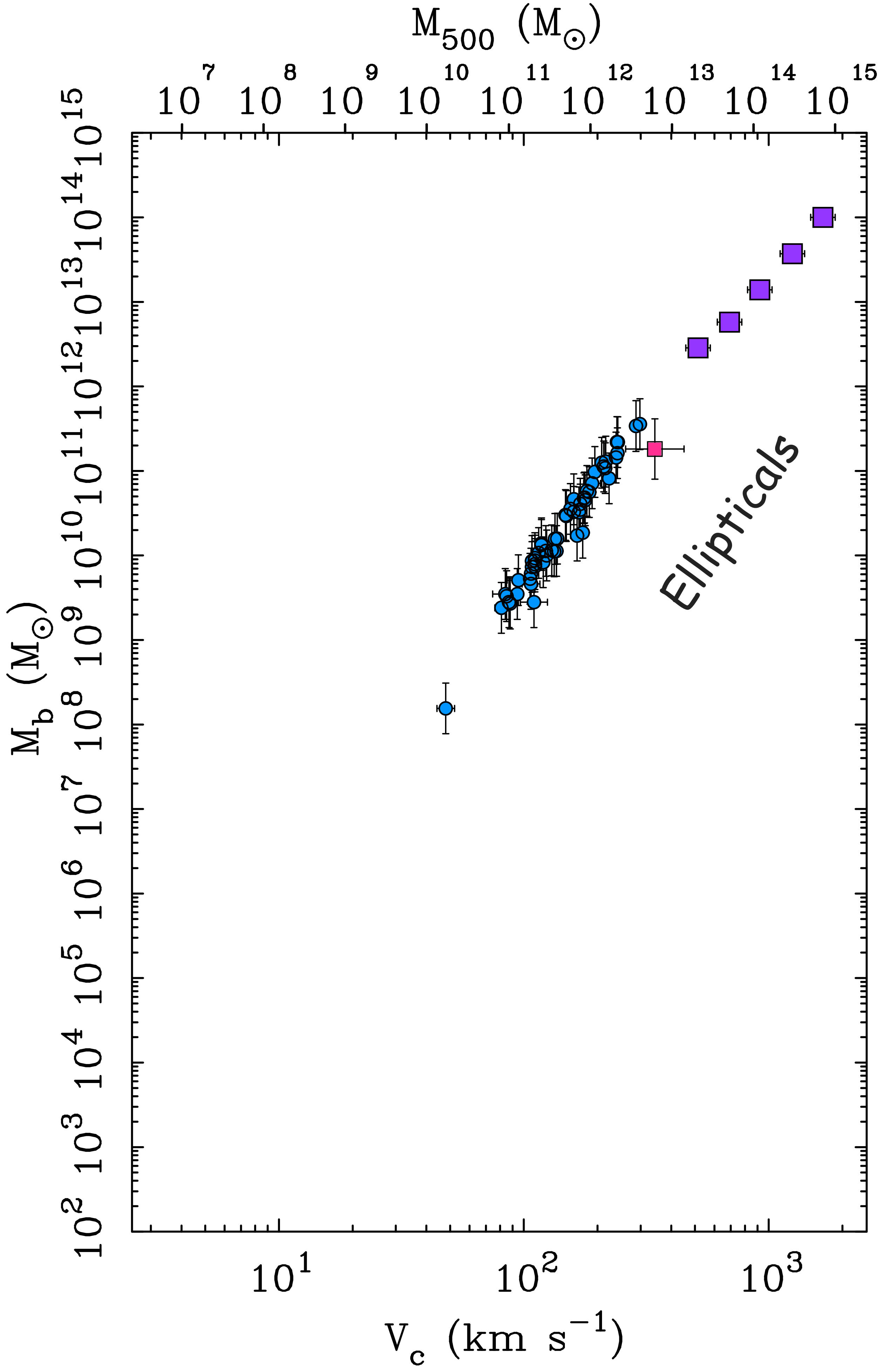

M_b-V_c Relation

Cluster data: Giodini et al. (2009)

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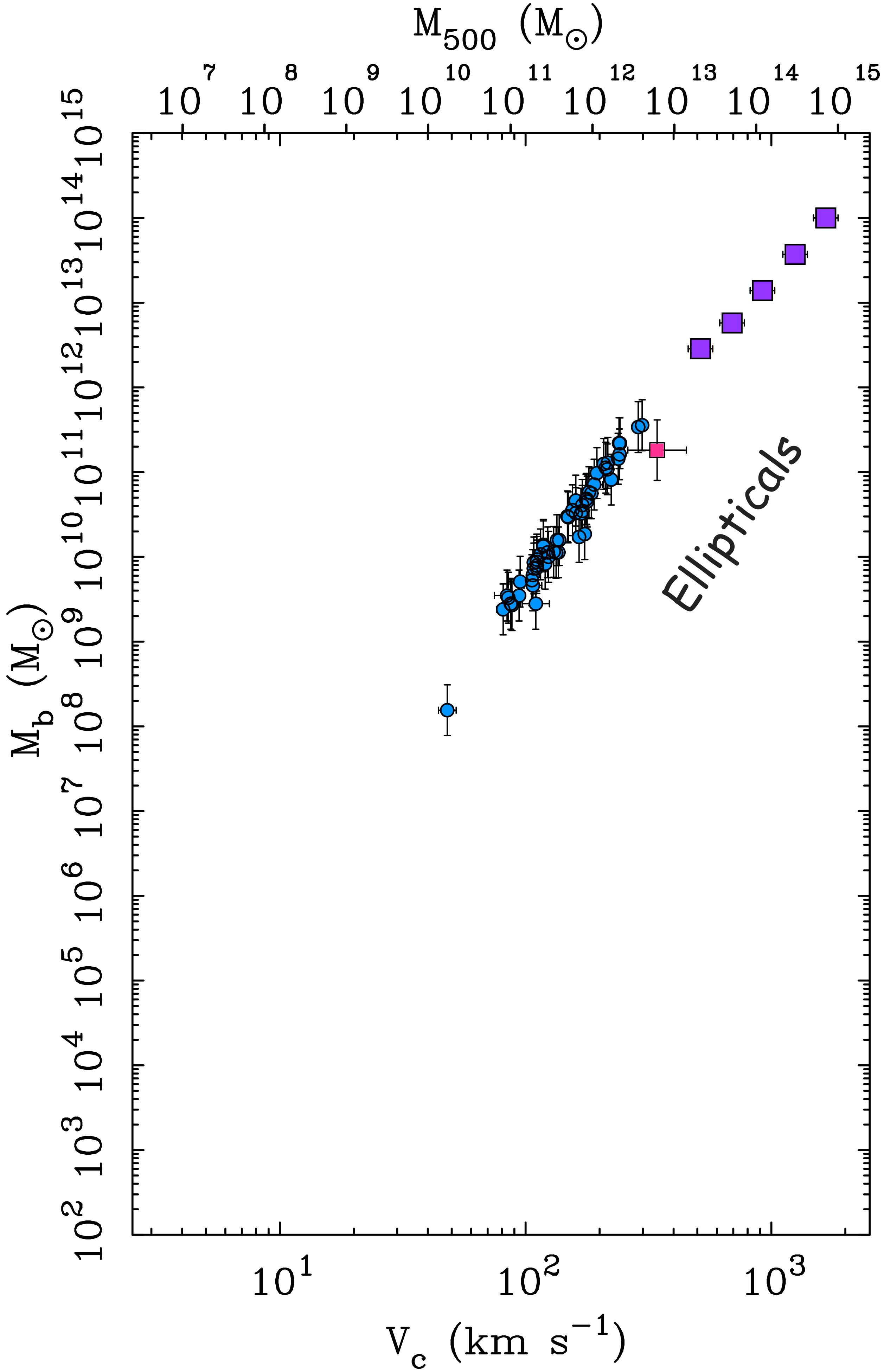
Spirals: McGaugh (2004; 2005)

Ellipticals, Gravitational Lensing: Gavazzi et al. (2007)



M_b-V_c Relation

Cluster data: Giodini et al. (2009)

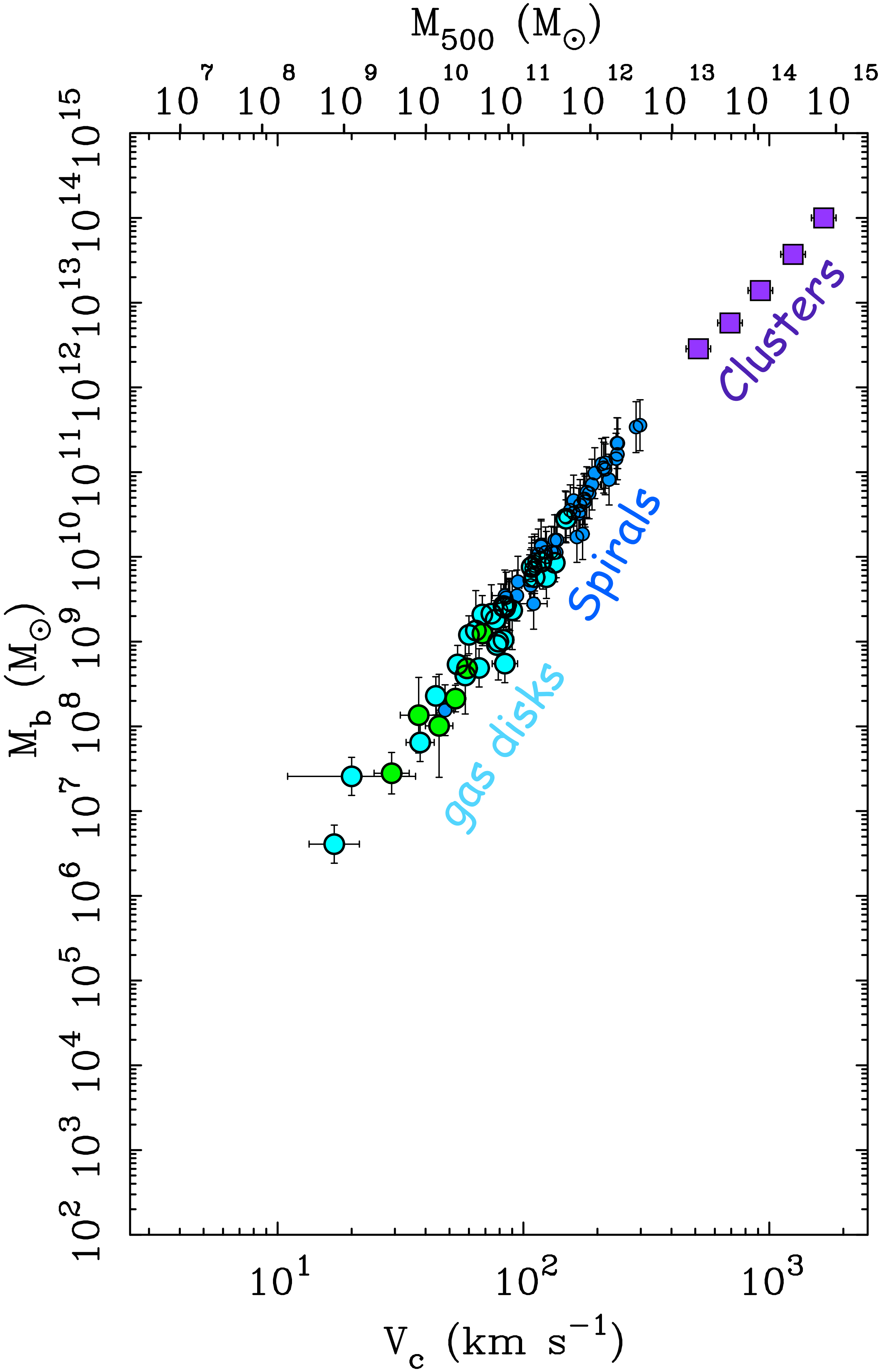
assume $V_c = 1.1V_{500}$

Spirals: McGaugh (2004; 2005)

Ellipticals, Gravitational Lensing:
Gavazzi et al. (2007)

Ellipticals may have lower baryon fractions, depending on how M_{500} is estimated.

M_b-V_c Relation



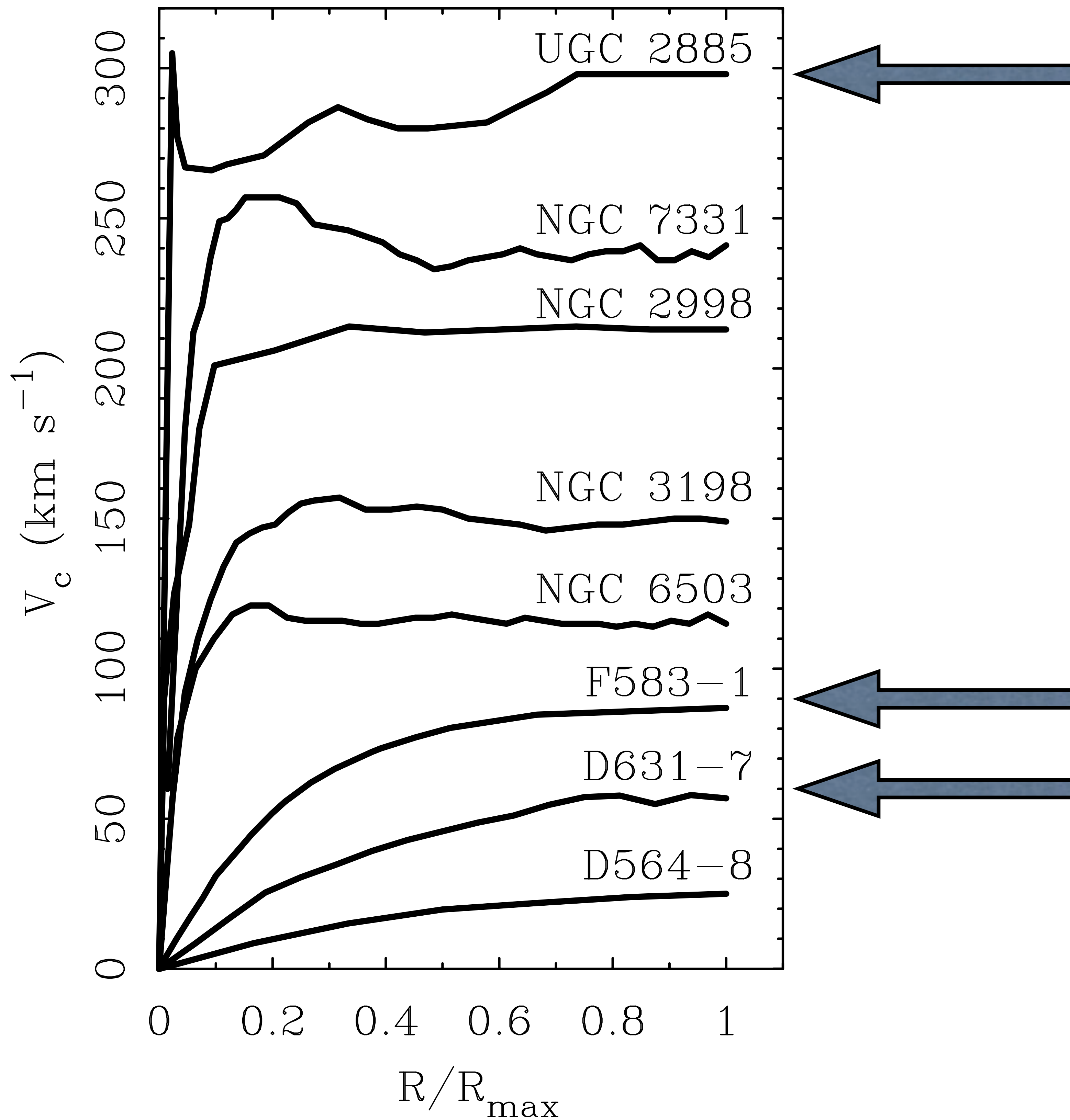
Cluster data: Giodini et al. (2009)

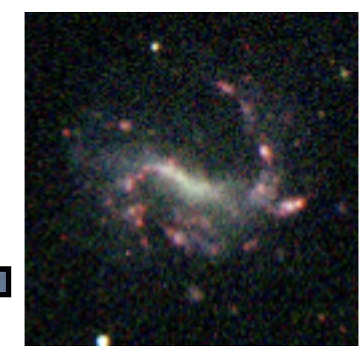
assume $V_c = 1.1 V_{500}$

Spirals: McGaugh (2004; 2005)

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

Rotation curves of spirals
and low mass dIrrs with $M_* < M_g$.

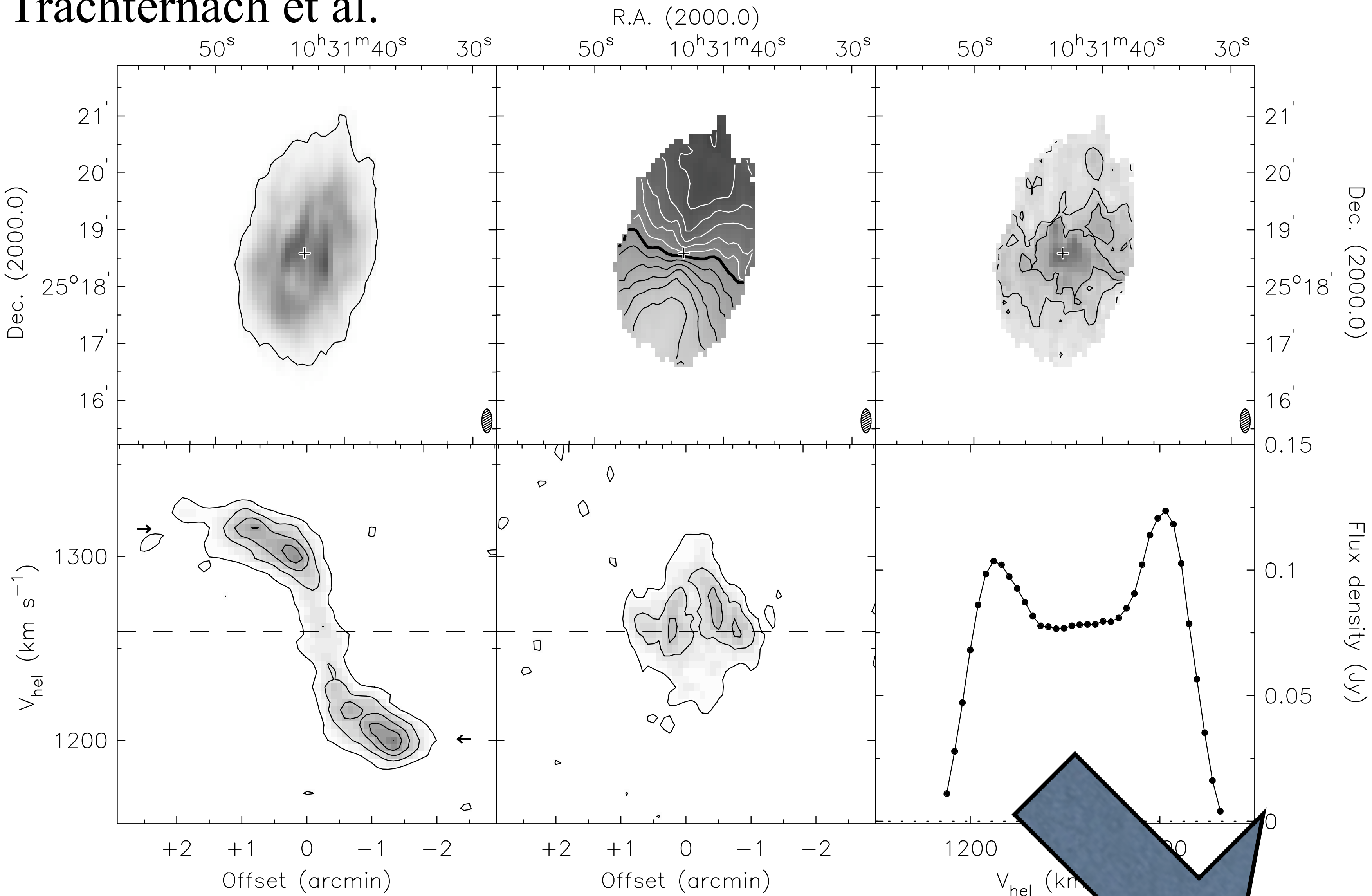




Rotation curves of
late type disks
(Sd, Sm, Irr)

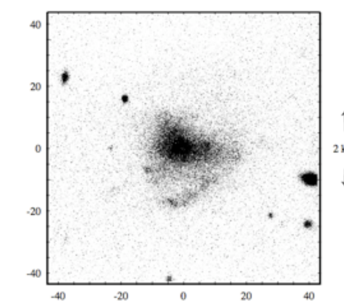
Kuzio de Naray et al.
(2006, 2008, 2009);
Trachternach et al.
(2009)
Stark et al. (2009)

Trachternach et al.

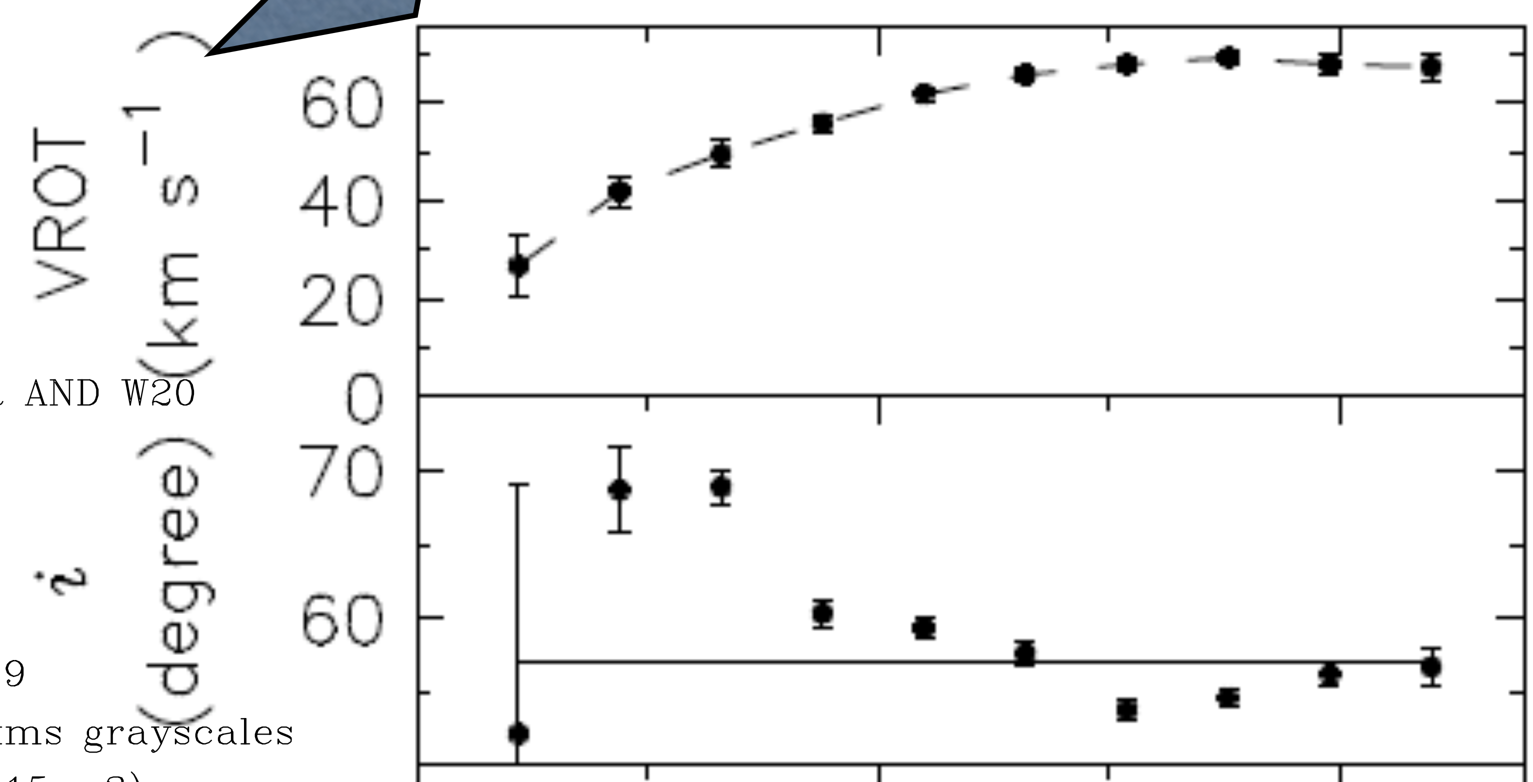


HI

Reduce dependence on stellar M*/L - select gas dominated galaxies with $M_\star < M_g$



optical



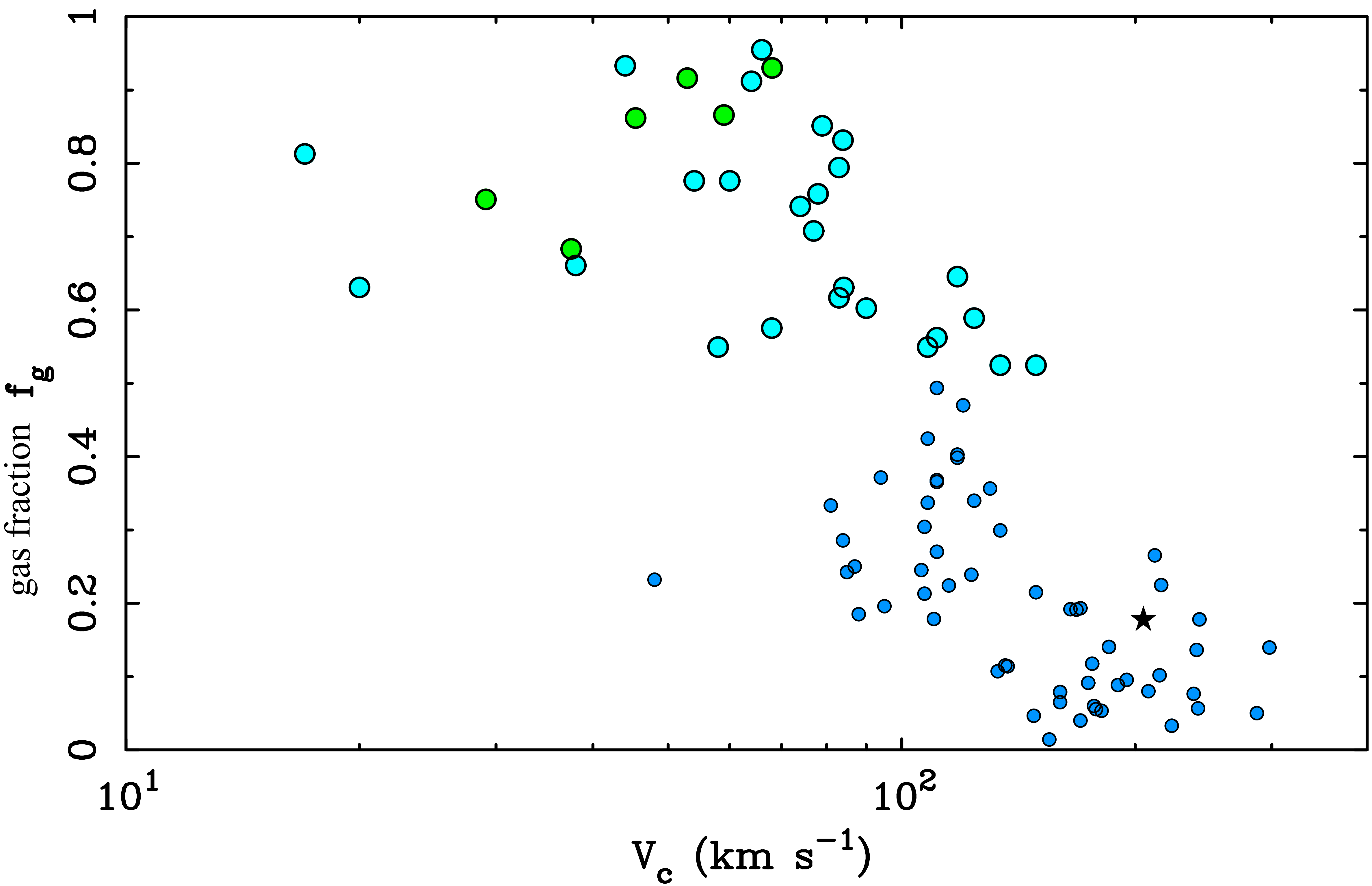
D500−2

"best−quality sample" Vrot AND Vflat AND W20
Vrot=67.7, vflat=68
I_{opt}=... I_{ell}=53 I_{kin}=57
box=−40 −40 40 40

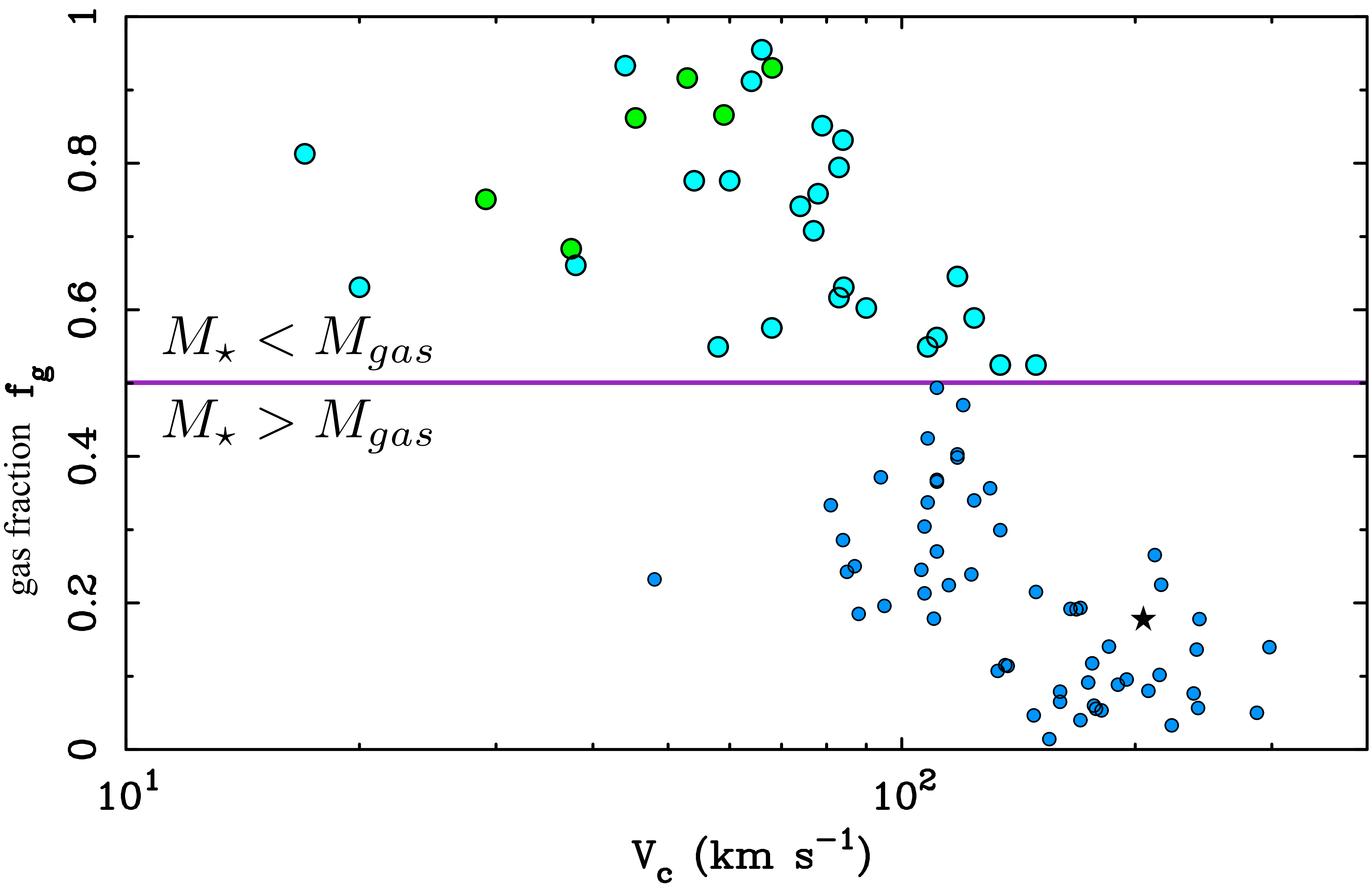
Vsys= 1259, deltaV=10km/s

3sigma=5,09mJy == nhi von 8.8 E+19

MOM2: 5,10,15 km/s contours, 2−40kms grayscales

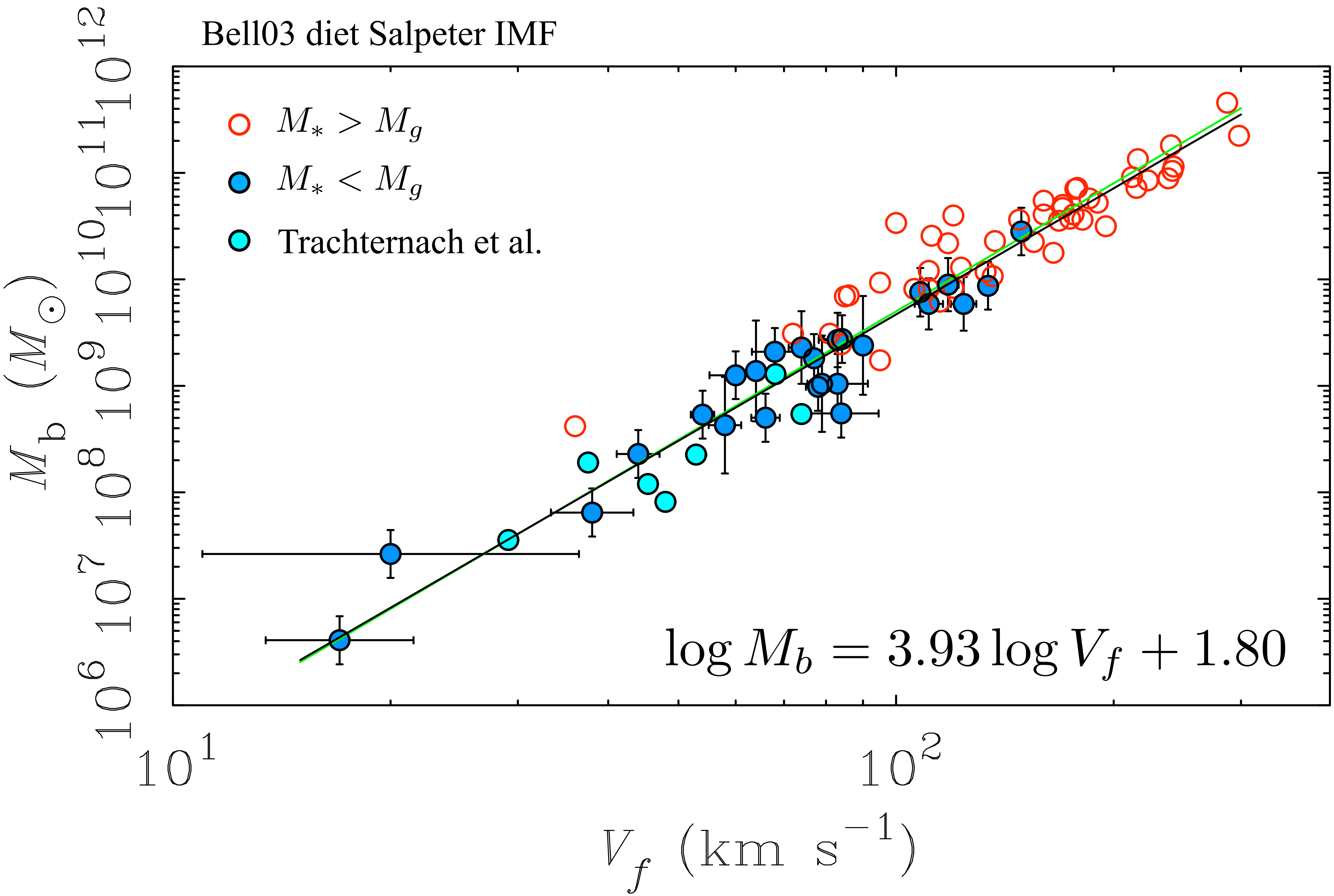


1
0.8
0.6
0.4
0.2
0
gas fraction f_g
10^1
10^2
V_c (km s^-1)



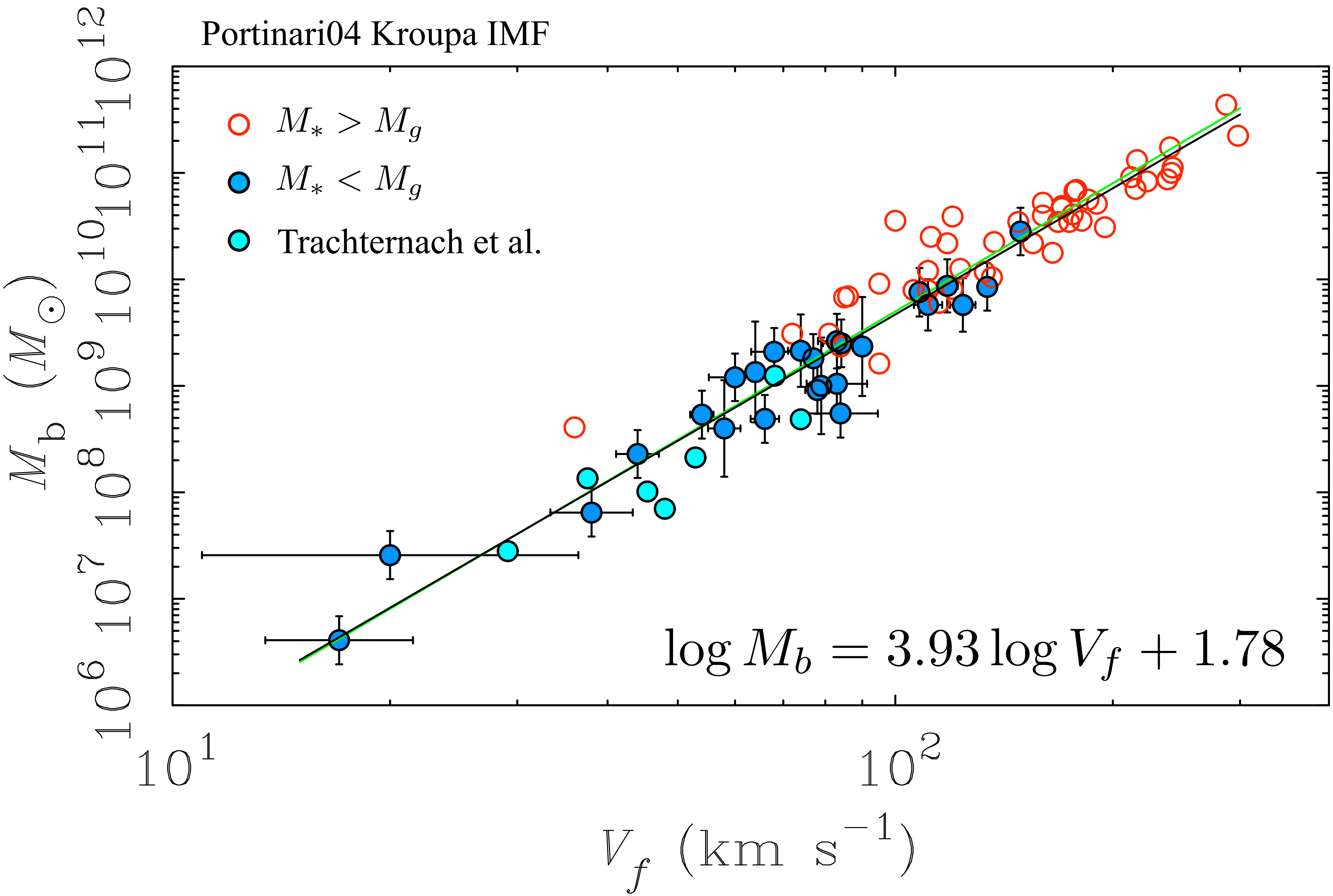
1
0.8
0.6
0.4
0.2
0
10^1
10^2
gas fraction f_g
V_c (km s^{-1})
$M_\star < M_{gas}$
$M_\star > M_{gas}$

Baryonic Tully-Fisher Relation
Stark, McGaugh, & Swaters (2009 AJ, 138, 392)



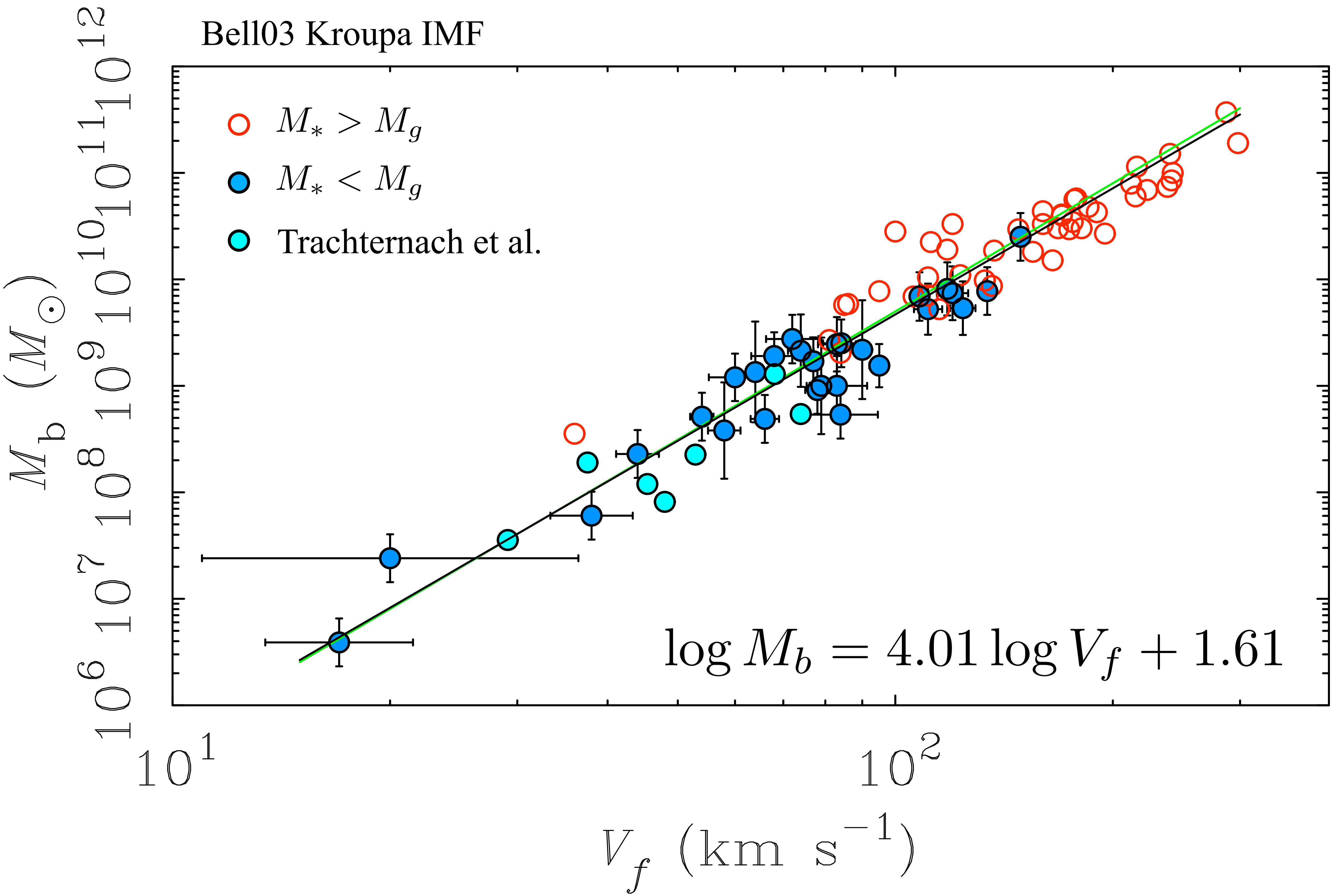
Baryonic Tully-Fisher Relation

Stark, McGaugh, & Swaters (2009 AJ, 138, 392)

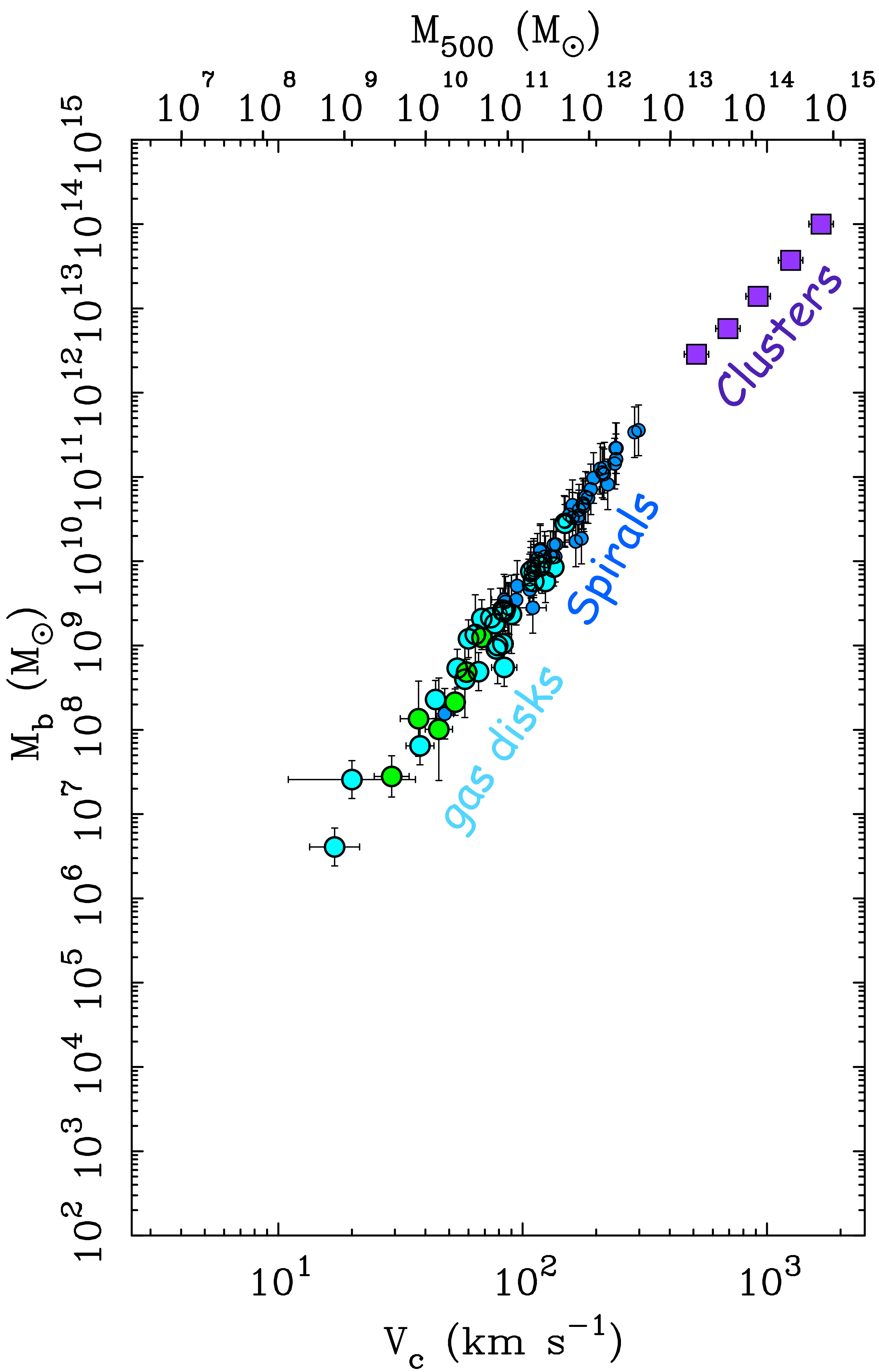


Baryonic Tully-Fisher Relation

Stark, McGaugh, & Swaters (2009 AJ, 138, 392)



M_b-V_c Relation



Cluster data: Giodini et al. (2009)

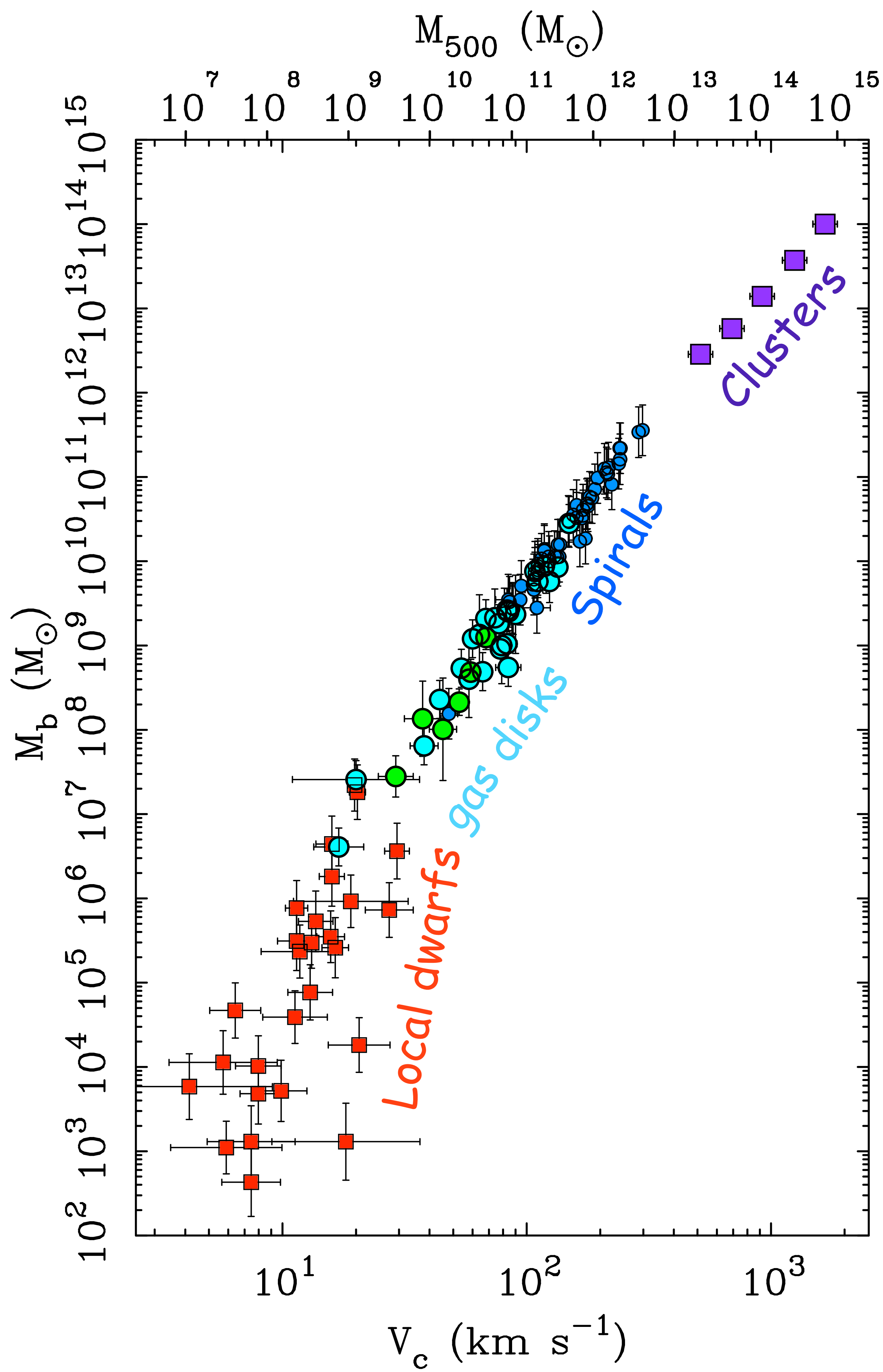
assume $V_c = 1.1V_{500}$

Spirals: McGaugh (2004; 2005)

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

Location in M_b-V_c plane fixed by M_g.

M_b-V_c Relation



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assume $V_c = 1.1 V_{500}$

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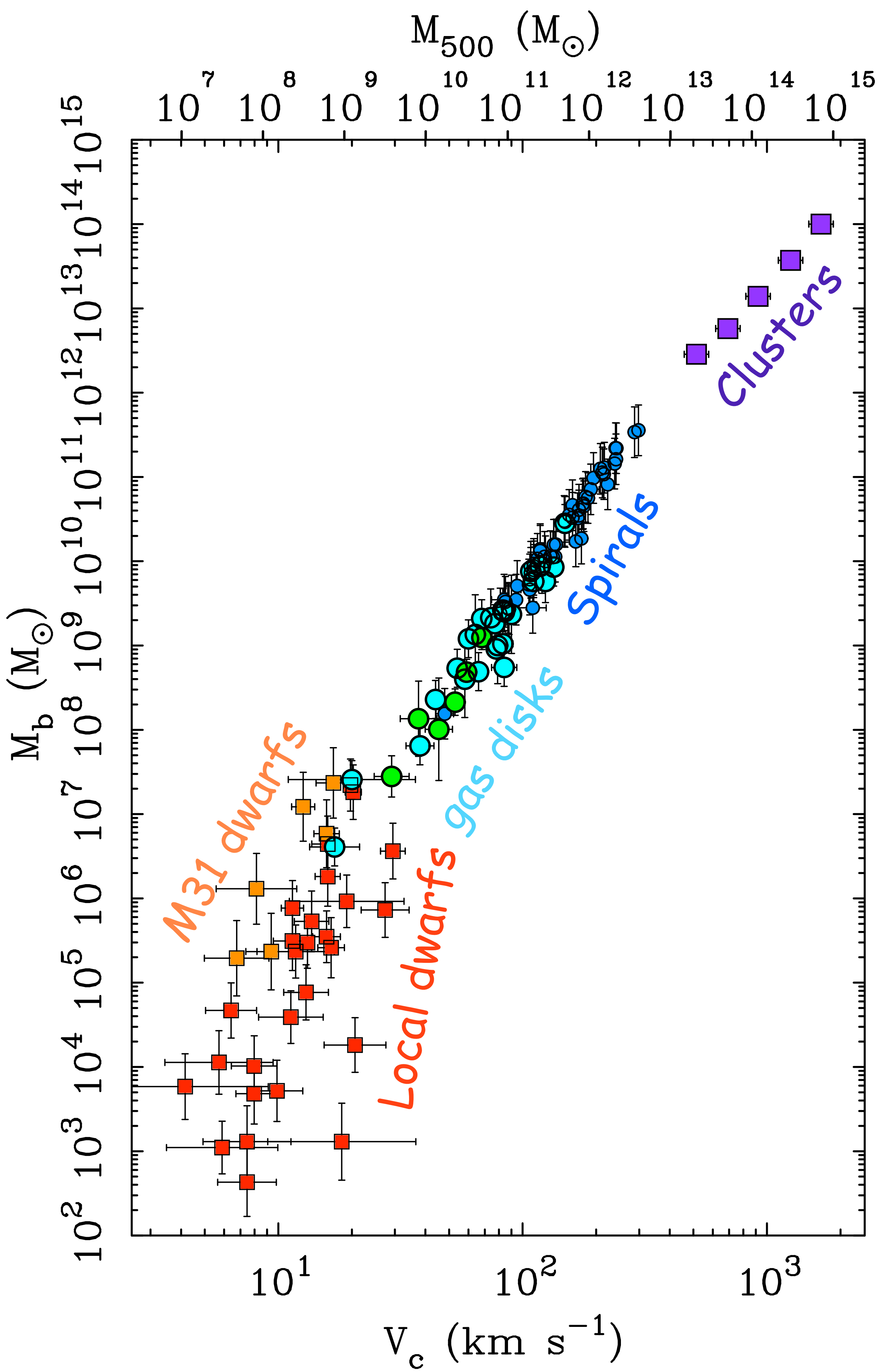
Gas dominated disks:
Stark et al. (2009)
Trachternach et al. (2009)

Local dwarf data: Walker et al. (2009)
<M*/L> = 1.3 (Mateo et al. 1998)
(Martin et al. 2008)

$$V_c = \sqrt{3}\sigma$$

Fornax



M_b-V_c Relation

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Gas dominated disks:
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$\langle M_*/L \rangle = 1.3$ (Mateo et al. 1998)
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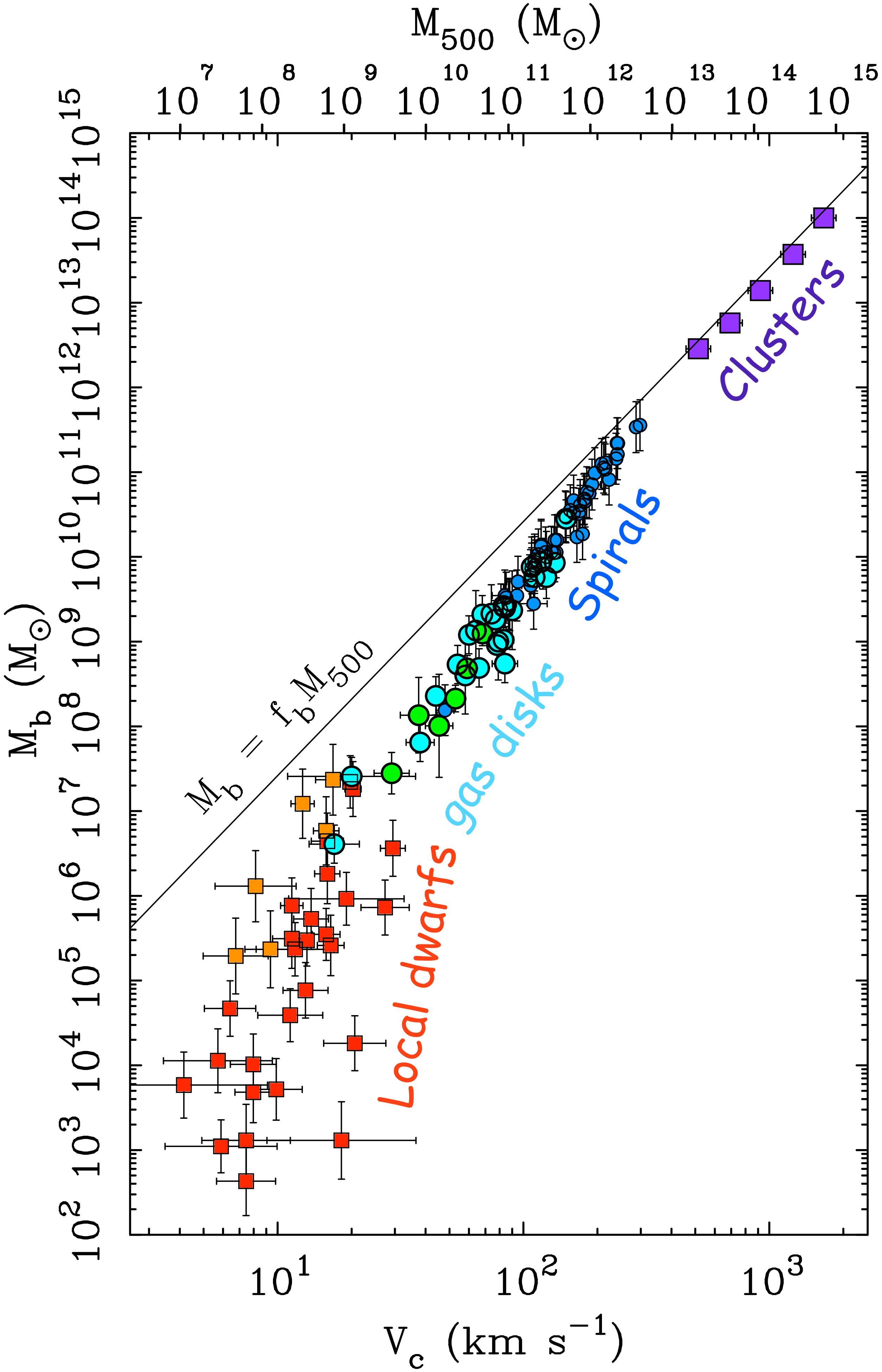
$$V_c = \sqrt{3}\sigma$$

Fornax

M_b-V_c Relation



Cluster data: Giodini et al. (2009)

assume $V_c = 1.1 V_{500}$

Spirals: McGaugh (2004; 2005)

Gas dominated disks:
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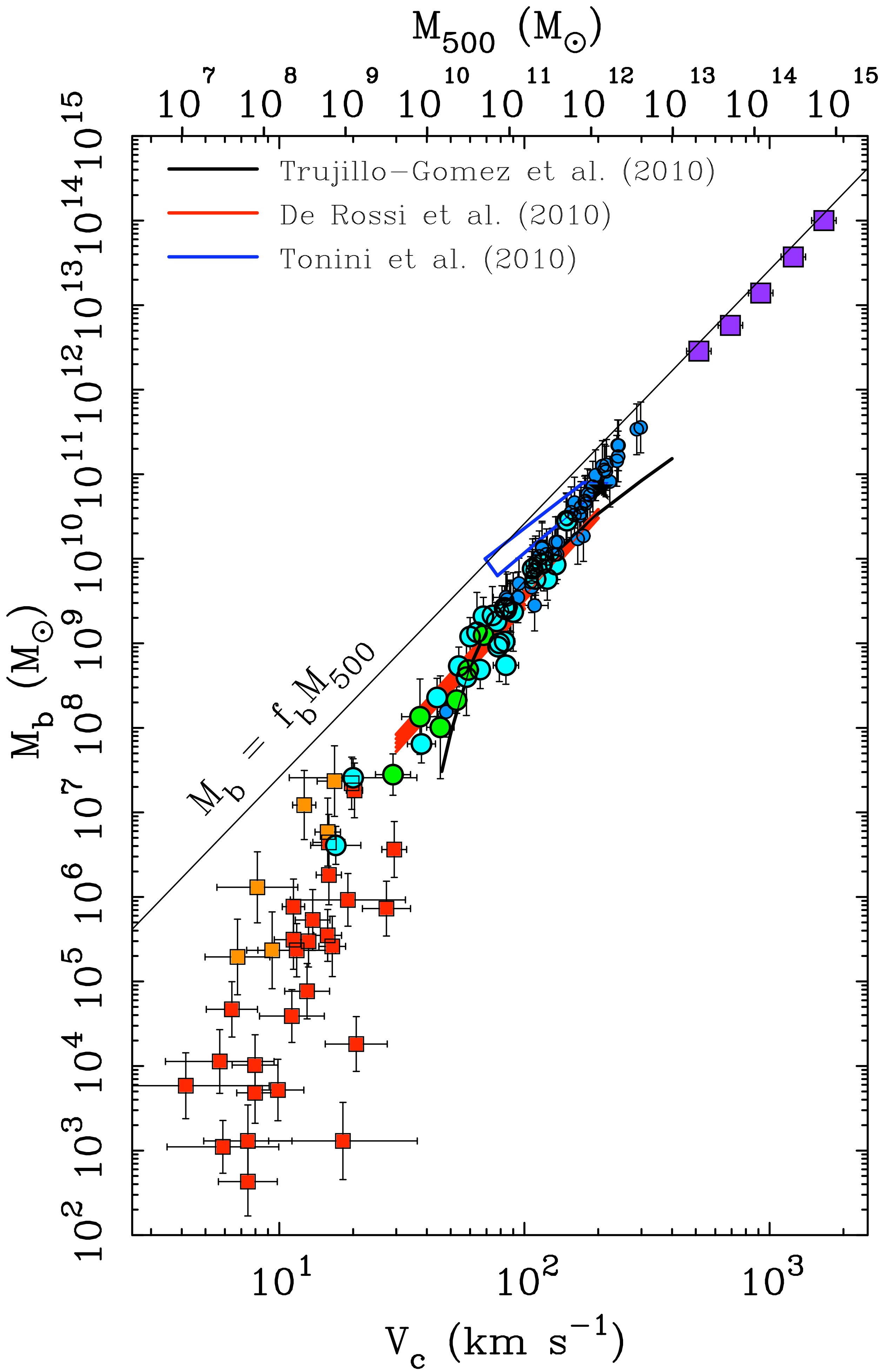
Local dwarf data: Walker et al. (2009)
$\langle M_*/L \rangle = 1.3$ (Mateo et al. 1998)
(Martin et al. 2008)

$$V_c = \sqrt{3}\sigma$$

$$M_b : M_{500} \neq 1 : 1$$



M_b-V_c Relation

Cluster data: Giodini et al. (2009)

assume $V_c = 1.1 V_{500}$

Spirals: McGaugh (2004; 2005)

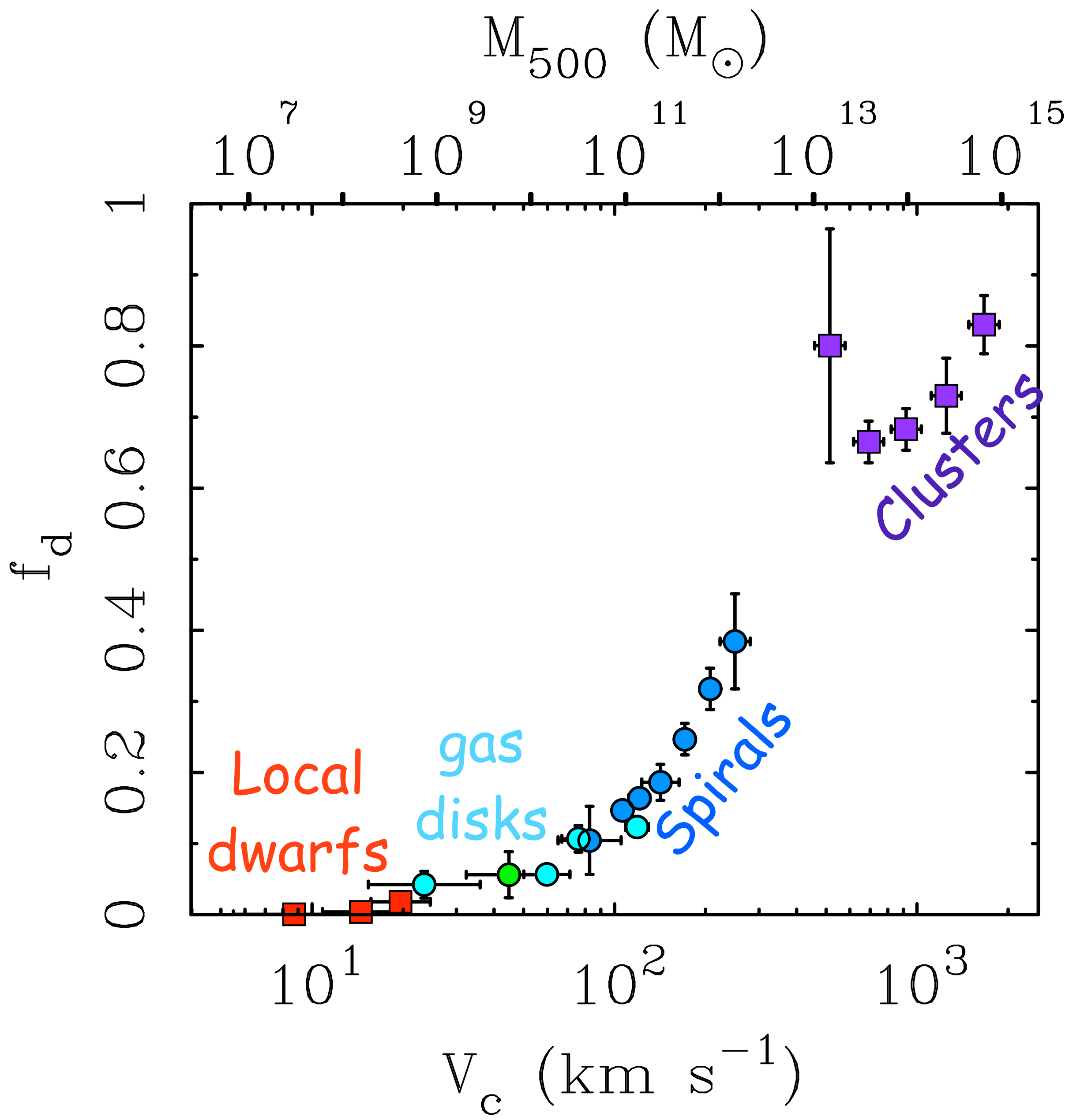
Gas dominated disks:
Stark et al. (2009)
Trachternach et al. (2009)

Local dwarf data: Walker et al. (2009)
<M*/L> = 1.3 (Mateo et al. 1998)
(Martin et al. 2008)

$V_c = \sqrt{3}\sigma$

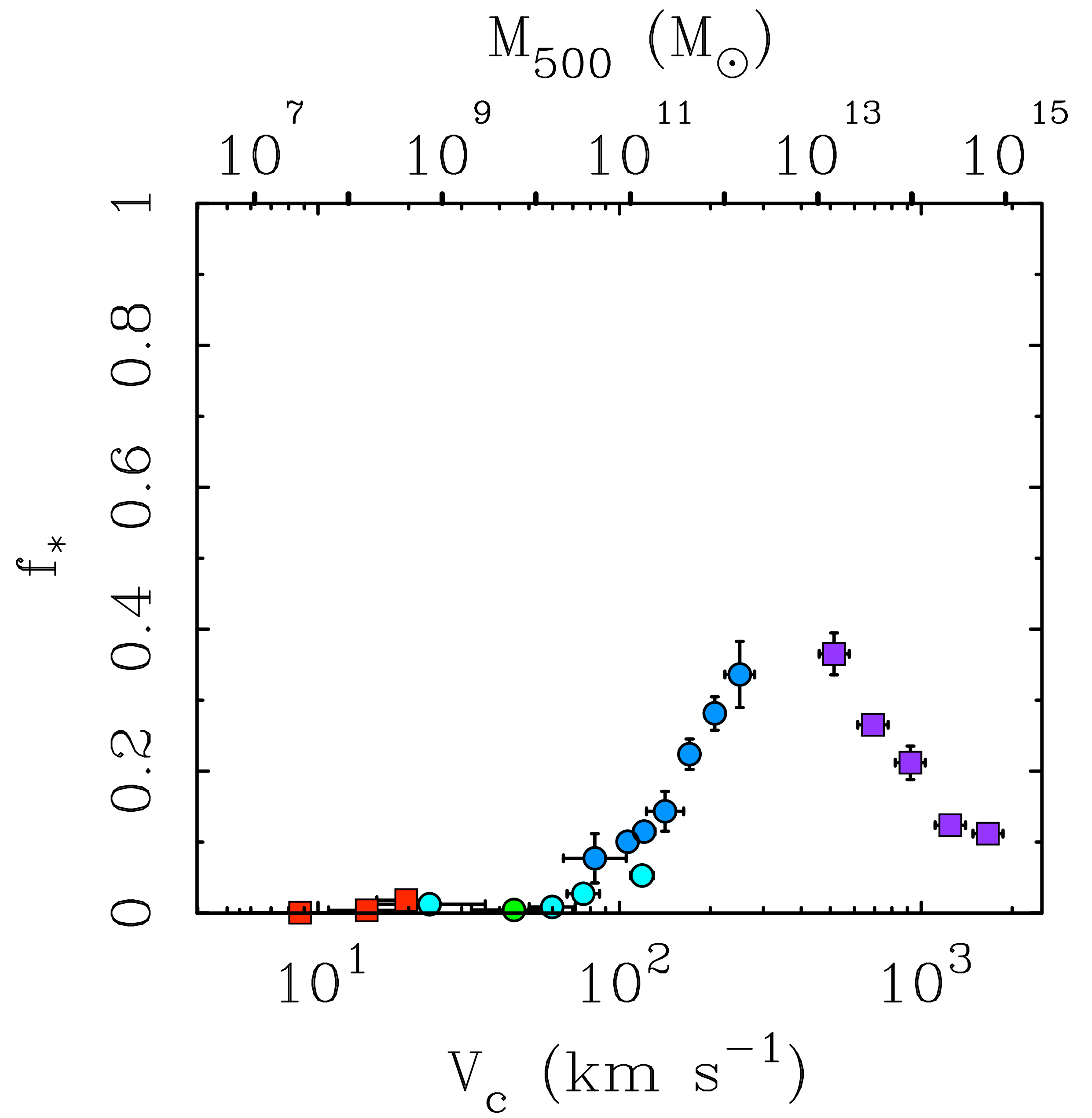
ΛCDM models differ

Divide out M ~ V^3



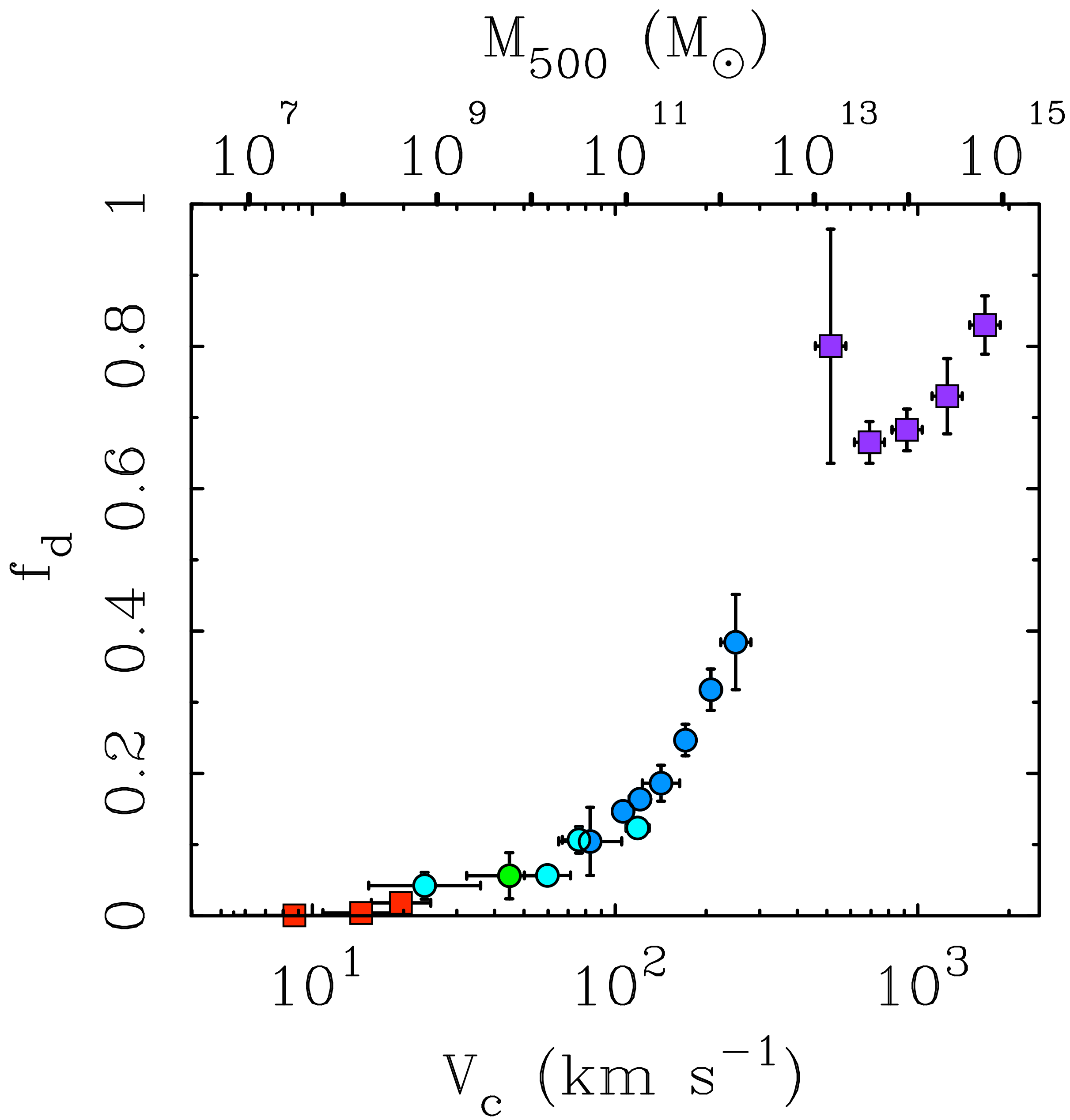
$$f_d = \frac{M_b}{f_b M_{500}}$$

detected baryon fraction

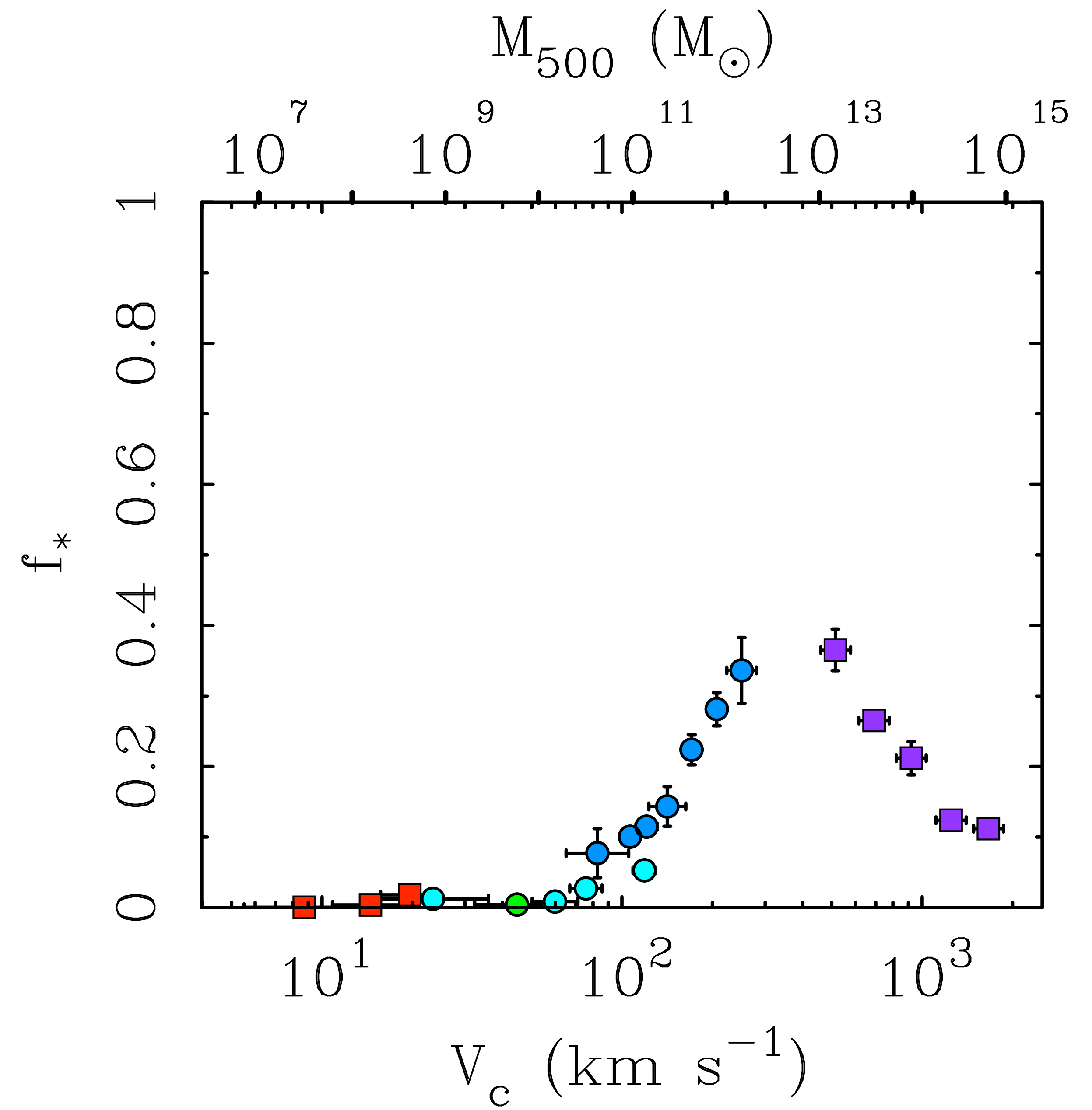


$$f_\star = \frac{M_\star}{f_b M_{500}}$$

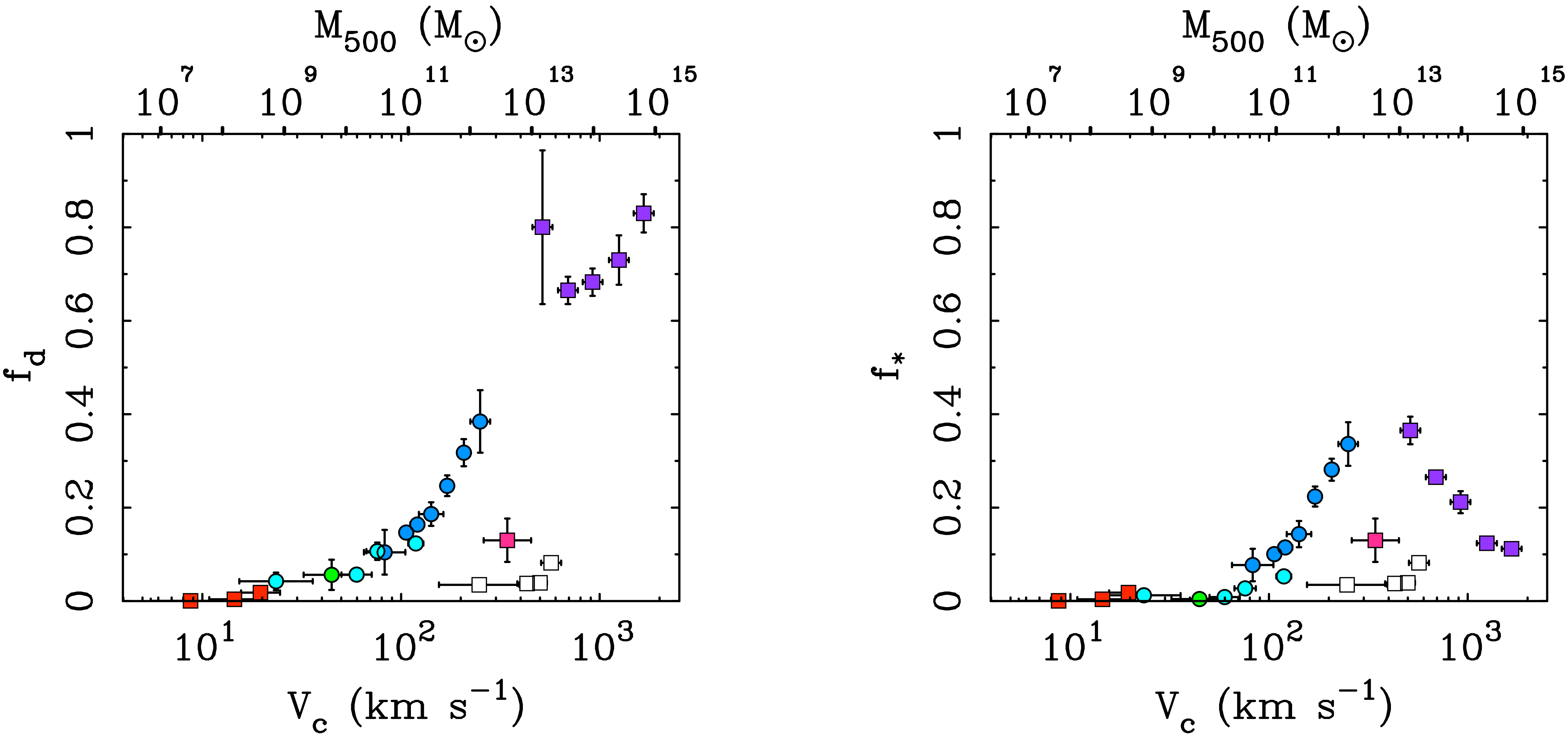
stellar fraction



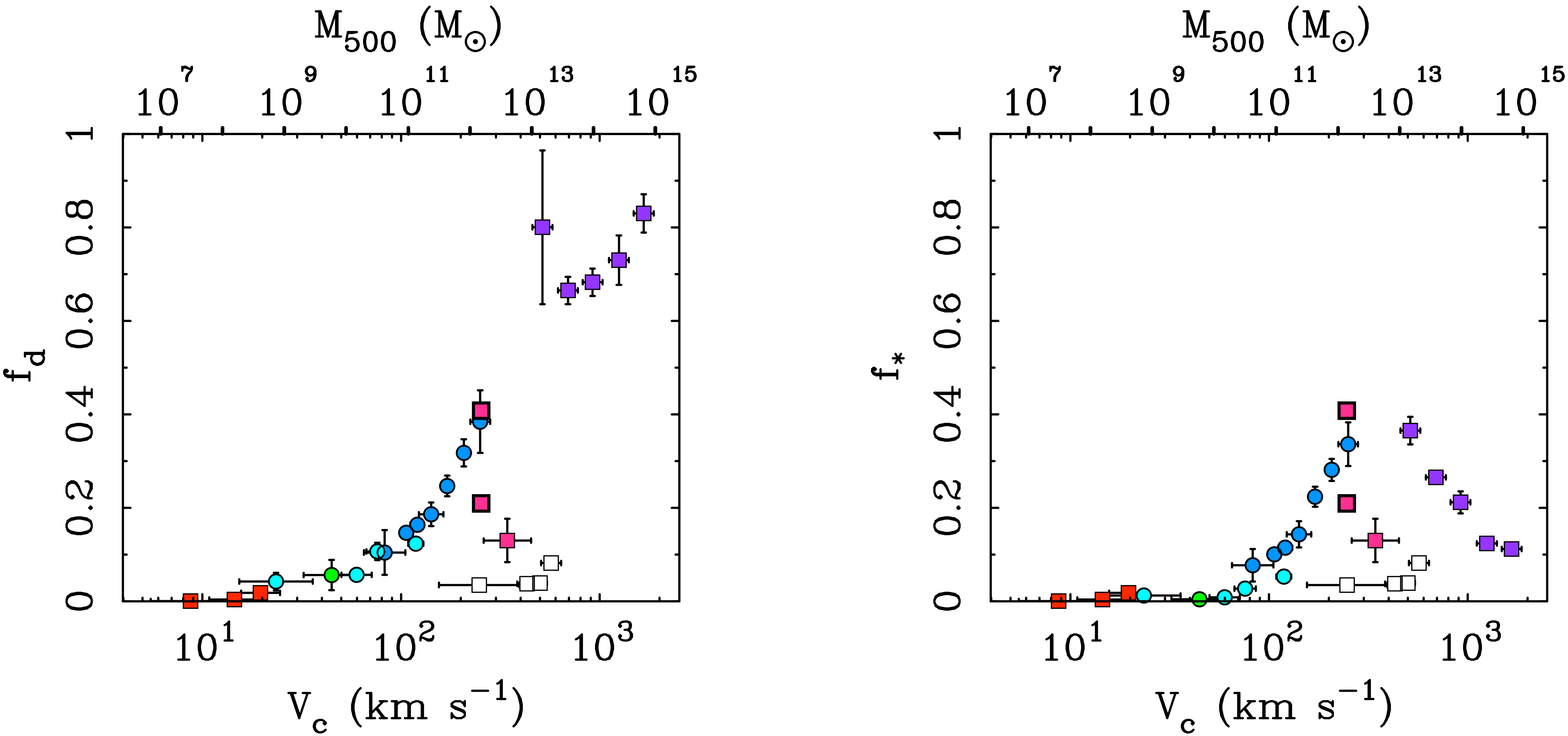
detected baryon fraction declines monotonically with decreasing mass.



stellar fraction peaks between $10^{12} < M_{500} < 10^{13} M_\odot$

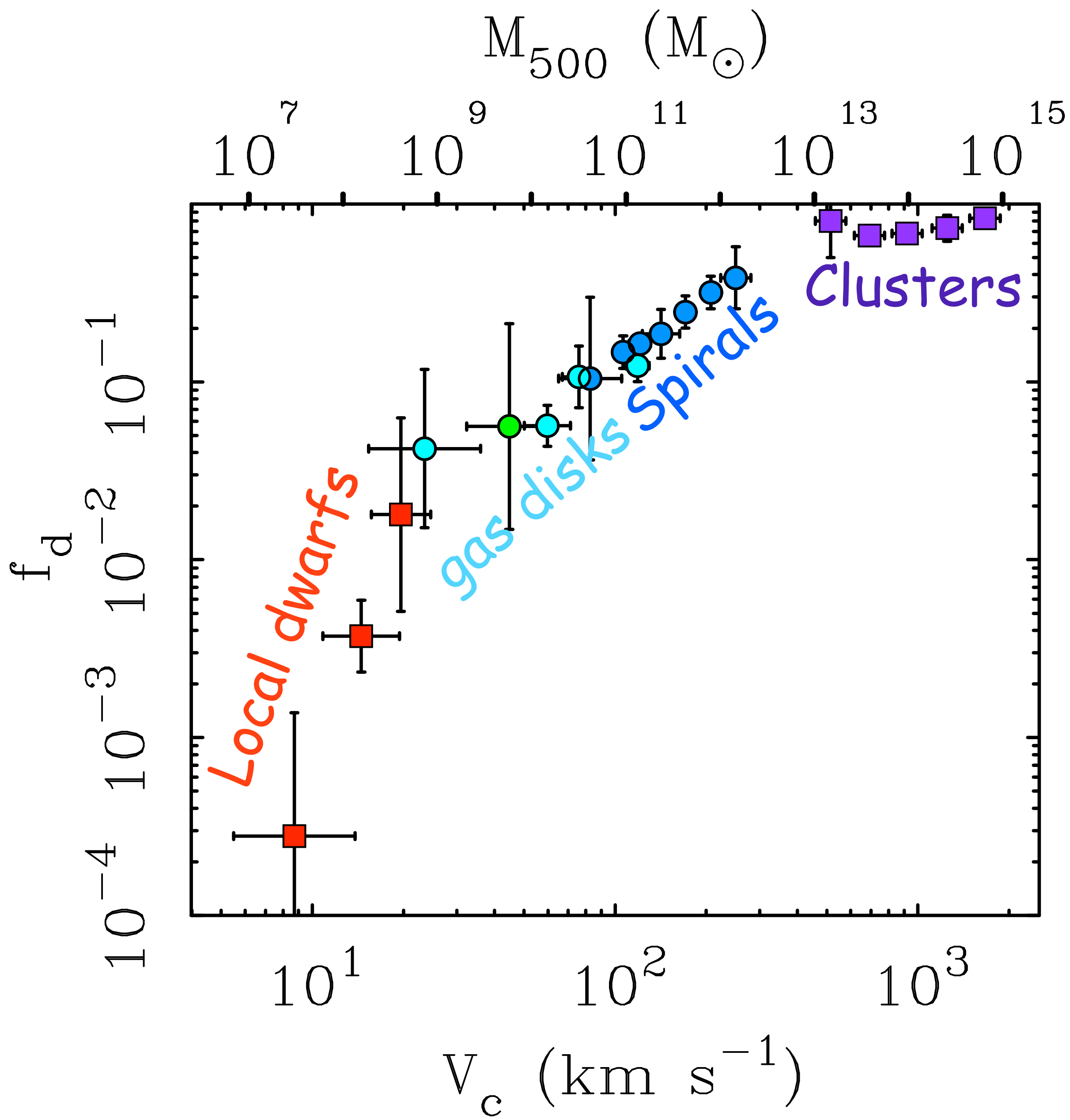


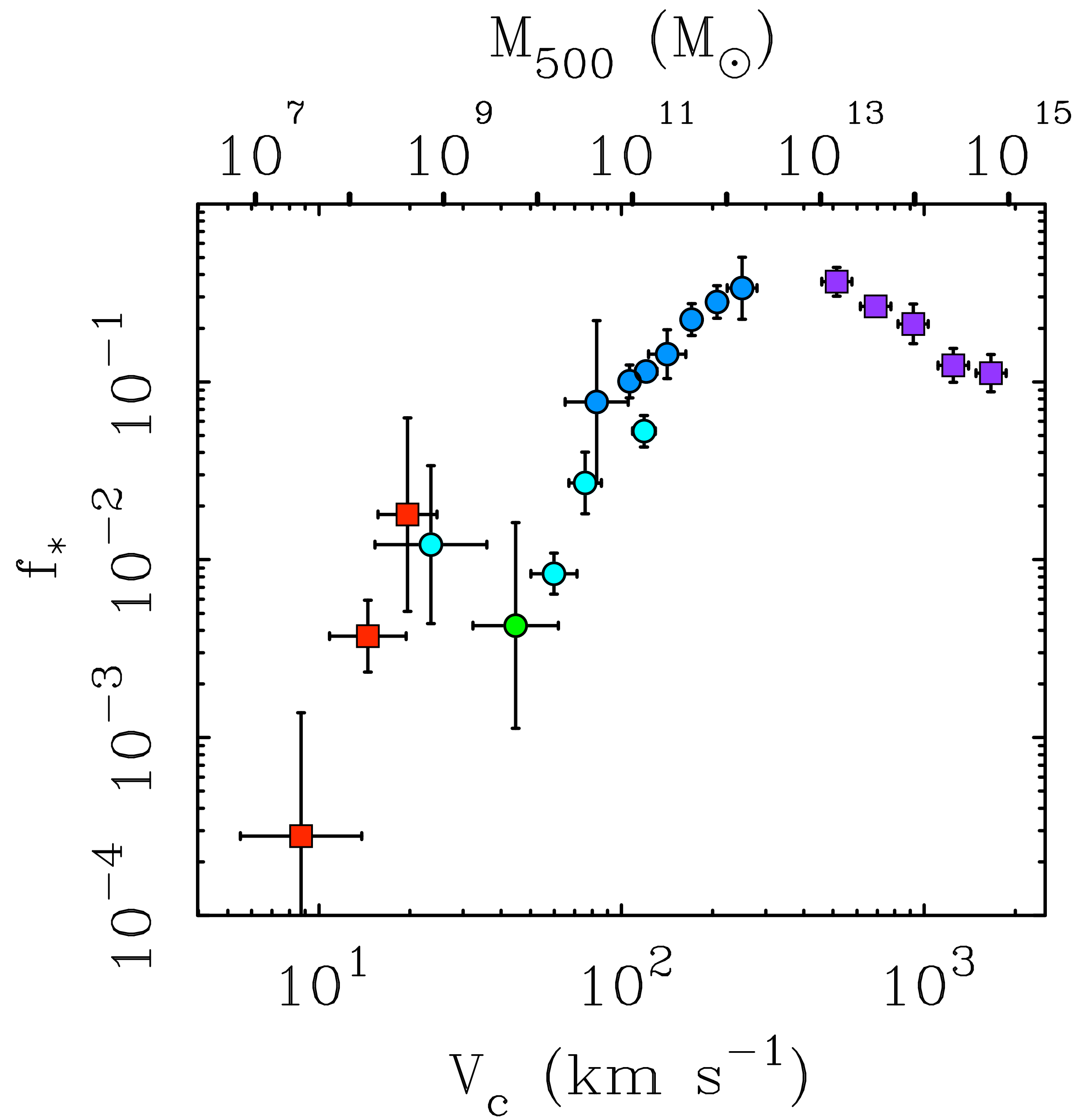
It is not obvious that giant Ellipticals or groups fill that gap.



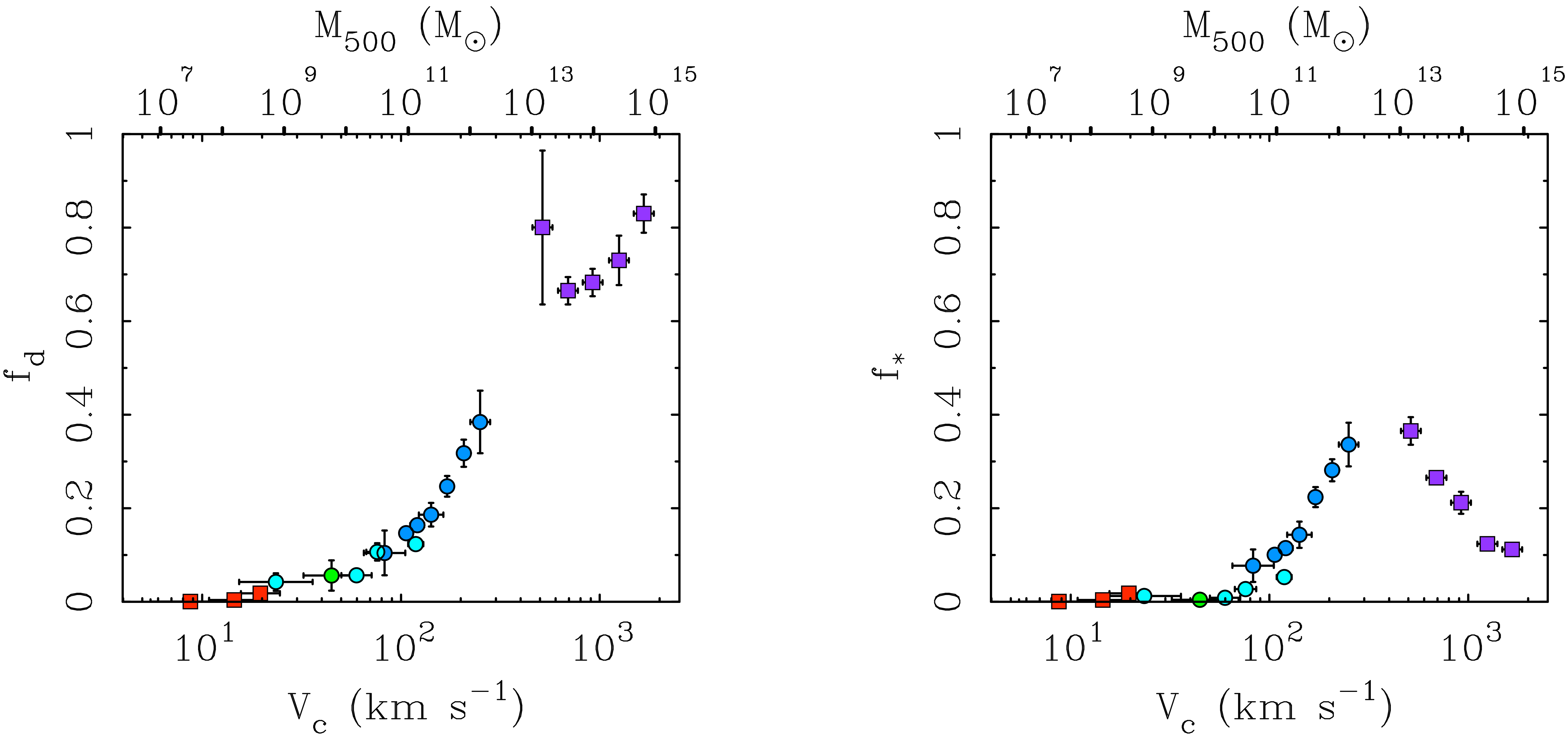
It is not obvious that giant Ellipticals or groups fill that gap.

Or maybe they do... lensing estimate by Hoekstra (2005) for two choices of IMF.



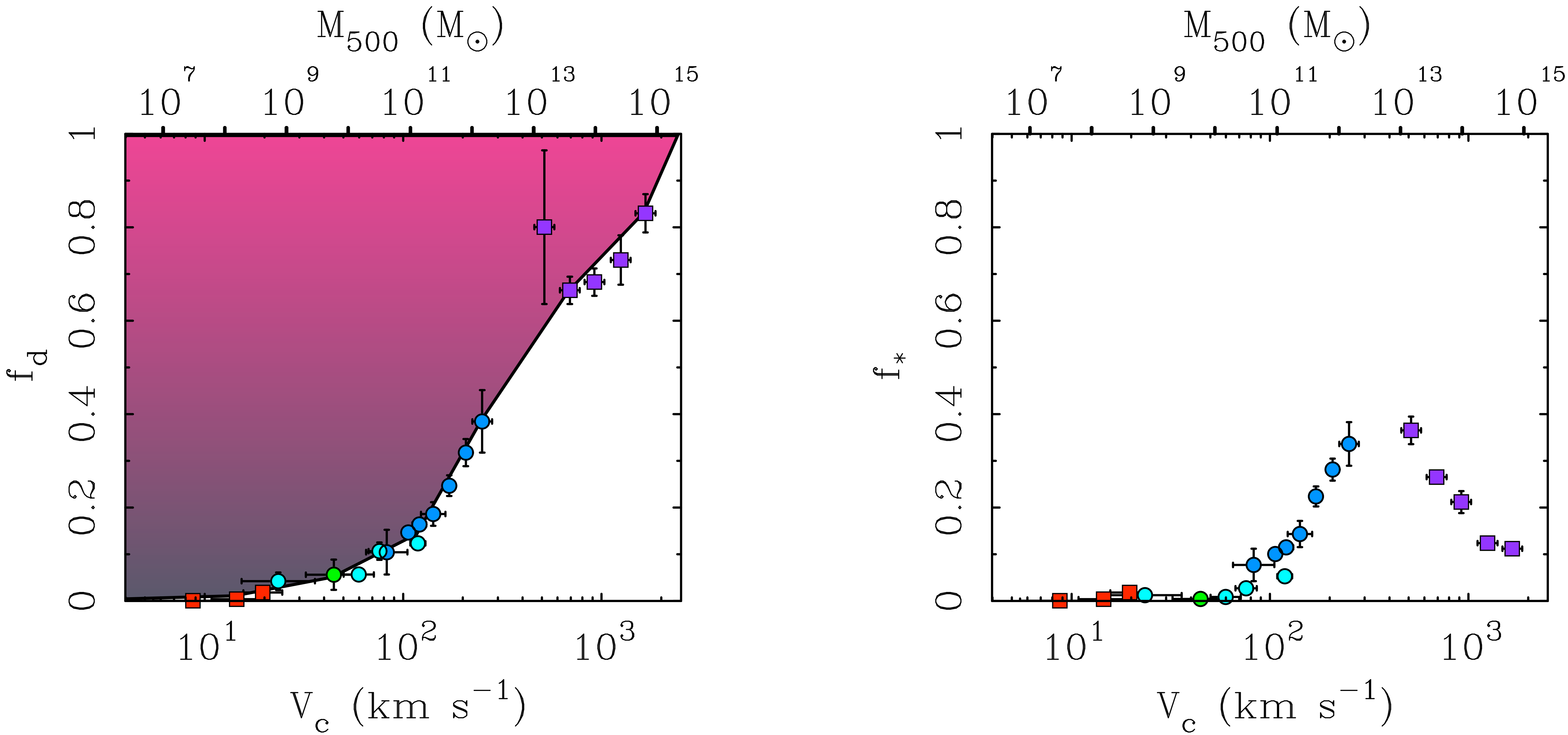


Logarithmic scale. Galaxies with $V_c < 100$ km/s are an order of magnitude shy of their cosmic share of baryons.



Galaxies suffer a baryon deficit -
a halo-by-halo missing baryon problem
distinct from the global BBN missing baryon problem.

Where are all these baryons?

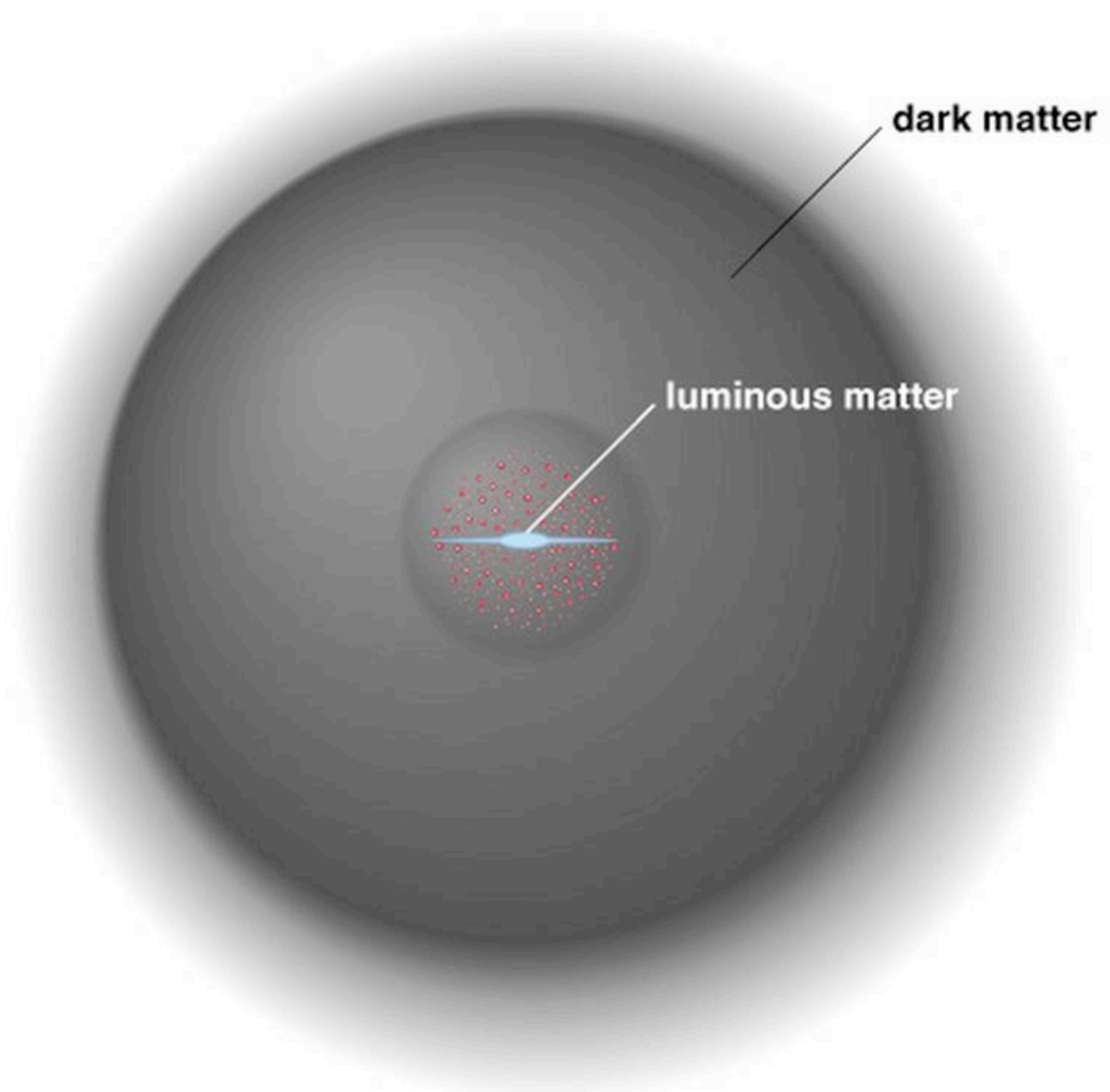


Galaxies suffer a baryon deficit -
a halo-by-halo missing baryon problem
distinct from the global BBN missing baryon problem.

Halo baryon discrepancy - possibilities

- The baryons are there but aren’t detected
- The baryons have been blown out
- The baryons never fell into the halos
- The mass-velocity relation is wrong

- The baryons are there but aren't detected



- The baryons are there but aren't detected

warm/hot ionized baryons still mixed with DM halo?

- The baryons are there but aren’t detected

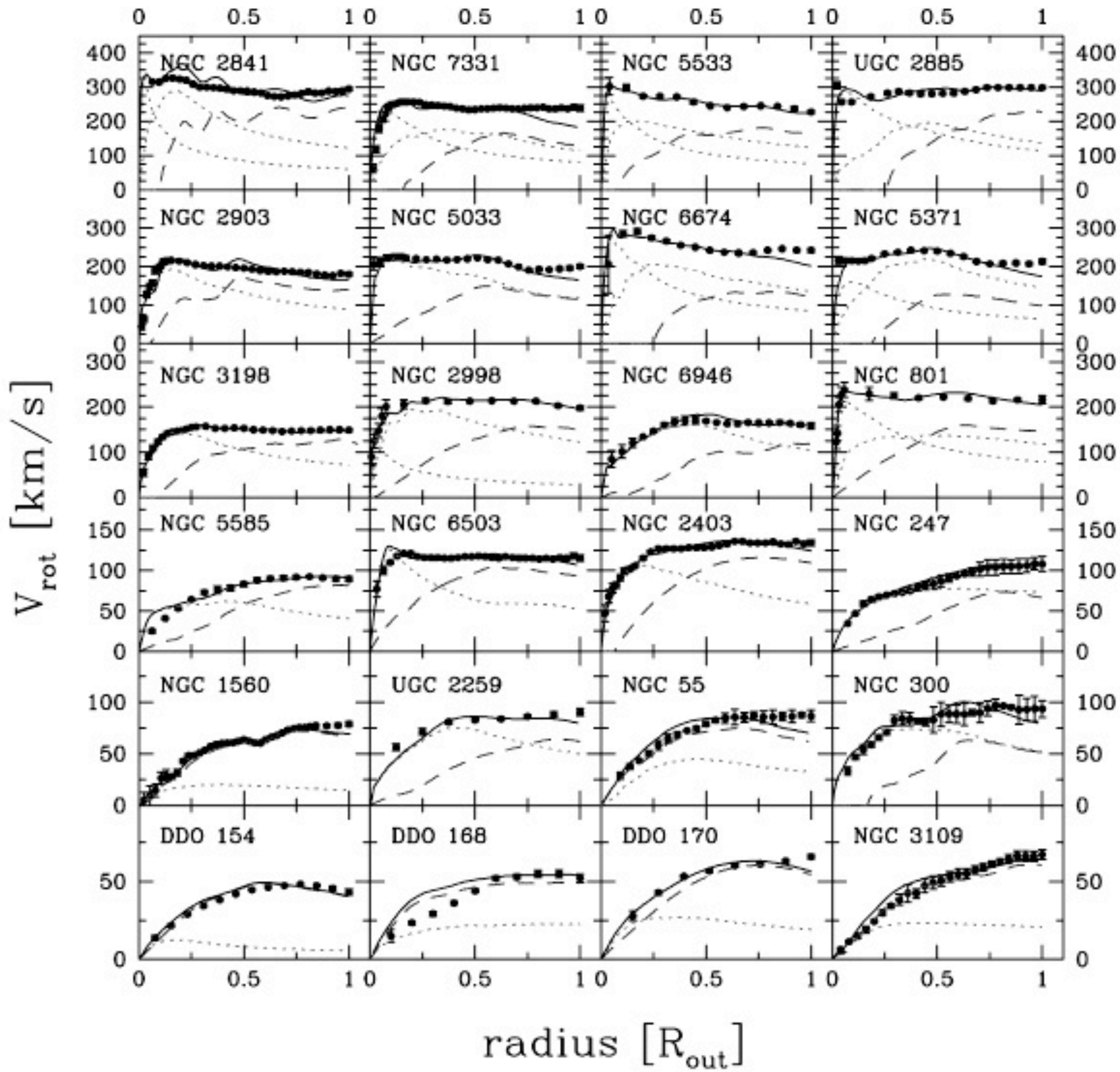
very cold molecular
gas in disk?

warm/hot ionized baryons still mixed with DM halo?

Unseen molecular gas in disk?

Pfenniger & Combes (1994)

456 *H. Hoekstra, T. S. van Albada and R. Sancisi* Hoekstra et al. (2001)



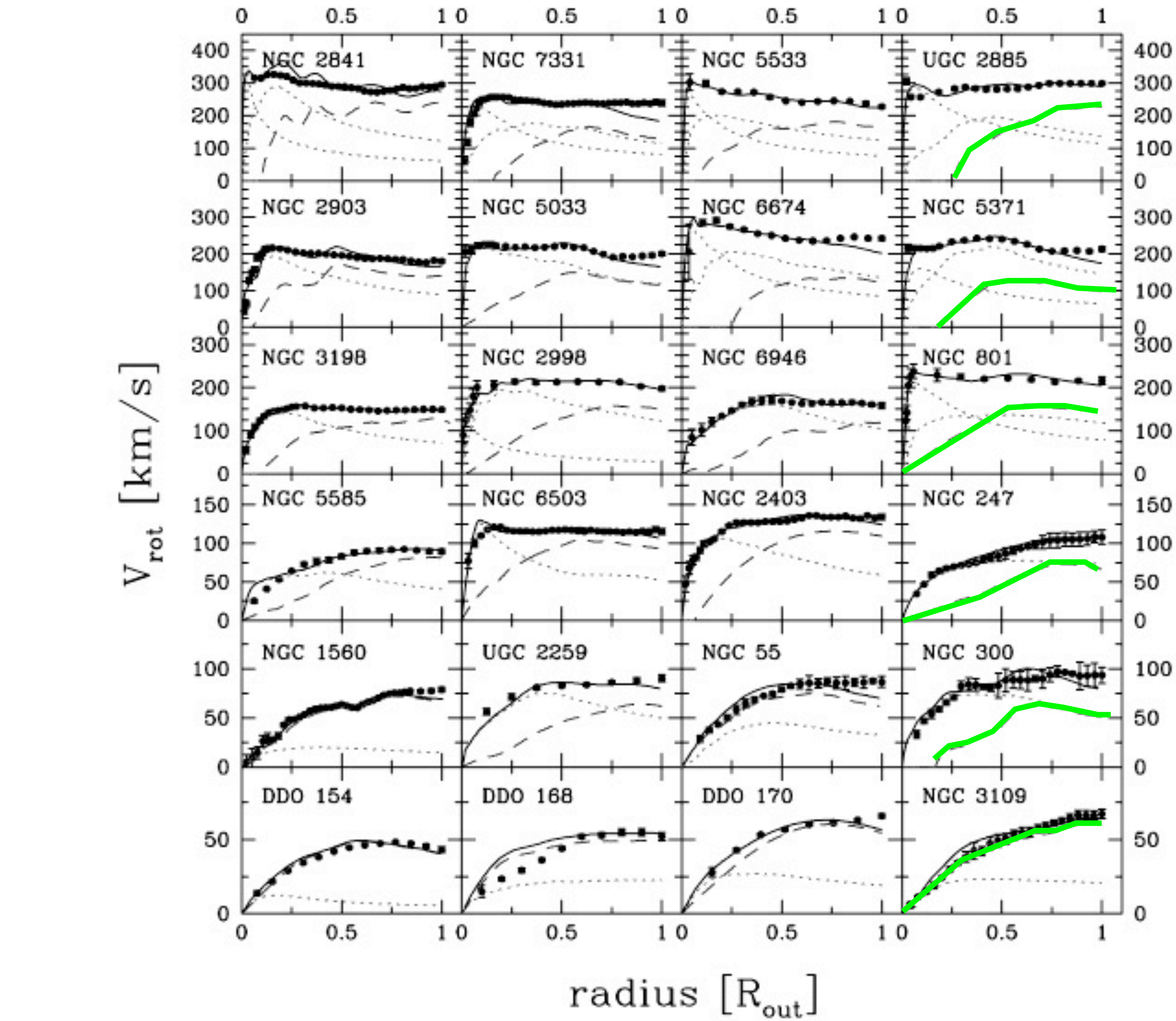
HI scaling:
treat ***η*** as free parameter;
scale to obtain fit.
Essentially and M/L for gas.

$$M_{gas} = \eta M_{HI}$$

Unseen molecular gas in disk?

Pfenniger & Combes (1994)

Hoekstra et al. (2001)



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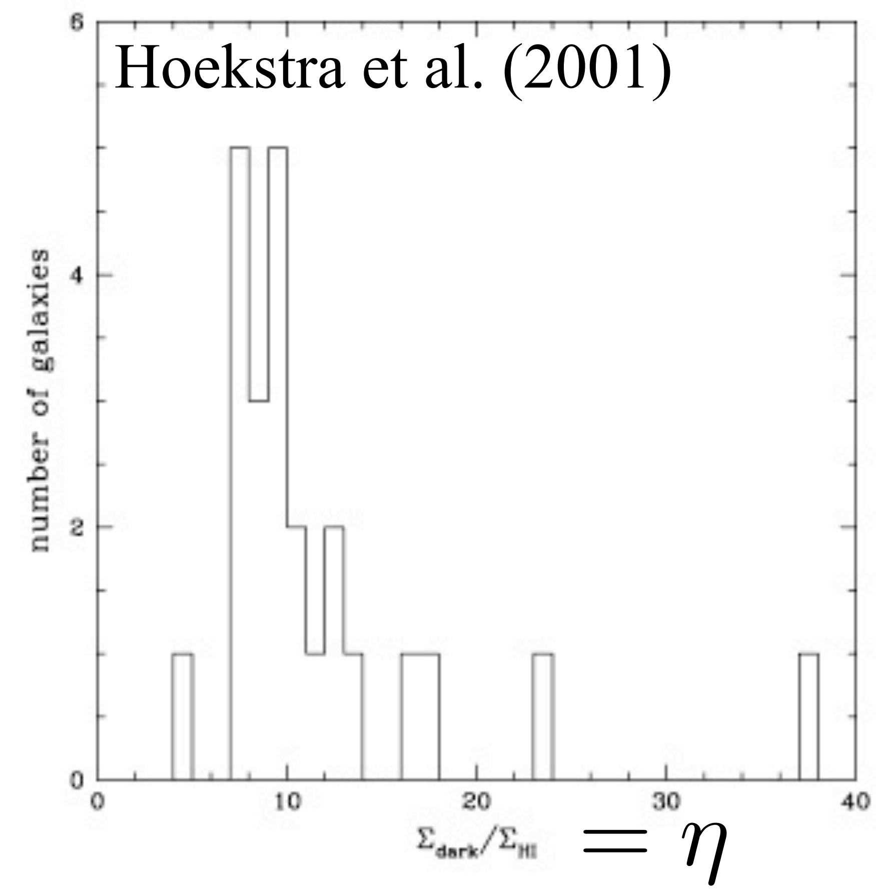
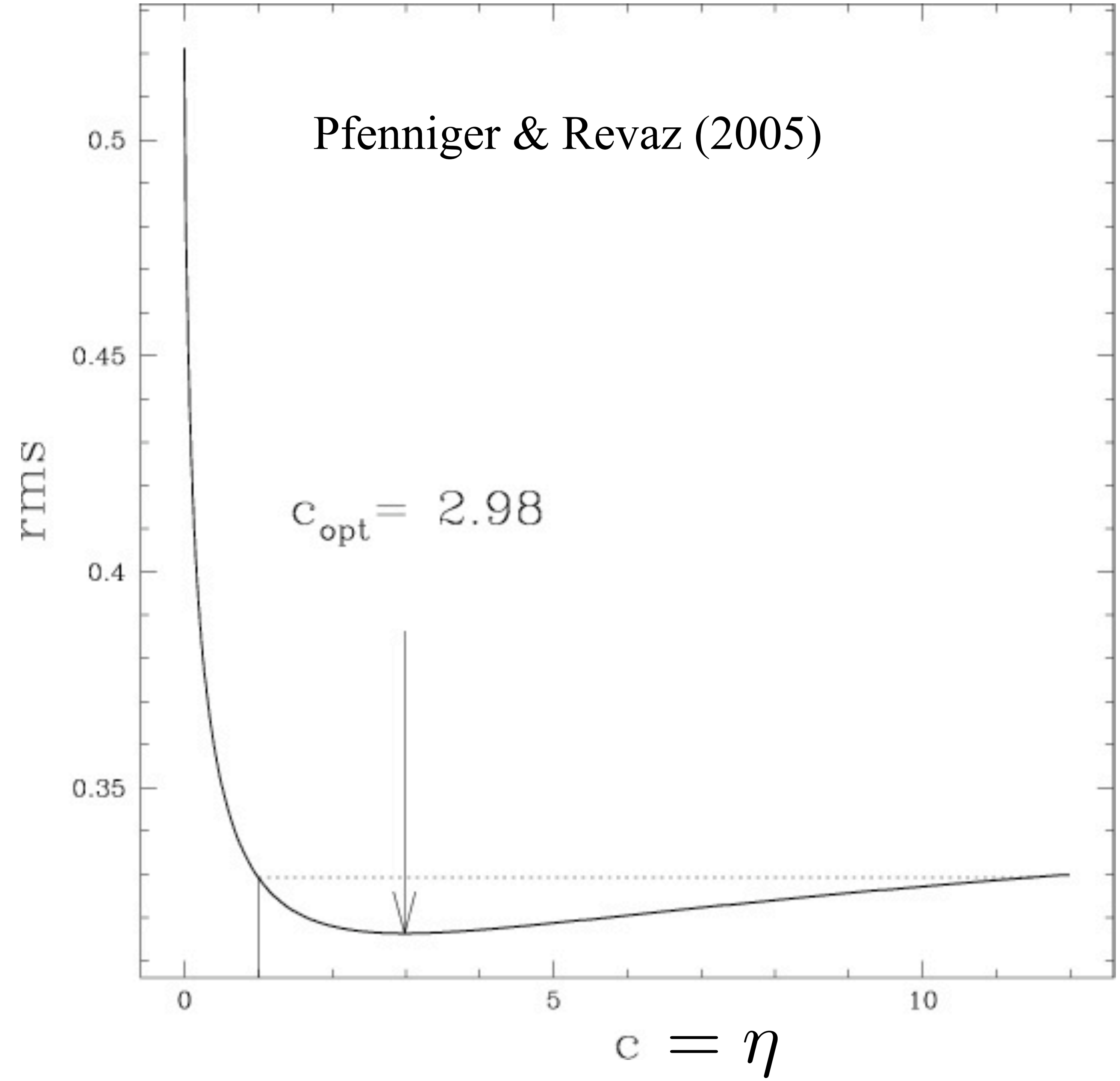


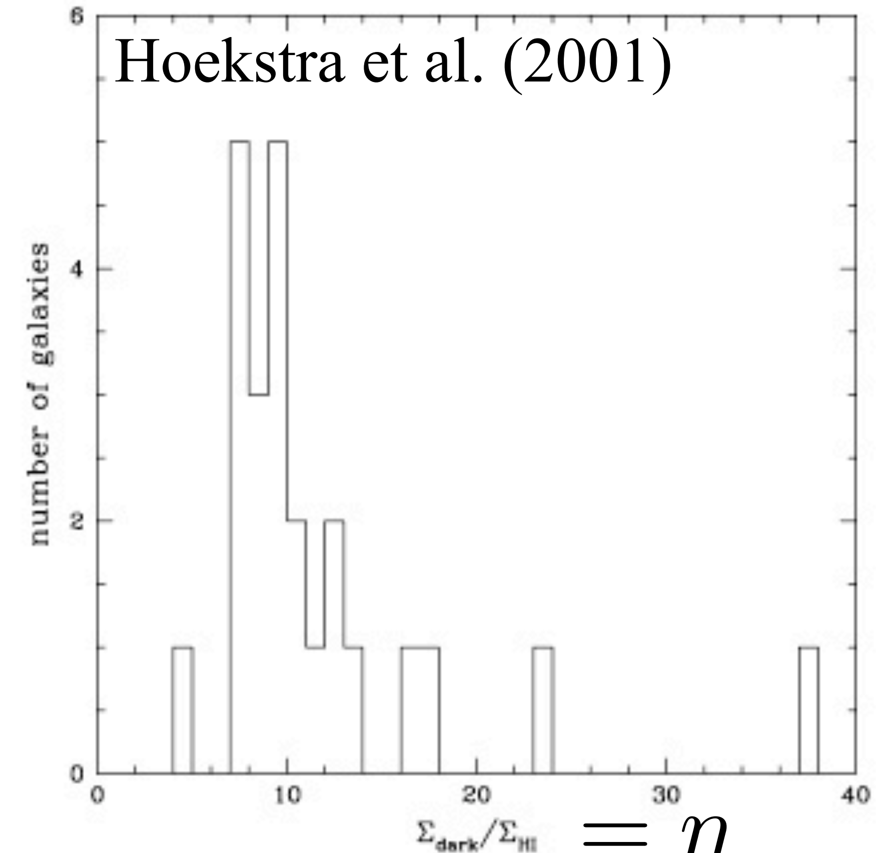
Figure 3. Frequency distribution of the scaling factor $\Sigma_{dark}/\Sigma_{HI}$ found for the galaxies in our sample.

surface density is approximately 6.5 times the gas surface density (i.e. H I + He). As can be seen from Table 2, the H I scalefactor does not change much with galaxy type, although the scatter increases towards earlier types.



$\eta \approx 7$ fits rotation curves

$\eta \approx 3$ minimizes scatter in BTFR (2000)



$= \eta$

Figure 3. Frequency distribution of the scaling factor $\Sigma_{dark}/\Sigma_{HI}$ found for the galaxies in our sample.

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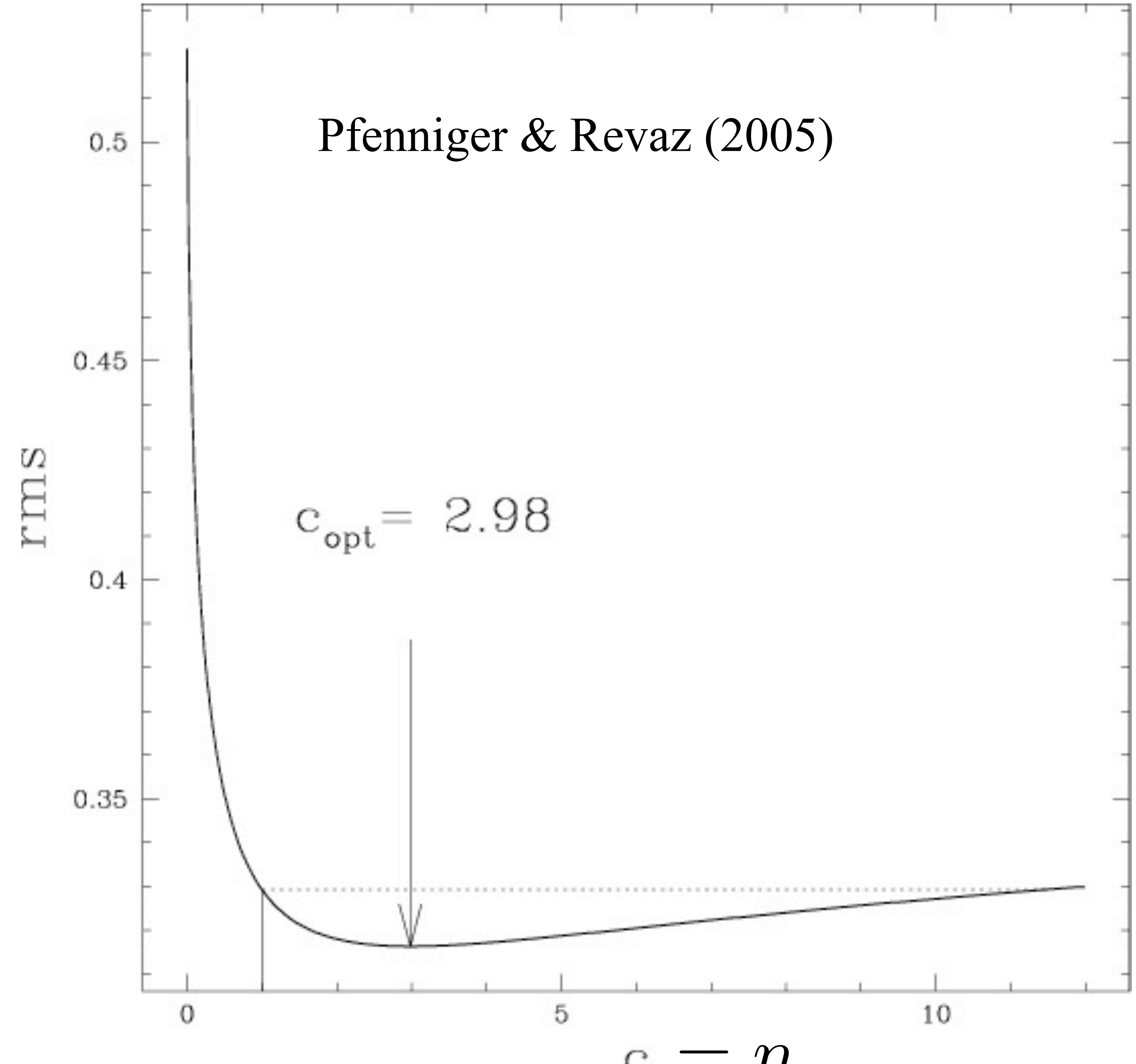
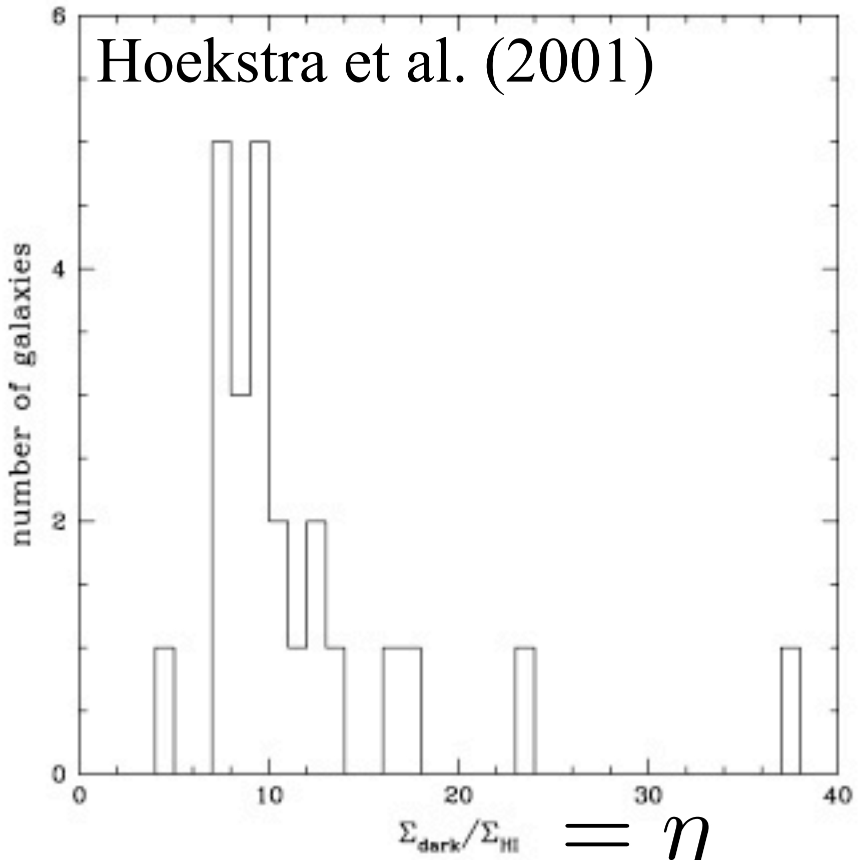


$= \eta$

$\eta \approx 3$ minimizes scatter in BTFR (2000)

BTFR (2009) already consistent with zero intrinsic scatter for

$$\eta \approx 1.4 \approx \frac{1}{X}$$



$= \eta$

Figure 3. Frequency distribution of the scaling factor $\Sigma_{dark}/\Sigma_{HI}$ found for the galaxies in our sample.

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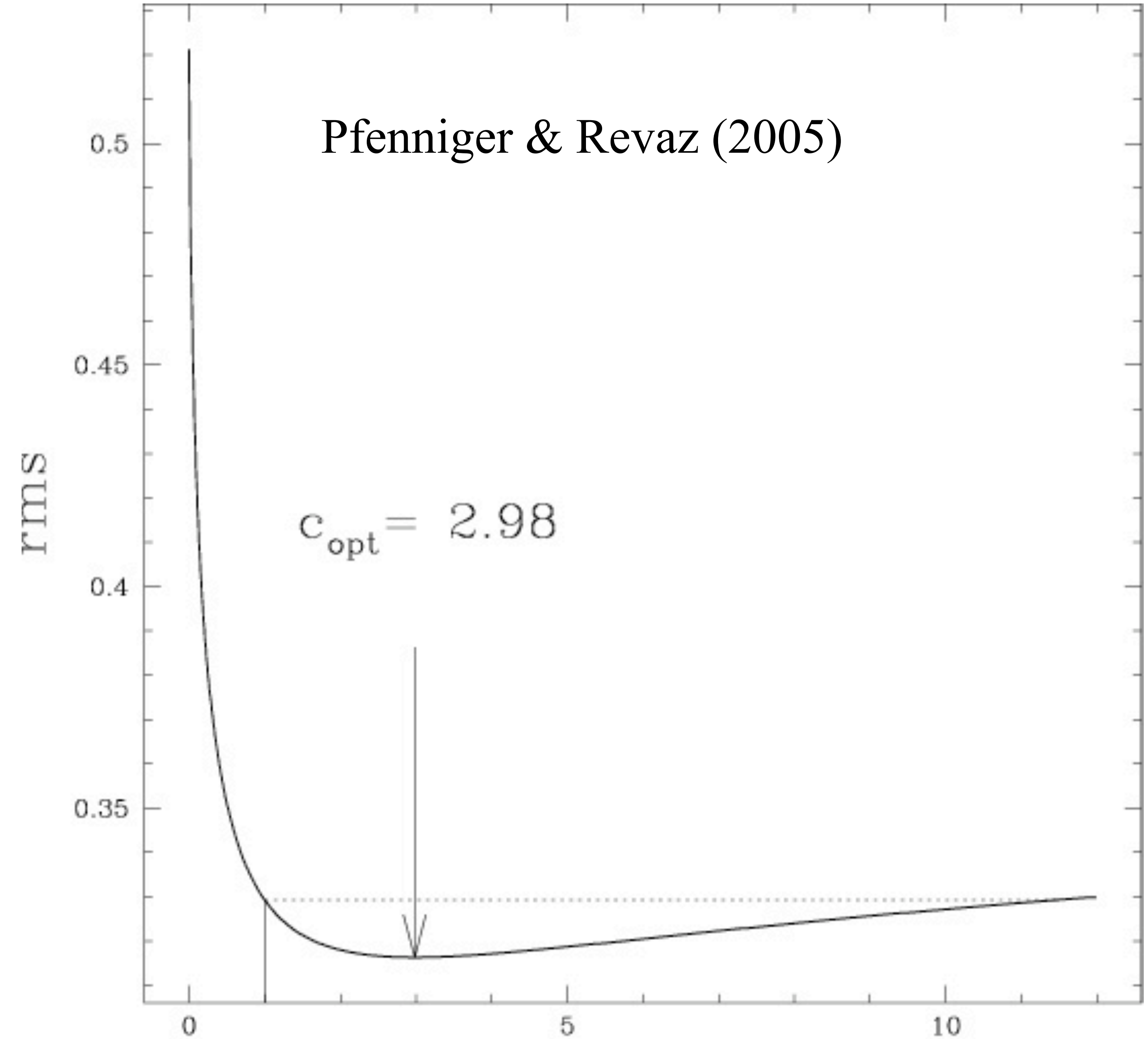


$c = \eta$

$\eta \approx 7$ fits rotation curves

Need $\eta(V_c)$;

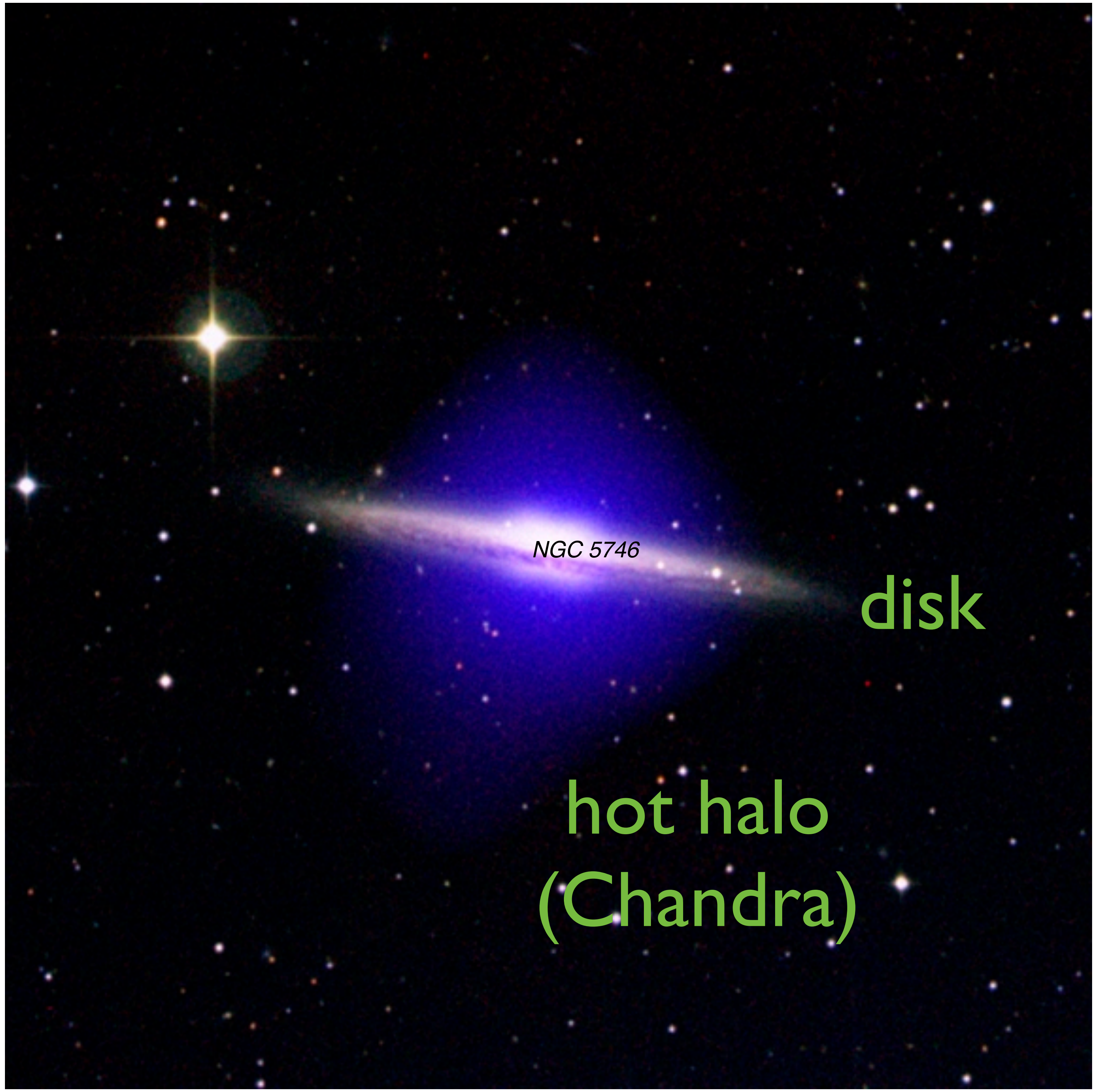
$\eta > 10$ for late types

$\eta \approx 3$ minimizes scatter in BTFR (2000)

BTFR (2009) already consistent with zero intrinsic scatter for

$$\eta \approx 1.4 \approx \frac{1}{X}$$

Warm/hot ionized baryons still mixed with DM halo?



NGC 5746 (Pedersen et al. 2006)

Warm/hot ionized baryons still mixed with DM halo?

- X-ray detection has proven difficult; most claimed detection have gone away
  - Limits: < 24% of missing baryons (Anderson & Bregman 2010)
- No positive evidence that a substantial mass of baryons exist in the halo
- Some restrictive constraints...

Warm/hot ionized baryons still mixed with DM halo?

Milky Way:

Anderson & Bregman (2010):

Table 1: Constraints on the Milky Way Hot Halo

Method	NFW profile: Hot halo mass ($10^9 M_\odot$)	NFW profile: n_e(50 kpc) (10^{-5} cm^{-3})	NFW profile: frac	Flattened profile: Hot halo mass ($10^9 M_\odot$)	Flattened profile: n_e(50 kpc) (10^{-5} cm^{-3})	Flattened profile: frac	Reference
LMC Pulsar DM	$< 12 - 15$	$< 7.7 - 10$	$< 0.04 - 0.05$	< 170	< 27	< 0.58	§3.1
Mag. Stream HI	$< 10 - 11$	< 7	$< 0.03 - 0.04$	< 53	< 8	< 0.18	Stanimirović et al. (2002)
HVCs	$< 5 - 9$	$< 3 - 6$	$< 0.02 - 0.03$	$< 19 - 39$	$< 3 - 6$	$< 0.06 - 0.13$	Fox et al. (2005)
Galactic XRB	$< 5.9 - 7.8$	$< 4 - 5$	$< 0.02 - 0.03$	< 110	< 17	< 0.38	Kuntz & Snowden (2000)

Parameters determined from fitting profiles to the constraints noted in section 3.2. *frac* is the ratio of the mass of the hot halo to the mass of the missing baryons from the Galaxy ($3 \times 10^{11} M_\odot$).

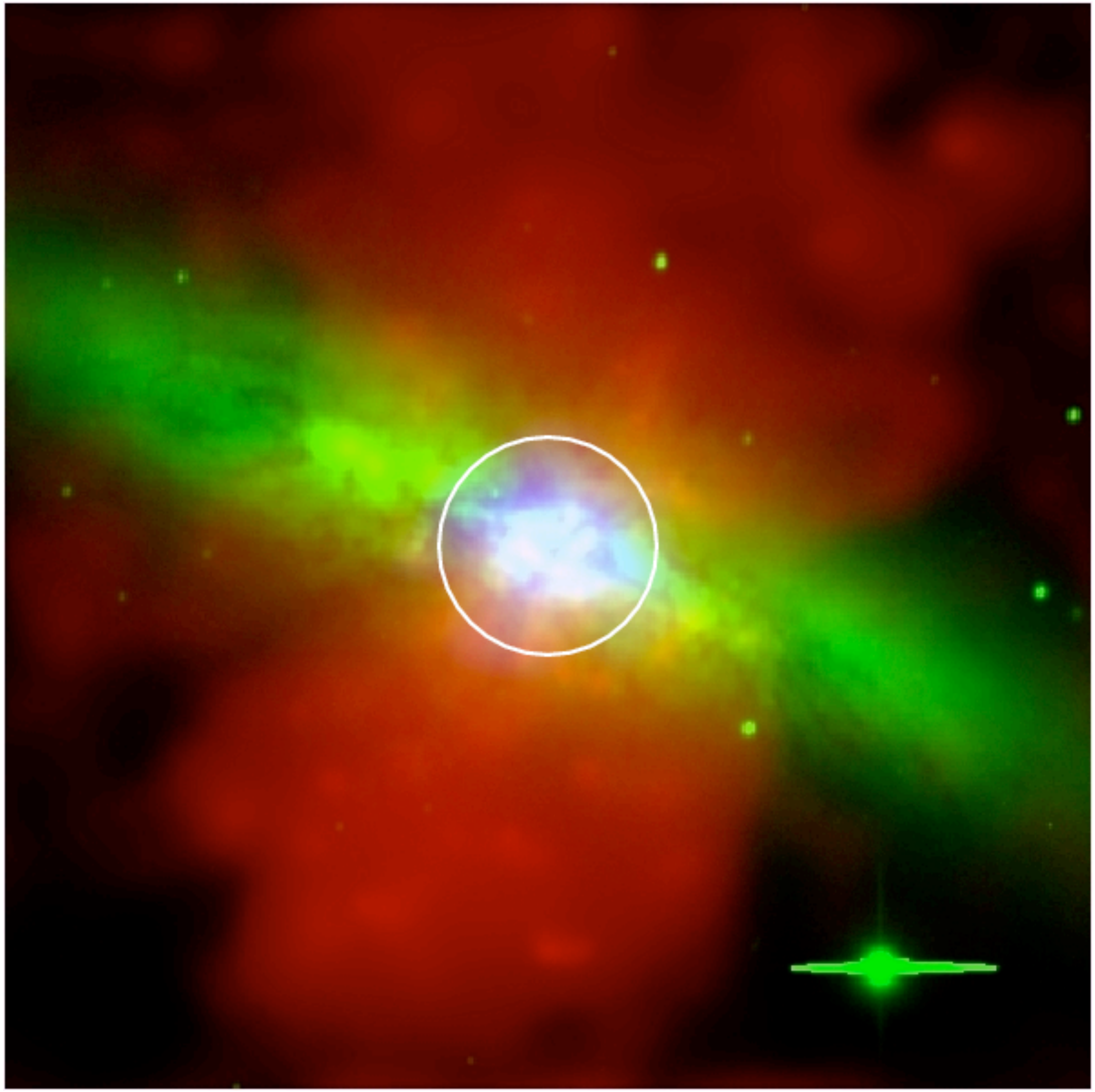
known baryonic mass $\approx 6 \times 10^{10}\ \mathrm{M}_\odot$

missing baryonic mass $\approx 2 \times 10^{11}\ \mathrm{M}_\odot$

plausible baryonic halo masses $\lesssim 10^{10}\ \mathrm{M}_\odot$

- The baryons have been blown out

e.g., feedback from supernovae



M82 (Strickland & Heckman 2009)

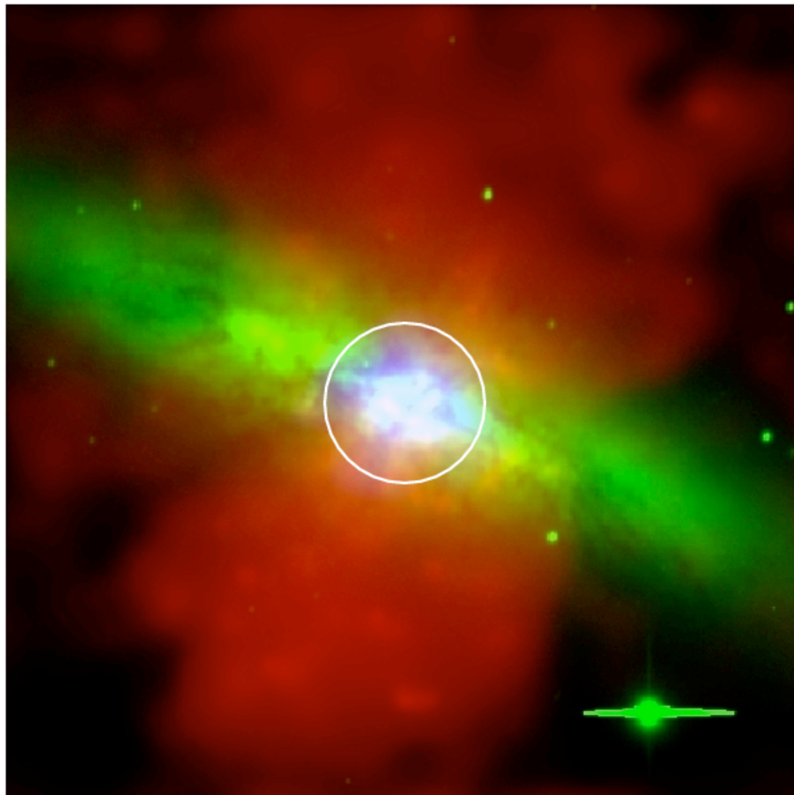
- The baryons have been blown out

<u>Feedback from supernovae</u>

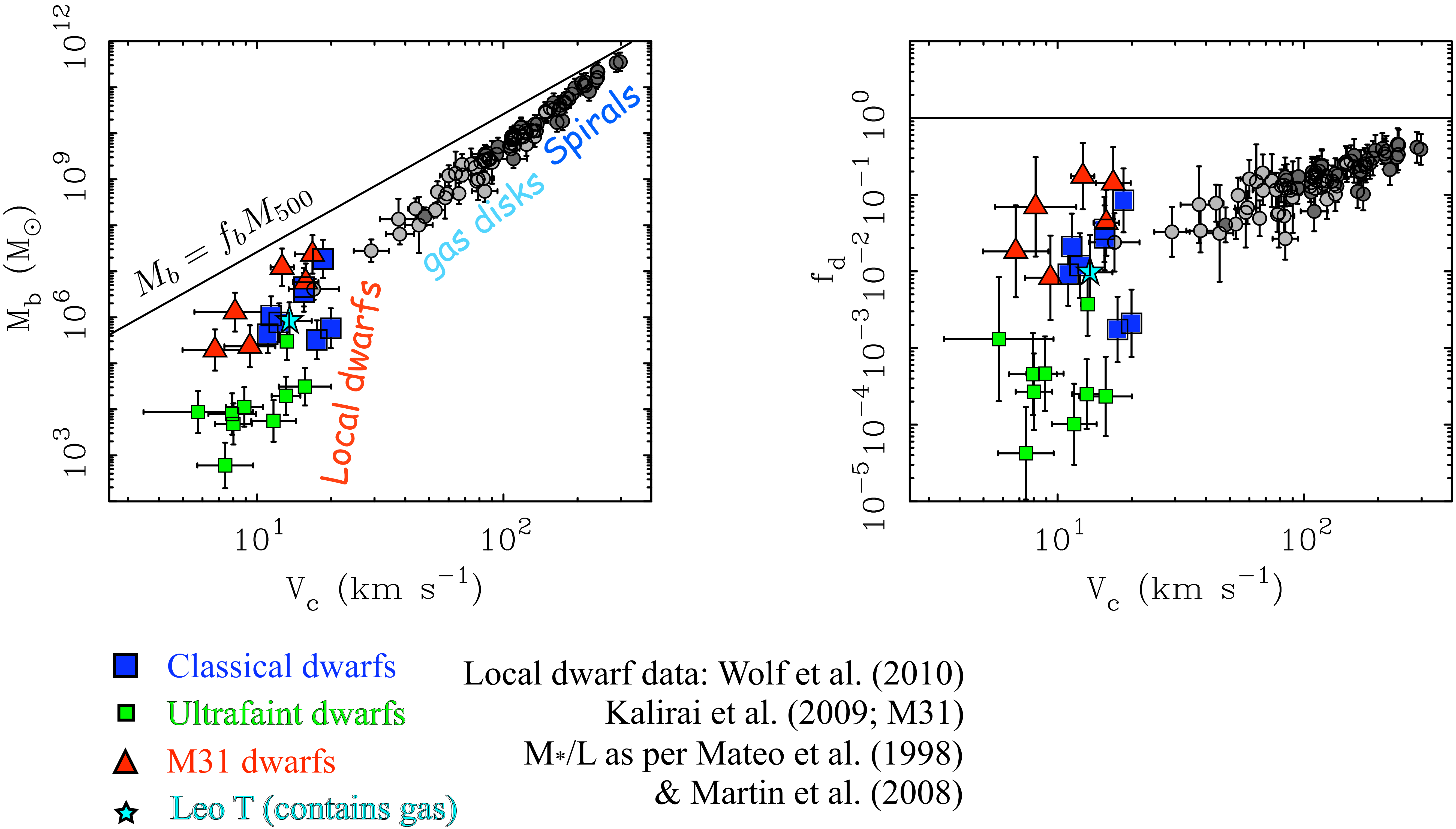
Chemical evolution followed by SN-driven blow-out of the remaining gas (e.g. Hartwick; Wyse) leads to a relation between metallicity and mass of expelled baryons:

$$M_{b,tot} = C M_b$$

$$C = 1 + 0.4 \times 10^{-[\mathrm{Fe/H}]}$$



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



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

Residuals of dwarf Spheroidals from Baryonic Tully-Fisher Relation
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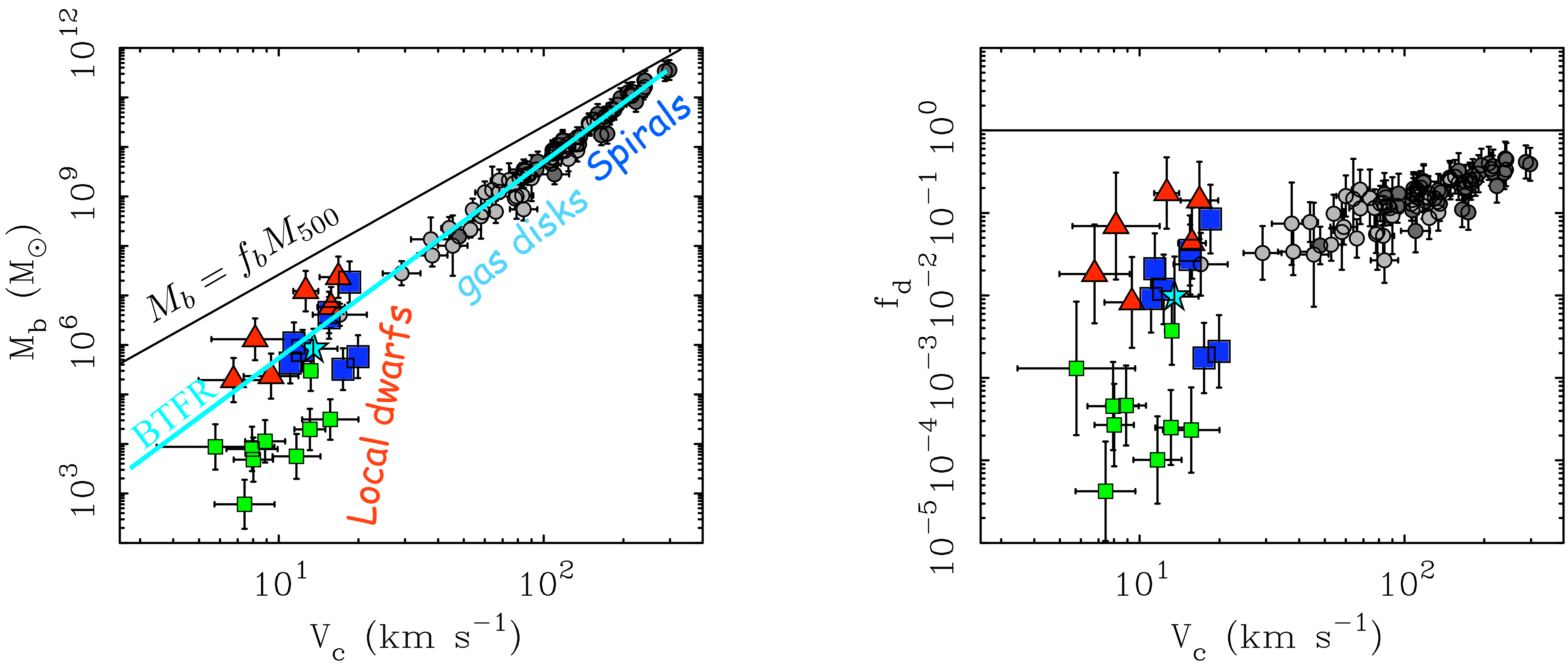

Classical dwarfs
Ultrafaint dwarfs
M31 dwarfs
Leo T (contains gas)

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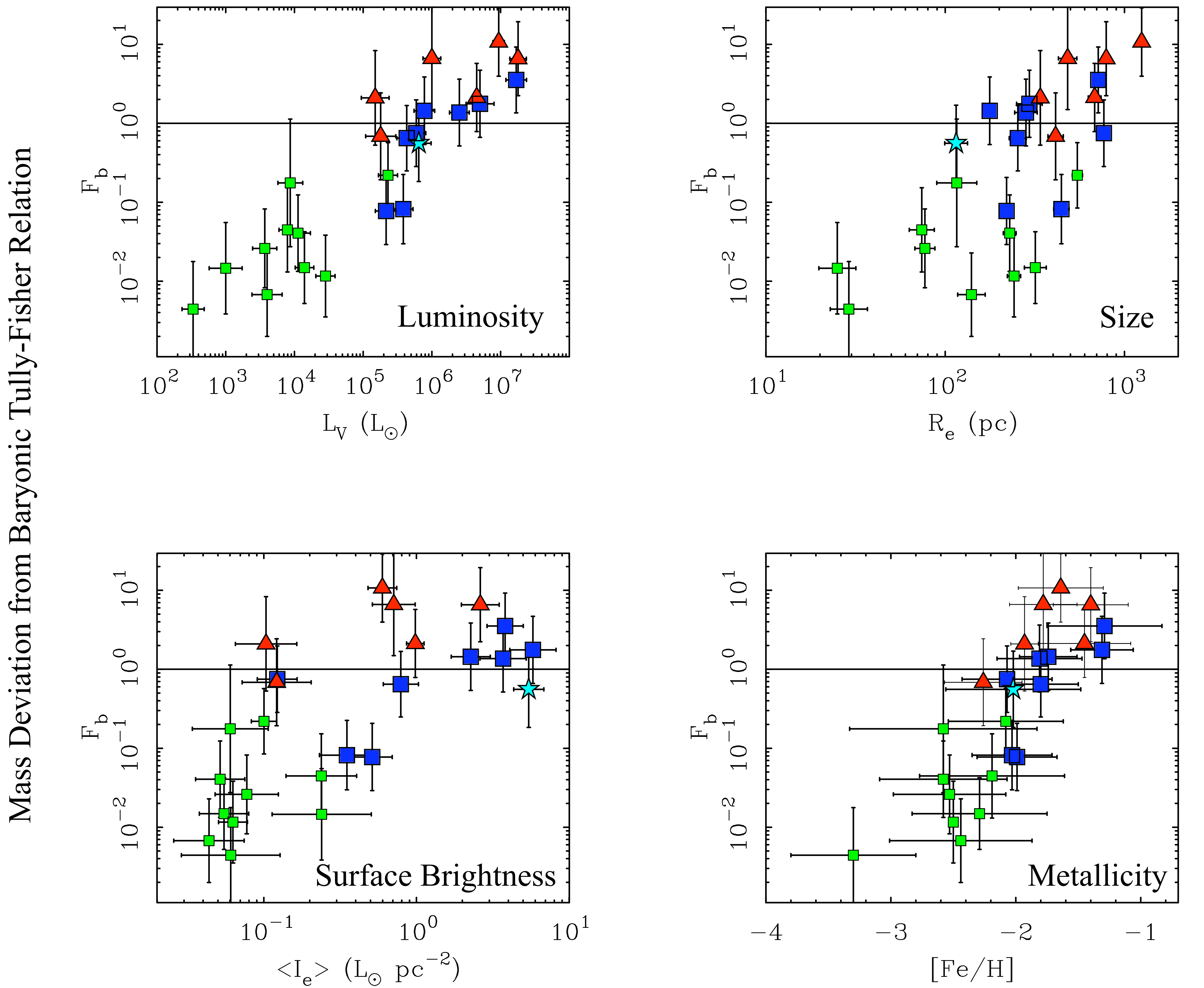
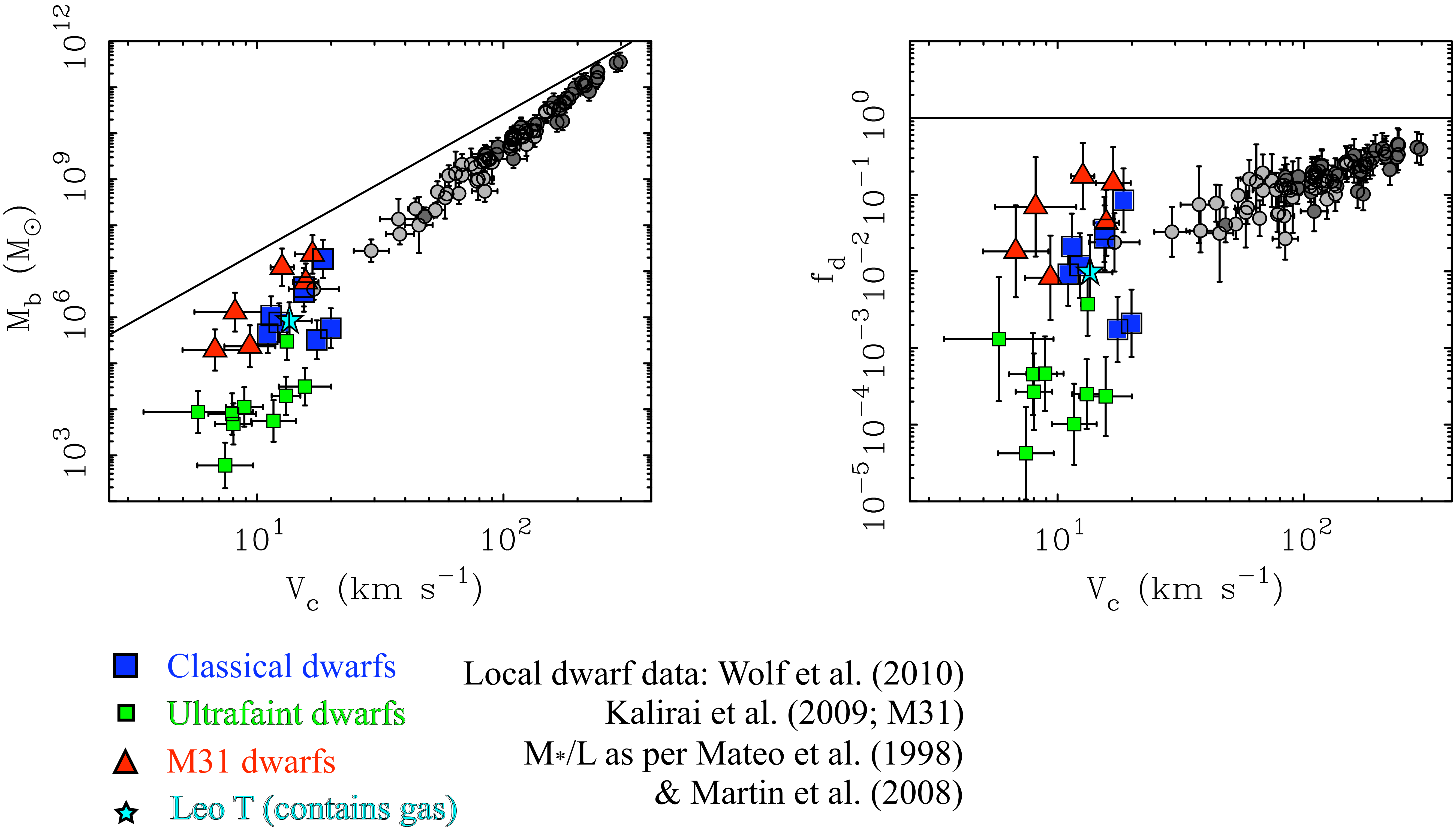


Mass Deviation from Baryonic Tully-Fisher Relation
depend on intrinsic properties
Luminosity
Size
Surface Brightness
Metallicity
F_b
L_V ($L_\odot$)
R_e (pc)
$<I_e>$ ($L_\odot$ pc^{-2})
[Fe/H]

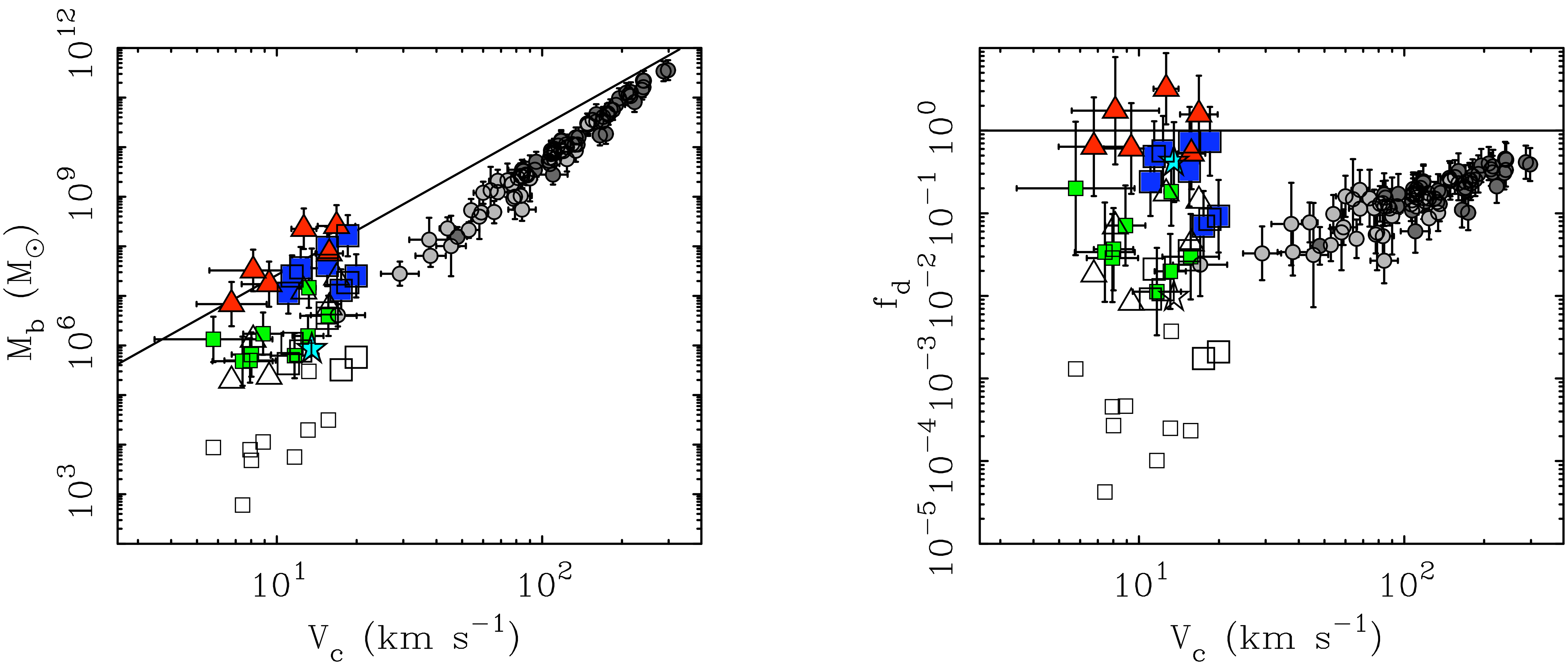
Residuals of dwarf Spheroidals from Baryonic Tully-Fisher Relation
McGaugh & Wolf (2010)



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

Does [Fe/H] predict the right correction factor?

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

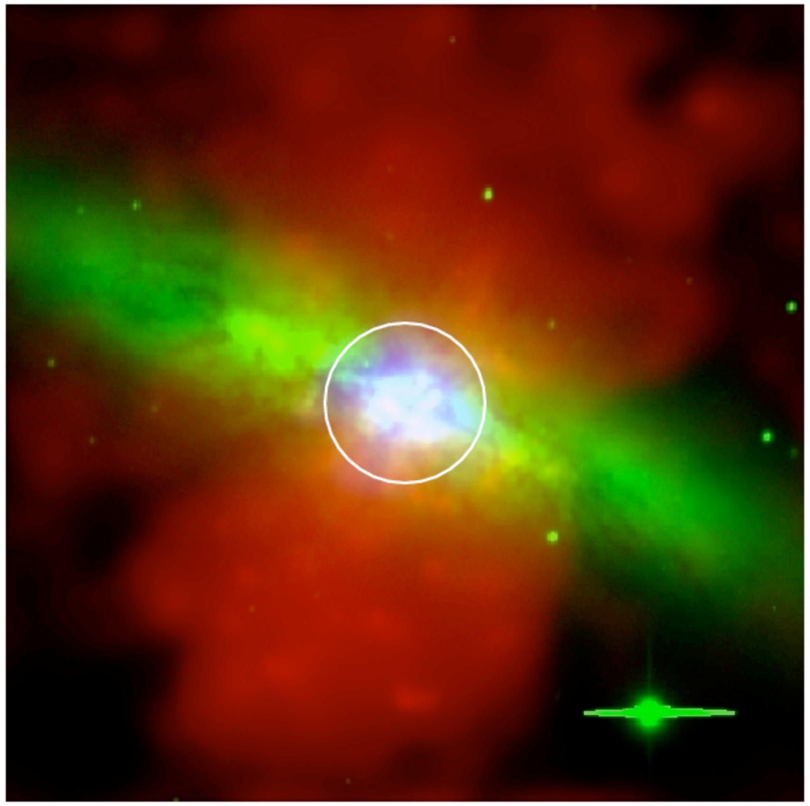


- Classical dwarfs
- Ultrafaint dwarfs
- M31 dwarfs
- Leo T (contains gas)

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

Sometimes!

- The baryons have been blown out

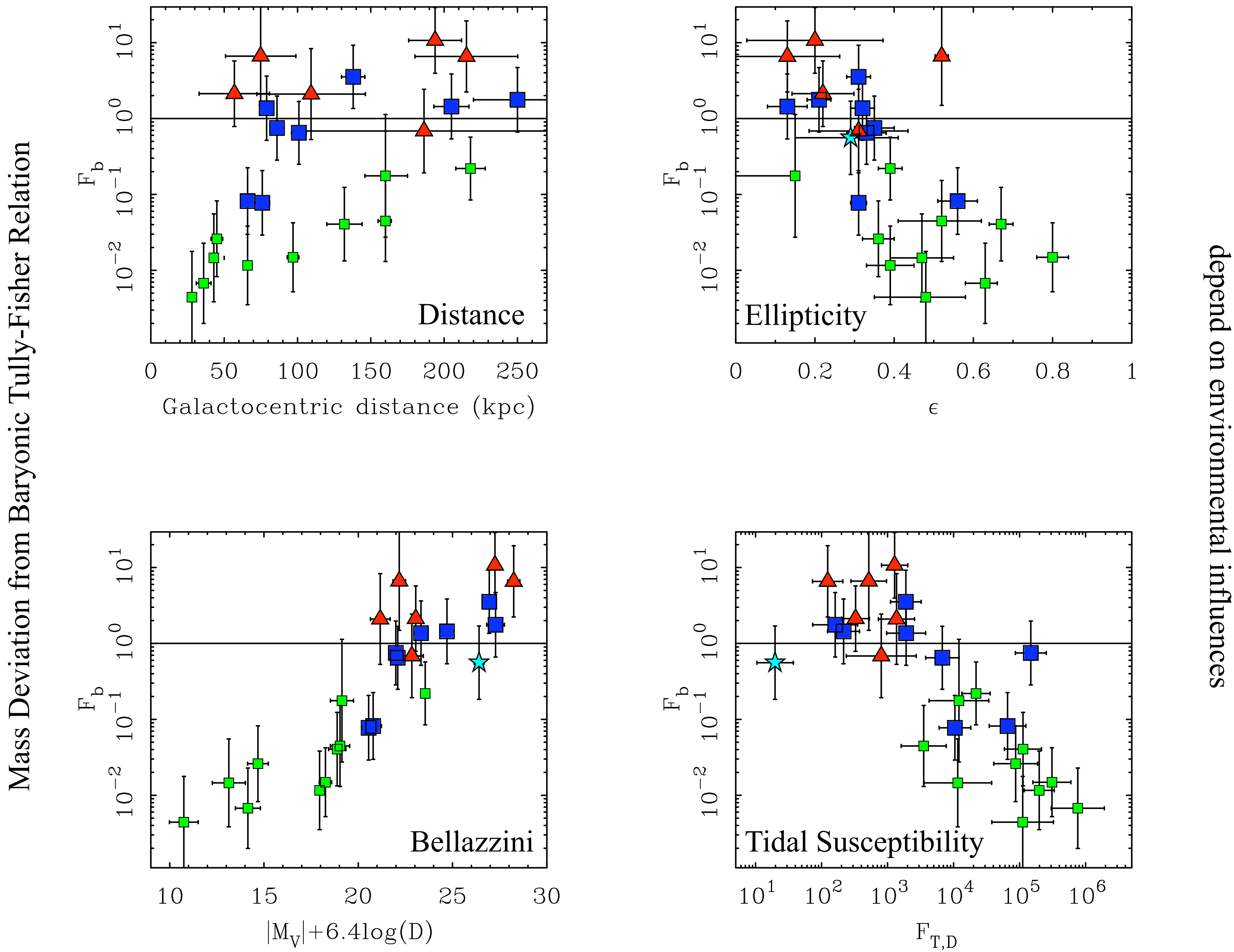


Feedback from supernovae

$$M_{b,tot} = C M_b$$

$$C = 1 + 0.4 \times 10^{-[\mathrm{Fe/H}]}$$

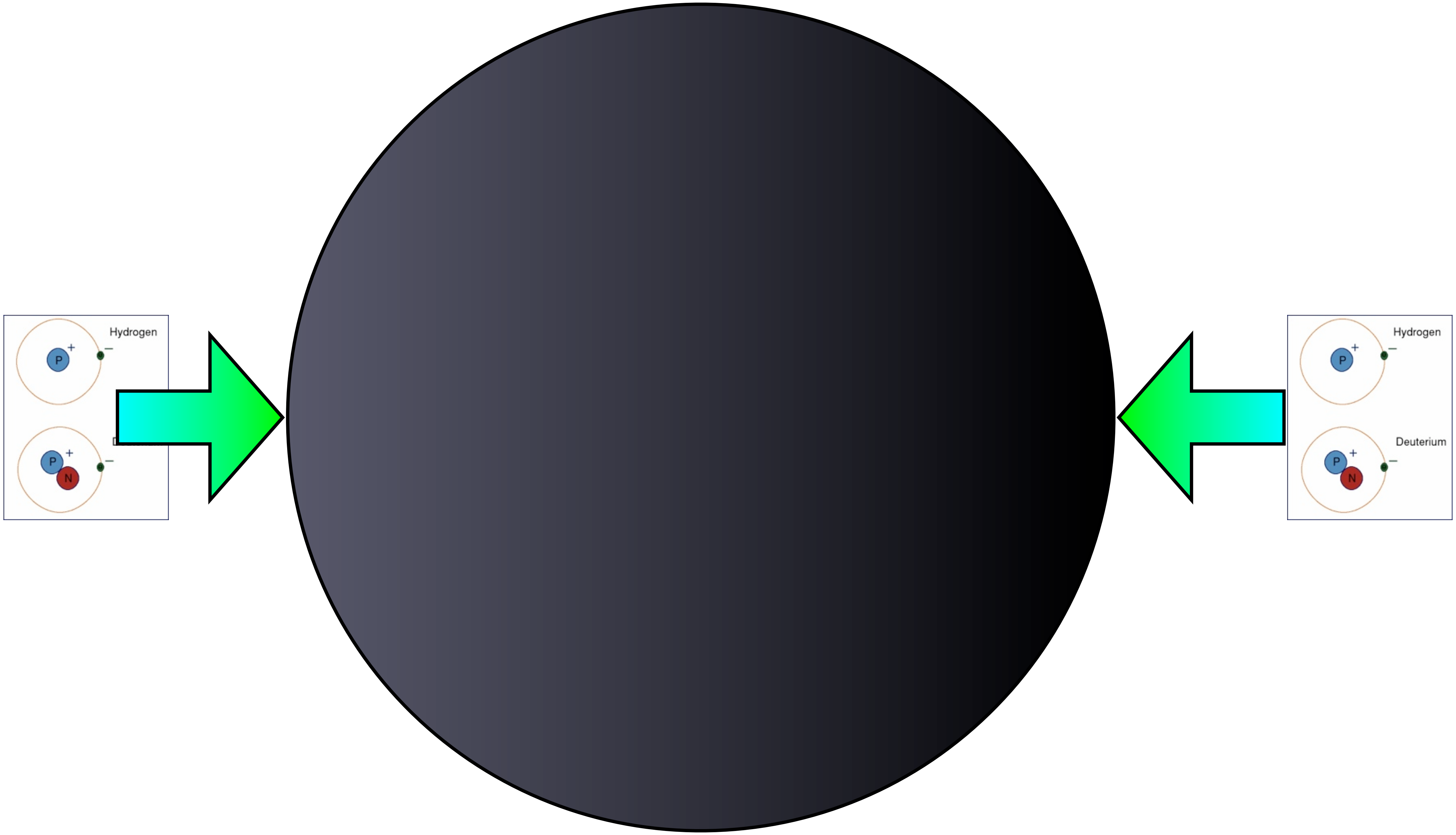
- Works well for classical dwarfs
- Only partial correction for ultrafaint dwarfs
- Not applicable to gas rich disks
  (model assumes old population, no further star formation)
- Looks promising; working to extend model to gas disks
- Environmental influences important for ultrafaint dwarfs



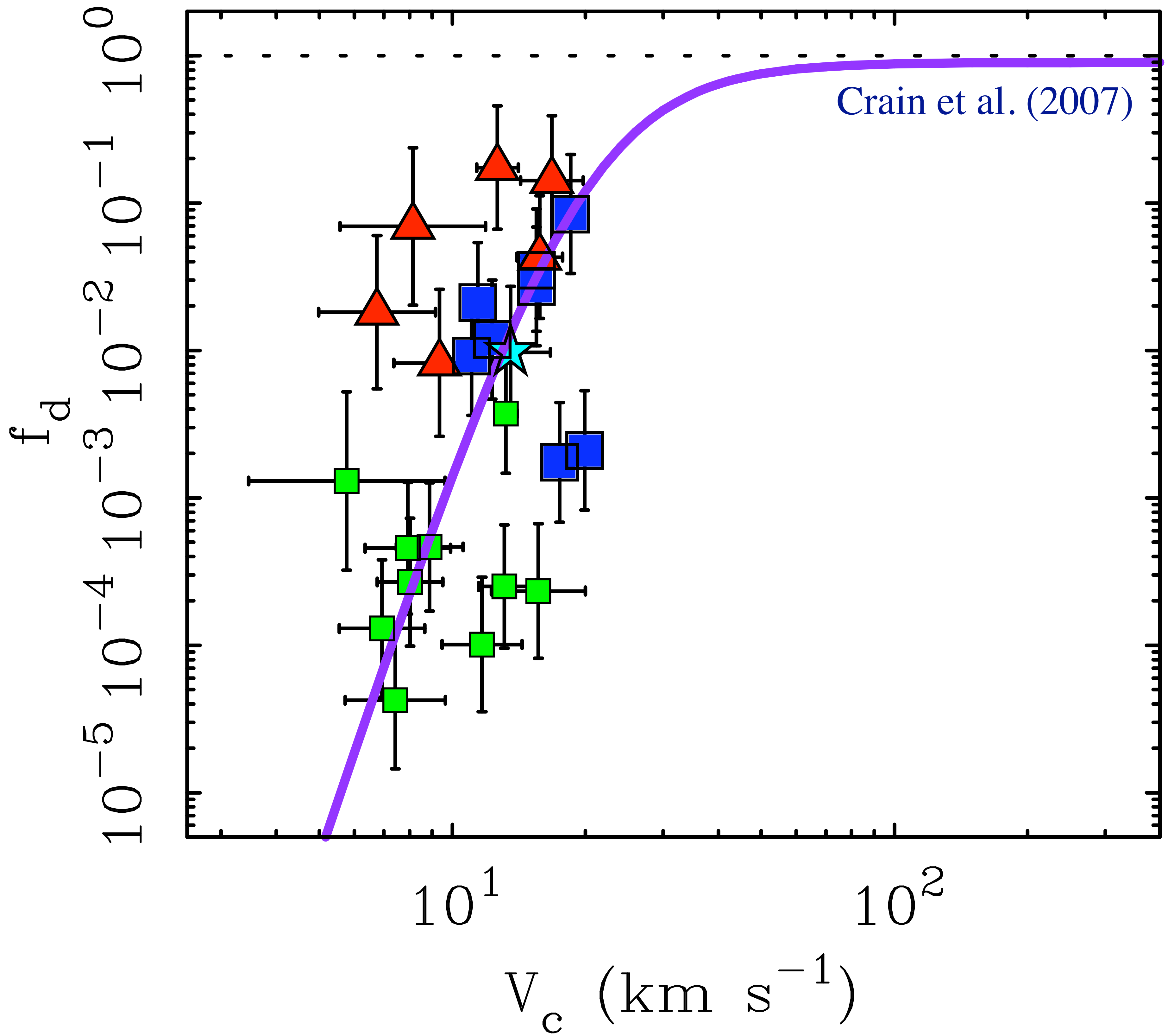
Mass Deviation from Baryonic Tully-Fisher Relation
depend on environmental influences
Distance
Galactocentric distance (kpc)
Ellipticity
ϵ
Bellazzini
|M_V|+6.4log(D)
Tidal Susceptibility
F_T,D
F_b

- The baryons never fell into the halos

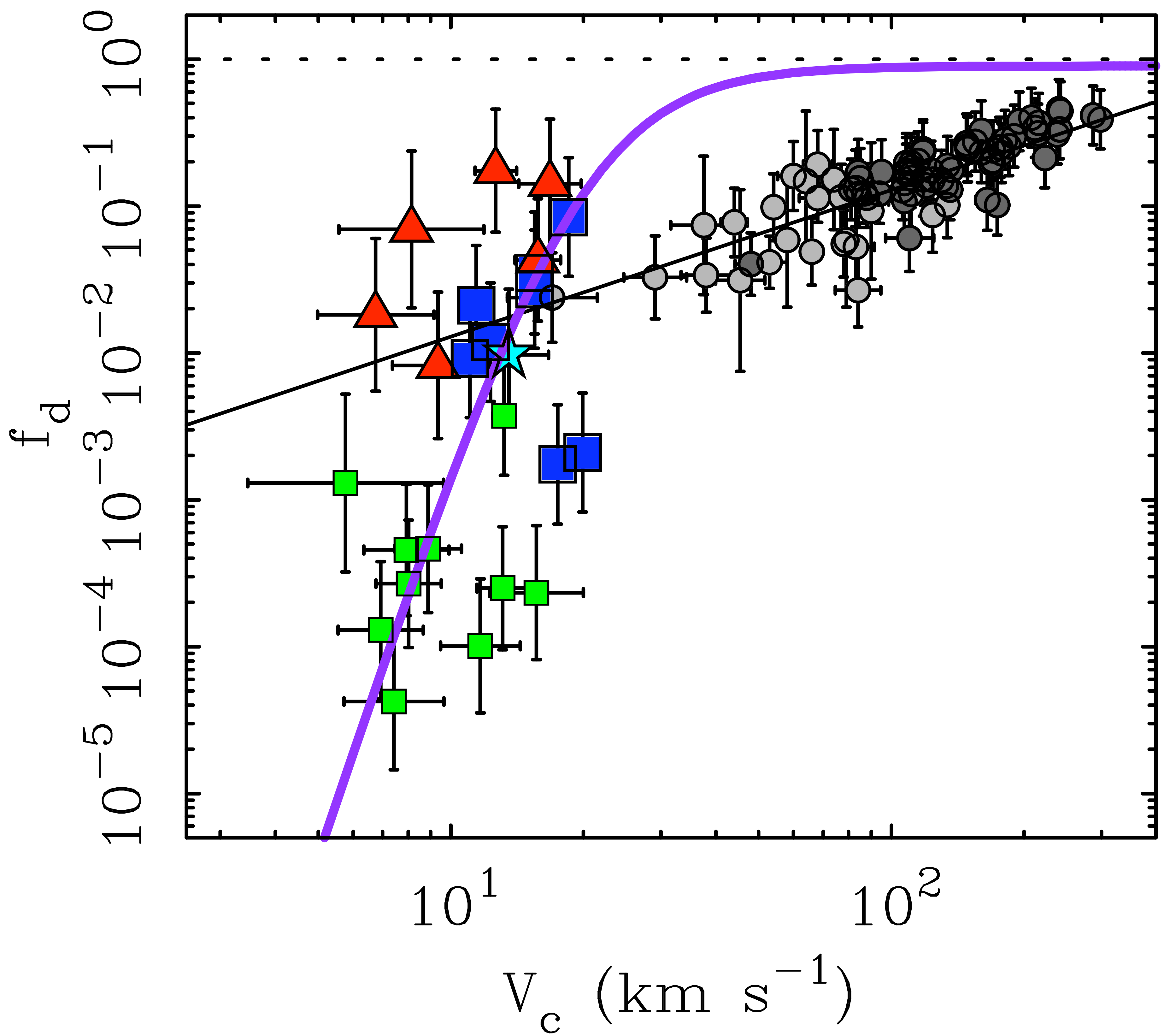
e.g., prevented from accreting by reionization



Reinoization



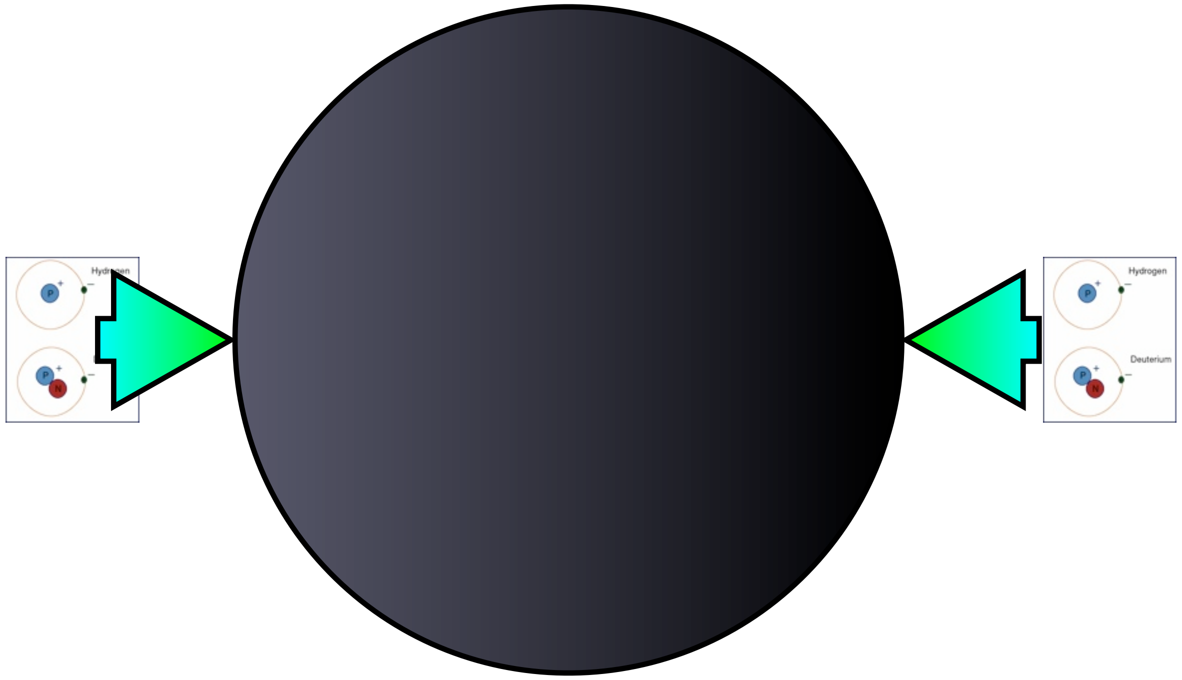
Reinoization



- The baryons never fell into the halos

e.g., prevented from accreting by reionization

• Appears to work for Local Group dwarfs, but
• does not simultaneously explain spirals
• does not explain correlation of BTFR residuals with environmental influences



BARYON DISCREPANCY PROBLEM

- most of the baryons that we expect to be associated with galaxies are missing
- this halo-by-halo missing baryon problem is distinct from the global BBN shortfall and distinct from the dynamical missing mass problem (need dark baryons as well as dark matter in each and every galaxy)
- galaxy scales interesting - pose a rich variety of challenges - e.g., cusp/core problem, missing satellite problem