Parameter Correlations for Dark Matter Halos in Late-Type and Dwarf Spheroidal Galaxies

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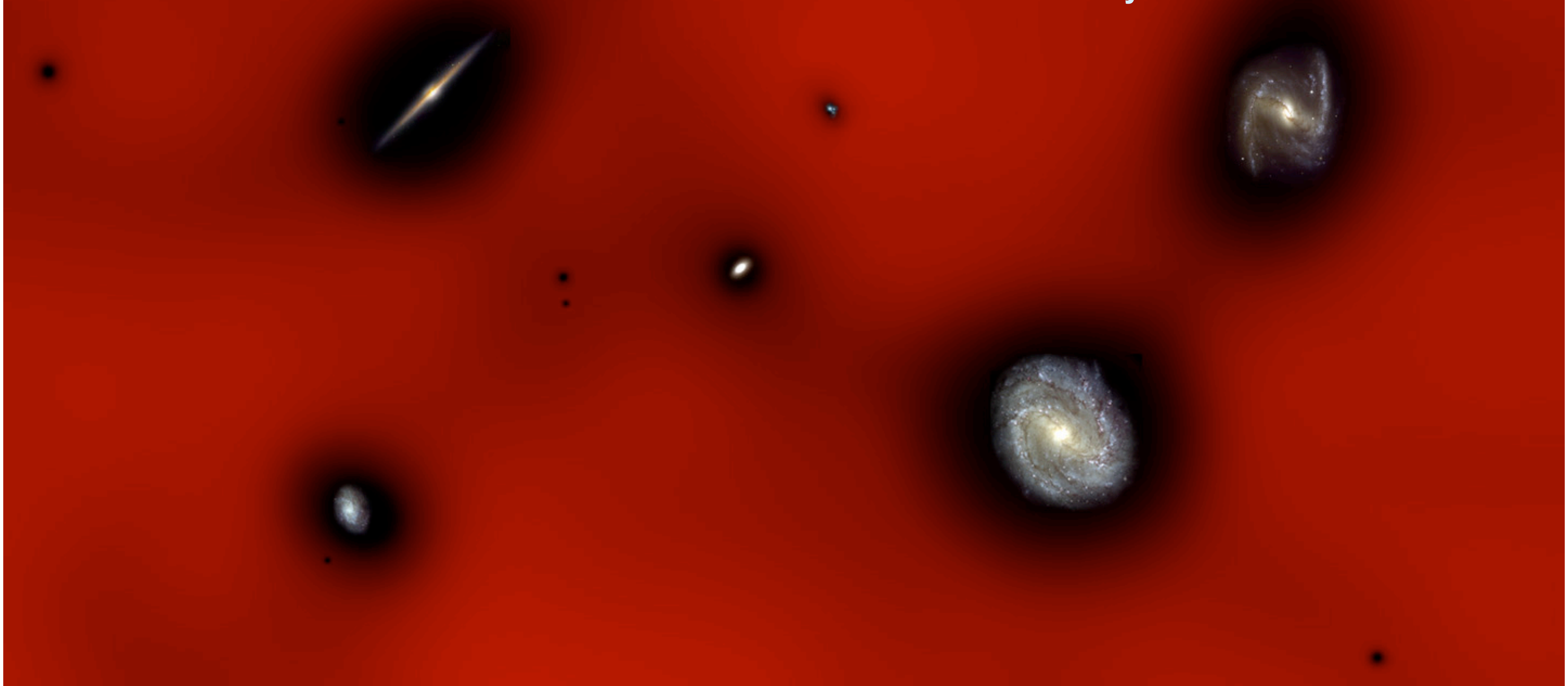
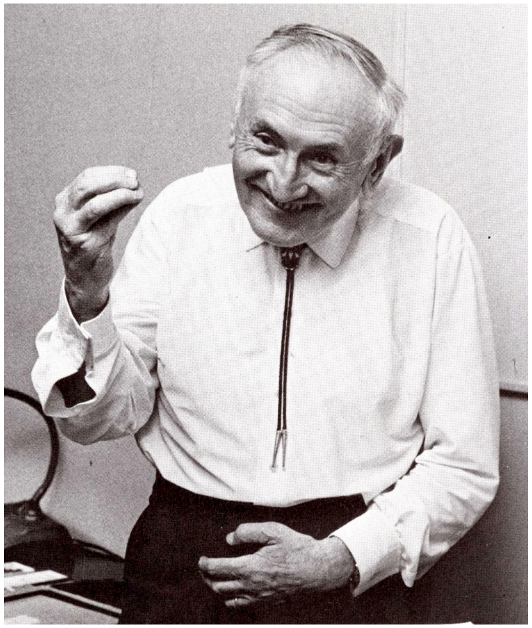




Some Conclusions

1 — DM correlations: $L_B \downarrow \;\Rightarrow\; \rho_{0,DM} \uparrow$, $r_{c,DM} \downarrow$, $\sigma_{DM} \downarrow$ $\forall$ disk galaxy L_B.

2 — Baryon loss > 1 dex for dIrr galaxies and ~ 2 dex for dSph galaxies.

3 — Galaxy baryon content → 0 at $V_{circ} \leq 42 \pm 4$ km s^{-1}; $\sigma_{DM} \approx 30 \pm 3$ km s^{-1}

4 — ∃ many dark dwarfs (very probably).

5 — DM surface density $\rho_{0,DM} \propto L_B^{0.057 \pm 0.067}$ is constant with galaxy L_B.

At the end, I discuss 3 problems with CDM galaxy formation.

Measuring DM parameters:

1 — Idealized case of massless test particles

Consider first the rotation curve of an isothermal sphere in the ideal case where we can measure a massless disk embedded in it. Then at $r \ll r_c$,

$$V \simeq \left(\frac{4\pi G\rho_0}{3}\right)^{1/2} r, \qquad (1)$$

and at $r \gg r_c$,

$$V \simeq 2^{1/2}\,\sigma = 2^{1/2}\left(\frac{4\pi G\rho_0 r_c^2}{9}\right)^{1/2}, \qquad (2)$$

where G is the gravitational constant. If we observe only the $V \propto r$ part of the rotation curve, we can measure ρ_0 but not r_c or σ. Because of this, ρ_0 is often the only halo parameter that we can measure in low-luminosity galaxies.

2 — Real world $\Longrightarrow$ $(M/L)_{\text{visible matter}} \neq 0$.

So: Decompose V(r) into visible matter and DM parts.

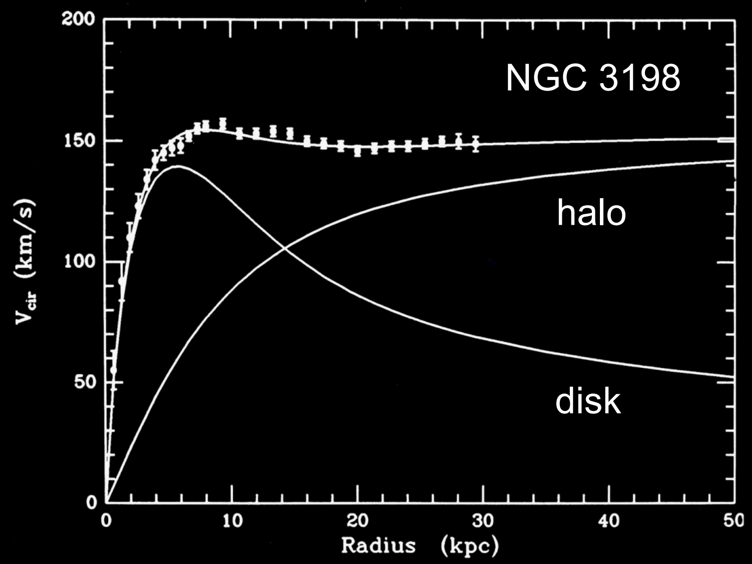
Rotation Curve Decomposition — NGC 3198

From surface brightness distribution and M/L, calculate the amount of rotation expected from the visible stars and molecular gas ("disk").

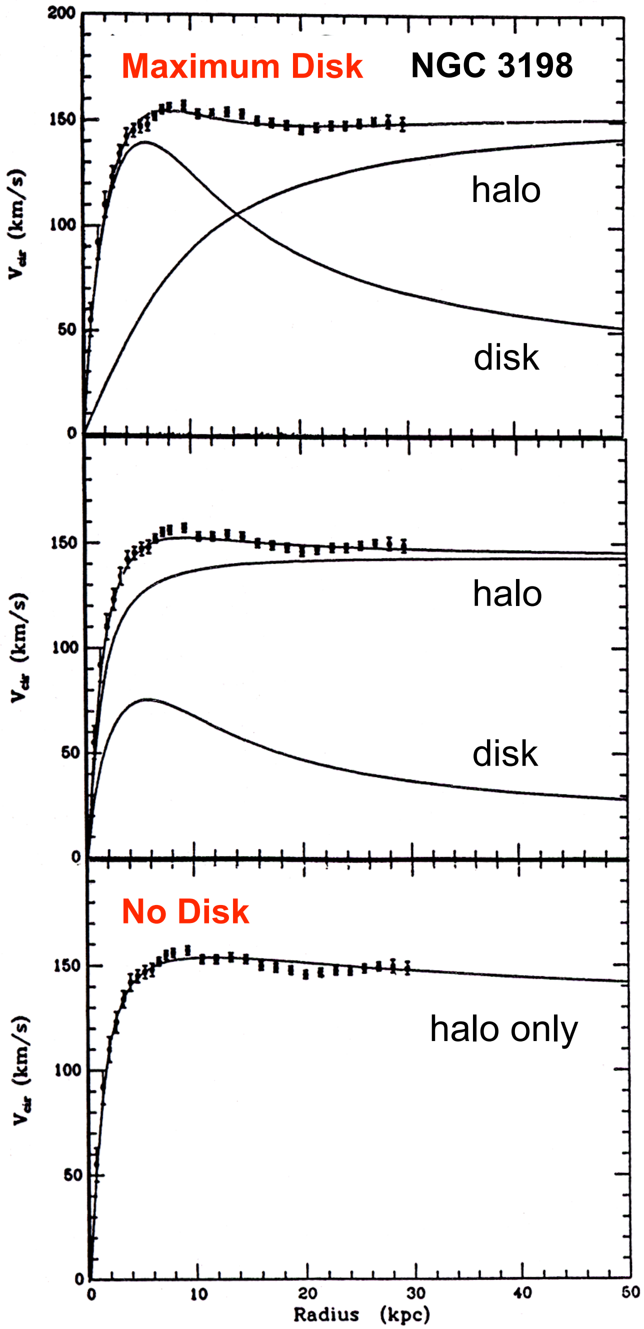
Estimate the rotation curve implied by HI, including a correction for He.

Subtract these in quadrature from the observed V(r). What's left is the rotation curve of the dark matter (labeled "halo").

Fit a dark matter model (e. g., an isothermal) to the halo rotation curve to estimate the dark matter parameters r_c, ρ_0, and σ.



van Albada et al. 1985, ApJ, 295, 305



Halo

$$\frac{\rho}{\rho_0} = \frac{1}{1 + \left(\frac{r}{a}\right)^{\gamma}}$$

$a = 8.5$ kpc
$\gamma = 2.1$
$\rho_0 = 0.0075\ M_\odot\ pc^{-3}$
$(M/L_V)_{disk} = 4.4$

$a = 1.3$ kpc
$\gamma = 2.05$
$\rho_0 = 0.27\ M_\odot pc^{-3}$
$(M/L_V)_{disk} = 1.3$

$a = 1.5$ kpc
$\gamma = 2.25$
$\rho_0 = 0.33\ M_\odot pc^{-3}$
$(M/L_V)_{disk} = 0$

Uncertainty in Rotation Curve Decomposition

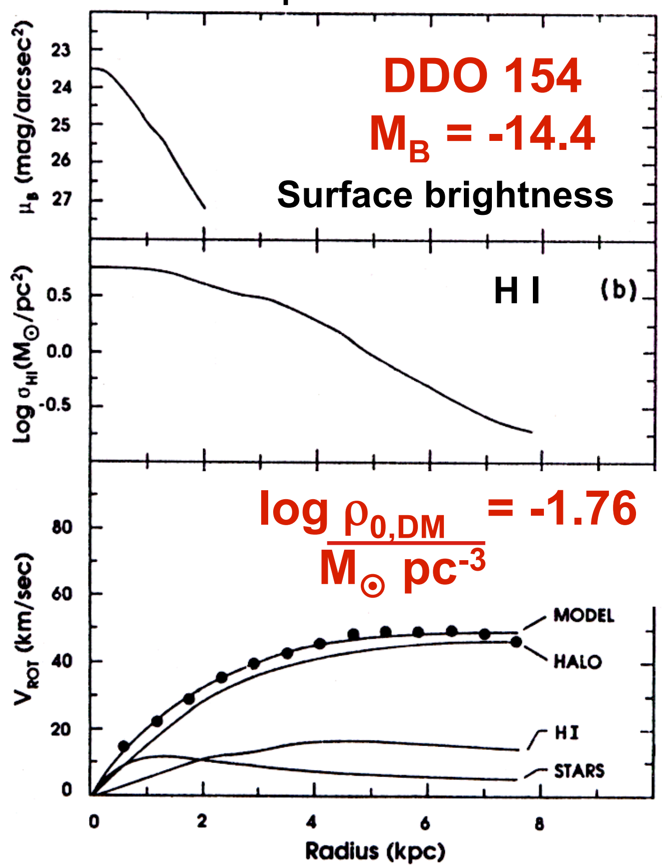
Usually any M/L between the maximum disk value and M/L = 0 allows a good fit to the rotation curve.

If we had no further constraints, we could say little about DM systematic properties.

Fortunately, dynamics of spiral structure, bars, etc. require that M/L ≈ maximum disk value (e. g., Athanassoula et al. 1987, A&A, 179, 23).

$M_B \approx -14$ Mostly DM Galaxies

$r_{max} / r_{exp} = 15.2$



Carignan & Freeman 1988: $M_{DM} / M_{total} \approx 0.92$ at $r \leq 7.6$ kpc

Dark Matter Parameters

Sc — Im galaxies ($M_B \leq -13$): Rotation curve decomposition

dSph, Im galaxies ($M_B > -13$): Jeans Equation + σ, r_c ➔ ρ_0

__Galaxy Selection Criteria__

Galaxy types Sc — Im and dSph ⇐ { no bulge; less compression of DM by baryons

Inclination $i \geq 40^{o}$

Rotation curve measurements reach out to $r_{max}/r_{exp} \geq 4.5$

Dark Matter Parameters

Assumptions

Rotation curves that flatten out to V(r) = constant stay flat.

Maximum disk decompositions*

DM model = nonsingular isothermal sphere**

*E. g., Athanassoula et al. 1987, Taga & Iye 1994, Sackett 1997, Debattista & Sellwood 1998, Bosma 1999, Wiener et al. 2001,
but not Bottema 1993, Courteau & Rix 1999

**E. g., Moore 1994, but not Navarro, Frenk & White 1996, 1997

To get a large sample, we want to combine results from authors who use the isothermal sphere to model DM and authors who use the pseudo-isothermal sphere (PITS):

$$\rho\,(r) = \rho_0/(1 + r^2/a^2).$$

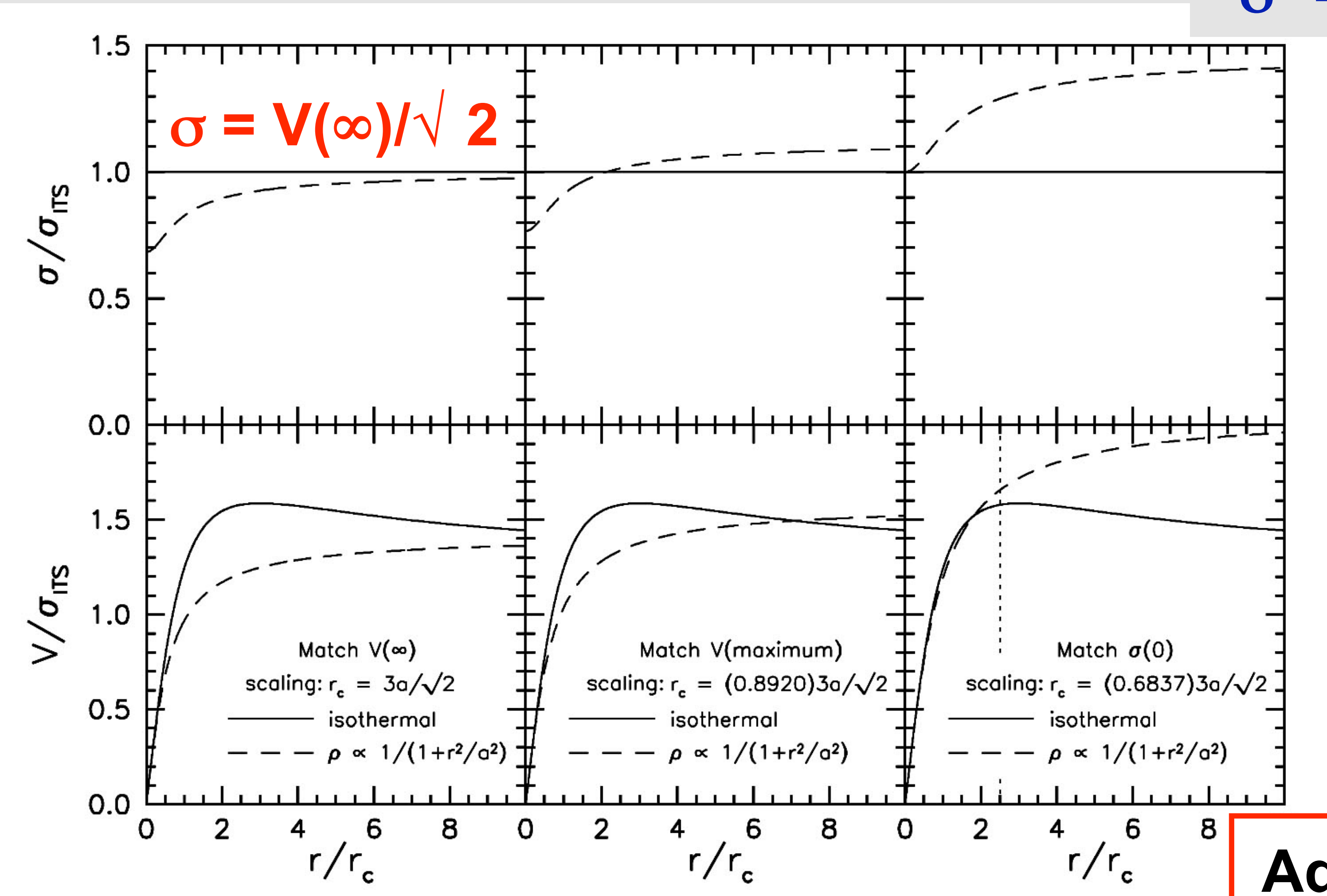
Here $\rho(r)$ = volume density profile,
ρ_0 = central density and
a = "core radius".

But the PITS is not isothermal.
Where x = r / a ,

$$\sigma^2(r) = V^2(\infty)\,(1 + x^2)\left(\frac{\pi^2}{8} - \frac{\tan^{-1} x}{x} - \frac{(\tan^{-1} x)^2}{2}\right)$$

Scalings the Pseudo-Isothermal to the Isothermal

$\sigma^2 = 4\pi G \rho_0 r_c^2/9$



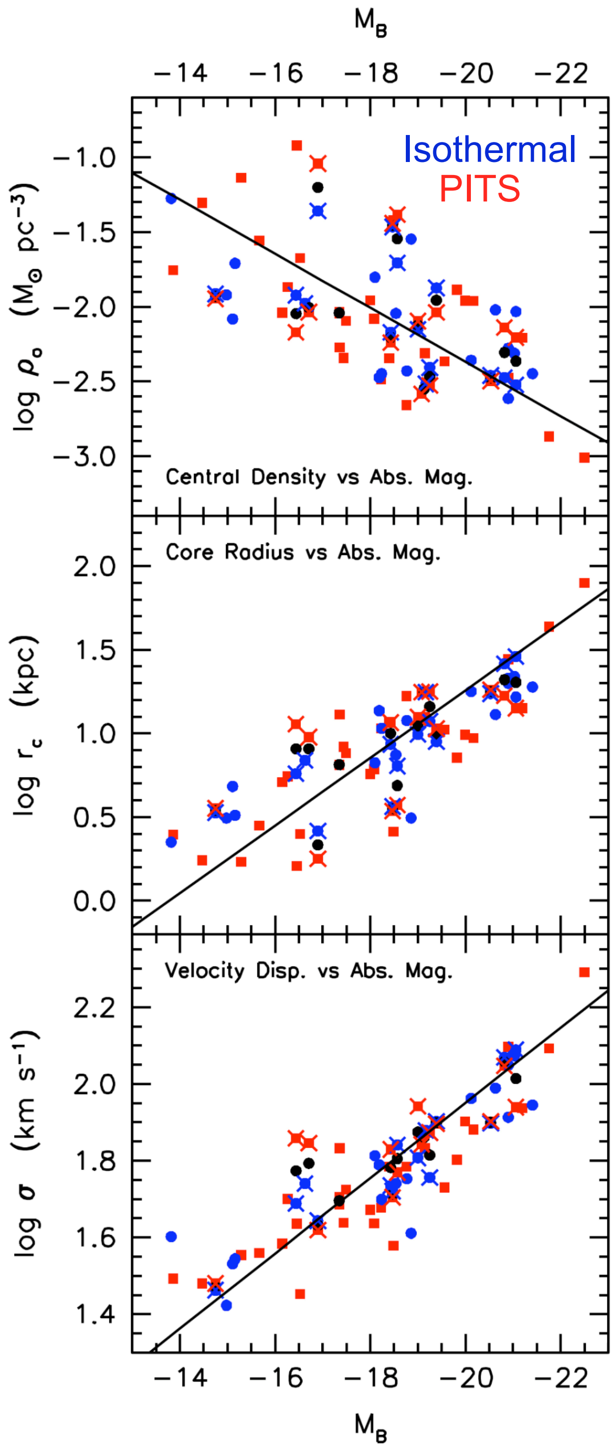
Match $V(\infty)$	Match V(maximum)	Match $\sigma(0)$
$\rho_0 = \rho_0$	$\rho_0 = \rho_0$	$\rho_0 = \rho_0$
$r_c = 2.12\ a$	$r_c = 1.89\ a$	$r_c = 1.45\ a$
$\sigma = \sigma$	$\sigma = 0.89\ \sigma$	$\sigma = 0.68\ \sigma$

Adopted scaling

$\rho_0 = 0.855\ \rho_0$

$r_c = 1.659\ a$

$\sigma = 0.723\ \sigma$



Calibrating the PITS to the Isothermal Sphere

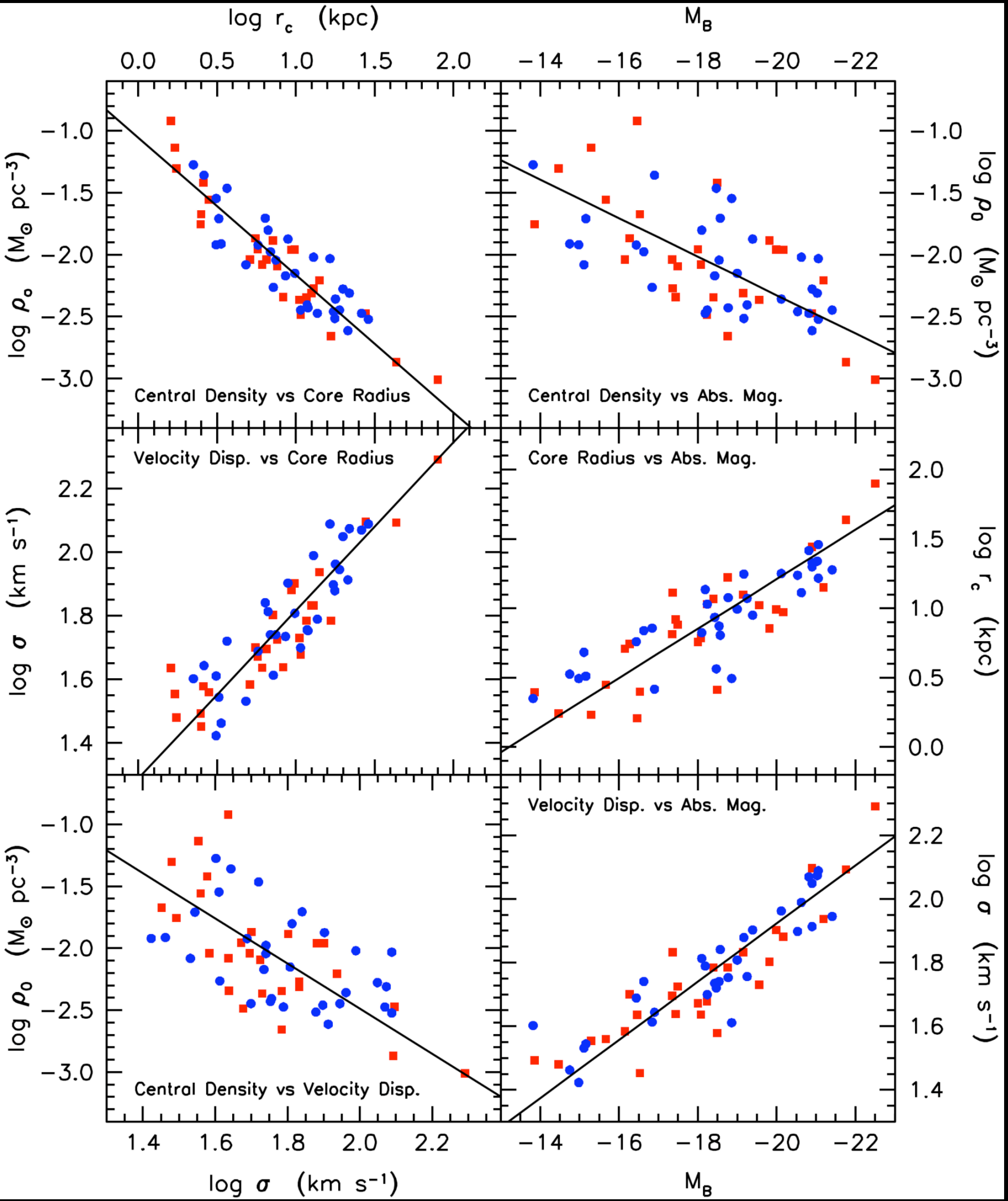
Sources:

Athanassoula et al. 1987, A&A, 179, 23
Blais-Ouellette et al. 1999, AJ, 118, 2123
Bosma, Kormendy, et al. unpublished
Carignan & Puche 1990, AJ, 100, 394
Carignan & Purton 1998, ApJ, 506, 125
Carignan et al. 1988, AJ, 95, 37
Chemin et al. 2006, AJ, 132, 2527
de Blok et al. 2002, A&A, 385, 816
Côté, S., et al. 2000, AJ, 120, 3027
Jobin & Carignan 1990, AJ, 100, 648
Martimbeau et al. 1994, AJ, 107, 543
Puche et al. 1991, AJ, 101, 447
Sicotte & Carignan 1997, AJ, 113, 609
Verdes-Montenegro et al. 1997, A&A, 321, 754

Broeils 1992, PhD Thesis, Univ. Groningen
Corbelli 2003, MNRAS, 342, 199
de Blok & McGaugh 1997, MNRAS, 290, 533
de Blok et al. 2001, ApJ, 122, 2396
de Blok et al. 2002, AJ, 385, 816
de Blok et al. 2008, AJ, 136, 2648
Gentile et al. 2004, MNRAS, 351, 903
Gentile, et al. 2007, MNRAS, 375, 199
Kuzio de Naray et al. 2008, ApJ, 676, 920
Miller & Rubin 1995, AJ, 110, 2692
Oh et al. 2011, AK, 141, 193
Swaters et al. 2000, ApJ, 531, L107
Swaters et al. 2003, ApJ, 583, 732
van Zee et al. 1997, AJ, 113, 1618
Verheijen 1997, PhD Thesis, Univ. Groningen
Weldrake et al. 2003, MNRAS, 340, 12

Combined Sample

59 Sc — Im galaxies



Conclusion:

The dark matter halos of Sc - Im galaxies satisfy scaling laws:

Lower luminosity galaxies have higher central DM densities ρ_0, smaller DM core radii r_c, and smaller DM velocity dispersion σ.

Dark matter parameter correlations from 59 galaxies

$$\rho_0 = \left(0.0136^{+0.0017}_{-0.0015}\ M_\odot\ \mathrm{pc}^{-3}\right)\left(\frac{L_B}{10^9\ L_{B\odot}}\right)^{-0.388\pm0.057};$$

$$r_c = \left(4.80^{+0.35}_{-0.33}\ \mathrm{kpc}\right)\left(\frac{L_B}{10^9\ L_{B\odot}}\right)^{0.446\pm0.035};$$

$\rho_0 r_c \propto L_B^{0.057\ \pm 0.067}$;

$$\sigma = \left(44.8^{+1.4}_{-1.3}\ \mathrm{km\ s}^{-1}\right)\left(\frac{L_B}{10^9\ L_{B\odot}}\right)^{0.229\pm0.014};\ \text{i.e.,}$$

$$L_B \propto \sigma^{4.37\pm0.28};$$

$\rho_0/\sigma^3 \propto L_B^{-1.085} \propto M^{-1.72}$

$$\rho_0 = \left(0.00685^{+0.00040}_{-0.00037}\ M_\odot\ \mathrm{pc}^{-3}\right)\left(\frac{r_c}{10\ \mathrm{kpc}}\right)^{-1.109\pm0.066};$$

$$\rho_0 = \left(0.00326^{+0.00058}_{-0.00050}\ M_\odot\ \mathrm{pc}^{-3}\right)\left(\frac{\sigma}{100\ \mathrm{km\ s}^{-1}}\right)^{-1.821\pm0.274};$$

$$\sigma = \left(65.5^{+1.9}_{-1.8}\ \mathrm{km\ s}^{-1}\right)\left(\frac{r_c}{10\ \mathrm{kpc}}\right)^{0.528\pm0.035}.$$

Power spectrum of initial density fluctuations, $|\delta_k|^2 \propto k^n$

Predicted Scaling*

$$\rho \propto R^{-3(3+n)/(5+n)} \; ;$$
$$\rho \propto \sigma^{-6(3+n)/(1-n)} \; ;$$
$$\sigma \propto R^{(1-n)/(10+2n)} \; .$$

*Peebles (1974); Gott & Rees (1975); Djorgovski (1992)

Observed Scaling

$$\rho_0 \propto r_c^{-1.109 \pm 0.066} \; ;$$
$$\rho_0 \propto \sigma^{-1.821 \pm 0.274} \; ;$$
$$\sigma \propto r_c^{0.528 \pm 0.035} \; .$$

$\Longrightarrow$ n = -1.83 ± 0.19; n = -2.07 ± 0.08; n = -2.08 ± 0.18;

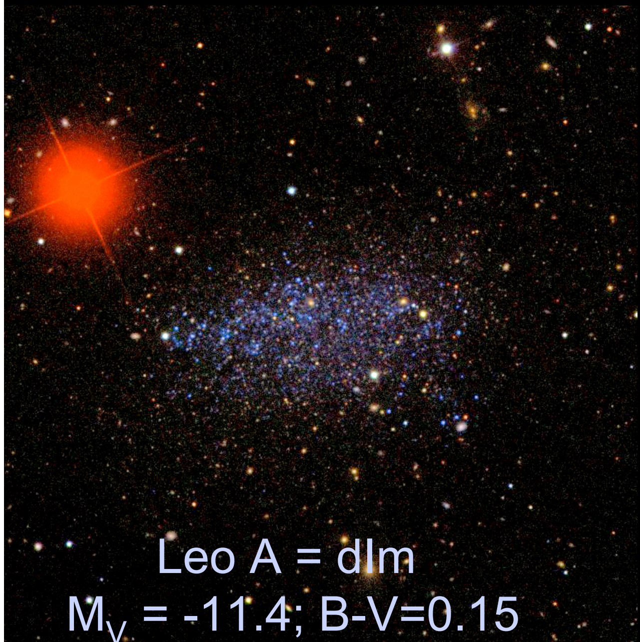
average n = -1.99 ± 0.10.

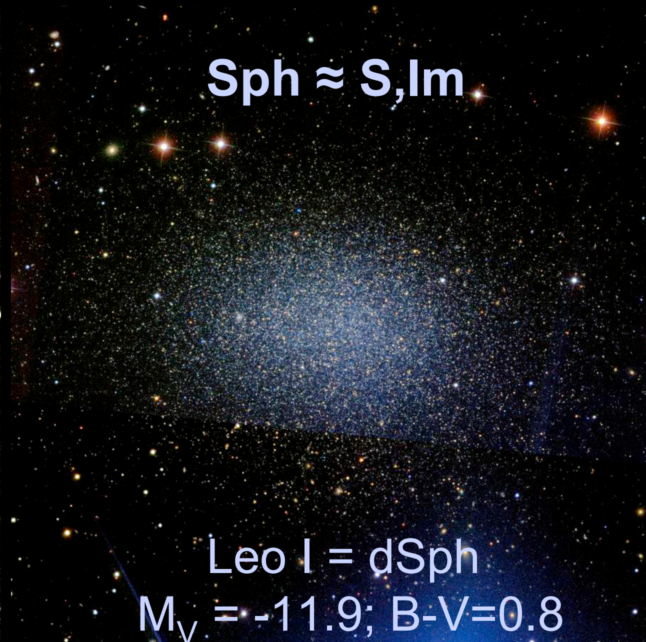
Good agreement with ΛCDM **

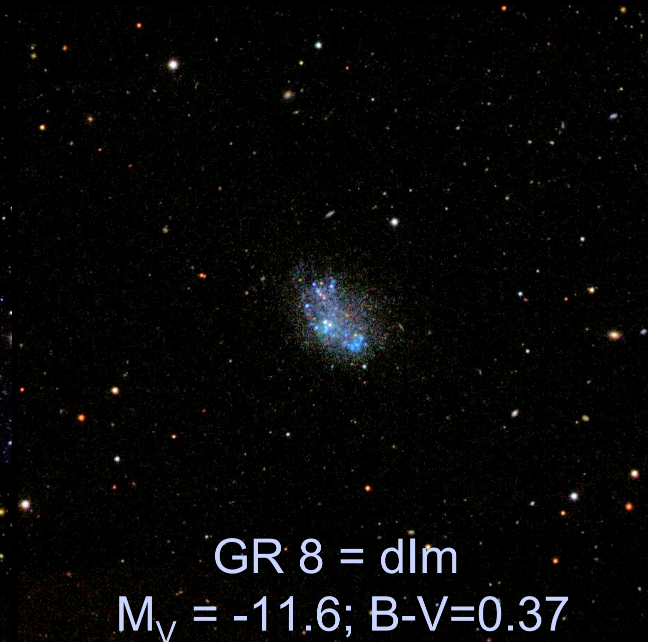
DM parameter correlations provide a measure of n on smaller mass scales than are accessible to most other techniques.

**E. g., Shapiro & Iliev 2002, ApJ, 565, L1

Sph and Im galaxies have similar, low surface brightnesses.

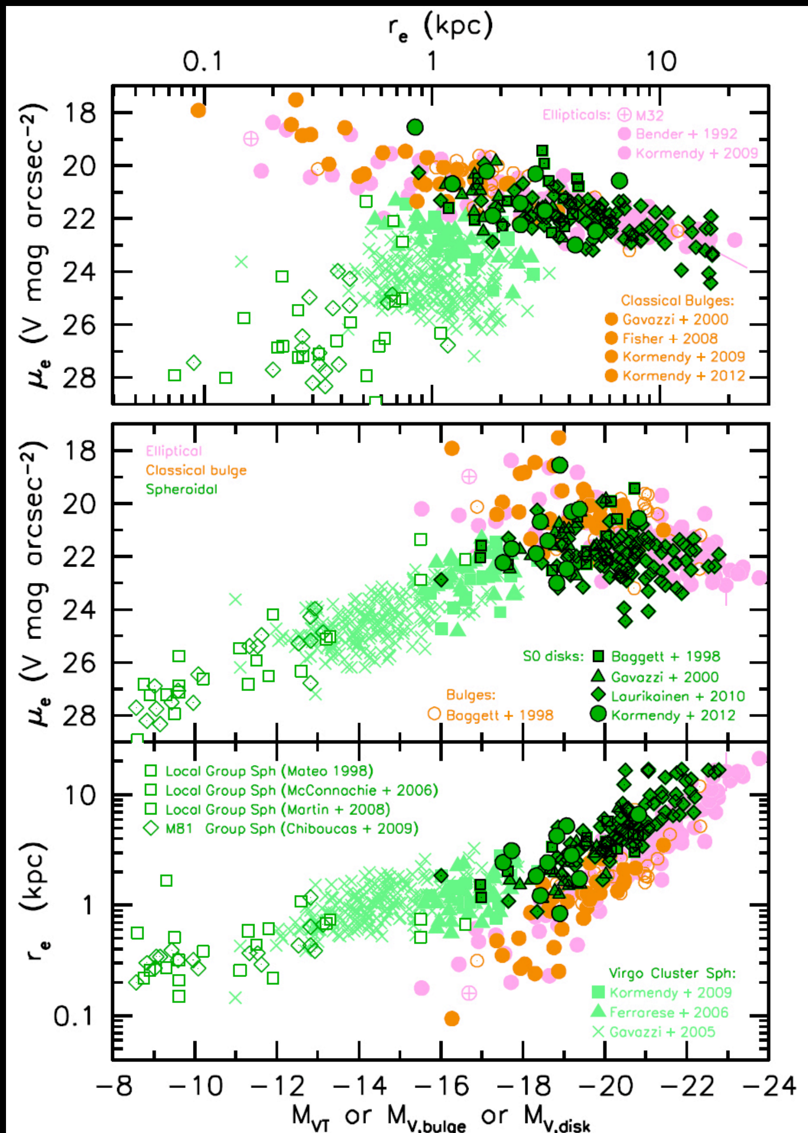


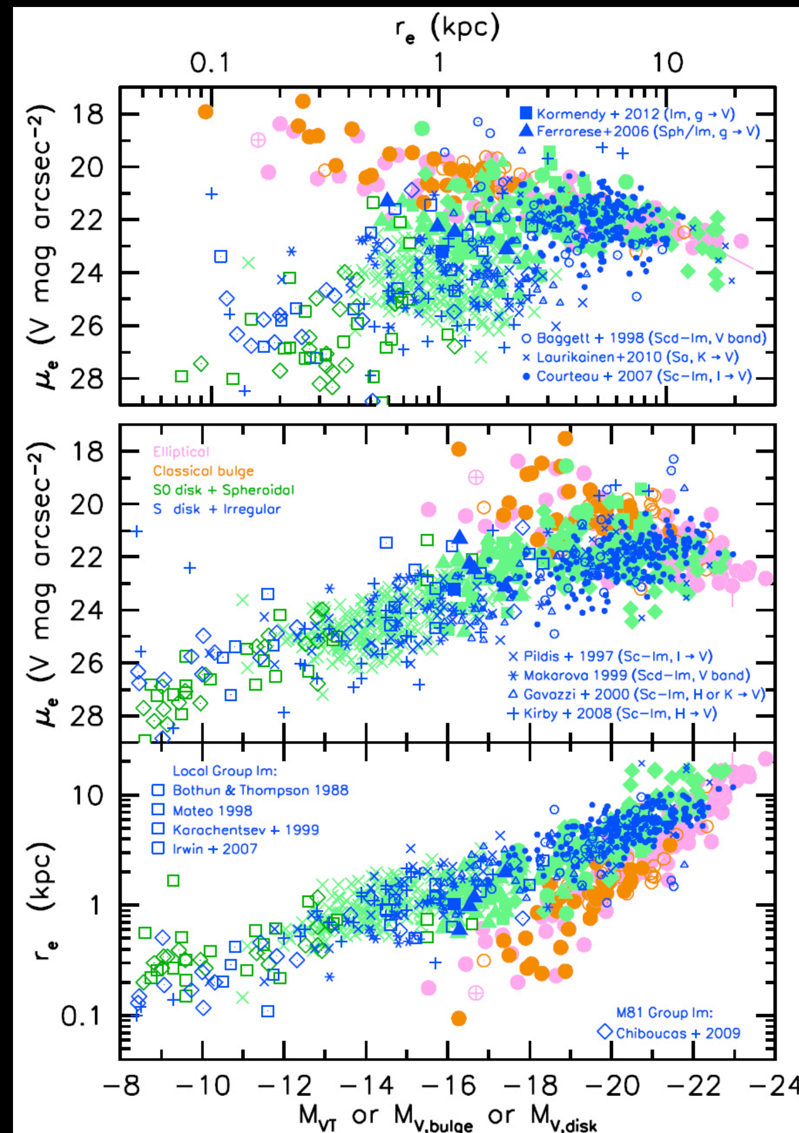




E ≠ Sph

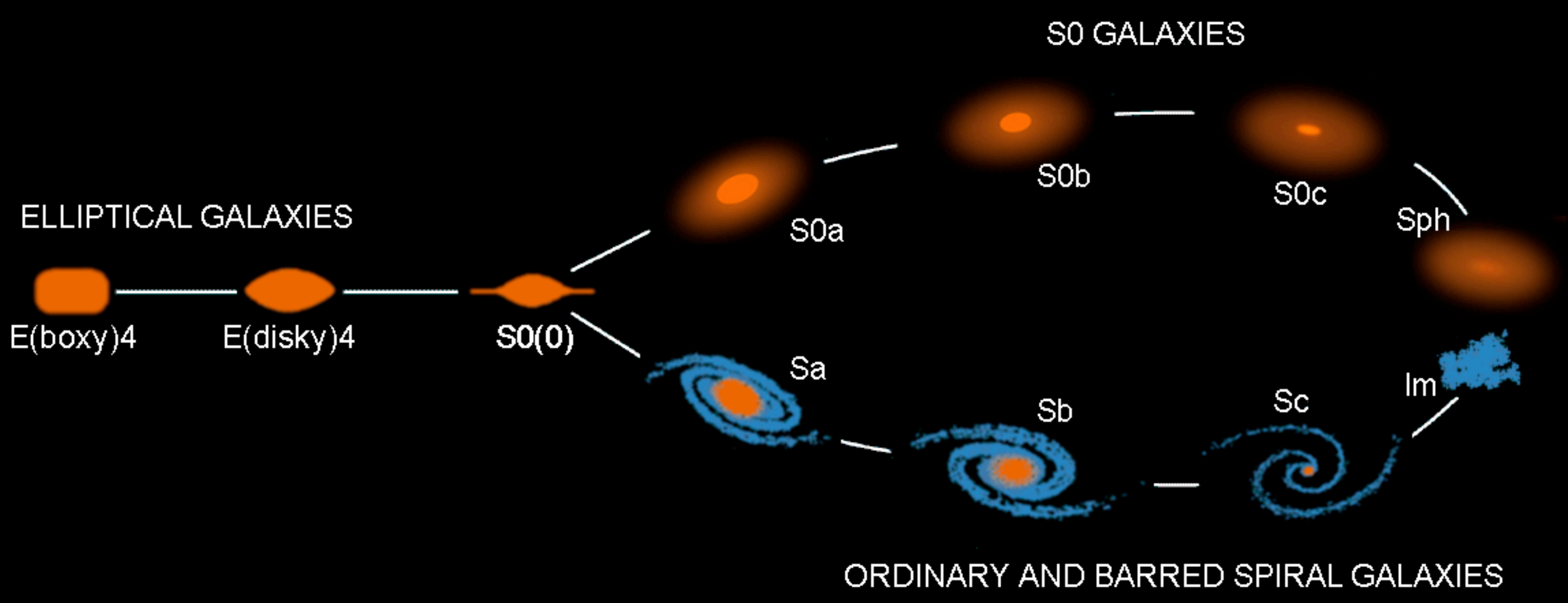
Sph galaxies are bulgeless S0 galaxies.
S0+Sph galaxies are transformed, “red and dead” S+Im galaxies.





Kormendy et al. 2009, ApJS, 182, 216 and Kormendy & Bender 2012, ApJS, 1982, 2

Revised Parallel Sequence Hubble Classification



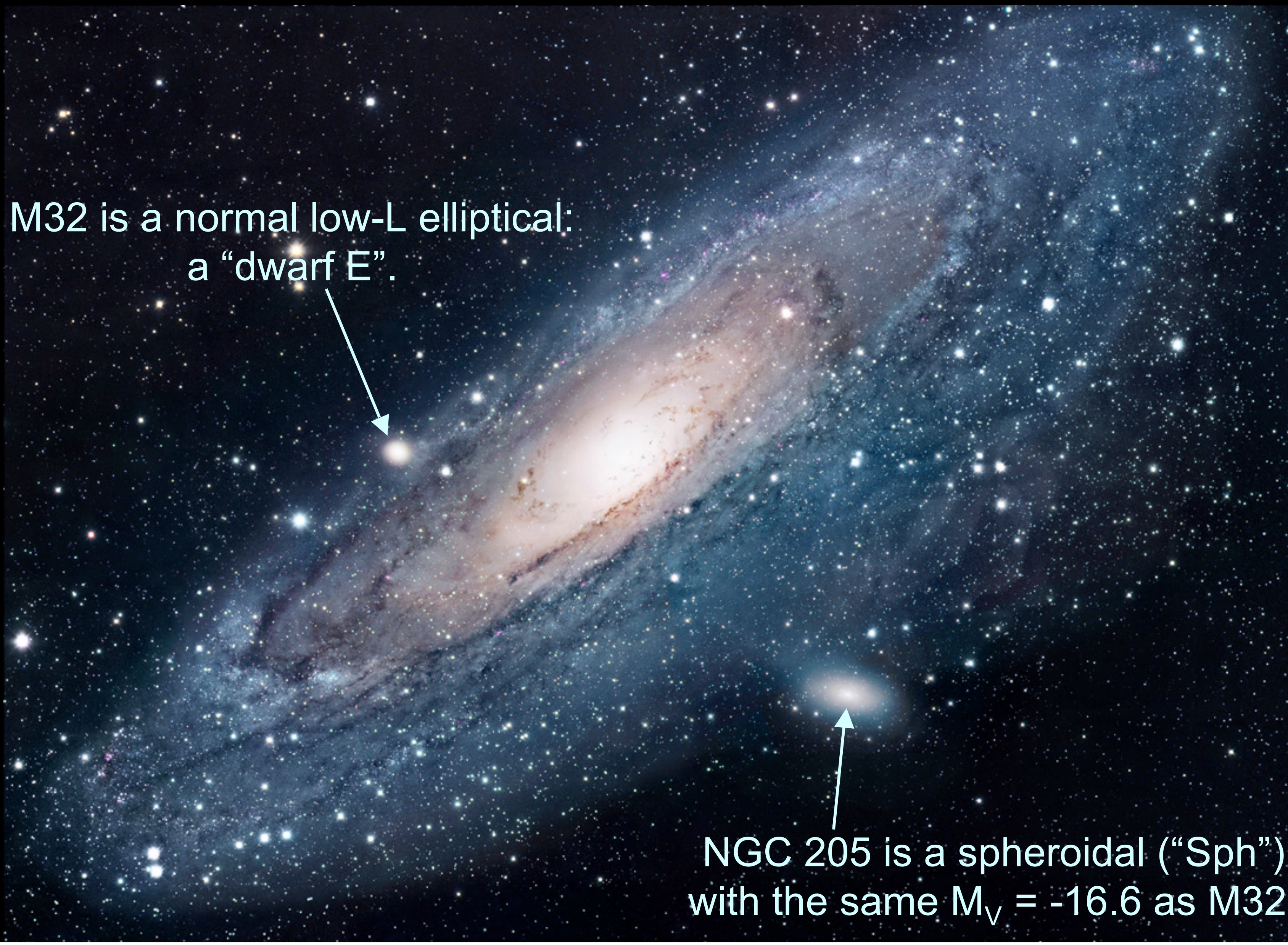
The distribution of structural properties for S0 galaxies is similar to that for Sa — Sc galaxies combined (van den Bergh 1976) → a sequence of S0a – S0b – S0c galaxies parallels the sequence of spirals.

Now we know a few S0 galaxies that are structurally similar to Sc — Sm galaxies:
NGC 4762 (B/T = 0.13) is an SB0bc.
NGC 4452 (PB/T = 0.017) is an SB0c.

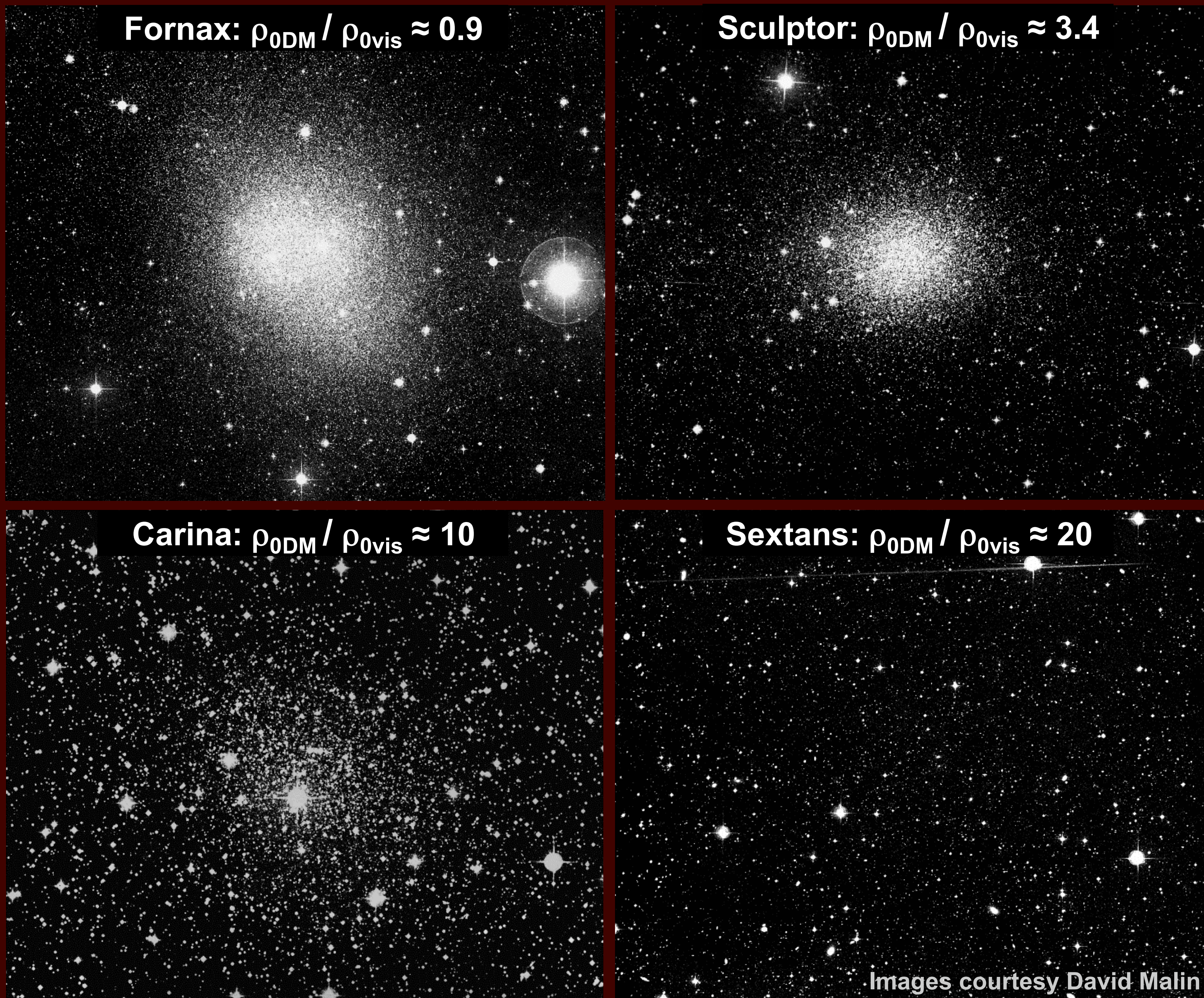
The completely bulgeless galaxies in the S0 sequence are the spheroidals.

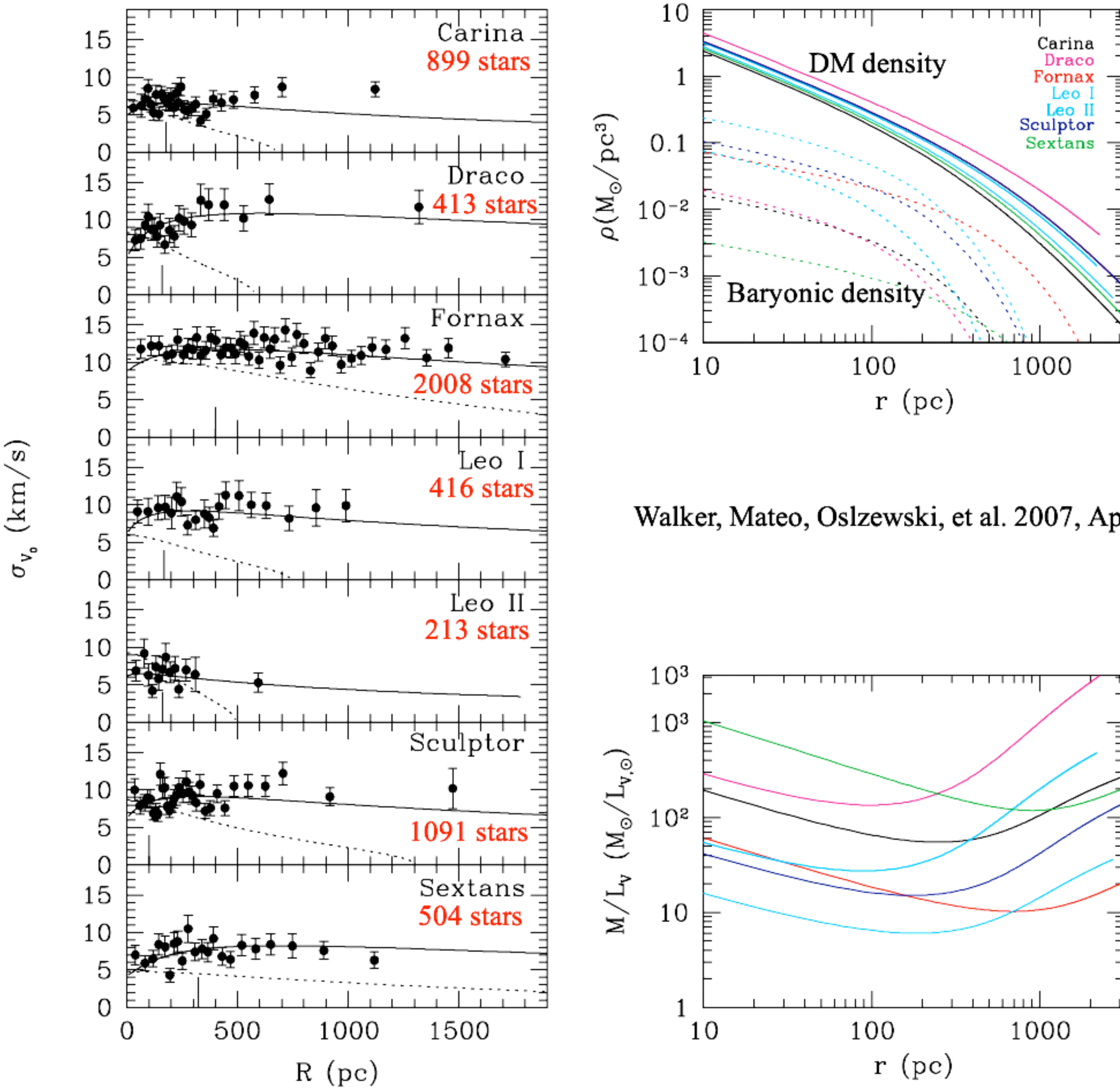
Kormendy & Bender 2012, ApJS, 1982, 2

Spheroidals are not small ellipticals.
They are transformed (“red and dead”) S+Im galaxies.



Fainter Dwarf Spheroidals Are More Dominated by Dark Matter





Walker, Mateo, Oslzewski, et al. 2007, ApJ, 667, L53

FIG. 2.—*Left*: Projected velocity dispersion profiles for seven Milky Way dSph satellites. Overplotted are profiles corresponding to mass-follows-light (King 1962) models (*dashed lines*; these fall to zero at the nominal "edge" of stellar distribution), and best-fitting NFW profiles that assume $\beta =$ constant. Short, vertical lines indicate luminous core radii (IH95). Distance moduli are adopted from Mateo (1998). *Right*: Solid lines represent density, and M/L profiles corresponding to best-fitting NFW profiles. Dotted lines in the top panel are baryonic density profiles, following from the assumption that the stellar component (assumed to have $M/L = 1$) has exponentially falling density with scale length given by IH95.

Dwarf spheroidal and dwarf irregular galaxies provide “leverage” on DM correlations.

Problem: They are pressure-supported and the velocity dispersion σ data do not reach far enough out to constrain r_c.

Assumptions:
Visible matter density is negligible;
visible matter lives entirely within the constant-density core of the dark matter.

We observe that $\sigma(r)$ = constant.

Then the spherical Jeans equation

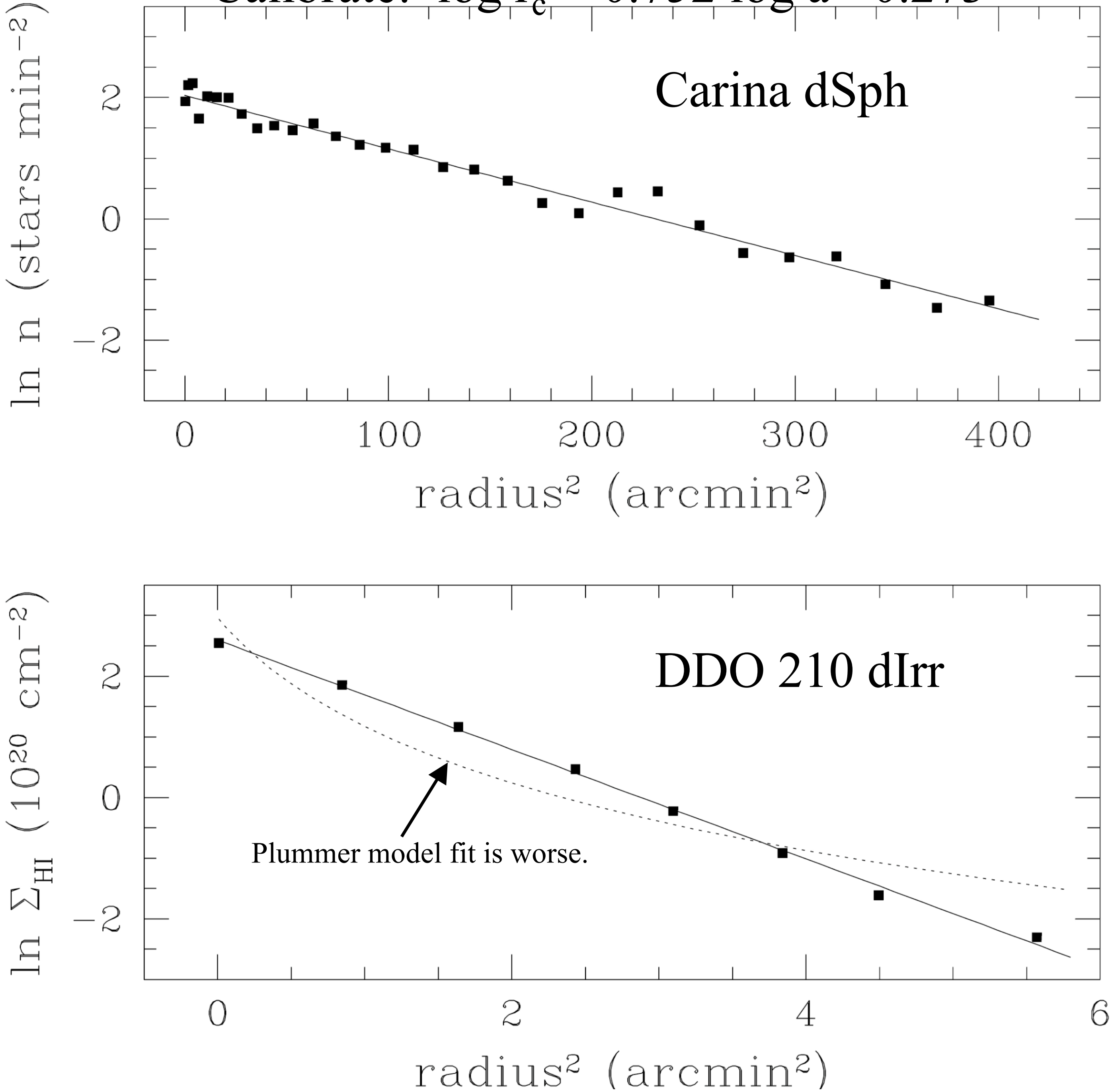
$$\frac{\sigma_*^2}{\rho_*}\frac{d\rho_*}{dr} = \frac{GM(r)}{r^2} = \frac{4\pi G\rho_\circ}{3}\, r$$

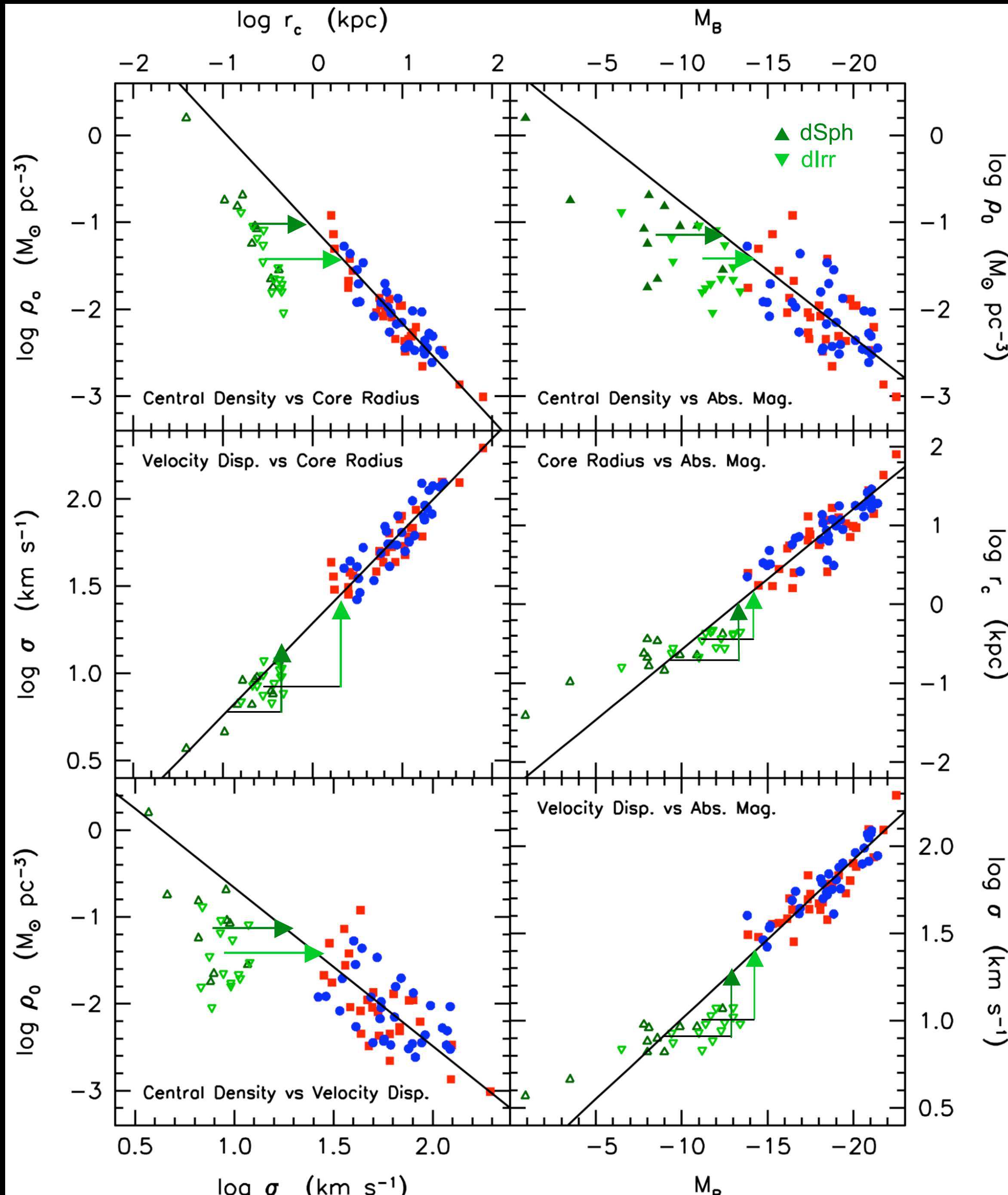
$\Rightarrow$ Volume and projected visible matter densities are both Gaussian,

$I(r) \propto \exp(-r^2/a^2)$.

$\Rightarrow$ Central dark matter density $\rho_0 = 3\sigma^2/2\pi G a^2$

Calibrate: $\log r_c = 0.752 \log a - 0.273$





Correlations

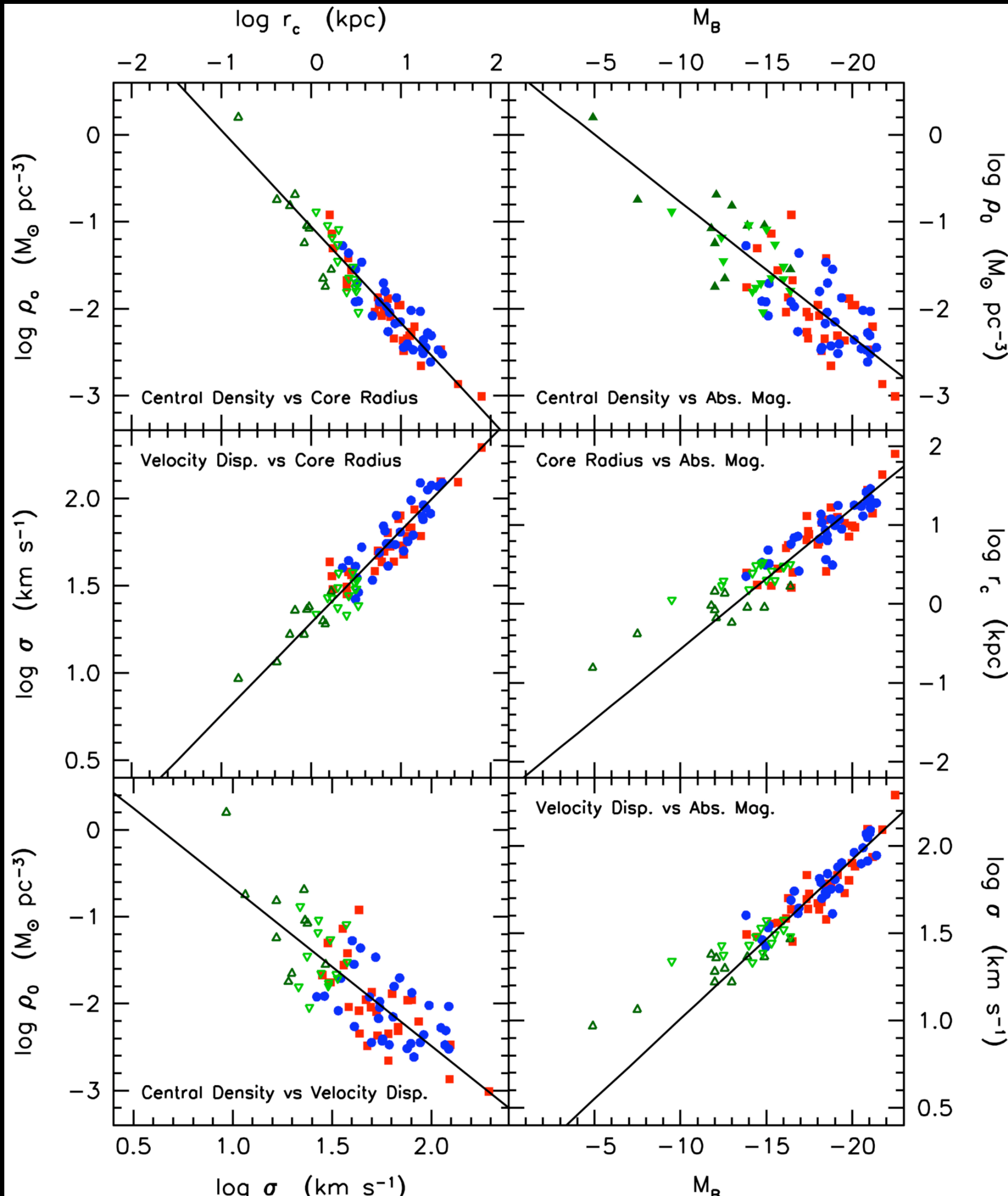
For dSph and dIrr galaxies,
ρ_0 is the central dark matter density,
but
r_c and σ are visible matter parameters.

dSph and dIrr galaxies with $M_B > -13$
have lost most of their baryons.

So: Assume that these galaxies
satisfy the correlations and:

Step 1: in
$\rho_0 - M_B$, shift them in M_B to agree.

Step 2:
Apply the same M_B shift to the
other M_B correlations to convert
visible matter r_c and σ
to
dark matter r_c and σ.



Correlations

For dSph and dIrr galaxies,
ρ_0 is the central dark matter density,
and
r_c and σ are <u>"corrected"</u> parameters for the dark matter.

Then for dIrr galaxies:
shift in M_B = -3.0 mag;
shift in ρ_0 = 0 dex;
shift in r_c = 0.85 dex;
shift in σ = 0.50 dex.

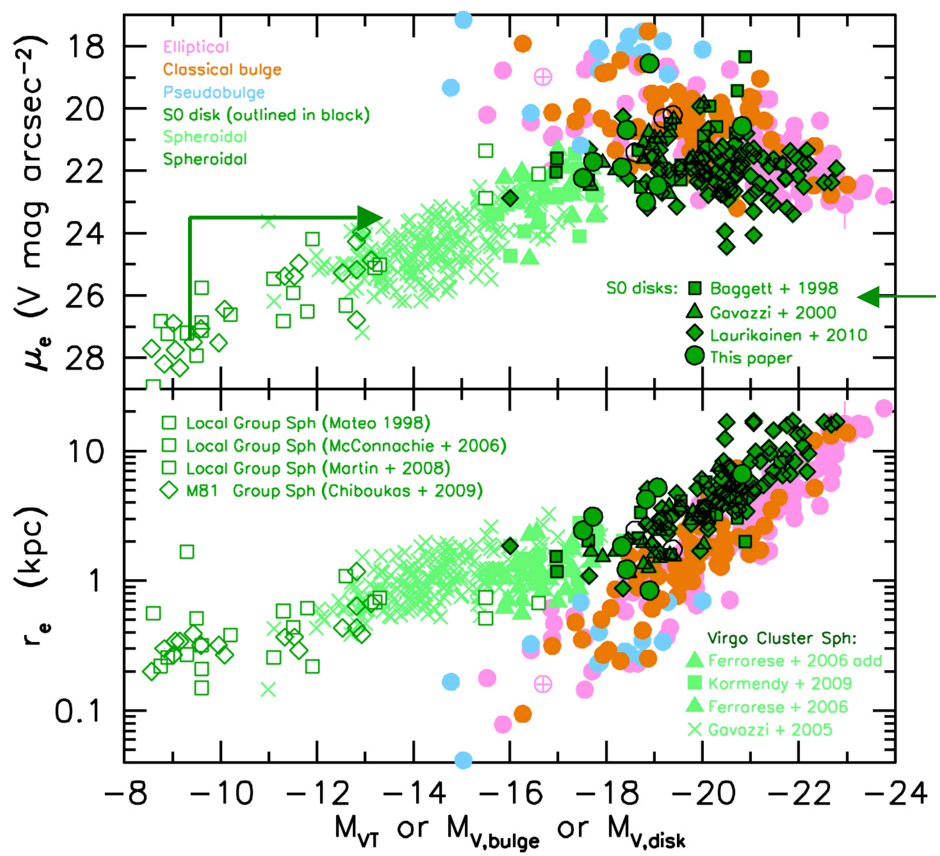
And for dSph galaxies:
shift in M_B = -4.0 mag;
shift in ρ_0 = 0 dex;
shift in r_c = 0.60 dex;
shift in σ = 0.40 dex.

We assumed that dSphs & dIrrs with $M_B > -13$ lost most of their baryons $\Leftarrow$ large measured mass-to-light rations ~ 10 to 10^2.

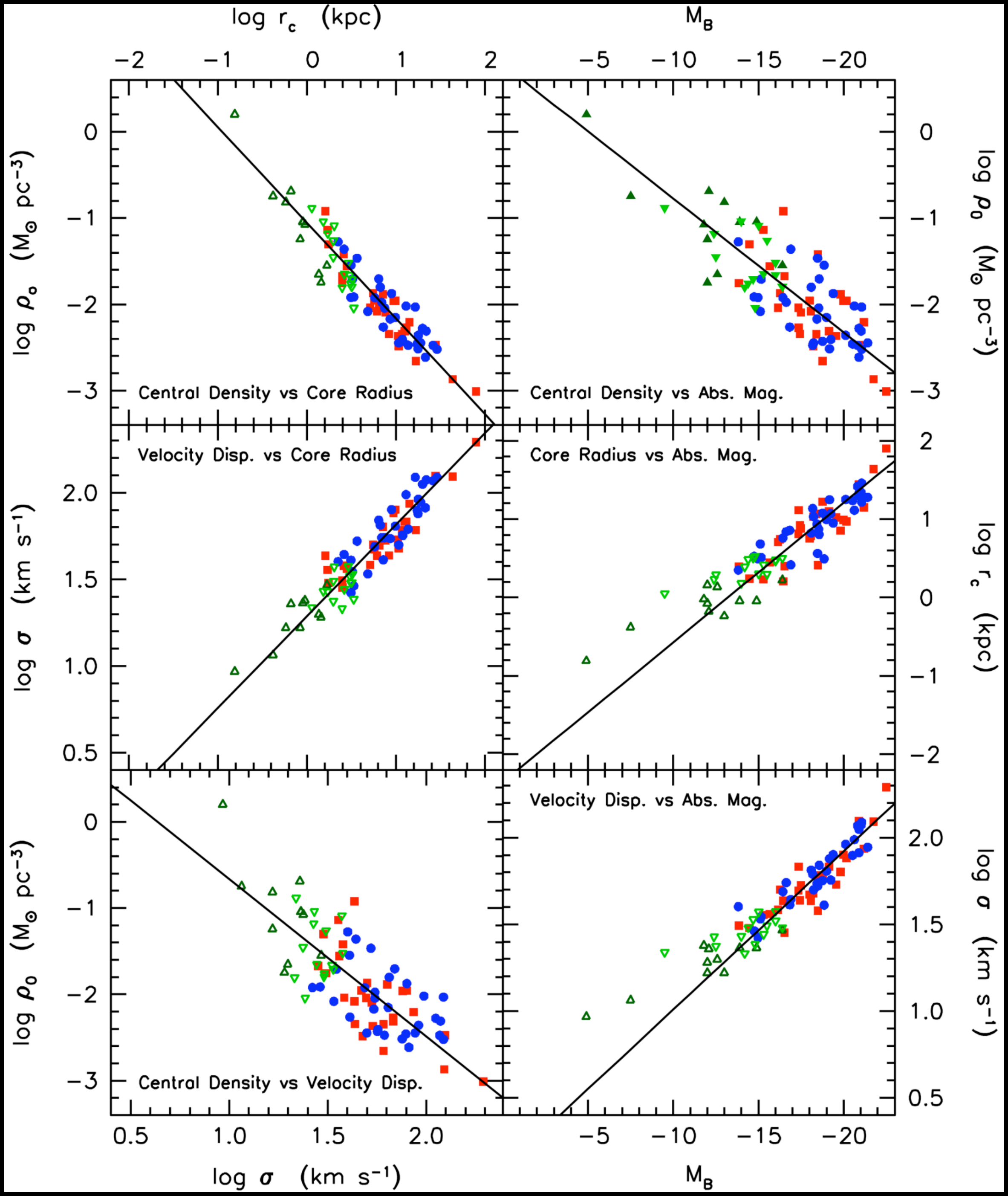
Derived M_B shifts ~ 3 mag for dIrr and ~ 4 mag for dSph consistently $\Rightarrow$ M/L ratios were normal before baryon ejection.

Therefore dSph & dIm galaxies are more massive than their visible matter σ suggests by $\Delta \log \sigma = 0.50$ (dIrr) and by $\Delta \log \sigma = 0.40$ (dSph).

The typical dSph galaxy has visible matter σ = 7.4 km s^{-1} and DM σ = 19 km s^{-1}.



127 S0 disks.



Conclusions

This consistency supports our assumption that dSphs and dIms have low visible matter densities because they lost most baryons.

— galactic winds (Dekel & Silk 1986)

— difficulty of accreting baryons in shallow DM potential wells when the Universe was ionized (Klypin et al. 1999; Tully et al. 2002).

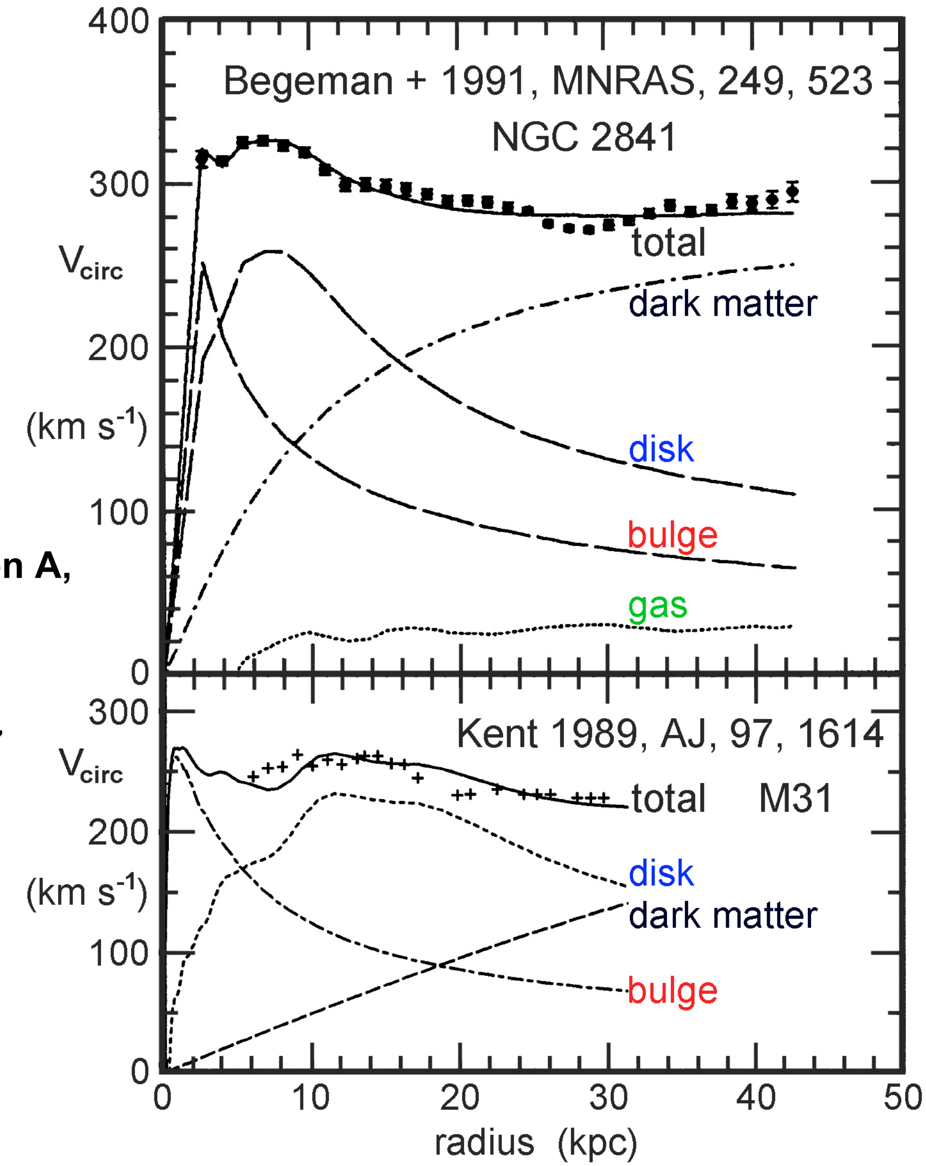
Reminder: DM and visible matter "conspire" to make nearly featureless, flat rotation curves.

Conspiracy references:

van Albada & Sancisi 1986, Phil. Trans. R. Soc. London A, 320, 477

Sancisi & van Albada 1987, IAU Symposium 117, p. 67

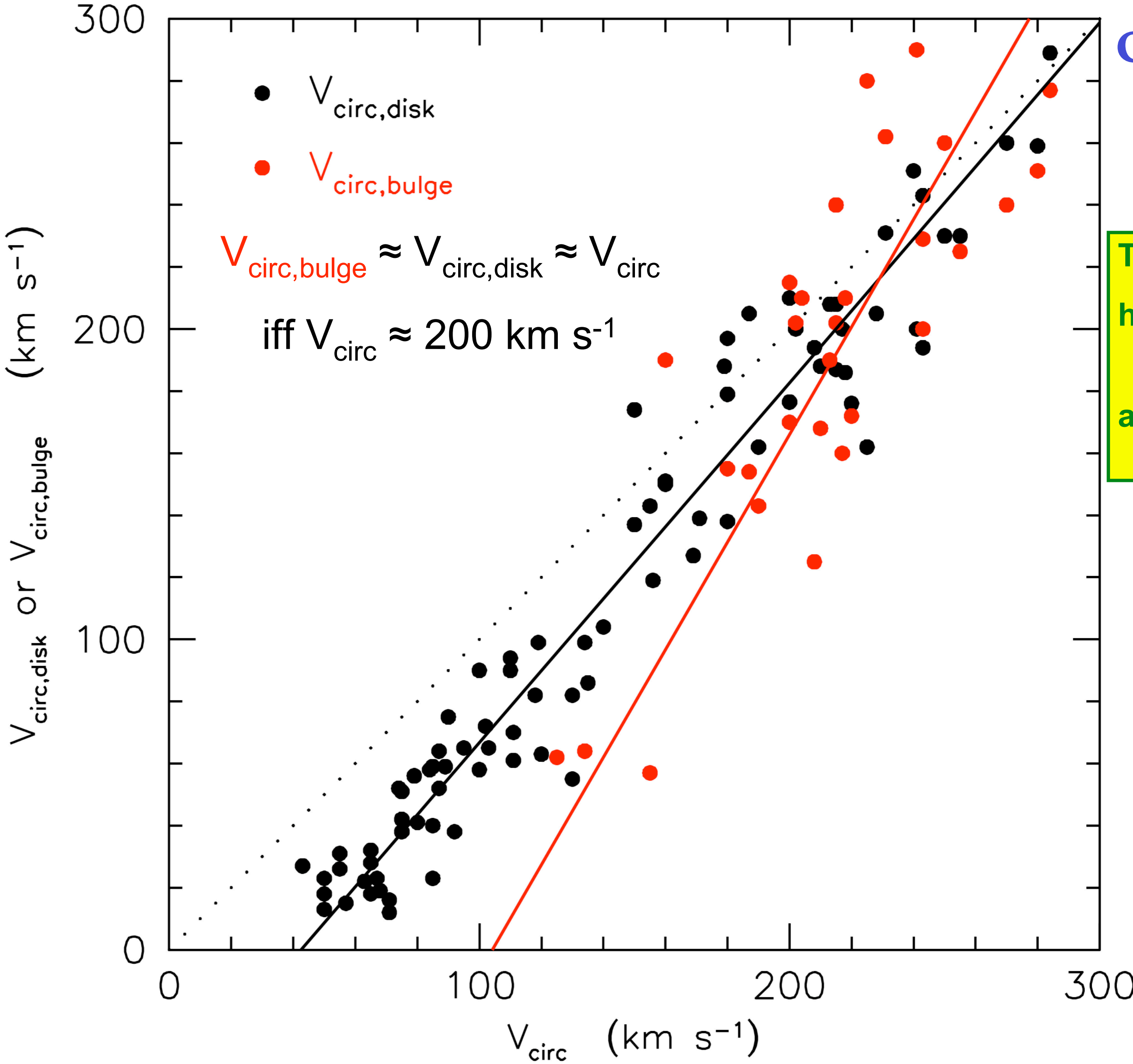
Casertano & van Gorkom 1991, AJ, 101, 1231



$V_{circ,bulge} \approx V_{circ,disk} \approx V_{circ,DM}$

iff $V_{circ,DM} \approx 200$ km s^{-1}

Conclusion: Galaxies are "dim" if $V_{circ} \lesssim 42 \pm 4$ km s^{-1}; $\sigma \lesssim 30 \pm 3$ km s^{-1}.



The typical dSph galaxy

has visible matter σ = 7.4 km s^{-1} and DM $\sigma \approx 19$ km s^{-1}

and is almost completely dark (M/L ~ 10^2).

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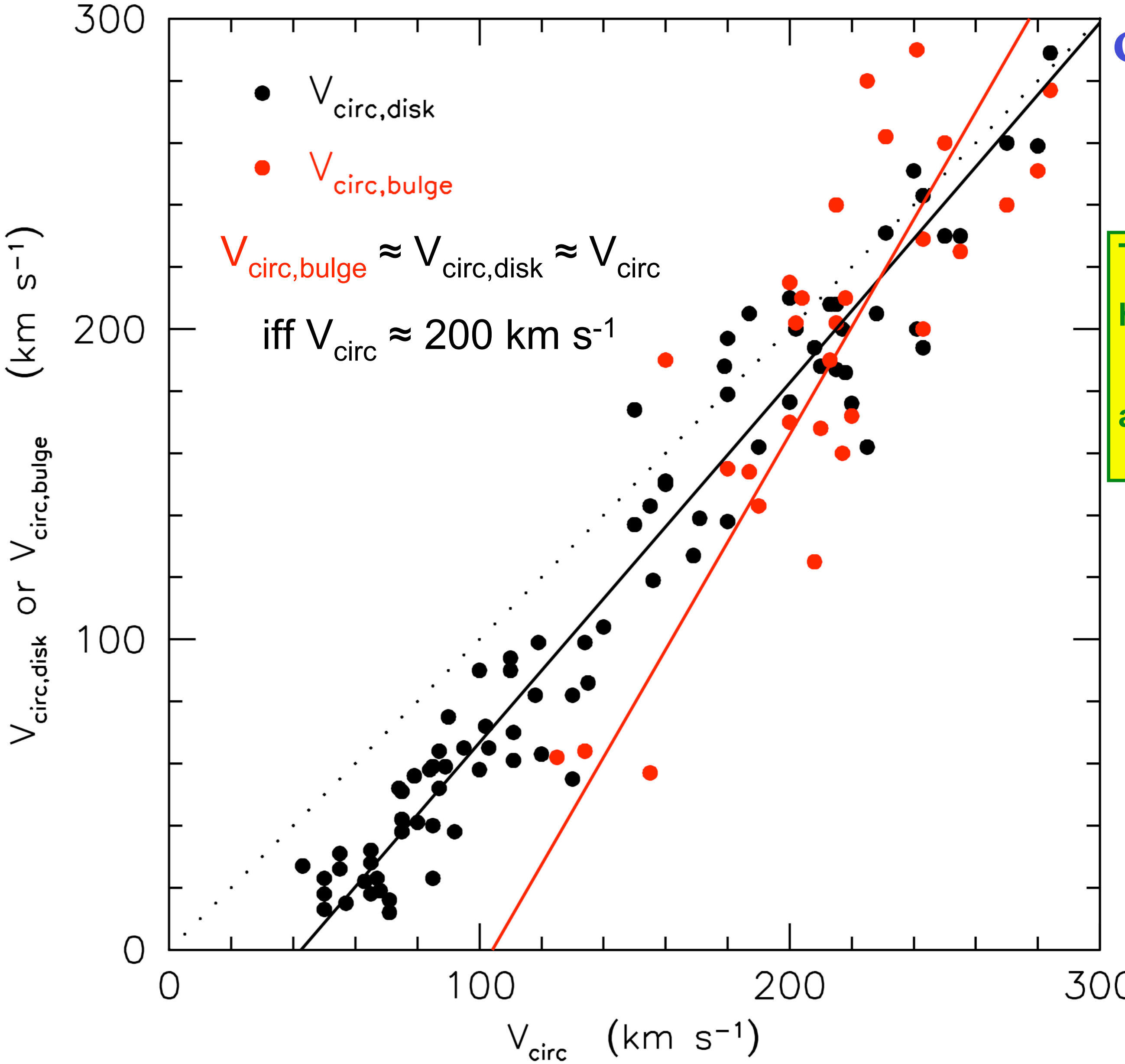

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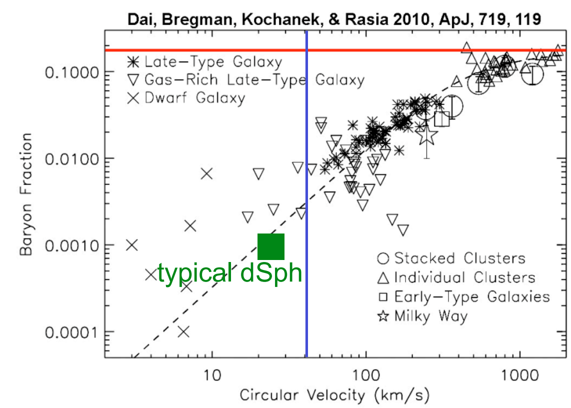

Figure 4. Baryon fractions as a function of potential well depth from dwarf galaxies to rich clusters. The circles are our stacked groups and clusters, the triangles are individual groups and clusters (Vikhlinin et al. 2006; Sun et al. 2009), the square is the ensemble of early-type lens galaxies (Gavazzi et al. 2007), asterisks are late-type galaxies (McGaugh 2005), upside-down triangles are gas-rich, late-type galaxies (Stark et al. 2009), crosses are dwarf galaxies (Walker et al. 2007), and the five-angle star is the Milky Way (Sakamoto et al. 2003; Flynn et al. 2006). The red line is the cosmic baryon fraction. The data points can be fit by a broken power-law model (dashed line) with the break at $V_c \sim 440$ km s^{-1}. The scatter of the data points around the mean relation is relatively small, which indicates that baryon fractions are largely set by the depths of a system's potential well.

REIONIZATION AND THE ABUNDANCE OF GALACTIC SATELLITES

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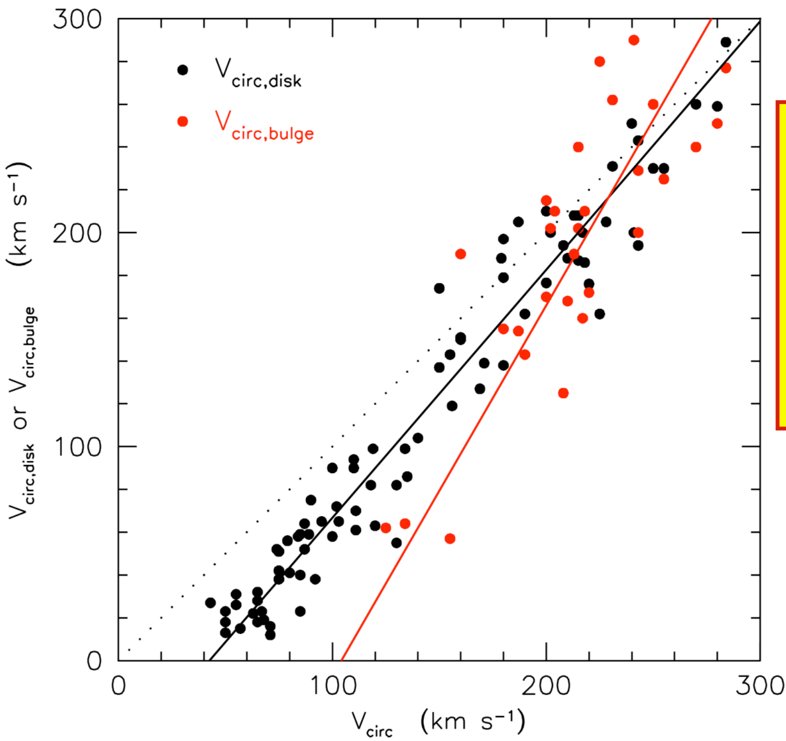
THE ASTROPHYSICAL JOURNAL, 539:517–521, 2000 August 20

ABSTRACT

One of the main challenges facing standard hierarchical structure formation models is that the predicted abundance of Galactic subhalos with circular velocities $v_c \sim 10$–30 km s^{-1} is an order of magnitude higher than the number of satellites actually observed within the Local Group. Using a simple model for the formation and evolution of dark halos, based on the extended Press-Schechter formalism and tested against N-body results, we show that the theoretical predictions can be reconciled with observations if gas accretion in low-mass halos is suppressed after the epoch of reionization. In this picture, the observed dwarf satellites correspond to the small fraction of halos that accreted substantial amounts of gas before reionization. The photoionization mechanism naturally explains why the discrepancy between predicted halos and observed satellites sets in at $v_c \sim 30$ km s^{-1}, and for reasonable choices of the reionization redshift ($z_{re} \sim 5$–12) the model can reproduce both the amplitude and shape of the observed velocity function of galactic satellites. If this explanation is correct, then typical bright galaxy halos contain many low-mass dark matter subhalos.

2.2. *Modeling Observable Satellites*

The second step in our model is to determine which of the surviving halos at $z = 0$ will host observable satellite galaxies. The key assumption is that, after the reionization redshift z_{re}, gas accretion is suppressed in halos with $v_c < v_T$. We adopt a threshold of $v_T = 30$ km s^{-1}, based on the results of Thoul & Weinberg (1996), who showed that galaxy formation is suppressed in the presence of a photoionizing background for objects smaller than ~ 30 km s^{-1}.



Conclusion: Good agreement with Bullock et al. 2000: threshold $V_{circ} \approx 30$ km s^{-1} and with Cattaneo et al. 2011, A&A, 533, A5: threshold $V_{circ} \approx 40$ km s^{-1}.

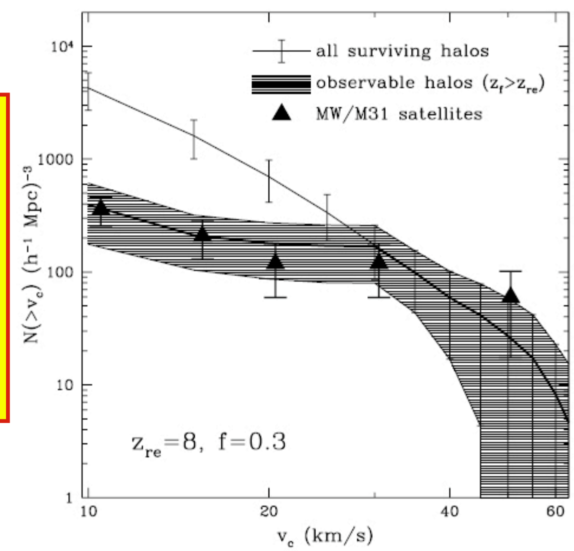
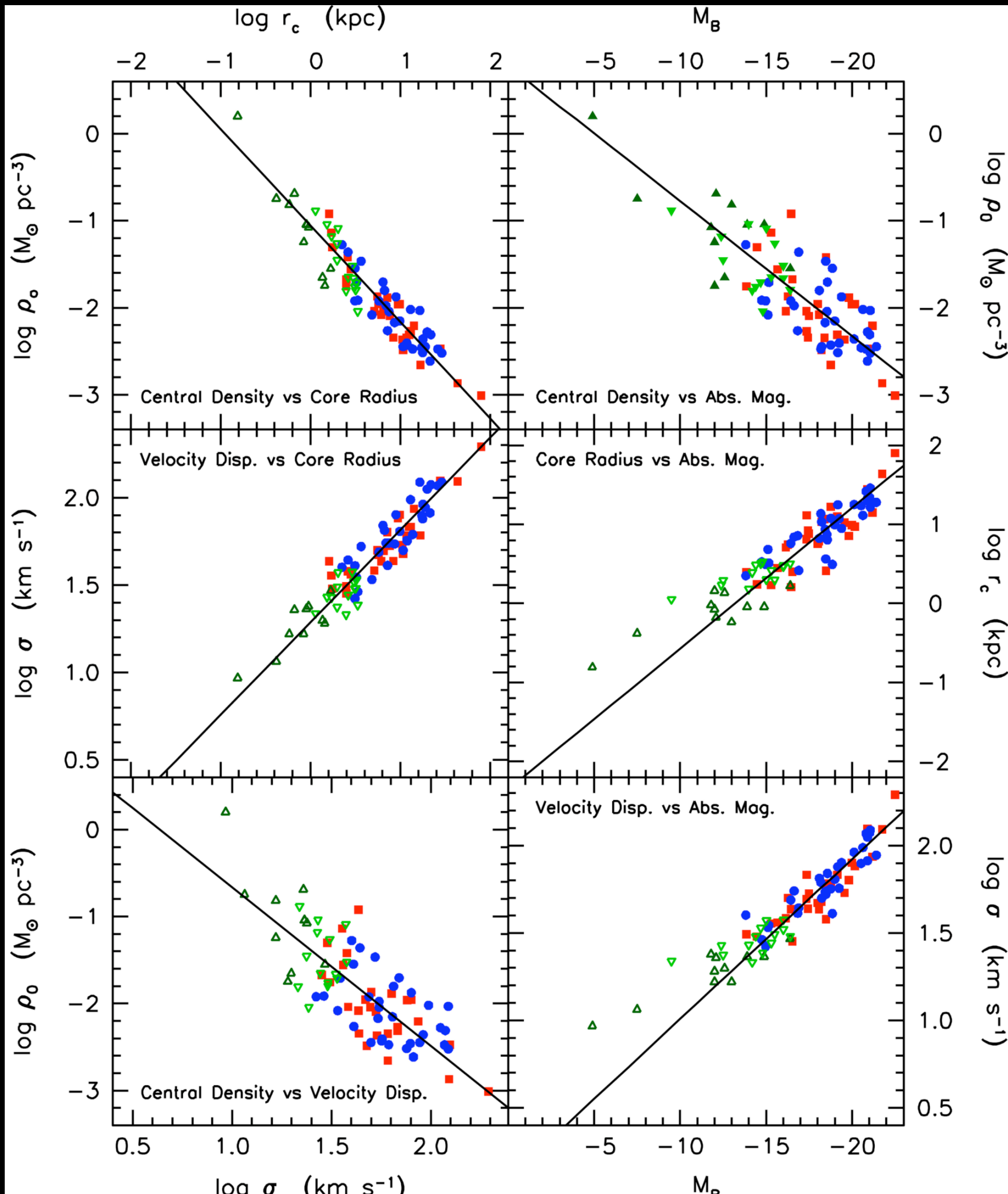


FIG. 2.—Cumulative velocity function of all dark matter subhalos surviving at $z = 0$ (*thin solid line*) and "observable" halos ($z_f > z_{re}$) (*thick solid line with shading*) for the specific choice of $z_{re} = 8$ and $f = 0.3$. The velocity function represents the average over 300 merger histories for halos of mass $M_{vir}(z = 0) = 1.1 \times 10^{12}\ h^{-1}\ M_\odot$. The error bars and shading show the dispersion measured from different merger histories. The observed velocity function of satellites around the Milky Way and M31 is shown by triangles.

Conclusion: Galaxies are "dim" if $V_{circ} \leq 42 \pm 4$ km s^{-1}.



$L_B \downarrow \Rightarrow$ dwarf galaxies become much more numerous and much more dominated by DM.

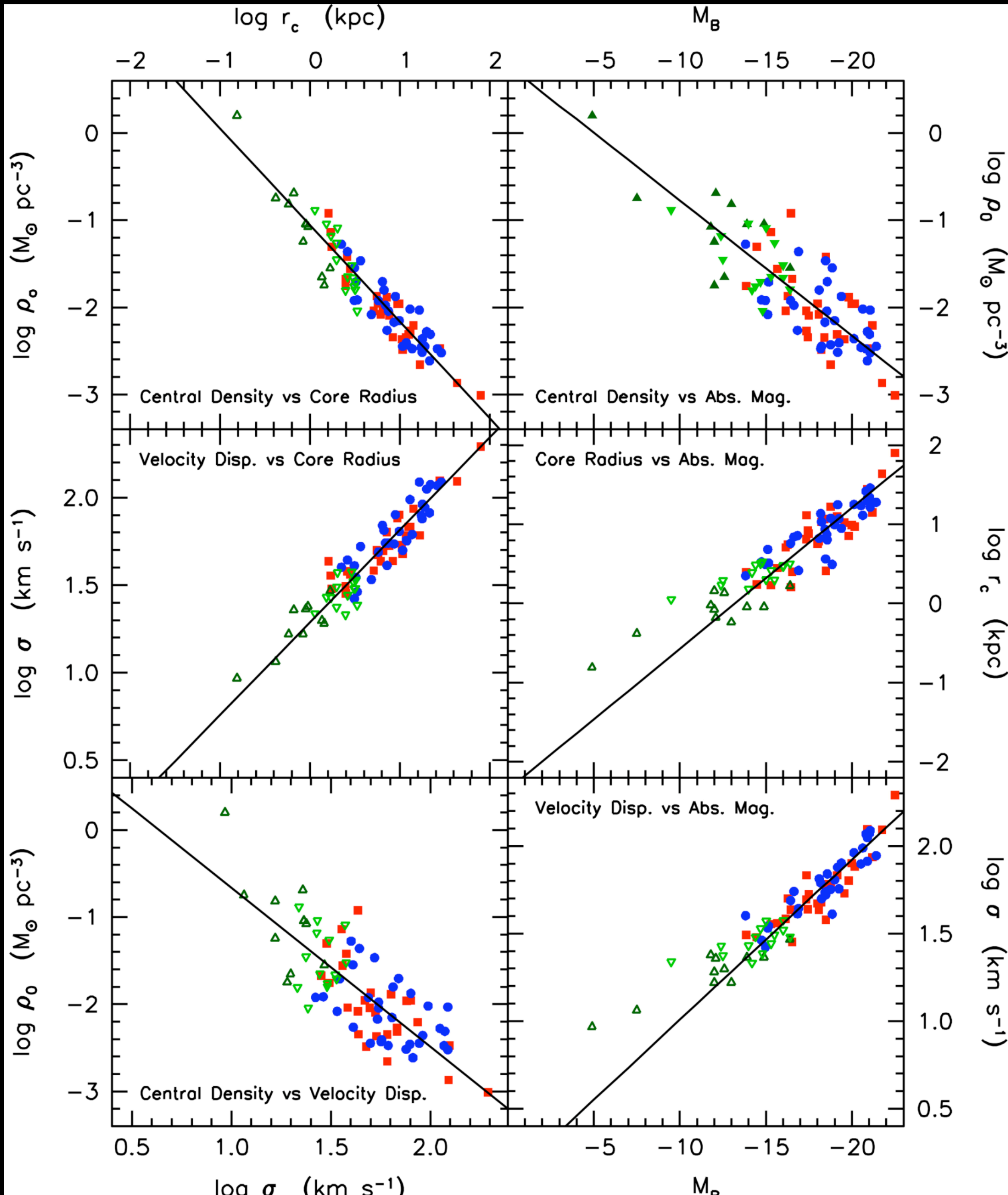
Suggests:

There may exist a large population of objects that are completely dark.

Undiscovered DM dwarfs would solve the problem that the CDM spectrum of initial density fluctuations predicts too many dwarf galaxies (Moore et al. 1999; Klypin et al. 1999).

Empty halos are likely to be small and dense and to have small total masses — like darker versions of Draco and UMi.

Conclusions



If dwarf spheroidal galaxy ρ_0 values are on the extrapolation to low L_B of the correlations for Sc — Im galaxies:

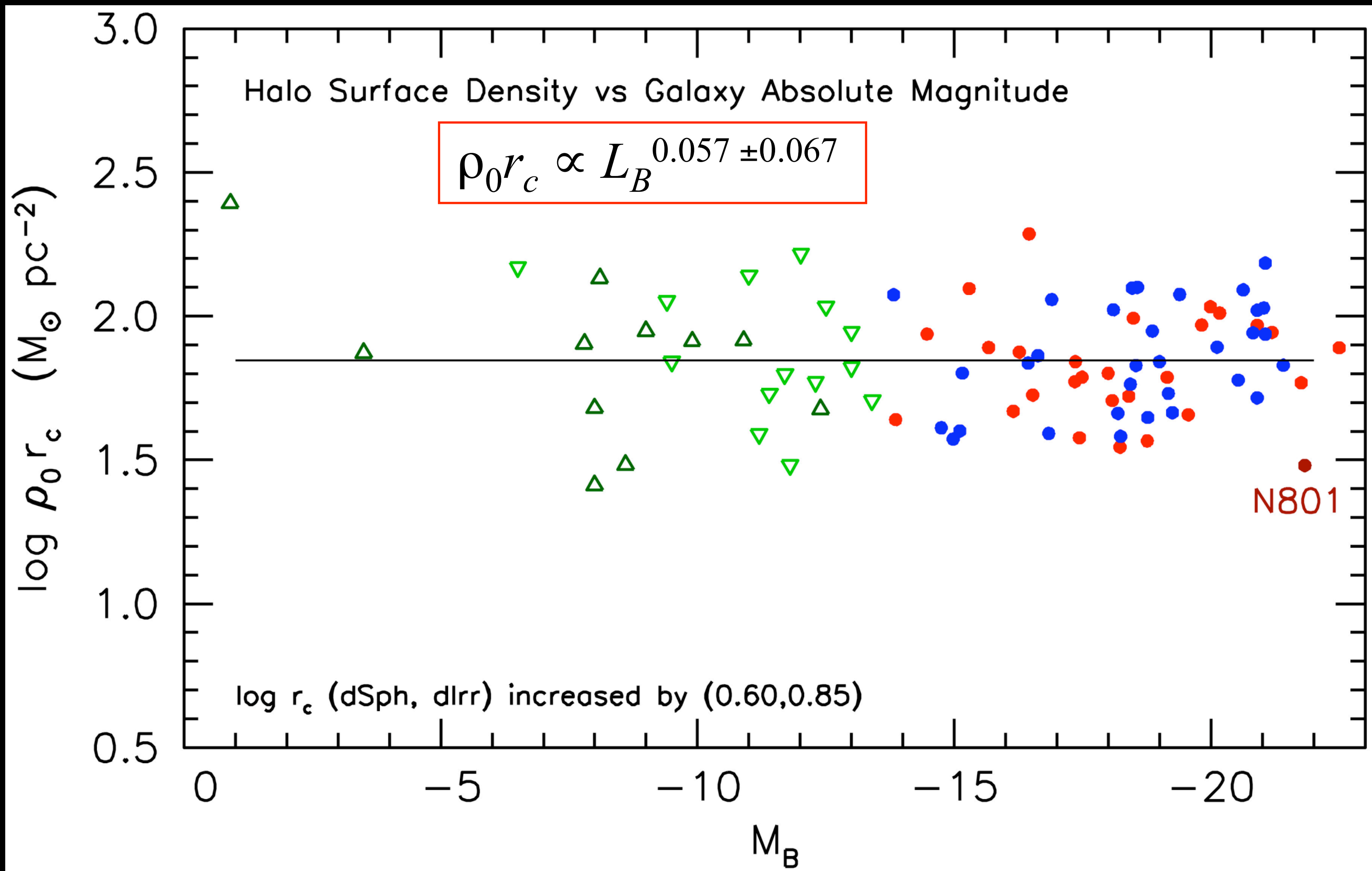
Then DM halos of dSph + Sc — Im galaxies form a continuous physical sequence as a function of DM core mass from $M_B \approx -8$ to $M_B \approx -22$.

The high DM densities in dSphs are normal for galaxies of such low L_B. Thus dSphs are real galaxies made from primordial density fluctuations.

These dSphs are not tidal fragments.

Tides cannot retain even the low DM densities in giant-galaxy progenitors (Barnes & Hernquist 1992).

Tides cannot increase the DM density to the high values characteristic of dwarf spheroidals.



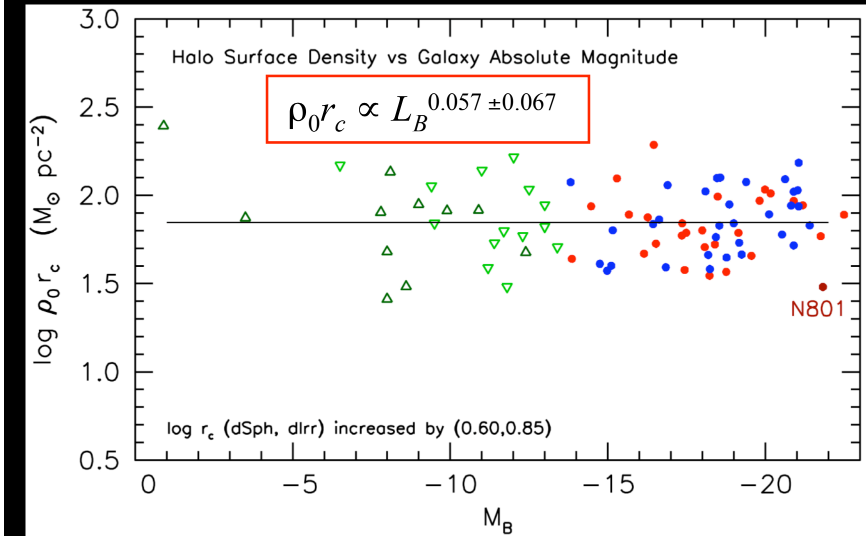
DM surface density = constant ⇒ $M \propto \sigma^2 r_c$ and $M \propto \rho_0 r_c^3$,

or $M \propto r_c^2$, since $\rho_0 r_c \approx$ constant.

So $M^{1/2} \propto r_c$. Therefore,

$M \propto \sigma^2 M^{1/2}$;

$M \propto \sigma^4$.



Donato, Salucci, et al. appear to get constant DM surface density using visible matter (not corrected) r_c.

We think that they must overestimate ρ_0.

Detailed dynamical modeling is clearly desirable.

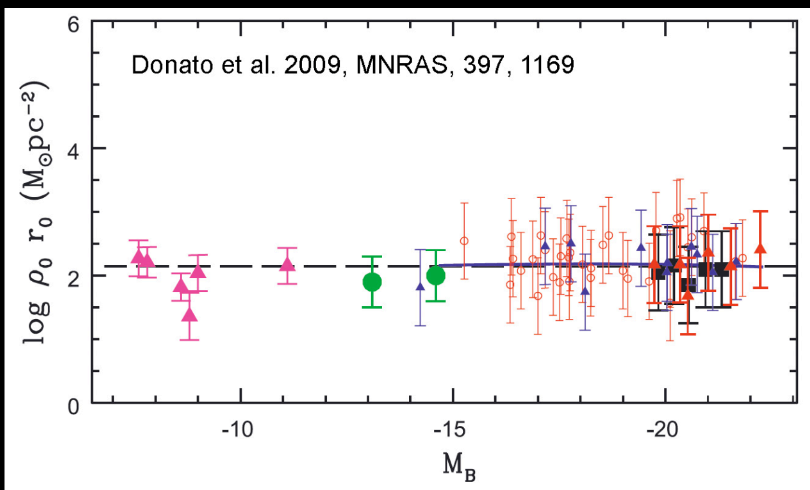


Figure 2. $\rho_0 r_0$ in units of $M_\odot$ pc^{-2} as a function of galaxy magnitude for different galaxies and Hubble types. The original Spano et al. (2008) data (empty small red circles) are shown as a reference of previous work. The new results come from: the URC (solid blue line), the dwarf irregulars (full green circles) N 3741 ($M_B = -13.1$) and DDO 47 ($M_B = -14.6$), spirals and ellipticals investigated by weak lensing (black squares), dSphs (pink triangles), nearby spirals in THINGS (small blue triangles), and early-type spirals (full red triangles). The long-dashed line is the result of this work.

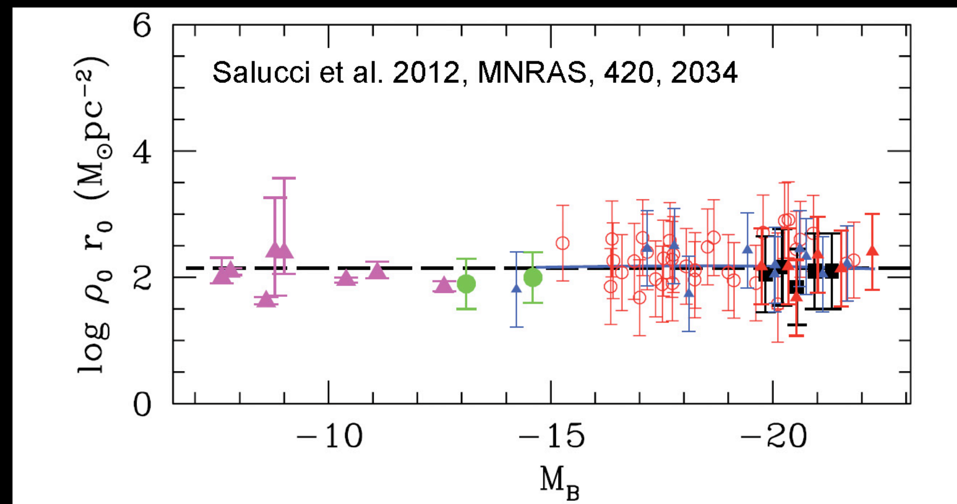
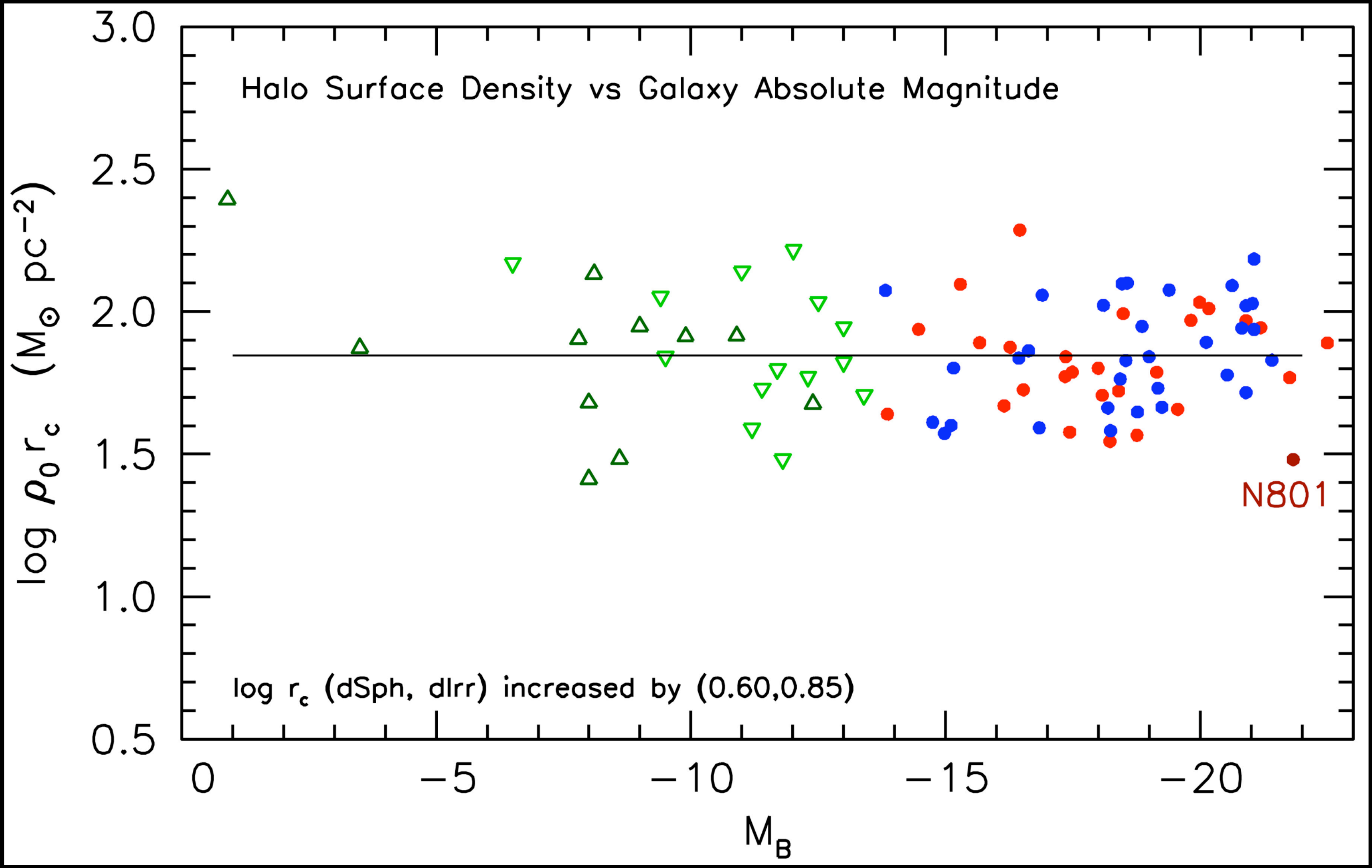


Figure 4. $\rho_0 r_0$ in units of $M_\odot$ pc^2 as a function of galaxy magnitude for different galaxies and Hubble types. The data are: (1) the Spano et al. (2008) sample of spiral galaxy data (open red circles); (2) the URC relation (solid blue line; Shankar et al. 2006); (3) the dwarf irregulars N3741 (M_B = 13.1; Gentile et al. 2007) and DDO 47 (M_B = 14.6; Gentile et al. 2005) (full green circles), spirals and ellipticals (black squares; Hoekstra et al. 2005) investigated by weak lensing; (4) Milky Way dSphs (pink triangles; this paper); (5) nearby spirals in the HI nearby galaxy survey (THINGS) (small blue triangles; Walter et al. 2008); and (6) early-type spirals (full red triangles; Noordermeer 2006; Noordermeer et al. 2007). The long-dashed line shows the Donato et al. (2009) result.



DM surface density = constant $\Rightarrow$ M $\propto \sigma^4$. We find: $L_B \propto \sigma^{4.37}$. So $M/L_B \propto L_B^{-0.37}$.

For ΔM_B = 14, M/L_B changes by a factor of 118. This is an excellent measure of how much Draco and UMi are more DM dominated than giant galaxies.

Conclusions

1 — DM correlations: $L_B \downarrow \Rightarrow \rho_{0,DM} \uparrow$, $r_{c,DM} \downarrow$, $\sigma_{DM} \downarrow$

2 — Single continuous sequence from Sc I ($M_B \approx -22$) to dSph ($M_B \approx -8$)

3 — Baryon loss $\Delta M_B \approx 3.0$ for dIrr galaxies and 4.0 for dSph galaxies.

4 — High dSph $\rho_{0,DM}$ is normal (low L_B) $\Rightarrow$ real galaxies, not tidal fragments.

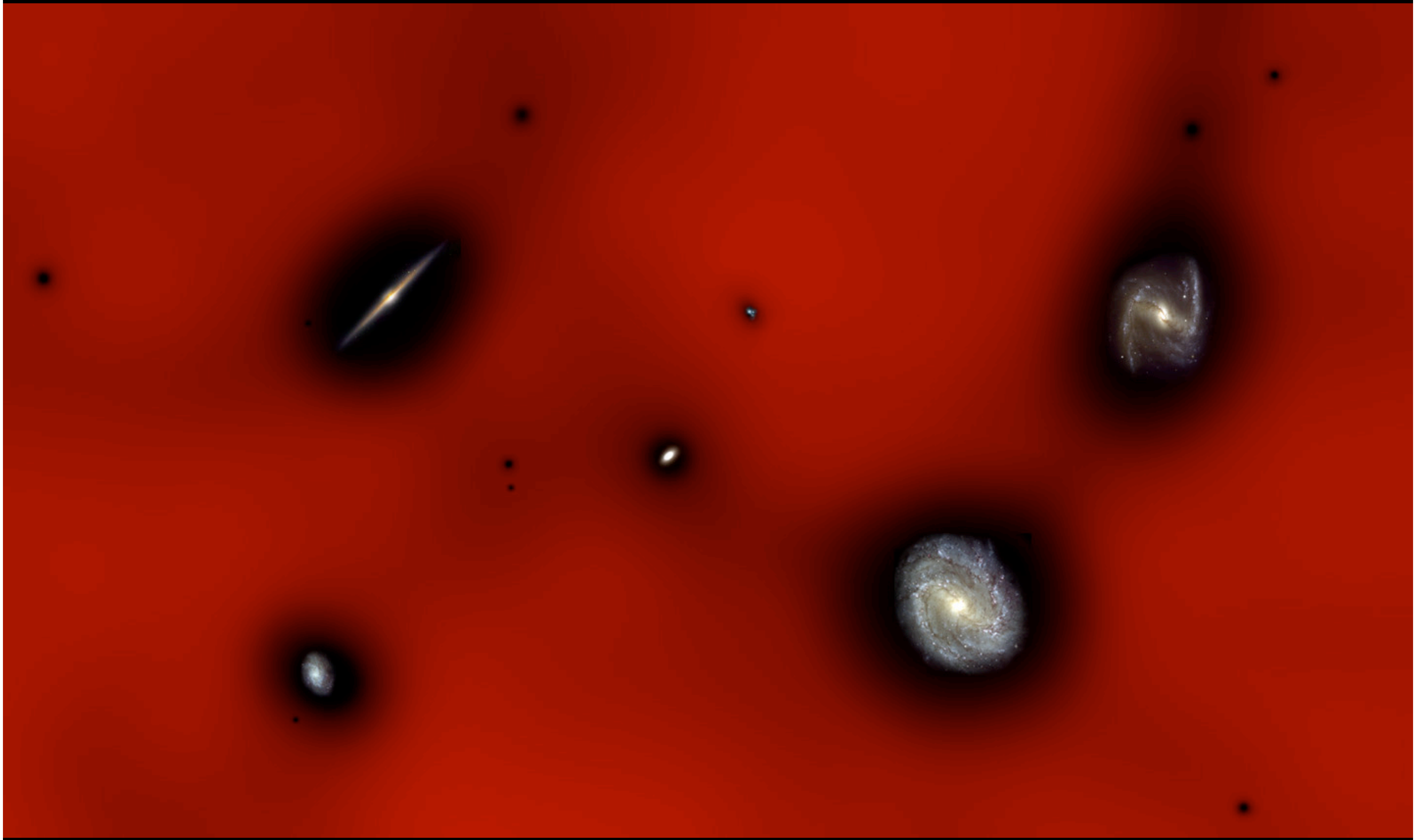
5 — Galaxy baryon content $\rightarrow 0$ at $V_{circ} \lesssim 42 \pm 4$ km s^{-1}; $\sigma_{DM} \approx 30 \pm 3$ km s^{-1}

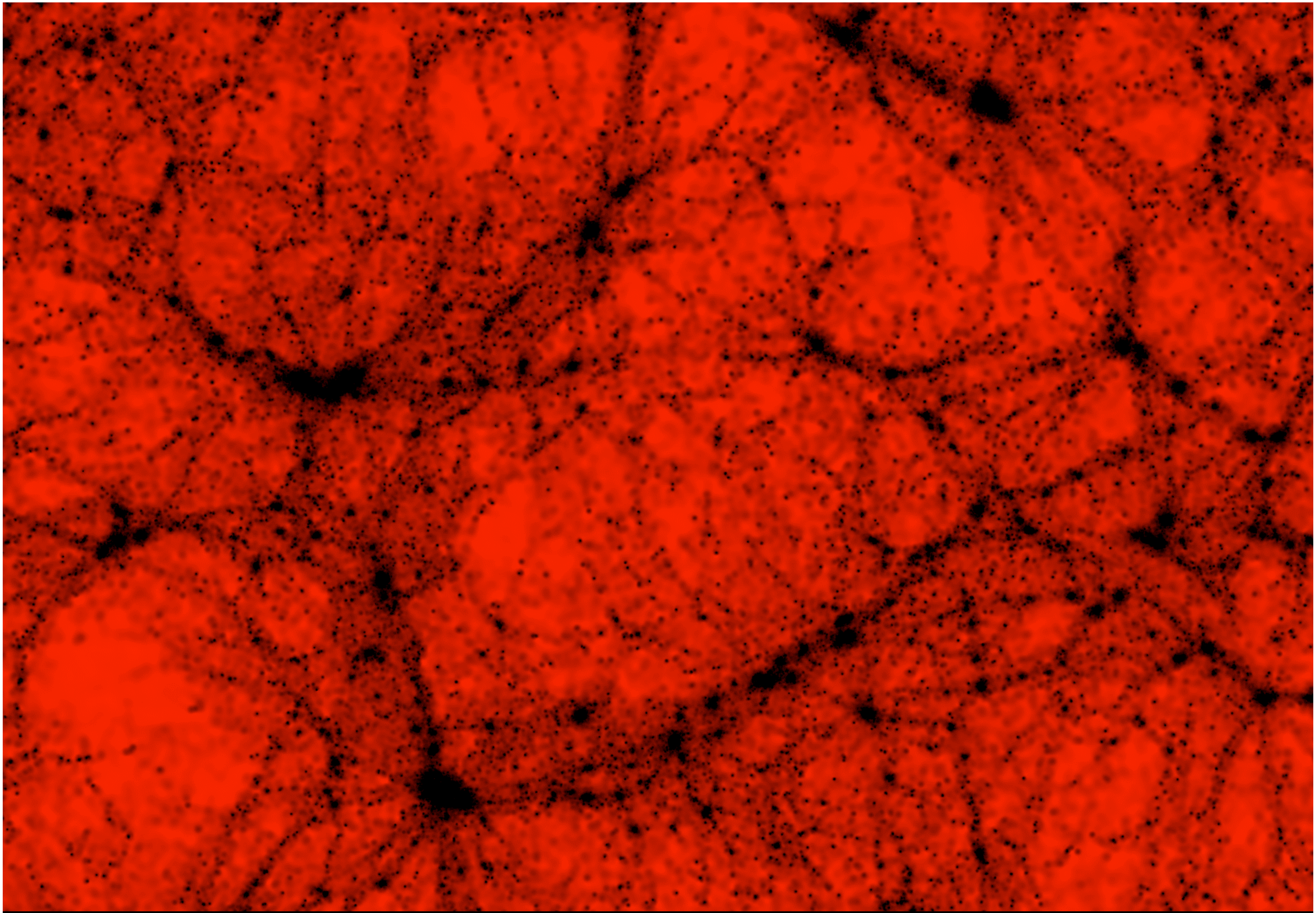
6 — Many dark dwarfs?

7 — Re $|\delta_k|^2 \propto k^n$: Correlation slopes $\Rightarrow n \approx -2.0 \pm 0.1$.

8 — DM surface density $\rho_{0,DM} \propto L_B^{0.057 \pm 0.067}$ is constant with galaxy L_B.

Problems with ΛCDM Galaxy Formation





Virgo consortium ΛCDM 100 Mpc simulation at http://star-www.dur.ac.uk/~moore/pictures/lcdm.jpg or http://www.mpa-garching.mpg.de/Virgo/LCDM.gif

CDM Problem 1 — The Crisis of the Missing Dwarfs

DARK MATTER SUBSTRUCTURE WITHIN GALACTIC HALOS

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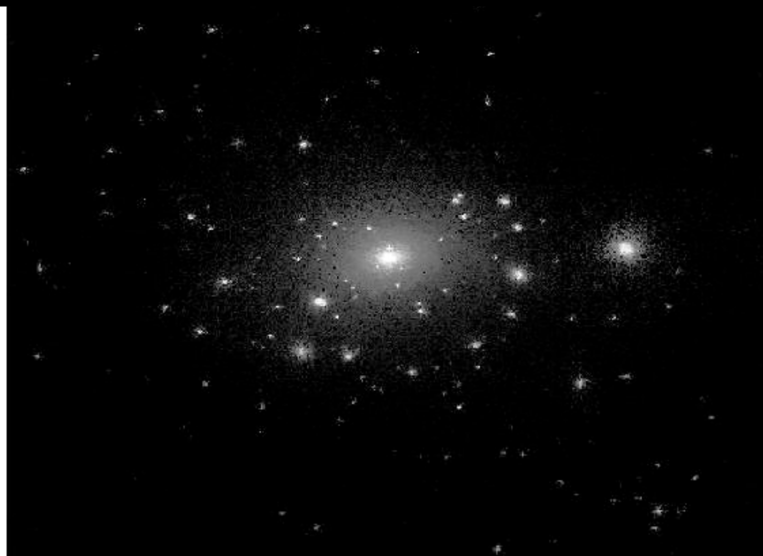
THE ASTROPHYSICAL JOURNAL, 524:L19–L22, 1999 October 10

ABSTRACT

We use numerical simulations to examine the substructure within galactic and cluster mass halos that form within a hierarchical universe. Clusters are easily reproduced with a steep mass spectrum of thousands of substructure clumps that closely matches the observations. However, the survival of dark matter substructure also occurs on galactic scales, leading to the remarkable result that galaxy halos appear as scaled versions of galaxy clusters. The model predicts that the virialized extent of the Milky Way's halo should contain about 500 satellites with circular velocities larger than the Draco and Ursa Minor systems, i.e., bound masses $\gtrsim 10^8\ M_\odot$ and tidally limited sizes $\gtrsim 1$ kpc. The substructure clumps are on orbits that take a large fraction of them through the stellar disk, leading to significant resonant and impulsive heating. Their abundance and singular density profiles have important implications for the existence of old thin disks, cold stellar streams, gravitational lensing, and indirect/direct detection experiments.

Also: Klypin et al. 1999, ApJ, 522, 82

From a DM point of view, clusters of galaxies ...



… should look the same as (scaled up) galaxies.

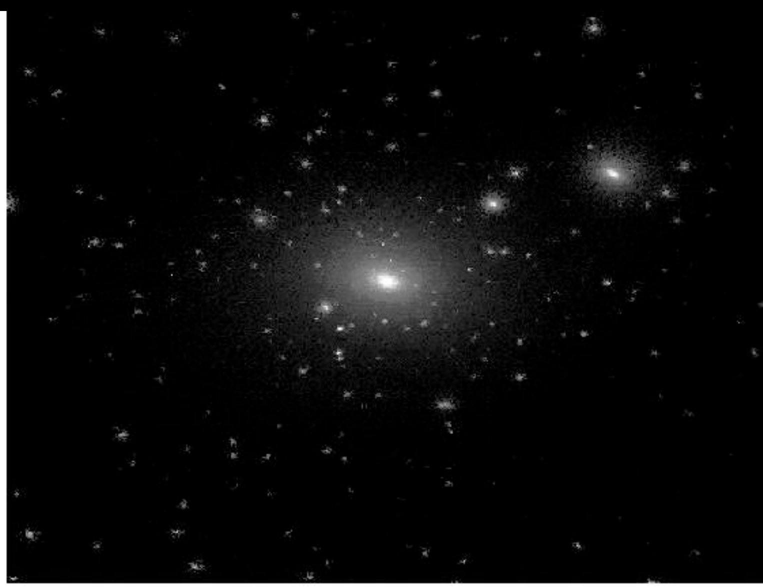


FIG. 1.—Density of dark matter within a cluster halo of mass $5 \times 10^{14}\ M_\odot$ (*top*) and a galaxy halo of mass $2 \times 10^{12}\ M_\odot$ (*bottom*). The edge of the box is the virial radius, 300 kpc for the galaxy and 2000 kpc for the cluster (with peak circular velocities of 200 and 1100 km s^{-1}, respectively).

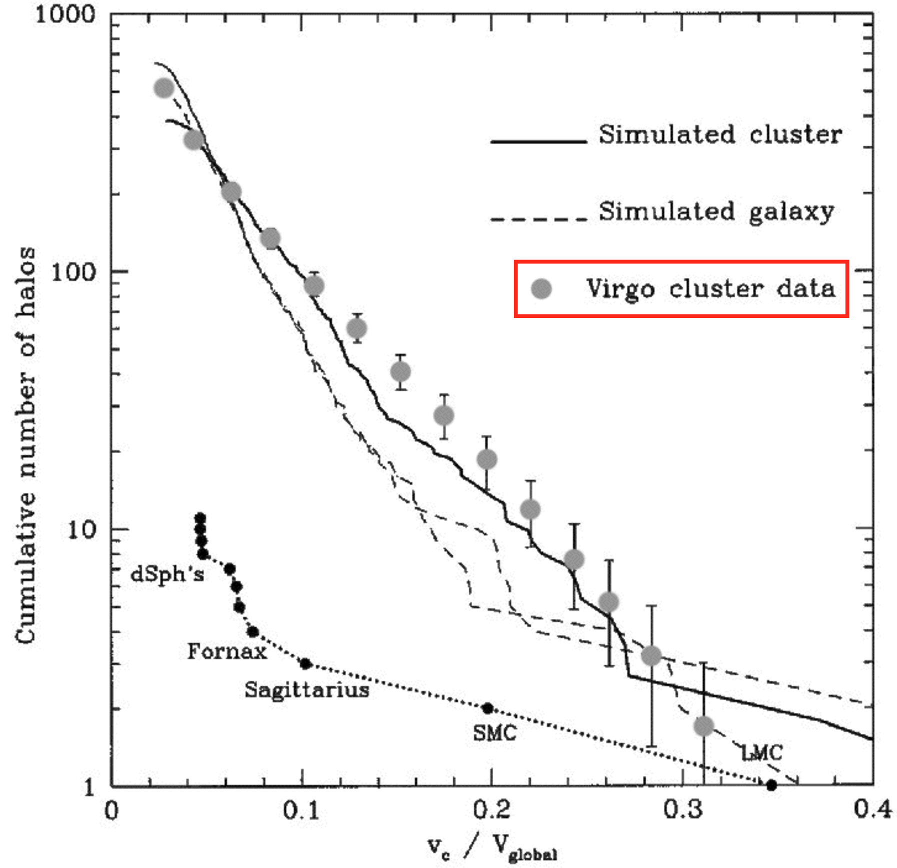


FIG. 2.—Abundance of cosmic substructure within the Milky Way, the Virgo Cluster, and our models of comparable masses. We plot the cumulative numbers of halos as a function of their circular velocity, $v_c = (Gm_b/r_b)^{1/2}$, where m_b is the bound mass within the bound radius r_b of the substructure, normalized to the circular velocity, $V_{\rm global}$, of the parent halo that they inhabit. The dotted curve shows the distribution of the satellites within the Milky Way's halo (Mateo 1998), and the open circles with Poisson errors are data for the Virgo Cluster (Binggeli et al. 1985). We compare these data with our simulated galactic mass halo (*dashed curves*) and cluster halo (*solid curve*).

There is no “missing dwarfs” problem in the Virgo cluster!

WHERE ARE THE MISSING GALACTIC SATELLITES?

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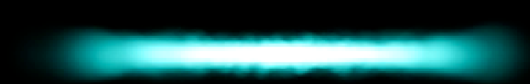
THE ASTROPHYSICAL JOURNAL, 522:82–92, 1999 September 1

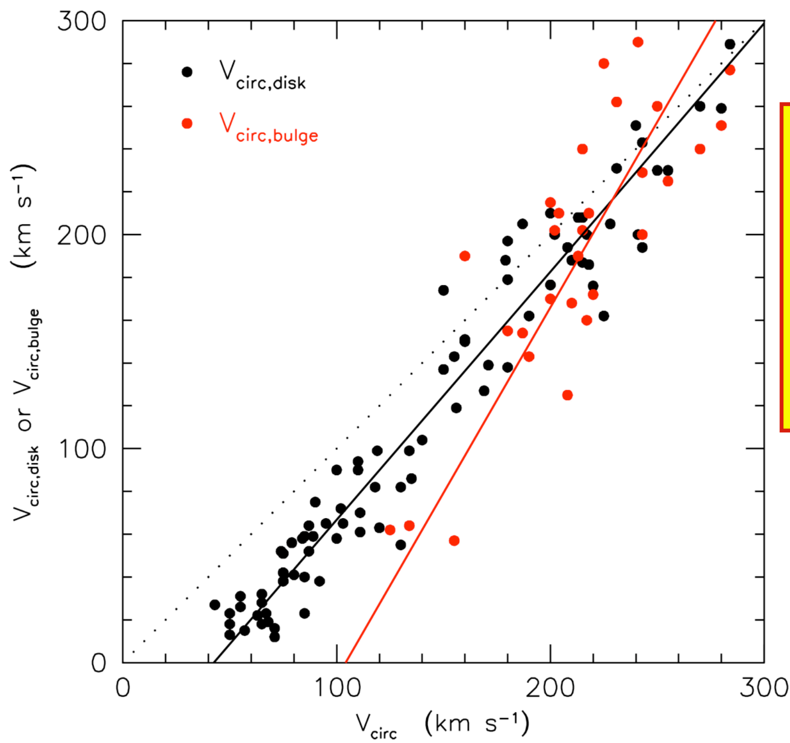
ABSTRACT

We discuss several possible explanations for this discrepancy including identification of some satellites with the high-velocity clouds observed in the Local Group and the existence of dark satellites that failed to accrete gas and form stars either because of the expulsion of gas in the supernovae-driven winds or because of gas heating by the intergalactic ionizing background.



Thanks to Greg Stinson.

Recall the good agreement between our measurement that galaxies are "dim" if $V_{circ} \lesssim 42 \pm 4$ km s^{-1} and theoretical estimates of which DM halos are too puny to accrete baryons after reionization.



Conclusion: Good agreement with Bullock et al. 2000: threshold $V_{circ} \approx 30$ km s^{-1} and with Cattaneo et al. 2011, A&A, 533, A5: threshold $V_{circ} \approx 40$ km s^{-1}.

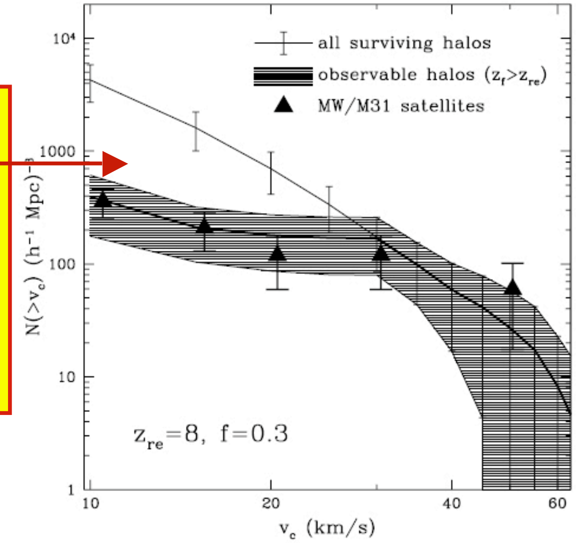


FIG. 2.—Cumulative velocity function of all dark matter subhalos surviving at $z = 0$ (*thin solid line*) and "observable" halos ($z_f > z_{re}$) (*thick solid line with shading*) for the specific choice of $z_{re} = 8$ and $f = 0.3$. The velocity function represents the average over 300 merger histories for halos of mass $M_{vir}(z = 0) = 1.1 \times 10^{12}\, h^{-1}\, M_{\odot}$. The error bars and shading show the dispersion measured from different merger histories. The observed velocity function of satellites around the Milky Way and M31 is shown by triangles.

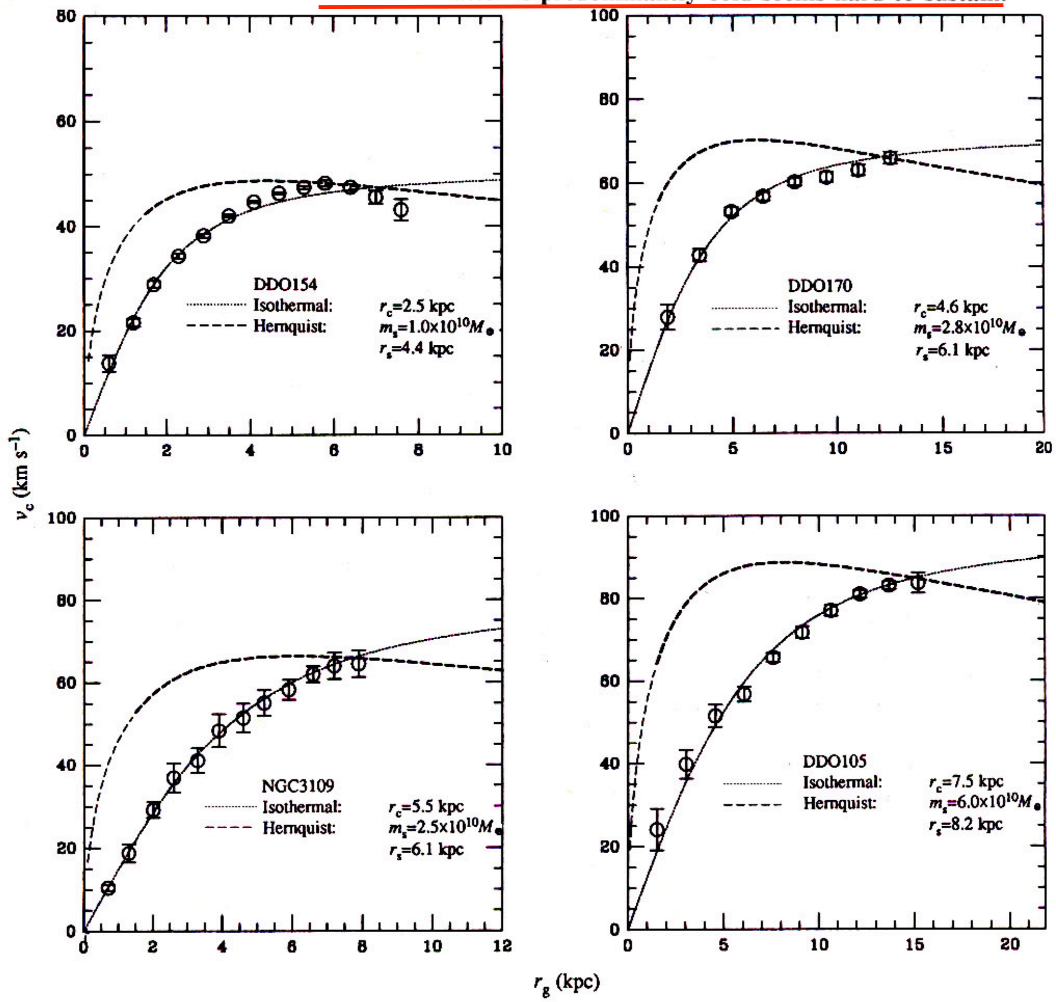
This suggests that ∃ lots of VERY dim galaxies.

Evidence against dissipation-less dark matter from observations of galaxy haloes

Ben Moore NATURE · VOL 370 · 25 AUGUST 1994 **629**

Several models have been proposed to provide the dark matter required within galaxy haloes for a flat universe, of which cold dark matter (CDM) has proved the most successful at reproducing the observed large-scale structure of the Universe[4-6].

Here I show that the modelled small-scale properties of CDM[7-9] are fundamentally incompatible with recent observations[10-13] of dwarf galaxies, which are thought to be completely dominated by dark matter on scales larger than a kiloparsec. Thus, the hypothesis that dark matter is predominantly cold seems hard to sustain.

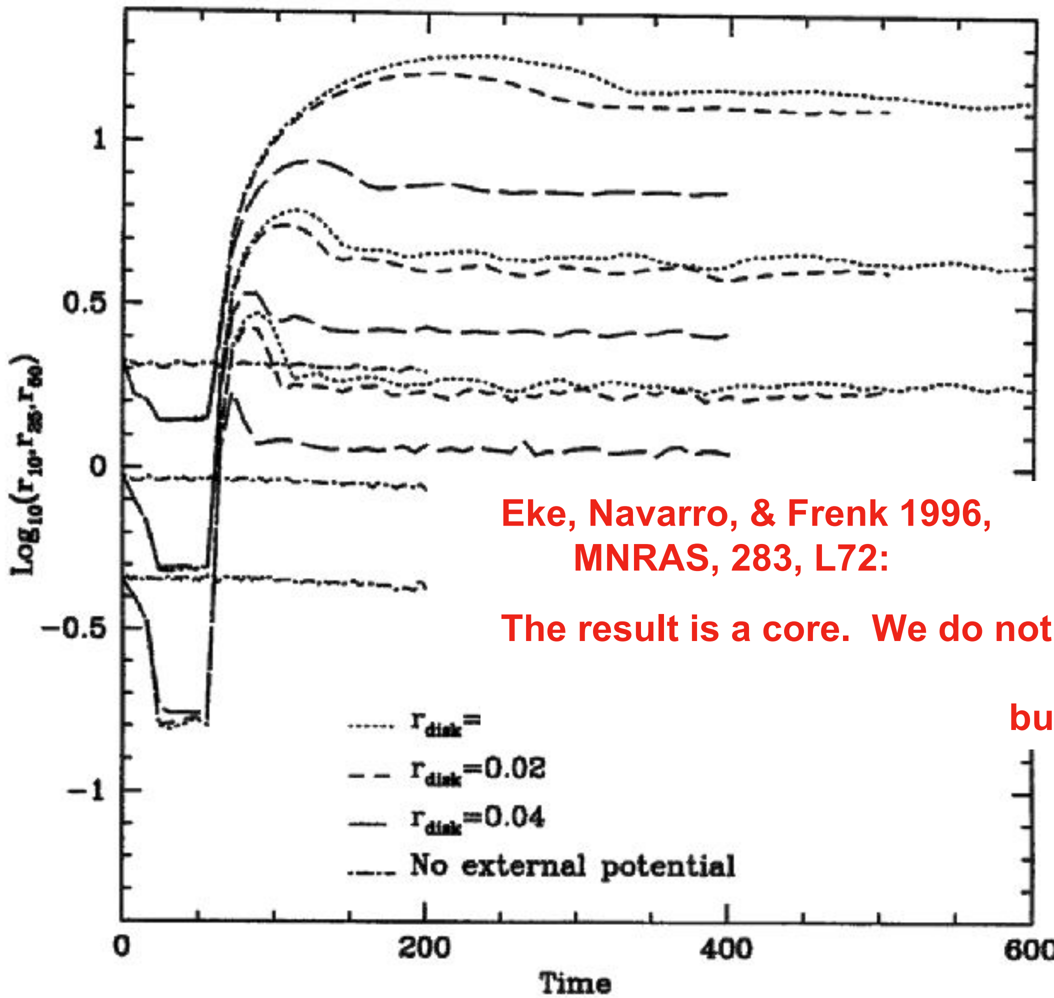


CDM Problem 2:

CDM predicts a cuspy dark matter density distribution and hence the dashed rotation curve. But we observe "cores" – central regions of nearly constant mass density – at least in dwarf galaxies.

Best solution: halo rebounds after gas gets blown away by supernovae, etc.
(Navarro, Eke, & Frenk 1996, MNRAS, 283, L72)

First the halo contracts slowly (“adiabatically”), pulled inward by the dissipating baryons.
Then it expands rapidly, as the baryons are instantaneously removed.
It expands more than it contracted.



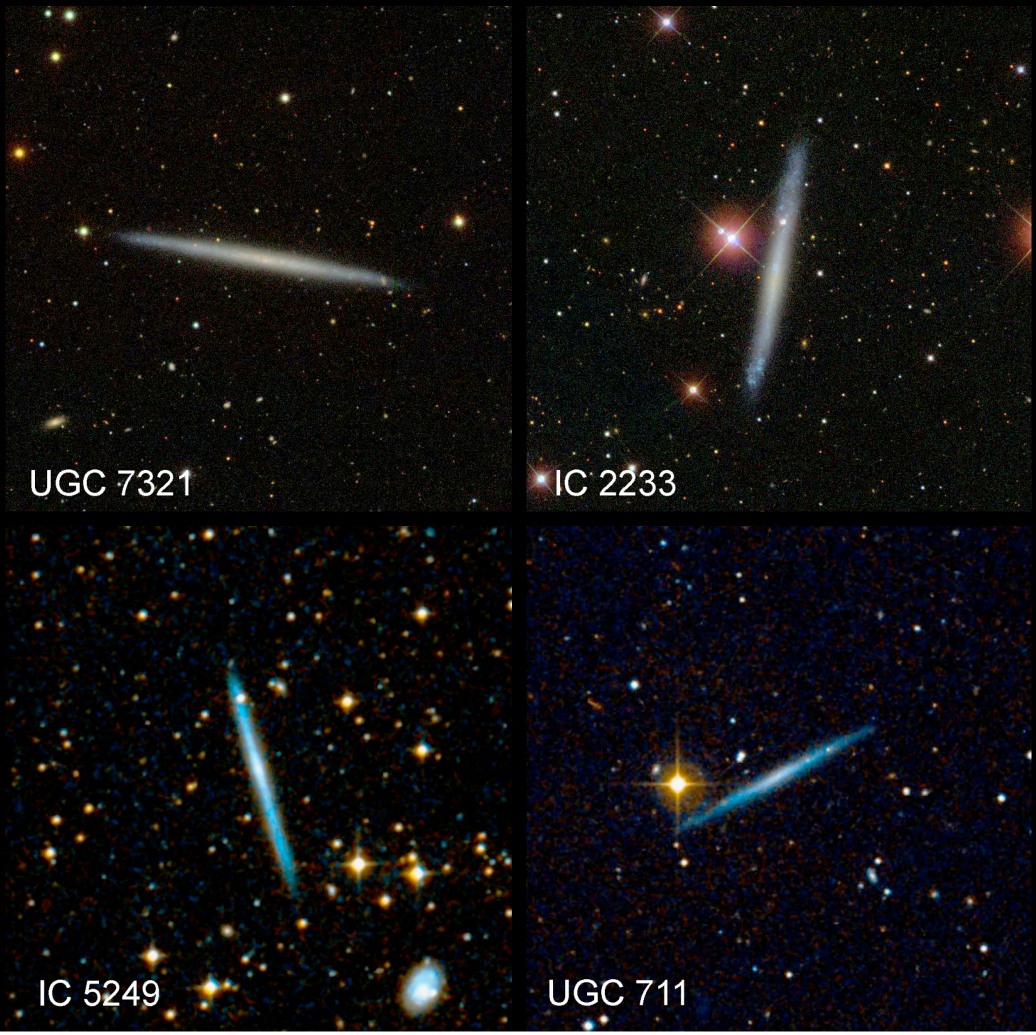
Eke, Navarro, & Frenk 1996, MNRAS, 283, L72:

The result is a core. We do not know that this is the correct explanation, but it is best suggestion.

Figure 1. The evolution of radial mass shells in a Hernquist model run in isolation (dot–dashed lines), or subject to the collapse and removal of an exponential disc potential of mass $M_{disc}=0.2$, and $r_{disc}=0.01$, 0.02 and 0.04 (dotted, short-dashed and long-dashed lines, respectively).

Fundamental Problem for ΛCDM and Hierarchical Clustering:

Why are there so many bulgeless disks?



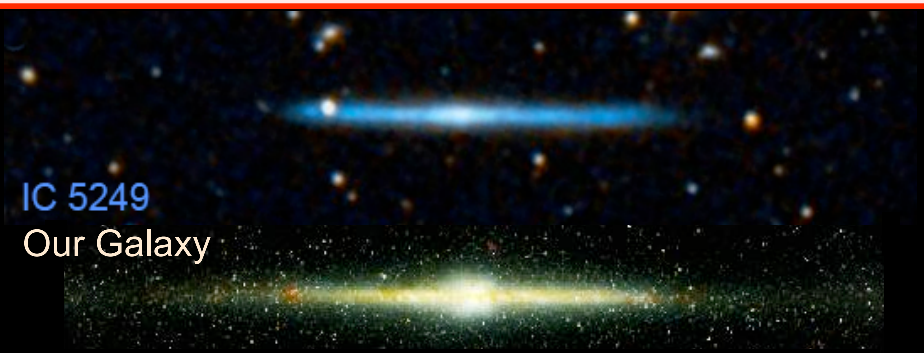
Fundamental Problem for ΛCDM and Hierarchical Clustering:

Why are there so many bulgeless disks?

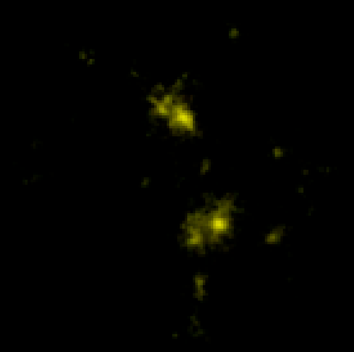
From a hierarchical clustering point of view, our Galaxy is a pure disk (the “boxy bulge” is an almost-end-on bar).

Why are there so many pure disk galaxies ?

How do you make these:

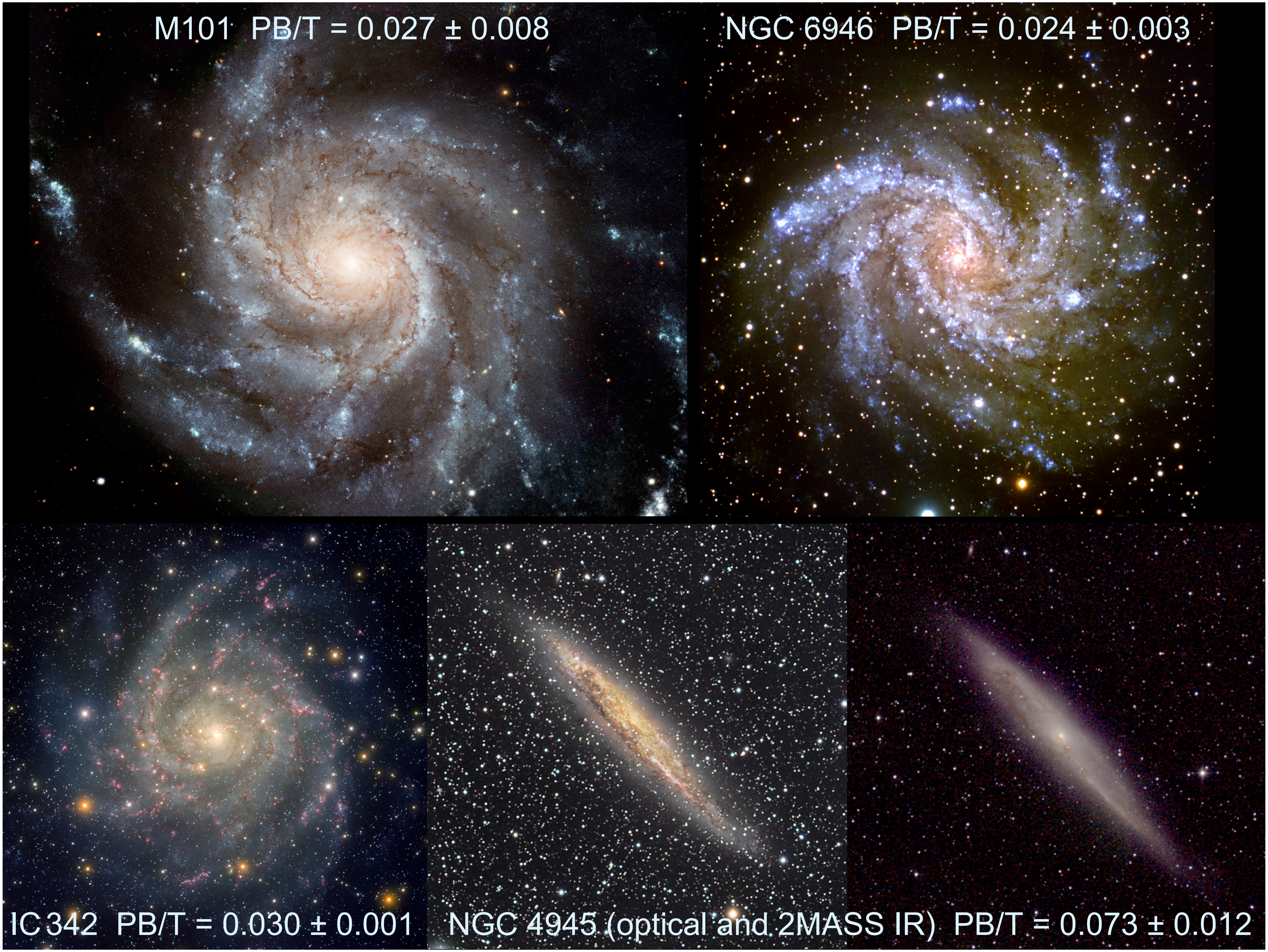


… when halos grow like this?



Biggest problem with galaxy formation by hierarchical clustering of CDM:
How do you make bulgeless, pure-disk galaxies
(Kormendy et al. 2012, ApJ, 723, 54)?

Secular formation of pseudobulges ⇒ fewer merger-built bulges
⇒ more pure-disk galaxies.


M101 PB/T = 0.027 ± 0.008
NGC 6946 PB/T = 0.024 ± 0.003
IC 342 PB/T = 0.030 ± 0.001
NGC 4945 (optical and 2MASS IR) PB/T = 0.073 ± 0.012

Statistics

(Kormendy et al. 2010, ApJ, 723, 54)

BULGE, PSEUDOBULGE, AND DISK INVENTORIES IN GIANT GALAXIES AT $D \leq 8$ MPC

Galaxy (1)	Type (2)	D (Mpc) (3)	M_K (4)	M_V (5)	V_{circ} (km s^{-1}) (6)	B/T (7)	PB/T (8)
NGC 6946	Scd	5.9	−23.61	−21.38	210 ± 10	0	0.024 ± 0.003
NGC 5457	Scd	7.0	−23.72	−21.60	210 ± 15	0	0.027 ± 0.008
IC 342	Scd	3.28	−23.23	−21.4 :	192 ± 3	0	0.030 ± 0.001
NGC 4945	SBcd	3.36	−23.21	−20.55	174 ± 10	0	0.036 ± 0.009
NGC 5236	SABc	4.54	−23.69	−21.0	180 ± 15	0:	0.074 ± 0.016
NGC 5194	Sbc	7.66	−23.94	−21.54	240 ± 20	0:	0.095 ± 0.015
NGC 253	SBc	3.62	−24.03	−20.78	210 ± 5	0:	0.15
Maffei 2	SBbc	3.34	−23.0 :	−20.8 :	168 ± 20	0:	0.16 ± 0.04
Galaxy	SBbc	0.008	−23.7	−20.8 :	220 ± 20	0:	0.19 ± 0.02
Circinus	SABb:	2.8	−22.8	−19.8	155 ± 5	0:	0.30 ± 0.03
NGC 4736	Sab	4.93	−23.36	−20.66	181 ± 10	0:	0.36 ± 0.01
NGC 2683	SABb	7.73	−23.12	−19.80	152 ± 5	0.05 ± 0.01	0:
NGC 4826	Sab	6.38	−23.71	−20.72	155 ± 5	0.10	0.10
NGC 2787	SB0/a	7.48	−22.16	−19.19	220 ± 10	0.11	0.28 ± 0.02
NGC 4258	SABbc	7.27	−23.85	−20.95	208 ± 6	0.12 ± 0.02	0:
M 31	Sb	0.77	−23.48	−21.20	250 ± 20	0.32 ± 0.02	0
M 81	Sab	3.63	−24.00	−21.13	240 ± 10	0.34 ± 0.02	0
Maffei 1	E	2.85	−23.1 :	−20.6 :	(264 ± 10)	1	0
NGC 5128	E	3.62	−23.90	−21.34	(192 ± 2)	1	0:

Statistics

(Kormendy et al. 2010, ApJ, 723, 54)

Distance ≤ 8 Mpc; V_{circ} ≥ 150 km s^{-1}

⇒ 19 galaxies: 11 show no sign of bulge (including M101, NGC 6946, IC 342);
2 may contain bulge + pseudobulge (NGC 2787, NGC 4826);
4 contain classical bulges (M31, M81, NGC 2683 NGC 4258);
2 are ellipticals (Maffei 1, NGC 5128).

⇒ 58 % of nearby local field galaxies show no sign of a major merger.

But: In the Virgo Cluster, > 2/3 of the stellar mass is in Es + classical bulges.

⇒ Problem of pure disk galaxies is a strong function of environment.

Observational Hints:

The problem of giant, pure-disk galaxies
and
the problem of the “missing” dwarf halos
are both strong functions of environment:

They are problems only in the field.

Their solutions presumably must
involve the environment.
Candidate “solutions” such as feedback
that depend mostly on galaxy mass
are “barking up the wrong tree”.

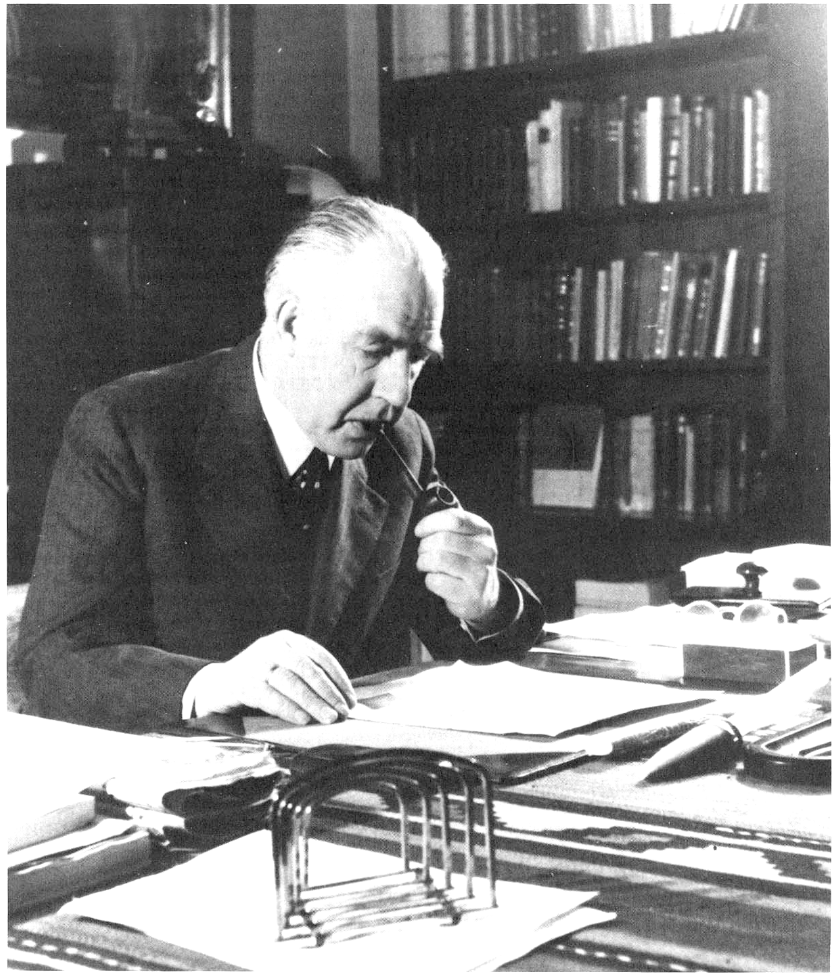
A caution re: WDM

When CDM people "resort to" messy baryonic physics to "solve" their problems, it may seem as though they are "grasping at straws" to save the theory.

But consider:
This may be a strength of CDM theory.

Baryonic physics is unavoidable.

If you "solve" all problems of galaxy formation using a new DM particle candidate and without resort to baryonic physics, then:
<u>New problems may occur when you eventually add baryonic physics to the mix.</u>



Niels Bohr in his study at the Carlsberg House of Honor.

Tomorrow is going to be wonderful,
because tonight I do not understand anything.

Niels Bohr