Baryons Matter:
Interpreting our Cosmological Model

Hot gas explodes out of young dwarf galaxies

Simulation by **Andrew Pontzen**, **Fabio Governato** and **Alyson Brooks** on the **Darwin Supercomputer**, Cambridge UK.

Simulation code **Gasoline** by **James Wadsley** and **Tom Quinn** with metal cooling by **Sijing Sheng**.

Visualization by **Andrew Pontzen**.

Alyson Brooks

Grainger Postdoctoral Fellow, U Wisconsin - Madison

(Rutgers U, as of Sept 2013)

In collaboration with the University of Washington’s N-body Shop™

makers of quality galaxies

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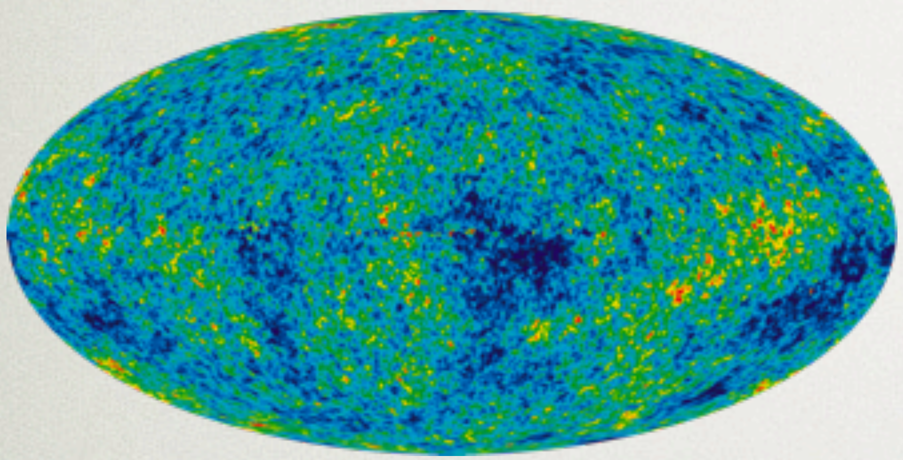
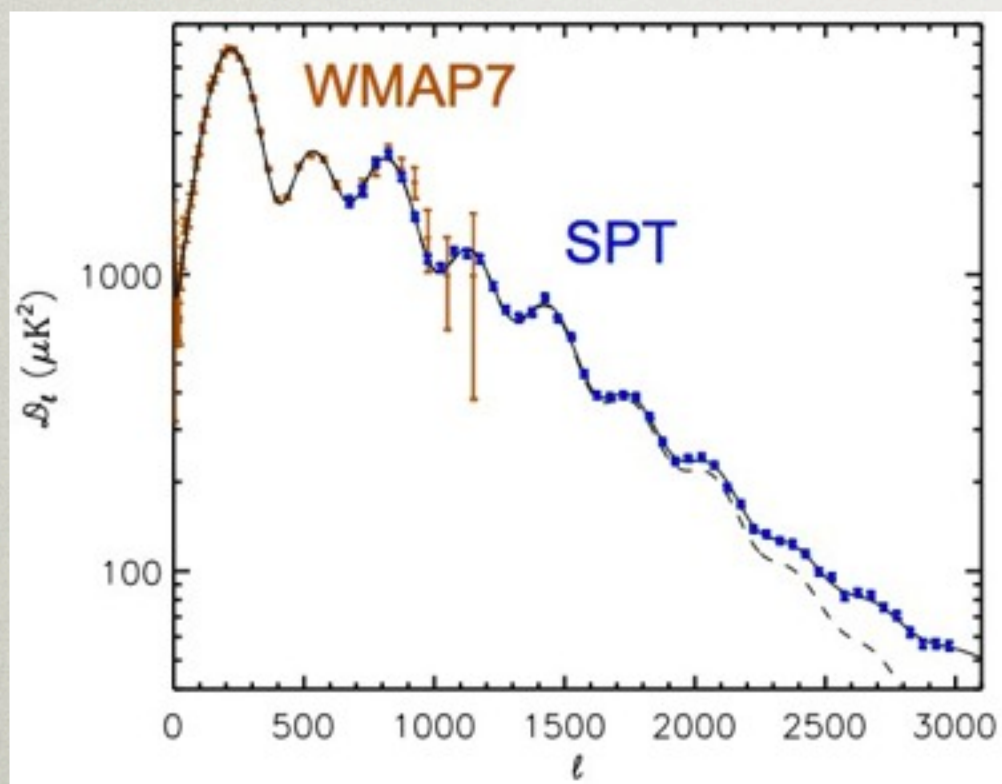
Dark Matter is the Dominant Form of Matter





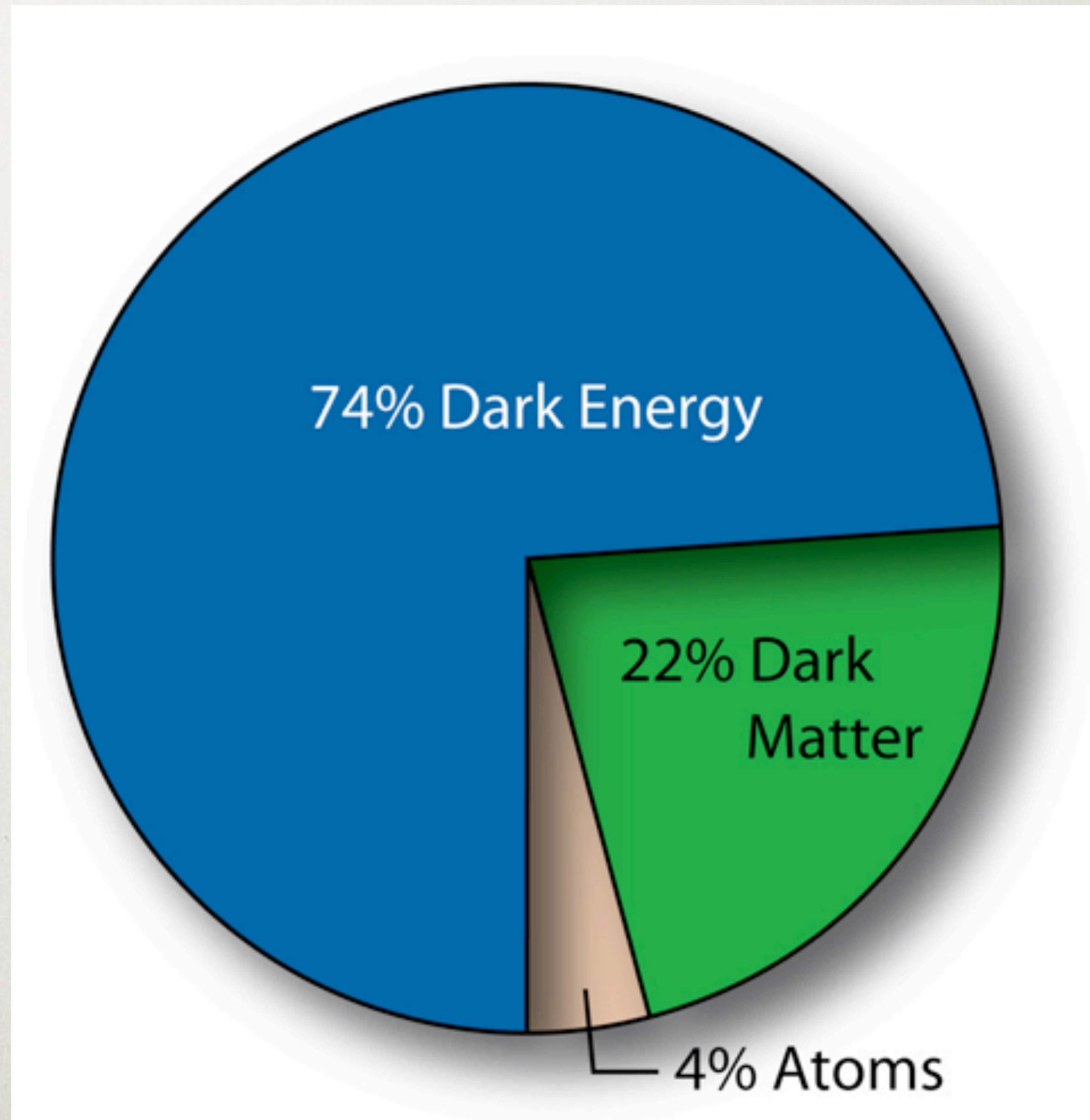


image courtesy of WMAP webpage

But...
The Small Scale "Crisis" of CDM

- The cusp/core problem
- Bulge-less disk galaxies
- The "Missing Satellites" problem
- The dense satellites problem

So...
CDM is Wrong?

So...
CDM is Wrong?

Maybe it needs to be modified?

Maybe some small amount of WDM is still allowed that washes out the small scales?

Maybe DM self-interacts and washes out the small scales?

So...
CDM is Wrong?

So... CDM is Wrong?

But what about the 4%?

The small scales where there are problems
are also the places dominated by baryons!

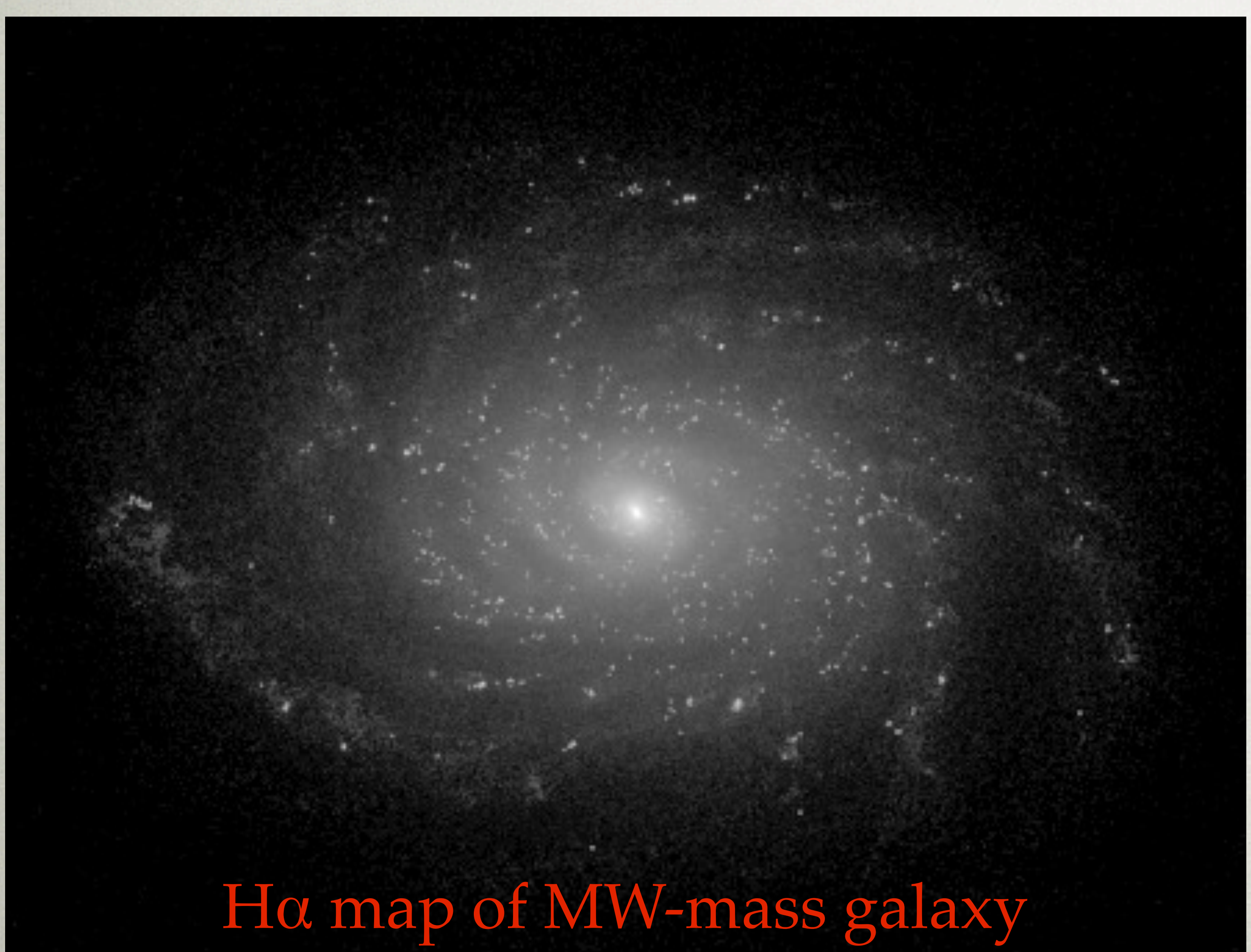
All of the predictions that lead to the small scale crises
are based on Dark Matter-only simulations.

The Formation of a Vc ~ 150 km/s Galaxy to z=0

~100 kpc across
Grey = gas density
Blue/Red = age/metallicity weighted stars

Gasoline

Simulations are Comparable to Eris...



Hα map of MW-mass galaxy

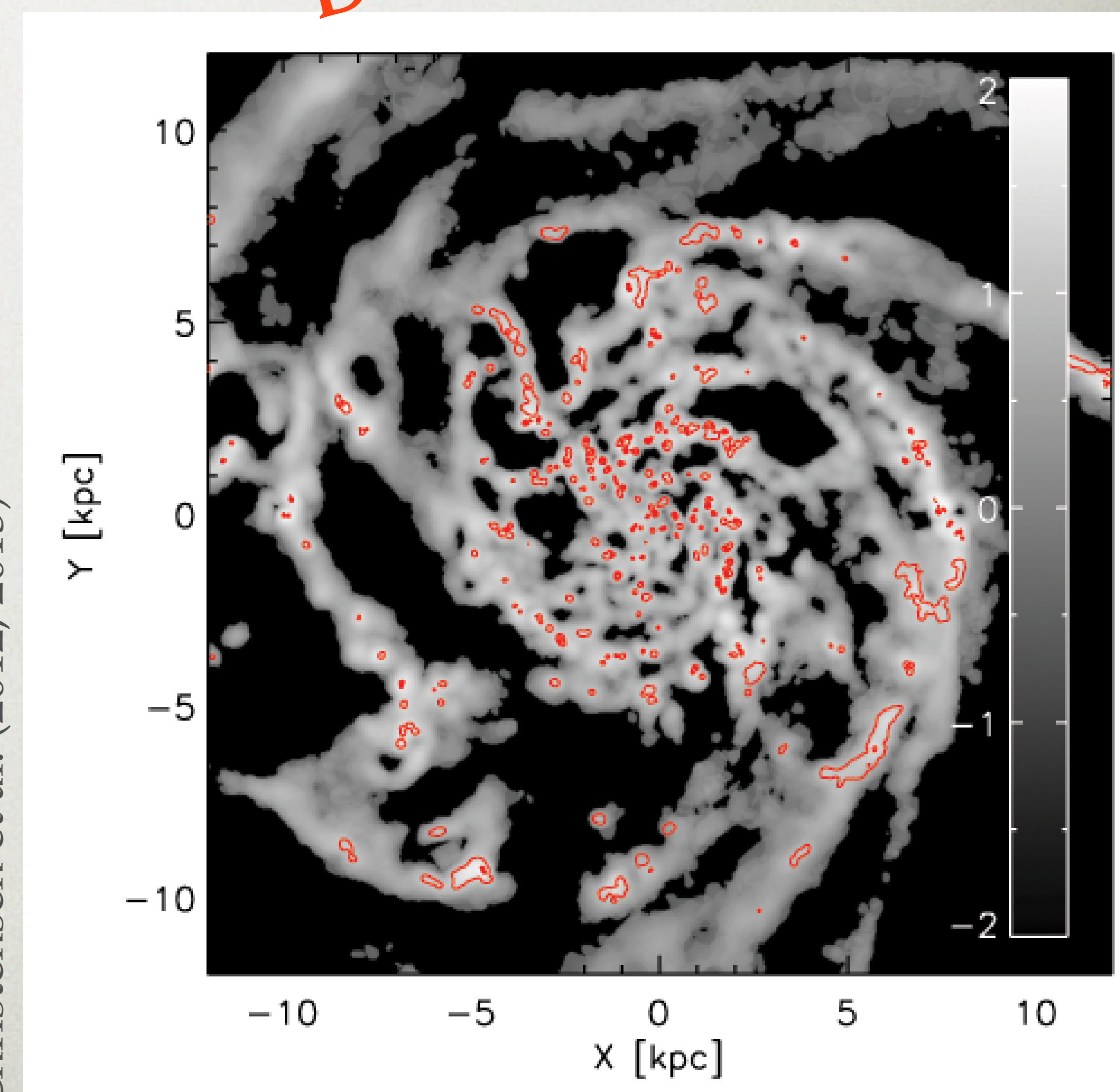
Gasoline

Simulations are Comparable to Eris...

But Better!

Hα map of MW-mass galaxy

Christensen et al. (2012, 2013)



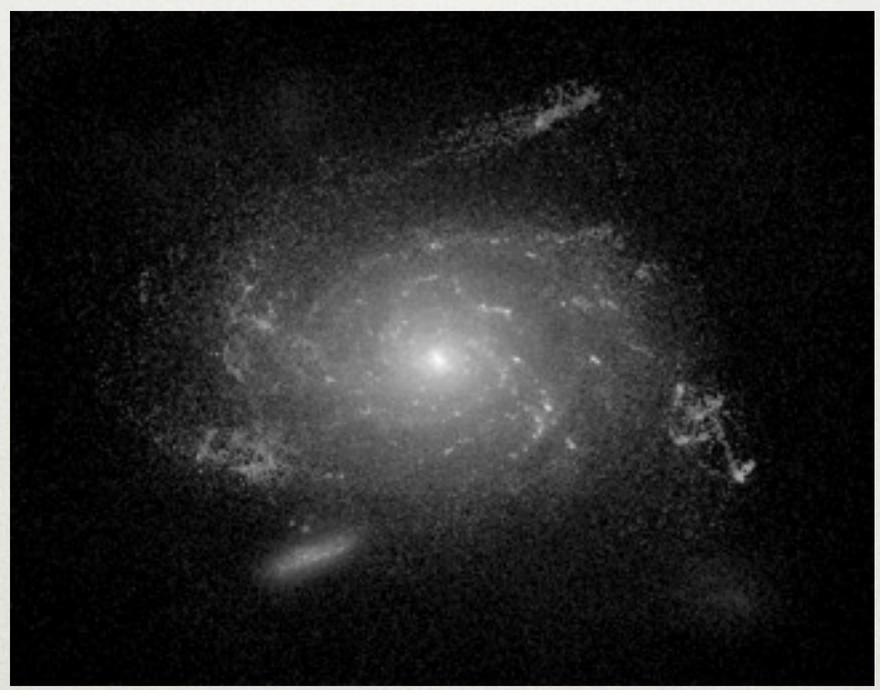
metal line cooling + H2 formation

Gasoline

Simulations are Comparable to Eris... But Better!

$\sim 10^{12}\,M_\odot$

x5



$\sim 10^{11}\,M_\odot$

x4

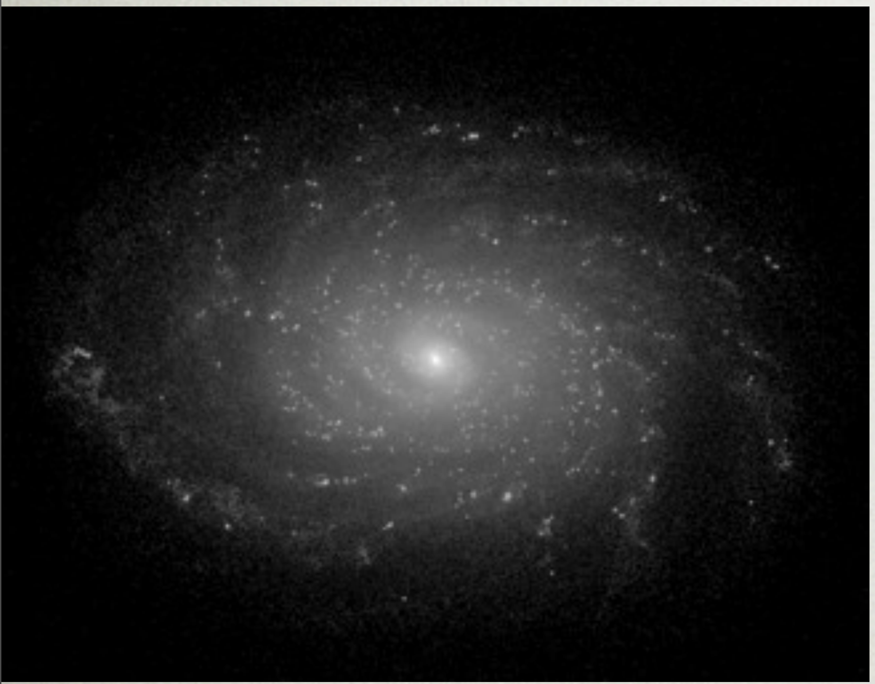
$< 10^{10}\,M_\odot$

> 10

Gasoline

Simulations are Comparable to Eris...

But Better!



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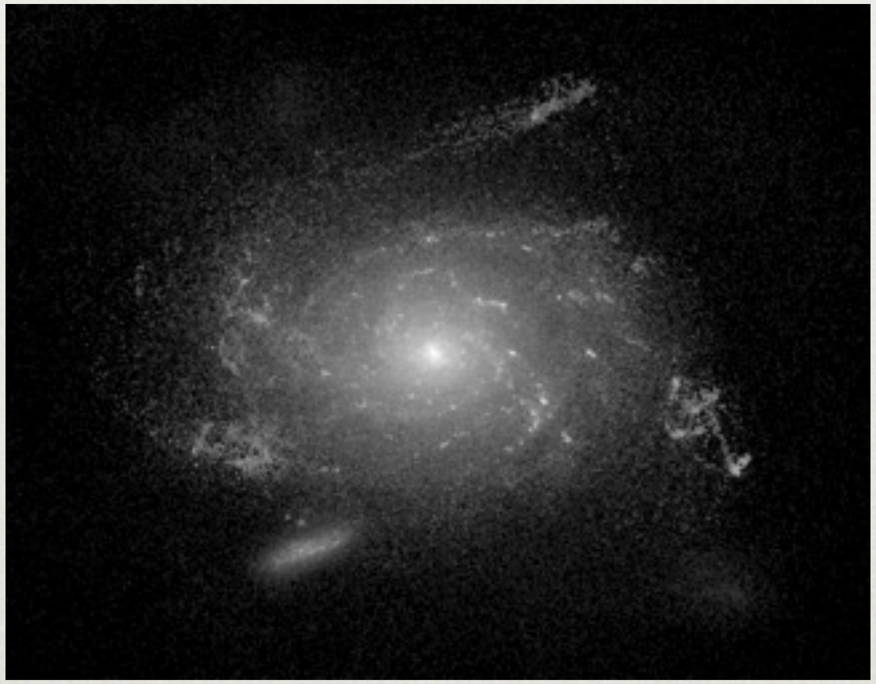

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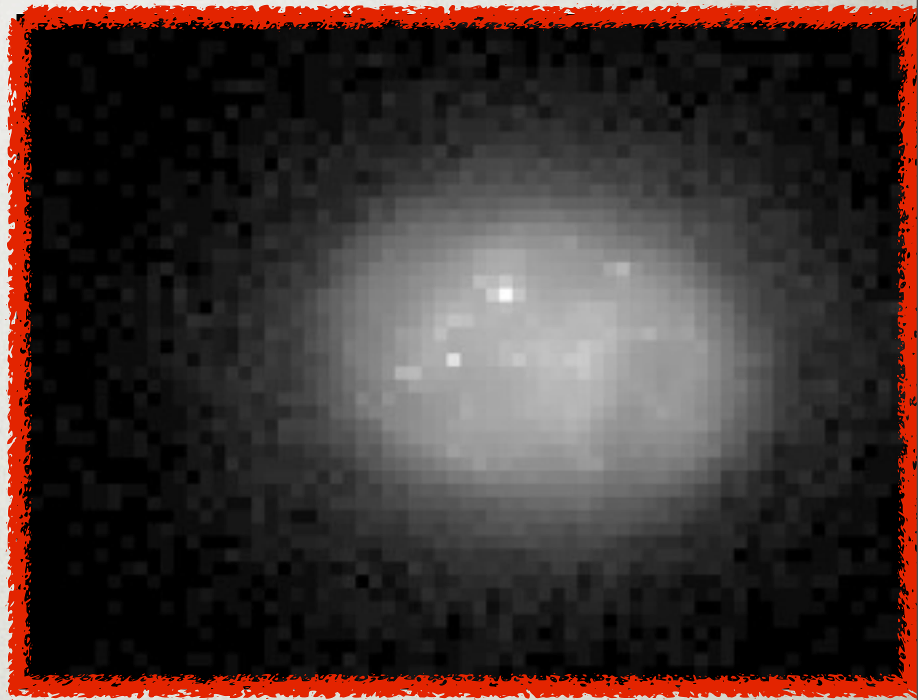

$< 10^{10}\ M_\odot$

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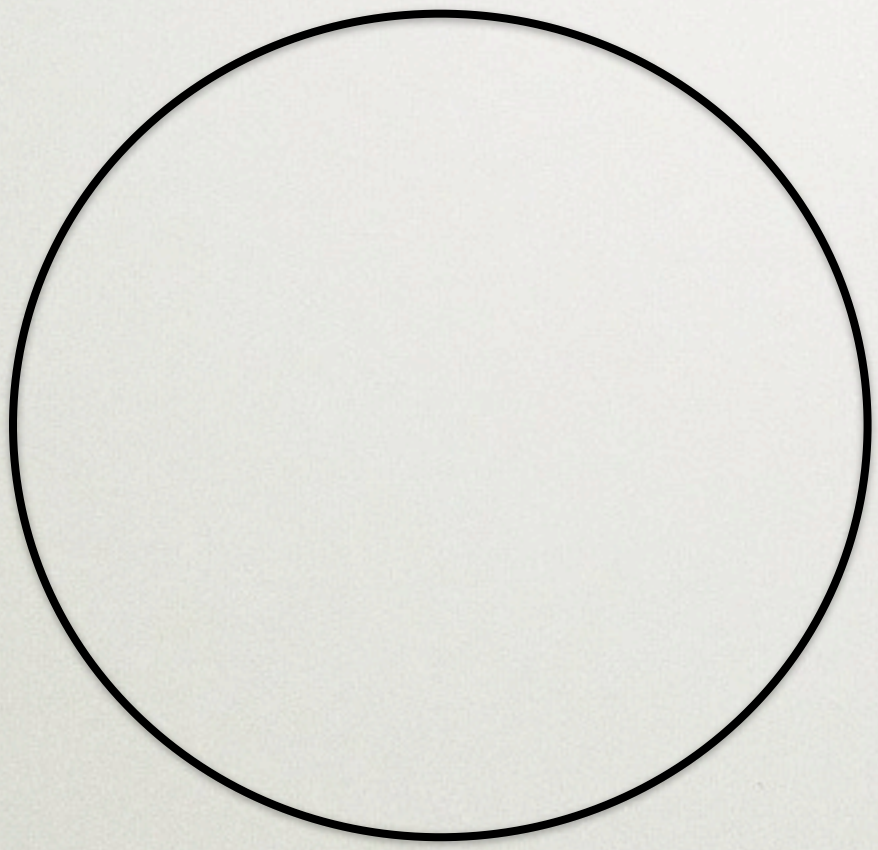
Outflows!



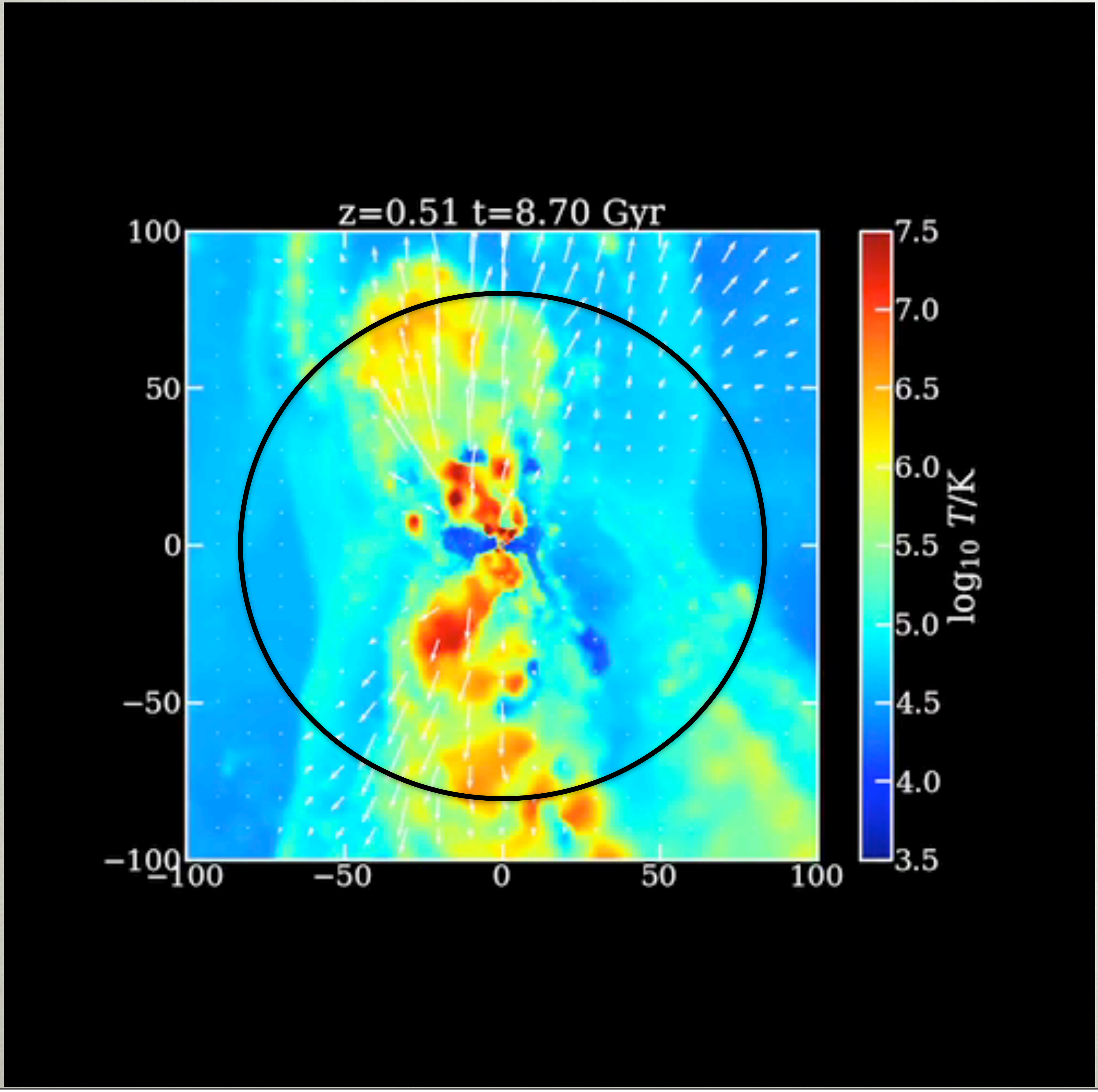
M_{vir} ~ 10^{10} M_{sun}
“dwarf galaxy”

Edge-on disk orientation

(arrows are velocity vectors)

Brook et al., 2011, MNRAS, 415, 1051

Outflows!



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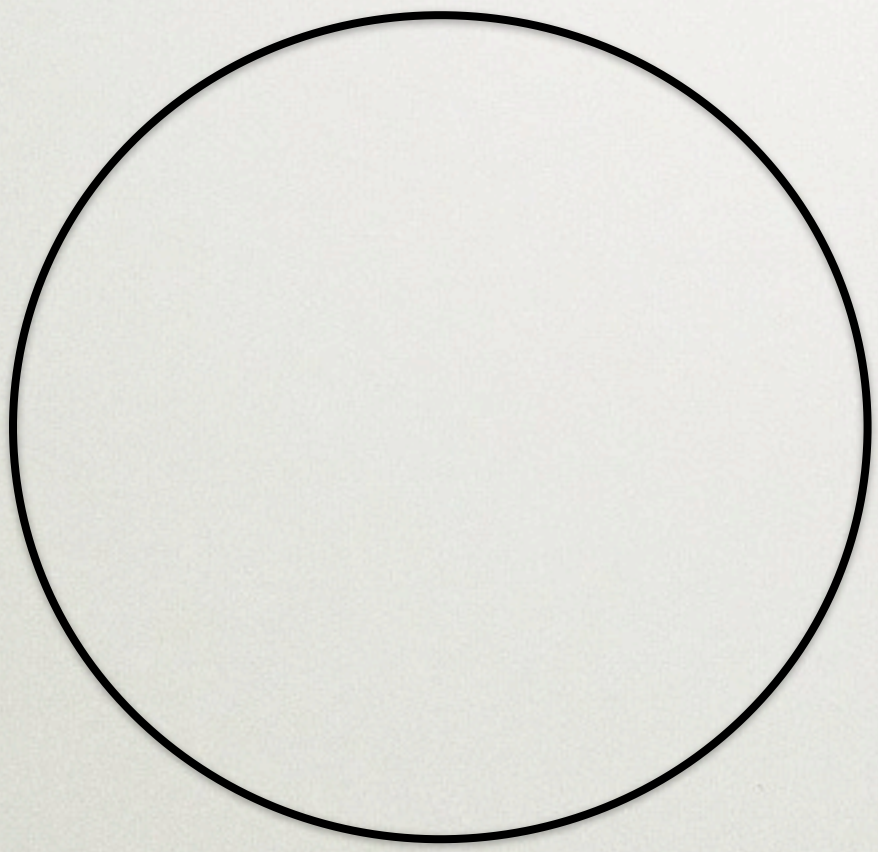

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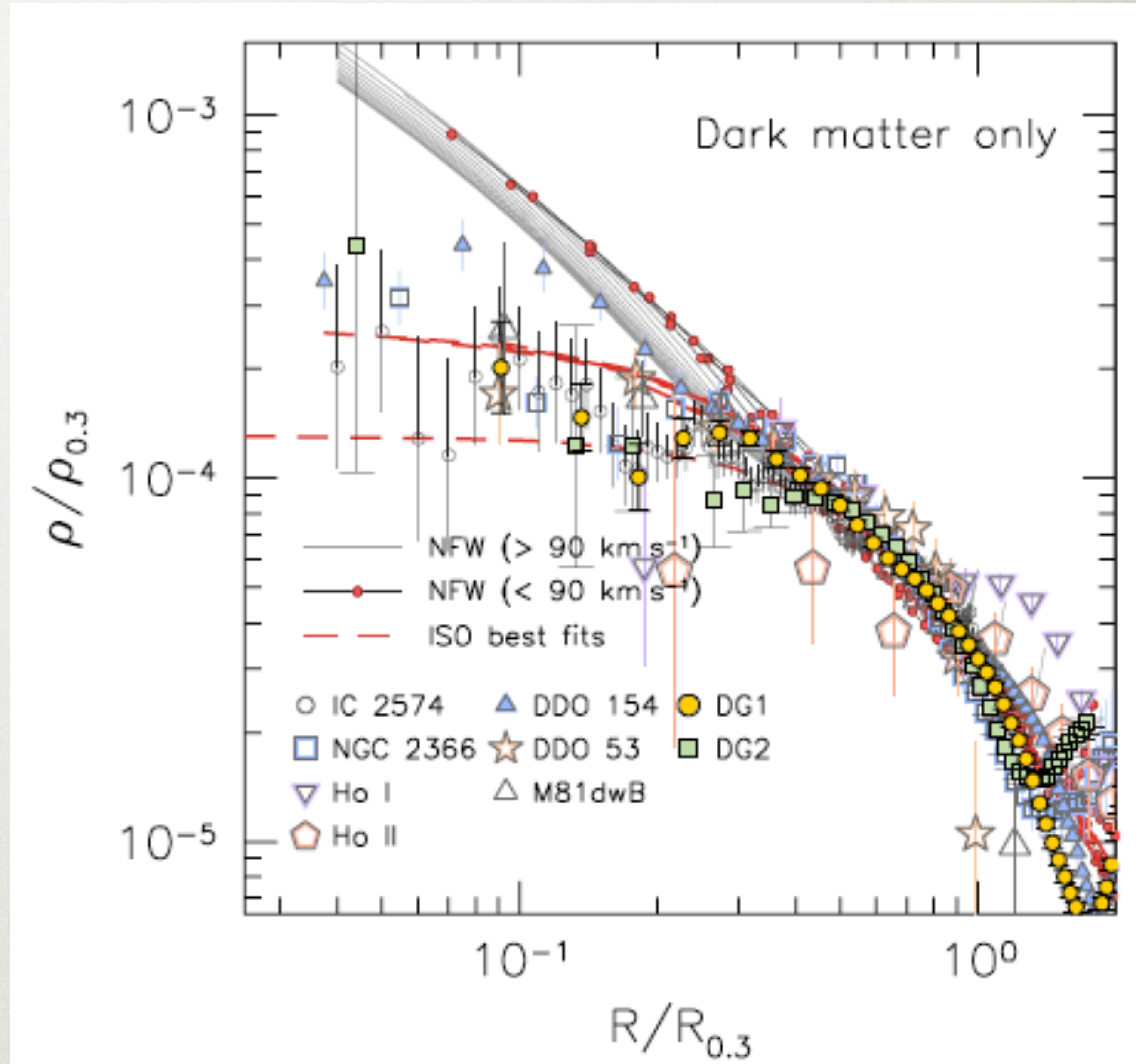
Creation of a Dark Matter Core



Oh et al., 2011, AJ, 142, 24

See also: Navarro et al. 1996; Read & Gilmore 2005; Mashchenko et al. 2006, 2008; Pasetto et al. 2010; de Souza et al. 2011; Cloet-Osselaer et al. 2012; Maccio et al. 2012; Teyssier et al. 2012; Ogiya & Mori 2012

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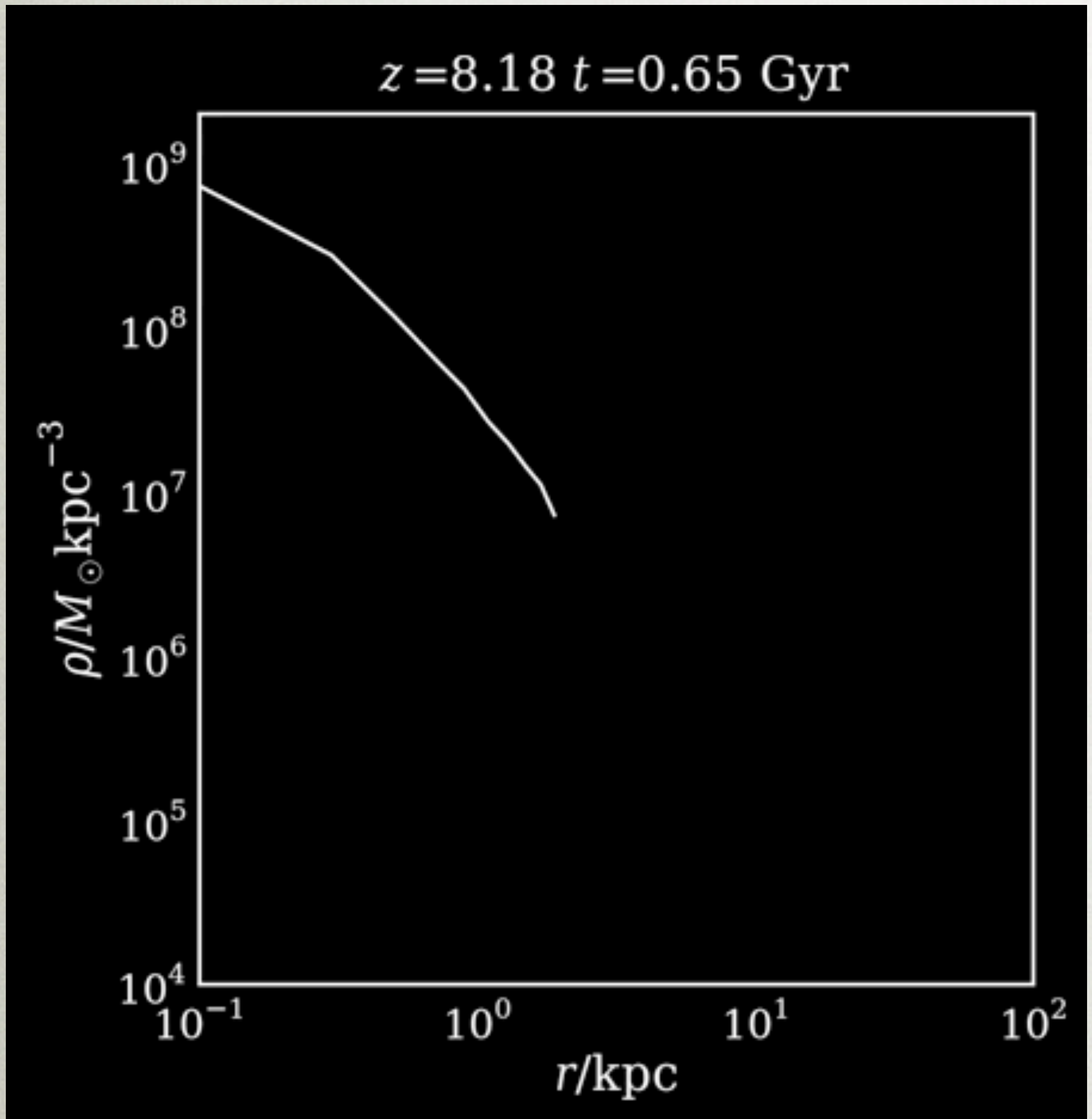

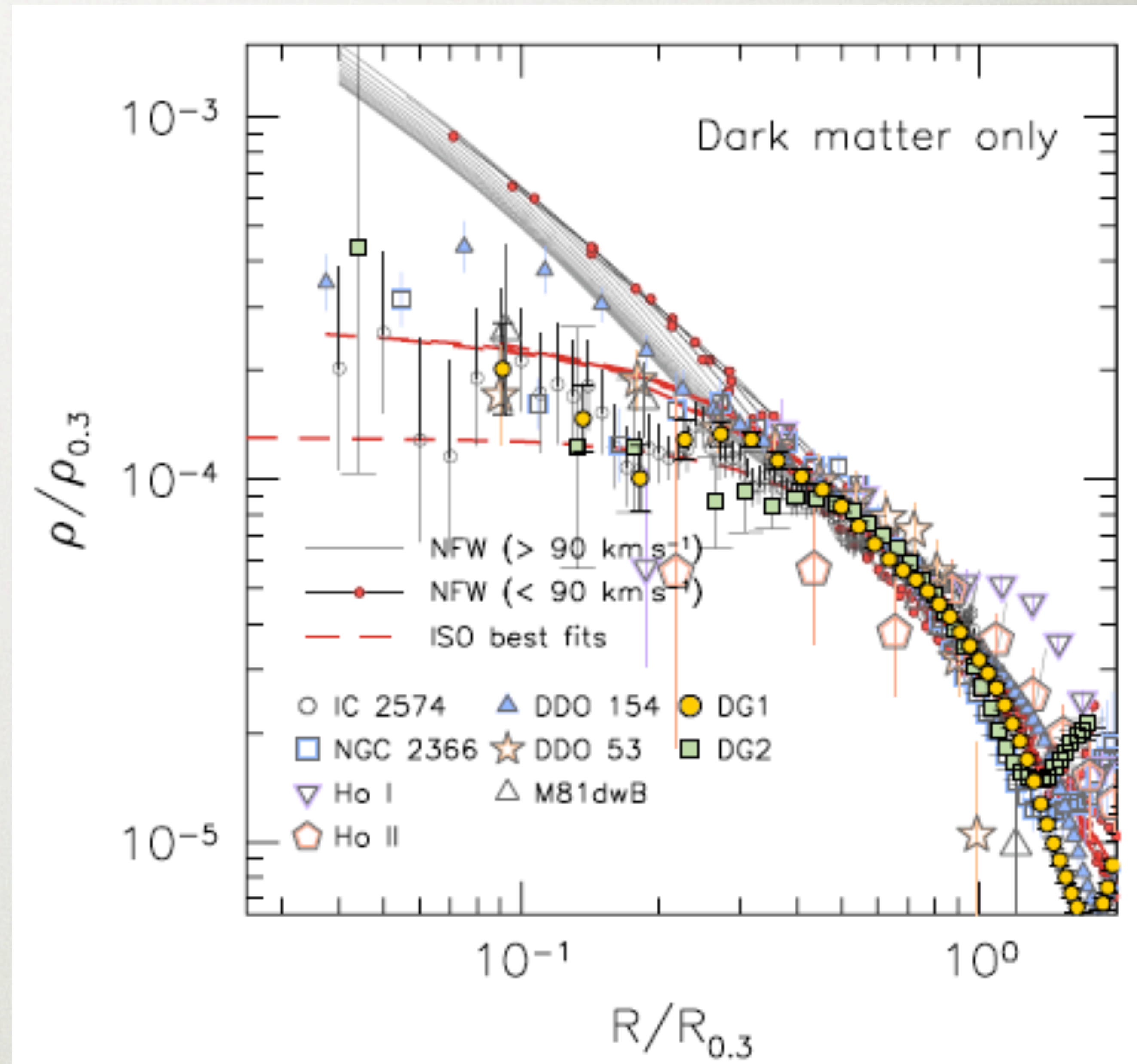

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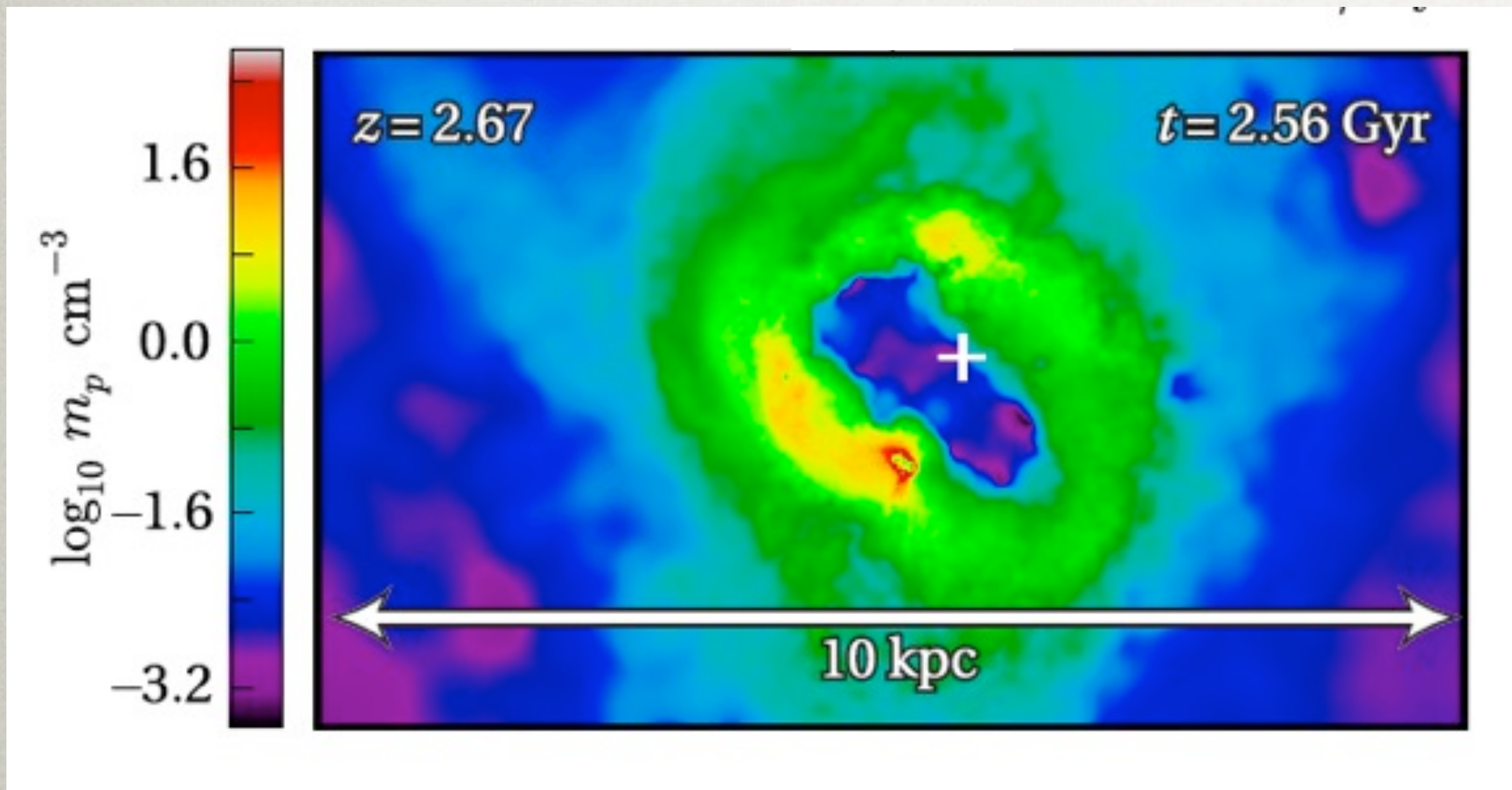
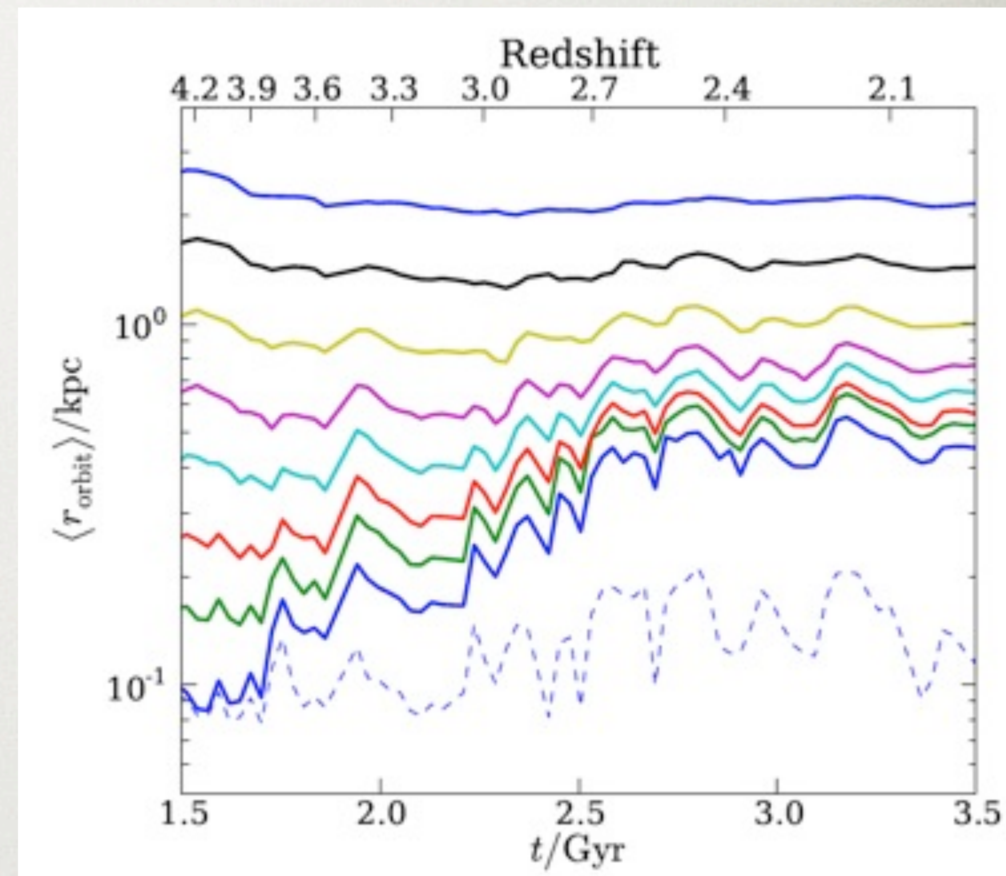
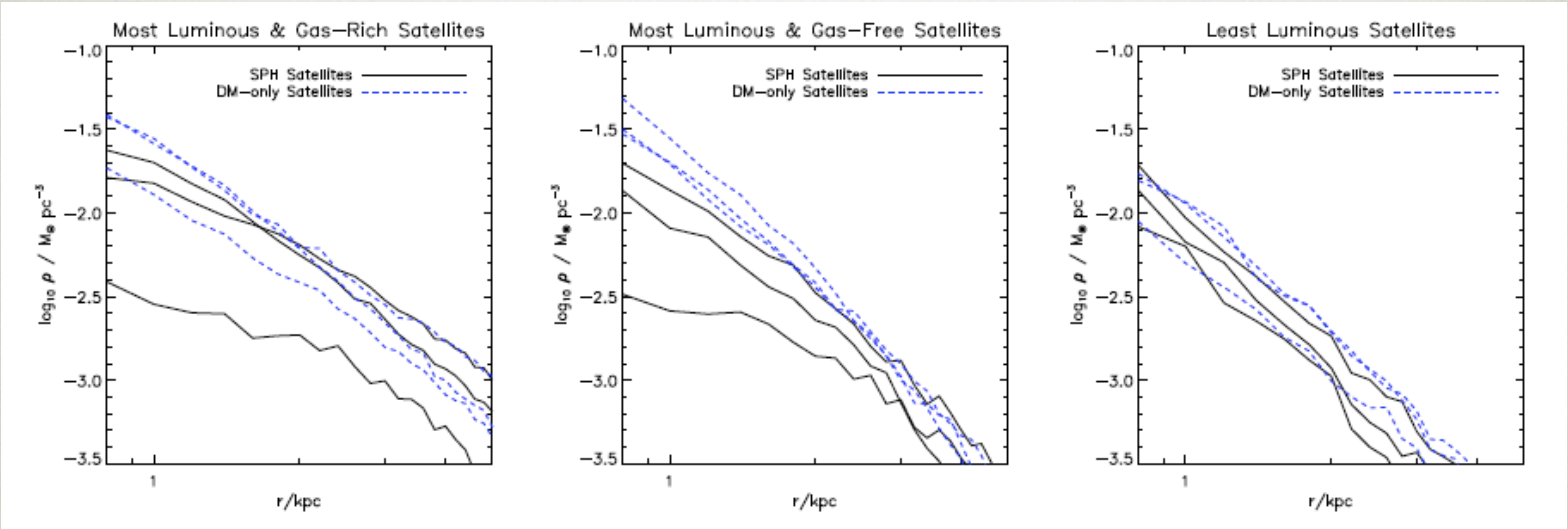
How are Cores Created?





Pontzen & Governato (2012), MNRAS, 421, 3464, arXiv:1106.0499

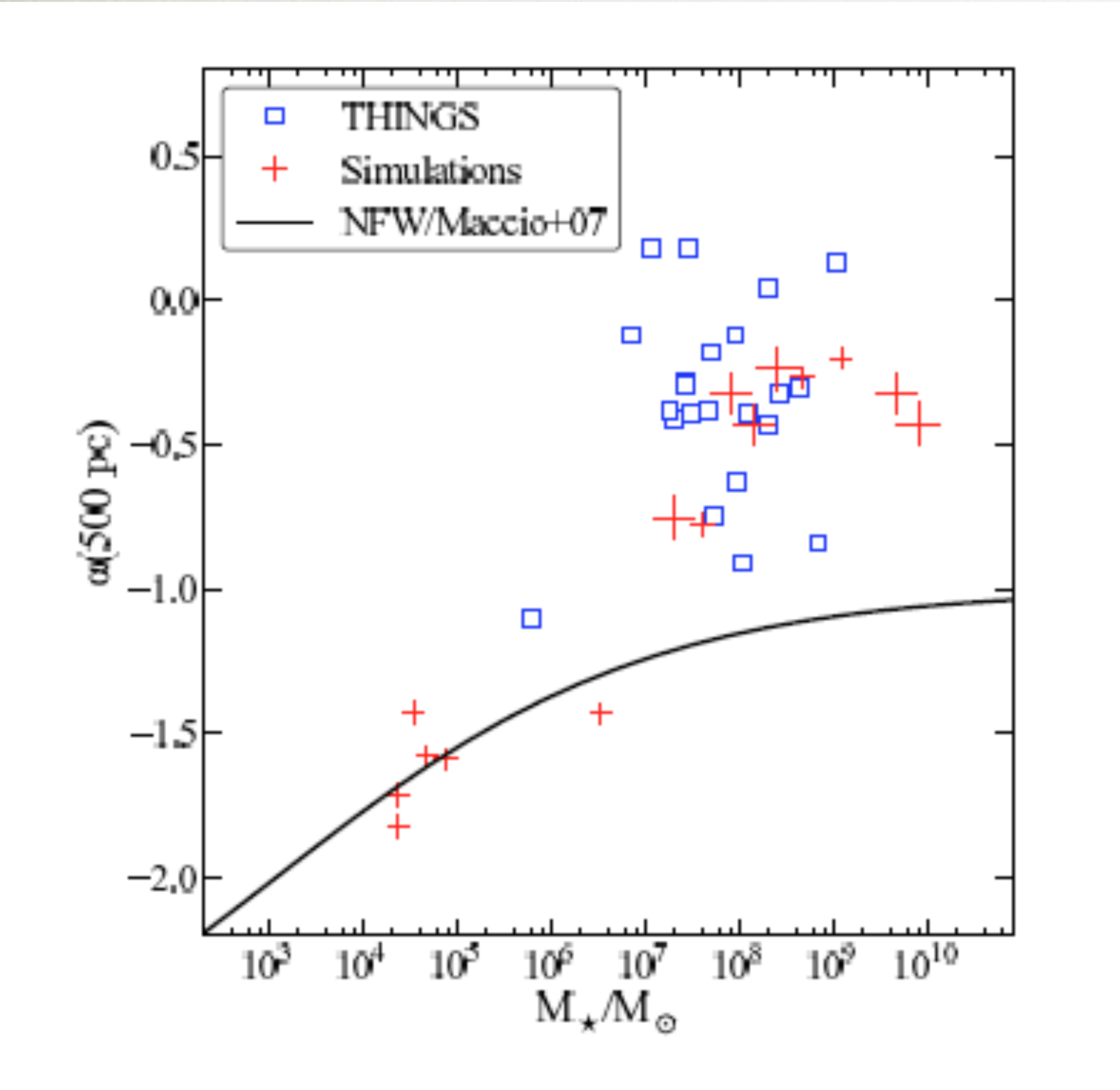
CDM predicts denser satellites than we observe (or does it?)

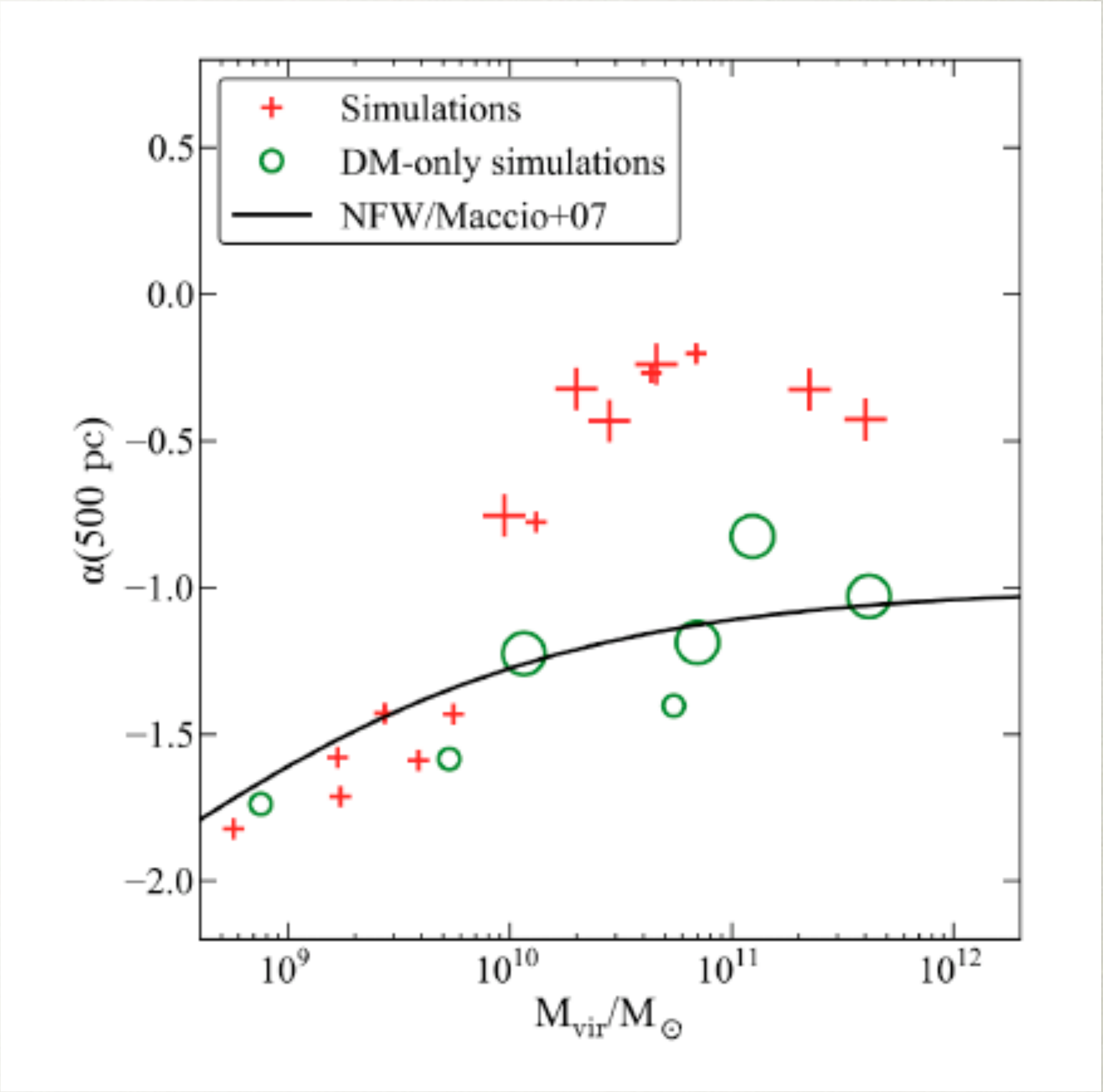


Zolotov, Brooks, et al., 2012, ApJ, 761, 71, arXiv:1207.0007

Core Creation varies with Mass!

because SF varies with mass





Galaxies in the THINGS survey have average α~-0.3

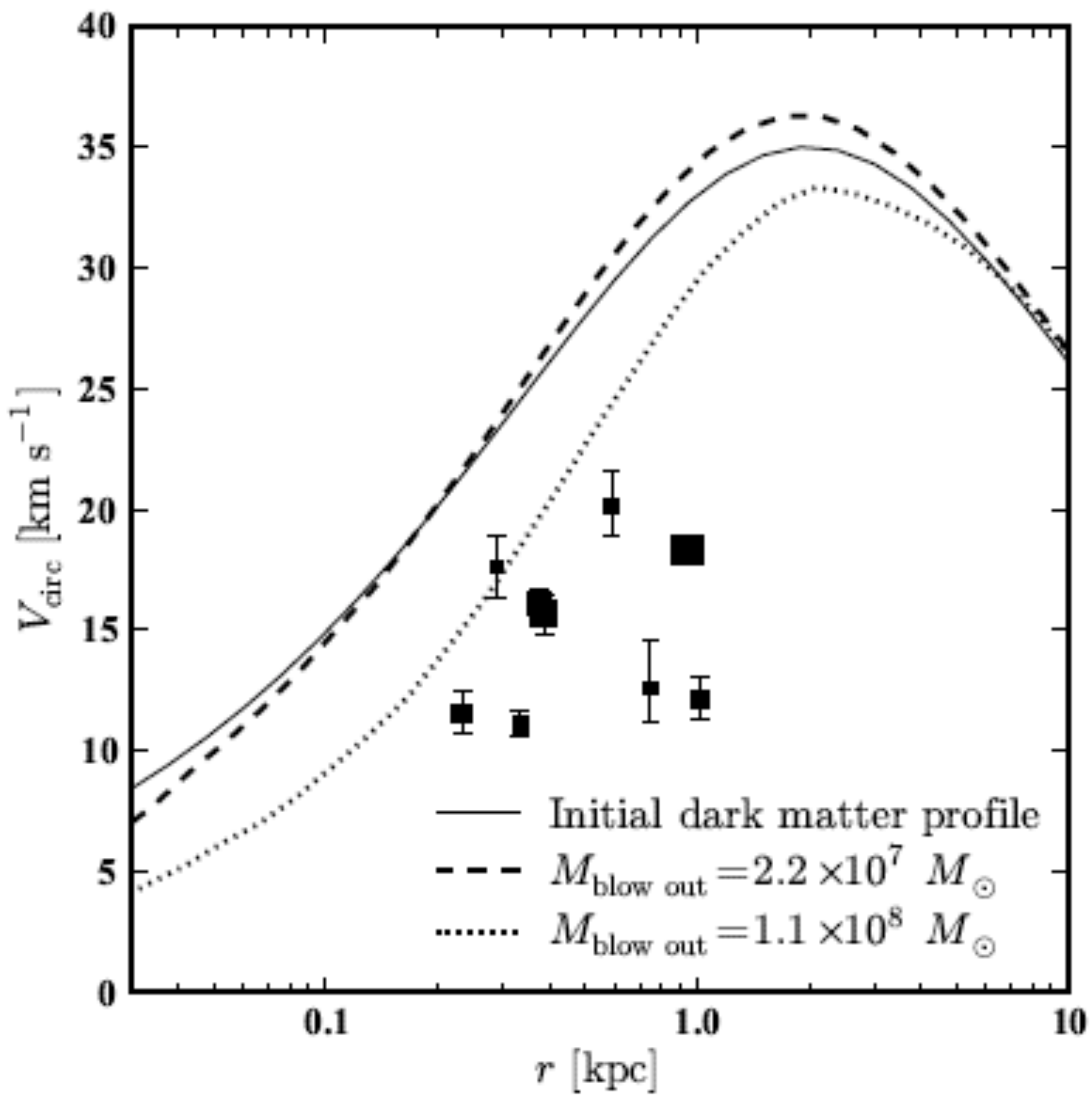
Lower mass galaxies do not undergo repeated bursts of SF; retain cusps

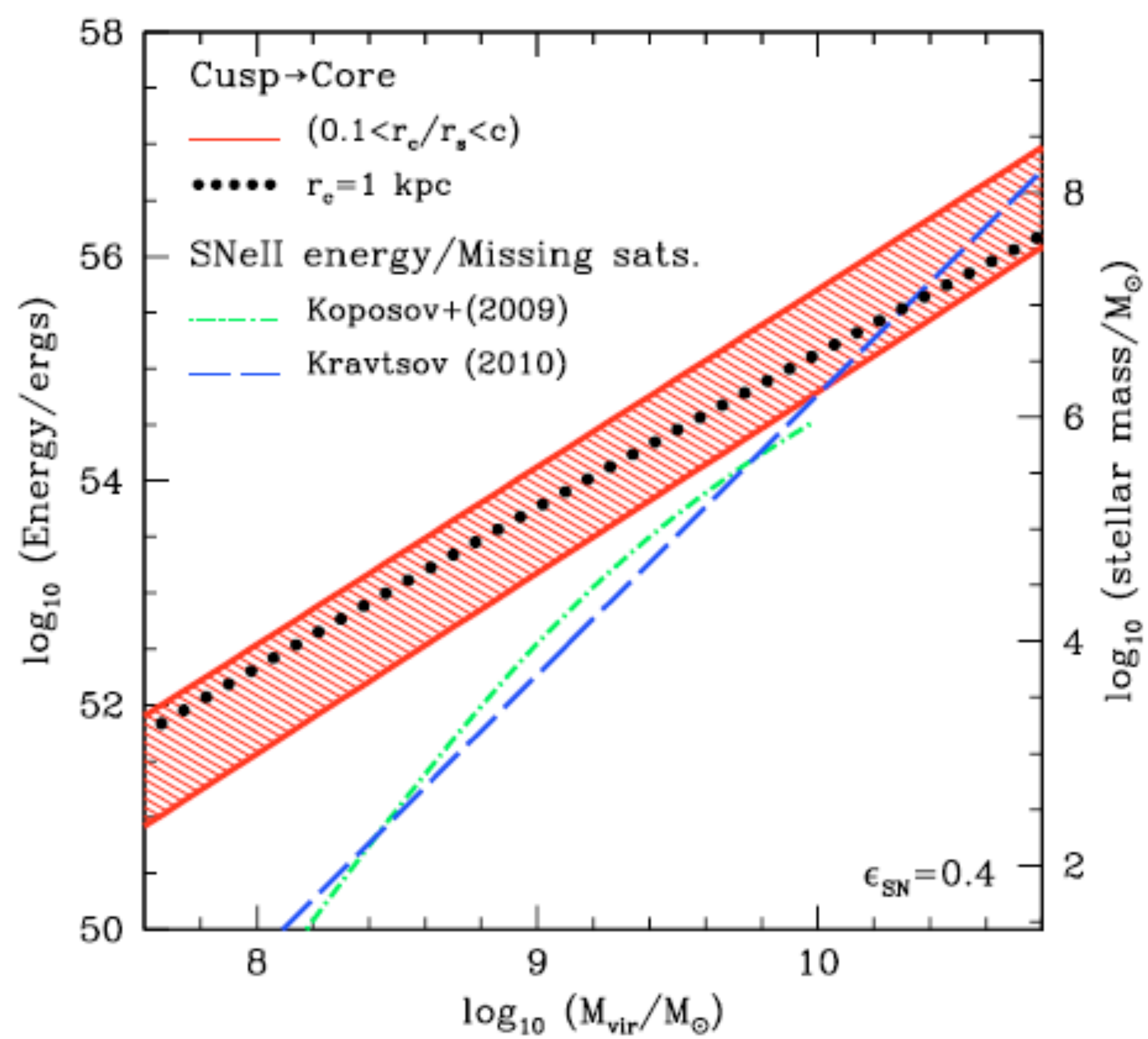
Governato et al., 2012, MNRAS, 422, 1231

Energetics

Boylan-Kolchin et al. (2012)

Penarrubia et al. (2012)





$M_{blowout}$ = [illegible] M_{star}

requires $M_{star} > 10^7\ M_\odot$

Energetics

Can Feedback Solve the Too Big to Fail Problem?

Shea Garrison-Kimmel⋆, Miguel Rocha, Michael Boylan-Kolchin†,
James S. Bullock, Jaspreet Lally
Center for Cosmology, Department of Physics and Astronomy, University of California, Irvine, CA 92697, USA

14 January 2013

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Simulation	m_p ($M_\odot$)	ϵ (pc)	N_p
HiRes	7.6×10^2	10	3,000,000

$= 2.3 \times 10^9\ M_\odot$

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HiRes	7.6×10^2	10	3,000,000

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We all agree!

Also: Baryons Make a Disk (Dark Matter Doesn't)

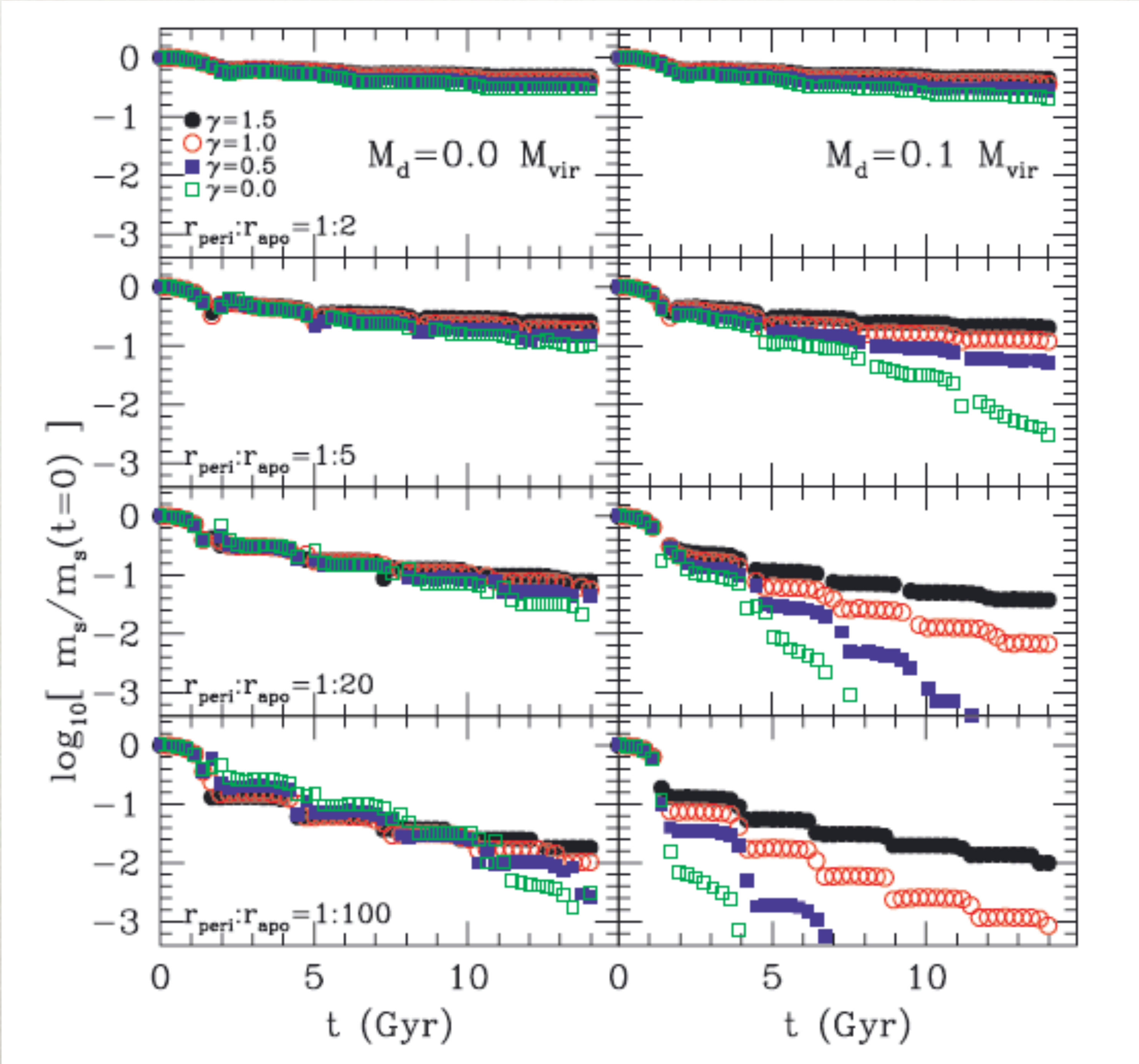
Dark Matter

Baryons

(or any central baryonic concentration)

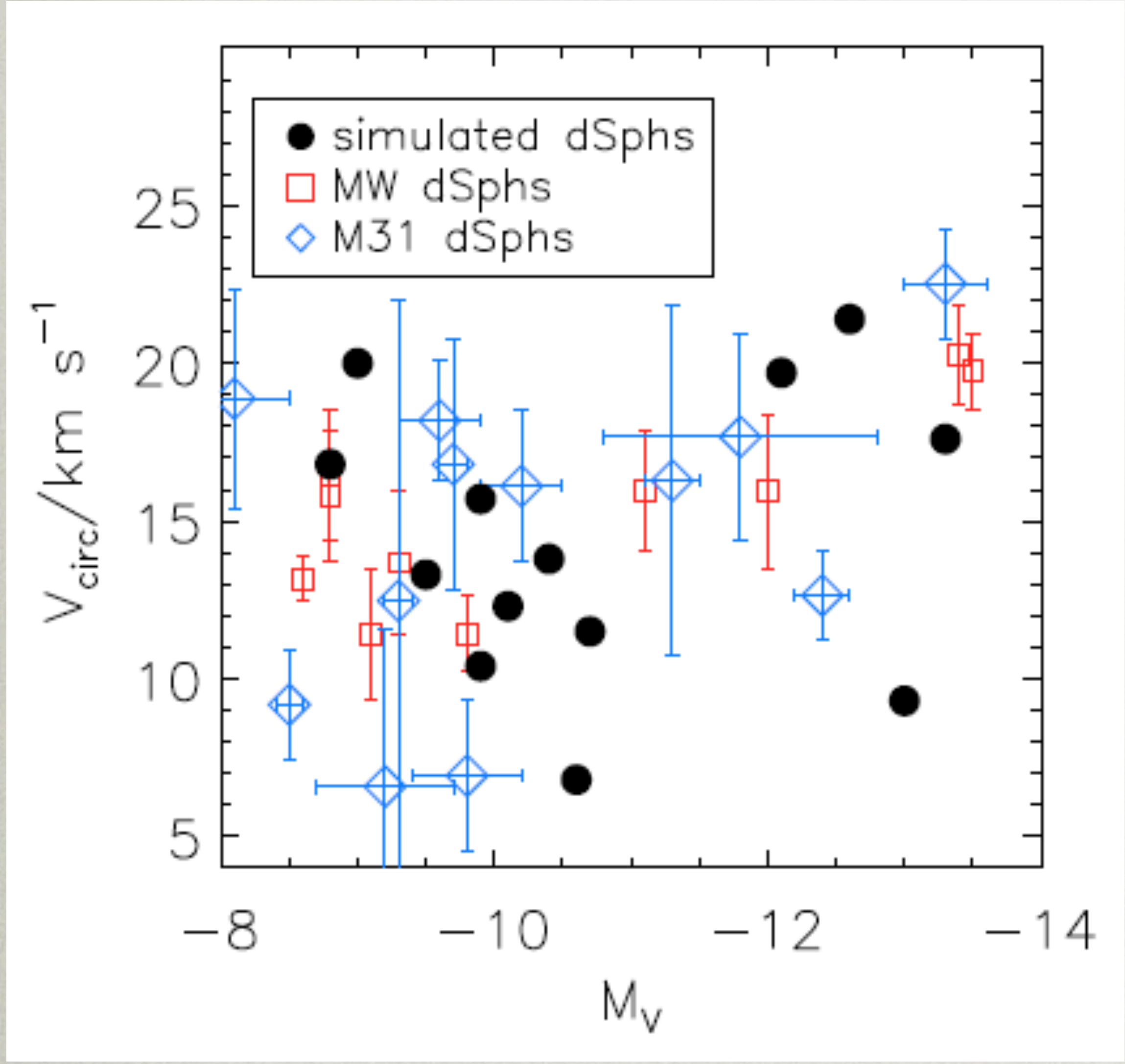
Chang et al. (2012)

Not Just Core Creation: The Tidal Effect of the Disk



Penarrubia et al. (2010), see also Arraki et al. (2012)

The First Simulated Dwarf Spheroidals to Match Observed Kinematics



- satellites show no trend across luminosity
- scatter fainter than M_V=-12 due to stripping after infall
- brighter than M_V=-12 have cores, even more stripping

Brooks & Zolotov (2012), arXiv:1207.2468

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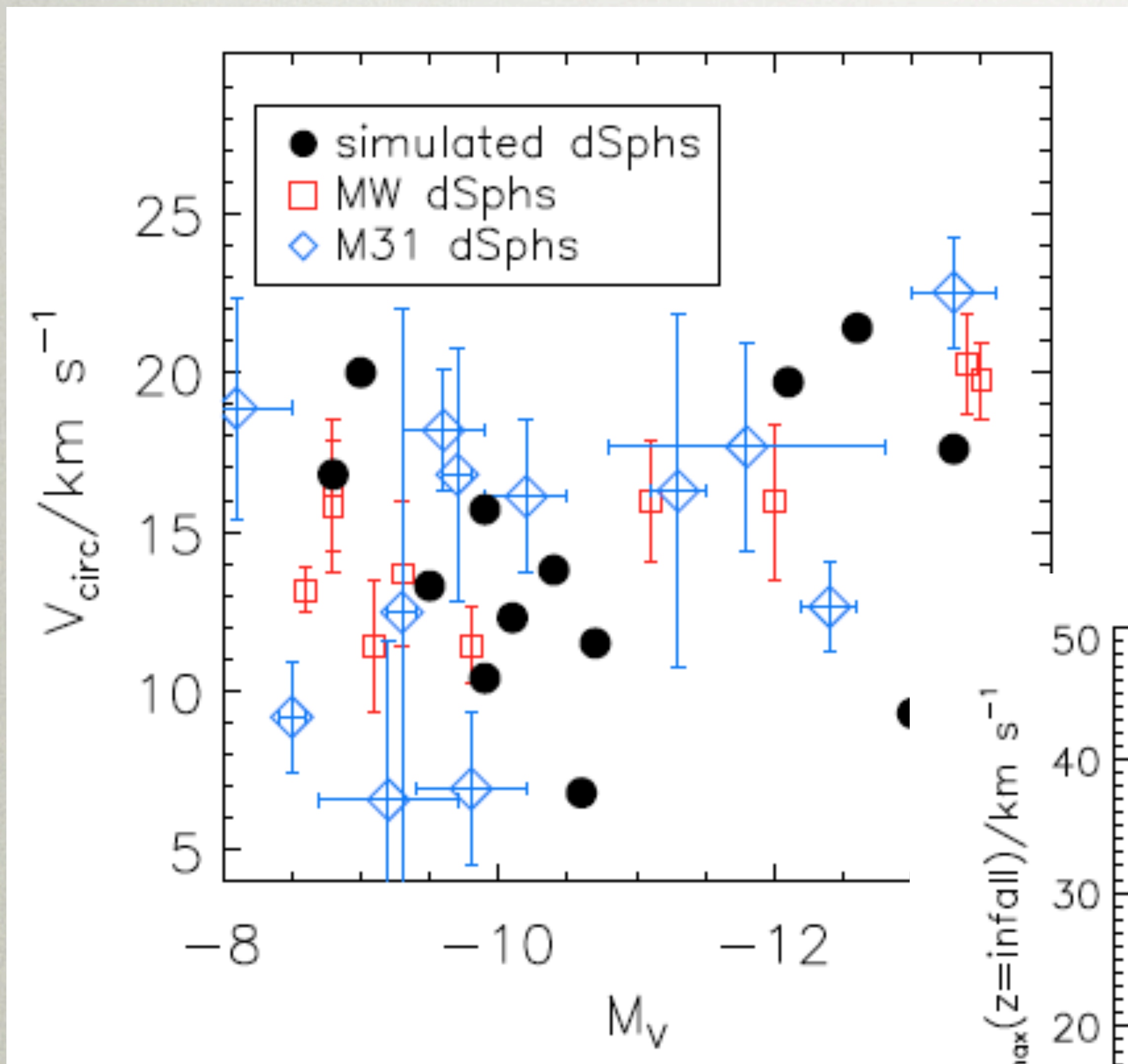

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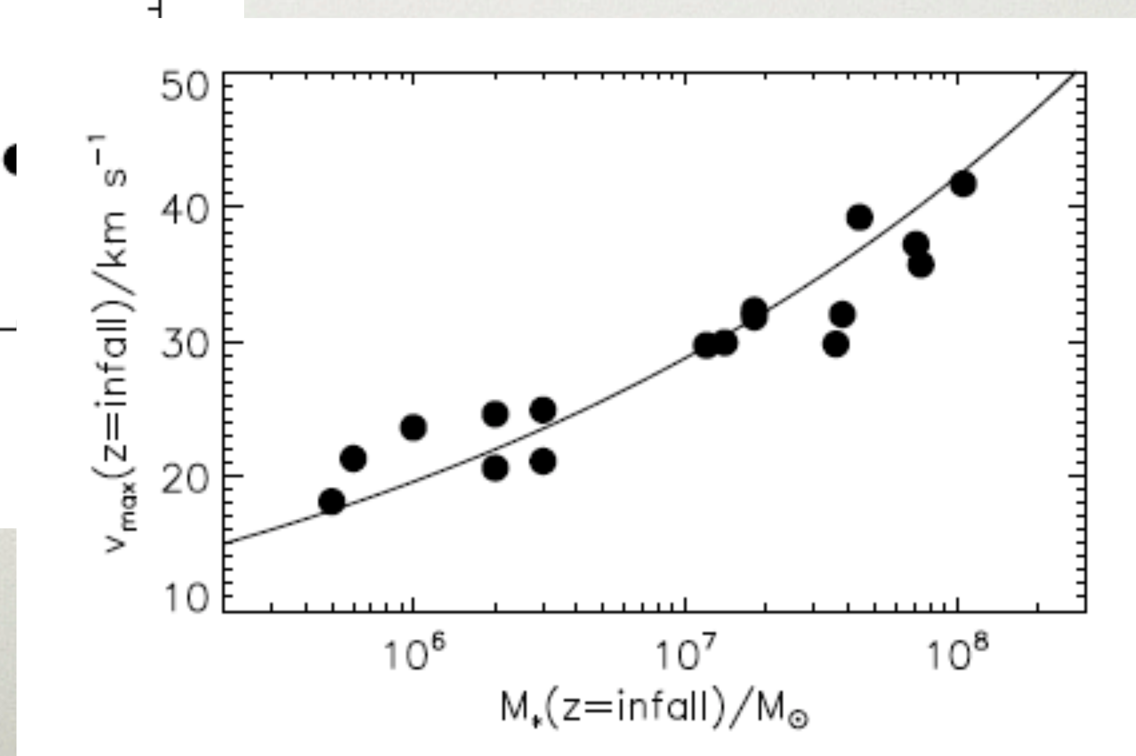

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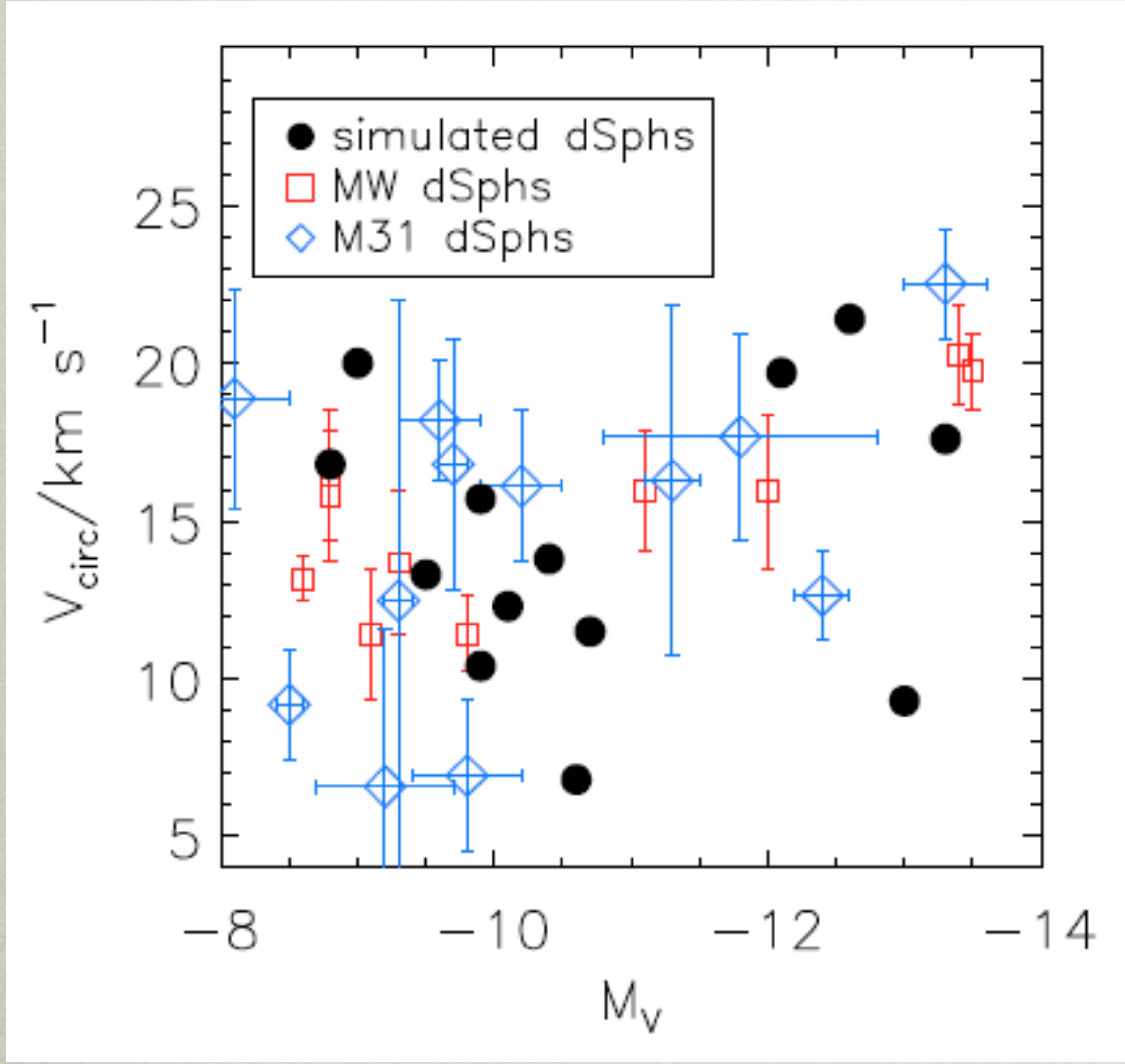

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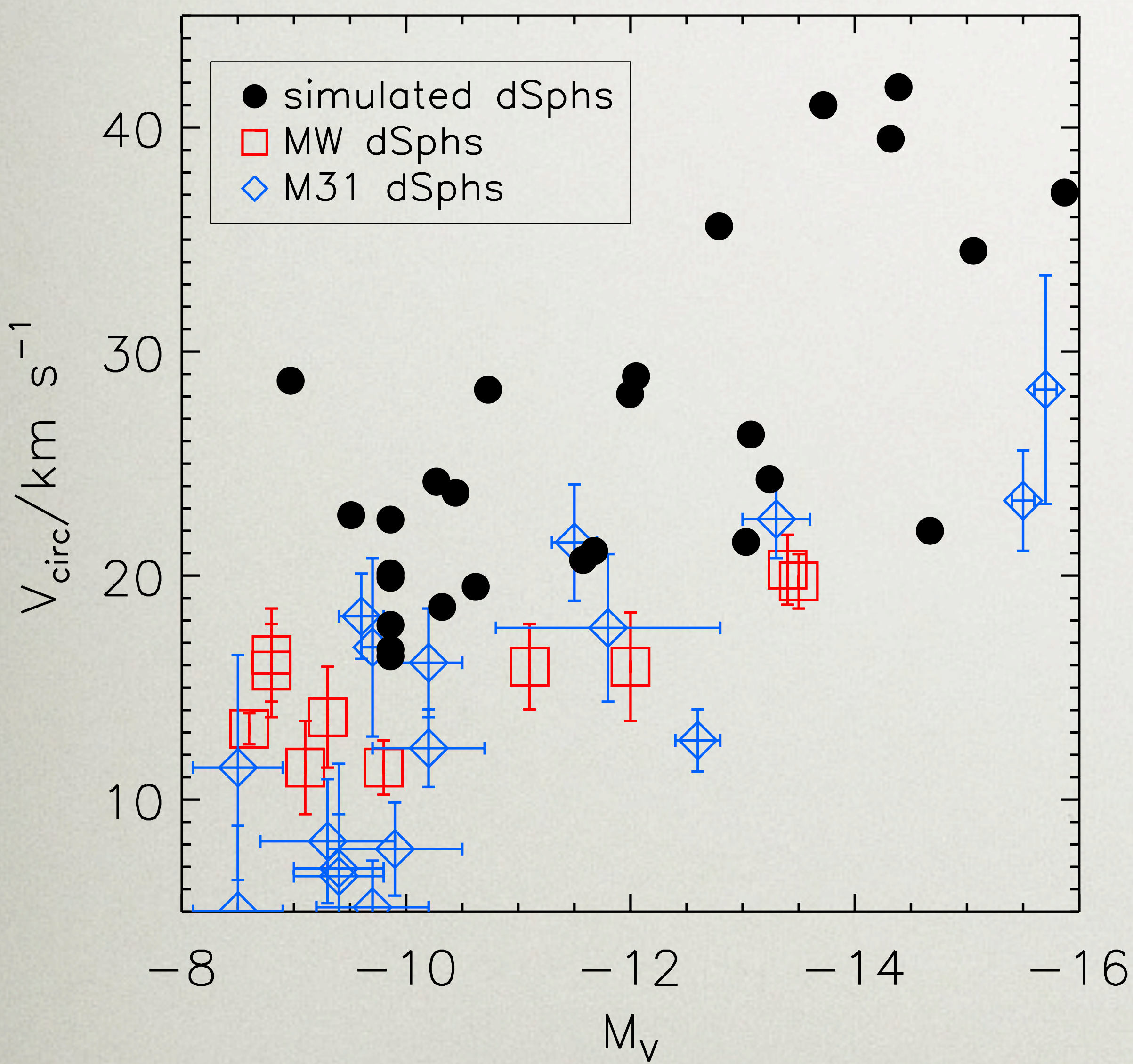

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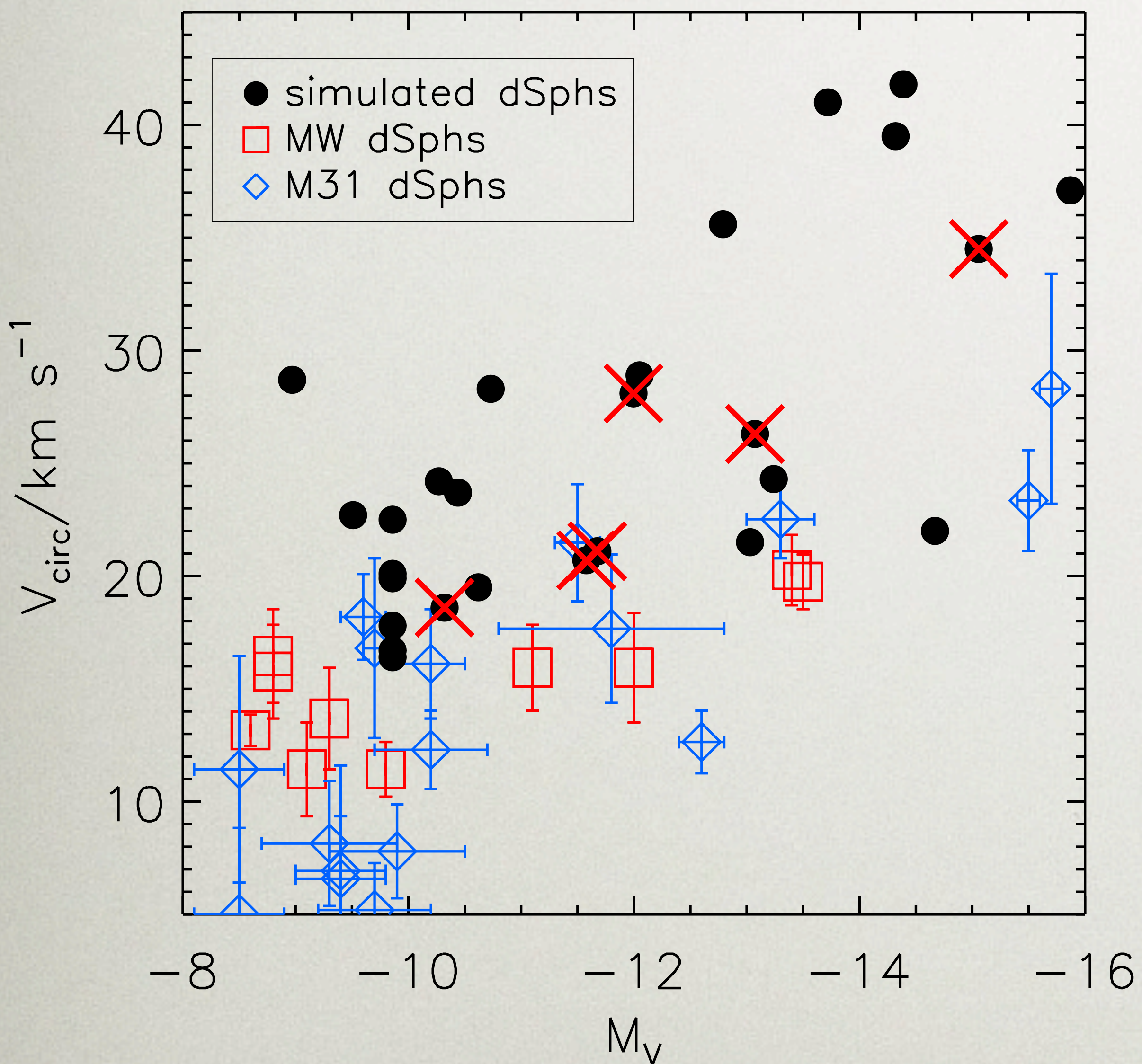

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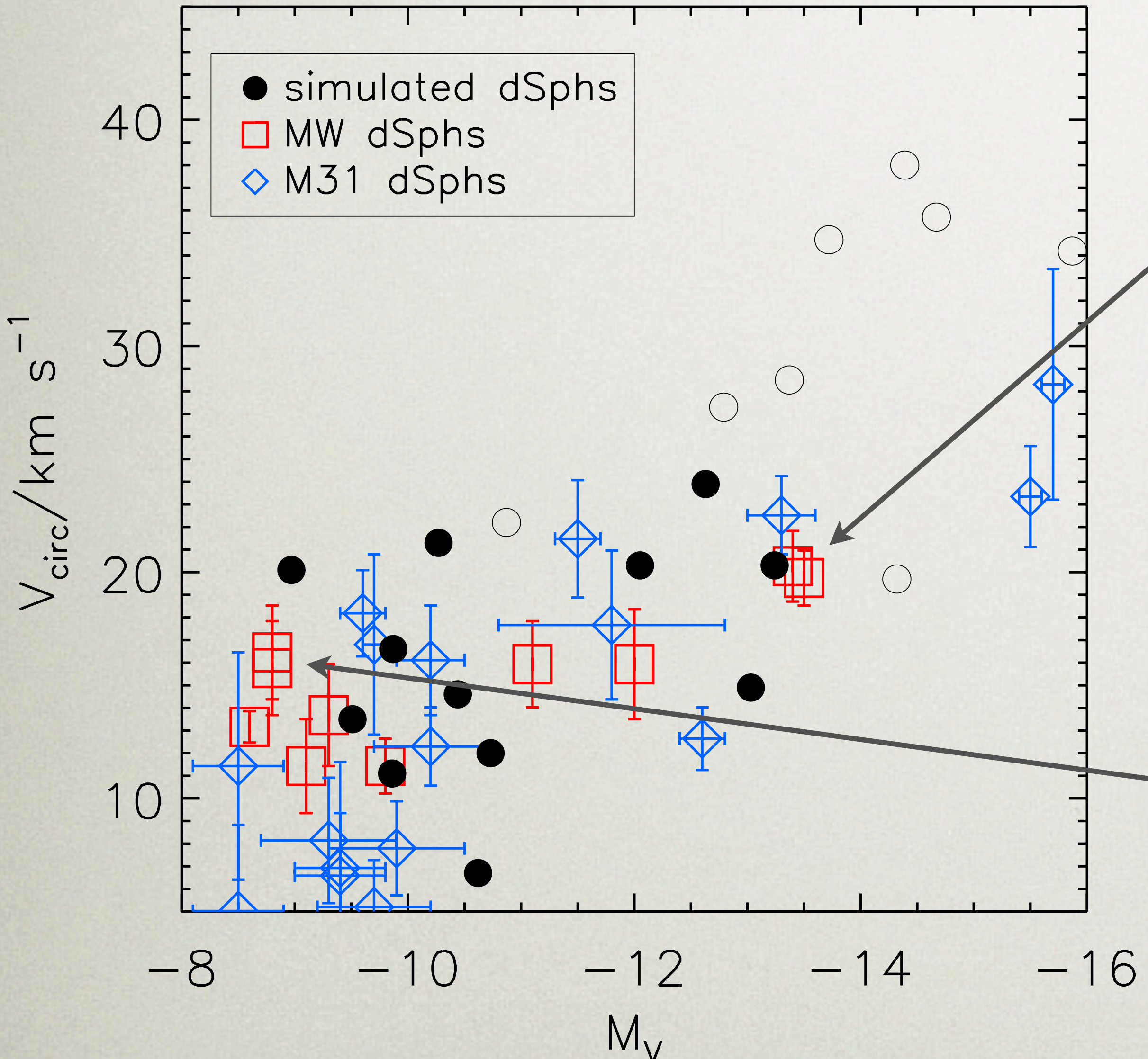


Fornax: evidence for a ~1kpc core

(Walker & Penarrubia 2011, Jardel & Gebhardt 2012, Breddels et al. 2012, Amorisco & Evans 2012; Battaglia et al. 2008, Agnello & Evans 2012, Goerdt et al. 2006, Cole et al. 2012)

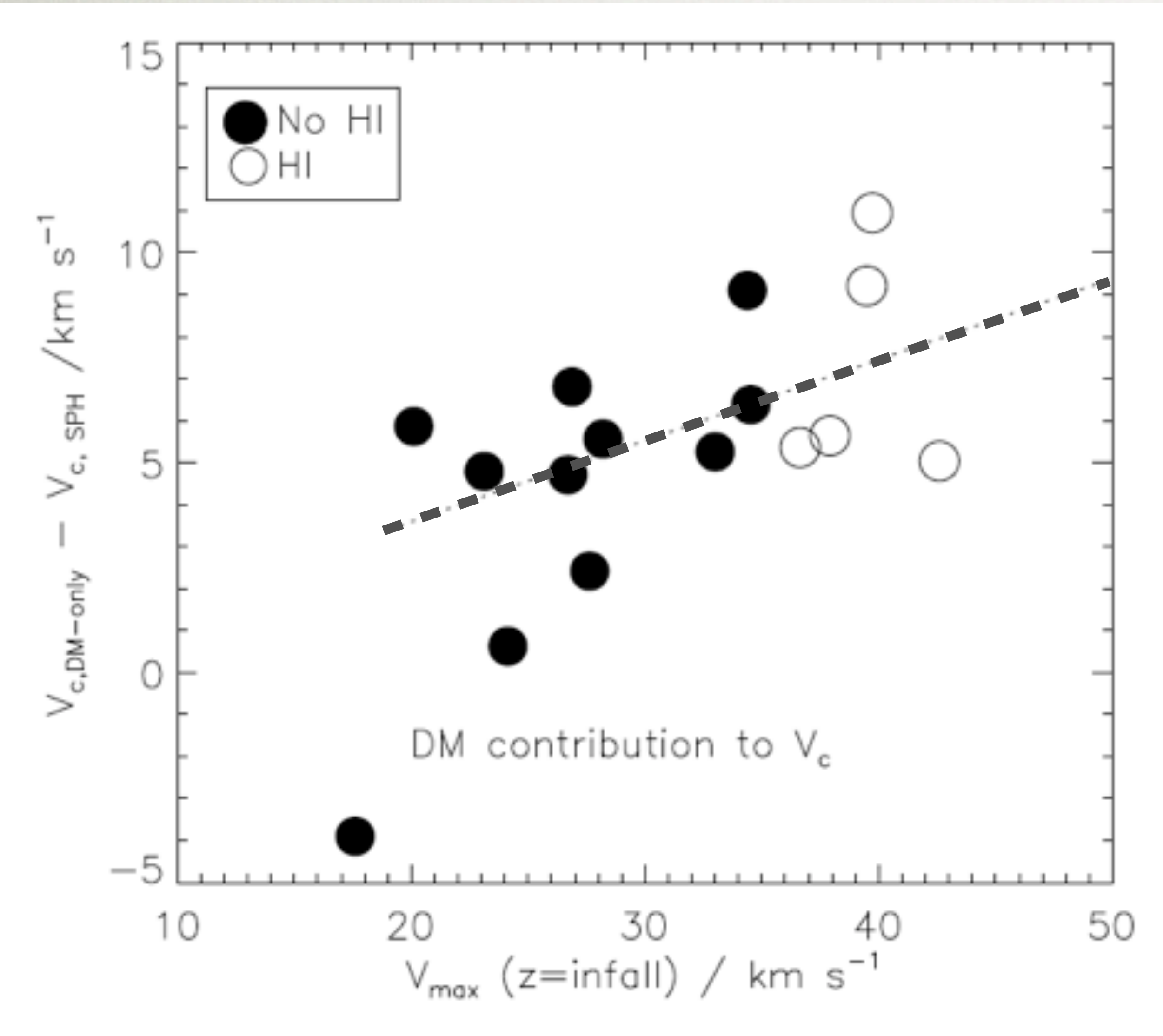
Draco: consistent with NFW

(Strigari et al. 2010, Jardel et al. 2013, but see Wolf & Bullock 2012)

Brooks & Zolotov (2012), arXiv:1207.2468

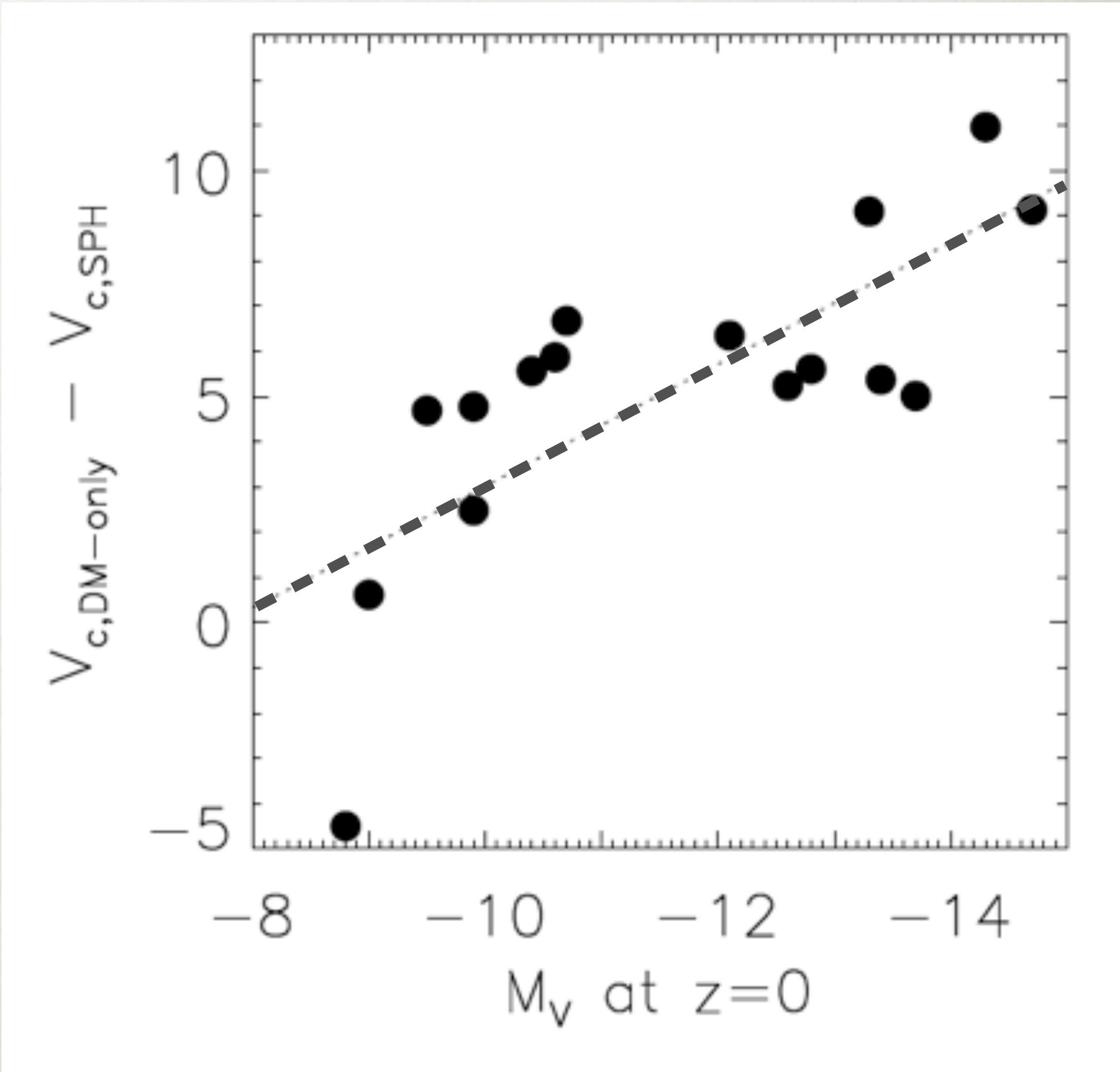
Corrections to DM-only DATA

Theory space:



$$\Delta(v_c, 1kpc) = 0.2 v_{peak,DM-only} - 0.26$$

Observer space:



$$\Delta(v_{c,1kpc}) = -10.47 - 1.35 \times M_V$$

Zolotov et al. (2012); Brooks & Zolotov (2012)

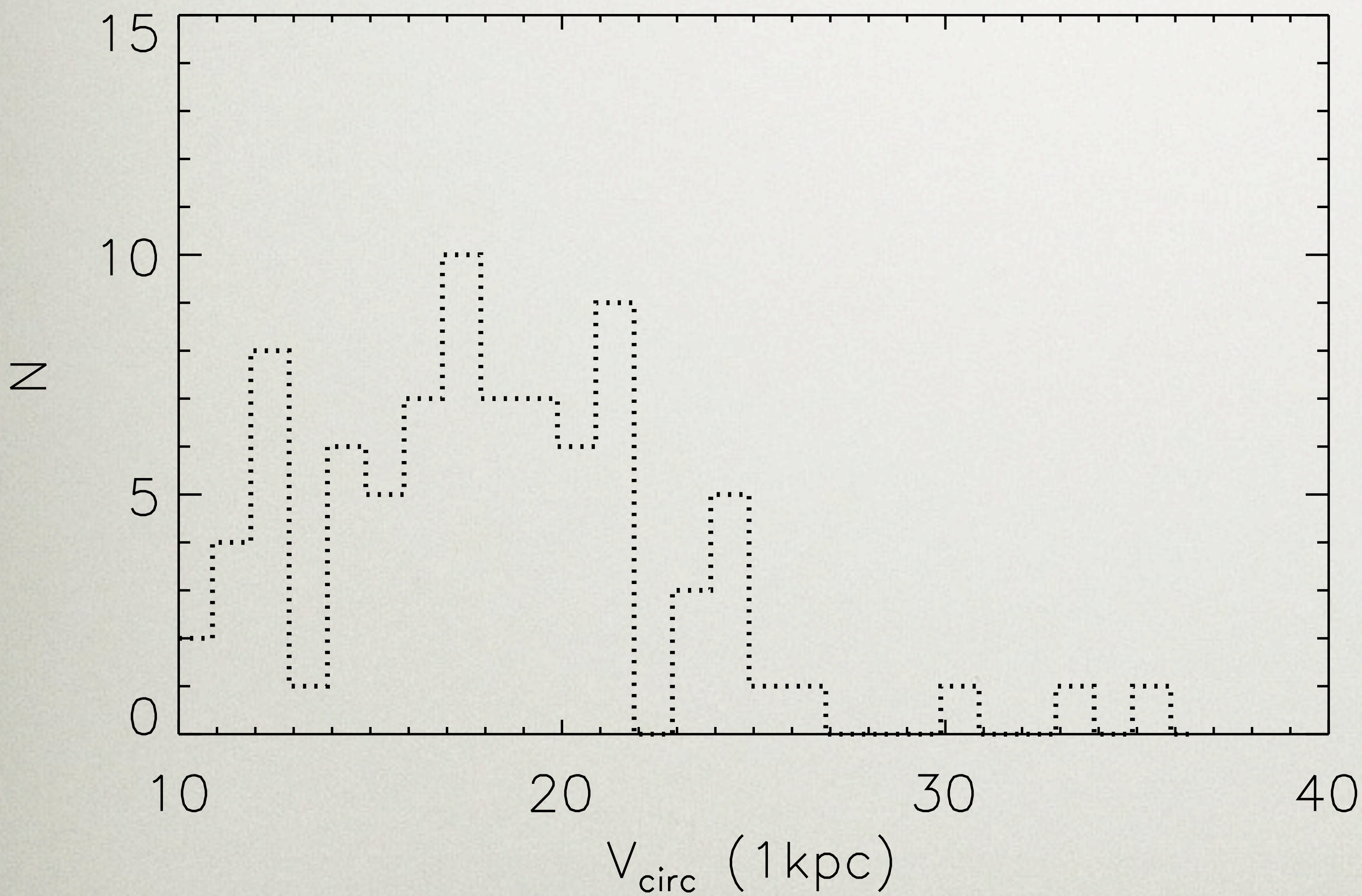
But...
What About the Number of Luminous Satellites?

1000's of satellites predicted

dozens seen

"Via Lactea"

But...
What About the Number of Luminous Satellites?



Apply the model to VL2:

VL2 has 28 subhalos with $v_{1kpc} > 20$ km/s

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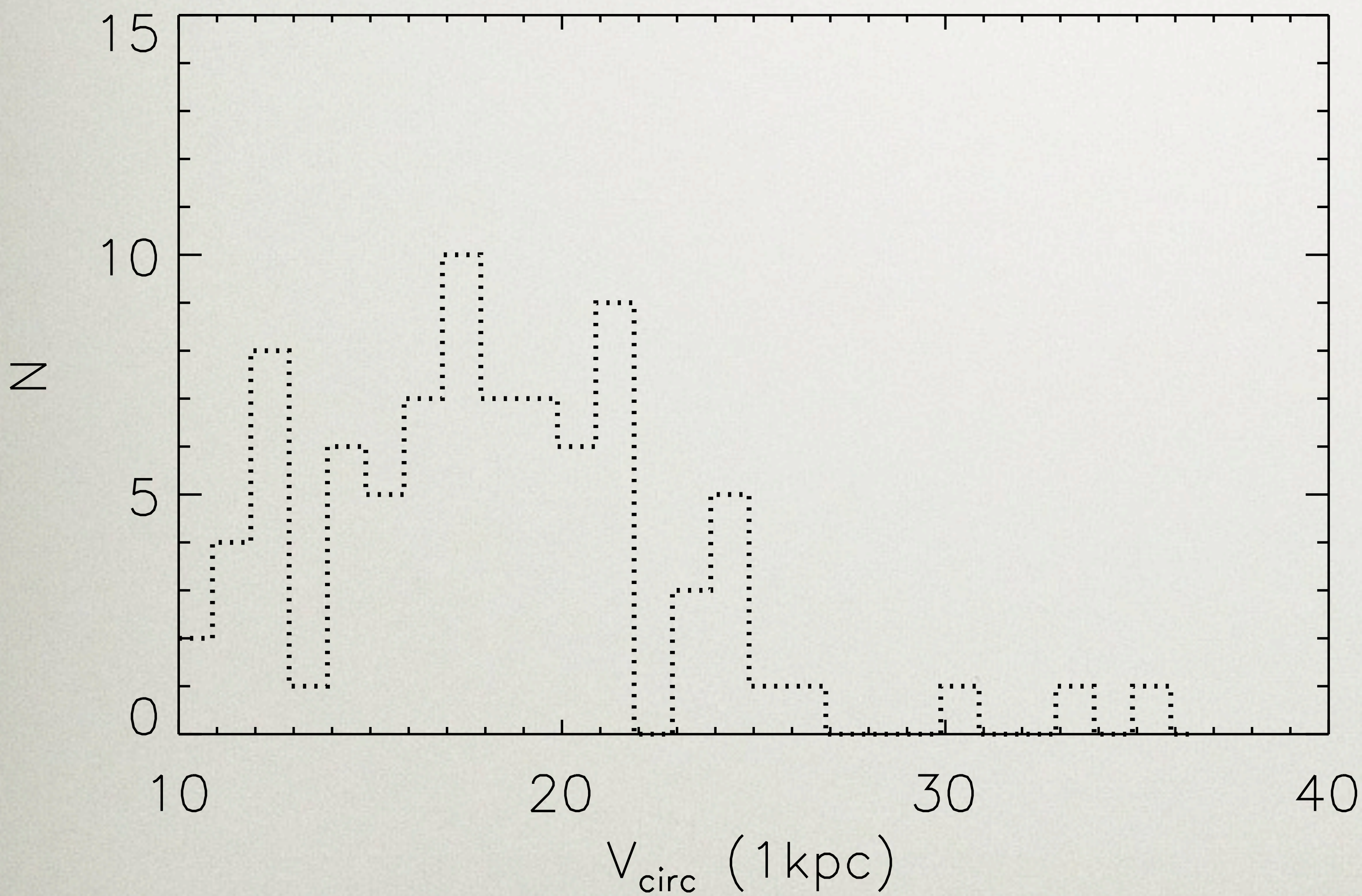

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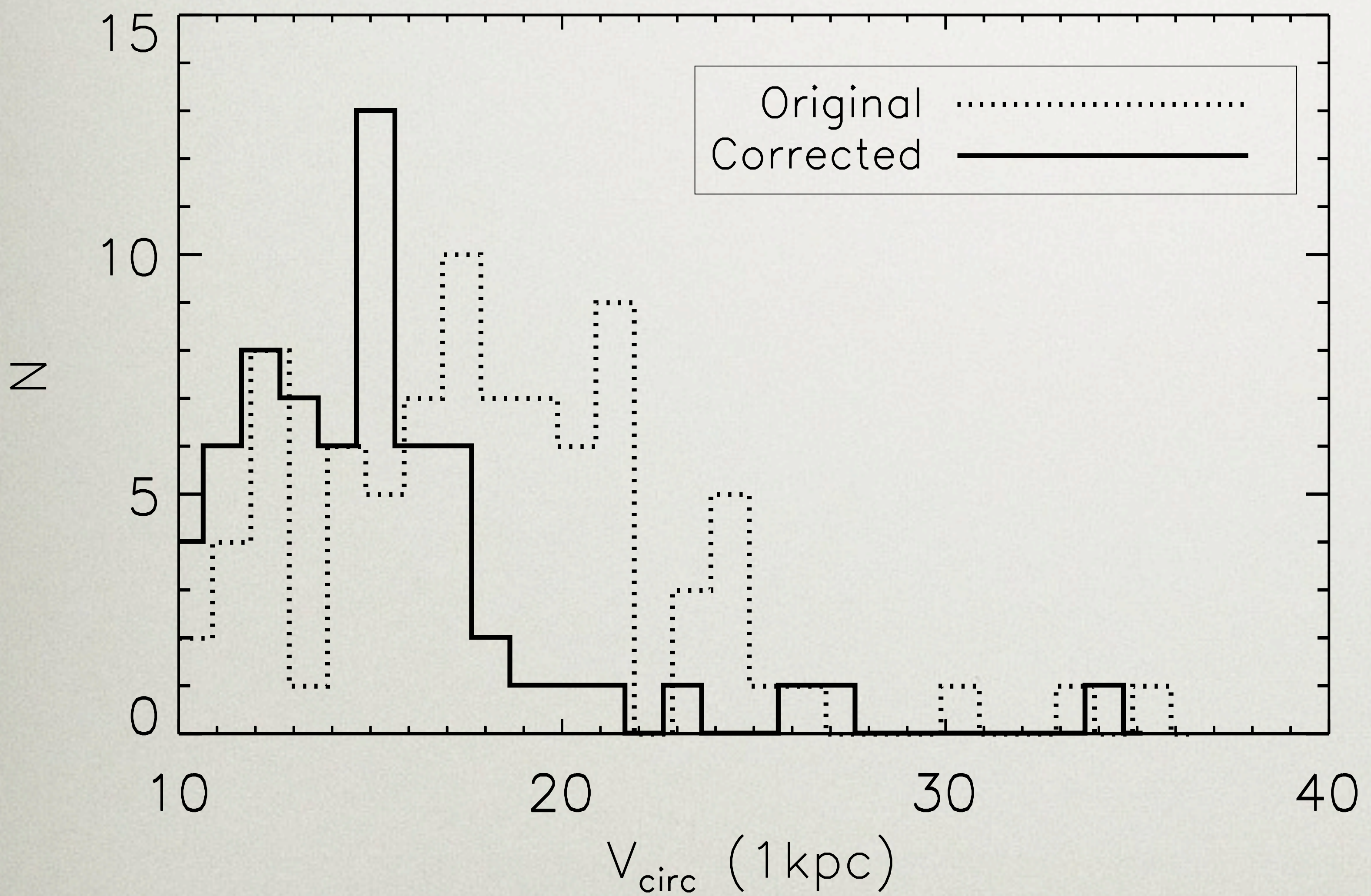

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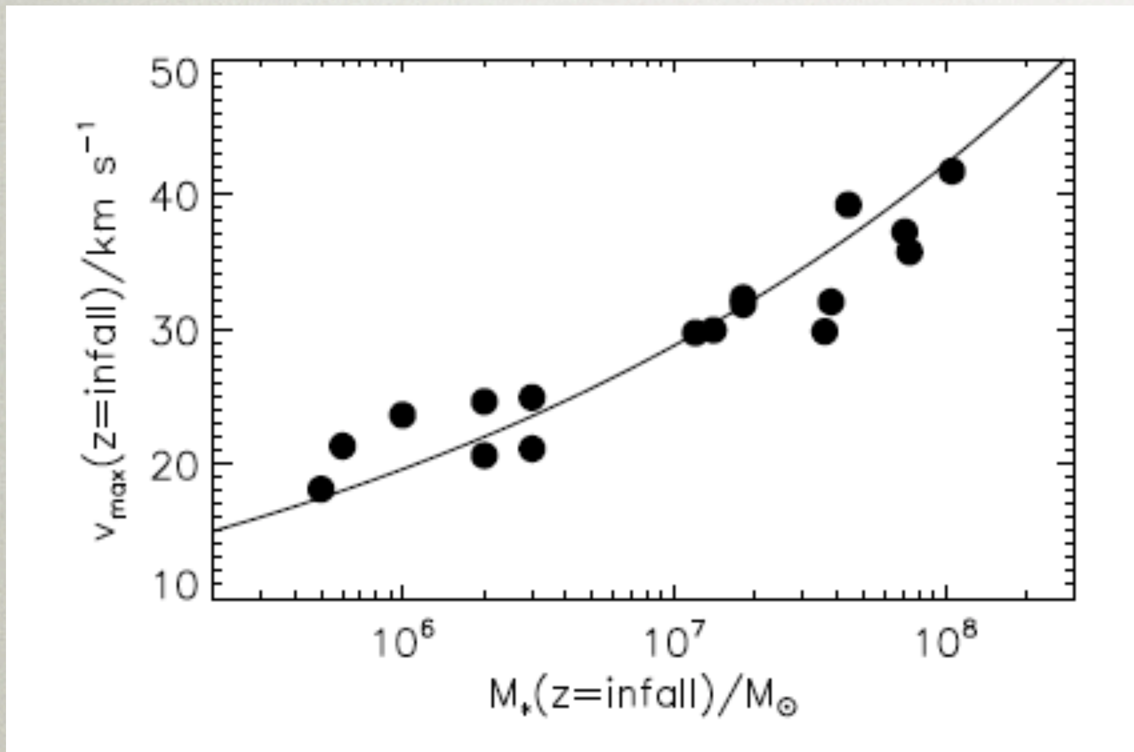
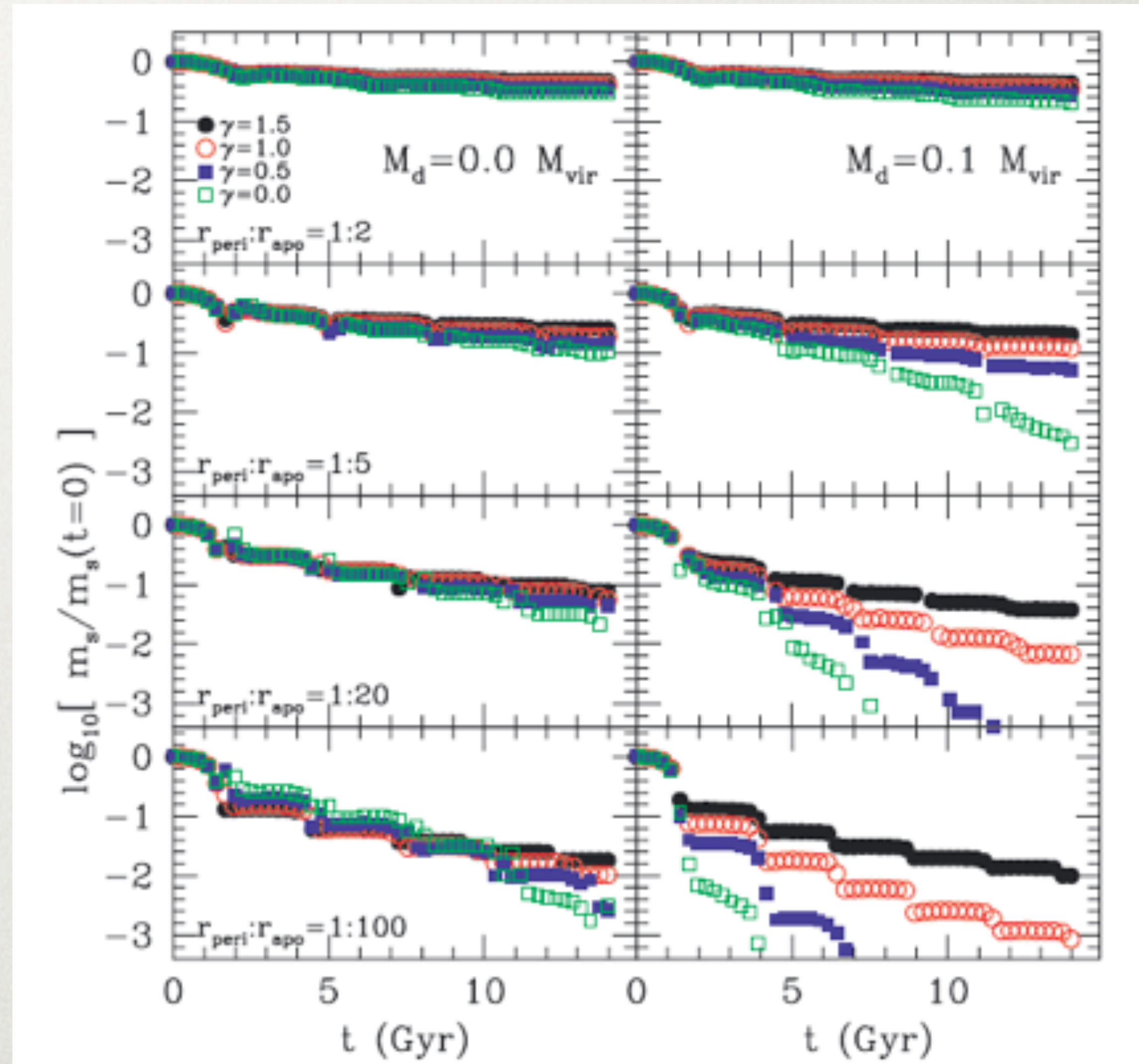
So the Number of Massive Satellites is Reduced...
but what about Luminous Satellites?



Assume

v_{peak} -- M_{star} relation



and destruction

Zolotov et al. (2012); Penarrubia et al. (2010)

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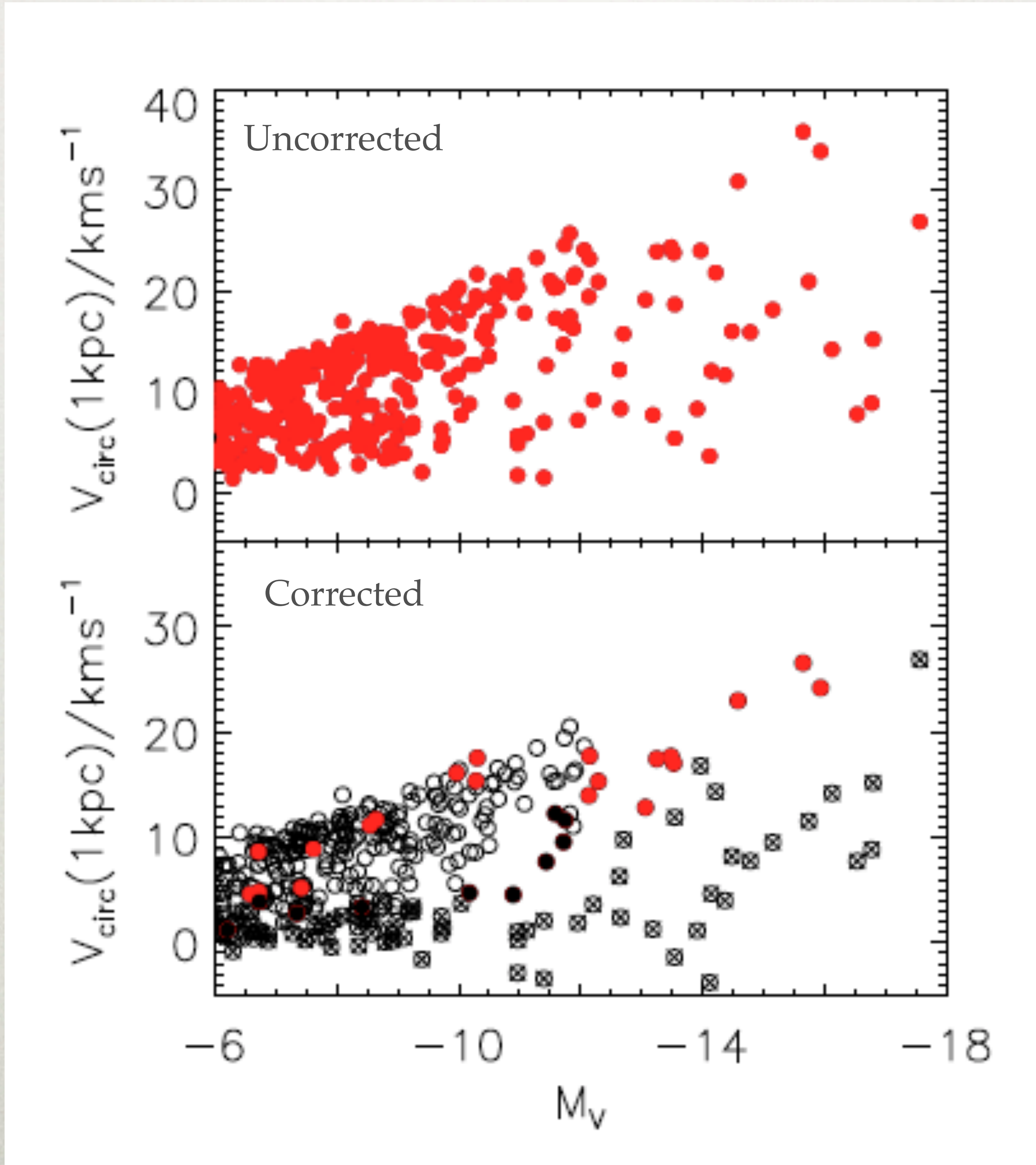
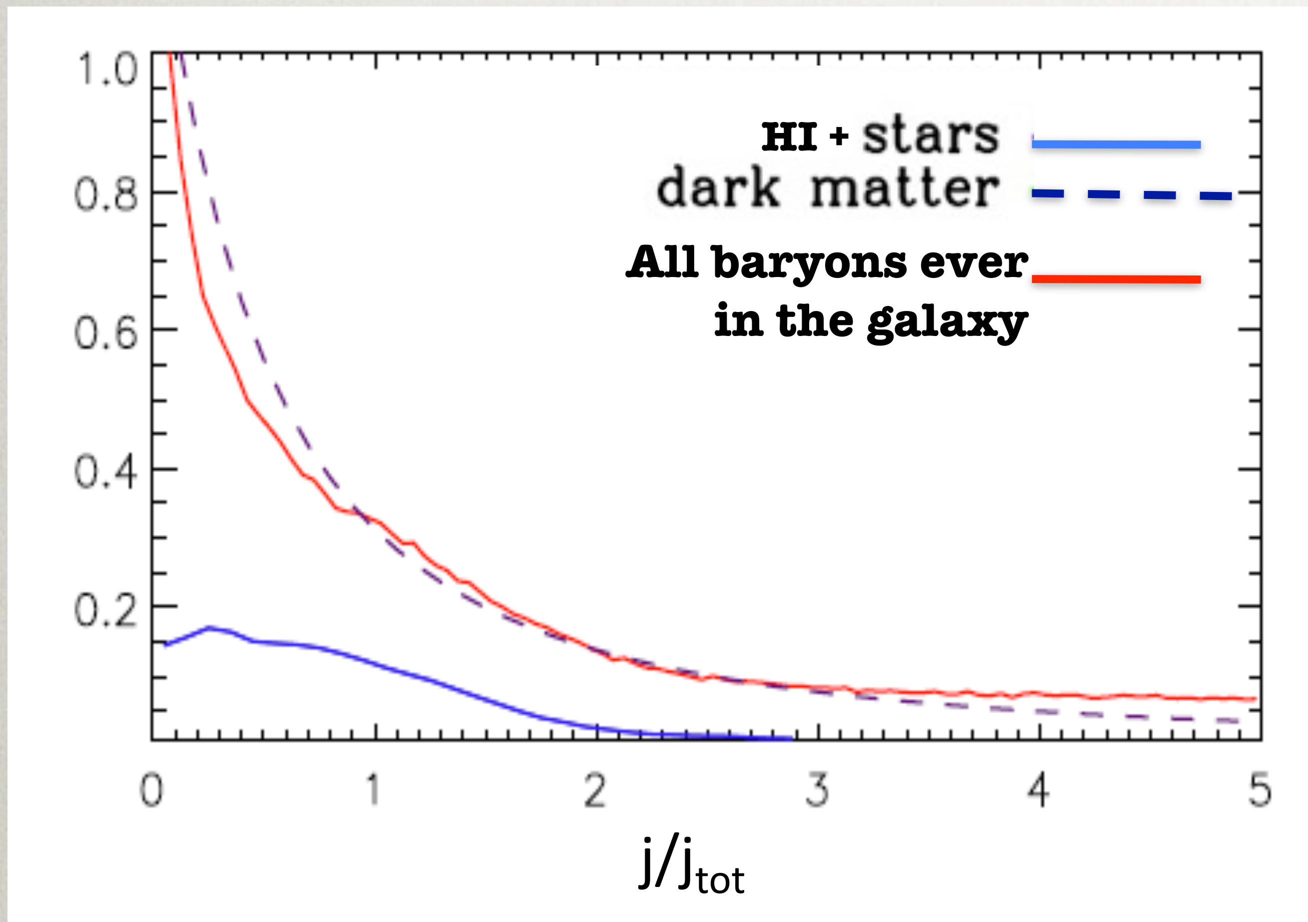


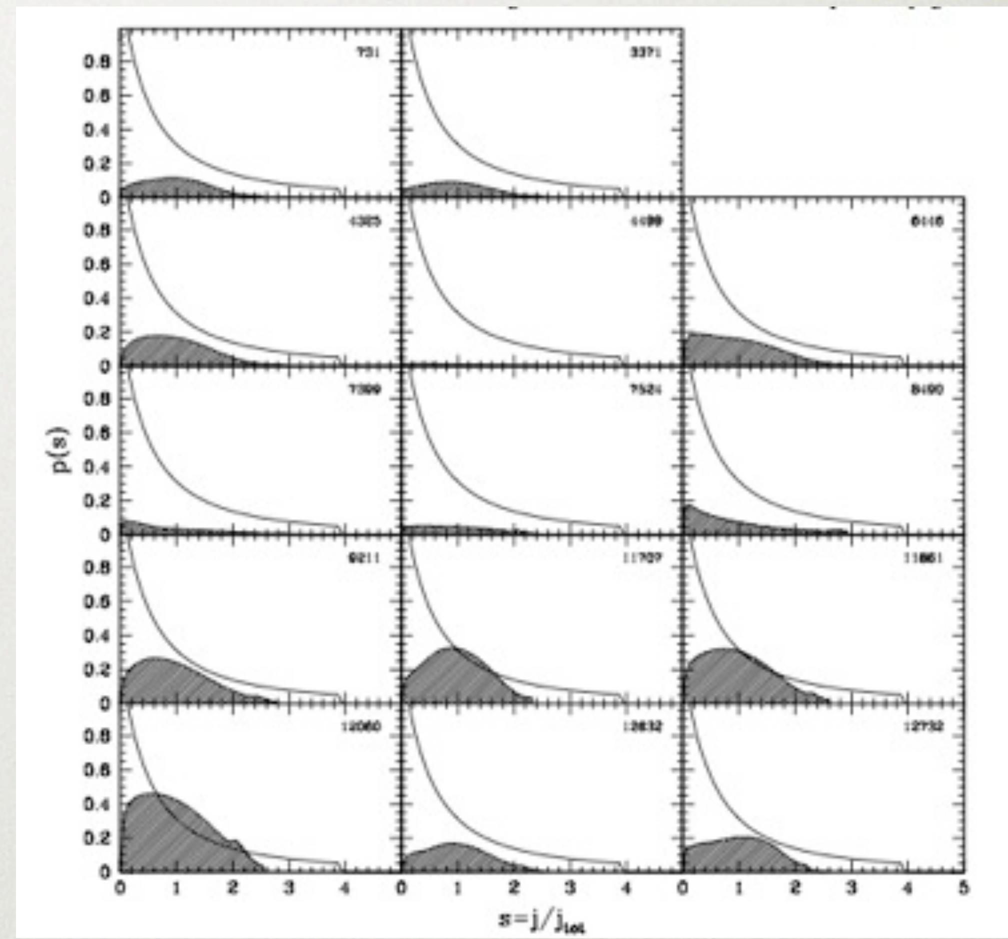
Brooks, Kuhlen, Zolotov, & Hooper (2012), ApJ, 765, 22, arXiv:1209.5394

the Bigger Picture:
The Small Scale "Crisis" of CDM

- Bulge-less disk galaxies
- The cusp/core problem
- The dense satellites problem
- The "Missing Satellites" problem

Supernovae Remove Low Angular Momentum Gas





producing smaller bulges and bulgeless disk galaxies

Governato et al. (2010)

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Cusps Transform into Cores

Repeated bursts of star formation flatten the central density slope

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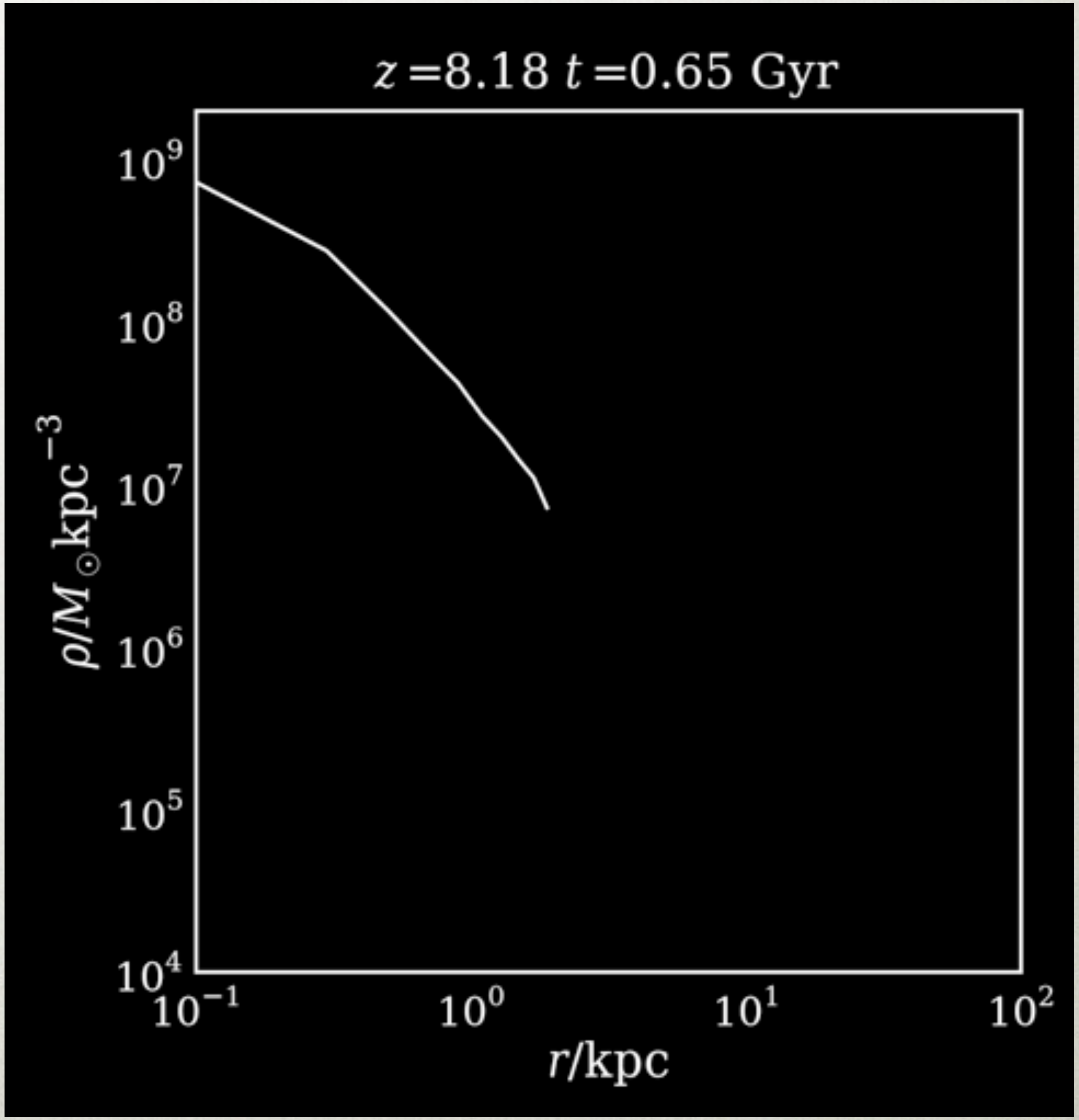
Repeated bursts of star formation flatten the central density slope



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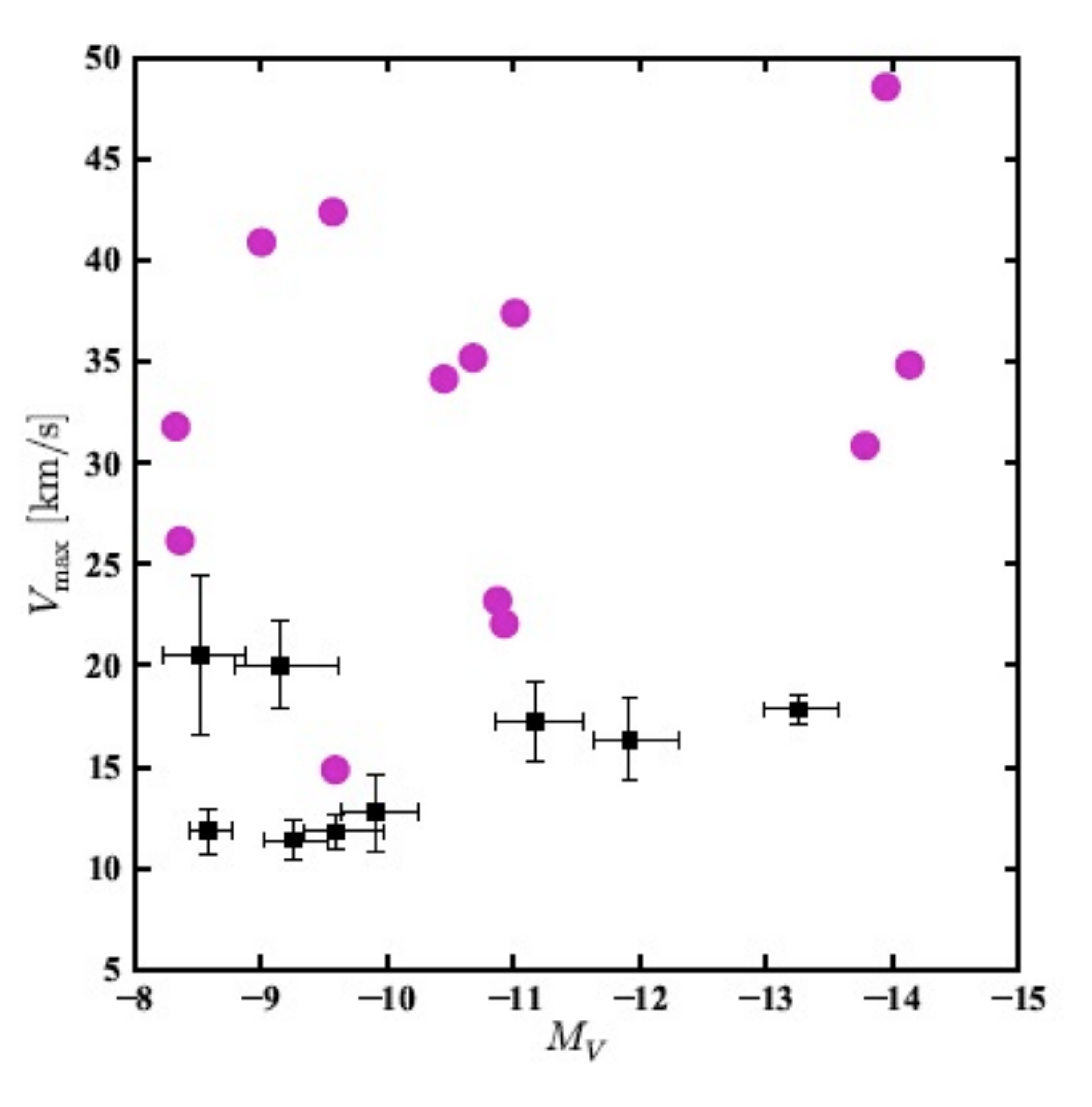
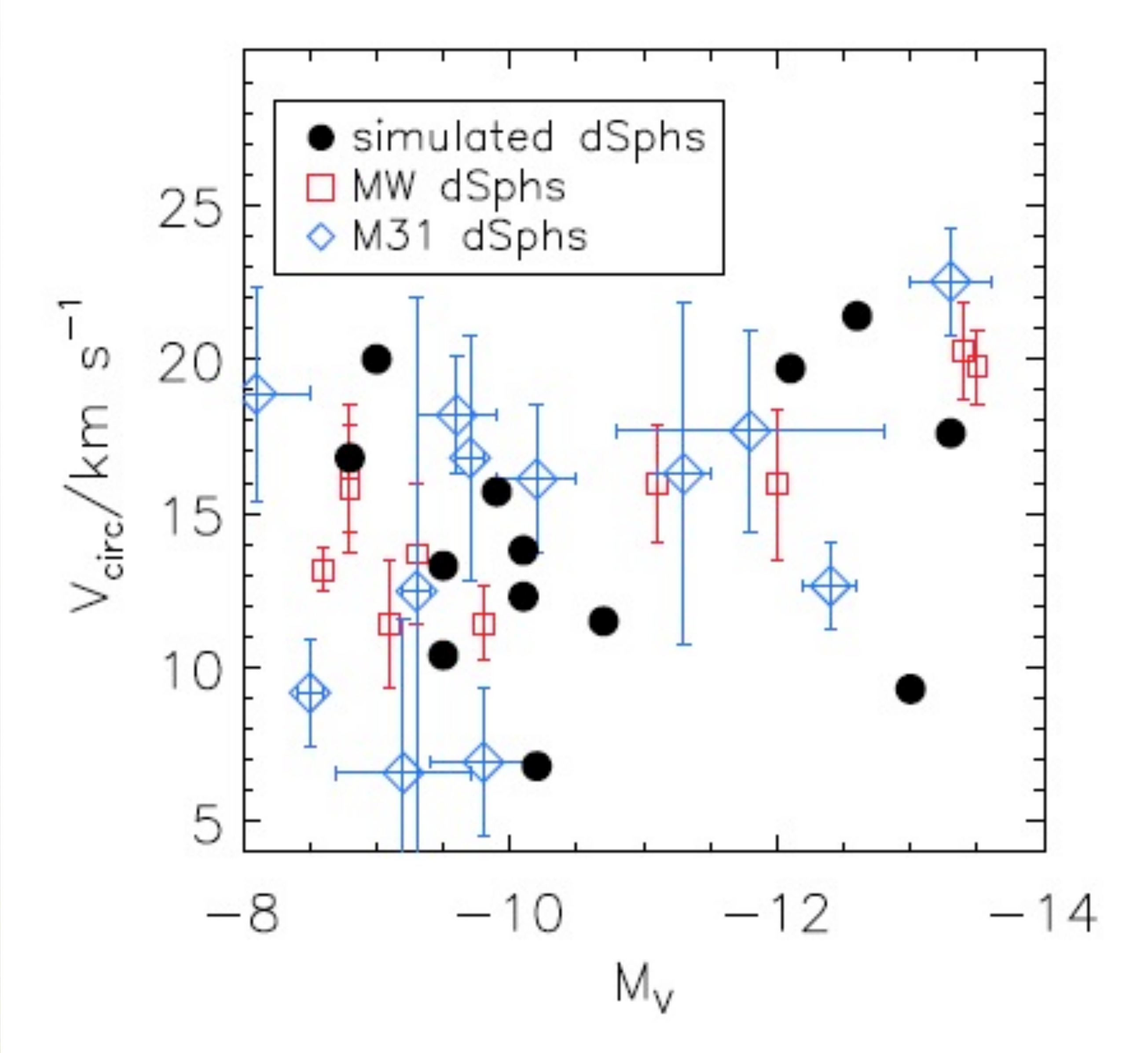
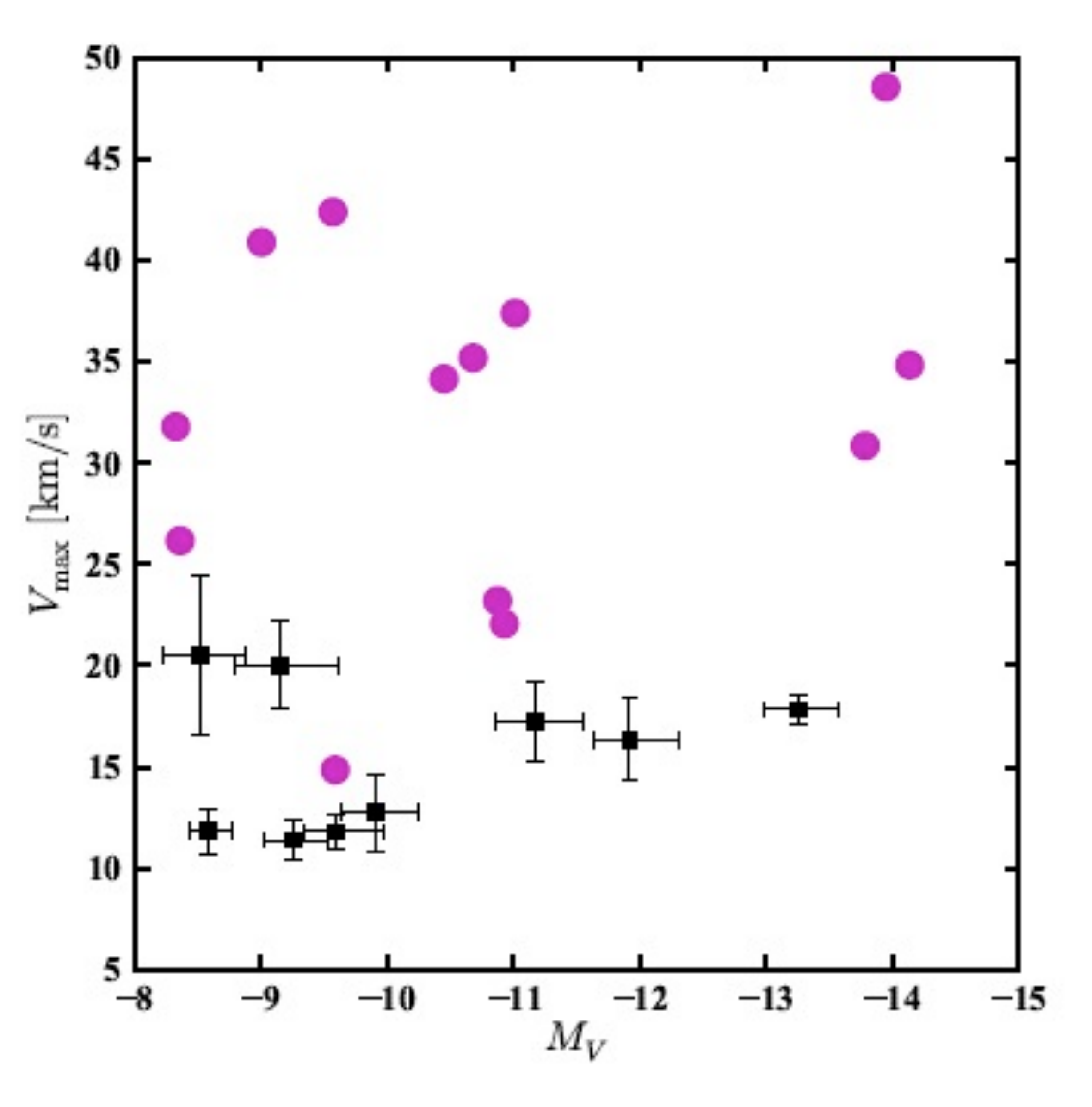
Satellites that are Too Dense

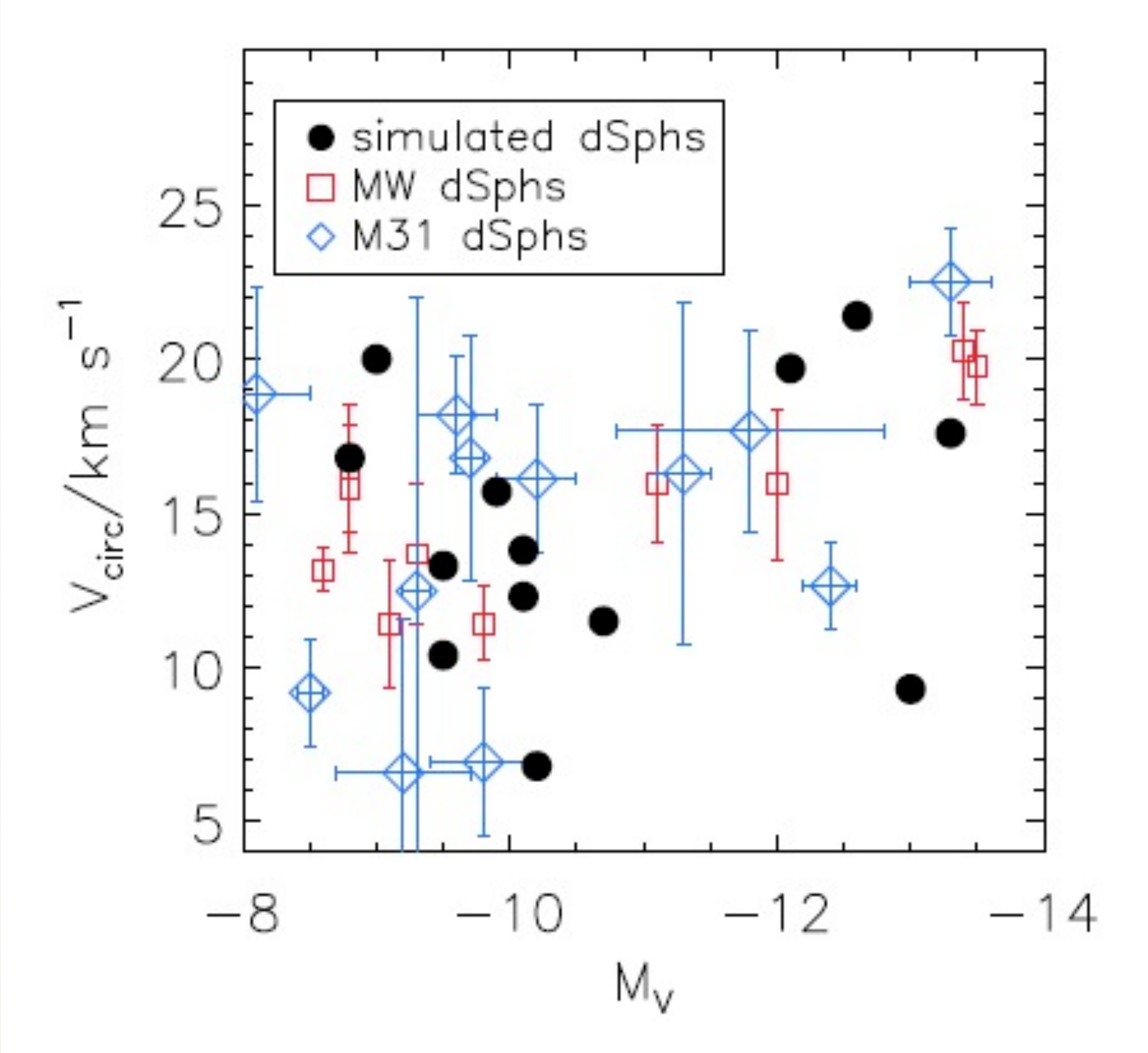




Boylan-Kolchin et al. (2012); Brooks & Zolotov (2012)

Satellites that are not Too Dense





Boylan-Kolchin et al. (2012); Brooks & Zolotov (2012)

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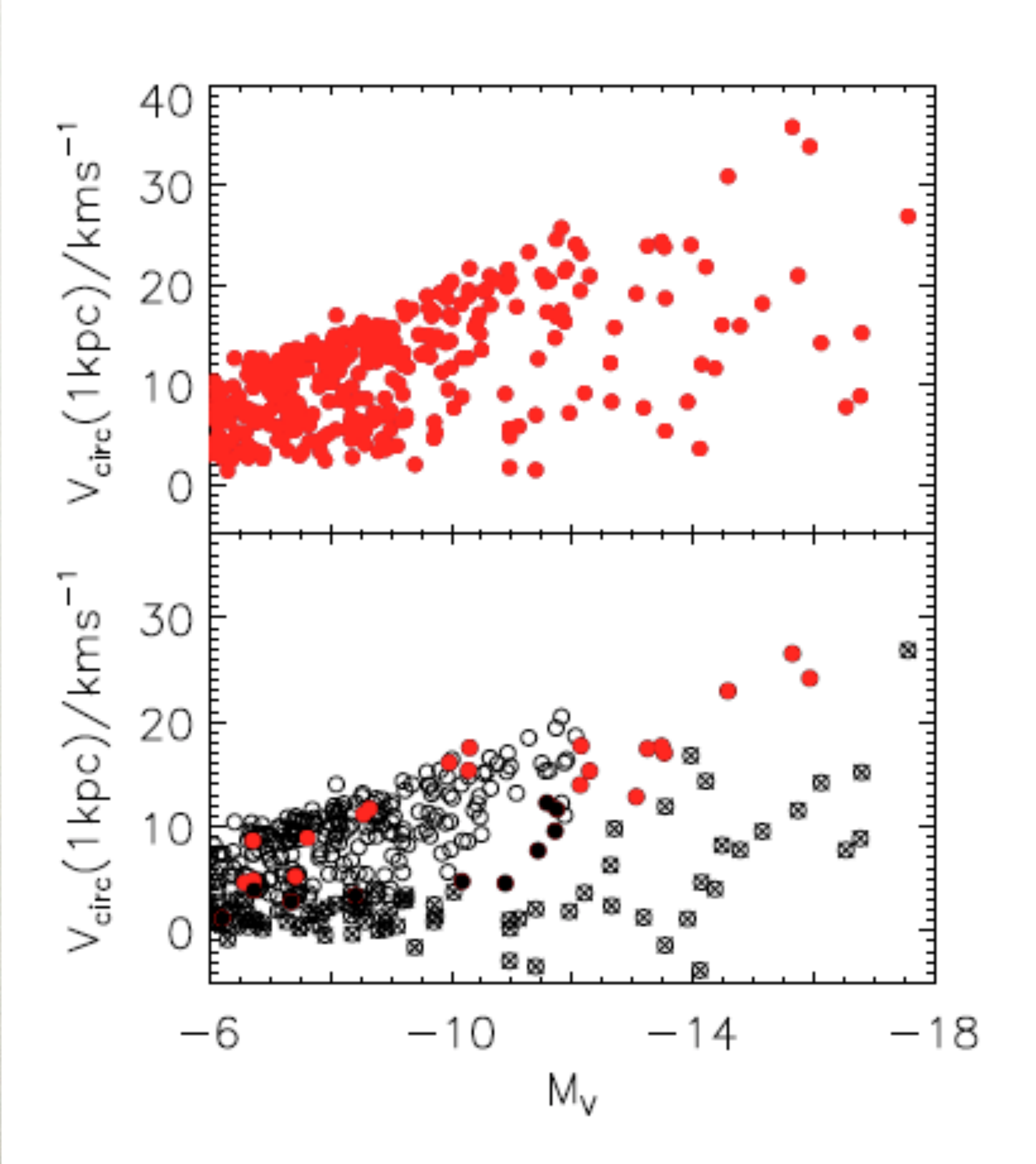
So the Number of Massive Satellites is Reduced...
but what about Luminous Satellites?



Brooks, Kuhlen, Zolotov, & Hooper (2012), ApJ, 765, 22, arXiv:1209.5394

the Bigger Picture:
The Small Scale "Crisis" of CDM

- Bulge-less disk galaxies ✓
- The cusp/core problem ✓
- The dense satellites problem ✓
- The "Missing Satellites" problem maybe

Conclusions

Simulations keep improving! (motivated by higher resolutions)

A more realistic treatments of SF leads to more realistic galaxies

Rapid and repeated gas removal transforms ‘cuspy’ NFW profiles into DM cores

Core creation varies with mass (because SF varies with mass): low mass galaxies that are inefficient at creating stars keep cuspy profiles

A better treatment of baryonic physics may alleviate the small scale crisis of CDM

We must understand the impact of baryonic physics on galaxy formation (in any model)!