Baryons Matter:
Interpreting the Dark Matter Model

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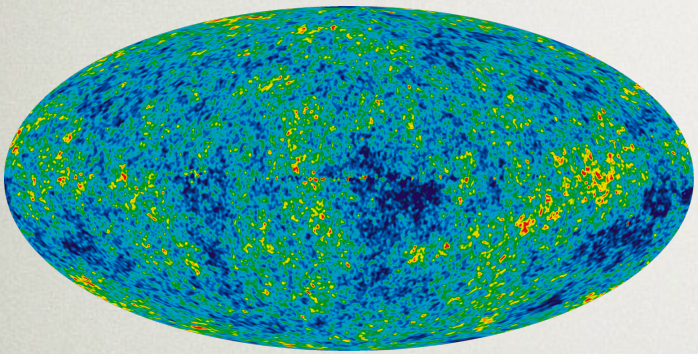
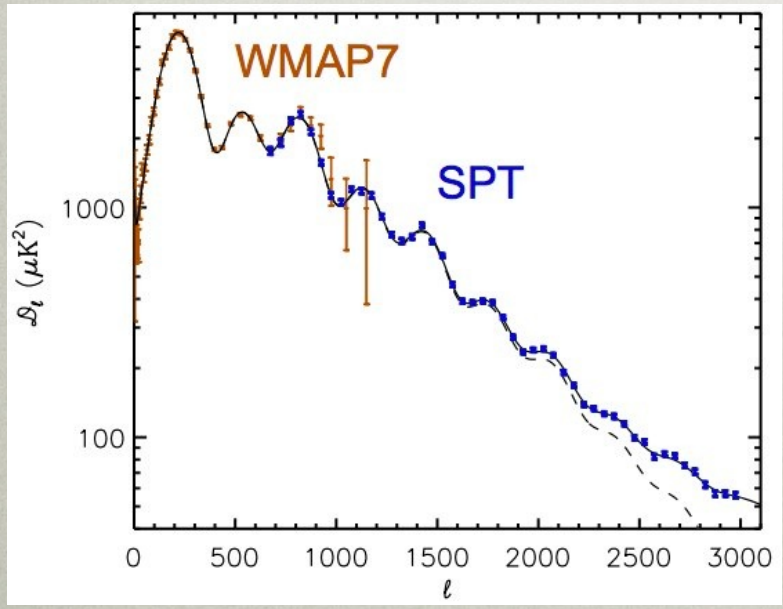
In collaboration with the University of Washington's N-body Shop™
makers of quality galaxies

Most of the Universe is Unknown Stuff





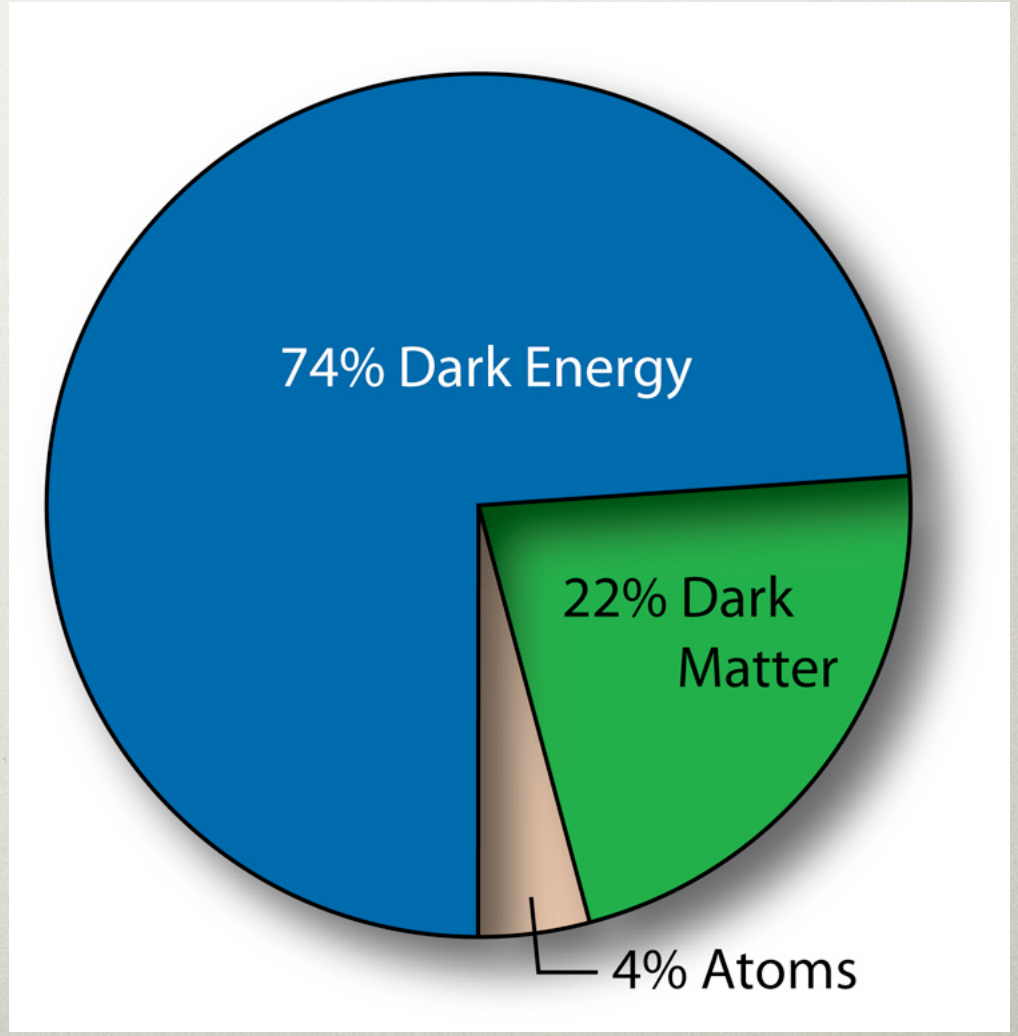
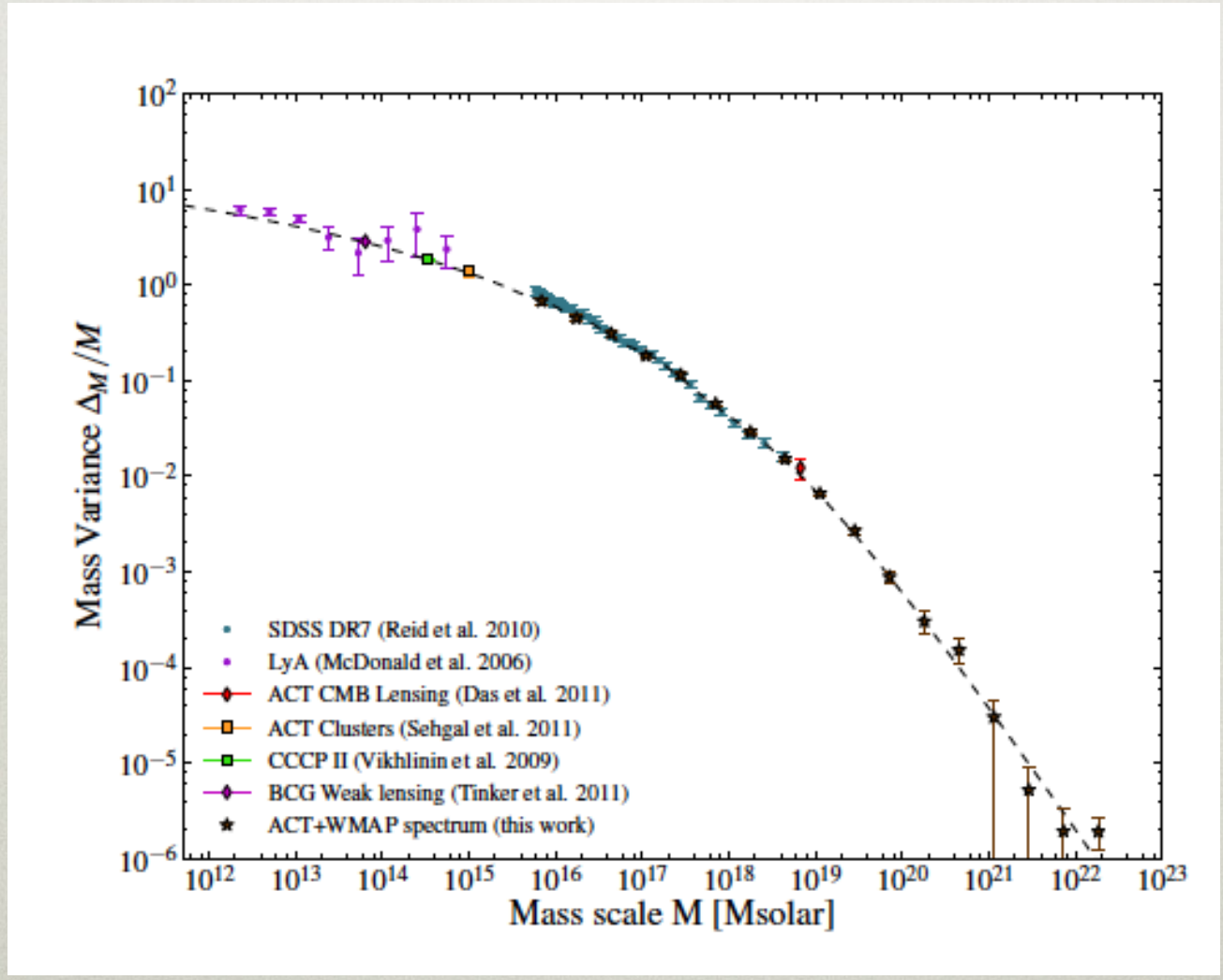


image courtesy of WMAP webpage

CDM is an Excellent Model for the Large Scale Structure of the Universe



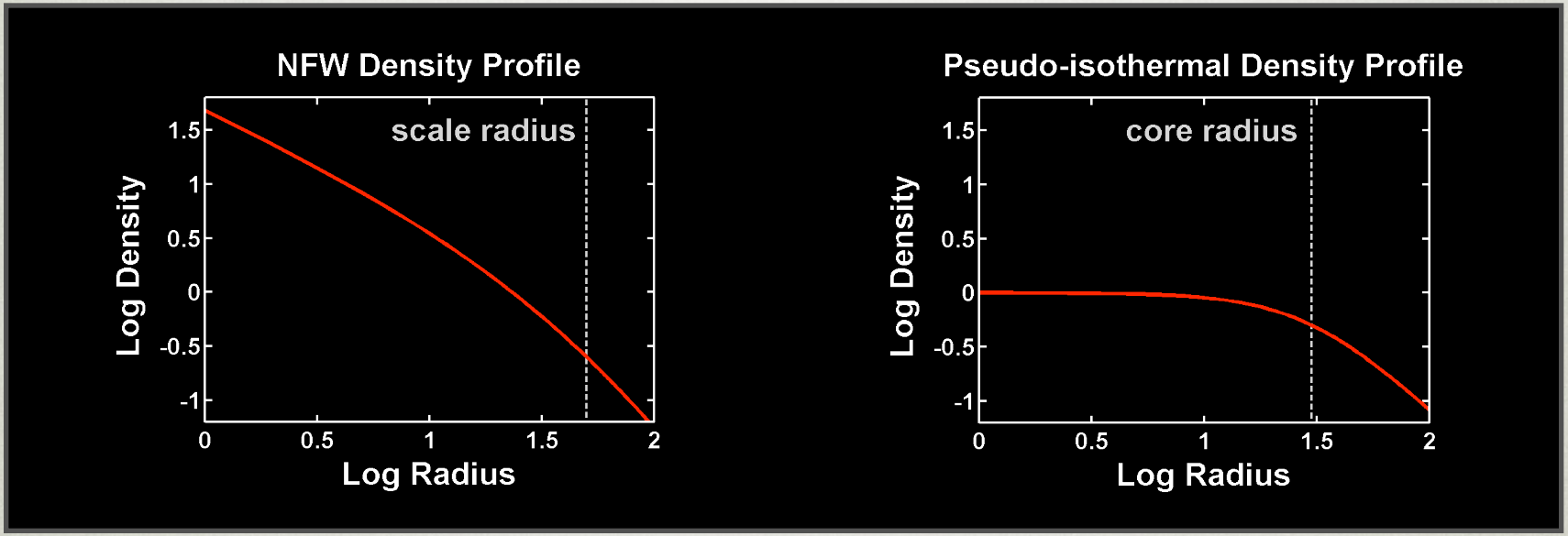
Hlozek et al. (2012)

But...

The Small Scale "Crisis" of CDM

- The cusp/core problem
- Bulge-less disk galaxies
- The "Missing Satellites" problem
- The "Too Big to Fail" (dense satellites) problem

The Cusp/Core Problem



Parameterize density profile as $\varrho(r) \propto r^{-\alpha}$

Simulations predict $\alpha \sim 1$ (central cusp)

Observations show $\alpha \sim 0$ (constant-density core)

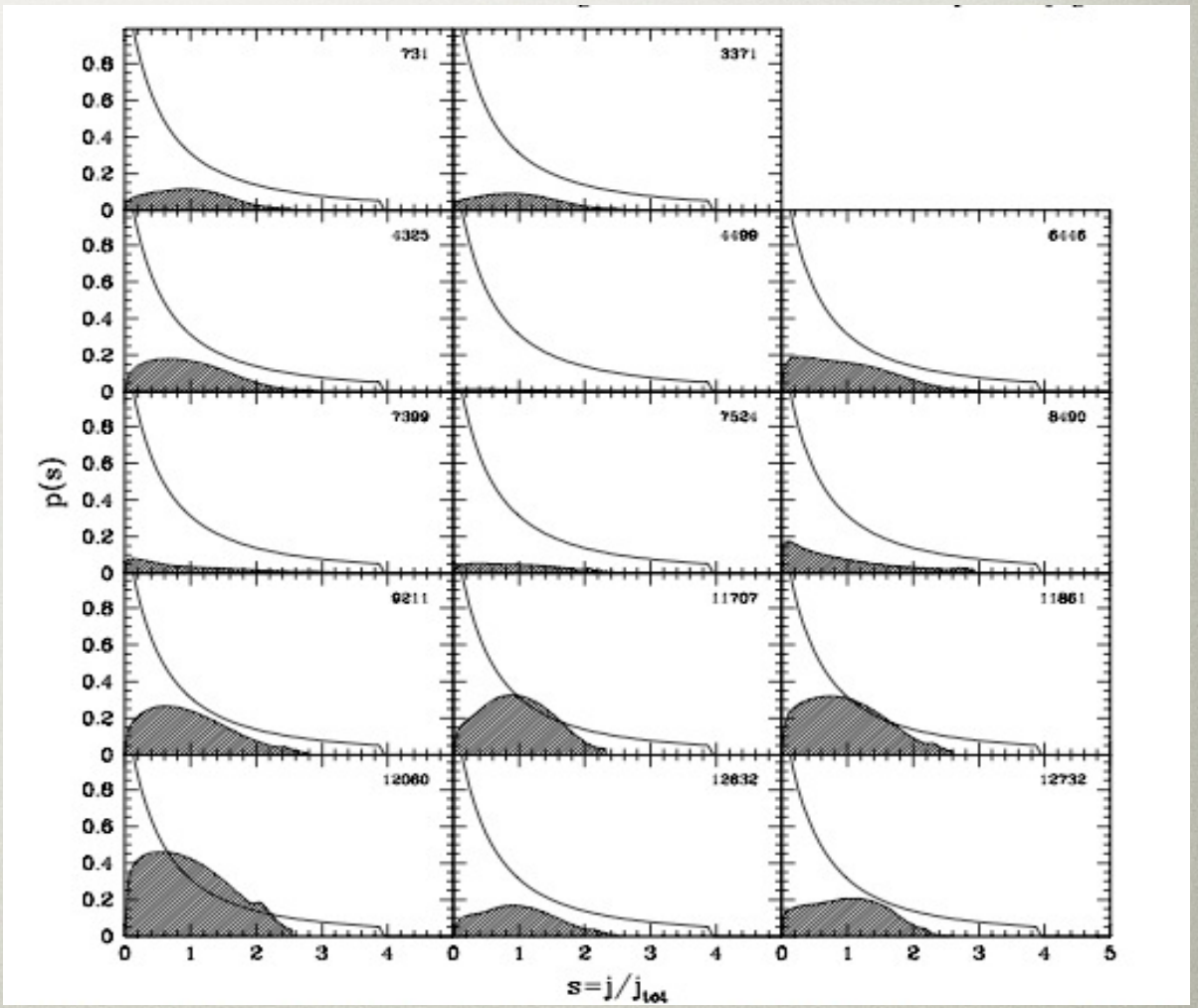
CDM predicts large bulges ...but we rarely see them

A large bulge

A "bulgeless" disk

CDM predicts large bulges ...but we rarely see them

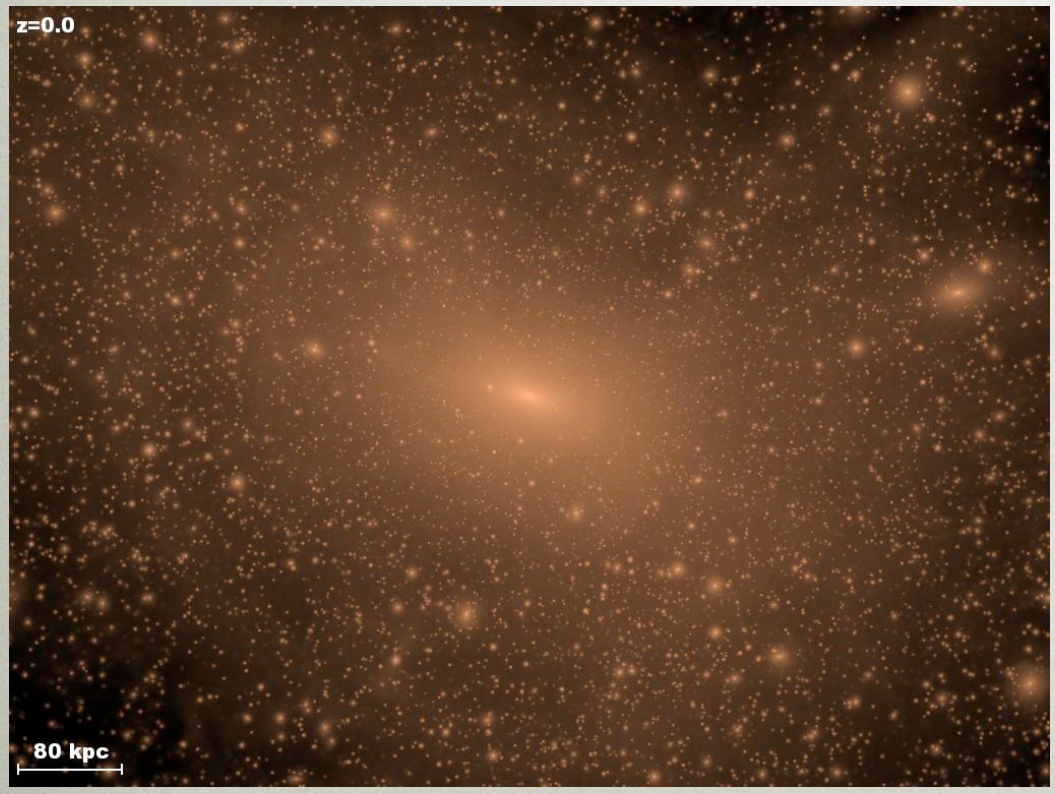
- Tidal torques: predict the sizes of disks well
- But over-predict the amount of low angular momentum gas



van den Bosch et al. (2001)

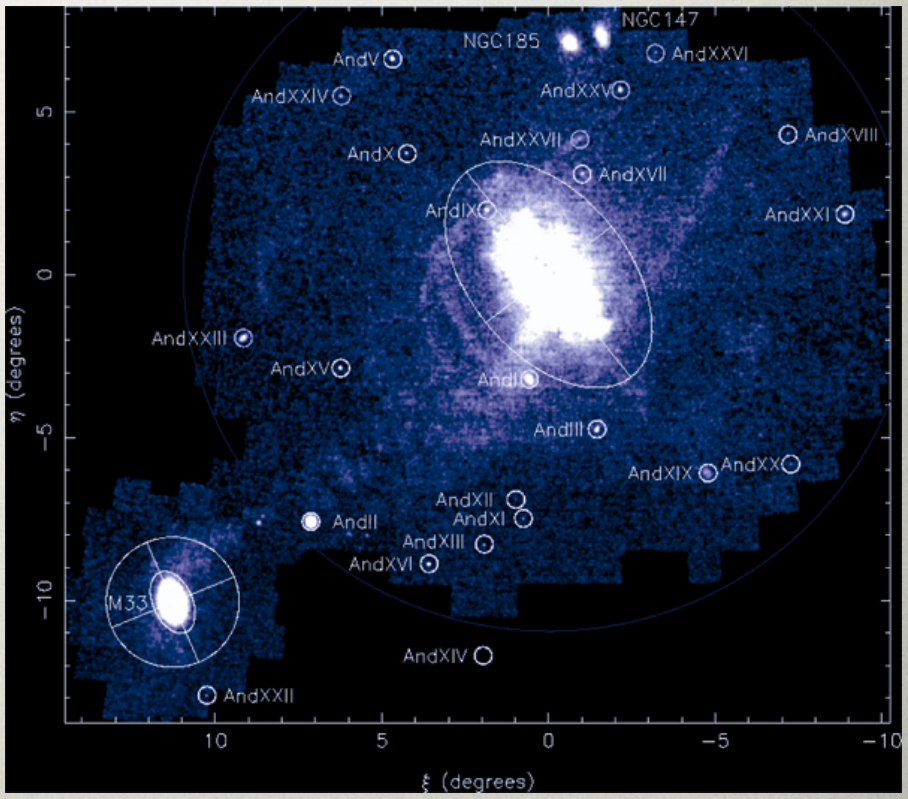
The "Missing Satellites" Problem

1000's of satellites predicted



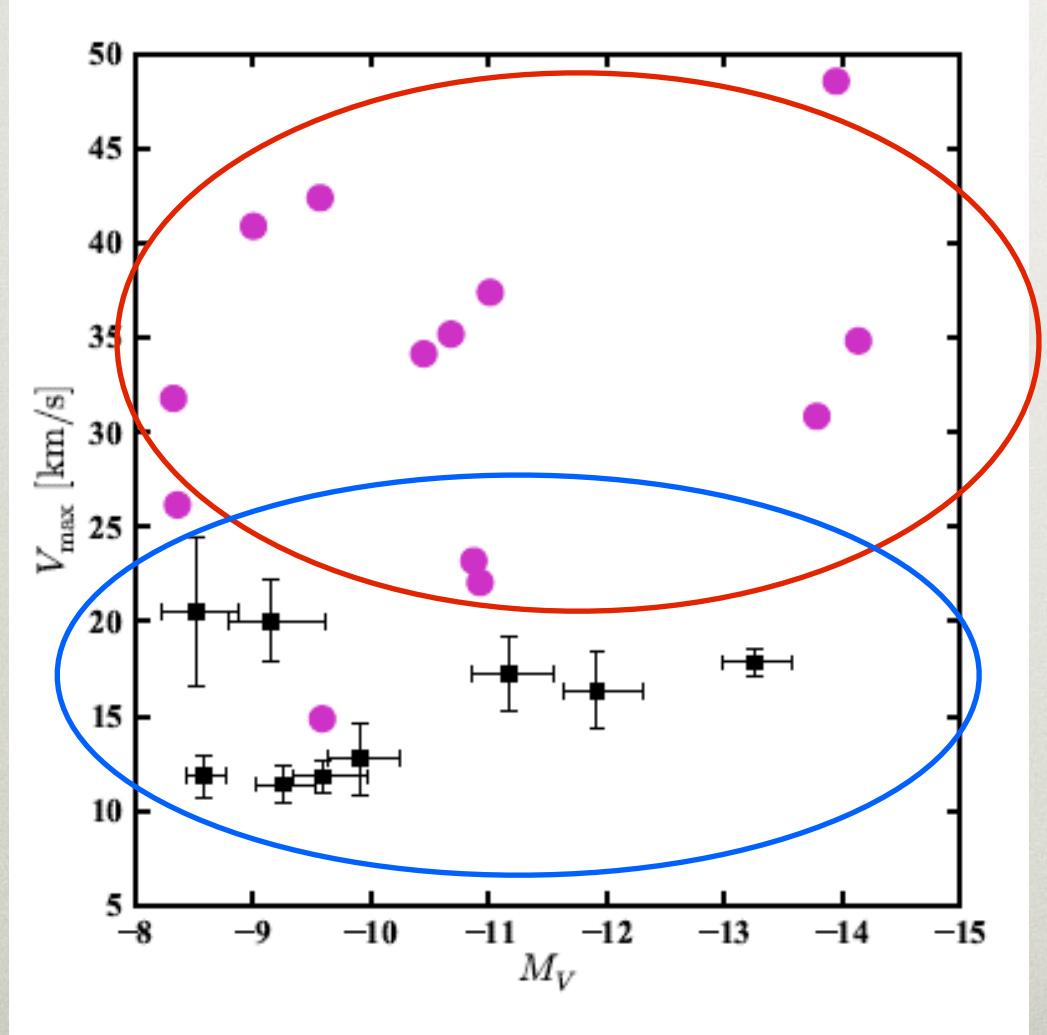
"Via Lactea" Simulation

dozens seen



Pan-ANDromeda Archeological Survey (PAndAS)

The Predicted Satellites are too Dense



Predicted

Observed

Boylan-Kolchin et al. (2012)

So...
CDM is Wrong?

Maybe it needs to be modified?

Maybe WDM that washes out the small scales?

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

So...
CDM is Wrong?

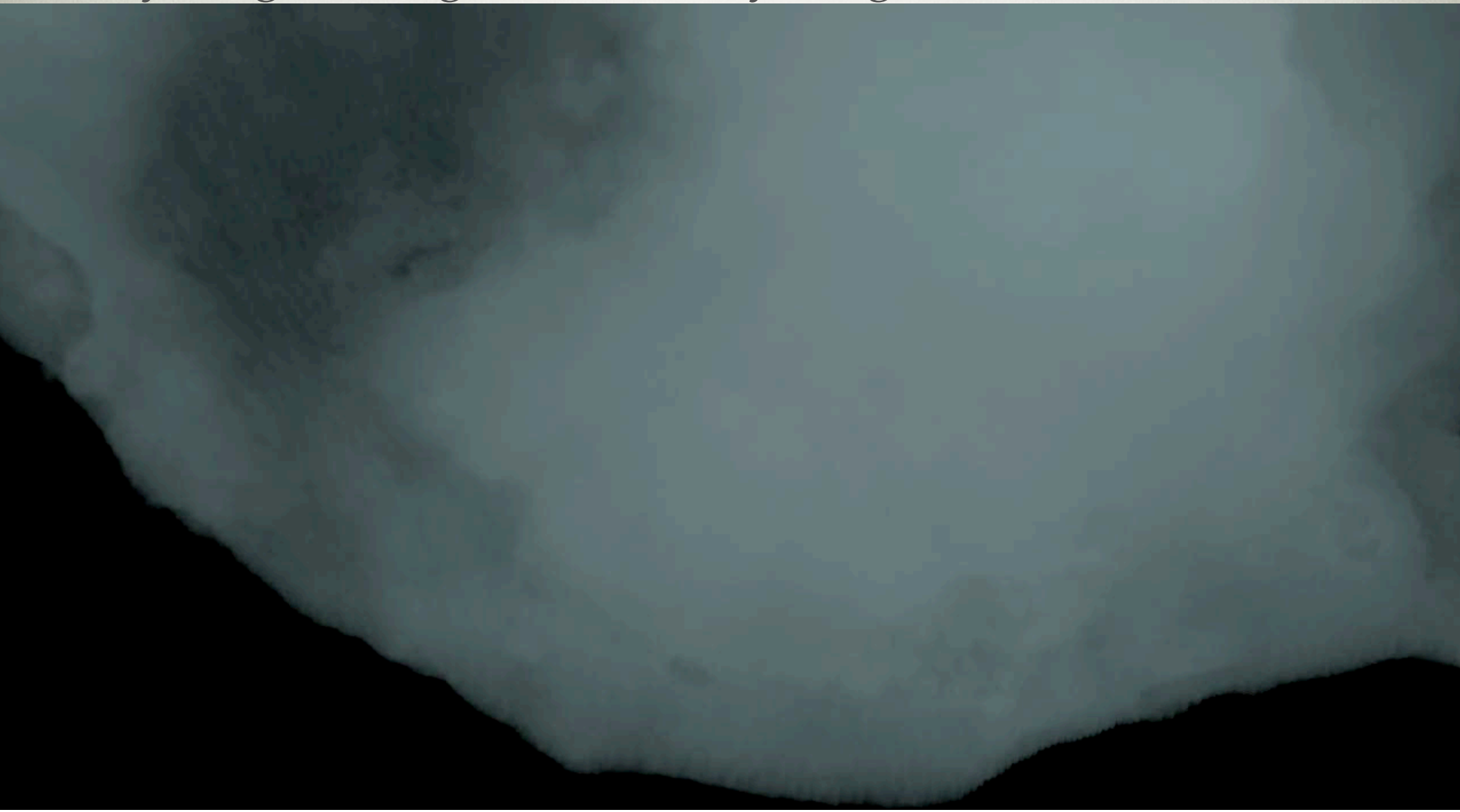
But what about the 4%?

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

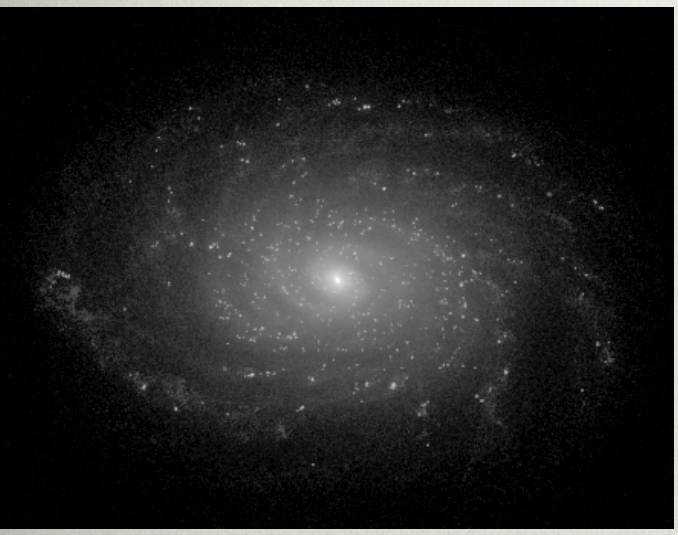
All of the predictions that lead to the small scale crises
are based on Dark Matter-only simulations.

Gas is Much More Complicated (and expensive)!

Greyish-green = gas Blue = young stars Red = old stars

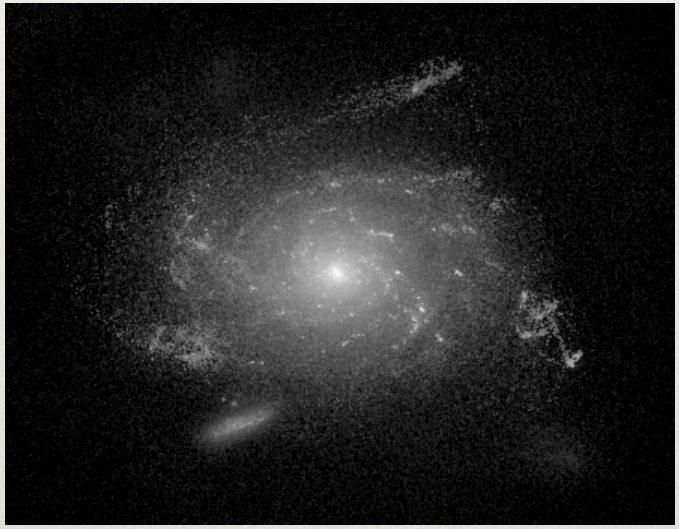


Gasoline



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

x5



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

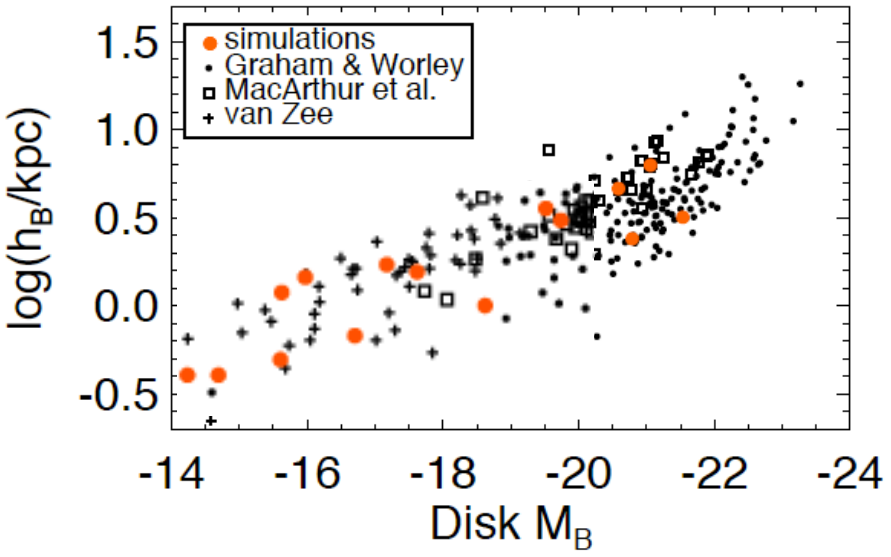
x4

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

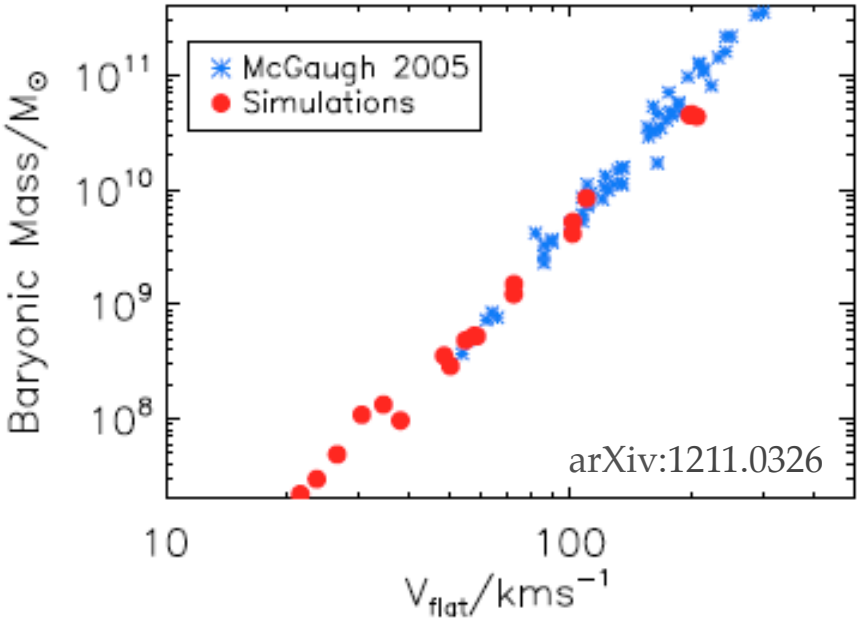
> 10

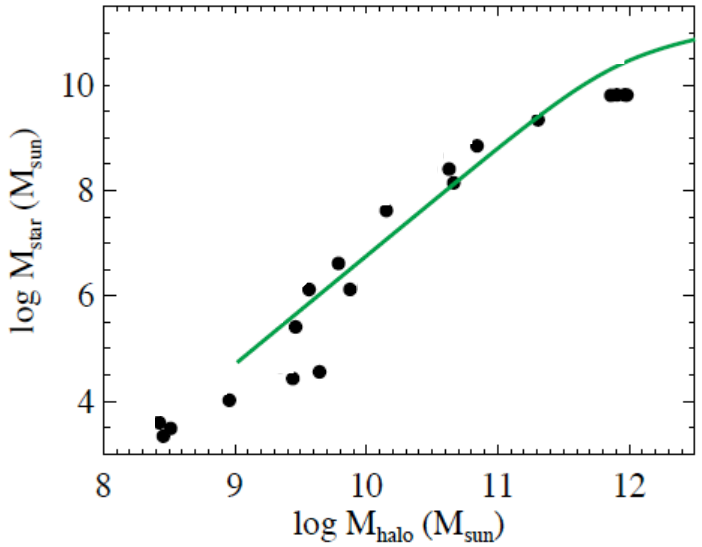
Resulting Galaxies Match Observed Scaling Relations

Size-Luminosity (Brooks et al. 2011)



Baryonic Tully-Fisher (Christensen et al., 2013)





Stellar-to-Halo Mass (Munshi et al. 2013)

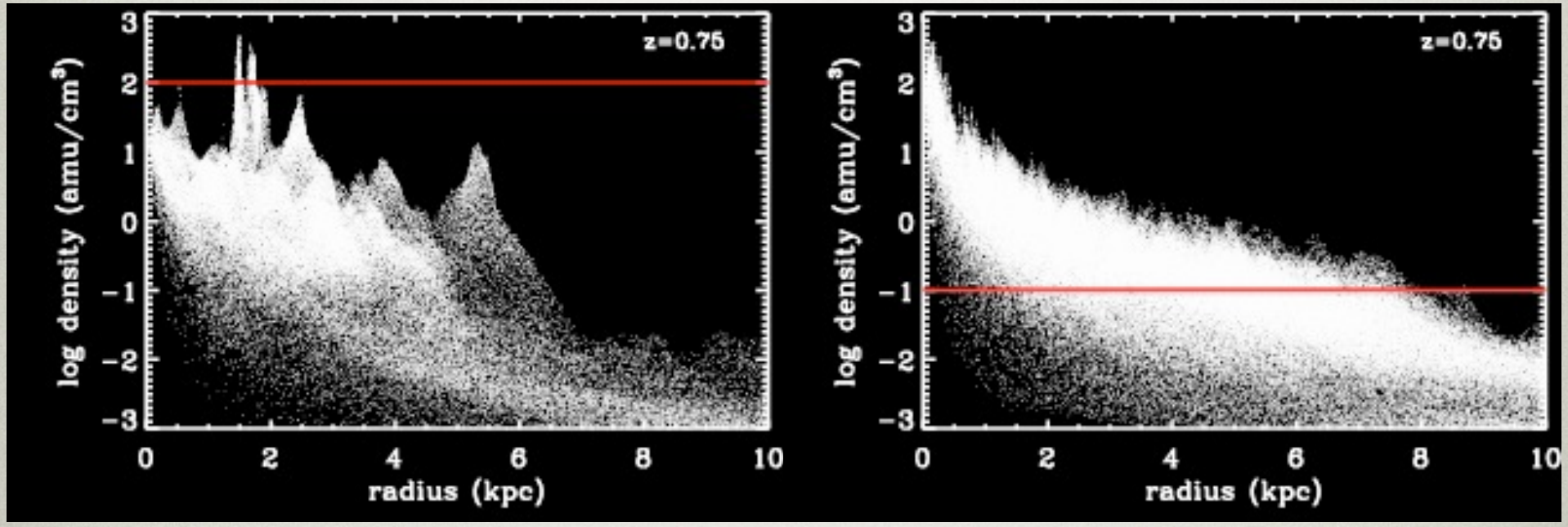
...and Mass-Metallicity (Brooks et al. 2007)

...and HI gas fractions (Munshi et al. 2013)

...etc

Why do resolution and feedback matter?

“Resolving” Star Formation Regions



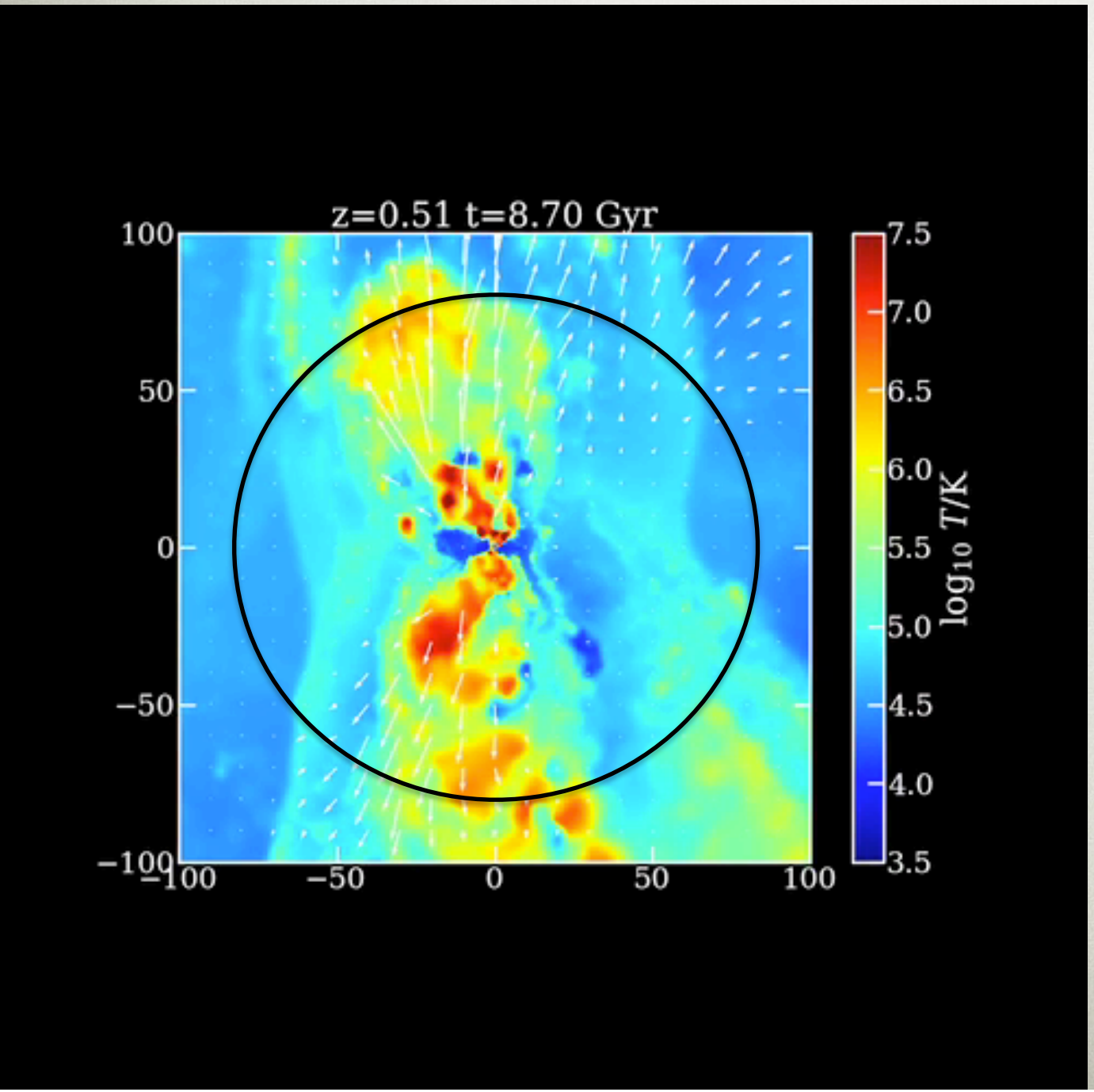
High threshold

Low threshold

Feedback becomes more efficient
(more outflows per unit mass of stars formed)

See also: Mashchenko et al. (2006, 2008), Ceverino & Klypin (2008)
Robertson & Kravtsov (2008), Tasker & Bryan (2008)

Outflows!



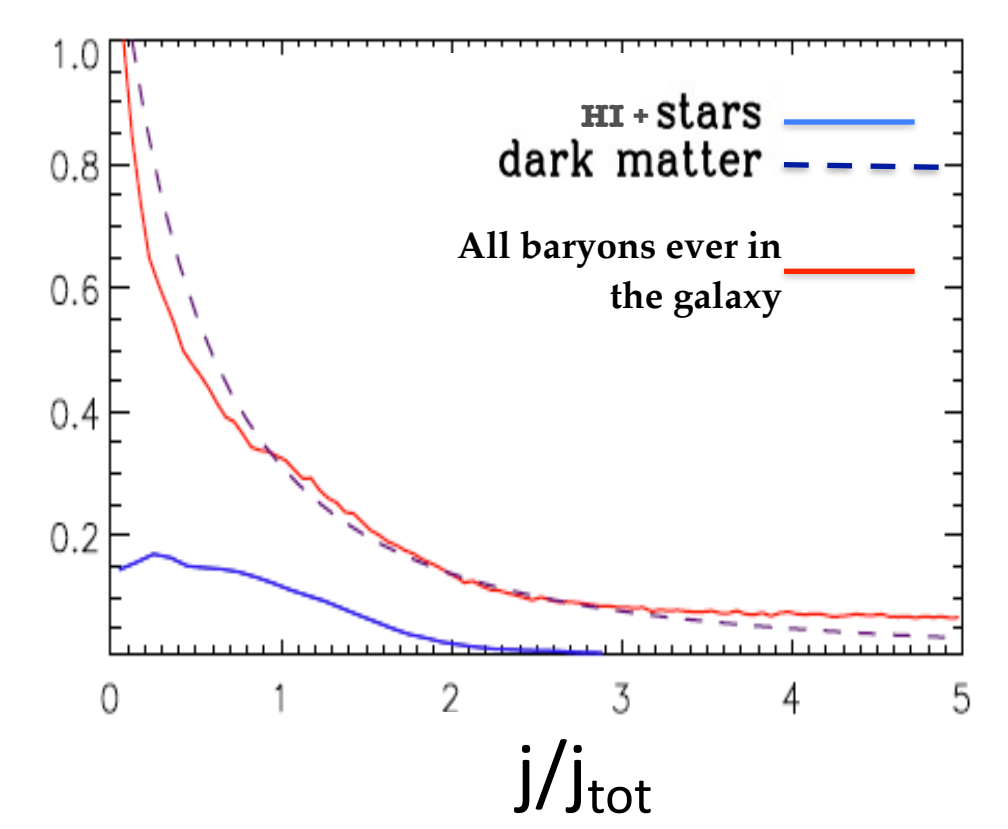
M_{vir} ~ 10^{10} M_{sun}
"dwarf galaxy"

Edge-on disk orientation

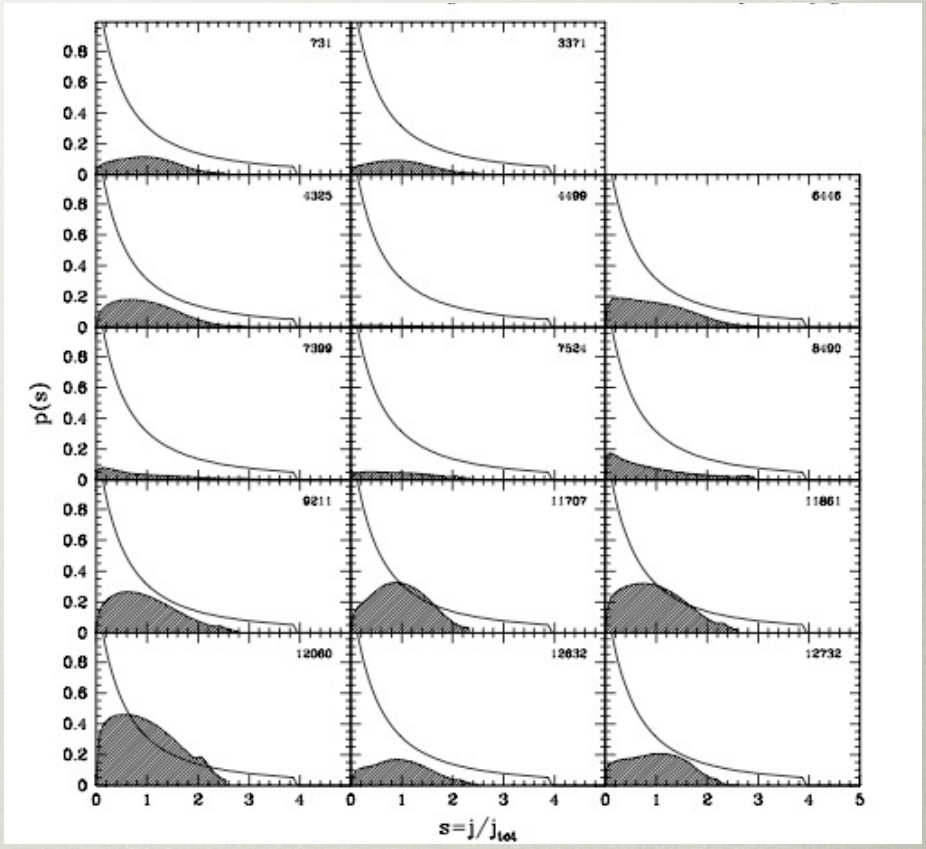
(arrows are velocity vectors)

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

Outflows Remove Low Angular Momentum Gas

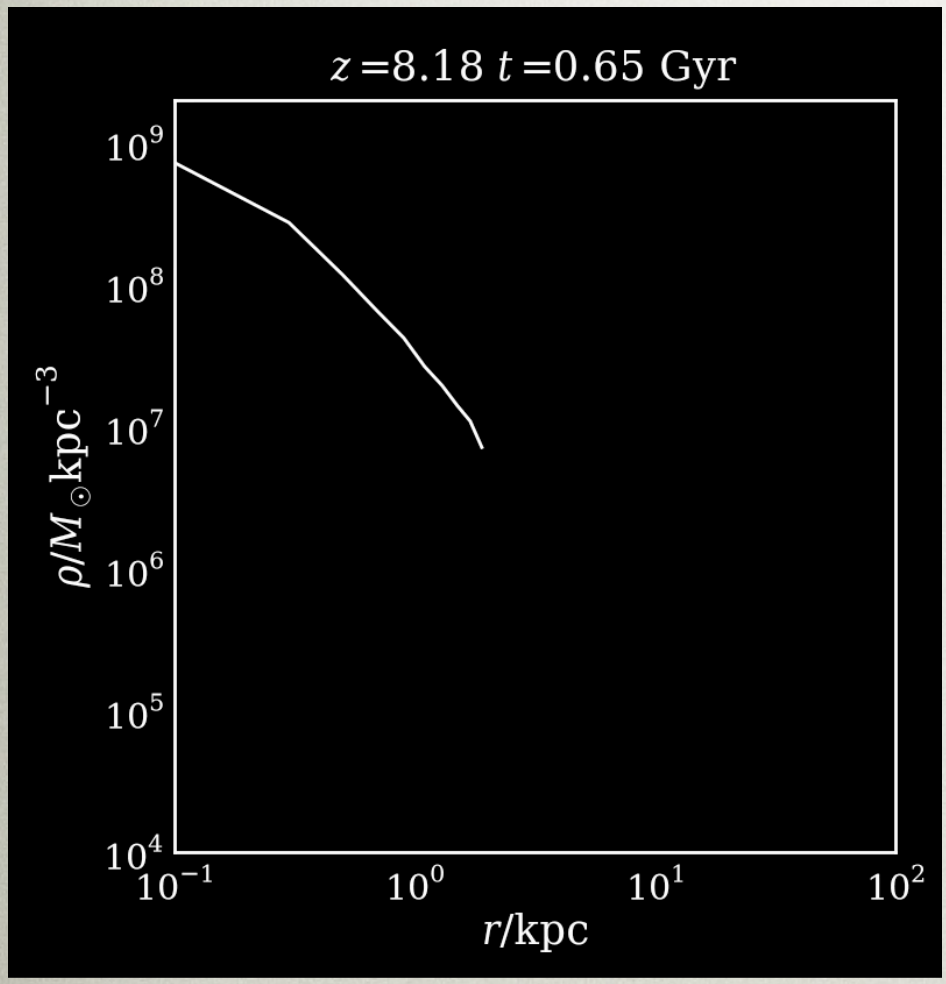


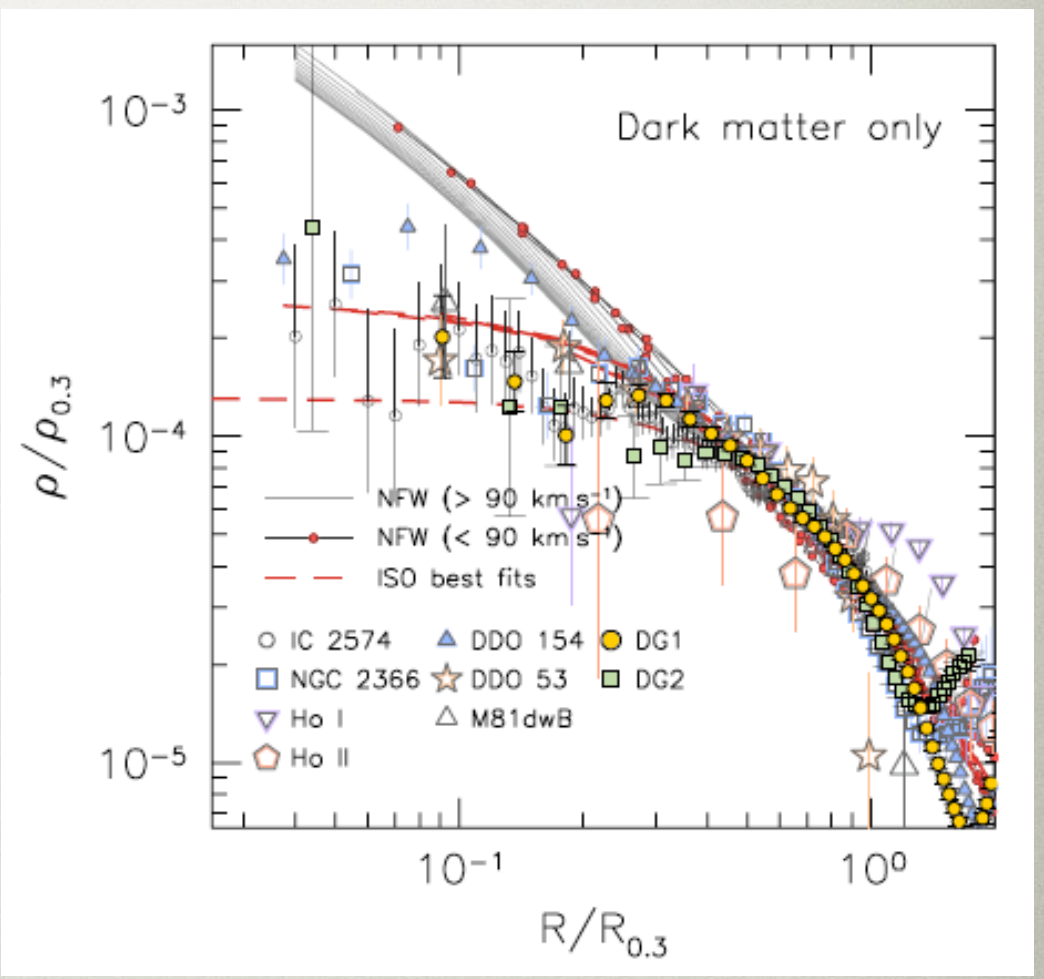
Brook et al., 2011, MNRAS, 415, 1051



van den Bosch et al. (2001)

Creation of a Dark Matter Core

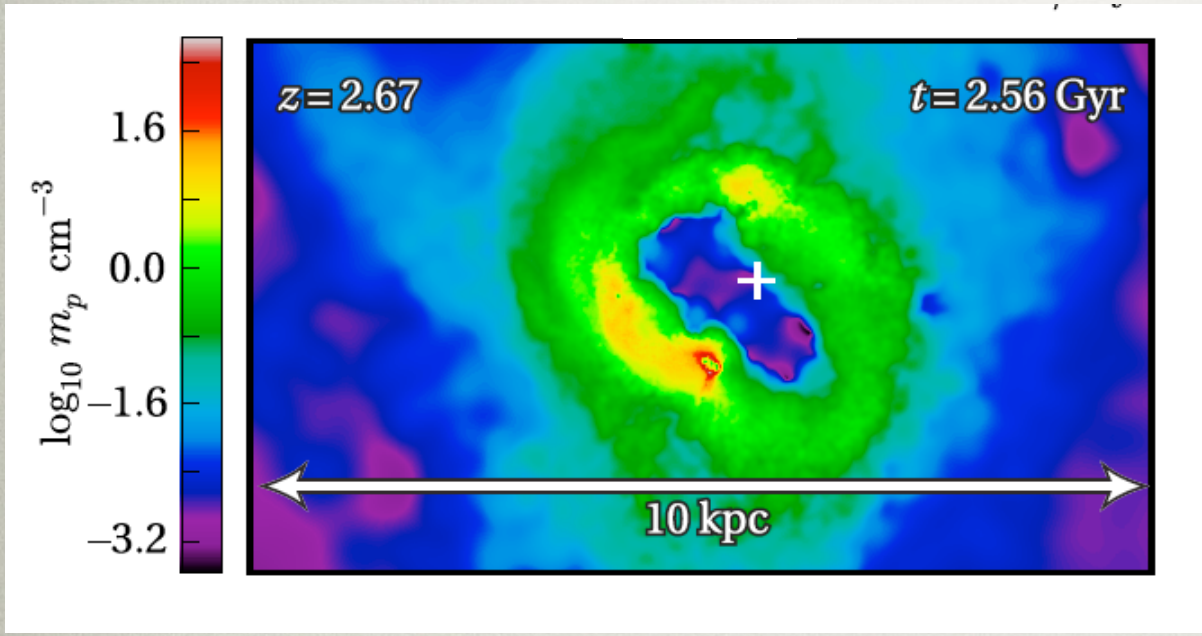


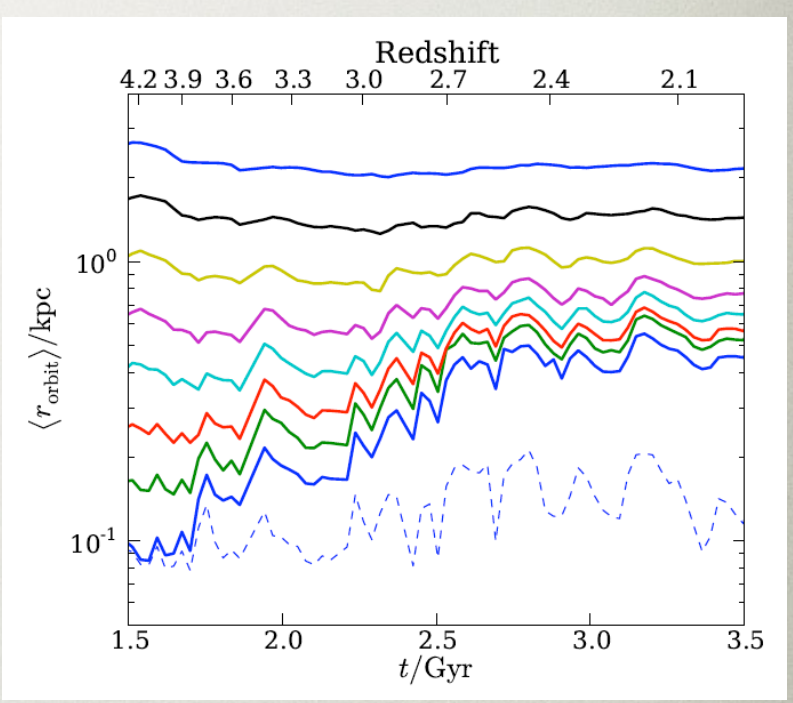


Oh et al., 2011, AJ, 142, 24

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

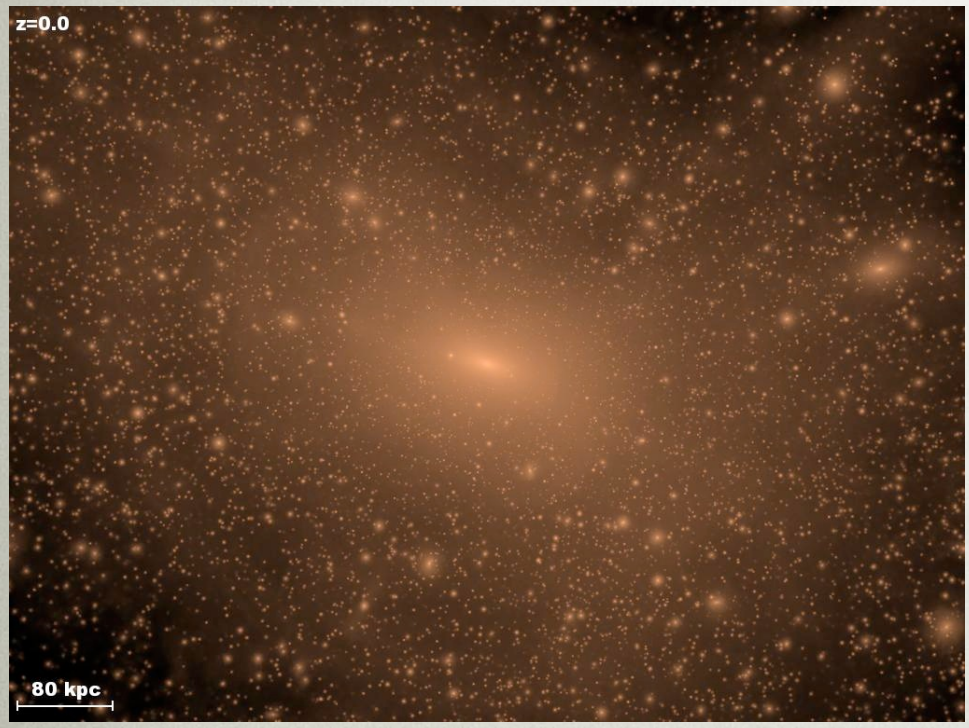
How are Cores Created?





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

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



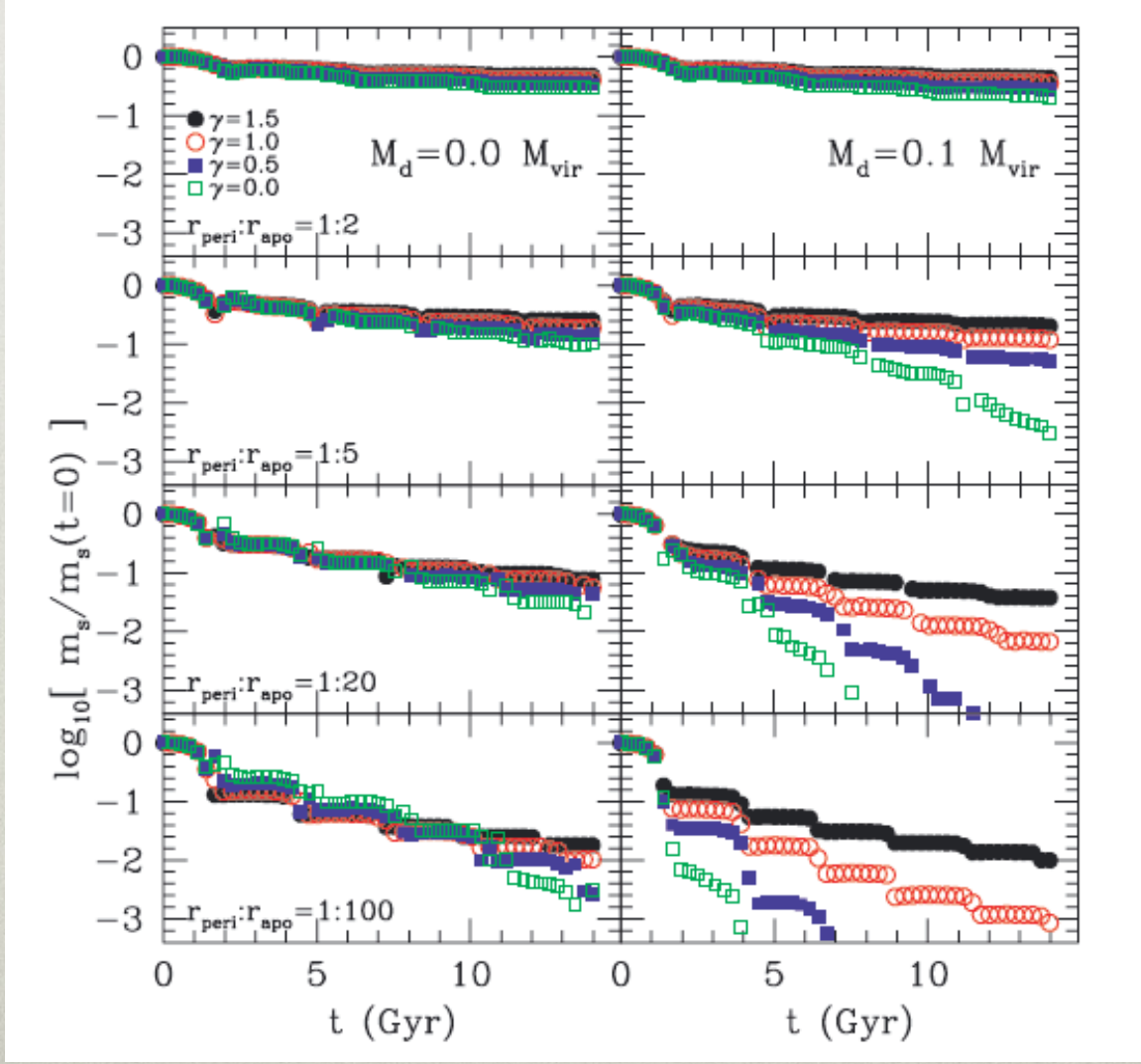
Dark Matter

Baryons

(or any central baryonic concentration)

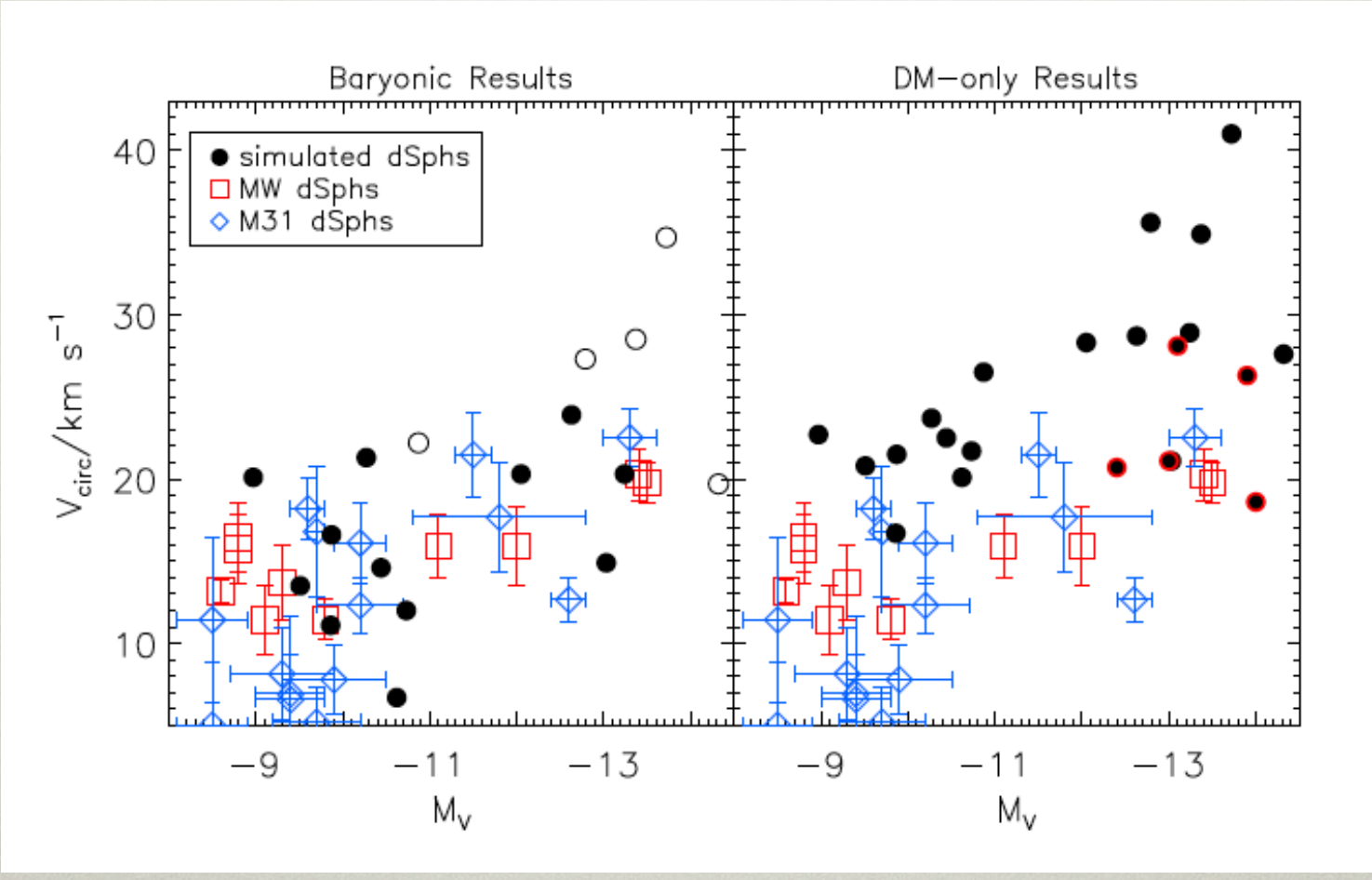
Chang et al. (2012)

Not Just Core Creation: The Tidal Effect of the Disk



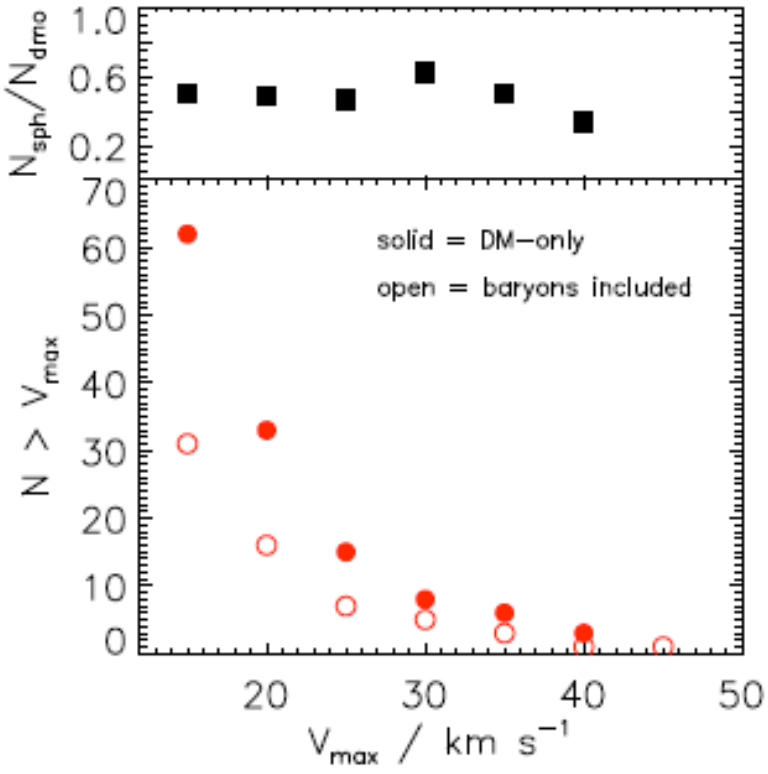
Penarrubia et al. (2010), see also Arraki et al. (2012)

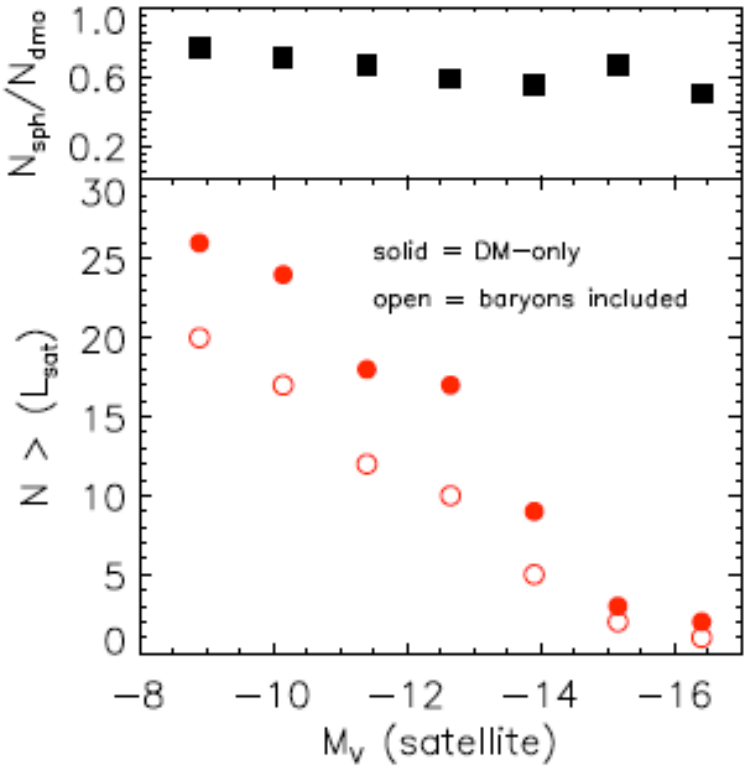
The First Simulated Dwarf Spheroidals to Match Observed Kinematics



Brooks & Zolotov (2014), ApJ, in press, arXiv:1207.2468

The Change to Mass and Luminosity Functions

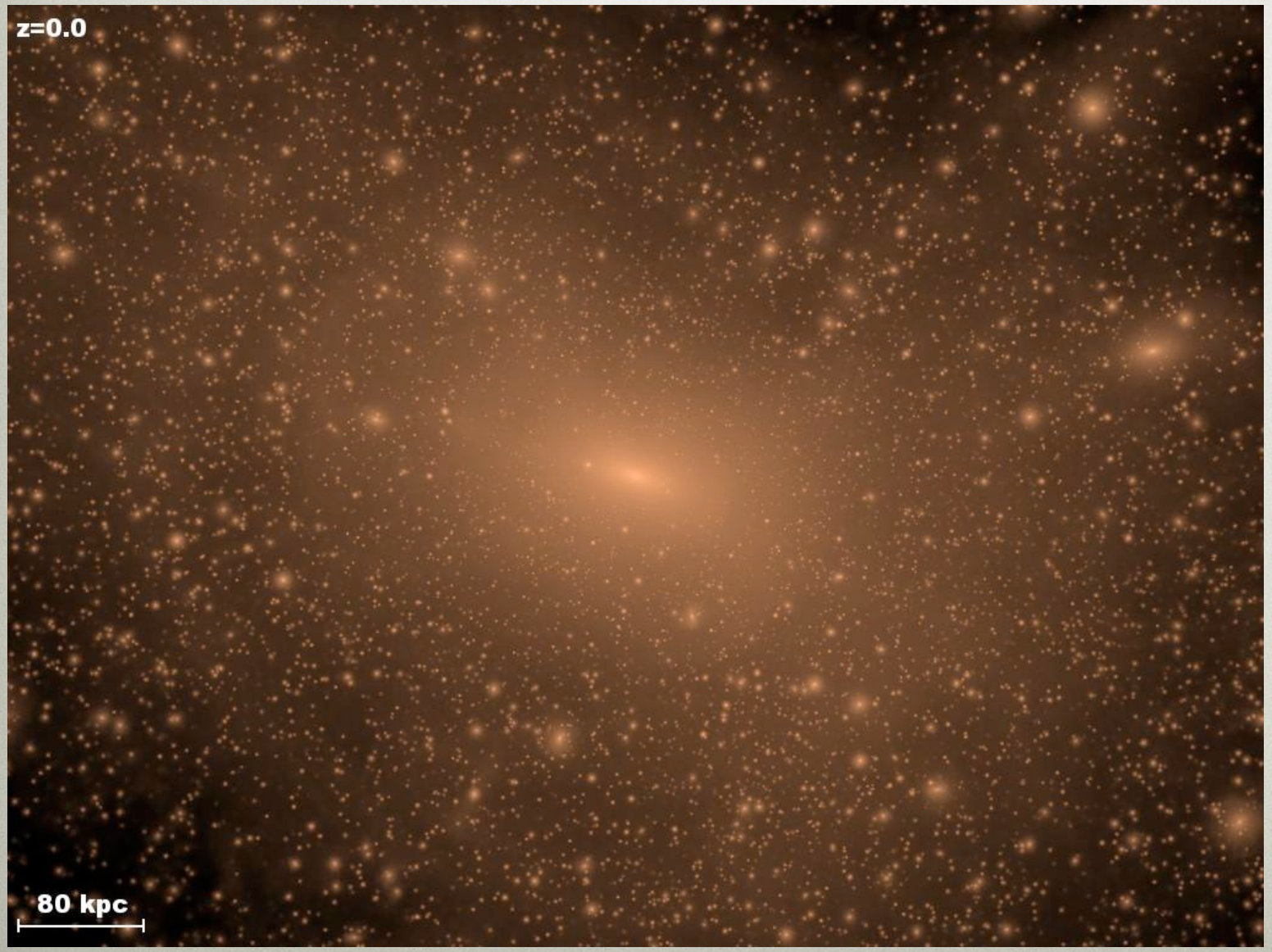




Brooks & Zolotov (2014), ApJ, in press, arXiv:1207.2468

But...

What About the Number of Luminous Satellites?



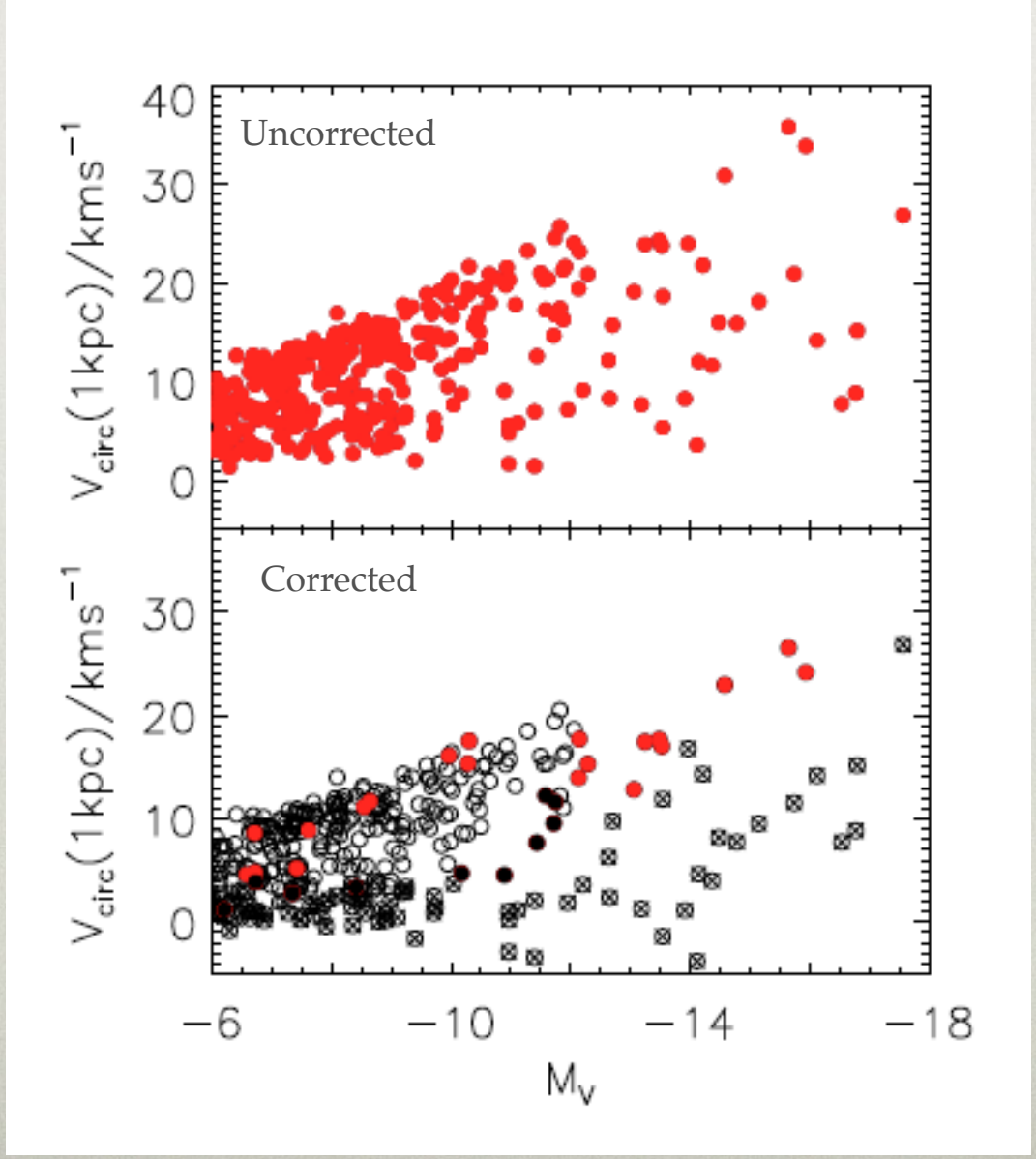
1000's of satellites predicted

dozens seen

"Via Lactea"

So the Number of Massive Satellites is Reduced...

but what about Luminous Satellites?



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

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)!