Baryons Matter

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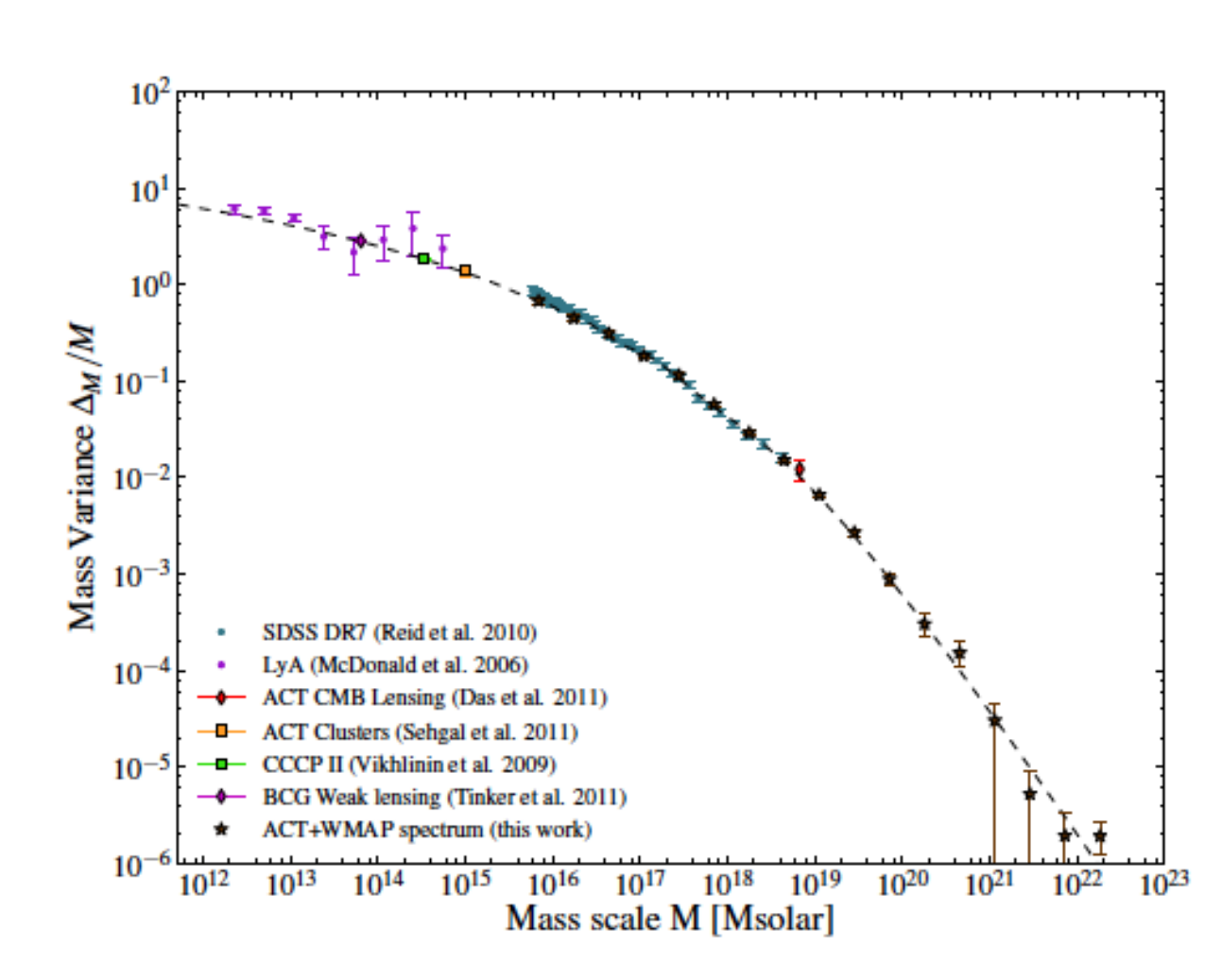
Rutgers, the State University of New Jersey

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

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

So...
(vanilla) 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?

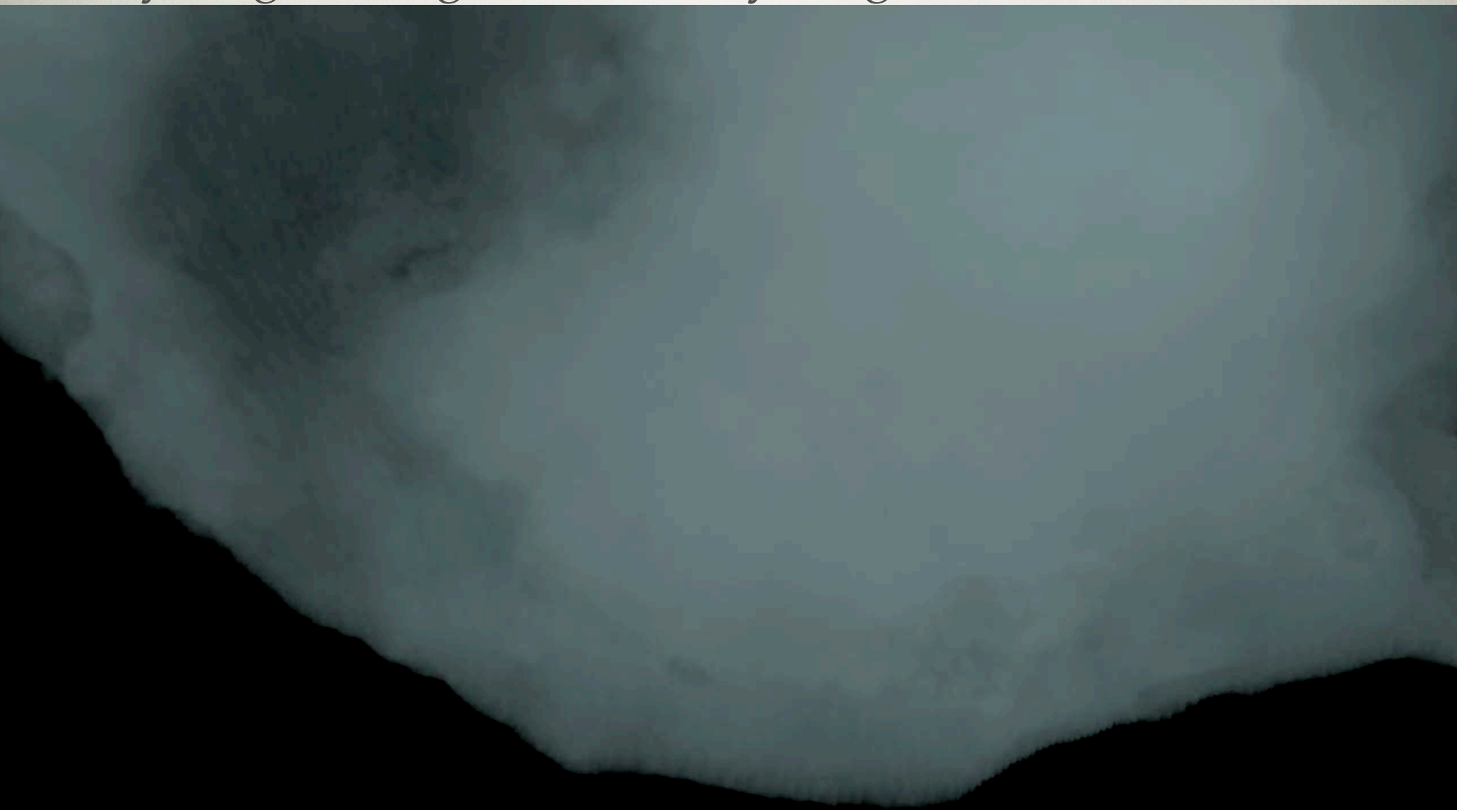
But what about the 4%?

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



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

	Baryons	WDM	SIDM
Bulge-less disk galaxies			
The Cusp/ Core Problem			
Too Big to Fail			
Missing Satellites			

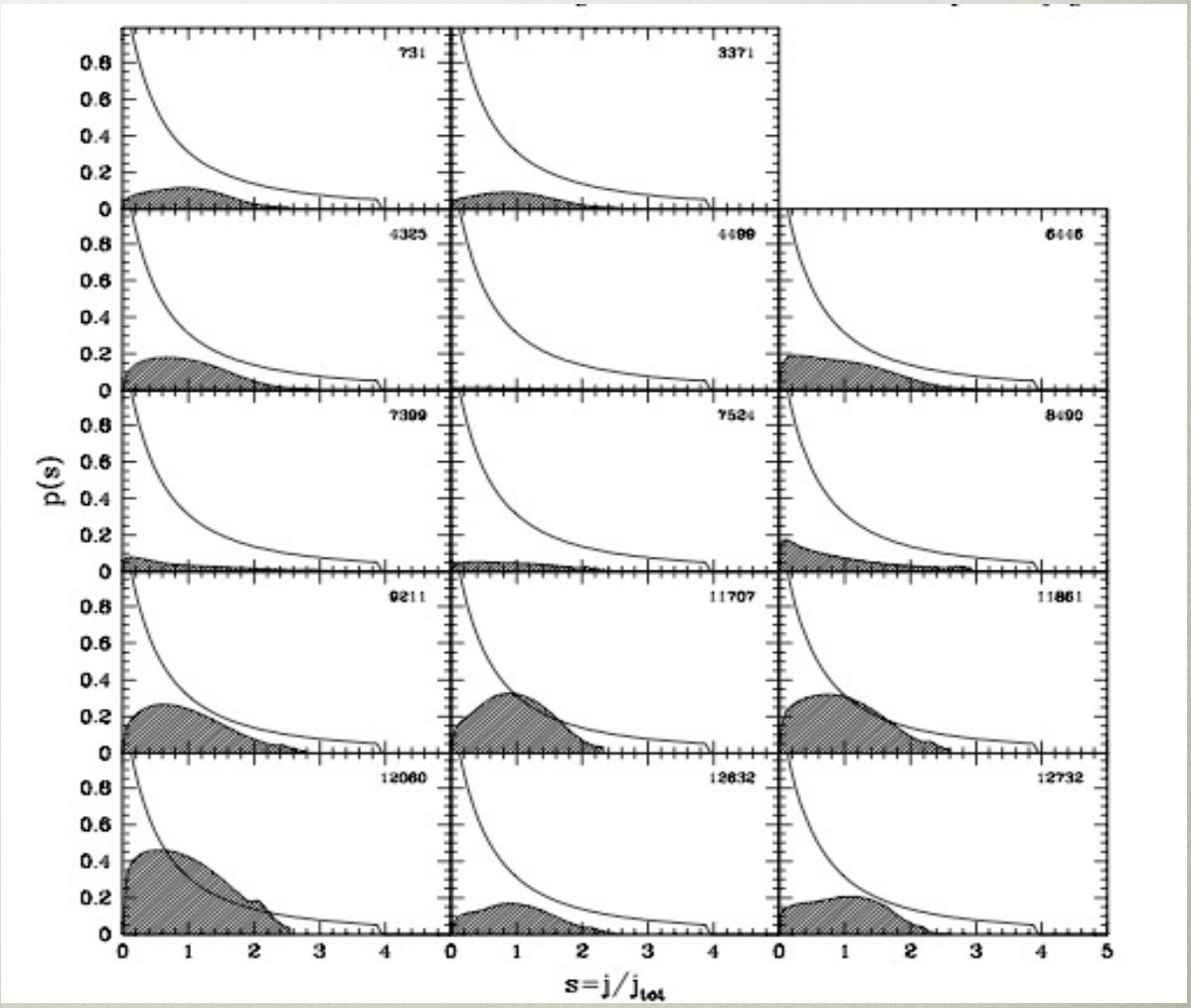
CDM predicts large bulges ...but we rarely see them

A large bulge

A "bulgeless" disk

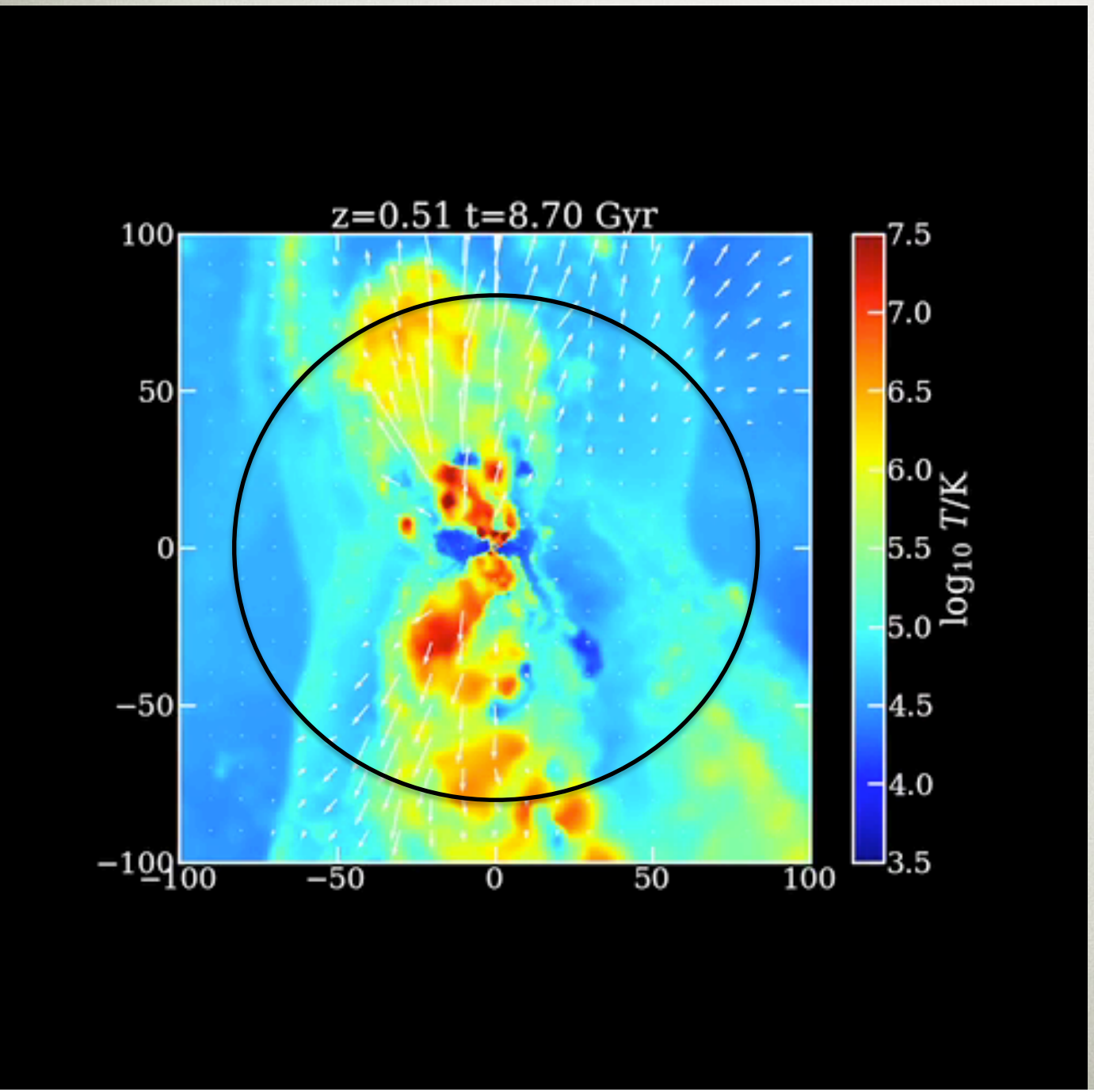
CDM predicts large bulges ...but we rarely see them

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



van den Bosch et al. (2001)

Outflows!



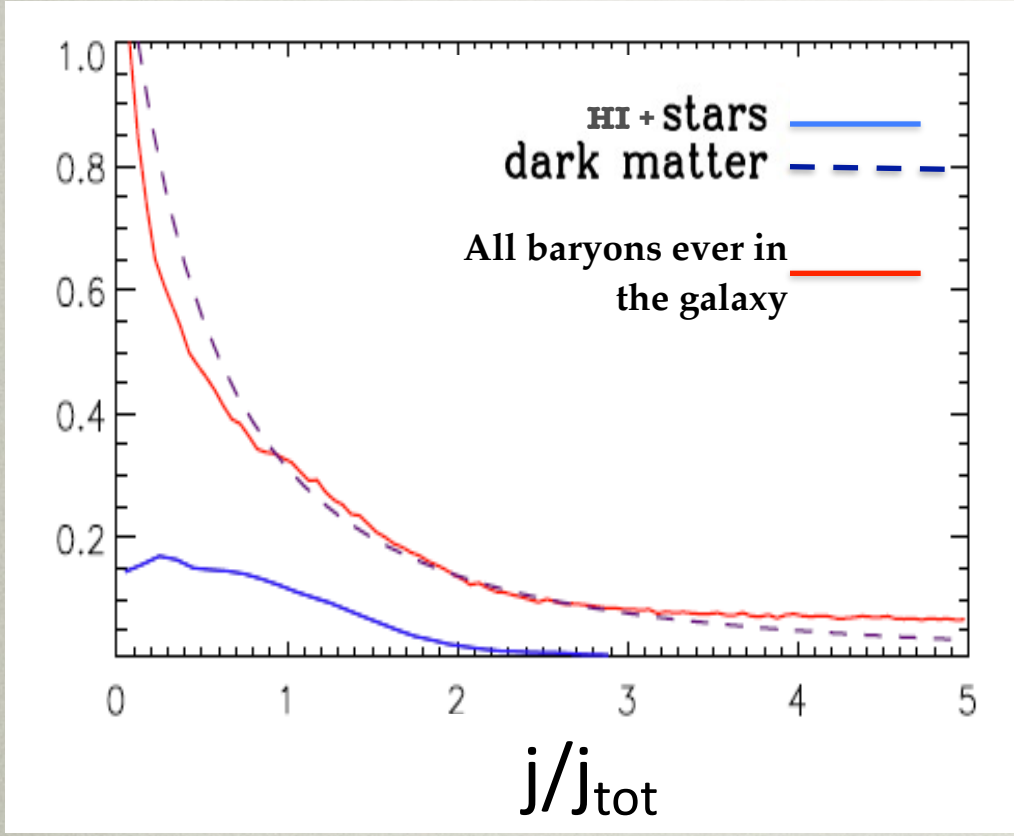
M_{vir} ~ 10^{10} M_{sun}
"dwarf galaxy"

Edge-on disk orientation

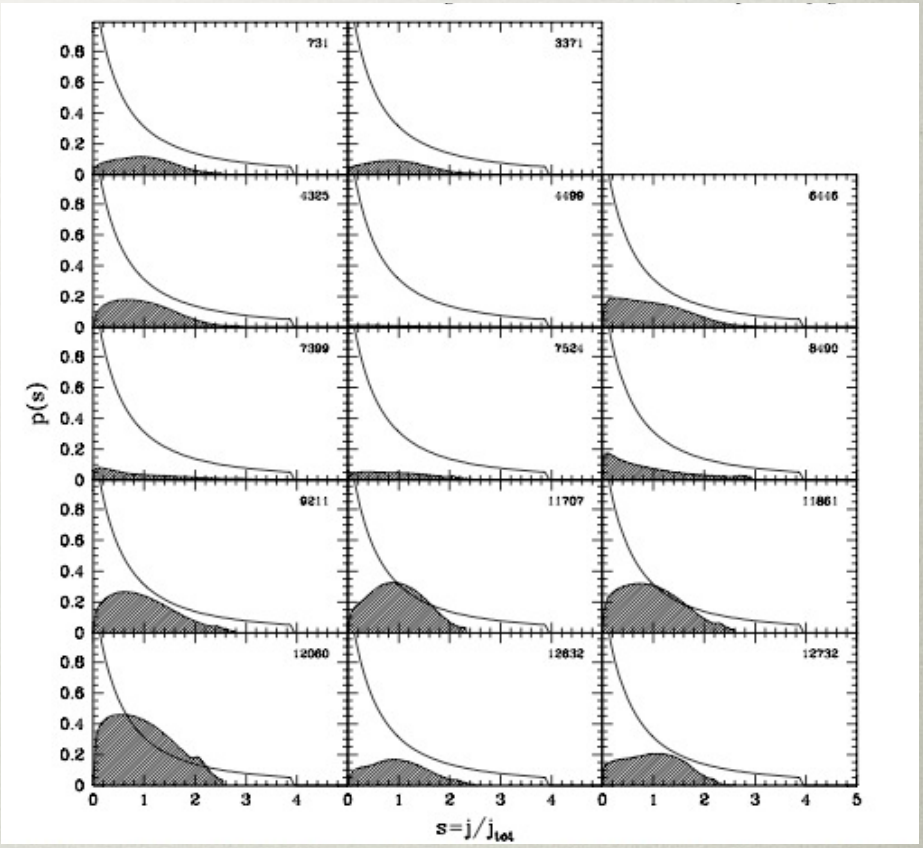
(arrows are velocity vectors)

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)

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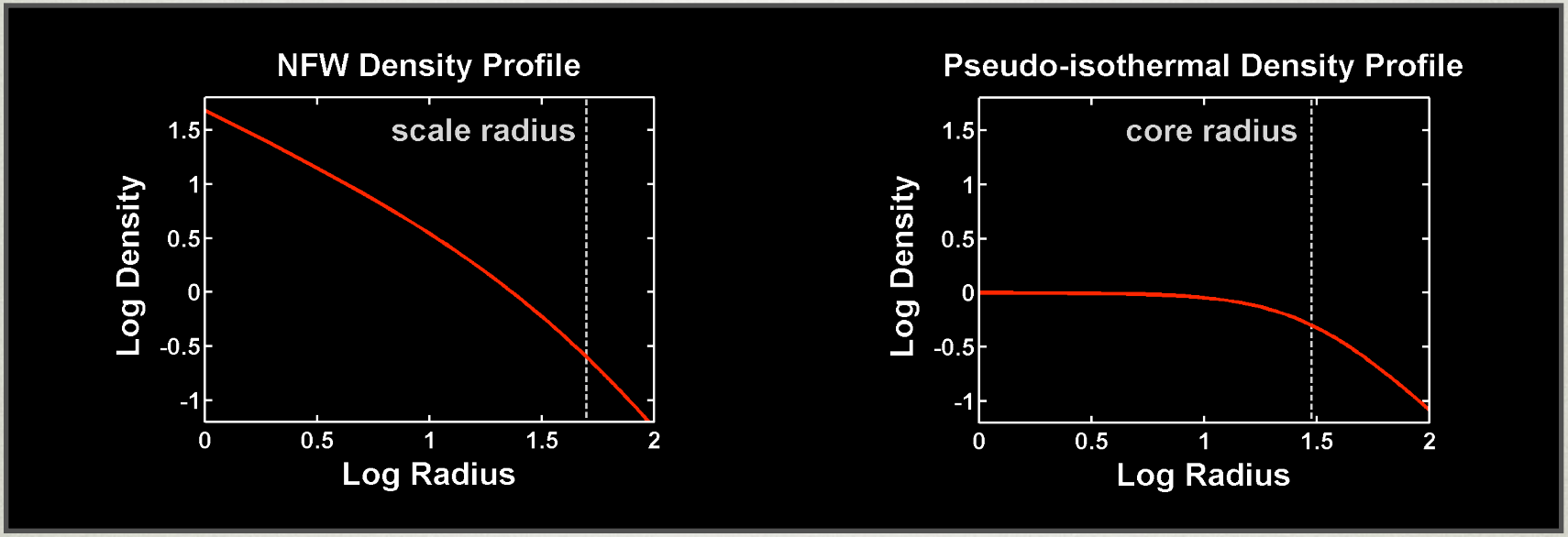
Bulge-less disk galaxies	✓		
The Cusp/ Core Problem			
Too Big to Fail			
Missing Satellites			

The Cusp/Core Problem

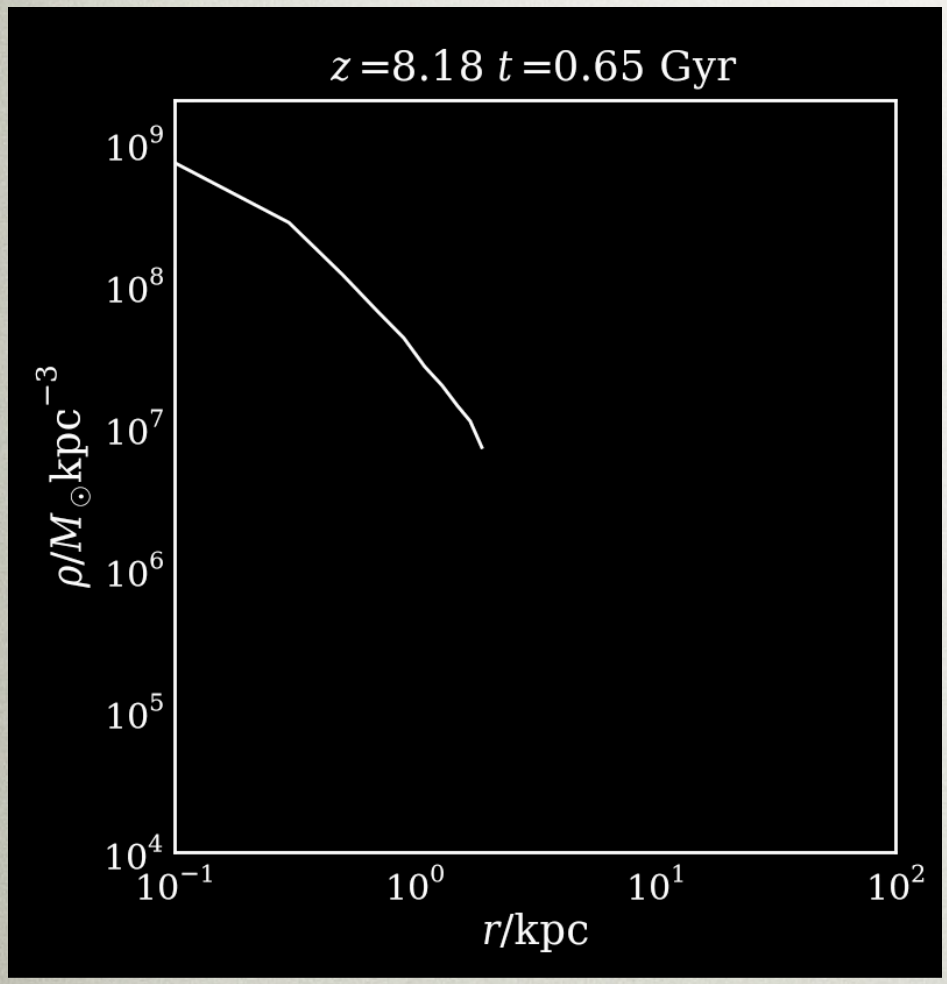


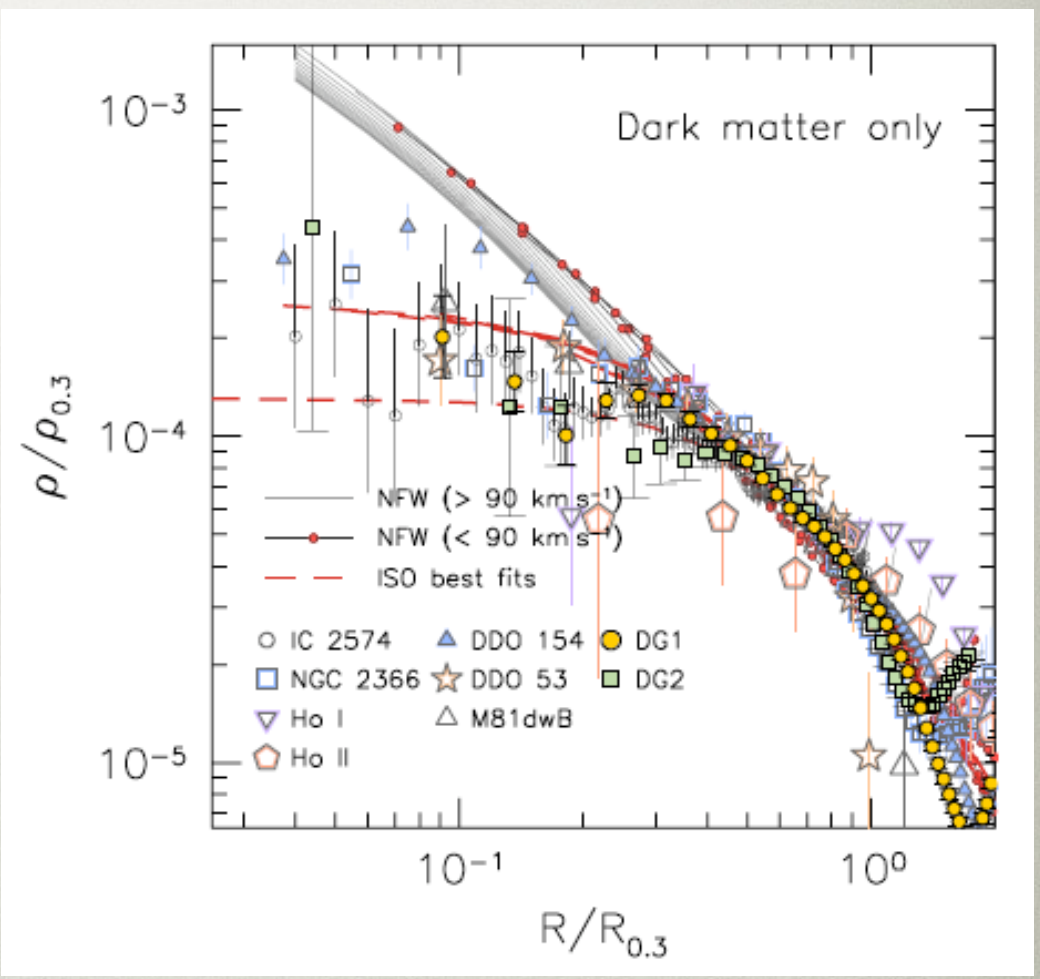
Parameterize density profile as $\rho(r) \propto r^{-\alpha}$

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

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

Creation of a Dark Matter Core

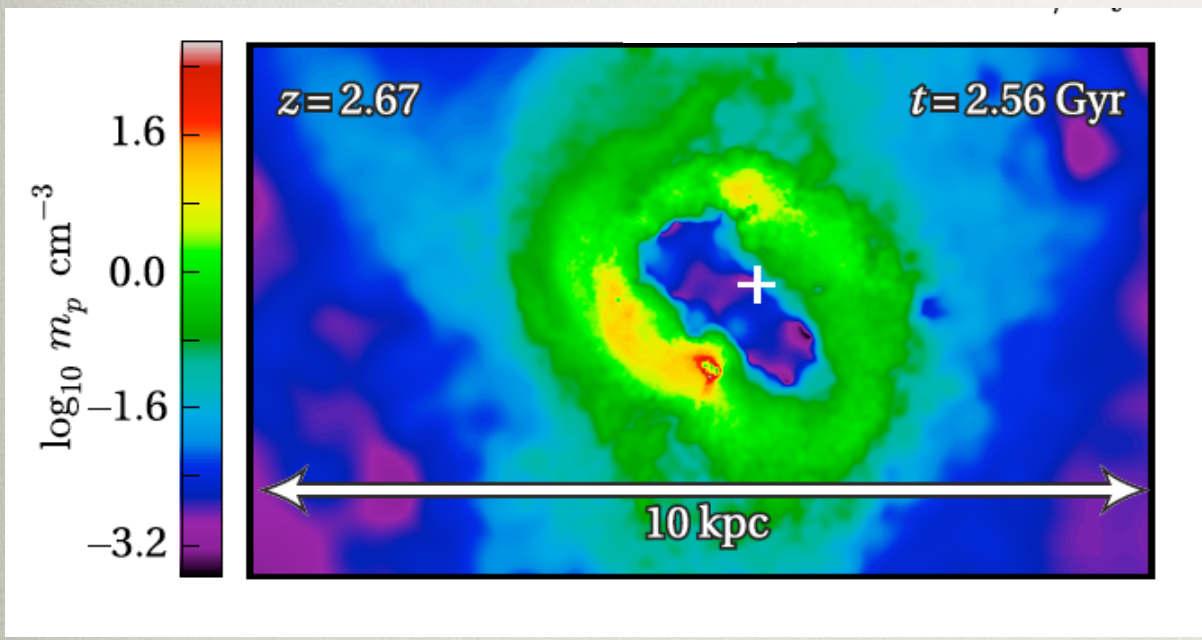


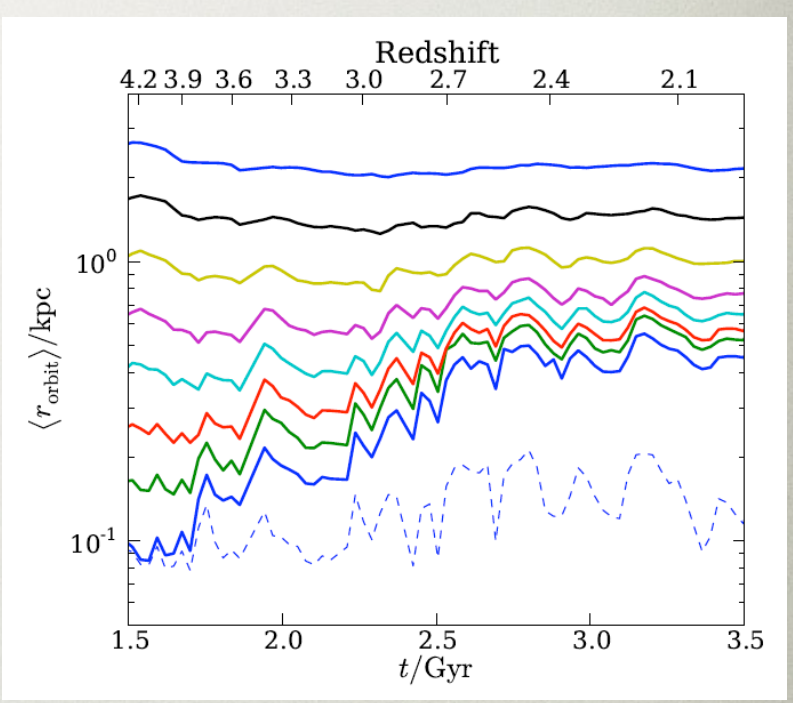


Oh et al., 2011, AJ, 142, 24

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

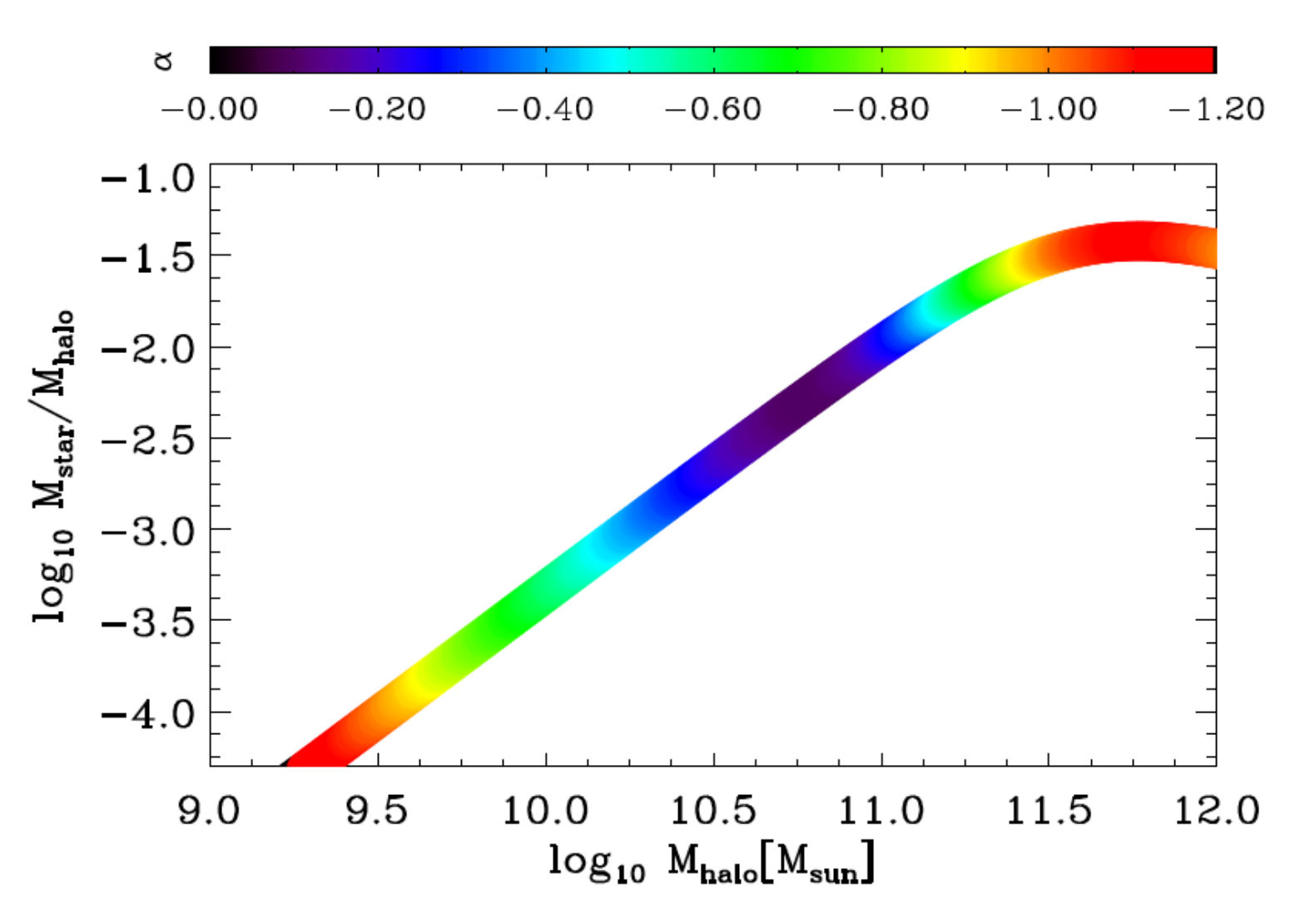
How are Cores Created?





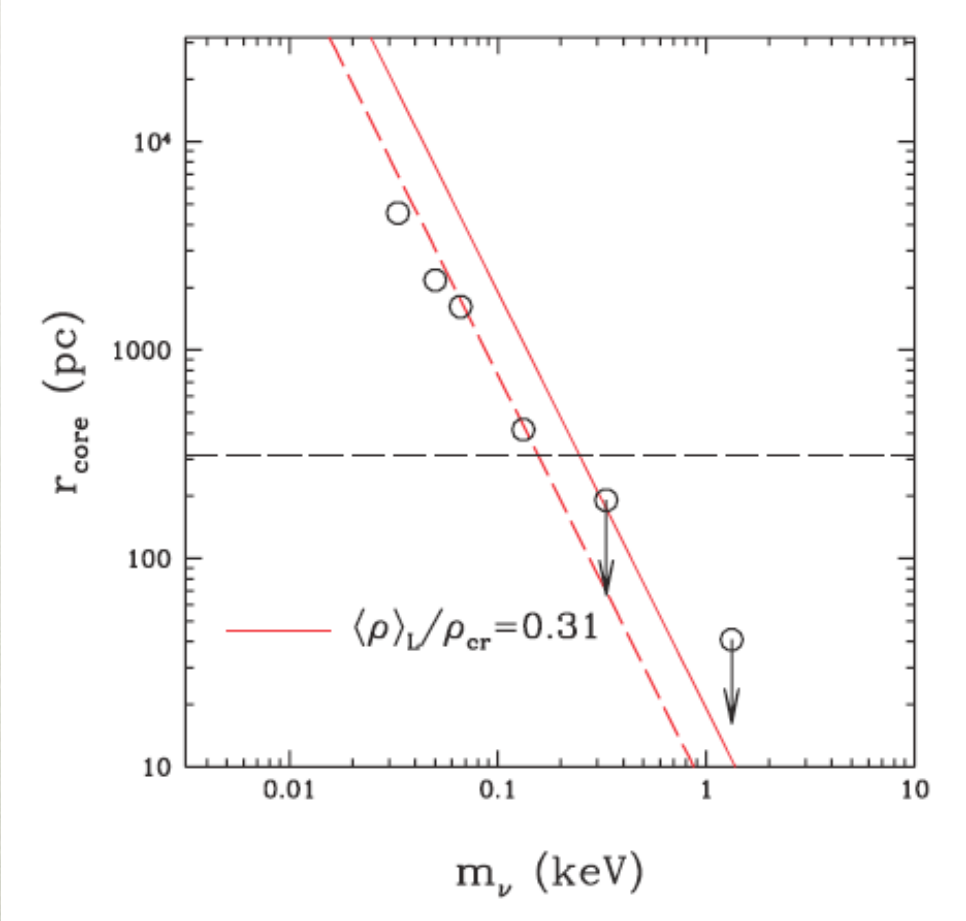
Pontzen & Governato (2012), MNRAS, 421, 3464, arXiv:1106.0499

Density Slope as a Function of Stellar/Halo Mass



di Cintio et al. (2014)

WDM doesn't create cores

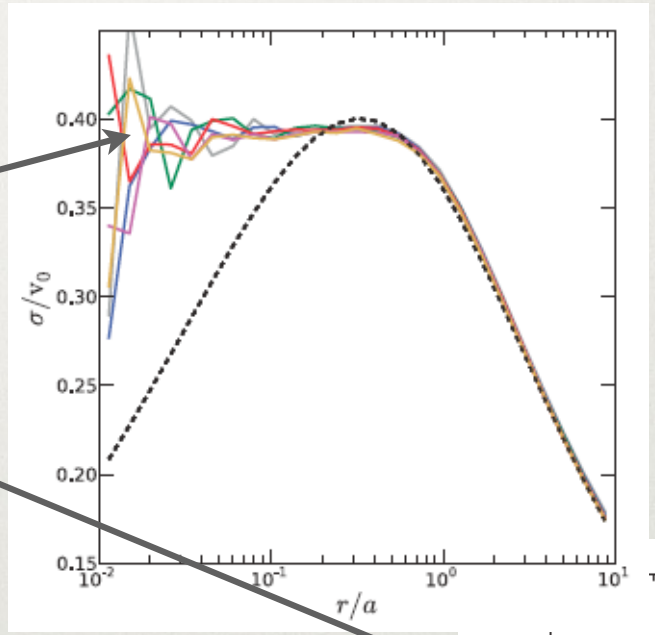


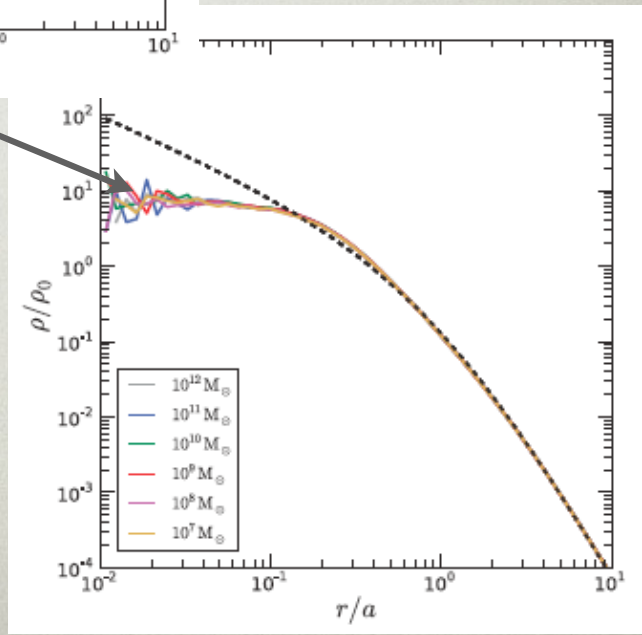
Maccio et al. (2012)

SIDM

scattering creates cores

- SIDM
- repeated elastic collisions equalize the velocities



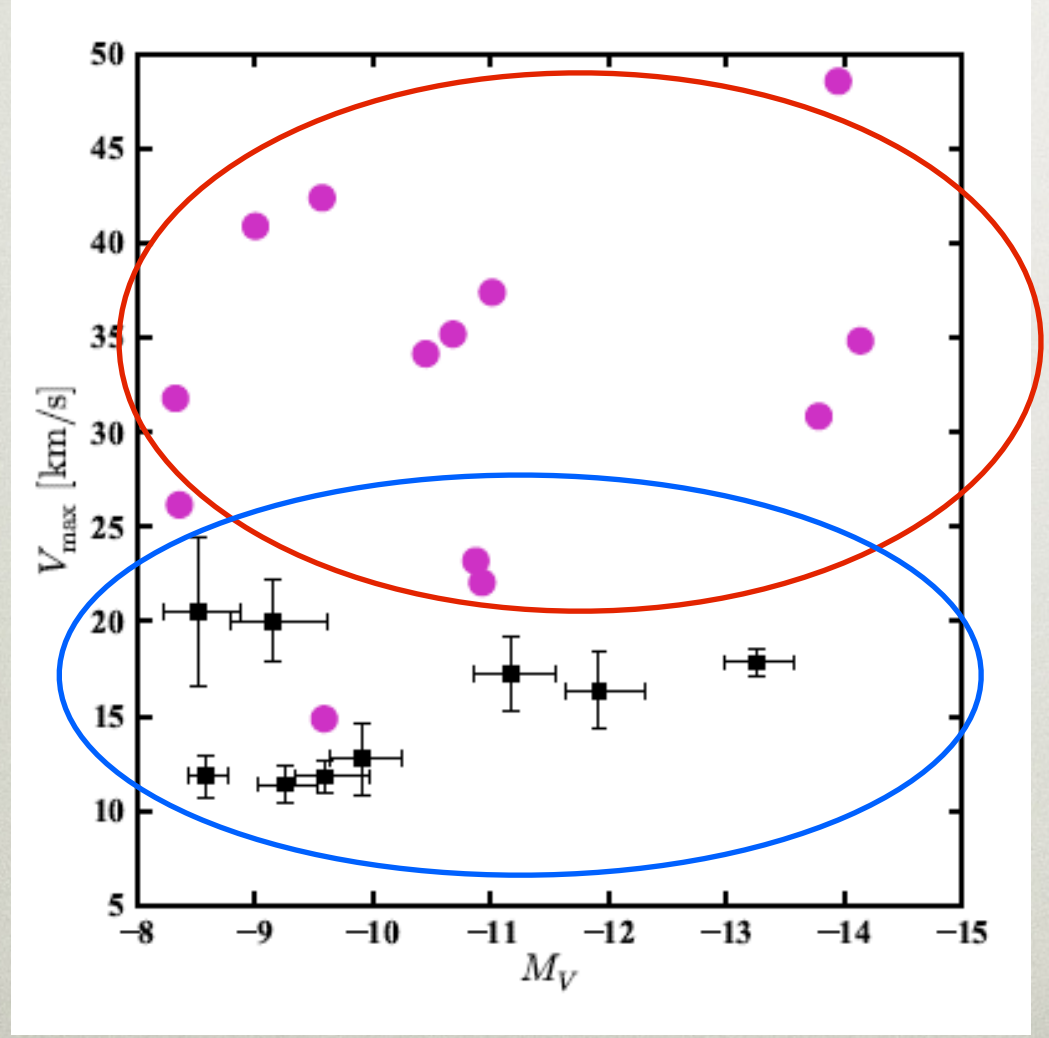


Vogelsberger, Zavala, & Loeb (2012)

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

	Baryons	WDM	SIDM
Bulge-less disk galaxies	✓		
The Cusp/ Core Problem	✓		✓
Too Big to Fail			
Missing Satellites			

The Predicted Satellites are too Dense

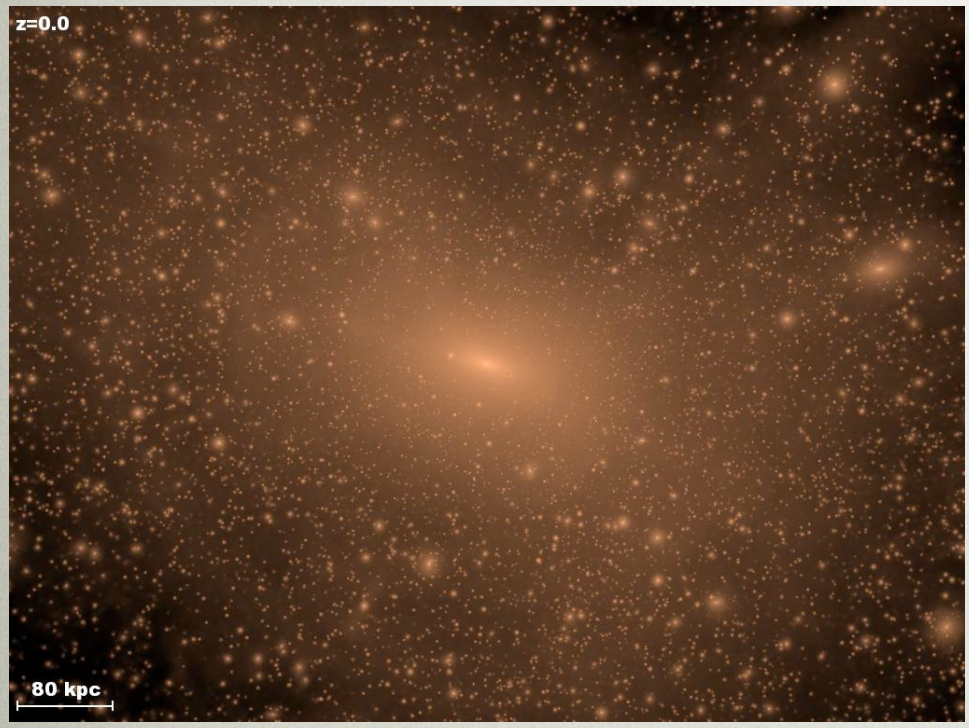


Predicted

Observed

Boylan-Kolchin et al. (2012)

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



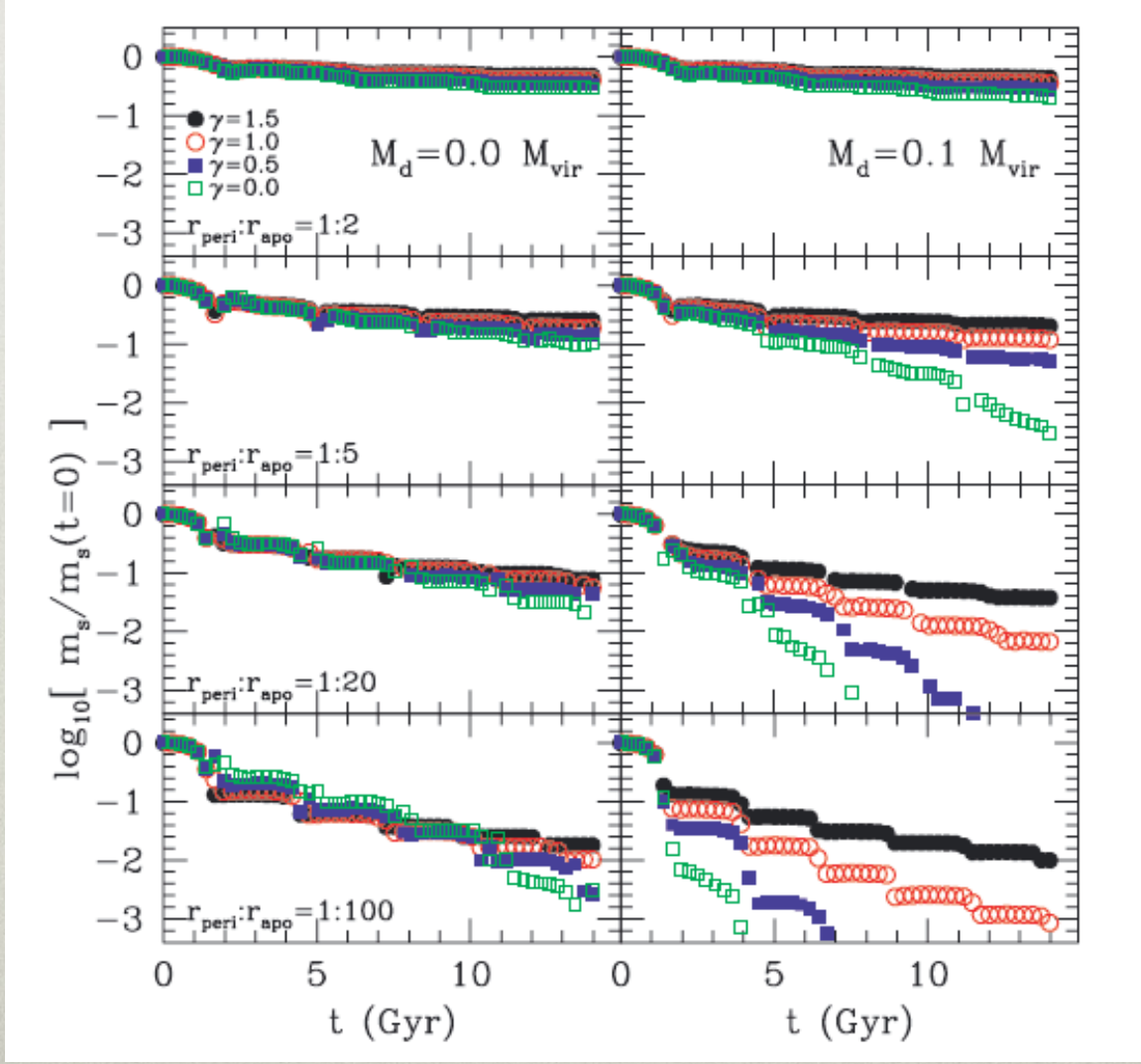
Dark Matter

Baryons

(or any central baryonic concentration)

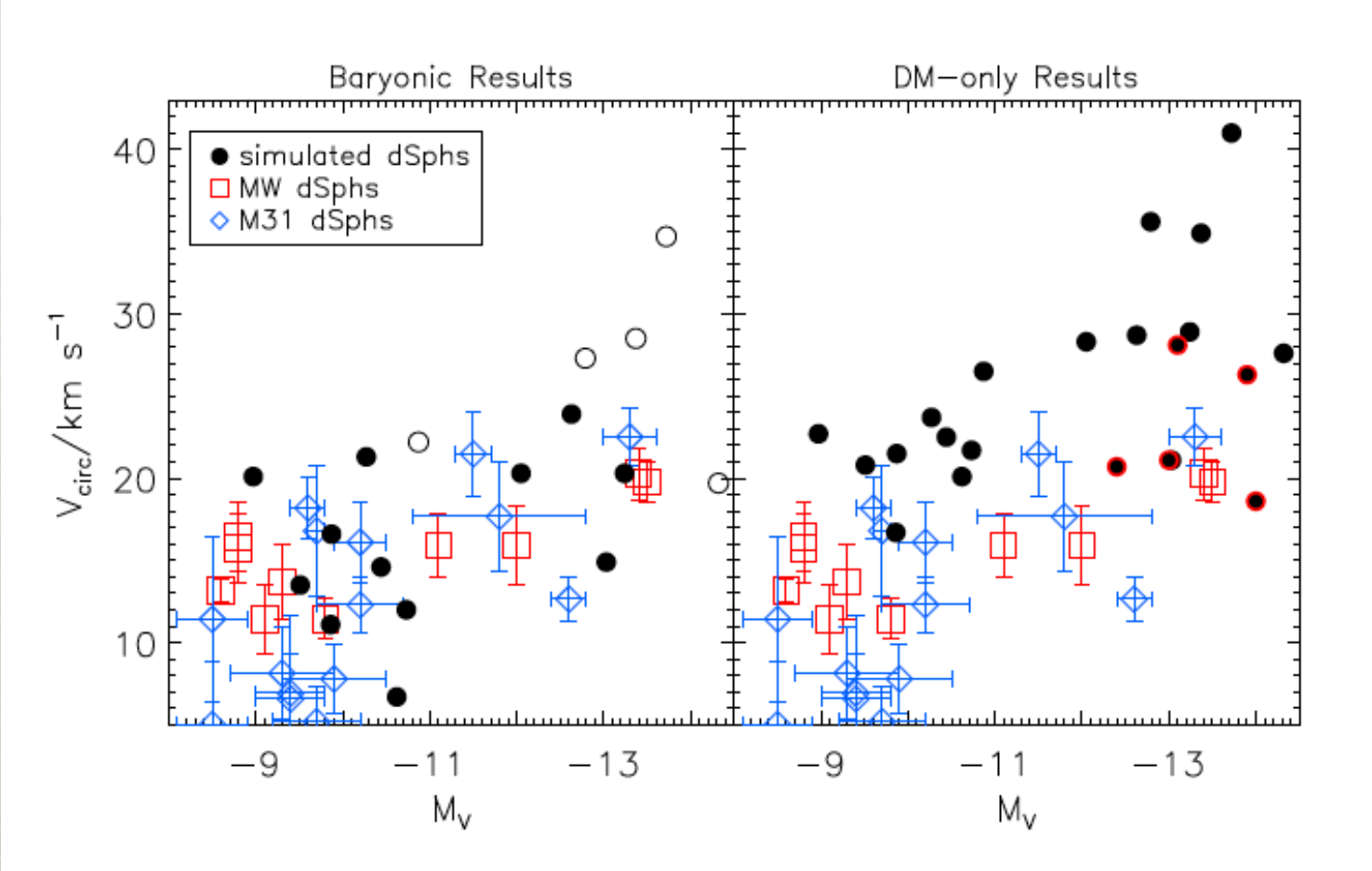
Chang et al. (2012)

Not Just Core Creation: The Tidal Effect of the Disk



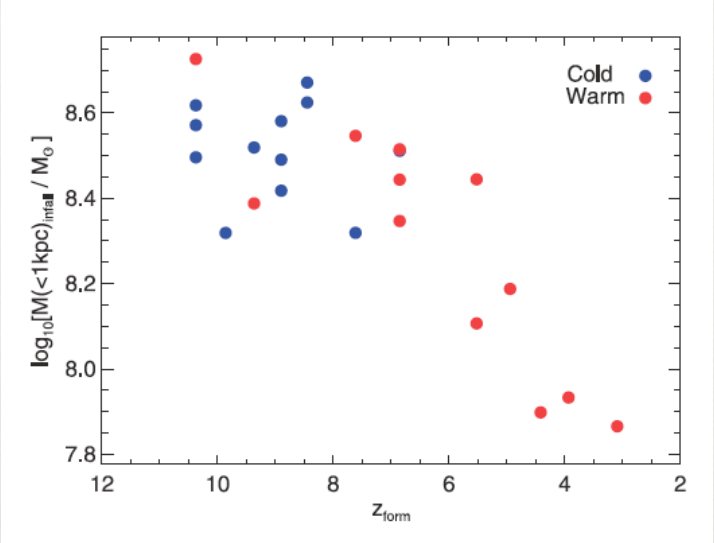
Penarrubia et al. (2010), see also Arraki et al. (2012)

Satellites that are not Too Dense

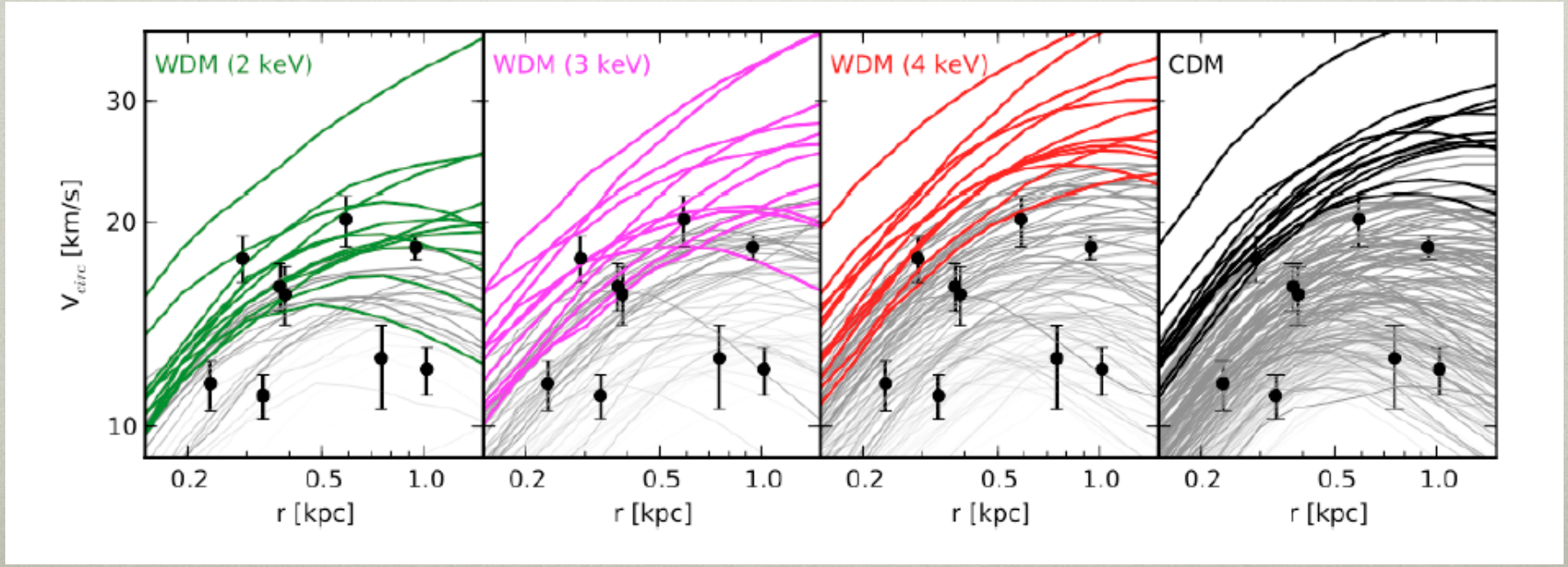


Brooks & Zolotov (2014), ApJ, 786, 87, arXiv:1207.2468

WDM may also solve the Too Big to Fail Problem



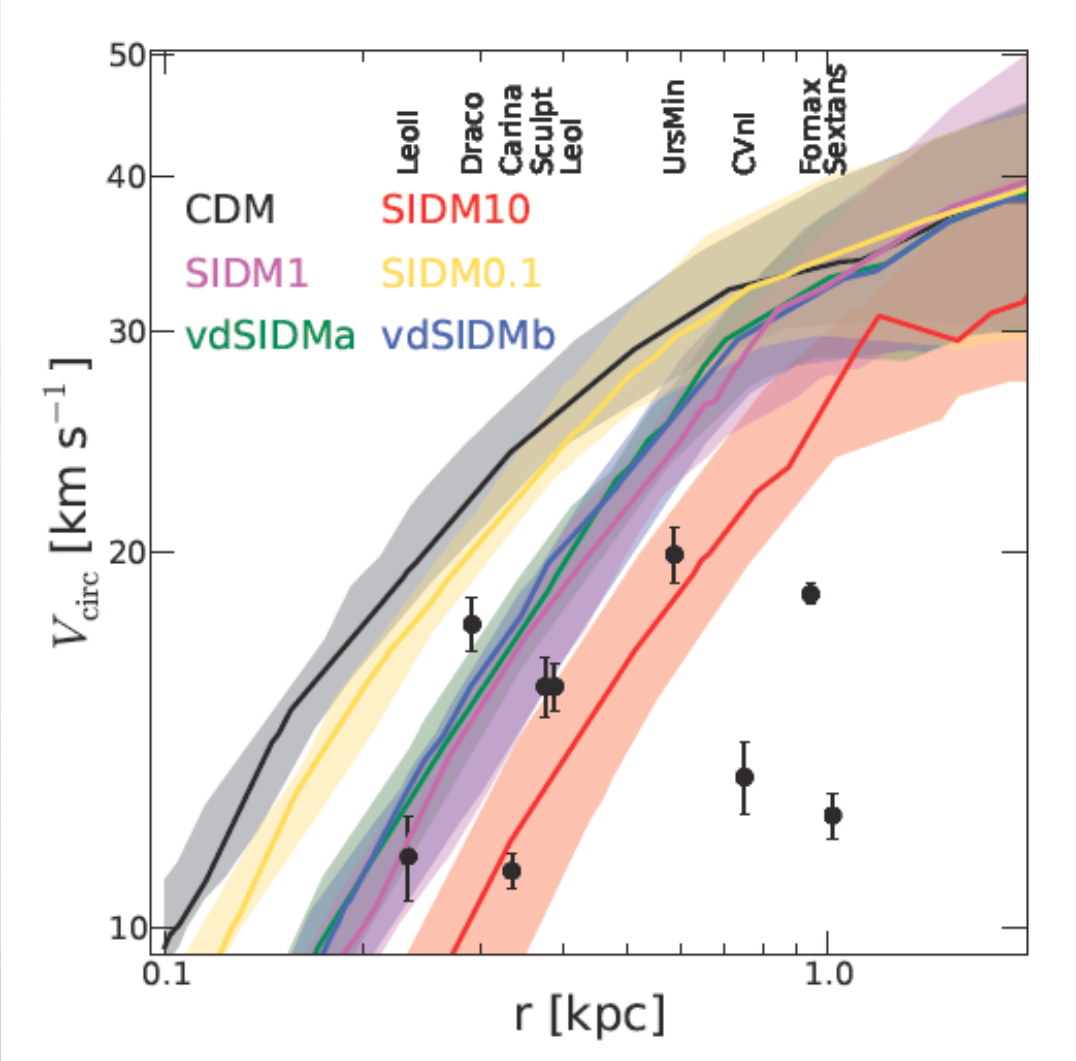
Lovell et al. (2012)



Schneider et al. (2013)

Can SIDM Solve the Too Big to Fail Problem?

- depends who you ask



Zavala et al. (2013)

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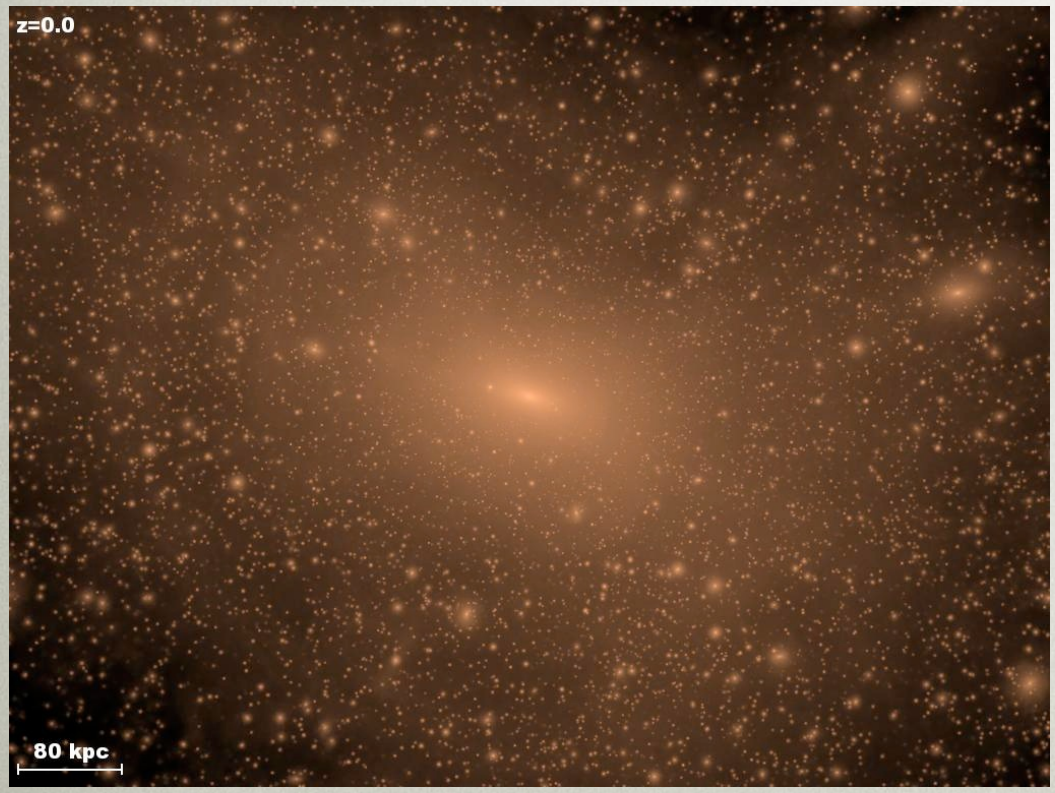
Bulge-less disk galaxies	✓		
The Cusp/ Core Problem	✓		✓
Too Big to Fail	✓	✓	✓
Missing Satellites			

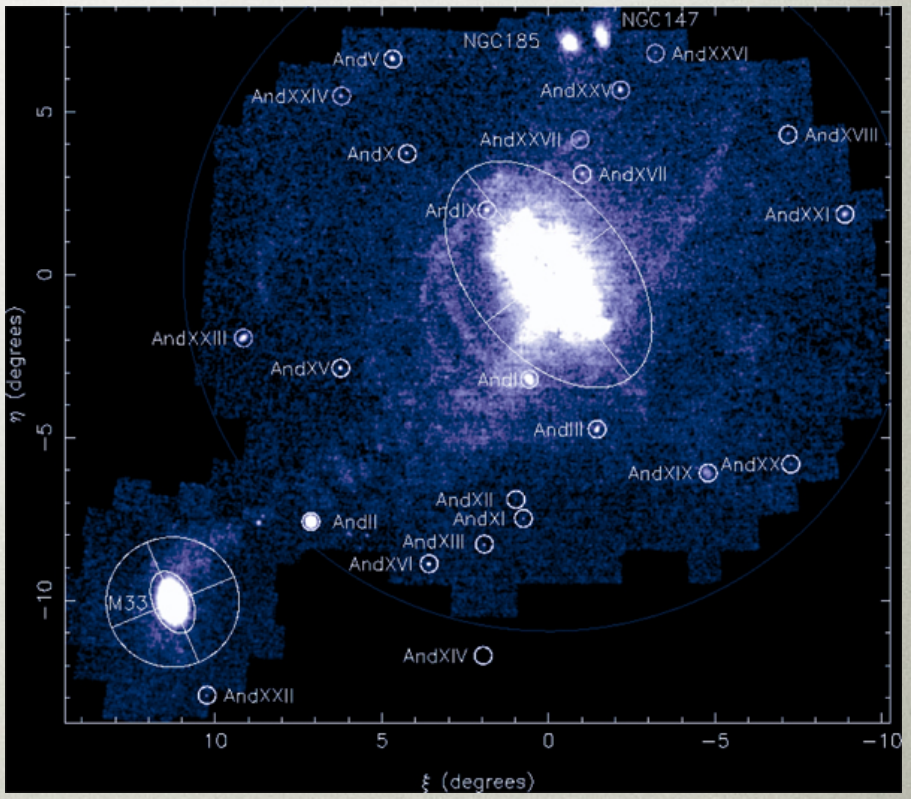
The "Missing Satellites" Problem

1000's of satellites predicted



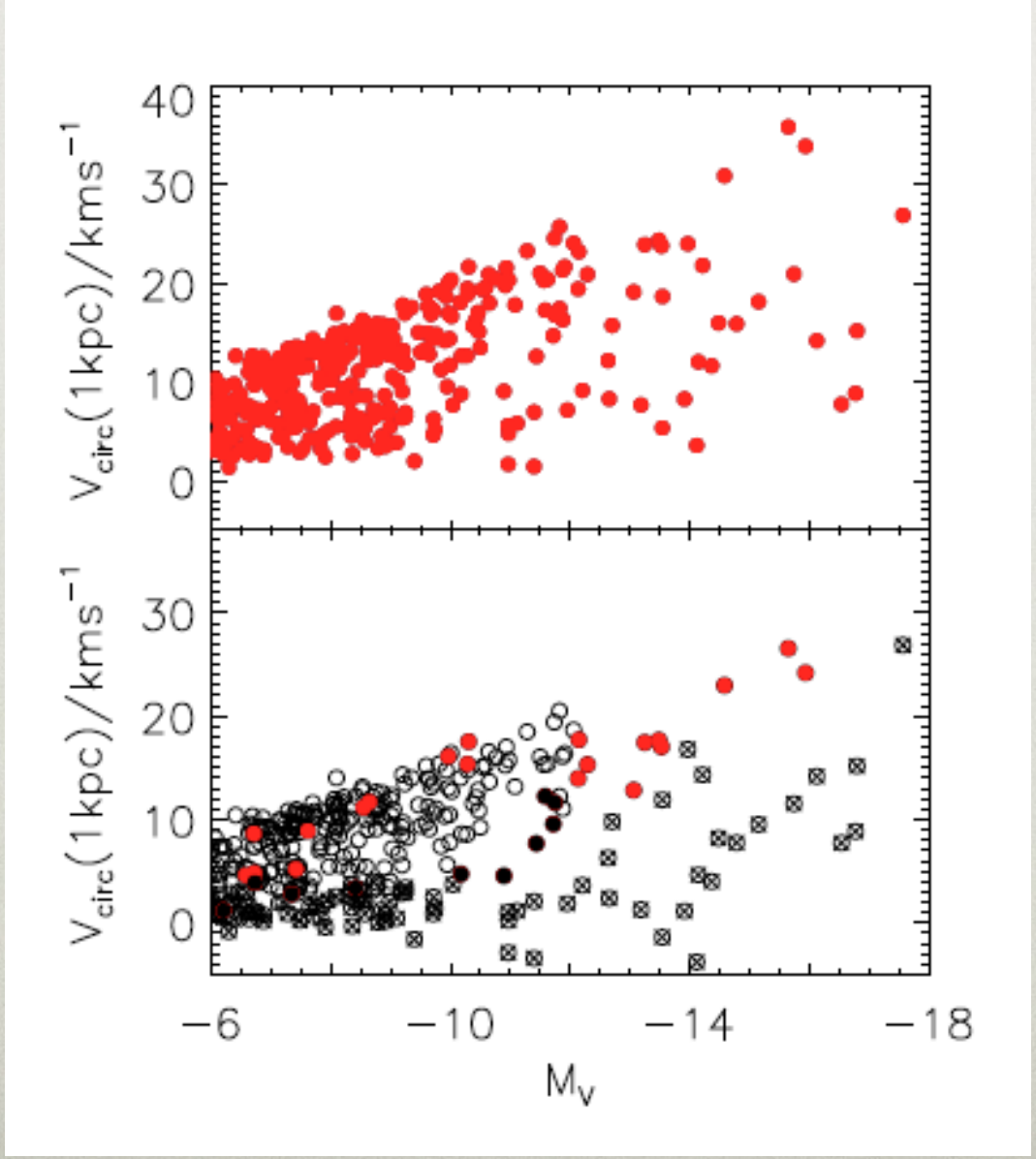
"Via Lactea" Simulation

dozens seen



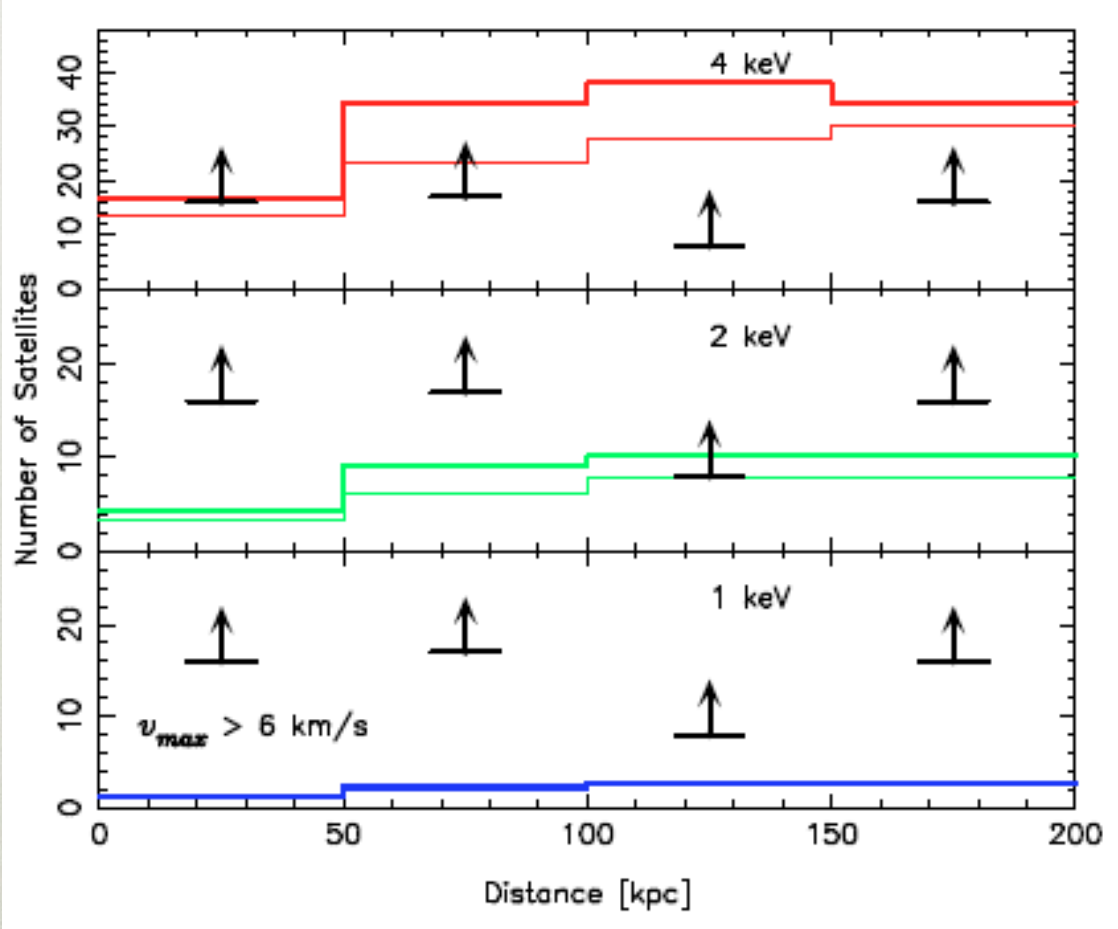
Pan-ANDromeda Archeological Survey (PAndAS)

Missing Massive Satellites?



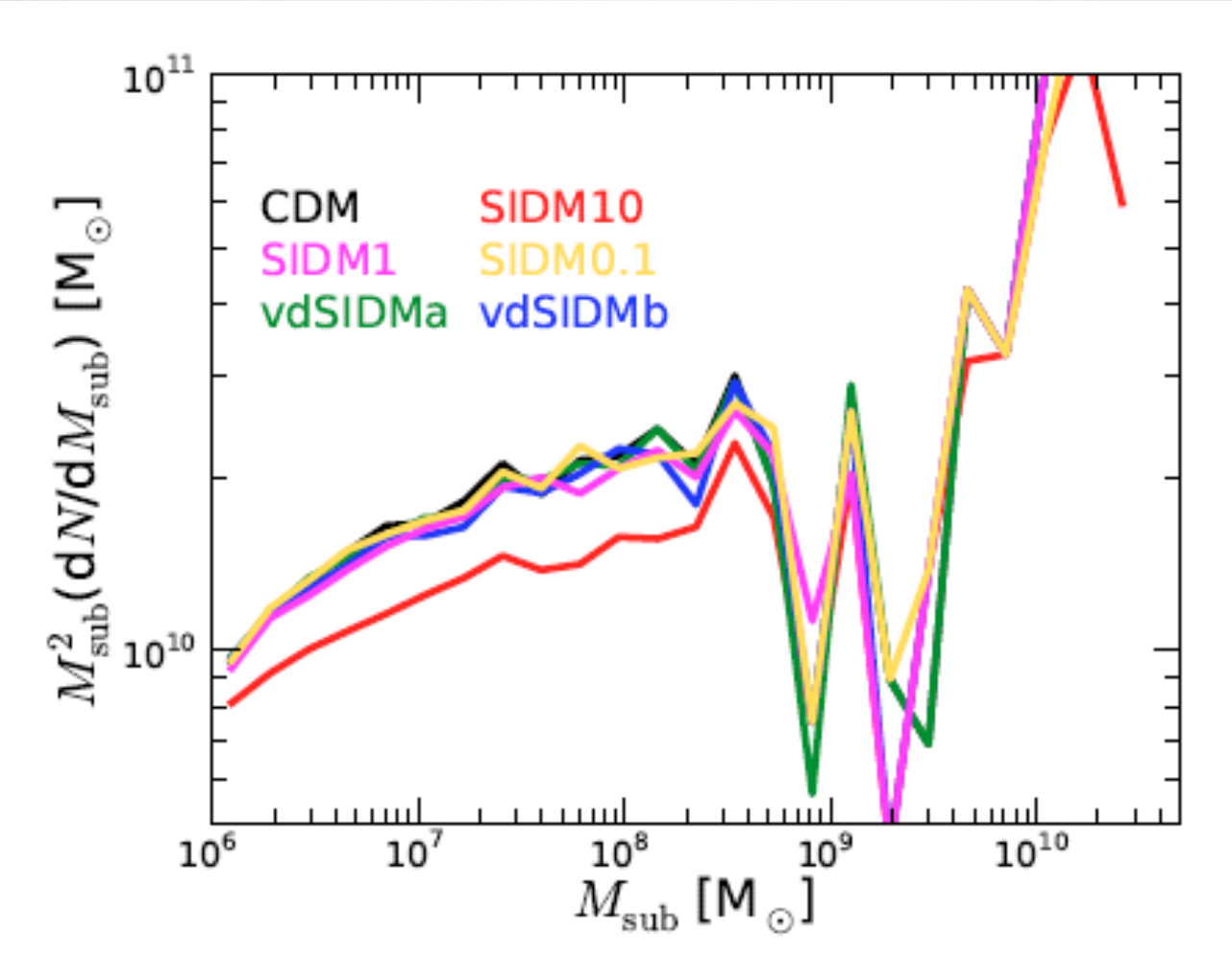
Brooks, Kuhlen, Zolotov, & Hooper (2012), ApJ, 765, 22, arXiv:1209.5394

Missing Satellites & WDM



Polisensky & Ricotti (2011)

Missing Satellites & SIDM



Zavala et al. (2013)

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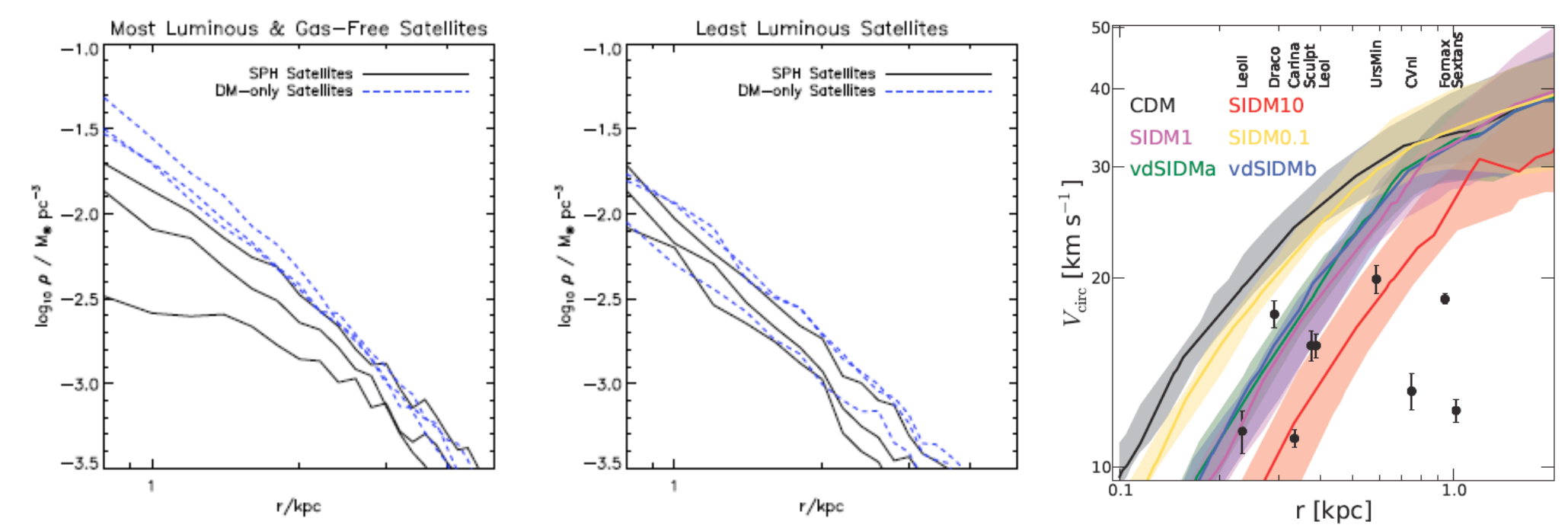
The Cusp/ Core Problem	✓		✓
Too Big to Fail	✓	✓	✓
Missing Satellites	✓	✓	

Future Work

(1) BARYONS in Alternative DM Models

(2) Quantifying the role of SN Feedback

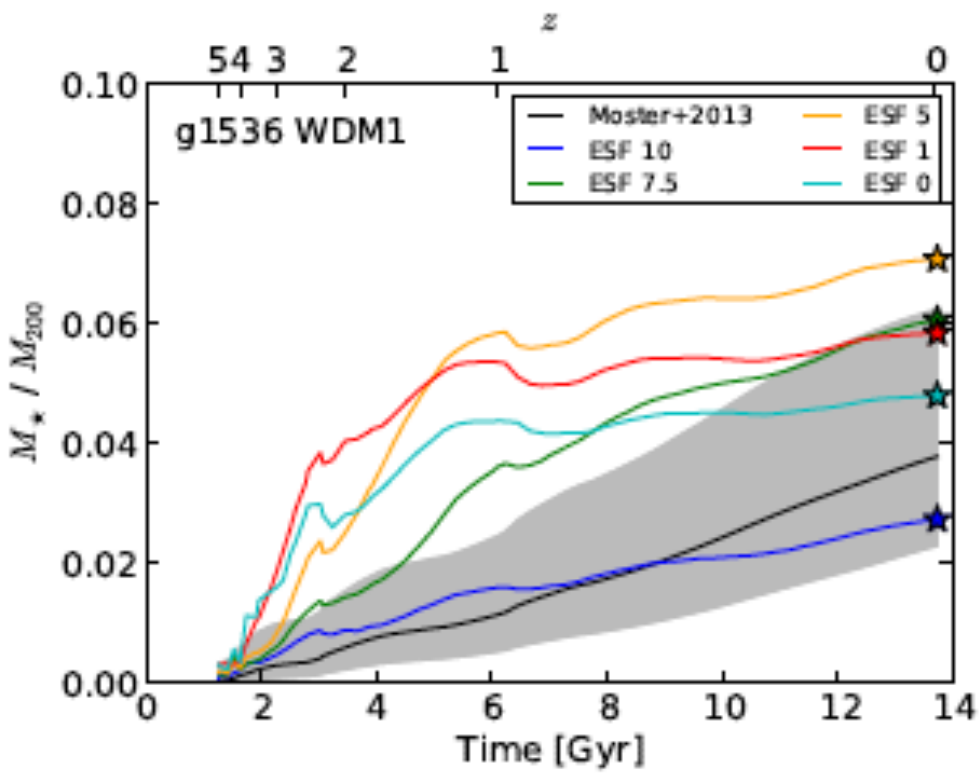
Core size vs Mass
as a test of DM Model

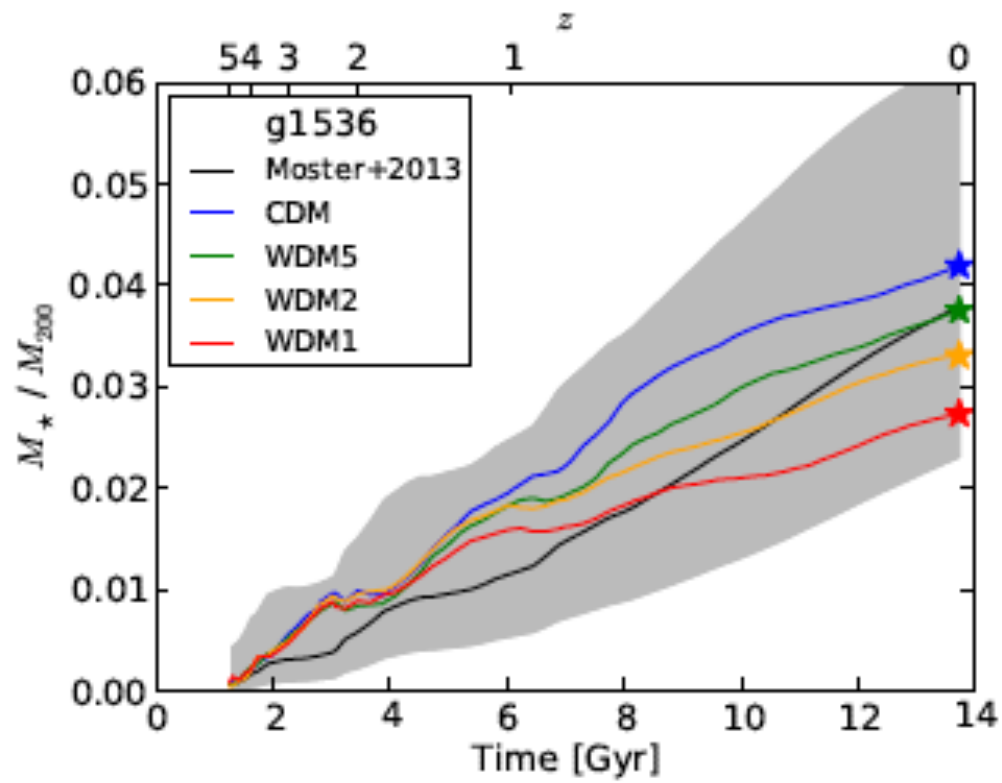


baryons

SIDM

WDM with baryons?



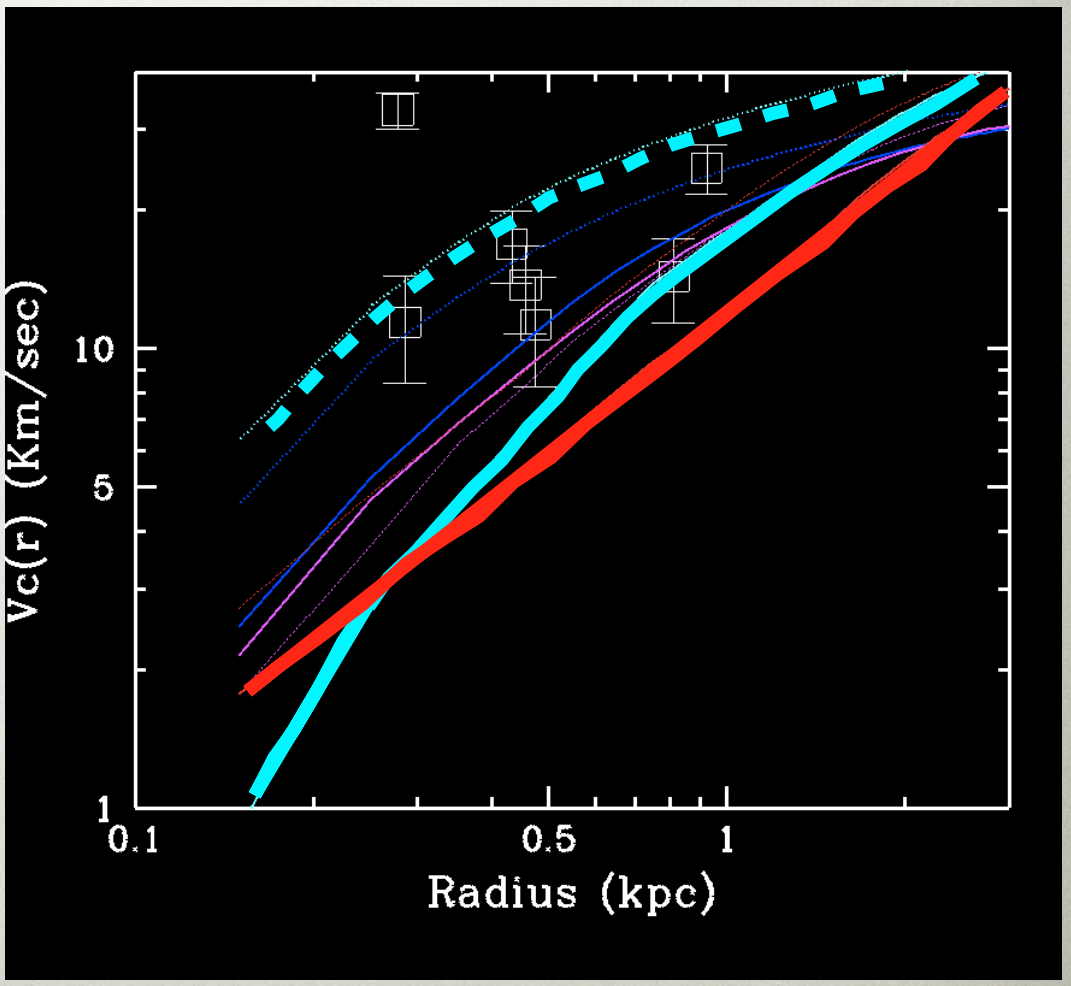


Herpich et al. (2014)

SIDM with baryons?

$M_{star} = 10^8\ M_\odot$

cyan: CDM
red:SIDM



Fry, Governato, et al. (in prep)
see also: Vogelsberger et al., arXiv:1405.5216;
Kaplinghat et al., arXiv:1311.6524

Conclusions

Baryonic feedback is essential to create bulgeless disk galaxies

The creation of bulgeless disk appears intimately tied with DM core creation

WDM: no cores without baryons, but current mass limits make it nearly indistinguishable from CDM

SIDM: need (more) predictions that include baryons!!!

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