Re-Examining Astrophysical Constraints on the Dark Matter Model

Alyson Brooks
Rutgers, the State University of New Jersey

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

Most of the Universe is Unknown Stuff

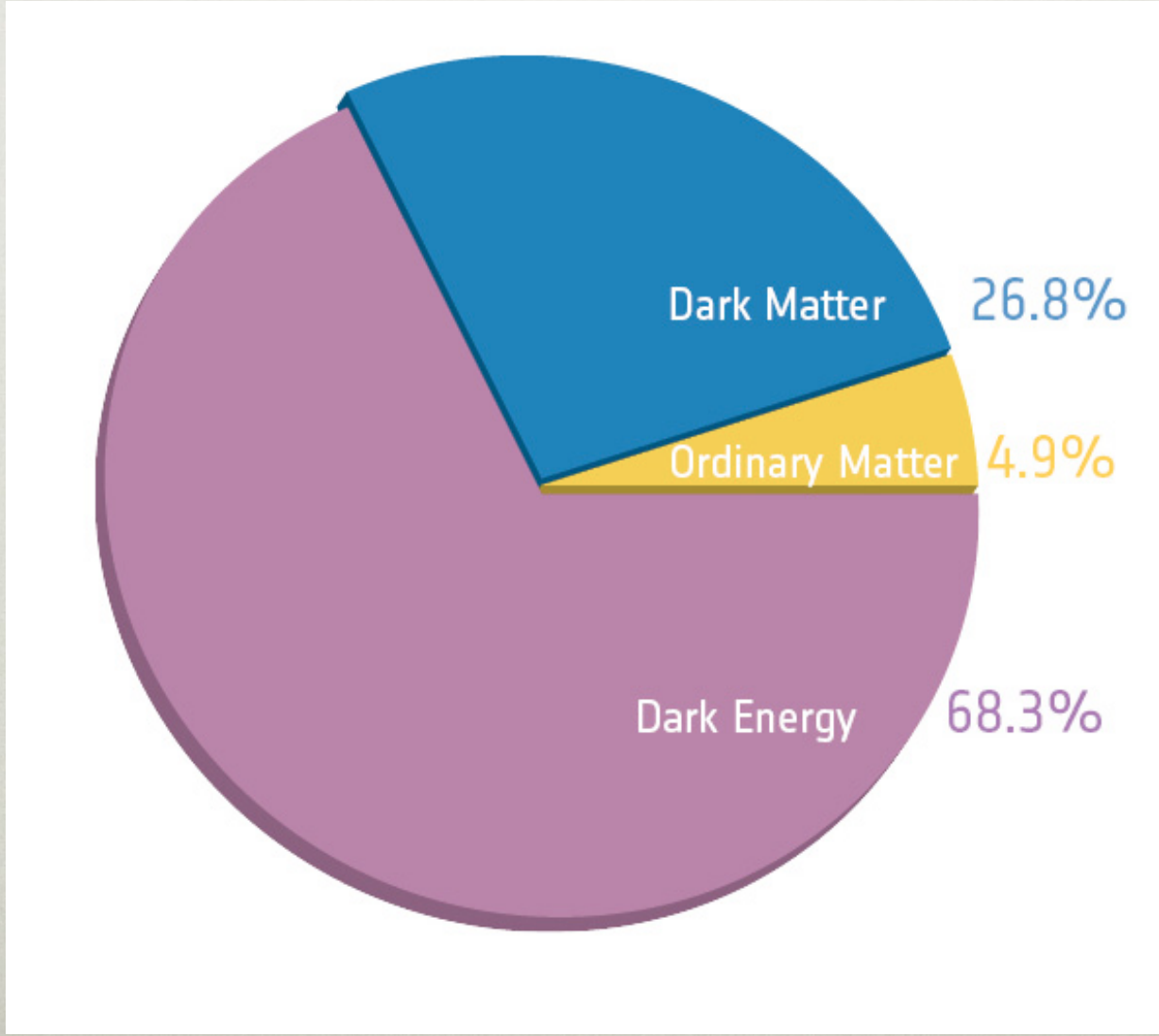
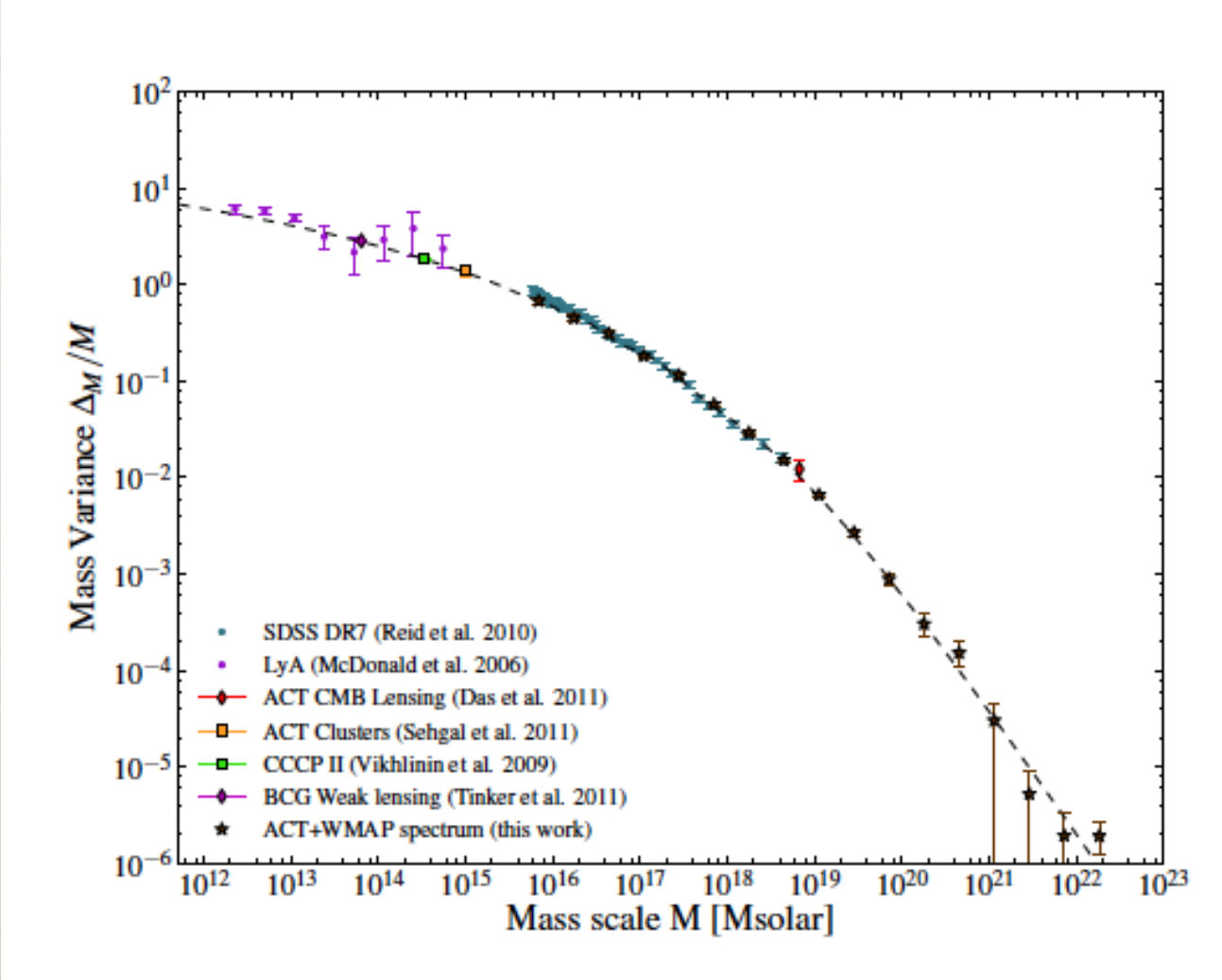


image credit: ESA/Planck

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



Hlozek et al. (2012)

But...

The Small Scale "Crisis" of CDM

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

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?

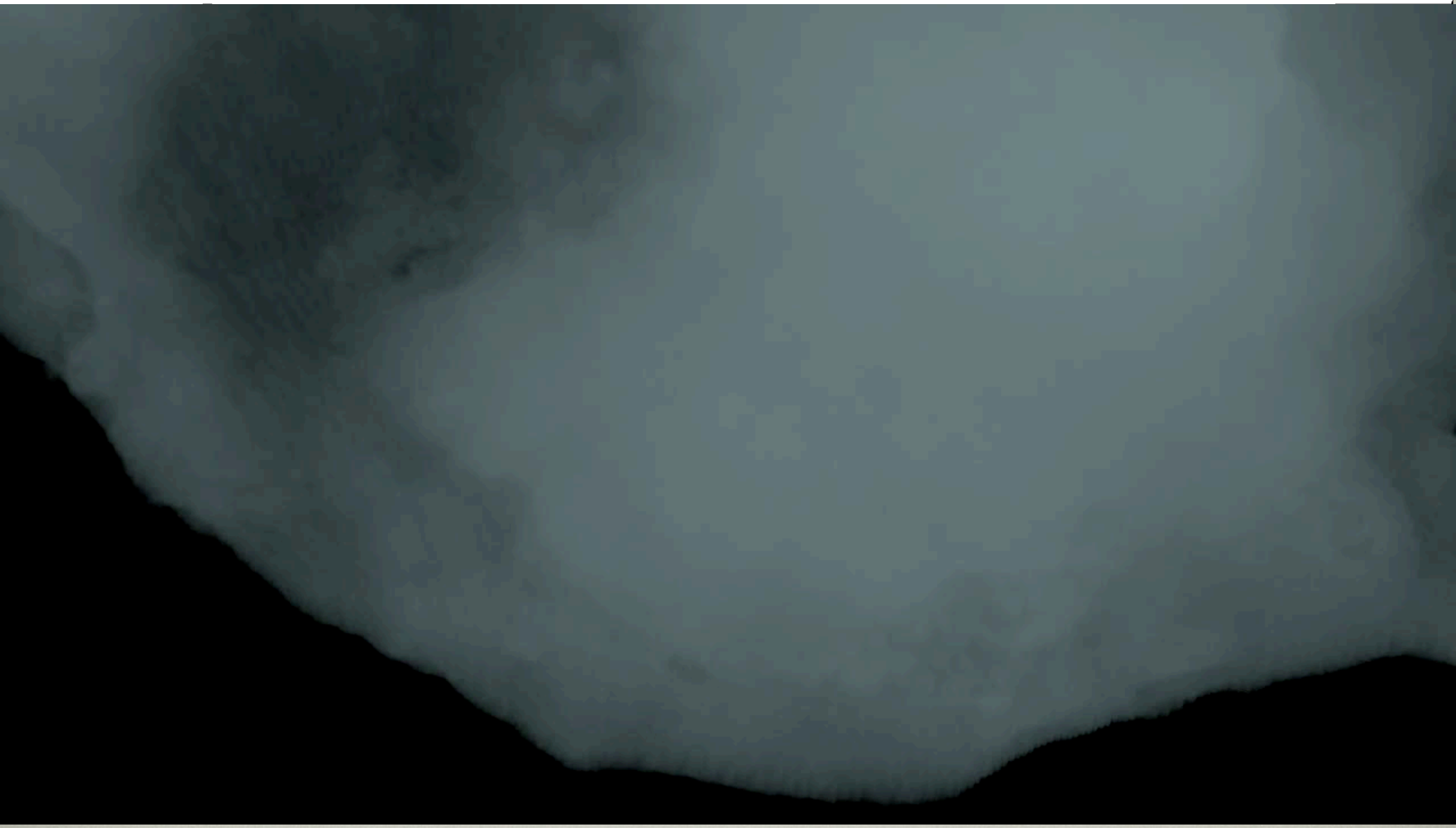
So...
CDM is Wrong?

But what about the 5%?

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.

Gasoline



~50 comoving kpc across
Grey = gas density, Blue/Red = age/metallicity weighted stars

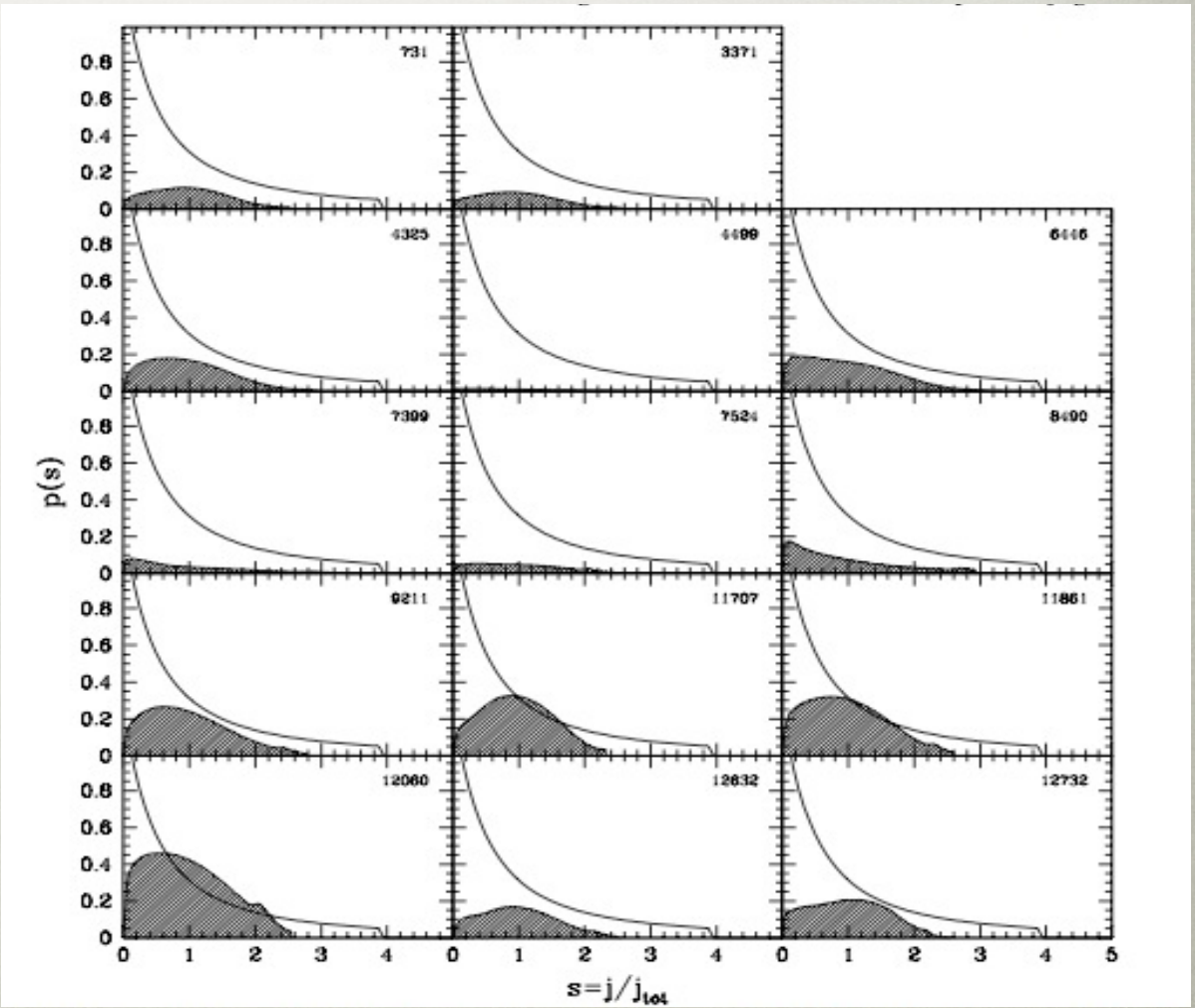
CDM predicts large bulges ...but we rarely see them

A large bulge

A "bulgeless" disk

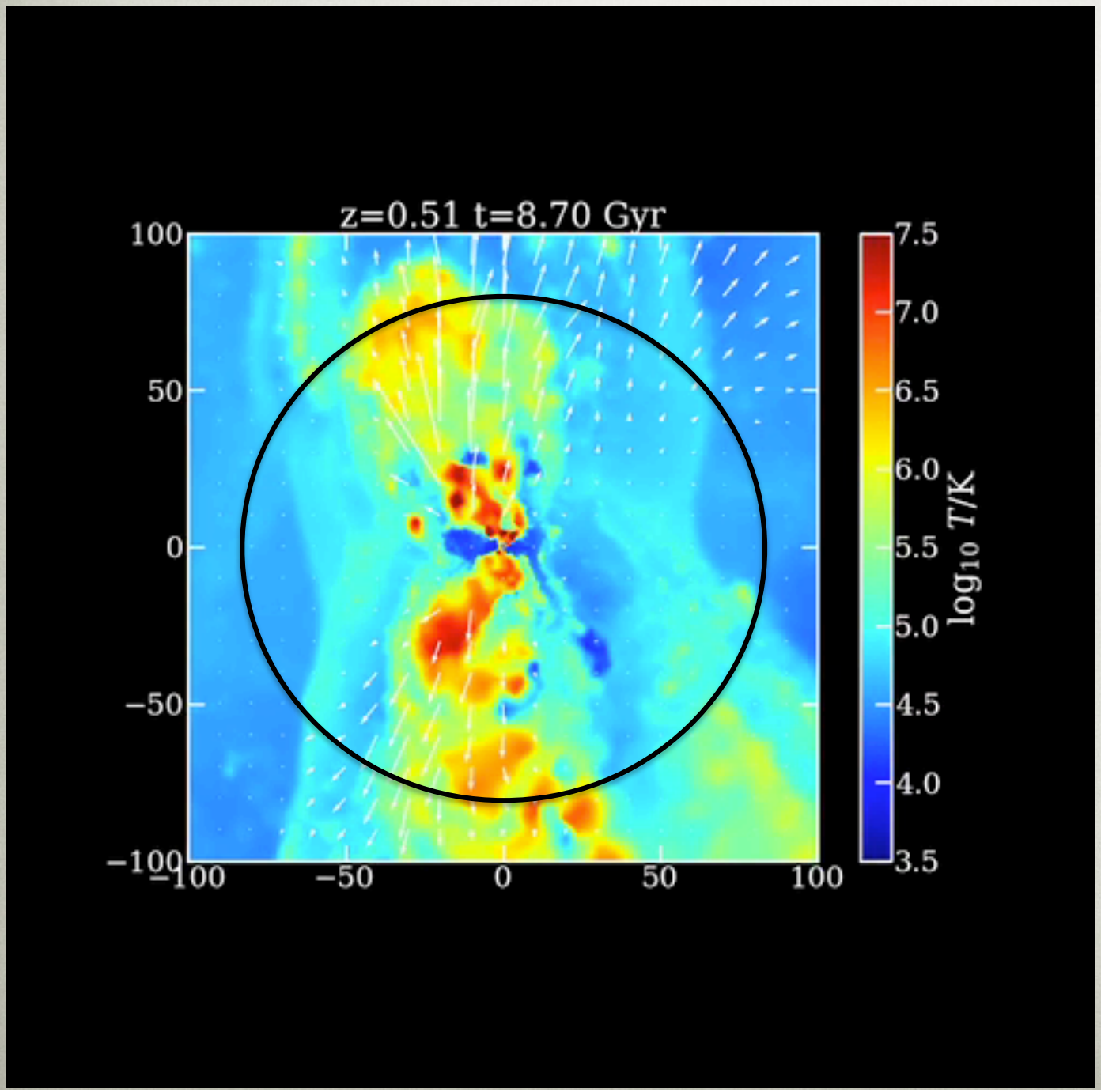
CDM predicts large bulges ...but we rarely see them

- 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!



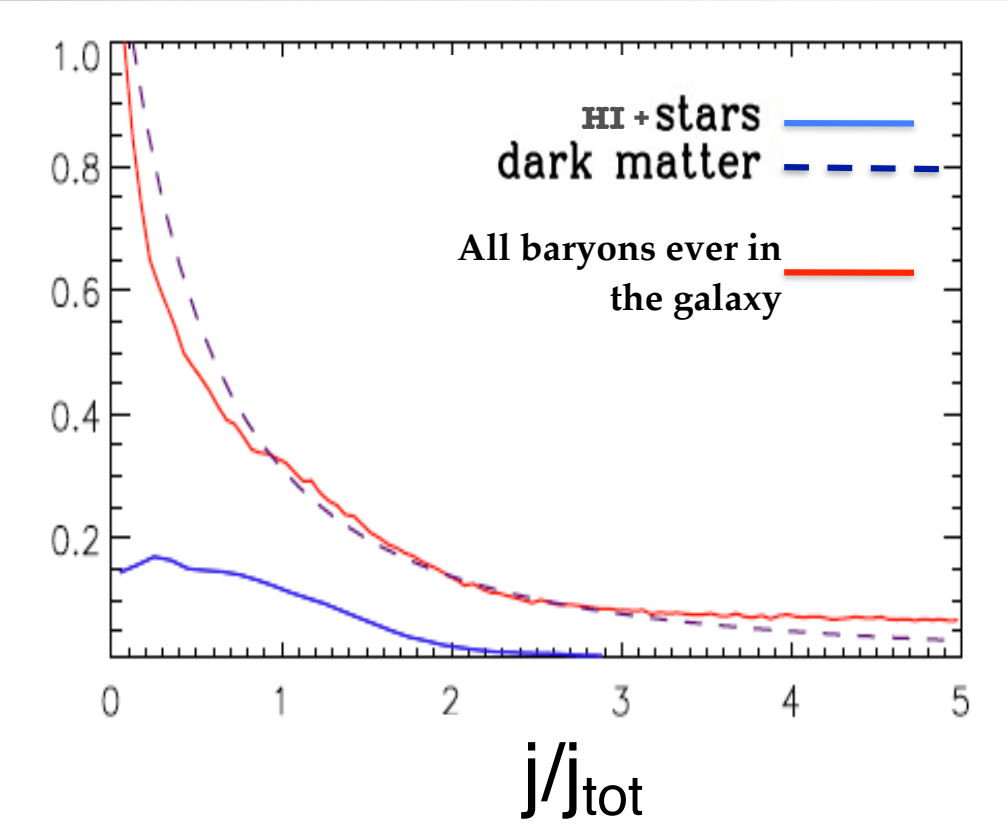
$M_{vir} \sim 10^{10}\ M_{sun}$
"dwarf galaxy"

Edge-on disk orientation

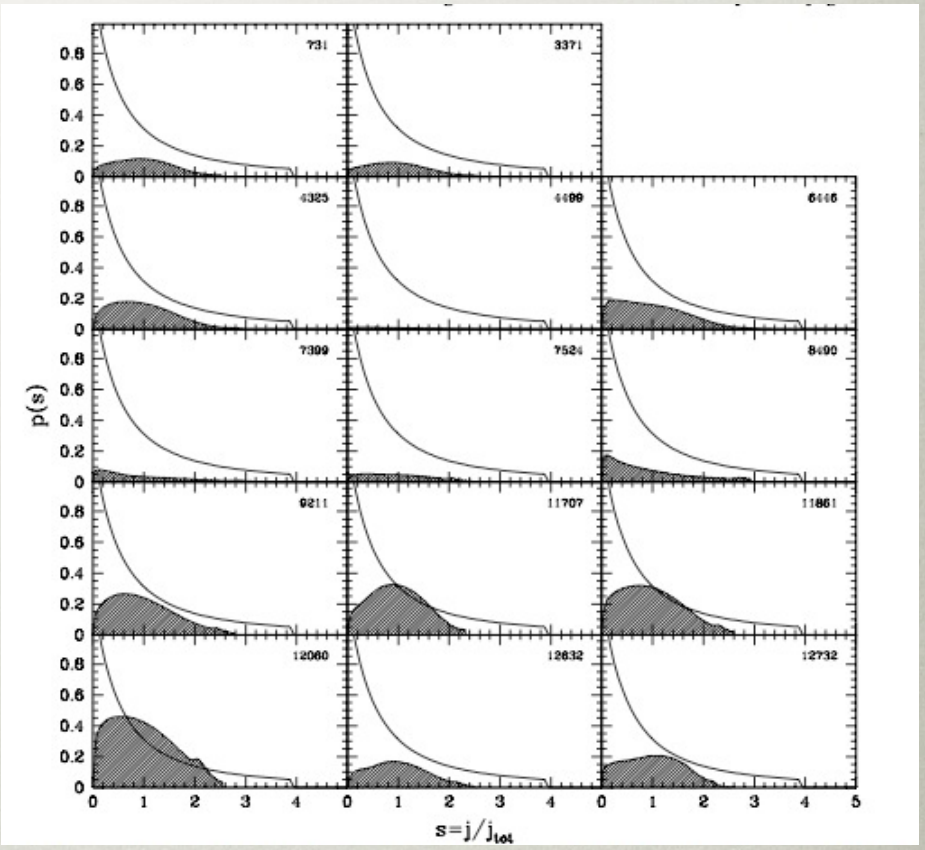
(arrows are velocity vectors)

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

Outflows Remove Low Angular Momentum Gas

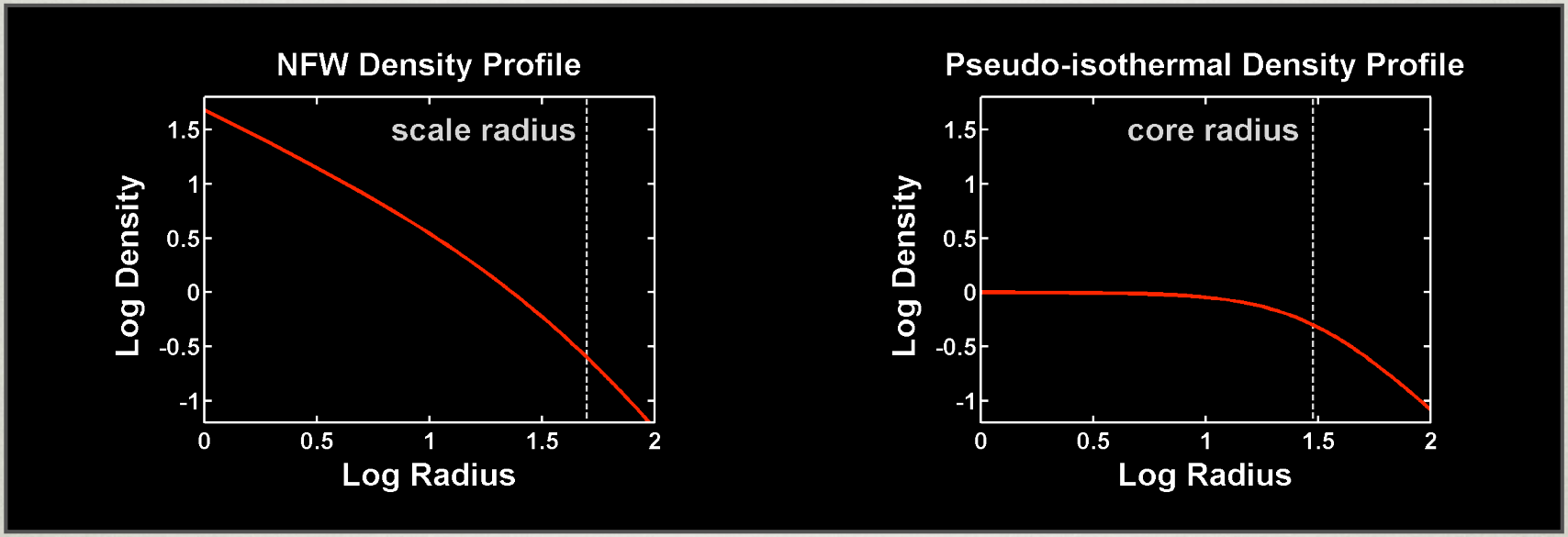


Brook et al., 2011, MNRAS, 415, 1051



van den Bosch et al. (2001)

The Cusp/Core Problem

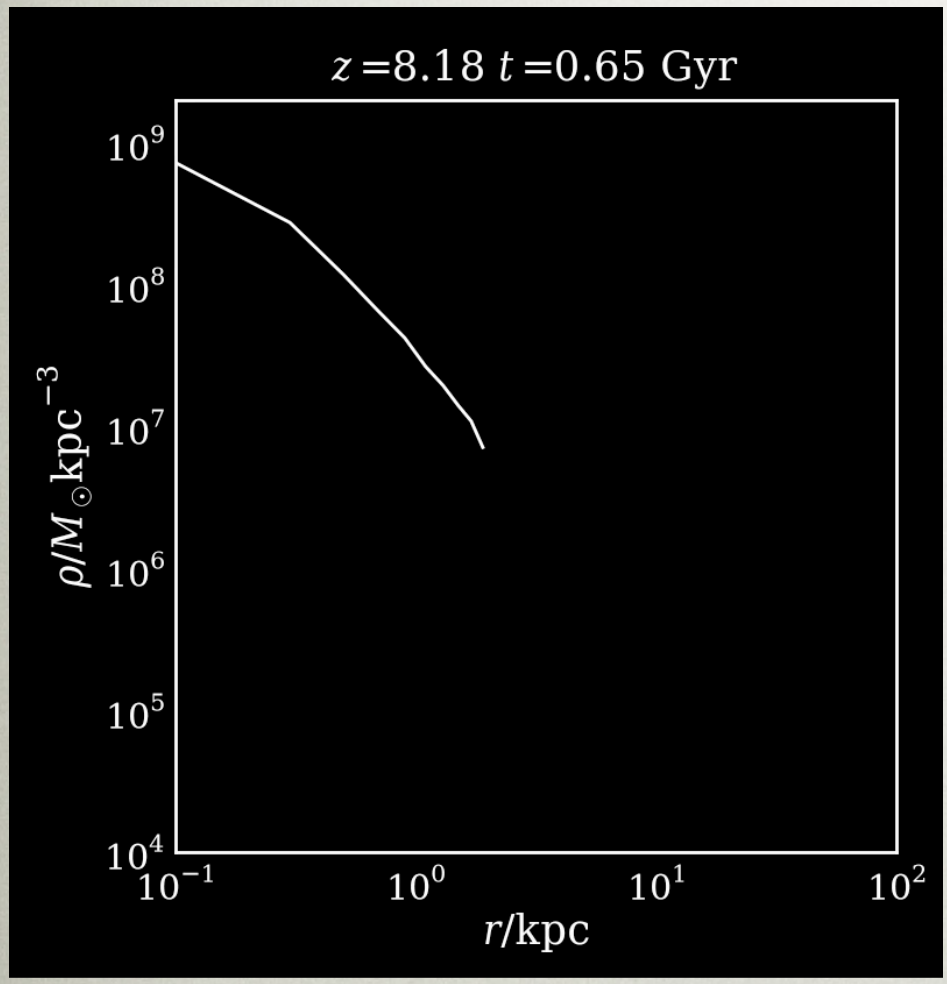


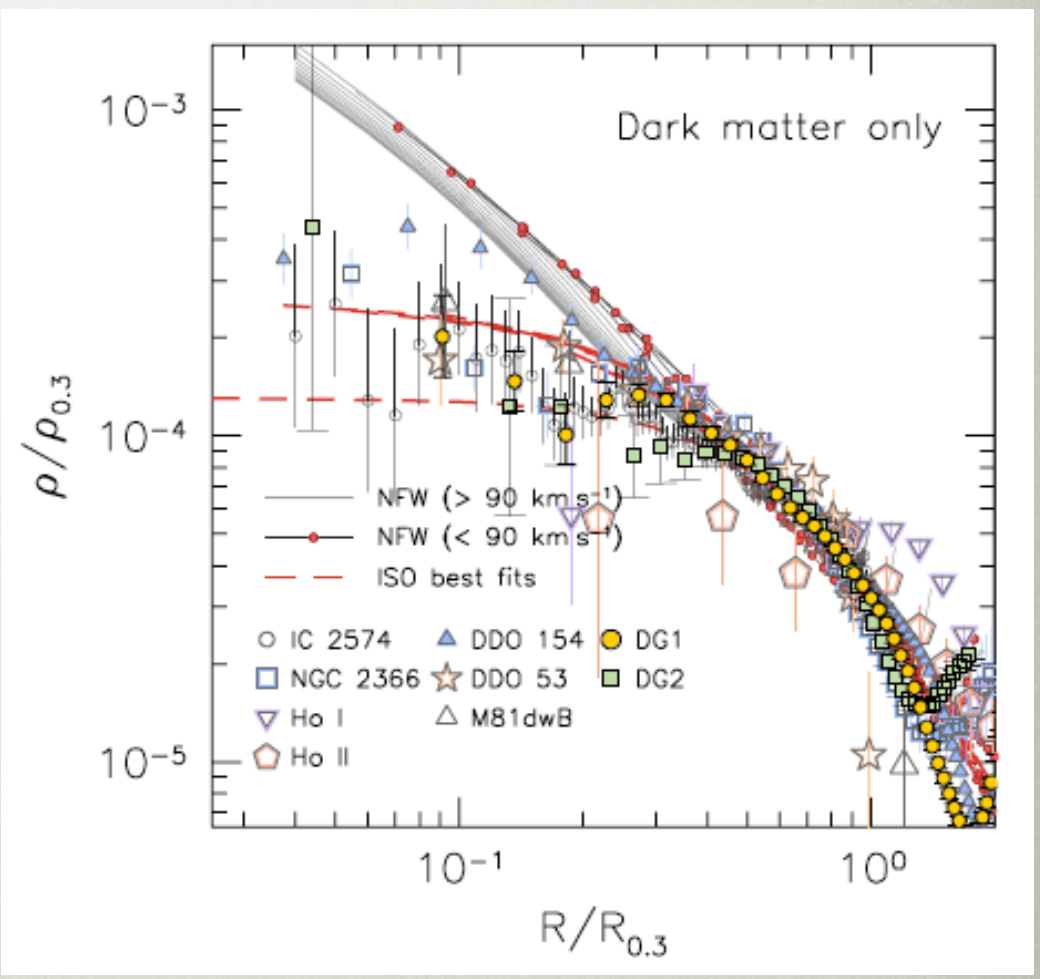
Parameterize density profile as $\rho(r) \propto r^{-\alpha}$

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

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

Creation of a Dark Matter Core

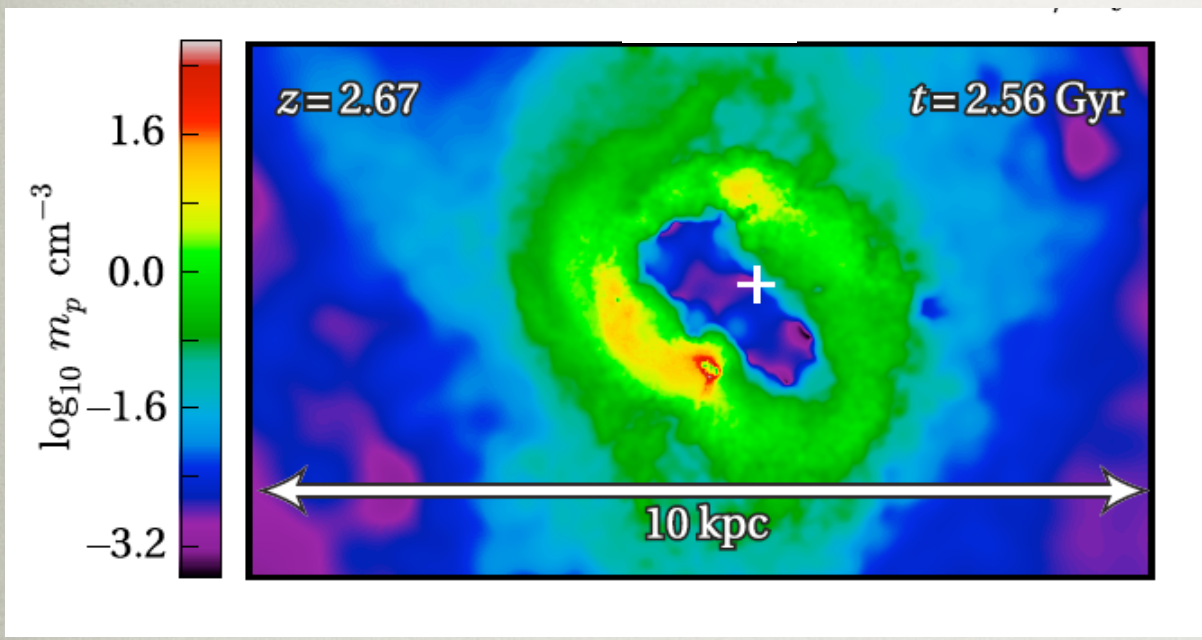


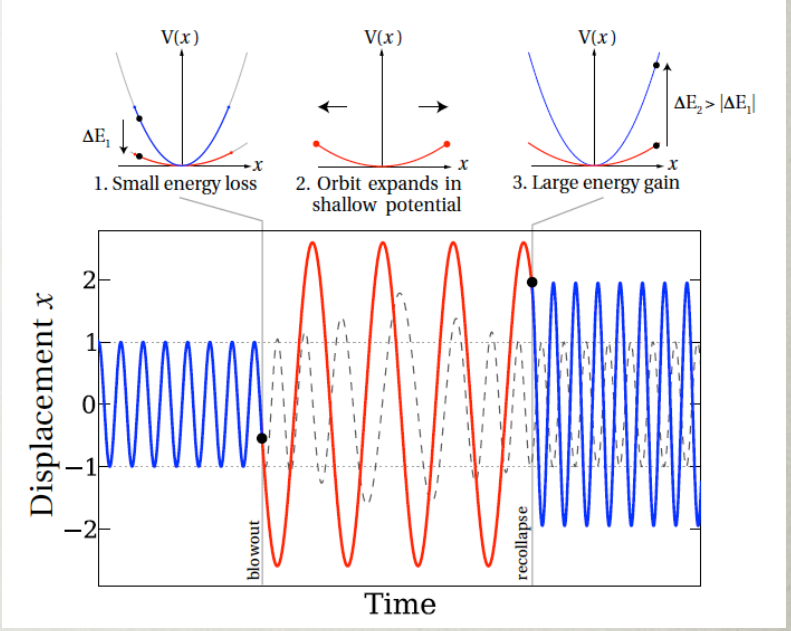


Oh et al., 2011, AJ, 142, 24

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

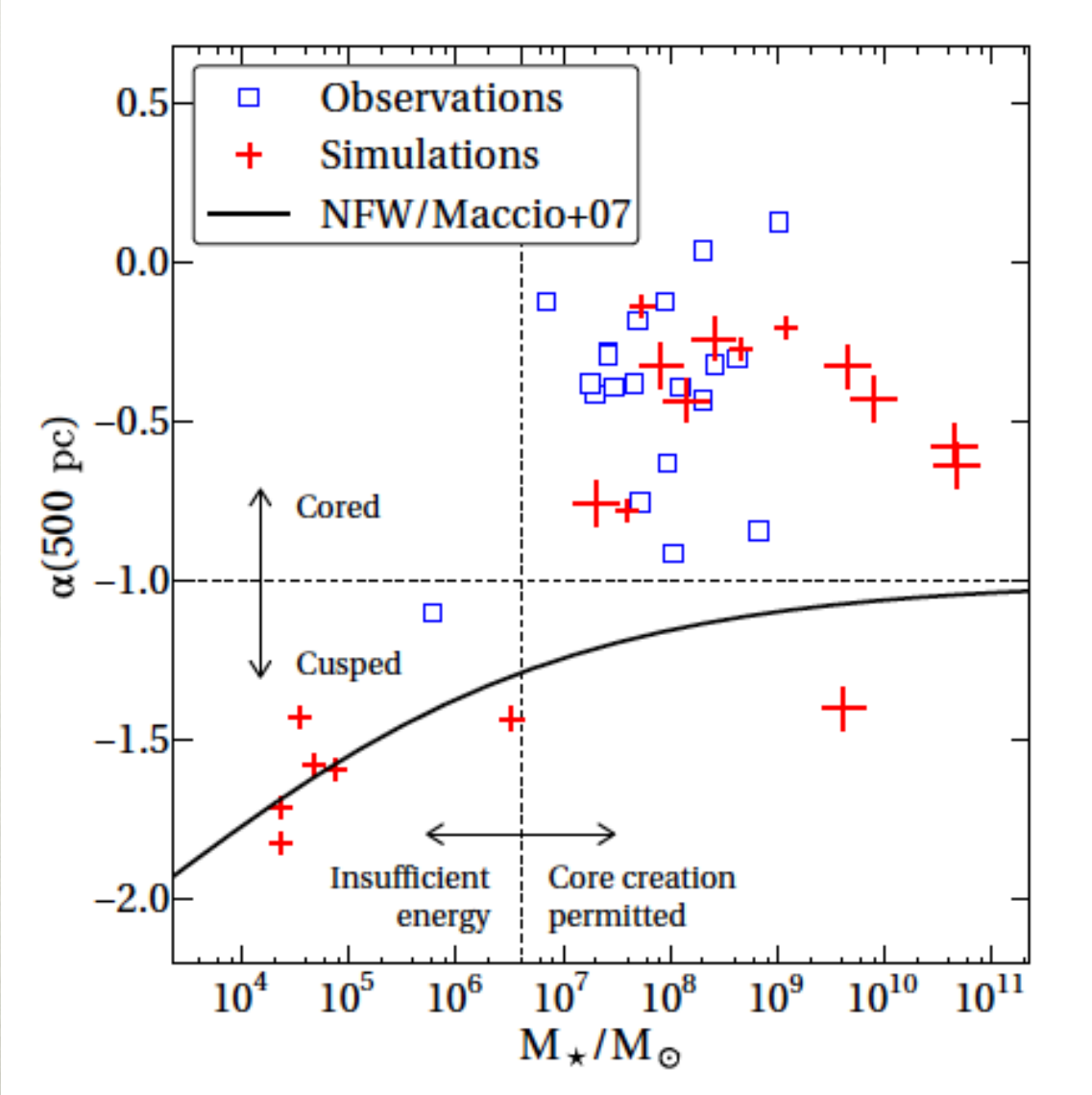
How are Cores Created?





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

Core Creation varies with Mass!

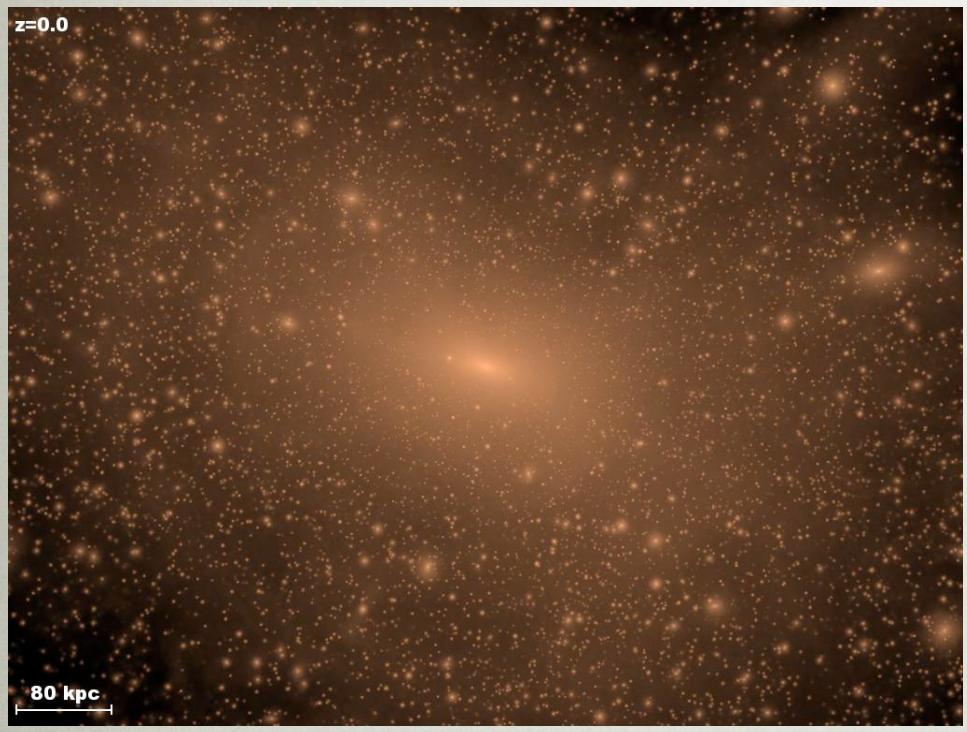


Governato et al., 2012, MNRAS, 422, 1231

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

- Bulge-less disk galaxies ✓
- The cusp/core problem ✓
- The "Too Big to Fail" problem
- The "Missing Satellites" problem
- The "Missing Dwarfs" problem

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



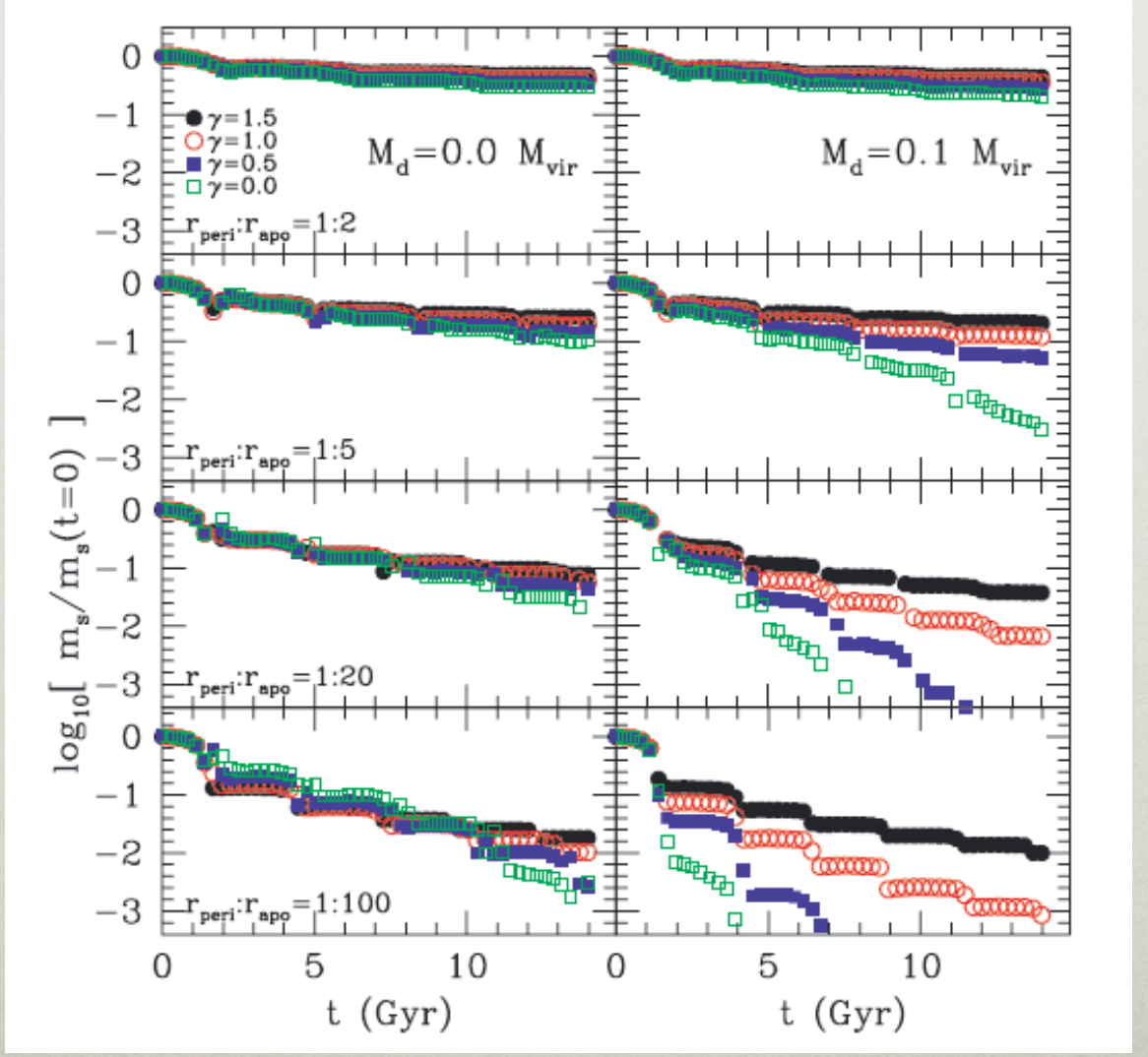
Dark Matter

Baryons

(or any central baryonic concentration)

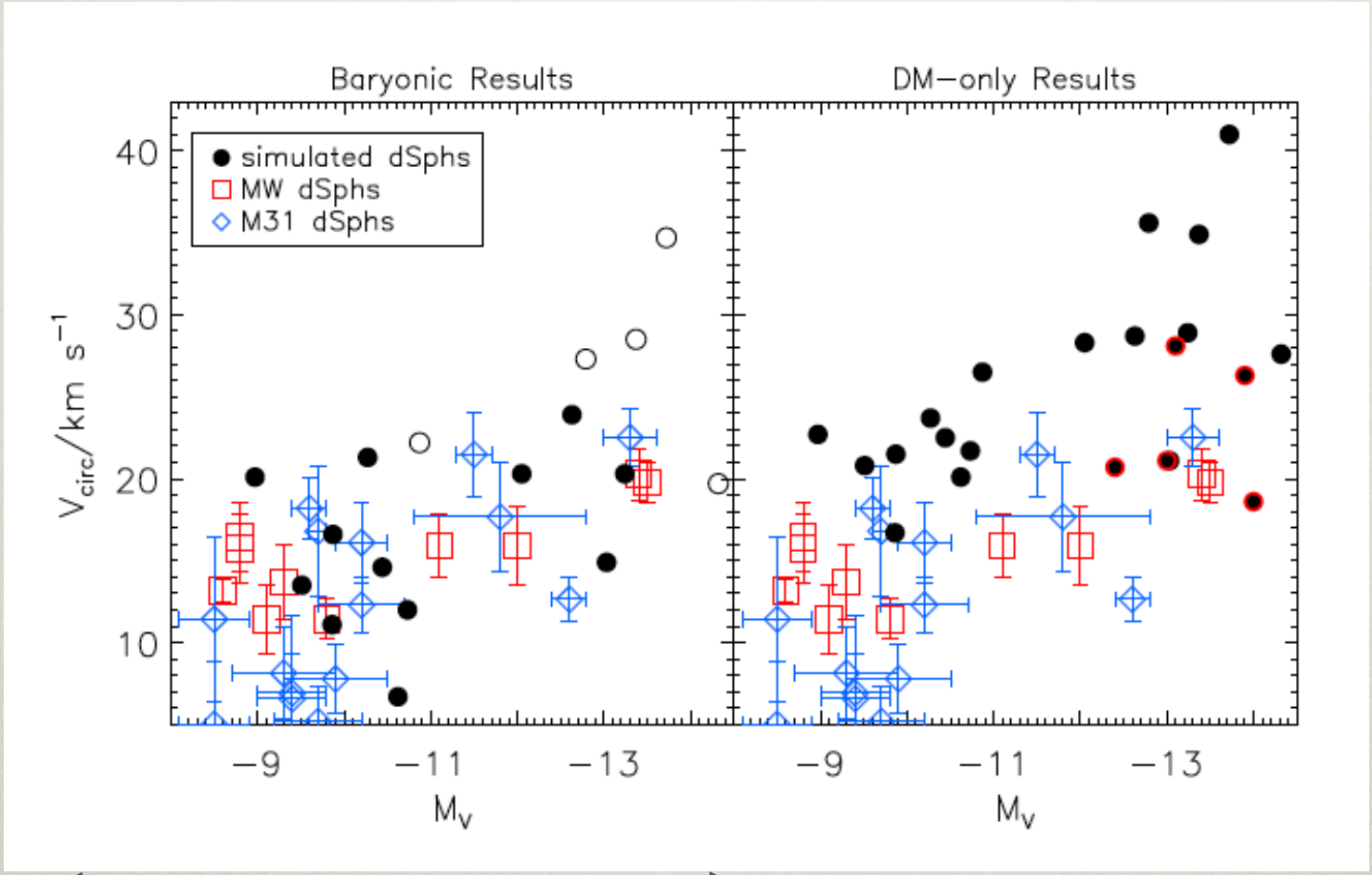
Chang et al. (2012)

Not Just Core Creation: The Tidal Effect of the Disk



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

A DISK REMOVES MASS VIA TIDAL FORCES FROM SATELLITE GALAXIES



More massive

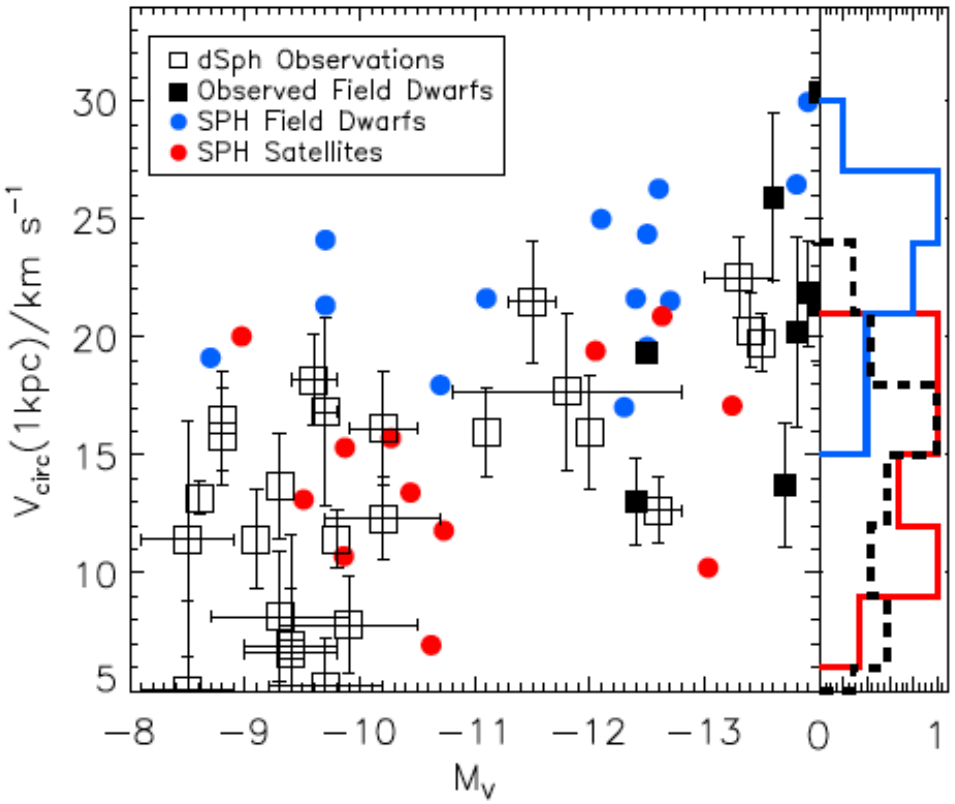
Less massive

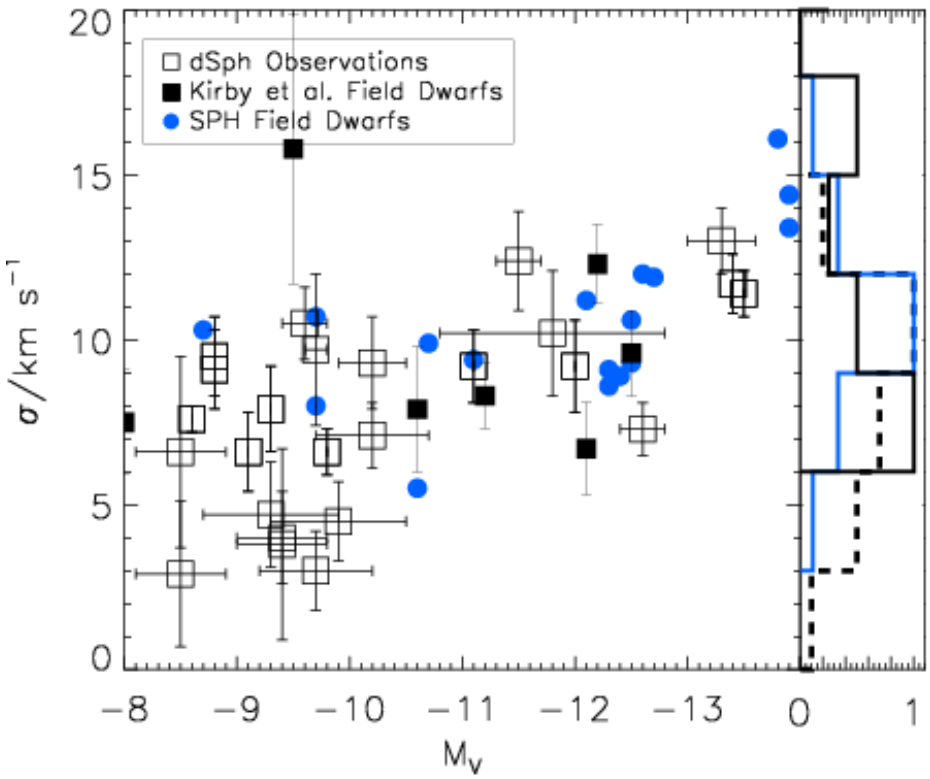
Fainter

Brighter

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

Tidal Effects should lead to lower masses in satellites





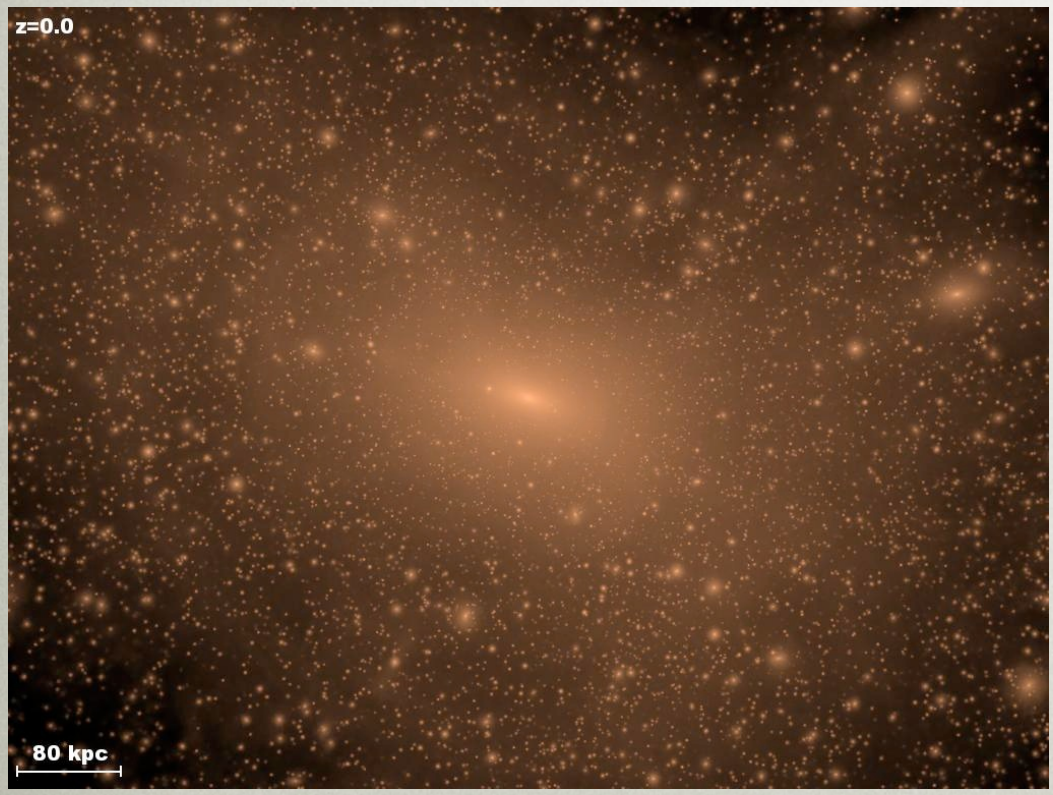
Brooks & Zolotov (2014), arXiv:1207.2468

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

- Bulge-less disk galaxies ✓
- The cusp/core problem ✓
- The "Too Big to Fail" problem ✓
- The "Missing Satellites" problem
- The "Missing Dwarfs" problem

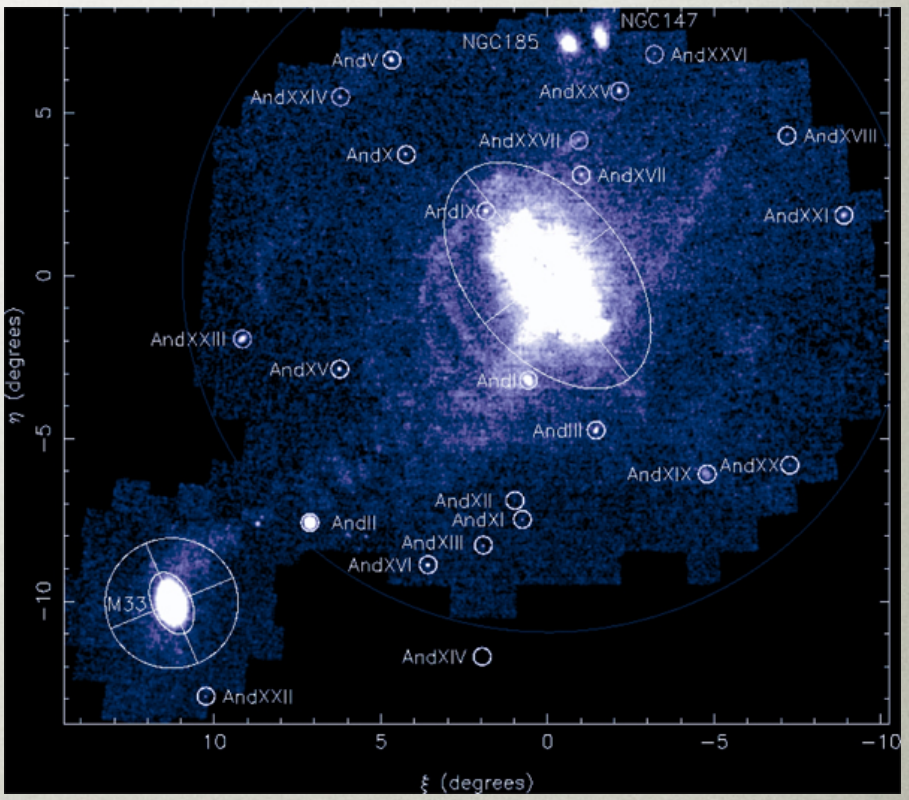
The "Missing Satellites" Problem

1000's of satellites predicted



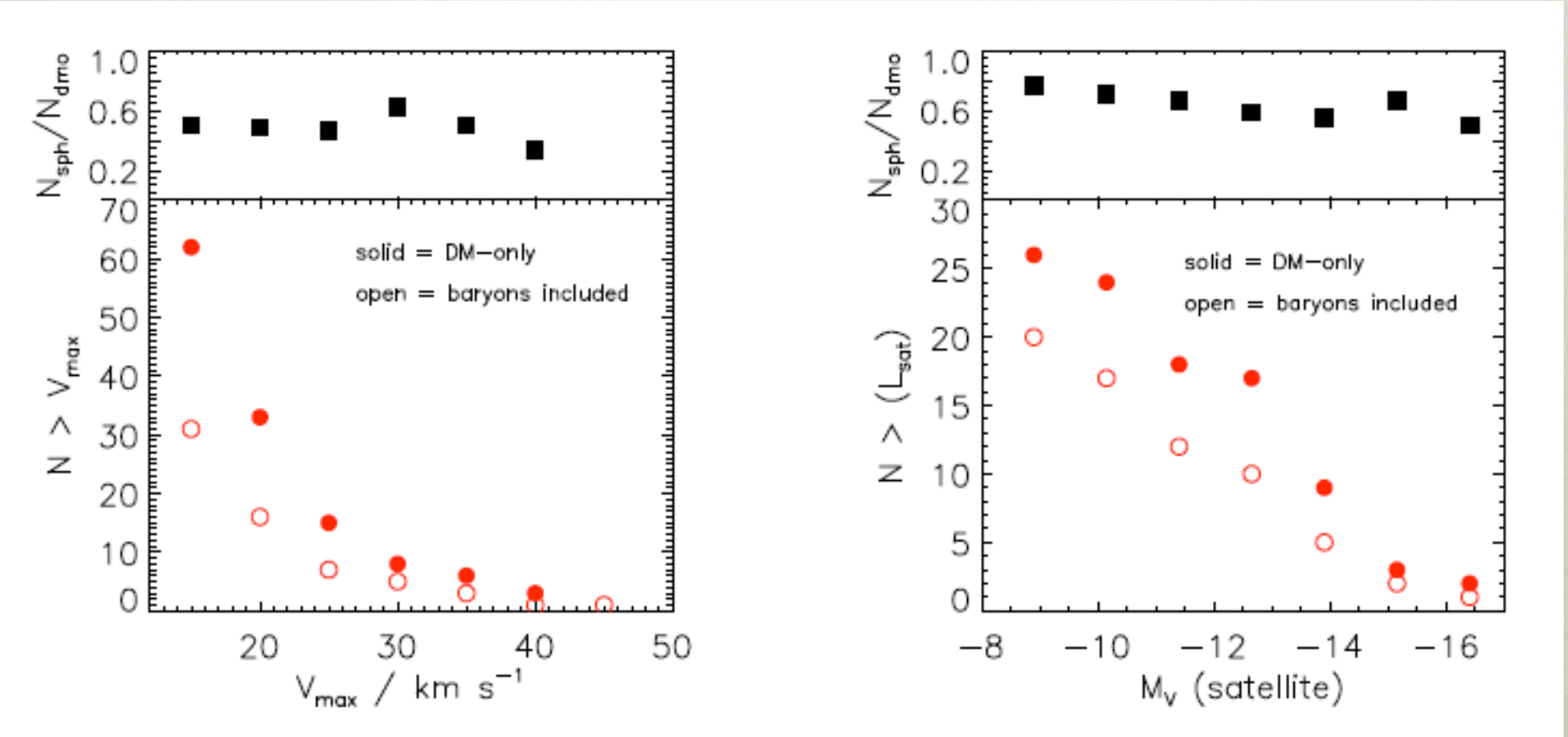
"Via Lactea" Simulation

dozens seen



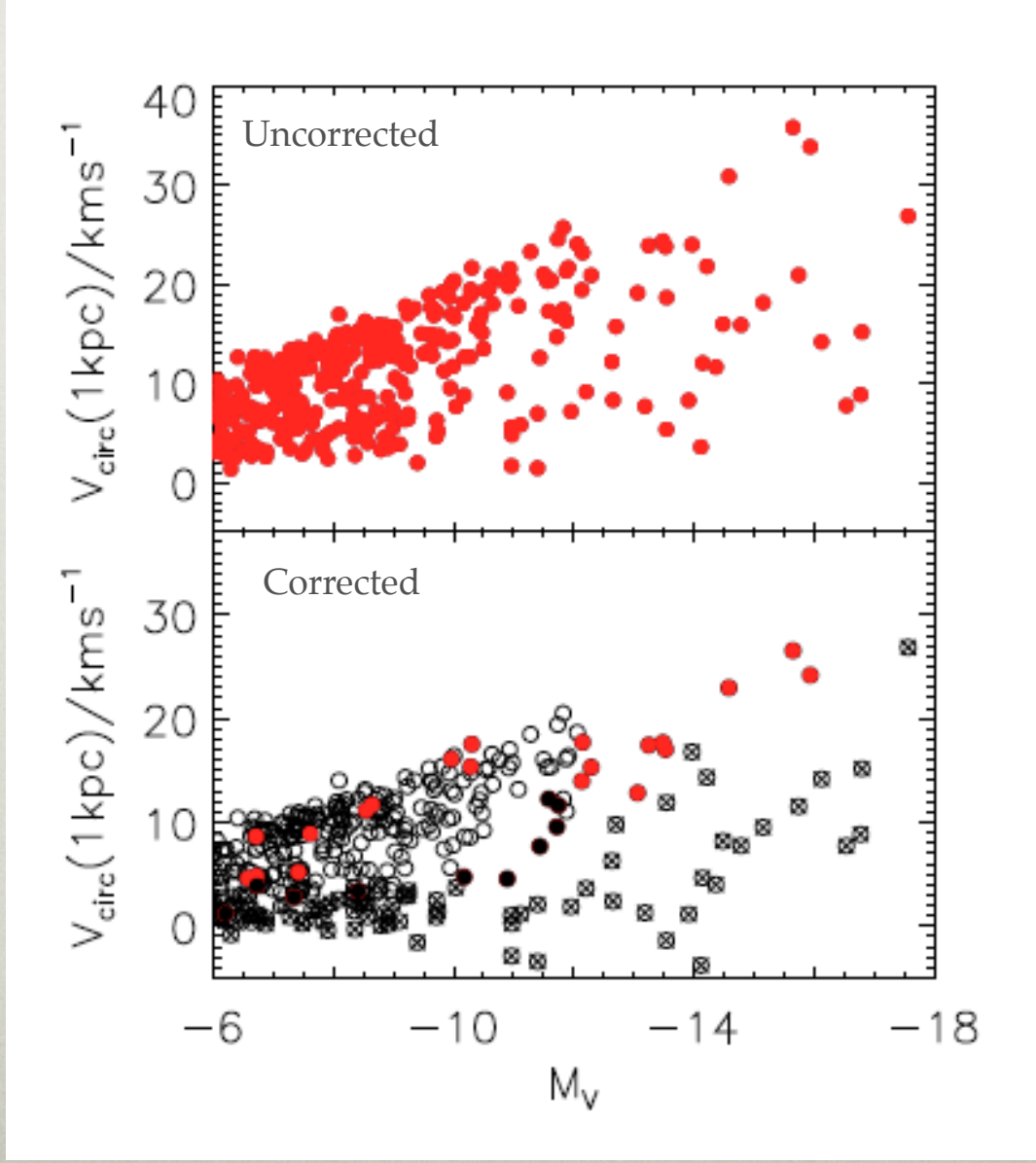
Pan-ANDromeda Archeological Survey (PAndAS)

The Change to Mass and Luminosity Functions



Brooks & Zolotov (2014), arXiv:1207.2468

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 "Too Big to Fail" problem ✓
- The "Missing Satellites" problem ✓
- The "Missing Dwarfs" problem

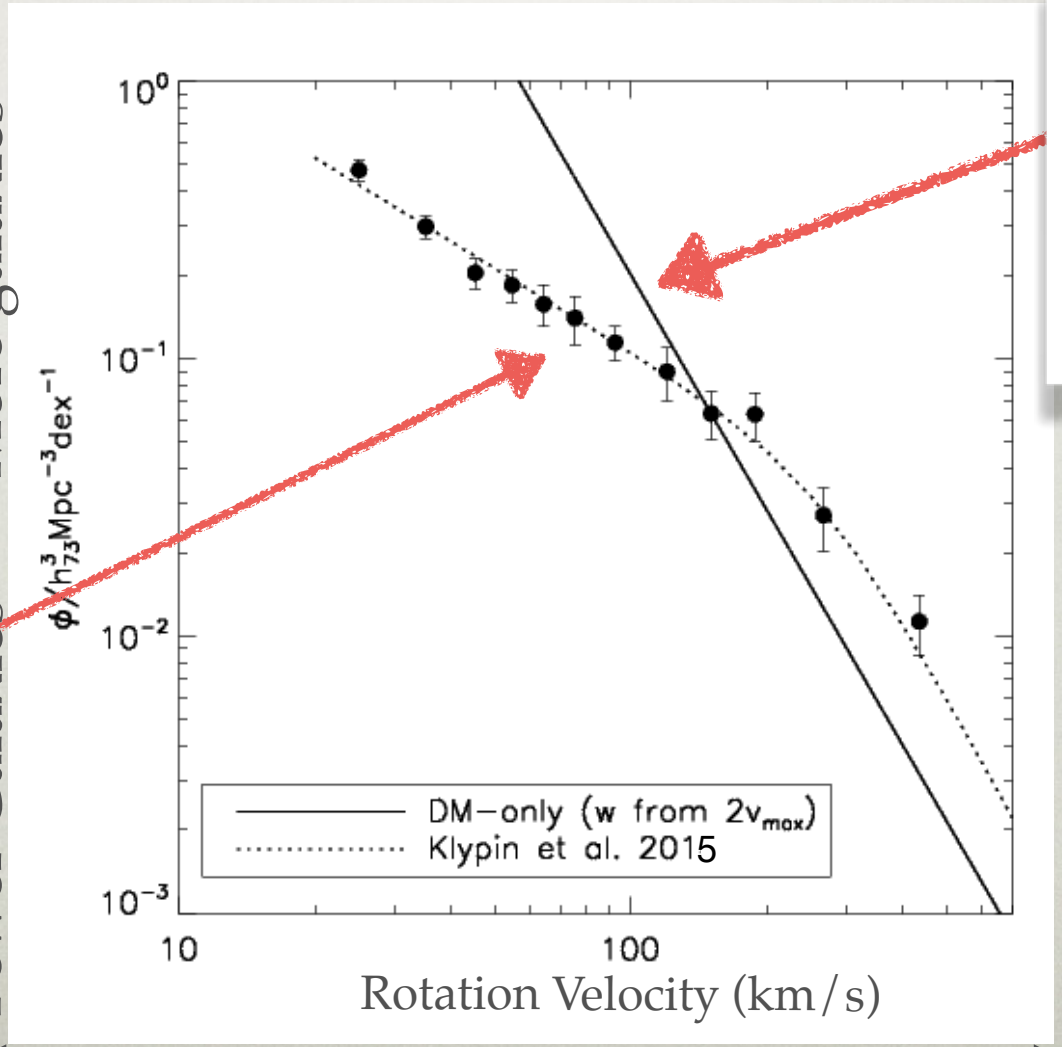
The Missing Dwarf Problem in the Field

Predicted number of galaxies

Observed number of galaxies

More galaxies

Fewer Galaxies

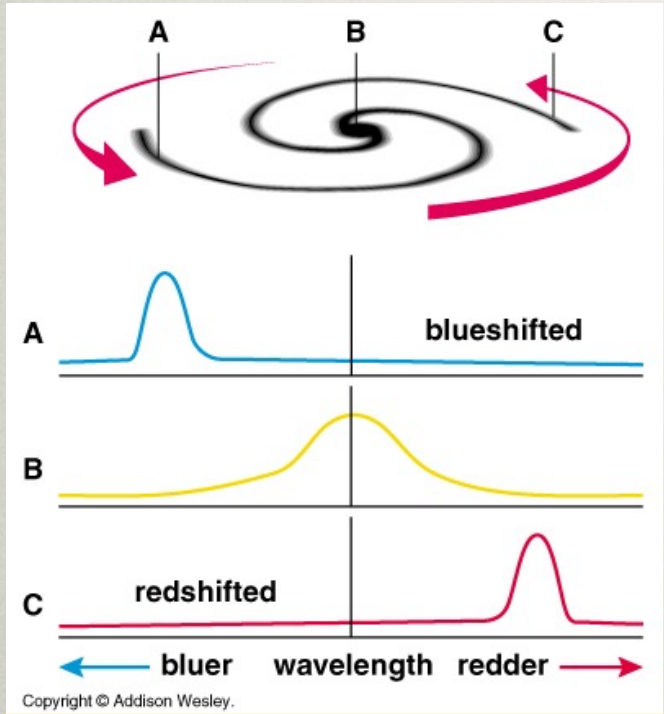


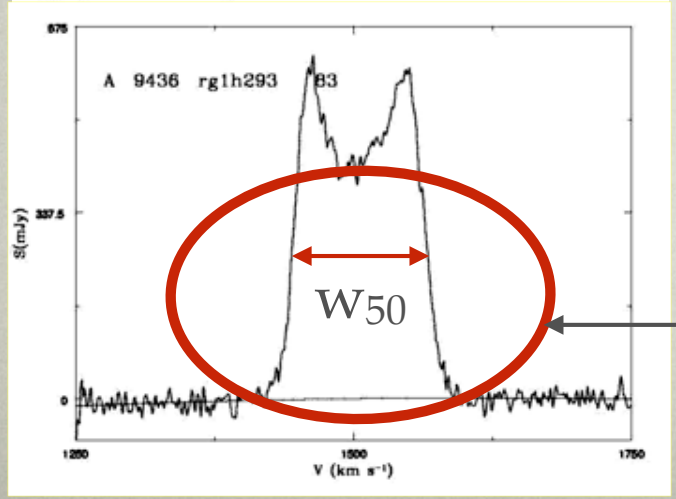
Less massive

More massive

Klypin et al. (2015)

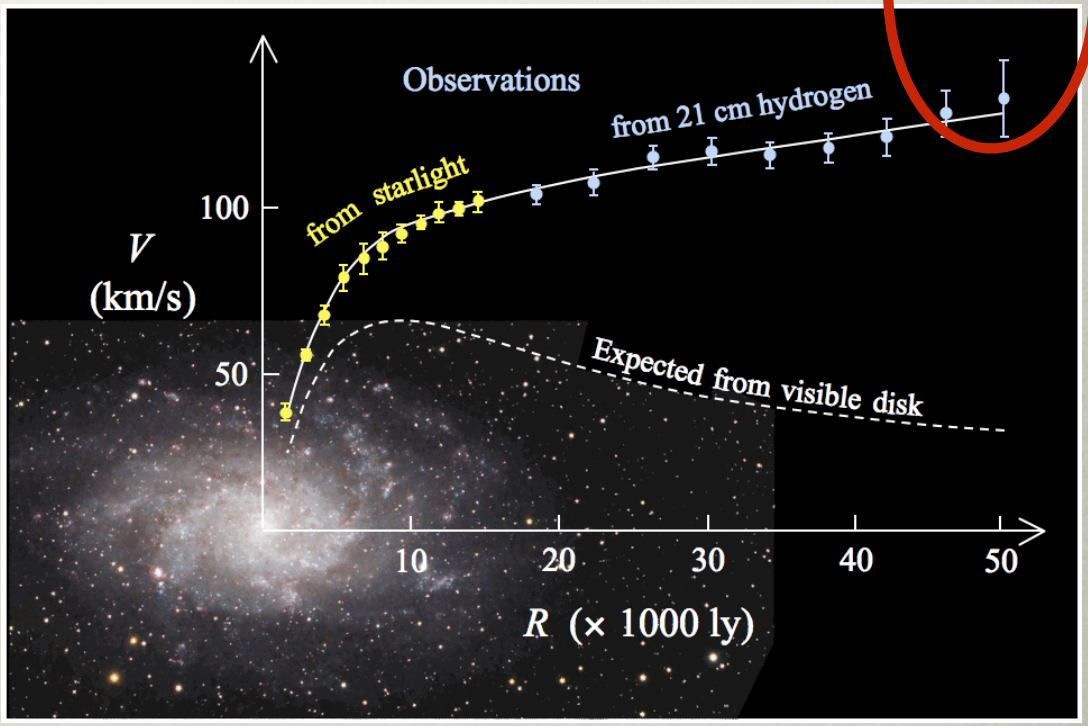
BUT: Two Ways to Measure Rotation (Resolved vs Unresolved)



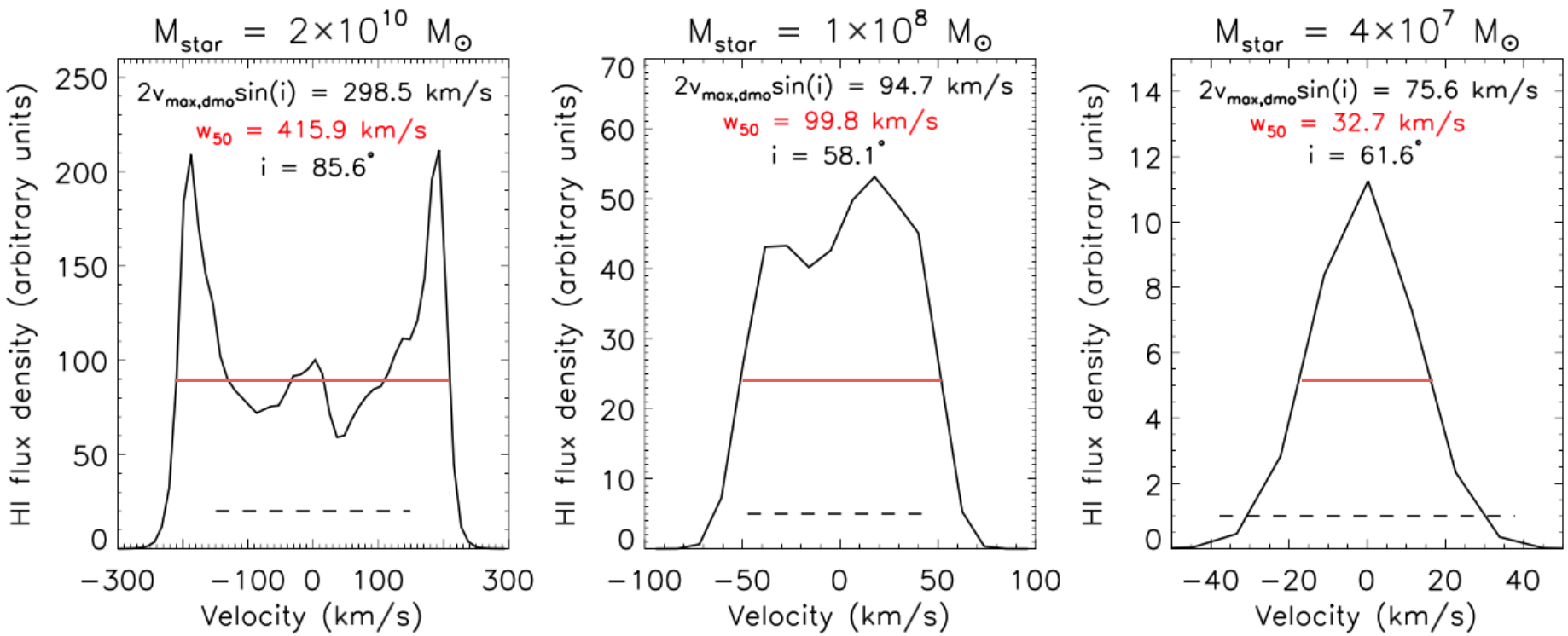


Observations

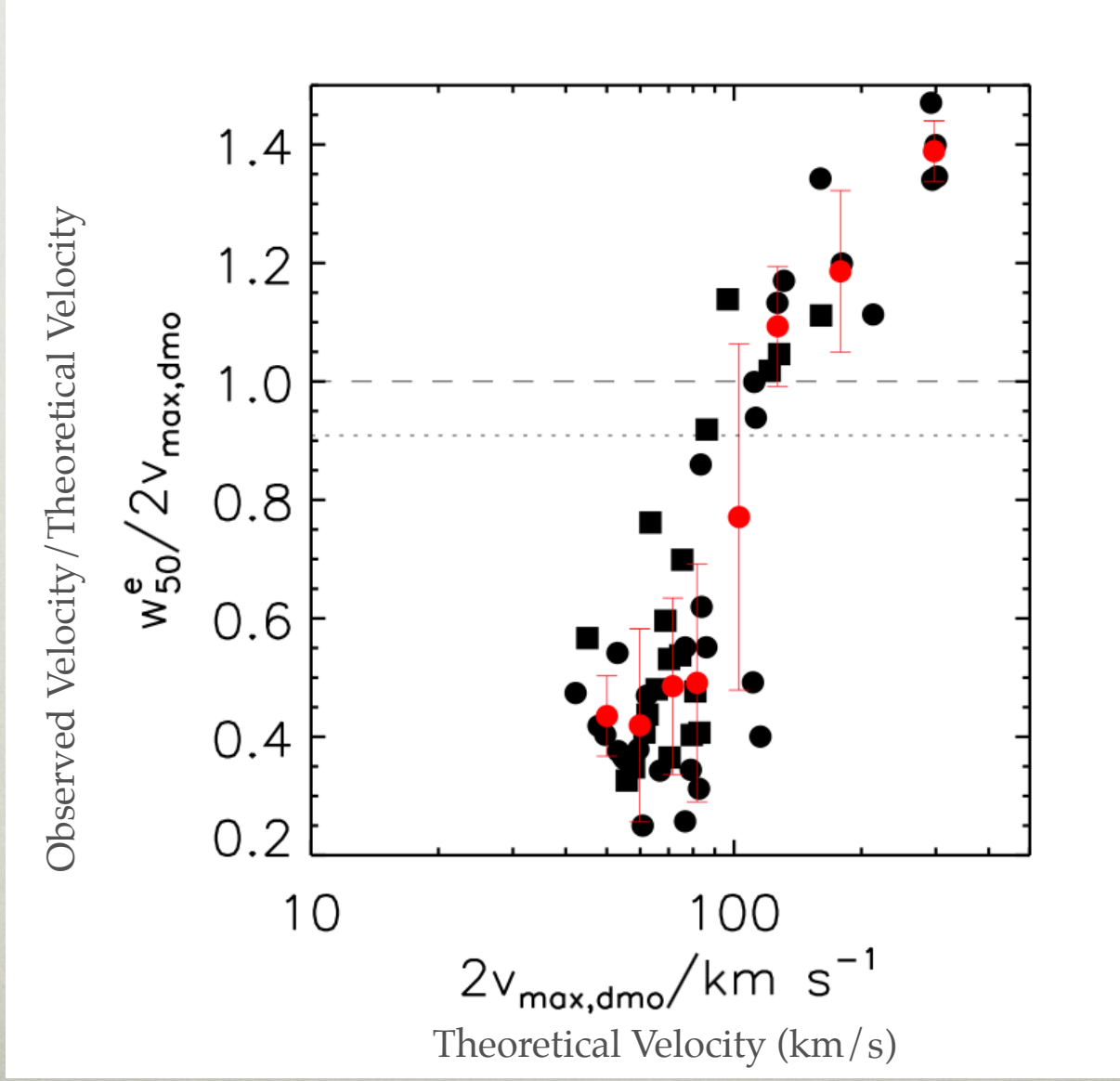
Theory → v_{max}



Creating Mock Observations

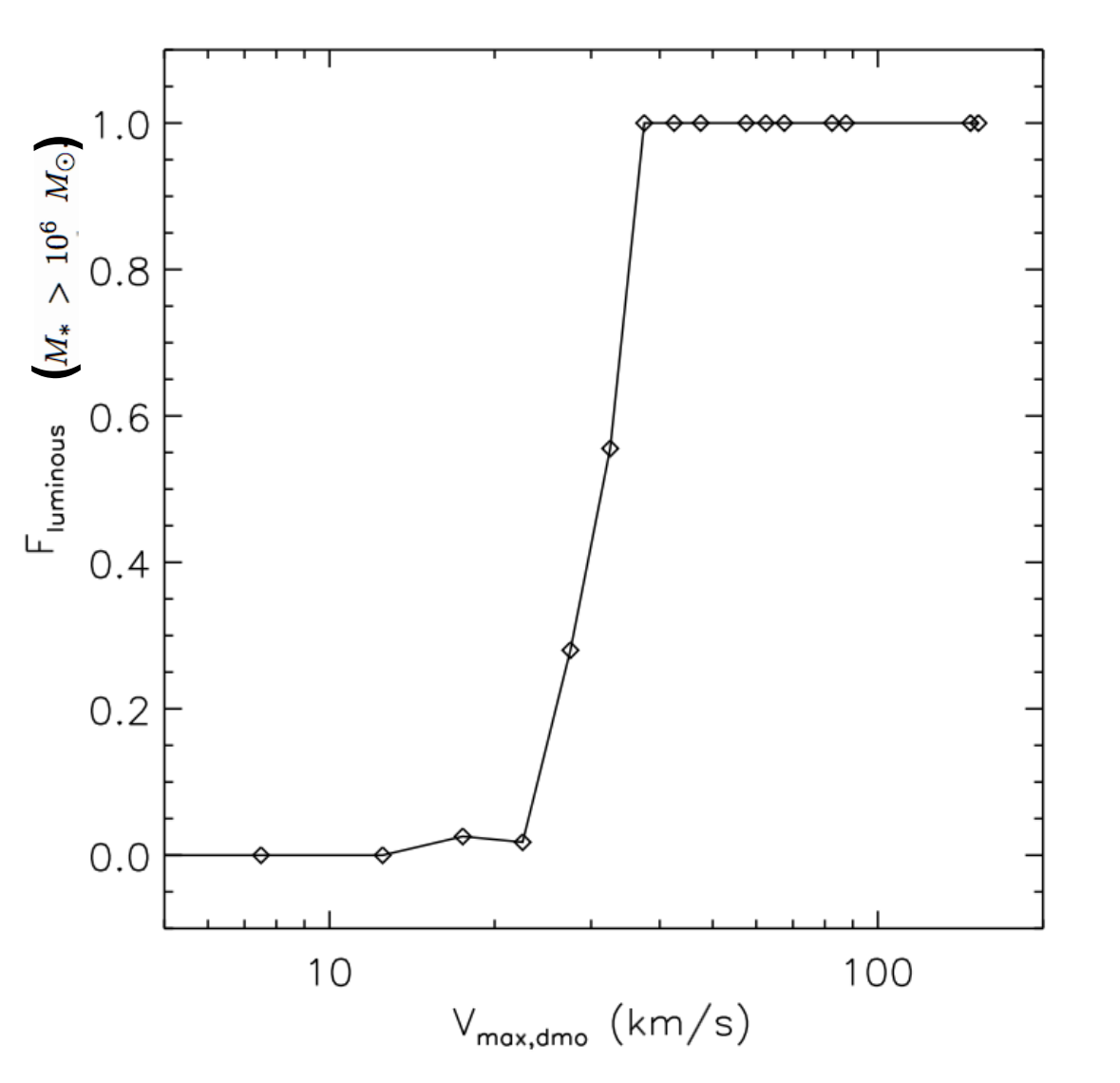


How Well Do Theory and Observation Match?



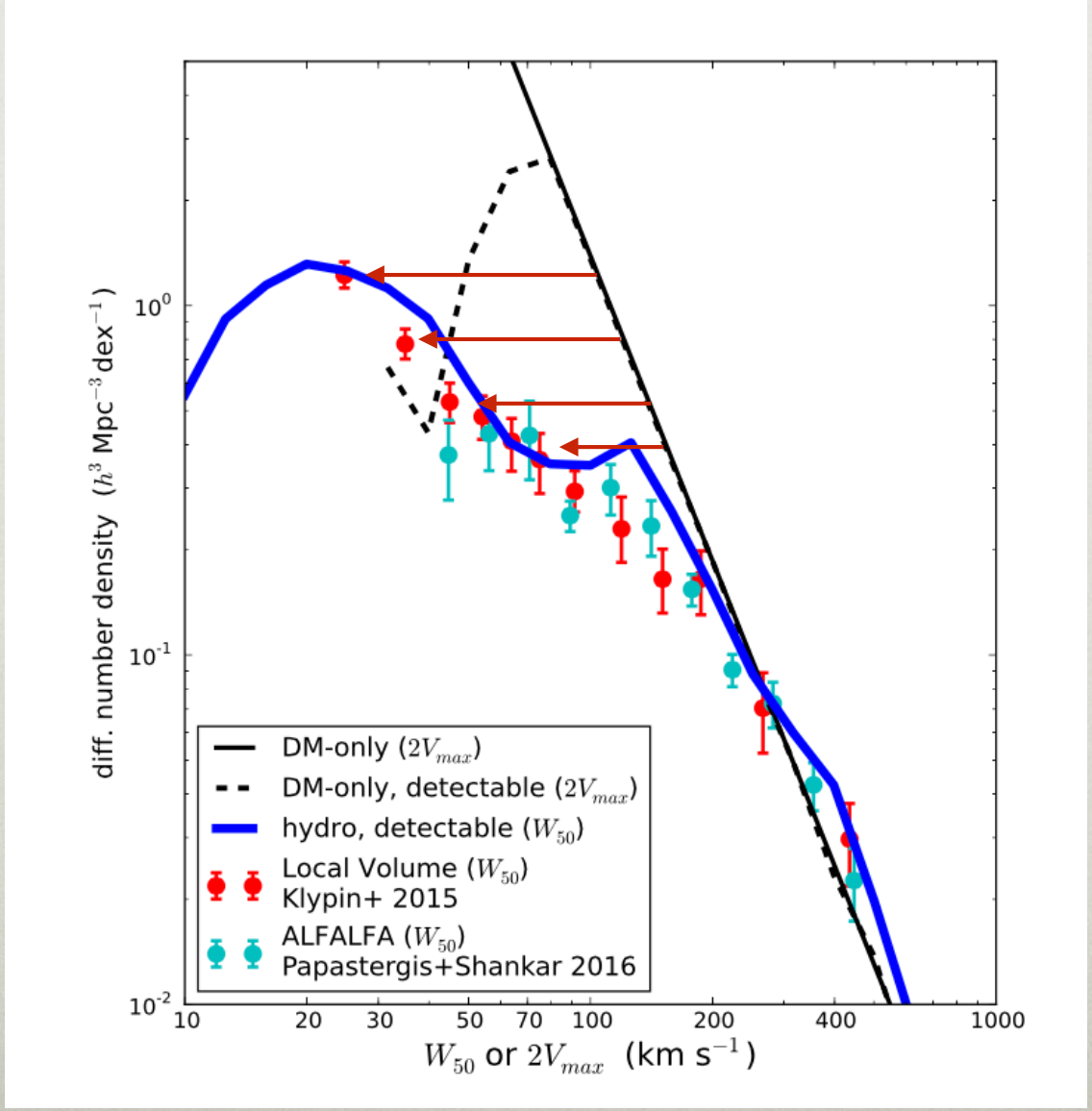
Brooks et al. (2017), arXiv:1701.07835

Must Also Consider Detectability



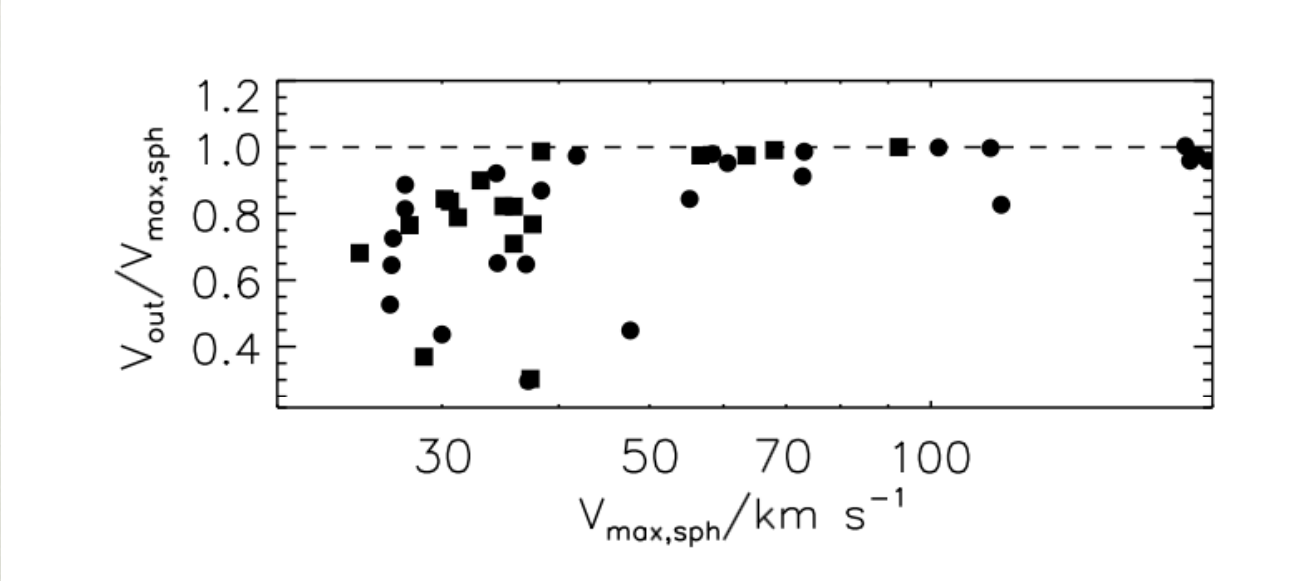
Brooks et al. (2017), arXiv:1701.07835

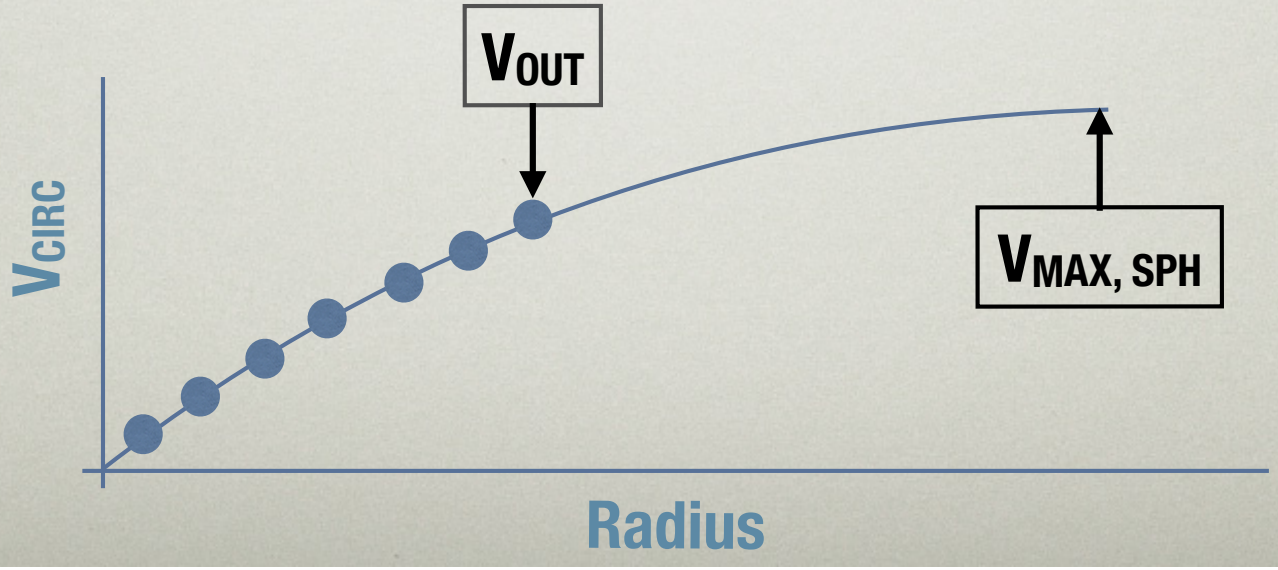
Putting it Together



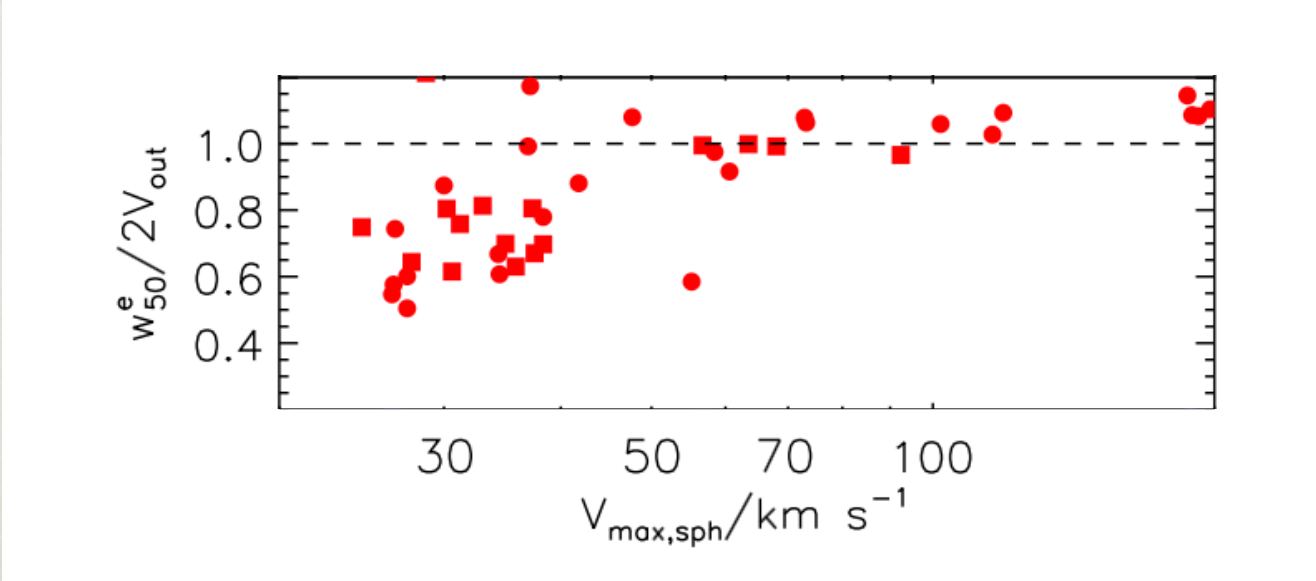
Brooks et al. (2017), arXiv:1701.07835

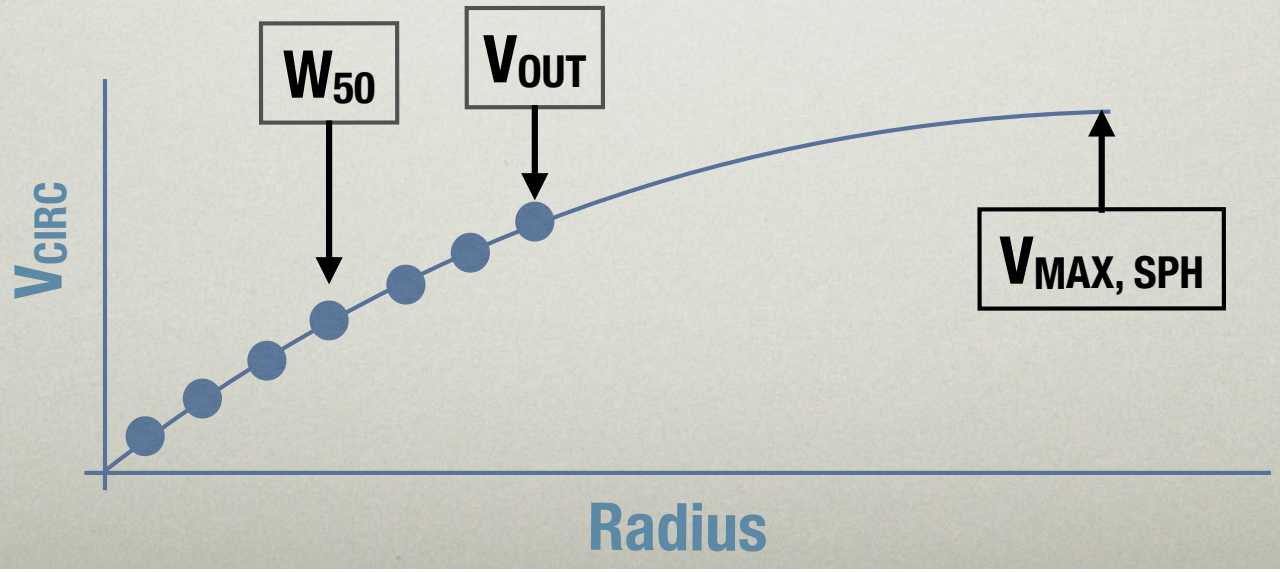
Why the Velocity Shift?



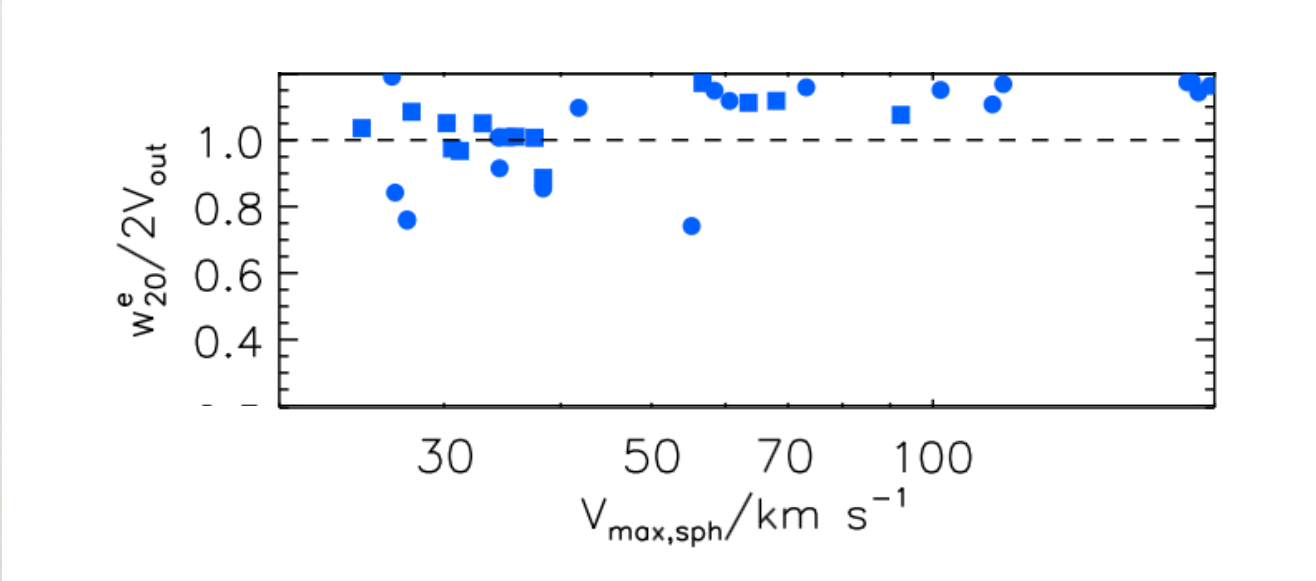


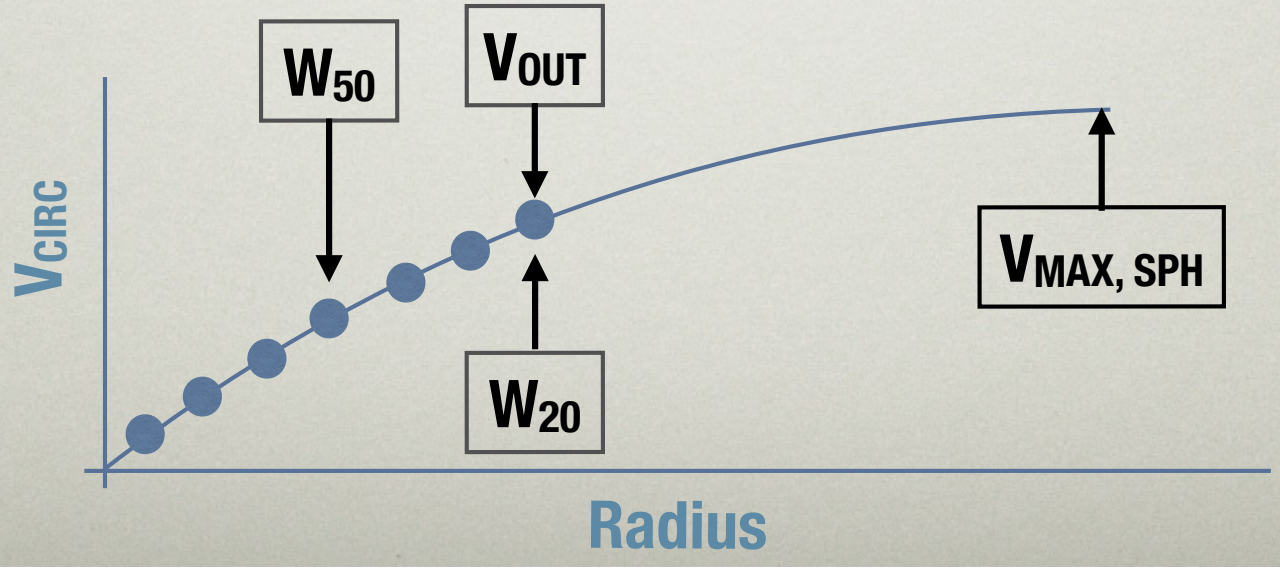
Why the Velocity Shift?



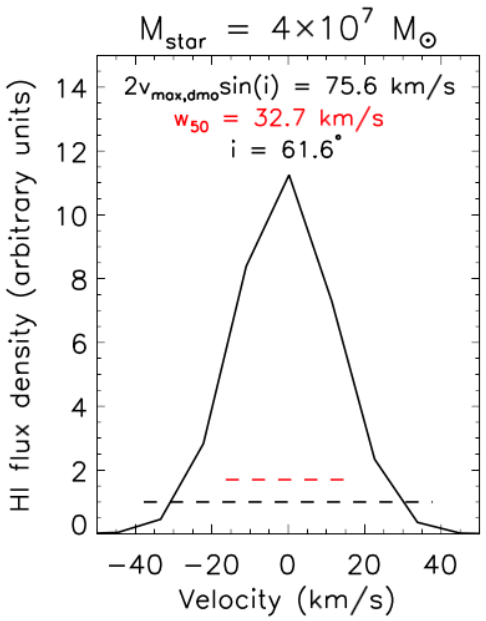


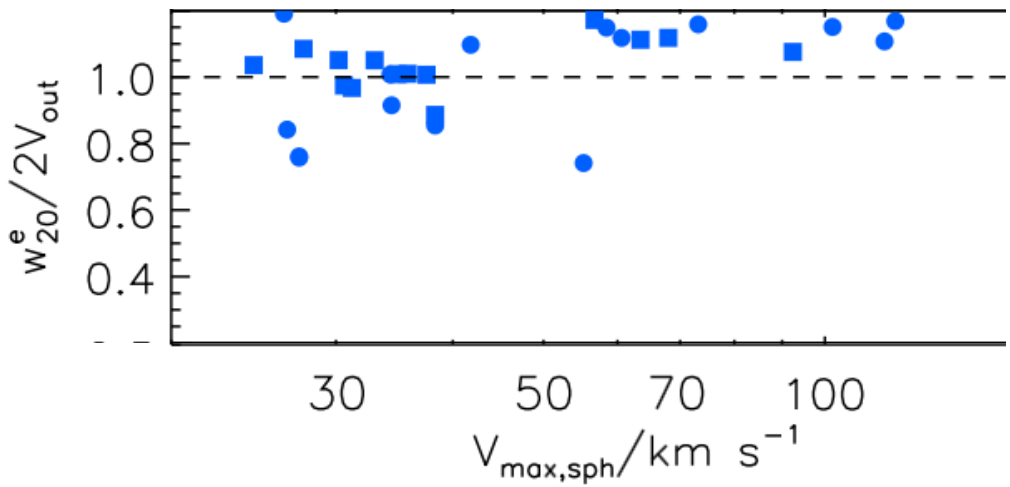
Why the Velocity Shift?

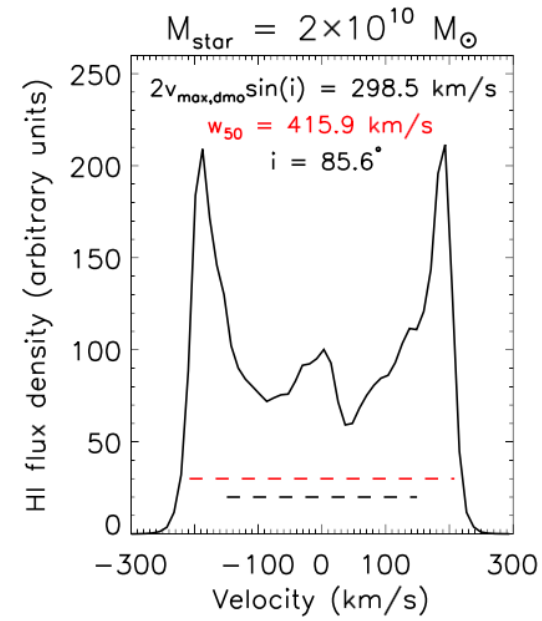


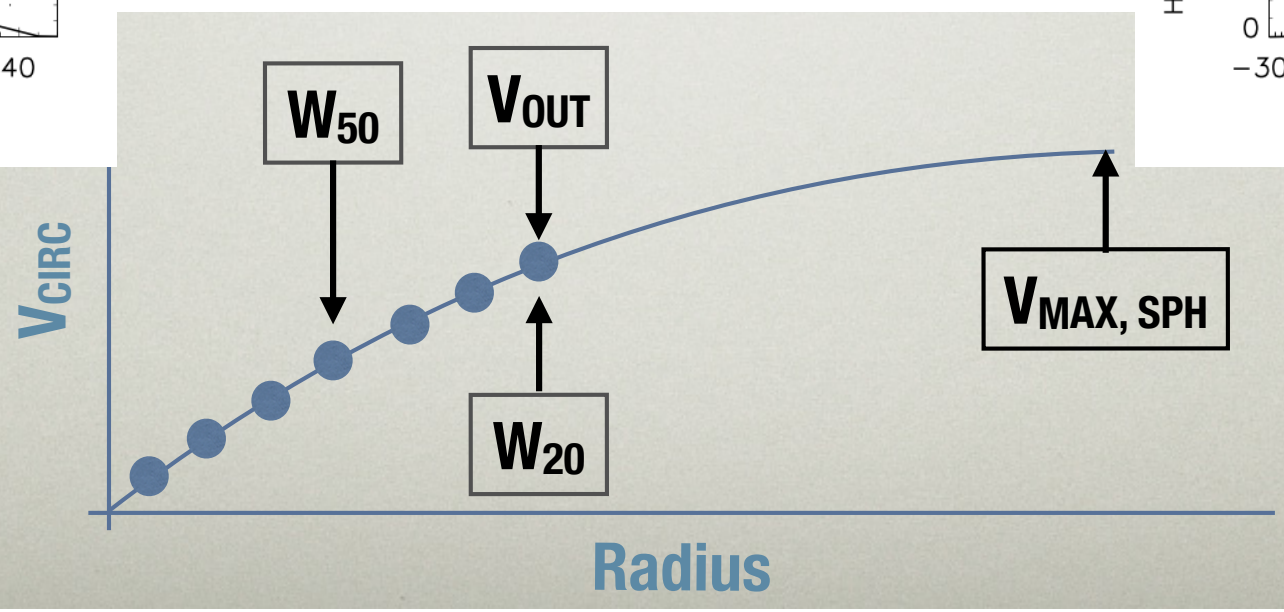


Why the Velocity Shift?

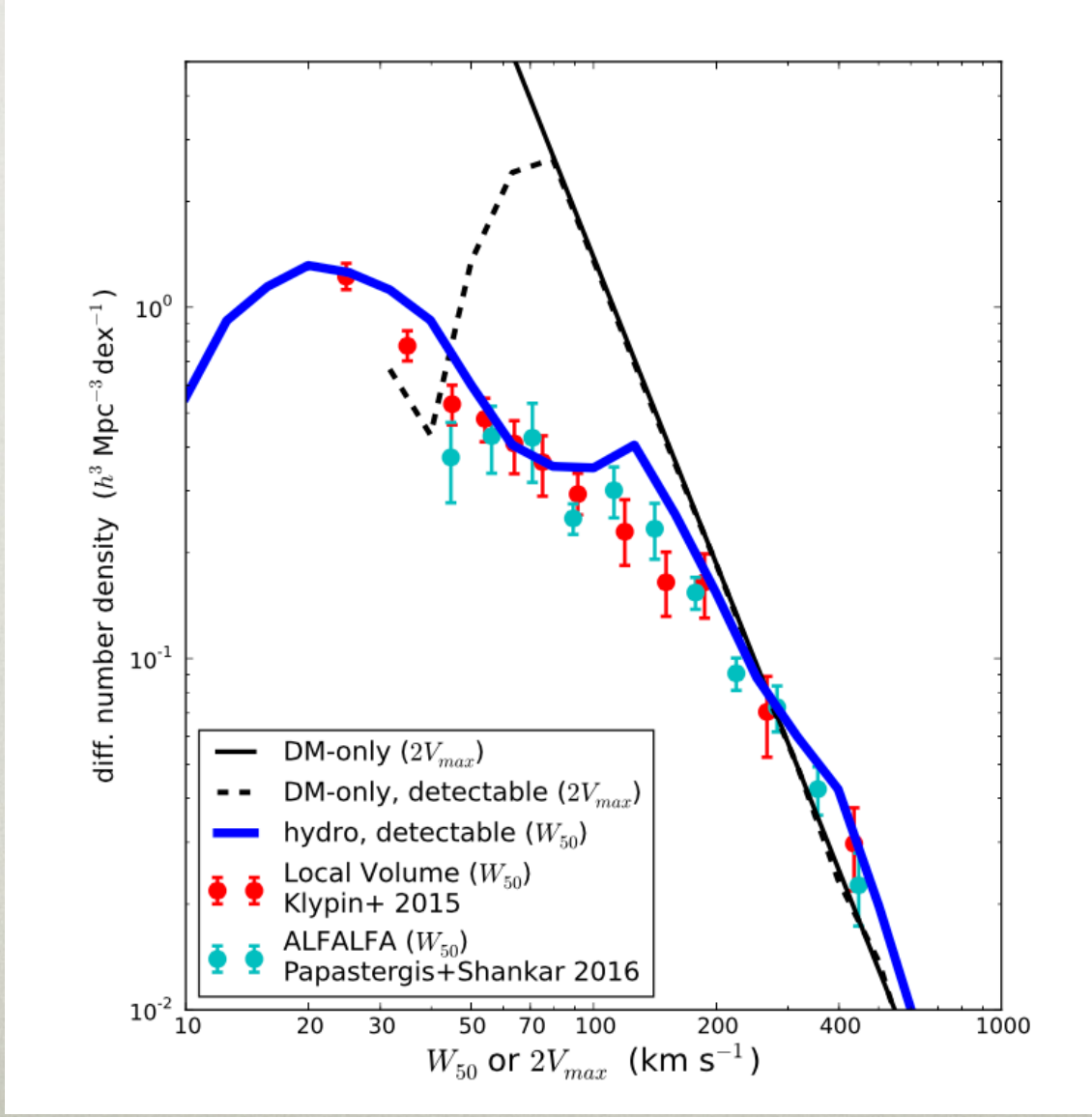








Putting it Together



Brooks et al. (2017), arXiv:1701.07835

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

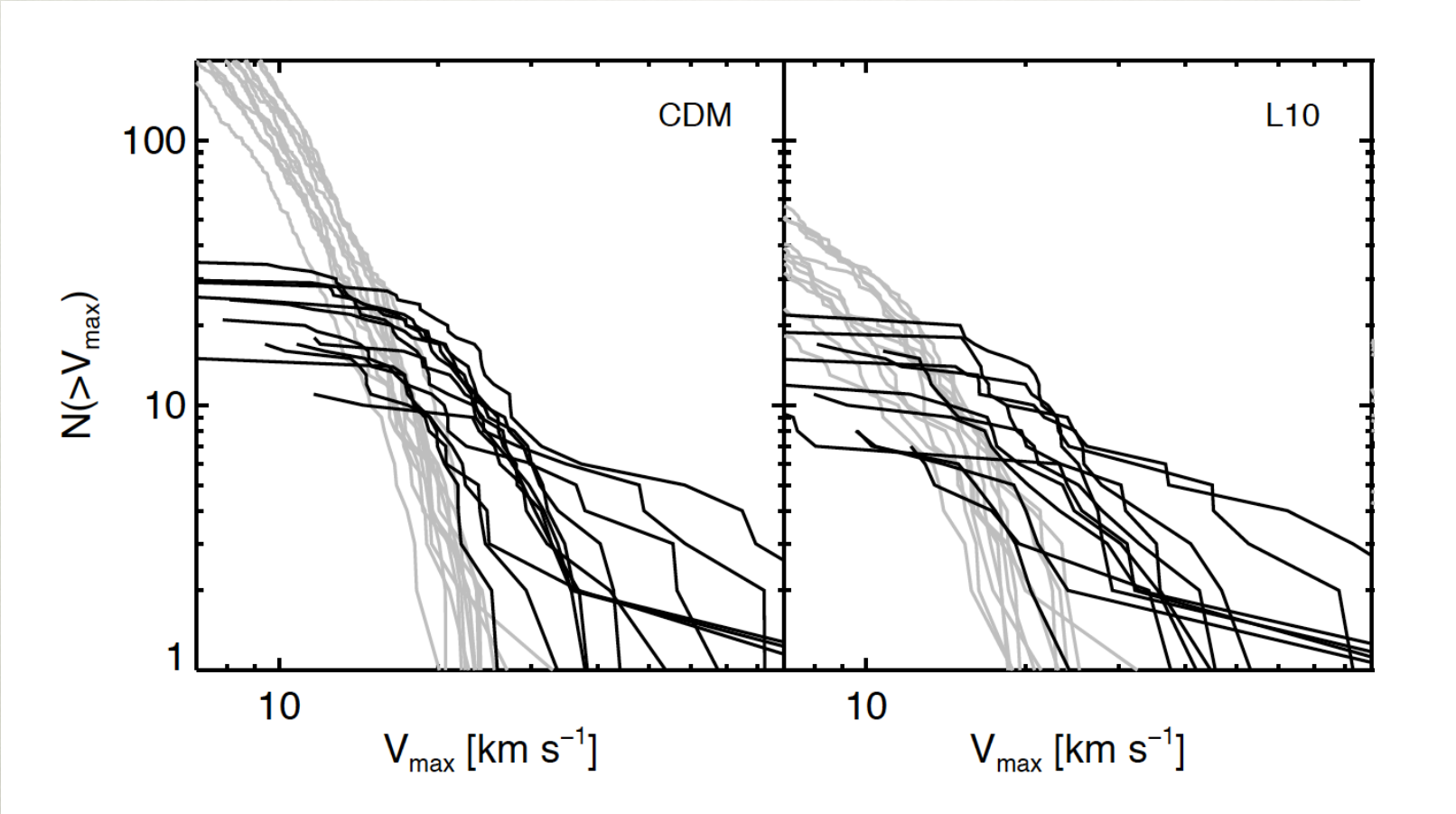
- Bulge-less disk galaxies ✓
- The cusp/core problem ✓
- The "Too Big to Fail" problem ✓
- The "Missing Satellites" problem ✓
- The "Missing Dwarfs" problem ✓

Ongoing Work

We need baryons in alternative DM models

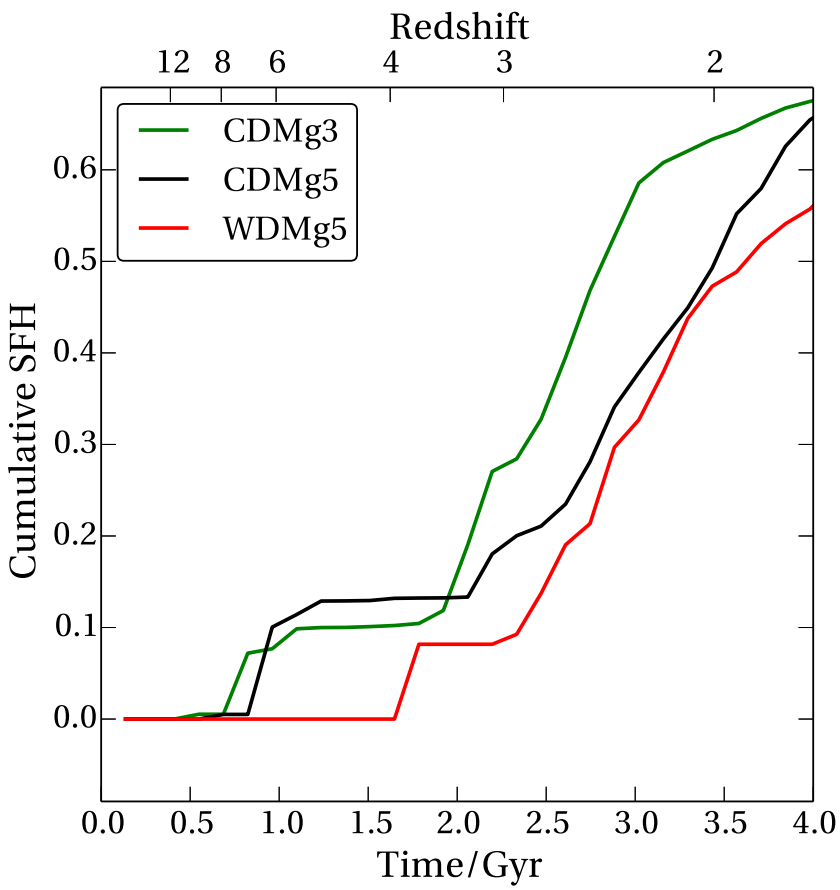
What is the smoking gun that points to a given DM model?

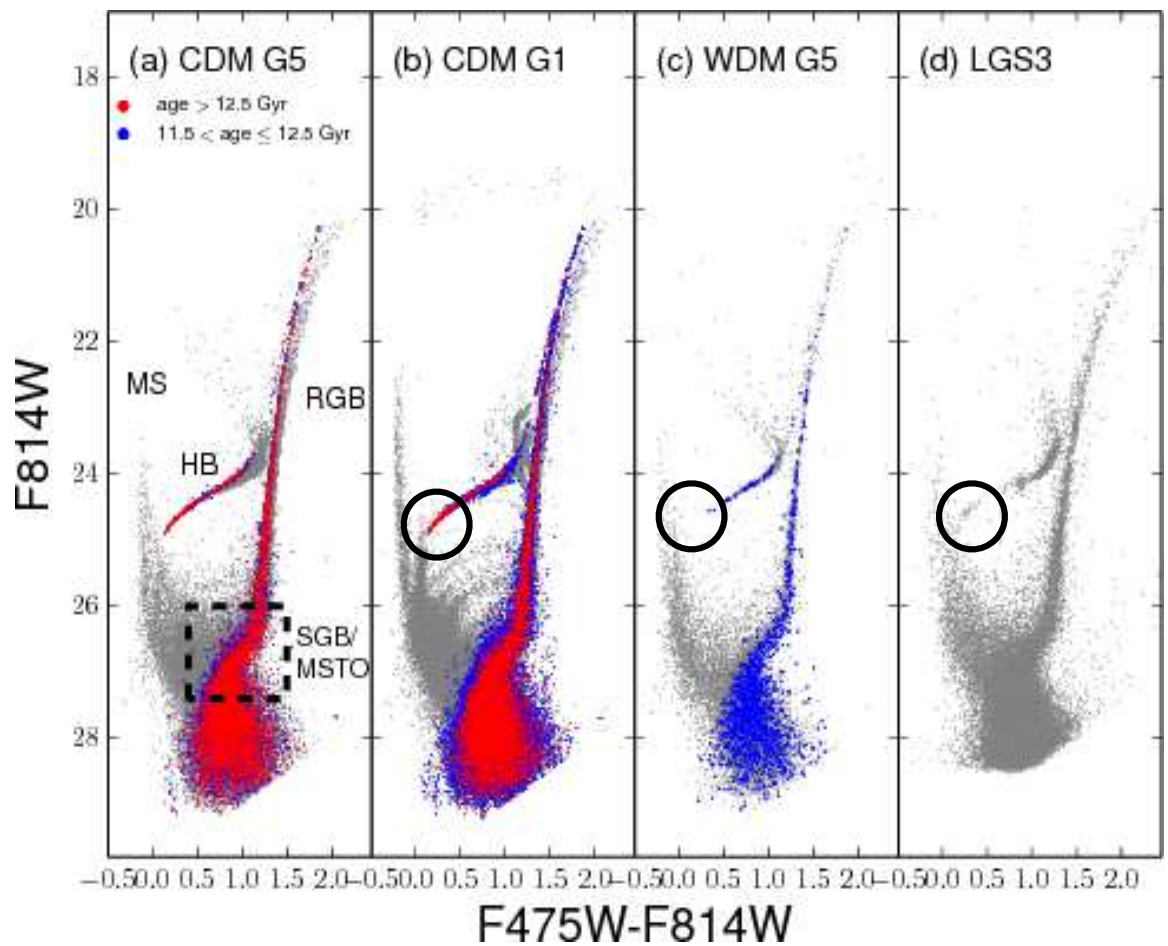
WDM: Walking a Fine Line



Lovell et al. (2016)

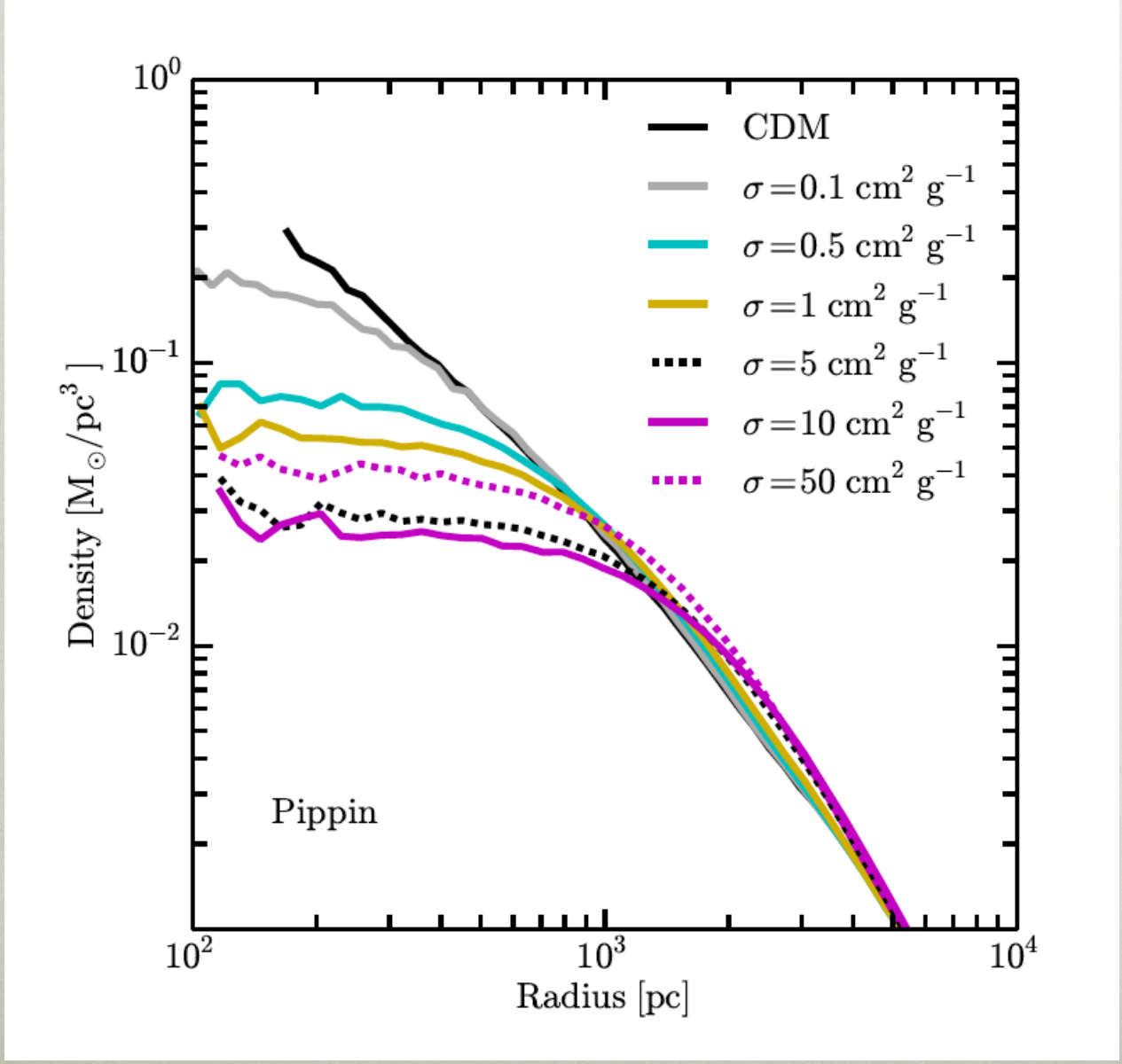
A Testable Prediction of delayed structure formation





Governato et al. (2014)

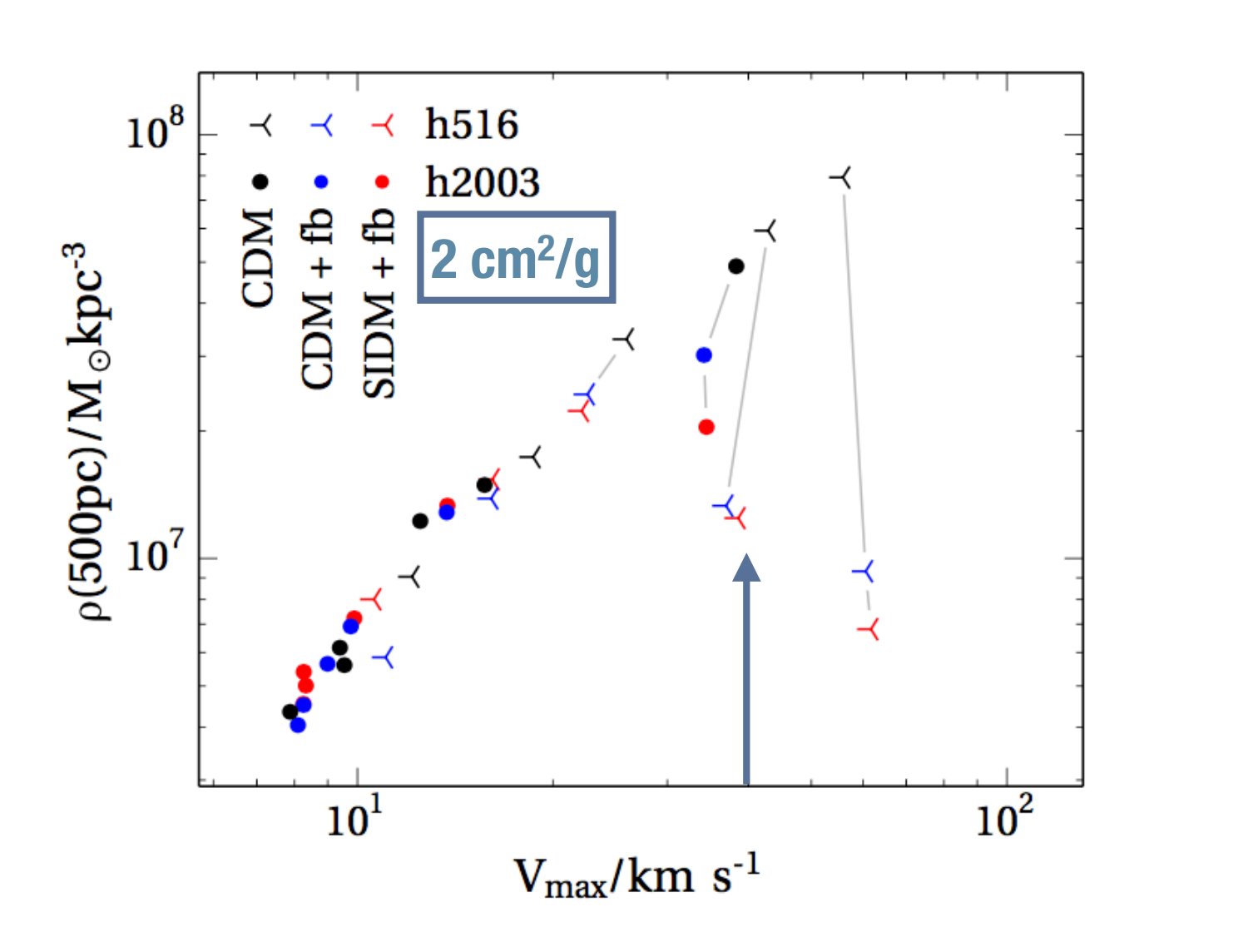
SIDM: the Constraints Are Weakening



results for a 9×10^9 M_{sun} halo

Elbert et al. (2015)

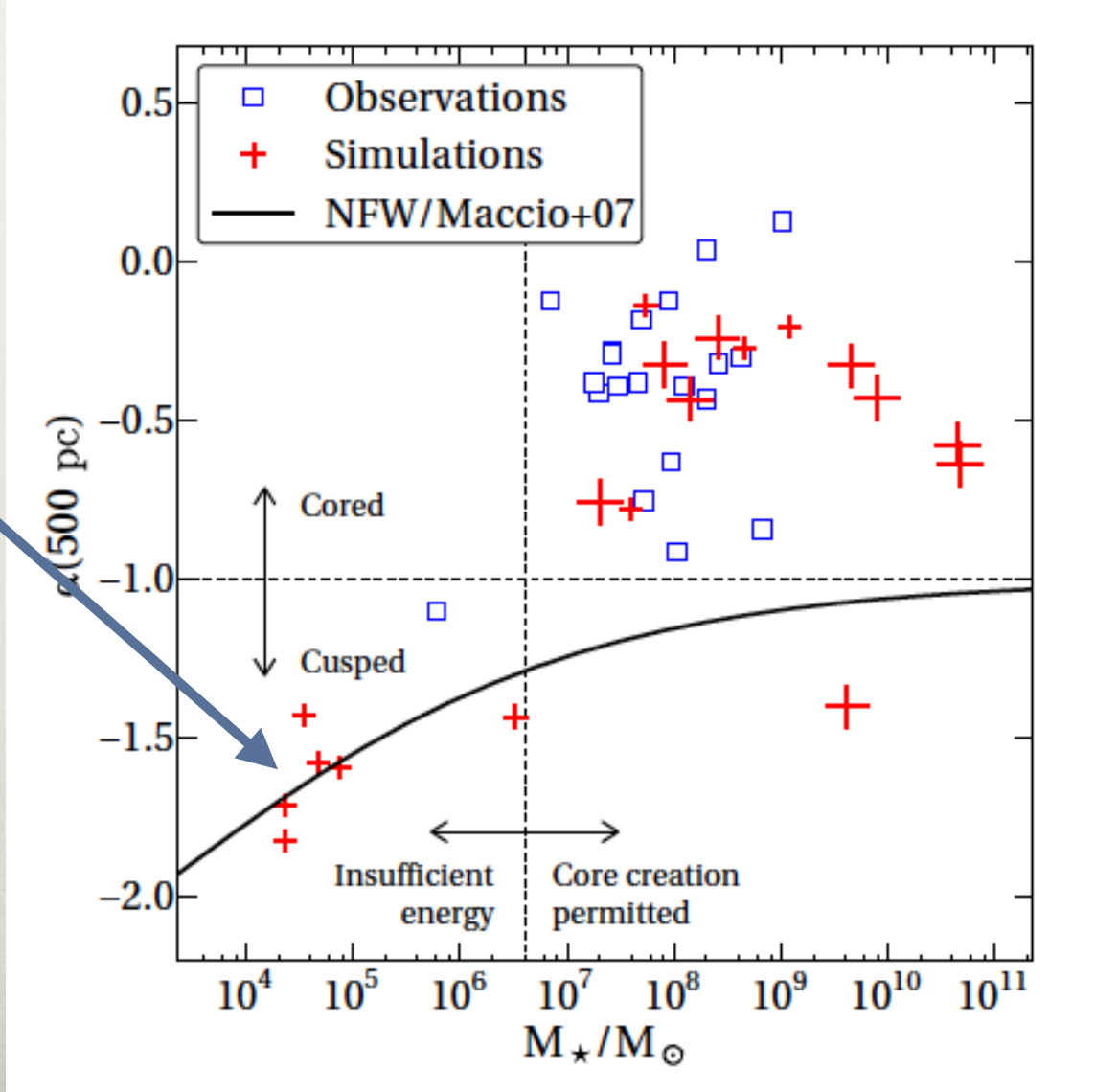
But... baryons win first



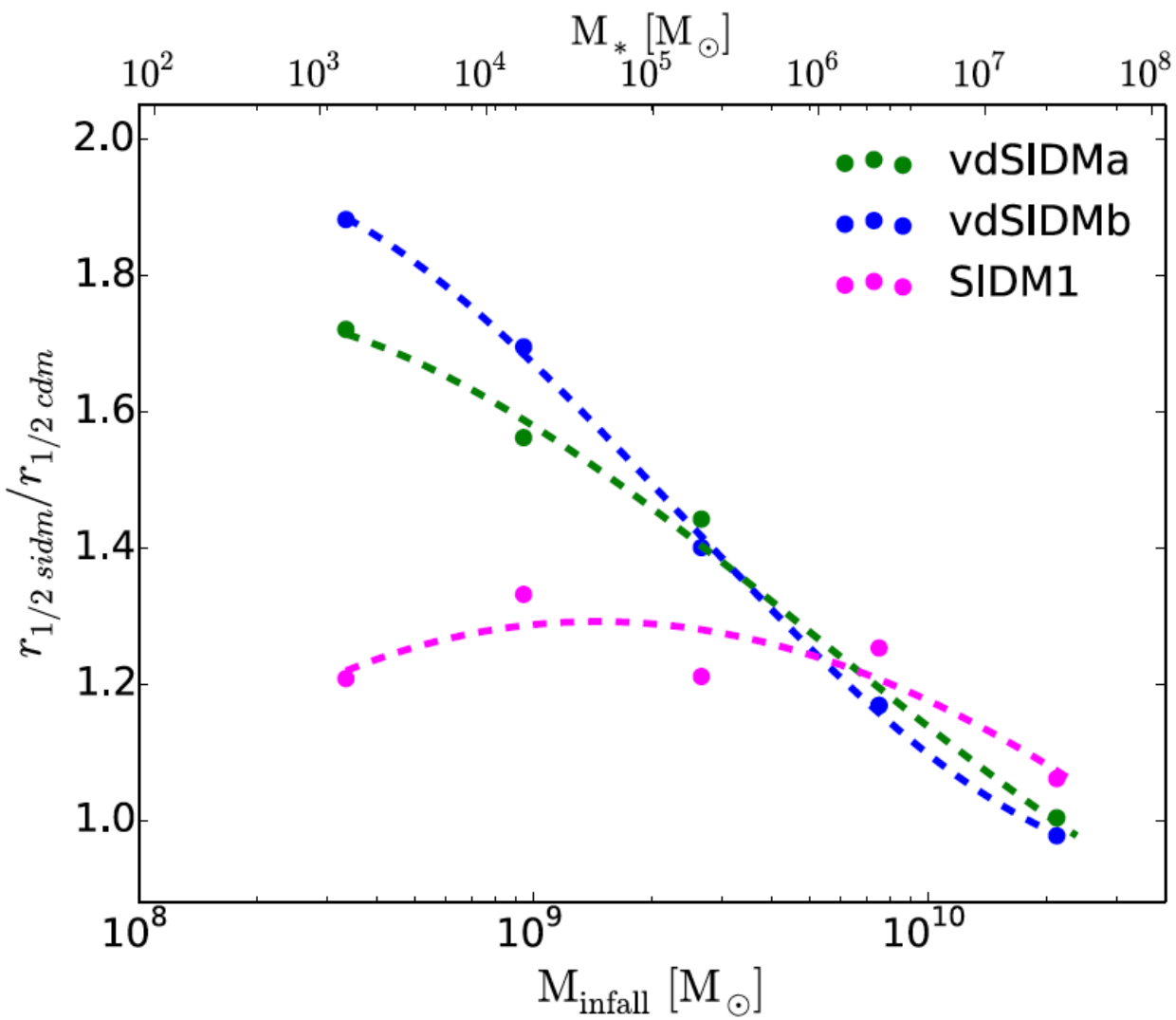
Bastidas-Fry et al. (2015)

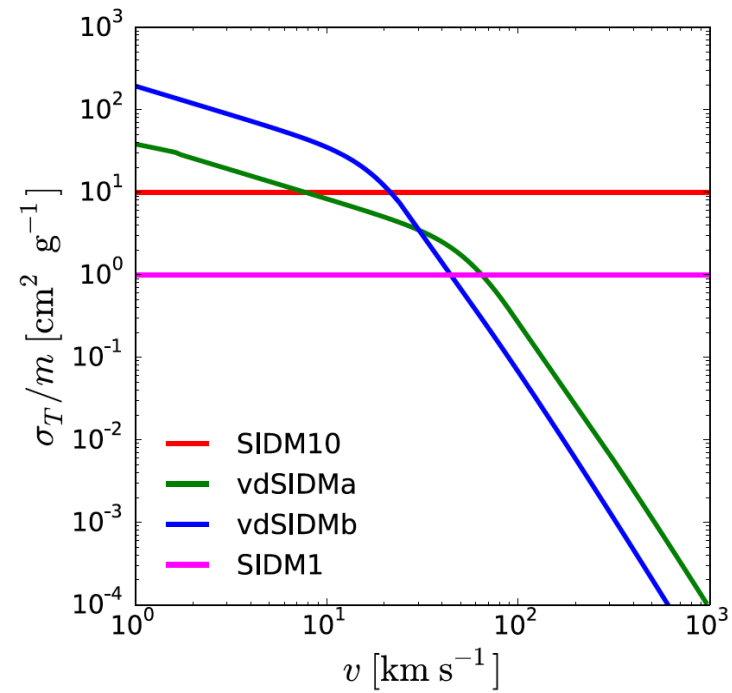
An Observational Test

If galaxies in this mass range are observed to have large cores, then something beyond CDM is necessary



Satellites as an Observational Probe





Dooley et al. (2016)

Conclusions

To constrain the Dark Matter model, we must understand the impact of baryonic physics on galaxy formation!

Baryonic physics alleviates the current problems with CDM

But that doesn't mean CDM is the correct model. All dark matter models must also include baryons!

Future observations of dwarf galaxies ($M_{star} < 10^7 M_{sun}$) are the best probes of non-vanilla CDM

see arXiv:1407.7544 for a review