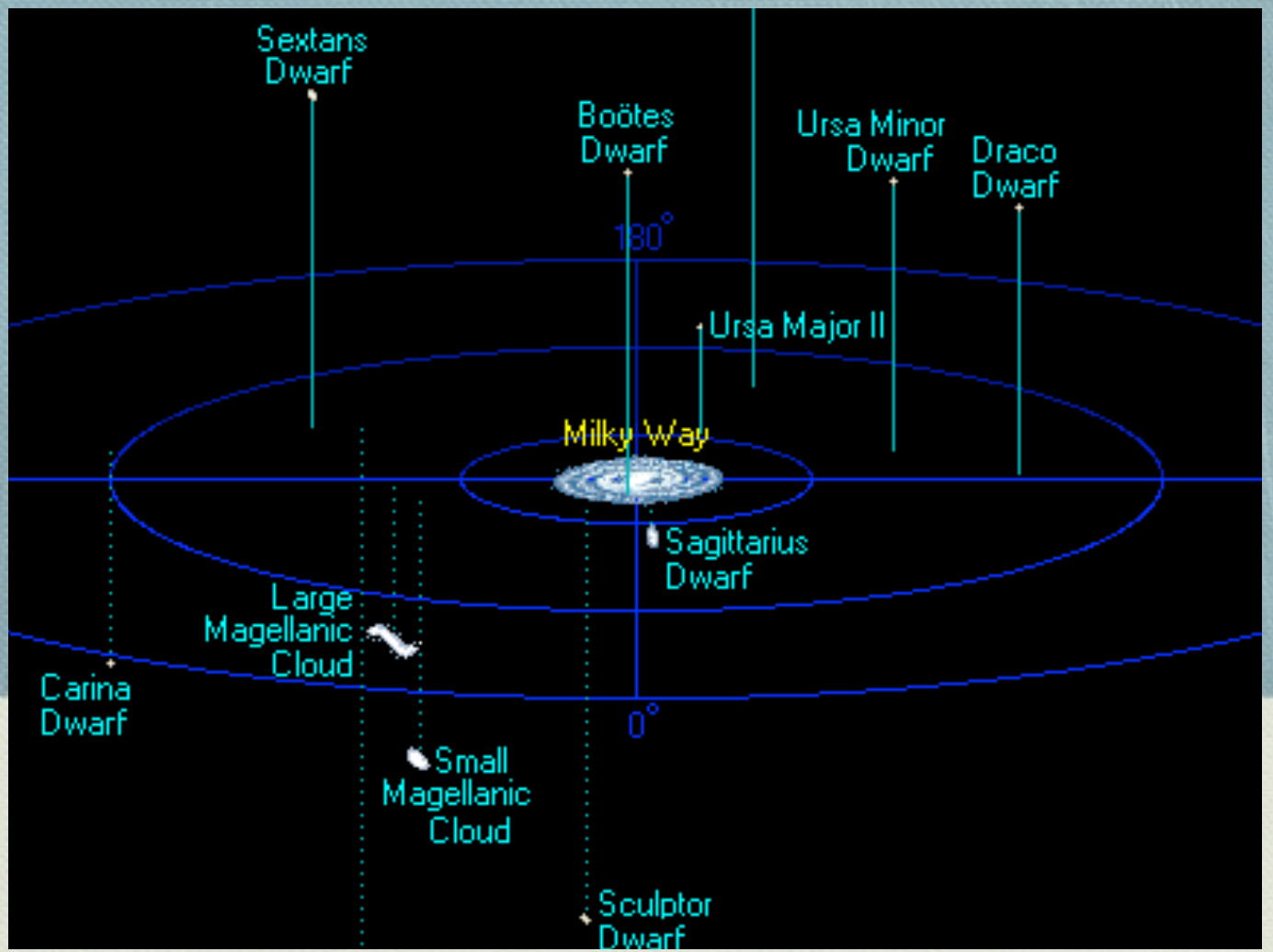
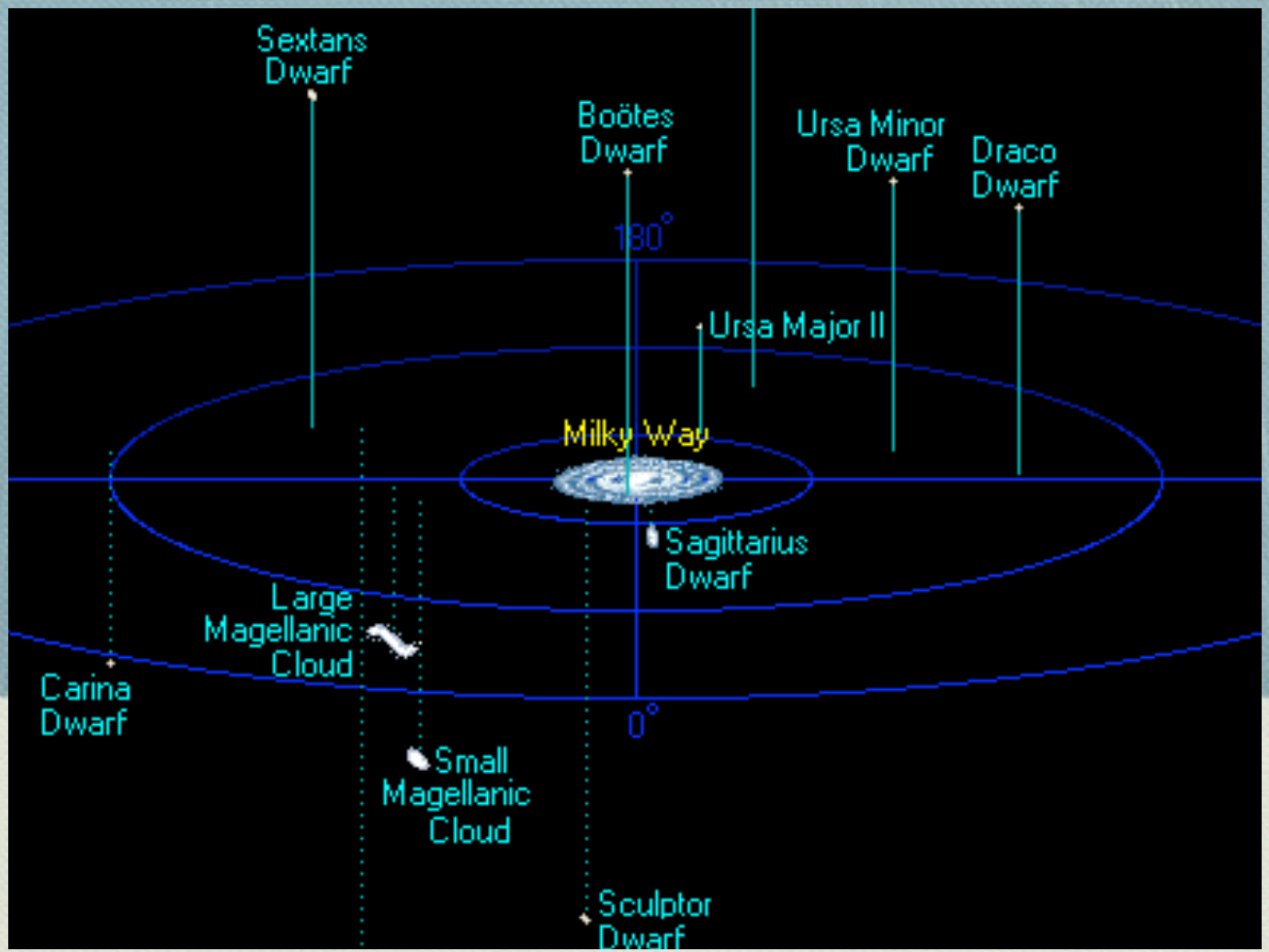
Constraints on dark matter from the non-linear regime



Manoj Kaplinghat, University of California, Irvine, USA

Reasons to think dark matter isn't a WIMP

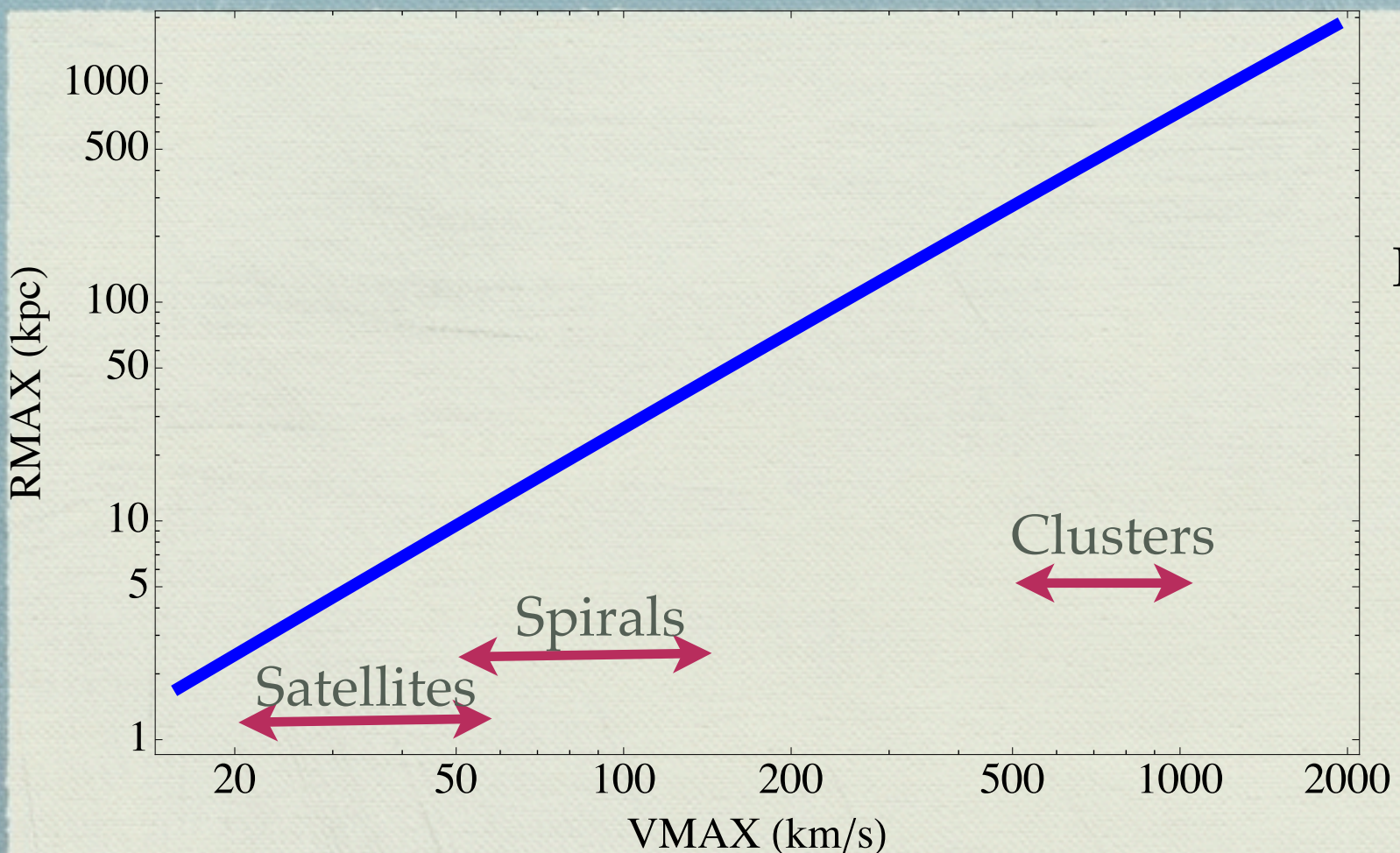


Manoj Kaplinghat, University of California, Irvine, USA

Clusters of Galaxies to Satellite galaxies of the Milky Way

- *Trouble with estimated dark matter densities*
  - **Clusters**: 10-50 kpc scales
    - **Lower densities than predicted, Cores**
  - **Spiral galaxies**: 0.5-5 kpc scales
    - **Classic core-cusp problem**
  - **MW satellites**: 0.3-1 kpc scales
    - **Massive subhalos in LCDM simulations of Milky Way: "Too big to fail?"**
    - **Dark matter cores in some satellites**
- *SIDM*: A possible solution to the observed reduced densities in the centers of halos

Size-Mass relation in hierarchical structure formation



$VMAX^2 = MAX(GM/R)$ occurs at $R=RMAX$

Derived for Cold Dark Matter (CDM) but should hold for any successful model of structure formation

Plan for the talk

- Summarize the issues on small scales related to comparison of densities *predicted* and *observed*.
- ``Look'' at three generic solutions
  - Baryonic feedback with **cold non-interacting dark matter** (CDM)
  - **Warm** dark matter (WDM) with no significant feedback
    - Warm enough to affect structure formation
  - **Self-interacting** dark matter (SIDM) with no significant feedback
    - Interact with itself strongly enough to affect structure formation

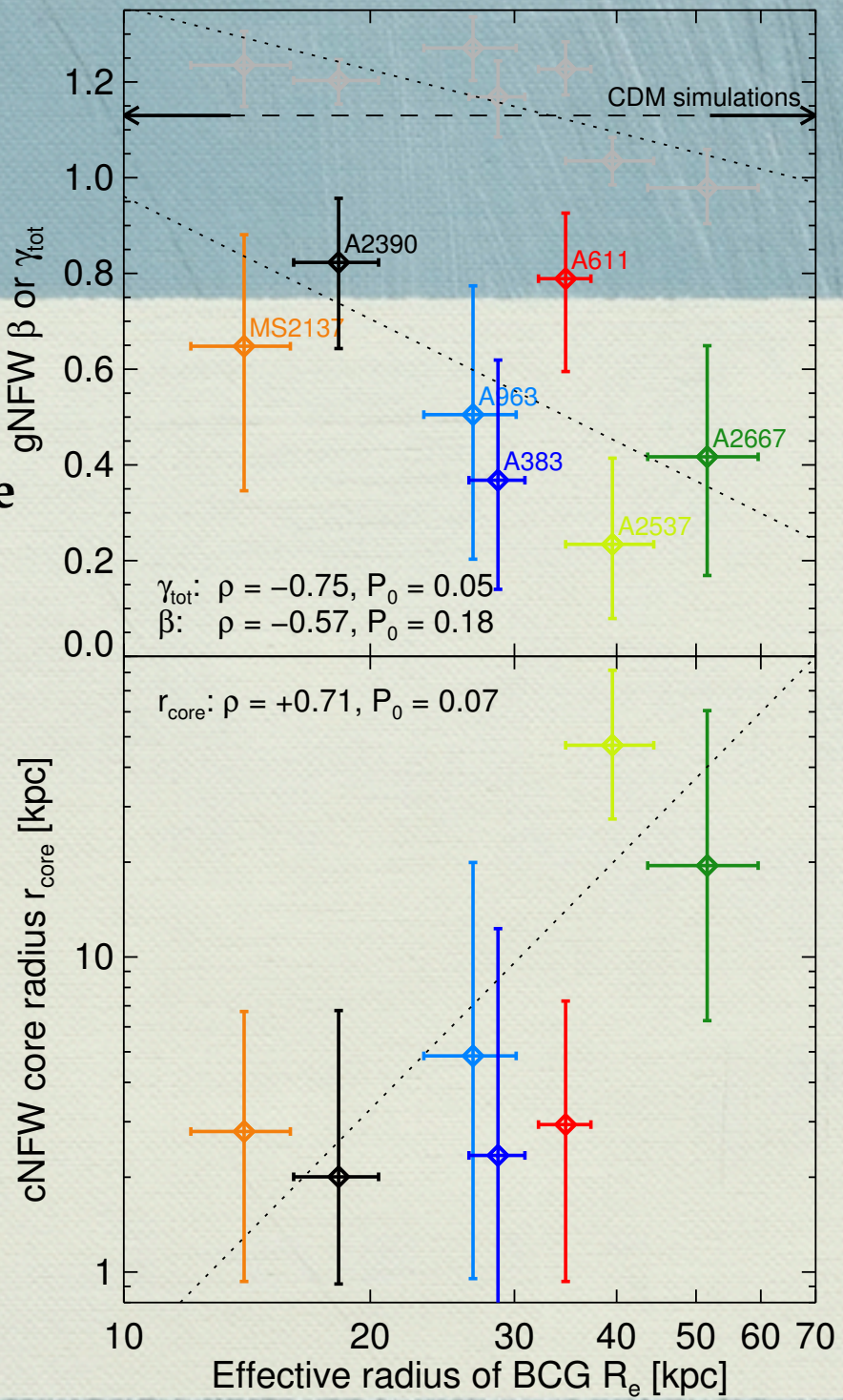
Clusters of galaxies

Massive clusters, with total mass in the vicinity of 10^{15} M_{sun}.

Weak lensing, strong lensing, kinematics of stars in the central galaxy.

``gNFW'' density $\propto 1/r^{\beta}(r_s+r)^{3-\beta}$
``cNFW'' density $\propto 1/(r+core)(r_s+r)^2$

Newman et al 2012

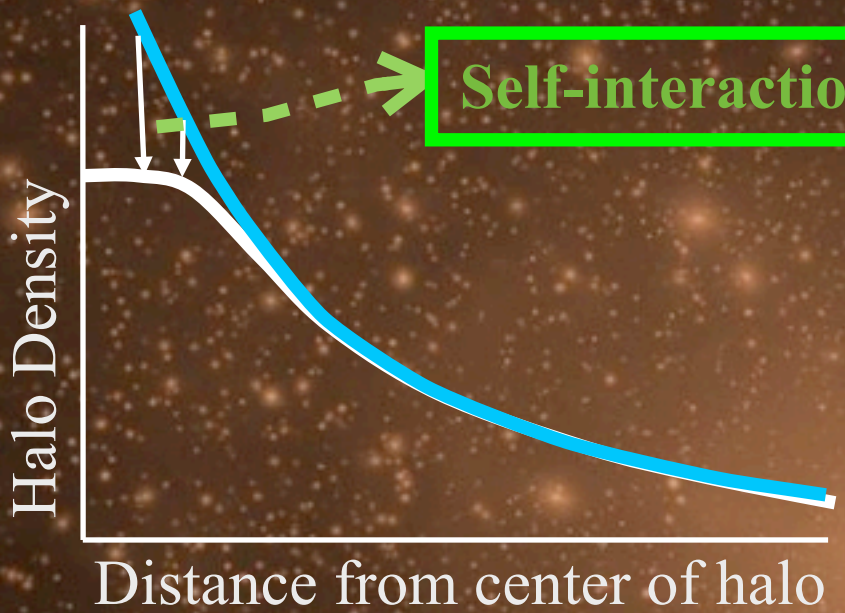


Solutions

- No concrete feedback solution yet to explain these lowered densities/cores.
- Viable warm dark matter models cannot create cores this large. (See this a bit later.)
- Self-interactions could. (Numbers for strength of self-interaction later.)

z=0.0

Warmness and Self-interactions

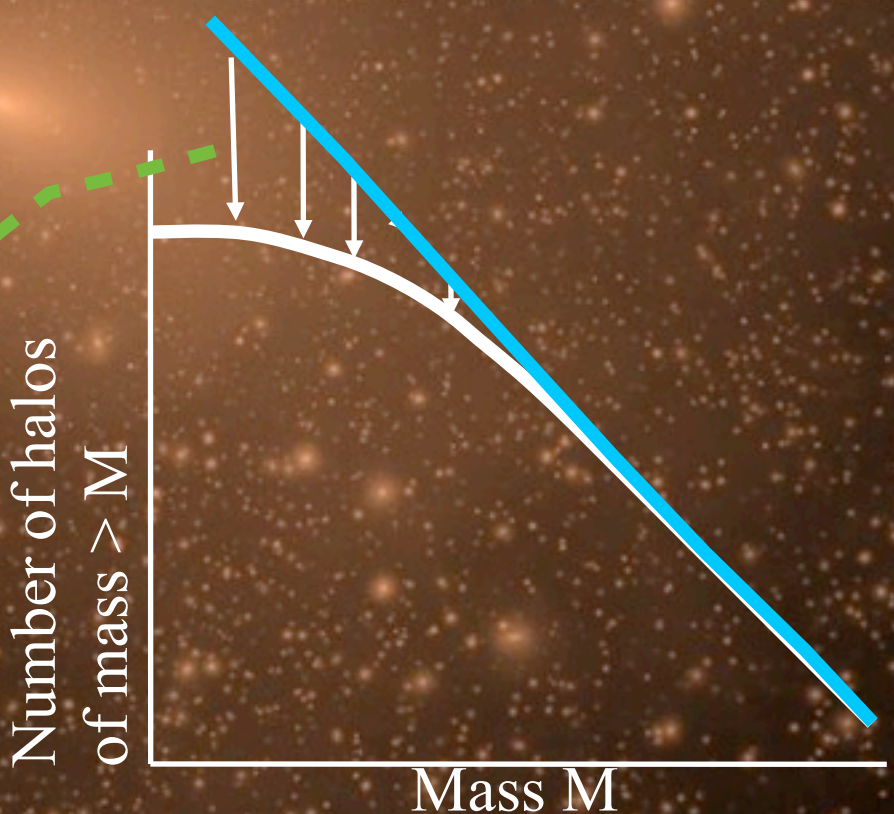


Self-interaction strength is dialed up

Warm dark matter also reduces central halo density but not so dramatically

Warmer

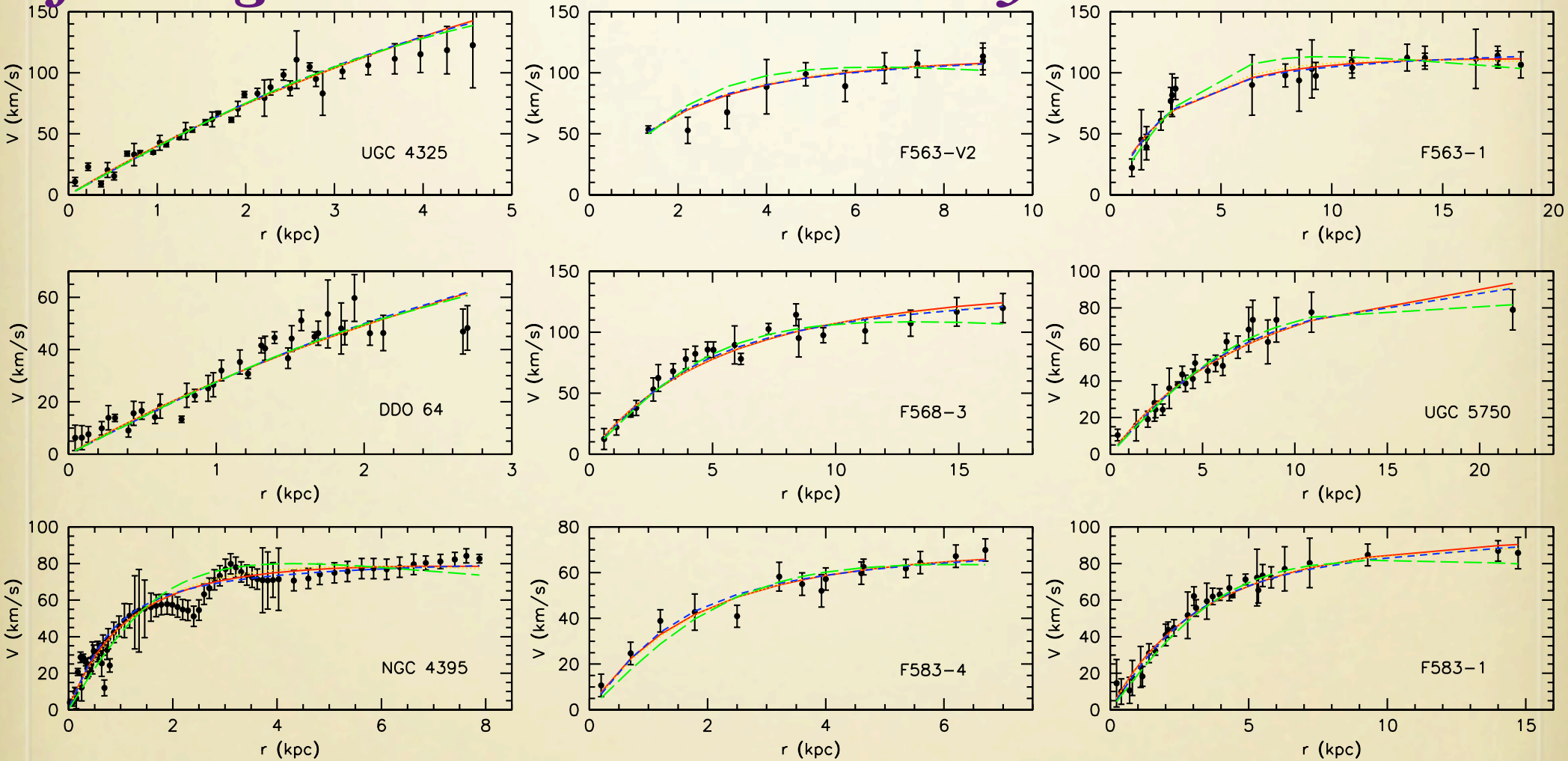
Similar effect for SIDM is rather benign



80 kpc

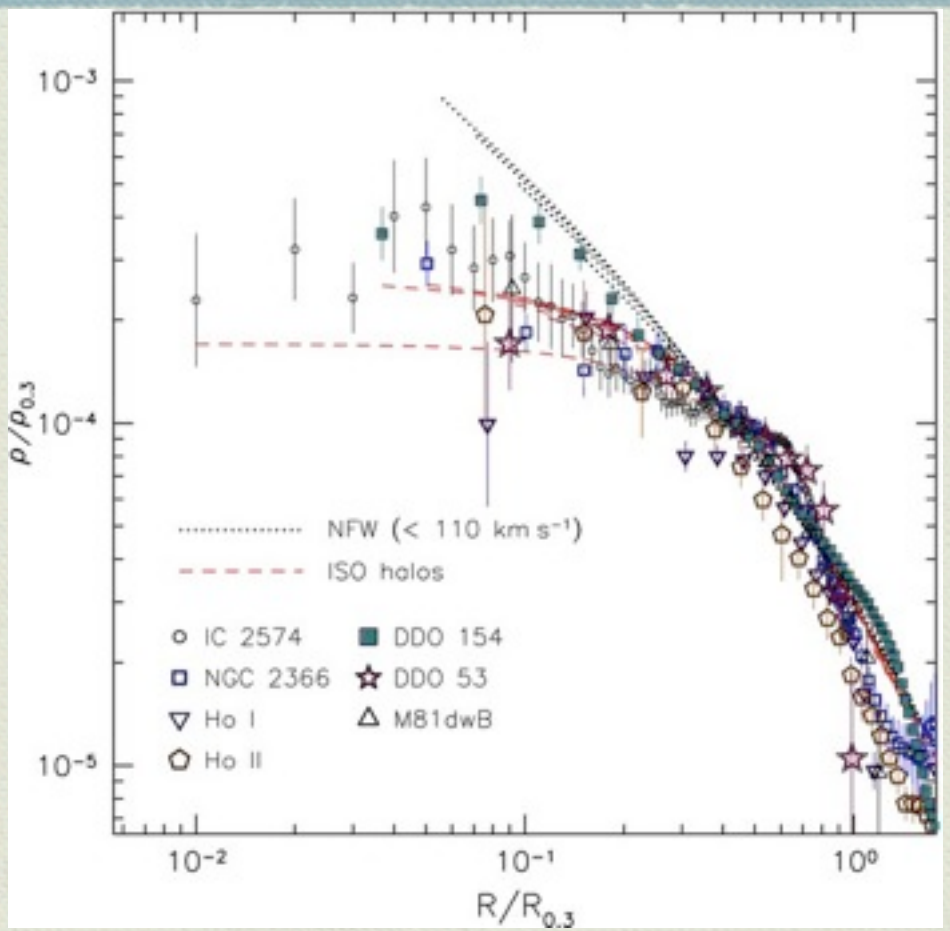
NEARBY SPIRAL (LOW SURFACE BRIGHTNESS) GALAXIES

Note the linear rise in rotation velocity at small radii for all galaxies => constant density cores



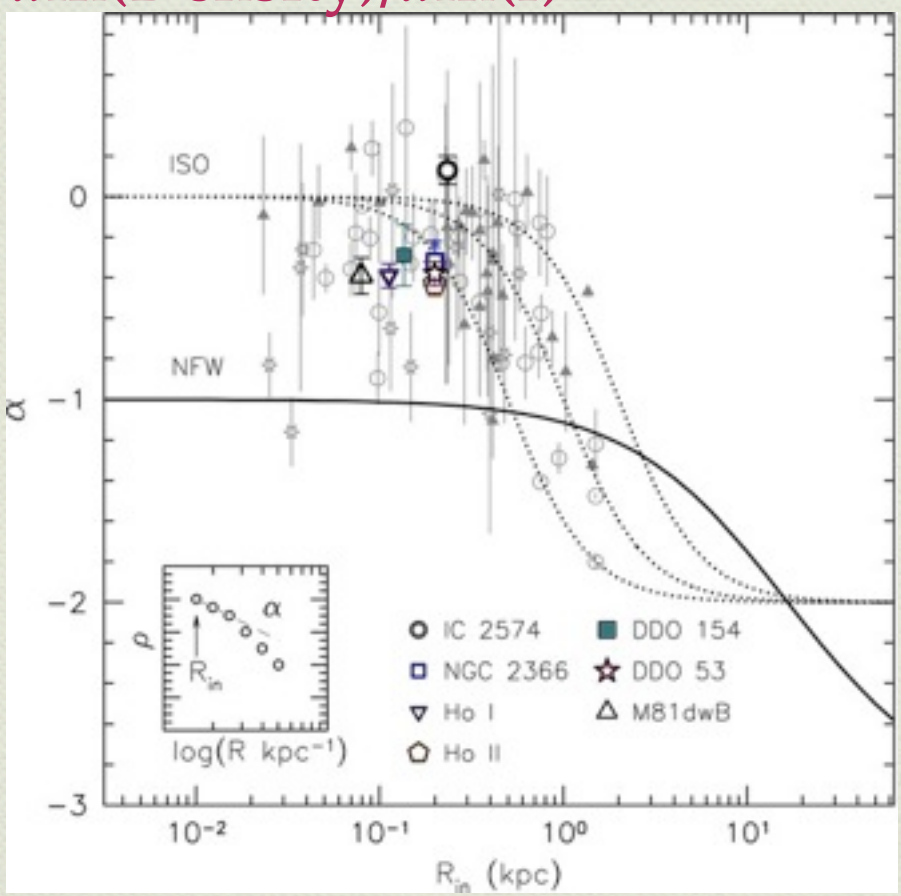
Kuzio de Naray, Martinez, Bullock, Kaplinghat, ApJL 2010

More nearby spiral galaxies



Close-by (< 5 Mpc), DM dominated, small (V ~ 30-100 km/s)

$\alpha = d\ln(\text{Density})/d\ln(r)$

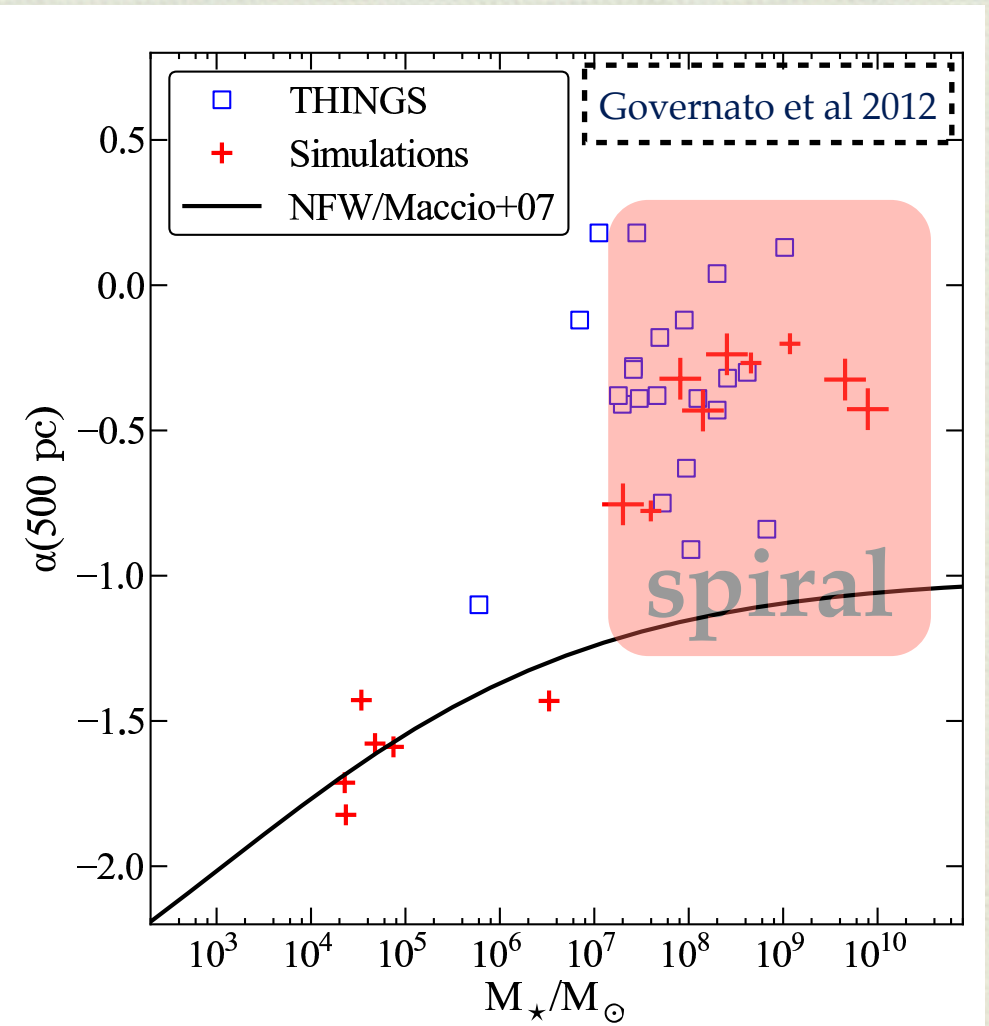


Oh et al 2011 (THINGS)

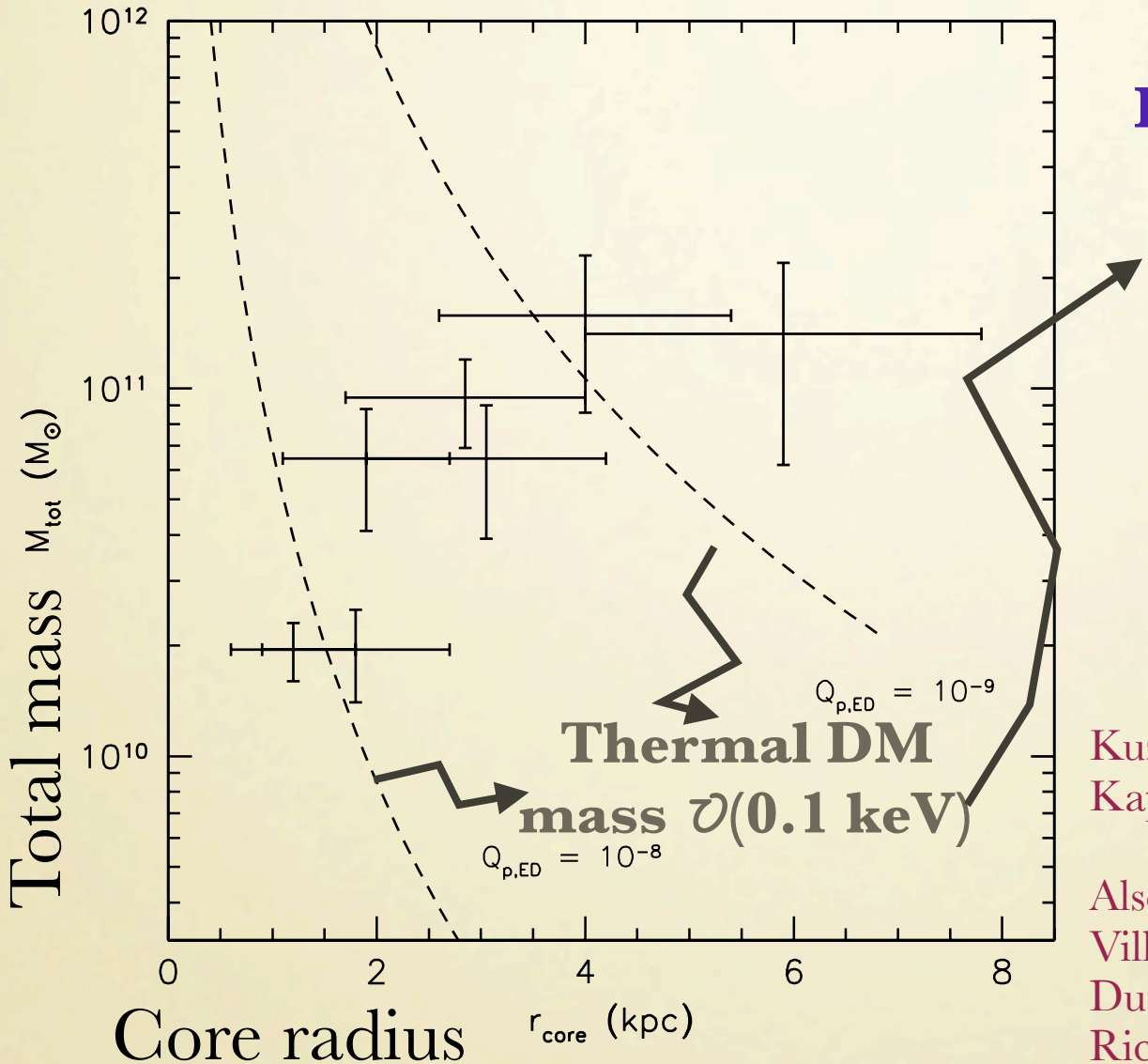
Feedback solution

- **Simulations with feedback from supernovae can create cores. [Governato et al 2012]**
  - **How realistic is this feedback and how do we test it?**
  - **How about feedback in LSIDM or LWDM cosmologies?**

$$\alpha = d\ln(\text{Density})/d\ln(r)$$



Warm dark matter (without feedback) does not explain these cores: Cores are not big enough for viable WDM models

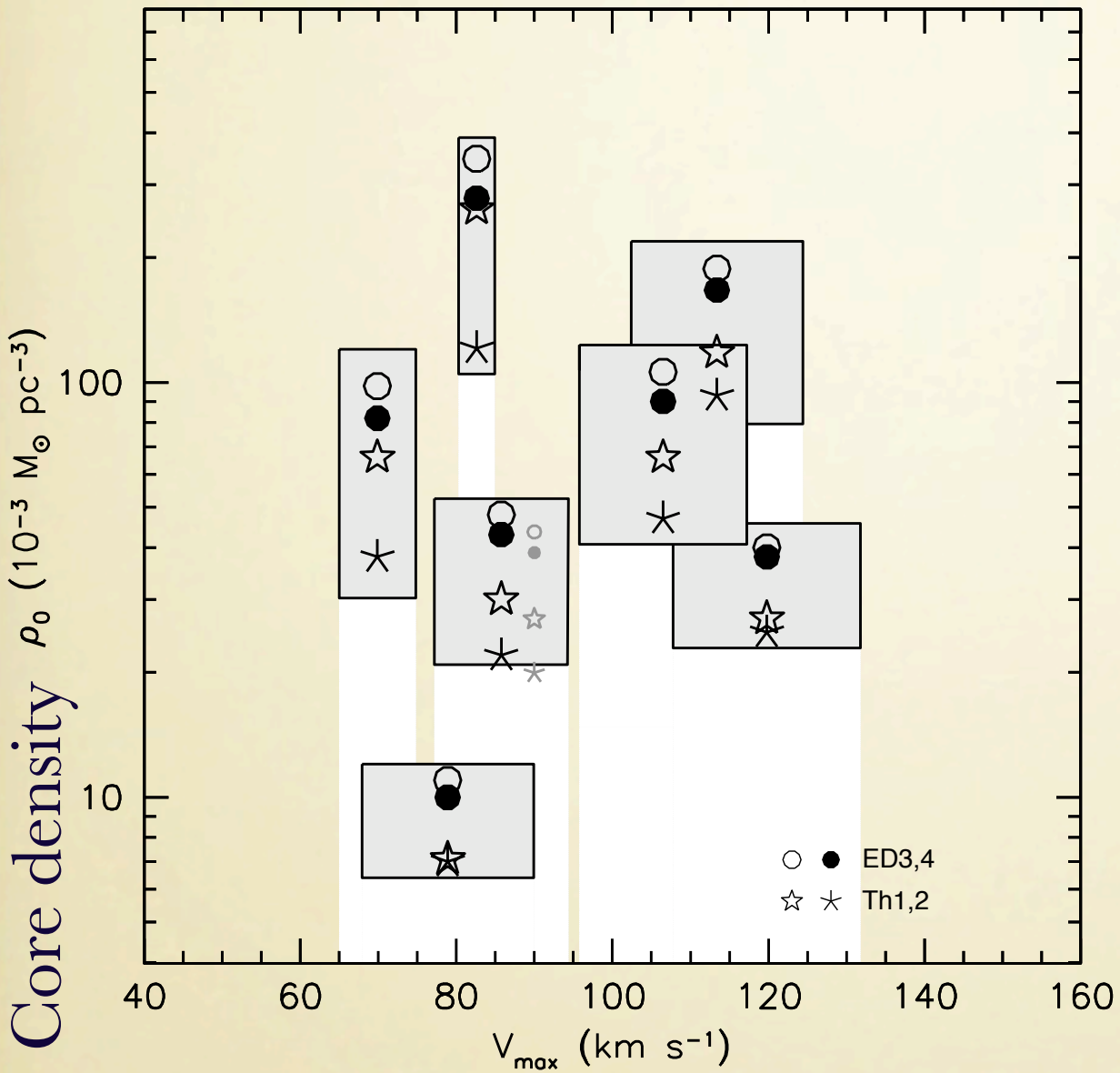


Ruled out by linear power spectrum constraints

Kuzio de Naray, Martinez, Bullock, Kaplinghat, ApJL 2010

Also:
Villaescusa-Navarro and Dalal 2011
Dunstan, Abazajian, Polisensky and Ricotti 2011

Does self-interacting dark matter explain this?



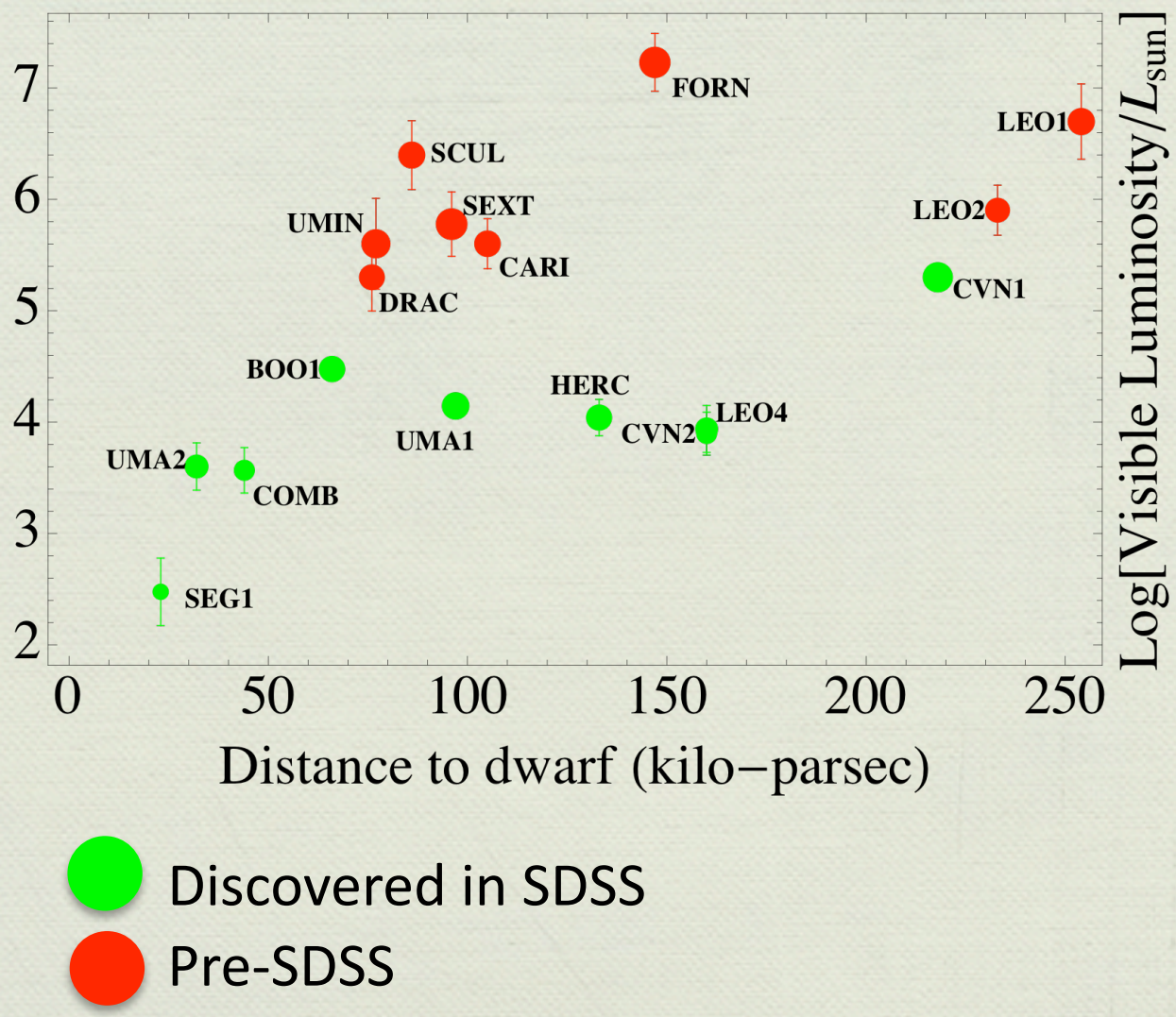
Does this look like a prediction of self-interacting dark matter?

Keep this in mind; we will touch upon this later.

Kuzio de Naray, Martinez, Bullock, Kaplinghat, ApJL 2010

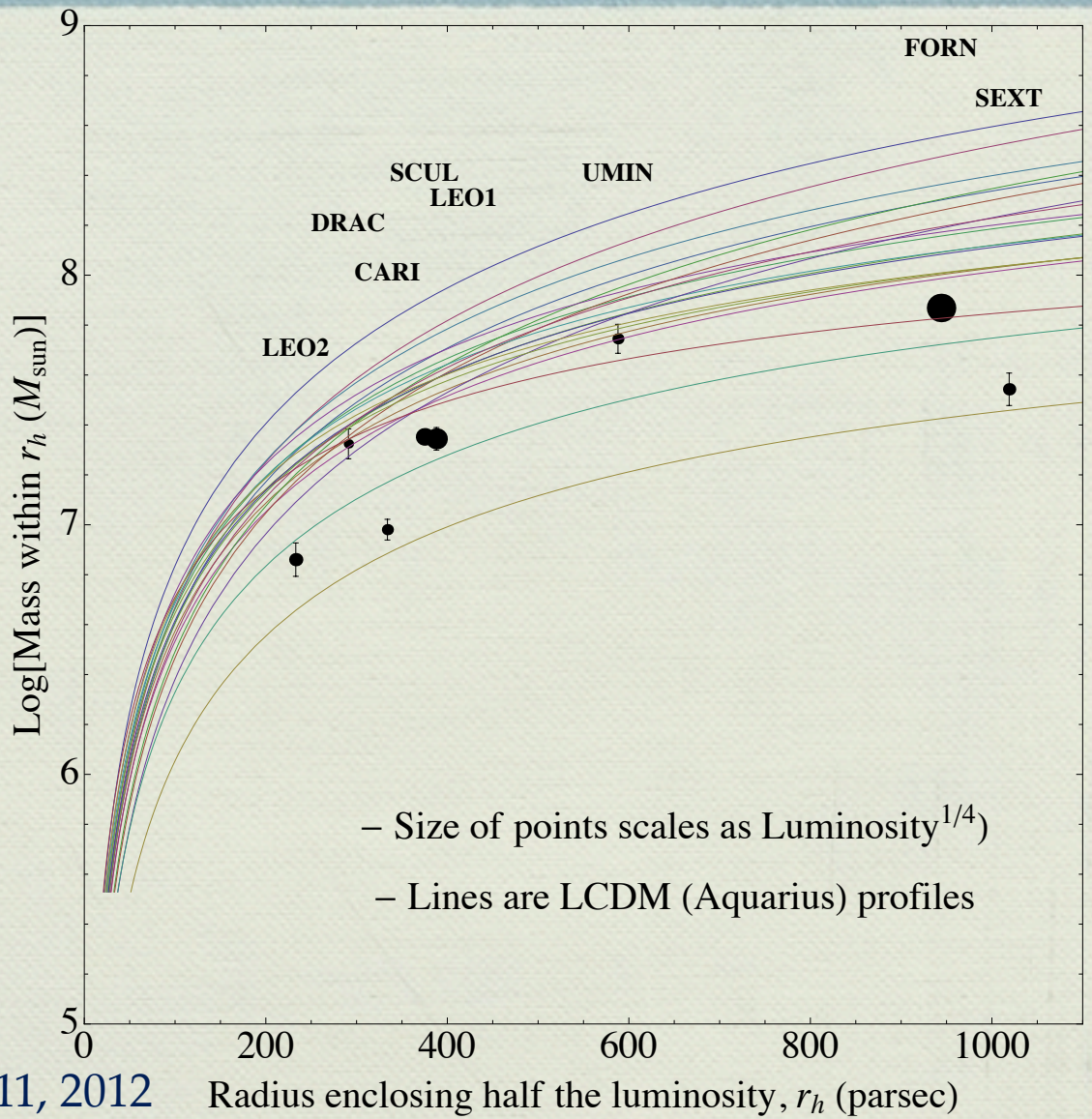
Milky Way satellites

Name	Year Discovered	
LMC	--	
SMC	--	
Sculptor	1937	Bright
Fornax	1938	
Leo II	1950	
Leo I	1950	
Ursa Minor	1954	
Draco	1954	
Carina	1977	
Sextans	1990	
Sagittarius	1994	
Ursa Major I	2005	Faint
Willman I	2005	
Ursa Major II	2006	
Bootes	2006	
Canes Venatici I	2006	
Canes Venatici II	2006	
Coma	2006	
Segue I	2006	
Leo IV	2006	
Hercules	2006	
Leo T	2007	
Bootes II	2007	
LeoIV	2008	



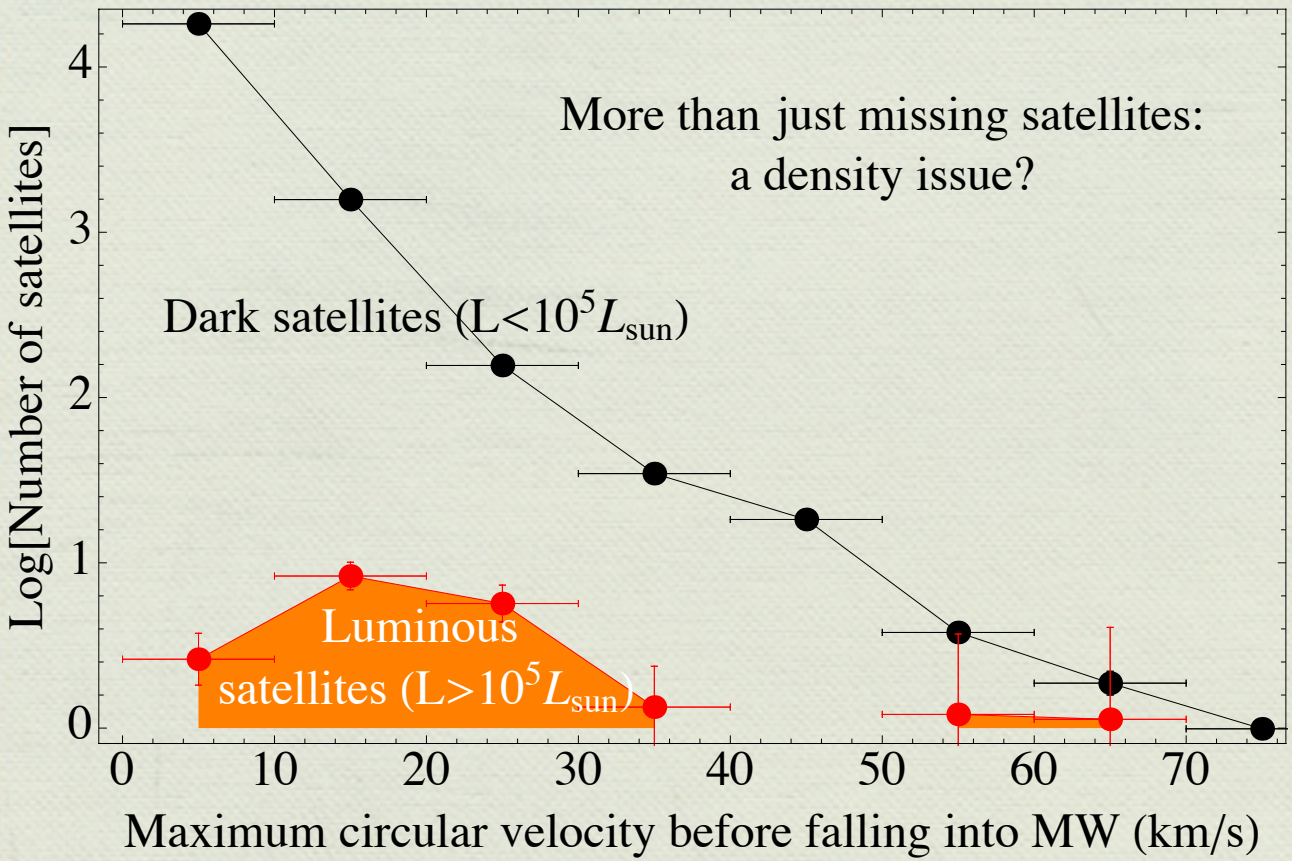
1: Too big to fail? The most massive apparently don't light up...

- NFW fits to mass profiles of the most massive subhalos from Aquarius simulation [Springel et al 2009] shown
- Bright satellites shown with estimated masses within half-light radii
- **Too many dense (massive) subhalos**



Boylan-Kolchin, Bullock, Kaplinghat 2011, 2012

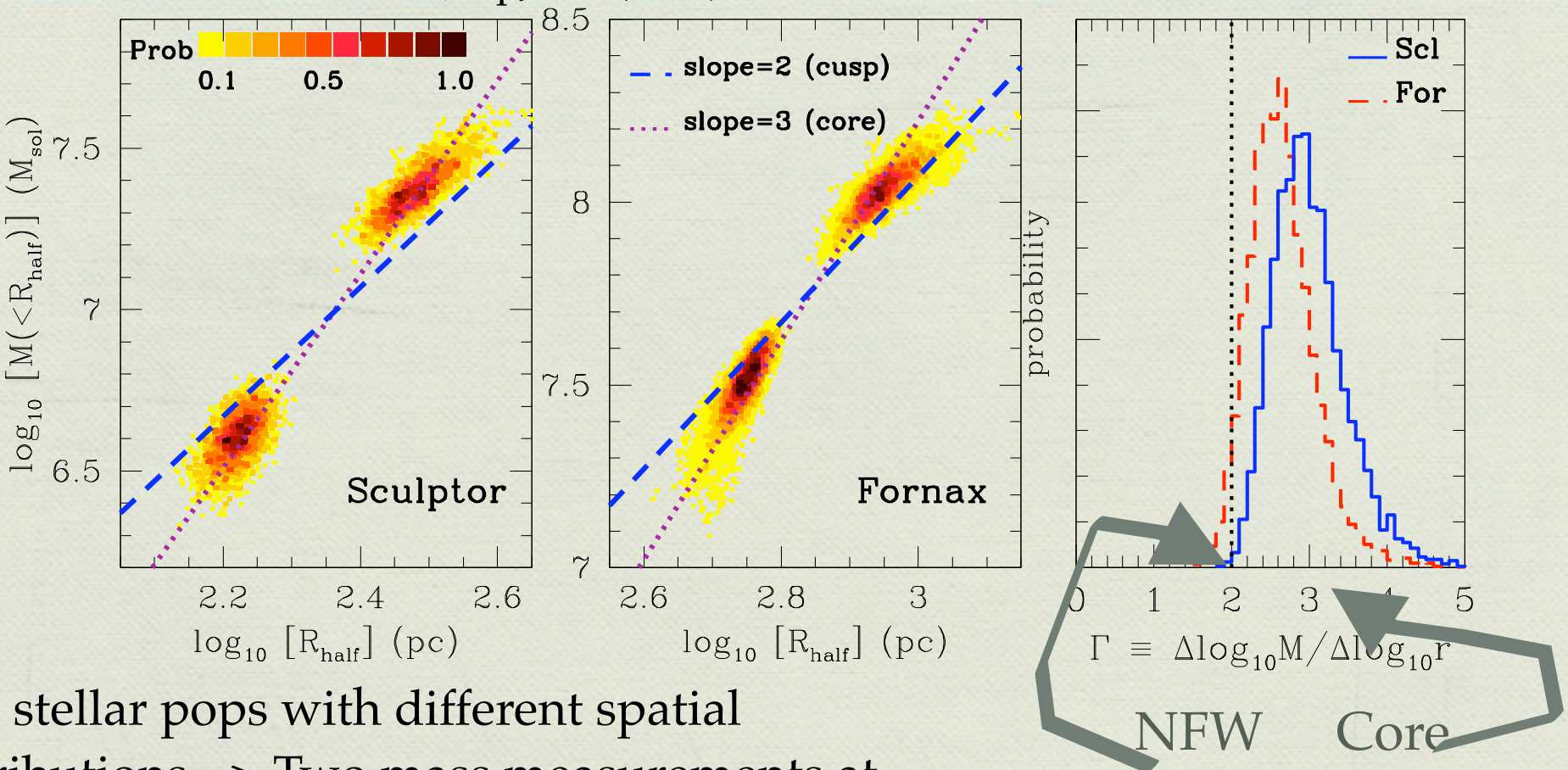
Not the ``missing satellites" problem: observed satellites are not dense enough



Brightest satellites are not dense enough in dark matter to inhabit the most massive subhalos predicted in LCDM.

2. Cores in the dark matter halos of satellites

Walker and Penarrubia, ApJ 742 (2011)



Two stellar pops with different spatial distributions => Two mass measurements at different (half-light) radii

Battaglia et al MNRAS 383, 183 (2008)

Amorisco and Evans MNRAS 411, 2118 (2011)

$\alpha = d\ln(\text{Density})/d\ln(r)$

$\Gamma \approx 3-\alpha$

Perhaps this isn't really a problem because MW is not as massive or just an outlier

- **The comparison to LCDM expectations is not valid because the Milky Way is not as massive as the range (9e11 to 2e12 Msun) in Aquarius [See also Wang, Frenk, Navarro and Gao 2012, Brooks, Kuhlen, Zolotov and Hooper 2012]**
  - Dynamics of Large Magellanic Cloud (rare if not bound)
  - Kinematics of Leo I (not bound if MW virial mass less than ~1e12 Msun)
  - Velocities of halo stars from SDSS argue for MW virial mass ~1e12 Msun.
- **Milky Way is an outlier and just doesn't have these subhalos. Live with it!**
  - Must explain Large and Small Magellanic Clouds
  - Andromeda satellites look similar! [Tollerud et al (SPLASH collaboration) 2011]

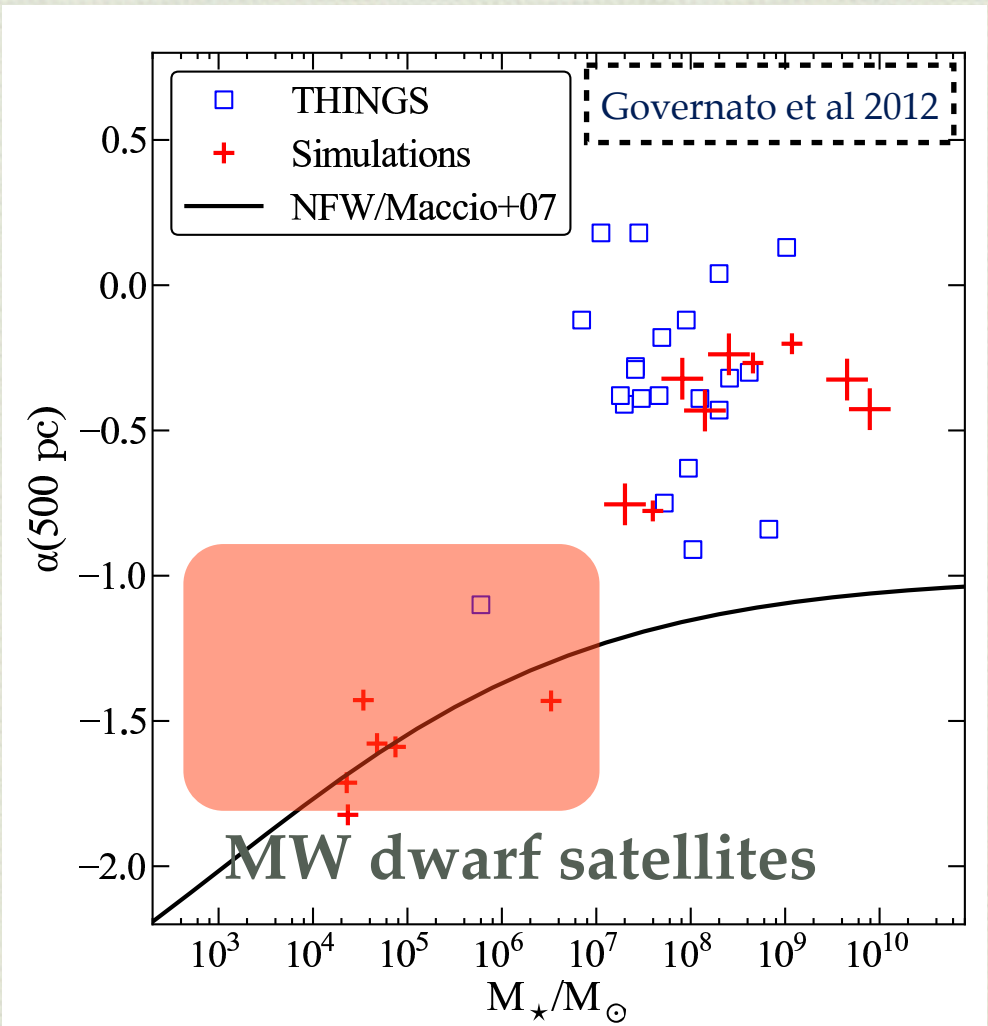
Boylan-Kolchin, Bullock, Kaplinghat 2012

Feedback solution

- **Most massive subhalos do become luminous but outflows due to feedback reduce their central densities. These "blow-out" scenarios don't seem to work effectively in satellites.**

  [e.g., Navarro, Eke, Frenk 1996, Governato et al 2012, Garrison-Kimmel et al 2013]

  - The meagre stellar content of the satellites is a stringent limitation.



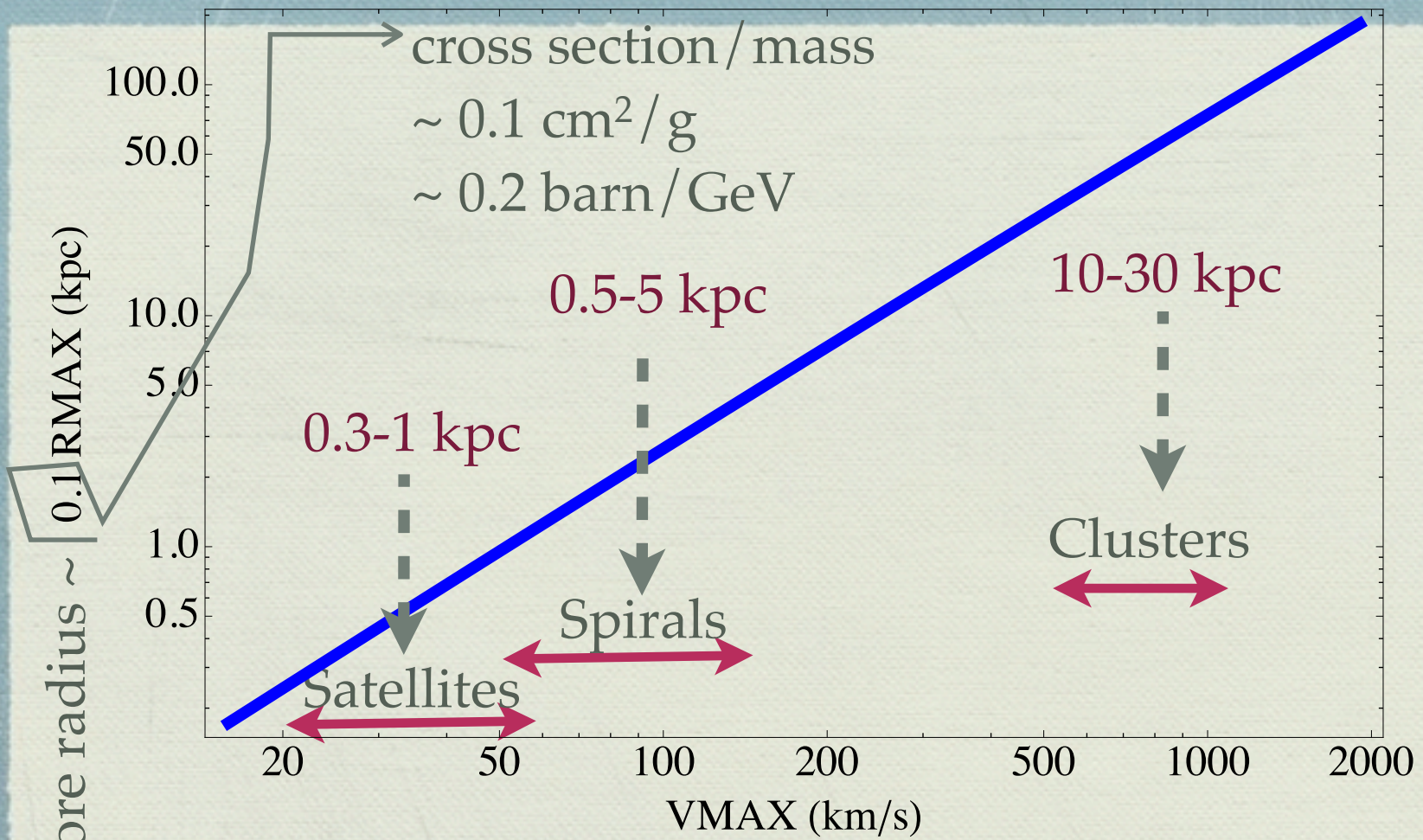
Warm dark matter solution

- Warm dark matter [Gunn and Tremaine 1979, Bond, Efstathiou, Silk 1980]
  - Q(satellites) ~ 0.1 Msun/pc^3/(20 kmps)^3 ~ 10^{-5} Msun/pc^3/kmps^3
    - This is the primordial phase space density of about 0.6 keV thermal WDM. There isn't a viable WDM candidate with this mass. However, lack of power also leads to lower densities in small halos and this could solve the TBTF problem [see Wang, Frenk, Navarro and Gao 2012].
    - Are there enough satellites in simulations where TBTF is solved?
    - Can large cores be produced?
- Models
  - Sterile neutrinos [Dodelson and Widrow 1994, Shi and Fuller 1998, Abazajian, Patel and Fuller 2001, Petraki and Kusenko 2008, Laine and Shaposhnikov 2008]
  - Weak-scale mass gravitinos [Kaplinghat 2005, Cembranos et al 2005]

Self-interacting dark matter solution

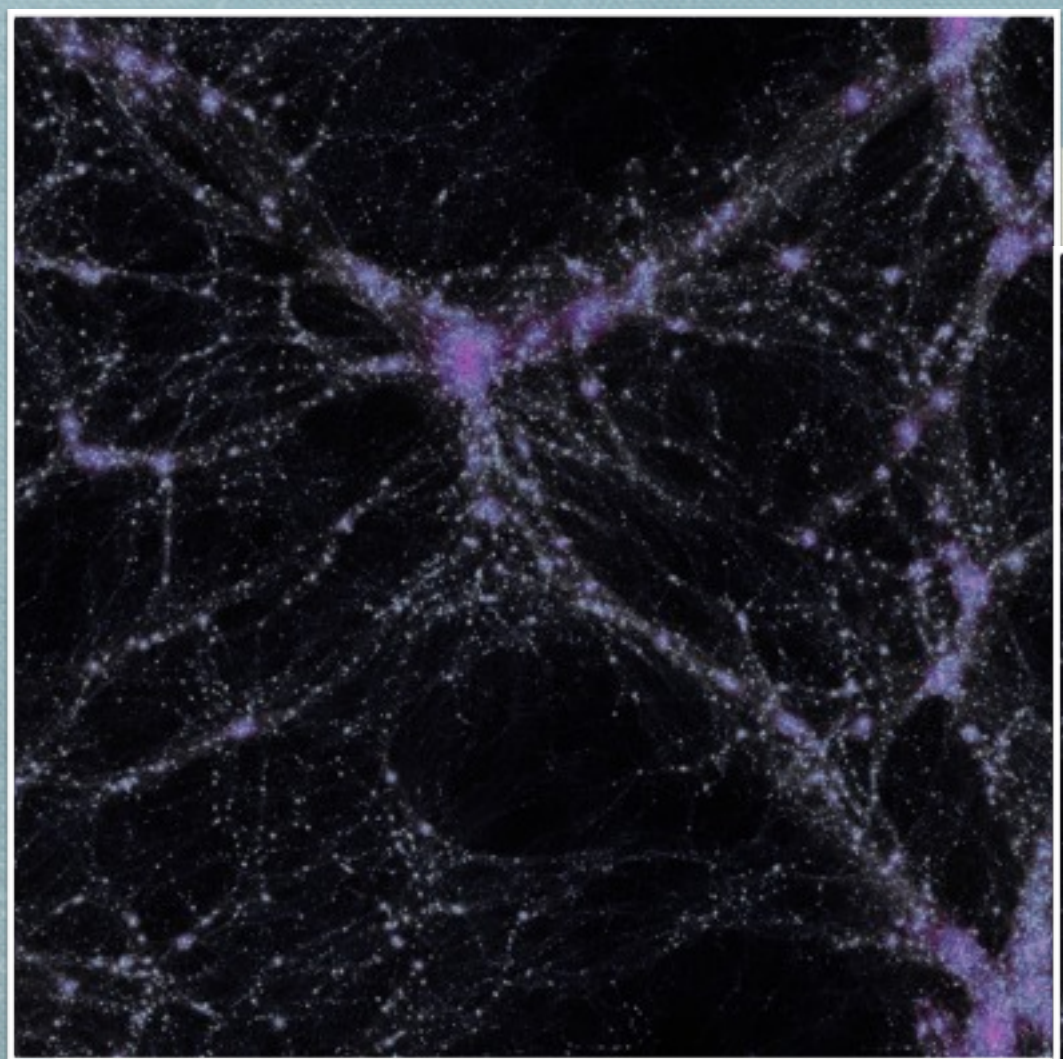
- Original proposals motivated by small-scale issues [Spergel and Steinhardt 2000, Firmani et al 2000]
- More recent work on astrophysically-interesting self-interactions in terms of massive and massless force carriers that ***lead to the right thermal relic density*** [Feng, Kaplinghat, Yu, Tu 2009, Feng, Kaplinghat, Yu 2010, Loeb and Weiner 2011]
  - **Implications for direct and indirect detection [Kaplinghat, Linden and Yu, in prep]**
- Enough freedom if you include velocity dependence that TBTF problem can be solved with the production of large cores. [Vogelsberger, Zavala and Loeb 2012, Vogelsberger, Zavala and Walker 2012]

Empirical solution to the *core size-halo mass* relation

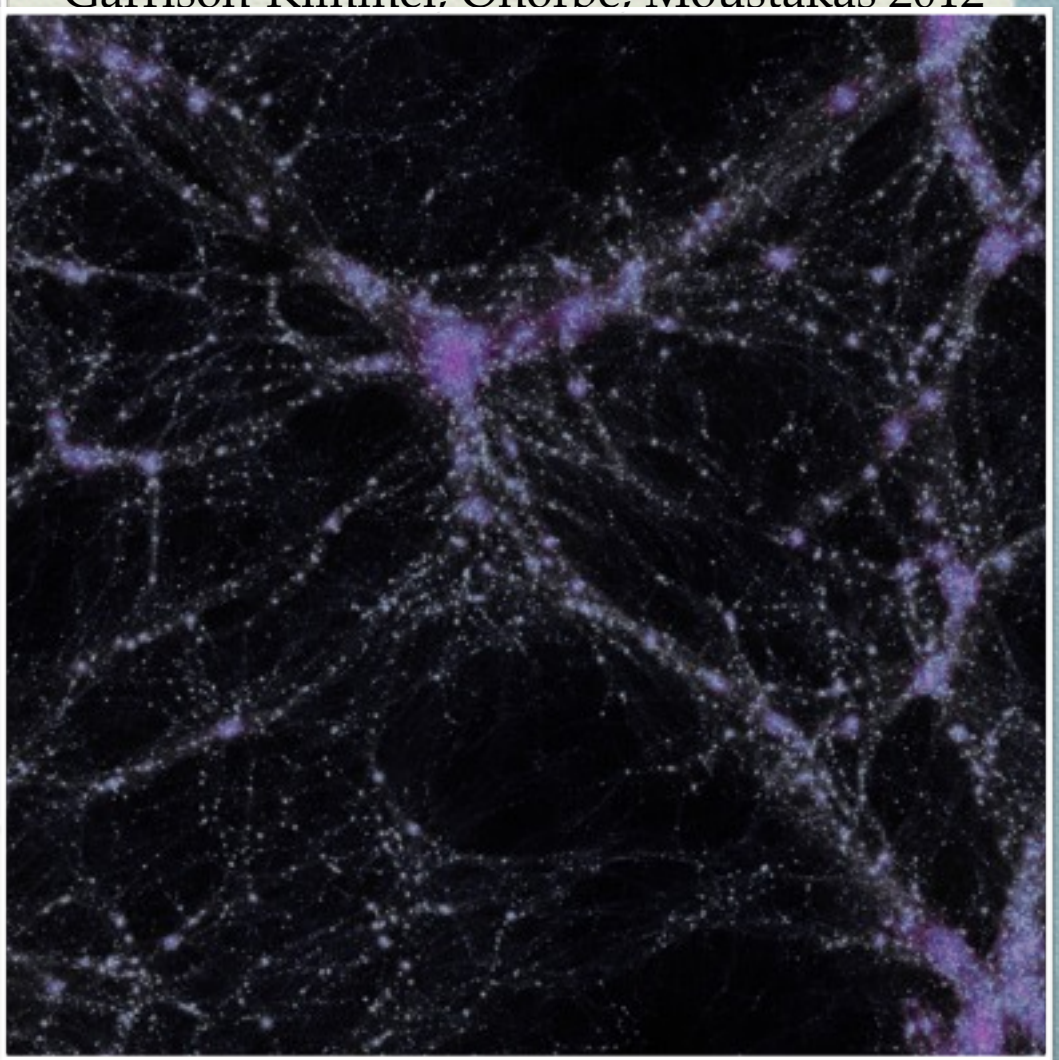


However, see Vogelsberger, Zavala and Walker 2012 for simulations that indicate that a cross section somewhat larger than 0.2 barn/GeV is needed to explain the densities of MW satellites

SIDM is the same as CDM on large scales

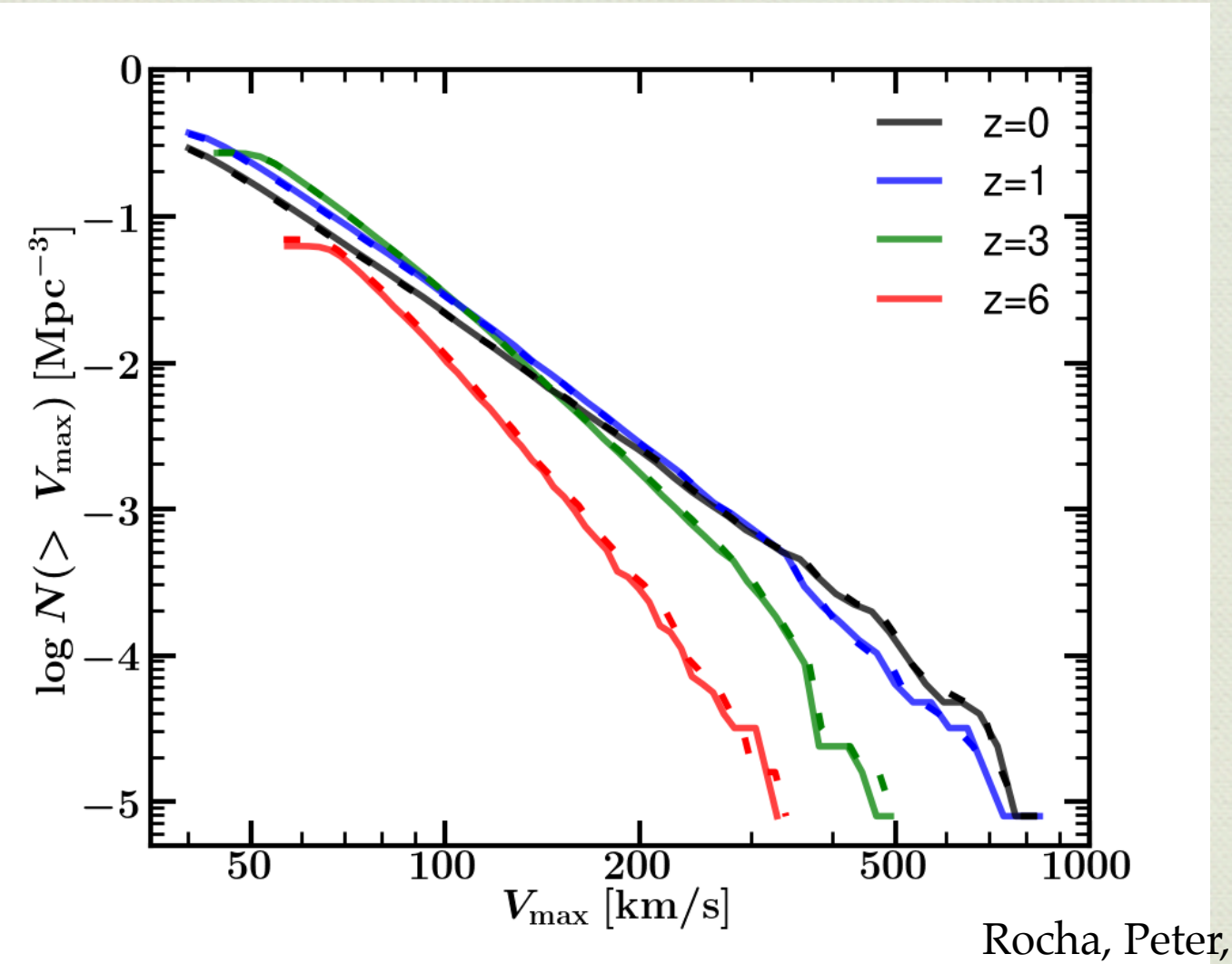


Rocha, Peter, Bullock, Kaplinghat, Garrison-Kimmel, Onorbe, Moustakas 2012



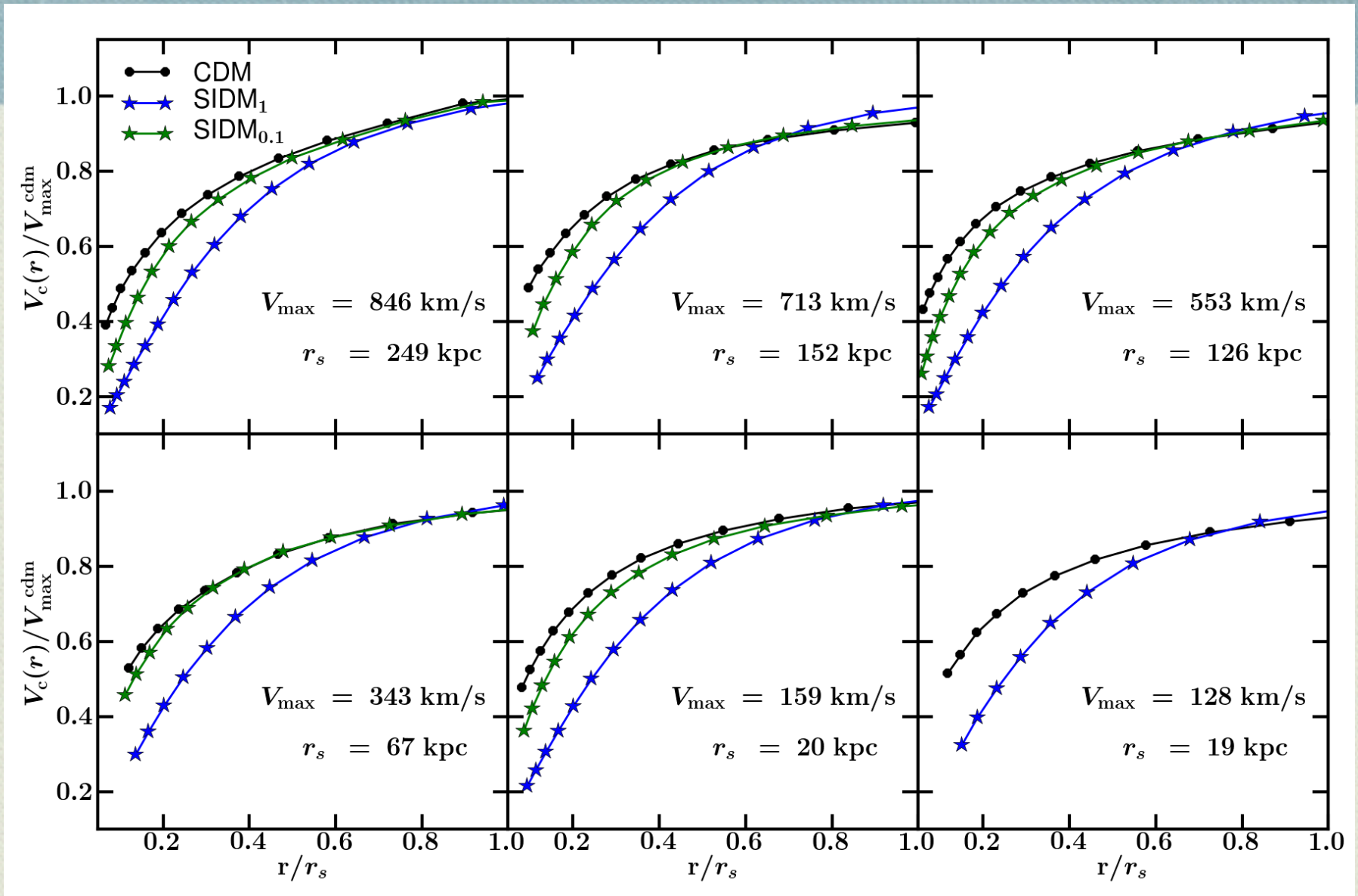
See also Vogelsberger, Zavala and Loeb 2012 for SIDM with v-dependent interaction

SIDM is the same as CDM on large scales



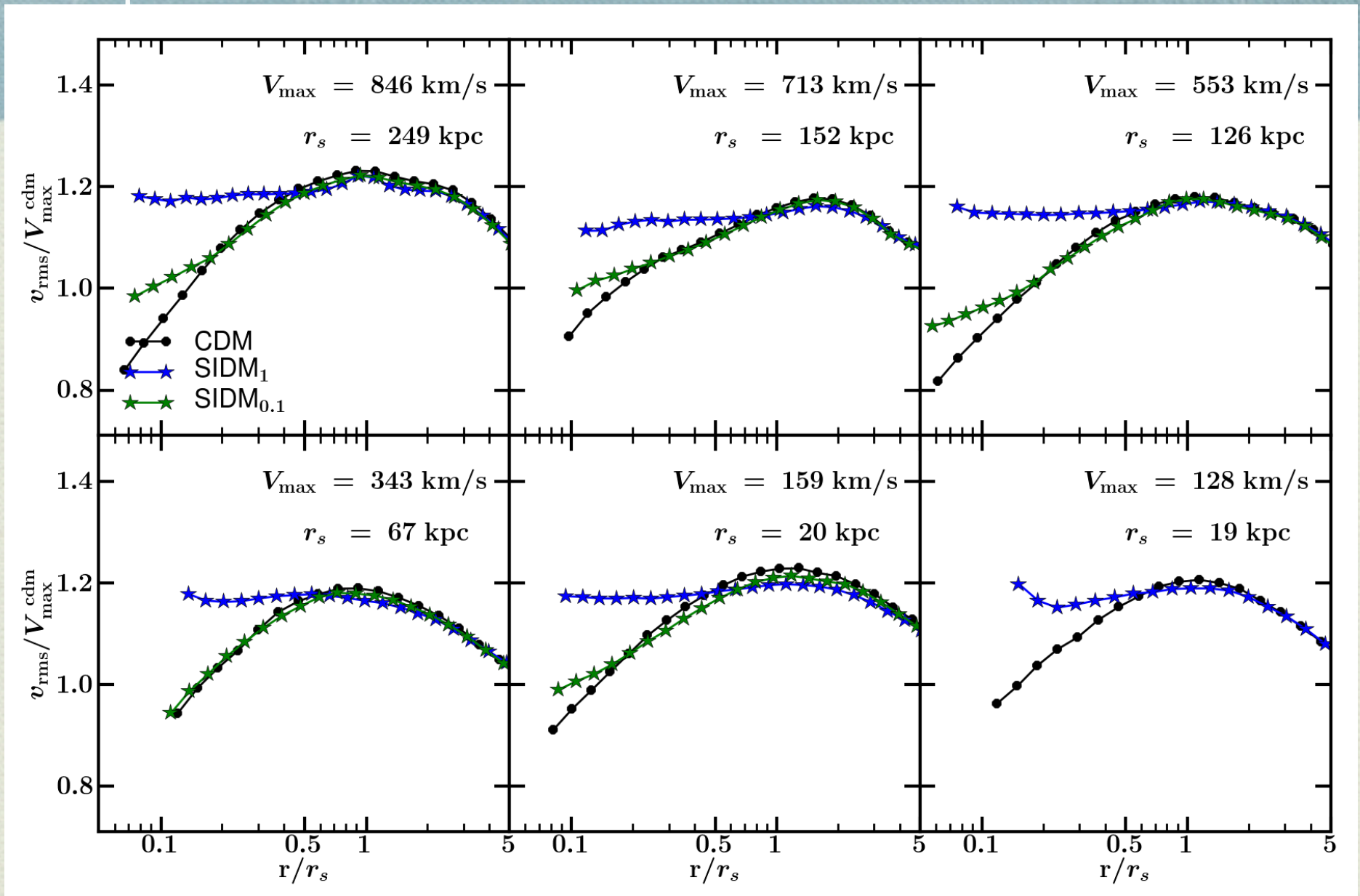
Rocha, Peter, Bullock, Kaplinghat, Garrison-Kimmel, Onorbe, Moustakas 2012

SIDM predictions for rotation speed: 6 example halos



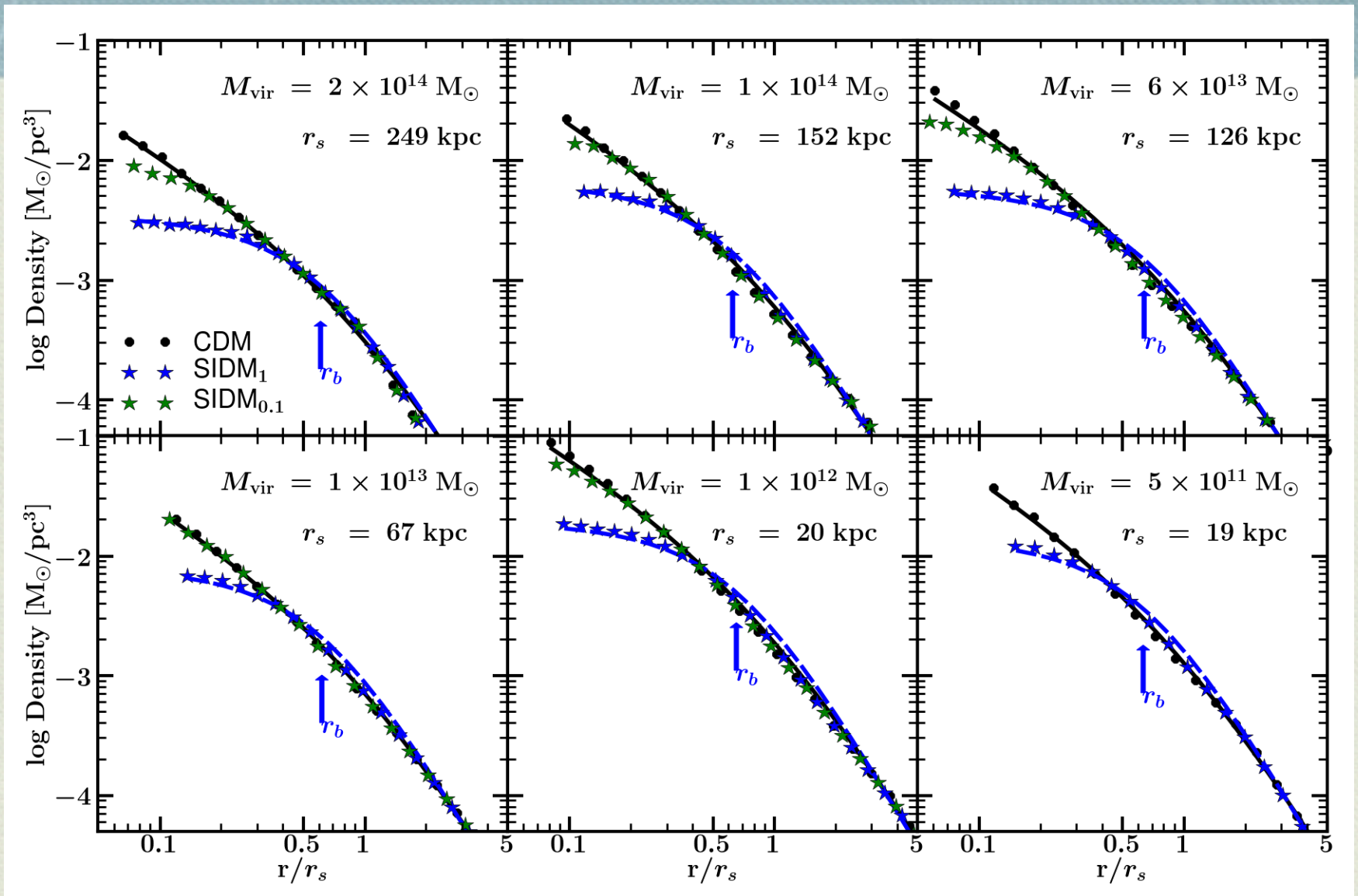
Rocha, Peter, Bullock, Kaplinghat, Garrison-Kimmel, Onorbe, Moustakas 2012

Dark matter temperature profile in SIDM: same 6 example halos as before



Rocha, Peter, Bullock, Kaplinghat, Garrison-Kimmel, Onorbe, Moustakas 2012

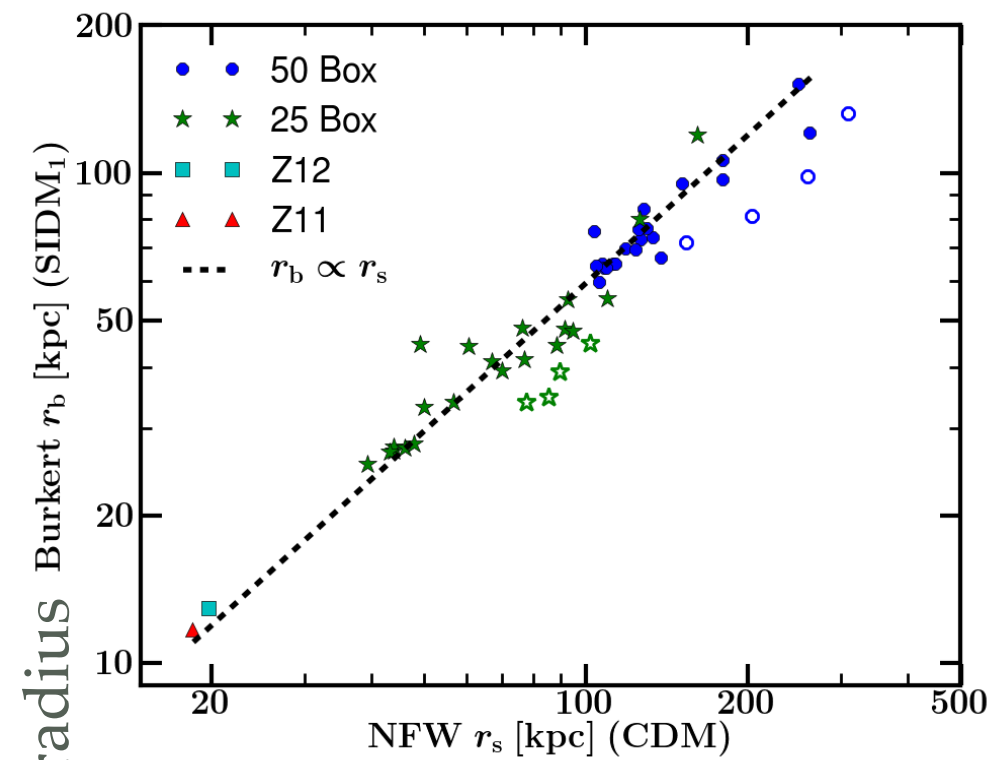
SIDM predictions for density profile: same 6 example halos as before



Rocha, Peter, Bullock, Kaplinghat, Garrison-Kimmel, Onorbe, Moustakas 2012

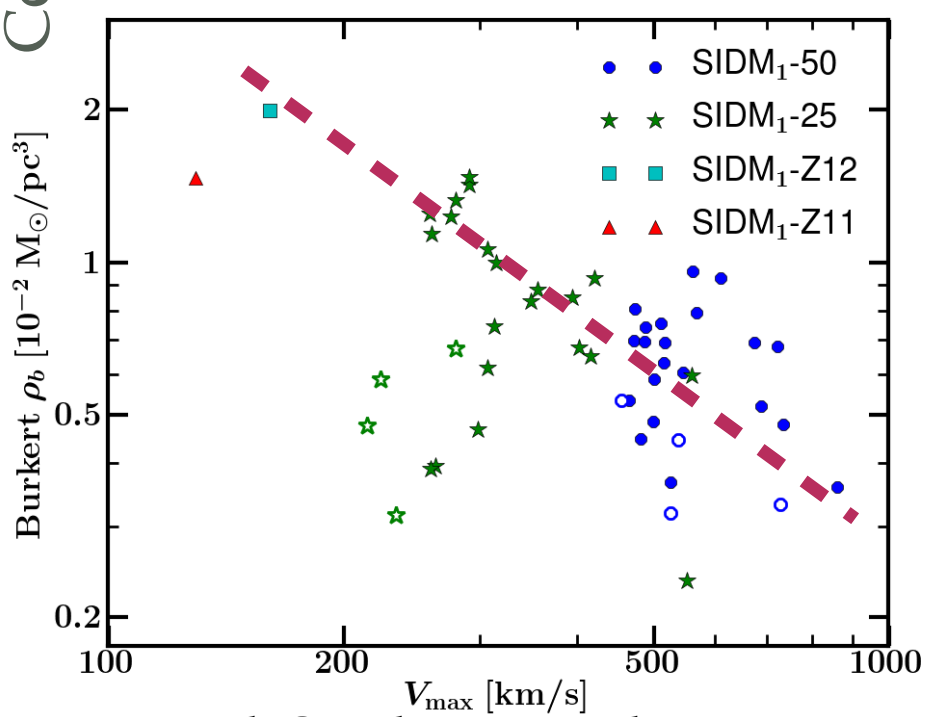
And finally, SIDM scaling relations

Core radius



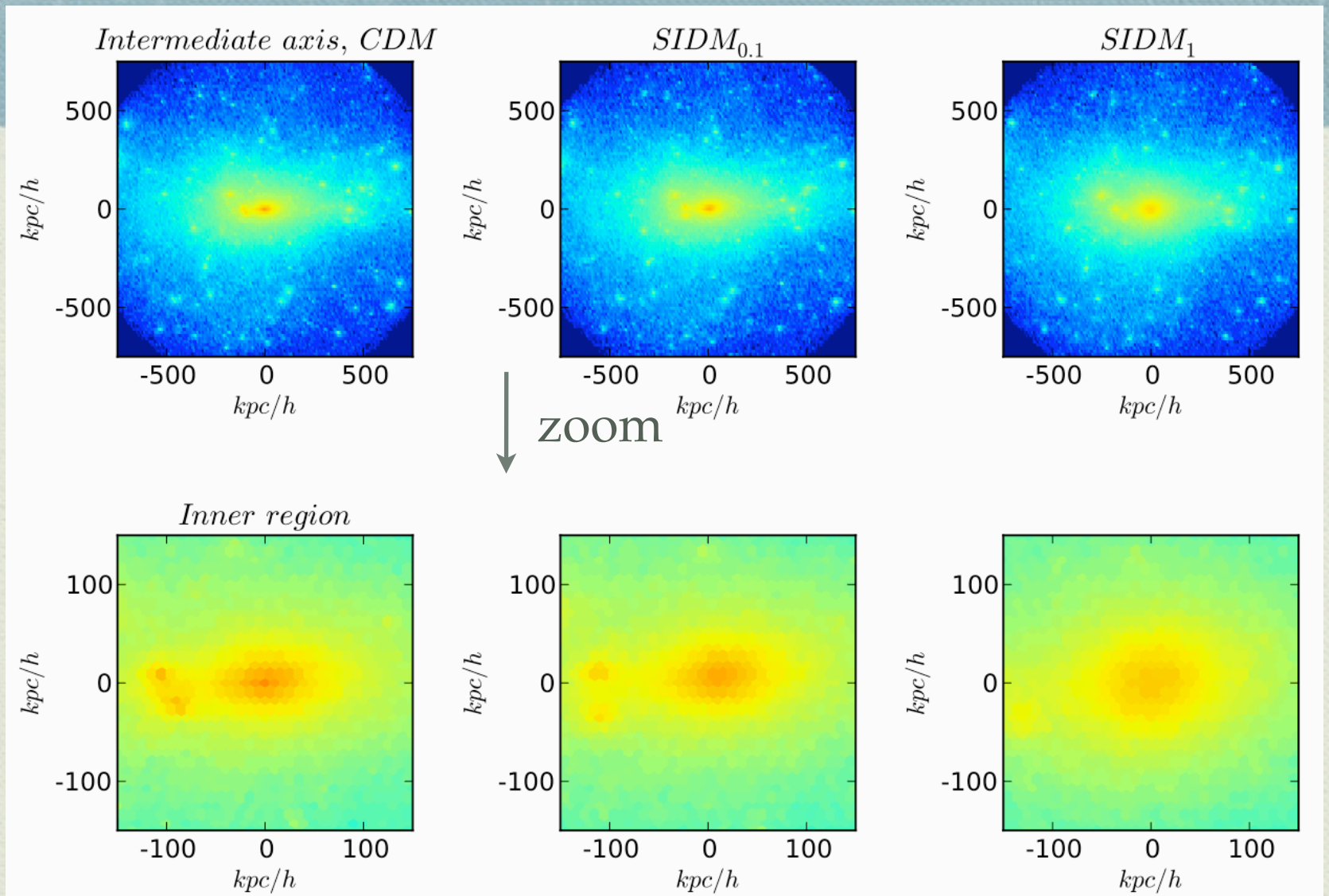
$r_s \sim RMAX/2.2$

Core density



Rocha, Peter, Bullock, Kaplinghat, Garrison-Kimmel, Onorbe, Moustakas 2012

Constraints from shapes of halos? Not really.



Peter, Rocha, Bullock, Kaplinghat 2012

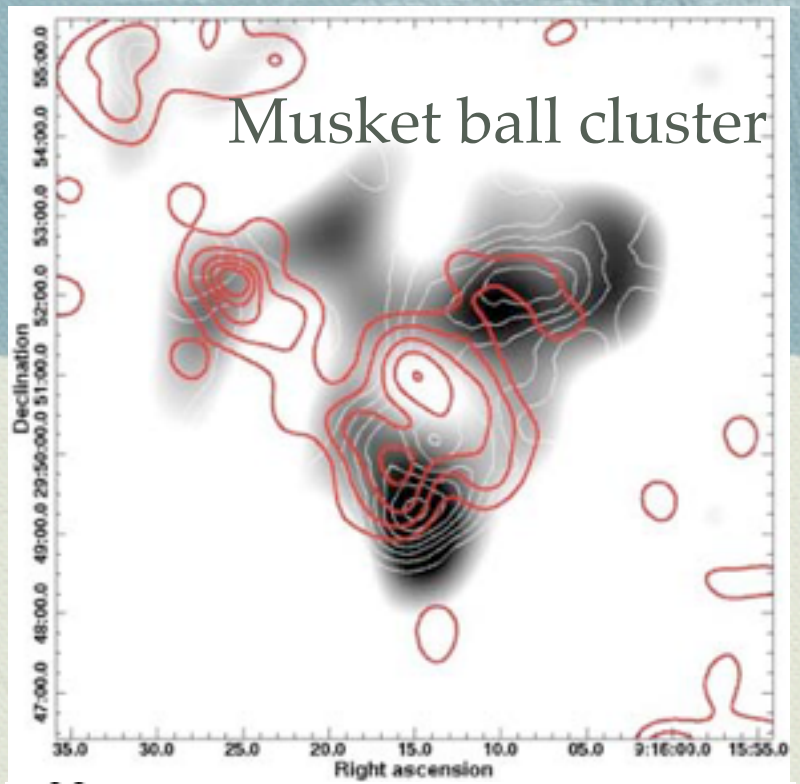
Shapes measured in big ellipticals from X-rays seems to be the best local measure but unlikely to constrain cross sections of order 0.1 cm^2/g.

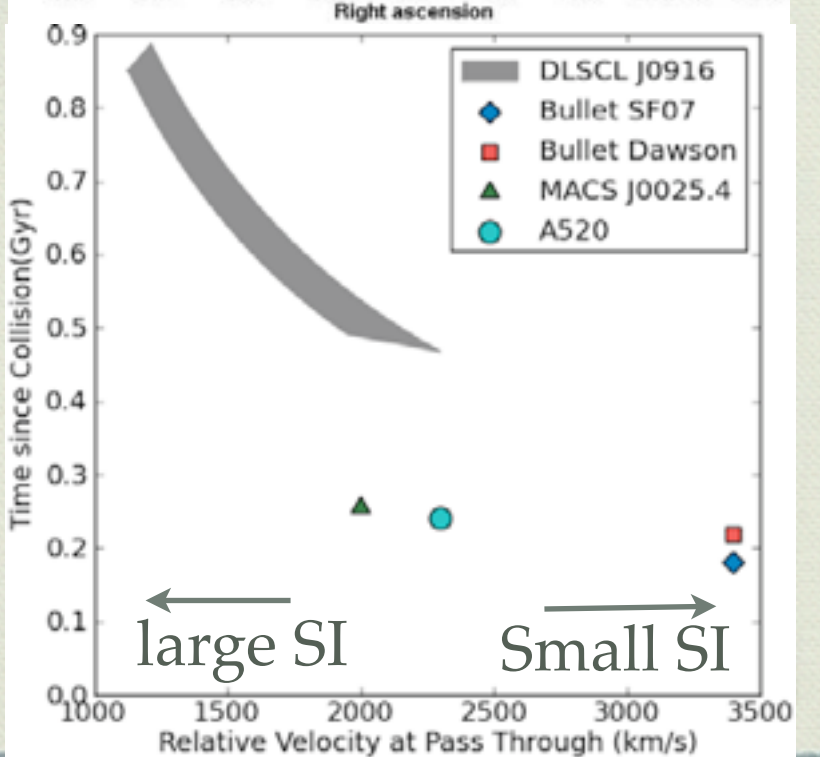
Merging clusters

Bullet cluster

Composite Credit: X-ray: NASA/CXC/CfA/ M.Markevitch et al.;
Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/ D.Clowe et al.
Optical: NASA/STScI; Magellan/U.Arizona/ D.Clowe et al.;

Bullet cluster constraints at about 0.7 cm²/g.





Dawson et al 2012

Summary

- Last 5 years have seen a revival of small-scale issues
  - New observations (Satellites, Spirals, Clusters)
  - Progress in simulations with baryons
- Using observations capable of resolving the innermost regions, estimated densities of dark matter are lower than LCDM predictions.
- LSIDM could naturally explain these densities while maintaining the successes of LCDM on larger scales.
- Milky Way Satellites: SIDM, WDM could explain this.
- Spirals: feedback, SIDM could explain this
  - Can the scatter in data be explained? We should really look at WDM +feedback, SIDM+feedback since feedback exists.
- Clusters: SIDM, Feedback?