Reasons to think dark matter isn't a WIMP

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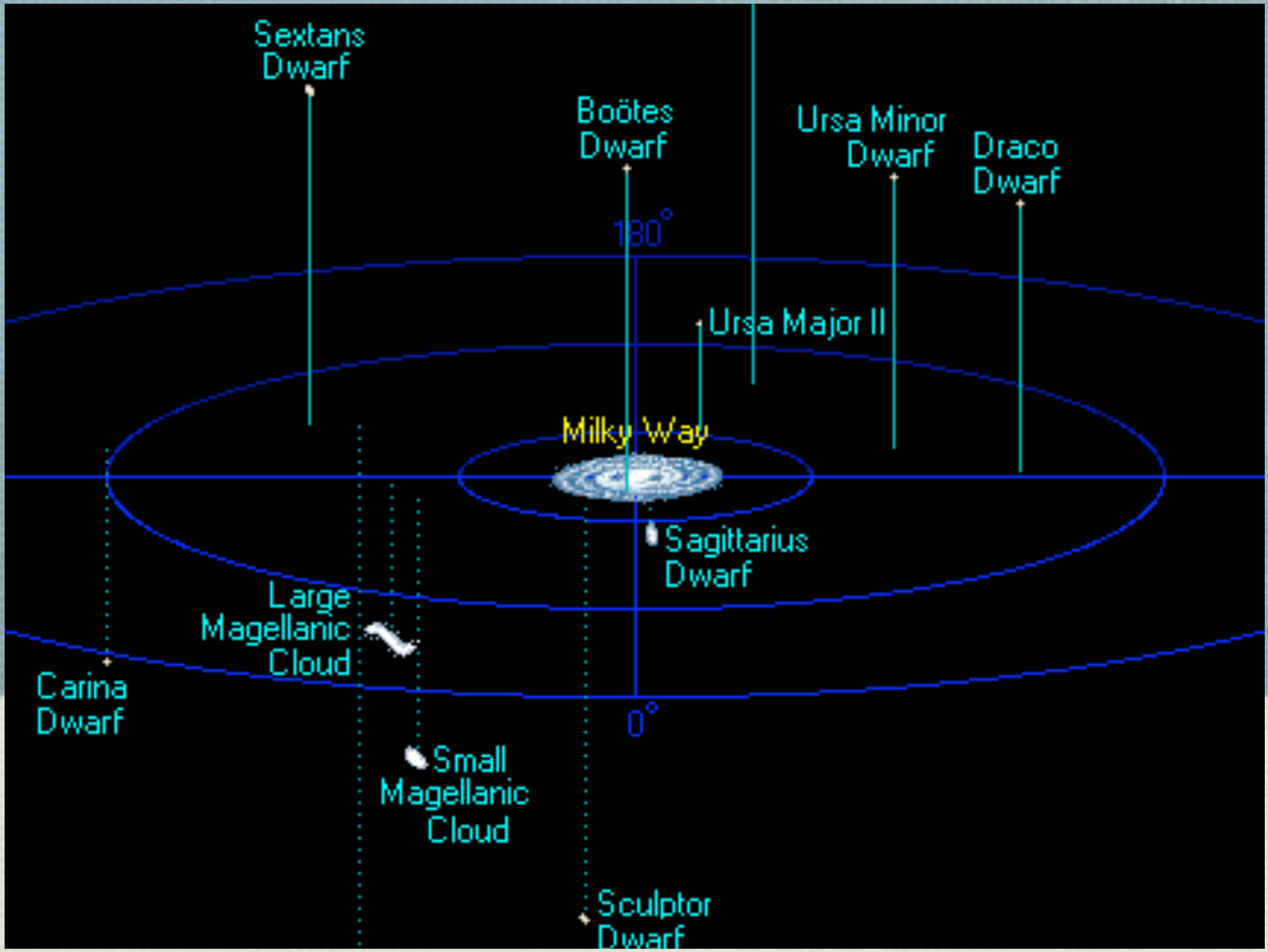
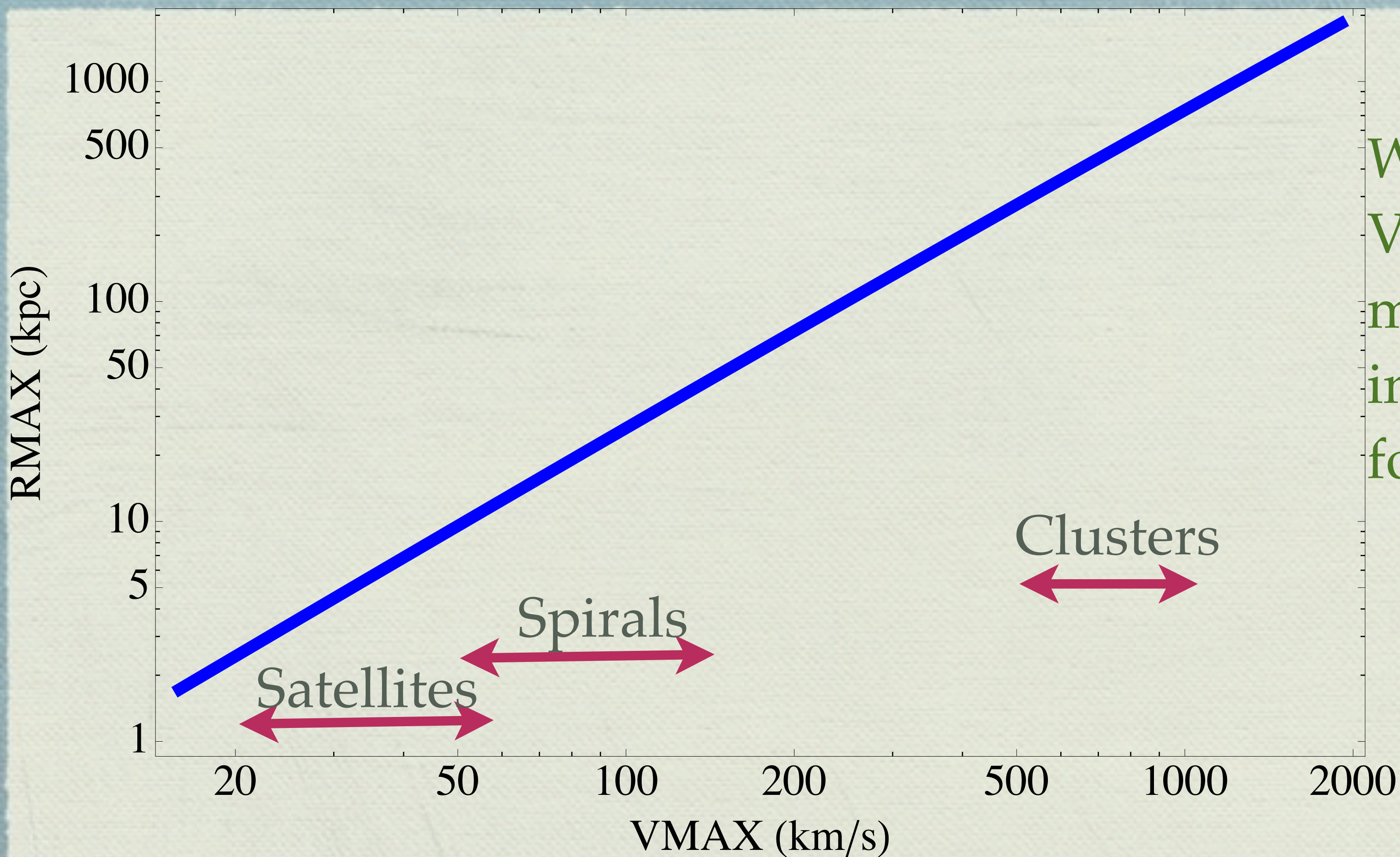


Manoj Kaplinghat, University of California, Irvine, USA

Clusters to MW satellites

- *Estimated DM densities*
  - **Clusters**: 10-50 kpc scales
    - **Lower densities than predicted, Cores**, Merging clusters
  - **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



We will use VMAX and mass of a halo interchangeably for this talk

Cold dark matter works amazingly well in explaining large scale structure data (CMB, distribution of galaxies)

Plan for the talk

- What are the issues on small scales related to comparison of densities *predicted* and *observed*?
- ``Look" at three generic solutions
  - 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

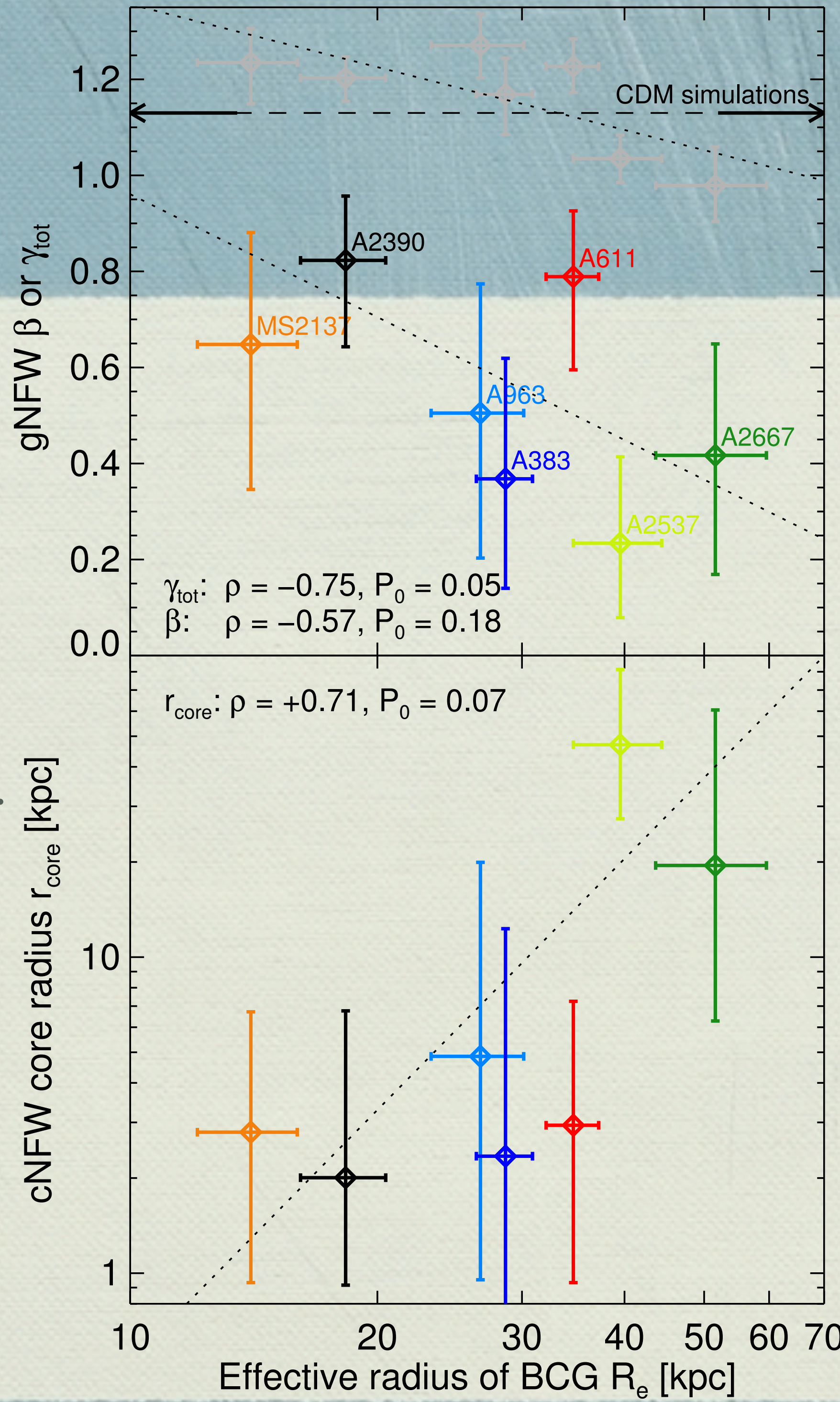
Clusters of galaxies

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

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

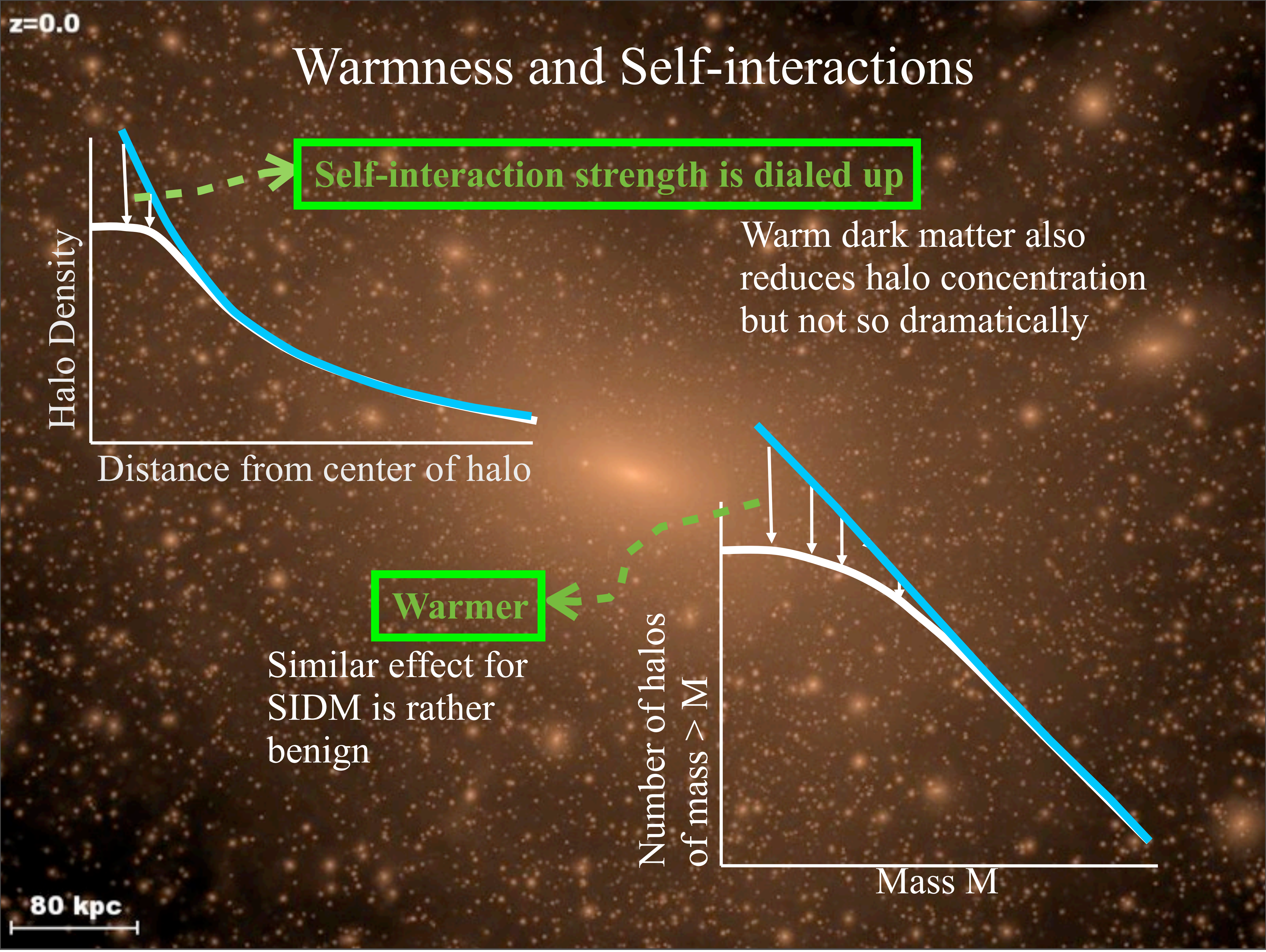
``gNFW" density $\propto 1/r^{\beta}(r_s+r)^{3-\beta}$
``cNFW" density $\propto 1/(r+core)(r_s+r)^2$

Newman et al 2012



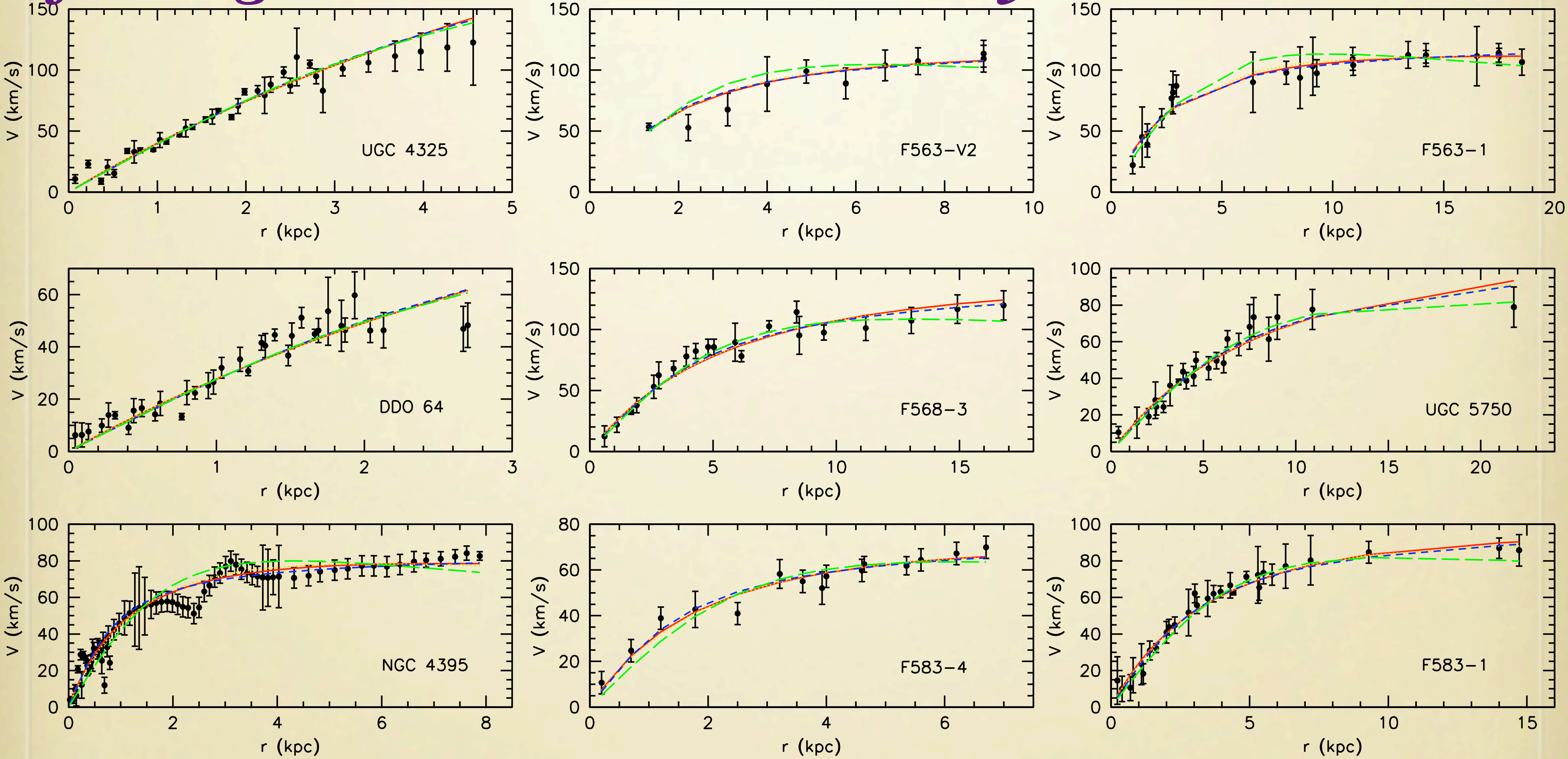
Solutions

- 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 halo concentration but not so dramatically
Halo Density
Distance from center of halo
Warmer
Similar effect for SIDM is rather benign
Number of halos of mass > M
Mass M
80 kpc

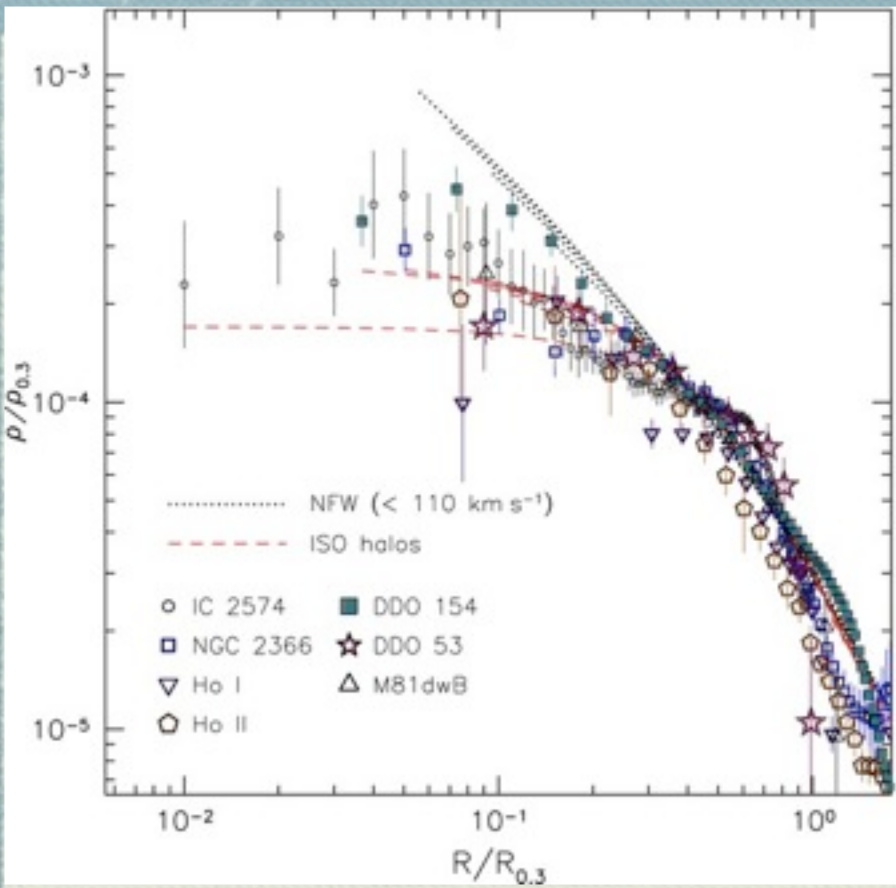
NEARBY SPIRAL (LOW SURFACE BRIGHTNESS) GALAXIES

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



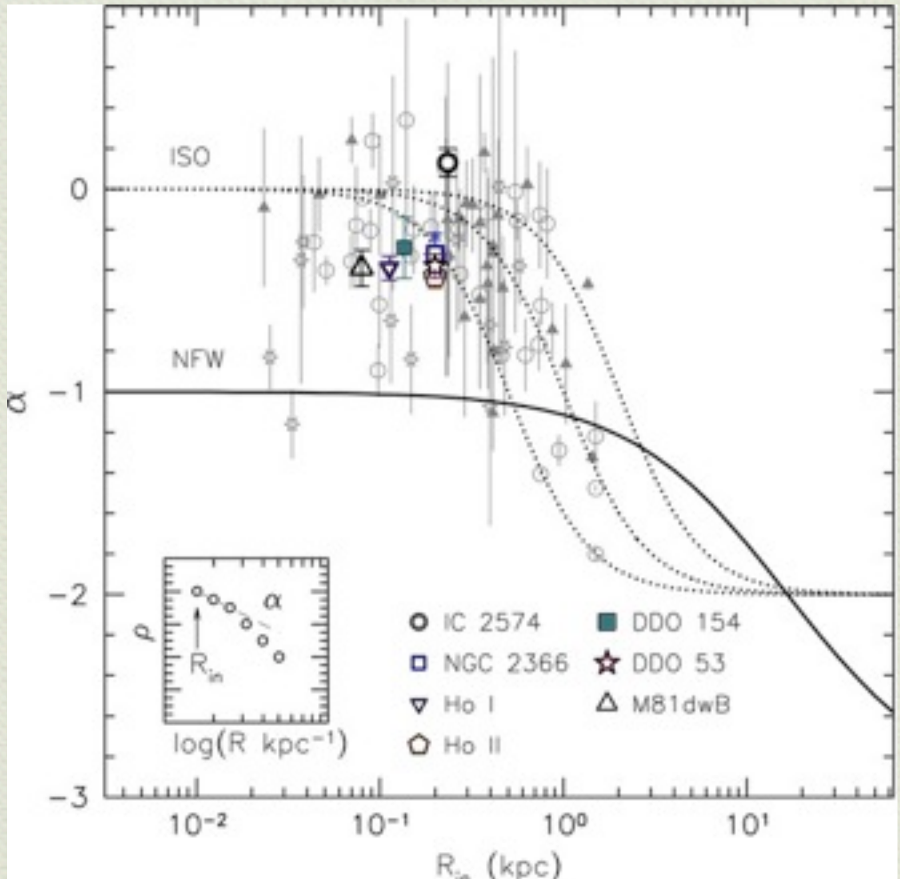
Kuzio de Naray, Martinez, Bullock, Kaplinghat, ApJL 2010

More nearby spiral galaxies



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

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



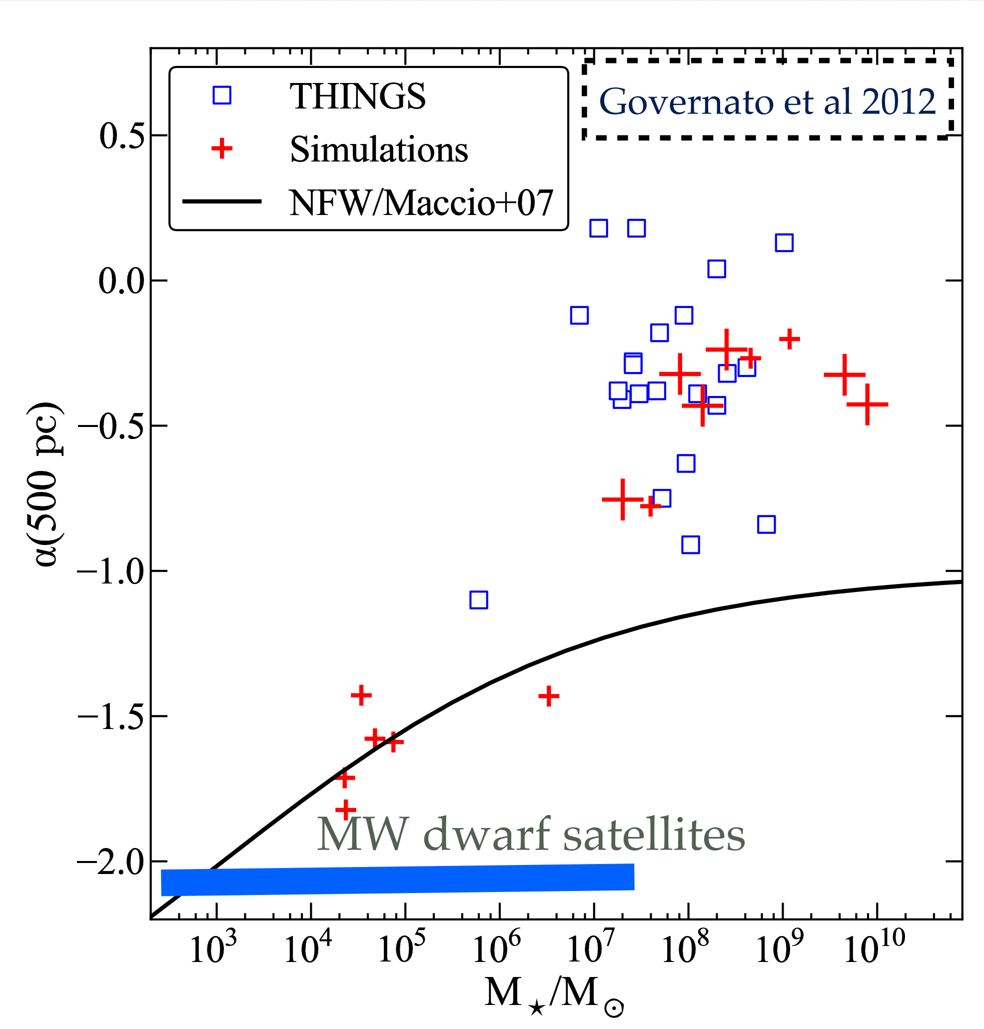
Oh et al 2011 (THINGS)

Friday, January 25, 13

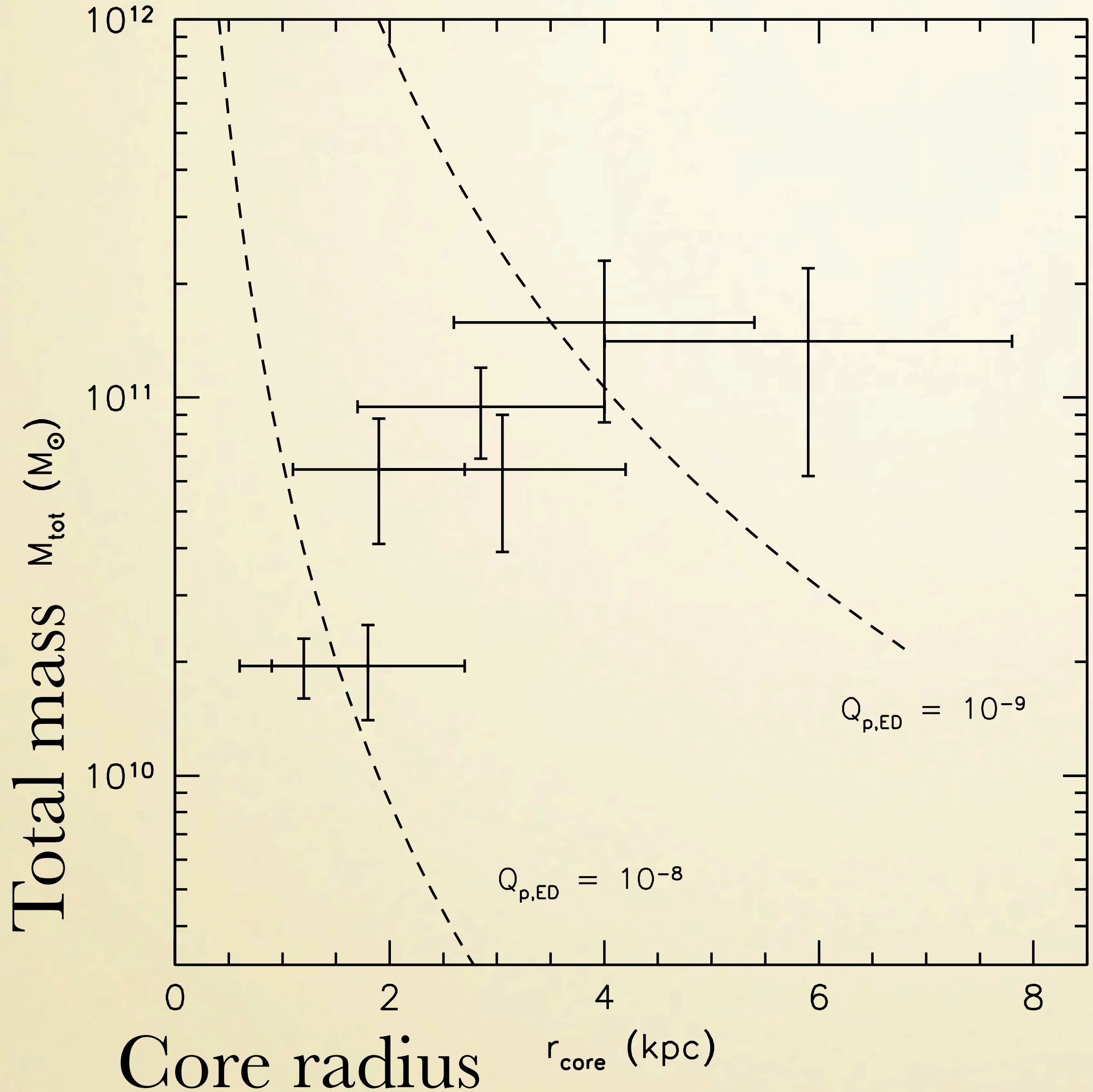
Feedback solution

- **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



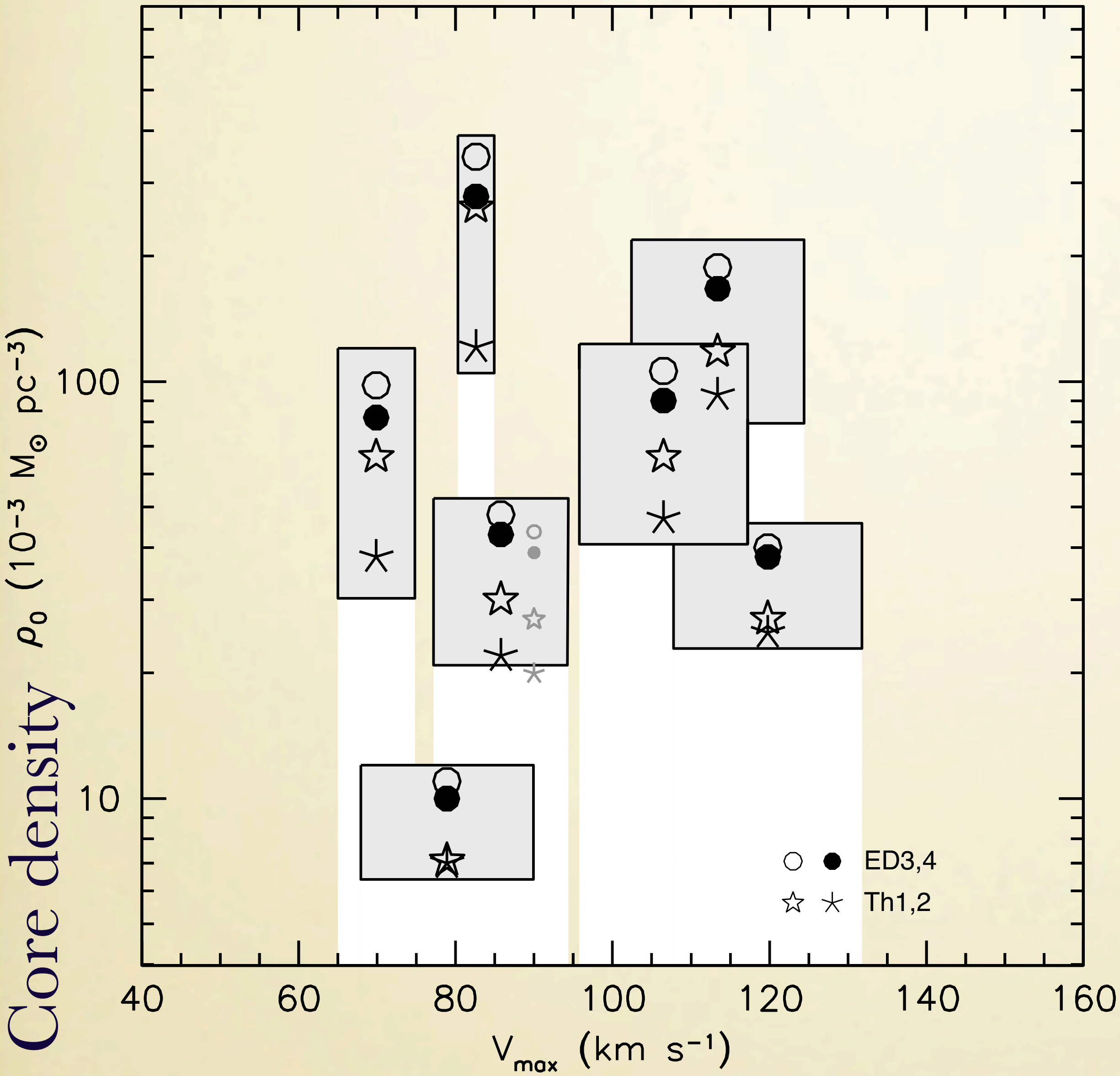
Q_p = primordial phase space density defined as density divided by RMS velocity cube

Note that we are not excluding the possibility that dark matter particle is warm with Q_p larger than those measured in these LSBs

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

Also see:
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 and we will touch upon this later.

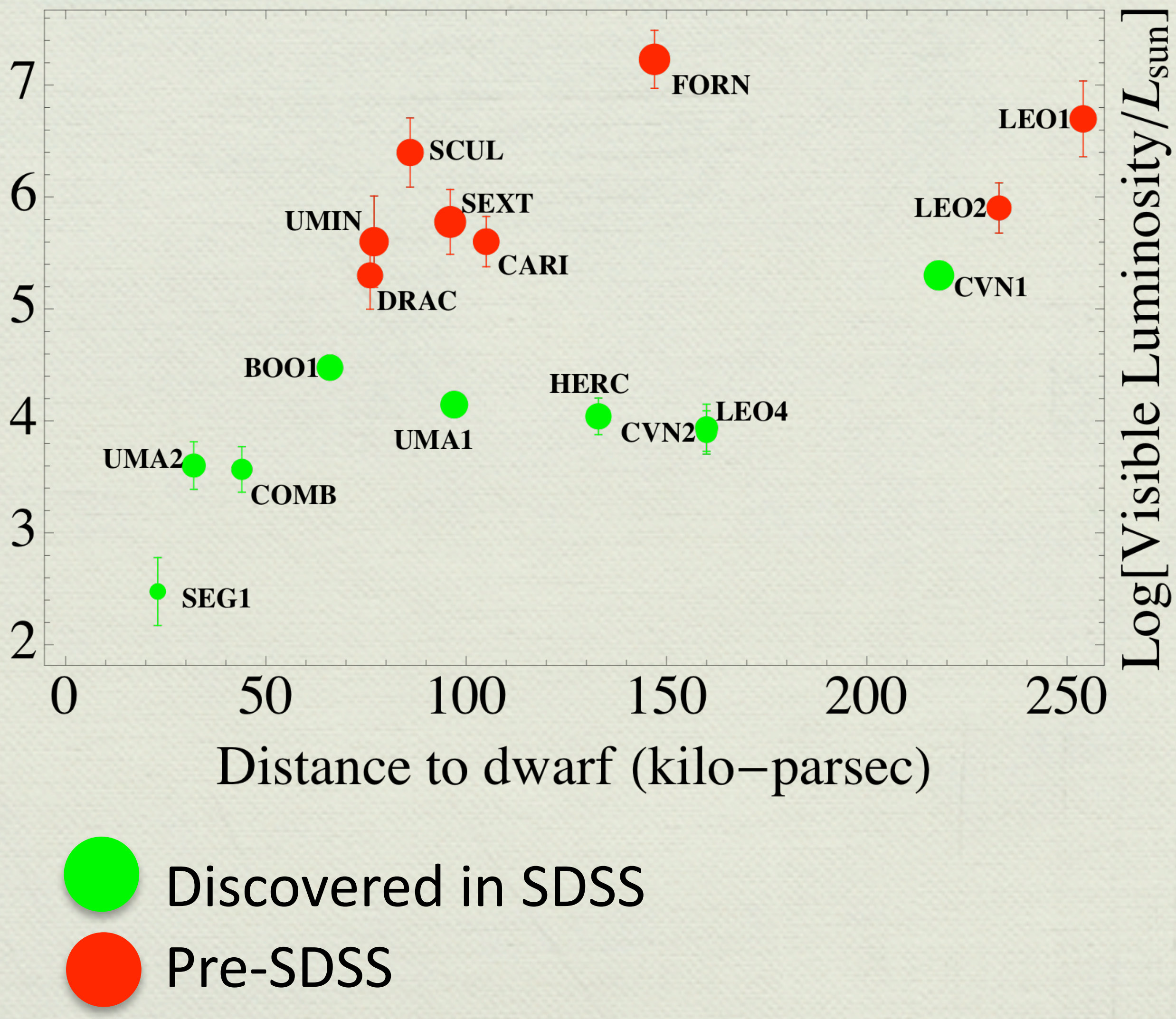
Kuzio de Naray, Martinez, Bullock, Kaplinghat, ApJL 2010

Milky Way satellites

Name	Year Discovered
LMC	--
SMC	--
Sculptor	1937
Fornax	1938
Leo II	1950
Leo I	1950
Ursa Minor	1954
Draco	1954
Carina	1977
Sextans	1990
Sagittarius	1994
Ursa Major I	2005
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

Bright

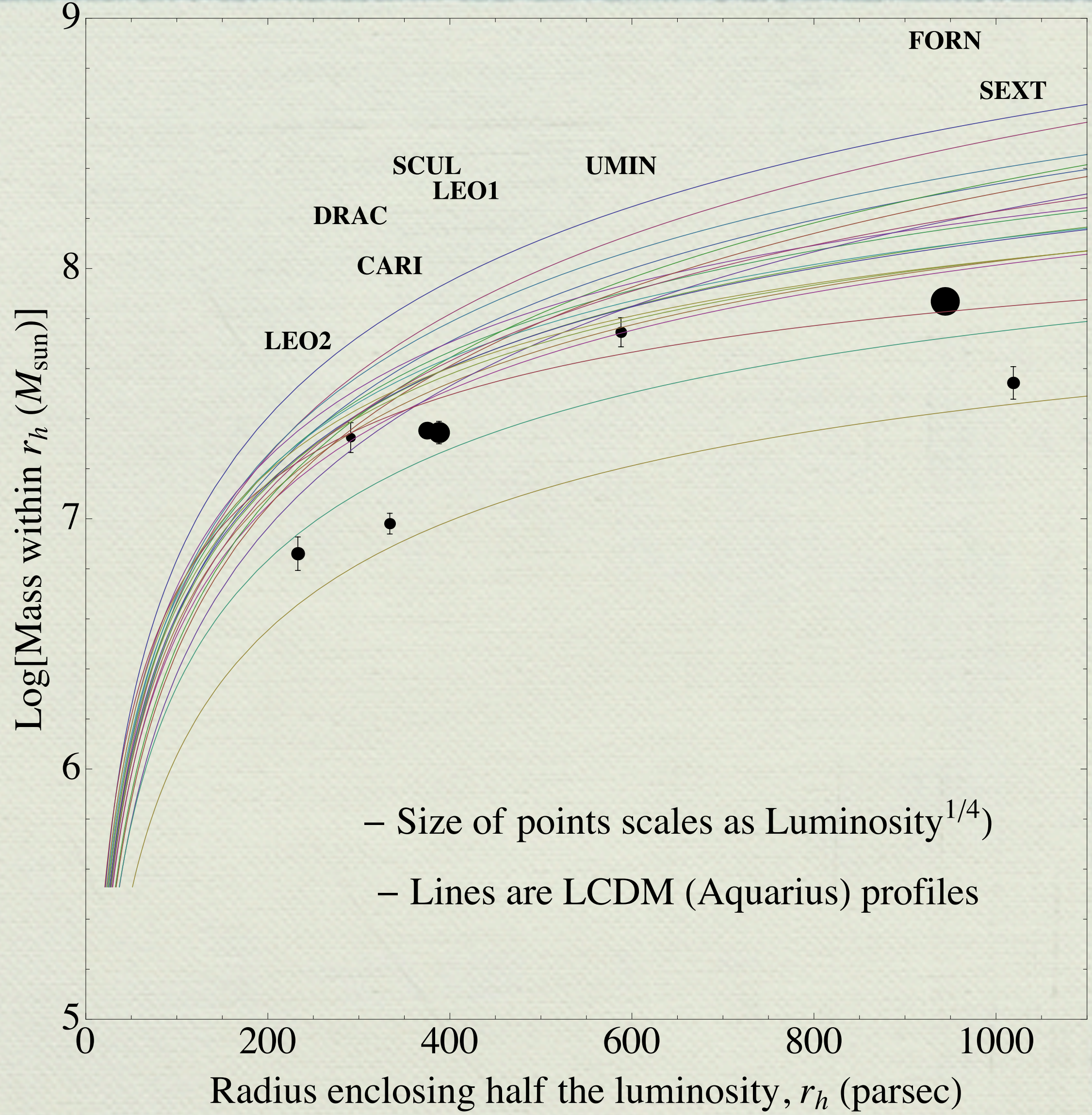
Faint



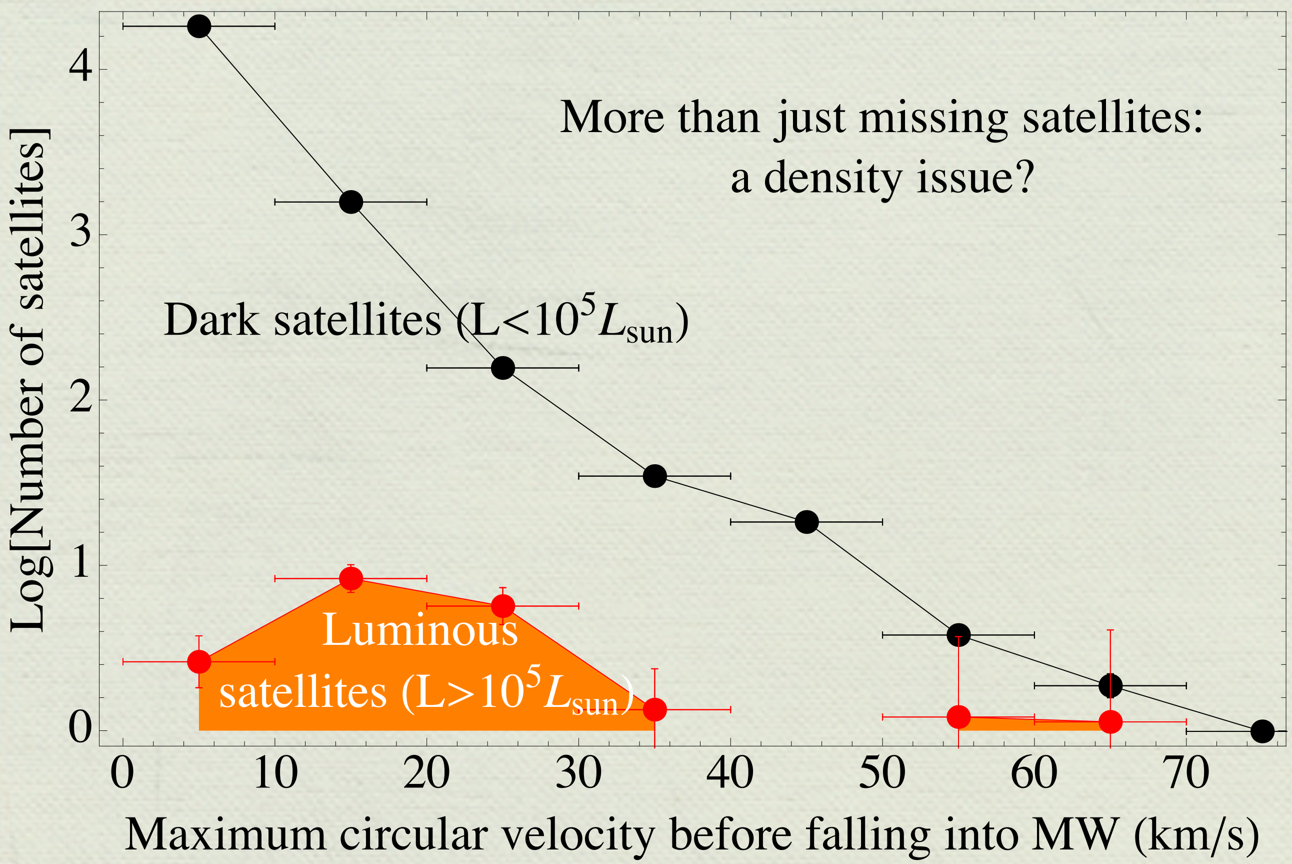
1: Too big to fail? The most massive apparently don't light up...

- NFW fits to mass profiles of the most massive subhalos from Aquarius simulation [Springel et al 2009] shown
- Bright satellites shown
- **Most massive subhalos are too dense**

Boylan-Kolchin, Bullock, Kaplinghat 2011



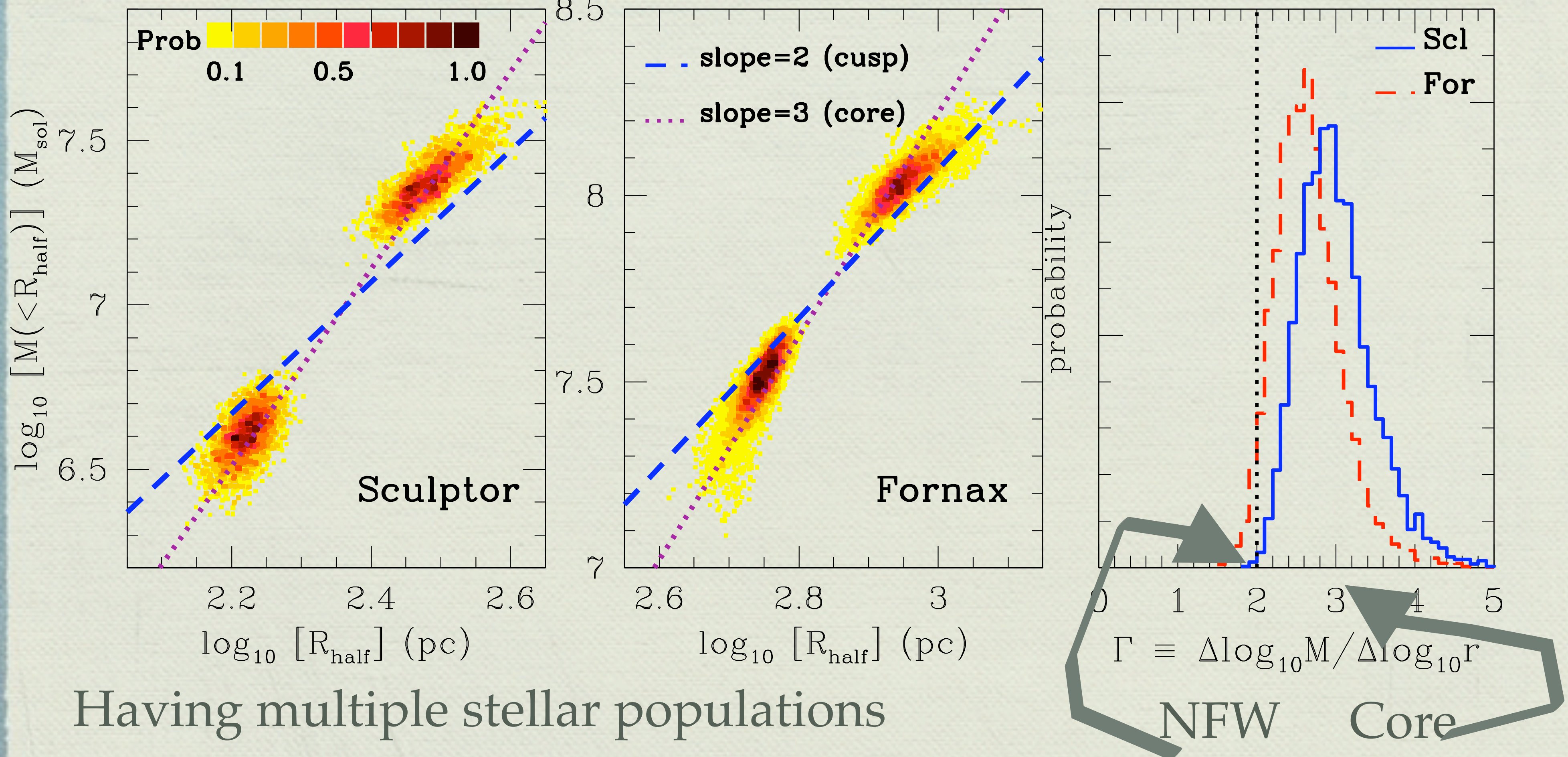
Not the ``missing satellites'' problem: observed satellites are not dense enough



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)



Having multiple stellar populations breaks degeneracies

Battaglia et al MNRAS 383, 183 (2008)

Amorisco and Evans MNRAS 411, 2118 (2011)

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

$\Gamma \approx 3-\alpha$

Possible solution: MW not as massive or 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.
  - Local circular velocity measurements also suggest similar mass range
- **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]

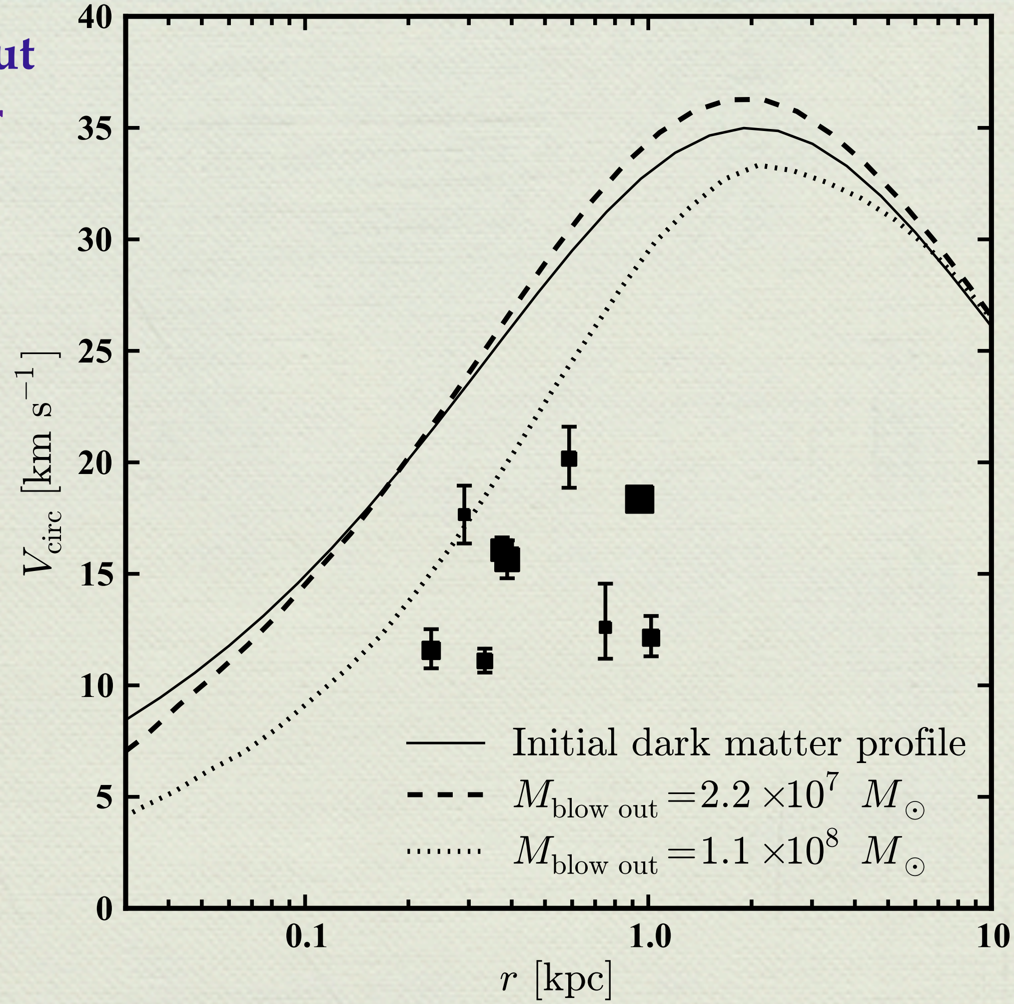
Boylan-Kolchin, Bullock, Kaplinghat 2011

Feedback solution

- **Most massive 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]

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



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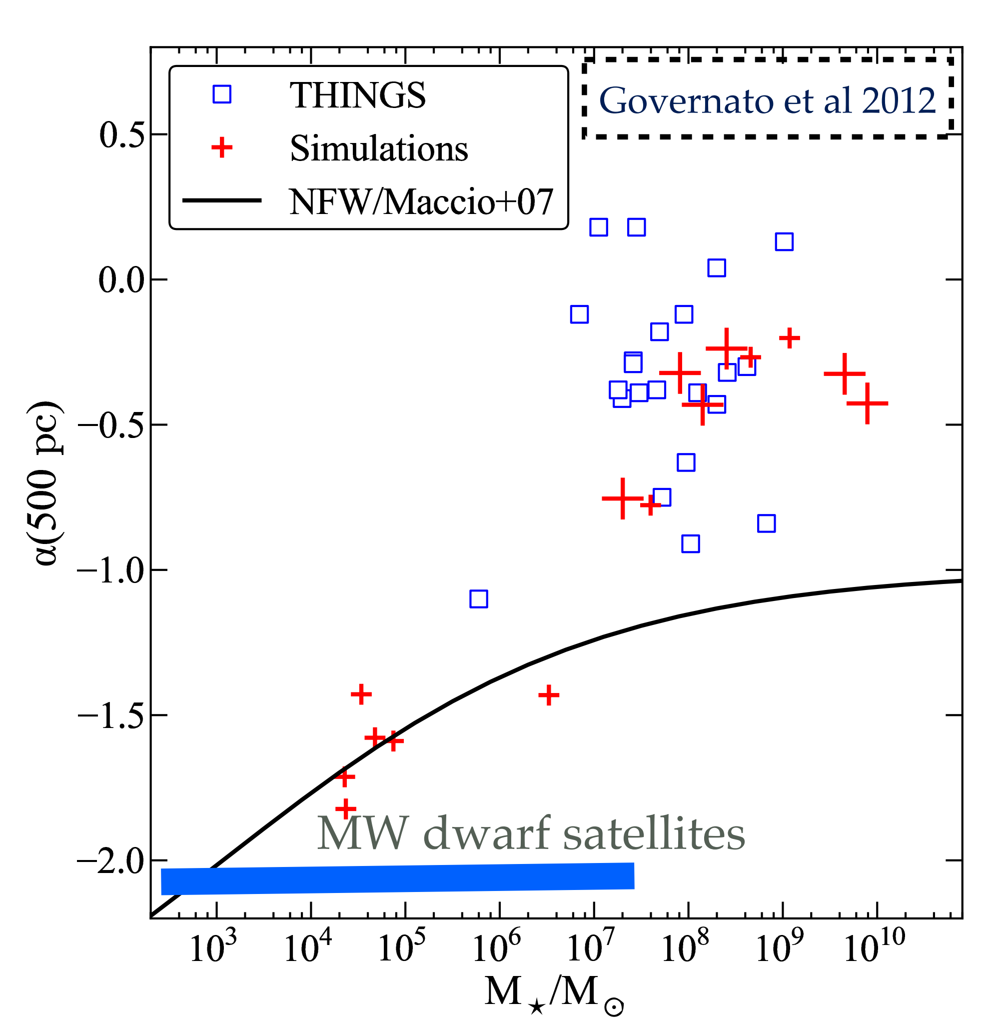


Warm dark matter solution

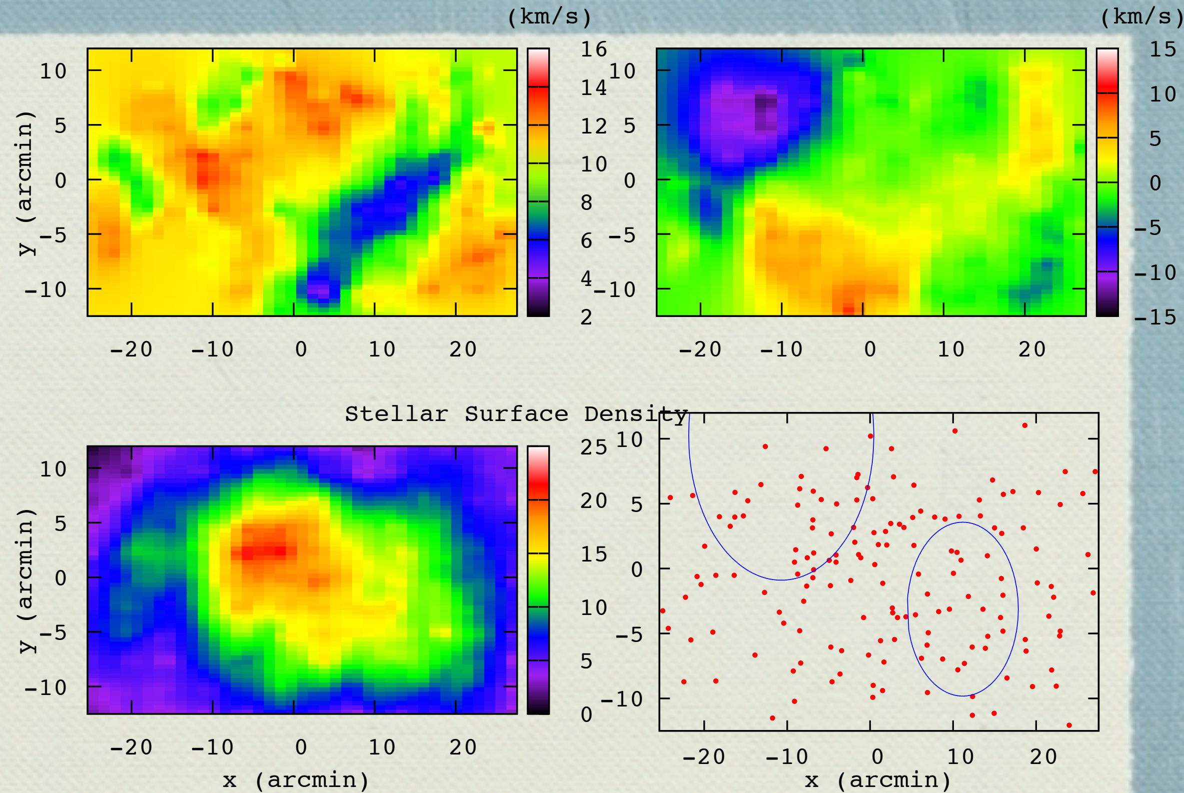
- Warm dark matter [Gunn and Tremaine 1979, Bond, Efstathiou, Silk 1980]
    - Q(satellites) ~ 0.1 Msun/pc^3/(20 kmps)^3 ~ 10^{-5} Msun/pc^3/kmps^3
        - This is the primordial phase space density of about 0.6 keV thermal WDM. So perhaps this is possible. [See Wang, Frenk, Navarro and Gao 2012]
        - How many subhalos survive?
- 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 [Feng, Kaplinghat, Yu, Tu 2009, Feng, Kaplinghat, Yu 2010, Loeb and Weiner 2011]
  - **Can get the right relic density (thermal) and large enough self-interaction cross section**
- Enough freedom if you include velocity dependence that this can be solved. [Vogelsberger, Zavala and Loeb 2012]

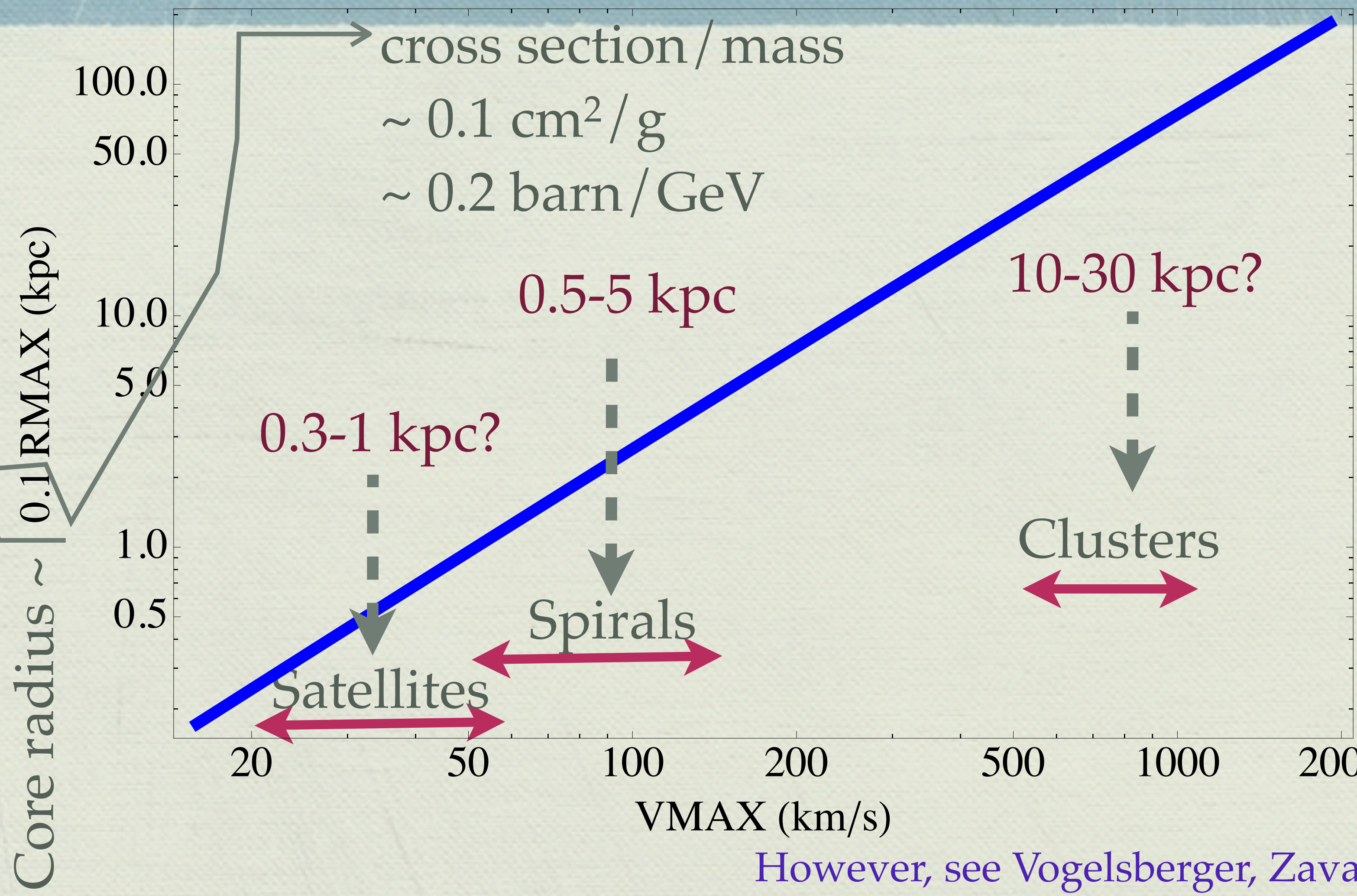
3. Substructure in satellites

- It is not easy for cold substructure to survive in a cusped halo
- Ursa Minor shows evidence for two substructures -- one being cold
  - This one was discovered by Kleyna et al 2003
  - Our analysis shows dispersion is closer to 4 km/s rather than 0.5 km/s
    - Satellite of a satellite?



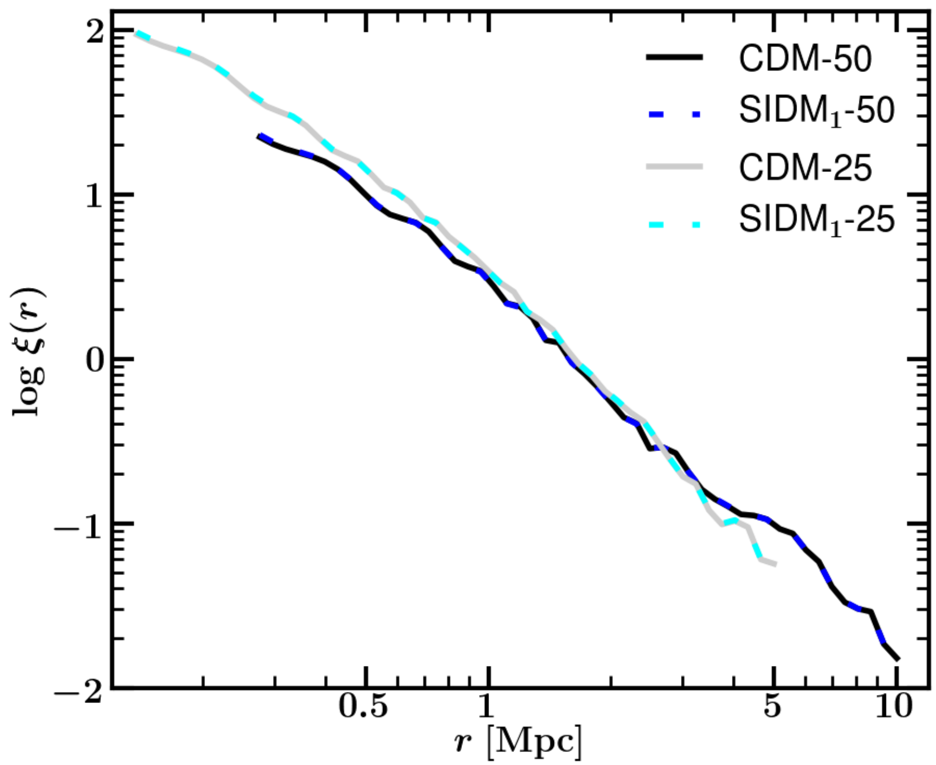
Ursa Minor: evidence for stellar substructure.
Pace et al, 2012

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

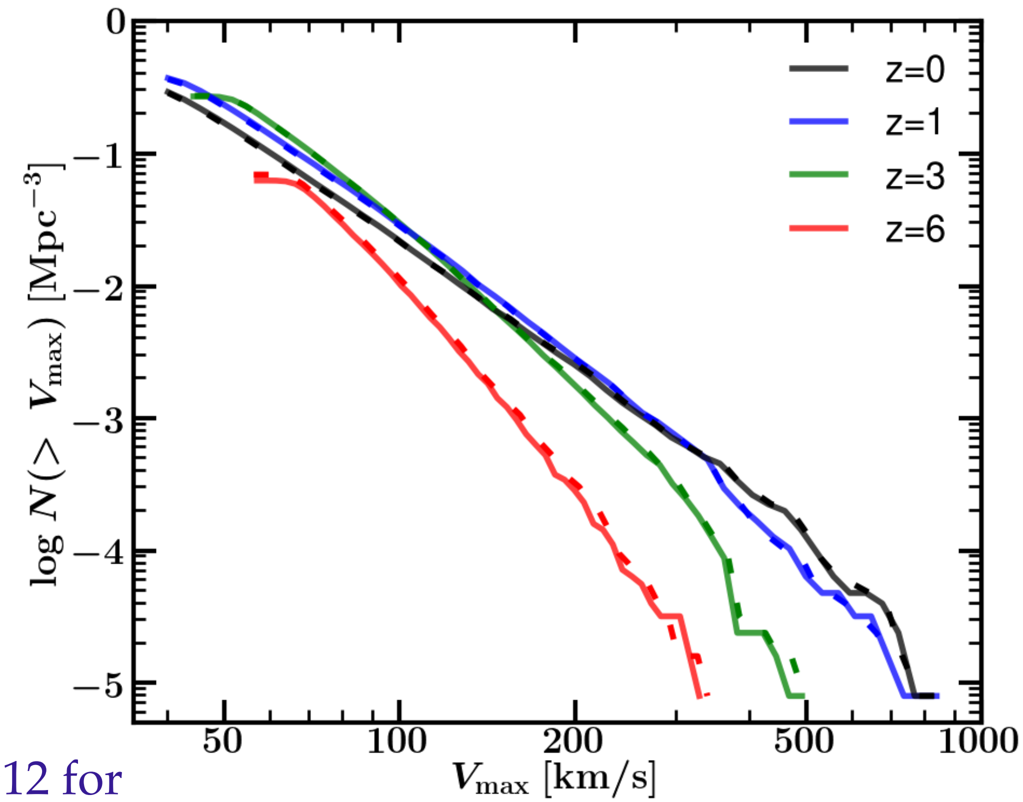


However, see Vogelsberger, Zavala and Walker 2012 for simulations that indicate 0.2 barn/GeV is not sufficient to explain TBTF

SIDM is the same as CDM on large scales

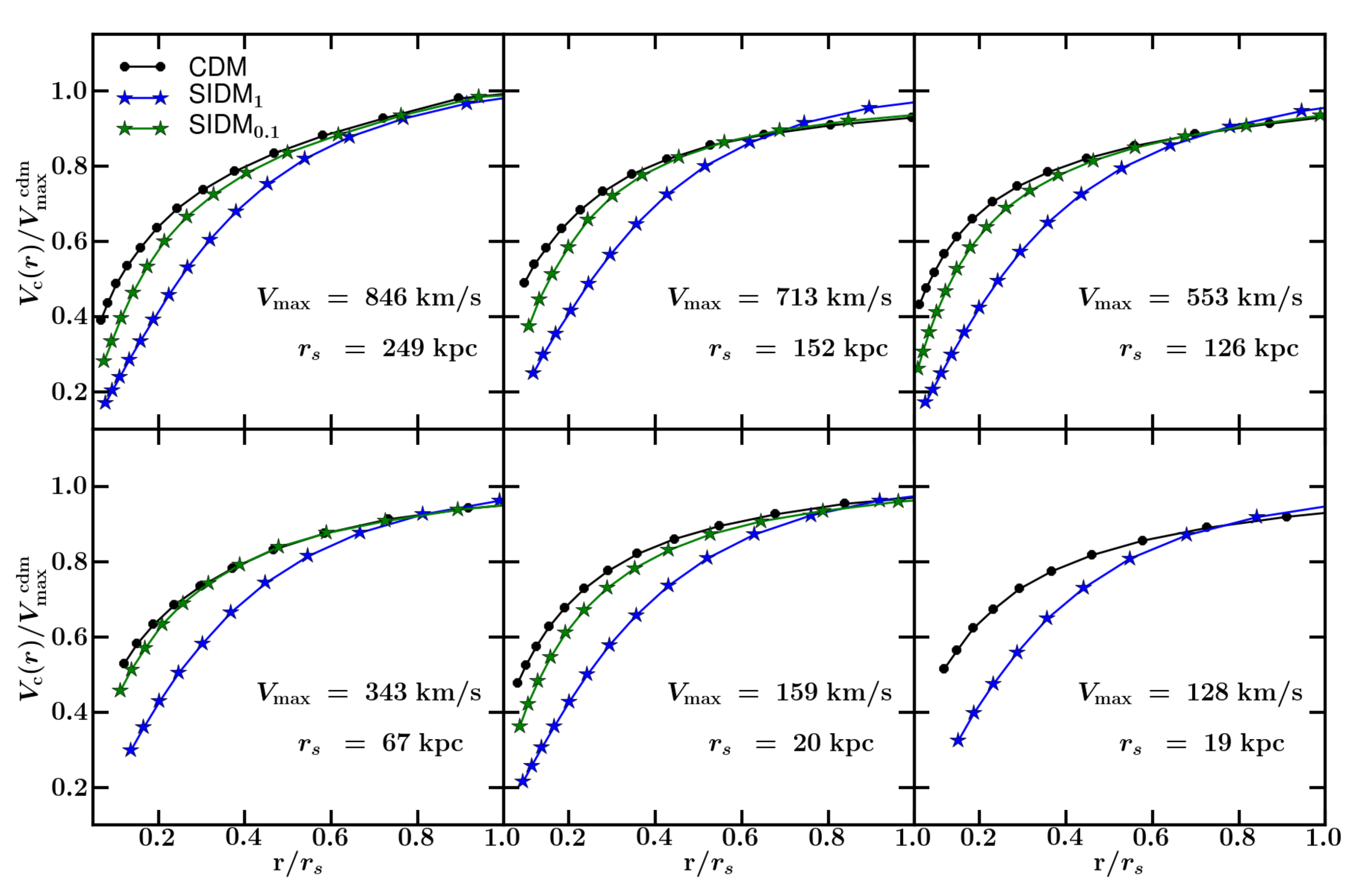


Rocha, Peter, Bullock, Kaplinghat, Garrison-Kimmel, Onorbe, Moustakas 2012

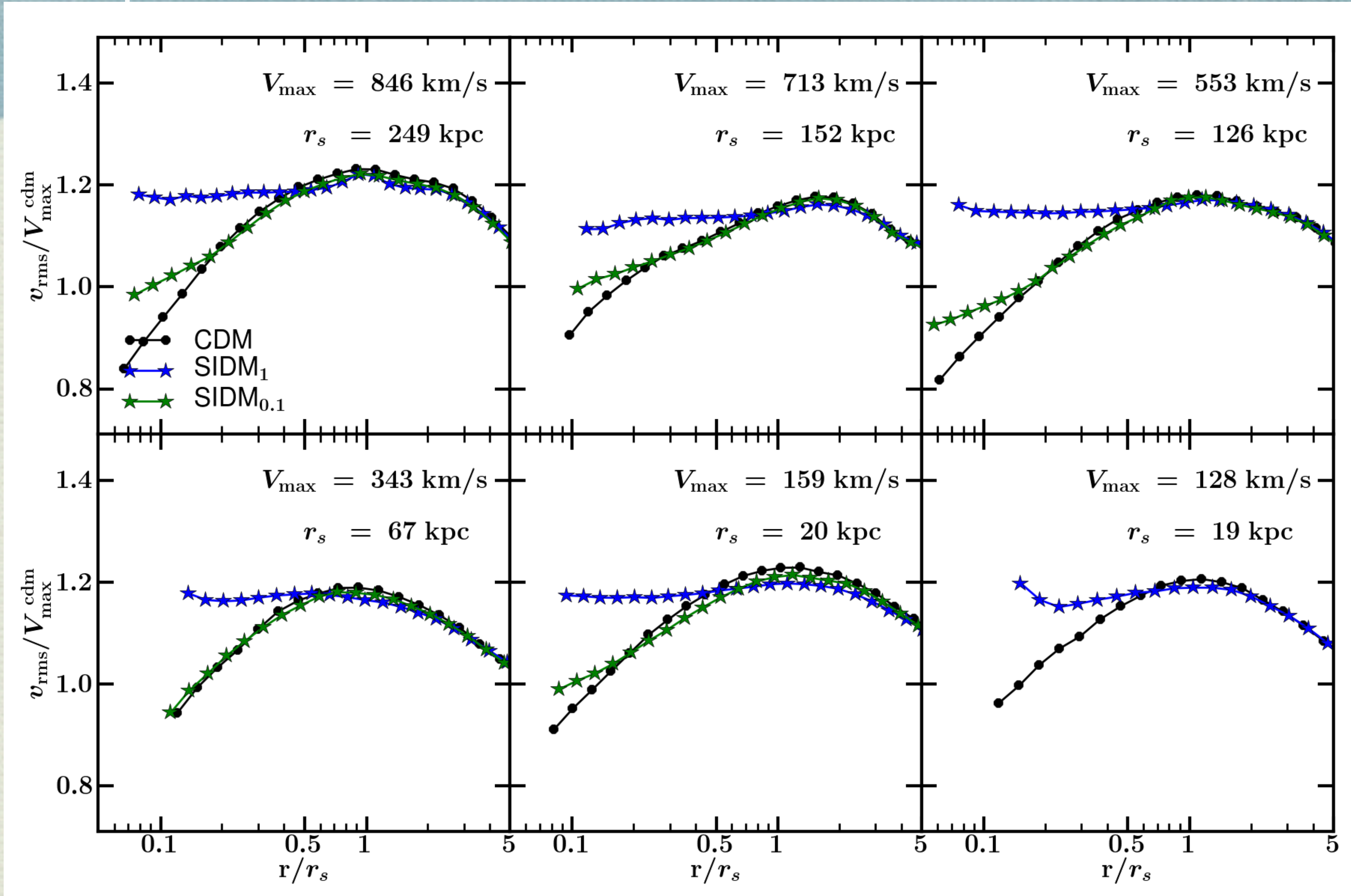


See also Vogelsberger, Zavala and Loeb 2012 for SIDM with v-dependent interaction

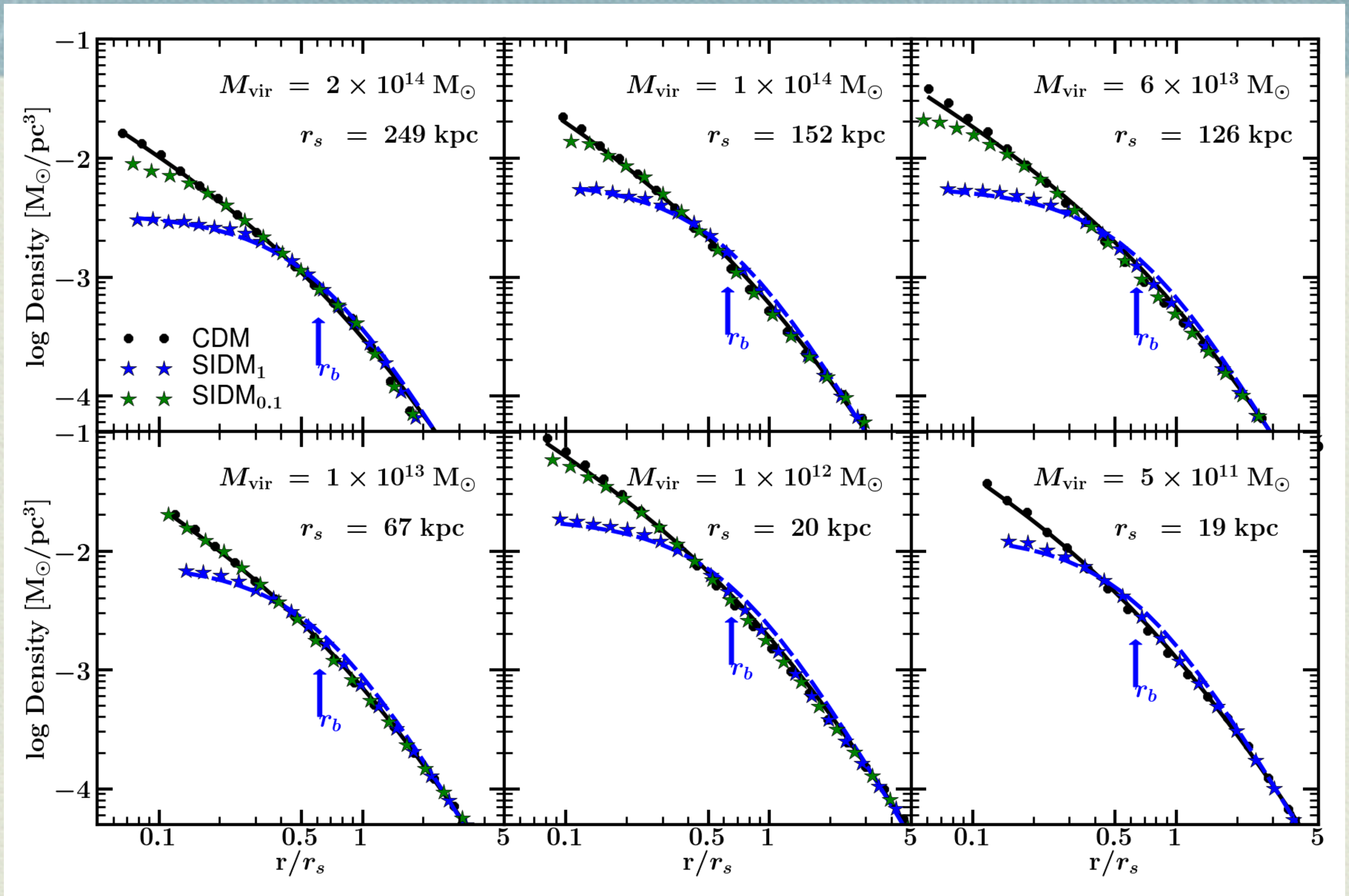
SIDM predictions for rotation speed: 6 example halos



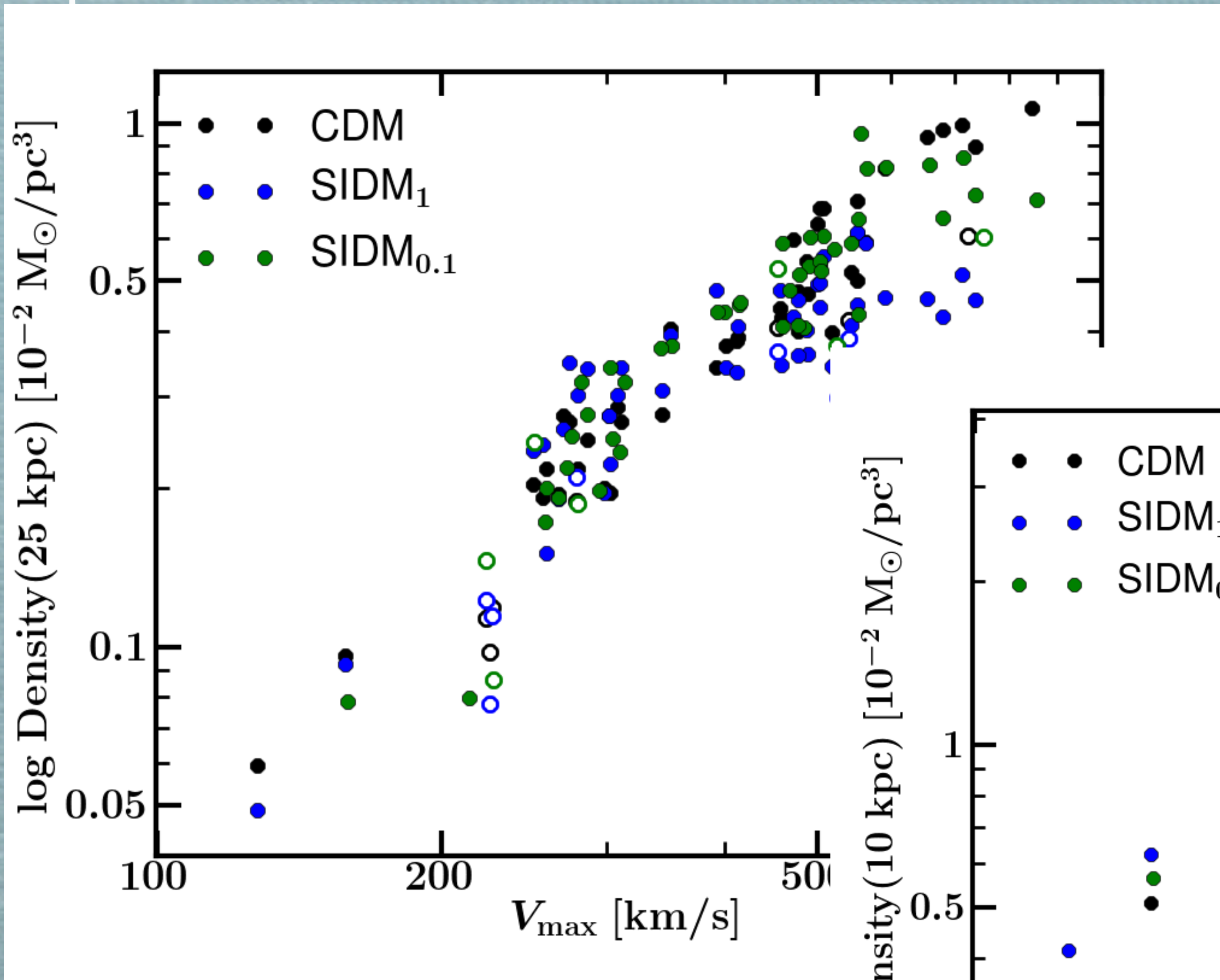
Dark matter temperature profile in SIDM: same 6 example halos as before



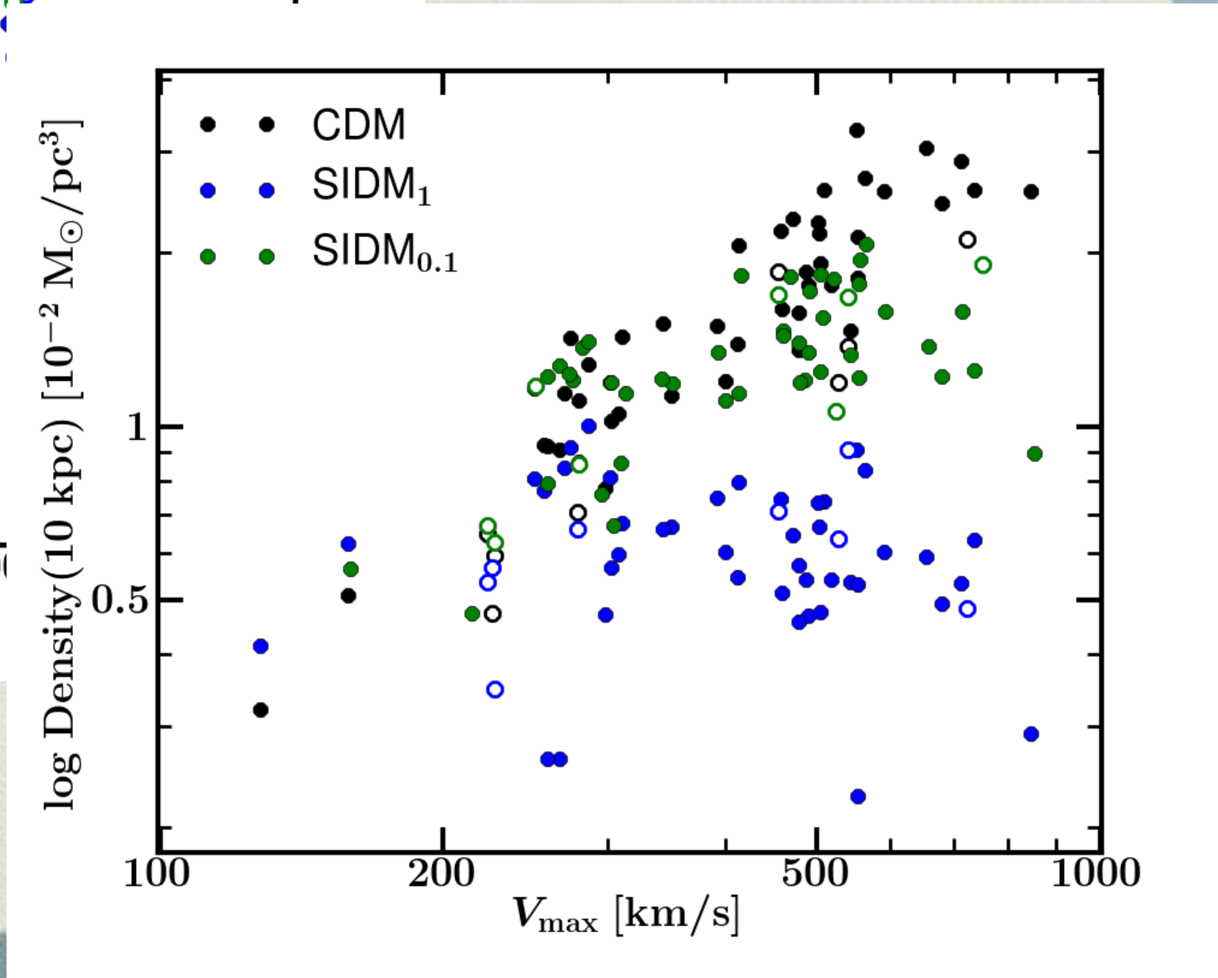
SIDM predictions for density profile: same 6 example halos as before



SIDM predictions for the dark matter density in the inner parts of halos

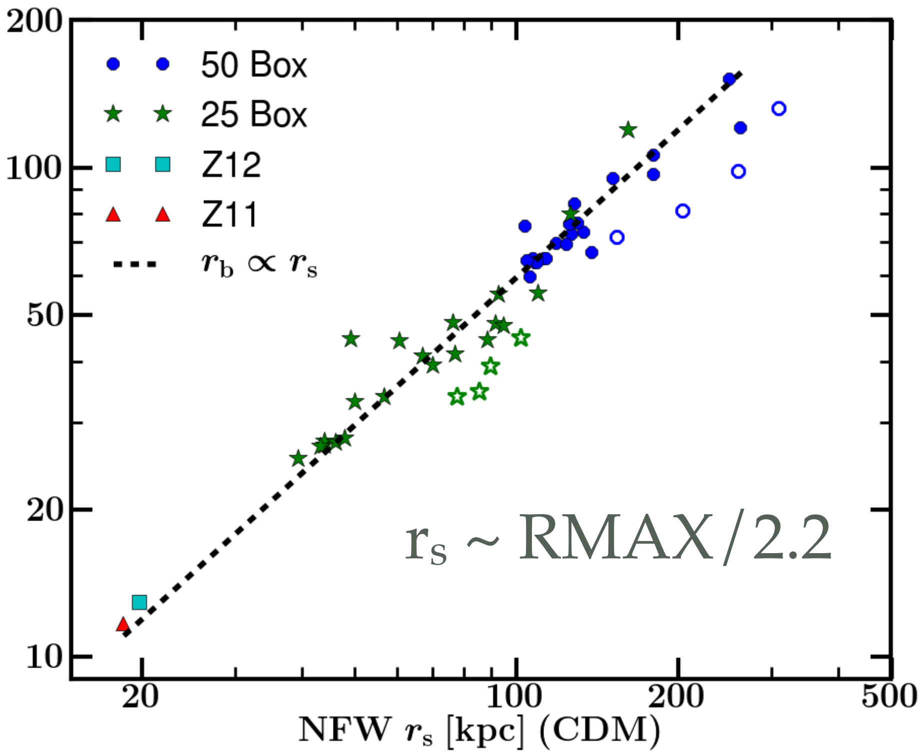


Densities are the way to constrain SIDM!

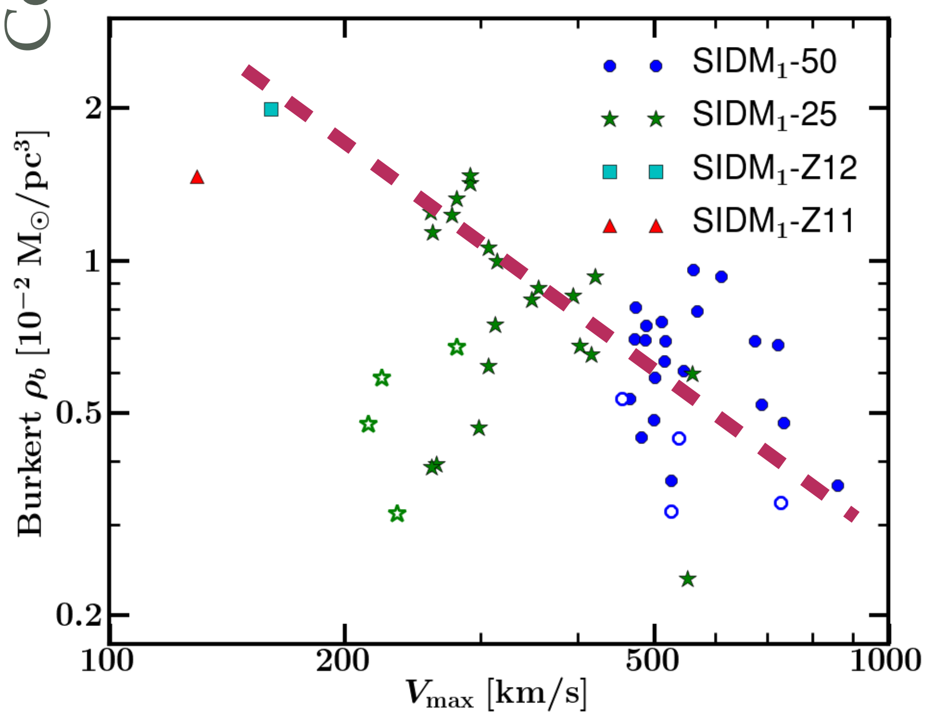


And finally, SIDM scaling relations

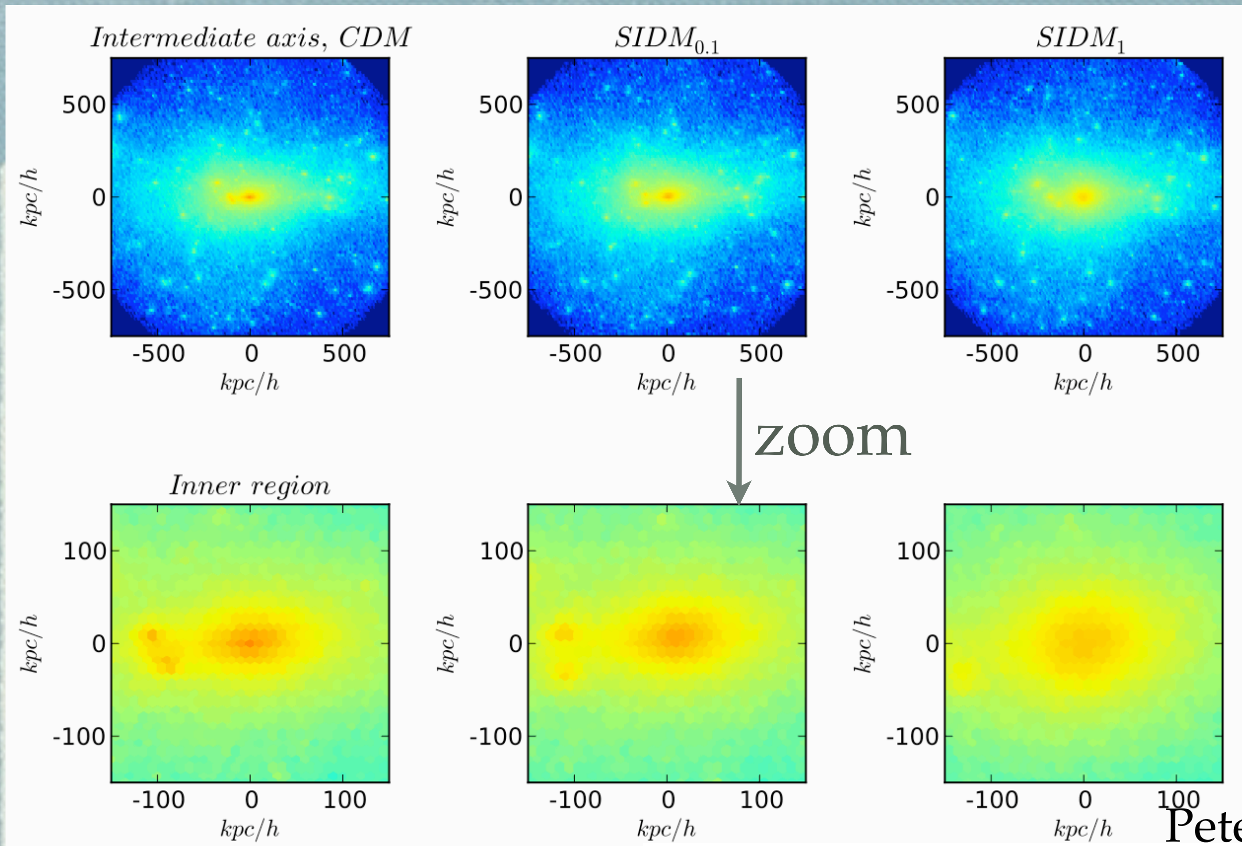
Core radius



Core density



Constraints from shapes of halos? Not really.

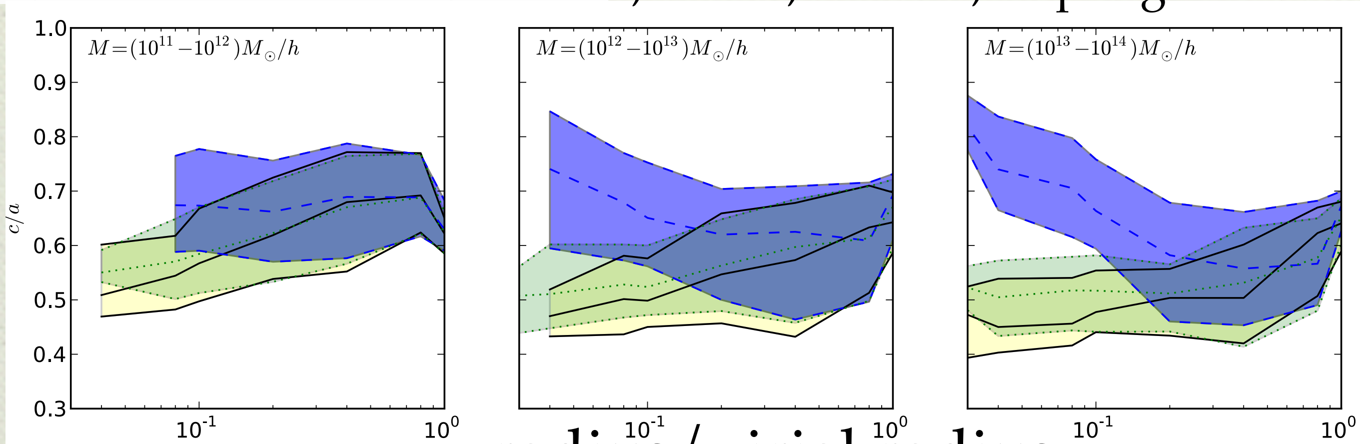


Shapes measured in big ellipticals from X-rays seems to be the best local measure but unlikely to constrain cross sections of order 0.1 cm²/g.

Bullet cluster constraints at about 0.7 cm²/g.

Peter, Rocha, Bullock, Kaplinghat 2012

axis ratio; smallest/biggest



radius / virial radius

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.

- Satellites: SIDM, WDM could explain this.
  - Ultra-faint satellites, especially Segue 1 still needs to looked at carefully (not done yet)
- 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?
  - Didn't discuss Merging clusters.