Where to Look for Dark Matter Weirdness

Dark Matter in Southern California (DaMaSC) - II

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Collaborators

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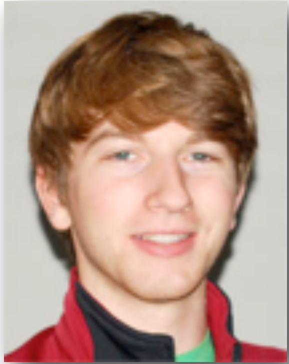


Oliver **Elbert**

Manoj **Kaplinghat**

Annika **Peter**
→ ***The*** Ohio Sate University

Jose **Oñorbe**

→ MPIA Heidelberg

Outline

1. Dwarf Galaxies and the Too Big to Fail Problem

2. Baryon Physics vs. Dark Matter Physics

- SIDM with $\sigma/m \sim (0.5\text{-}1)\ cm^2/g$ can solve the problem
- Feedback probably can't solve it, environment an issue.

3. Baryons + SIDM = Harder than we hoped (but fun)

4. Future directions

Smallest Dwarfs: Great DM Laboratories

$$M_\star \sim 10^6 M_\odot$$

$$\frac{M_{\rm DM}}{M_\star} \sim 50$$

$r_\star \sim 500\mathrm{pc}$

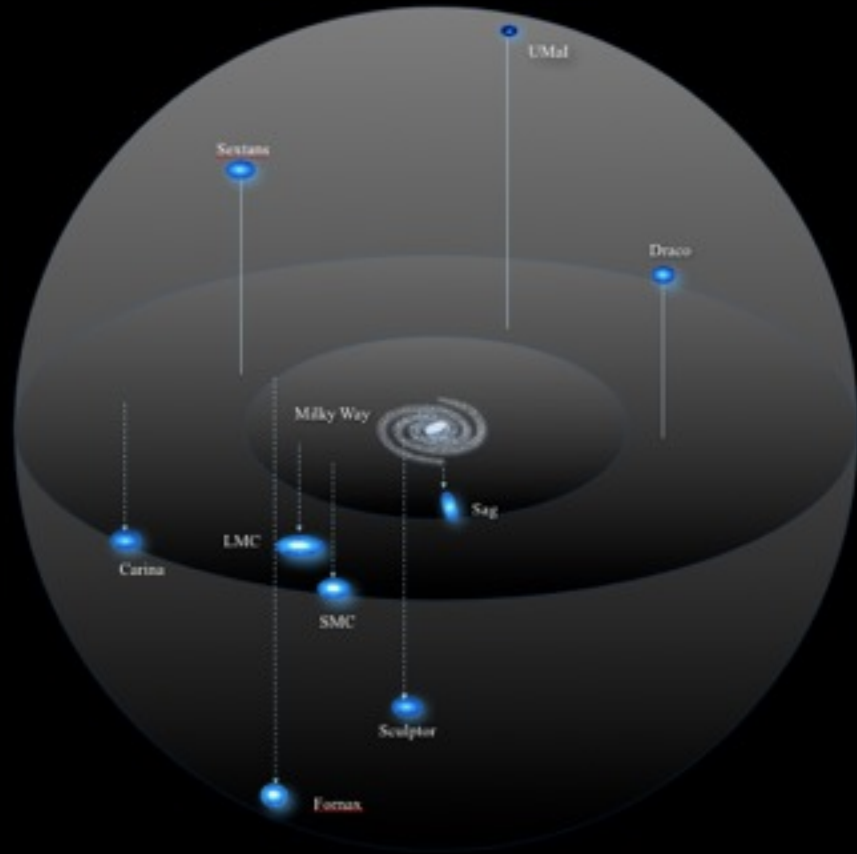
Dark Matter Dominated => Easy to interpret

Very Few Stars => SN Can't Alter DM

Best-studied dwarfs are satellites of MW

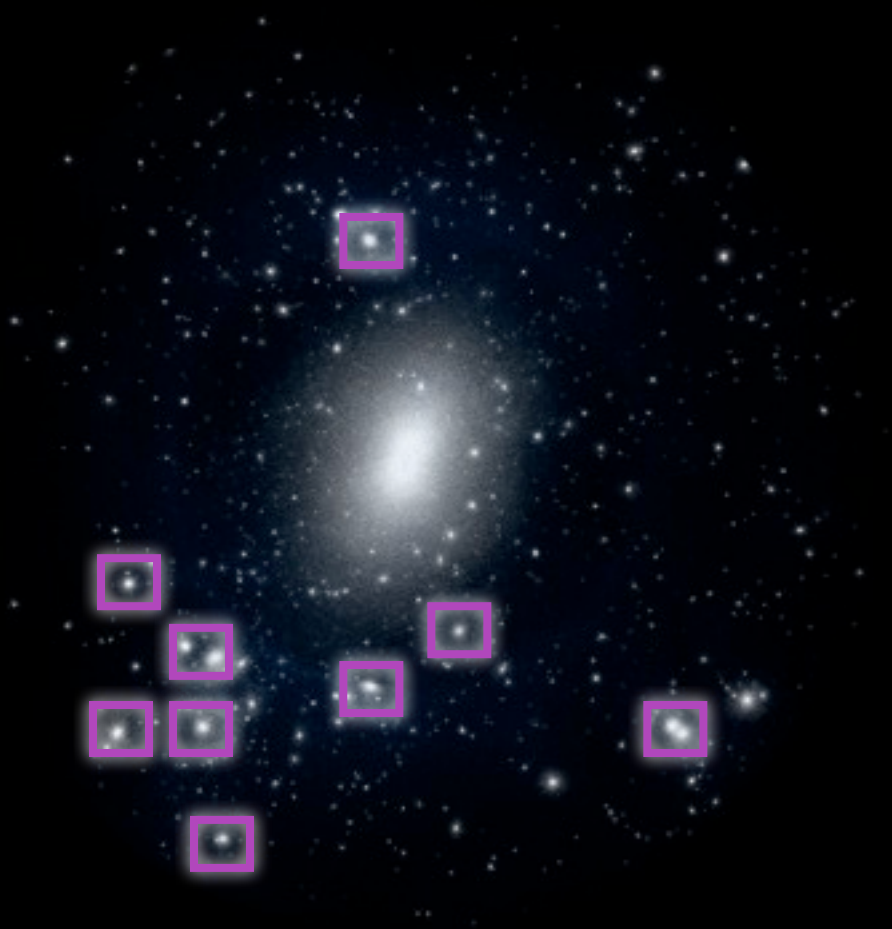
Simulated MW Halo

Garrison-Kimmel, JSB, Boylan-Kolchin



Bright Satellites of the MW
$L>10^5$ Lsun

Biggest subhalos = brightest satellites?



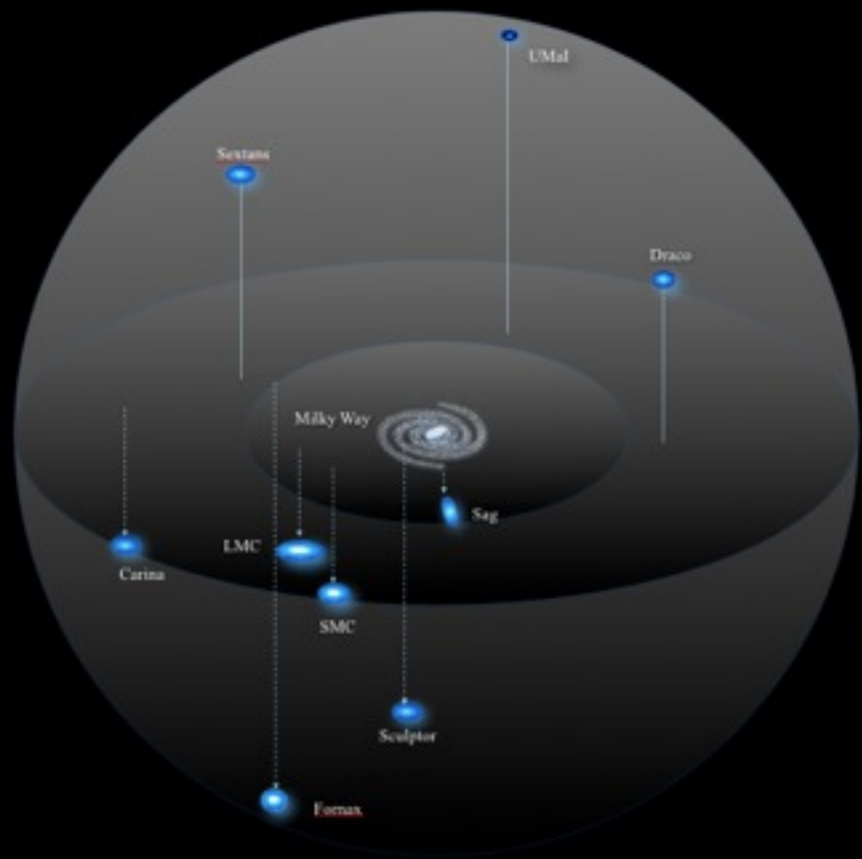


Image: Garrison-Kimmel

How do the masses compare?

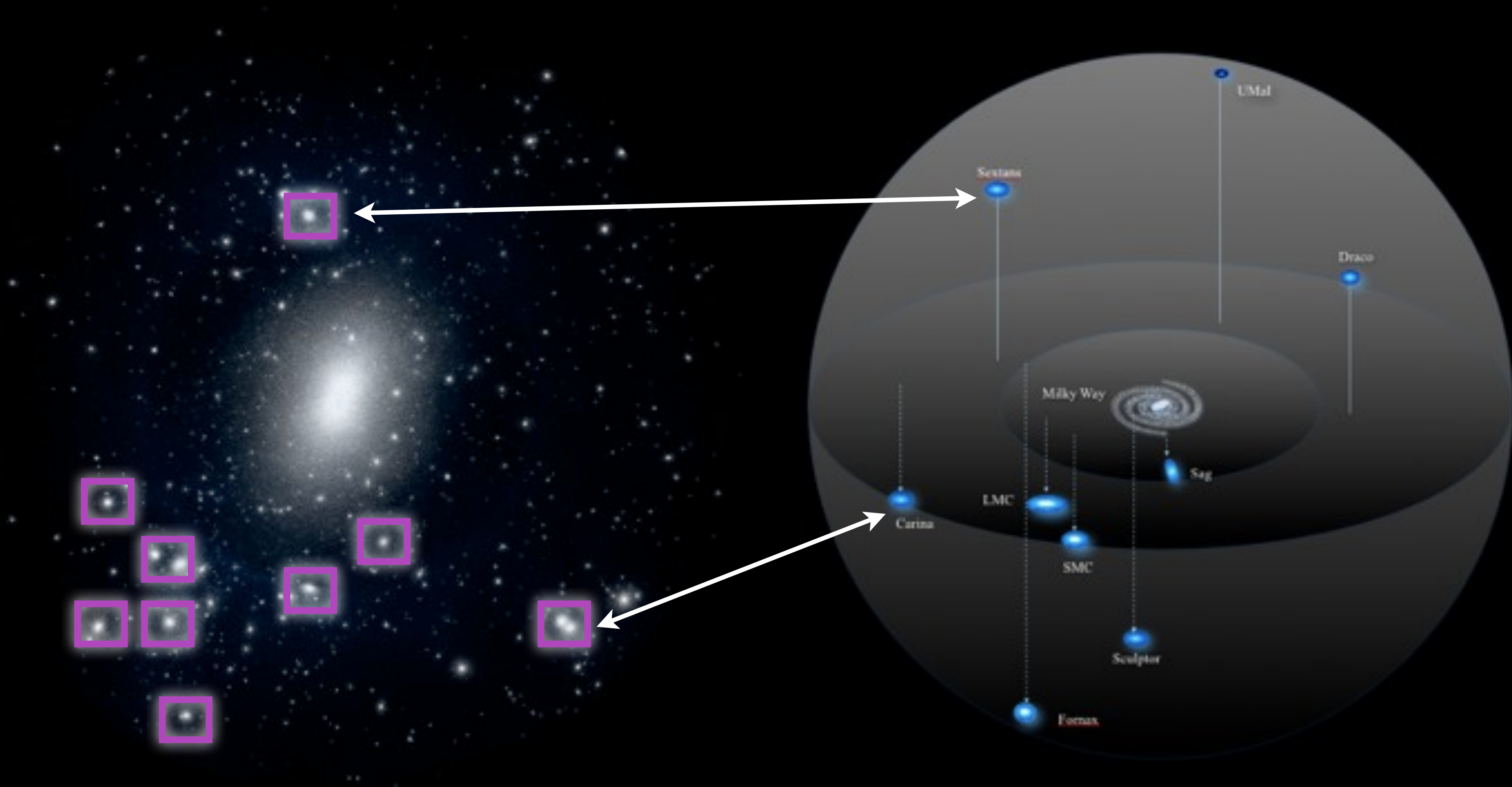
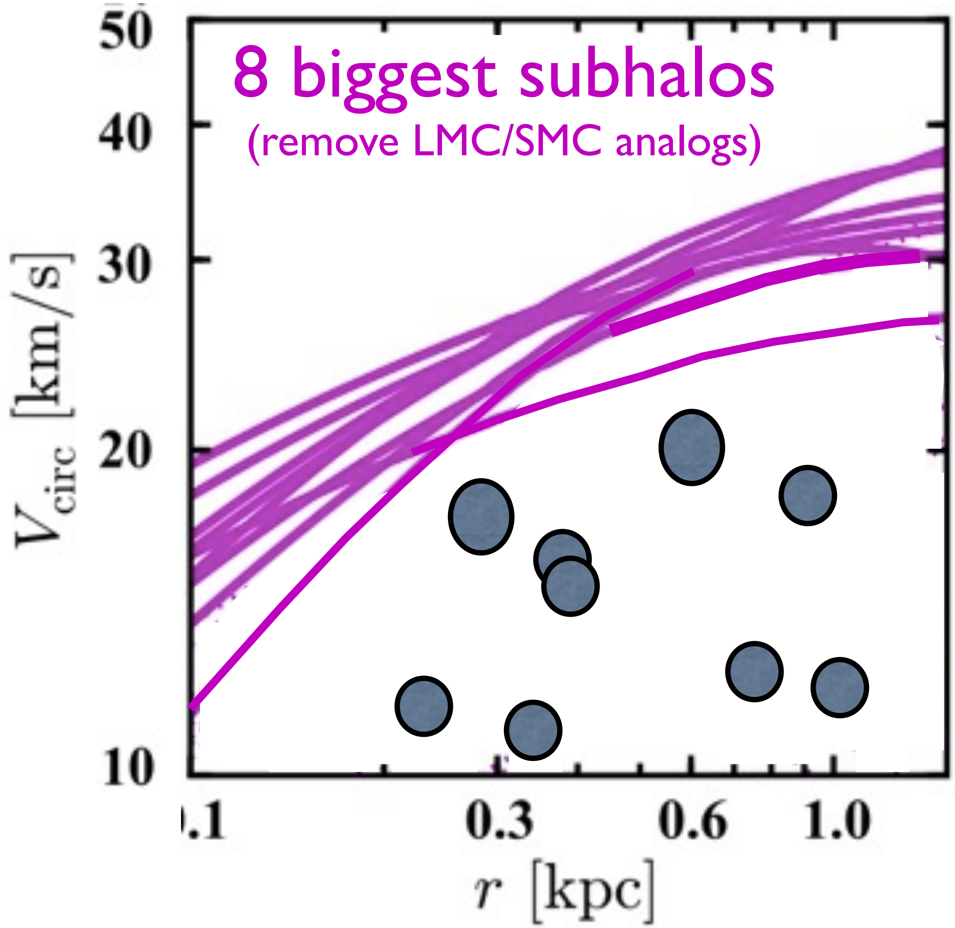
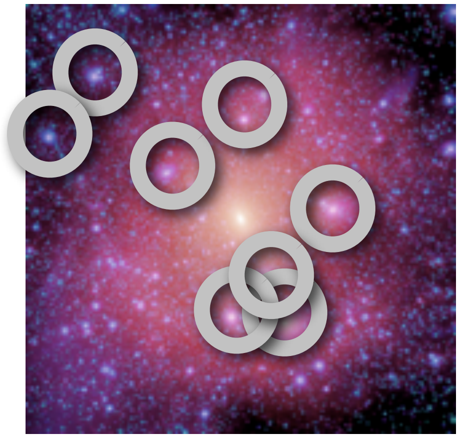


Image: Garrison-Kimmel

All bright MW dSphs ($L>10^5\ L_{sun}$)

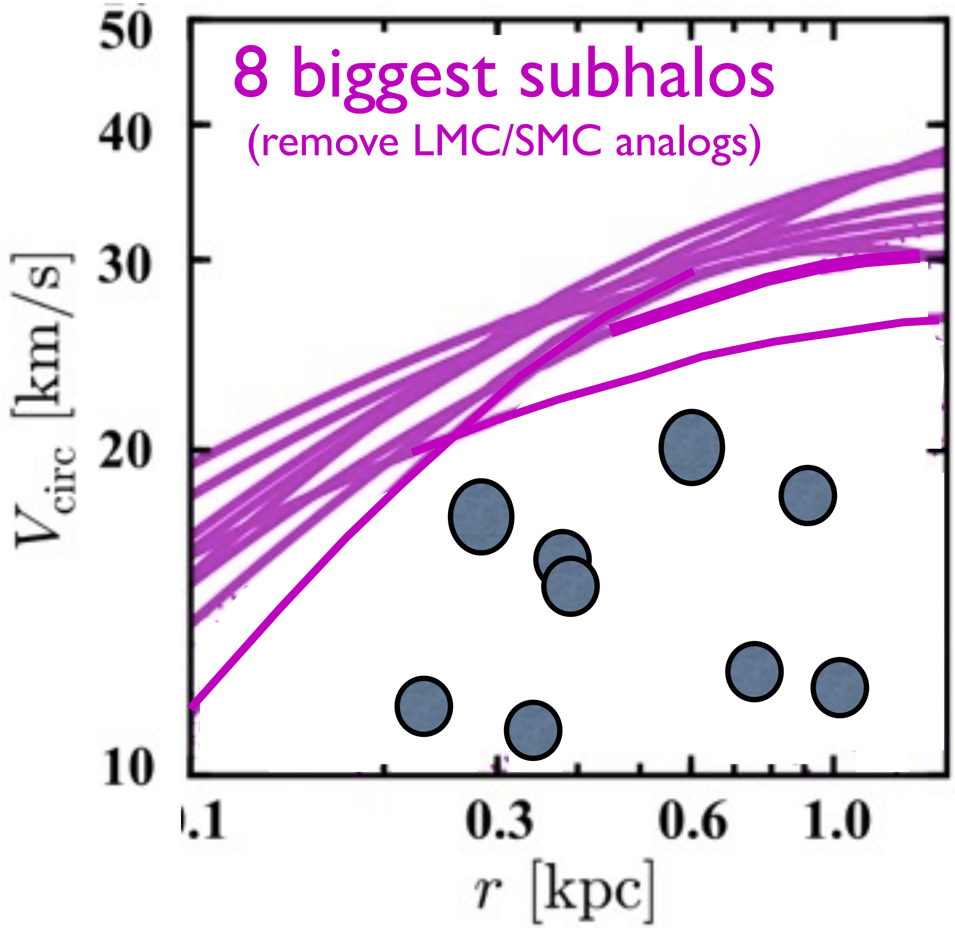


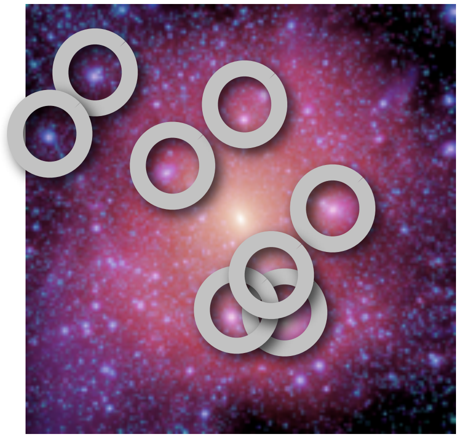


8 biggest subhalos are too dense to host ANY of MW dSph satellites

Boylan-Kolchin, JSB, Kaplinghat 2011,2012

Too Big to Fail Problem





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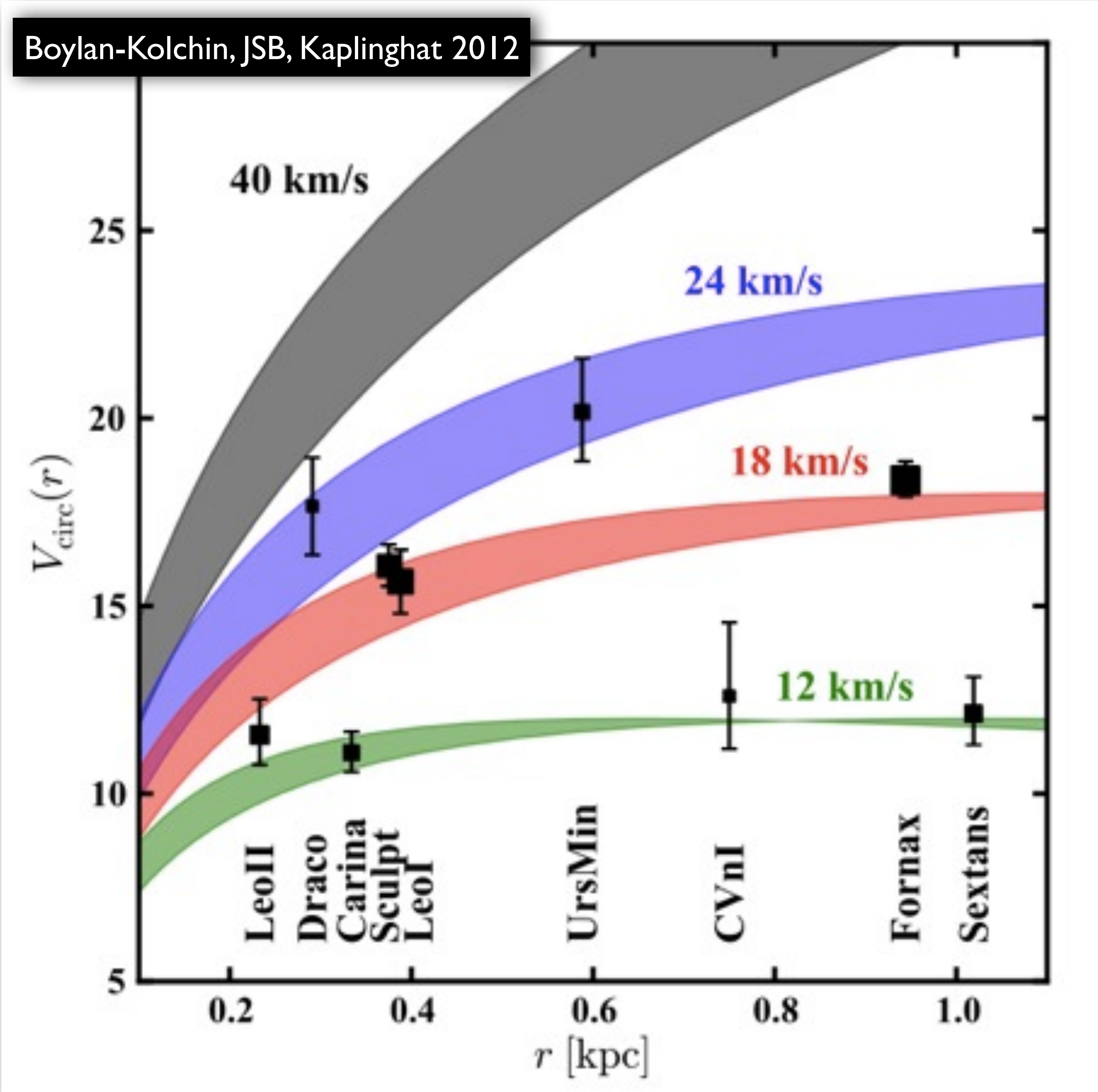
Summary of the Too Big To Fail problem:



Expect 5-40 subhalos with V_{max} >25 km/s

(from 48 simulations)

Garrison-Kimmel et al. in prep

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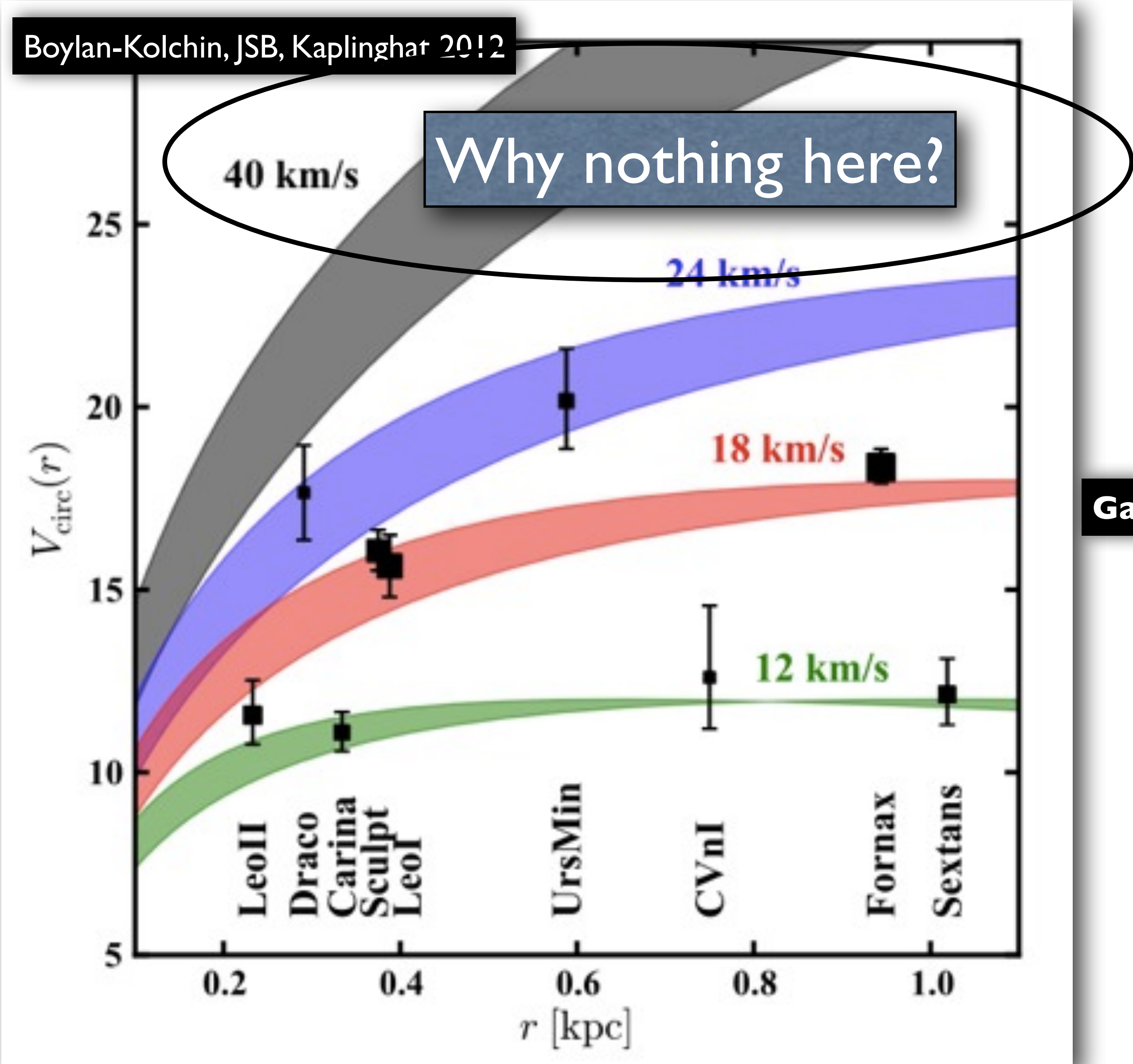

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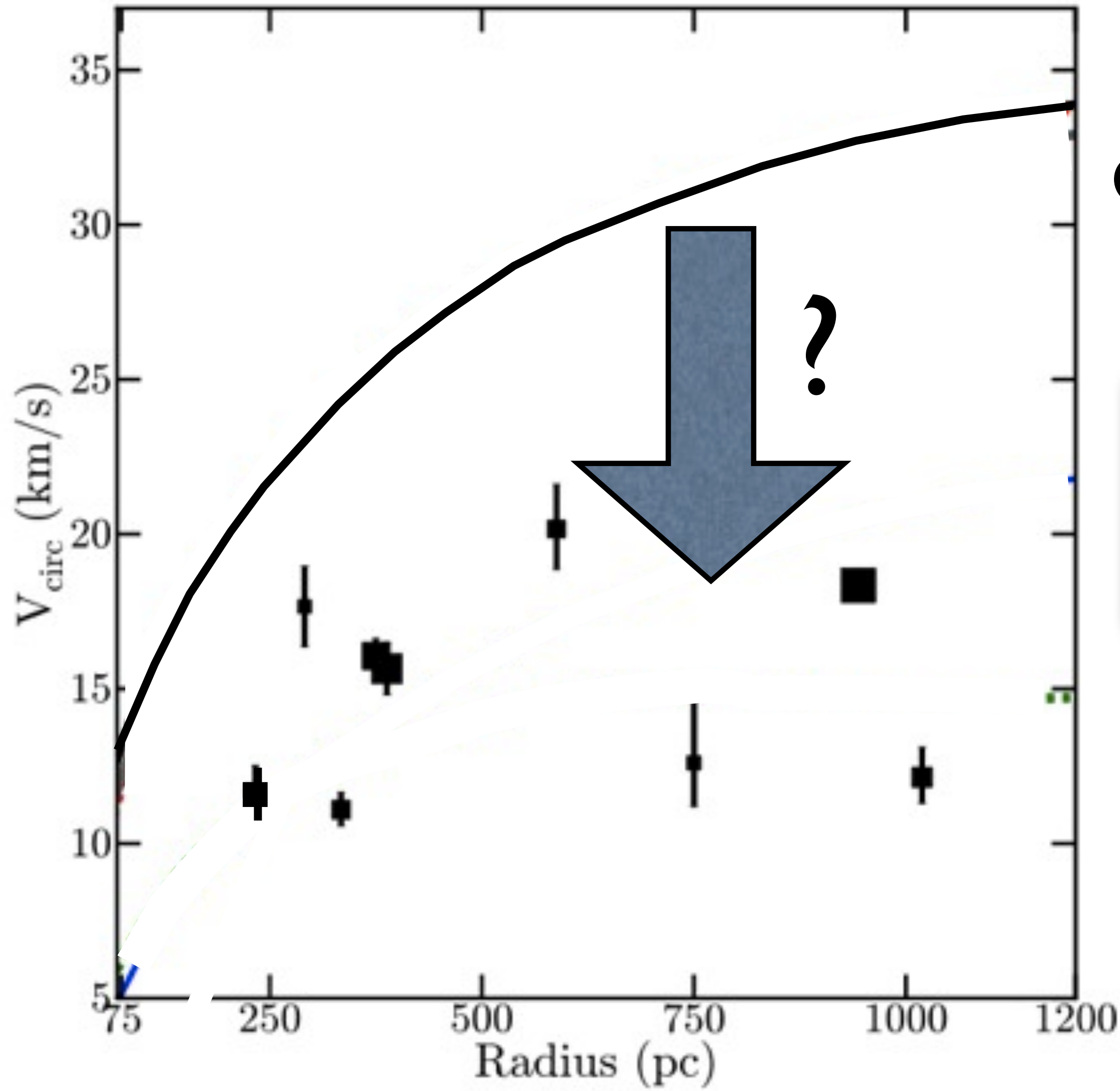
What Can Baryons Do?



Consider a $M_{*} \sim 10^6\ M_{sun}$ dwarf galaxy

What does it take to remove enough DM?

Basic Energy Argument Against SN Feedback

$$M_\star \sim 10^6 M_\odot \Longleftrightarrow \Delta M_{\rm DM} \sim 5 \times 10^7 M_\odot$$

Must remove ~50 times more dark matter than mass in stars!

Energy Required: $> 10^{55}\,\mathrm{ergs}$

Exceeds every supernovae that has gone off **coupled directly** to the dark matter.

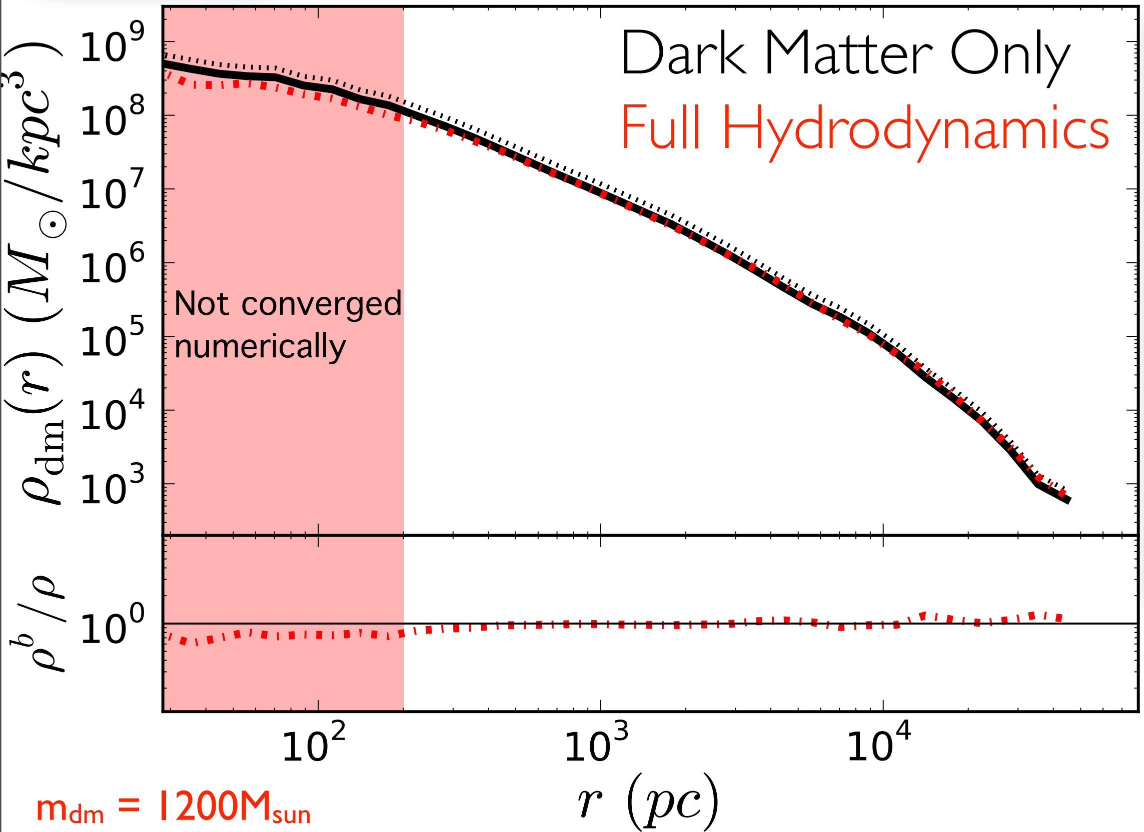
Penarrubia et al. 2012; Garrison-Kimmel et al. 2013

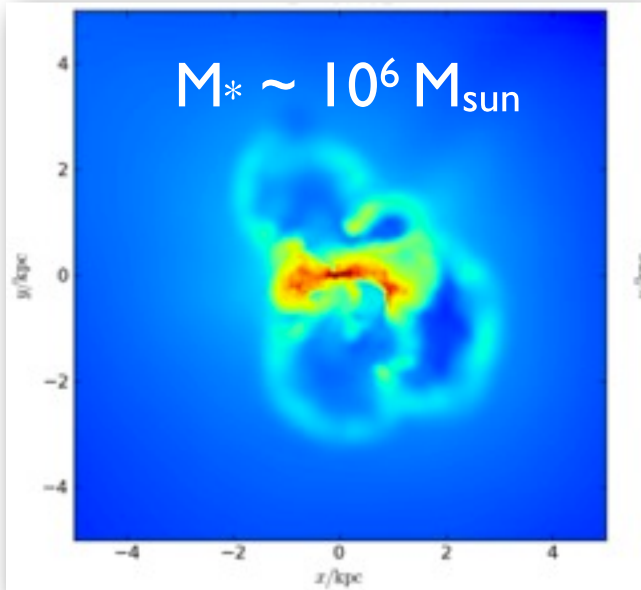
Jose Oñorbe

Oñorbe et al. (in prep)

Minimal change in DM density

Use “P-GADGET” SPH
- Overcomes most standard SPH issues
- Feedback of **Hopkins,** Quartaert, and Murray (2012)





m_{dm} = 1200M_{sun}
m_{gas} = 250M_{sun}
ϵ_{dm} = 40pc

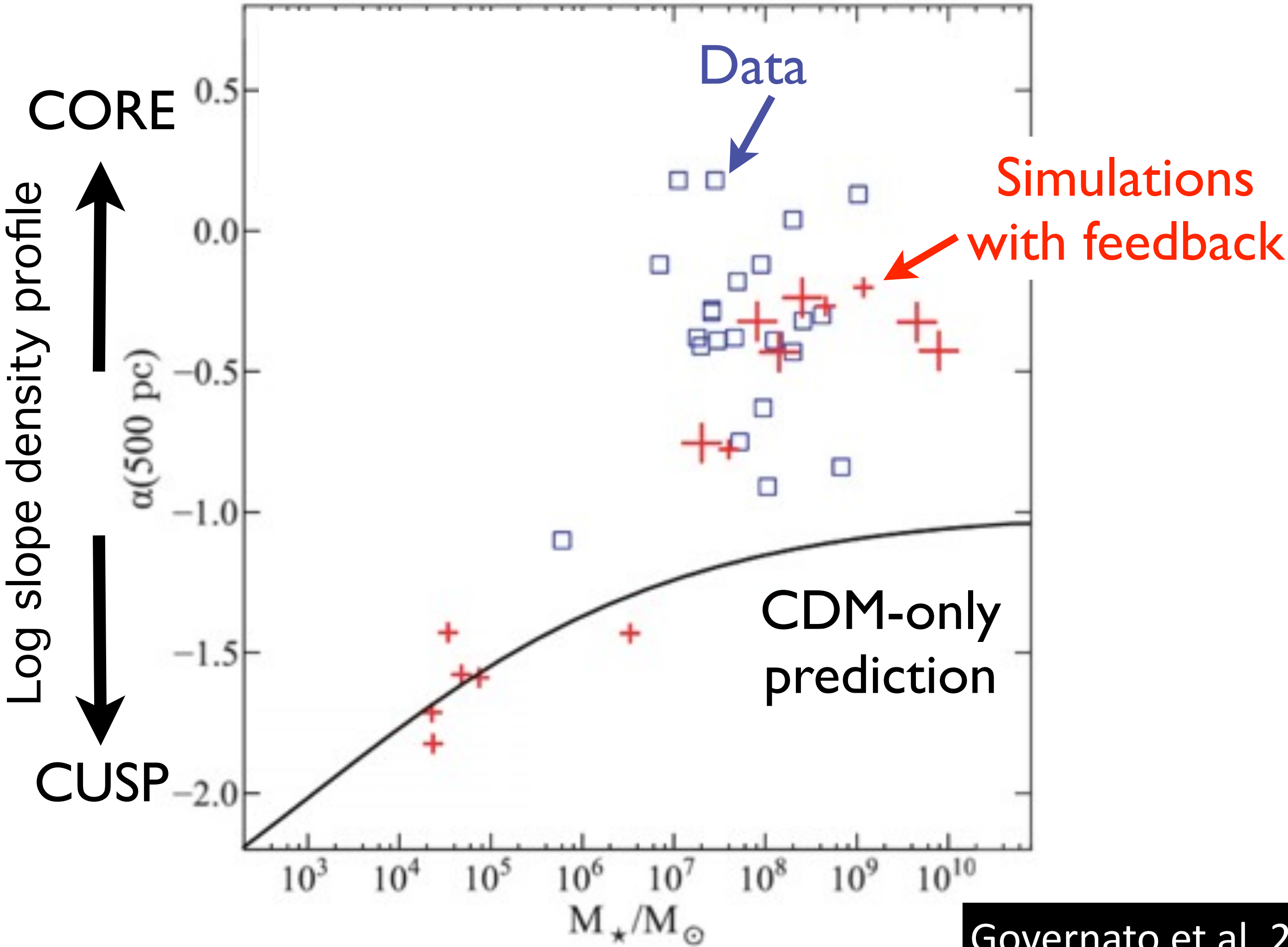
Z=0 Stats:

Abundance Matching [GOOD]

Fe/H ~ -2.5 [GOOD]

M_{gas}/M_* ~ 0.1 [OK]

Baryonic Feedback: Not so effective for M* < 10^7



Governato et al. 2012

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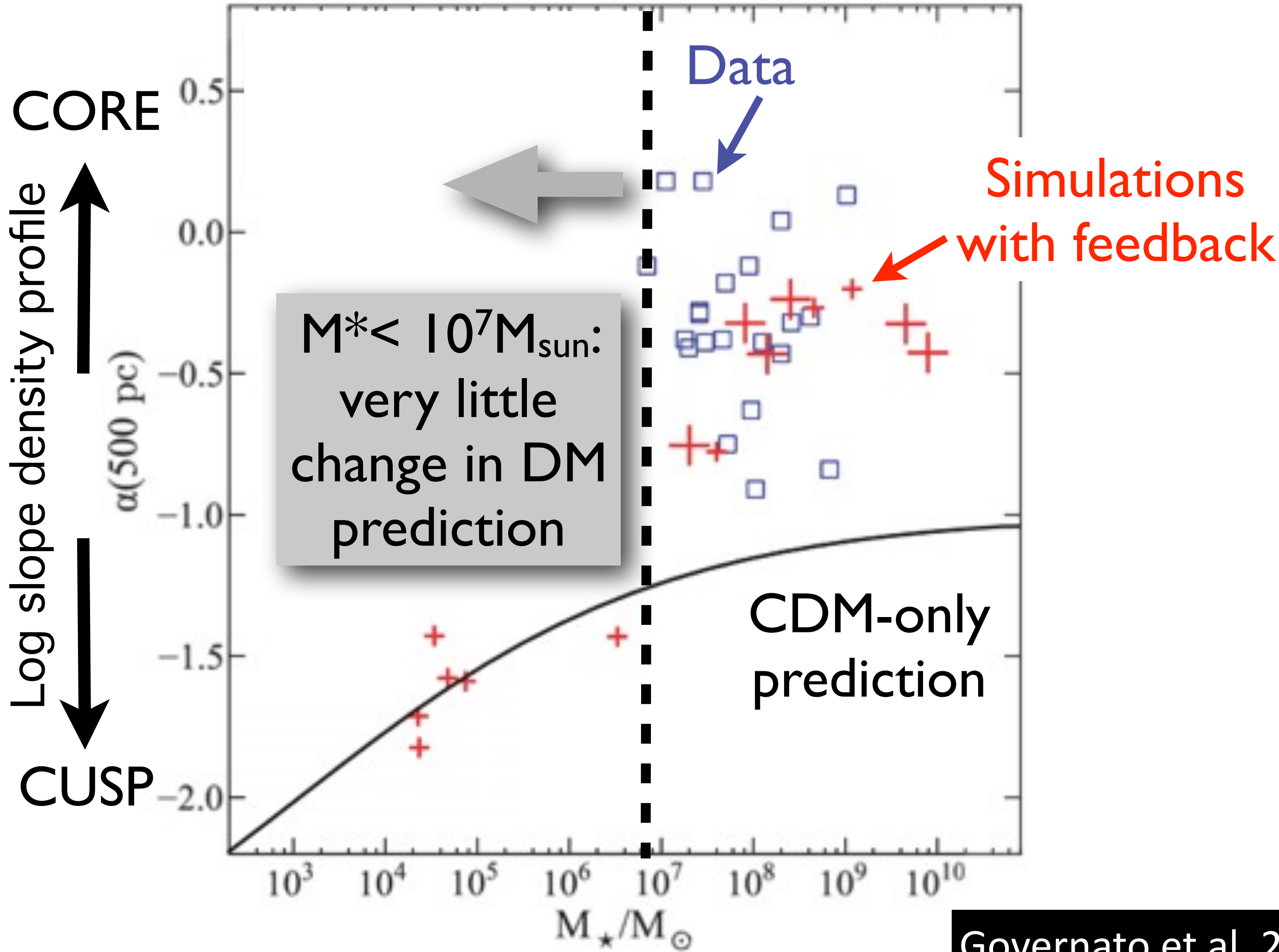


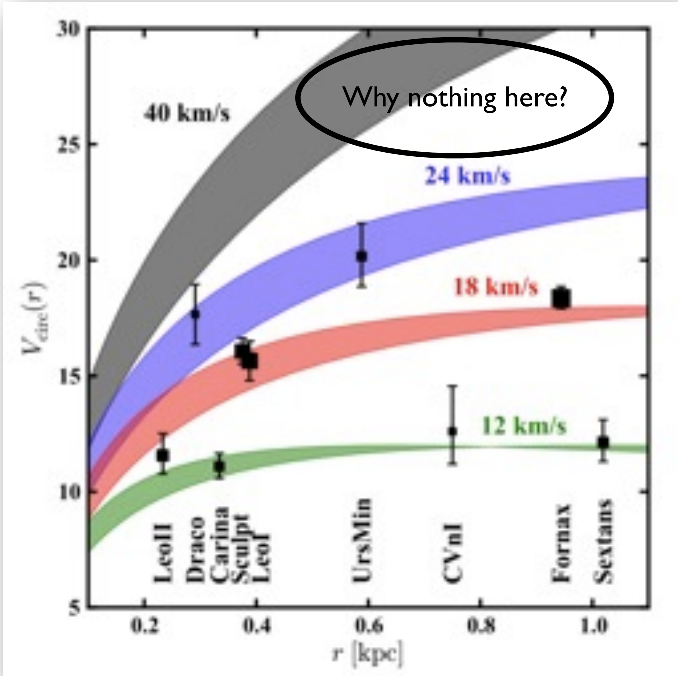
Governato et al. 2012

Is there a baryonic solution to Too Big to Fail?

SN Feedback alone: No

- **Not Enough Energy**: hard to affect densities with < $10^6 M_{sun}$ of stars (<10^4 SN)

Garrison-Kimmel et al. 2013; Governato et al. 2012; Penarrubia et al. 2012

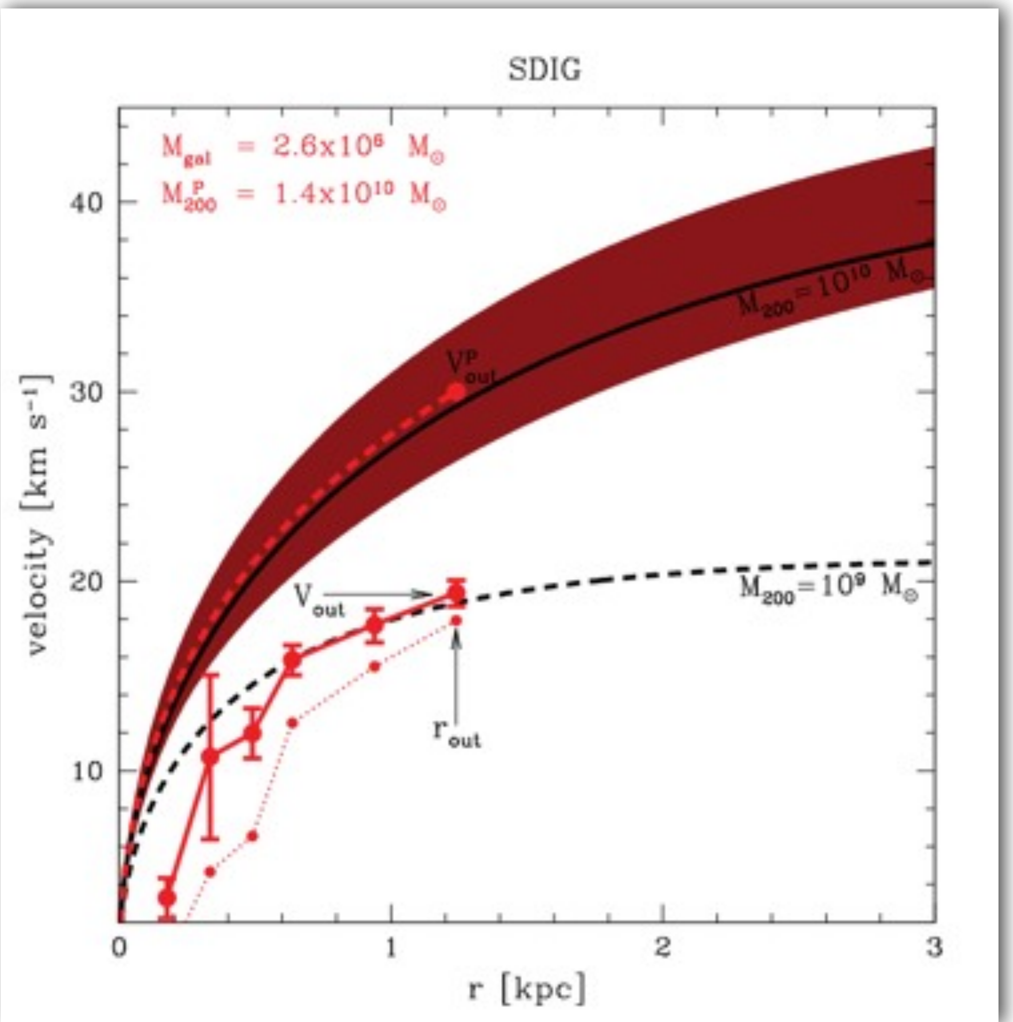


Environment: best bet

- Tidal forces (extra from disk) and ram-pressure stripping provide additional sources of energy to remove DM

Brooks & Zolotov 2012; Zolotov et al. 2012; Arraki et al. 2012

What's next?
Extend these studies to the field (no ram-pressure or tides)



Ferrero, Abadi, Navarro, Sales, & Gurovich 2012

- Examine rotation curves of field dwarfs with M_{gal}~10^{6-7} M_{sun}

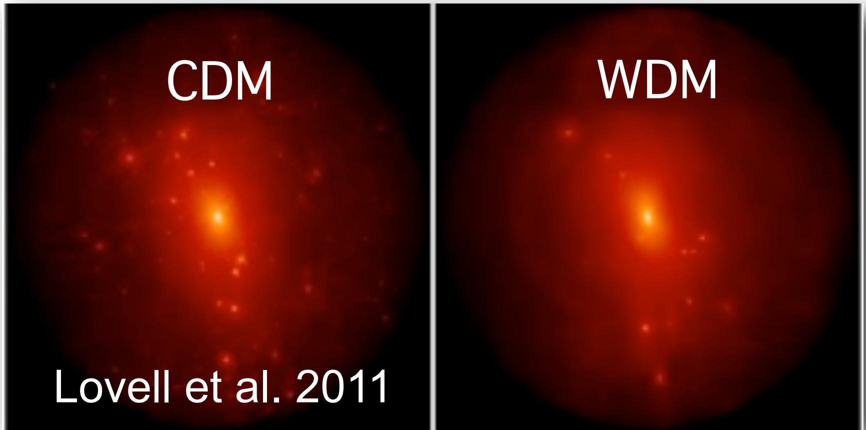
- **Same problem**: not dense enough

- Hard to reconcile with DM halo mass function + observed lum function

Abstract:
.... Resolving this challenge seems to require new insights into dwarf galaxy formation, or perhaps a radical revision of the prevailing paradigm.

Beyond Cold Dark Matter?

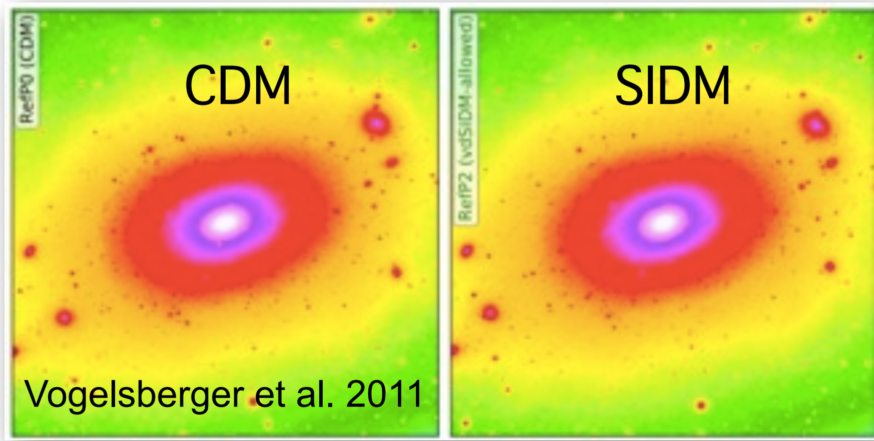
Warm Dark Matter:



$$m_{\rm dm} \sim {\rm keV}$$

Lovell et al. 2011

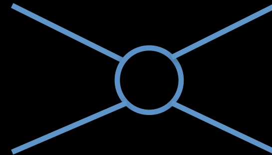
Self-interacting Dark Matter:



$$\sigma / m_{\rm dm} \sim 1\,{\rm cm}^2/g$$

Vogelsberger et al. 2011, 2012;
Rocha et al. 2012; Peter et al. 2012;
Spergel & Steinhardt (2000)

Simulating Self-interacting DM



Scattering rate: $$\Gamma = \rho_{\rm dm} \left(\frac{\sigma}{m}\right) v_{\rm rms}$$

For now: Elastic, Velocity Independent, Isotropic

Interesting things happen when $\Gamma \sim H_0$

$$\Rightarrow \quad \frac{\sigma}{m} \sim 1\,{\rm cm}^2/g$$

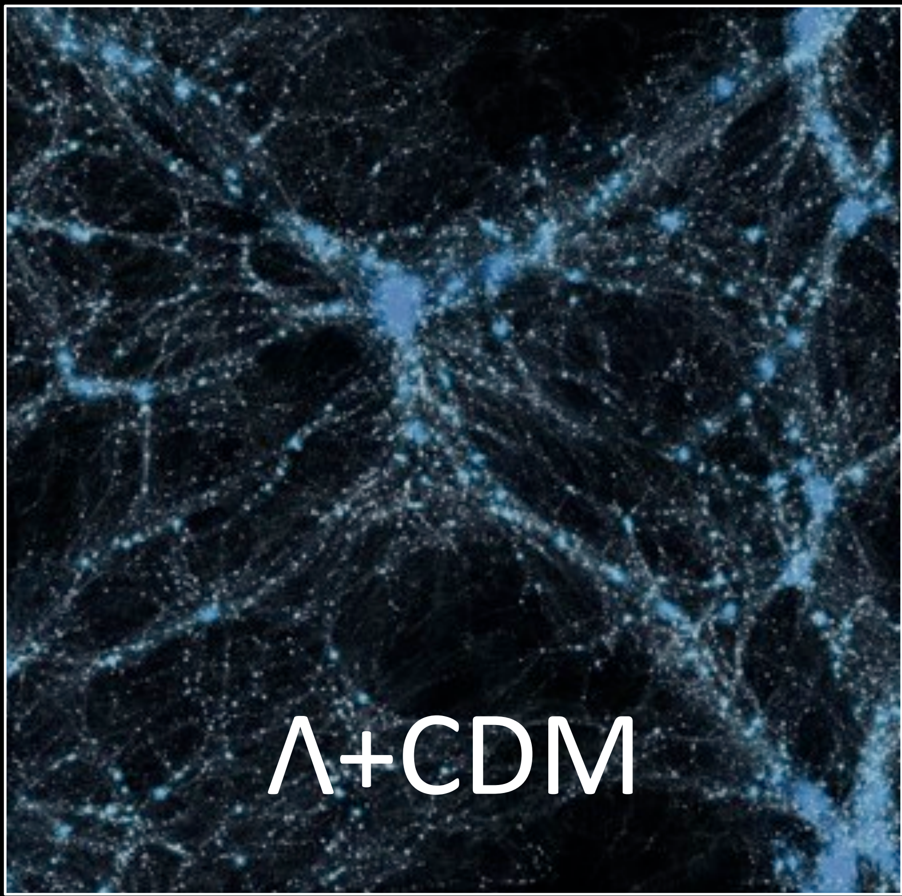
Miguel Rocha

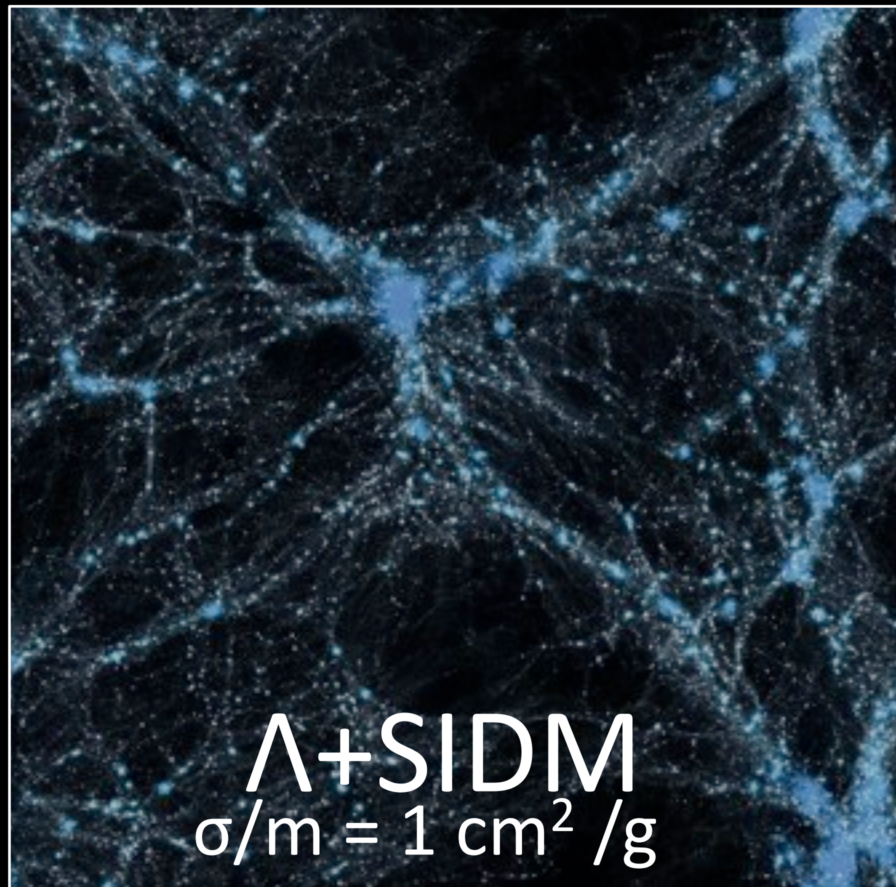
Annika Peter

Manoj Kaplinghat

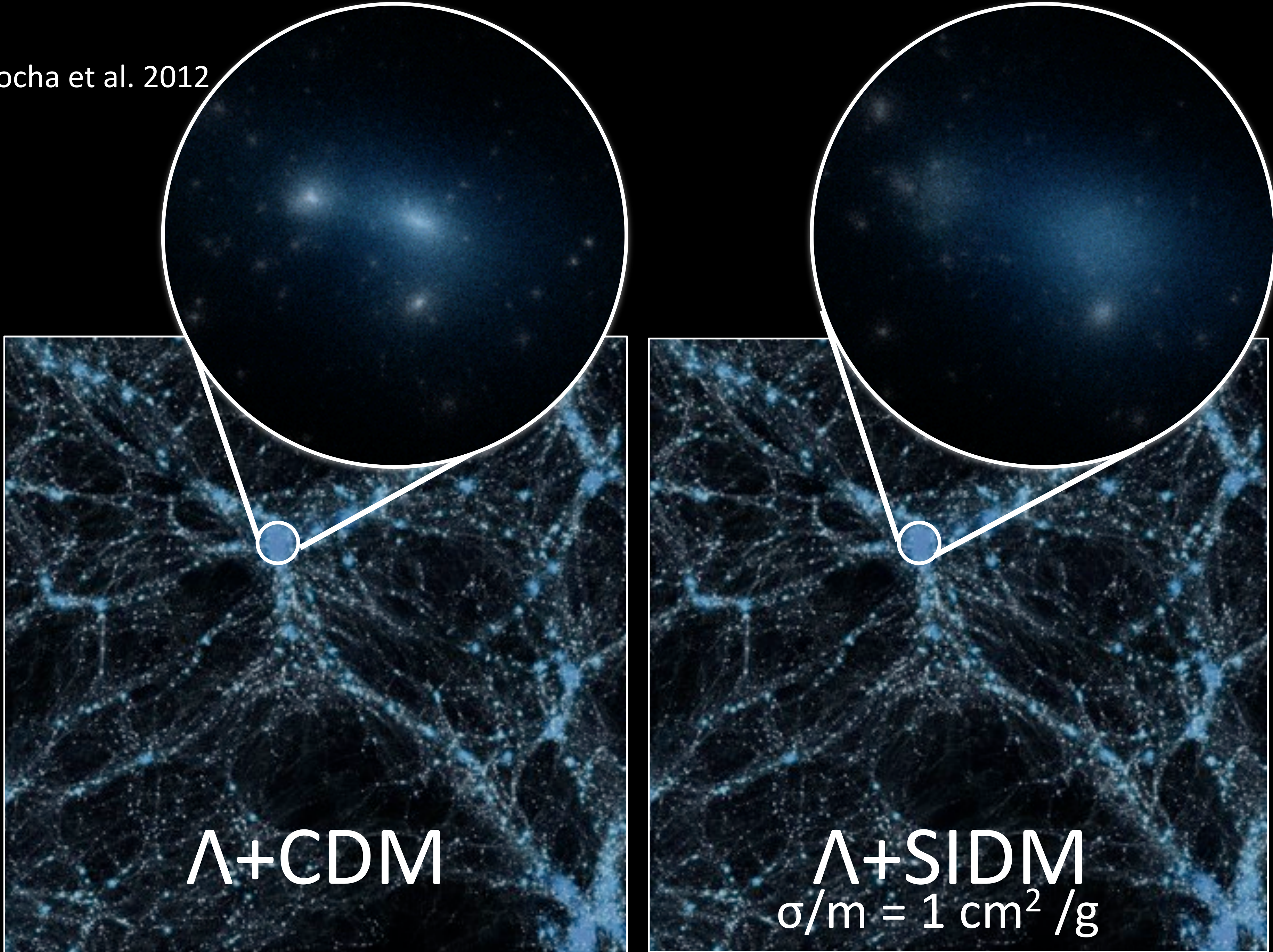
Rocha et al. 2012

Identical large-scale structure





Rocha et al. 2012



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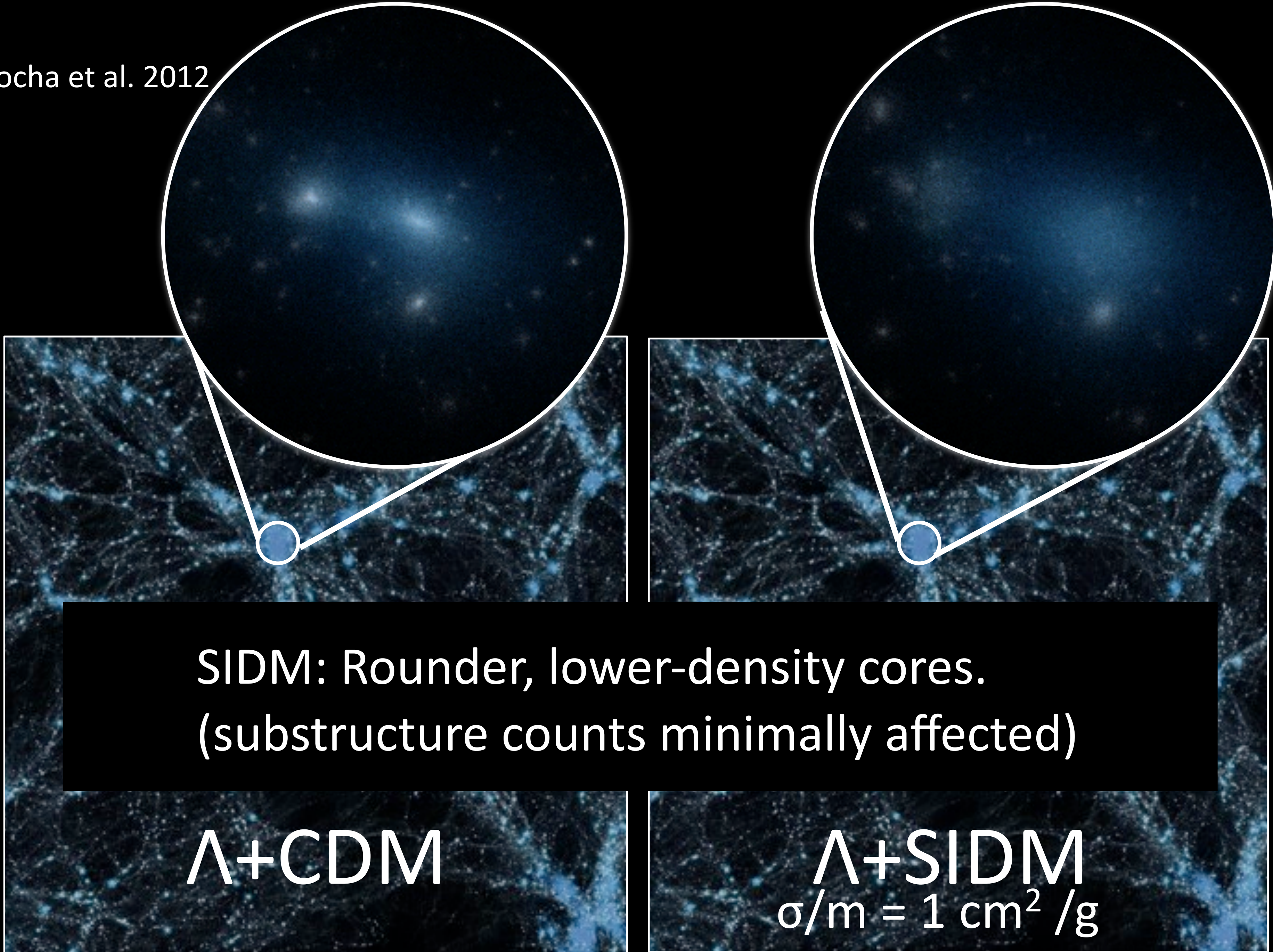
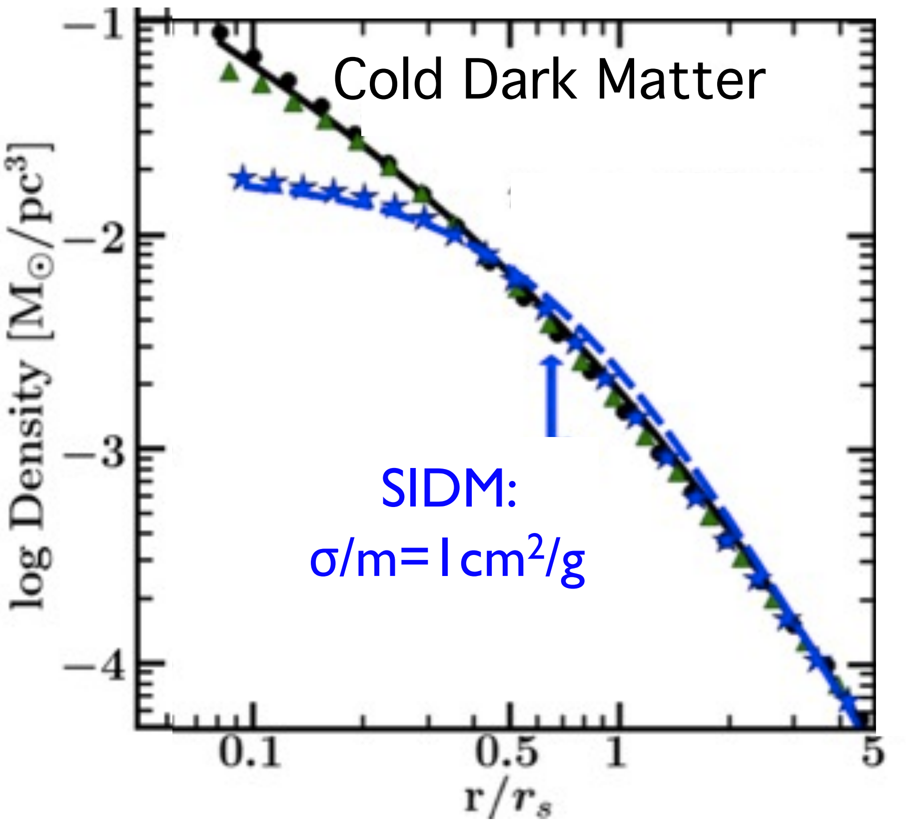


SIDM: Rounder, lower-density cores.
(substructure counts minimally affected)

SIDM Makes Cored Halos

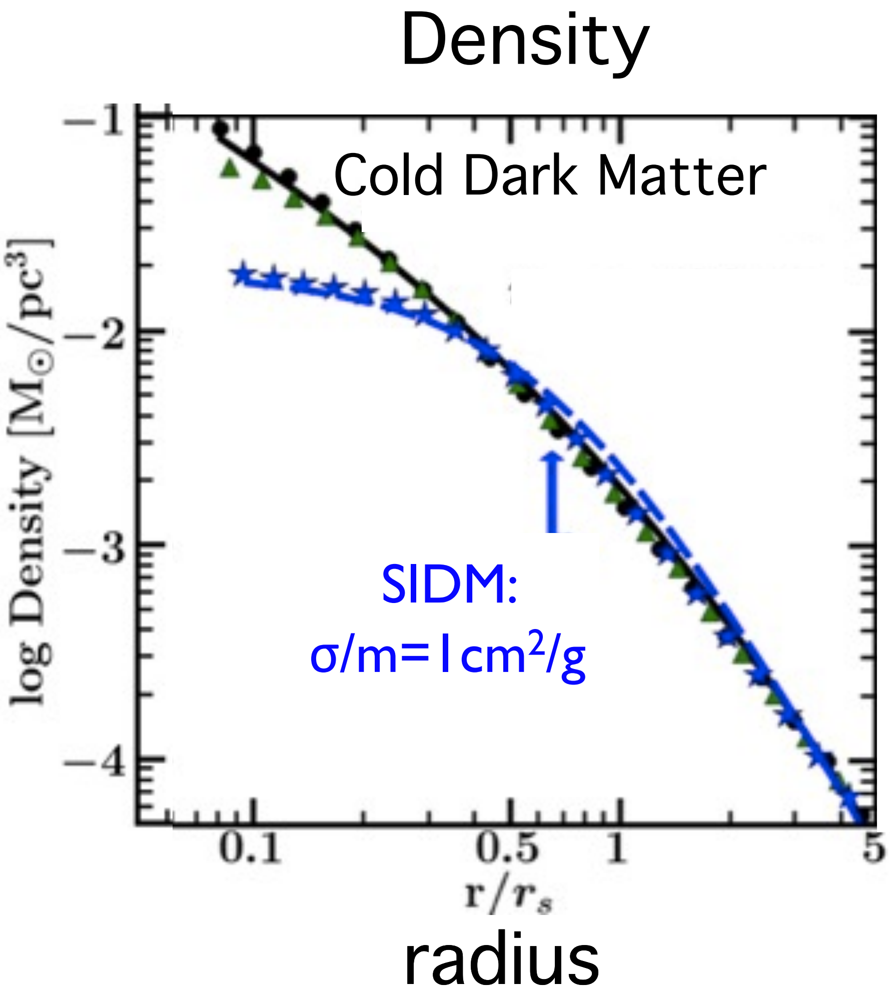
Density

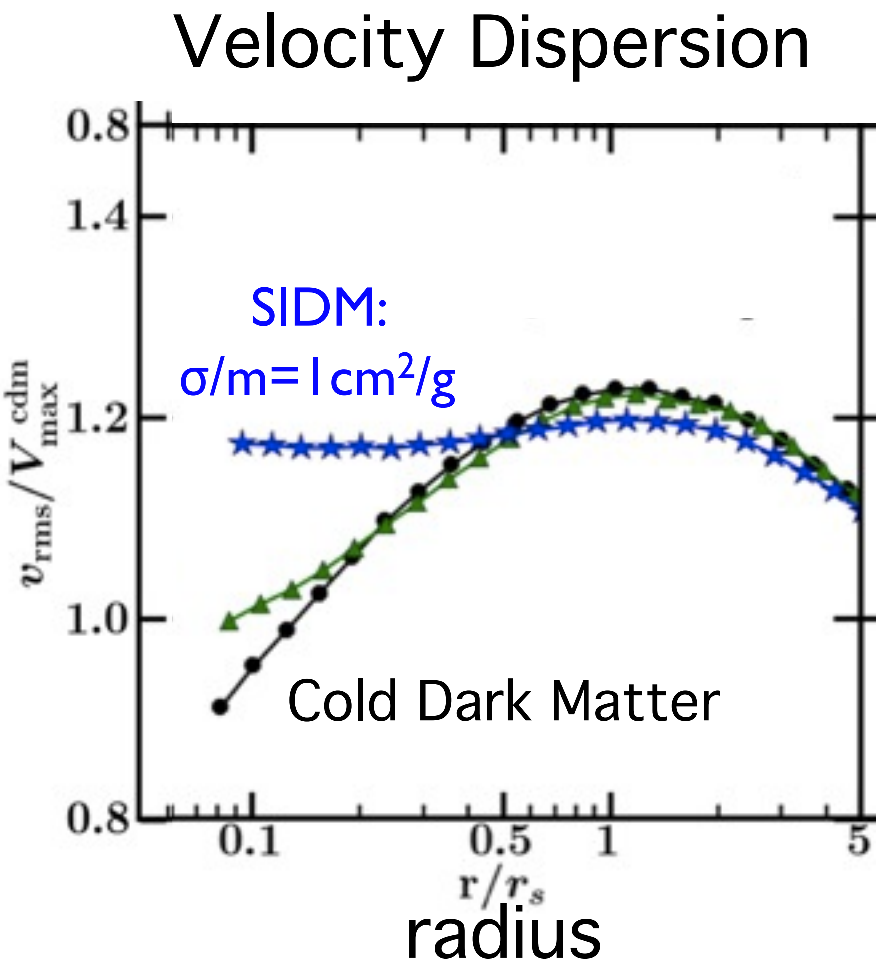


radius

Rocha et al. 2012

SIDM Makes Cored Halos

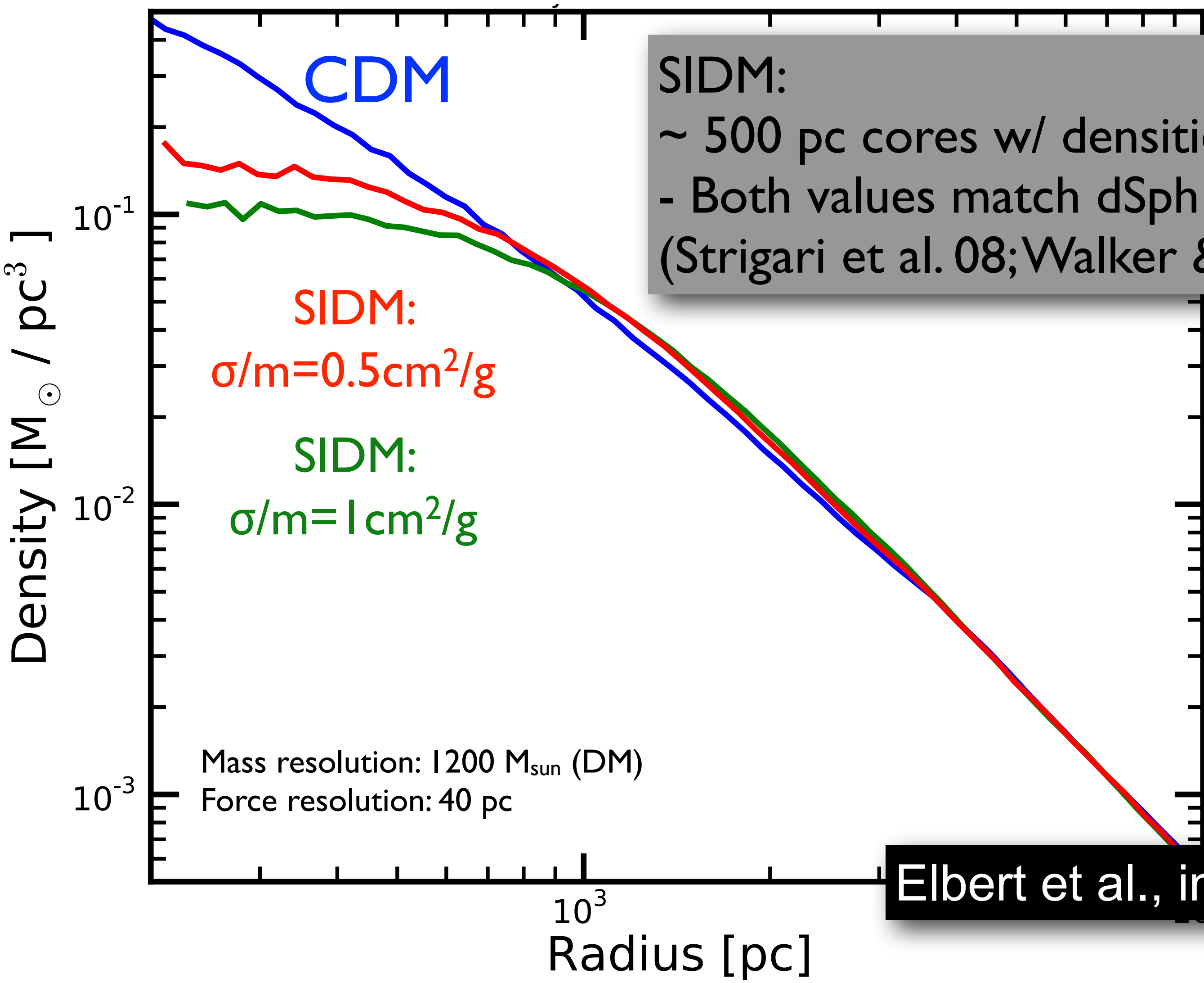




Rocha et al. 2012

Isothermal velocity profile creates core.

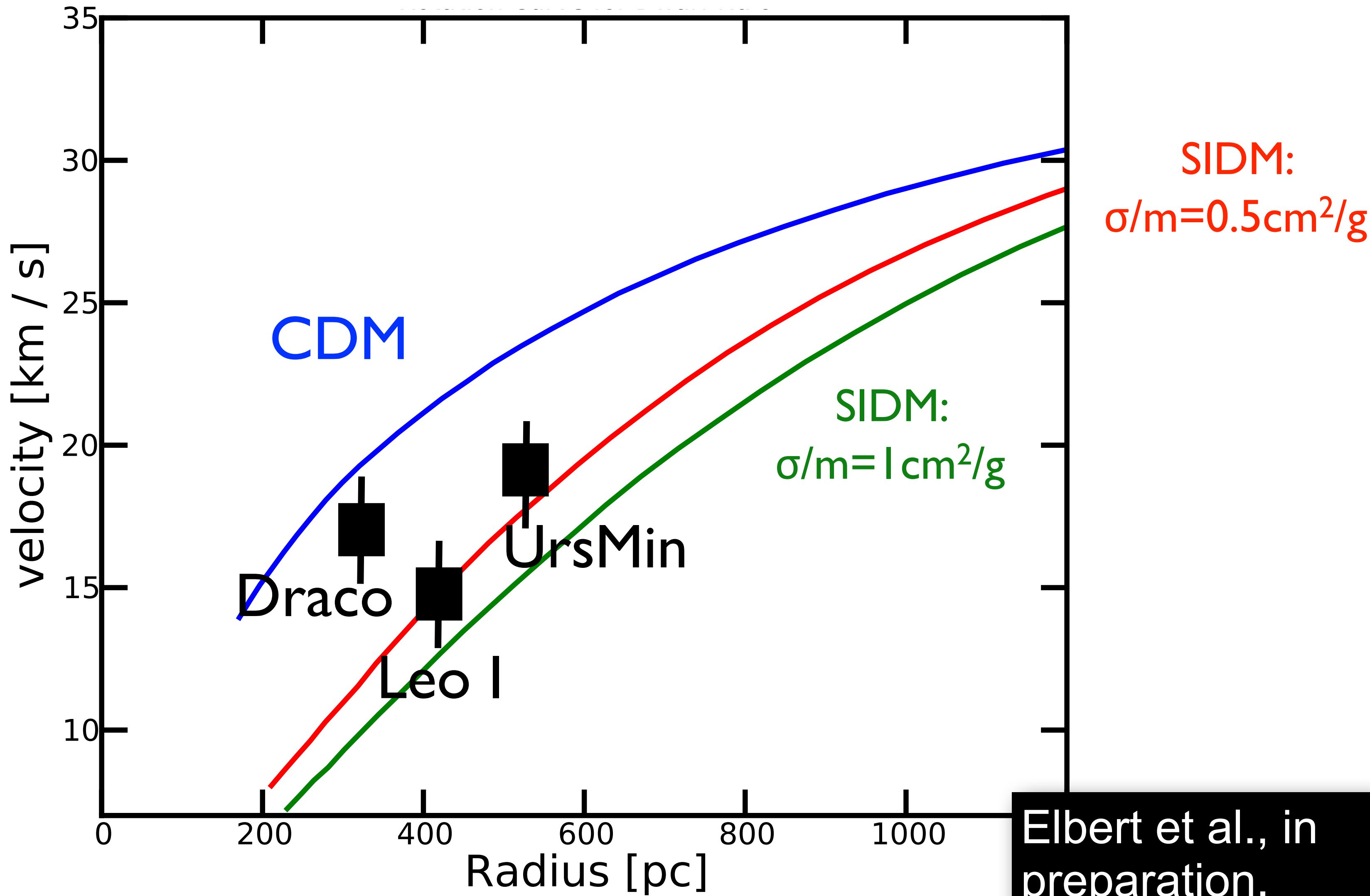
Fully cosmological zoom of isolated dwarf halo: V_{max}~35km/s



SIDM:
~ 500 pc cores w/ densities ~0.1 M_{sun}/pc^3
- Both values match dSph observations
(Strigari et al. 08; Walker & Penarrubia 12)

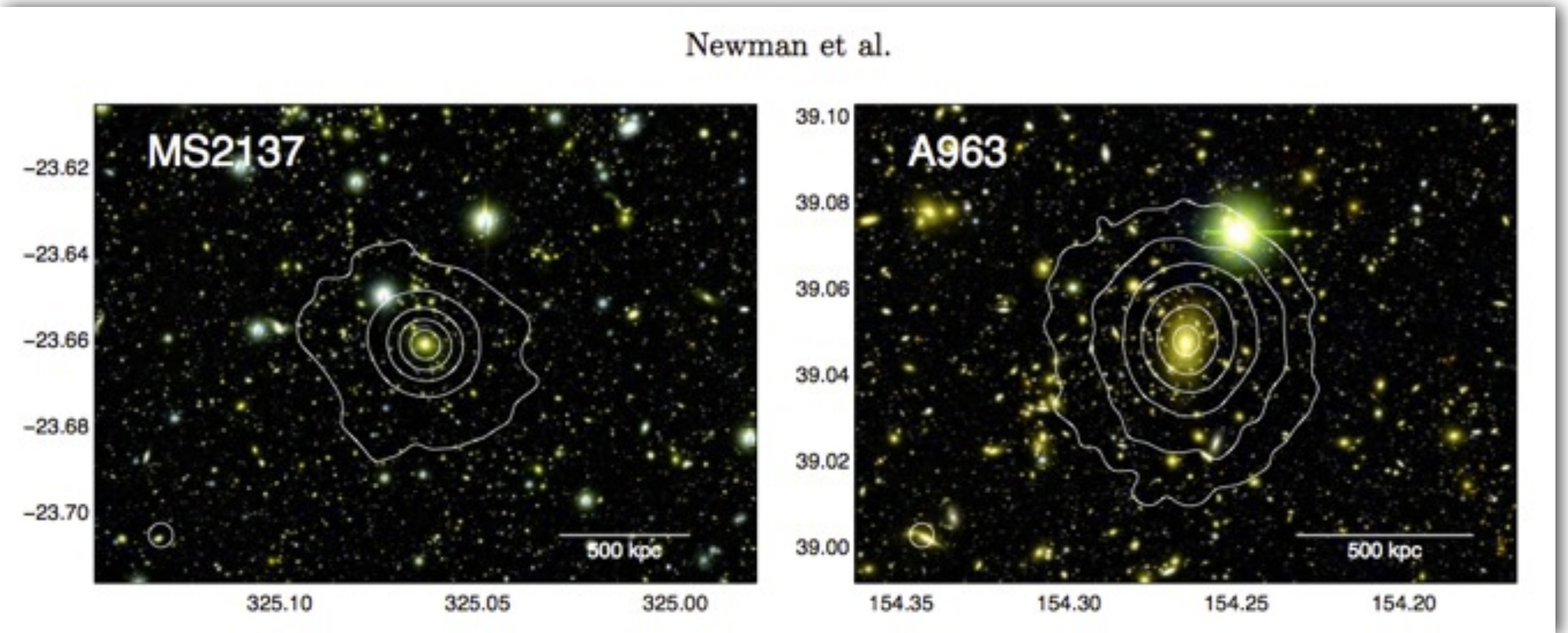
Elbert et al., in preparation

SIDM with σ/m=(0.5-1)cm²/g Solves Too Big To Fail Problem



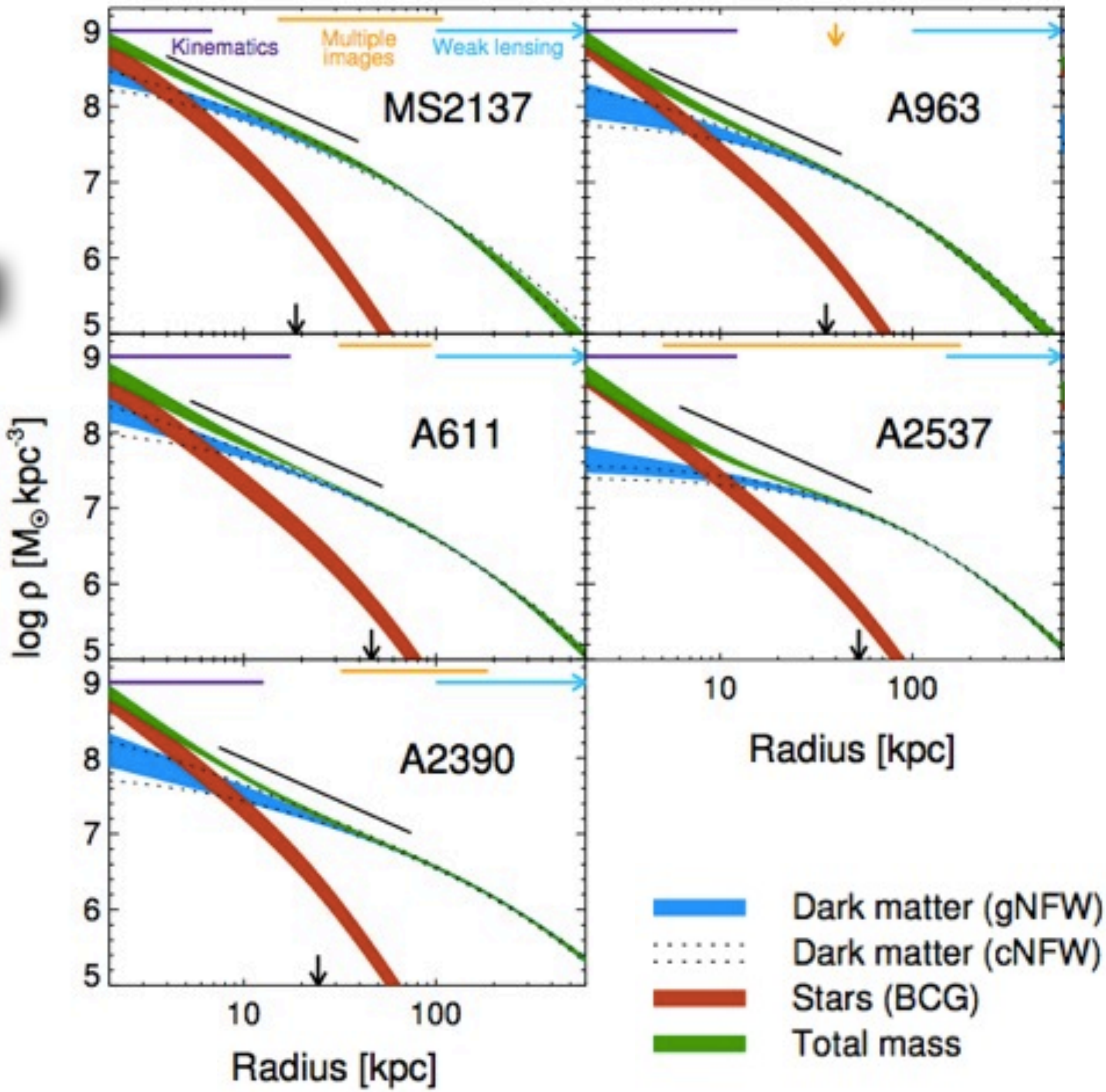
Elbert et al., in preparation.

Galaxy Clusters as a Probe of SIDM ?

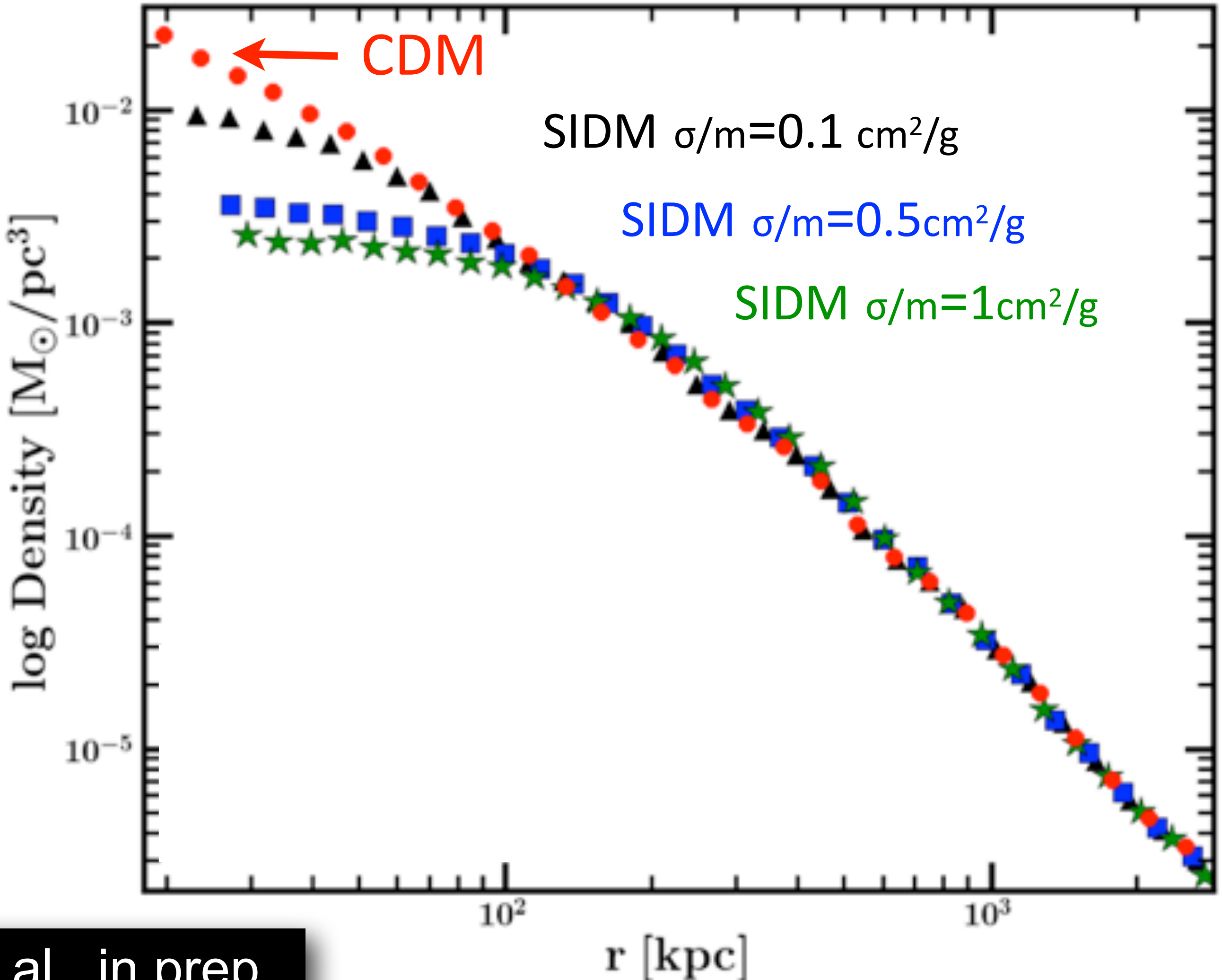


Less than cuspy cluster cores?

Newman ,Treu, Ellis, & Sand



Cosmological Sim of a Galaxy Cluster: 10^{15} M_{sun}



Rocha et al., in prep.

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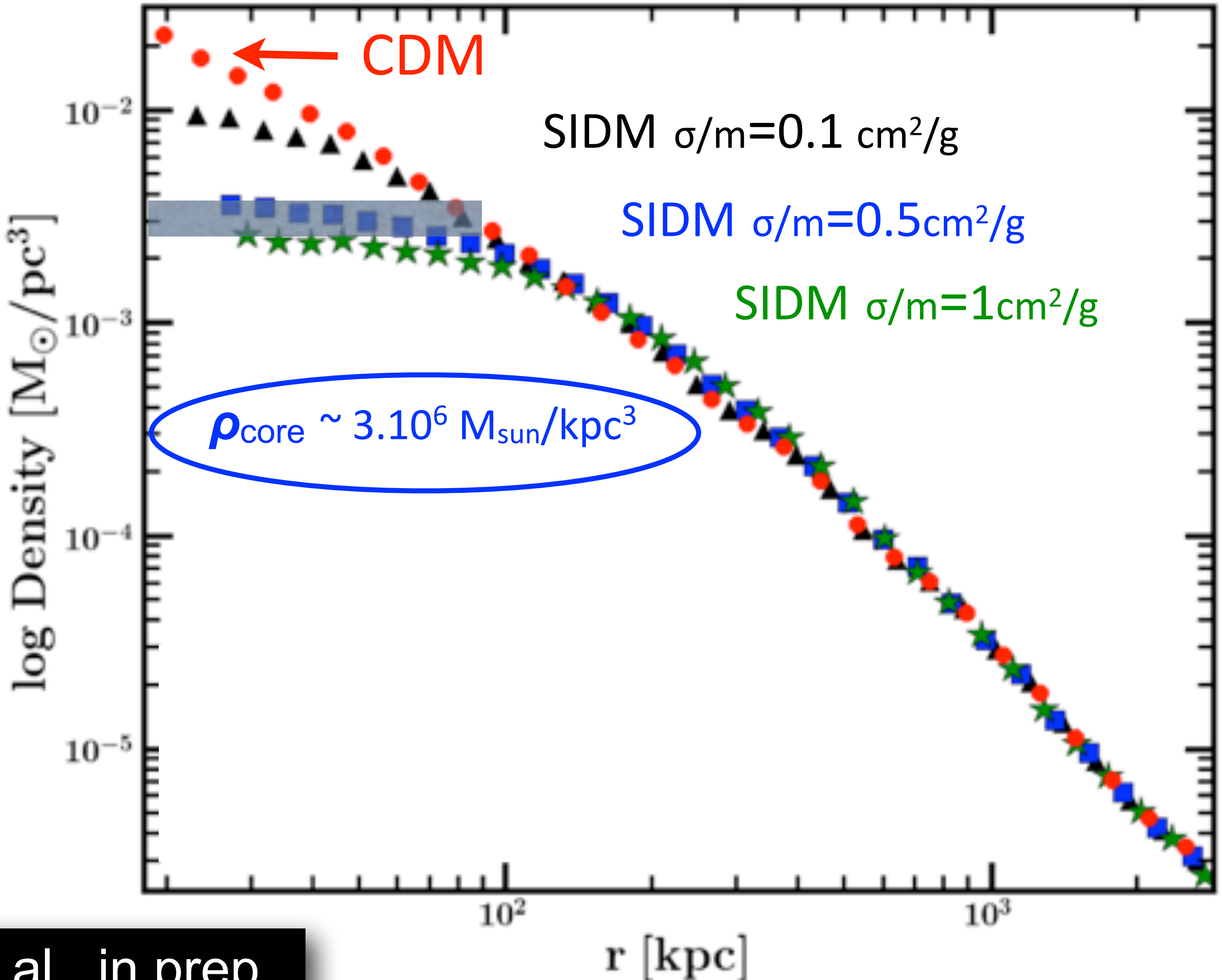
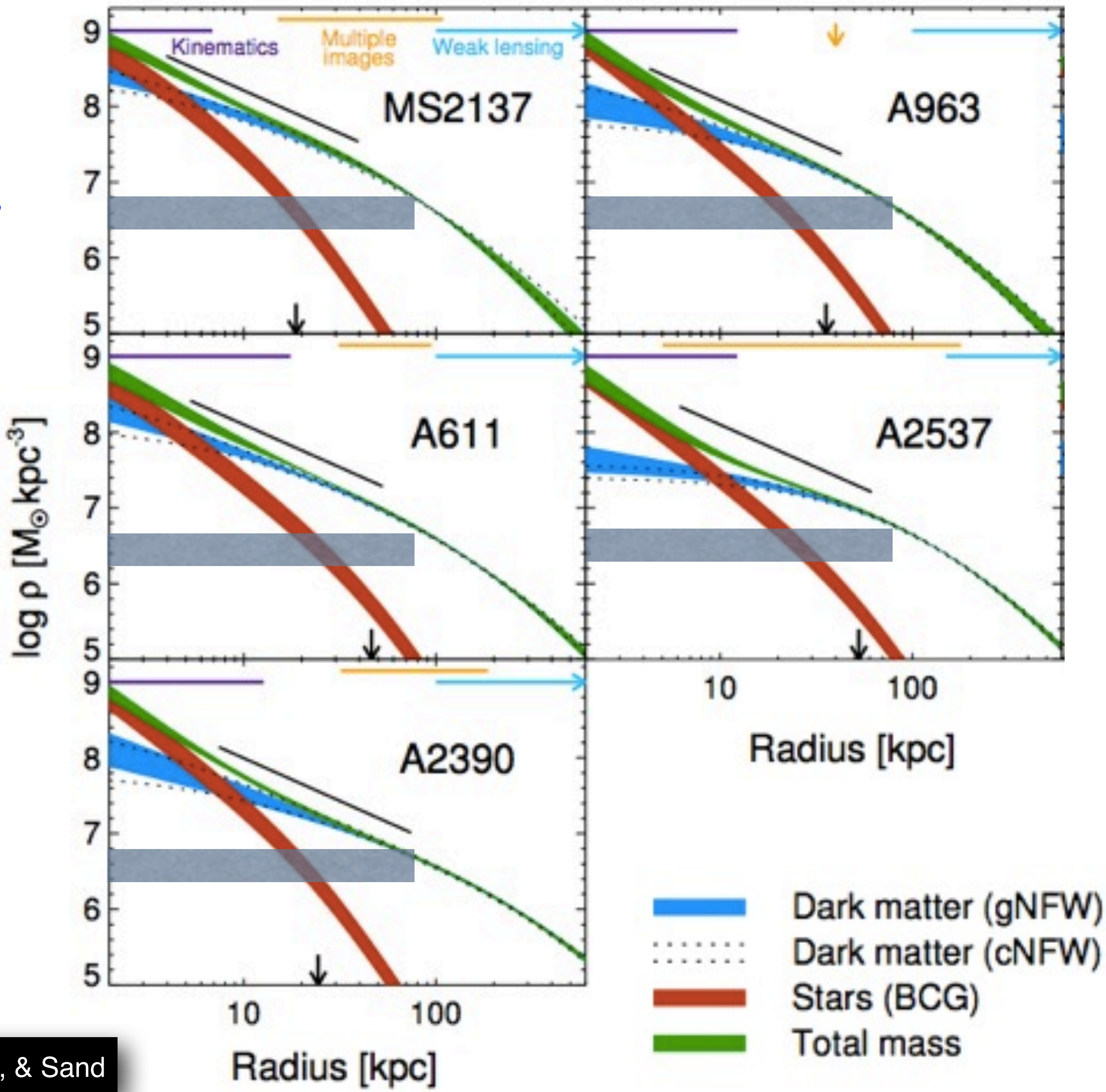


Rocha et al., in prep.

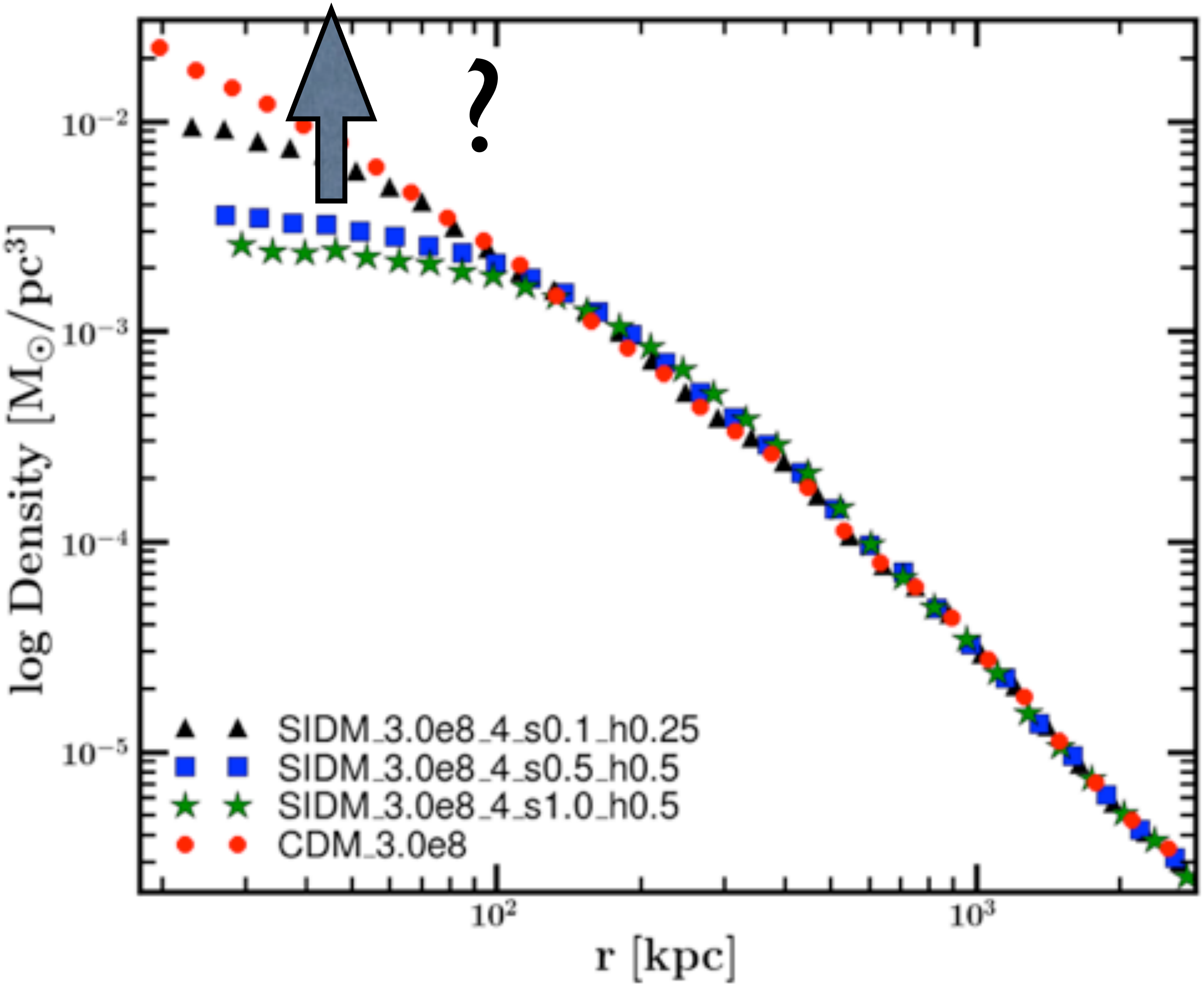
SIDM $\sigma/m = 0.5 cm^2/g$

$\rho_{core} \sim 3.10^6 M_{sun}/kpc^3$

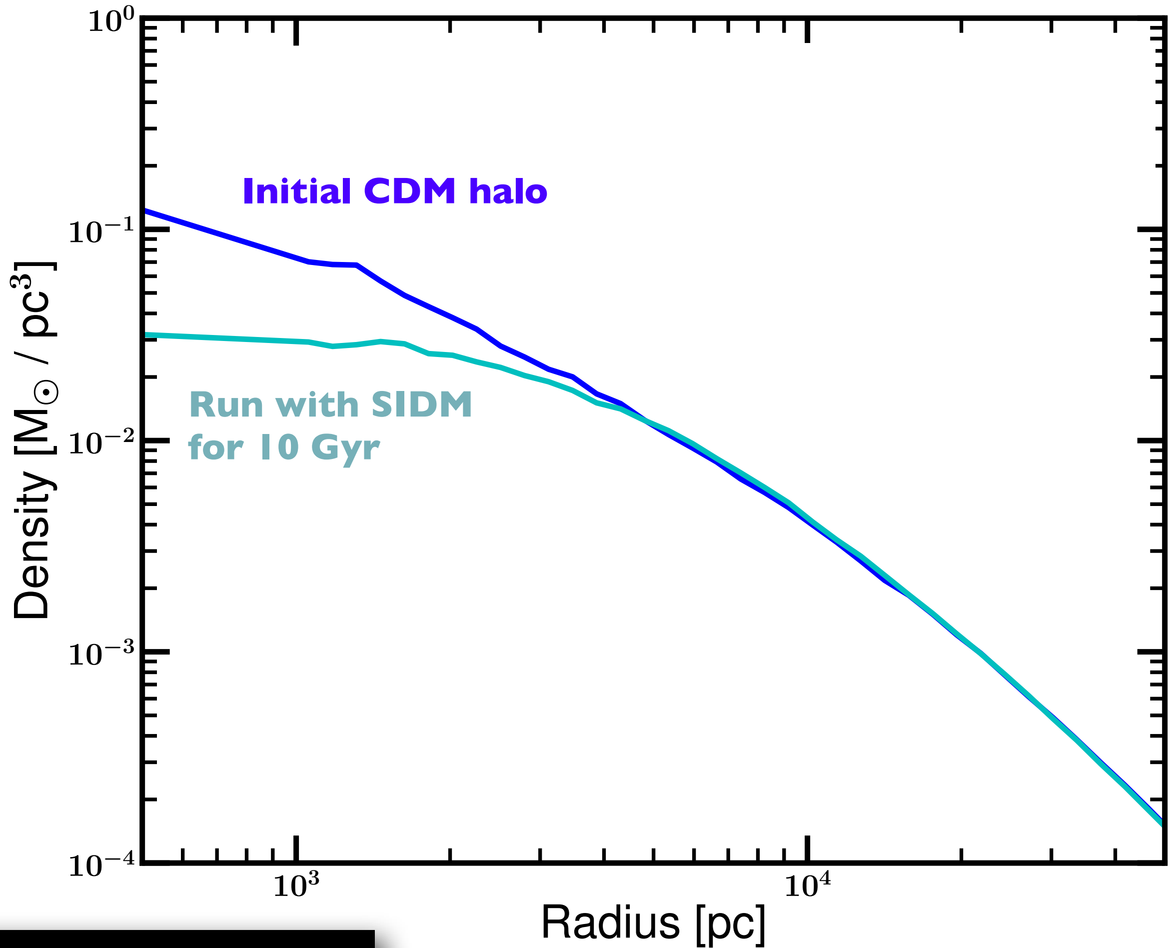


Newman ,Treu, Ellis, & Sand

What Do Baryons Do?



SIDM vs. CDM (no baryonic component)



Elbert et al., in preparation

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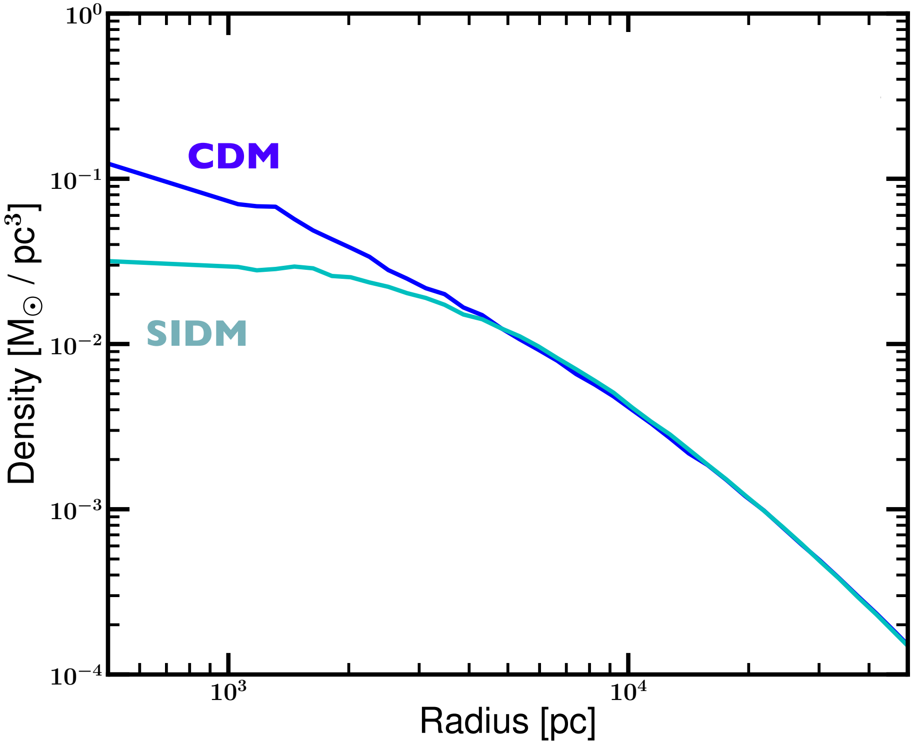

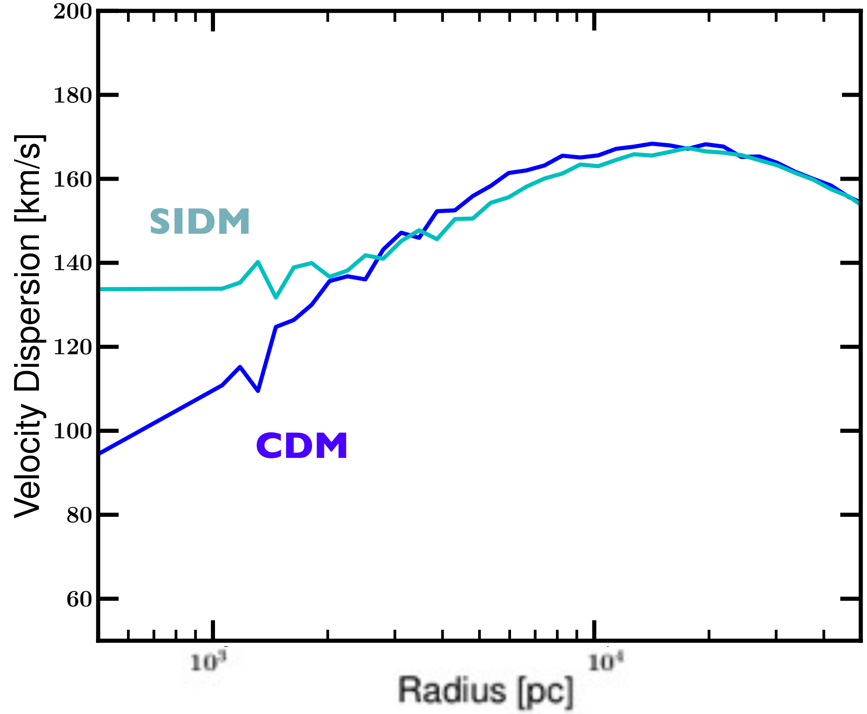

Elbert et al., in preparation

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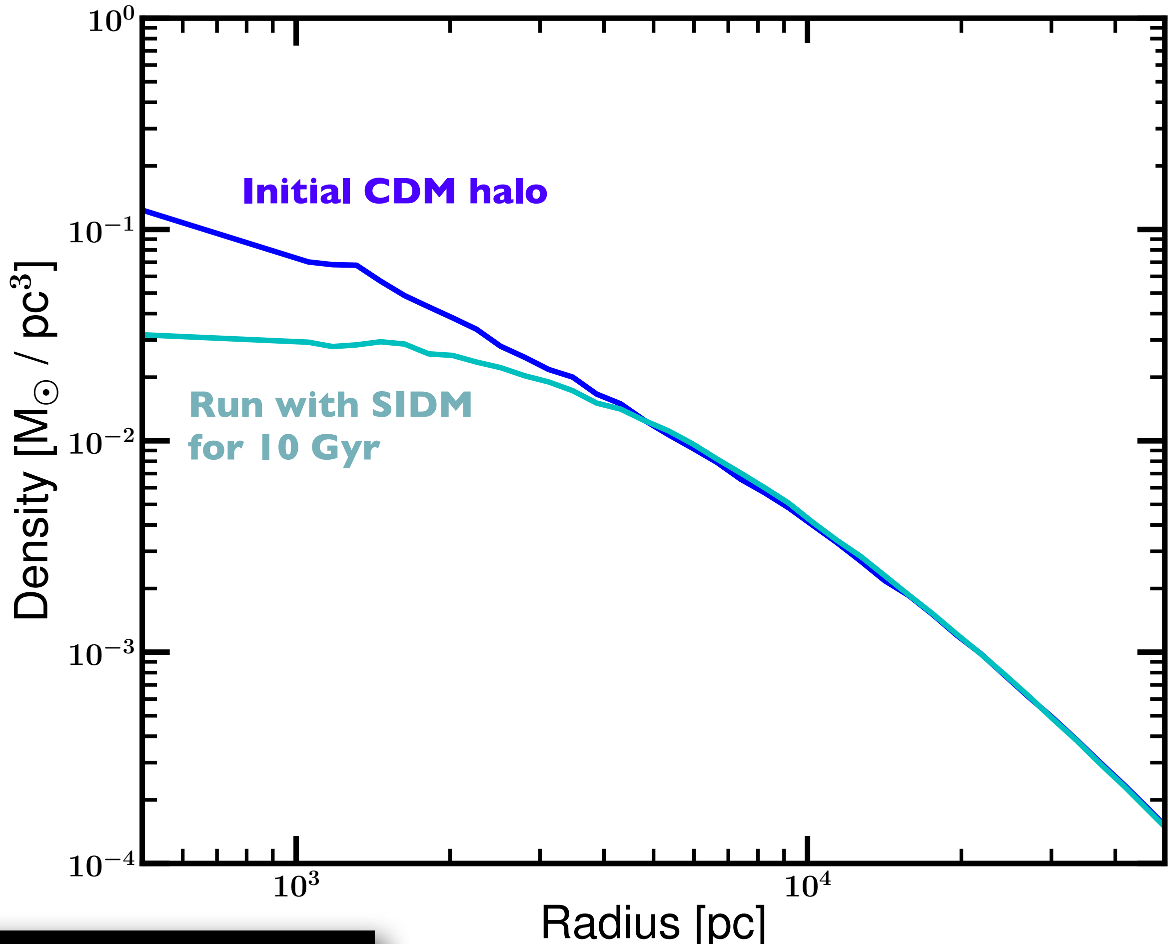
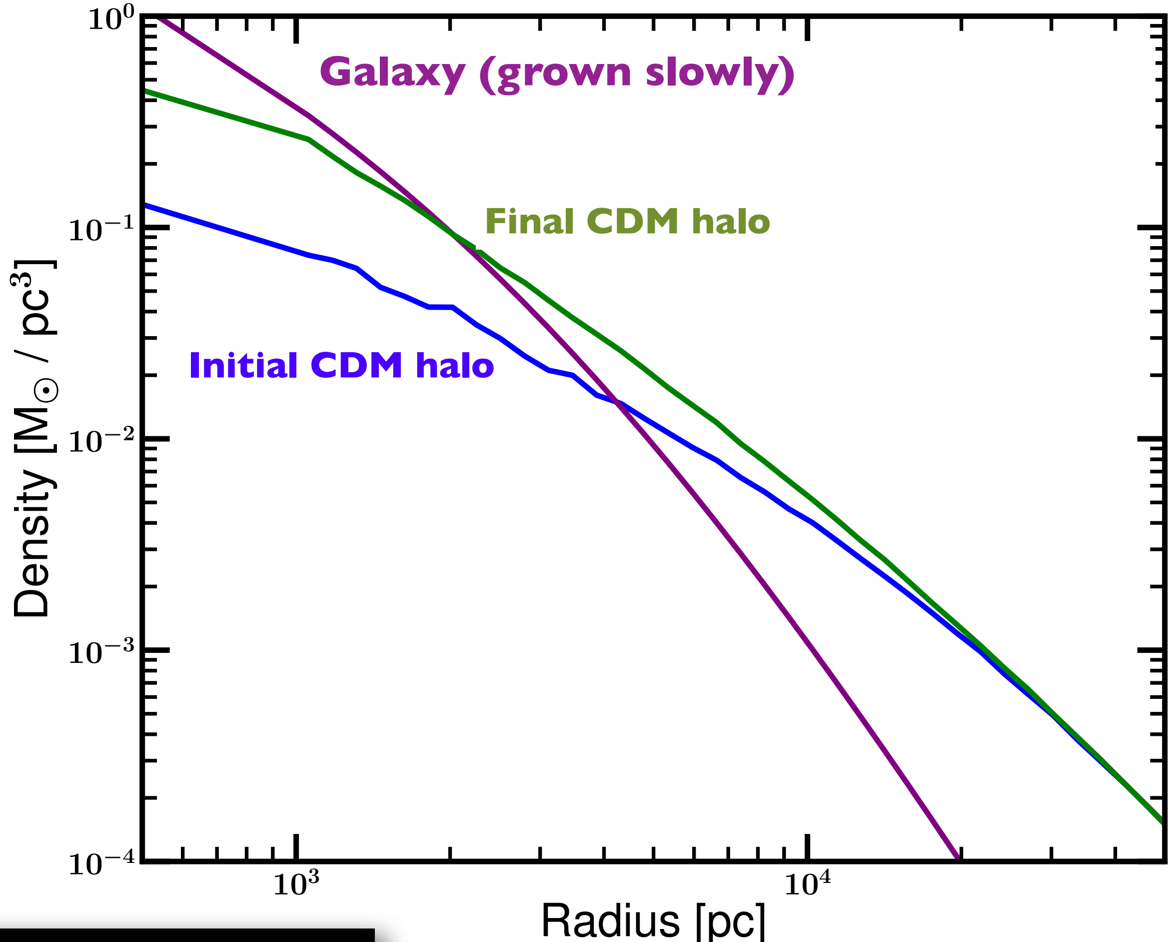


Elbert et al., in preparation

Simulating Baryonic Contraction

e.g. Blumenthal et al. 1986



Elbert et al., in preparation

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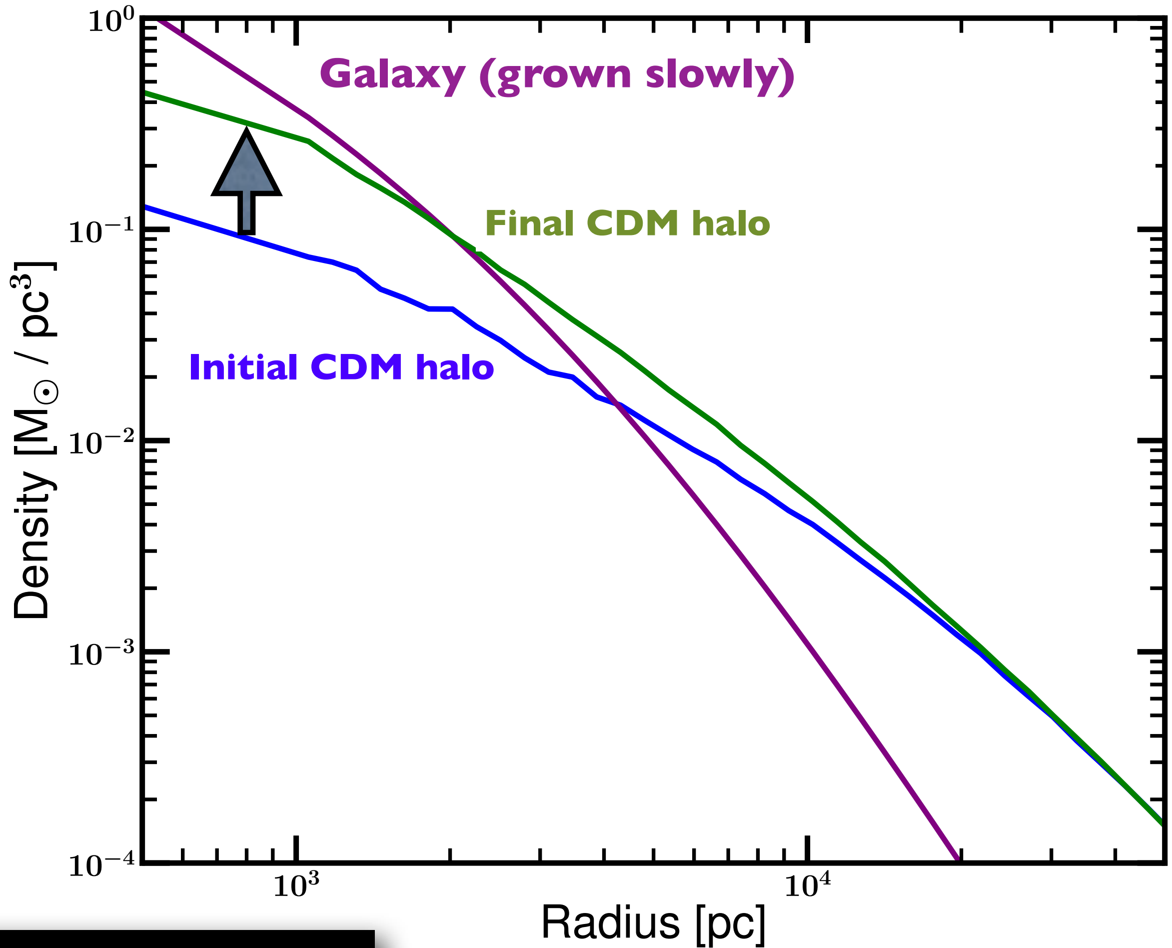
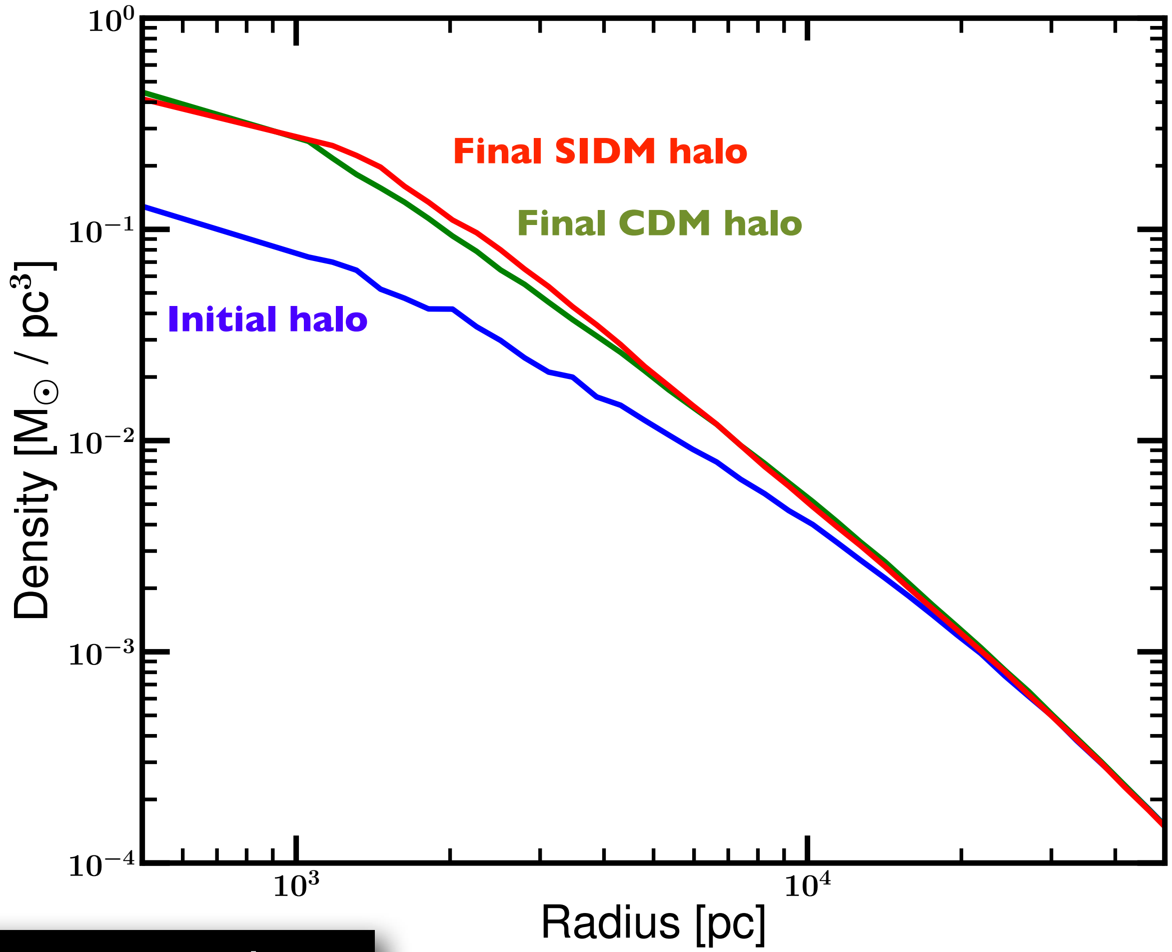
e.g. Blumenthal et al. 1986



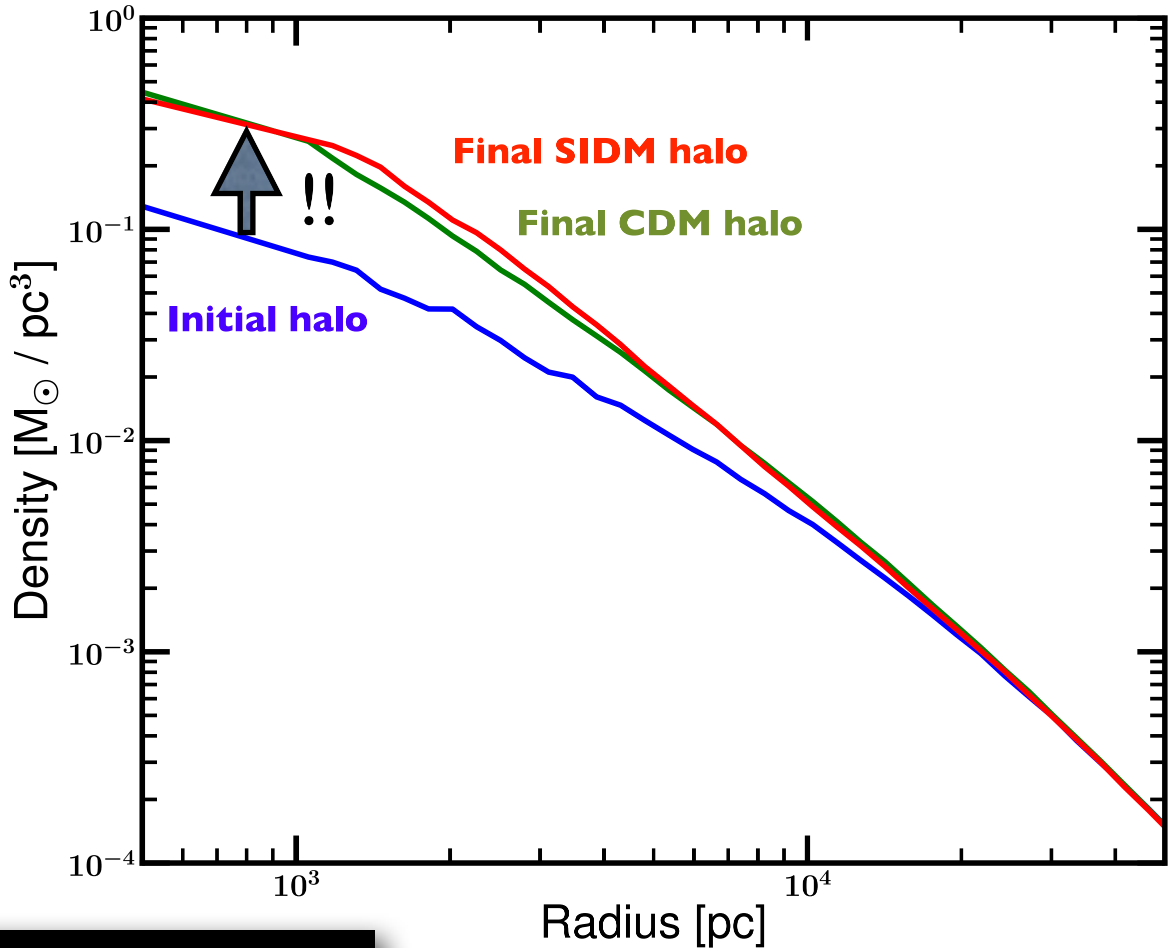
Elbert et al., in preparation

Baryons + SIDM



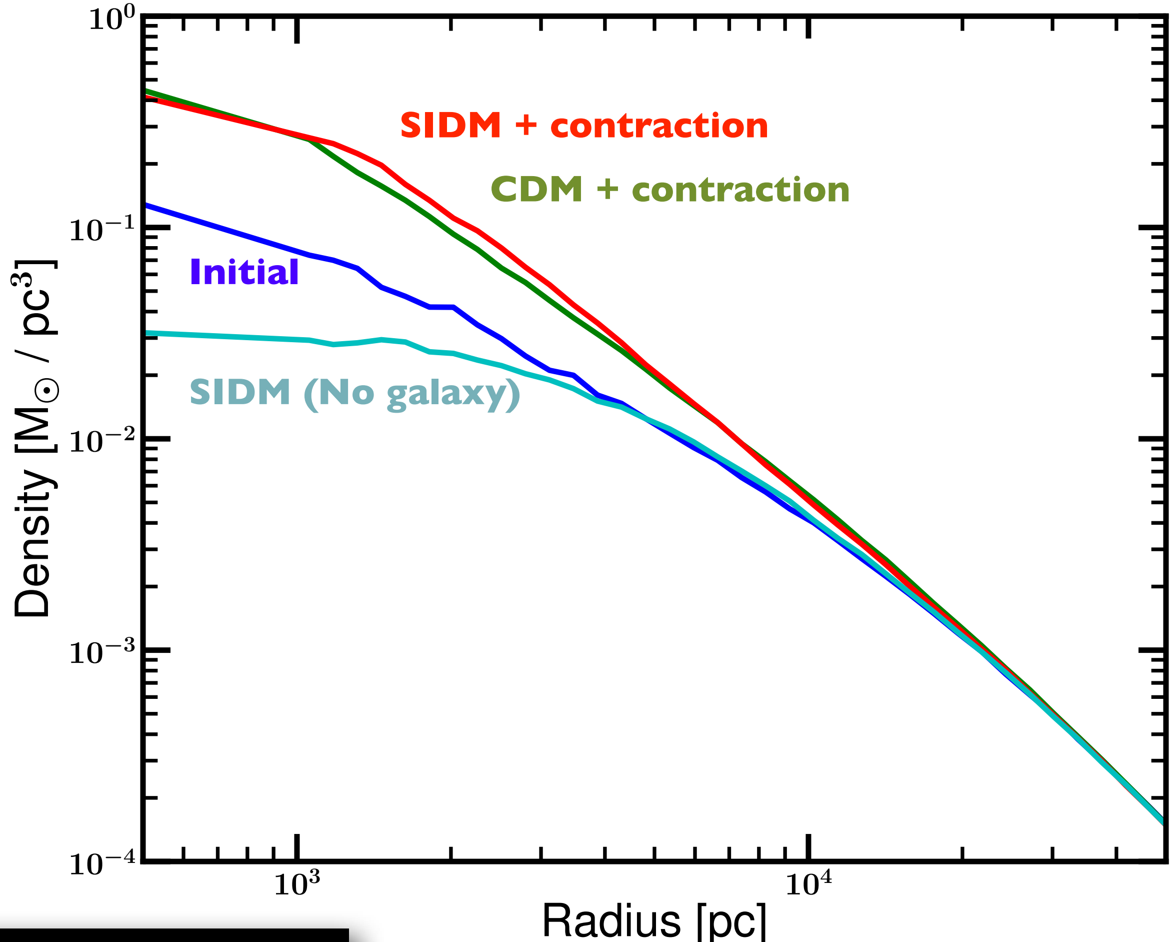
Elbert et al., in preparation

Baryons + SIDM



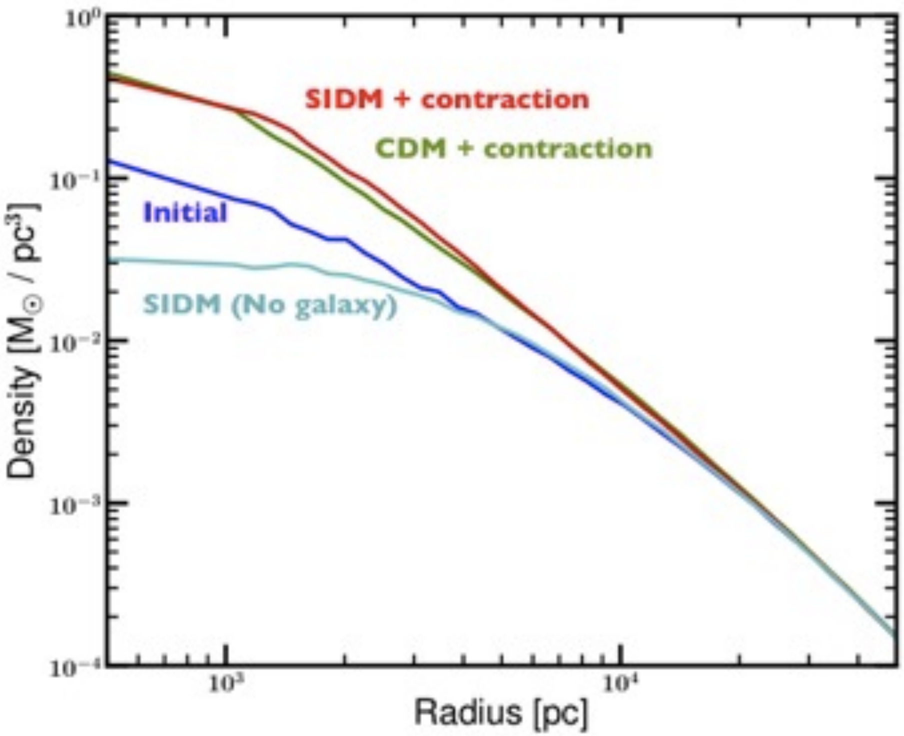
Elbert et al., in preparation

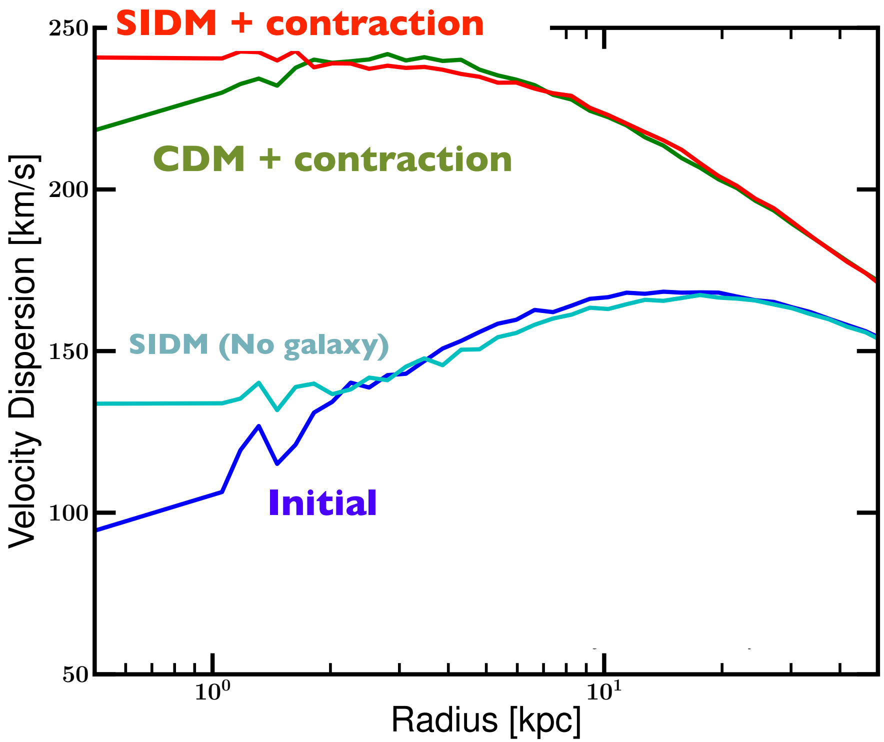
Baryons make SIDM predictions complicated



Elbert et al., in preparation

SIDM + Baryons = Hard (~CDM + Baryons)

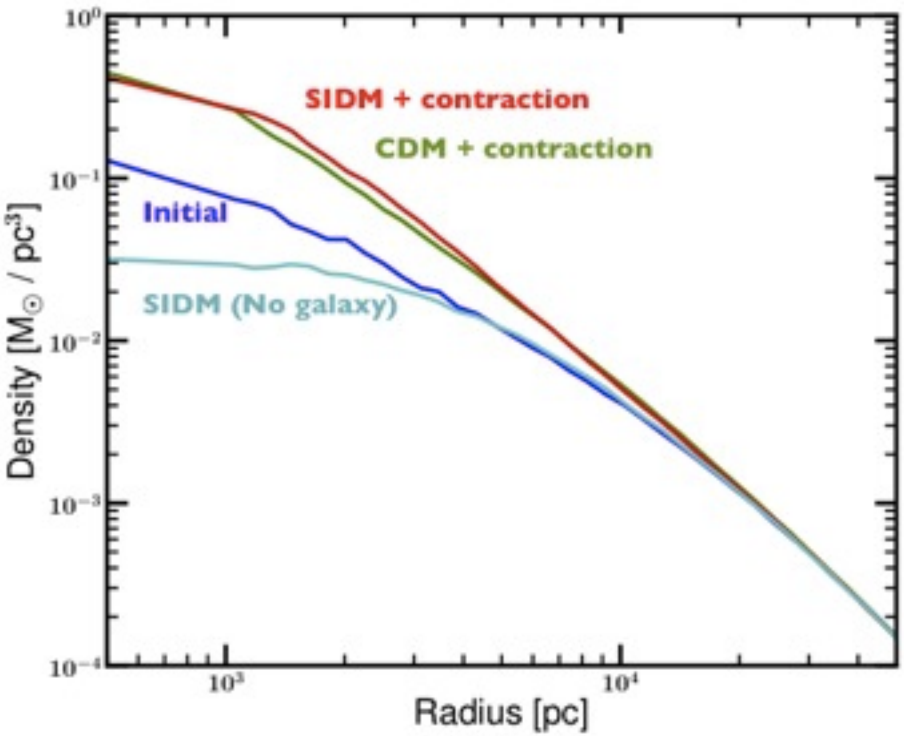


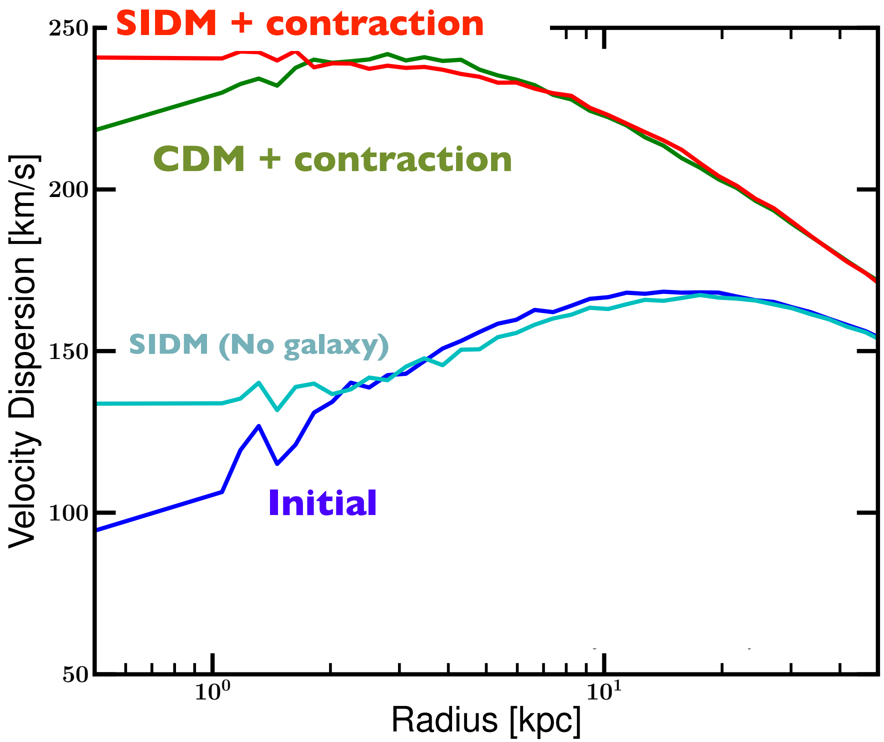


Elbert et al., in preparation

SIDM + Baryons = Hard (~CDM + Baryons)

Size of SDM core will relate to baryonic distribution





Elbert et al., in preparation

Smallest Dwarfs: Great DM Laboratories

$$M_\star \sim 10^6 M_\odot$$

$$\frac{M_{\rm DM}}{M_\star} \sim 50$$

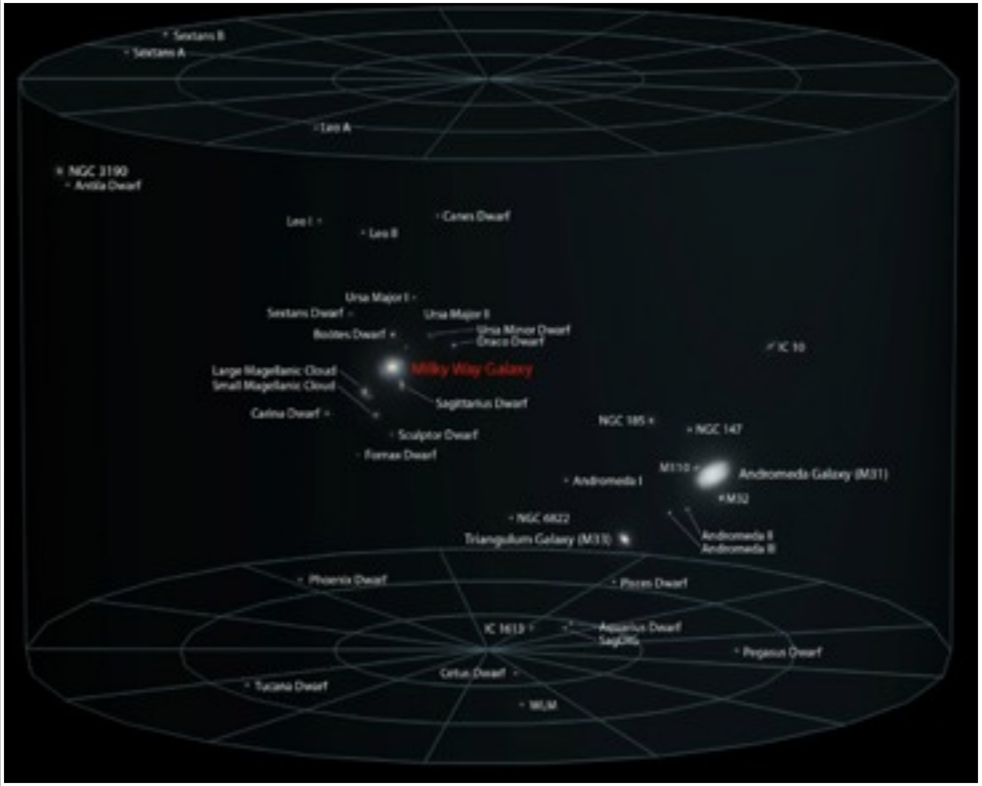
$r_\star \sim 500{\rm pc}$

Dark Matter Dominated => Easy to interpret

Very Few Stars => SN Can't Alter DM

The Local Volume is the Next Frontier

Observation



Masses of LG dwarfs

Evan Kirby et al., in prep

Theory

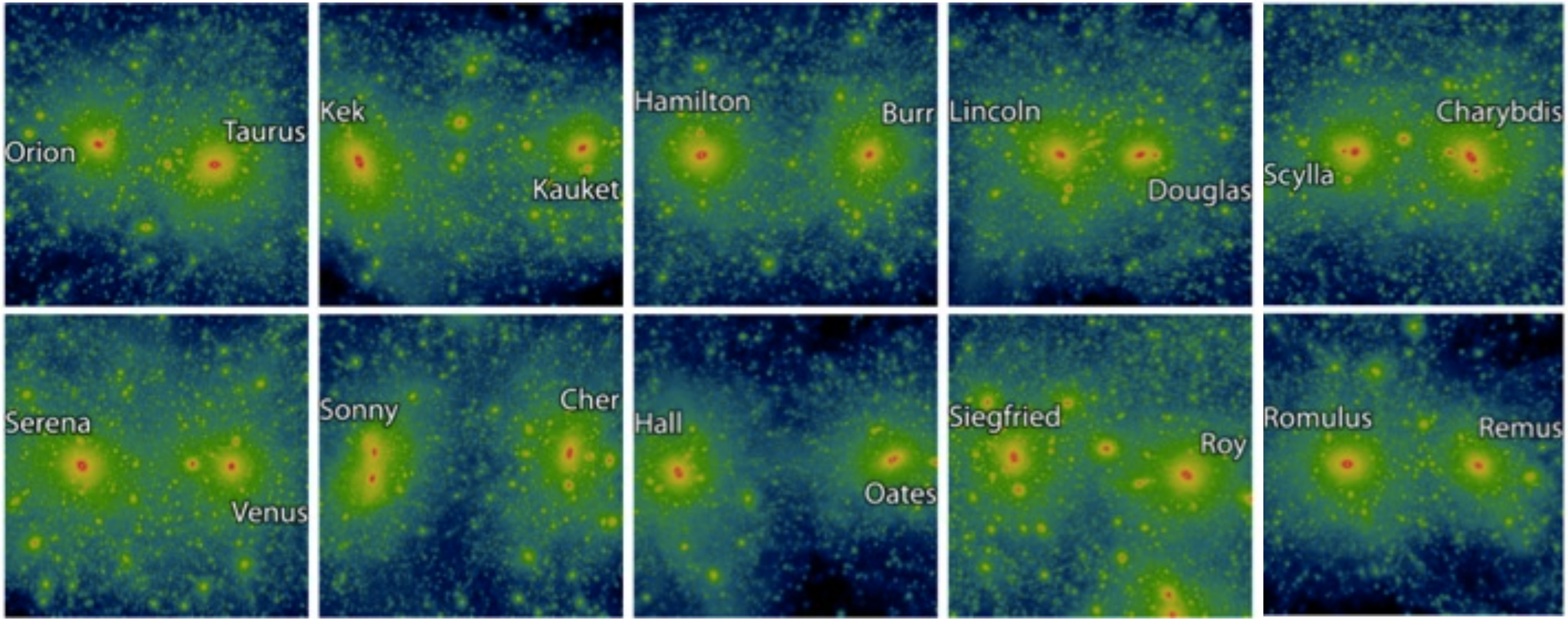
Simulating Local Groups...

Garrison-Kimmel et al., in prep

ELVIS

[Exploring the Local Volume In Simulations]

Garrison-Kimmel, Boylan-Kolchin, JSB



Take-Aways

1. The Too Big to Fail Problem

Satellites of MW have lower dark matter densities than expected.
- Where are the most massive/dense subhalos?

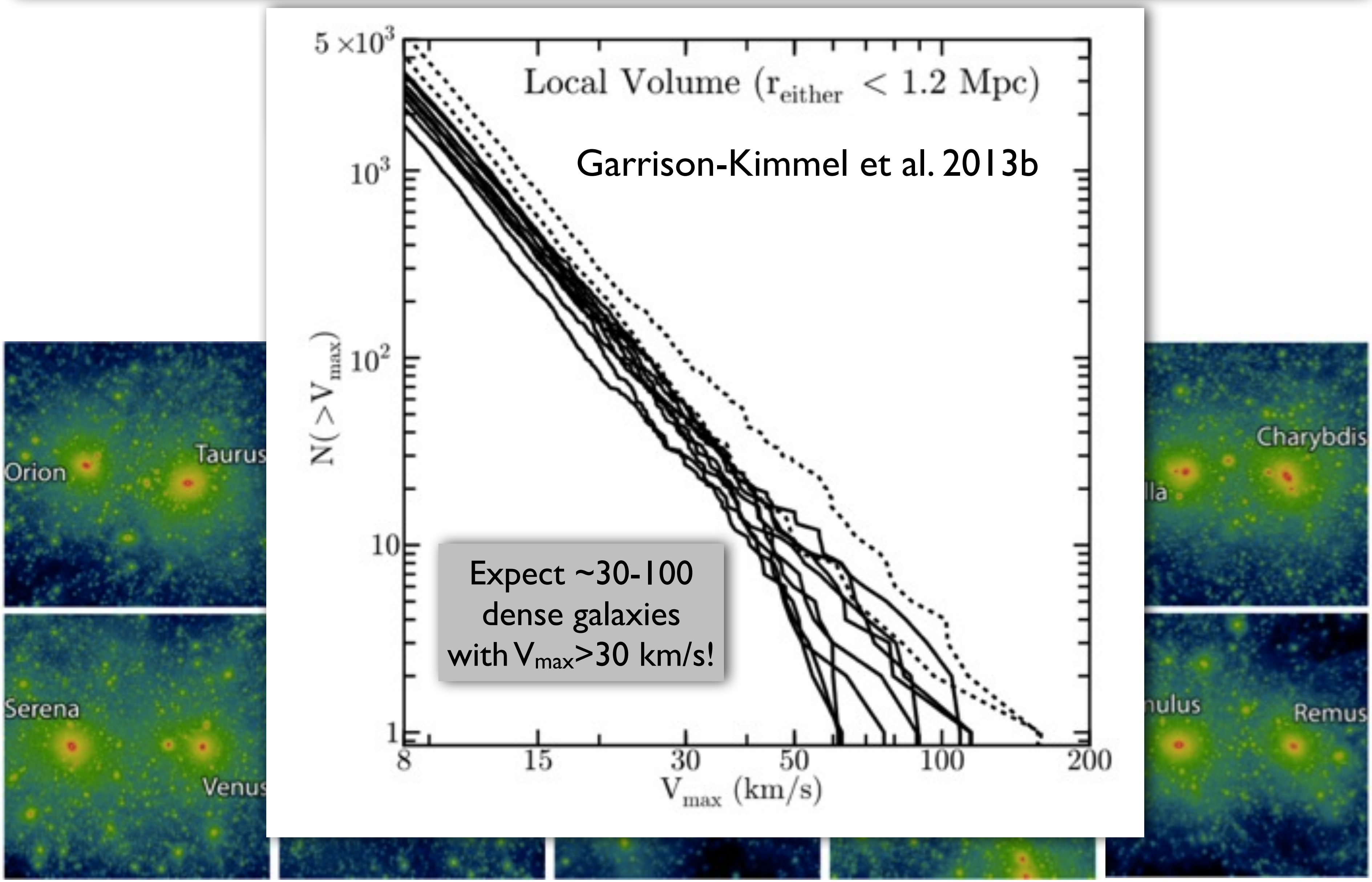
2. Possible solutions

- **SN Feedback?** Not enough stars to do it.
- **Any Baryonic process?** Could be environmental
    - test w/ obs of isolated dwarfs
- **Dark Matter physics?**
    - **SIDM** with **$\sigma/m \sim 0.5\text{-}1\ cm^2/g$** can do it.

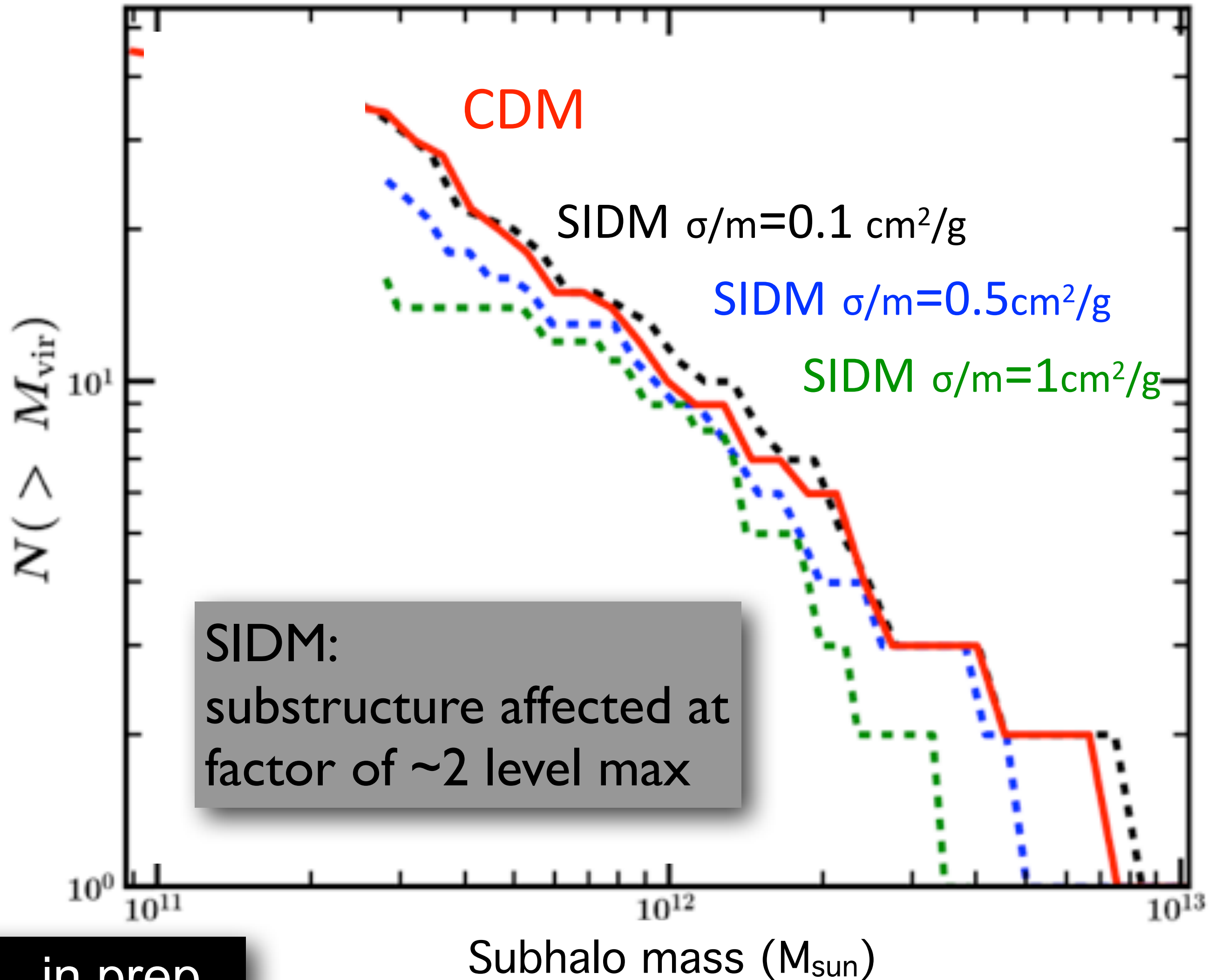
3. Where to look for DM weirdness?

Baryon-dominated systems are interesting in SIDM but HARD
Dark matter dominated dSph's in the "Local Field" may be the best bet.

The Local Volume Looks Problematic too

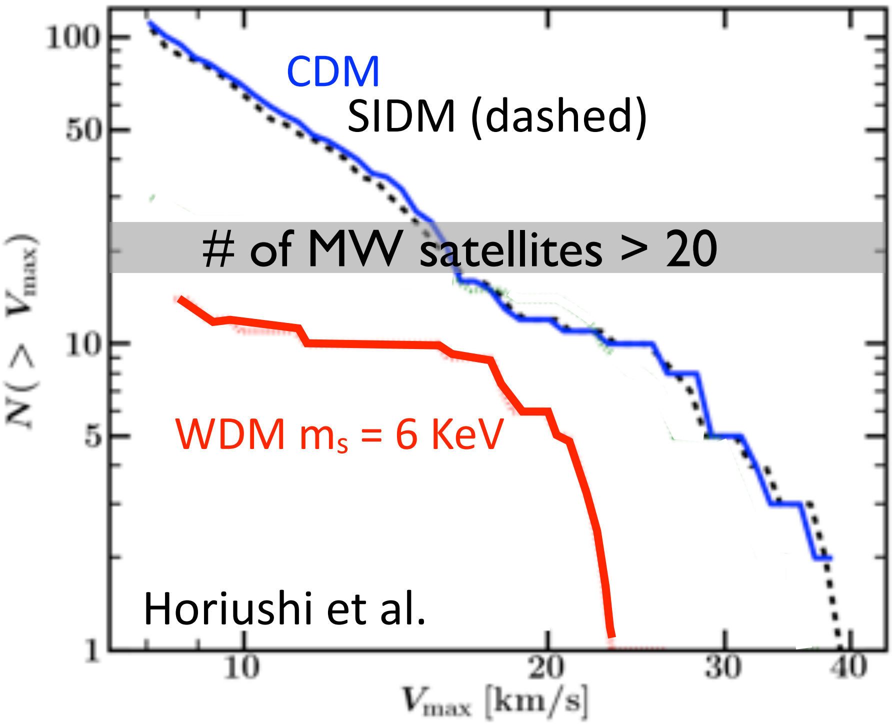


Massive Galaxy Cluster: 10^{15} M_{sun}



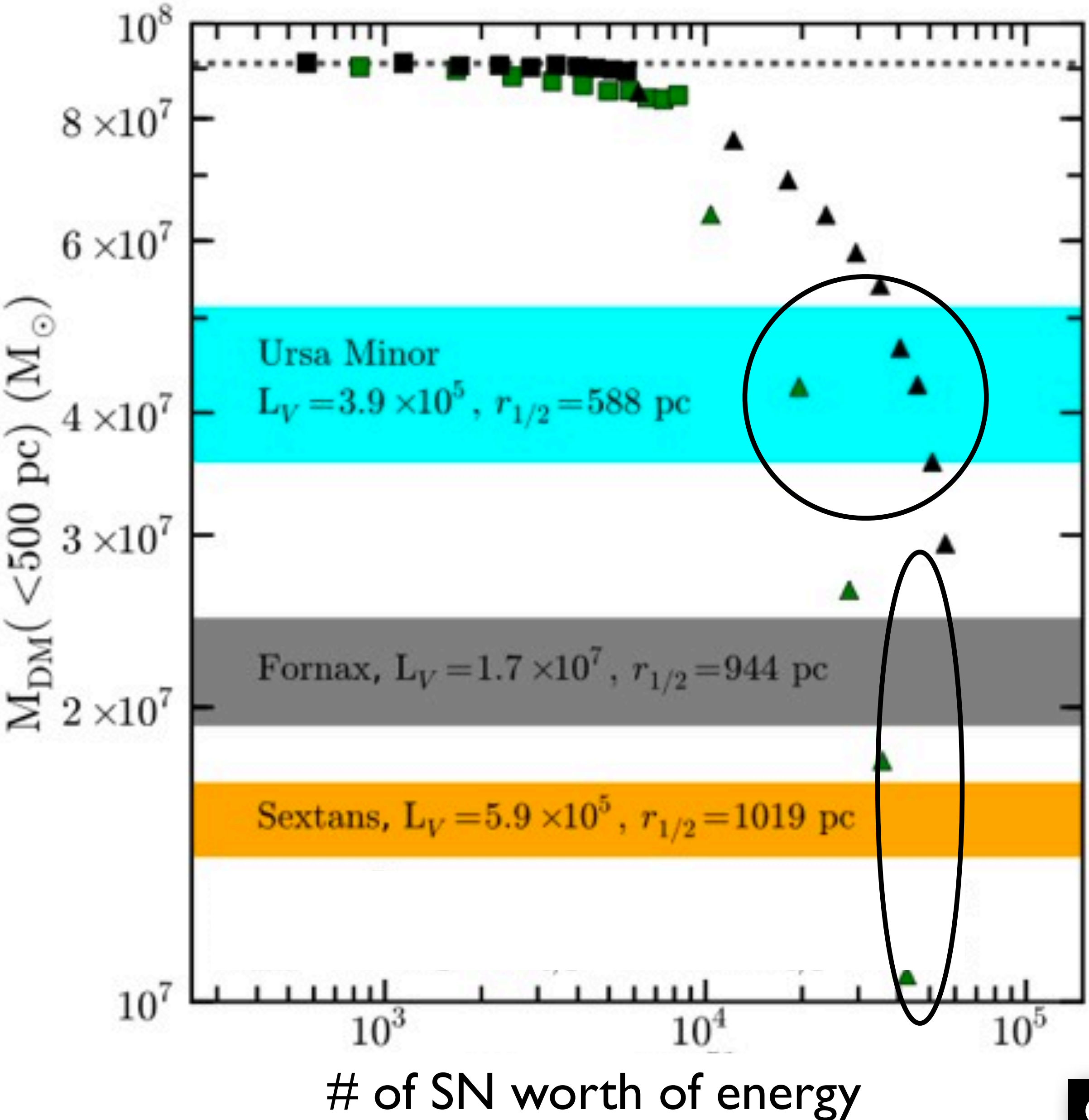
Rocha et al., in prep.

Dark Matter Phenomenology: Substructure



WDM:
- Solves Too Big To Fail by removing offending subhalos all together.

Problem:
- For models that solve the TBTF: *not enough subhalos to explain known satellite count*
- Same models also struggle to explain Ly-alpha forest clumping



Expect:
0.01 Supernova per solar mass of stars.

Req. more energy than sum of all supernovae in this galaxy!

Slightly more energy input unbinds the halo all together (fine-tuning problem)

Garrison-Kimmel et al. 2013a