Solving Too Big to Fail: Baryonic or Dark Matter Physics?

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Collaborators

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Outline

1. Can Supernova Feedback Fix Dwarf Densities?

- **Unlikely** in the smallest dwarfs ($M_{star} < 10^6\ M_{sun}$).
- Not enough energy available to remove dark matter

2. Can Self-Interacting DM do it?

- Yes. $\sigma/m \sim (0.5\text{-}1)\ cm^2/g$ works.

3. Can Warm DM do it?

- Maybe, but it doesn't look good.

Smallest Dwarfs: Great DM Laboratories

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

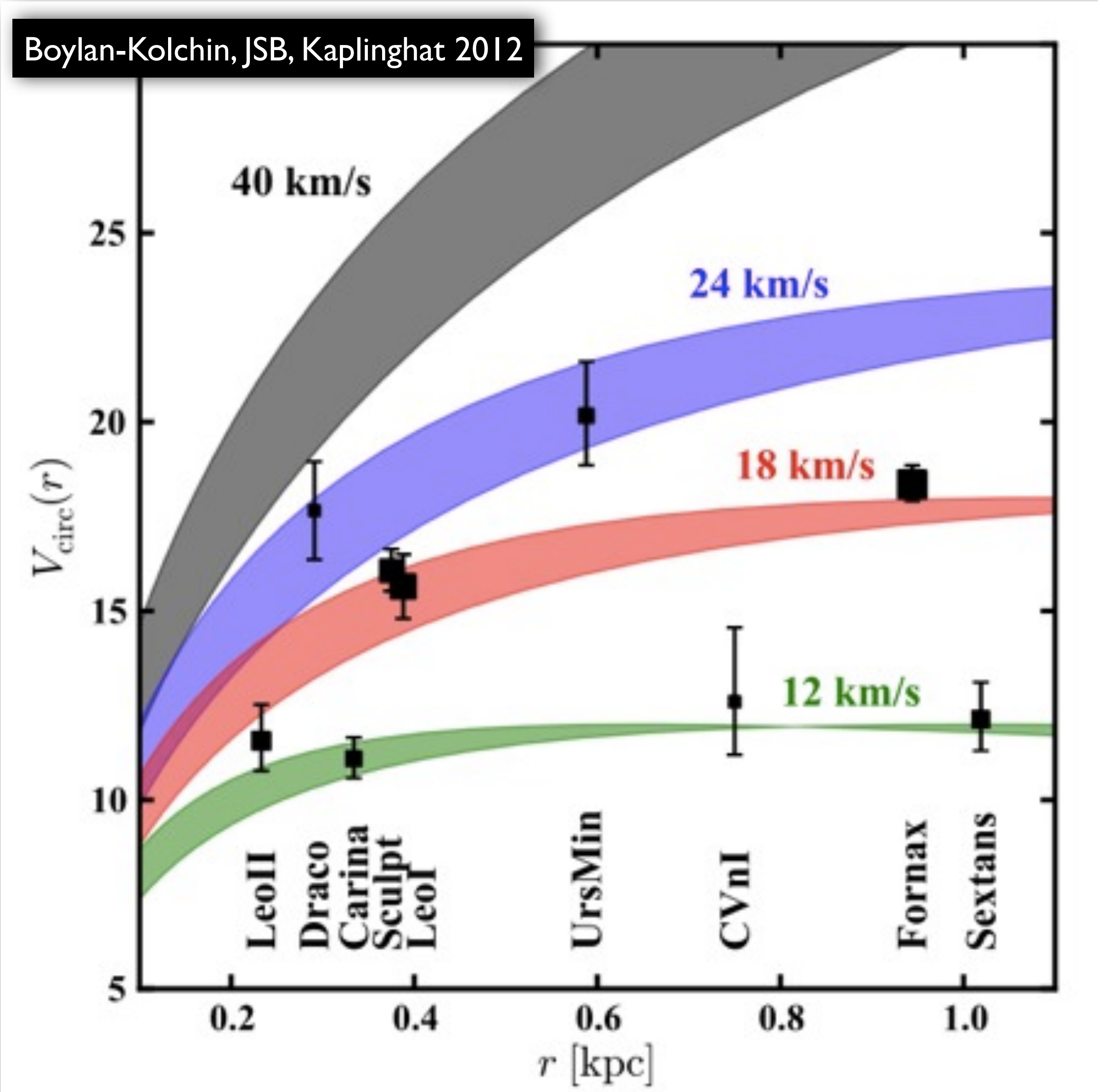
$$\frac{M_{\rm DM}}{M_\star} \sim 50$$

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

Dark Matter Dominated => Easy to interpret

Very Few Stars => SN Can't Alter DM

Summary of the Too Big To Fail problem:



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

(from 44 simulations)

Garrison-Kimmel et al. in prep

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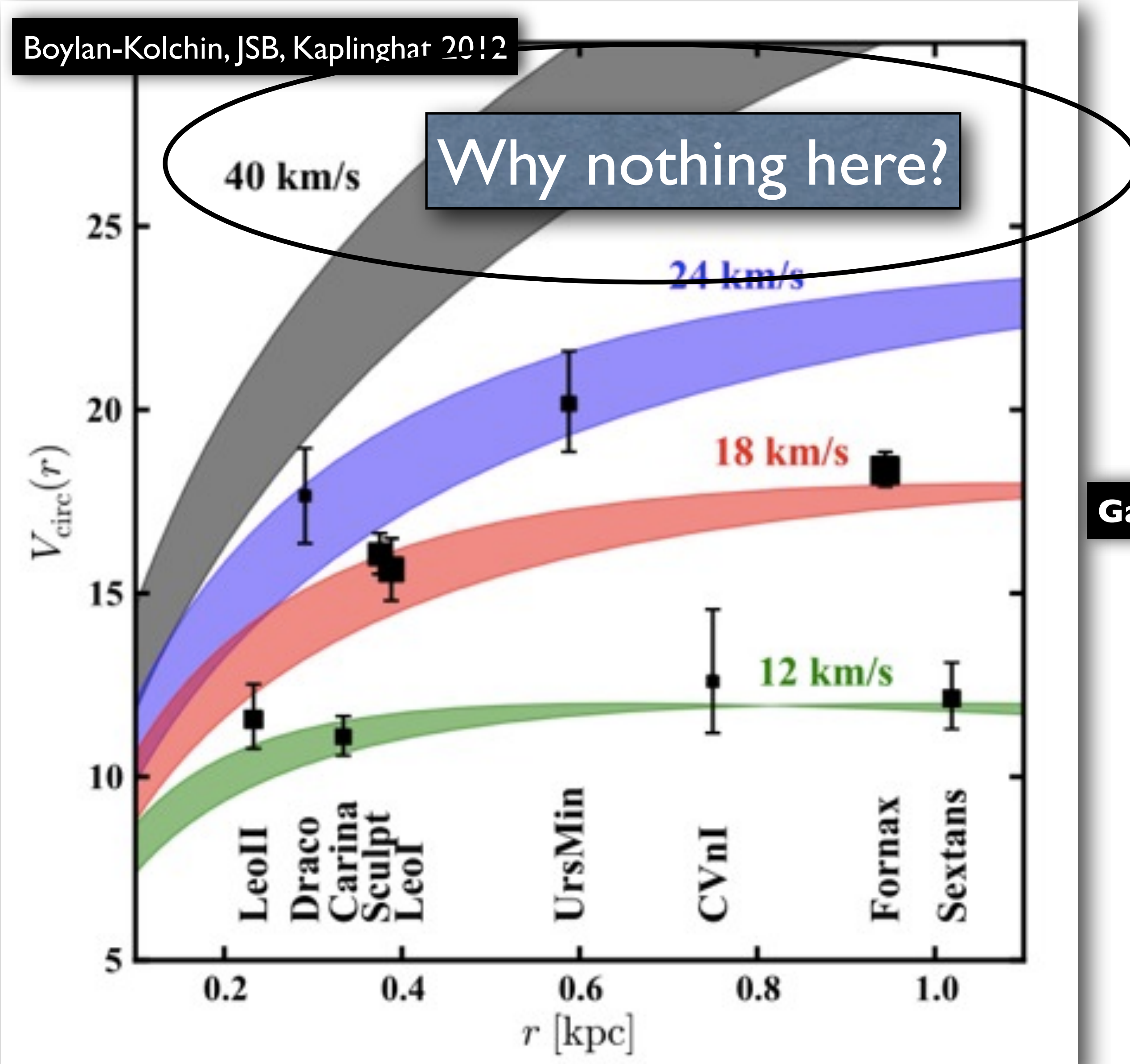

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Basic Energy Argument Against SN Feedback

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

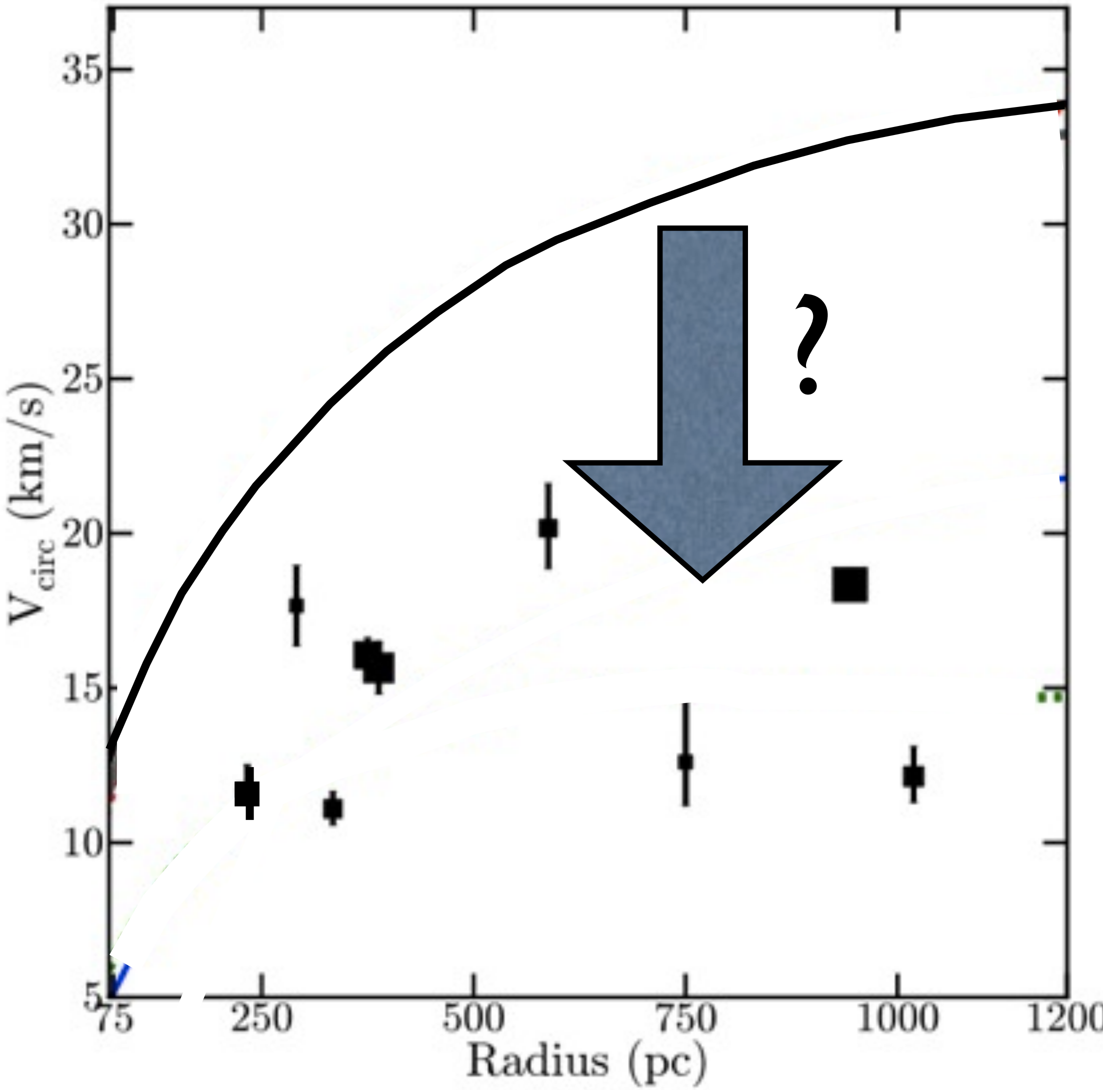
Must remove ~50 times more dark matter than mass in stars!

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

Numerical Experiment



Consider a M* ~10^6 M_{sun} dwarf galaxy

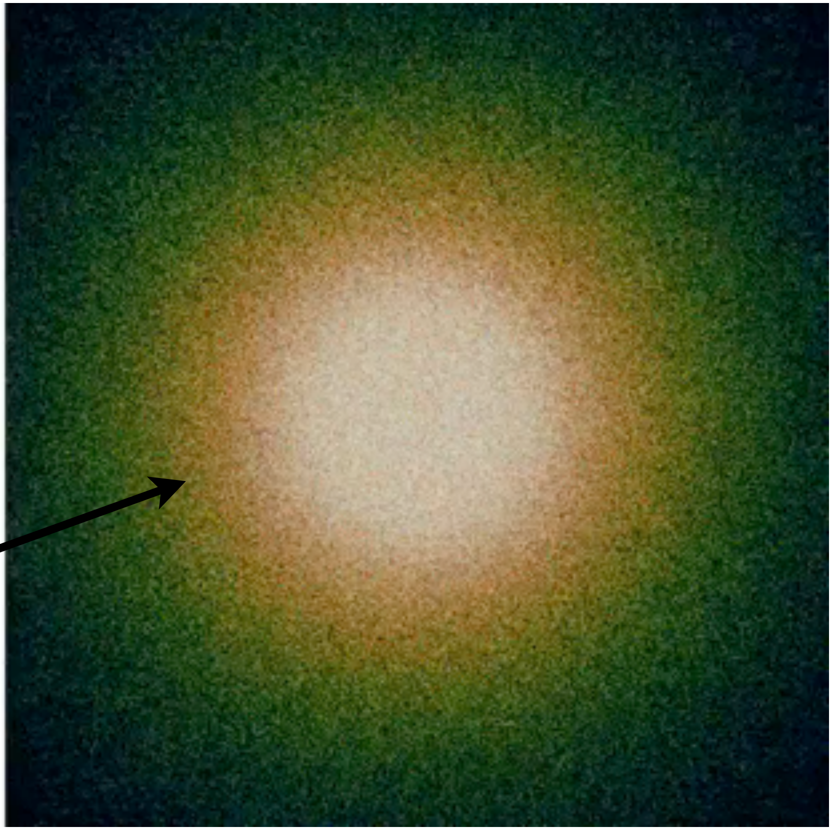
What does it take to remove enough DM?

Numerical Experiment

Live DM Halo

m_{dm} = 8000 M_{sun}

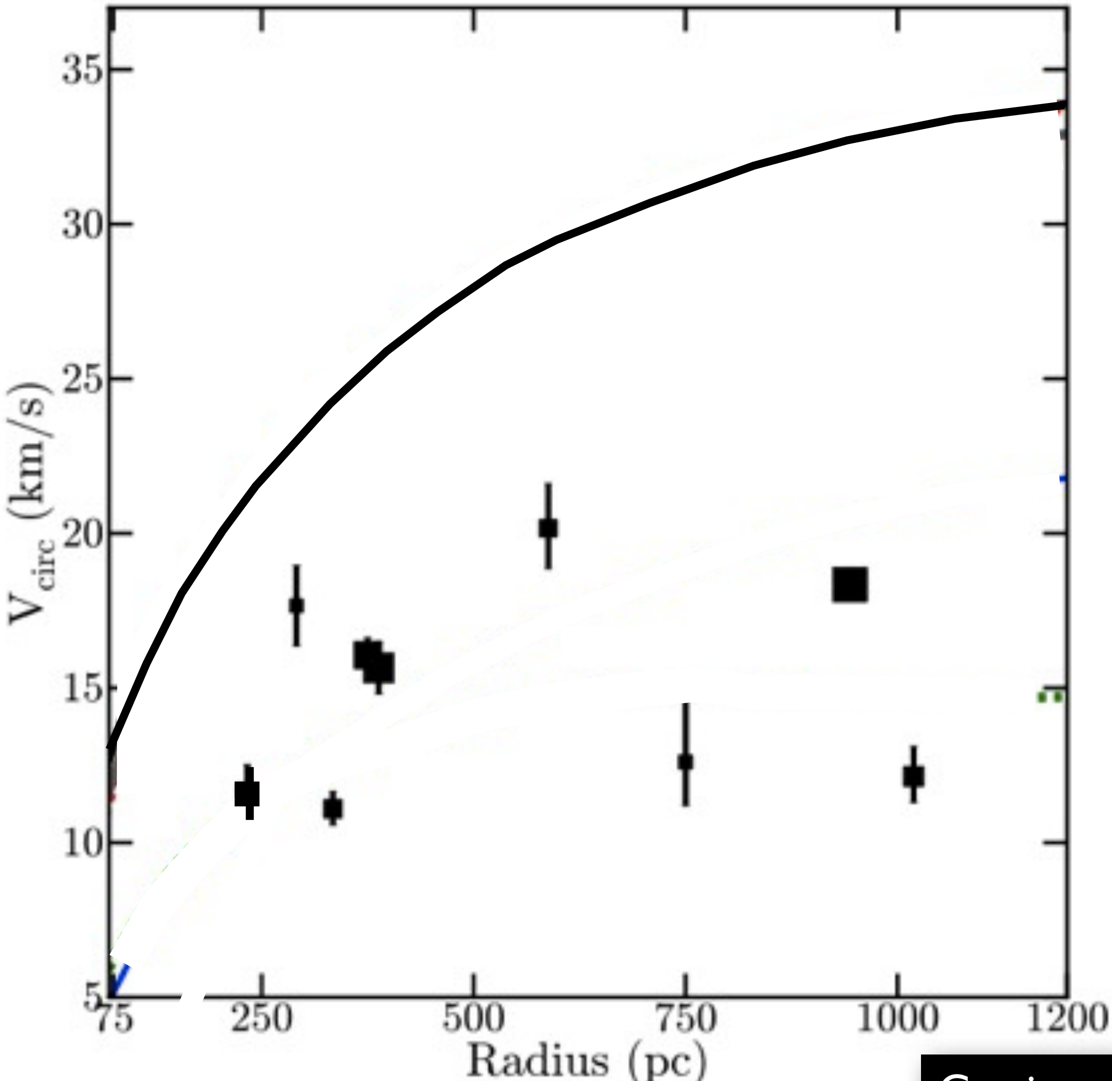
ϵ = 10pc (spline = 14pc)



Dwarf galaxy potential w/ variable mass dial stuck in the middle. (*Mimics episodes of star formation & feedback*)

Garrison-Kimmel et al. 2013a

What does it take to solve the problem?



$M_* \sim 10^6\ M_{sun}$ Galaxy

Garrison-Kimmel et al. 2013a

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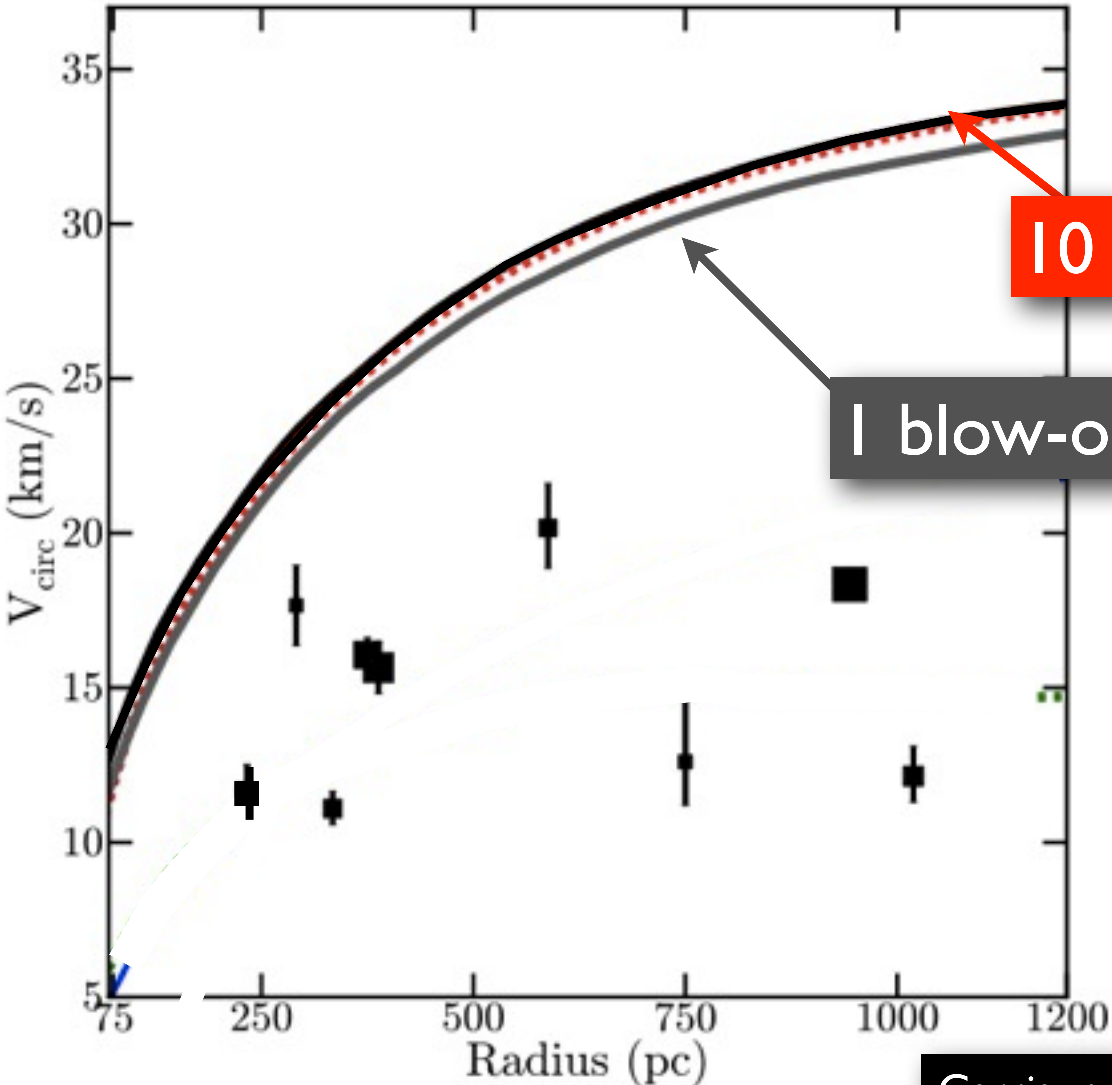

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Garrison-Kimmel et al. 2013a

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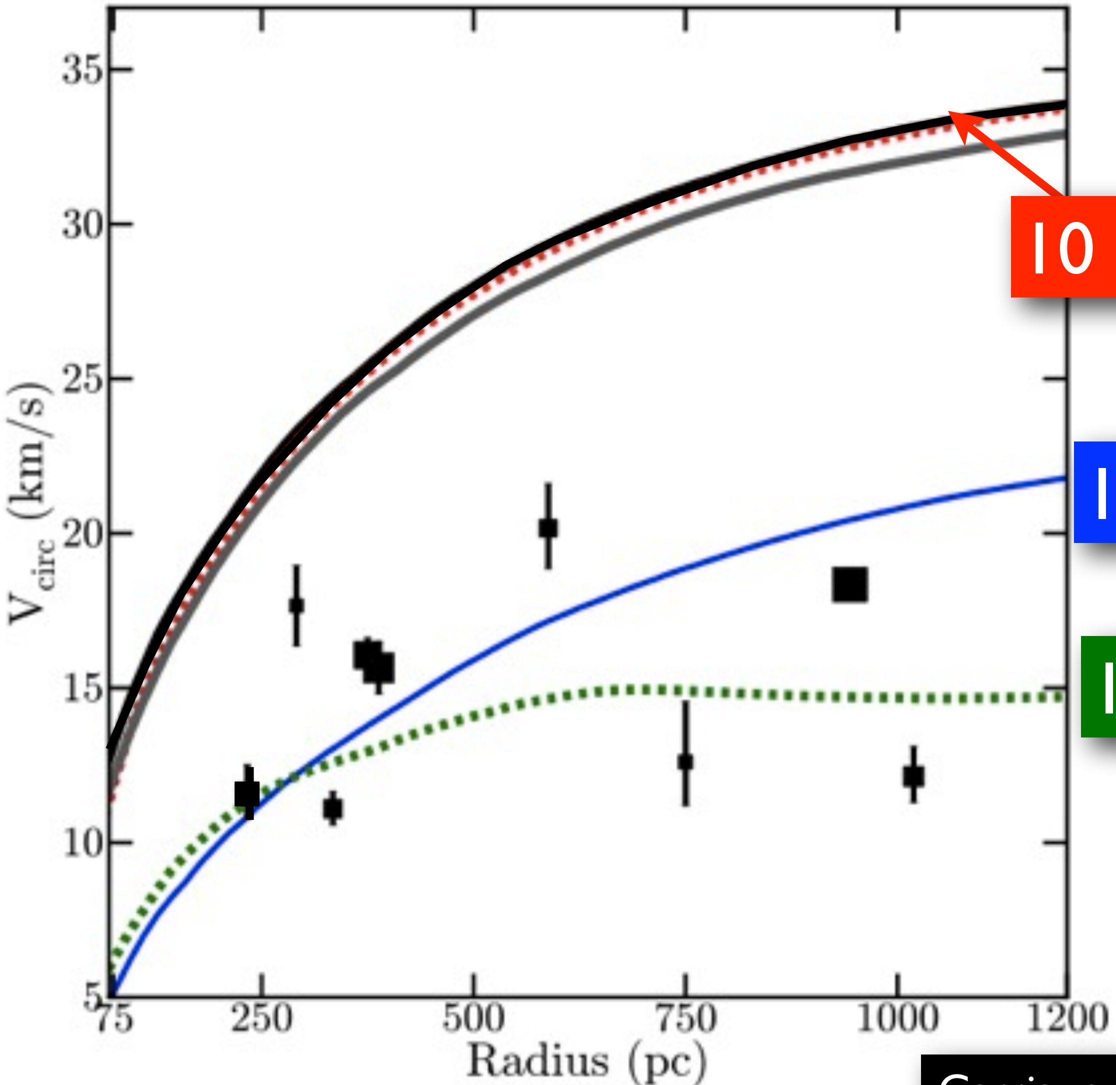


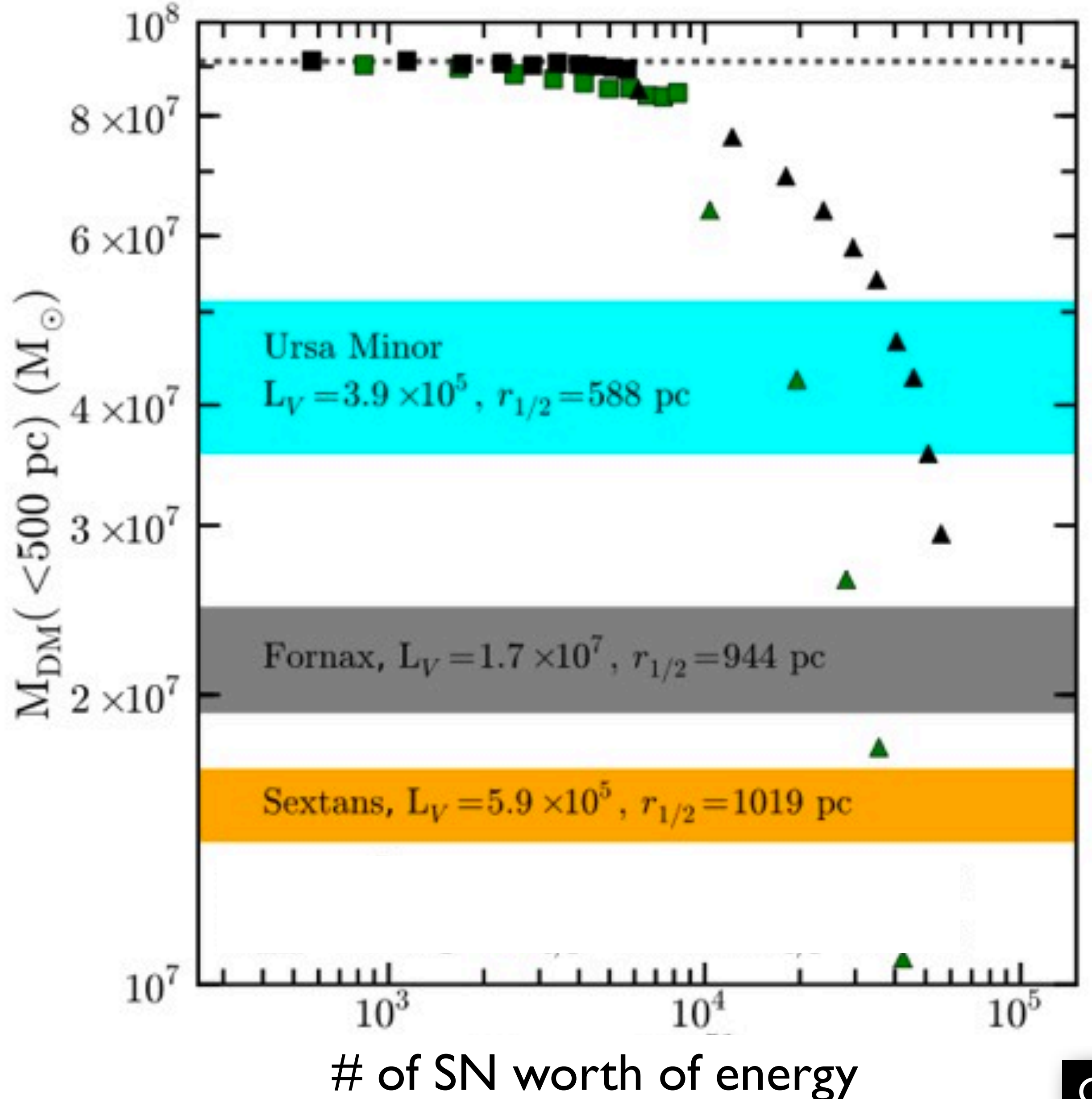
$M_* \sim 10^6\ M_{sun}$ Galaxy

10 blow-outs of $10^7\ M_{sun}$

10 blow-outs of $10^8\ M_{sun}$

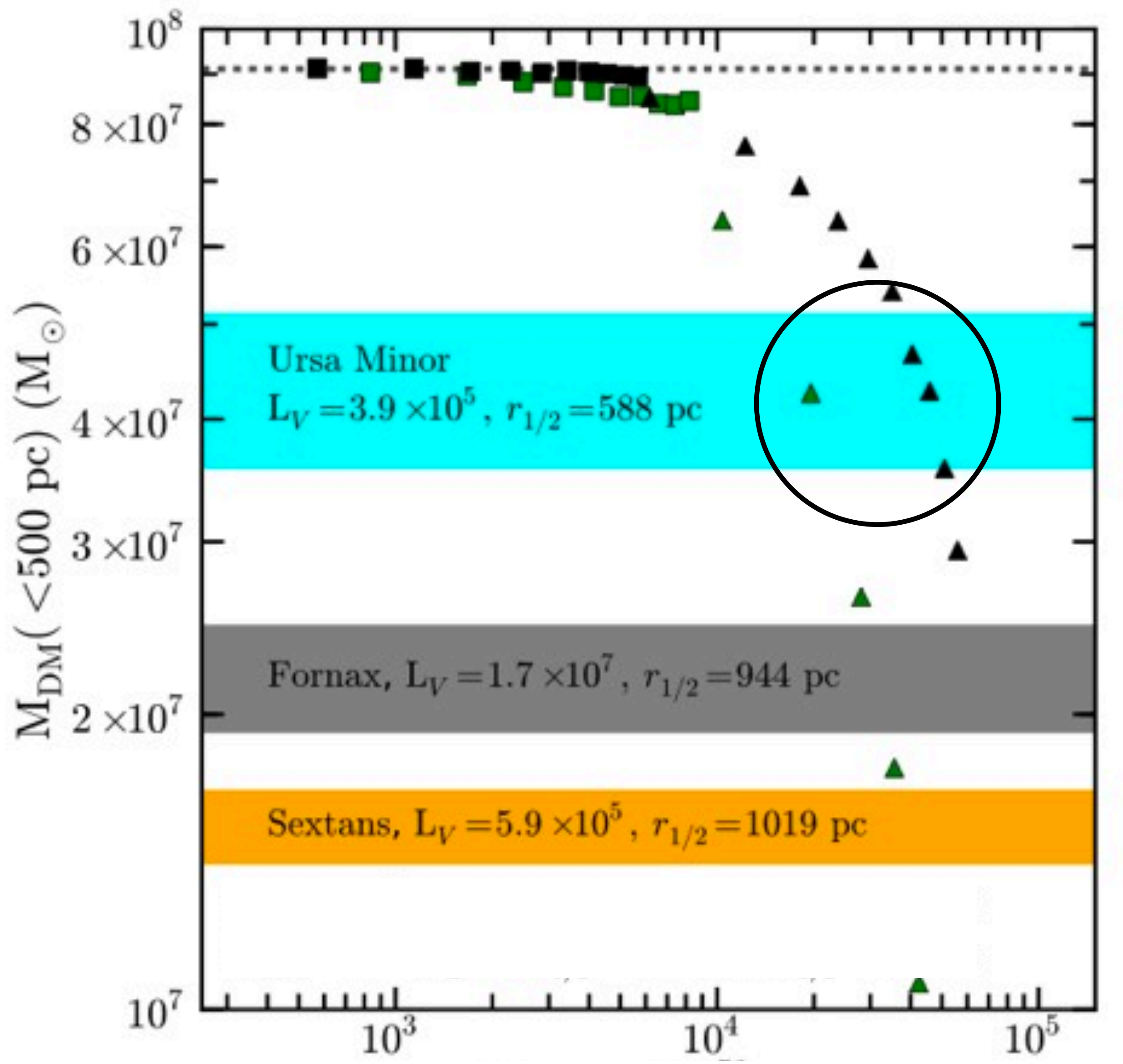
1 blow-out of $10^9\ M_{sun}$

Garrison-Kimmel et al. 2013a



Expect:
0.01 Supernova per solar mass of stars.

Garrison-Kimmel et al. 2013a



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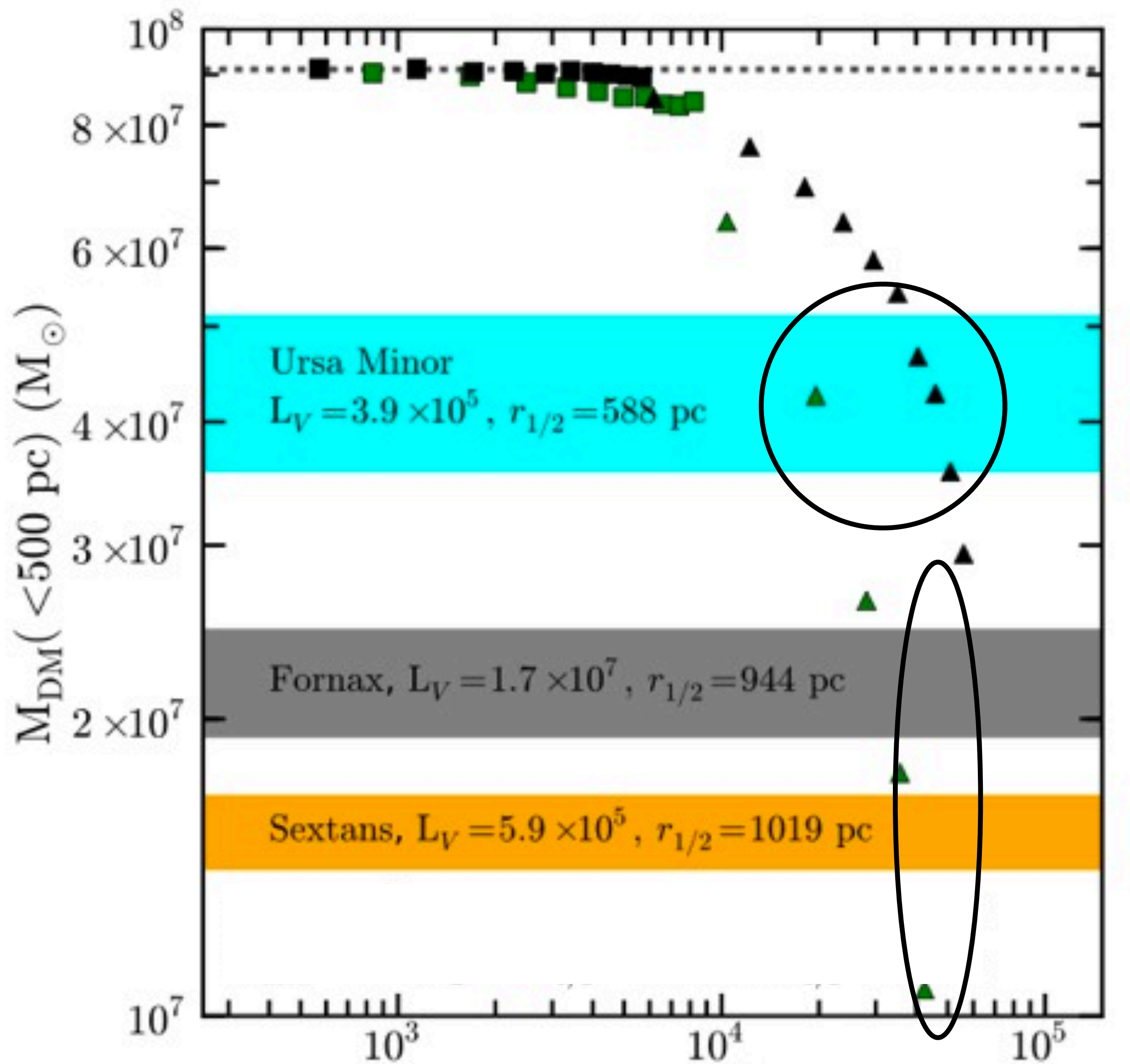
Req. more energy than sum of all supernovae in this galaxy!

Garrison-Kimmel et al. 2013a



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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

Jose Oñorbe

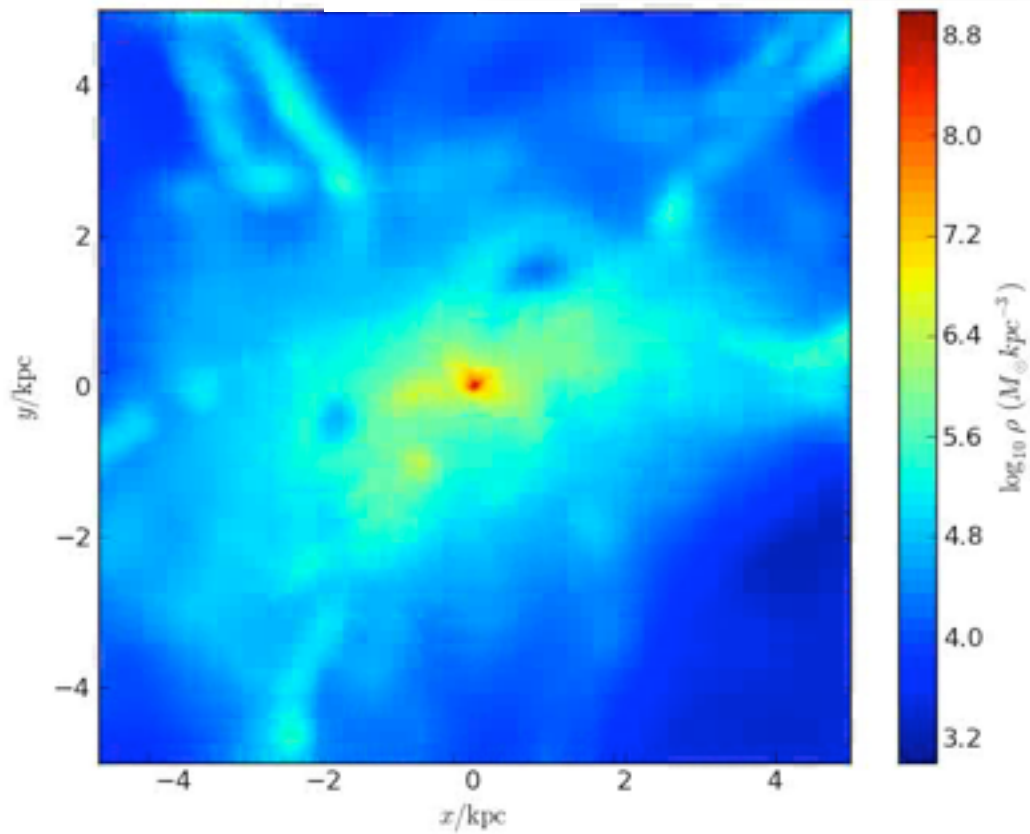
Cosmological Dwarf Halo: V_{max}=35 km/s

Use "P-GADGET" SPH
- Overcomes most standard SPH issues
- Hopkins, Quartaert, and Murray (2012)

Oñorbe et al. (in prep)

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

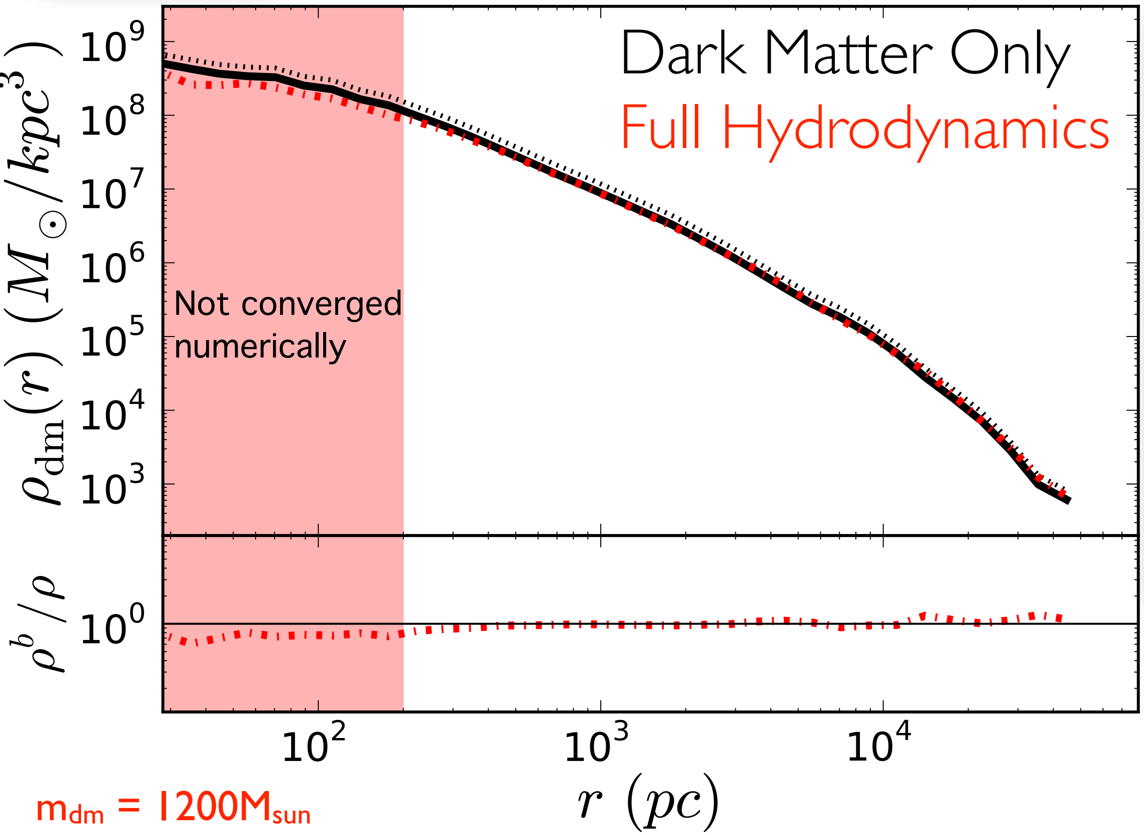
- Self-consistent ISM.
- **Hydro never turned off.**
- Fine-structure cooling to ~100K
- SNe (II & Ia), Radiation pressure from stellar winds, Photoionization (HII Regions)
- Stellar feedback inputs (energy, momentum, metal fluxes) directly from stellar pop models

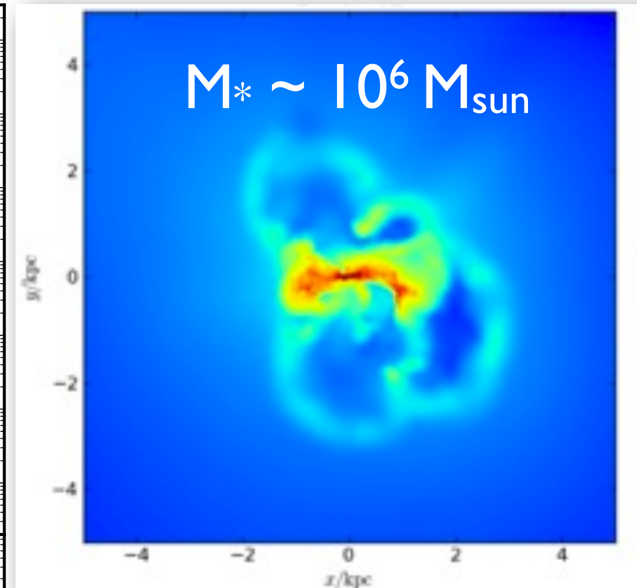


Jose Oñorbe

Oñorbe et al. (in prep)

Minimal change in DM density



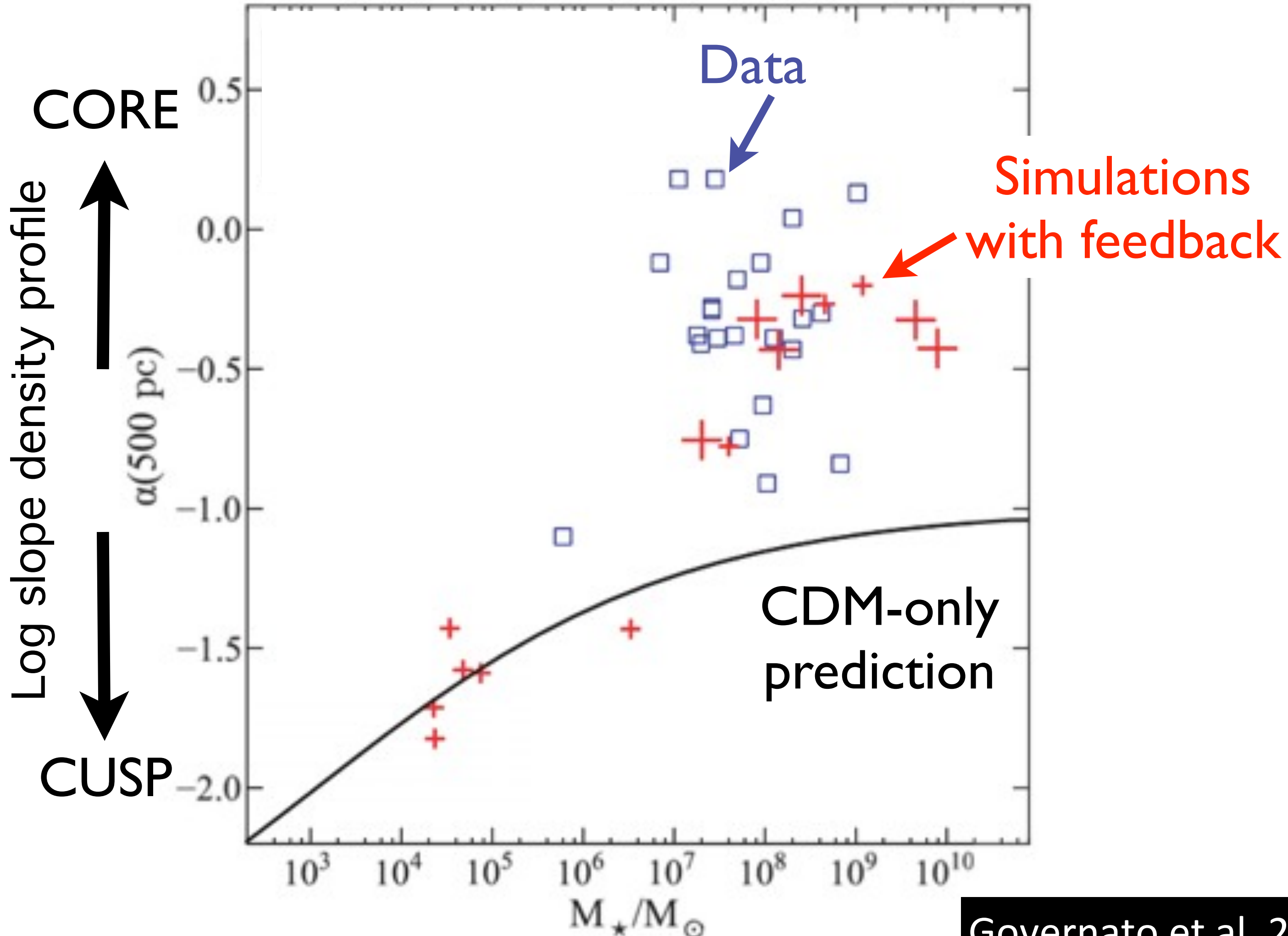


m_{dm} = 1200M_{sun}
m_{gas} = 250M_{sun}
ϵ_{dm} = 40pc

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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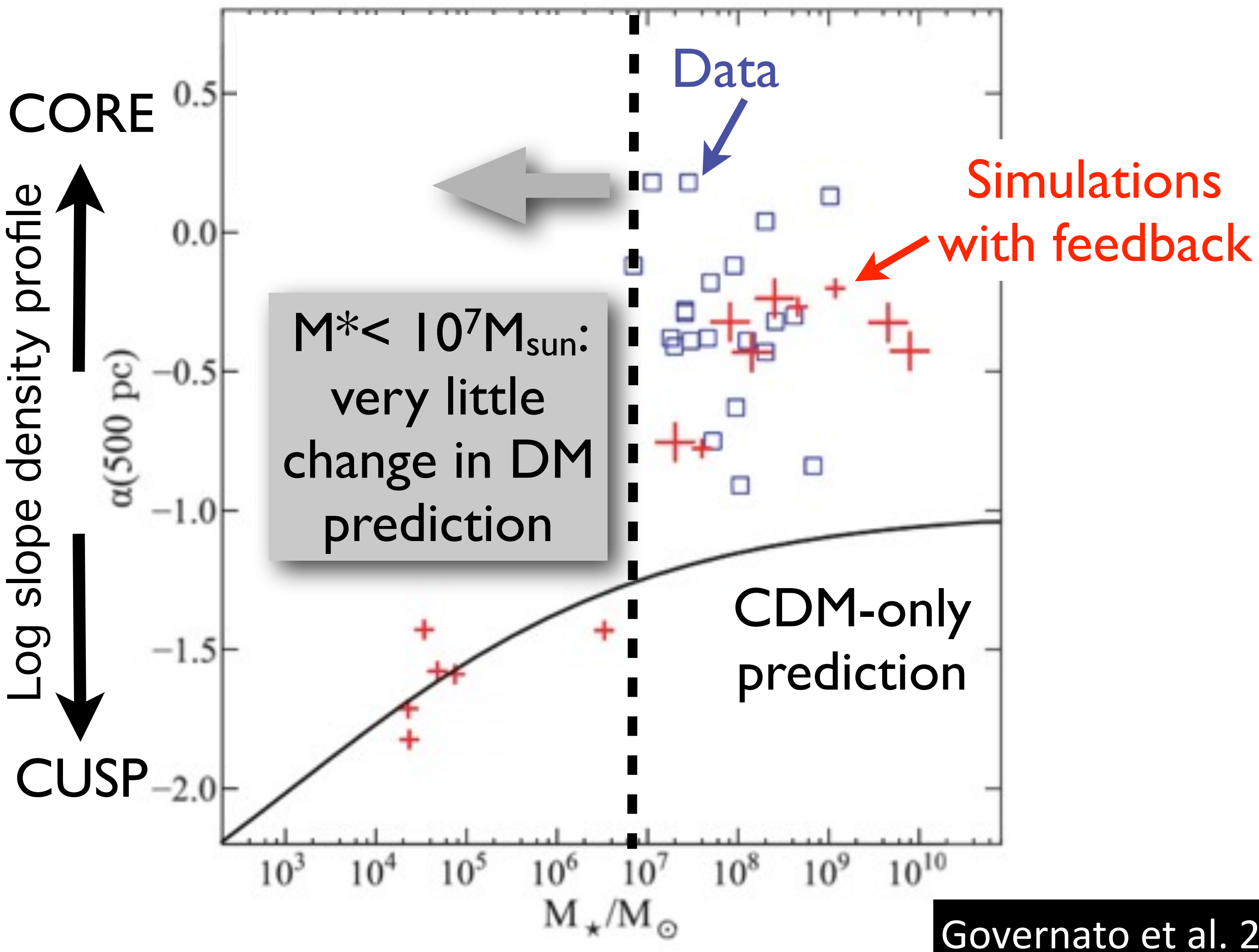


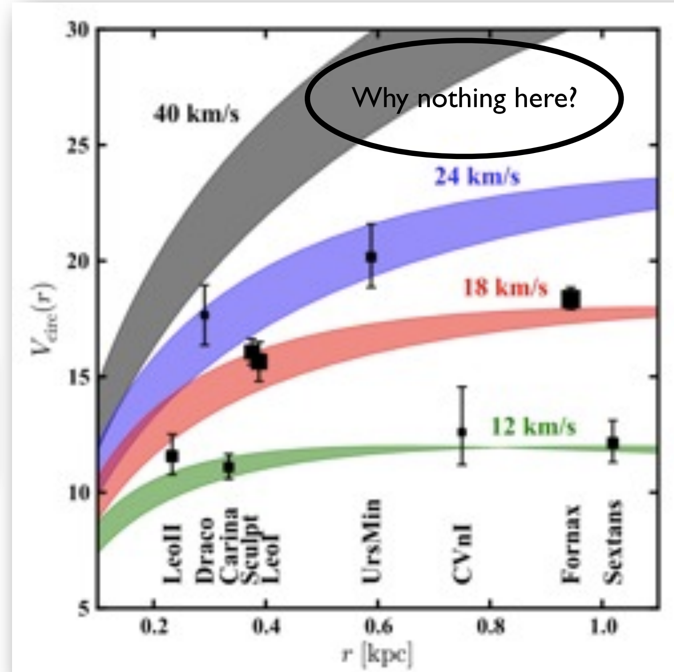
Governato et al. 2012

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

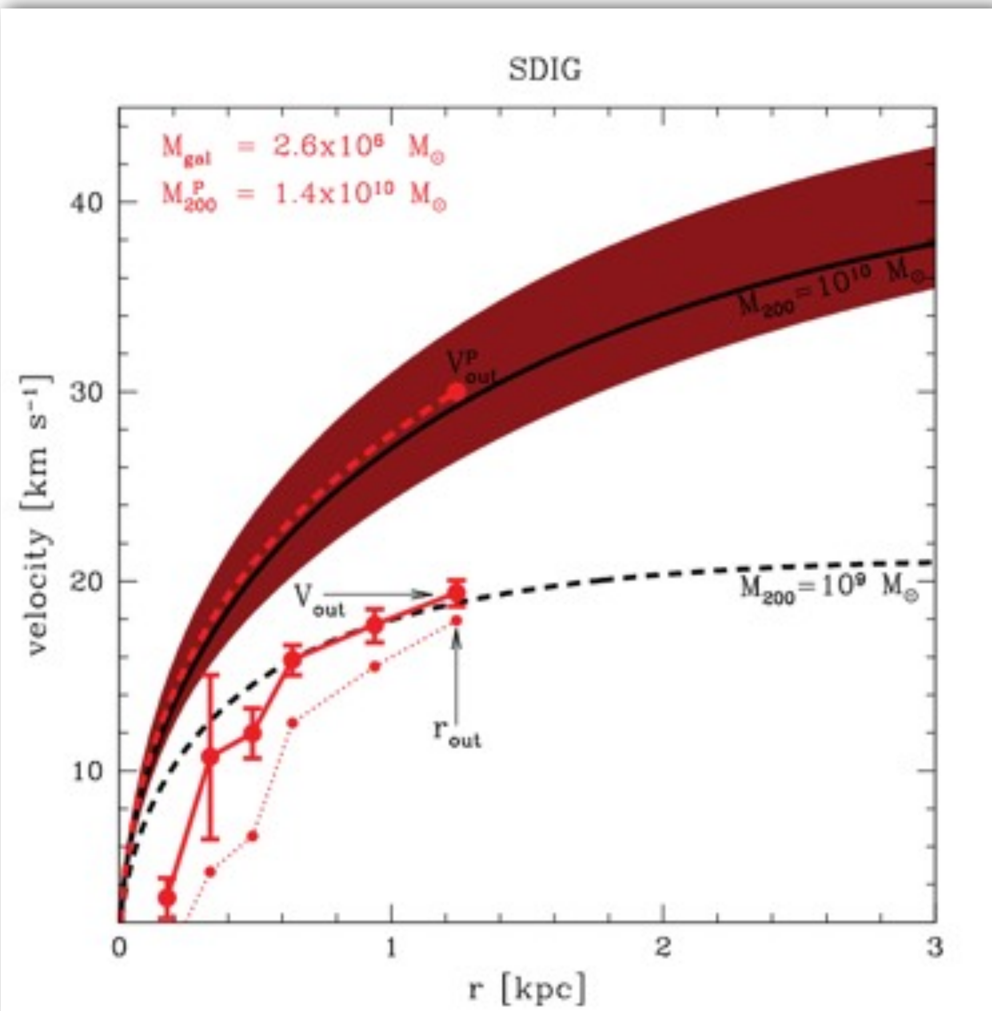


Environment: best bet

- 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}

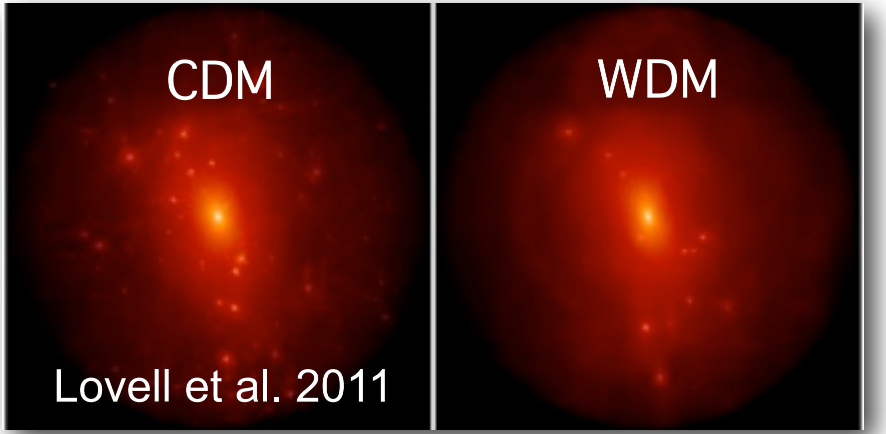
- **Same problem**: not dense enough

- 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?

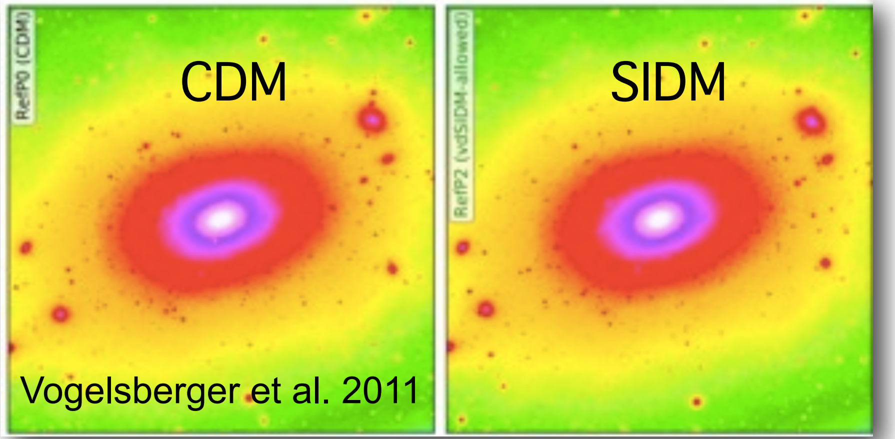
Warm Dark Matter:



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

Lovell et al. 2011

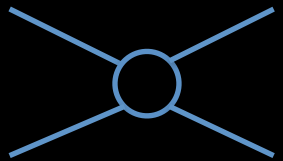
Self-interacting Dark Matter:



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

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

Simulating Self-interacting DM



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

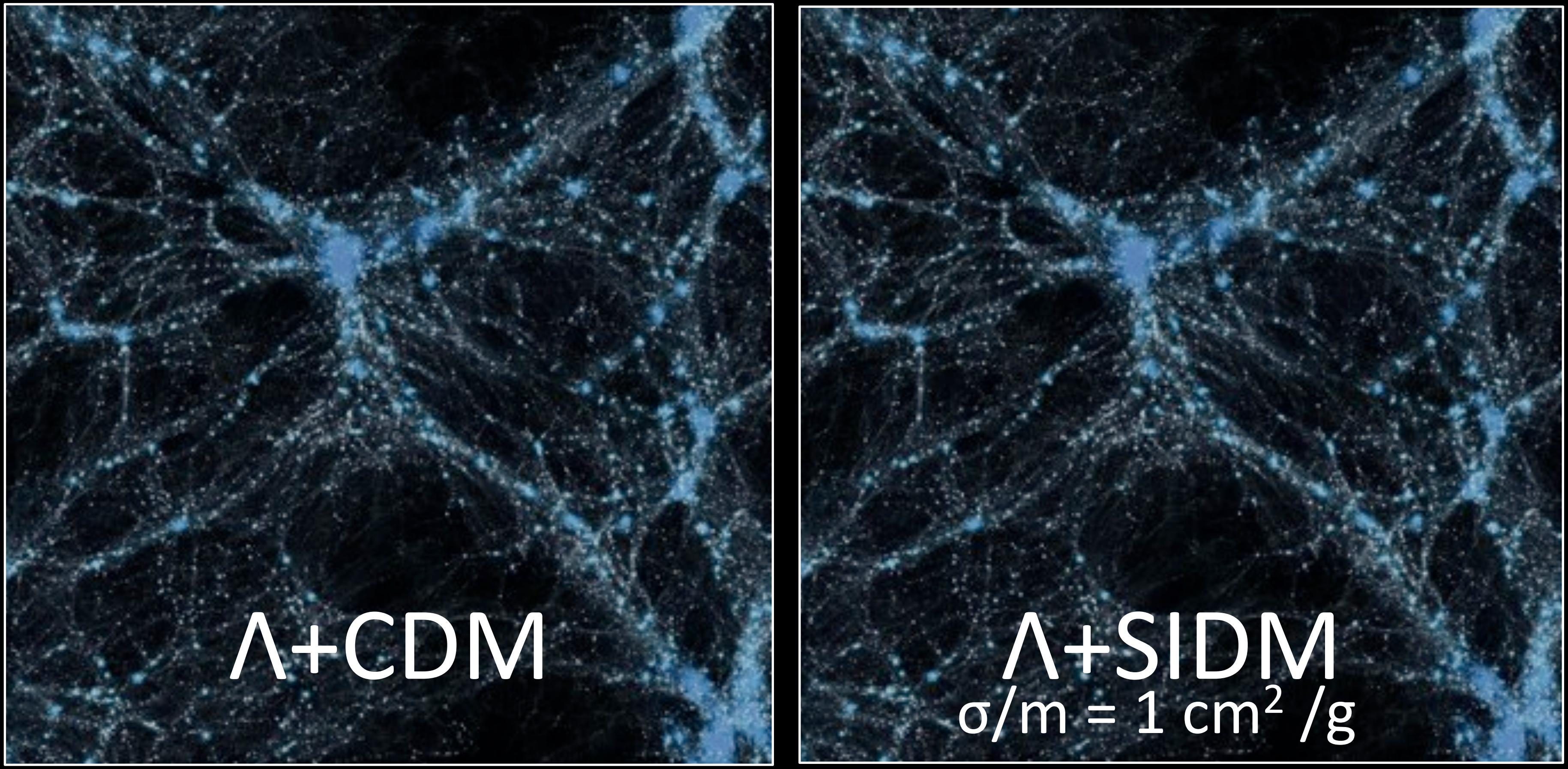
For now: Elastic, Velocity Independent, Isotropic

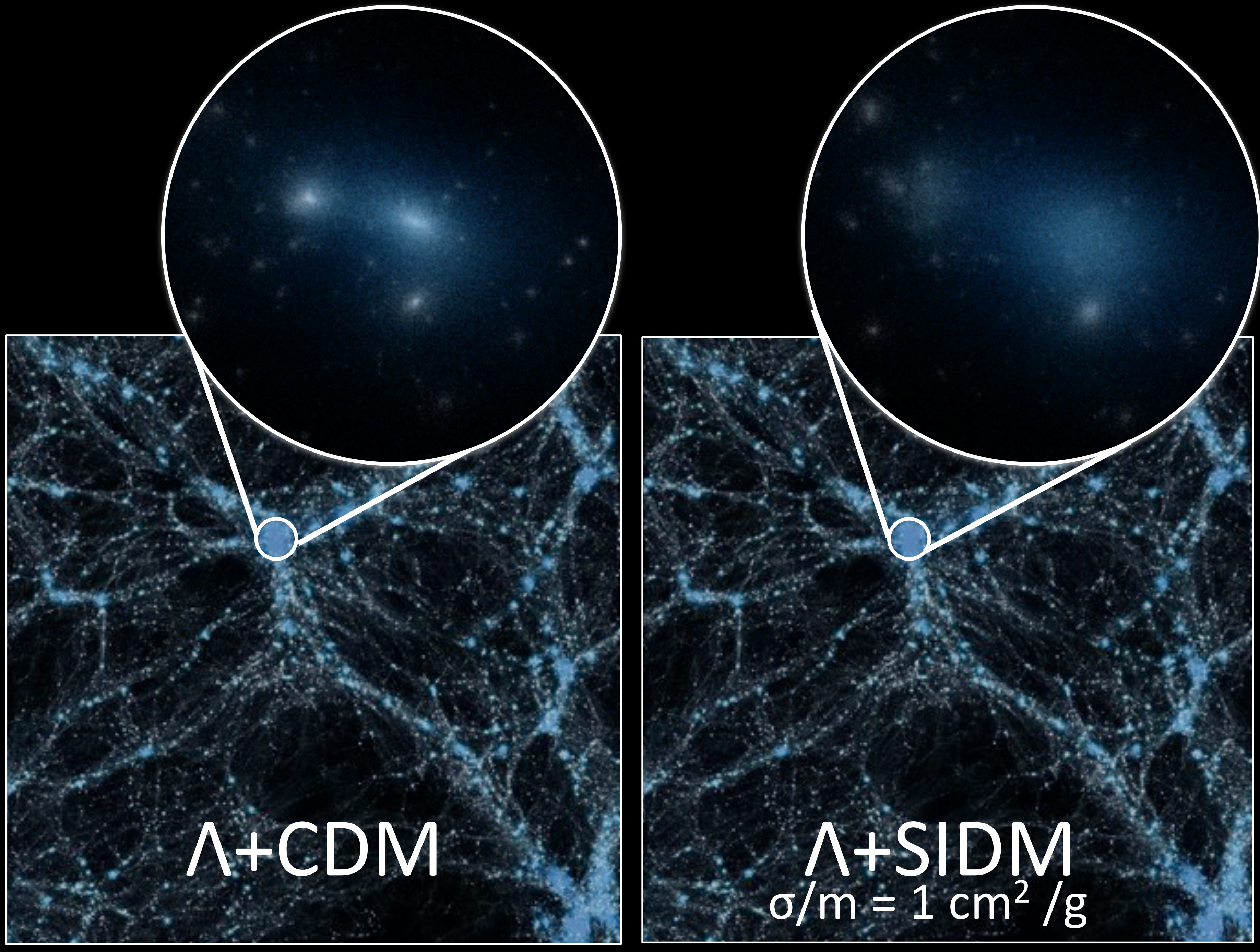
Interesting things happen when $\Gamma \sim H_0$

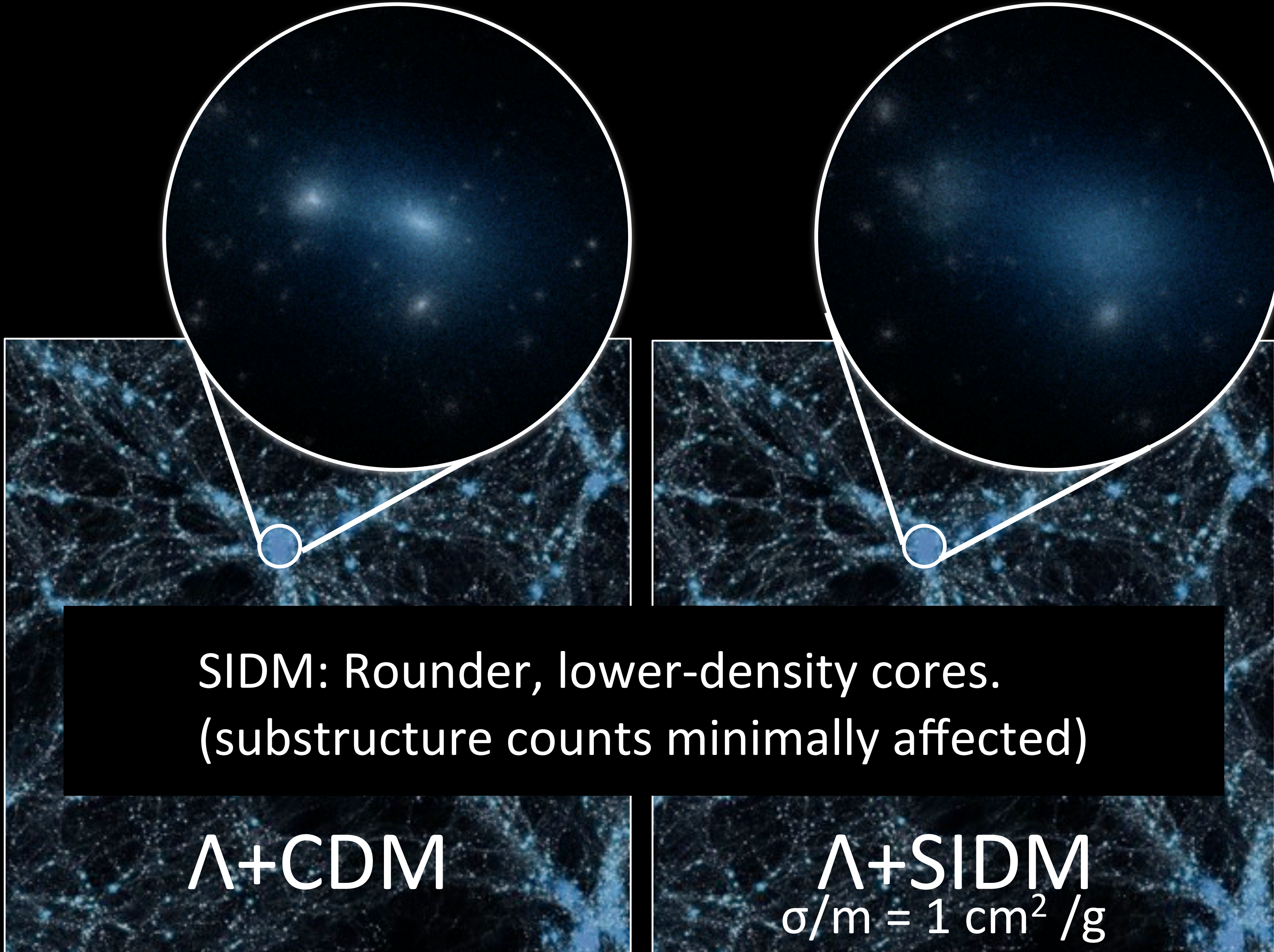
For discussion of our method see talk by Miguel Rocha

$$P_{ij} = \left(\frac{\sigma}{m}\right) M_p \Delta v_{ij}\, g_{ij}\, \delta t$$

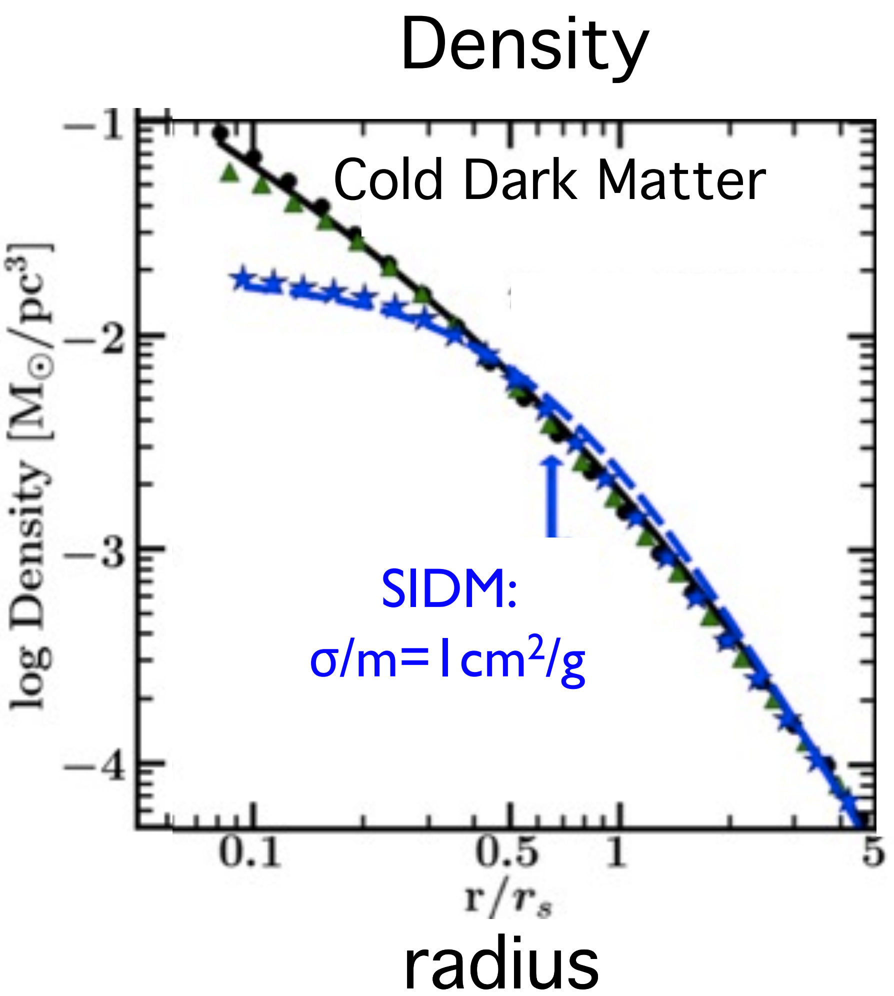
Identical large-scale structure




Λ+CDM
Λ+SIDM
σ/m = 1 cm² /g


SIDM: Rounder, lower-density cores.
(substructure counts minimally affected)
Λ+CDM
Λ+SIDM
σ/m = 1 cm² /g

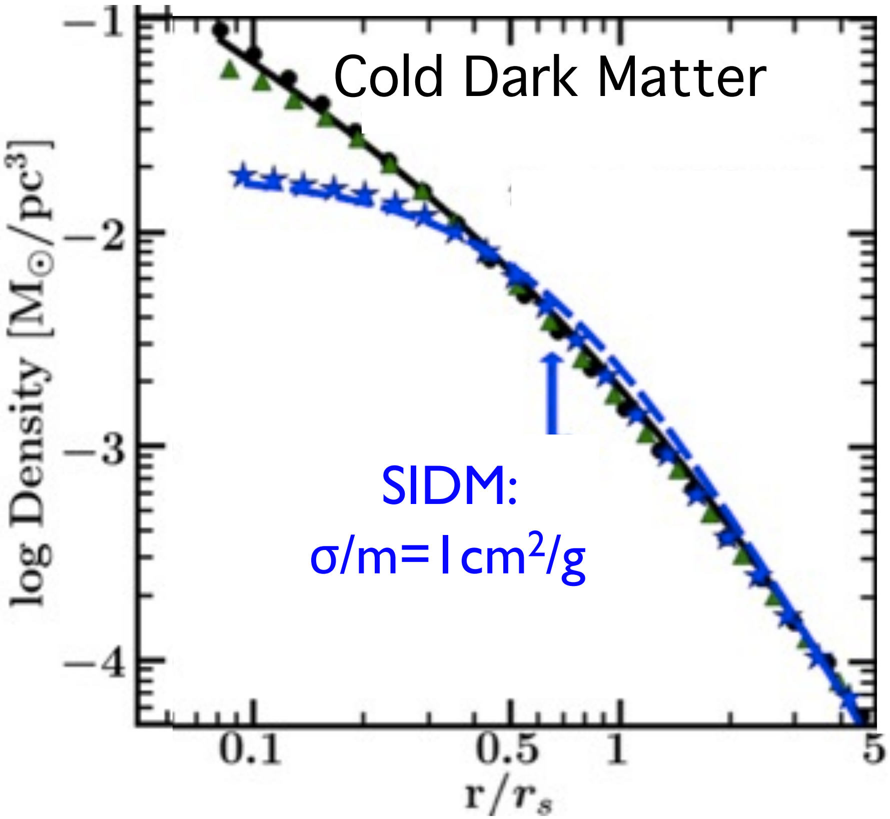
SIDM Makes Cored Halos



Rocha et al. 2012

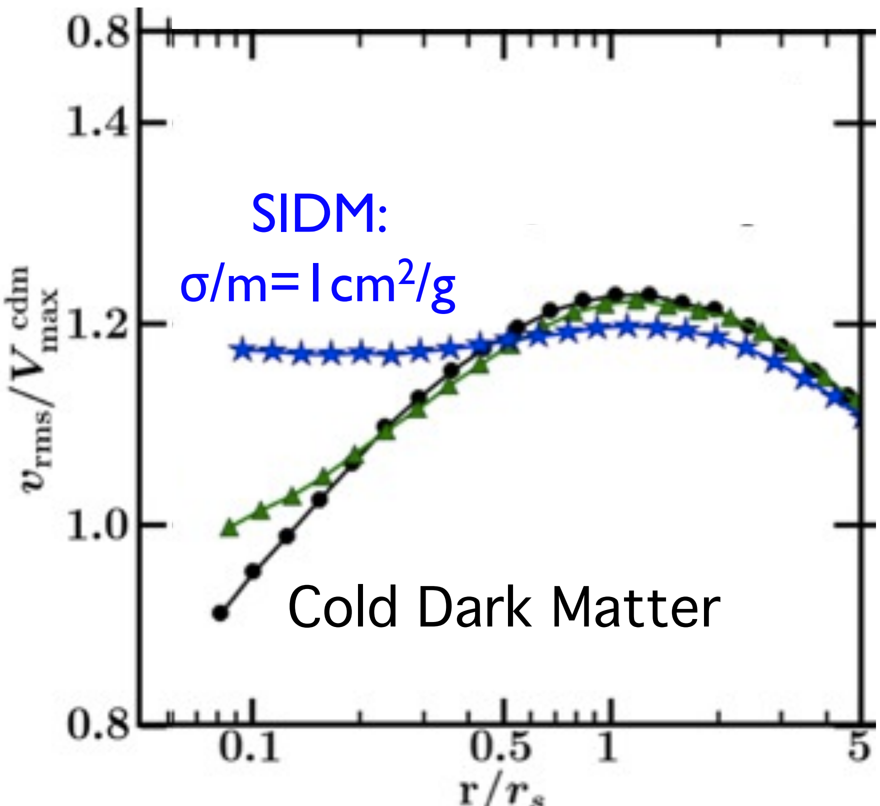
SIDM Makes Cored Halos

Density



radius

Velocity Dispersion

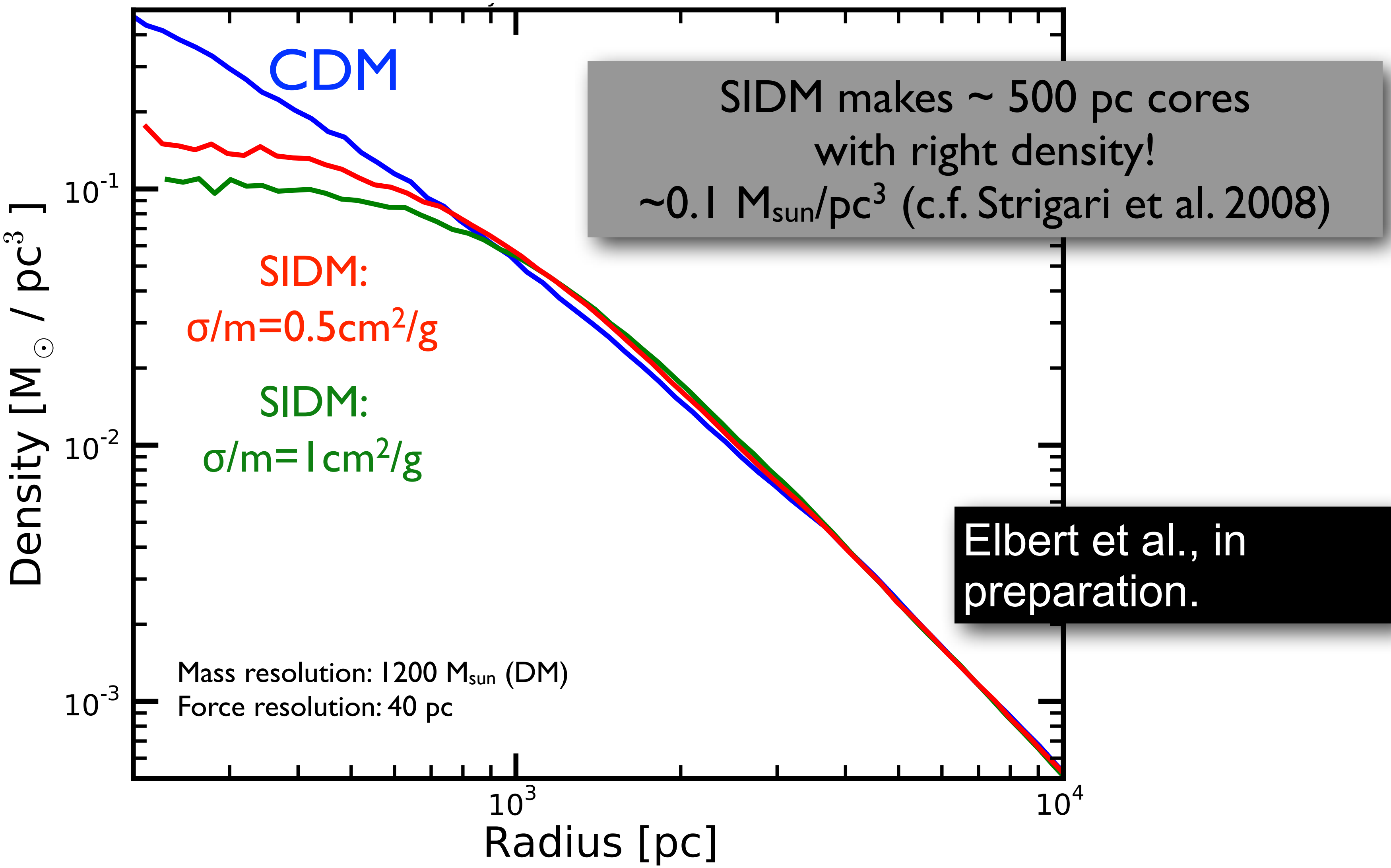


radius

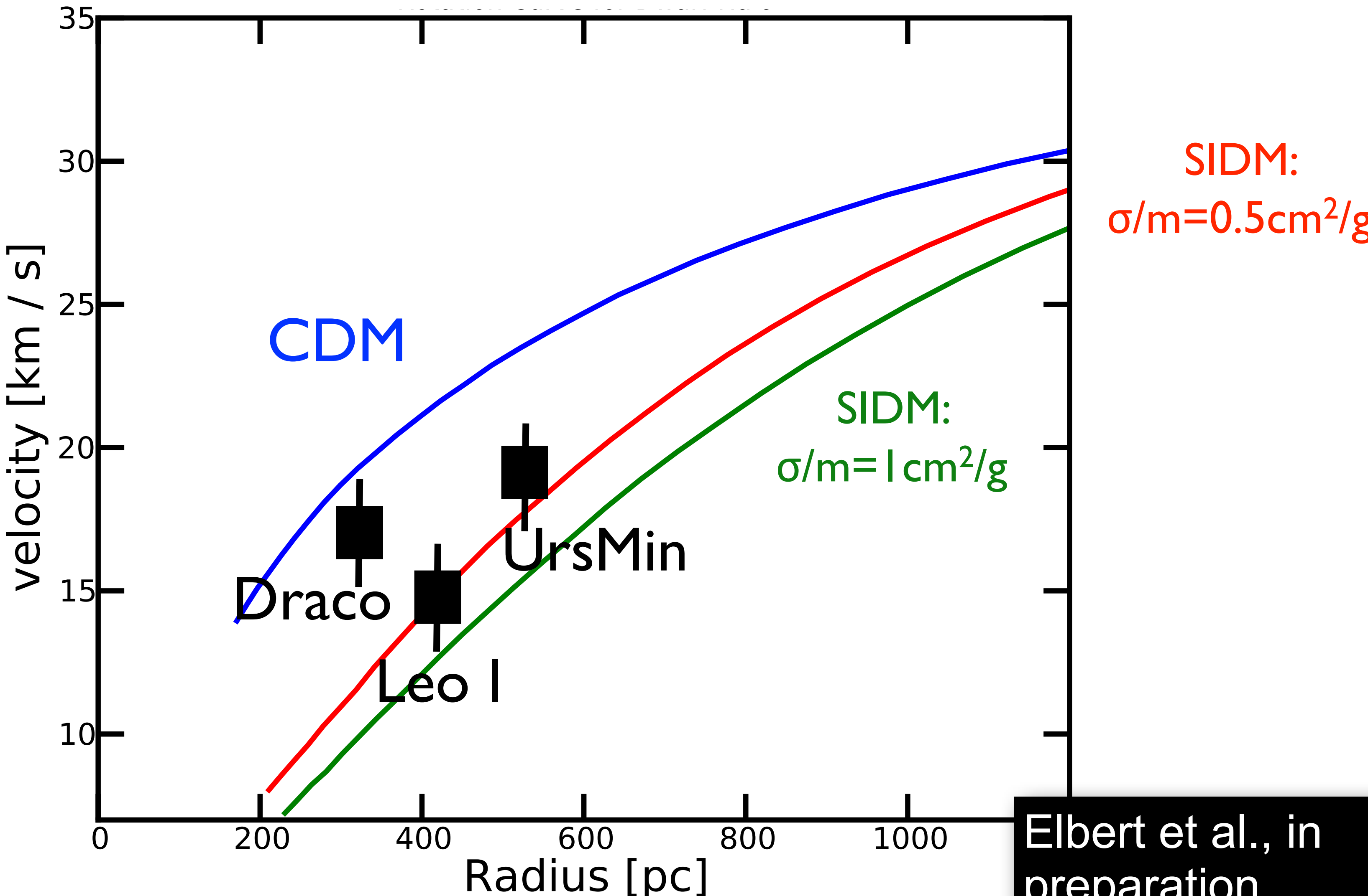
Rocha et al. 2012

Isothermal velocity profile creates core.

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



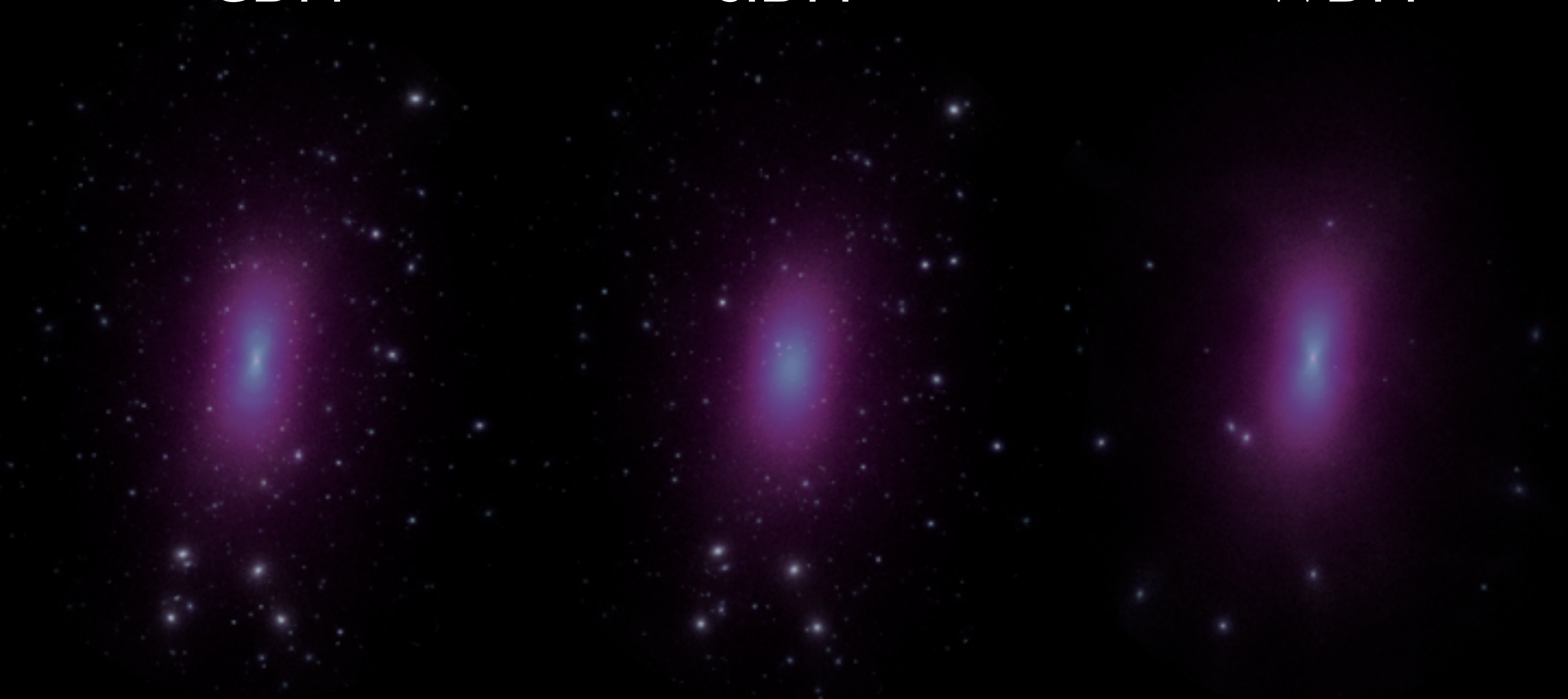
SIDM with σ/m=(0.5-1)cm²/g Solves Too Big To Fail Problem



Elbert et al., in preparation.

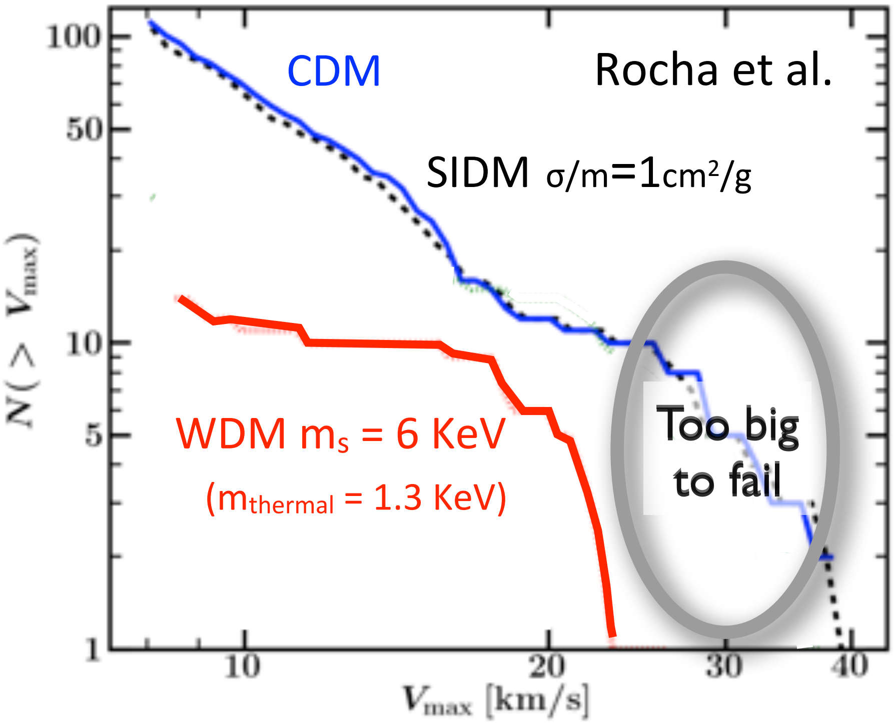
Phenomenology of SIDM vs. WDM

CDM SIDM WDM



Rocha et al., in prep.

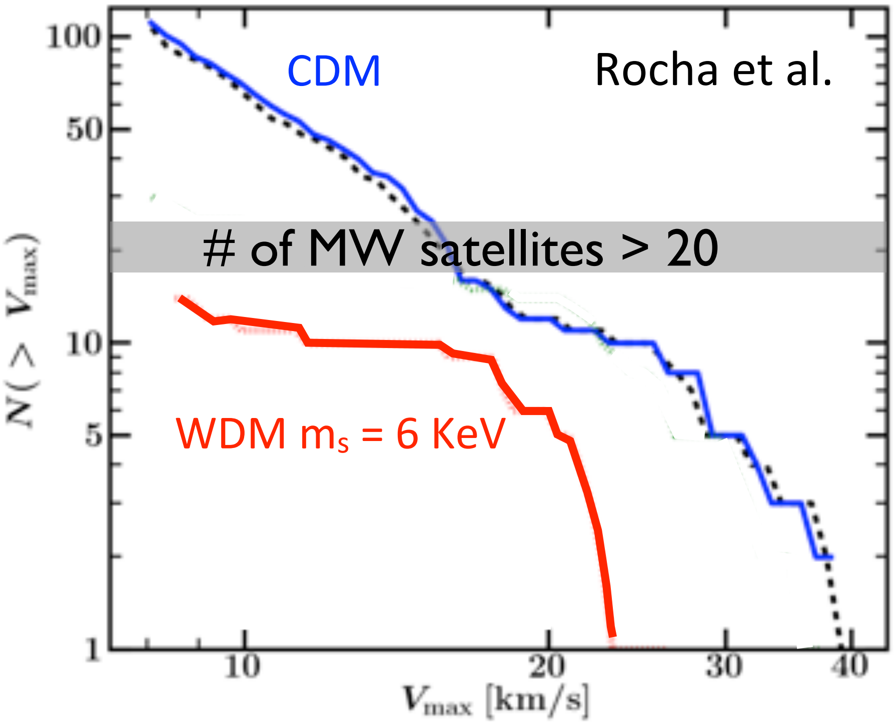
Dark Matter Phenomenology in the Milky Way Halo



WDM:
- Many fewer subhalos

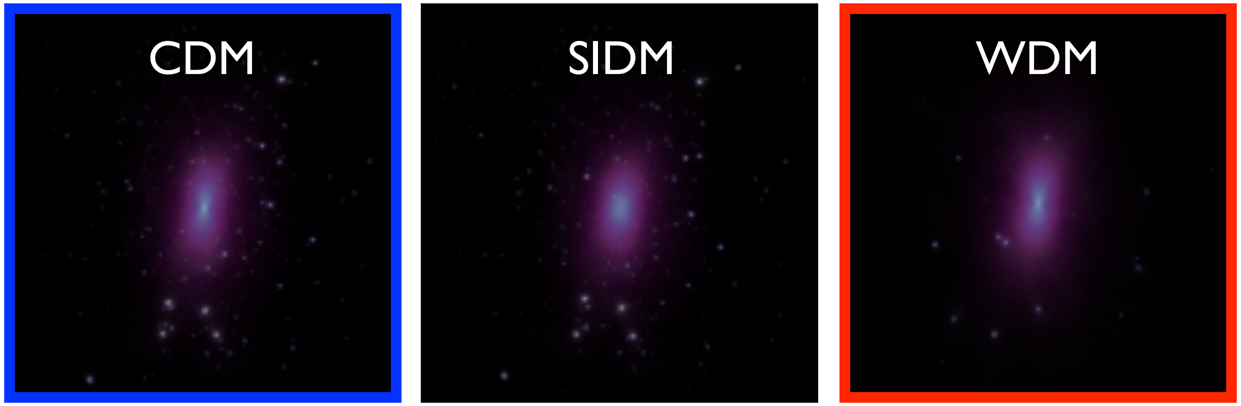
SIDM:
- Roughly same *number* of subhalos
- Solves Too Big To Fail by creating cores in all halos

Dark Matter Phenomenology in the Milky Way Halo

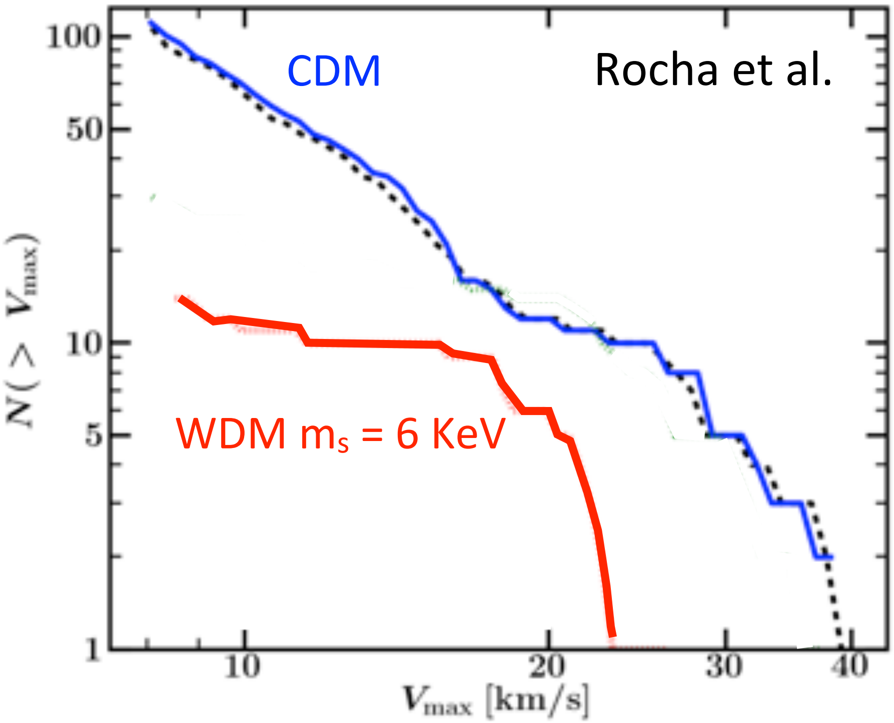


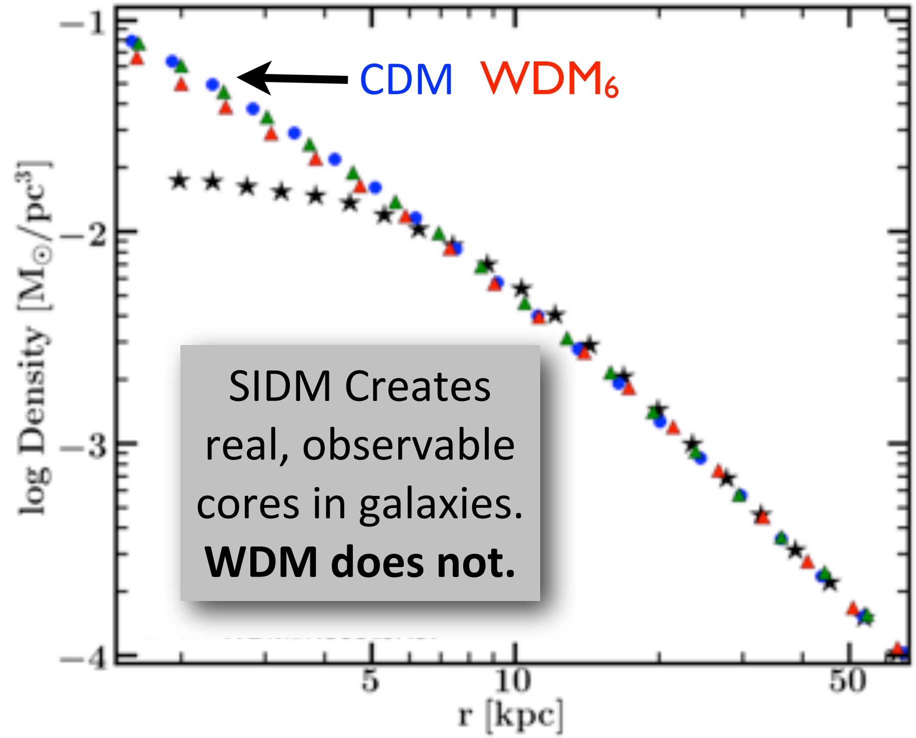
WDM:
- Solves Too Big To Fail by removing offending subhalos all together.

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



Dark Matter Phenomenology in the Milky Way Halo





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
  - tides from disk/ram-pressure stripping; test w/ obs of isolated dwarfs
- **Dark Matter physics?**
  - WDM: struggles w/ satellite counts, ly-a forest, reionization. No big cores.

  - **SIDM** with **$\sigma/m \sim$ 0.5-1 cm^2/g** can do it.

  (This cross section appears consistent w/ Bullet Cluster, cluster shapes, galaxy densities, but tests are ongoing. See W. Dawson / A. Peter talks.)