Simulating Dark Matter Self-Interactions

Miguel Rocha - UC Irvine

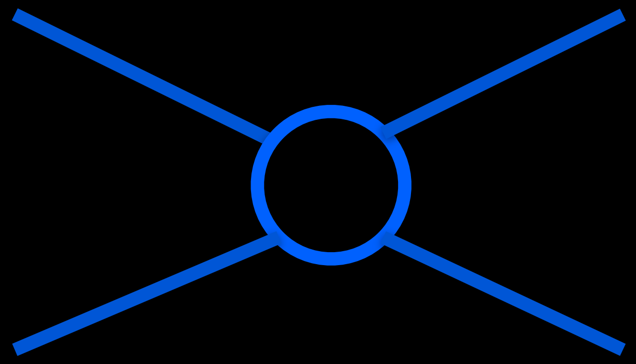
Harvard Self-Interacting Dark Matter Workshop

08/06/2013

Outline

- Implementing DM self-iteractions - A new self-consistent algorithm
- Results from cosmological simulations - Halo densities, shapes and substructure
- Work in progress and future goals - Expand simulation sample, merging clusters, etc ...

Simulating DM Self-Interactions

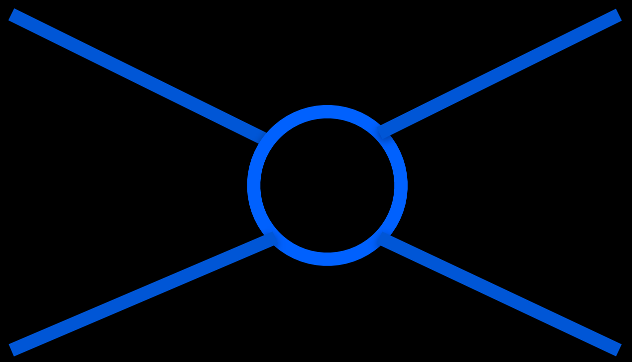


large mean free paths

Collisionality

short mean free paths

Simulating DM Self-Interactions



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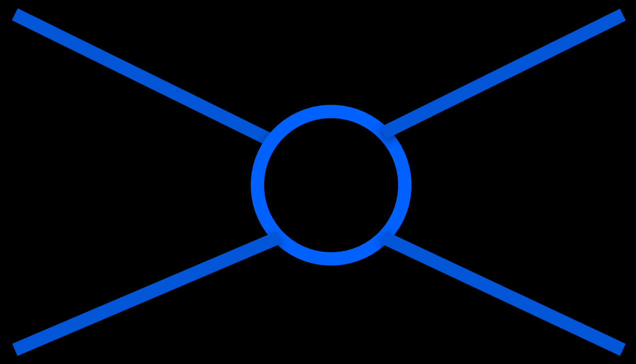
Vlavsov equation solved with collisionless N-body

Simulating DM Self-Interactions



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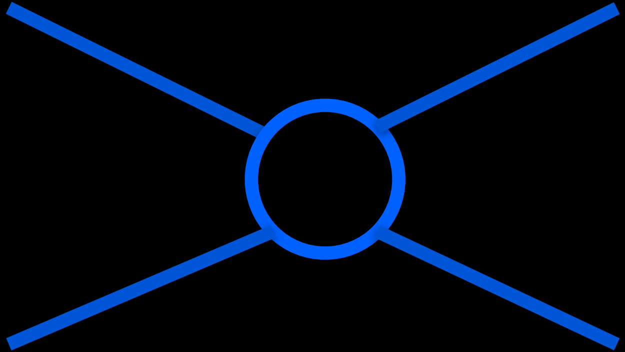

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Spergerl & Steinhardt 2000

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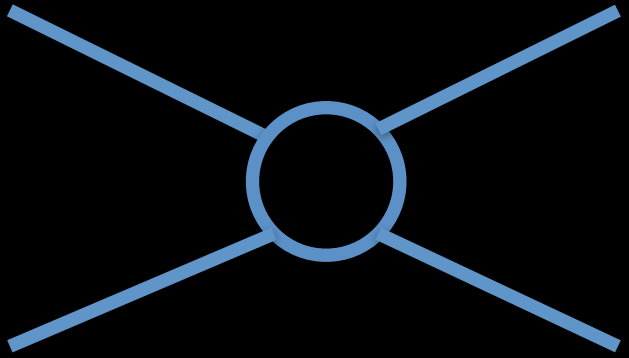
Simulating DM Self-Interactions



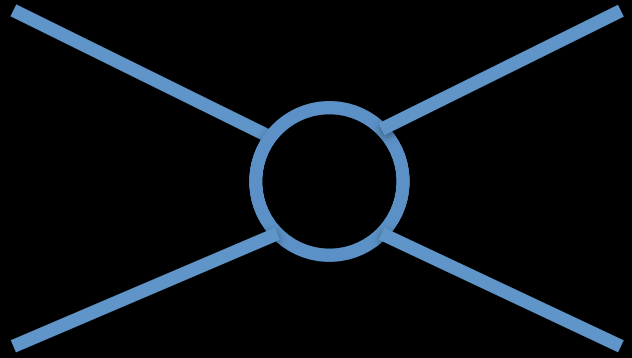
Spergerl & Steinhardt 2000

$$\xrightarrow[\text{Elastic - Velocity Independent - Isotropic}]{}$$

Elastic - Velocity Independent - Isotropic

$$\Gamma = \rho \left(\frac{\sigma}{m} \right) v_{rel}$$

Simulating DM Self-Interactions



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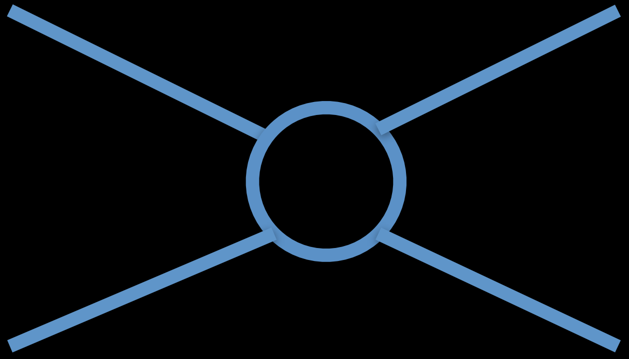
$$\Gamma = \rho \left(\frac{\sigma}{m}\right) v_{rel}$$

$$P_i = \rho_i \left(\frac{\sigma}{m}\right) V_i \Delta t$$

Burkert 2000, Kochaneck & White
2000, Yoshida et al. 2000b

Simulating DM Self-Interactions



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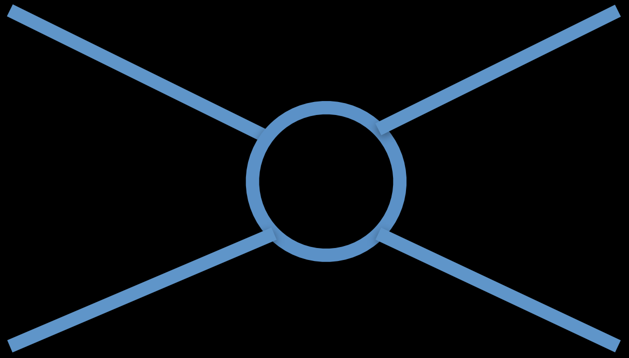
$$P_i = \sum_j m W(|\hat{\mathbf{x}}_i - \hat{\mathbf{x}}_j|, h_j) \left(\frac{\sigma}{m}\right) |\hat{\mathbf{v}}_i - \hat{\mathbf{v}}_j| \Delta t$$

Koda & Shapiro 2011, Vogelsberger et al. 2012

Simulating DM Self-Interactions



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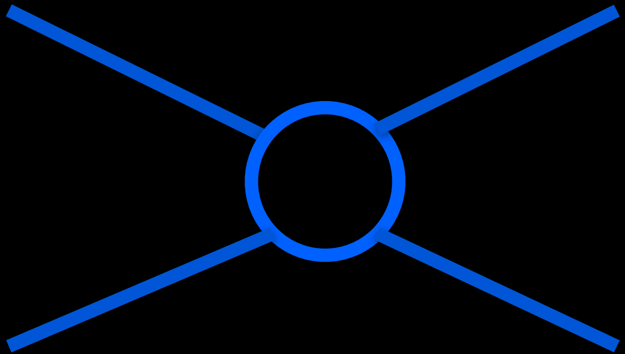
$$P(i|j) \neq P(j|i)$$

Simulating DM Self-Interactions



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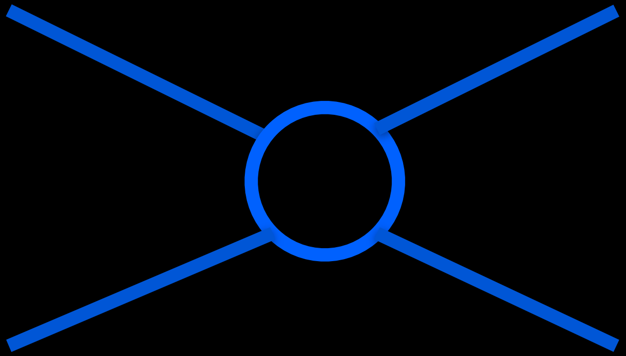

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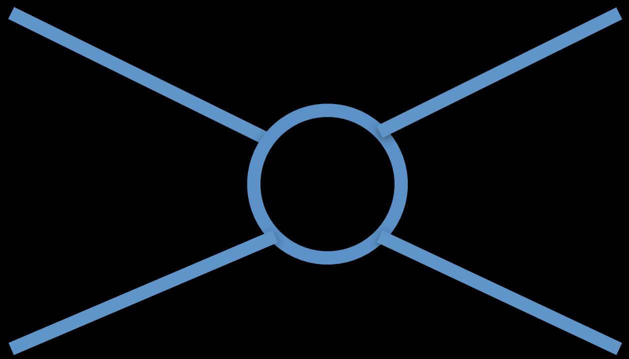
Need to step back and derive an algorithm from the Boltzmann Equation

Simulating DM Self-Interactions - A new self-consistent algorithm



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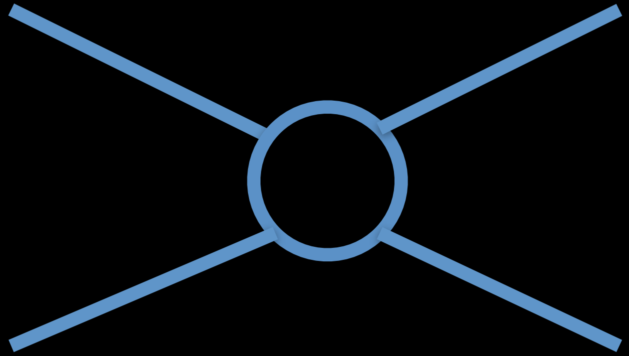
phase-space evolution given by the Boltzmann Eq. with a hard-sphere collision operator

$$\begin{aligned} \frac{Df(\mathbf{x},\mathbf{v},t)}{Dt} &= \Gamma[f,\sigma] \\ &= \int d^3\mathbf{v}_1 \int d\Omega \frac{d\sigma}{d\Omega} \left|\mathbf{v}-\mathbf{v}_1\right| \left[f(\mathbf{x},\mathbf{v}',t) f(\mathbf{x},\mathbf{v}_1',t) - f(\mathbf{x},\mathbf{v},t) f(\mathbf{x},\mathbf{v}_1,t) \right] \end{aligned}$$

Simulating DM Self-Interactions - A new self-consistent algorithm



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$$\hat{f}(\mathbf{x},\mathbf{v},t) = \sum_i (M_i/m) W(|\mathbf{x}-\mathbf{x}_i|;h_i)\delta^3(\mathbf{v}-\mathbf{v}_i)$$

Simulating DM Self-Interactions - A new self-consistent algorithm

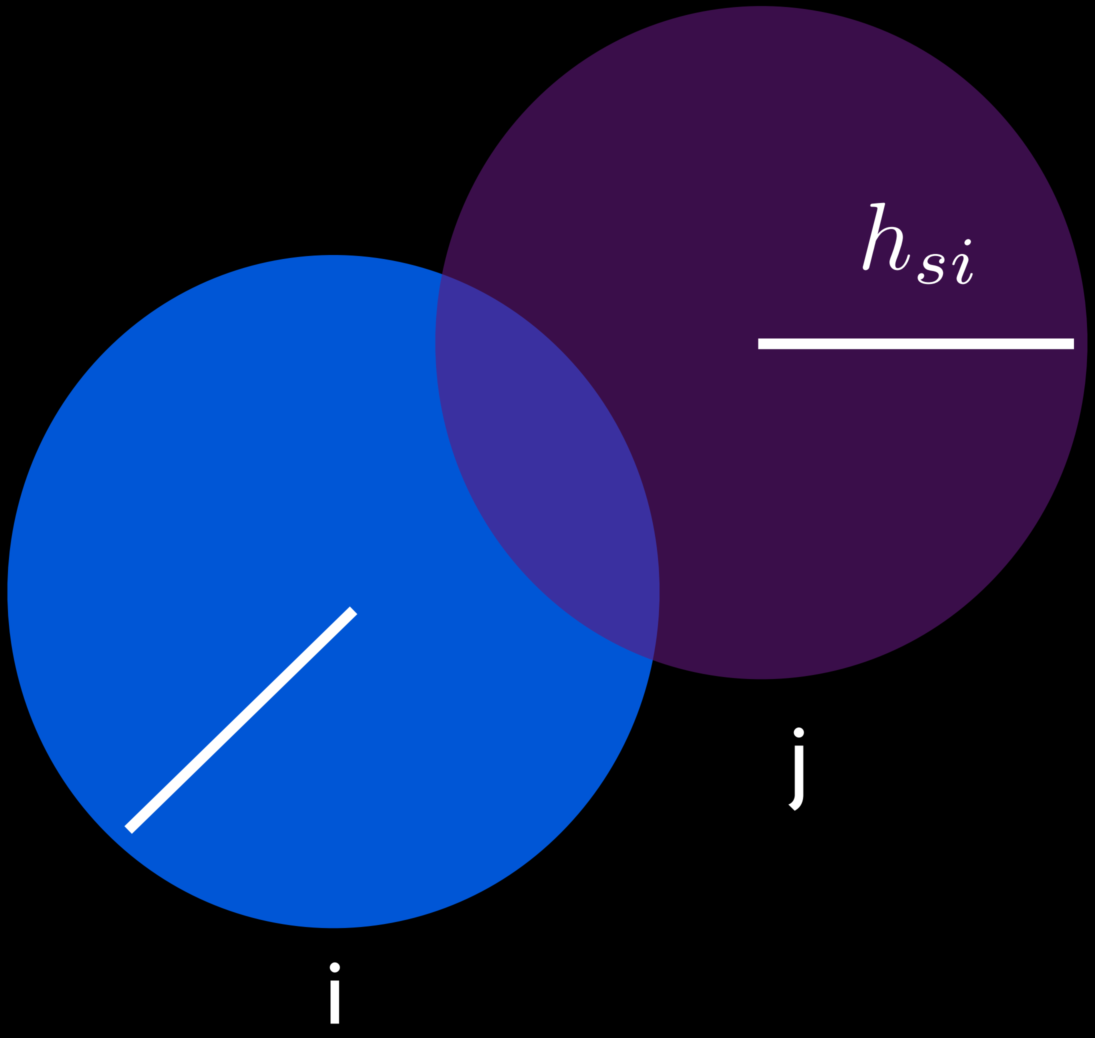
Consistent Pair-Wise Probability

$$\Gamma(i|j) = (\sigma/m)m_{\rm p}|\mathbf{v}_i - \mathbf{v}_j|g_{ji}$$

$$g_{ji} = \int_0^{h_{\rm si}} d^3\mathbf{x}' W(|\mathbf{x}'|, h_{\rm si}) W(|\delta\mathbf{x}_{ji} + \mathbf{x}'|, h_{\rm si})$$

$$P(i|j) = \Gamma(i|j)\,\delta t$$

$$P(i|j) = P(j|i)$$



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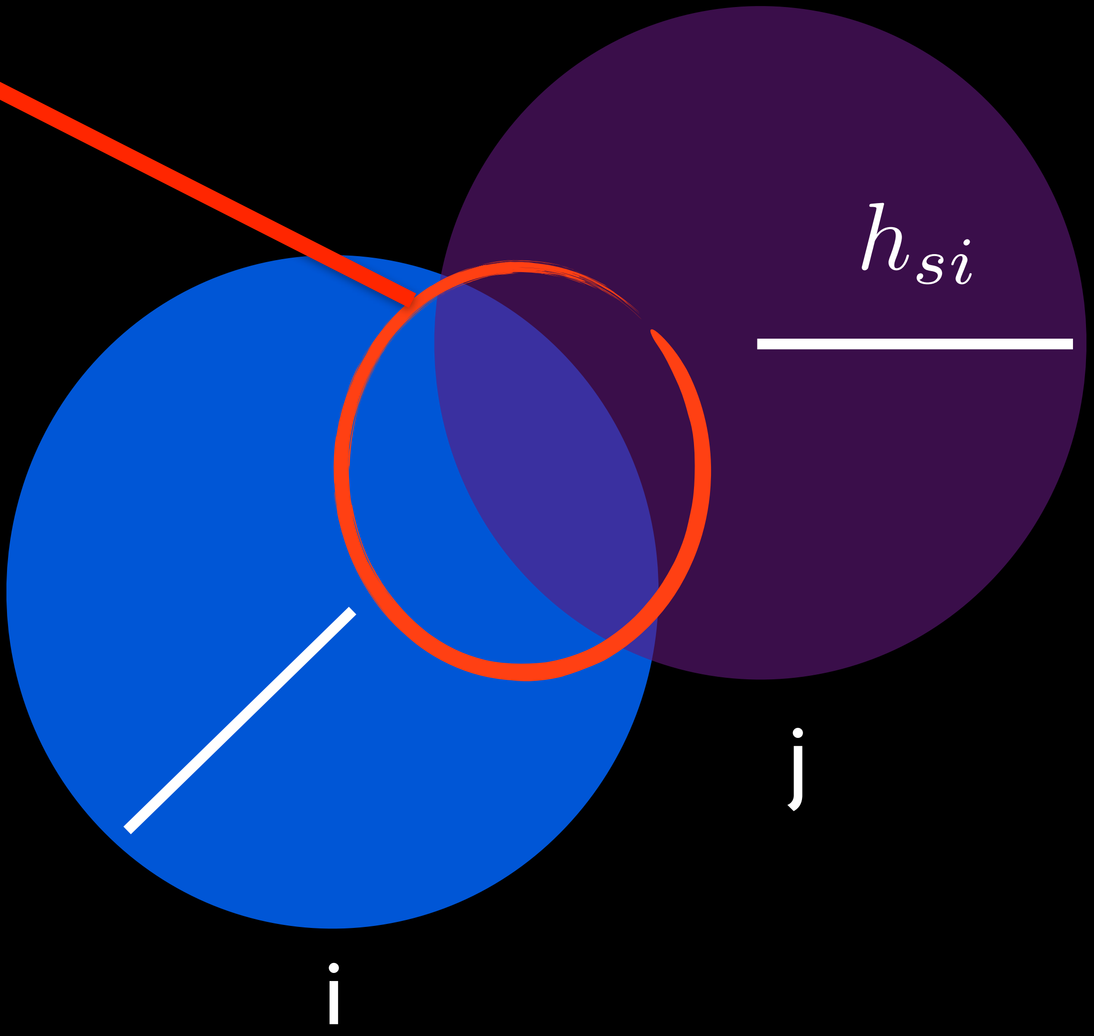
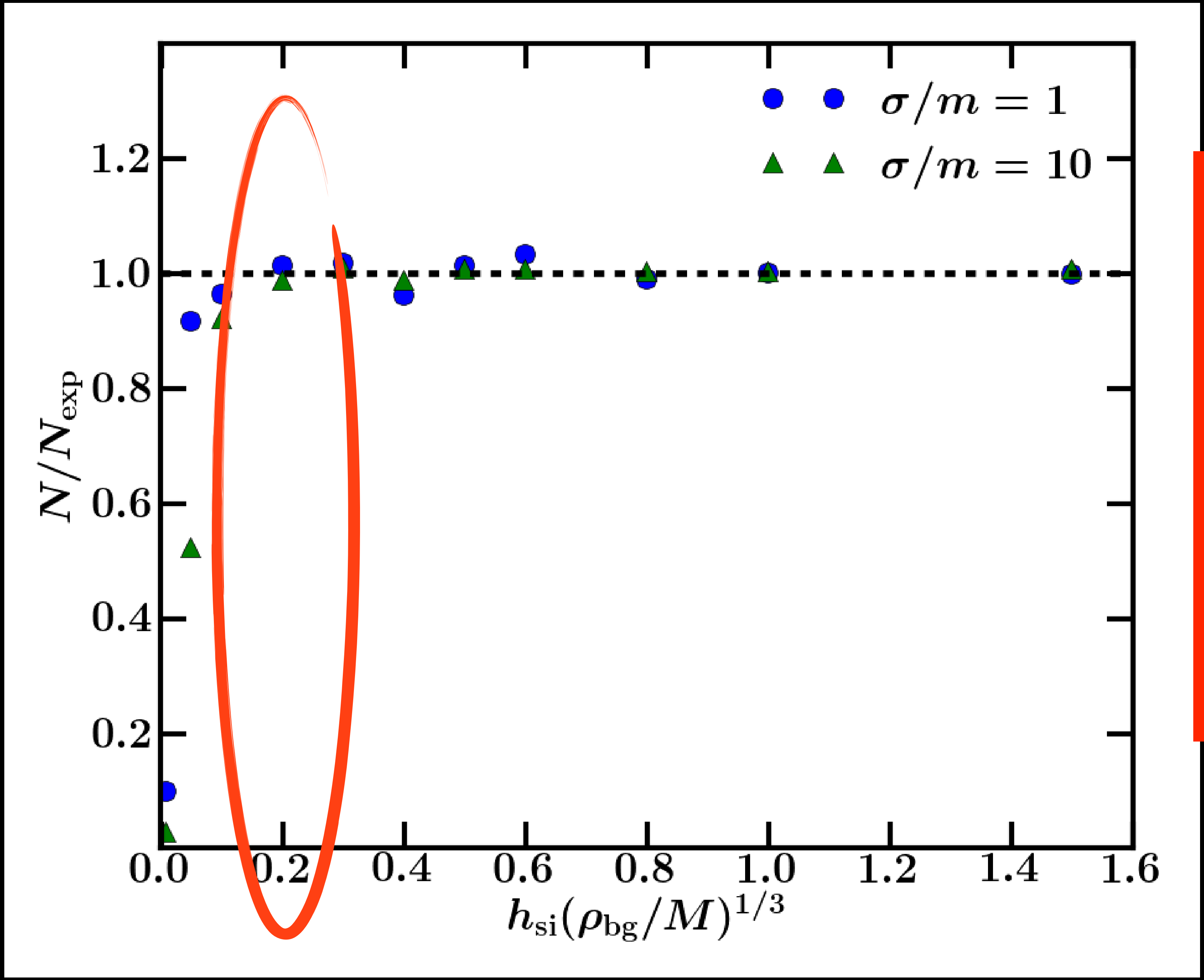


Simulating DM Self-Interactions - A new self-consistent algorithm

Wind Tunnel Test



Interaction rate converges to the expected value when h_{si} >0.2* (the interparticle separation)

Rocha et al. 2013
Peter et al. 2013

Simulating DM Self-Interactions - A new self-consistent algorithm

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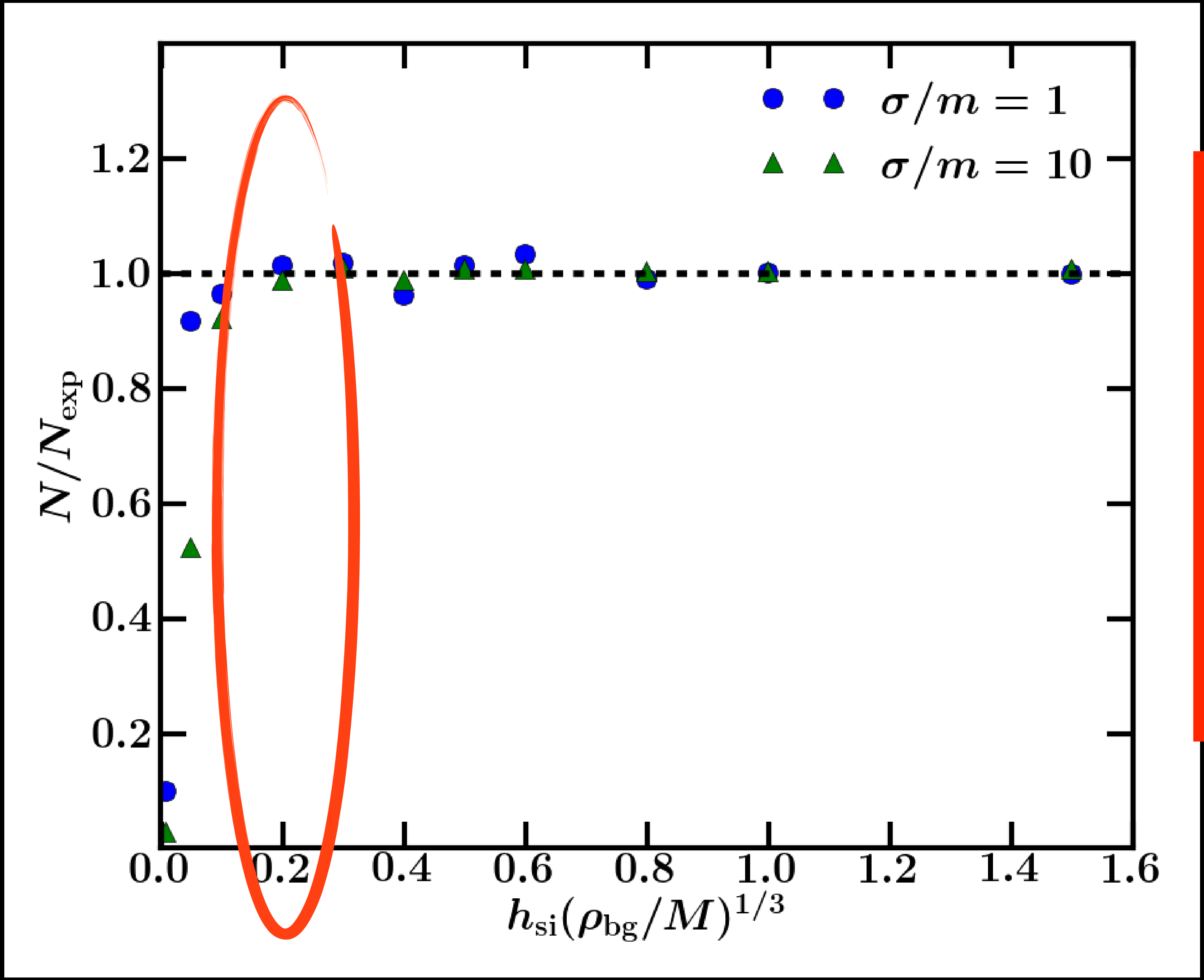

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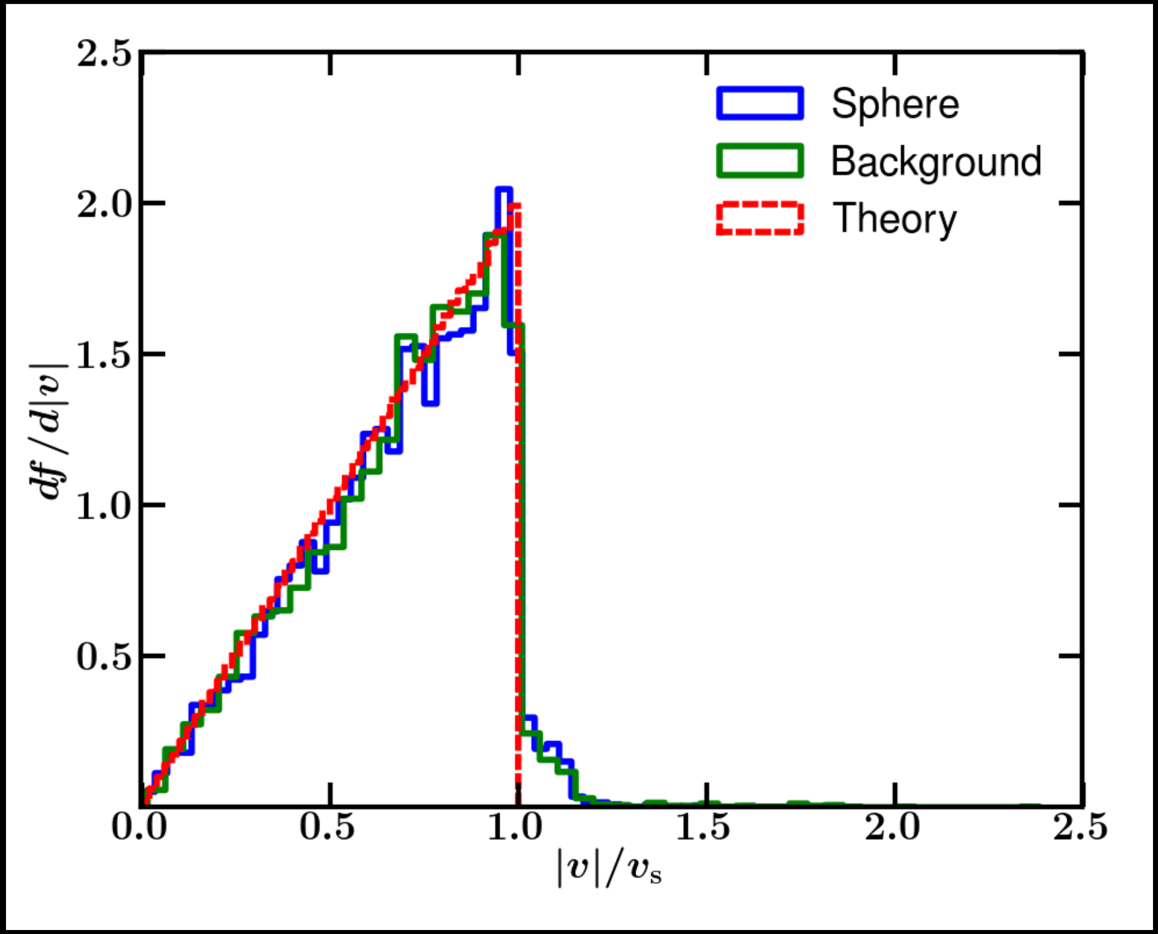
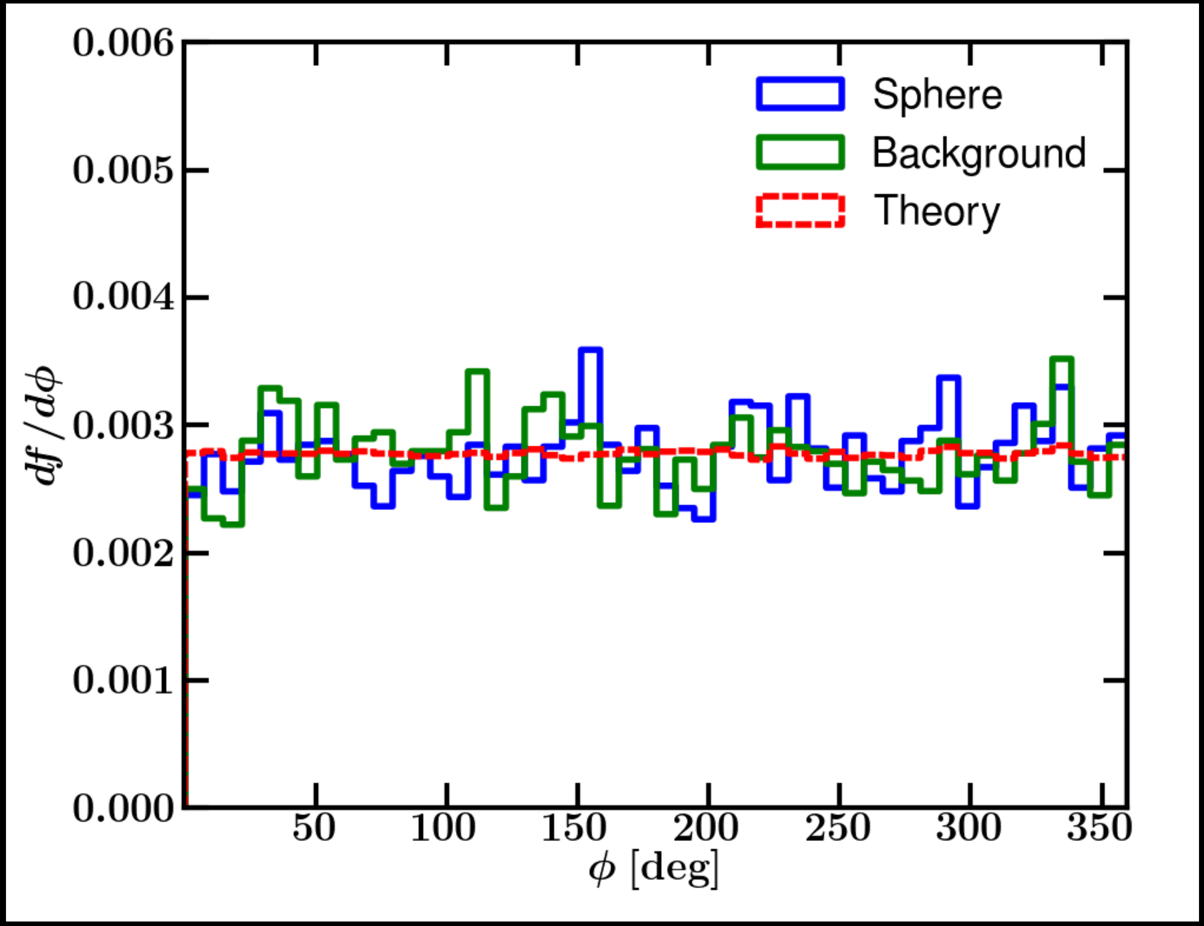
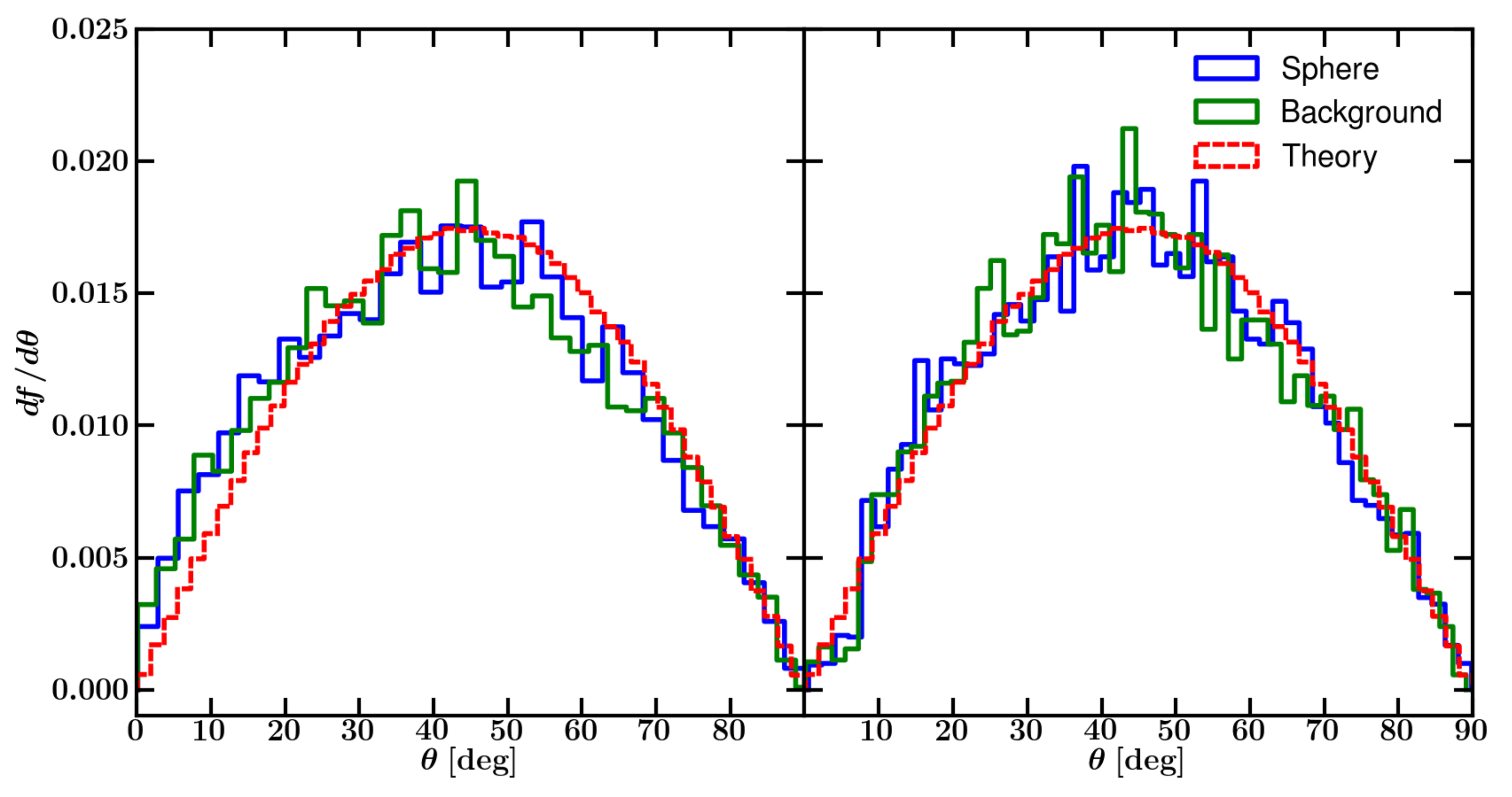




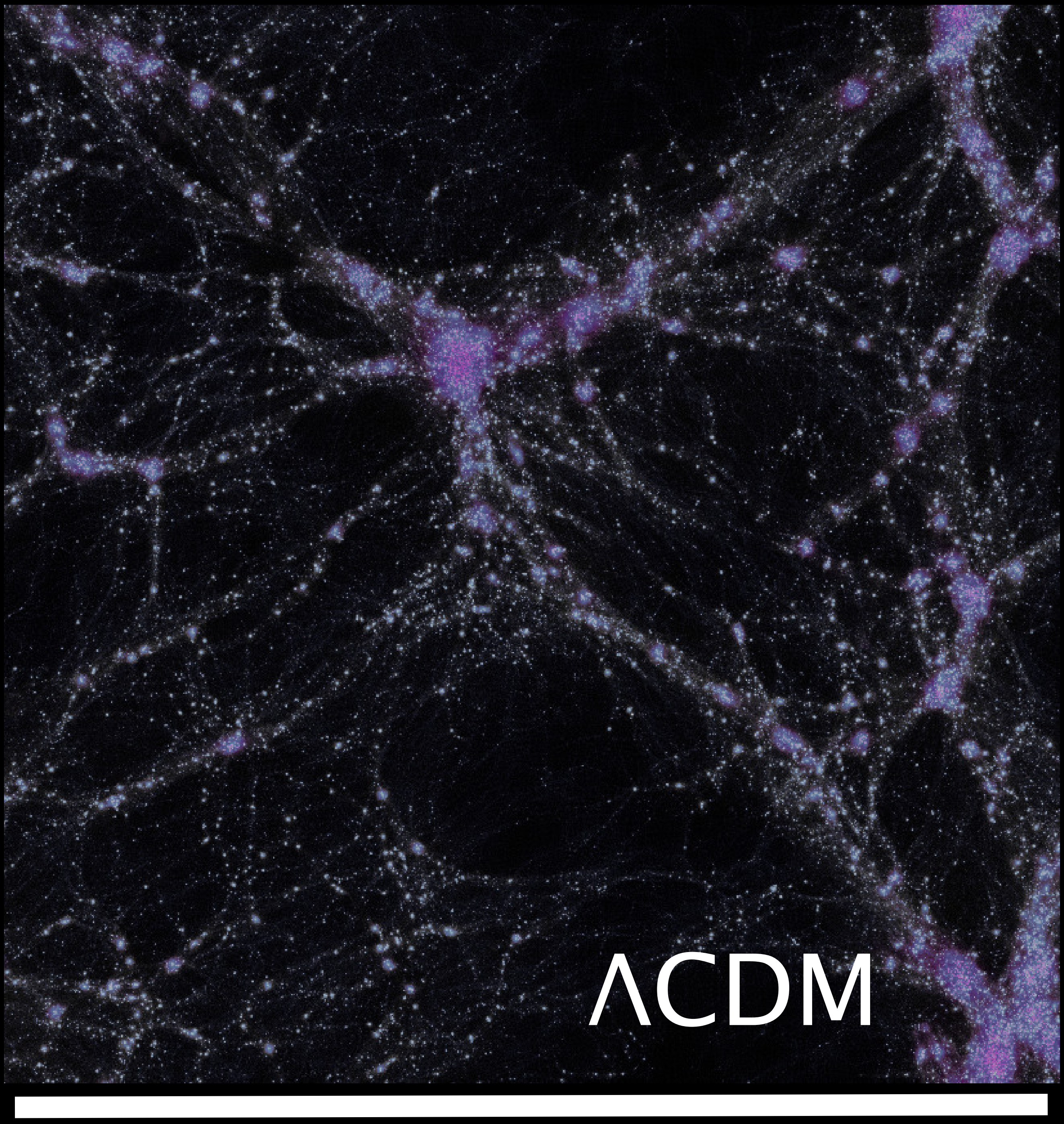
✓

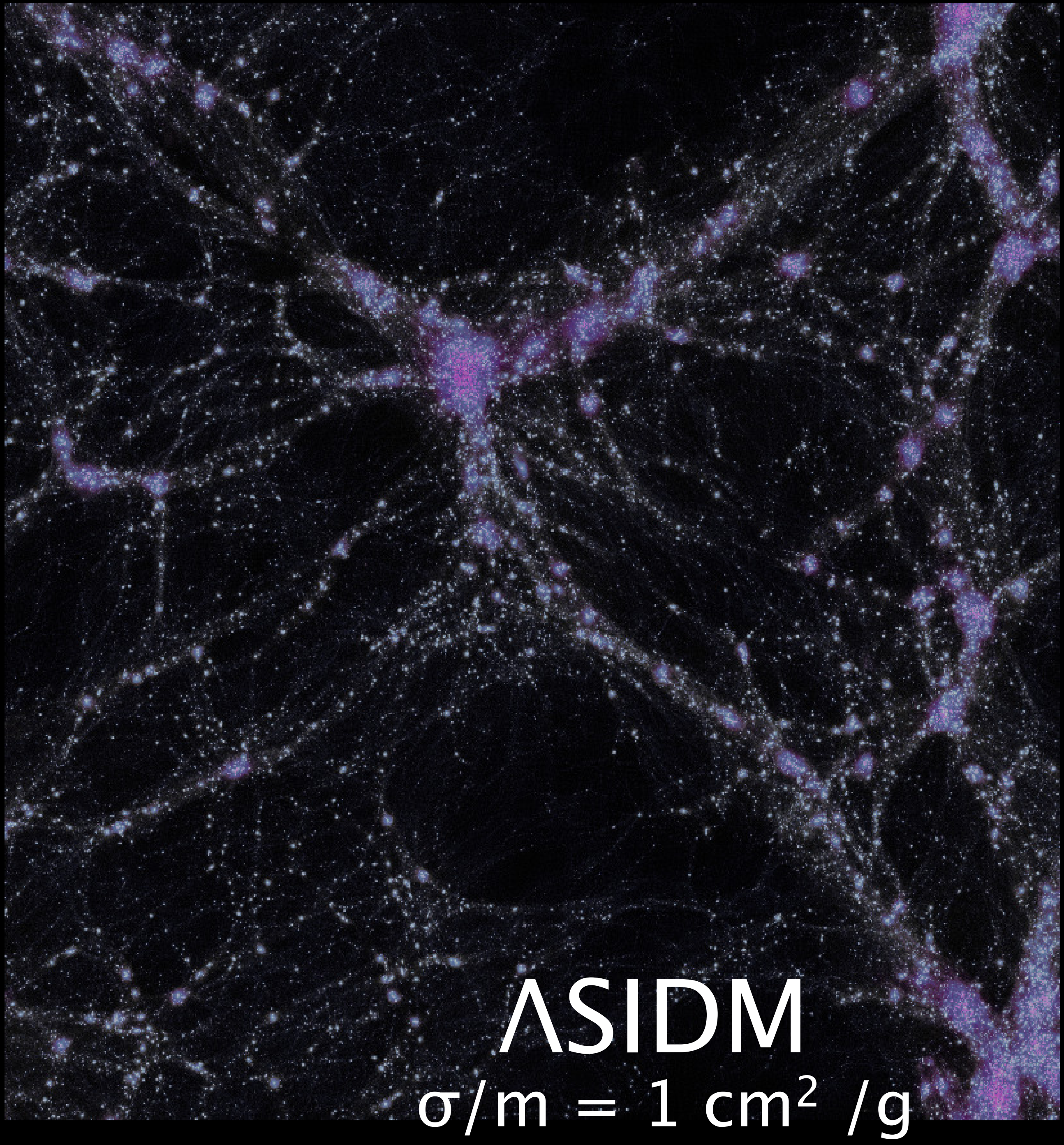
Correct post-scatter kinematics



Results from cosmological simulations - Halo densities, shapes & substructure

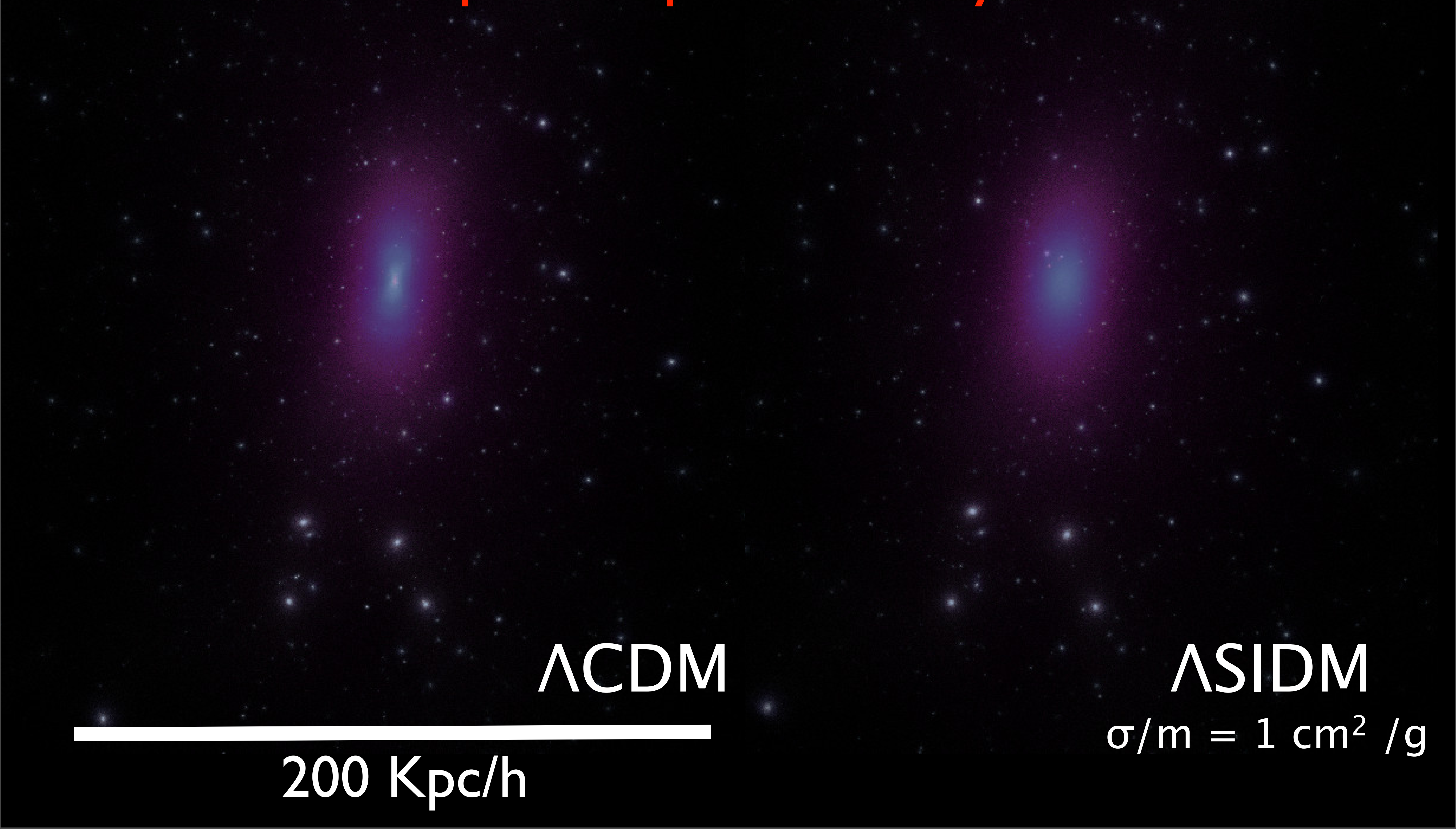
Identical large-scale structure





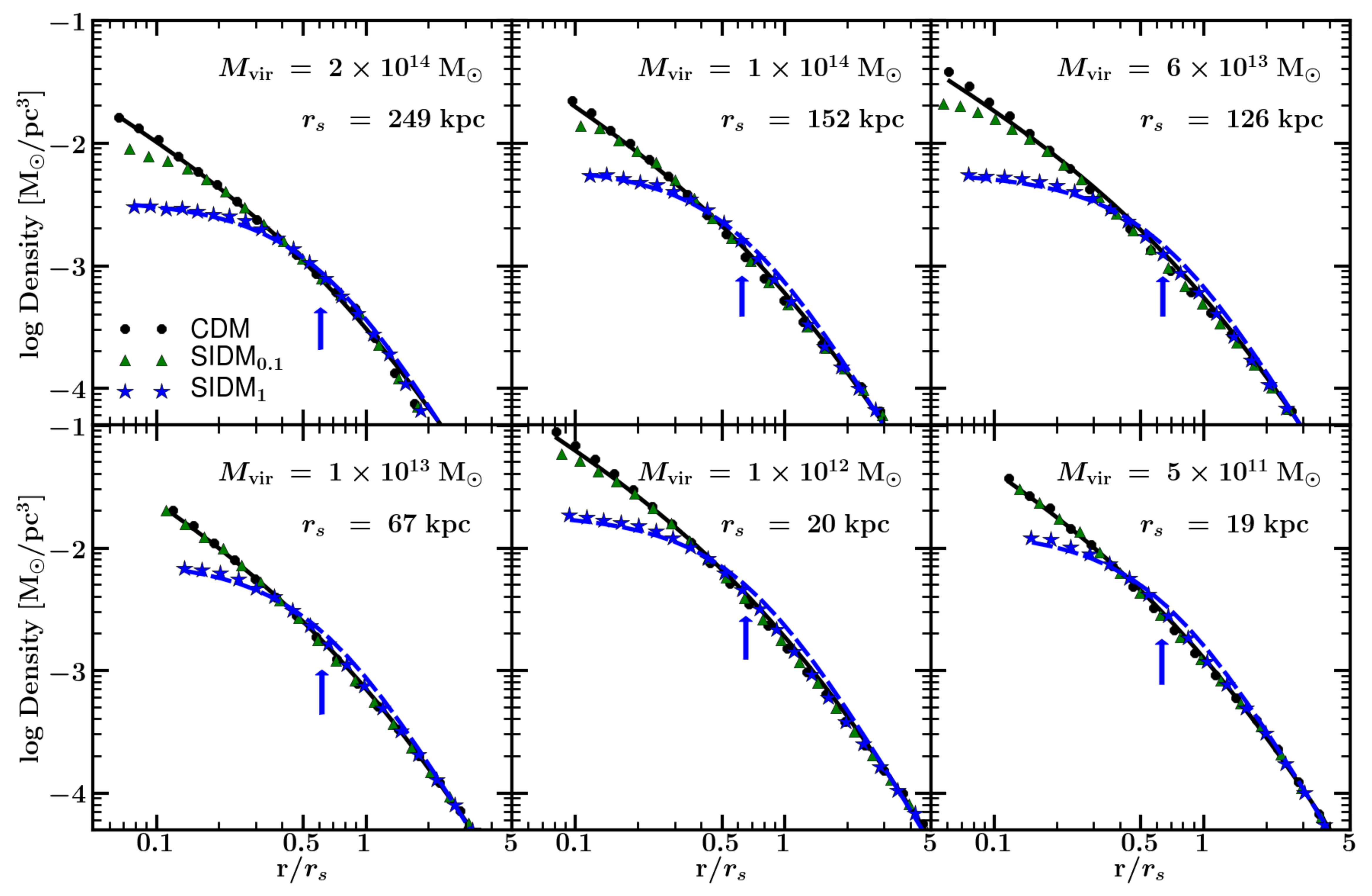
Results from cosmological simulations - Halo densities, shapes & substructure

Lower central phase-space density in SIDM halos



Results from cosmological simulations - Halo densities

Density



Radius/rs

σ/m = 1

σ/m = 0.1

Rocha et al. 2013

Peter et al. 2013

Resolving the cores of SIDM halos

Artificial 2-body scattering when $t_{relax} \sim \frac{1}{H_o}$

Power et al. 2003

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Power et al. 2003

- **Need ~ 10^6–10^7 particles within the virial radius to resolve the cores of σ/m = 1–0.1 cm^2/g halos**

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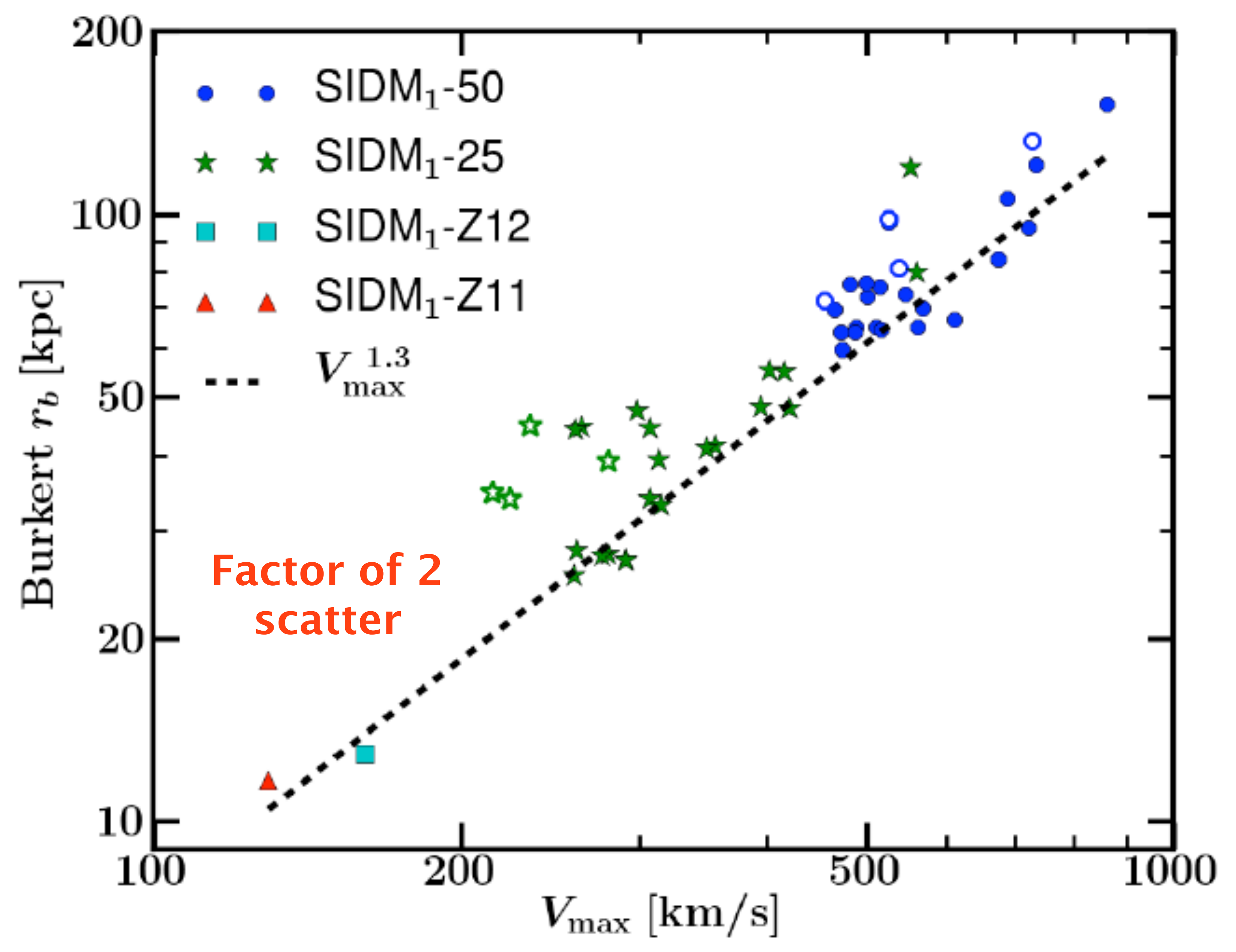
- ✤ **For a fixed volume and mass resolution cored halos are harder to resolve!!**

Results from cosmological simulations - Halo densities

Core Sizes



Factor of 2 scatter

Dwarf galaxies

Milky Way

10^{15} $M_\odot$ clusters

Rocha et al. 2013
Peter et al. 2013

Results from cosmological simulations - Halo densities

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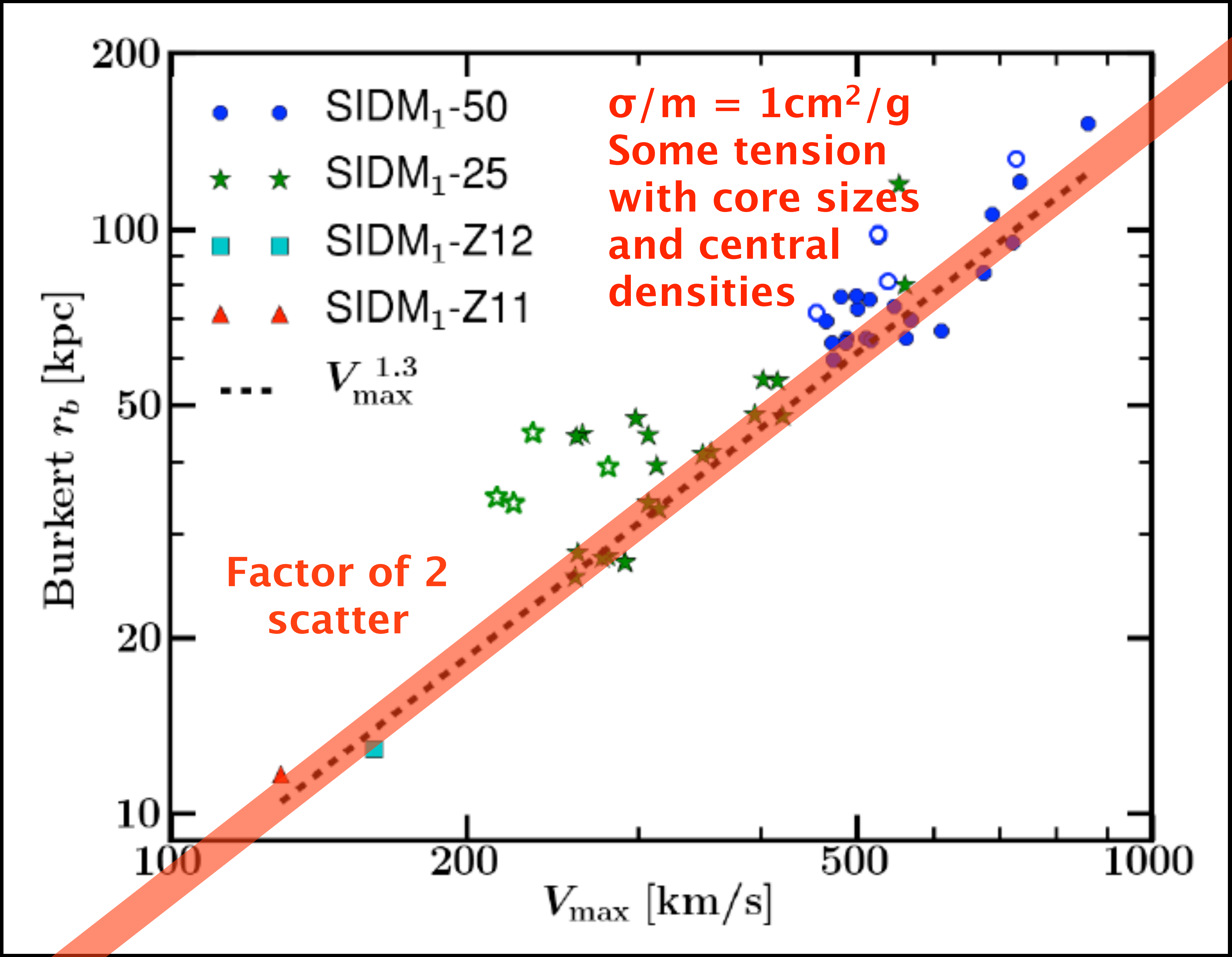

σ/m = 1cm²/g
Some tension with core sizes and central densities

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Results from cosmological simulations - Halo densities

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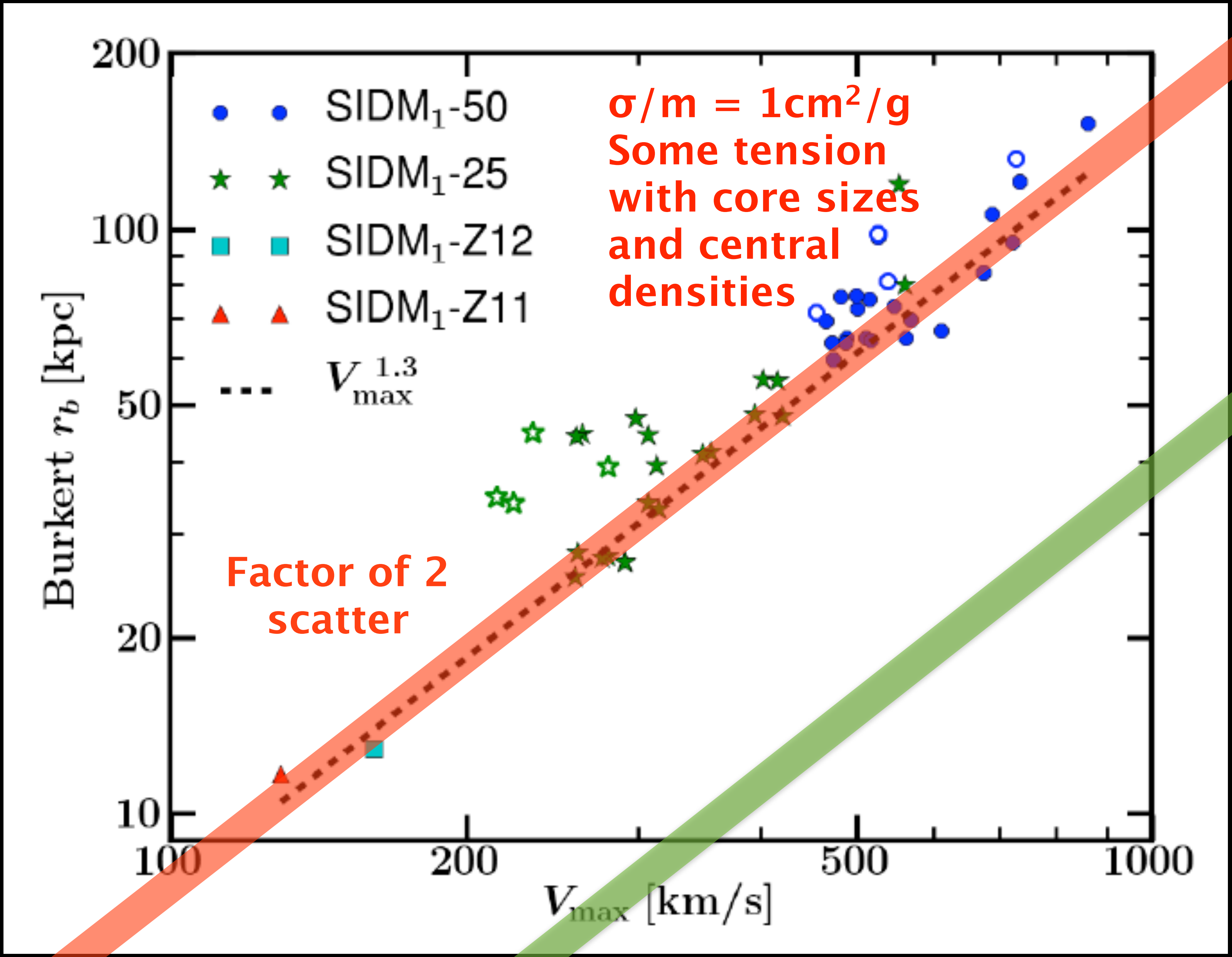

σ/m = 1cm^2/g
Some tension with core sizes and central densities

Factor of 2 scatter

✓

σ/m = 0.1
looks good across all scales!

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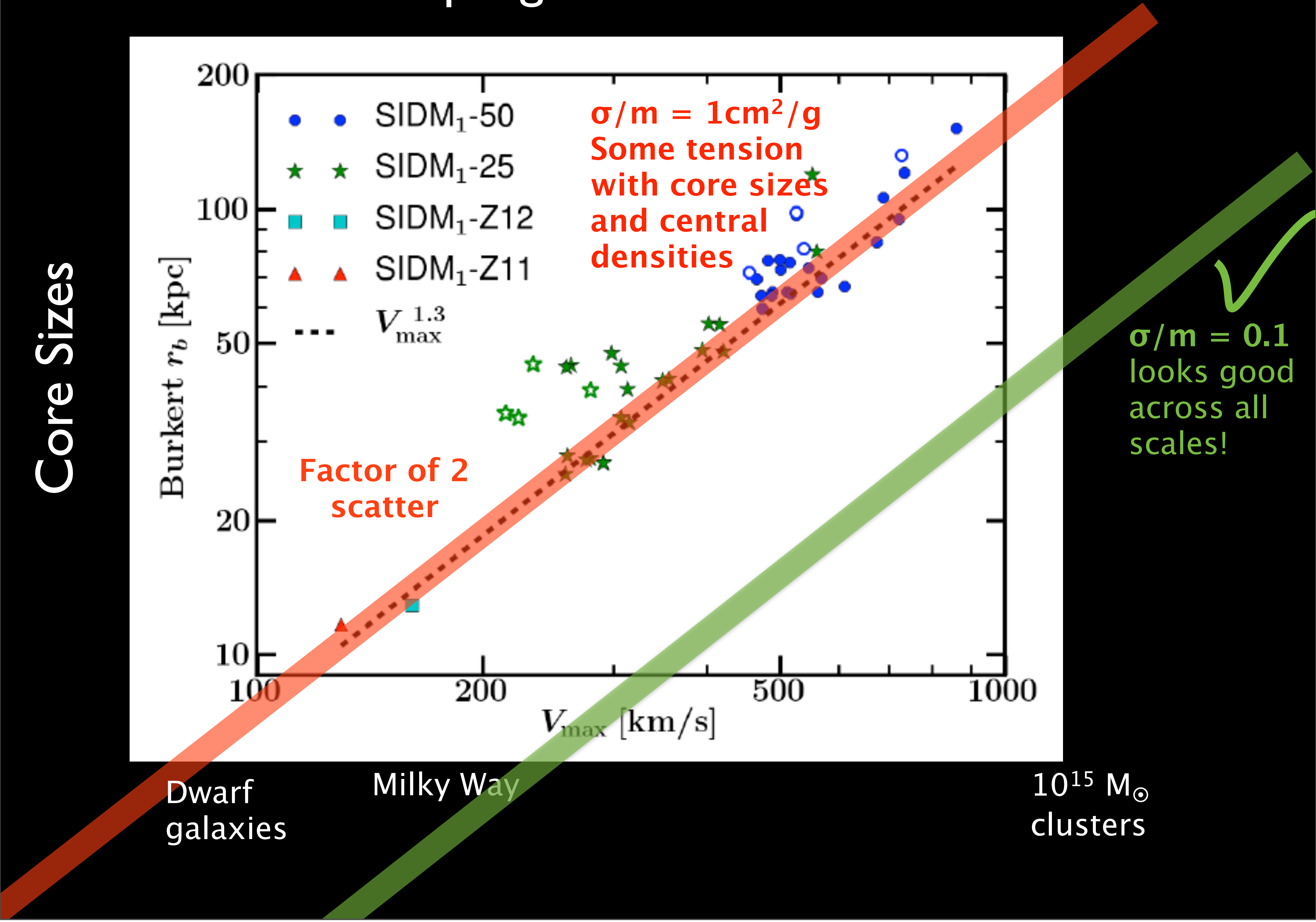
Work in progress - More simulations

Core Sizes



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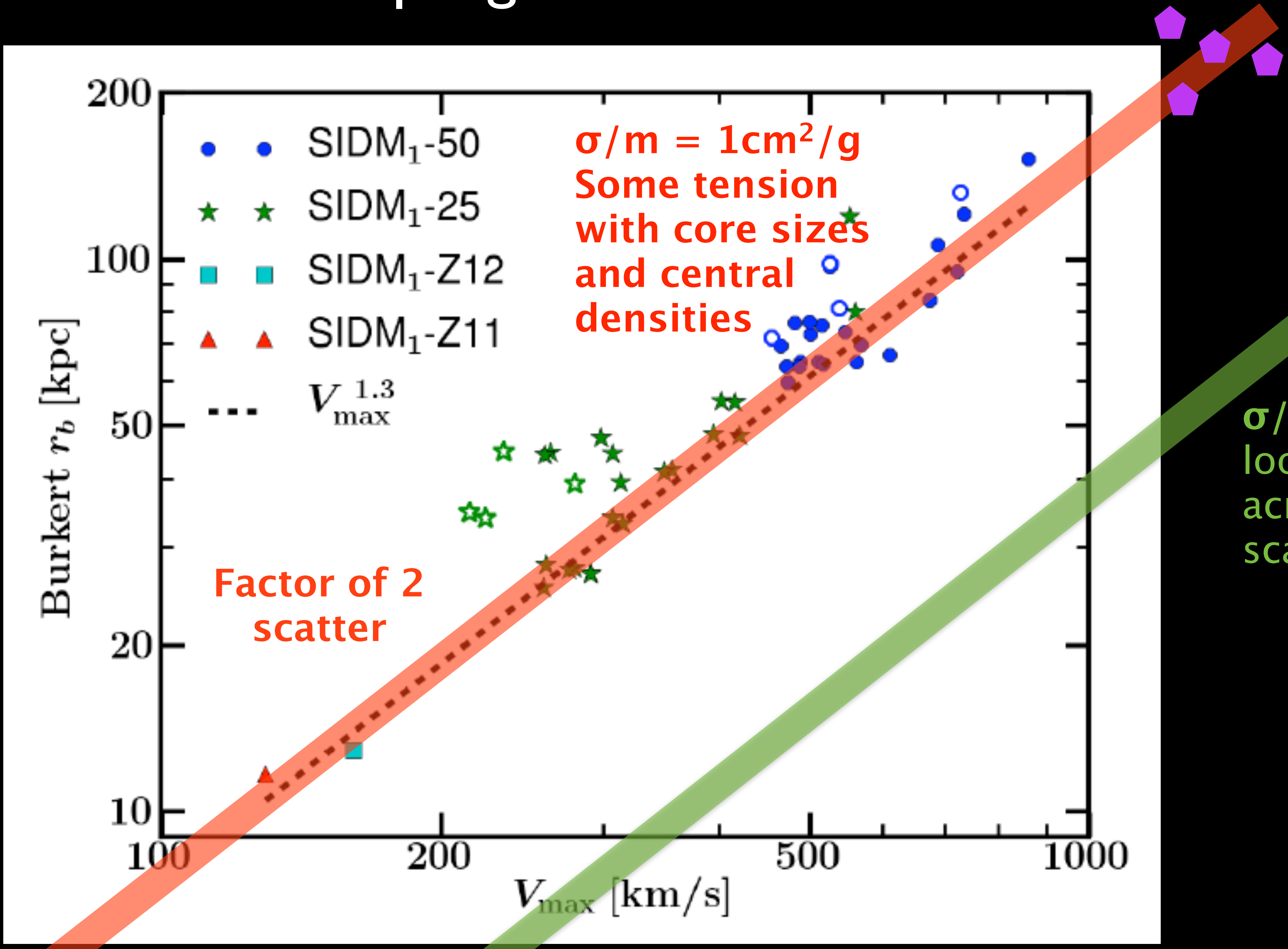

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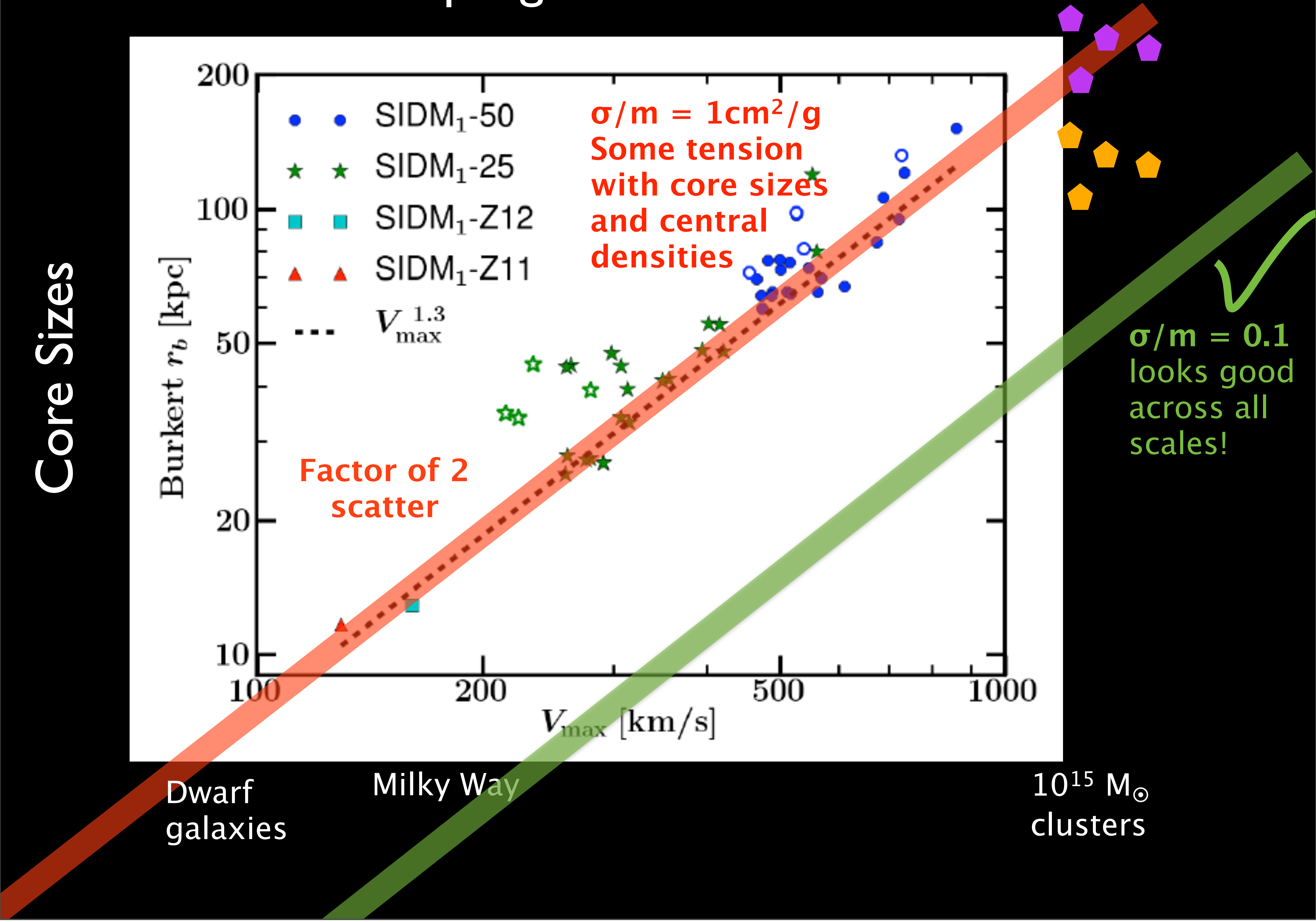

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Dwarf galaxies

Milky Way

10^{15} M⊙ clusters

Work in progress - More simulations

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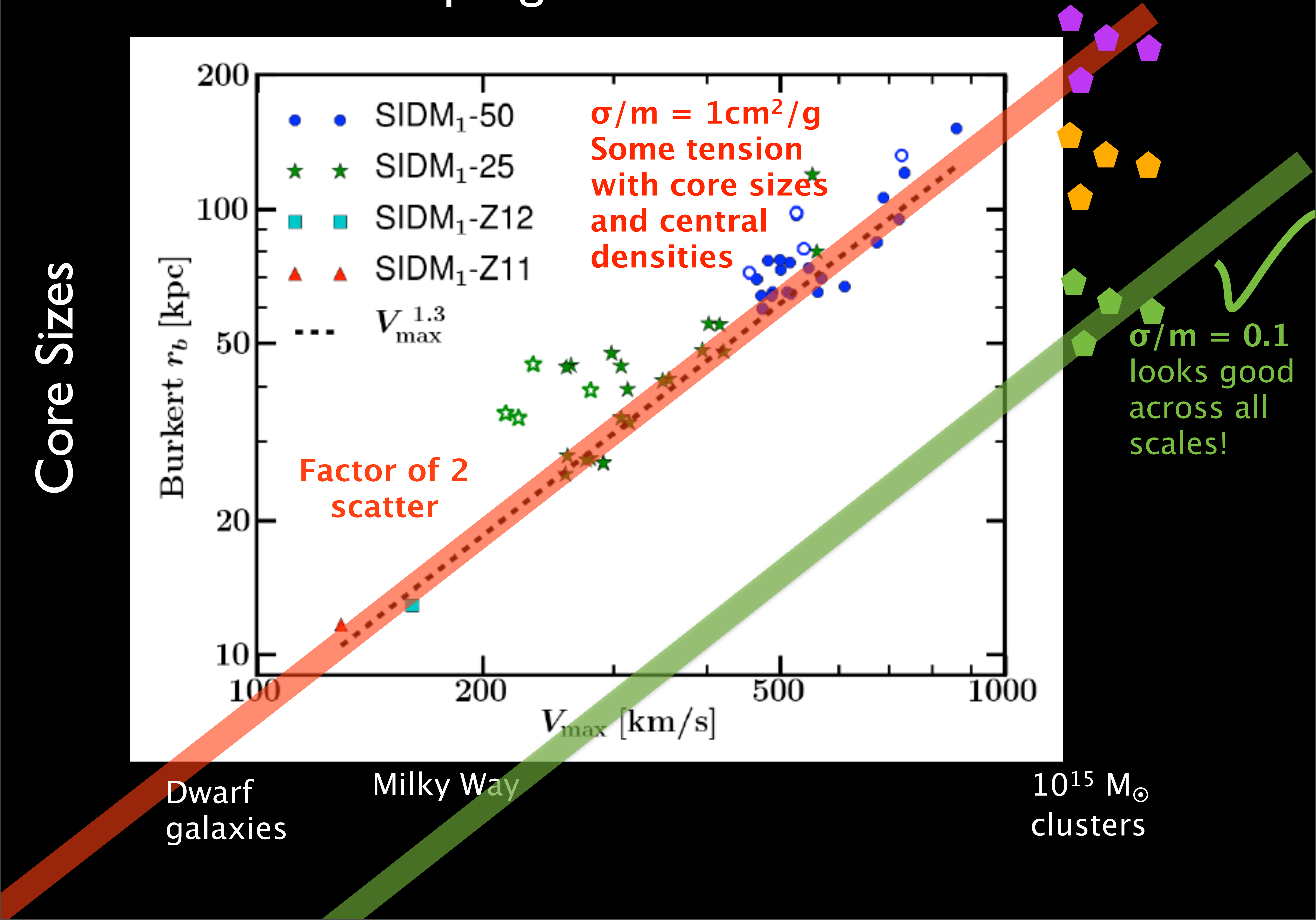

σ/m = 1cm^2/g
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Dwarf
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Work in progress - More simulations

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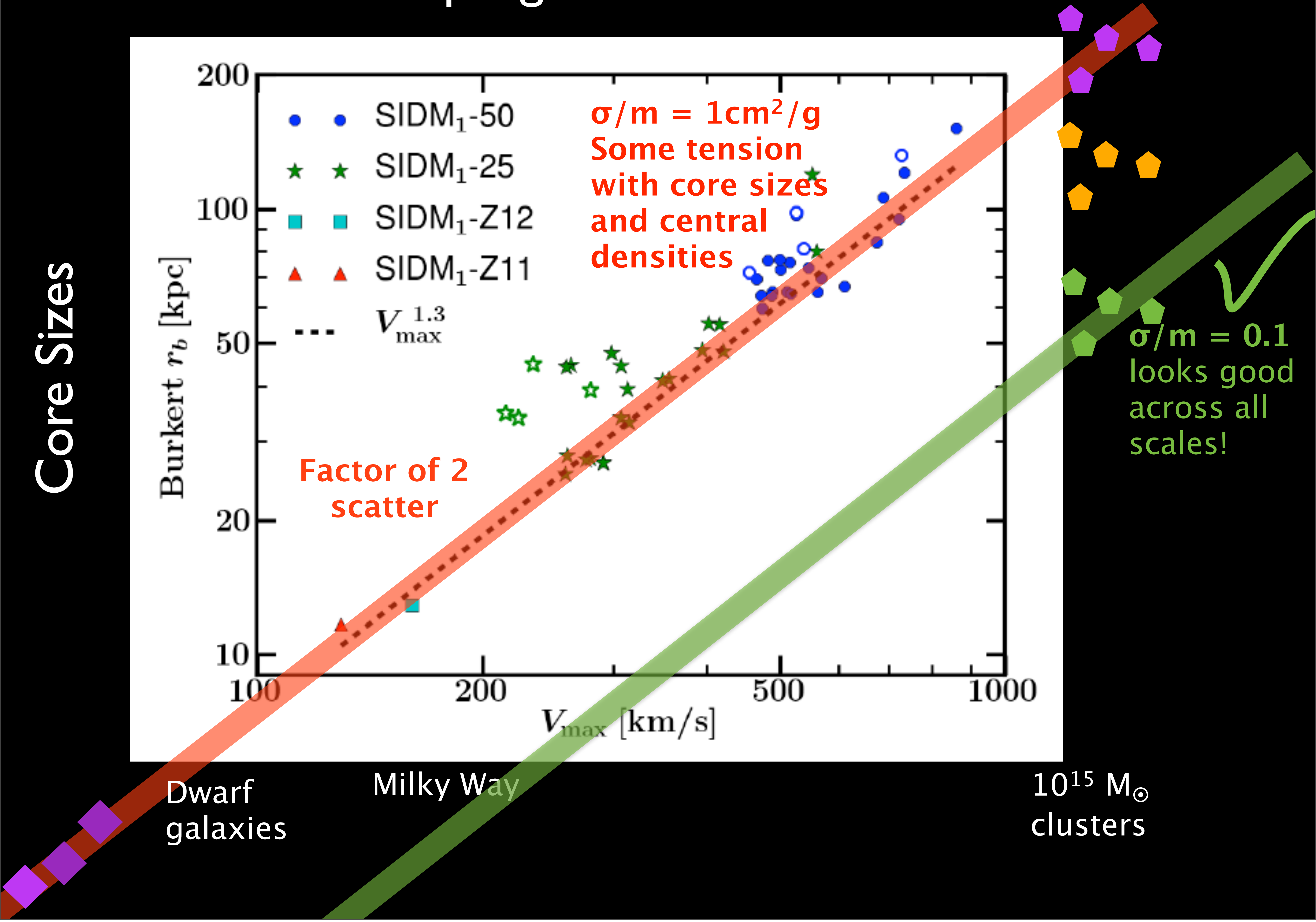

$\sigma/m = 1\mathrm{cm}^2/\mathrm{g}$
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Work in progress - More simulations

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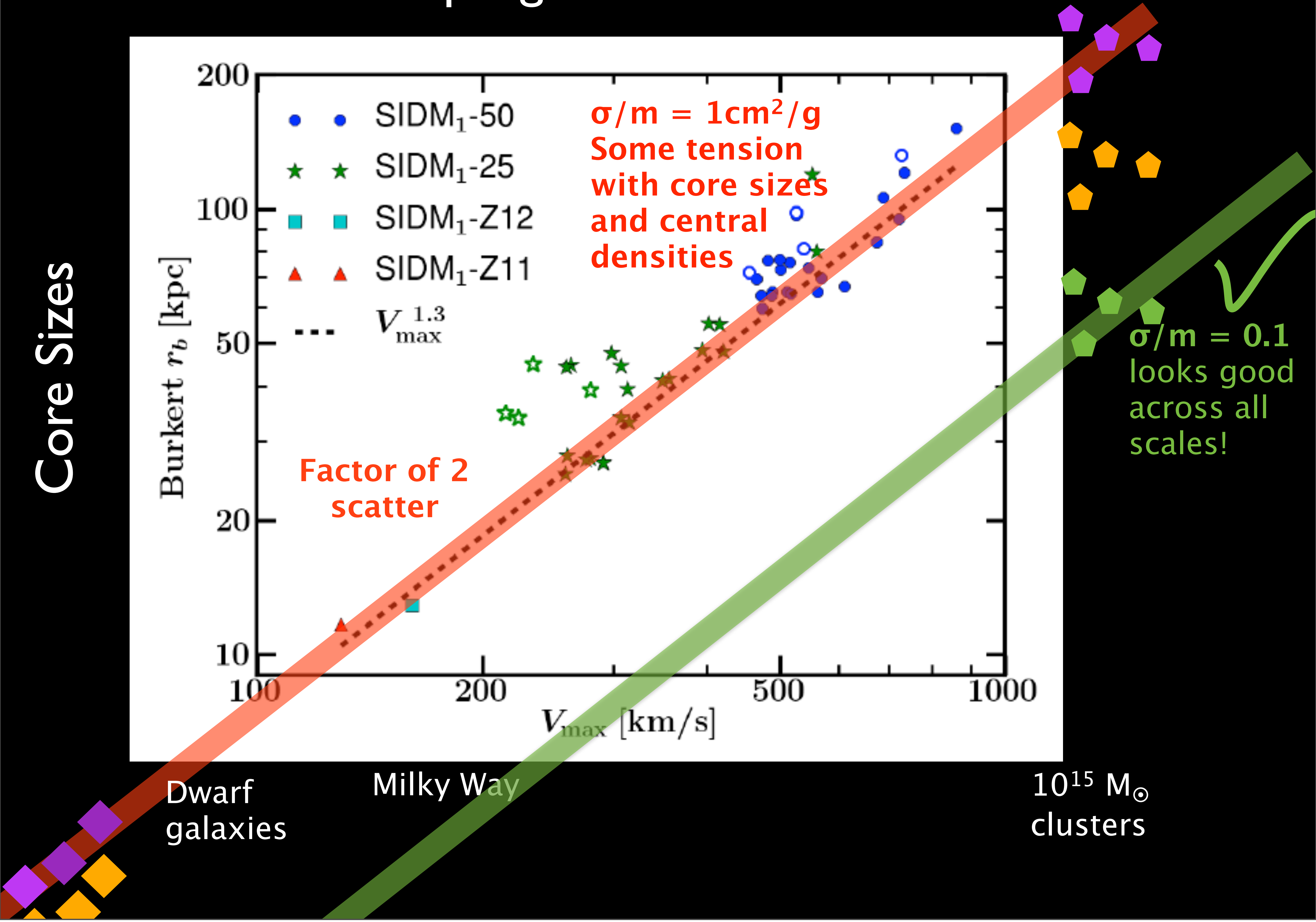

σ/m = 1cm²/g Some tension with core sizes and central densities

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Dwarf galaxies

Milky Way

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Work in progress - More simulations

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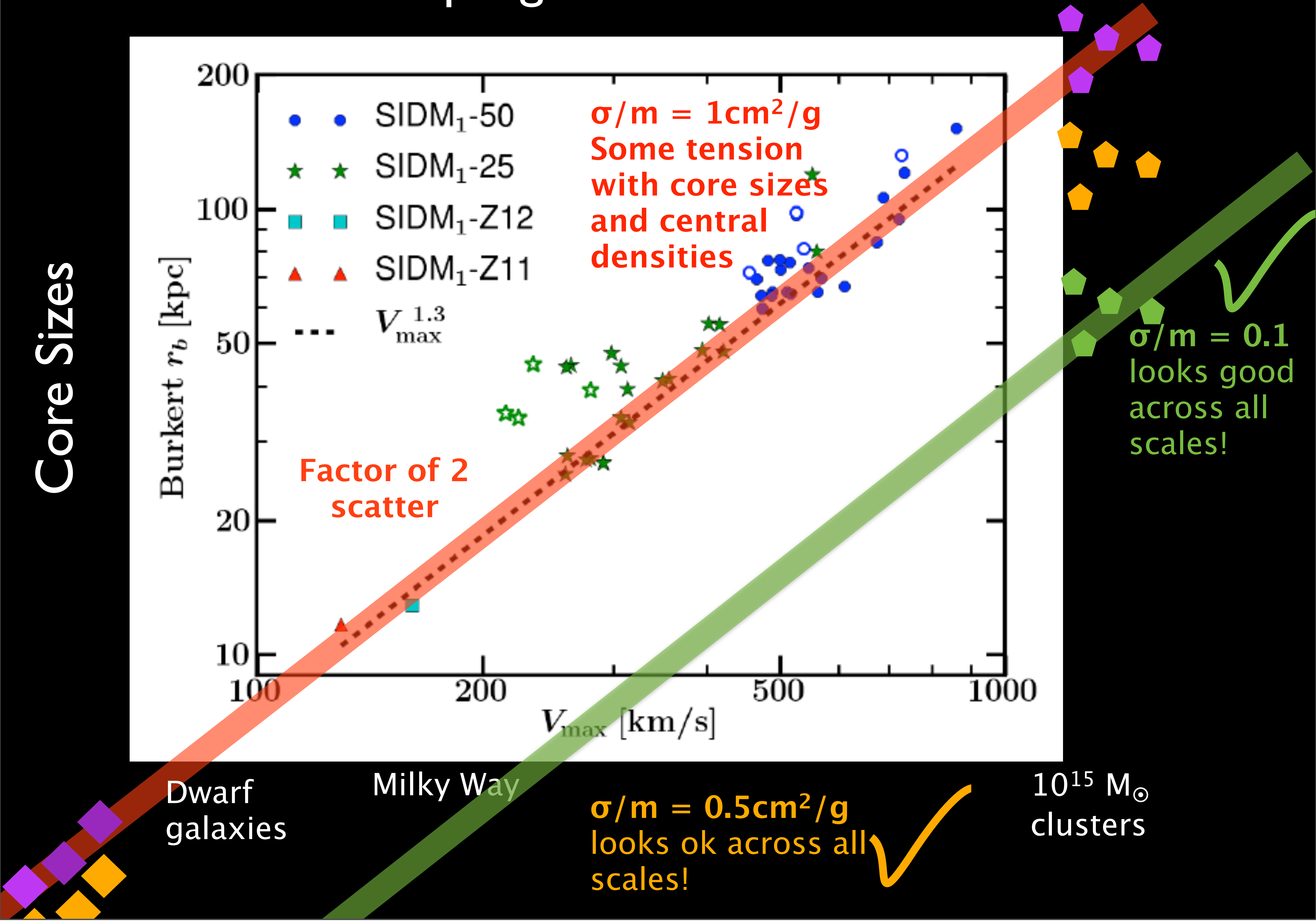


$\sigma/m = 1 cm^2/g$
Some tension with core sizes and central densities

Factor of 2 scatter

$\sigma/m = 0.1$
looks good across all scales!

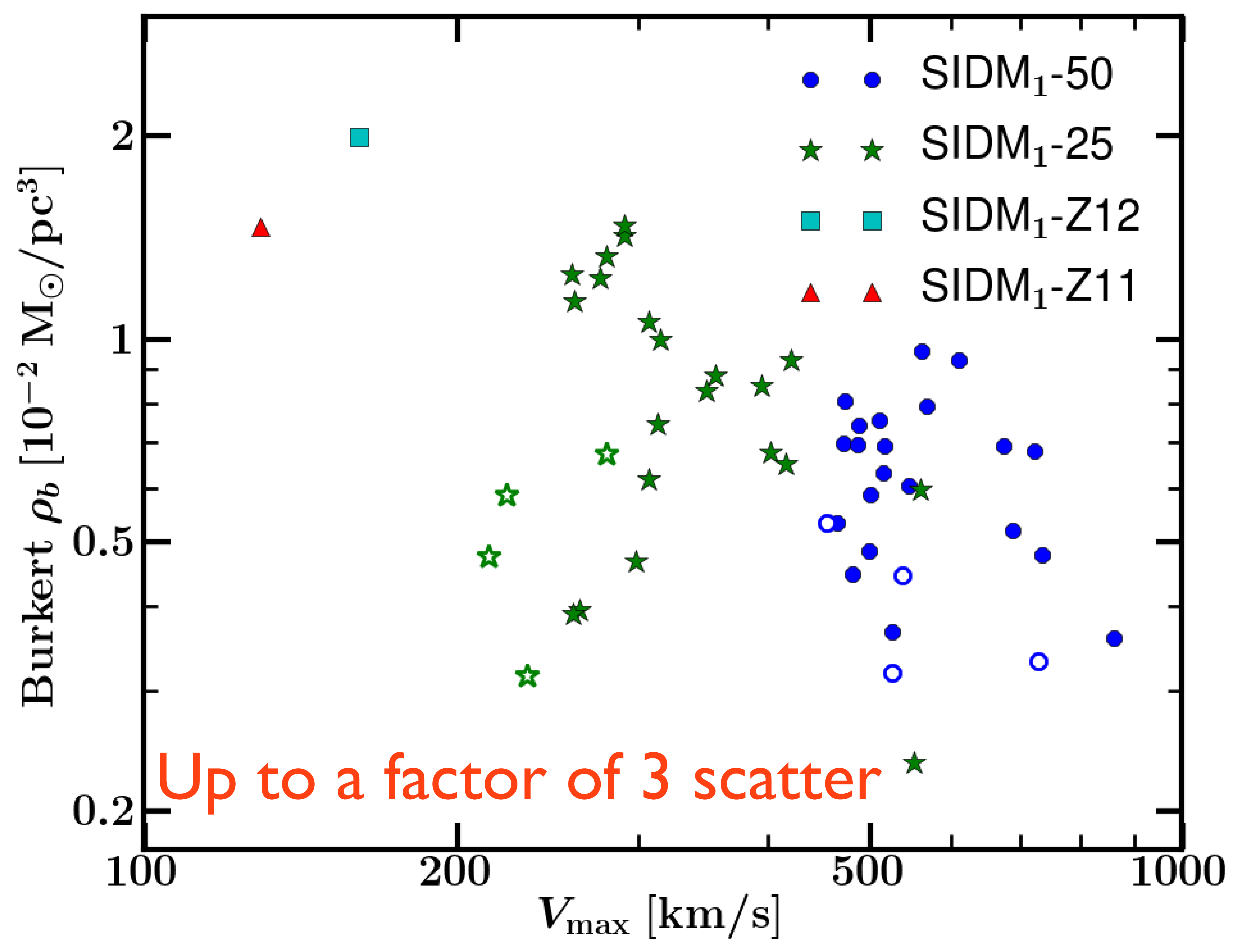
Dwarf galaxies

Milky Way

$\sigma/m = 0.5 cm^2/g$
looks ok across all scales! ✓

$10^{15}\ M_\odot$ clusters

Results from cosmological simulations - Halo densities



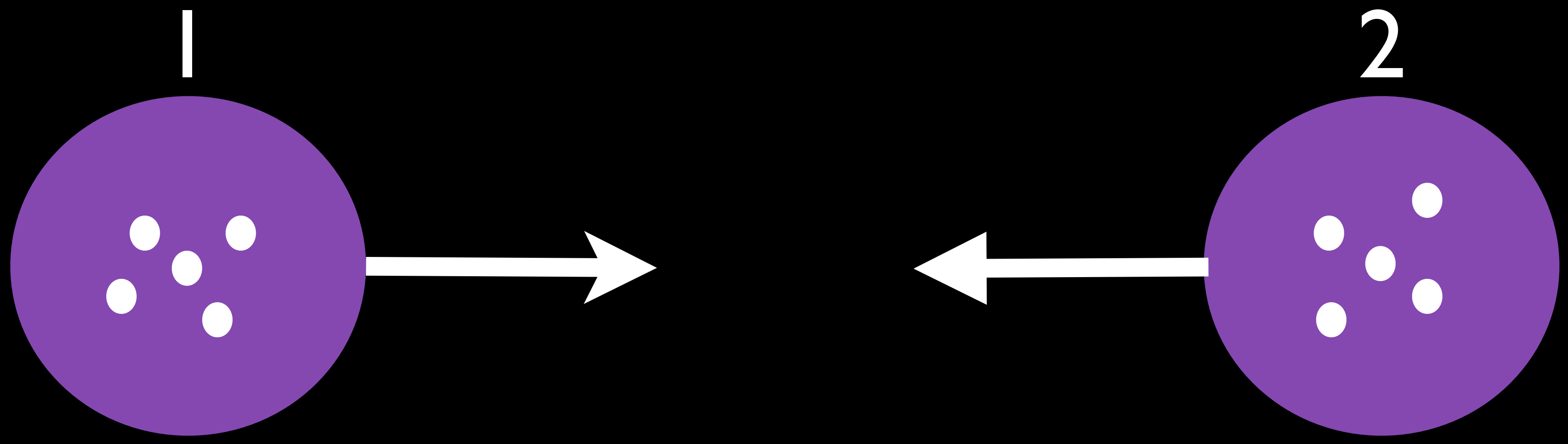
Up to a factor of 3 scatter

$\sigma/m = 1$ cm^2 /g

Rocha et al. 2013
Peter et al. 2013

Work in progress - Merging clusters

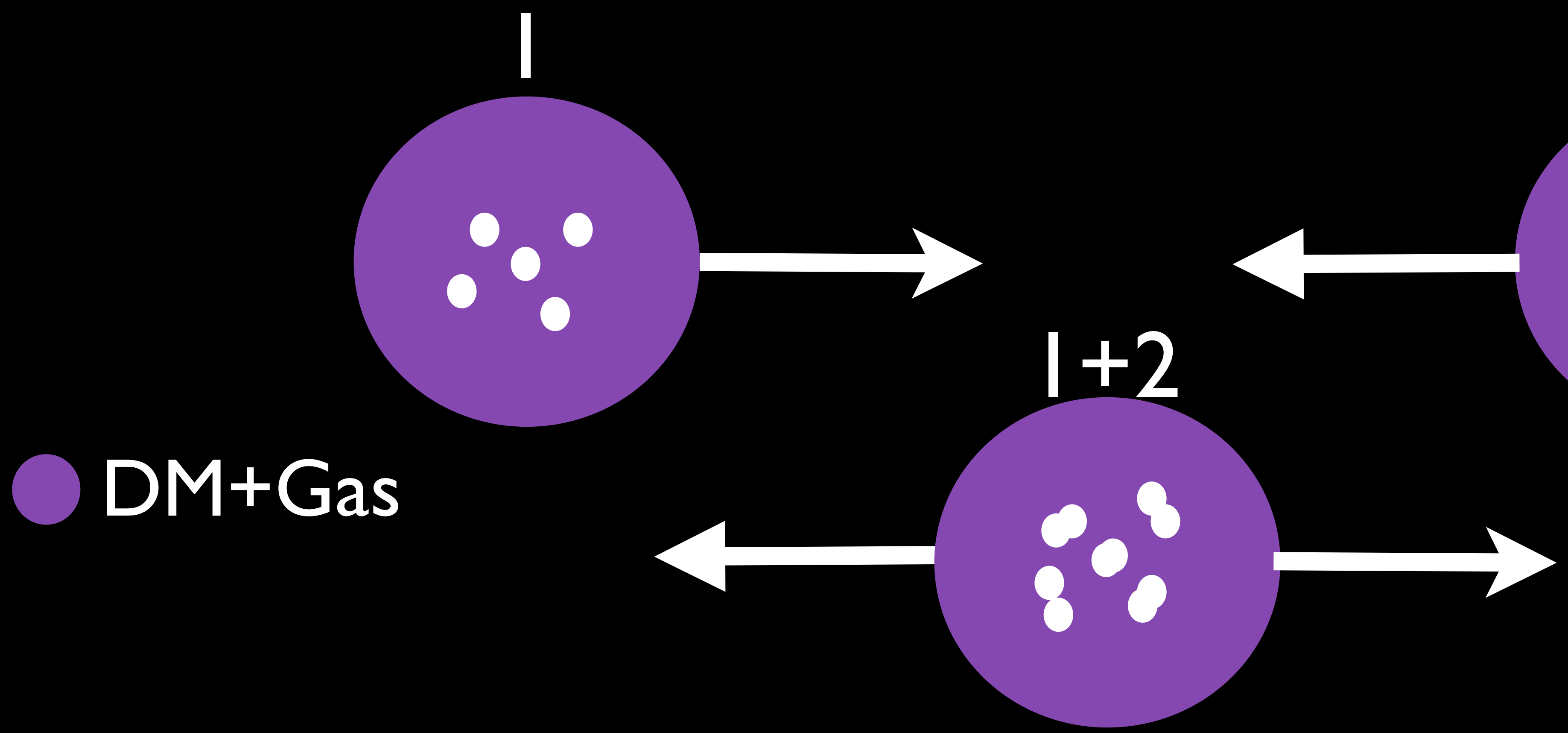
Dissociative Clusters



● DM+Gas

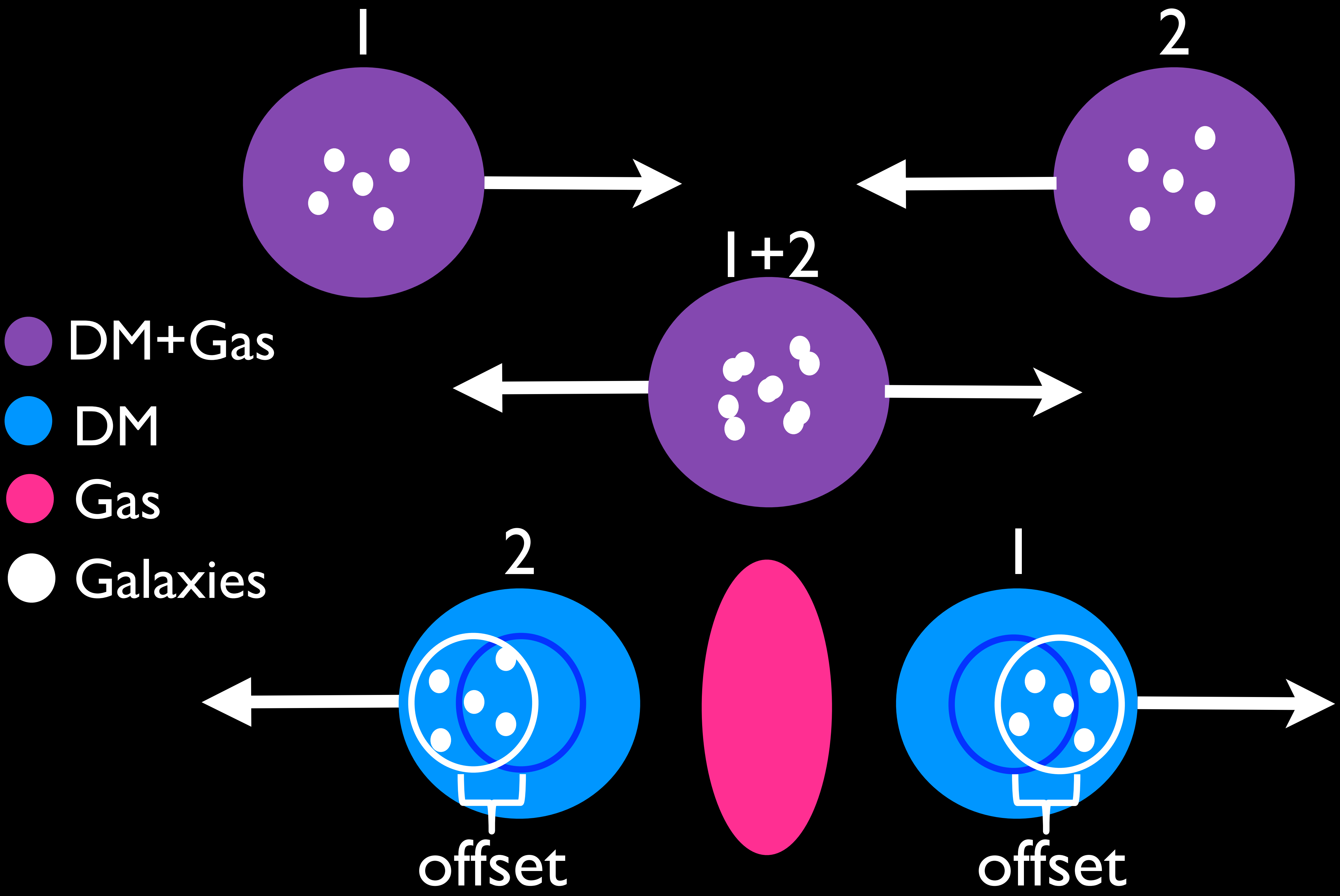
Work in progress - Merging clusters

Dissociative Clusters



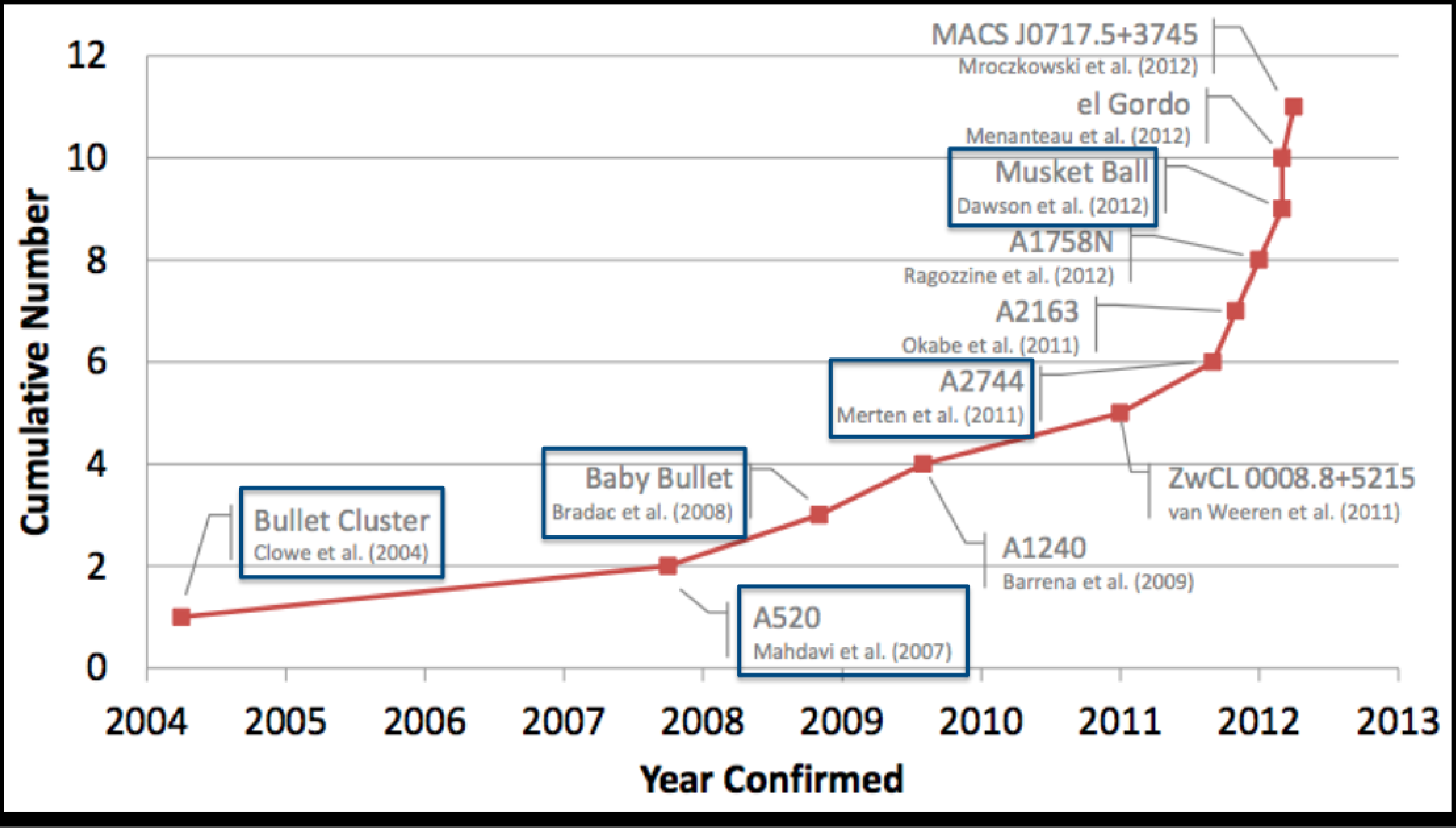
Work in progress - Merging clusters

Dissociative Clusters



Work in progress - Merging clusters

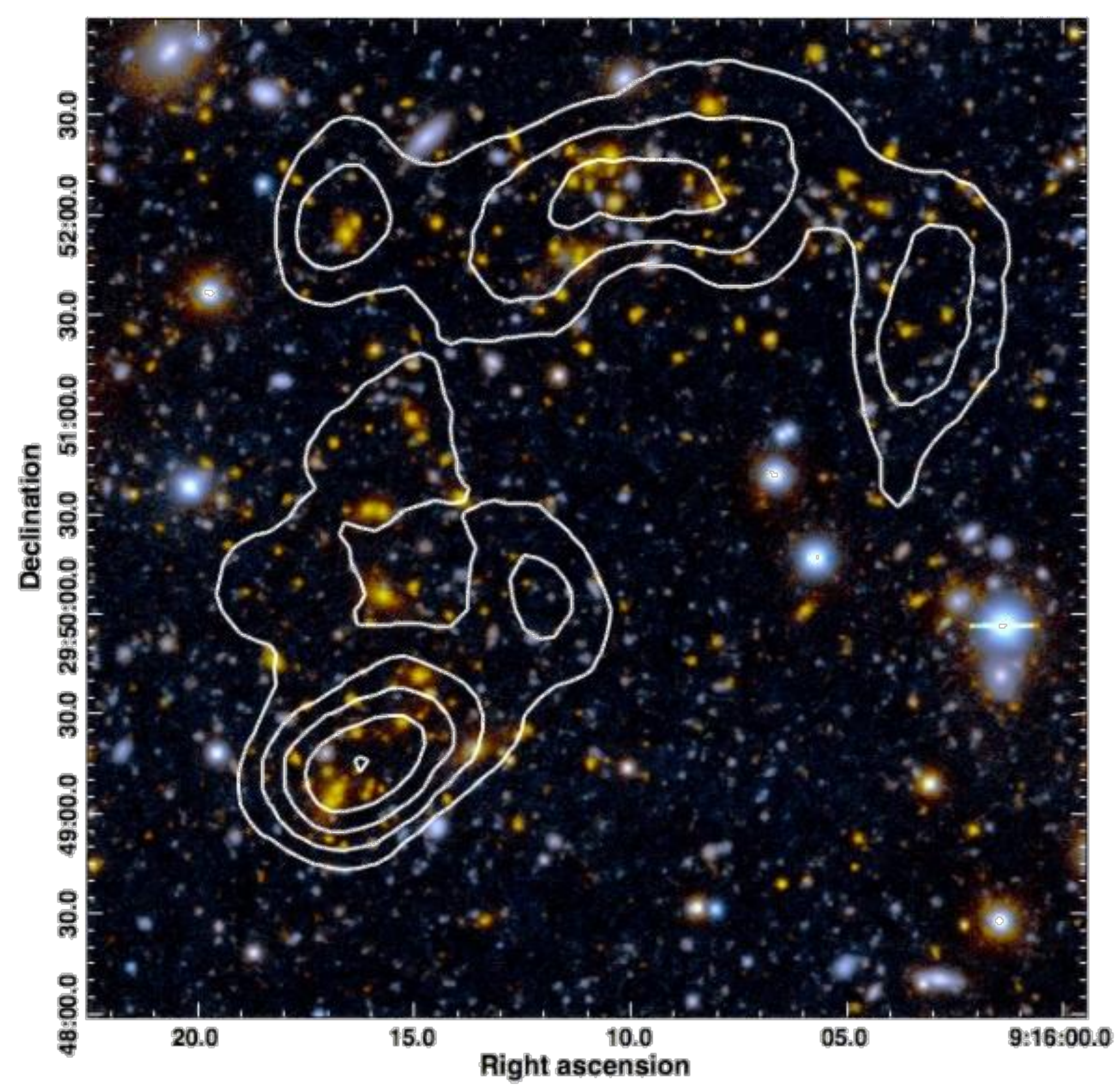
Observations



Work in progress - Merging clusters

Observations

The Musket Ball



Dawson et al. 2012

Work in progress - Merging clusters

Observations

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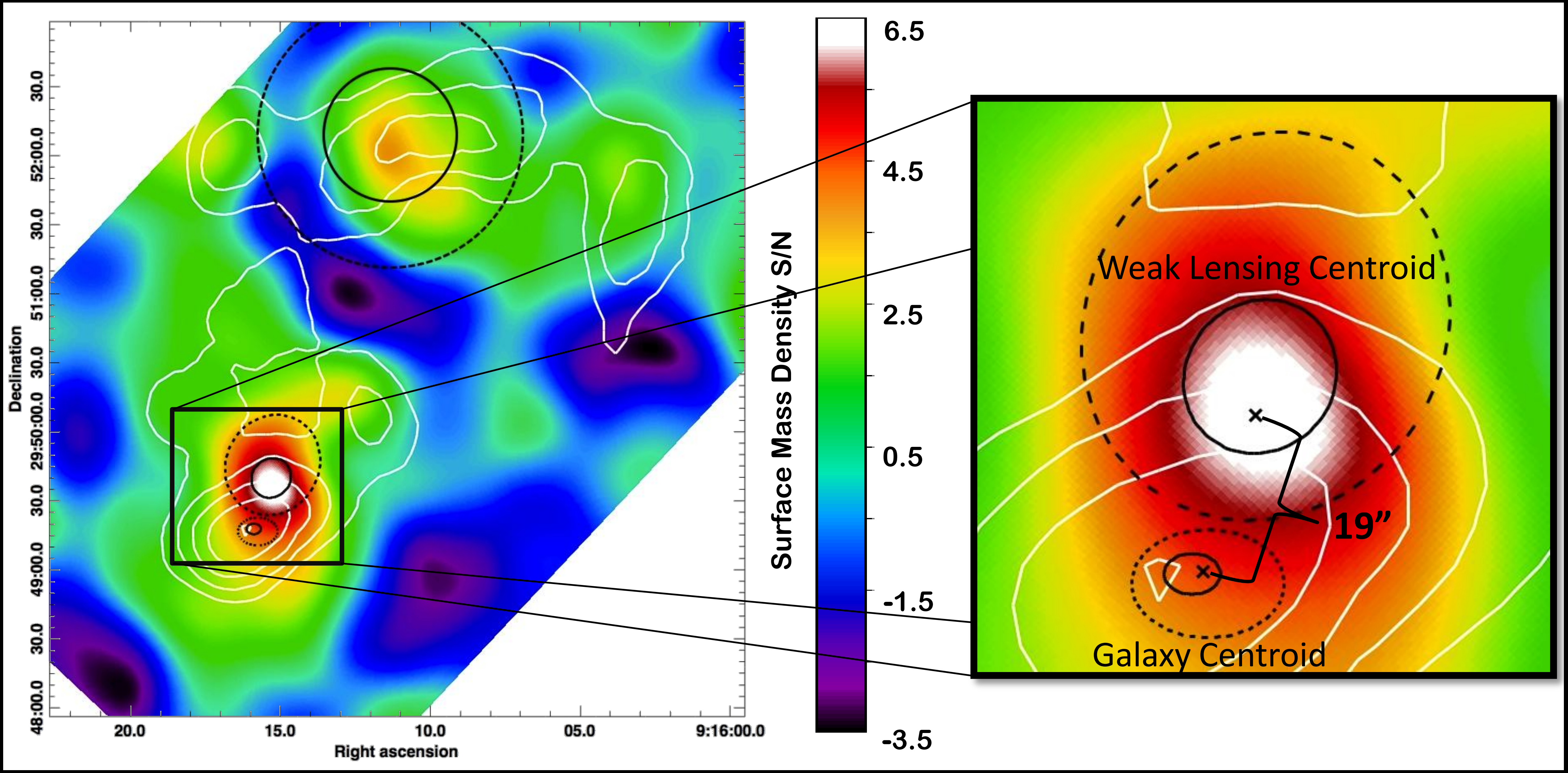


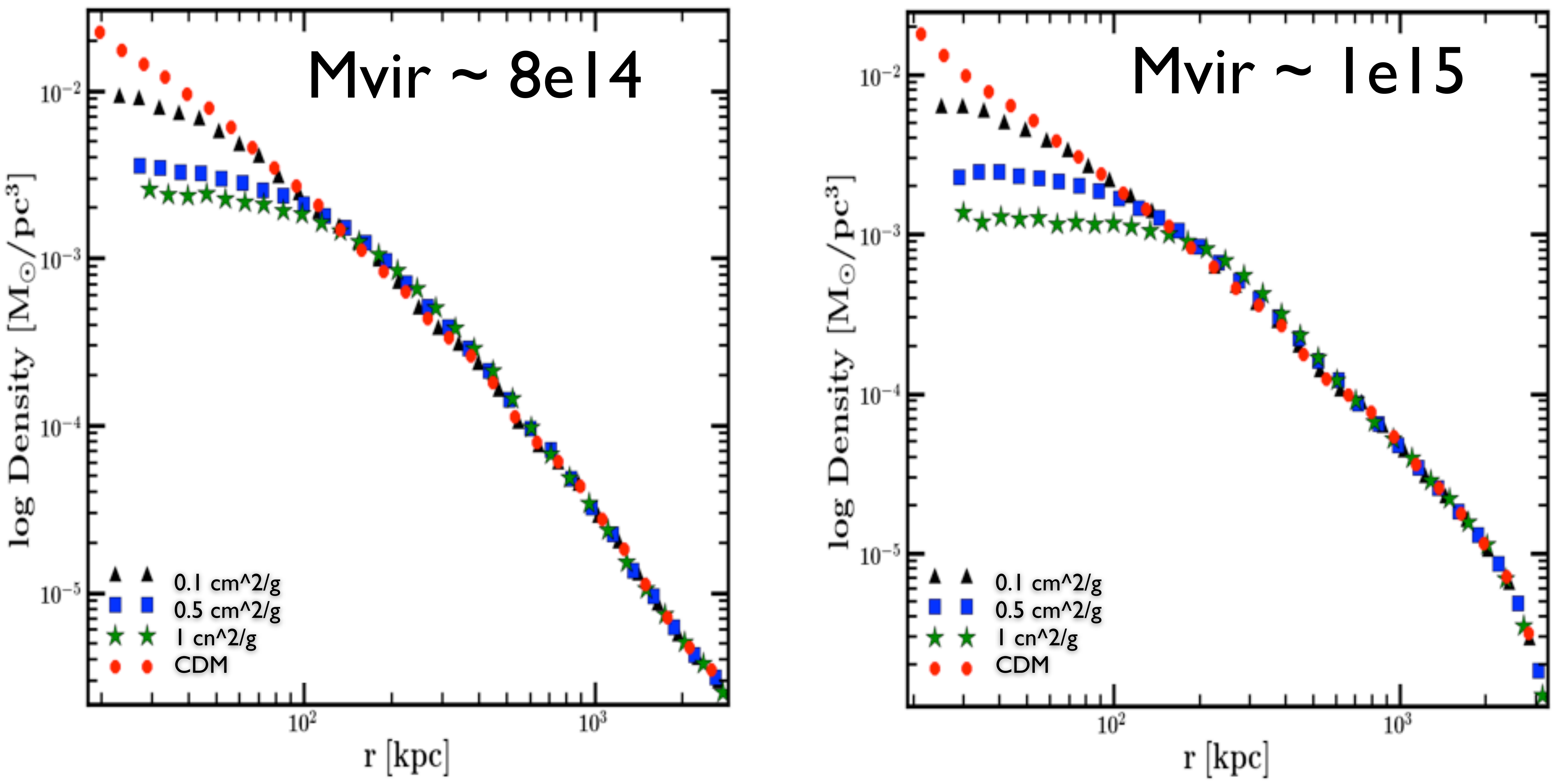
Dawson et al. 2012

Conclusions

- SIDM with $\sigma/m < 1$ cm^2/g is alive!
- $0.1 < \sigma/m < 0.5$ cm^2/g is the interesting regime, able to solve the cusp/core problem and TBTF while still consistent with cluster observations.
- Merging clusters are a promising way to probe the $\sigma/m > 0.1$ cm^2/g regime. MCC will either yield a measurement or rule out the astrophysical interesting cross sections.

Thank You

Work in progress - More simulations



$\sigma/m = 0.1\text{–}0.5\ \mathrm{cm}^2\ /\mathrm{g}$ not ruled out

Results from cosmological simulations - Halo densities

	Observed	$\sigma/m=1\ cm^2/g$	$\sigma/m=0.1\ cm^2/g$
Clusters 700-1000 km/s	0.06-0.025 [Msun/pc^3] Arabadjis et al. 2002, Sand et al. 2004, 2008, Saha et al 2006, Saha & Read 2009 Newman et al. 2009,2011	~0.005-0.004 [Msun/pc^3]	~0.04 [Msun/pc^3]
Low-Mass Spirals 50-130 km/s	0.5-0.01 [Msun/pc^3] de Blok et al. 2001, Simon et al. 2005, Sanchez-Salcedo 2005, Kuzio de Naray et al. 2008,2010, Oh et al . 2011, Salucci et al. 2012	~0.02-0.01 [Msun/pc^3]	~0.2-0.1 [Msun/pc^3]
MW dSphs 20-50 km/s	~0.1 [Msun/pc^3] Strigari et al. 2008, Wolf et al. 2010, Walker & Penarrubia 2011, Amorisco & Evans 2012, Wolf & Bullock 2012	~0.04-0.02 [Msun/pc^3]	~0.5-0.2 [Msun/pc^3]

Rocha et al. 2013
Peter et al. 2013

Results from cosmological simulations - Halo densities

	Observed	$\sigma/m=1\ cm^2/g$	$\sigma/m=0.1\ cm^2/g$
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Low-Mass Spirals 50-130 km/s	0.5-0.01 [Msun/pc^3] de Blok et al. 2001, Simon et al. 2005, Sanchez-Salcedo 2005, Kuzio de Naray et al. 2008,2010, Oh et al . 2011, Salucci et al. 2012	~0.02-0.01 [Msun/pc^3]	~0.2-0.1 [Msun/pc^3]
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Low-Mass Spirals 50-130 km/s	0.5-0.01 $[M_{sun}/pc^3]$ de Blok et al. 2001, Simon et al. 2005, Sanchez-Salcedo 2005, Kuzio de Naray et al. 2008,2010, Oh et al . 2011, Salucci et al. 2012	~~~0.02-0.01 $[M_{sun}/pc^3]$~~	~0.2-0.1 $[M_{sun}/pc^3]$
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Results from cosmological simulations - Halo densities

	Observed	$\sigma/m=1\ cm^2/g$	✓ $\sigma/m=0.1\ cm^2/g$
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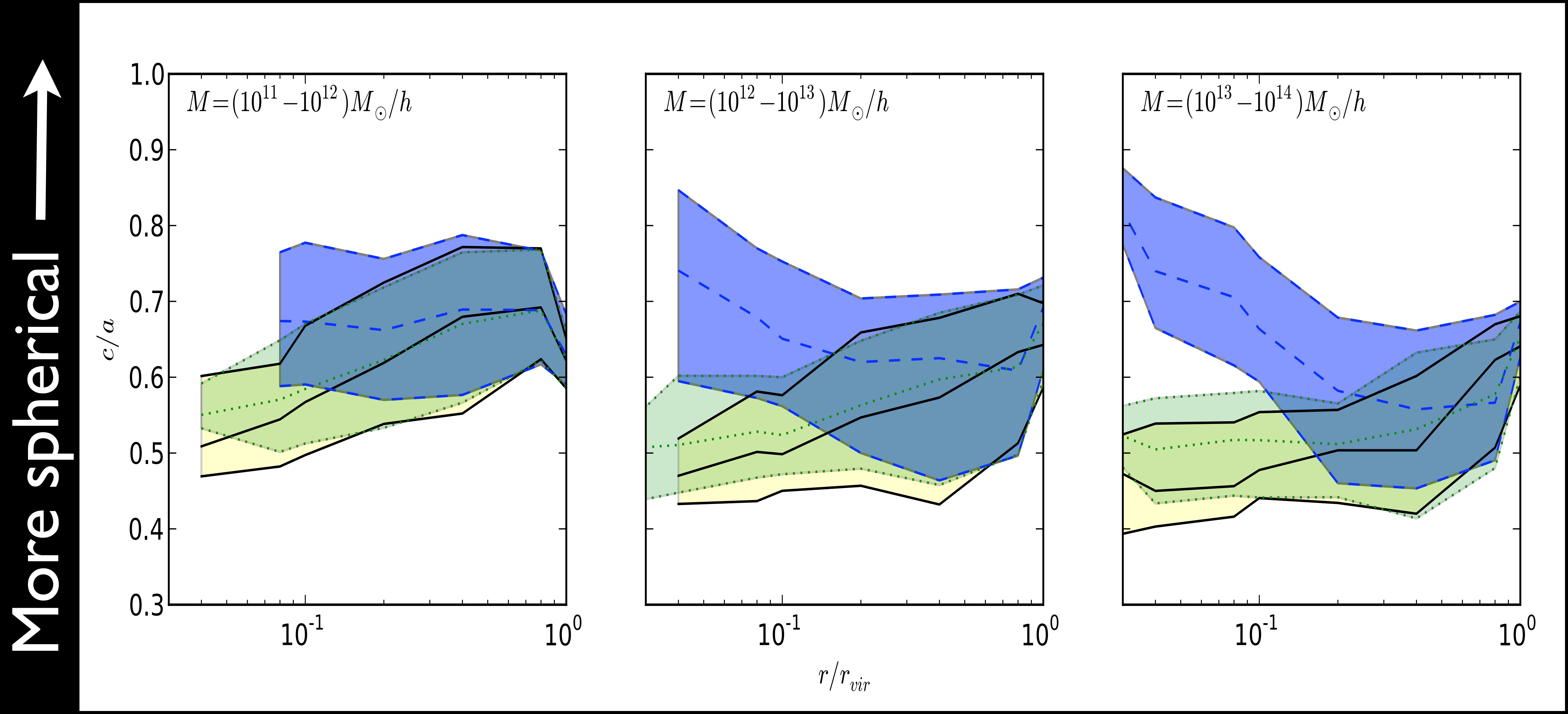
MW dSphs 20-50 km/s	~0.1 [M_{sun}/pc^3] Strigari et al. 2008, Wolf et al. 2010, Walker & Penarrubia 2011, Amorisco & Evans 2012, Wolf & Bullock 2012	~~~0.04-0.02 [M_{sun}/pc^3]~~	~0.5-0.2 [M_{sun}/pc^3]

Rocha et al. 2013
Peter et al. 2013

Results from cosmological simulations - Halo shapes



Radius/rvir

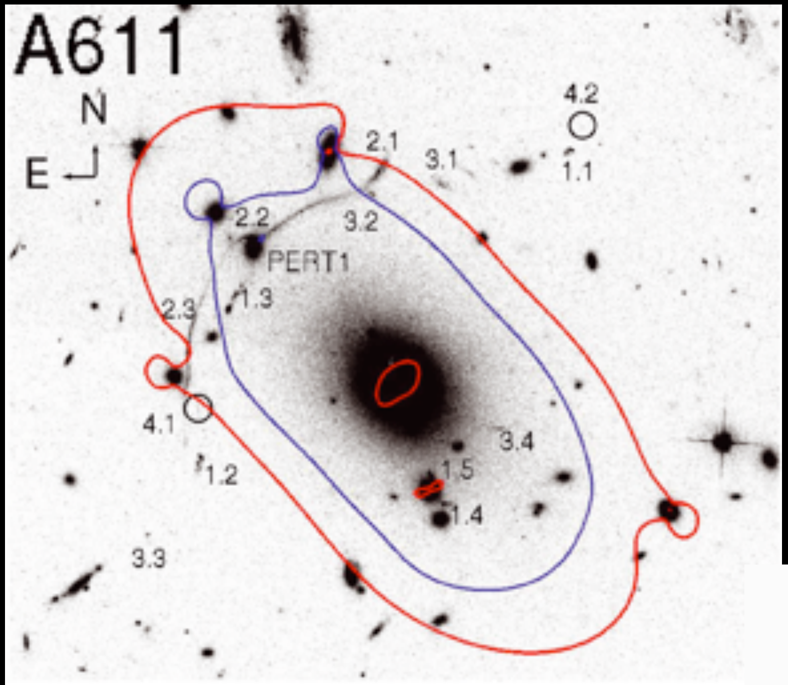
$\sigma/m = 1\ \mathrm{cm}^2/\mathrm{g}$

$\sigma/m = 0.1\ \mathrm{cm}^2/\mathrm{g}$

collisionless

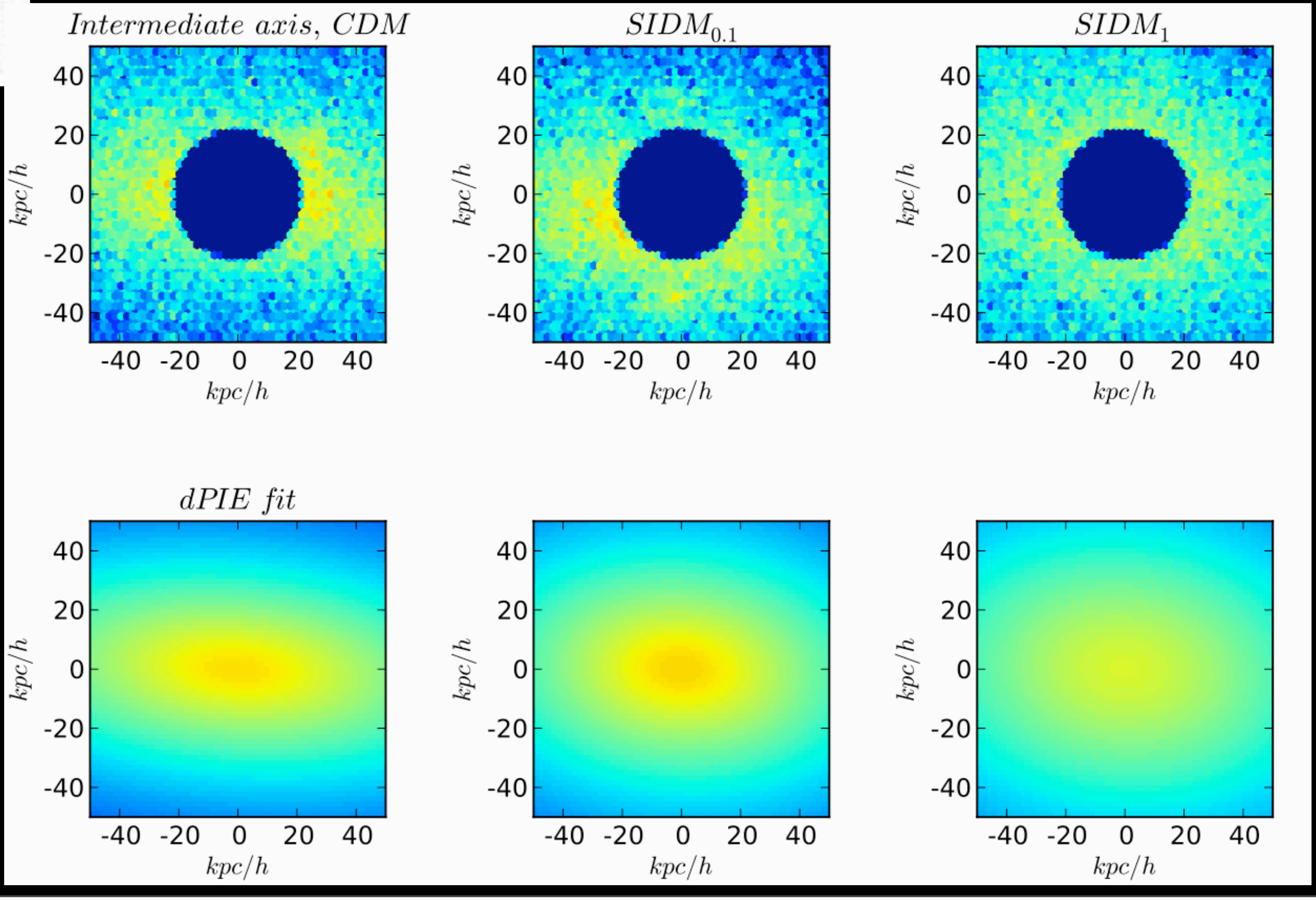
Rocha et al. 2013
Peter et al. 2013

Results from cosmological simulations - Halo shapes



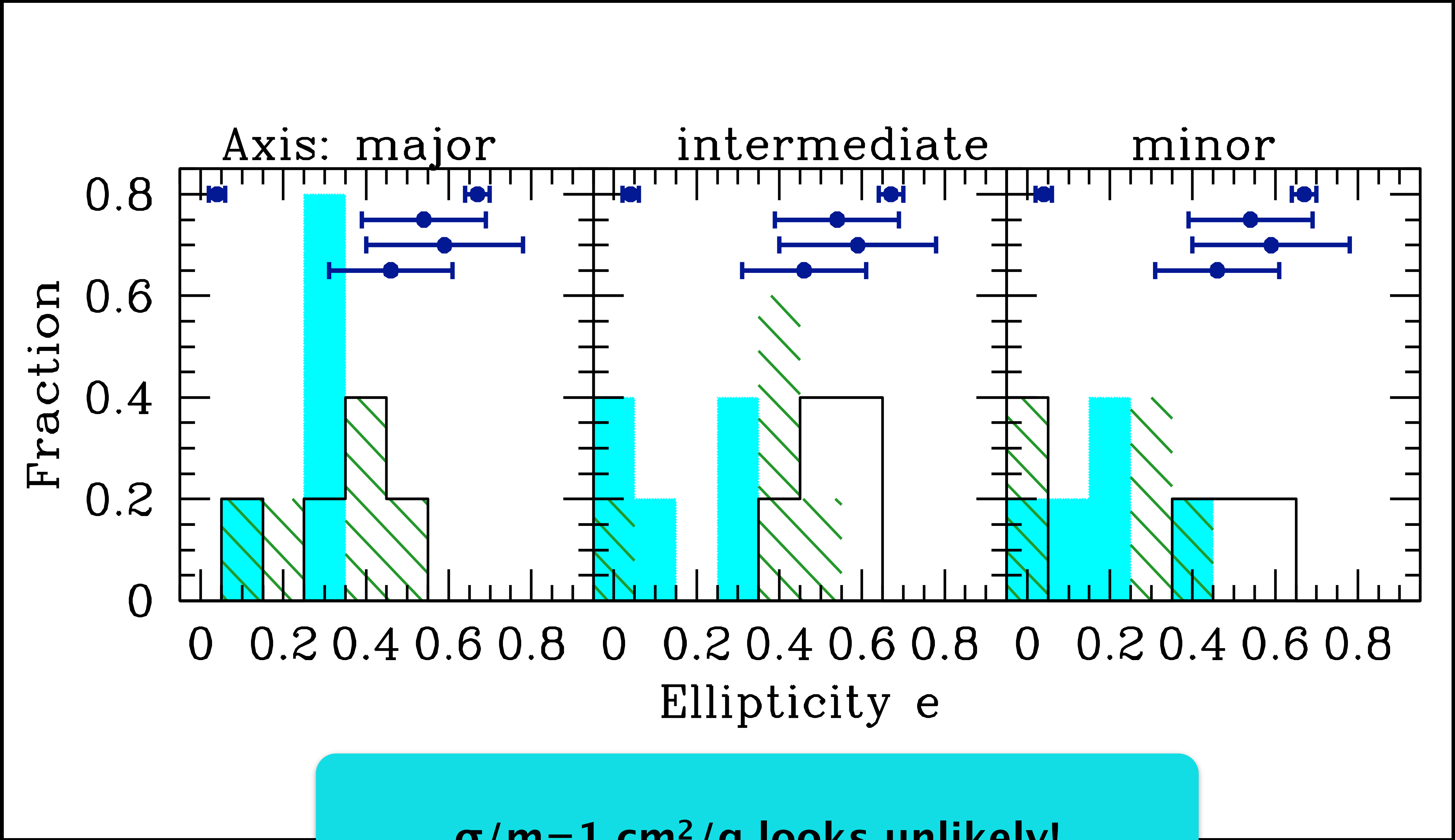
From LoCuSS sample
Richard+ 2010

We see surface density (or gravitational potentials) in projection.



Rocha et al. 2013
Peter et al. 2013

Results from cosmological simulations - Halo shapes



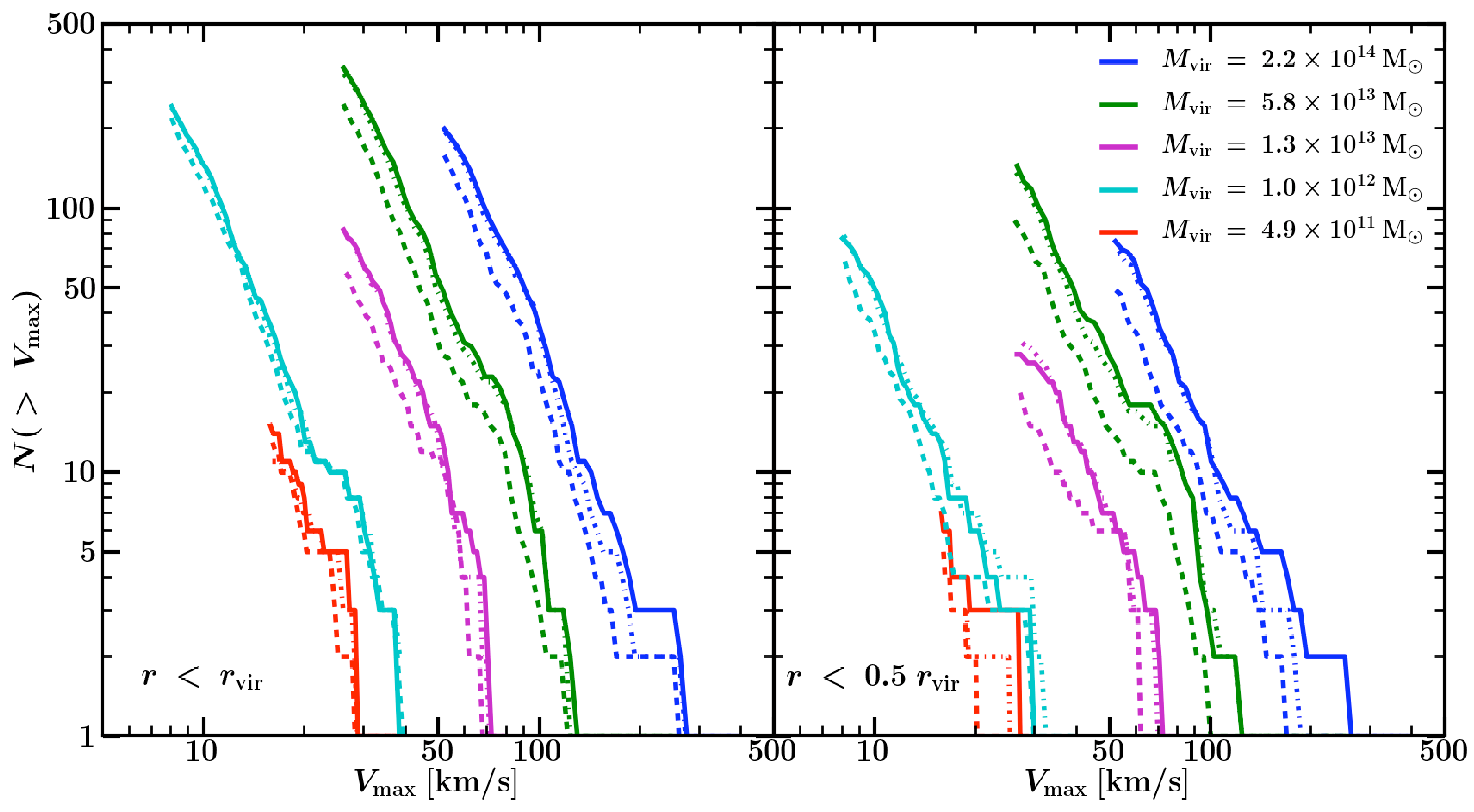
σ/m=1 cm²/g looks unlikely!

This is more than an order of magnitude less stringent than Miralda-Escude (2002), the reason is that:

- Halos get spherical only within the cores
- If inner parts have flattened density, outer parts have even greater weight.

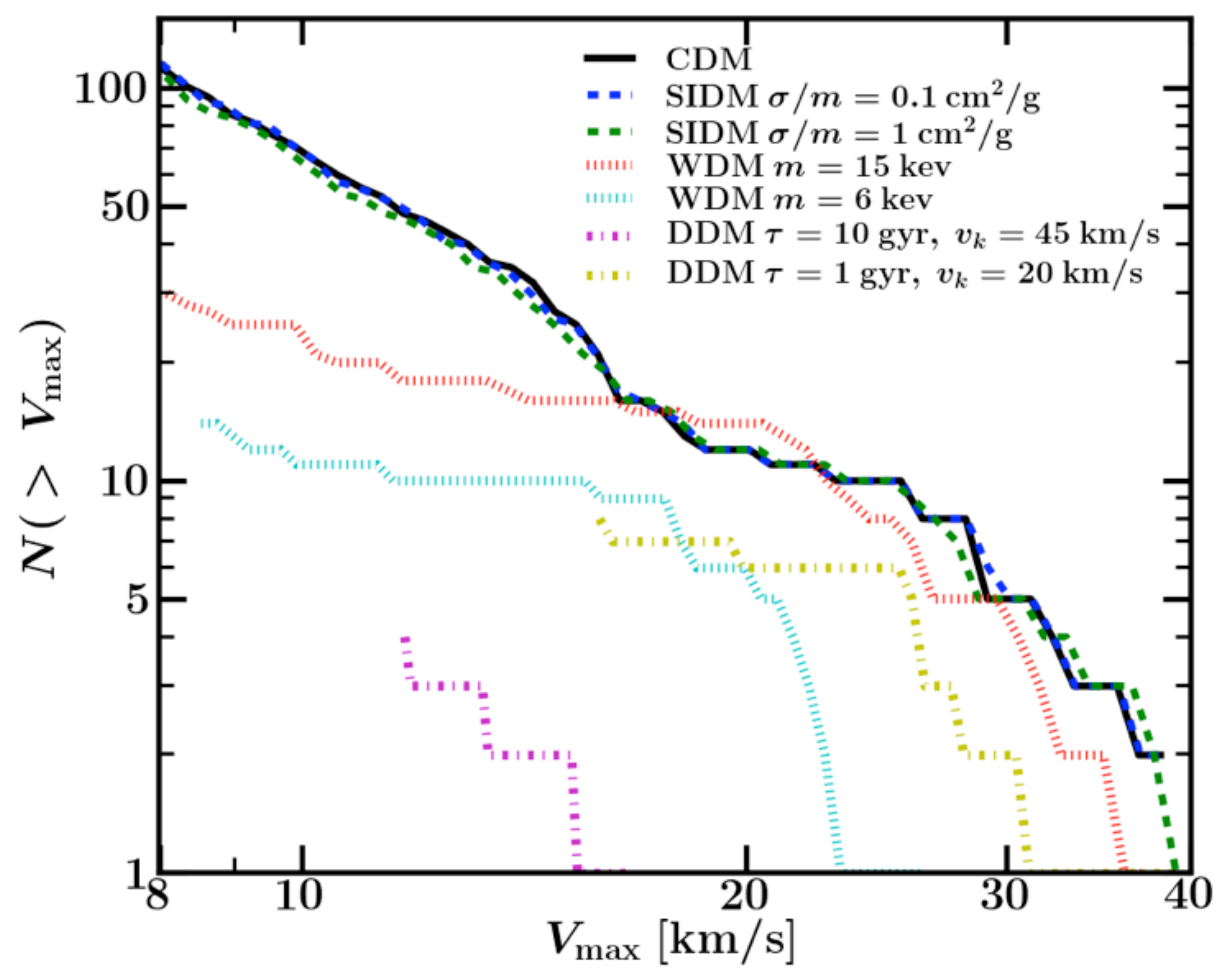
Results from cosmological simulations - Substructure

SIDM & CDM have very similar subhalo Vmax functions

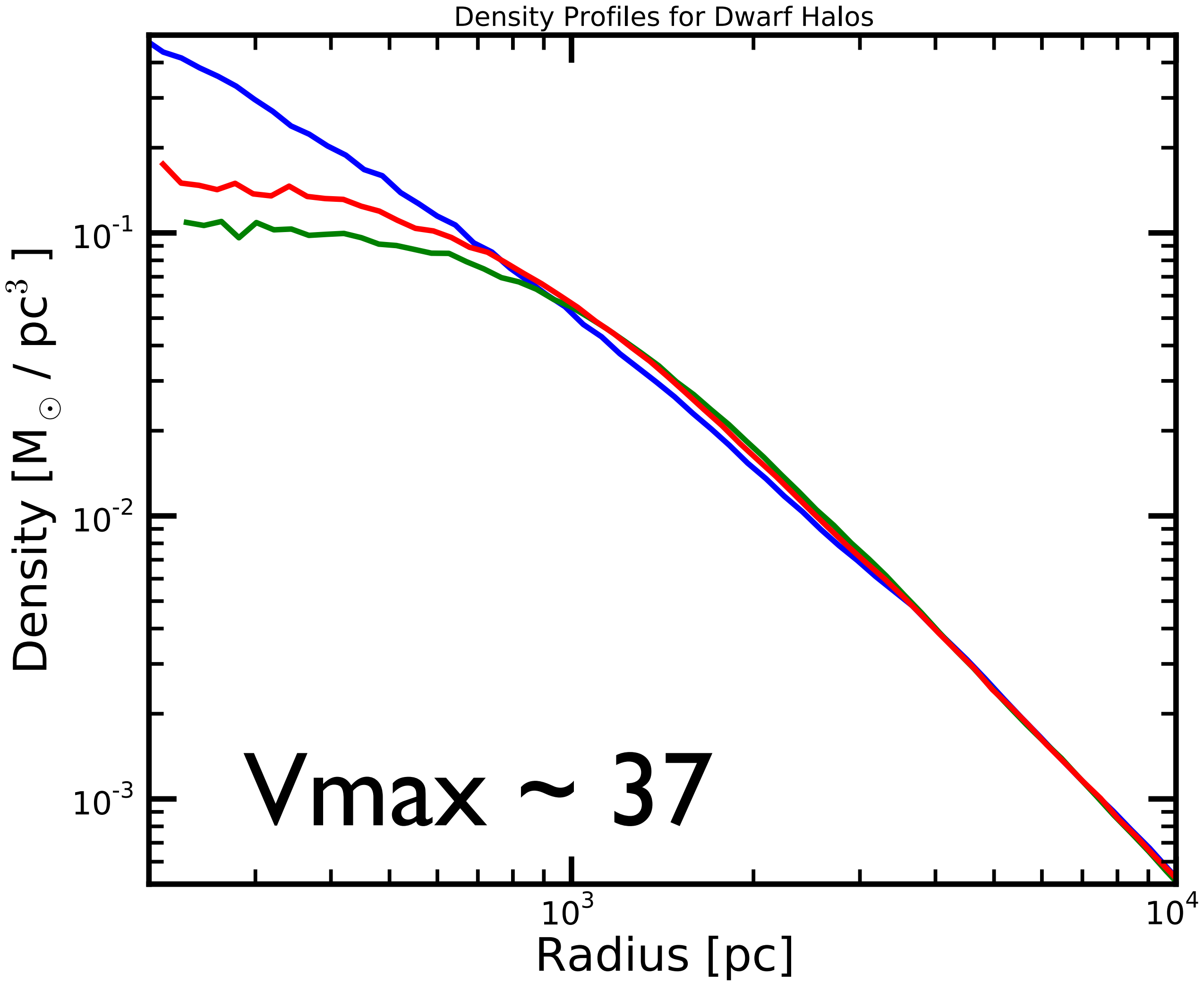


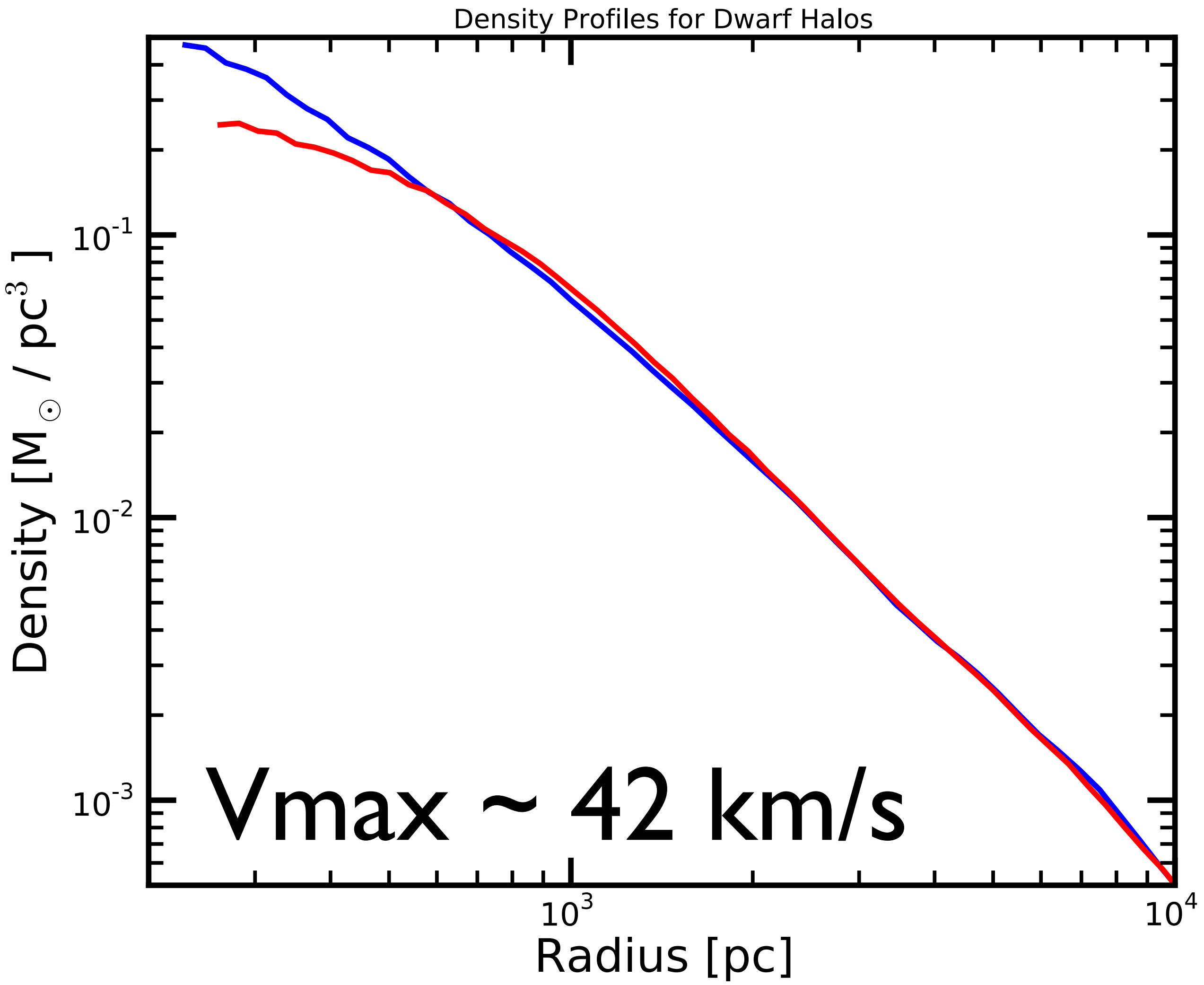
Rocha et al. 2013
Peter et al. 2013

Results from cosmological simulations - Substructure



Work in progress - More simulations





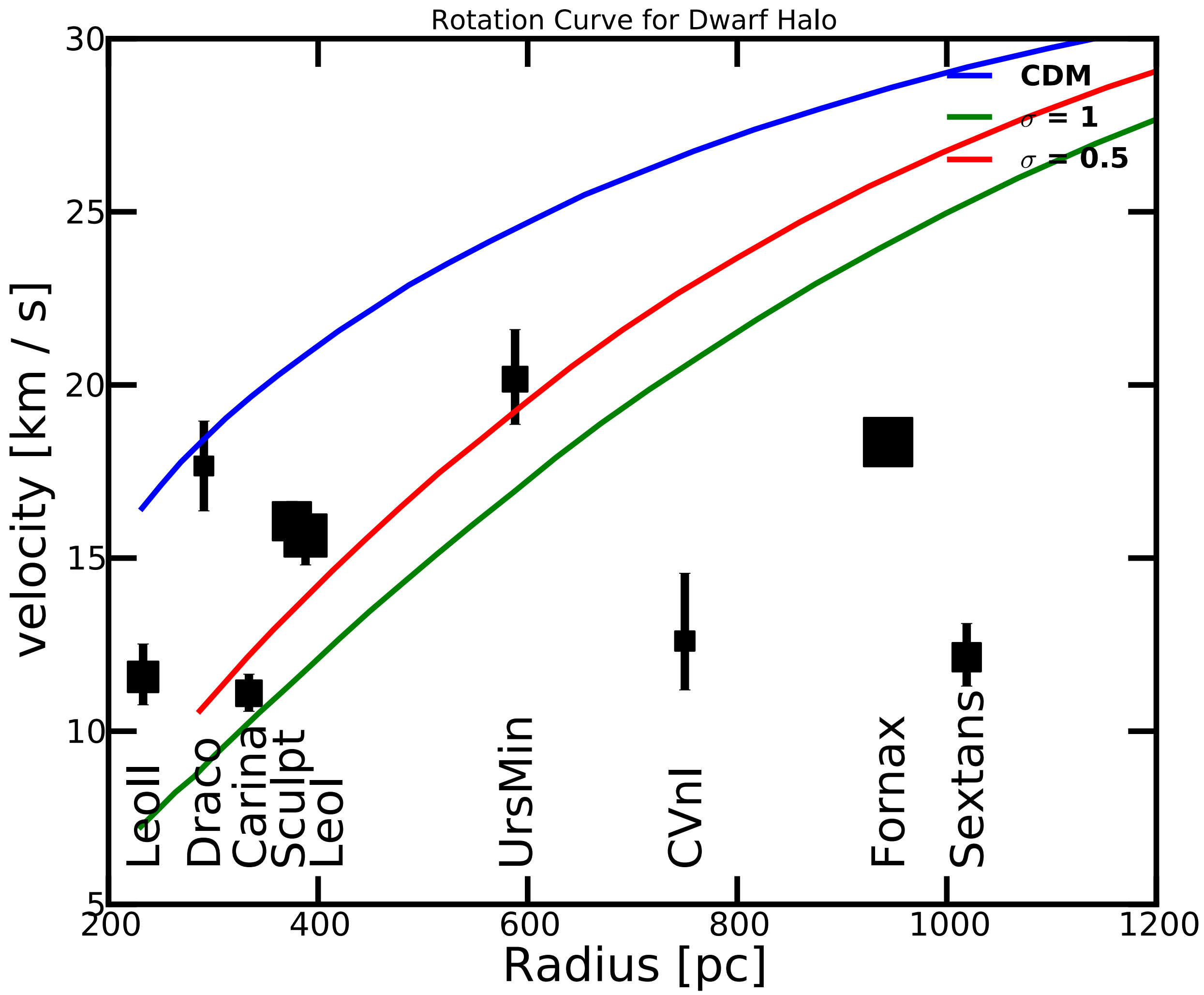
Core size of ~0.6-8 kpc and Central densities of ~0.05 Msun/pc^3 for $\sigma/m = 0.5$ cm^2 /g

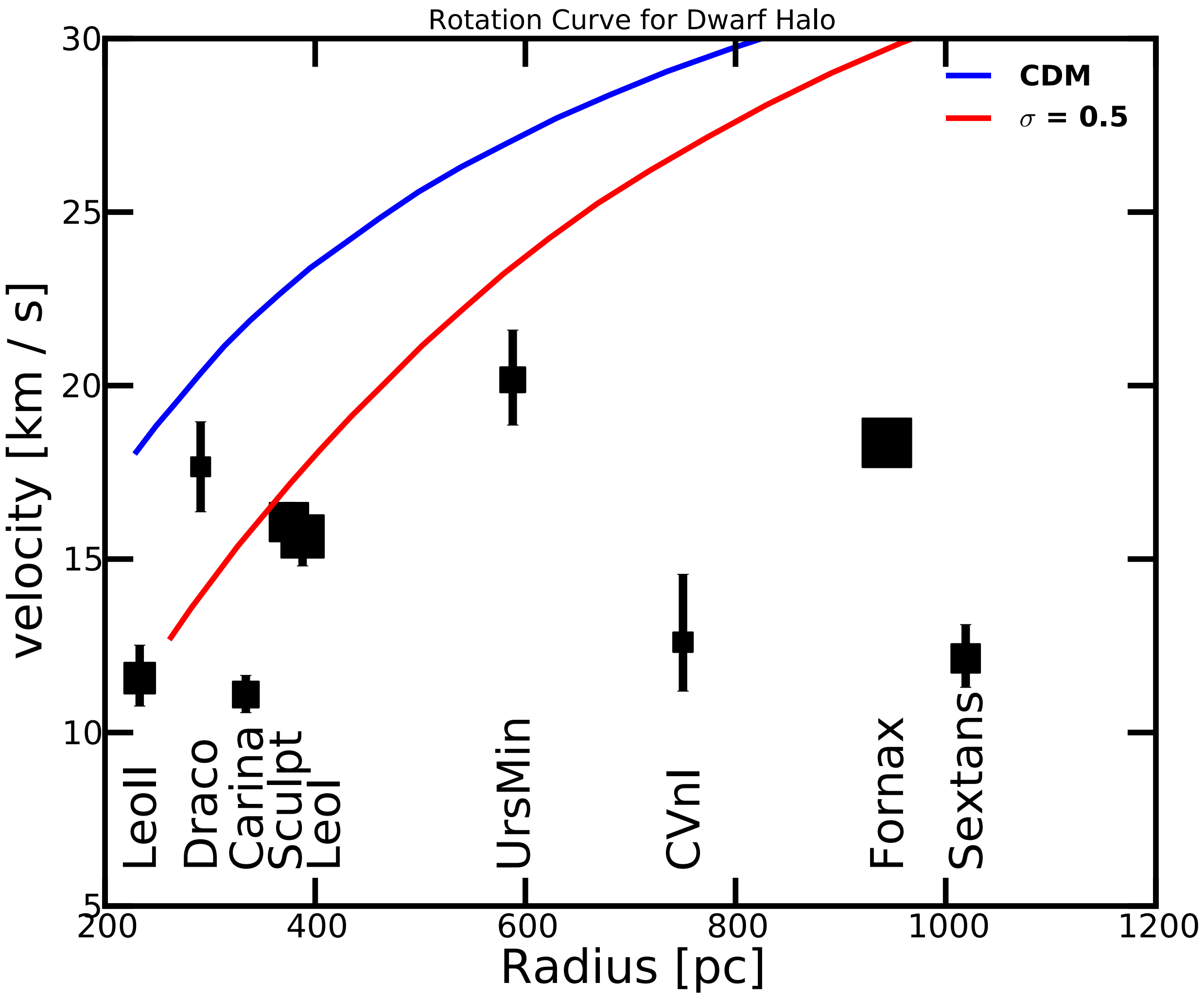
Oliver Elbert et al. in prep

Work in progress - More simulations

Vmax ~ 37 km/s

Vmax ~ 42 km/s





Consitent with the most lominous MW dwarfs

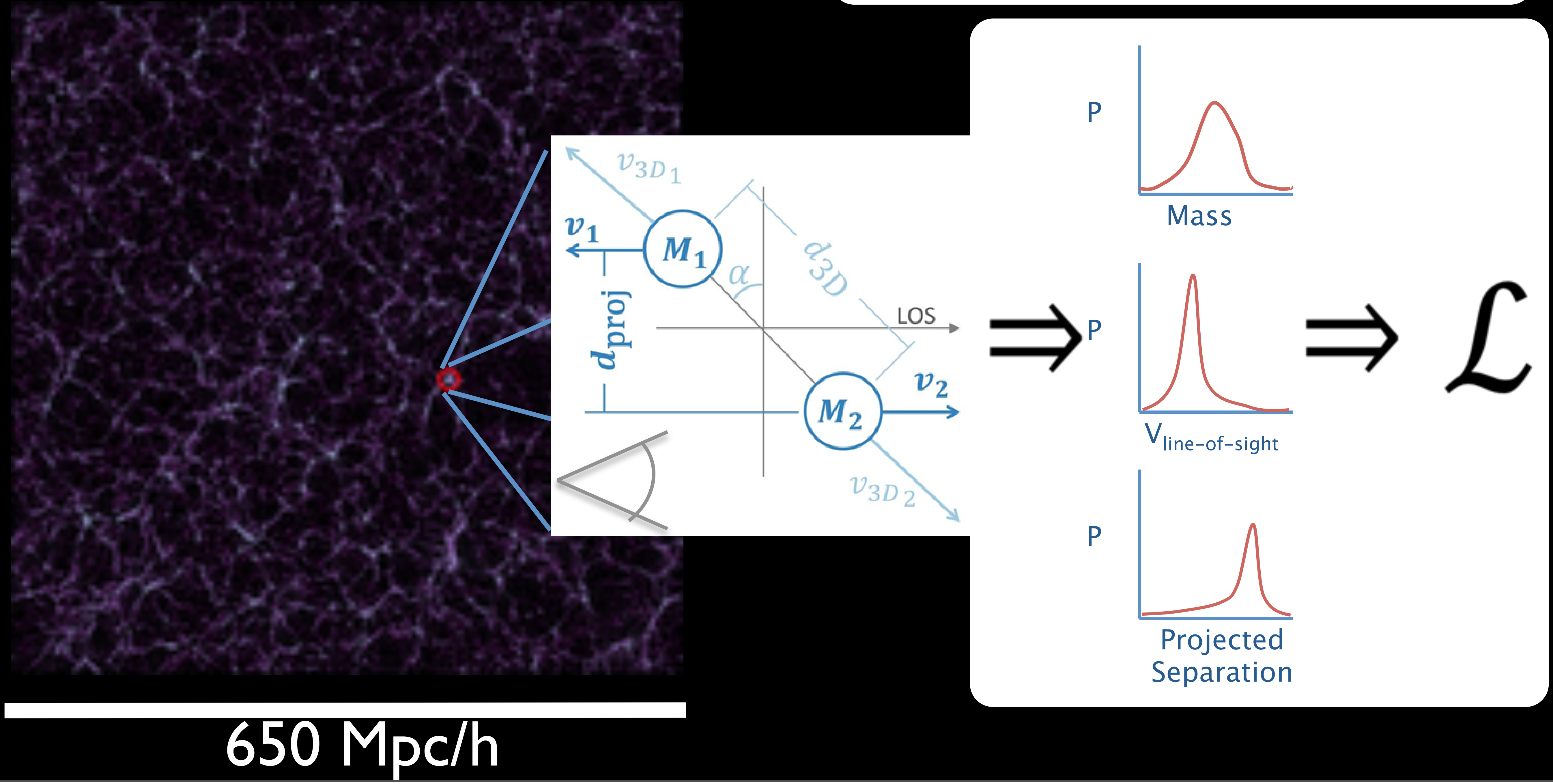
Oliver Elbert et al. in prep

Work in progress - Merging clusters

Predictions vs. Observations

Importance Sampling

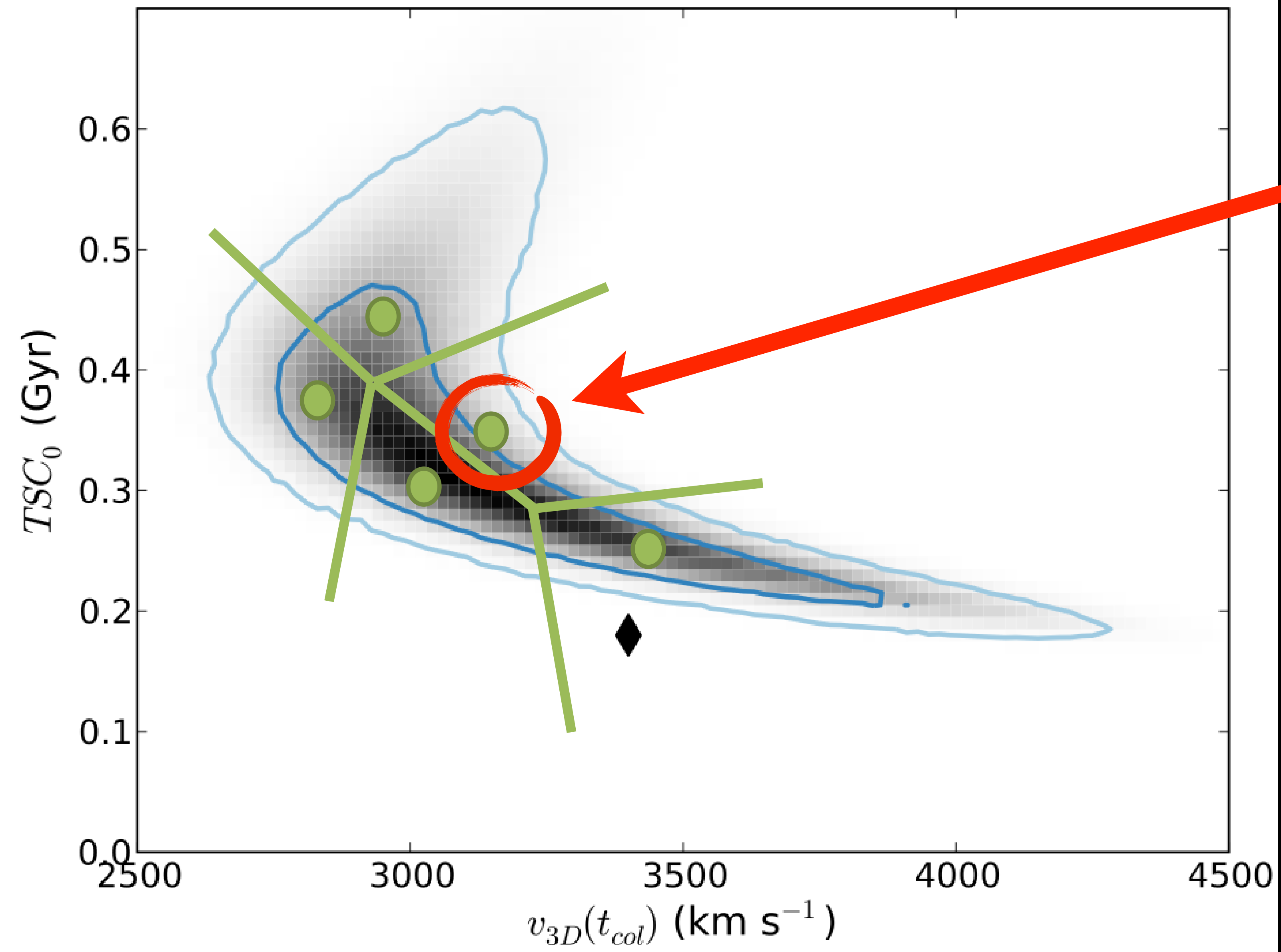
Merging Cluster Collaboration



Work in progress - Merging clusters

Predictions vs. Observations

MERGING
CLUSTER
COLLABORATION



Zoom in simulations with hi-res and SIDM

MCC will either yield a measure or rule out the astrophysically interesting SIDM cross sections!!

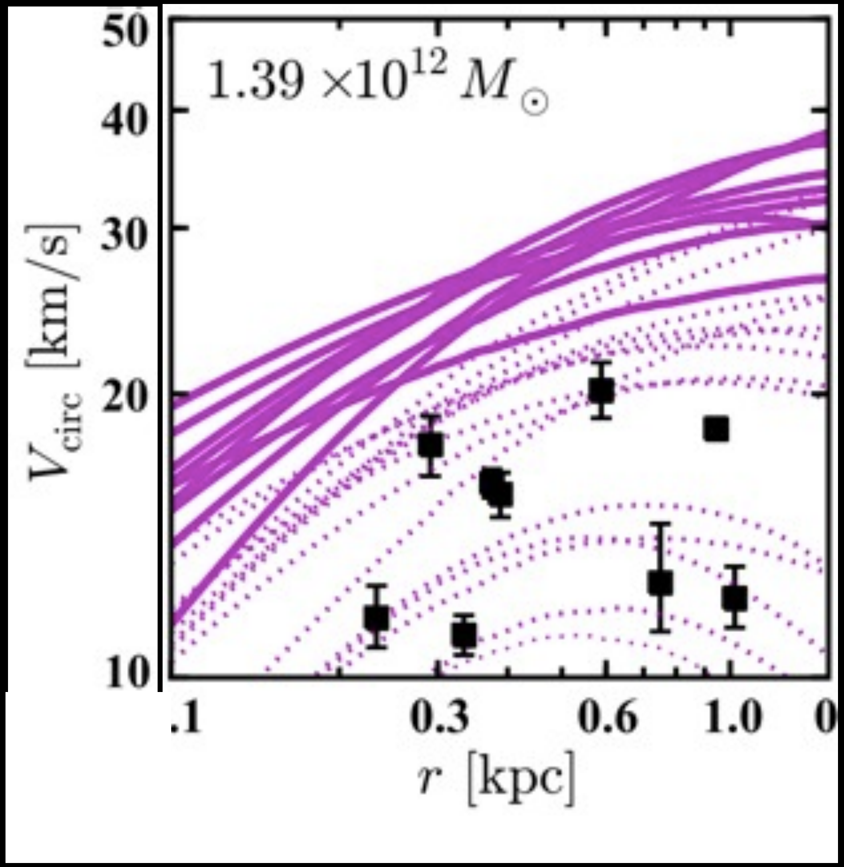
Results from cosmological simulations - Halo densities, shapes & substructure

Observations

Results from cosmological simulations - Halo densities, shapes & substructure

Observations

Milky Way dwarfs



“Too big to fail”
(Boylan-Kolchin+ 2011)

Need less DM in ~100 pc in 10^9–10^{10} $M_\odot$ halos

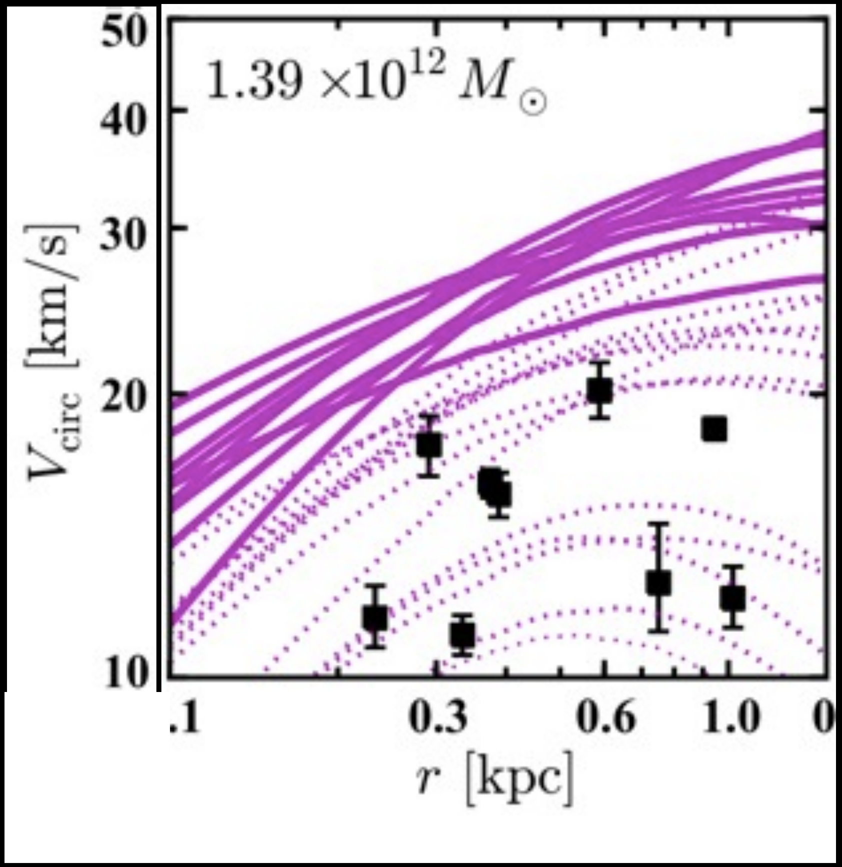
Cores in ~0.5 kpc observed
Walker&Penarrubia 2011

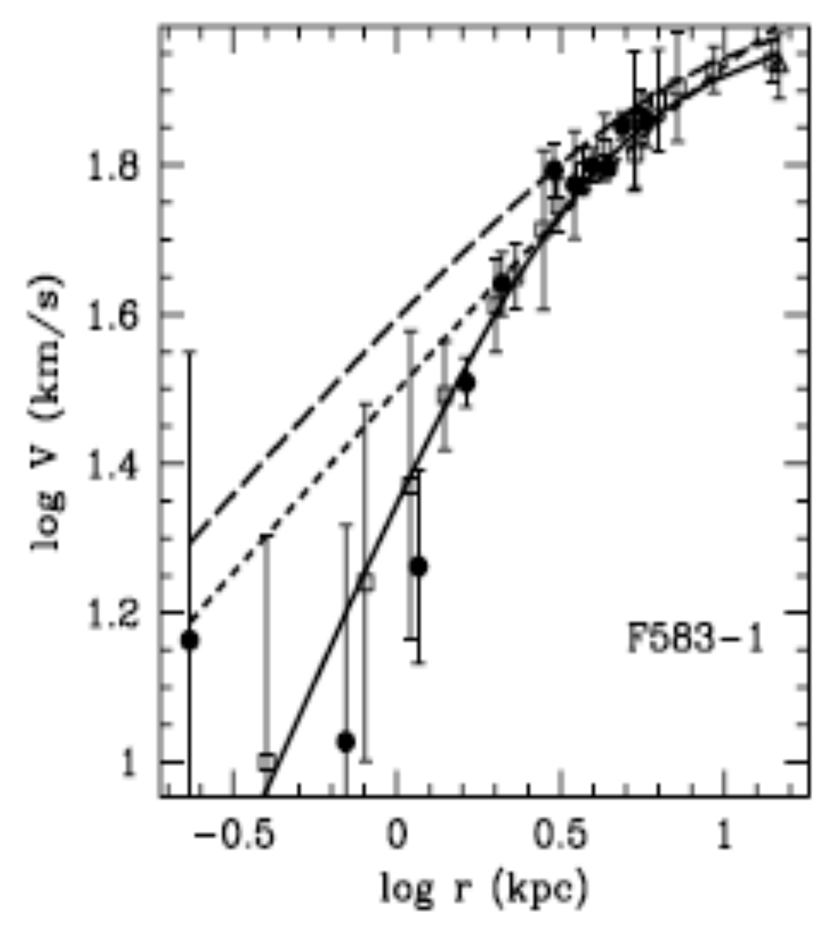
Results from cosmological simulations - Halo densities, shapes & substructure

Observations

Milky Way dwarfs

Low-mass Spirals





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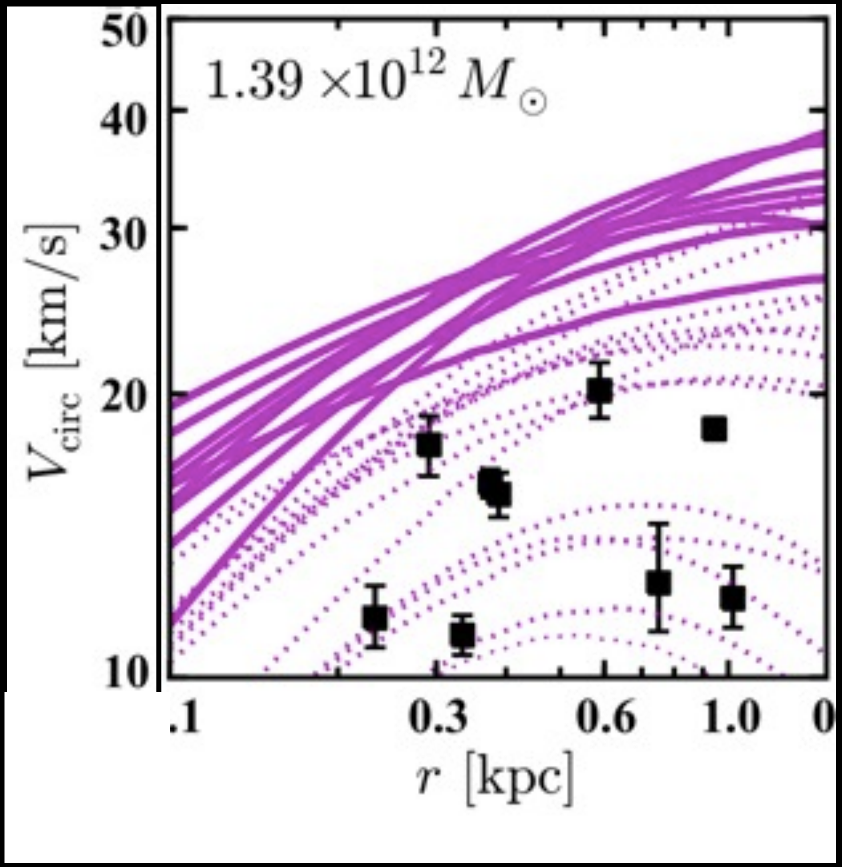
Dwarf core problem
(Kuzio de Naray+ 2008)

Need cores in ~0.5–5 kpc in 10^{11} $M_\odot$ halos

Results from cosmological simulations - Halo densities, shapes & substructure

Observations

Milky Way dwarfs



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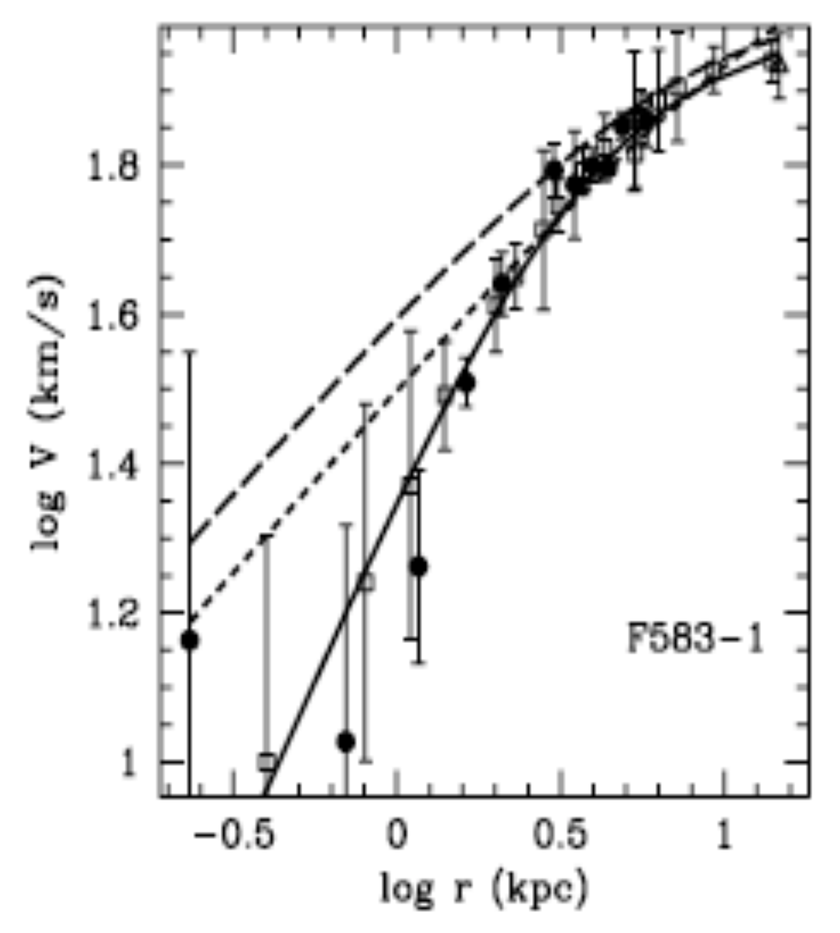

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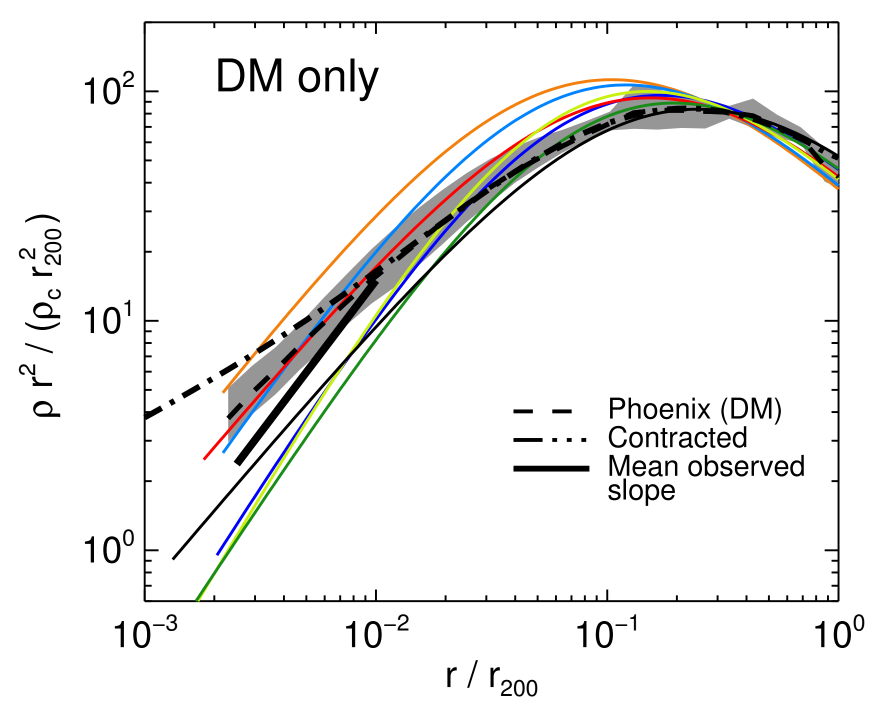
Galaxy Clusters



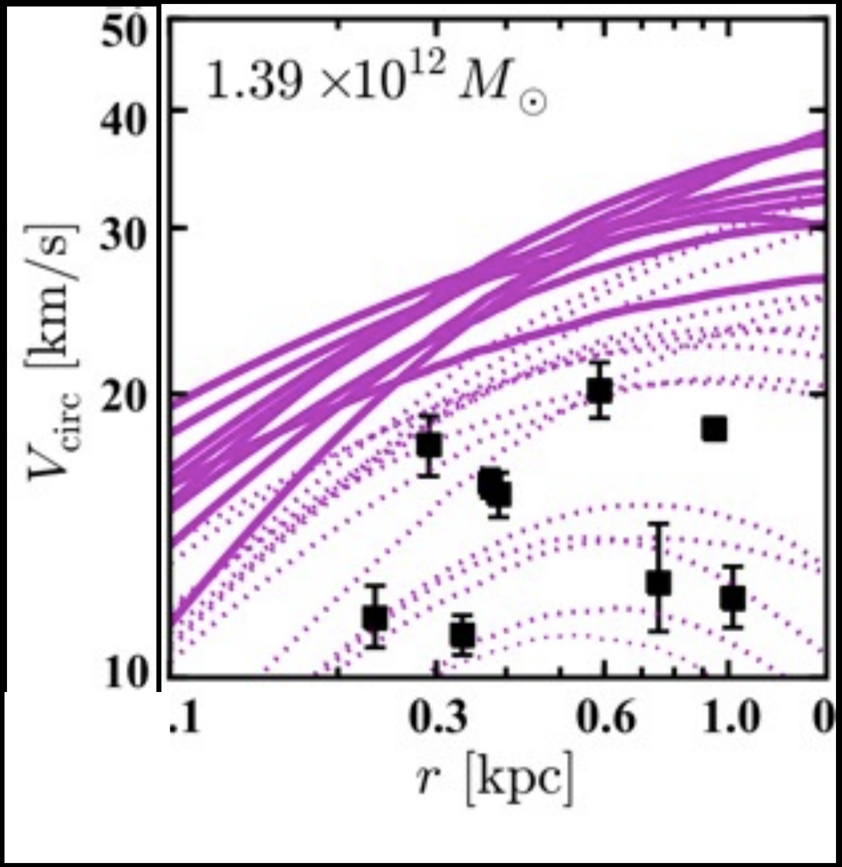
Galaxy cluster densities
$\rho \sim r^{-\beta}$
Drew Newman
(Newman+ 2012a,b)

Allow cores of ~30 kpc in 10^{15} $M_\odot$ halos

Results from cosmological simulations - Halo densities, shapes & substructure

Observations

Milky Way dwarfs



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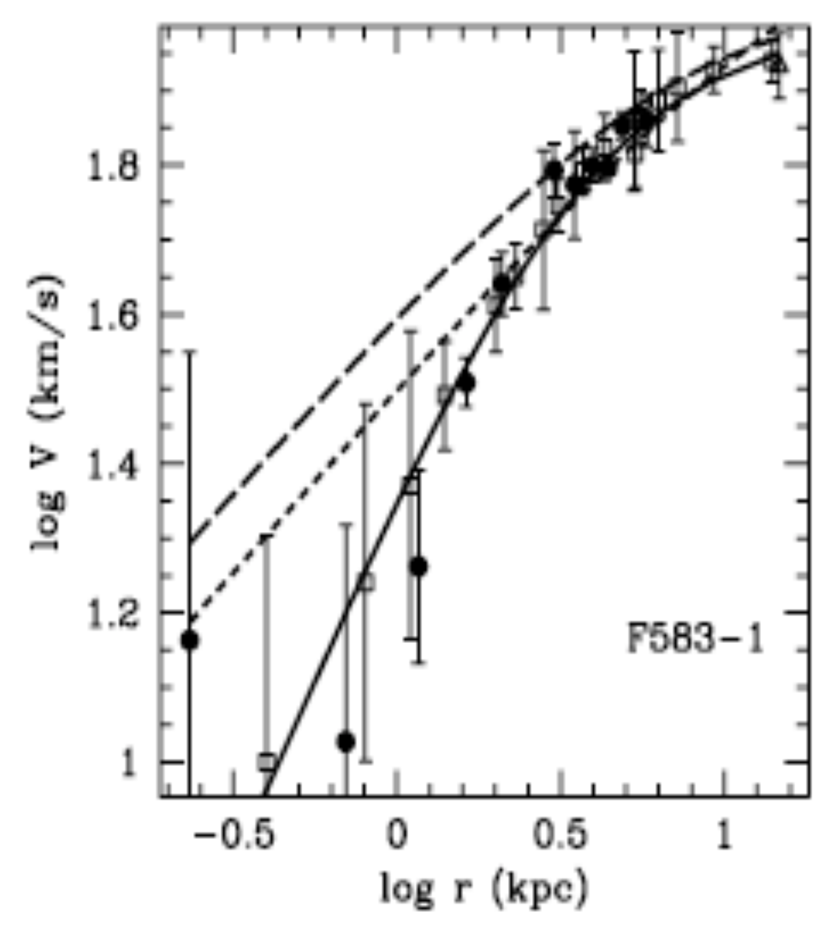

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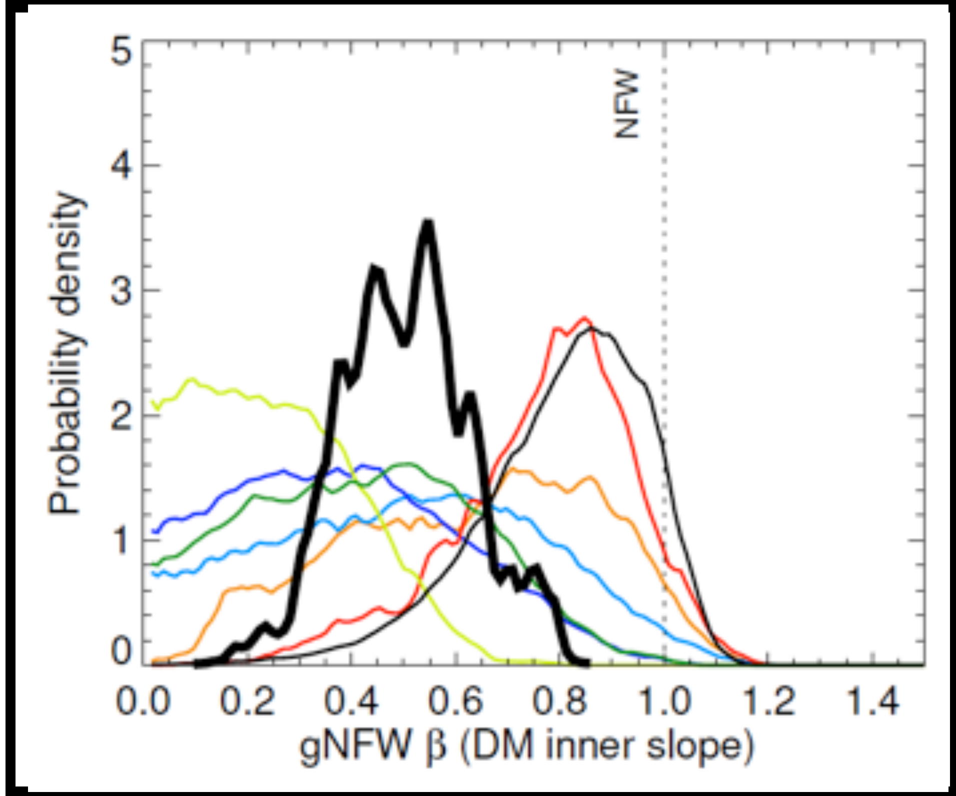

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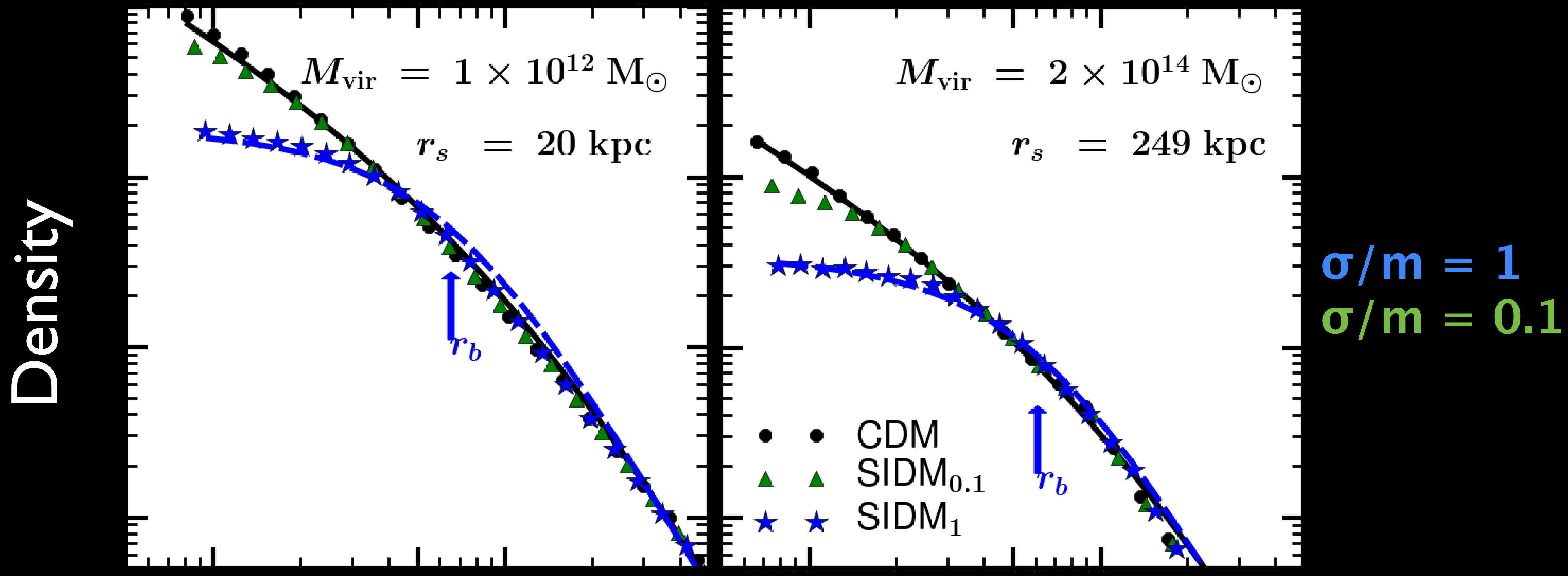
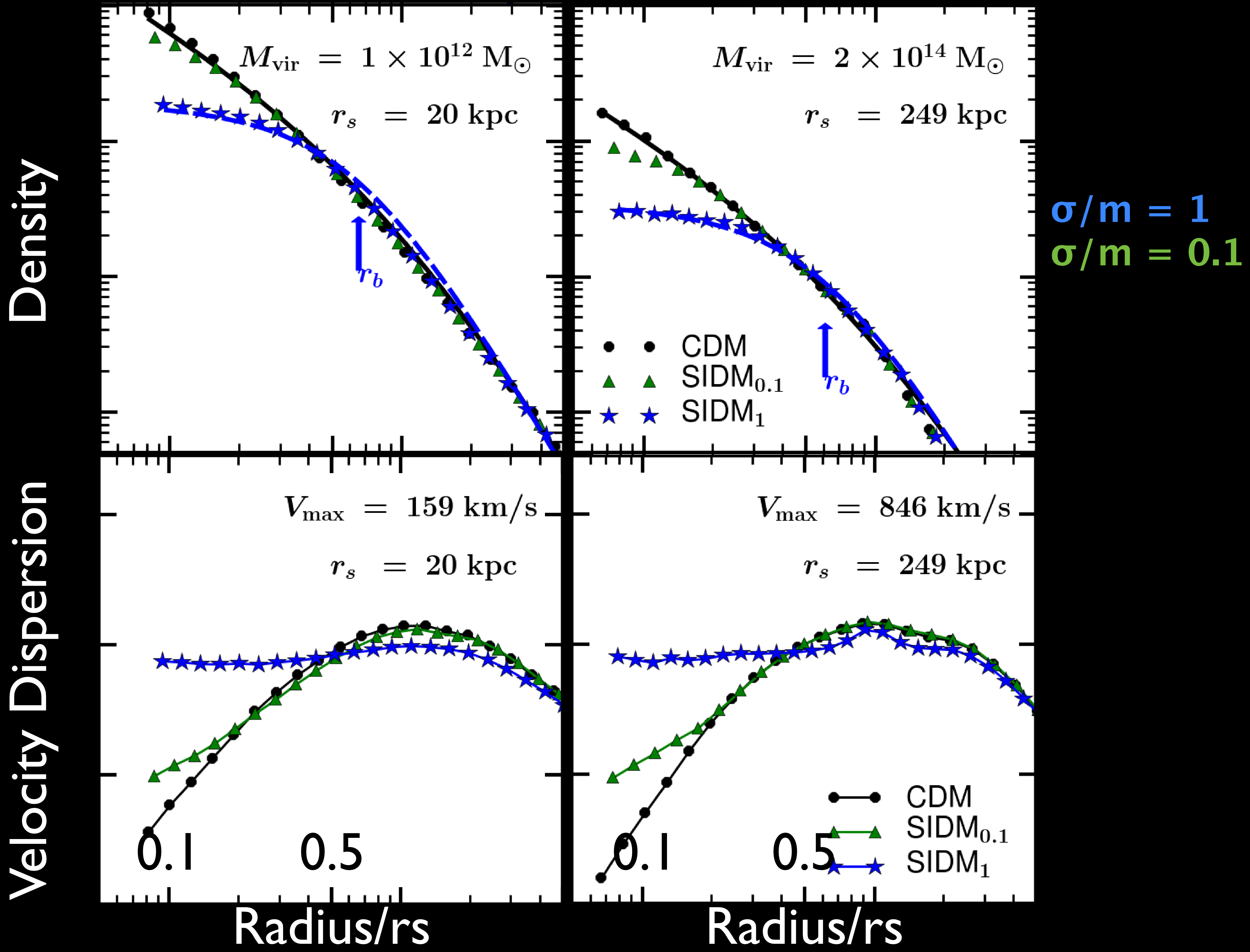
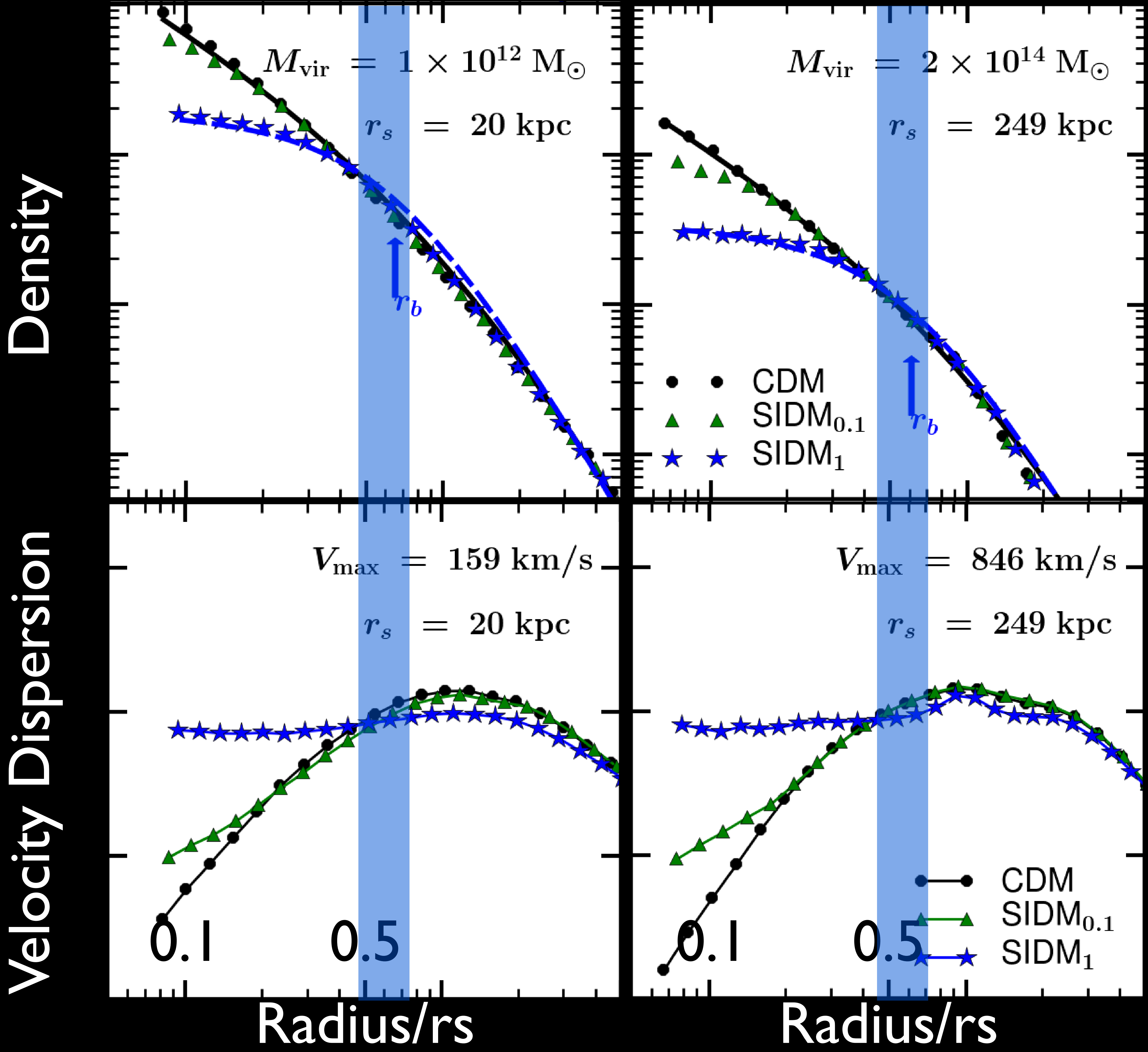


Radius/rs Radius/rs


Density
Velocity Dispersion
$M_{\rm vir} = 1 \times 10^{12}\ {\rm M}_\odot$
$r_s = 20$ kpc
r_b
$M_{\rm vir} = 2 \times 10^{14}\ {\rm M}_\odot$
$r_s = 249$ kpc
r_b
CDM
SIDM$_{0.1}$
SIDM$_1$
$\sigma/m = 1$
$\sigma/m = 0.1$
$V_{\rm max} = 159$ km/s
$r_s = 20$ kpc
$V_{\rm max} = 846$ km/s
$r_s = 249$ kpc
0.1
0.5
0.1
0.5
CDM
SIDM$_{0.1}$
SIDM$_1$
Radius/rs
Radius/rs



$\sigma/m = 1$

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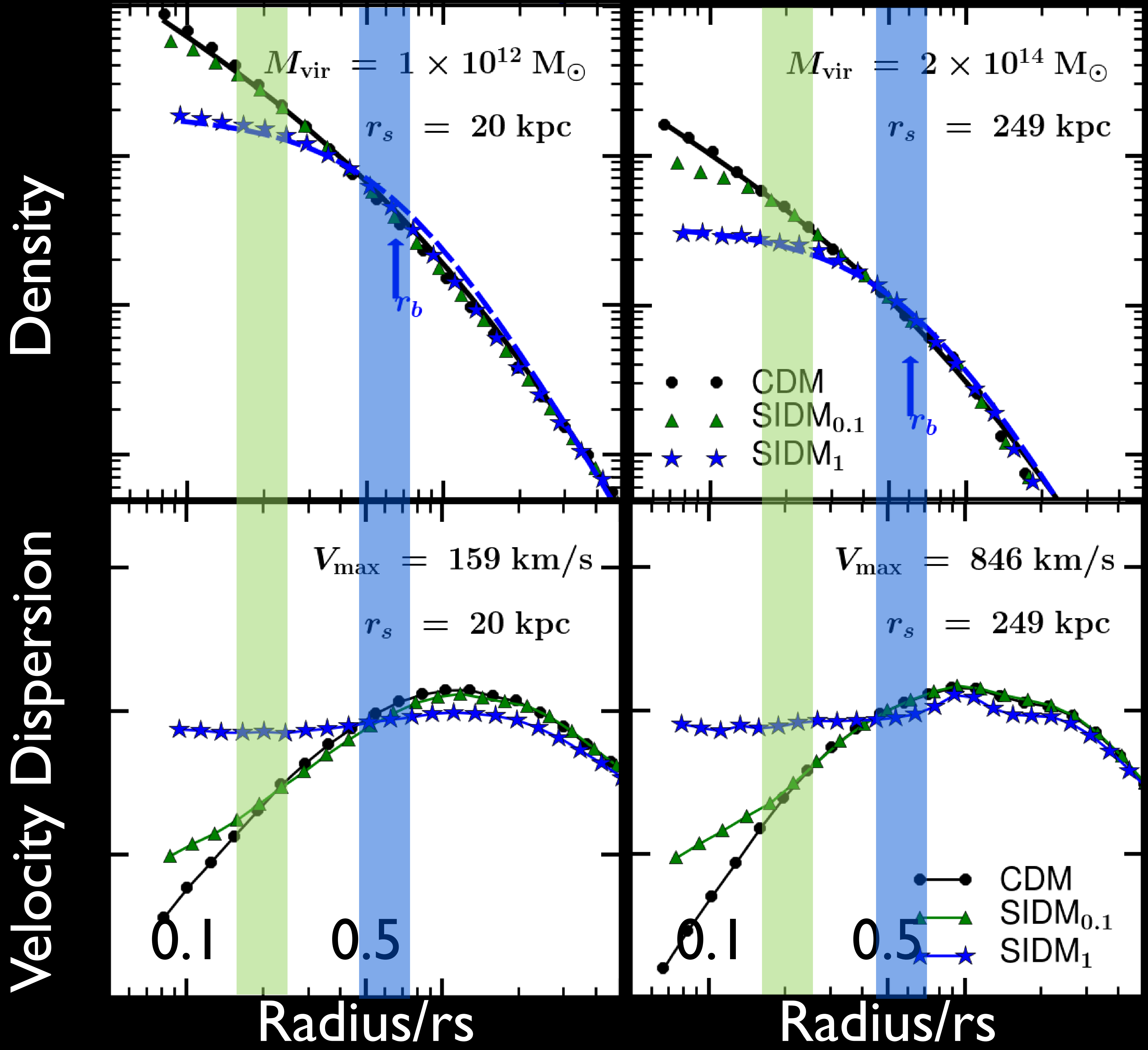
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CDM
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SIDM_1
0.1
0.5
0.1
0.5
Radius/rs
Radius/rs

σ/m = 1

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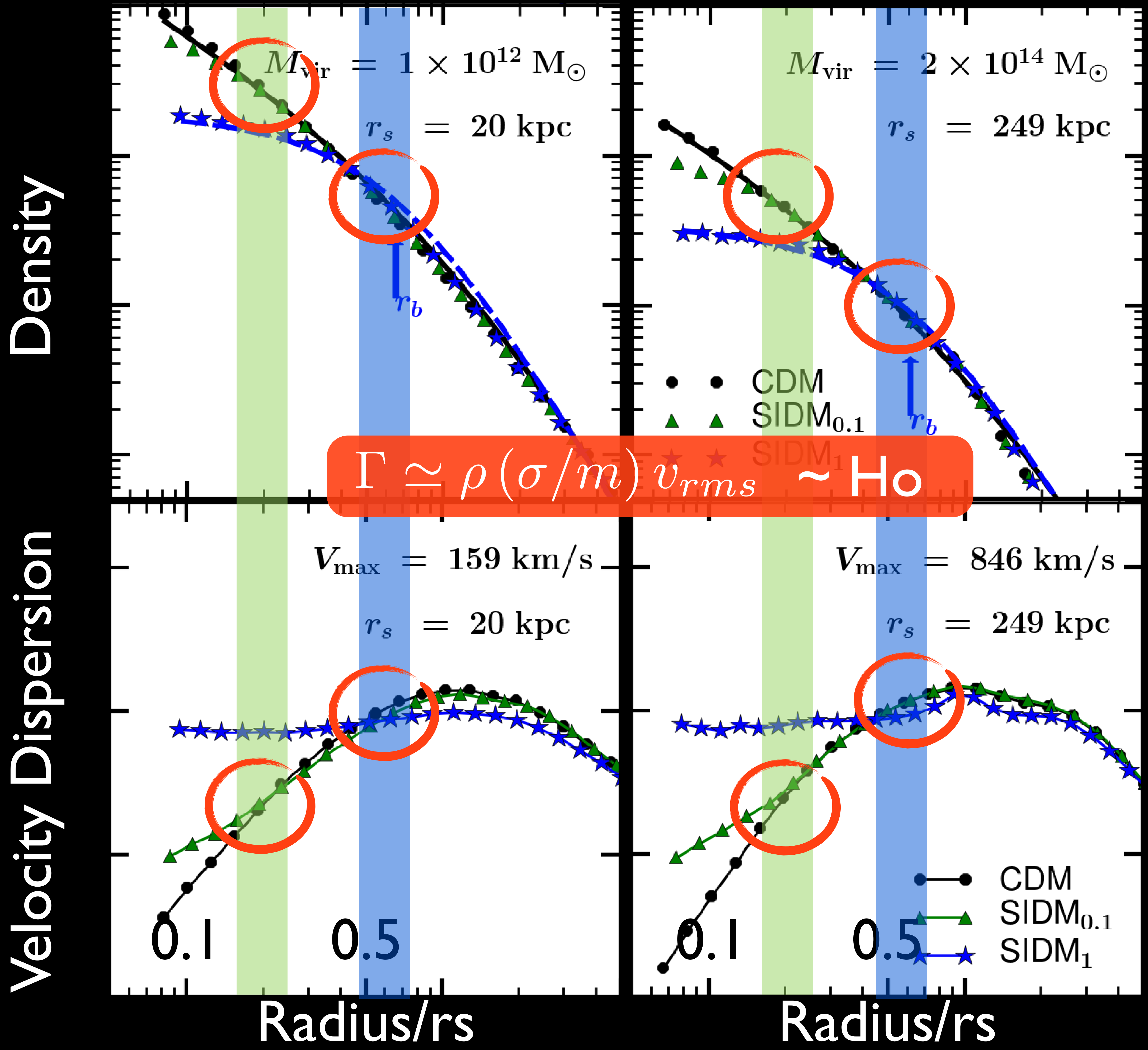

$\sigma/m = 1$

$\sigma/m = 0.1$

$$\Gamma \simeq \rho\,(\sigma/m)\,v_{rms} \quad \sim \mathrm{Ho}$$

Previous Constraints

Reference	Constraint [cm^2 /g]	From	Problem
Yoshidal et. al 2000	$\sigma/m < \sim 0.1$	Cluster density core	One cluster
Dave et. al 2001	$\sigma/m = 0.1–10$	Dwarfs density Cores	Narrow mass range
Gnedin & Ostriker 2001	$\sigma/m < 0.3$	Subhalo evaporation	Overestimated subhalo evaporation
Miralda-Escude 2002	$\sigma/m < 0.02$	Halo shapes	Overestimated halo sphericity
Randall et al. 2008	$\sigma/m < 0.7–1.25$	Bullet Cluster	High central densities and relative vel.

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Today's Constraints

Reference	Constraint [cm^2 /g]	From	Problem
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Dave et. al 2001	$\sigma/m = 0.1-$~~10~~	Dwarfs cores	Narrow mass range
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Vogelsberger et al.2012 Zavala et al. 2012	$\sigma/m > 0.1$ Velocity dependence may be needed	MW dwarfs solves TBTF	MW dwarfs only (resolution?)
MCC	**Expect best constraints stay tuned!!**	Merging Clusters	**Time will tell**

Today's Constraints

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Dave et. al 2001	$\sigma/m\ = 0.1-\cancel{10}$	Dwarfs cores	Narrow mass range
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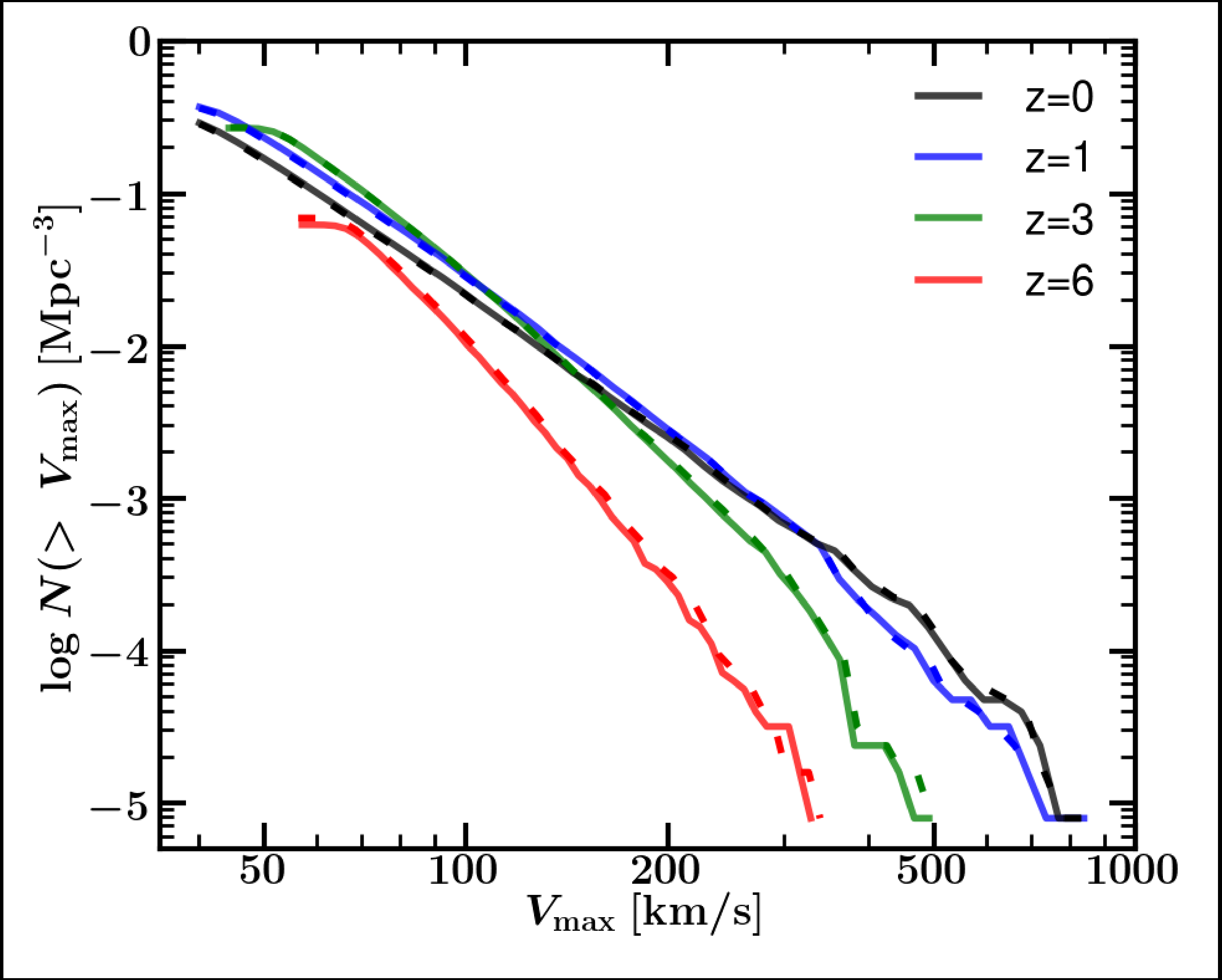
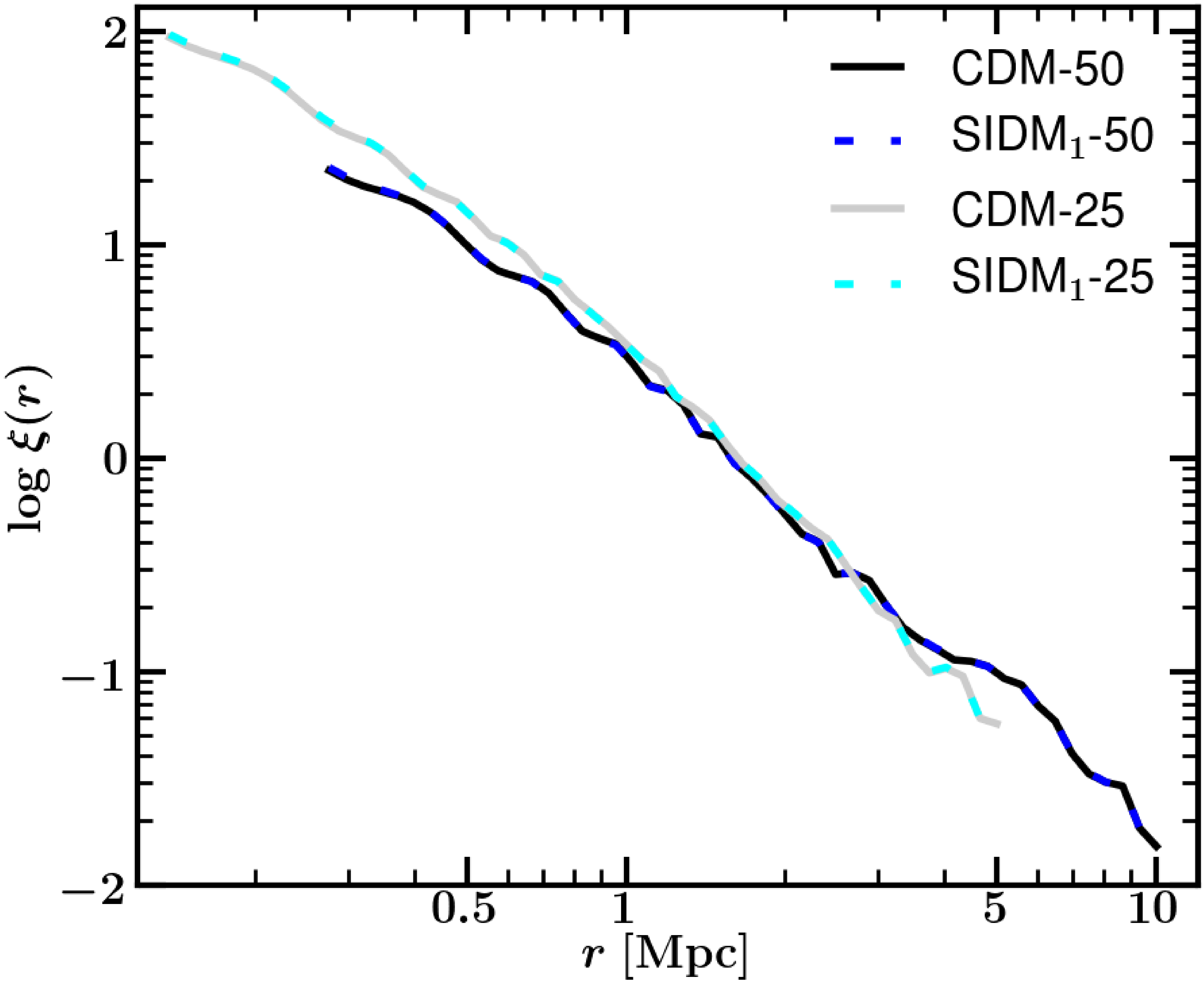
MCC	**Expect best constraints stay tuned!!**	Merging Clusters	**Time will tell**

For Gev particles these are equivalent to strong force interactions (nucleon–nucleon scattering)!!

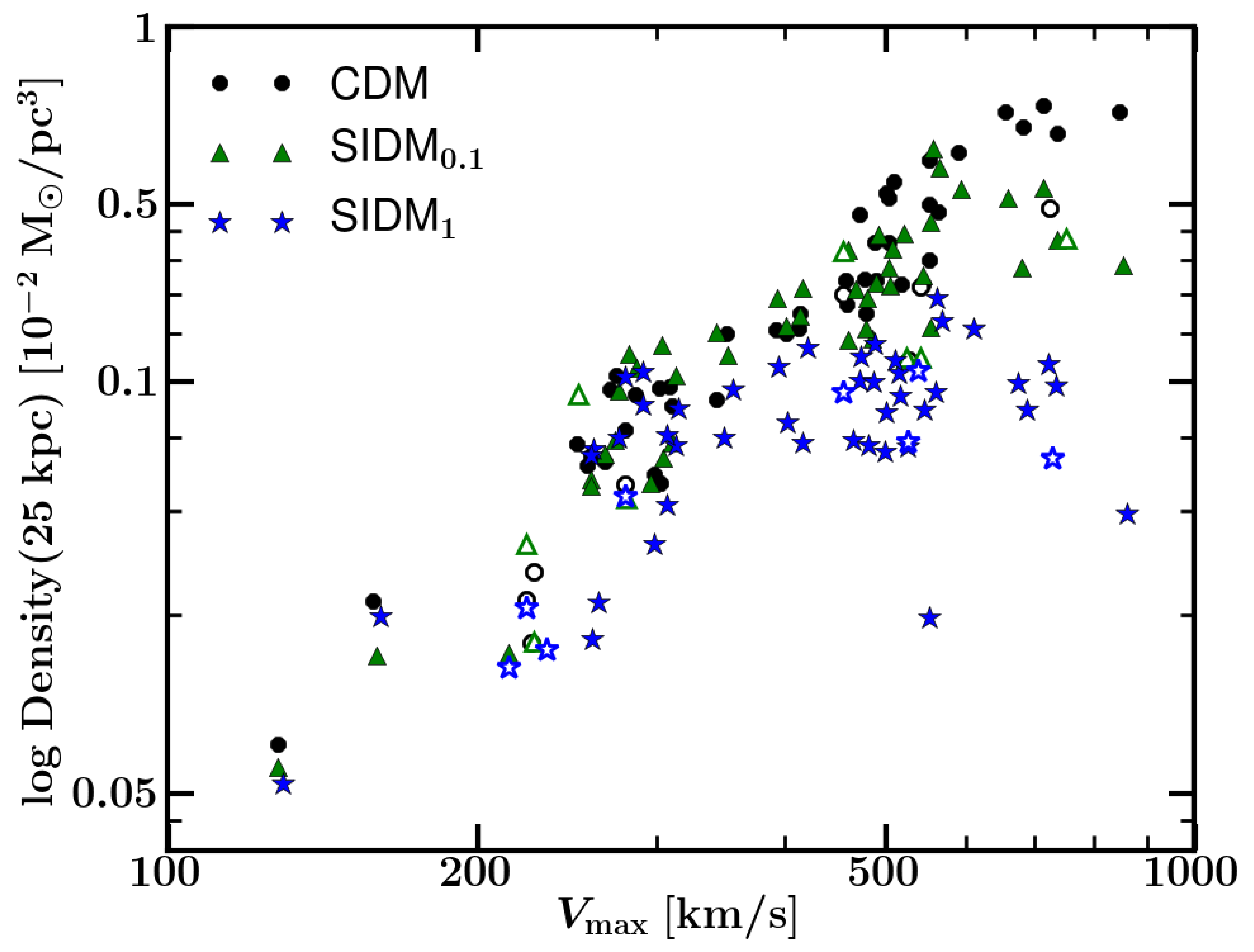
Identical Abundance of Halos

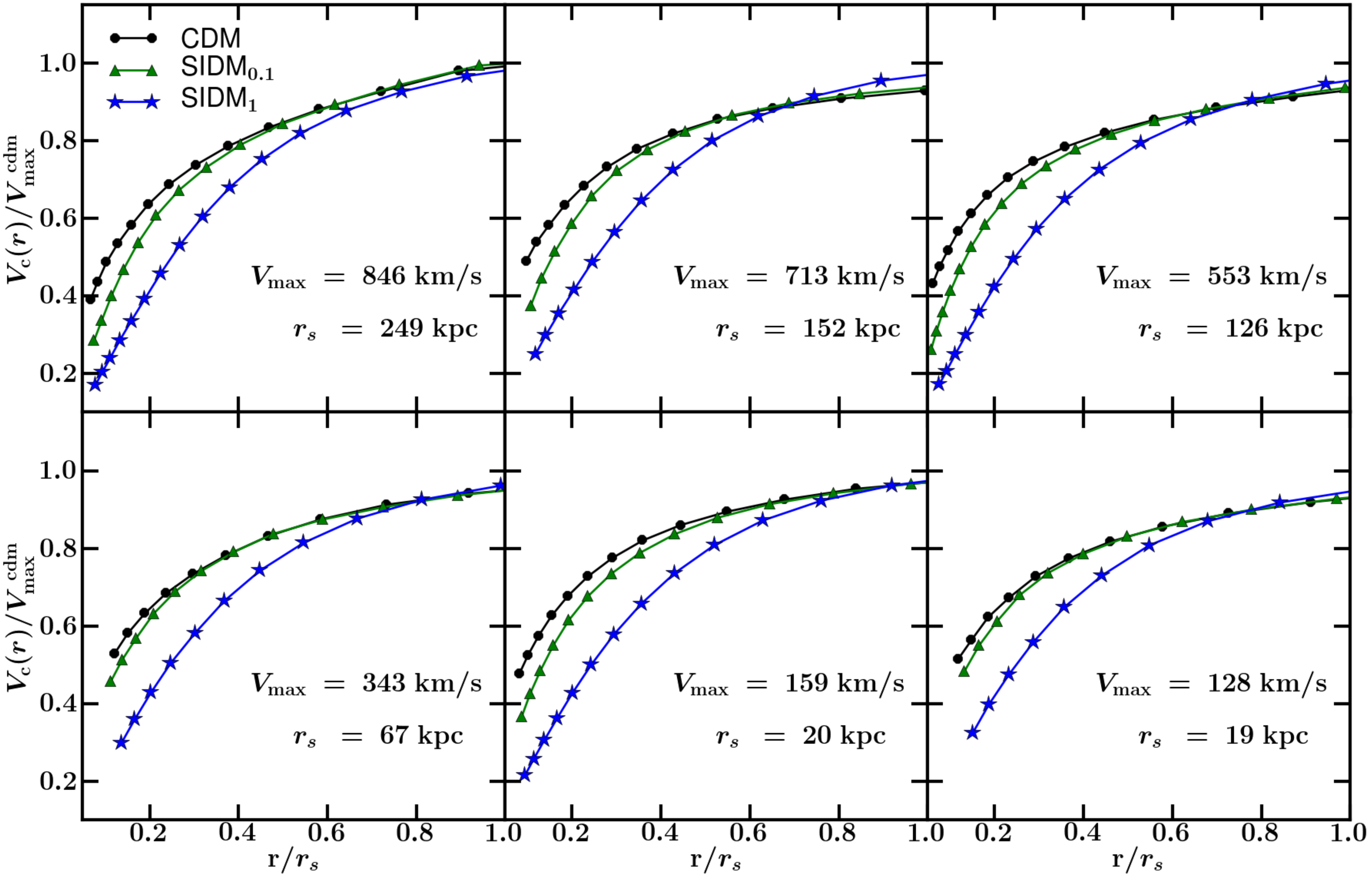


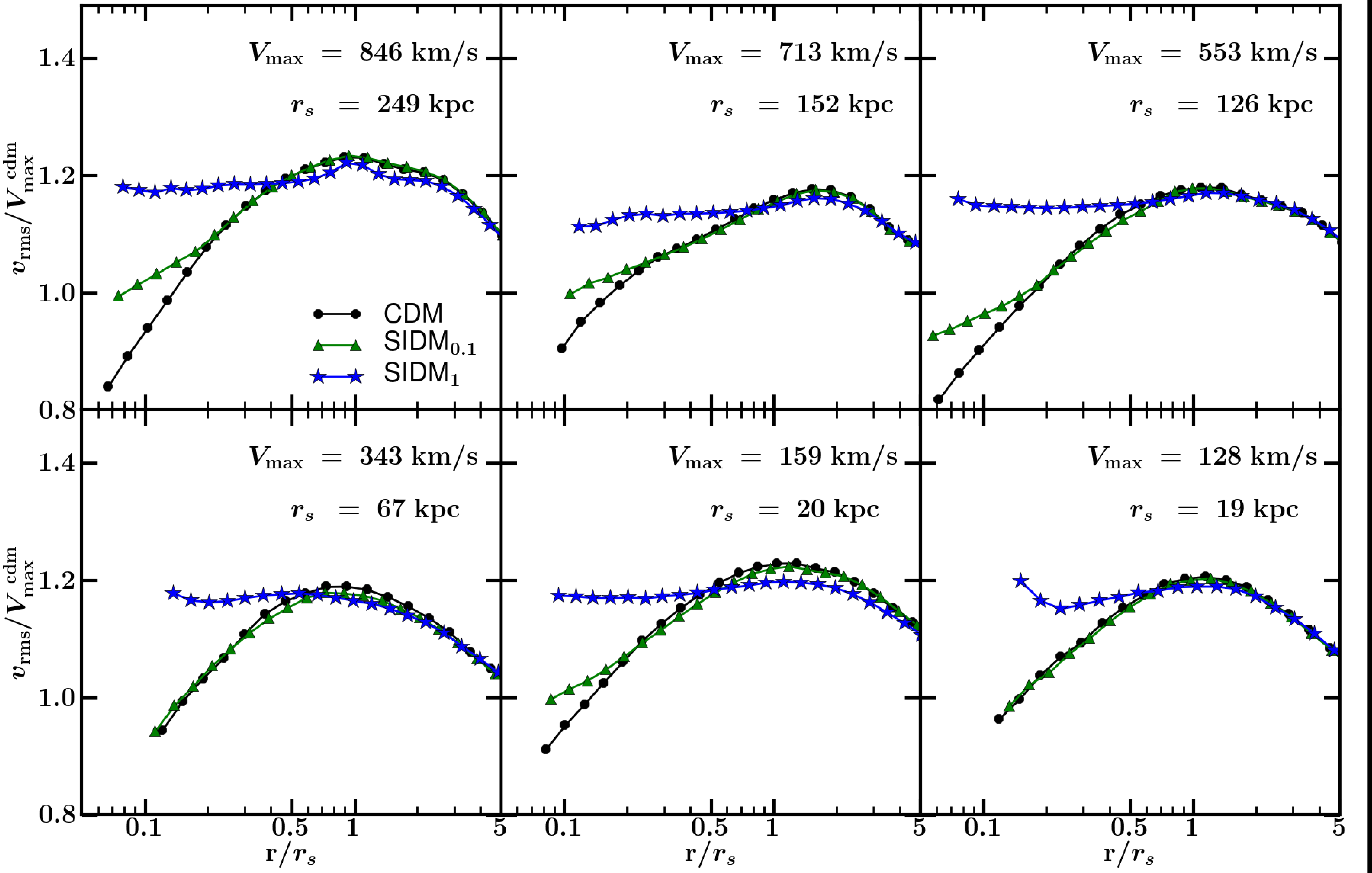


CDM-50
SIDM_1-50
CDM-25
SIDM_1-25
$\log \xi(r)$
2
1
0
−1
−2
0.5
1
5
10
r [Mpc]

Reduced Central Densities




CDM
$\mathrm{SIDM}_{0.1}$
SIDM_1
$V_{\mathrm{c}}(r)/V_{\mathrm{max}}^{\mathrm{cdm}}$
$V_{\mathrm{max}} = 846$ km/s
$r_s = 249$ kpc
$V_{\mathrm{max}} = 713$ km/s
$r_s = 152$ kpc
$V_{\mathrm{max}} = 553$ km/s
$r_s = 126$ kpc
$V_{\mathrm{max}} = 343$ km/s
$r_s = 67$ kpc
$V_{\mathrm{max}} = 159$ km/s
$r_s = 20$ kpc
$V_{\mathrm{max}} = 128$ km/s
$r_s = 19$ kpc
0.2
0.4
0.6
0.8
1.0
r/r_s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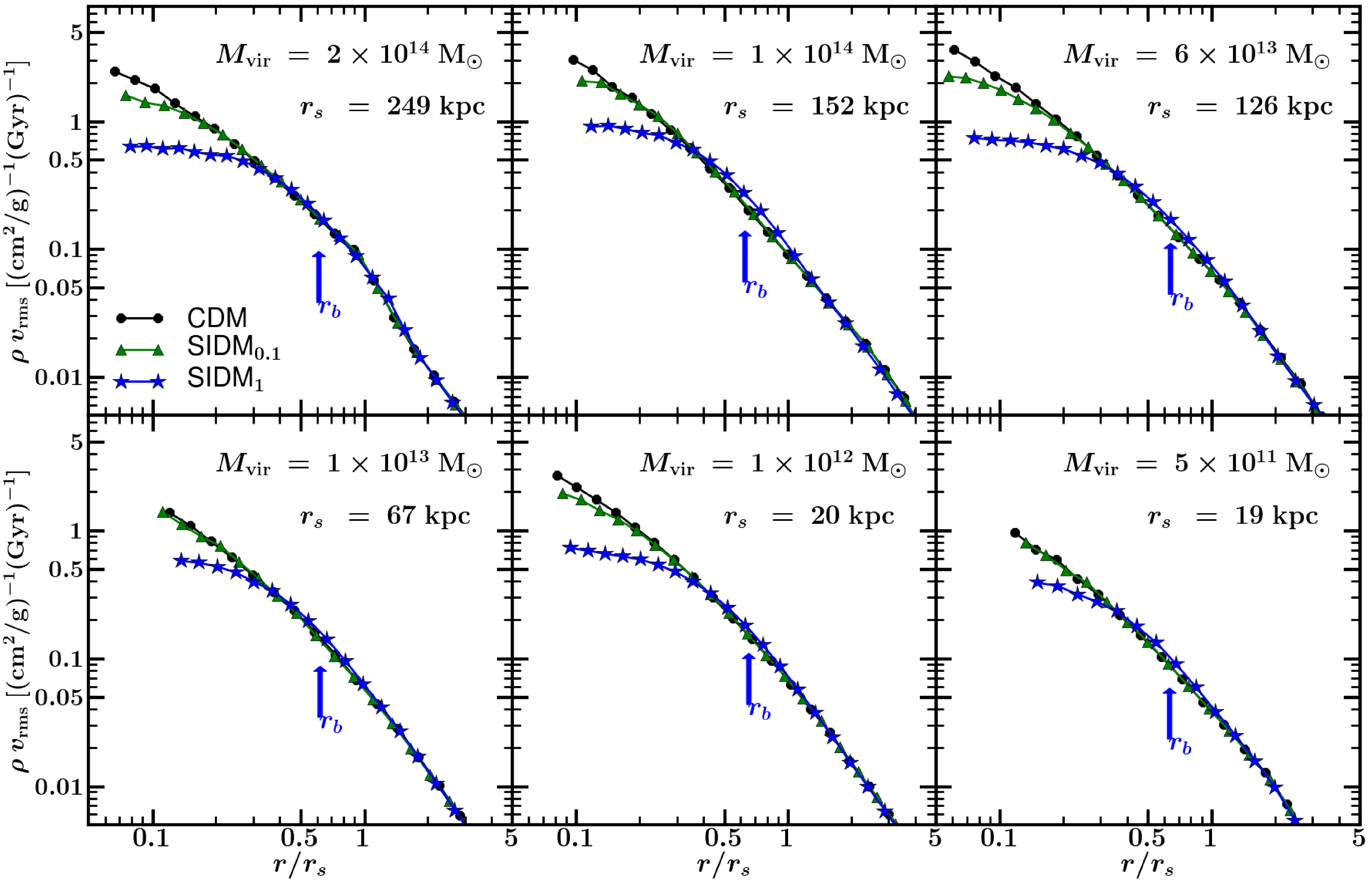
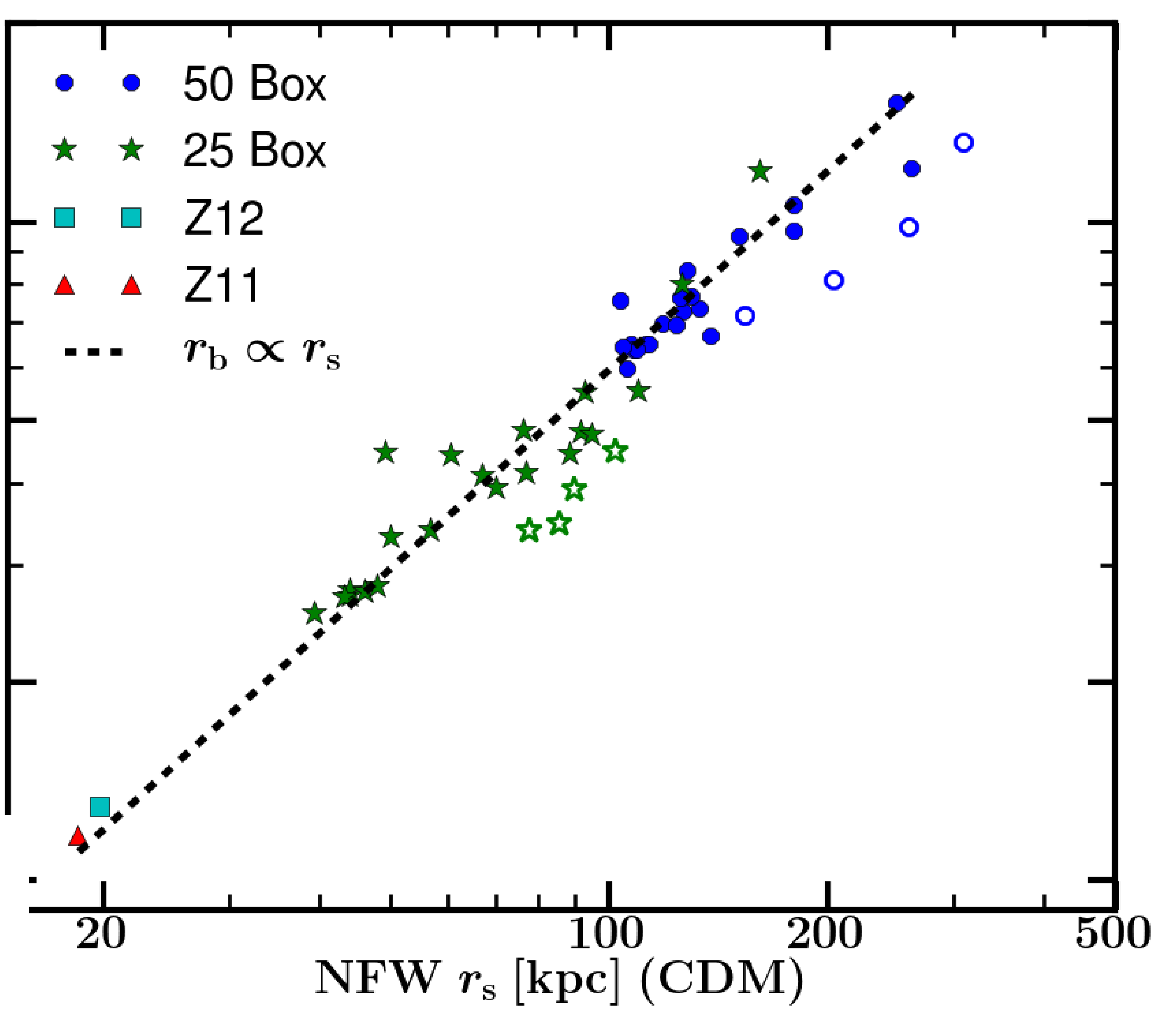
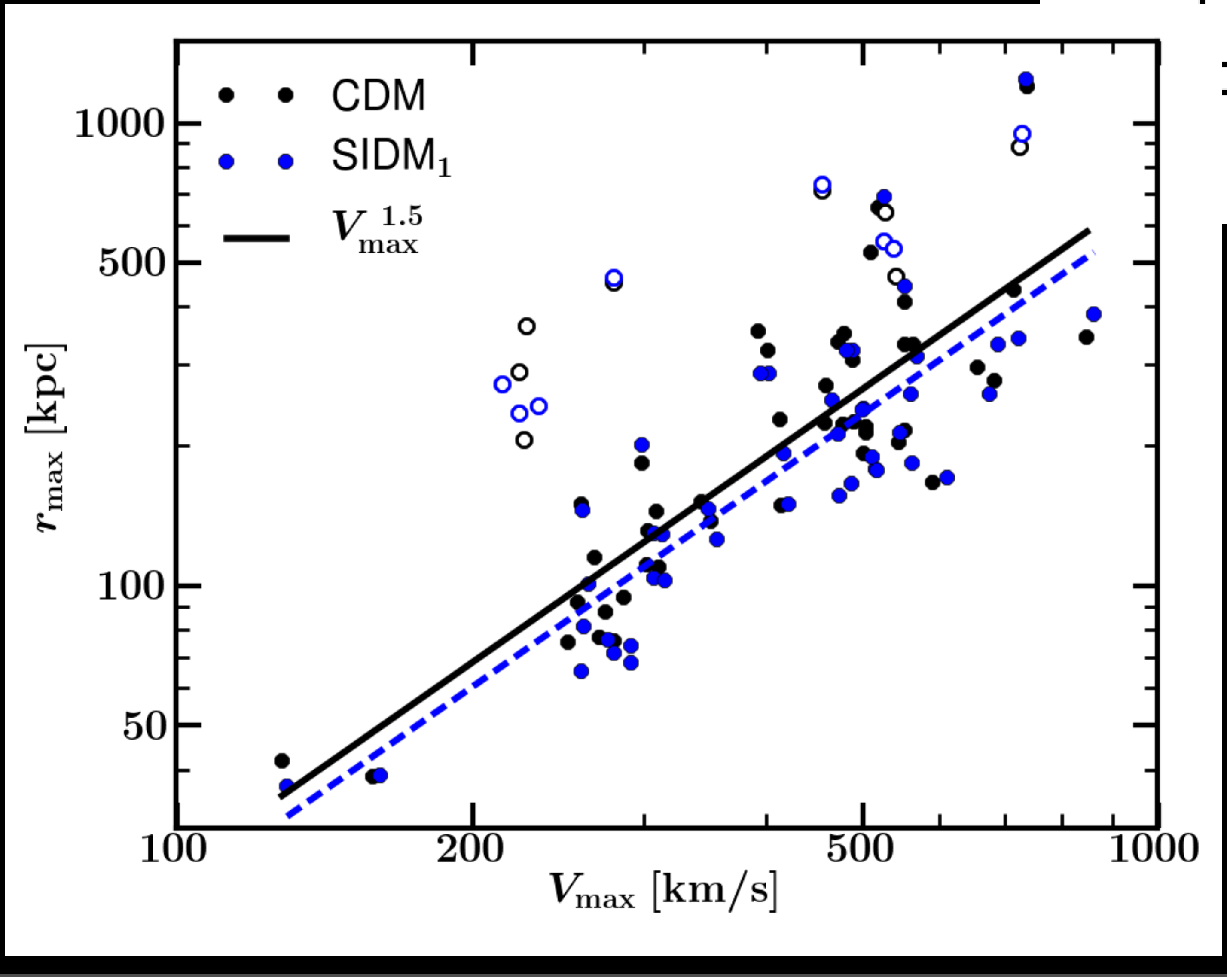
r_s = 67 kpc
$V_{\rm max}$ = 159 km/s
r_s = 20 kpc
$V_{\rm max}$ = 128 km/s
r_s = 19 kpc
CDM
$\rm SIDM_{0.1}$
$\rm SIDM_1$
$v_{\rm rms}/V_{\rm max}^{\rm cdm}$
1.4
1.2
1.0
0.8
0.1
0.5
1
5
r/r_s


$M_{\rm vir} = 2 \times 10^{14}$ M$_\odot$
$r_s = 249$ kpc
$M_{\rm vir} = 1 \times 10^{14}$ M$_\odot$
$r_s = 152$ kpc
$M_{\rm vir} = 6 \times 10^{13}$ M$_\odot$
$r_s = 126$ kpc
$M_{\rm vir} = 1 \times 10^{13}$ M$_\odot$
$r_s = 67$ kpc
$M_{\rm vir} = 1 \times 10^{12}$ M$_\odot$
$r_s = 20$ kpc
$M_{\rm vir} = 5 \times 10^{11}$ M$_\odot$
$r_s = 19$ kpc
CDM
SIDM$_{0.1}$
SIDM$_1$
r_b
$\rho\, v_{\rm rms}\ [({\rm cm}^2/{\rm g})^{-1}({\rm Gyr})^{-1}]$
r/r_s
5
1
0.5
0.1
0.05
0.01
0.1
0.5
1
5

$\sigma/m = 1\ \mathrm{cm}^2\ /\mathrm{g}$

rb/rs ~ 1





- Vmax/Rmax similar to CDM
- Vmax-Rmax relation unchanged

Rocha et al. 2012
arXiv:1208.3025

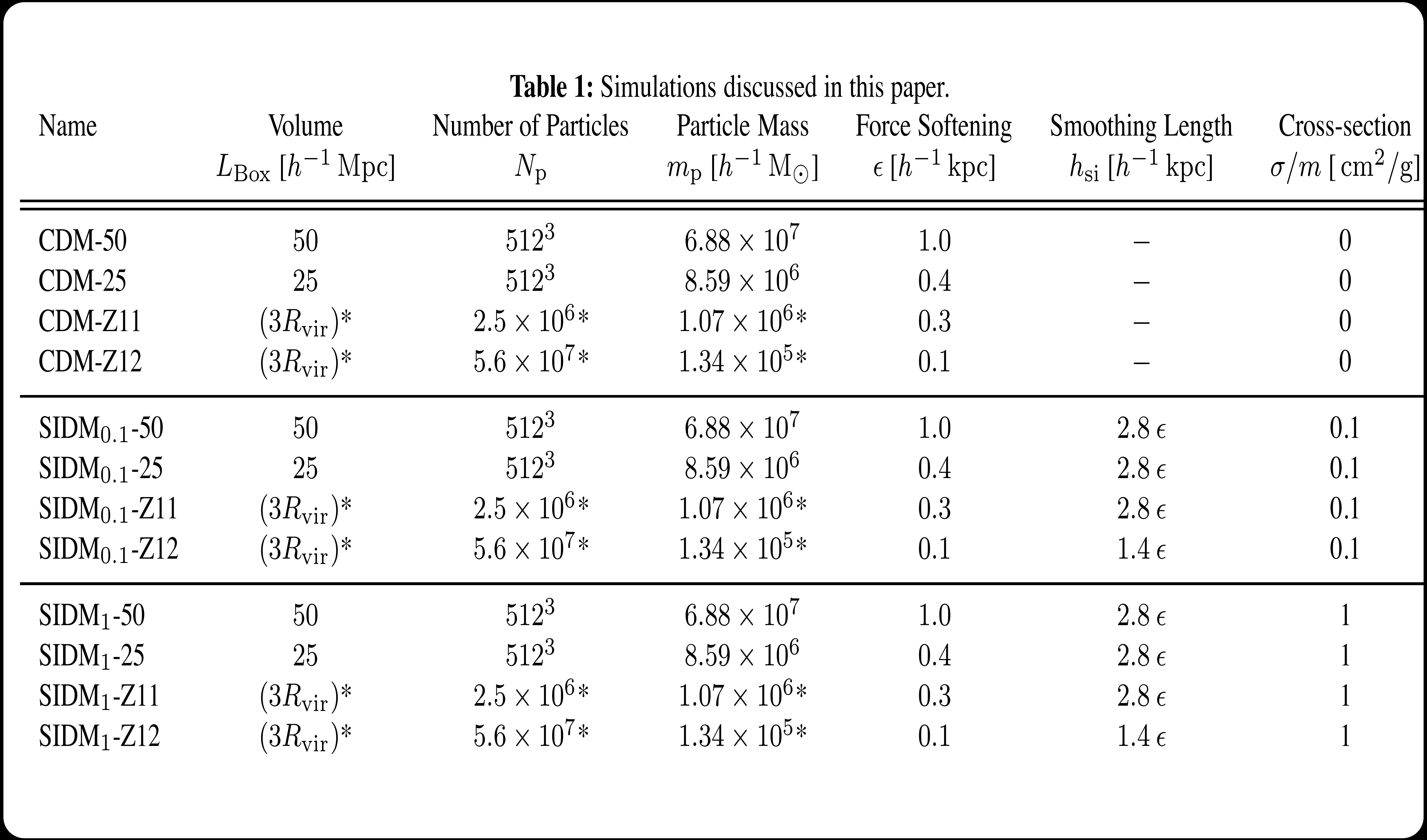


Table 1: Simulations discussed in this paper.

Name	Volume $L_{\rm Box}$ [h^{-1} Mpc]	Number of Particles $N_{\rm p}$	Particle Mass $m_{\rm p}$ [h^{-1} M$_\odot$]	Force Softening ϵ [h^{-1} kpc]	Smoothing Length $h_{\rm si}$ [h^{-1} kpc]	Cross-section σ/m [cm^2/g]
CDM-50	50	512^3	6.88×10^7	1.0	–	0
CDM-25	25	512^3	8.59×10^6	0.4	–	0
CDM-Z11	$(3R_{\rm vir})$*	2.5×10^6*	1.07×10^6*	0.3	–	0
CDM-Z12	$(3R_{\rm vir})$*	5.6×10^7*	1.34×10^5*	0.1	–	0
SIDM$_{0.1}$-50	50	512^3	6.88×10^7	1.0	$2.8\,\epsilon$	0.1
SIDM$_{0.1}$-25	25	512^3	8.59×10^6	0.4	$2.8\,\epsilon$	0.1
SIDM$_{0.1}$-Z11	$(3R_{\rm vir})$*	2.5×10^6*	1.07×10^6*	0.3	$2.8\,\epsilon$	0.1
SIDM$_{0.1}$-Z12	$(3R_{\rm vir})$*	5.6×10^7*	1.34×10^5*	0.1	$1.4\,\epsilon$	0.1
SIDM$_1$-50	50	512^3	6.88×10^7	1.0	$2.8\,\epsilon$	1
SIDM$_1$-25	25	512^3	8.59×10^6	0.4	$2.8\,\epsilon$	1
SIDM$_1$-Z11	$(3R_{\rm vir})$*	2.5×10^6*	1.07×10^6*	0.3	$2.8\,\epsilon$	1
SIDM$_1$-Z12	$(3R_{\rm vir})$*	5.6×10^7*	1.34×10^5*	0.1	$1.4\,\epsilon$	1

Comparison to observed core sizes

	Observed	$\sigma/m=1\ \mathrm{cm^2/g}$	$\sigma/m=0.1\ \mathrm{cm^2/g}$
Clusters 700-1000 km/s	10-75 kpc Arabadjis et al. 2002, Sand et al. 2004, 2008, Saha et al 2006, Saha & Read 2009 Newman et al. 2009,2011	95-155 kpc	16-20 kpc
Low-Mass Spirals 50-130 km/s	0.5-8 kpc de Blok et al. 2001, Simon et al. 2005, Sanchez-Salcedo 2005, Kuzio de Naray et al. 2008,2010, Oh et al . 2011, Salucci et al. 2012	3-10 kpc	0.6-2.5 kpc
MW dSphs 20-50 km/s	0.2-1 kpc Walker & Penarrubia 2011	0.9-3 kpc	0.2-0.6 kpc

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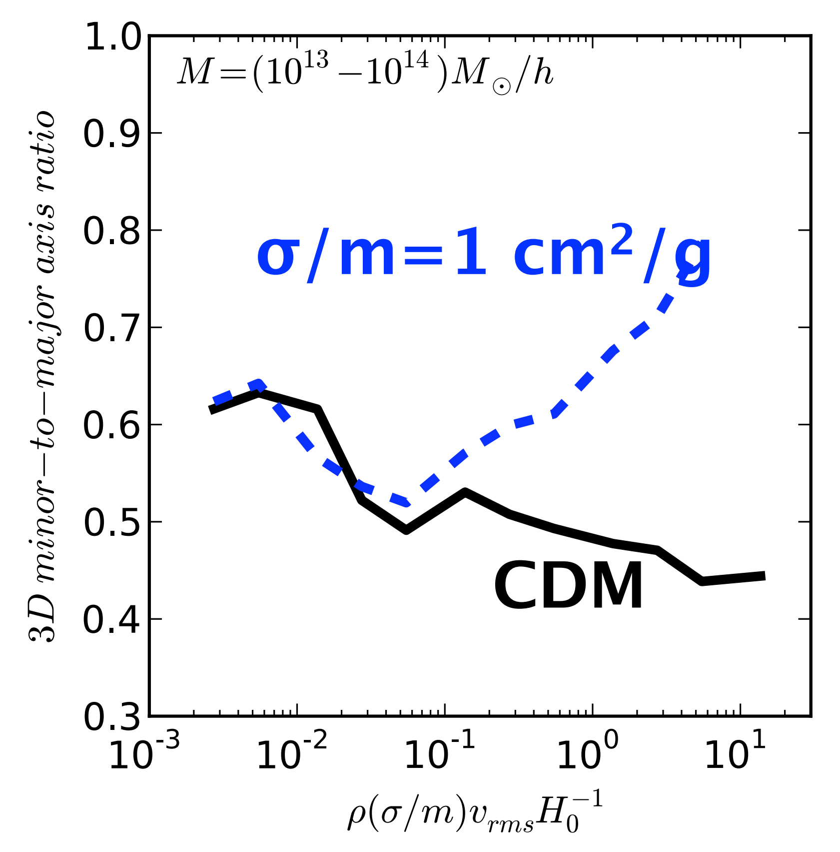
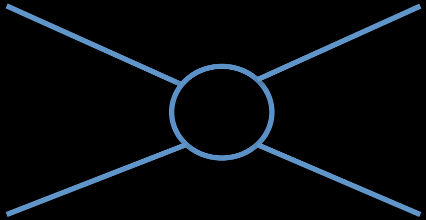
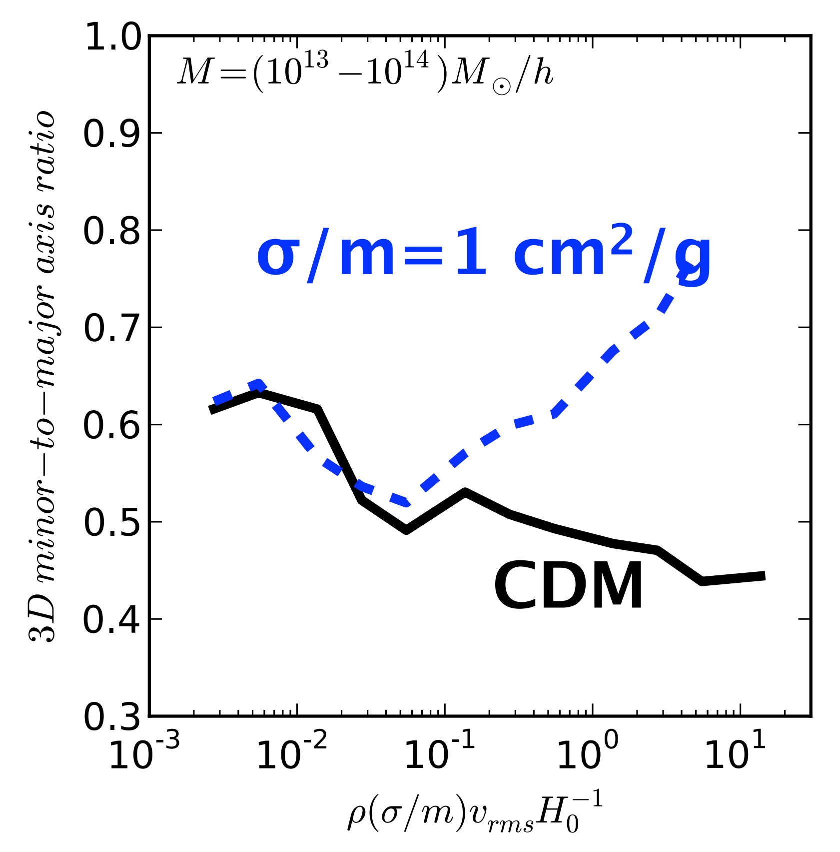
The problem with shapes



- We see surface density (or gravitational potentials) in projection.
- If inner parts have flattened density, outer parts have even greater weight.

The problem with shapes





$$\Gamma/H_0 \gg 10$$

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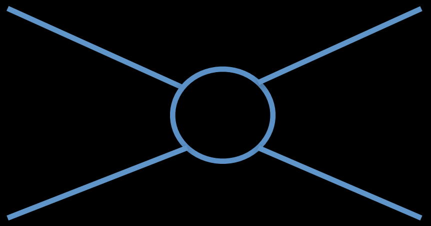

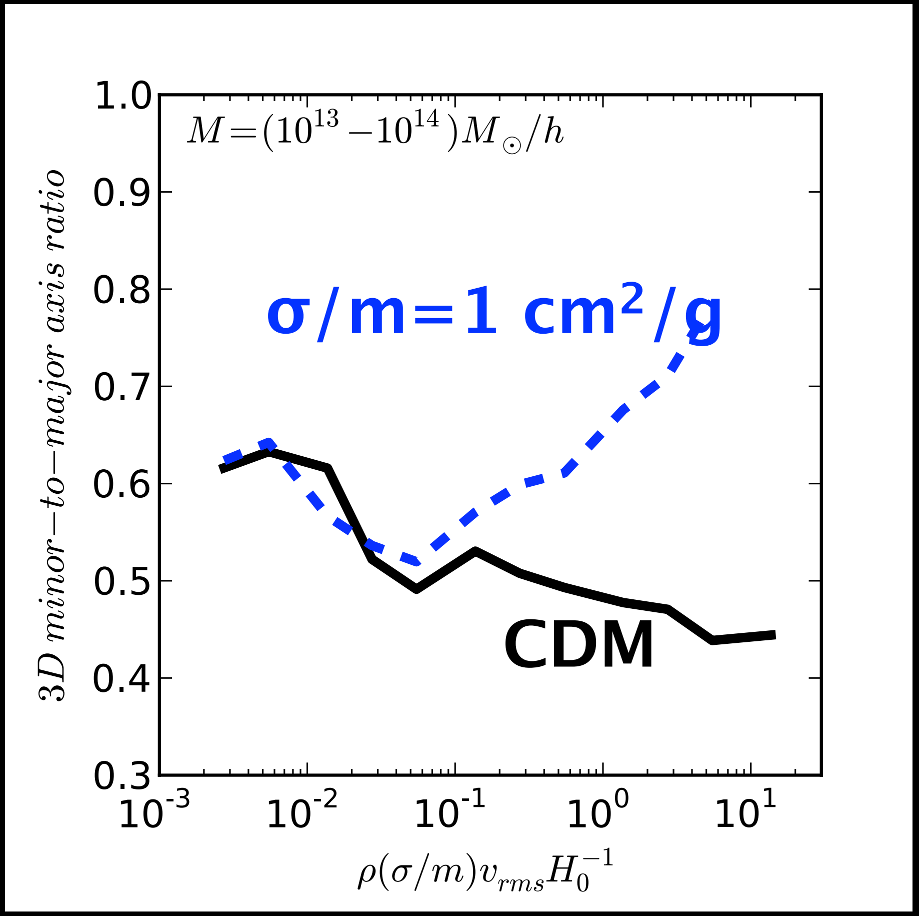

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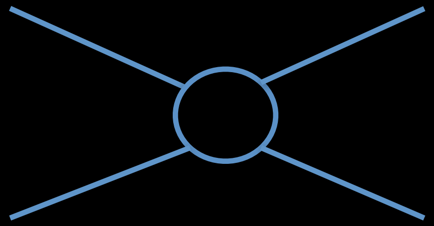

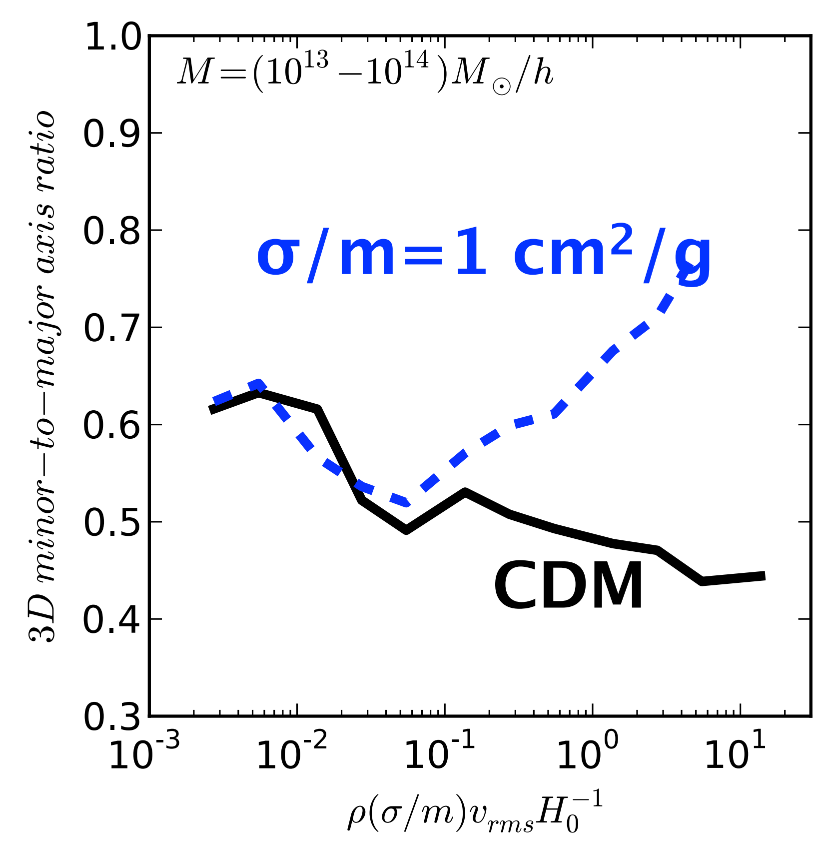

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Revisit

Miralda-Escude (2002)

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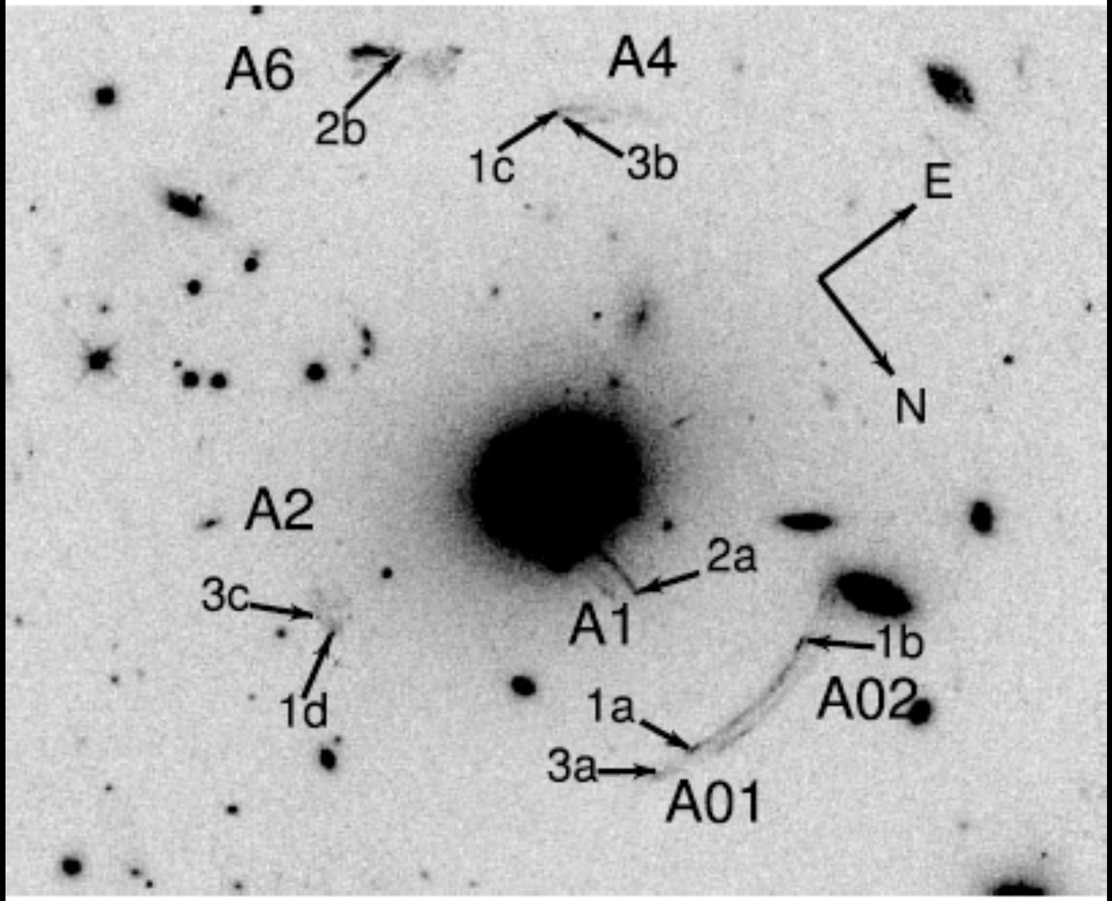
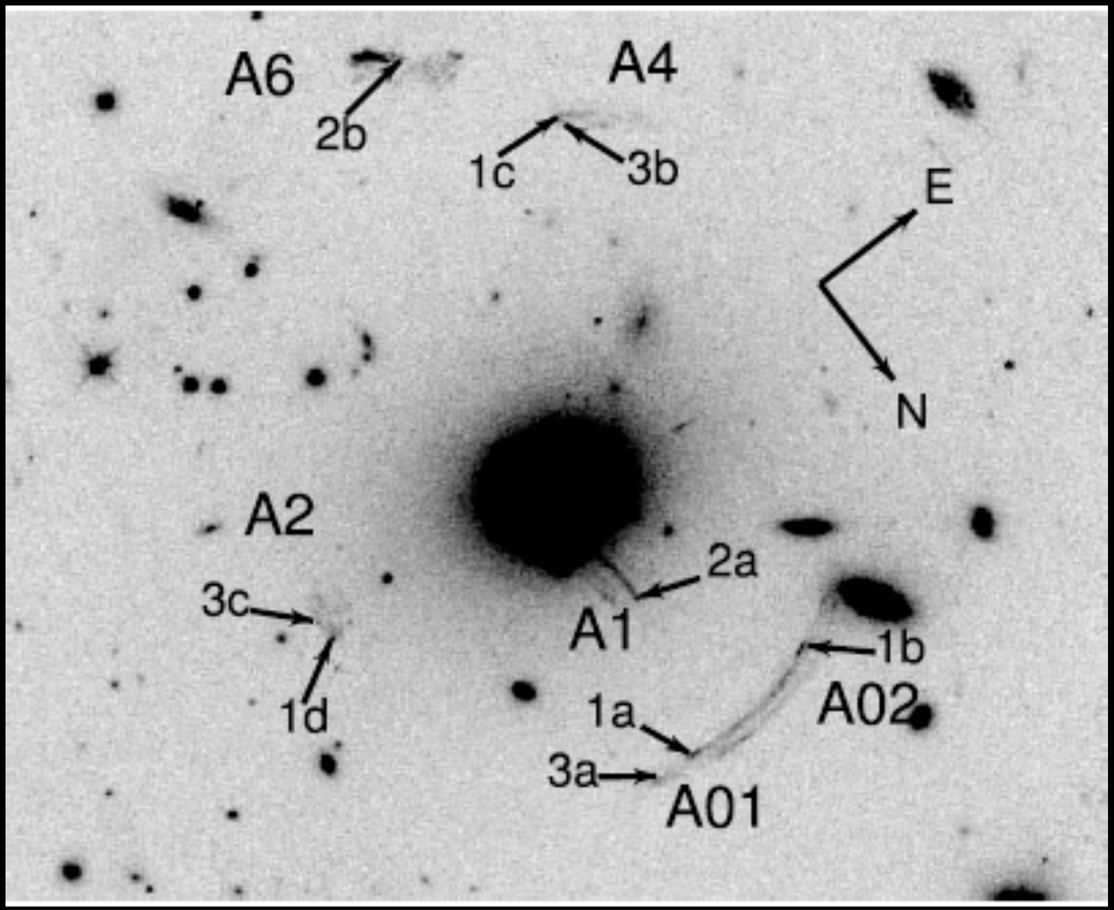


MS 2137-23

Sand et al. 2008

Revisit

Miralda-Escude (2002)



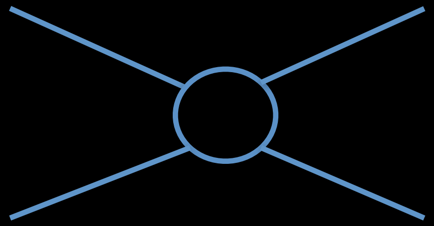
MS 2137-23
Sand et al. 2008

Requires a non-circularly-symmetric surface density at r > 70 kpc.

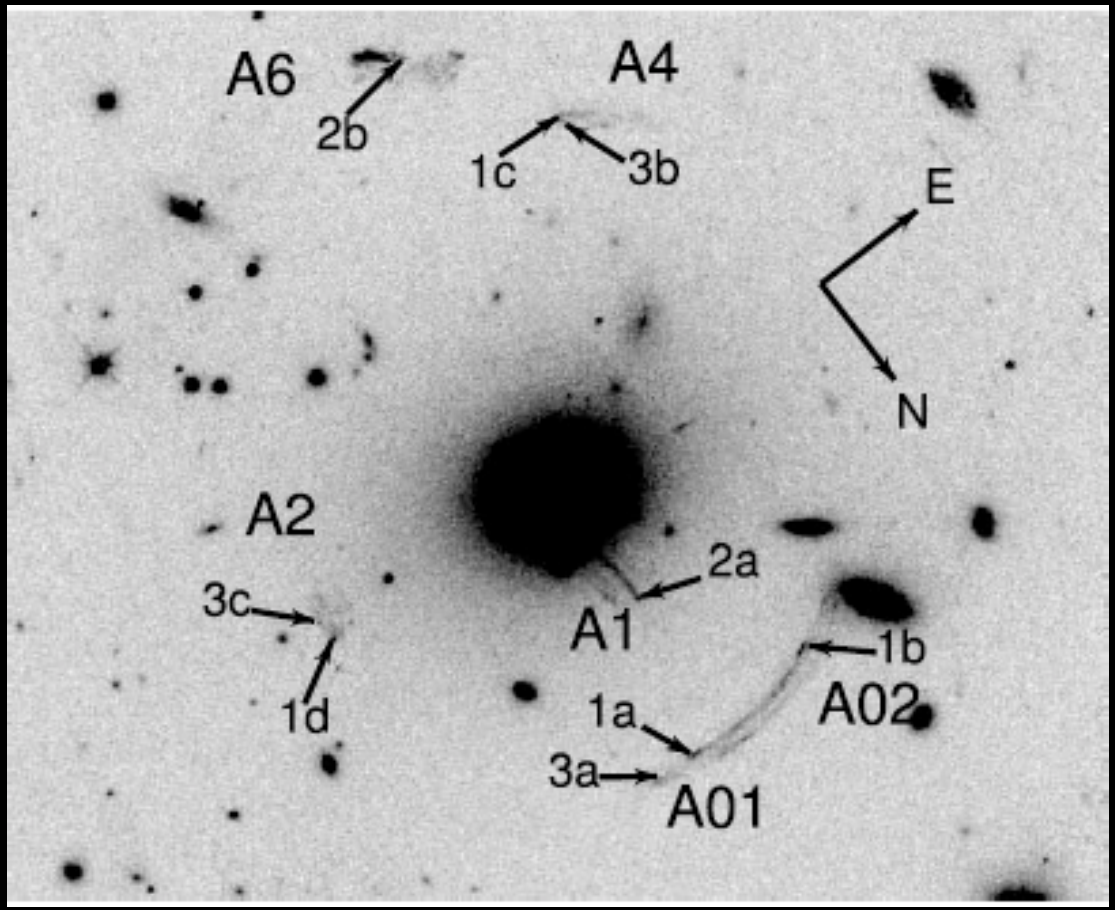
Assume ε=0 if $\Gamma/H_0 \gtrsim 1$.

➔ $\sigma/m < 0.02$ cm^2/g.

Revisit



Miralda-Escude (2002)



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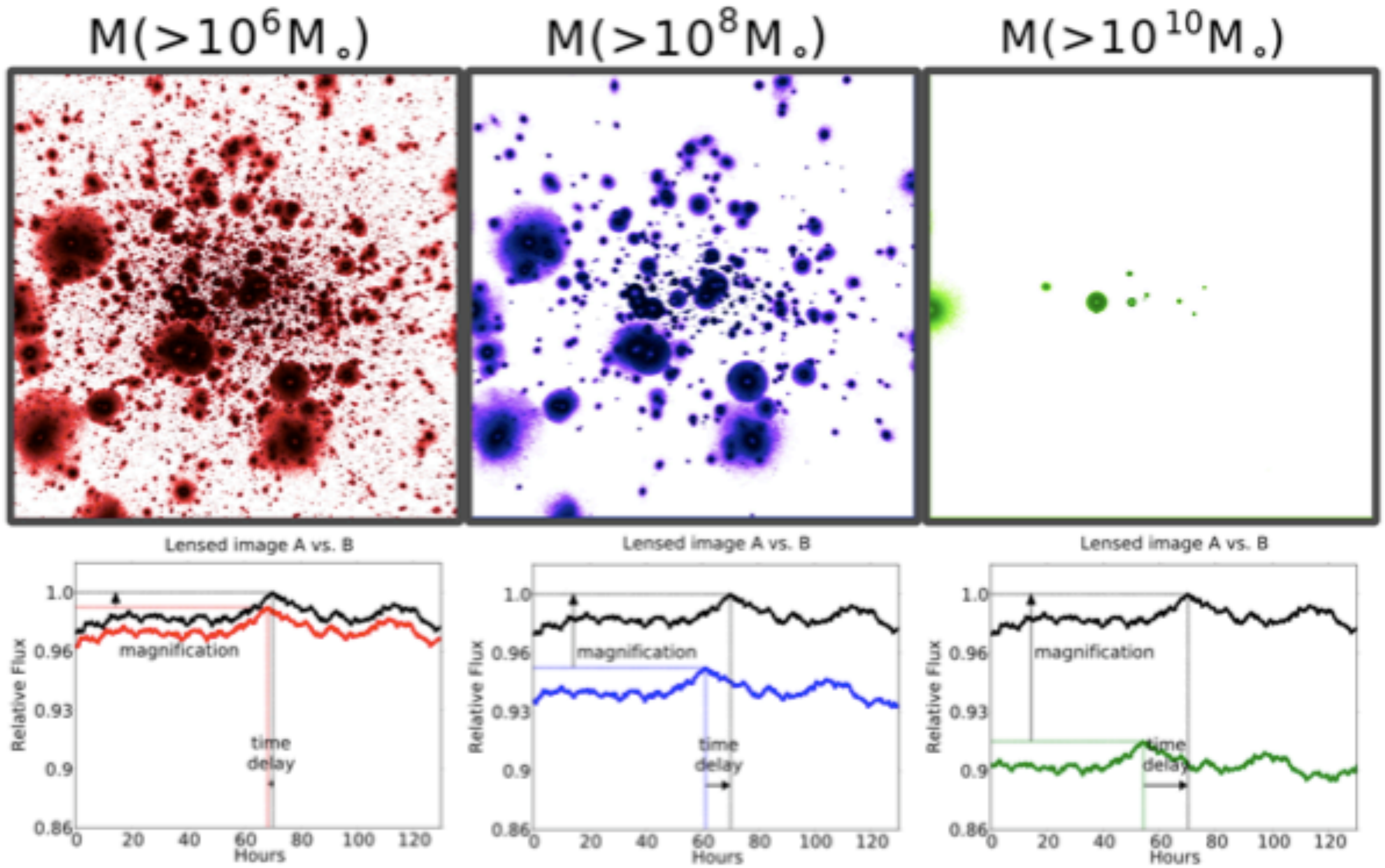
➔ σ/m < 0.02 cm^2/g.

Tightest constraint by far (by > 10x)!

Constraints from: substructure

Observations



flux vs time light curves, for image pairs

Ackn. M. Kuhlen, D. Coe, +