Self-Interacting Dark Matter

Miguel Rocha - UC Irvine

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In Collaboration With

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Oliver Elbert

The SIDM model

$$\Lambda\text{CDM} + \frac{\sigma}{m} \neq 0$$

The SIDM model

$$+ \quad \frac{\sigma}{m} \neq 0$$

Interesting phenomenology if

$$\frac{\sigma}{m} = 0.1 - 100 \text{ cm}^2/\text{g}$$

Spergerl & Steinhardt 2000

The SIDM model

ΛCDM + $\frac{\sigma}{m} \neq 0$

Interesting phenomenology if

σ/m =1 cm^2/g = 2 barn/Gev = neutron-proton scattering

Spergerl & Steinhardt 2000

Is this a crazy idea?

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For most astronomers it is exotic

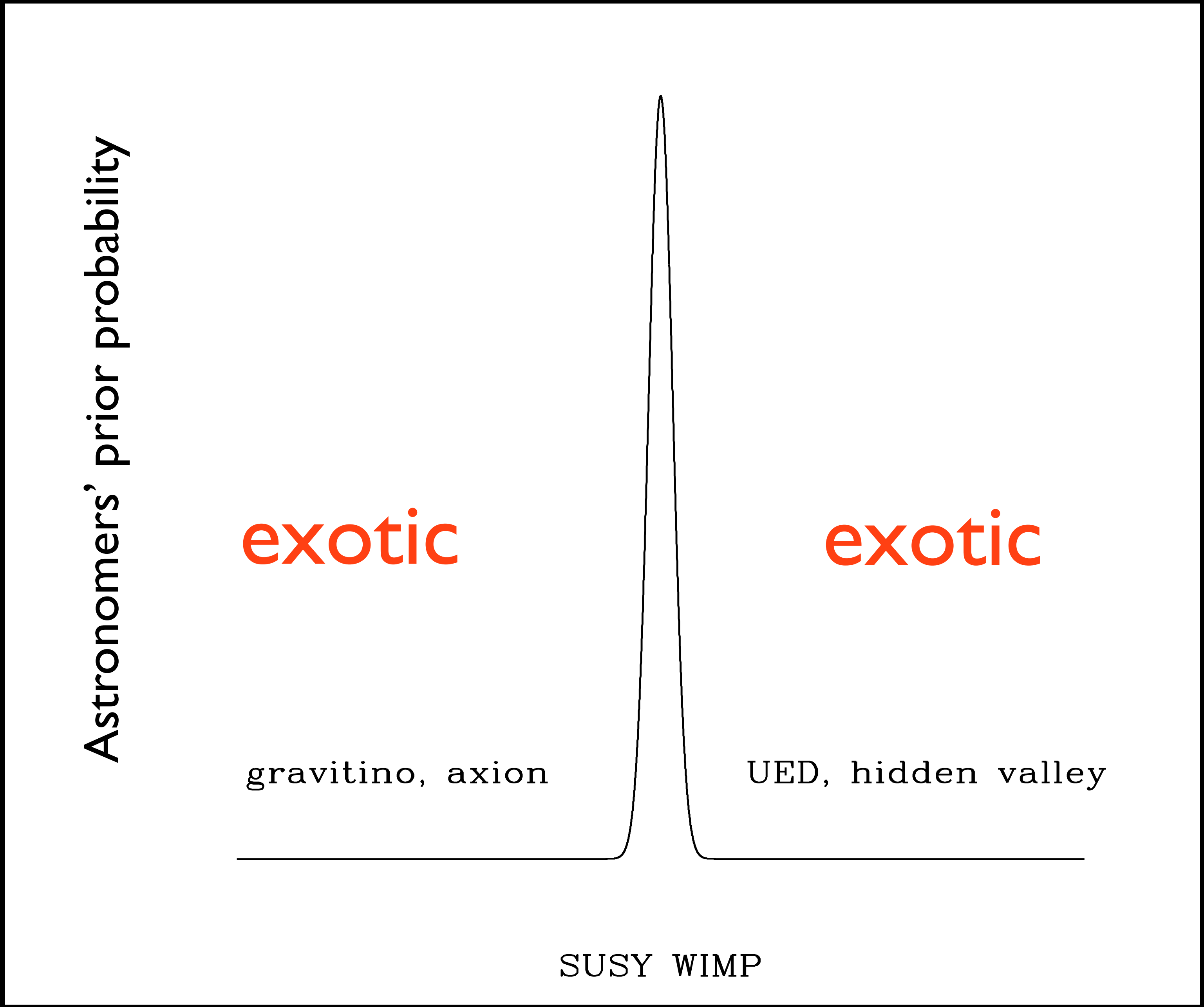


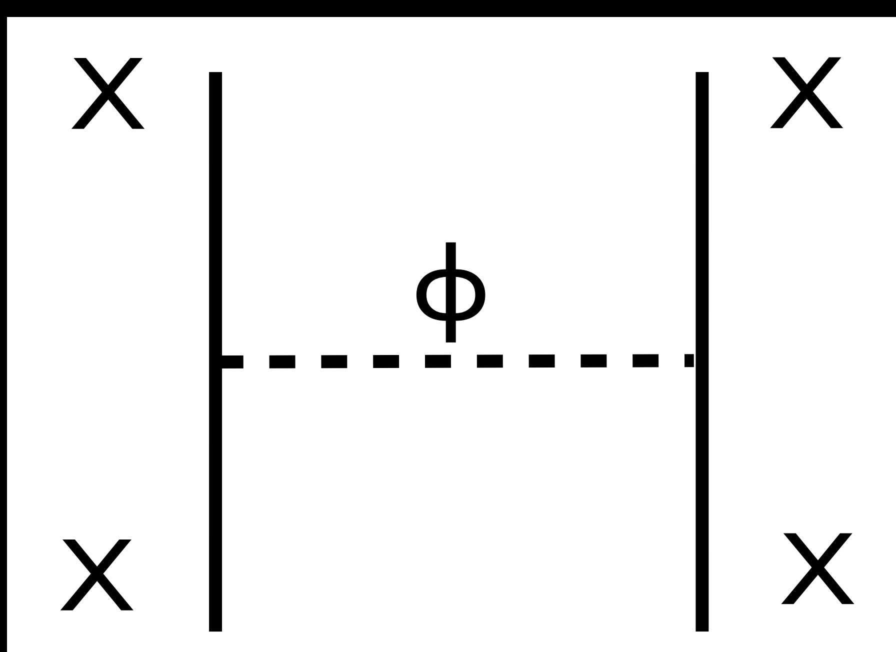
Image courtesy of Annika Petter

Is this a crazy idea?

For physicist it is a generic consequence of many models beyond the Standard Model

Just add a new force at the ~sub-Gev scale

$m_\phi = O(\mathrm{Mev})$



If your prejudice is that new physics can only be at O(TeV), then this large cross-sections will seem crazy

Is this a crazy idea?

For physicist it is a generic consequence of many models beyond the Standard Model

Examples:

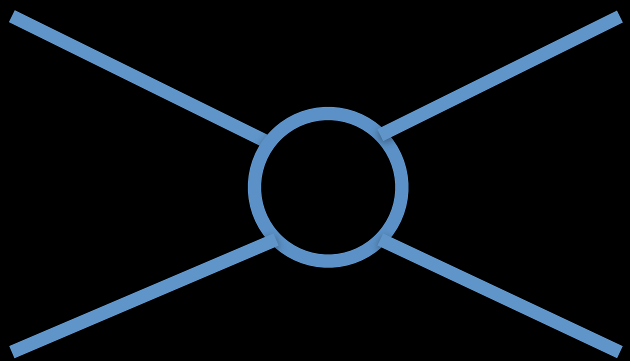
Asymmetric DM - Nussinov (1985);Kaplan (1992);Kaplan,Luty, Zurek (2009); Shelton, Zurek (2011); Buckley, Randall (2011); Morrissey, Sigurdson, Tulin (2010); Buckley (2011); Lin, Hai-Bo Yu, Zurek (2011).

Hidden Charge DM - Feng, Tu, Hai-Bo Yu (2008); Ackerman, Buckley, Carroll, Kamionkowski (2008);Feng, Kaplinghat, Tu, HBY (2009).

Atomic DM - Foot (2003); Kaplan, Krnjaic, Rehermann, Wells (2009);Feng, Kaplinghat, Tu, Hai-Bo Yu (2009);Cline, Liu, Wei Xue (2012);Francis-Yan Cyr-Racine,Kris Sigurdson (2013).

Double Disk DM - Fan, Katz, Randall, Reece (2013); McCullough,Randall (2013)

Phenomenology of DM Self-Interactions

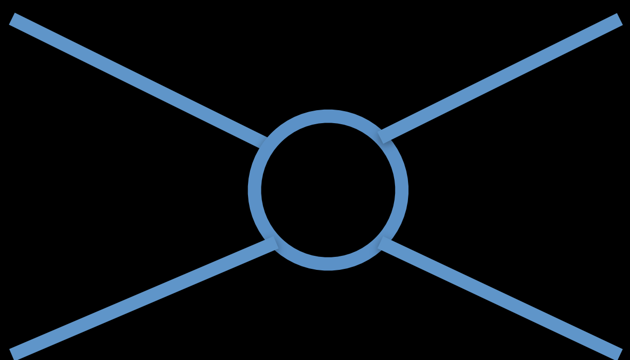


Spergerl & Steinhardt 2000

Elastic - Velocity Independent - Isotropic

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

Phenomenology of DM Self-Interactions



Spergerl & Steinhardt 2000

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Where $\Gamma / H_0 \gtrsim 1$ (central regions of DM halos)

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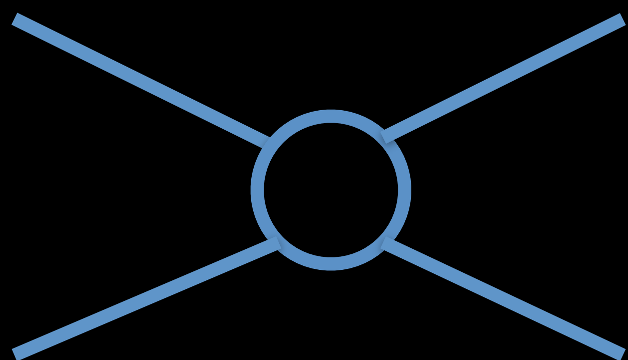

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- The energy transfer results in isothermal low density cores

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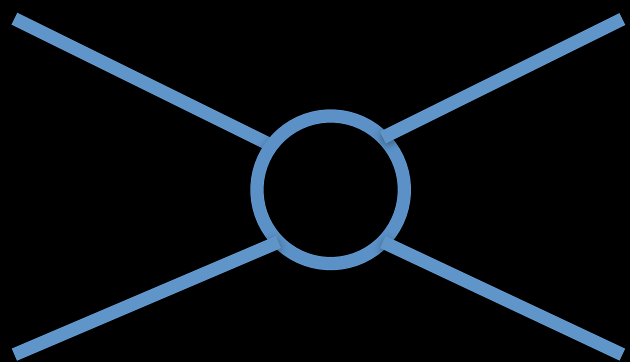

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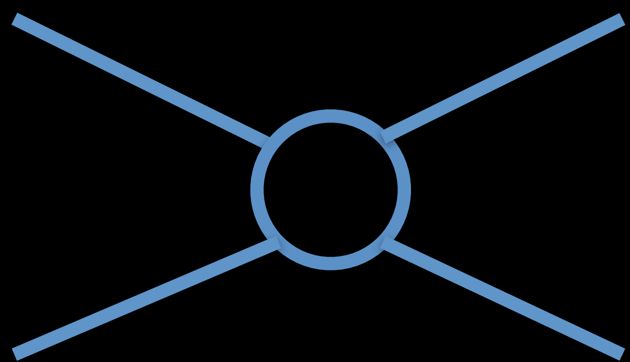
Phenomenology of DM Self-Interactions



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- The hot dense medium results in substructure evaporation

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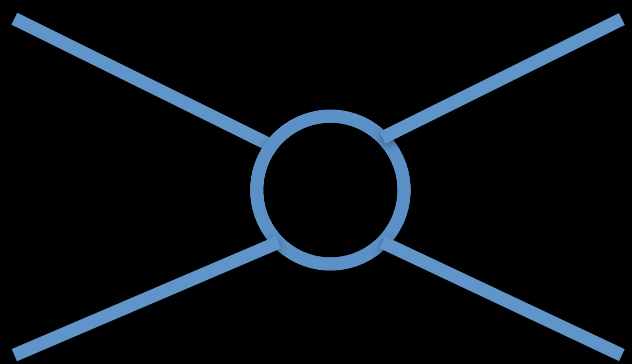

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- The energy transfer results in isothermal low density cores
- The isotropic scattering produces near-spherical cores
- The hot dense medium results in substructure evaporation
- In merging systems the drag that the DM experiences would be different to that of the collisionless galaxies, resulting in an offset between the surface mass centroids and the galaxy centroids + lower M/L ratios

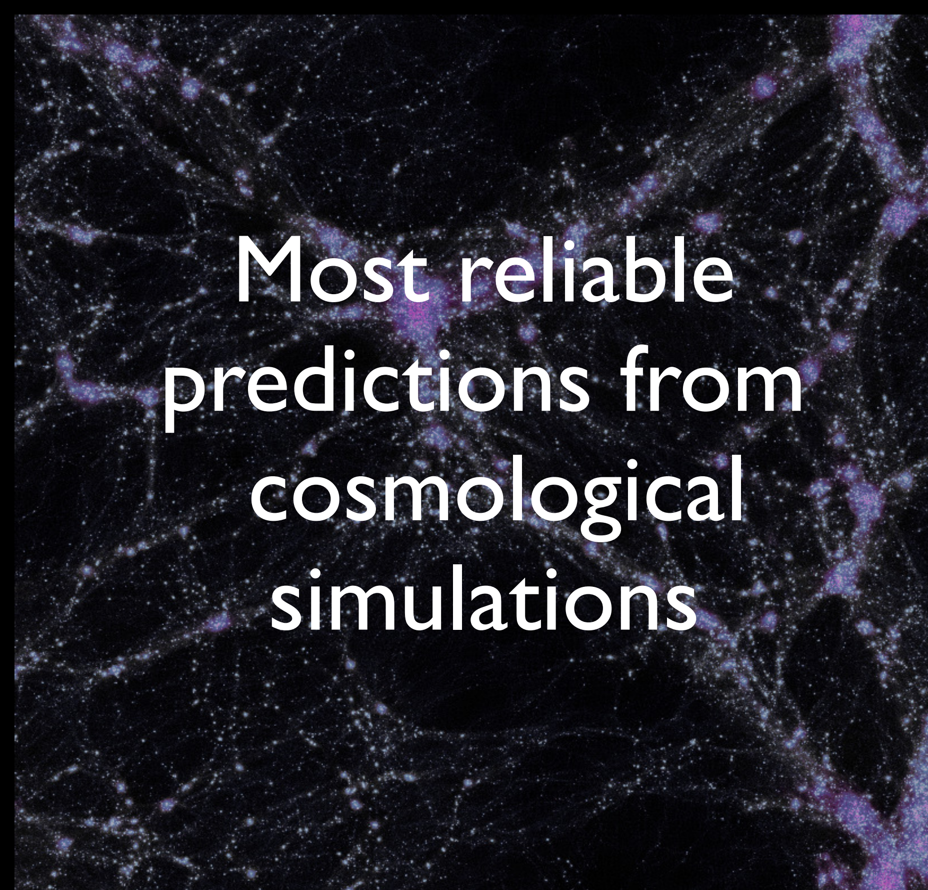
Astrophysical Constraints

Phenomenology → Predictions ⇄ Observations

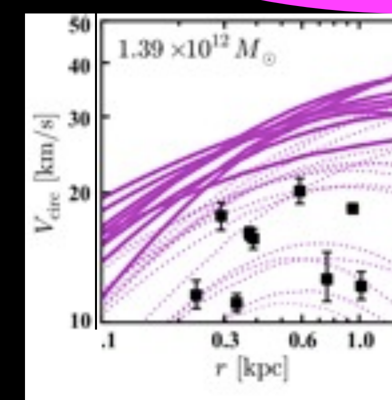
σ/m

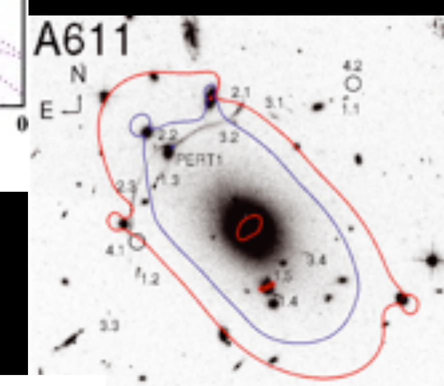
- Core sizes & densities
- Shapes
- Substructure
- Merging clusters: offsets & M/L ratios

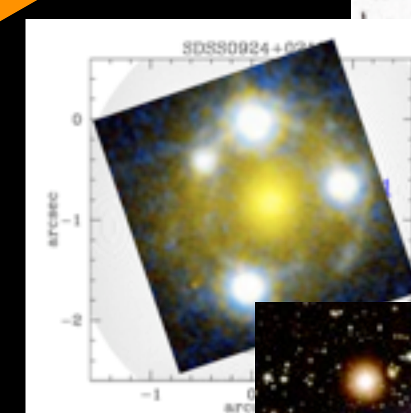
→

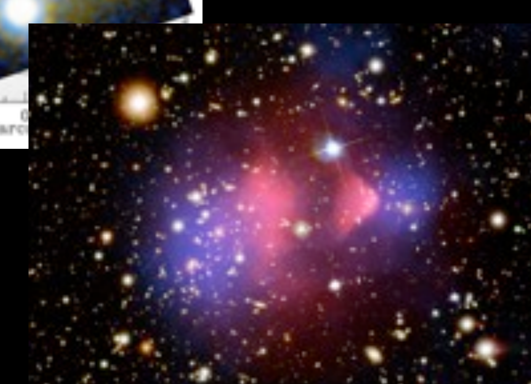


σ/m ⟷

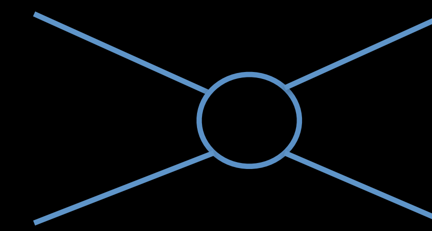




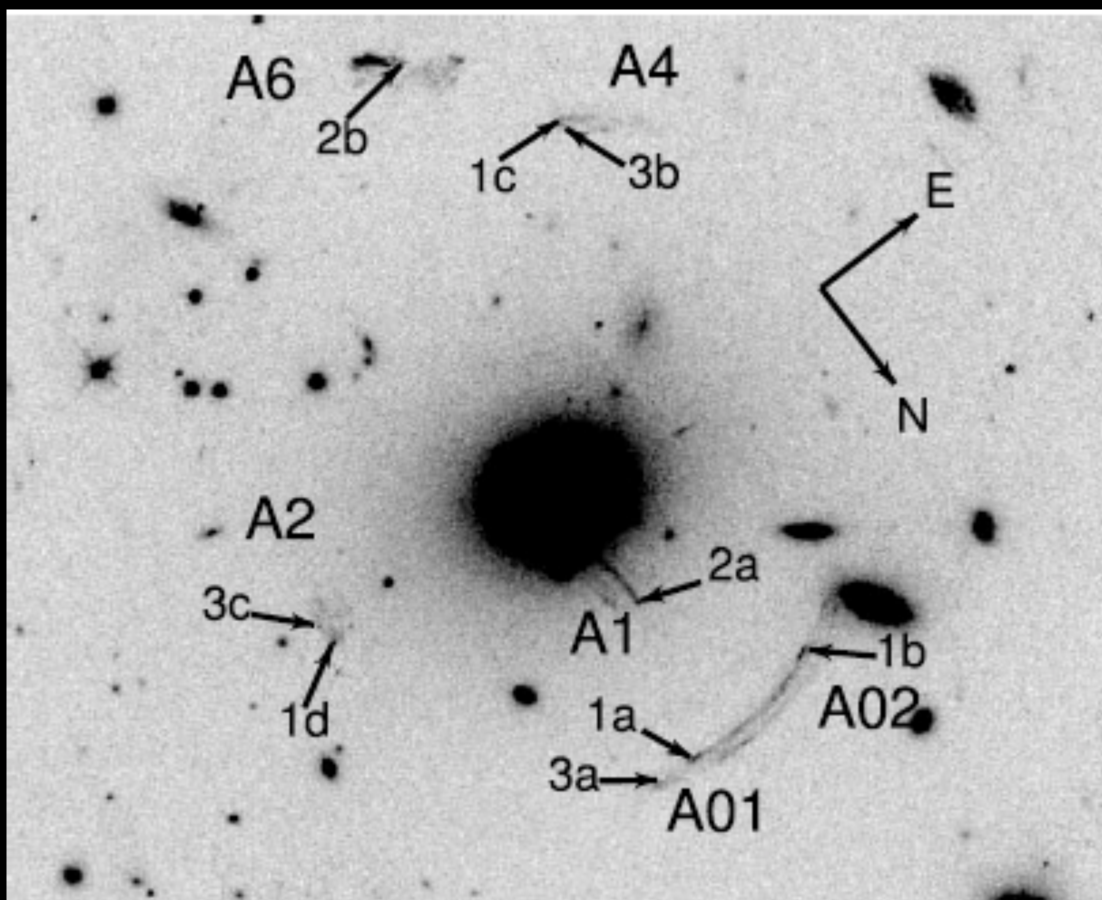




The TKO of SIDM



Miralda-Escude (2002)



MS 2137-23
Sand et al. 2008

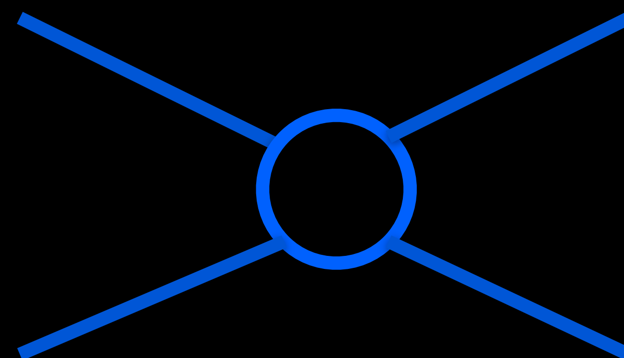
Requires a non-circularly-symmetric surface density at r > 70 kpc.

Assume ε=0 if $\Gamma/H_0 \gtrsim 1$

➔ σ/m < 0.02 cm^2/g.

Tightest constraint by far (by > 10x)!

Simulating DM Self-Interactions



large mean free paths

Collisionality

short mean free paths

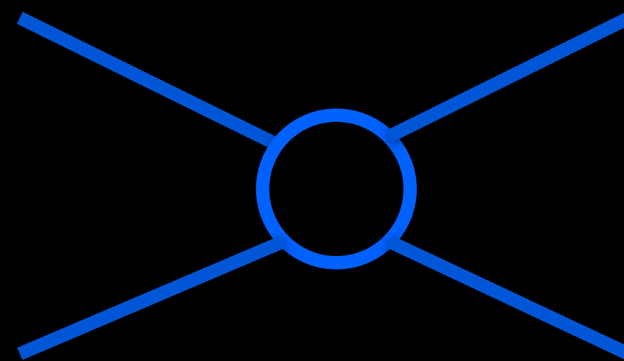
Spergerl & Steinhardt 2000

$$\frac{\sigma}{m} = 0.1 - 100 \ \mathrm{cm}^2/\mathrm{g}$$

Vlavsov equation solved with collisionless N-body

Fluid equations solved with hydro methods

Simulating DM Self-Interactions



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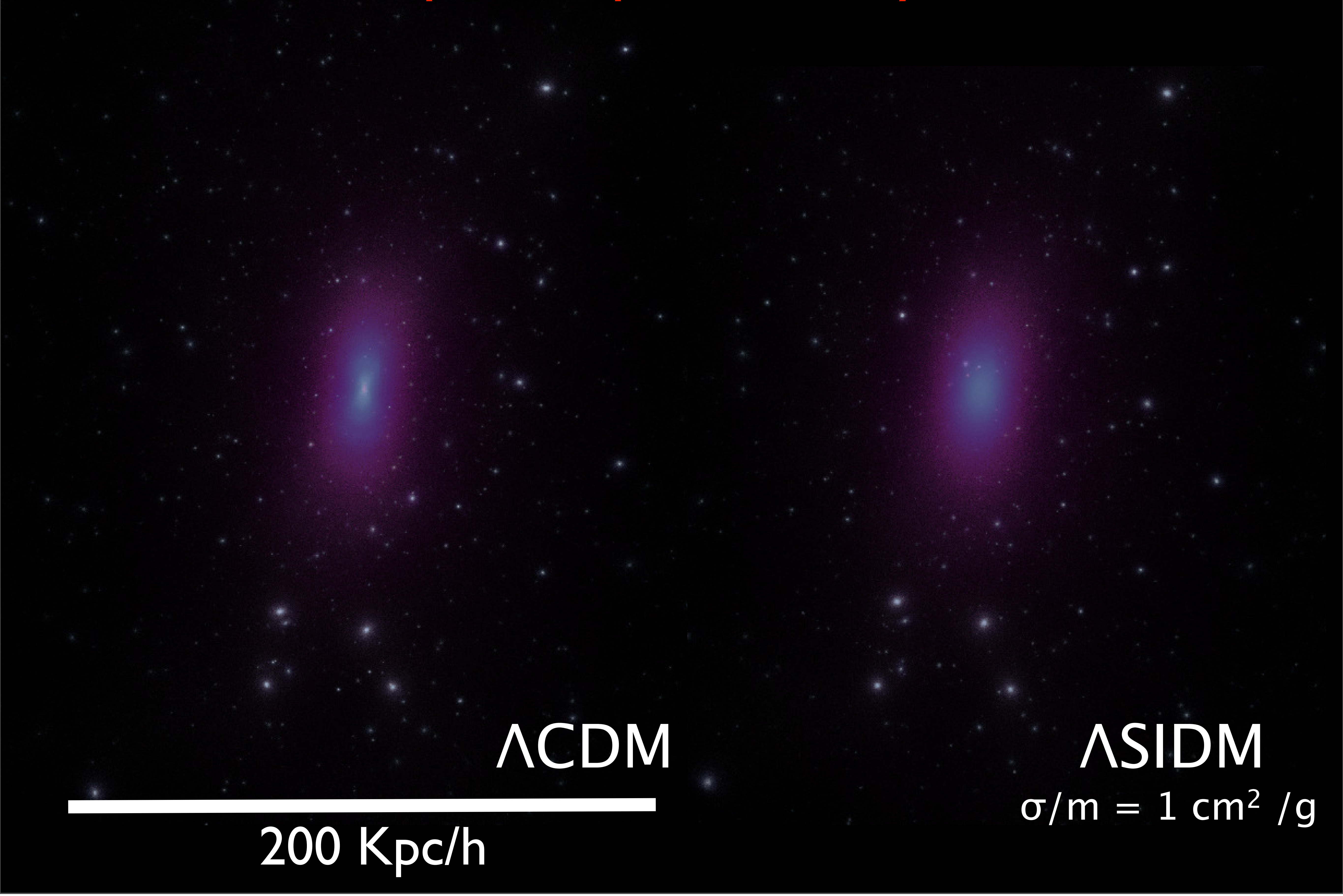
Need to step back and derive an algorithm from the Boltzmann Equation

Lower central phase-space density in SIDM halos



Results from cosmological simulations - Summary

Core Sizes
&
Central Densities

See also Vogelsberger et al. 2012 & Zavala et al. 2013

$\sigma/m < 1$

$\sigma/m = 0.1$-0.5 in better agreement with observations

Shapes

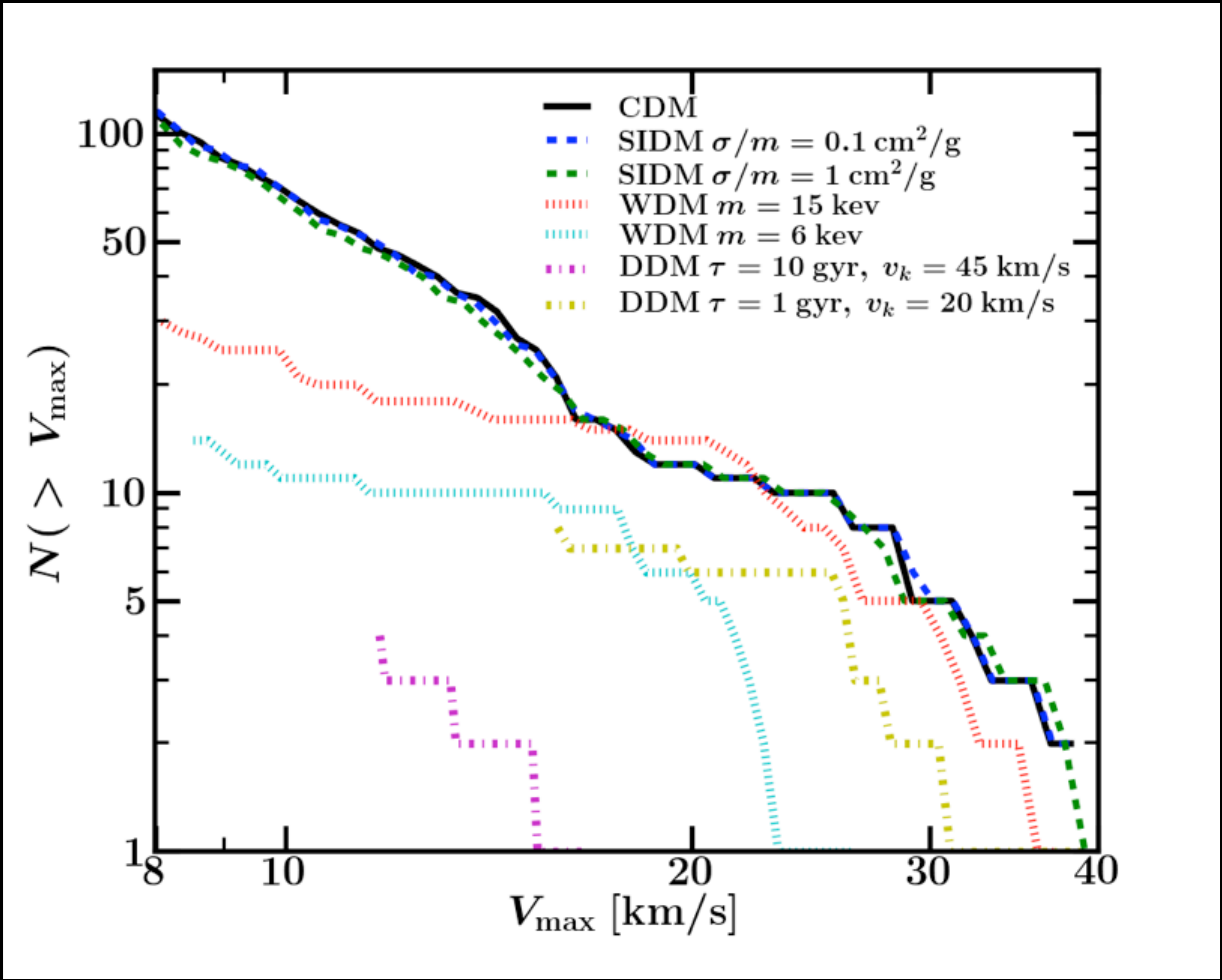
$\sigma/m < 1$

Substructure

Subhalo count within 1 Rvir of the host are identical to CDM

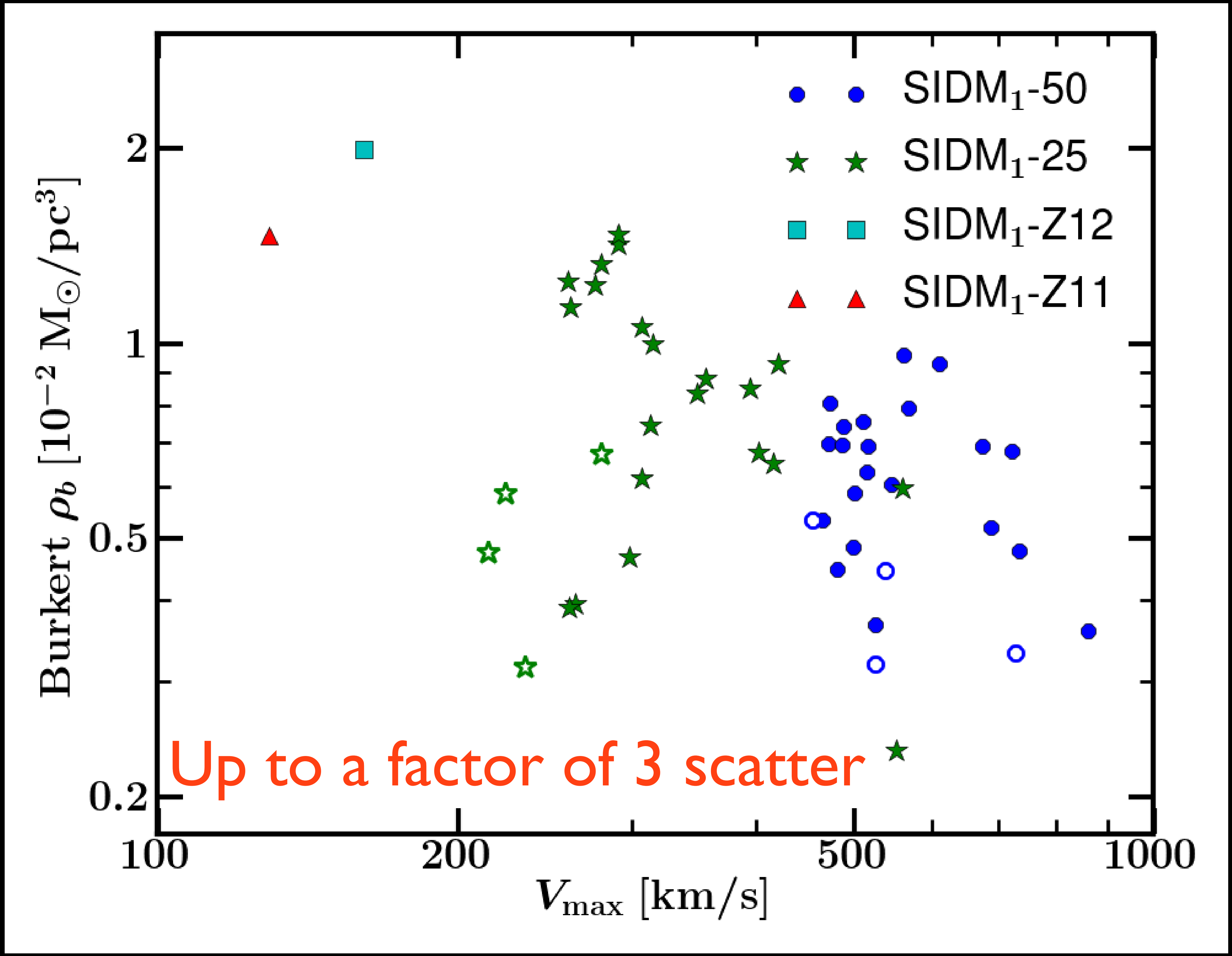
For r < Rvir/2 we only see differences of ~10-15%

Results from cosmological simulations - Substructure



Rocha et al. in prep

Results from cosmological simulations - Halo densities

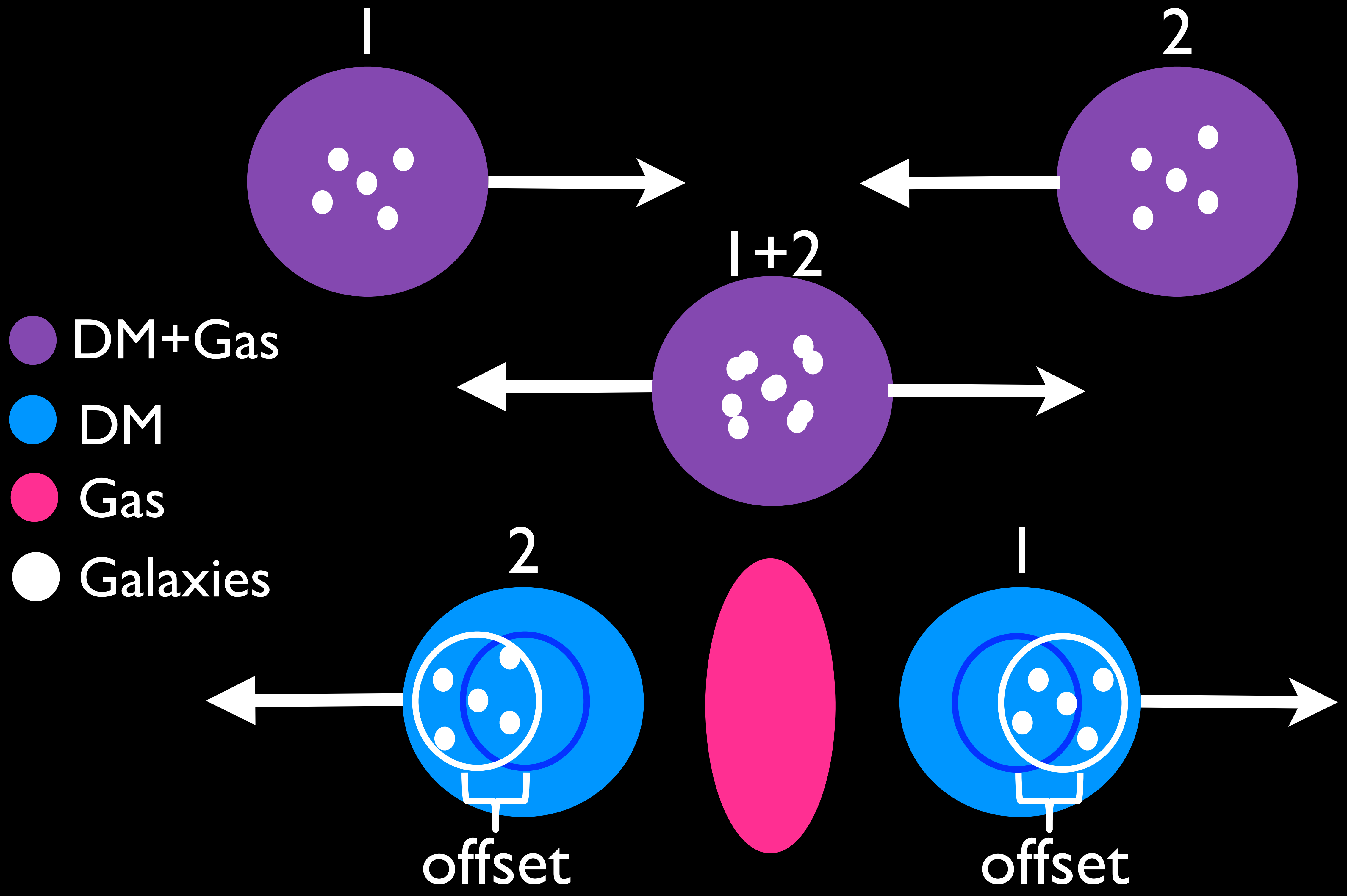


$\sigma/m = 1$ cm^2 /g

Rocha et al. 2013

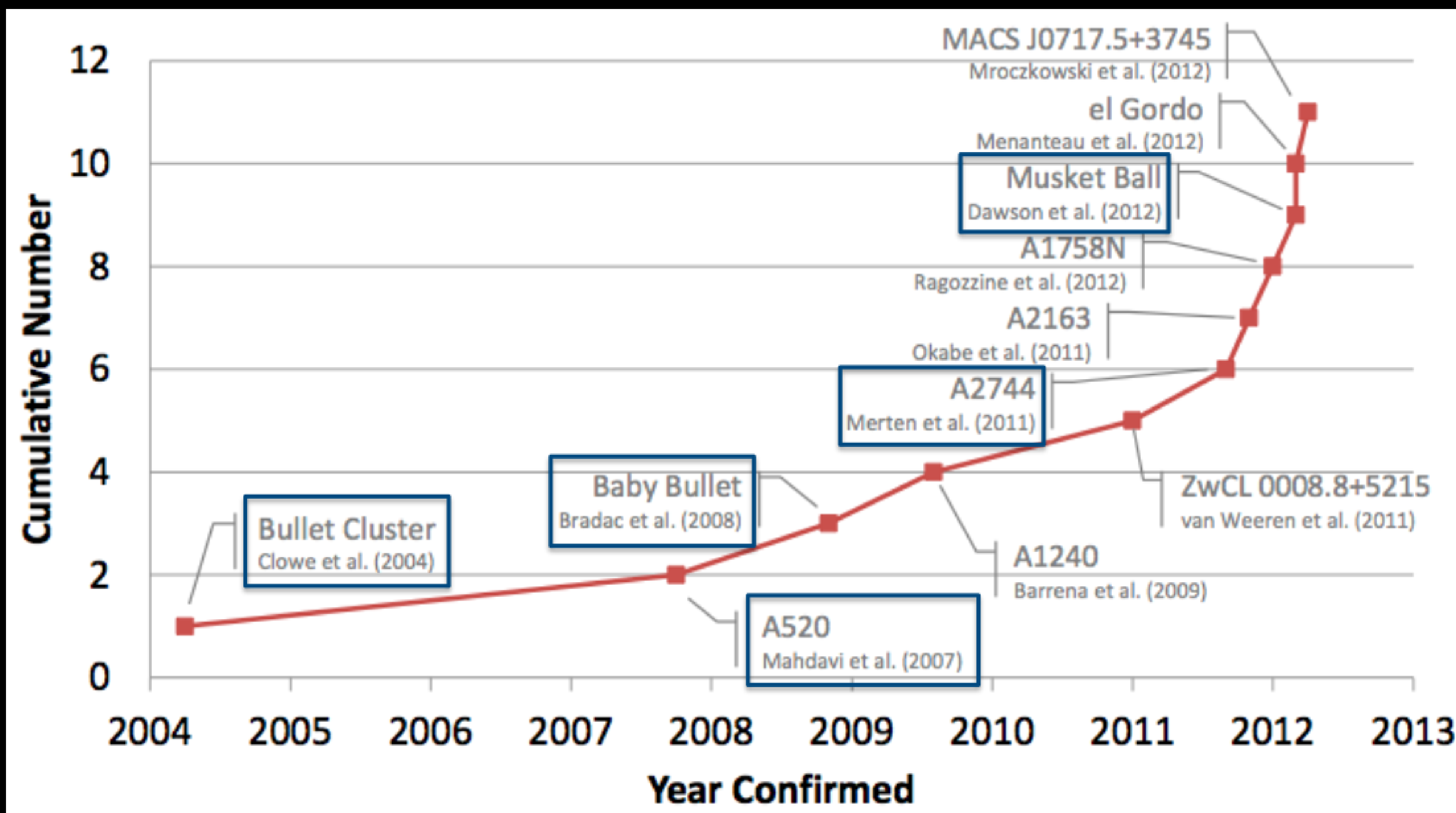
Work in progress - Merging clusters

Dissosiative Clusters



Work in progress - Merging clusters

Observations

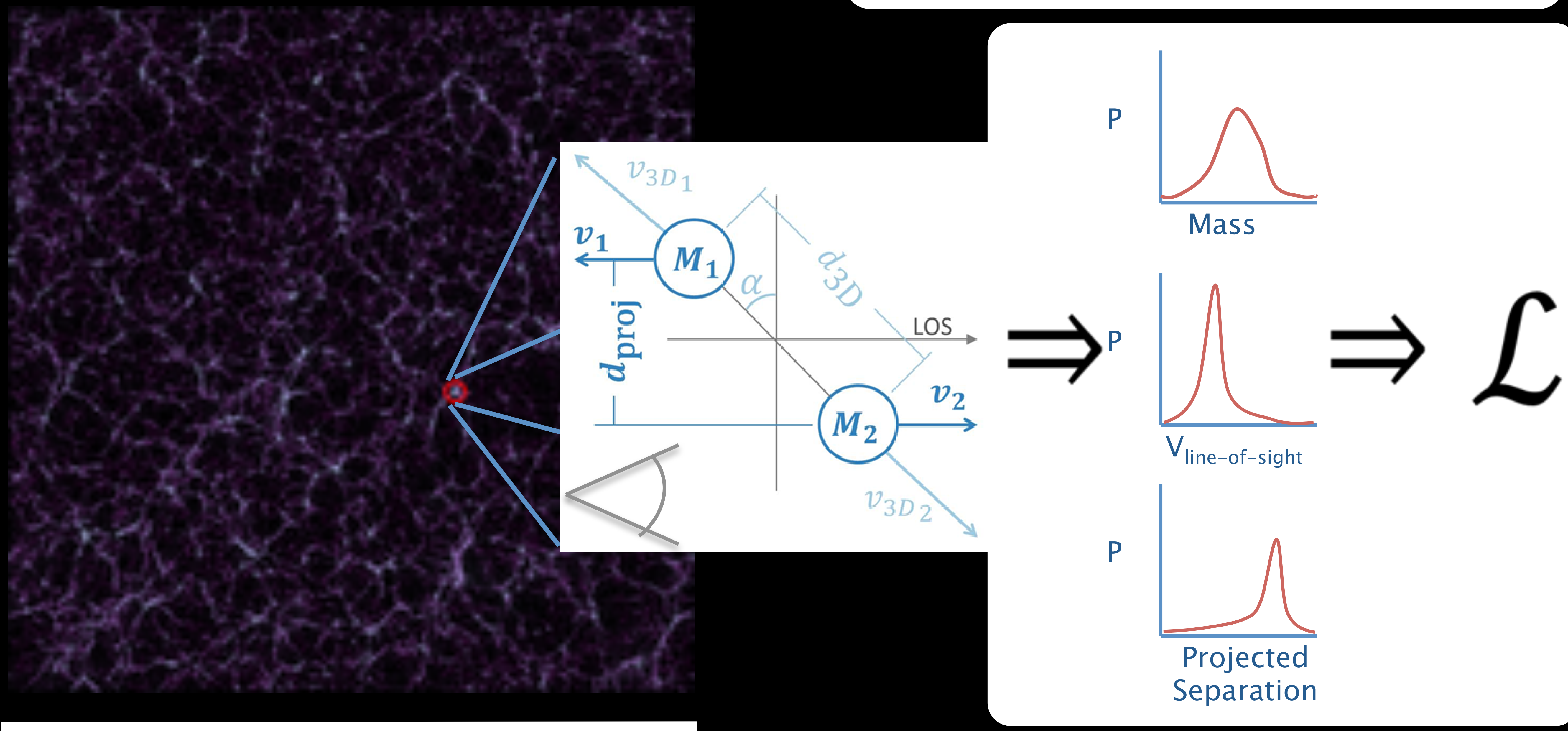


Work in progress - Merging clusters

Predictions vs. Observations

Importance Sampling

Merging Cluster Collaboration



650 Mpc/h

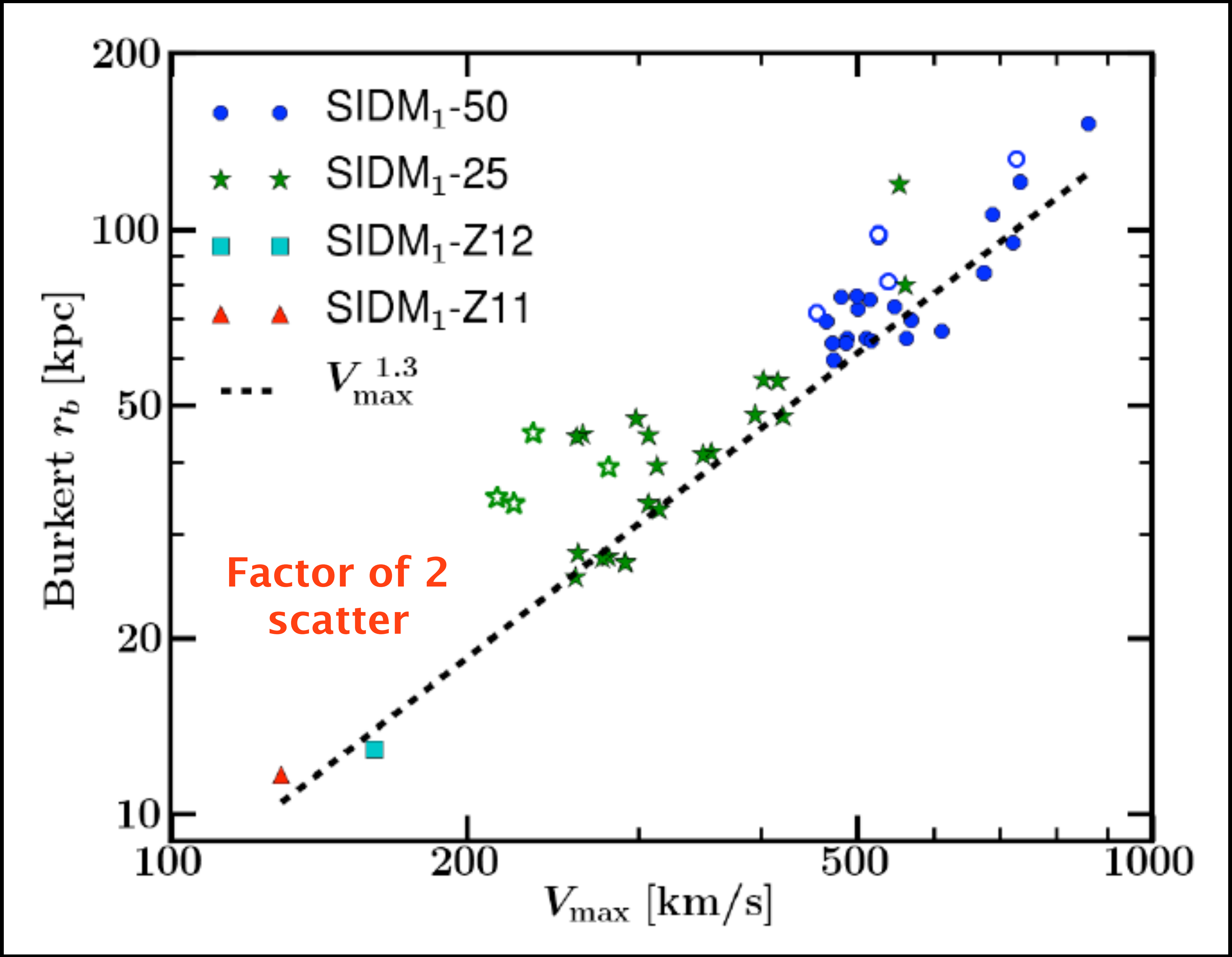
Conclusions

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

Thank You

Results from cosomological simulations - Core sizes

Core Sizes



Dwarf galaxies

Milky Way

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

Rocha et al. 2013

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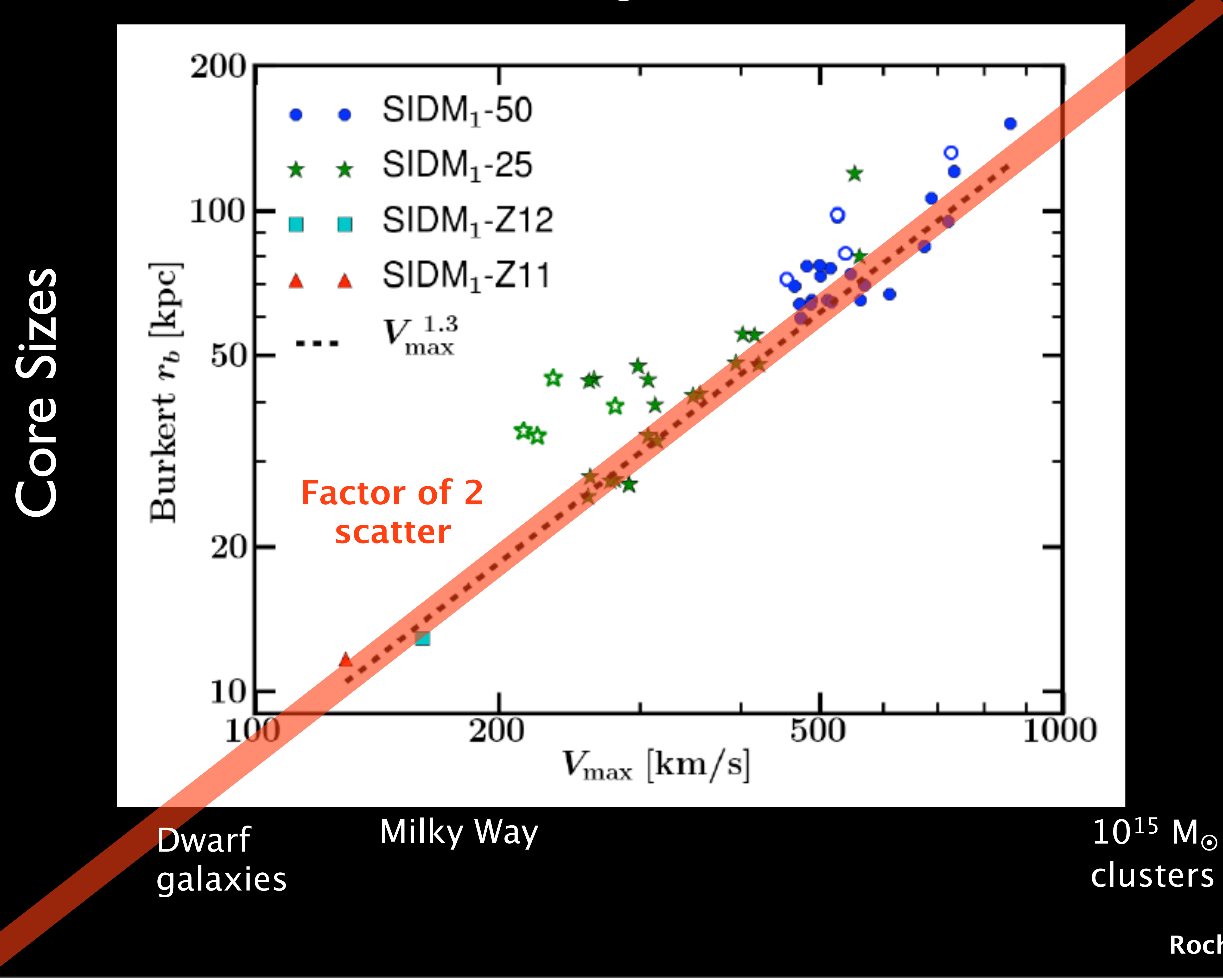

Rocha et al. 2013

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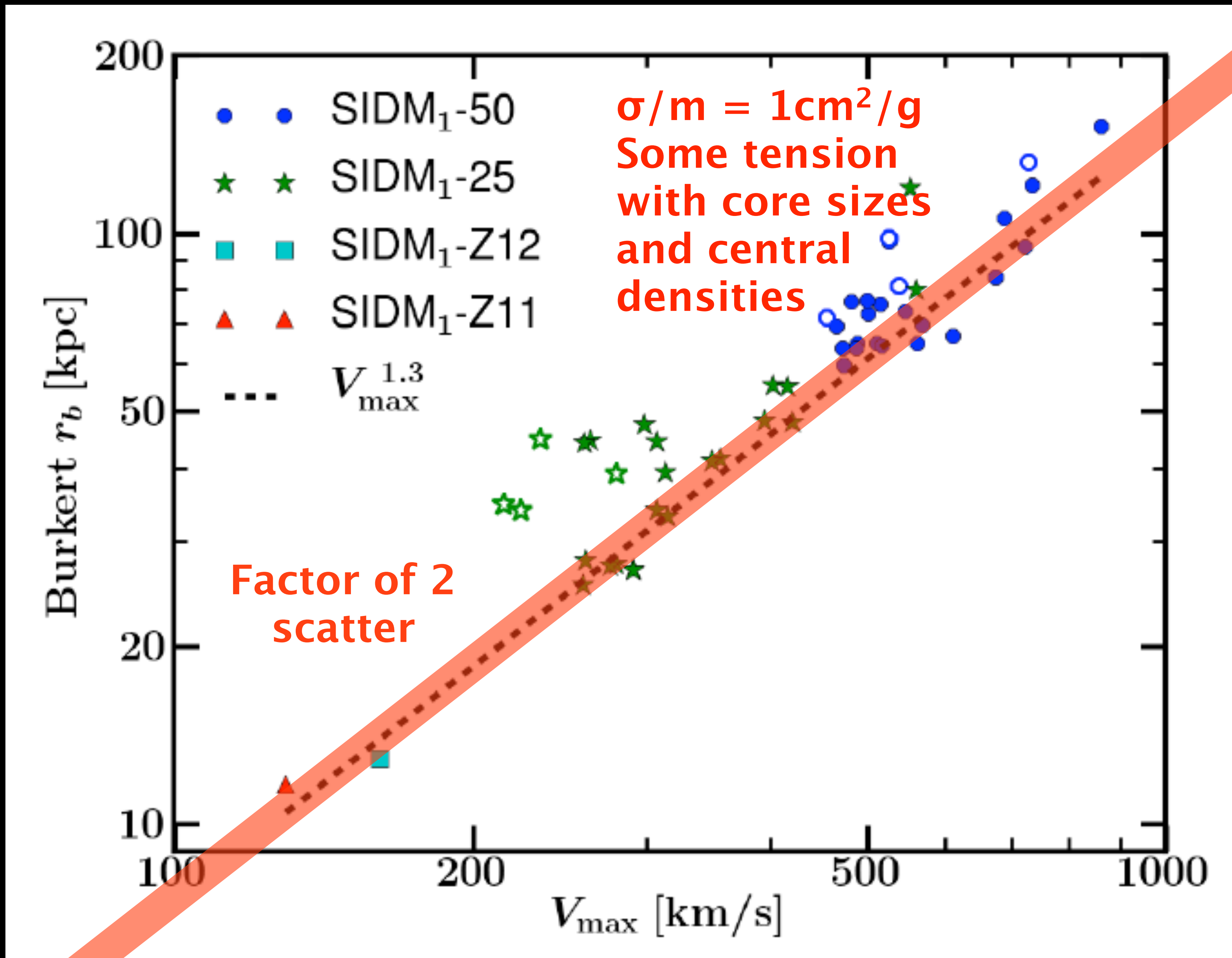

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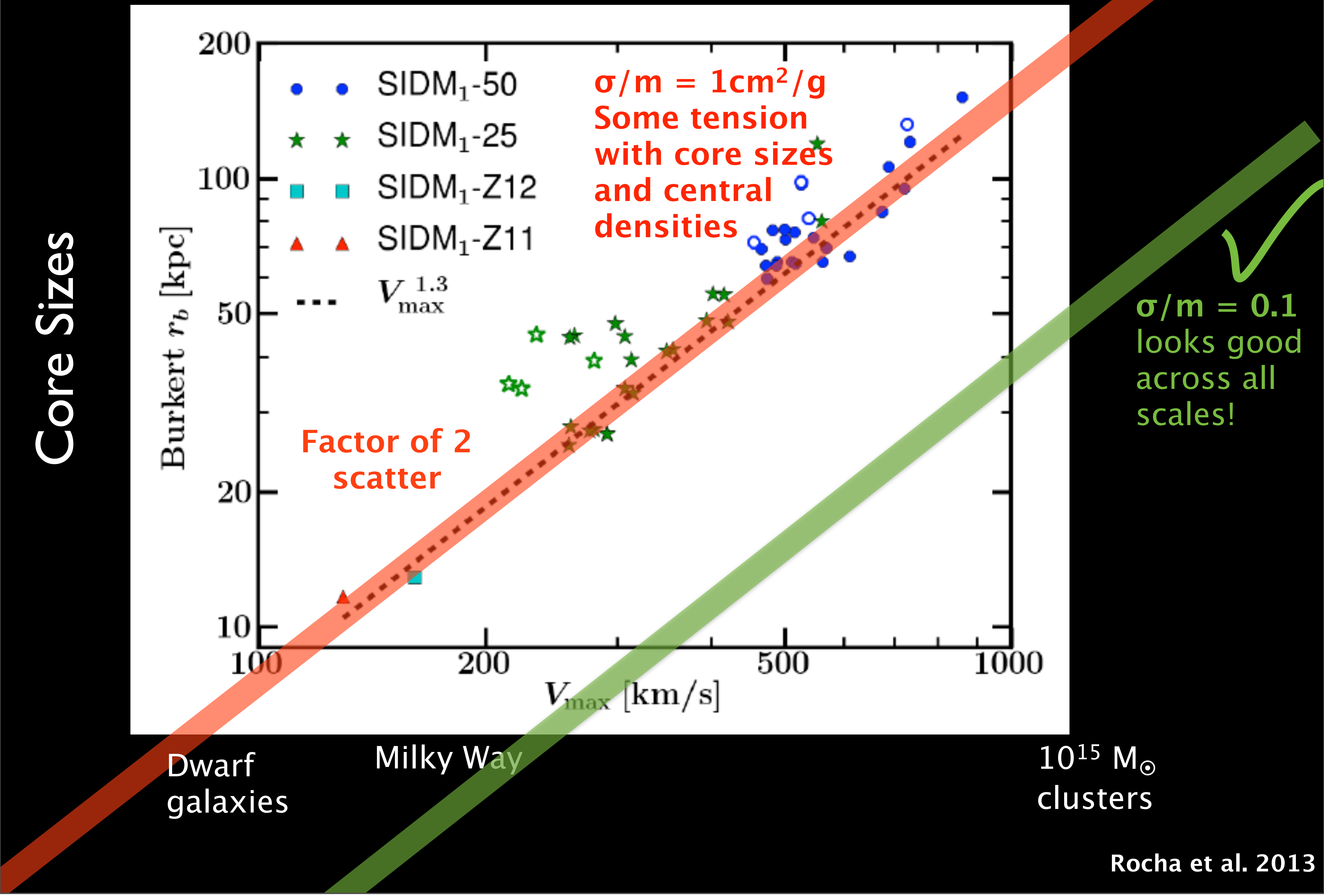

Rocha et al. 2013

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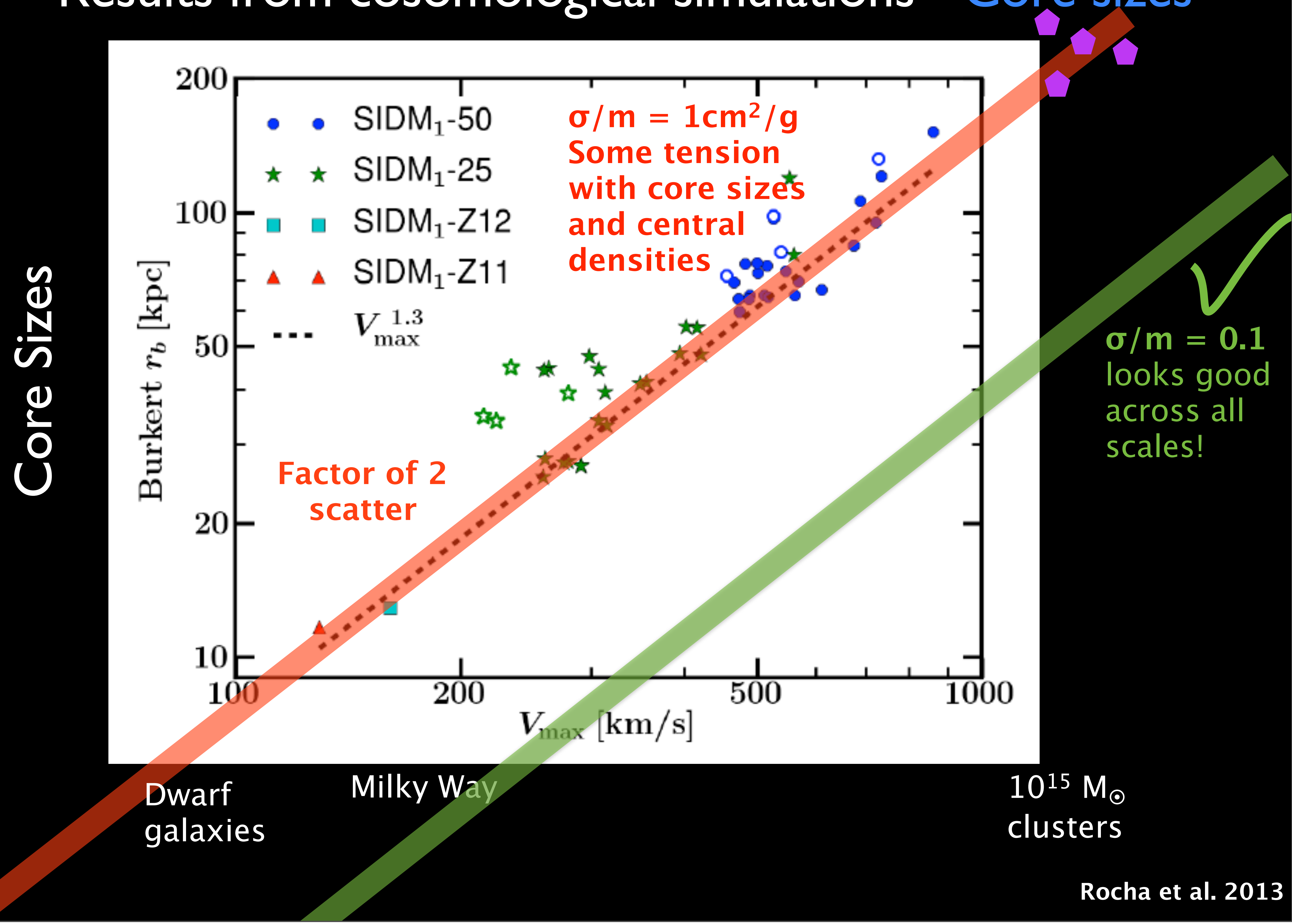

Rocha et al. 2013

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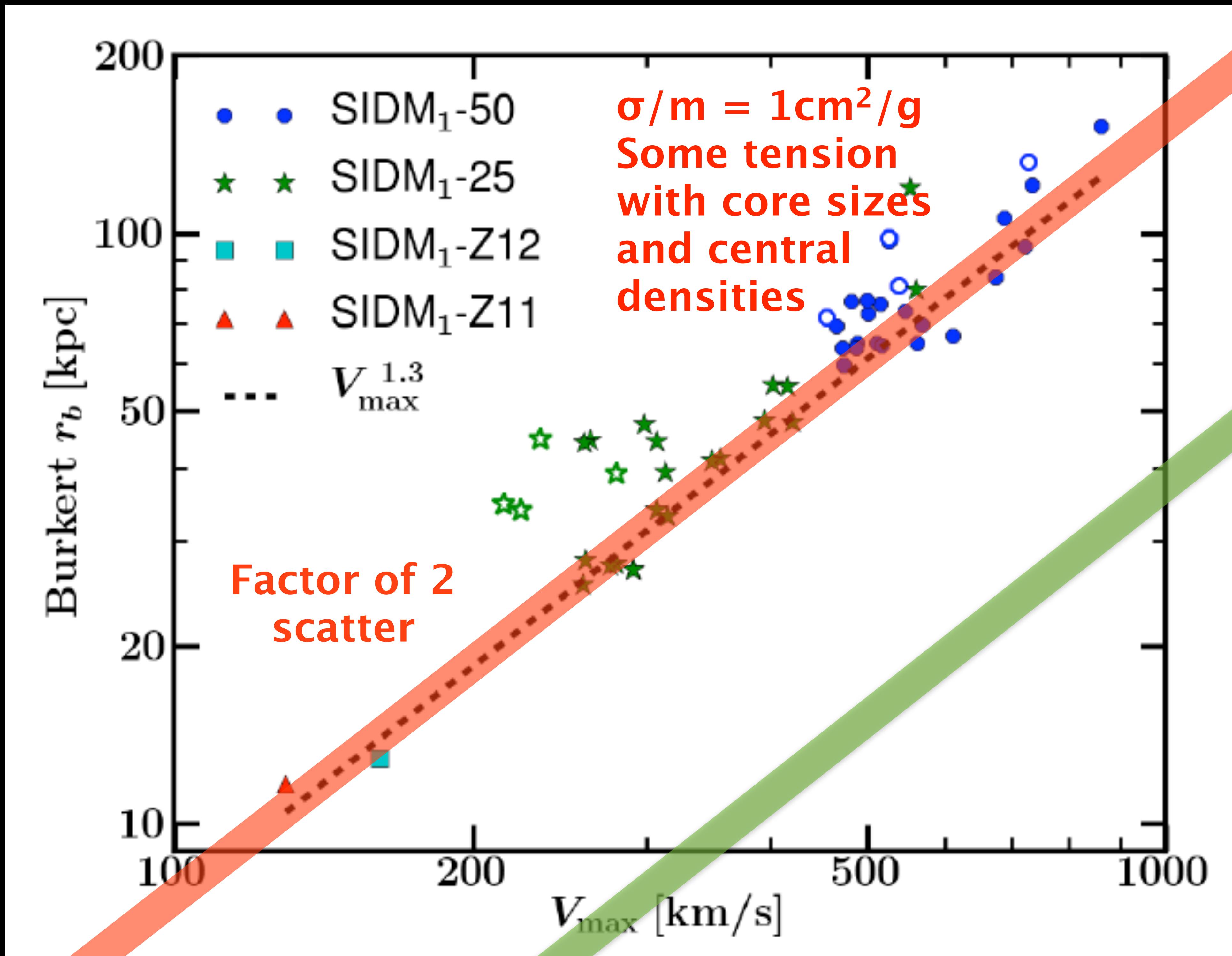

Dwarf galaxies

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10^{15} $M_\odot$ clusters

σ/m = 0.1
looks good
across all
scales!

Rocha et al. 2013

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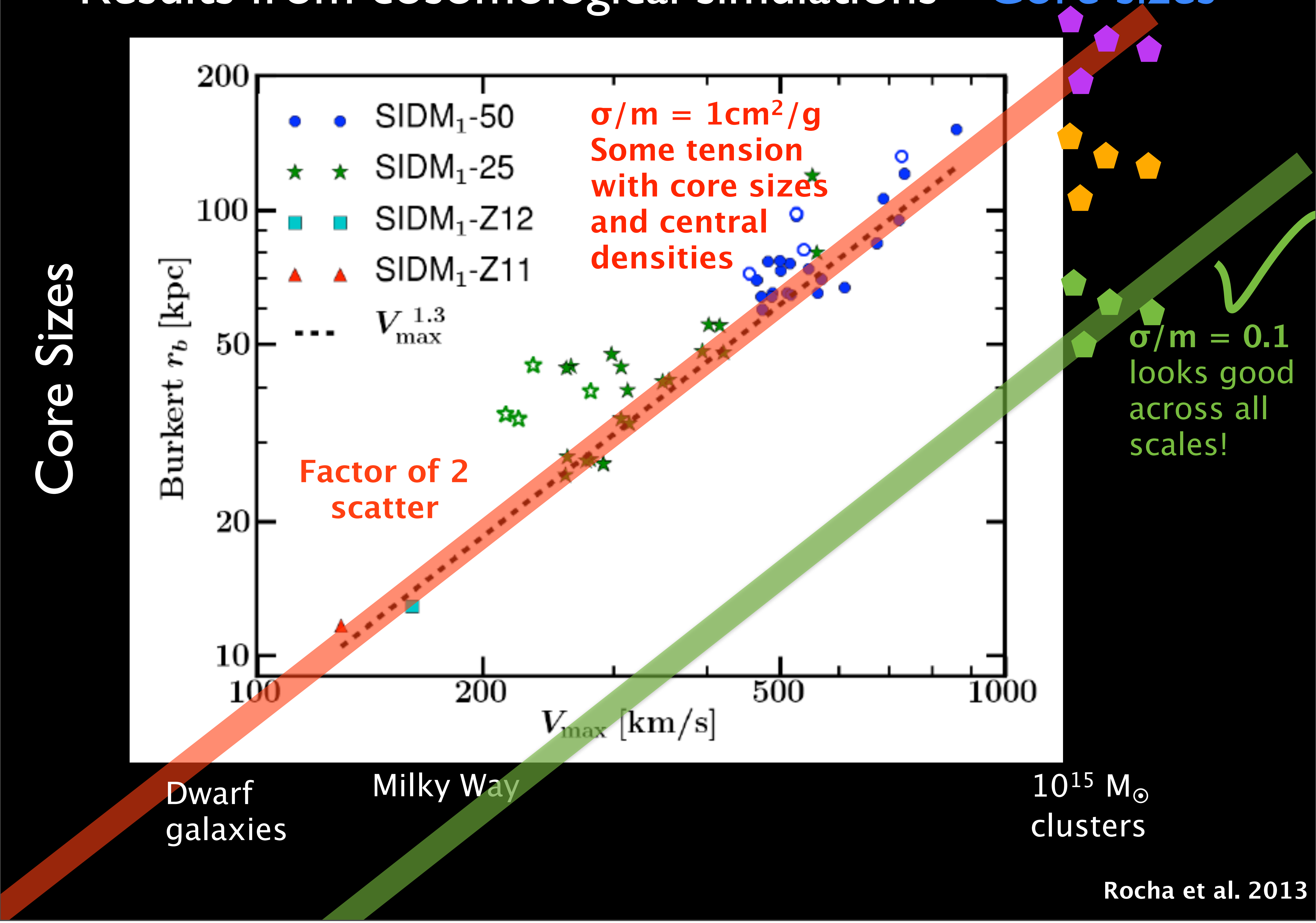

Rocha et al. 2013

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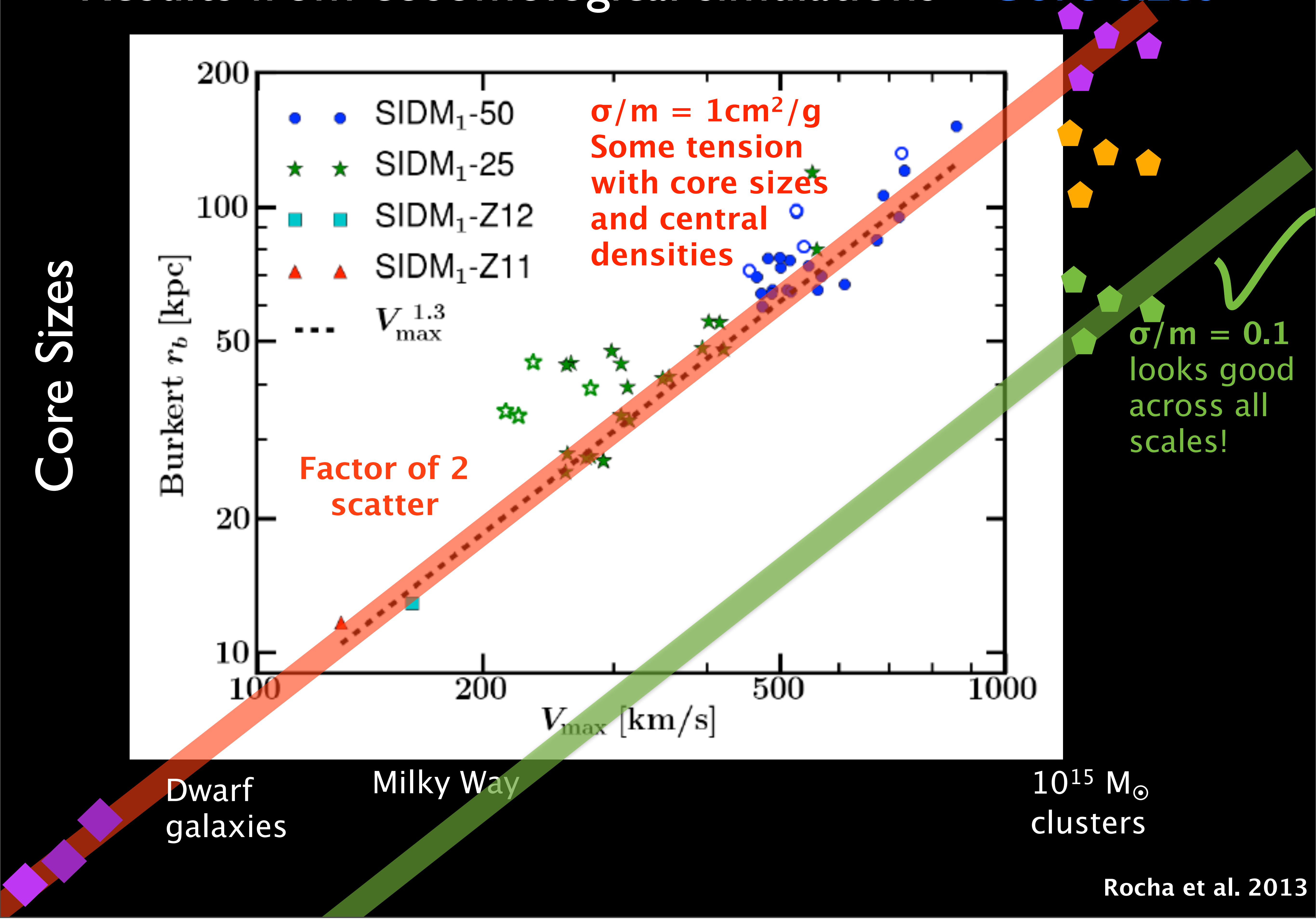

Rocha et al. 2013

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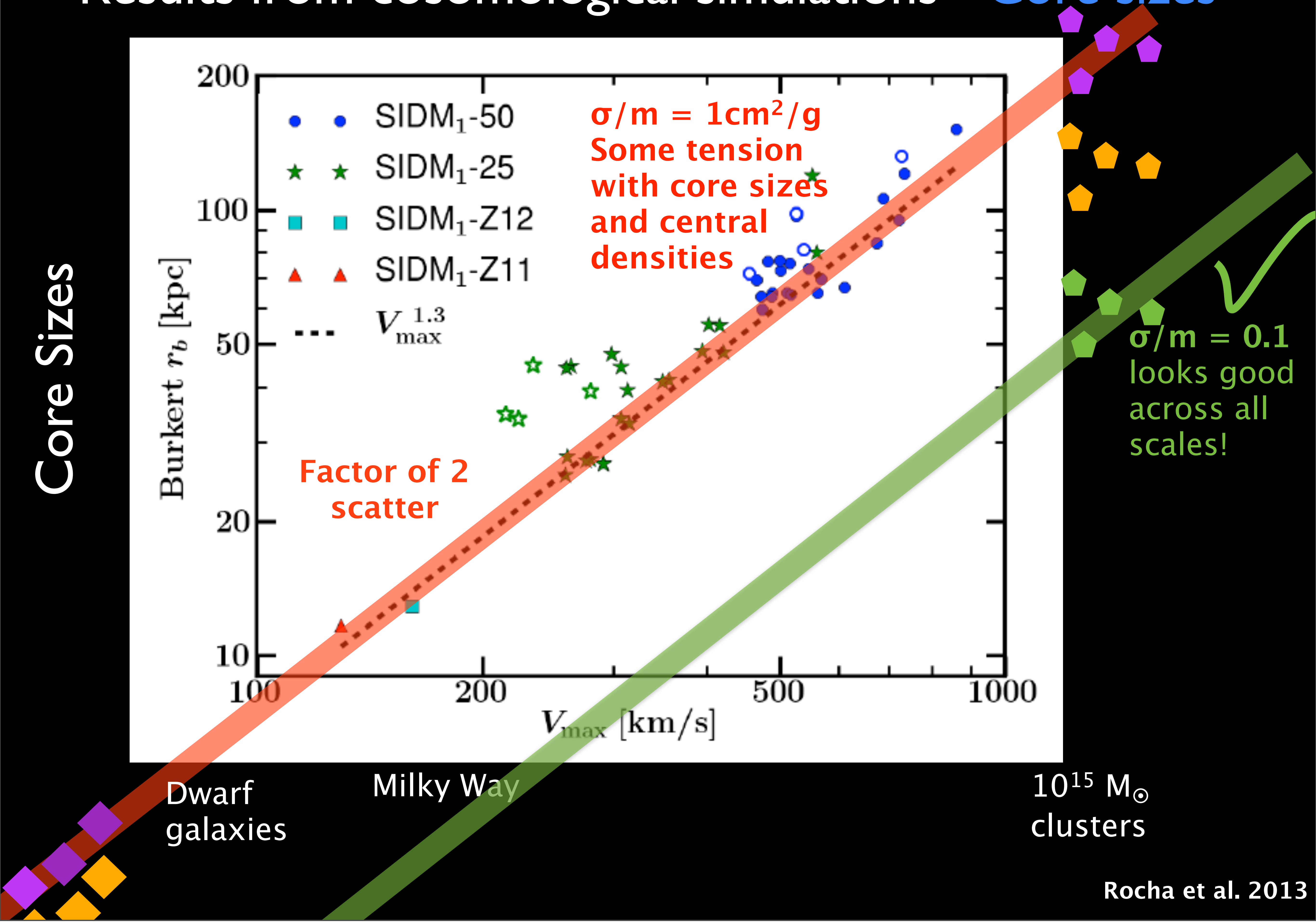

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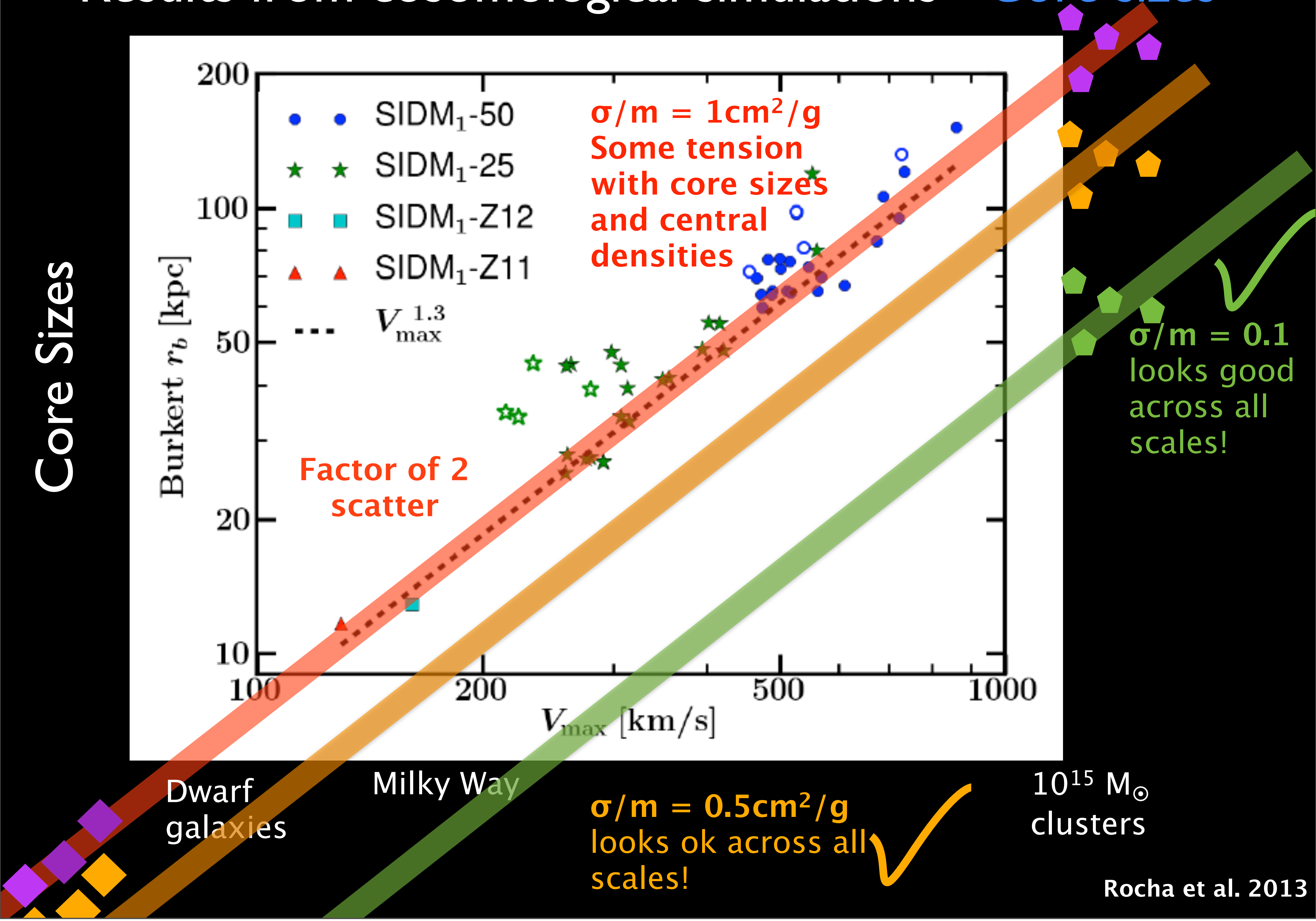
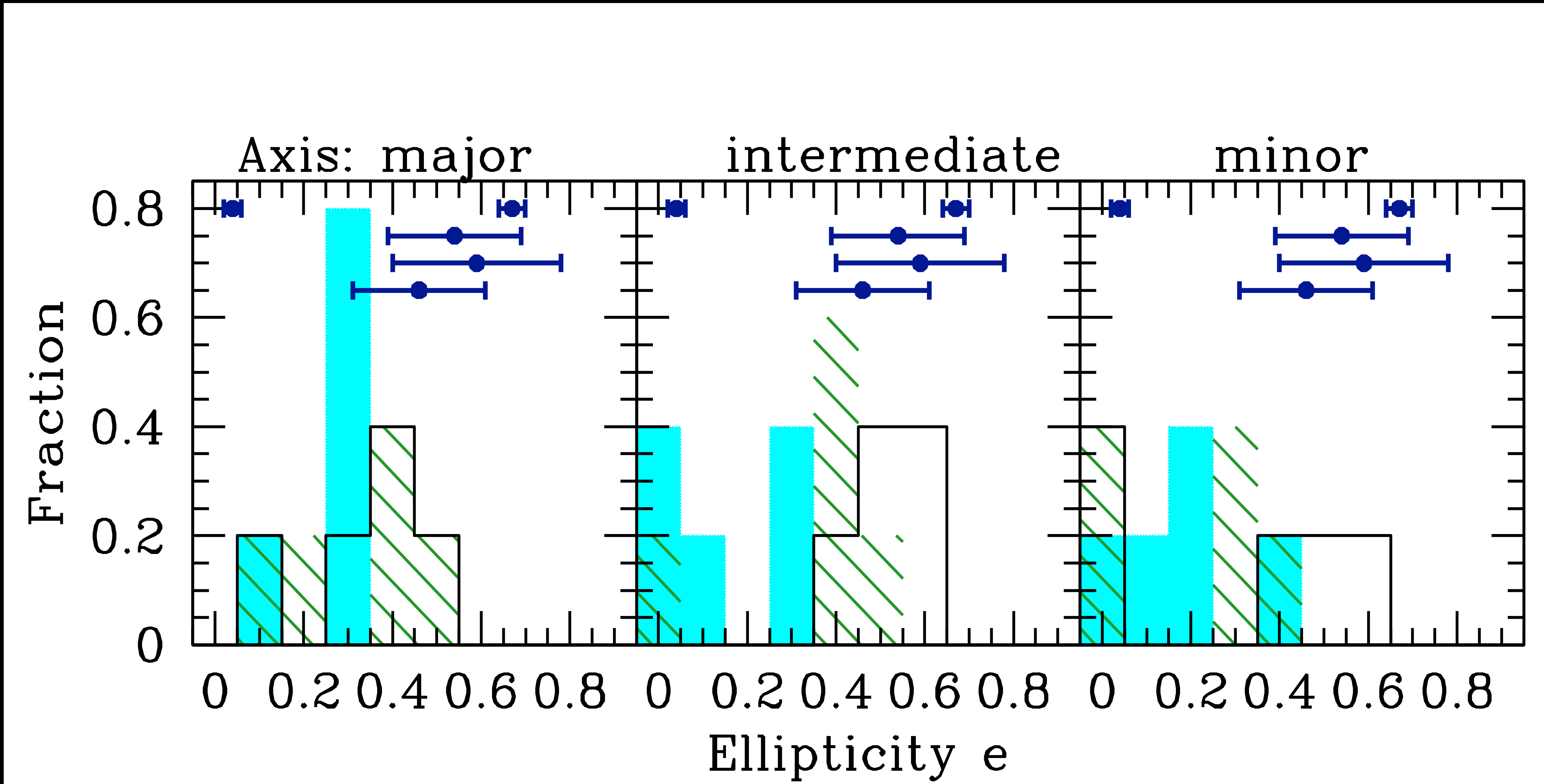


Results from cosomological simulations - Halo shapes



$\sigma/m < 1\ cm^2/g$ looks more likely!

Peter et al. 2013

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 - 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 [M_{sun}/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 [M_{sun}/pc^3]	~0.04 [M_{sun}/pc^3]
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]
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

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Comparison to observed core sizes

	Observed	σ/m=1 cm²/g	σ/m=0.1 cm²/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
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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

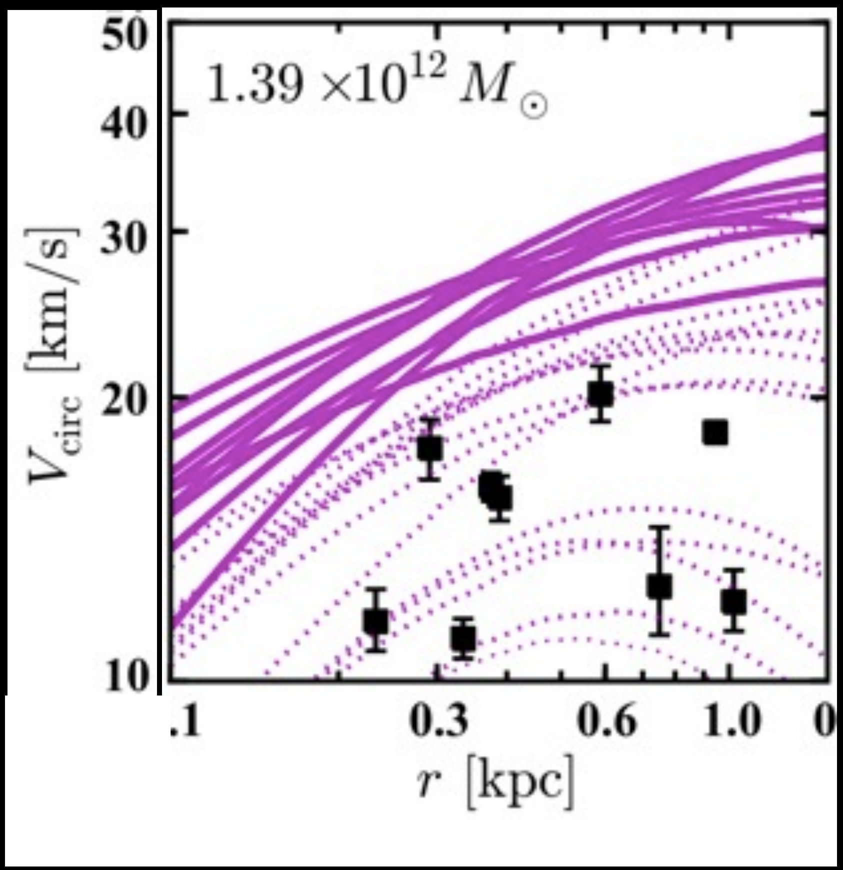
Results from cosmological simulations - Halo densities, shapes & substructure

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

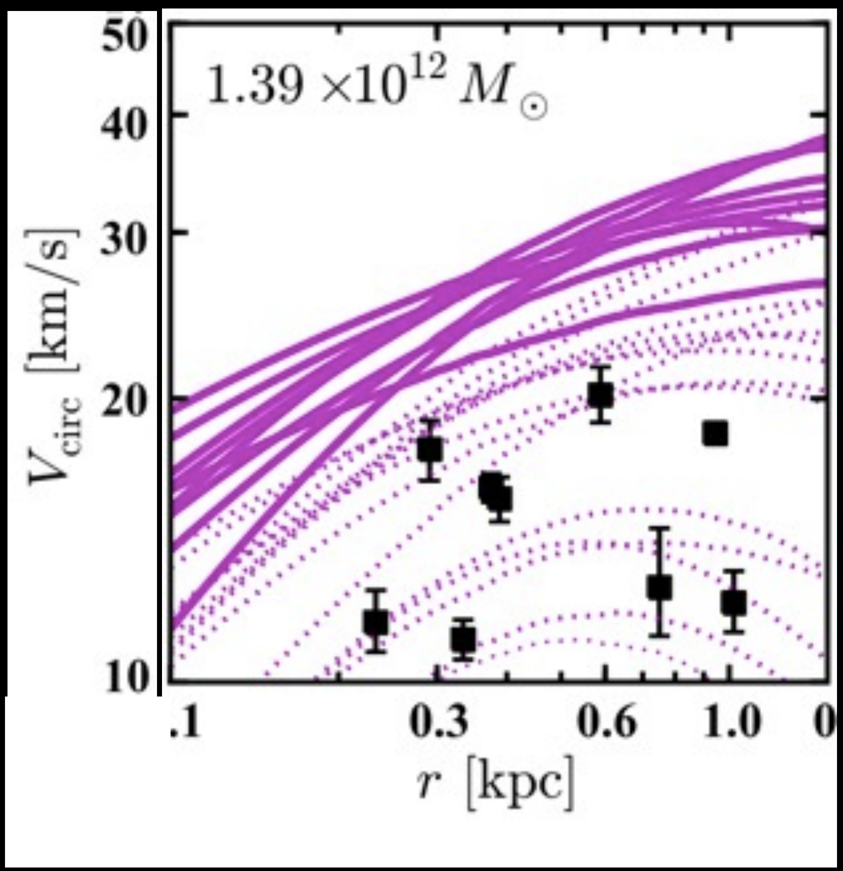
Cores in ~0.5 kpc observed

Walker&Penarrubia 2011

Results from cosmological simulations - Halo densities, shapes & substructure

Observations

Milky Way dwarfs | **Low-mass Spirals**



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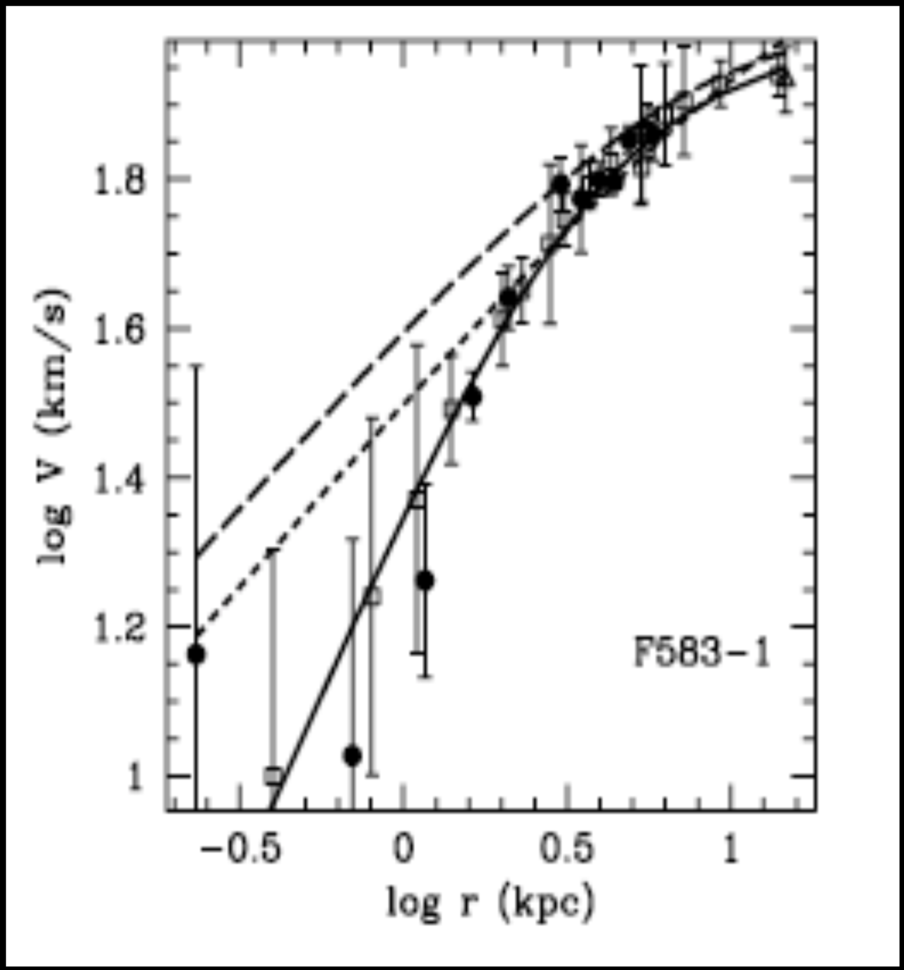


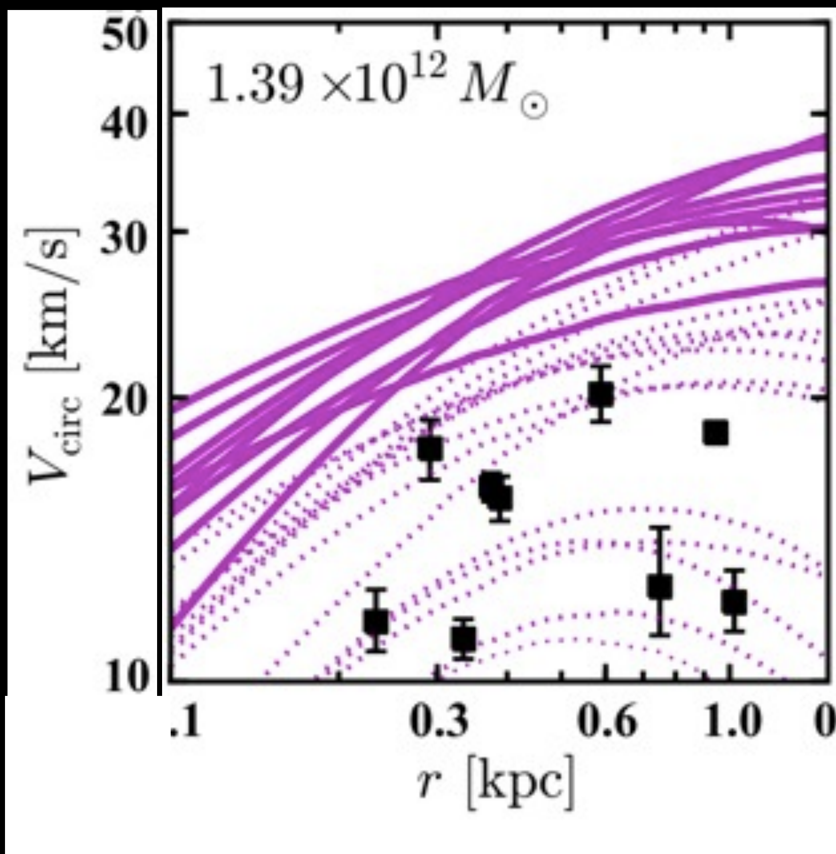
Dwarf core problem
(Kuzio de Naray+ 2008)

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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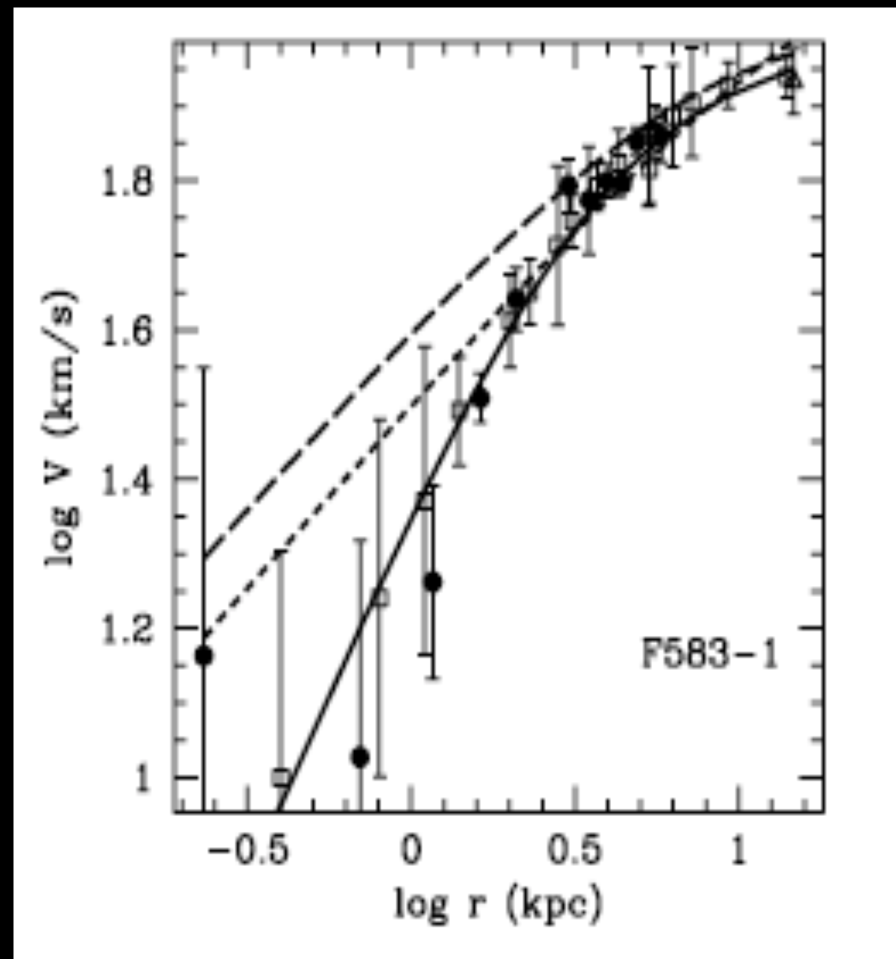

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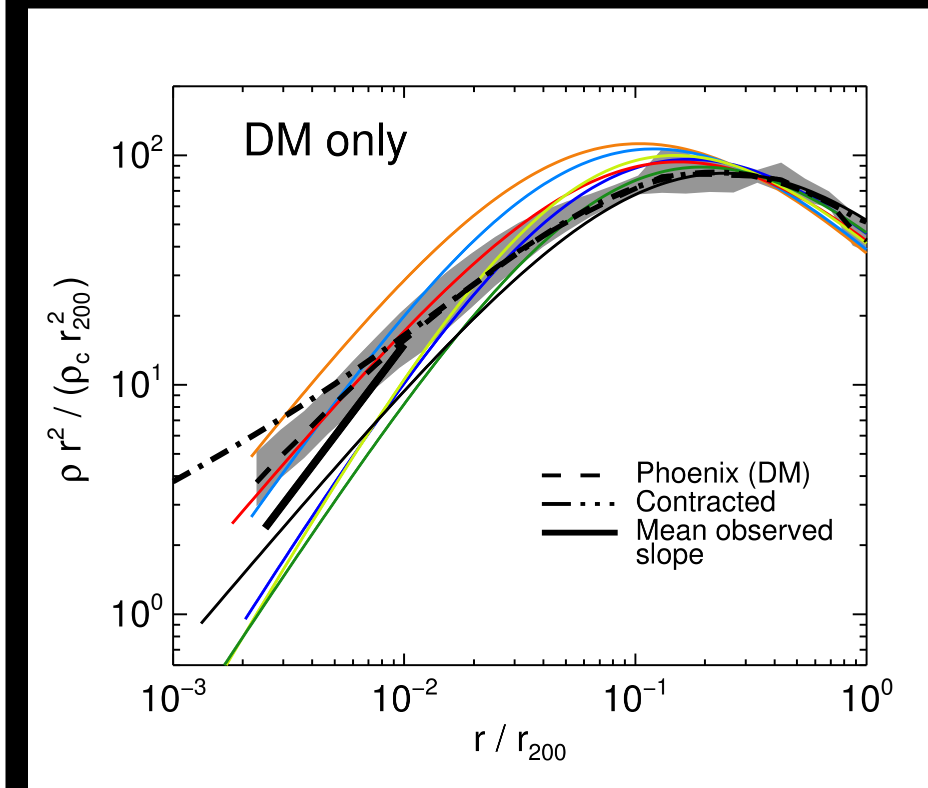
Galaxy Clusters



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

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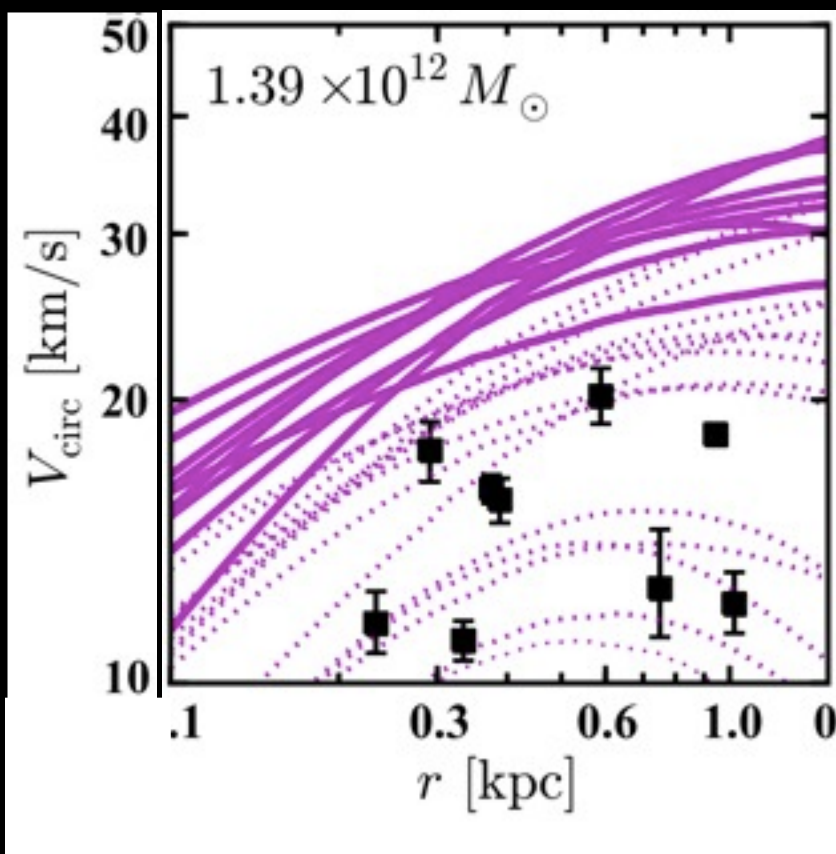

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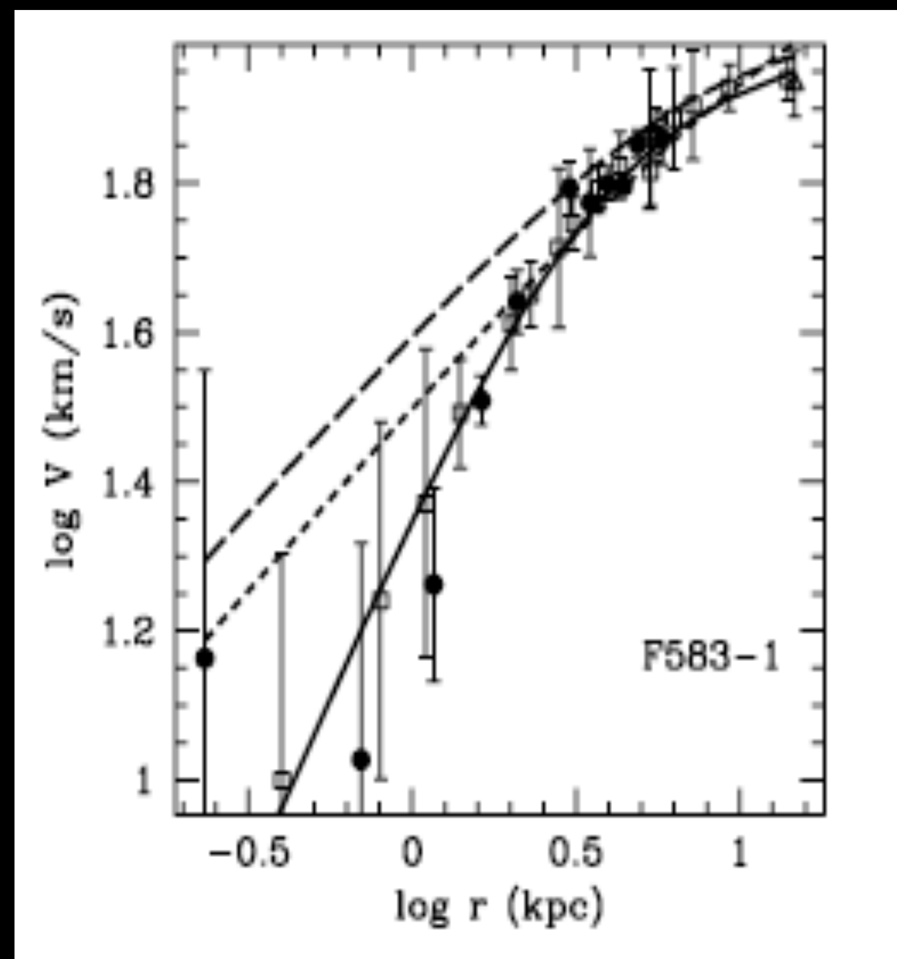

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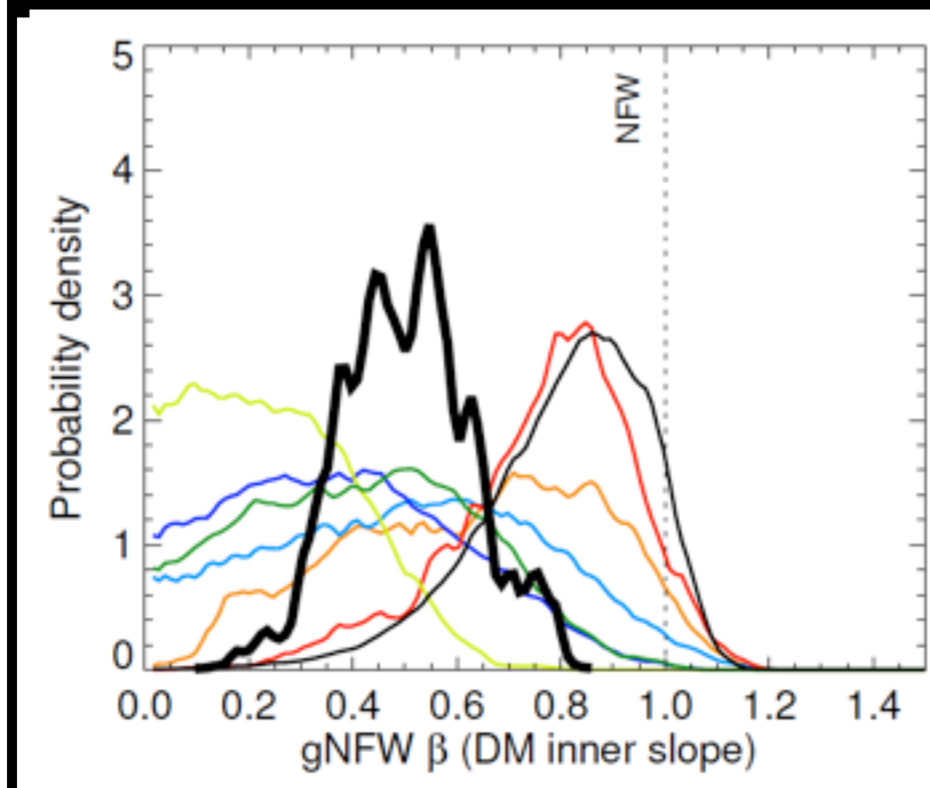

Galaxy cluster densities
$\rho \sim r^{-\beta}$
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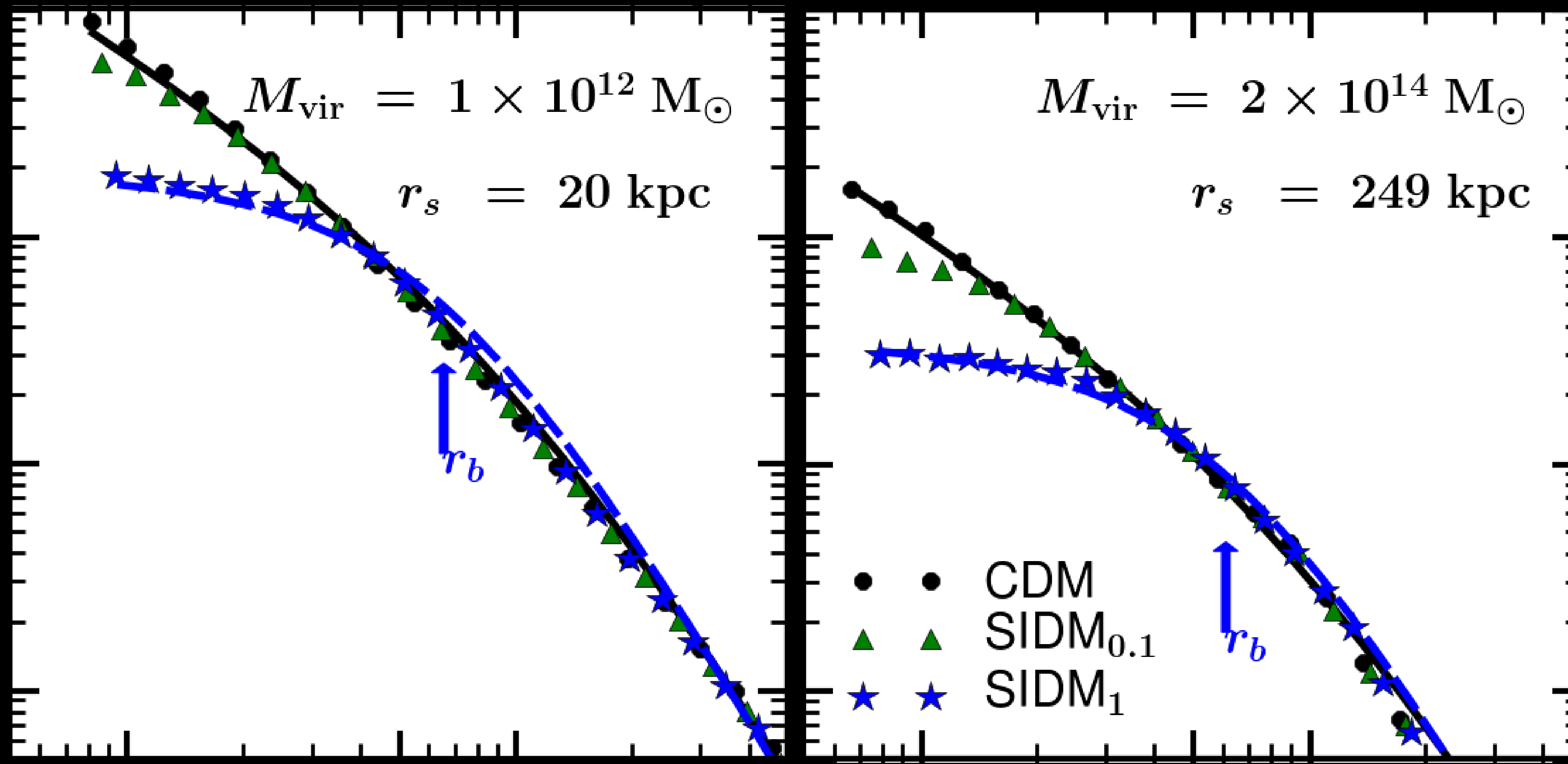
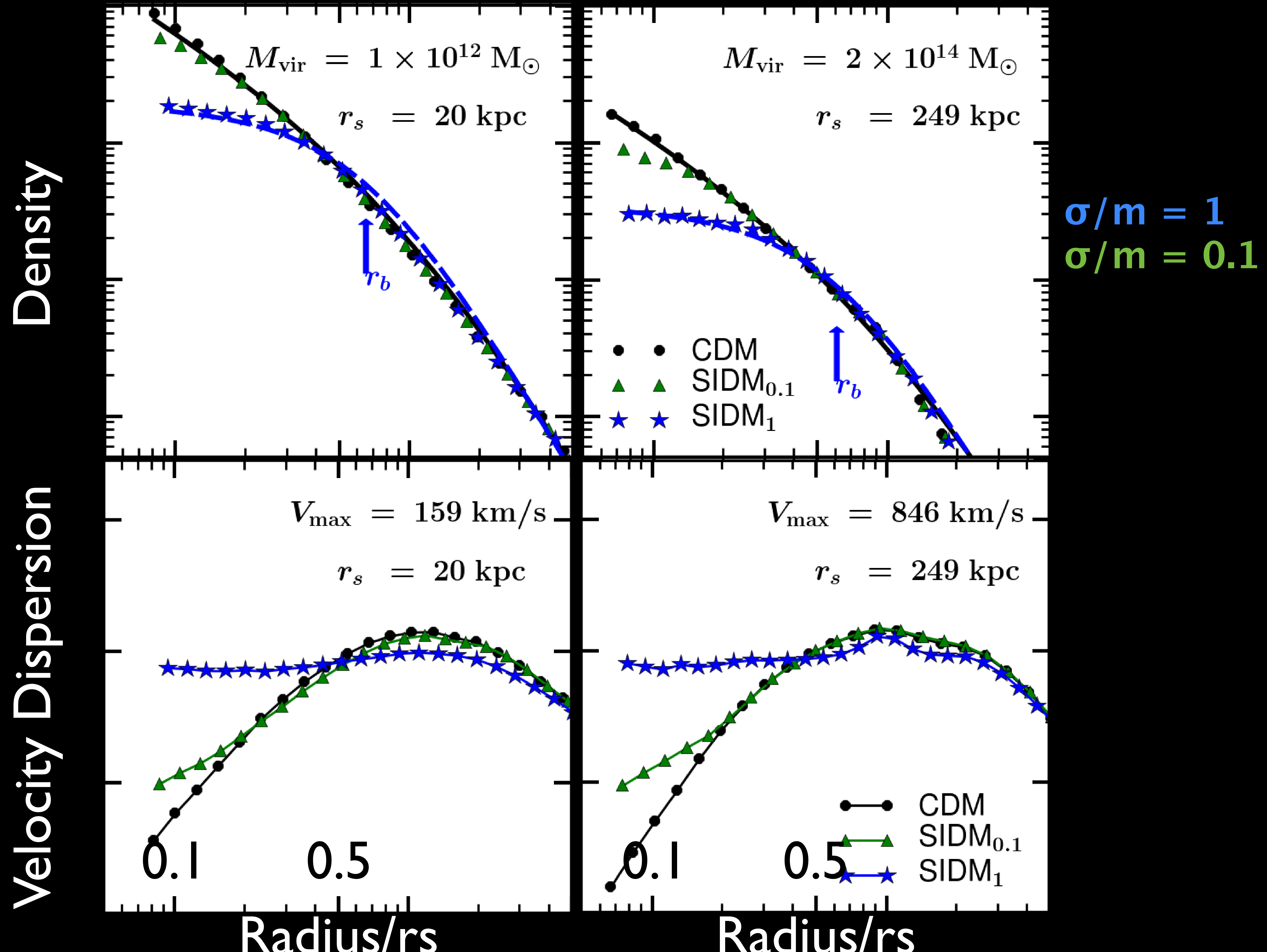
Allow cores of ~30 kpc in 10^{15} $M_\odot$ halos

Density

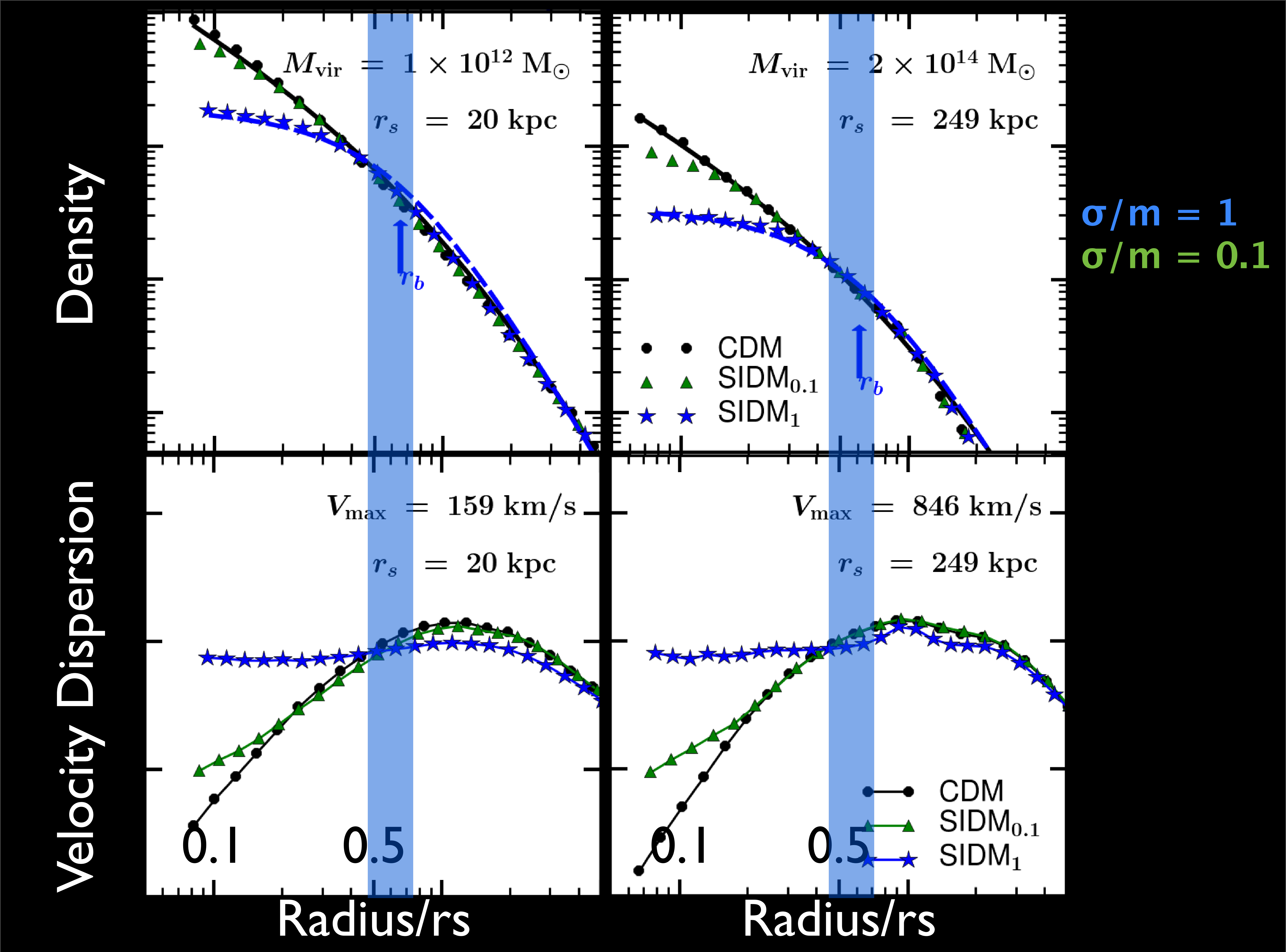


σ/m = 1
σ/m = 0.1

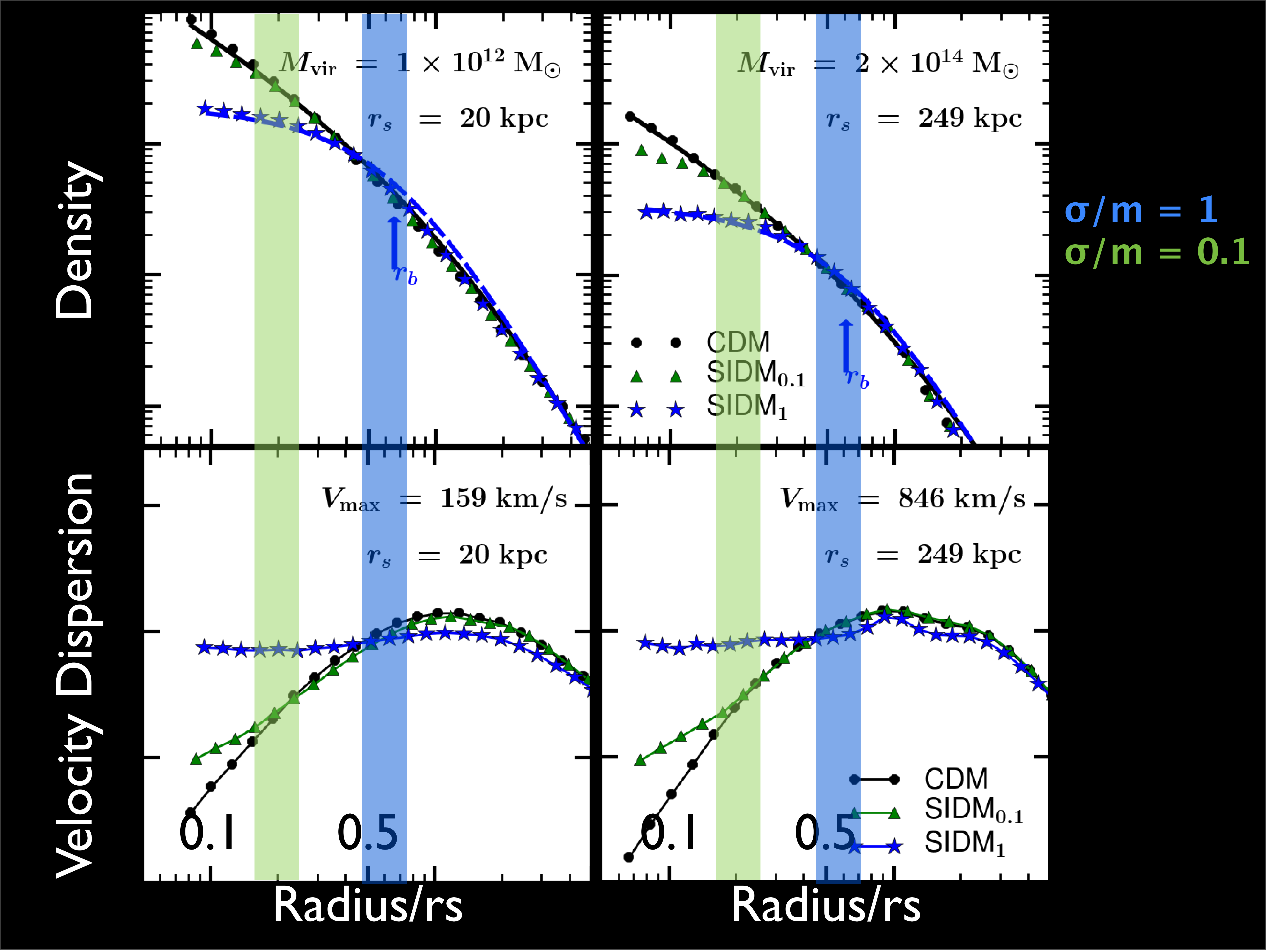
Radius/rs Radius/rs



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



Thursday, August 15, 13


Density
Velocity Dispersion
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$r_s = 20$ kpc
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$r_s = 249$ kpc
r_b
CDM
$SIDM_{0.1}$
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0.1
0.5
Radius/rs
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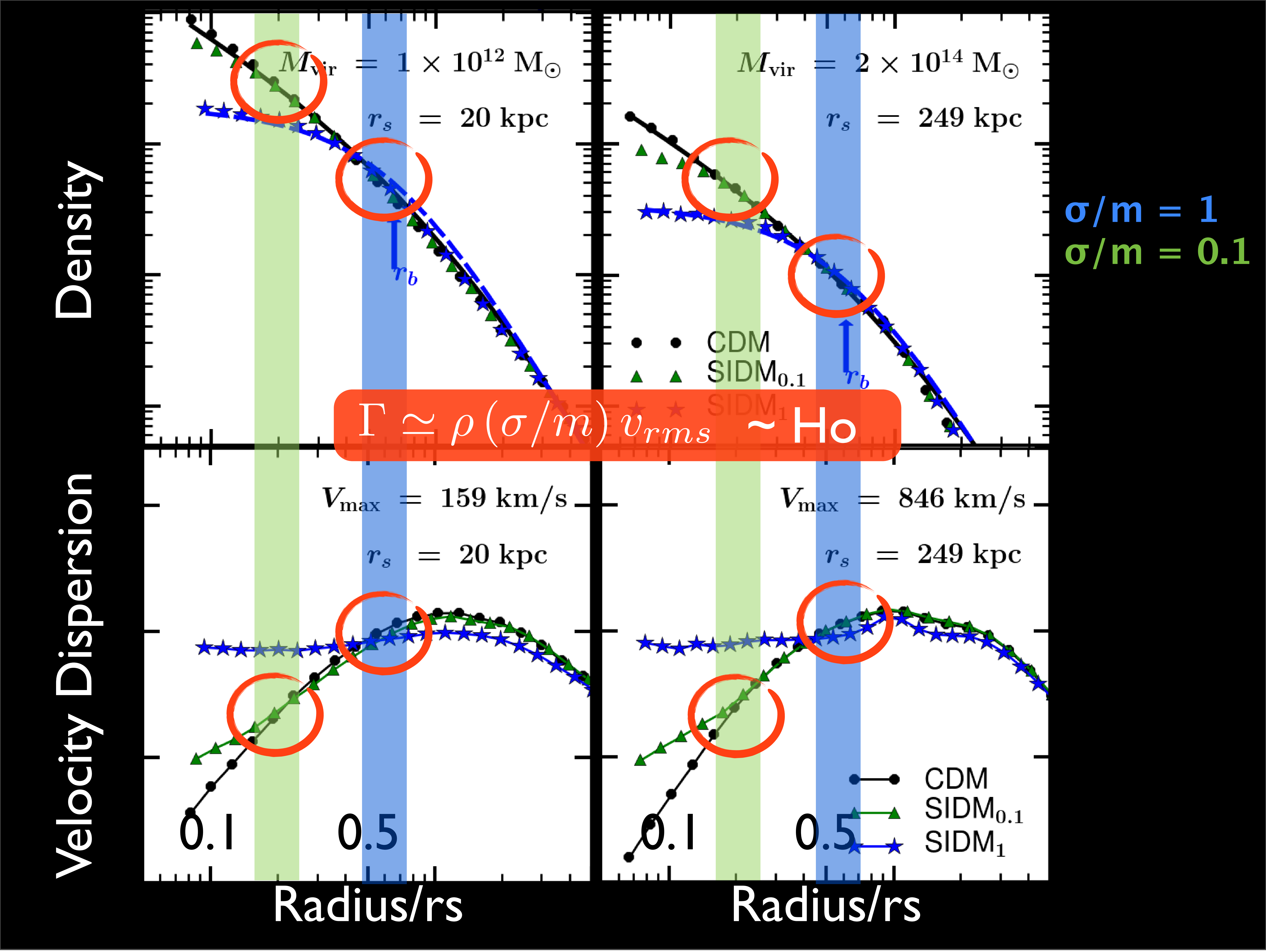
Density
Velocity Dispersion
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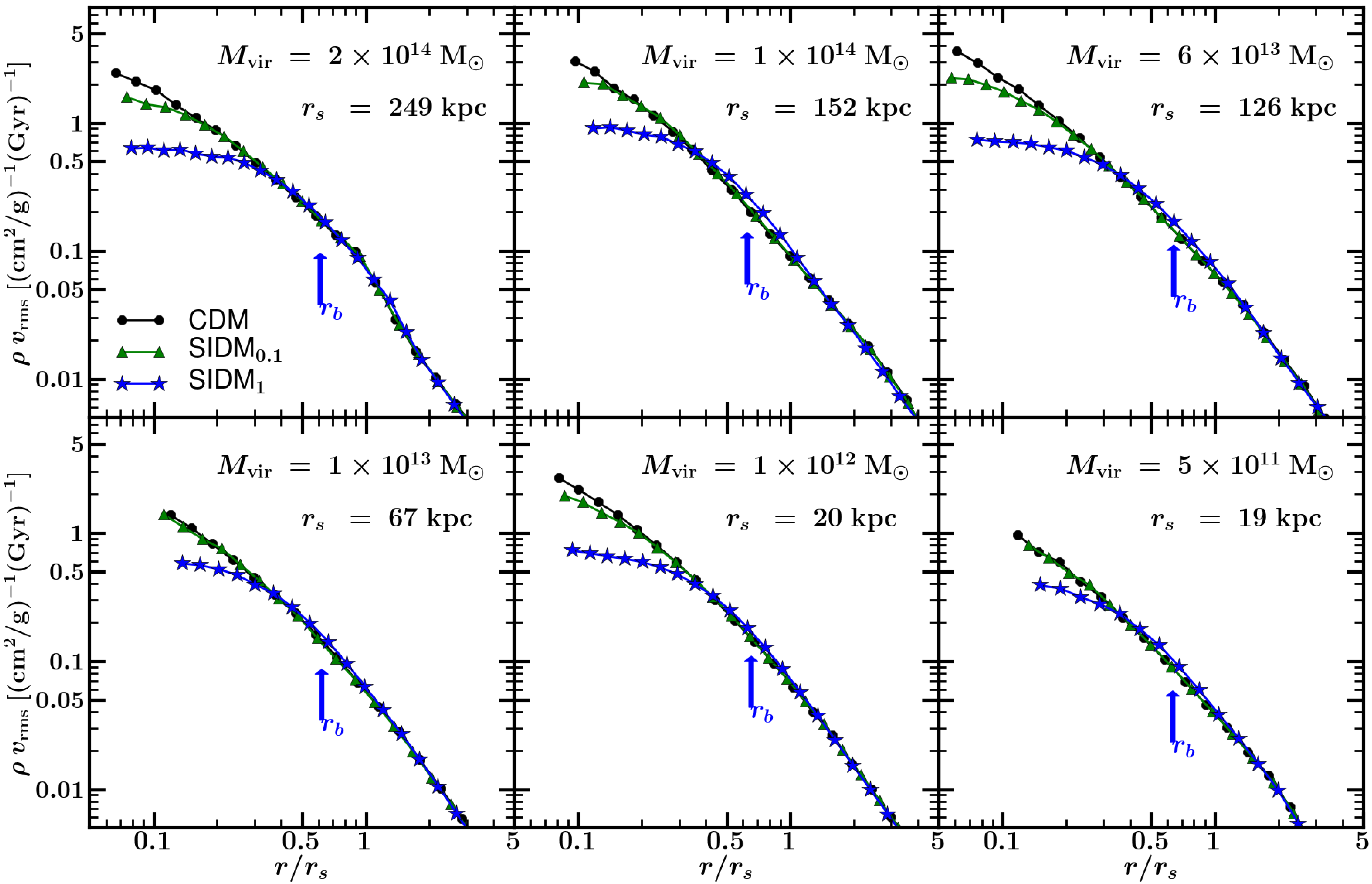
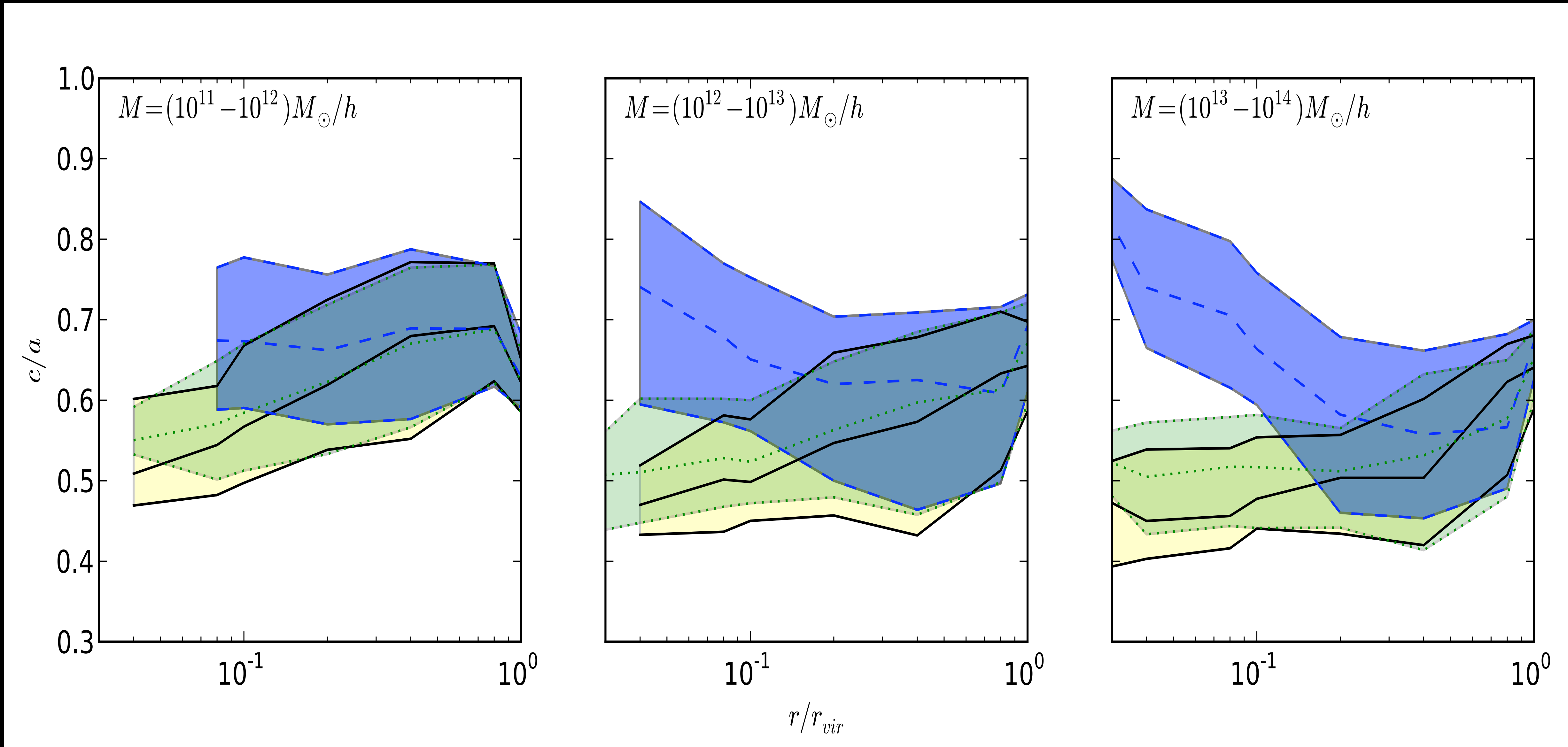
r_b
CDM
SIDM$_{0.1}$
SIDM$_1$
$\Gamma \simeq \rho\,(\sigma/m)\, v_{rms}$ ~ Ho
$V_{\rm max} = 159$ km/s
$r_s = 20$ kpc
$V_{\rm max} = 846$ km/s
$r_s = 249$ kpc
0.1
0.5
Radius/rs
σ/m = 1
σ/m = 0.1



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

Results from cosmological simulations - Halo shapes

More spherical →



Radius/rvir

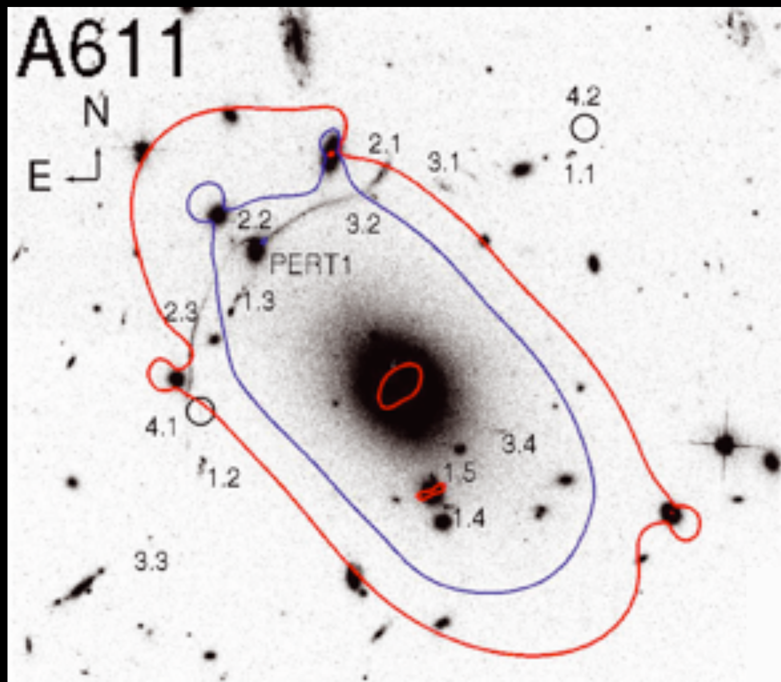
σ/m = 1 cm²/g

σ/m = 0.1 cm²/g

collisionless

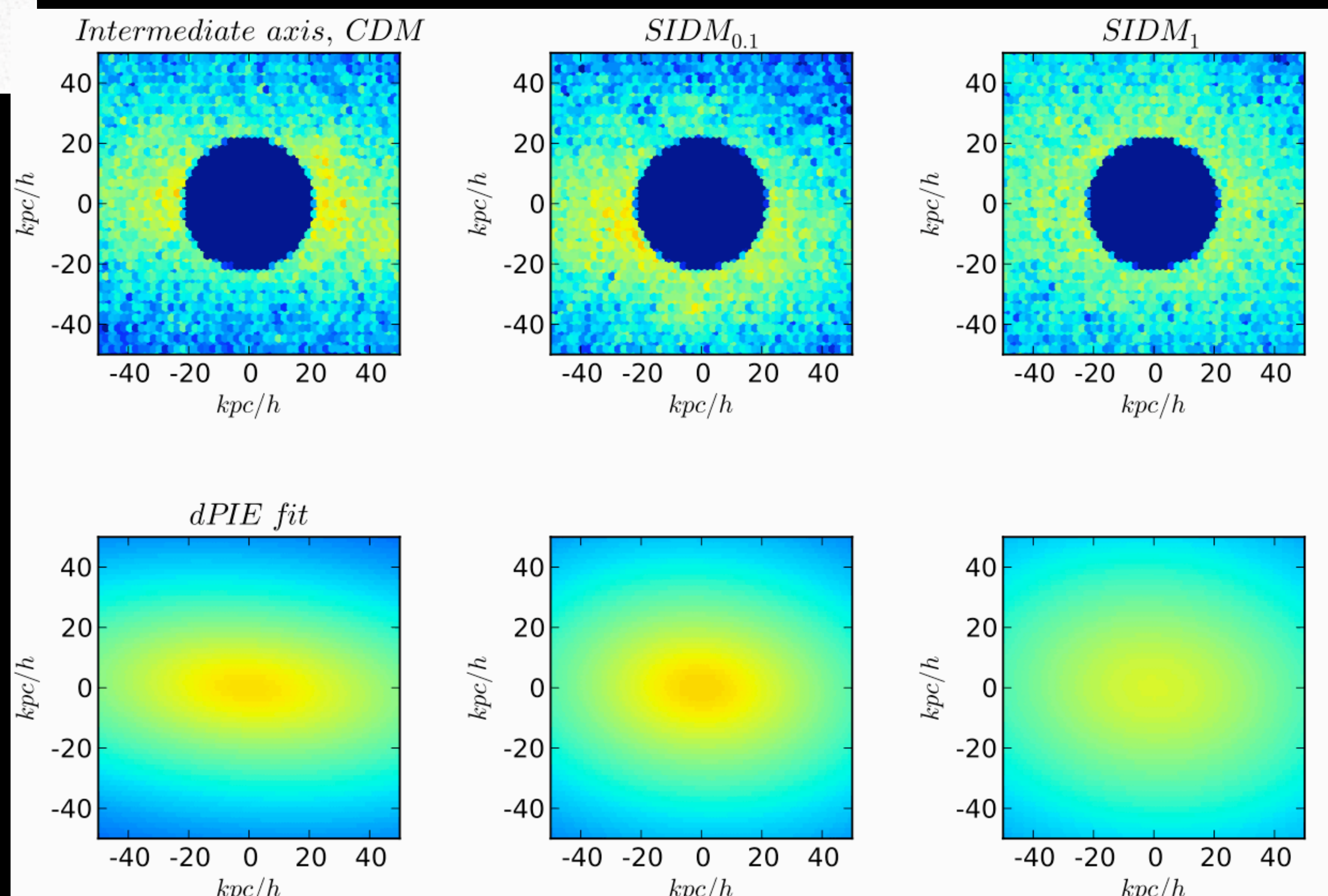
Rocha et al. 2013
Peter et al. 2013

Results from cosmological simulations - Halo shapes



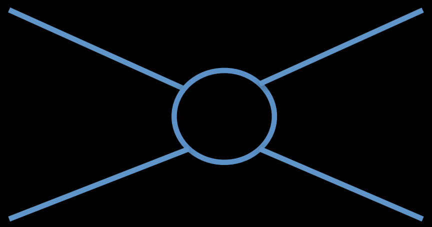
From LoCuSS sample
Richard+ 2010

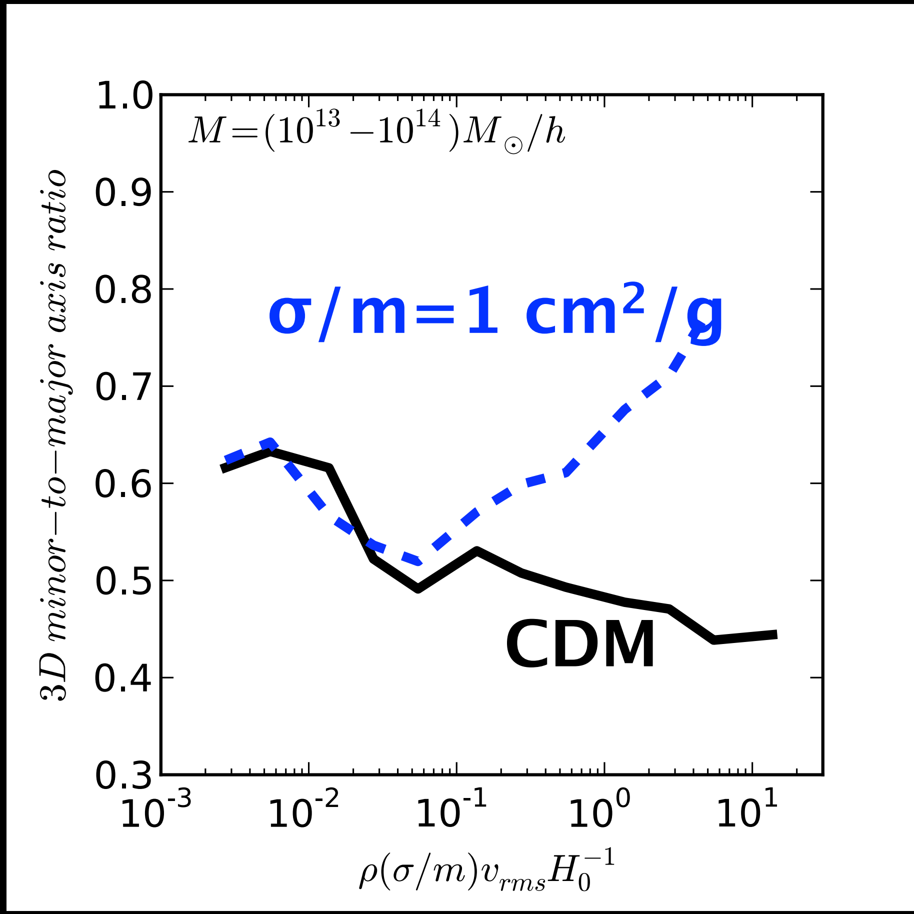
We see surface density (or gravitational potentials) in projection.



Rocha et al. 2013
Peter et al. 2013

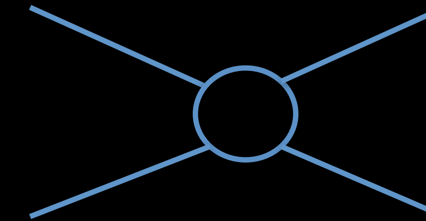
The problem with shapes

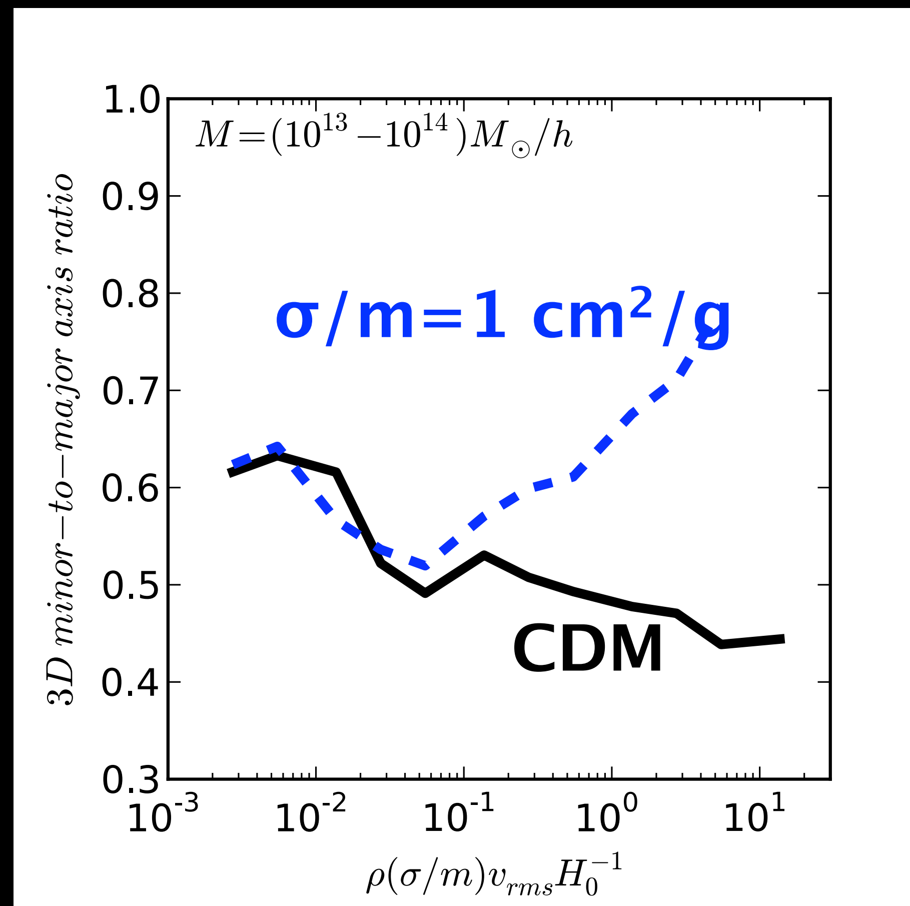




- We see surface density (or gravitational potentials) in projection.
- If inner parts have flattened density, outer parts have even greater weight.

The problem with shapes





$$\Gamma/H_0 \gg 10$$

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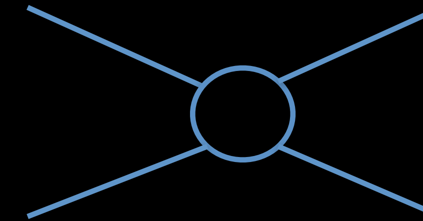

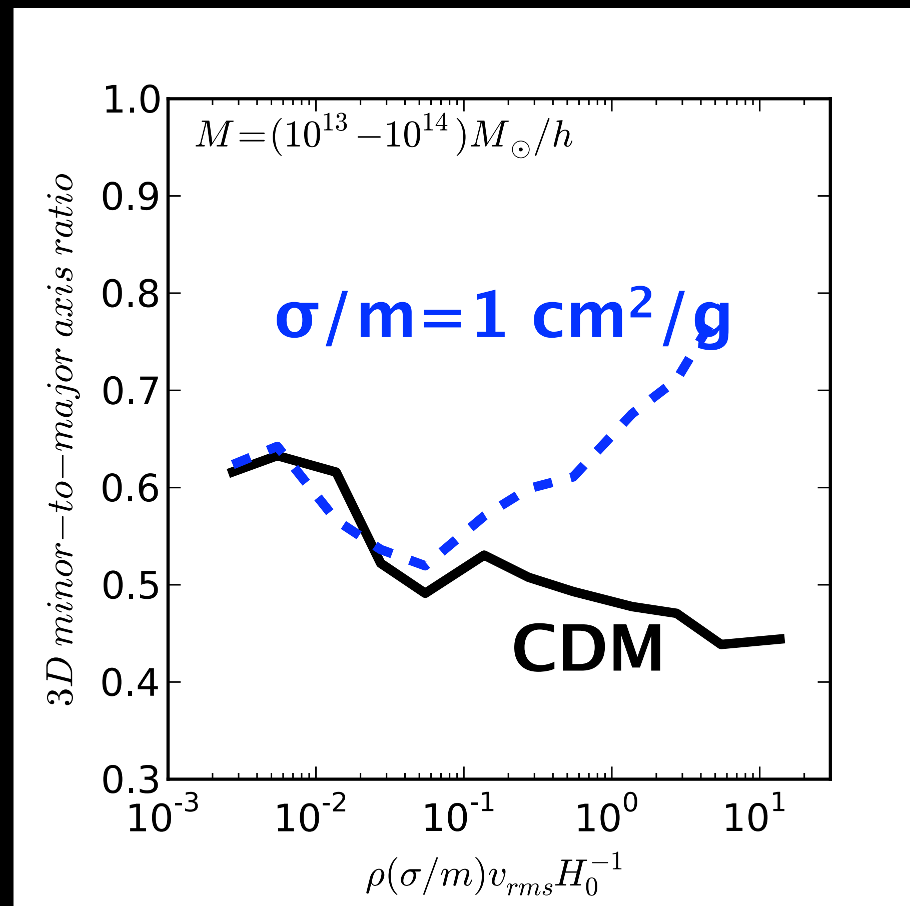

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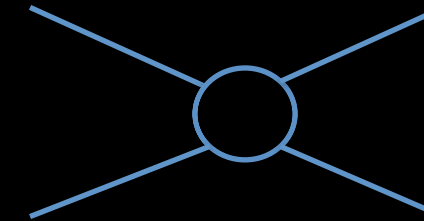

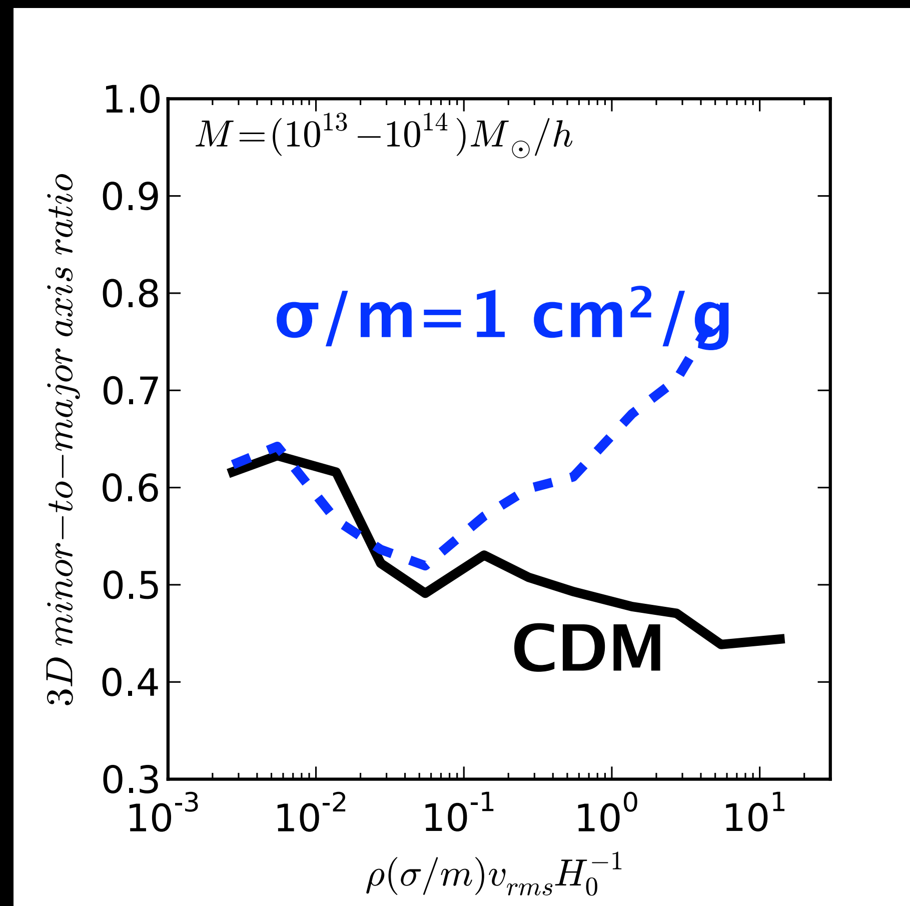

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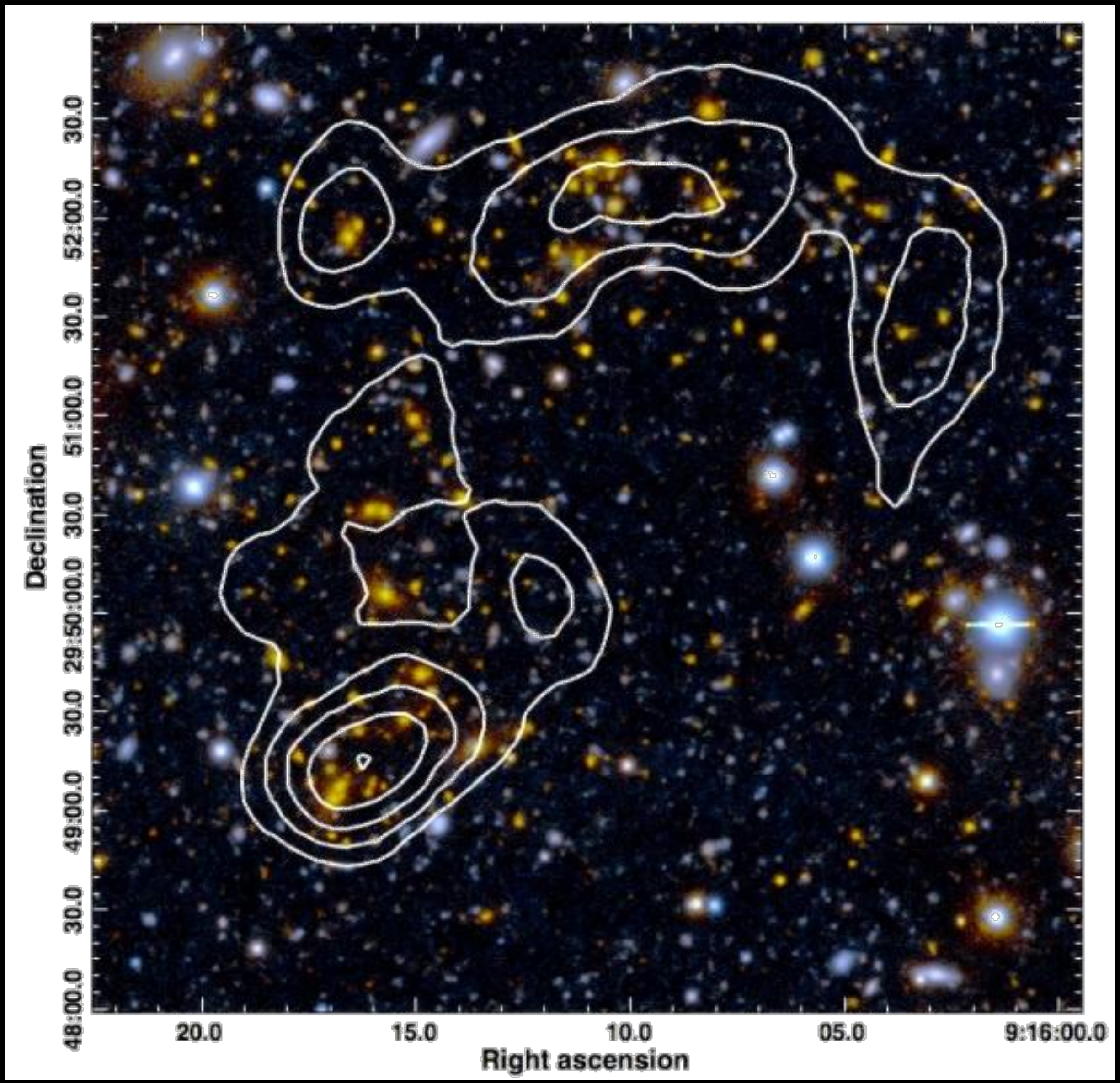
Work in progress - Merging clusters

Observations

The Musket Ball



Dawson et al. 2012

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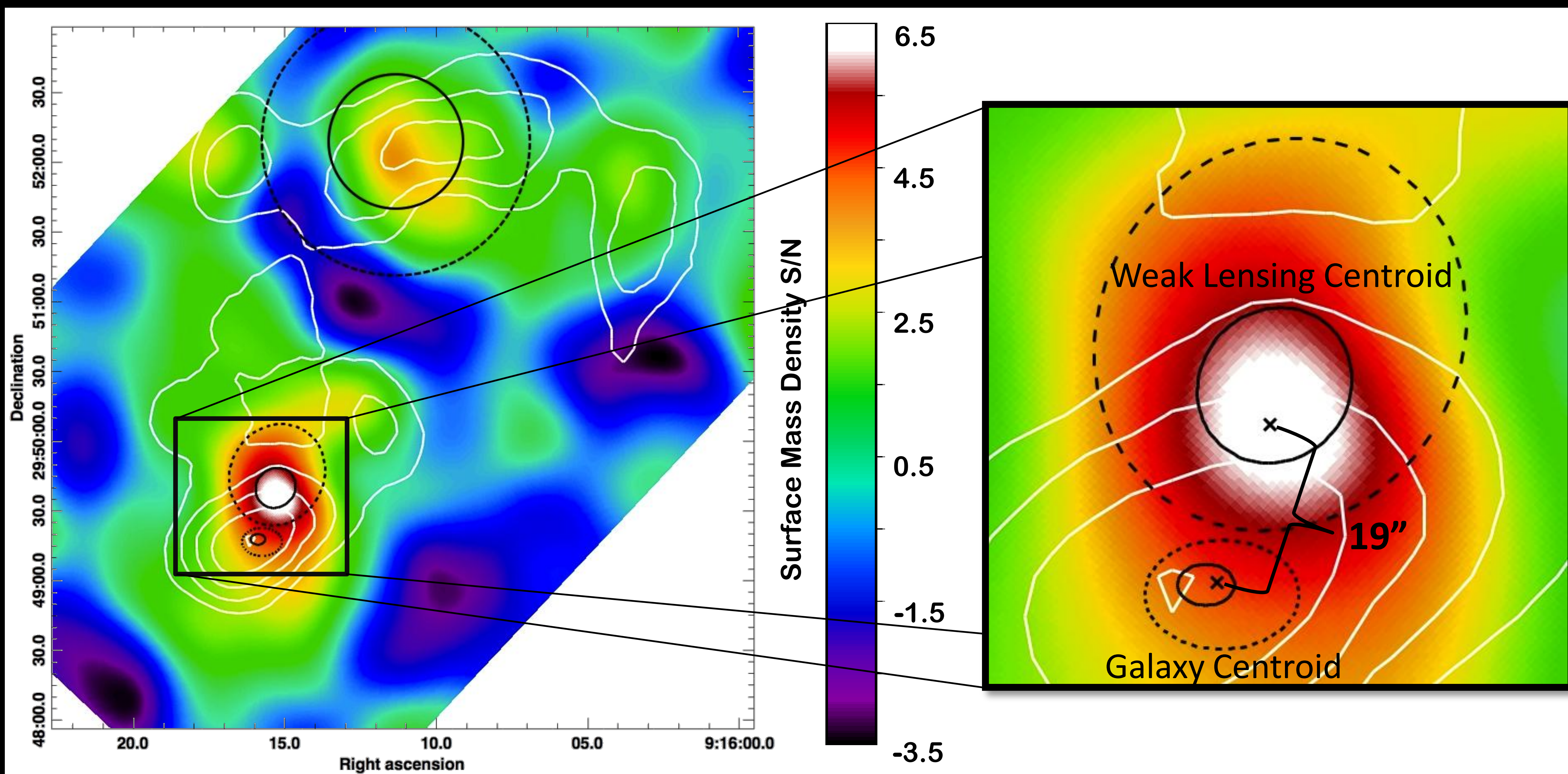
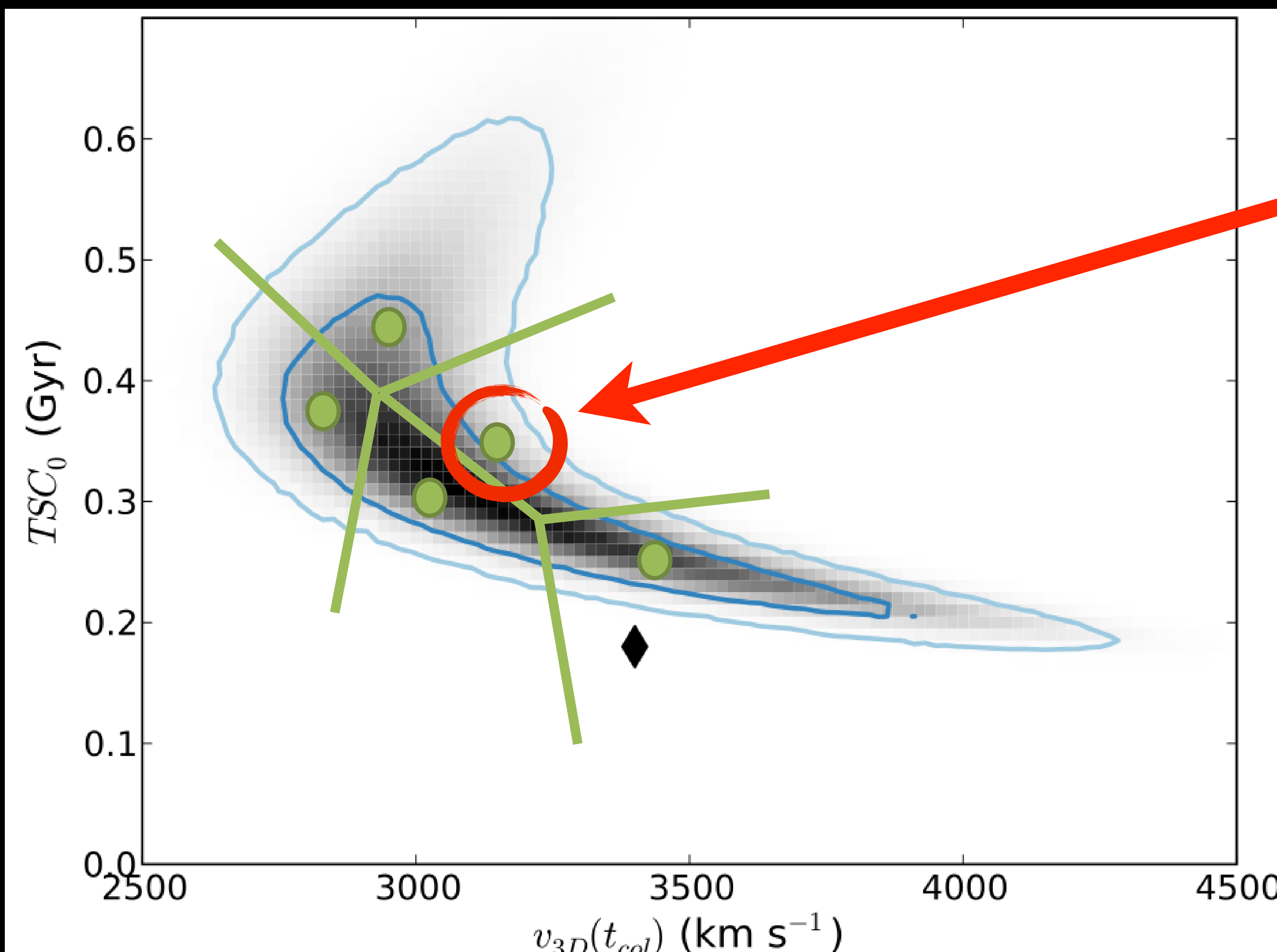


Dawson et al. 2012

Work in progress - Merging clusters

Predictions vs. Observations

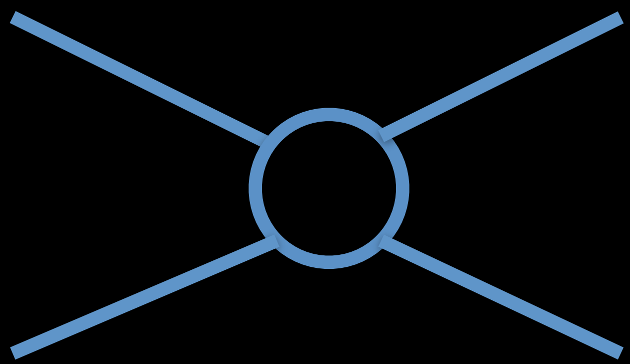
MERGING CLUSTER COLLABORATION



Zoom in simulations with hi-res and SIDM

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

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



Spergerl & Steinhardt 2000

Elastic - Velocity Independent - Isotropic

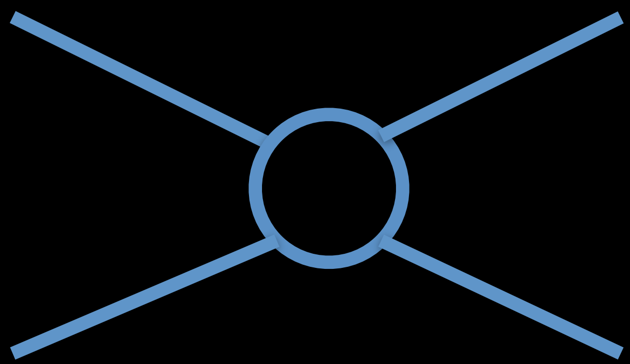
$$\Gamma = \rho \left(\frac{\sigma}{m} \right) v_{rel}$$

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

$$\frac{Df(\mathbf{x},\mathbf{v},t)}{Dt} = \Gamma[f,\sigma]$$

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

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

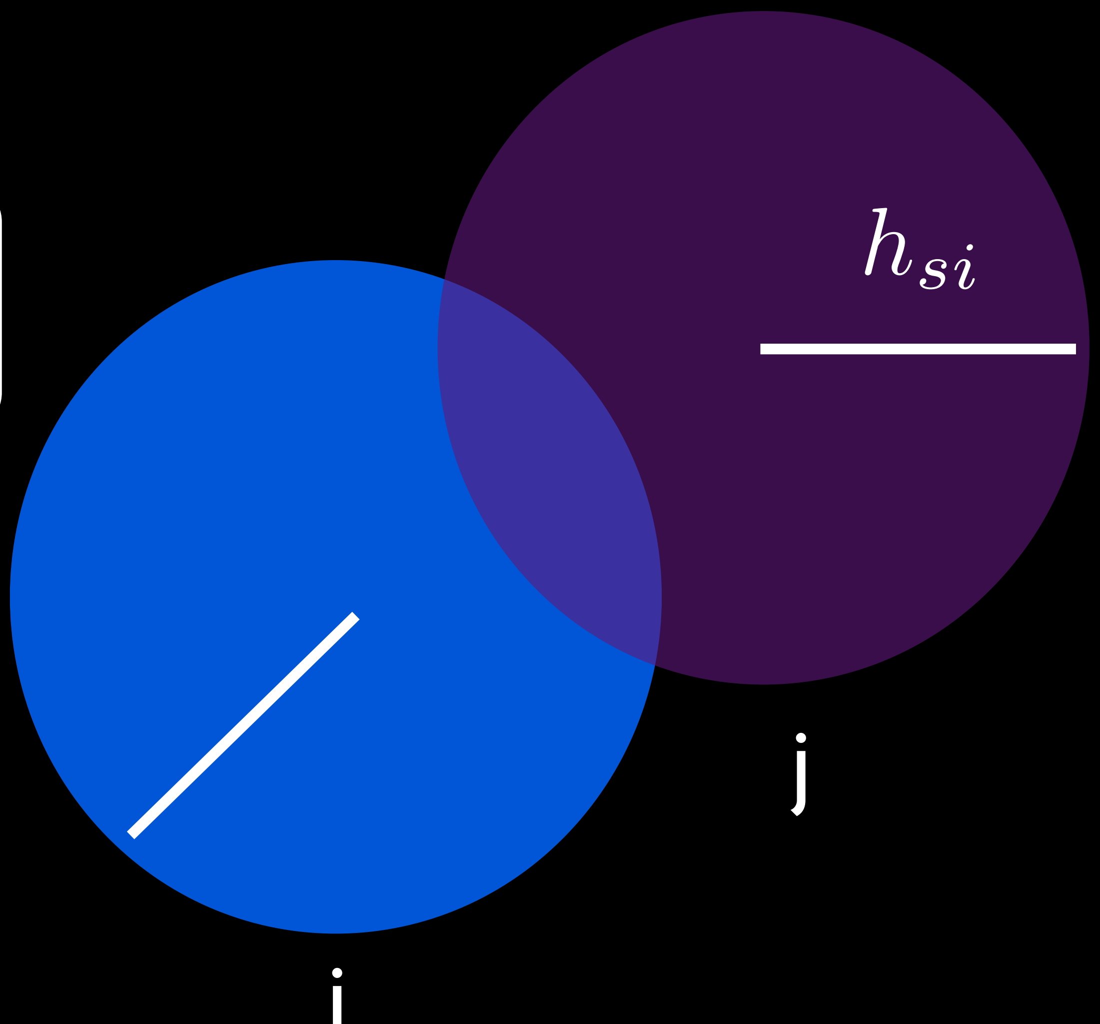
Consistent Pair-Wise Probability

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

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

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

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



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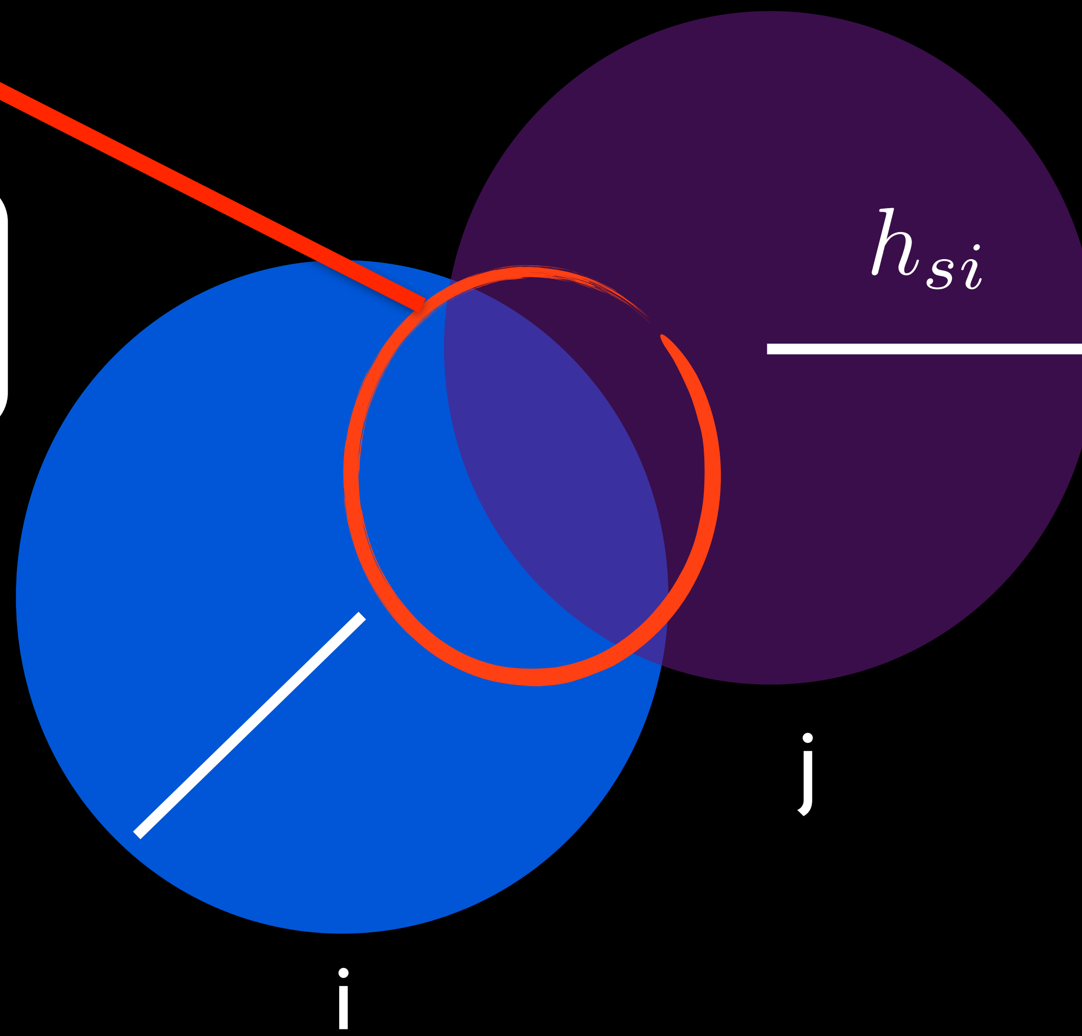
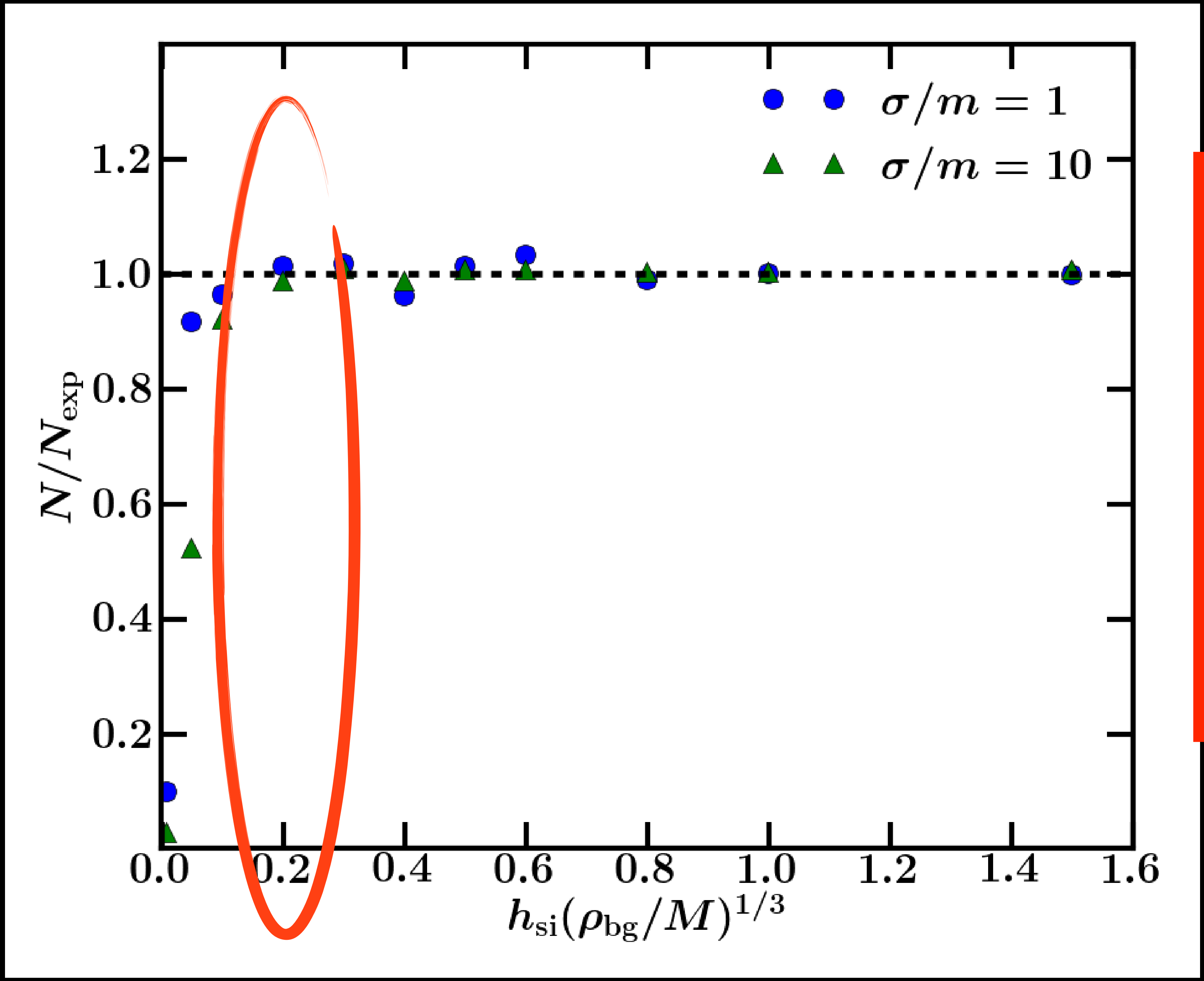


Simulating DM Self-Interactions - A new self-consistent algorithm

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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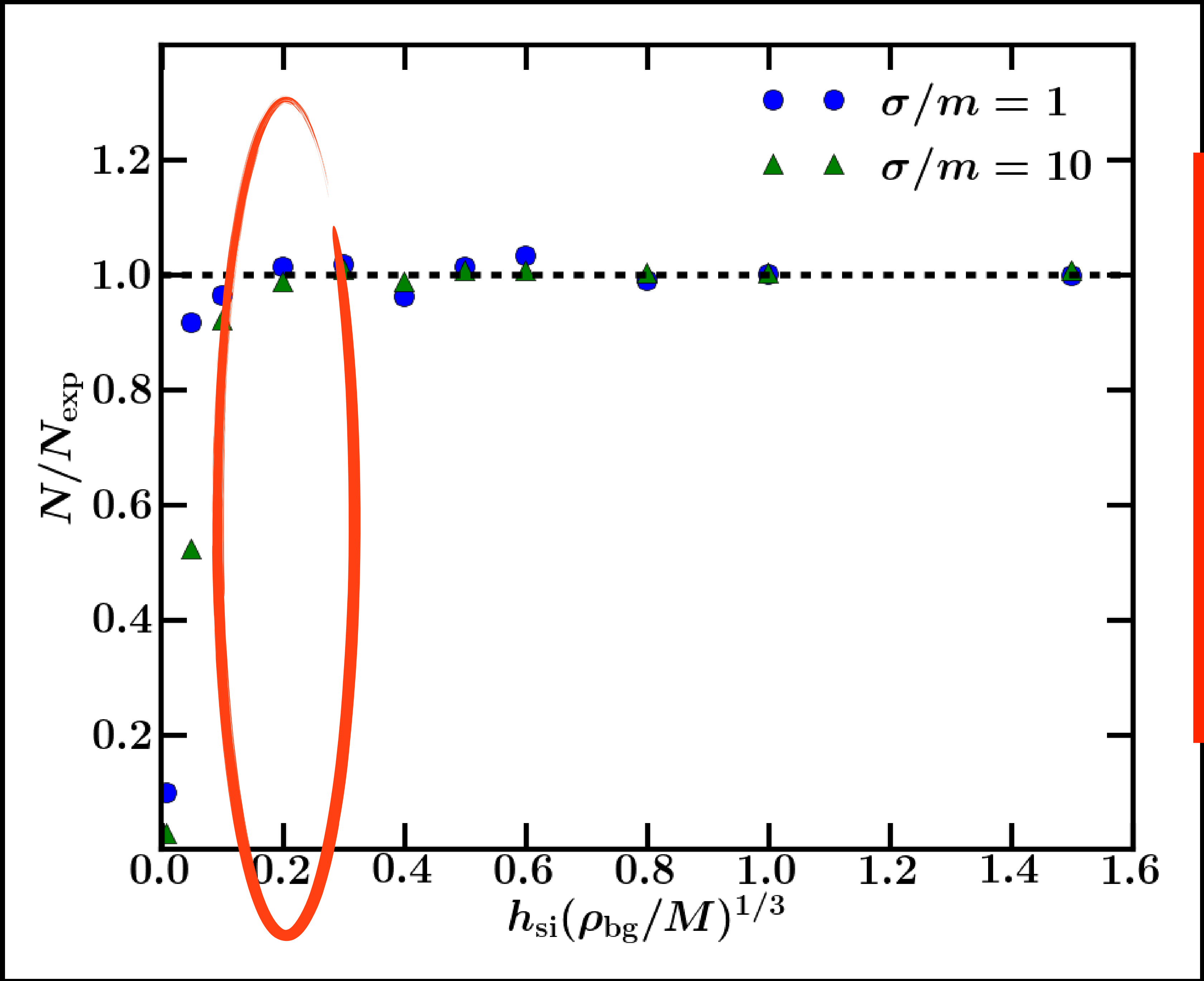

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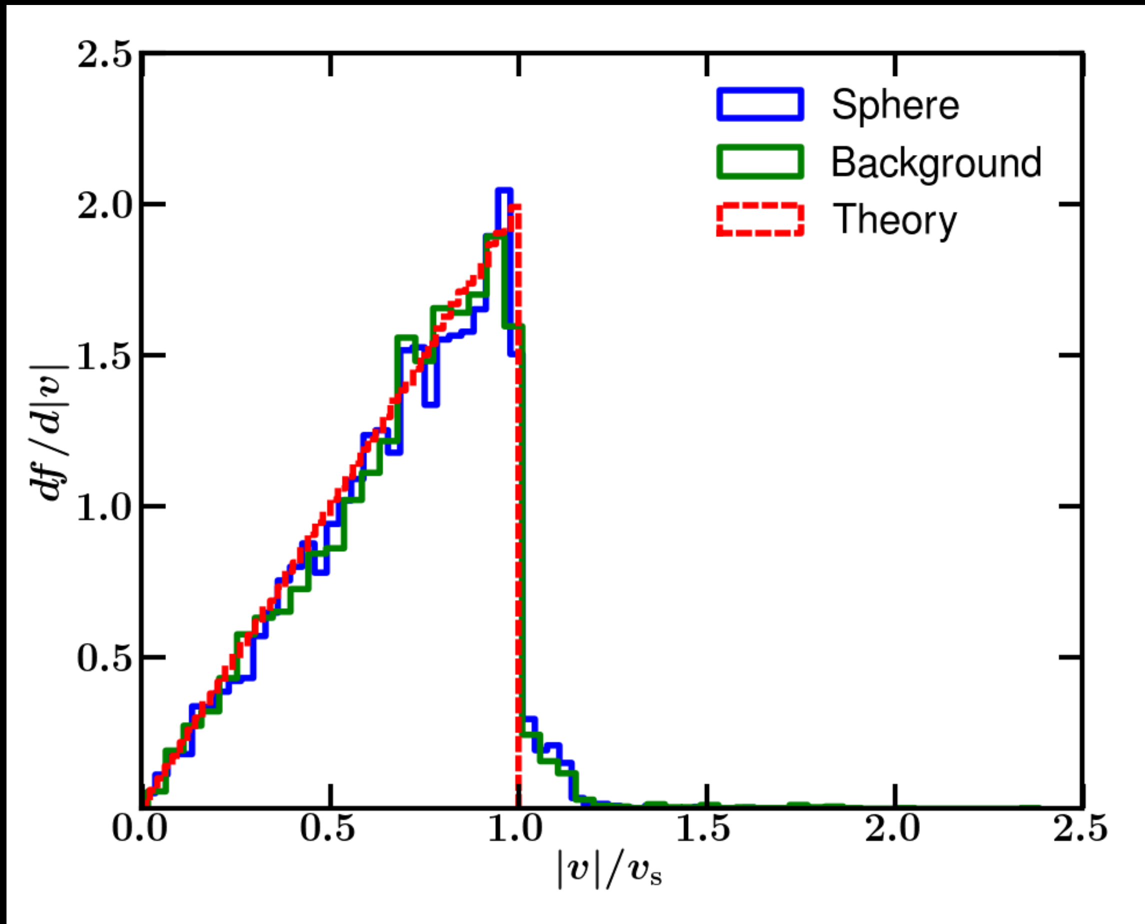

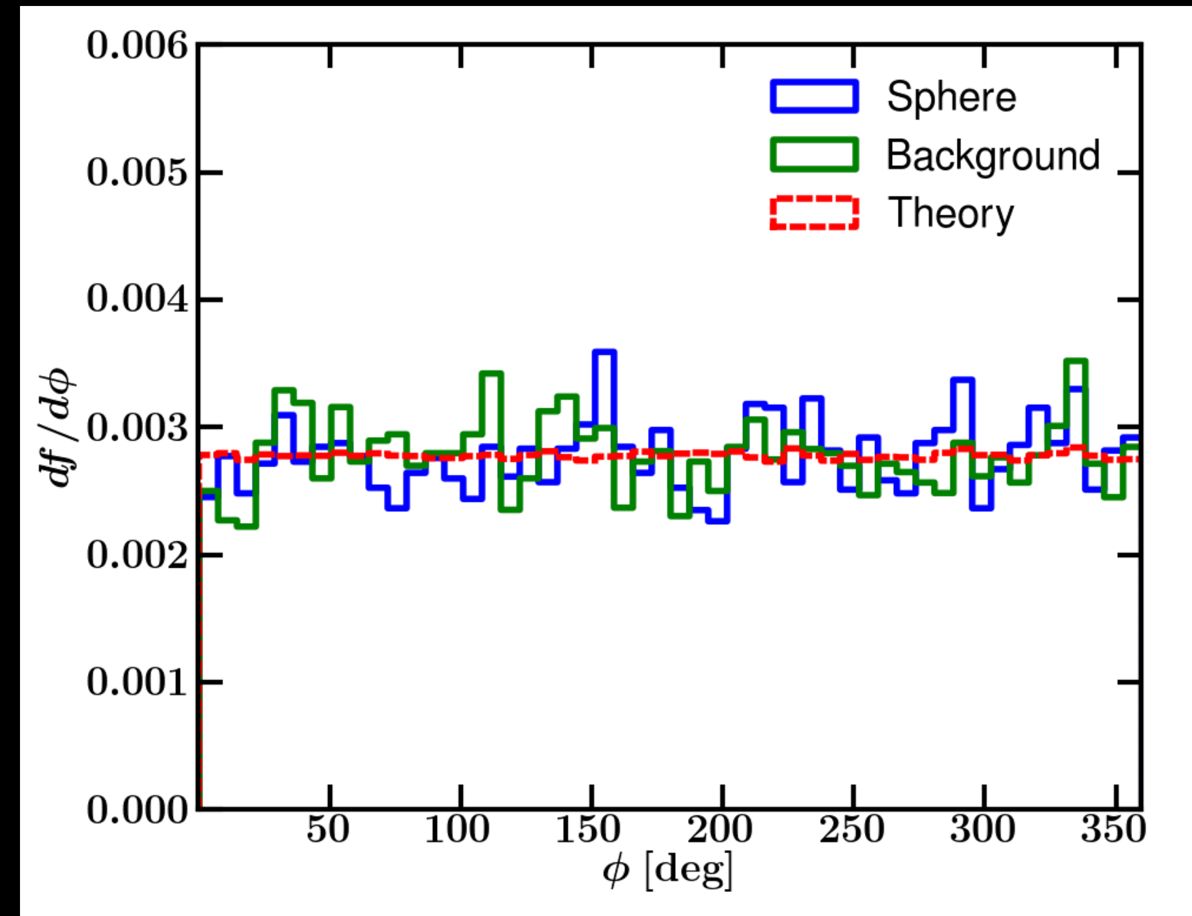

✓

Correct post-scatter kinematics