Self-Interacting Dark Matter & Structure Formation (II)

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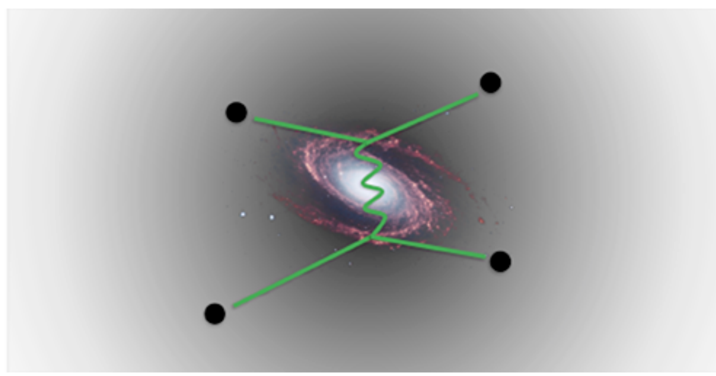
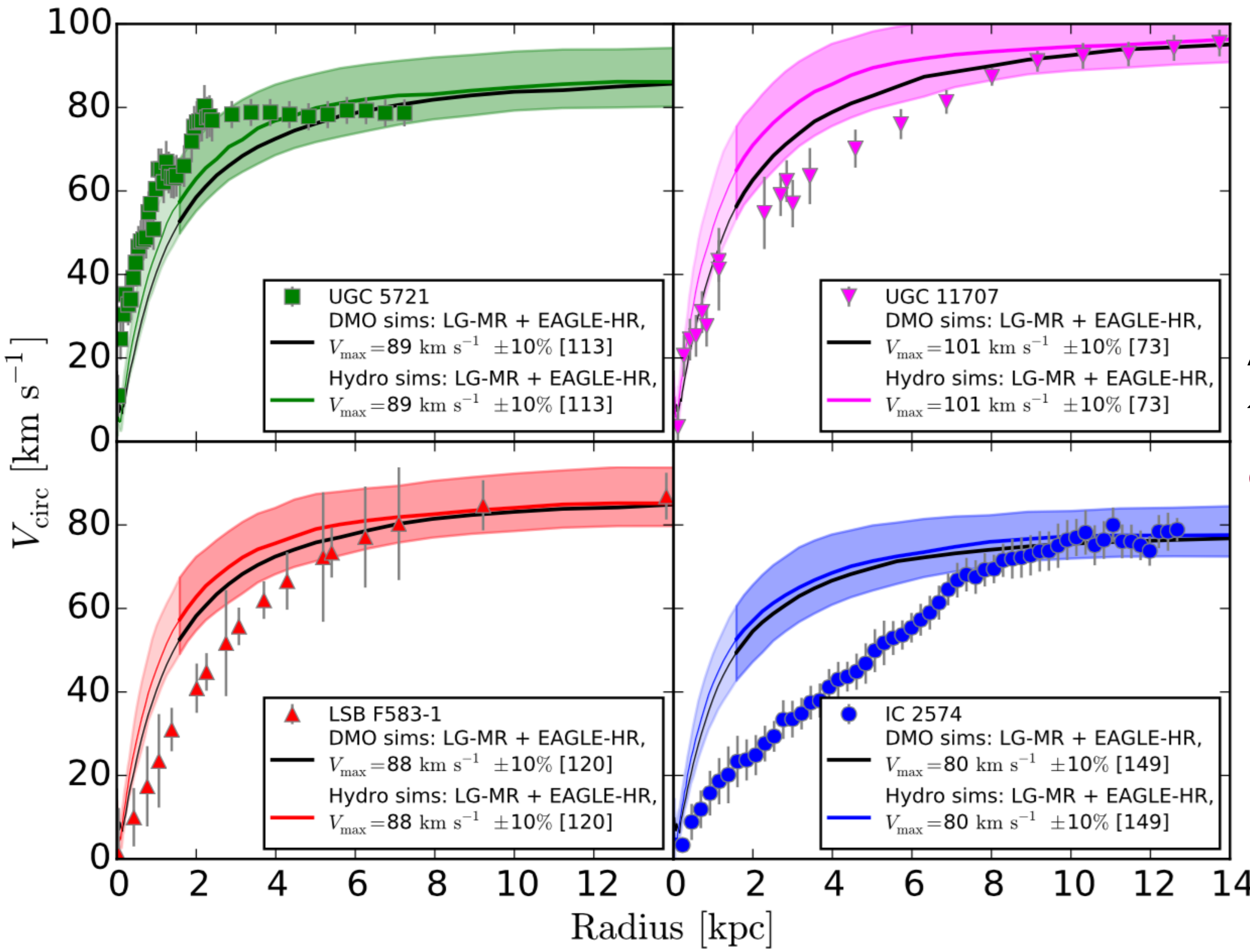


RESCEU Summer School, July 27-30, 2018

Review for Physics Reports: Tulin & HBY (2017)

The Diversity Problem



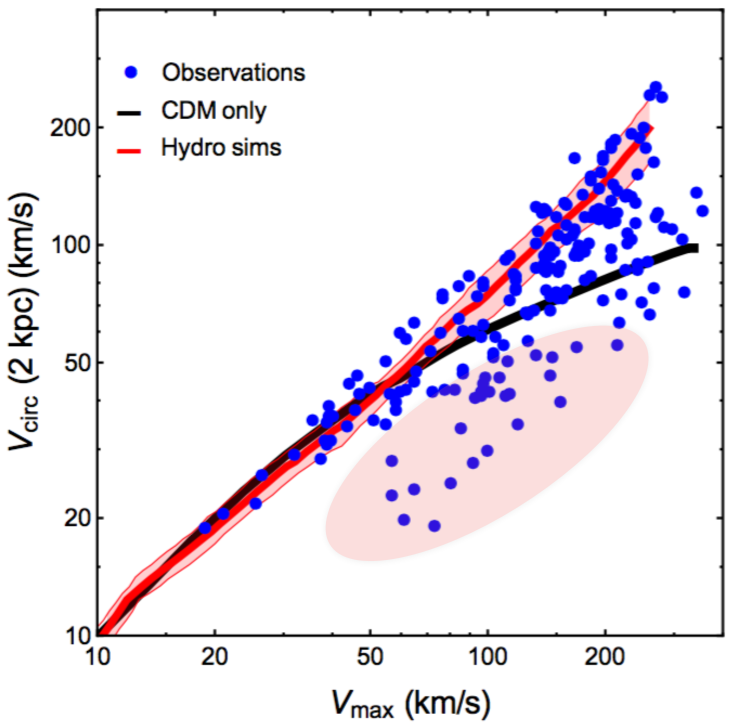
All galaxies have the same observed Vmax!

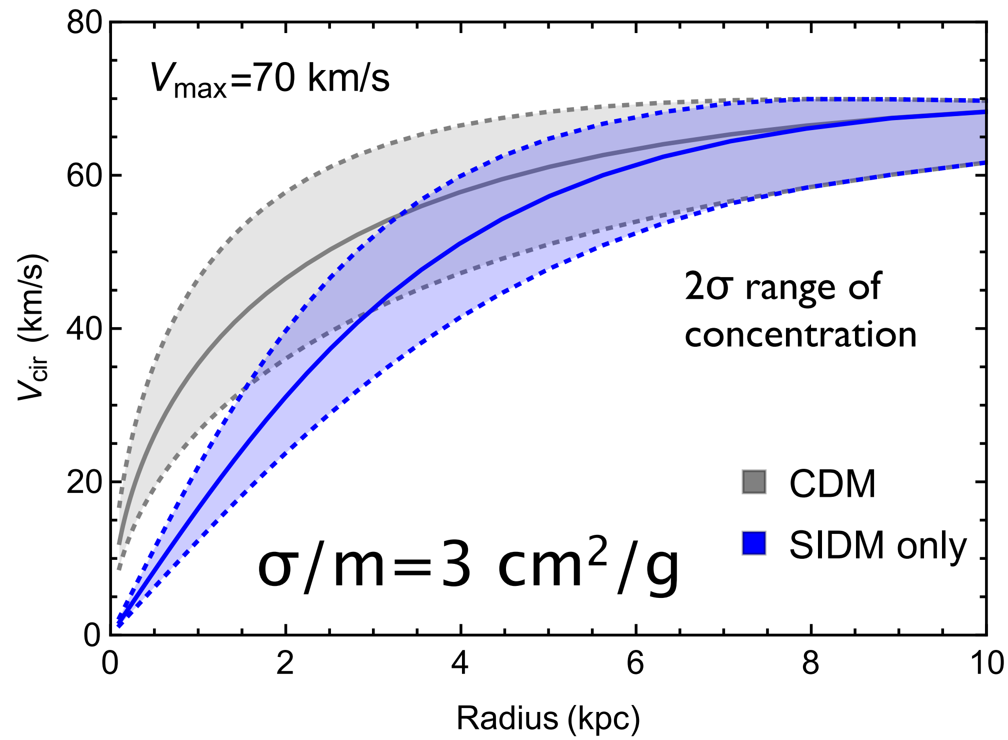
Oman et al. (2015)

Colored bands: hydrodynamical simulations of ΛCDM

Addressing the Diversity Problem

- DM self-interactions thermalize the inner halo





DM-dominated galaxies: Lower the central density and the circular velocity

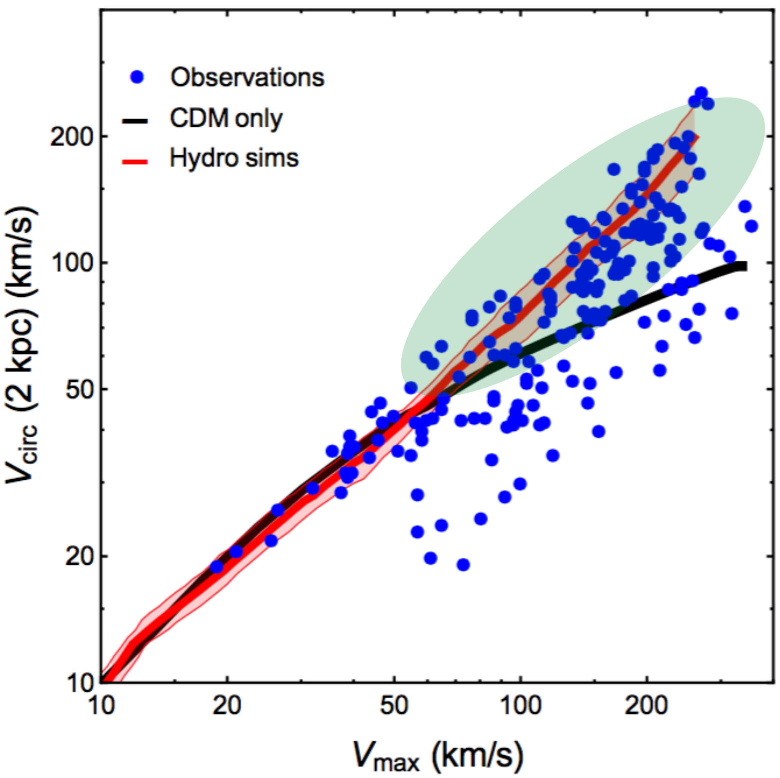
Isothermal distribution

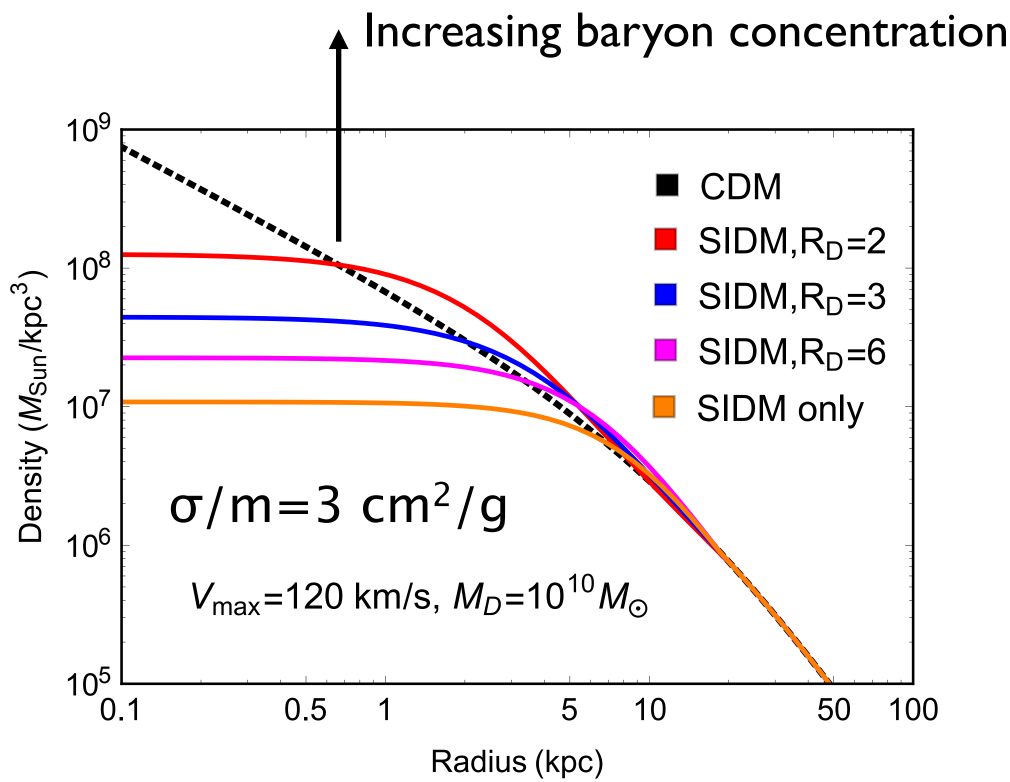
$$\rho_X \sim e^{-\Phi_{\rm tot}/\sigma_0^2} \sim e^{-\Phi_X/\sigma_0^2}$$

with Kamada, Kaplinghat, Pace (PRL 2016)

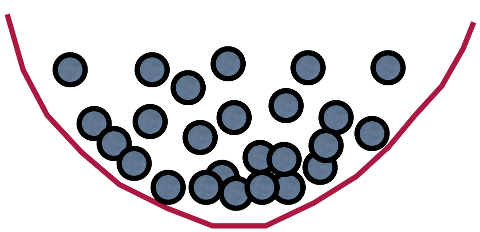
Addressing the Diversity Problem

- DM self-interactions tie DM together with baryons





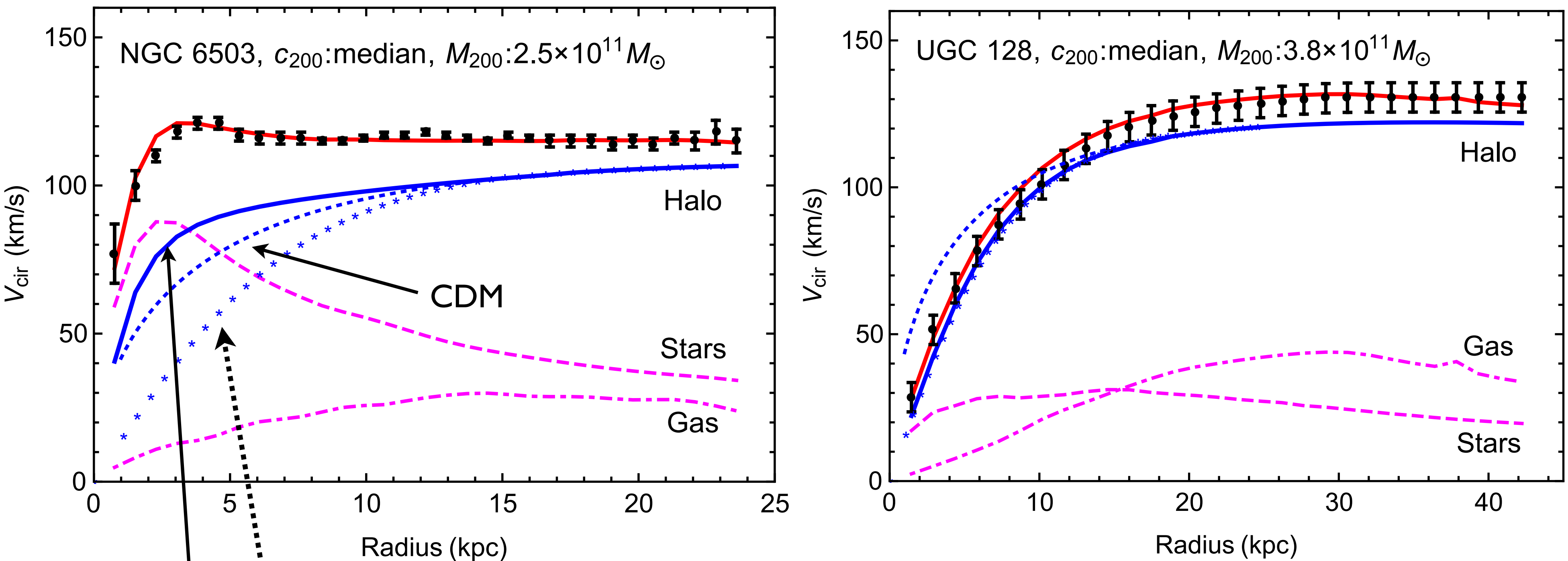
Thermalization leads to higher DM density due to the baryonic influence



$$\rho_X \sim e^{-\Phi_{\rm tot}/\sigma_0^2} \sim e^{-\Phi_{\rm B}/\sigma_0^2}$$

with Kamada, Kaplinghat, Pace (PRL 2016)

Solving the Diversity Problem



Isothermal profile without the baryonic influence

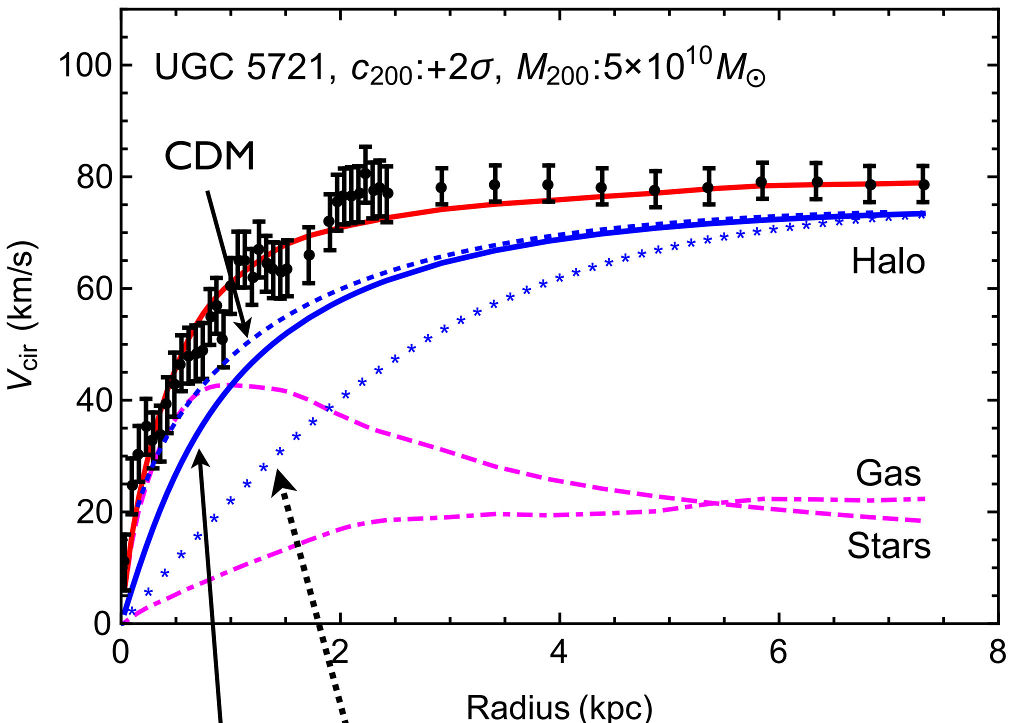
True SIDM profile with the baryonic influence

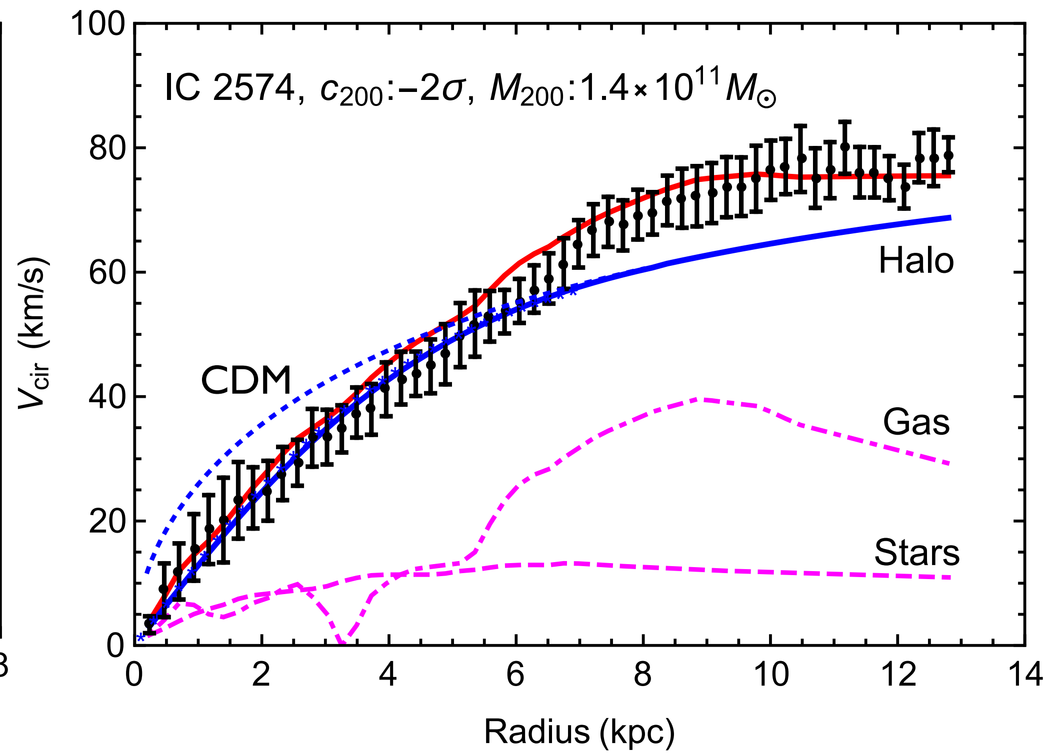
Different baryon distributions, thermalization links DM to baryon distributions

High surface brightness galaxies (NGC 6503): small and dense core
Low surface brightness galaxies (UGC 128): large and shallow core

30 galaxies V_{max}~25-300 km/s with Kamada, Kaplinghat, Pace (PRL, 2016)

Solving the Diversity Problem



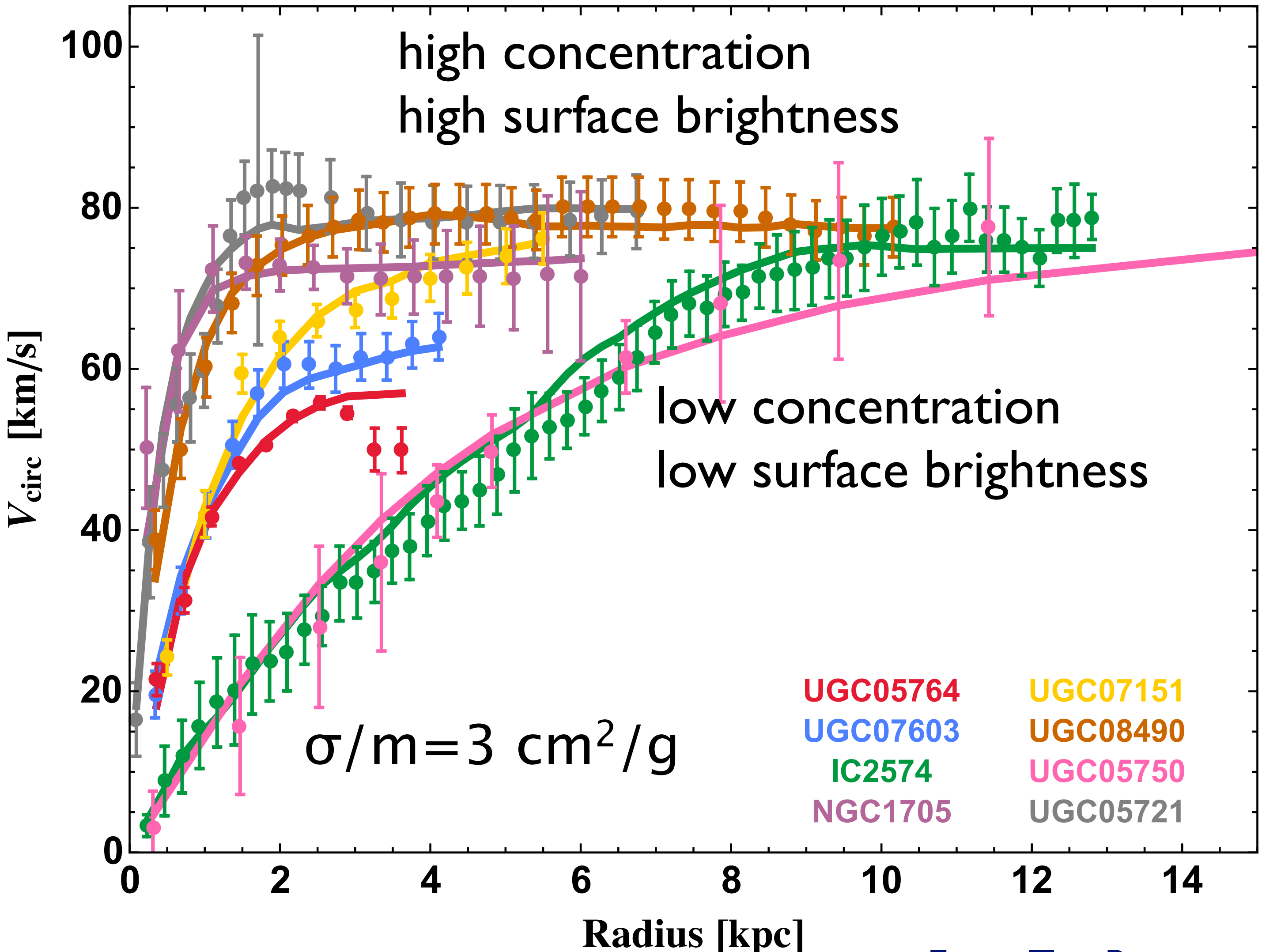


Isothermal profile without the baryonic influence

True SIDM profile with the baryonic influence

Scatter in the halo concentration-mass relation

with Kamada, Kaplinghat, Pace (PRL, 2016)

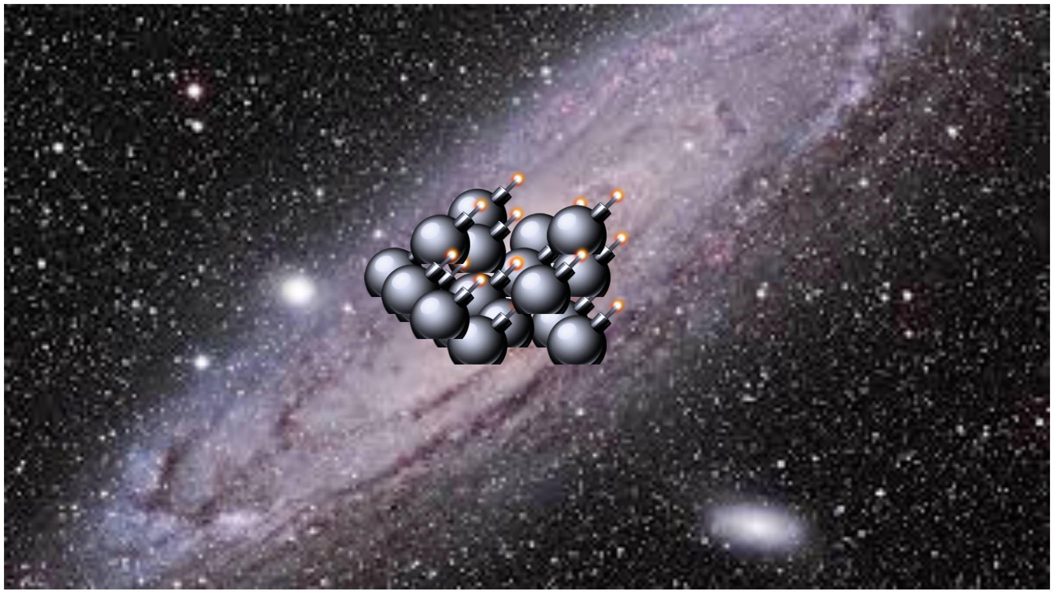


From Tao Ren

- Scatter in the halo concentration-mass relation (~2σ)
- Baryon distribution
- SIDM thermalization ties DM and baryon distributions

Isolated N-body simulations: with Creasey, Sameie, Sales et al. (MNRAS 2016)

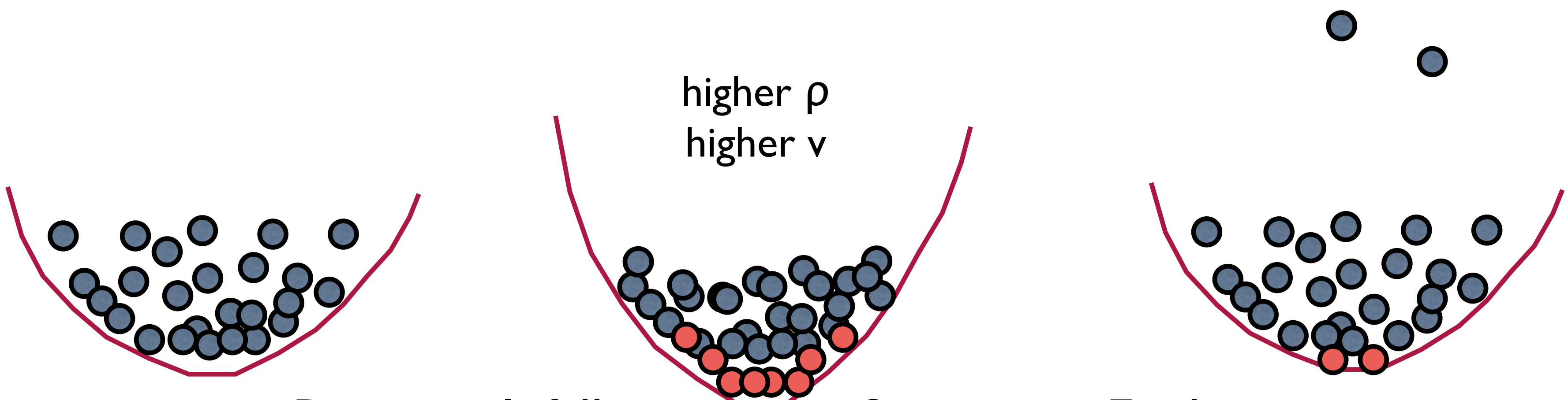
Baryonic Feedback



gas density threshold

weak/smooth feedback:
0.1-1 atoms/cm^3
no cores

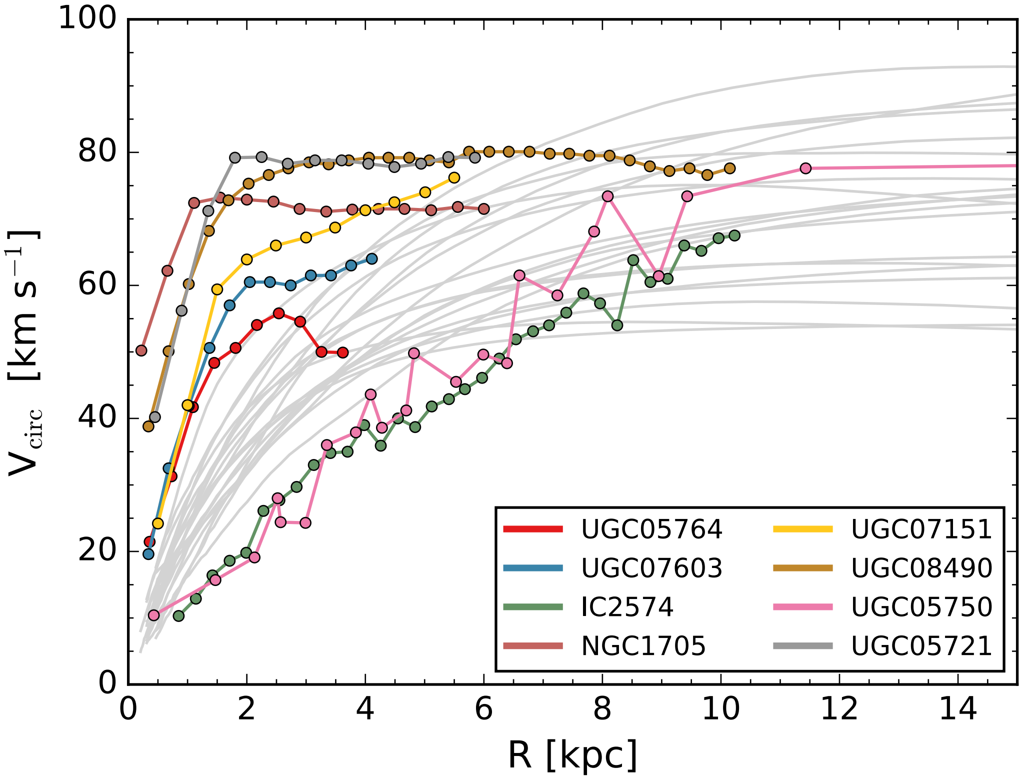
Strong/violent feedback:
100-1000 atoms/cm^3
~1kpc cores



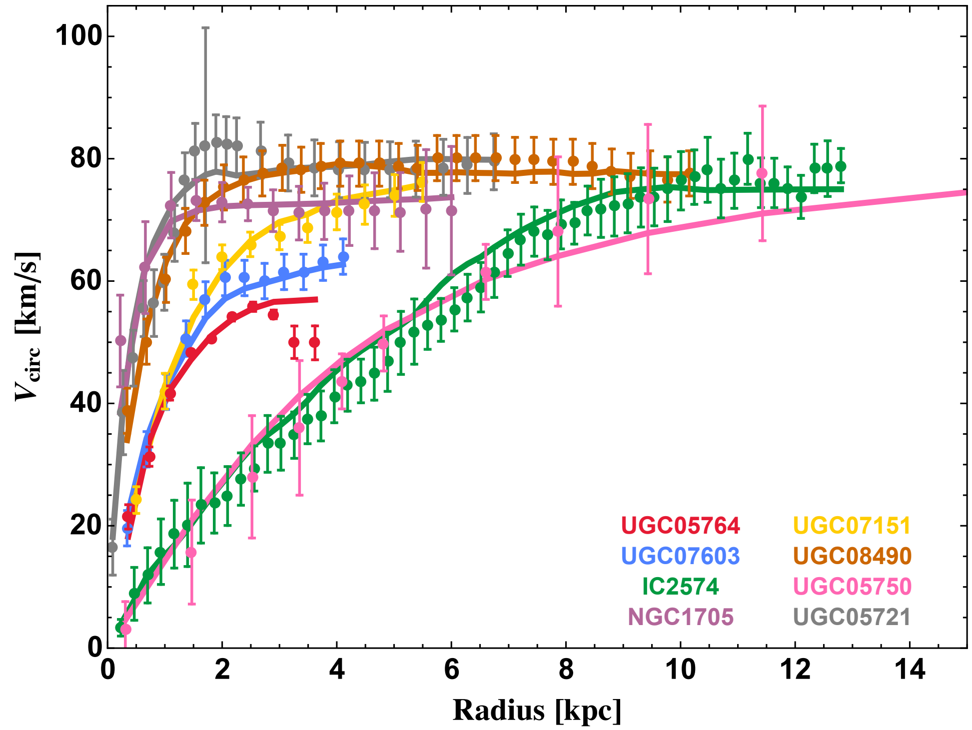
Baryonic Infall   Supernova Explosion

Navarro, Eke, Frenk (1996)

Strong Feedback vs SIDM



Santos-Santos et al. (2017)



From Tao Ren

Gray: NIHAO CDM simulations

"strong/violent" feedback

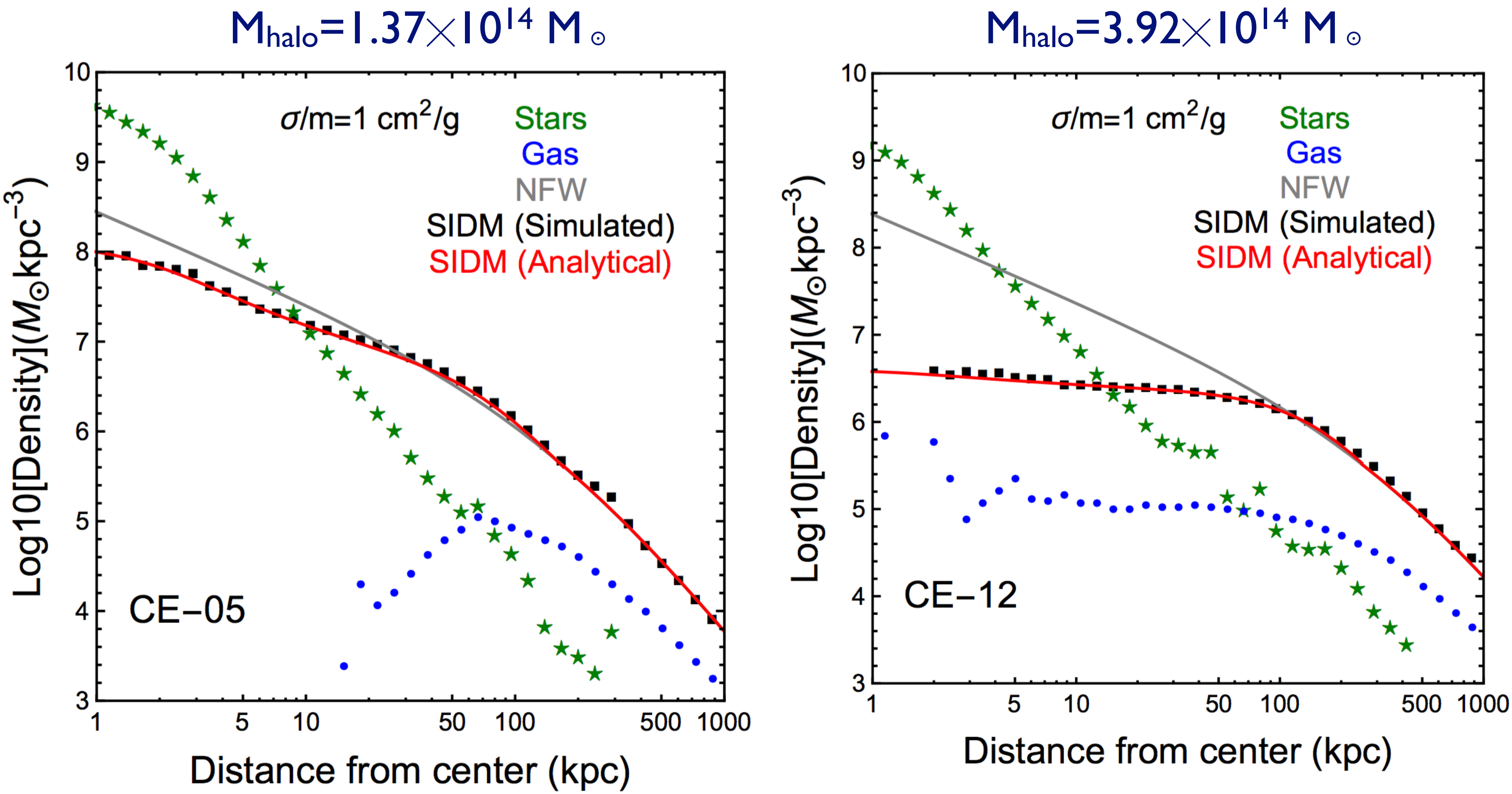
Observed scatter: ~4 (3σ away)

Simulations: ~2

Solid lines: SIDM fits

(~2σ in the c_{200}-M_{200} relation)

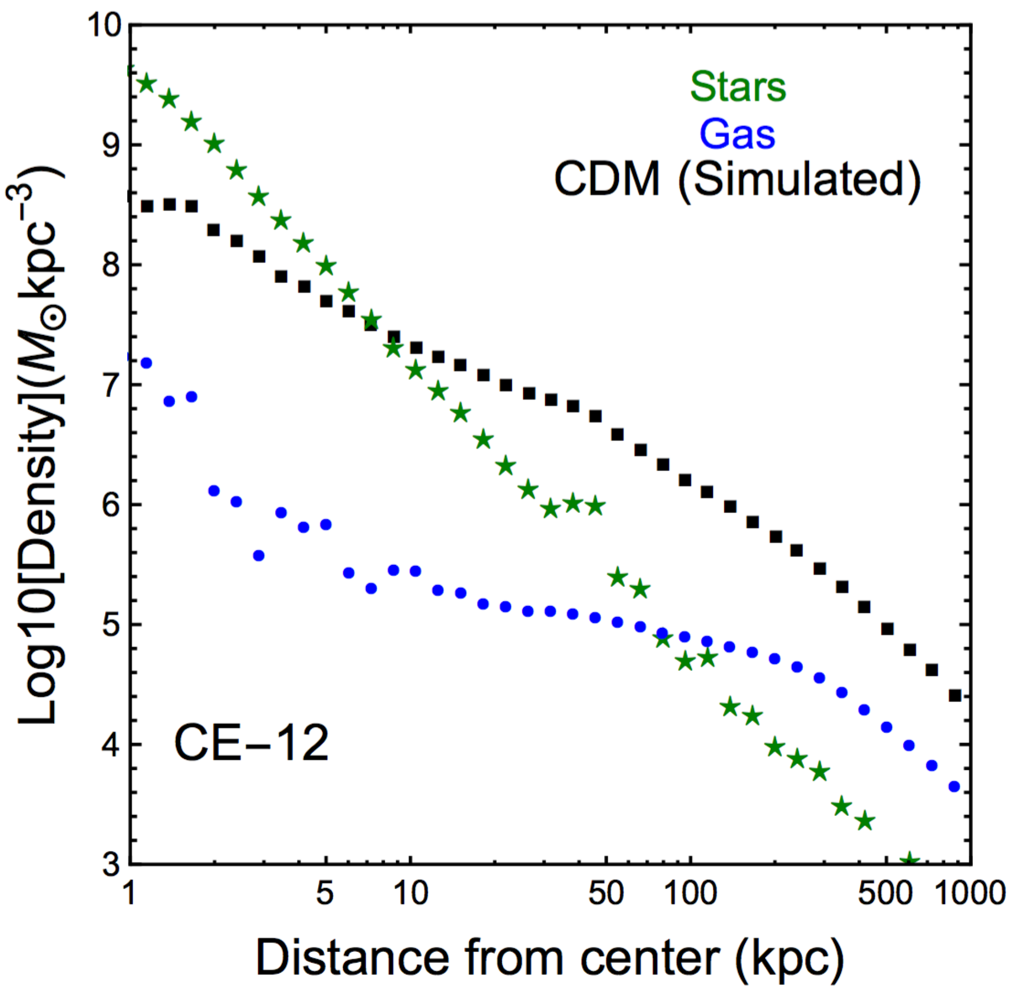
Hydro SIDM Simulations

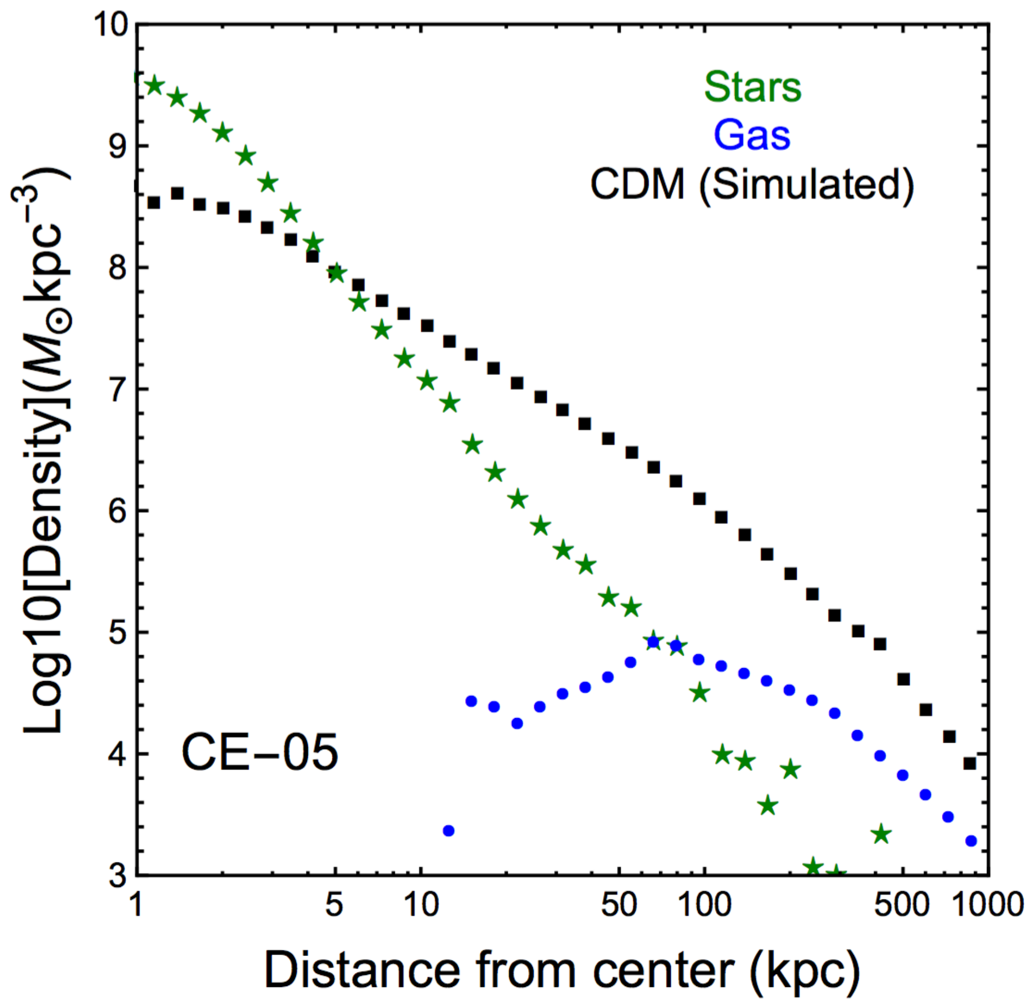


With Robertson, Massey, Eke, Tulin, et al. (MNRAS Letters, 2017)

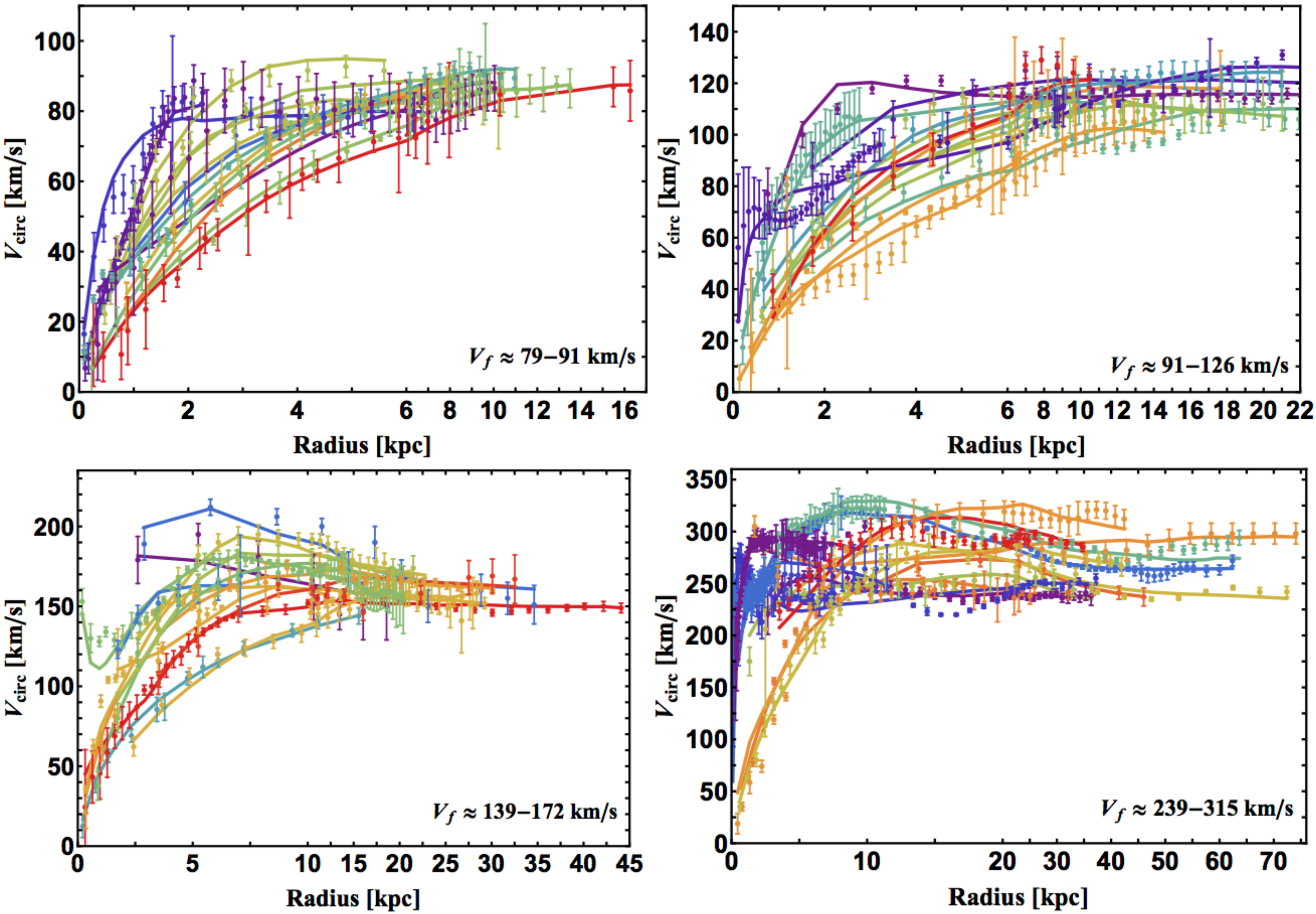
- The SIDM distribution is sensitive to the final baryon distribution
- But, it is not sensitive to the formation history

Hydro SIDM vs CDM



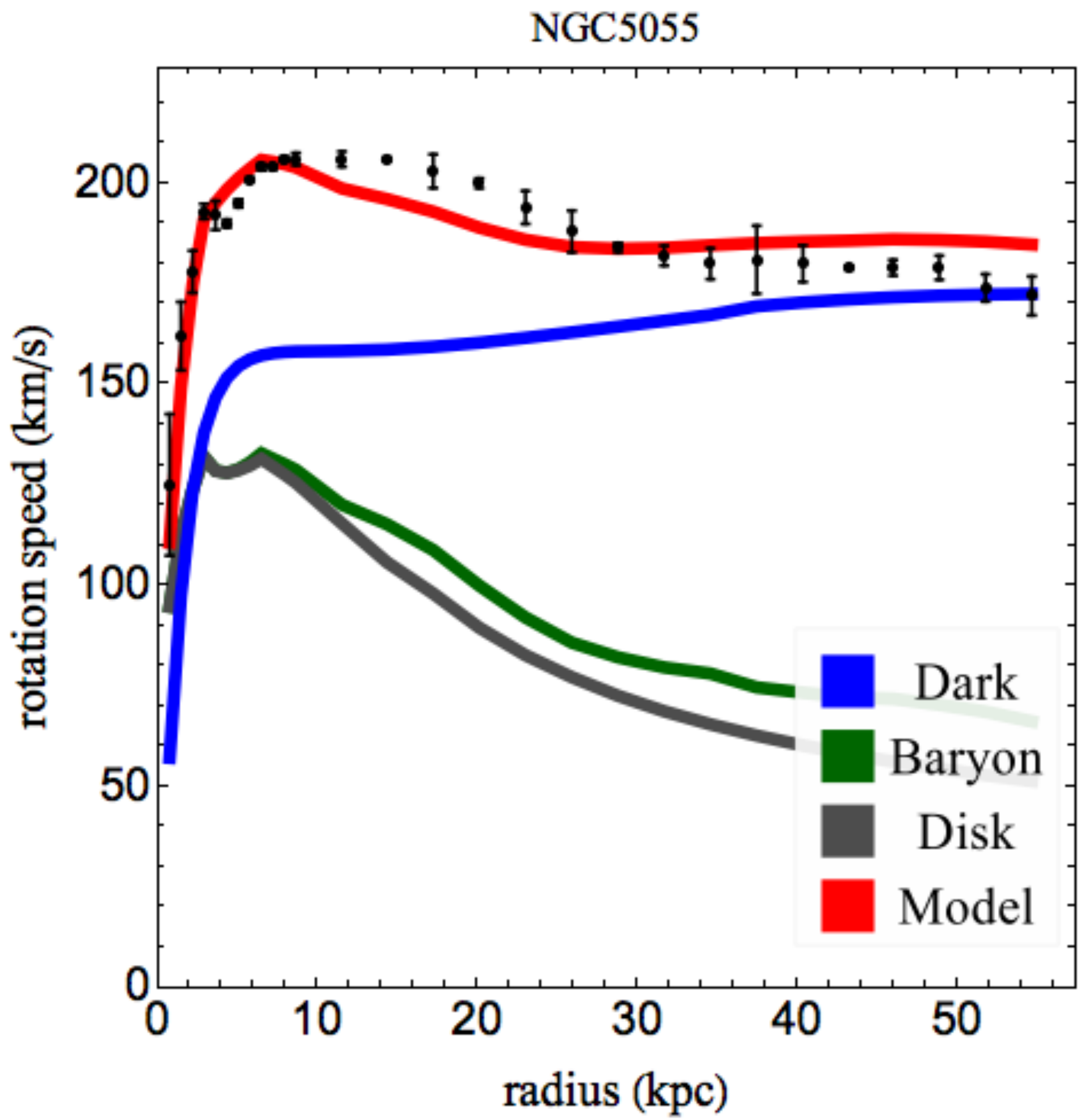


With Robertson, Massey, Eke, Tulin, et al. (MNRAS Letters, 2017)



We have fitted to 135 galaxies

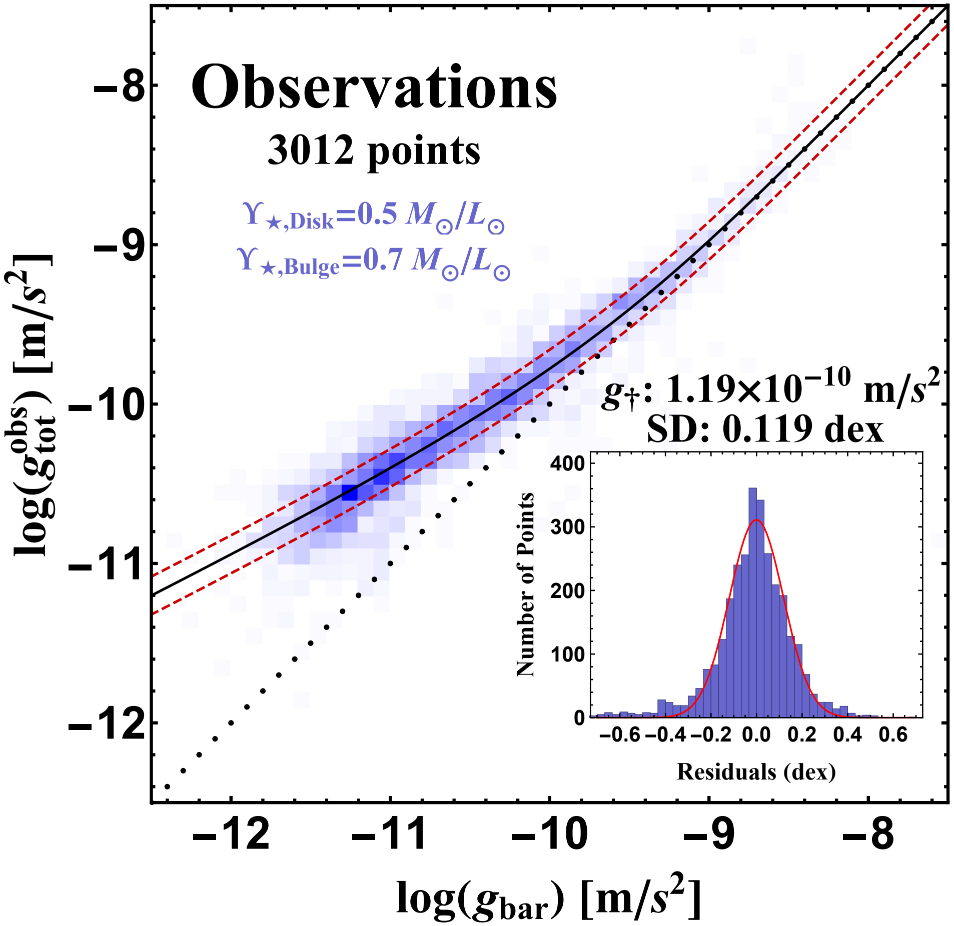
with Ren, Kwa, Kaplinghat (in prep)



with Ren, Kwa, Kaplinghat (in prep)

The worst fit, χ^2/d.o.f ~44, but it is completely driven by the tiny error bars

Radial Acceleration Relation



$$g_{\mathrm{tot}} = \frac{g_{\mathrm{bar}}}{1 - e^{-\sqrt{g_{\mathrm{bar}}/g_\dagger}}}$$

$$g_{\mathrm{tot}} \approx \sqrt{g_{\mathrm{bar}} g_\dagger}$$

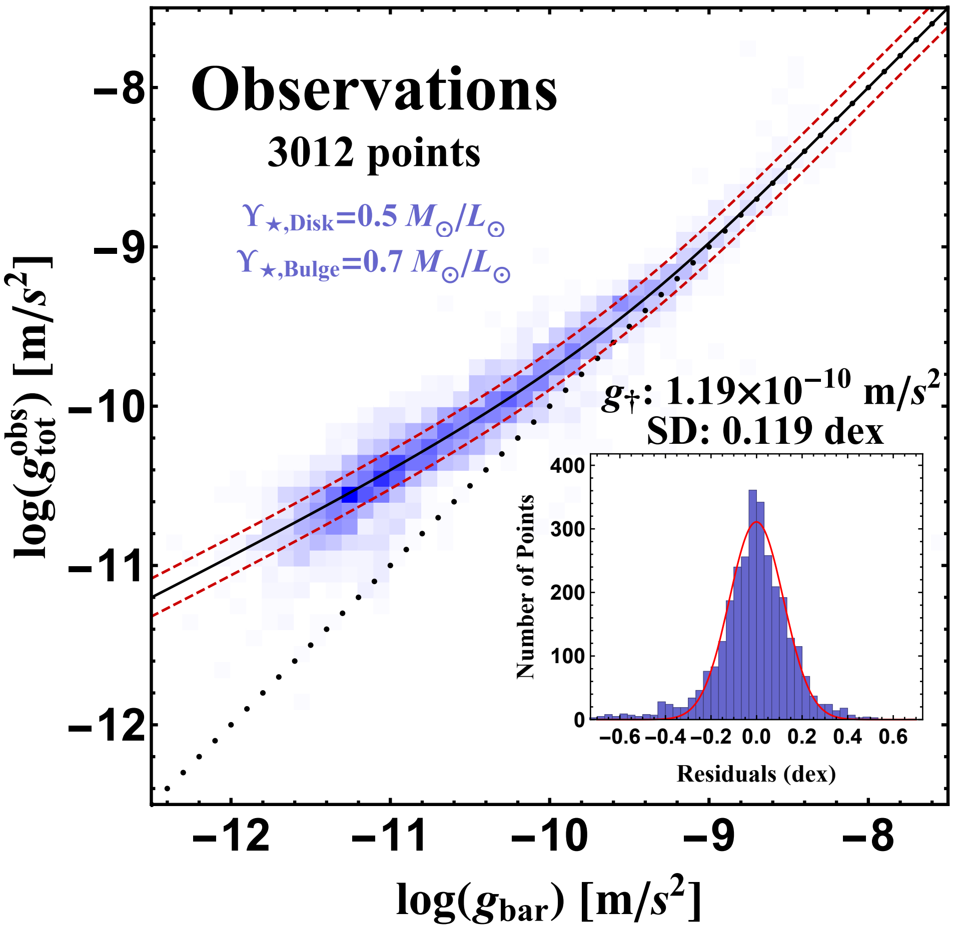
when $g_{\mathrm{bar}} < g_\dagger$

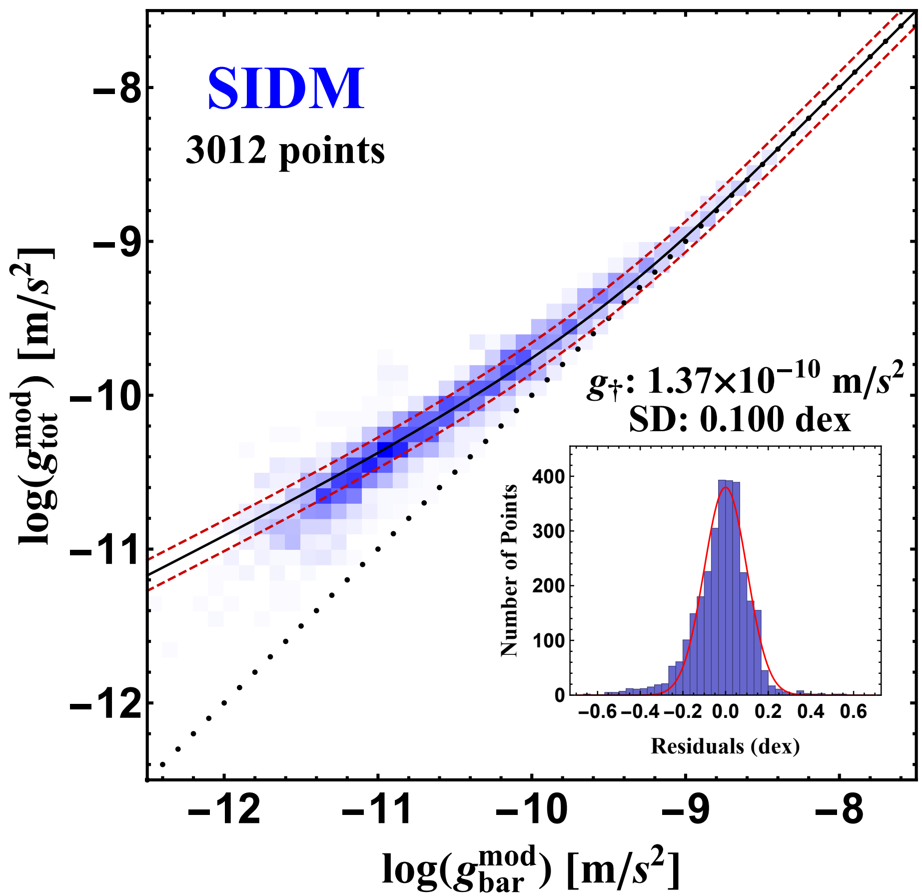
MOND, Milgrom's law (1983)

Reproduced, see McGaugh, Lelli, Schombert (PRL 2016)

135 galaxies "Uniformity"

Uniformity in SIDM



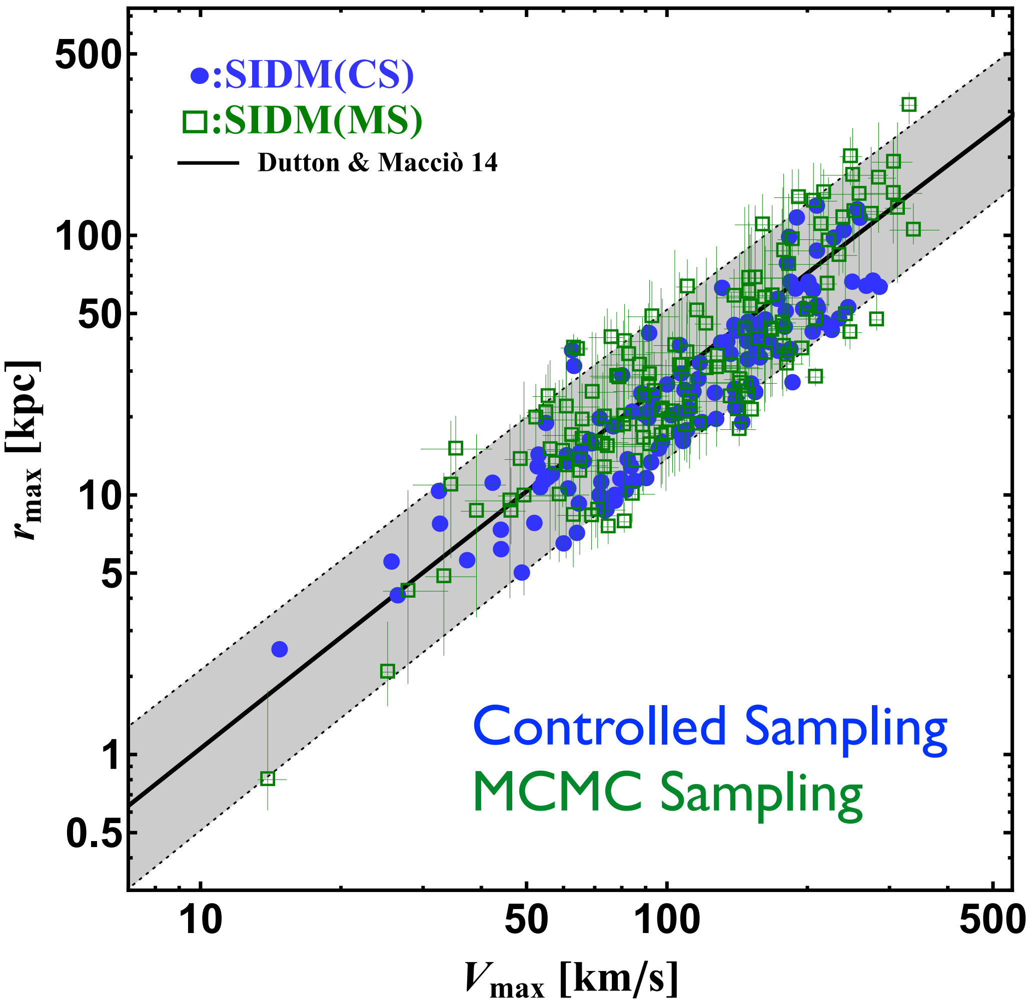


McGaugh, Lelli, Schombert (PRL 2016)

With Ren, Kwa, Kaplinghat (in prep)

135 galaxies

Properties of the Hosting Halos



~95% galaxies can be fitted within 2σ

with Ren, Kwa, Kaplinghat (in prep)

$$(\rho_0, \sigma_0) \leftrightarrow (\rho_s, r_s) \leftrightarrow (V_{\max}, r_{\max})$$

Gray: 2σ band predicted in hierarchical structure formation
Dutton & Maccio (2014)

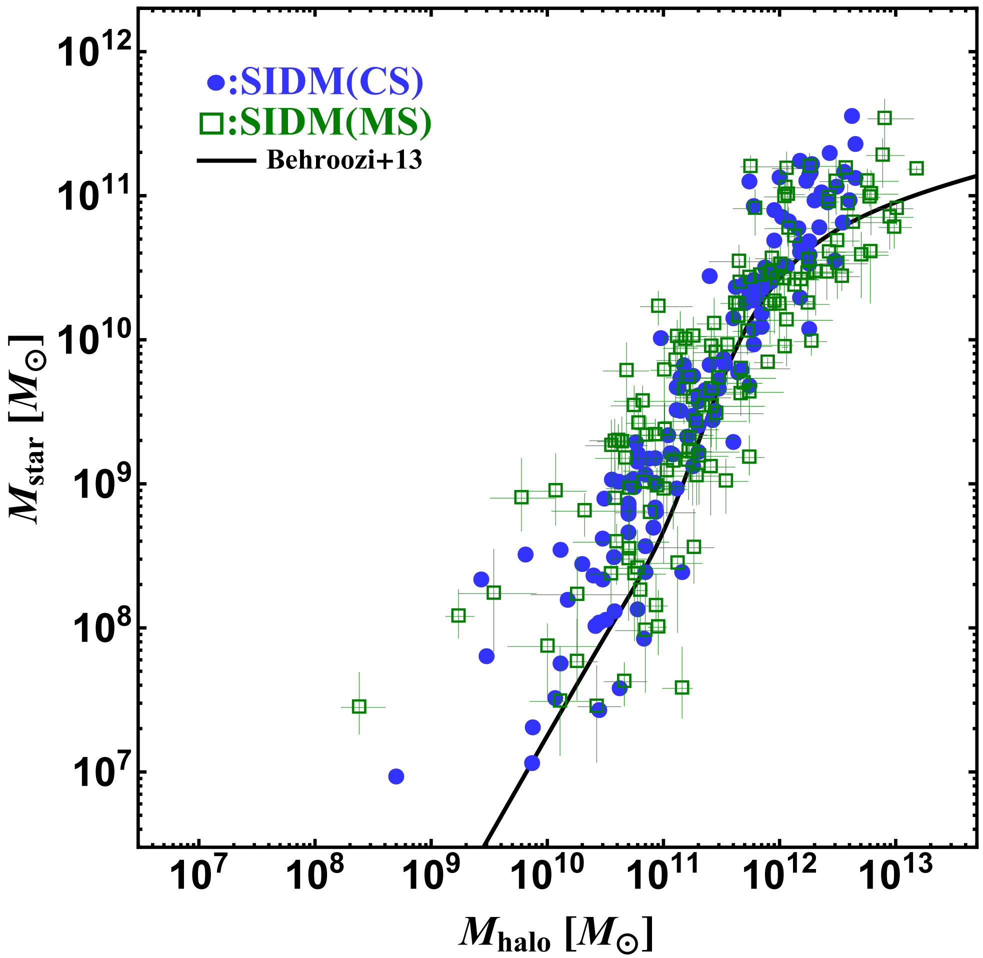
The origin of the acceleration scale:

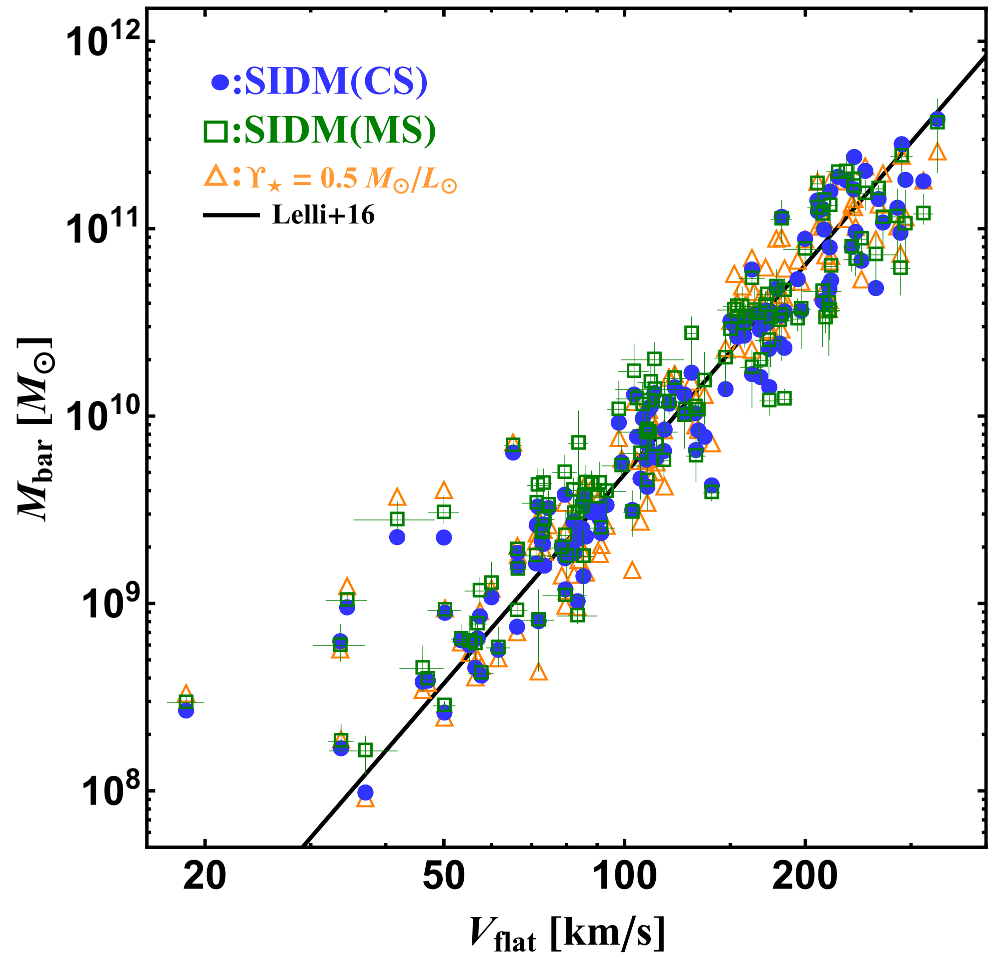
$$r_{\max} = 27\ \mathrm{kpc}(V_{\max}/100\ \mathrm{km/s})^{1.4}$$

$$a|_{r=0} \approx 1.0 \times 10^{-10}\ \mathrm{m/s^2} \left(\frac{V_{\max}}{240\ \mathrm{km/s}}\right)^{0.6}$$

$$a|_{r=0} \equiv GM/r^2|_{r\to 0} \approx 2\pi G\rho_s r_s \approx 2\pi V_{\max}^2/(1.26 r_{\max})$$

Baryon-Halo Relations



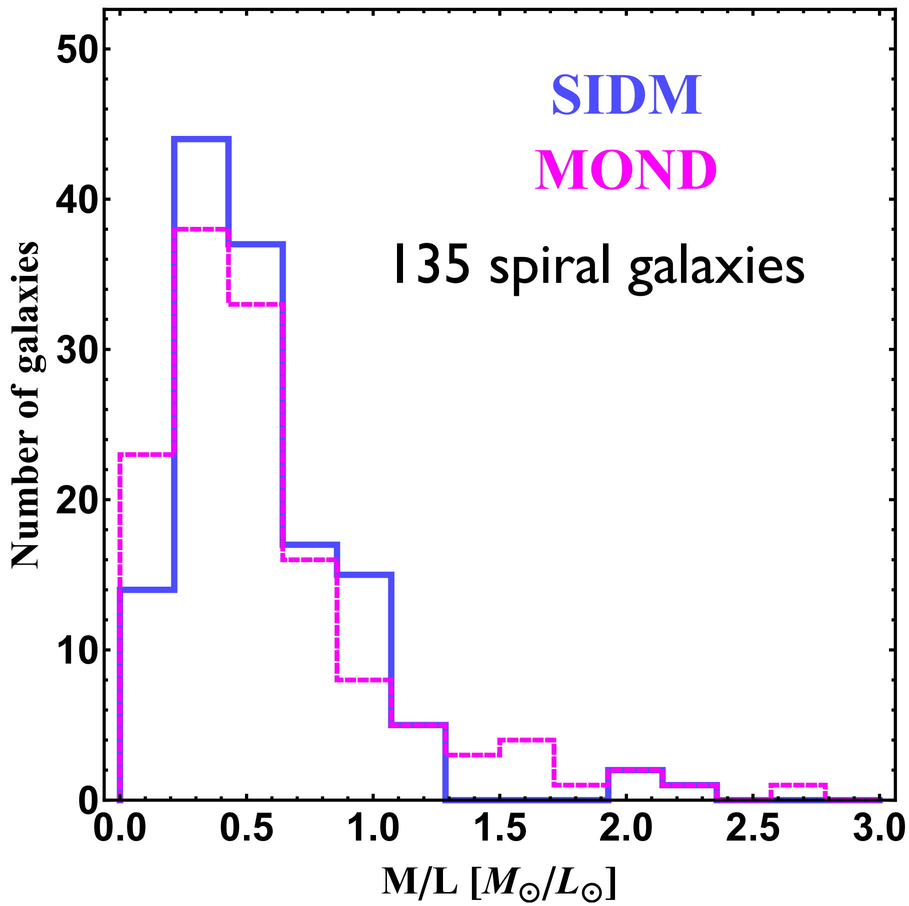


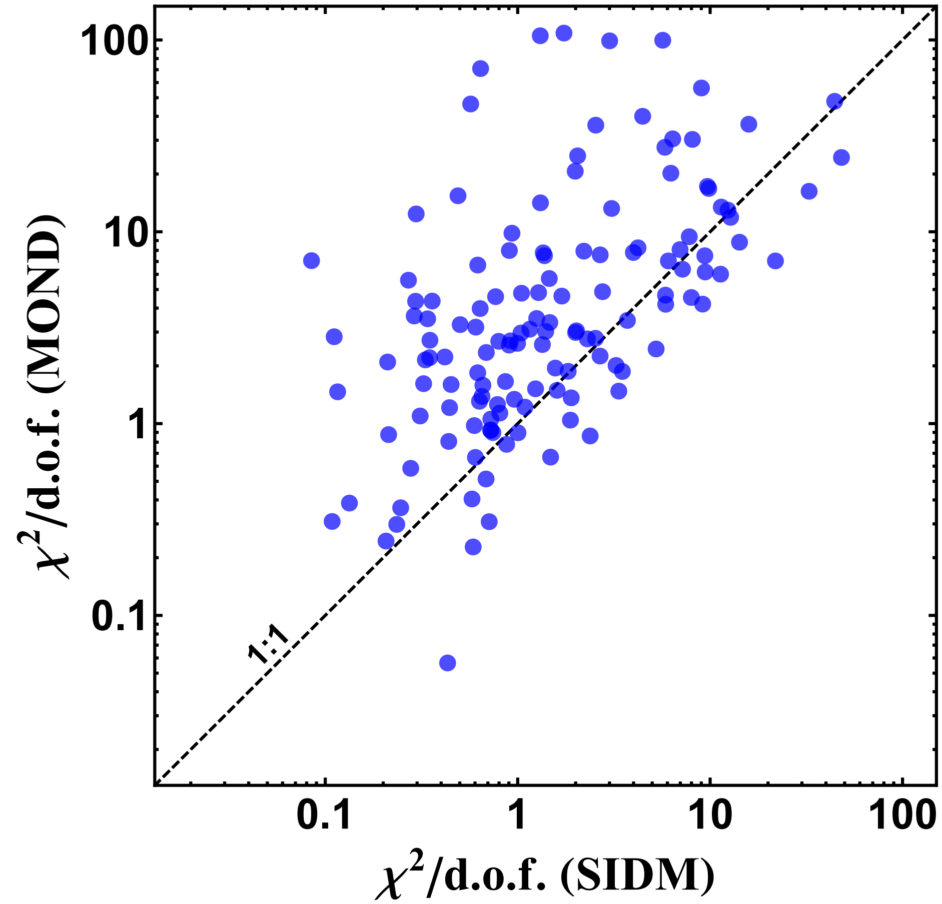
$M_{\rm bar} \propto V_f^s$, $s \approx 3.46$ (CS), 3.25 (MS), and 3.58 ($0.5 M_\odot/L_\odot$)

with Ren, Kwa, Kaplinghat (in prep)

Not 4, predicted in MOND

SIDM vs MOND



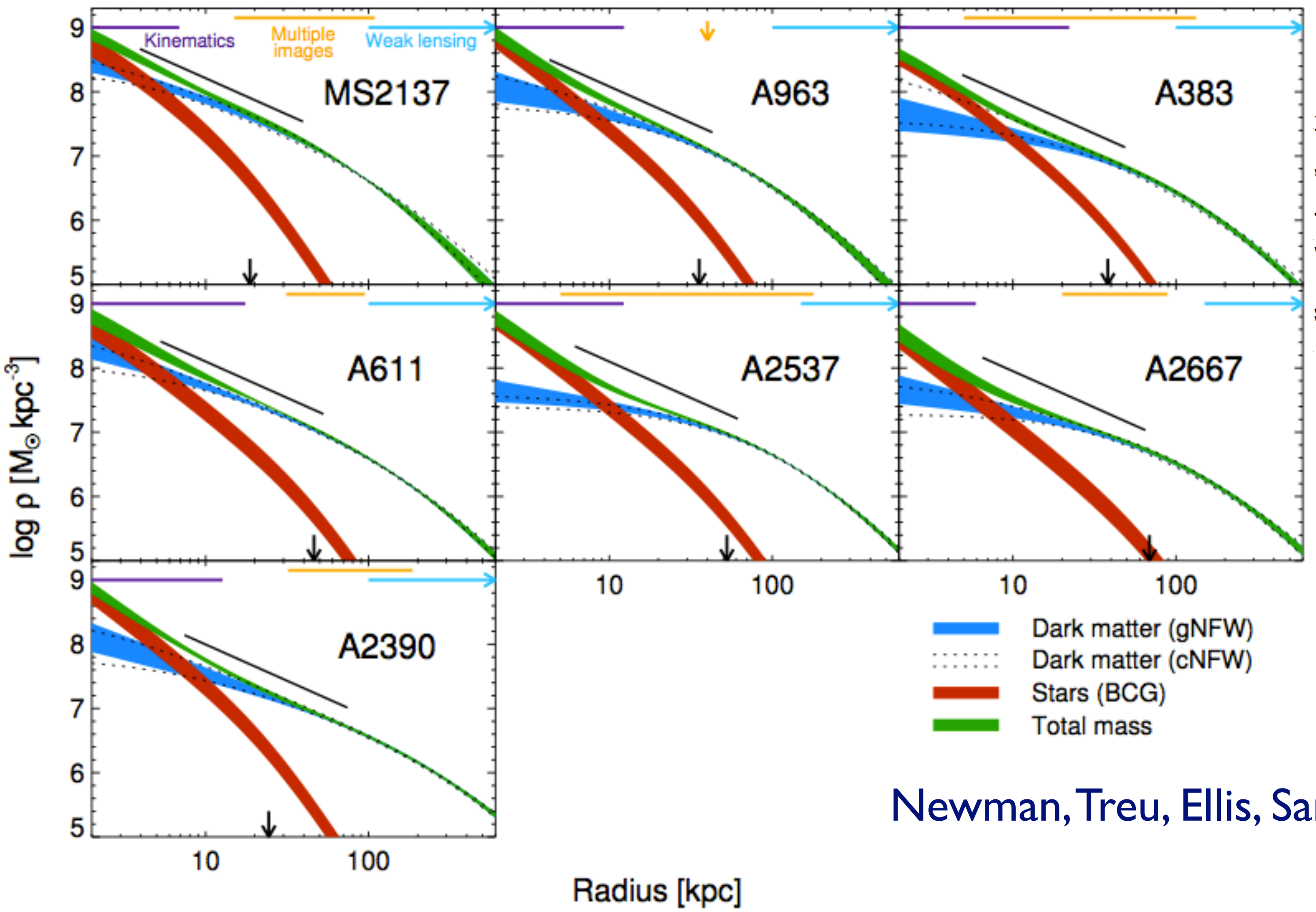


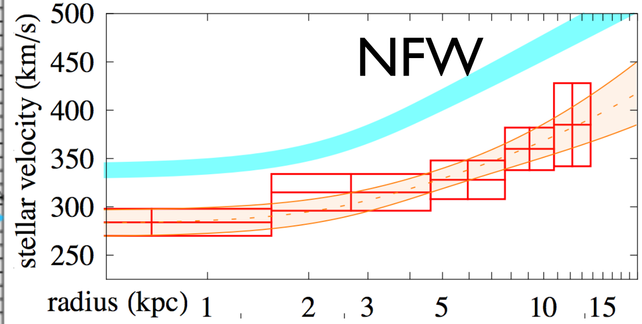
- Both SIDM and MOND fits have the disk mass-to-light ratio peaked around $0.5M_\odot/L_\odot$.
- For 77% of the galaxies, the SIDM fits are better than the MOND ones.
- SIDM explains both the diversity and the uniformity

With Ren, Kwa, Kaplinghat (in prep)

Galaxy Clusters

- Seven well-resolved galaxy clusters



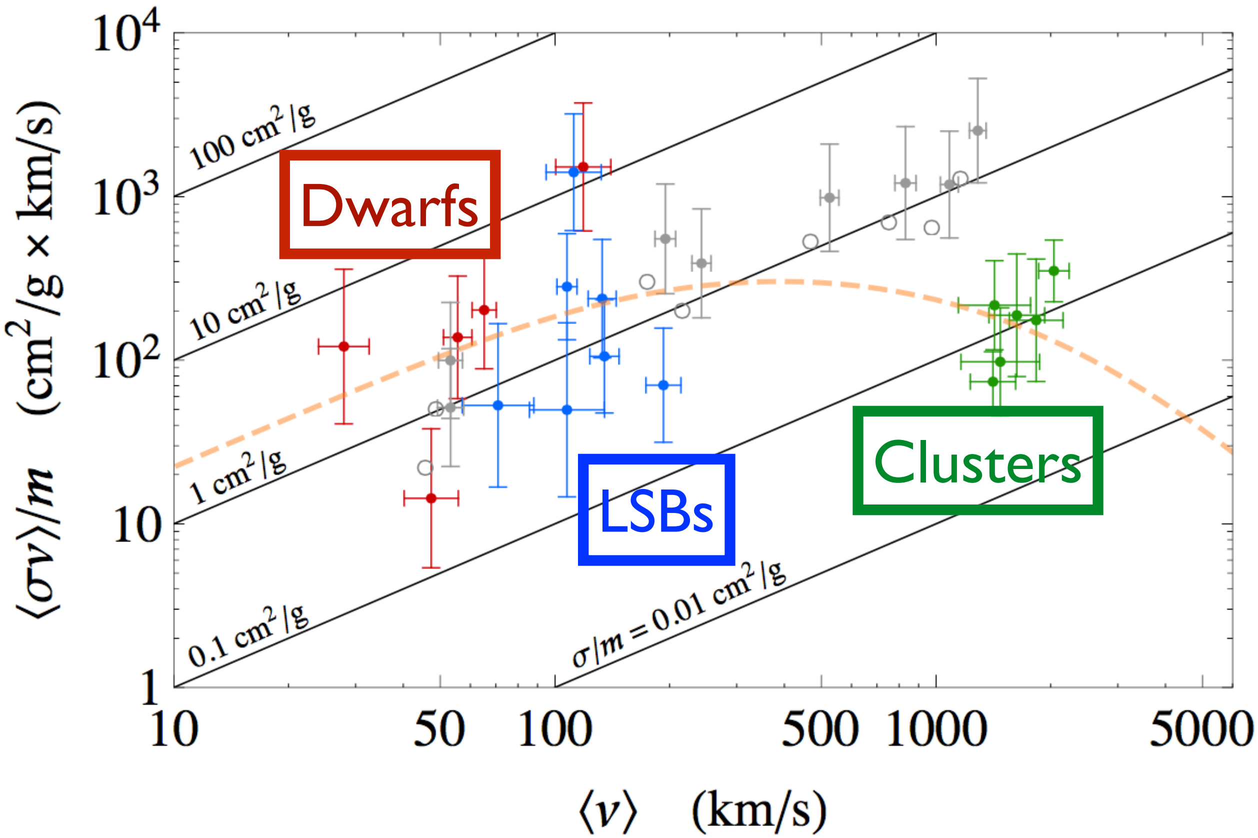


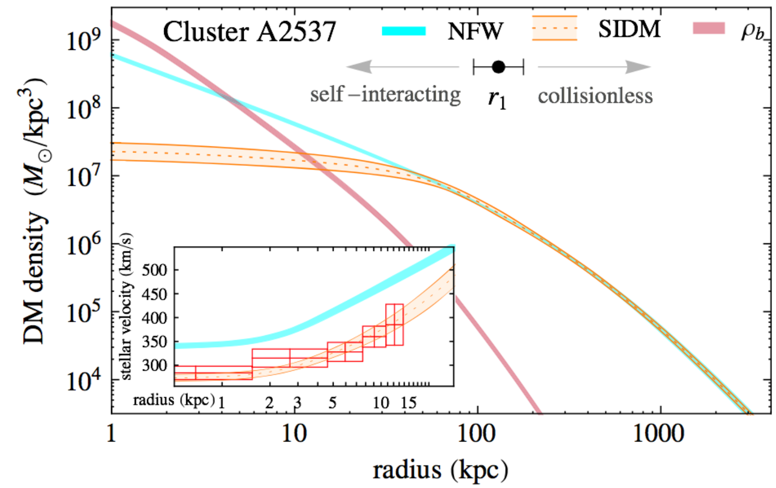
Newman, Treu, Ellis, Sand (2013)

- CDM halos contain more DM in the central regions than needed

SIDM from Dwarfs to Clusters

Galaxies: M_{halo}~10^9-10^{12} $M_\odot$ Clusters: M_{halo}~10^{14}-10^{15} $M_\odot$





Core size in clusters: ~10 kpc

Galaxies: ~2 cm^2/g

Clusters: ~0.1 cm^2/g

DM halos as particle colliders

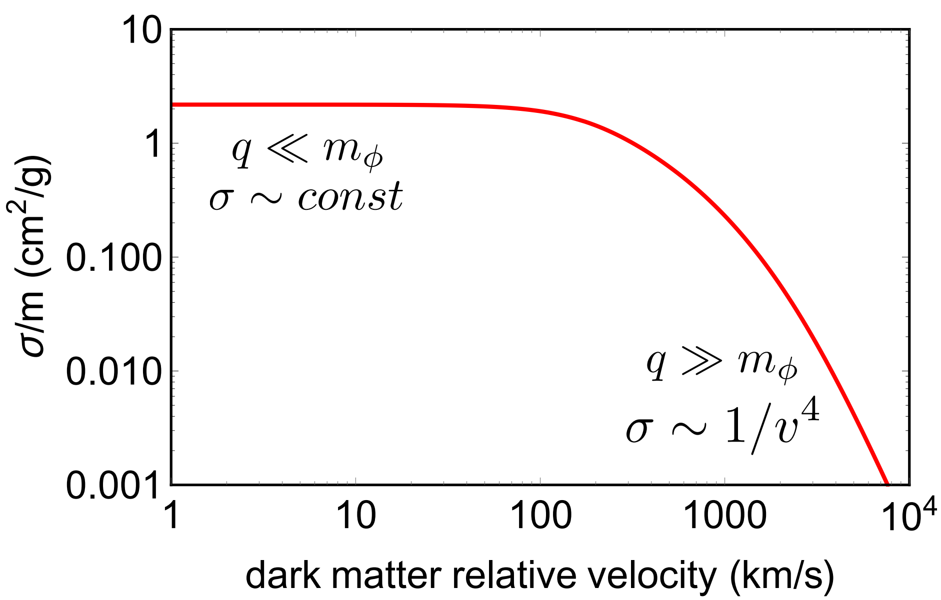
With Kaplinghat, Tulin (PRL, 2015)

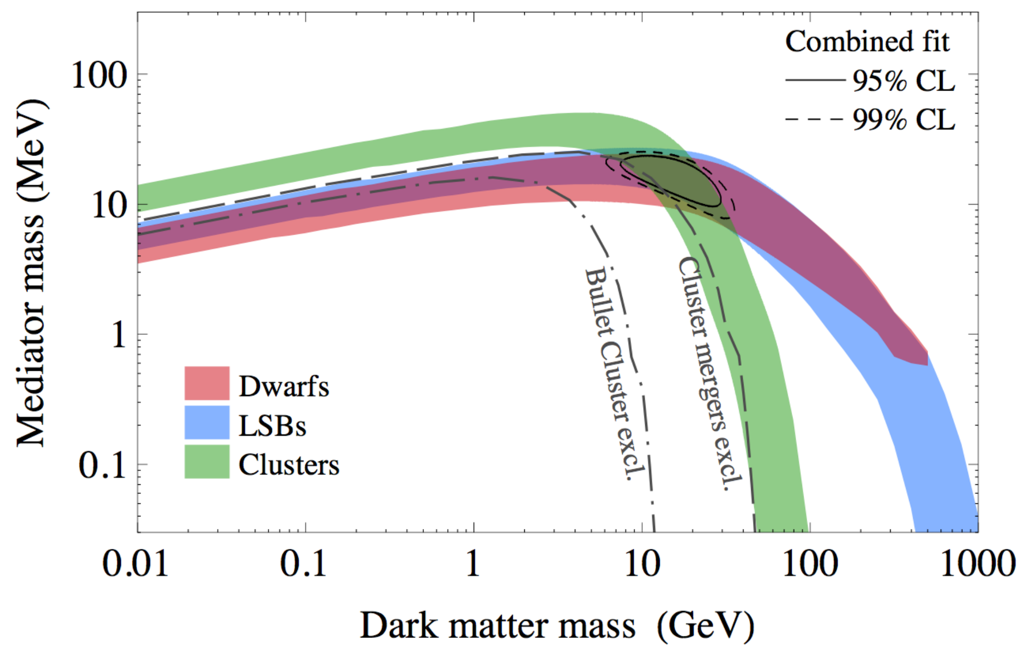
See also Yoshida et al. (APJ Letters, 2000)

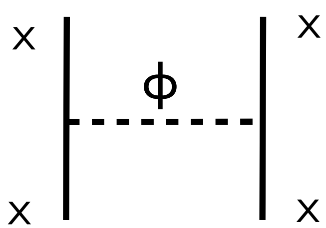
Merging Clusters: < ~2 cm^2/g

Measuring Dark Matter Mass

- Self-scattering kinematics determines SIDM mass







$$V(r) = \frac{\alpha_X}{r} e^{-m_\phi r}$$

$\alpha_X = 1/137$

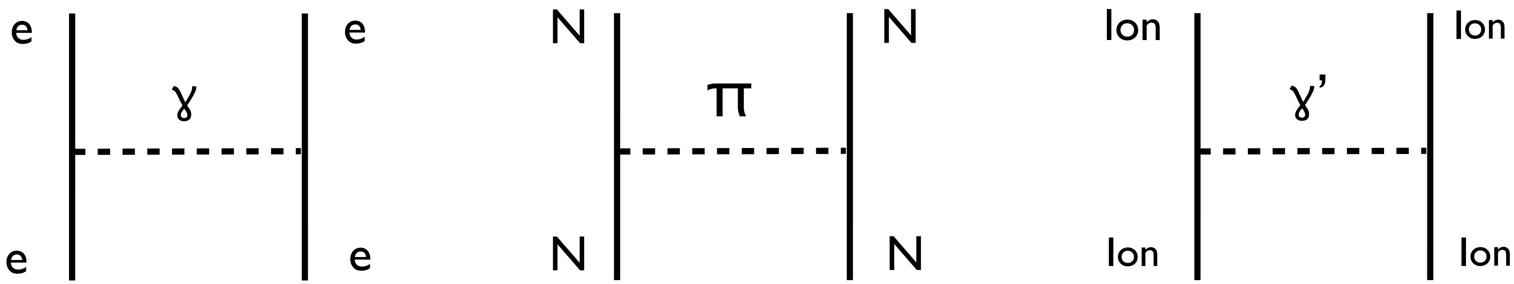
m_X: ~15 GeV, m_ϕ: ~17 MeV

with Feng, Kaplinghat (PRL 2012)

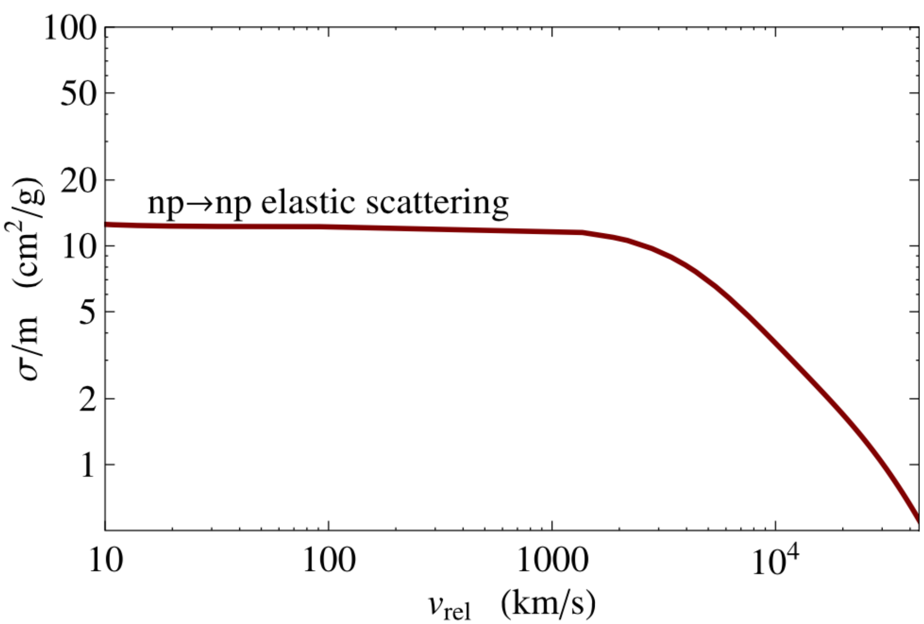
with Kaplinghat, Tulin (PRL 2015)

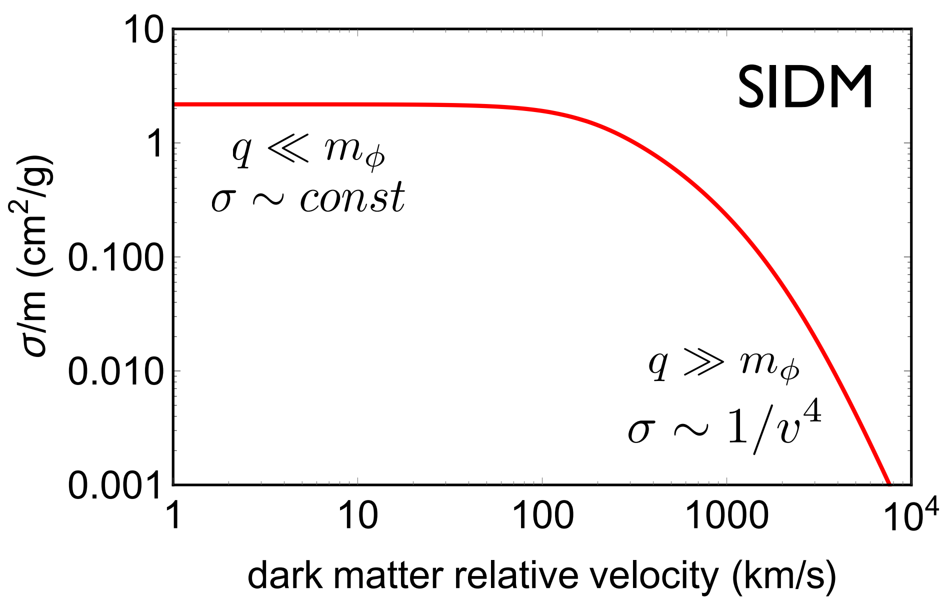
Particle Physics of SIDM

- Familiar examples in the visible sector

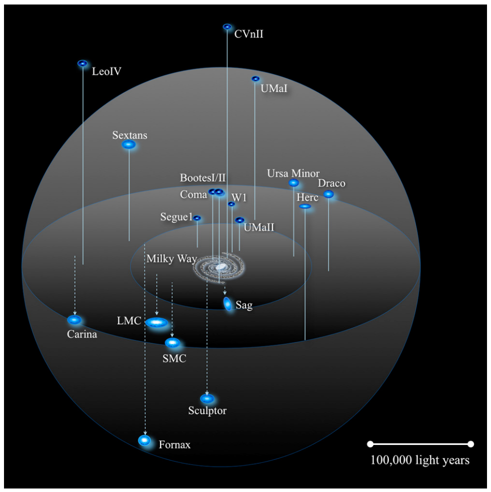
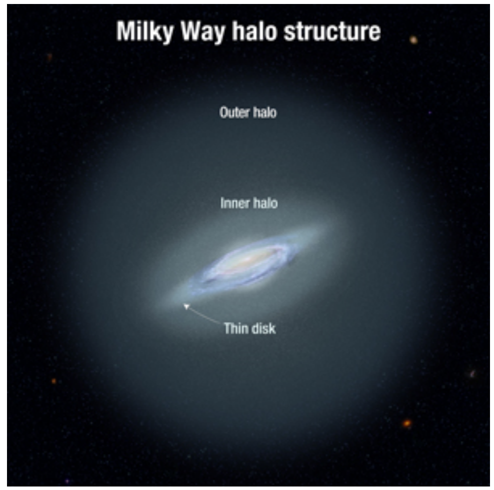
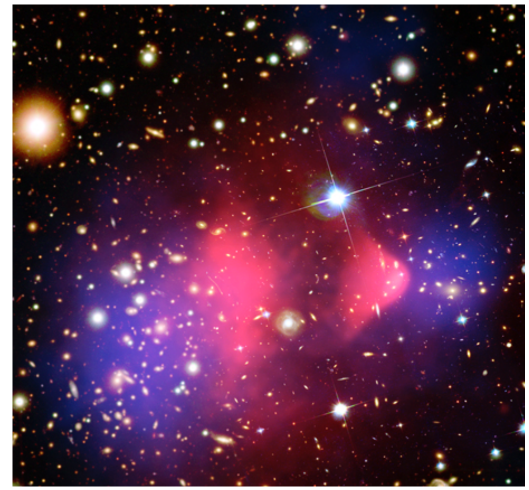


$$V(r) = \frac{\alpha_{\rm EM}}{r} \qquad V(r) = \frac{1}{r} e^{-m_\pi r} \qquad V(r) = \frac{\alpha_{\rm EM}}{r} e^{-m_D r}$$





Dark Matter "Colliders"

Dwarf galaxies	MW-size galaxies	Clusters
		
"B-factory" (v~30 km/s)	"LEP" (v~200 km/s)	"LHC" (v~1000 km/s)

Observations on all scales

Self-scattering kinematics →

Measure particle physics parameters
σ_x, m_x, g_x

Particle Properties

XSIDM

PDG particle data group

Positive observations	σ/m	v_{rel}	Observation	Refs.
Cores in spiral galaxies (dwarf/LSB galaxies)	$\gtrsim 1\ \mathrm{cm}^2/\mathrm{g}$	$30 - 200\ \mathrm{km/s}$	Rotation curves	[77, 93]
Too-big-to-fail problem				
Milky Way	$\gtrsim 0.6\ \mathrm{cm}^2/\mathrm{g}$	$50\ \mathrm{km/s}$	Stellar dispersion	[87]
Local Group	$\gtrsim 0.5\ \mathrm{cm}^2/\mathrm{g}$	$50\ \mathrm{km/s}$	Stellar dispersion	[88]
Cores in clusters	$\sim 0.1\ \mathrm{cm}^2/\mathrm{g}$	$1500\ \mathrm{km/s}$	Stellar dispersion, lensing	[93, 103]
~~*Abell 3827 subhalo merger*~~	~~$\sim 1.5\ \mathrm{cm}^2/\mathrm{g}$~~	~~$1500\ \mathrm{km/s}$~~	~~DM-galaxy offset~~	~~[104]~~
Abell 520 cluster merger	$\sim 1\ \mathrm{cm}^2/\mathrm{g}$	$2000 - 3000\ \mathrm{km/s}$	DM-galaxy offset	[105, 106, 107]
Constraints				
Halo shapes/ellipticity	$\lesssim 1\ \mathrm{cm}^2/\mathrm{g}$	$1300\ \mathrm{km/s}$	Cluster lensing surveys	[86]
Substructure mergers	$\lesssim 2\ \mathrm{cm}^2/\mathrm{g}$	$\sim 500 - 4000\ \mathrm{km/s}$	DM-galaxy offset	[92, 108]
Merging clusters	$\lesssim \mathrm{few}\ \mathrm{cm}^2/\mathrm{g}$	$2000 - 4000\ \mathrm{km/s}$	Post-merger halo survival (Scattering depth $\tau < 1$)	Table II
Bullet Cluster	$\lesssim 0.7\ \mathrm{cm}^2/\mathrm{g}$	$4000\ \mathrm{km/s}$	Mass-to-light ratio	[81]

Tulin & HBY (2017)

Summary

- SIDM provides a unified explanation to the stellar kinematics from dwarf galaxies to galaxy clusters.

- It simultaneously explains the diversity and the uniformity of the galactic rotation curves.

- There is a strong hint that the inner halos are thermalized.


Thank You!