Self-Interacting Dark Matter

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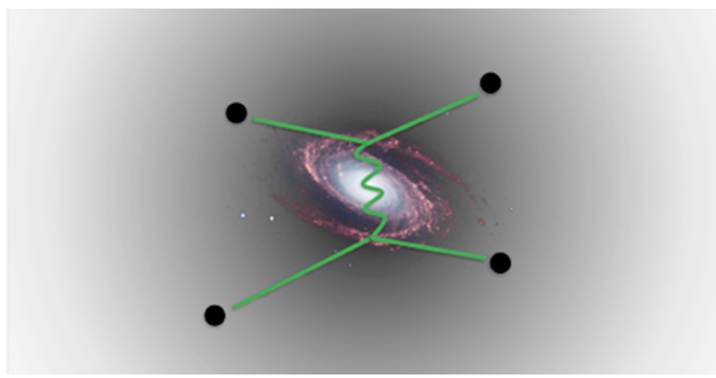
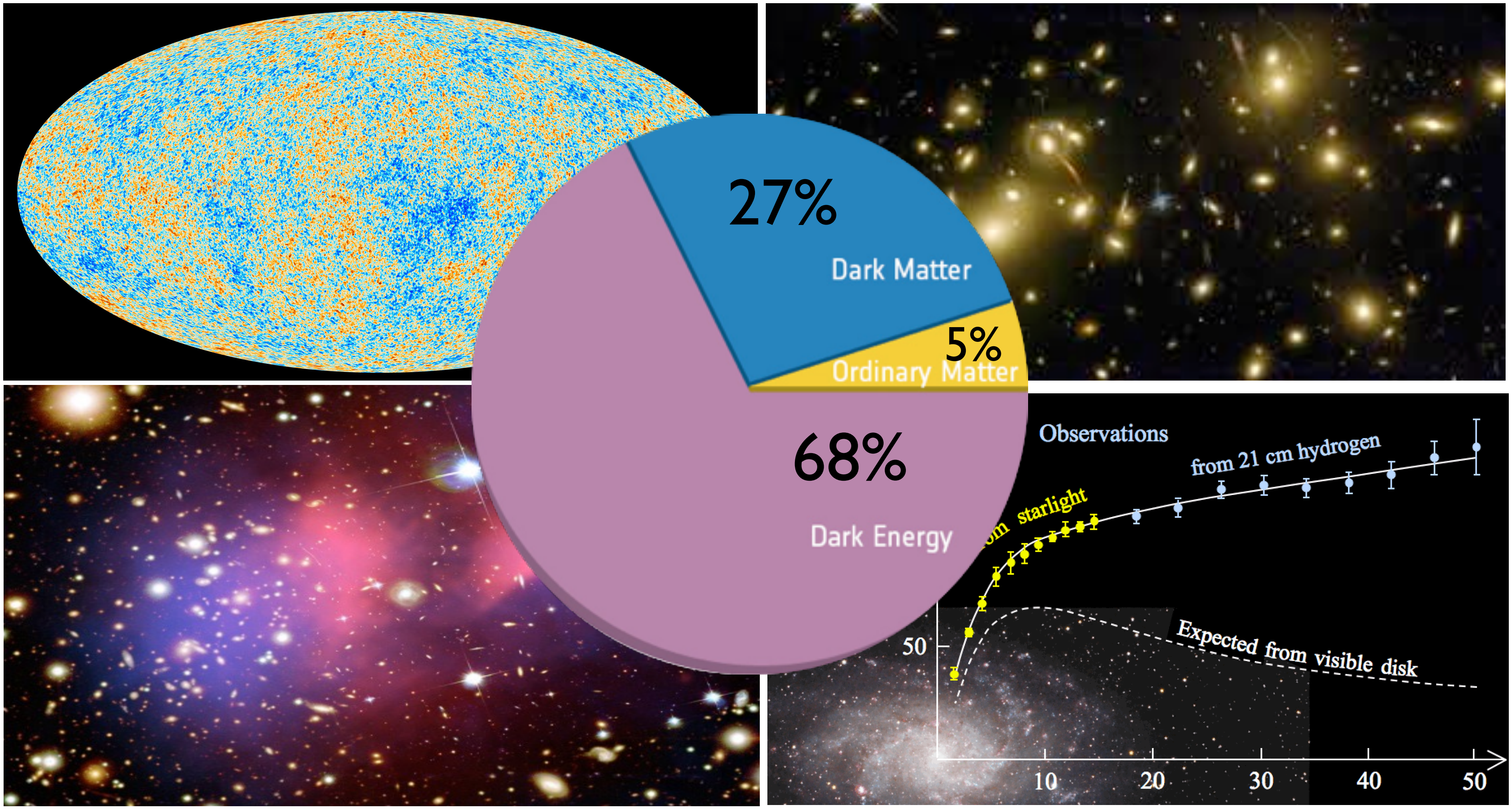


IPMU Seminar, August 1, 2018

Review for Physics Reports: Tulin & HBY (2017)

Dark Matter



27%
Dark Matter
5%
Ordinary Matter
68%
Dark Energy
Observations
from 21 cm hydrogen
starlight
Expected from visible disk
50
10
20
30
40
50

Beyond the WIMP Paradigm

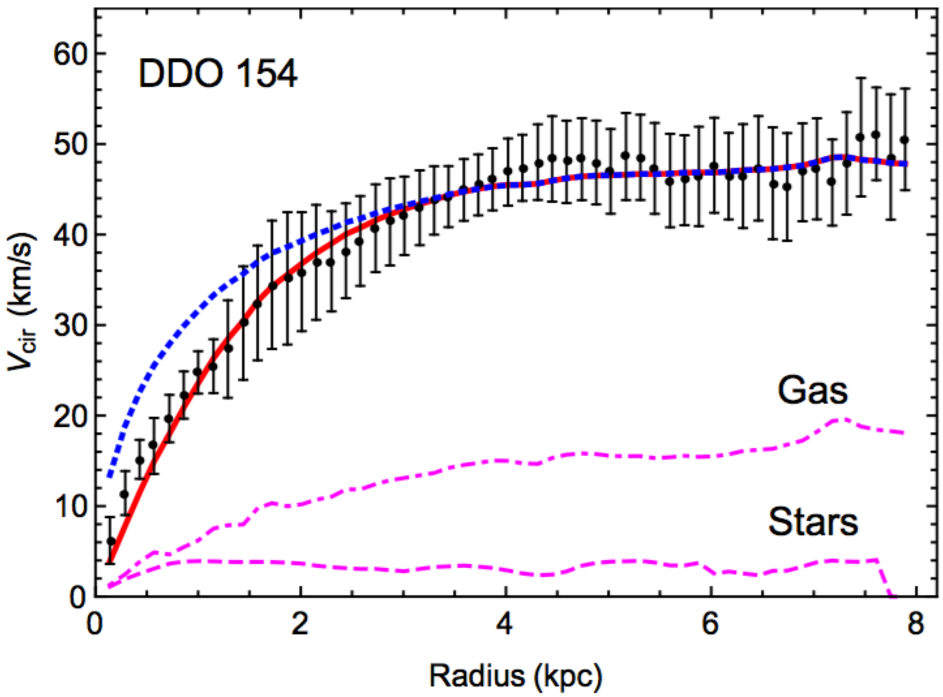
Some guidance

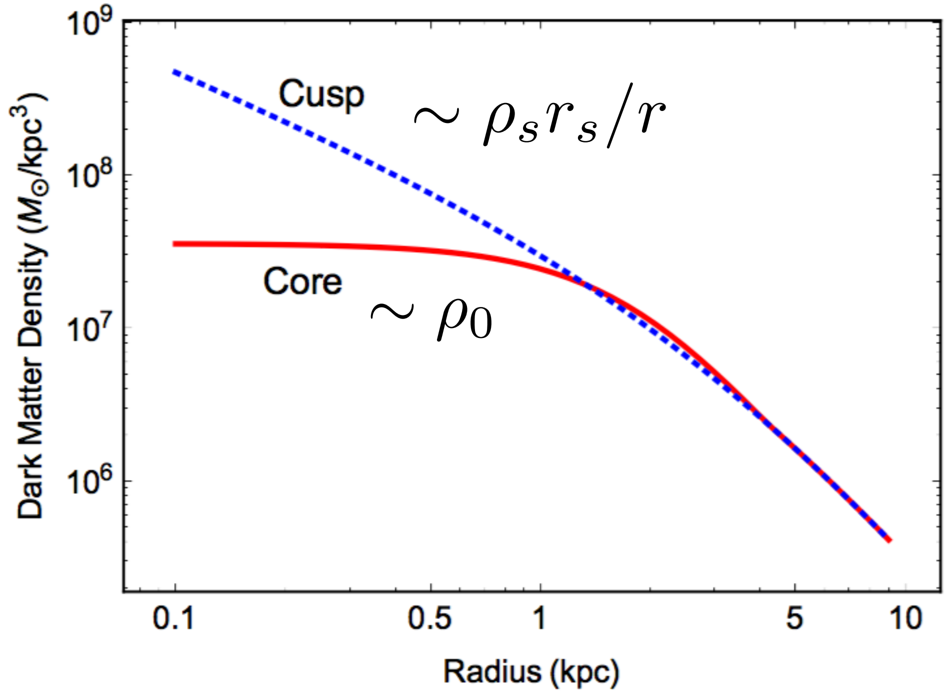
- Theory-driven: different production mechanisms
- Technology-driven: what can we do with current technologies?
- Observation-driven: how can we determine the particle nature of DM from astrophysical observations?

- Note the WIMP is a typical collisionless cold dark matter (CDM) candidate
- CDM works very well on large scales, >O(100) kpc

Core vs Cusp Problem

- DM-dominated systems (dwarfs, LSBs)





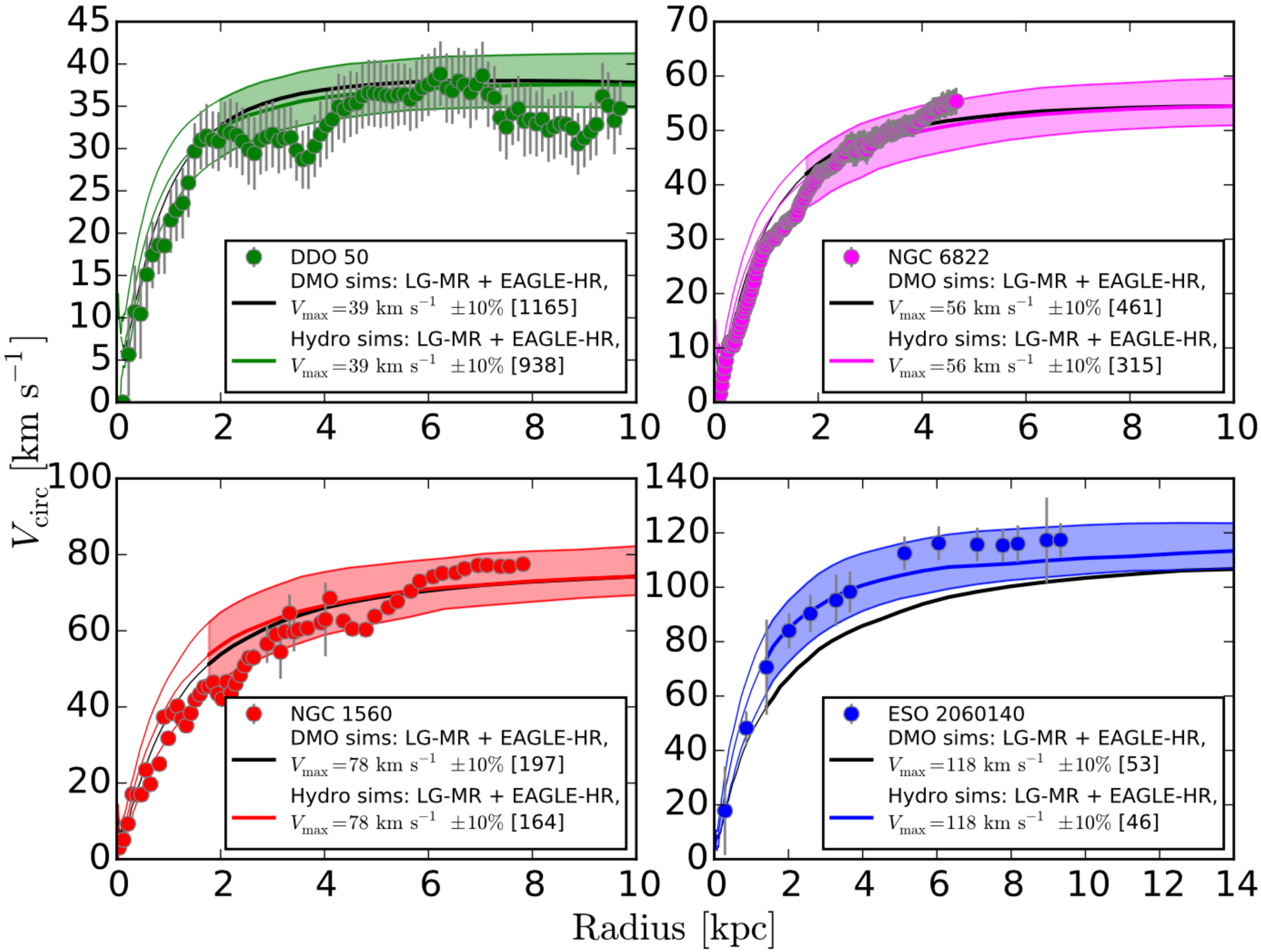
$$V_{\rm circ}(r) = \sqrt{V_{\rm halo}(r)^2 + \Upsilon_* V_{\rm star}(r)^2 + V_{\rm gas}(r)^2}$$

$$\frac{\rho_s}{r/r_s(1+r/r_s)^2}$$

Navarro, Frenk, White (1995, 1996)

Flores, Primack (1994), Moore (1994)…

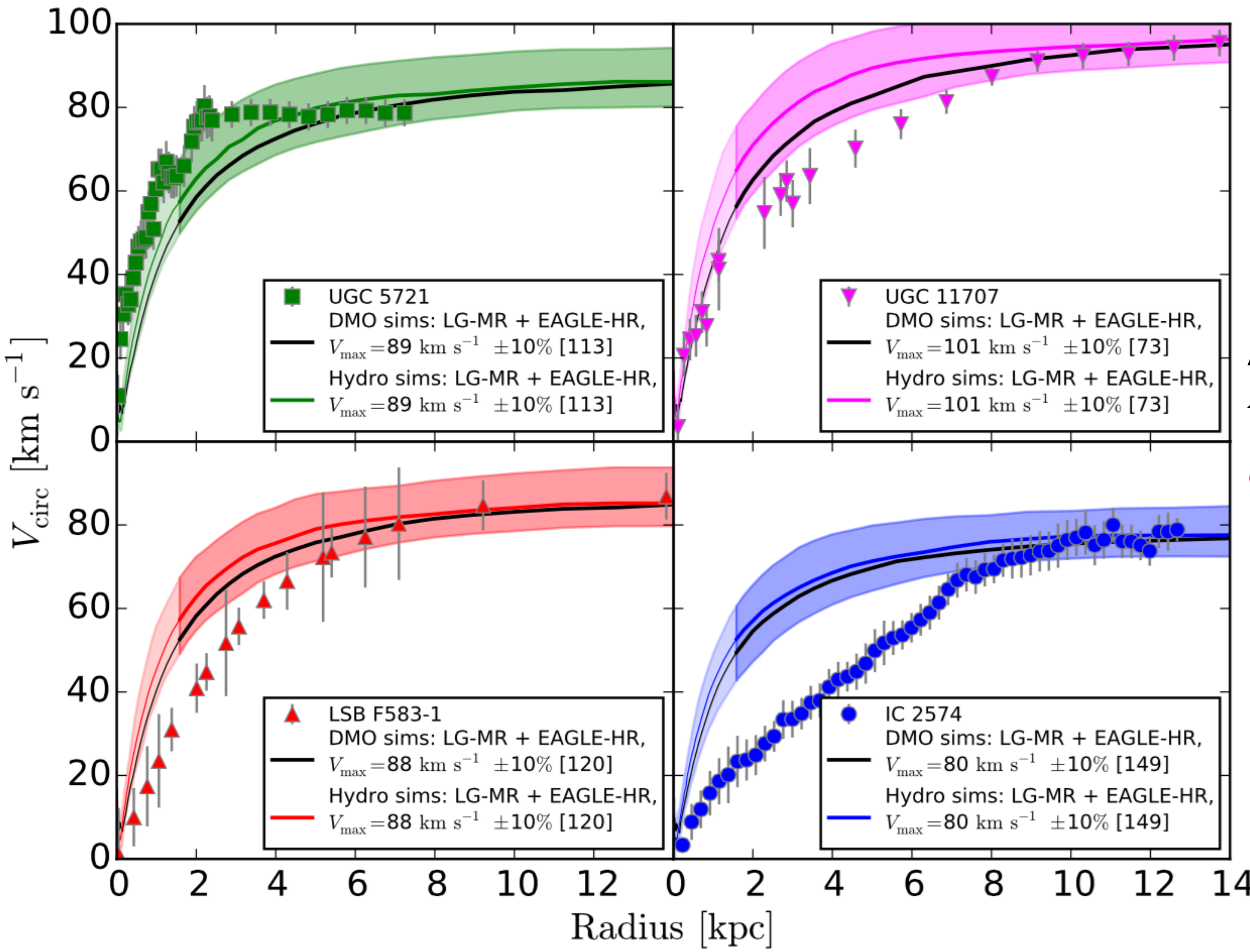
The Diversity Problem



Colored bands: hydrodynamical simulations of ΛCDM, “smooth/weak” baryonic feedback

Oman et al. (2015)

The Diversity Problem

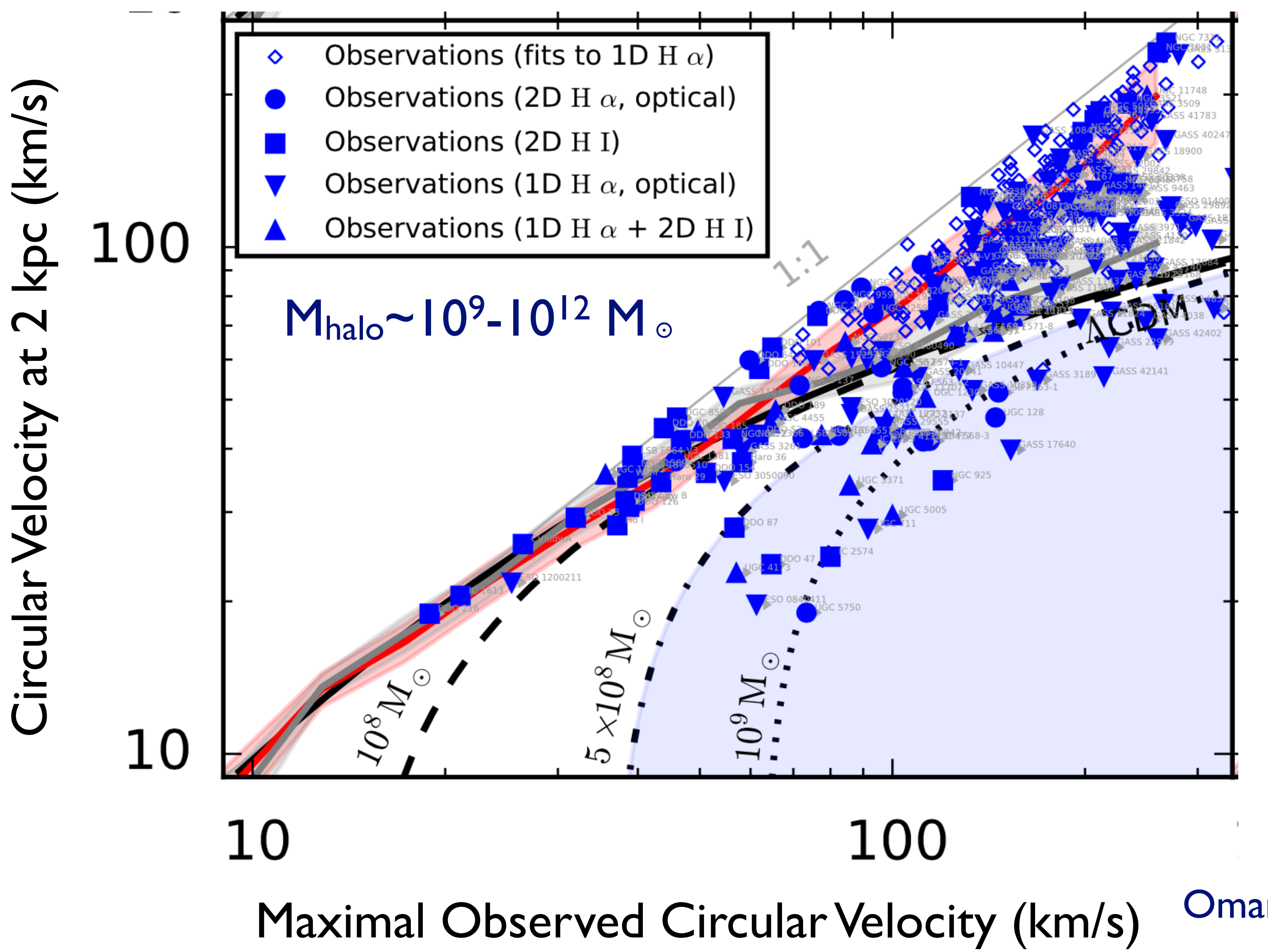


All galaxies have the same observed Vmax!

Oman et al. (2015)

Colored bands: hydrodynamical simulations of ΛCDM

A Big Challenge



Oman et al. (2015)

V_{circ}(2kpc) has a factor of ~4 scatter for fixed V_{max}

Mon. Not. R. Astron. Soc. **000**, 000–000 (0000) Printed 10 July 2015 (MN LaTeX style file v2.2)

The unexpected diversity of dwarf galaxy rotation curves

Kyle A. Oman[1,⋆], Julio F. Navarro[1,2], Azadeh Fattahi[1], Carlos S. Frenk[3], Till Sawala[3], Simon D. M. White[4], Richard Bower[3], Robert A. Crain[5], Michelle Furlong[3], Matthieu Schaller[3], Joop Schaye[6], Tom Theuns[3]

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[3] *Institute for Computational Cosmology, Department of Physics, University of Durham, South Road, Durham DH1 3LE, United Kingdom*
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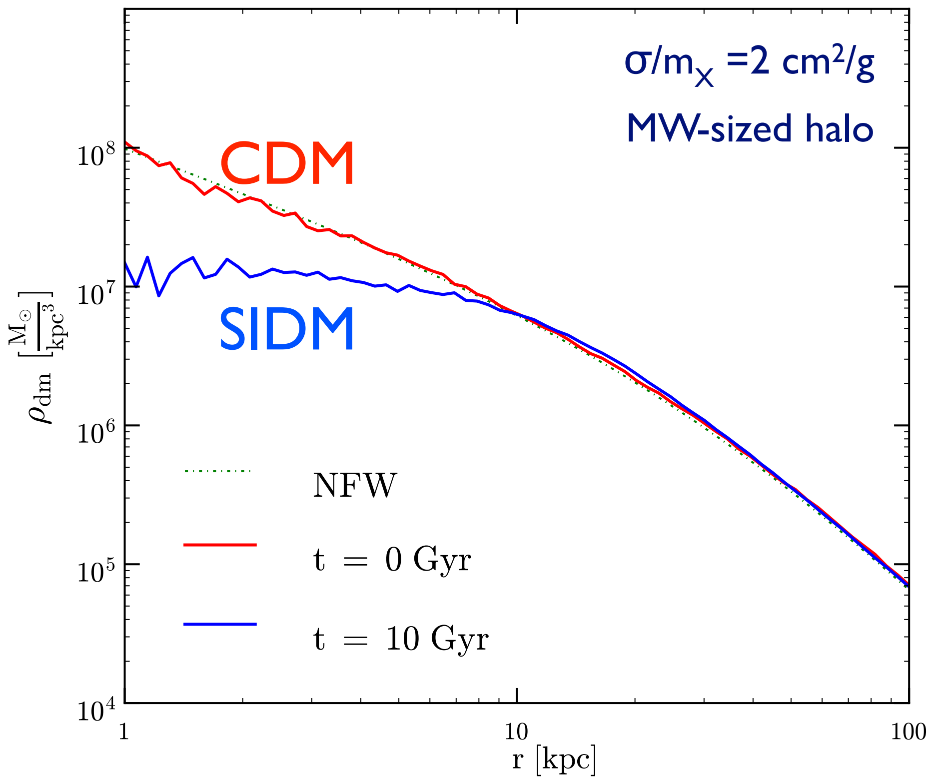
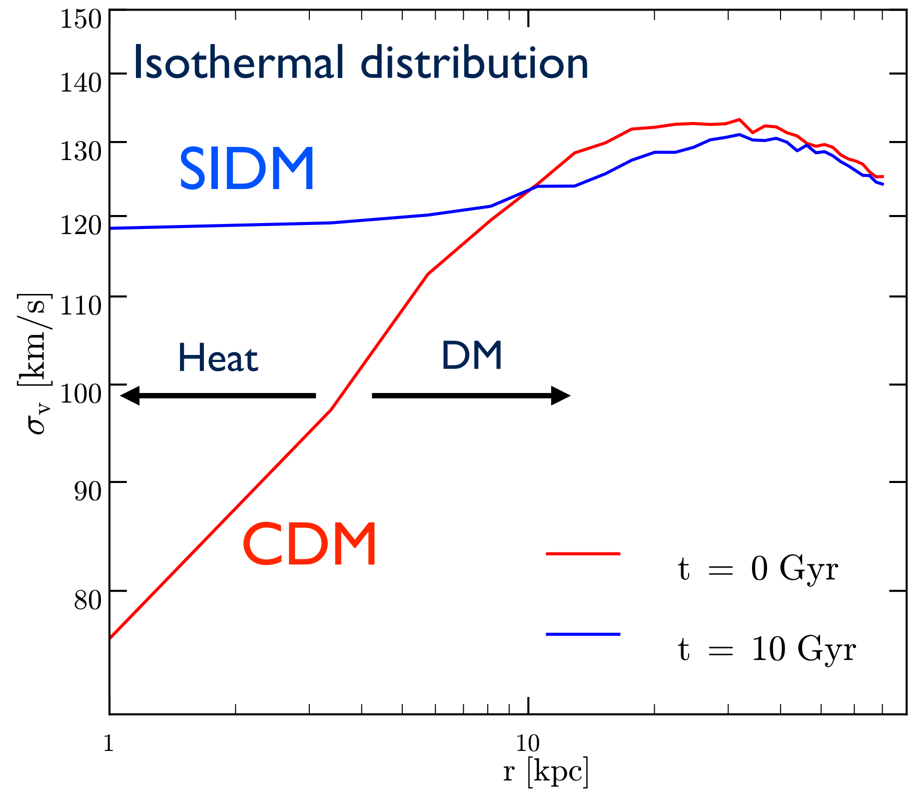
[5] *Astrophysics Research Institute, Liverpool John Moores University, IC2, Liverpool Science Park, 146 Brownlow Hill, Liverpool, L3 5RF, United Kingdom*
[6] *Leiden Observatory, Leiden University, PO Box 9513, NL-2300 RA Leiden, the Netherlands*

The diversity is expected if dark matter has strong self-interactions

Self-Interacting Dark Matter

- Self-interactions thermalize the inner halo, not the outer halo





$\sigma/m_X \sim 1\ \mathrm{cm}^2/\mathrm{g}$ (nuclear scale)

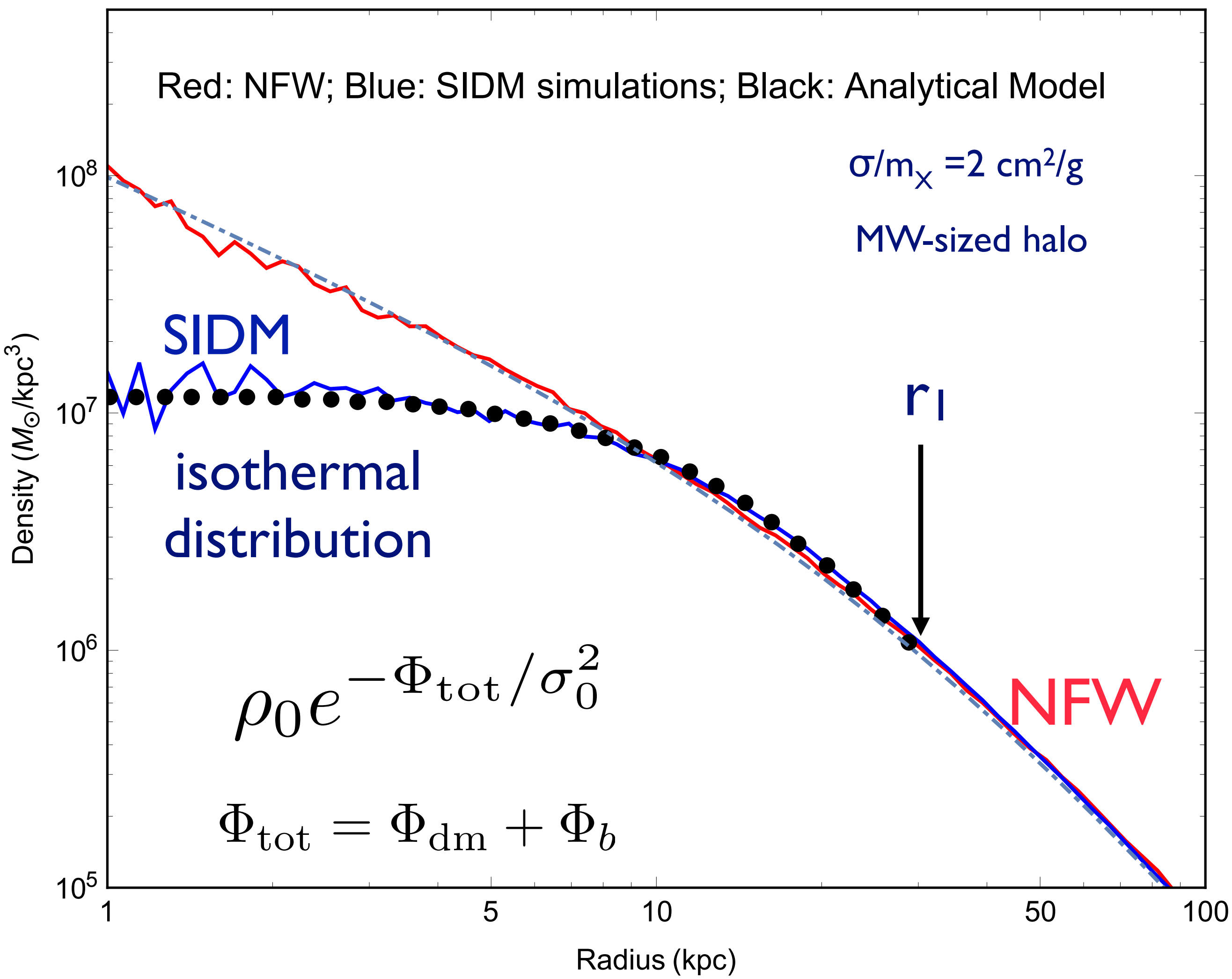
$$\Gamma \simeq n\sigma v = (\rho/m_X)\sigma v \sim H_0$$

Spergel & Steinhardt (PRL 1999)

From Ran Huo

see Tulin & HBY (2017) for a review

Modelling SIDM Halos



$$\nabla^2 \Phi_{\rm tot} = 4\pi G(\rho_{\rm dm} + \rho_b)$$

Ideal gas: PV=nRT

$$\text{rate} \times \text{time} \approx \frac{\langle \sigma v \rangle}{m} \rho(r_1)\, t_{\rm age} \approx 1$$

$$\rho(r) = \begin{cases} \rho_{\rm iso}(r)\,, & r < r_1 \\ \rho_{\rm NFW}(r)\,, & r > r_1 \end{cases}$$

Matching conditions:

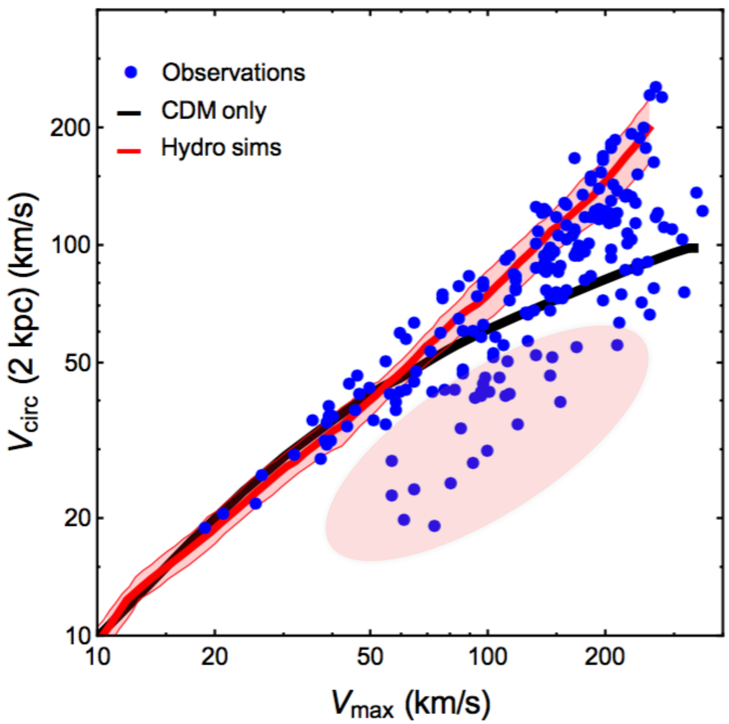
$$\rho_{\rm iso}(r_1) = \rho_{\rm NFW}(r_1)$$
$$M_{\rm iso}(r_1) = M_{\rm NFW}(r_1)$$

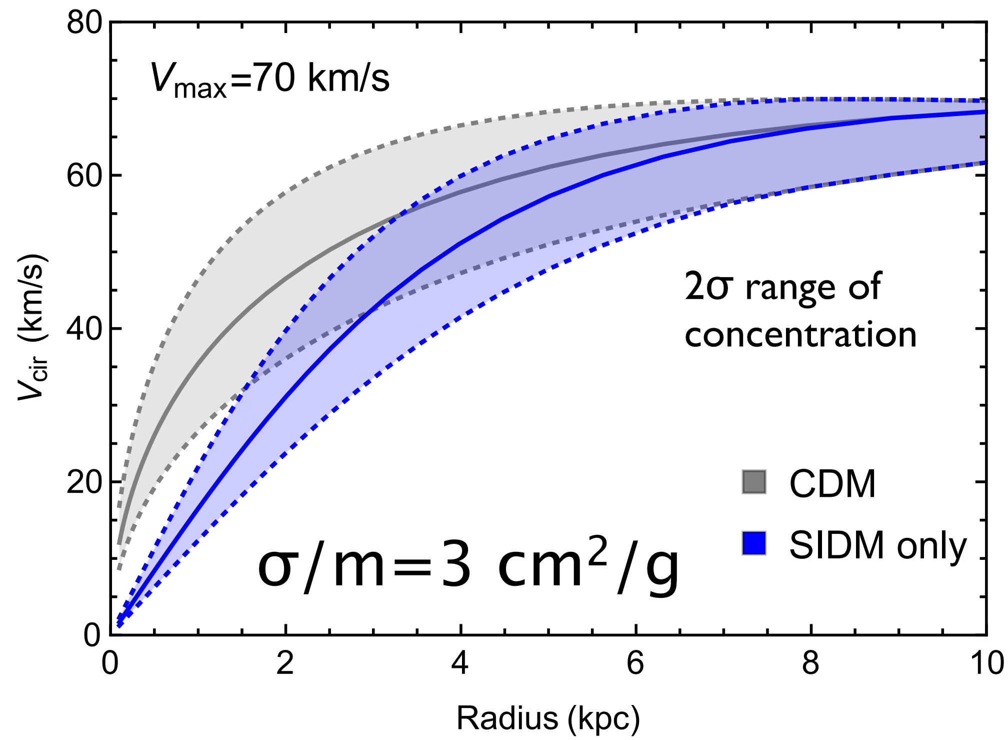
$$(\rho_0, \sigma_0) \leftrightarrow (\rho_s, r_s)$$

with Kaplinghat, Keeley, Linden (PRL 2013)
with Kaplinghat, Tulin (PRL 2015)
with Kamada, Kaplinghat, Pace (PRL 2016)

Addressing the Diversity Problem

- DM self-interactions thermalize the inner halo





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

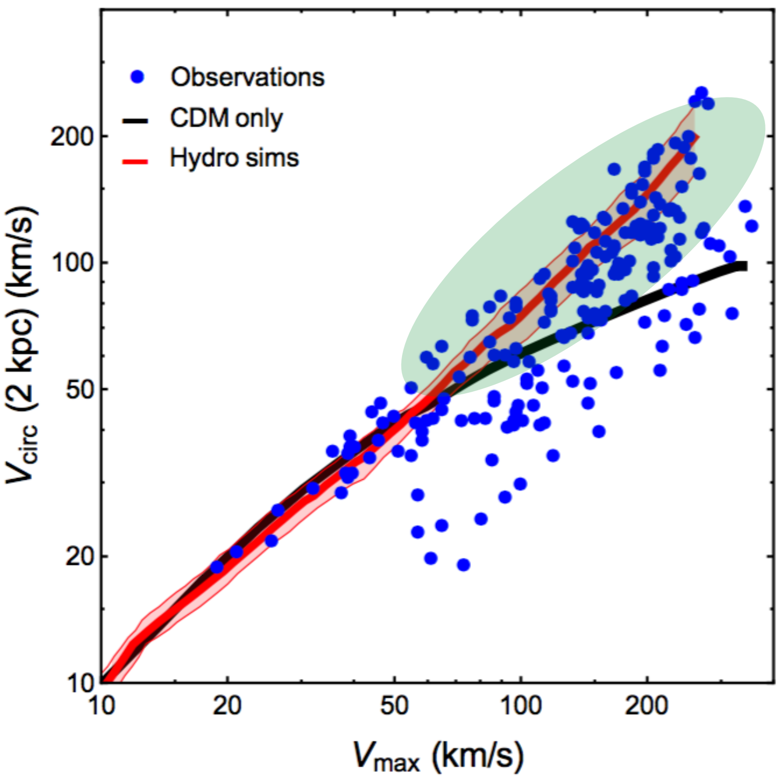
Isothermal distribution

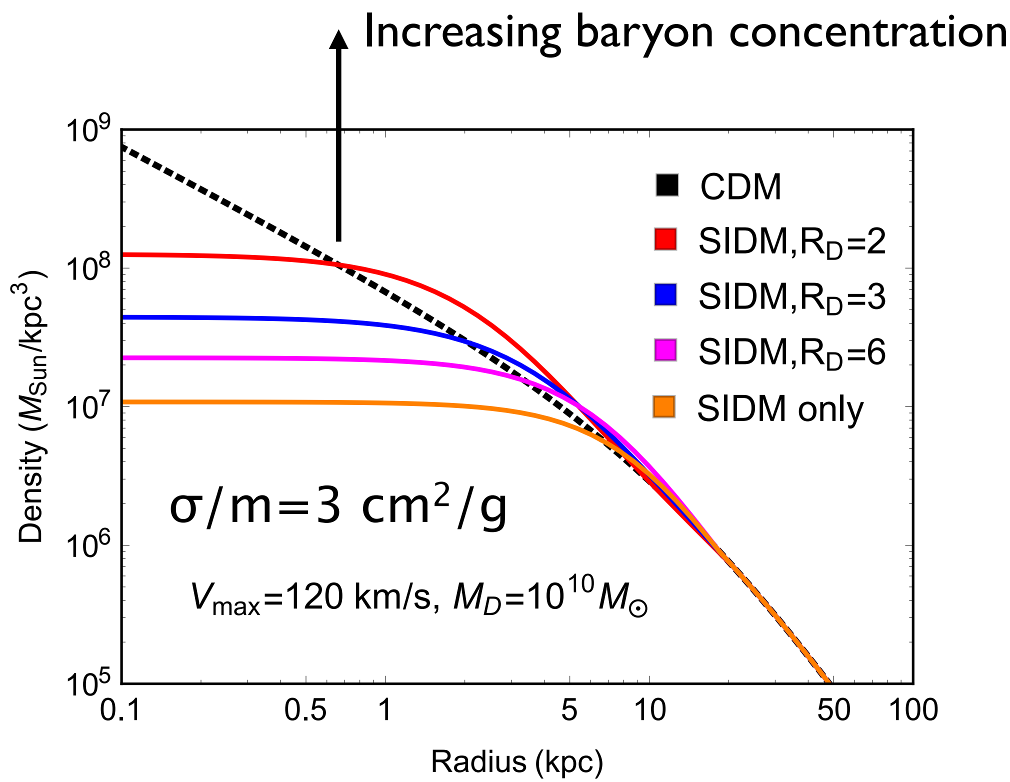
$$\rho_X \sim e^{-\Phi_{\rm tot}/\sigma_0^2} \sim e^{-\Phi_X/\sigma_0^2}$$

with Kamada, Kaplinghat, Pace (PRL 2016)

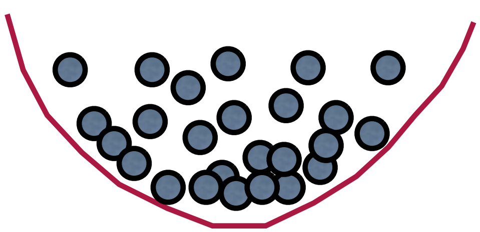
Addressing the Diversity Problem

- DM self-interactions tie DM together with baryons





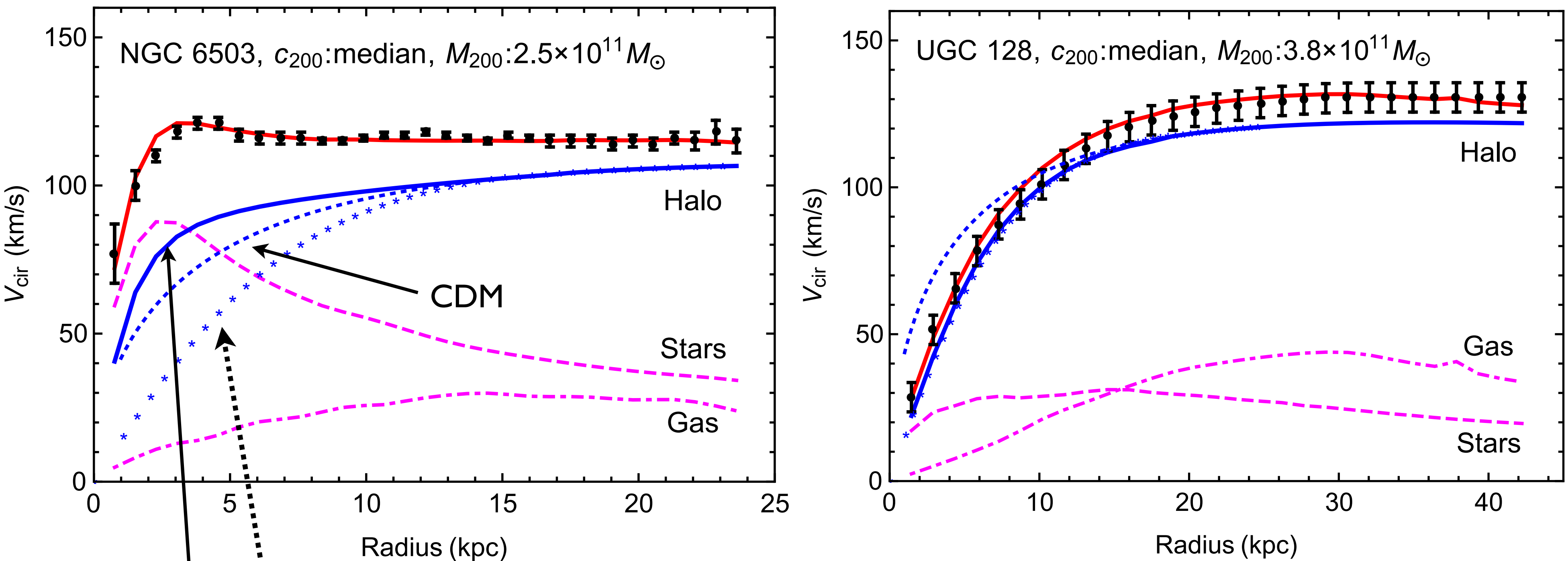
Thermalization leads to higher DM density due to the baryonic influence



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

with Kamada, Kaplinghat, Pace (PRL 2016)

Solving the Diversity Problem



Isothermal profile without the baryonic influence

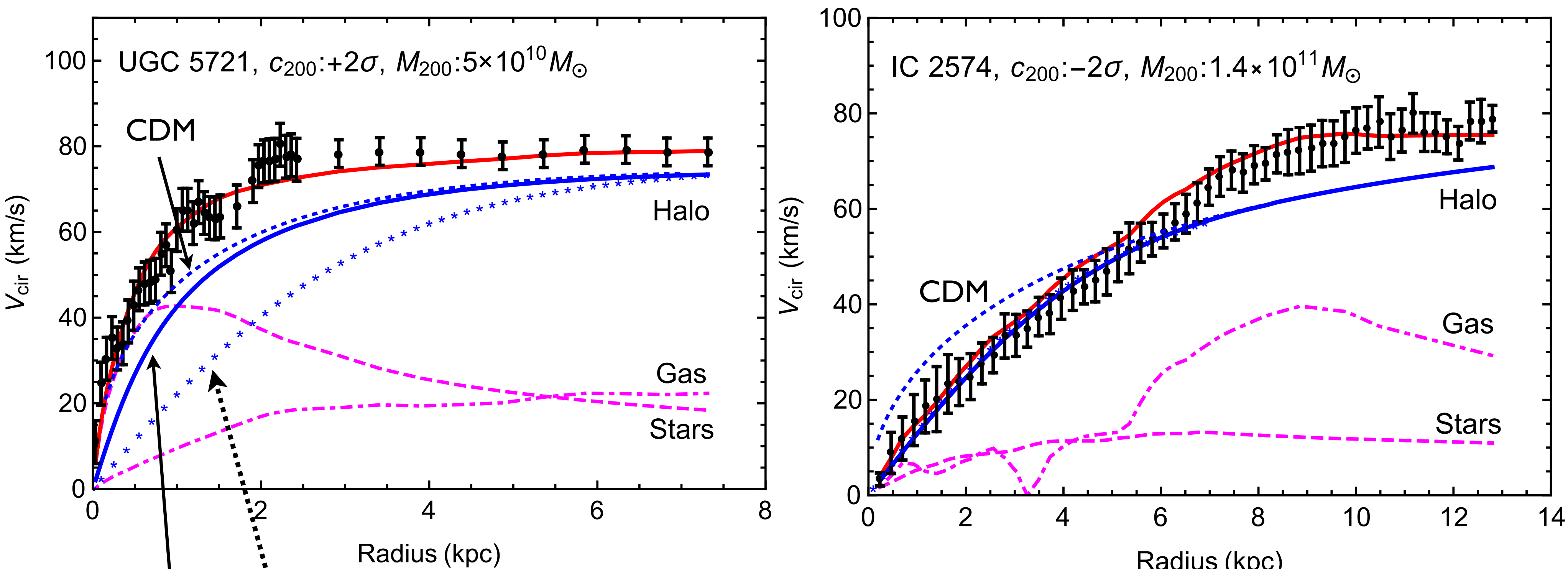
True SIDM profile with the baryonic influence

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

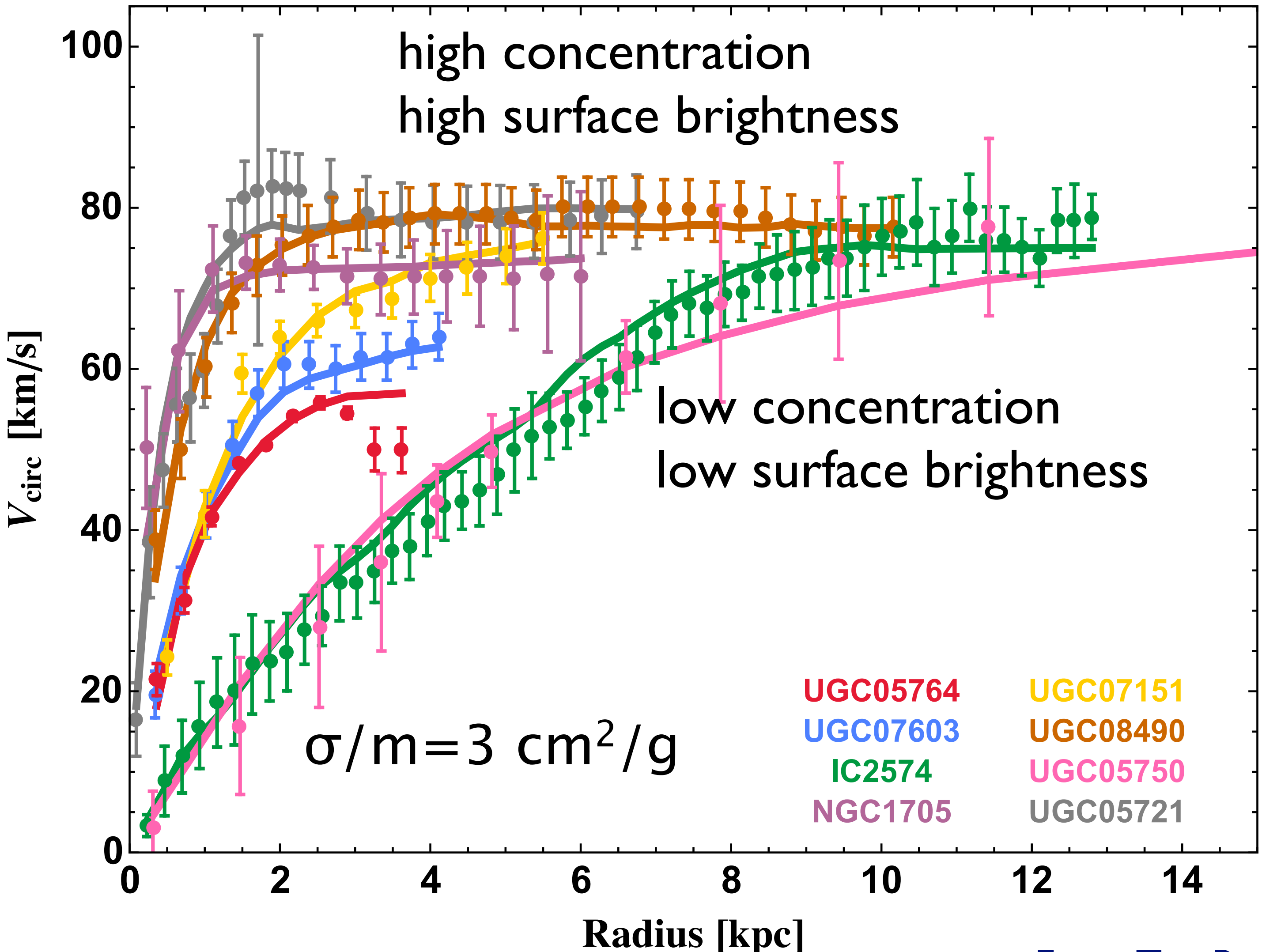


Isothermal profile without the baryonic influence

True SIDM profile with the baryonic influence

Scatter in the halo concentration-mass relation

with Kamada, Kaplinghat, Pace (PRL, 2016)

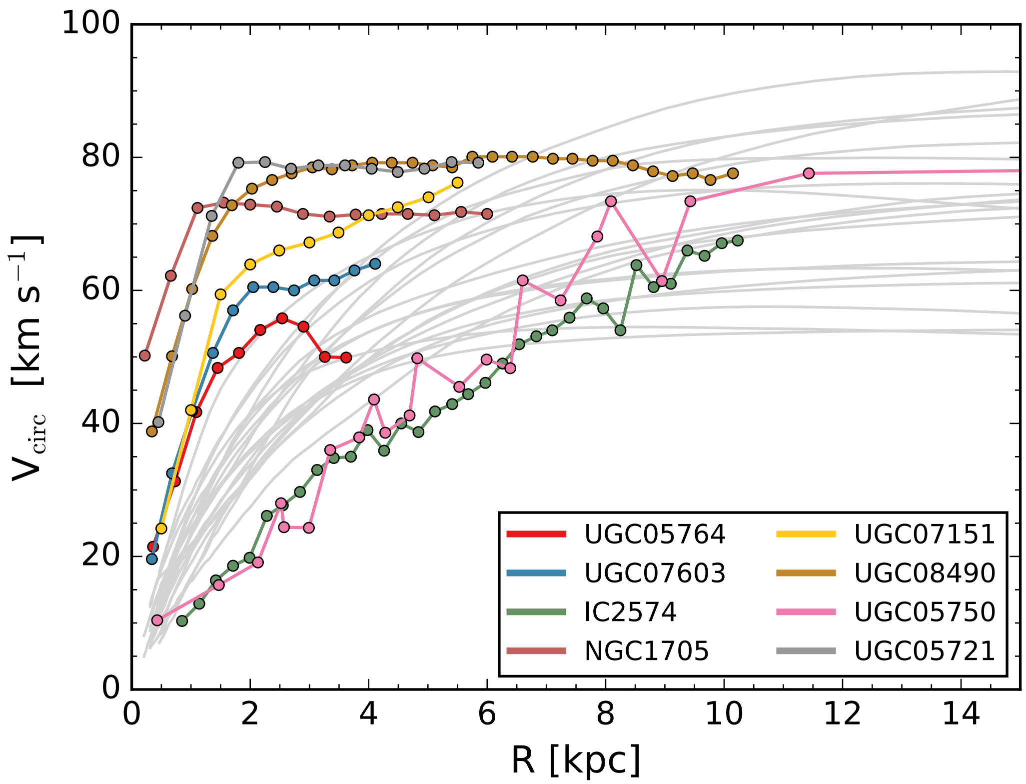


From Tao Ren

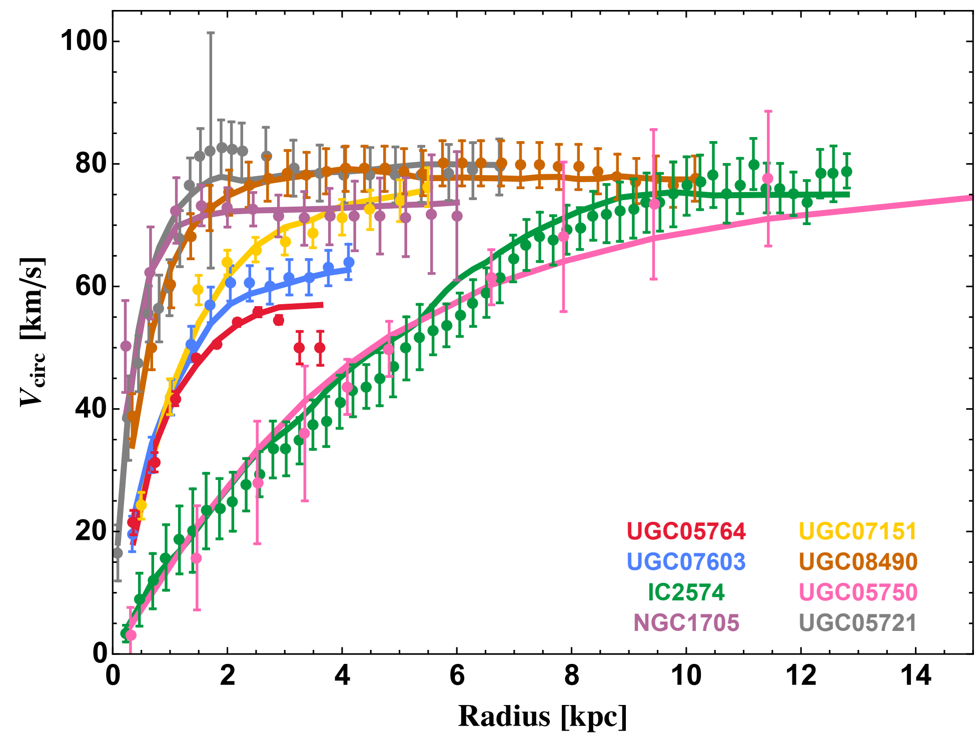
- Scatter in the halo concentration-mass relation (~2σ)
- Baryon distribution
- SIDM thermalization ties DM and baryon distributions

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

Strong Feedback vs SIDM



Santos-Santos et al. (2017)



From Tao Ren

Gray: NIHAO CDM simulations

"strong/violent" feedback

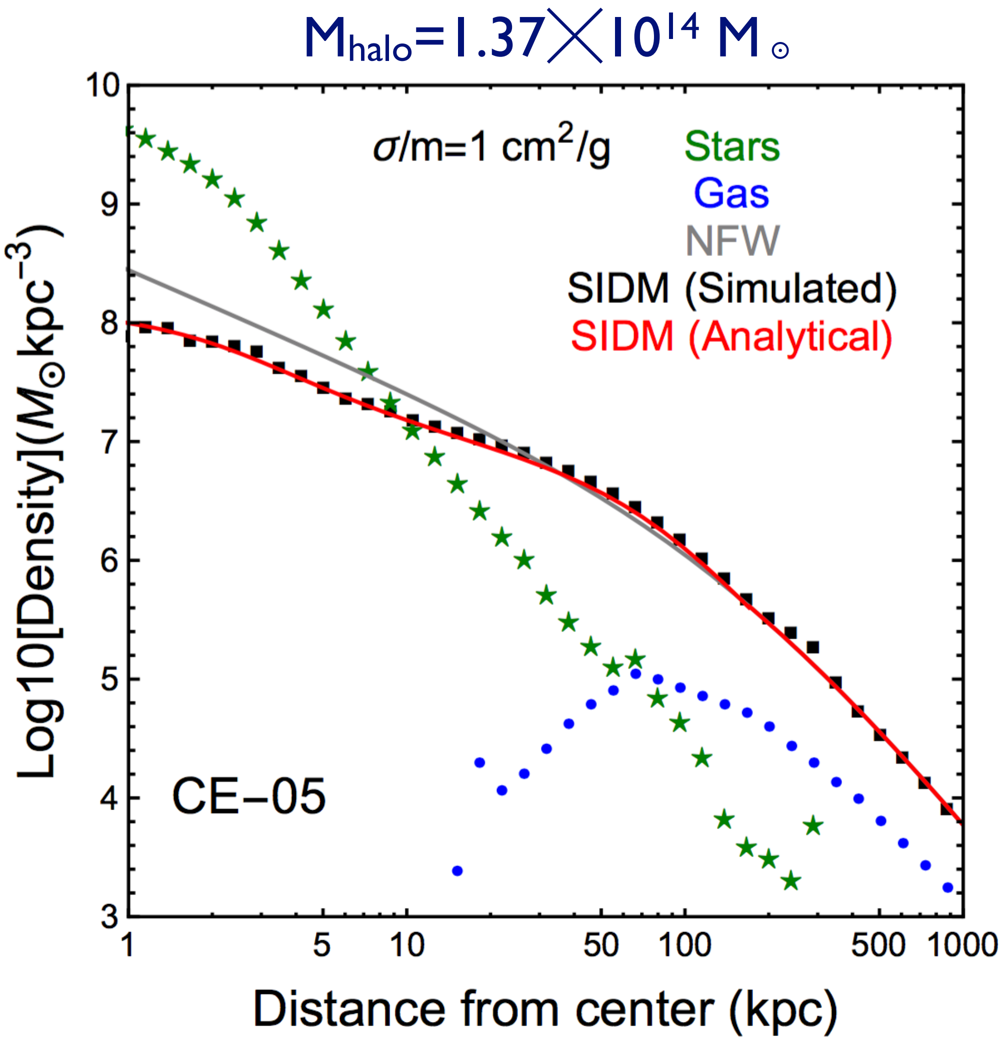
Observed scatter: ~4 (3σ away)

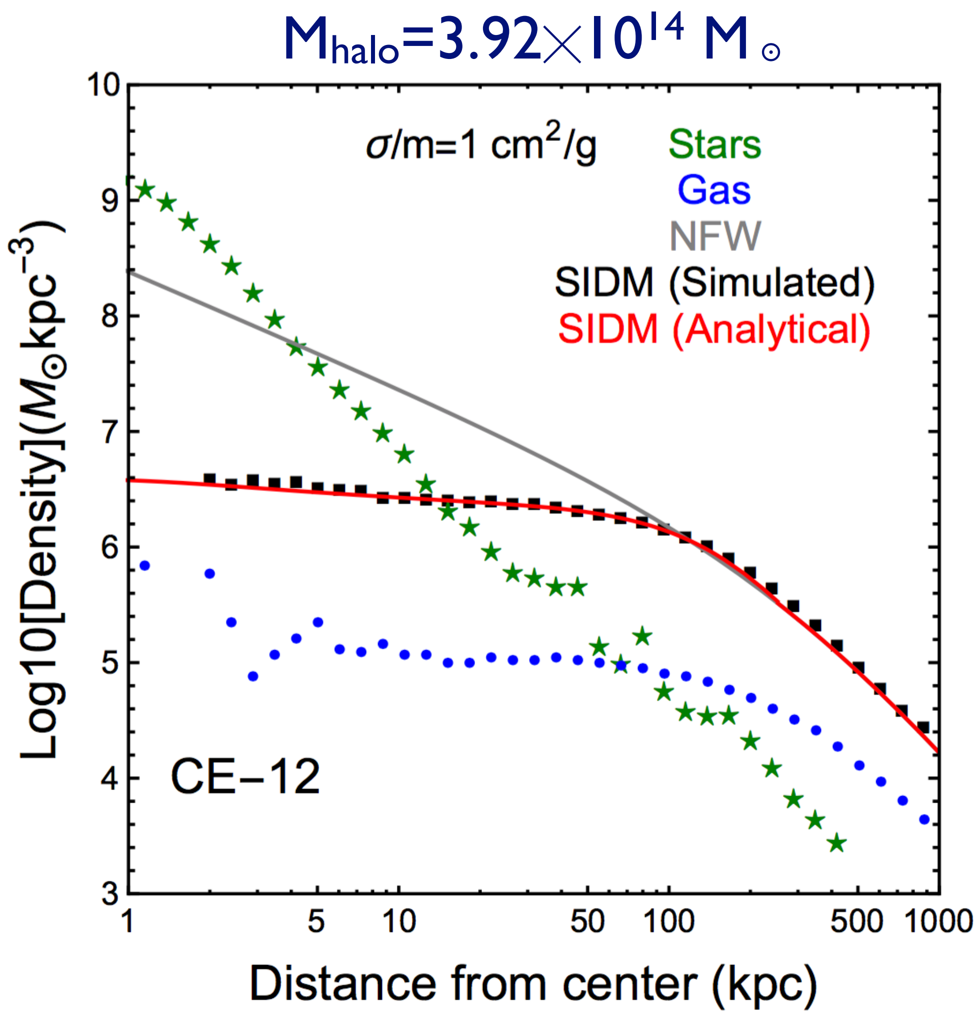
Simulations: ~2

Solid lines: SIDM fits

(~2σ in the c_{200}-M_{200} relation)

Hydro SIDM Simulations

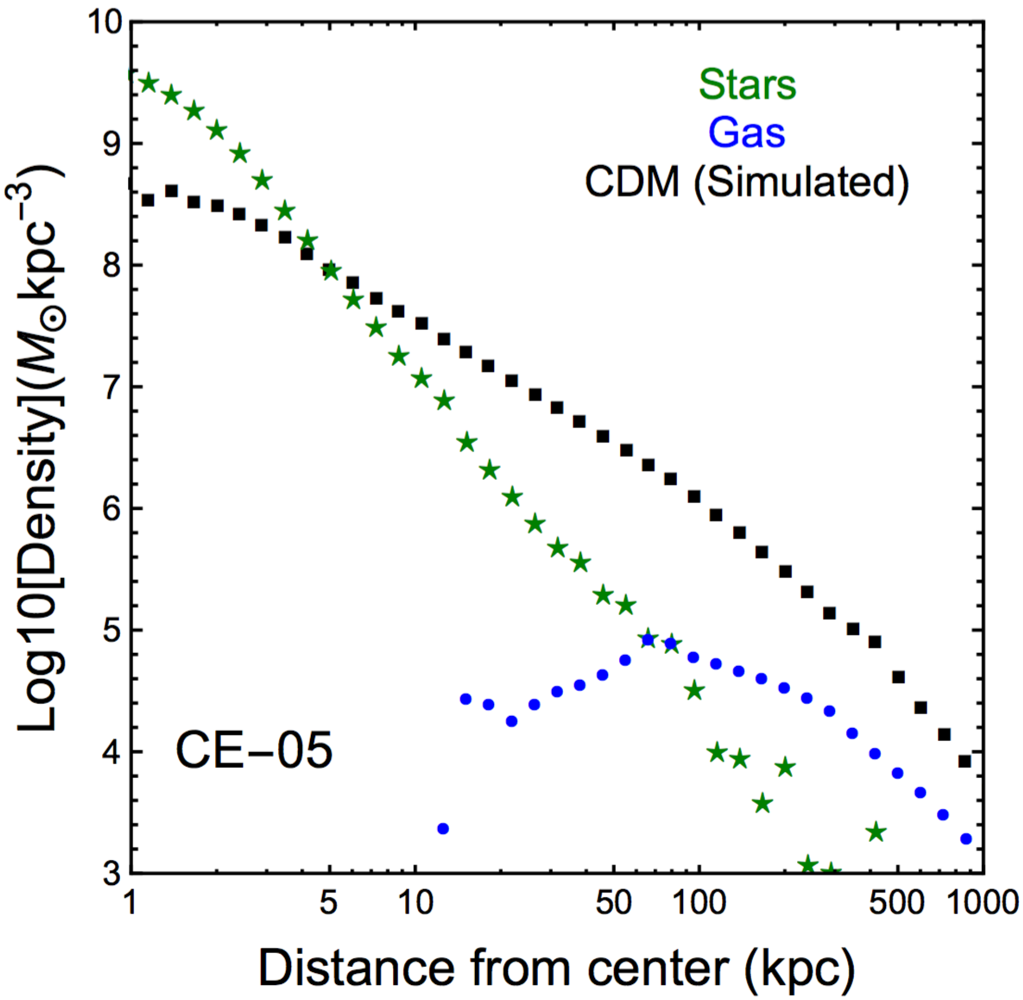


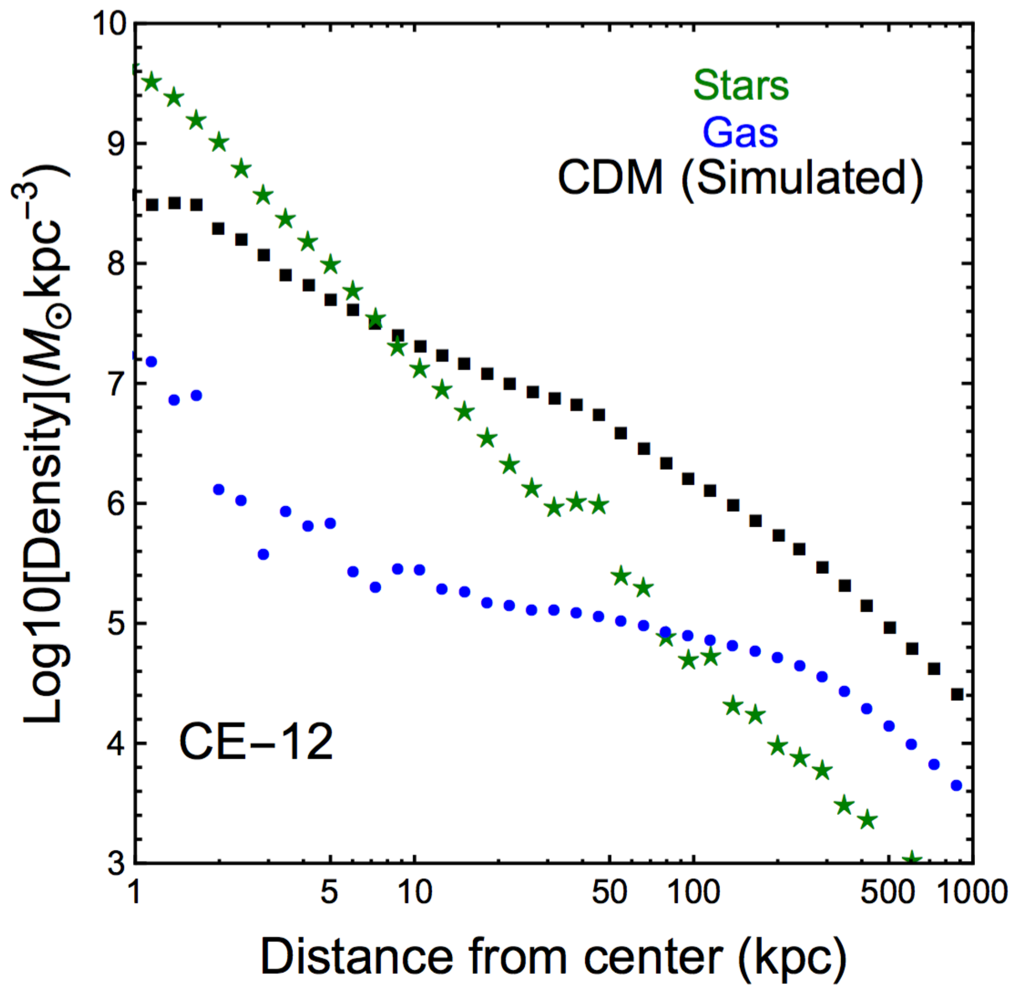


With Robertson, Massey, Eke, Tulin, et al. (MNRAS Letters, 2017)

- The SIDM distribution is sensitive to the final baryon distribution
- But, it is not sensitive to the formation history
- Both baryon and DM distributions are different

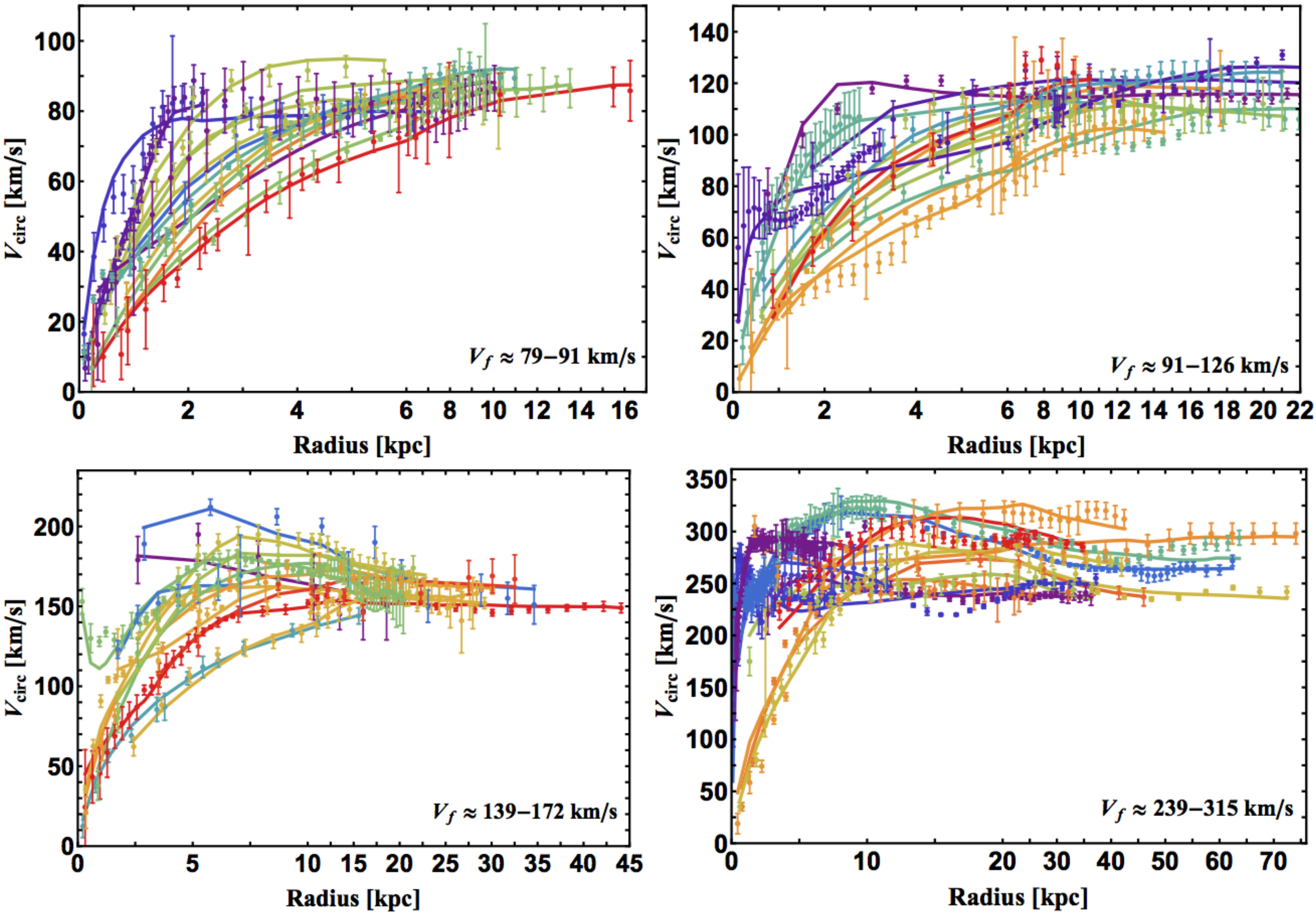
Hydro SIDM vs CDM





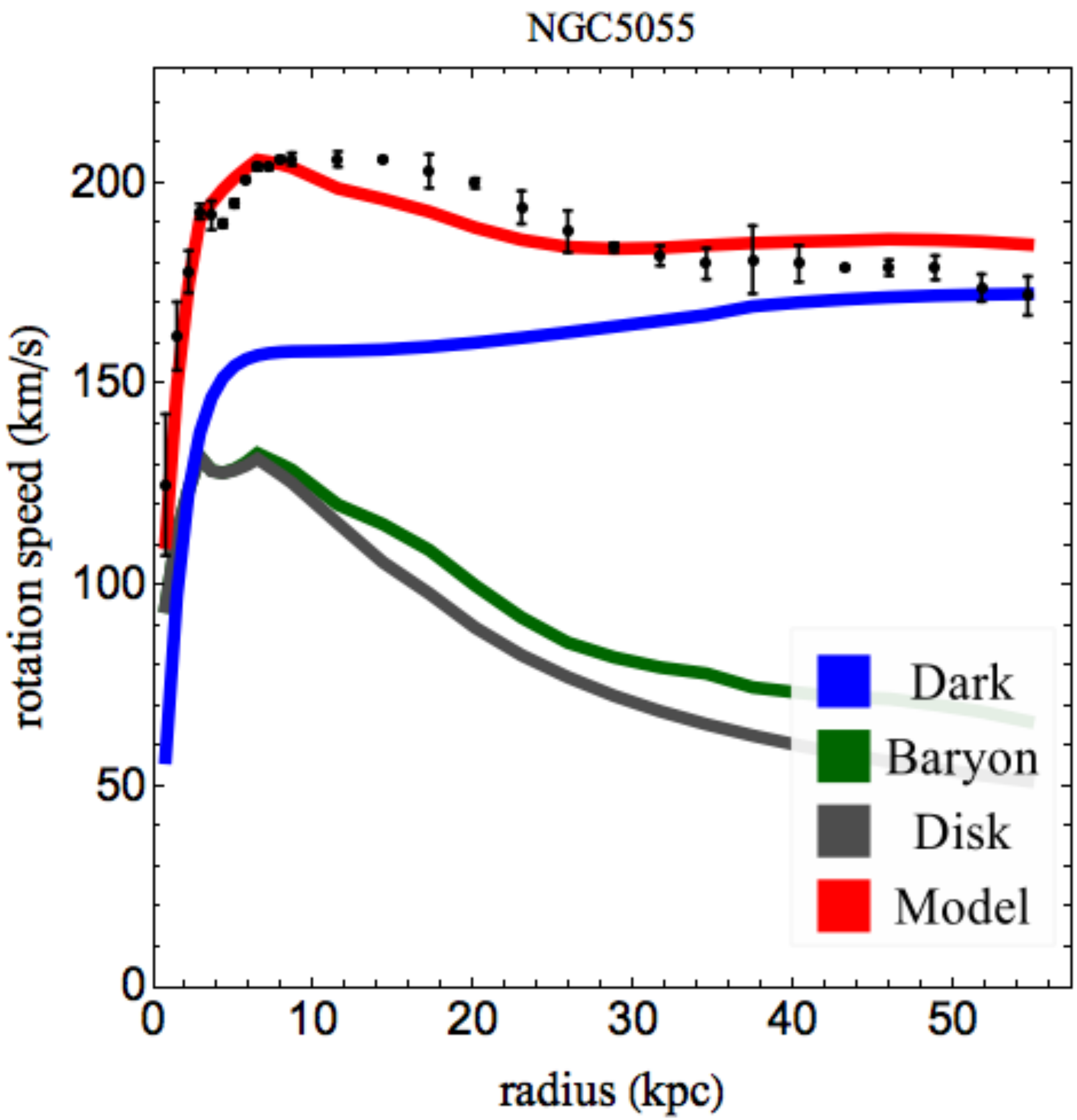
With Robertson, Massey, Eke, Tulin, et al. (MNRAS Letters, 2017)

Both the DM and baryon distributions are more diverse in the SIDM case than the CDM one.



We have fitted to 135 galaxies

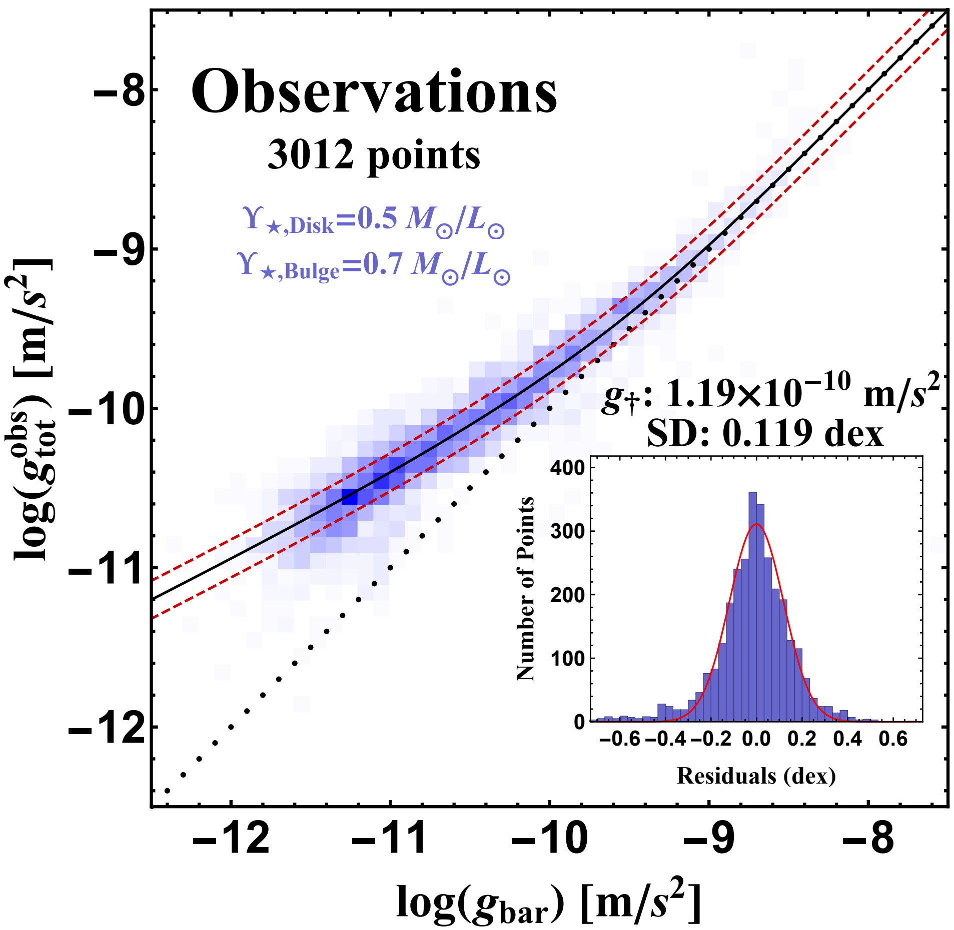
with Ren, Kwa, Kaplinghat (in prep)



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



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

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

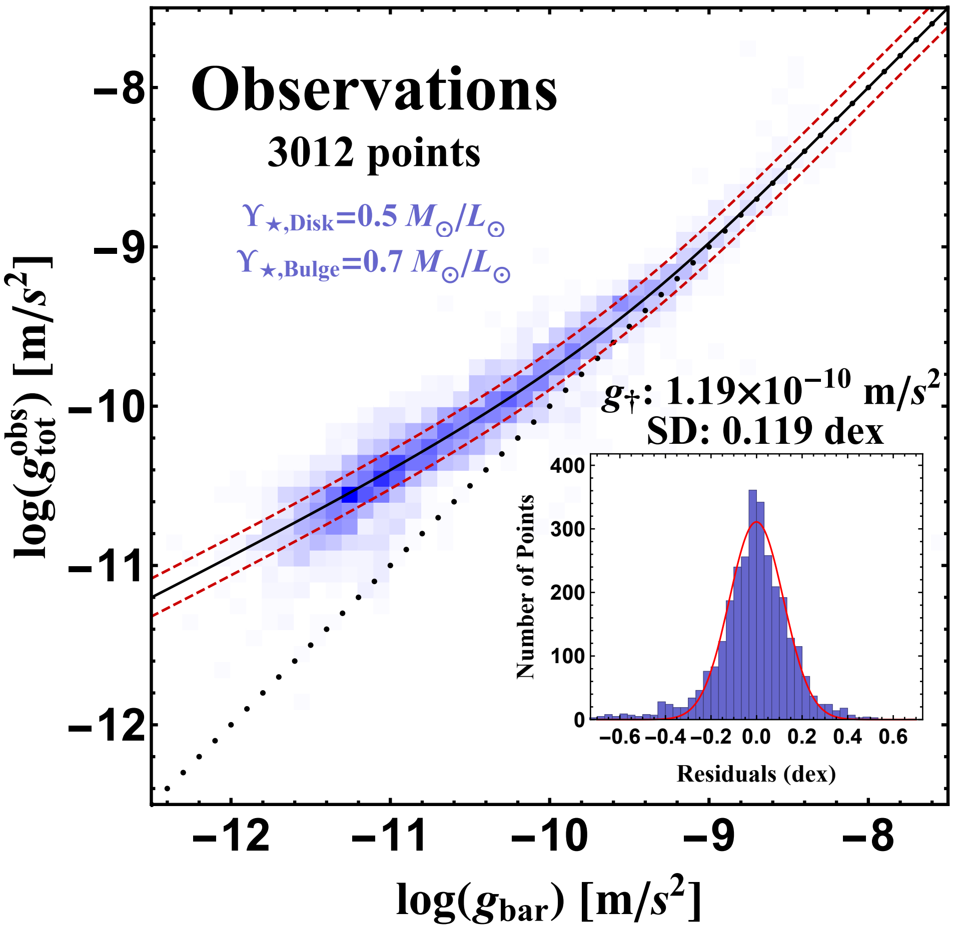
when $g_{\mathrm{bar}} < g_\dagger$

MOND, Milgrom's law (1983)

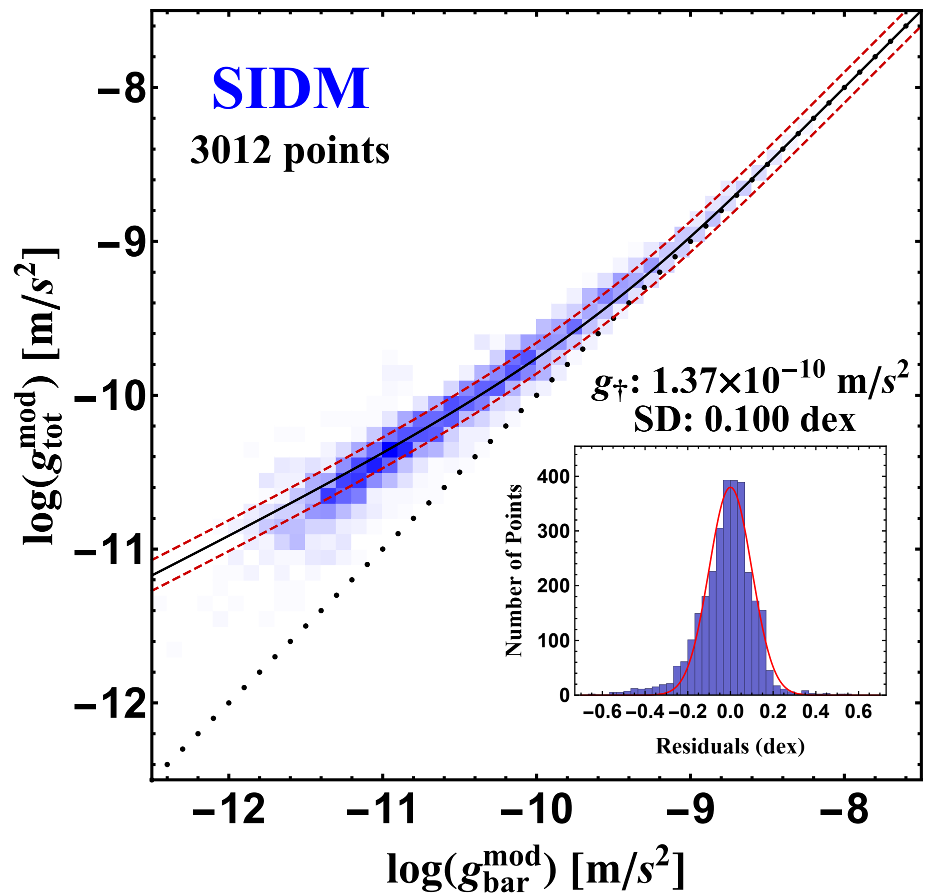
Reproduced, see McGaugh, Lelli, Schombert (PRL 2016)

135 galaxies "Uniformity"

Uniformity in SIDM

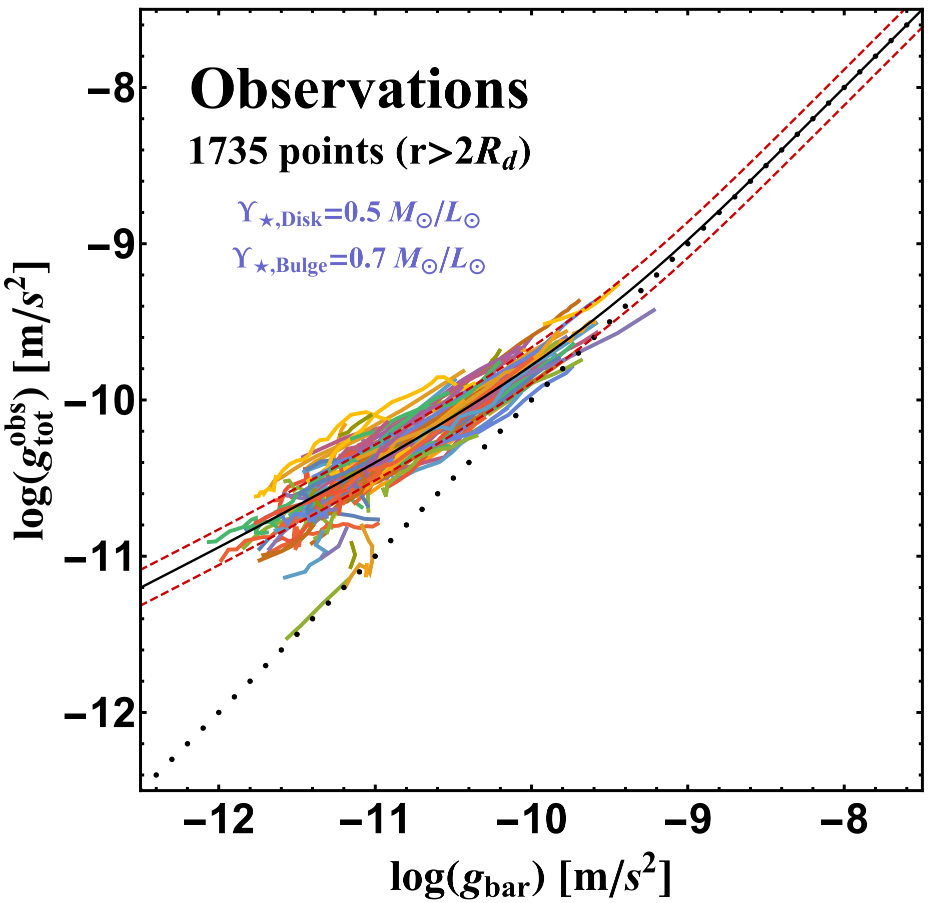


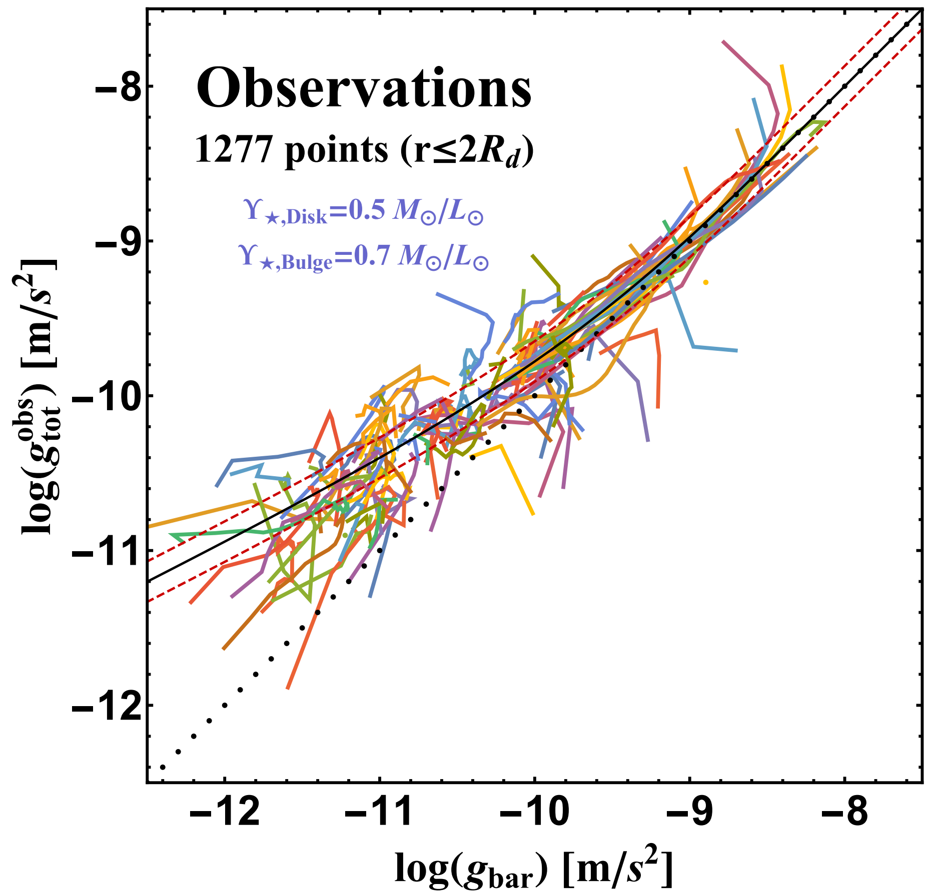
135 galaxies



With Ren, Kwa, Kaplinghat (in prep)

Diversity in the RAR

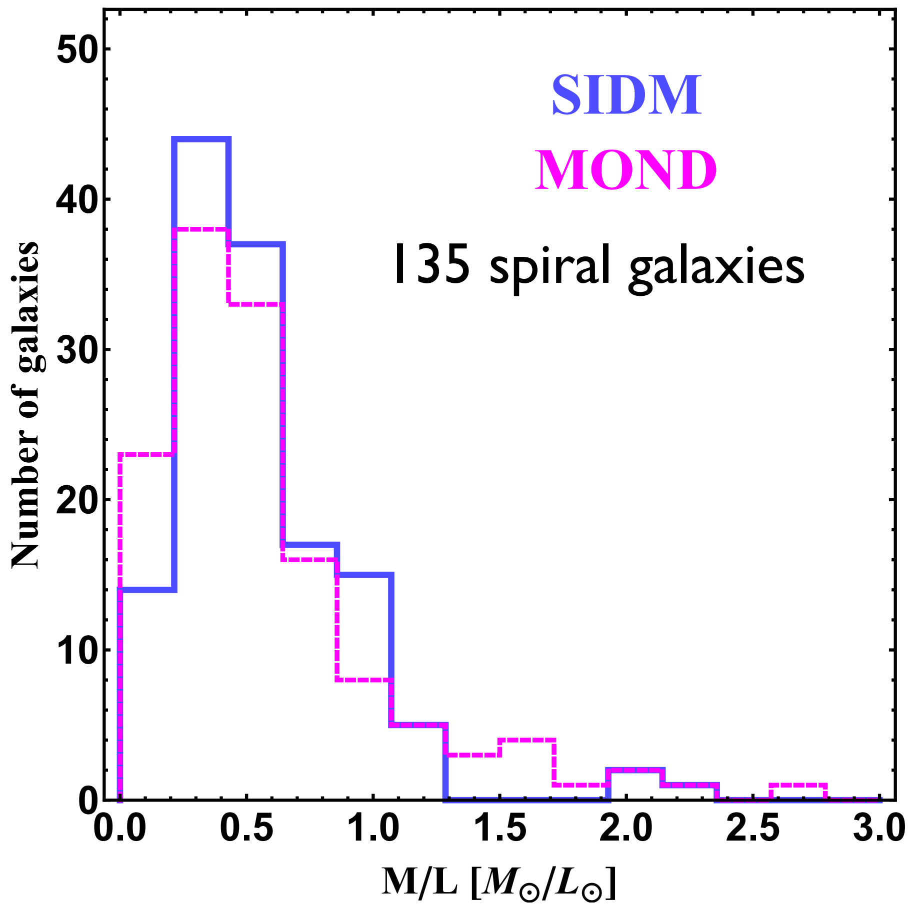


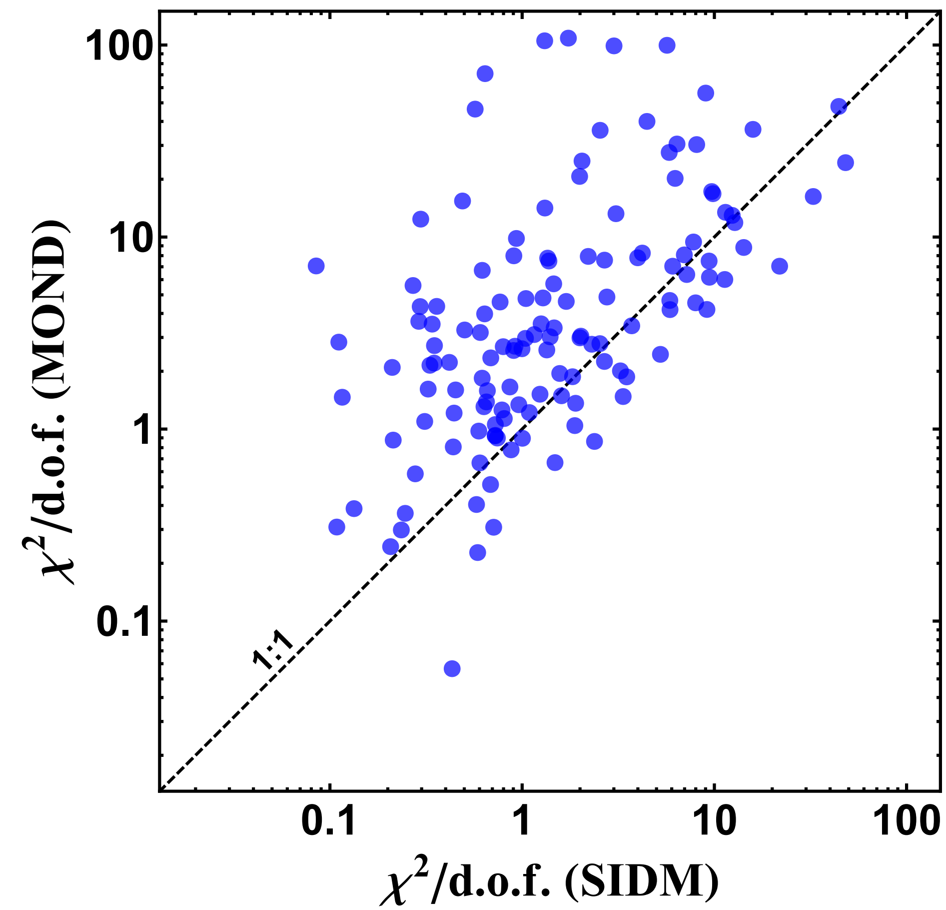


- The RAR has a large scatter for the inner regions
- The acceleration scale inferred from the SIDM fits is an average quantity over the sample, not a universal value for all the galaxies as in MOND.

With Ren, Kwa, Kaplinghat (in prep)

SIDM vs MOND

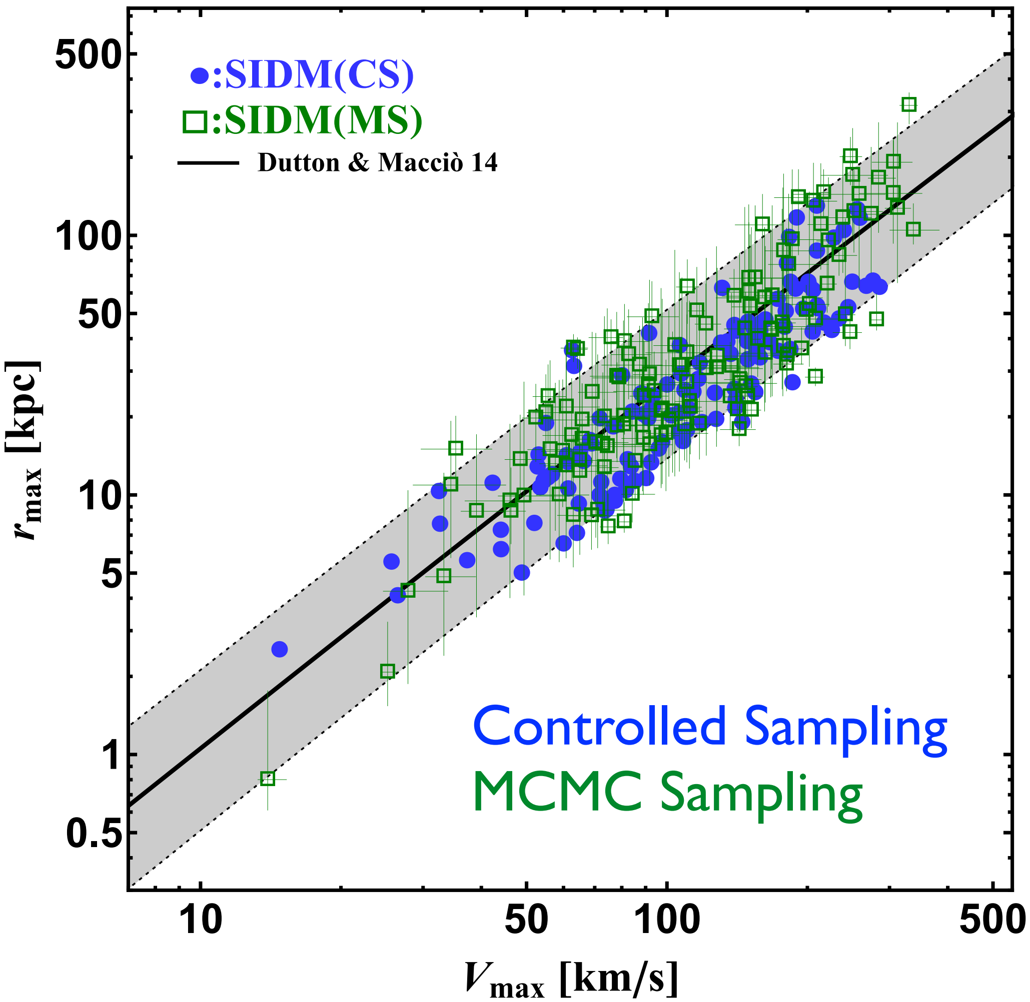




- Both SIDM and MOND fits have the disk mass-to-light ratio peaked around $0.5 M_\odot/L_\odot$.
- For 77% of the galaxies, the SIDM fits are better than the MOND ones.
- SIDM explains both the diversity and the uniformity

with Ren, Kwa, Kaplinghat (in prep)

Properties of the Hosting Halos



~95% galaxies can be fitted within 2σ

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

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

The origin of the acceleration scale:

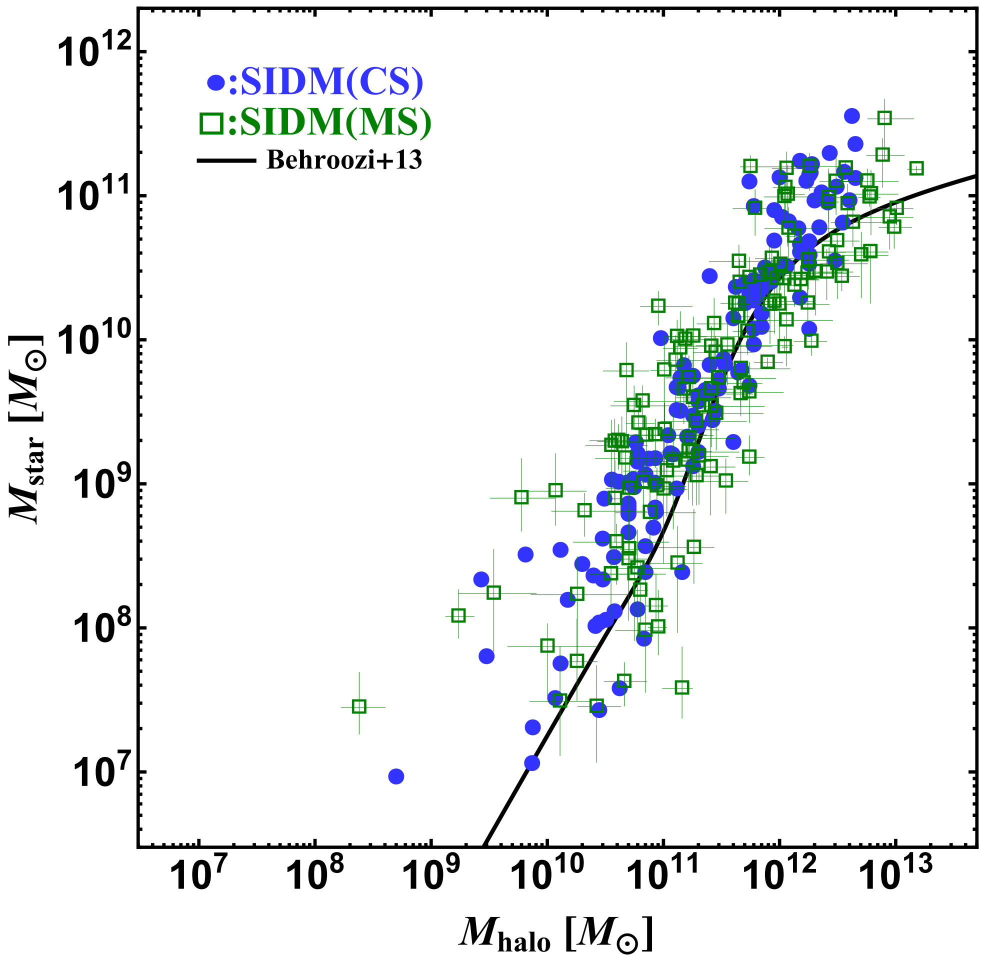
$$r_{\rm max} = 27\ {\rm kpc}(V_{\rm max}/100\ {\rm km/s})^{1.4}$$

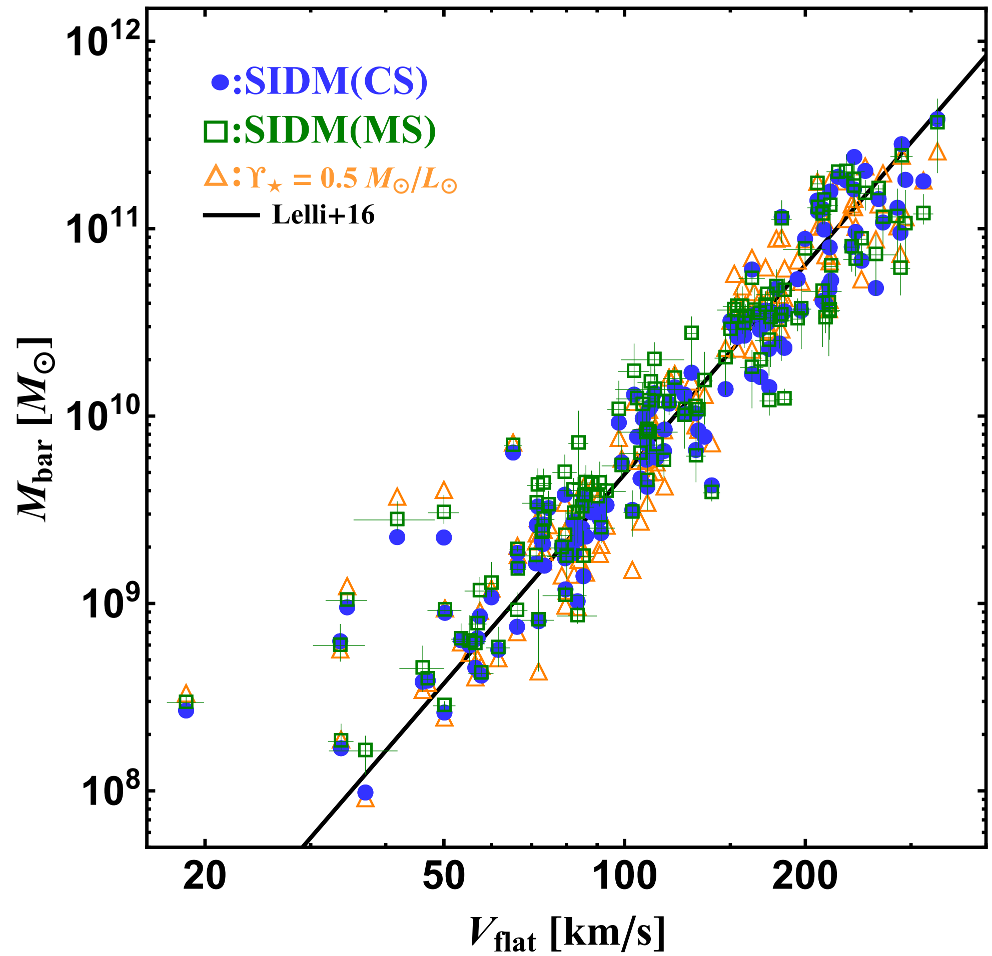
$$a|_{r=0} \approx 1.0 \times 10^{-10}\ {\rm m/s^2} \left(\frac{V_{\rm max}}{240\ {\rm km/s}}\right)^{0.6}$$

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

with Ren, Kwa, Kaplinghat (in prep)

Baryon-Halo Relations



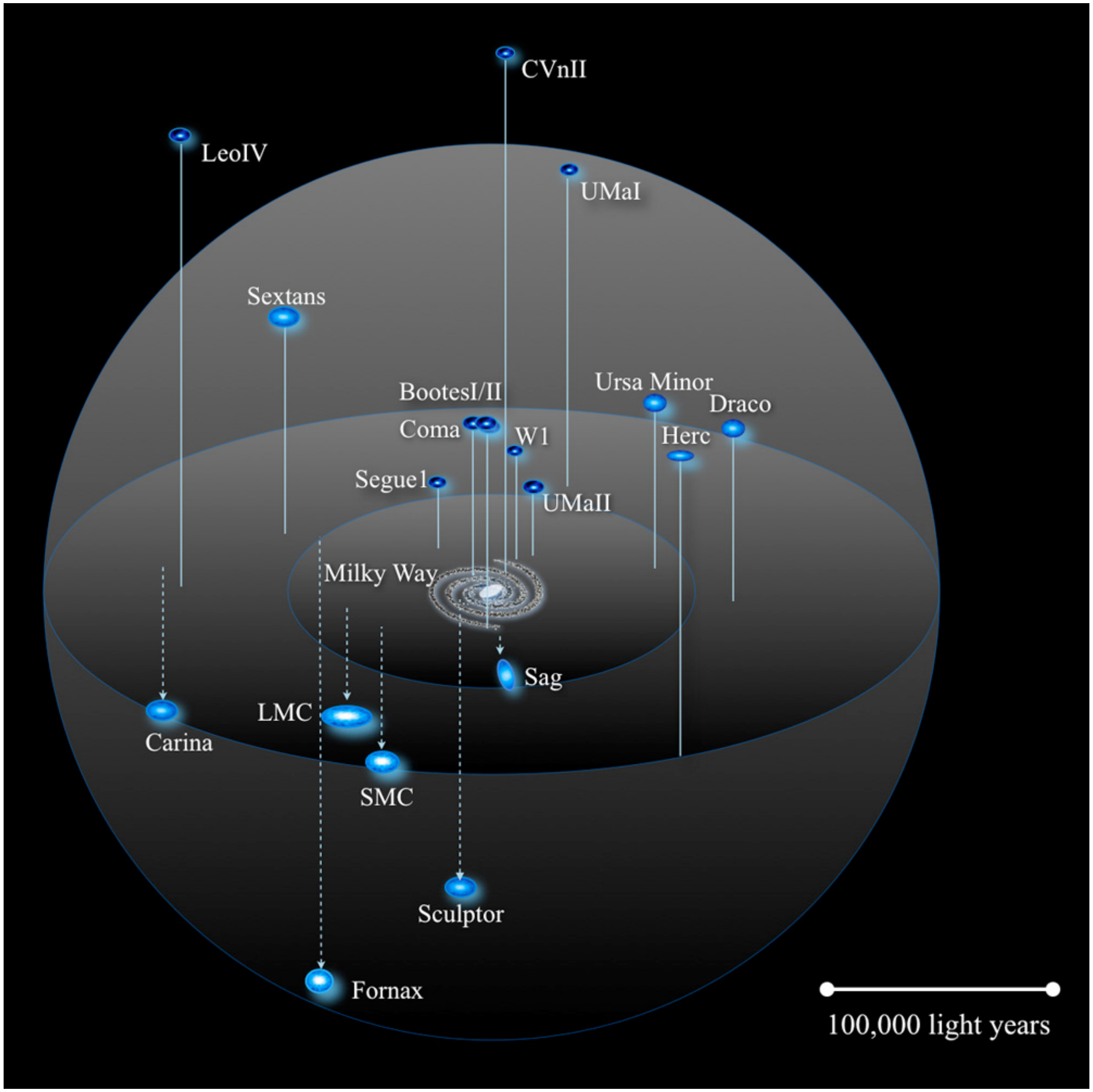


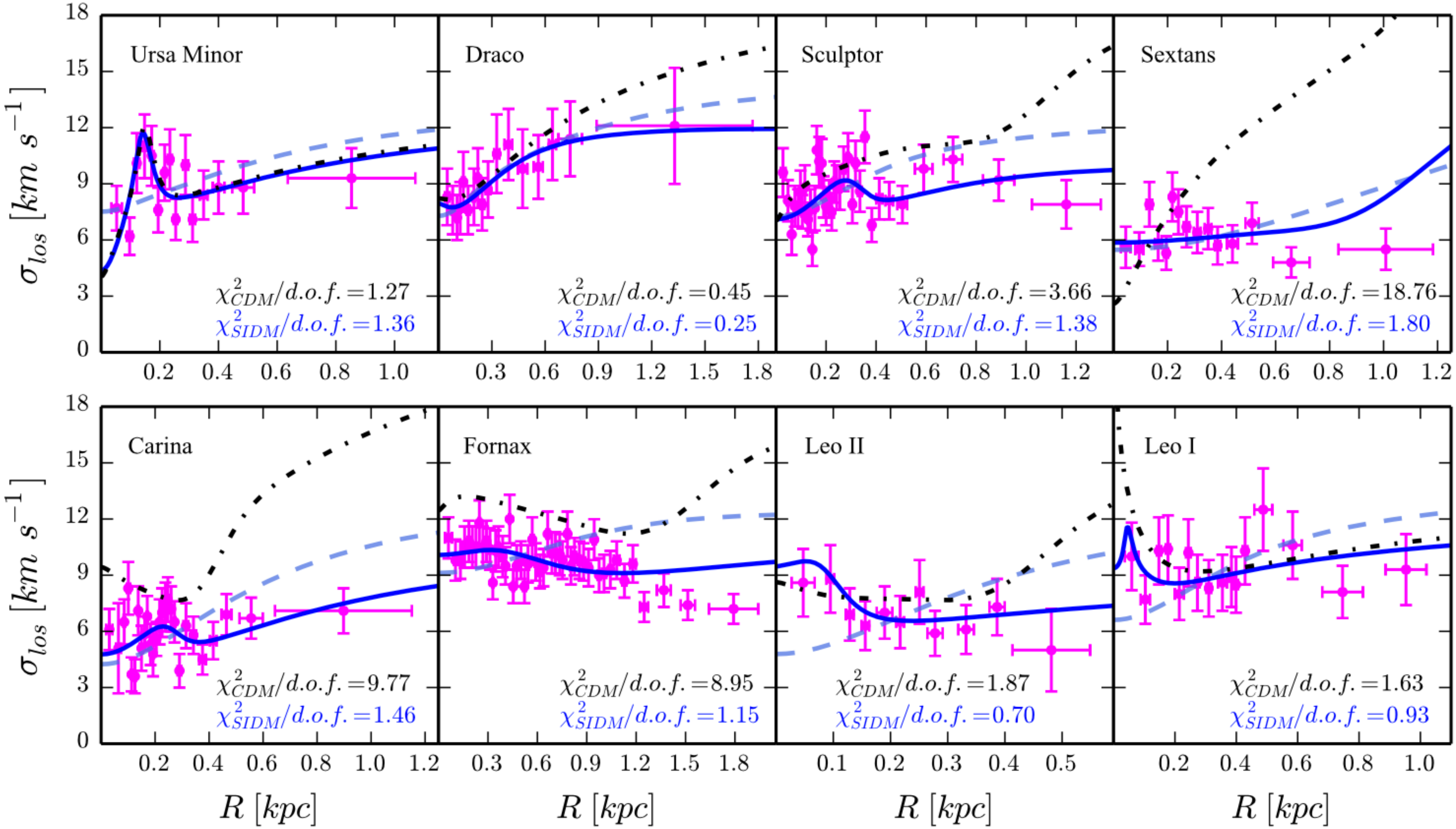
with Ren, Kwa, Kaplinghat (in prep)

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

Not 4, predicted in MOND

Dwarf Spheroidal Galaxies





Dot-dashed black: CDM (best fit)

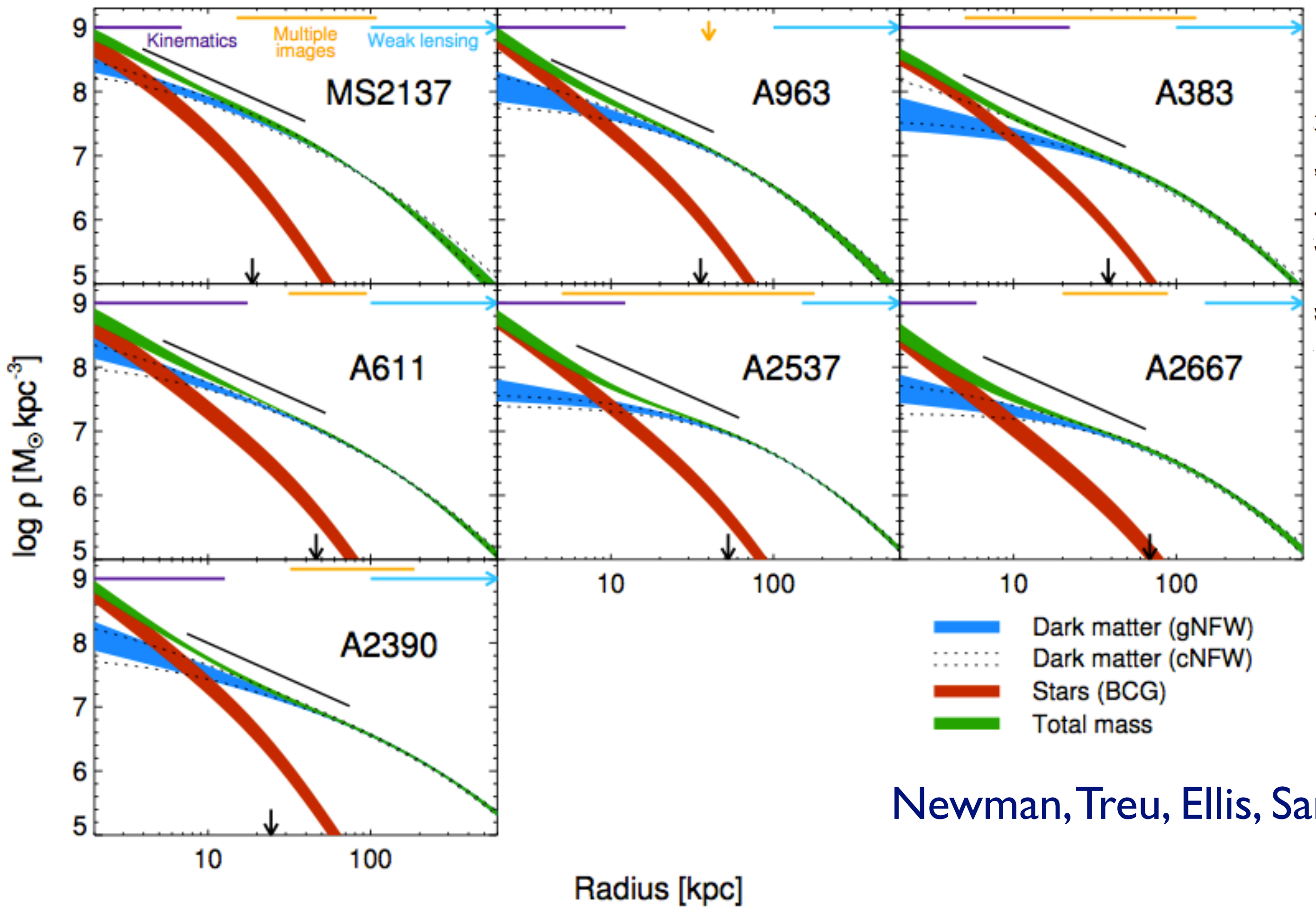
Solid blue: SIDM (spatially varying stellar anisotropy)

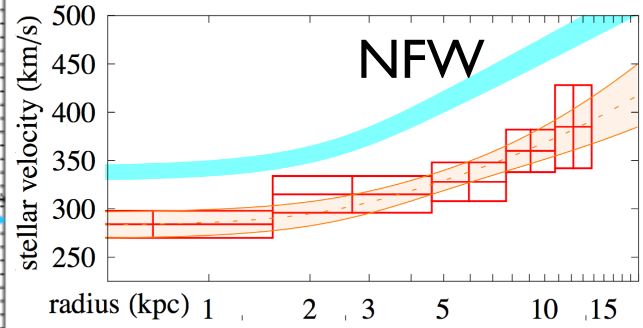
Dashed blue: SIDM (spatially constant stellar anisotropy)

Valli & HBY (Nature Astronomy, 2017)

Galaxy Clusters

- Seven well-resolved galaxy clusters





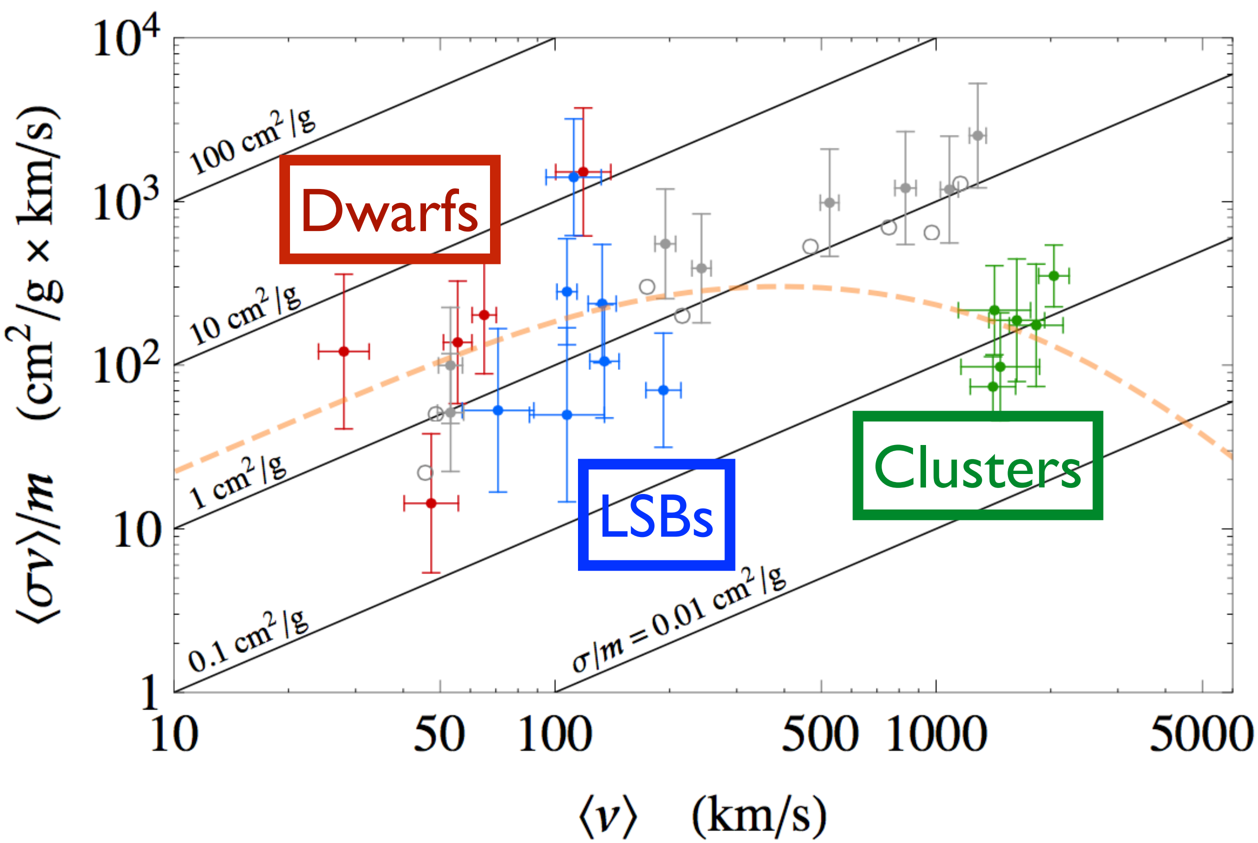
Newman, Treu, Ellis, Sand (2013)

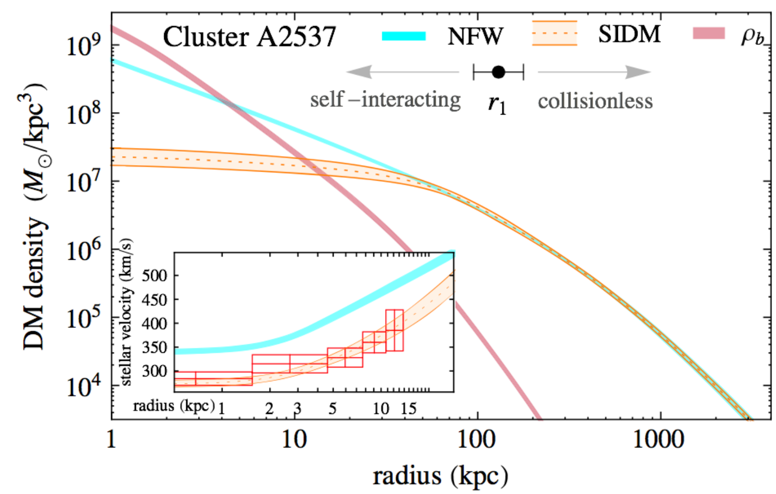
- CDM halos contain more DM in the central regions than needed

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 cm²/g

Clusters: ~0.1 cm²/g

DM halos as particle colliders

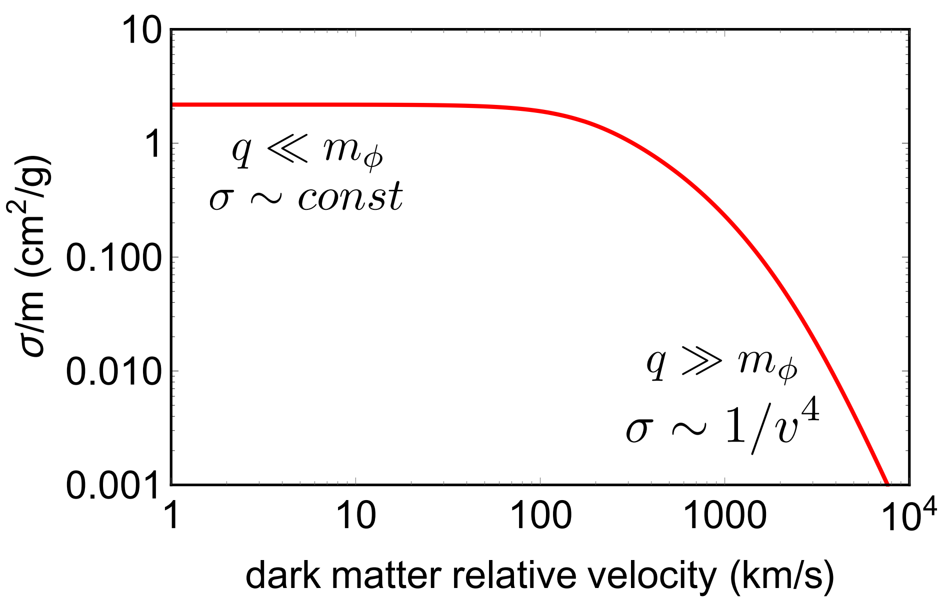
With Kaplinghat, Tulin (PRL, 2015)

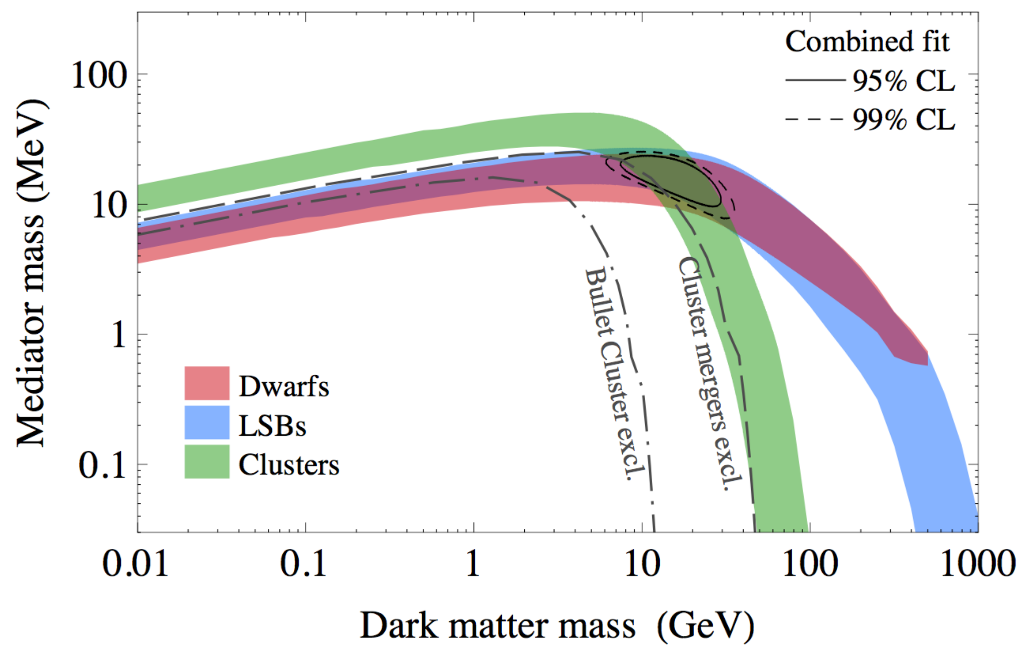
See also Yoshida et al. (APJ Letters, 2000)

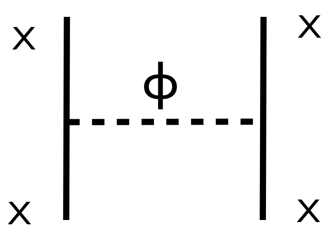
Merging Clusters: < ~2 cm²/g

Measuring Dark Matter Mass

- Self-scattering kinematics determines SIDM mass







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

α_X=1/137

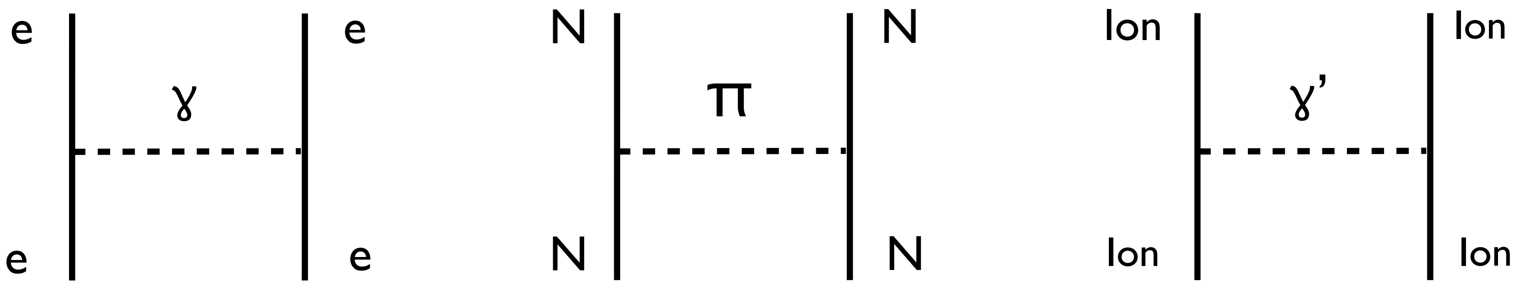
m_X: ~15 GeV, m_ϕ: ~17 MeV

with Feng, Kaplinghat (PRL 2012)

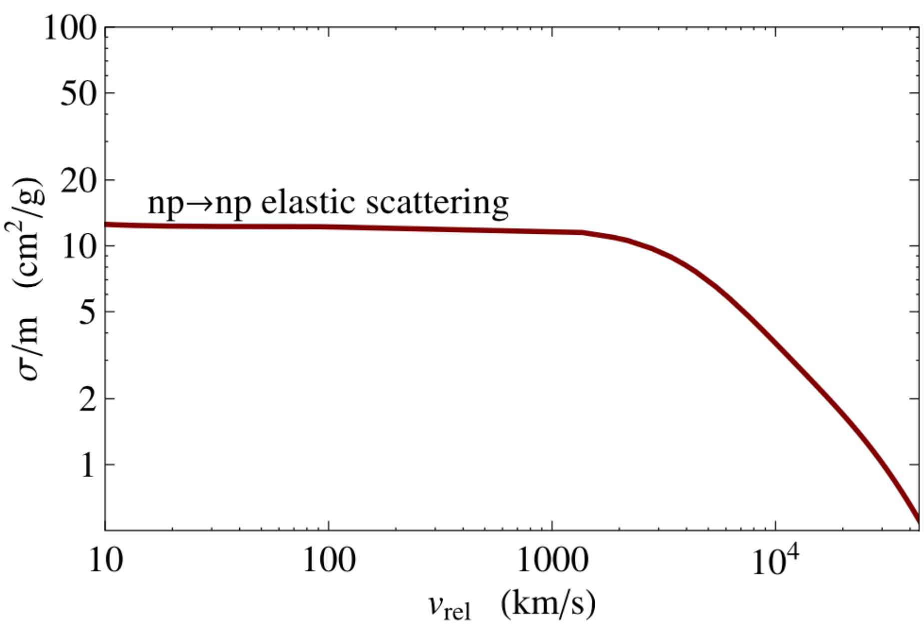
with Kaplinghat, Tulin (PRL 2015)

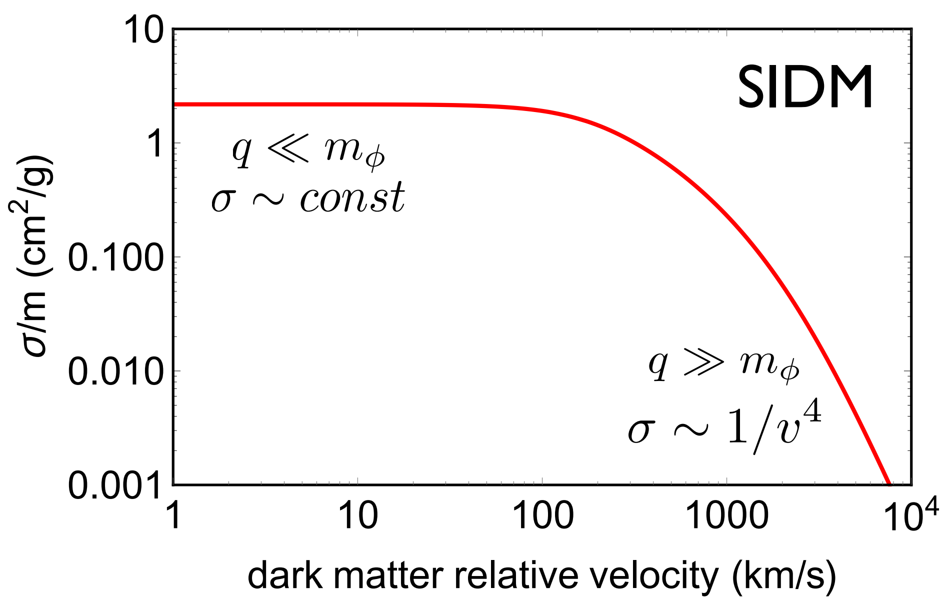
Particle Physics of SIDM

- Familiar examples in the visible sector



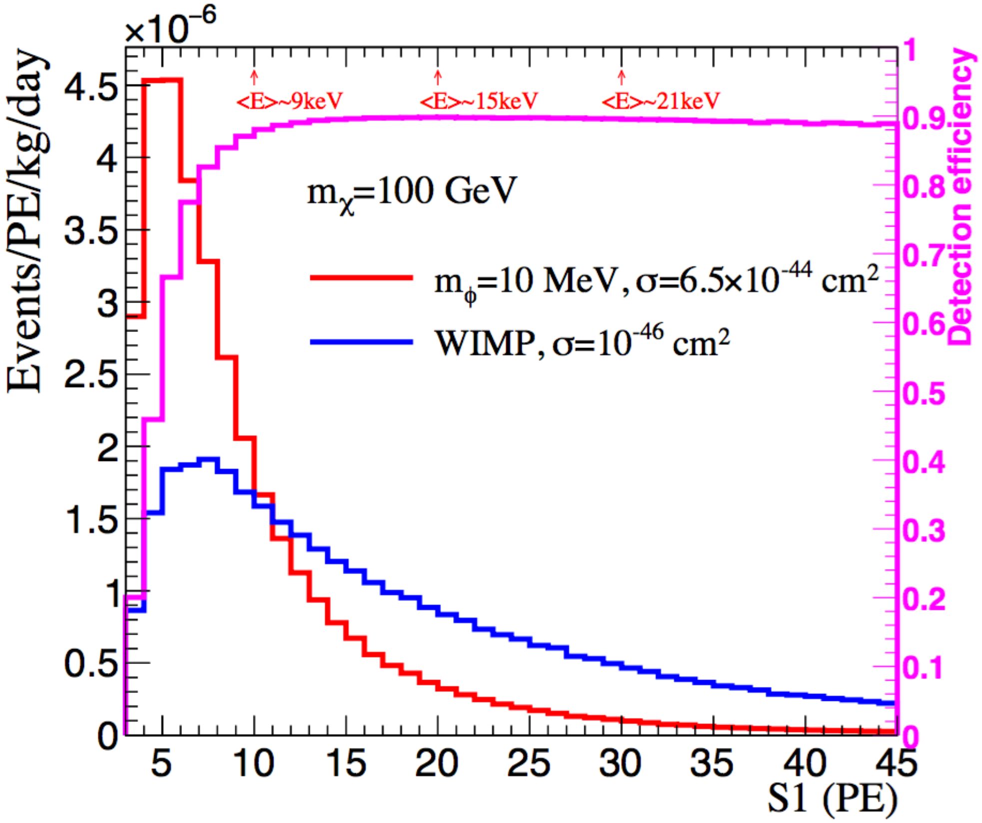
$$V(r) = \frac{\alpha_{\rm EM}}{r} \qquad V(r) = \frac{1}{r}e^{-m_\pi r} \qquad V(r) = \frac{\alpha_{\rm EM}}{r}e^{-m_D r}$$

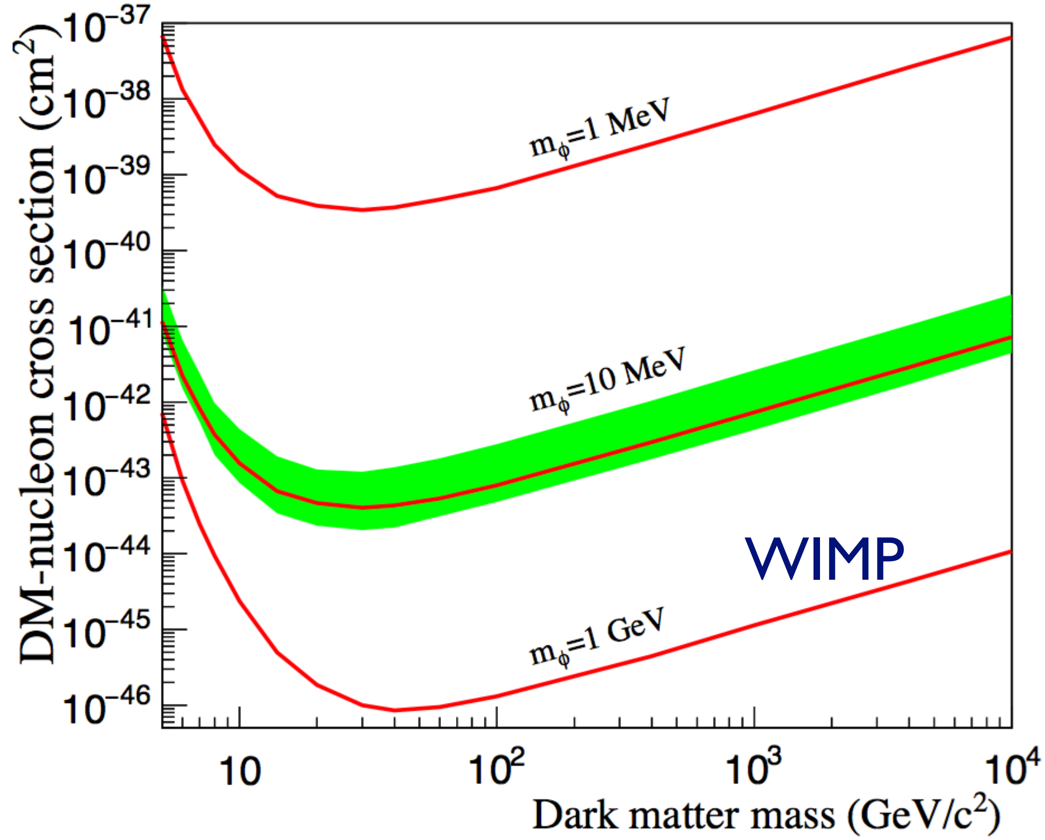


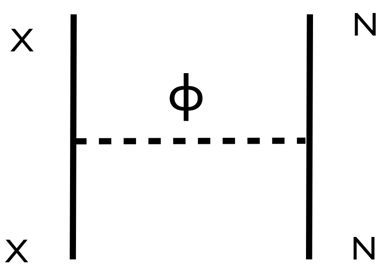


Tulin & HBY (2017)

Direct Detection





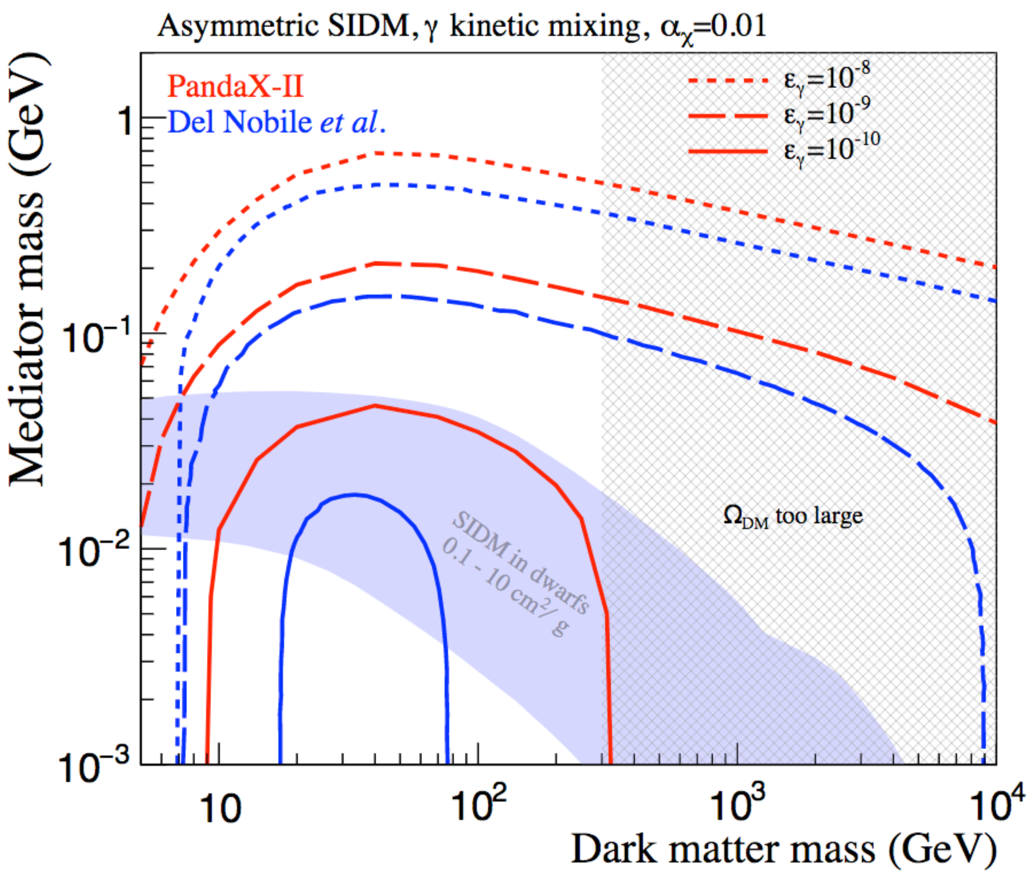


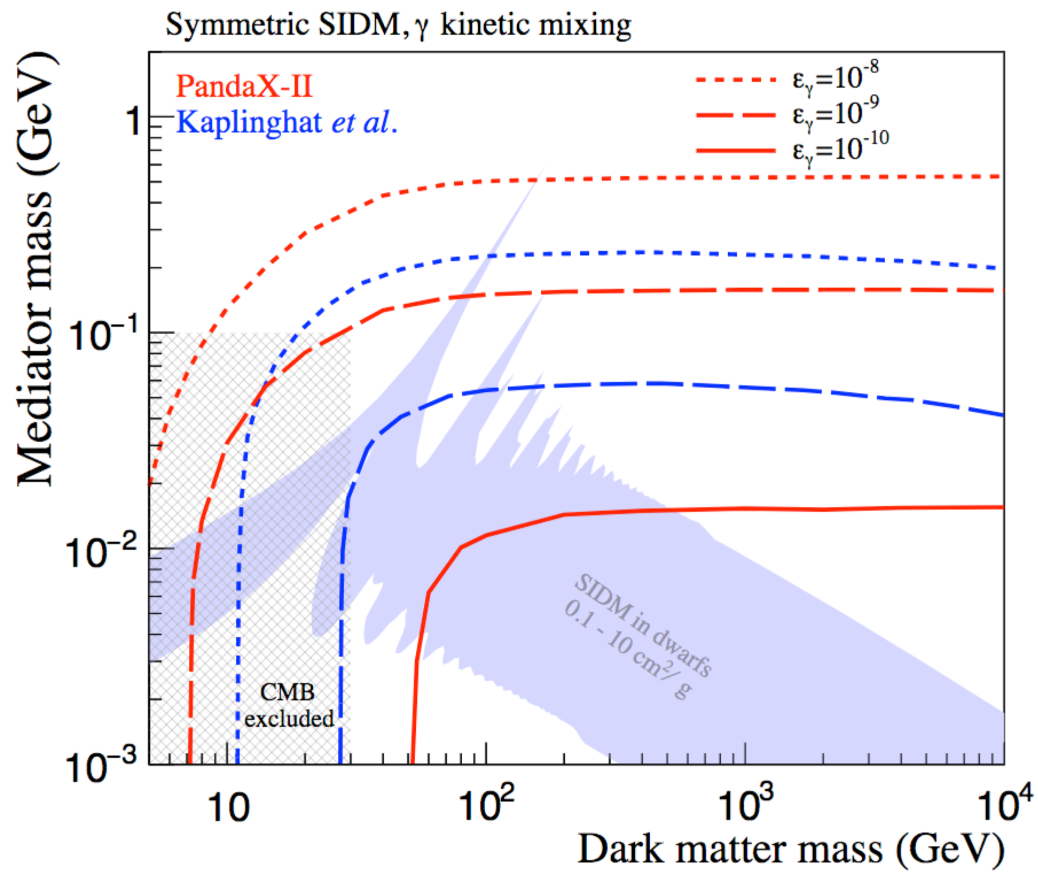
WIMP: m_ϕ~1 TeV>>q
SIDM: m_ϕ~10 MeV~q

Smoking-gun signature

With Ren et al., the PandaX-II collaboration (PRL, 2018)

Direct Detection Constraints





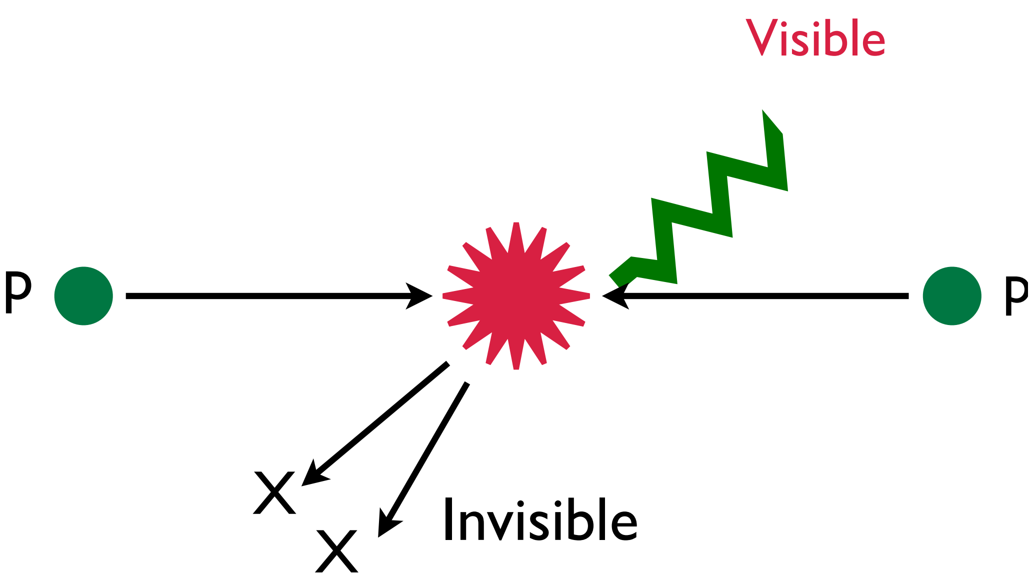
$$\epsilon_\gamma F^{\mu\nu} \phi_{\mu\nu}$$

With Ren et al., the PandaX-II collaboration (PRL, 2018)

SIDM at Colliders

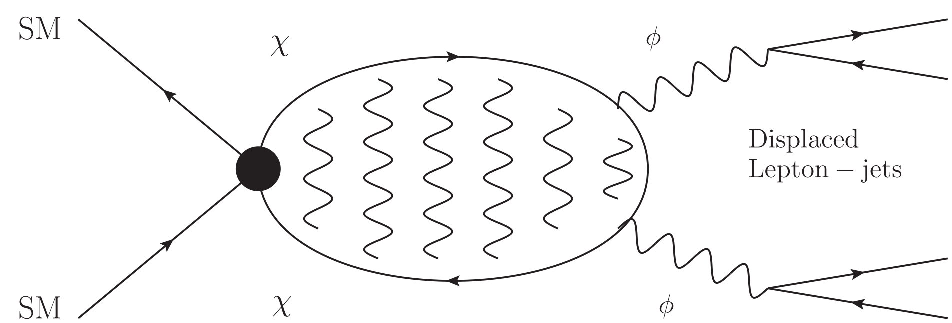
- Striking collider signals

WIMP



pp→Monojet+Missing Energy

SIDM



With Ren, Tsai, Xu (in prep)

Shepherd, Tait, Zaharijas (PRD 2009)

An, Echenard, Pospelov, Zhang (PRL 2015)

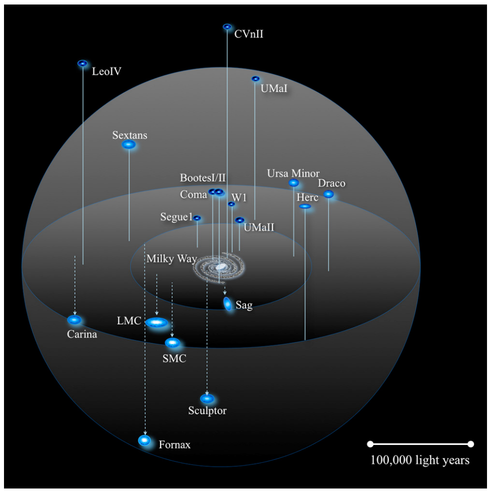
Tsai, Wang, Zhao (PRD 2015)

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.
- SIDM has other interesting signals in terrestrial experiments, cosmological and astrophysical observations.

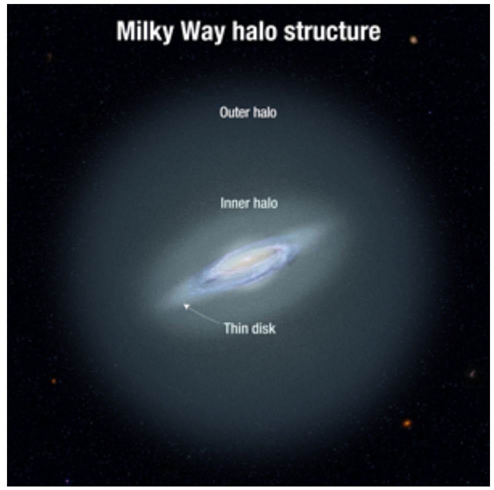
Dark Matter "Colliders"

Dwarf galaxies



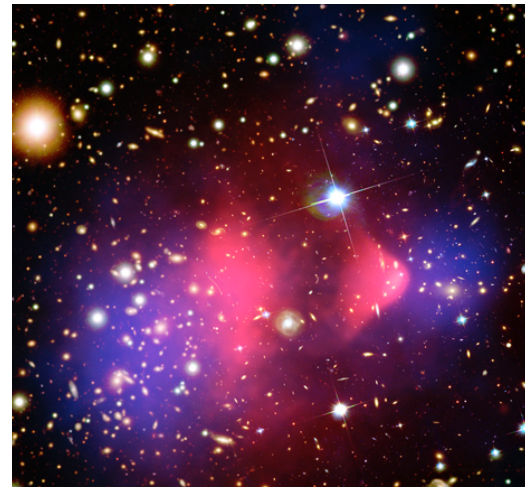
"B-factory" (v~30 km/s)

MW-size galaxies



"LEP" (v~200 km/s)

Clusters



"LHC" (v~1000 km/s)

Observations on all scales

Self-scattering kinematics →

Measure particle physics parameters σ_X, m_X, g_X

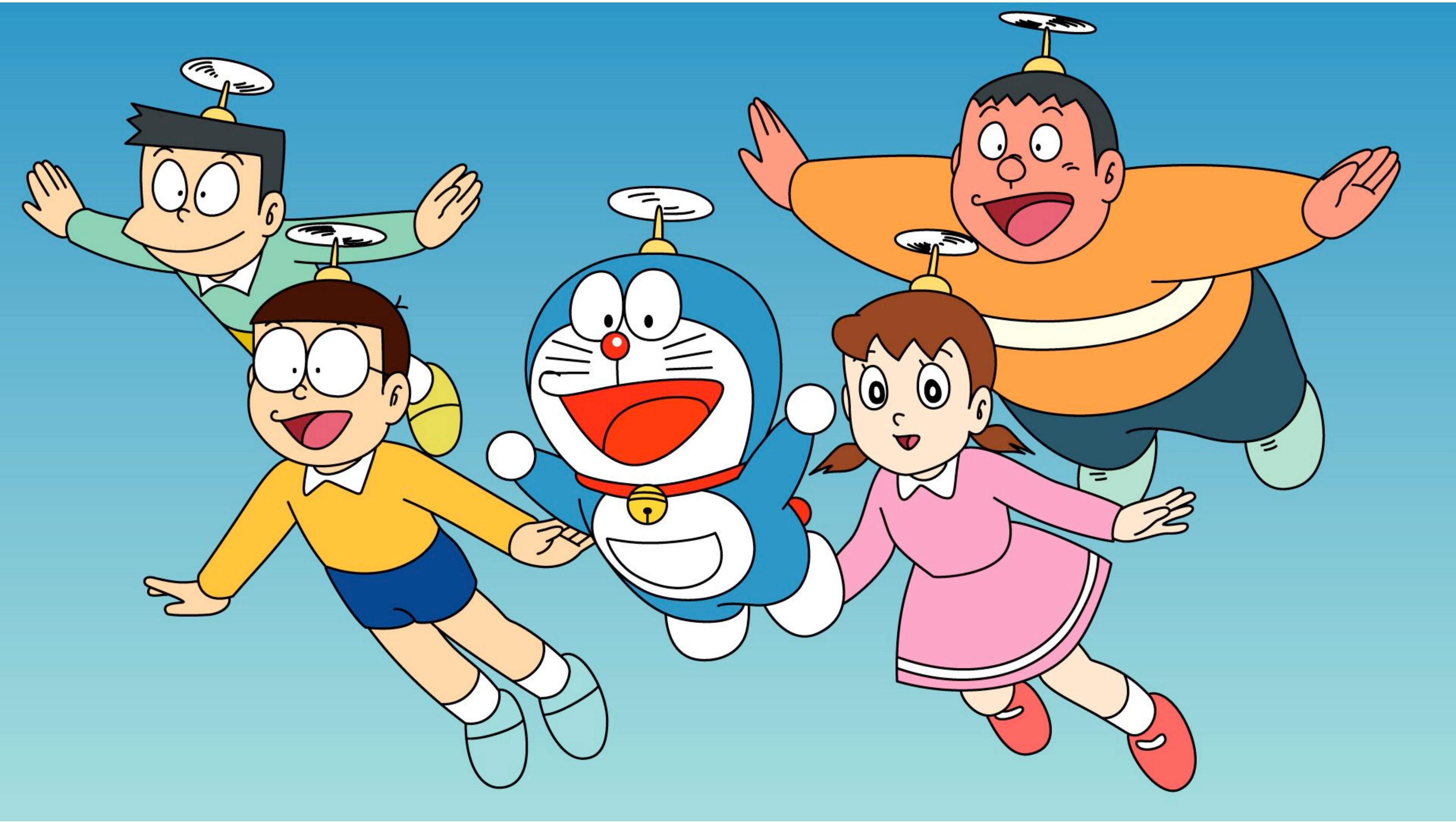
Particle Properties

XSIDM

PDG particle data group

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

Tulin & HBY (2017)



Thank you!