Self-Interacting Dark Matter and Diverse Galactic Rotation Curves

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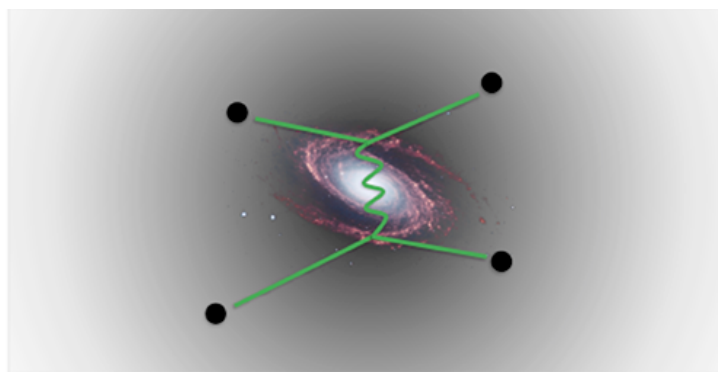


Thirteenth Conference on the Intersections of Particle and Nuclear Physics

Review for Physics Reports: Tulin & HBY (2017)

Beyond the WIMP Paradigm

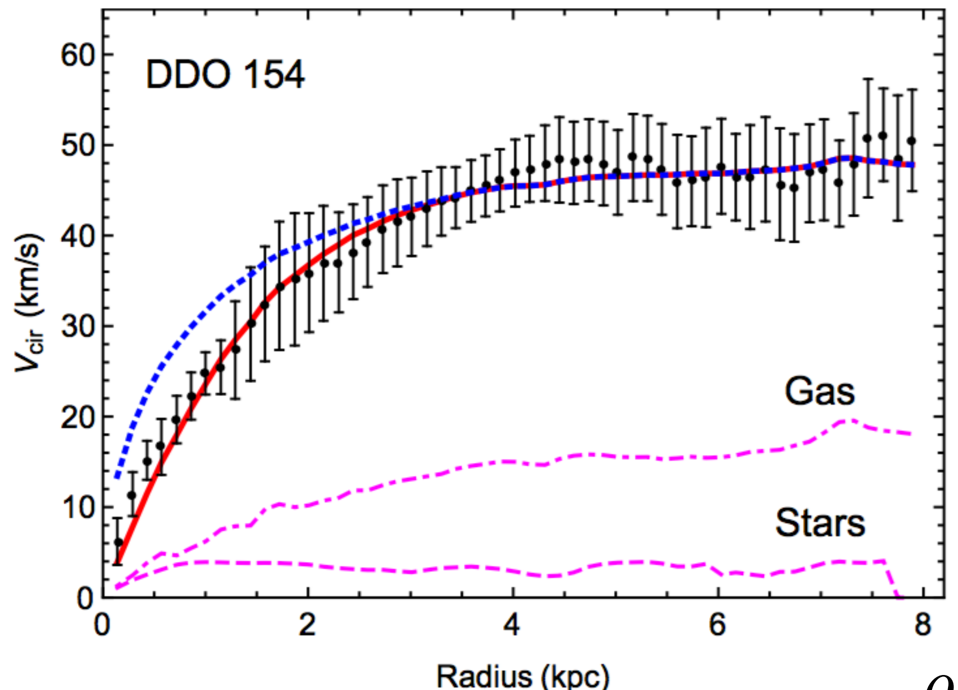
Some guidance

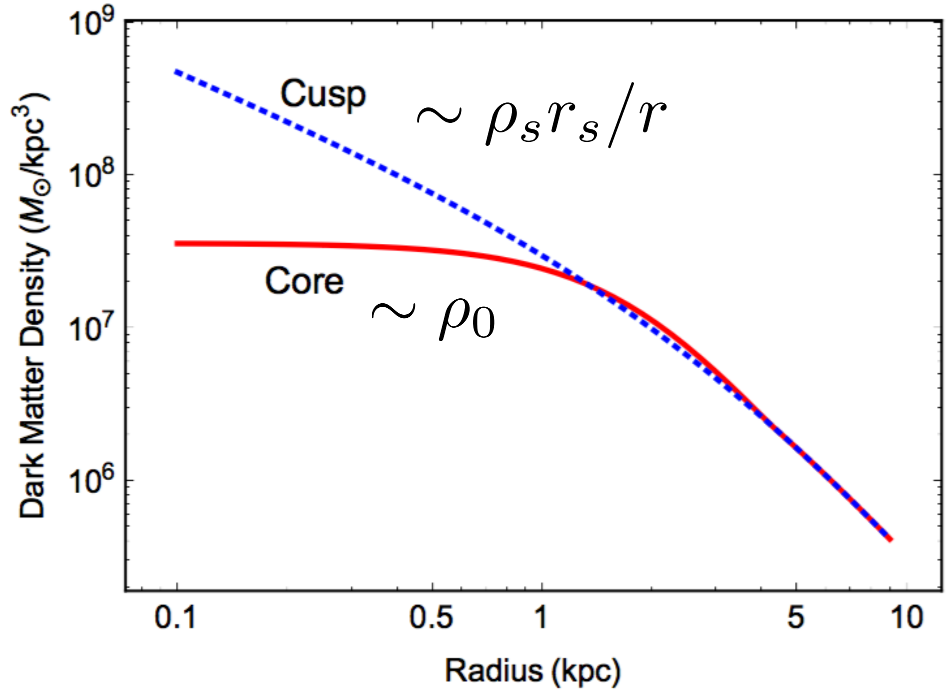
- Theory-driven: different production mechanisms
- Technology-driven: what can we do with current technologies?
- Observation-driven: how can we determine the particle nature of DM from astrophysical observations?

- 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)





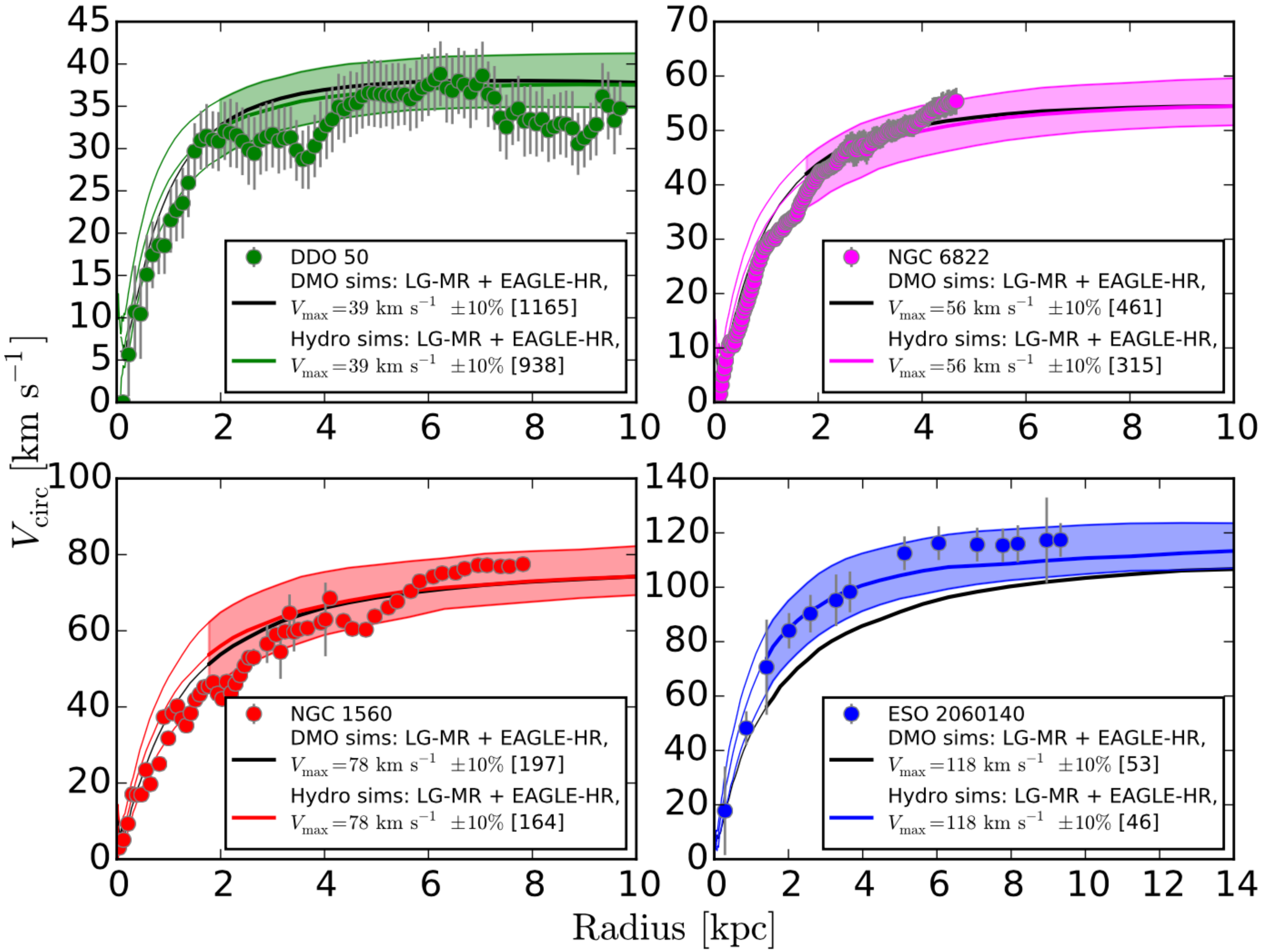
$$\frac{\rho_s}{r/r_s(1+r/r_s)^2}$$

Navarro, Frenk, White (APJ 1995, 1996)

Many dwarf galaxies prefer a shallow density core, instead of a steep density cusp

Flores, Primack (1994), Moore (1994)…

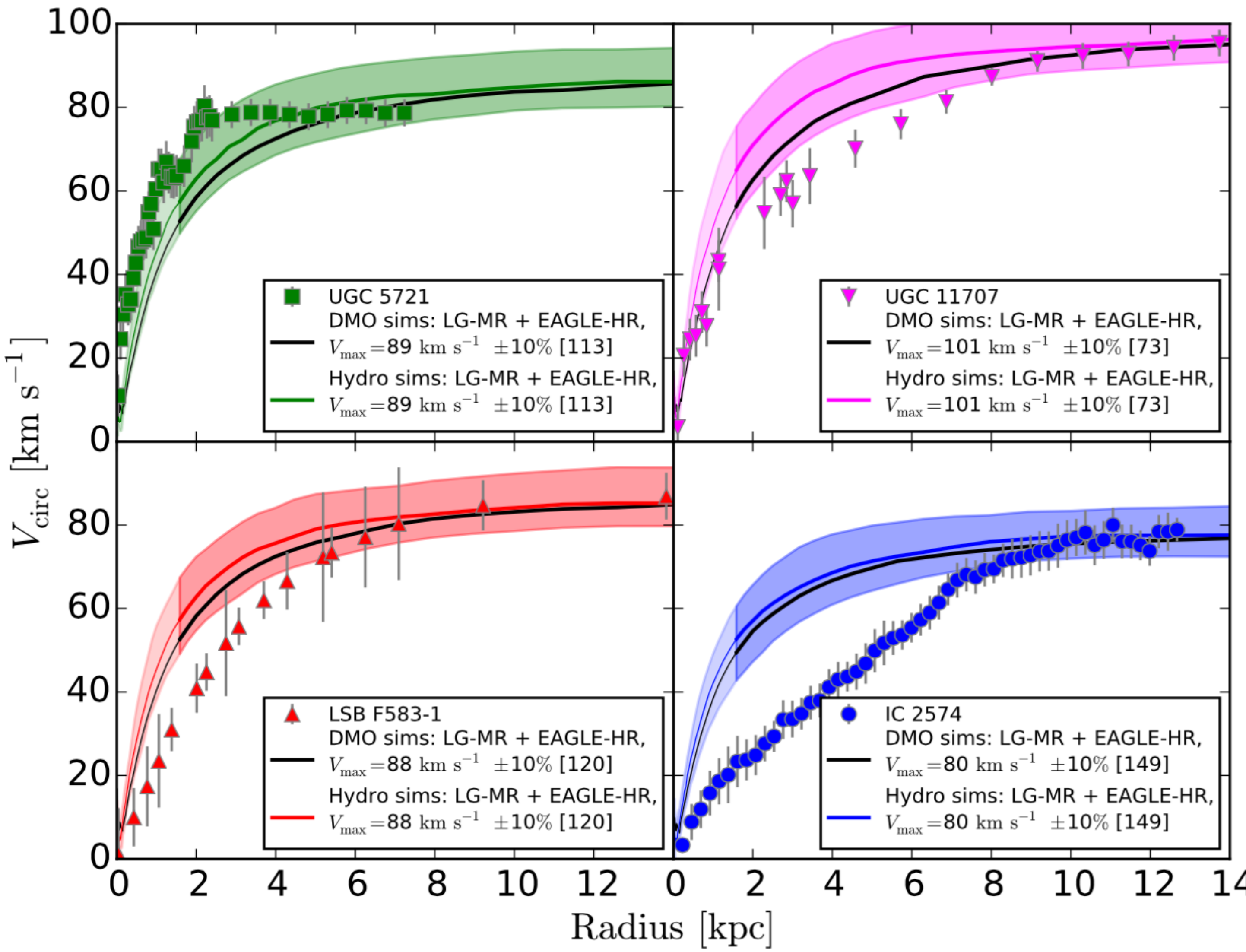
The Diversity Problem



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

Oman et al. (2015)

The Diversity Problem

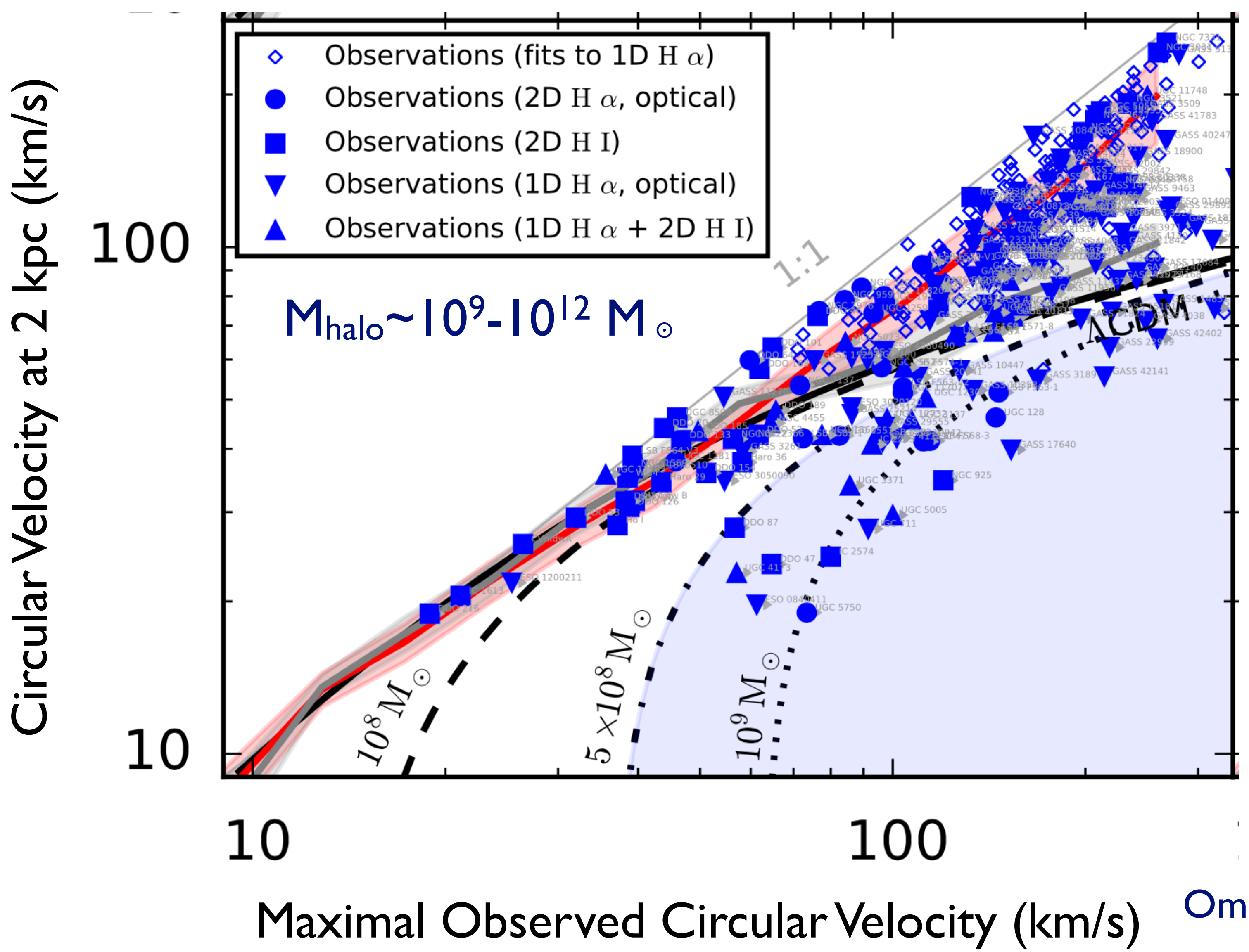


All galaxies have the same observed Vmax!

Oman et al. (2015)

Colored bands: hydrodynamical simulations of ΛCDM

A Big Challenge to ΛCDM



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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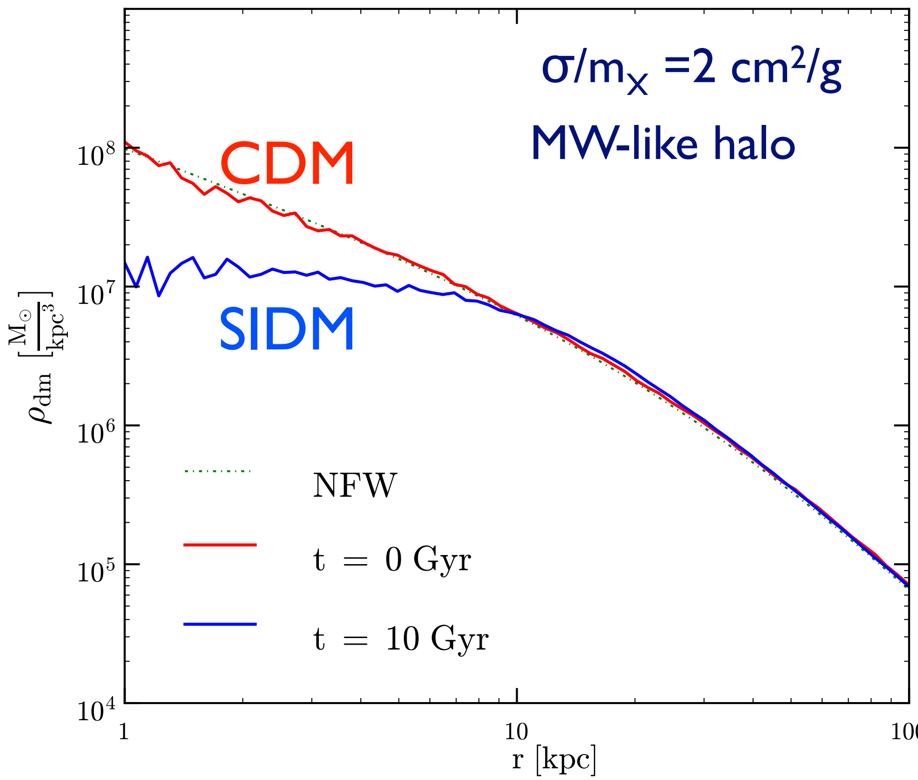
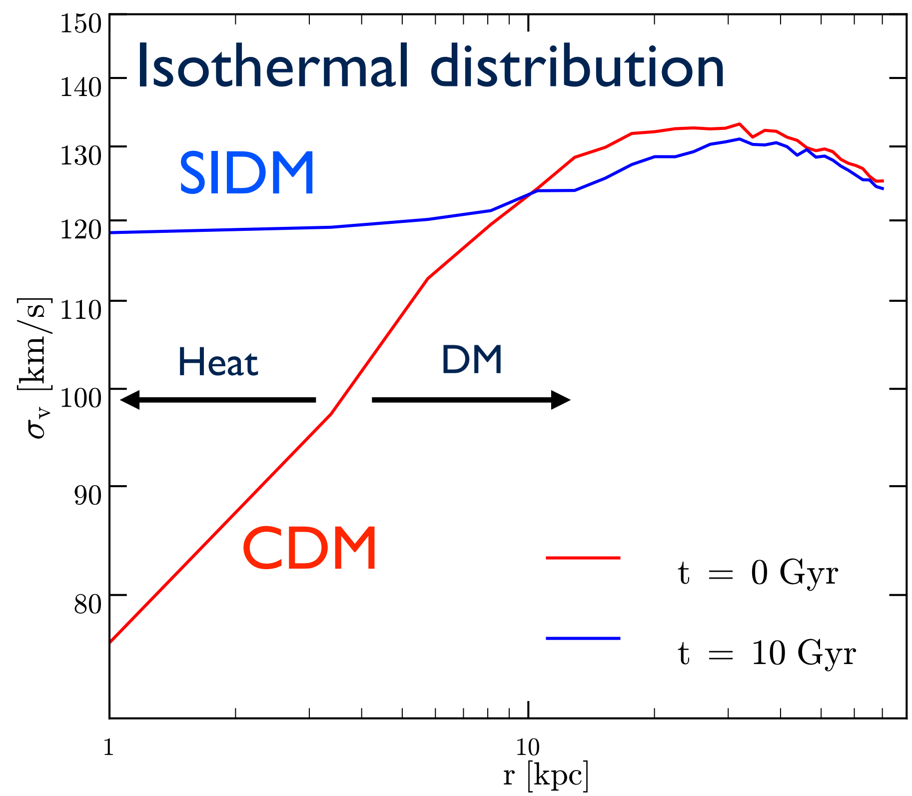
[2] *Senior CIfAR Fellow*
[3] *Institute for Computational Cosmology, Department of Physics, University of Durham, South Road, Durham DH1 3LE, United Kingdom*
[4] *Max-Planck Institute for Astrophysics, Garching, Germany*
[5] *Astrophysics Research Institute, Liverpool John Moores University, IC2, Liverpool 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





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

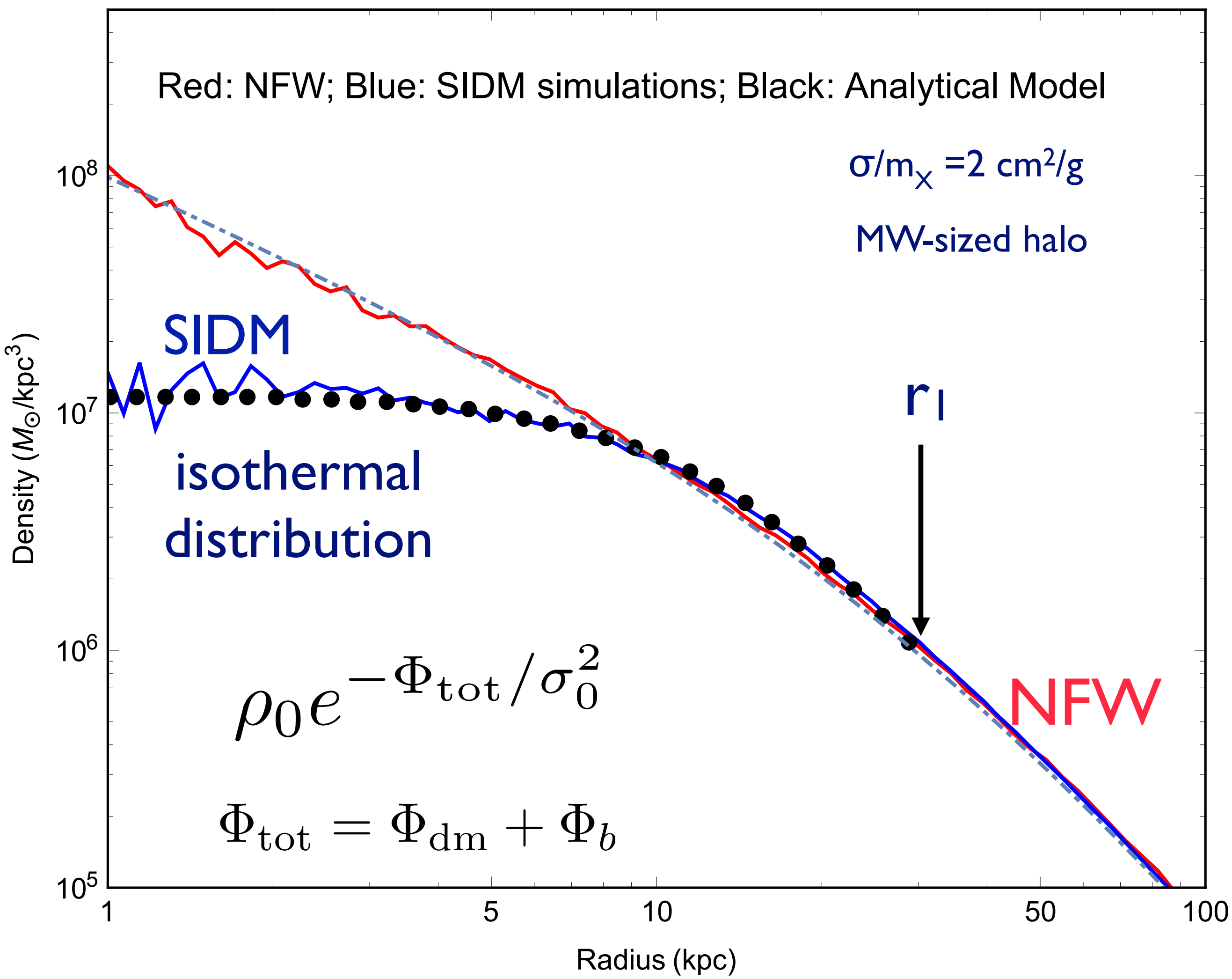
$$\Gamma \simeq n\sigma v = (\rho/m_X)\sigma v \sim H_0$$

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:

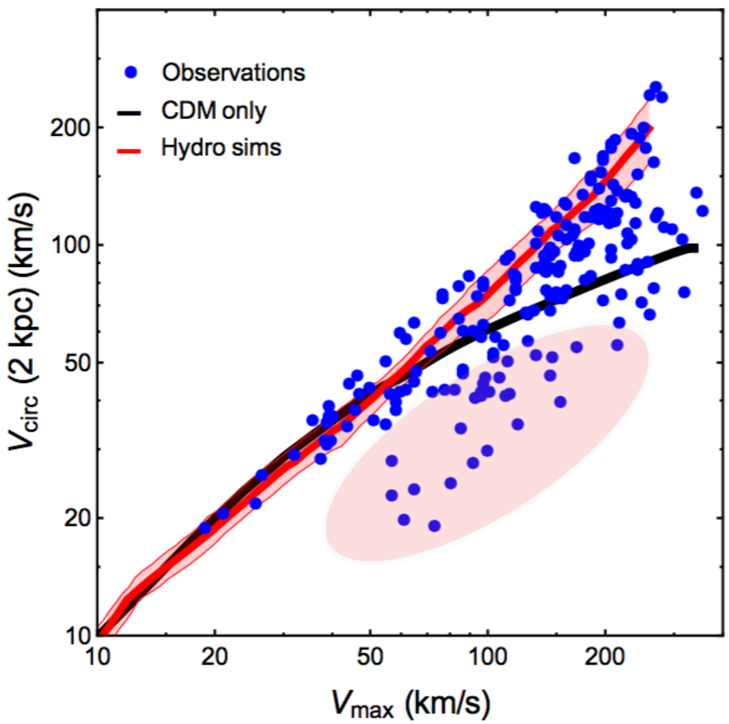
$$\rho_{\rm iso}(r_1) = \rho_{\rm NFW}(r_1)$$
$$M_{\rm iso}(r_1) = M_{\rm NFW}(r_1)$$

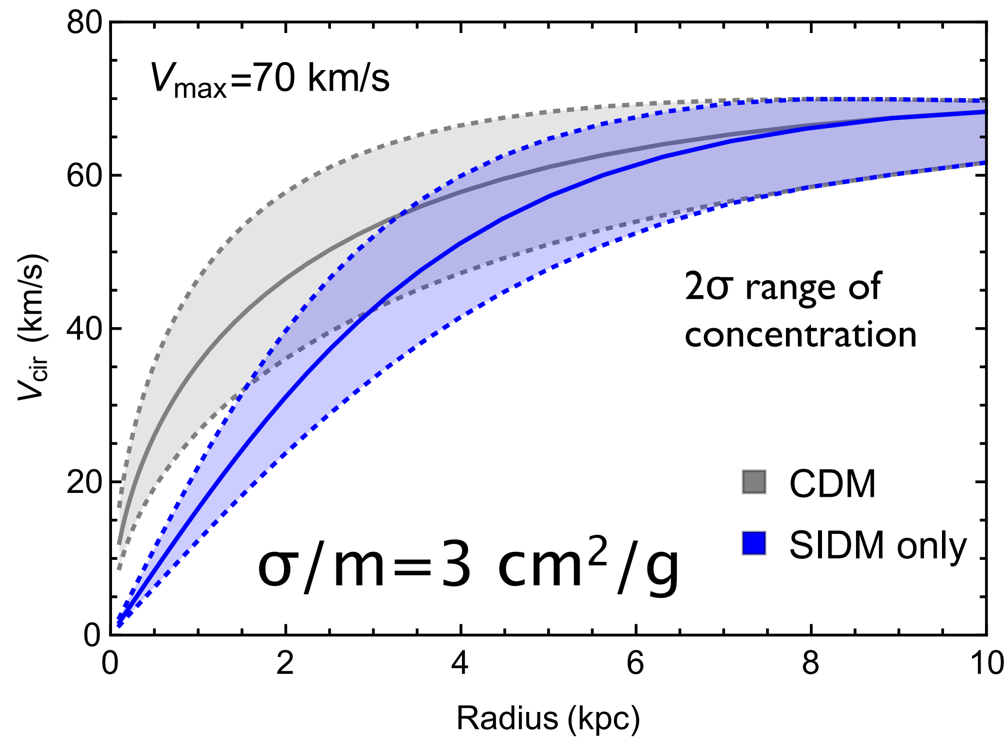
$$(\rho_0, \sigma_0) \leftrightarrow (\rho_s, r_s)$$

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

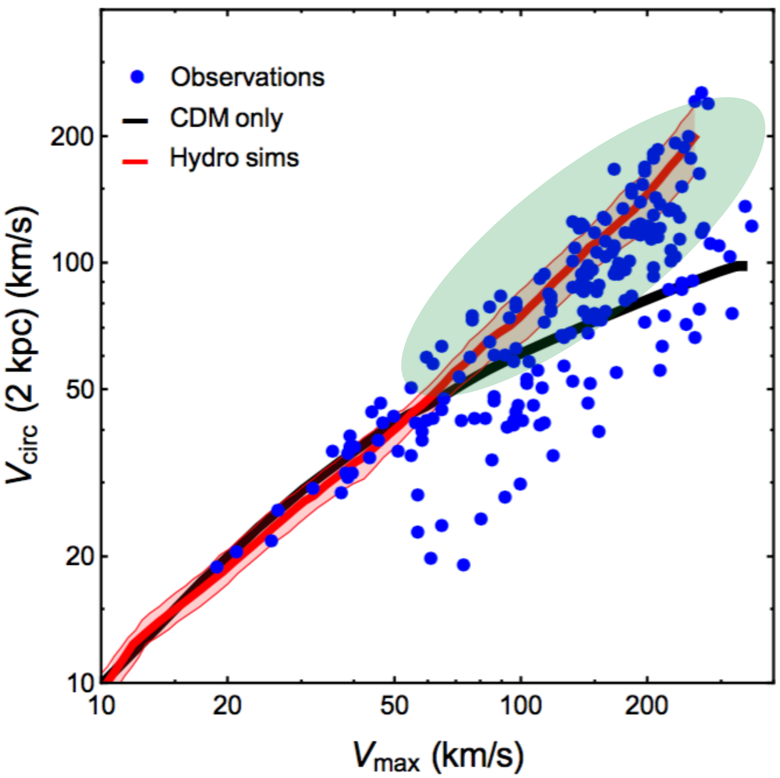
Isothermal distribution

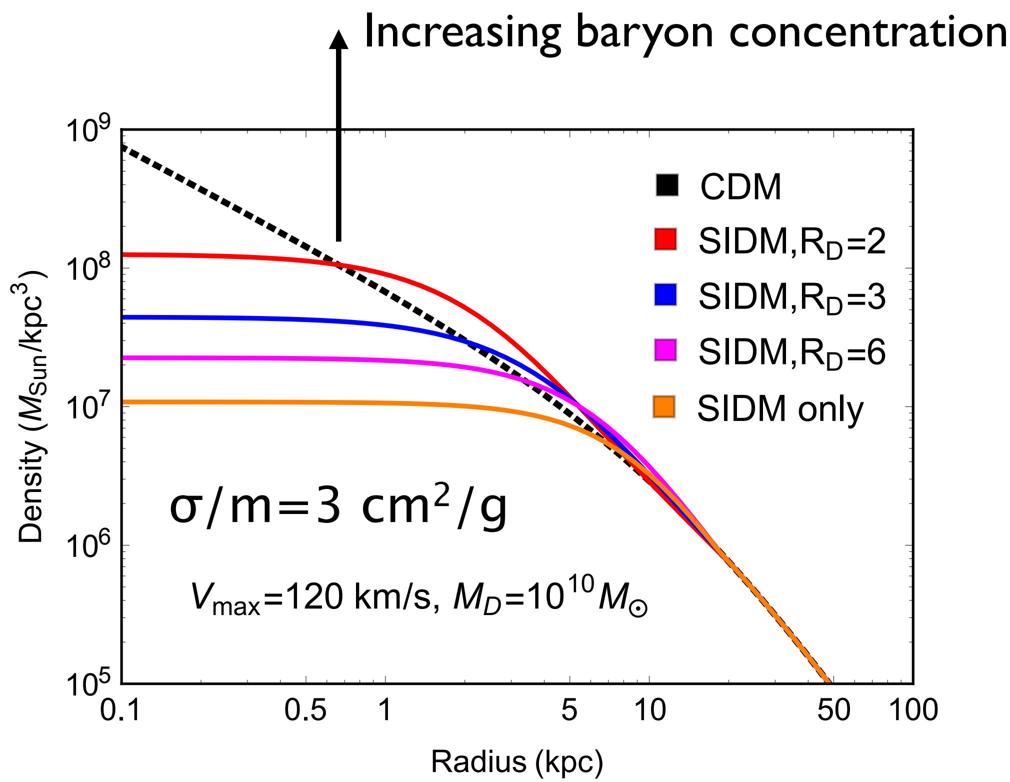
$$\rho_X \sim e^{-\Phi_{tot}/\sigma_0^2} \sim e^{-\Phi_X/\sigma_0^2}$$

with Kamada, Kaplinghat, Pace (PRL 2016)

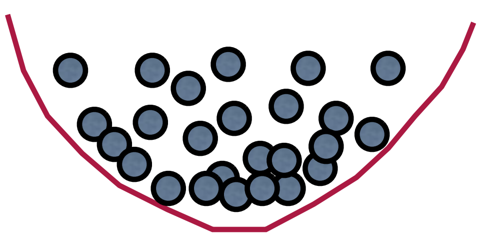
Addressing the Diversity Problem

- DM self-interactions tie DM together with baryons



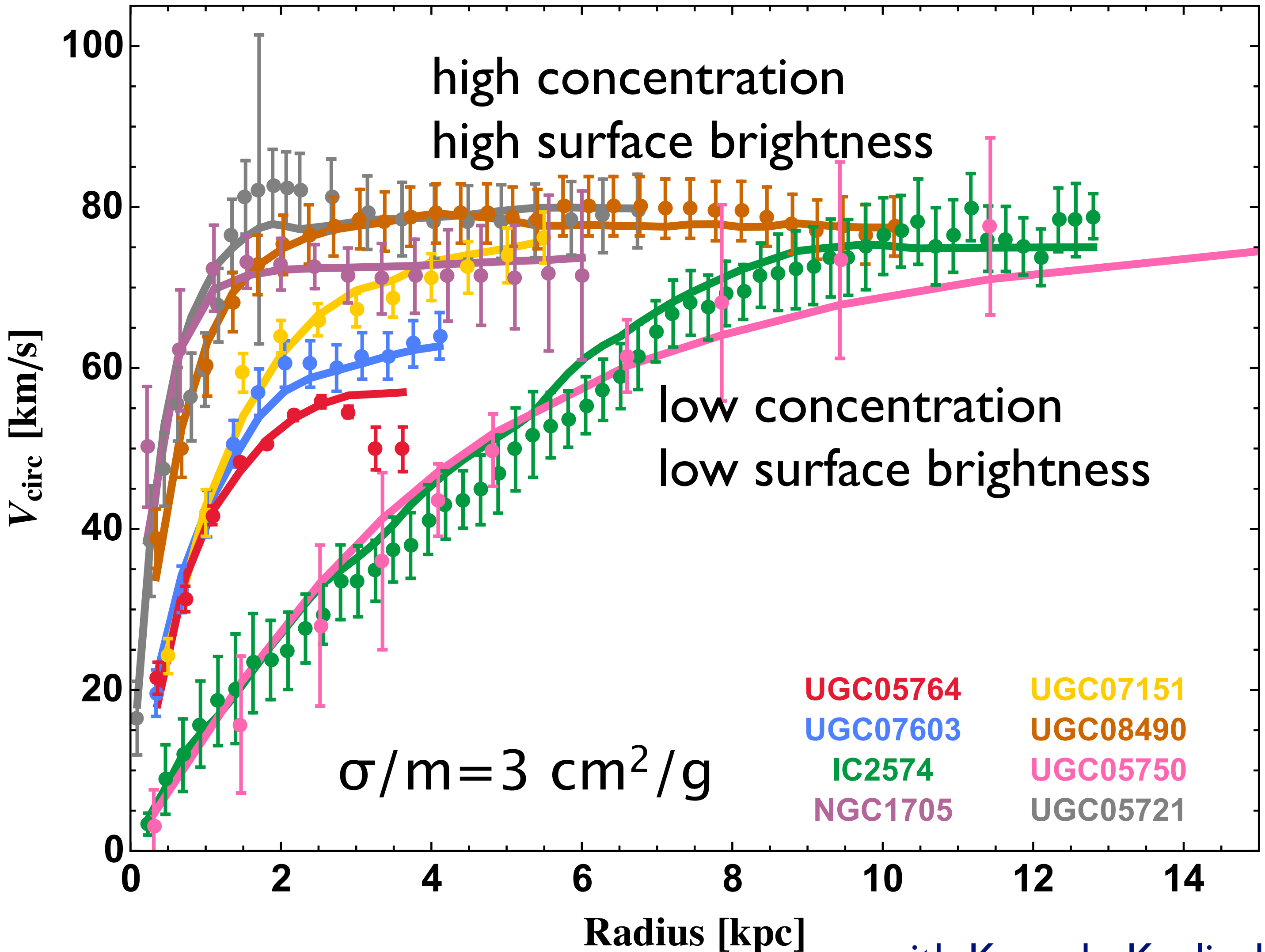


Thermalization leads to higher DM density due to the baryonic influence



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

with Kamada, Kaplinghat, Pace (PRL 2016)



30 galaxies

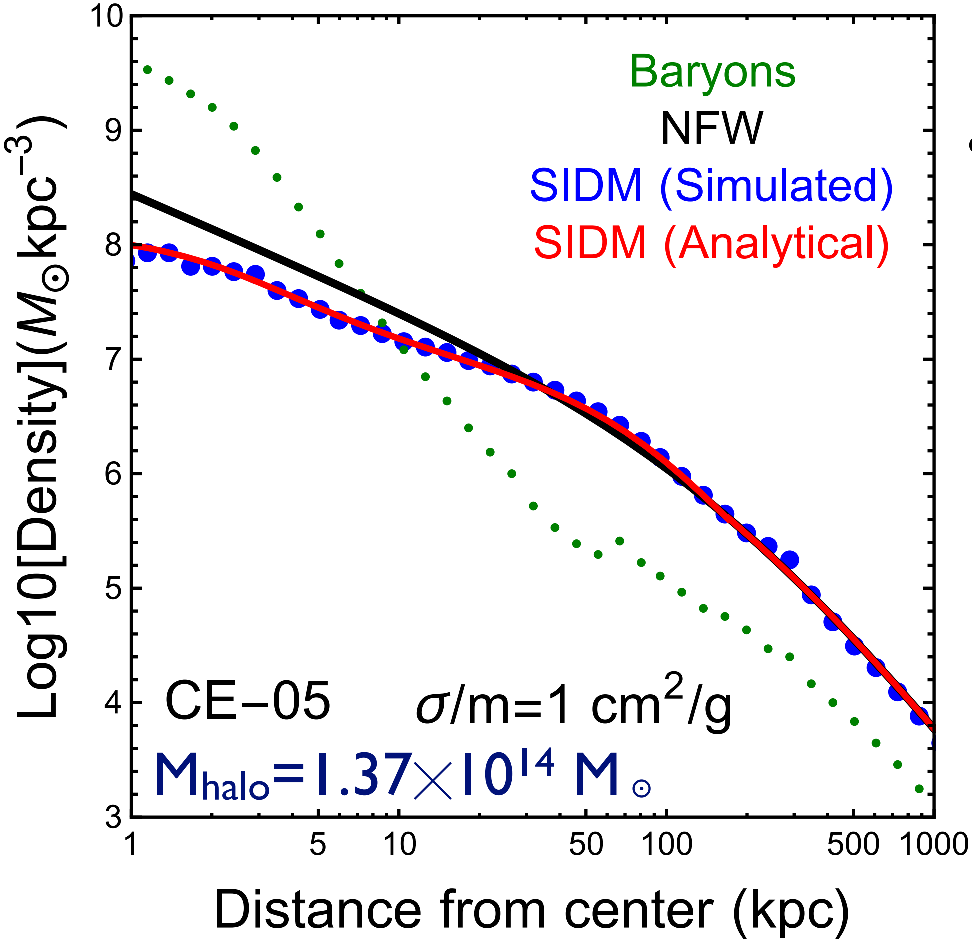
V_{max}~25-300 km/s

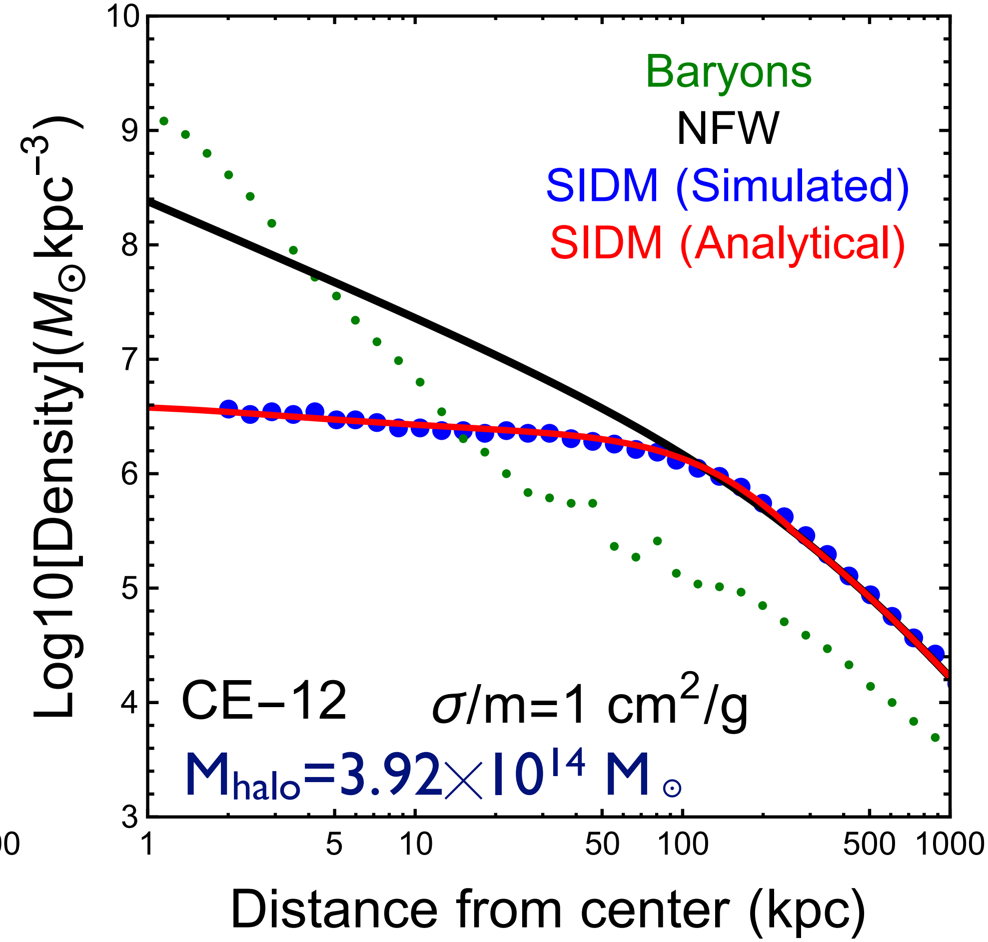
with Kamada, Kaplinghat, Pace (PRL 2016)

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

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

Hydro SIDM Simulations



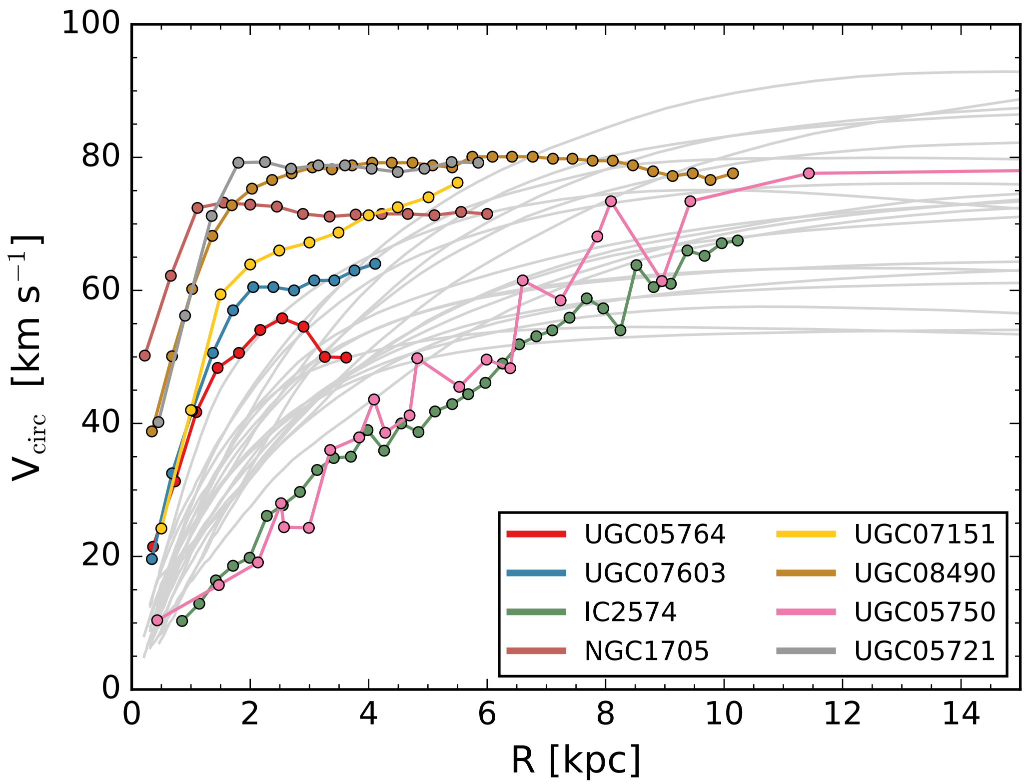


With Robertson, Massey, Eke, Tulin, et al. (MNRAS Letters, 2017)

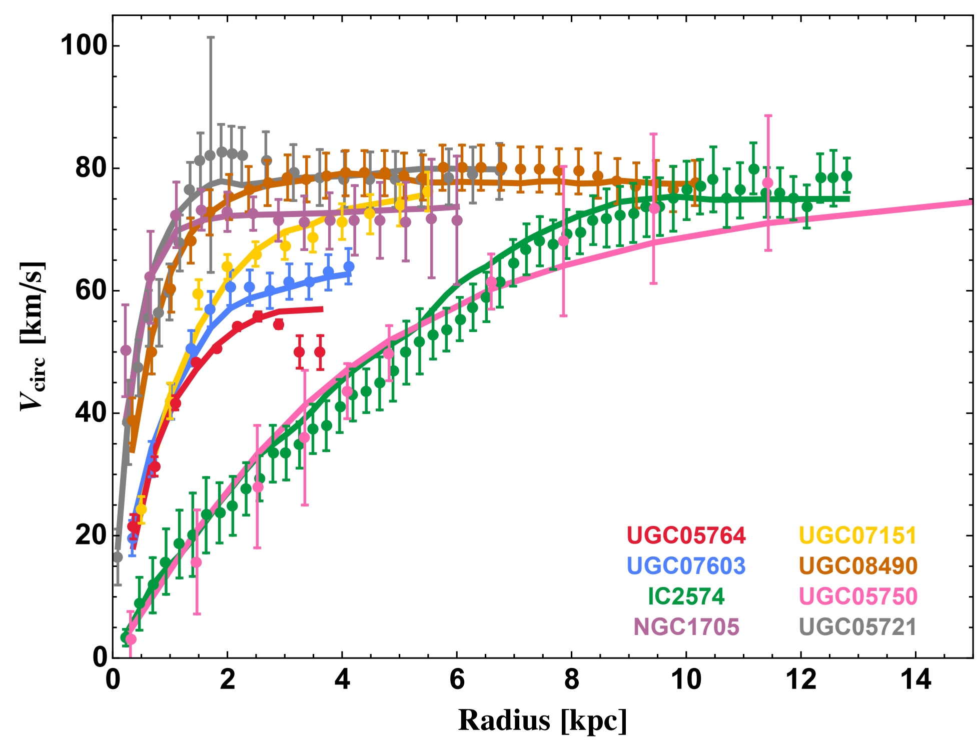
- The SIDM distribution is sensitive to the final baryon distribution
- But, it is not sensitive to the formation history

Predicted in Kaplinghat, Keeley, Linden, HBY (PRL 2013)

Strong Feedback vs SIDM



Santos-Santos et al. (2017)



with Kamada, Kaplinghat, Pace (PRL 2016)

Gray: NIHAO CDM simulations

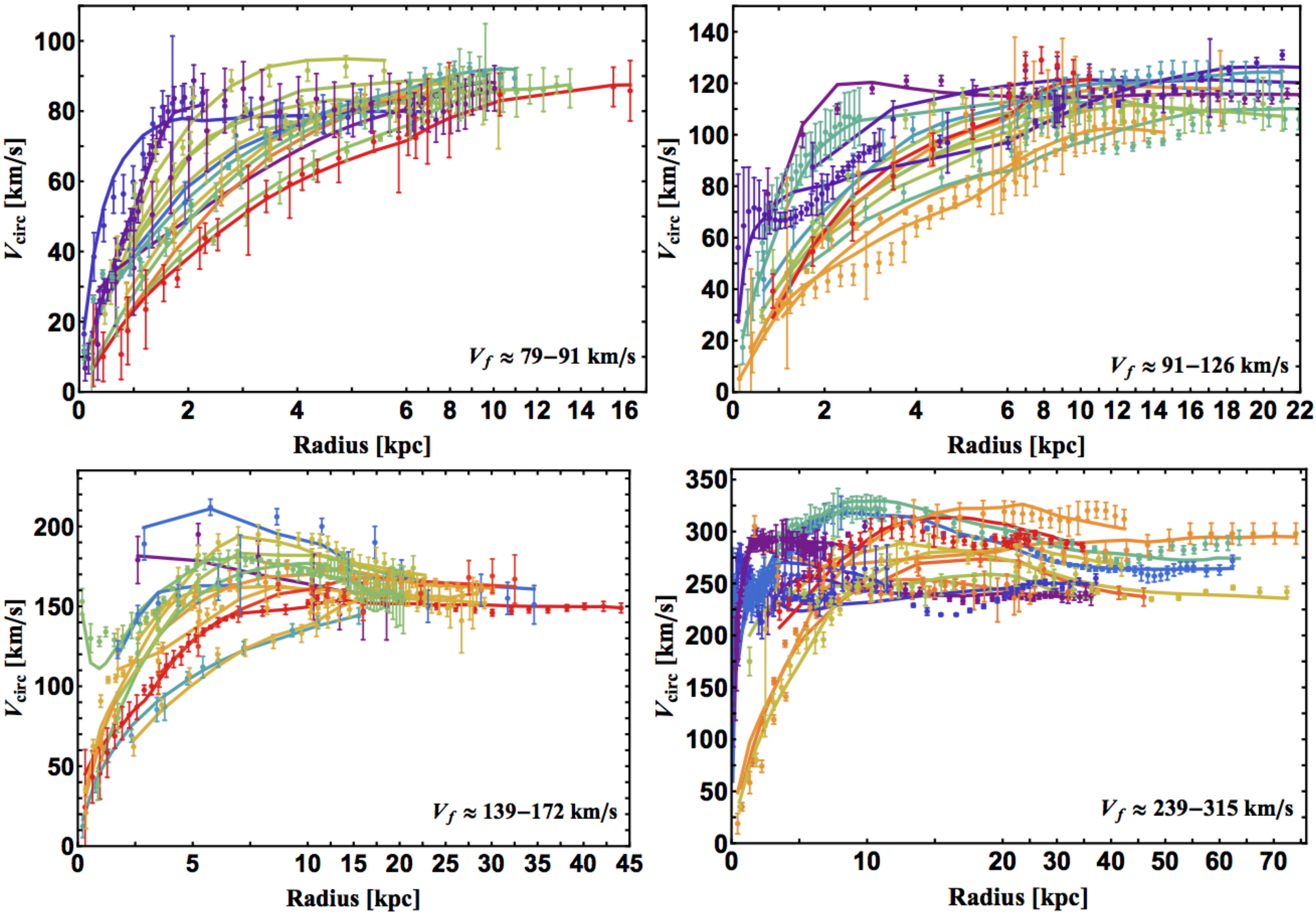
"strong/violent" feedback

Observed scatter: ~4 (3σ away)

Simulations: ~2

Solid lines: SIDM fits

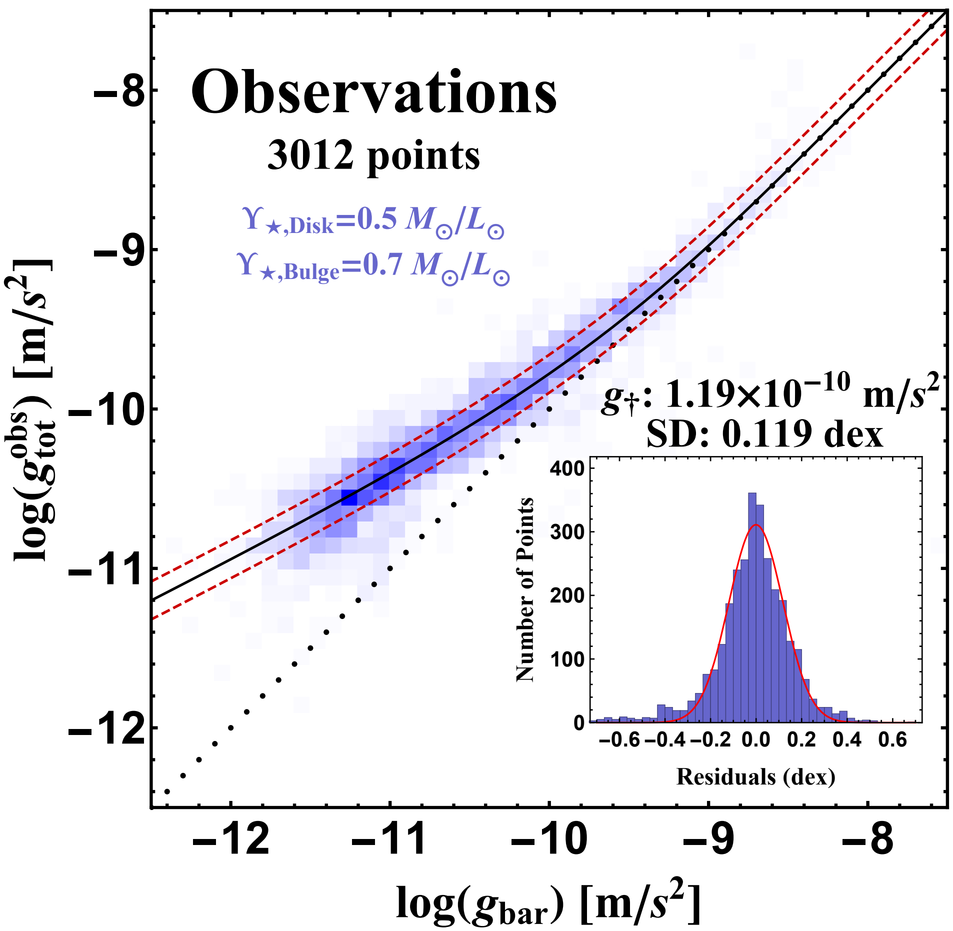
(~2σ in the c_{200}-M_{200} relation)

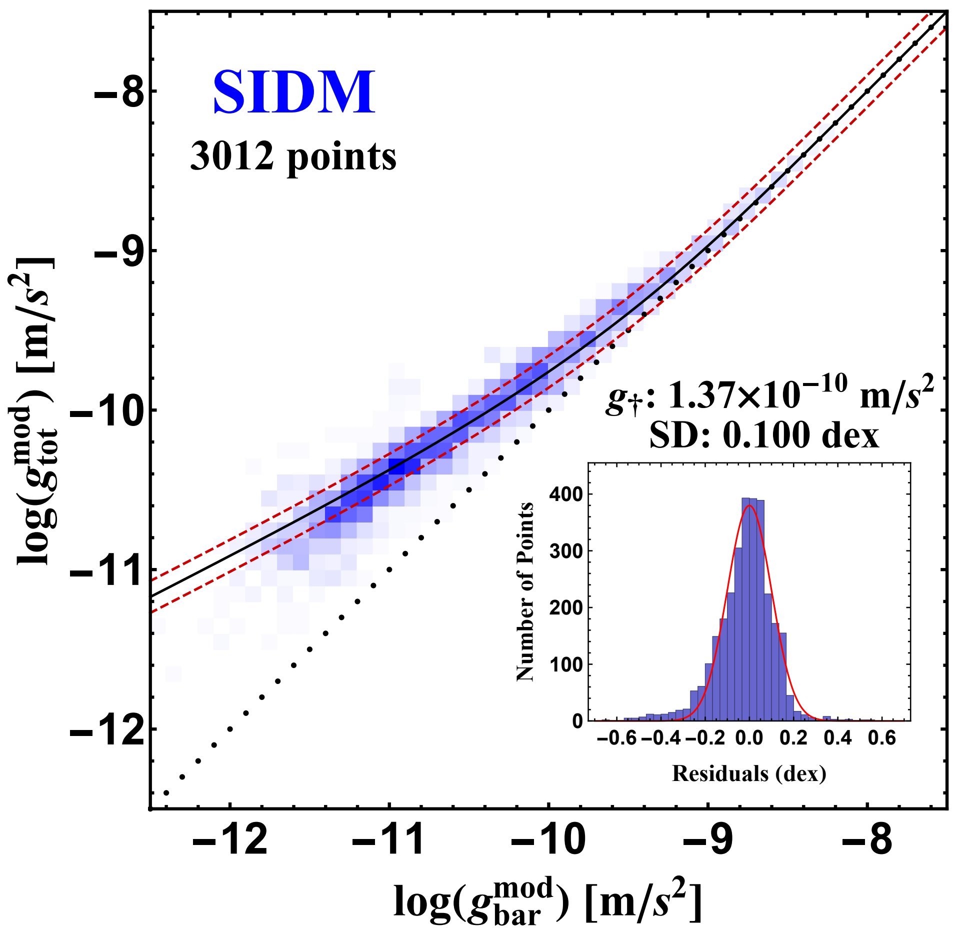


We have fitted to 135 galaxies

with Kaplinghat, Kwa, Ren (in prep)

Radial Acceleration Relation





McGaugh, Lelli, Schombert (PRL 2016)

With Kaplinghat, Kwa, Ren (in prep)

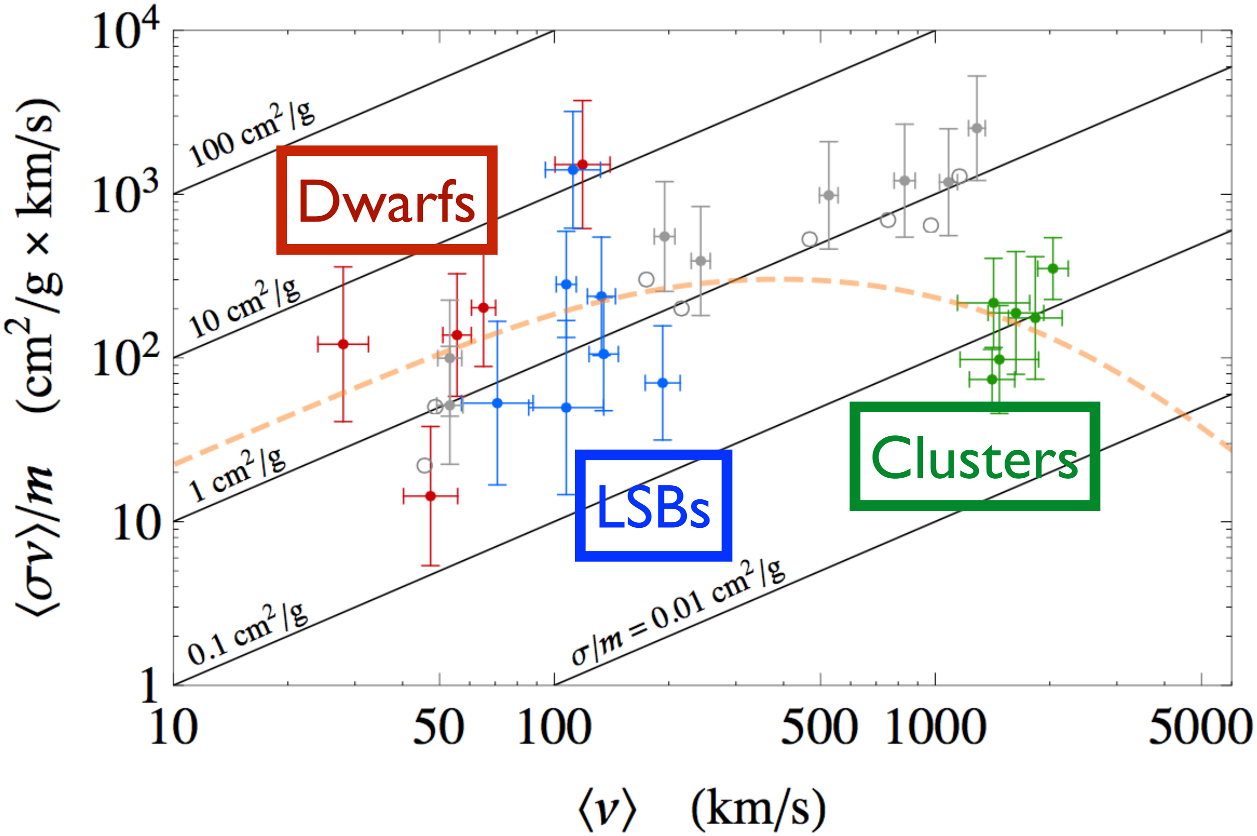
$$g_{\mathrm{tot}} = \frac{g_{\mathrm{bar}}}{1 - e^{-\sqrt{g_{\mathrm{bar}}/g_\dagger}}}$$

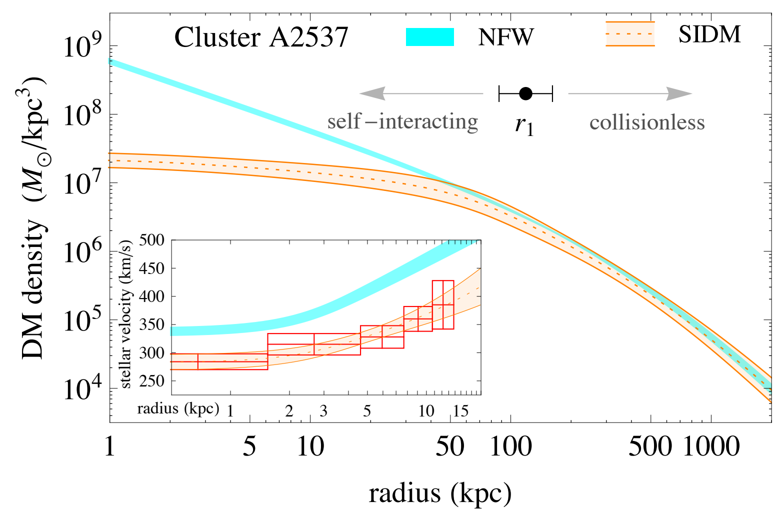
135 galaxies

SIDM from Dwarfs to Clusters

Galaxies: $M_{halo} \sim 10^9\text{-}10^{12}\ M_\odot$

Clusters: $M_{halo} \sim 10^{14}\text{-}10^{15}\ M_\odot$





Core size in clusters: ~10 kpc

Clusters: ~0.1 cm^2/g

Galaxies: ~2 cm^2/g

Bullet Cluster: < ~2 cm^2/g

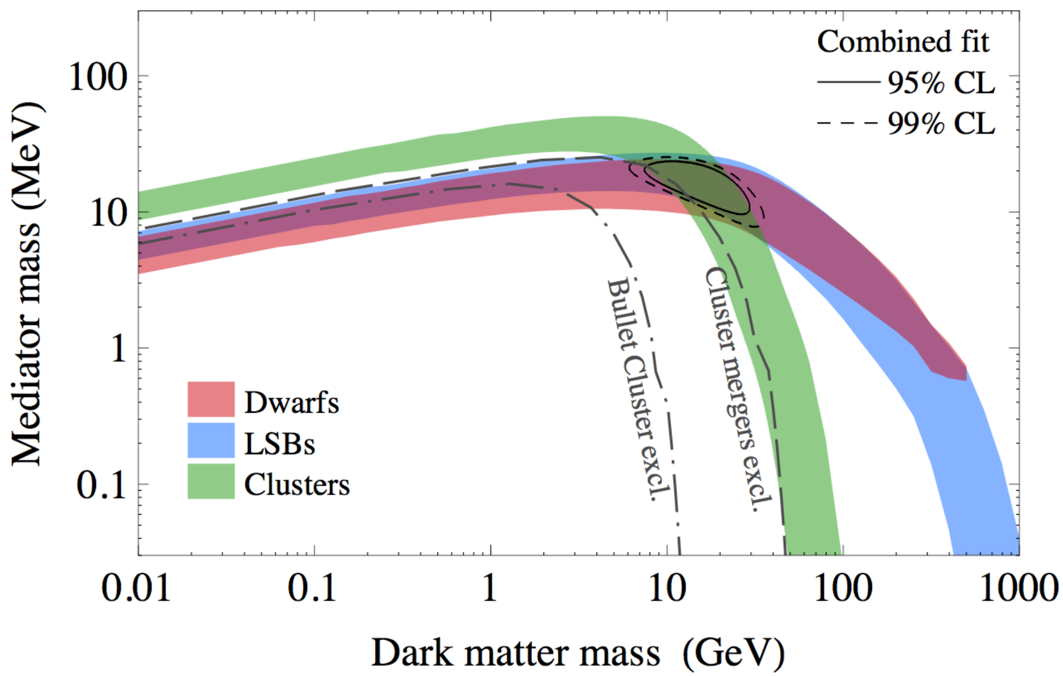
DM halos as particle colliders

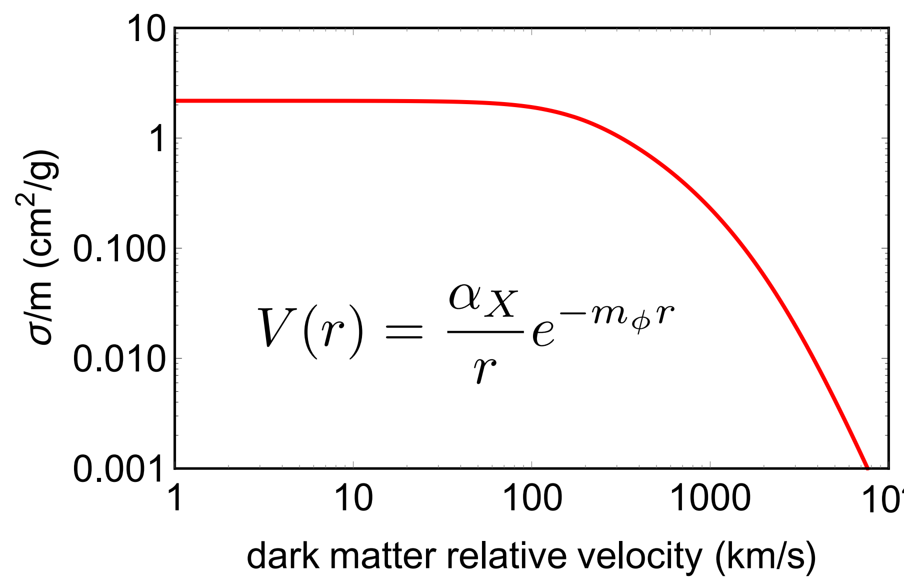
With Kaplinghat, Tulin (PRL, 2015)

Using the data from Newman et al. (2013)

Measuring Dark Matter Mass

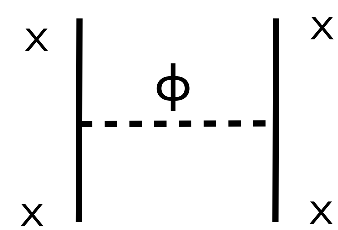
- Self-scattering kinematics determines SIDM mass





α_X=1/137

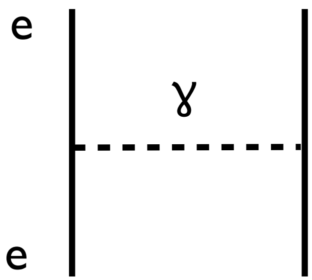
m_X: ~15 GeV, m_ϕ: ~17 MeV

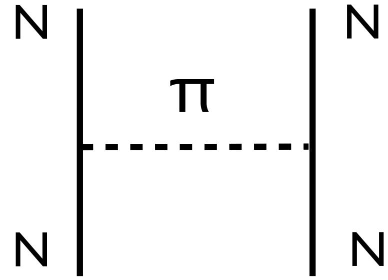


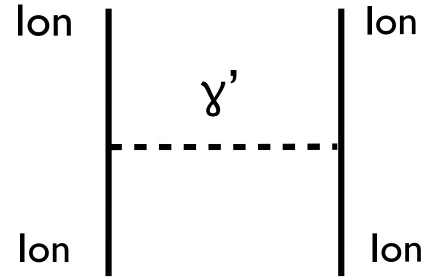
with Kaplinghat, Tulin (PRL 2015)

Particle Physics of SIDM

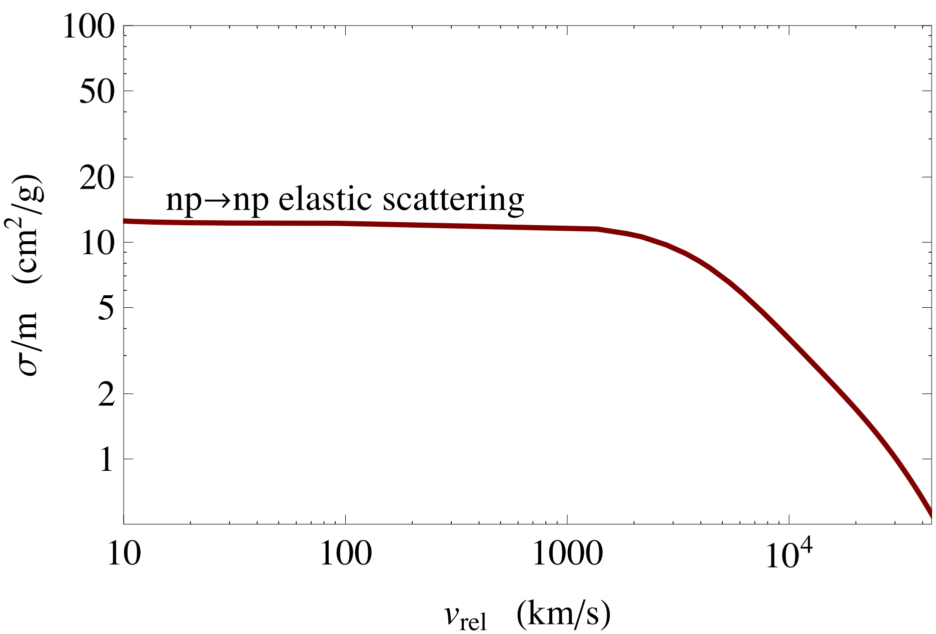
- Familiar examples in the visible sector

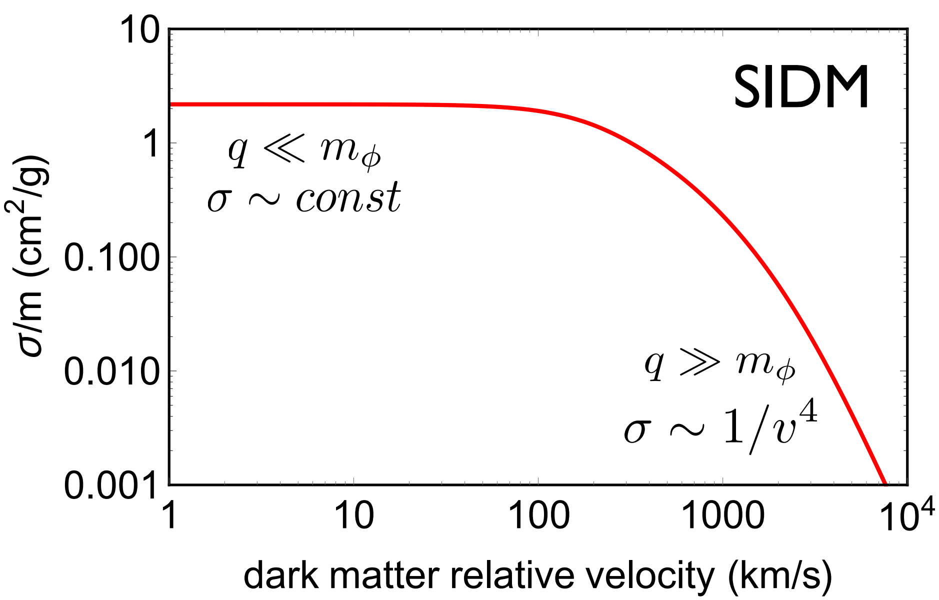






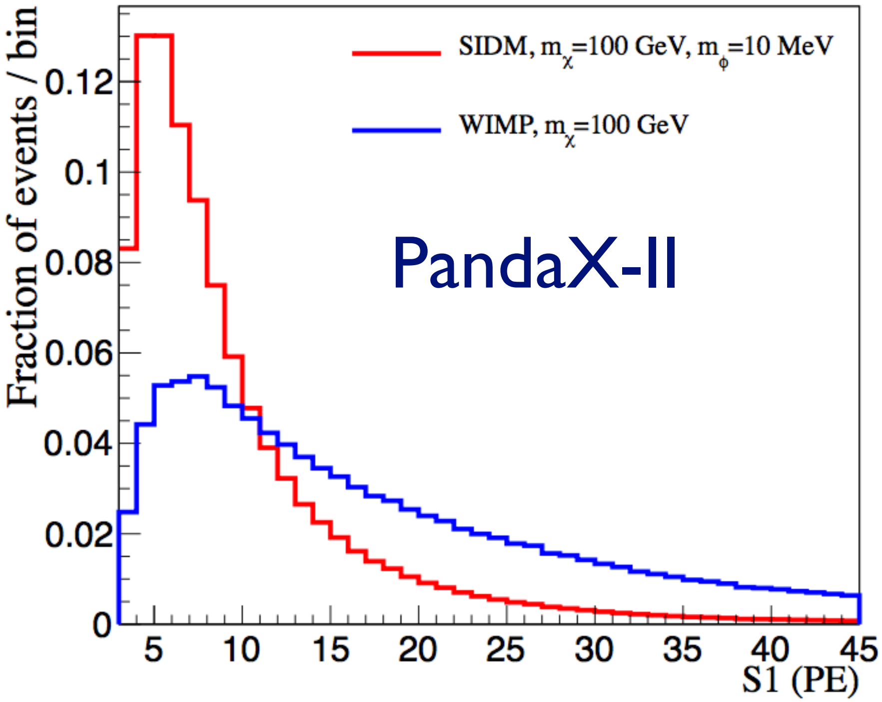
$$V(r) = \frac{\alpha_{\rm EM}}{r} \qquad V(r) = \frac{1}{r}e^{-m_\pi r} \qquad V(r) = \frac{\alpha_{\rm EM}}{r}e^{-m_D r}$$

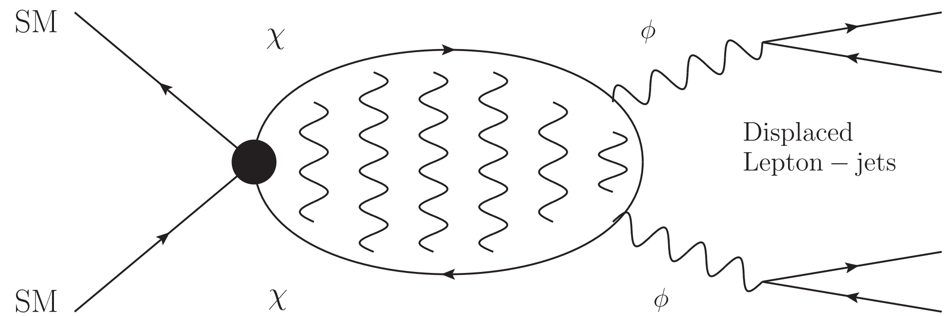




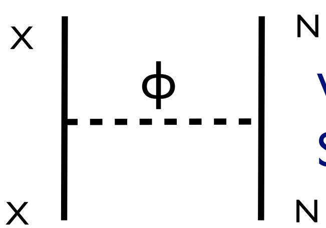
Tulin & HBY (2017)

Terrestrial Experiments





SIDM at the LHC



WIMP: m_ϕ~1 TeV>>q
SIDM: m_ϕ~10 MeV~q

WIMP: Mono-X+Missing Energy

With Ren, Tsai, Xu (in prep)

Shepherd, Tait, Zaharijas (PRD 2009)

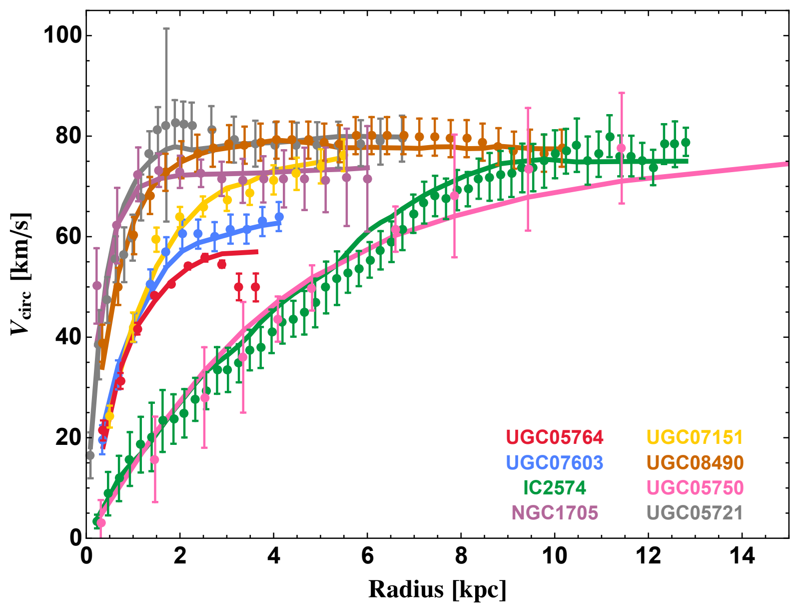
An, Echenard, Pospelov, Zhang (PRL 2015)

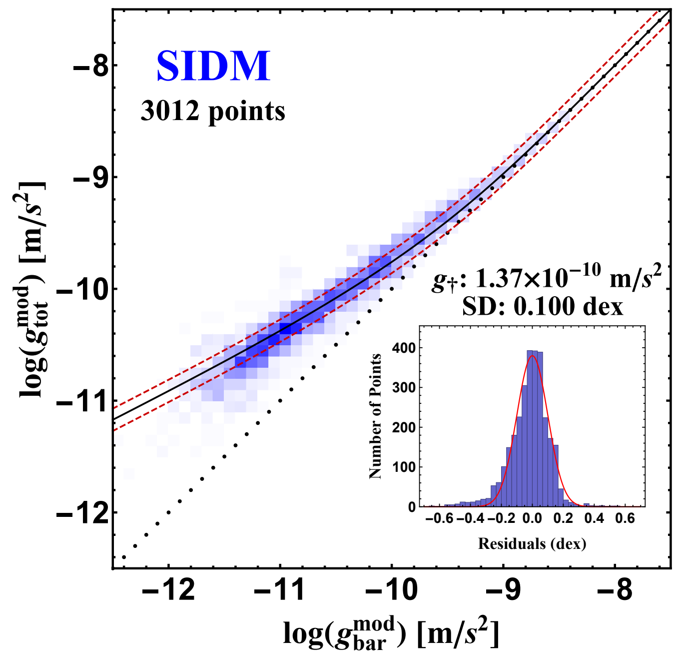
Tsai, Wang, Zhao (PRD 2015)

With Del Nobile, Kaplinghat (2015)

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

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 halo is thermalized.


Thank You!