Self-Interacting Dark Matter

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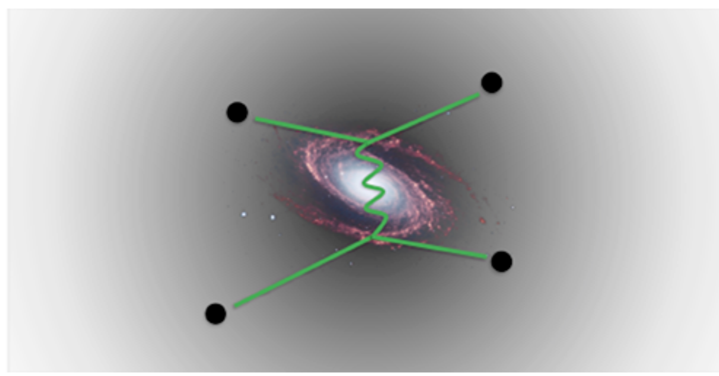
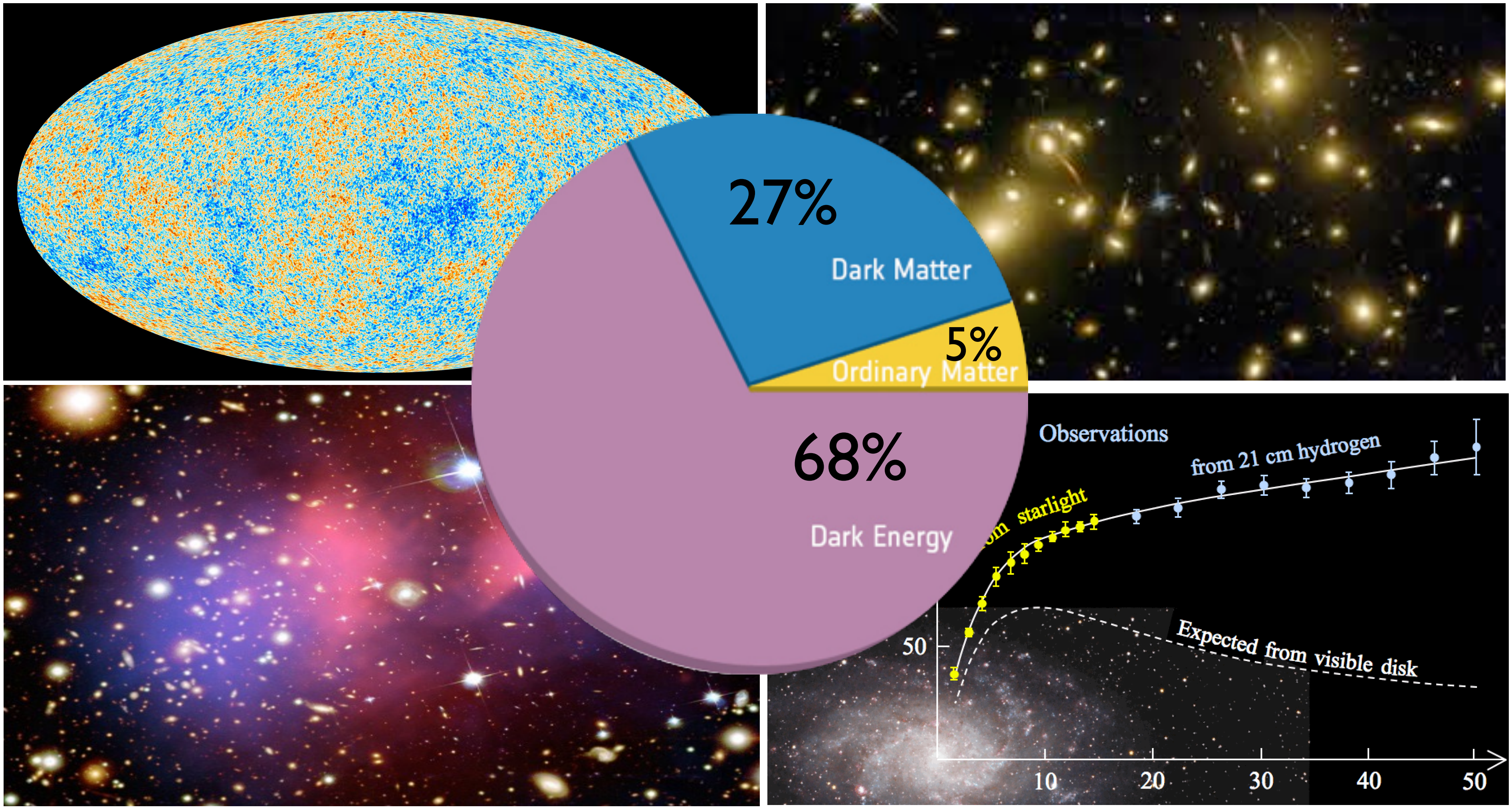


SOLVAY WORKSHOP: THE DARK SIDE OF BLACK HOLES

April 3, 2019

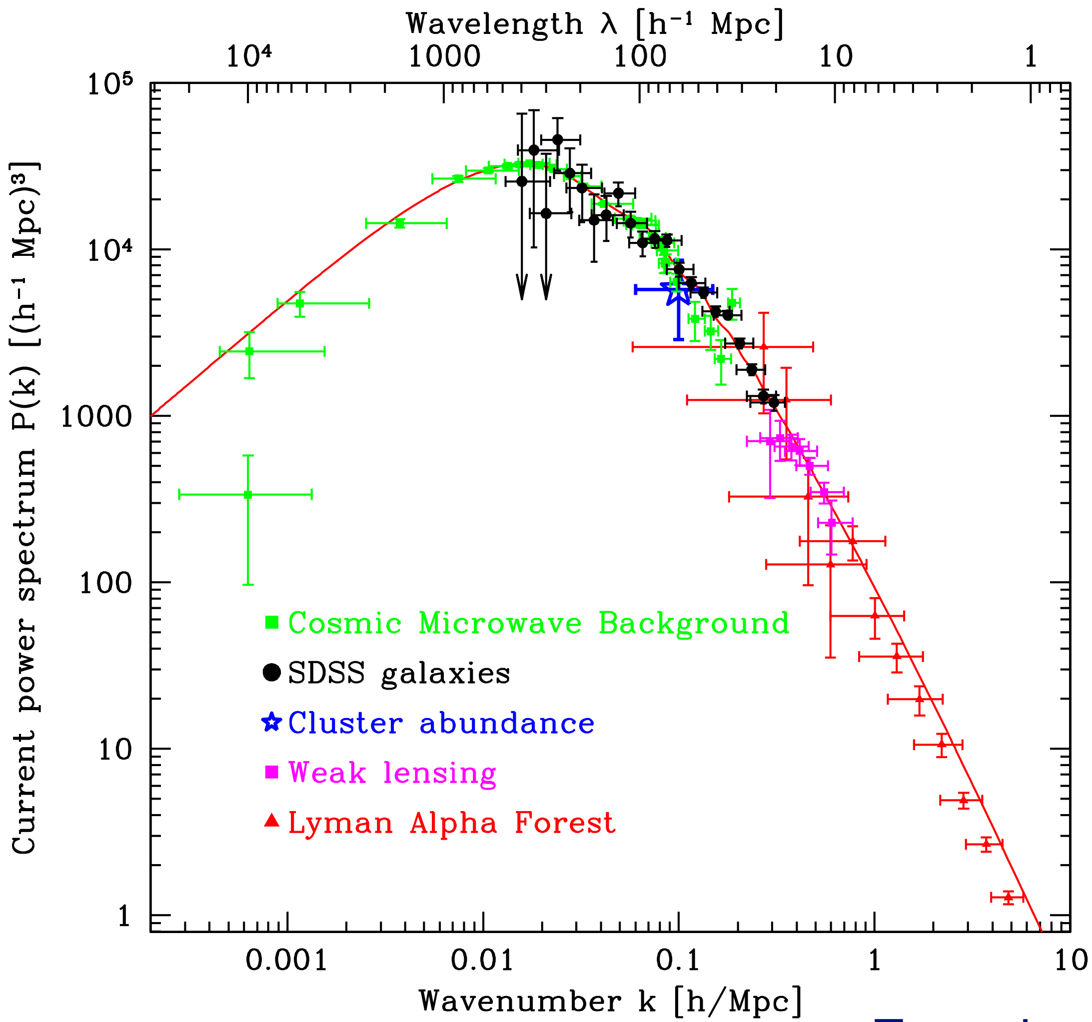
Dark Matter



Dark matter candidates: WIMPs, Axions, Black Holes…

CDM on Large Scales

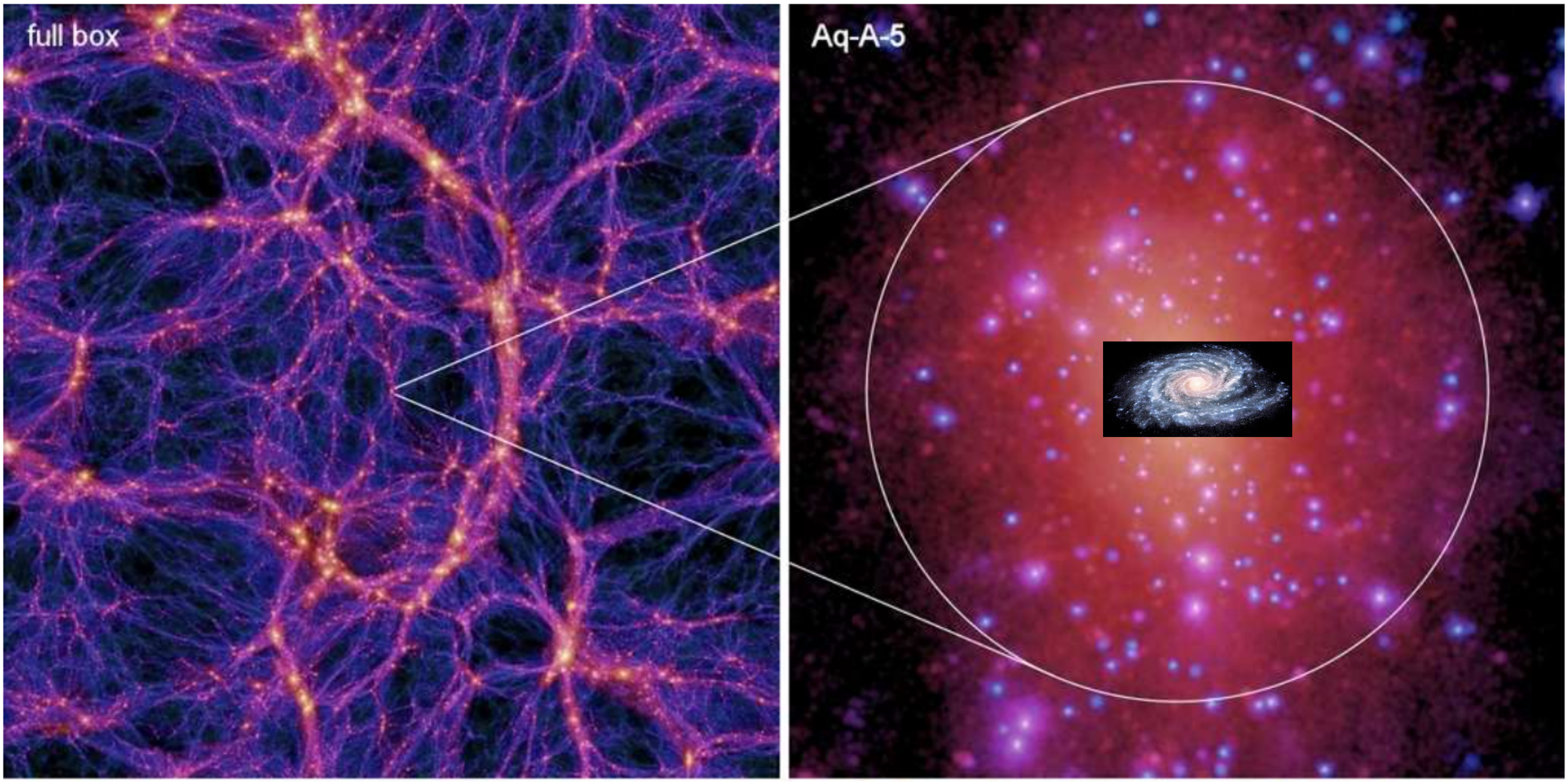
- works very well, >O(100) kpc



Tegmark+ (2004)

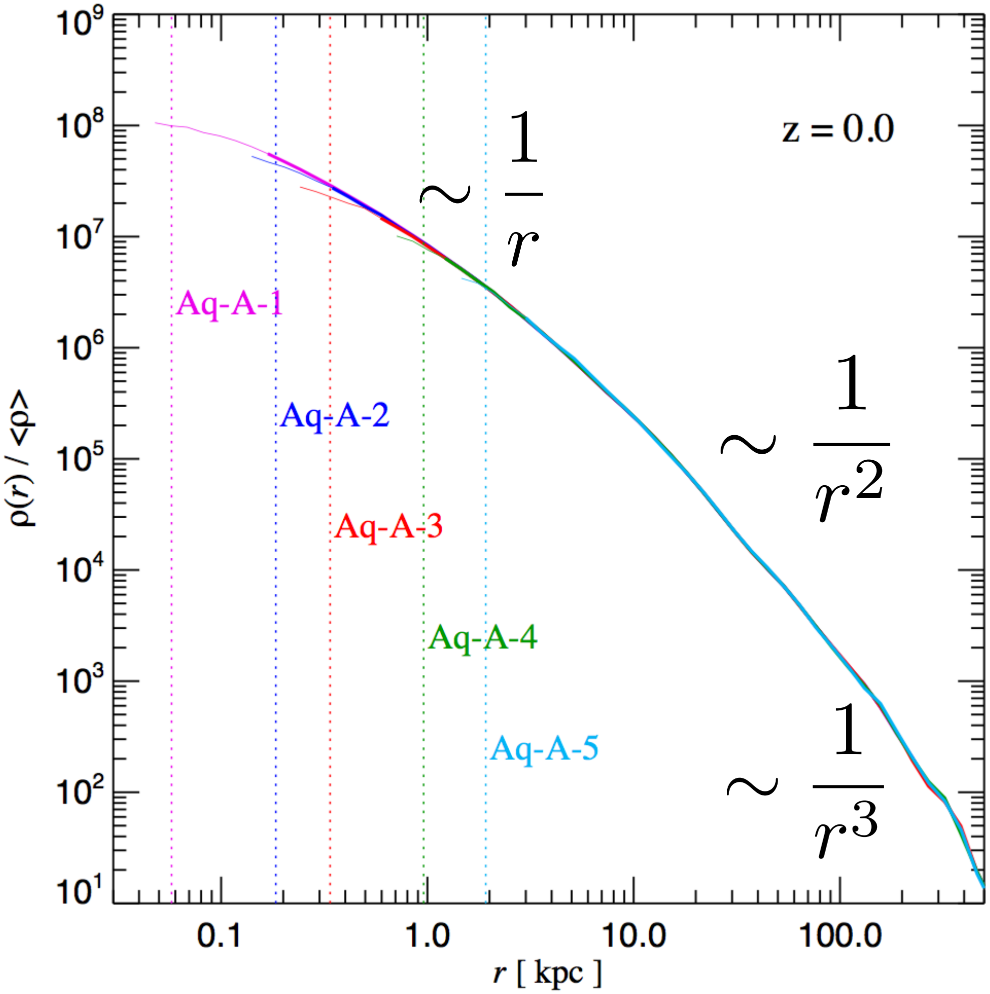
CDM Predictions on Small Scales

- CDM on galactic scales <O(10-100) kpc



Aquarius Project, Springel+(2008)

Universal Density Profile



Aquarius Project, Springel+ (2008)

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

the Navarro-Frenk-White (NFW) profile (1996)

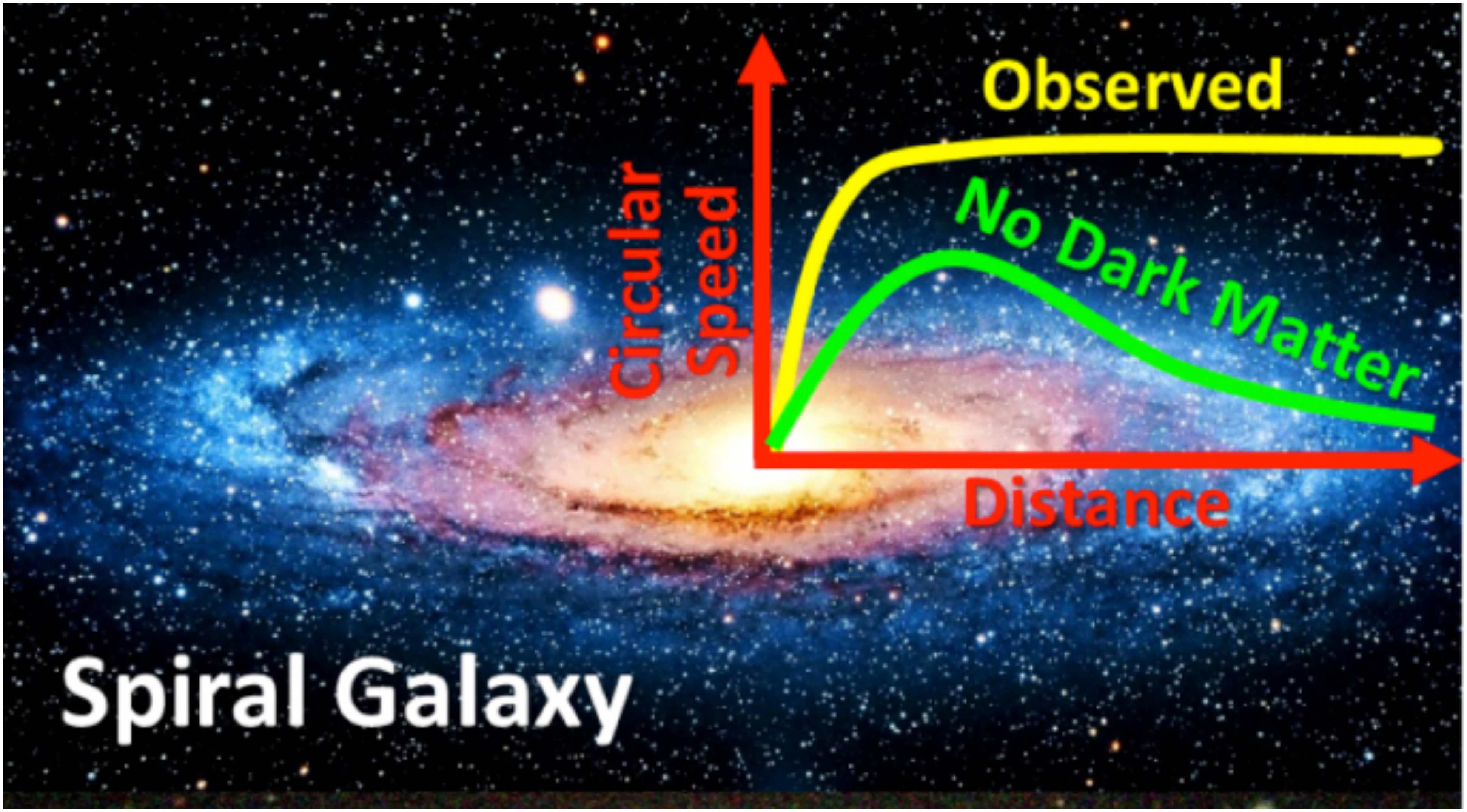
ρ_s and r_s are strong correlated

"the concentration-mass relation"

Specify a halo with one parameter+scatter

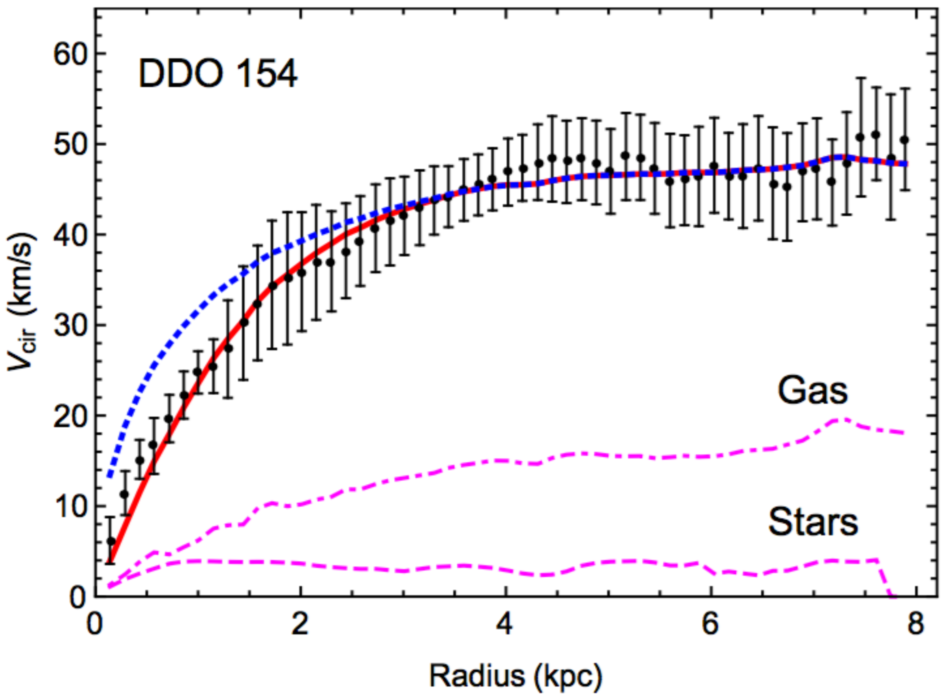
CDM-only cosmological simulations

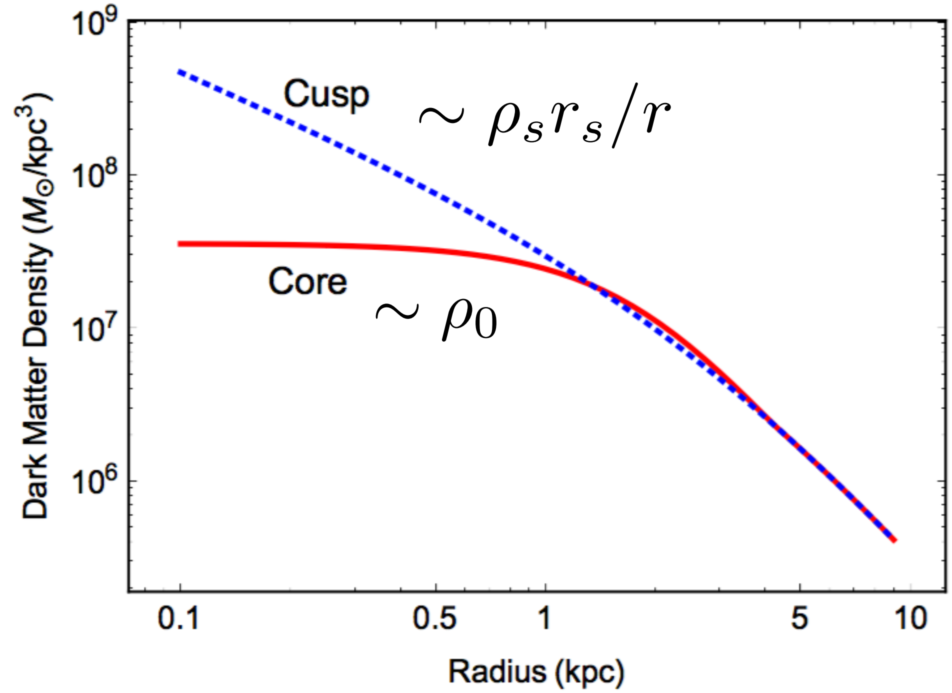
Testing Ground



Core vs Cusp Problem

- DM-dominated systems (dwarfs, LSBs)





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

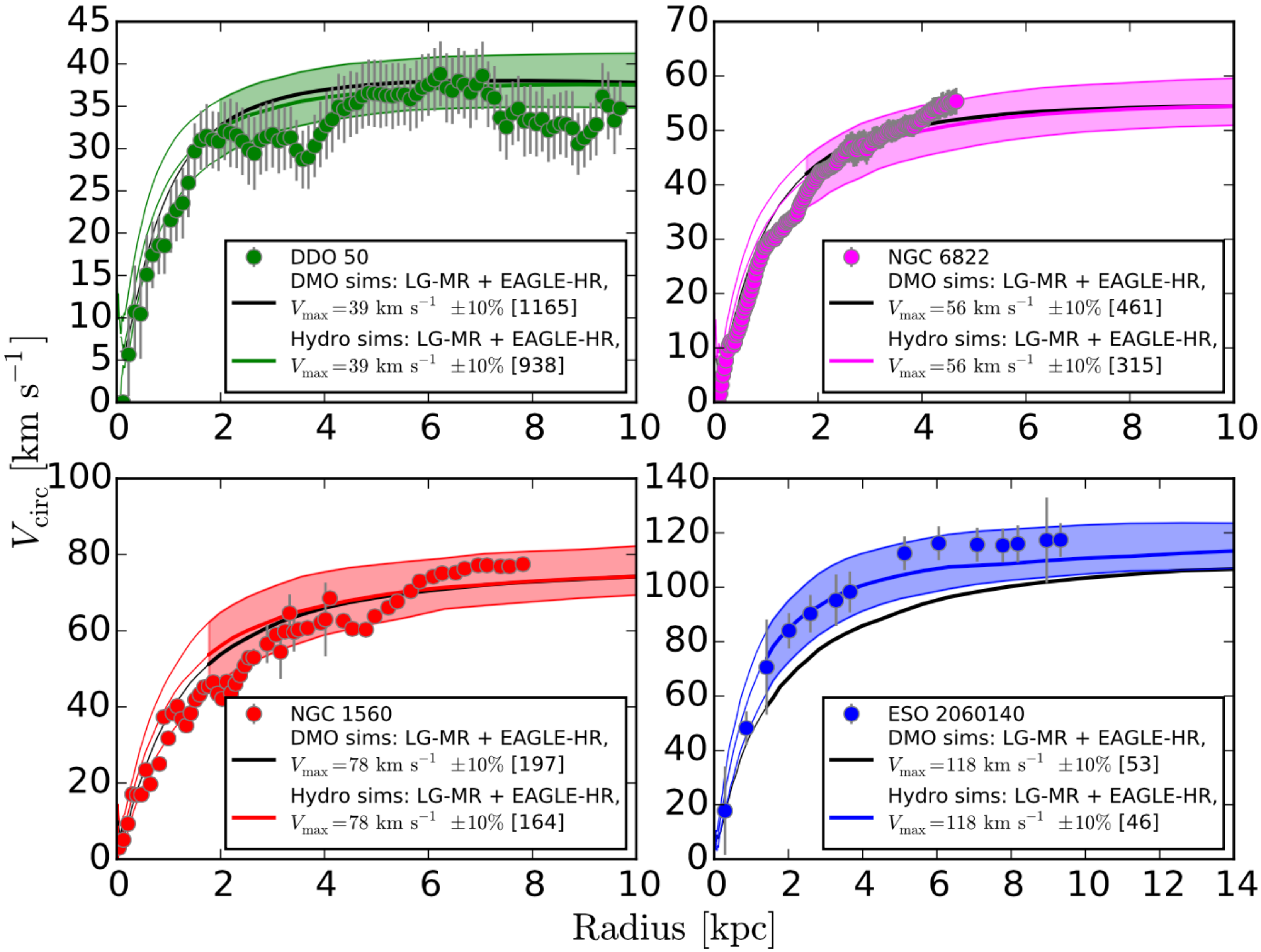
mass-to-light ratio

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

NFW (1996)

Flores & Primack (1994); Moore (1994); de Blok & McGaugh (1997)…

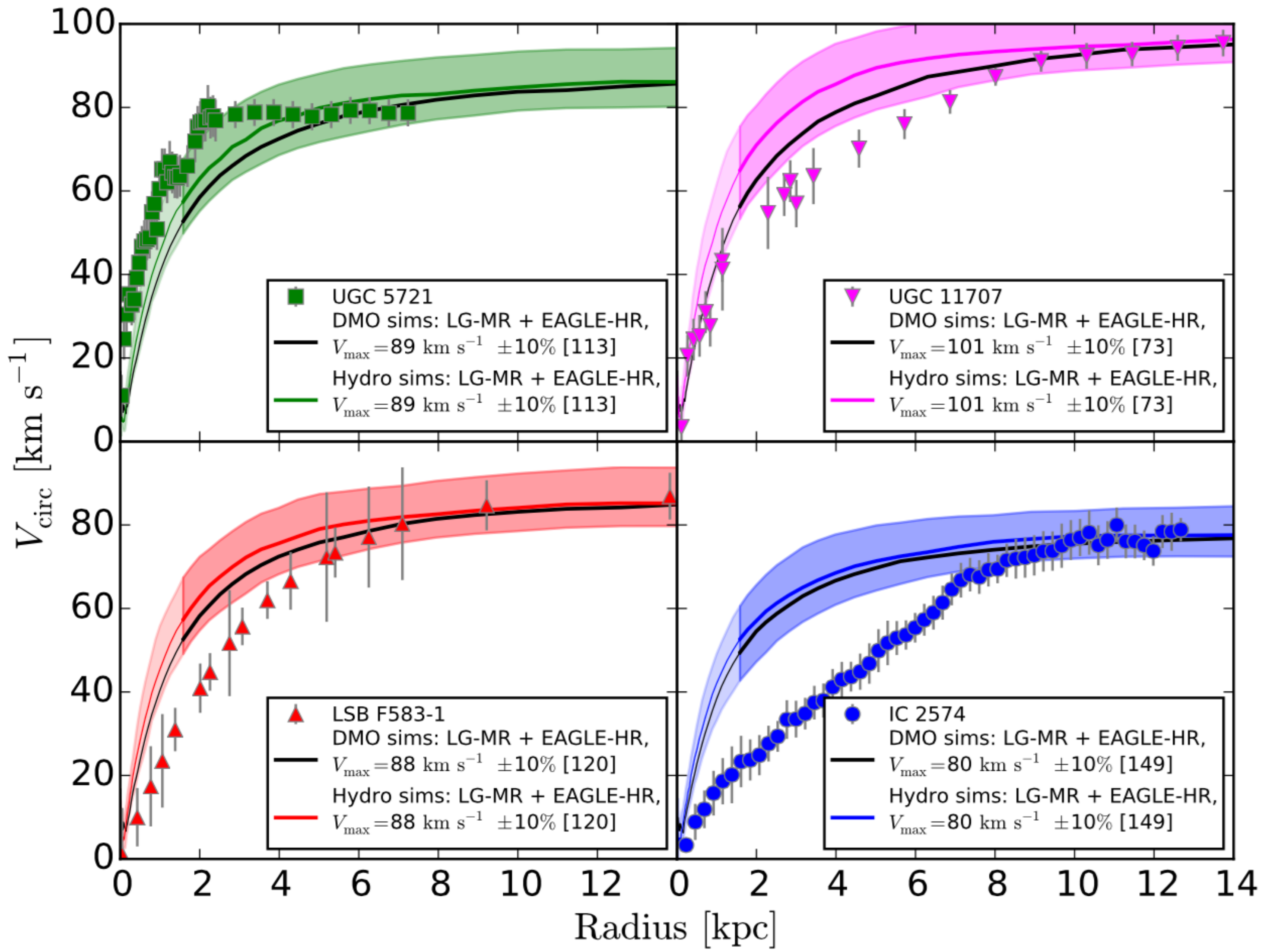
The Diversity Problem



Colored bands: hydrodynamical simulations of CDM
"smooth/weak" baryonic feedback (~0.1 atoms/cc)

Oman, Navarro+(2015)

The Diversity Problem



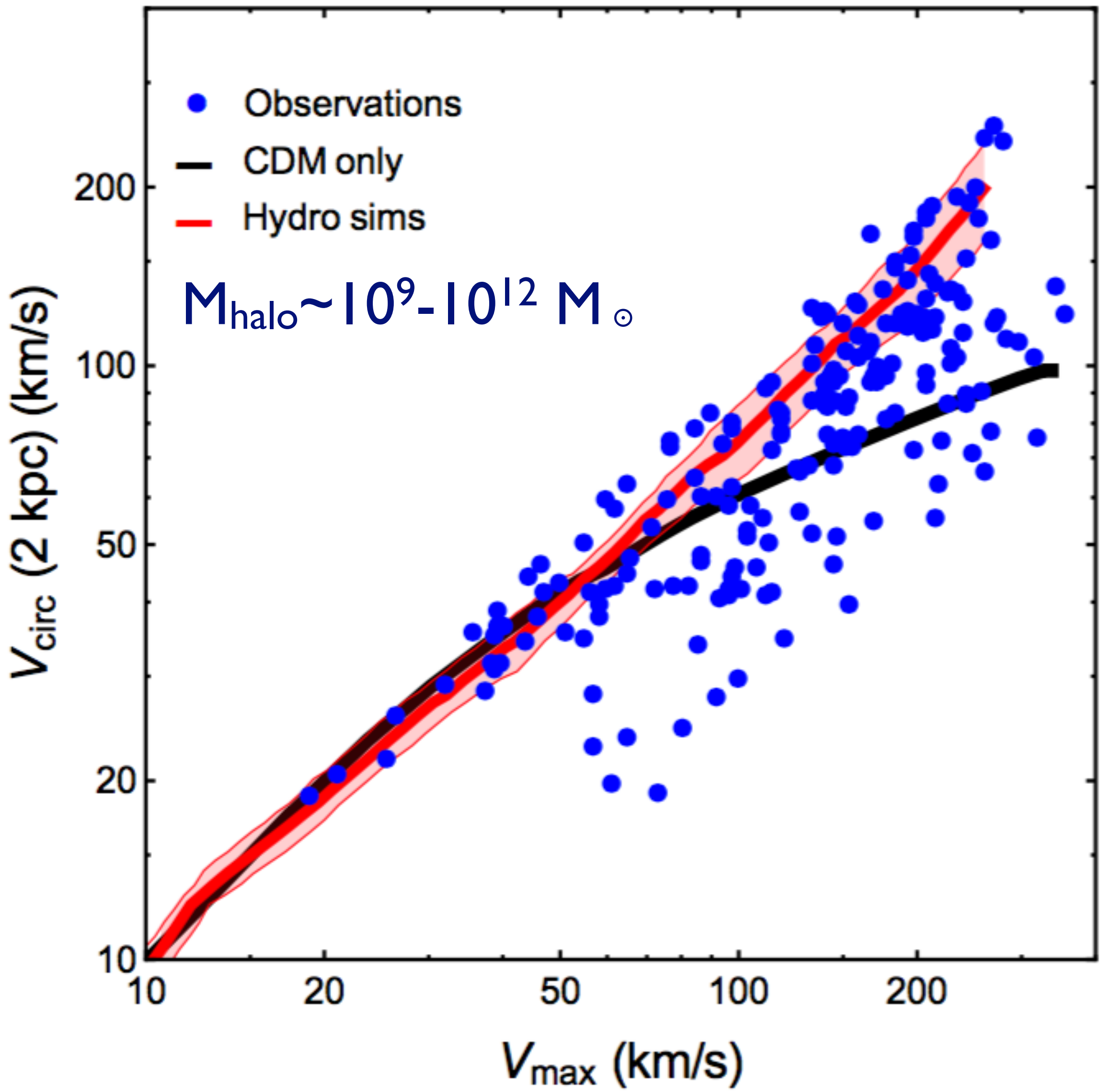
All galaxies have the same observed Vmax!

Colored bands: hydrodynamical simulations of CDM

Oman, Navarro+(2015)

See also: McGaugh (PRL, 2005); Kuzio de Naray, Martinez, Bullock, Kaplinghat (ApJ, 2010)

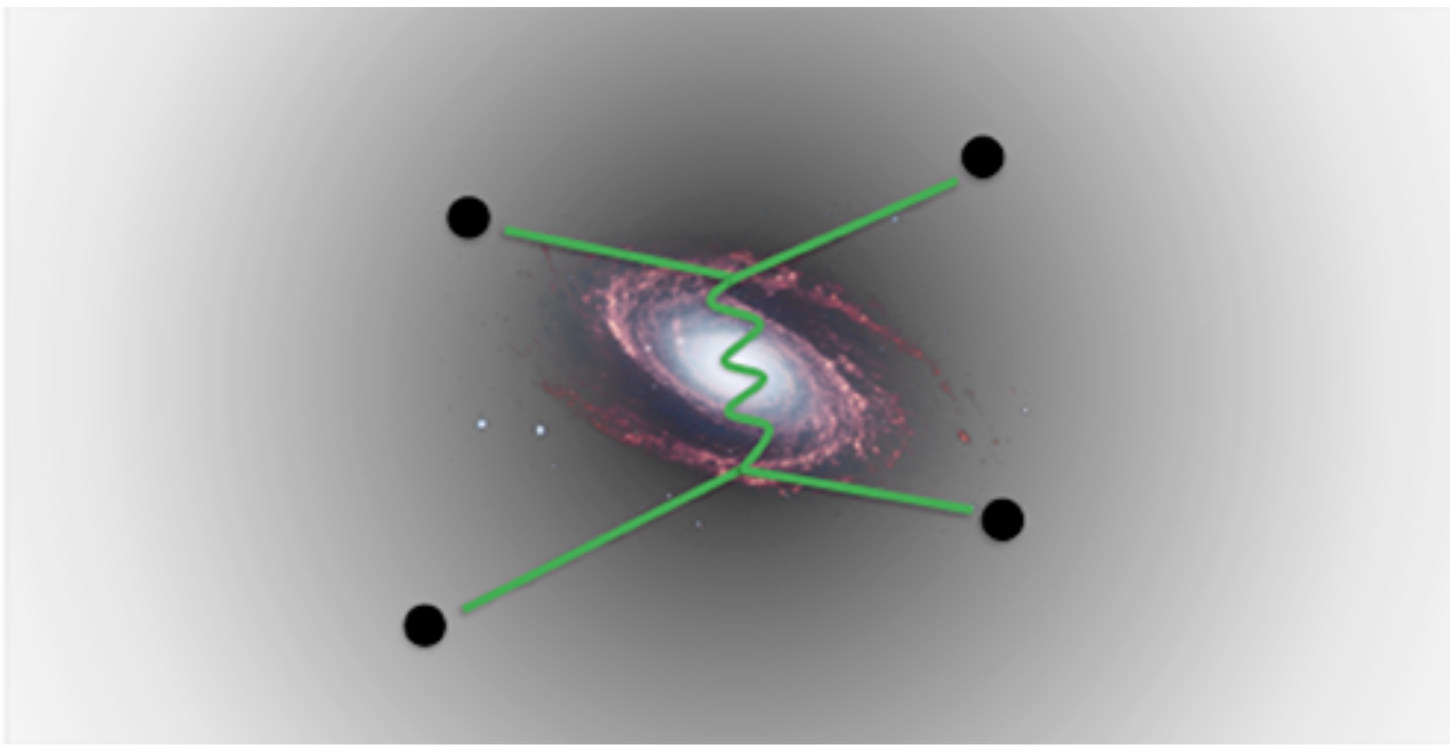
A Big Challenge



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

Reproduced from the data compiled in Oman, Navarro+(2015)

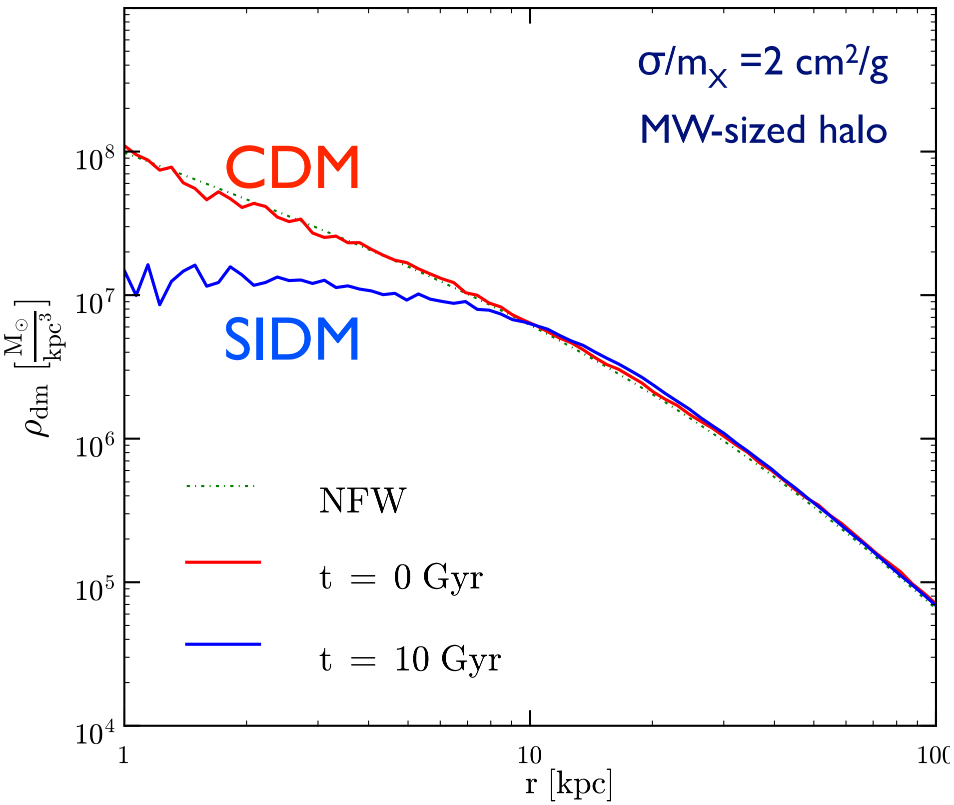
The diversity is expected if dark matter has strong self-interactions

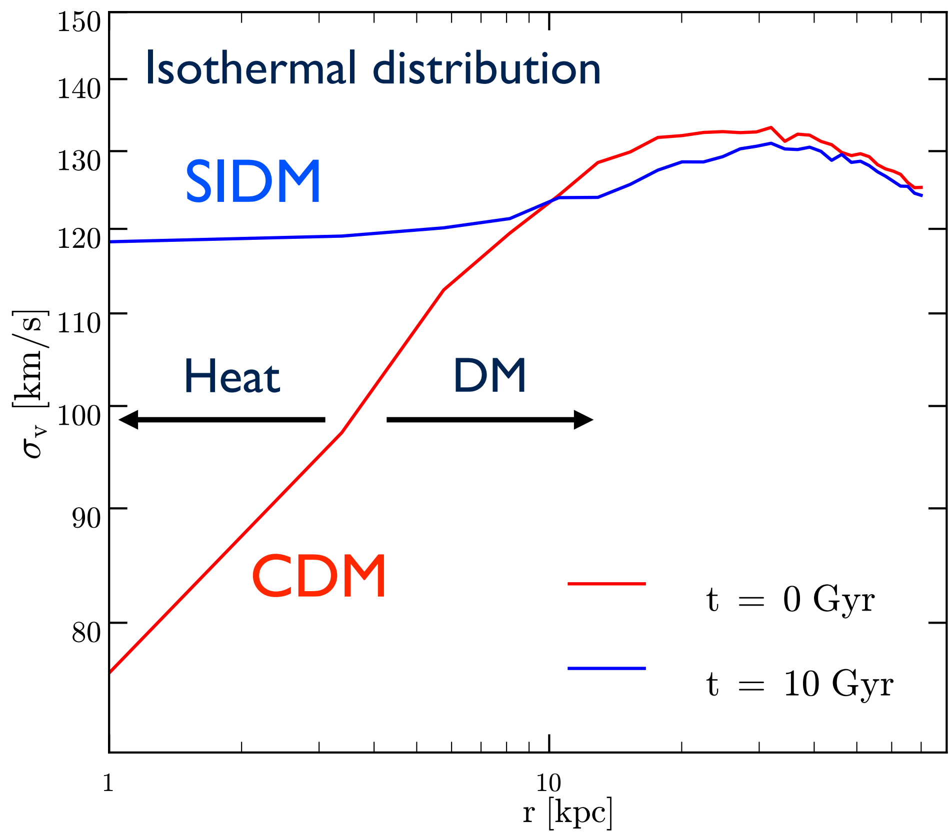


Self-Interacting Dark Matter

- Self-interactions thermalize the inner halo

Spergel & Steinhardt (PRL, 2000)





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

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

From Ran Huo

Review: Tulin & HBY (Physics Reports 2017)

Modelling SIDM Halos

semi-analytical approach

Inner halo

Ideal gas: PV=nRT

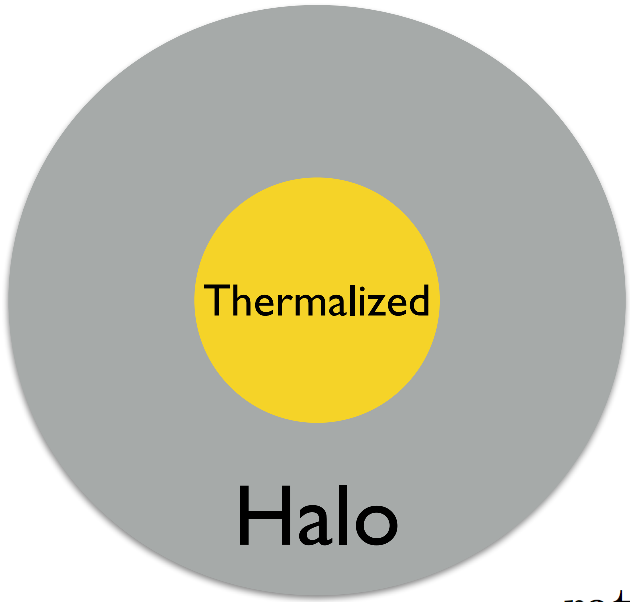
isothermal distribution

$$\rho_0 e^{-\Phi_{\rm tot}/\sigma_0^2}$$

$$\Phi_{\rm tot} = \Phi_{\rm dm} + \underline{\Phi_b}$$

Known

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



Outer halo

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

The boundary is set by

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

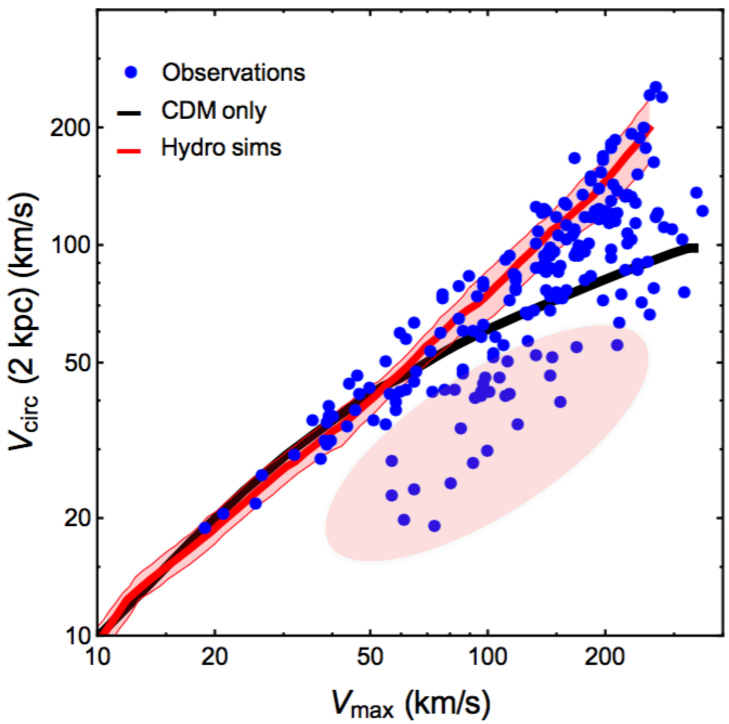
$$(\rho_0, \sigma_0) \leftrightarrow (\rho_s, r_s) \leftrightarrow (V_{\rm max}, r_{\rm max})$$

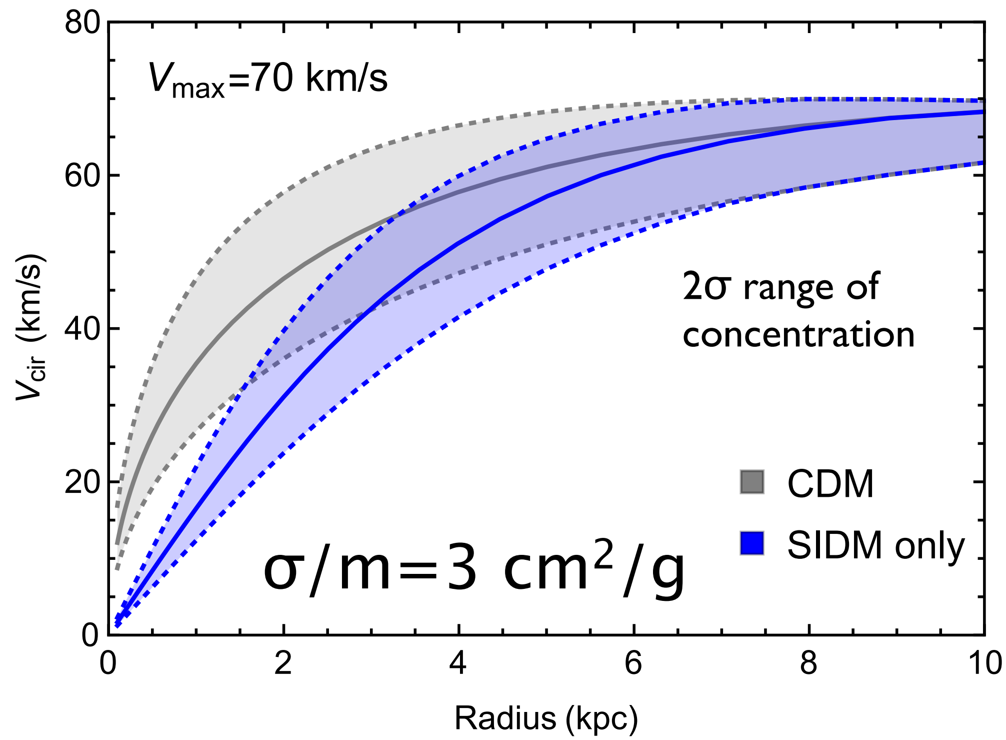
with Kaplinghat, Keeley, Linden (PRL 2014)
with Kaplinghat, Linden (RPL 2015)
with Kaplinghat, Tulin (PRL 2016)
with Kamada, Kaplinghat, Pace (PRL 2017)

VS

Addressing the Diversity Problem

- DM self-interactions thermalize the inner halo





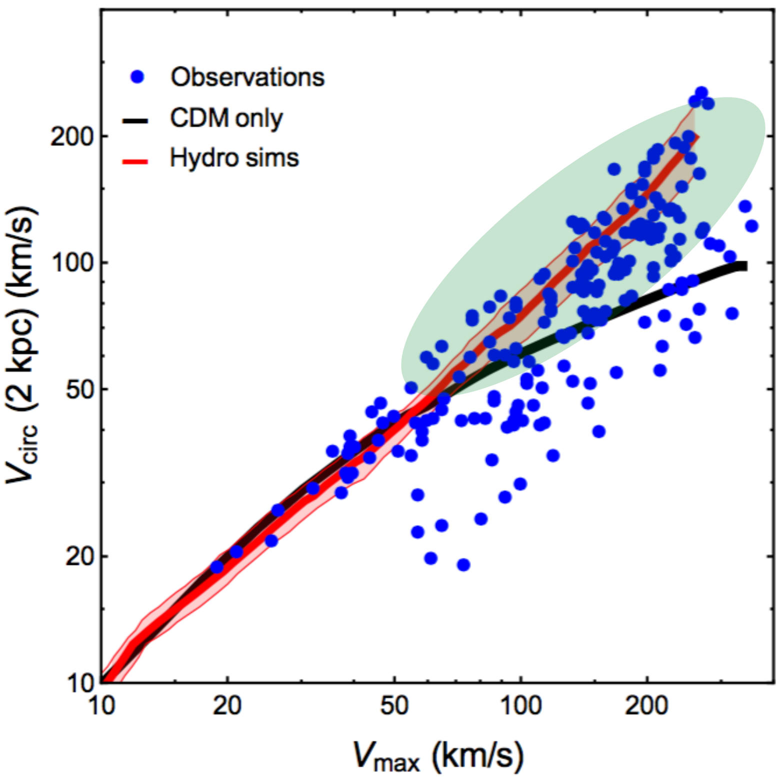
DM-dominated galaxies: Lower the central density and the circular velocity

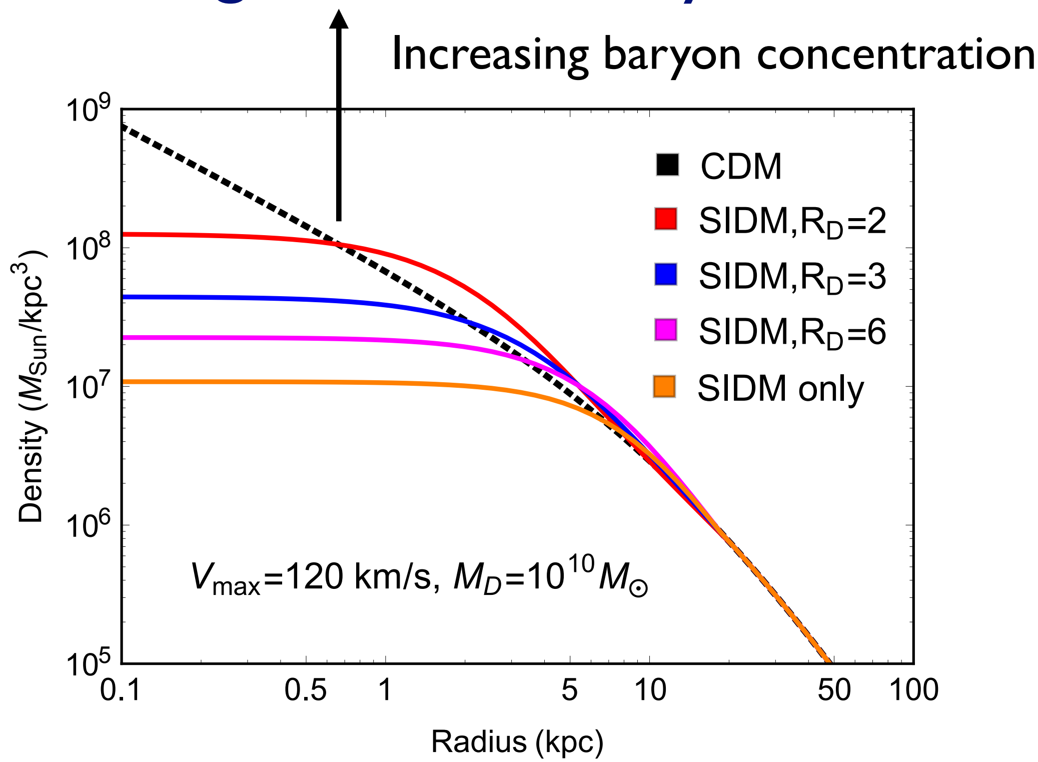
Isothermal distribution

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

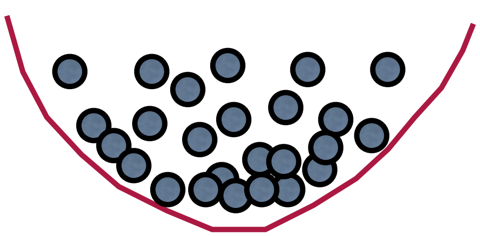
High Surface Brightness Galaxies

- DM self-interactions tie DM together with baryons





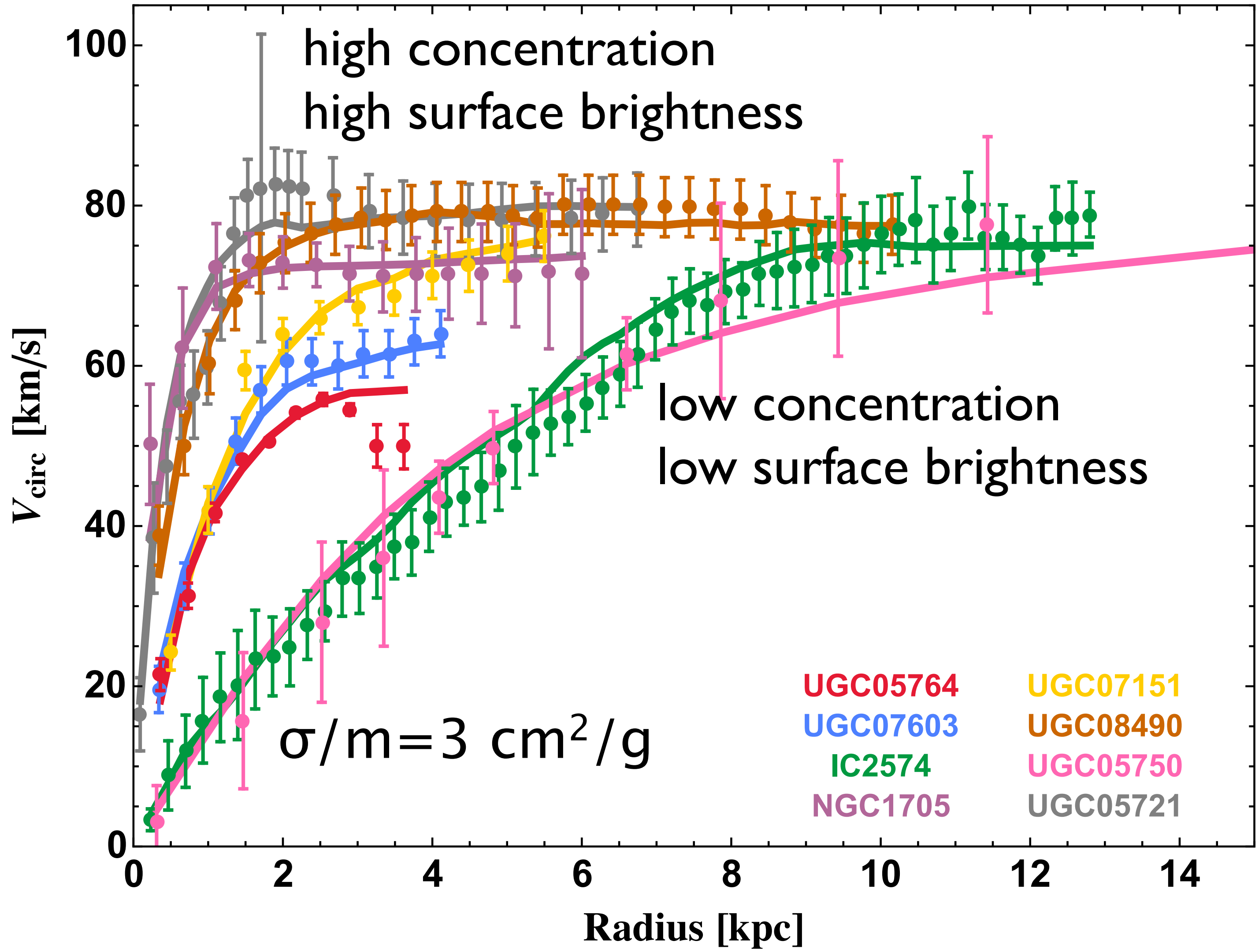
Thermalization leads to higher DM density due to the baryonic influence



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

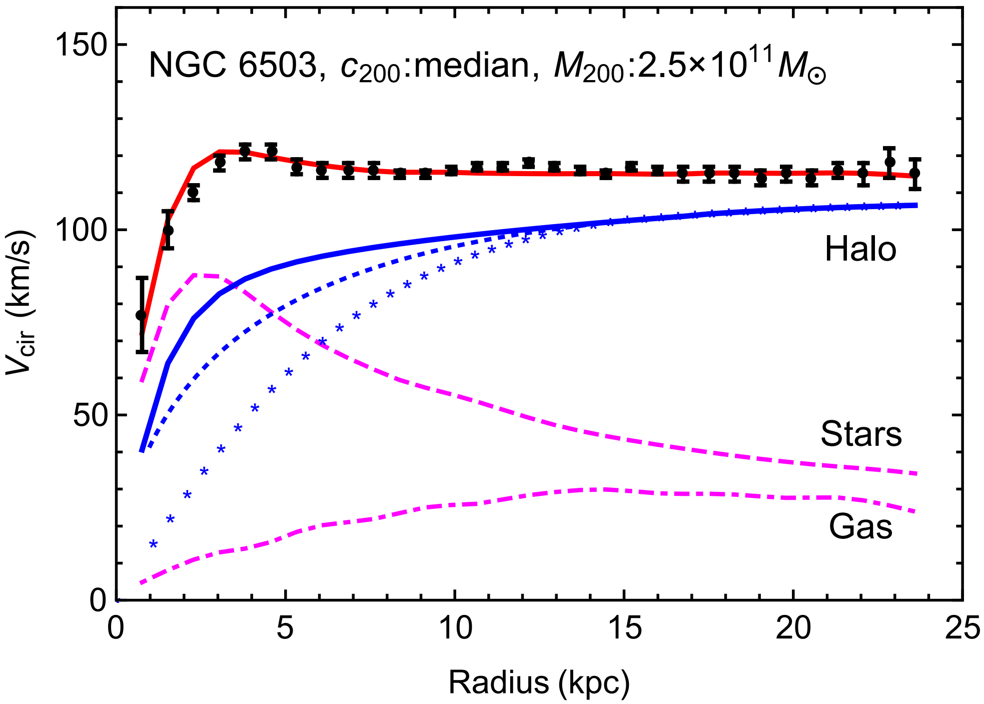
NO cored SIDM profile if the baryonic profile ~$1/r^2$

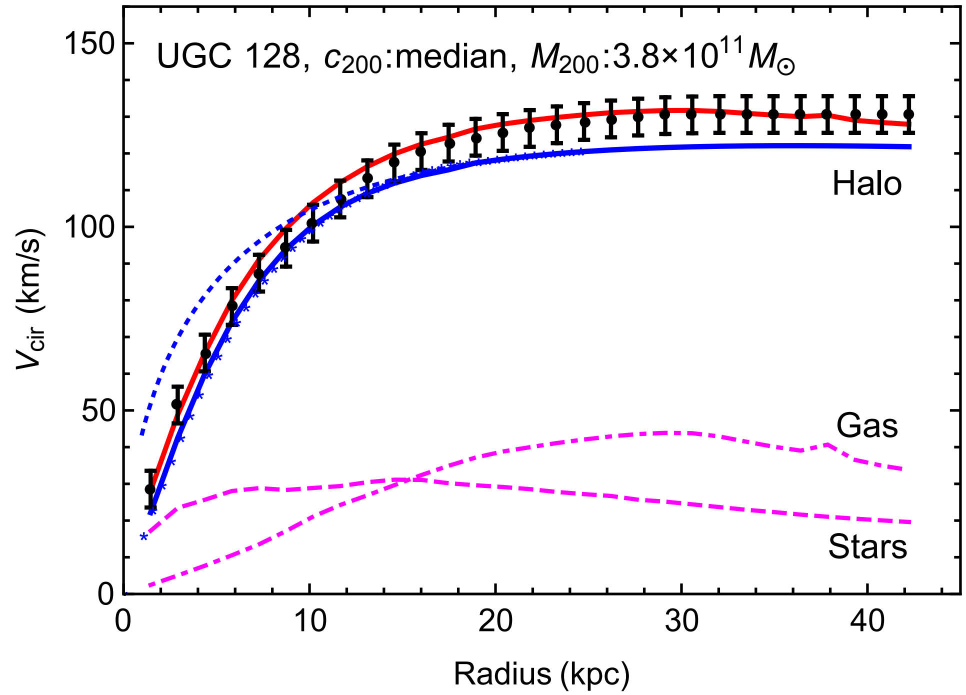
with Kaplinghat, Keeley, Linden (PRL 2014)

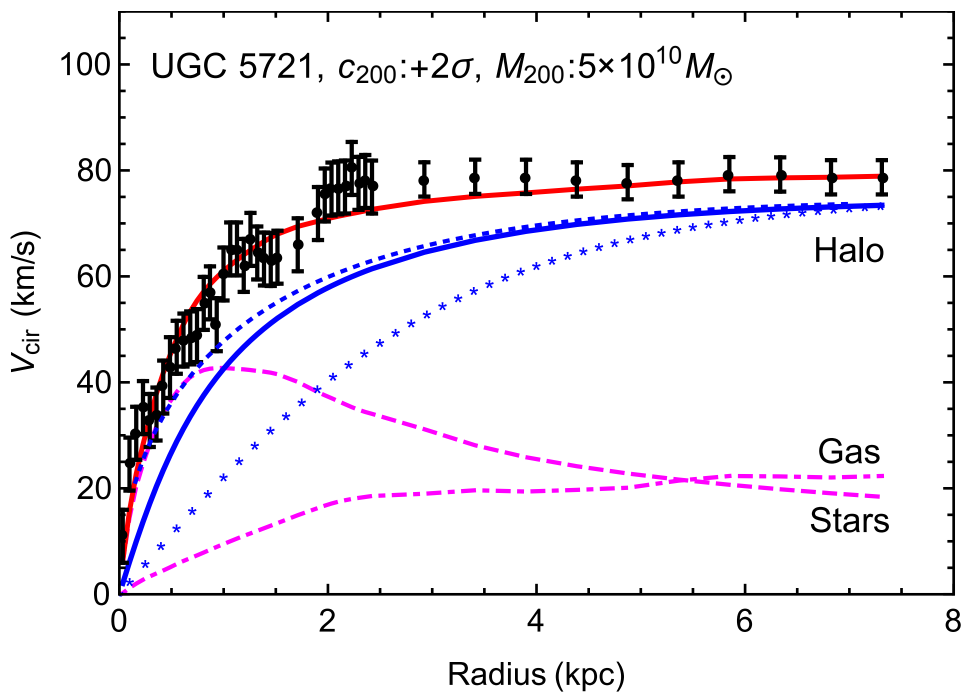


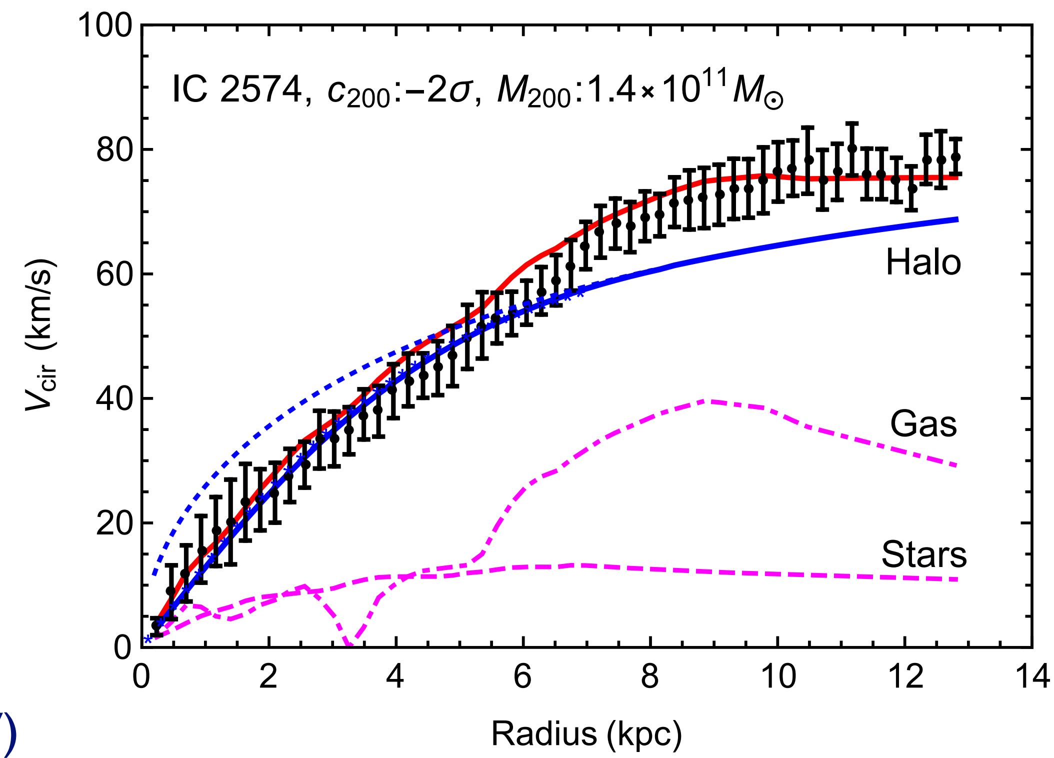
- Intrinsic scatter in the halo concentration-mass relation
- Diverse baryon distributions
- SIDM thermalization ties DM and baryon distributions in the RIGHT way

with Kamada, Kaplinghat, Pace (PRL 2017) 30 galaxies $\sigma/m = 3\ \mathrm{cm}^2/\mathrm{g}$



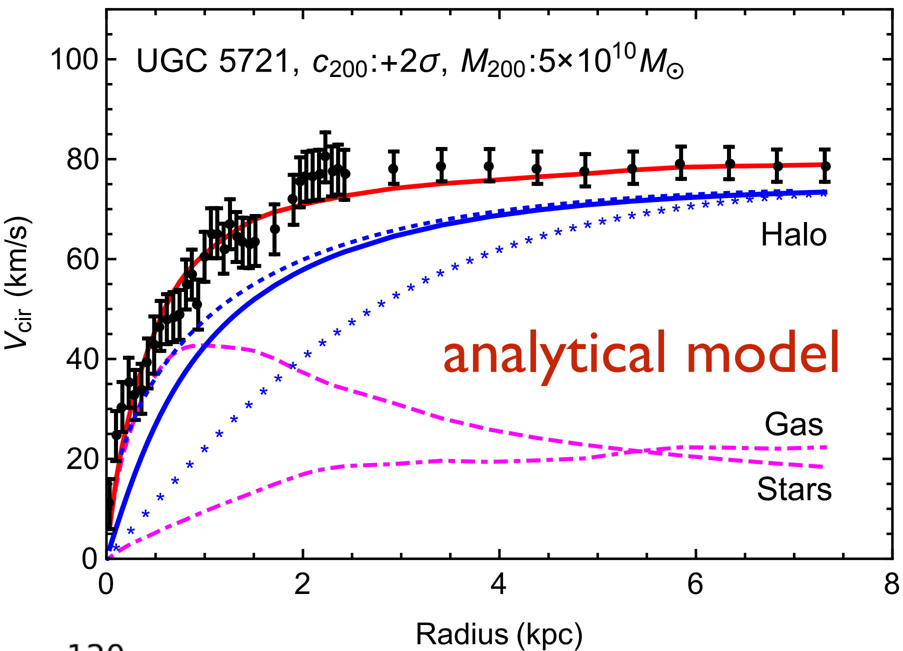


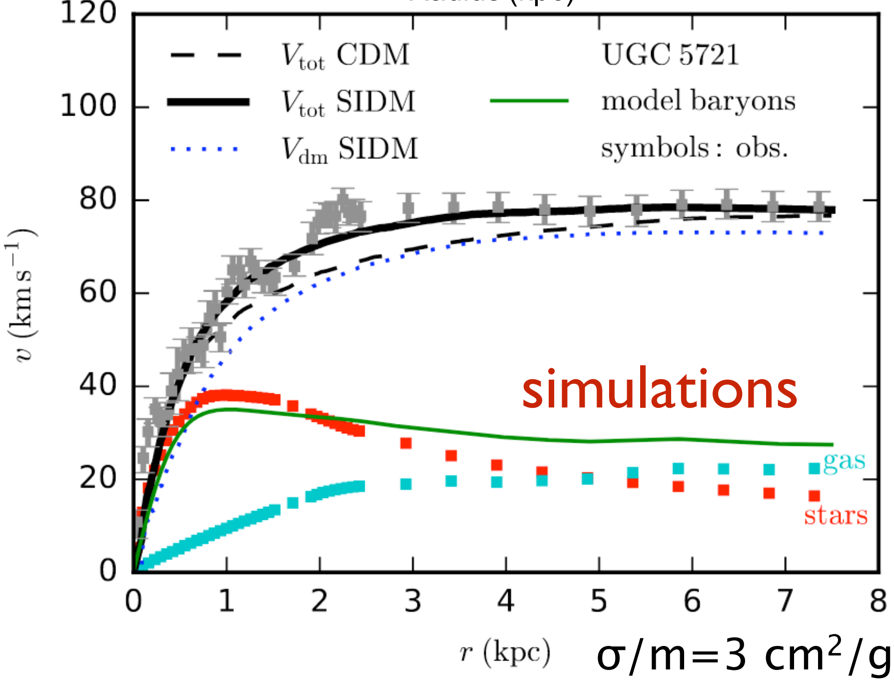




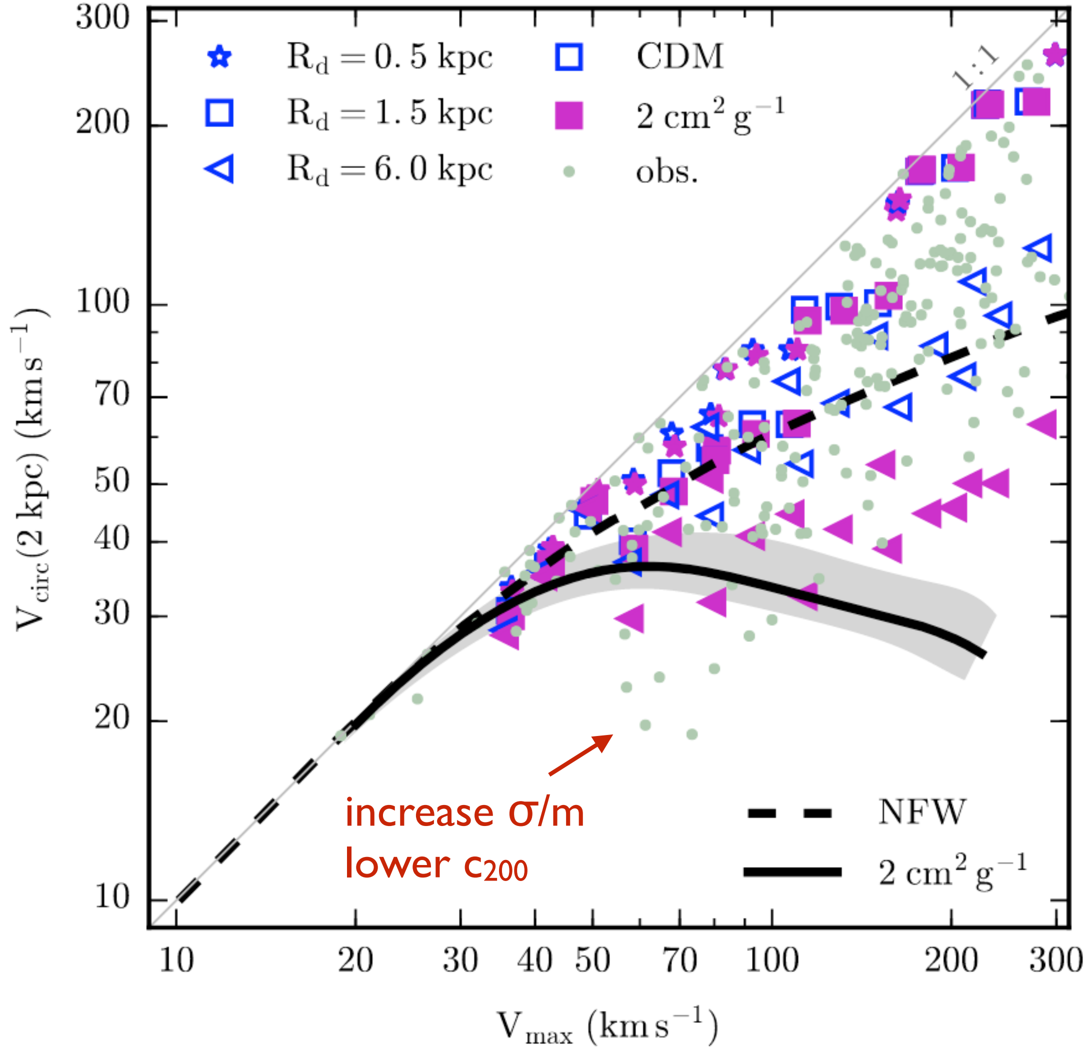
with Kamada, Kaplinghat, Pace (PRL 2017)

Tests with Controlled Simulations



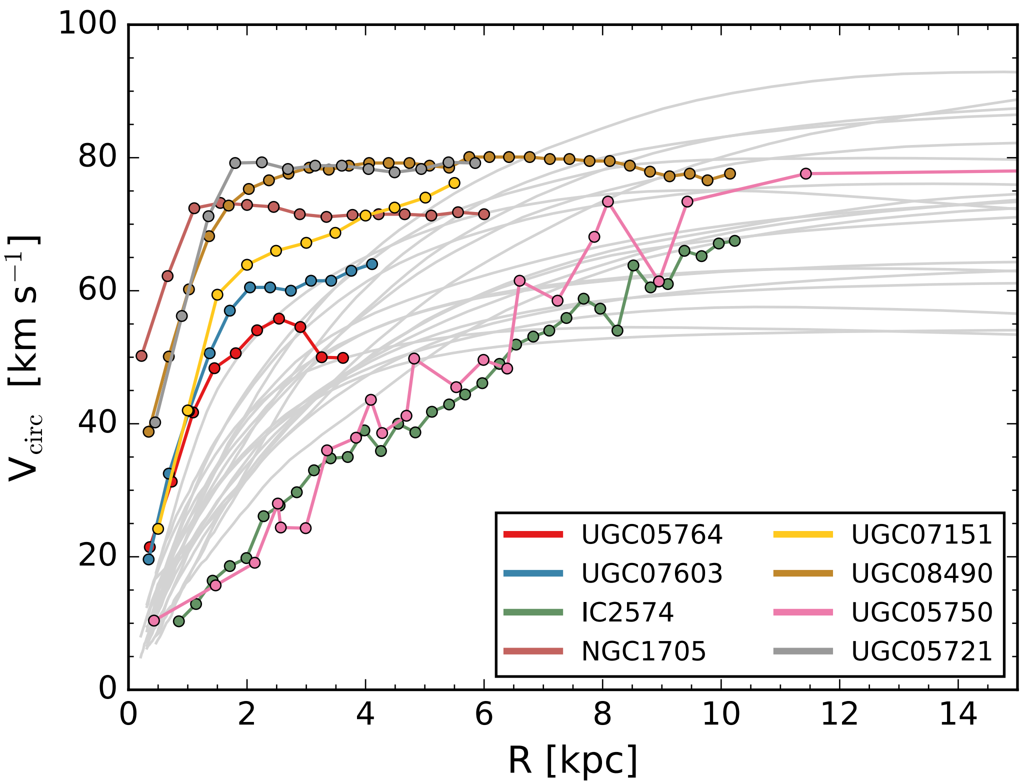


σ/m=3 cm²/g

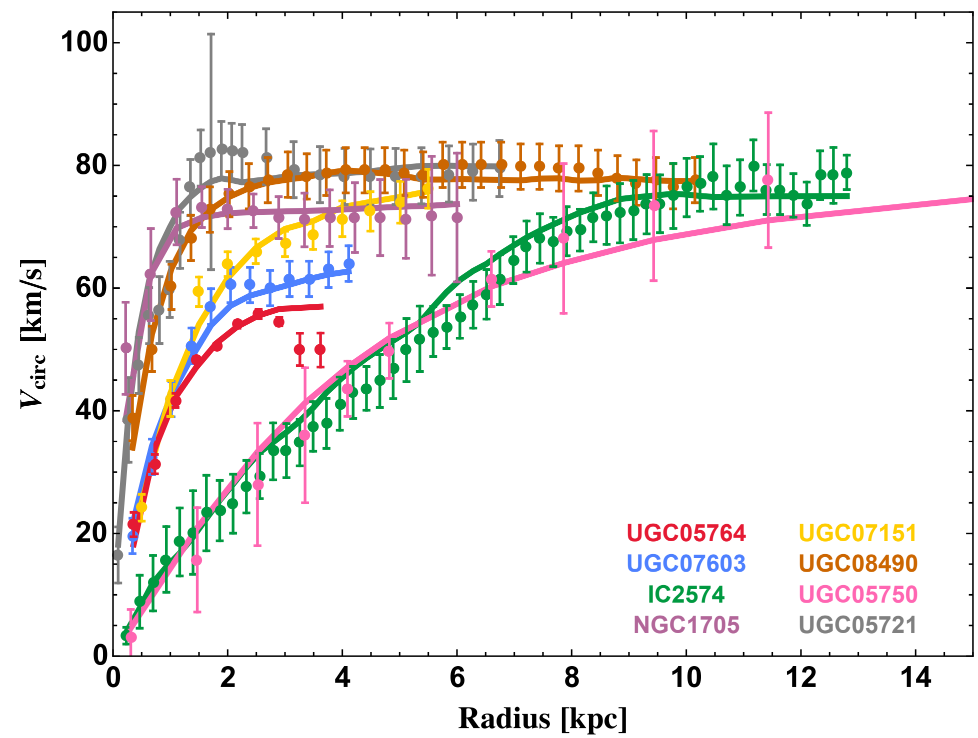


with Creasey, Sameie, Sales, Vogelsberger, Zavala (MNRAS 2017)

CDM w/Strong Feedback vs SIDM



Santos-Santos+(2017)



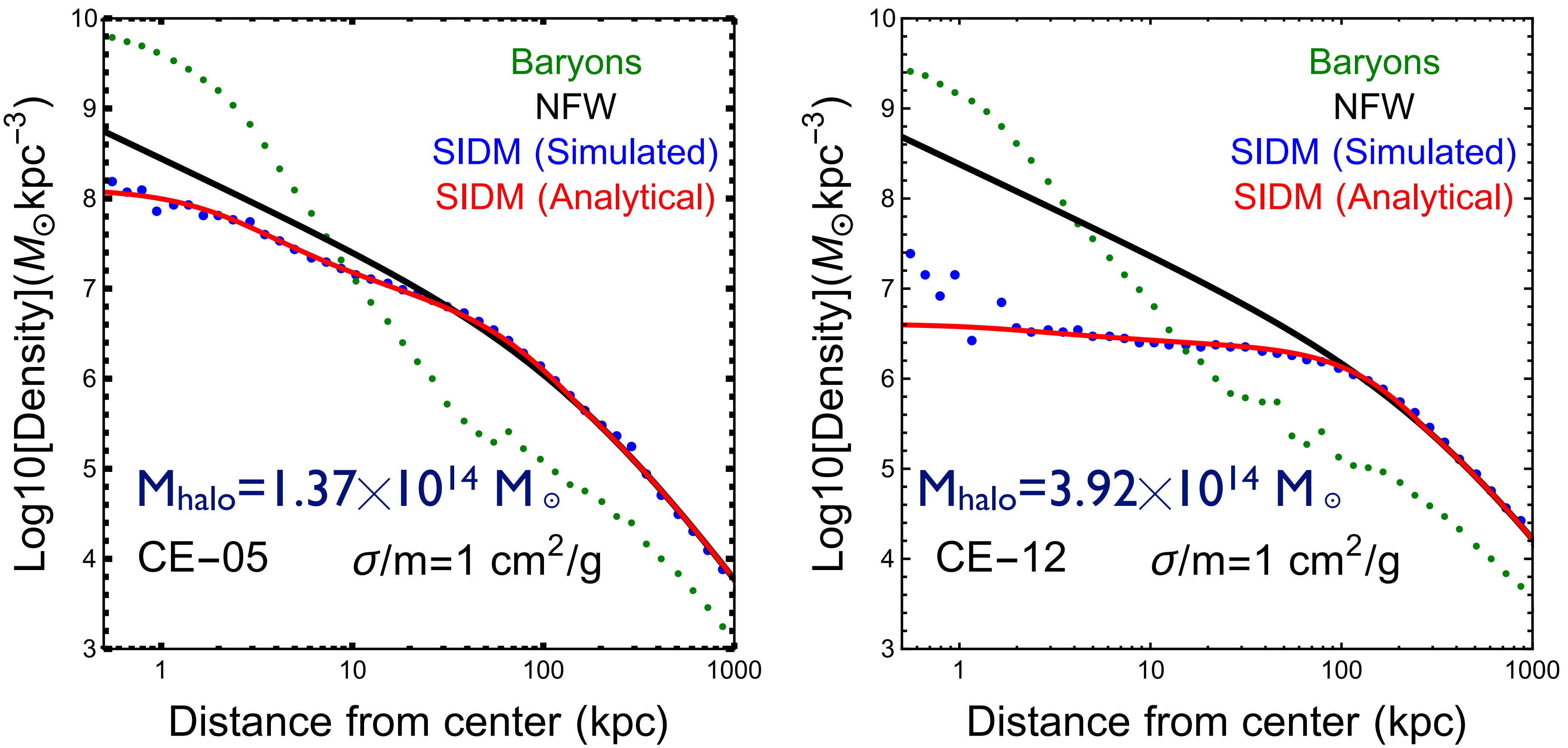
Gray lines: NIHAO simulations of CDM (3σ band)

"strong/violent" feedback

Solid lines: SIDM fits

(~2σ in the c_{200}-M_{200} relation)

Hydro SIDM Simulations

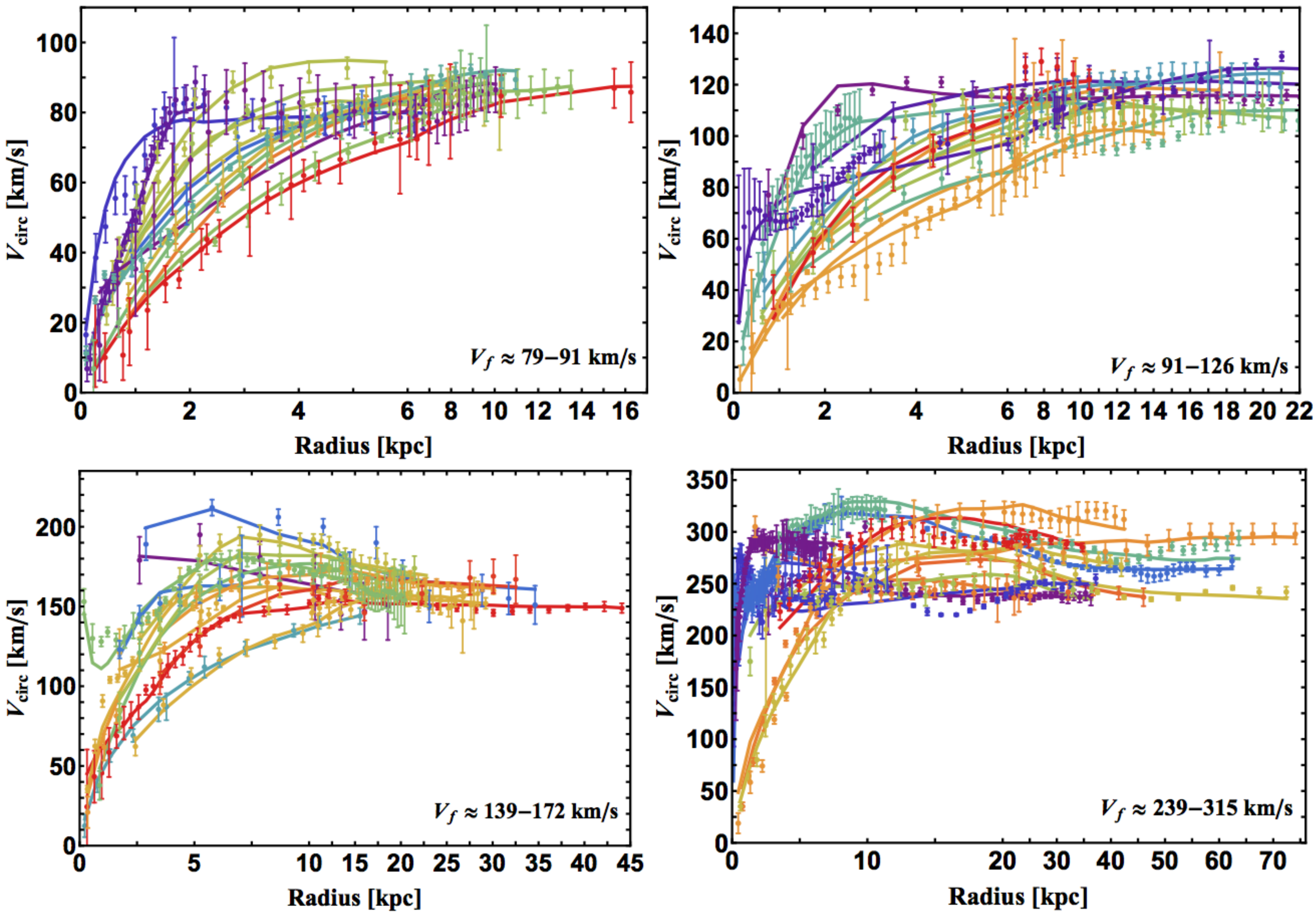


With Robertson, Massey, Eke, Tulin+(MNRAS Letters, 2018)

- The SIDM distribution is sensitive to the final baryon distribution
- It is robust to formation history due to collisional thermalization

$\rho_0 e^{-\Phi_{\rm tot}/\sigma_0^2}$ Predicted in Kaplinghat, Keeley, Linden, Yu (PRL 2014)

A Much Larger Sample

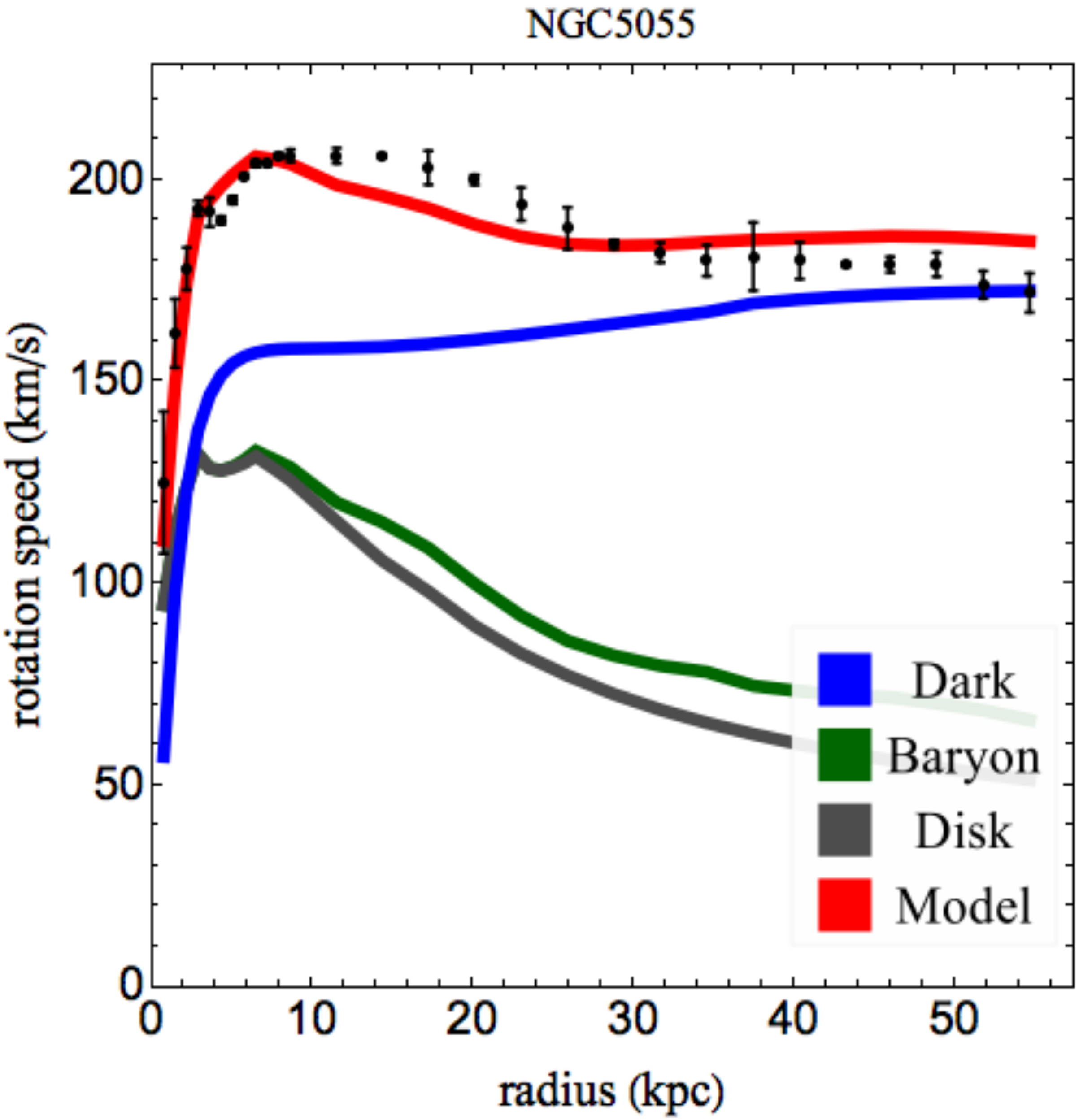


We fitted 135 galaxies (3.6 μm band)!

SPARC dataset, Lelli, McGaugh,Schombert (2016)

With Ren, Kwa, Kaplinghat (2018)

See Appendix for detailed fits for all galaxies

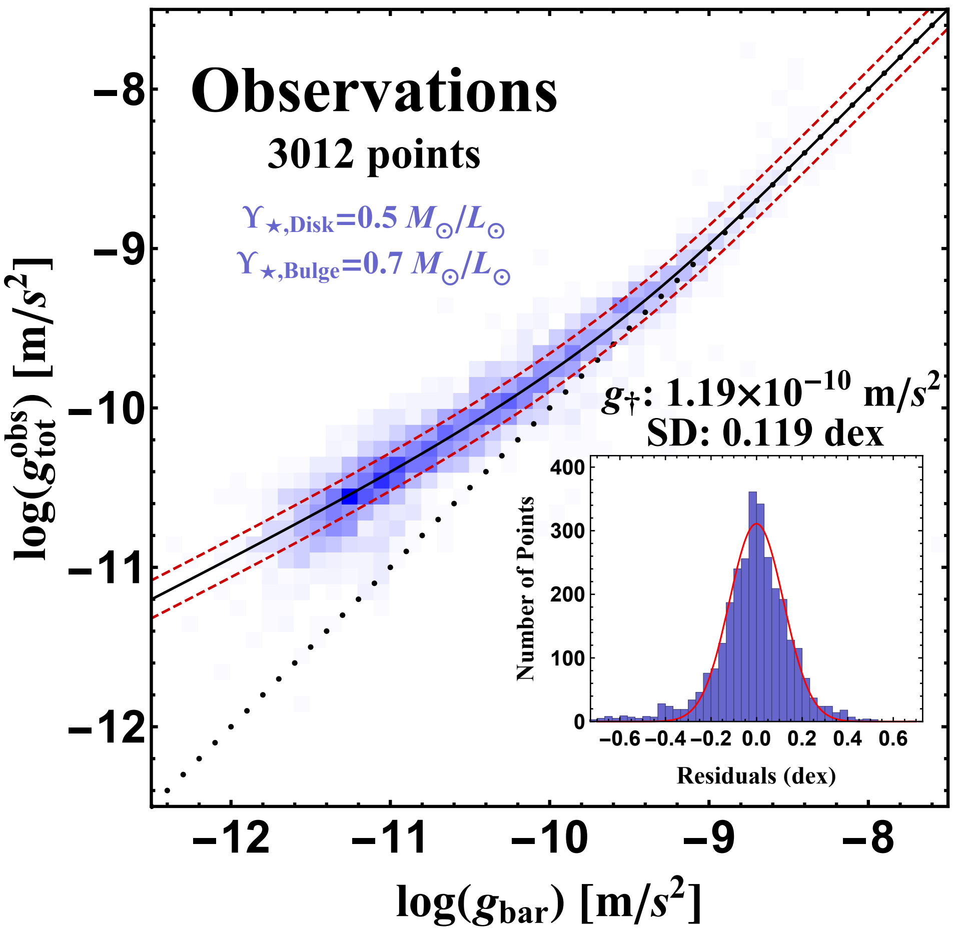


with Ren, Kwa, Kaplinghat (2018)

The “worst” fit, χ^2/d.o.f ~44

But, they are also well-organized

- Radial Acceleration Relation



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

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

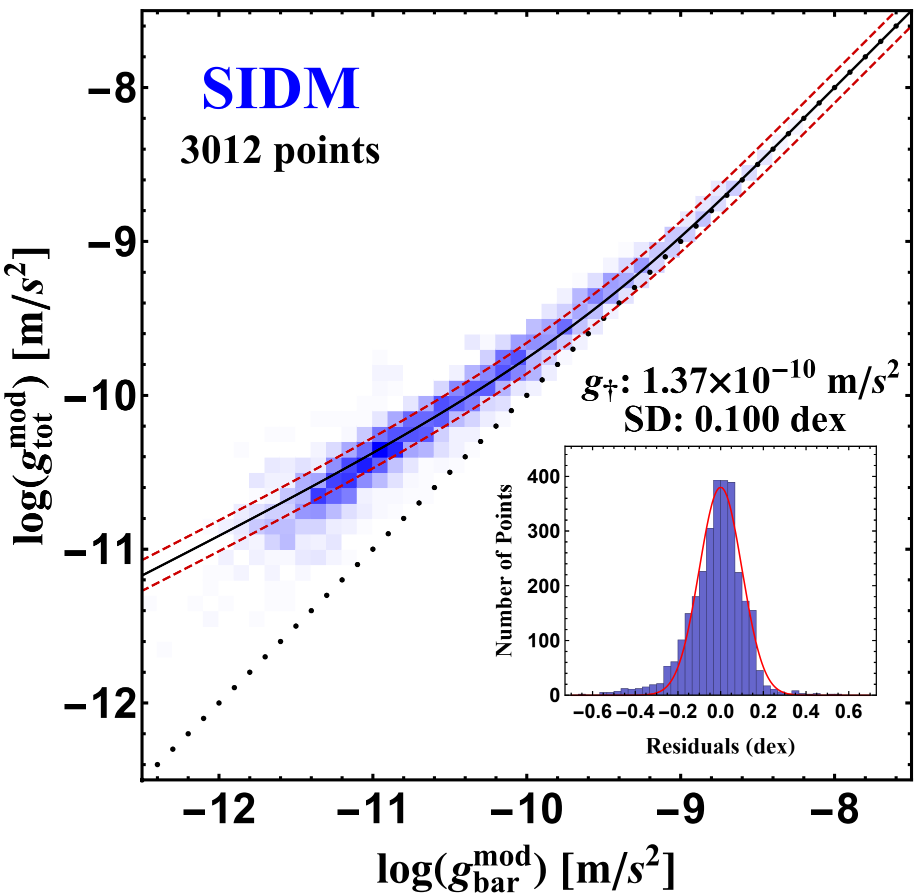
when $g_{\mathrm{bar}} < g_\dagger$

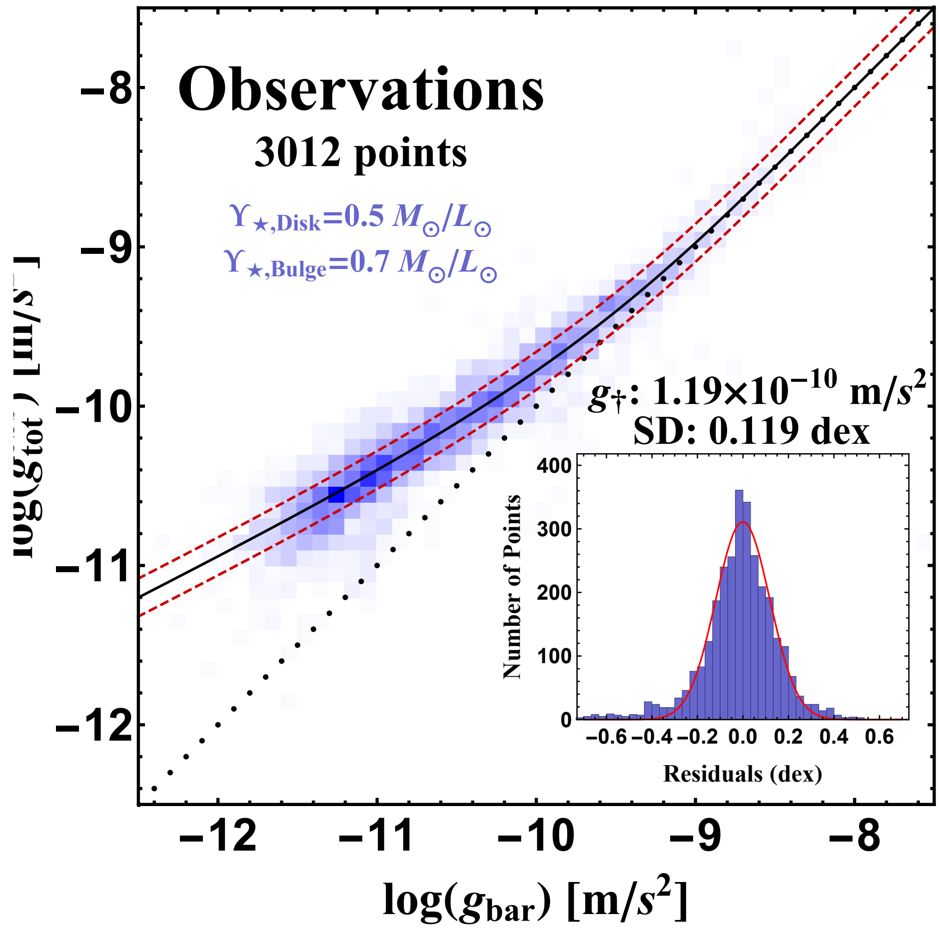
MOND, Milgrom's law (1983)

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

135 galaxies "Uniformity"

Uniformity in SIDM



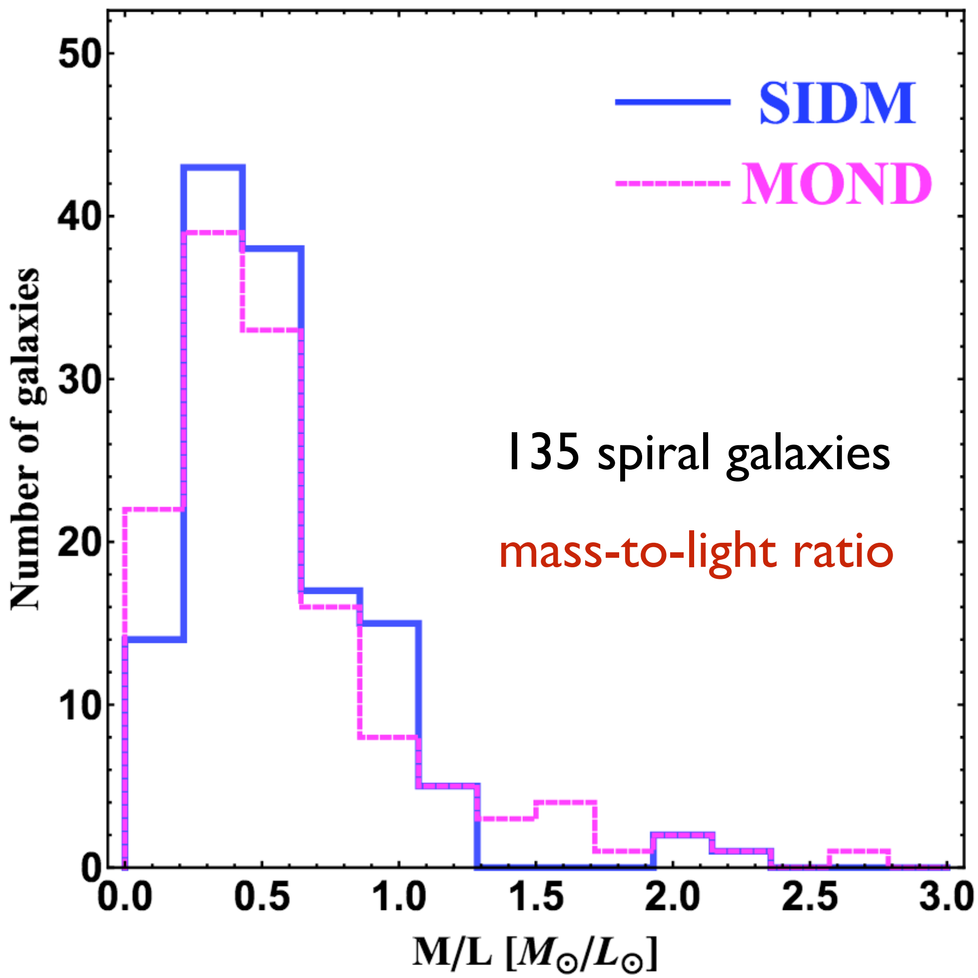


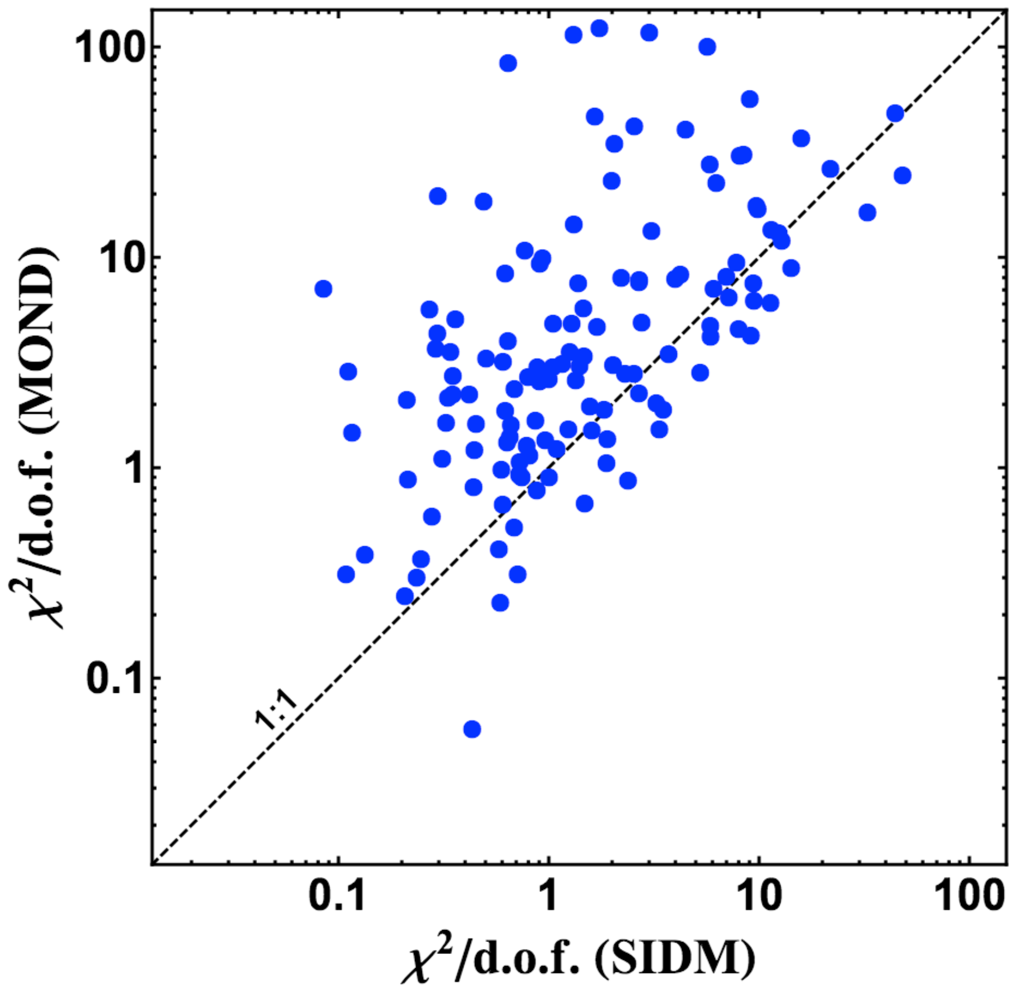
135 galaxies

with Ren, Kwa, Kaplinghat (2018)

SIDM explains both the diversity and uniformity of galaxy rotation curves

SIDM vs MOND

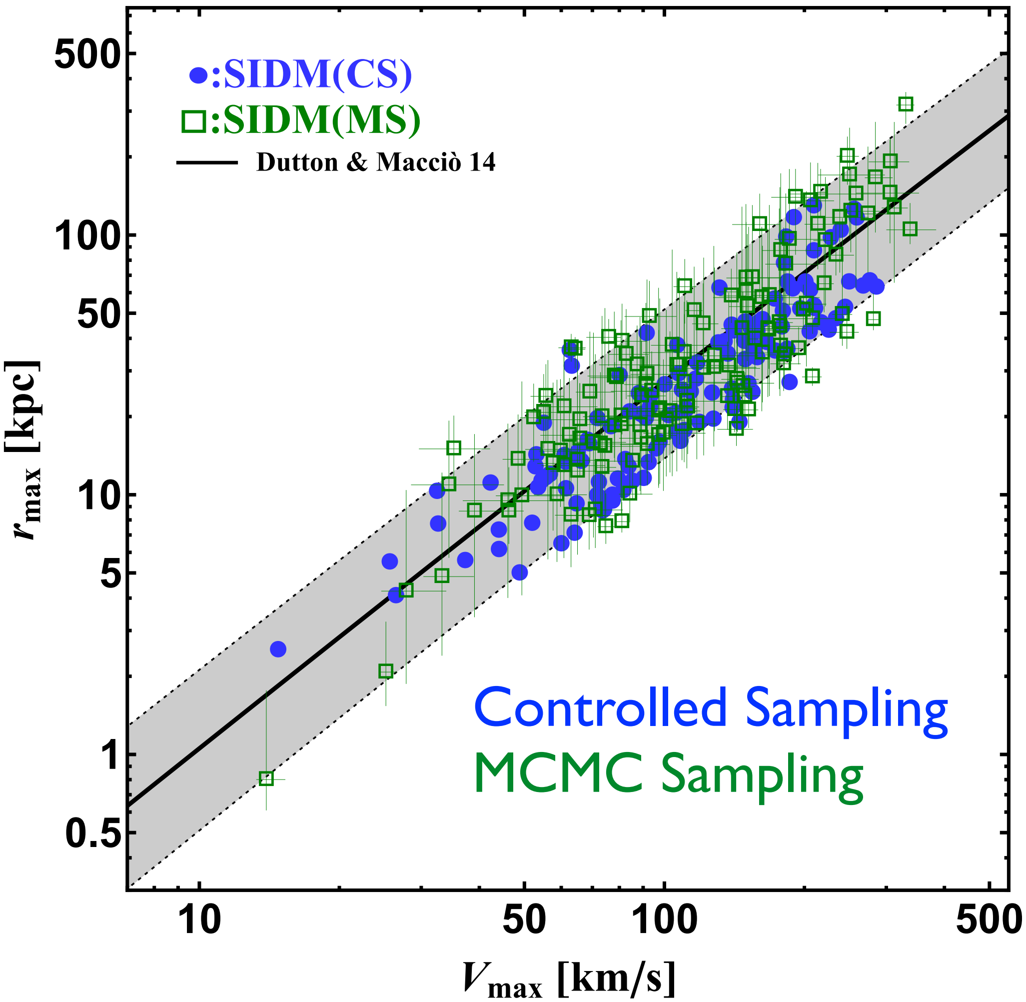




- Both SIDM and MOND fits have the disk mass-to-light ratio peaked around $0.5M_\odot/L_\odot$.
- In both cases, we did NOT impose $0.5M_\odot/L_\odot$ as a prior
- The SIDM fits are either comparable to or much better than the MOND fits.

with Ren, Kwa, Kaplinghat (2018)

Properties of the Host Halos



~97% galaxies can be fitted within 2σ

with Ren, Kwa, Kaplinghat (2018)

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

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

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

The origin of the acceleration scale:

$$a|_{r=0} = 2\pi V_{\rm max}^2/(1.26 r_{\rm max})$$

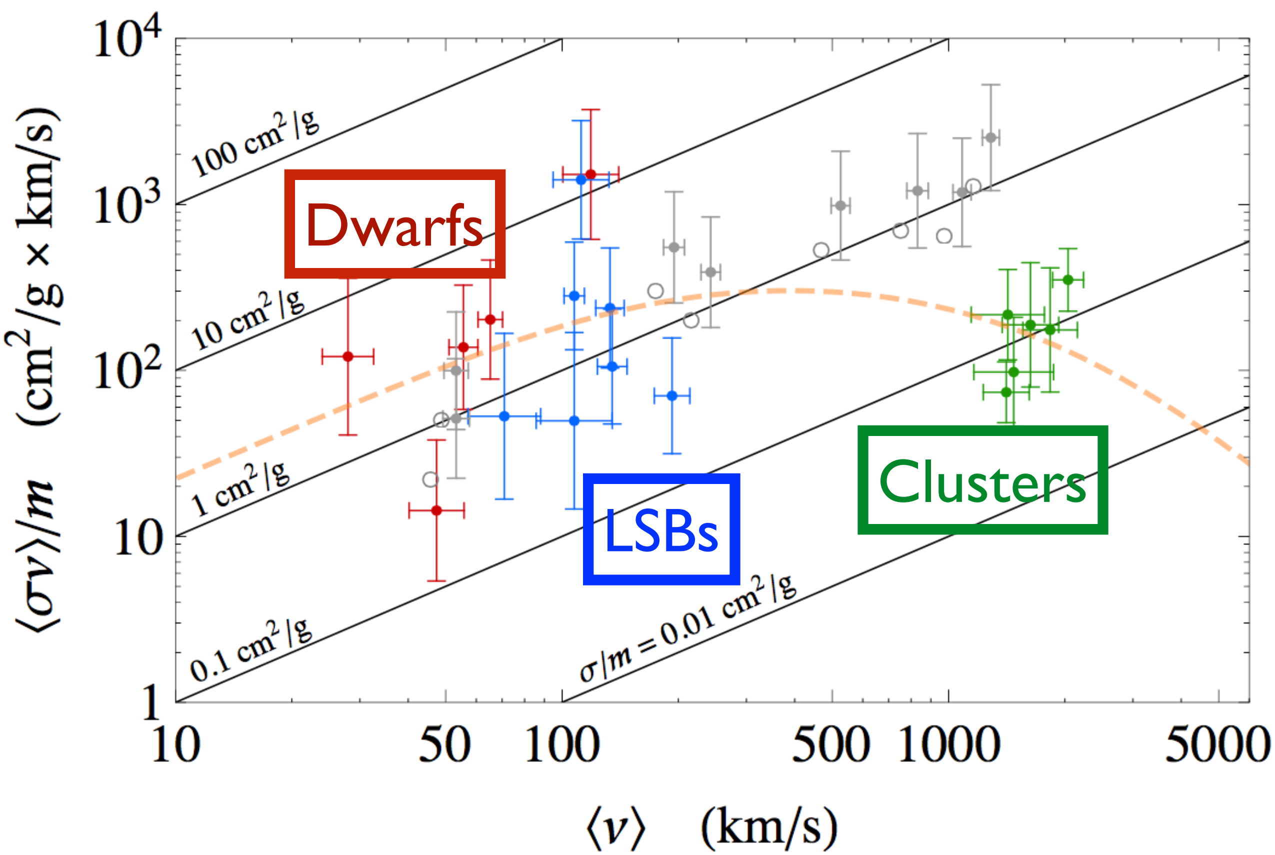
$$a|_{r=0} \approx 1.0 \times 10^{-10}\ {\rm m/s^2} \left(\frac{V_{\rm max}}{240\ {\rm km/s}}\right)^{0.6}$$

Not a constant

g_+ is the average over the sample

SIDM from Dwarfs to Clusters

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

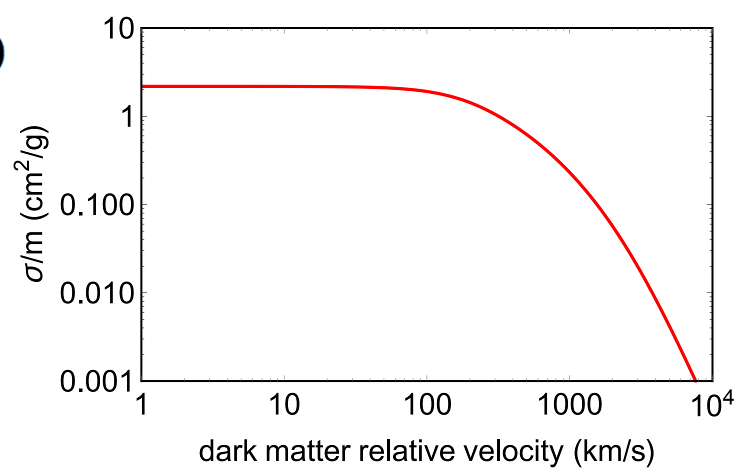


The cluster data: Newman+(2013)

Core size in clusters: ~10 kpc

Two challenges:
large cross section
right velocity dependence

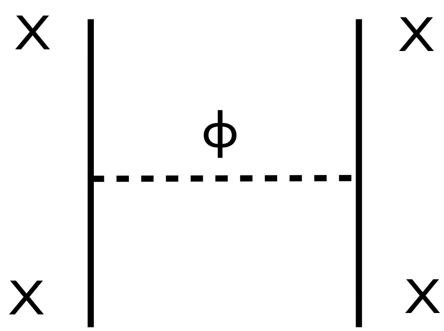
With Kaplinghat, Tulin (PRL, 2015)



DM halos as particle colliders

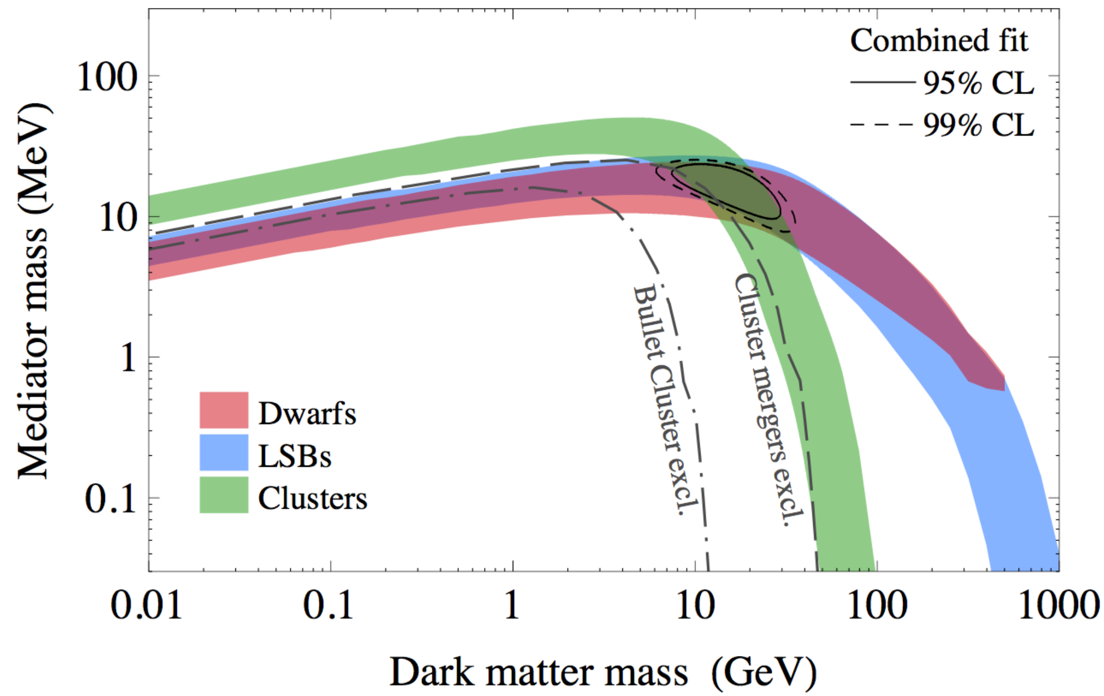
DM Models with a Light Mediator

- Self-scattering kinematics determines SIDM mass



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

Yukawa potential



with Kaplinghat, Tulin (PRL 2015)

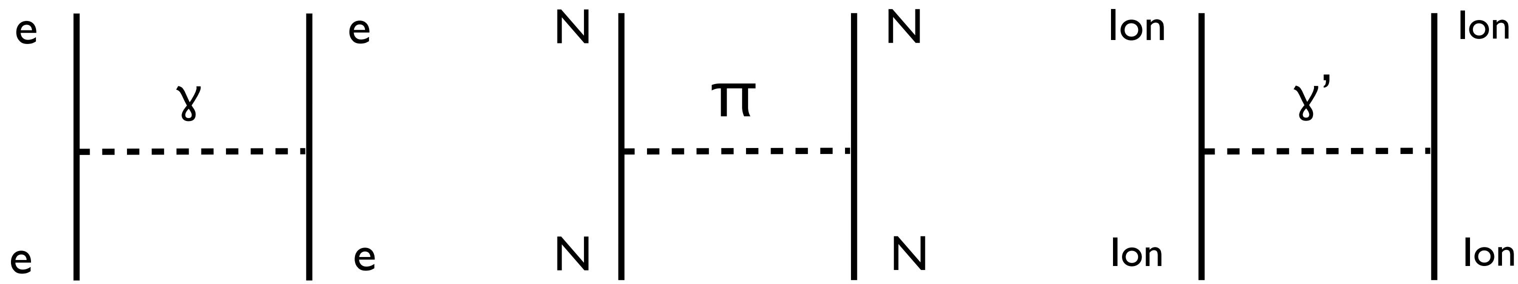
Fix α_X=1/137

Predict: m_X~15 GeV, m_ϕ ~17 MeV

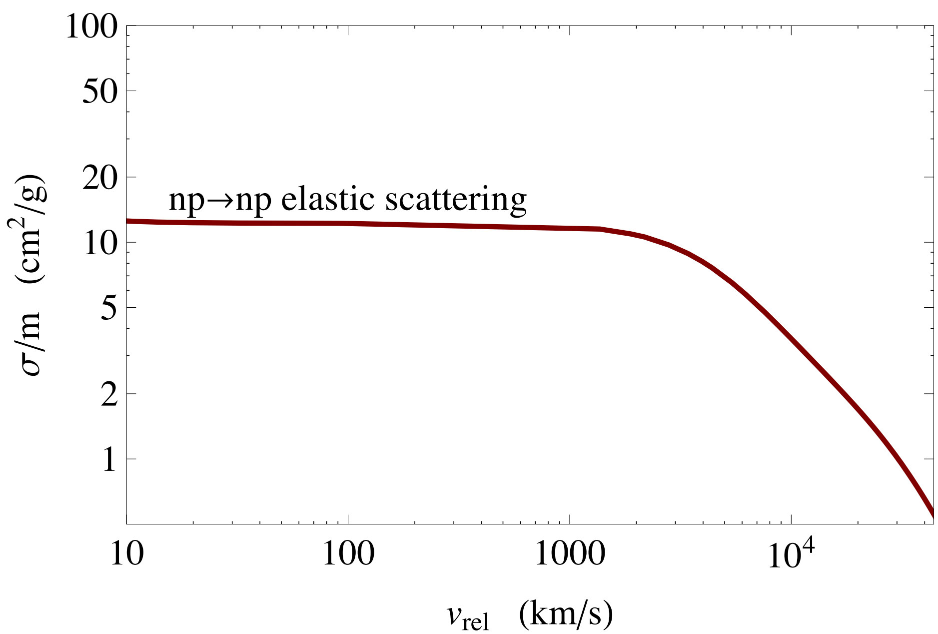
The nightmare scenario is not hopeless!

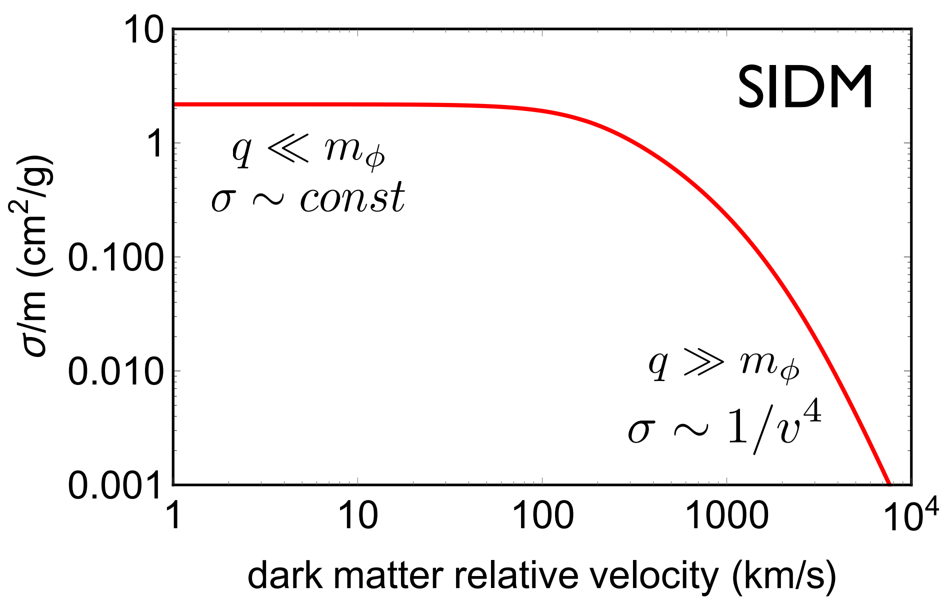
SIDM is Natural

- Familiar examples in the visible sector



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



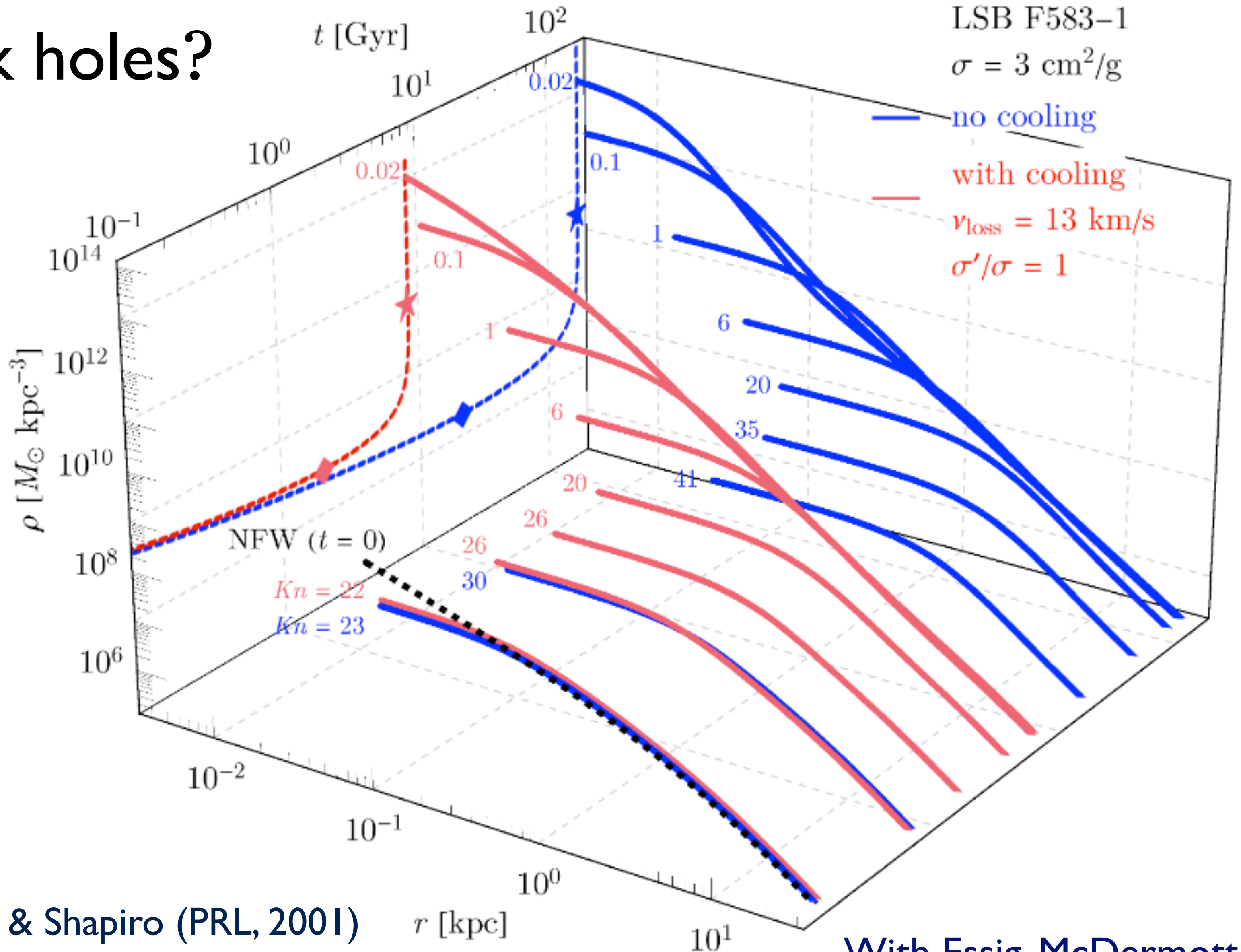


Tulin & HBY (2017); data from Obloinsk+(2011)


SIDM

Gravothermal Catastrophe

Black holes?

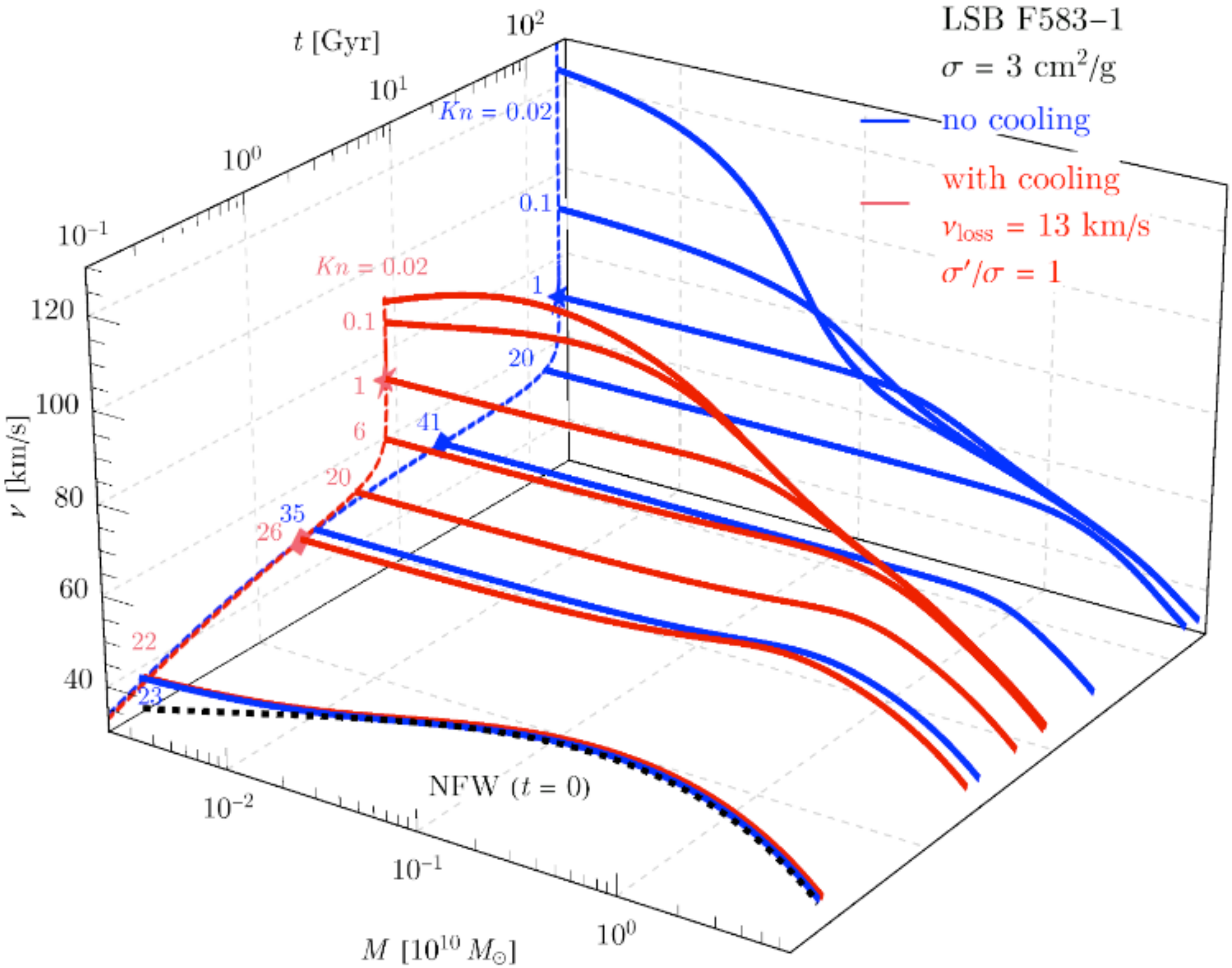


Balberg & Shapiro (PRL, 2001)

With Essig, McDermott, Zhong (2018)

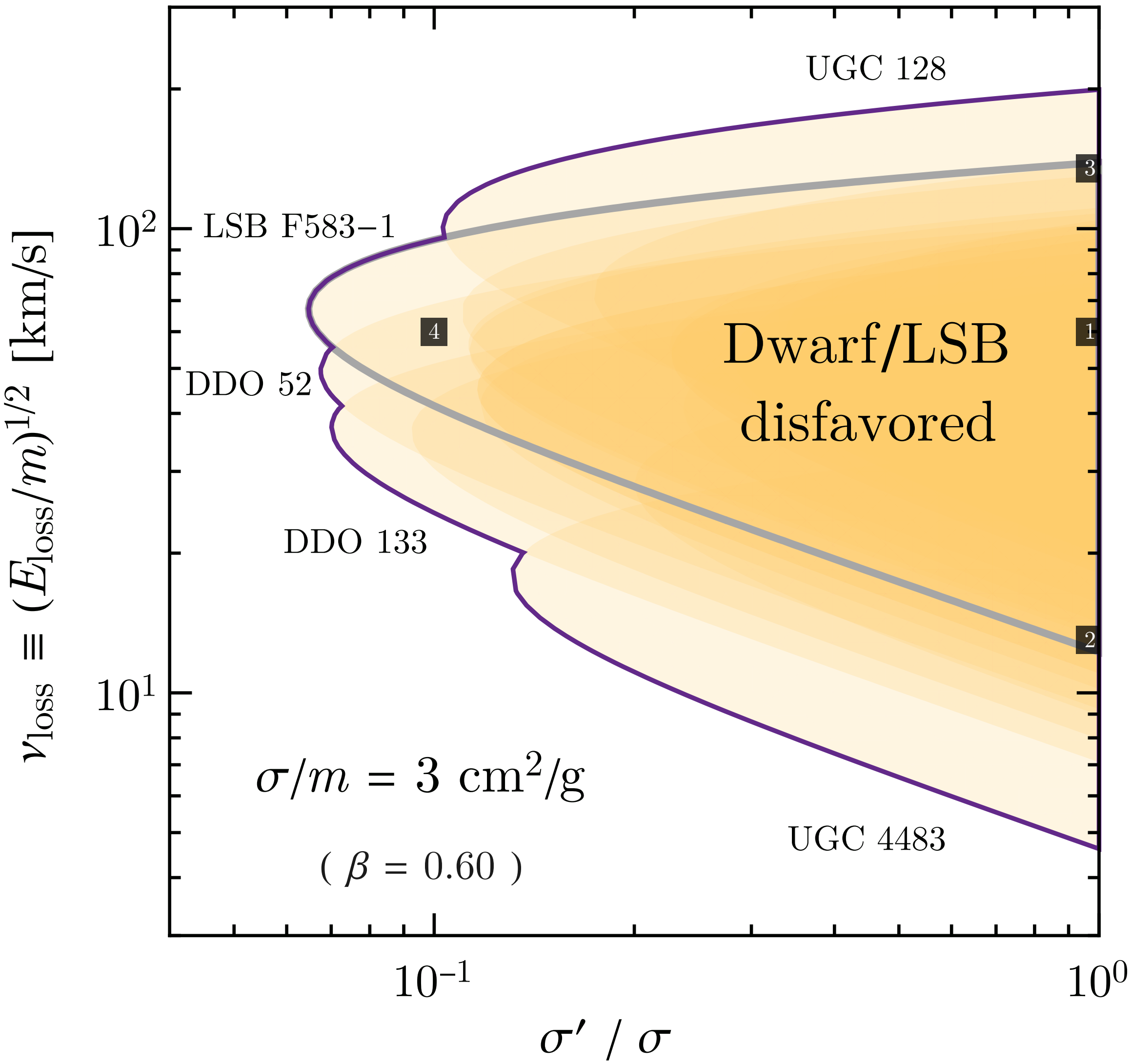
- Dissipative DM self-interactions could seed up "gravothermal catastrophe"

Issues



With Essig, McDermott, Zhong (2018)

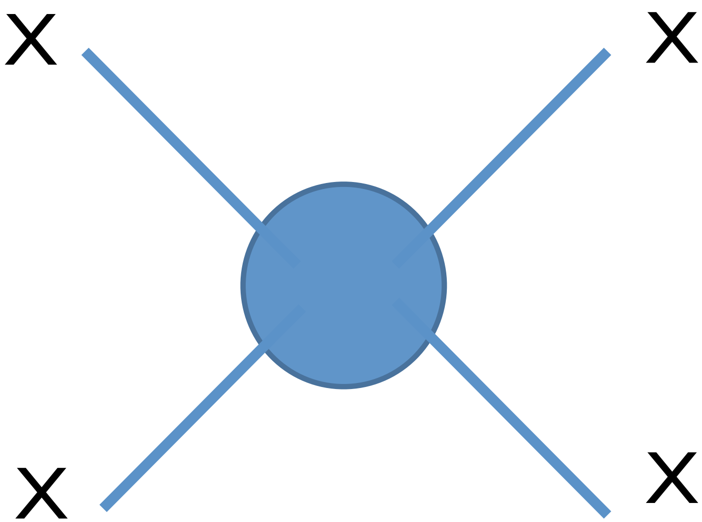
Dissipative DM Self-Interactions



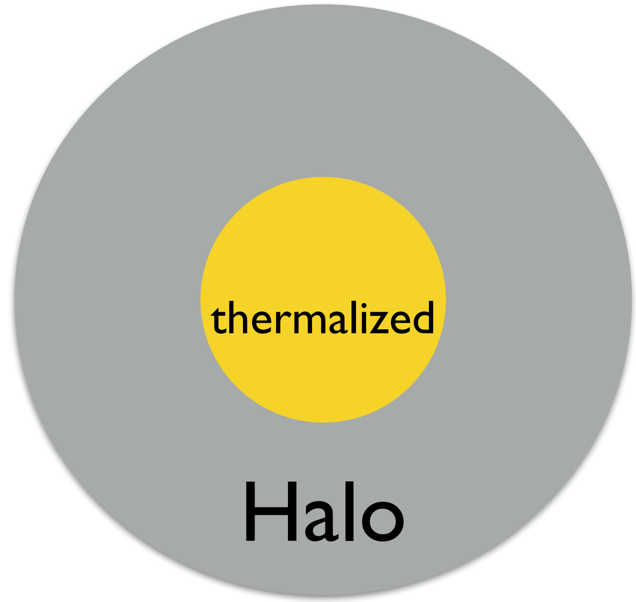
- Dissipative DM self-interactions could seed up "gravothermal catastrophe"
- The presence of the density cores constrain the interaction strength

With Essig, McDermott, Zhong (2018)

Summary



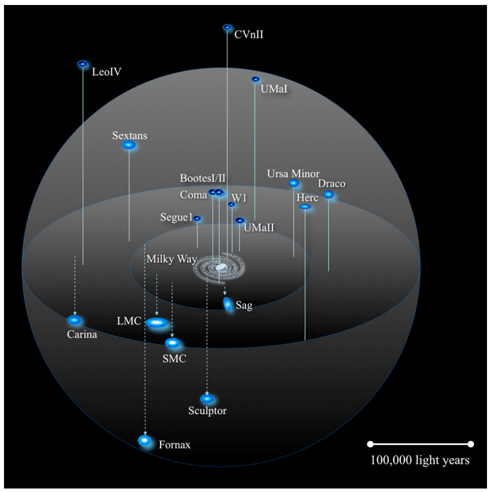
Strong hints



- SIDM explains both the diversity and uniformity of galaxy rotation curves with only one more parameter (puzzled us for >20 years)
- Our results are robust to baryonic feedback/galaxy formation history due to collisional thermalization
- Novel signatures; "gravothermal catastrophe" (leading to the formation of black holes?)

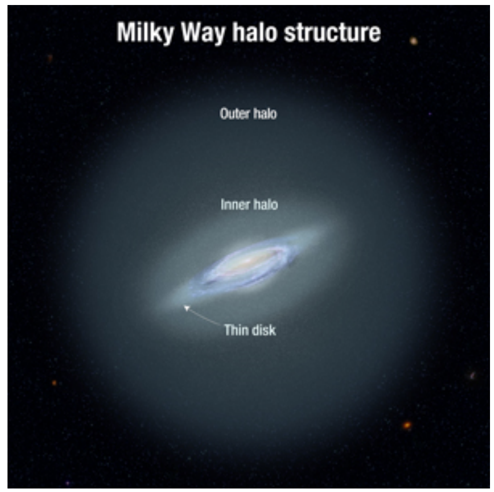
Dark Matter "Colliders"

Dwarf galaxies



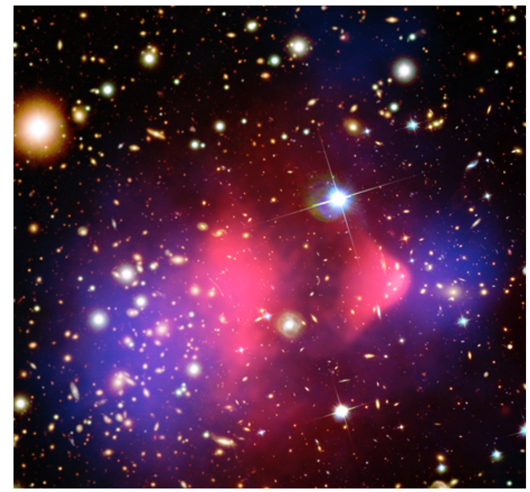
"B-factory" (v~30 km/s)

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, m_ϕ


Thank You!