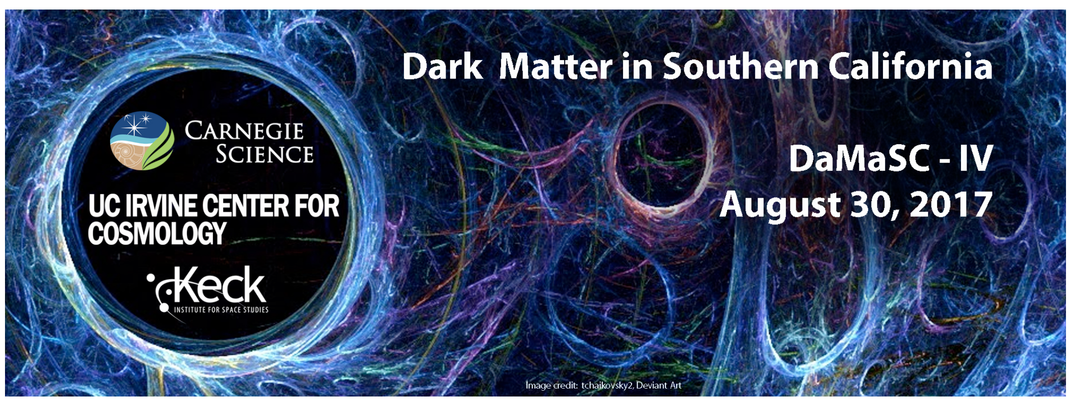
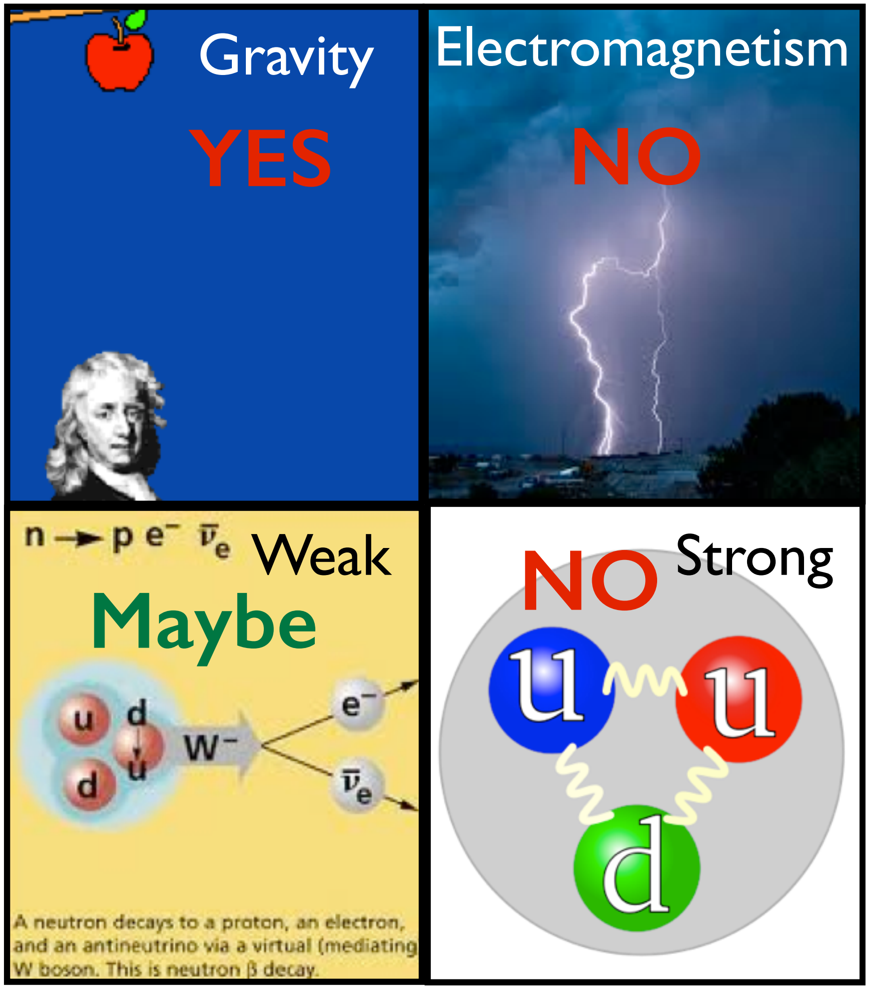
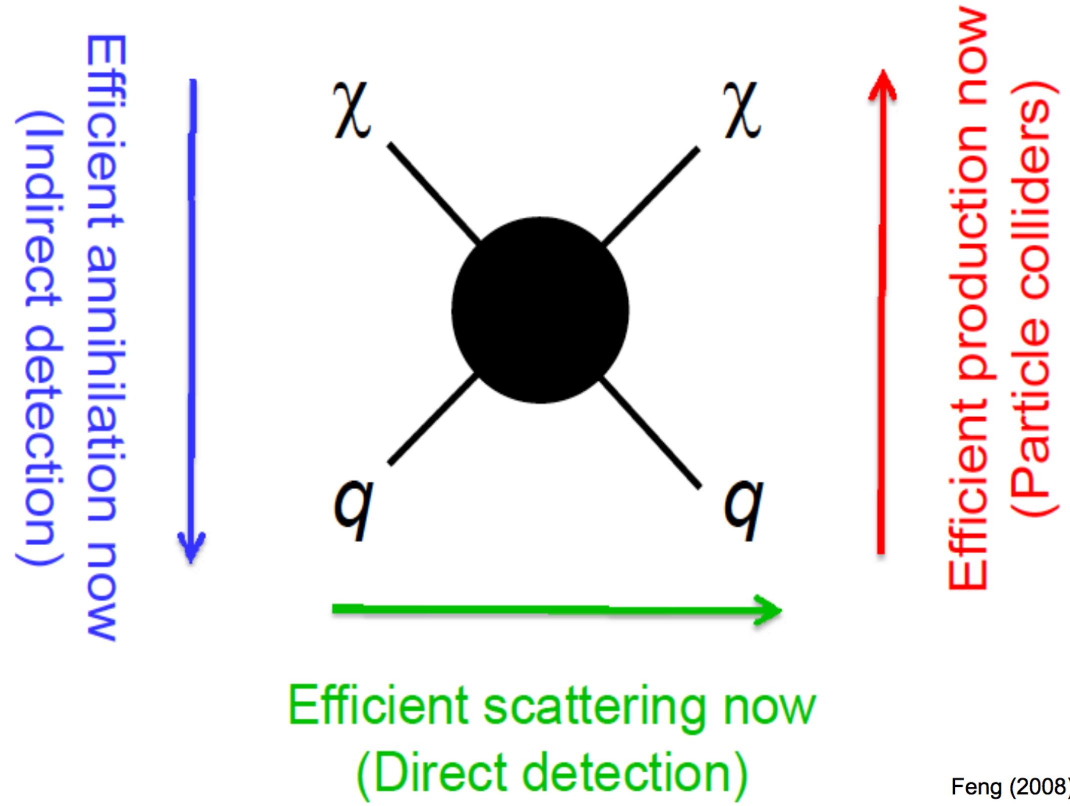
Dark Matter at "Colliders"

Hai-Bo Yu
University of California, Riverside



The WIMP Paradigm



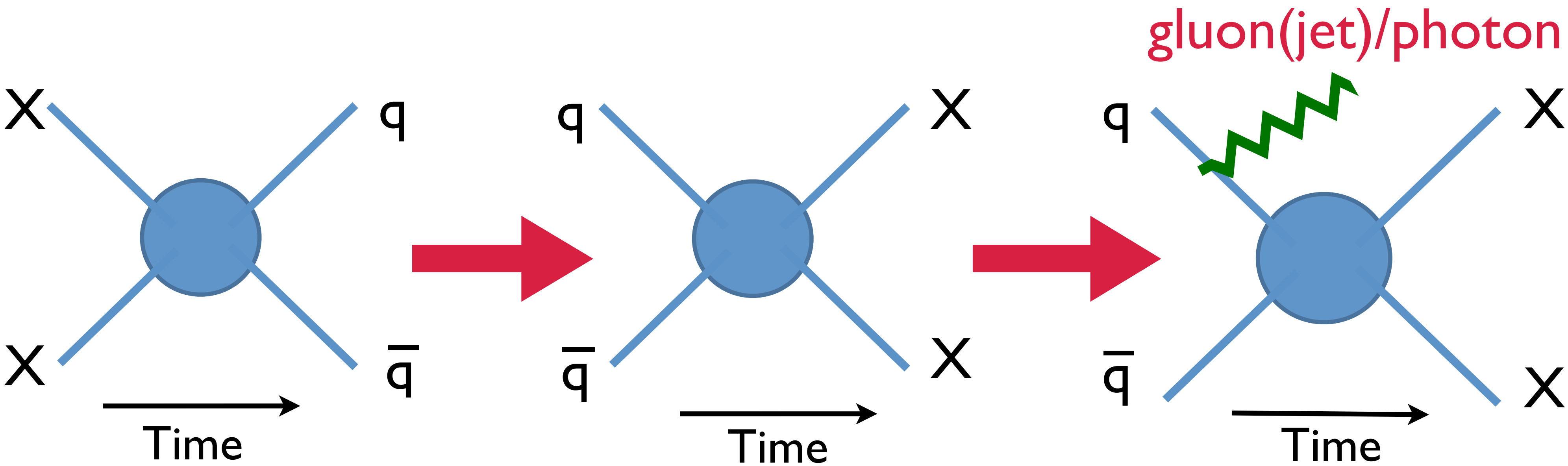


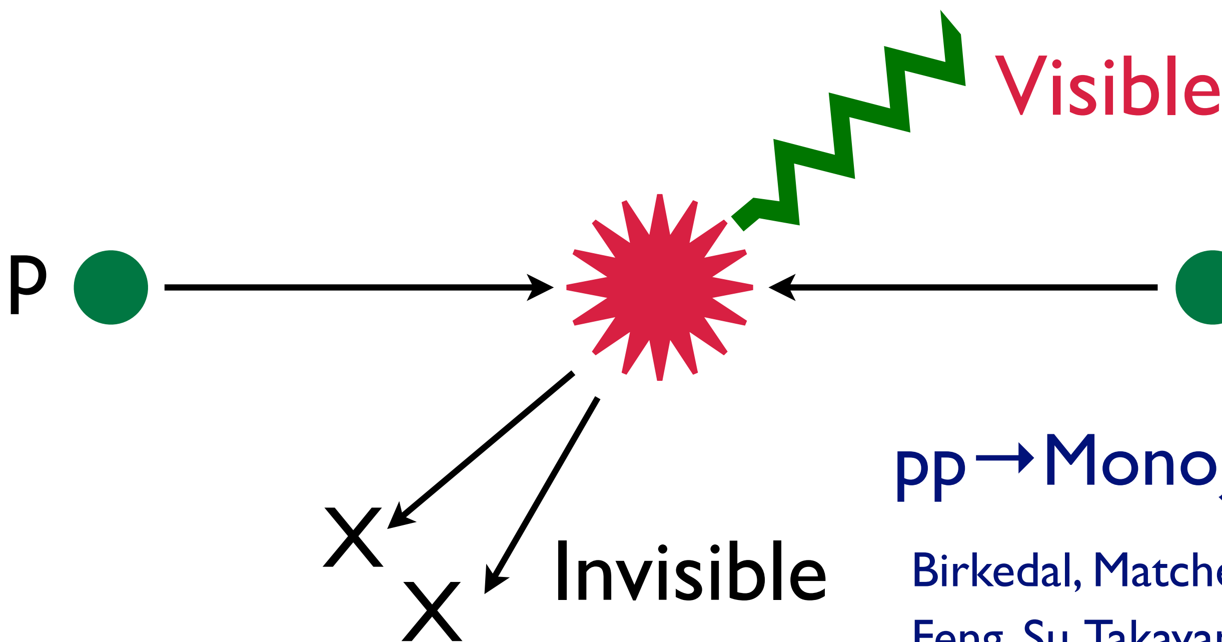
Feng (2008)

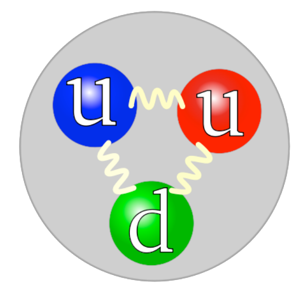
Weakly-Interacting Massive Particle (WIMP)

mass~100 GeV, it carries the weak (scale) interaction

WIMP at the LHC







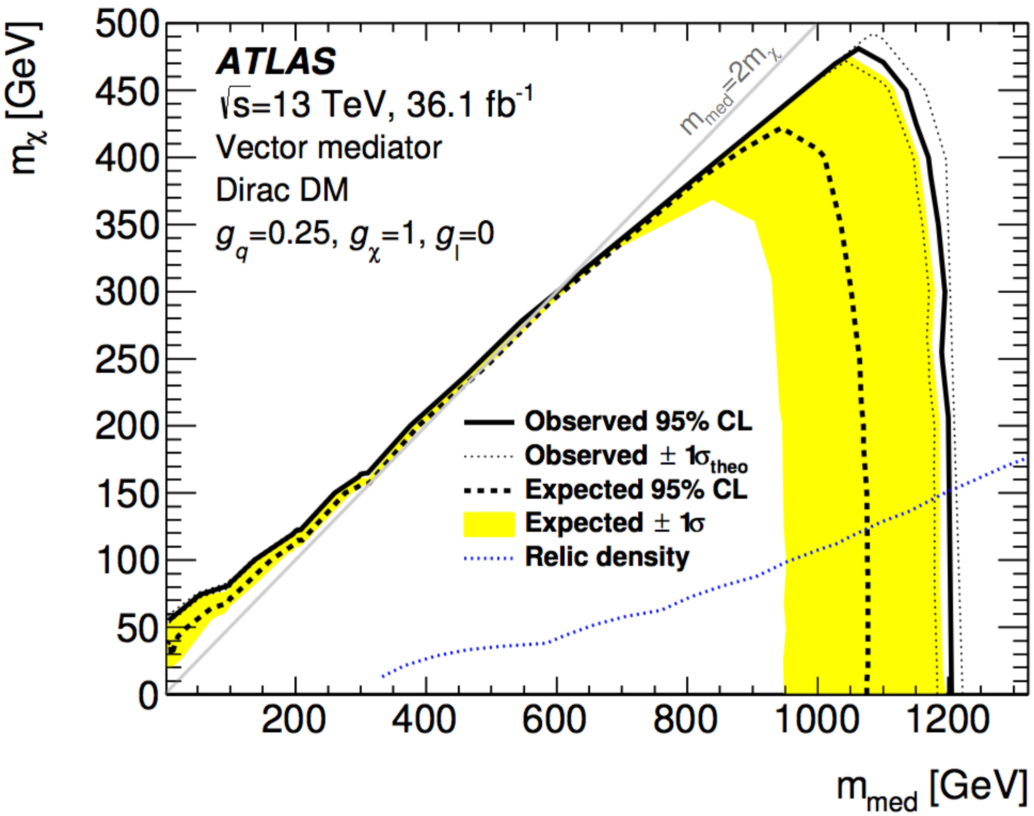
pp→Monojet+Missing Energy

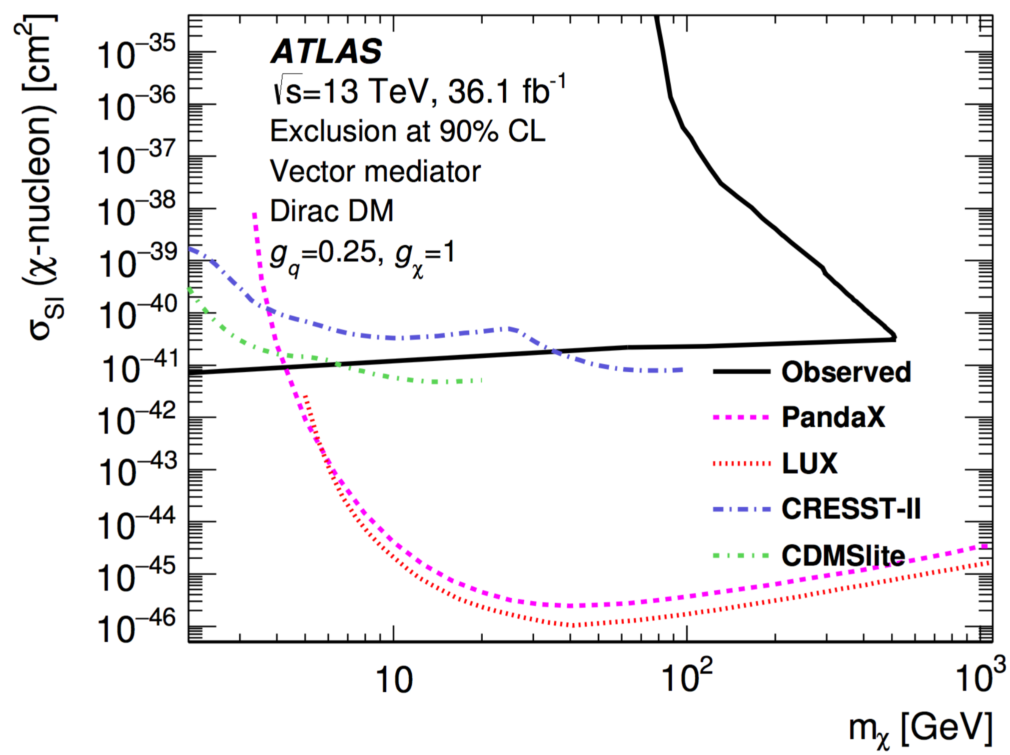
Birkedal, Matchev, Perelstein (2004)

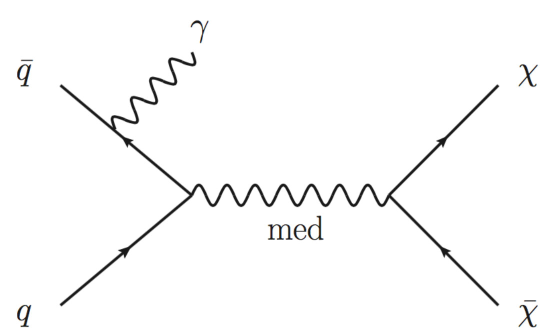
Feng, Su, Takayama (2006)

Goodman, Ibe, Rajaraman, Shepherd, Tait, HBY (2010)

LHC Constraints







ATLAS Collaboration (EPJC, 2017)

The WIMP is a typical CDM candidate

Small-Scale Issues of ΛCDM

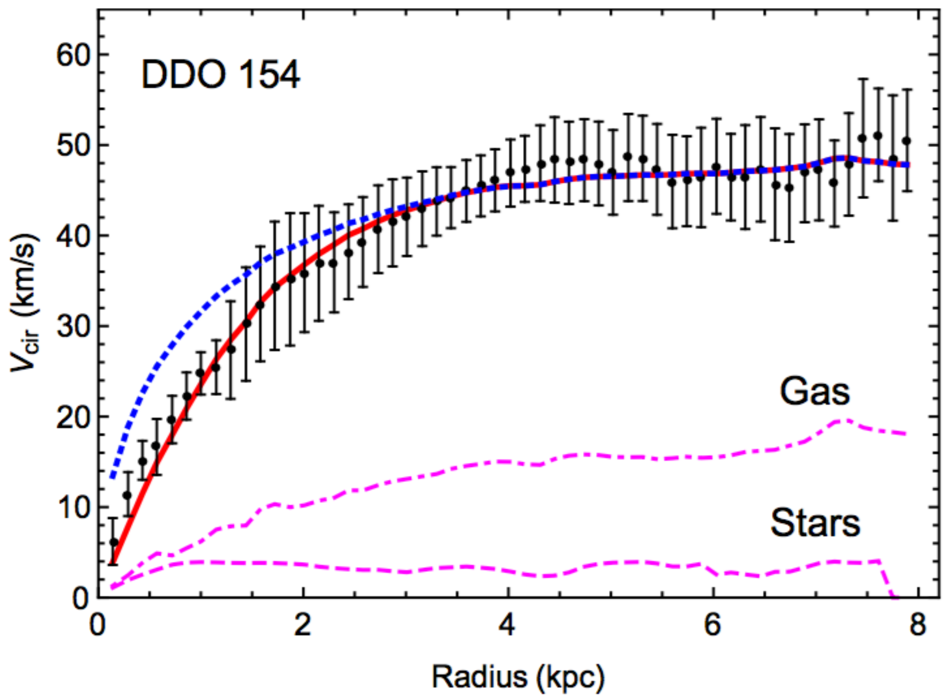
Core vs. Cusp
Diversity
Missing Satellites
Too-Big-To-Fail

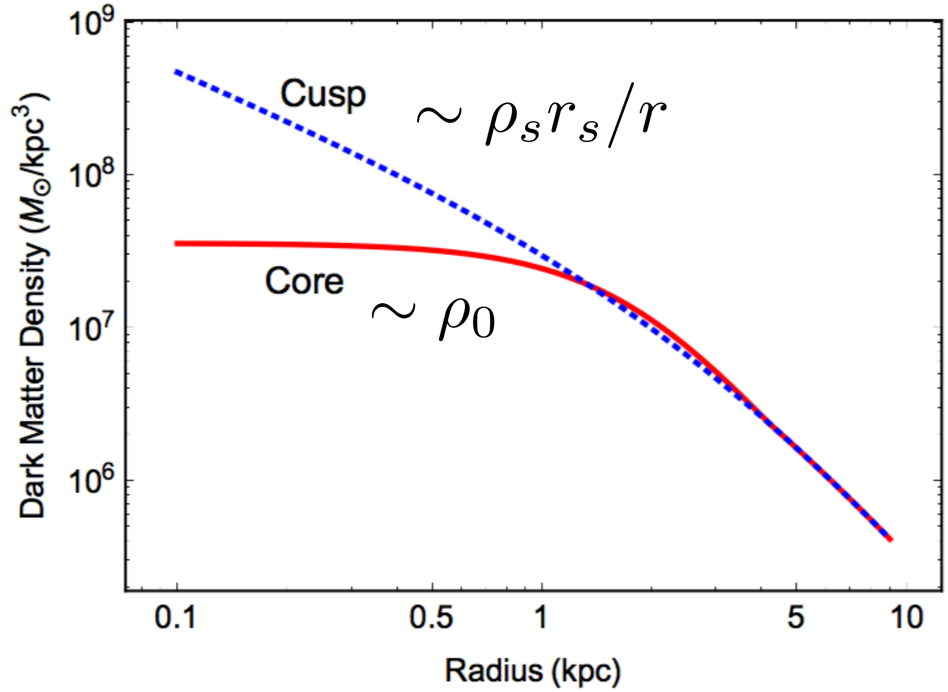
- Solutions

Observational uncertainties (?)
Baryon physics (?)
New physics (?)

Core vs. Cusp Problem

- DM-dominated systems (dwarfs, LSBs)





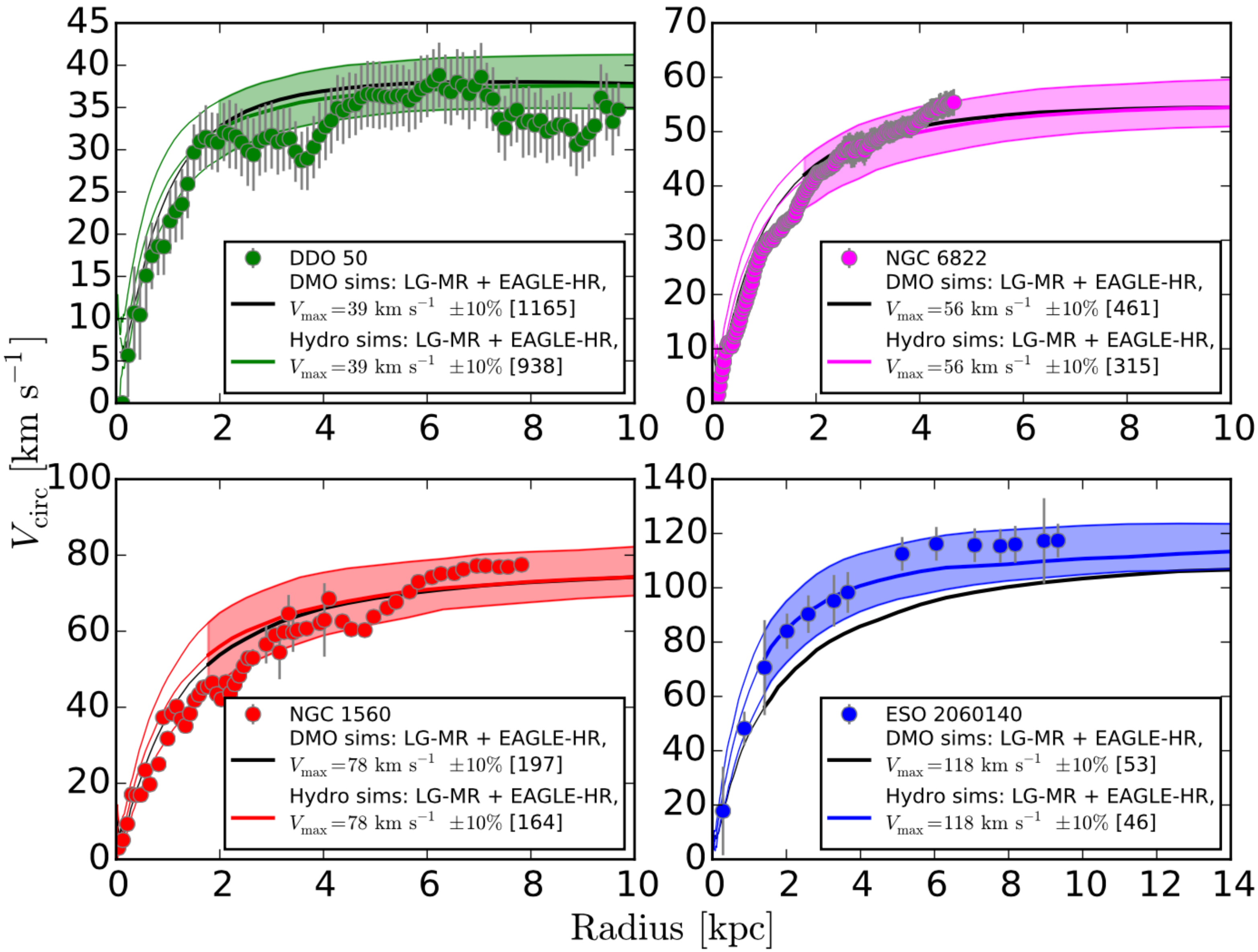
$$\frac{\rho_s}{r/r_s(1+r/r_s)^2}$$

Navarro, Frenk, White (1996)

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

Flores, Primack (1994), Moore (1994)…

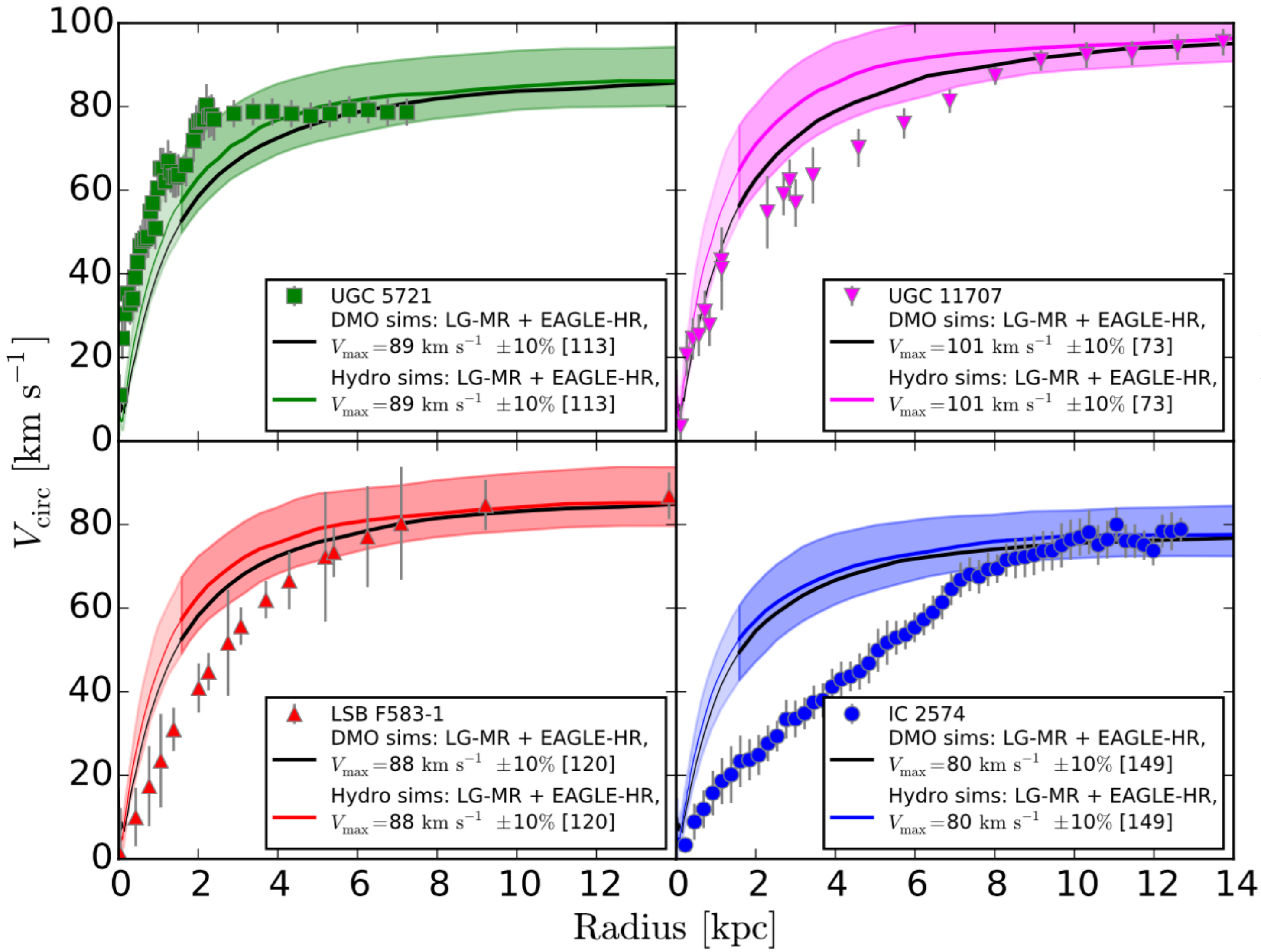
The Diversity Problem



Colored bands: hydrodynamic simulations of ΛCDM, "weak/adiabatic feedback"

Oman et al. (2015)

The Diversity Problem



All galaxies have the same Vmax!

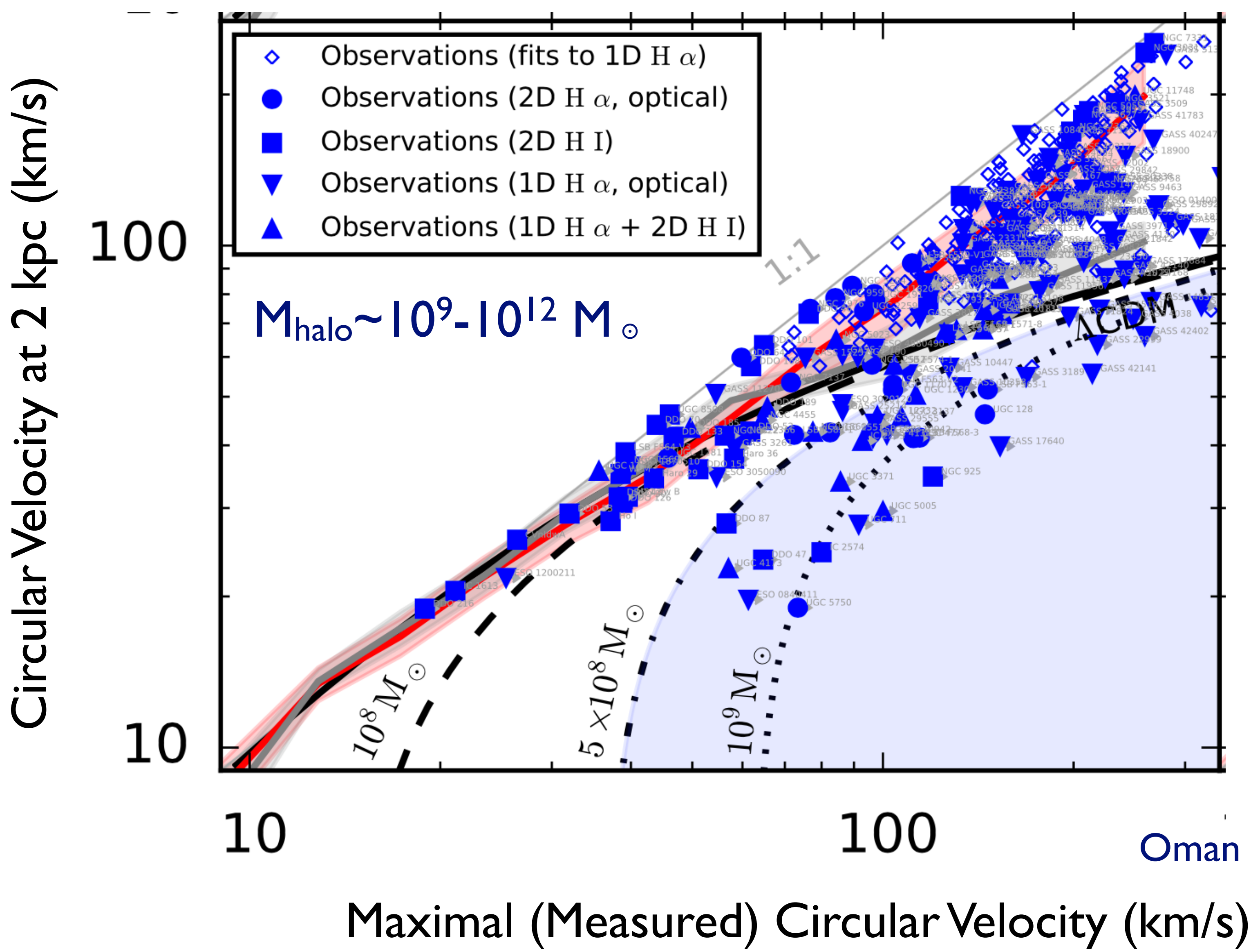
Maximal (Measured) Velocity

Oman et al. (2015)

Colored bands: hydrodynamic simulations of ΛCDM

See also Kuzio de Naray, Martinez, Bullock, Kaplinghat (2009)

A Big Challenge for ΛCDM



Oman et al. (2015)

V_{circ}(2kpc) has a factor of 3-4 scatter for fixed V_{max}

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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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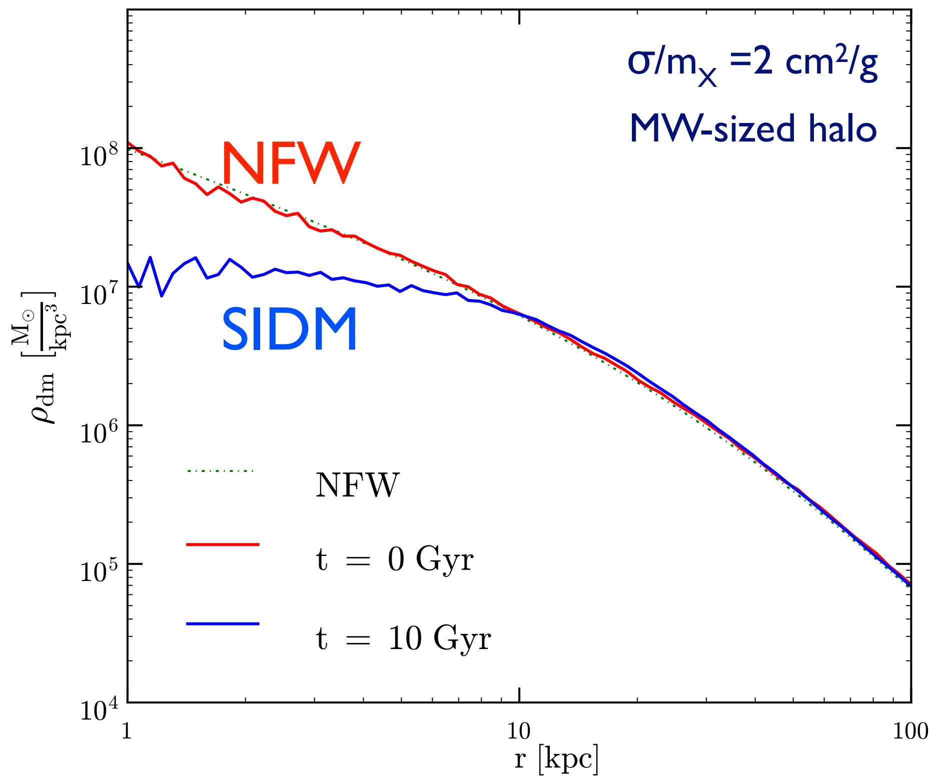
[6] *Leiden Observatory, Leiden University, PO Box 9513, NL-2300 RA Leiden, the Netherlands*

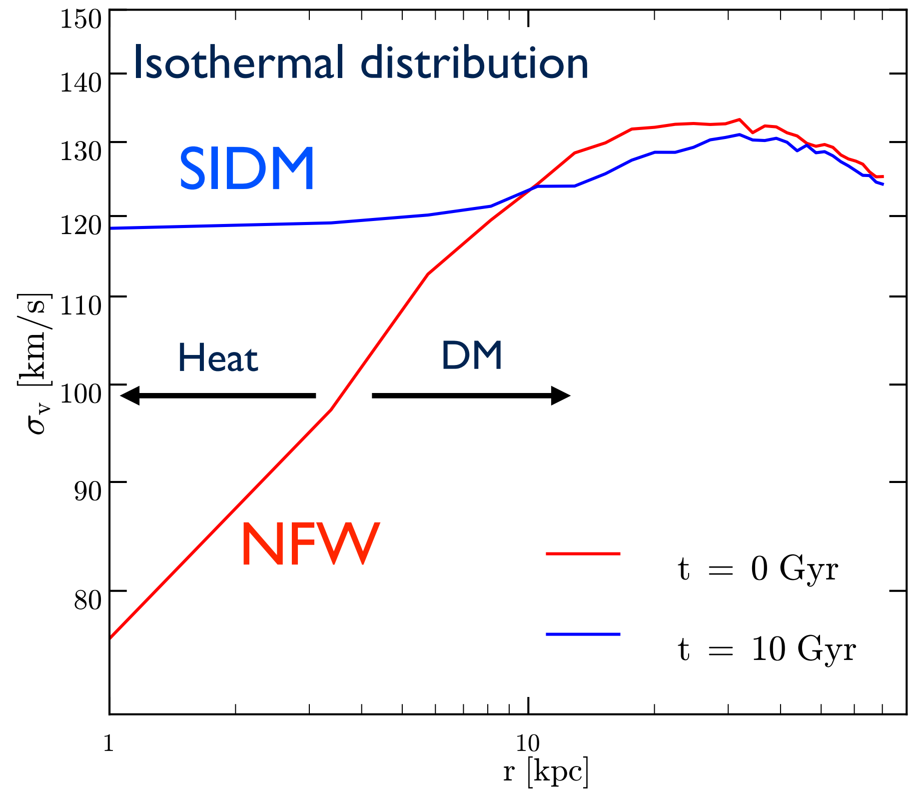
"NFW"

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

Self-Interacting Dark Matter

- Self-interactions thermalize the inner halo





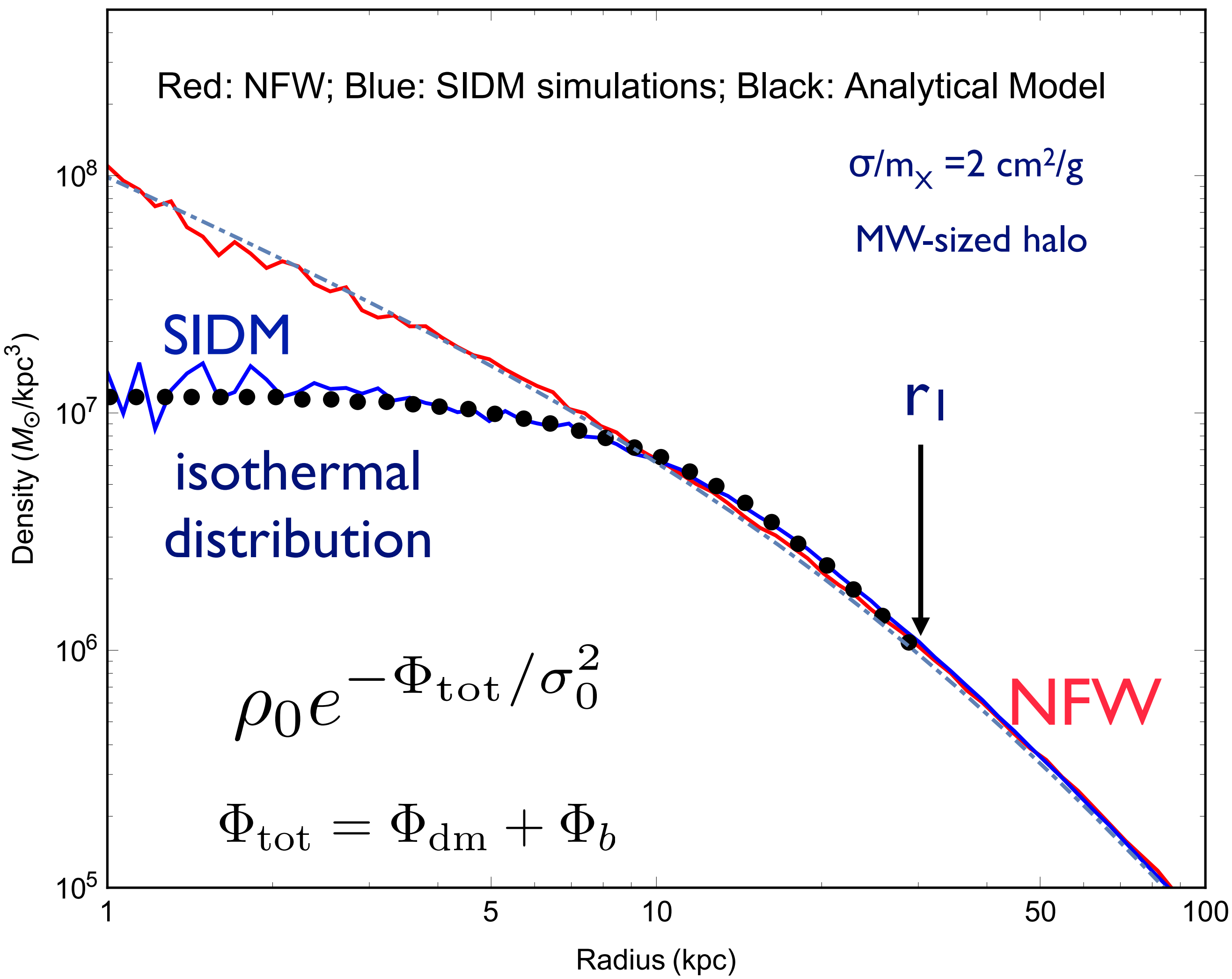
$\sigma/m_X \sim 1\ \mathrm{cm^2/g}$

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

From Huo and Sameie

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:

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

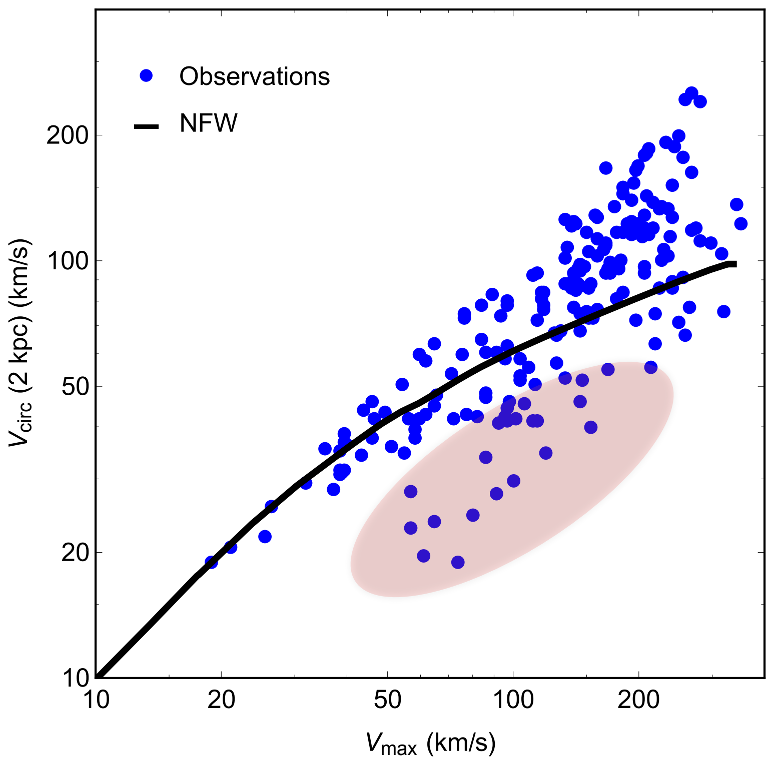
$$(\rho_0, \sigma_0) \leftrightarrow (\rho_s, r_s)$$

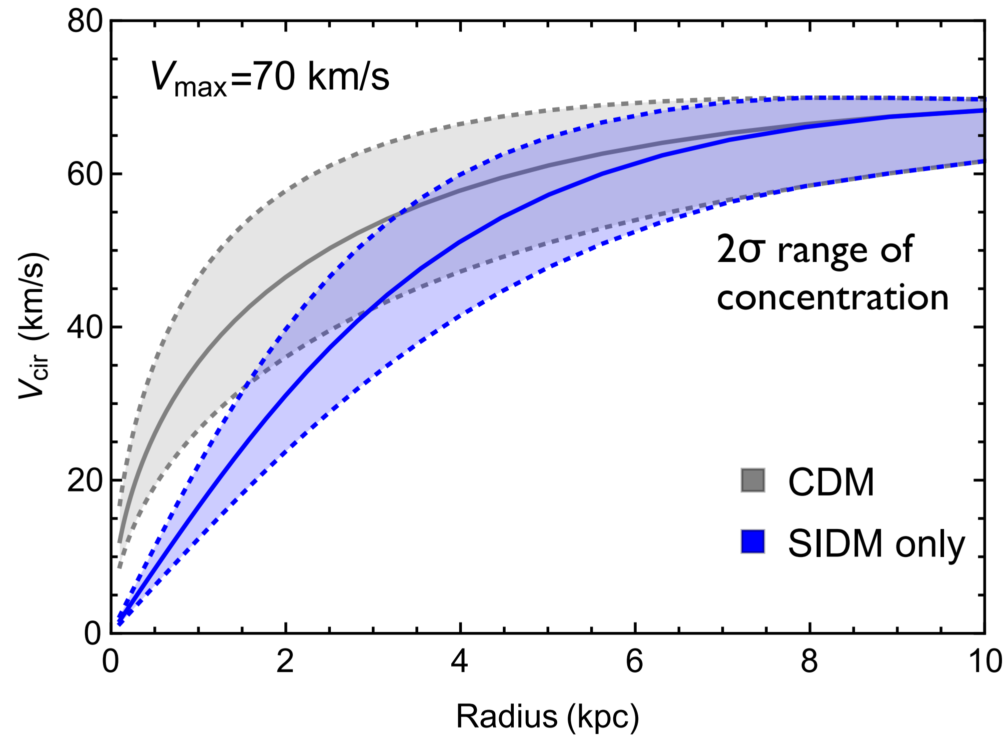
with Kaplinghat, Tulin (2015)

with Kamada, Kaplinghat, Pace (2016)

Addressing the Diversity Problem

- DM self-interactions thermalize the inner halo





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

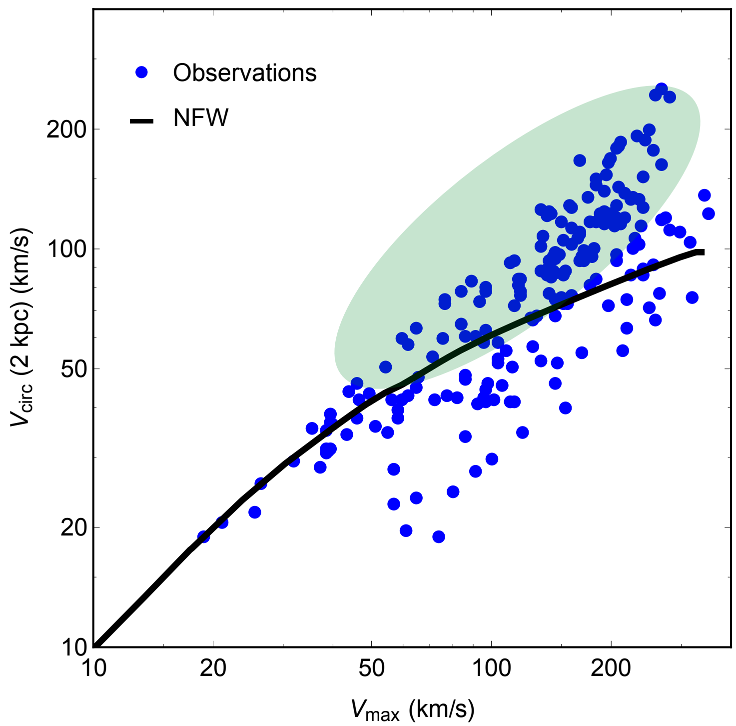
Isothermal distribution

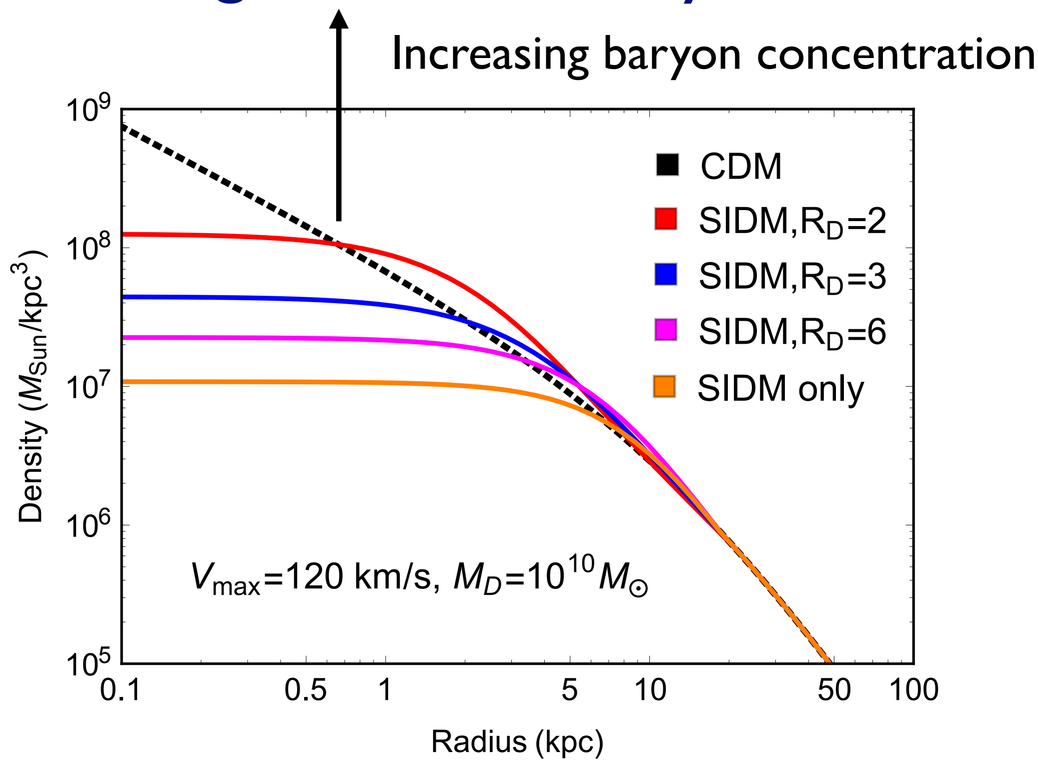
$$\rho_X \sim e^{-\Phi_{\rm tot}/\sigma_0^2} \sim e^{-\Phi_X/\sigma_0^2}$$

with Kamada, Kaplinghat, Pace (2016)

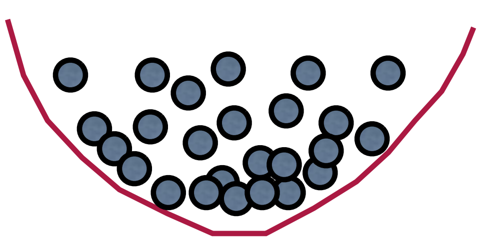
High Luminous Galaxies

- DM self-interactions tie DM together with baryons





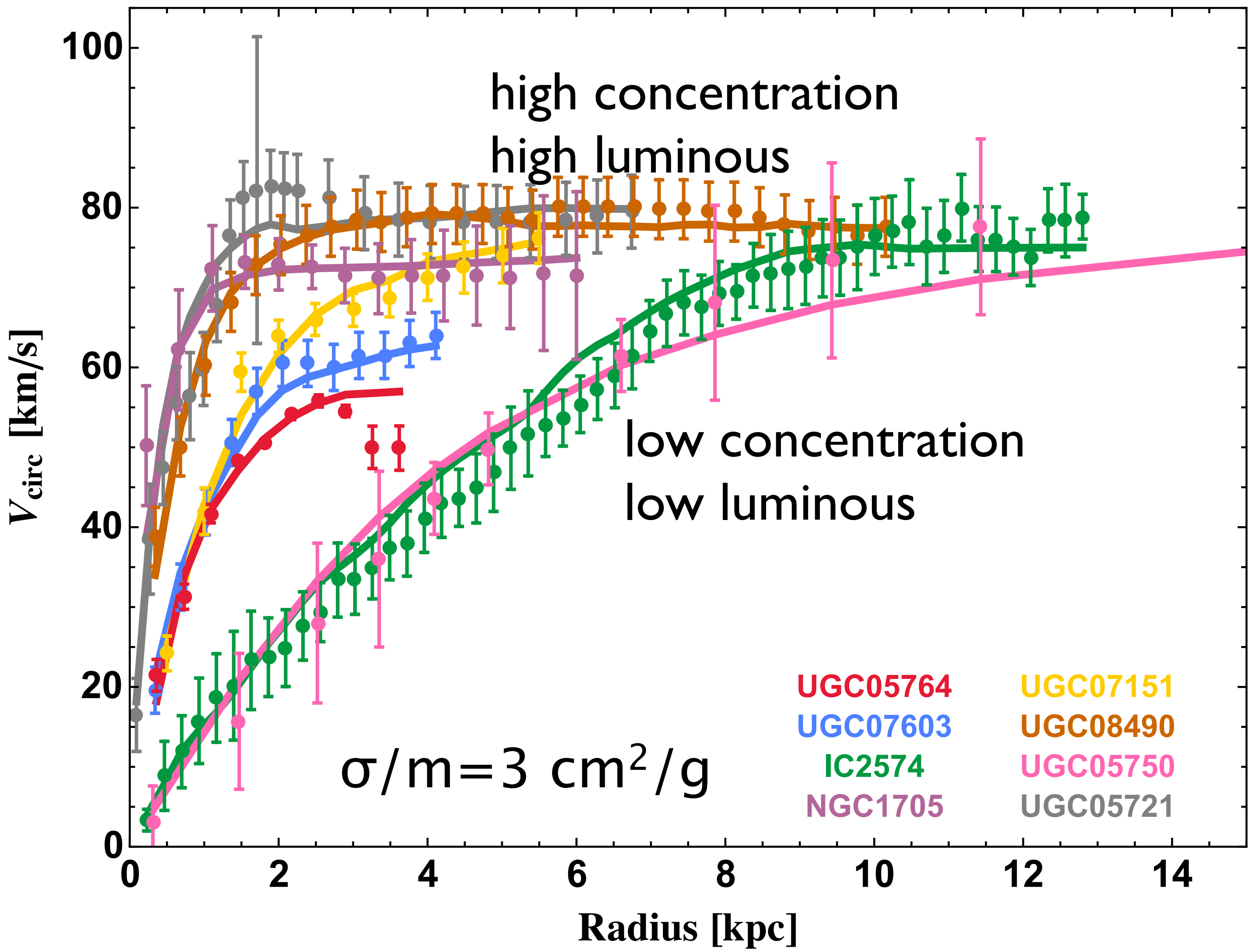
Thermalization leads to higher DM density due to the baryonic influence



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

with Kamada, Kaplinghat, Pace (2016)

with Kaplinghat, Keeley, Linden (2013)



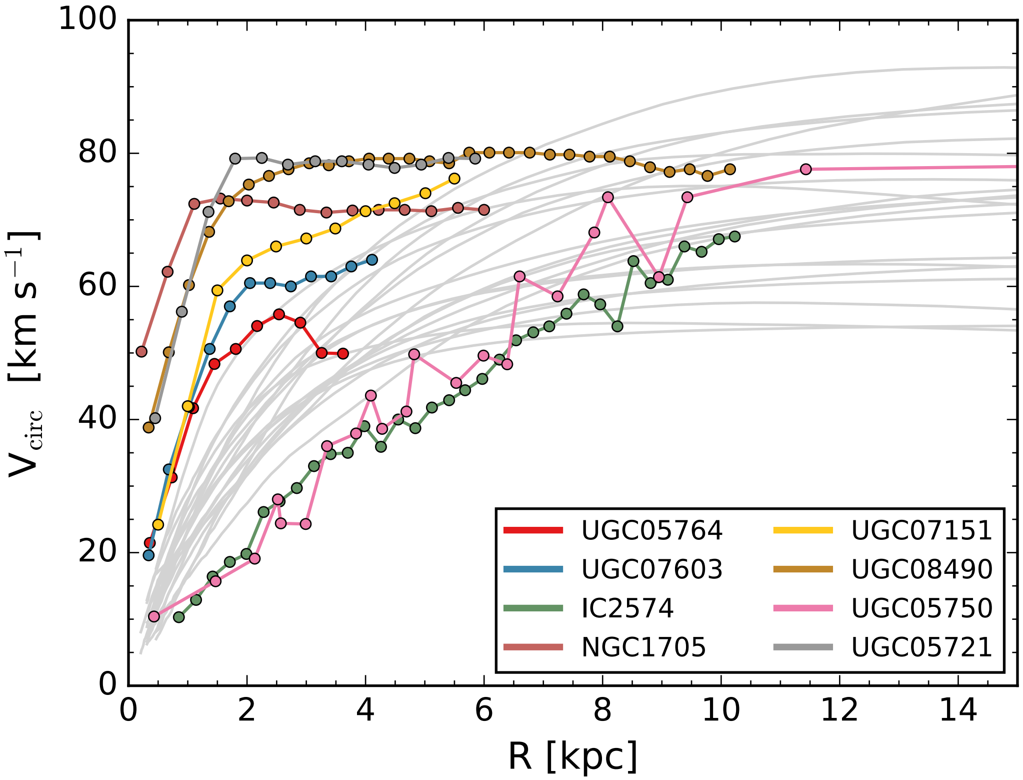
30 galaxies

V_{max}~25-300 km/s

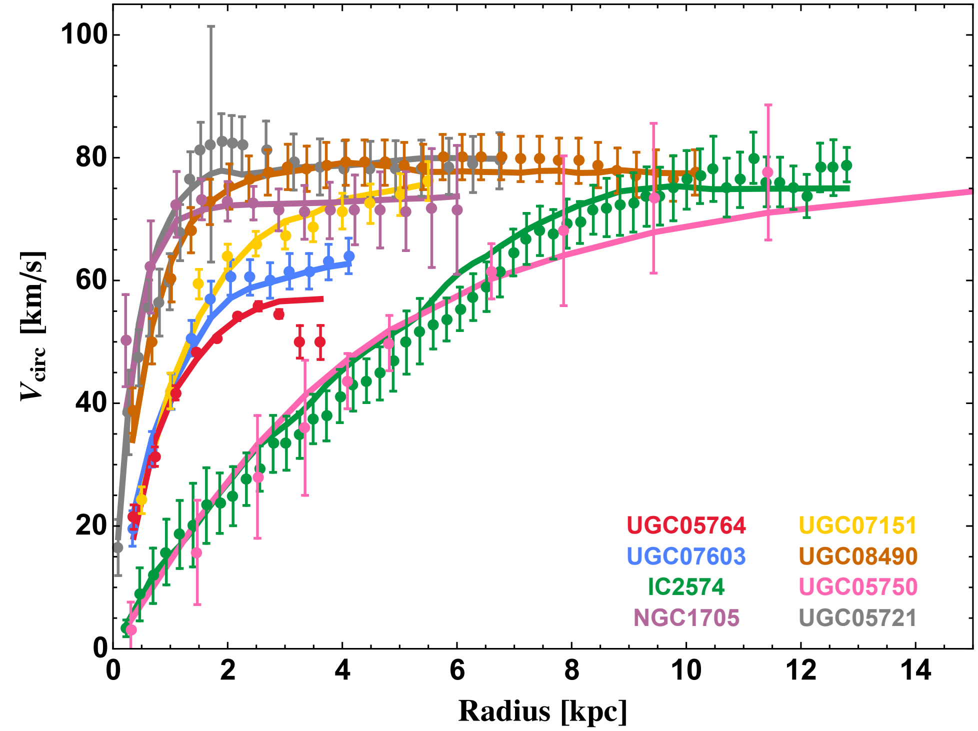
- Scatter in the halo concentration-mass relation
- Baryon distribution
- DM self-interactions correlate DM and baryon distributions

with Kamada, Kaplinghat, Pace (2016)   with Kaplinghat, Kwa, Ren (in prep)

Strong Feedback vs. SIDM



Santos-Santos et al. (2017)



with Kamada, Kaplinghat, Pace (2016)
with Kaplinghat, Kwa, Ren (in prep)

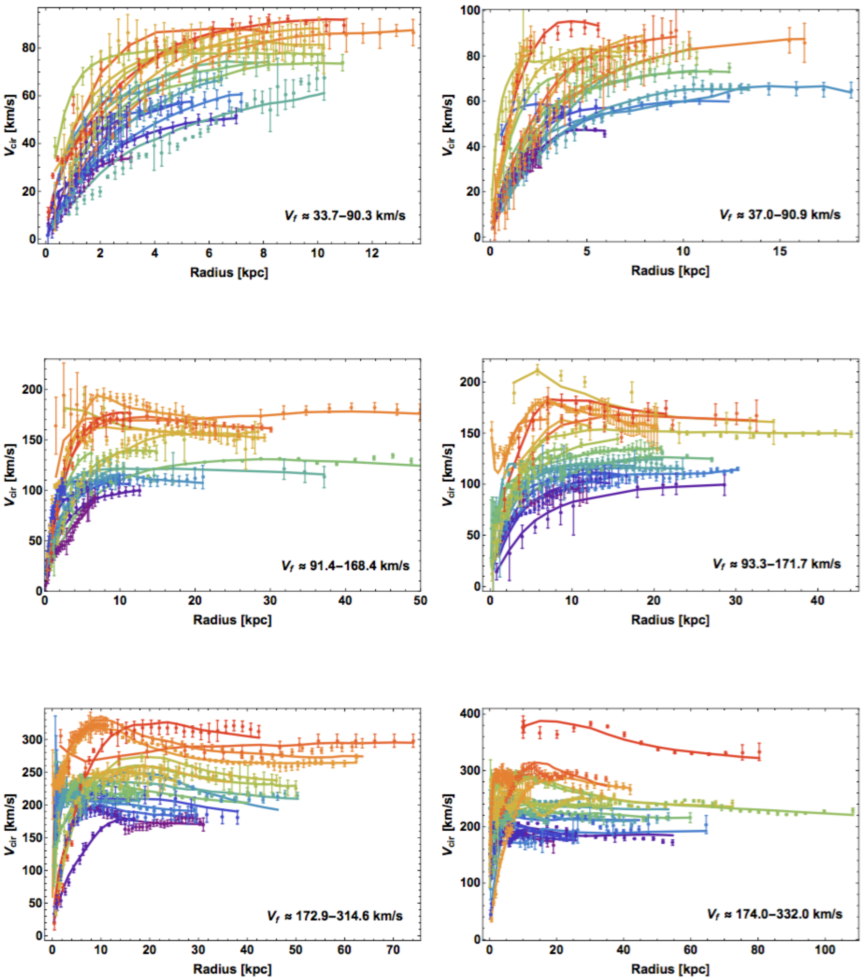
NIHAO simulations of ΛCDM

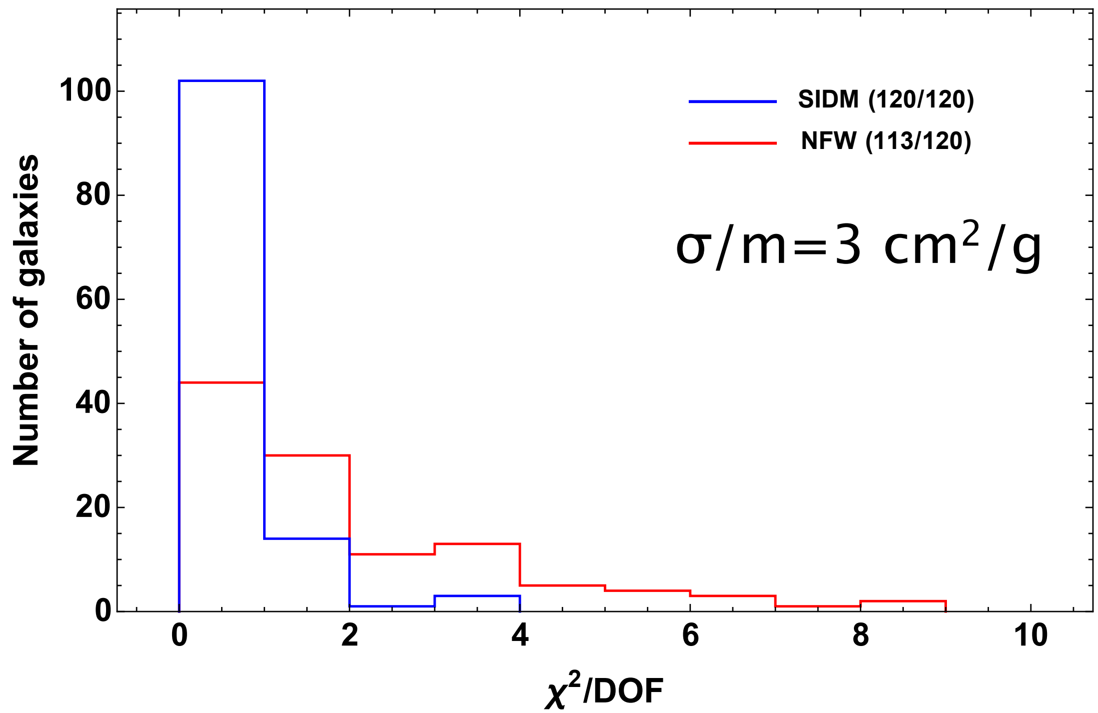
"strong/violent" feedback

Observed scatter: ~4
Simulations: ~2

SIDM

More Galaxies…





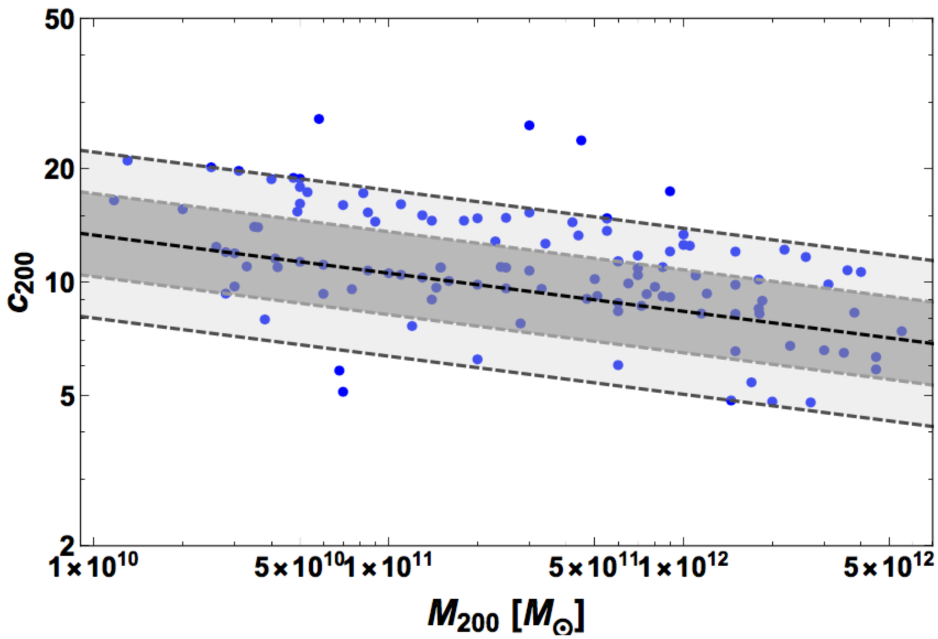
with Kaplinghat, Kwa, Ren (in prep)

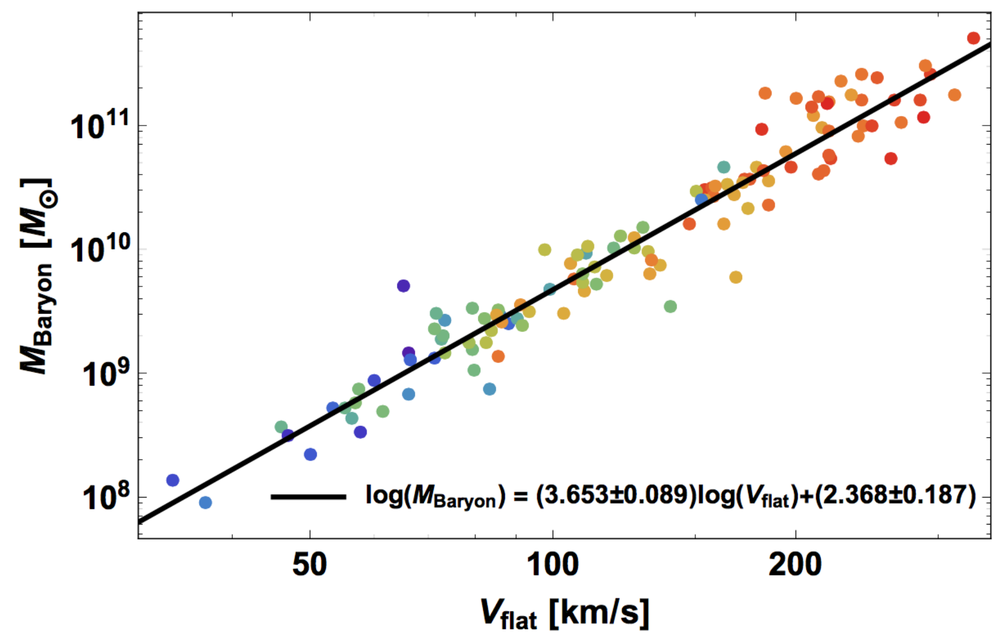
120 spiral galaxies with high-quality data from the SPARC dataset

Two independent approaches:
UCR: thin desk model, Poisson's equation on a grid
UCI: spherical stellar model, MCMC

Agreement is within <~10%

More Galaxies…



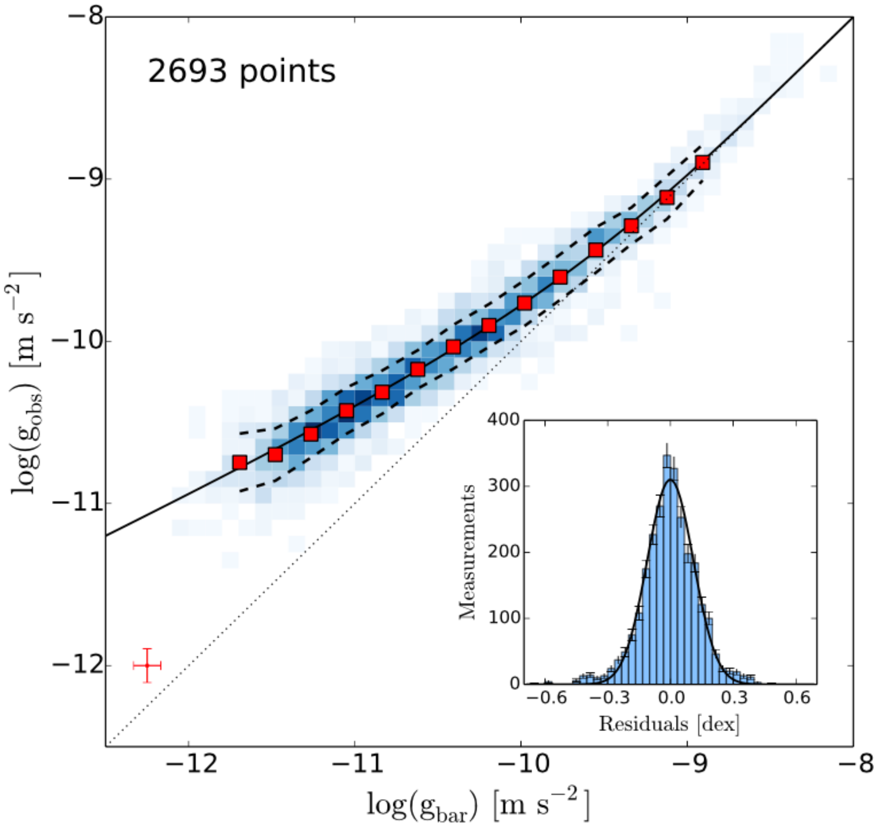


With Kaplinghat, Kwa, Ren (in prep)

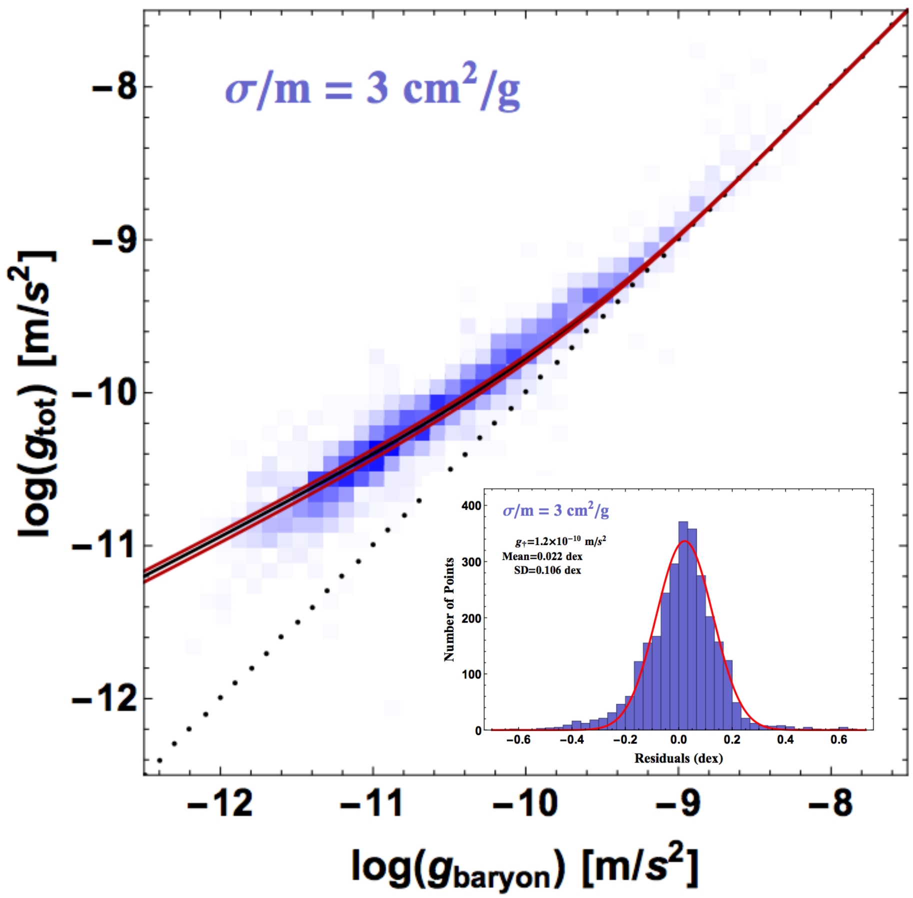
- ~114/120 galaxies can be fitted within 2σ range of the halo concentration-mass relation predicted in ΛCDM cosmology (from Dutton, Maccio, 2014)

- The SIDM fits reproduce the Tully-Fisher relation

Radial Acceleration Relation



McGaugh, Lelli, Schombert (2016)

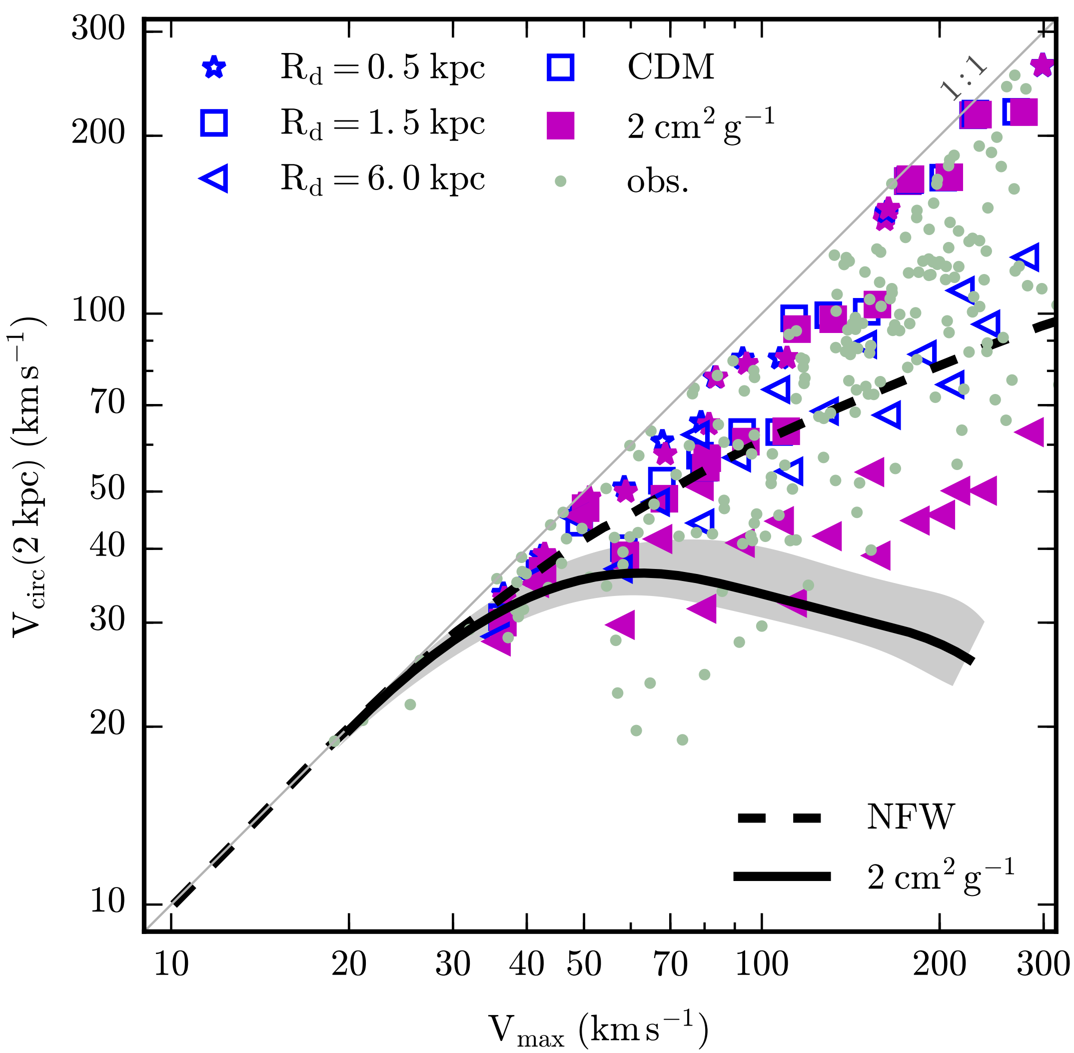


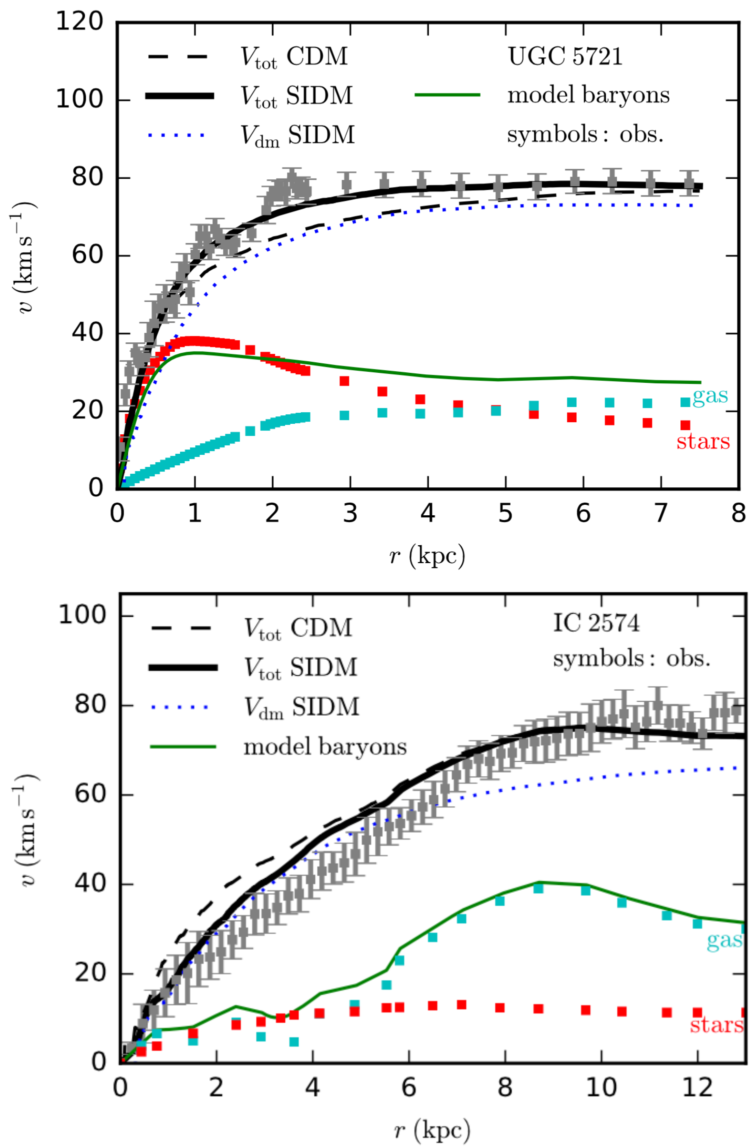
With Kaplinghat, Kwa, Ren (in prep)

The same SPARC dataset

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

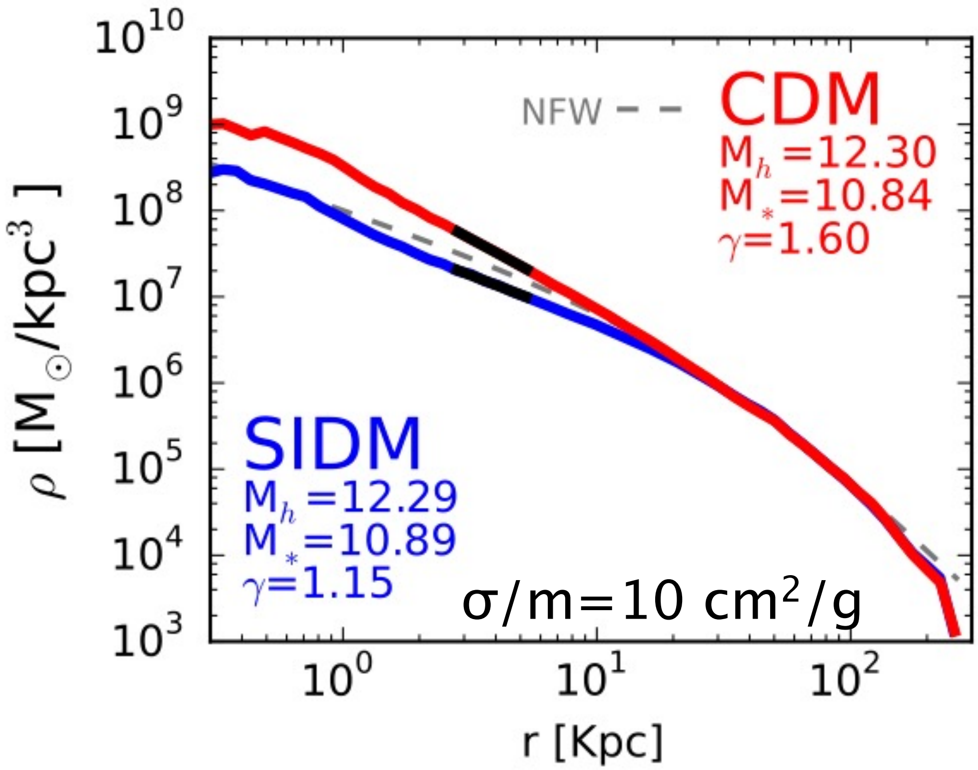
Simulations

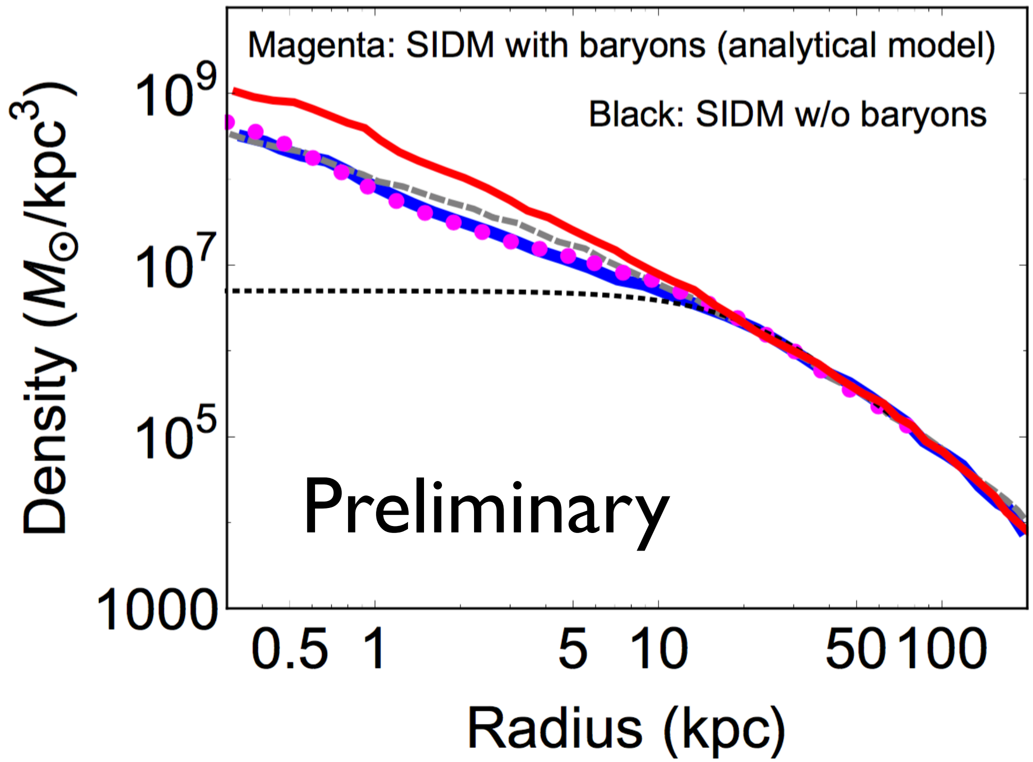




Controlled N-body simulations: with Creasey, Sales, Sameie+ (2016)

SIDM with Strong Feedback





Di Cintio et al. (2017)

$$\rho_X \sim e^{-\Phi_{\rm tot}/\sigma_{\rm v0}^2}$$

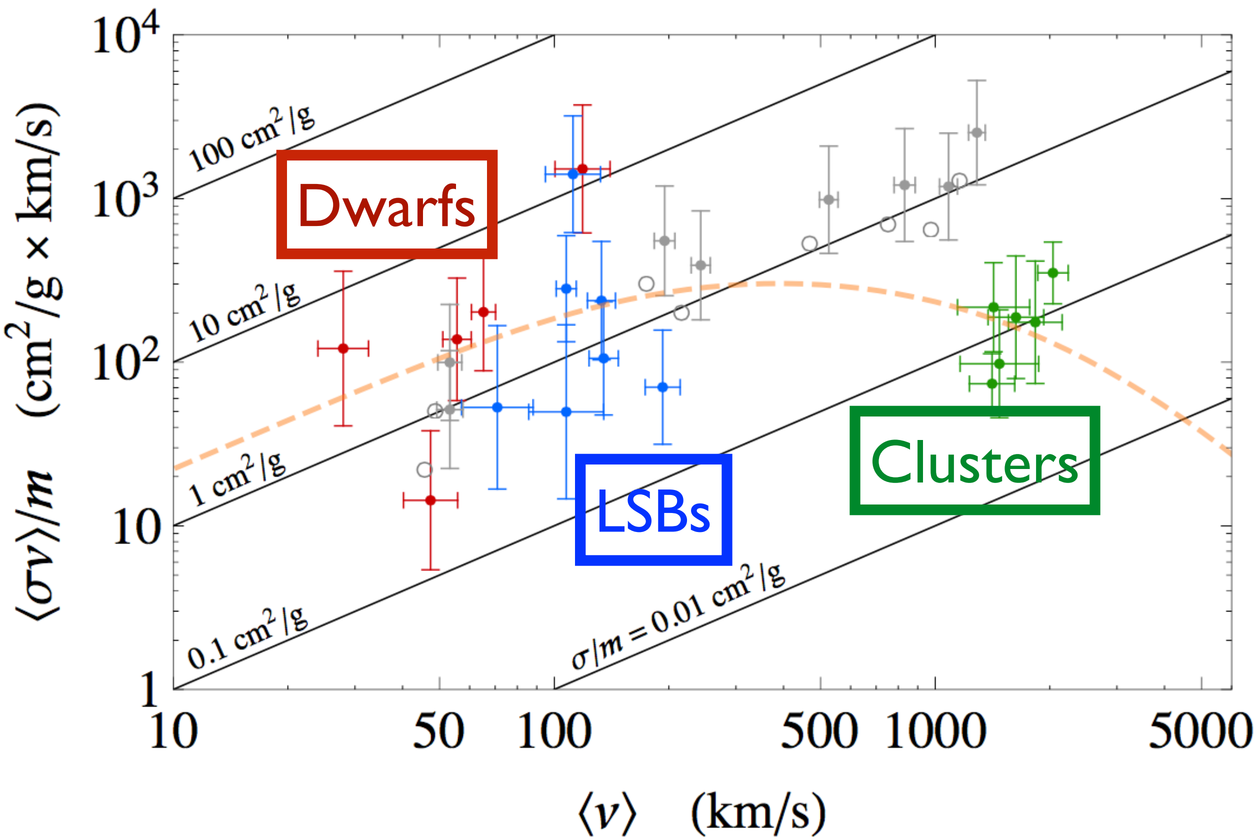
- The SIDM distribution is sensitive to the final baryon distribution
- But, it is not sensitive to the formation history

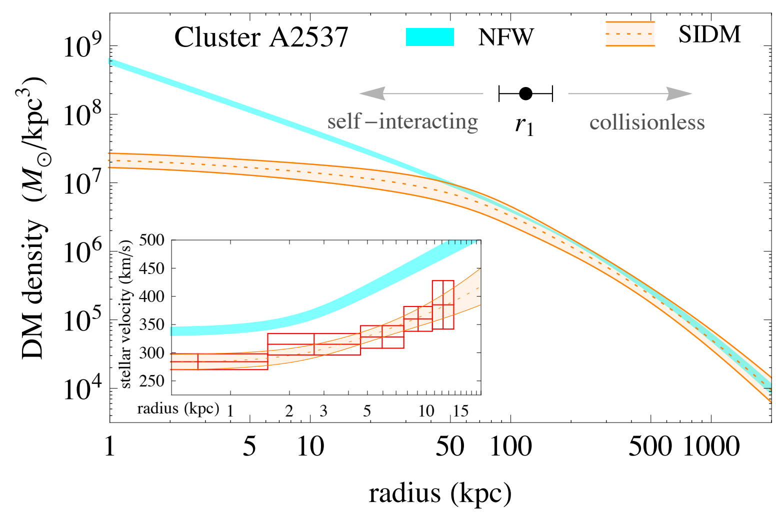
The SIDM halo is FIRE-proof, see Robles et al. (2017)

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

Clusters: ~0.1 cm^2/g

Galaxies: ~2 cm^2/g

Bullet Cluster: < ~2 cm^2/g

DM halos as particle colliders

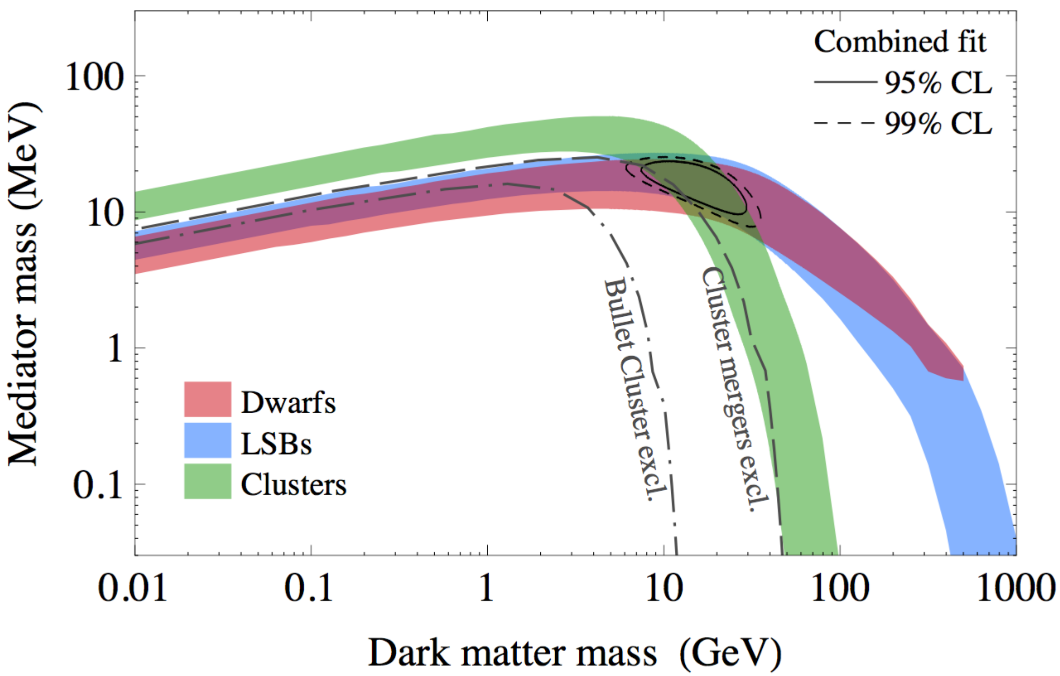
Using the data from Newman et al. (2013)

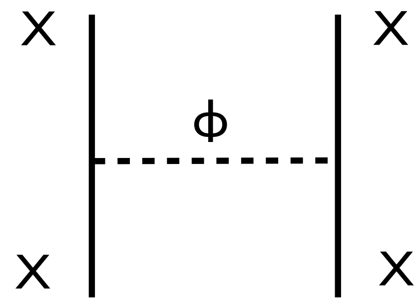
With Kaplinghat, Tulin (2015)

Elbert et al. (2016)

Measuring Dark Matter Mass

- Self-scattering kinematics determines SIDM mass





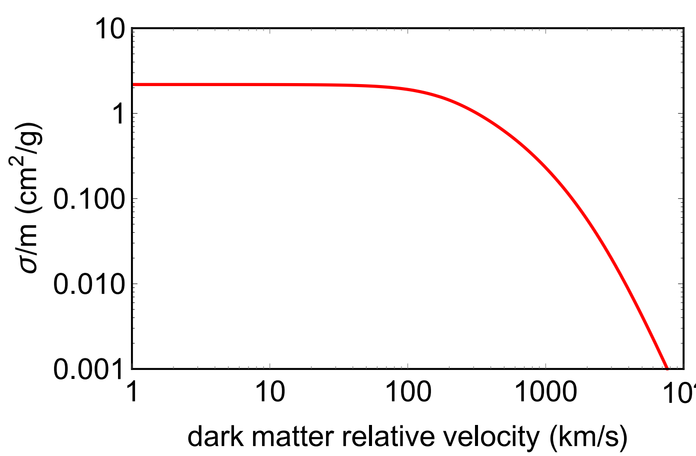
$$V(r) = \frac{\alpha_X}{r} e^{-m_\phi r}$$

with Feng, Kaplinghat (2009)

α_X=1/137

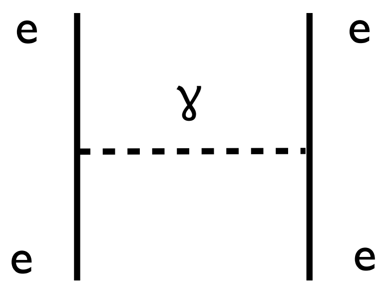
m_X: ~15 GeV, m_ϕ: ~17 MeV

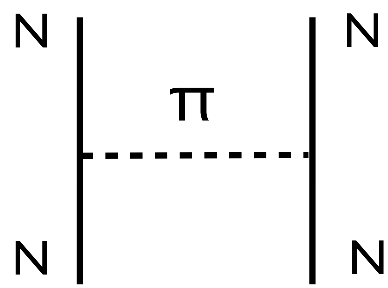
with Kaplinghat, Tulin (2015)

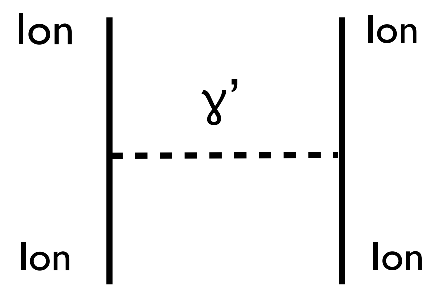


Particle Physics of SIDM

- Familiar examples in the visible sector



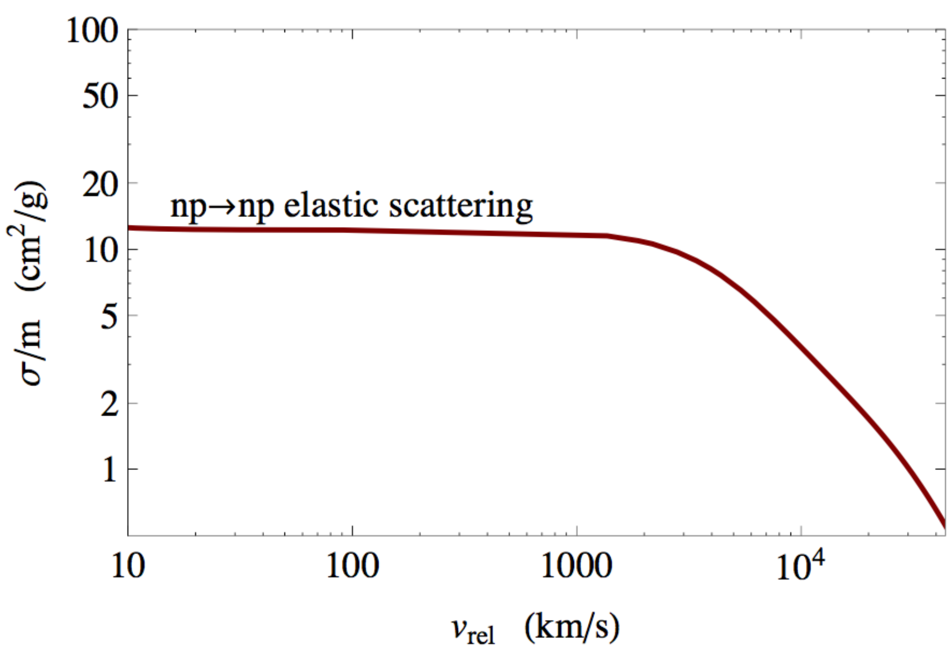




$$V(r) = \frac{\alpha_{\rm EM}}{r}$$

$$V(r) = \frac{1}{r} e^{-m_\pi r}$$

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



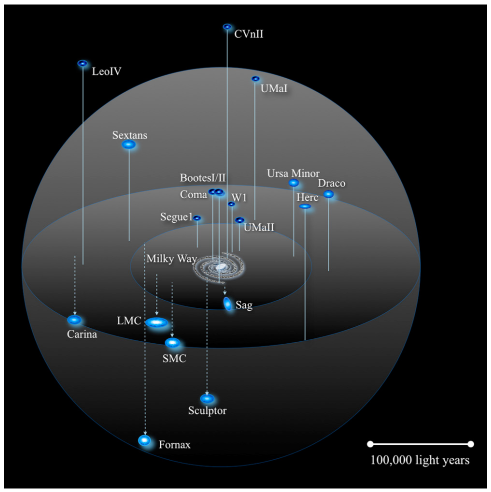
Other examples: atomic DM, SU(N) composite DM…

Need two scales to generate v-dependence

with Tulin (2017)

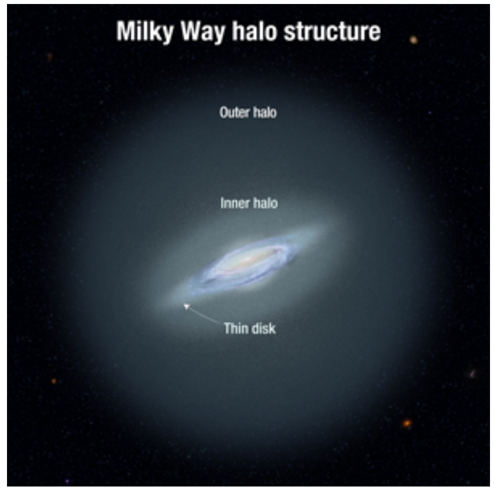
Dark Matter "Colliders"

Dwarf galaxies



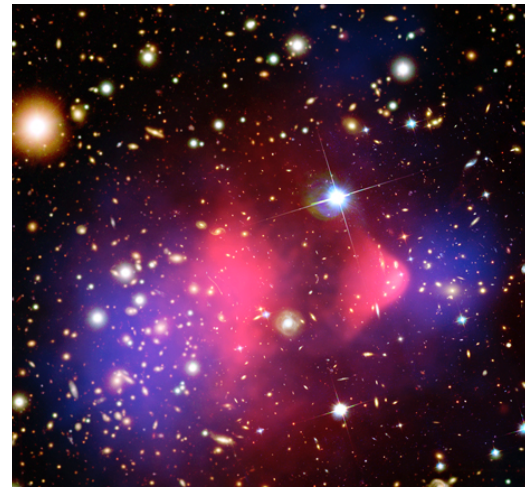
"B-factory" (v~30 km/s)

MW-size galaxies



"LEP" (v~200 km/s)

Clusters



"LHC" (v~1000 km/s)

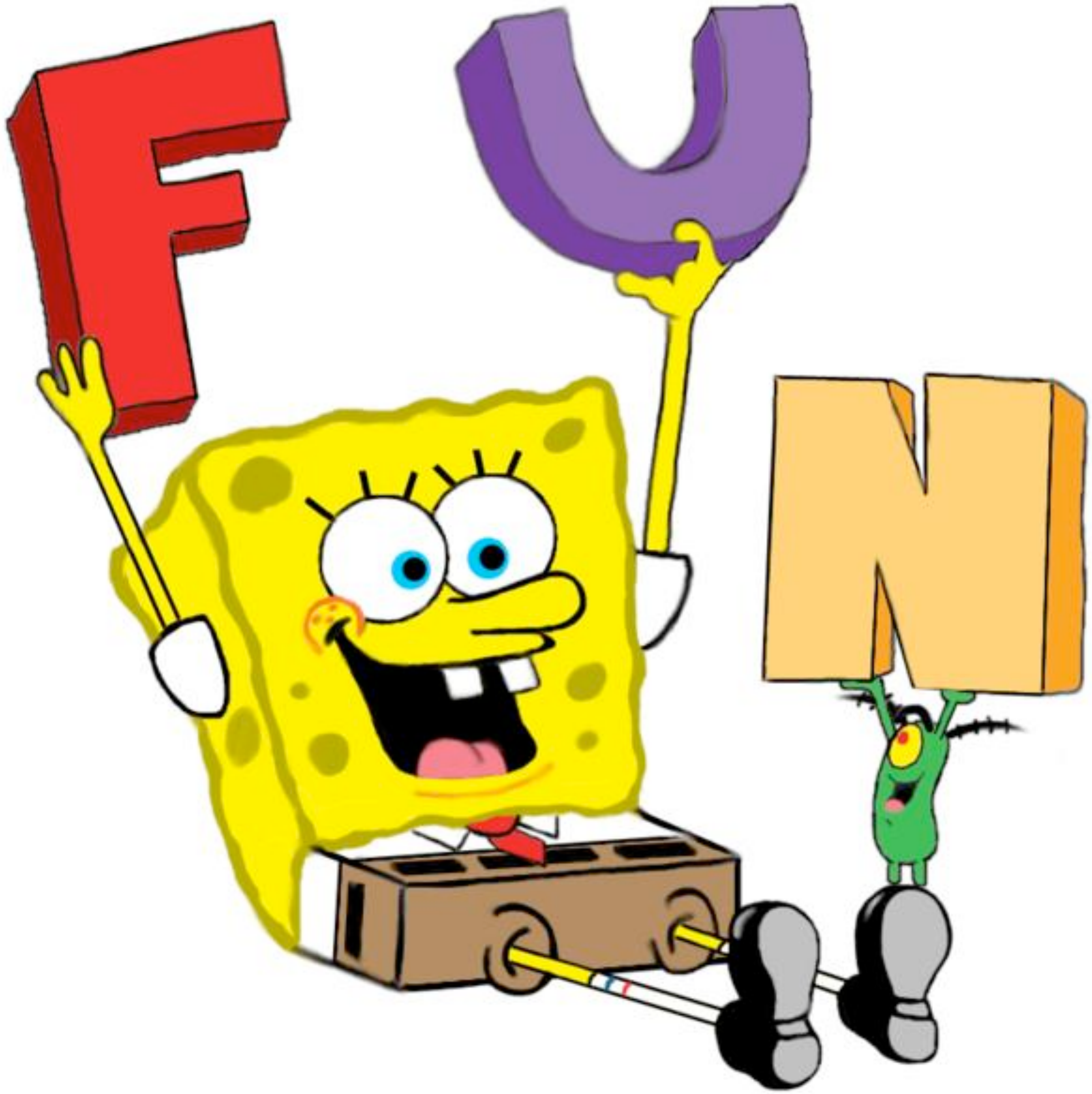
Self-scattering kinematics

Observations on all scales → Measure particle physics parameters σ_x, m_x, g_x

X_{SIDM}

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	$\lesssim$ few cm^2/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]

with Tulin (2017)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