Diverse Galactic Rotation Curves & Self-Interacting Dark Matter

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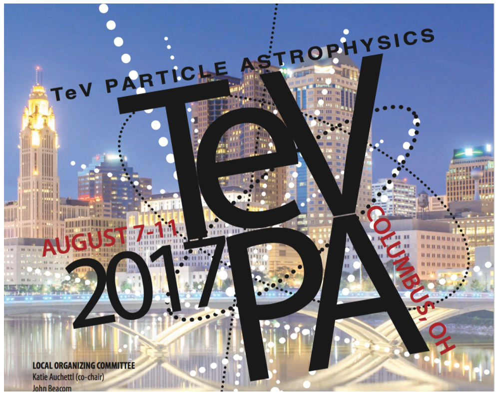
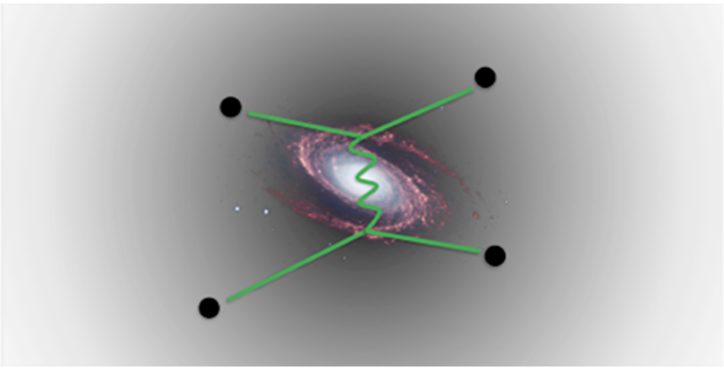




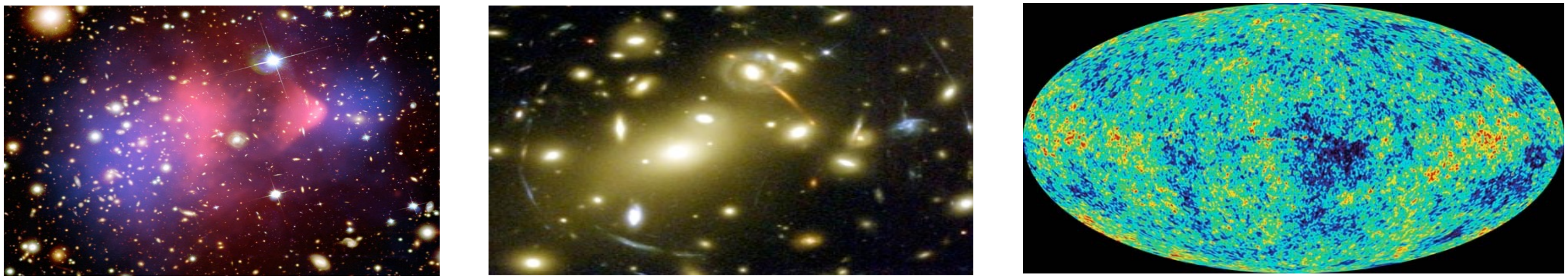
TeVPA, August 7, 2017

See Anna Kwa's talk

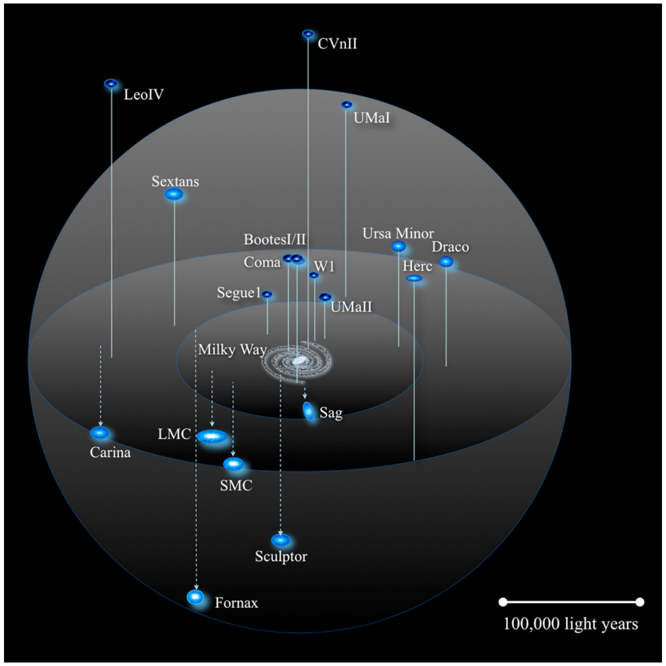
Review for Physics Reports: Sean Tulin, HBY arXiv: 1705.02358

ΛCDM Cosmology

- Success on large scales: larger than ~10-100 kpc



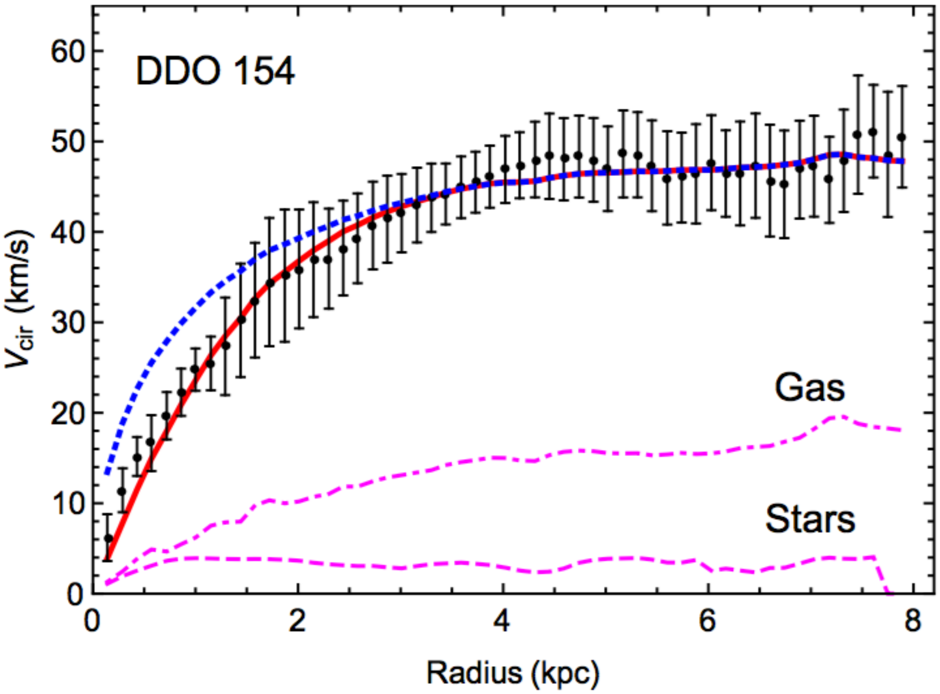
- Crisis on small scales: galactic scales, <10-100 kpc

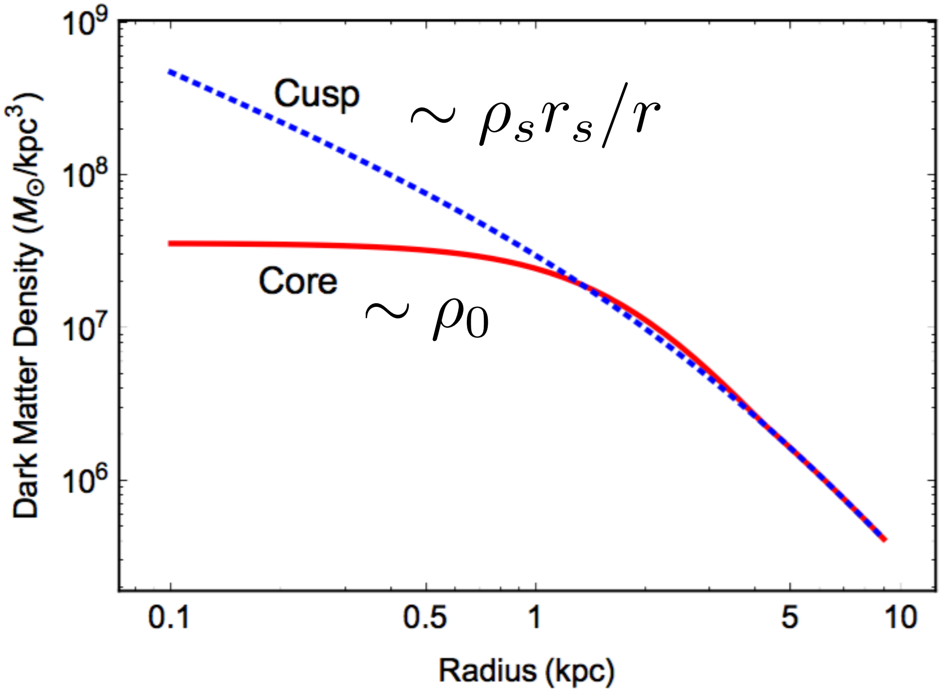


Core vs. Cusp
Diversity
Missing Satellites
Too-Big-To-Fail

Core vs. Cusp Problem

- DM-dominated systems (dwarfs, LSBs)





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

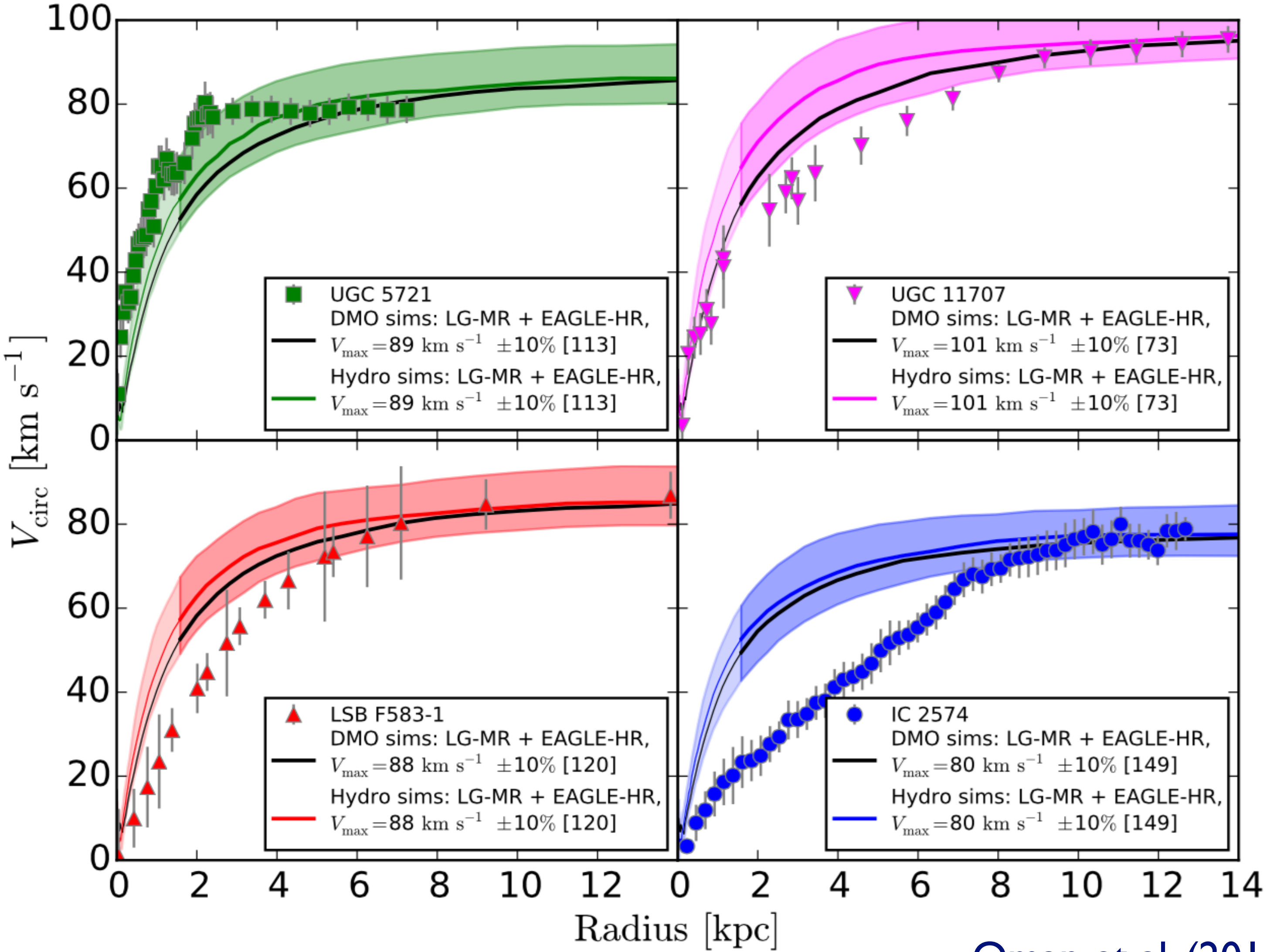
Navarro, Frenk, White (1996)

universal density profile, NFW profile

ρ_s and r_s are strongly correlated

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

The Diversity Problem



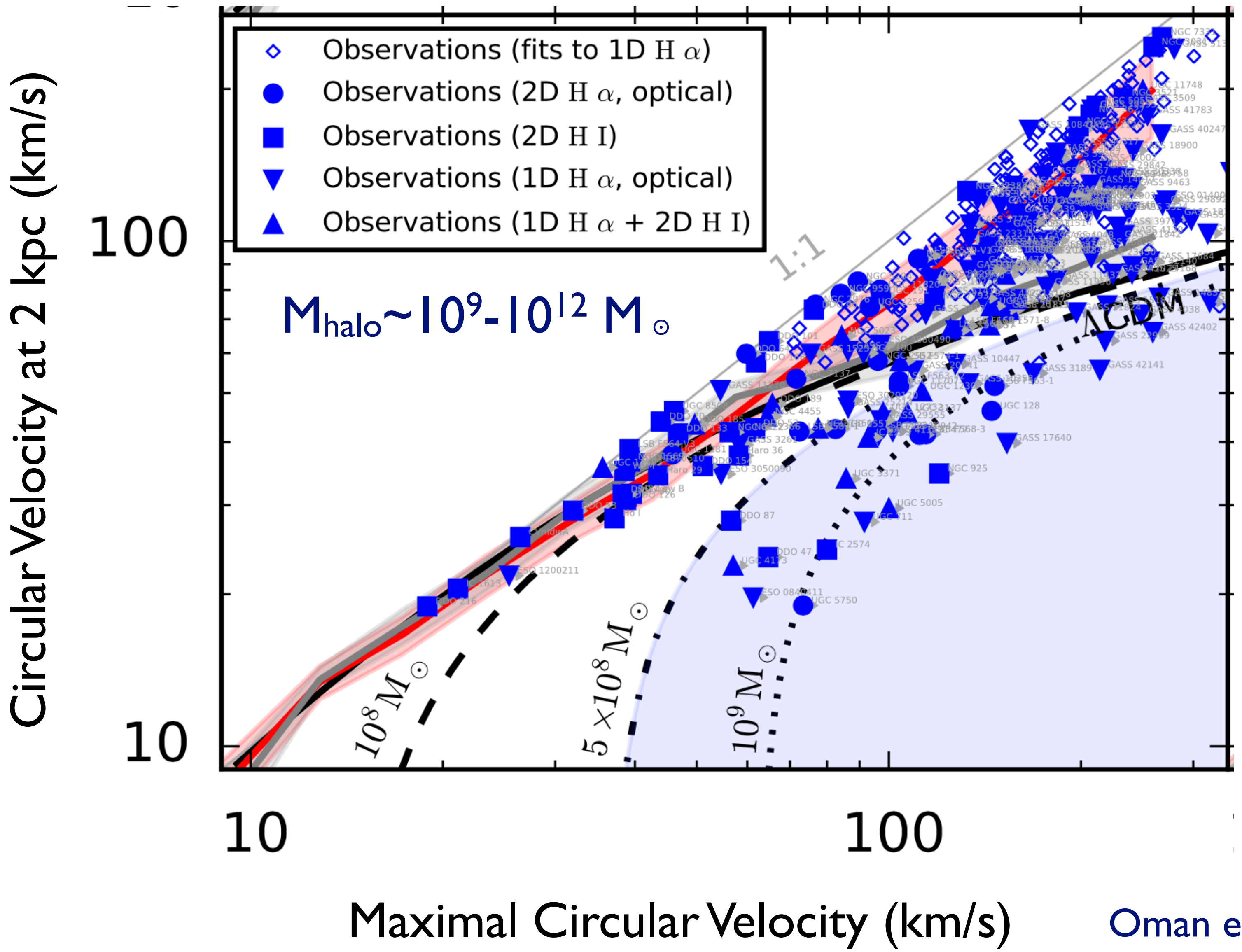
All galaxies have the same Vmax!

Oman et al. (2015)

Colored bands: hydrodynamic simulations of ΛCDM

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

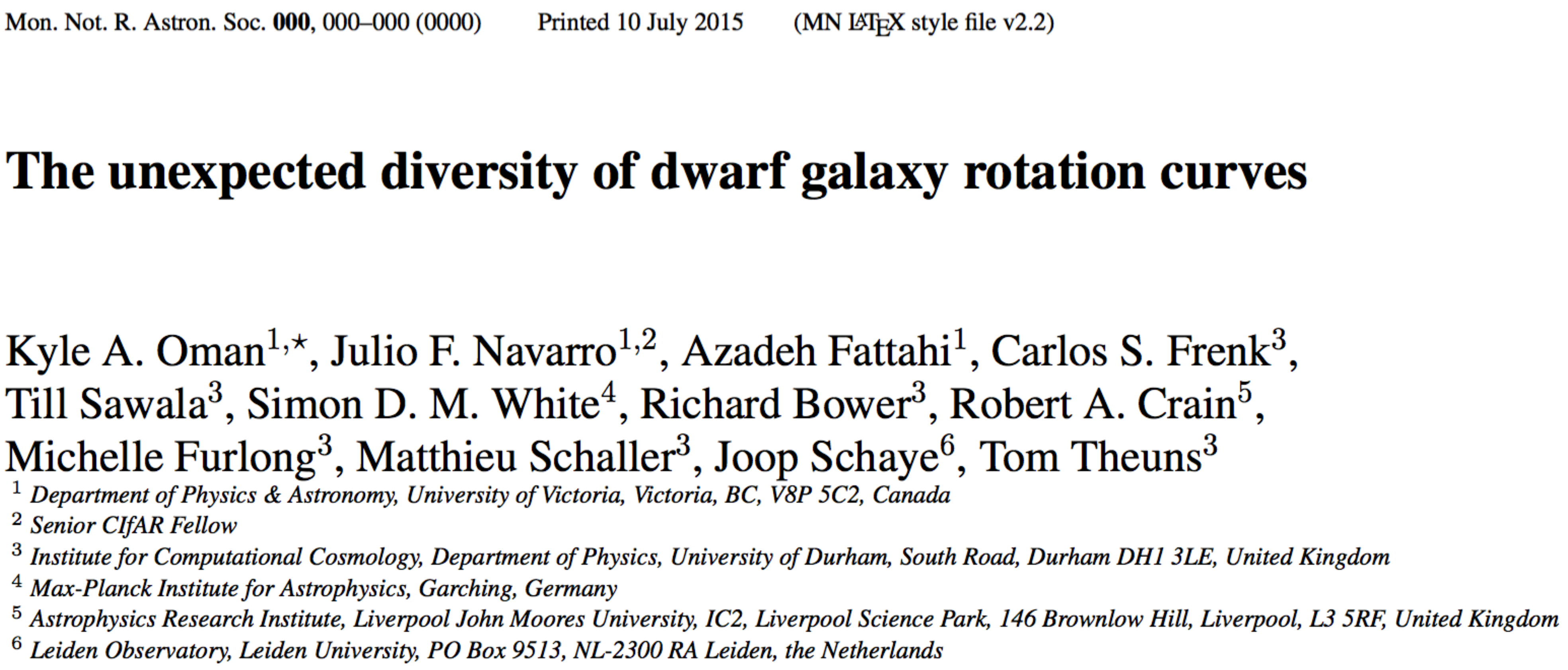
A Big Challenge for ΛCDM



M_{halo}~10^9-10^{12} $M_\odot$

Oman et al. (2015)

V_{circ}(2kpc) has a factor of 3-4 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

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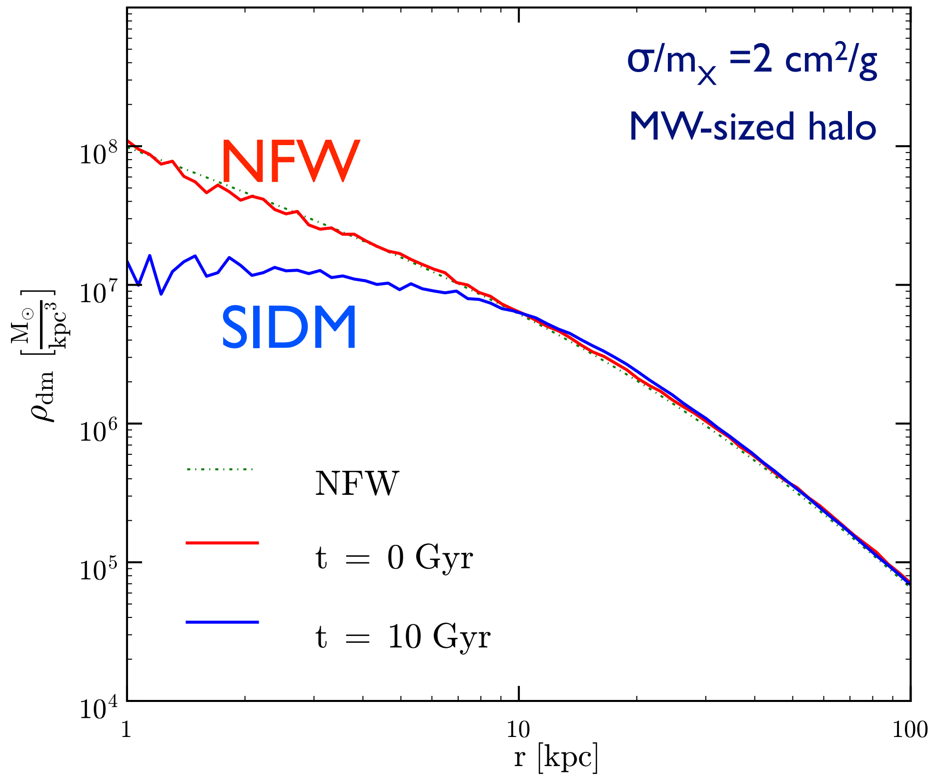
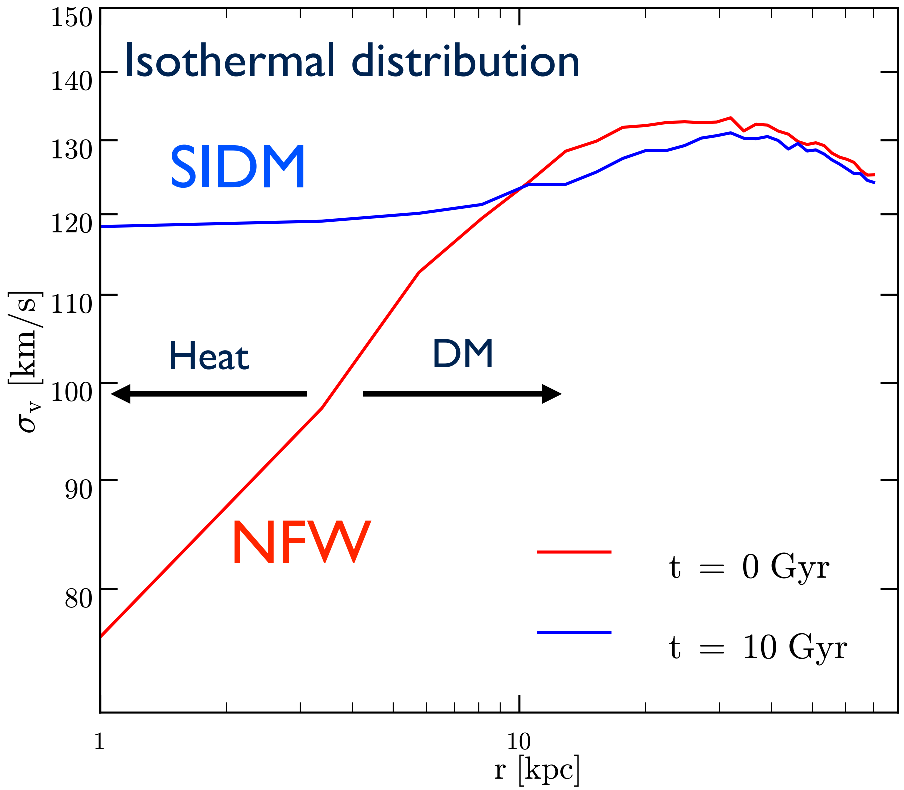
The diversity is expected if dark matter has strong self-interactions

Self-Interacting Dark Matter

- Self-interactions thermalize the inner halo





$\sigma/m_X \sim 1$ cm^2/g

From Huo & Sameie (UCR SIDM code)

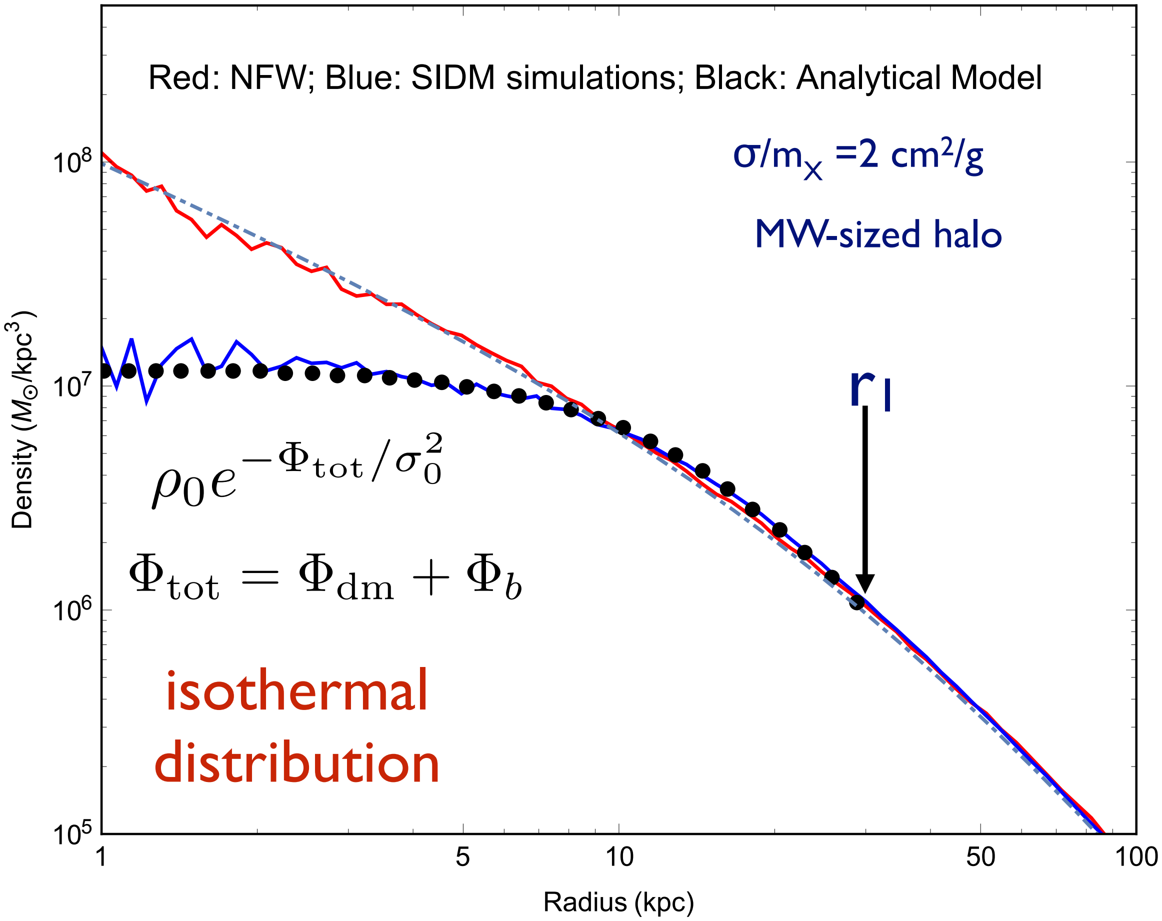
$$\Gamma \simeq n\sigma v = (\rho/m_X)\sigma v \sim H_0$$

Ideal gas: PV=nRT

Spergel, Steinhardt (2000)   Tulin, HBY (2017) for a review

Modelling SIDM Halos

- The model works well remarkably



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

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

isothermal distribution

DM velocity dispersion
Simulations: 119 km/s
Model: 122 km/s

also tested with MIT/UCI simulation results

MIT: Vogelsberger et al. (2012)
UCI: Rocha et al., Peter et al. (2012)

Ideal gas: PV=nRT

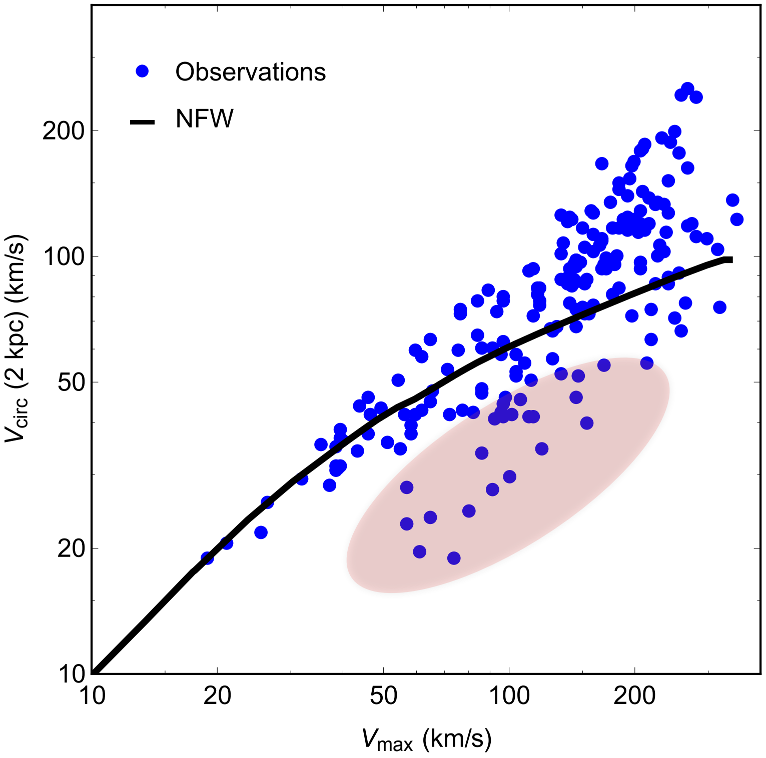
$$\frac{\rho_s}{r/r_s(1+r/r_s)^2}$$

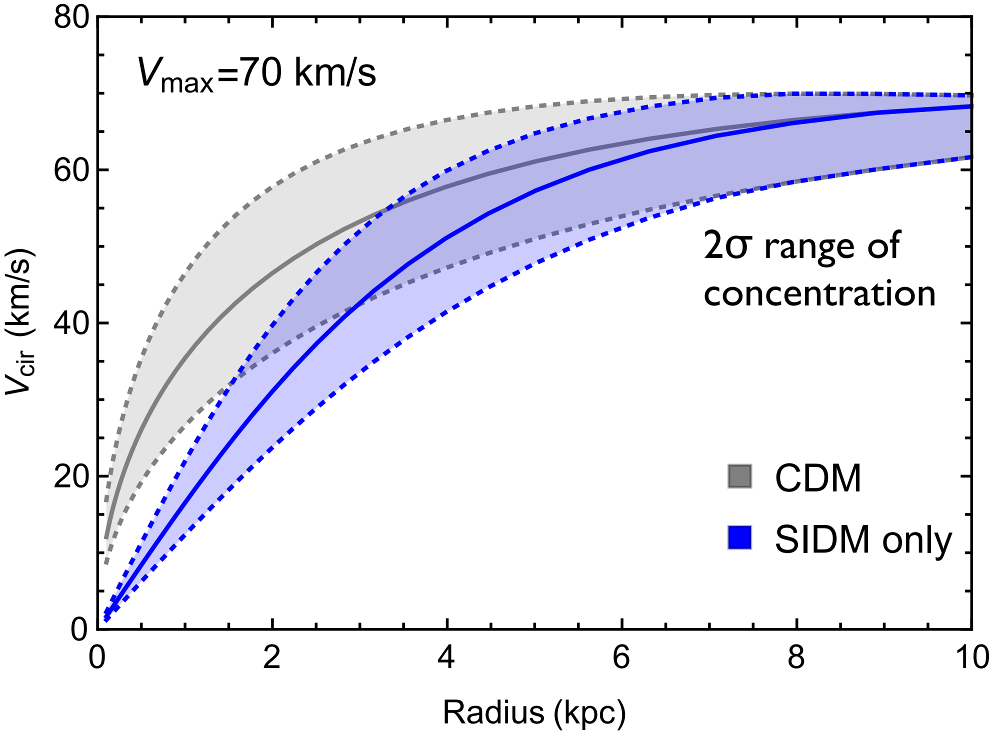
with Kaplinghat, Tulin (PRL 2015)

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

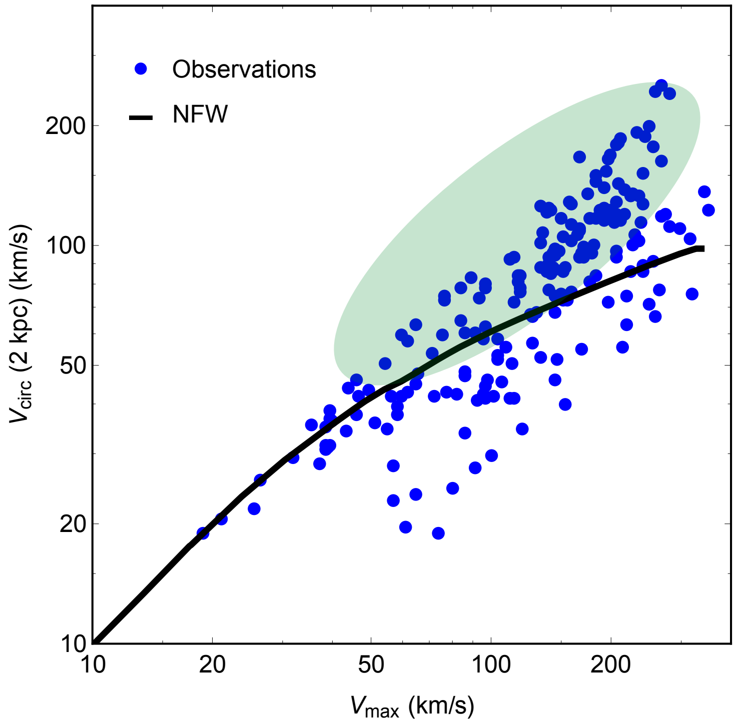
Isothermal distribution

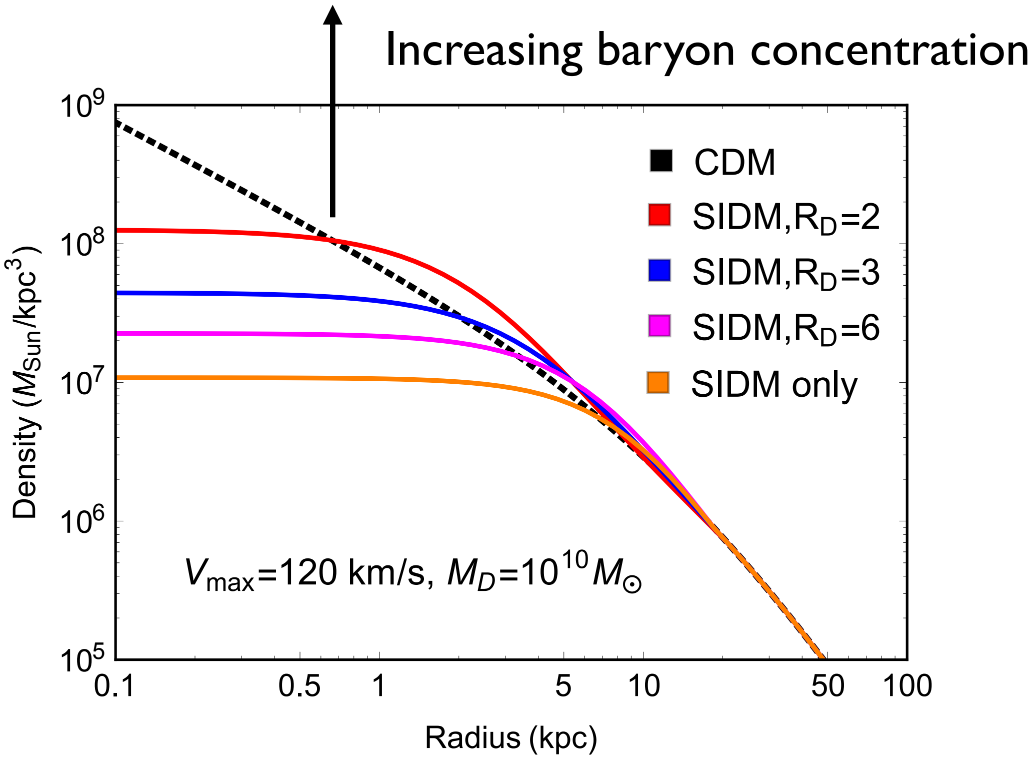
$$\rho_X \sim e^{-\Phi_{\rm tot}/\sigma_0^2} \sim e^{-\Phi_X/\sigma_0^2}$$

with Kamada, Kaplinghat, Pace (PRL 2016)

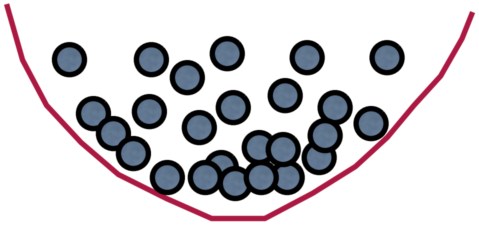
High Luminous Galaxies

- DM self-interactions tie DM together with baryons




Increasing baryon concentration

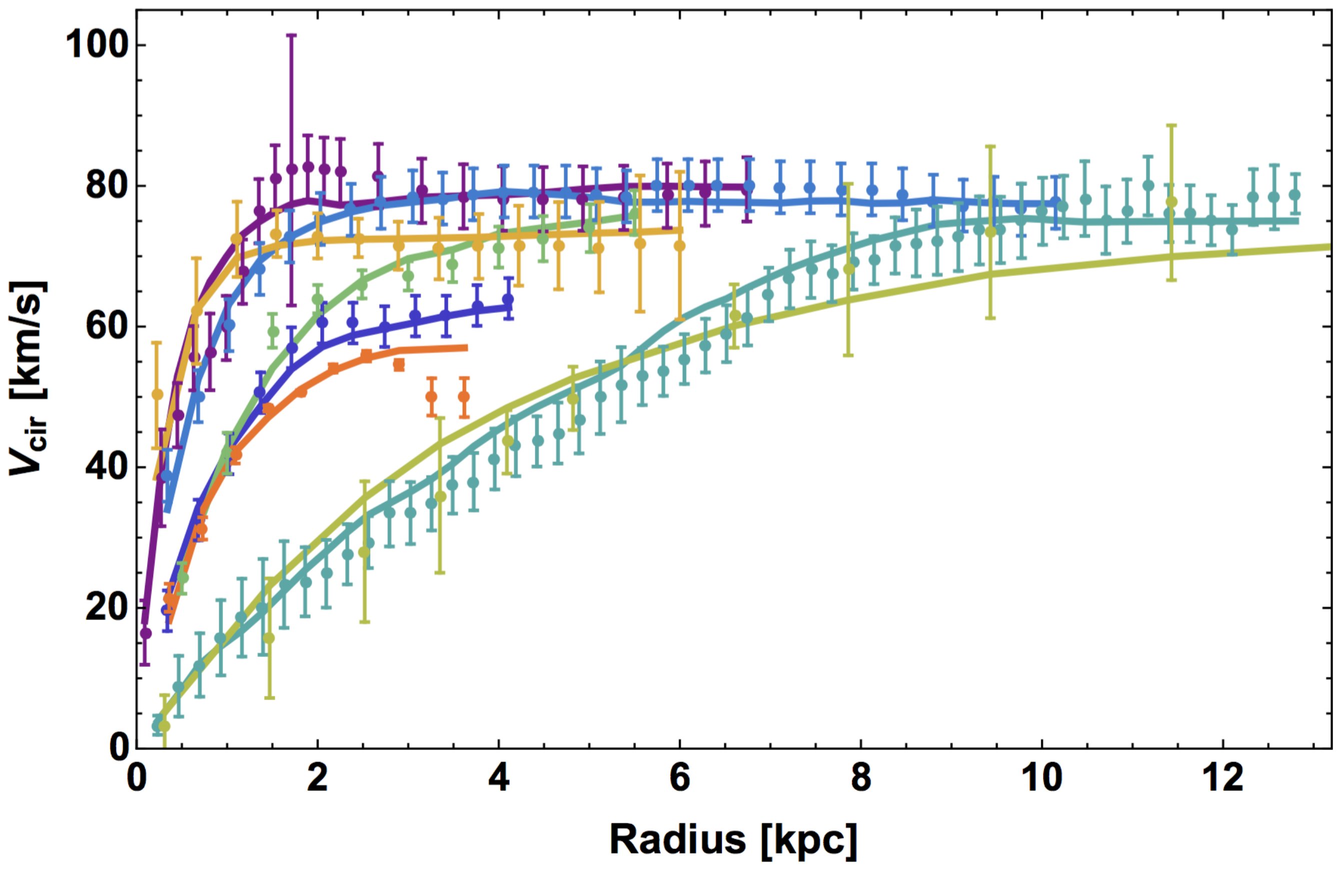
Thermalization leads to higher DM density due to the baryonic influence



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

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

Solving the Diversity Problem

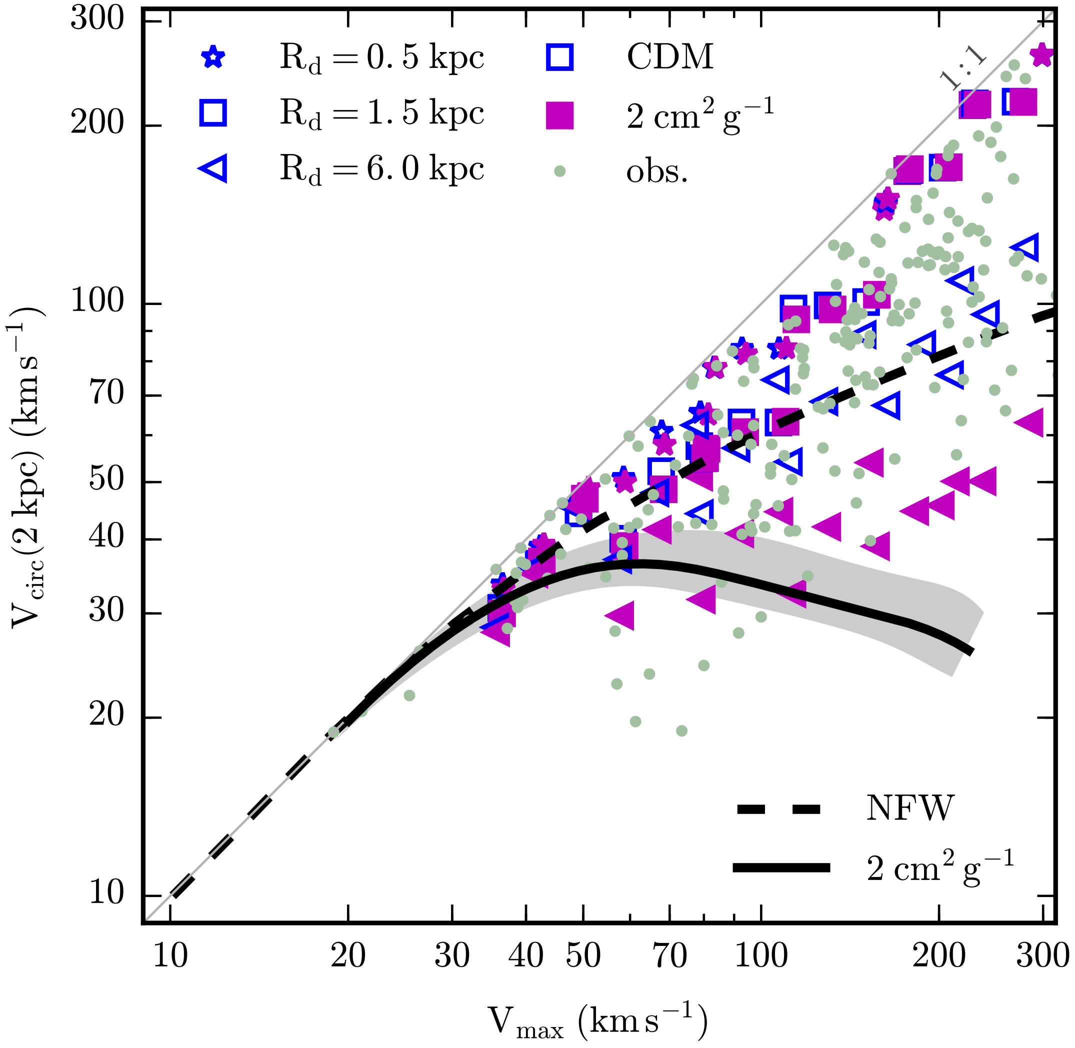


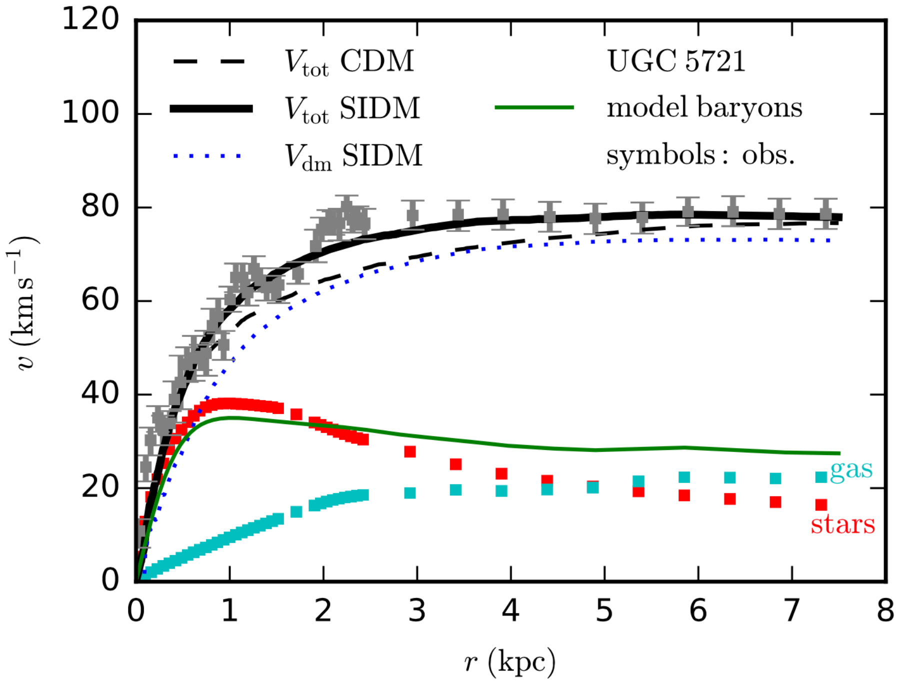
See Anna's talk: ~120 galaxies

- Scatter in the halo concentration
- Spread in the baryon distribution
- Self-interactions tie the DM and baryon distributions together

with Kamada, Kaplinghat, Pace (PRL 2016) (30 galaxies, Vmax=25-300 km/s)

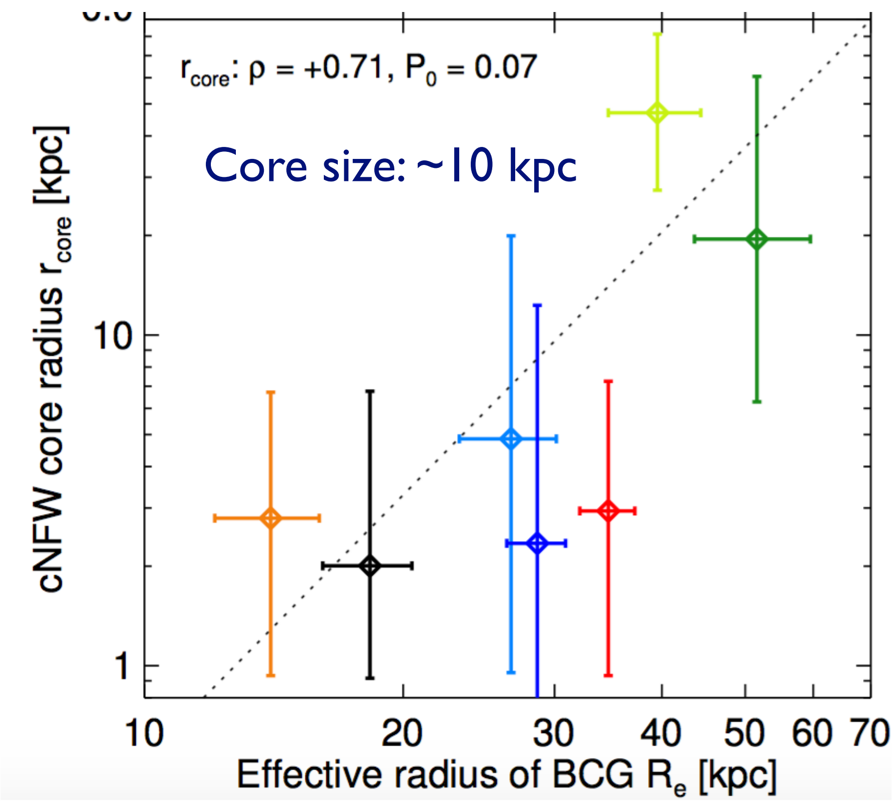
Simulations





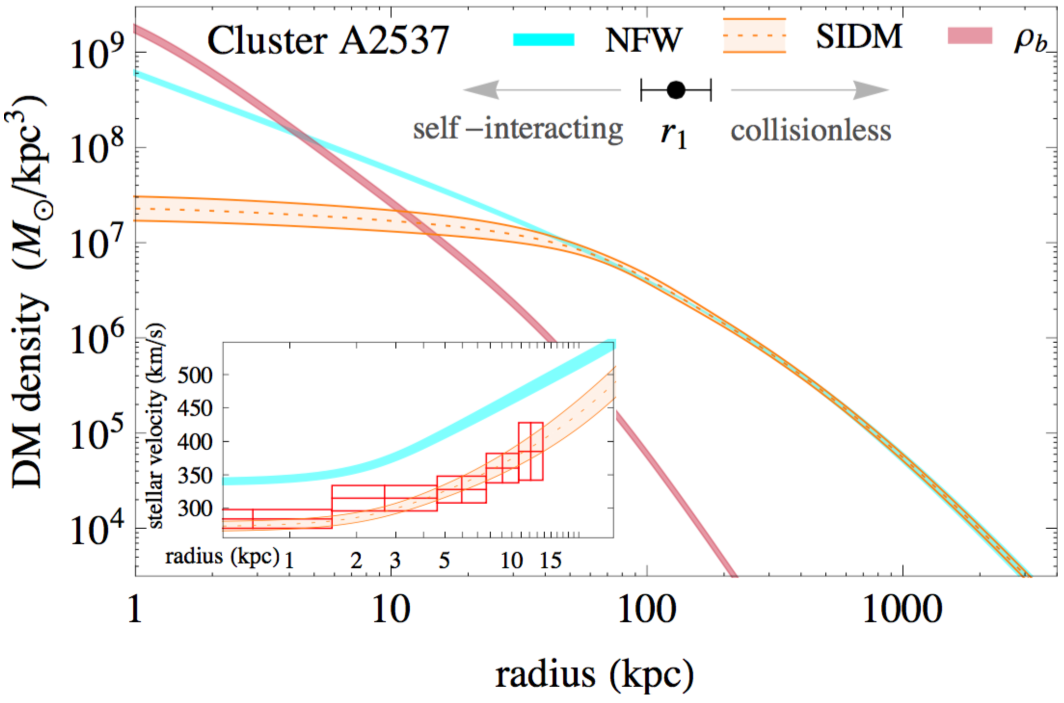
Controlled N-body simulations: with Creasey, Sameie, Sales, Vogelsberger, Zavala (MNRAS 2016)

Density Cores in Galaxy Clusters



Core size: ~10 kpc

Newman et al. (2013)



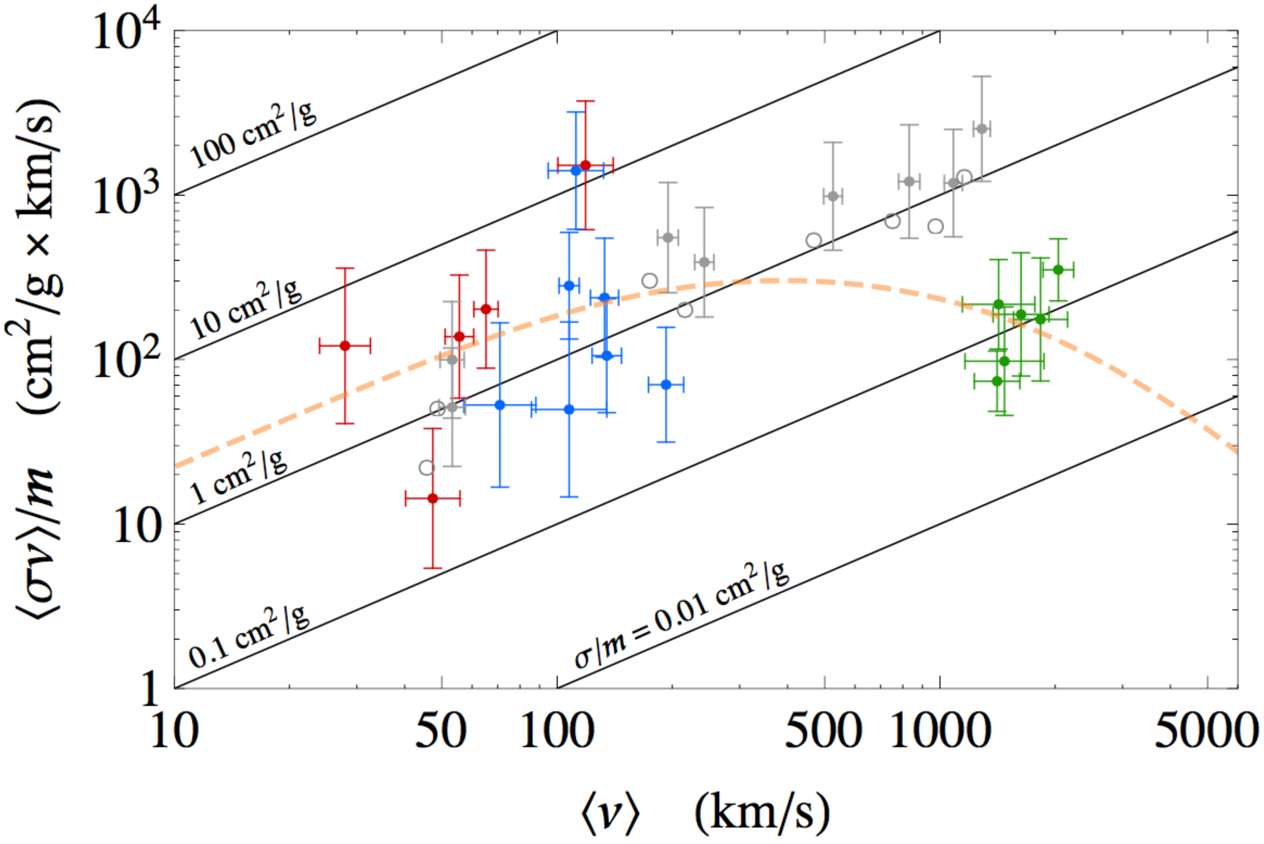
with Kaplinghat, Tulin (PRL 2015)

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

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

SIDM from Dwarfs to Clusters

- Consider 5 THINGS dwarfs (red), 7 LSBs (blue), 6 galaxy clusters (green)
- 8 simulated halos with $\sigma/m=1$ cm^2/g (gray) for calibration



Galaxies: ~2-3 cm^2/g

Clusters: ~0.1 cm^2/g

Core size in clusters: ~10 kpc

If it were ~1 cm^2/g in clusters, the core size would be ~100 kpc

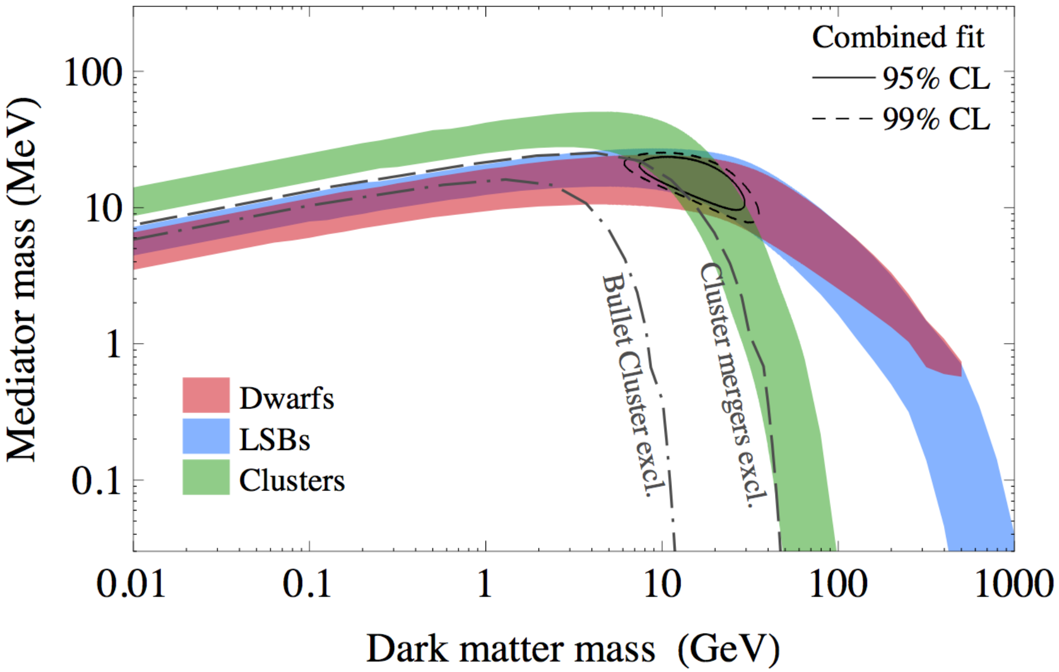
The strongest limit!

DM halos as “particle colliders”

with Kaplinghat, Tulin (PRL 2015)

Measuring Dark Matter Mass

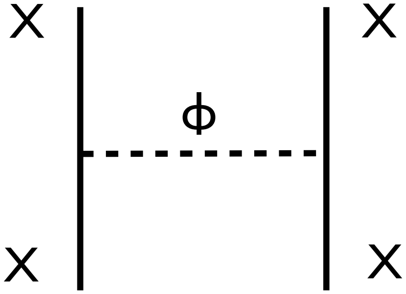
- Self-scattering kinematics determines SIDM mass



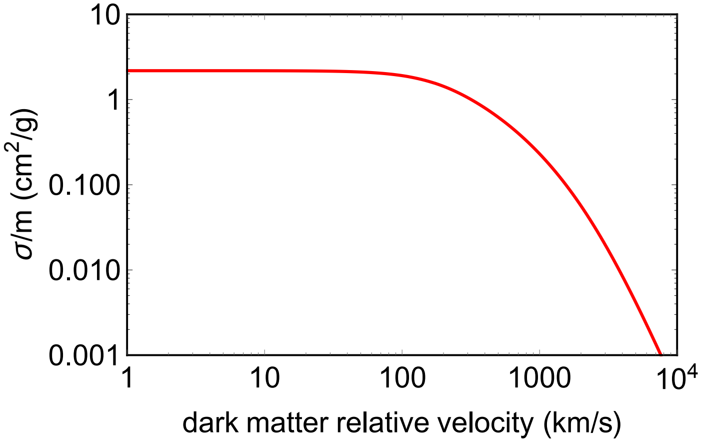
α_X=1/137

m_X: ~15 GeV, m_ϕ: ~17 MeV

with Kaplinghat, Tulin (PRL 2015)

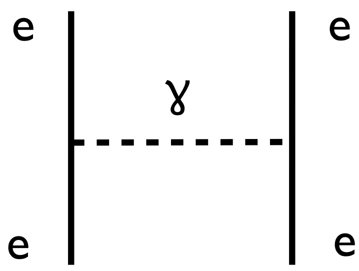


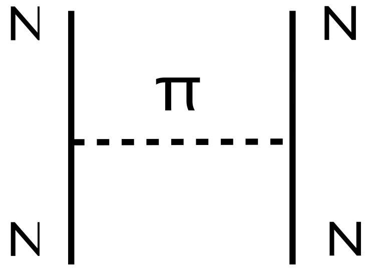
$$V(r) = \frac{\alpha_X}{r} e^{-m_\phi r}$$

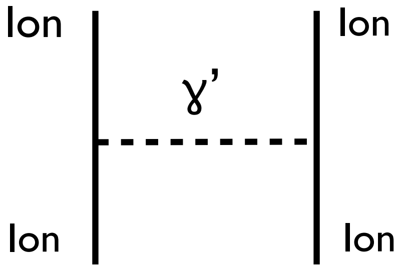


Particle Physics of SIDM

- Familiar examples in the visible sector



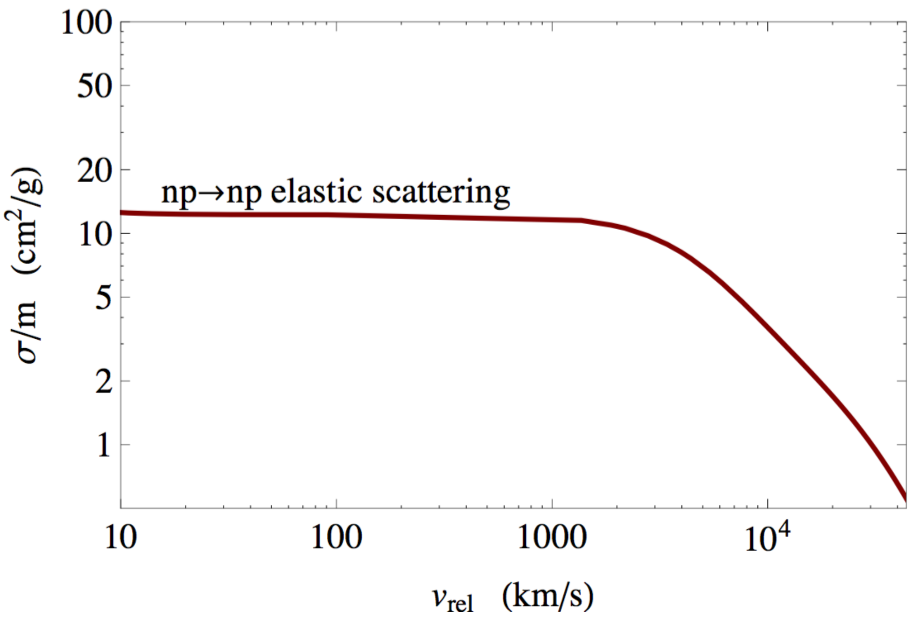




$$V(r) = \frac{\alpha_{\rm EM}}{r}$$

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

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



Tulin, HBY (2017)

Data: Obloinsk et al. (2011)

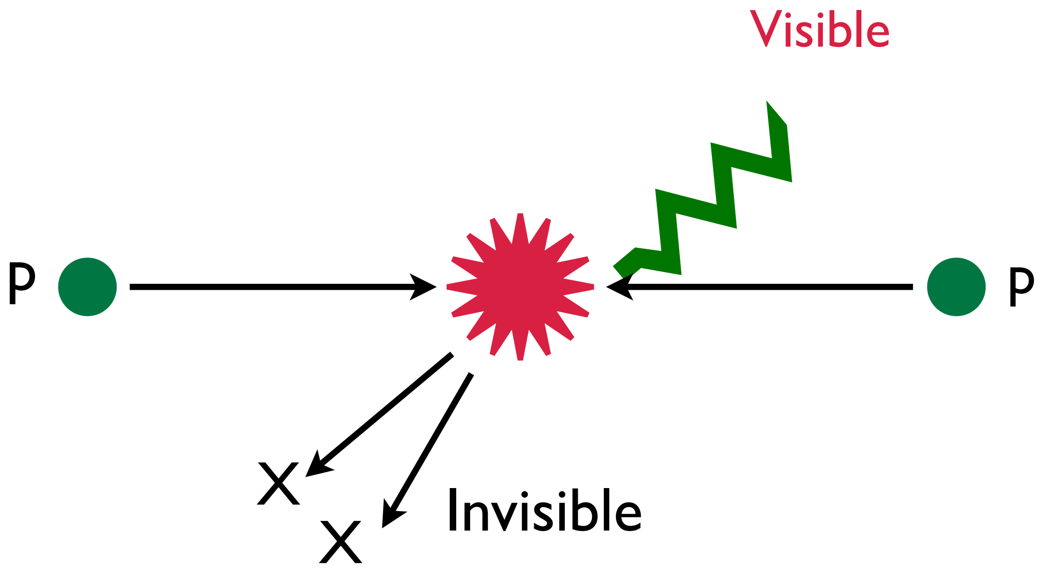
Other examples: atomic DM, SU(N) composite DM…

Need two scales to generate the v-dependence

SIDM at Colliders

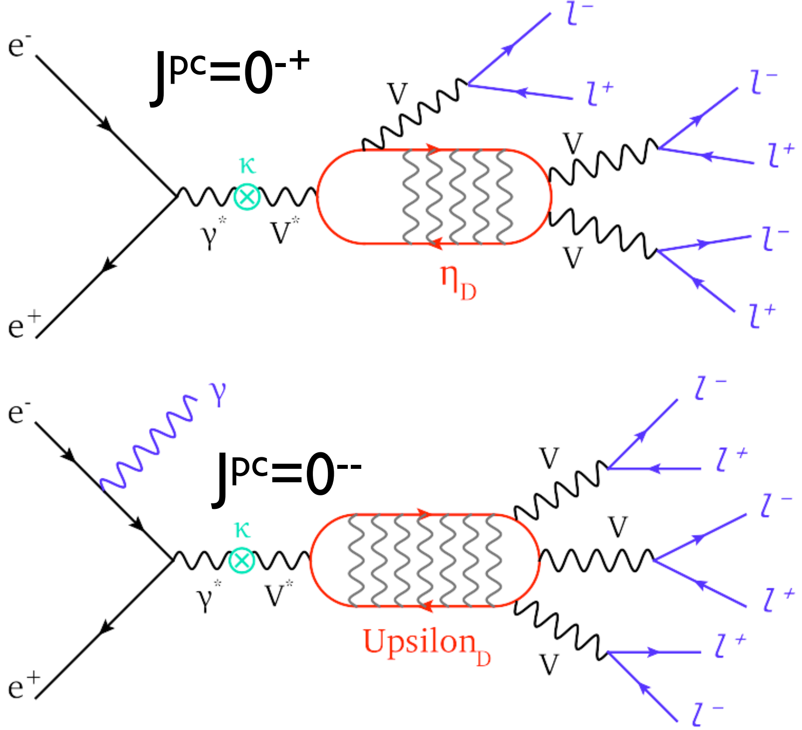
- Striking collider signals

WIMP



pp → Monojet+Missing Energy

SIDM

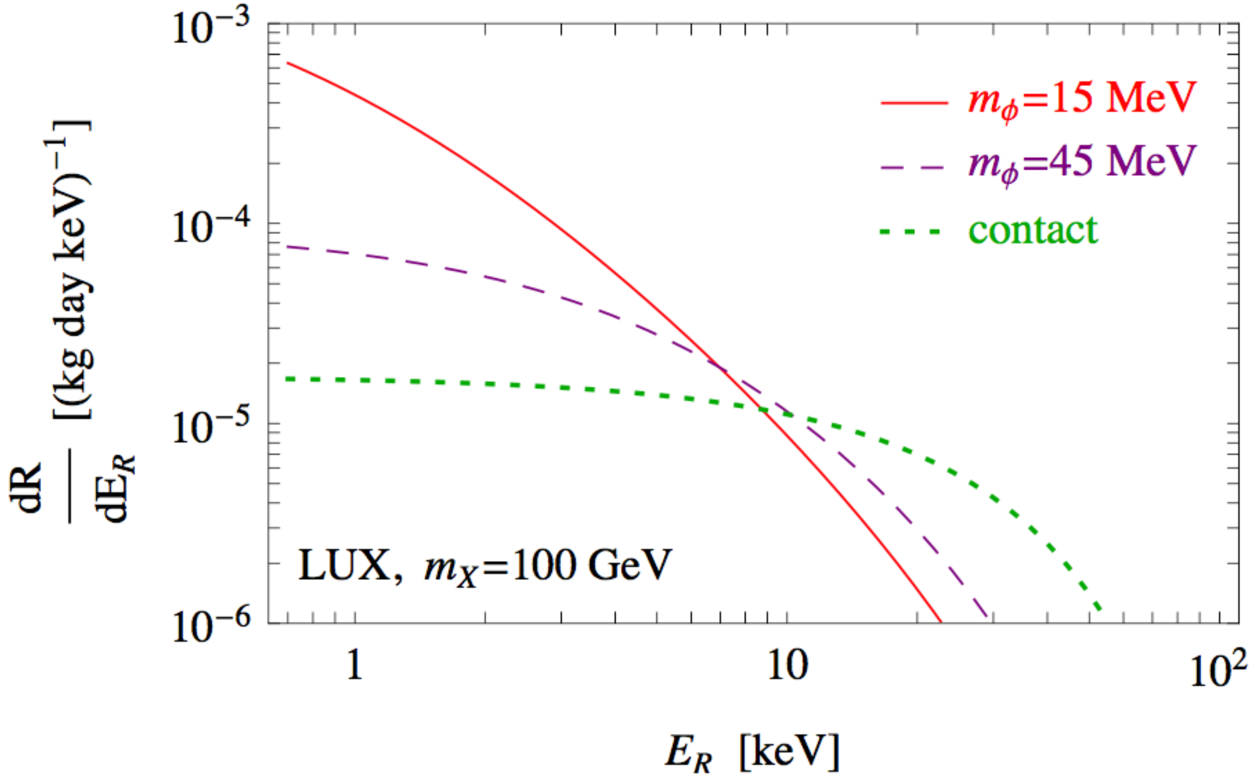


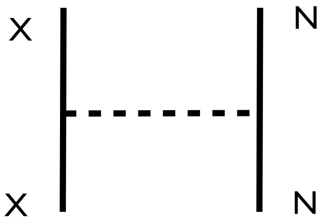
An, Echenard, Pospelov, Zhang (PRL 2015)

Tsai, Wang, Zhao (PRD 2015)

Shepherd, Tait, Zaharijas (PRD 2009)

SIDM Direct Detection





$$\frac{d\sigma}{dq^2} = \frac{4\pi\alpha_{em}\alpha_X\epsilon^2 Z^2}{(q^2+m_\phi^2)^2 v^2}$$

$$q^2 = 2m_N E_R$$

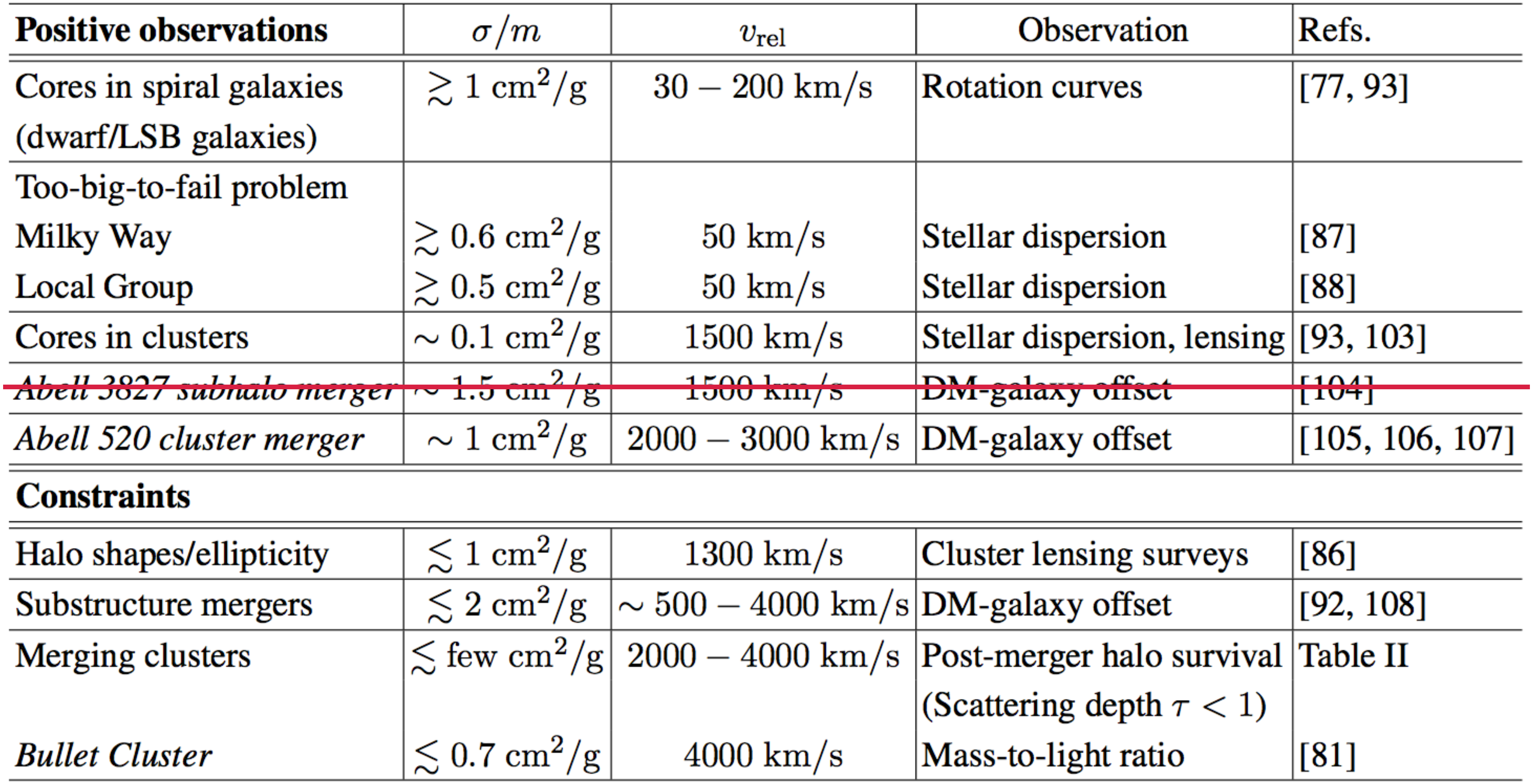
WIMPs: $m_w >> q$
SIDM: $m_\phi \sim q$

with Del Nobile, Kaplinghat (JCAP 2015)
with Kaplinghat, Tulin (PRD 2013)

- Experiments with different targets
- Annual modulation

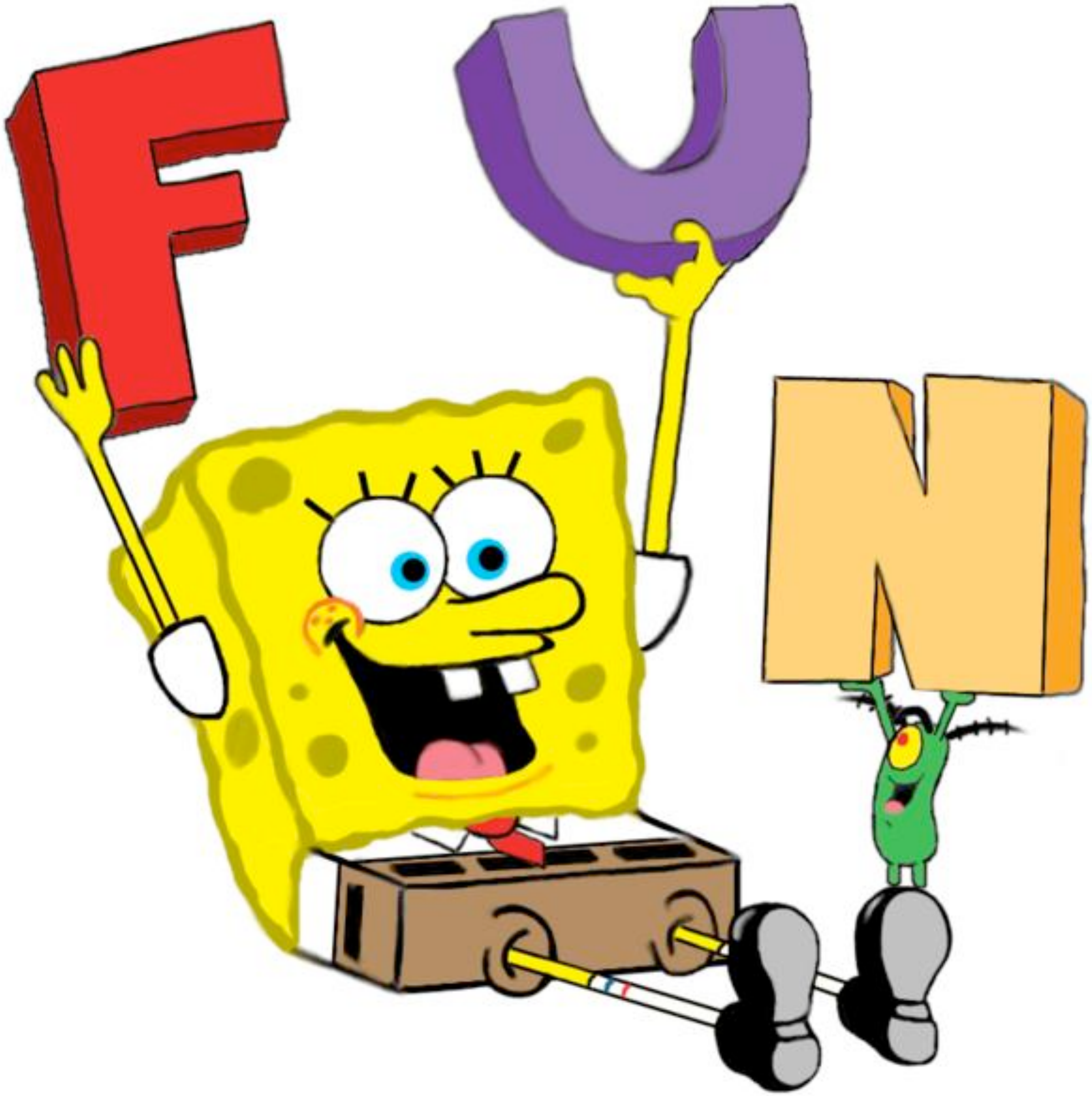
Particle Properties

XSIDM



Positive observations	σ/m	$v_{\rm rel}$	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]

Tulin, HBY (2017)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