The Self-Interacting Dark Matter Paradigm

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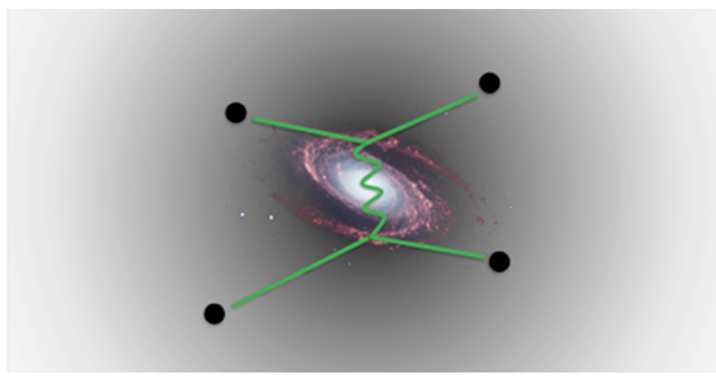
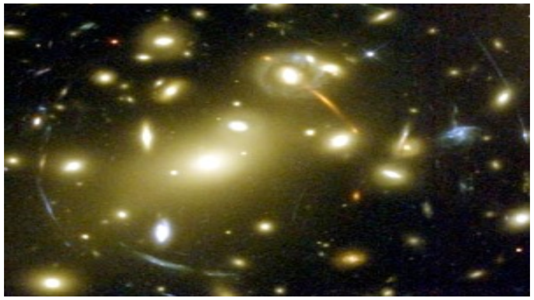


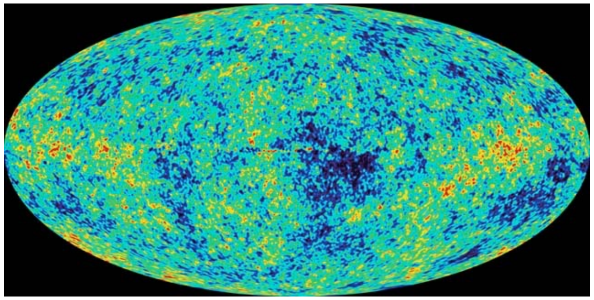
THE UNIVERSITY OF CHICAGO

KICP Workshop, October 13-15, 2016

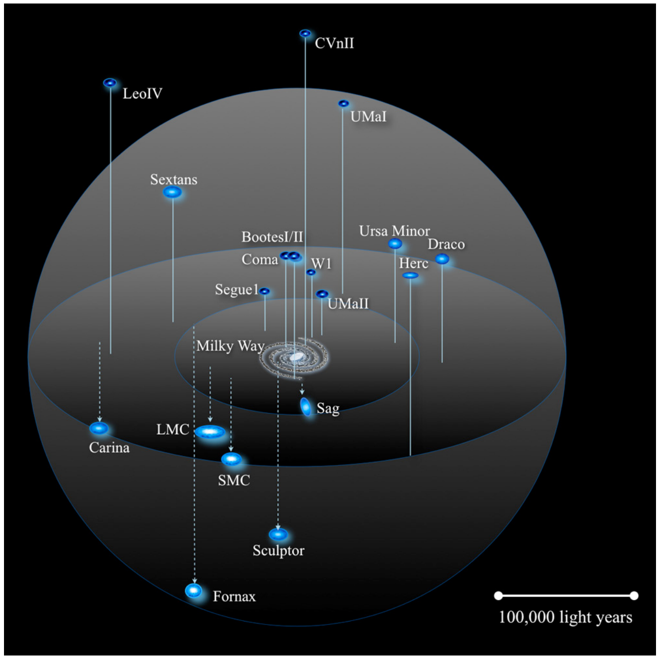
Cold Dark Matter

- Large scales: very well



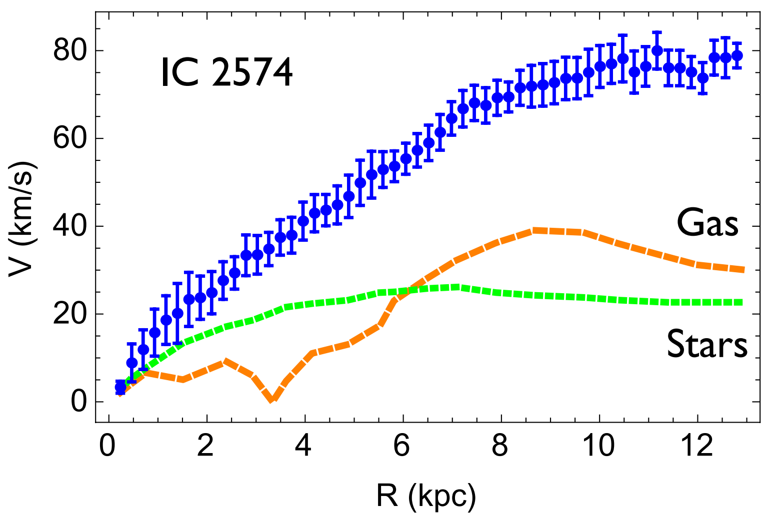


- Small scales (dwarf galaxies, sub-halos, galaxy clusters): ?



Core VS. Cusp Problem

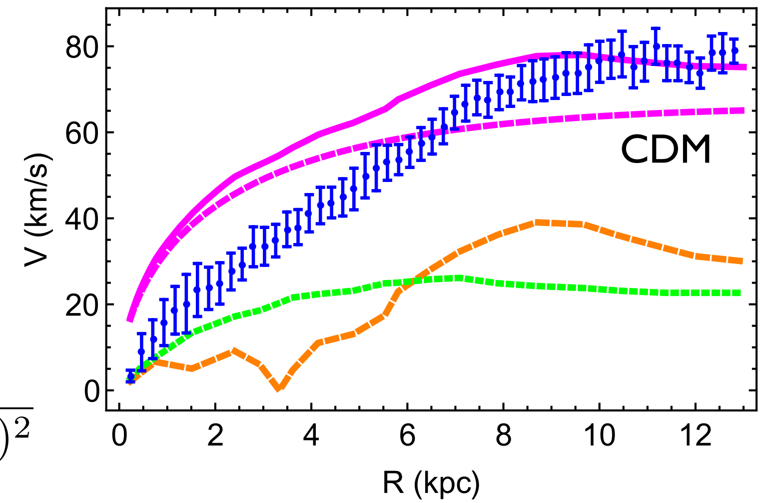
- DM-dominated systems (dwarfs, LSBs) from THINGS Oh+(2011)

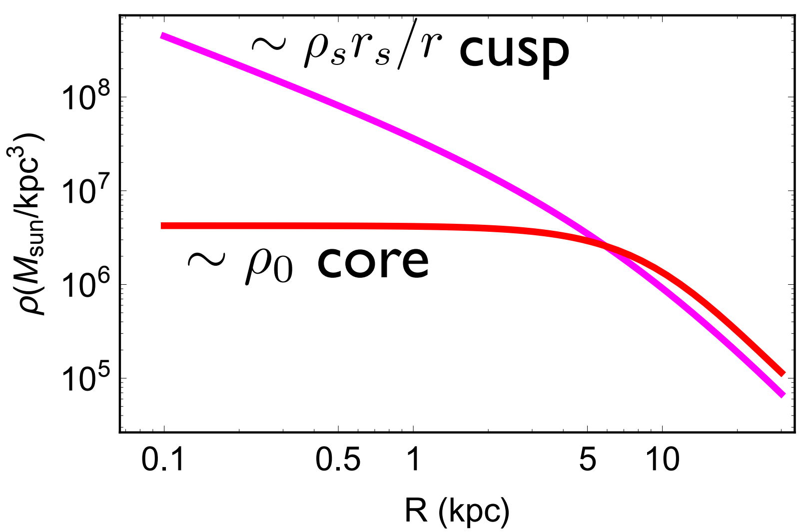


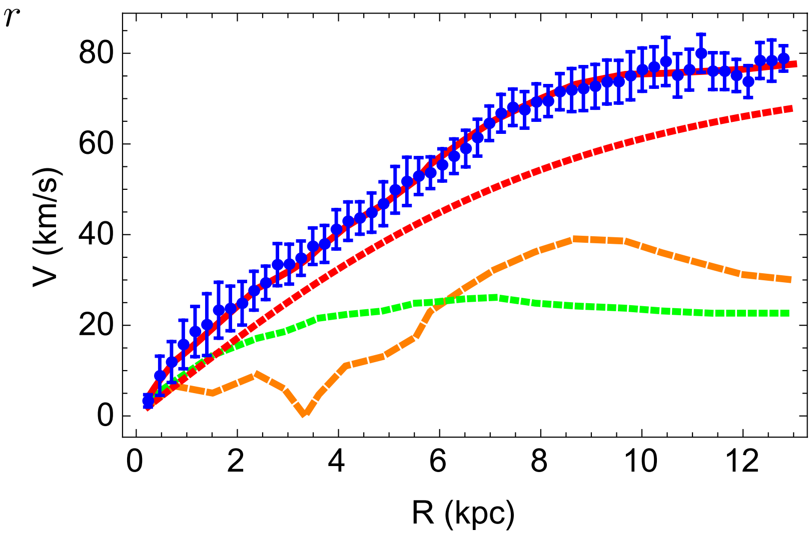
NFW

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

$$V \sim \sqrt{GM_</r}$$



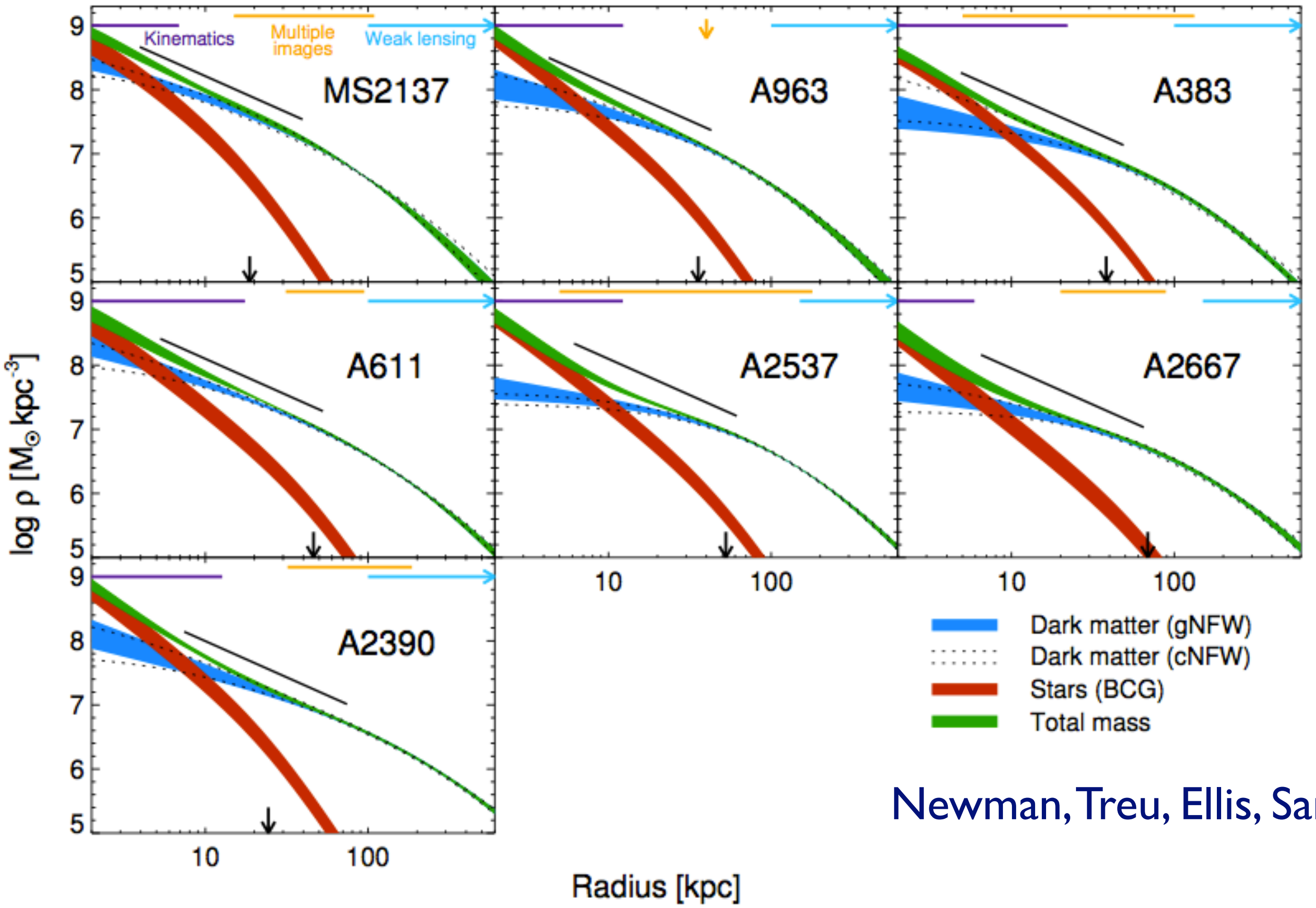


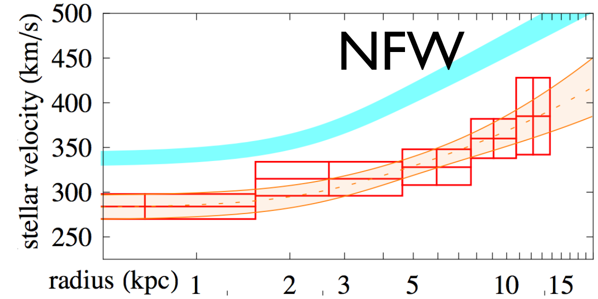


Flores, Primack (1994), Moore (1994), Persic+(1996), de Naray+(2008), de Blok+(2008), Oh+(2011,2015)…

Even Galaxy Clusters

- Seven well-resolved galaxy clusters



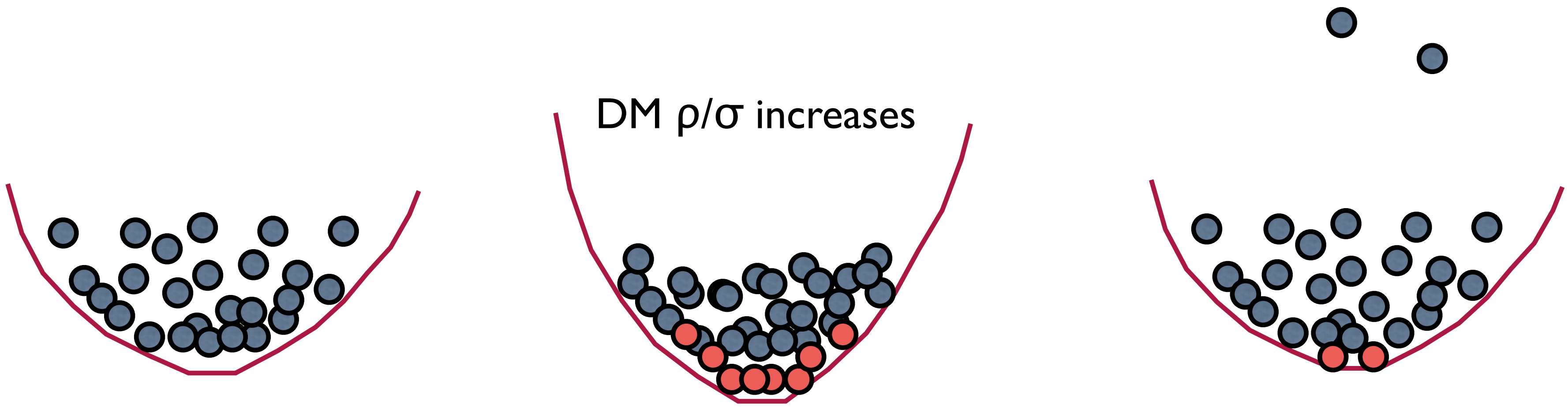


Newman, Treu, Ellis, Sand (2013)

- CDM halos are too massive in their inner regions

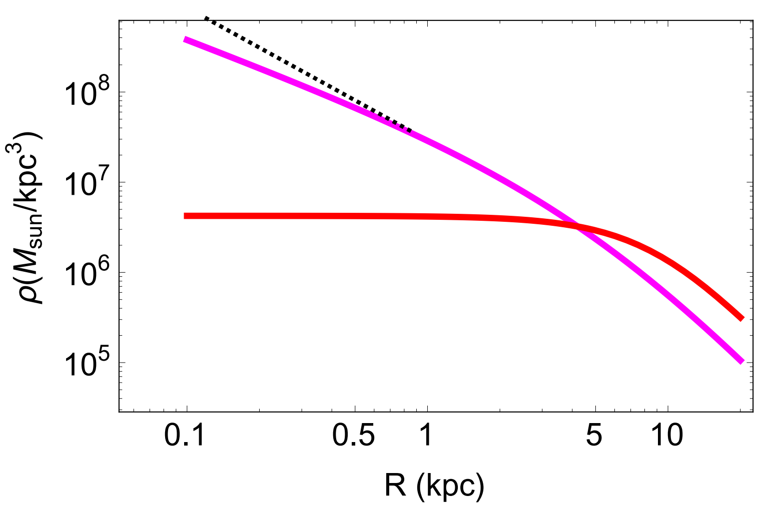
Baryon Physics

- Violent baryonic feedback process



Baryonic Infall

Supernova Explosion



Blumenthal, Flores, Primack (1986)

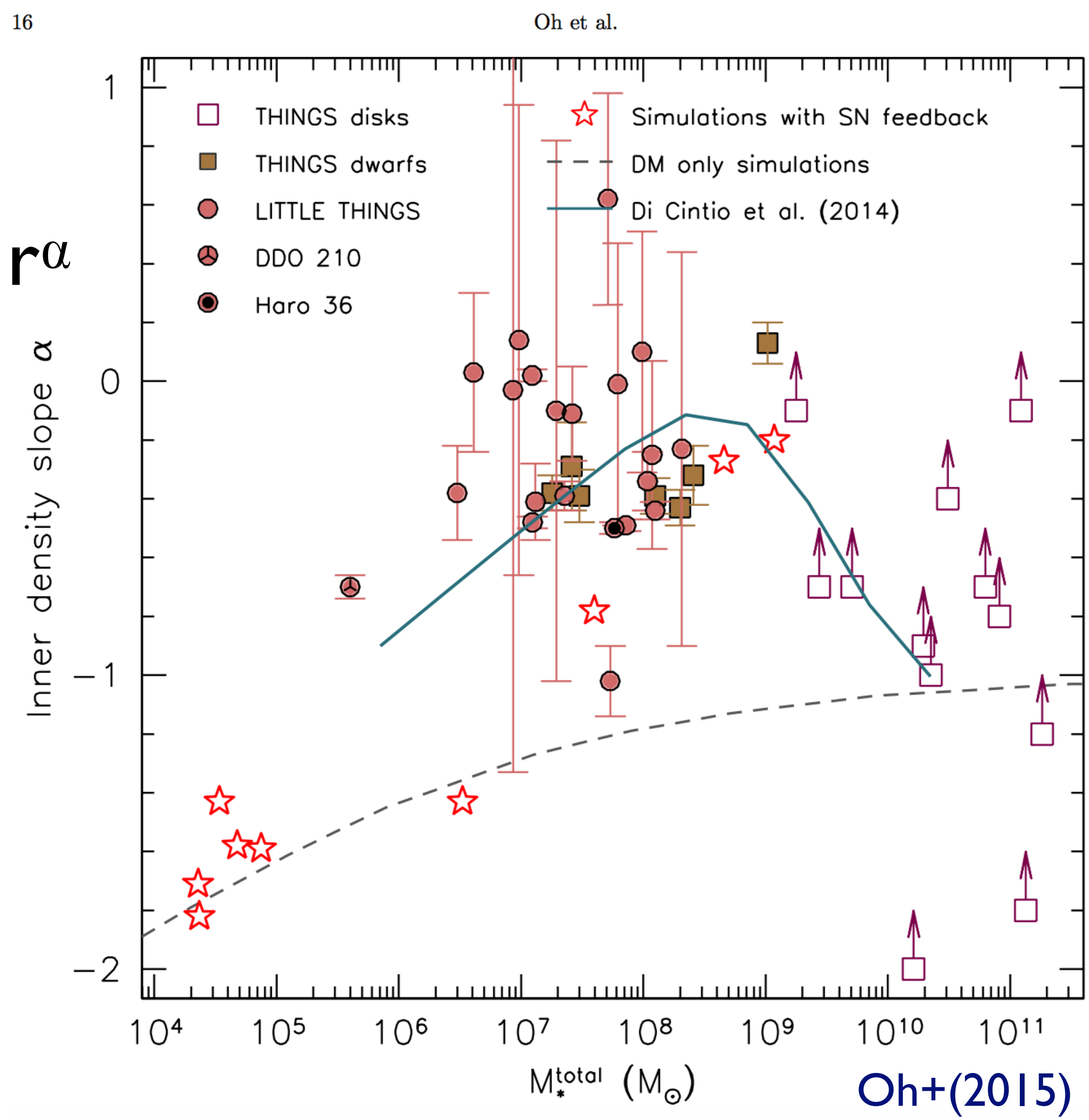
- not adiabatic
- gravitational binding energy VS. energy injection from supernovae
- only works $r<r_*$

Navarro, Eke, Frenk (1996)

Governato+ (2012), Di Cintio+(2014), Wetzel+(2016)

Baryon Physics

- Violent baryonic feedback process



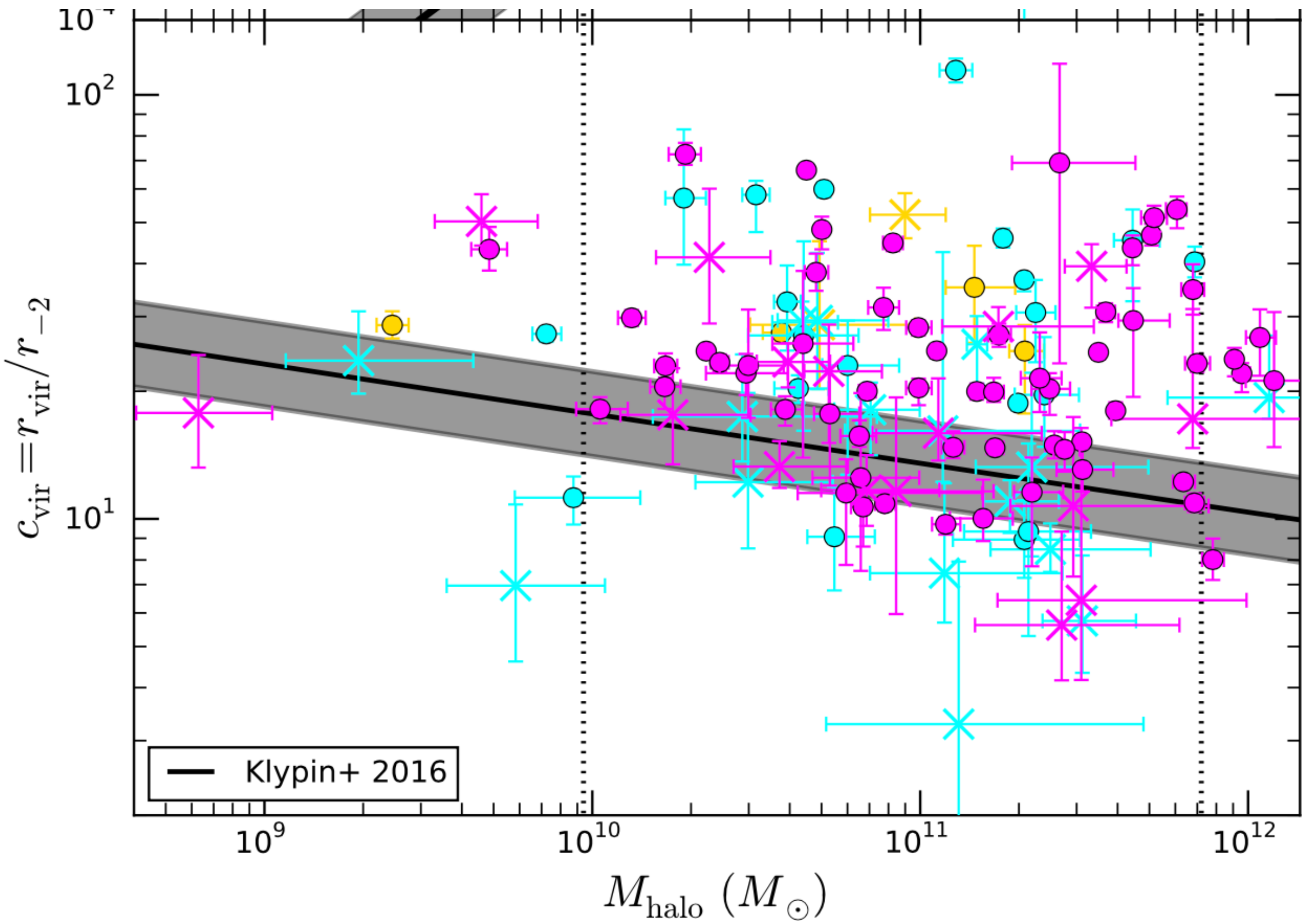
Oh+(2015)

α is a function of the halo mass and stellar mass

Governato+ (2012)
Di Cintio+(2014)

Baryon Physics

- Consistency with the prediction from ΛCDM cosmology?



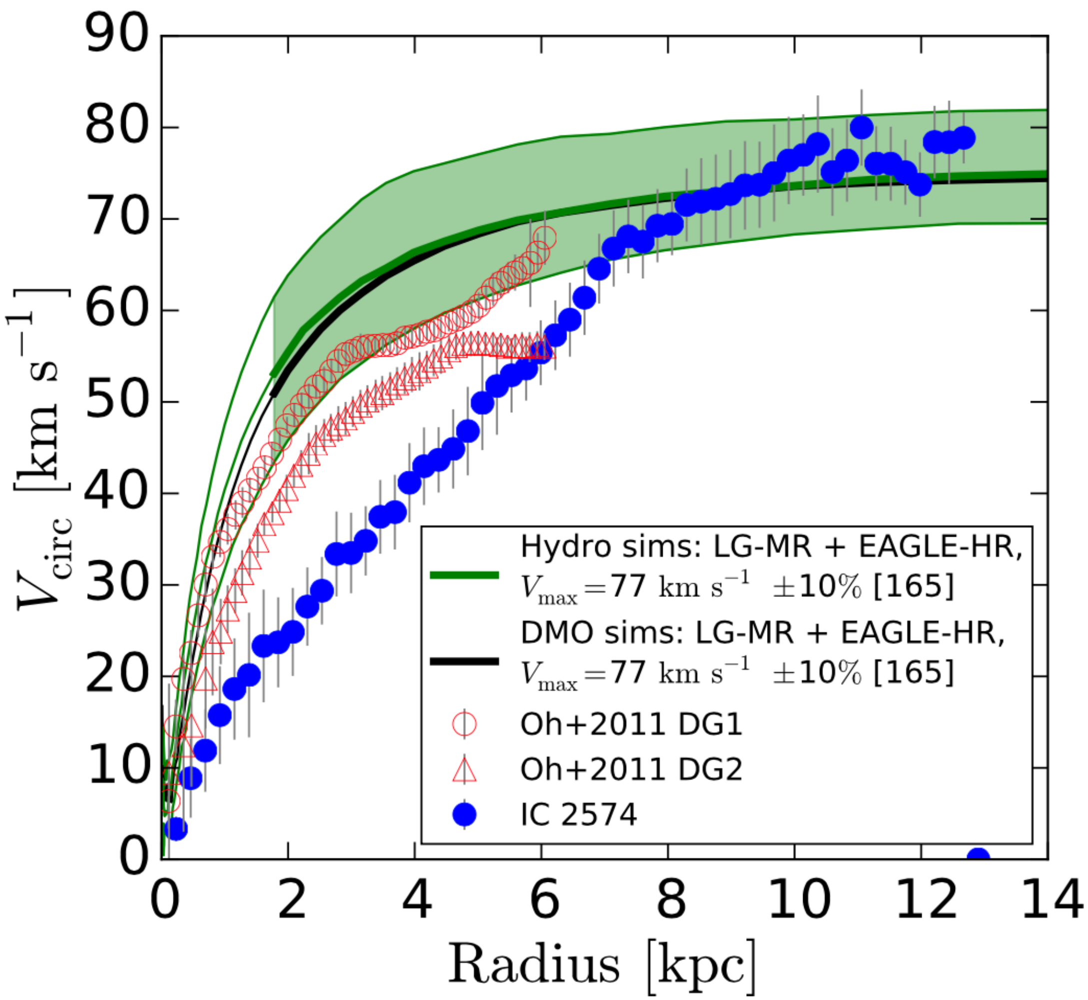
Fit to ~100 galaxies
get CDM parameters (ρ_s, r_s)
or (halo mass, concentration)

ρ_s-r_s correlation

Pace (2016)

but see Katz+(2016)

Baryon Physics



Depends on the recipe of hydrodynamical simulations!

EAGLE simulations did not see any effect at all (the NFW group)

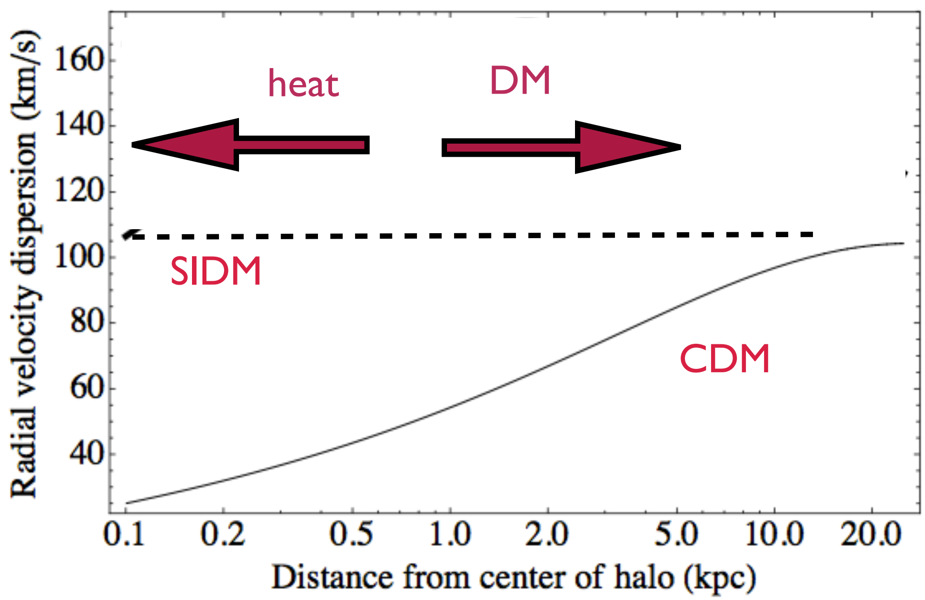
We are still debating!

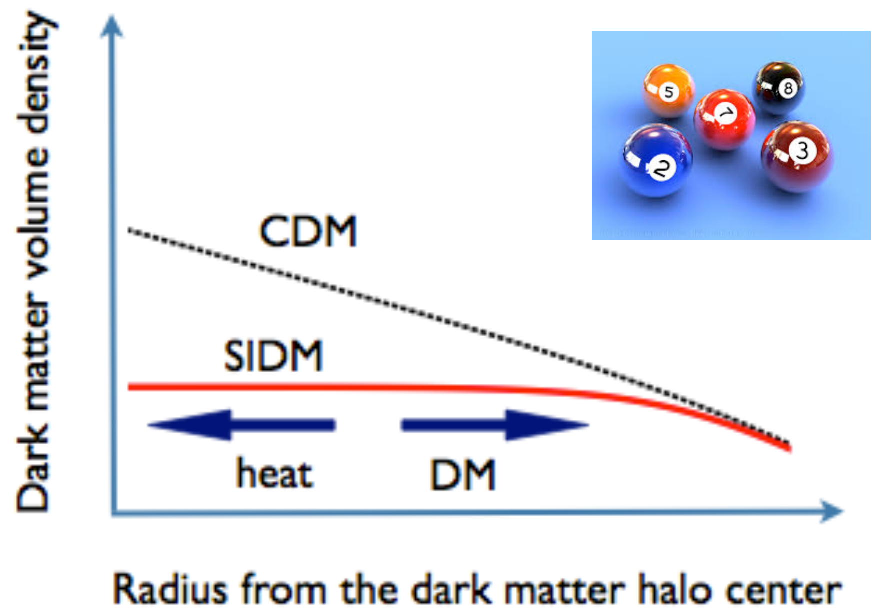
Oman+ (2015)

Dark Matter Physics

- Self-interactions can reduce the central DM density

Spergel, Steinhardt (2000)





$\sigma/m_X \sim 1\ \mathrm{cm^2/g}$ for $v \sim 40\text{-}100$ km/s

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

Challenges

- A really large scattering cross section!

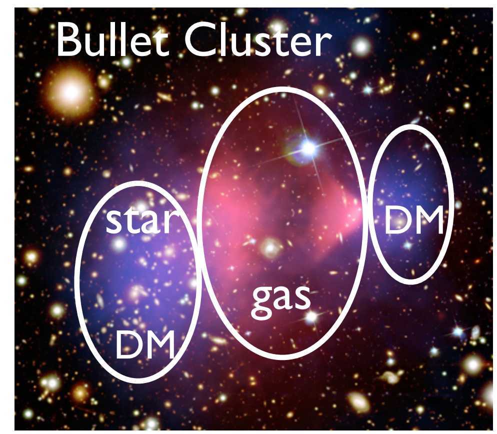
a nuclear-scale cross section

$\sigma \sim 1 cm^2 (m_X/g) \sim 2\times10^{-24} cm^2 (m_X/GeV)$

For a WIMP: $\sigma \sim 10^{-38} cm^2 (m_X/100 GeV)$

SIDM indicates a new mass scale

- How to avoid the constraints on large scales?



$\sigma/m_X < 2 cm^2/g$ for 3000 km/s (Bullet cluster)

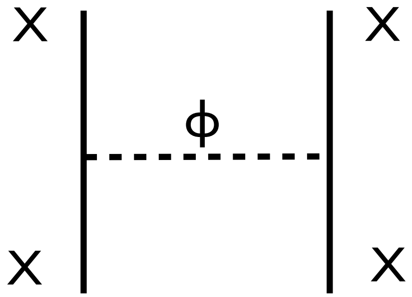
Robertson+(2016)

$\sigma/m_X <$ 0.1 cm^2/g for 1500 km/s (stellar kinematics)

Kaplinghat, Tulin, HBY (2015)

In particular, if $\sigma\sim$constant

SIDM Particle Physics

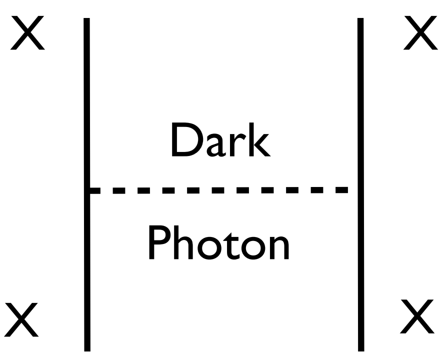


- SIDM indicates light mediators

$$\sigma \approx 5 \times 10^{-23}\,\mathrm{cm}^2 \left(\frac{\alpha_X}{0.01}\right)^2 \left(\frac{m_X}{10\,\mathrm{GeV}}\right)^2 \left(\frac{10\,\mathrm{MeV}}{m_\phi}\right)^4$$

in the perturbative and small velocity limit

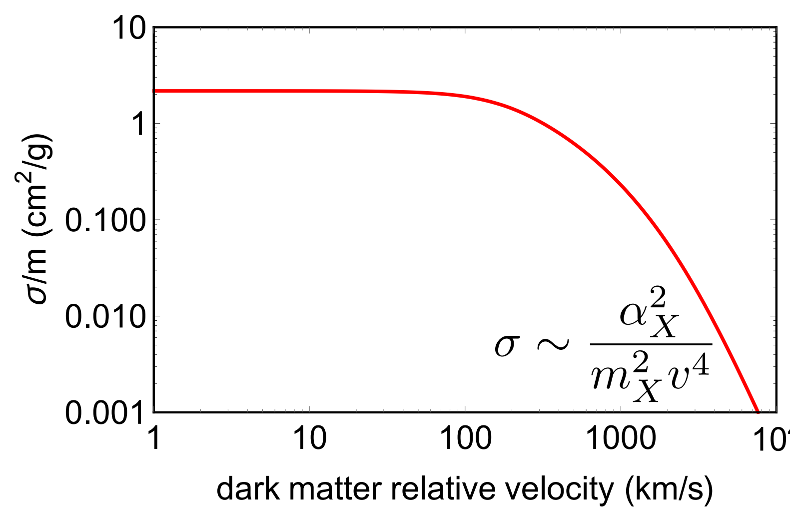
- With a light mediator, DM self-scattering is velocity-dependent



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

$m_X v >> m_\phi$ Rutherford limit

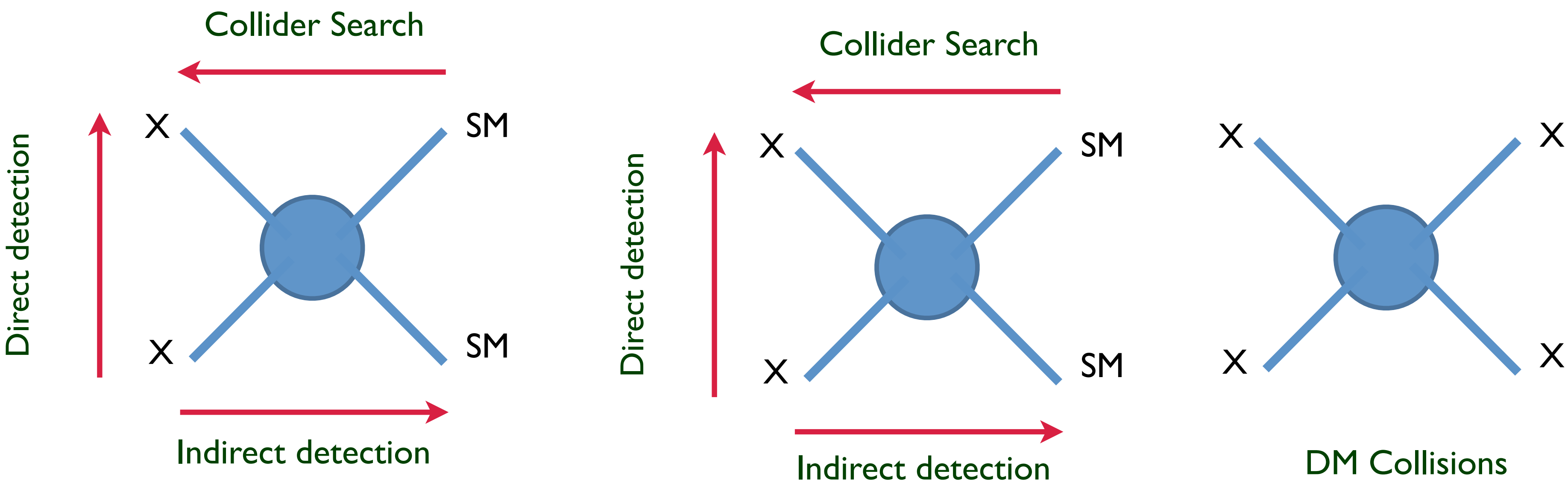
$m_X v << m_\phi$ contact interaction



Feng, Kaplinghat, HBY (2009); Buckley, Fox (2009); Loeb, Weiner (2010); Tulin, HBY, Zurek (2012) (2013)

The SIDM Paradigm

- The SIDM paradigm is predictive

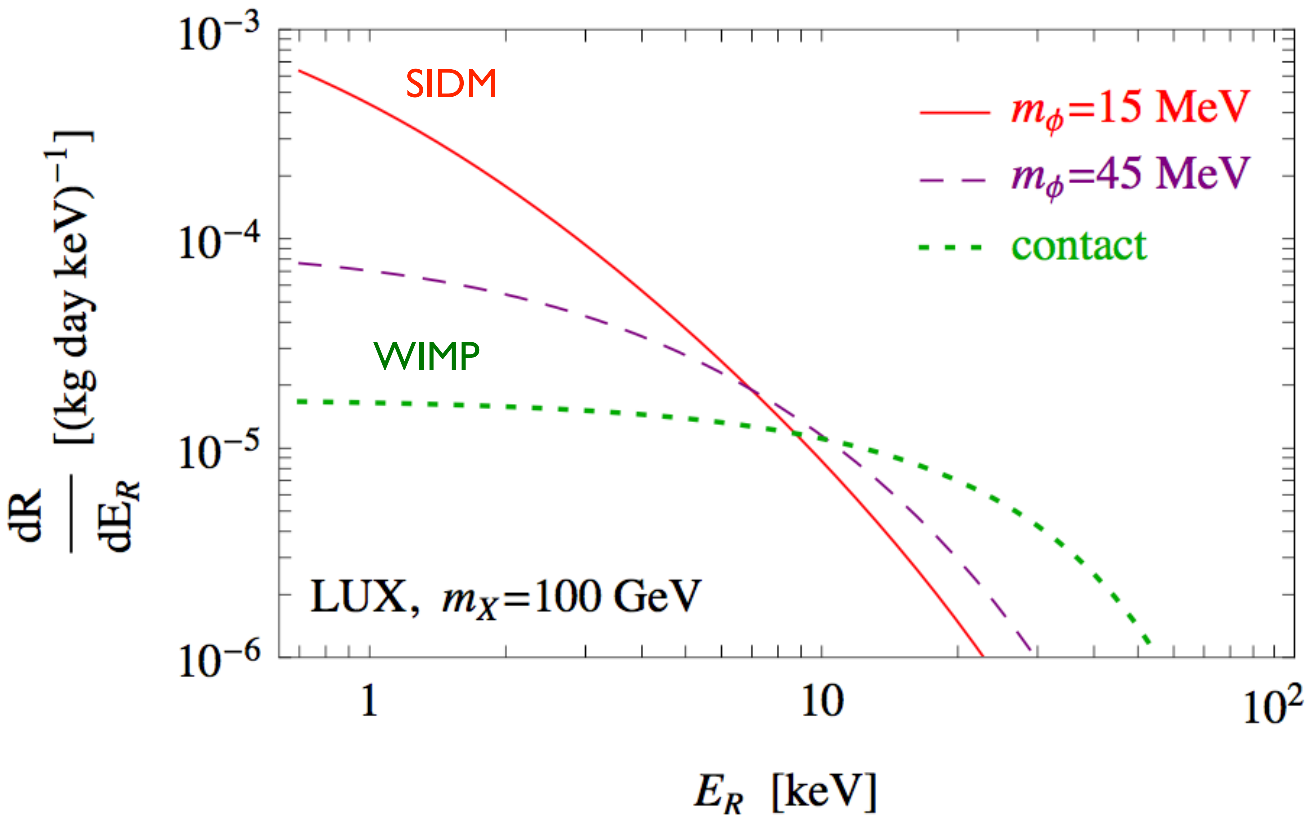


the WIMP paradigm

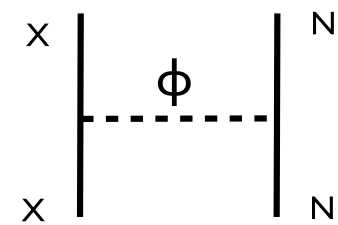
the SIDM paradigm

SIDM Direct Detection

- Characteristic signal spectrum



Del Nobile, Kaplinghat, HBY (JCAP 2015)



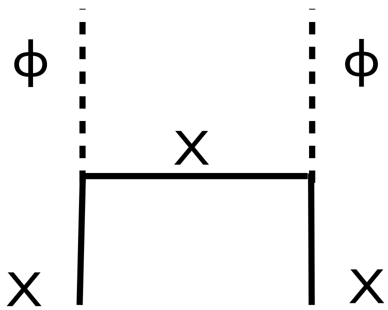
$$\frac{d\sigma}{dq^2} = \frac{4\pi\alpha_{em}\alpha_X\epsilon^2 Z^2}{(q^2+m_\phi^2)^2 v^2}$$

$$q^2 = 2m_N E_R$$

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

SIDM Indirect Detection

- Lighting up the galactic center, but not dwarf galaxies!

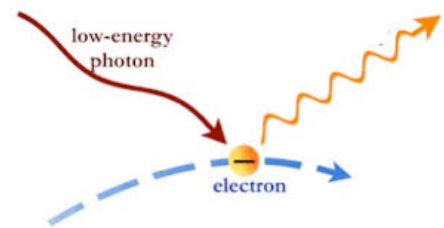


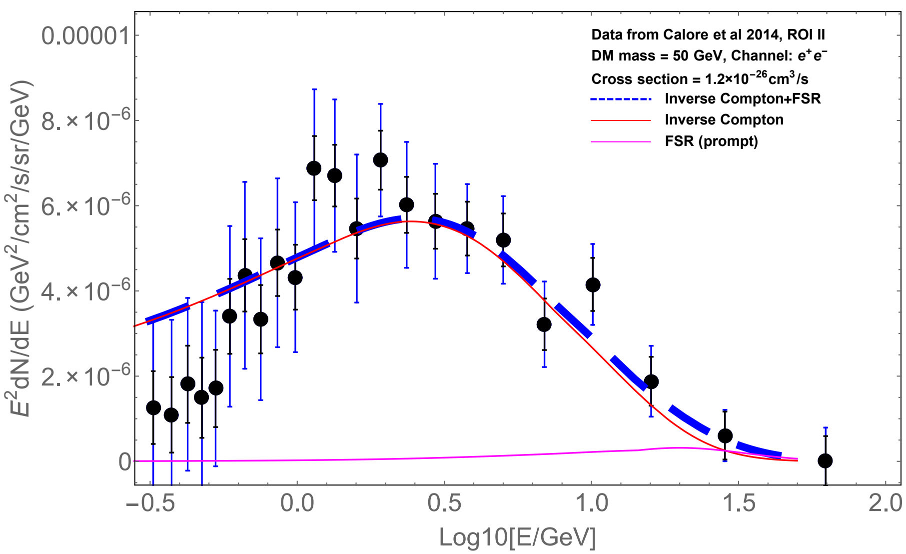
$m_\phi \sim 10$ MeV

$\phi \rightarrow$ electrons/neutrinos

Inverse Compton scattering

starlight





Kaplinghat, Linden, HBY (PRL 2015)

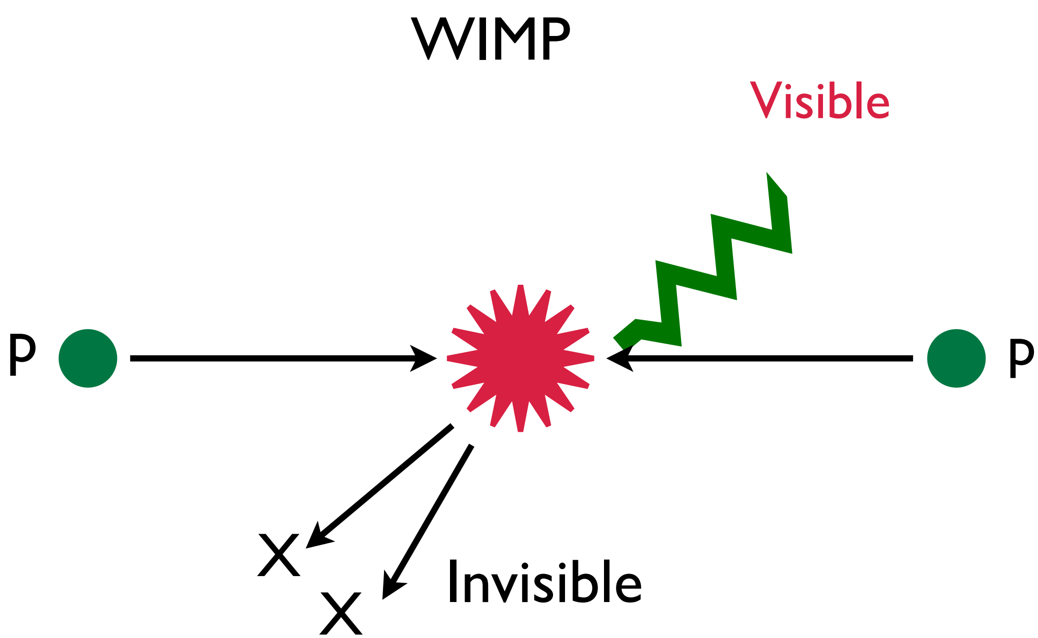
$$\sim (20\ \mathrm{GeV}/m_e)^2 E_{\mathrm{ISRF}}$$

$$E_{\mathrm{ISRF}} \sim 1\ \mathrm{eV}$$

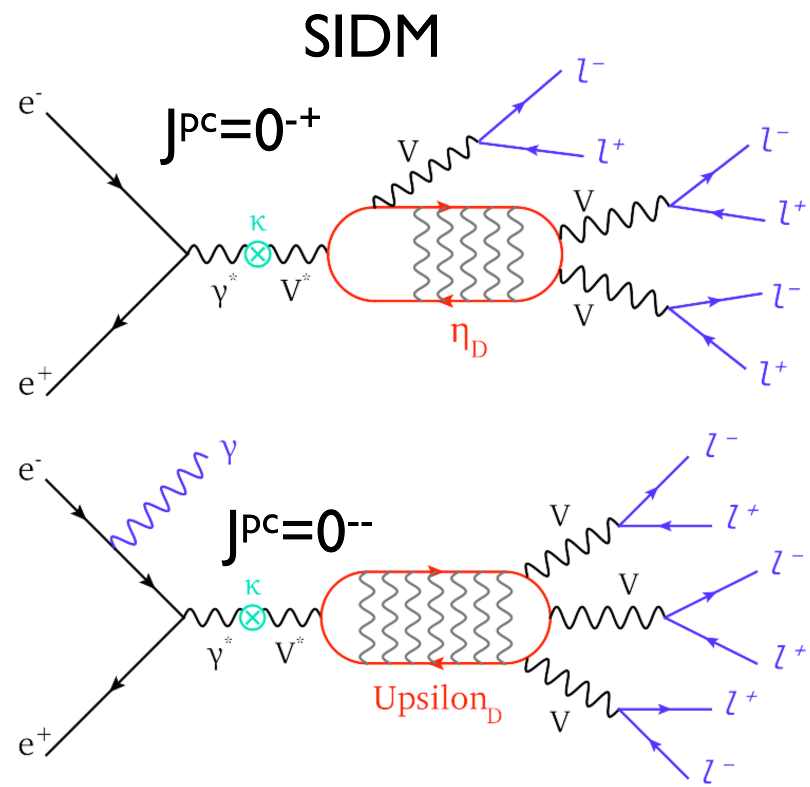
- No IC signal from dwarfs
- Soft electron spectrum (AMS02)
- The IC signal is spherically symmetric

SIDM at Colliders

- Striking collider signals



pp→Monojet+Missing Energy



An, Echenard, Pospelov, Zhang (PRL 2015)

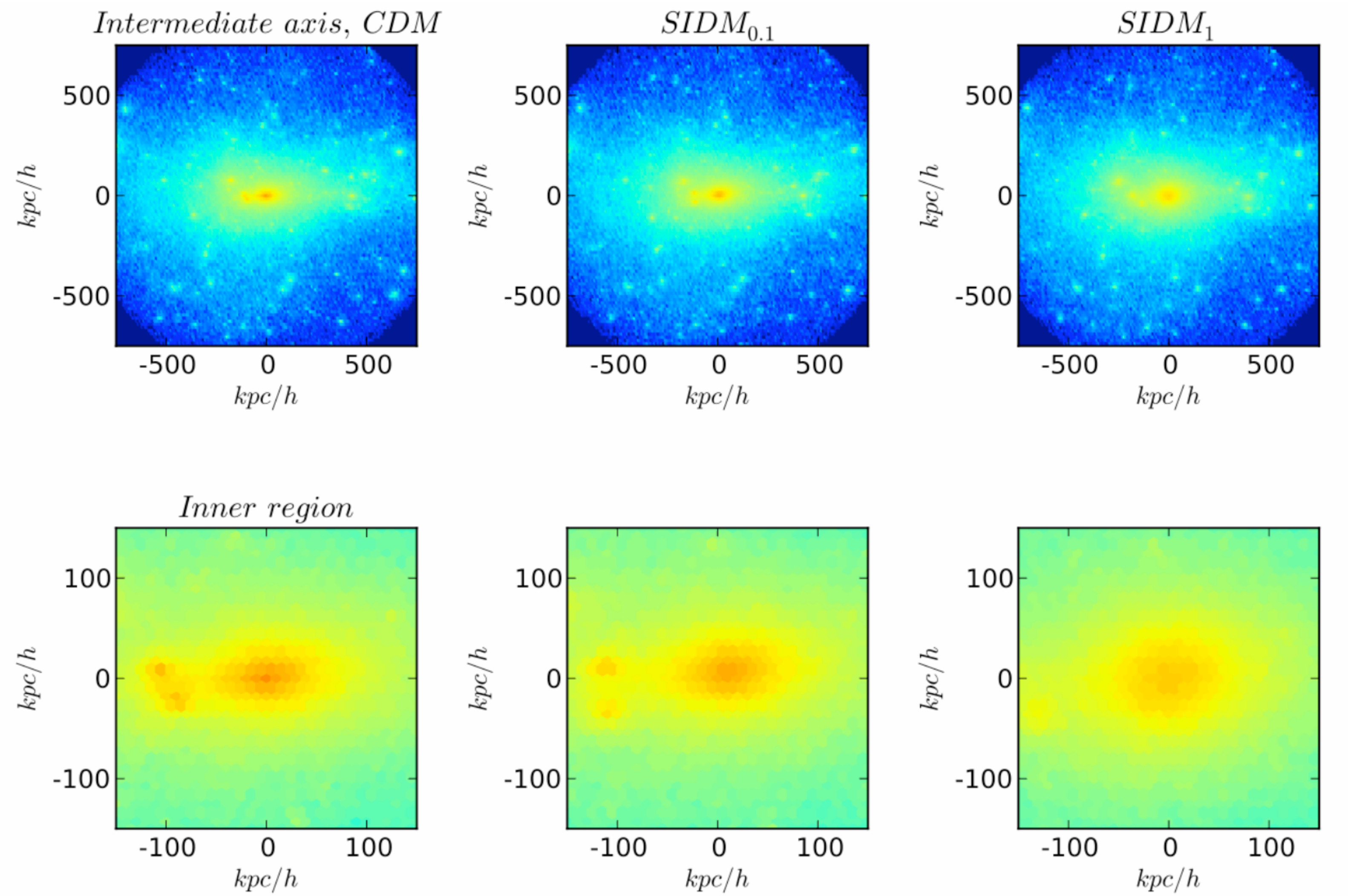
Tsai, Wang, Zhao (PRD 2015)

Shepherd, Tait, Zaharijas (PRD 2009)

Focus on smoking-gun signals, independent of DM-SM interactions

Idea1: Halo Morphology

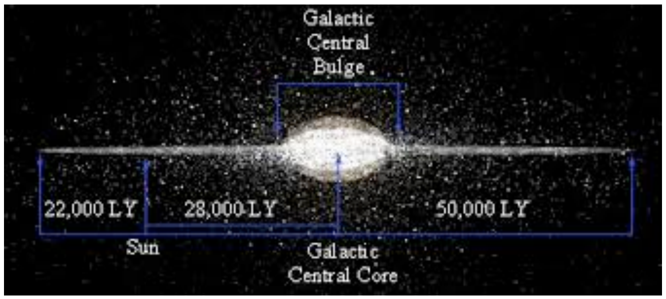
- SIDM halos are more spherically symmetric than CDM ones



Peter+(2013)

Tying SIDM to Baryons

- SIDM may follow the stellar distribution; halo morphology



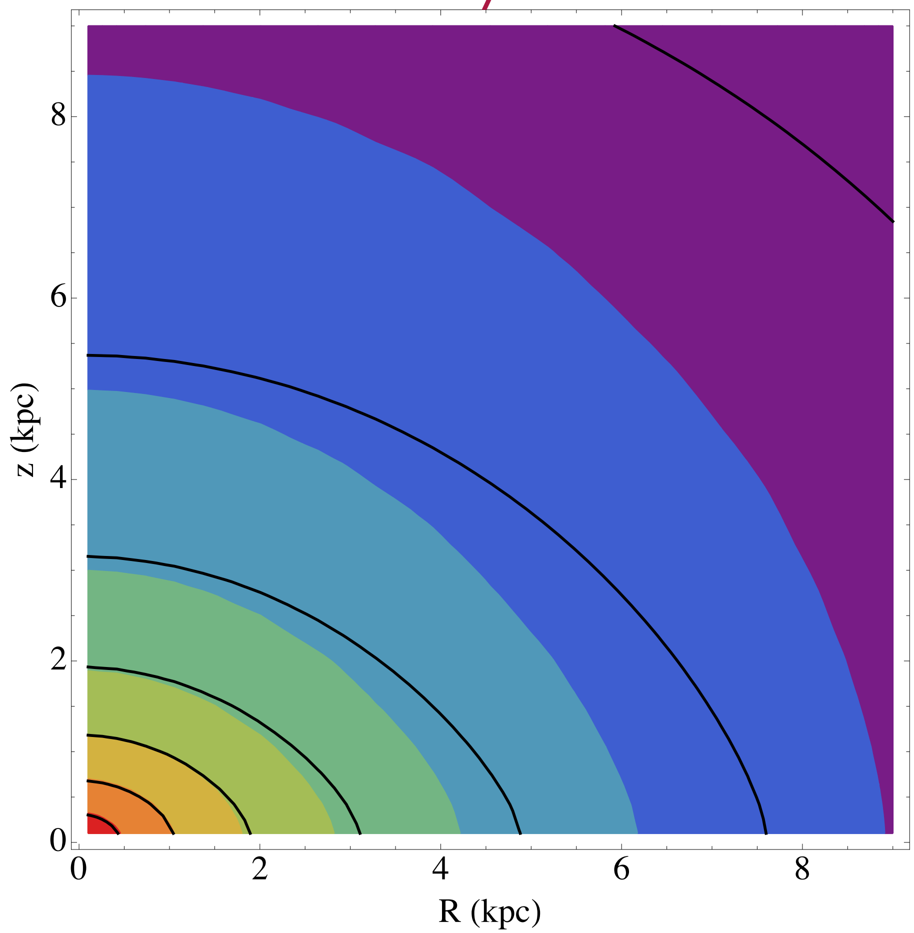
Maxwell distribution

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

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

$$\rho = \rho_0 e^{-\Phi_b/\sigma_0^2}$$

SIDM density contour

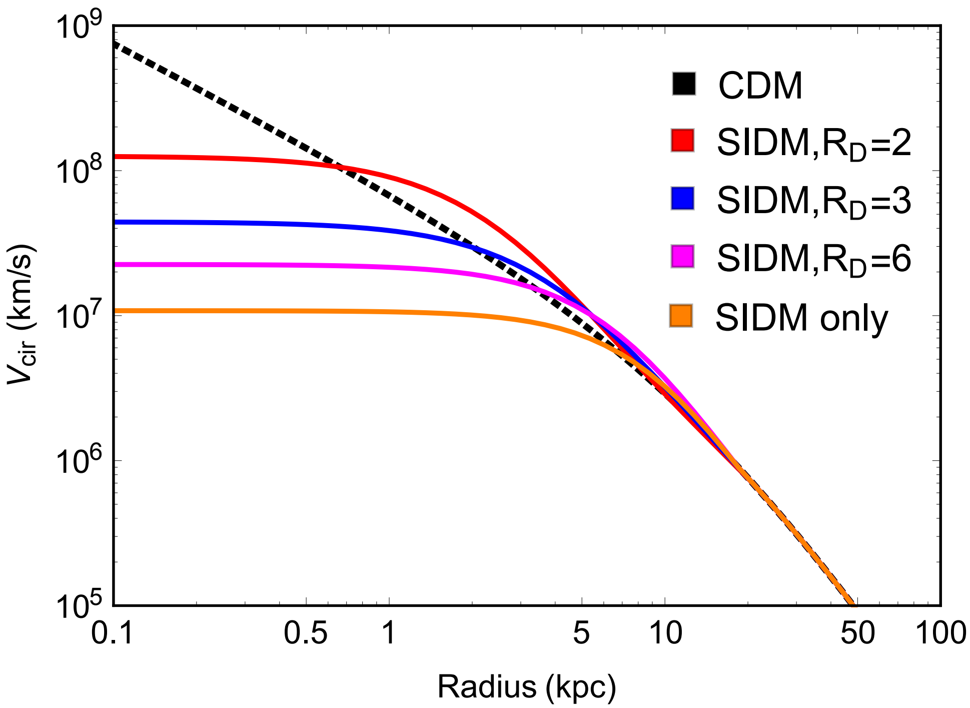


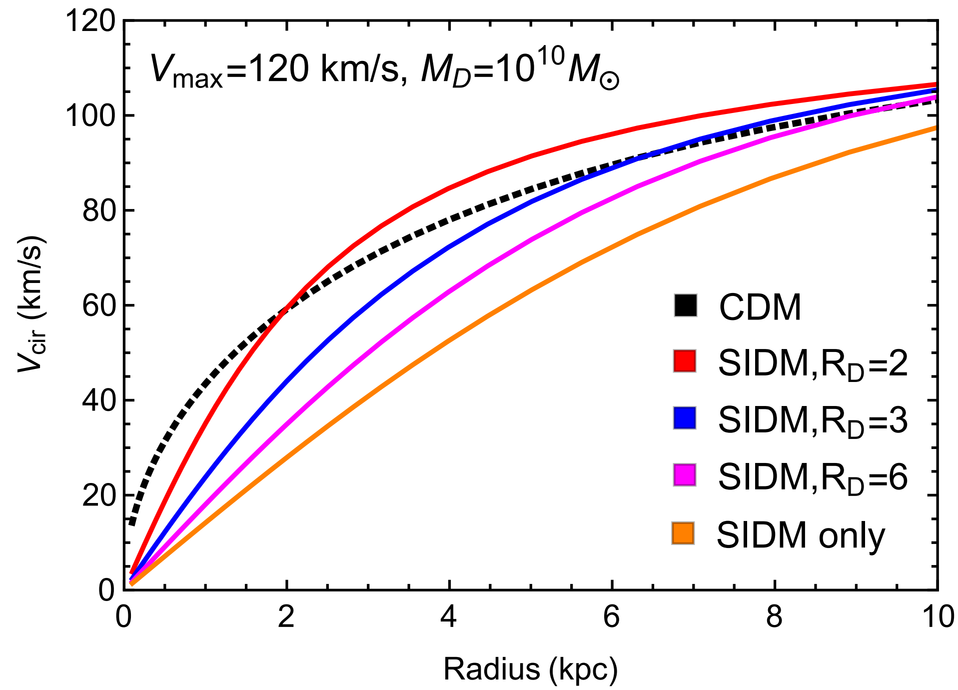
Correlation between the stellar distribution and the SIDM distribution

Kaplinghat, Linden, Keeley, HBY (PRL 2014)

Backreaction of Stellar Disk

- Spirals with only the stellar disk



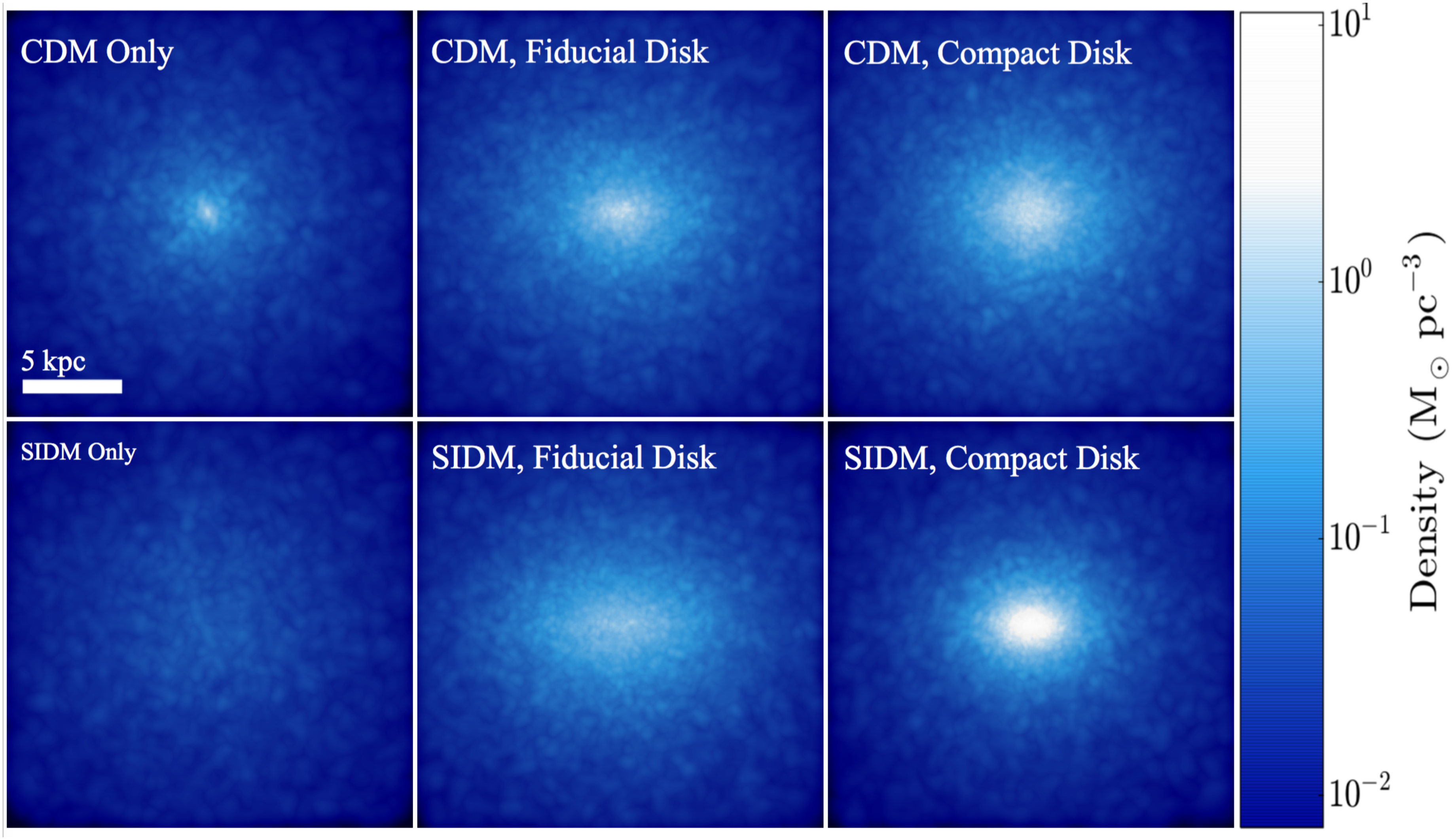


- Stellar disk could compress the SIDM halo profile
- The SIDM halo could be diverse, depending on the baryon concentration

Kamada, Kaplinghat, Pace, HBY (in prep)

Tying SIDM to Baryons

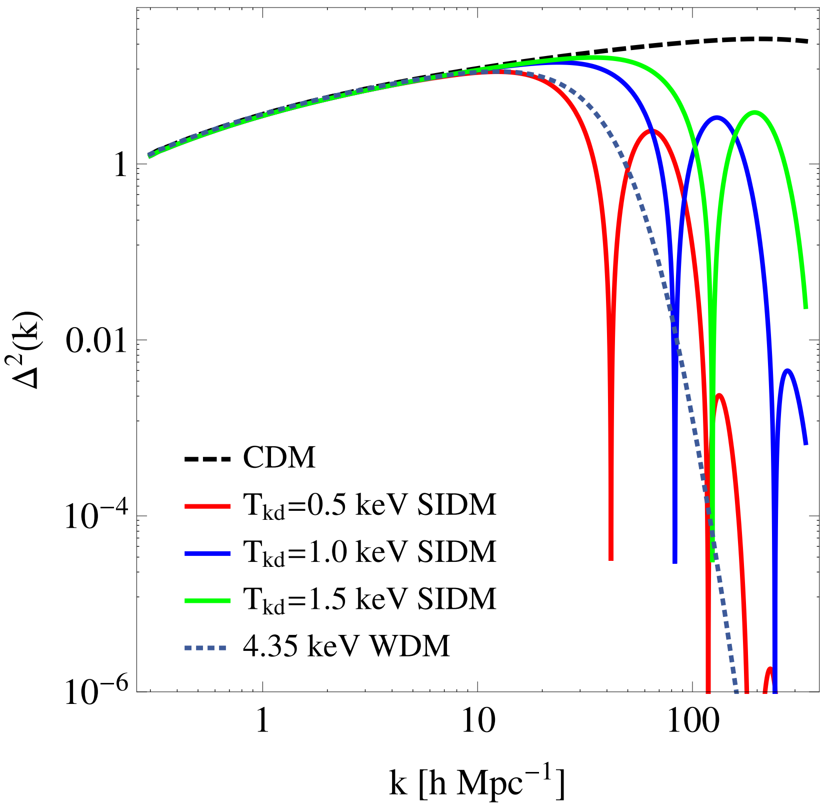
- Confirmed by simulations

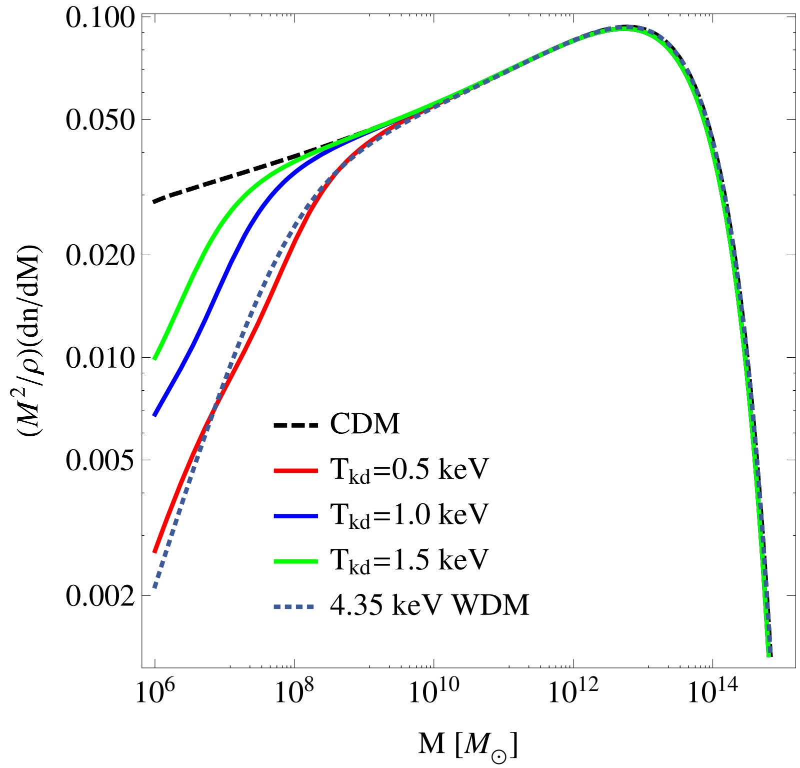


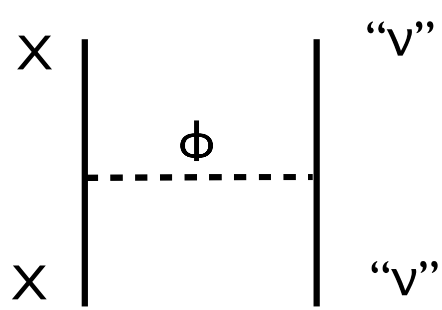
Elbert+ (2016)

Idea II: Dark Acoustic Oscillation

- Roles of dark radiation, damped SIDM power spectrum







Ran, Kaplinghat, HBY (in prep)

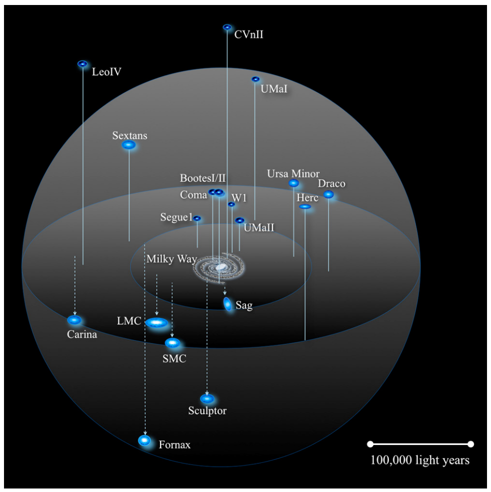
Feng, Kaplinghat, HBY (2009)

CDM (WIMP): m_ϕ~1 TeV, T_{kd}~30 MeV

SIDM: m_ϕ~10 MeV, T_{kd}~1 keV

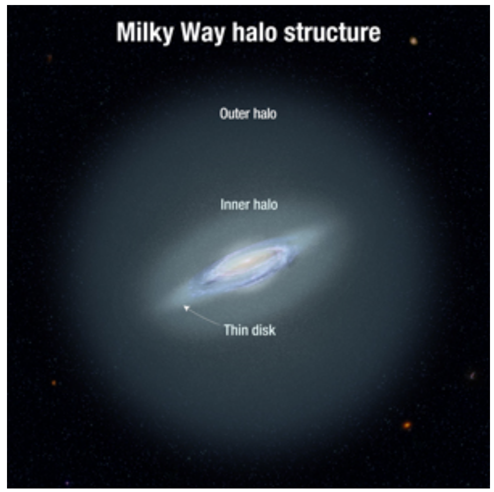
Idea III: Dark Matter "Colliders"

Dwarf galaxies



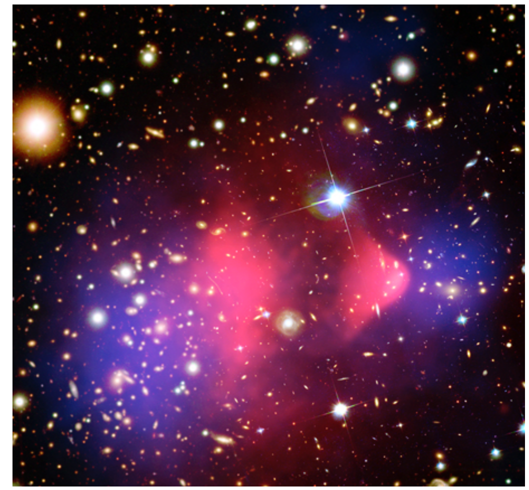
"B-factory" (v~30 km/s)

MW-size galaxies



"LEP" (v~200 km/s)

Clusters



"LHC" (v~1000 km/s)

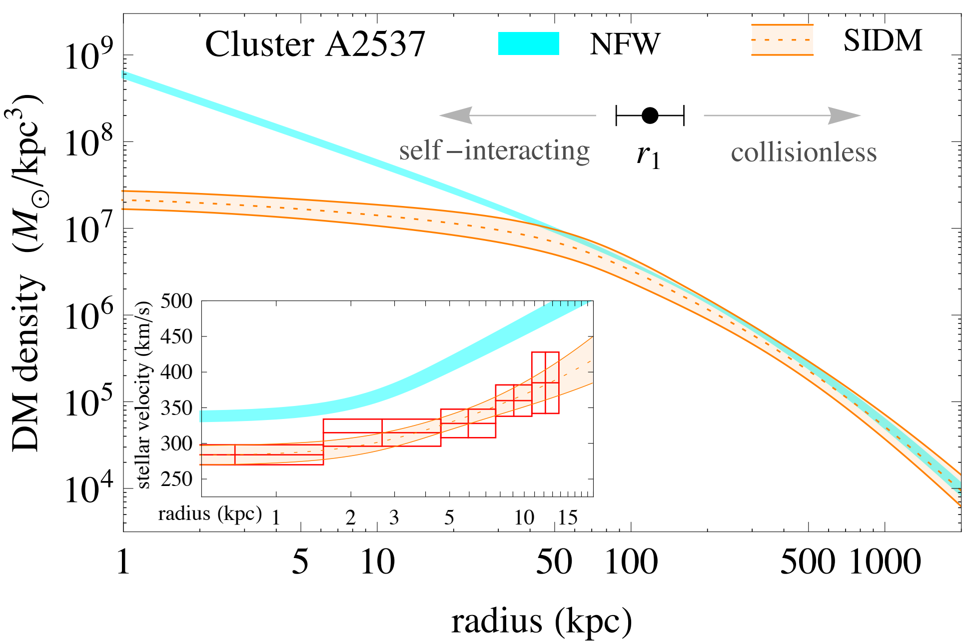
Self-scattering kinematics

Observations on all scales → Measure particle physics parameters

σ_x, m_x, g_x

Modelling SIDM Halos

- An analytical model based on simulations



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

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

Matching conditions:

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

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

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

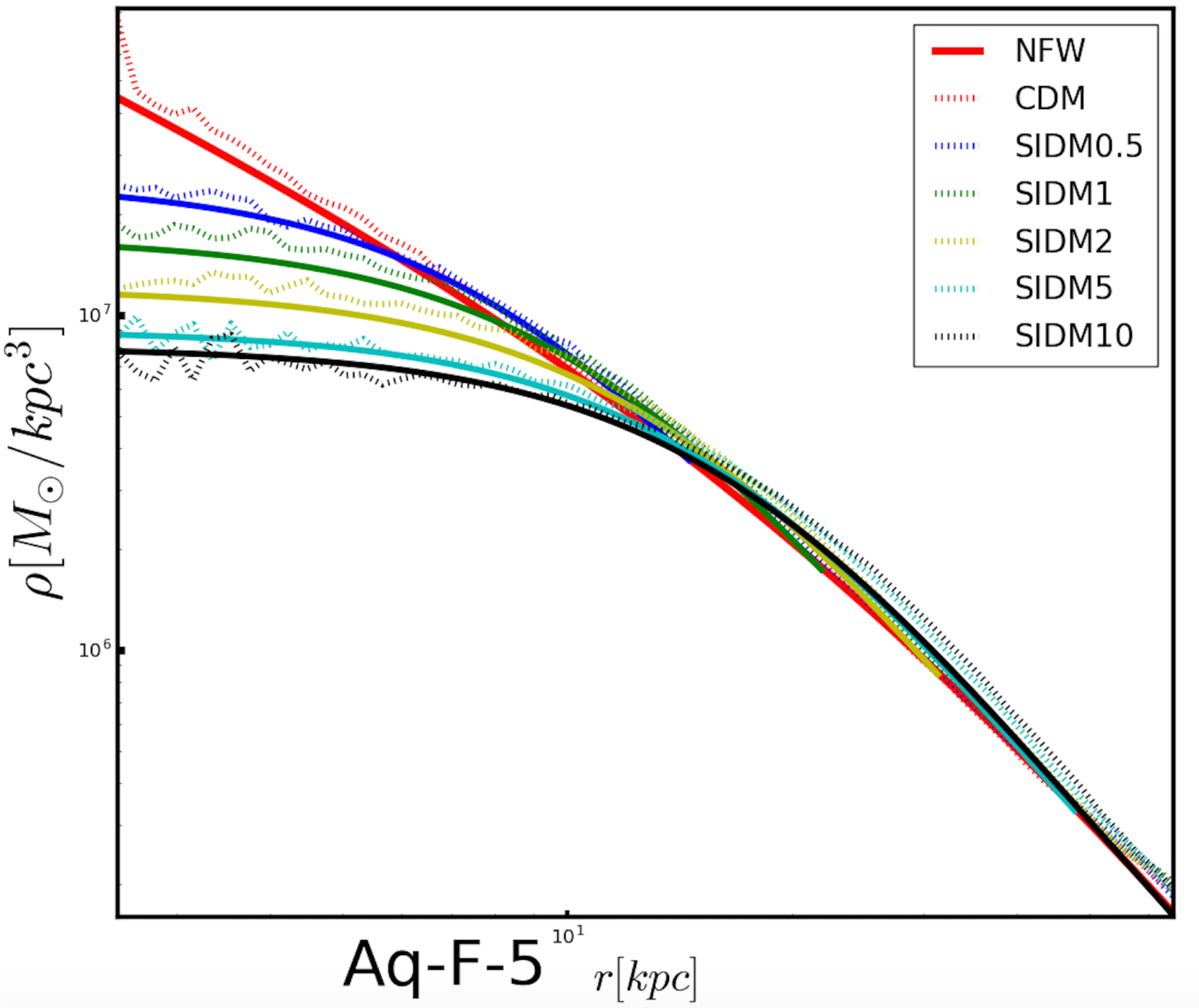
Maxwell distribution

NFW

Kaplinghat, Tulin, HBY (PRL 2015)

Modelling SIDM Halos

- This method works remarkably well



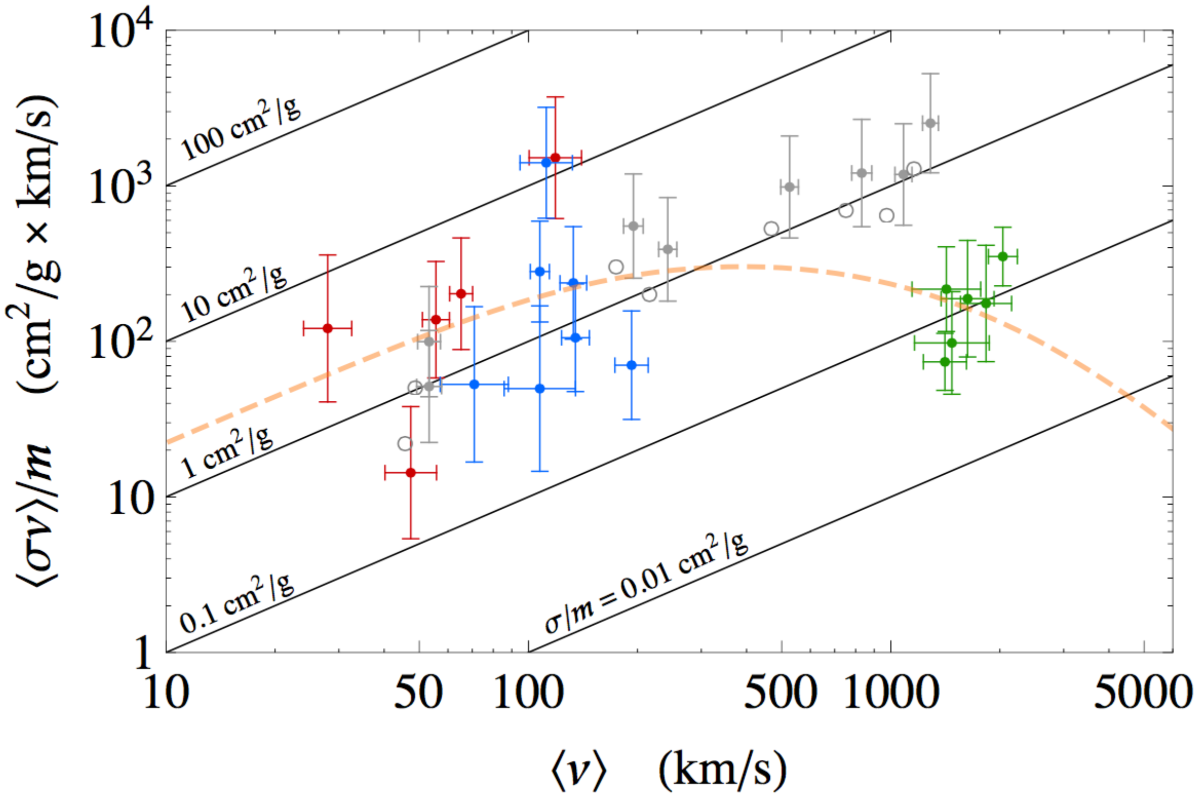
Solid: analytical modelling
Dotted: N-body simulations

The agreement is better than 5-10%

Figure: Omid Sameie

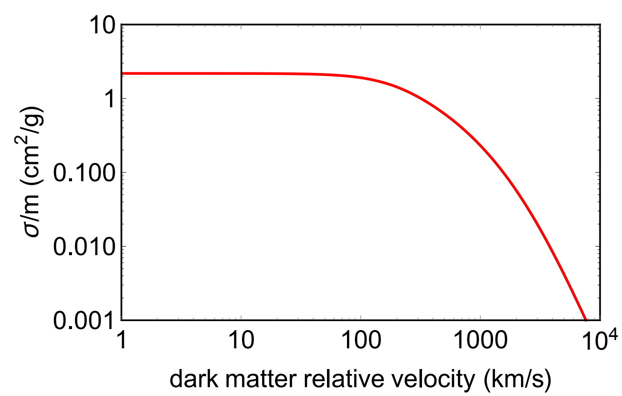
SIDM From Dwarfs to Clusters

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



Outliers:
Due to scatter in halo concentration

favors a mild v-dependence



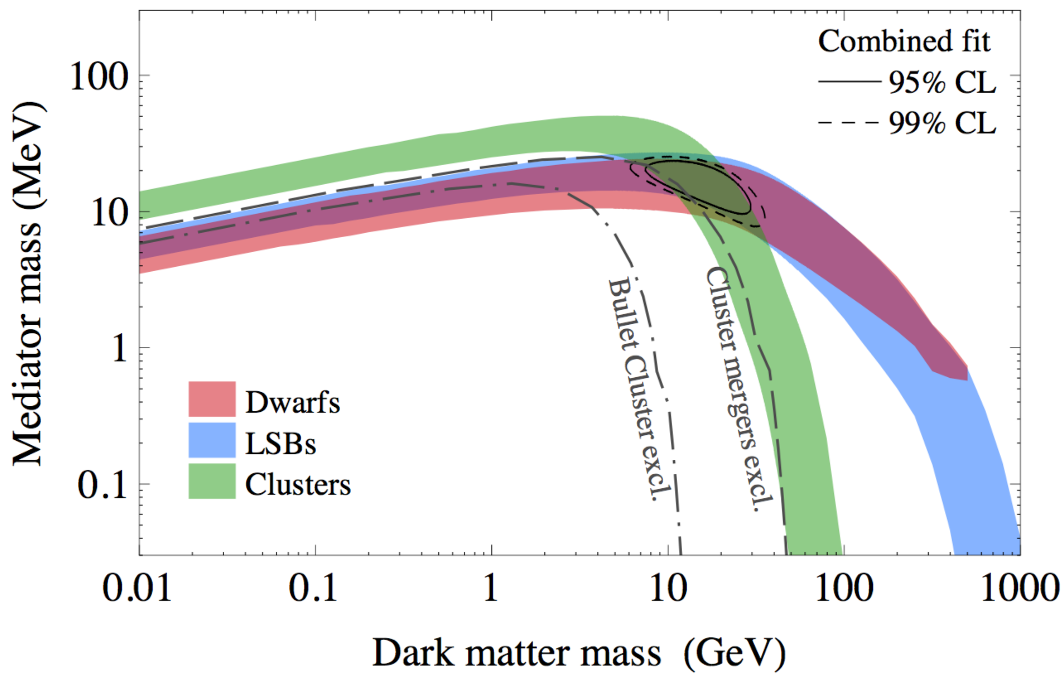
Galaxies: ~1–2 cm^2/g
Clusters: ~0.1 cm^2/g

Bullet Cluster: <1 cm^2/g

Kaplinghat, Tulin, HBY (PRL 2015)

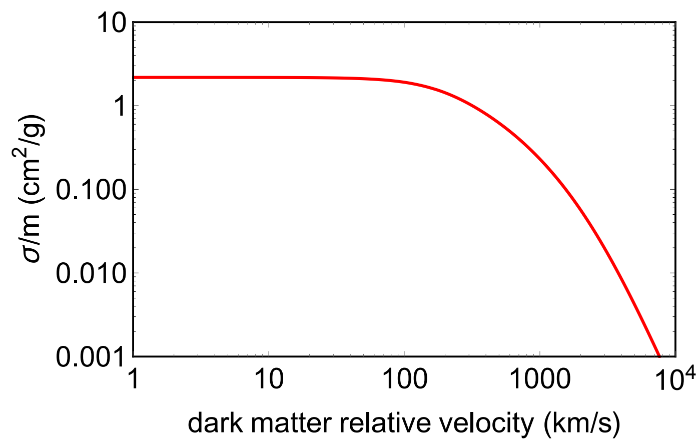
Measuring Dark Matter Mass

- Self-scattering kinematics determines SIDM mass



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

$m_X v$ VS. m_ϕ $10^{-3}\, m_X \sim m_\phi$



α_X=1/137

m_X: ~15 GeV, m_ϕ: ~17 MeV

without detecting DM directly

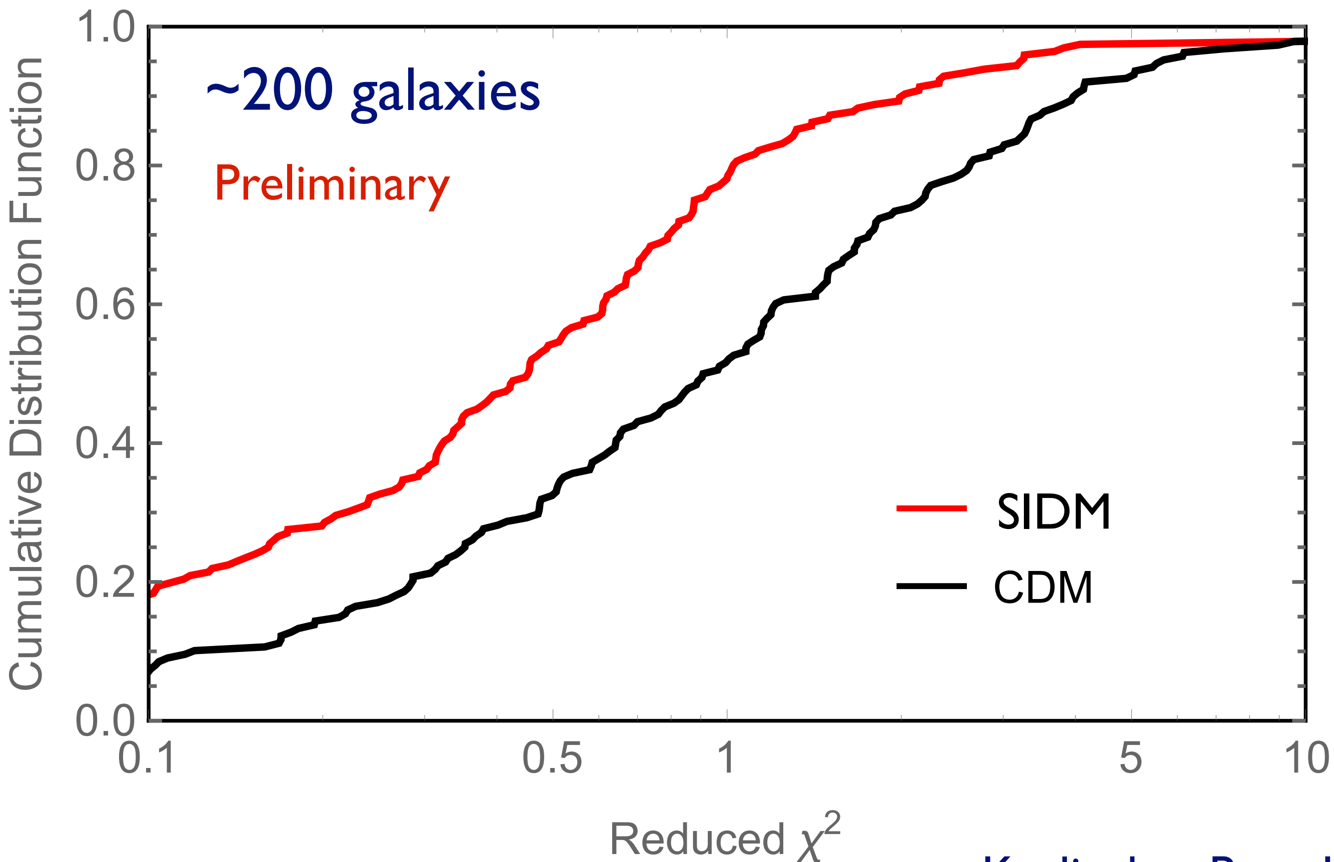
Kaplinghat, Tulin, HBY (PRL 2015)

mild dependence on α_X

α_X=0.001–0.1

m_X: ~5-30 GeV

More Galaxies…

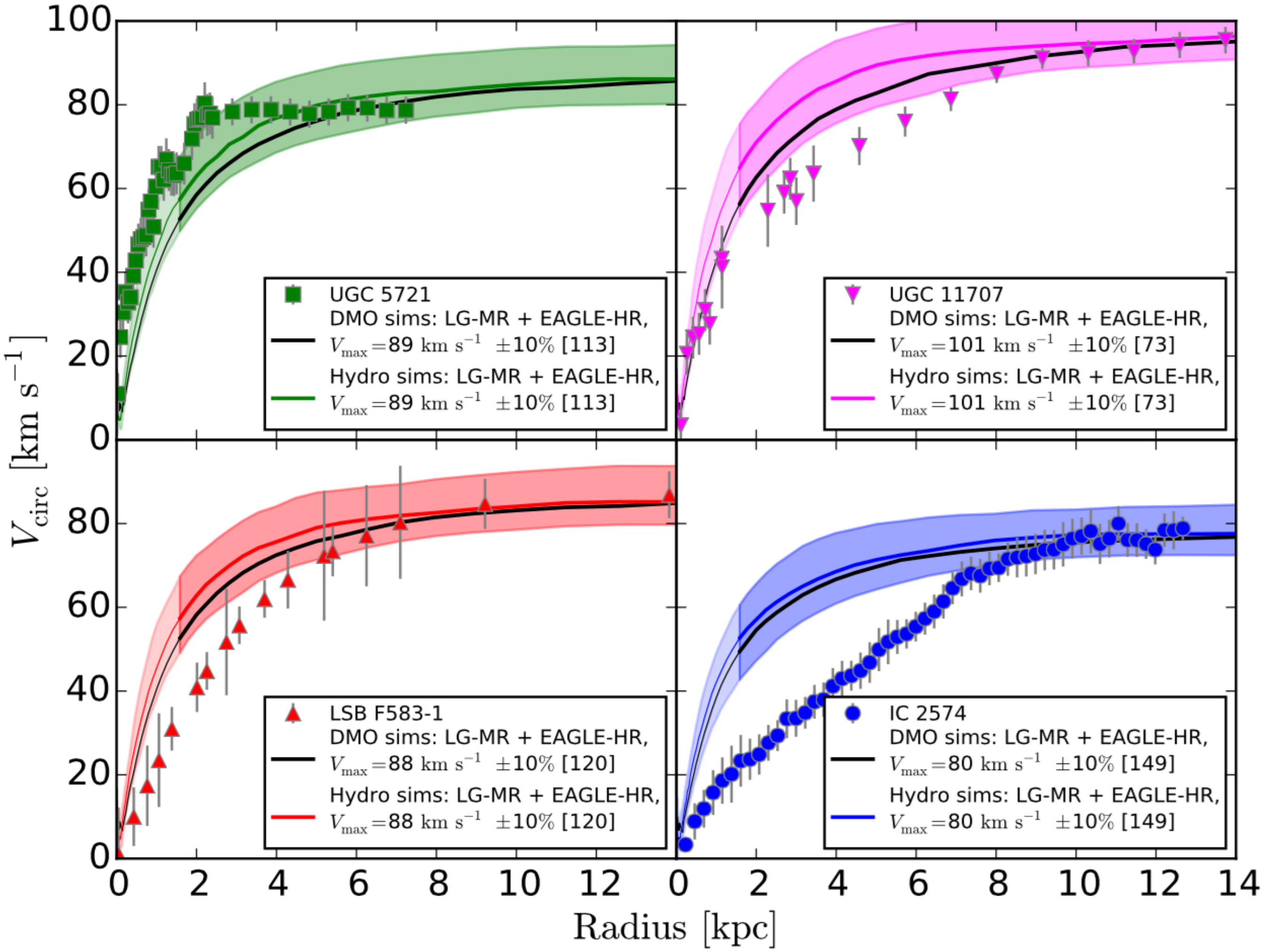


Kaplinghat, Pace, HBY (in prep)

SIDM is doing systematically better than CDM in explaining rotation curves of spiral galaxies

The Diversity Problem

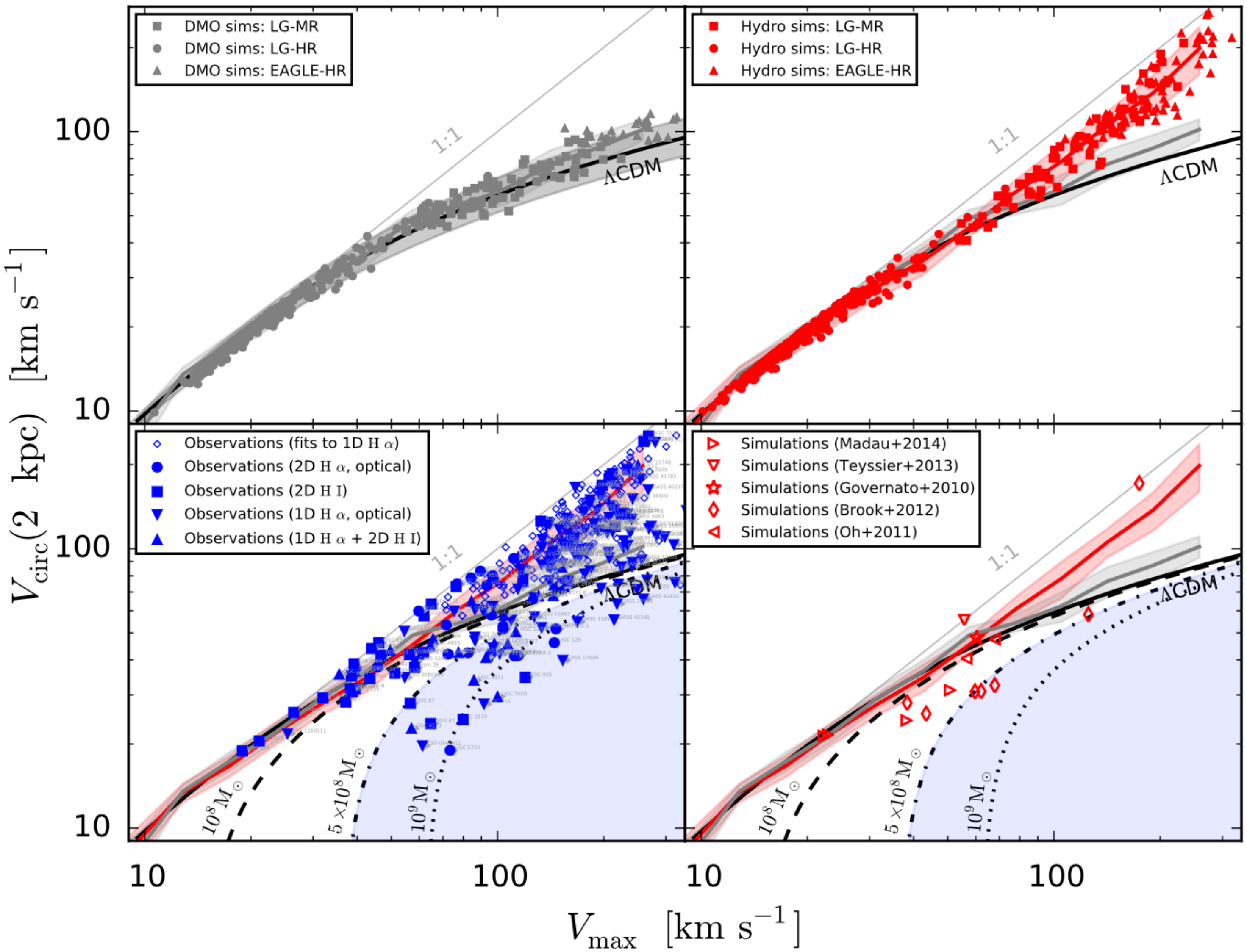
- Rotation curves of spirals are diverse



Oman+ (2015) (the NFW group)

de Naray, Martinez, Bullock, Kaplinghat (2009)

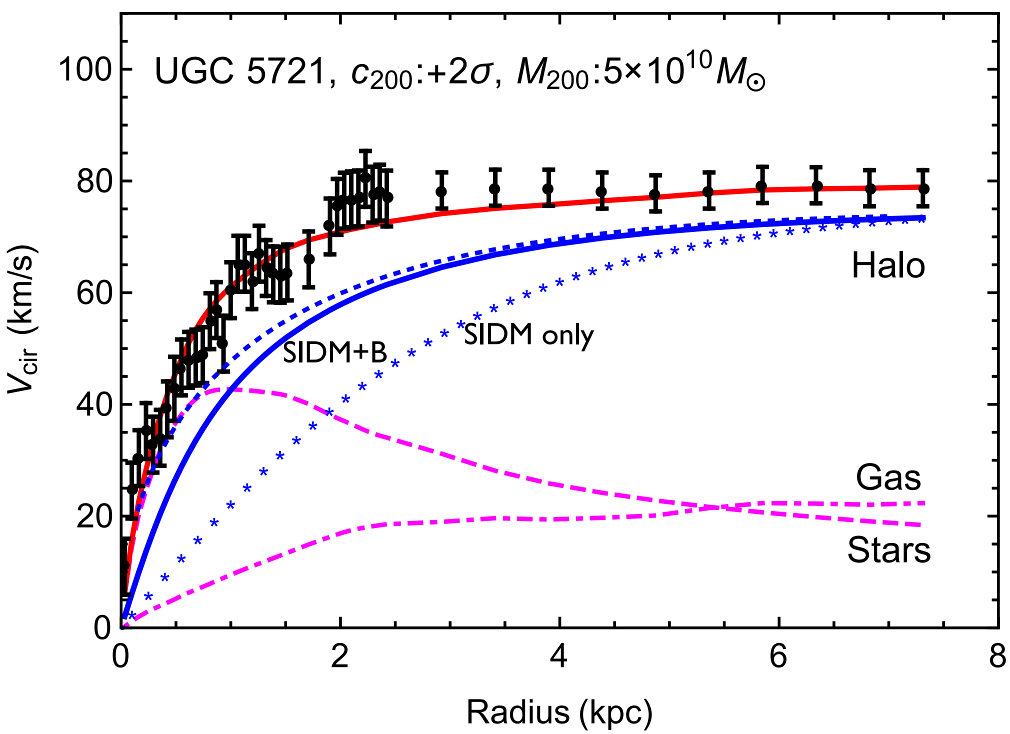
The Diversity Problem

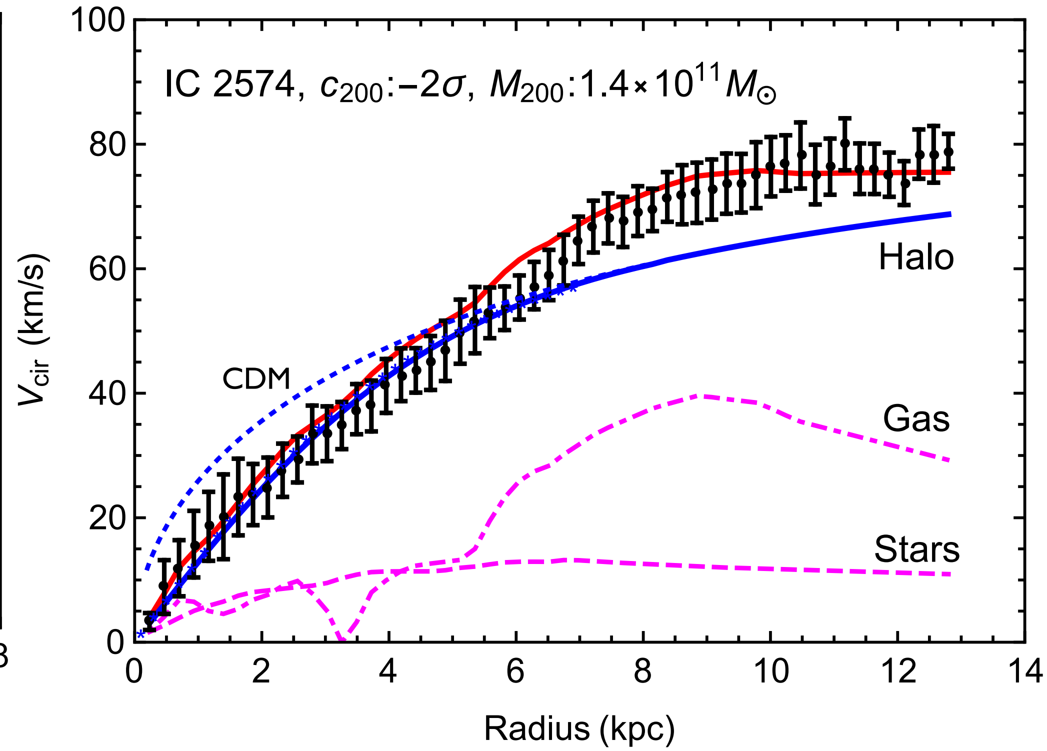


EAGLE simulations (the NFW group) Oman+ (2015)

SIDM+Baryons

- Solving the diversity problem with SIDM

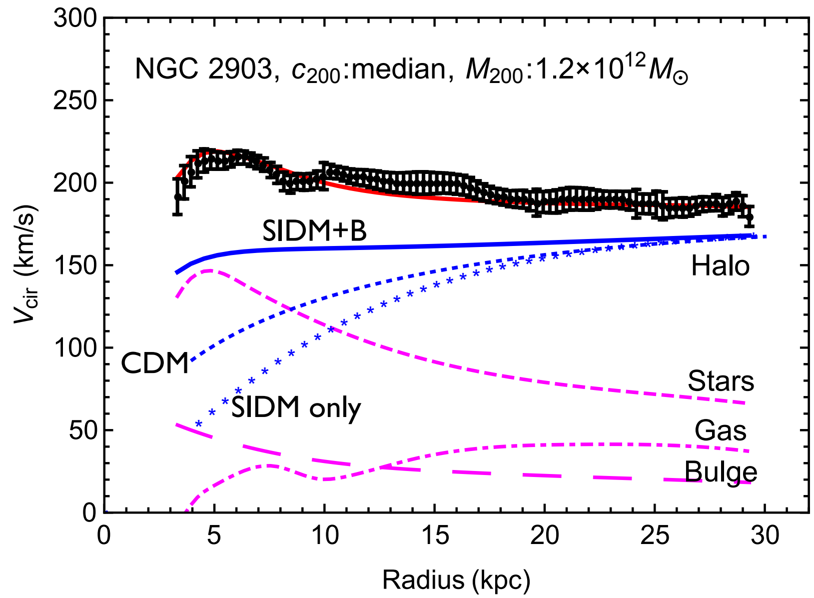


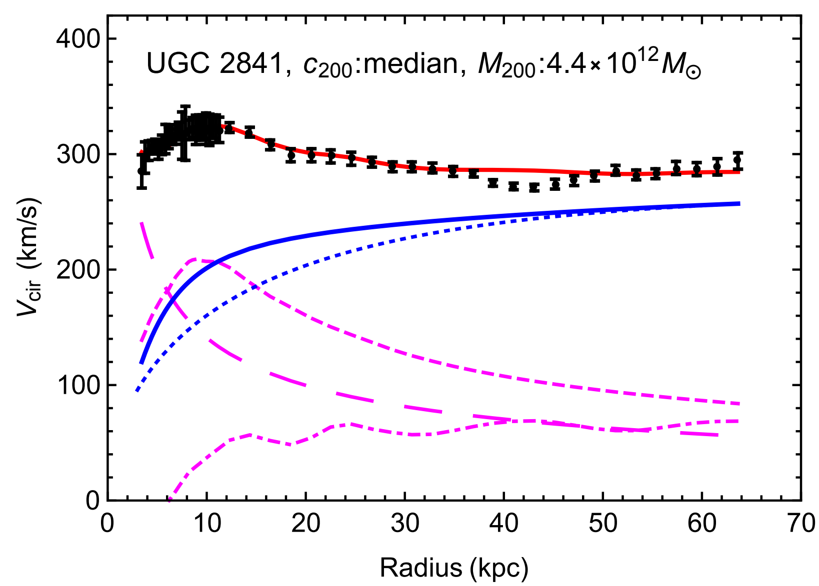


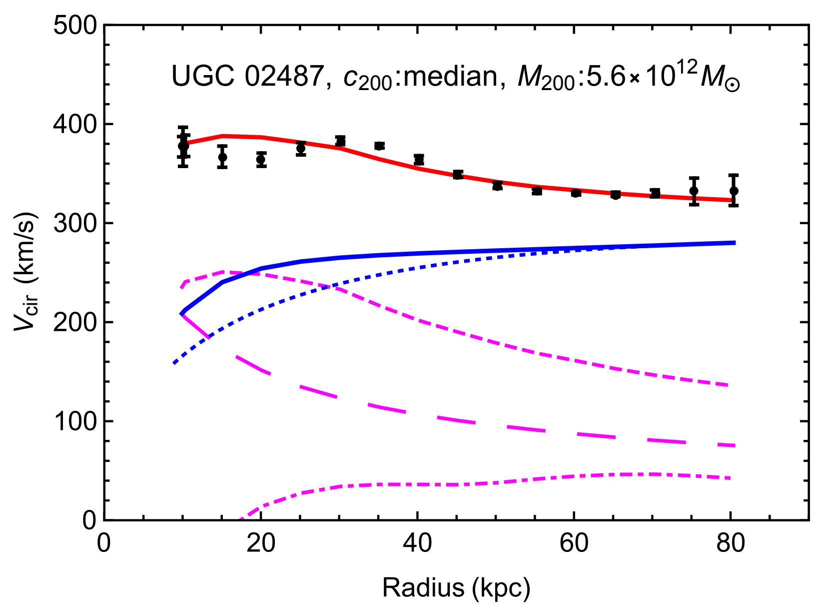
- self-interactions generate cores
- scatter in halo concentration
- baryon distribution
- baryon compression effect on the SIDM halo

Kamada, Kaplinghat, Pace, HBY (in prep)

Very Massive Spirals

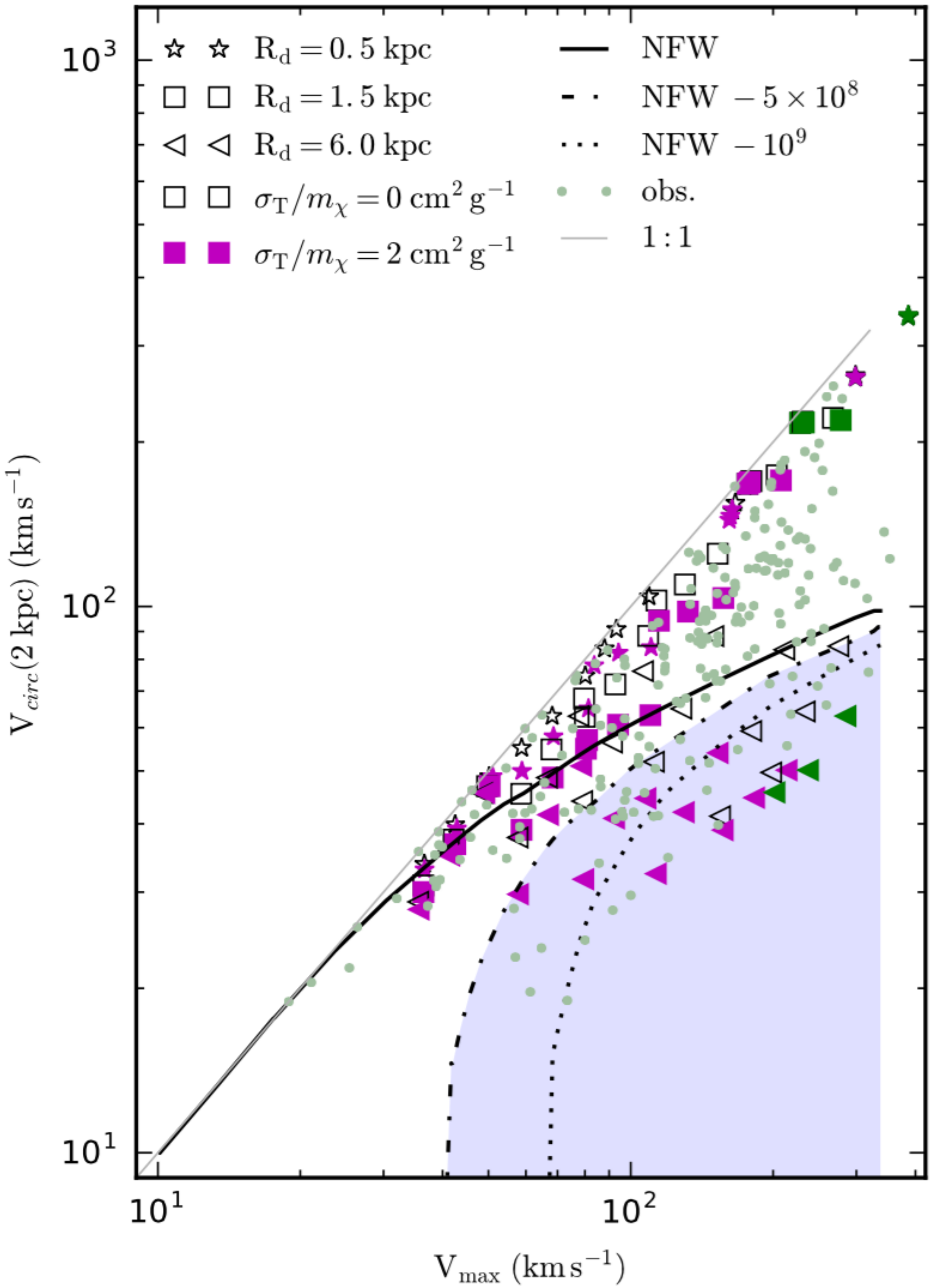






Naturally explain "disk-halo conspiracy"
SIDM particles follow isothermal distribution together with baryons, and the total density scales as $1/r^2$

Kamada, Kaplinghat, Pace, HBY (in prep)



Confirmed by SIDM simulations with baryons (not due to the feedback process)

Creasey, Sameie, Sales, HBY, Zavala, Vogelsberger (in prep)

Summary

- It is time to think about new approaches to the dark matter problem
- CDM may break down on galactic scales
- The SIDM paradigm provides a solution with interesting features
  - Smoking-gun signatures in direct and indirect detection experiments
  - Measure dark matter mass via self-scattering kinematics
  - Tie dark matter to baryons
  - Damped power spectrum
- With SIDM, we may address more general problems in galaxy formation