# The Self-Interacting Dark Matter Paradigm

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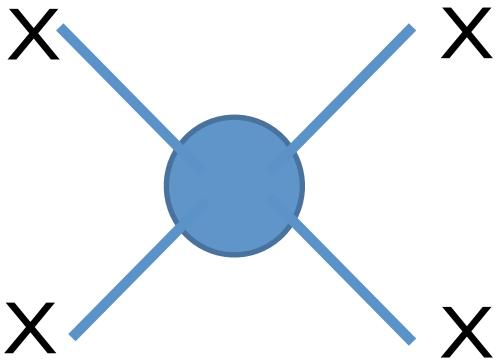
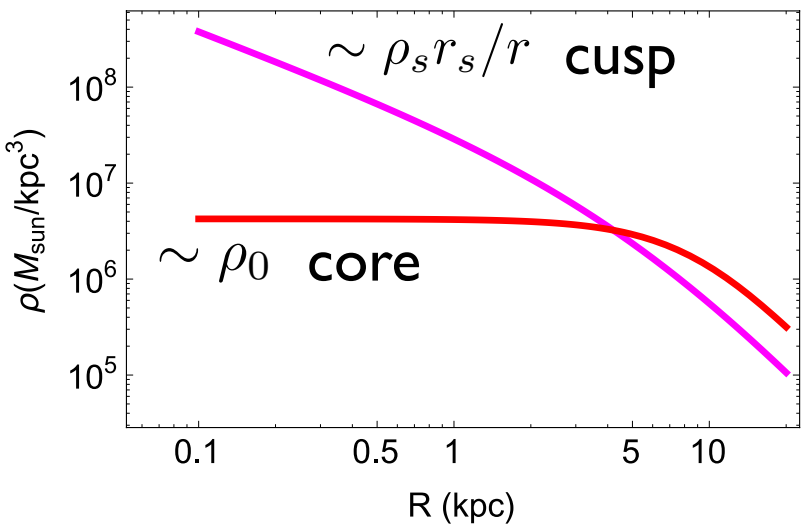



UCLA Dark Matter 2016, February 17-19, 2016

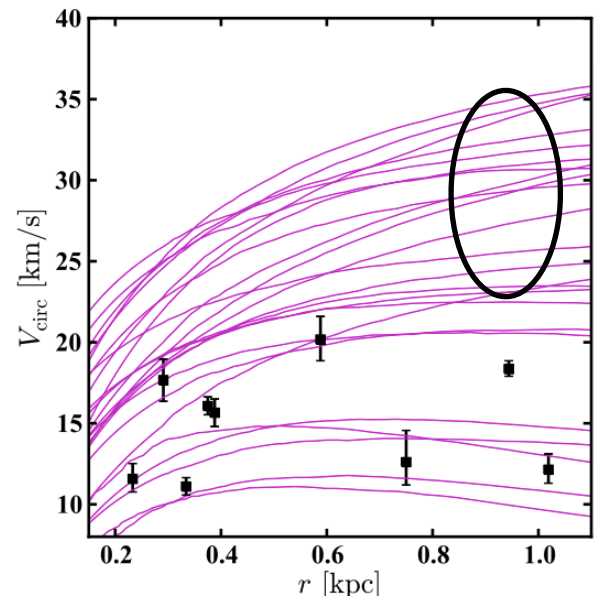
# Small Scale Issues

- Core VS. Cusp problem




Flores, Primack (1994), Moore (1994)

- Too-big-to-fail problem




Biggest predicted subhalos from CDM simulations

Brightest observed galaxies in the MW

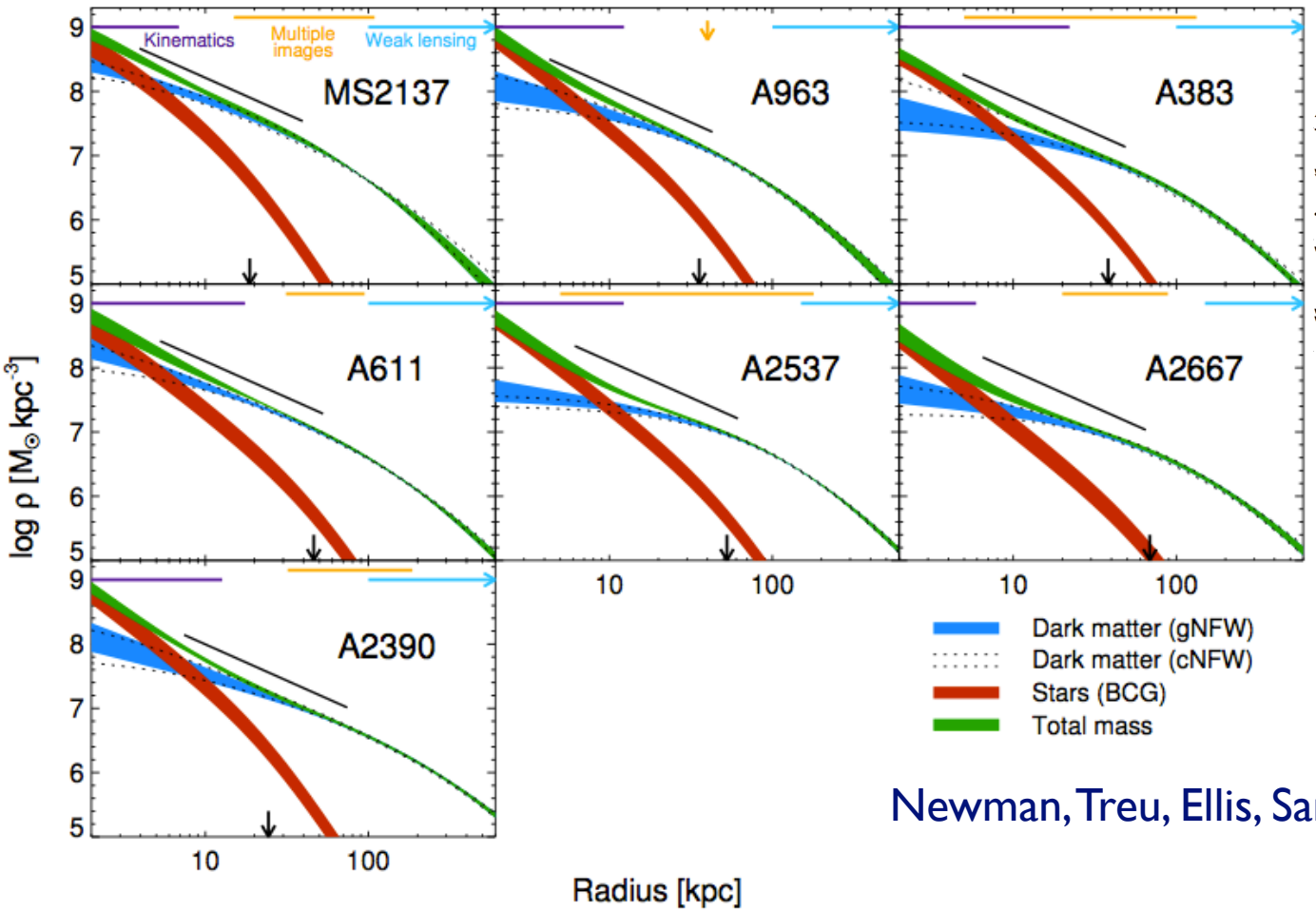
Boylan-Kolchin, Bullock, Kaplinghat (2011)

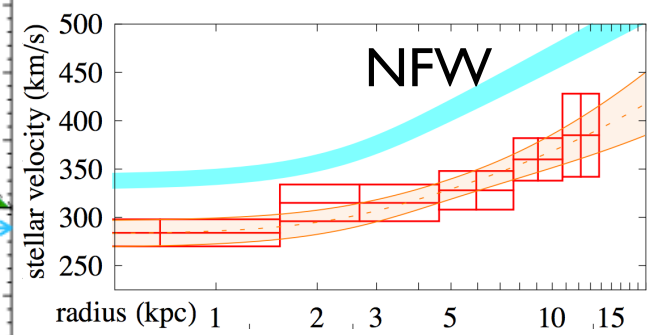
See James Bullock's talk

- CDM halos contain more DM in the central region than indicated by data; the DM deficit problem

# Even Galaxy Clusters

- Seven well-resolved galaxy clusters



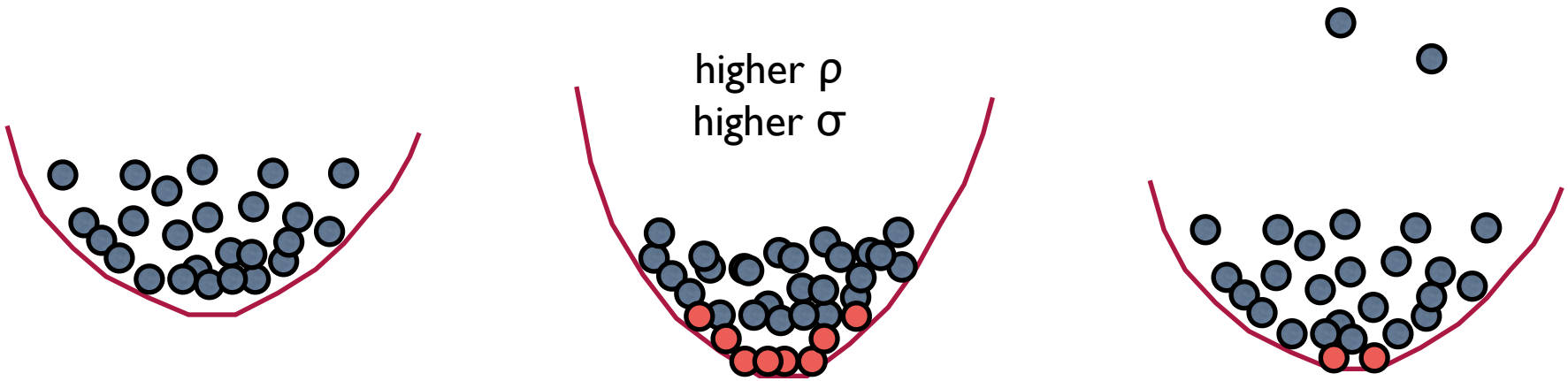




Newman, Treu, Ellis, Sand (2013)

- Remove DM from the central region of halos

# Baryon Physics?

- Violent baryonic feedback process




Baryonic infall

Supernova explosion

Gravitational binding energy VS. Energy injection from supernovae

Navarro, Eke, Frenk (1996)

# Baryon Physics?

- Violent baryonic feedback process

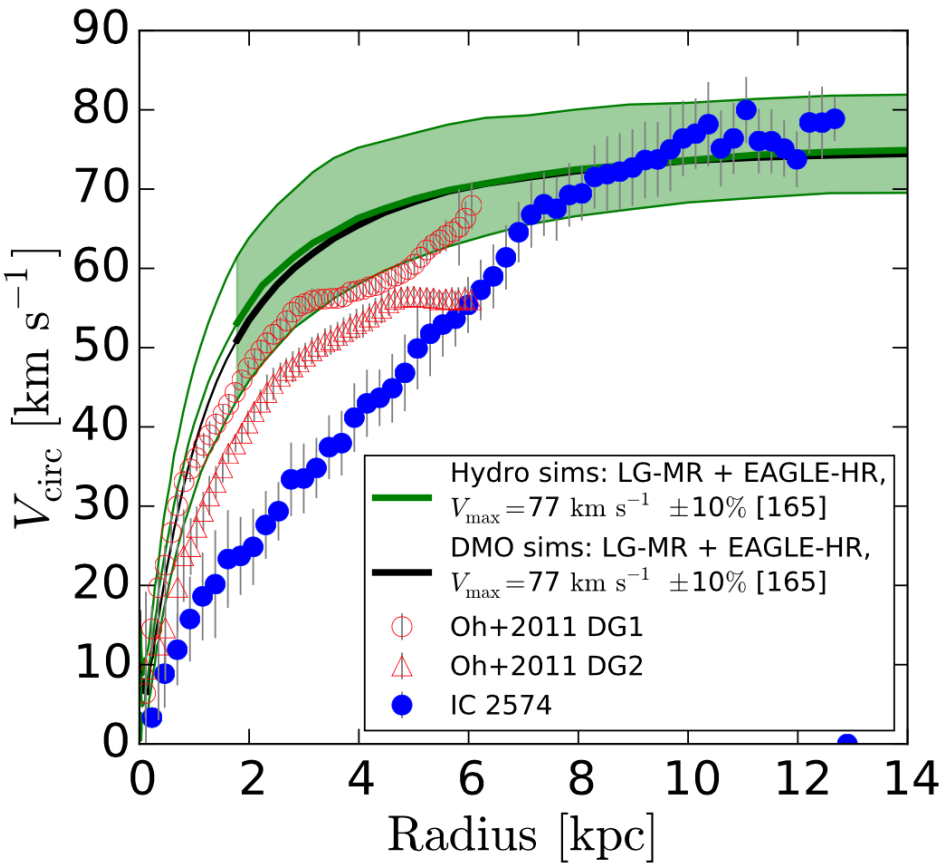
depends on the stellar mass
Governato+ (2012)

depends on when it occurs
Onorbe+(2015)

galaxies with cores larger than $r_*$
Papastergis, Shankar (2015)

**depends on the recipe of hydrodynamical simulations!**

Other group did not see the effect
Oman+ (2015) ("NFW" group)

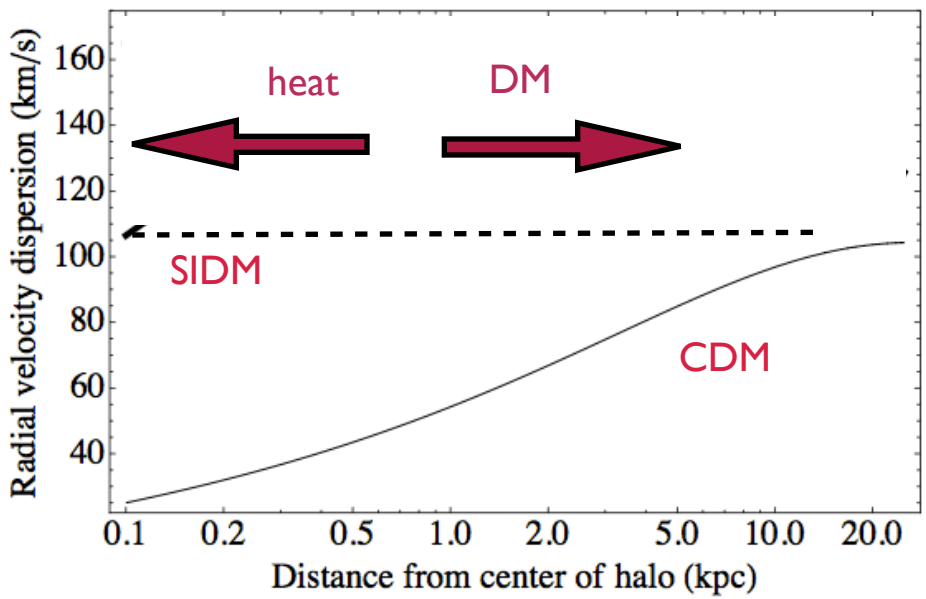


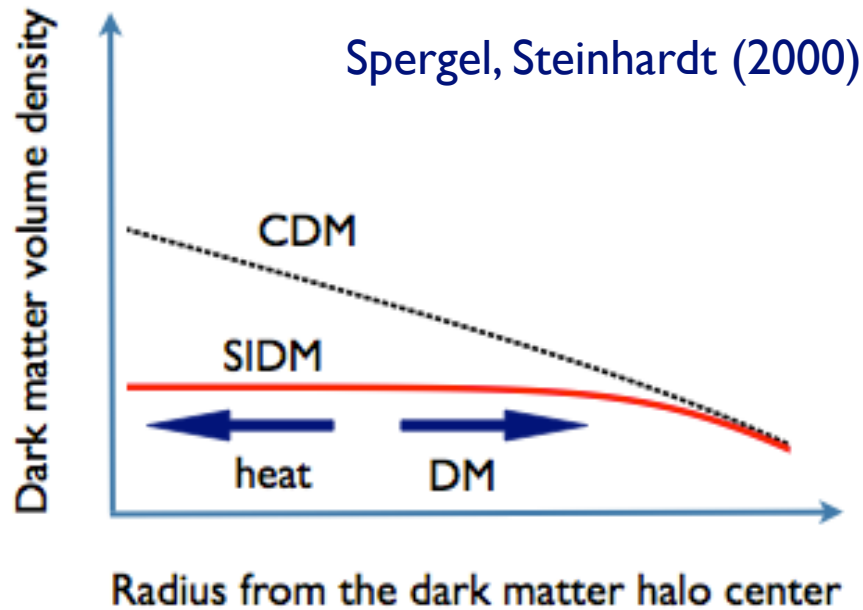

Oman+ (2015)

We are still debating!

# Dark Matter Physics?

- Self-interactions can reduce the central DM density




Recent simulations: Irvine group, MIT group

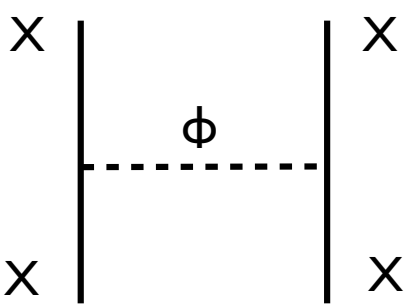
$\sigma/m_X \sim 1\ \mathrm{cm}^2/\mathrm{g}$

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

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

NOT a WIMP: $\sigma \sim 10^{-38}\ \mathrm{cm}^2\,(m_X/100\ \mathrm{GeV})$

# SIDM Particle Physics

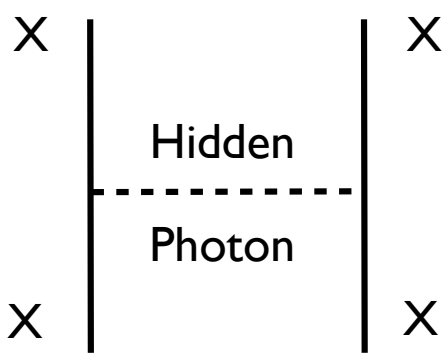



- SIDM indicates light mediators

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

in the perturbative and small velocity limit

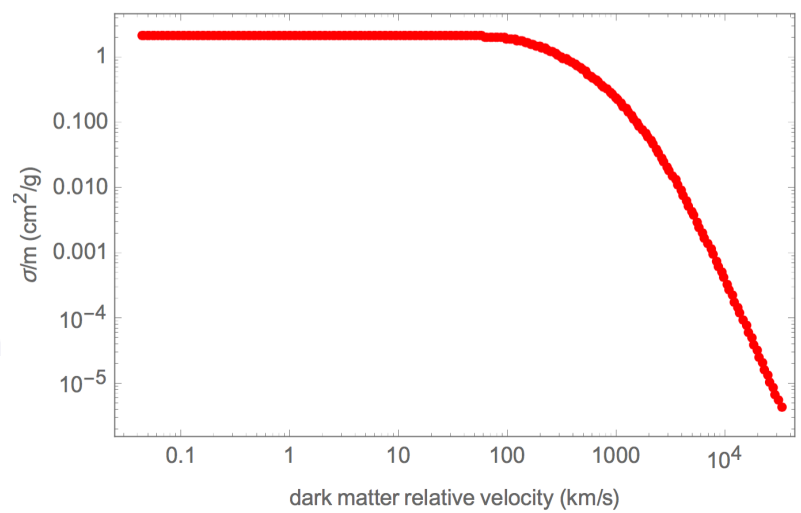
- With a light mediator, DM self-scattering is velocity-dependent




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

$m_X v >> m_\phi$ Rutherford limit

$m_X v << m_\phi$ contact interaction

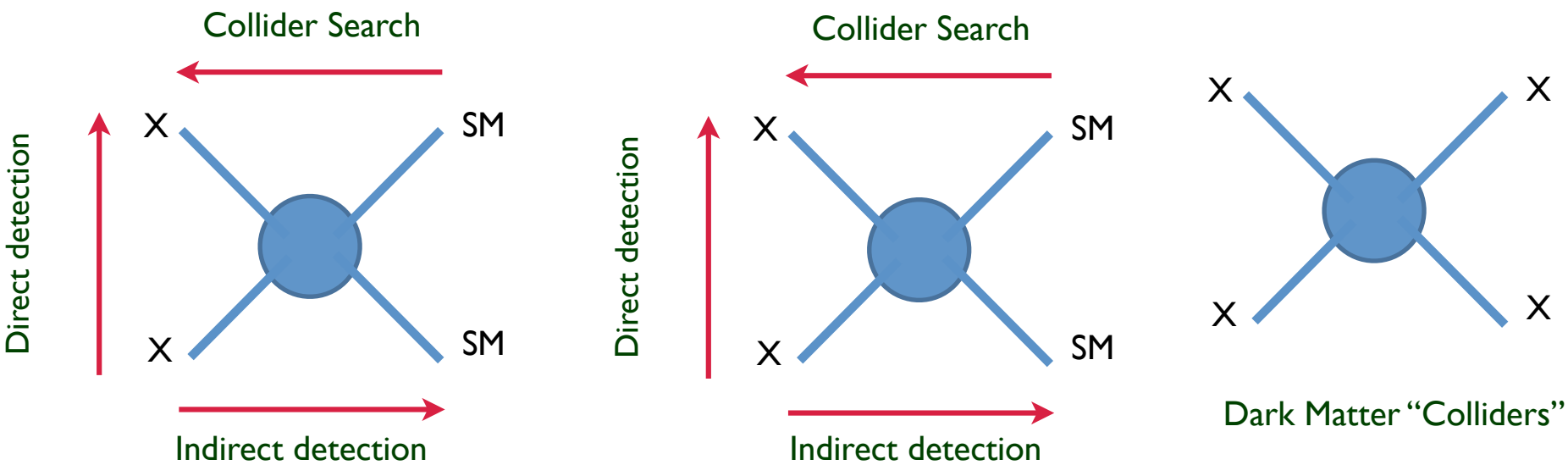



Feng, Kaplinghat, HBY (2009); Buckley, Fox (2009), Loeb, Weiner (2010); Tulin, HBY, Zurek (2012) (2013)

See Kim Boddy's talk for SIDM models

# The SIDM Paradigm

- The SIDM paradigm is predictive




the WIMP paradigm

the SIDM paradigm

Collider search: Bjorken, Essig, Schuster, Toro (2009); Bai, Rajaraman (2011), Daci, De Bruyn, Lowette, Tytgat, Zaldivar (2015); An, Echenard, Pospelov, Zhang (2015); Tsai, Wang, Zhao (2015)

Indirect search: Boddy+ (2014); Kaplinghat, Linden, HBY (2015); Feng, Smolinsky, Tanedo (2015,2016)

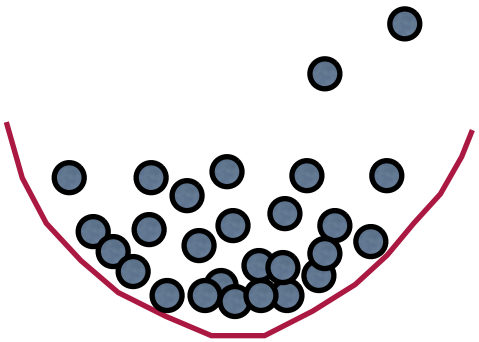
Direct search: Del Nobile, Kaplinghat, HBY (2015)

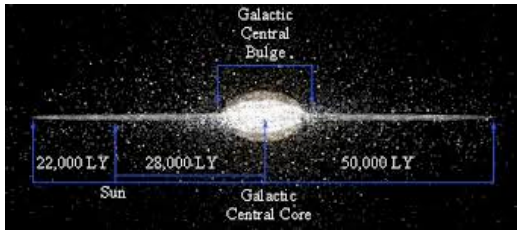
Focus on smoking-gun signatures, independent of DM-SM interactions

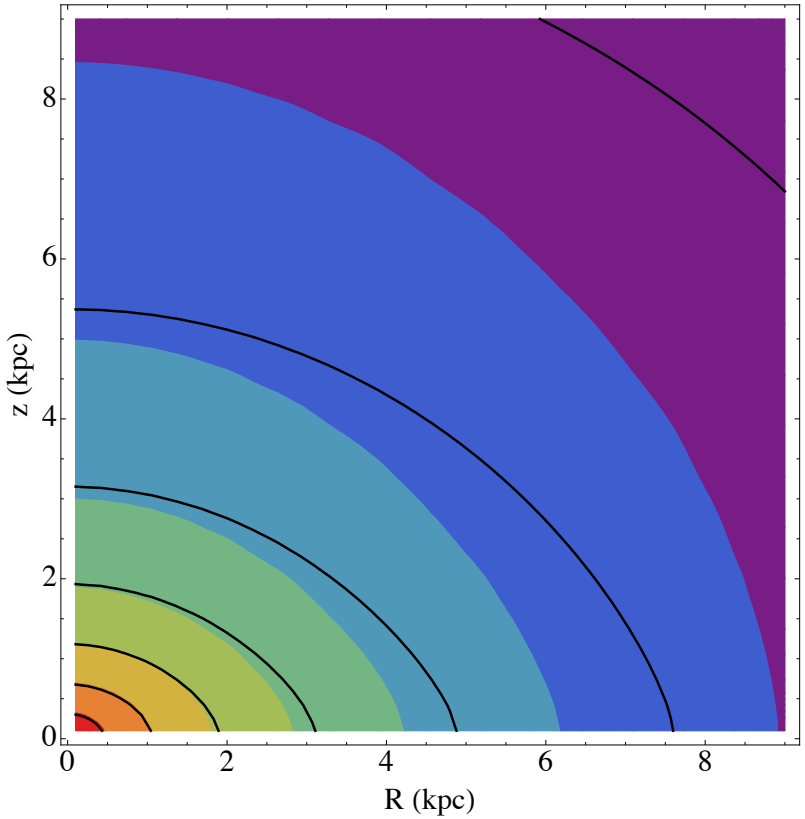
# Idea 1: Tying SIDM to Baryons

- SIDM may follow the stellar distribution; halo morphology

ideal gas with gravity





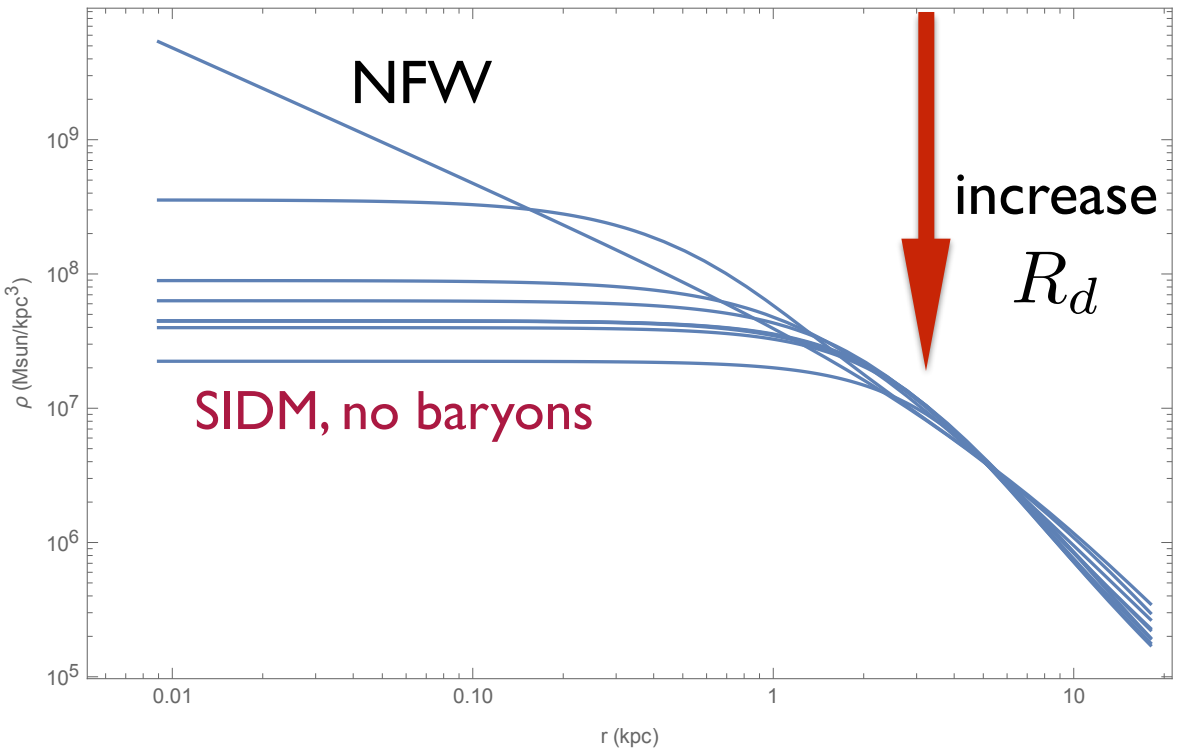




Kaplinghat, Linden, Keeley, HBY (PRL 2013)

Correlation between the stellar distribution and the SIDM distribution

# Backreaction of Baryons

- Baryons may also change the SIDM density profile




$$\Sigma = \Sigma_0 e^{-r/R_d}$$

For a given total desk mass, vary the scale radius

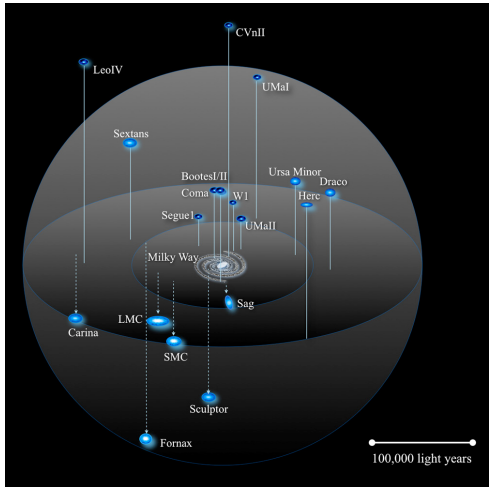
The SIDM halo could be diverse depending on the baryon concentration

Kamada, Kaplinghat, HBY (in preparation)

We are analyzing the rotation curve data for ~170 galaxies

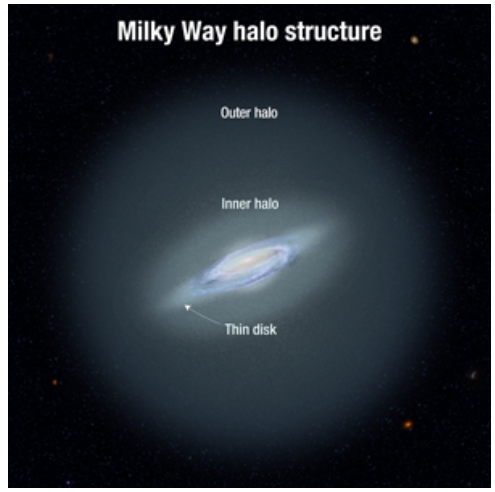
# Idea 2: Dark Matter "Colliders"

Dwarf galaxies



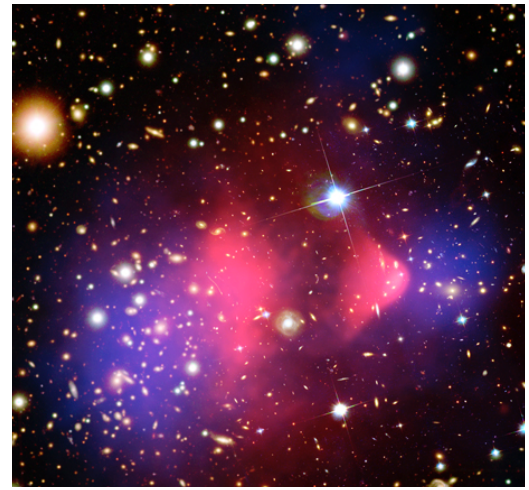

"B-factory" (v~30 km/s)

MW-size galaxies




"LEP" (v~200 km/s)

Clusters



"LHC" (v~1000 km/s)

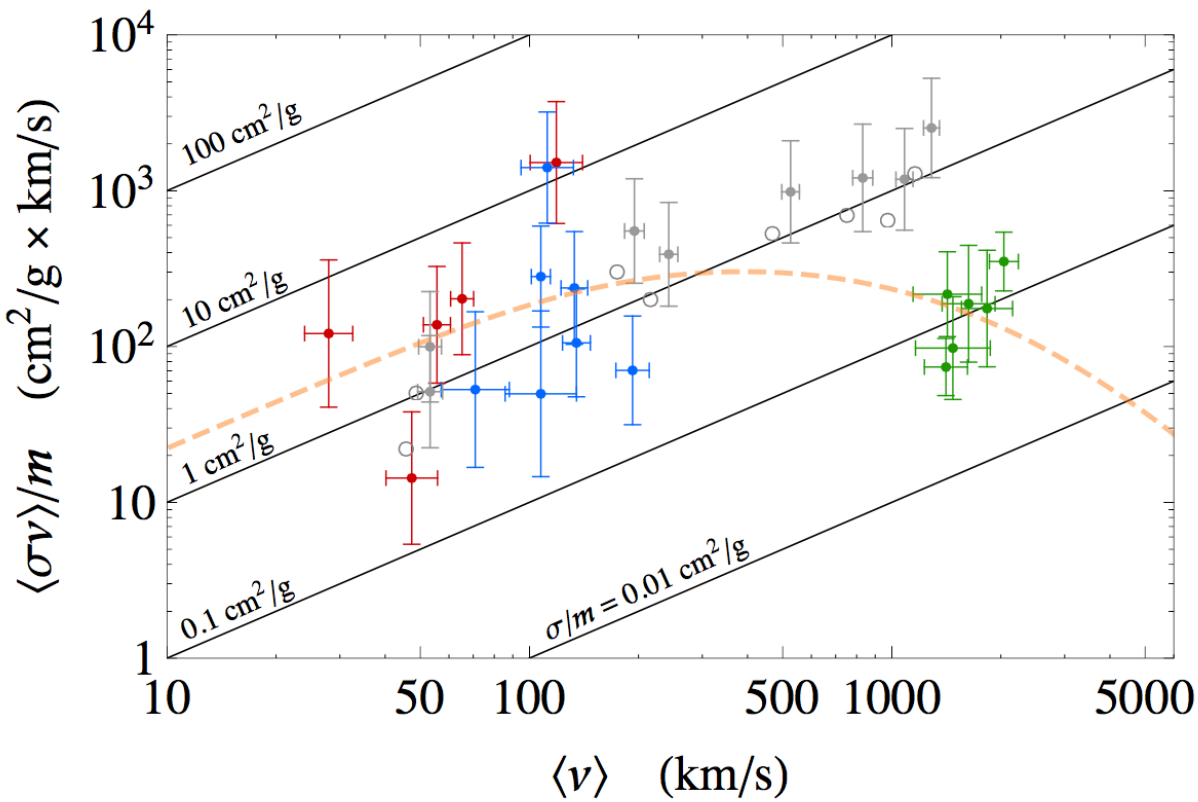
Self-scattering kinematics

Observations on all scales

Measure particle physics parameters $\sigma_X$, $m_X$, $g_X$

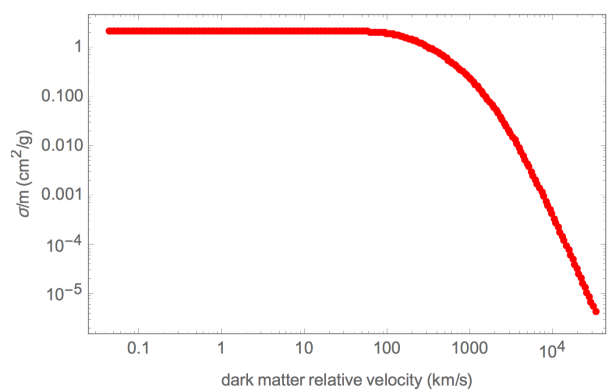
# SIDM From Dwarfs to Clusters

- 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




Outliers:
Due to scatter in halo concentration

favors a mild v-dependence

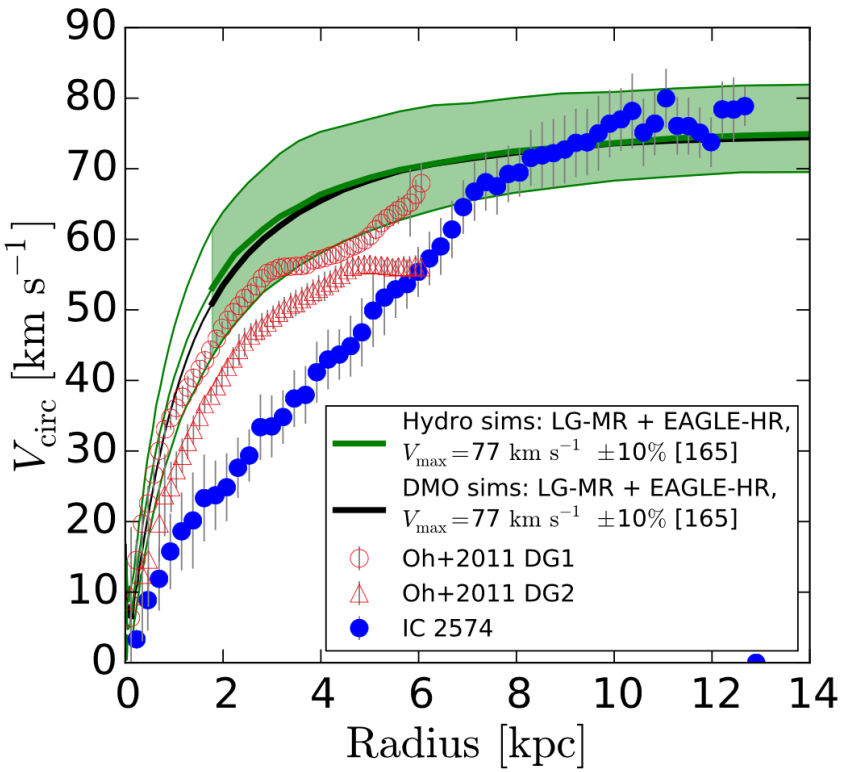



Galaxies: ~2 $cm^2/g$
Clusters: ~0.1 $cm^2/g$

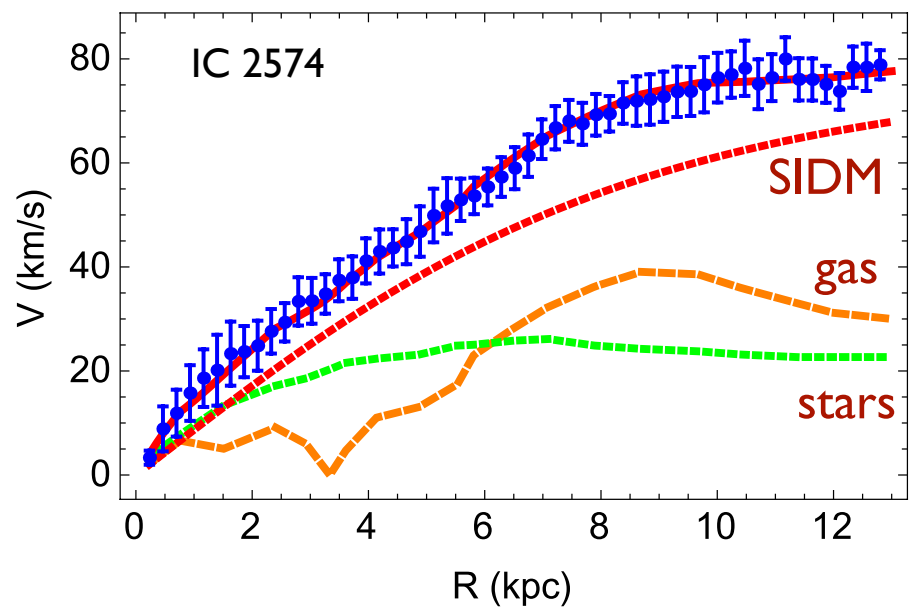
Bullet Cluster: <1 $cm^2/g$

Kaplinghat, Tulin, HBY (PRL 2015)

# Example



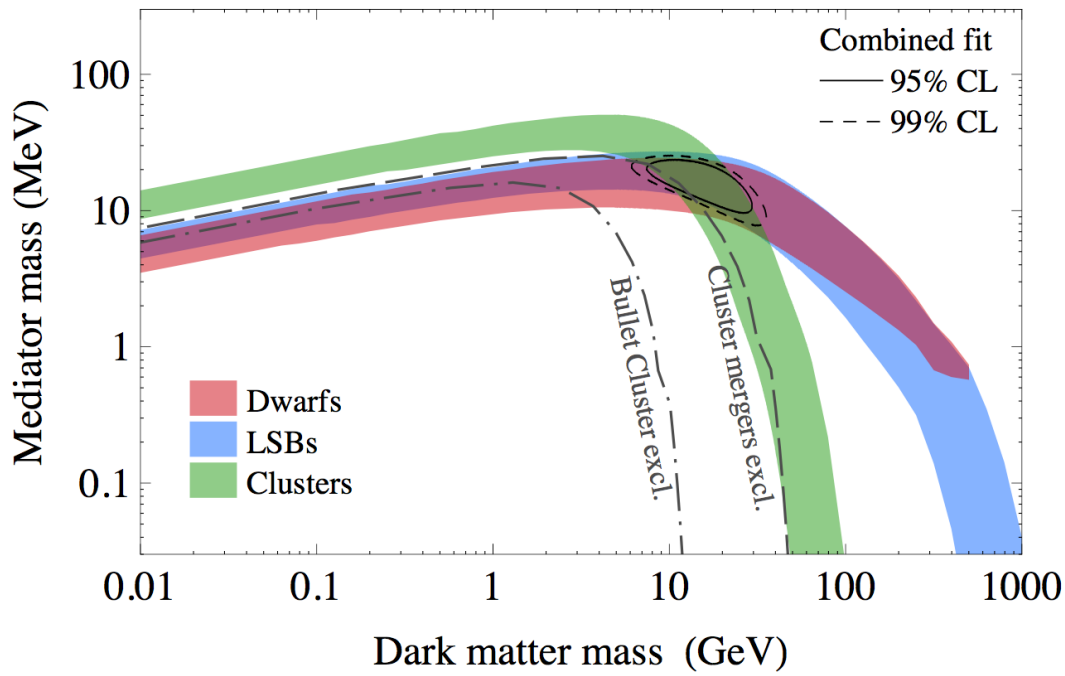

Oman+ (2015)




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. $m_\phi$ $10^{-3}$ $m_X \sim m_\phi$

If $m_X$ is too large, $\sigma \sim 1/v^4$, which is too small for clusters

If $m_X$ is too small, $\sigma \sim$const, which is too large for clusters

$\alpha_X$=0.01
$m_X$: ~15 GeV, $m_\phi$: ~15 MeV

Kaplinghat, Tulin, HBY (PRL 2015)

mild dependence on $\alpha_X$

$\alpha_X$=0.001-0.1
$m_X$: ~5-30 GeV

# Summary

- It is time to think about new approaches to the dark matter problem
- CDM has serious issues on galactic scales
- The SIDM paradigm provides a solution with novel features
  - Smoking-gun signatures in direct and indirect detection experiments
  - Measure dark matter mass via self-scattering kinematics
  - Tie dark matter to baryons

Go beyond the dark matter mass deficit problem