The Self-Interacting Dark Matter Paradigm

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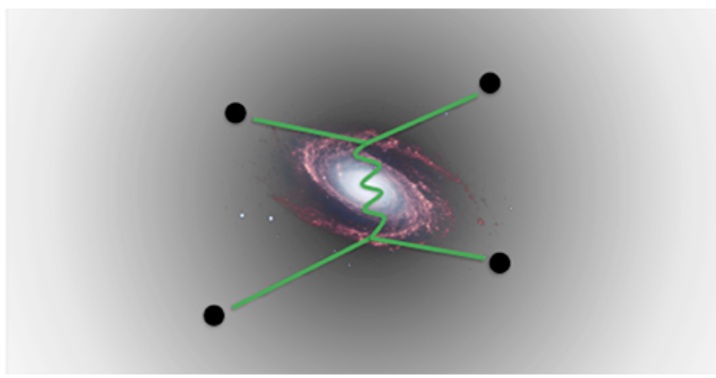
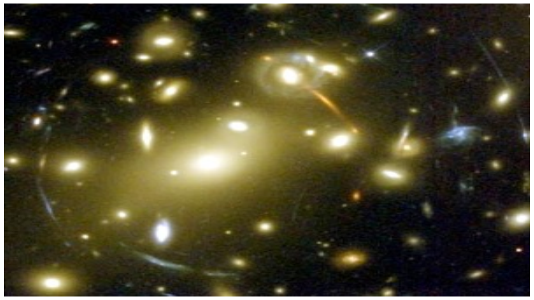
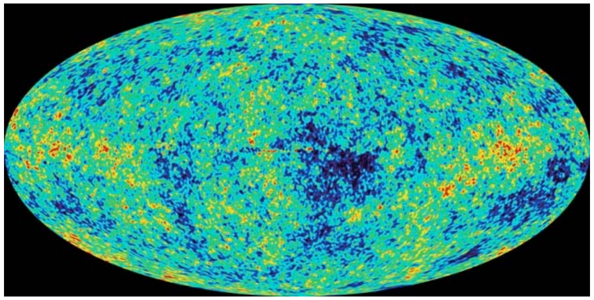


CERN TH INSTITUTE, August 23, 2016

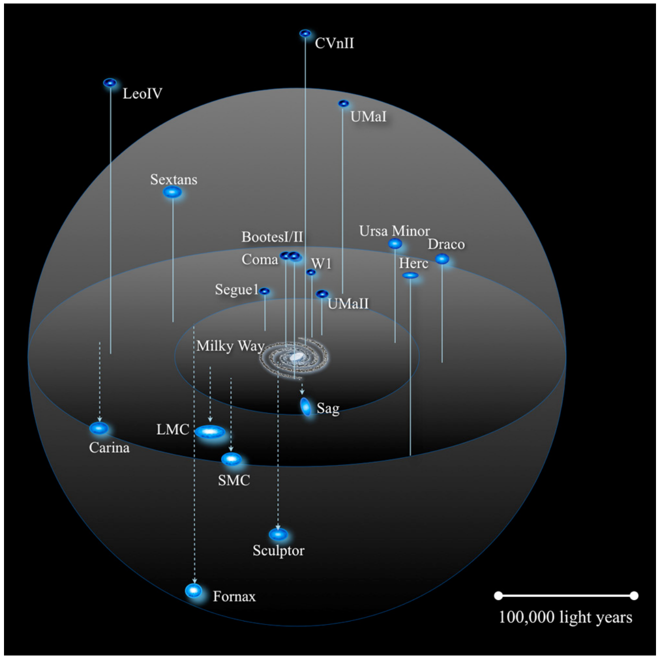
Review for Physics Reports: Sean Tulin, HBY arXiv: 1609.XXXXX

Cold Collisionless Dark Matter

- Large scales: very well

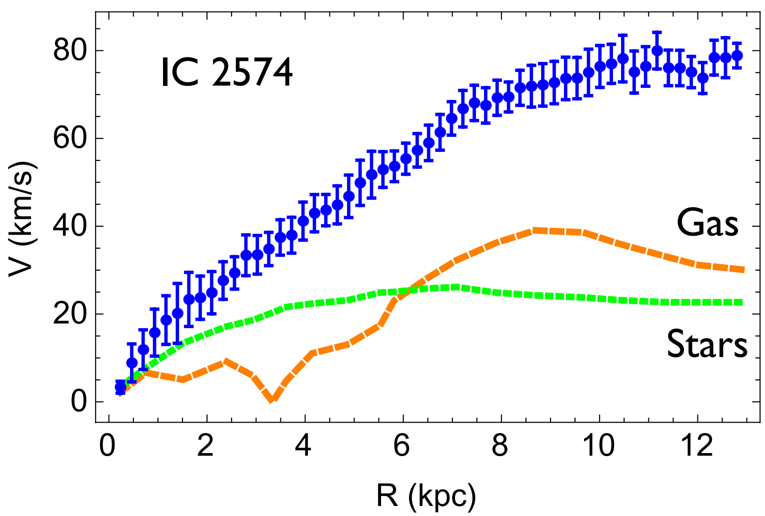




- Small scales (dwarf galaxies, subhalos, galaxy clusters): ?



Core VS. Cusp Problem

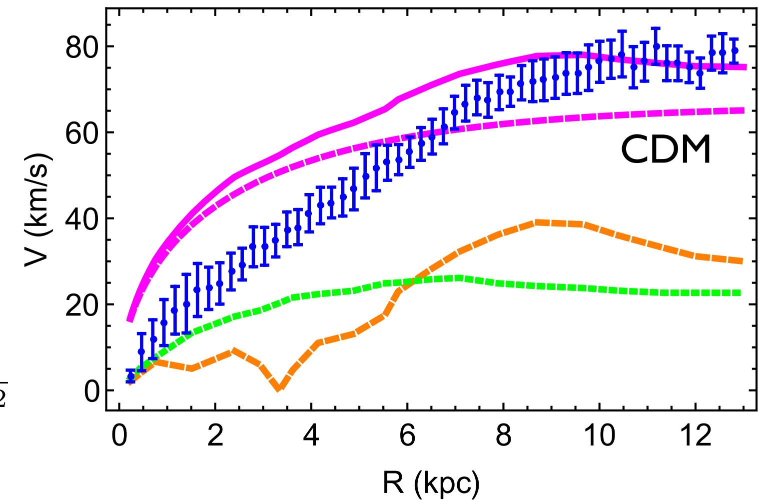
- DM-dominated systems (dwarfs, LSBs) from THINGS Oh+(2011)

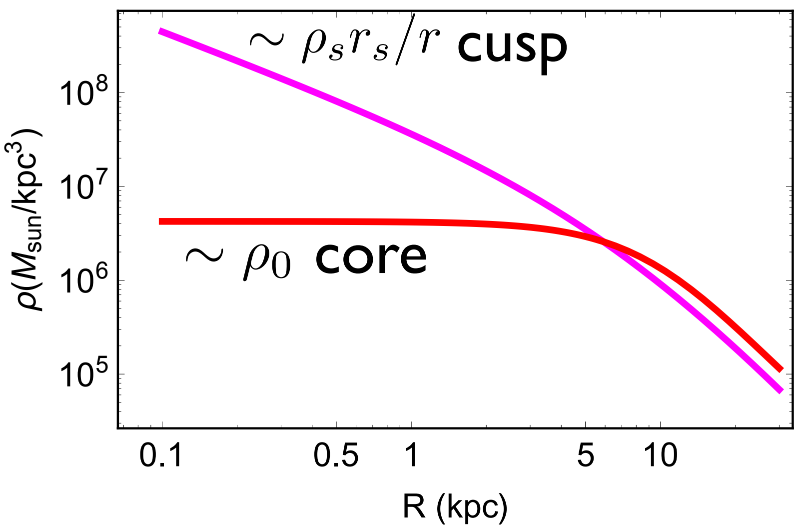


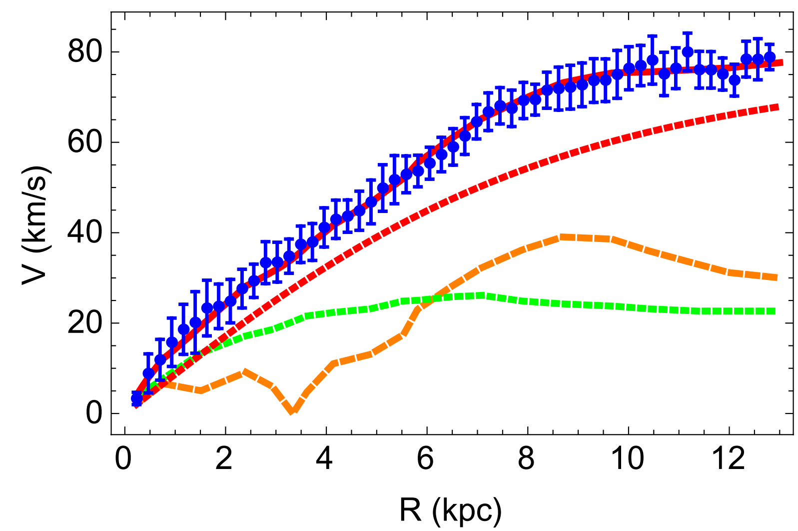
NFW

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

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



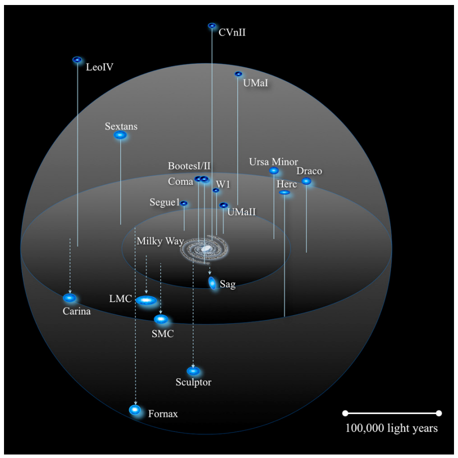




Flores, Primack (1994), Moore (1994)

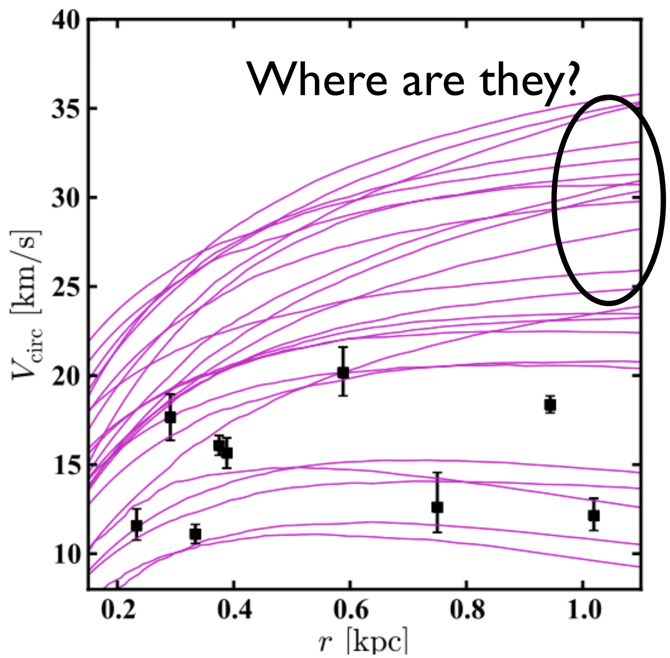
Too-Big-to-Fail Problem

- Milky Way dwarf galaxies   Boylan-Kolchin, Bullock, Kaplinghat (2011)



$$M_{1/2} = 3\,G^{-1}\langle\sigma_{\rm los}^2\rangle\, r_{1/2}$$

$$V_{\rm circ}(r_{1/2}) = \sqrt{3\,\langle\sigma_{\rm los}^2\rangle}\,.$$



Biggest predicted subhalos from CDM simulations

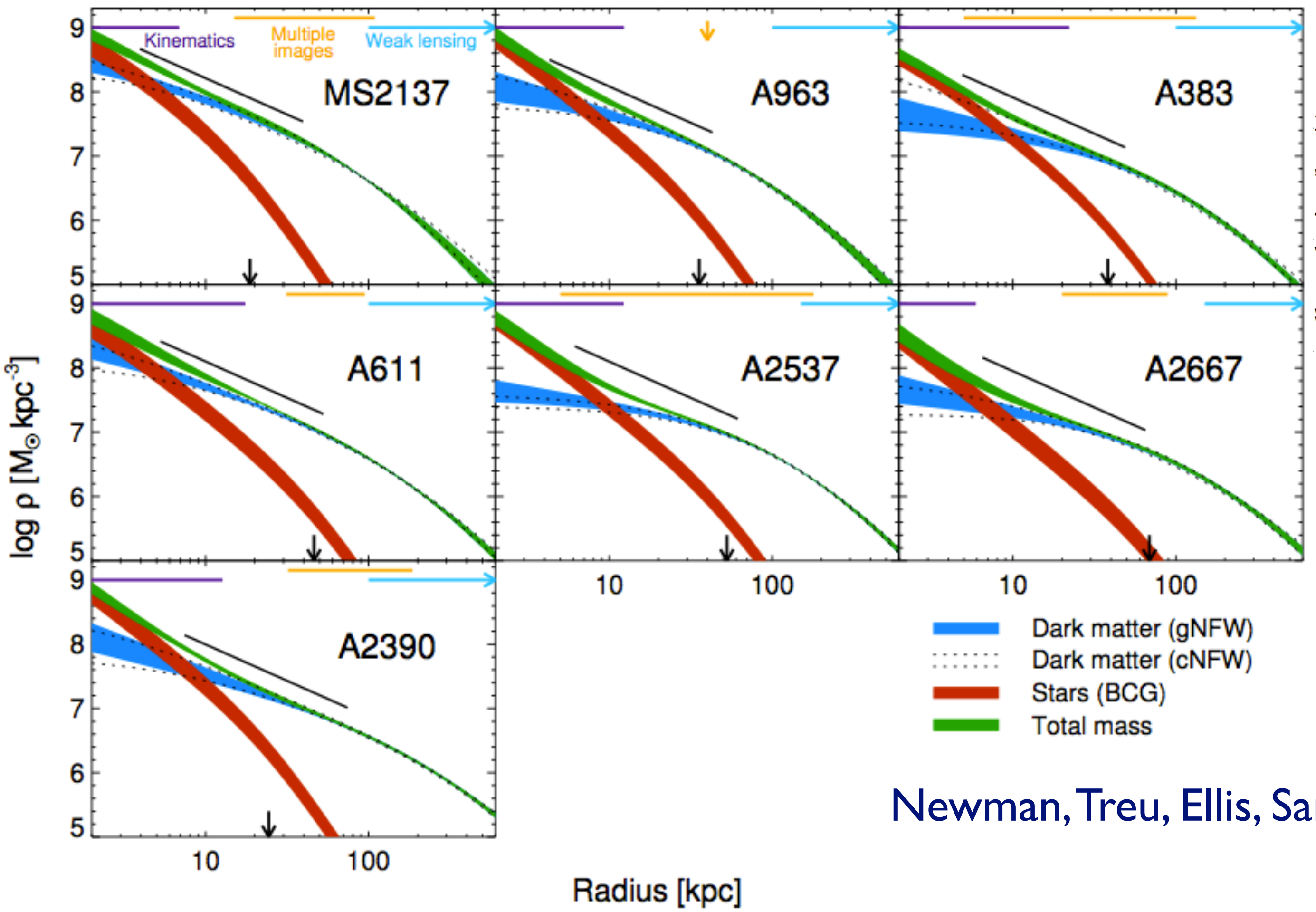
Brightest observed galaxies in the MW

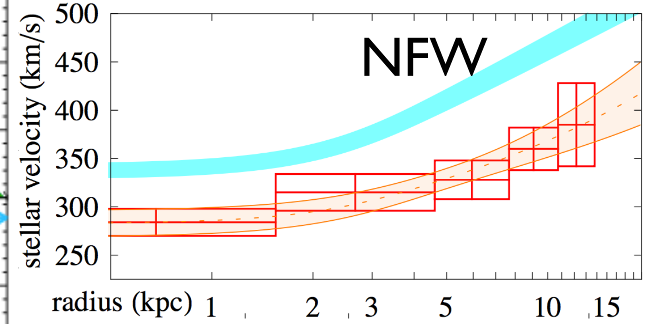
- Most massive subhalos in CDM simulations are too dense to host observed galaxies in the Milky Way
- On the other hand, it is easier for stars to form in massive subhalos

subhalos in Andromeda, field dwarfs in Local Group, and field galaxies

Even Galaxy Clusters!

- Seven well-resolved galaxy clusters





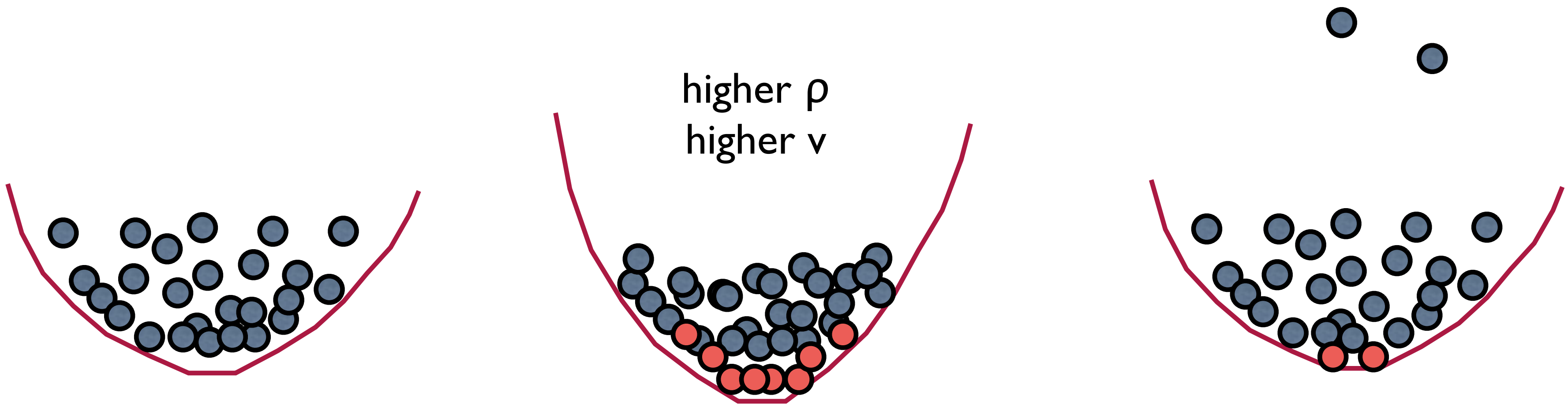
Newman, Treu, Ellis, Sand (2013)

- CDM halos contain more DM in the central regions than needed

Dark matter deficit problem

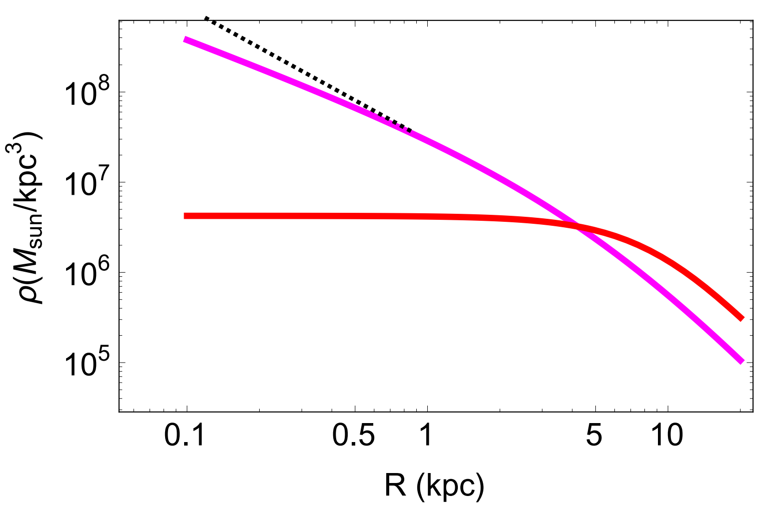
Baryon Physics?

- Violent baryonic feedback process



Baryonic Infall

Supernova Explosion



gravitational binding energy VS.
energy injection from supernovae

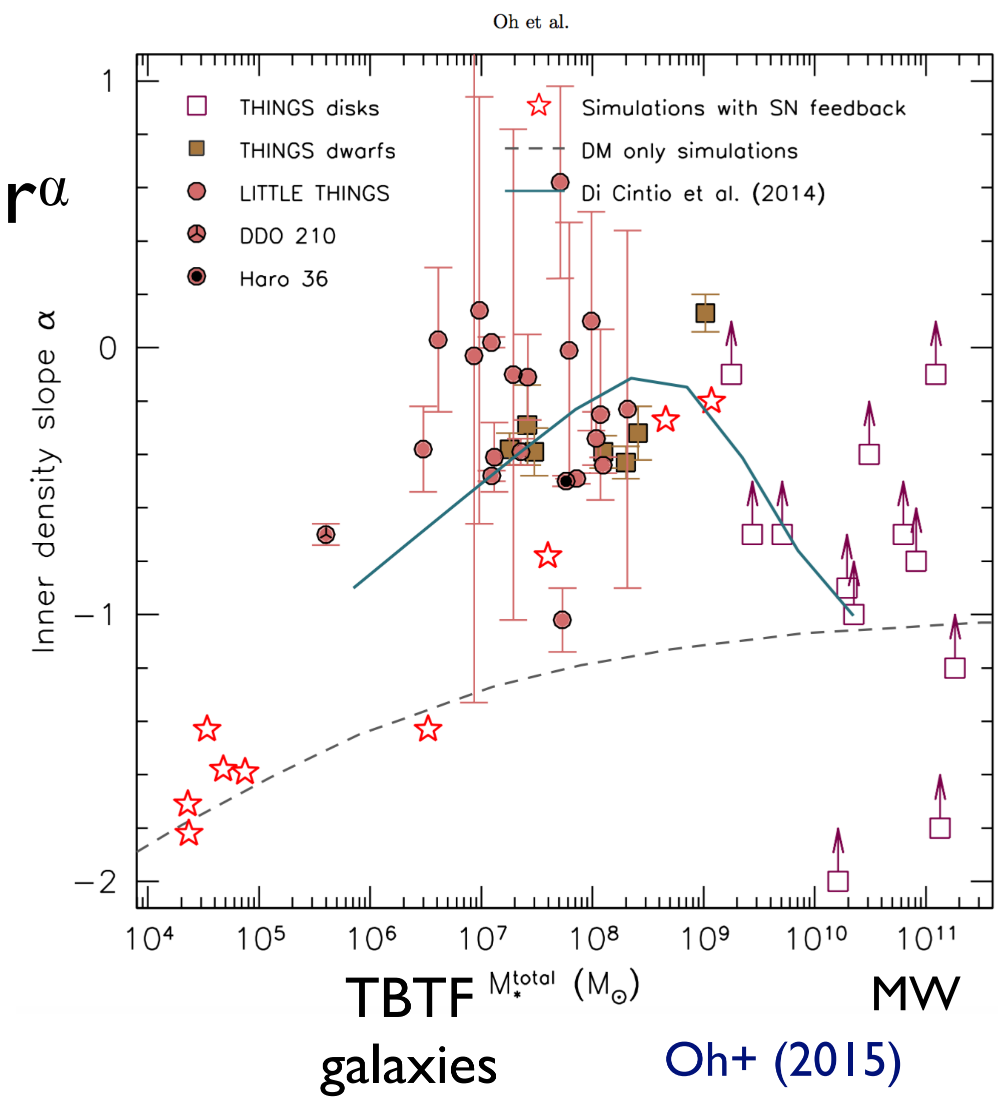
only works r<r* (inner regions)

Blumenthal, Flores, Primack (1986)

Navarro, Eke, Frenk (1996)

Baryon Physics?

- Violent baryonic feedback process



Oh+ (2015)

depends on the stellar mass
Governato+ (2012)

depends on when it occurs
Onorbe+(2015)

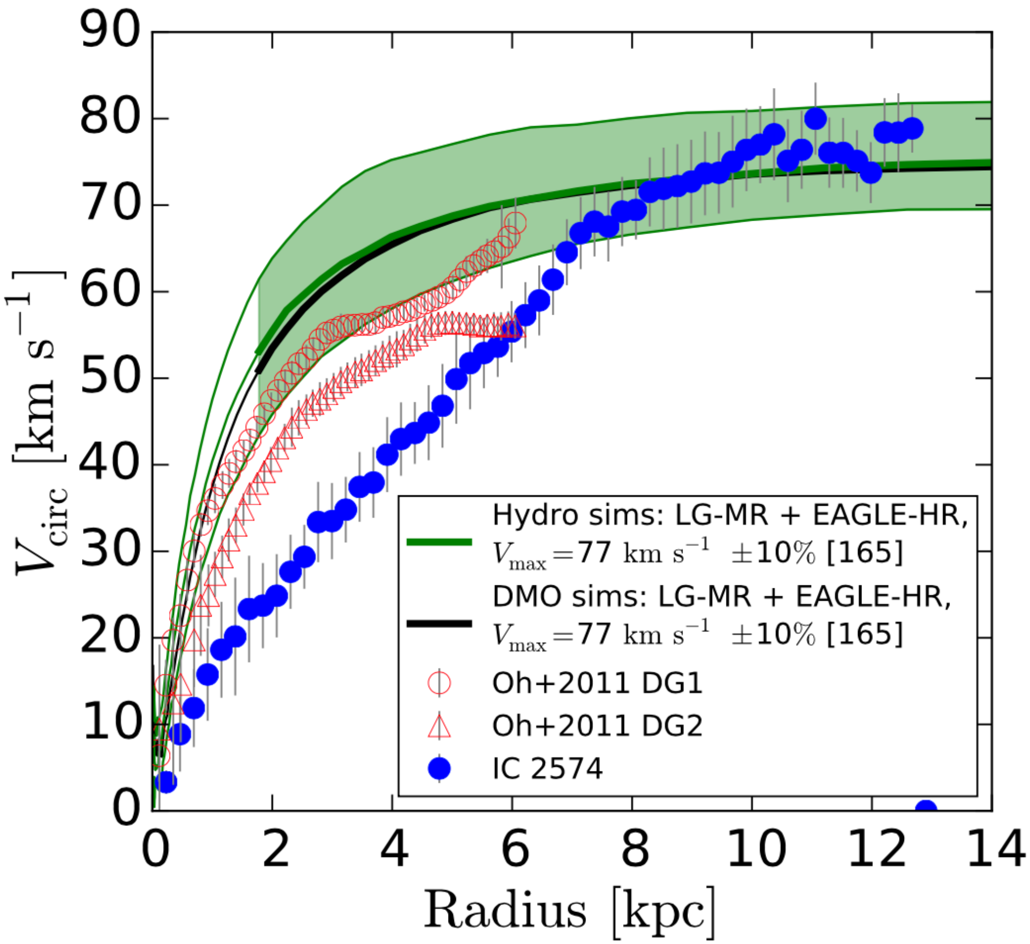
galaxies with cores larger than r*
Papastergis, Shankar (2015)

depends on the recipe of hydrodynamical simulations!

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

Baryon Physics?

- Violent baryonic feedback process



Oman+ (2015) (the NFW group)

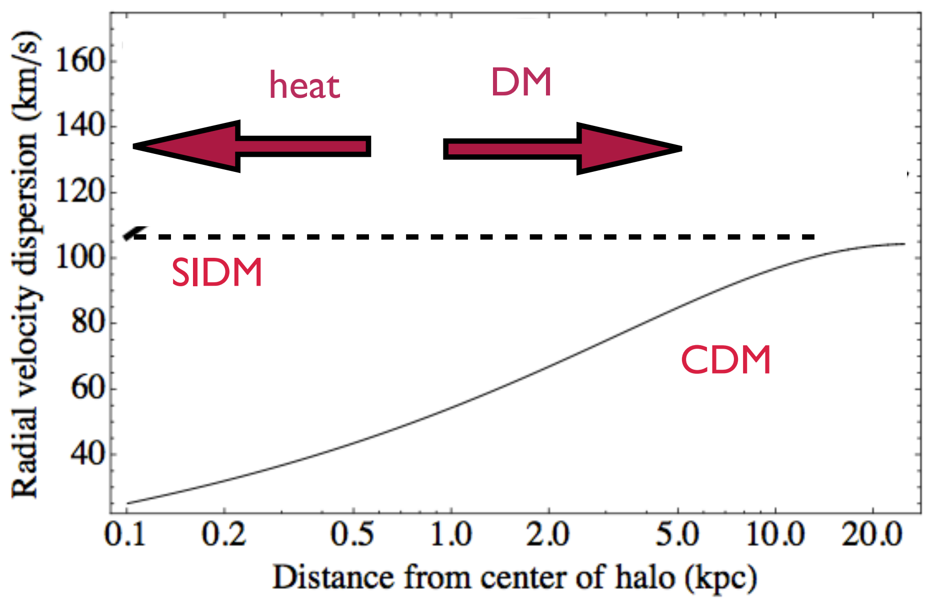
The feedback effect depends on how you implement the feedback process!

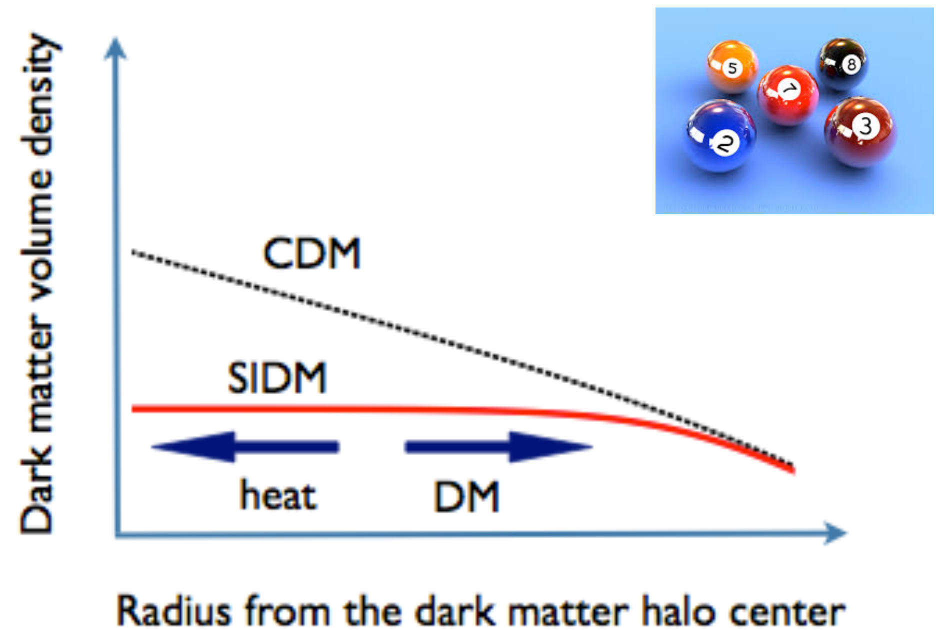
We are still debating!

Dark Matter Physics?

- Self-interactions can reduce the central DM density

Spergel, Steinhardt (2000)





Recent simulations: Irvine group, MIT group, ETHOS Collaboration

See Zavala's talk

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

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

Challenges

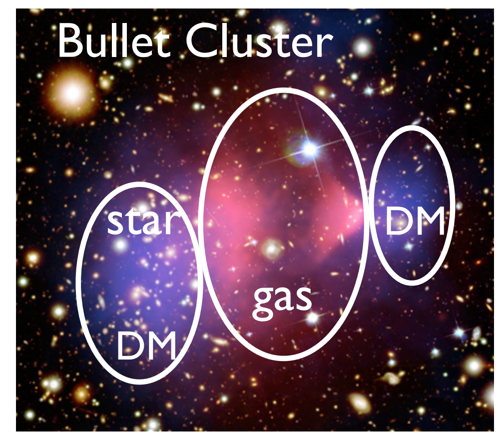
- A really large scattering cross section!

a nuclear-scale cross section

$\sigma \sim 1 cm^2 (m_X/g) \sim 2\times 10^{-24} cm^2 (m_X/GeV)$

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)

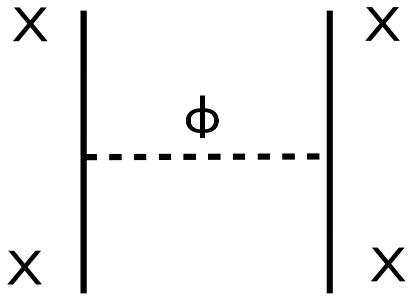
Robertson+(2016)

$\sigma/m_X <$ 0.1 cm^2/g for 1000 km/s (stellar kinematics)

Kaplinghat, Tulin, HBY (PRL 2015)

In particular, if σ~constant

SIDM Particle Physics

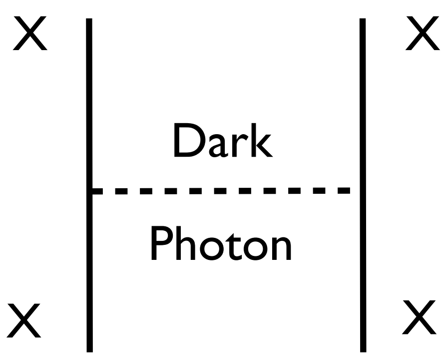


- SIDM indicates light mediators

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

in the perturbative and small velocity limit

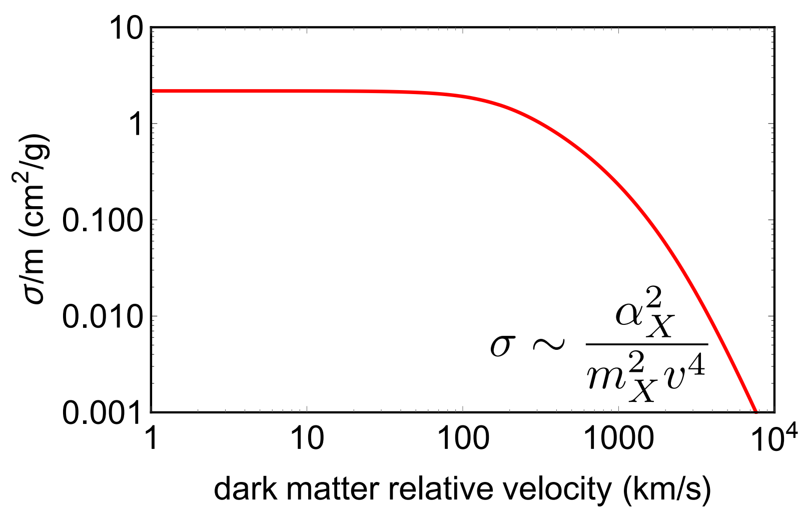
- With a light mediator, DM self-scattering is velocity-dependent



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

$m_X v >> m_\phi$ Rutherford limit

$m_X v << m_\phi$ contact interaction

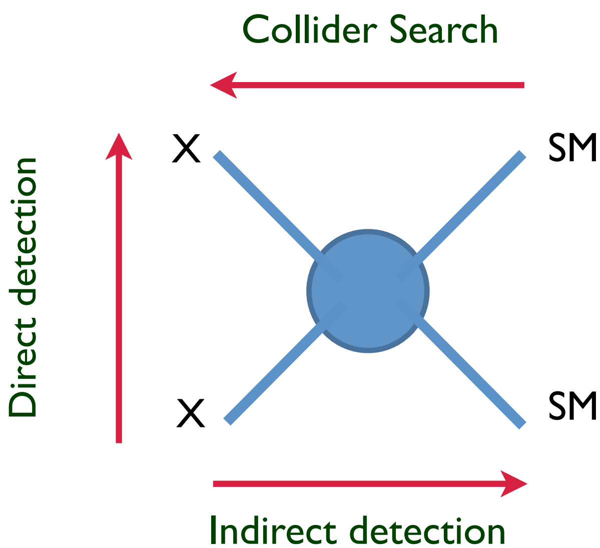


Feng, Kaplinghat, HBY (2009); Buckley, Fox (2009), Loeb, Weiner (2010); Tulin, HBY, Zurek (2012) (2013)

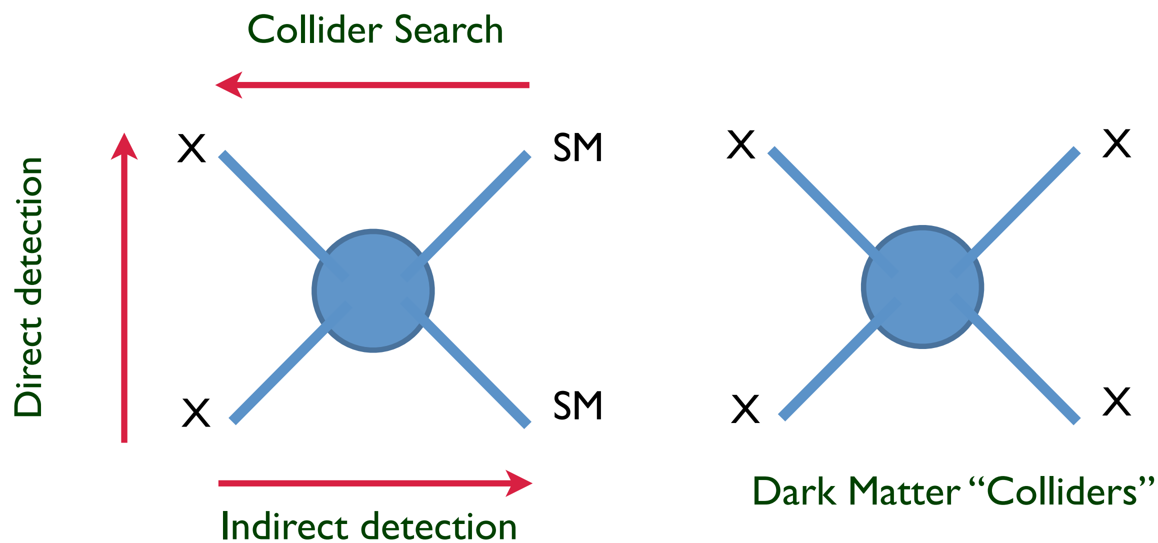
The first SIDM simulations with a Yukawa potential: Vogelsberger, Zavala, Loeb (2012)

The SIDM Paradigm

- The SIDM paradigm is predictive



the WIMP paradigm

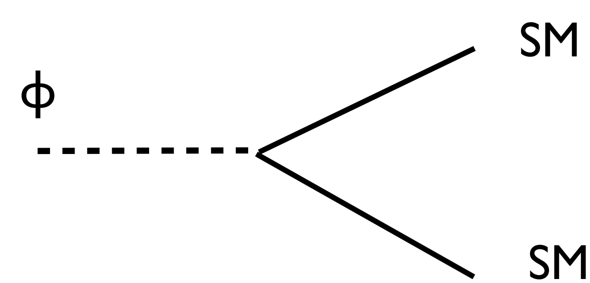


the SIDM paradigm

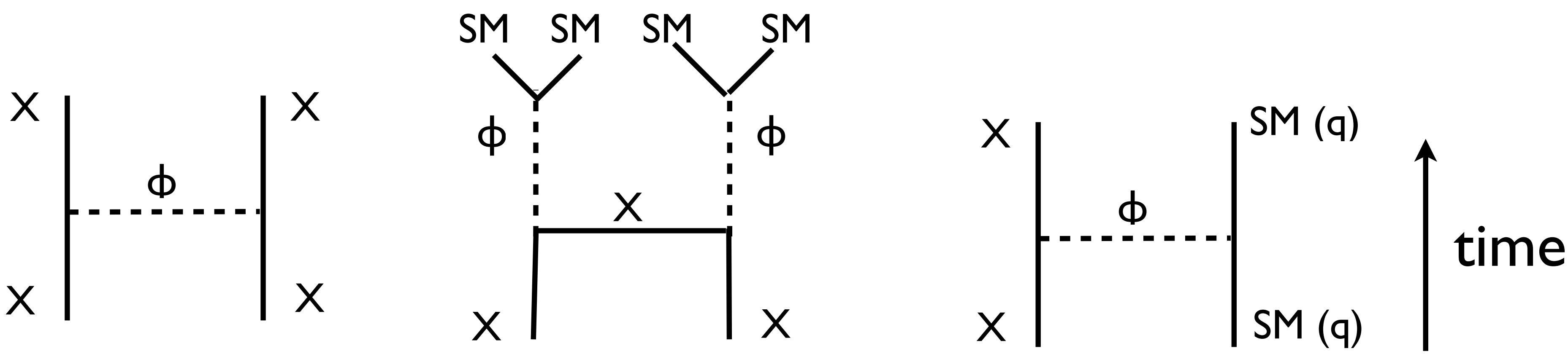
Mixing with the SM Sector

- The mediator may dominate the energy density of the Universe
- The mediator decays before BBN: lifetime of ϕ is ~1 second

$$\epsilon \gtrsim 10^{-10}\sqrt{10\ \mathrm{MeV}/m_\phi}$$



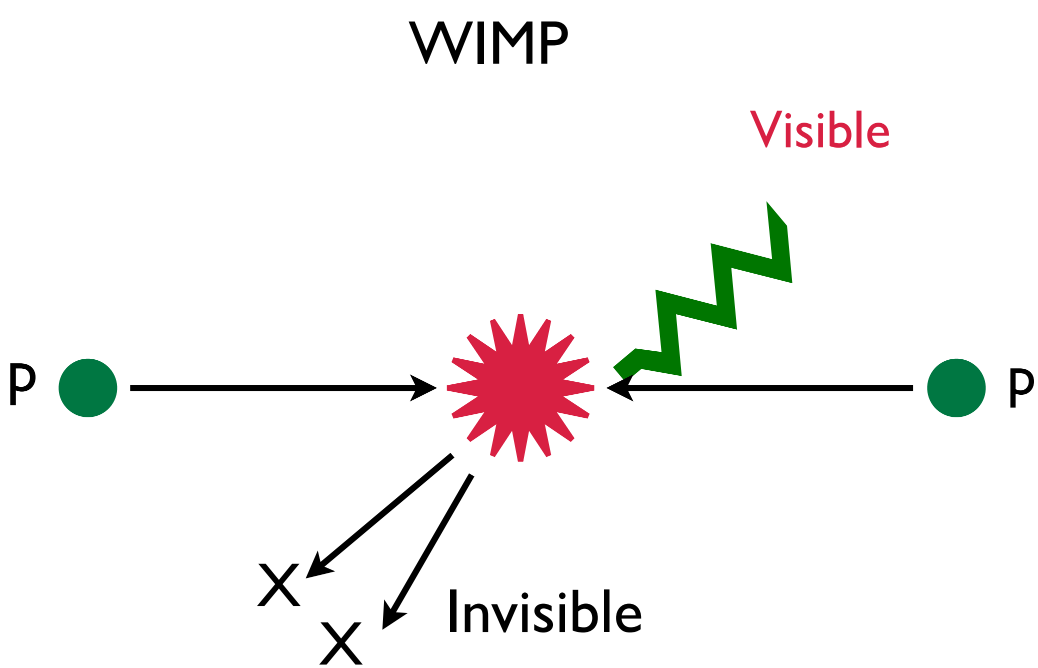
A simple (super) model



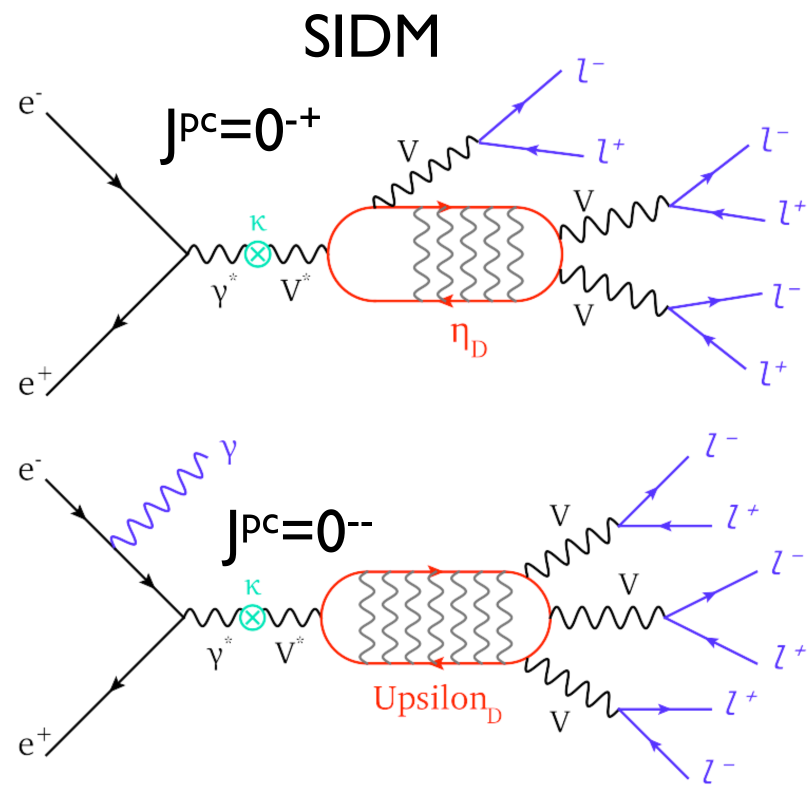
Kaplinghat, Tulin, HBY (PRD 2013)

SIDM at Colliders

- Striking collider signals



pp→Monojet+Missing Energy



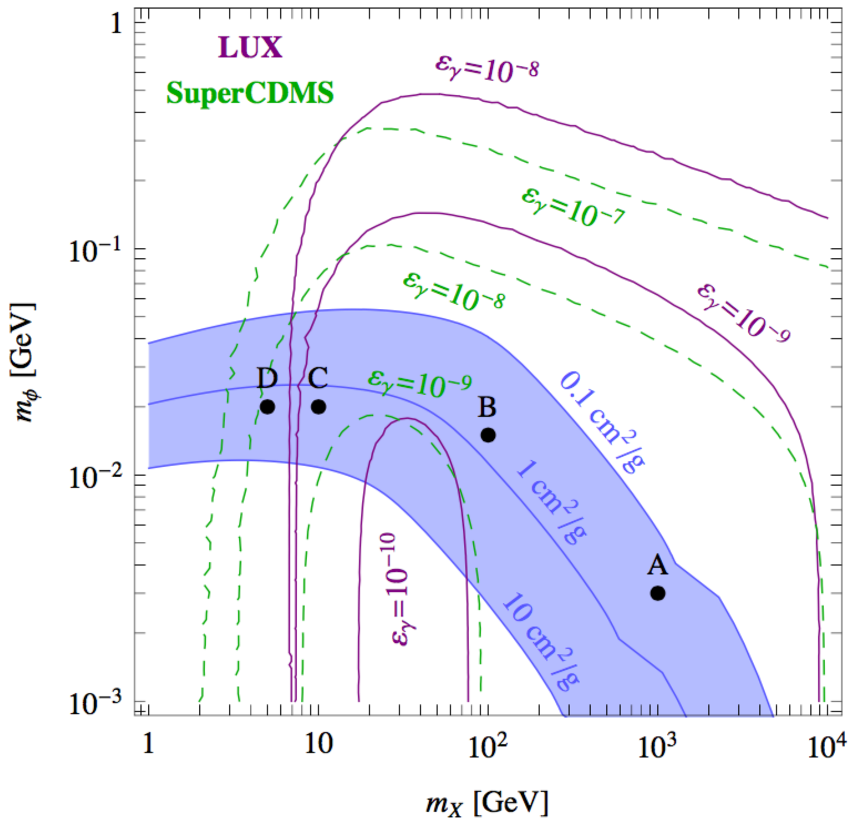
An, Echenard, Pospelov, Zhang (PRL 2015)

Tsai, Wang, Zhao (PRD 2015)

Shepherd, Tait, Zaharijas (PRD 2009)

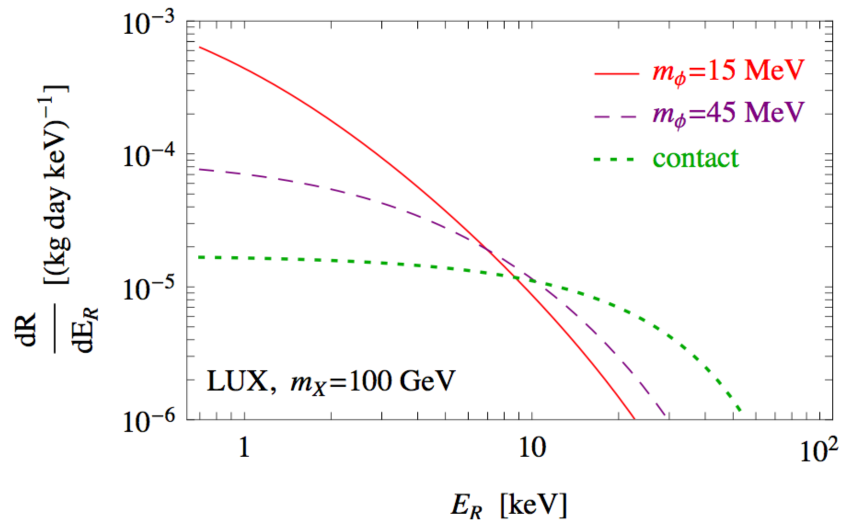
SIDM Direct Detection

- Bound on the mixing parameter and smoking-gun signatures

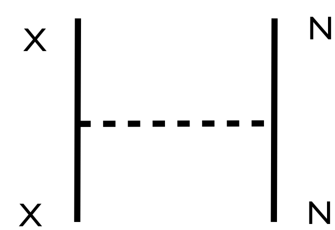


Kaplinghat, Tulin, HBY (PRD 2013)

Del Nobile, Kaplinghat, HBY (JCAP 2015)



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



$$q^2 = 2m_N E_R$$

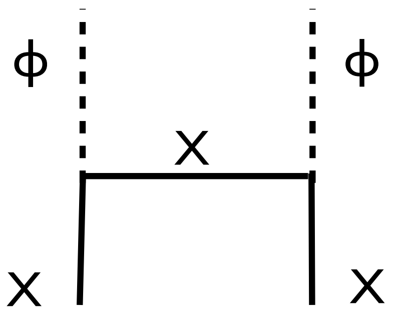
q~1 MeV

WIMPs: m_W>>q, SIDM: m_ϕ~q

experiments with different targets/modulation

SIDM Indirect Detection

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

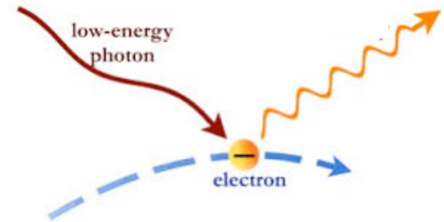


$m_\phi \sim 10$ MeV

$\phi \rightarrow$ electrons/neutrinos

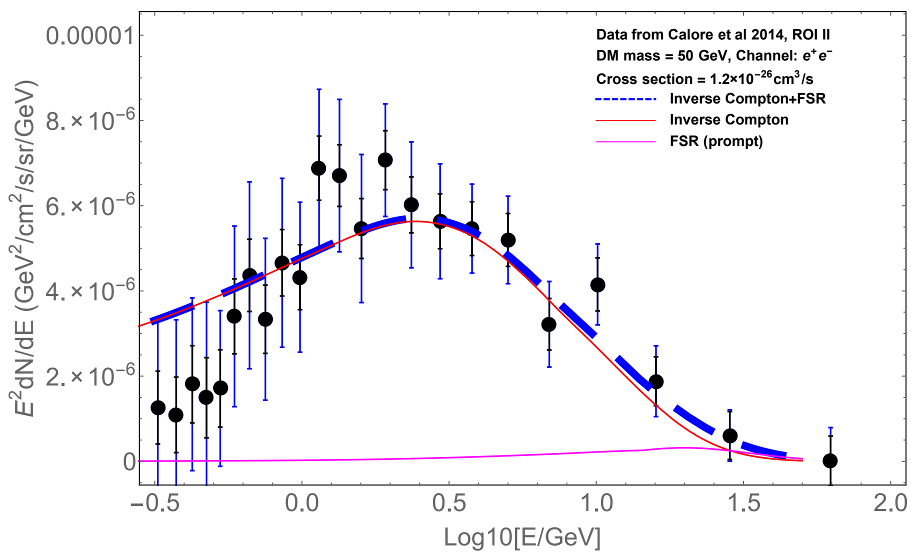
Inverse Compton scattering

starlight



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

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



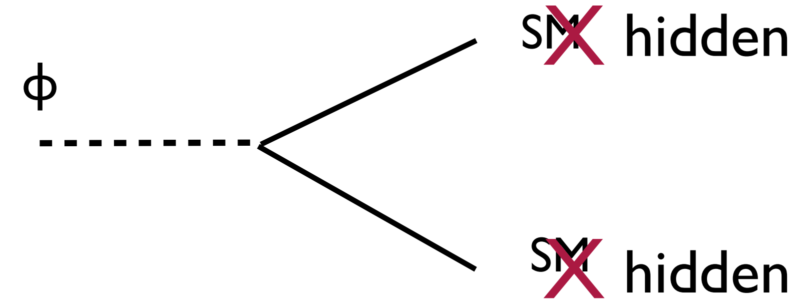
Kaplinghat, Linden, HBY (PRL 2015)

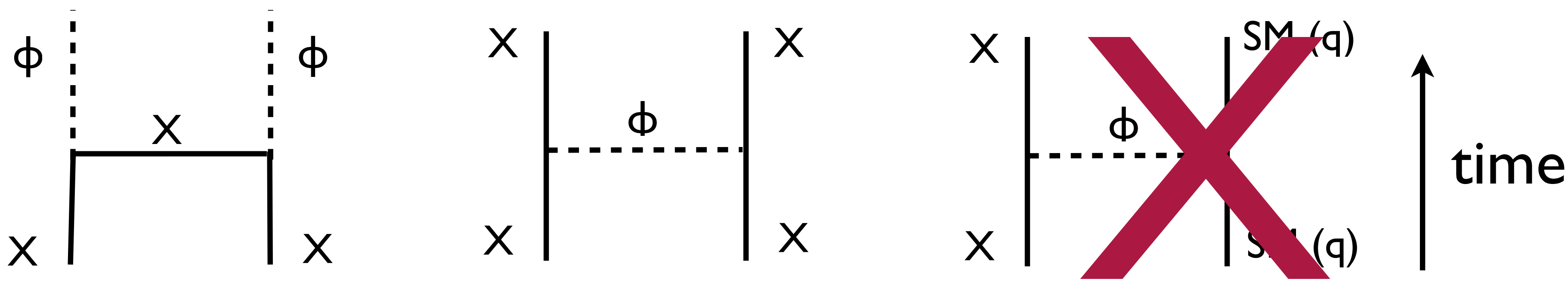
- No IC signal from dwarfs
- Soft electron spectrum (AMS02)
- The IC signal is spherically symmetric

What if SIDM is Hidden…

- The mediator decays before BBN: lifetime of ϕ is ~1 second

$$\epsilon \gtrsim 10^{-10}\sqrt{10\ \mathrm{MeV}/m_\phi}$$





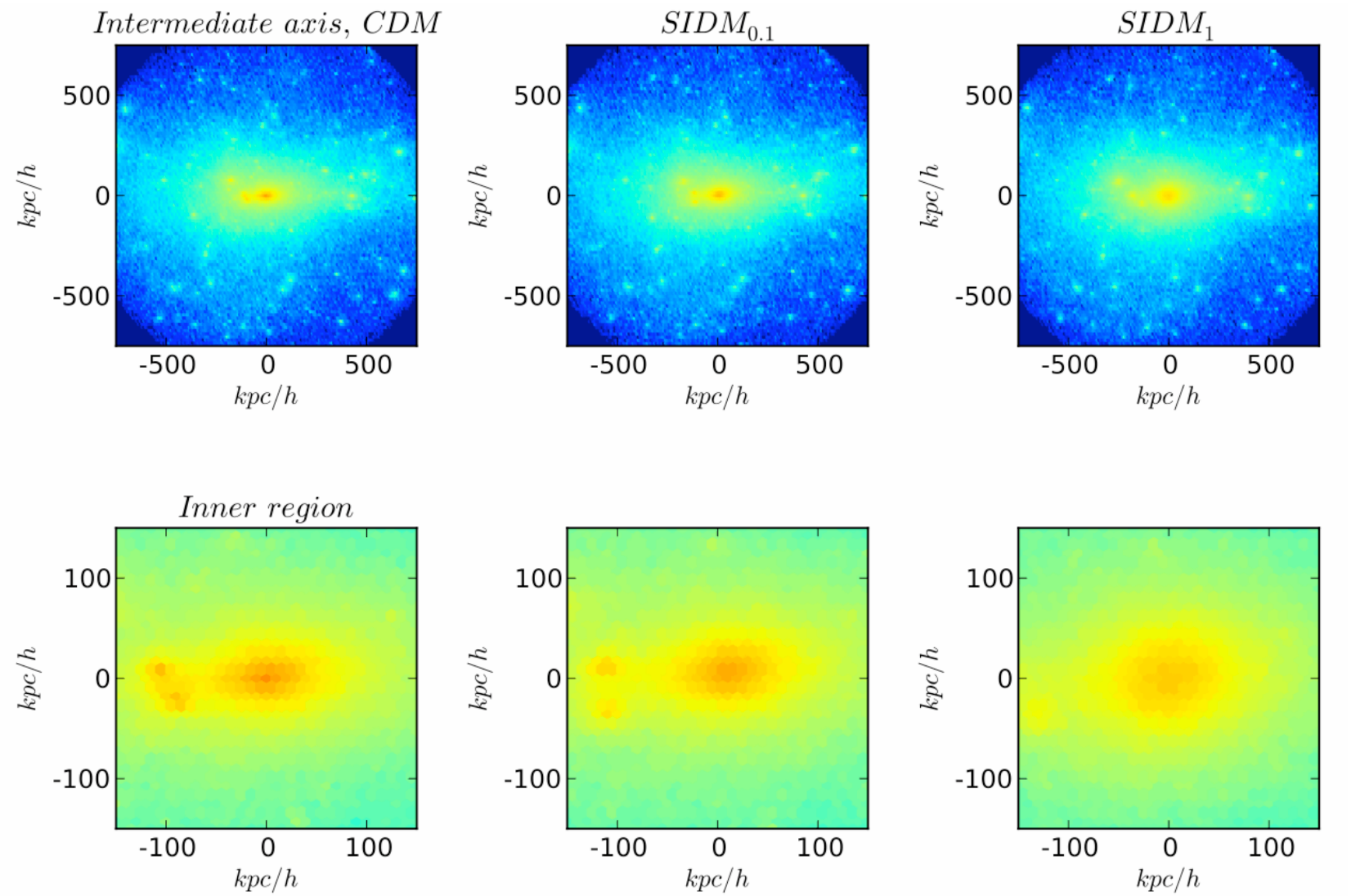
ϕ →electrons/neutrinos

Nightmare scenario?

Need unique signatures, independent of DM-SM interactions

Idea1: Halo Morphology

- SIDM halos are more spherically symmetric than CDM ones

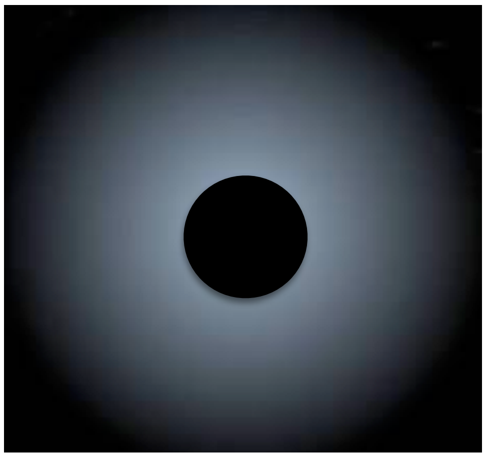


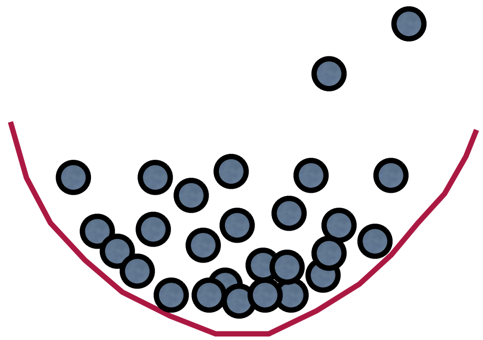
Peter+(2013)

Tying SIDM to Baryons

- SIDM: equilibrium

ideal gas with gravity

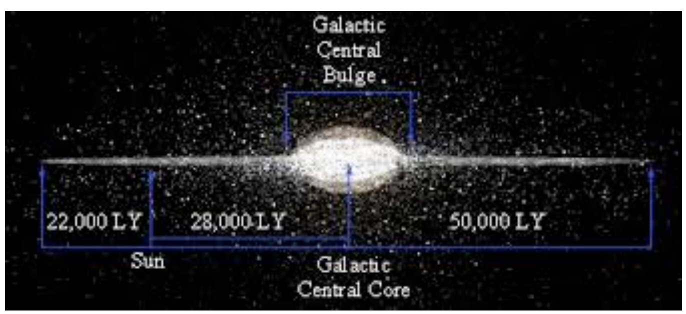




Isothermal
Maxwellian distribution

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

- If $\Phi_{tot} \sim \Phi_b$, SIDM follows the stellar distribution! $\rho = \rho_0 e^{-\Phi_b/\sigma_0^2}$

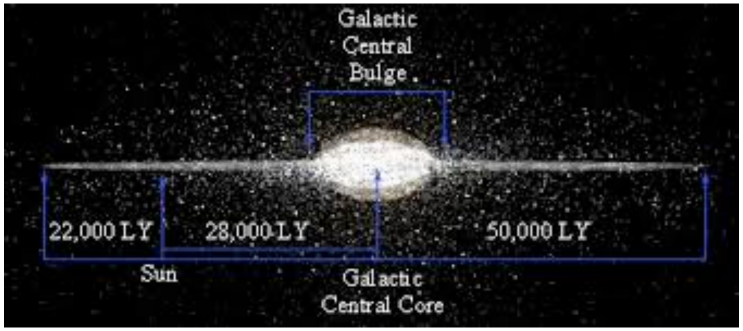


Stellar bulge in the Milky Way

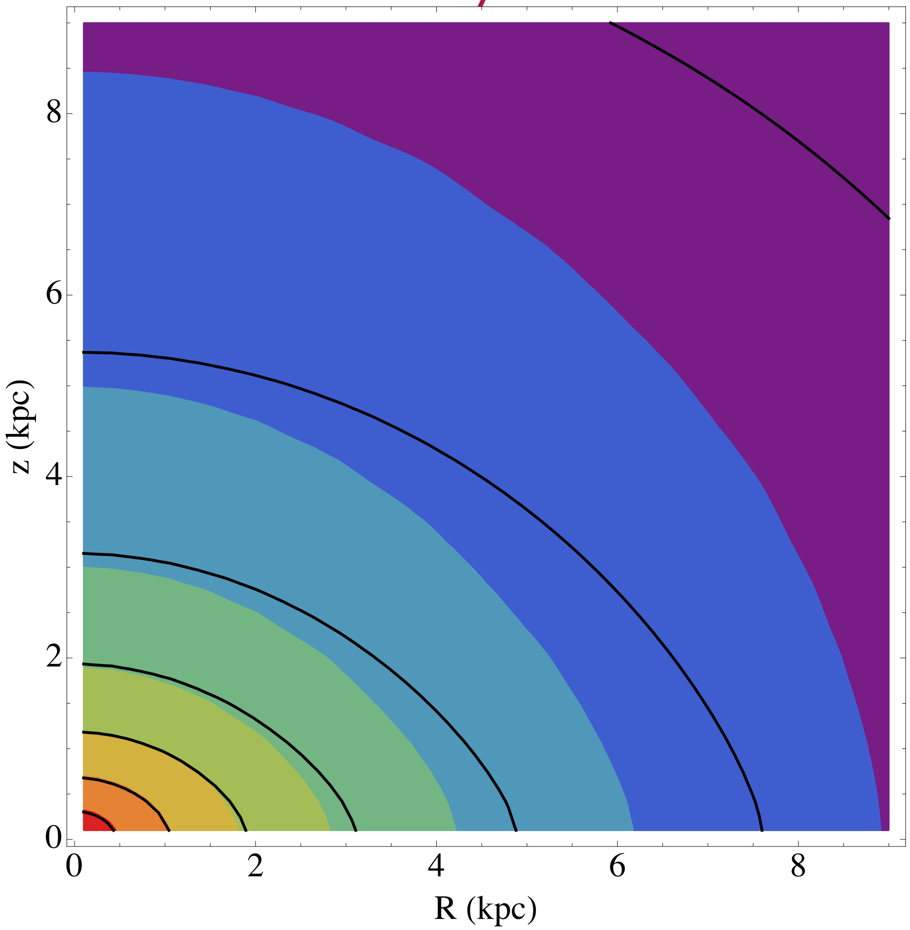
Kaplinghat, Linden, Keeley, HBY (PRL 2014)

Tying SIDM to Baryons

- SIDM may follow the stellar distribution; halo morphology



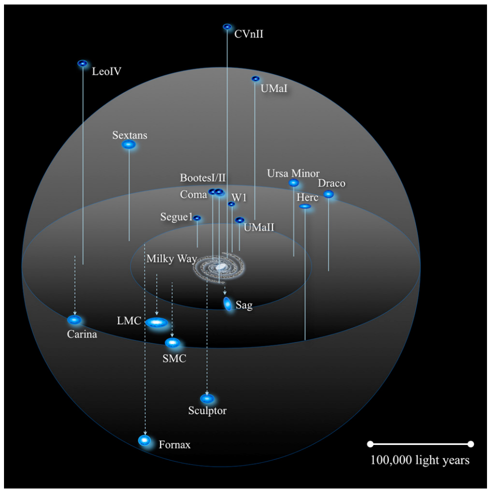
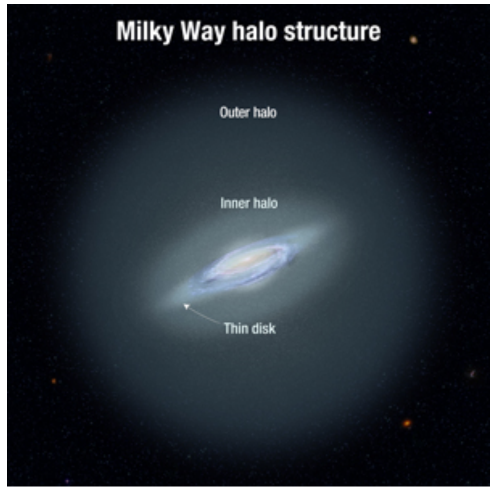
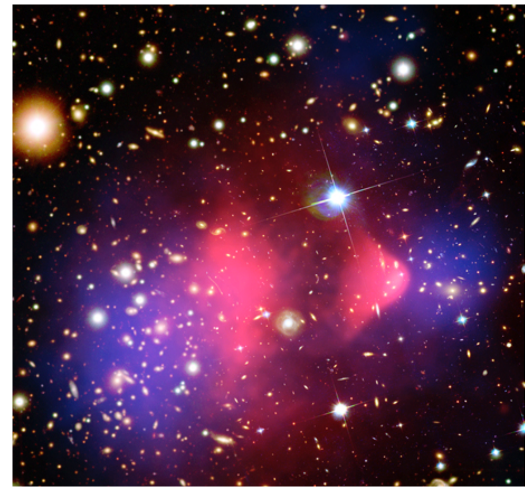
SIDM density contour



Kaplinghat, Linden, Keeley, HBY (PRL 2014)

Correlation between the stellar distribution and the SIDM distribution

Idea 2: Dark Matter "Colliders"

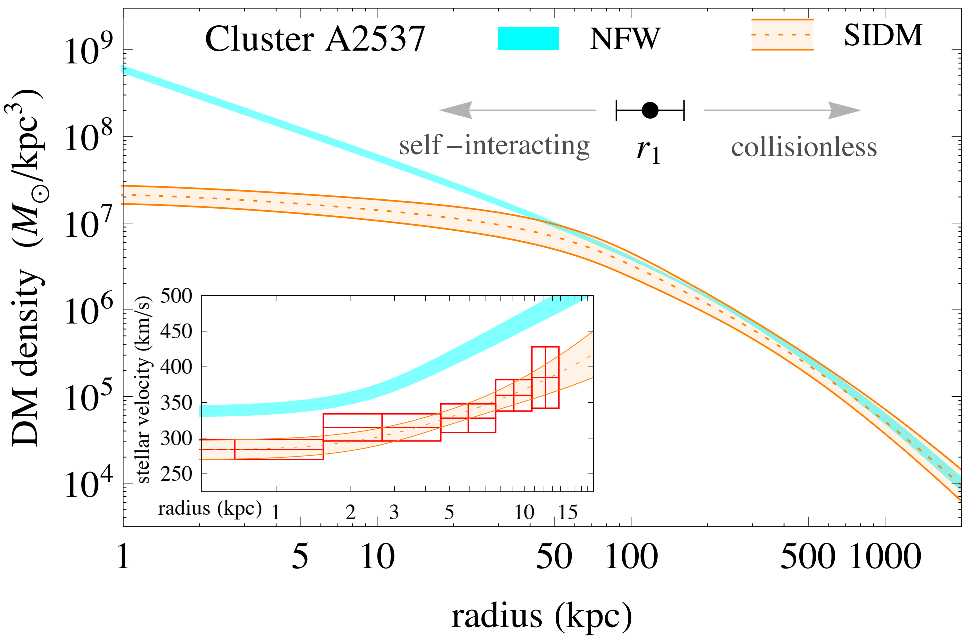
Dwarf galaxies	MW-size galaxies	Clusters
		
"B-factory" (v~30 km/s)	"LEP" (v~200 km/s)	"LHC" (v~1000 km/s)

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:

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

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

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

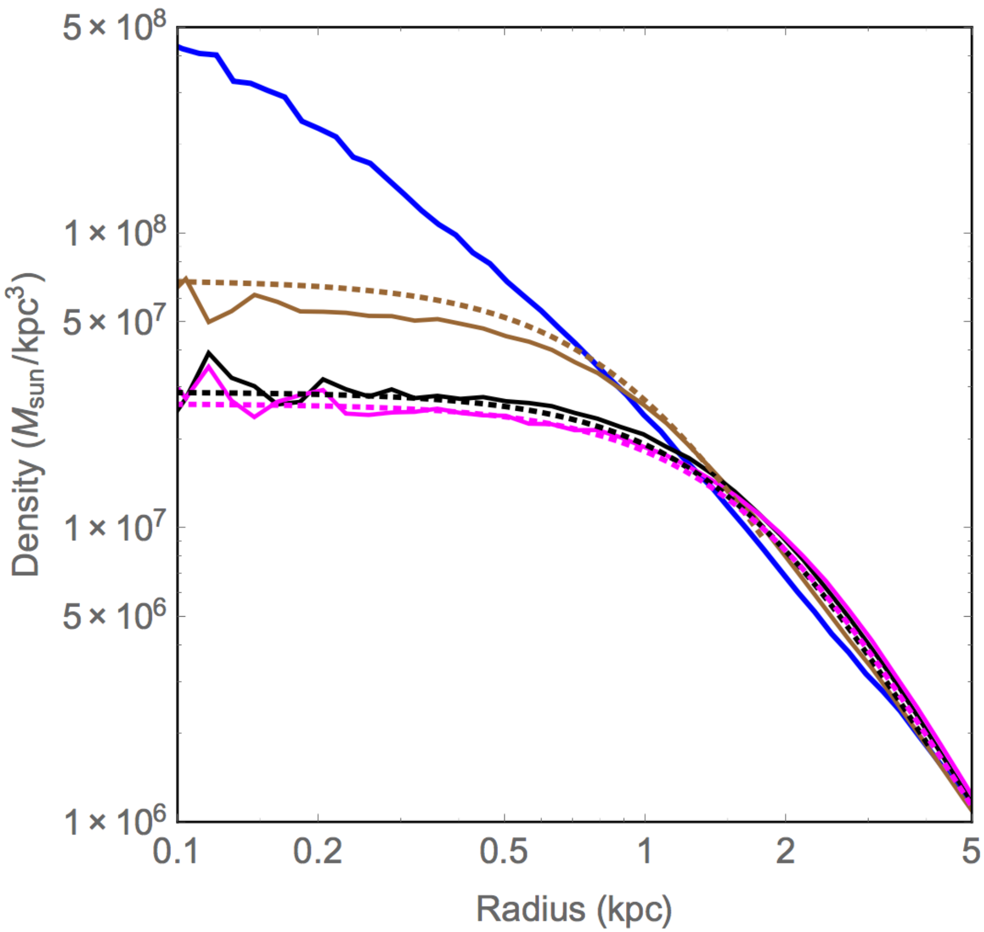
isothermal distribution

NFW

Kaplinghat, Tulin, HBY (PRL 2015)

Modelling SIDM Halos

- The model works remarkably



Solid: simulations, Elbert+(2015)
Dashed: analytical modelling

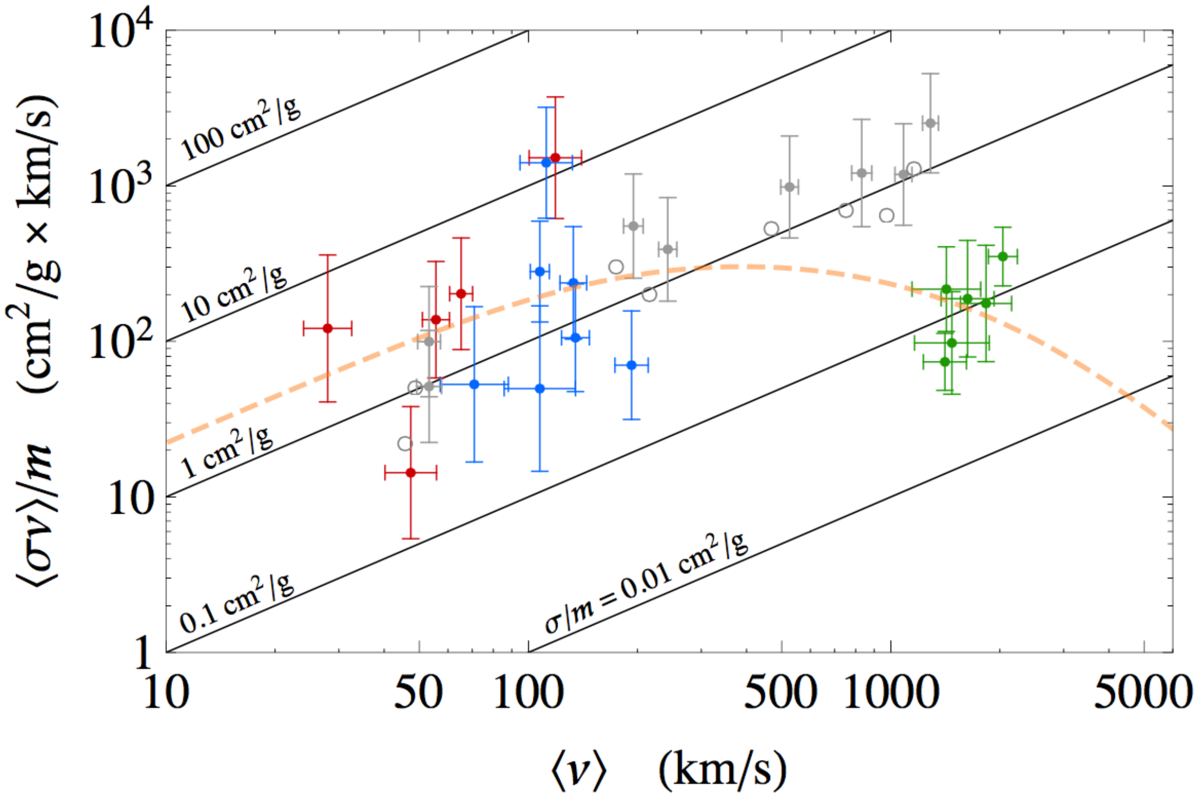
0 cm^2/g
1cm^2/g
5 cm^2/g
10 cm^2/g

The equilibrium assumption works!

Kaplinghat, Tulin, HBY (PRL 2015)

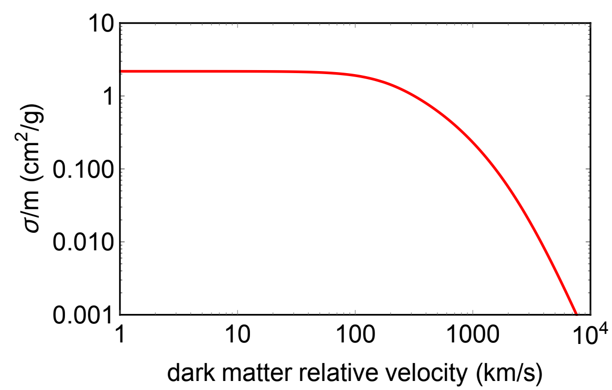
SIDM from Dwarfs to Clusters

- 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 of the CDM halo

favors a mild v-dependence



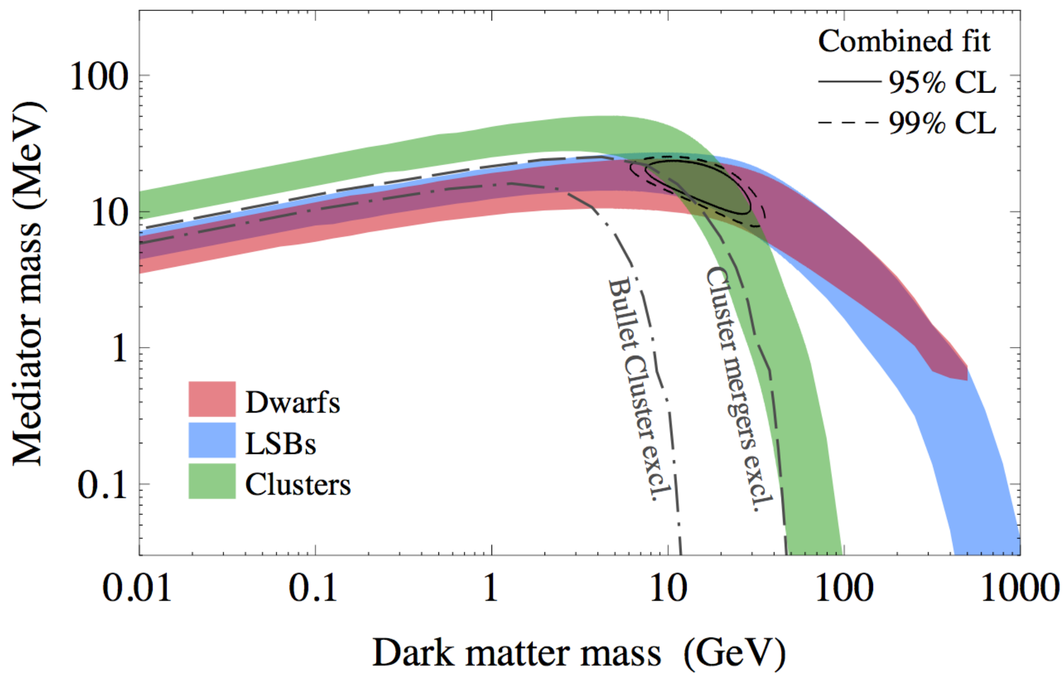
Galaxies: ~2 cm^2/g
Clusters: ~0.1 cm^2/g

Bullet Cluster: < 2 cm^2/g

Kaplinghat, Tulin, HBY (PRL 2015)

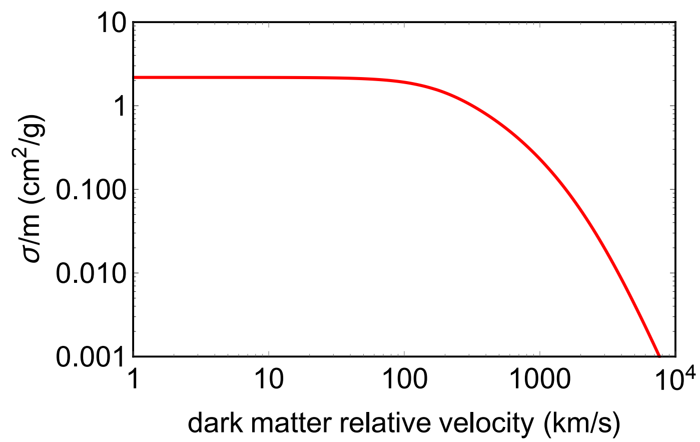
Measuring Dark Matter Mass

- 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

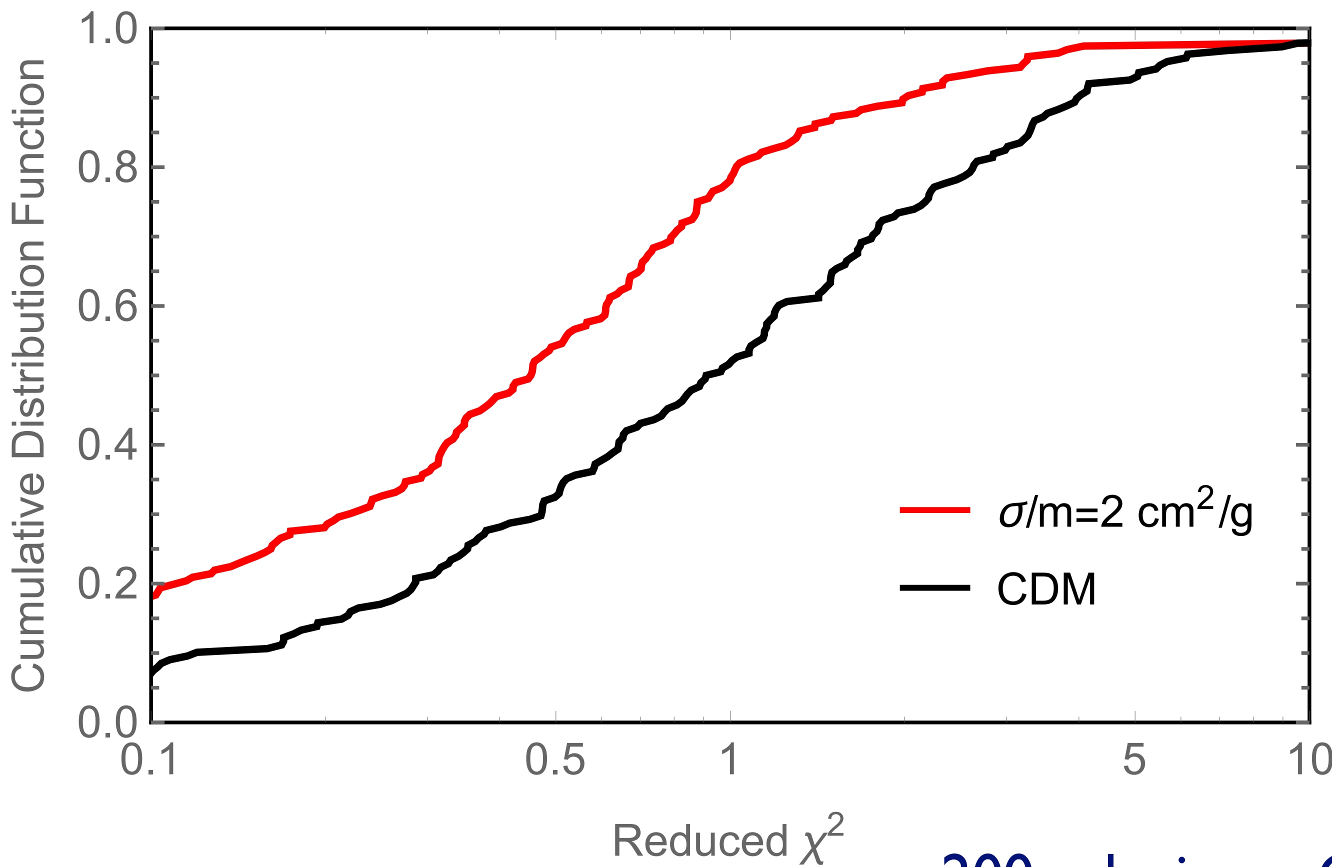
Kaplinghat, Tulin, HBY (PRL 2015)

mild dependence on α_X

α_X=0.001–0.1

m_X: ~5-30 GeV

More Galaxies…

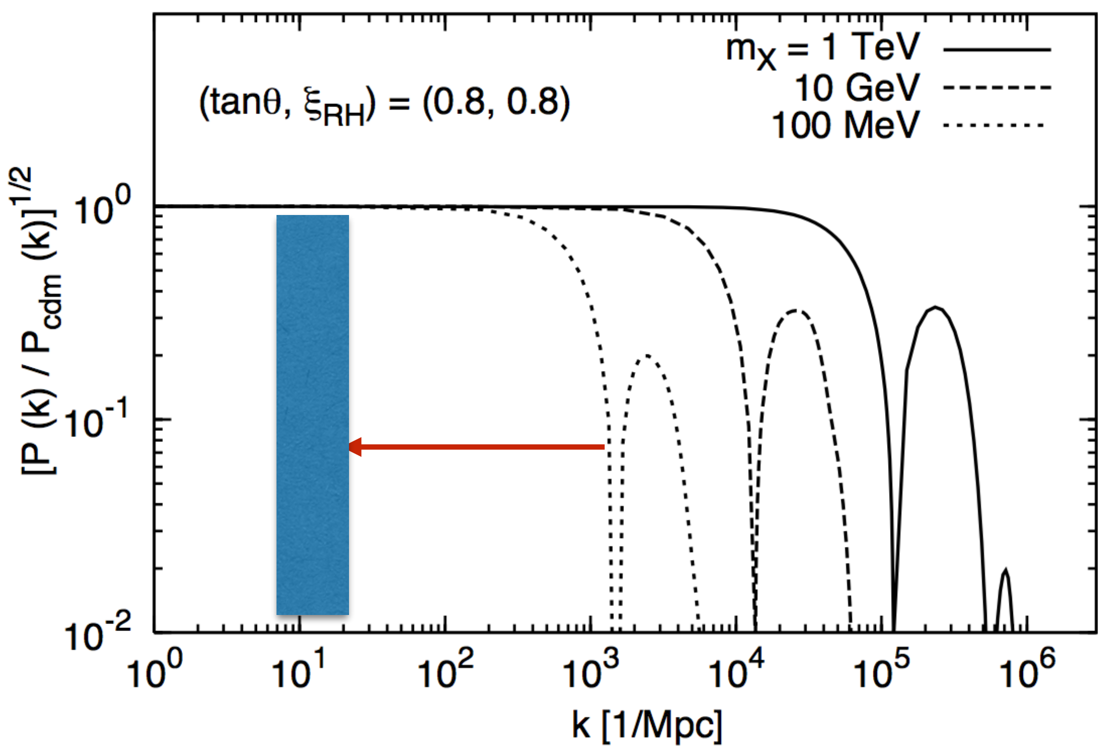


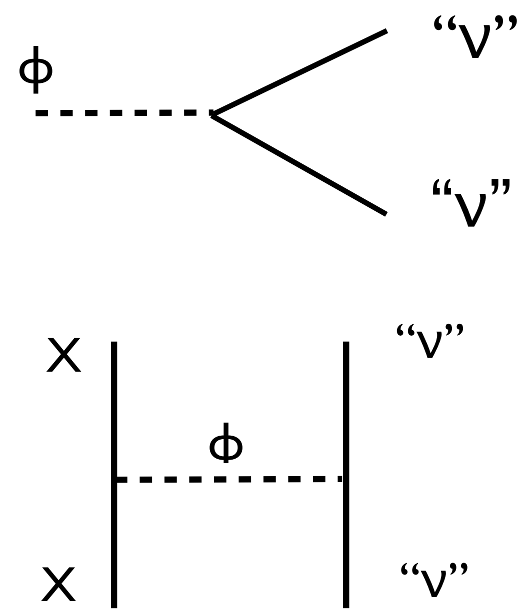
~200 galaxies Credit: Pace

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

Idea 3: Dark Acoustic Oscillation

- Roles of dark radiation





Feng, Kaplinghat, Tu, HBY (JCAP 2009)
Ran, Kaplinghat, HBY (in preparation)

- extra d.o.f., CMB/BBN
- damp the DM power spectrum
- reduce the number of sub-halos

ETHOS Collaboration, See Zavala's talk

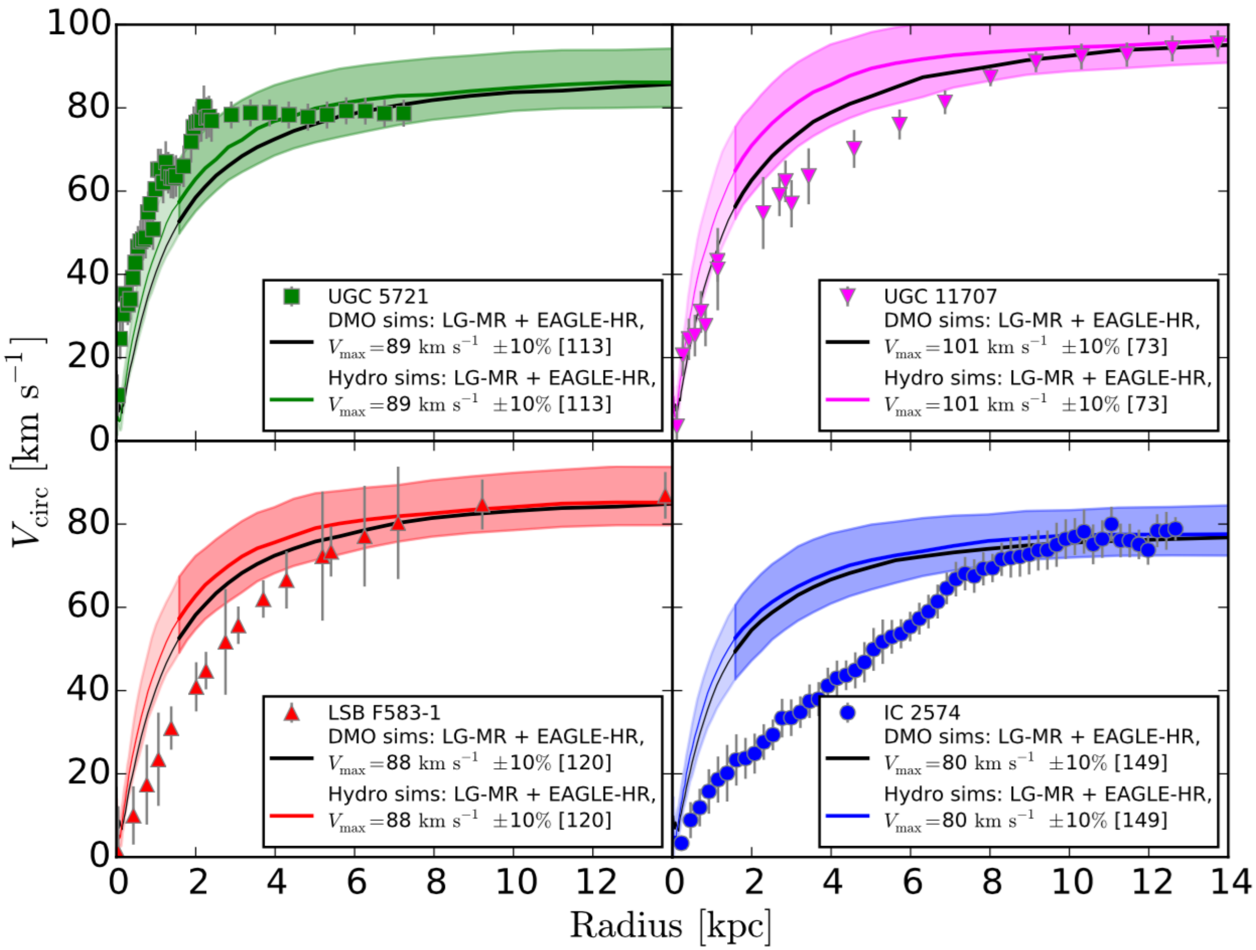
Summary and Outlook

- 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

Diversity

- Puzzle 1: The diversity of spiral galaxies

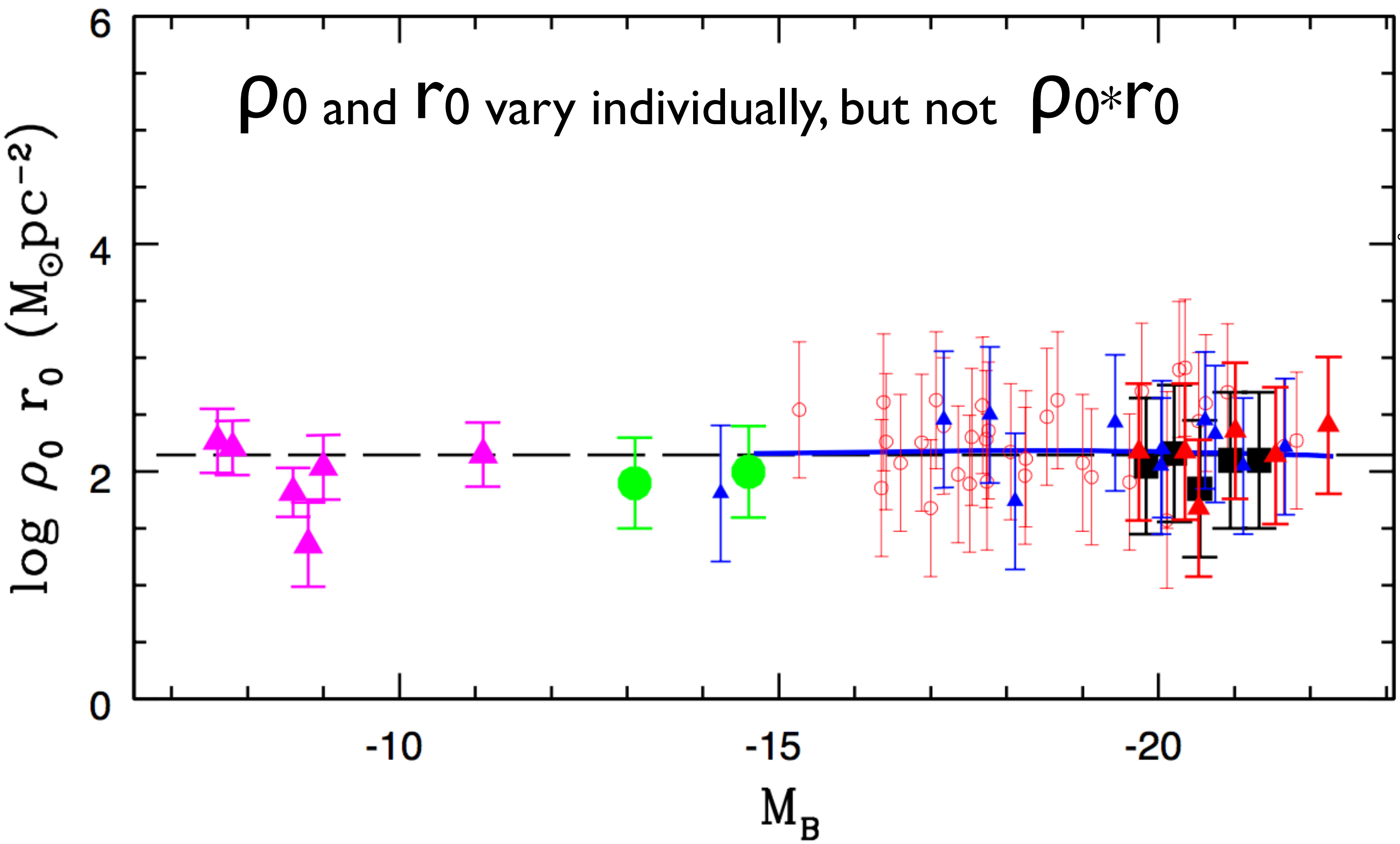


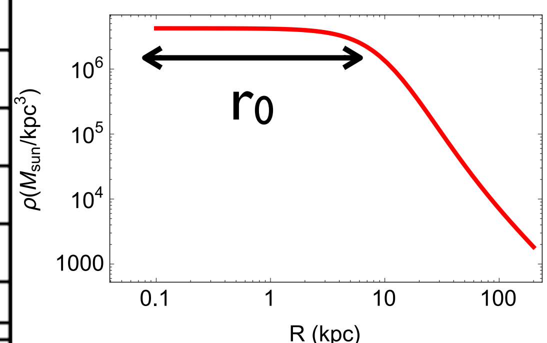
Oman+ (2015)

de Naray, Martinez, Bullock, Kaplinghat (2009)

Uniformity

- Puzzle 2: Constant DM halo surface density





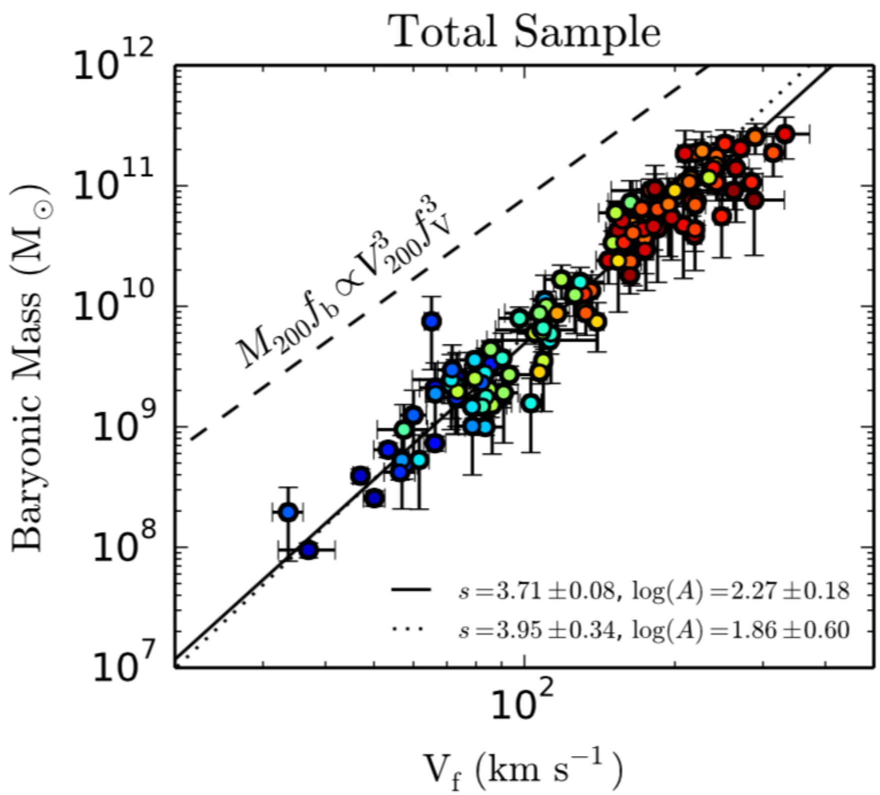
$$\rho(r_0) = \rho_0/2$$

Donato+(2009)

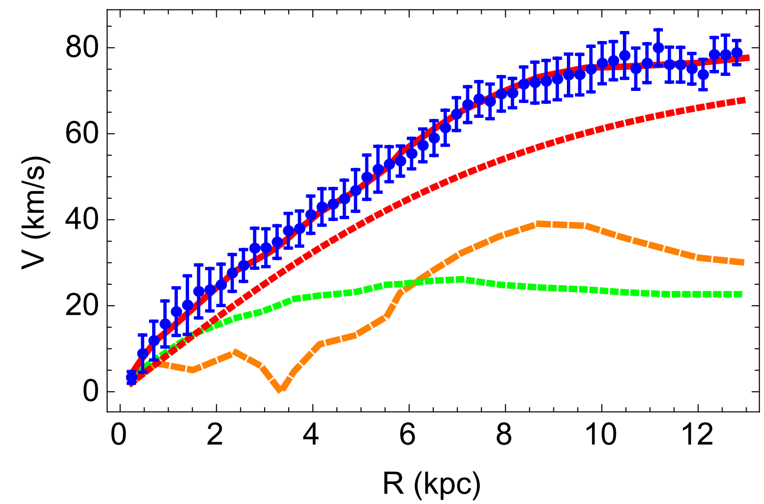
Kormendy, Freeman (2004)

Disk-Halo Conspiracy

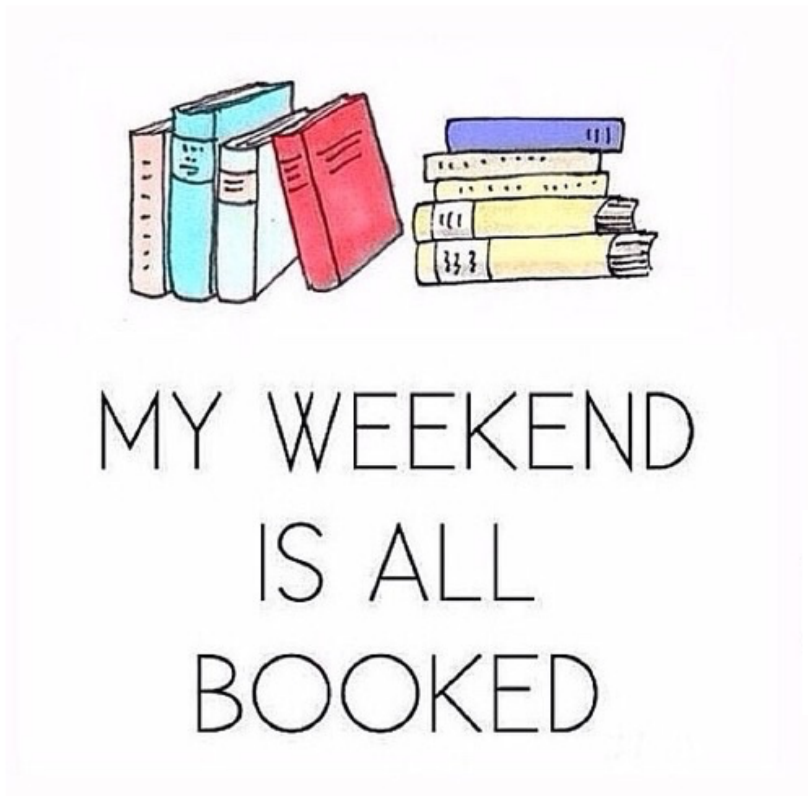
- Puzzle 3: The baryonic Tully-Fisher relation



Lelli, McGaugh, Schombert (2016)



We have a lot to do!



Stay tuned!

Thank You