Title: The Self-Interacting Dark Matter Paradigm

Date: Apr 26, 2016 01:00 PM

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Abstract: <p>Astrophysical observations spanning dwarf galaxies to galaxy clusters indicate that dark matter halos are less dense in their central regions compared to expectations from collisionless dark matter N-body simulations. Using detailed fits to dark matter halos of galaxies and clusters, we show that self-interacting dark matter may provide a consistent solution to the dark matter deficit problem across all scales, even though individual systems exhibit a wide diversity in halo properties. </p>

The Self-Interacting Dark Matter Paradigm

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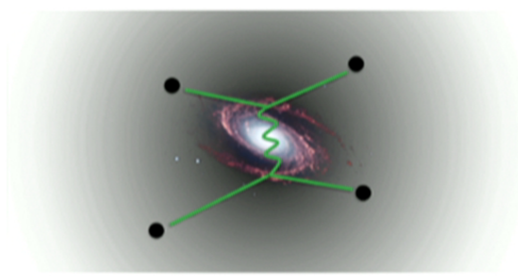
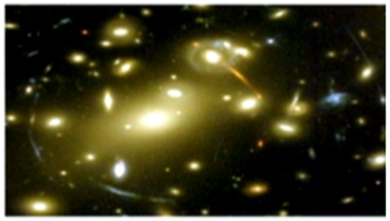


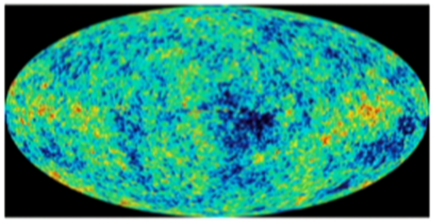
PI Particle Physics Seminar April 26, 2016

A review article for Physics Reports: Sean Tulin, HBY arXiv: 1605.XXXXX

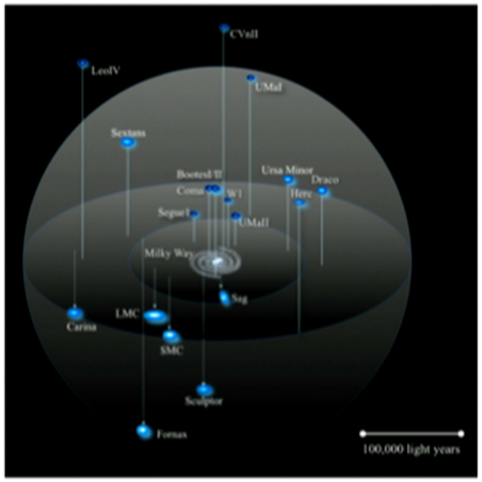
Cold Dark Matter

- Large scales: very well



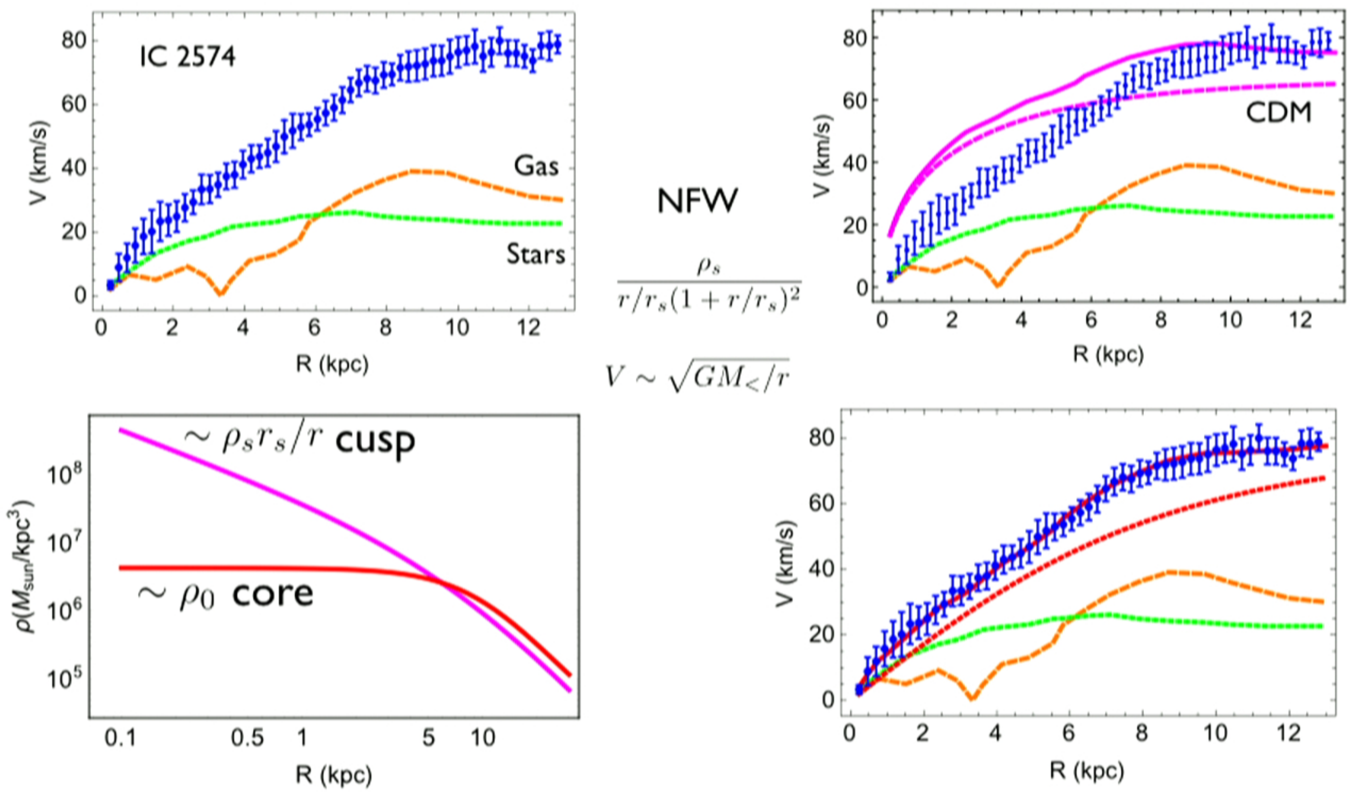


- Small scales (dwarf galaxies, subhalos, galaxy clusters): ?



Core VS. Cusp Problem

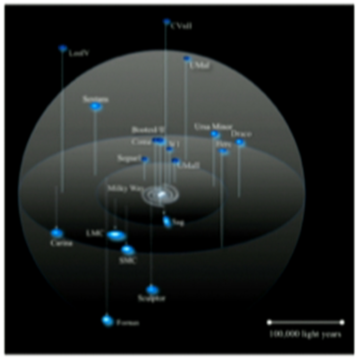
- DM-dominated systems (dwarfs, LSBs) from THINGS Oh+(2011)



Flores, Primack (1994), Moore (1994)

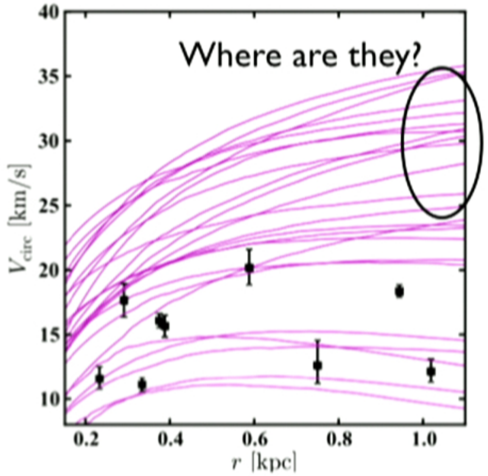
Too-Big-to-Fail Problem

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



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

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



Biggest predicted subhalos from CDM simulations

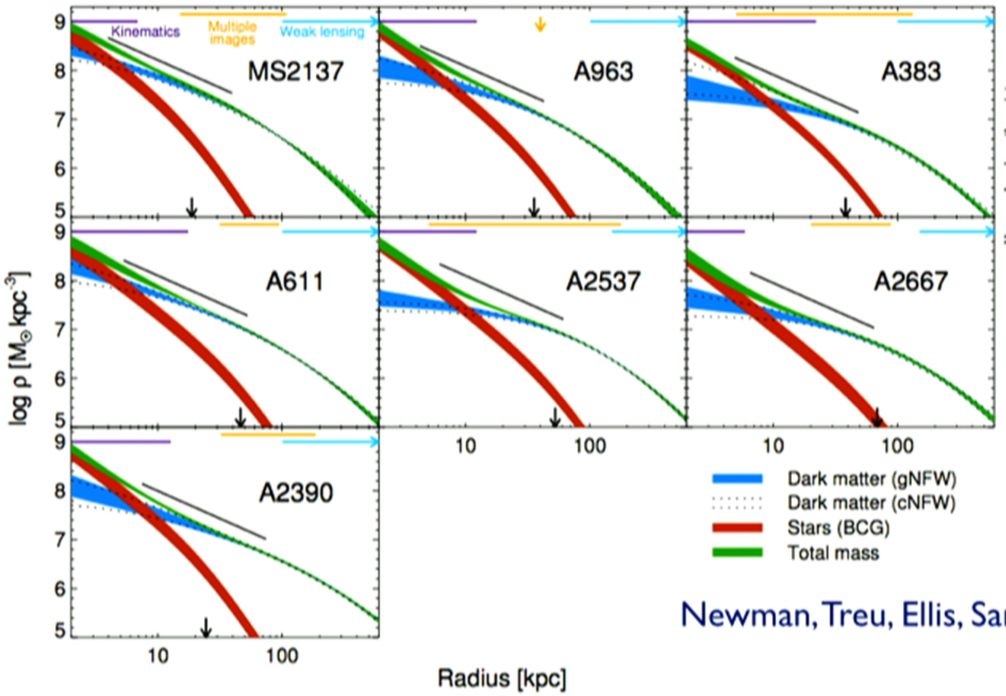
Brightest observed galaxies in the MW

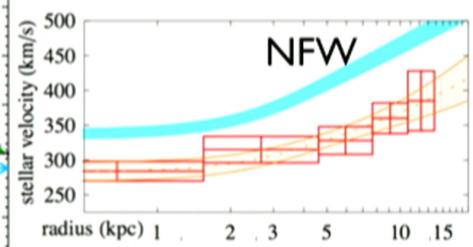
- Most massive subhalos in CDM simulations are too dense to host observed galaxies in the Milky Way
- On the other hand, it is easier for stars to form in massive subhalos

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

Even Galaxy Clusters!

- Seven well-resolved galaxy clusters



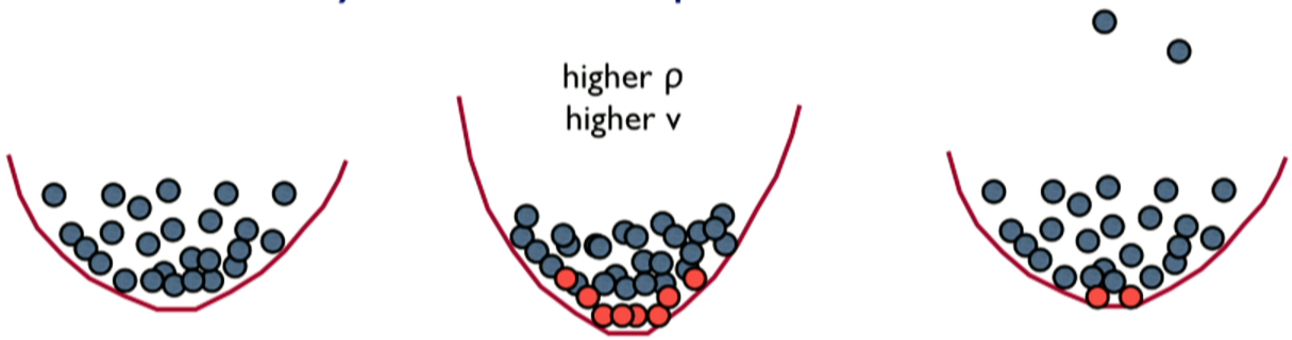


Newman, Treu, Ellis, Sand (2013)

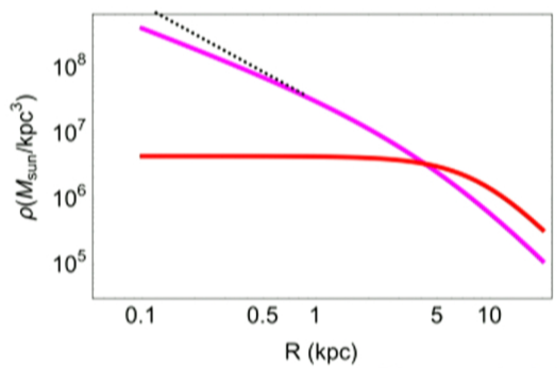
- CDM halos contain more DM in the central regions than needed

Baryon Physics?

- Violent baryonic feedback process



Baryonic Infall   Supernova Explosion



gravitational binding energy VS.
energy injection from supernovae

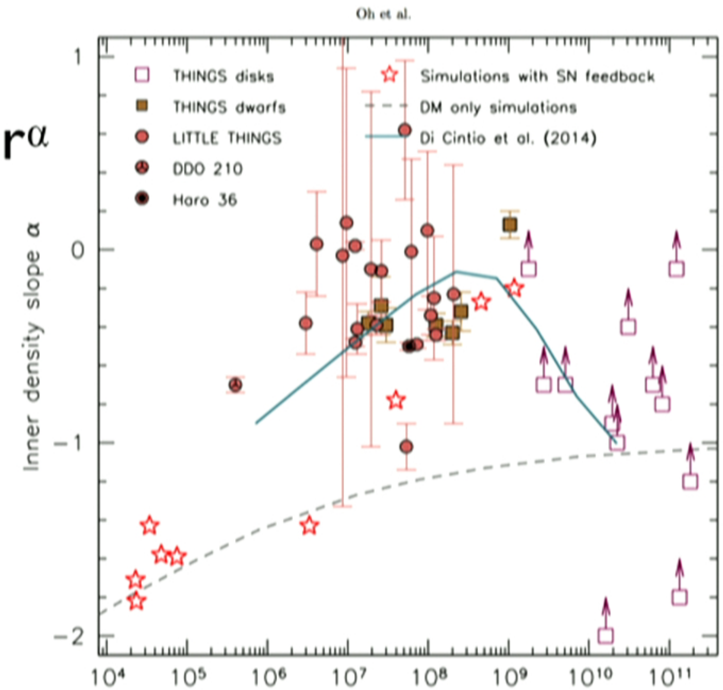
only works $r<r_*$

Blumenthal, Flores, Primack (1986)   Navarro, Eke, Frenk (1996)

Baryon Physics?

- Violent baryonic feedback process

r^{α}



TBTF galaxies

MW

Oh+ (2015)

depends on the stellar mass
Governato+ (2012)

depends on when it occurs
Onorbe+(2015)

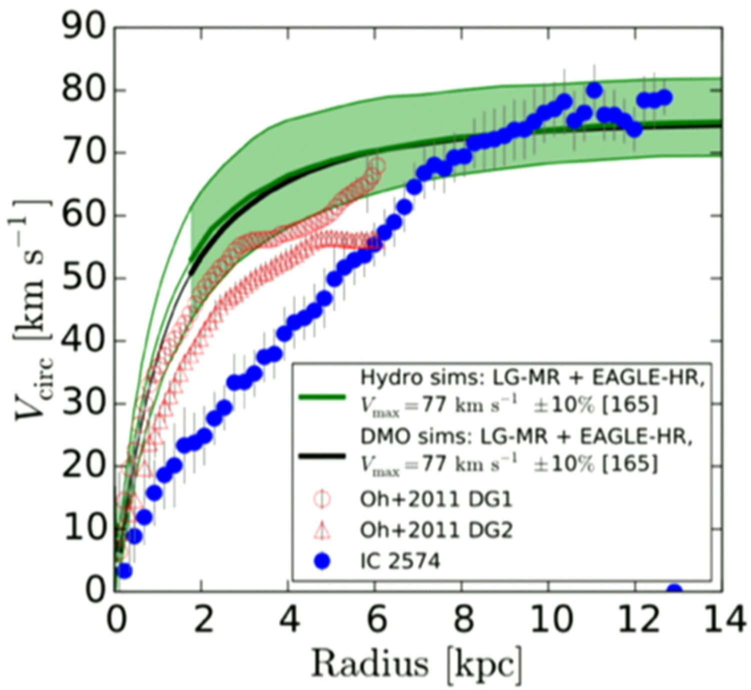
galaxies with cores larger than r_*
Papastergis, Shankar (2015)

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)

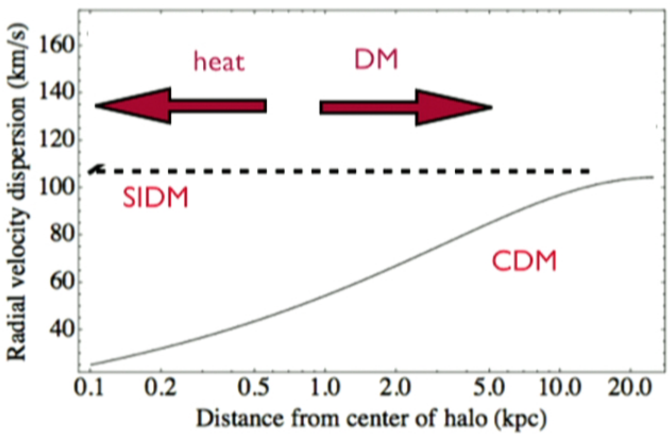
The feedback effect depends on how you implement the feedback process!

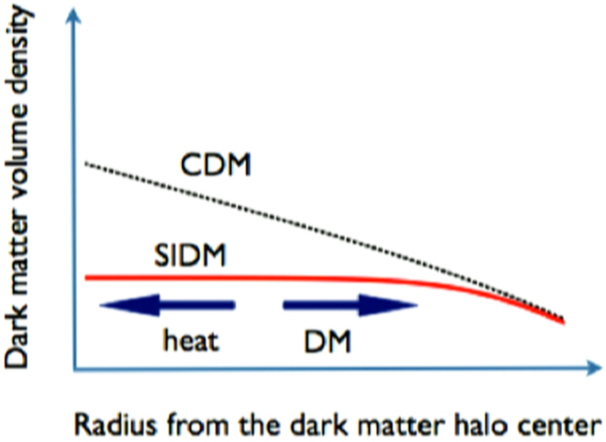
We are still debating!

Dark Matter Physics?

- Self-interactions can reduce the central DM density

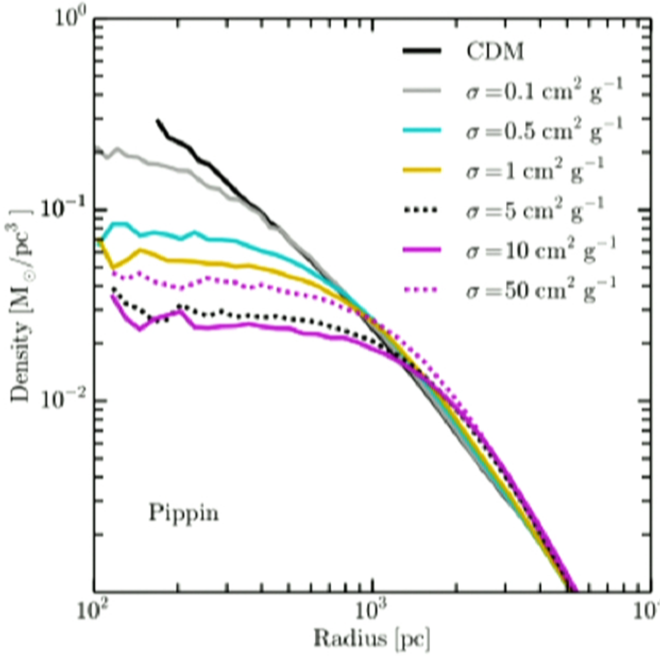
Spergel, Steinhardt (2000)

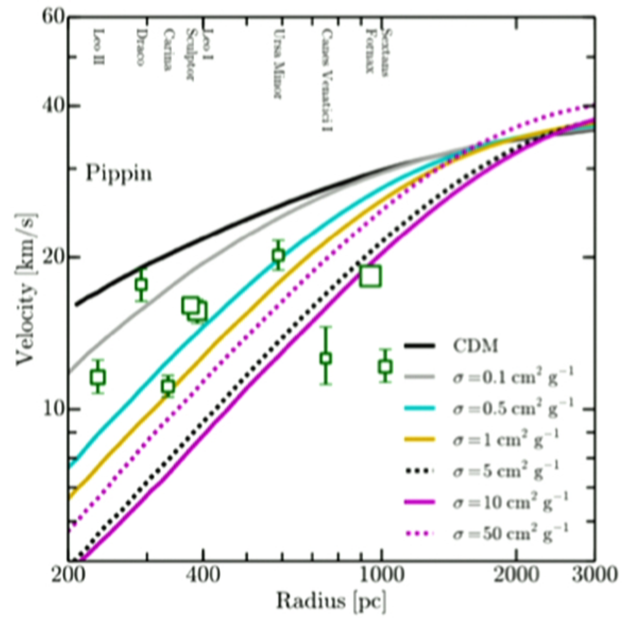




Self-interacting Dark Matter

- Self-interactions can reduce the central DM density





Elbert+ (2014)

$\sigma/m_X \sim 1$ cm^2/g for v ~ 30 km/s

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

Challenges

- A really large scattering cross section!

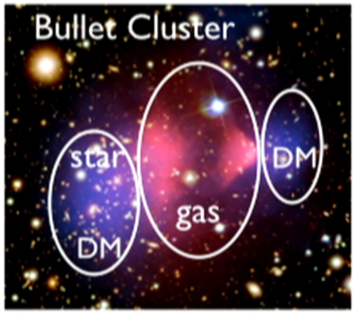
a nuclear-scale cross section

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

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

SIDM indicates a new mass scale

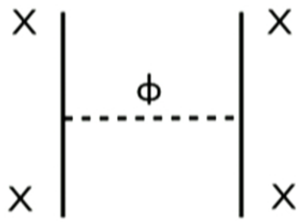
- How to avoid the constraints on large scales?



$\sigma/m_X < 1 \mathrm{cm}^2/\mathrm{g}$ for 3000 km/s (Bullet cluster)

In particular, if $\sigma \sim$constant   Spergel, Steinhardt (2000)

SIDM Particle Physics

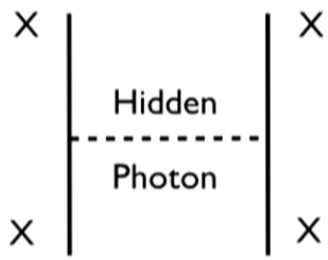


- SIDM indicates light mediators

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

in the perturbative and small velocity limit

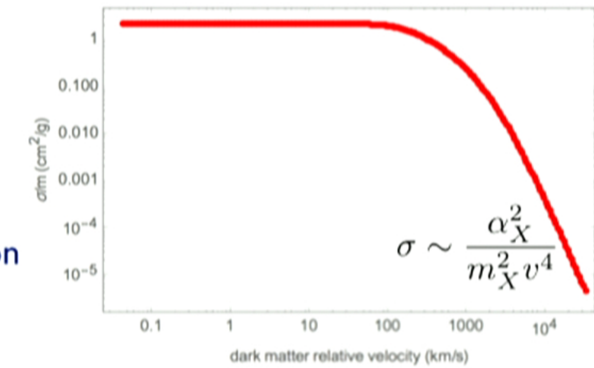
- With a light mediator, DM self-scattering is velocity-dependent



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

$m_X v >> m_\phi$ Rutherford limit

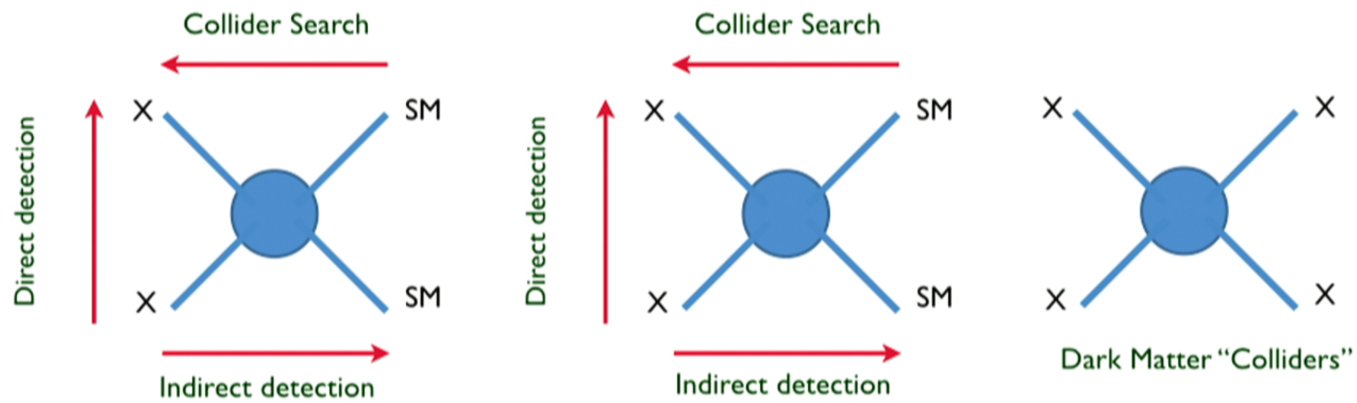
$m_X v << m_\phi$ contact interaction



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

The SIDM Paradigm

- The SIDM paradigm is predictive



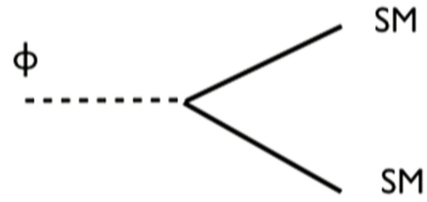
the WIMP paradigm the SIDM paradigm

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)

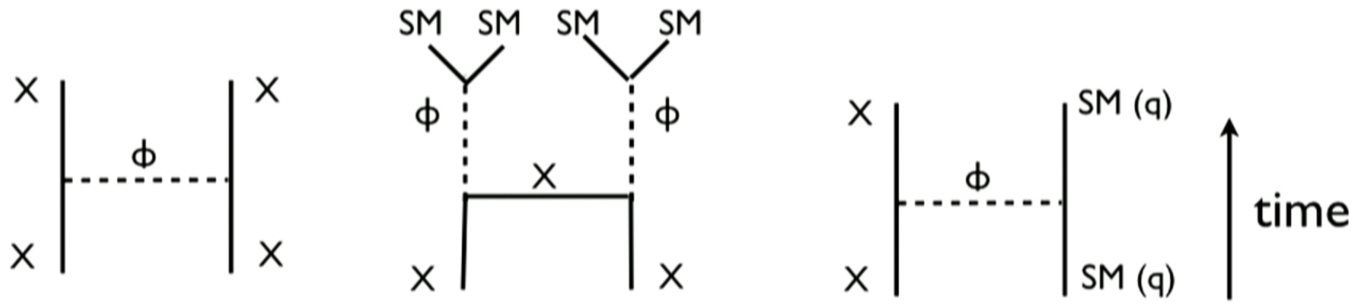
SIDM Cosmology

- 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



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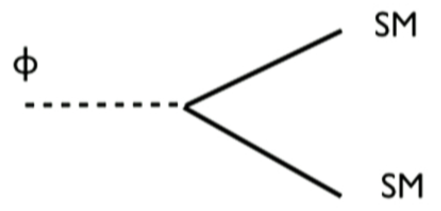

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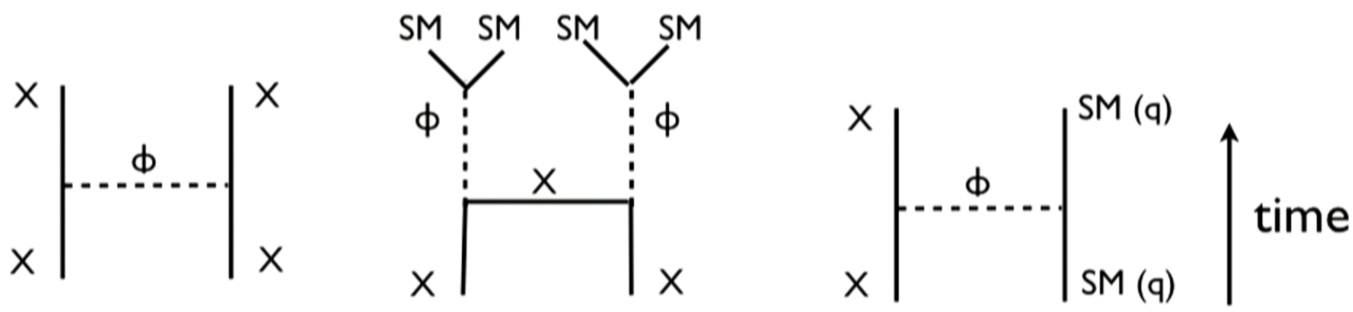
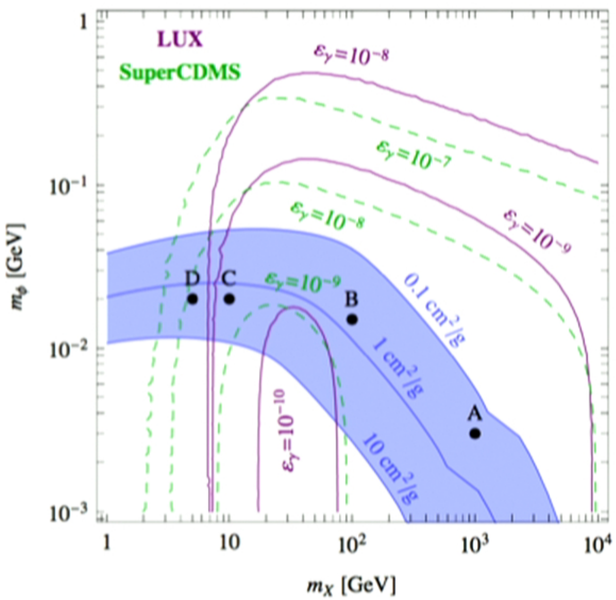
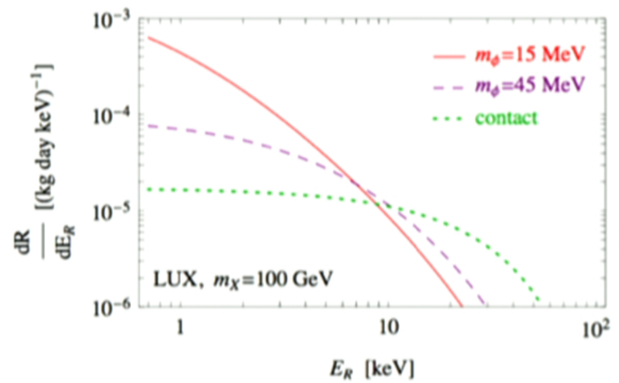


SIDM Direct Detection

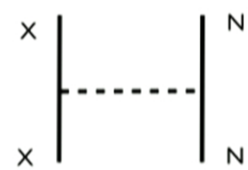
- Strong bound on the mixing parameter





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

$$q^2 = 2m_N E_R$$

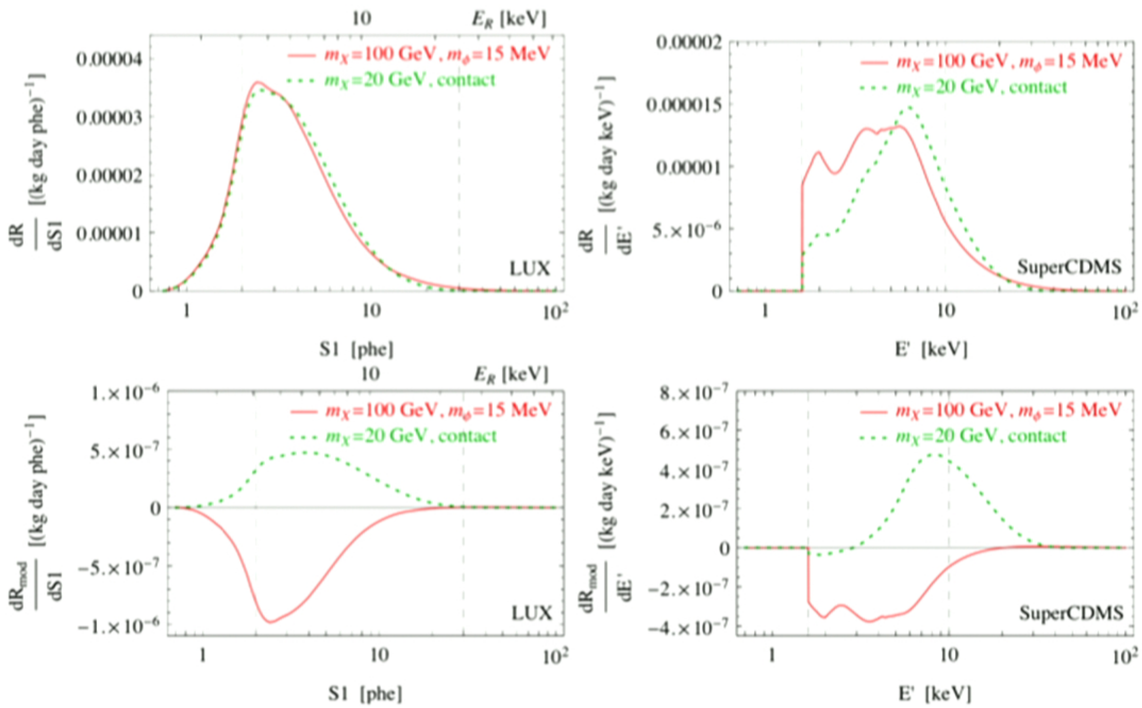


Del Nobile, Kaplinghat, HBY (JCAP 2015)

Kaplinghat, Tulin, HBY (PRD 2013)

Smoking-Gun Signatures

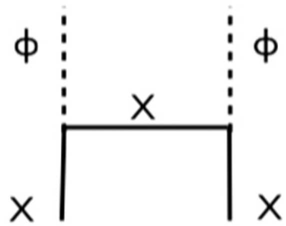
- Different nuclear targets and modulation signals



Del Nobile, Kaplinghat, HBY (JCAP 2015)

SIDM Indirect Detection

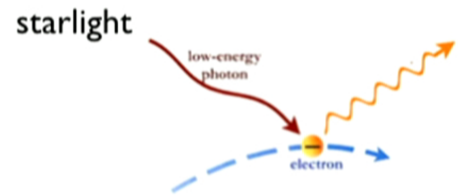
- Lighting up the galactic center, but not dwarf galaxies!

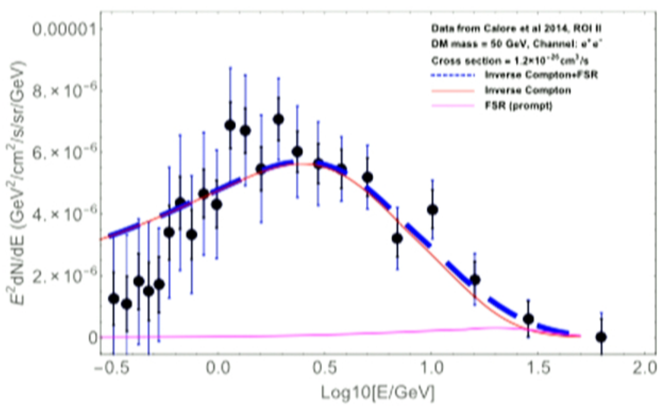


$m_\phi \sim 10$ MeV

$\phi \to$ electrons/neutrinos

Inverse Compton scattering





Kaplinghat, Linden, HBY (PRL 2015)

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

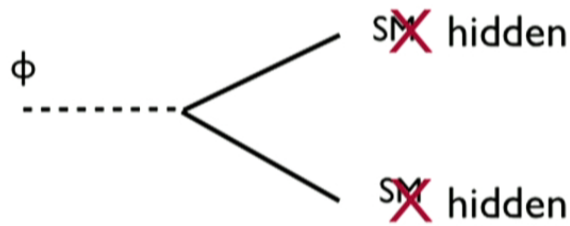
$$E_{\mathrm{ISRF}} \sim 1\ \mathrm{eV}$$

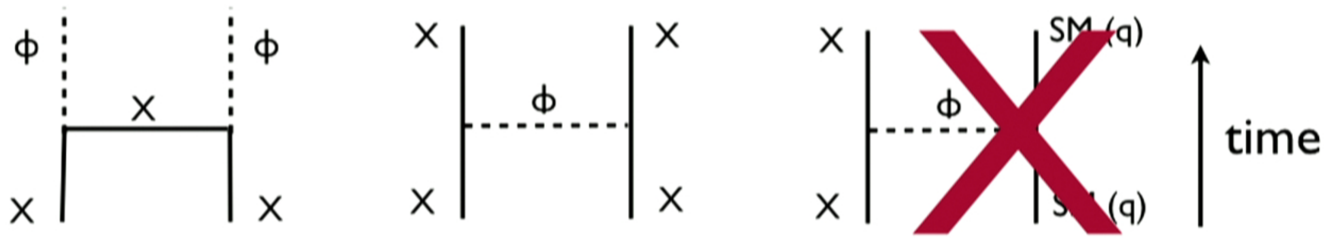
- No IC signal from dwarfs
- Soft electron spectrum (AMS02)
- The IC signal is spherically symmetric

What if SIDM is Hidden…

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

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





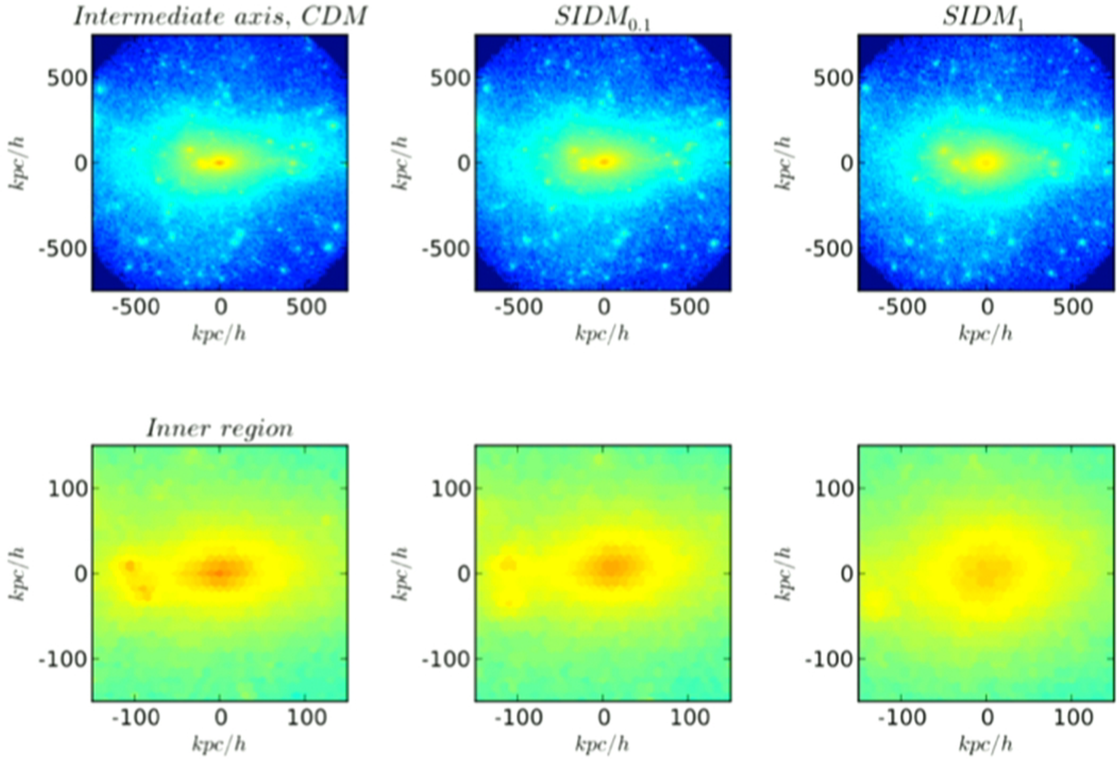
ϕ → electrons/neutrinos

Nightmare scenario?

Need unique signatures, independent of DM-SM interactions

Idea 1: Halo Morphology

- SIDM halos are more spherically symmetric than CDM ones

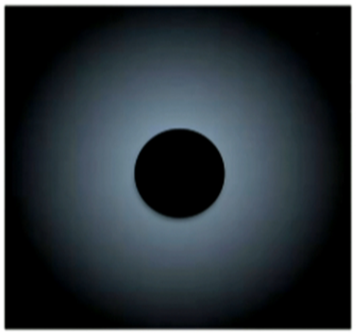


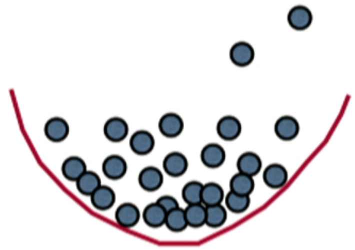
Peter et al. (2013)

Tying SIDM to Baryons

- SIDM: equilibrium

ideal gas with gravity





$$p = k_B T \rho / m$$

$$\boldsymbol{\nabla} p = -\rho \boldsymbol{\nabla} \Phi$$

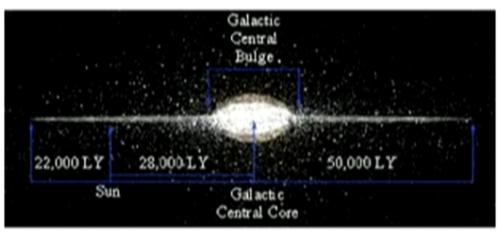
$$\nabla^2 \Phi = 4\pi G(\rho + \rho_B)$$

$$\sigma_0^2 \nabla^2 \ln \rho = -4\pi G(\rho + \rho_B)$$

neglect

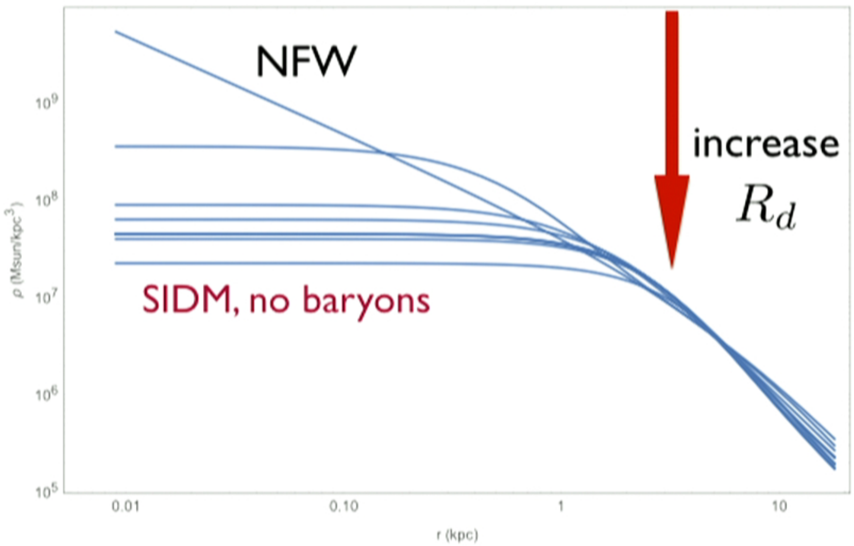
- If $\Phi \sim \Phi_B$, SIDM follows the stellar distribution!

$$\sigma_0^2 \nabla^2 \ln \rho = -4\pi G(\rho_B)$$



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

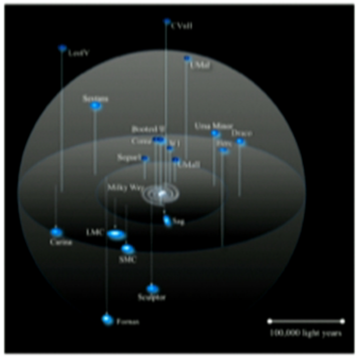
The SIDM halo could be diverse depending on the baryon concentration

Kamada, Kaplinghat, HBY (in preparation)

We are analyzing the rotation curve data for ~170 galaxies

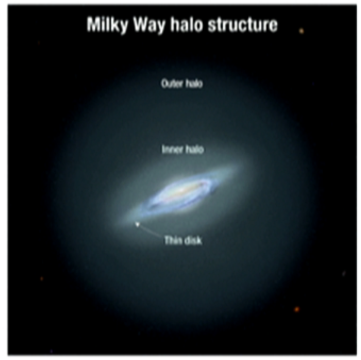
Idea 2: Dark Matter "Colliders"

Dwarf galaxies



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

MW-size galaxies



"LEP" (v~200 km/s)

Clusters

"LHC" (v~1000 km/s)

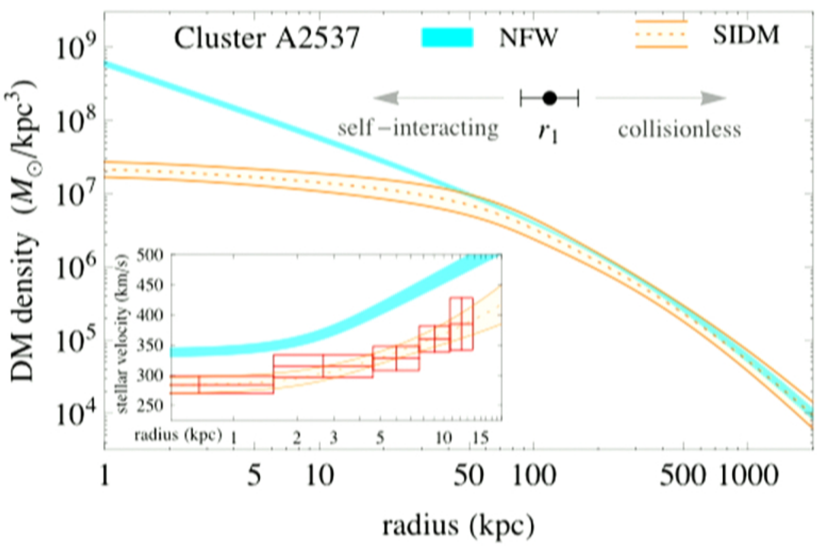
Observations on all scales

Self-scattering kinematics →

Measure particle physics parameters σ_X, m_X, g_X

Modelling SIDM Halos

- A semi-analytical model based on simulations



$$\sigma_0^2 \nabla^2 \ln \rho = -4\pi G(\rho + \rho_B) \qquad \frac{\rho_s}{r/r_s(1+r/r_s)^2}$$

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

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

Matching conditions:

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

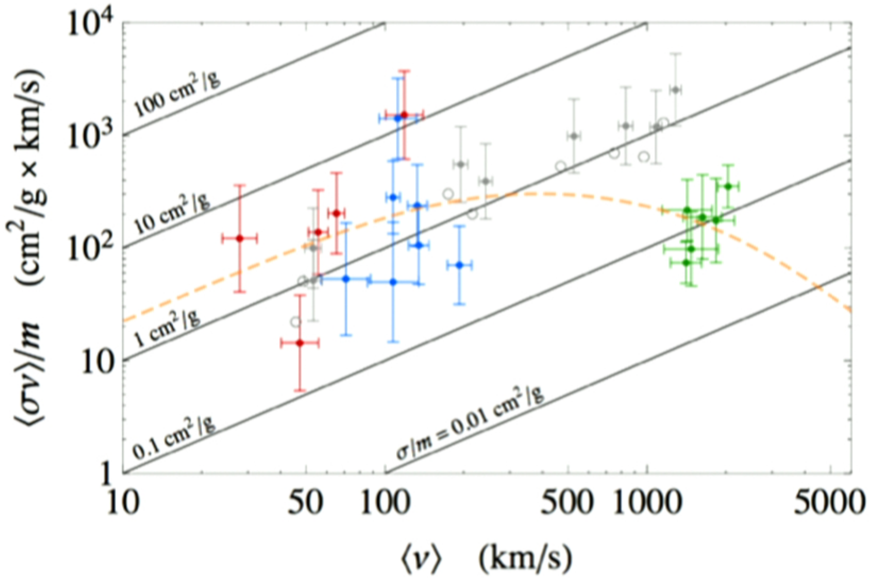
Scan over (ρ_0, σ_0, r_1)

to fit data of stellar kinematics

Kaplinghat, Tulin, HBY (PRL 2015)

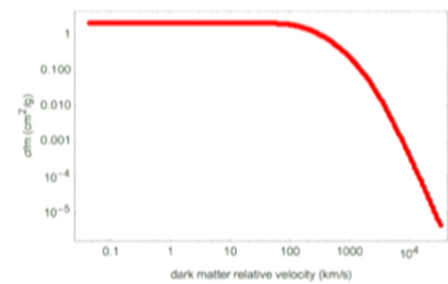
SIDM from Dwarfs to Clusters

- Consider 5 THINGS dwarfs (red), 7 LSBs (blue), 6 galaxy clusters (green)
- 8 simulated halos with σ/m=1 cm²/g (gray) for calibration



Outliers:
due to scatter in halo
concentration of the CDM halo

favors a mild v-dependence



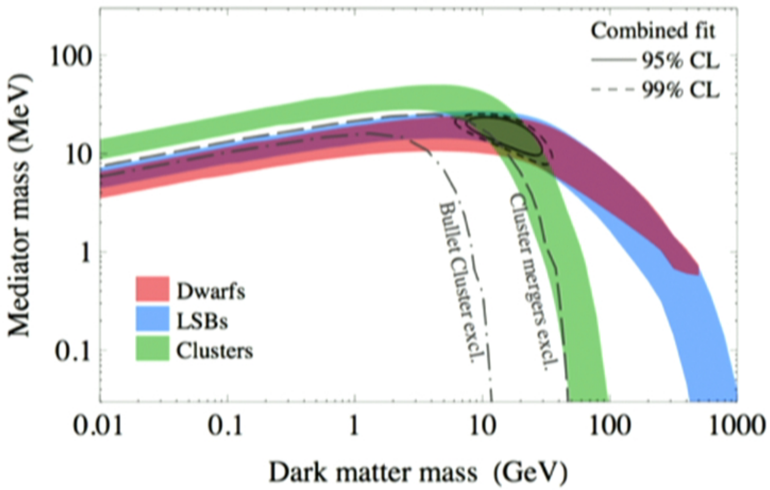
Galaxies: ~2 cm²/g
Clusters: ~0.1 cm²/g

Bullet Cluster: <1 cm²/g

Kaplinghat, Tulin, HBY (PRL 2015)

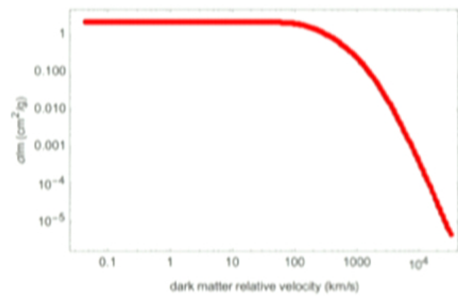
Measuring Dark Matter Mass

- Self-scattering kinematics determines SIDM mass



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

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



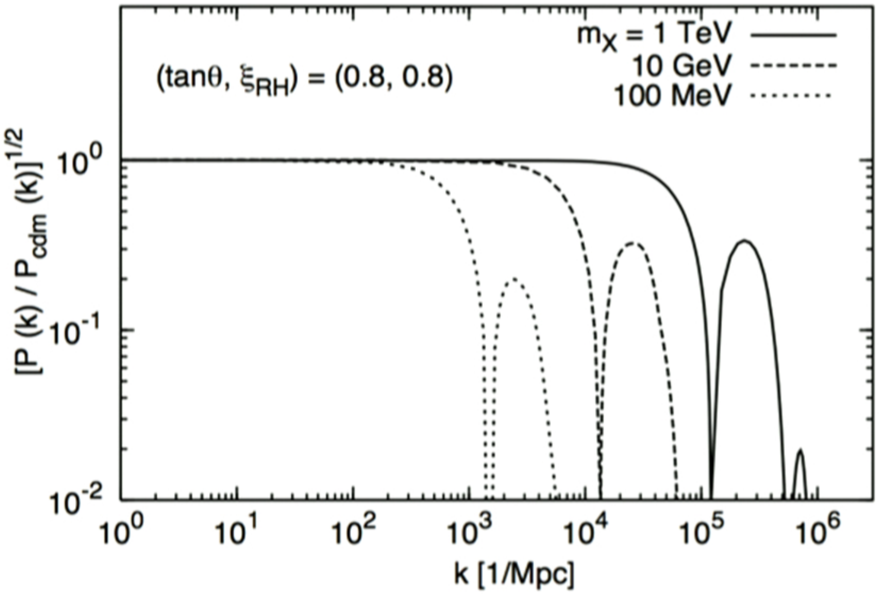
$\alpha_X = 1/137$
m_X: ~15 GeV, m_ϕ: ~15 MeV

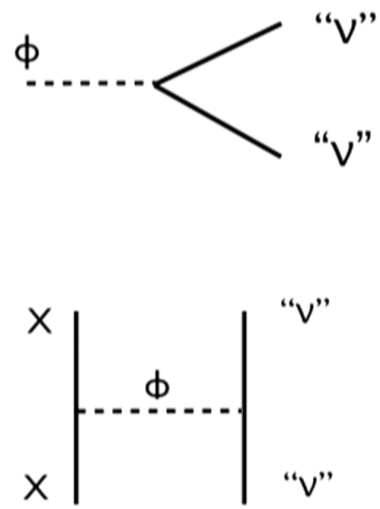
Kaplinghat, Tulin, HBY (PRL 2015)

mild dependence on α_X

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

Idea 3: Dark Acoustic Oscillation

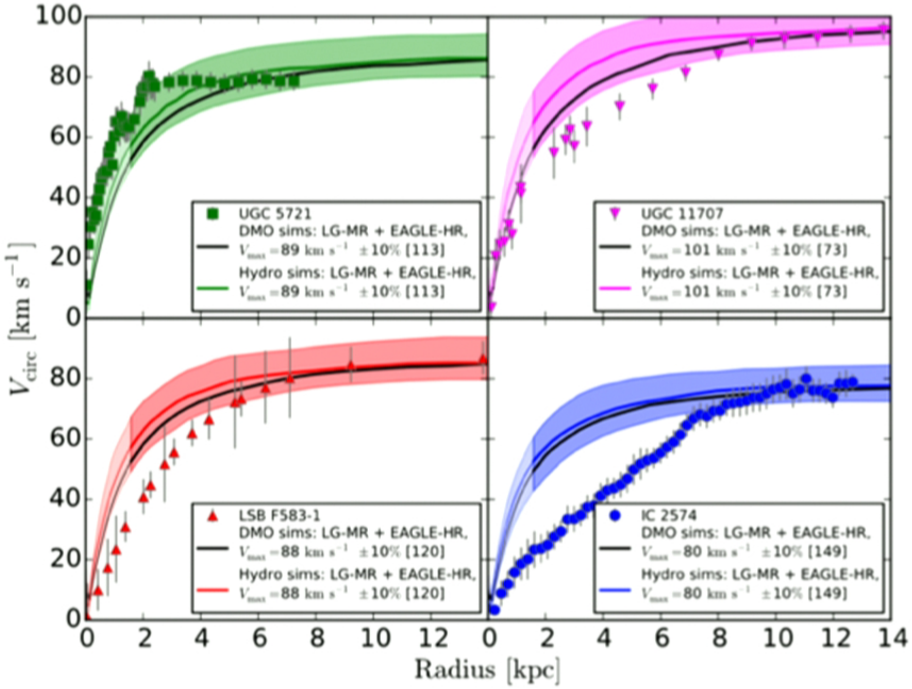




Feng, Kaplinghat, Tu, HBY (JCAP 2009)

Diversity

- Puzzle 1: The diversity of spiral galaxies



diversity issue:
related to halo concentration
scatter in CDM halos
baryonic effect

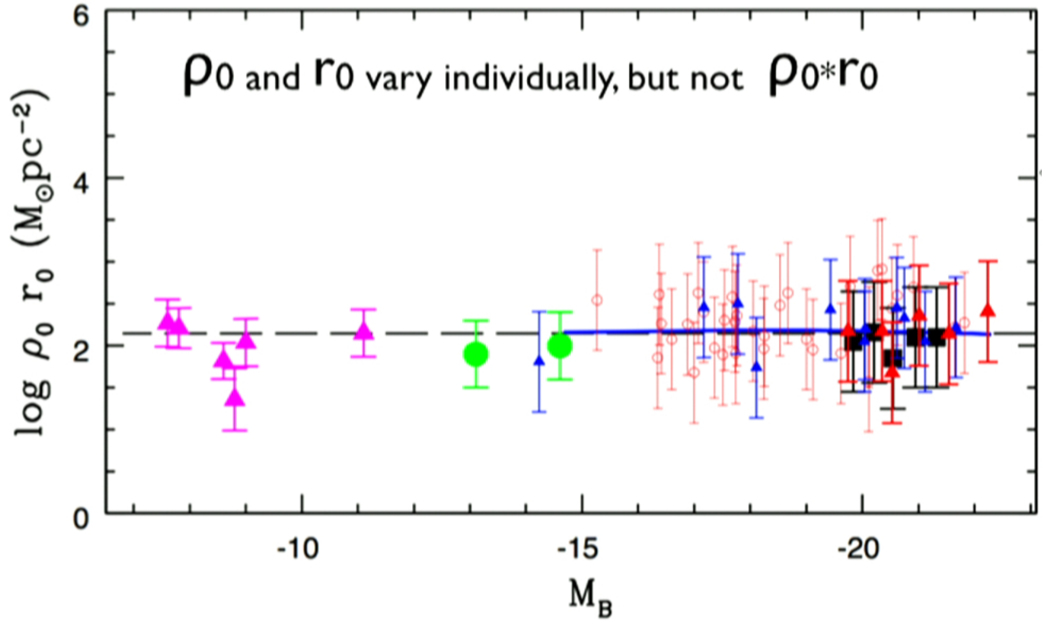
More sample galaxies

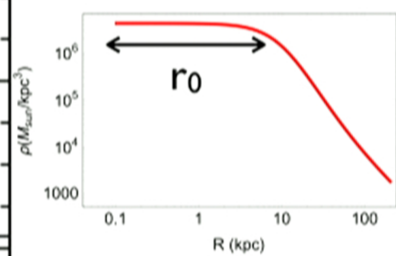
Oman+ (2015)

de Naray, Martinez, Bullock, Kaplinghat (2009)

Uniformity

- Puzzle 2: Constant DM halo surface density





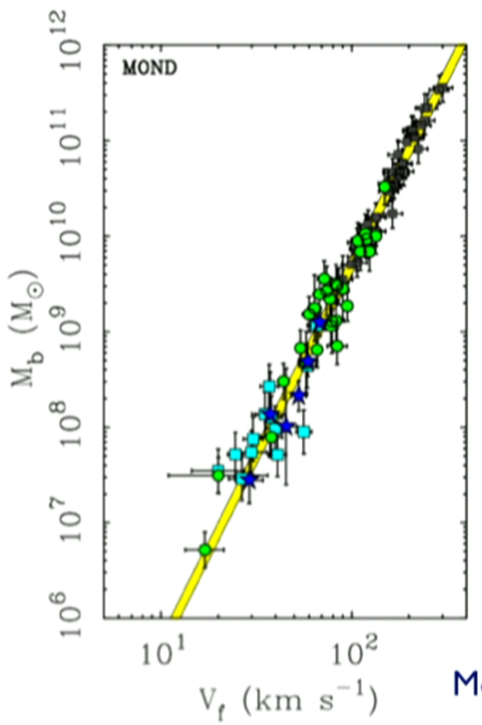
$$\rho(r_0) = \rho_0/2$$

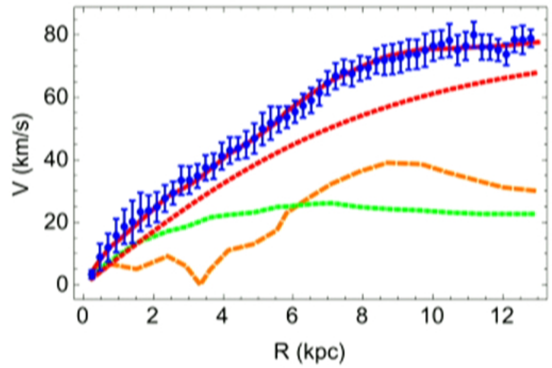
Donato+(2009)

Kormendy, Freeman (2004)

Baryon-DM Conspiracy

- Puzzle 3: The baryonic Tully-Fisher relation





$$M_b = AV_f^4 \text{ with } A = 47 \pm 6\ \mathrm{M_\odot\ km^{-4}\ s^4}$$

McGaugh (2011)

We have a lot to do!

MY WEEKEND
IS ALL
BOOKED

Stay tuned!

Thank You