

Title: Dark matter halos as particle colliders

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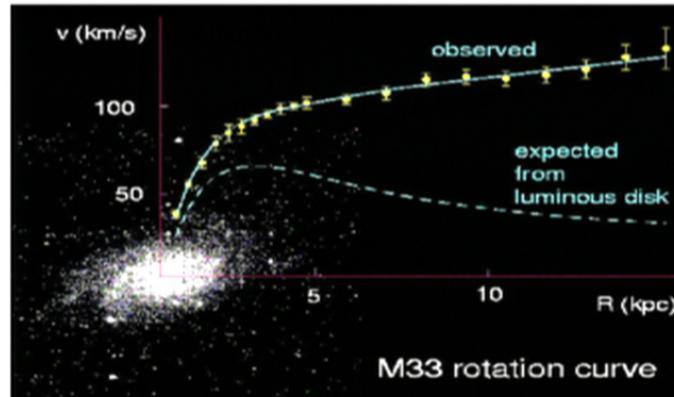
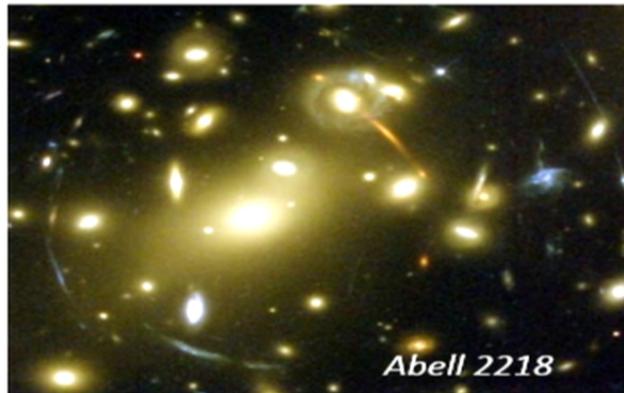
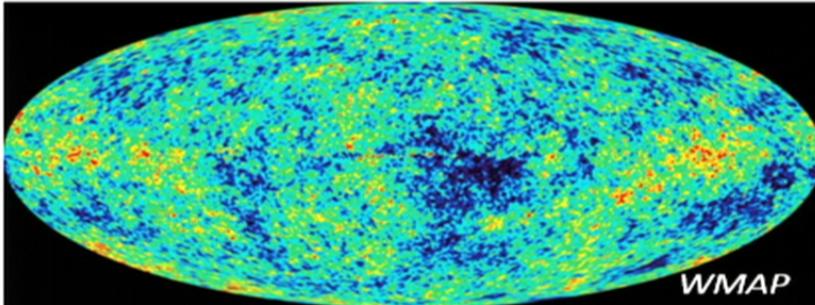
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Abstract:

Astrophysical observations of the structure of galaxies and clusters are no longer simply proving the existence of DM, but have sharpened into a discovery tool probing the particle physics of dark matter. I discuss small scale structure anomalies for cold dark matter and their possible implications for dark matter physics, such as the existence of forces in the dark sector. New results on cluster scales provide a new important handle for constraining dark matter's particle interactions.

Cold collisionless dark matter paradigm

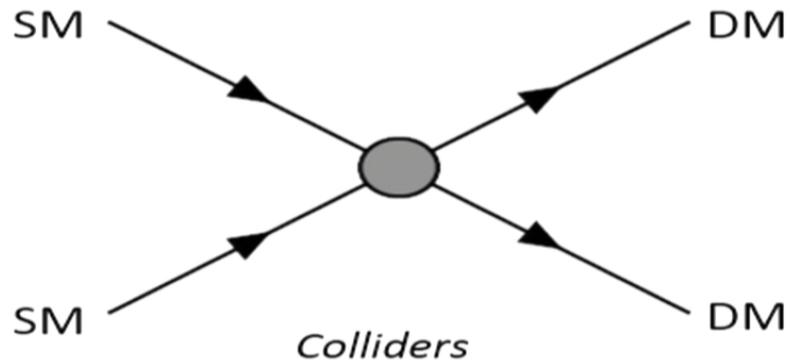
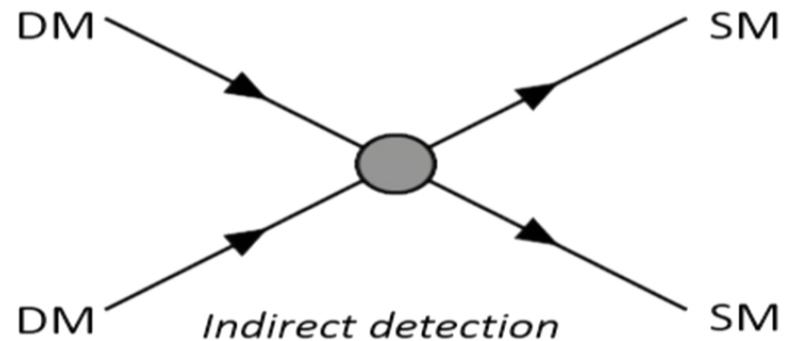
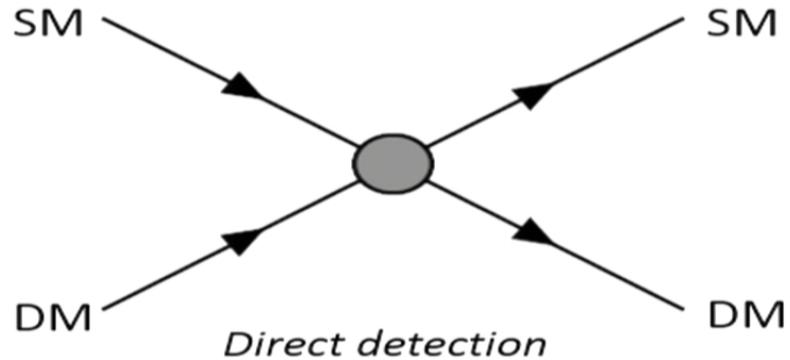
Dark matter (DM) is about 25% of the Universe



Cold collisionless dark matter (CDM) provides a good description of the structure of matter in the Universe

To date, evidence for DM from gravity only

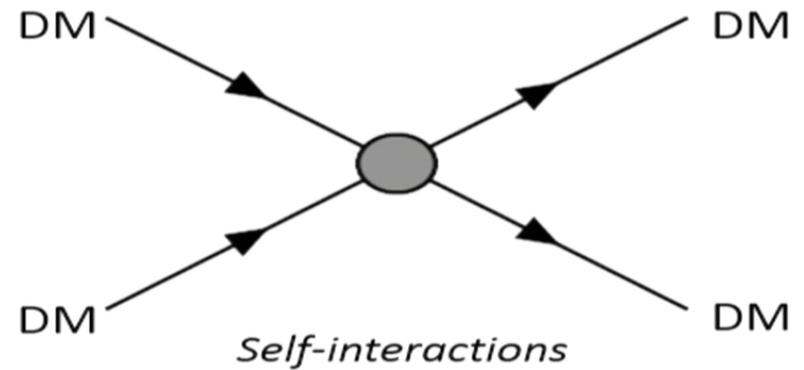
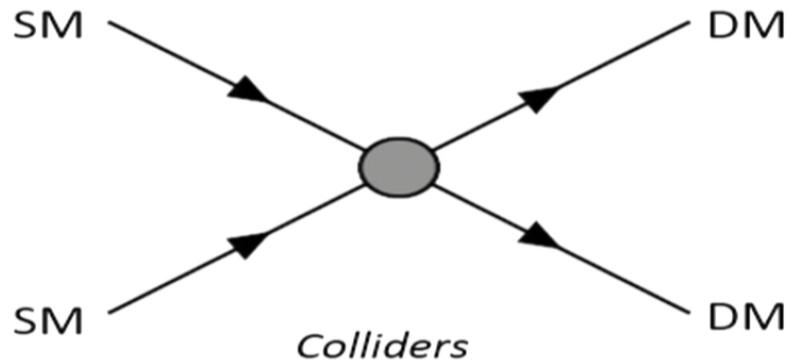
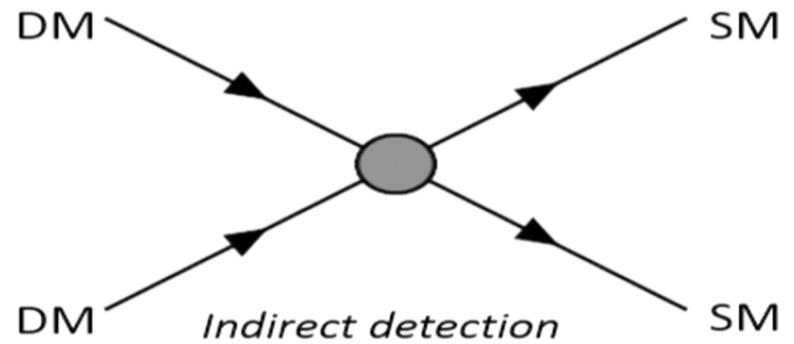
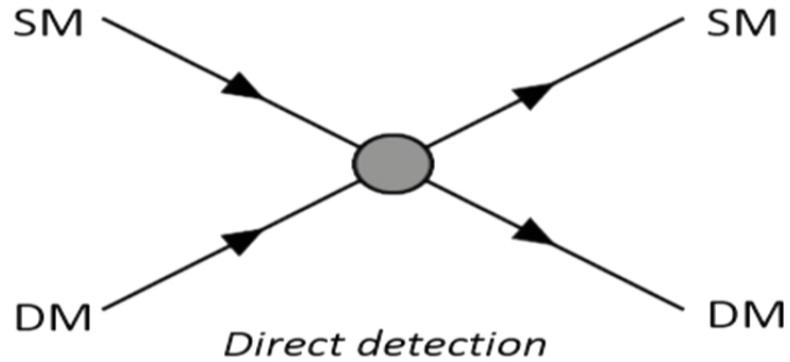
Exploring the dark sector



WIMP paradigm: expect dark matter in one or more of these channels

Can we learn about the dark sector if DM has highly suppressed couplings to SM?

Exploring the dark sector



Outline

- Issues with CDM (cold collisionless DM)
 - Discrepancies between N-body simulations and astrophysical observations
- DM may have self-interactions
 - Particle physics implications
 - Using dark matter halos as colliders
 - Complementarity with WIMP searches

CDM in trouble

1. **Core-vs-cusp problem** *Moore (1994), Flores & Primack (1994)*
 - Central densities of halos exhibit cores
DM density: $\rho \sim r^\alpha$ $\alpha \sim -1$ (cusp, NFW) or $\alpha \sim 0$ (core)
2. **Too-big-to-fail problem** *Boylan-Kolchin, Bullock, Kaplinghat (2011 + 2012)*
 - Simulations predict O(10) massive MW satellites more massive than observed MW dSphs
3. **Missing satellite problem** *Klypin et al (1999), Moore et al (1999)*
 - Fewer small MW dSphs than predicted by simulation
 - Small enough to fail

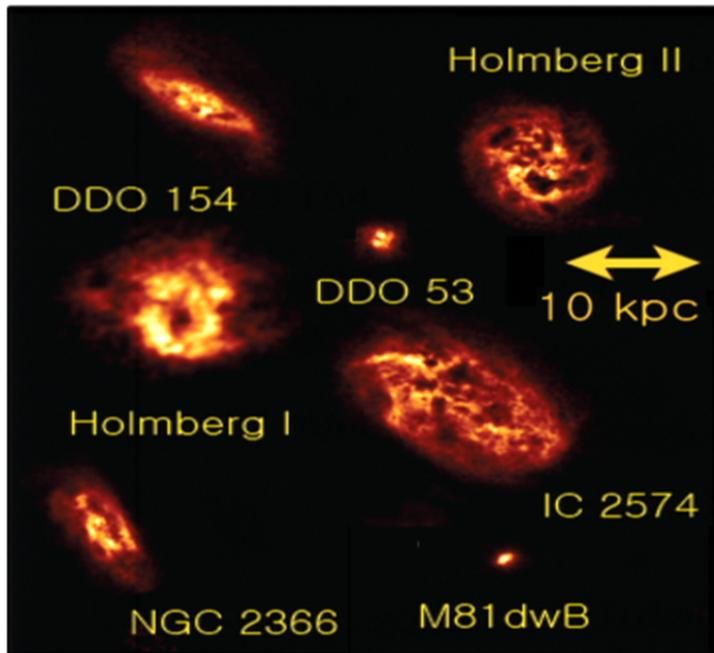
1. Core-vs-cusp problem

Cores seem fairly ubiquitous:

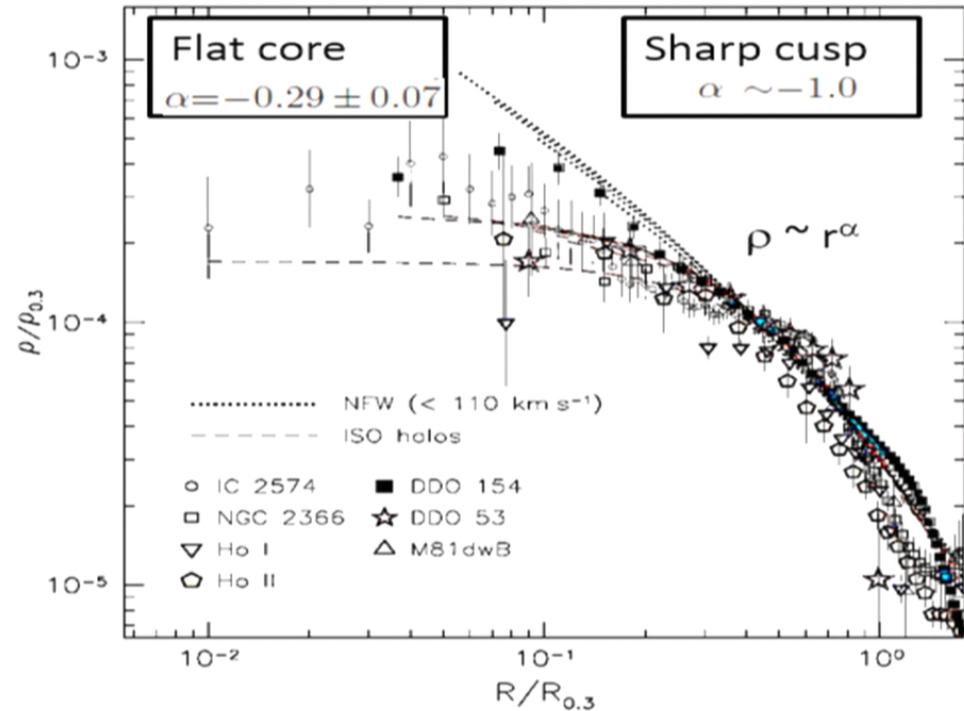
1. Field dwarfs
2. Satellite dwarf galaxies
3. Low surface brightness galaxies (LSBs)
4. Clusters

1. Cores in field dwarfs

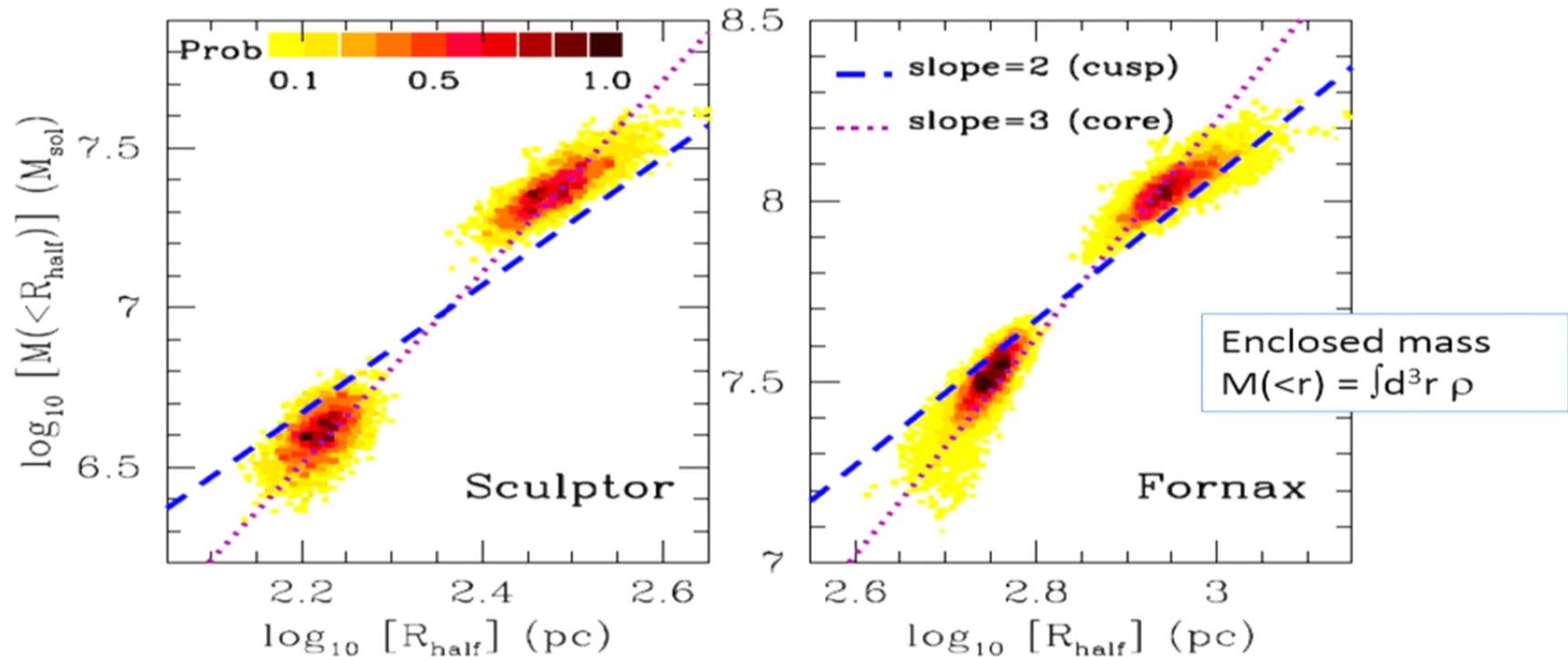
Moore (1994), Flores & Primack (1994), ...



THINGS (dwarf galaxy survey) - Oh et al. (2011)



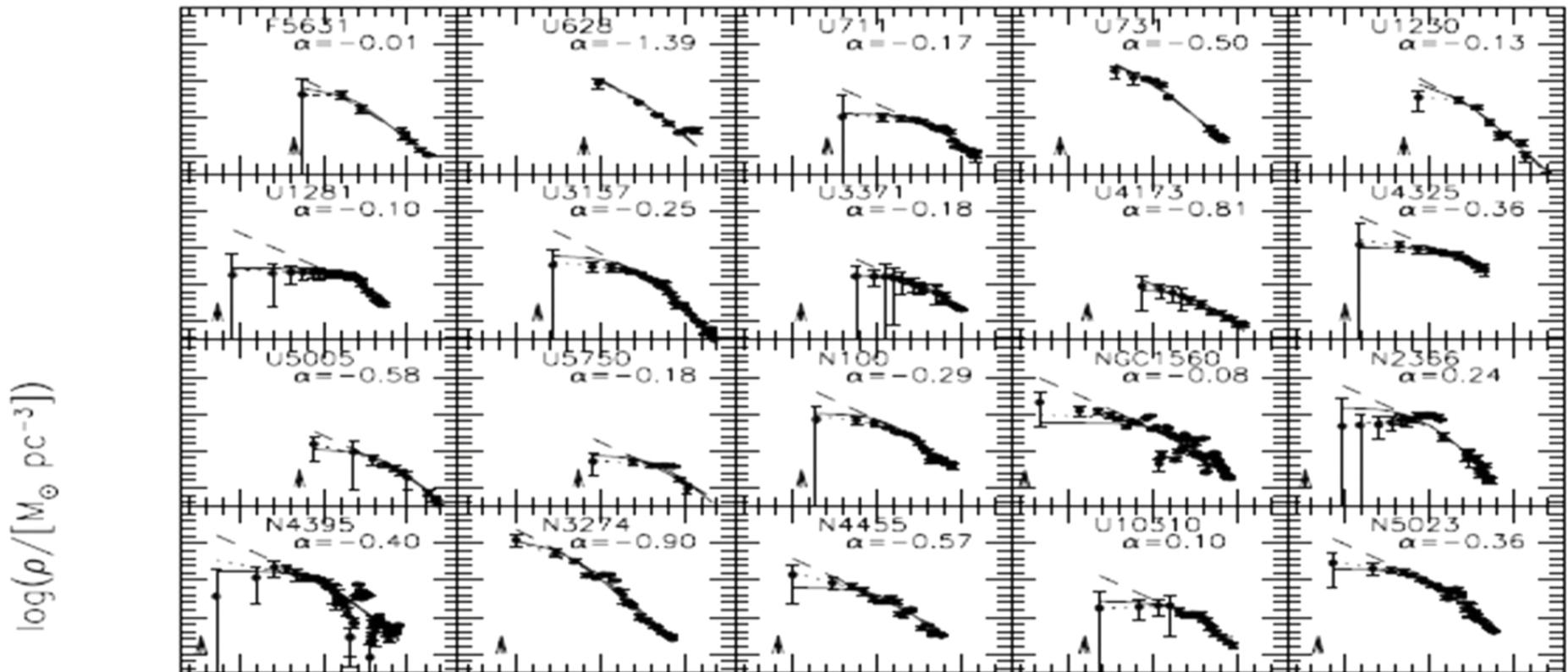
1. Cores in MW dwarf spheroidals



Stellar subpopulations (metal-rich & metal-poor) as “test masses” in gravitational potential

Walker & Penarrubia (2011)

1. Cores in LSBs



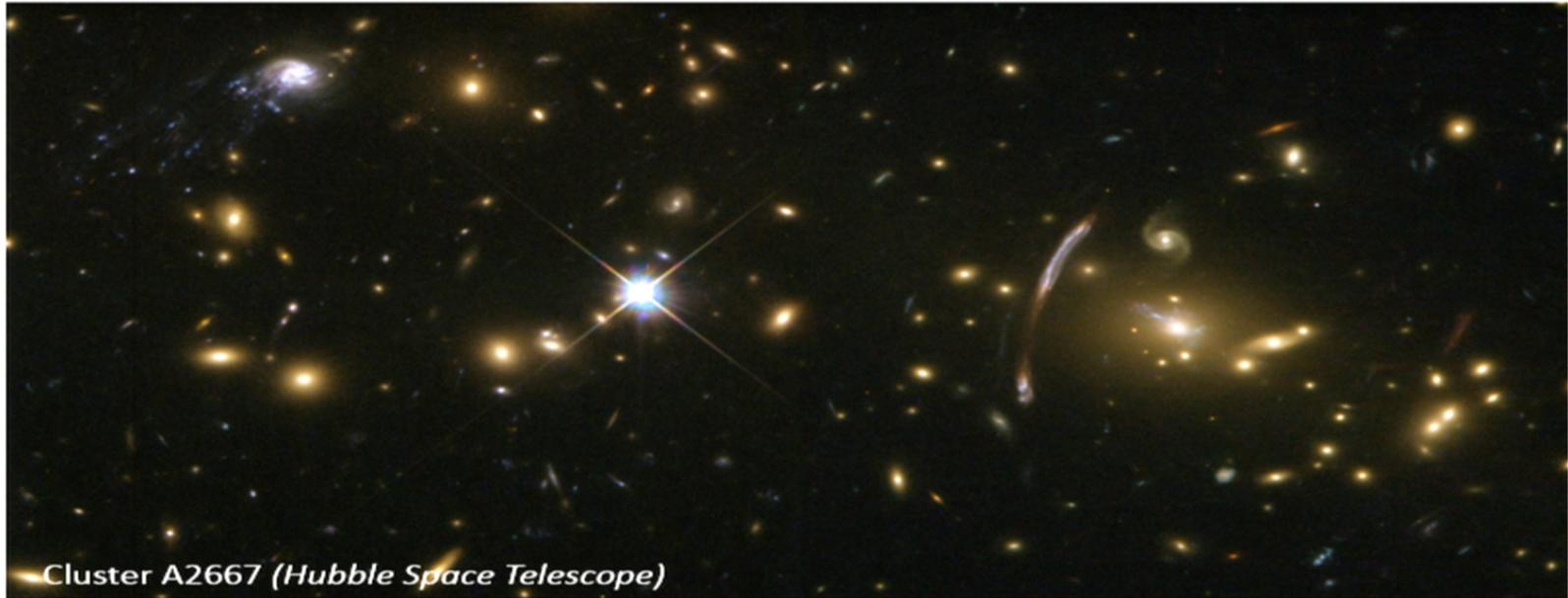
de Blok & Bosma (2002)

$\log(R/\text{kpc})$

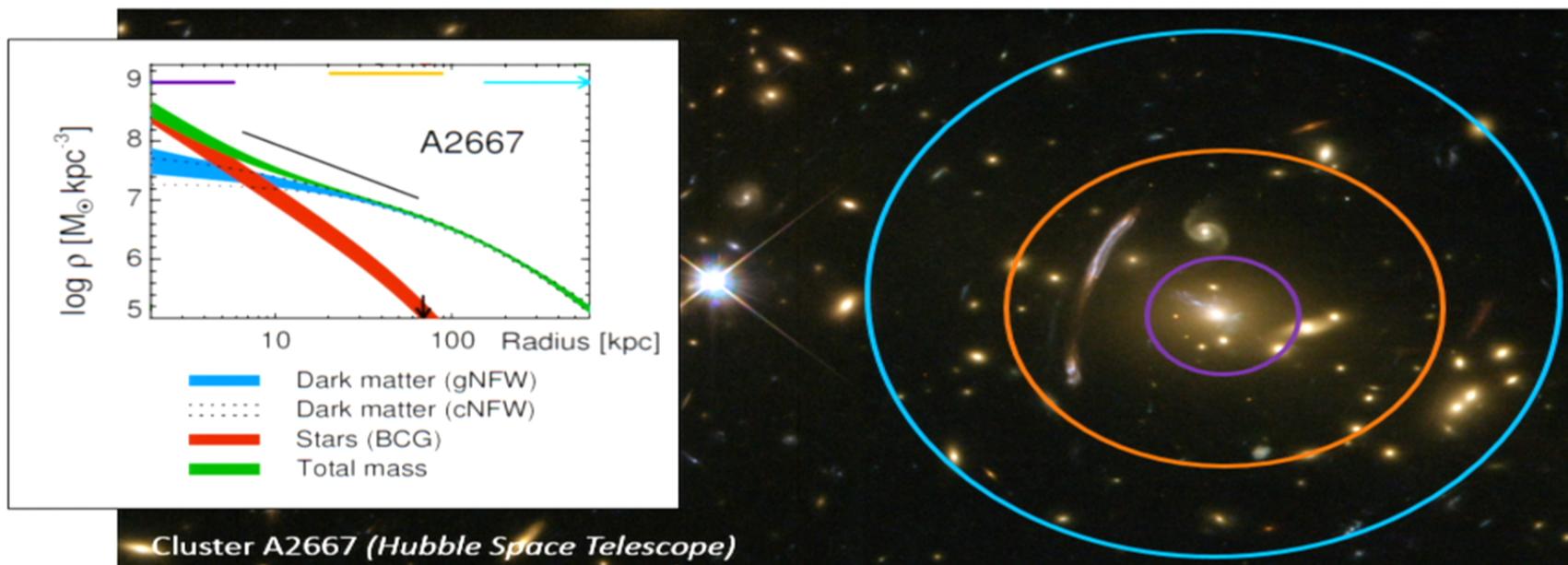
LSB = low surface brightness galaxy

See also: Kuzio de Naray et al (2007); Kuzio de Naray & Spekkens (2011)

1. Cores in clusters



1. Cores in clusters



Use multiple measurements to study dark matter halo

Weak gravitational lensing
at large distance

Gravitational lensing arcs
(strong lensing) at
medium distance

Stellar kinematics for
the cluster center

Newman et al (2012)

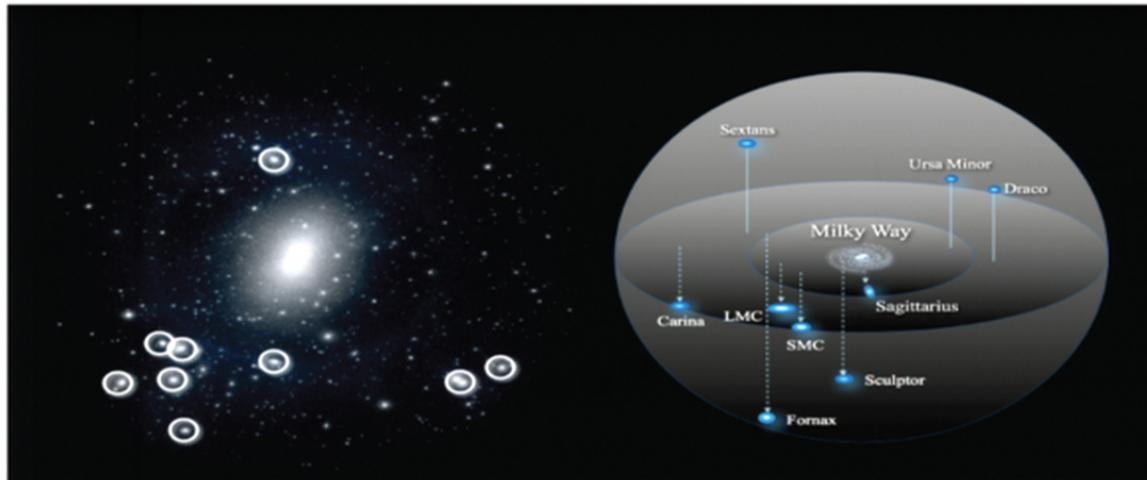
$$\beta = \frac{\beta_S}{\left(\frac{r}{r_S}\right)^\beta \left(1 + \frac{r}{r_S}\right)^{\beta-1}}$$

$$\beta = \frac{\beta_S \left(\frac{r_S}{r}\right)}{\left(1 + \frac{r}{r_S}\right) \left(1 + \frac{r}{r_S}\right)}$$

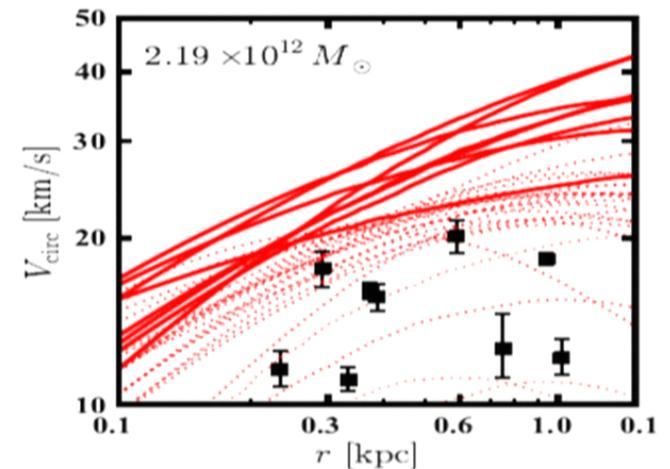
2. Too-big-to-fail problem

Boylan-Kolchin, Bullock, Kaplinghat (2011 + 2012)

MW galaxy should have $O(10)$ satellite galaxies which are more massive than the most massive (classical) dwarf spheroidals



From Weinberg, Bullock, Governato, Kuzio de Naray, Peter (2013)



Also TBTF problem found in Andromeda and Local Group satellite populations

Tollerud et al. (2014), Garrison-Kimmel et al. (2014)

CDM Problems

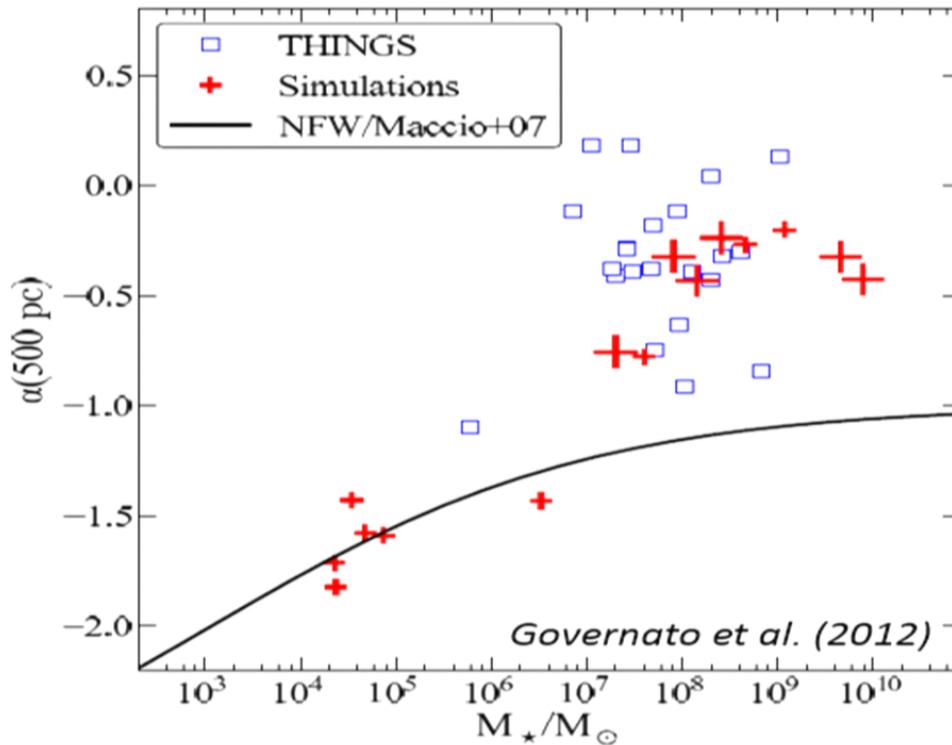
- Problem with our interpretation of observations
 - Can't use DM-only simulations to model real DM+baryons Universe
 - Astrophysical observations not being modeled correctly
 - ...
- Dark matter may not be CDM

CDM Problems

- Problem with our interpretation of observations
 - Can't use DM-only simulations to model real DM+baryons Universe
 - Astrophysical observations not being modeled correctly
 - ...
- Dark matter may not be CDM

Core-vs-cusp from baryonic physics

CDM-only simulations poor representation of DM+baryon Universe



Supernova feedback may form cores in THINGS dwarfs (gas-rich dwarfs)

Requires bursty star formation history

Depends on implementation sub-grid physics

Core-vs-cusp from baryonic physics

1. Field dwarfs

- Supernova feedback from bursty star formation history *Governato et al. (2012)*

2. MW satellites

- Interaction with baryonic disk of Milky Way *Zolotov et al (2012)*

3. Low surface brightness galaxies

- ??? *Kuzio de Naray & Spekkens (2011)*

4. Clusters

- Feedback from AGN *Martizzi et al (2012)*
Schaller et al (2014)

Too-big-to-fail problem from baryons

Variation in number of satellites (~10% “tuning”)

Purcell & Zentner (2012)

MW mass might be smaller

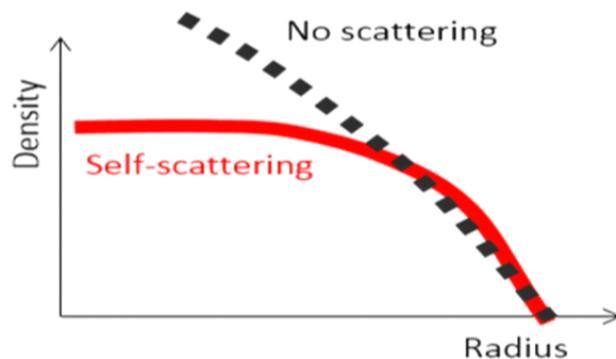
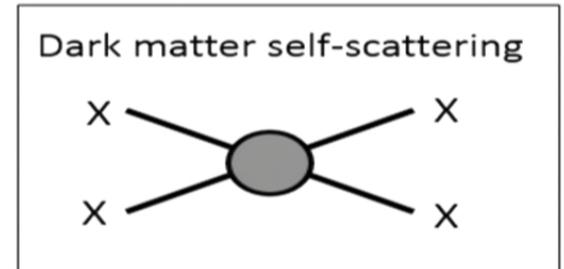
Baryons are important

- Environmental effect from parent galaxy generates cores and modifies rotation curves
- Explains TBTF in MW and Andromeda, but not Local Group field dwarfs

Self-interacting dark matter

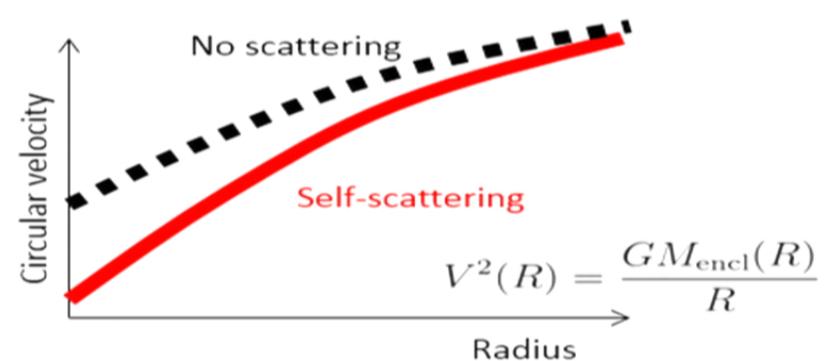
CDM structure problems are solved if dark matter is **self-interacting**

Dark matter particles in halos elastically scatter with other dark matter particles. *Spergel & Steinhardt (2000)*



Self-interactions solve core-vs-cusp

Particles get scattered out of dense halo centers

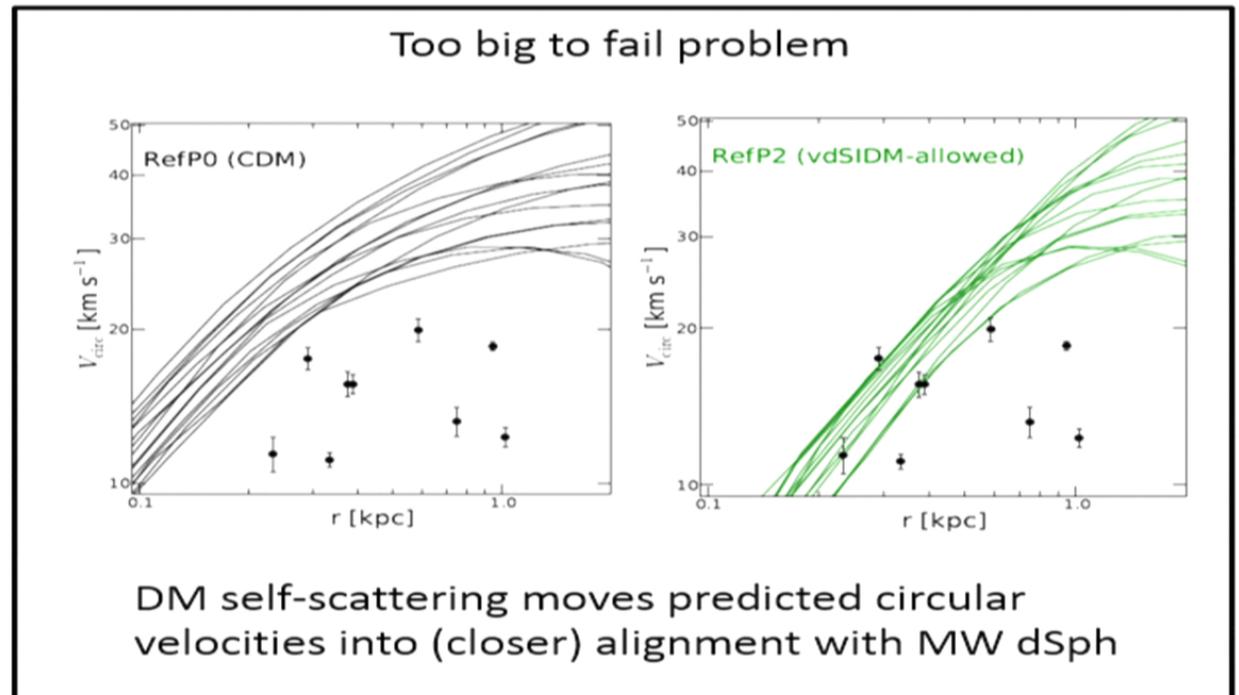
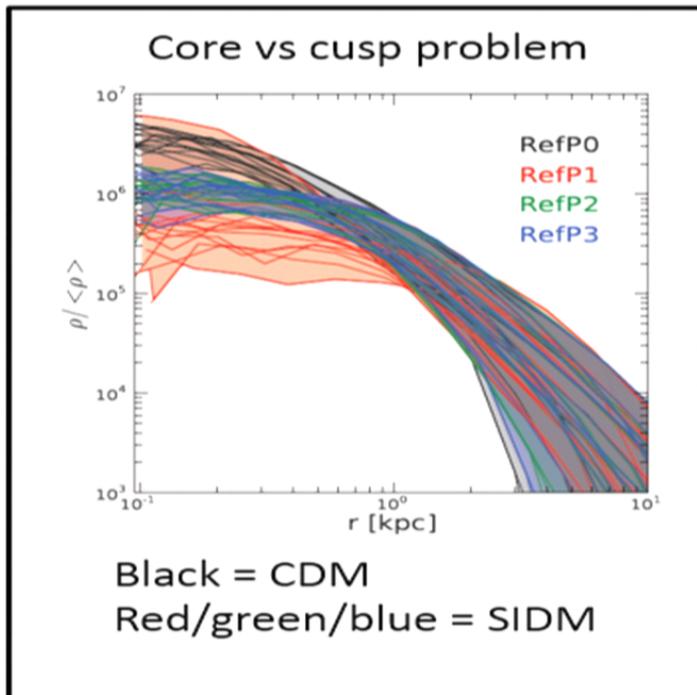


Self-interactions solve too-big-to-fail

*Rotation curves reduced (less enclosed mass)
Simulated satellites matched to observations*

N-body simulations for SIDM

Vogelsberger, Zavala, Loeb (2012); see also Rocha et al, Peter et al (2012)



Self-interacting dark matter

- What does this tell us about the underlying particle physics theory of the dark sector?

Number of scatterings = $\sigma \times (\rho/m) \times \text{velocity} \times t_{\text{age}}$

Figure-of-merit: $\sigma/m_\chi \sim 1 \text{ cm}^2/\text{g} \approx 2 \text{ barns/GeV}$

Cross section required to solve small scale anomalies

Self-interacting dark matter

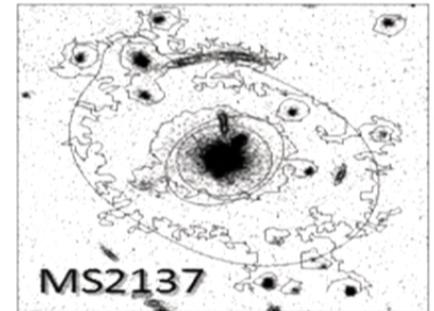
- What does this tell us about the underlying particle physics theory of the dark sector?
- History of SIDM
 1. Contact interaction proposed to solve small-scale structure issues $\sigma = \text{const}$ *Spergel & Steinhardt (2000), Dave et al (2000)*
 2. Large enough cross section excluded on cluster scales
 - Velocity dependent cross section ($\sigma \sim 1/v$) *Yoshida et al (2000)*
 - SIDM disfavored
 3. Improved SIDM simulations *Vogelsberger, Zavala, Loeb (2012); Rocha et al, Peter et al (2012)*
 4. Improved SIDM particle physics models
Ackerman et al (2008), Feng et al (2009), Buckley & Fox (2009), Loeb & Weiner (2010), ST, Yu, Zurek (2012 + 2013), Cyr-Racine et al (2013), Fan et al (2013), Cline et al (2013), Boddy et al (2014), ...

Constraints on self-interactions

Ellipticity inferred by gravitational lensing arcs

$\sigma/m < 0.02 \text{ cm}^2/\text{g}$ *Miralda-Escude (2003)*

Peter et al. (2012): bound overestimated by 10^2 (!)



Halo shape constraints from elliptical galaxy

Buote et al. (2002); Feng et al. (2010)

Weaker than previously thought due to baryonic contribution to the potential *Kaplinghat et al (2014)*



Bullet cluster constraint: $\sigma/m < 1 \text{ cm}^2/\text{g}$

Randall et al. (2007)

Constant cross section $\sigma/m \sim 0.5 - 1 \text{ cm}^2/\text{g}$

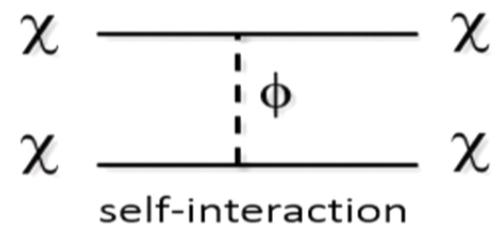
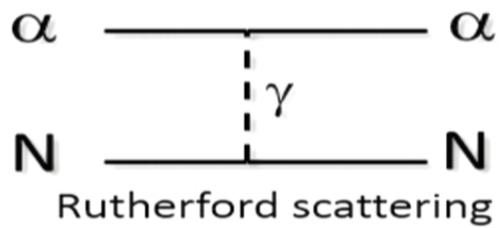
may be OK with all constraints

Vogelsberger, Zavala, Loeb (2012); Rocha et al, Peter et al (2012)



Particle physics lessons for SIDM

Dark matter self-interactions

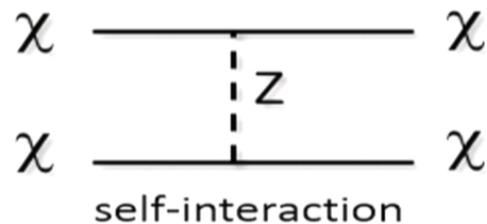


χ = dark matter particle

ϕ = mediator particle

Particle physics lessons for SIDM

WIMPs have self-interactions (weak interaction)



χ = dark matter (e.g. SUSY particle)

Z boson = mediator particle

Cross section:

$$\sigma \sim \frac{g^4 m_\chi^2}{m_Z^4} \sim 10^{-36} \text{ cm}^2$$

Mass:

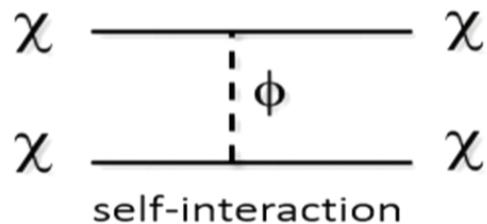
$$m_\chi \sim m_Z \sim 100 \text{ GeV}$$

WIMP self-interaction cross section is way too small

$$\sigma/m_\chi \sim 10^{-14} \text{ cm/g}$$

Particle physics lessons for SIDM

Large cross section required $\sigma/m_\chi \sim 1 \text{ cm}^2/\text{g}$



Cross section: $\sigma \sim \frac{g^4 m_\chi^2}{m_\phi^4}$

Mediator mass below than weak scale

$$m_\phi \sim 1 - 100 \text{ MeV}$$

Lesson #1: self-interactions require new dark sector states (mediator) below 1 GeV.

Particle physics lessons for SIDM

Lesson #2: Light mediator implies velocity-dependent scattering cross section

Extreme examples:

Contact interaction
(e.g. Fermi theory)

$$m_\phi \gg m_\chi v$$

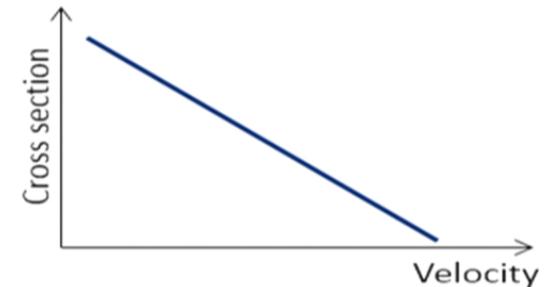
$$\sigma = \text{constant}$$



Massless mediator
(e.g. Rutherford scattering)

$$m_\phi \ll m_\chi v$$

$$\sigma \propto 1/v^4$$



Particle physics lessons for SIDM

Lesson #2: Light mediator implies velocity-dependent scattering cross section

Extreme examples:

Contact interaction
(e.g. Fermi theory)

$$m_\phi \gg m_\chi v$$

$$\sigma = \text{constant}$$

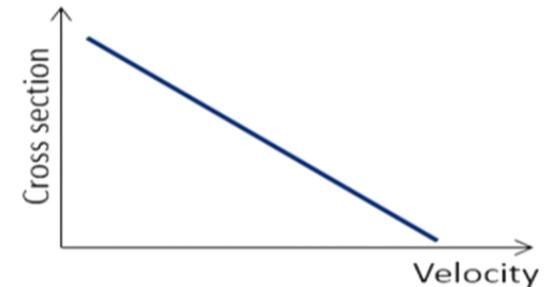


Complicated velocity
dependence

Massless mediator
(e.g. Rutherford scattering)

$$m_\phi \ll m_\chi v$$

$$\sigma \propto 1/v^4$$



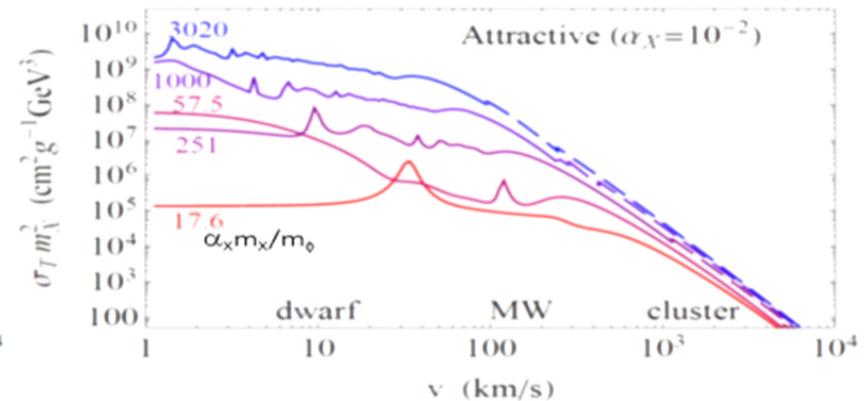
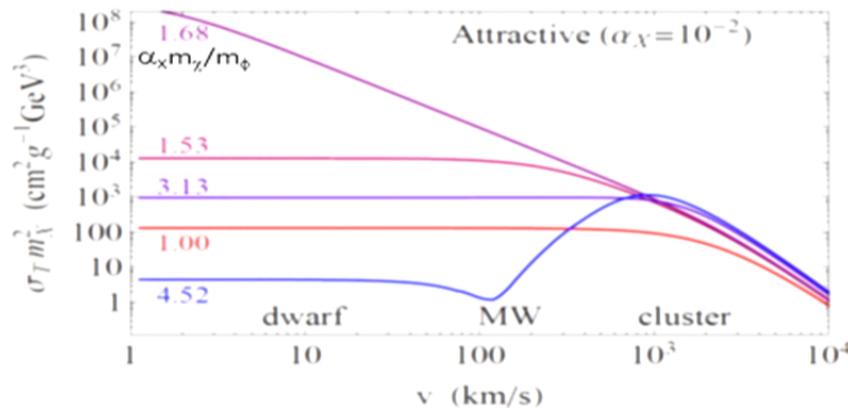
Particle physics lessons for SIDM

Complicated velocity dependent cross section

Not a contact interaction in general

Want to consider $\sigma(v)$, rather than σ as a fixed number

ST, Yu, Zurek (2013)



Different halos have different velocities

Cores in different systems are probing self-interactions at different energies



Dwarf galaxy

Low energies ($v/c \sim 10^{-4}$)



Spiral galaxy

Medium energies ($v/c \sim 10^{-3}$)



Cluster of galaxies

High energies ($v/c \sim 10^{-2}$)

Lesson #3: Different size dark matter halos have different characteristic velocities

Different halos have different velocities

Cores in different systems are probing self-interactions at different energies



Low energies ($v/c \sim 10^{-4}$)

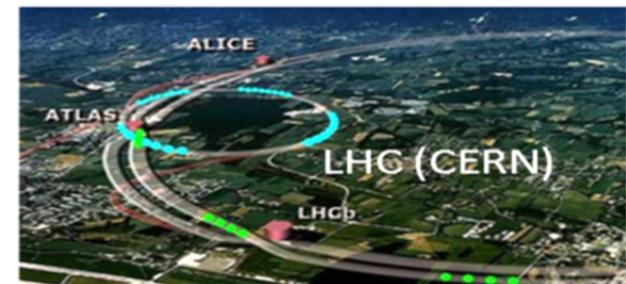


Medium energies ($v/c \sim 10^{-3}$)



High energies ($v/c \sim 10^{-2}$)

Each galaxy and cluster is like a different particle physics collider with a different beam energy



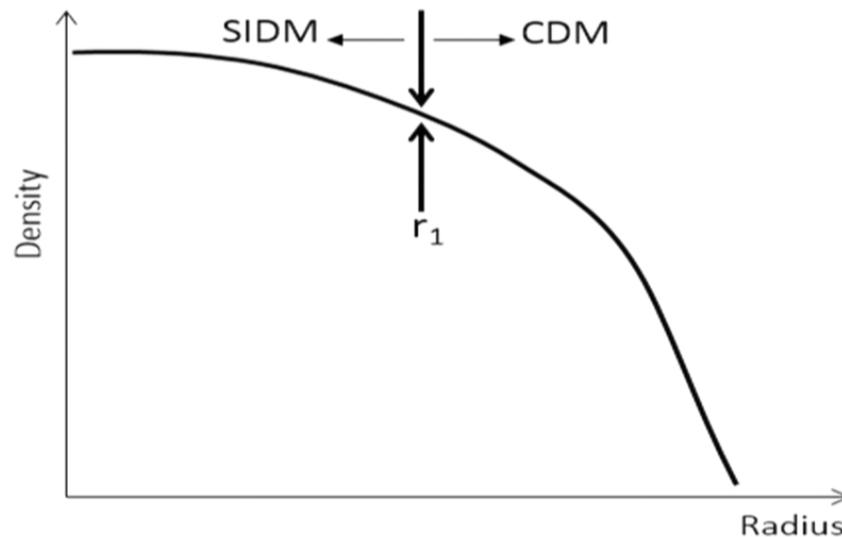
Dark matter halos as colliders

- Goal: Can observations of cores in dwarfs, LSBs, and clusters be explained in a consistent particle physics picture
- Caveat: assuming no baryonic feedback to generate cores (background)
- 2nd caveat: preliminary

Kaplinghat, ST, Yu (in preparation)

Particle physics from astrophysics

Expect there is a transition radius r_1 between SIDM profile and NFW profile



Inner halo ($r < r_1$): expect DM to be pseudo-isothermal profile

$$N_{\text{scat}} \sim \langle \sigma v \rangle / m \rho t_{\text{age}} > 1$$

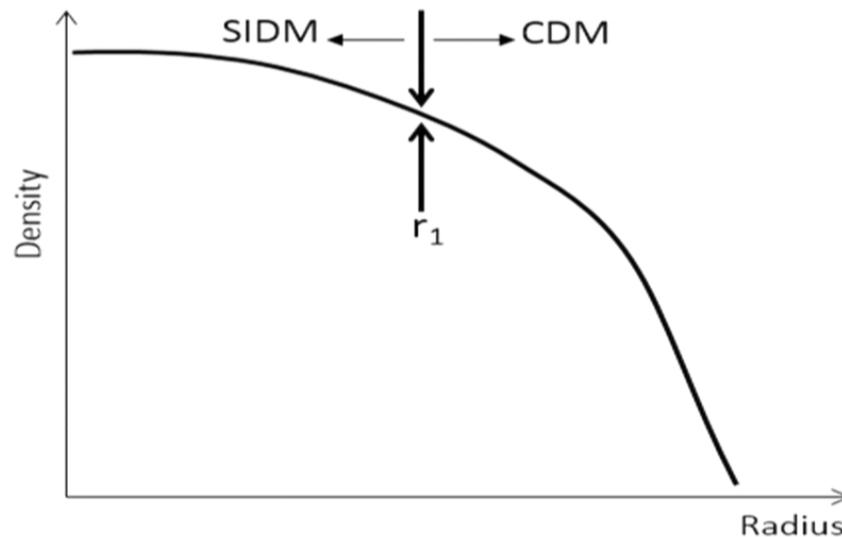
Outer halo ($r > r_1$): expect DM to be CDM (NFW)

$$N_{\text{scat}} \sim \langle \sigma v \rangle / m \rho t_{\text{age}} < 1$$

Given a DM density profile, want to know $\rho(r_1)$ because $\langle \sigma v \rangle / m = 1 / \rho(r_1) t_{\text{age}}$

Particle physics from astrophysics

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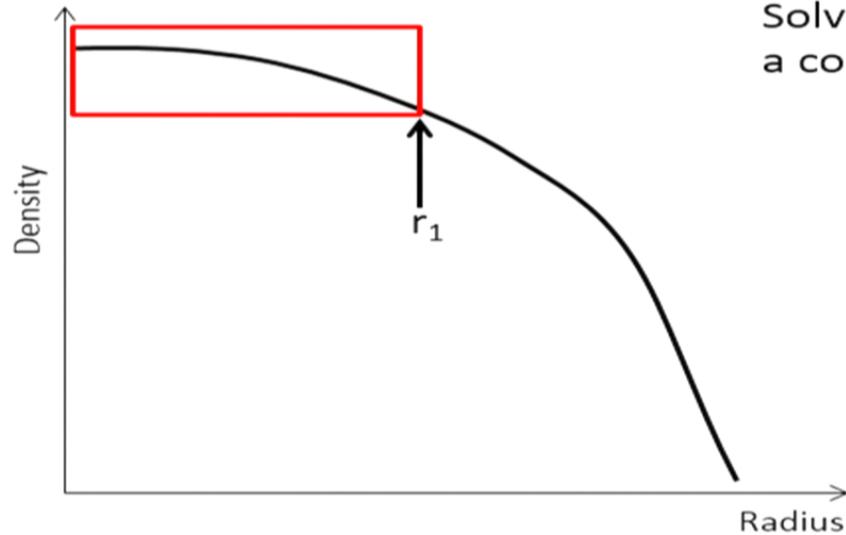
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Particle physics from astrophysics



Solve inner region using the Jeans equation with a constant isotropic dispersion

$$\frac{1}{\rho} \frac{d\rho}{dr} \sigma_0^2 = - \frac{d\Phi}{dr}$$

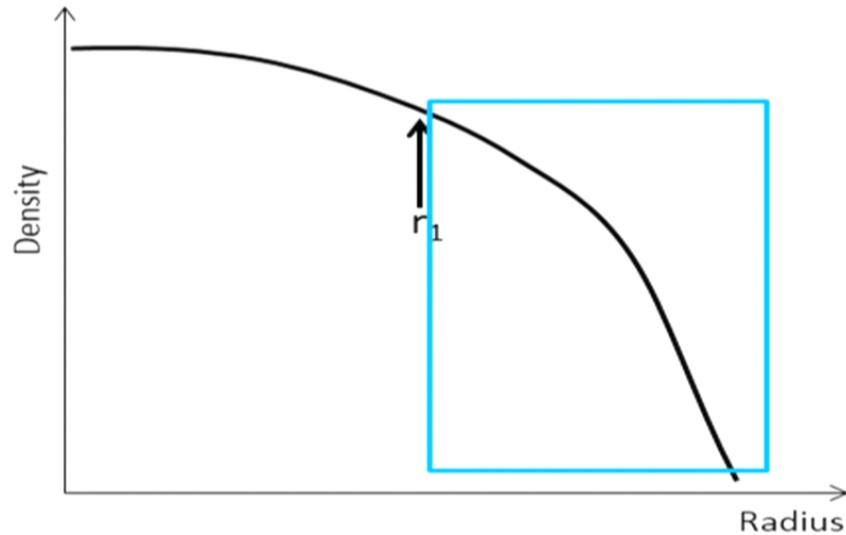
σ_0 is DM velocity dispersion
 Φ is total potential (DM + baryons)

Choose $\sigma_0, \rho(0)$.
Solve $\rho(r)$ for $0 < r < r_1$.

$$P = k_B \frac{\rho}{m} T = \sigma_0^2 \rho$$

$$\nabla P = -\rho \nabla \Phi$$

Particle physics from astrophysics



Match the outer region onto NFW solution

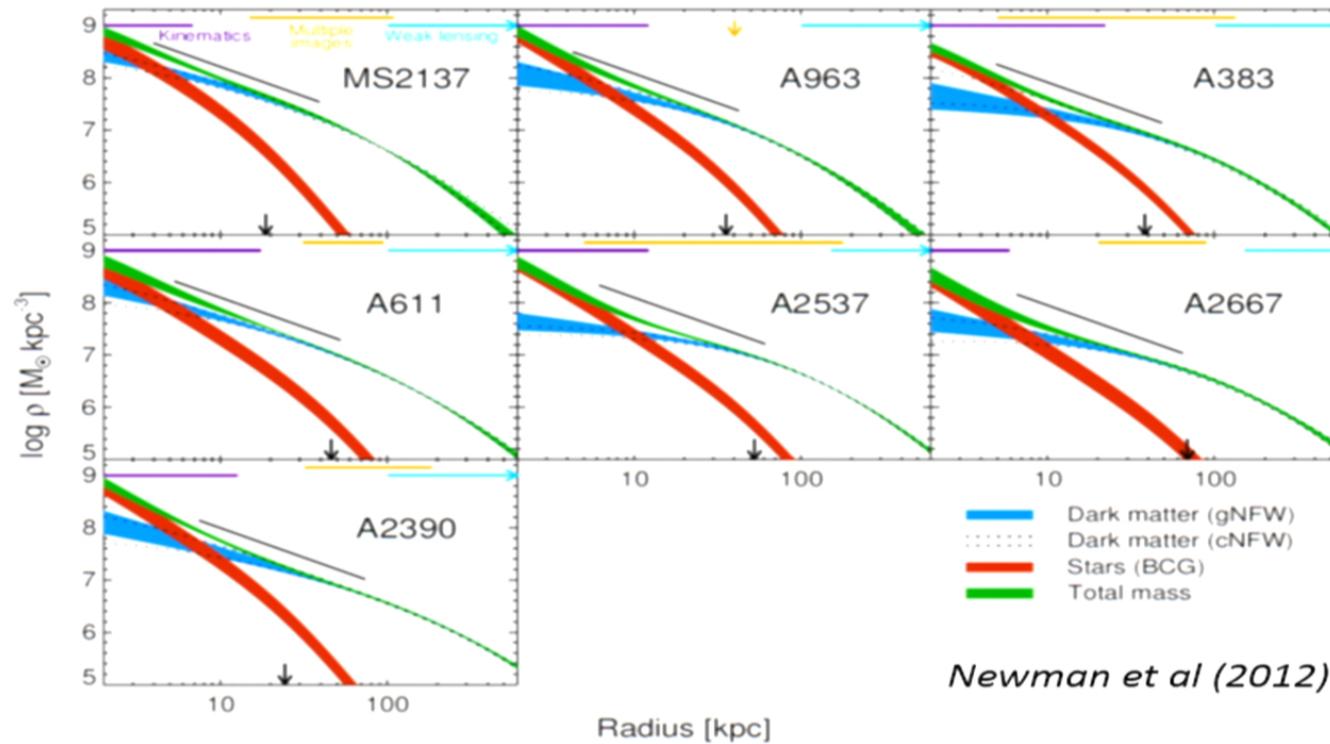
Require $\rho(r)$ and $M_{\text{encl}}(r)$ are continuous at $r = r_1$.

In practice, r_1 is unknown.
Need to scan over r_1 to find best fit to both SIDM and CDM regions.

Clusters

Fantastic data for fitting SIDM:

1. Dark matter density obtained for large range of radius (spanning $r > r_1$ and $r < r_1$)
2. Baryon density is easy to include in Φ



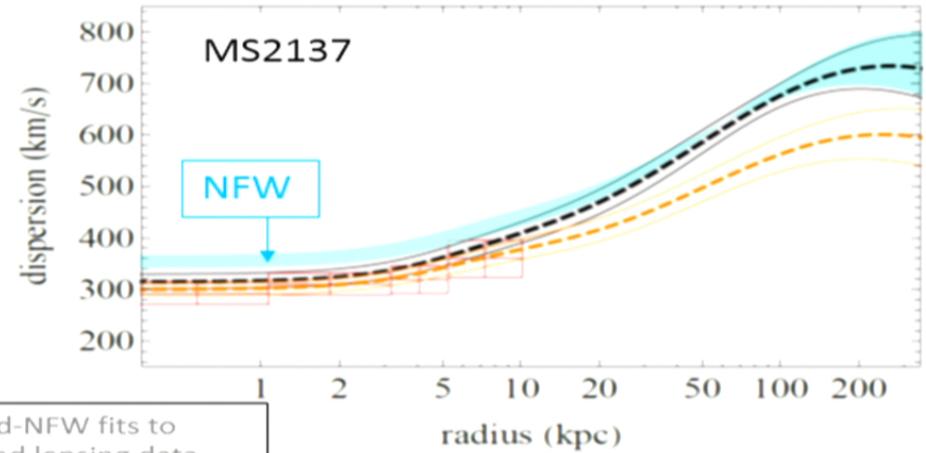
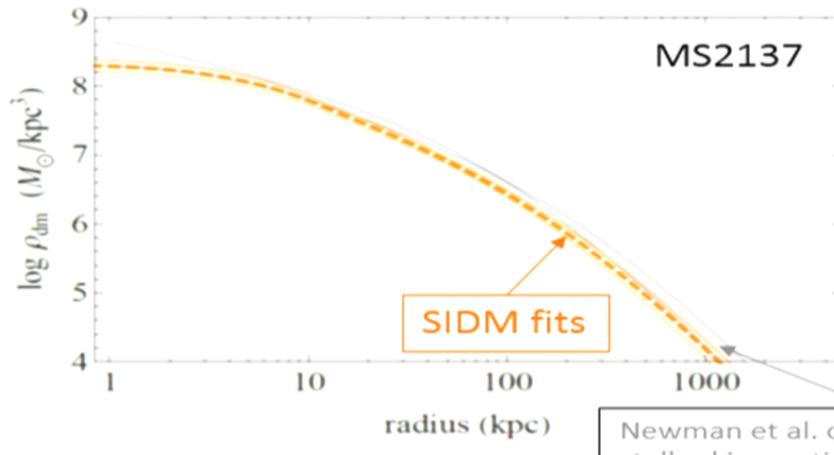
Cluster fits by MCMC scan

Scan over $\{\sigma_0, \rho(0), r_1\}$ and fit to:

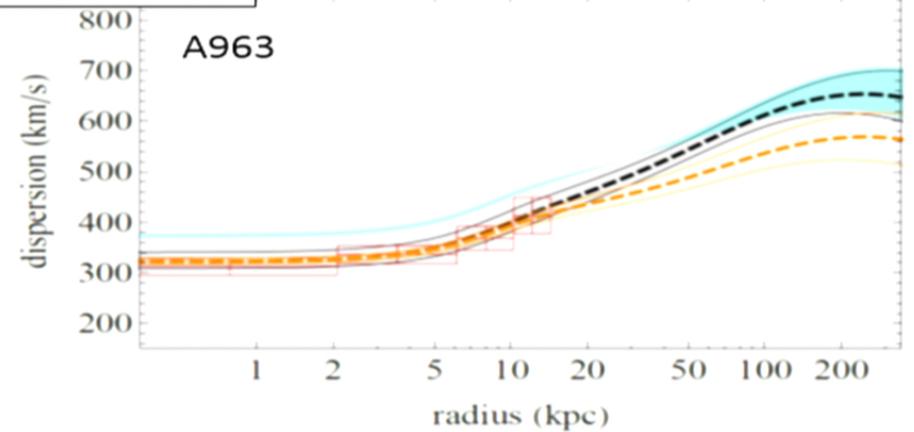
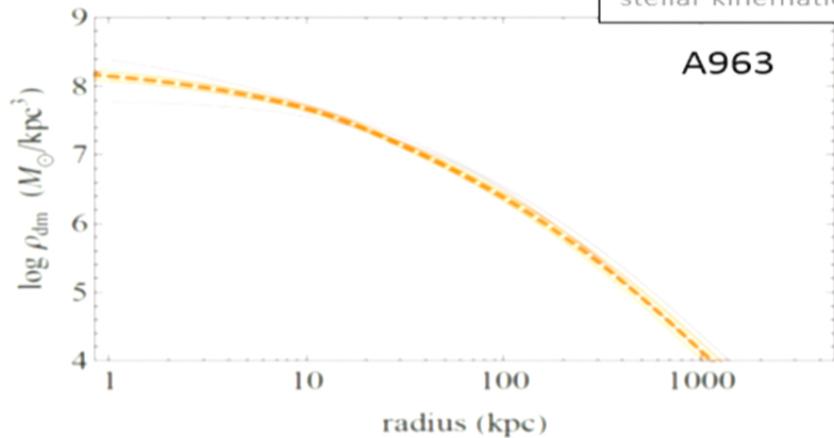
- Stellar kinematics data for central galaxy in the cluster (small r)
- Fit to M_{200} at large r (from strong/weak lensing).
- Continuity between SIDM and NFW at $r = r_1$.

Cluster fits by MCMC scan

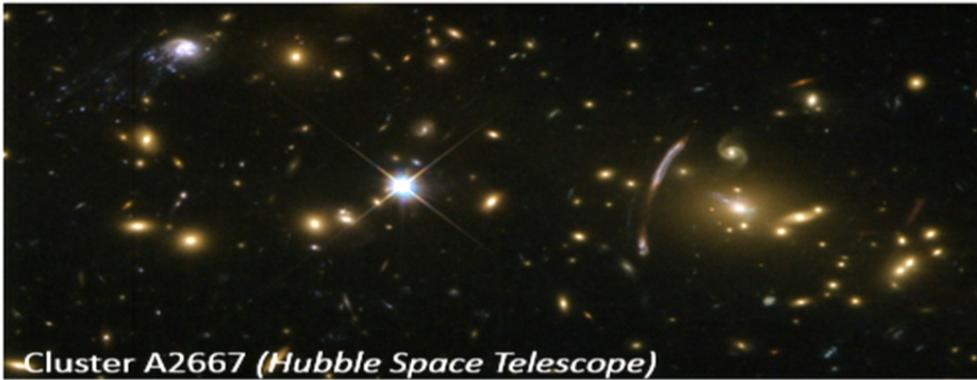
Caveat: not all systematics included in SIDM fits



Newman et al. cored-NFW fits to stellar kinematics and lensing data

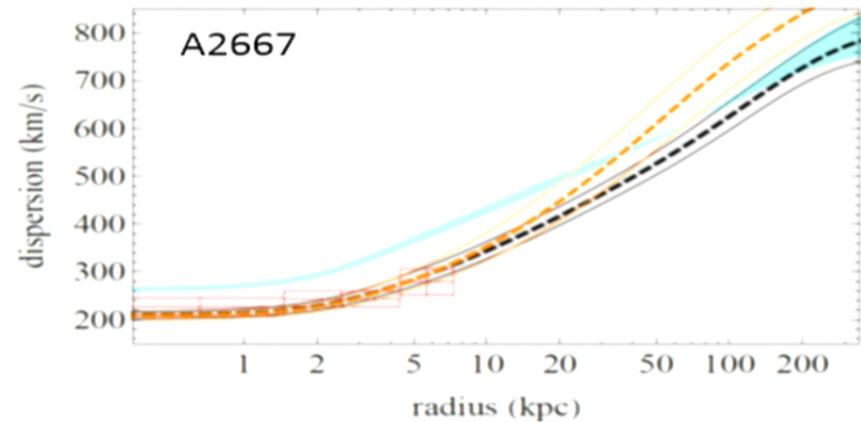
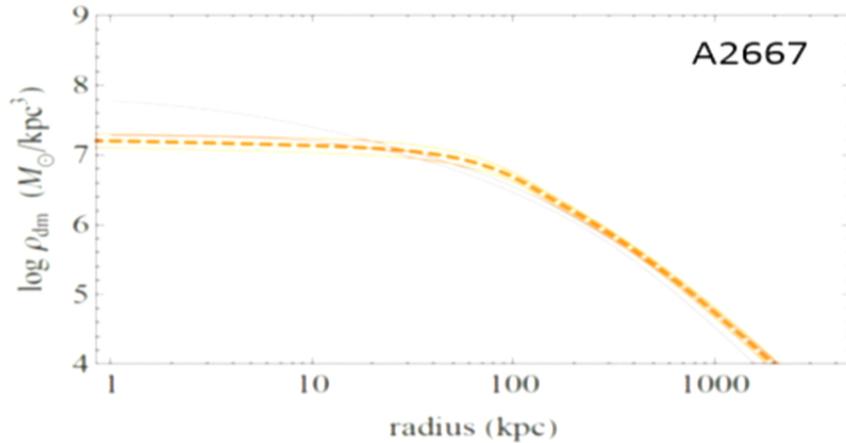


Cluster fits by MCMC scan



Cluster with large core

Our procedure produces flatter profile compared to fits (DM velocity dispersion overestimated)



SIDM fits to dwarfs and LSBs

7 THINGS dwarf galaxies (Oh et al 2011)
7 LSB galaxies (Kuzio de Naray et al 2007)

Cored isothermal profiles
provide a better fit to velocity
data compared to NFW profile

Scan over $(\sigma_0, \rho(0), r_1)$ and fit to:

- Match to isothermal profile $(\rho(0), r_{\text{core}})$
- Continuity between SIDM and NFW at $r = r_1$.
- NFW profile at $r > r_1$ is “cosmologically acceptable”

N-body simulations for CDM provide ρ_s - r_s correlation

$$\rho_s = 10^{7.16 \pm 0.20} M_{\odot} \text{kpc}^{-3} \times (r_s / \text{kpc})^{-0.45}$$

Cross section data from dark matter halos

Instead of σ/m vs v_{rel} , better to think of $\langle\sigma v_{\text{rel}}\rangle/m$ vs $\langle v_{\text{rel}}\rangle$

Rate
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Relative velocity
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Cross section data from dark matter halos

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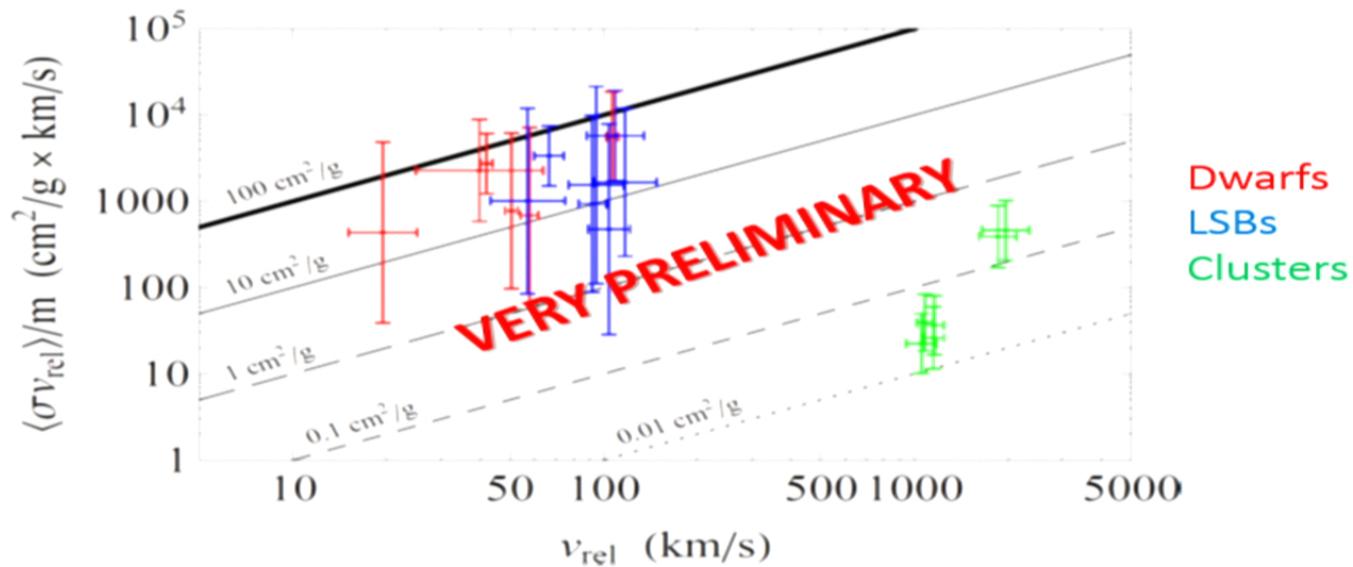
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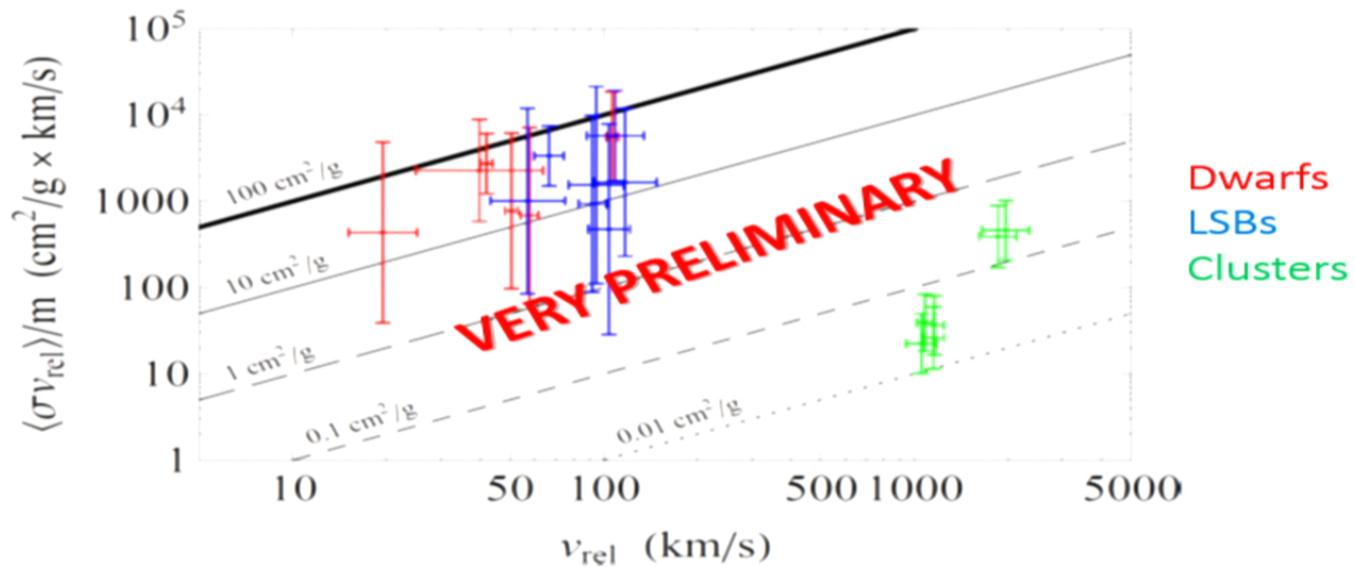


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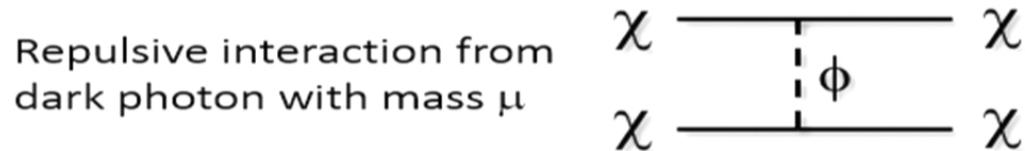
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Particle physics model

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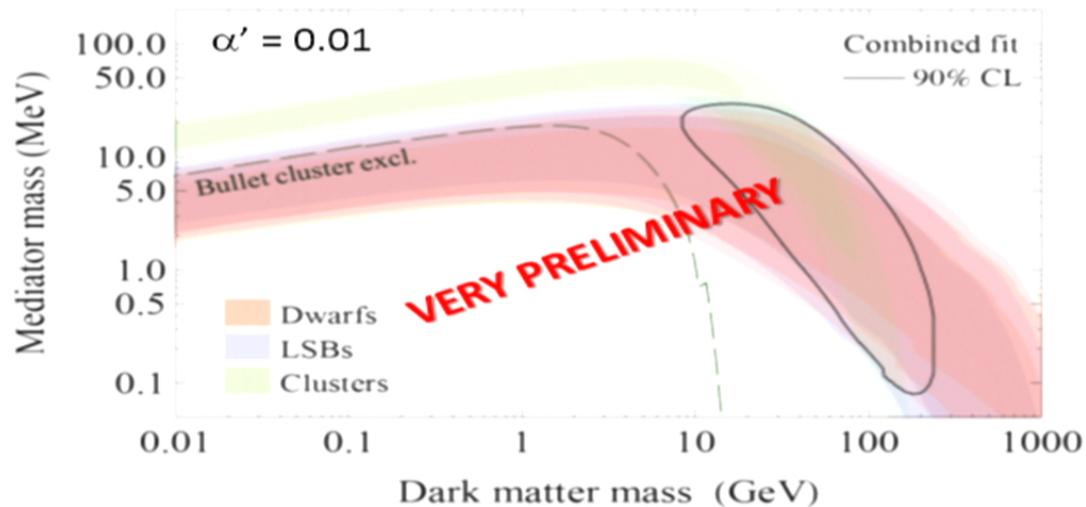
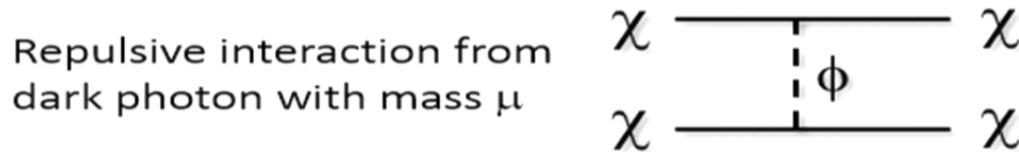
Simple particle physics model for self-interactions $V(r) = \frac{\alpha'}{r} e^{-\mu r}$



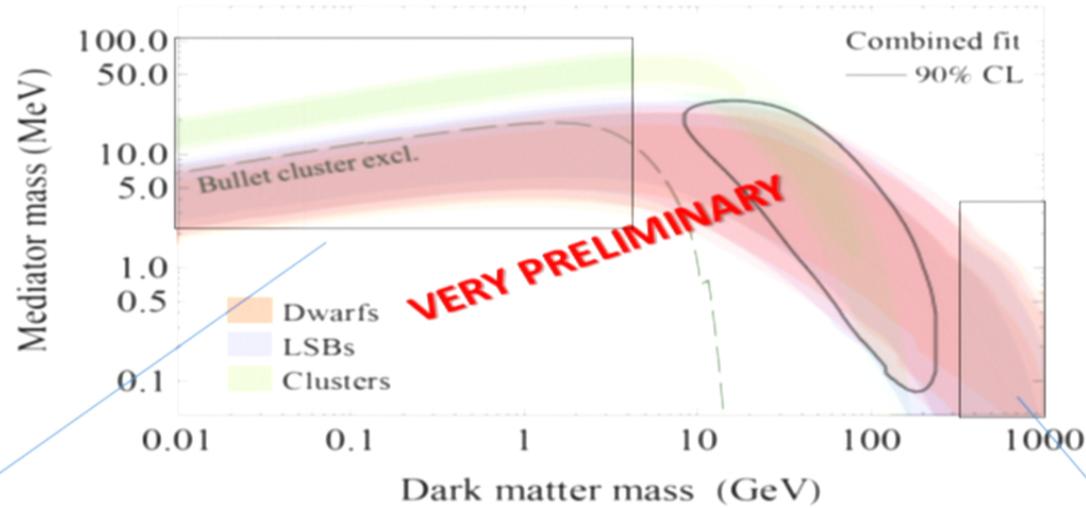
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Particle physics model



Light dark matter
Velocity-independent
cross section

$$\sigma \sim \frac{g^4 m_\chi^2}{m_\phi^4}$$

TeV dark matter
Steep velocity-dependent
cross section

$$\sigma \propto 1/(m_\chi^2 v^4)$$

Conclusions

- Astrophysical observations of structure offer possibility to explore dark matter interactions beyond WIMP paradigm and may be hidden from visible sector
- Long-standing issues for CDM and structure, but jury still out
- Galaxies and clusters offer huge complementary power for exploring particle physics of SIDM (but need to understand the backgrounds).