Self-interacting dark matter: astrophysics

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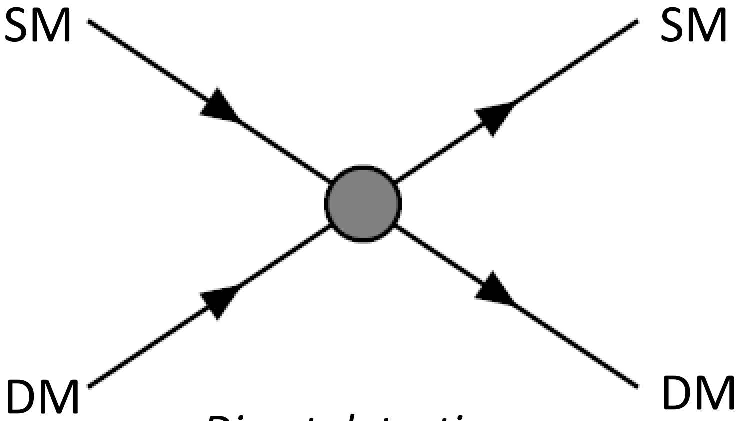
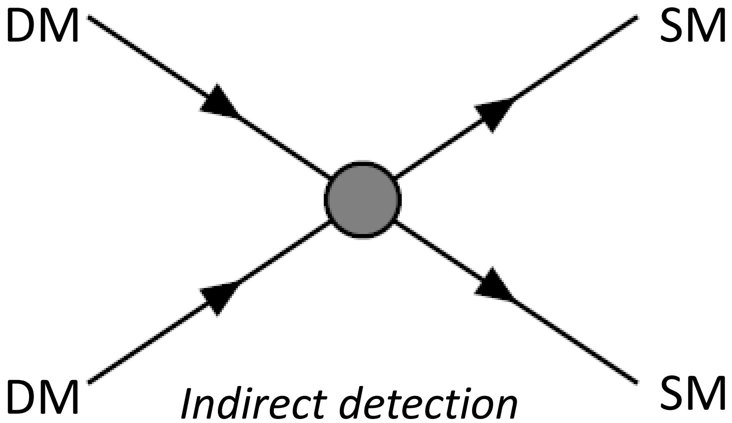
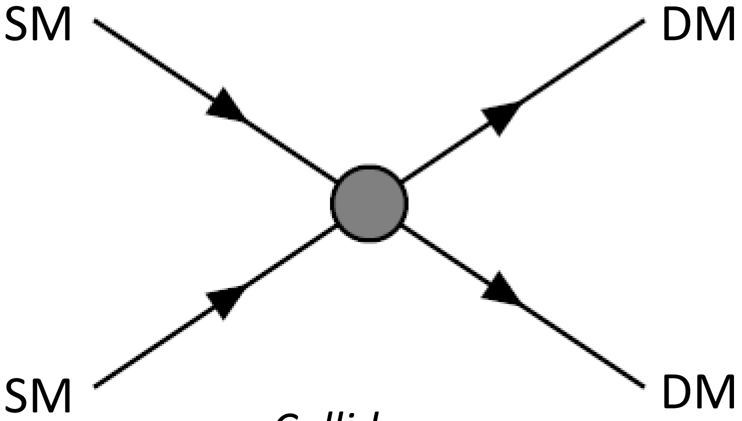
Non-gravitational dark matter interactions



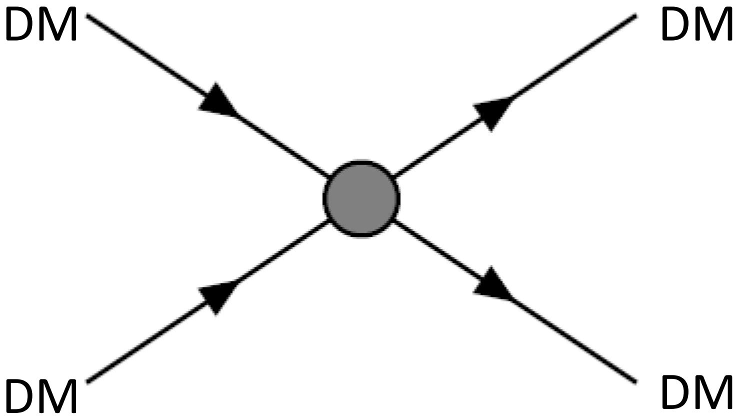
Direct detection



Indirect detection



Colliders



Self-interactions

Outline

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

} Upcoming talk by Hai-Bo Yu

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

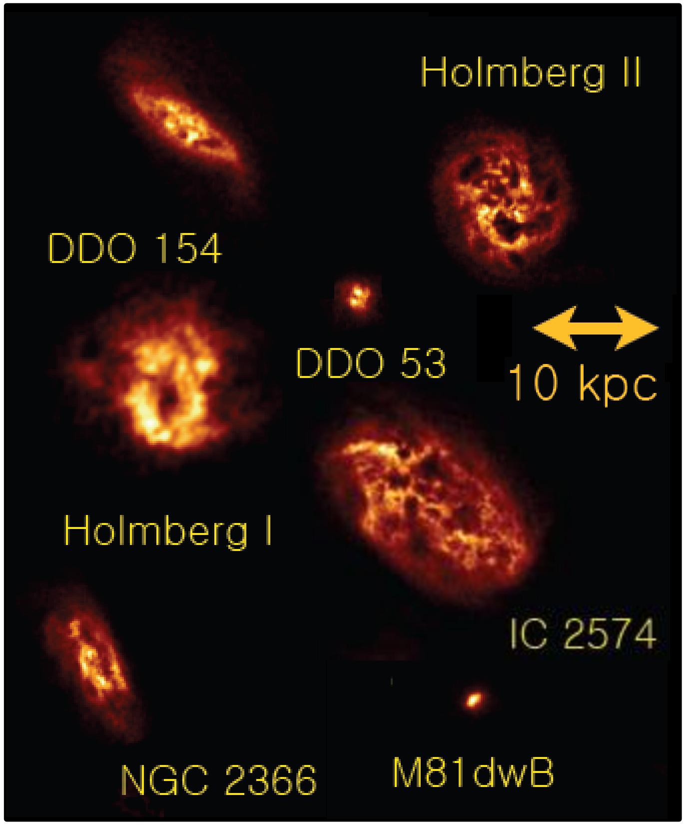
1. Core-vs-cusp problem

Cores seem fairly ubiquitous:

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

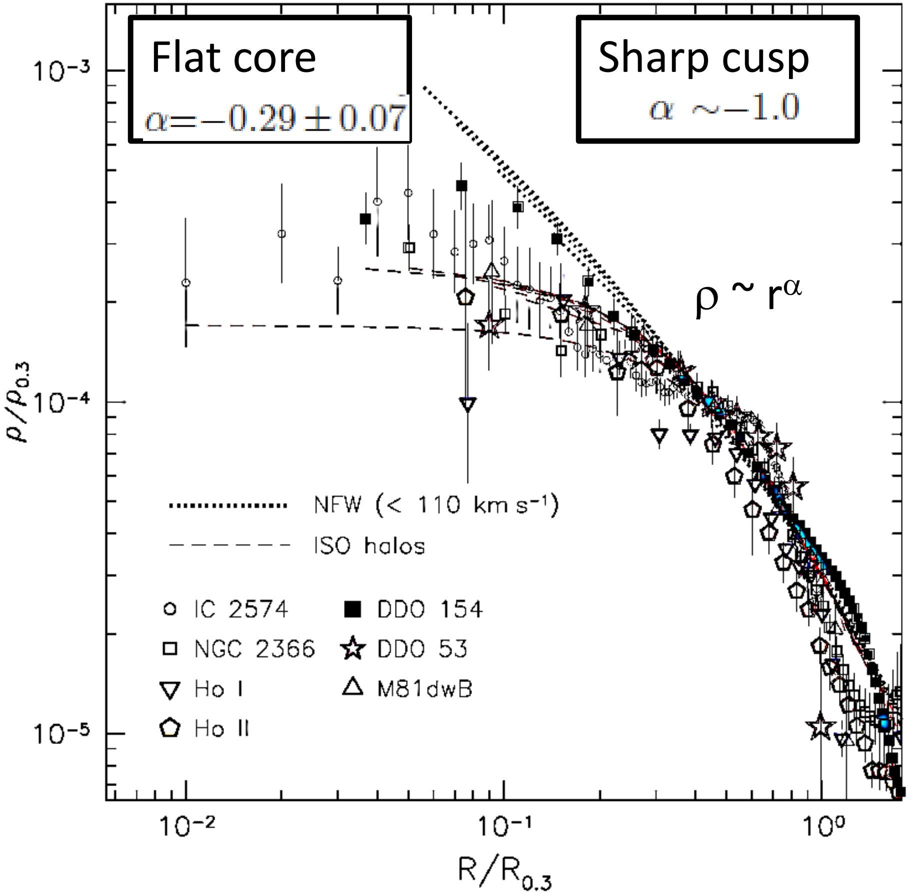
1. Cores in field dwarfs

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



21 cm emission from gas

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


Flat core

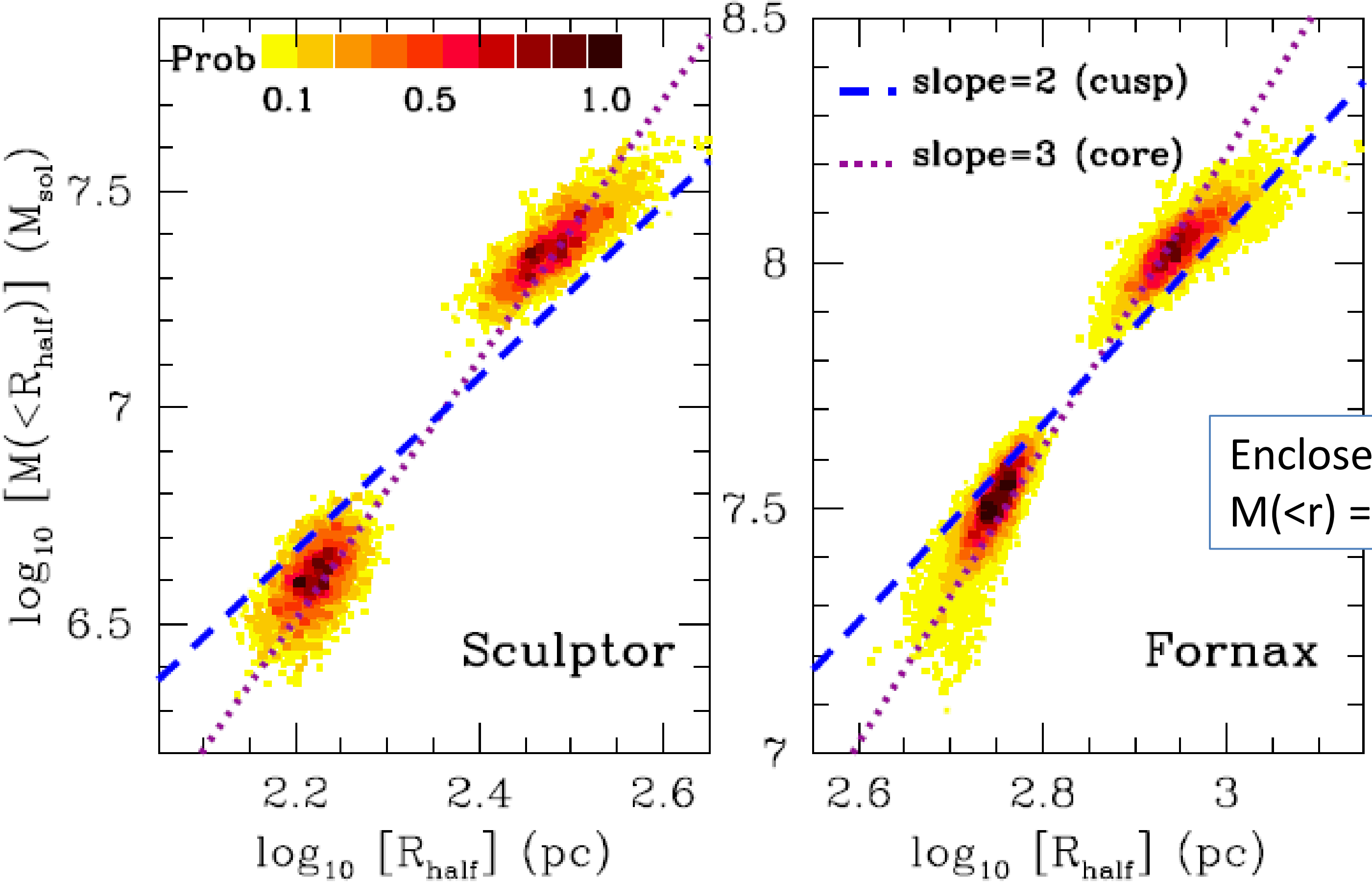
$\alpha = -0.29 \pm 0.07$

Sharp cusp

$\alpha \sim -1.0$

$\rho \sim r^{\alpha}$

1. Cores in MW dwarf spheroidals

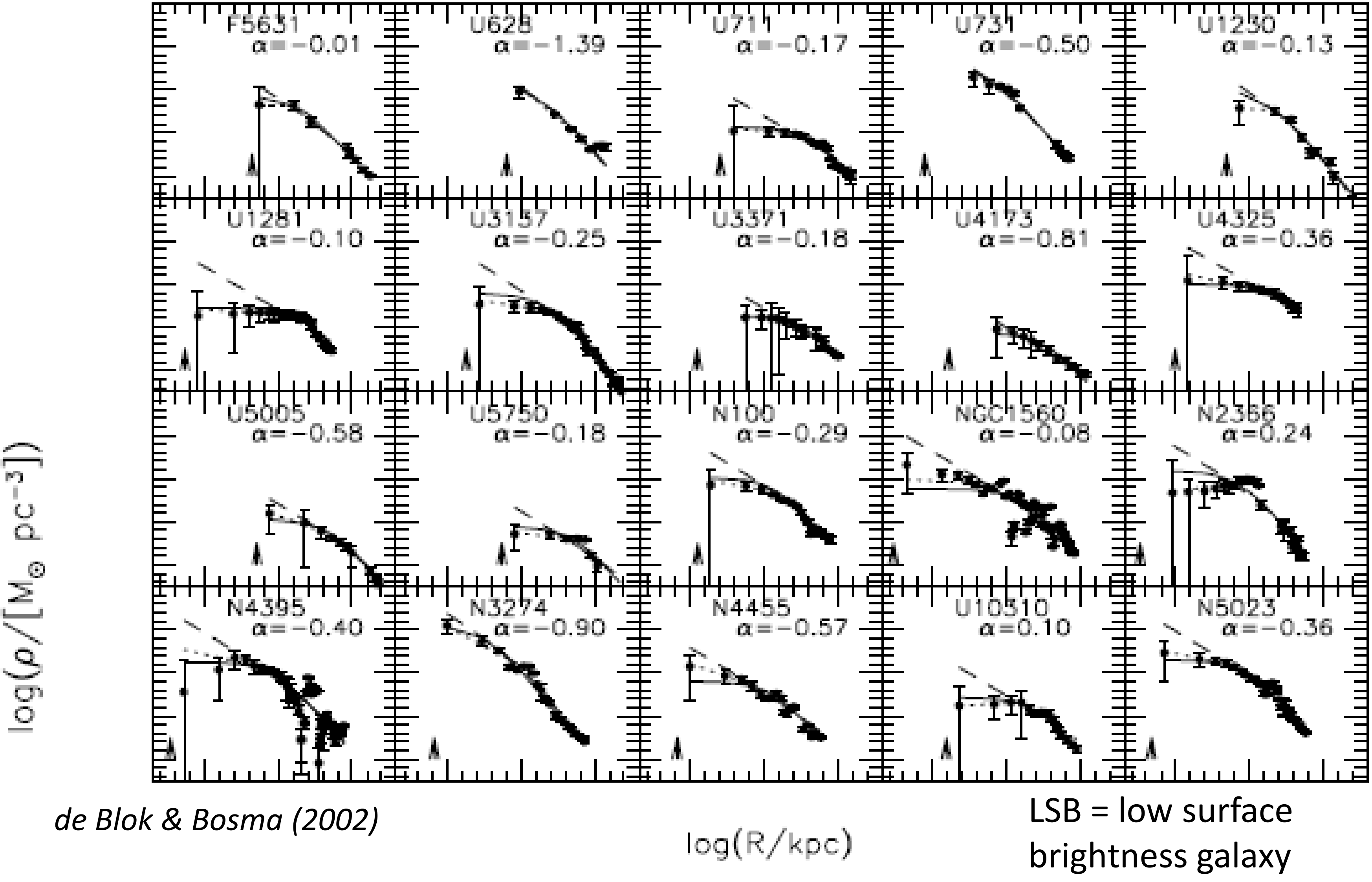


Enclosed mass
$M(<r) = \int d^3r\, \rho$

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

Walker & Penarrubia (2011)

1. Cores in LSBs

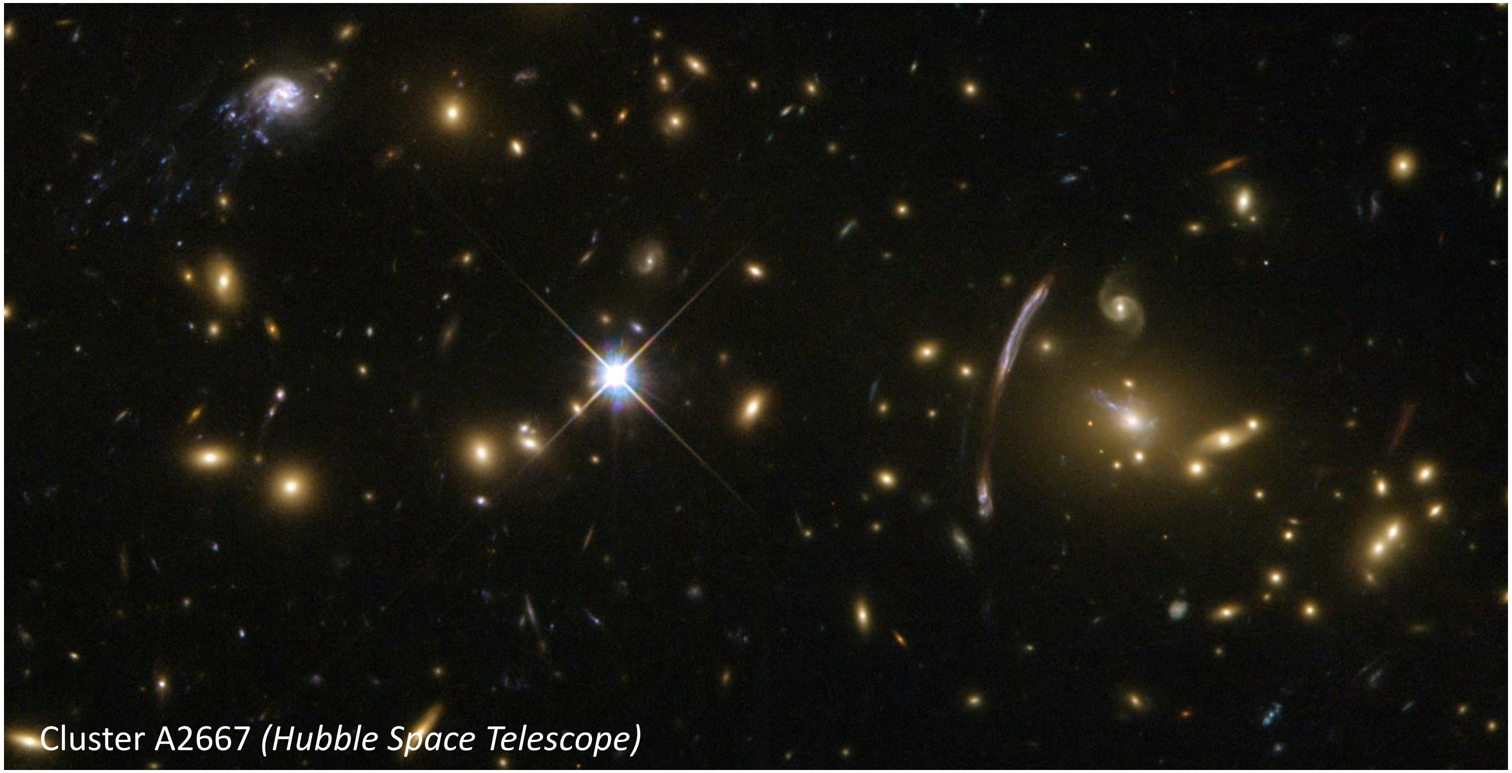


de Blok & Bosma (2002)

LSB = low surface brightness galaxy

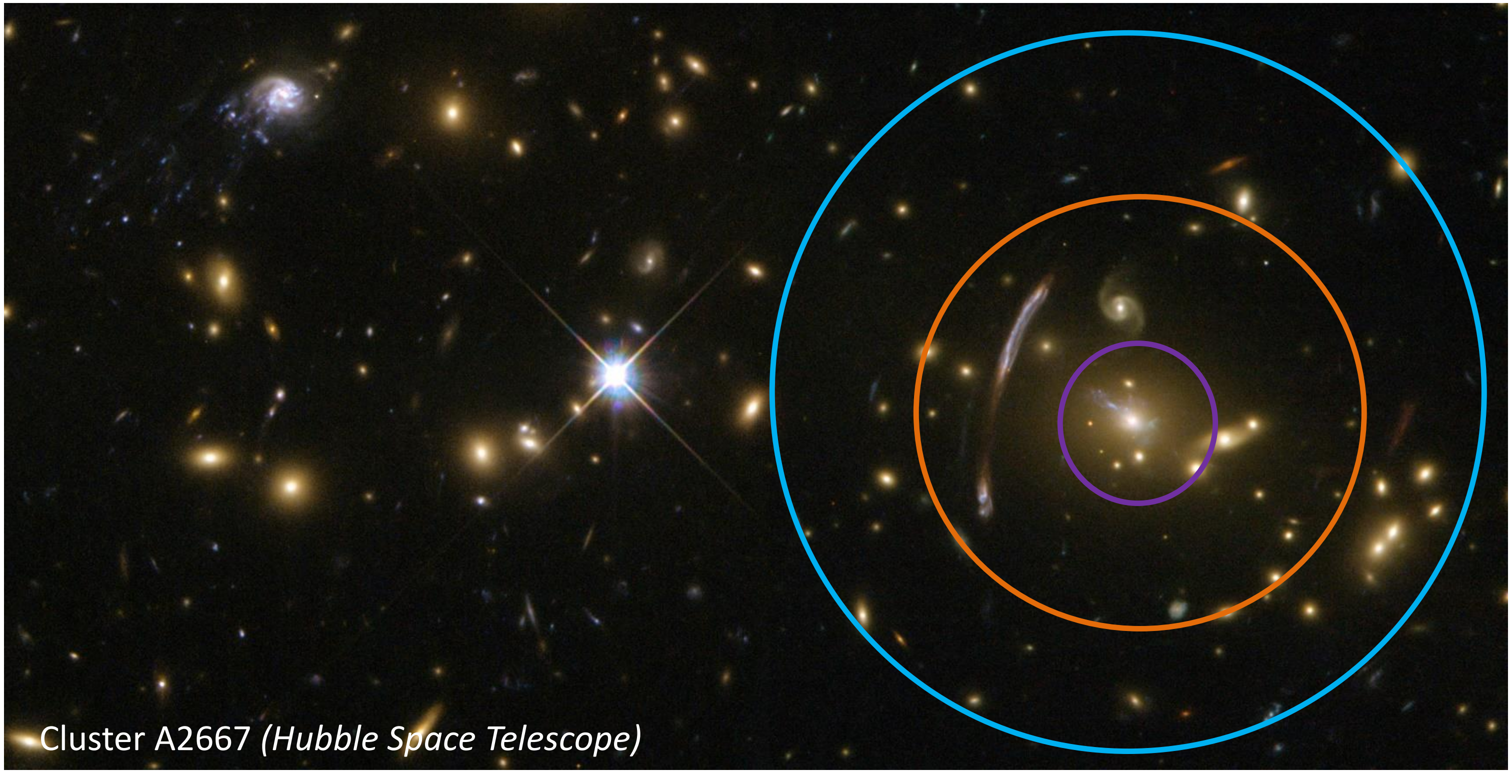
See also: Kuzio de Naray et al (2007); Kuzio de Naray & Spekkens (2011)

1. Cores in clusters



Cluster A2667 *(Hubble Space Telescope)*

1. Cores in clusters



Cluster A2667 *(Hubble Space Telescope)*

Use multiple measurements to study dark matter halo

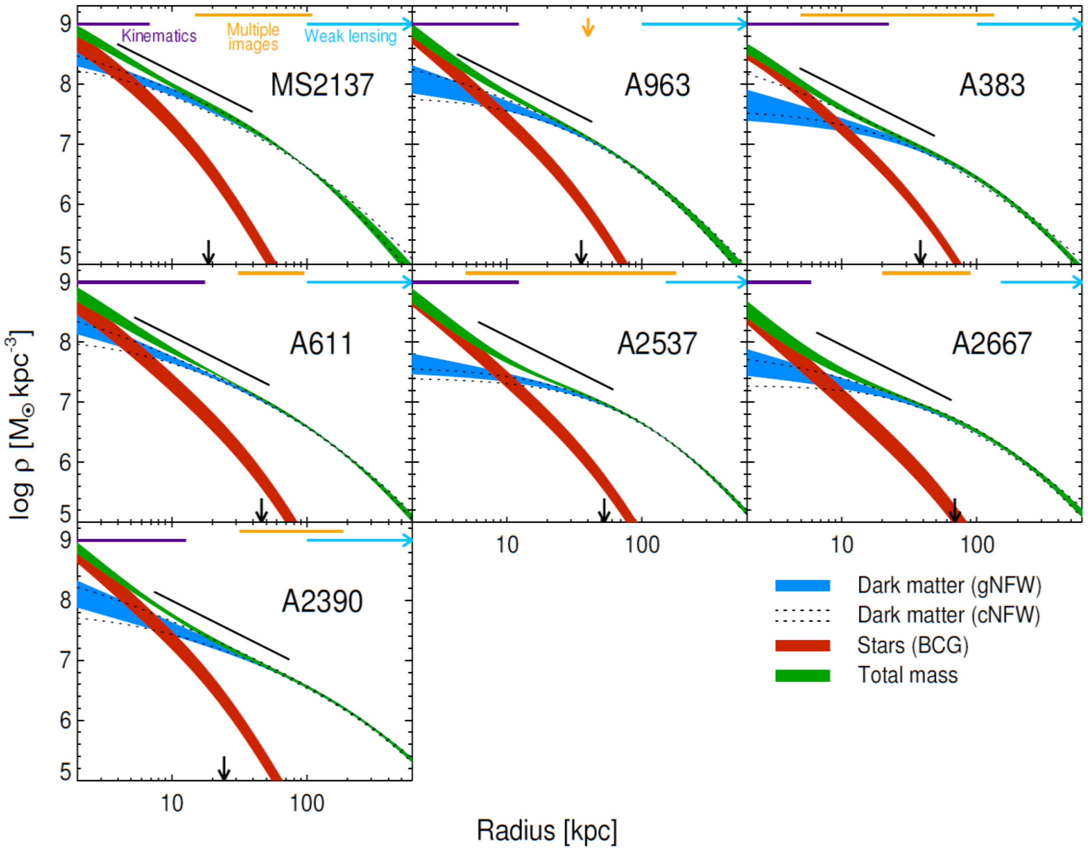
Newman et al (2012)

Weak gravitational lensing at large distance

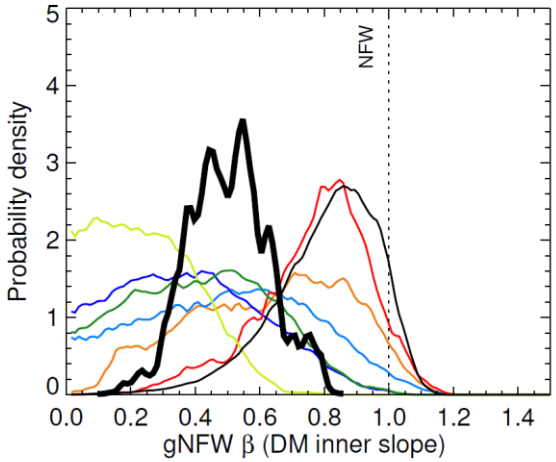
Gravitational lensing arcs (strong lensing) at medium distance

Stellar kinematics for the cluster center

1. Cores in clusters



Newman et al (2012)



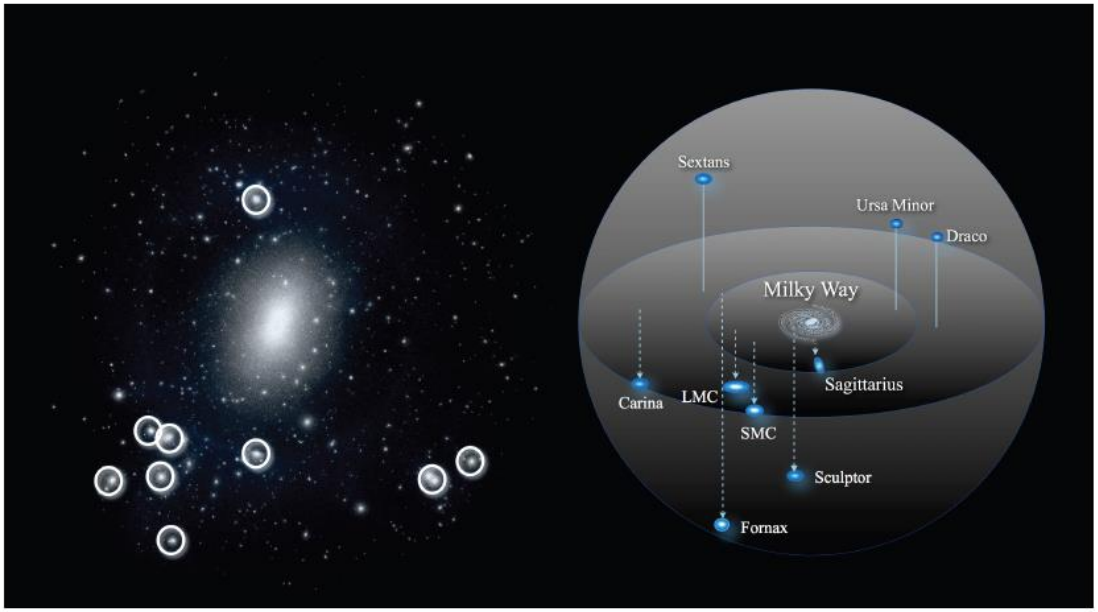
gNFW fit:

$$\rho_{\rm DM}(r) = \frac{\rho_s}{(r/r_s)^{\beta}(1+r/r_s)^{3-\beta}}$$

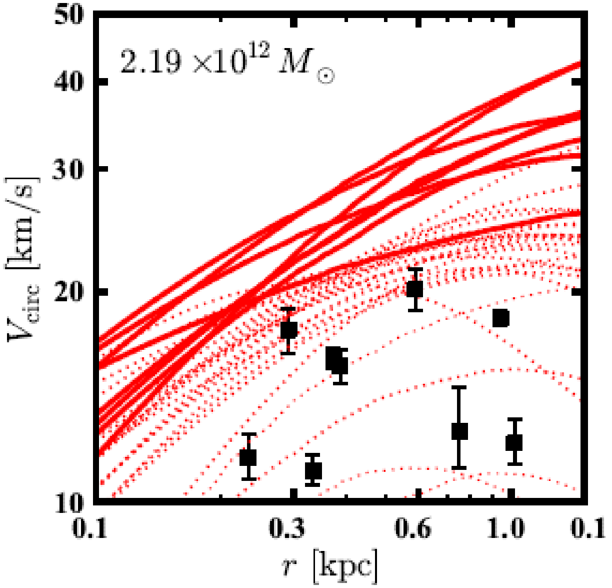
2. Too-big-to-fail problem

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

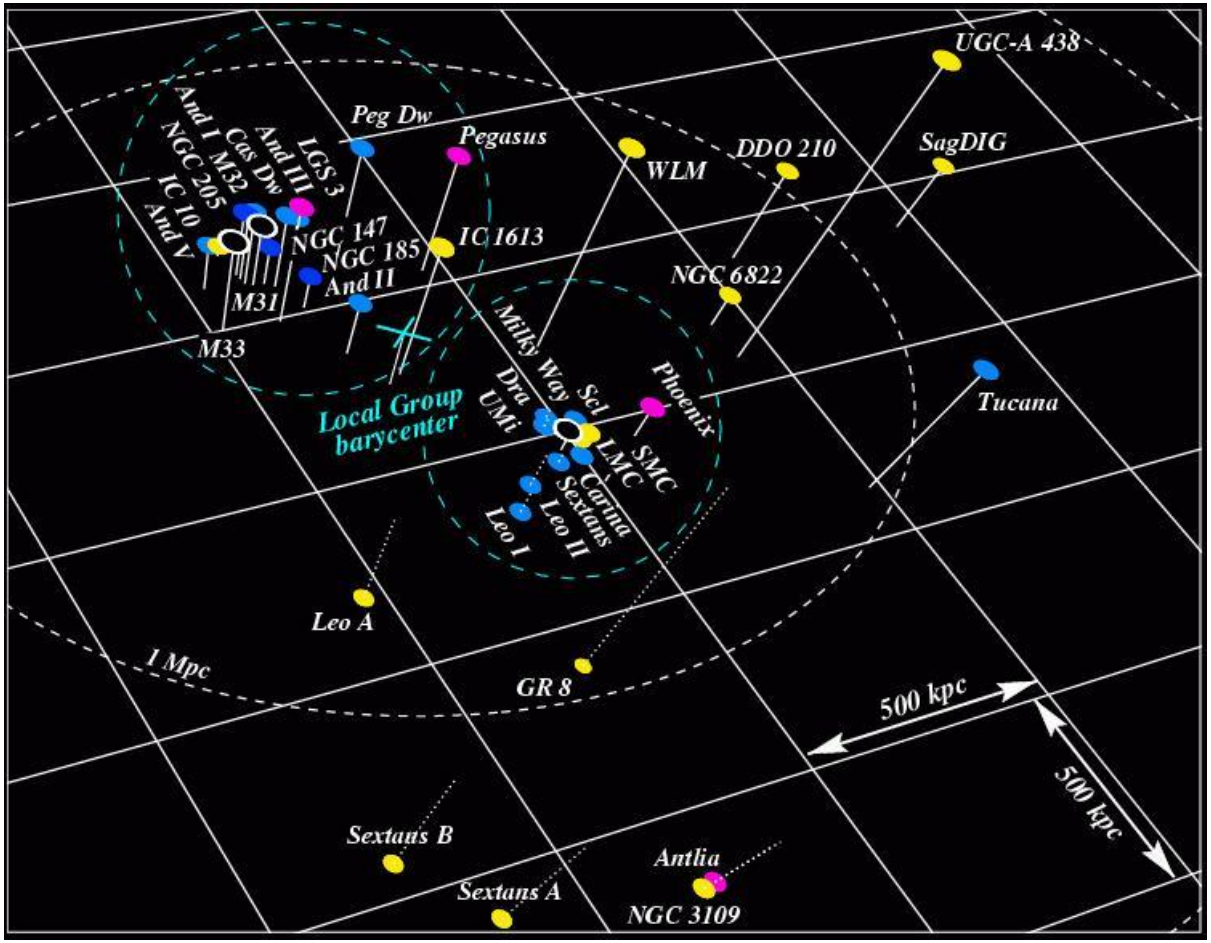


From Weinberg, Bullock, Governato, Kuzio de Naray, Peter (2013)



2. Too-big-to-fail problem

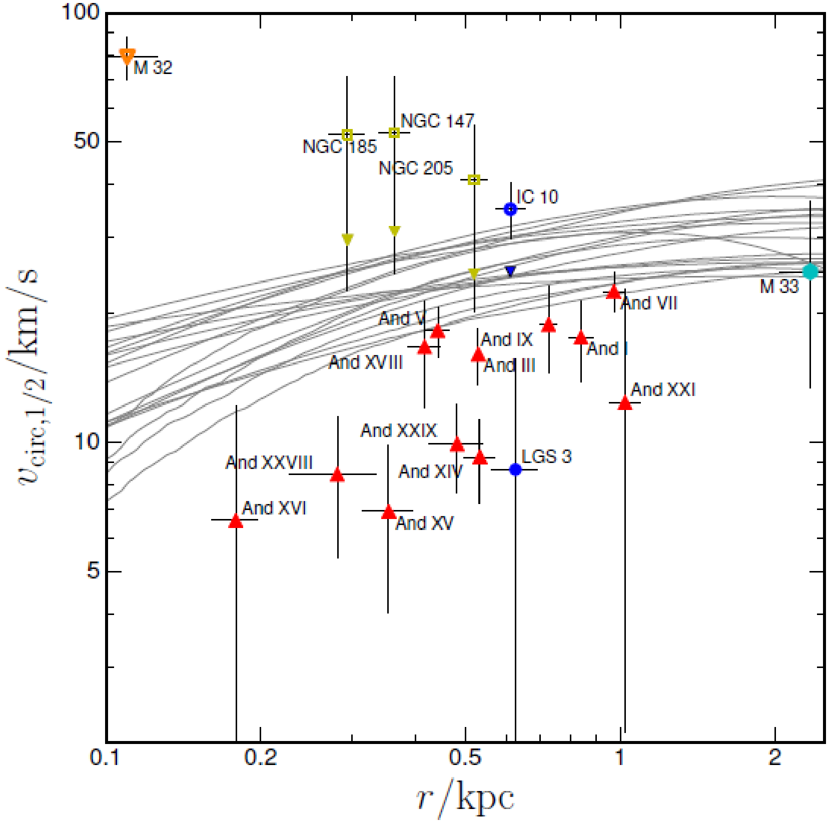
Is there a problem beyond the Milky Way?



2. Too-big-to-fail problem

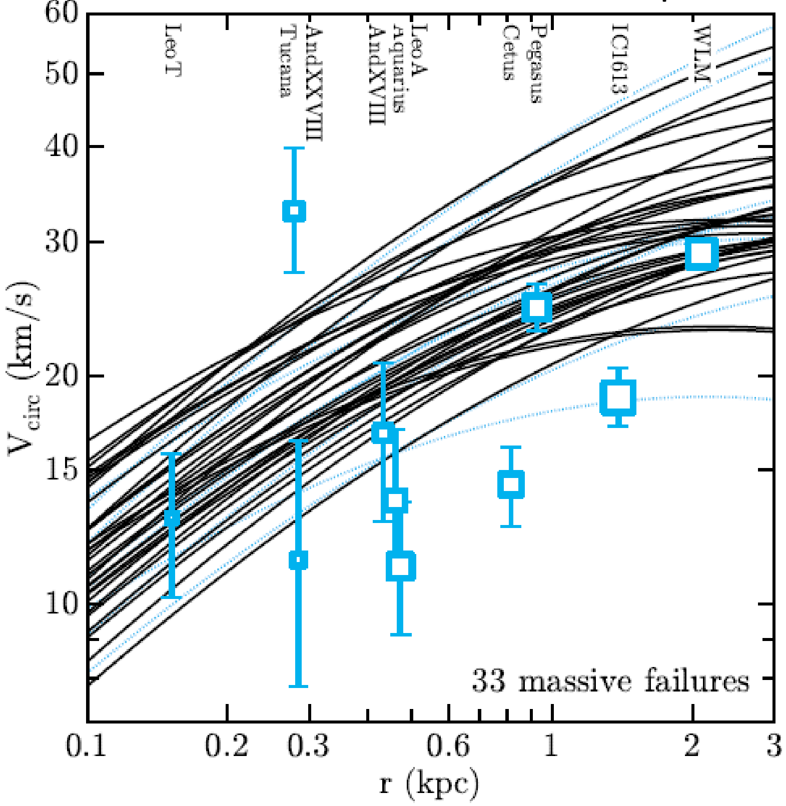
Is there a problem beyond the Milky Way?

Satellites of the Andromeda galaxy (M31)



Tollerud et al. (2014)

Field dwarfs in the Local Group



Garrison-Kimmel et al. (2014)

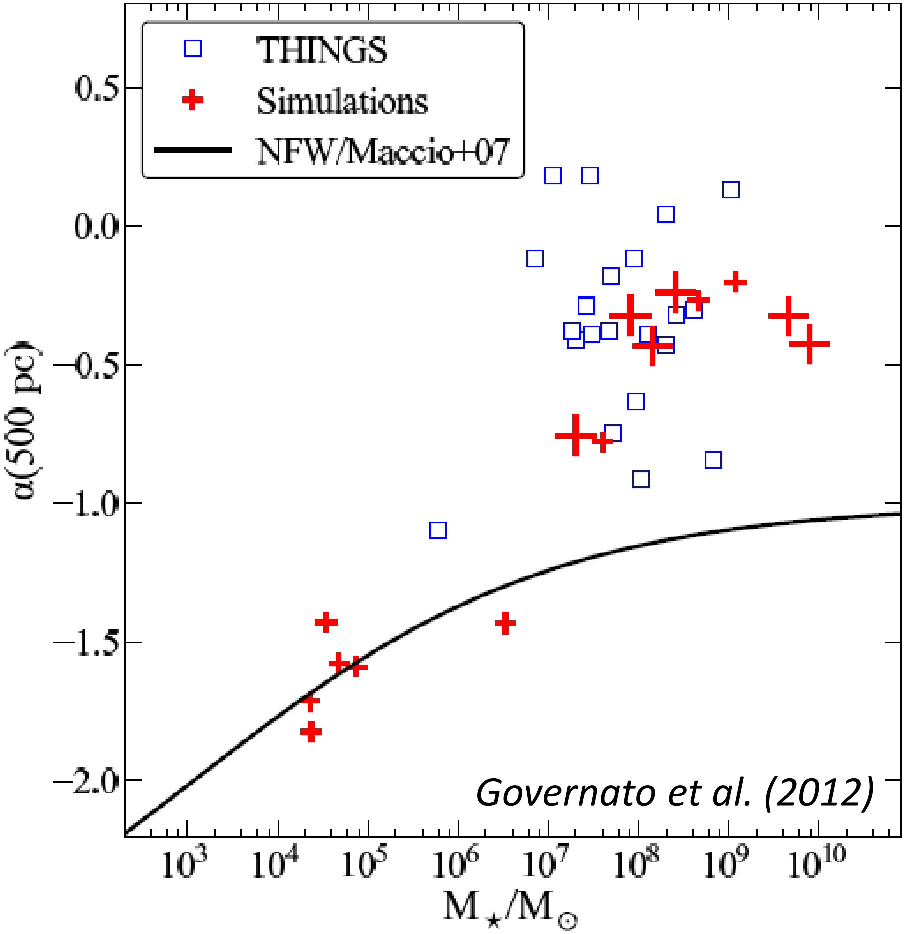
CDM Problems

- 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

1. Cores in field dwarfs

CDM-only simulations poor representation of DM+baryon Universe



Governato et al. (2012)

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

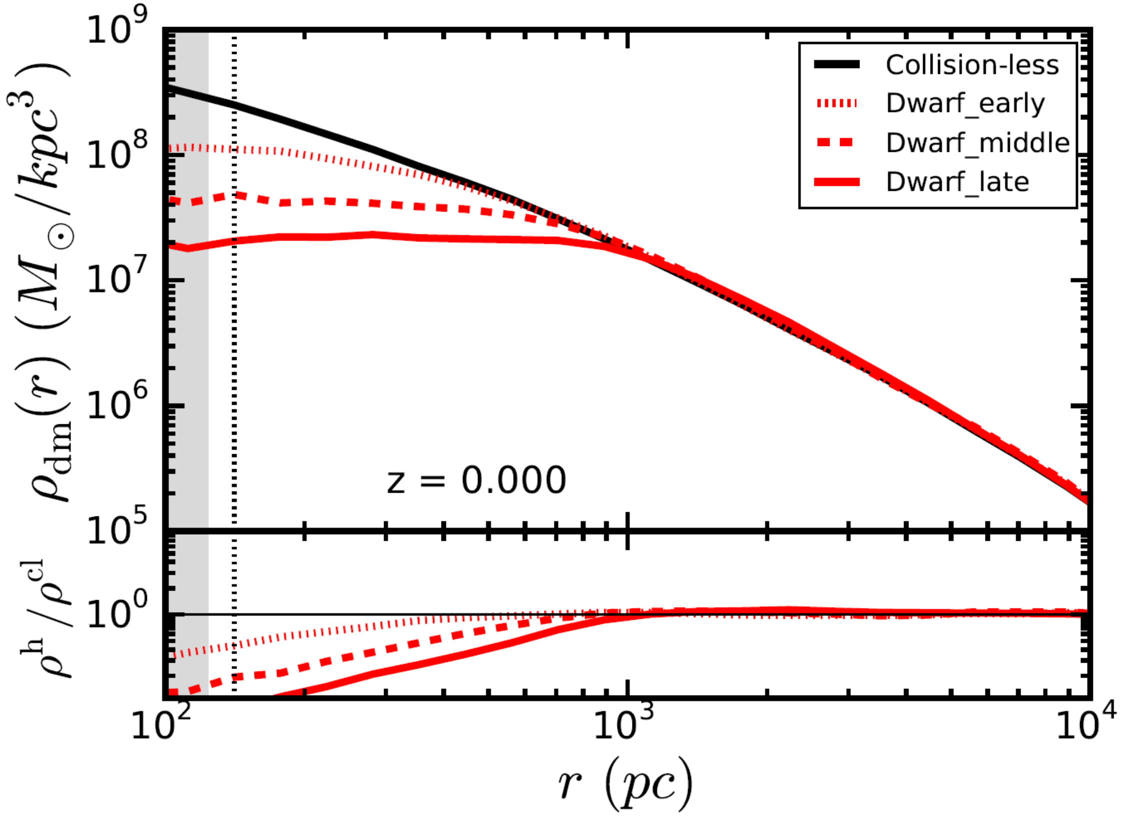
Depends on implementation sub-grid baryonic physics

Requires bursty star formation history

In Governato et al sim, cores formed around z ~ 2 – 4.

1. Cores in field dwarfs

CDM-only simulations poor representation of DM+baryon Universe



Another simulation with supernova feedback

Feedback confirmed, but requires *late-time* star formation epoch (z < 2)

Onorbe et al (2015)

1. Cores in MW satellites

CDM-only simulations poor representation of DM+baryon Universe

- Supernova feedback mechanism insufficient (not enough baryons)

  Garrison-Kimmel, et al (2013)

- Supernova feedback may work in biggest satellites with the right star formation history

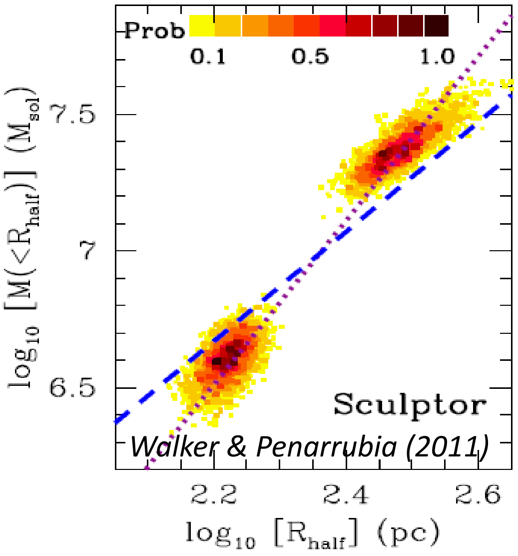
  Onorbe, et al (2015)

- Environmental effect from MW baryonic disk can form DM cores

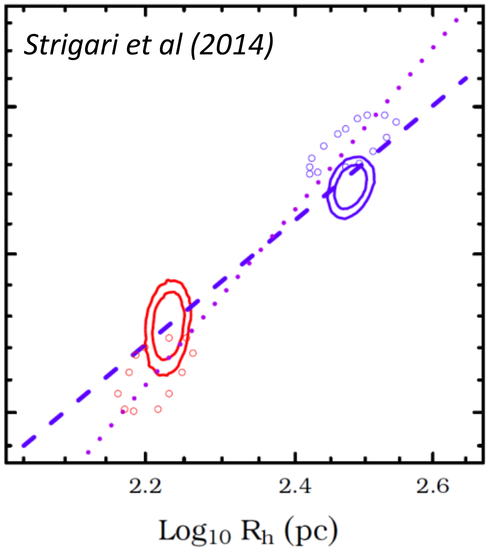
  Zolotov, et al (2012)

1. Cores in MW satellites

Systematic uncertainty in astrophysical interpretation



Walker & Penarrubia (2011)



Strigari et al (2014)

No cores in MW satellites?

Conclusions depend on assumptions for stellar kinematic distribution

(Only observe line-of-sight velocity and projected position)

1. Cores in LSBs

- Still an open challenge for baryonic physics
  - Metal-poor (not much star formation)
  - Not recently bursty
  - More massive than THINGS dwarfs (harder to blow out baryons)

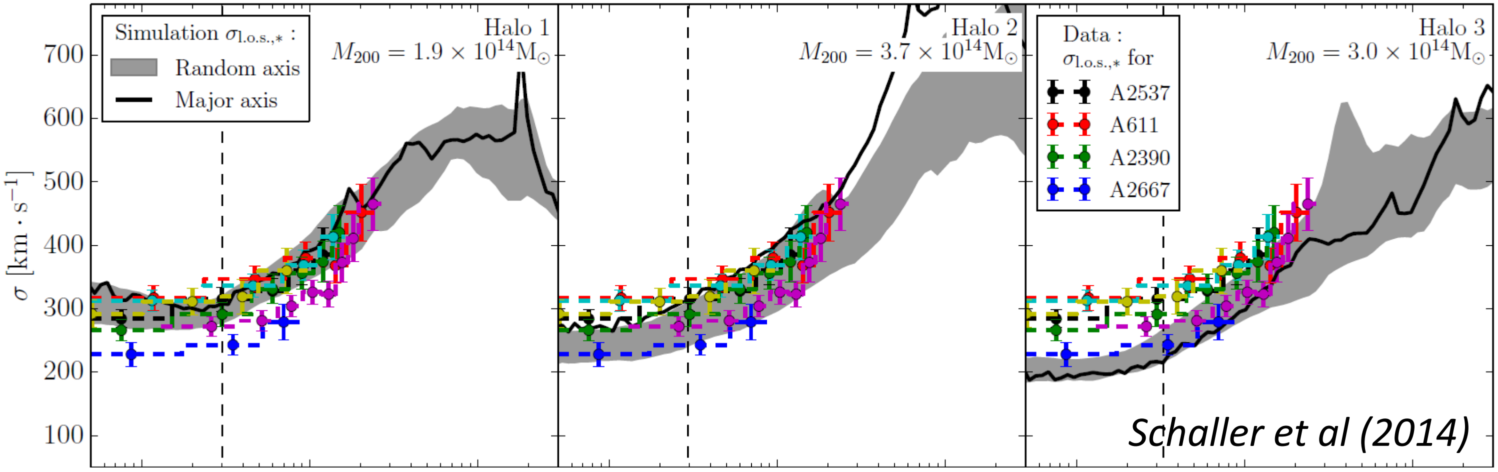
1. Cores in clusters

CDM-only simulations poor representation of DM+baryon Universe

- AGN feedback may generate cores *Martizzi et al (2012)*
- AGN feedback may be insufficient *Schaller et al (2014)*

Systematic uncertainty in astrophysical interpretation

- Existence of core inferred from stellar kinematics
- Depends on assumptions for the stellar kinematic distribution



Schaller et al (2014)

Stellar line-of-sight velocity dispersion

Radius

2. Too-big-to-fail problem

Caveats:

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

Purcell & Zentner (2012)

MW mass might be smaller (but combined mass of MW+M31 is relatively well constrained) *Tollerud et al. (2014)*

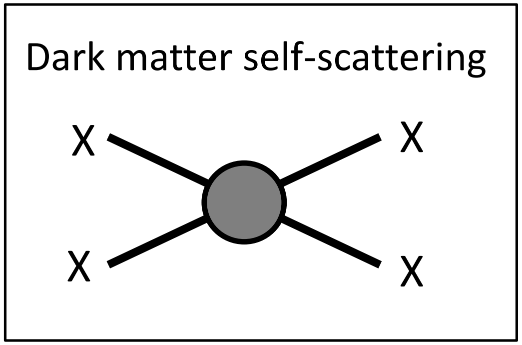
Baryons are important

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

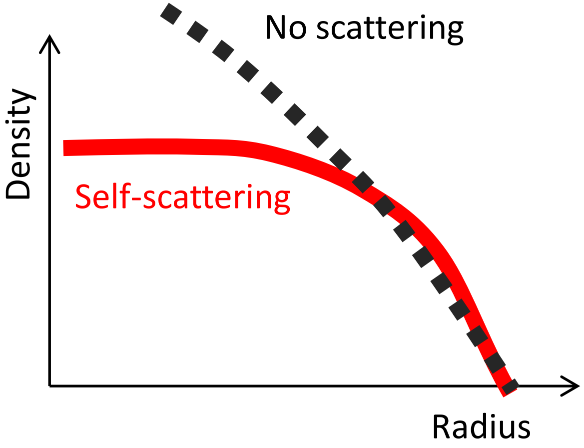
Self-interacting dark matter

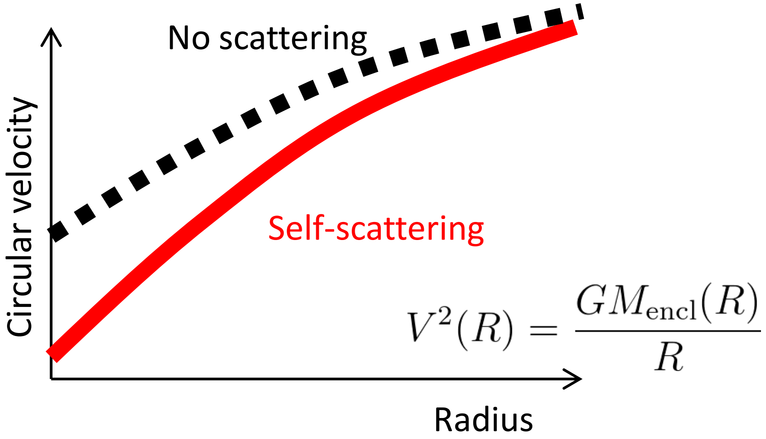
CDM structure problems are solved if dark matter is **self-interacting**

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



Dark matter self-scattering





$$V^2(R) = \frac{GM_{\mathrm{encl}}(R)}{R}$$

Self-interactions solve core-vs-cusp

Particles get scattered out of dense halo centers

Self-interactions solve too-big-to-fail

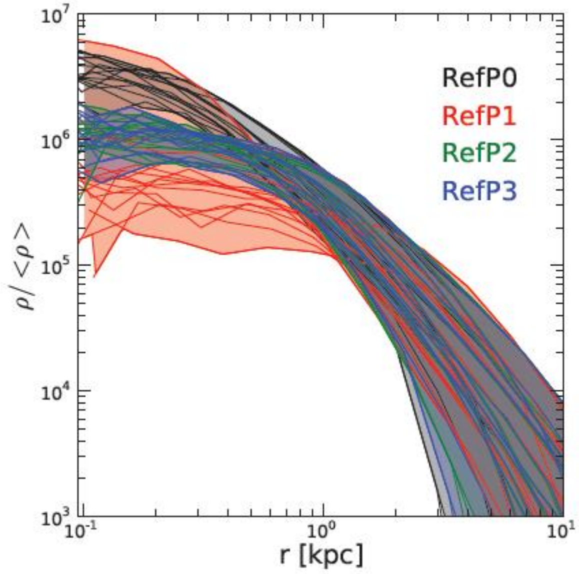
Rotation curves reduced (less enclosed mass)

Simulated satellites matched to observations

N-body simulations for SIDM

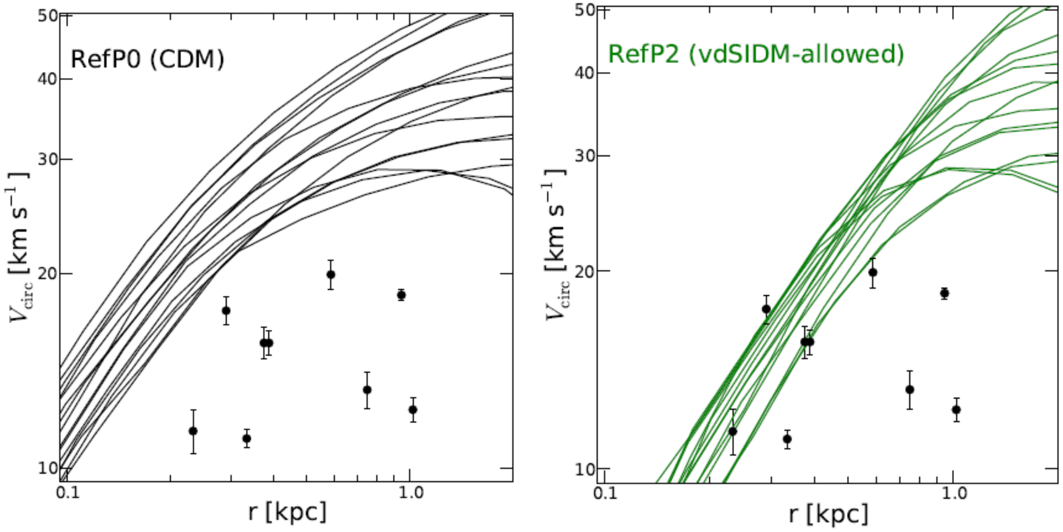
Vogelsberger, Zavala, Loeb (2012); see also Rocha et al, Peter et al (2012)

Core vs cusp problem



Black = CDM
Red/green/blue = SIDM

Too big to fail problem



DM self-scattering moves predicted circular velocities into (closer) alignment with MW dSph

Self-interacting dark matter

- What is the self-scattering cross section?

Number of scatterings = σ x (ρ/m) x velocity x t_{age}

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

Cross section “required” to solve small scale anomalies

Constraints on self-interactions

Constraints from large scales weaker than previously thought

Miralda-Escude bound (grav. lensing by elliptical cluster): $\sigma/m < 0.02\ \mathrm{cm}^2/\mathrm{g}$

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: $\sigma/m < 1\ \mathrm{cm}^2/\mathrm{g}$

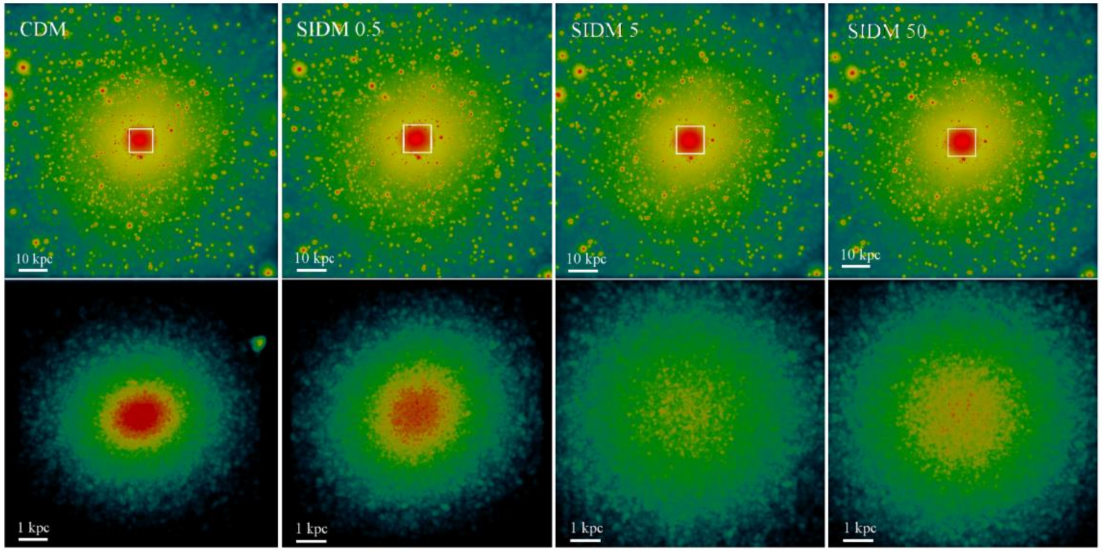
Randall et al. (2007)

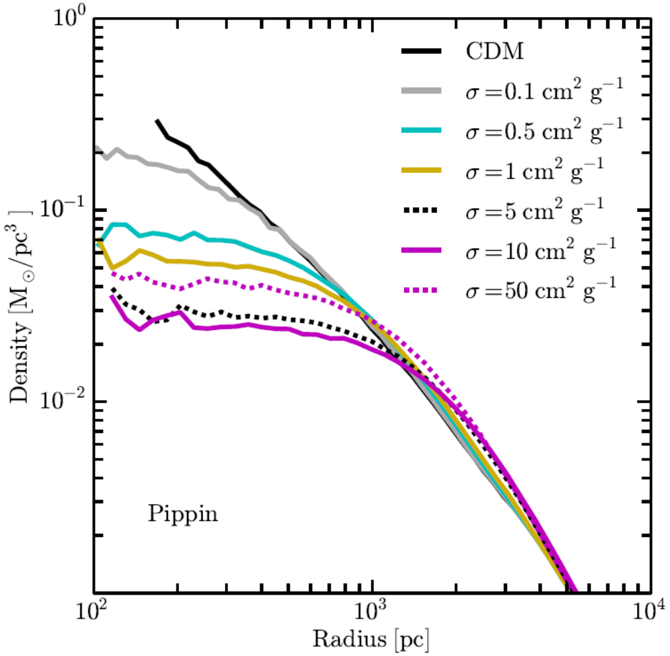
Constant cross section $\sigma/m \sim 0.5 - 1\ \mathrm{cm}^2/\mathrm{g}$ may be OK with all constraints

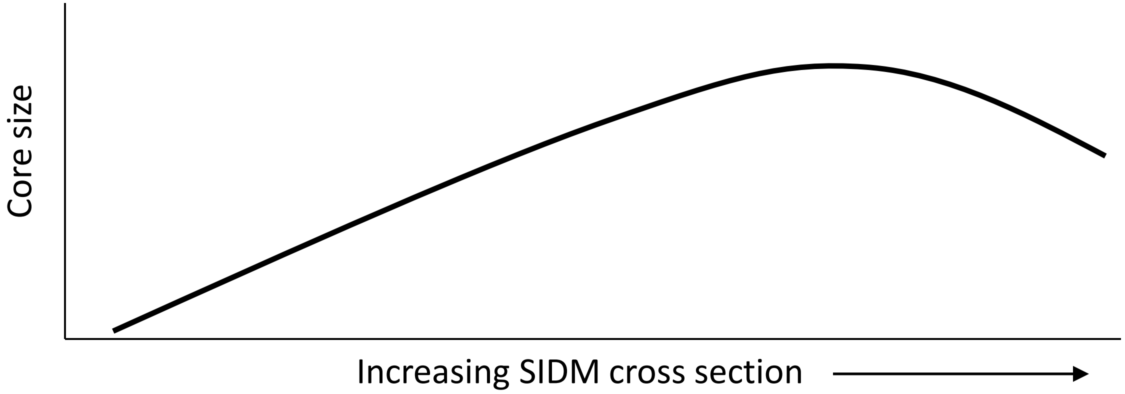
Vogelsberger, Zavala, Loeb (2012); Rocha et al, Peter et al (2012)

What is the cross section for dwarfs?

Elbert et al (2015)







Dwarf galaxies consistent with a wide range of cross sections

Fixed core size may be consistent with two-fold degeneracy in σ

Cluster Abell 3827

Elliptical galaxy N1 appears separated from its DM halo by

$$1.62^{+0.47}_{-0.49}\,\mathrm{kpc}$$

Massey et al (2015)

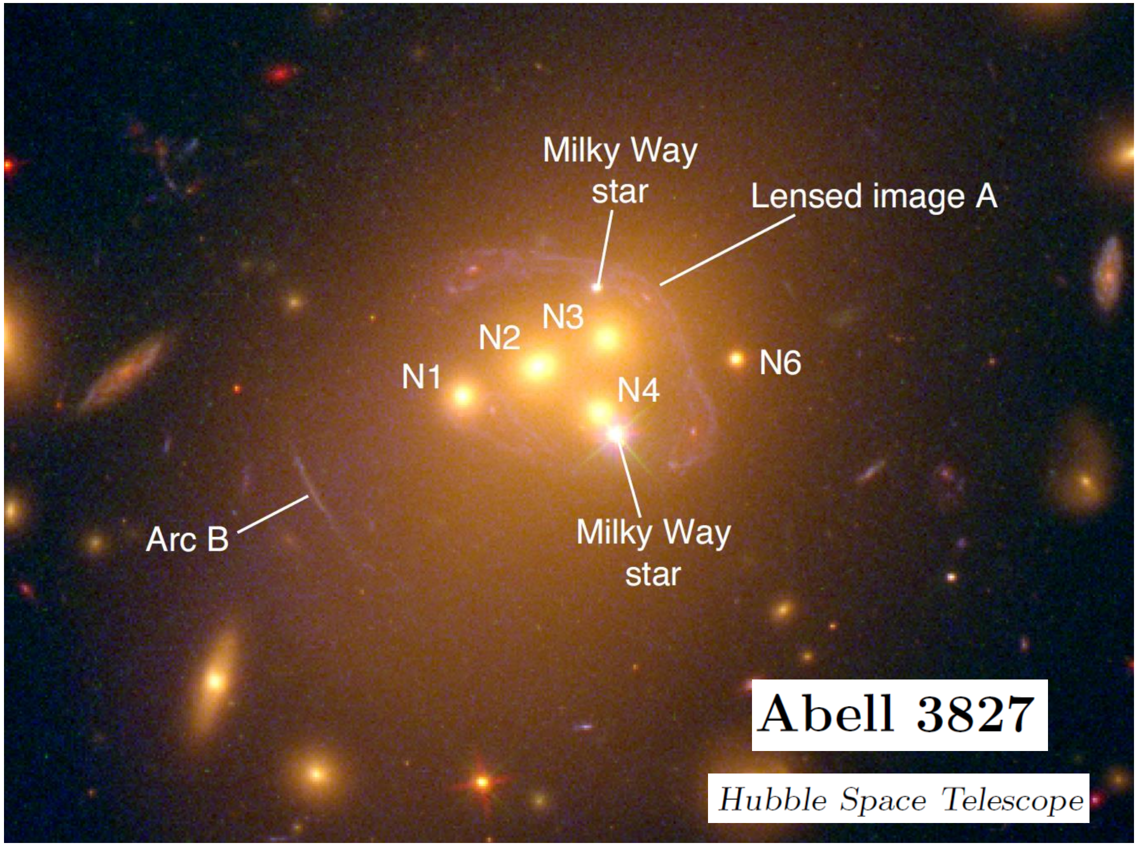
$\sim 3\sigma$ outlier from expected off-set from N-body sim.

Schaller et al (2015)

Required SIDM cross section:

$$\sigma/m \sim (1.7 \pm 0.7) \times 10^{-4} \left(\frac{t_{\mathrm{infall}}}{10^9\ \mathrm{yrs}}\right)^{-2} \mathrm{cm}^2/\mathrm{g}$$

Massey et al (2015)



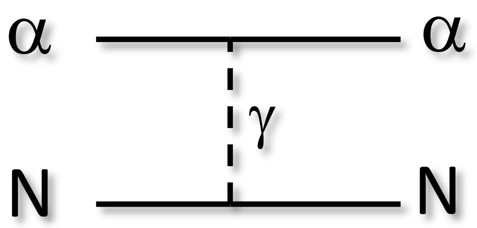
Limit assumed off-set = $\Delta x \sim \Delta f_{\mathrm{drag}}\, t^2$ but neglected restoring force attracting DM and baryons

$\sigma/m \sim 1.5 - 3\ \mathrm{cm}^2/\mathrm{g}$ (depending on angular dependence of scattering)

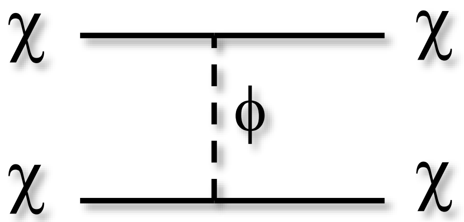
Kahlhoefer et al (2015)

From astrophysics to particle physics

Dark matter self-interactions



Rutherford scattering



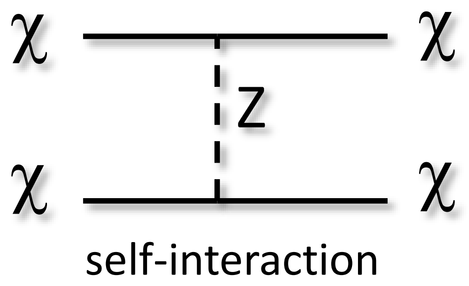
self-interaction

χ = dark matter particle

ϕ = mediator particle
(dark photon, dark Higgs,
dark pion, …)

From astrophysics to particle physics

WIMPs have self-interactions (weak interaction)



Cross section:

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

Mass:

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

χ = dark matter (e.g. SUSY particle)

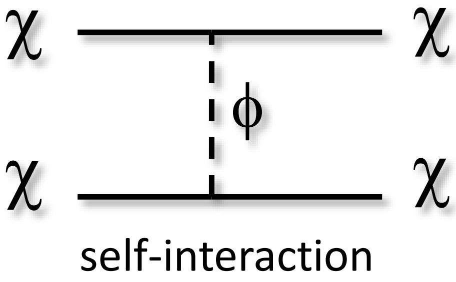
Z boson = mediator particle

WIMP self-interaction cross section is way too small

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

From astrophysics to particle physics

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



self-interaction

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

Mediator mass below than weak scale

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

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

From astrophysics to particle physics

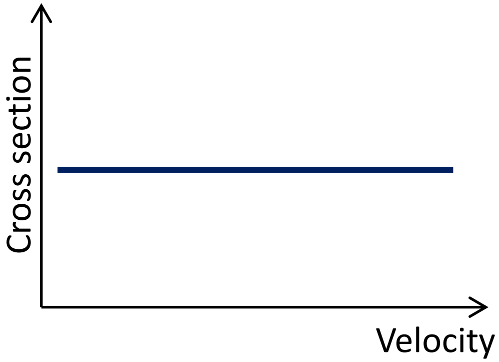
Lesson #2: Light mediator implies velocity-dependent scattering cross section

Extreme examples:

Contact interaction
(e.g. Fermi theory)

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

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

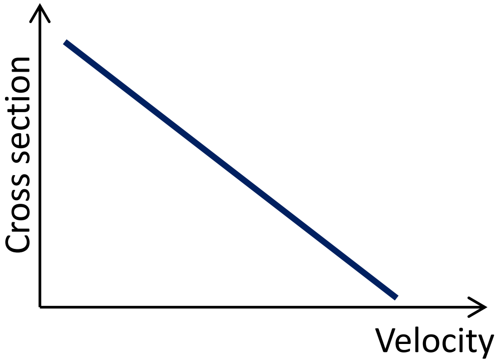


Complicated velocity dependence

Massless mediator
(e.g. Rutherford scattering)

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

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



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

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

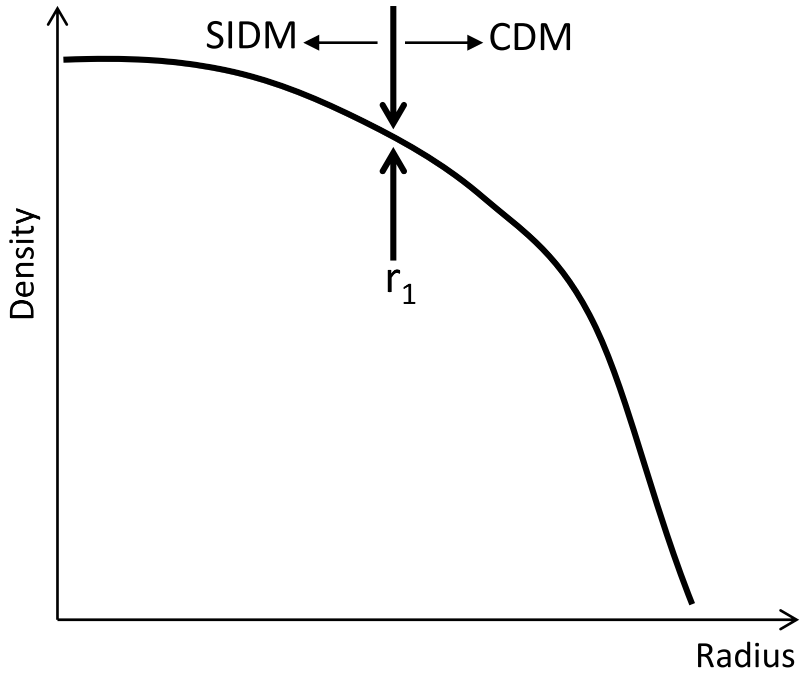
- Cores in dwarfs, LSBs, and clusters probing $\sigma(v)$ at different v
- Can observations of cores in all systems be explained in a consistent particle physics picture?
- Caveat: assuming no baryonic feedback to generate cores

Kaplinghat, ST, Yu (in preparation)

Particle physics from astrophysics

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

Rocha et al (2012)



Inner halo ($r < r_1$): expect DM to be thermalized

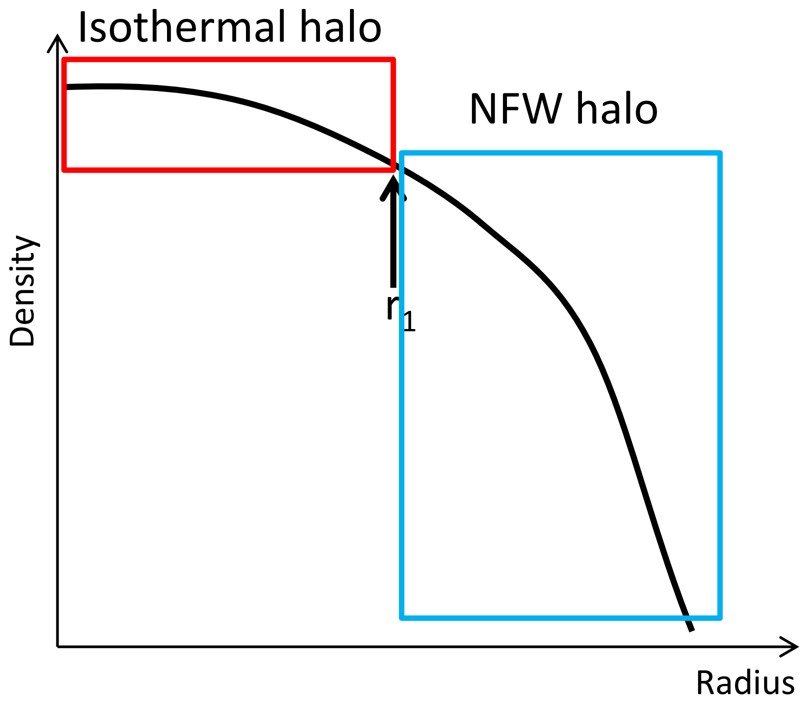
$$N_{scat} \sim \langle \sigma v \rangle / m \; \rho \; t_{age} > 1$$

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

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

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

Particle physics from astrophysics



Inner region: isothermal halo

Hydrostatic equilibrium + ideal gas law

$$\nabla p = -\rho \nabla \Phi \qquad p = k_B T \rho / m$$

Outer region: NFW halo

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

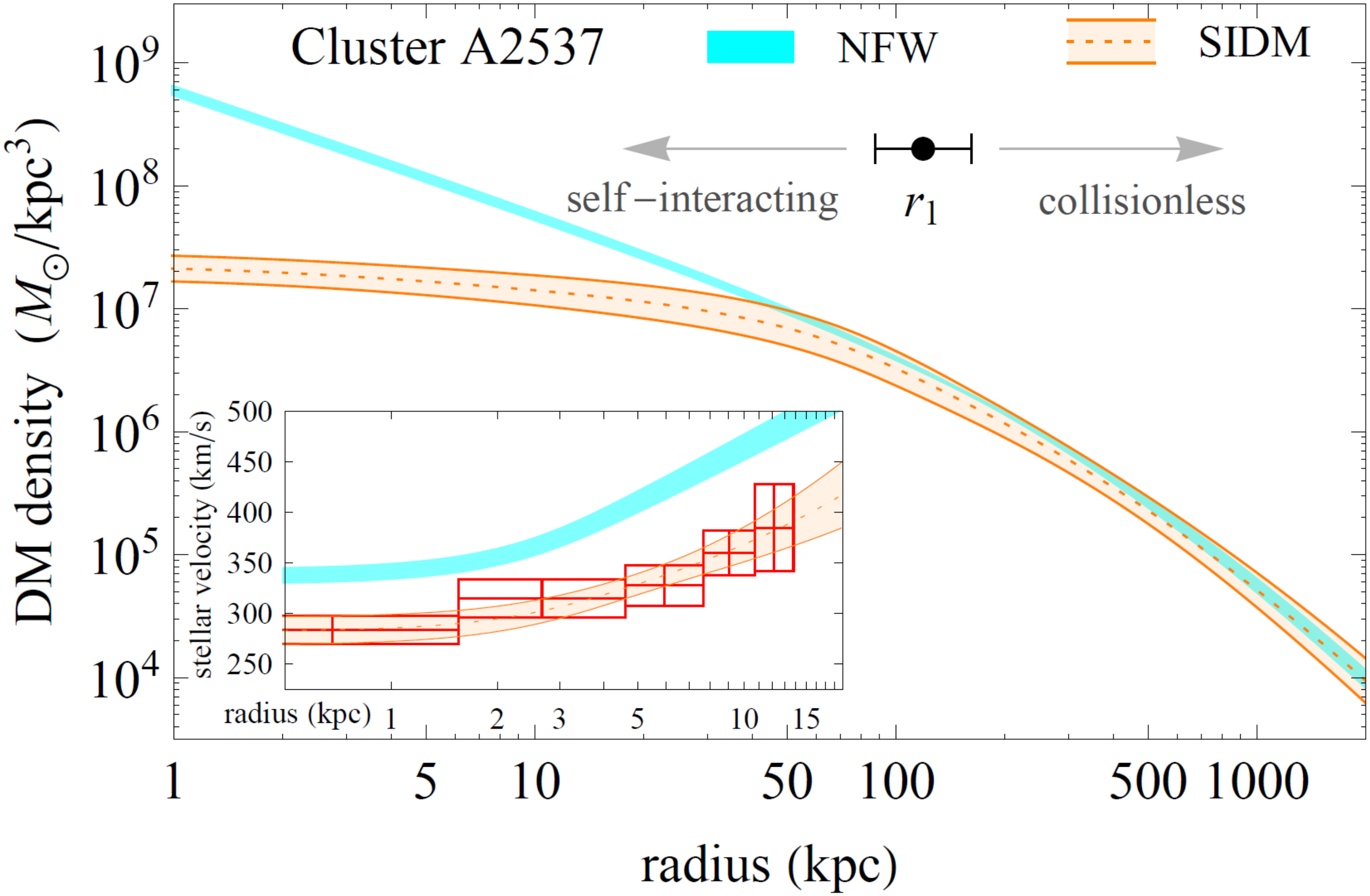
Three unknown parameters to fix $\rho(r)$.

Central density ρ_0, 1D velocity dispersion $\sigma_0 = \sqrt{k_B T/m}$, and r_1.

Also want to know baryon density (entering potential Φ)

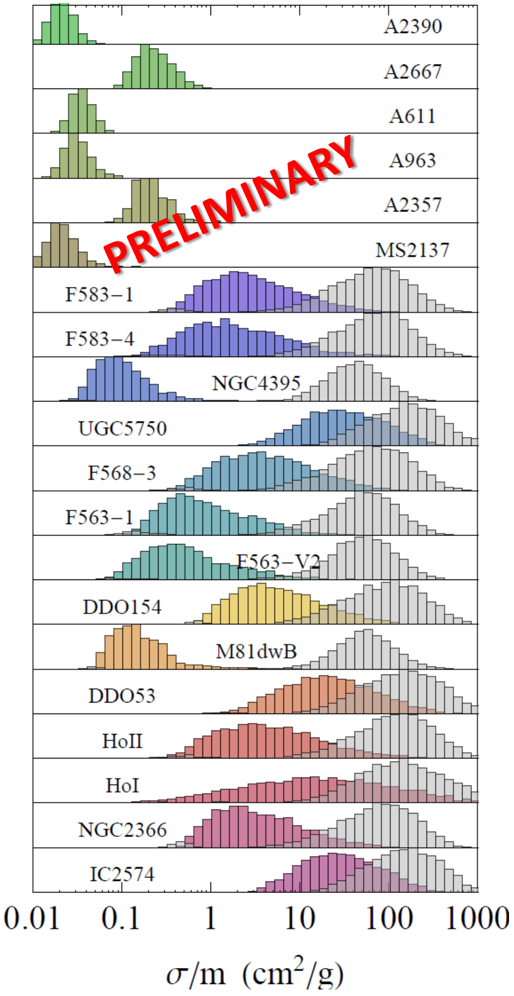
Clusters

Scan over SIDM halo parameters and fit to stellar kinematics data



SIDM fits to dwarfs, LSBs, and clusters

Fit with constant σ/m



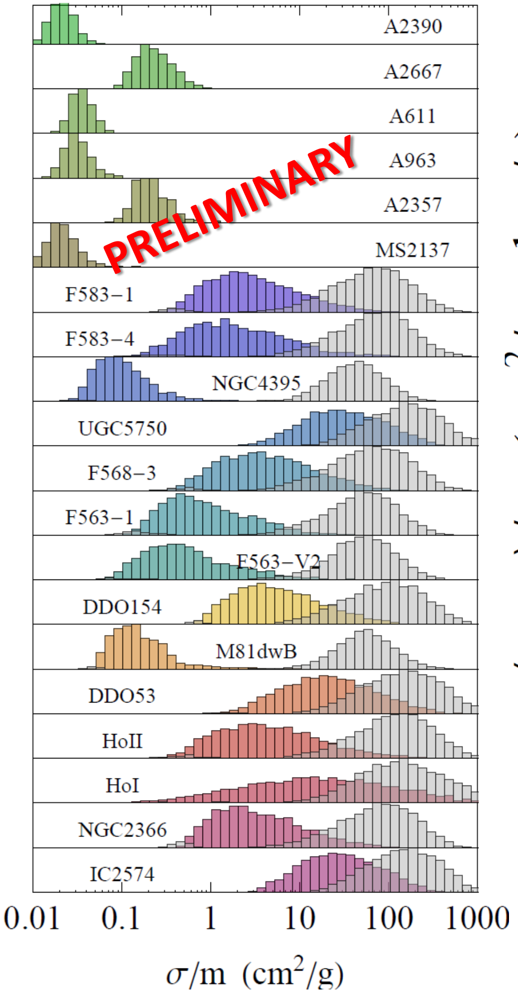
6 Clusters
Newman et al (2012)

7 LSB galaxies
Kuzio de Naray et al (2007)

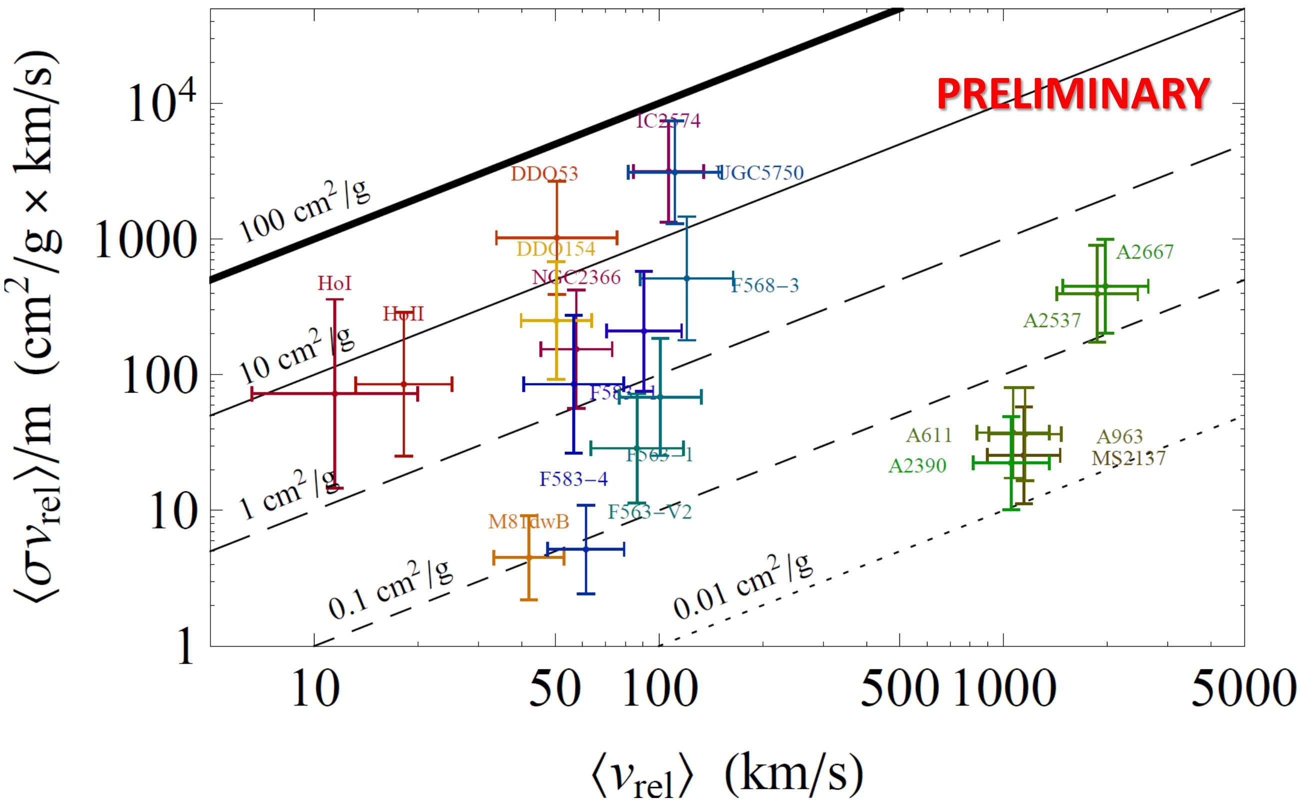
7 THINGS dwarf galaxies
Oh et al 2011

SIDM fits to dwarfs, LSBs, and clusters

Fit with constant σ/m

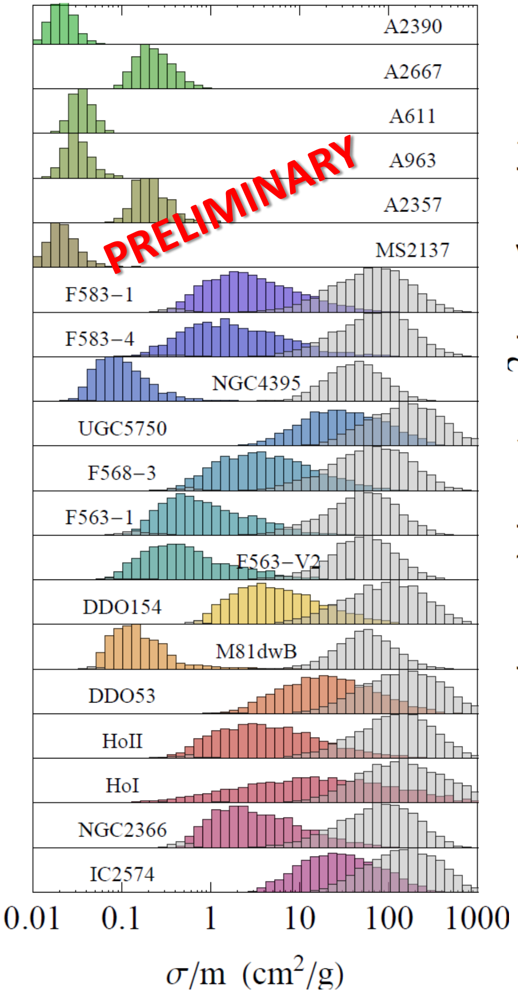


Velocity-dependent σ/m (core growing solutions only)

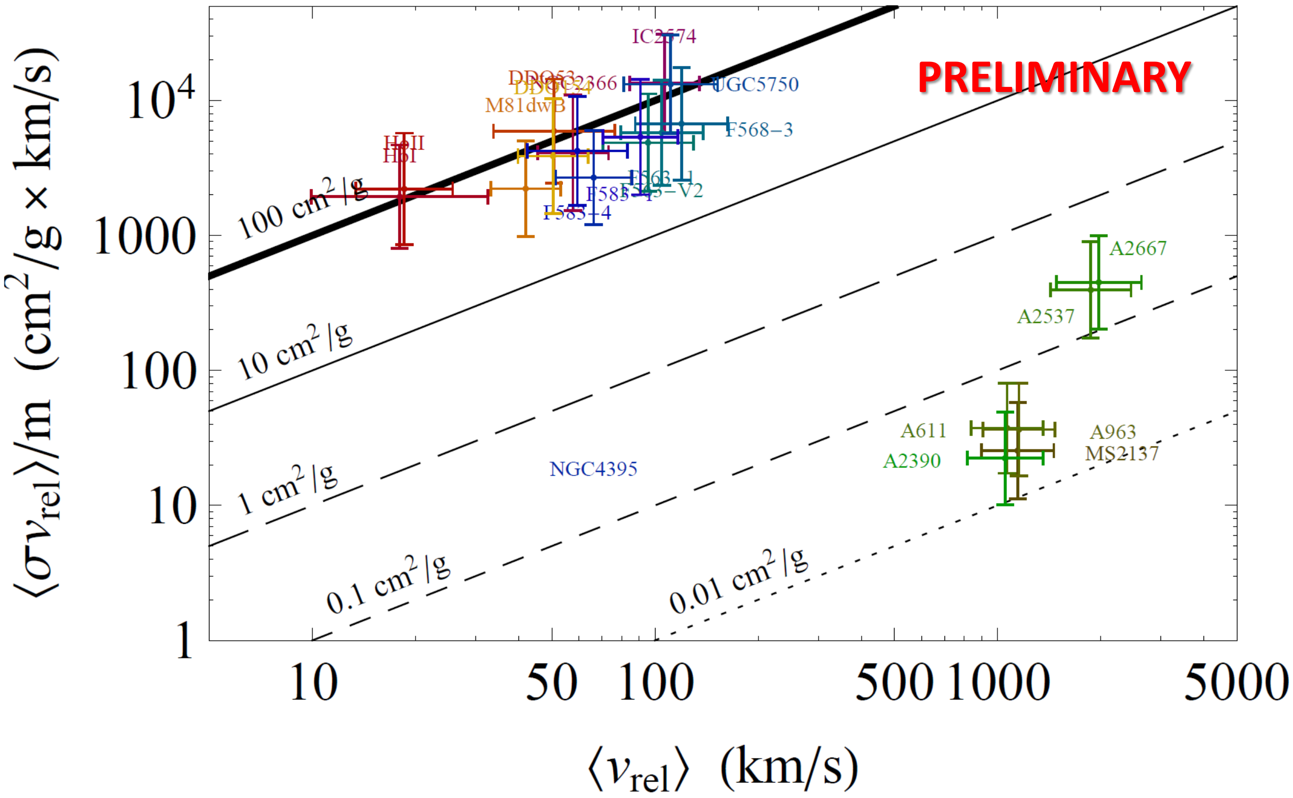


SIDM fits to dwarfs, LSBs, and clusters

Fit with constant σ/m



Velocity-dependent σ/m (core collapse solutions only)

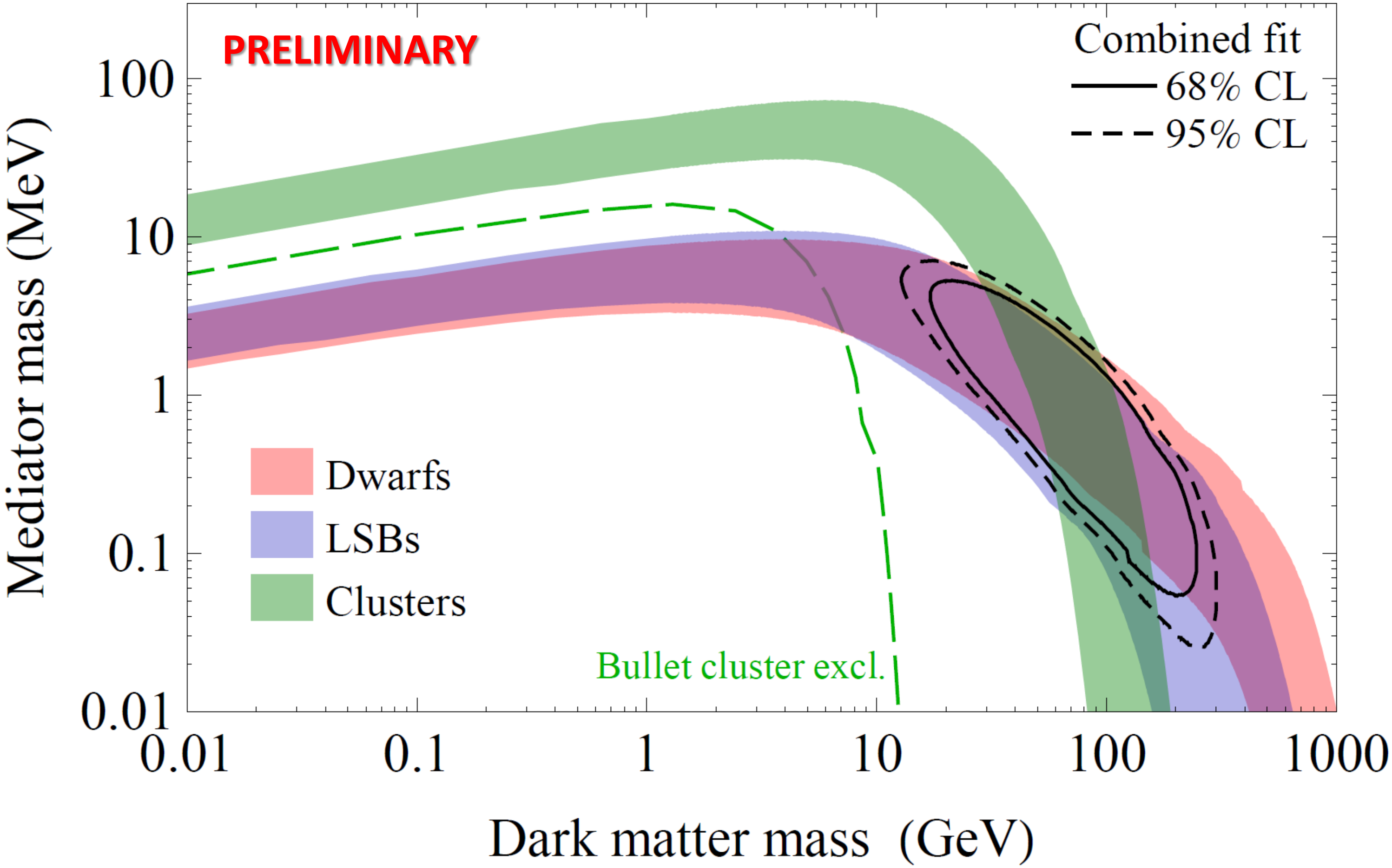


SIDM model

Asymmetric dark matter
with repulsive interaction

$V(r) = \frac{\alpha'}{r} e^{-\mu r}$

Dark photon with $\alpha' = \alpha$



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.

Conclusions

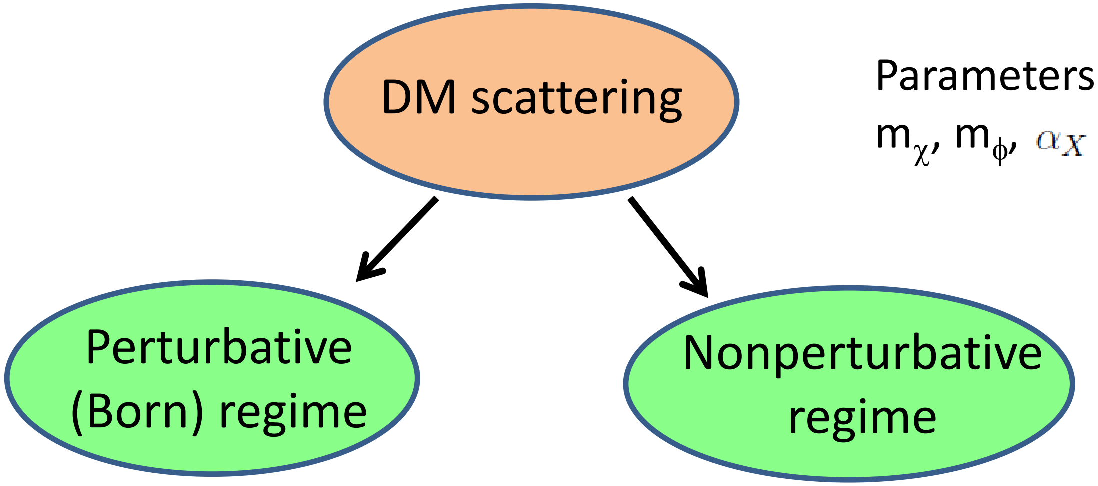
- Standard lore: $\sigma/m \sim 1\ \mathrm{cm}^2/\mathrm{g}$ enough to produce cores

- Observed galaxies have a range of core sizes, from sub-kpc to ~10 kpc. May not be able to find a consistent SIDM solution at $\sigma/m \sim 1\ \mathrm{cm}^2/\mathrm{g}$.

- Surprisingly, a large cross section $\sigma/m \sim 50\ \mathrm{cm}^2/\mathrm{g}$ seems able to match all galaxies pretty well.

- Definitely σ/m must be velocity-dependent to avoid cluster limits.

DM self-interaction cross section



DM scattering

Perturbative (Born) regime

Nonperturbative regime

Parameters:

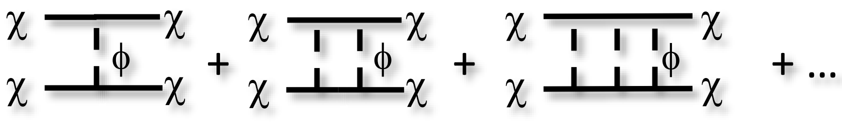
m_χ, m_ϕ, $\alpha_X = g_X^2/(4\pi)$

Easy to compute

Use partial wave analysis

Solve Schrodinger equation with Yukawa potential $V(r) = \pm\frac{\alpha_X}{r}e^{-m_\phi r}$

Sommerfeld enhancement for scattering



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)