Dark matter self-interactions and small scale structure

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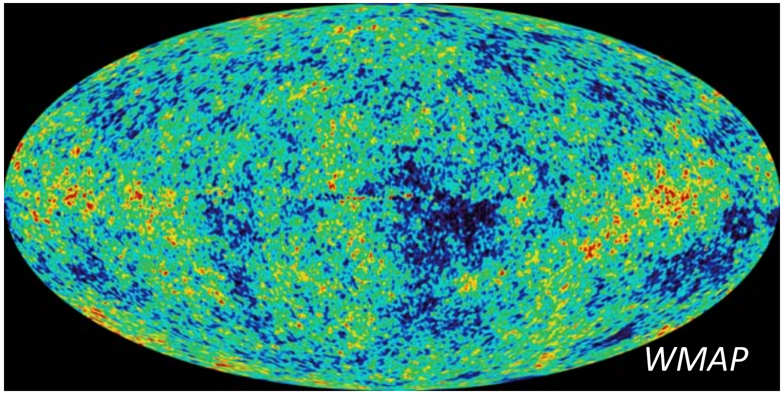
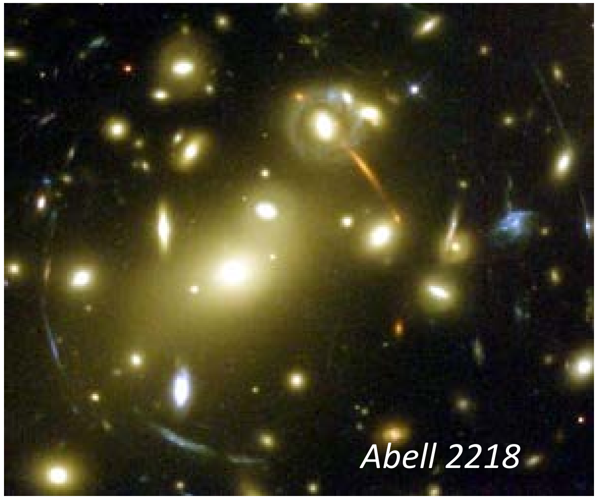
Cold collisionless dark matter paradigm

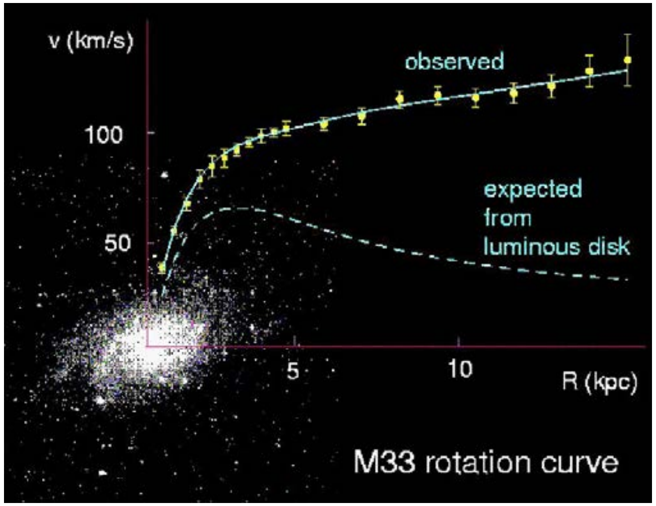
Dark matter (DM) is about 25% of the Universe



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

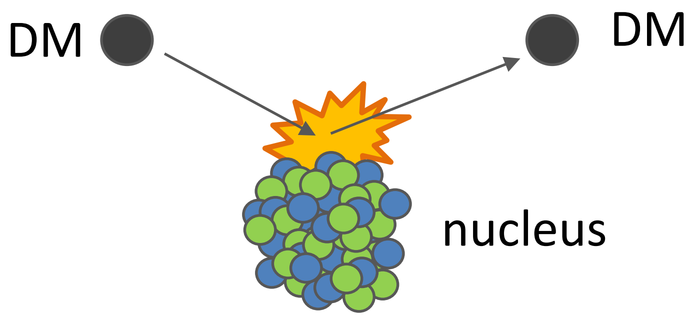
To date, evidence for DM from gravity only



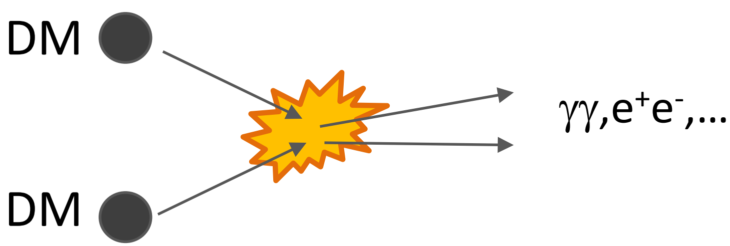


Exploring the dark sector

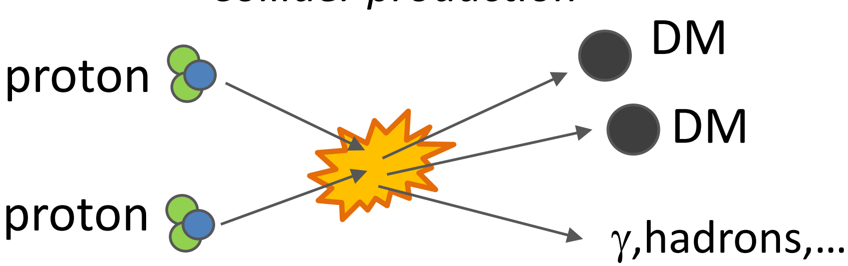
Direct detection



Indirect detection



Collider production



Weakly interacting massive particle (WIMP) paradigm:

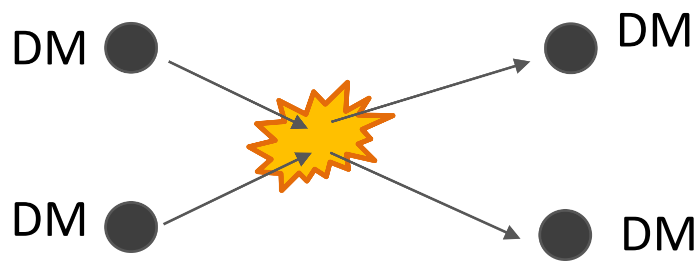
DM interacts with Standard Model via weak-scale physics

We should see evidence of DM in one/all of these channels!

Exploring the dark sector

What if dark matter has **suppressed** couplings to Standard Model particles?

Self-interactions



Non-gravitational interactions leave an imprint on the structure of the Universe.

We can probe the particle interactions of dark matter even if it has **no** coupling to the Standard Model.

Outline

- CDM issues (small scale structure problems)

- DM may have self-interactions

  What are the particle physics implications?

Problem 1: Core-vs-cusp

Central densities of halos are too shallow

Moore (1994), Flores & Primack (1994)

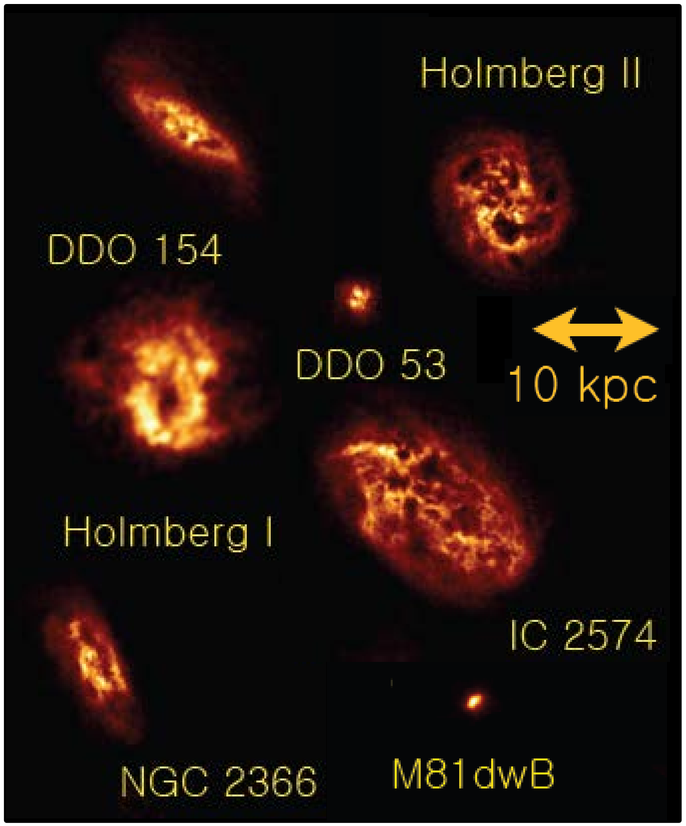
Parametrize DM density in inner halo: $\rho \sim r^{\alpha}$

Theory prediction: $\alpha \sim -1$ (cusp/NFW profile)
Observation: $\alpha \sim 0$ (core)

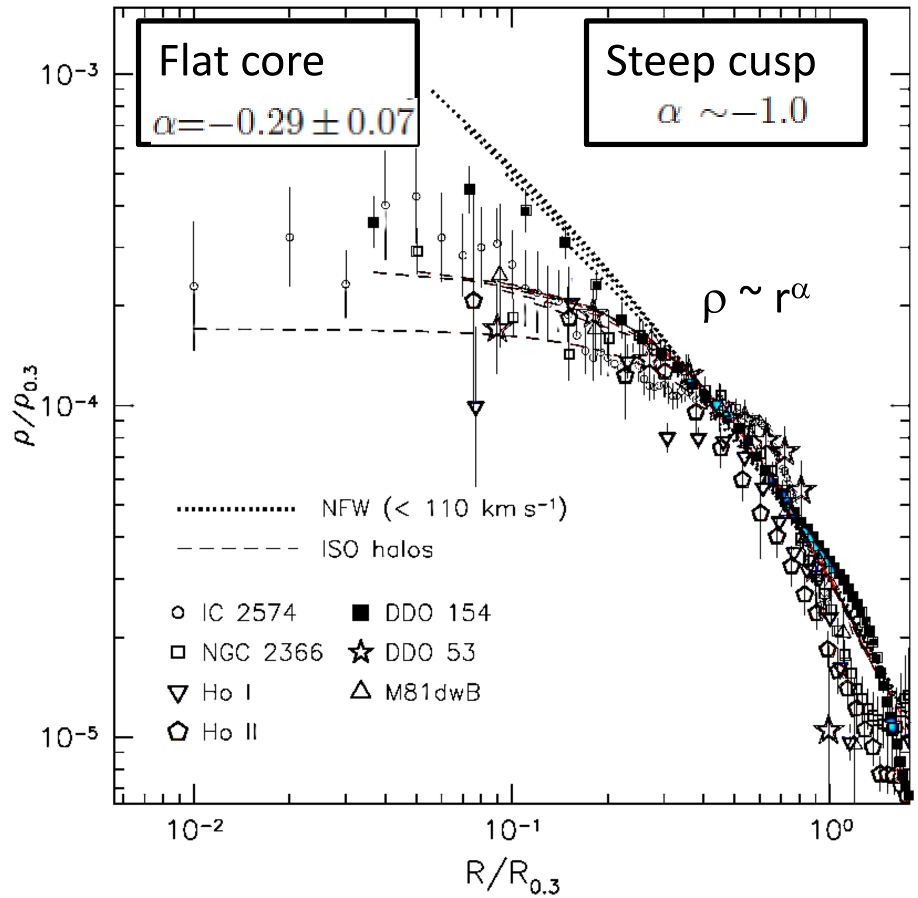
Cores seem very ubiquitous, from dwarf galaxies to clusters

Cores in field galaxies

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

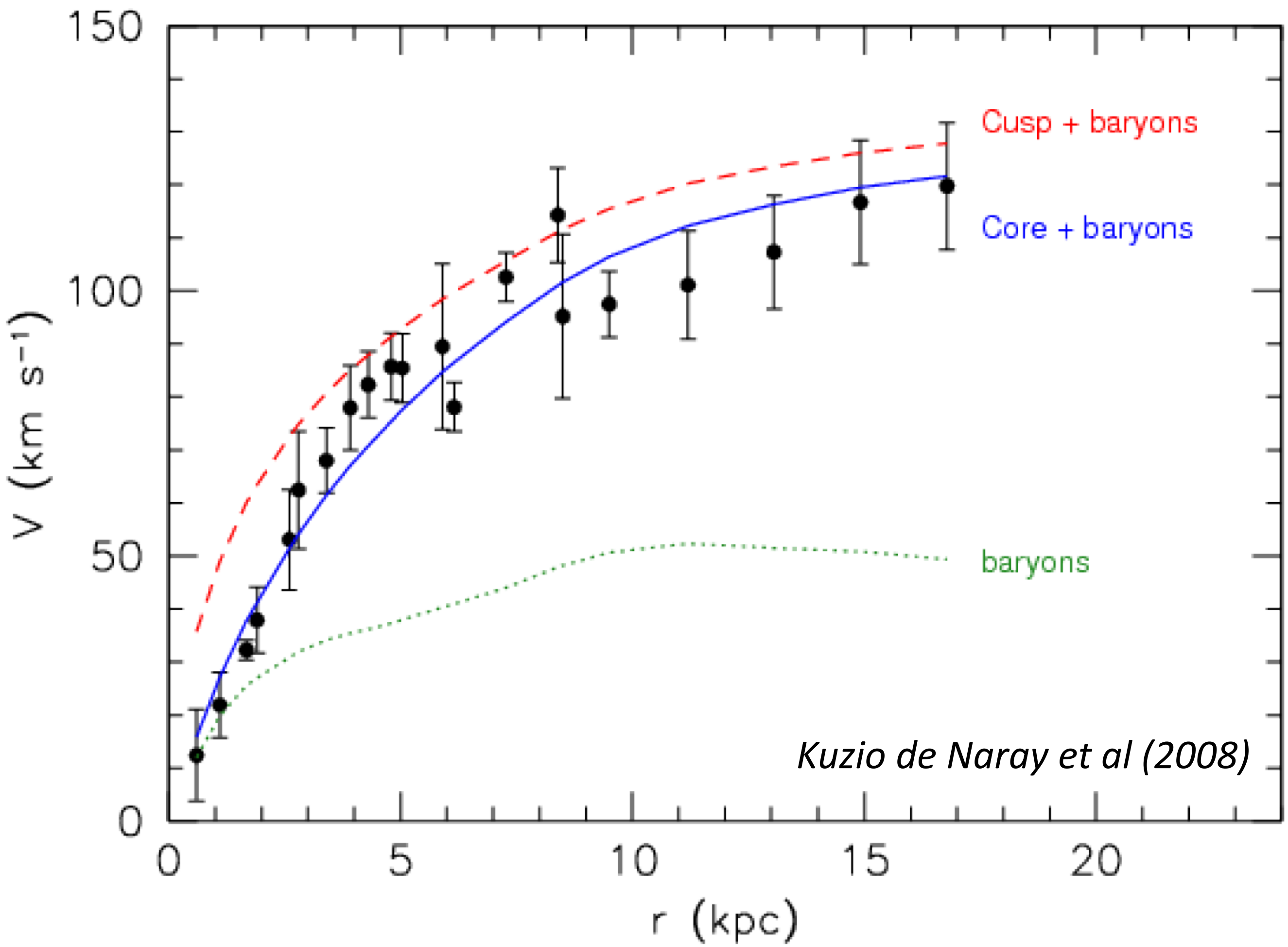


21 cm emission from gas



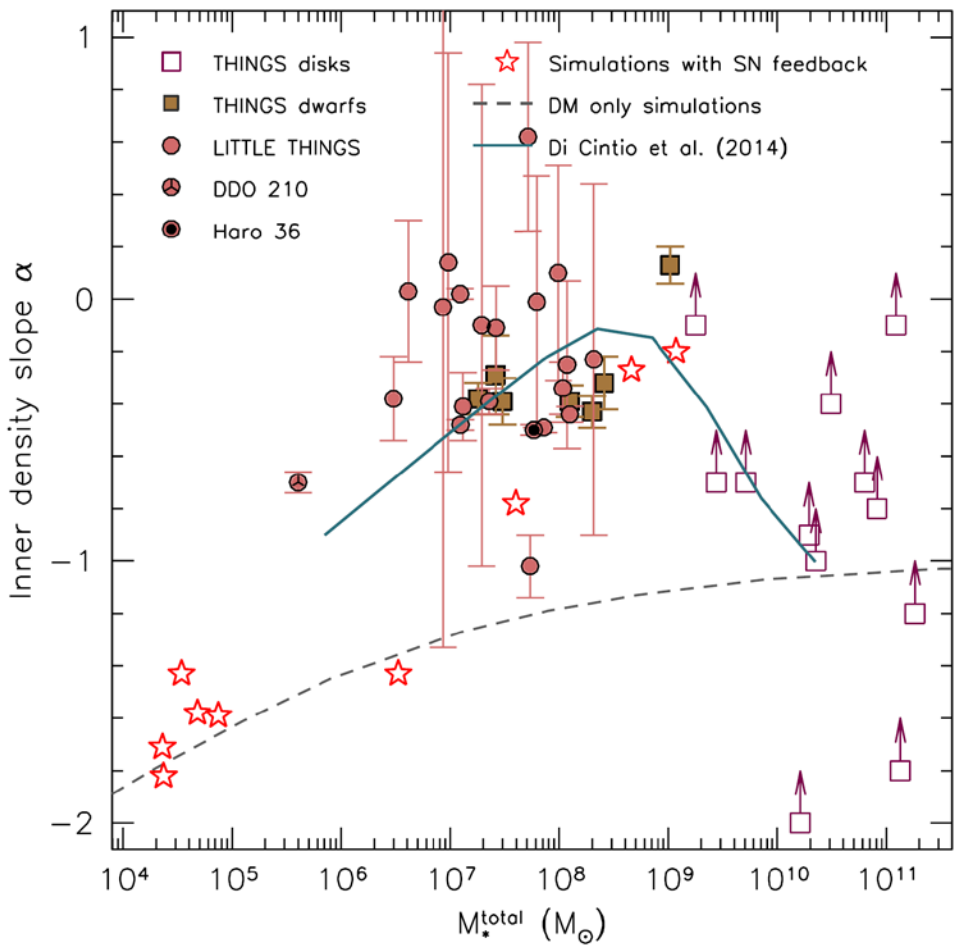
Cores in field galaxies

Low surface brightness galaxy F568-3

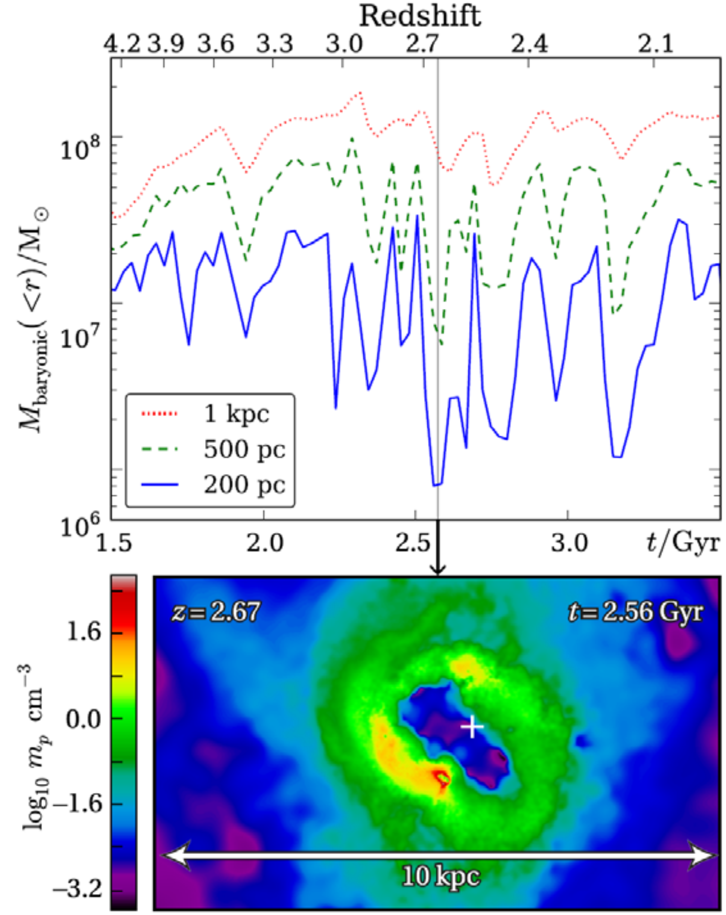


Feedback from supernovae

Oh et al (2015)

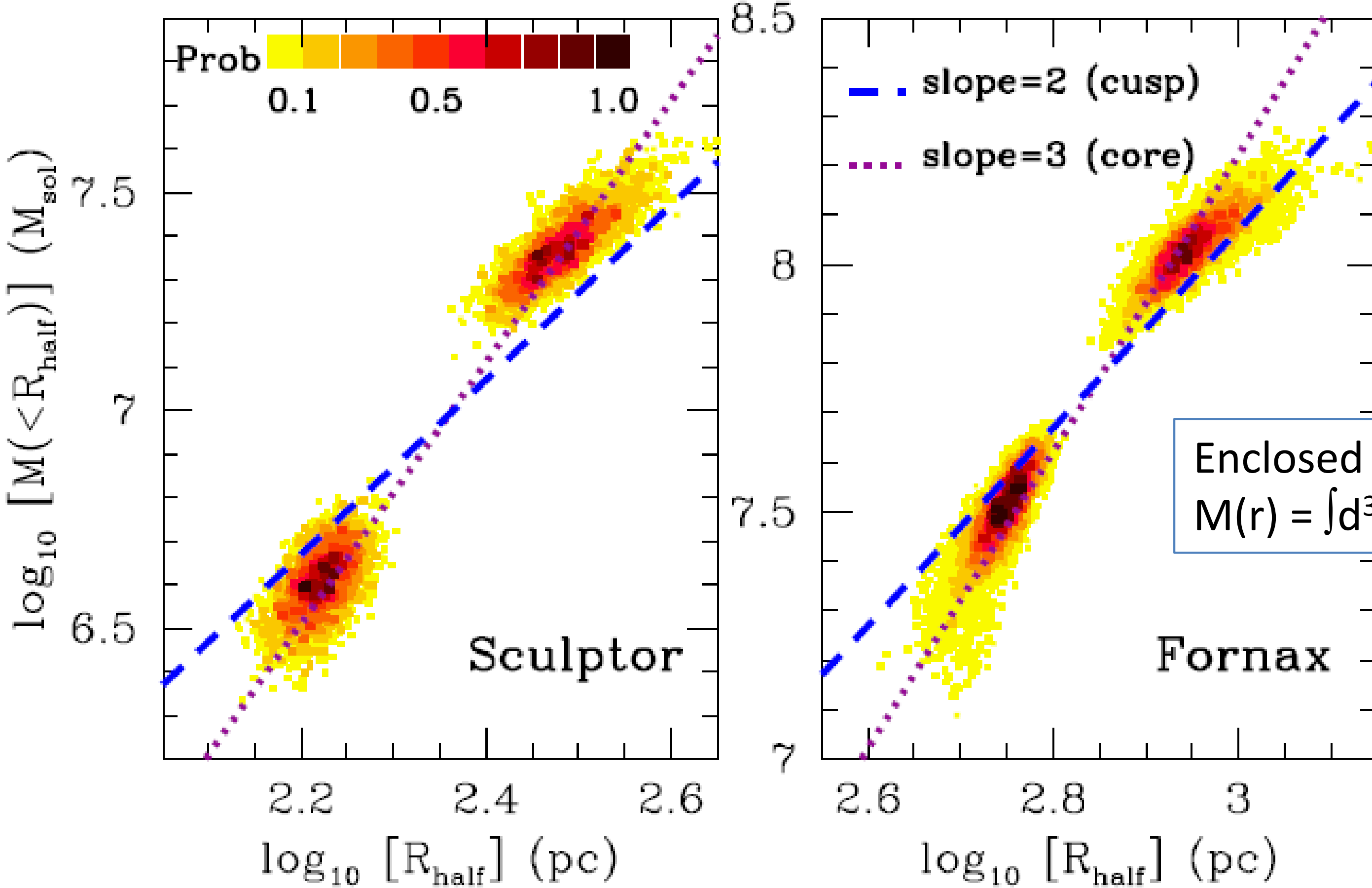


Pontzen & Governato (2011)



Competition between feedback and adiabatic contraction
Depends on feedback implementation (bursty star formation history with large coupling to gas)

Cores in satellite galaxies

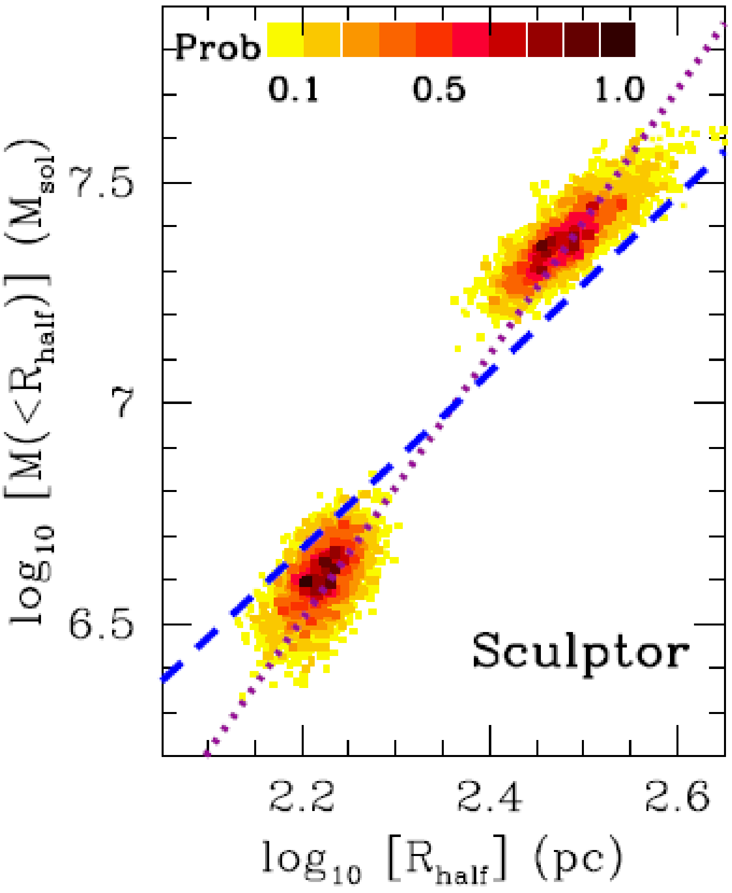


Enclosed mass
$M(r) = \int d^3r\, \rho \sim r^{\alpha+3}$

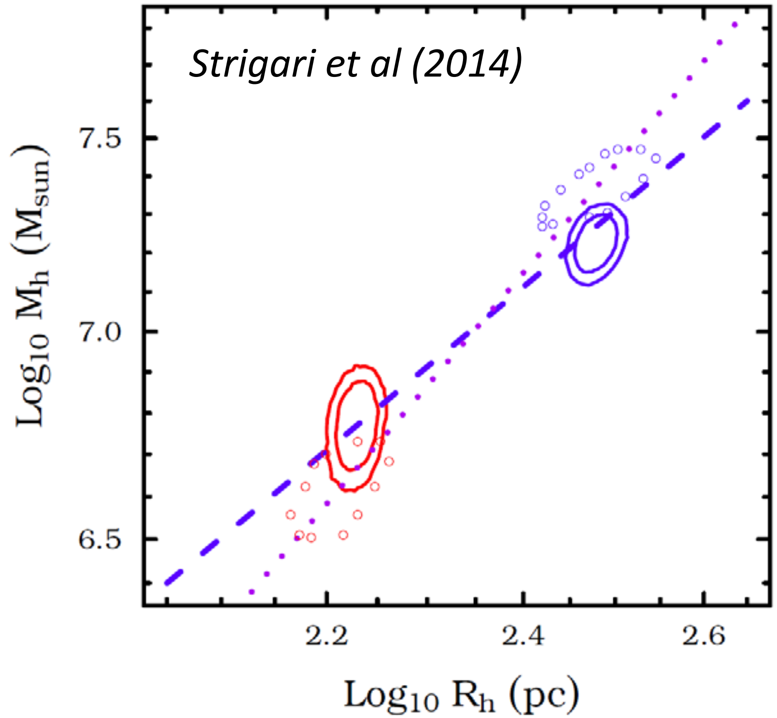
Stellar subpopulations (metal-rich & metal-poor) as “test masses” in gravitational potential

Walker & Penarrubia (2011)

Cores in satellite galaxies

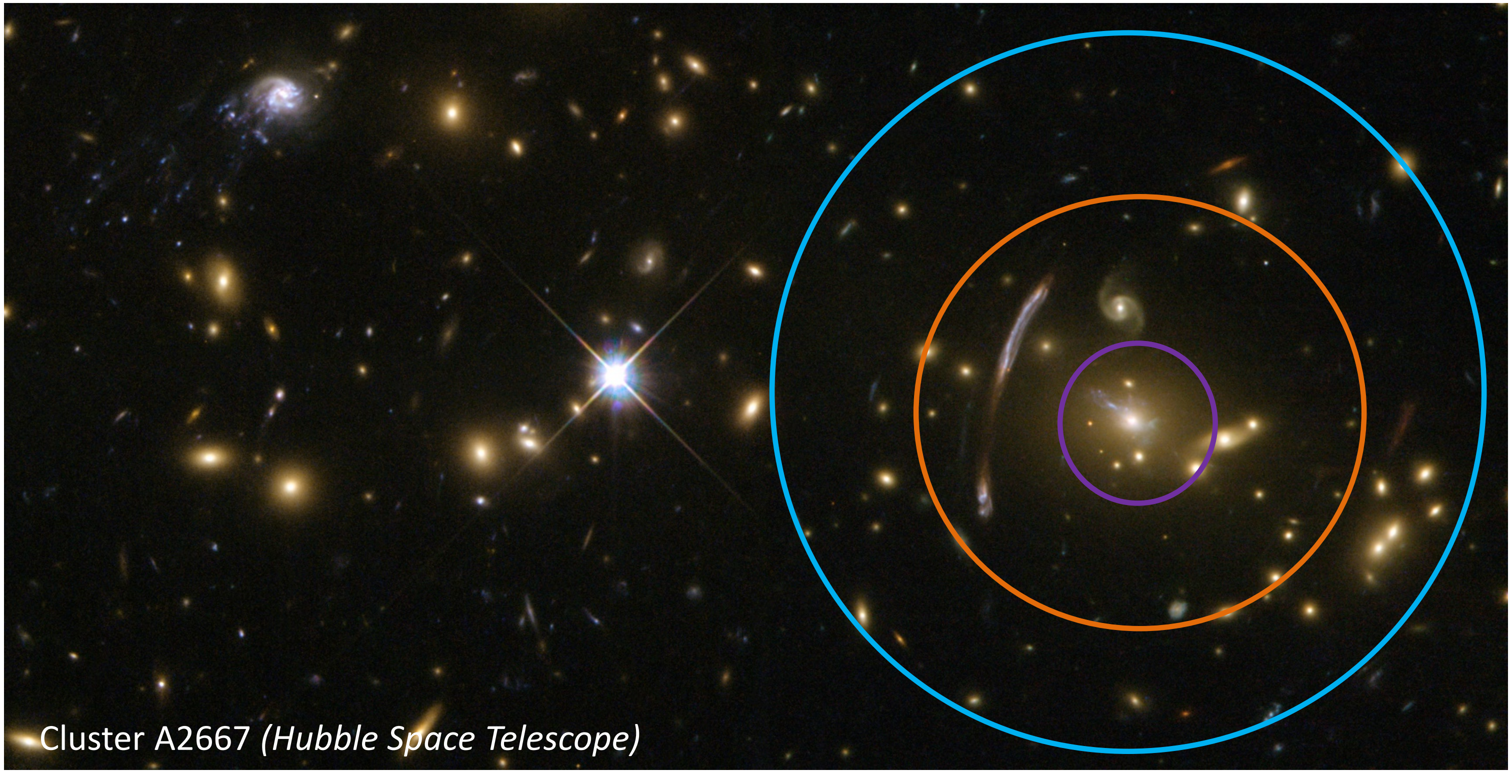


Walker & Penarrubia (2011)



Systematic uncertainties due to modeling stellar kinematics. Consistent with NFW profiles.

Cores in clusters



Use multiple measurements to study dark matter halo

Newman et al (2012)

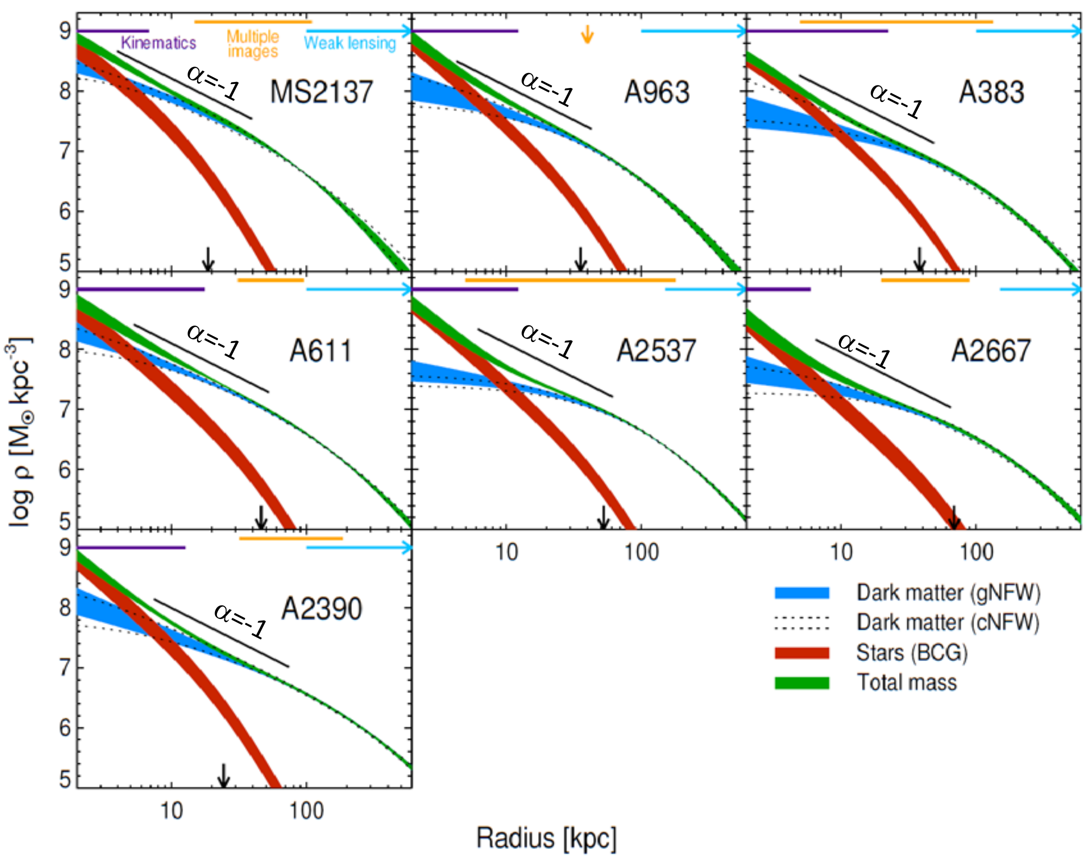
Weak gravitational lensing at large distance

Gravitational lensing arcs (strong lensing) at medium distance

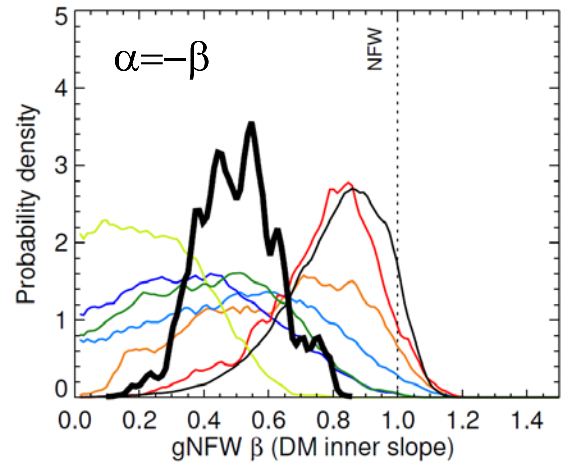
Stellar kinematics for the cluster center

Cores in clusters

Newman et al (2012)



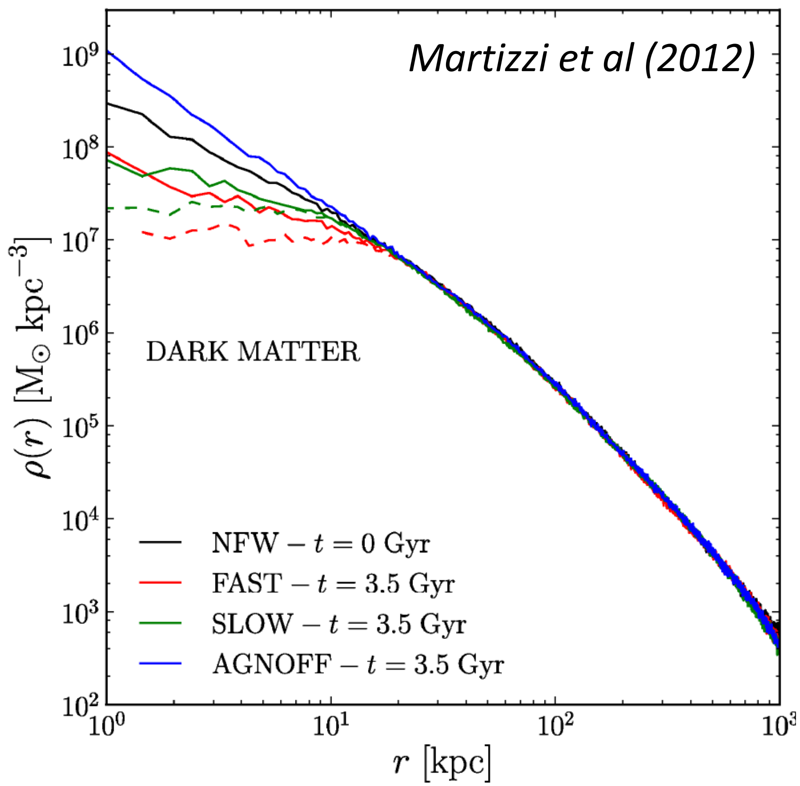
Best-fit inner slope



Generalized-NFW fit:

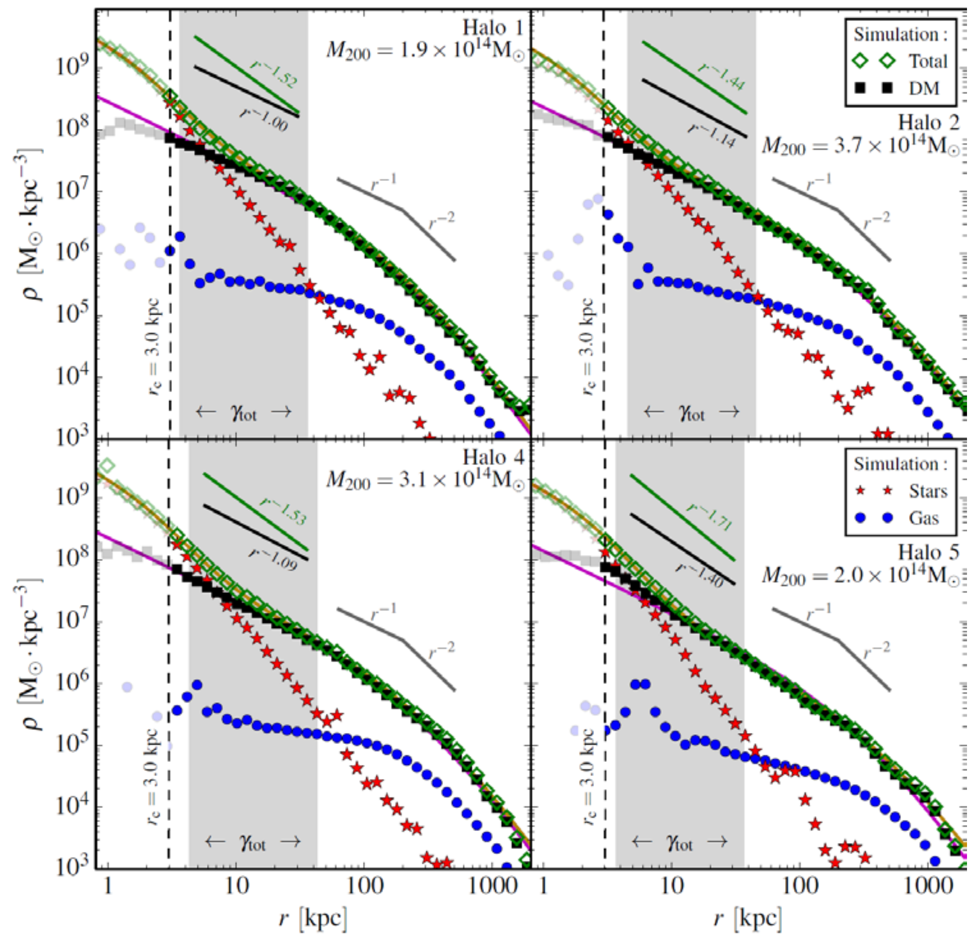
$$\rho_{\rm DM}(r) = \frac{\rho_s}{(r/r_s)^\beta (1 + r/r_s)^{3-\beta}}$$

AGN feedback in clusters



Feedback leads to a core from initial NFW halo

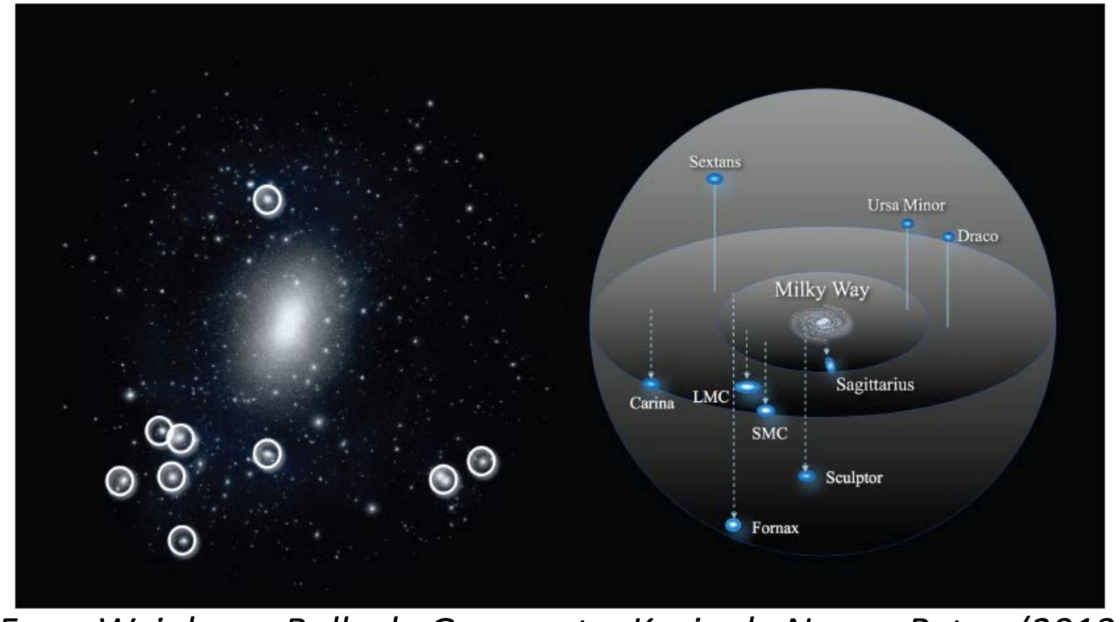
Schaller et al (2014)



Feedback does not form dark matter cores

Problem 2. Too-big-to-fail

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

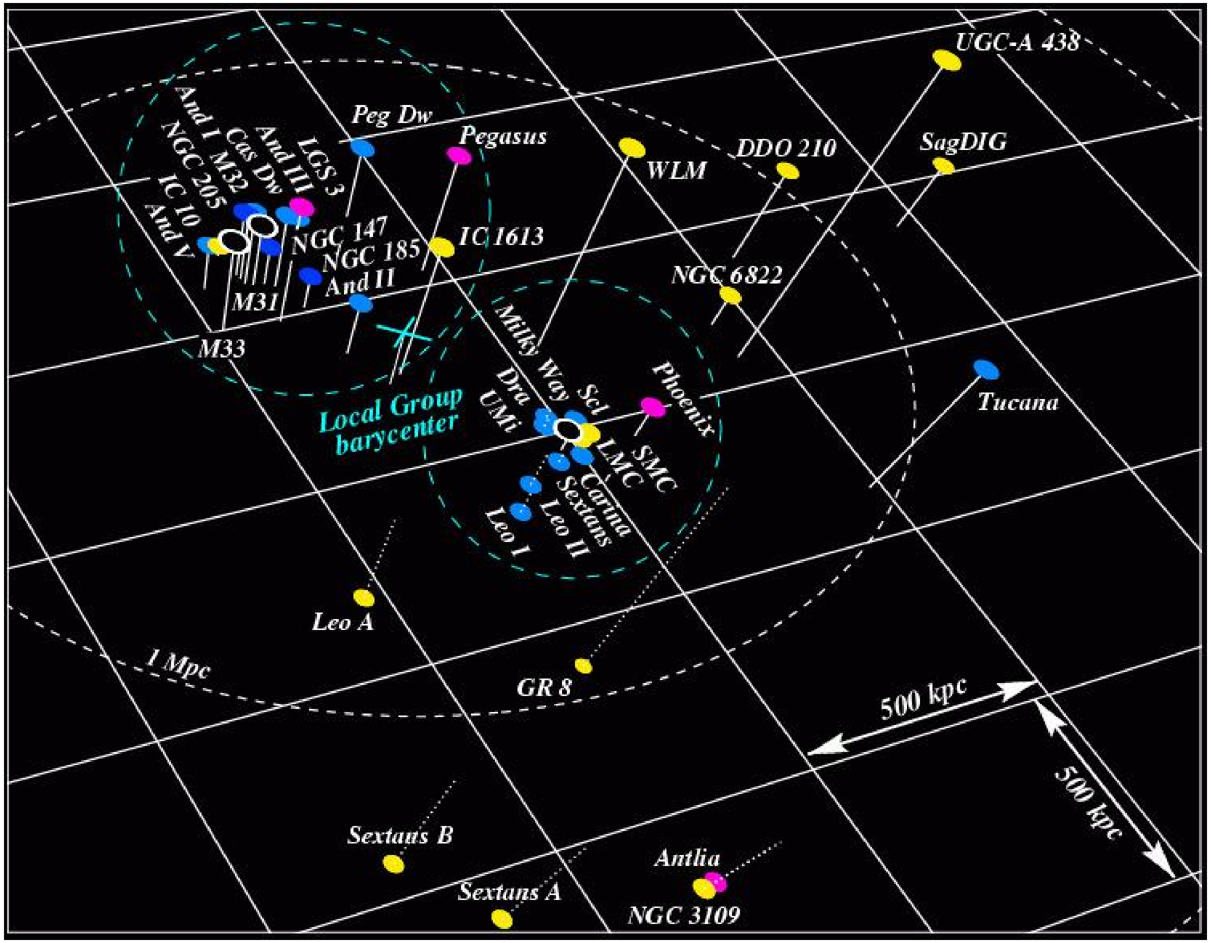


From Weinberg, Bullock, Governato, Kuzio de Naray, Peter (2013)

Predicted Milky Way satellites more massive (larger velocity dispersions) than observed ones.

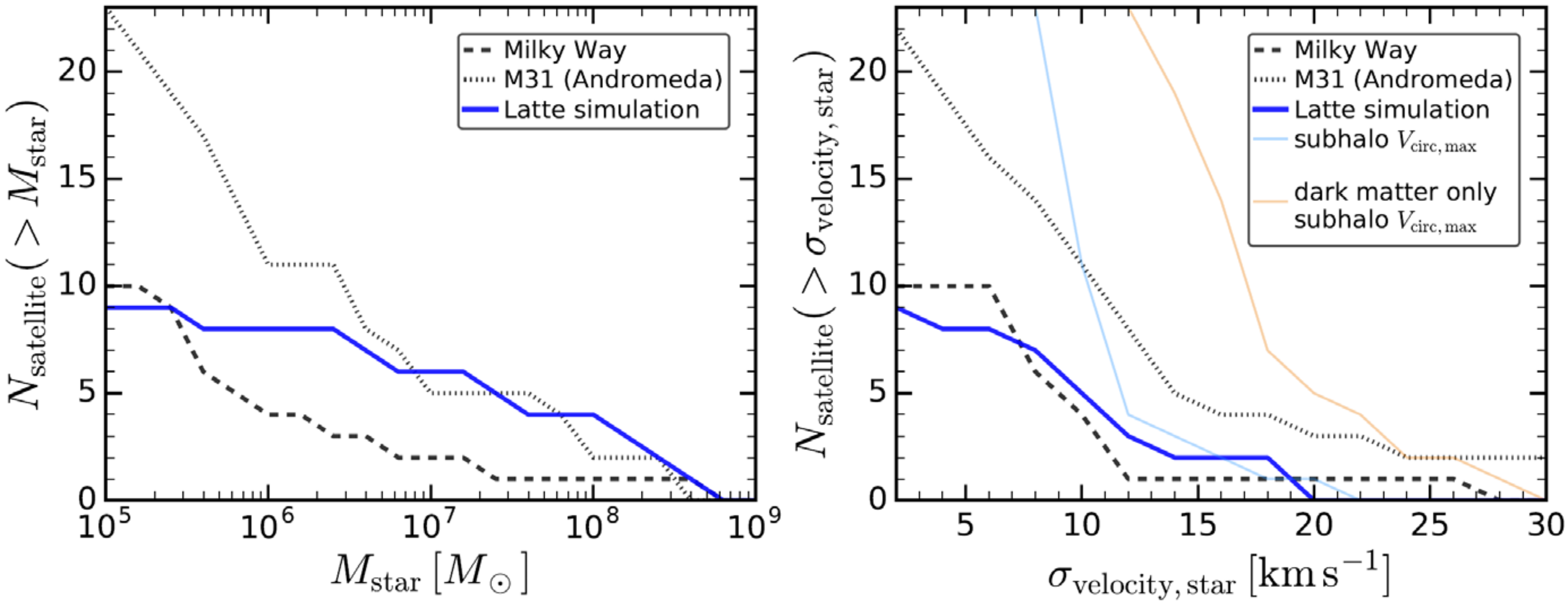
Too-big-to-fail problem

Is there a problem beyond the Milky Way? *Tollerud et al. (2014)* *Garrison-Kimmel et al. (2014)*



Feedback in MW subhalos

Wetzel et al (2016)



Cored profiles for satellites (lower velocity dispersions) from supernova feedback and tidal disruption from interaction with host stellar disk

But agreement is not perfect (for MW): order of magnitude more stars required

CDM Problems

Cored profiles seem to be a better fit to many observations compared to NFW profile from CDM-only simulations

- Problem with our interpretation of observations

  Can’t use DM-only simulations to model real DM+baryons Universe

  Astrophysical observations not being modeled correctly (systematic uncertainties)

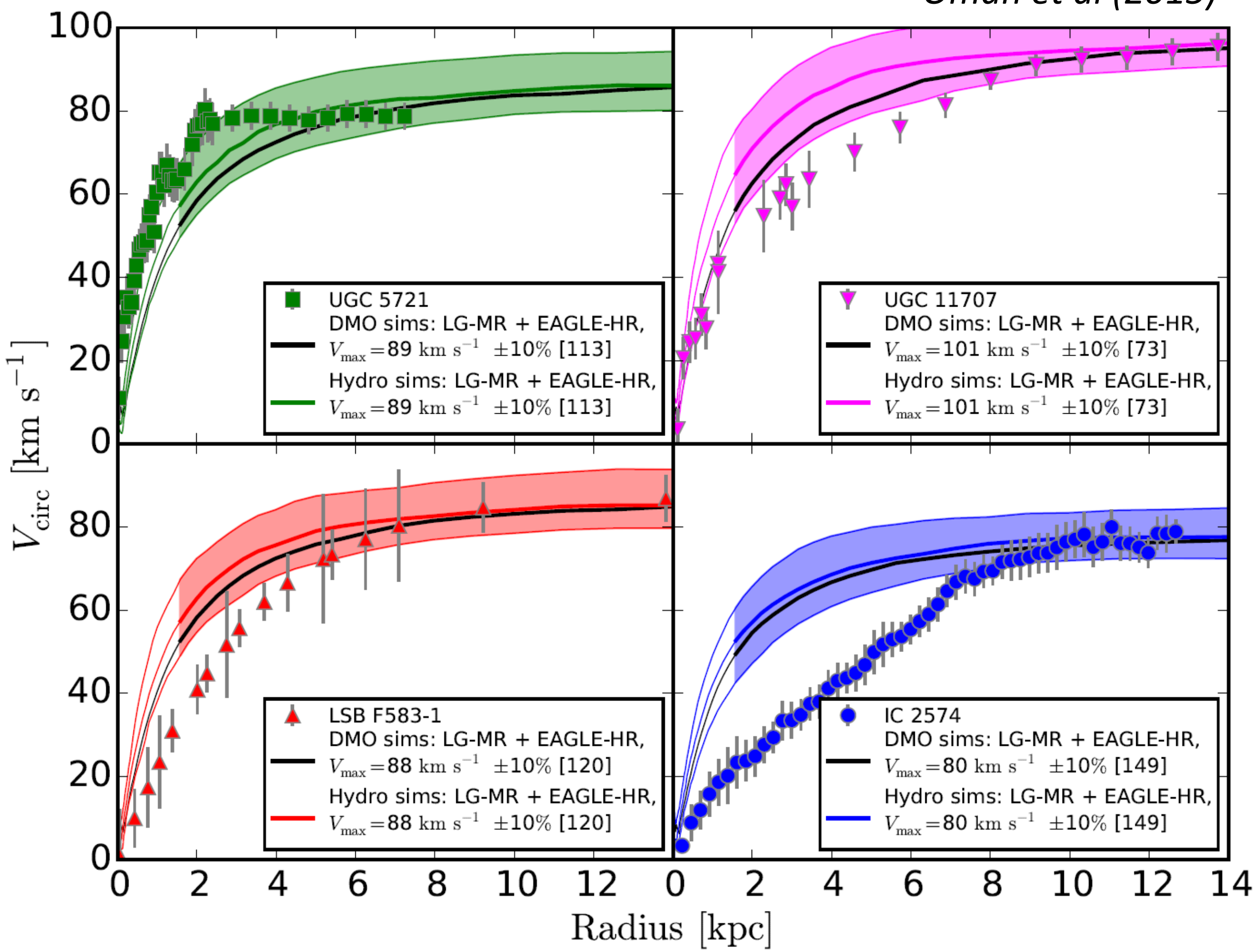
- Dark matter may not be CDM

Does baryonic feedback solve all problems?

Some open questions…

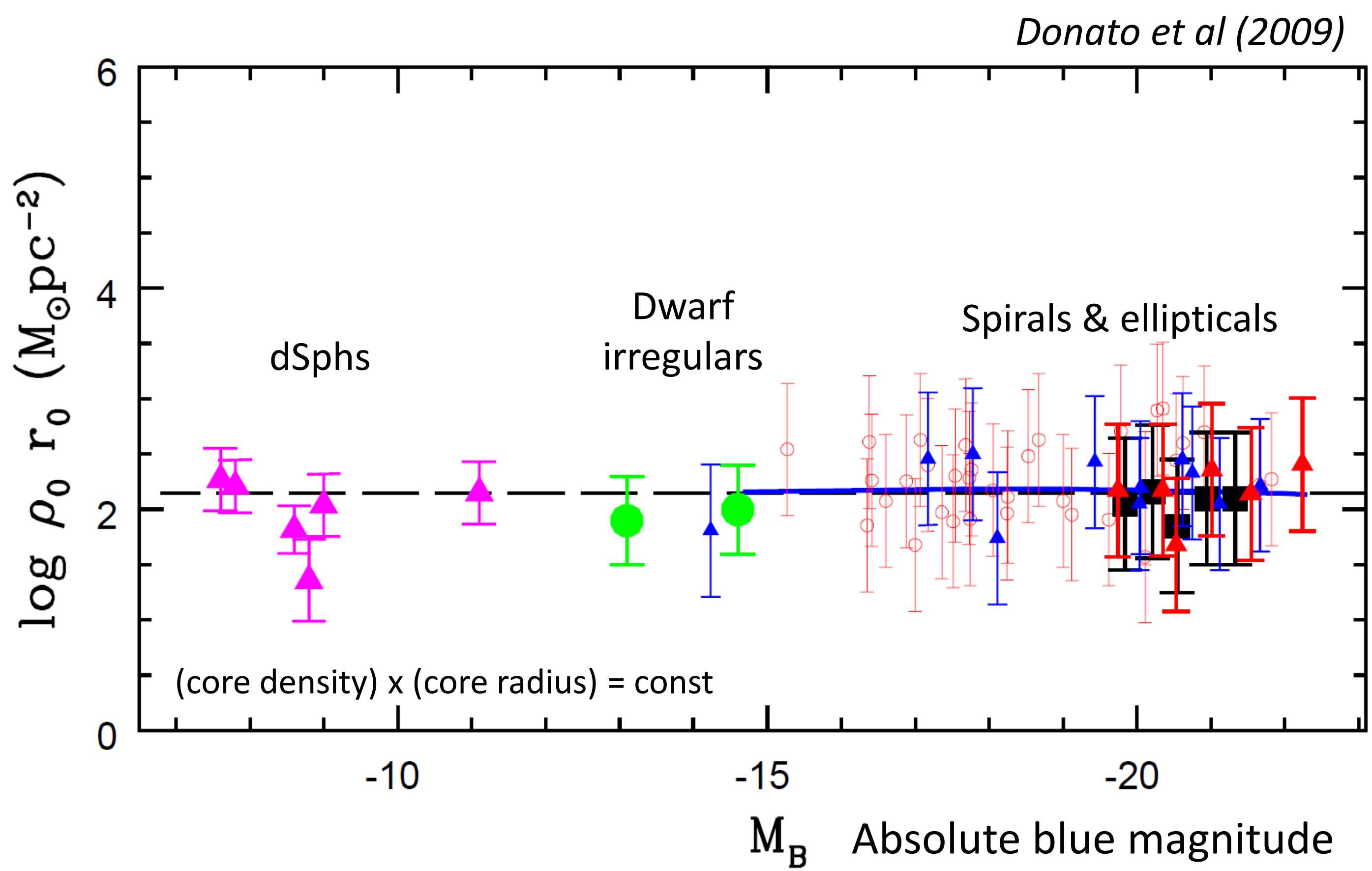
Diversity problem

Oman et al (2015)

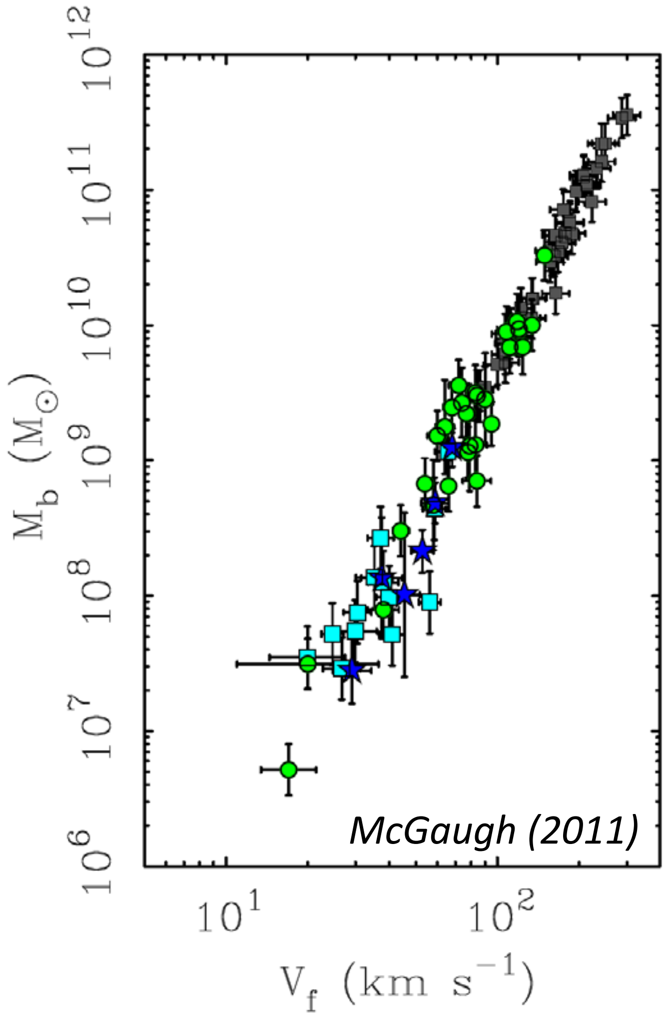


Similar mass halos can have very different core sizes

Uniformity problem



Conspiracy problem



Baryonic Tully-Fisher relation

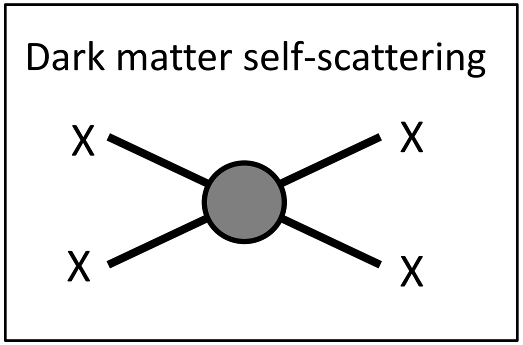
$$M_b \propto V_f^4$$

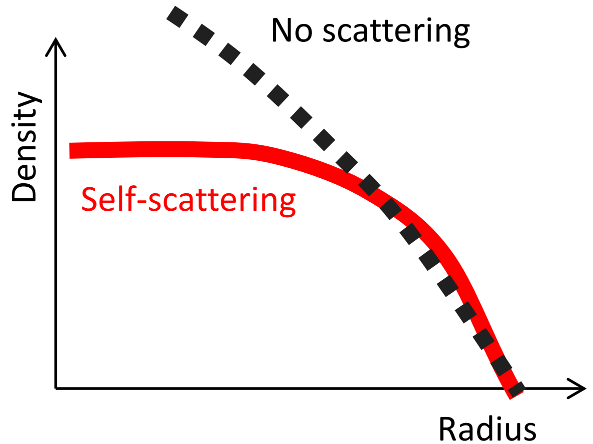
Relation between baryons and dark matter

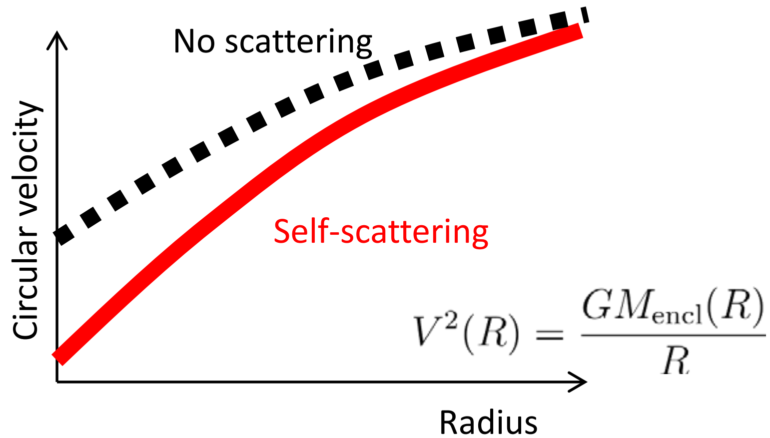
Self-interacting dark matter

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

Self-interacting dark matter

- What is the self-scattering cross section?

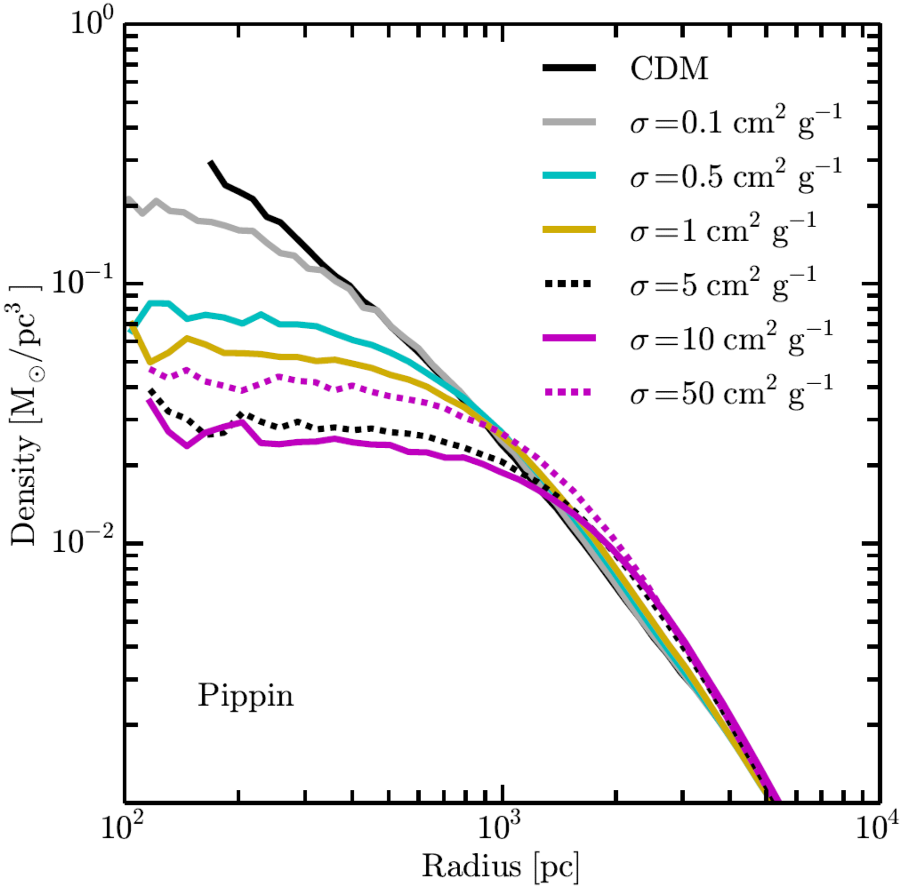
Number of scatterings = σ x (ρ/m) x velocity x t_{age}

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

Typical cross section required to solve small scale anomalies

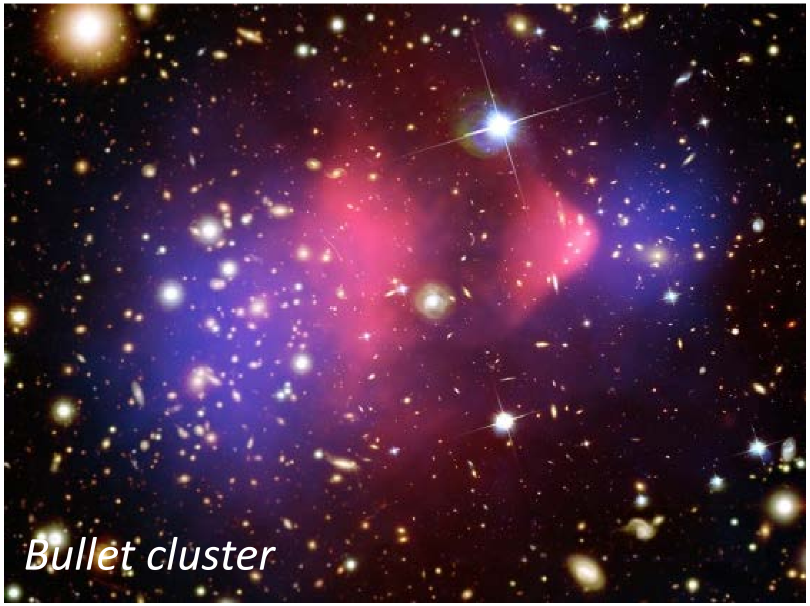
N-body simulations for SIDM

Elbert et al (2014). See also Rocha et al, Peter et al (2012); Vogelsberger, Zavala, Loeb (2012).



$\sigma/m \sim 0.5 - 50$ cm^2/g to form kpc core in dwarf galaxy

Constraints from merging clusters

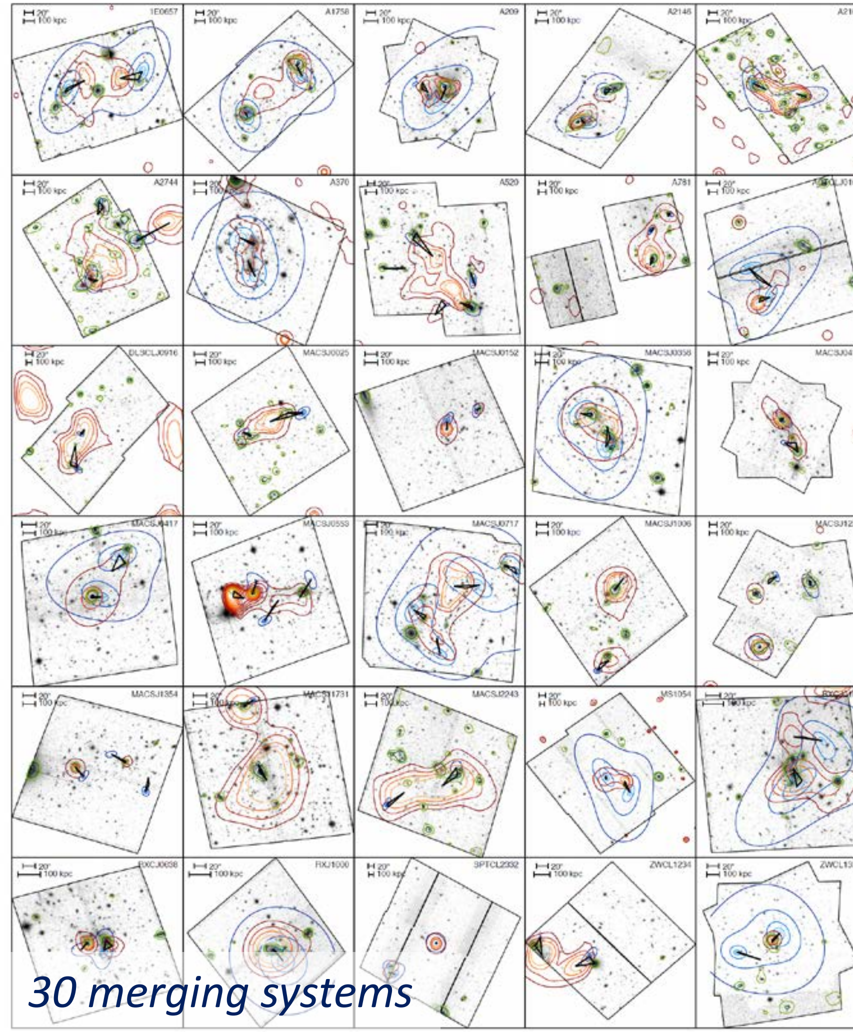


Constraint: $\sigma/m < 1.25\ cm^2/g$ (68%)

Randall et al. (2007)

Many other circa-2000 constraints are weaker than previously thought

Peter et al (2012)

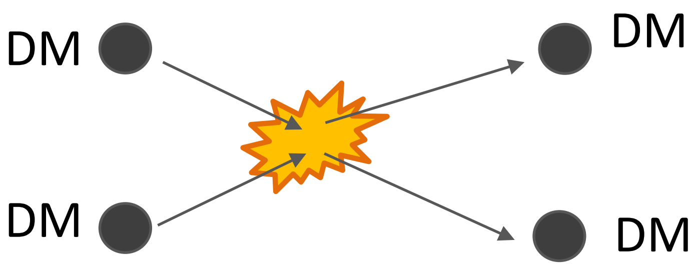


Constraint: $\sigma/m < 0.47\ cm^2/g$ (95%)

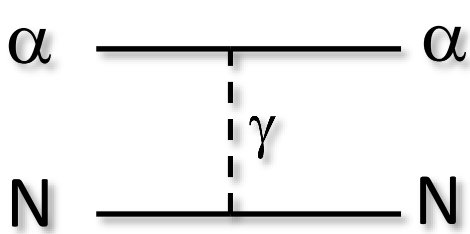
Harvey et al. (2015)

Particle physics of self-interactions

Self-interactions



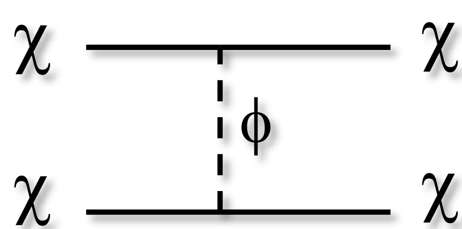
What forces and interactions are responsible for scattering?



Rutherford scattering

$$V(r) = \frac{\alpha}{r}$$

Coulomb potential



self-interaction

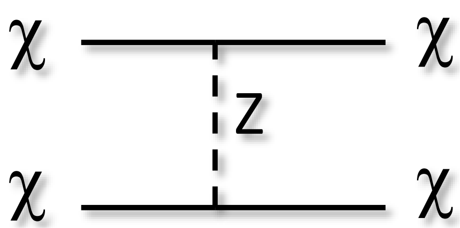
$$V(r) = \pm\frac{\alpha'}{r}e^{-\mu r}$$

Yukawa potential

χ = dark matter particle
ϕ = mediator particle

Particle physics of self-interactions

WIMPs have self-interactions (weak interaction)



self-interaction

χ = WIMP dark matter (e.g. SUSY particle)

Z boson = mediator particle

Cross section:

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

Mass:

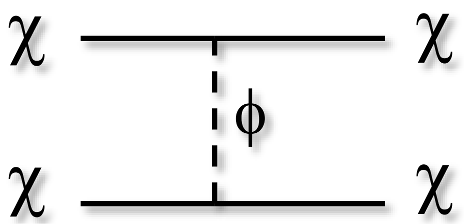
$$m_\chi \sim m_Z \sim 100\ \mathrm{GeV}$$

WIMP self-interaction cross section is way too small

$$\sigma / m_\chi \sim 10^{-14}\ \mathrm{cm}^2/\mathrm{g}$$

Particle physics of self-interactions

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 weak scale

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

Self-interactions require new dark sector states (mediator) below 1 GeV.

Different halos are complementary

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

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

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

Cross section depends on scattering energy.
Different size dark matter halos have different velocities.

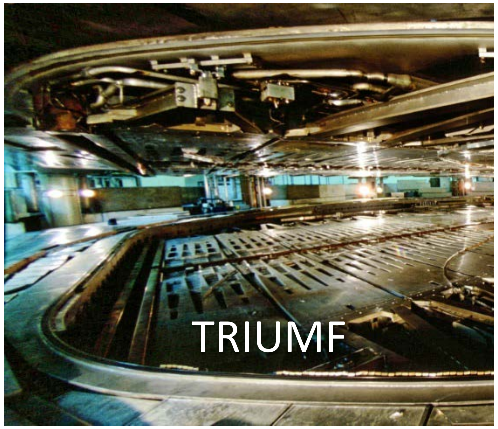
Different halos are complementary

Low energies (v/c ~ 10^{-4})

Medium energies (v/c ~ 10^{-3})

High energies (v/c ~ 10^{-2})

Like a different particle physics collider with a different beam energy

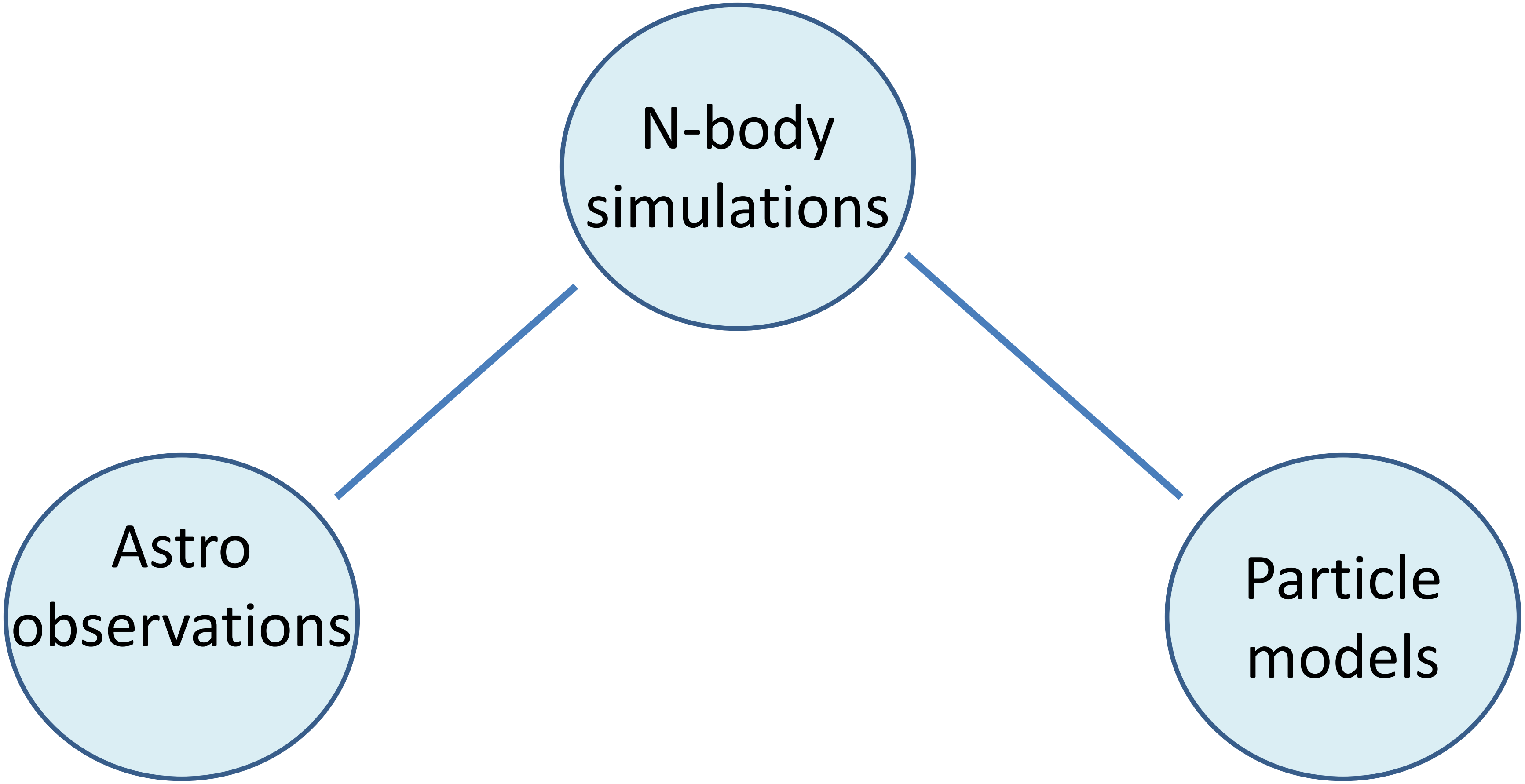


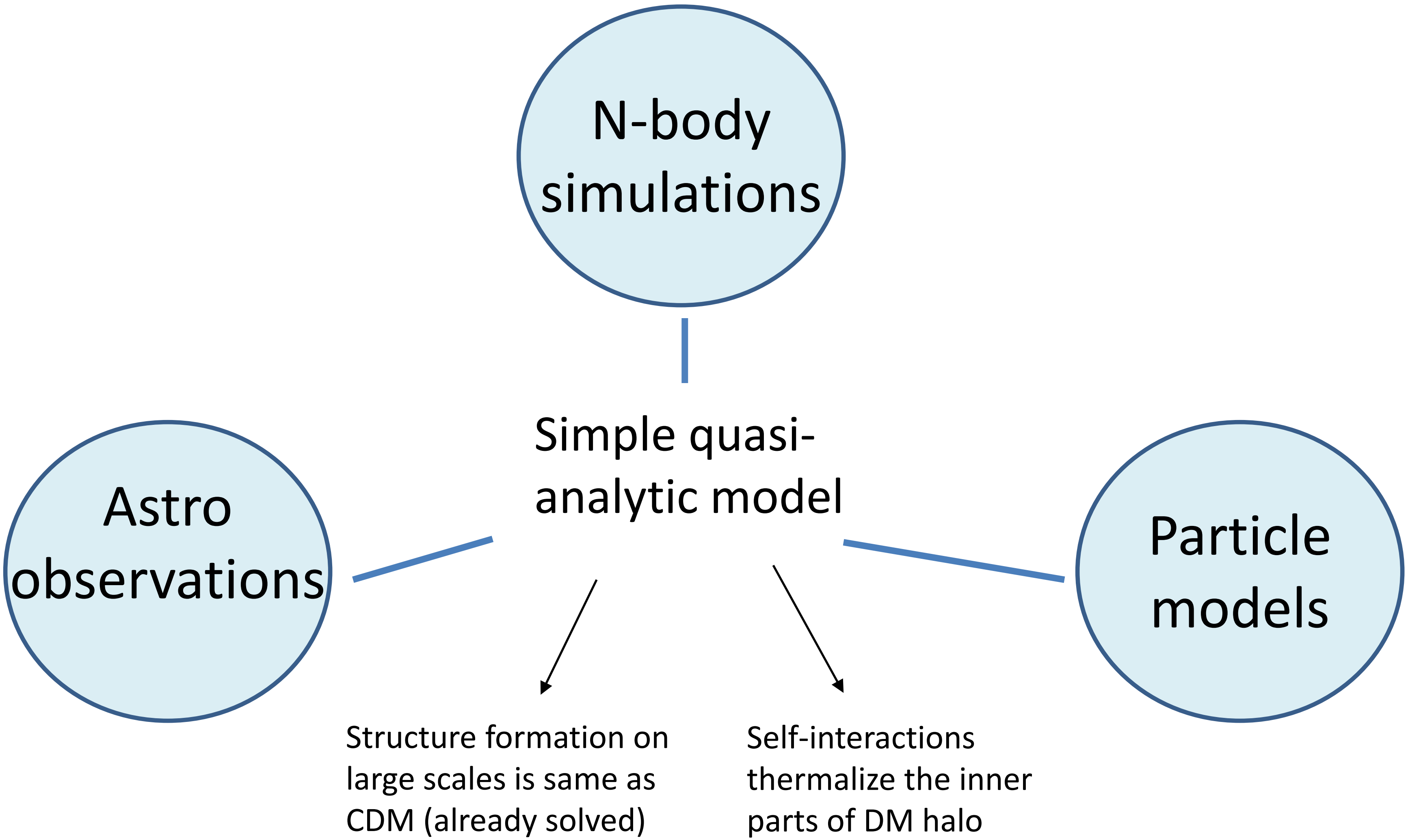
Does SIDM explain all cores?

- What do astrophysical observations tell us about the cross section vs velocity, $\sigma(v)$?

- Can observations of cores in all systems be explained in a consistent particle physics picture?

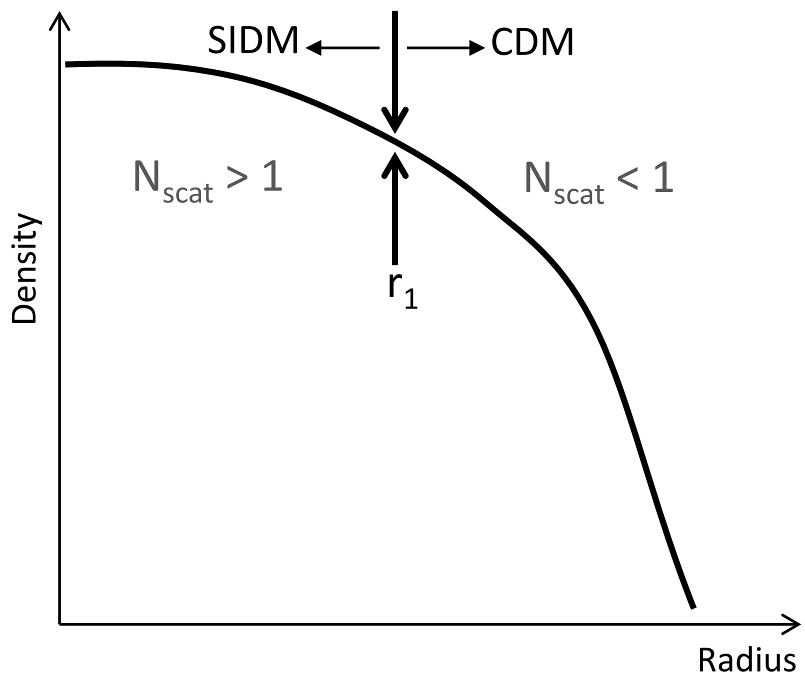
Kaplinghat, ST, Yu (2015)


N-body simulations
Astro observations
Particle models


N-body simulations
Astro observations
Simple quasi-analytic model
Particle models
Structure formation on large scales is same as CDM (already solved)
Self-interactions thermalize the inner parts of DM halo

Modeling SIDM halos

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

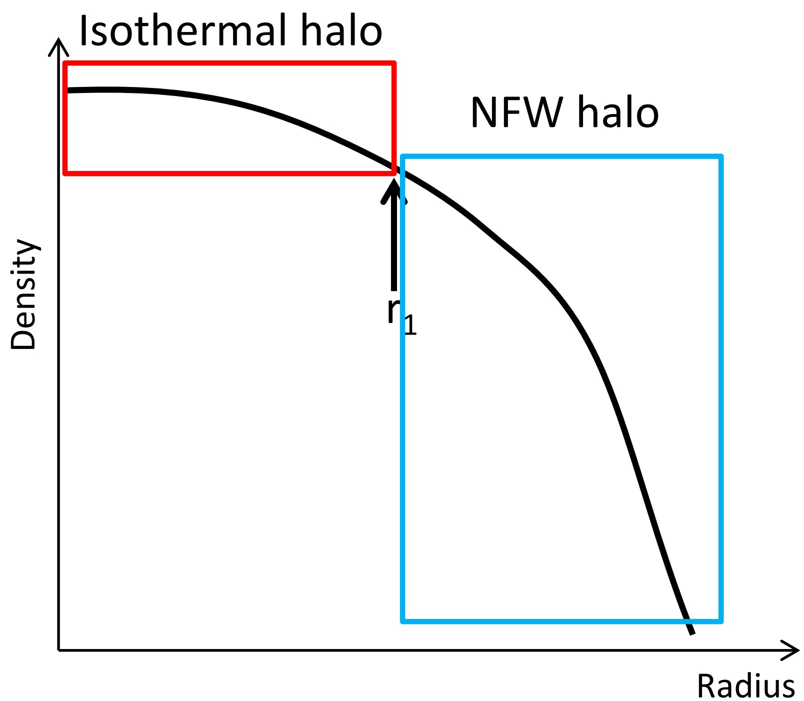


Inner halo ($r < r_1$): expect DM to be thermalized

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

Density at r_1 defines cross section where 1 scattering has occurred

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 (CDM)

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

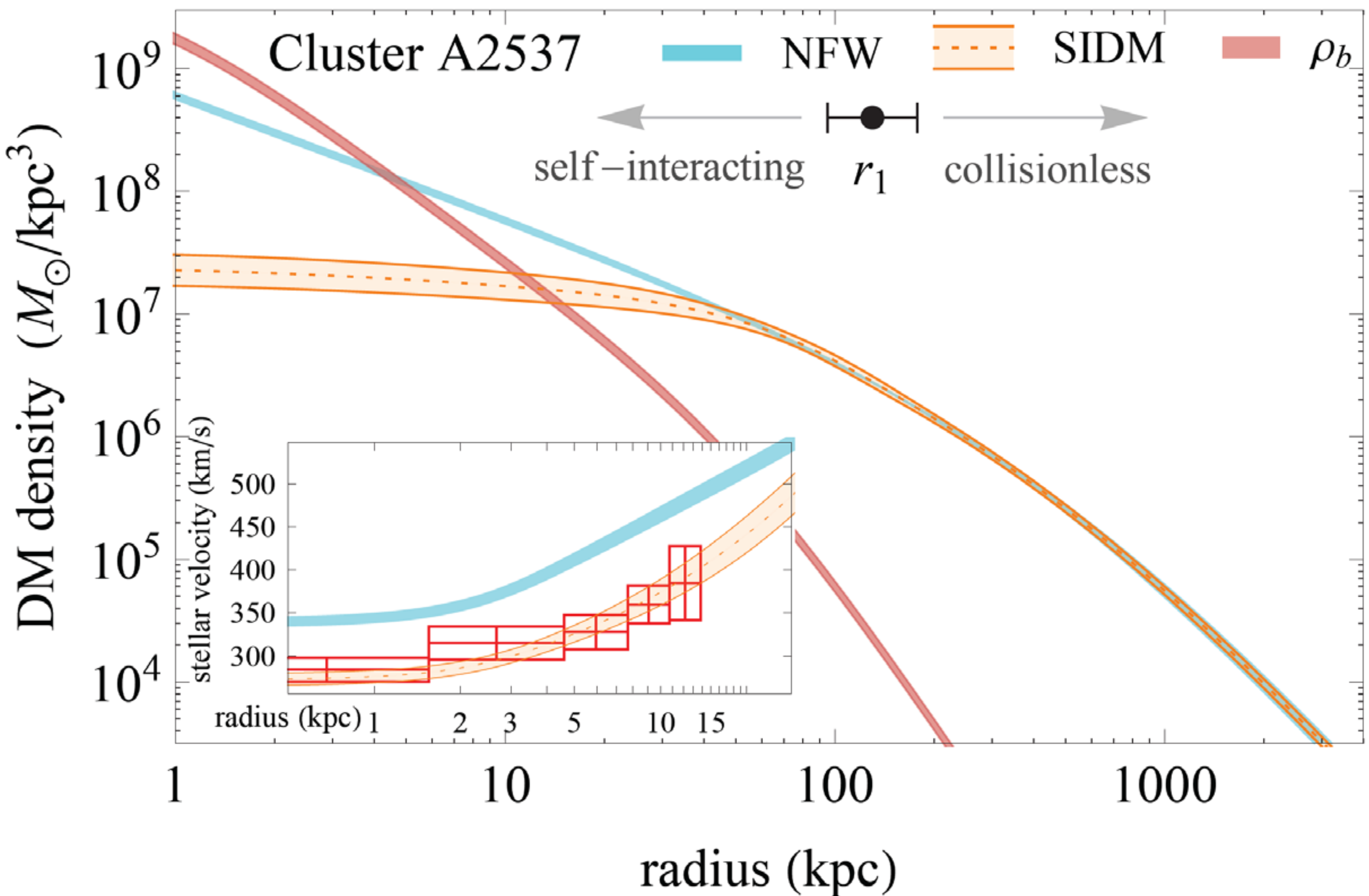
Parametrizing the SIDM halo:

- core density $\rho(r=0)$
- velocity dispersion σ^2 (= $k_B T/m$)
- matching radius r_1

SIDM halo fit for one cluster

Stellar kinematics within
brightest central elliptical galaxy

Strong and weak gravitational lensing



SIDM fits to dwarfs, LSBs, and clusters

Astrophysical dataset:

Clusters MS2137, A963, A611, A2537, A2667, A2390
Newman et al (2012)

Stellar kinematics + lensing data

LSB galaxies UGC4325, F563-V2, F563-1, F568-3, UGC5750, F583-4, F583-1
Kuzio de Naray et al (2007)

THINGS dwarf galaxies IC2574, NGC2366, HO II, M81dwB, DDO154
Oh et al (2011)

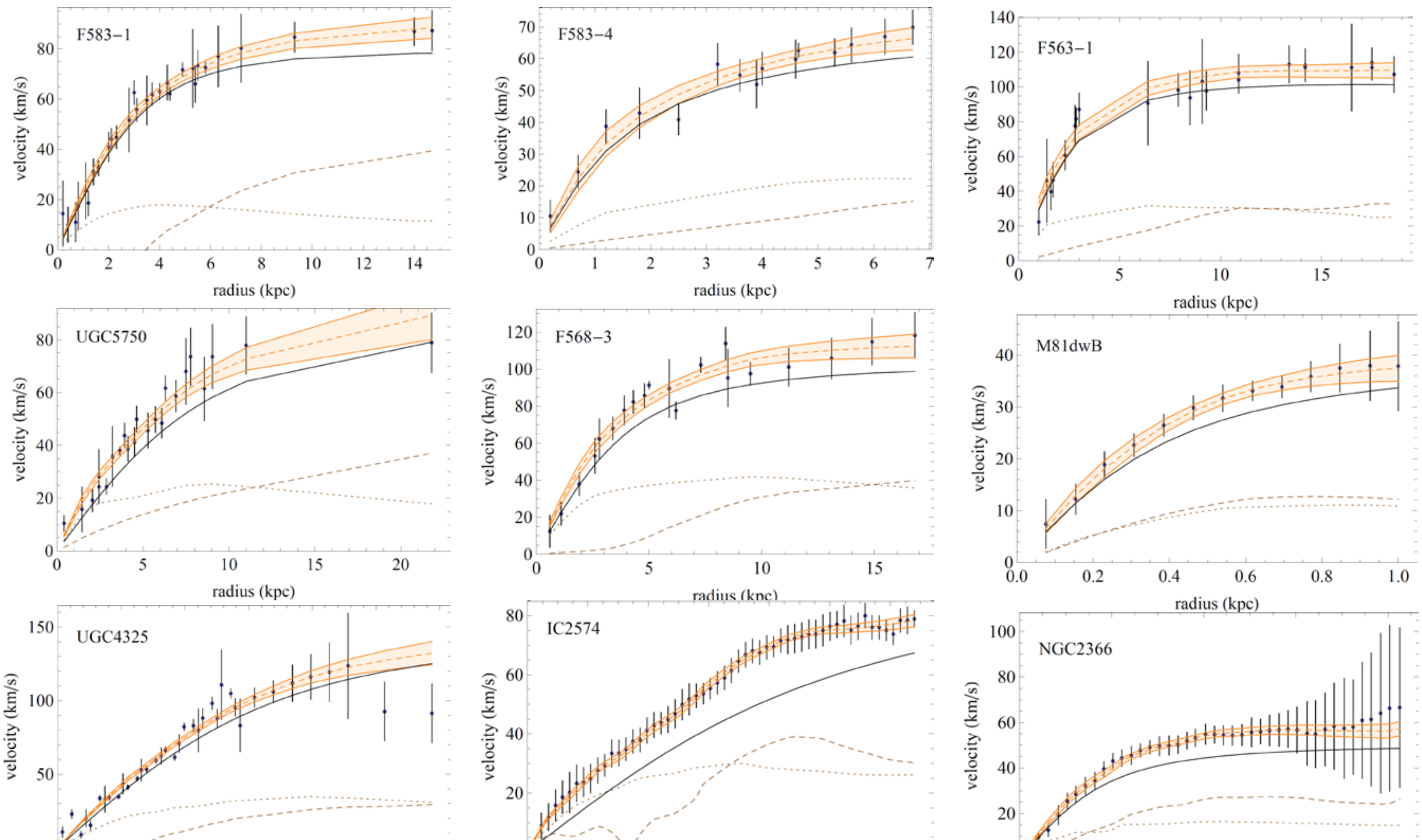
Rotation curves + assumption no core collapse

What is the cross section? Want σ/m vs velocity v
One scattering-per-particle at radius $r=r_1$ over the lifetime of halo (t_{age})

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

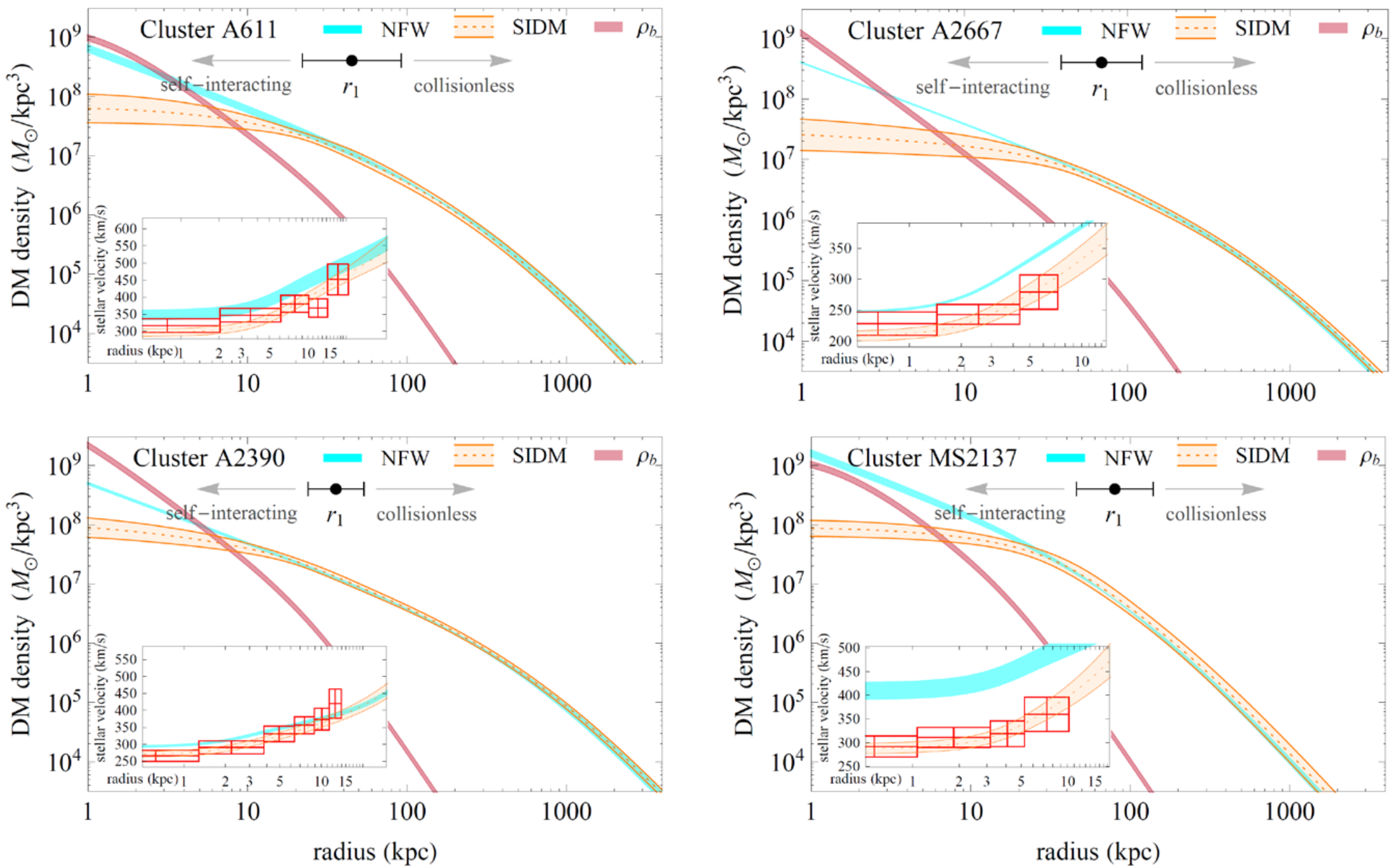
Instead of σ/m, we consider velocity-weighted cross section averaged over halo velocities

Galaxy rotation curves for SIDM

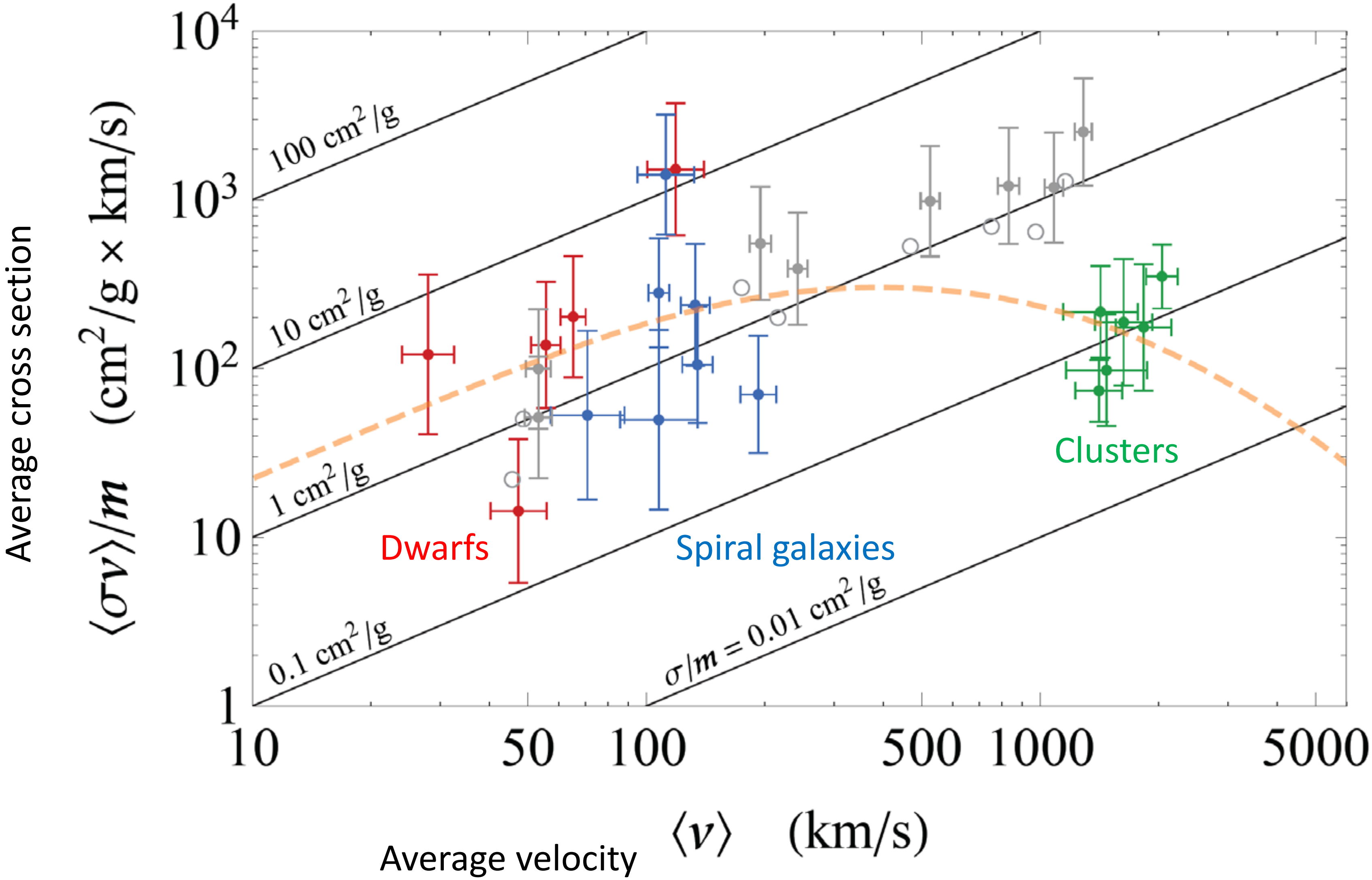


Even better fit than MOND

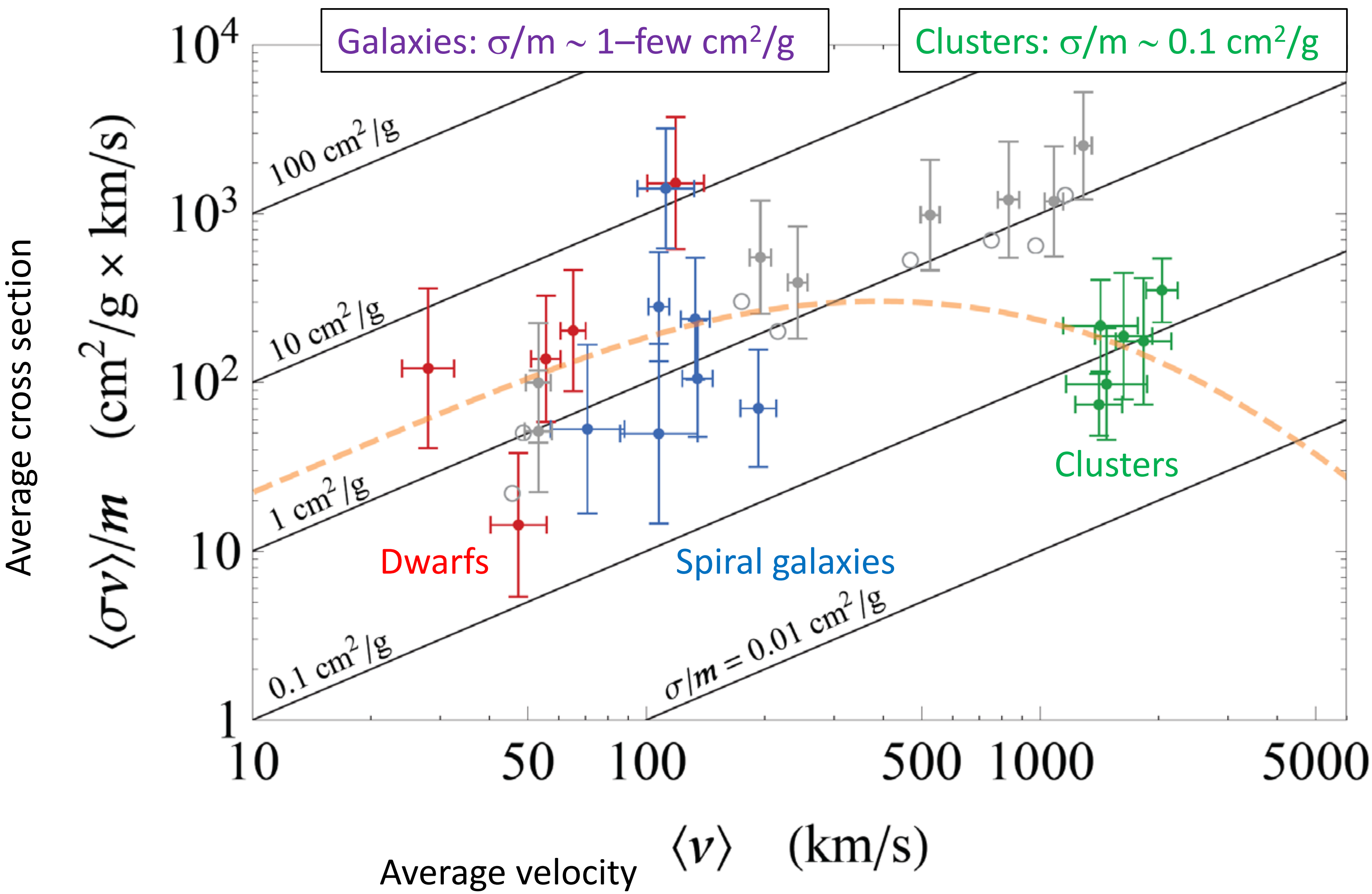
More SIDM fits to clusters



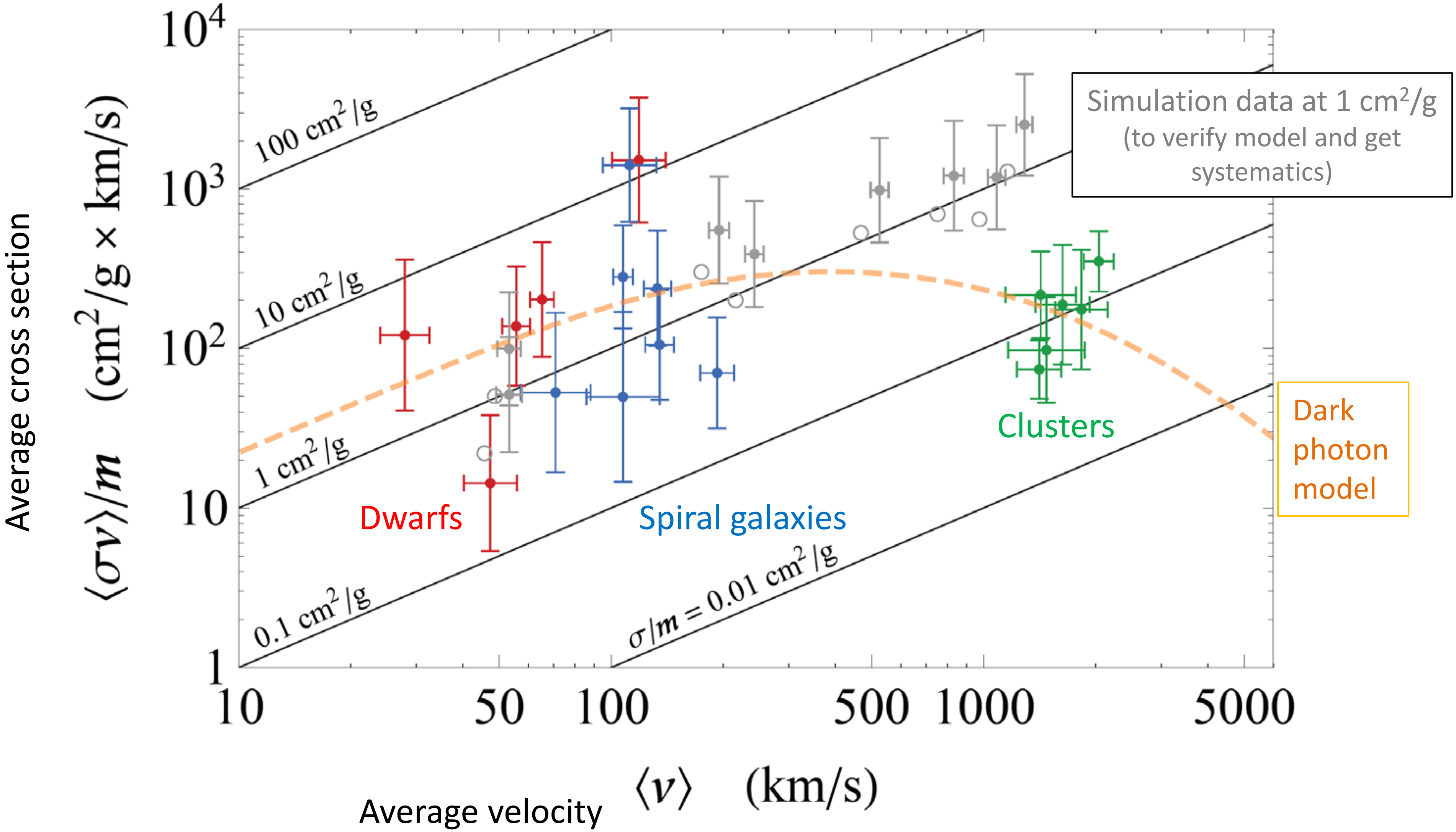
SIDM fits to dwarfs, LSBs, and clusters



SIDM fits to dwarfs, LSBs, and clusters



SIDM fits to dwarfs, LSBs, and clusters

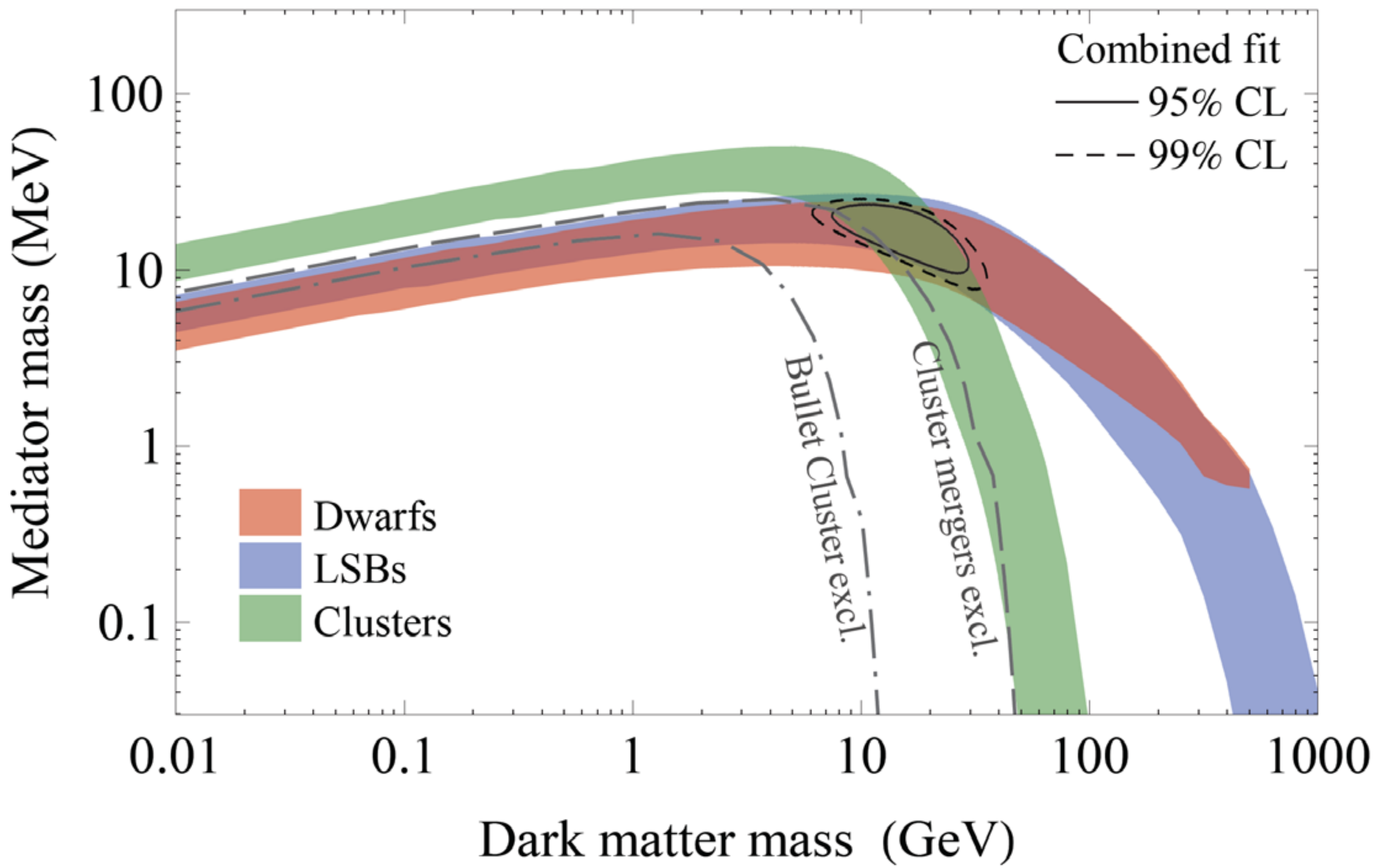


Dark matter with dark photon

Scattering through Yukawa potential

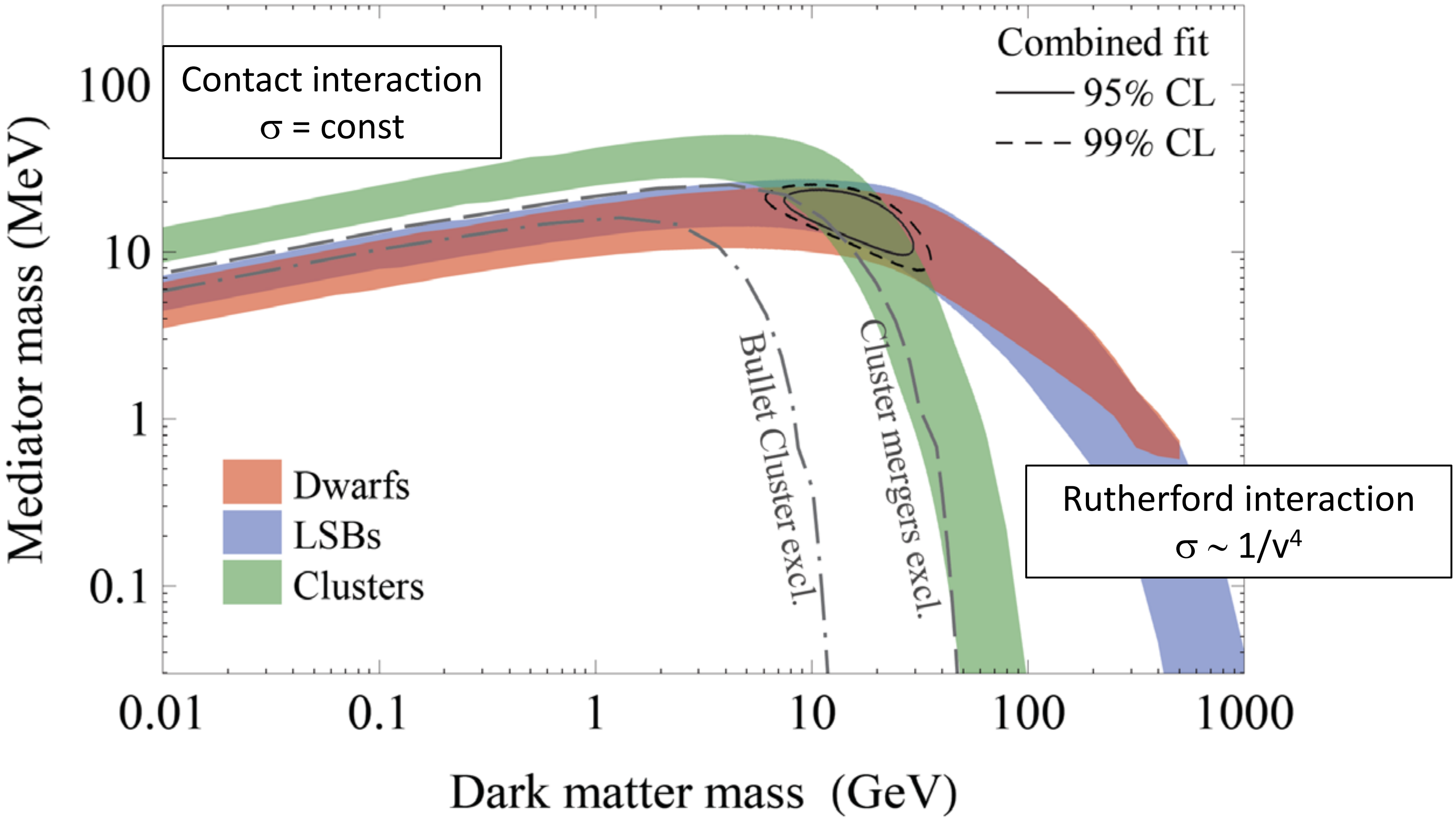
$$V(r) = \pm \frac{\alpha'}{r} e^{-\mu r}$$

$\alpha'=1/137$

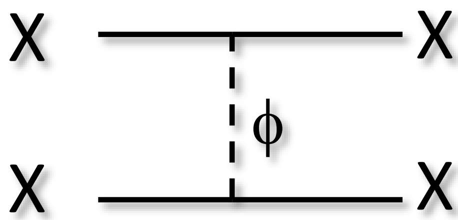


Dark matter with dark photon

Scattering through Yukawa potential $V(r) = \pm \frac{\alpha'}{r} e^{-\mu r}$ $\alpha' = 1/137$



Self-interacting dark matter paradigm

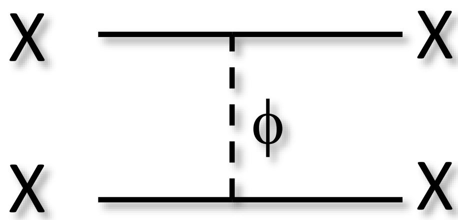


Self-interactions

DM particle X + mediator particle ϕ

ϕ = dark photon, dark Higgs, dark pion, …

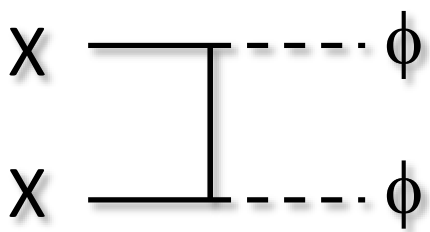
Self-interacting dark matter paradigm



Self-interactions

DM particle X + mediator particle ϕ

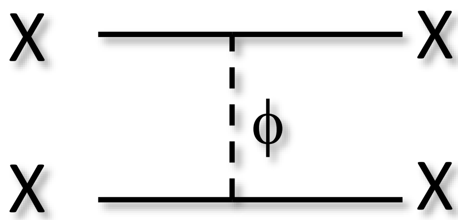
ϕ = dark photon, dark Higgs, dark pion, …



Annihilation

Set relic density
via freeze-out

Self-interacting dark matter paradigm



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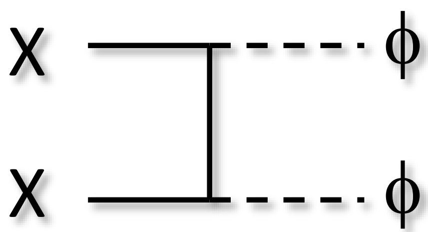

Annihilation

Set relic density
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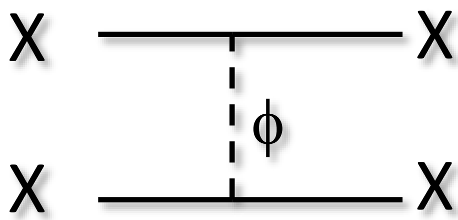
$\phi \longrightarrow$ SM

Decay

(Deplete ϕ density)

Self-interacting dark matter paradigm



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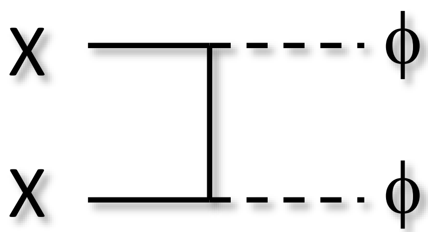

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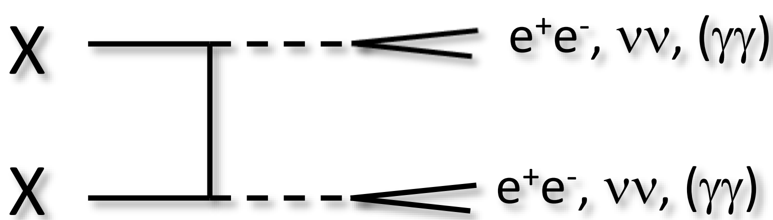
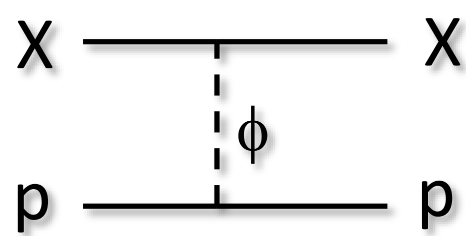


Indirect detection



Direct detection
Capture in sun/earth

Conclusions

- Astrophysical observations of structure offer possibility to explore dark matter interactions beyond WIMP paradigm *(even if hidden from visible sector)*

- Long-standing issues for CDM and structure, but jury still out

- Can high energy messengers give us insight into how baryonic feedback operates to affect structure formation?