Self-interacting dark matter and new light forces

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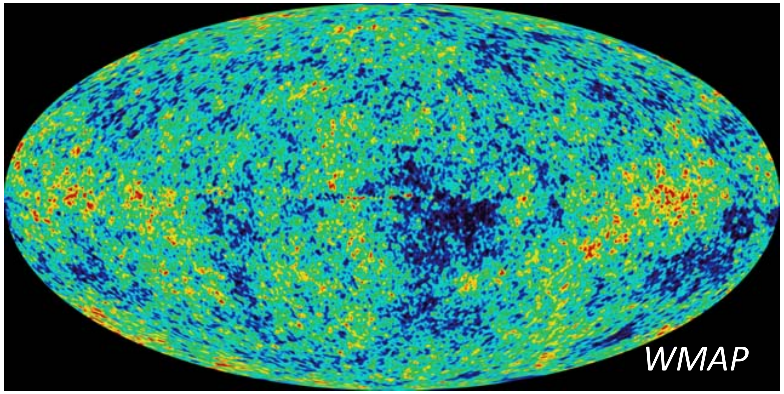
Phys. Rep. on SIDM in prep. w/ Hai-Bo Yu

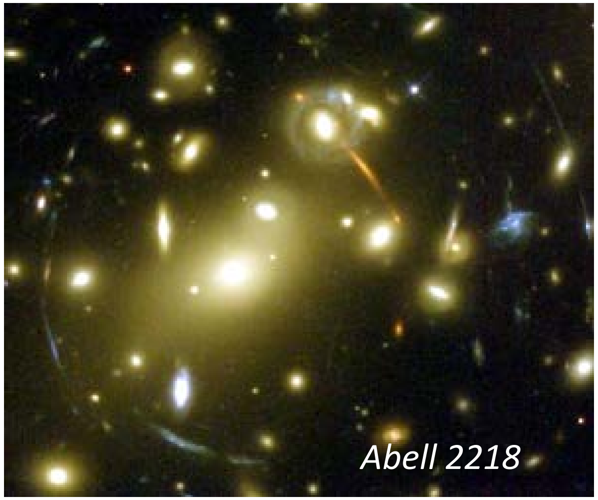
Cold collisionless dark matter paradigm

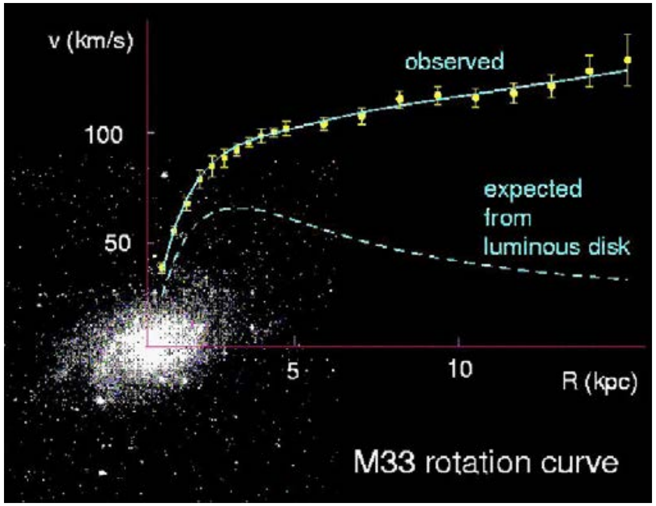
Dark matter (DM) is about 25% of the Universe



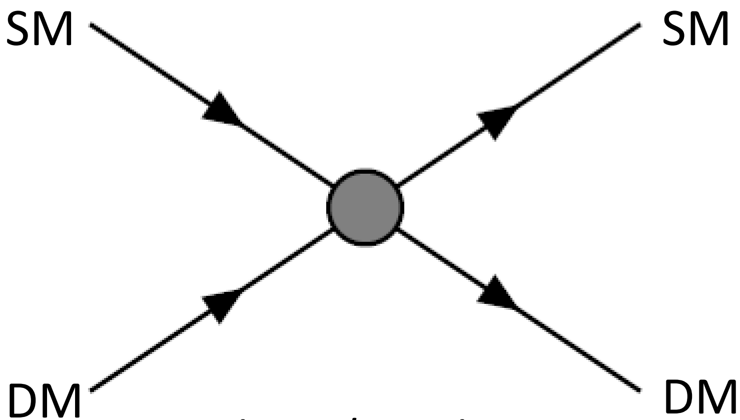
Cold collisionless dark matter (CDM) provides a good description of the structure of matter in the Universe

To date, evidence for DM from gravity only

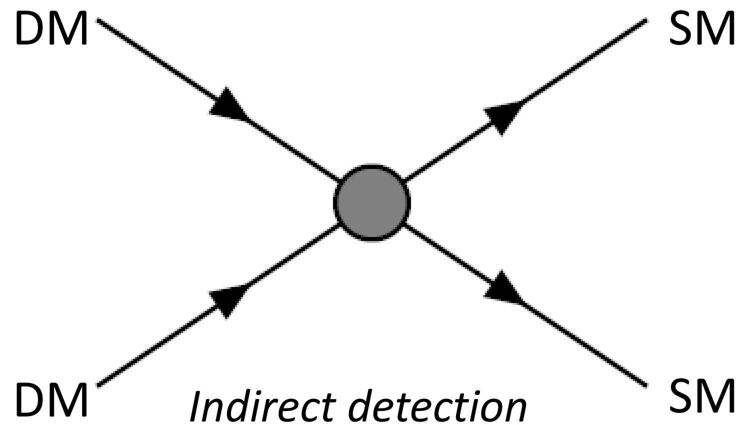




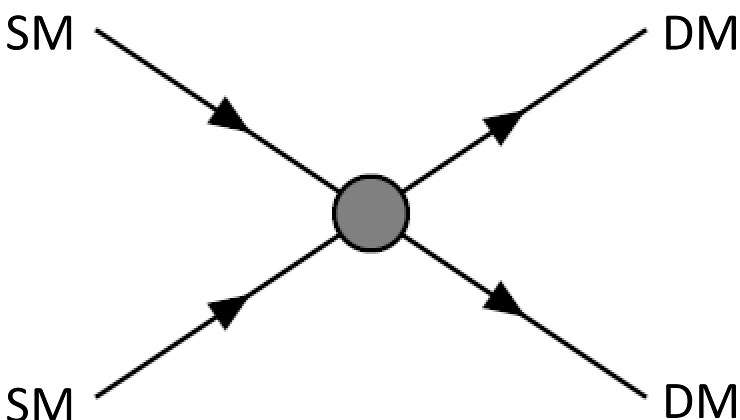
Exploring the dark sector



Direct detection



Indirect detection

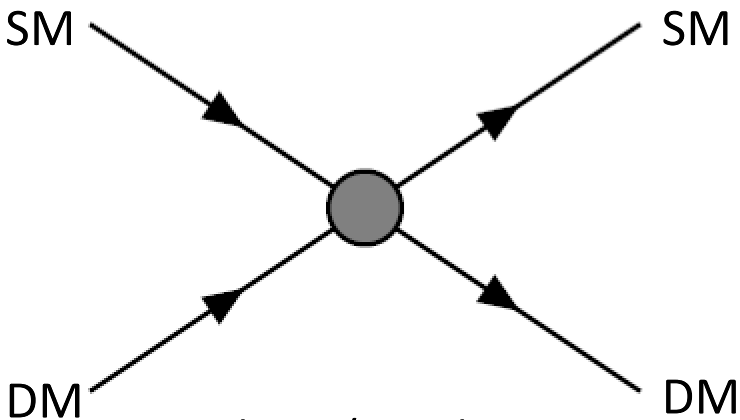


Colliders

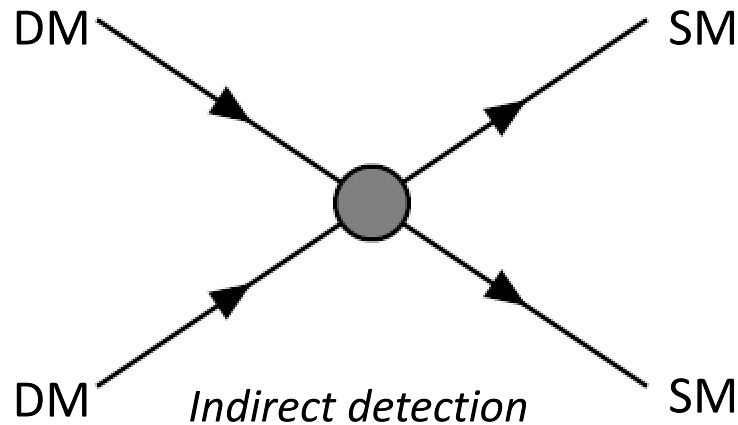
WIMP paradigm: expect dark matter in one or more of these channels

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

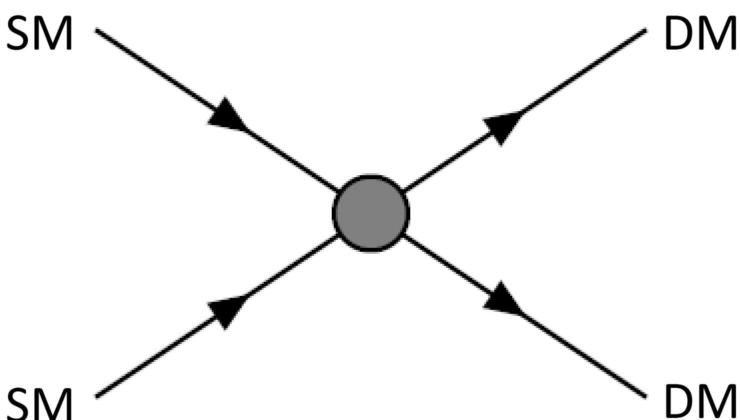
Exploring the dark sector



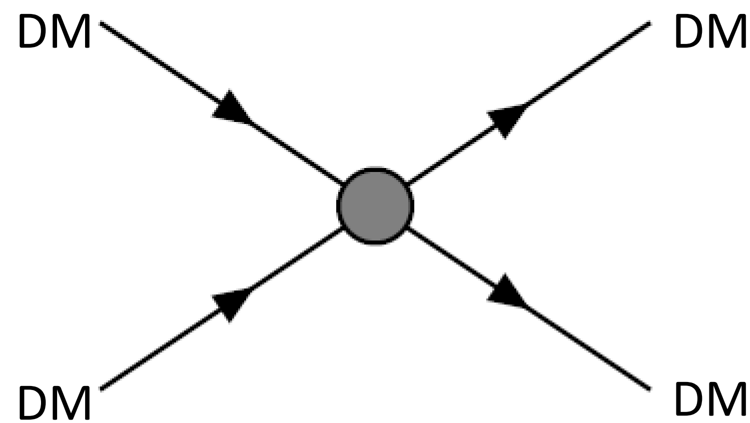
Direct detection



Indirect detection



Colliders



Self-interactions

Outline

- CDM issues (small scale structure problems)

- DM may have self-interactions

  What are the particle physics implications?

  Dark sector states below 1 GeV

- Complementarity with WIMP searches

  Portals for coupling to Standard Model

Problem 1. Core-vs-cusp problem

Central densities of halos are too shallow

Moore (1994), Flores & Primack (1994)

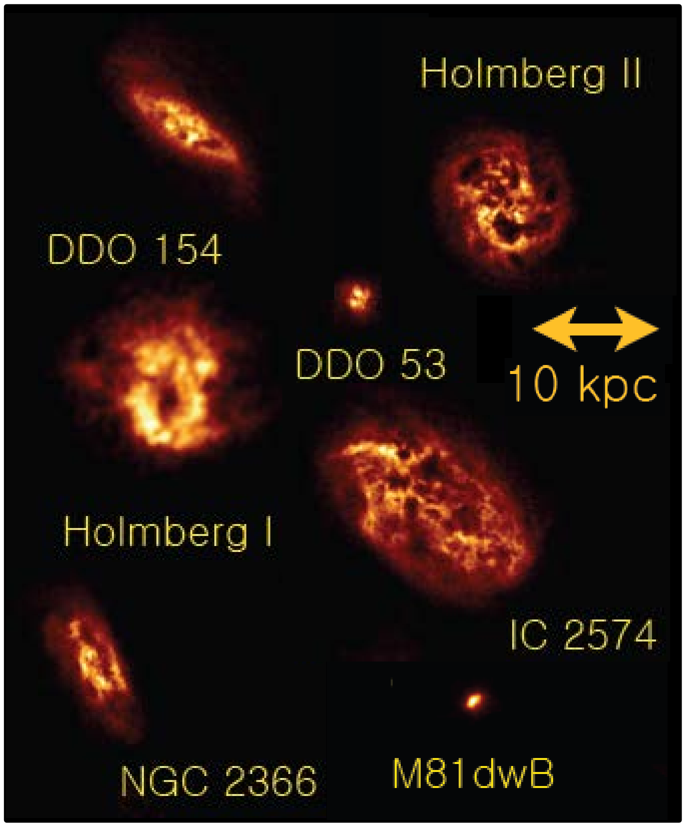
Parametrize DM density in inner halo: $\rho \sim r^{\alpha}$

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

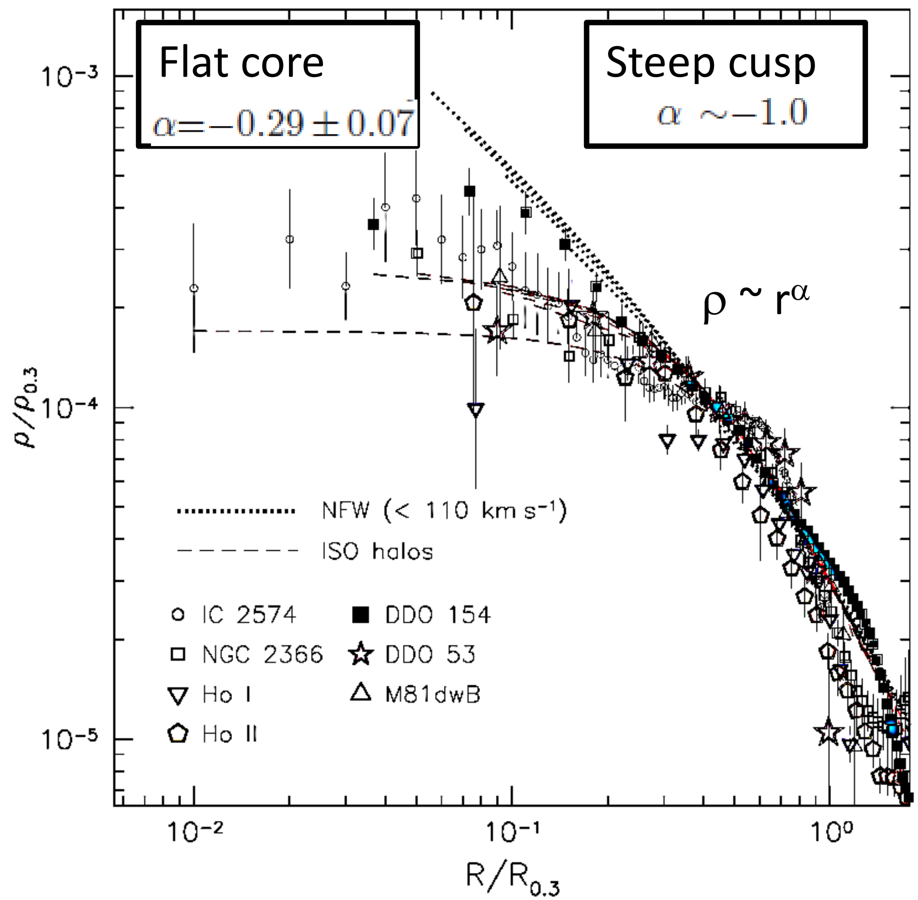
Cores seem very ubiquitous: dwarf galaxies, low surface brightness spirals, clusters

Cores in field galaxies

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



21 cm emission from gas



Cores in field galaxies

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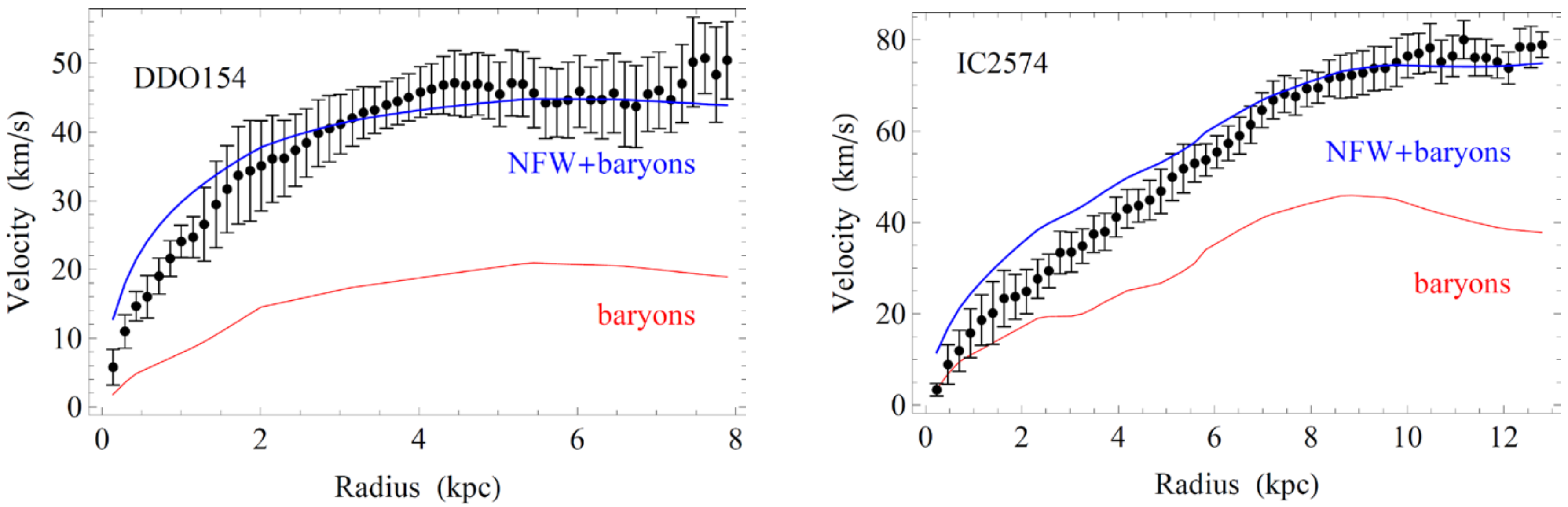
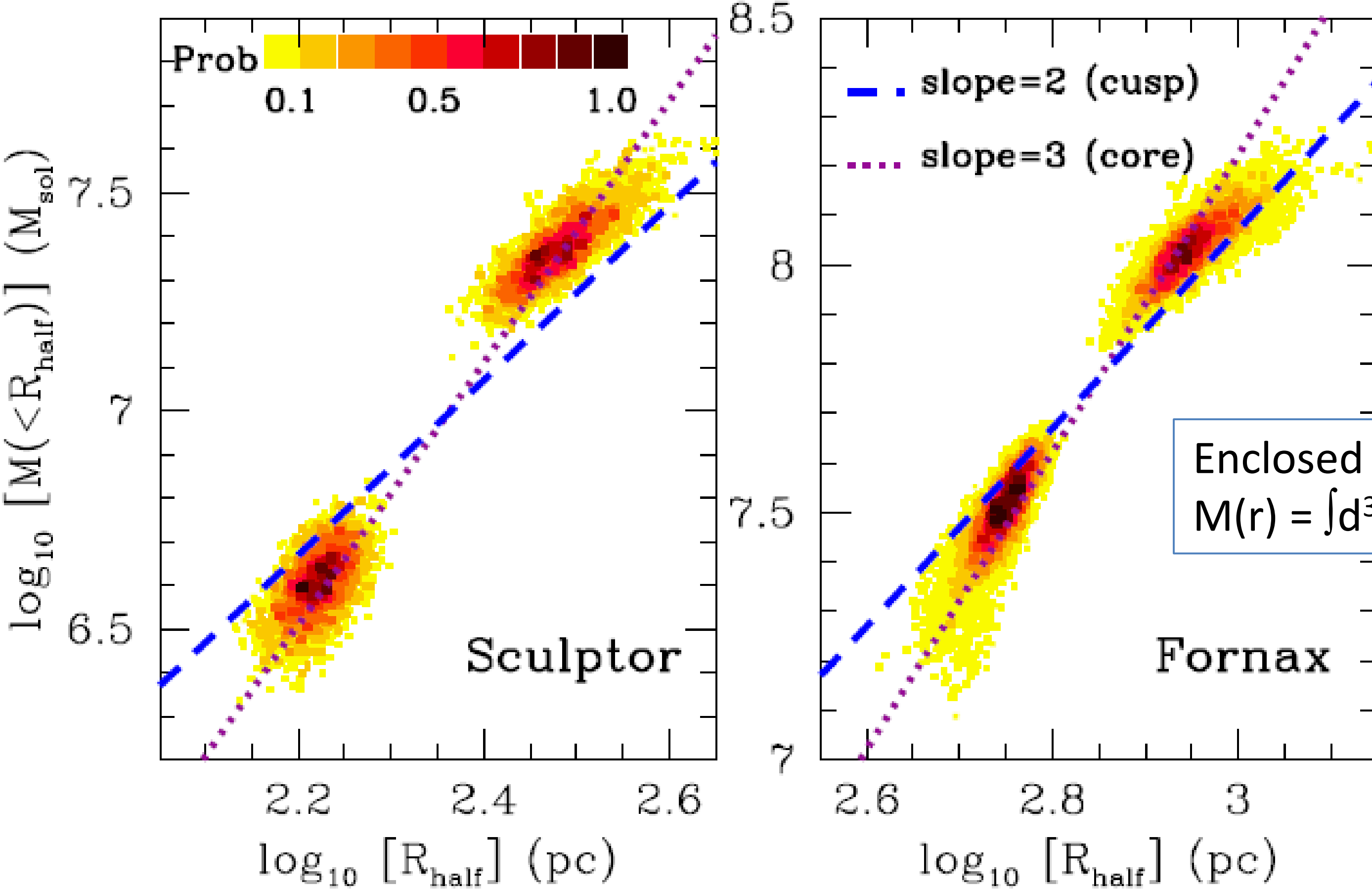


Deficit of dark matter in the inner halo compared to NFW

Cores in satellite galaxies

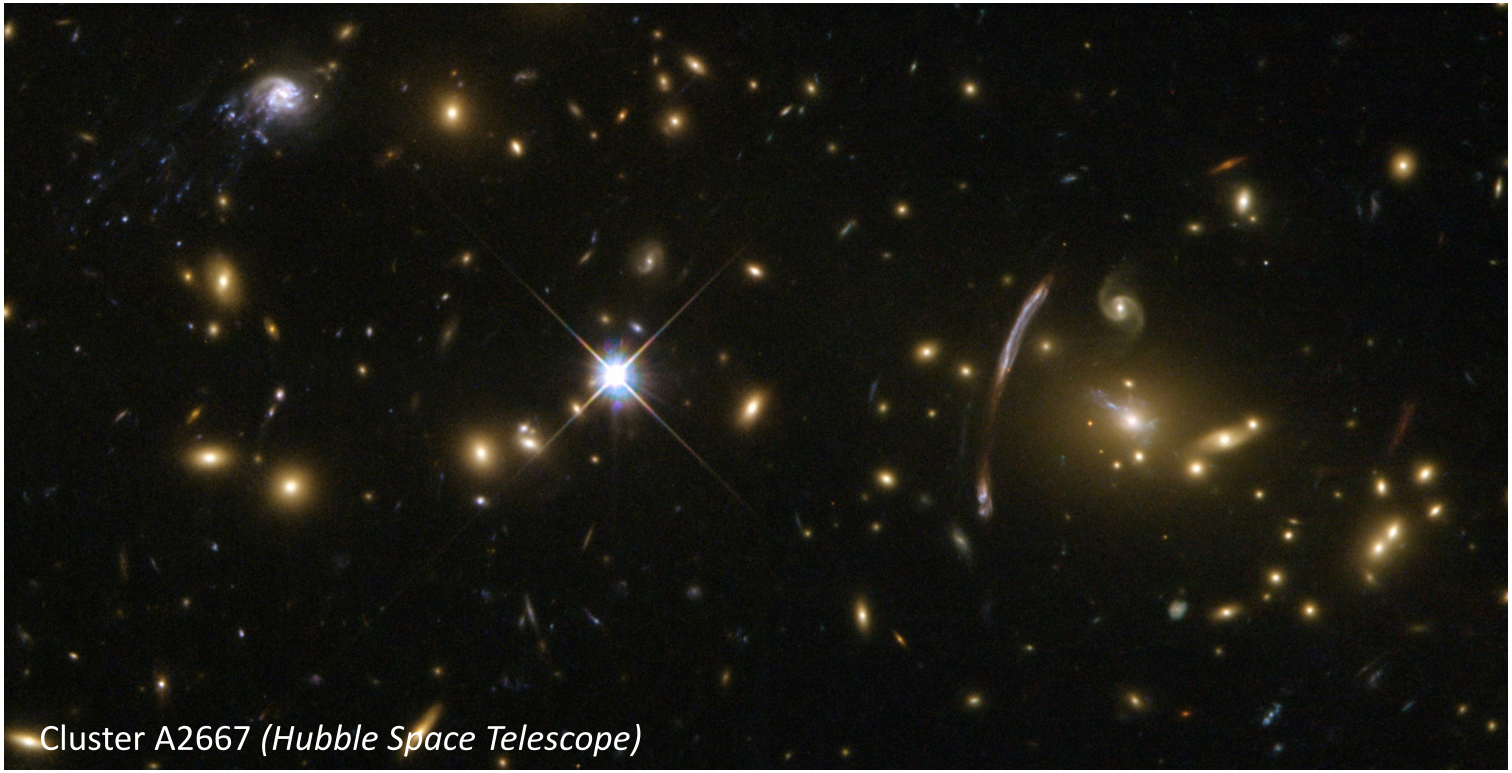


Enclosed mass
$M(r) = \int d^3r\, \rho \sim r^{\alpha+3}$

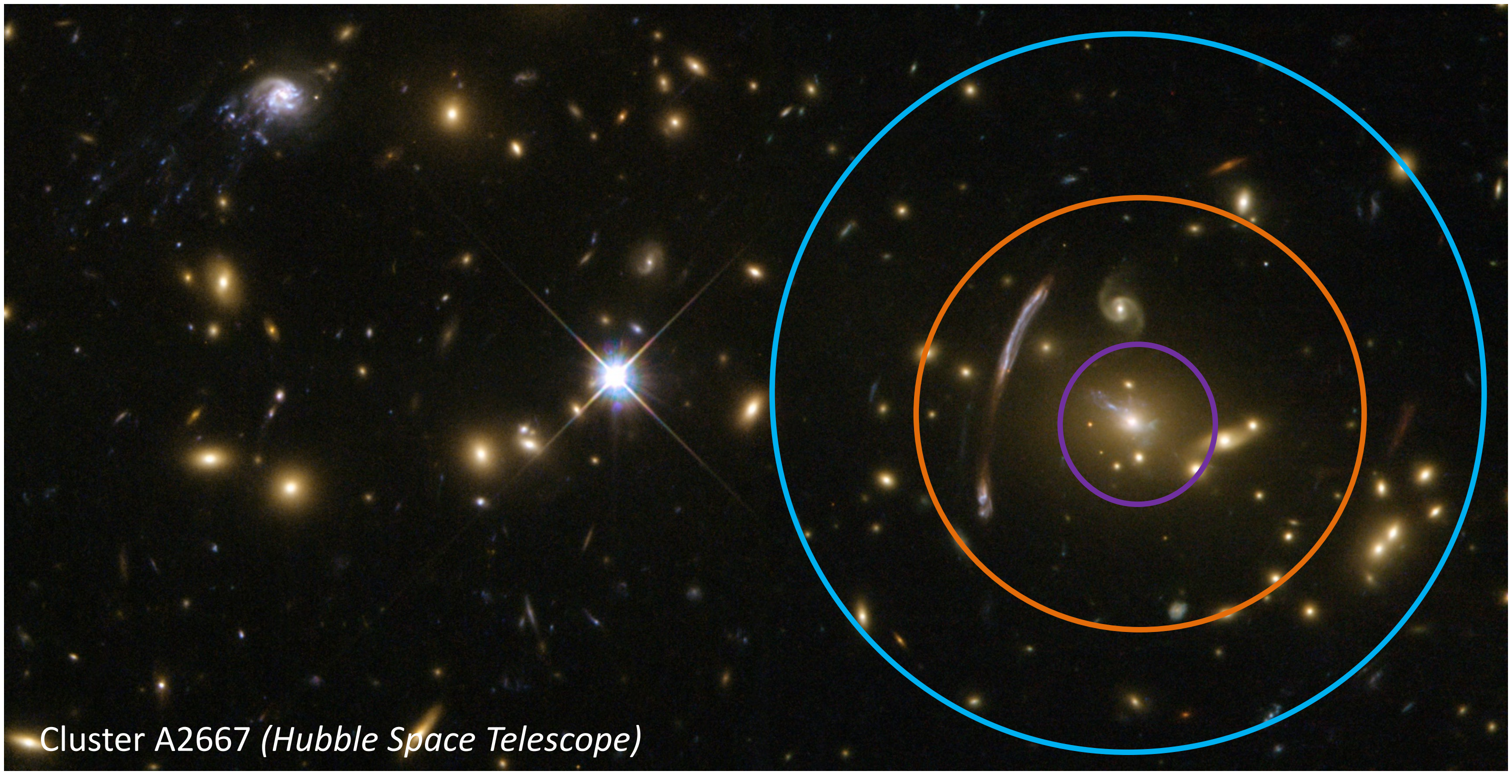
Stellar subpopulations (metal-rich & metal-poor) as "test masses" in gravitational potential

Walker & Penarrubia (2011)

Cores in clusters



Cores in clusters



Use multiple measurements to study dark matter halo

Newman et al (2012)

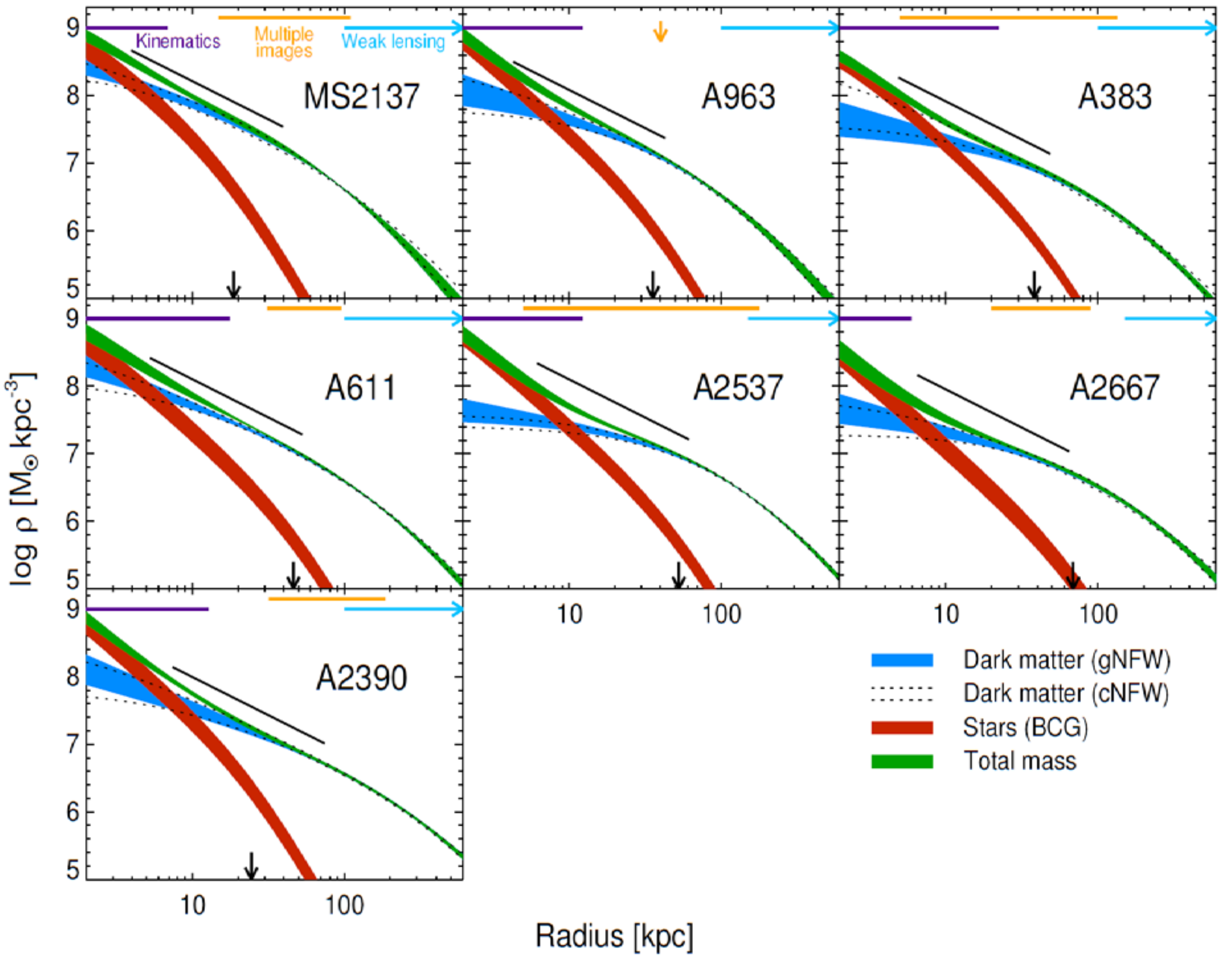
Weak gravitational lensing at large distance

Gravitational lensing arcs (strong lensing) at medium distance

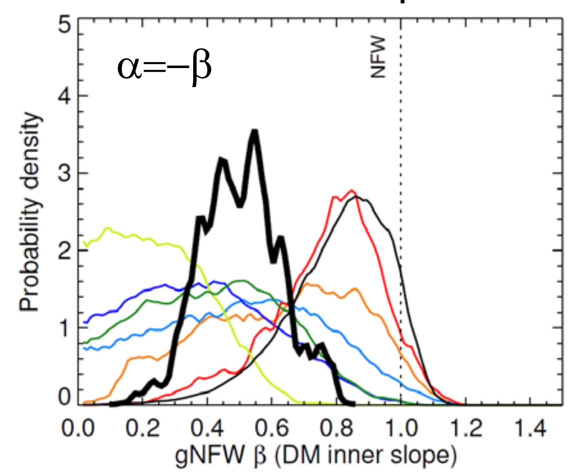
Stellar kinematics for the cluster center

Cores in clusters

Newman et al (2012)



Best-fit slope



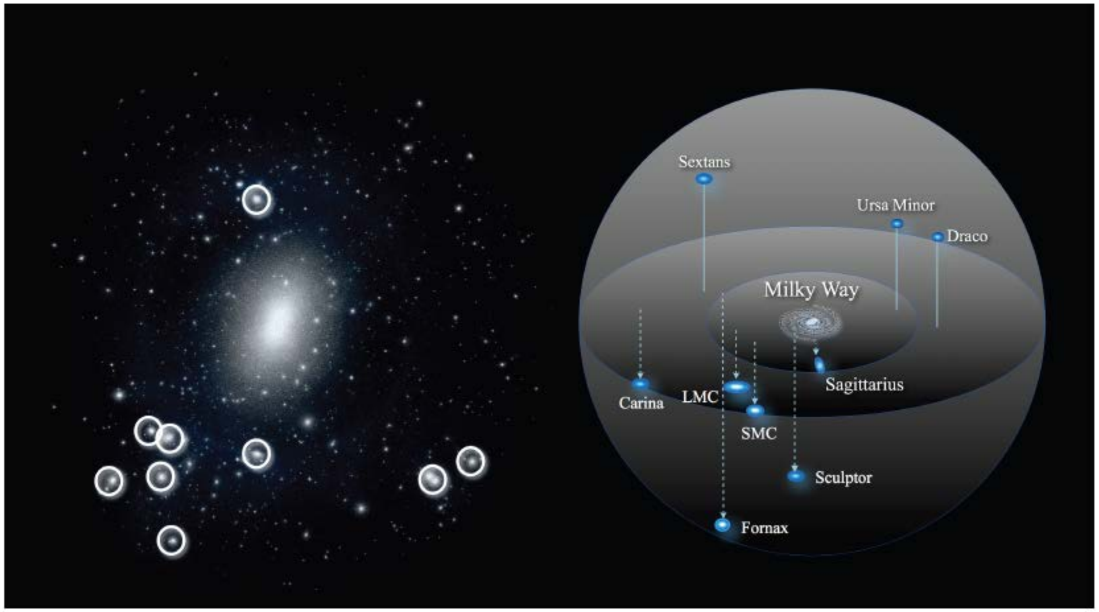
Generalized-NFW fit:

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

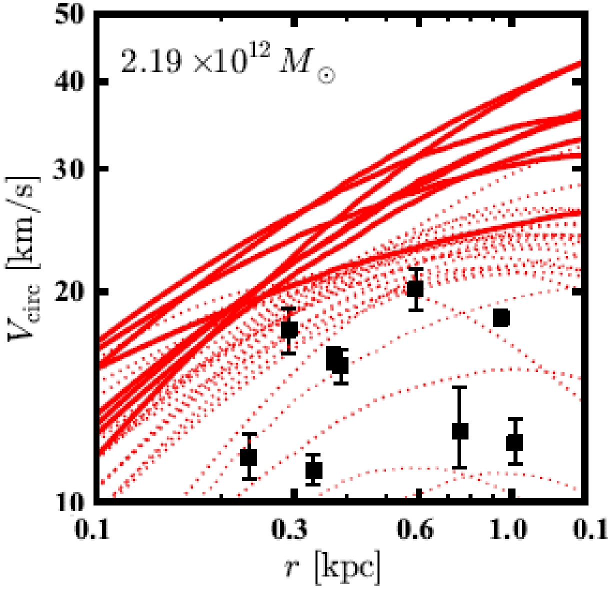
Problem 2. Too-big-to-fail problem

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

Predicted Milky Way satellites more massive (higher circular velocities) than observed ones.

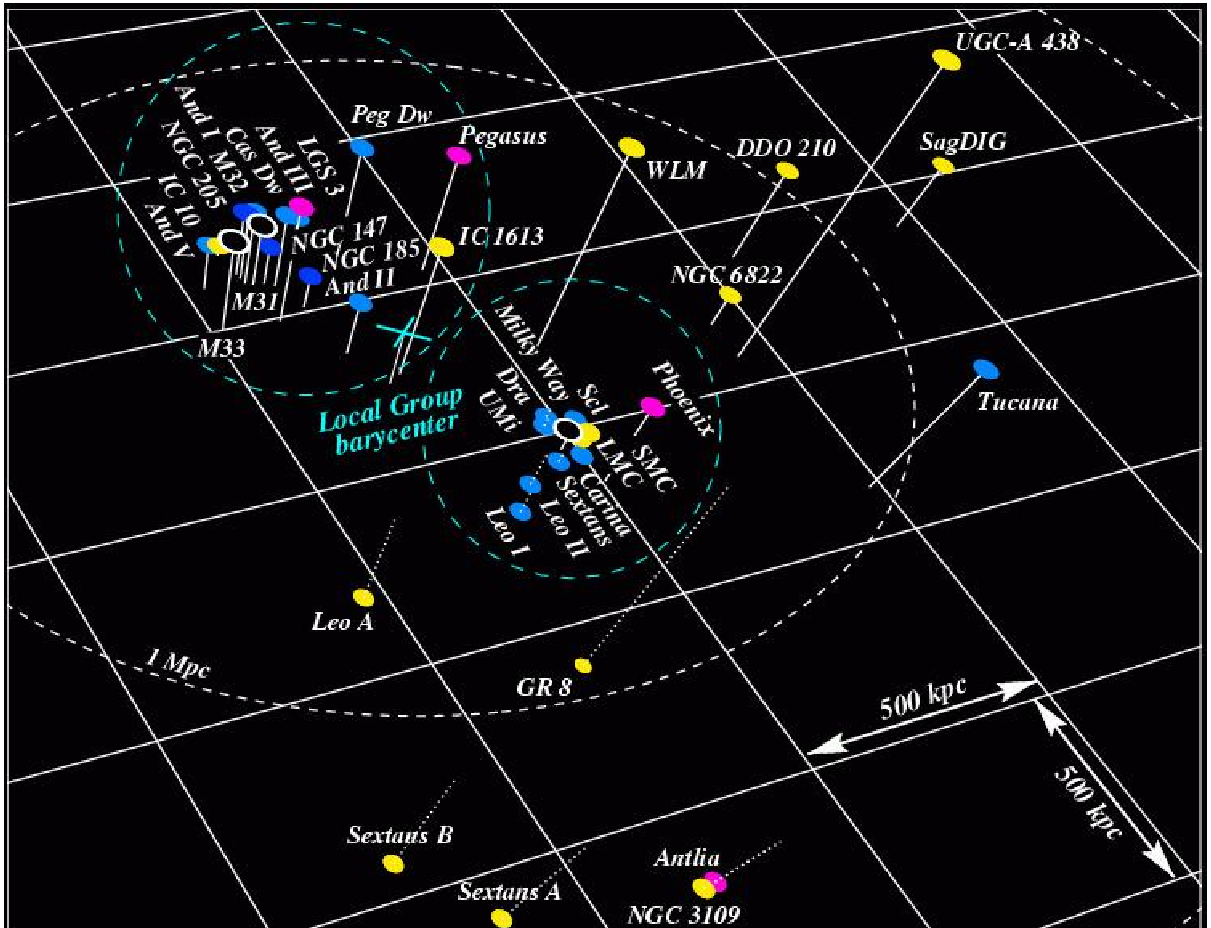


From Weinberg, Bullock, Governato, Kuzio de Naray, Peter (2013)



Problem 2. Too-big-to-fail problem

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



CDM Problems

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

- Dark matter may not be CDM

- Problem with our interpretation of observations

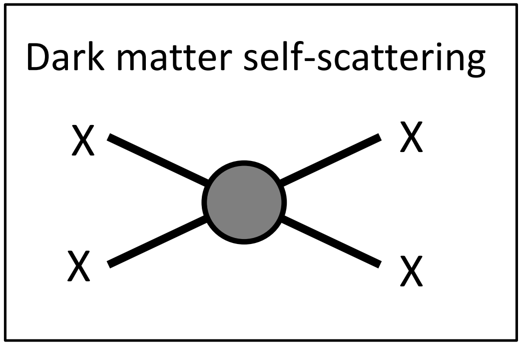
  Can’t use DM-only simulations to model real DM+baryons Universe (feedback)

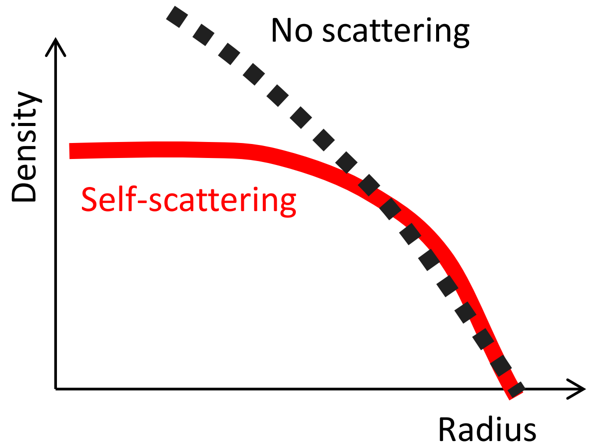
  Astrophysical observations not being interpretted correctly (systematic uncertainties)

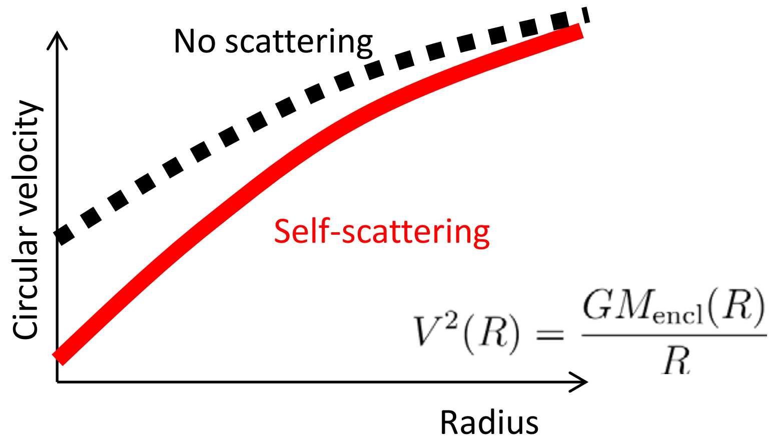
Self-interacting dark matter

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}

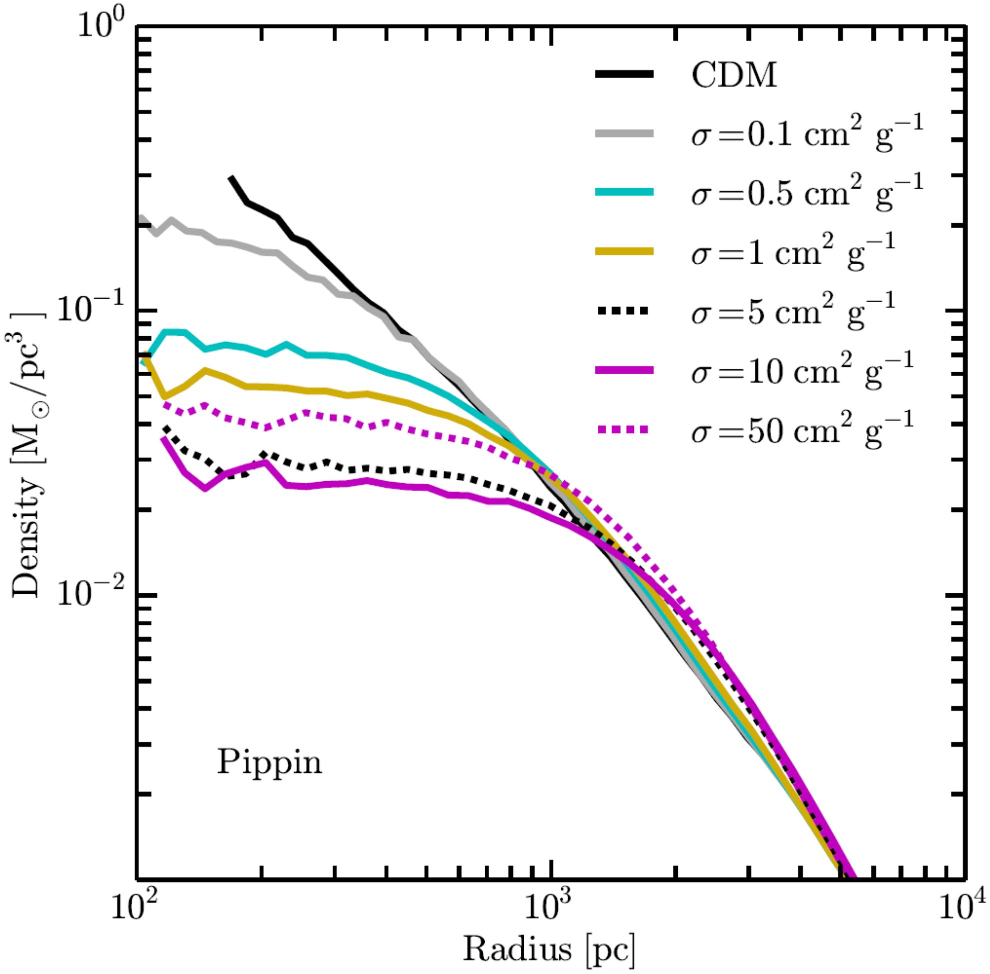
Figure-of-merit: $$\sigma/m_\chi \sim 1 \text{ cm}^2/\text{g} \;\approx\; 2 \text{ barns/GeV}$$

Typical cross section required to solve small scale anomalies

Leaves large scale structure of ΛCDM unchanged

N-body simulations for SIDM

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



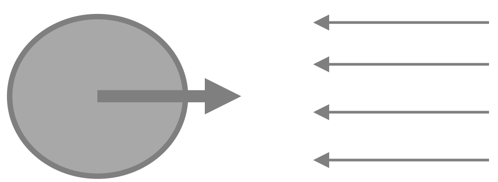
σ/m ~ 0.5 – 50 $\mathrm{cm^2/g}$ to form kpc core in dwarf galaxy

Missing satellites problem

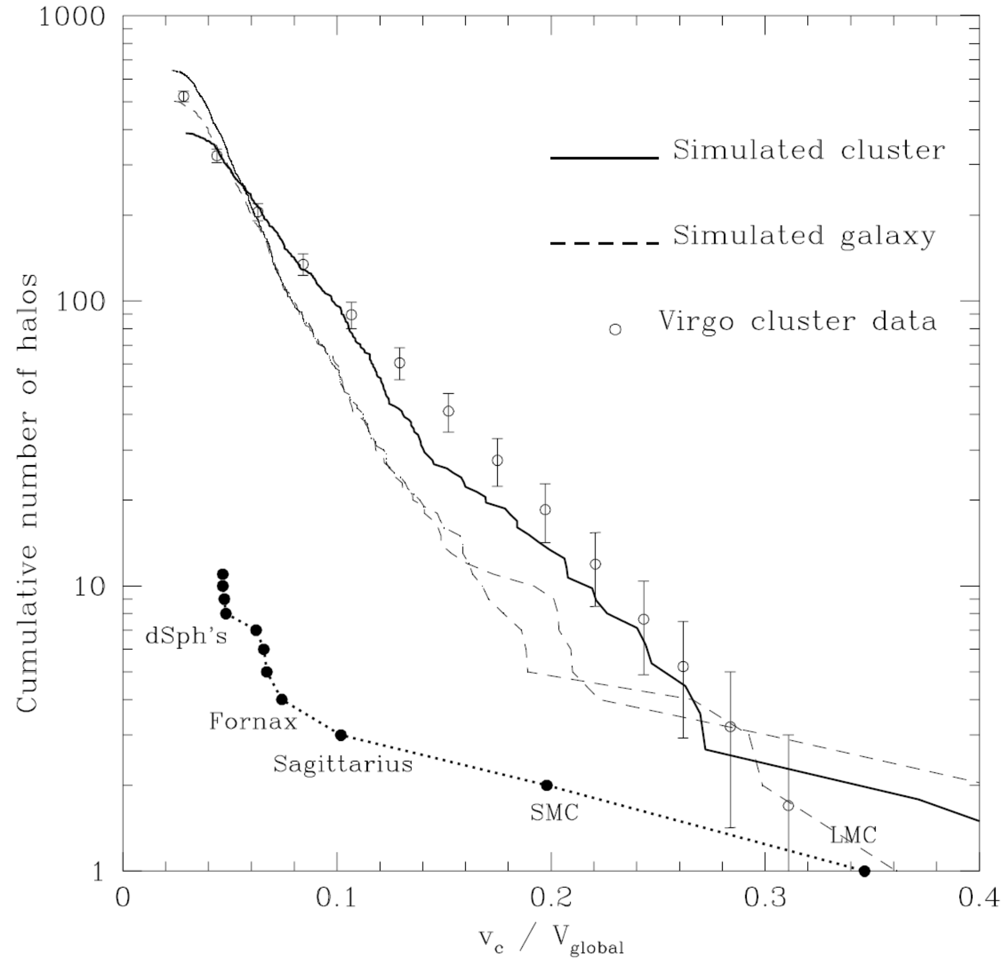
Less substructure in Milky Way than predicted by CDM simulations

No "missing galaxies" problem for clusters (at least until relatively smaller scales)

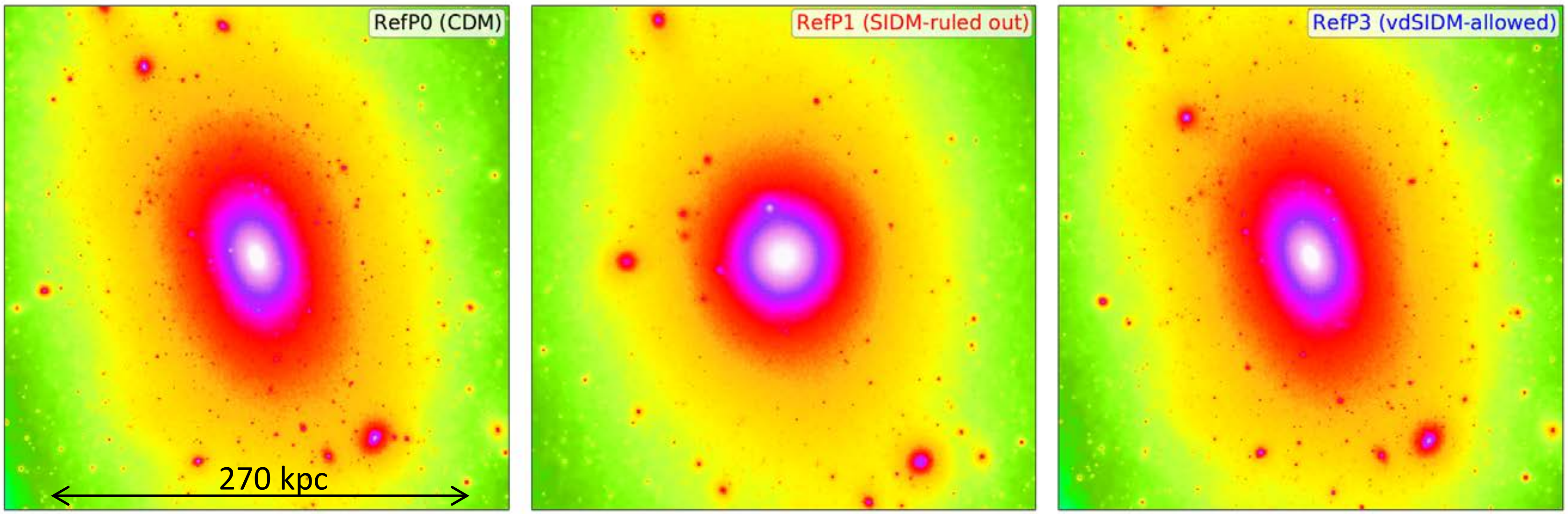
Original SIDM idea:
Evaporate dwarfs via ram pressure stripping in host halo



Moore et al (2000)



Missing satellites problem



Collisionless DM

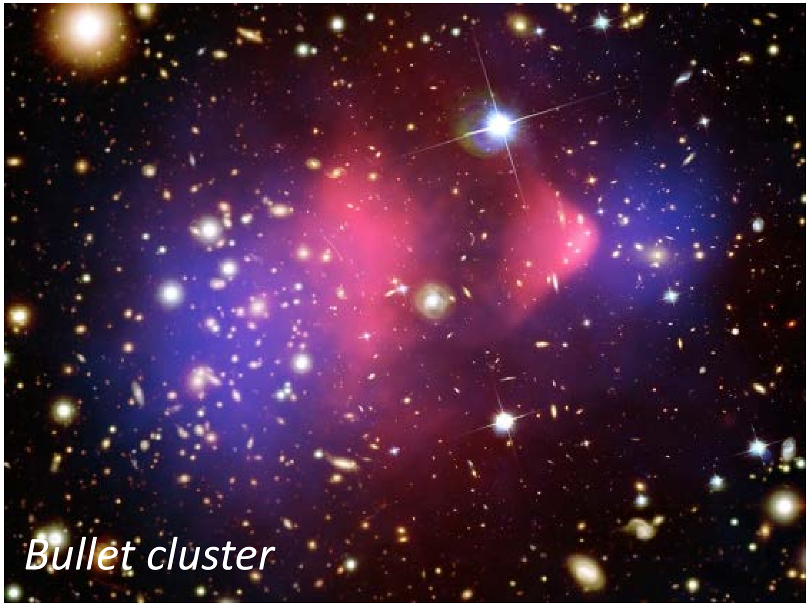
SIDM 10 cm^2/g

Velocity-dependent SIDM
30 cm^2/g for v = 10 km/s
0.01 cm^2/g for v = 200 km/s

Substructure only affected if σ/m large on MW scales

Excluded because makes halos too elliptical on O(50 kpc) scales

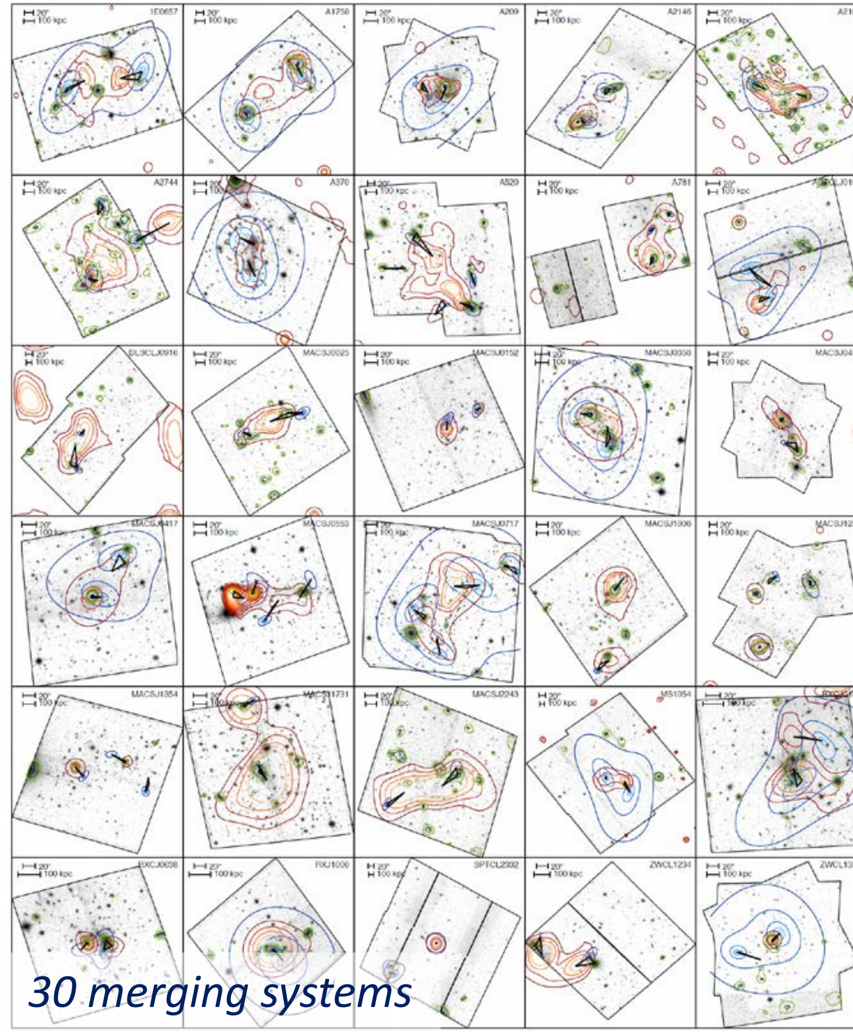
Constraints from merging clusters



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

Randall et al. (2007)

Many other circa-2000 constraints are weaker than previously thought
$\sigma/m < 1$ cm^2/g is OK on cluster and elliptical galaxy scales *Peter et al (2012)*



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

Harvey et al. (2015)

Baryonic feedback

Violent baryonic outflows from the centers of galaxies/clusters feedback gravitationally to affect DM distribution

Time scale for changing baryon distribution << dynamical time scale

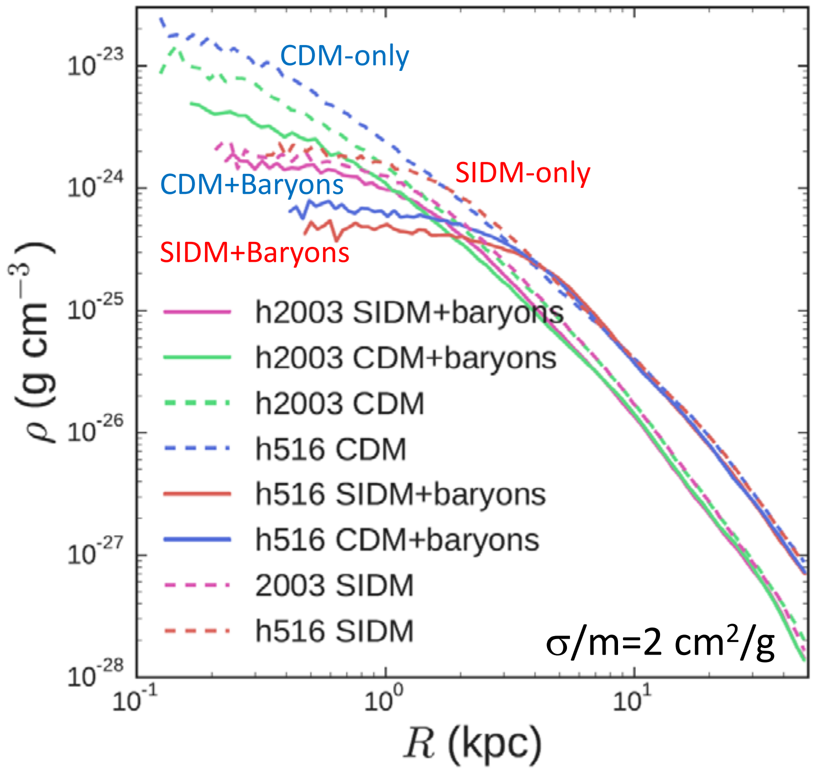
Galaxies: Supernova feedback

Clusters: AGN feedback

Feedback from supernovae

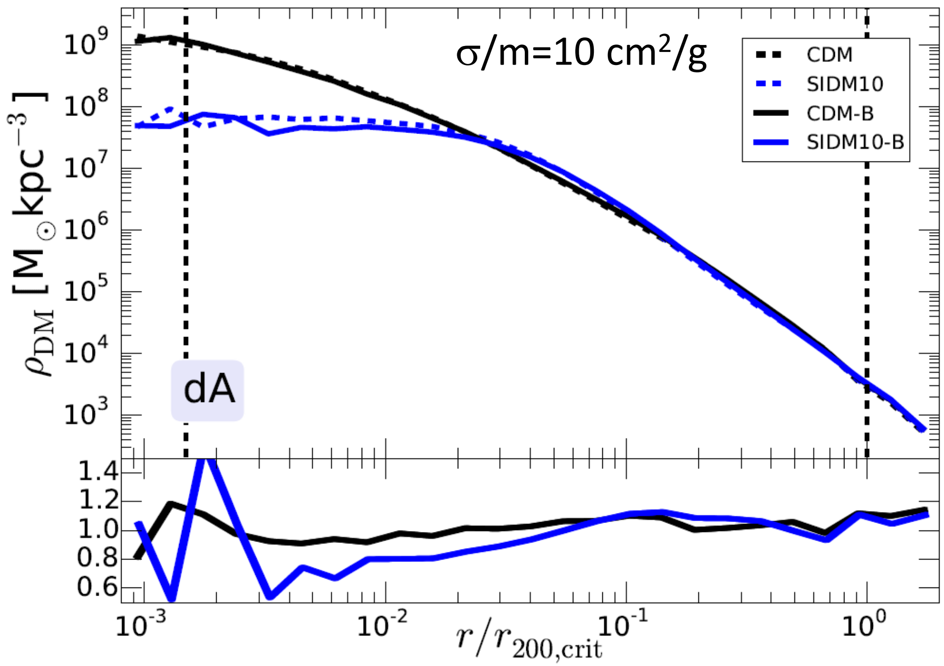
N-body simulations with self-interactions and baryons

Fry et al. (2015)



Bursty star formation
(High density threshold
for star formation)

Vogelsberger et al. (2014)

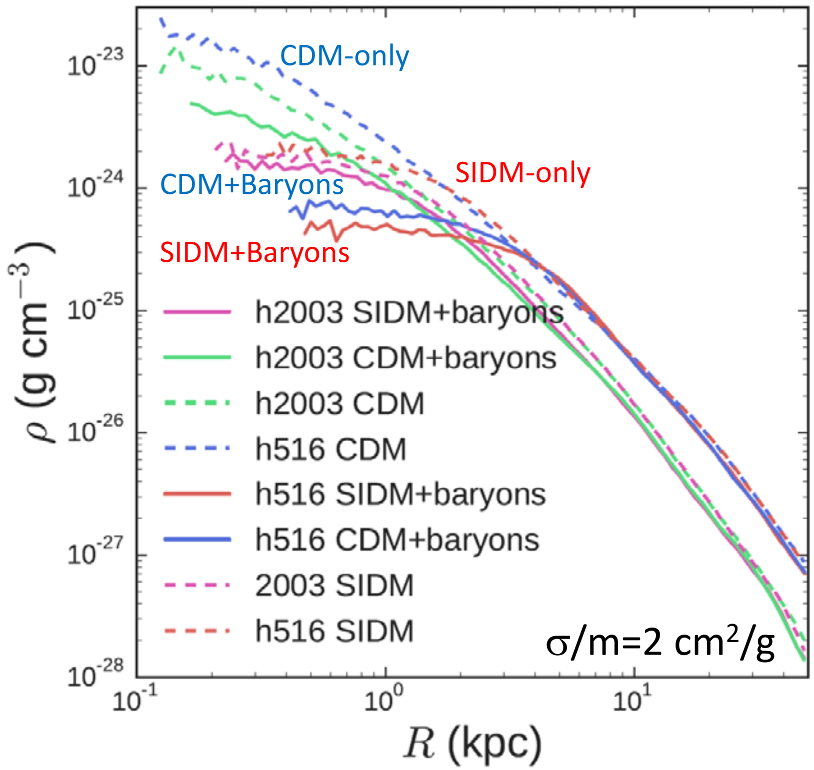


Smooth star formation
(Low density threshold)

Feedback from supernovae

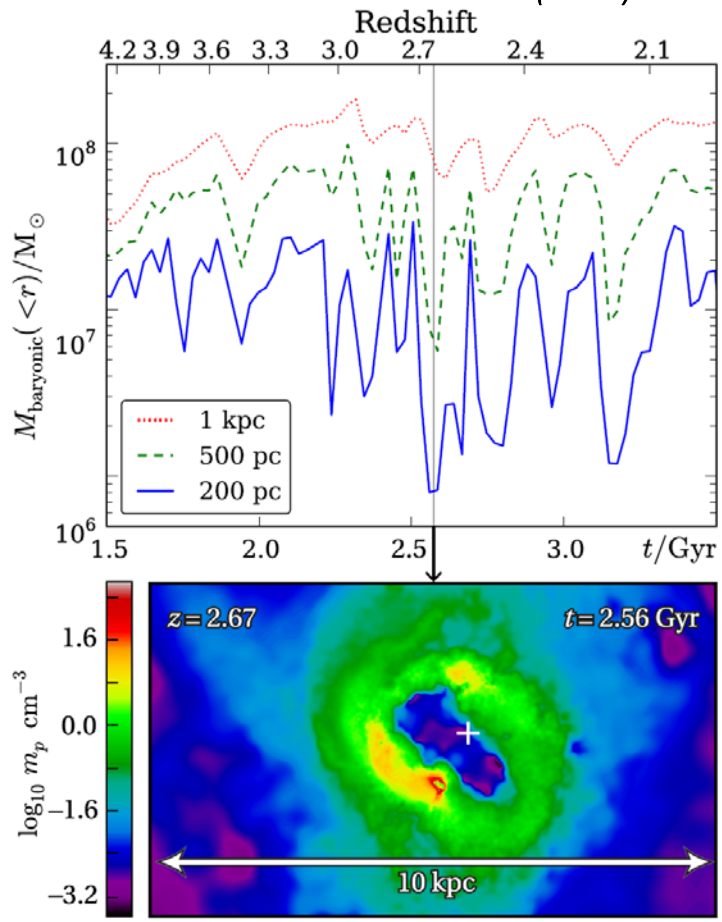
N-body simulations with self-interactions and baryons

Fry et al. (2015)

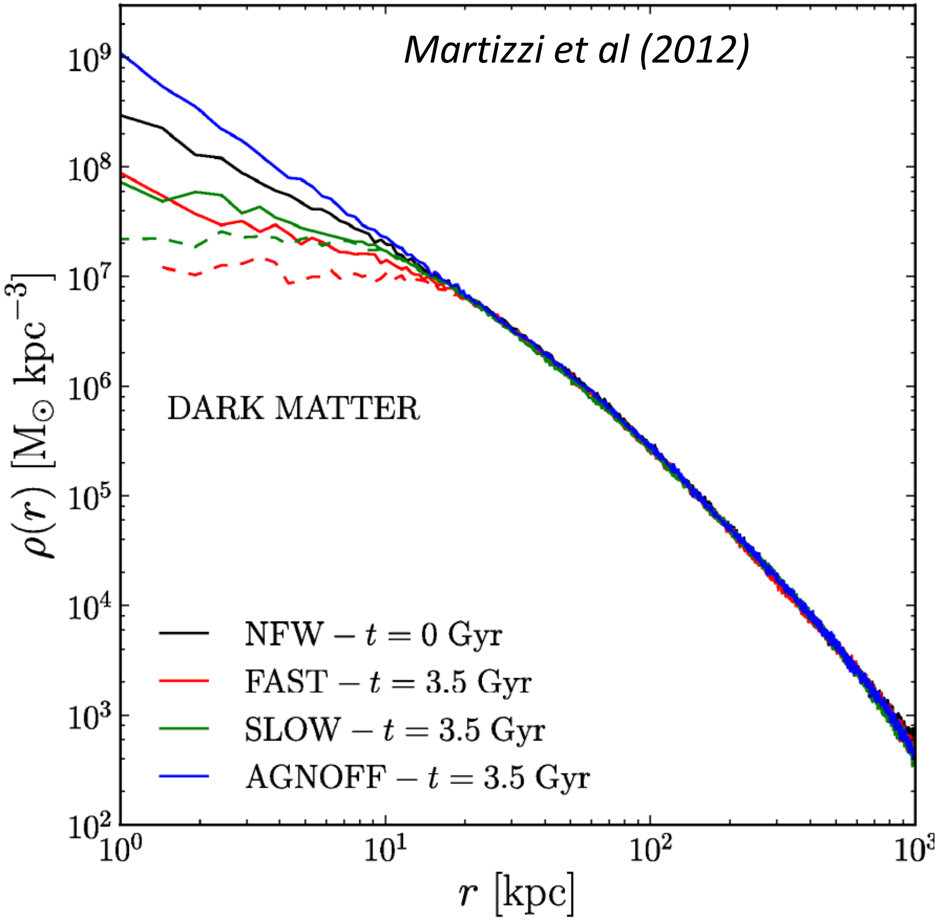


Bursty star formation

Pontzen & Governato (2011)



AGN feedback in clusters

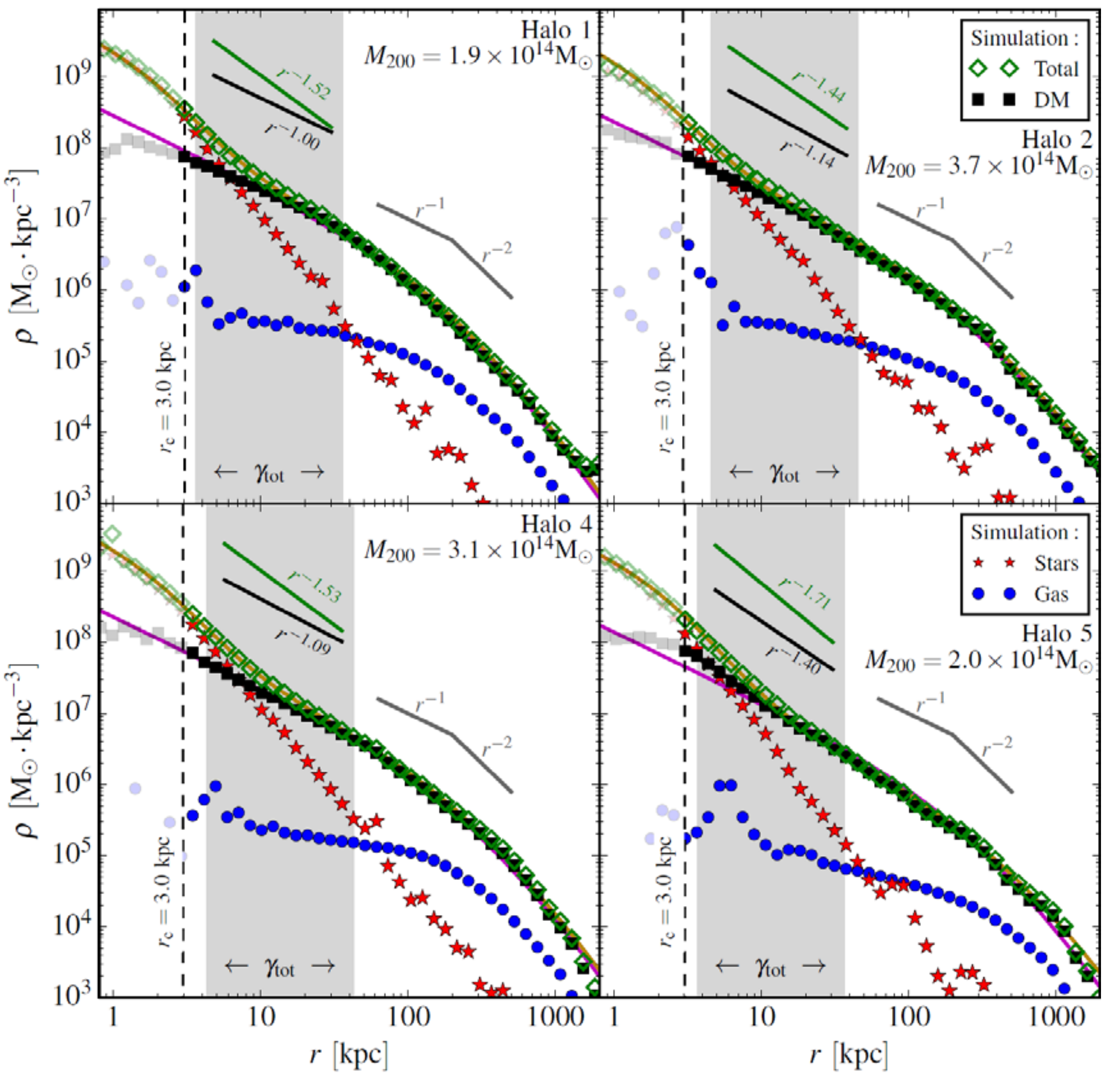


Start with isolated cluster halo and let some H gas clouds fall in

Feedback leads to a core from initial NFW halo

No feedback makes DM halo steeper (adiabatic contraction)

AGN feedback in clusters



Schaller et al (2014)

Cosmological simulations (EAGLE) of cluster halos

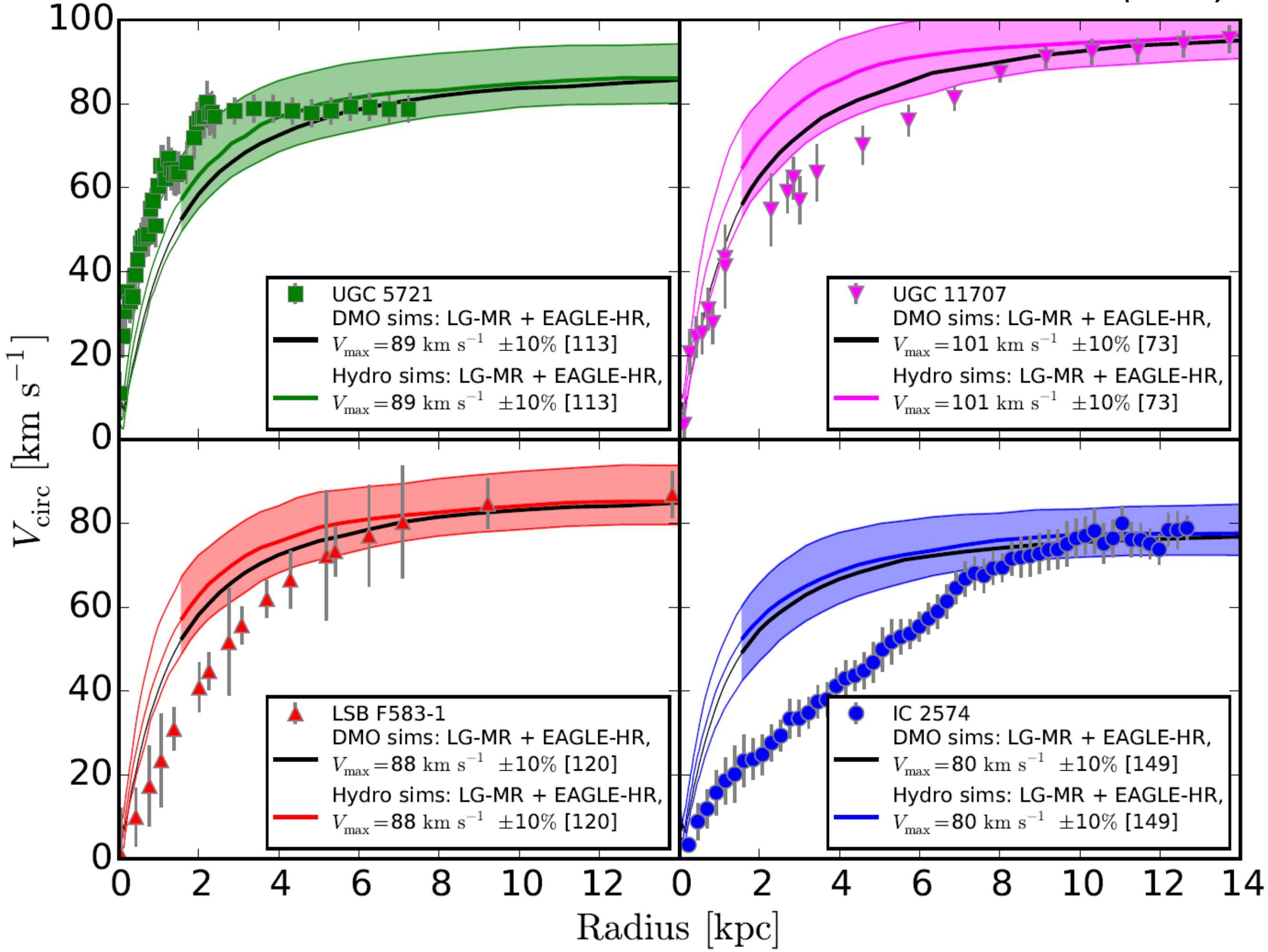
Feedback **does not** form dark matter cores

Does baryonic feedback solve all problems?

Some open questions…

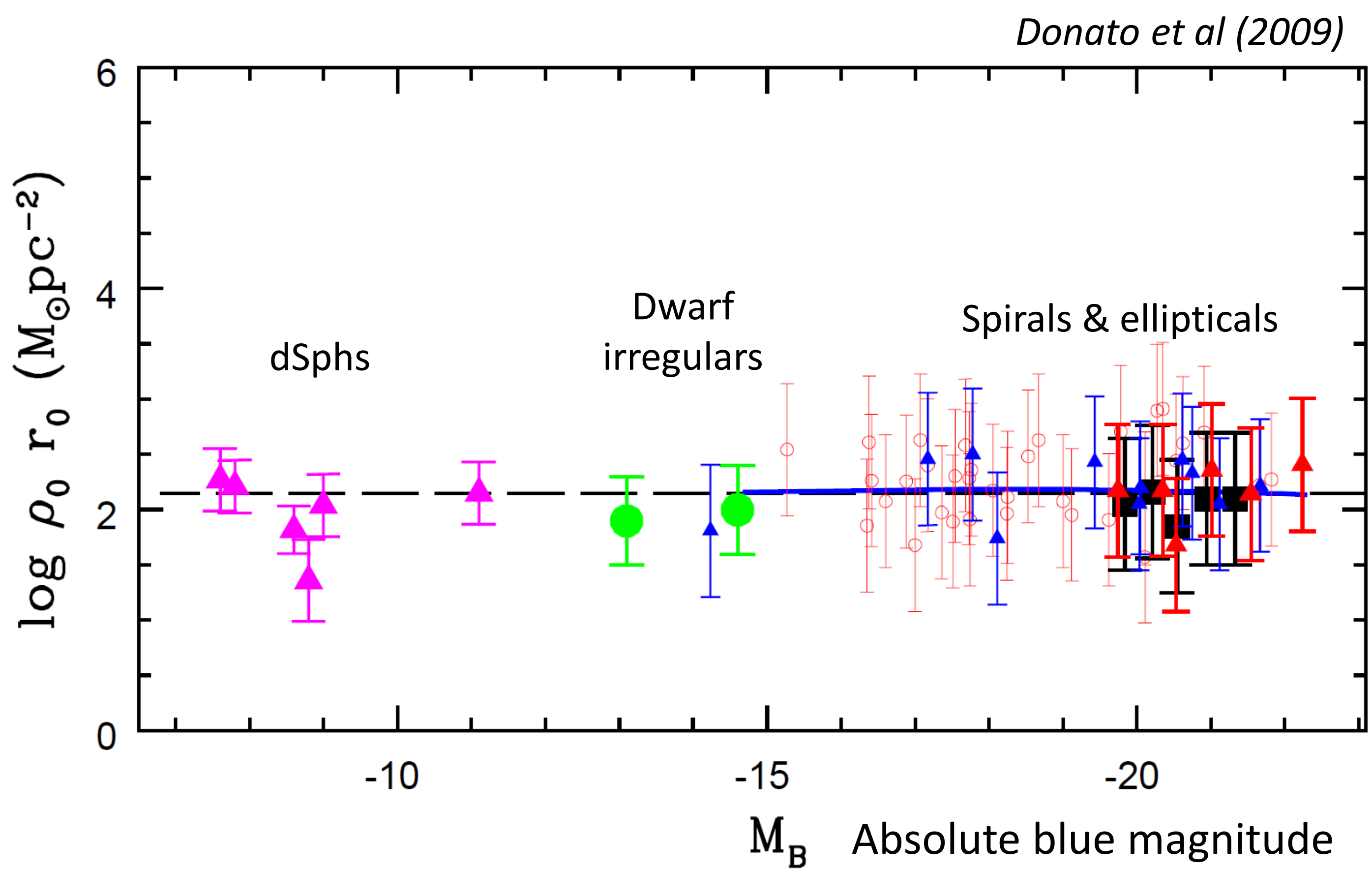
Diversity problem

Oman et al (2015)



Similar mass halos can have very different core sizes

Uniformity problem



Central density x core radius = const

If feedback or self-interactions solves small scale issues, must address both the diversity and uniformity of galaxies

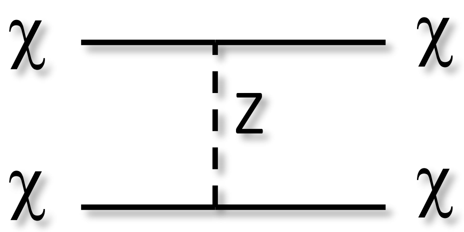
From astrophysics to particle physics

If dark matter is self-interaction, what are the particle physics implications?

Some notation: χ or X = dark matter particle

From astrophysics to particle physics

WIMPs have self-interactions (weak interaction)



self-interaction

χ = dark matter (e.g. SUSY particle)

Z boson = mediator particle

Cross section:

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

Mass:

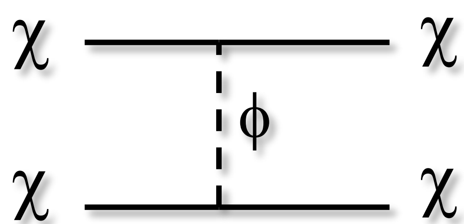
$$m_\chi \sim m_Z \sim 100\ \mathrm{GeV}$$

WIMP self-interaction cross section is way too small

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

From astrophysics to particle physics

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



self-interaction

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

Mediator mass below than weak scale

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

Self-interactions require new dark mediator below 1 GeV.

Other models: dark atoms, dark hadrons, SIMPs, ϕ^4-theory…

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.

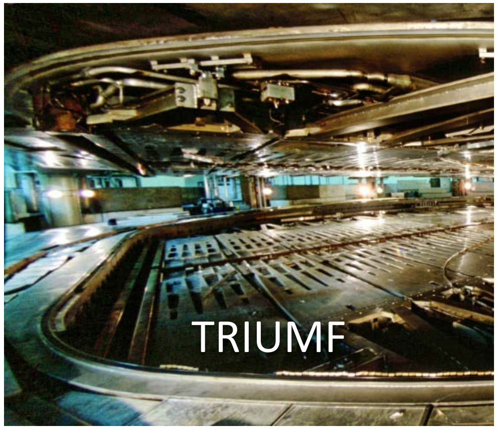
Different halos are complementary

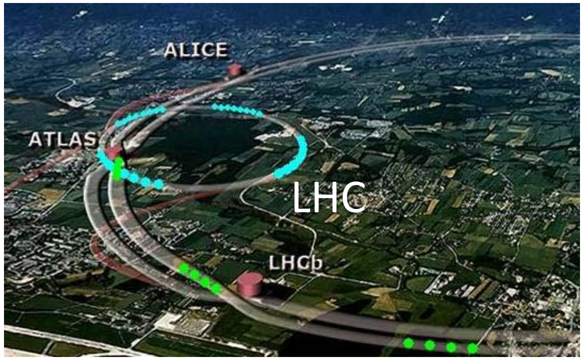
Low energies
(v/c ~ 10^{-4})

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

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

Like a different particle physics collider with a different beam energy



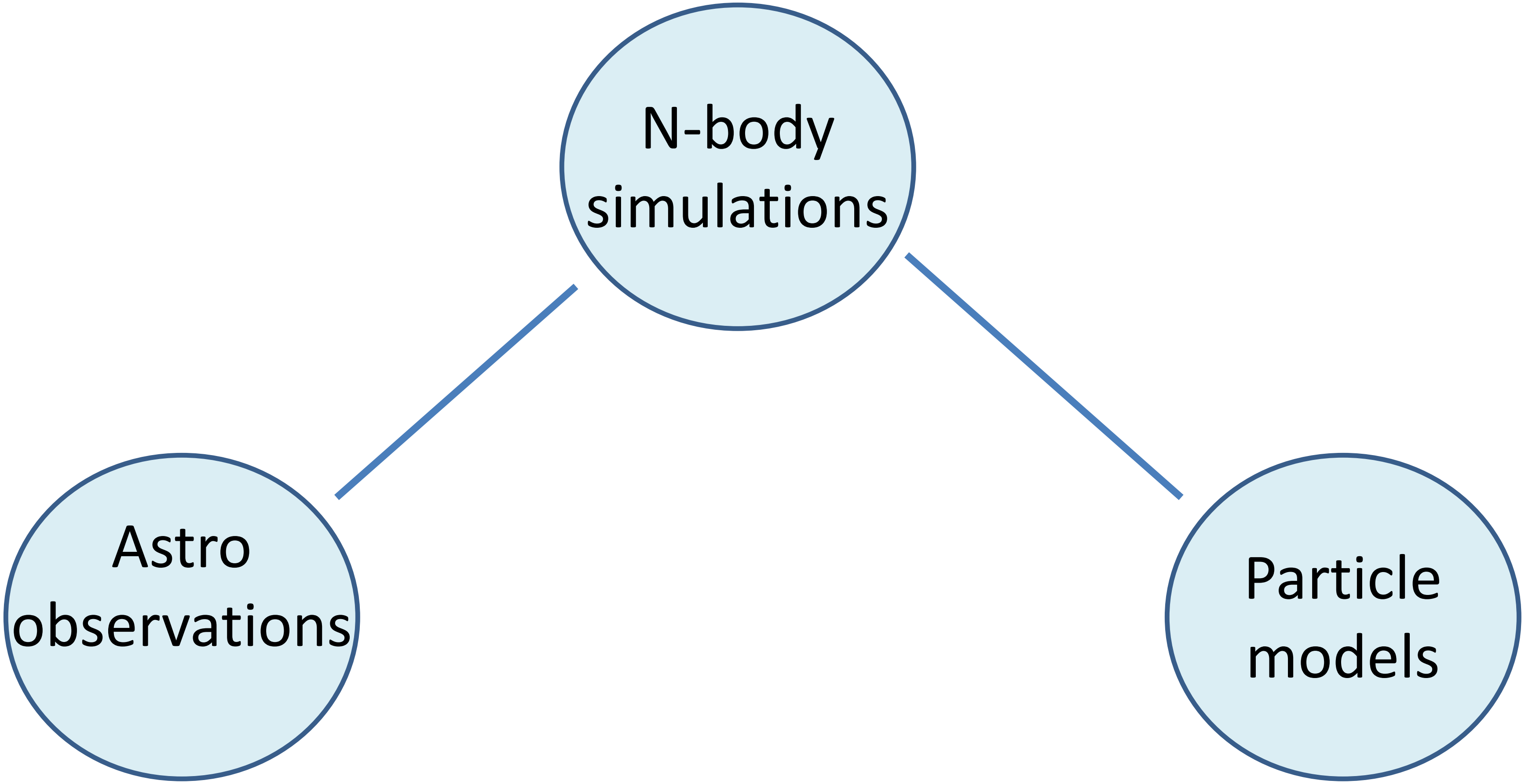


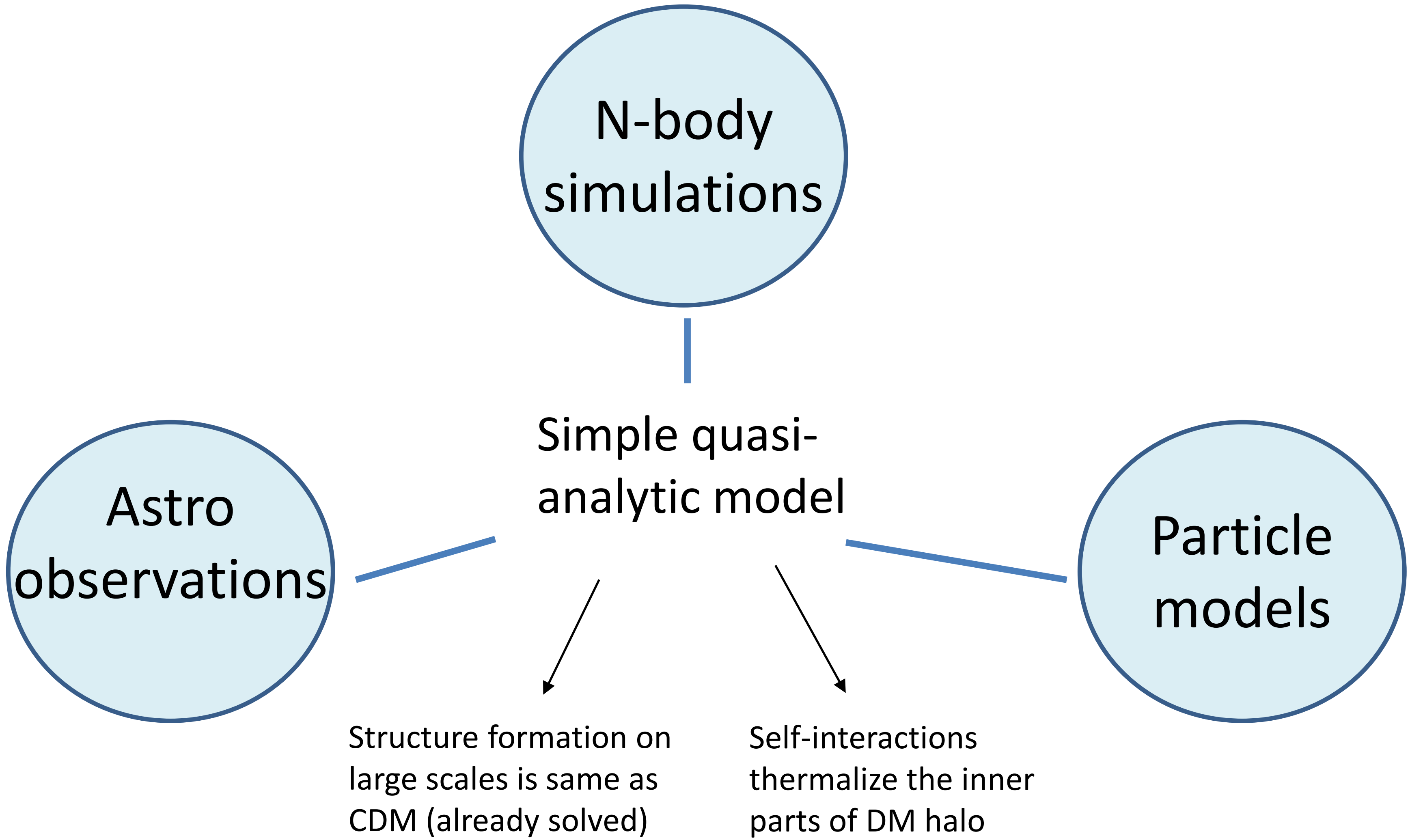
Does SIDM explain all cores?

- 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?

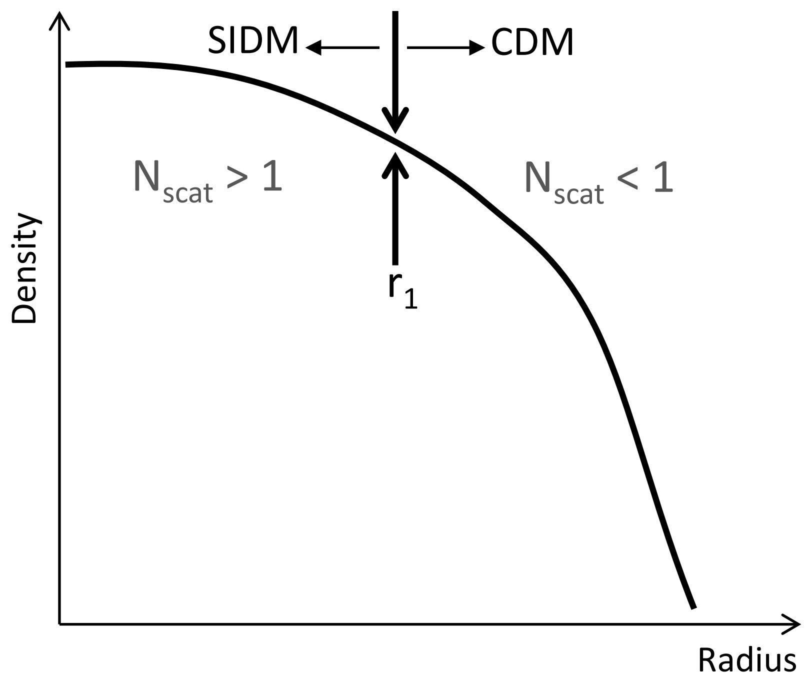
Kaplinghat, ST, Yu (2015)


N-body simulations
Astro observations
Particle models


N-body simulations
Simple quasi-analytic model
Astro observations
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

Self-interactions only affect the inner halo where density is highest
Expect there is a transition radius r_1 between SIDM profile and NFW profile

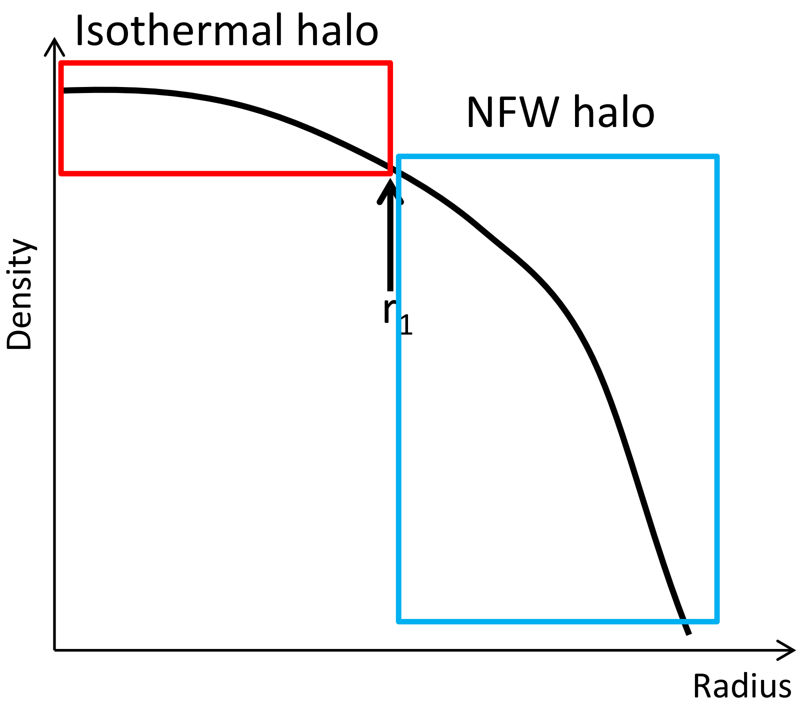


Inner halo ($r < r_1$): expect DM to be thermalized

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

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

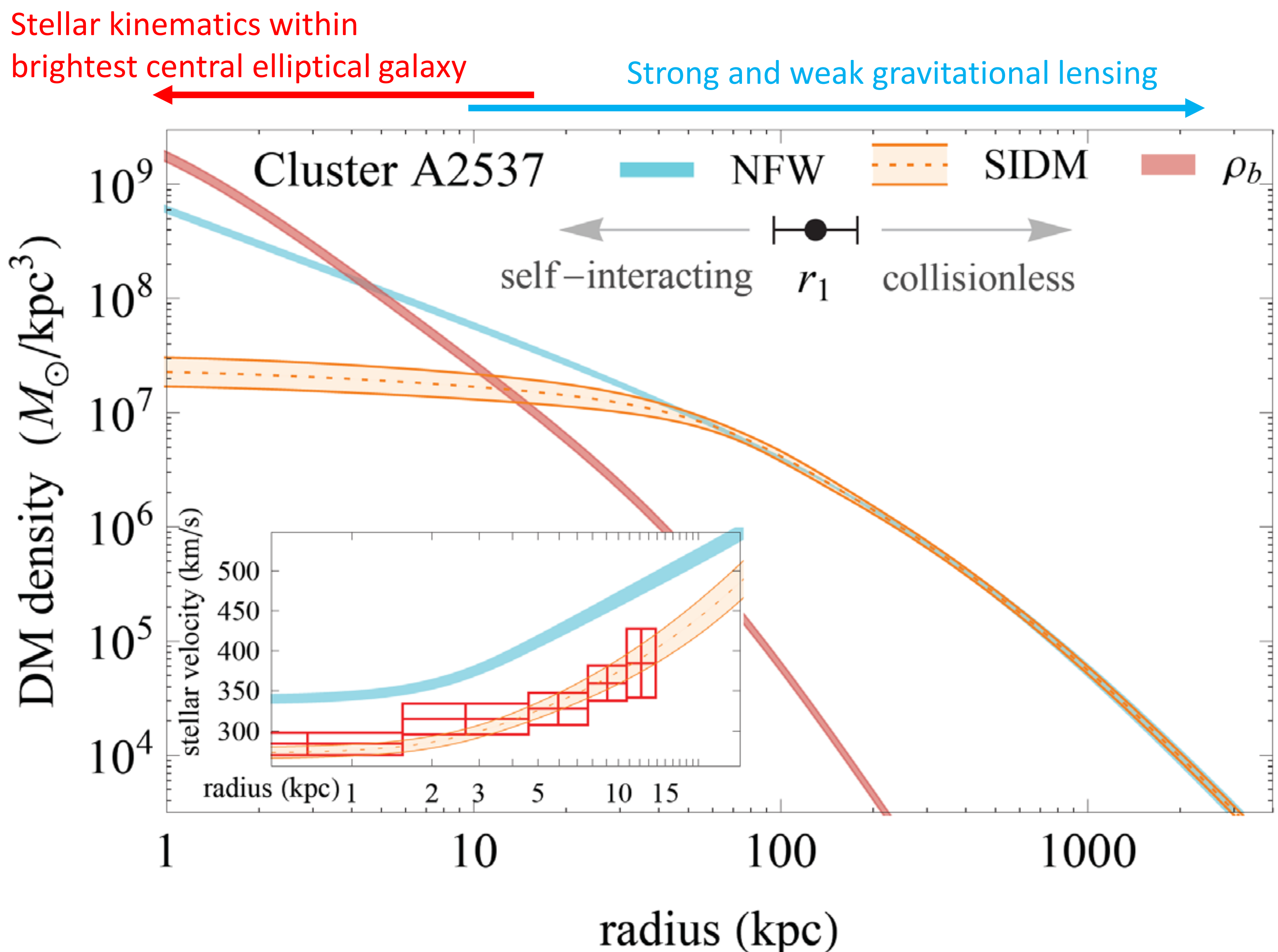
Outer region: NFW halo (CDM)

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



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)

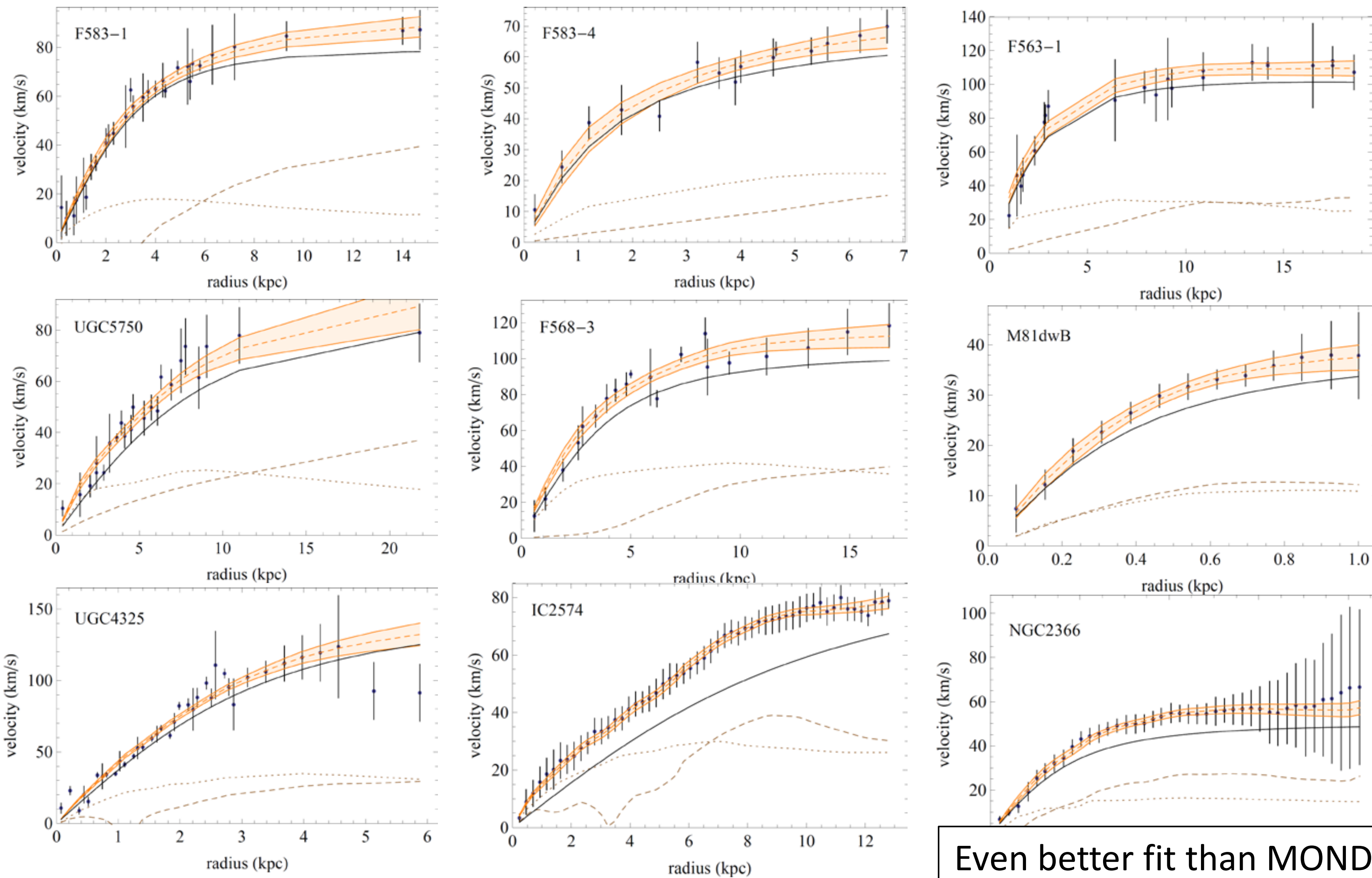
Rotation curves + assumption no core collapse

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})

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

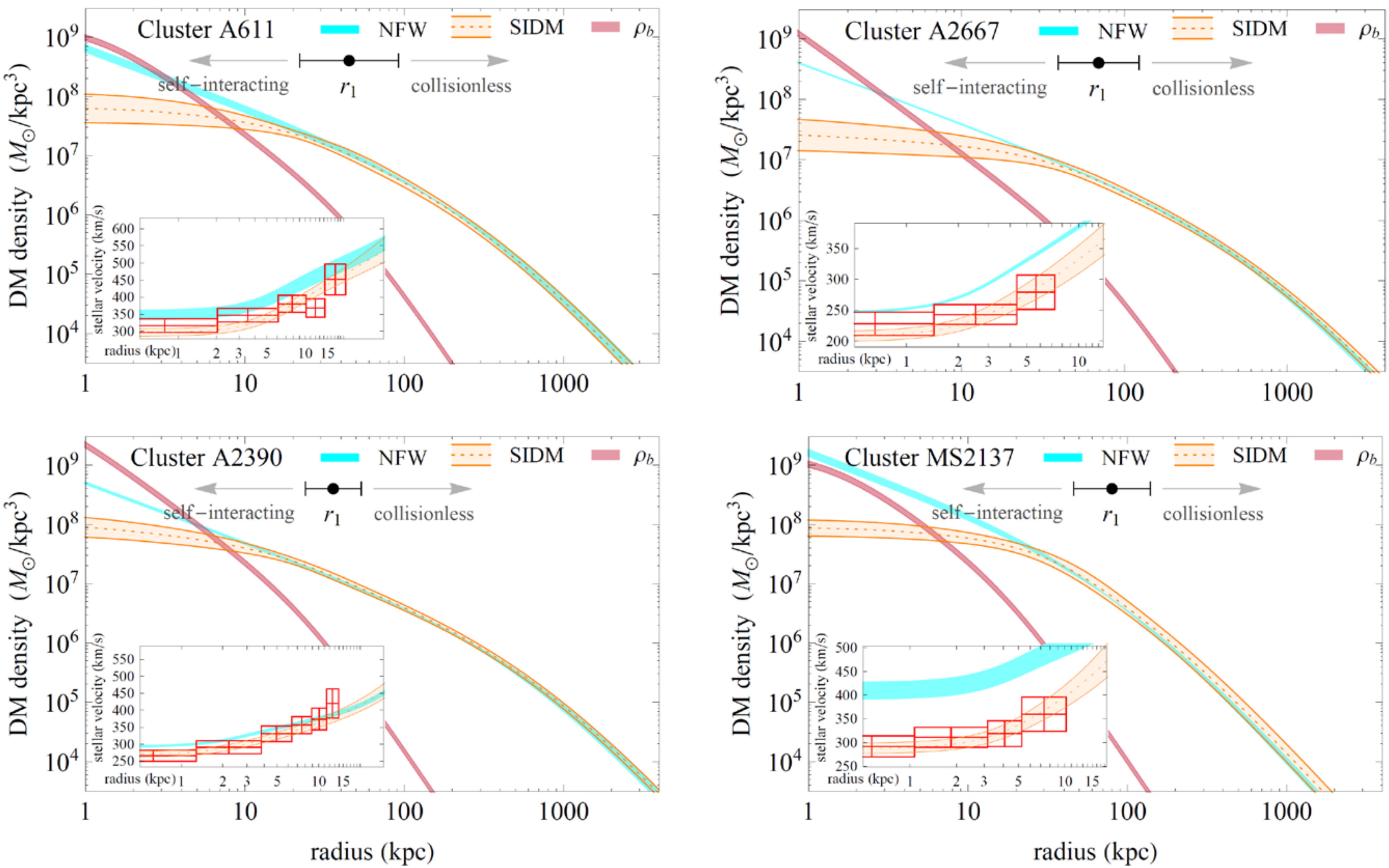
Instead of σ/m, we consider velocity-weighted cross section averaged over halo velocities

Galaxy rotation curves for SIDM

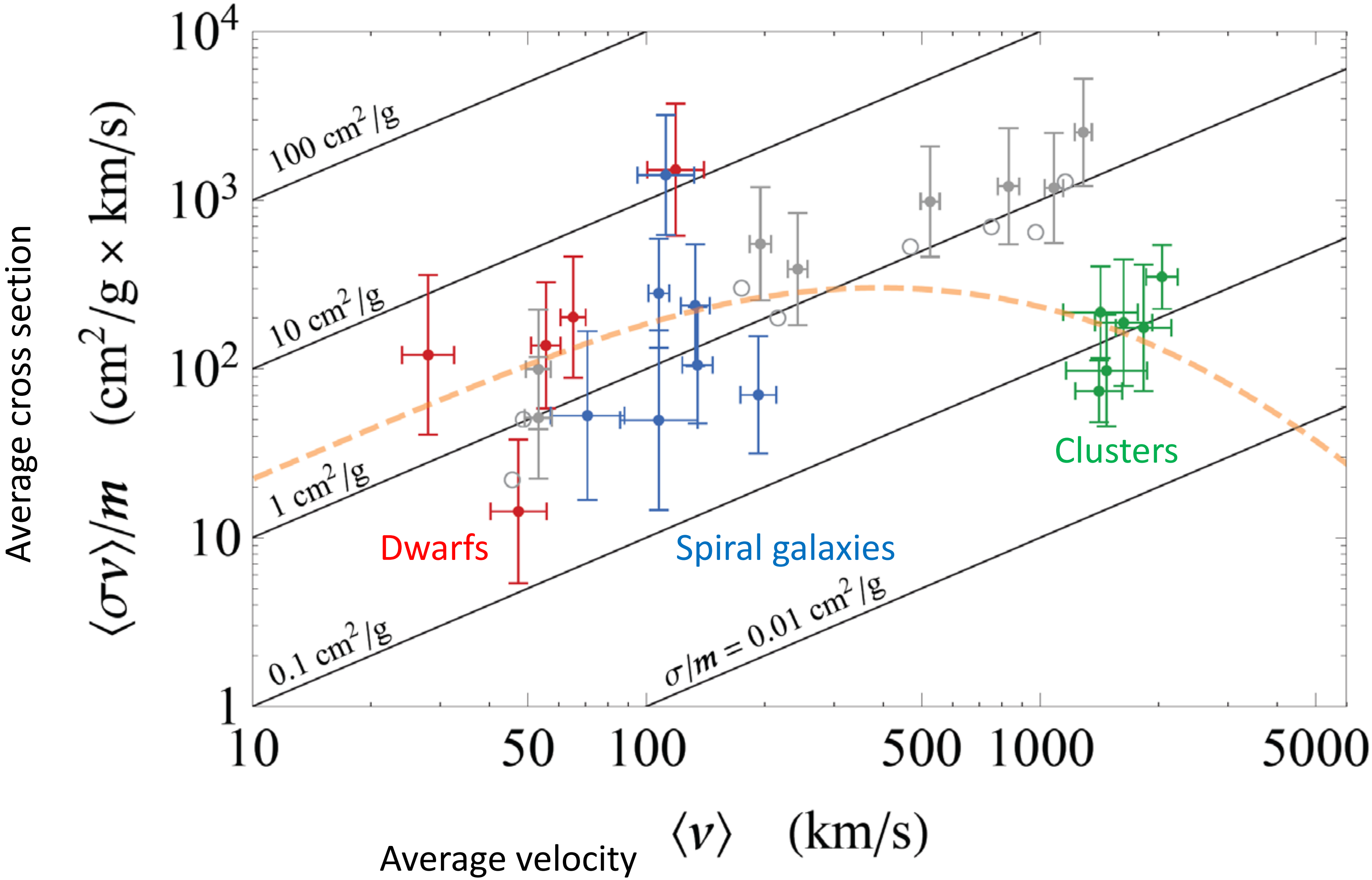


Even better fit than MOND

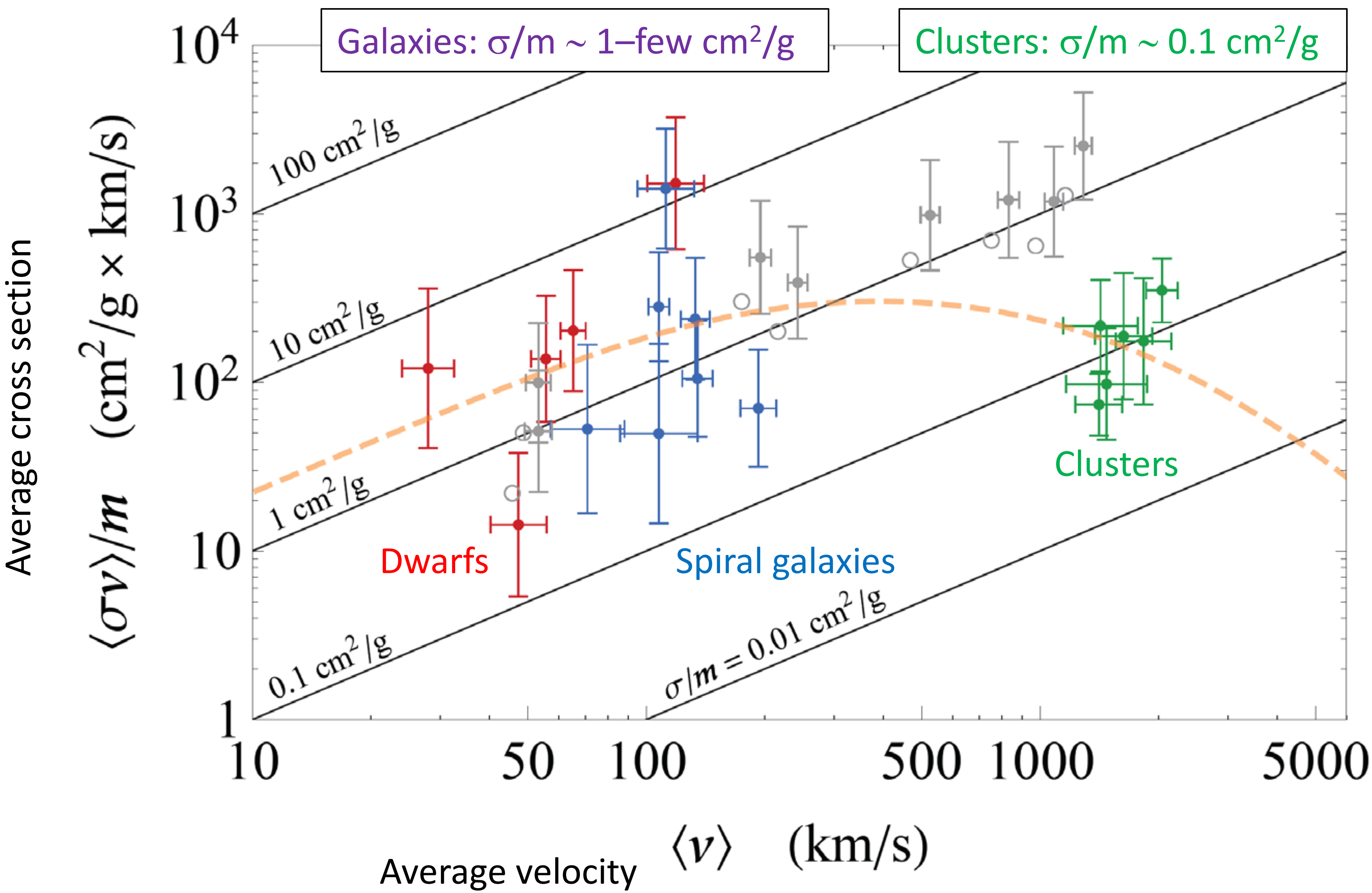
More SIDM fits to clusters



SIDM fits to dwarfs, LSBs, and clusters



SIDM fits to dwarfs, LSBs, and clusters



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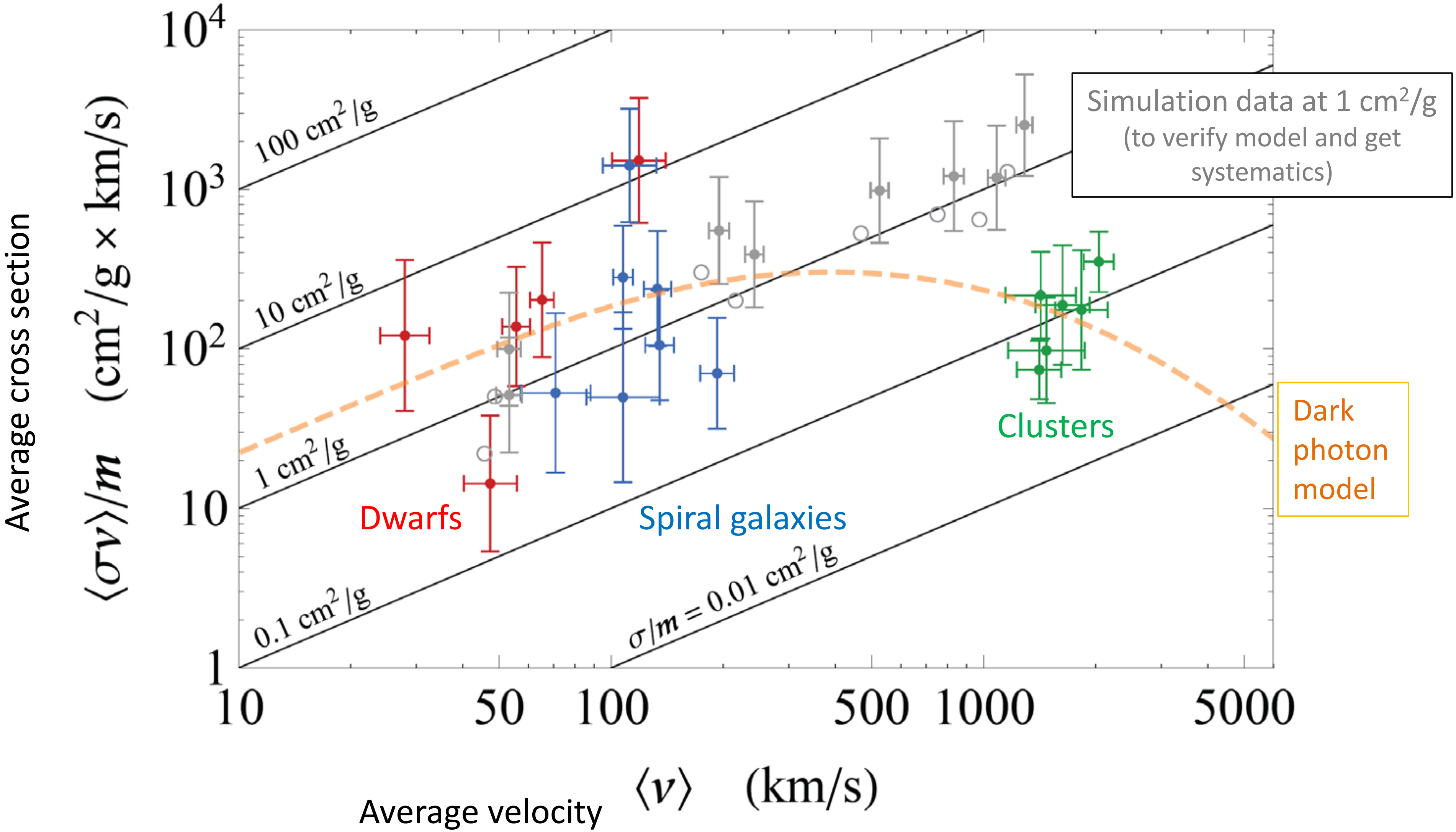


SIDM fits to dwarfs, LSBs, and clusters

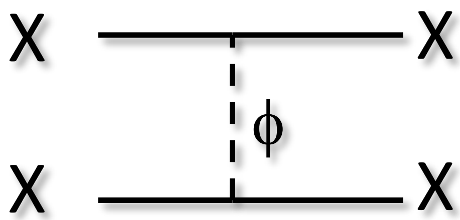
New constraints from clusters are very important

Constant cross section (contact interactions) is disfavored

Velocity-dependent self-interactions are preferred

1 – few cm^2/g in dwarf galaxies and **0.1 cm^2/g** in clusters

Dark photon model



DM particle X + vector boson ϕ

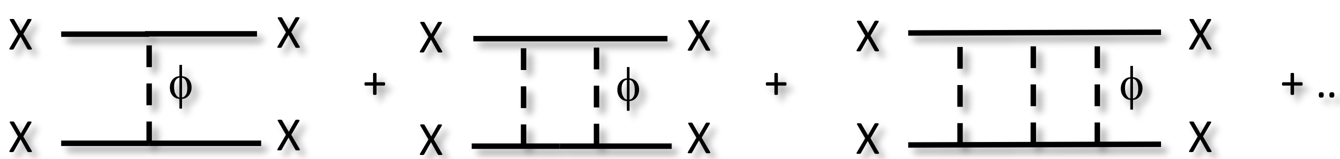
Only three parameters: DM mass, ϕ mass, coupling α'

DM self-interaction cross section

- Nonperturbative calculation

Buckley & Fox (2009),
ST, H.-B. Yu, K. Zurek (2012 + 2013)

  – Similar to Sommerfeld enhancement for annihilation



  – Equivalent to solving the Schrodinger equation
    - Yukawa potential $V(r) = \pm \frac{\alpha_X}{r} e^{-m_\phi r}$
    - Compute phase shifts $\frac{d\sigma}{d\Omega} = \frac{1}{k^2} \left| \sum_{\ell=0}^{\infty} (2\ell+1) e^{i\delta_\ell} P_\ell(\cos\theta) \sin\delta_\ell \right|^2$
    - Transfer cross section $\sigma_T \equiv \int d\Omega \, (1 - \cos\theta) \, d\sigma / d\Omega$

Comparison to previous work

M. Buckley & P. Fox (2009)

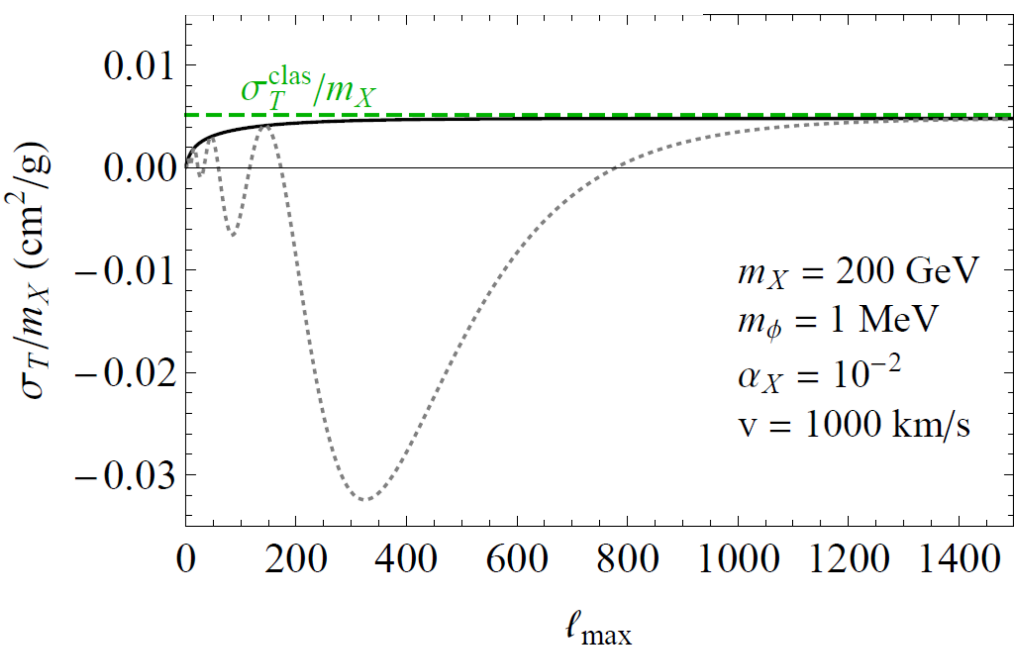
1. More efficient method for matching onto asymptotic solution of Bessel functions, not sines (B&F had $\ell_{max} = 5$)
2. More efficient formula for summing partial waves

$$\sigma_T = \frac{4\pi}{k^2}\sum_{\ell=0}^{\infty \to \ell_{max}}\left[(2\ell+1)\sin^2\delta_\ell - 2(\ell+1)\sin\delta_\ell\sin\delta_{\ell+1}\cos(\delta_{\ell+1}-\delta_\ell)\right]$$

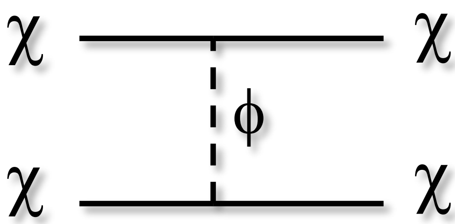
Buckley & Fox 2009

$$\sigma_T = \frac{4\pi}{k^2}\sum_{\ell=0}^{\infty \to \ell_{max}}(\ell+1)\sin^2(\delta_{\ell+1}-\delta_\ell)$$

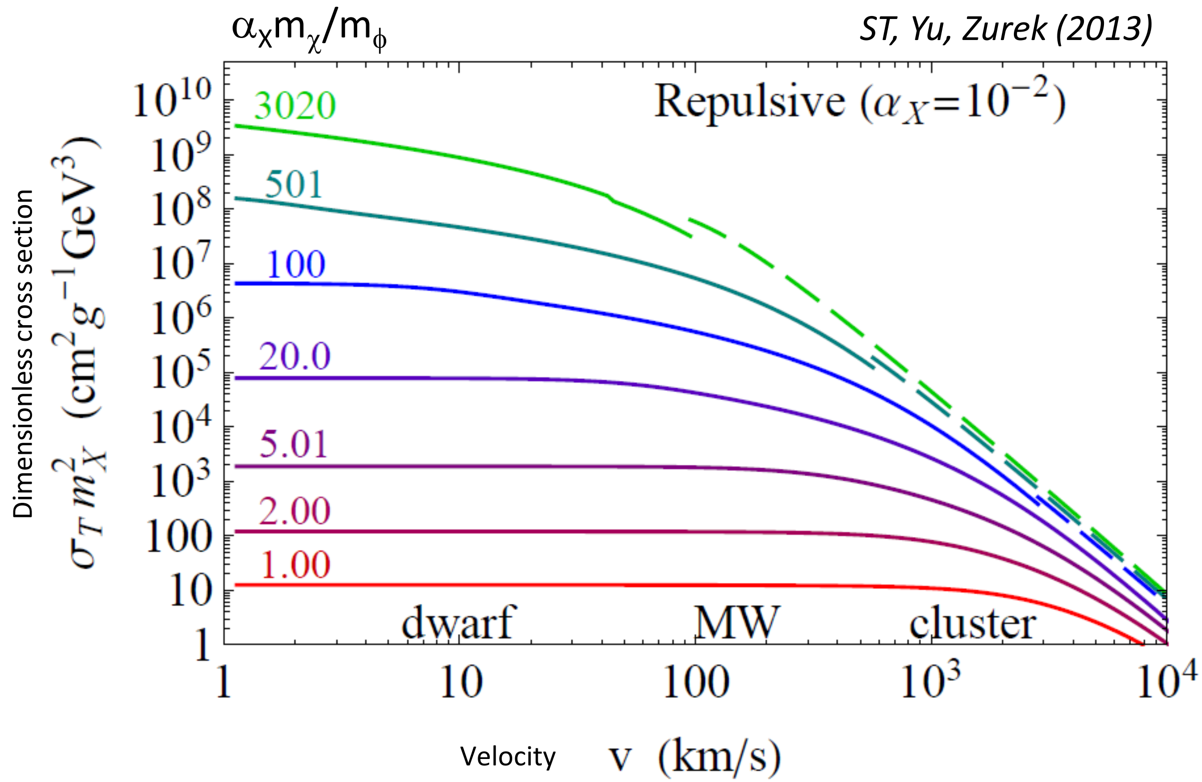
ST, H.-B. Yu, K. Zurek (2013)



Asymmetric DM with dark photon

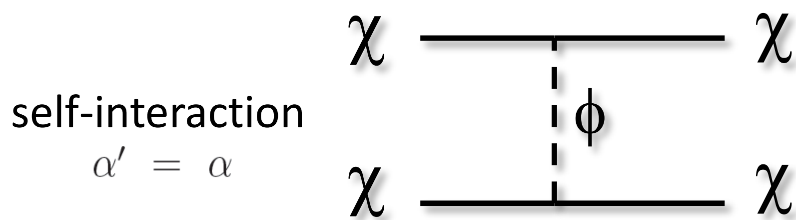


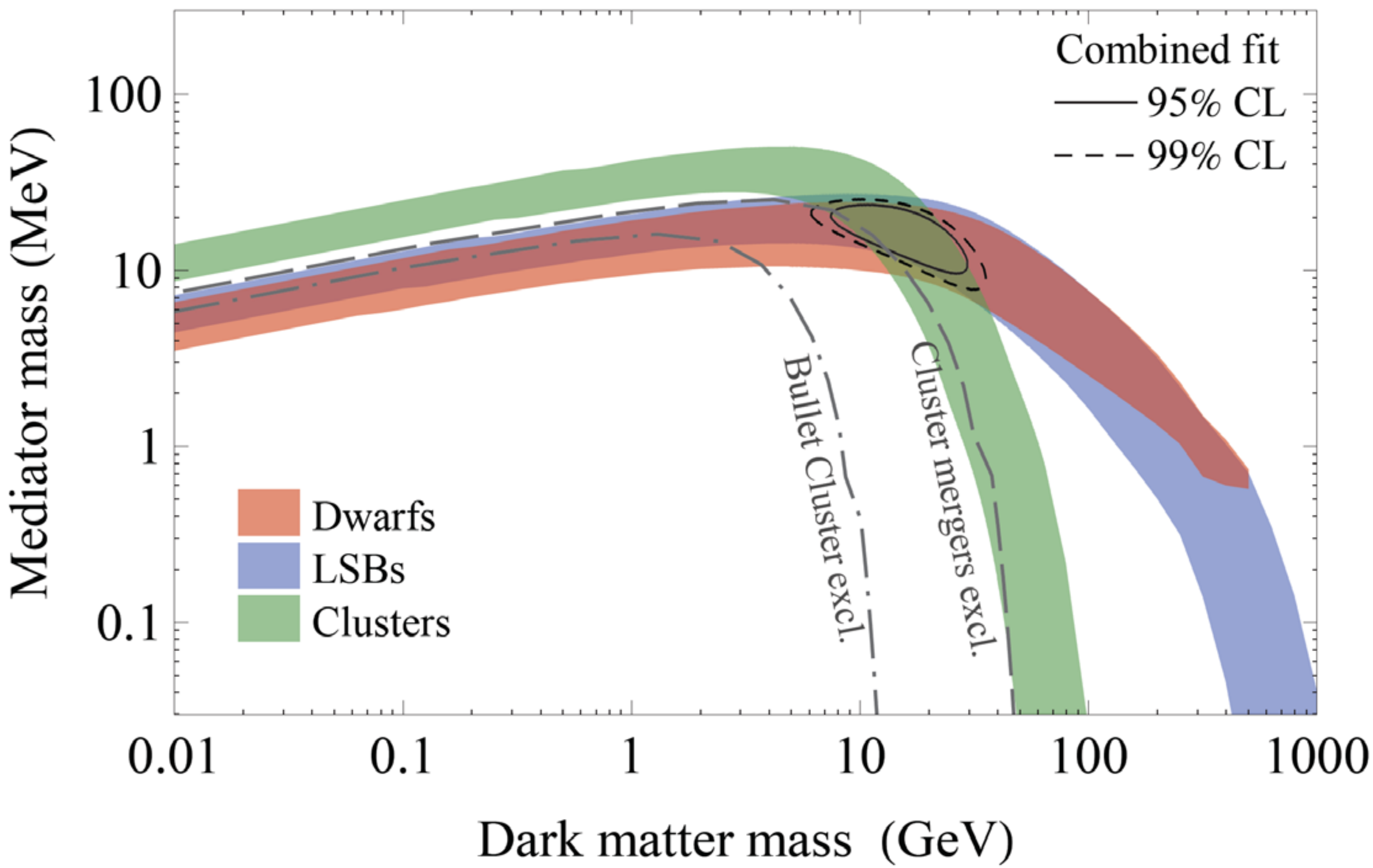
self-interaction



Want $\sigma/m \sim 1\ cm^2/g$ on galaxy scales, $0.1\ cm^2/g$ on cluster scales

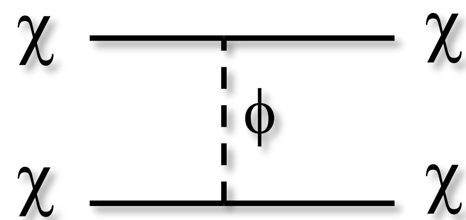
Asymmetric DM with dark photon

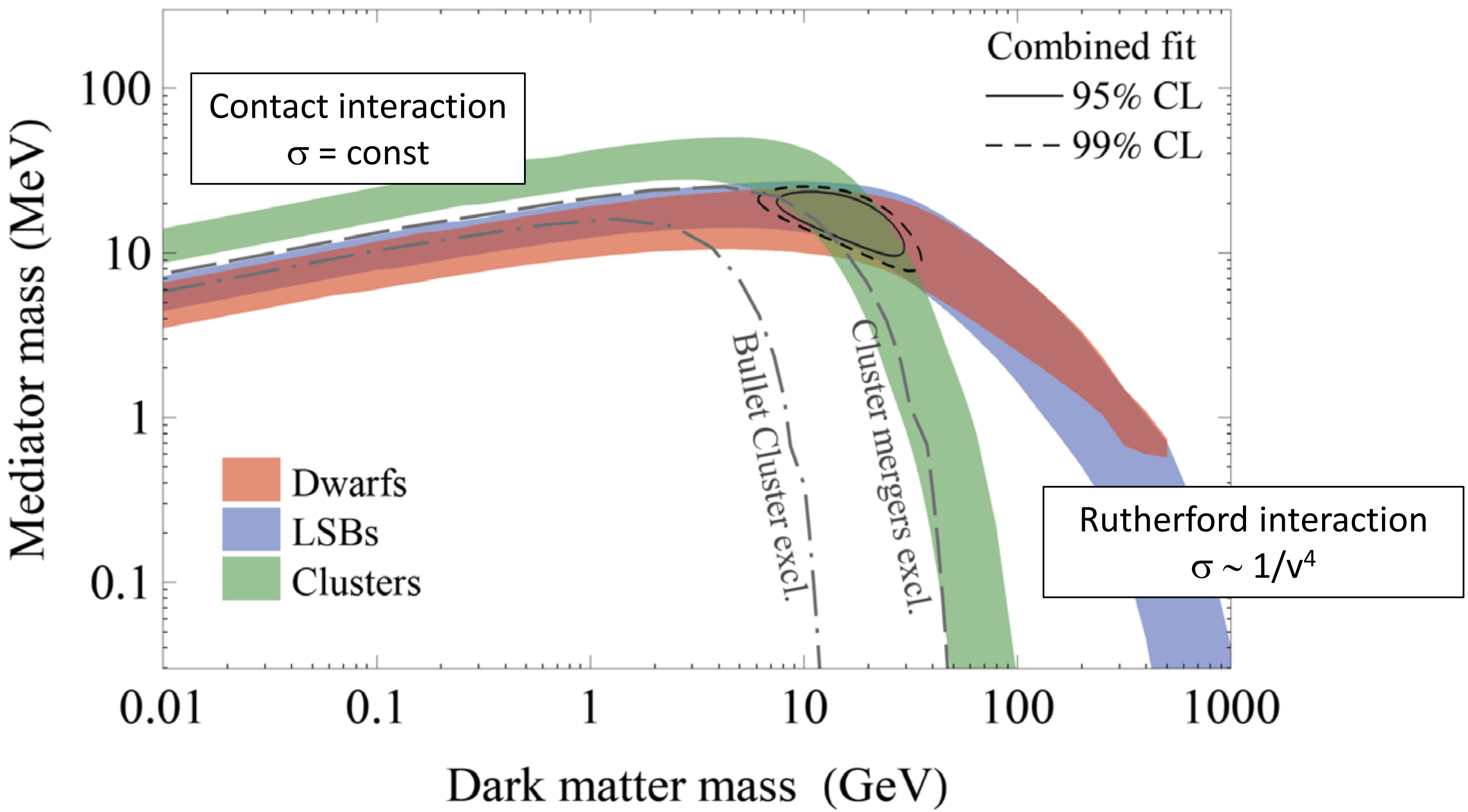




Asymmetric DM with dark photon

self-interaction
$\alpha' = \alpha$





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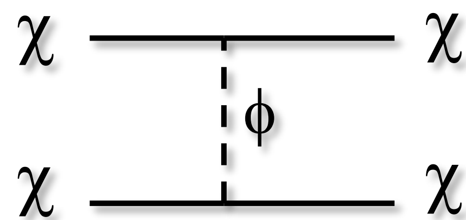
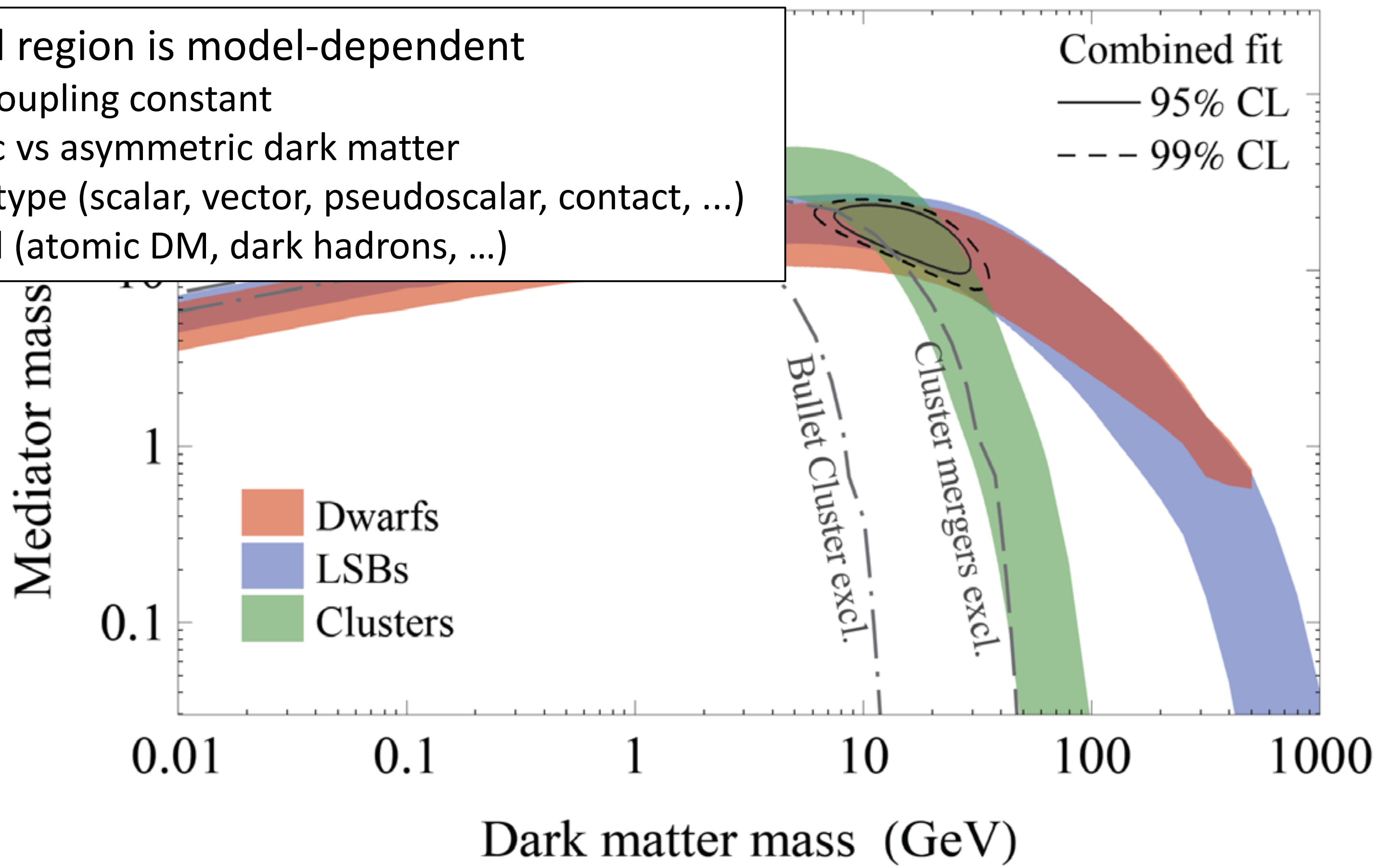
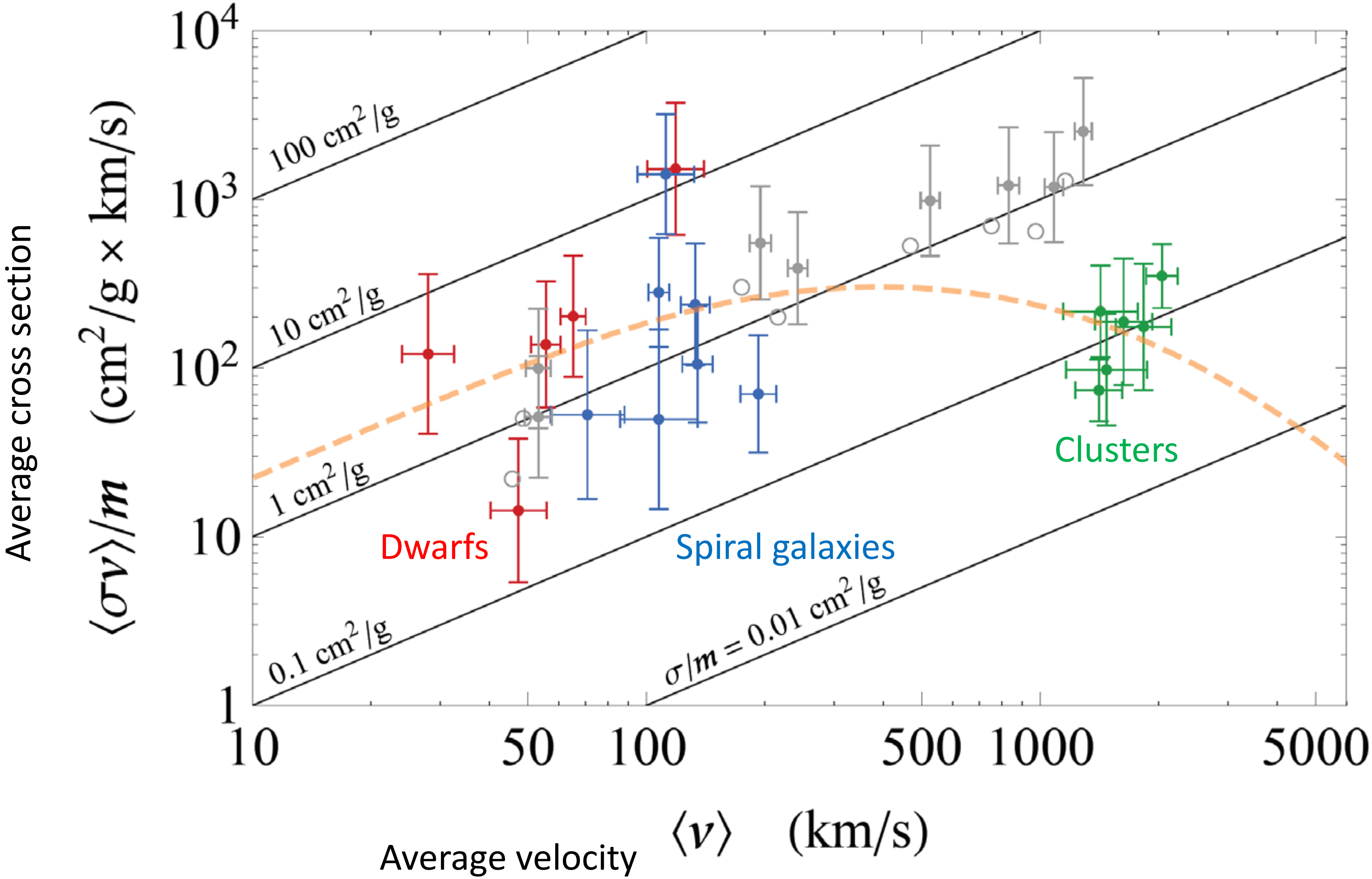


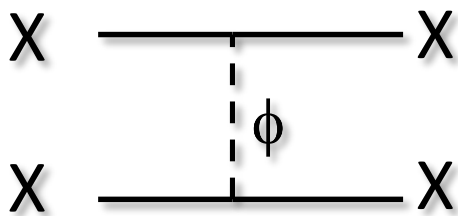
Preferred region is model-dependent
α'= dark coupling constant
Symmetric vs asymmetric dark matter
Mediator type (scalar, vector, pseudoscalar, contact, ...)
DM model (atomic DM, dark hadrons, …)



SIDM fits to dwarfs, LSBs, and clusters



Self-interacting dark matter paradigm

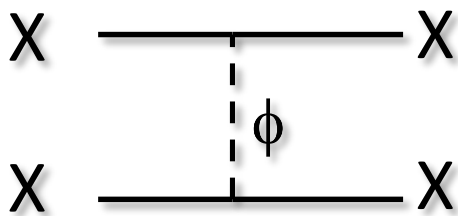


Self-interactions

DM particle X + mediator particle ϕ

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

Self-interacting dark matter paradigm



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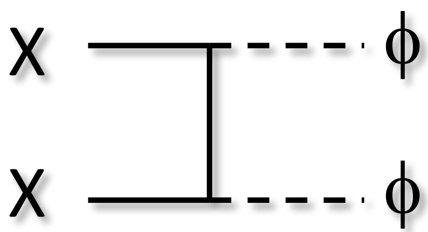
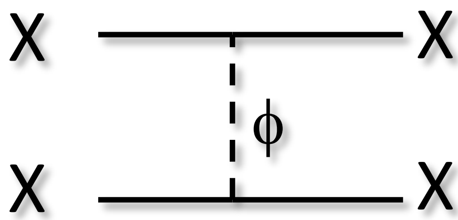


Annihilation

Set relic density
via freeze-out

Self-interacting dark matter paradigm



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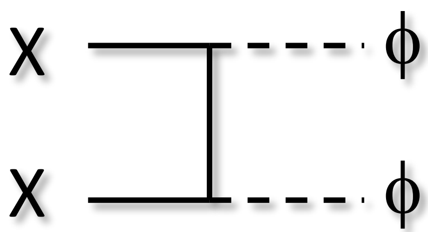


Annihilation

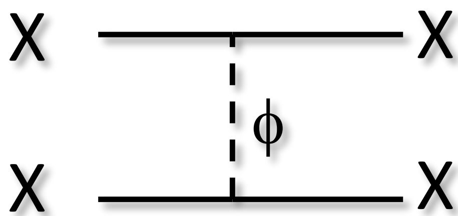
Set relic density via freeze-out

$\phi \longrightarrow$ SM

Decay

(Deplete ϕ density)

Self-interacting dark matter paradigm



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DM particle X + mediator particle ϕ

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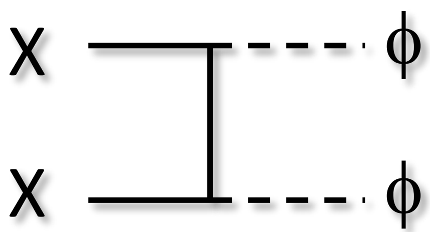

Annihilation

Set relic density via freeze-out

$\phi \longrightarrow \text{SM}$

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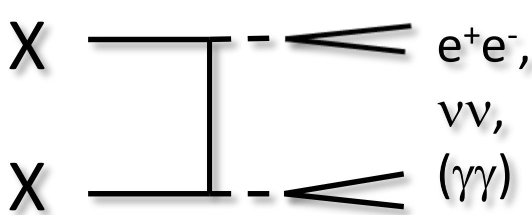
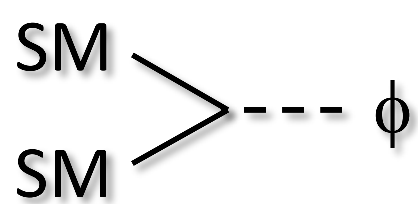
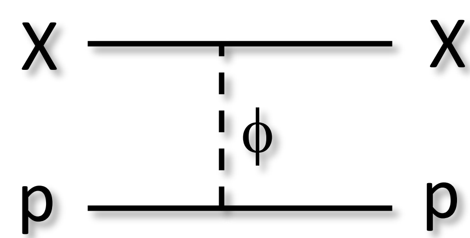


Indirect detection



Dark photon searches

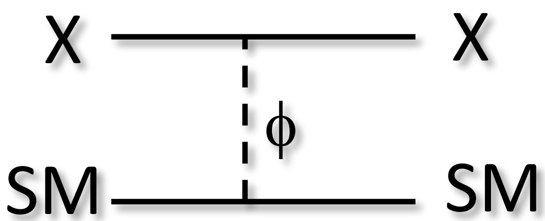


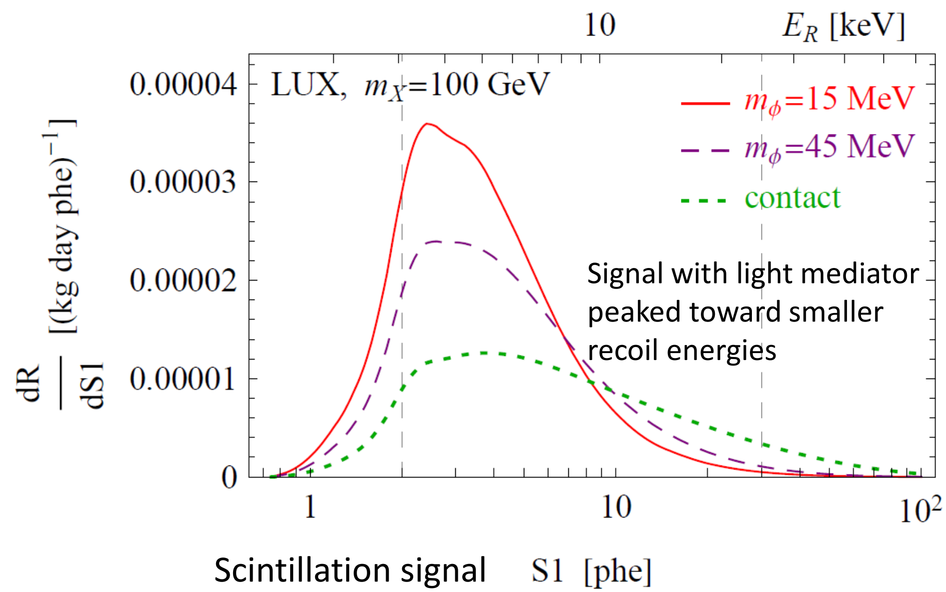
Direct detection

Capture in sun/earth

Direct detection

Kaplinghat, Tulin, Yu (2013); Del Nobile et al (2015)





Nontrivial feature of SIDM: mediator mass m_ϕ^2 can be comparable to q^2

m_X (GeV)	m_ϕ (MeV)	q_{Xe} (MeV)	q_{Ge} (MeV)
1000	3	127	74
100	15	62	46
10	20	10	10
5	20	5	5

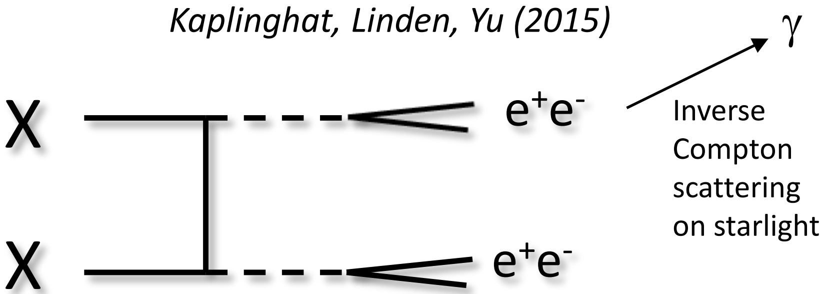
Typical momentum transfer for Xenon/Germanium

Combination of total rate + annual modulation can distinguish SIDM from WIMPs

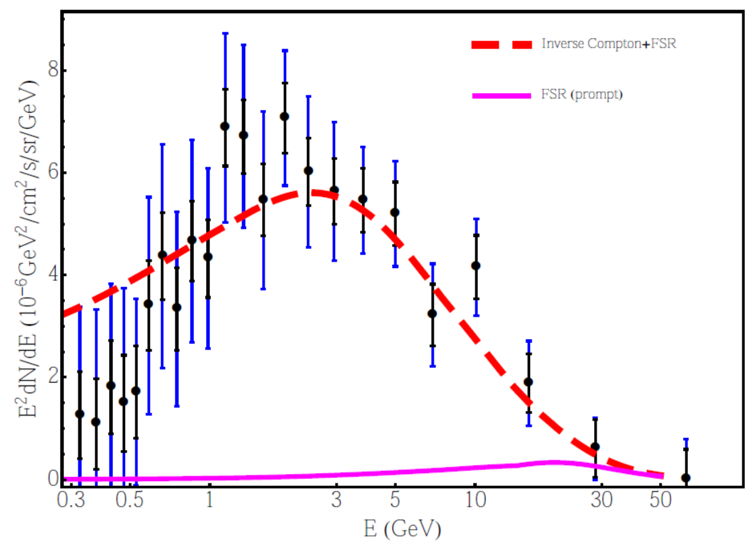
Indirect detection

Annihilation & galactic center excess

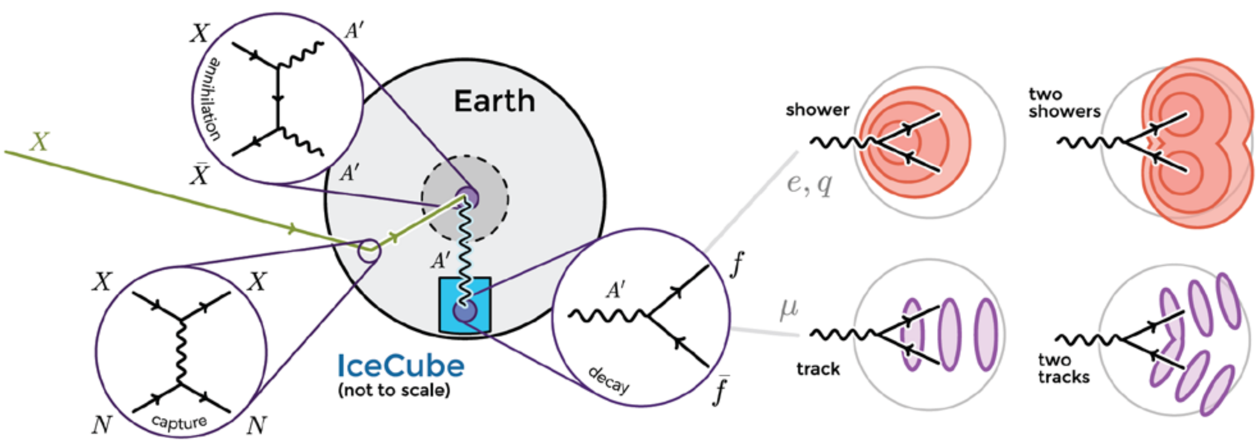
Kaplinghat, Linden, Yu (2015)



γ-ray signal from 50 GeV DM



Dark matter capture in the earth & IceCube signals from long-lived mediator decays



Feng, Smolinsky, Tanedo (2016)

Conclusions

- Small scale structure offers possibility to explore DM beyond WIMP paradigm *(even if decoupled from SM)*

- Jury still out on whether small scale issues are actually a problem

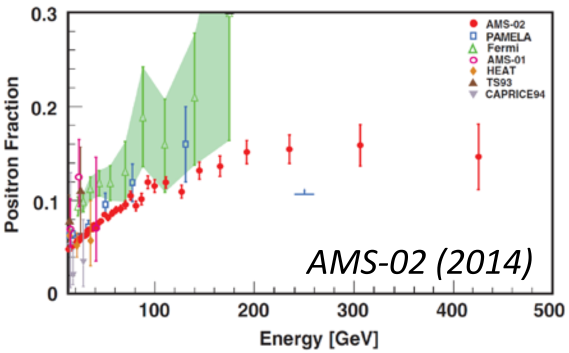
- If SIDM solves small scale issues in dwarfs, then velocity-independent cross section favored (new light mediators)

Conclusions

- Usual motivations for dark photons

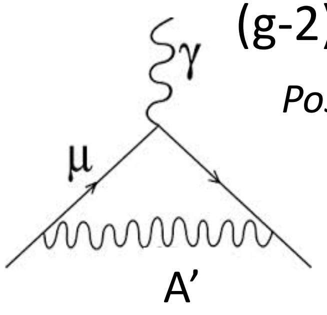
DM anomalies
Pamela/AMS-02
positron excess

Pospelov & Ritz (2008); Arkani-Hamed et al (2008)



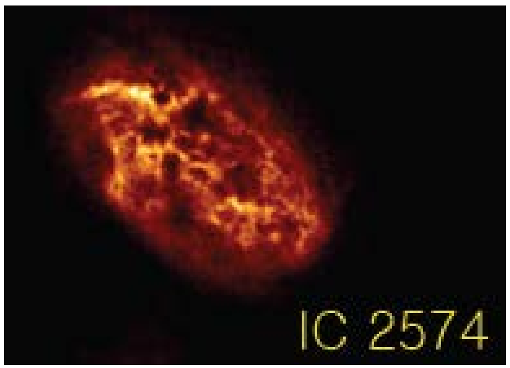
$(g\text{-}2)_\mu$ anomaly

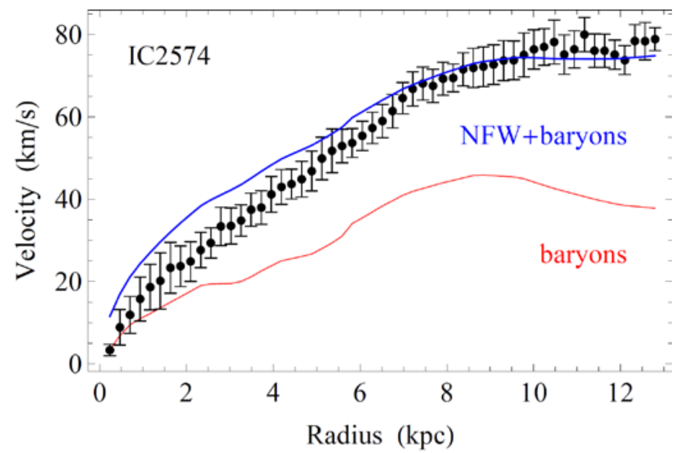
Pospelov (2008)

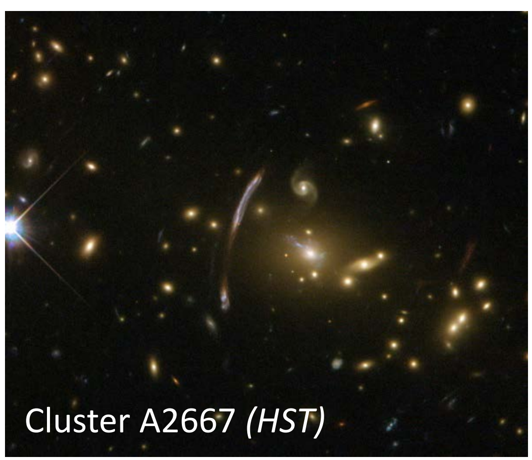


Conclusions

- Small scale structure issues are another motivation for sub-GeV dark physics (but doesn't say how it couples to SM)






Cluster A2667 *(HST)*