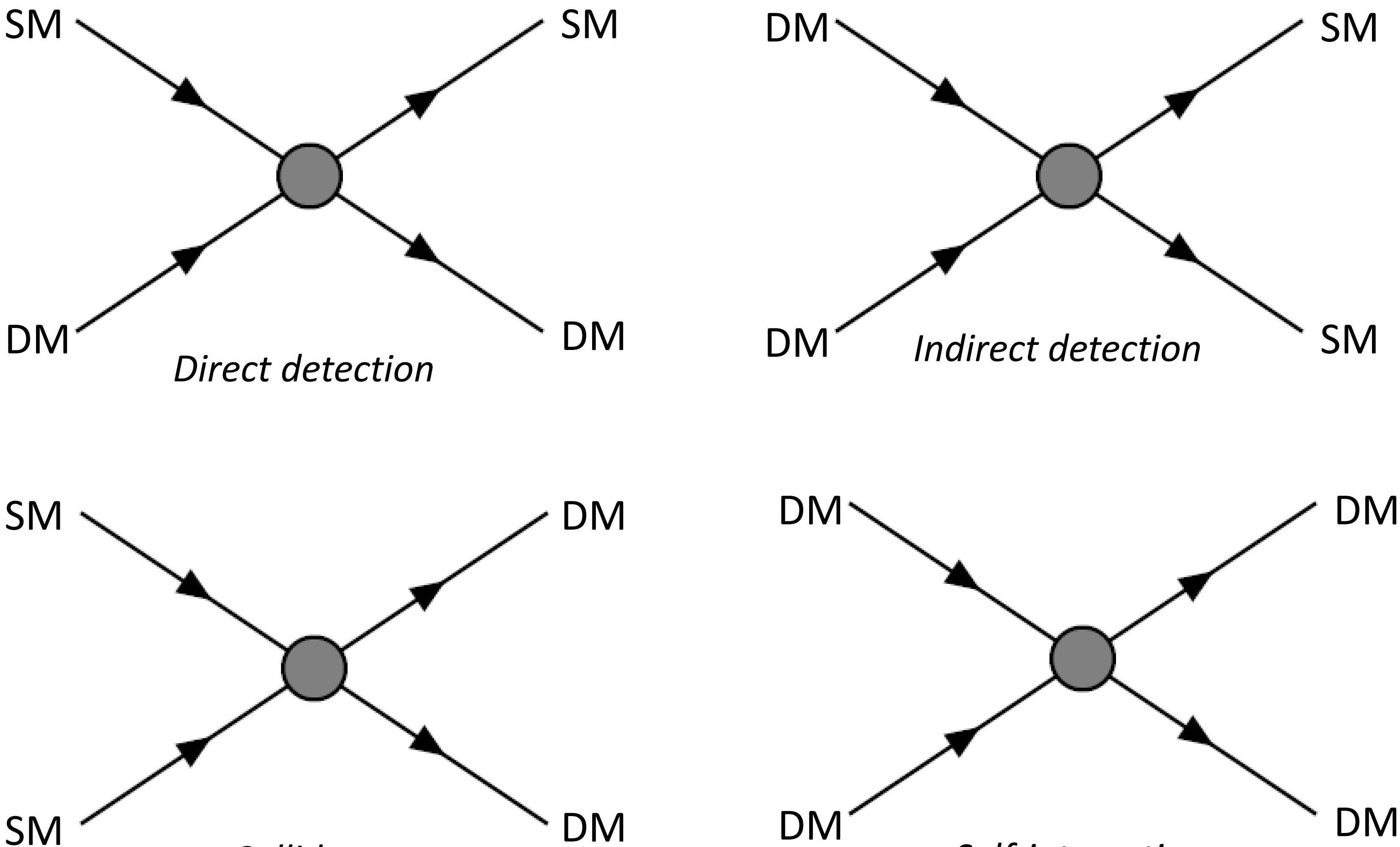
Self-interacting dark matter

Sean Tulin

YORK UNIVERSITÉ UNIVERSITY

Phys. Rep. review in prep. w/ Hai-Bo Yu

Exploring the dark sector



Direct detection

Indirect detection

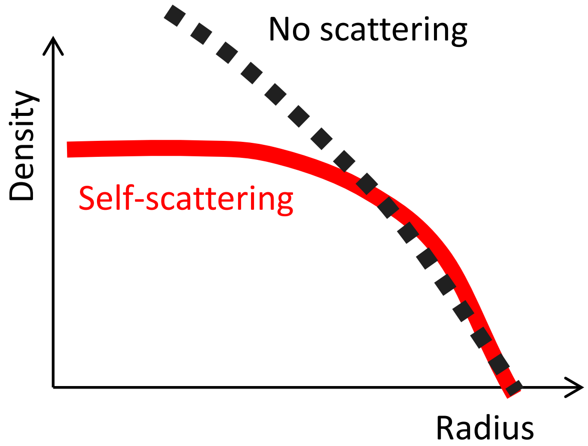
Colliders

Self-interactions

Beyond the collisionless paradigm

Cold collisionless DM

N-body simulations (DM-only) predict cuspy density profiles (NFW)



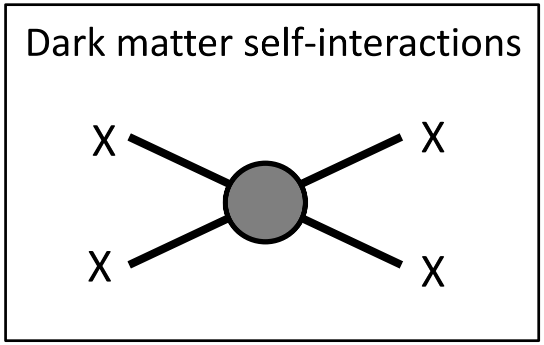
Particles get scattered out of dense halo centers

Self-interacting DM (SIDM)

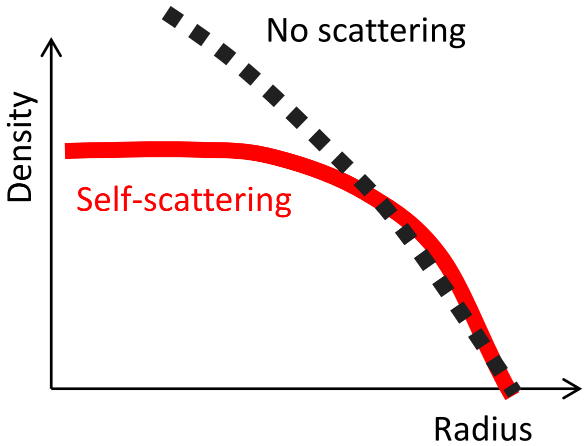
DM particles self-scatter in halos

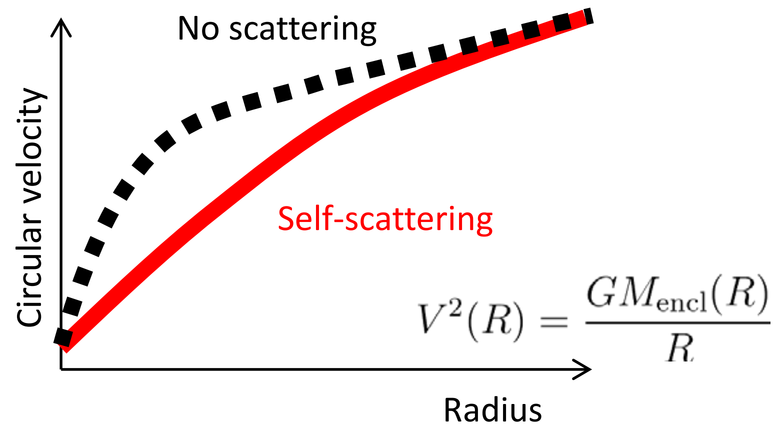
Density profiles become shallower (cored profiles)

Spergel & Steinhardt (2000)



Beyond the collisionless paradigm





Particles get scattered out of dense halo centers

Rotation curves reduced (apparent mass deficit in inner halo)

Motivation: Core-cusp problem/mass deficit problem

Moore (1994), Flores & Primack (1994)

Core-cusp problem:

Inner halo: $\rho(r) \sim r^{\alpha}$

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

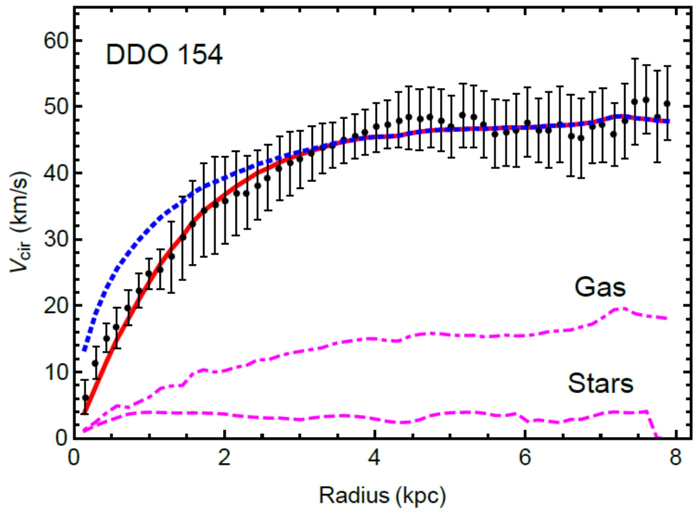
Mass deficit problem:

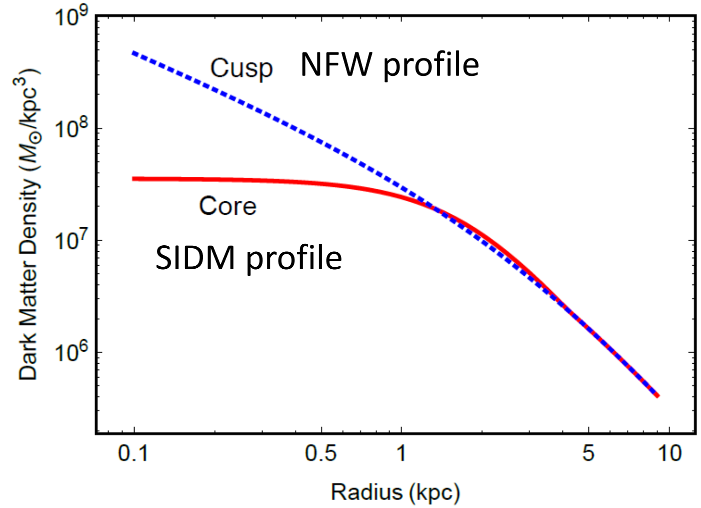
Inner halos have less DM mass than predicted from CDM

Small scale issues are prevalent in observations:

DM-dominated spiral galaxies in the field (Dwarf and low surface brightness galaxies)	Rotation curves
Milky Way satellites	Stellar velocity dispersion
Massive clusters	Stellar dispersion + lensing

Rotation curves in spiral galaxies





Tulin & Yu (in prep); Data from Oh et al [LITTLE THINGS] (2015)

Circular velocity (DM + stars + gas):

$$V_{\rm circ}(r) = \sqrt{V_{\rm halo}(r)^2 + \Upsilon_* V_{\rm star}(r)^2 + V_{\rm gas}(r)^2}$$

Unknowns:

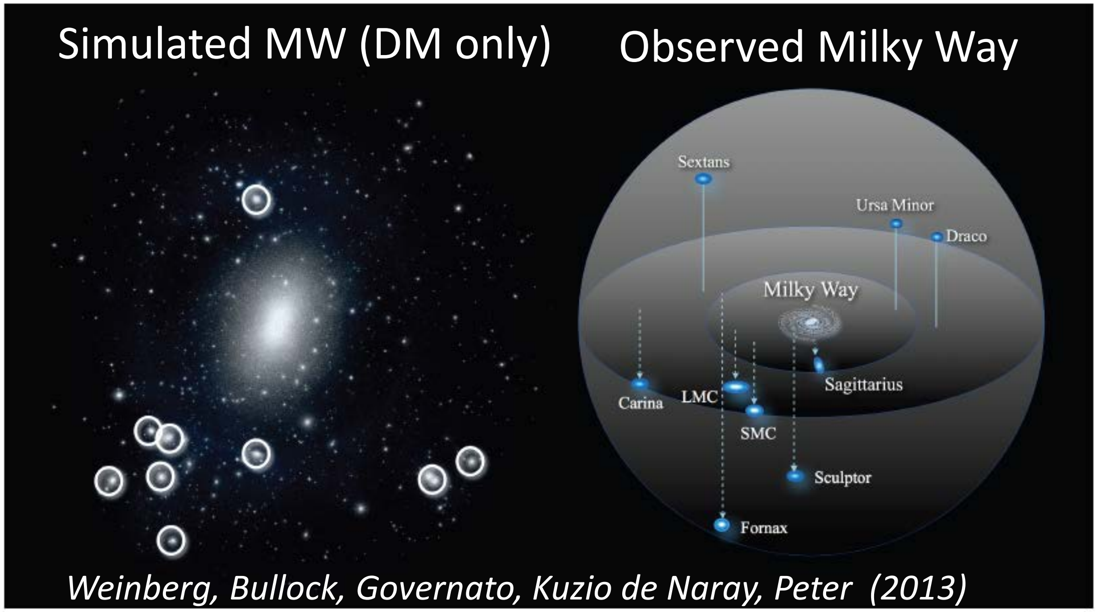
$$V_{\rm halo}(r) = \sqrt{G M_{\rm halo}(r)/r}$$

Stellar mass-to-light ratio Υ_*

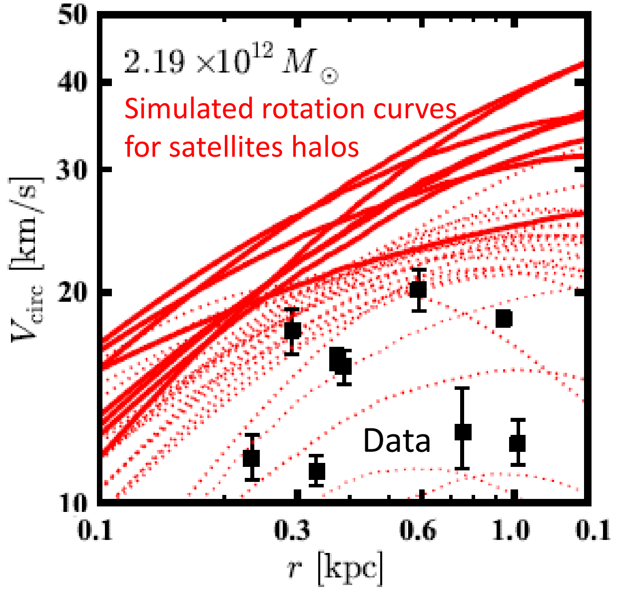
Mass deficit problem: NFW profile fit to V_{cir} at large radii predicts too-large V_{cir} at small radii

Mass deficit problem in MW satellites

Too big to fail problem *Boylan-Kolchin, Bullock, Kaplinghat (2011 + 2012)*



Biggest satellites should be in most massive halos



Observations: Line-of-sight stellar velocity dispersion

$$\sigma^2_{LOS} \approx 2.5 \frac{GM(R_{half})}{R_{half}}$$

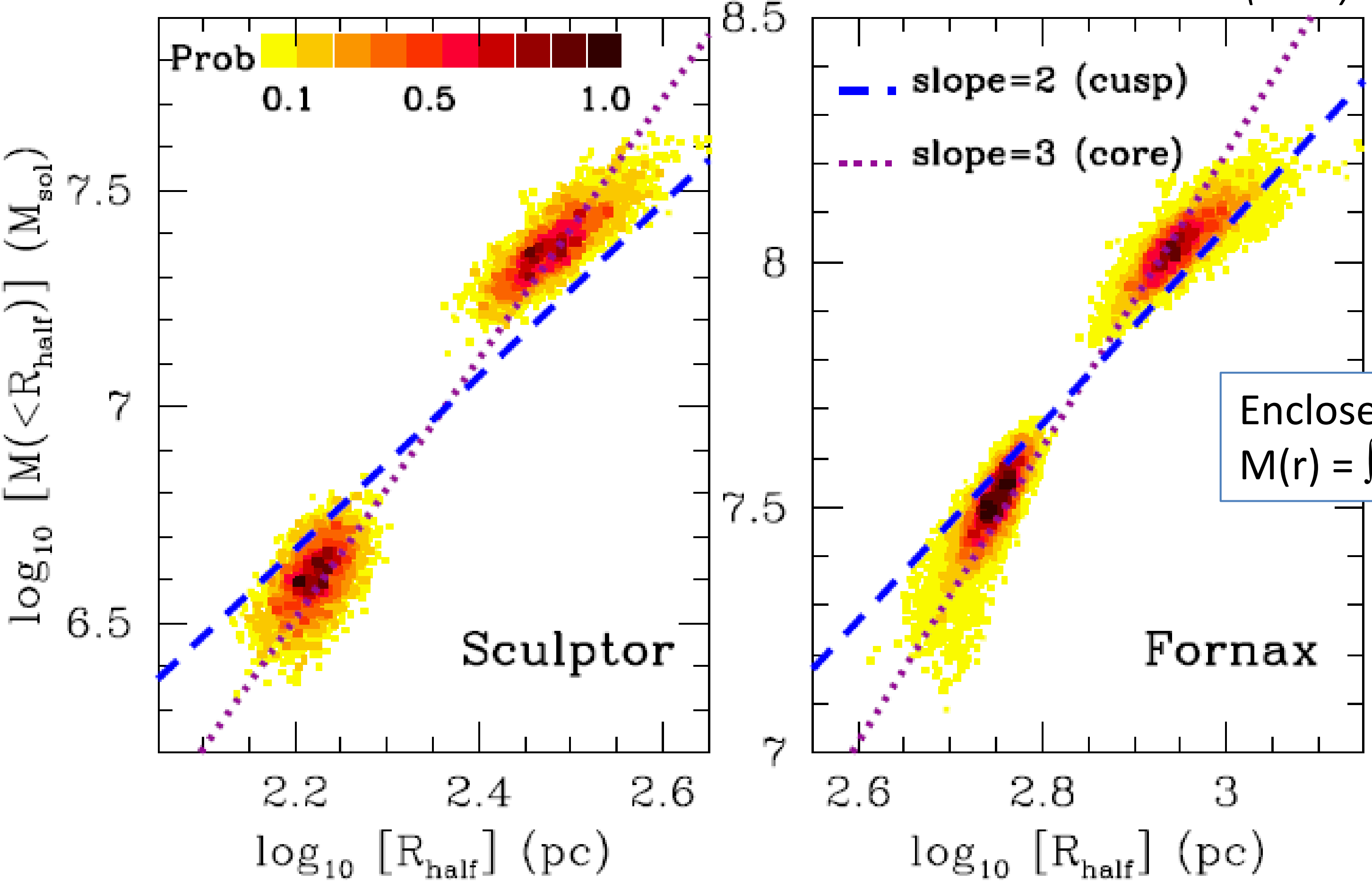
Walker et al (2009)

Obtain enclosed mass M at half-light radius
Only **one point** on rotation curve for each satellite
All have M_{half} too small compared to predictions

Core-cusp problem in MW satellites

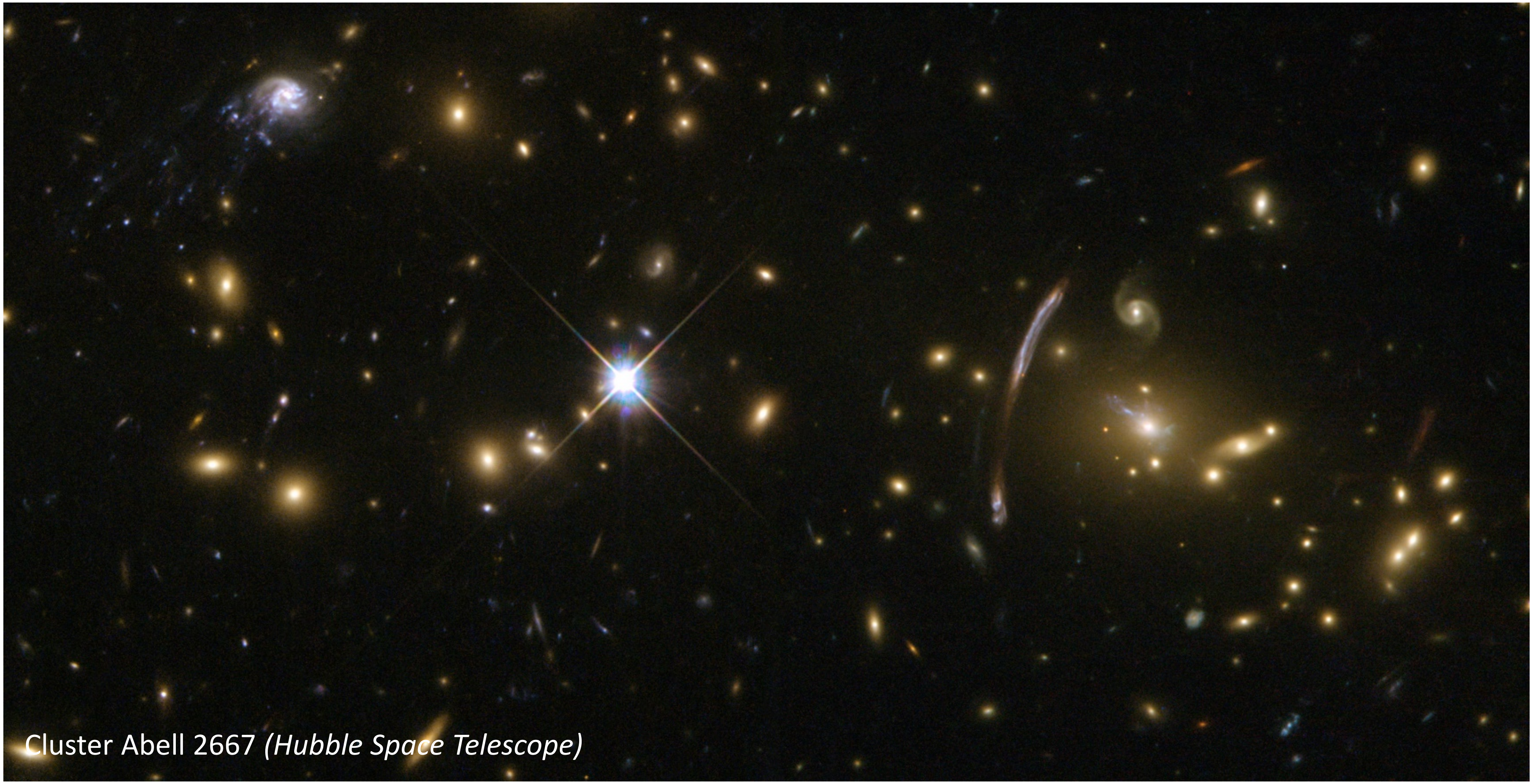
Divide stars into two subpopulations (metal-rich & metal-poor)
"Test masses" in gravitational potential
Calculate slope of rotation curve from two points

Walker & Penarrubia (2011)

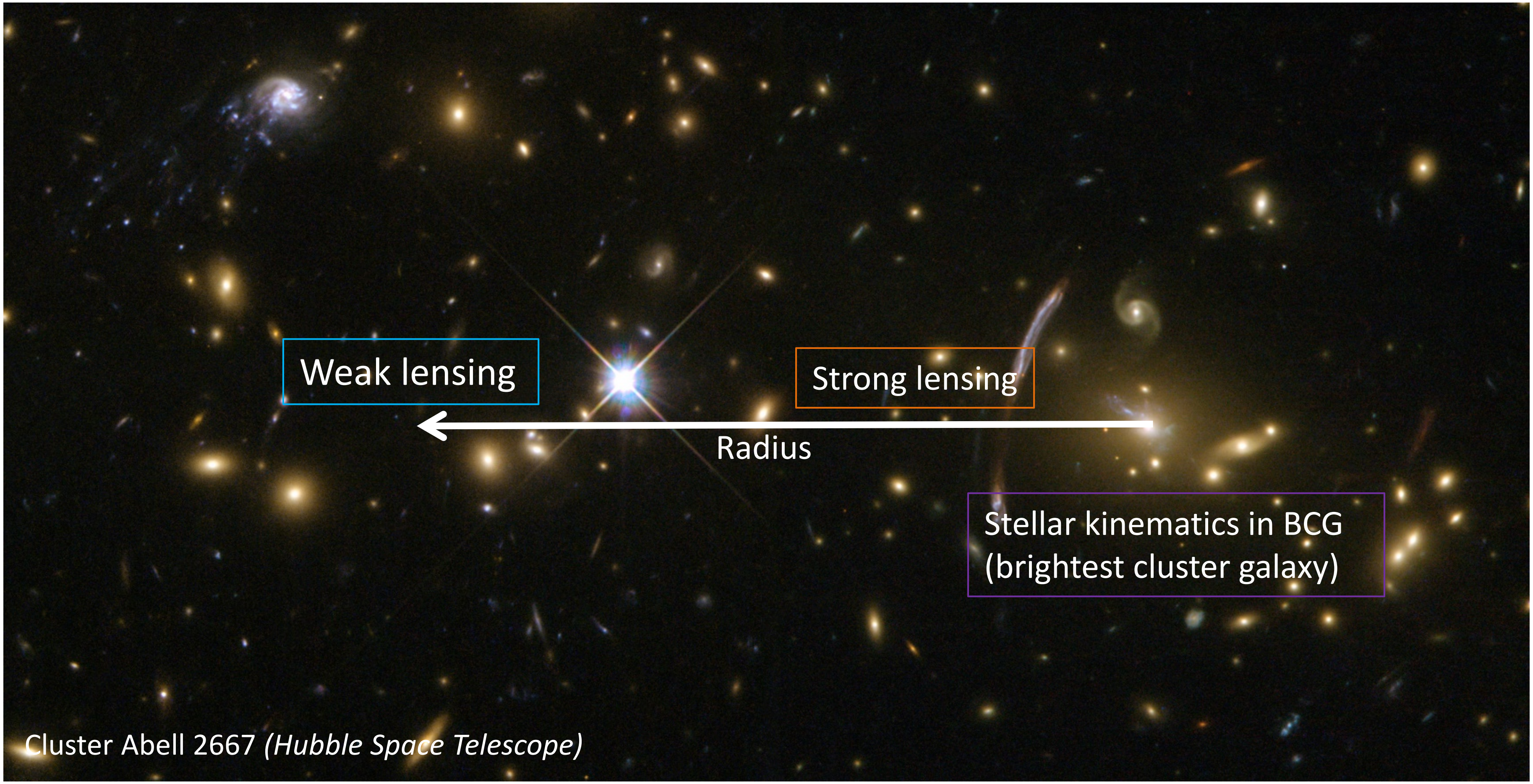


Enclosed mass
$M(r) = \int d^3r\ \rho \sim r^{\alpha+3}$

Cores in massive clusters



Cores in massive clusters

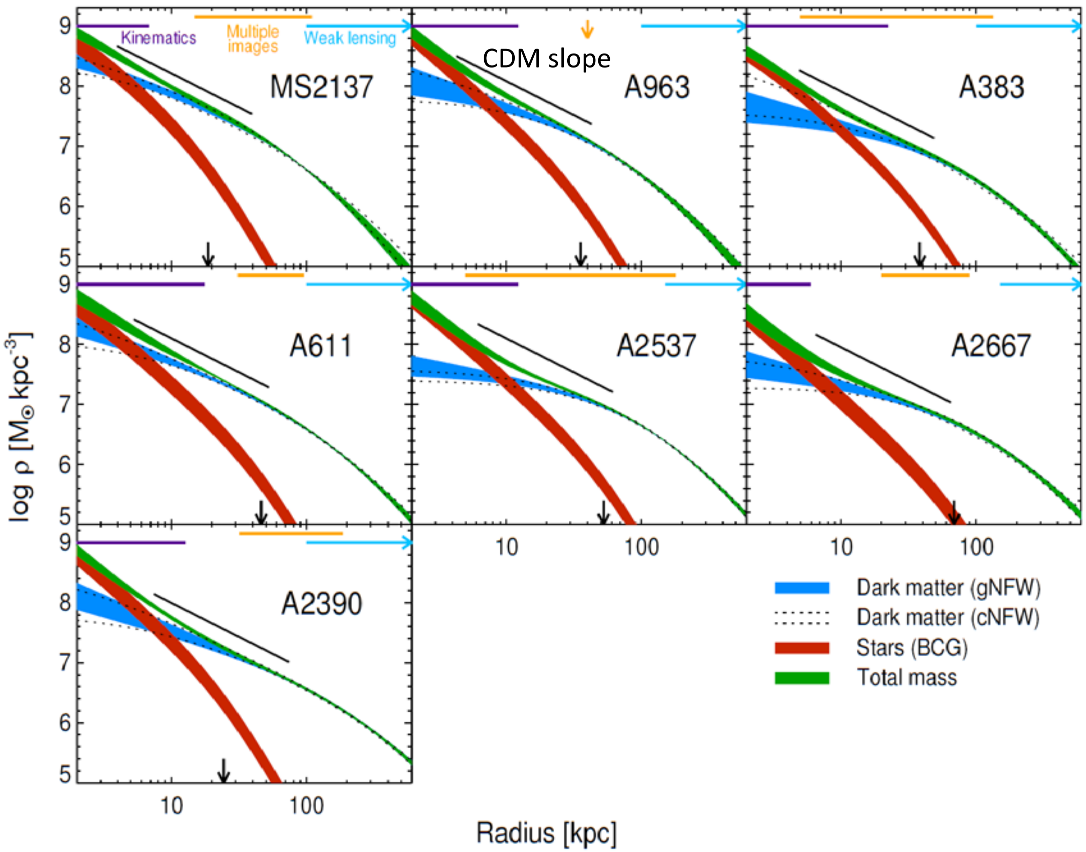


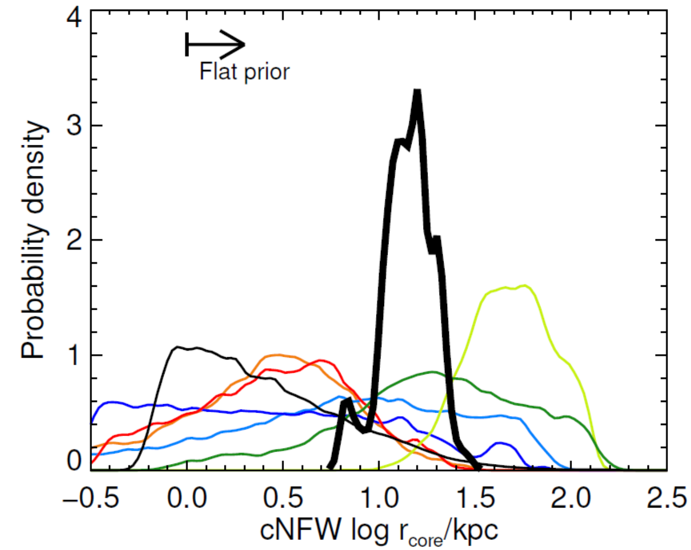
Use multiple measurements to study dark matter halo across 1-1000 kpc

Newman et al (2012)

Cores in massive clusters

Fit to seven 10^{15} M_{sol} relaxed clusters
Assuming common mass-to-light (BCG homogeneity)

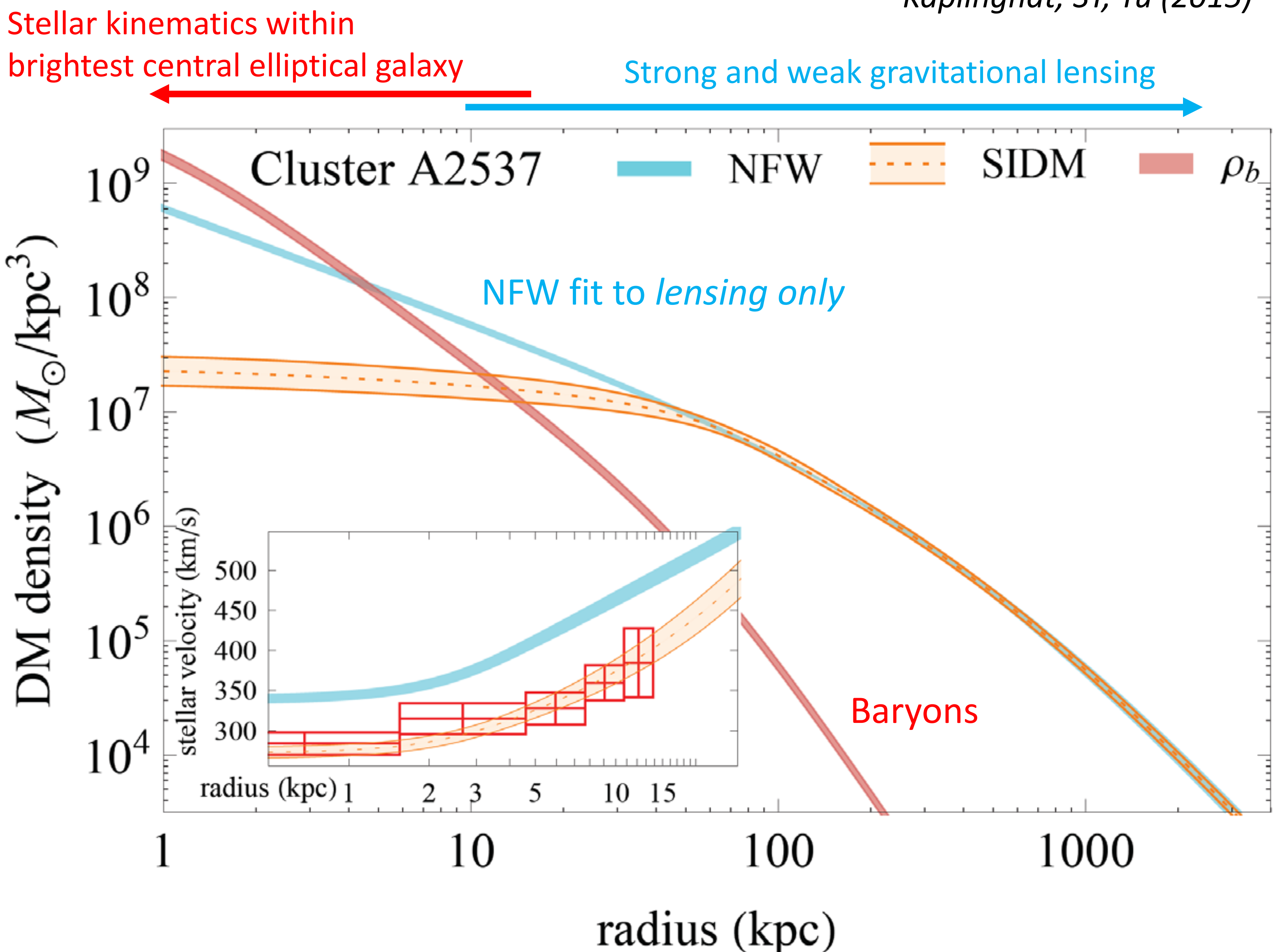




Newman et al (2012)

Cored density profile for one cluster

Kaplinghat, ST, Yu (2015)



Cores seem to be (fairly) ubiquitous

Satellite dwarf spheroidal galaxies

Dwarf and low surface brightness galaxies in the field (Rotation curves)

Massive clusters

Explanations:

1. Failure of DM theory (need to go beyond collisionless CDM)
2. Failure in DM-only simulations to describe real halos in DM+baryons Universe
3. Failure from other systematics in interpreting observations

Self-interacting dark matter

What scattering cross section value is needed?

Rate equation:

$$R_{\rm scat} = \sigma v_{\rm rel} \rho_{\rm dm}/m \approx 0.1\ {\rm Gyr}^{-1} \times \left(\frac{\rho_{\rm dm}}{0.1\ M_\odot/{\rm pc}^3}\right)\left(\frac{v_{\rm rel}}{50\ {\rm km/s}}\right)\left(\frac{\sigma/m}{1\ {\rm cm}^2/{\rm g}}\right)$$

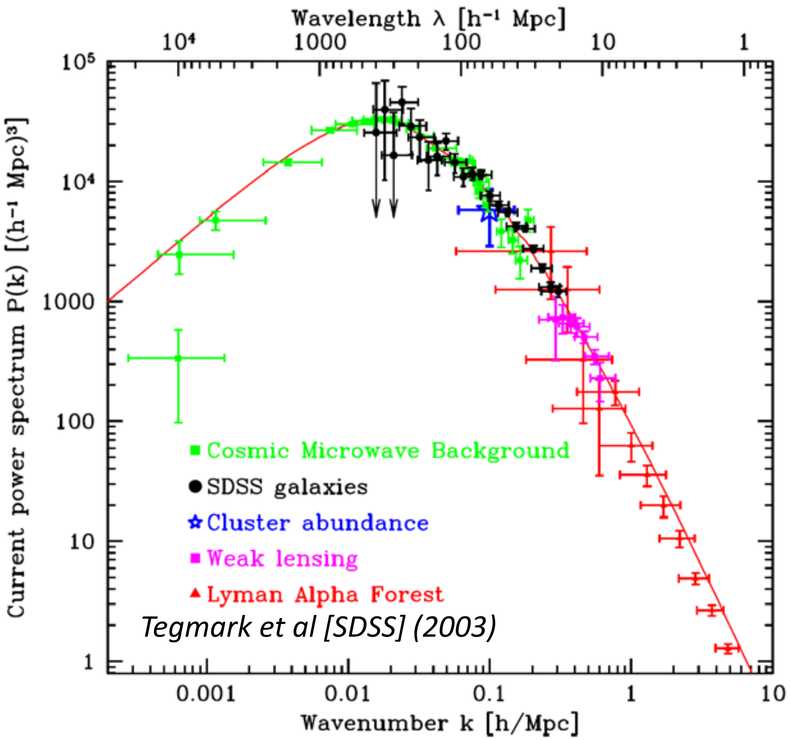
Figure-of-merit: $\sigma/m_\chi \sim 1\ {\rm cm}^2/{\rm g}\ \approx\ 2\ {\rm barns/GeV} \approx \left(\frac{1}{60\ {\rm MeV}}\right)^3$

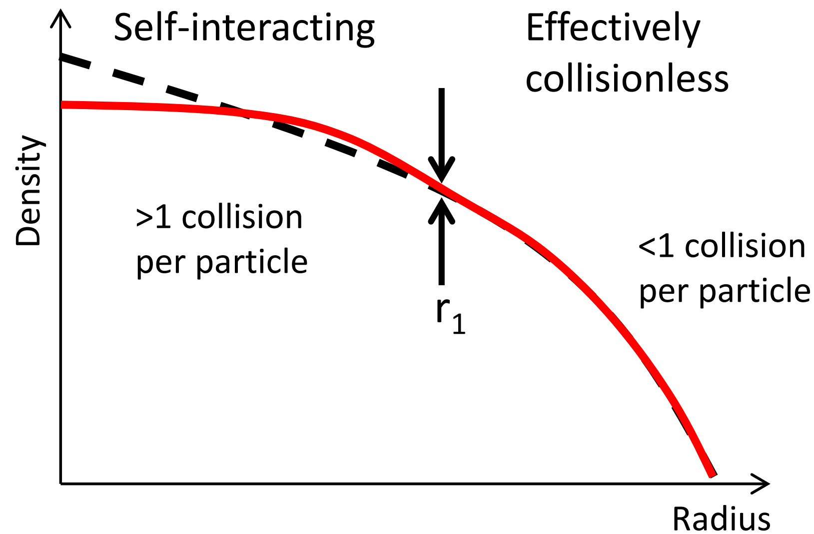
Typical cross section required to solve small scale anomalies

Astrophysics points to dark physics at the MeV-GeV scale

Motivates searches for light dark states but doesn't say how they couple to SM

Self-interacting dark matter





Success of ΛCDM for large scale structure unaffected

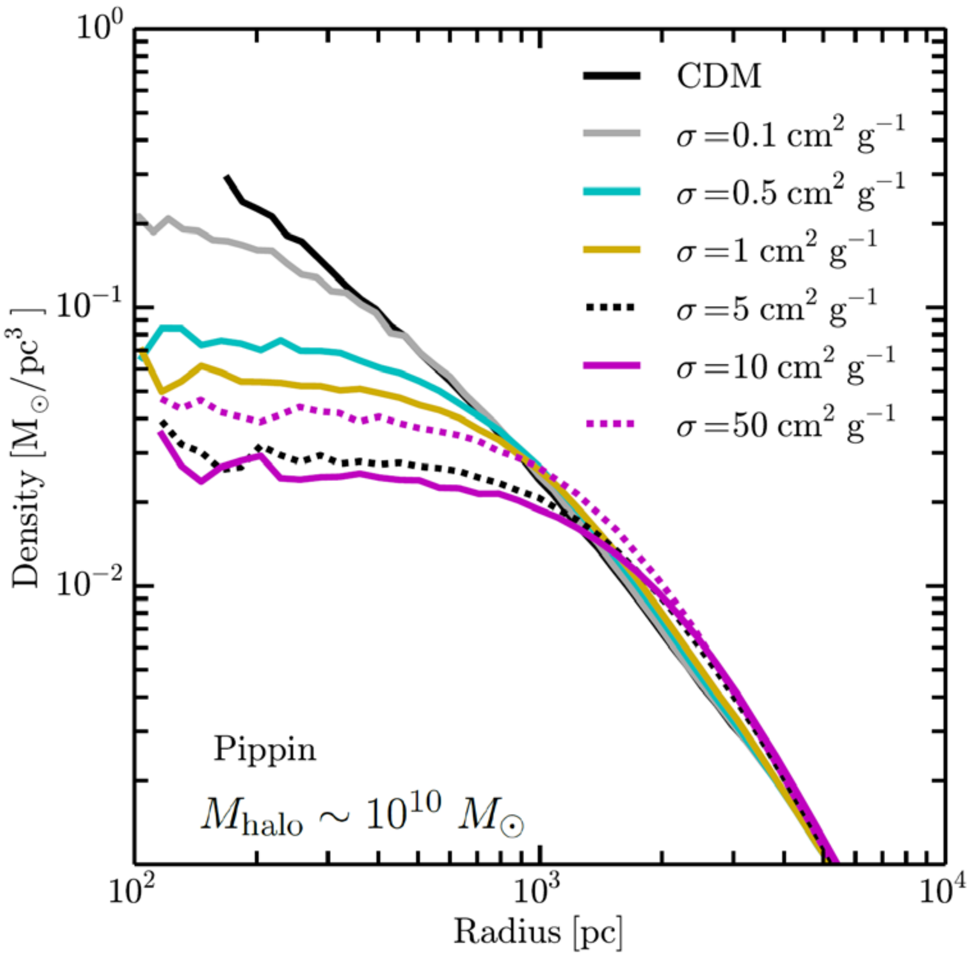
R_{scat} x t_{eq} << 1

Self-interactions only affect inner halos where

R_{scat} x t_{halo} > 1 (t_{halo} ~ 5—10 Gyr)

Cross section need not be fine tuned

N-body simulation of SIDM halo for dwarf galaxy.
Elbert et al. (2015)



$\sigma/m \sim 0.5 - 50\ \mathrm{cm^2/g}$
Form ~kpc core in dwarf galaxies

Cross section degenerate with scatter due to assembly history (Scatter in mass-concentration)

$\sigma/m < 0.5$ – Cores too small

$\sigma/m >> 50$ – Gravothermal collapse (Cuspier than NFW)

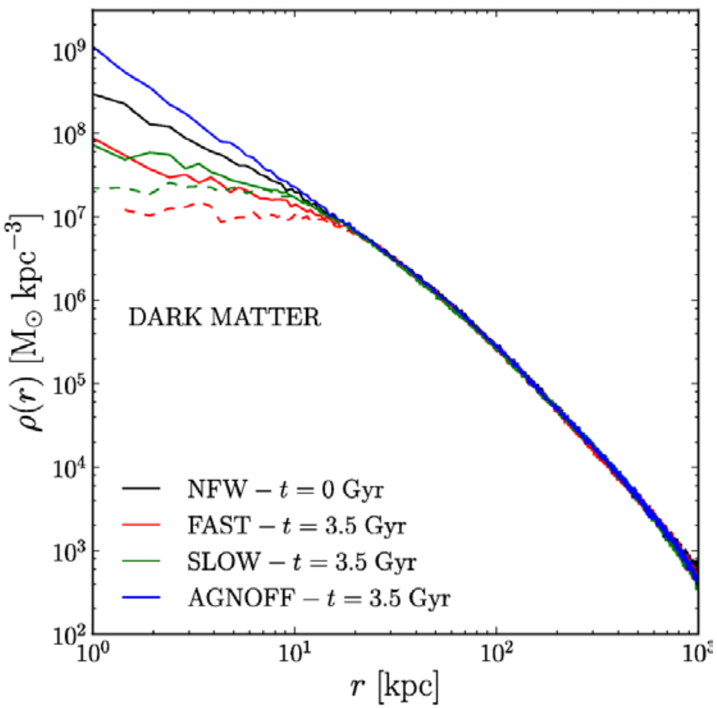
Baryonic astrophysics

Does including baryons in simulations solve small scale structure issues?

Feedback from AGN in clusters

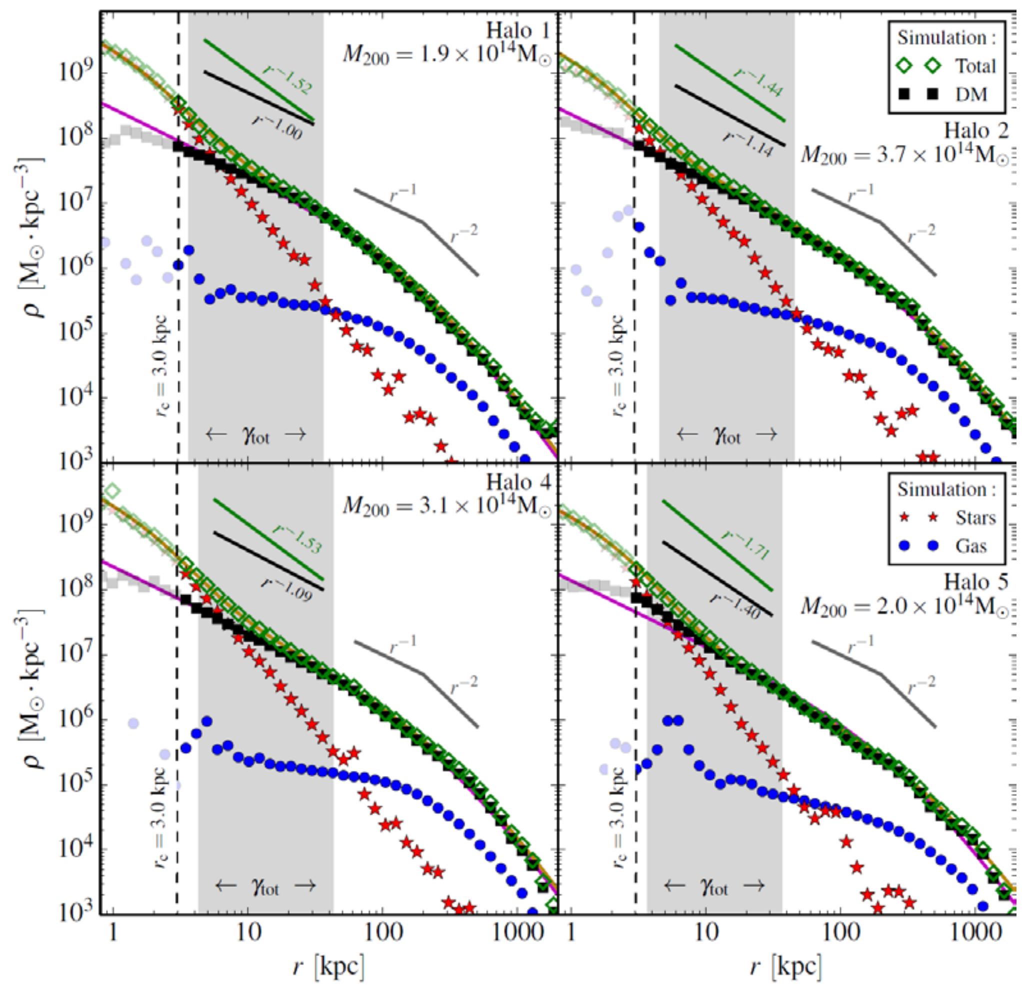
N-body simulations with baryons

Martizzi et al (2012)



Feedback leads to a core from initial NFW halo

Schaller et al (2014)

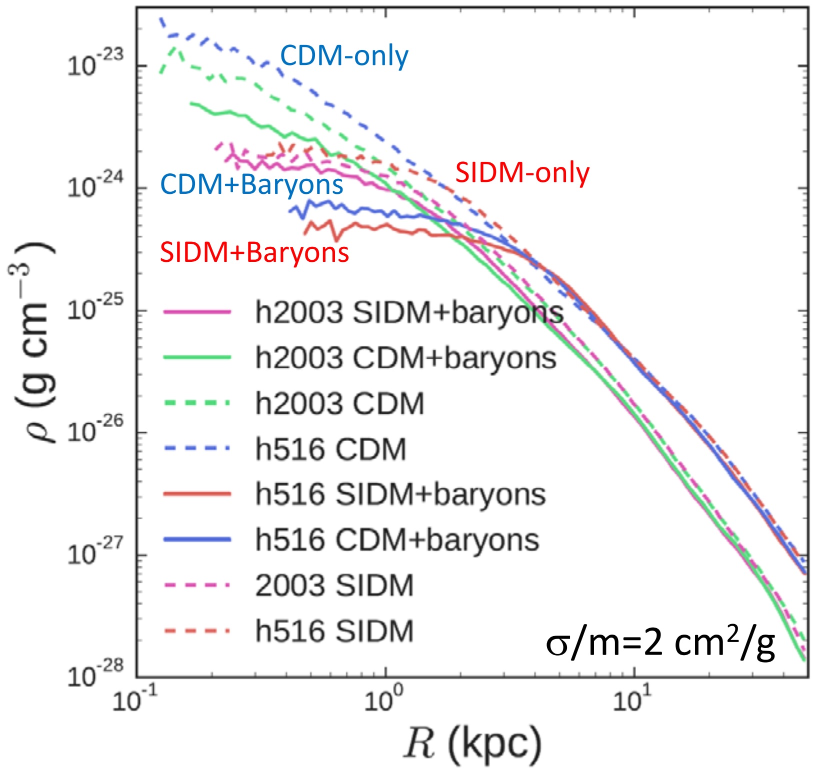


Feedback does not form dark matter cores

Feedback from supernovae

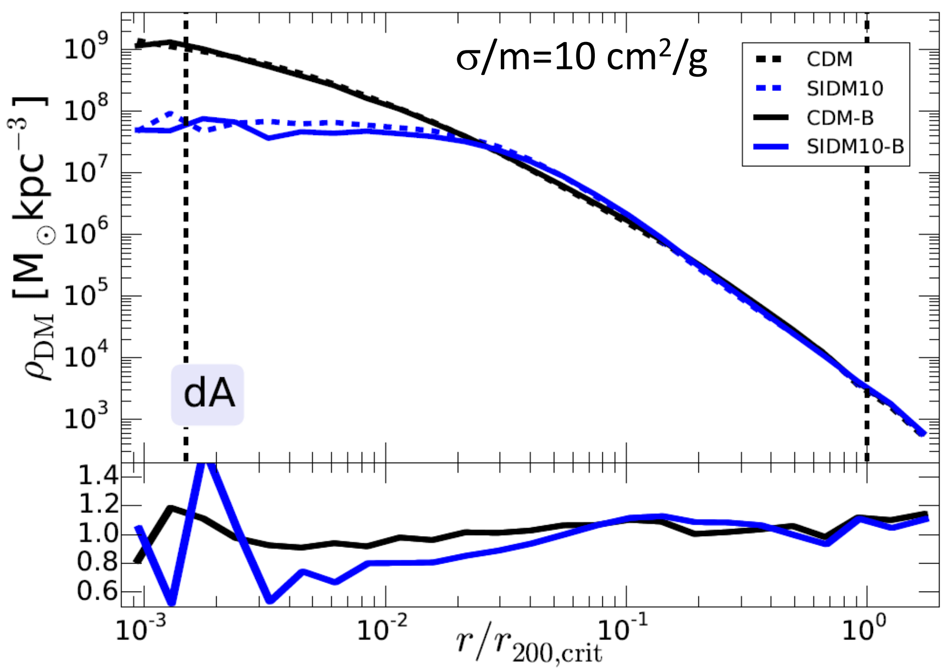
N-body simulations with self-interactions and baryons

Fry et al. (2015)



Bursty star formation
(High density threshold
for star formation)

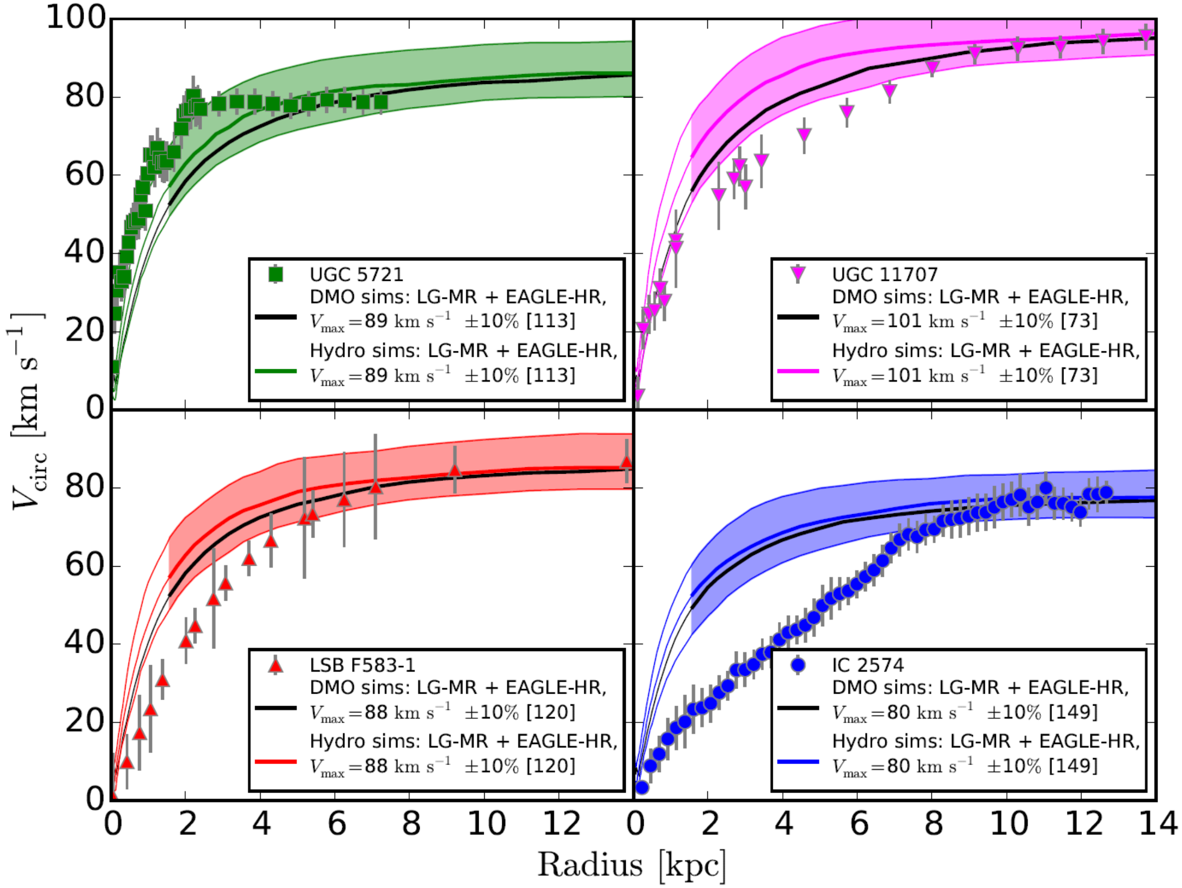
Vogelsberger et al. (2014)



Smooth star formation
(Low density threshold)

Diversity problem: challenge for feedback

Oman et al (2015)



<u>Rotation curve-ology:</u>

V_{max} = max velocity
Observational proxy for halo mass

Central density ~ slope of rising rotation curve

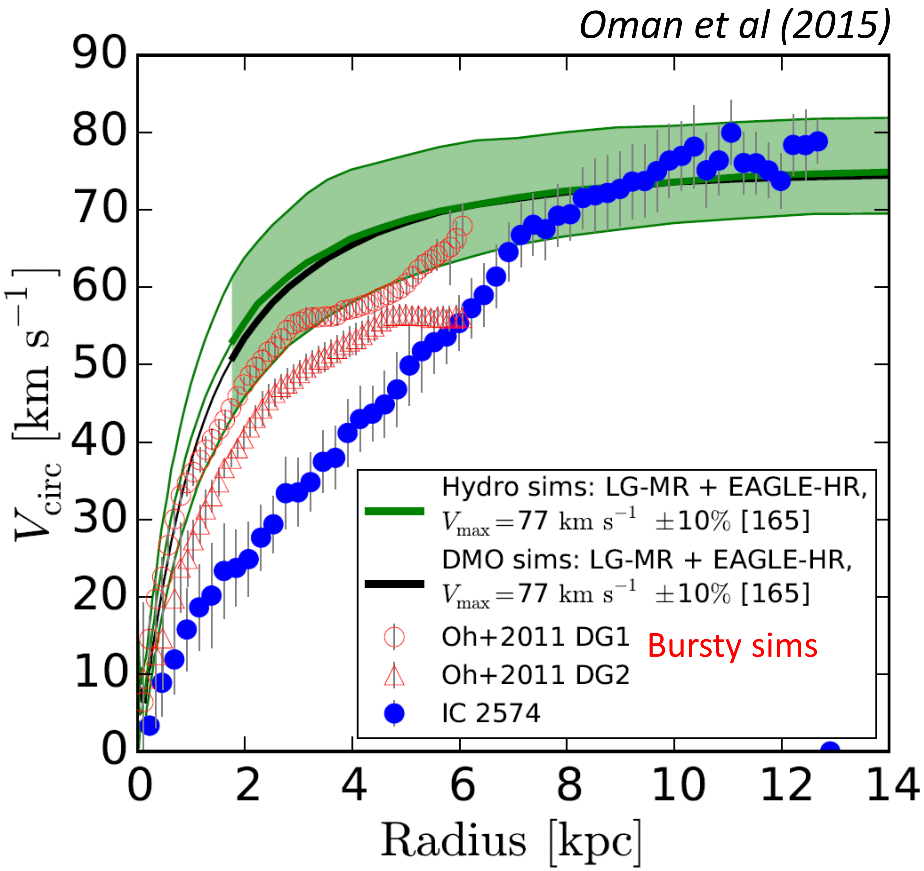
Core radius ~ break in slope from rising to flat

Similar V_{max} halos can have very different core sizes and central densities
Some rotation curves are perfectly consistent with CDM

Outliers with large cores

Even bursty prescriptions have trouble making cores > few kpc.

Example: *IC 2574*
DM mass deficit within 5 kpc greater than total mass in stars

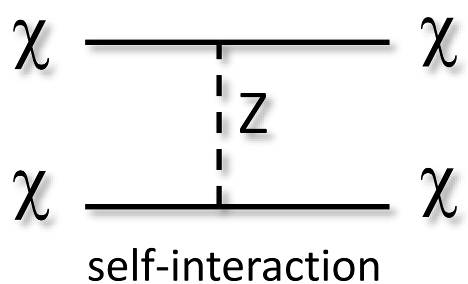


Questions

- If dark matter is self-interacting, what are the particle physics implications?
- Does SIDM give a consistent solution to small scale issues from dwarfs to clusters?
- Is SIDM consistent with the observed diversity in rotation curves?

Particle physics of self-interactions

WIMPs have self-interactions (weak interaction)



χ = dark matter (e.g. SUSY particle)

Z boson = mediator particle

Cross section:

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

Mass:

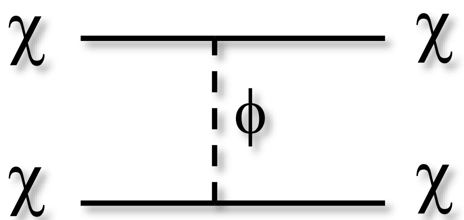
$$m_\chi \sim m_Z \sim 100\ \mathrm{GeV}$$

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 $\sigma / m_\chi \sim 1 \text{ cm}^2/\text{g}$



self-interaction

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

Mediator mass below than weak scale

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

Self-interactions require new dark sector states < 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.

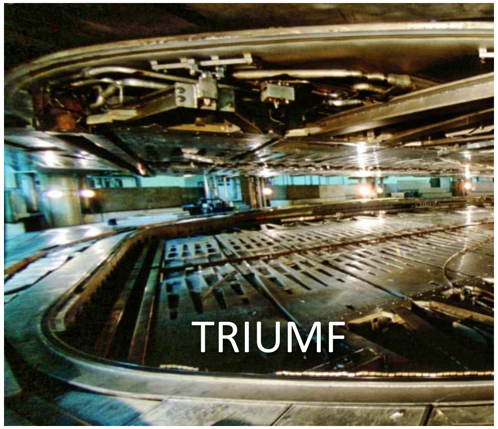
Different halos are complementary

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

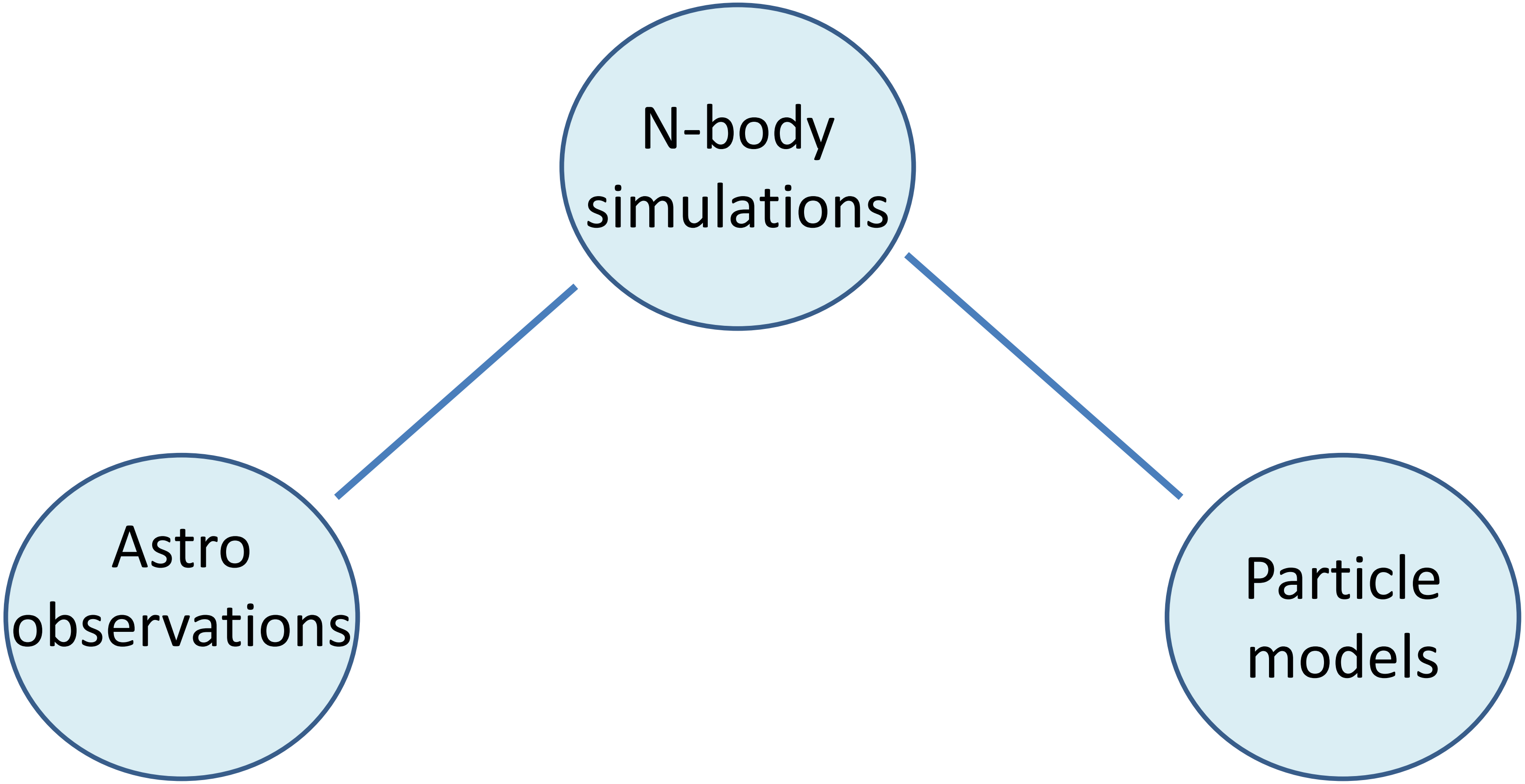


Does SIDM explain all cores?

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

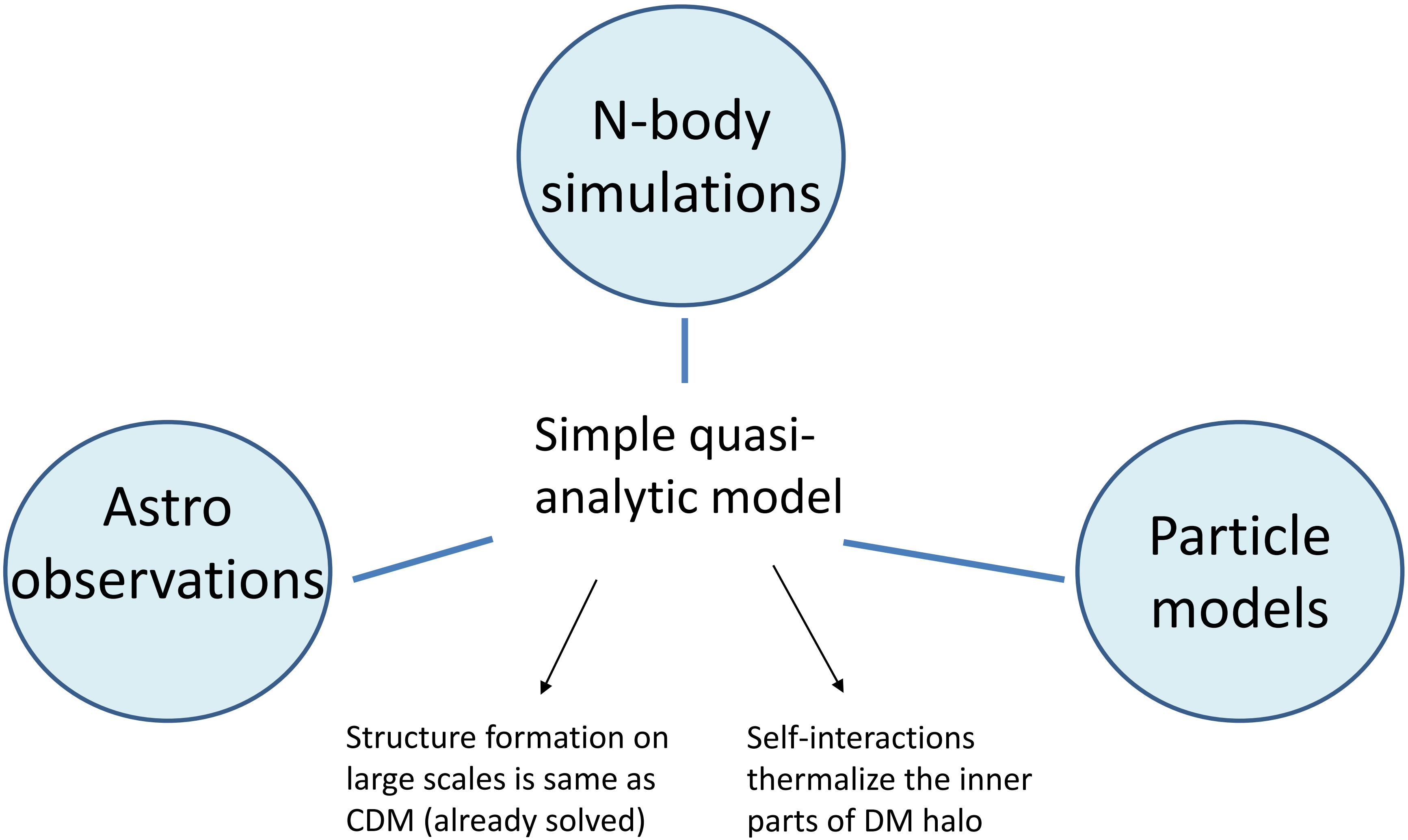
- Can observations of cores in all systems be explained in a consistent particle physics picture?

Kaplinghat, ST, Yu (2015)



No 1:1 correspondence between simulated and observed objects

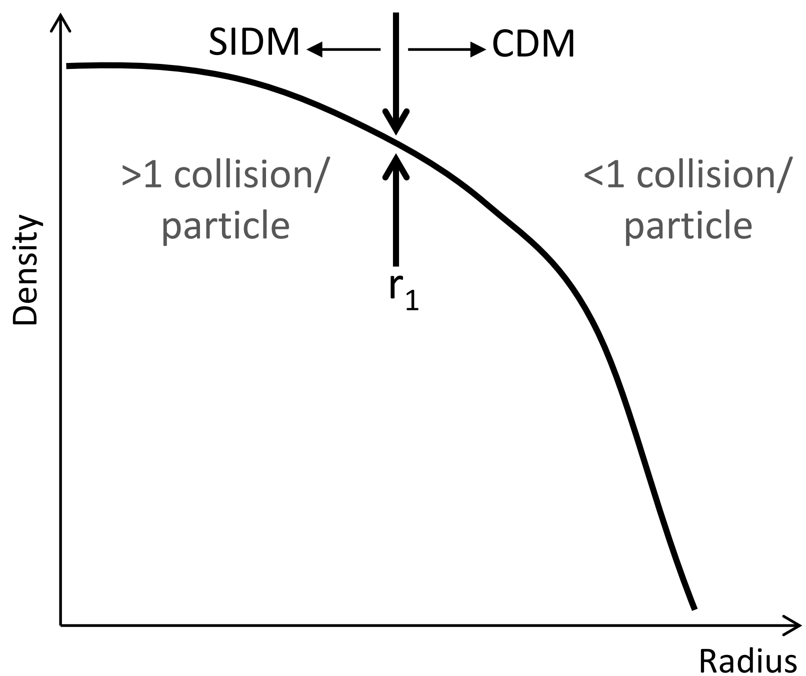
Space of particle models too vast to scan over using simulations



Test method against N-body simulations

Modeling SIDM halos

Self-interactions only affect the inner halo where density is highest



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

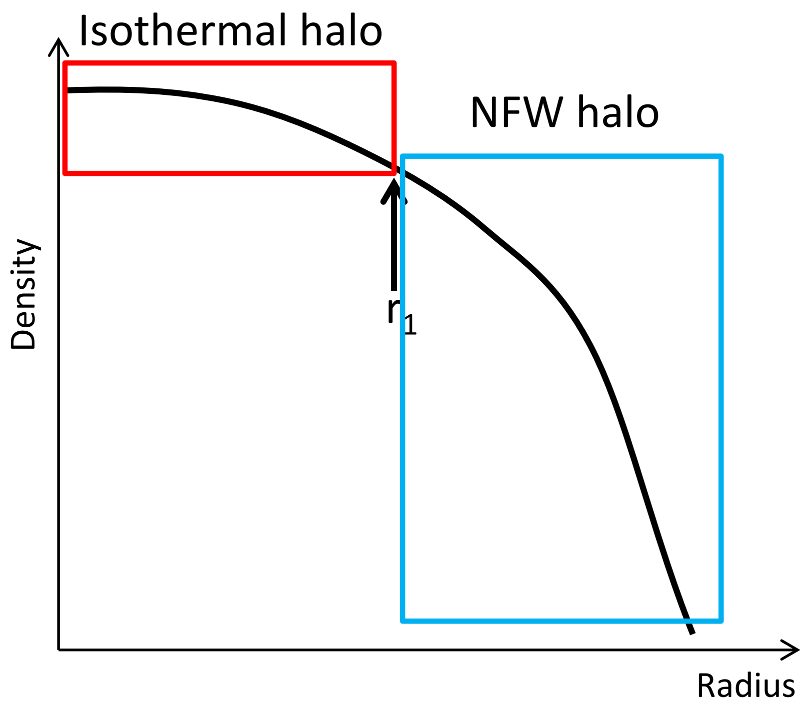
Outer halo ($r > r_1$): expect DM to be CDM (NFW)

Density at r_1 defines cross section where 1 scattering has occurred

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

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

Modeling SIDM halos



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:

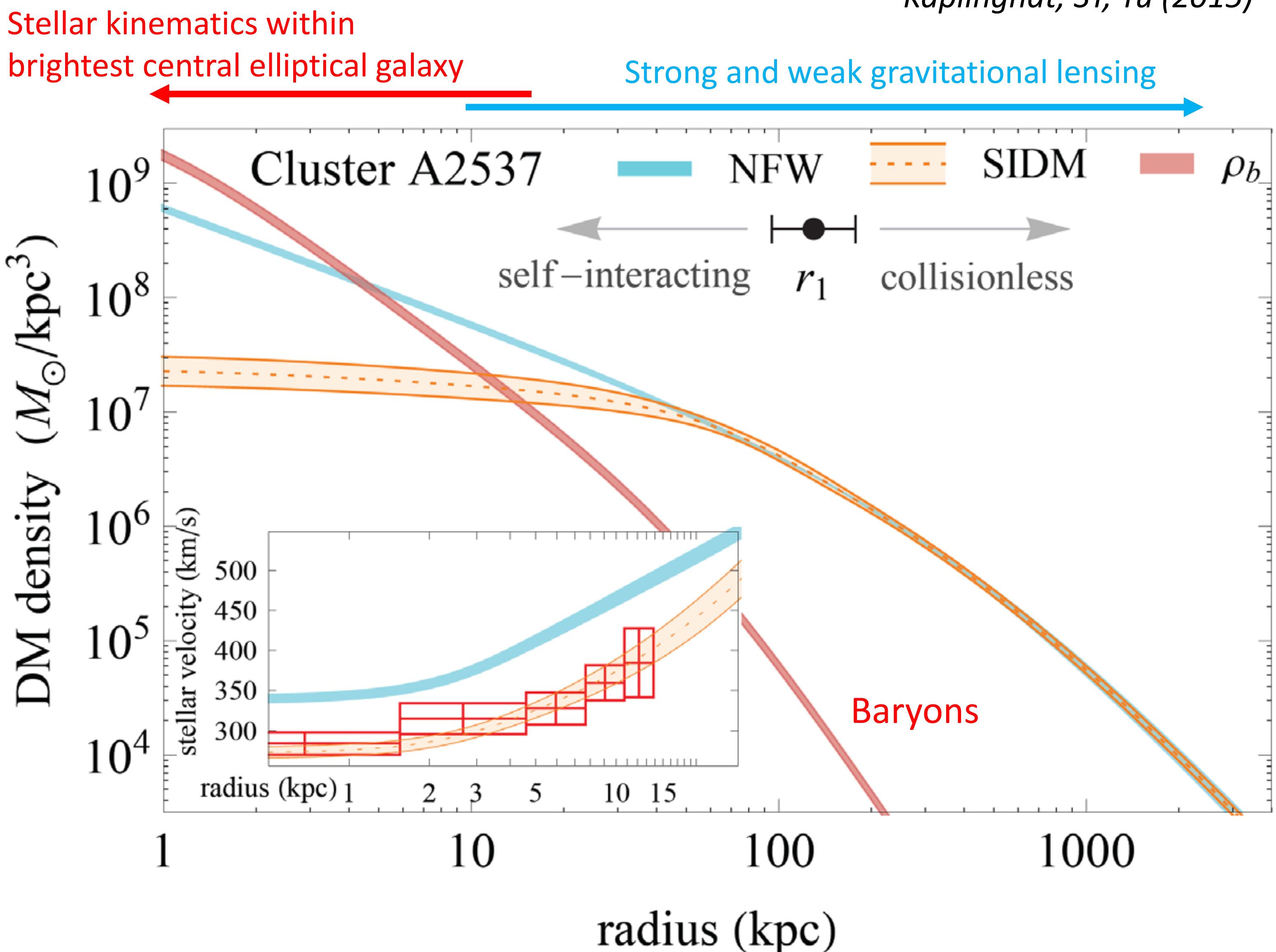
- core density $\rho(r=0)$
- velocity dispersion σ^2 (= $k_B T/m$)
- matching radius r_1

Solving rate equation at r_1:

$$\frac{\langle \sigma v_{\rm rel} \rangle}{m} = \frac{1}{\rho_{\rm dm}(r_1) t_{\rm age}}$$

SIDM profile for Abell 2537

Kaplinghat, ST, Yu (2015)



Astrophysical dataset

12 spiral galaxies + 6 clusters:

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

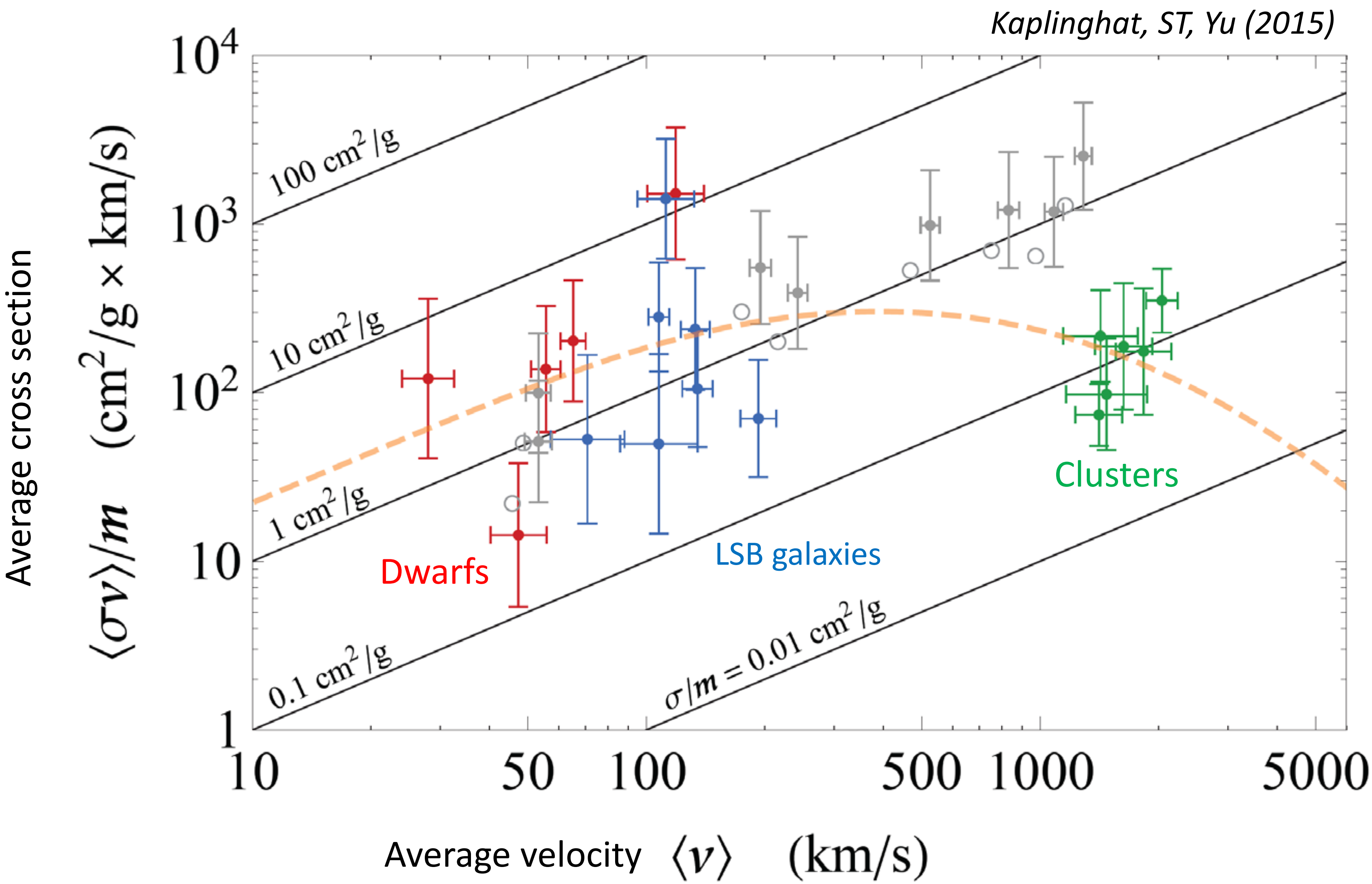
Stellar kinematics
+ lensing data

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

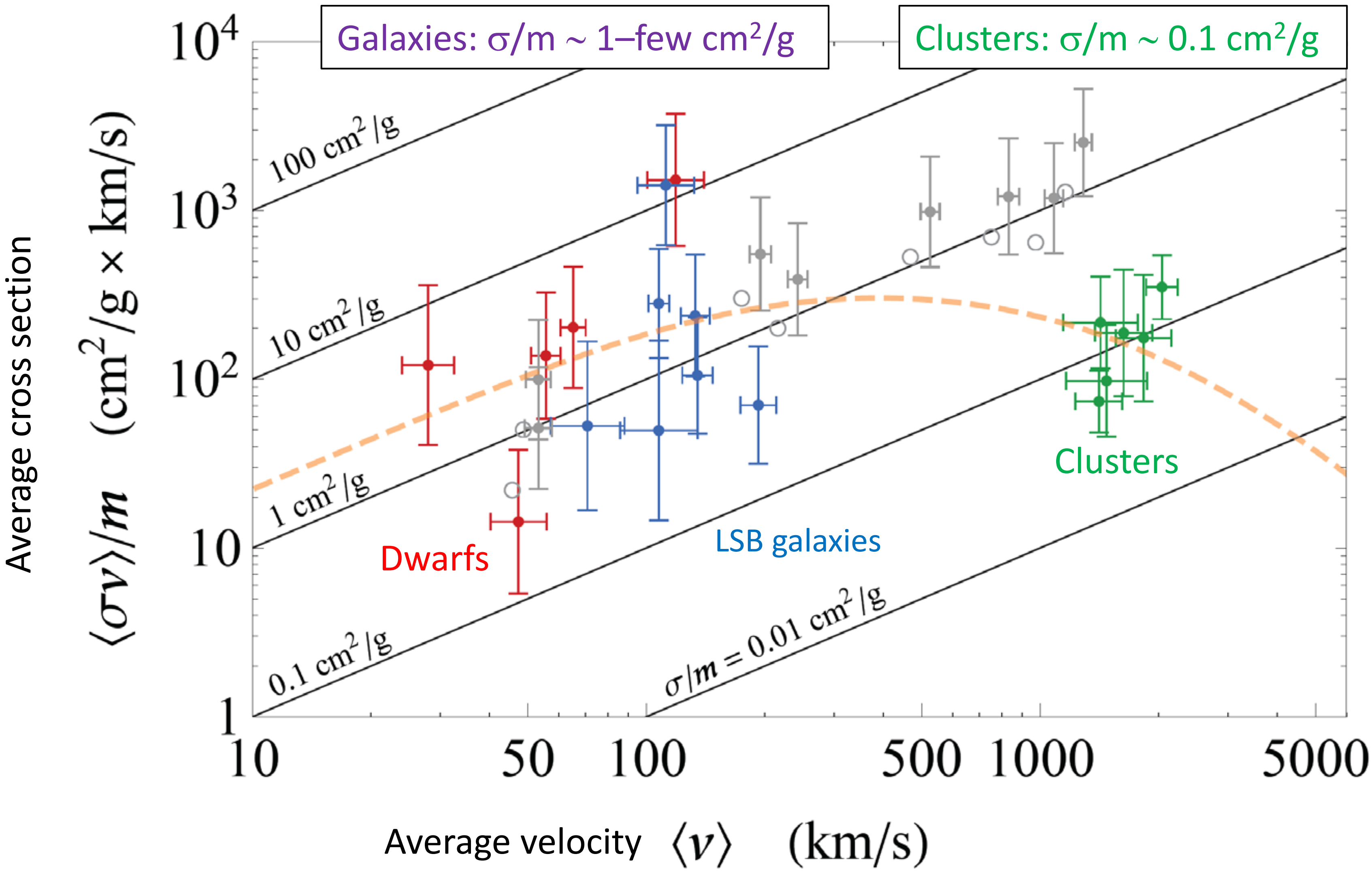
THINGS dwarf galaxies IC2574, NGC2366, HO II, M81dwB, DDO154
Oh et al (2011)

Rotation curves +
assumption no
core collapse

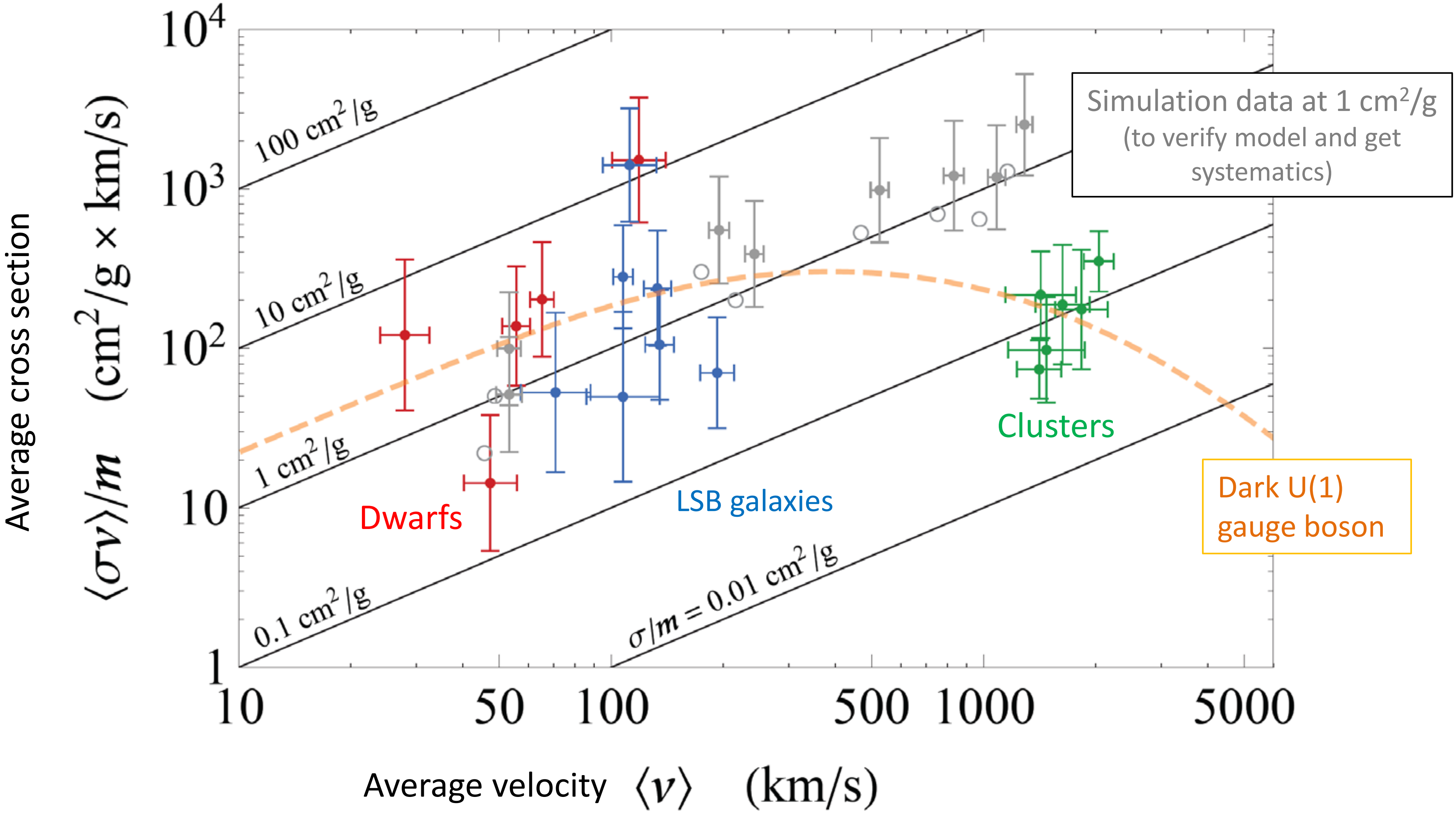
Cross section for each system



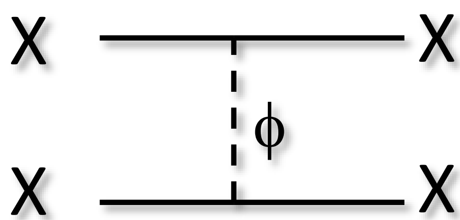
Cross section for each system



Cross section for each system



Dark matter + dark photon model



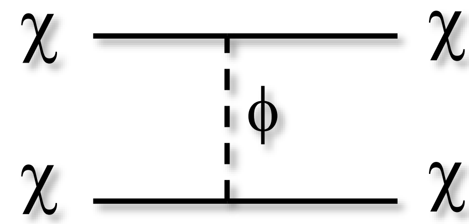
DM particle X + Massive $U(1)_X$ gauge boson ϕ

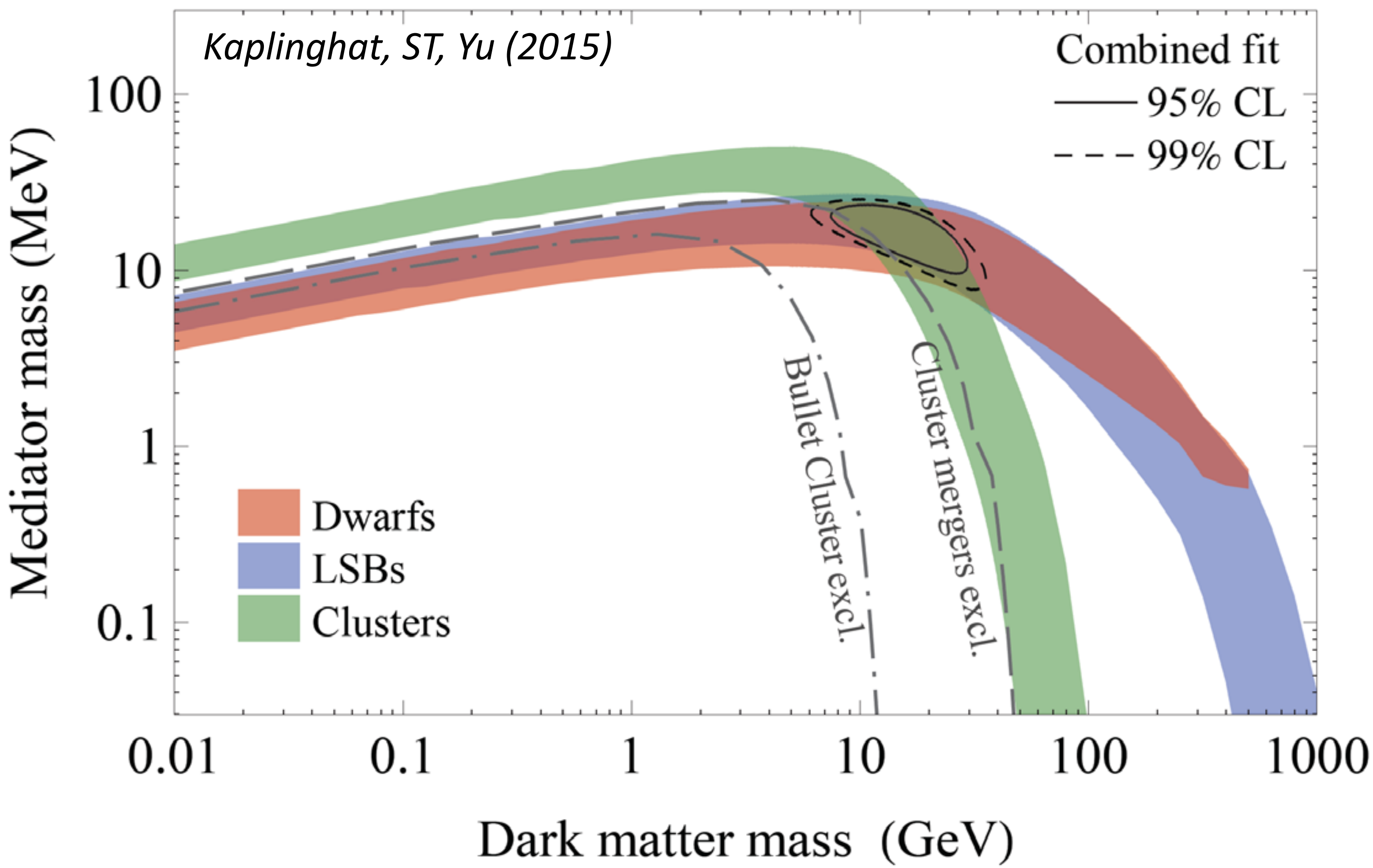
Only three parameters: DM mass, ϕ mass, coupling α'
(Note: No kinetic mixing required)

Compute σ/m using nonrelativistic QM *Tulin, Yu, Zurek (2013)*

Dark matter + dark photon model

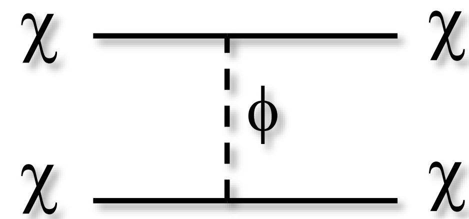
Caveat: Plot is very model dependent
Repulsive interaction (ADM)
Dark fine structure constant: $\alpha' = \alpha$

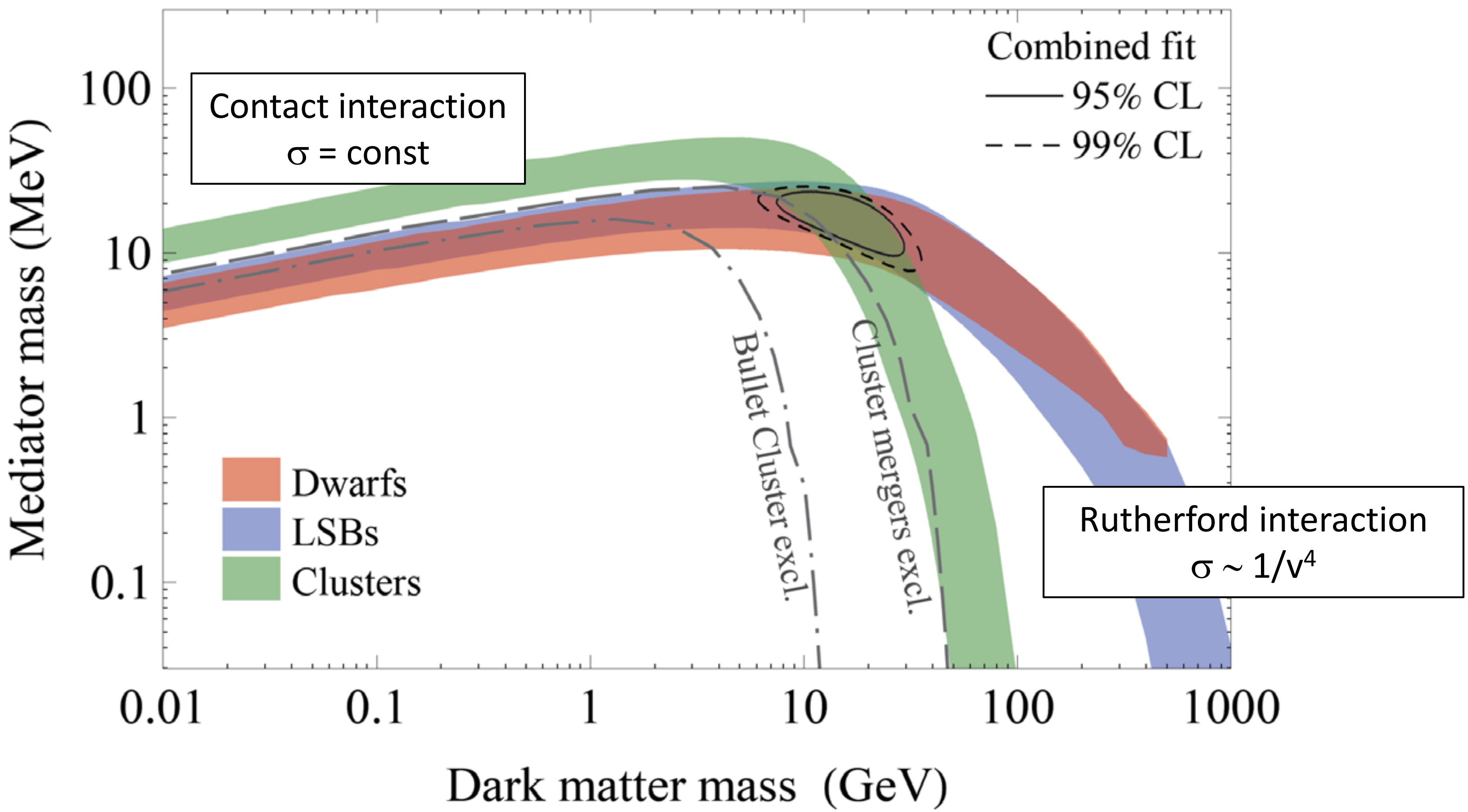




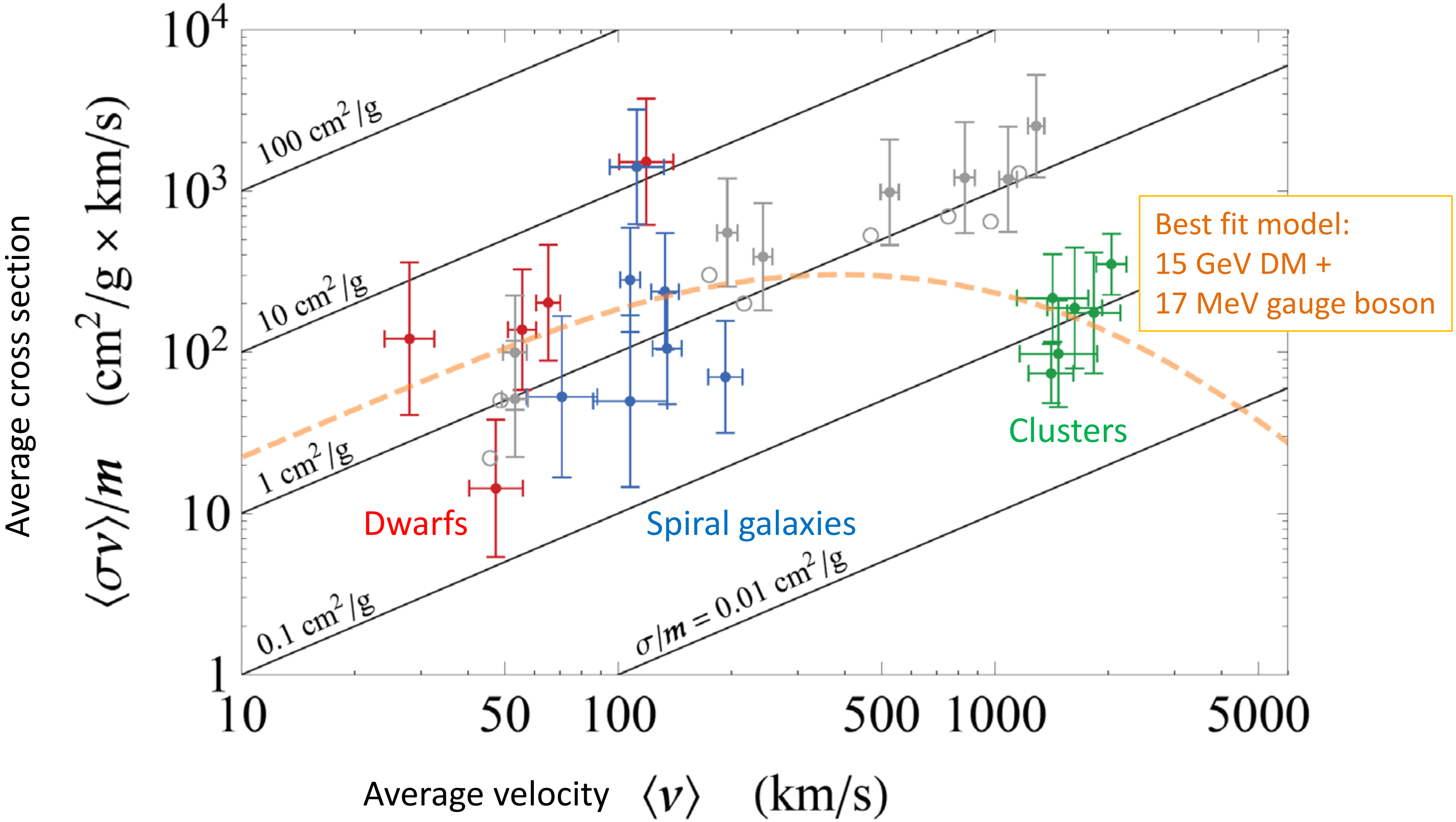
Dark matter + dark photon model

Caveat: Plot is very model dependent
Repulsive interaction (ADM)
Dark fine structure constant: $\alpha' = \alpha$

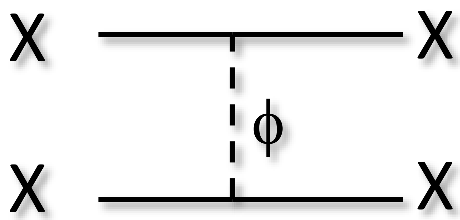




Dark matter + dark photon model



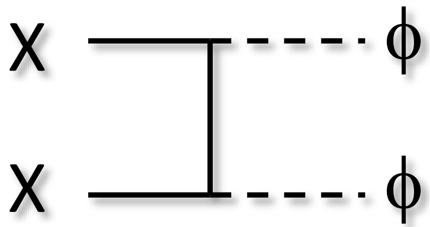
Self-interacting dark matter paradigm



Self-interactions

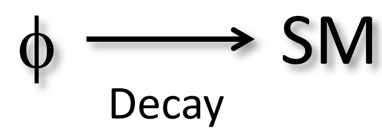
DM particle X + mediator particle ϕ

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

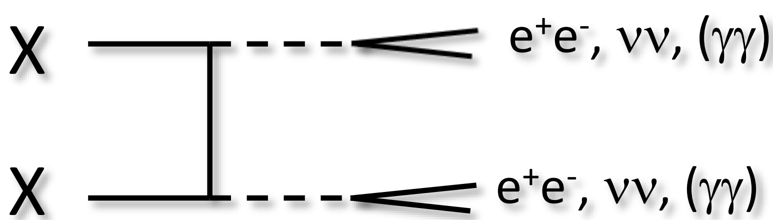


Annihilation

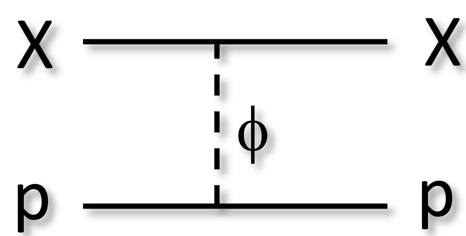
Set relic density
via freeze-out



(Deplete ϕ density)



Indirect detection



Direct detection
Capture in sun/earth

Diversity problem for rotation curves

- Is SIDM consistent with the diversity of rotation curves?

- Are SIDM halos consistent with CDM on large scales (outside r_1)?

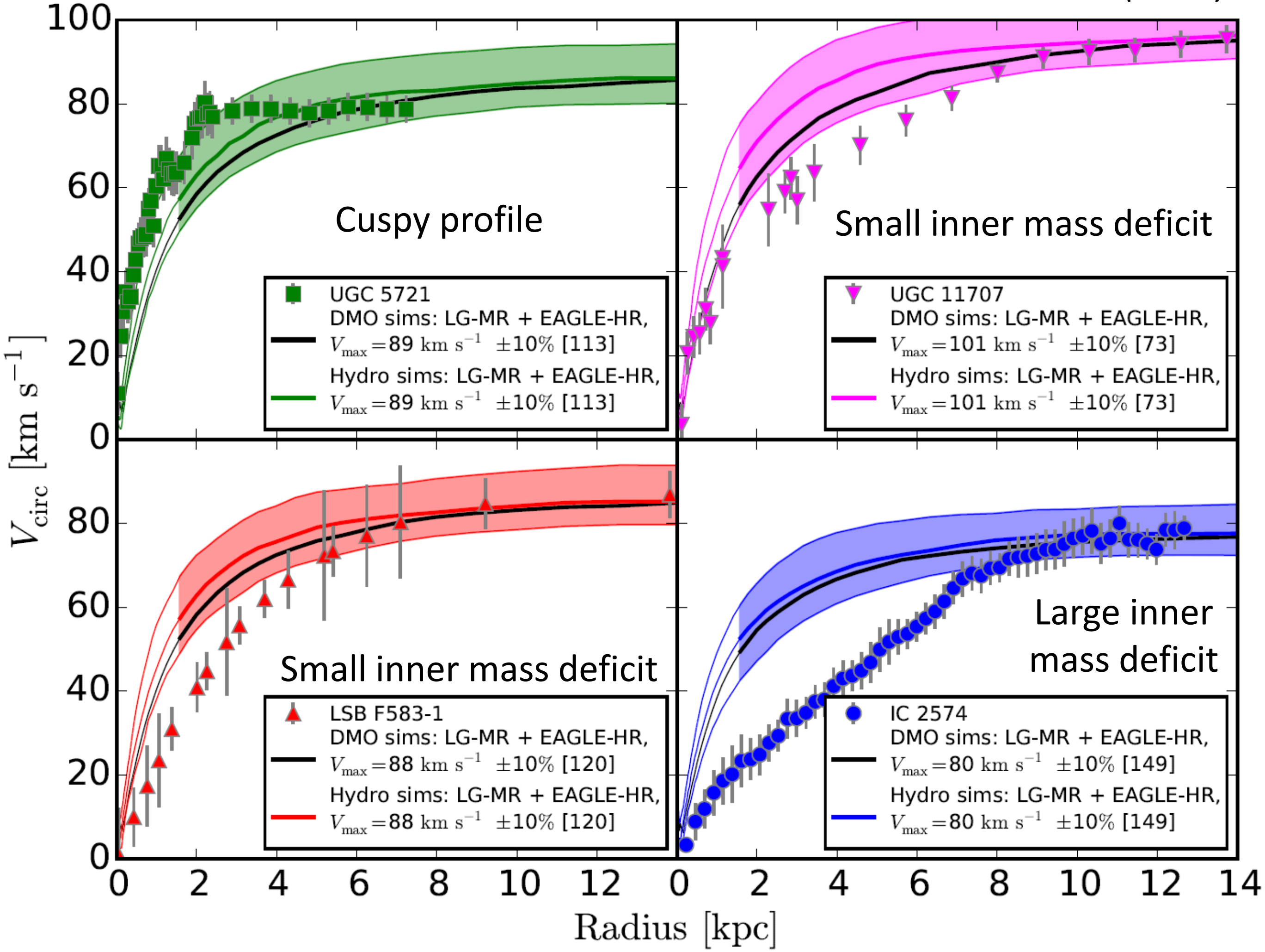
  SIDM + NFW halos matched together at r1

  Are those NFW halos cosmologically realistic?

  Must satisfy concentration-mass relation (within scatter)

Diversity problem: challenge for feedback

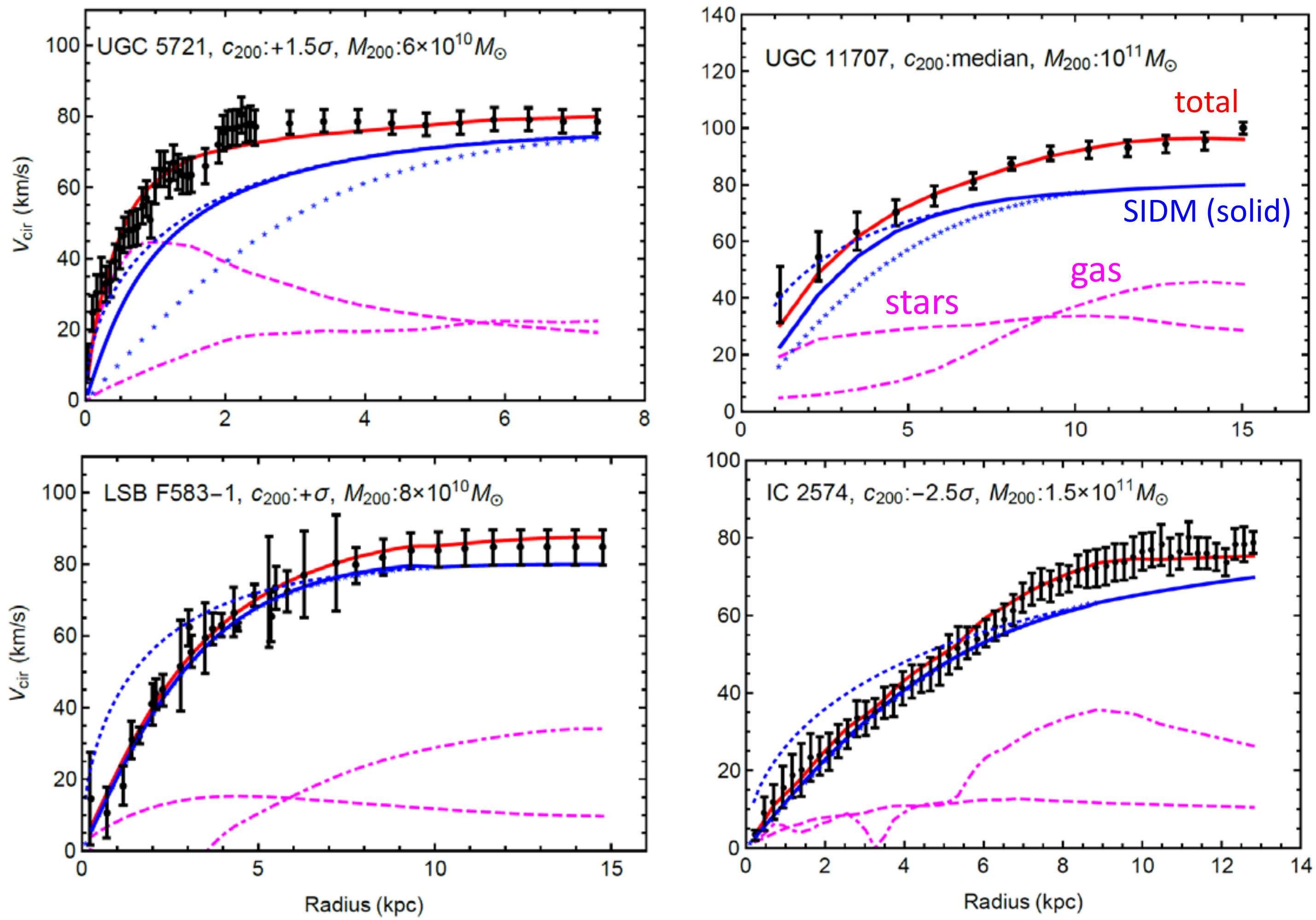
Oman et al (2015)



SIDM consistent with diverse halos

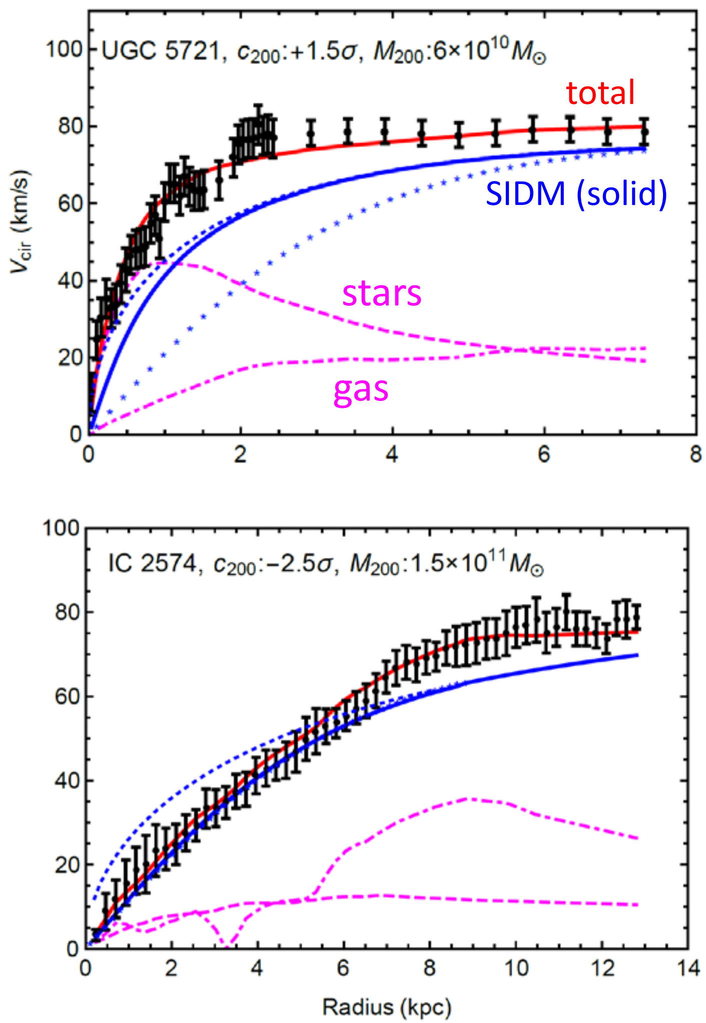
σ/m = 3 cm²/g for all halos

Kamada et al (2016)



Extreme outliers

Kamada et al (2016)



Two effects:

1. Scatter in concentration-mass relation (same as CDM halos)

2. In more luminous galaxies, gravitational effect of baryons shrinks cores (unique to SIDM)

$$\rho_{\rm dm}(r) = \rho_0 \, e^{-\frac{\Phi_{\rm tot}(r)}{\sigma^2}}$$

Isothermal density profile for SIDM in hydrostatic equilibrium
Velocity dispersion σ=const

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

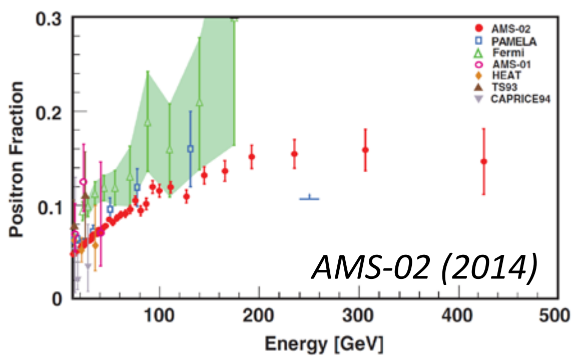
- If SIDM solves small scale issues in dwarfs, then velocity-dependent cross section favored (new light mediators)

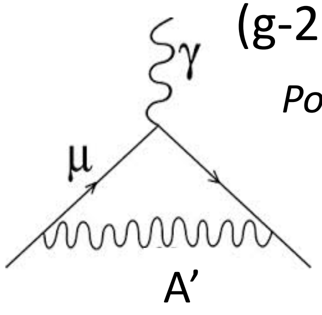
Conclusions

- Usual motivations for light dark sector states:

DM anomalies
Pamela/AMS-02
positron excess

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



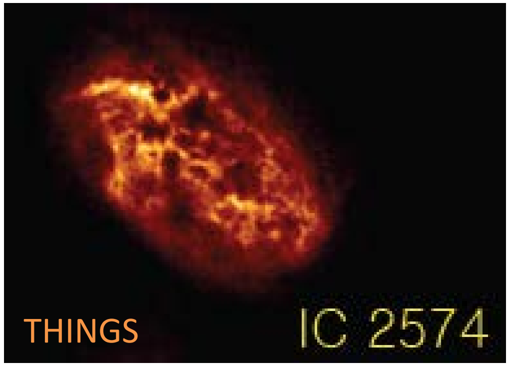


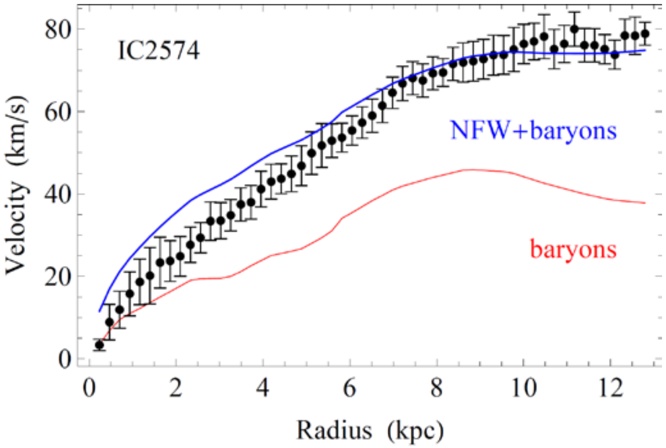
$(g\text{-}2)_\mu$ anomaly

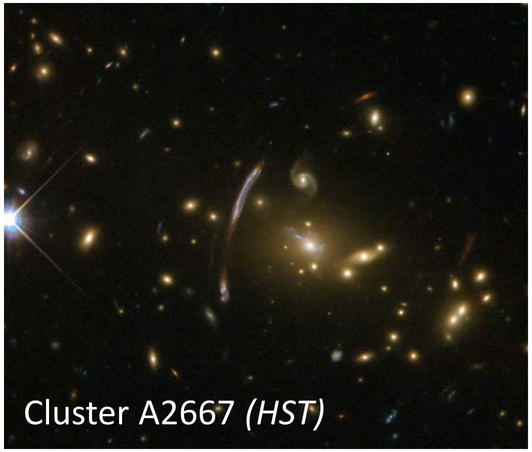
Pospelov (2008)

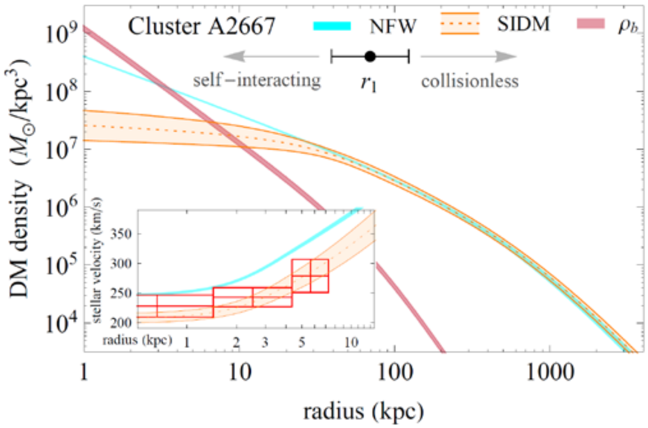
Conclusions

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

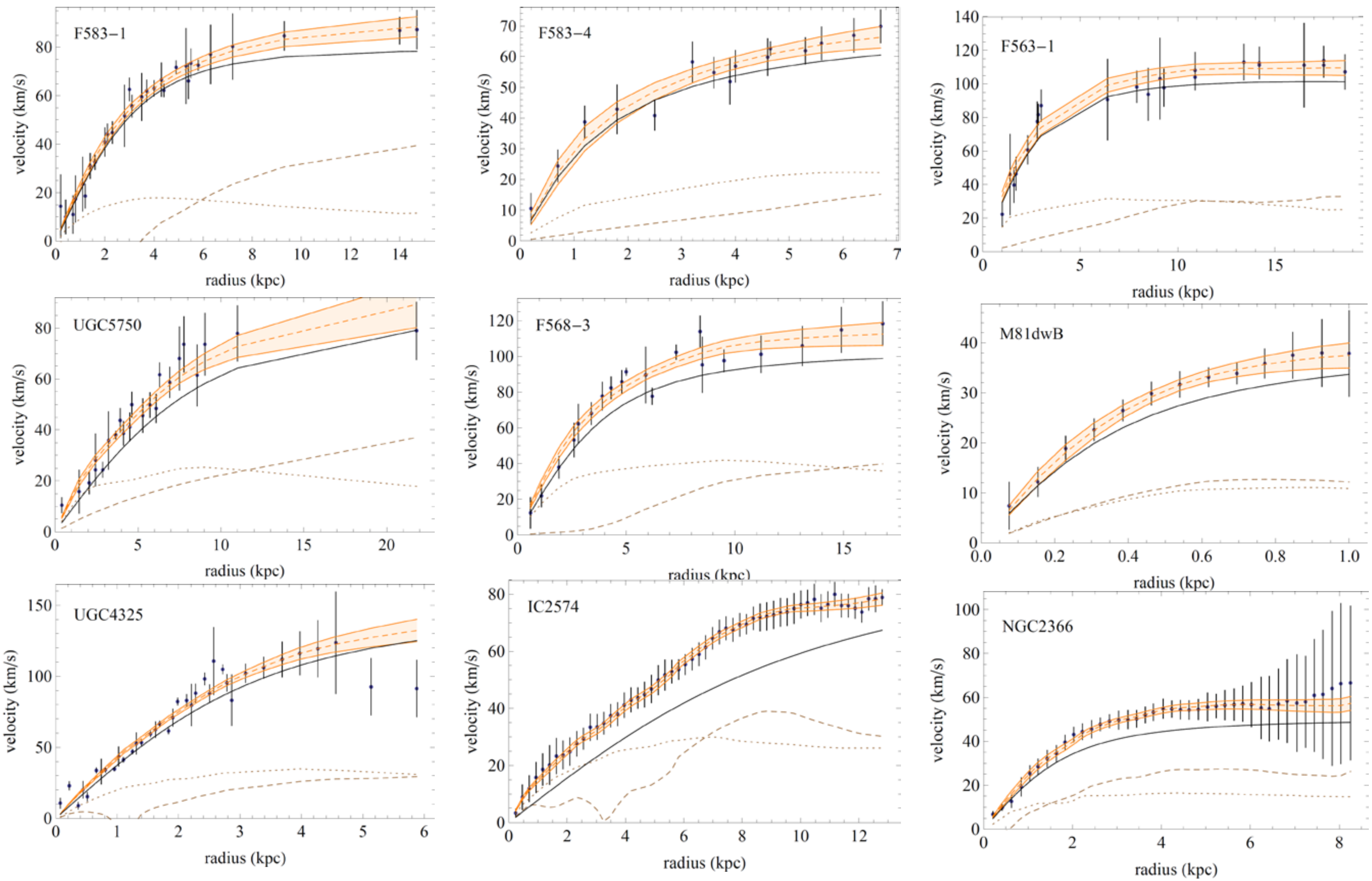








Galaxy rotation curves for SIDM



More SIDM fits to clusters