# Self-interacting dark matter

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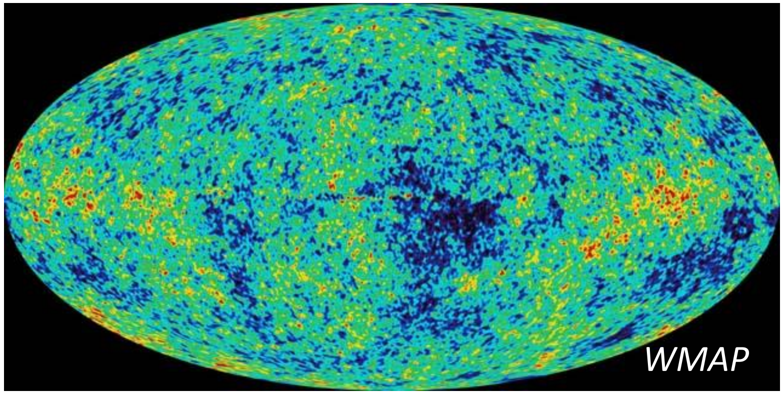
# Cold collisionless dark matter paradigm

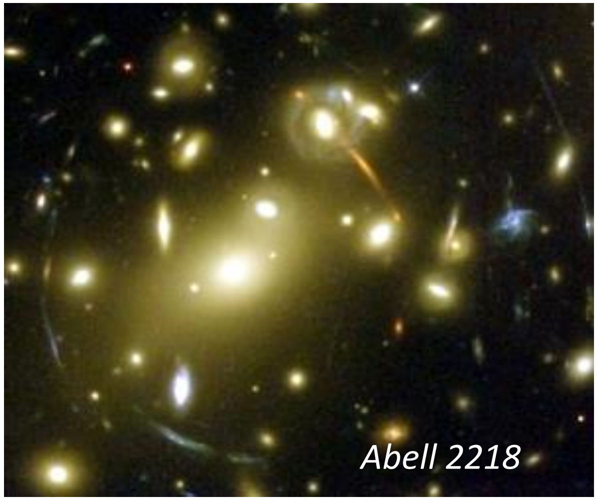
Dark matter (DM) is about 25% of the Universe

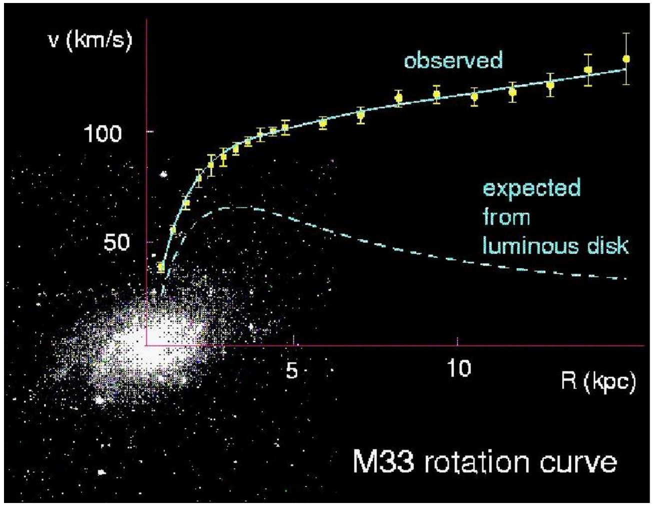




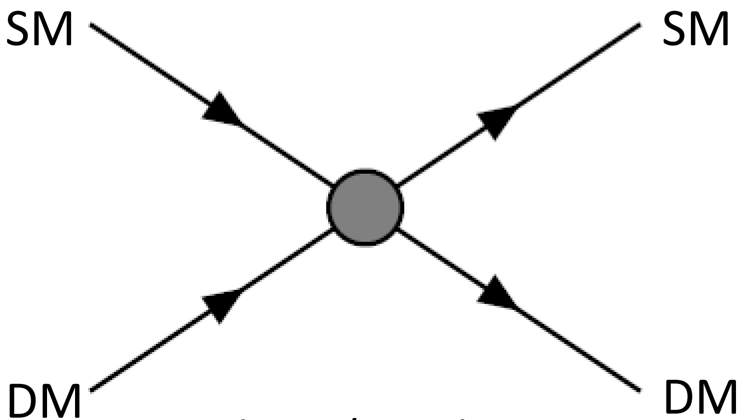
Cold collisionless dark matter (CDM) provides a good description of the structure of matter in the Universe

To date, evidence for DM from gravity only

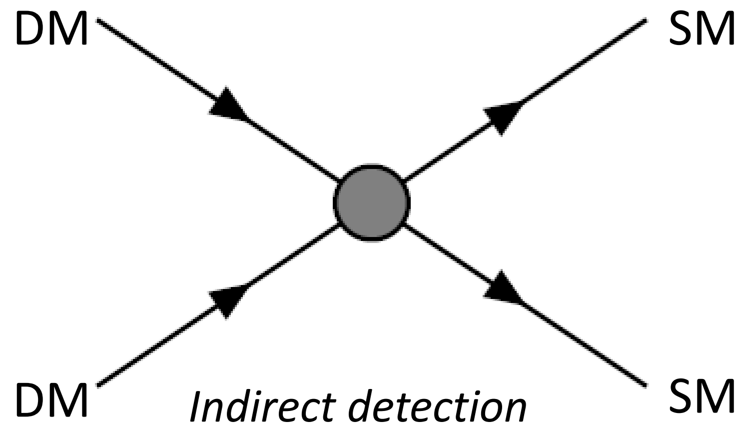


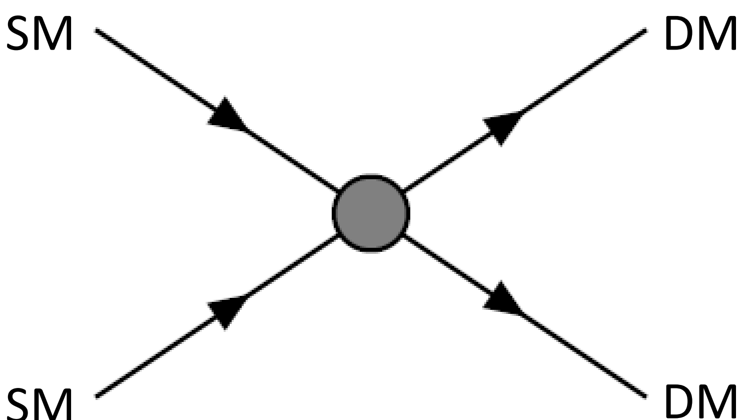
# Non-gravitational dark matter interactions




*Direct detection*




*Indirect detection*

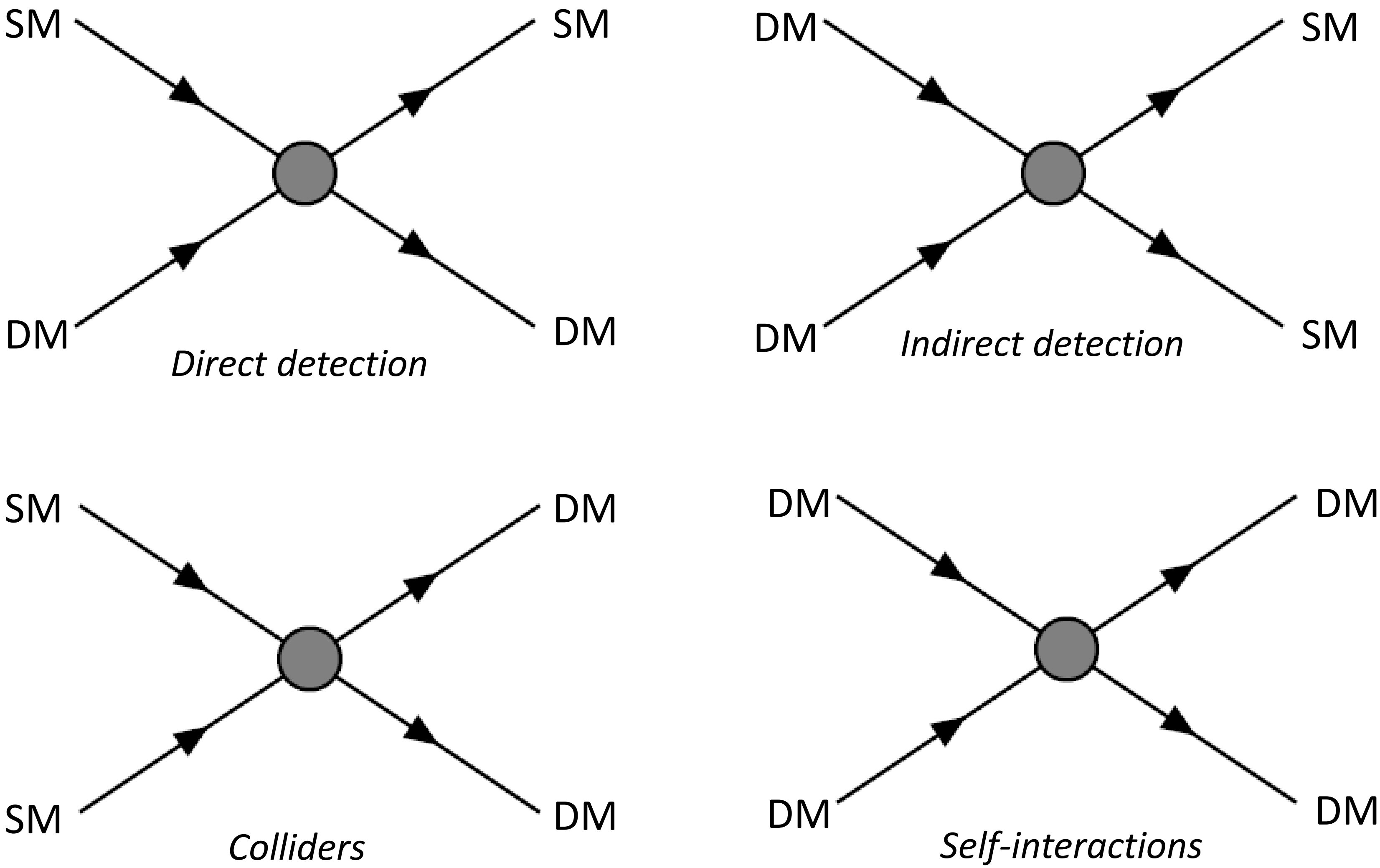



*Colliders*

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?

# Non-gravitational dark matter interactions



# Outline

- Issues with CDM (cold collisionless DM)
  - Discrepancies between N-body simulations and astrophysical observations
- Self-interacting dark matter
  - Probe dark sector independent of couplings to SM
  - Particle physics implications
  - Complementarity with WIMP searches

# CDM in trouble

1. Core-vs-cusp problem *Moore (1994), Flores & Primack (1994)*
   – Central densities of halos are cored

     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

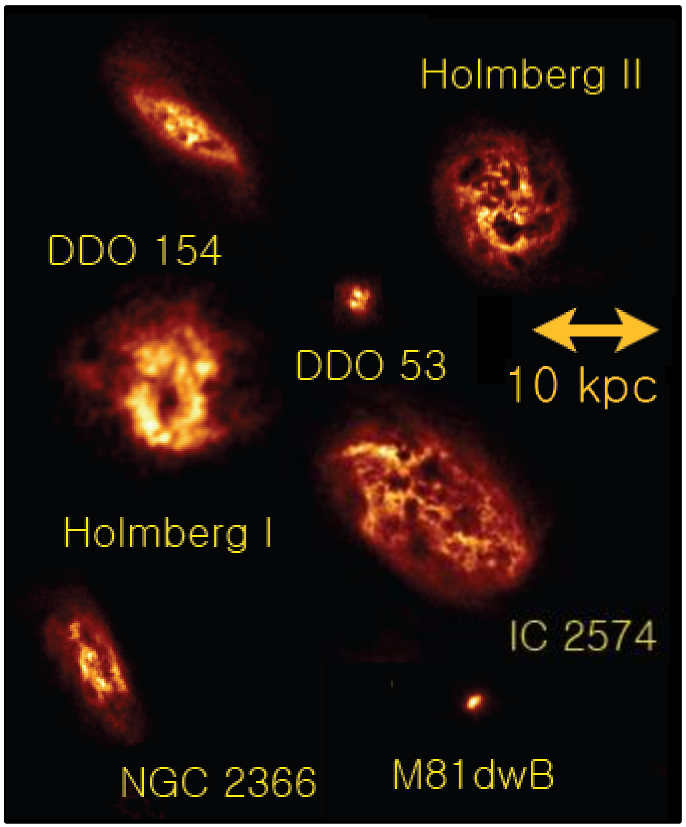
# 1. Core-vs-cusp problem

Cores seem fairly ubiquitous:

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

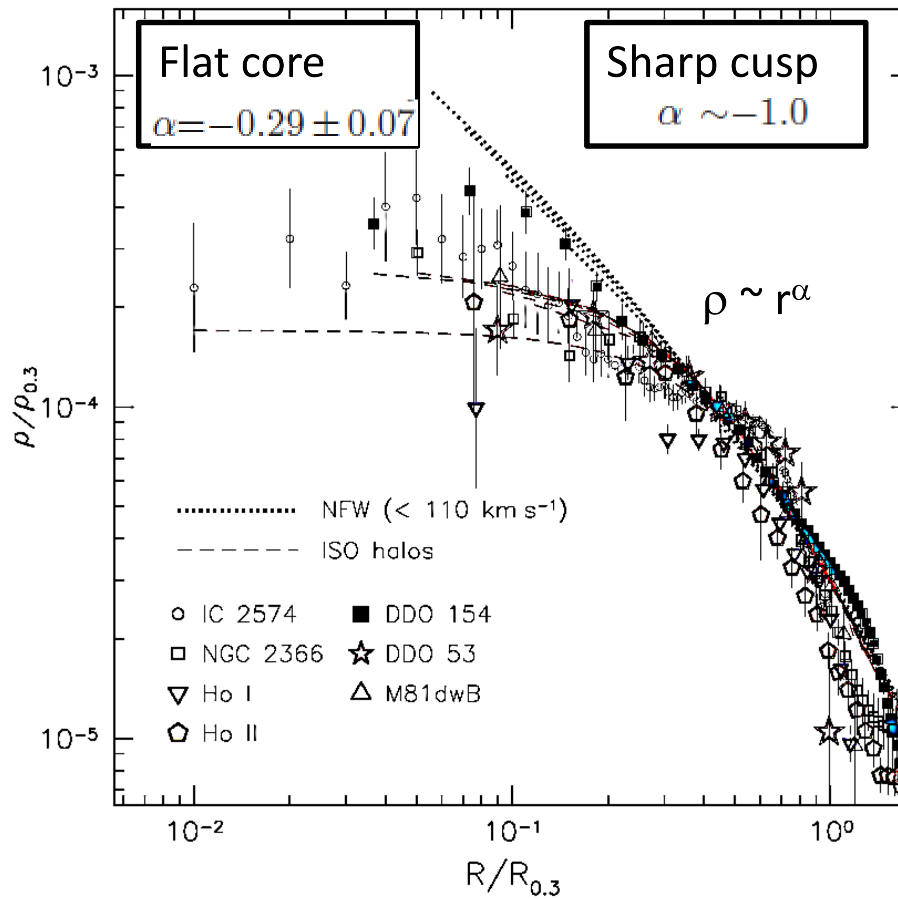
# Cores in field dwarfs

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

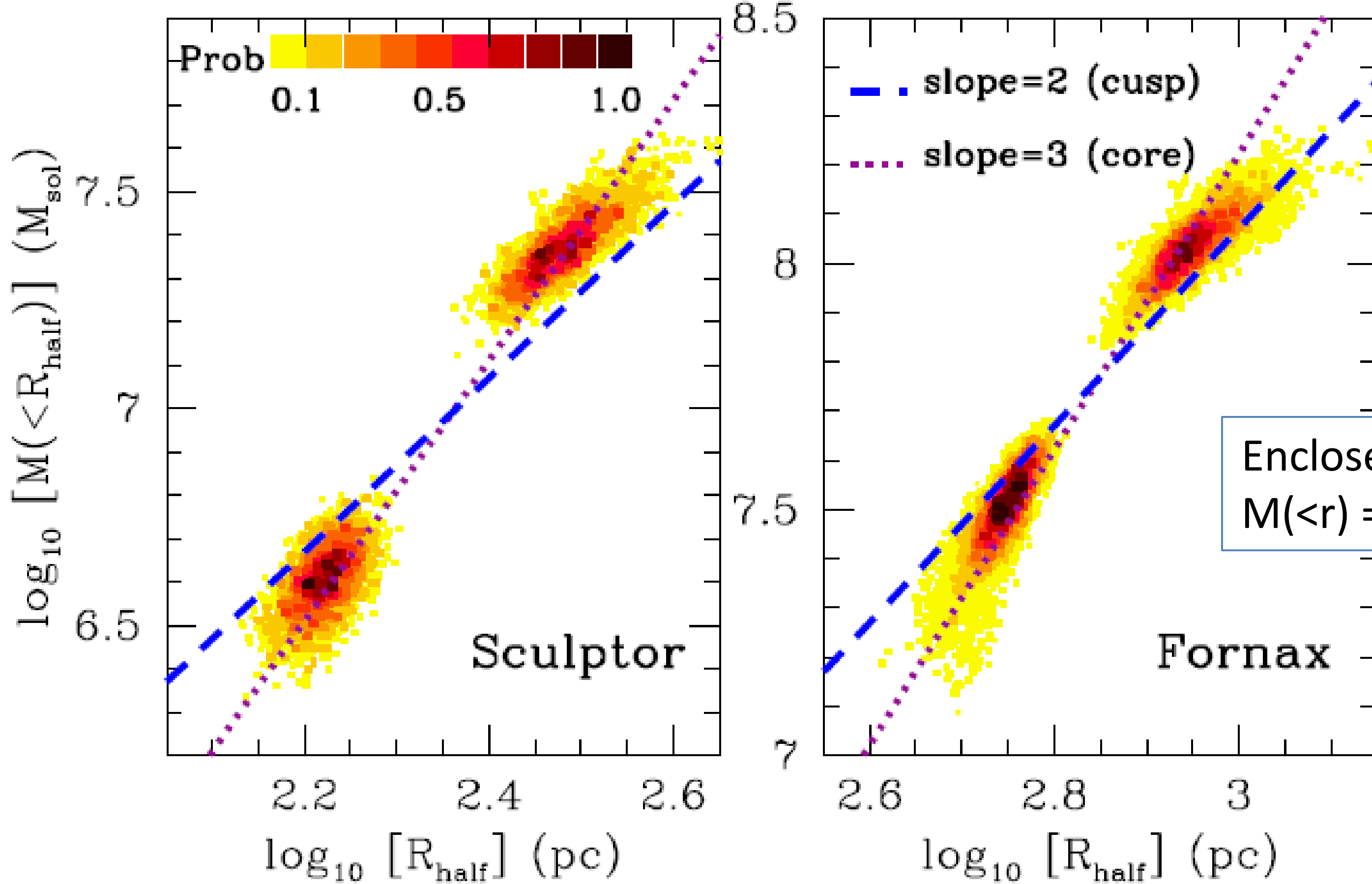



21 cm emission from gas

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



# Cores in MW dwarf spheroidals

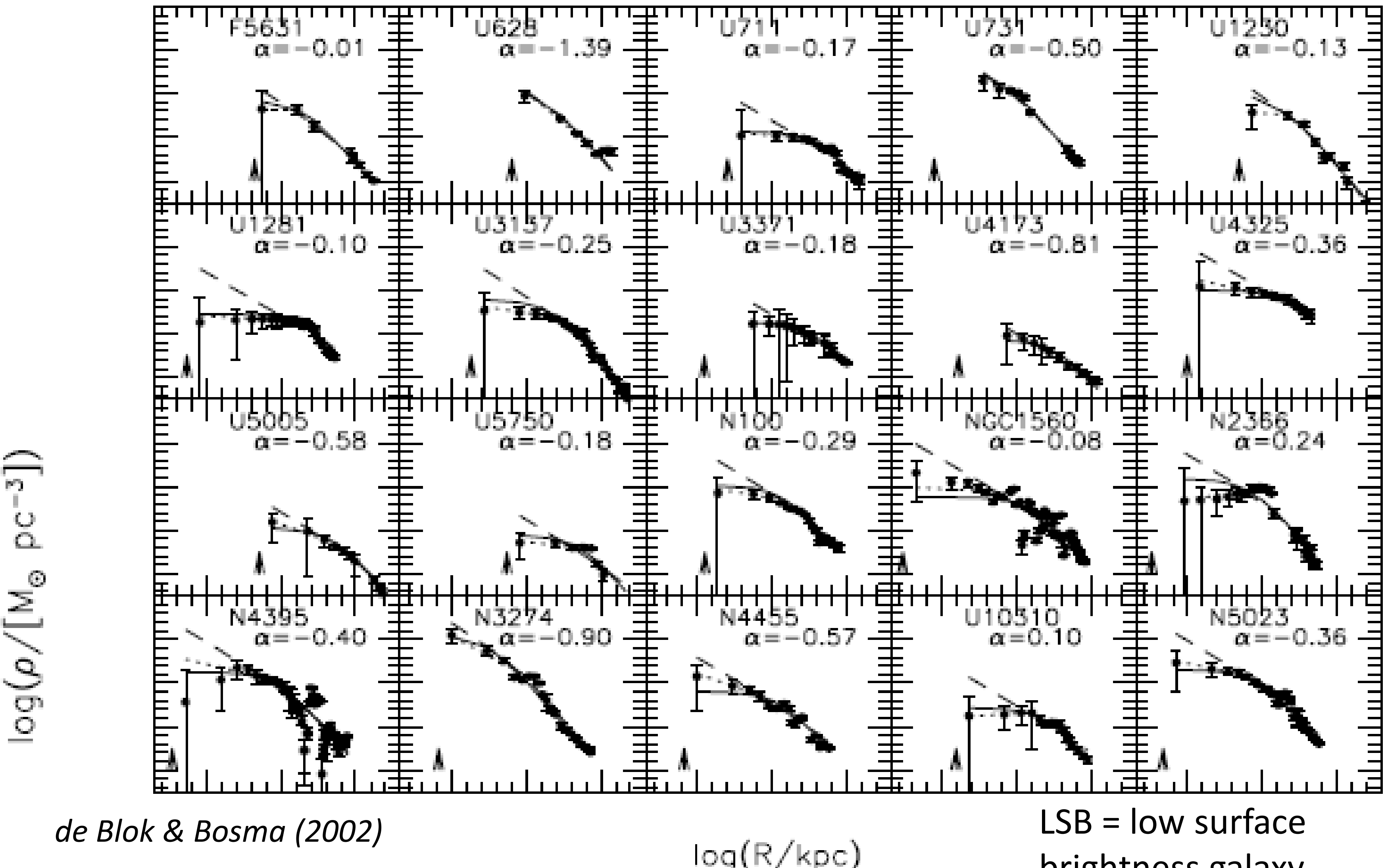



Enclosed mass
$M(<r) = \int d^3r\, \rho$

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

*Walker & Penarrubia (2011)*

# Cores in LSBs

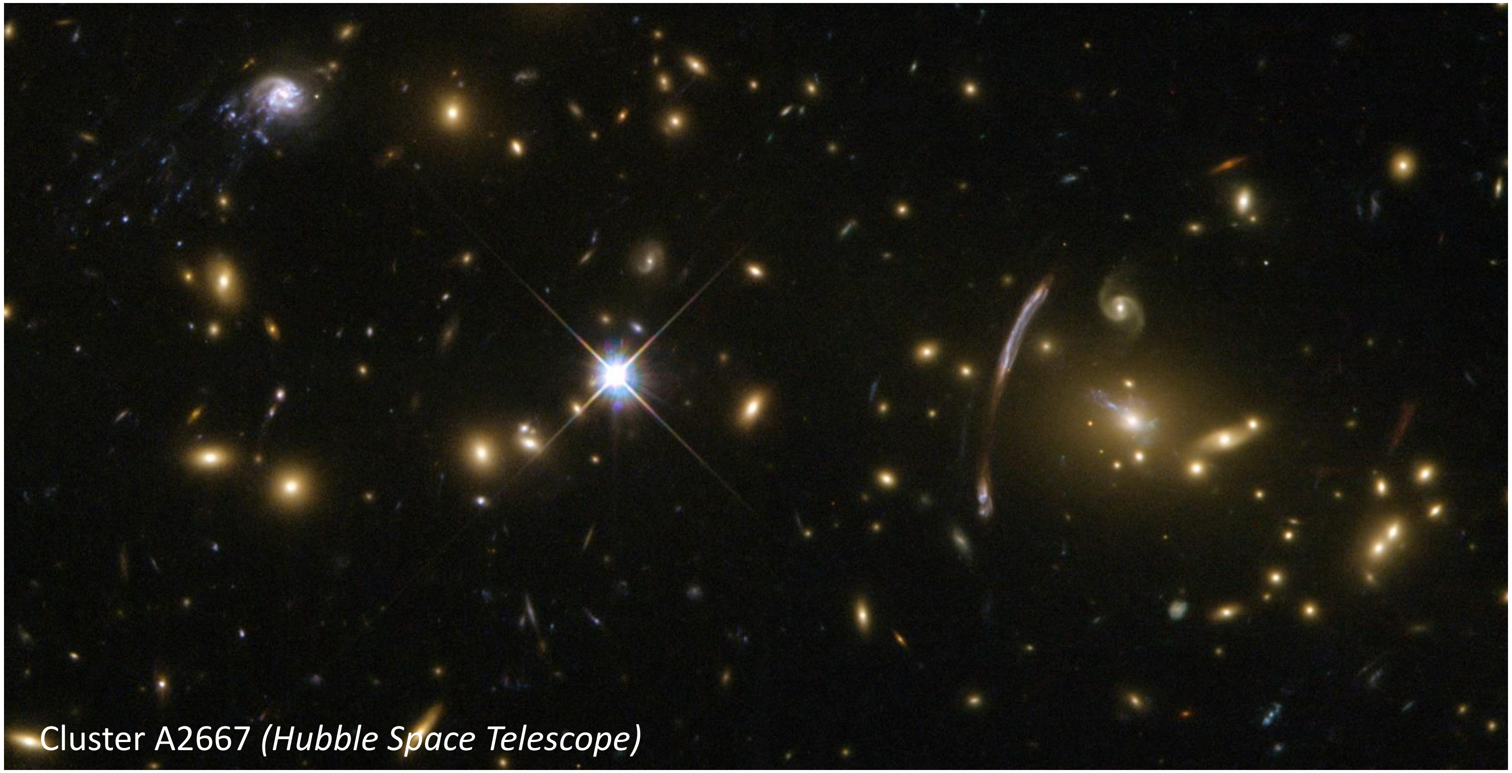



*de Blok & Bosma (2002)*

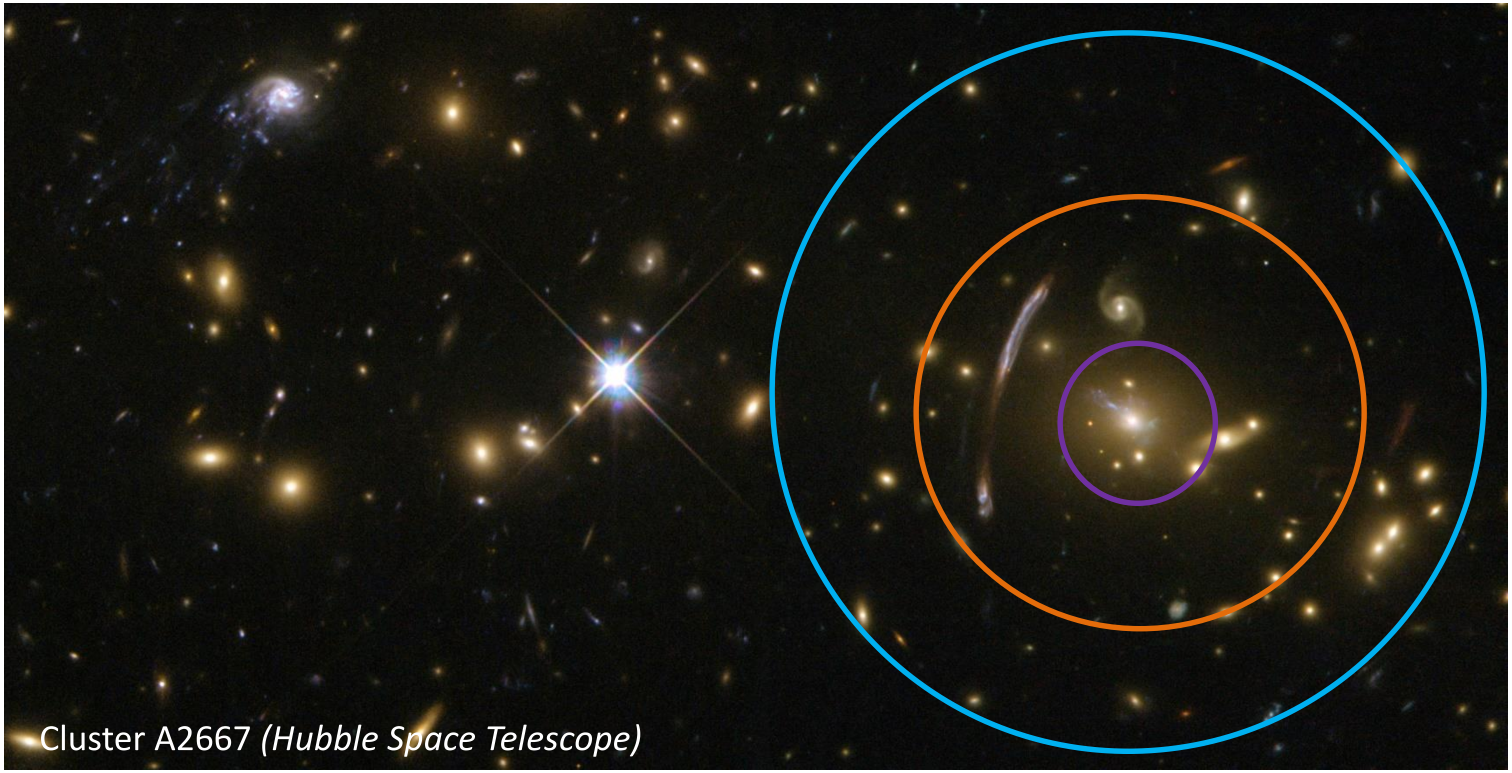
LSB = low surface brightness galaxy

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

# Cores in clusters



# Cores in clusters




Use multiple measurements to study dark matter halo

*Newman et al (2012)*

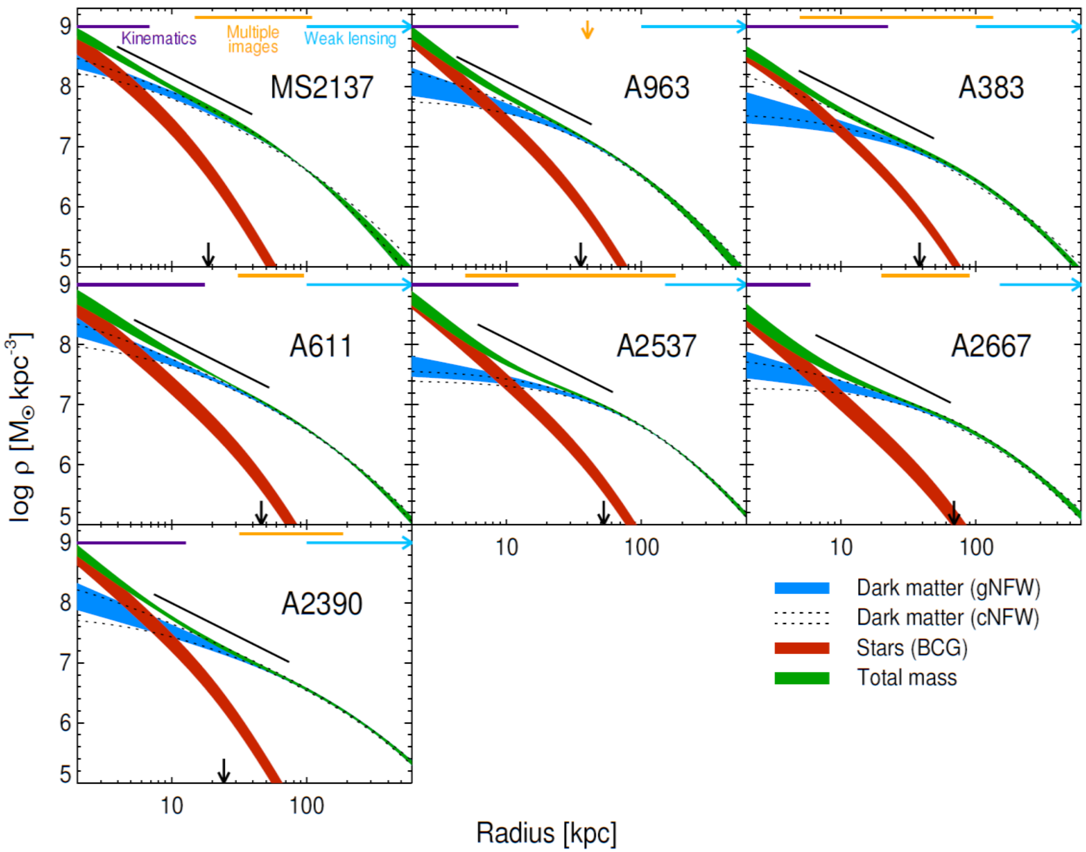
Weak gravitational lensing at large distance

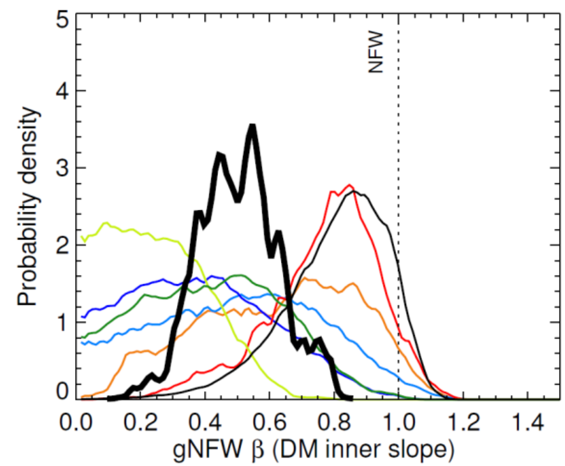
Gravitational lensing arcs (strong lensing) at medium distance

Stellar kinematics for the cluster center

# Cores in clusters

*Newman et al (2012)*



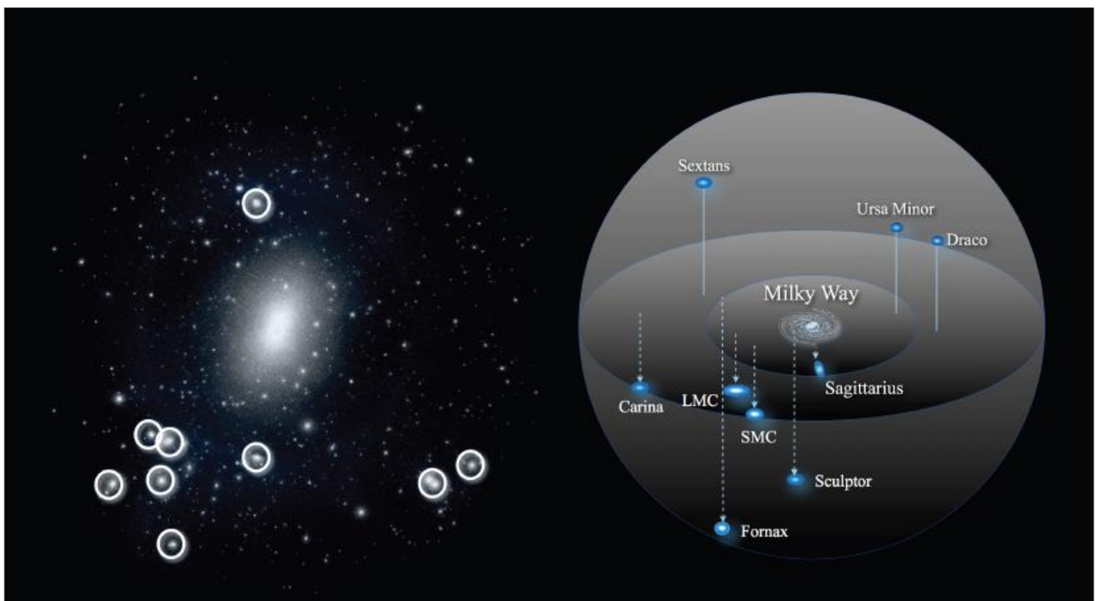

gNFW fit:

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

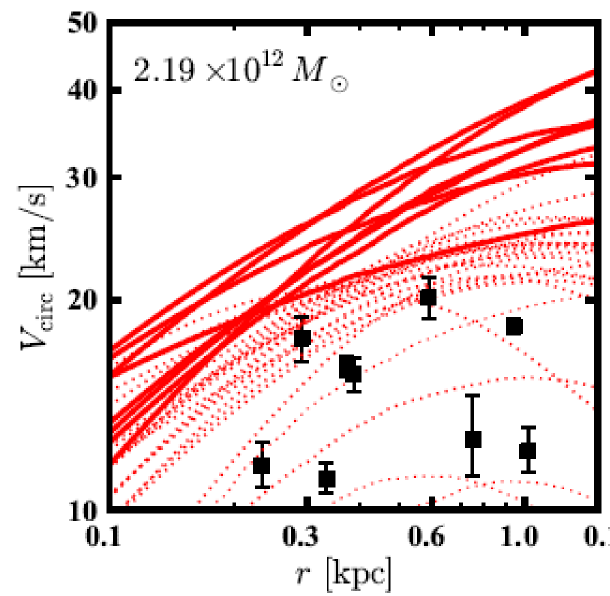
# 2. Too-big-to-fail problem

*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



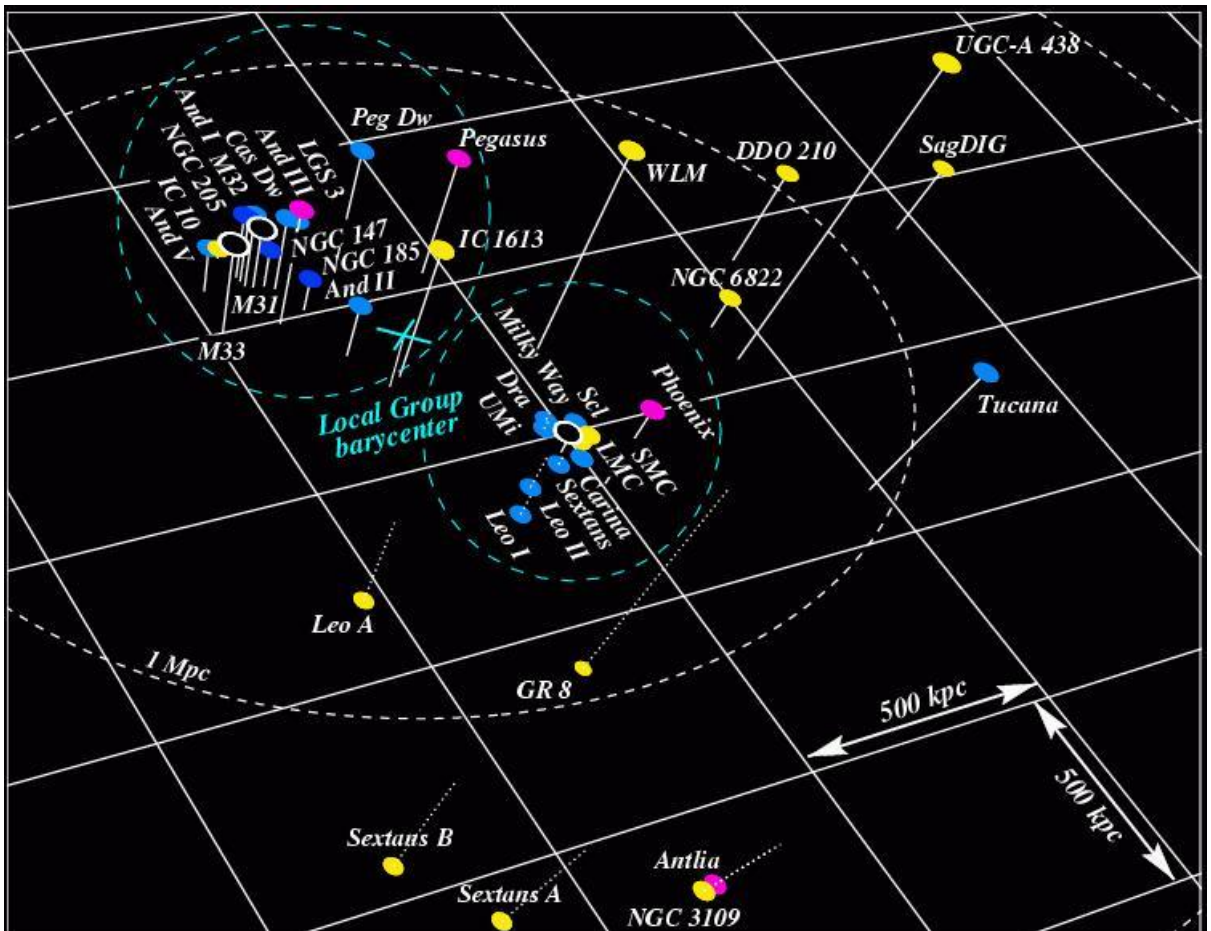

*From Weinberg, Bullock, Governato, Kuzio de Naray, Peter (2013)*



# 2. Too-big-to-fail problem

## Is there a problem beyond the Milky Way?

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



# CDM Problems

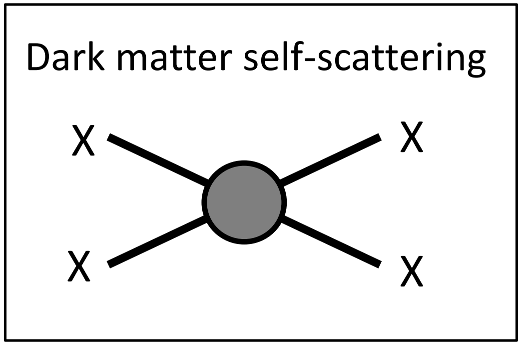
- Problem with our interpretation of observations
  - Can't use DM-only simulations to model real DM+baryons Universe
    - Supernova feedback (THINGS dwarfs) *Governato et al. (2012); Onorbe et al (2015)*
    - Environmental interaction (MW satellites) *Zolotov, et al (2012)*
    - AGN feedback (clusters) *Martizzi et al (2012)*
  - Astrophysical observations not being modeled correctly
    - Intrinsic scatter in number of MW satellites (Too big to fail) *Purcell & Zentner (2012)*
    - MW halo mass unknown within factor of two (Too big to fail)
    - Anisotropy in stellar motions (MW satellites and clusters) *Strigari et al (2014); Schaller et al (2014)*

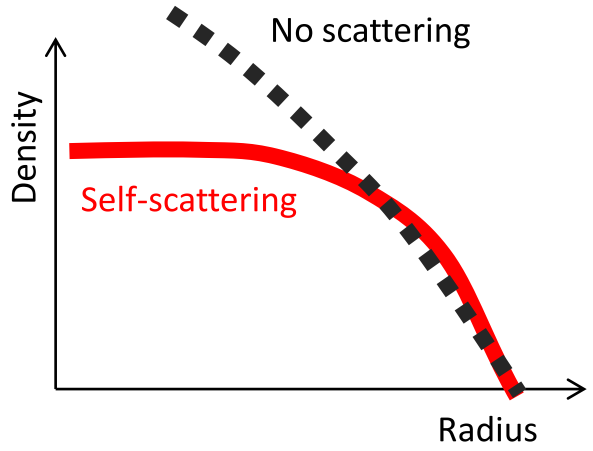
- Dark matter may not be CDM

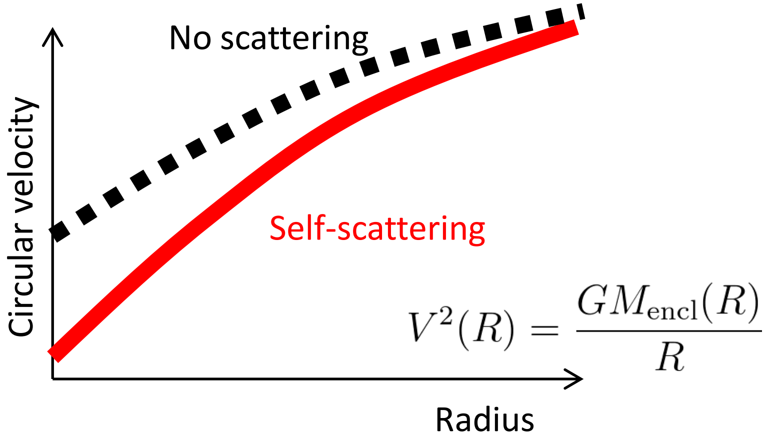
# Self-interacting dark matter

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

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




**Self-interactions solve core-vs-cusp**

*Particles get scattered out of dense halo centers*

**Self-interactions solve too-big-to-fail**

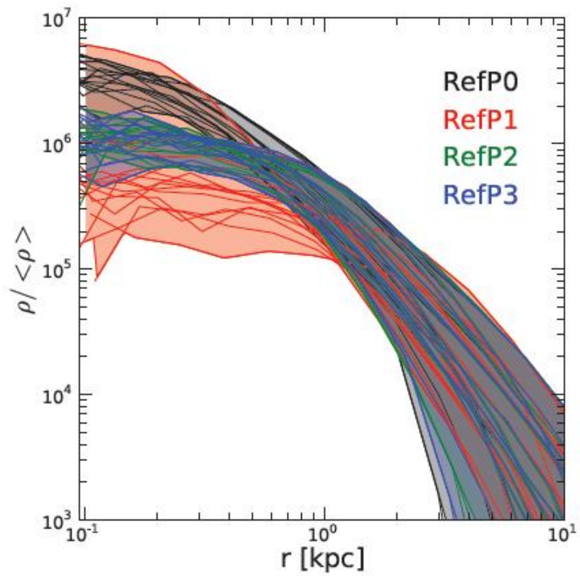
*Rotation curves reduced (less enclosed mass)*

*Simulated satellites matched to observations*

# N-body simulations for SIDM

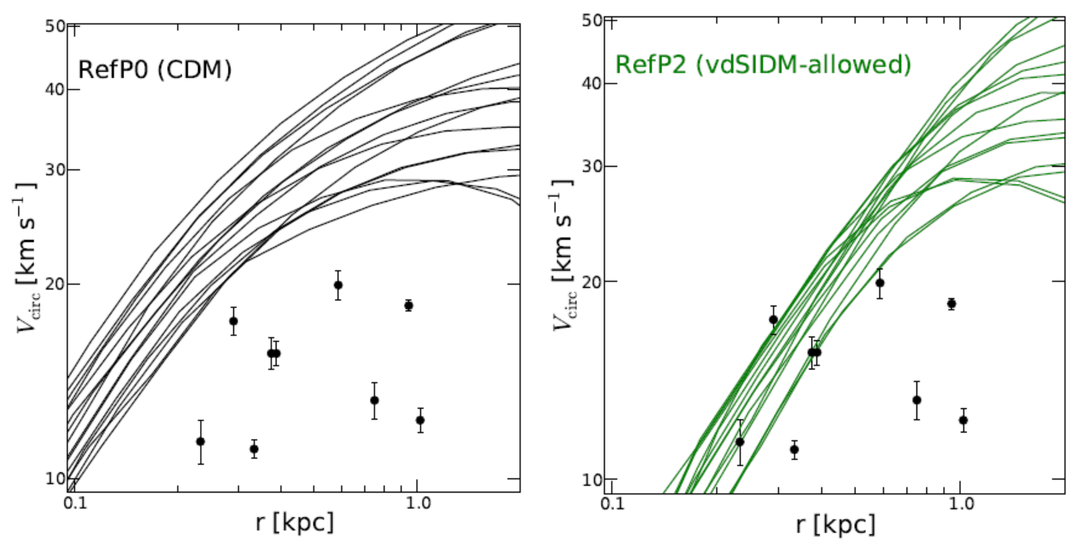
*Vogelsberger, Zavala, Loeb (2012); see also Rocha et al, Peter et al (2012)*

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 = $\sigma$ x ($\rho$/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

# Constraints on self-interactions

Ellipticity of galaxy cluster MS2137 (gravitational lensing)

Miralda-Escude bound (2003): $\sigma/m < 0.02$ cm$^2$/g

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


Ellipticity of massive elliptical galaxy (x-rays)

*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: $\sigma/m < 1$ cm$^2$/g

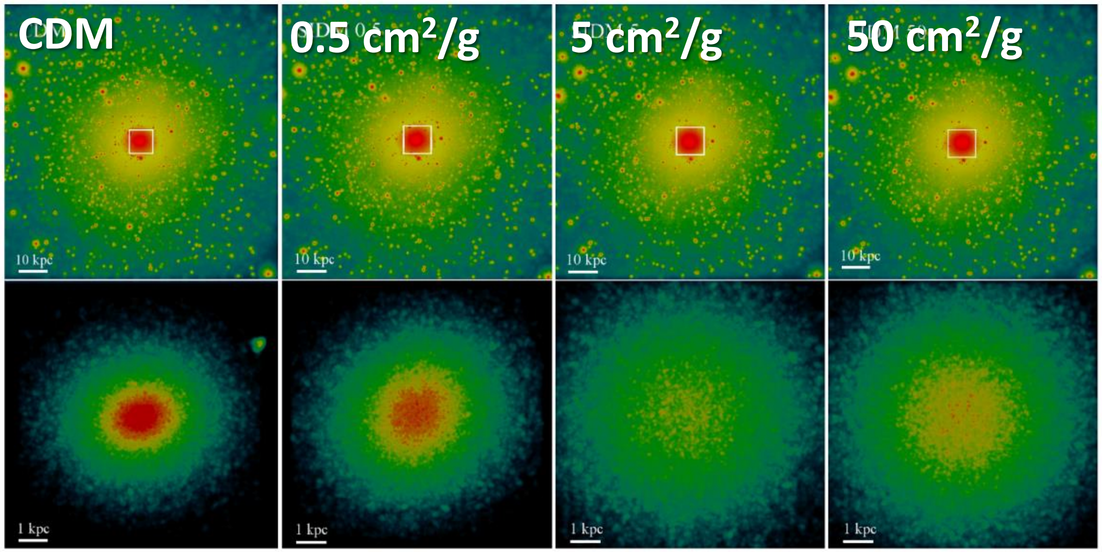
*Randall et al. (2007)*

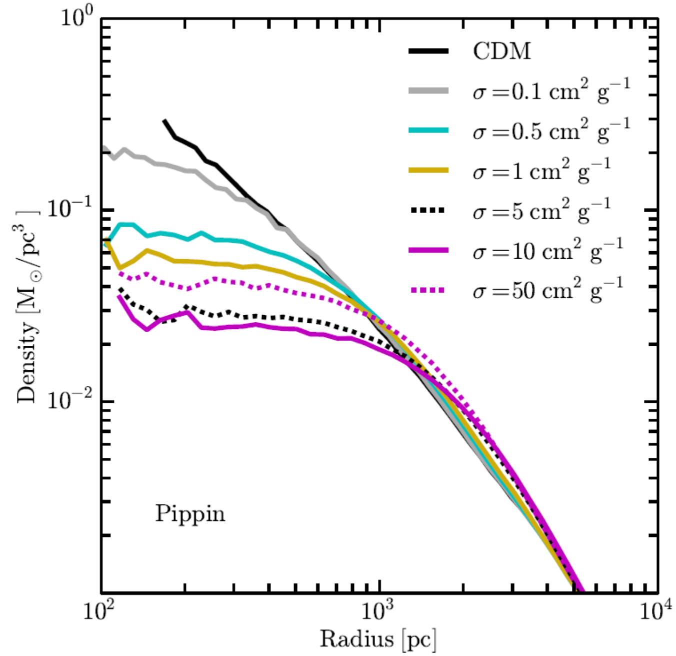
Constant cross section $\sigma/m \sim 0.5 - 1$ cm$^2$/g may be OK with all constraints

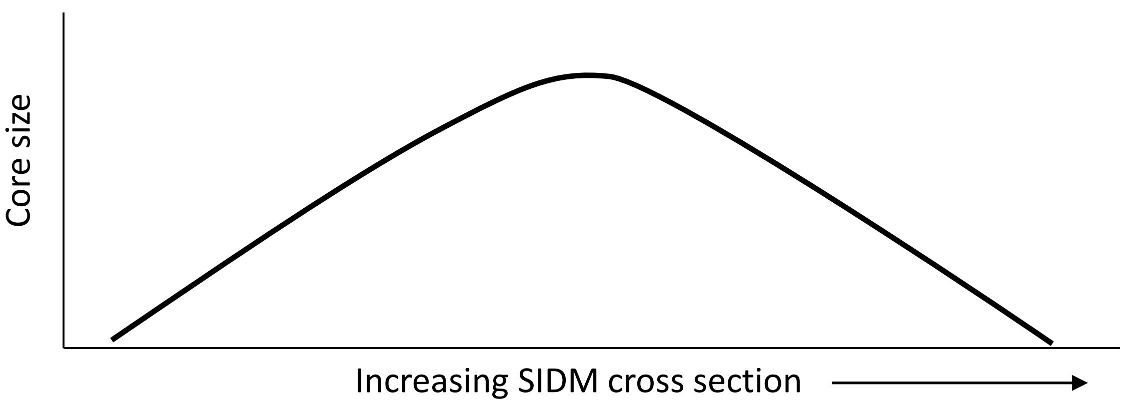
*Vogelsberger, Zavala, Loeb (2012); Rocha et al, Peter et al (2012)*

# 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 $\sigma$

# 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)*

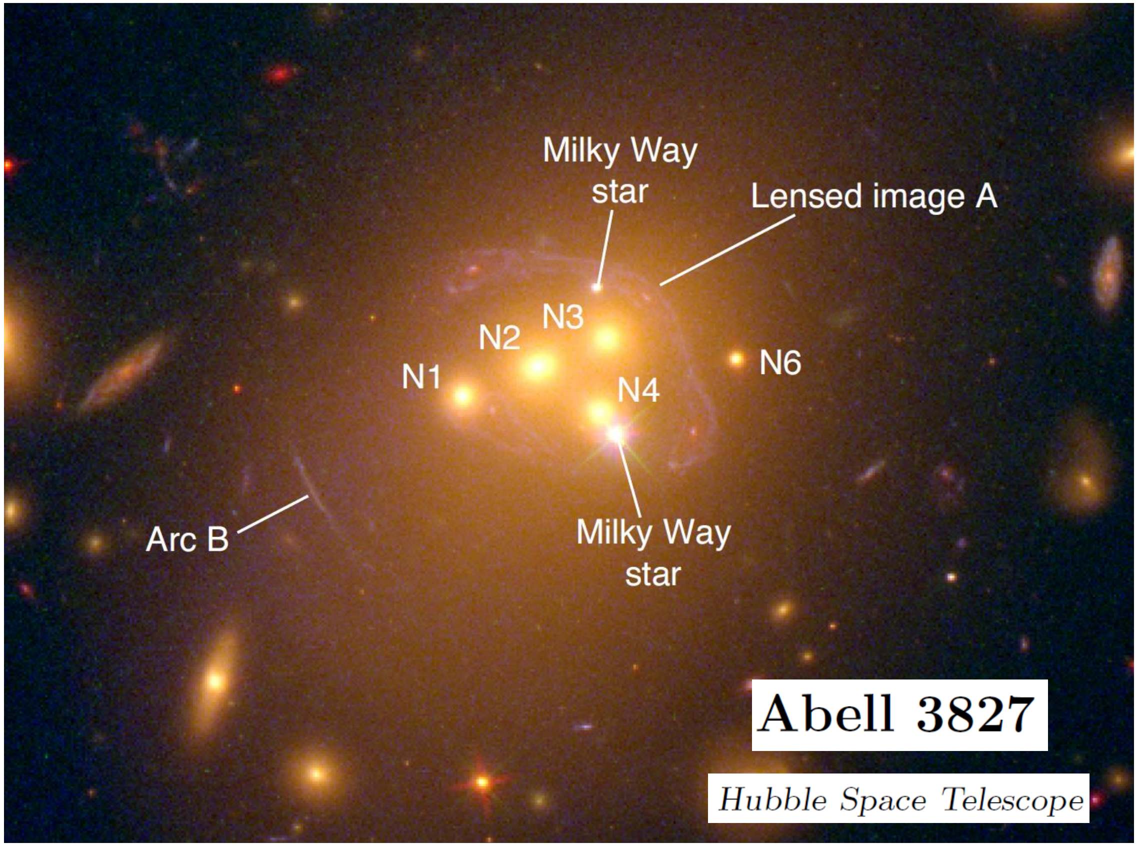
$\sim 3\sigma$ outlier from expected off-set from N-body sim.

*Schaller et al (2015)*

Required SIDM cross section:

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

*Massey et al (2015)*



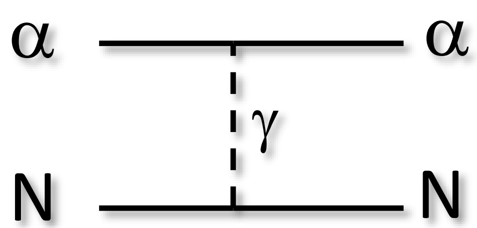

Limit assumed off-set = $\Delta x \sim \Delta f_{drag}\, t^2$ but neglected restoring force attracting DM and baryons

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

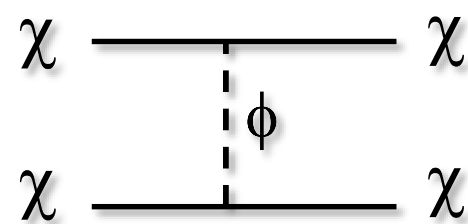
*Kahlhoefer et al (2015)*

# From astrophysics to particle physics

## Dark matter self-interactions




Rutherford scattering




self-interaction

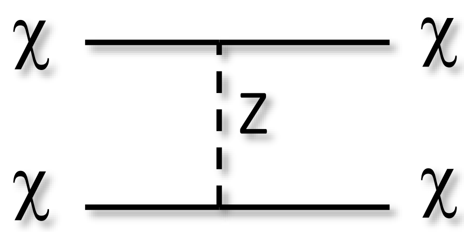
$\chi$ = dark matter particle

$\phi$ = mediator particle
(dark photon, dark Higgs,
dark pion, …)

Lots of model building possibilities

# From astrophysics to particle physics

## WIMPs have self-interactions (weak interaction)




self-interaction

$\chi$ = 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:

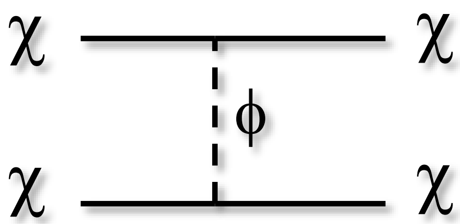
$$m_\chi \sim m_Z \sim 100\ \mathrm{GeV}$$

WIMP self-interaction cross section is way too small

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

# 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

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

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

# From astrophysics to particle physics

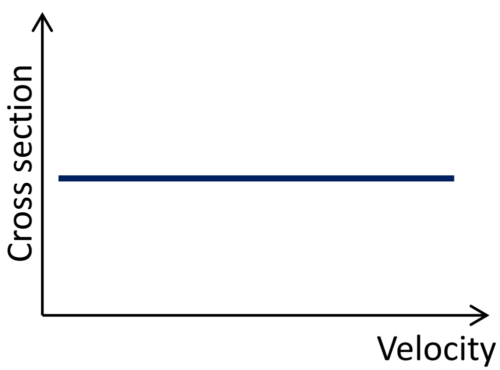
Lesson #2: Light mediator implies velocity-dependent scattering cross section

Extreme examples:

Contact interaction
(e.g. Fermi theory)

$m_\phi \gg m_\chi v$

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

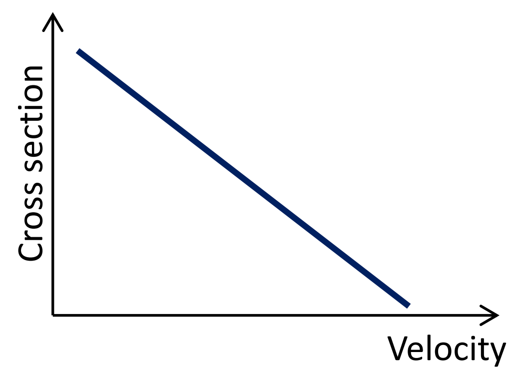



Complicated velocity dependence

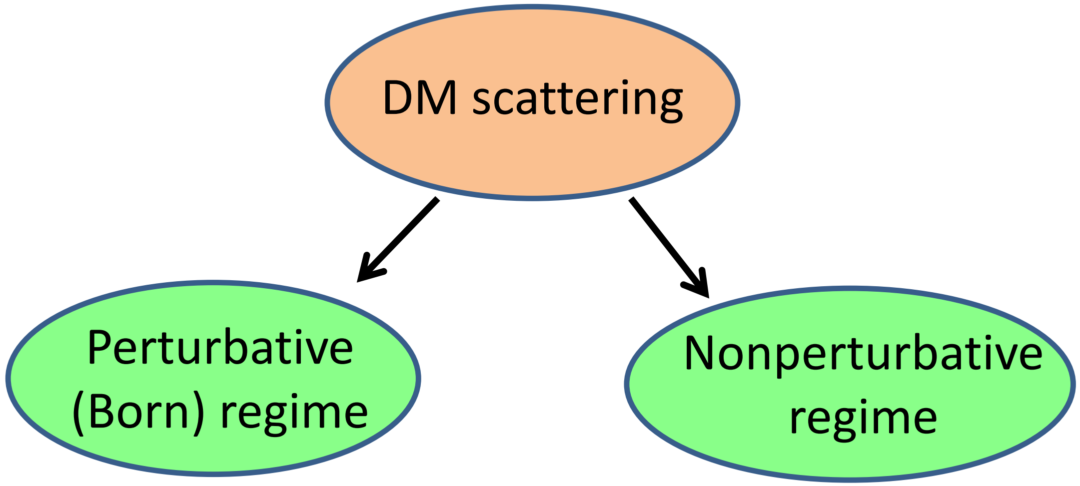
Massless mediator
(e.g. Rutherford scattering)

$m_\phi \ll m_\chi v$

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

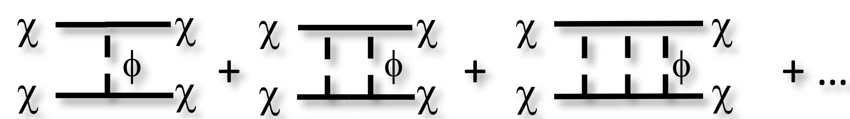


# DM self-interaction cross section




Easy to compute

Compute nonrelativistic potential V(r)
Solve Schrodinger equation for phase shifts
Cross section obtained from partial waves




Like Sommerfeld enhancement for scattering

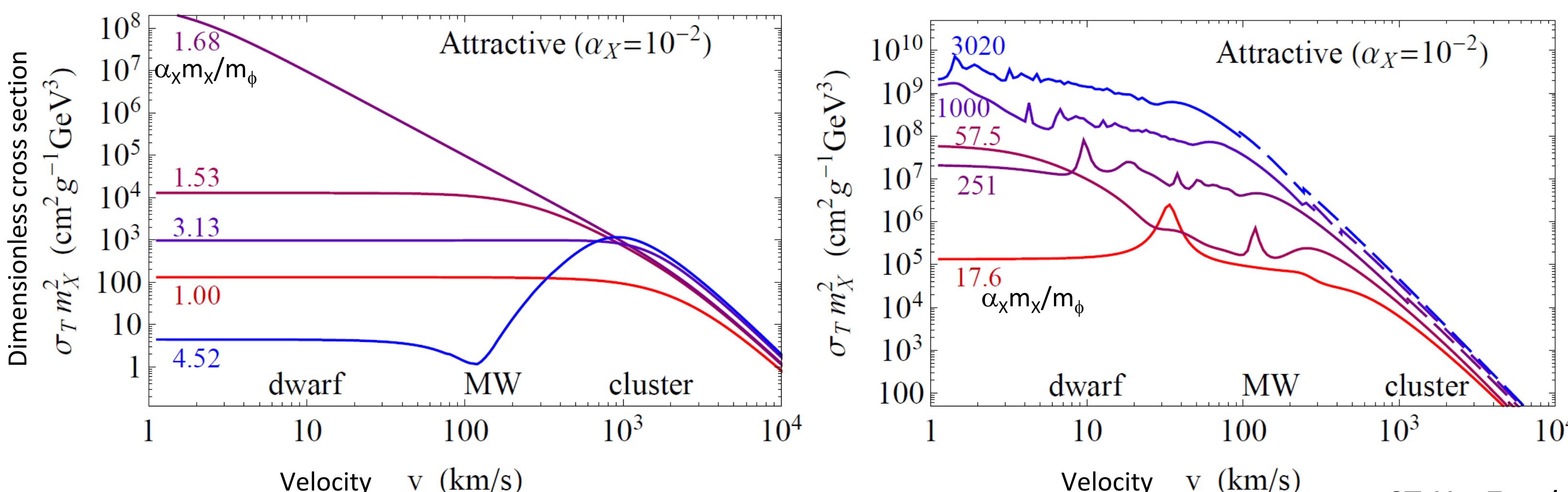
# DM self-interaction cross section

Example: Dark matter + dark photon model $\mathscr{L}_{\text{int}} = g_X \bar{X}\gamma^\mu X \phi_\mu$

Potential: $V(r) = \pm\frac{\alpha_X}{r} e^{-m_\phi r}$ Parameters: $m_\chi$, $m_\phi$, $\alpha_X$

Complicated velocity dependent cross section

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




*ST, Yu, Zurek (2013)*

Even simple DM + dark photon model has a complicated behavior

# 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



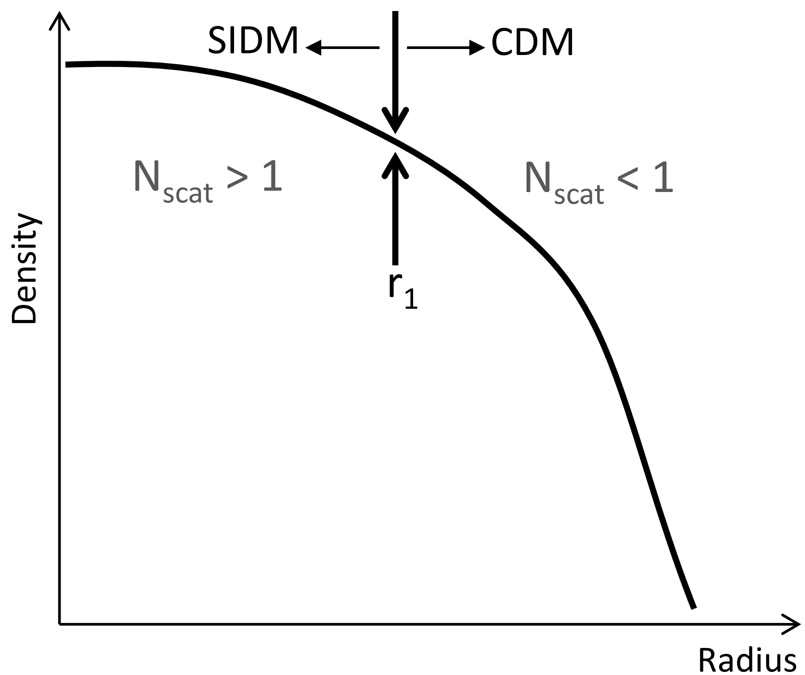
# Dark matter halos as colliders

*Kaplinghat, ST, Yu (2015)*

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

# Modeling SIDM without N-body simulations

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

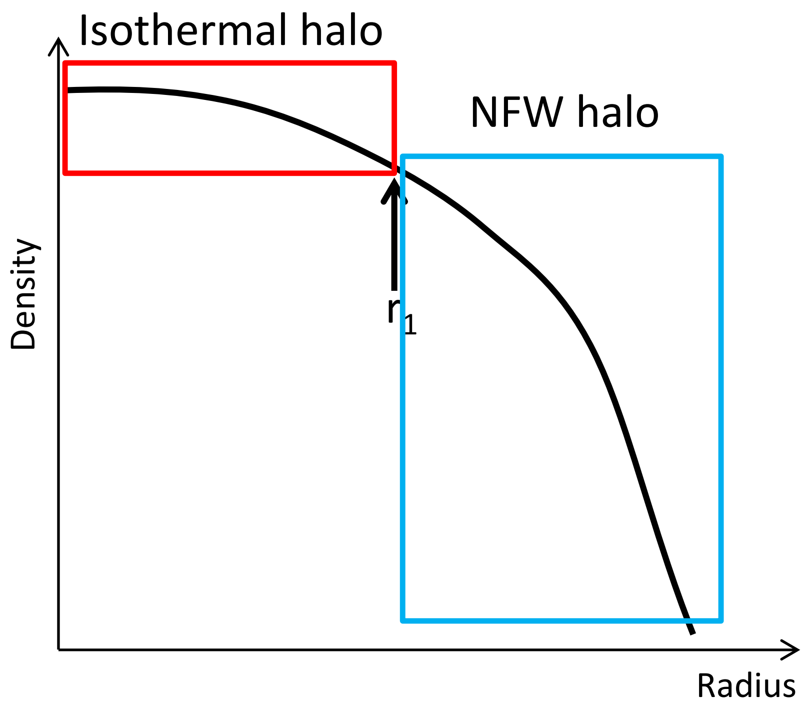



Inner halo ($r < r_1$): expect DM to be thermalized

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

Density at $r_1$ defines cross section where 1 scattering has occurred

# Modeling SIDM without N-body simulations




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 $r = r_1$.

Strategy: Scan over halo parameters and fit to astrophysical data.
Only consider core-growing solution (smaller cross section)

Relaxing this assumption: work in progress: *Sophia Nasr, ST*

# SIDM fits to dwarfs, LSBs, and clusters

*Kaplinghat, Tulin, Yu (2015)*

Astrophysical dataset:

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

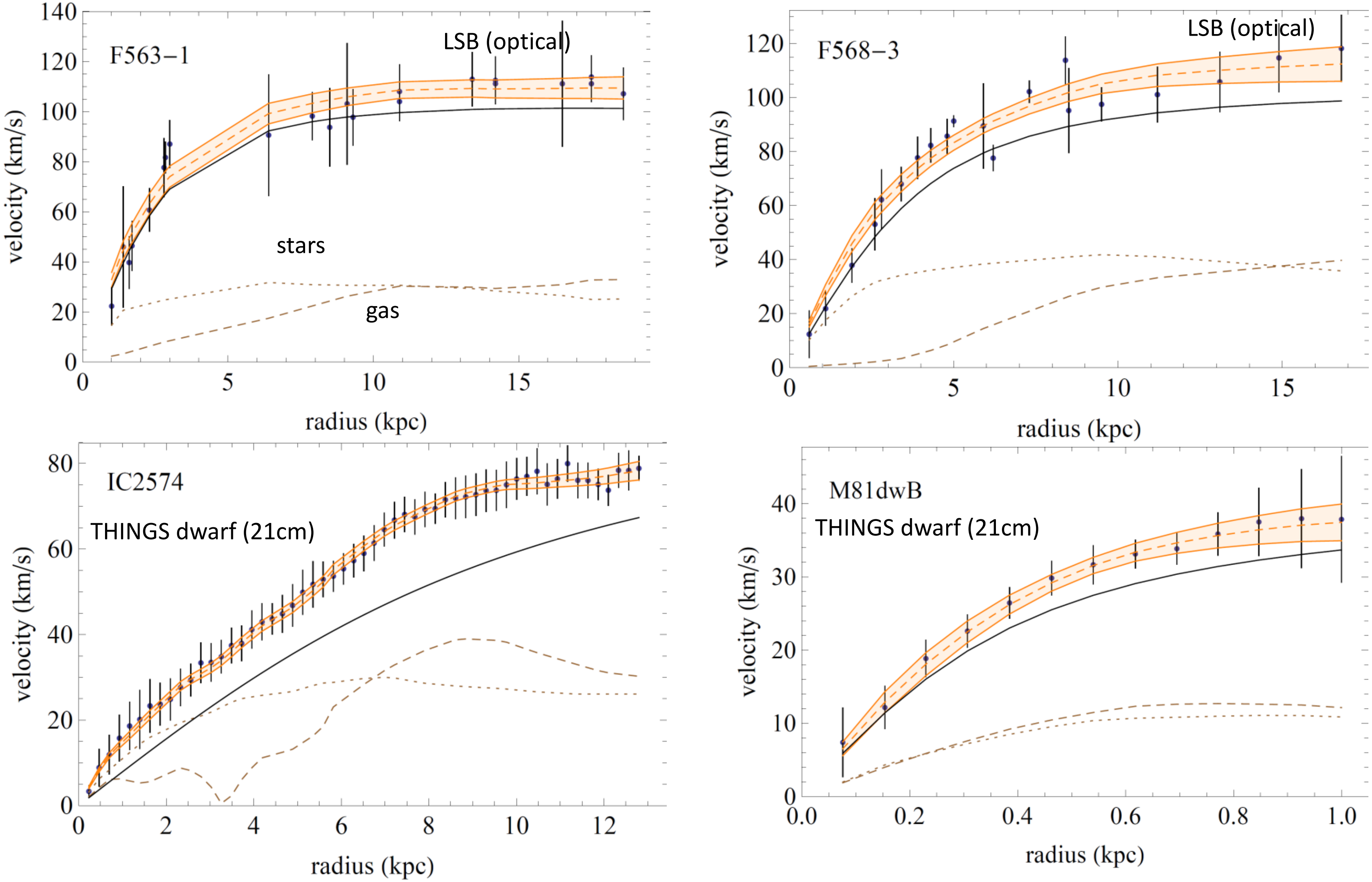
8 LSB galaxies (UGC4325, F563-V2, F563-1, DDO64, F568-3, UGC5750, F583-4, F583-1)
*Kuzio de Naray et al (2007)*

6 THINGS dwarf galaxies (IC2574, NGC2366, HO II, DDO53, M81dwB, DDO154)
*Oh et al 2011*

Work in progress: expanding data set with ~100 galaxies
*Pace, Kaplinghat, Tulin, Yu, Andrade*

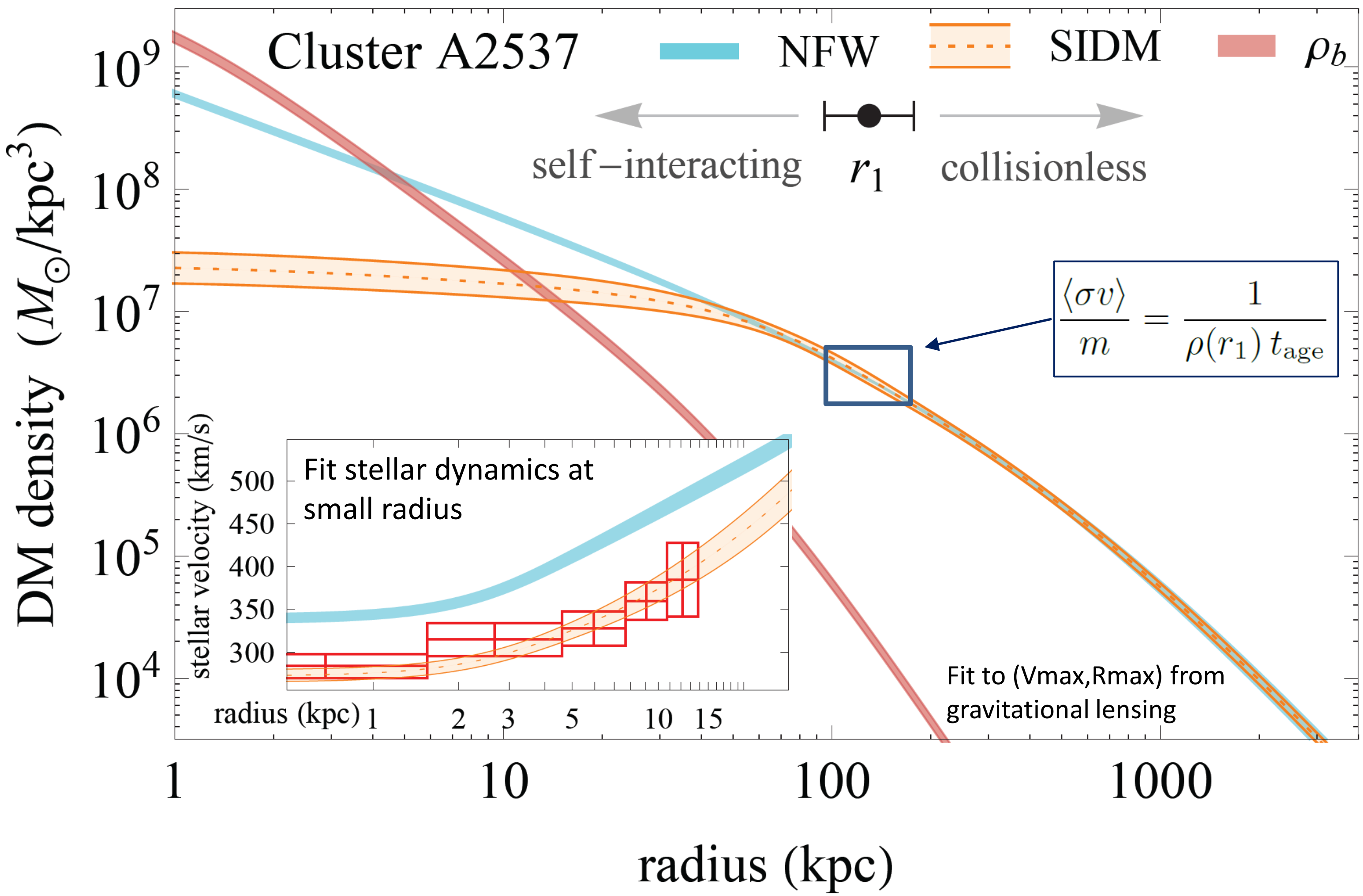
# Galactic rotation curves

(Even better fit than MOND)

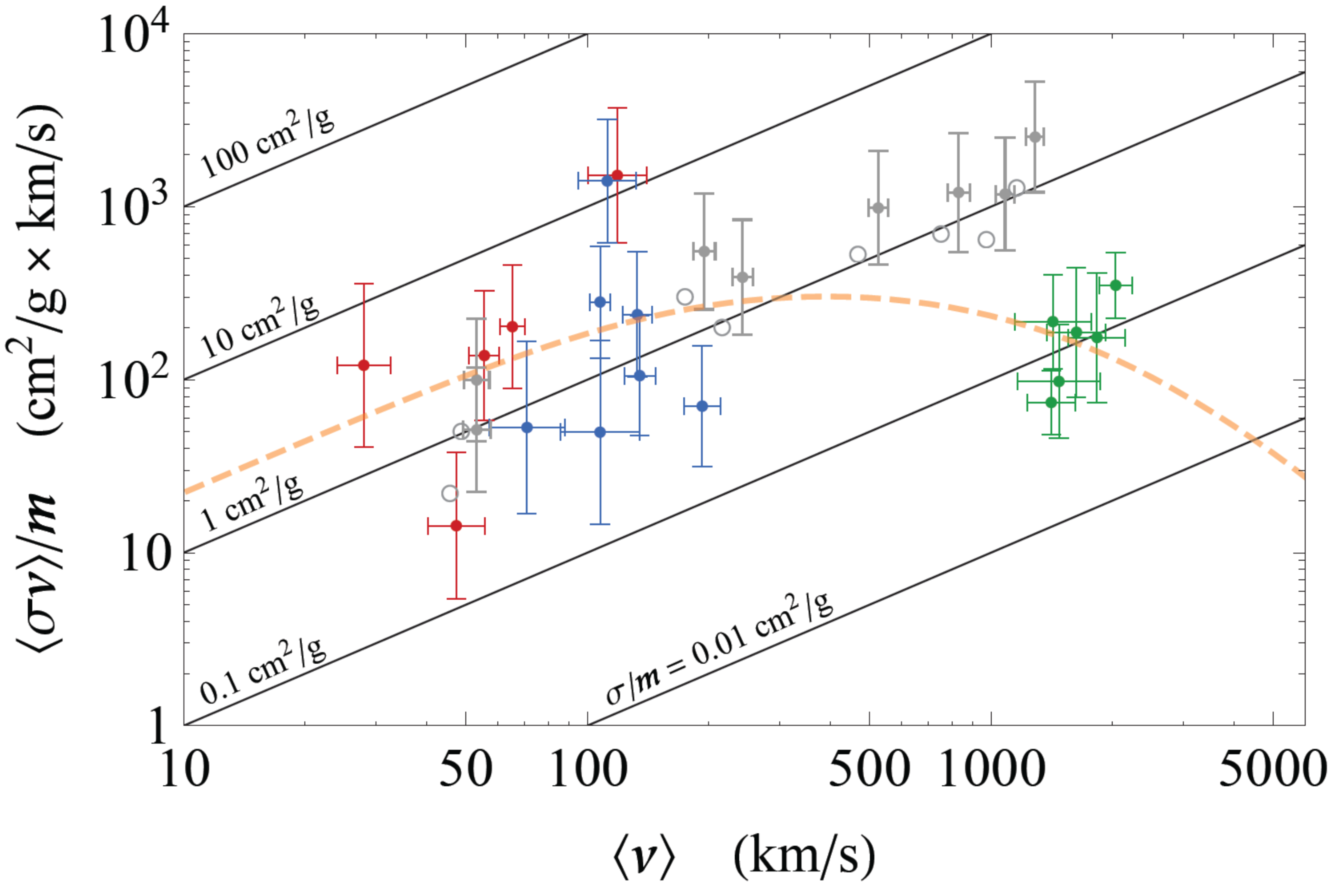


# Clusters

Scan over SIDM halo parameters and fit to stellar kinematics data



# SIDM fits to dwarfs, LSBs, and clusters




N-body sim data for SIDM 1cm$^2$/g (calibration)

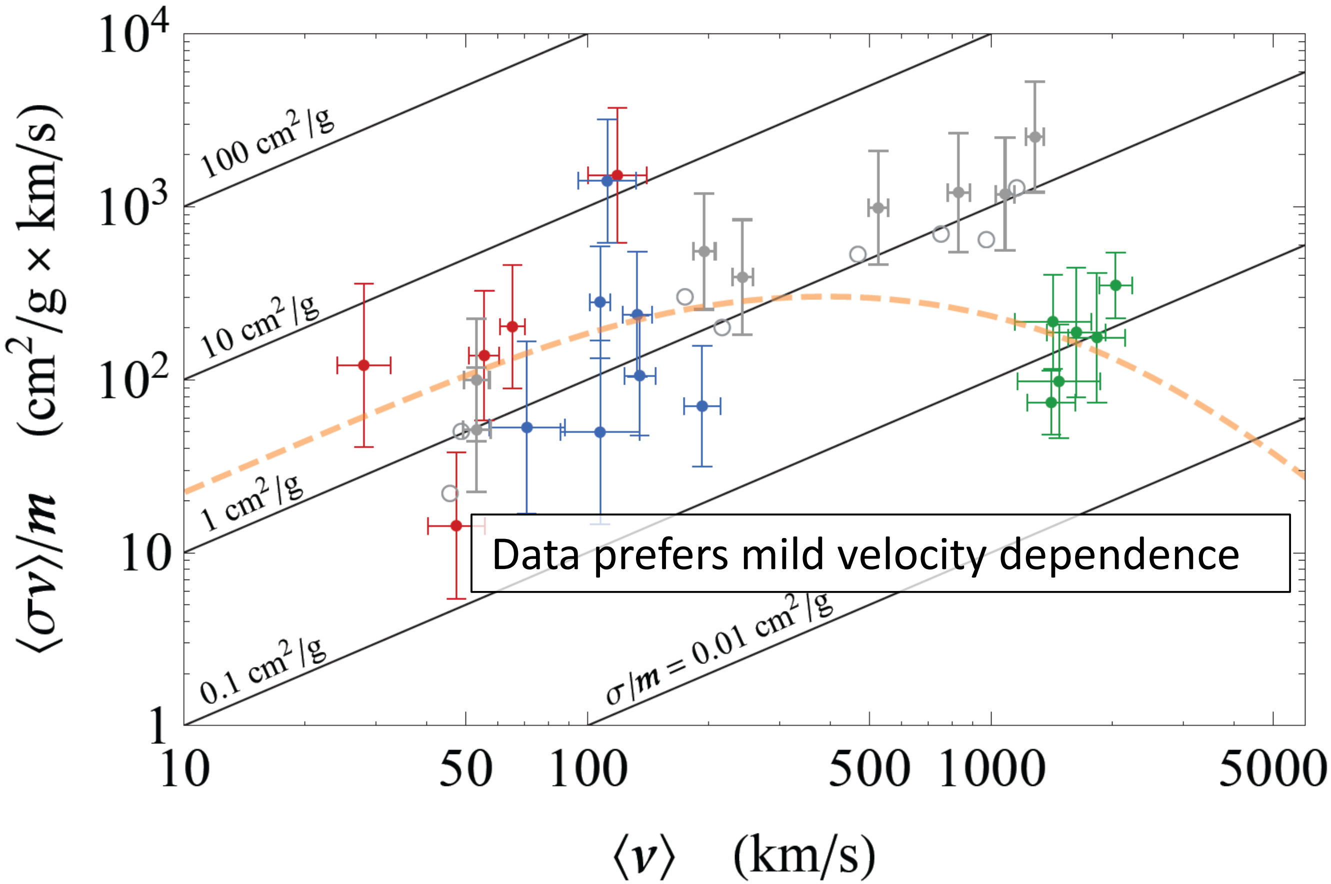
Note: error bars don't include **systematic** errors (factor of 2)

THINGS dwarfs

LSB spiral galaxies

clusters

# SIDM fits to dwarfs, LSBs, and clusters




N-body sim data for SIDM 1cm$^2$/g (calibration)

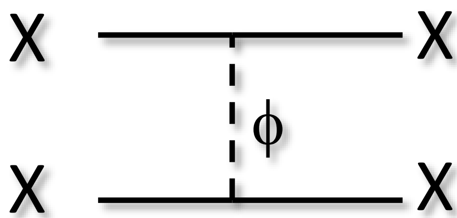
Note: error bars don't include **systematic** errors (factor of 2)

THINGS dwarfs

LSB spiral galaxies

clusters

# Self-interacting DM model




DM particle X + mediator particle $\phi$

Example case: Asymmetric dark matter with dark photon

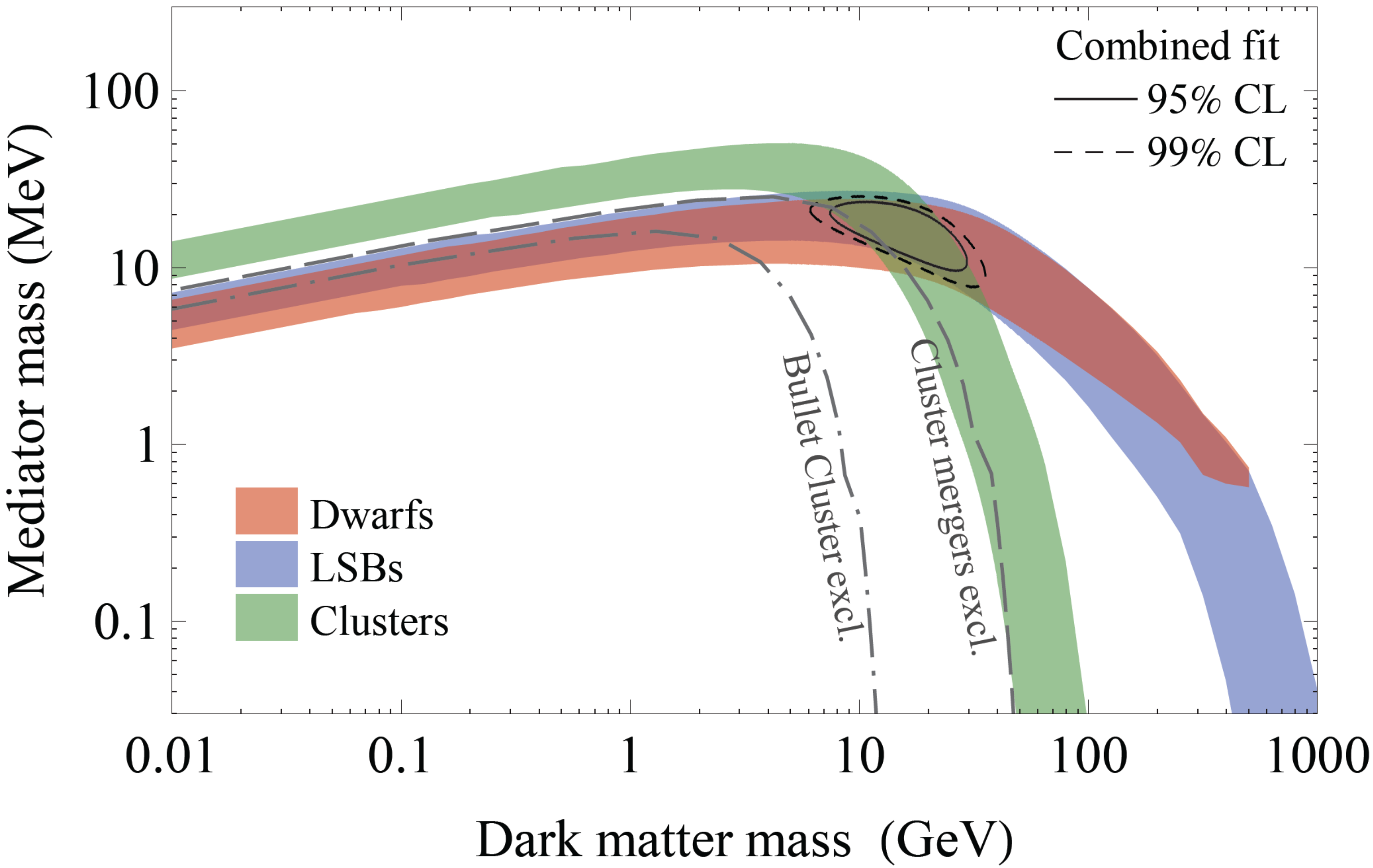
Nonrelativistic scattering described by repulsive Yukawa potential

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

Only three parameters: DM mass, $\phi$ mass, coupling $\alpha'$

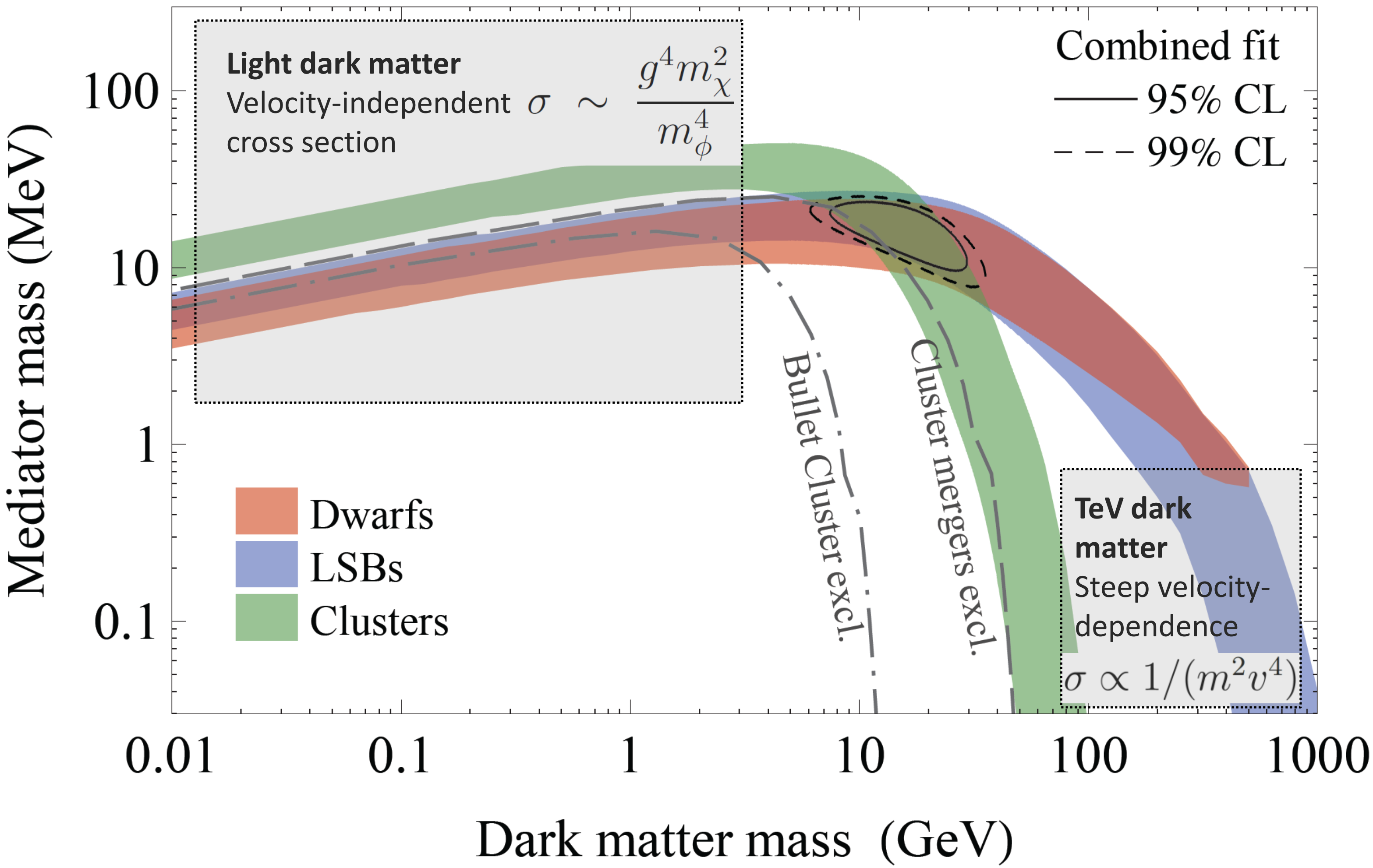
# Self-interacting DM model

Dark coupling constant $\alpha' = \alpha_{em} = 1/137$

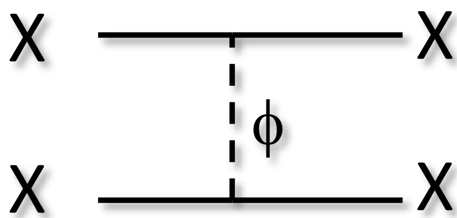


# Self-interacting DM model

Dark coupling constant $\alpha' = \alpha_{em} = 1/137$



# SIDM paradigm




DM particle X + mediator particle $\phi$

Self-interactions can provide a consistent explanation of the shapes of dark matter halos from dwarf galaxies to clusters

Are there any other implications?

# SIDM and the visible sector (SM)

SIDM story is independent of how mediator couples to SM.

MeV-GeV scale mediator $\phi$ must decay, otherwise dominates DM density.
Minimal possibility: $\phi \rightarrow$ SM particles.

Dark photon model: mediator $\phi$ couples via kinetic mixing with photon

$$\mathscr{L}_{\rm mix} = -\frac{\varepsilon_\gamma}{2}\,\phi_{\mu\nu}F^{\mu\nu}$$

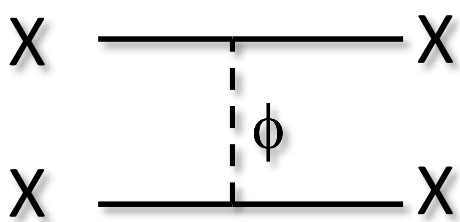
*Holdom (1984), Pospelov et al (2007), Arkani-Hamed et al (2009), + many others*

Decay lifetime: $\tau_\phi \approx 3 \text{ seconds} \times \left(\frac{\varepsilon_\gamma}{10^{-10}}\right)^{-2}\left(\frac{m_\phi}{10 \text{ MeV}}\right)^{-1}$

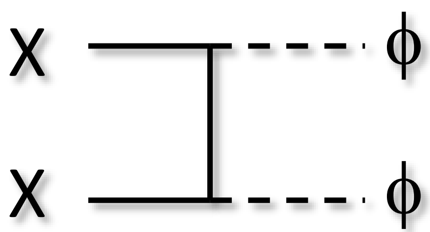
Lifetime $\tau < 1$ sec OK. Longer lifetimes may have tension with BBN (entropy dilution, energetic decay products)

BBN sets **minimal** coupling between DM and SM.

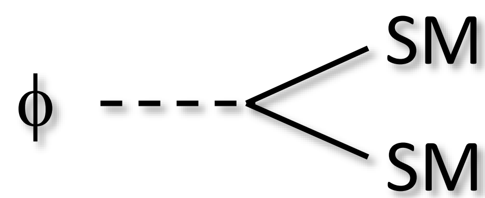
# SIDM paradigm




DM particle X + mediator particle $\phi$

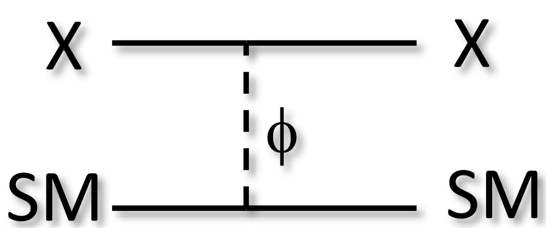



Annihilation

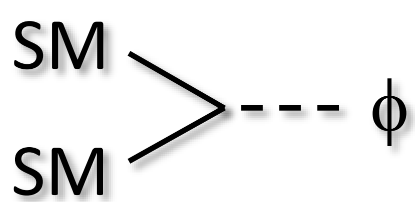



Decay

*Relic density*
*Indirect detection*
*Early Universe (BBN)*




Direct detection

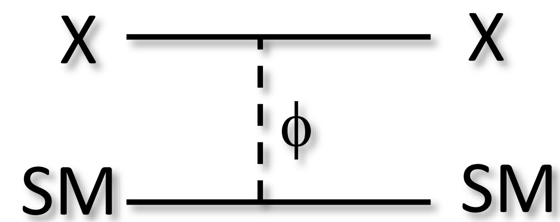



Direct production
*Dark photon searches at colliders*

# Direct detection

Minimal coupling from BBN constraint ($\varepsilon_\gamma \sim 10^{-10}$) puts SIDM just within reach for direct detection

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




Spin-independent proton-DM cross section (momentum transfer $q^2 = 0$)

$$\sigma_{Xp}^{\mathrm{SI}} \approx 1.5 \times 10^{-24}\ \mathrm{cm}^2 \times \varepsilon_\gamma^2 \times \left(\frac{\alpha_X}{10^{-2}}\right)\left(\frac{m_\phi}{30\ \mathrm{MeV}}\right)^{-4}$$

Nontrivial feature of SIDM: mediator mass $m_\phi^2$ can be comparable to $q^2$

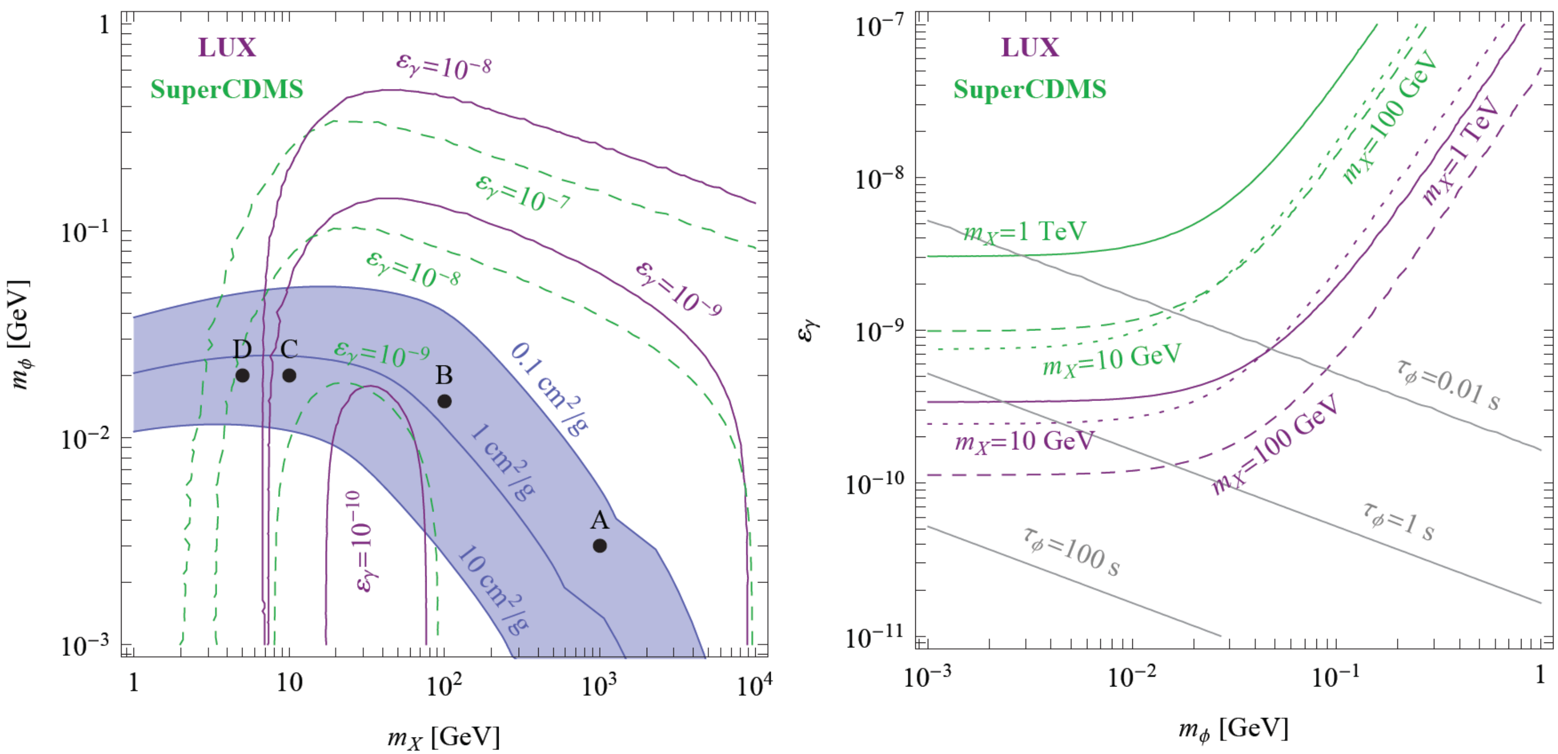
| $m_X$ (GeV) | $m_\phi$ (MeV) | $q_{\mathrm{Xe}}$ (MeV) | $q_{\mathrm{Ge}}$ (MeV) |
|---|---|---|---|
| 1000 | 3 | 127 | 74 |
| 100 | 15 | 62 | 46 |
| 10 | 20 | 10 | 10 |
| 5 | 20 | 5 | 5 |

Typical momentum transfer for Xenon/Germanium

*Del Nobile et al (2015)*

# Direct detection limits on SIDM

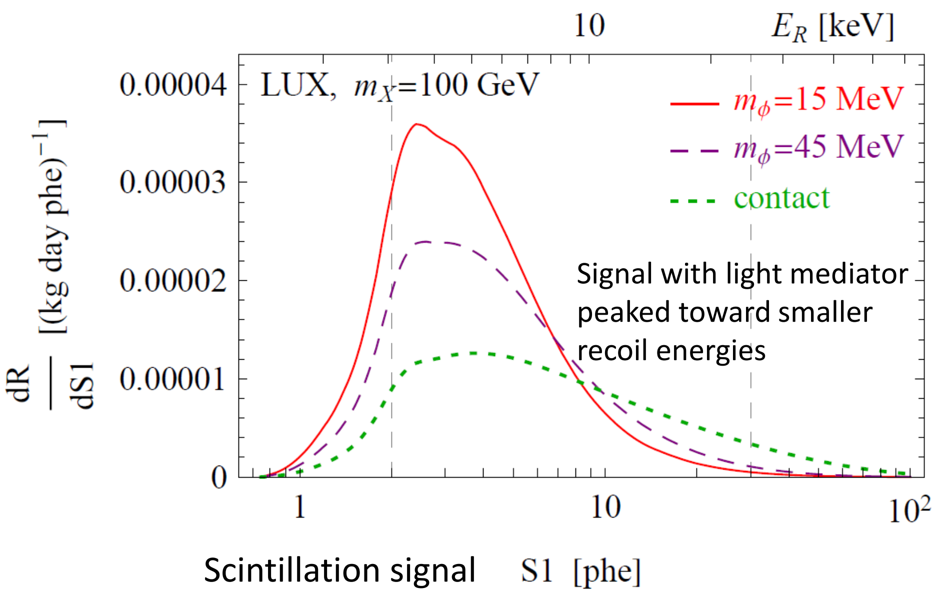
*Del Nobile et al (2015)*

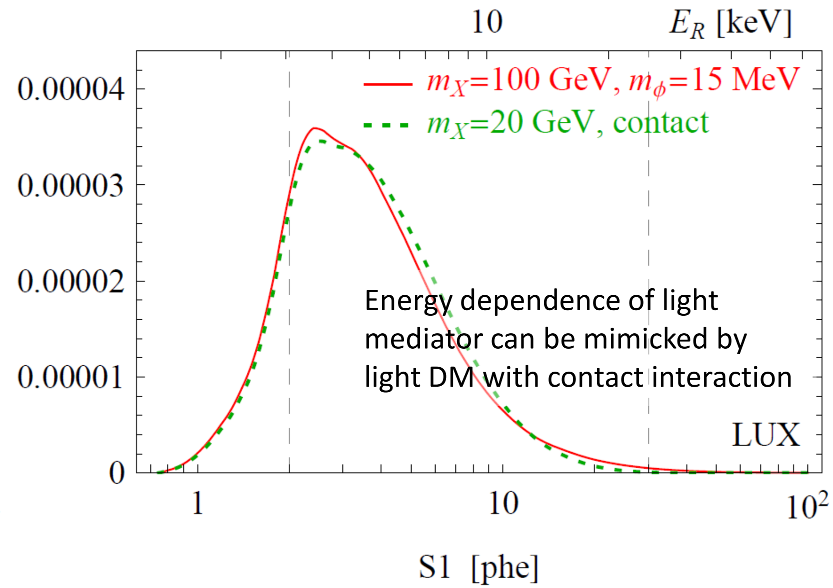



Nuclear recoil rate suppressed by form factor.
Sensitivity plateaus for $m_\phi < q$.

$$\frac{m_\phi^4}{(m_\phi^2 + q^2)^2}$$

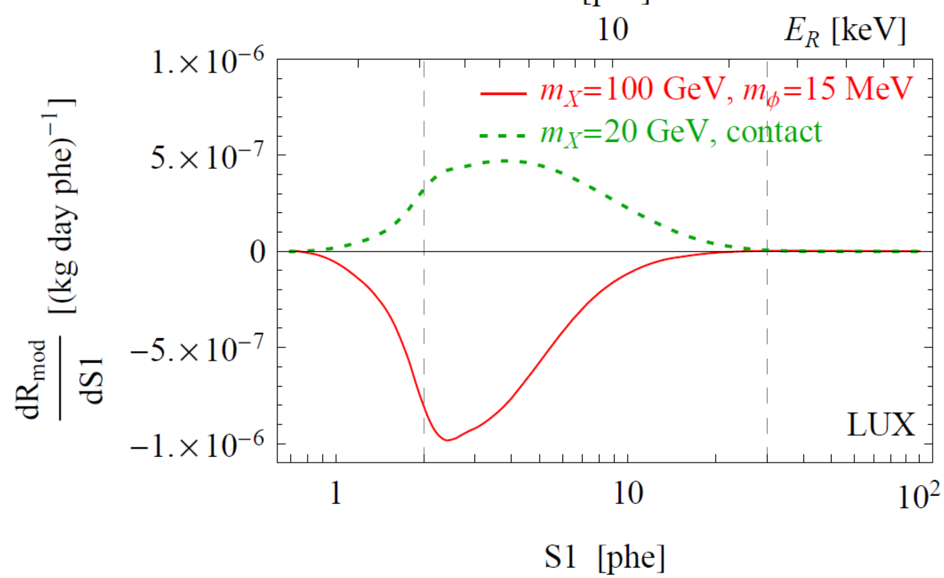
# Distinguishing SIDM from WIMPs




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

*Del Nobile et al (2015)*



# Other SIDM models

- $\phi^4$-theory (contact interaction), $m_\phi \sim 10$ MeV
  e.g. dark glueballs, dark pions, SIMPs
  *Hochberg et al, Boddy et al*

- Scalar/vector mediators (Yukawa potential)
  e.g. Dark photon, dark Higgs, composite sectors
  *Loeb & Weiner; Buckley & Fox; Ackerman et al (+many others)*

- Pseudoscalar interactions (one pion-exchange potential)
  e.g. dark nuclear physics, pseudo-Nambu-Goldstone bosons
  *Bellazzini et al*

- Axial vector/dipole moment interactions (more complicated potentials)

- Dark atoms (Van der Waals potential)
  *Cline et al, Cyr-Racine & Sigurdson*

Self-interactions described by nonrelativistic potential V(r) in Schrodinger equation

# Some thoughts on pseudoscalar mediators for SIDM

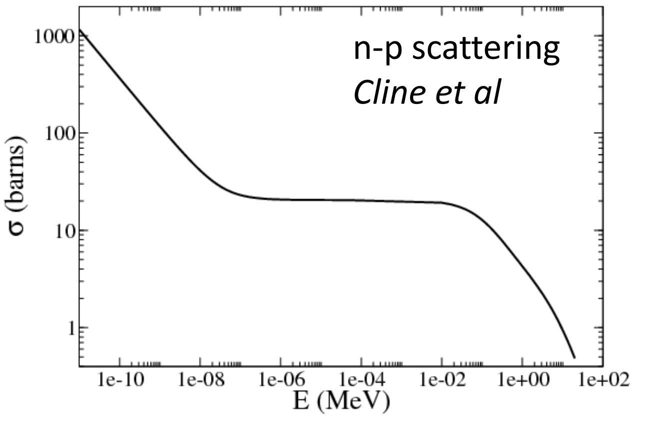
## (motivated by Felix's talk)

*Work in progress*

# Pseudoscalar mediator

"Natural" SIDM model
pNGB mediator can be very light
Dark nuclear interactions

$$\mathscr{L}_{\rm int} = i g_X \, \bar{\chi} \gamma_5 \chi \, \phi$$




Schrodinger equation analysis is rather complicated

$$V(\mathbf{r}) = \frac{\alpha_X}{m_X^2} e^{-m_\phi r} \left[ (\mathbf{S}_1 \cdot \hat{\mathbf{r}})(\mathbf{S}_2 \cdot \hat{\mathbf{r}}) \left( \frac{3}{r^3} + \frac{3 m_\phi}{r^2} + \frac{m_\phi^2}{r} \right) - (\mathbf{S}_1 \cdot \mathbf{S}_2) \left( \frac{1}{r^3} + \frac{m_\phi}{r^2} + \frac{4\pi}{3} \delta^3(\mathbf{r}) \right) \right]$$

Tensor operator couples orbital angular momenta ℓ, ℓ±2

$$S_{12}(\mathbf{r}) \equiv 3(\boldsymbol{\sigma}_1 \cdot \hat{\mathbf{r}})(\boldsymbol{\sigma}_2 \cdot \hat{\mathbf{r}}) - (\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2)$$

Singular potential ~ $1/r^3$ must be regulated and renormalized
(Cross section depends on input for counter terms, predictability?)

# Pseudoscalar mediator

But the perturbative calculation (Born approx) gives a very simple result:

$$\frac{d\sigma}{d\Omega} = \frac{\alpha_X^2 m_X^2 v^4 \sin^4 \frac{\theta}{2}}{16(m_\phi^2 + m_X^2 v^2 \sin^2 \frac{\theta}{2})^2} = \frac{1}{4}\left(\frac{d\sigma}{d\Omega}\right)_s + \frac{3}{4}\left(\frac{d\sigma}{d\Omega}\right)_t$$

Cross section highly suppressed on dwarf scales
$\sigma/m \sim (v/c)^4 \sim 10^{-16}$ for v ~ 30 km/s

When is the Born approximation valid? Consider only spin singlet scattering.

Spin-singlet potential $V_s(r) = -\frac{\alpha_X m_\phi^2}{4m_X^2}\frac{e^{-m_\phi r}}{r} + \frac{\pi \alpha_X}{m_X^2}\delta^3(\mathbf{r})$

Born approx. valid for $\frac{\alpha_X m_\phi}{m_X} \ll 1$ Generally satisfied for $m_\phi \ll m_X$

Different than condition for vector/scalar interactions $\frac{\alpha_X m_X}{m_\phi} \ll 1$

# Pseudoscalar mediator

Does the pseudoscalar theory preclude large self-interactions (in dwarfs)?

Claim: No – self-interactions can be sizable, *even in the Born limit*

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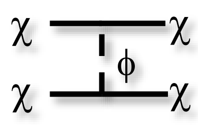
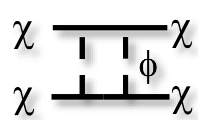



Leading-order
$q^2$-suppressed

Pseudoscalar potential




Second-order
$q^2$-unsuppressed
(virtual momentum)

Yukawa potential

Two pion exchange looks like scalar exchange (σ meson from QCD) *Oshima et al*

$$V(r) = -\frac{\alpha_\sigma}{r} e^{-m_\sigma r} \qquad \alpha_\sigma \sim \frac{\alpha_X^2}{4\pi}$$

Low velocity limit:
$\sigma/m \sim$ barn/GeV for $m_\sigma \sim 10$ MeV, $\alpha_X \sim 0.1$, $m_X \sim 10$ GeV

# Conclusions

- We know DM interacts gravitationally and we can test whether gravity is the *only* force influencing DM structure

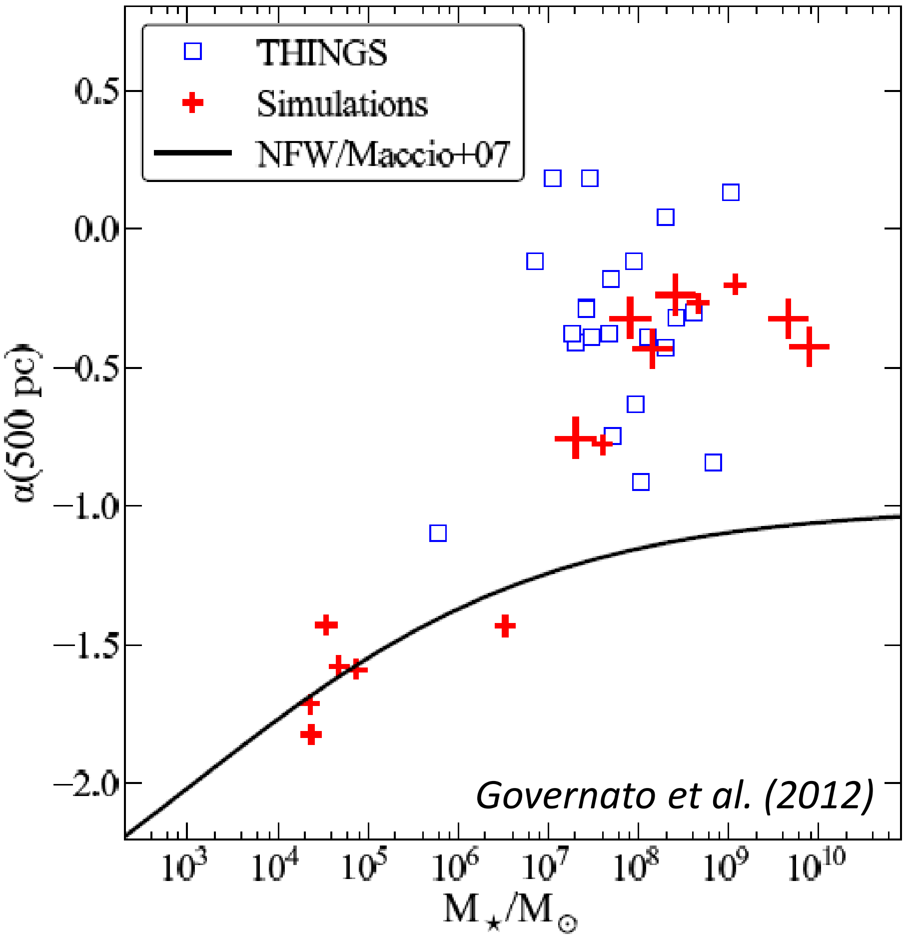
- Long-standing issues for CDM and structure.  Jury still out, but SIDM can provide a consistent solution if there are new light states coupled to DM.

- SIDM paradigm has rich model space and phenomenology

# Back up

# Cores in field dwarfs

CDM-only simulations poor representation of DM+baryon Universe




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

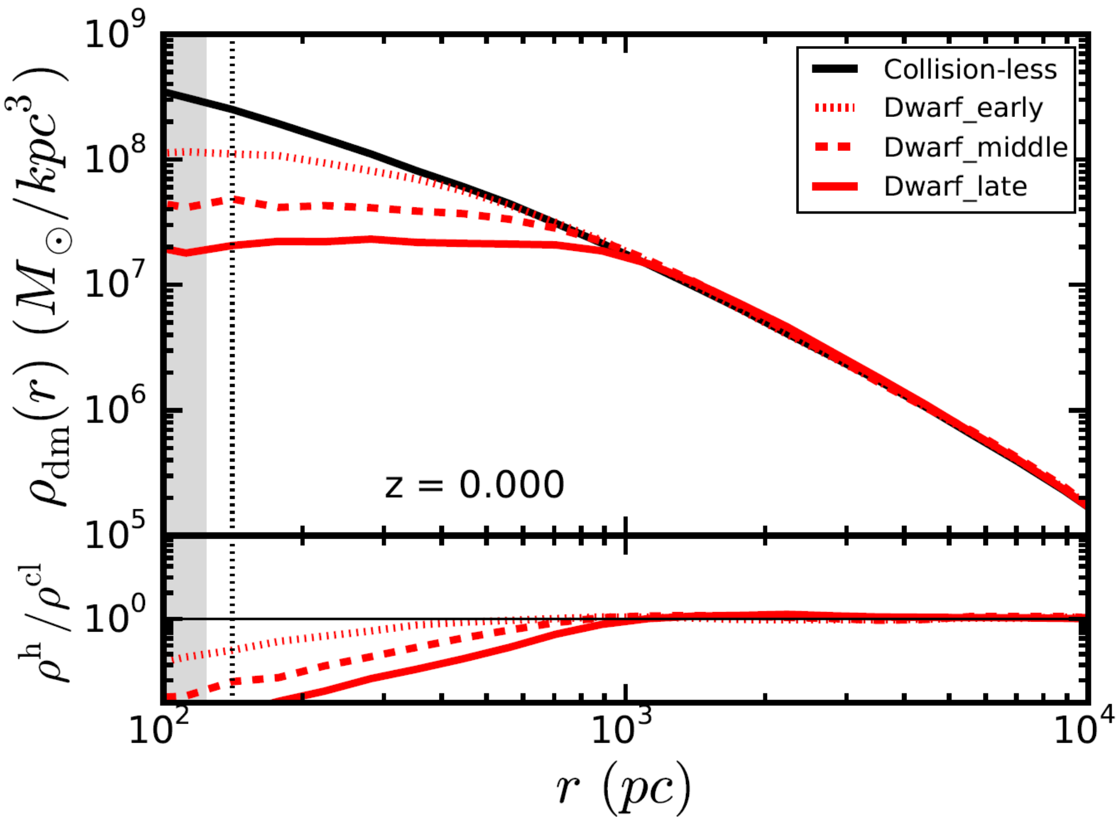
Depends on implementation sub-grid baryonic physics

Requires bursty star formation history

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

# 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)*

# 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

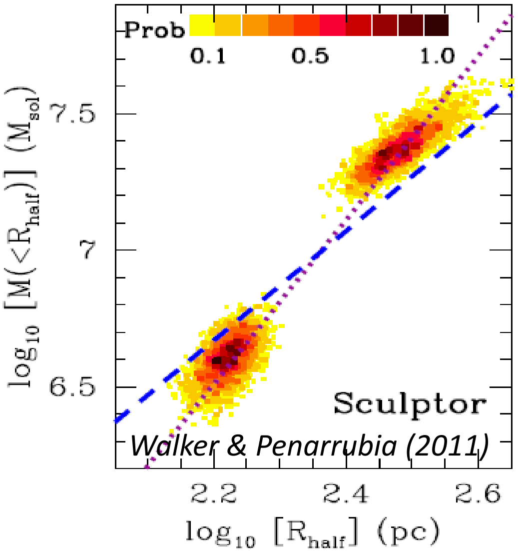
  *Onorbe, et al (2015)*

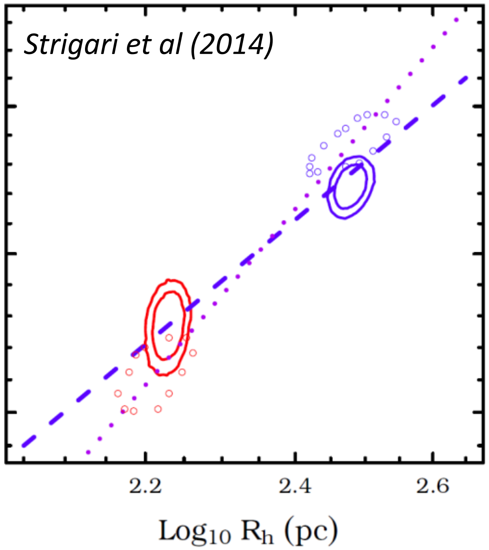
- Environmental effect from MW baryonic disk can form DM cores

  *Zolotov, et al (2012)*

# Cores in MW satellites

Systematic uncertainty in astrophysical interpretation




No cores in MW satellites?

Conclusions depend on assumptions for stellar kinematic distribution

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

# 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)

# Cores in clusters

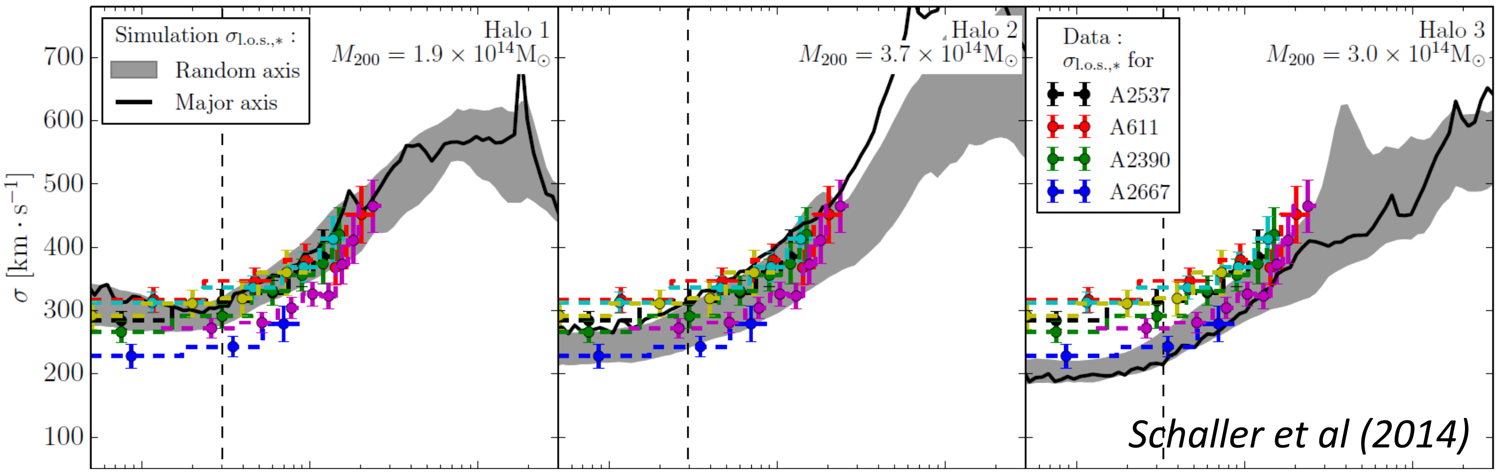
CDM-only simulations poor representation of DM+baryon Universe

- 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

Stellar line-of-sight velocity dispersion

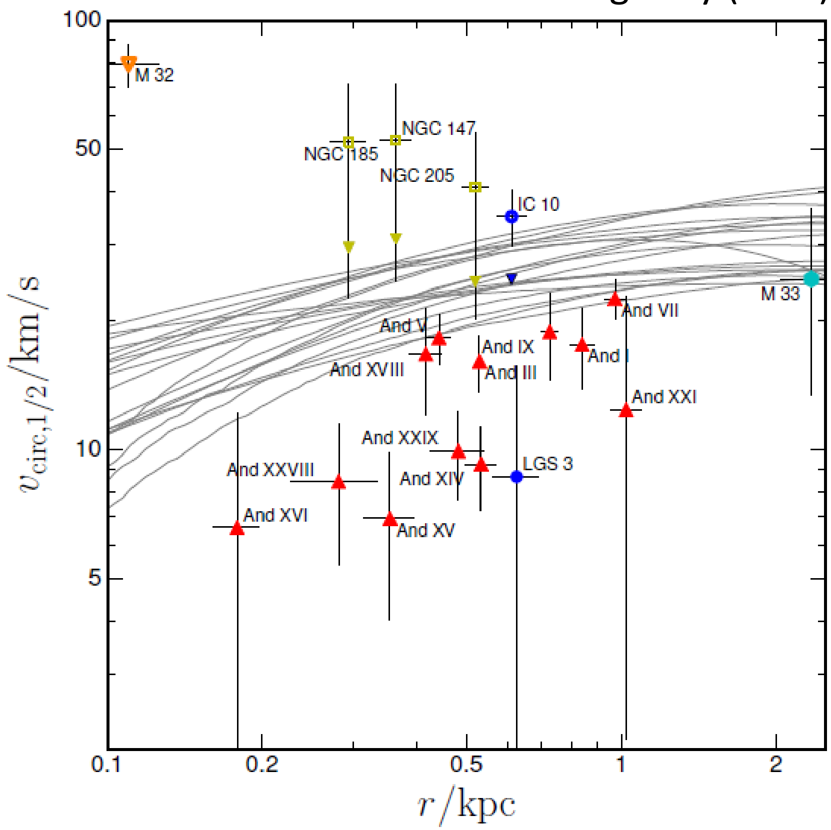



Radius

# Too-big-to-fail problem

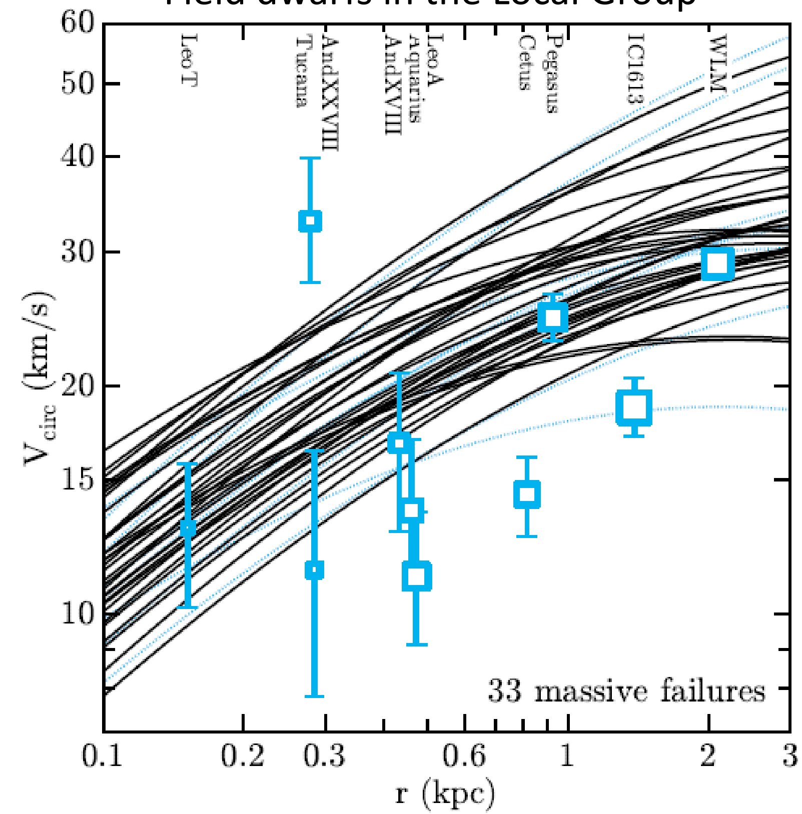
## Is there a problem beyond the Milky Way?

Satellites of the Andromeda galaxy (M31)




*Tollerud et al. (2014)*

Field dwarfs in the Local Group




*Garrison-Kimmel et al. (2014)*

# 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