Dark matter halos as particle colliders

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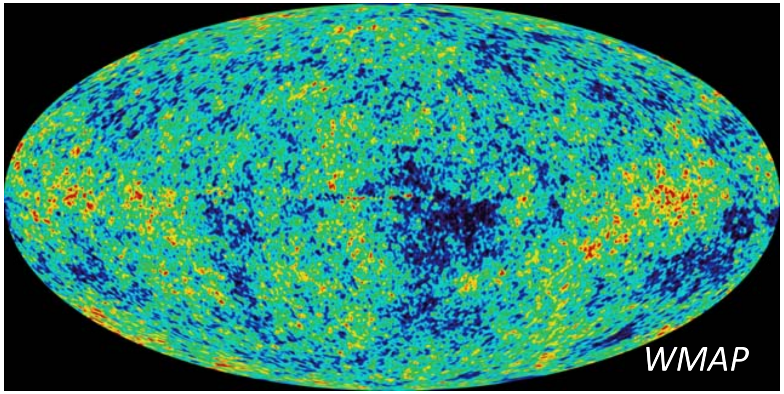
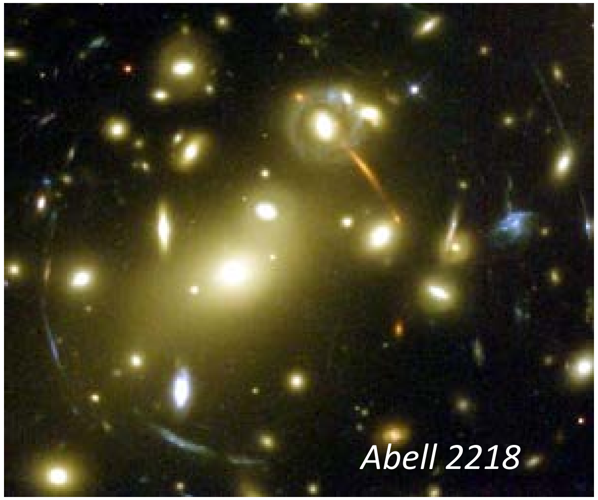
Cold collisionless dark matter paradigm

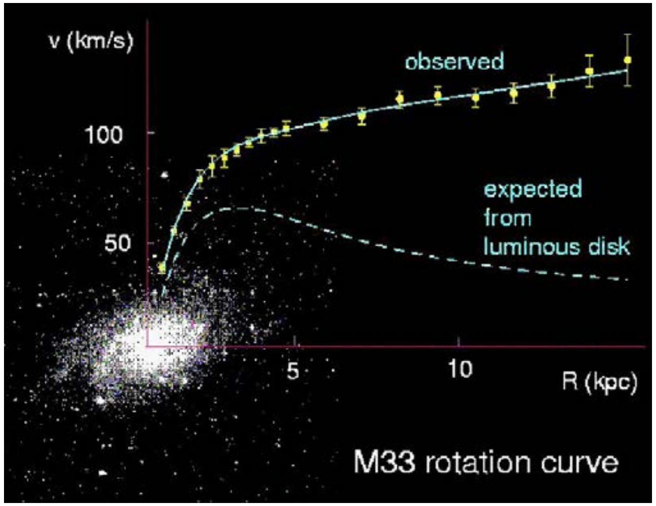
Dark matter (DM) is about 25% of the Universe



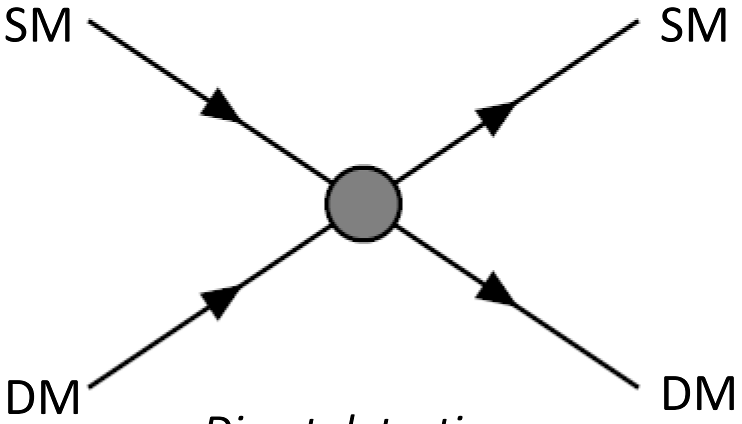
Cold collisionless dark matter (CDM) provides a good description of the structure of matter in the Universe

To date, evidence for DM from gravity only

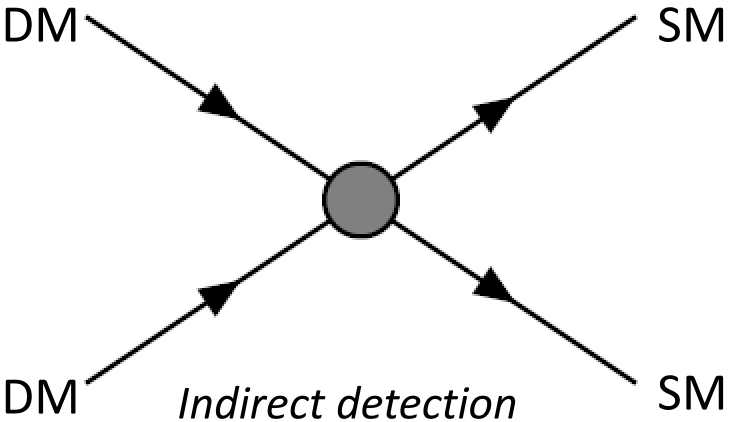




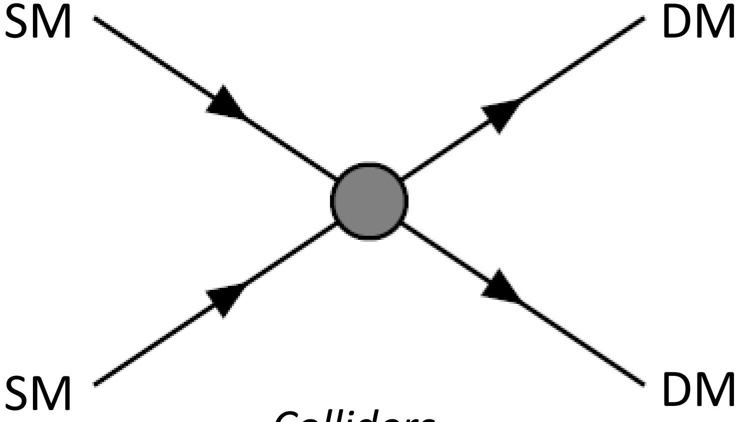
Exploring the dark sector



Direct detection



Indirect detection

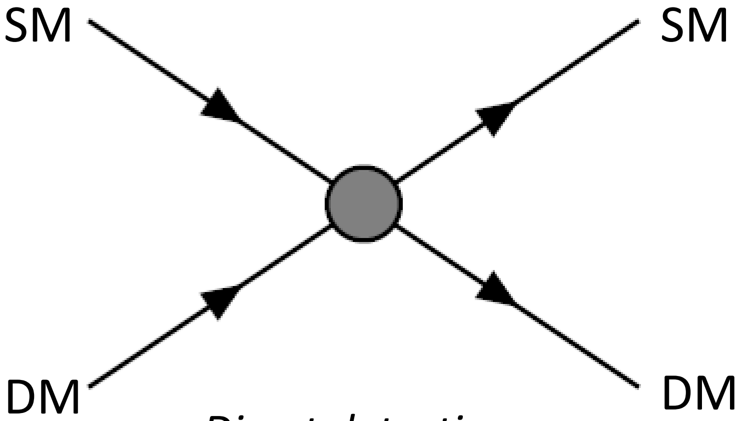


Colliders

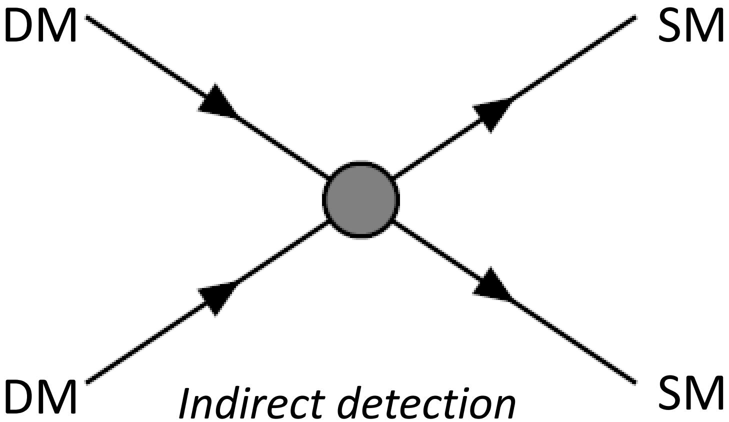
WIMP paradigm: expect dark matter in one or more of these channels

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

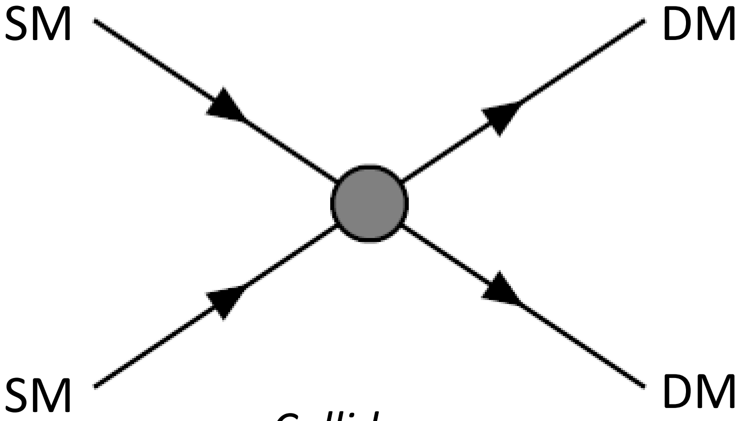
Exploring the dark sector



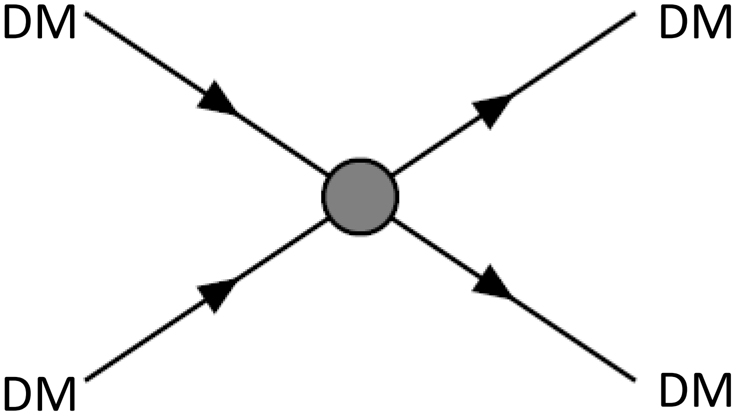
Direct detection



Indirect detection



Colliders



Self-interactions

Outline

- Issues with CDM (cold collisionless DM)
  - Discrepancies between N-body simulations and astrophysical observations

- DM may have self-interactions
  - Particle physics implications
  - Using dark matter halos as colliders
  - Complementarity with WIMP searches

CDM in trouble

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

     DM density: $\rho \sim r^\alpha$ $\alpha \sim -1$ (cusp, NFW) or $\alpha \sim 0$ (core)

2. Too-big-to-fail problem *Boylan-Kolchin, Bullock, Kaplinghat (2011 + 2012)*
   - Simulations predict O(10) massive MW satellites more massive than observed MW dSphs

3. Missing satellite problem *Klypin et al (1999), Moore et al (1999)*
   - Fewer small MW dSphs than predicted by simulation
   - Small enough to fail

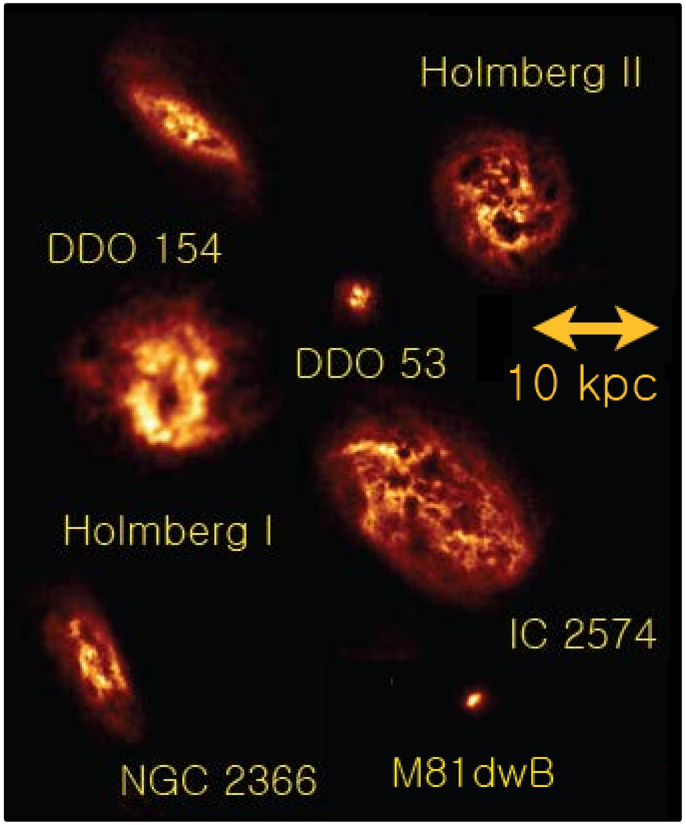
1. Core-vs-cusp problem

Cores seem fairly ubiquitous:

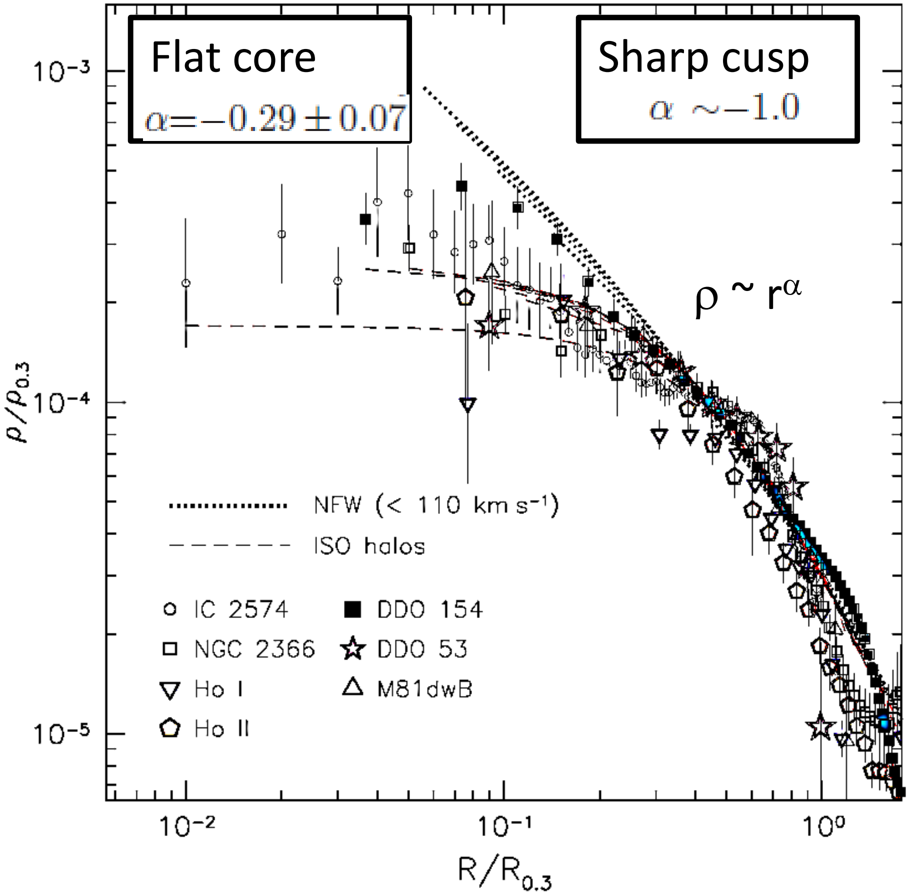
1. Field dwarfs
2. Satellite dwarf galaxies
3. Low surface brightness galaxies (LSBs)
4. Clusters

1. Cores in field dwarfs

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



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

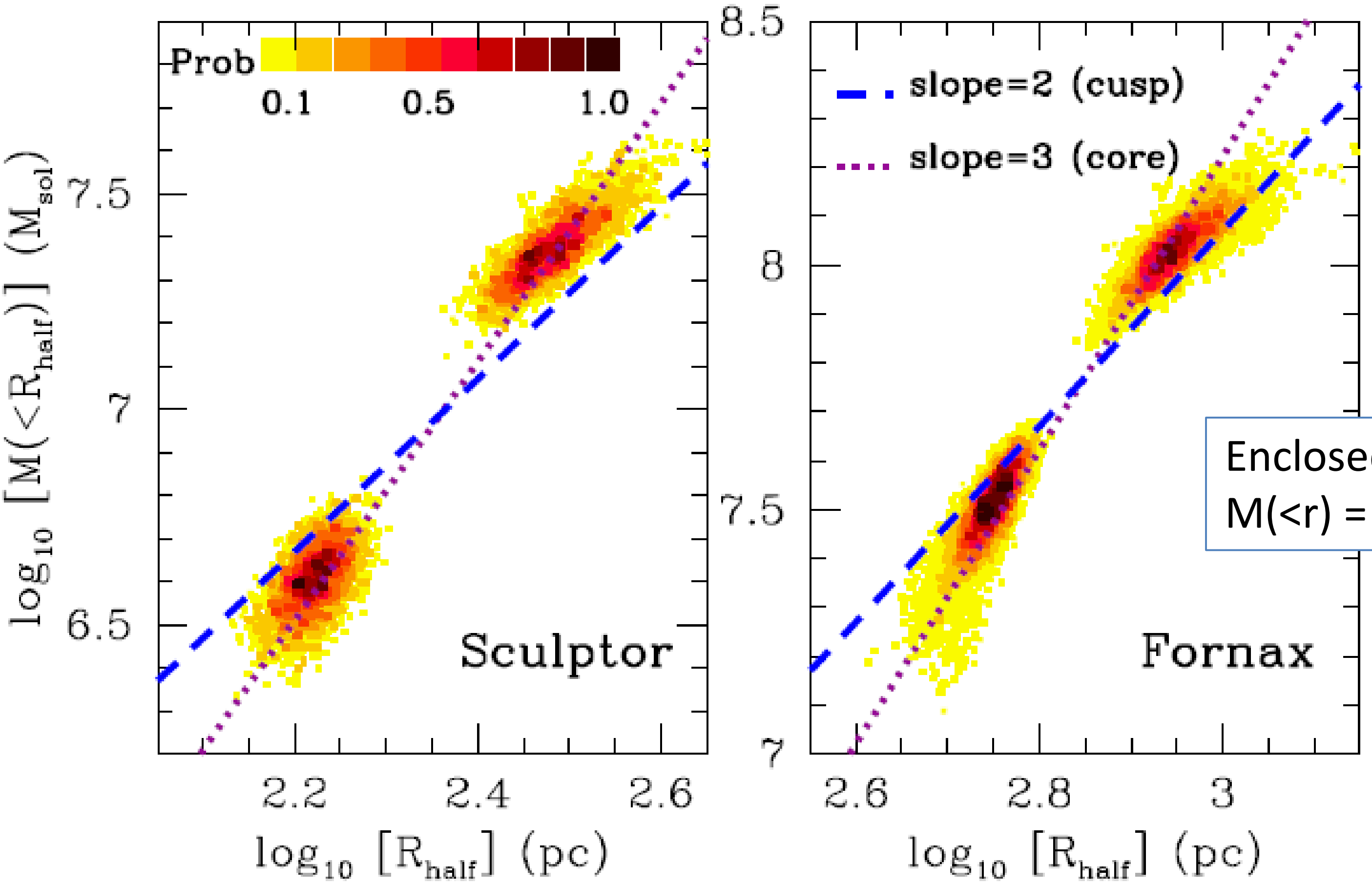


Flat core
$\alpha = -0.29 \pm 0.07$

Sharp cusp
$\alpha \sim -1.0$

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

1. Cores in MW dwarf spheroidals

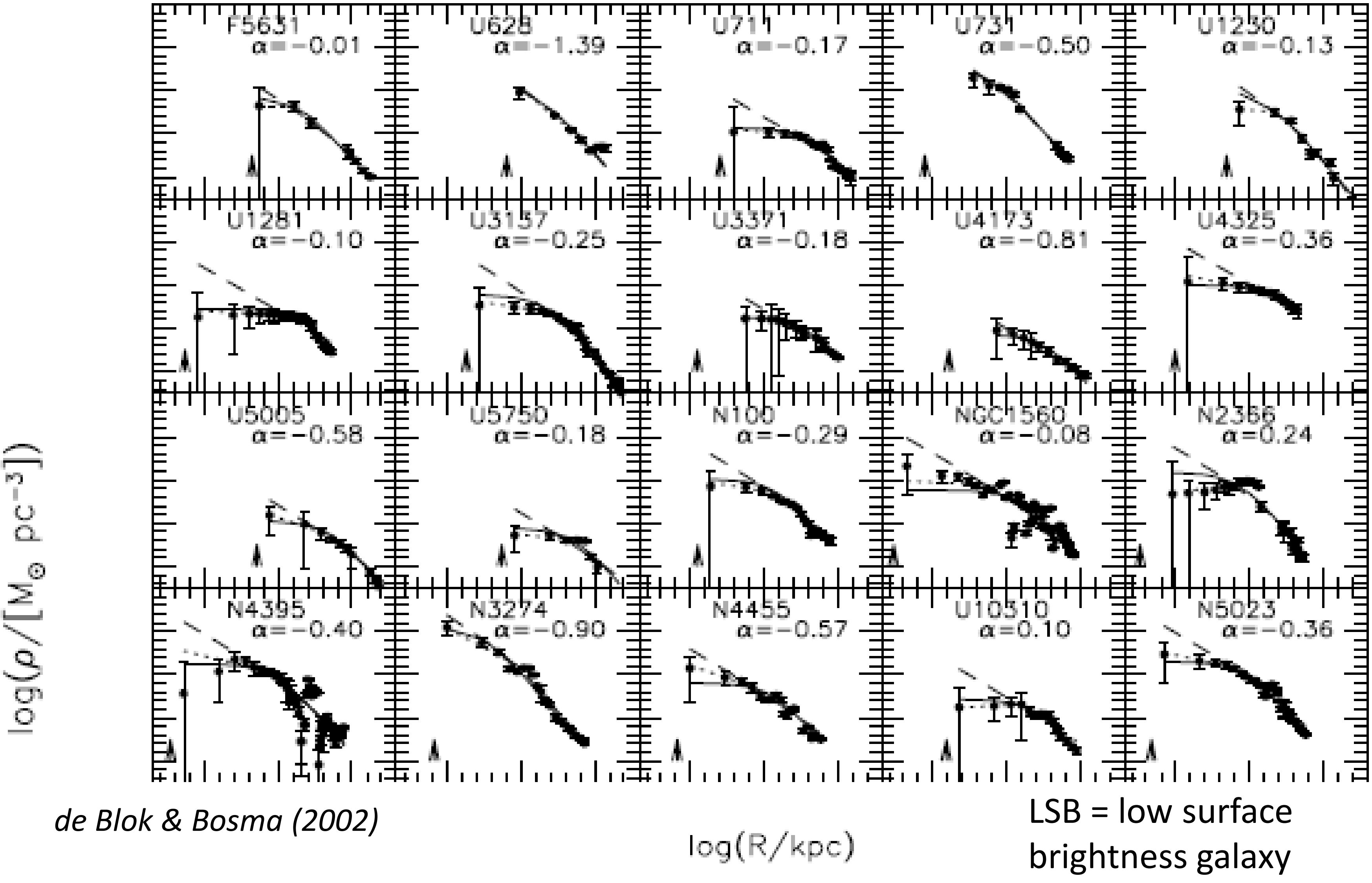


Enclosed mass
$M(<r) = \int d^3r\ \rho$

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

Walker & Penarrubia (2011)

1. Cores in LSBs

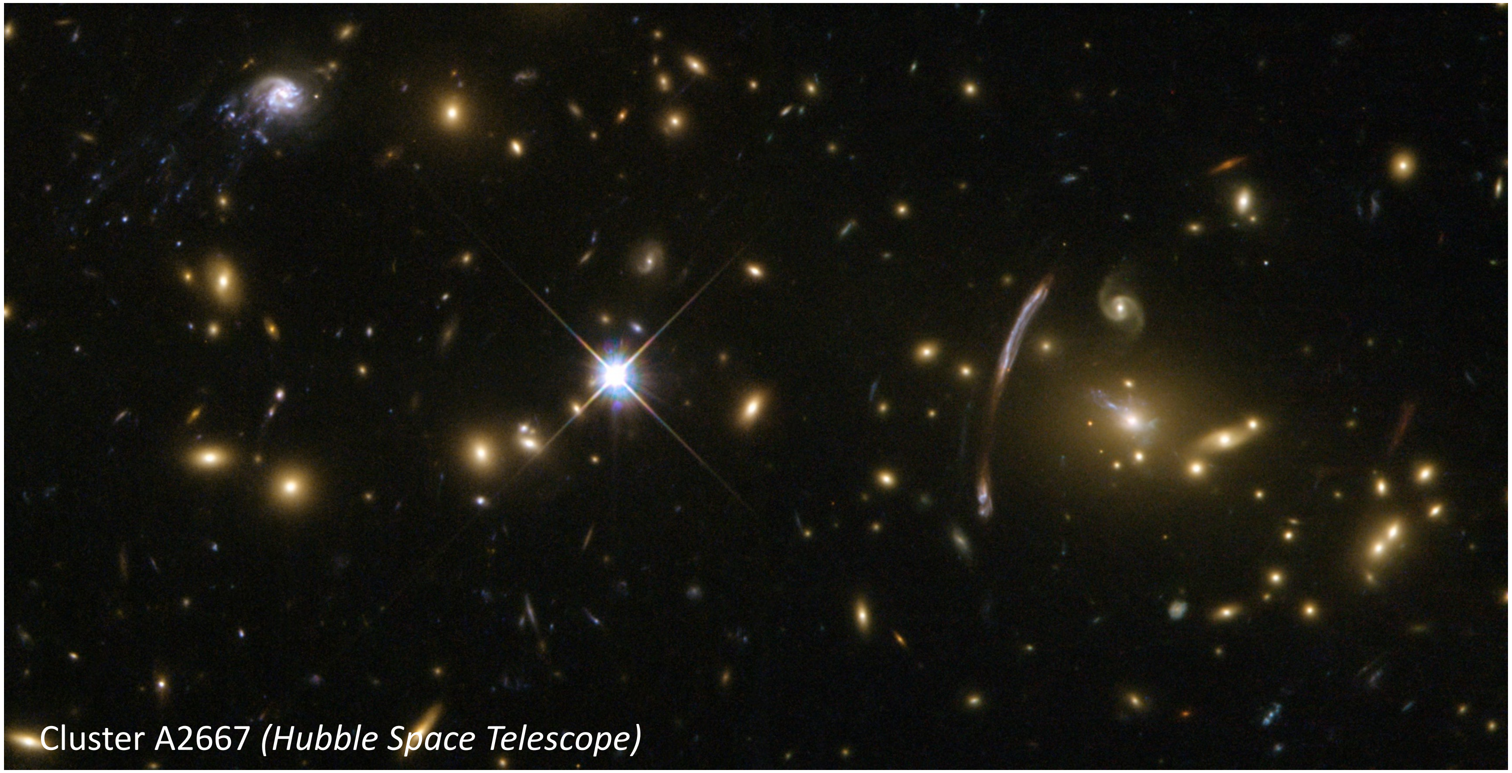


de Blok & Bosma (2002)

LSB = low surface brightness galaxy

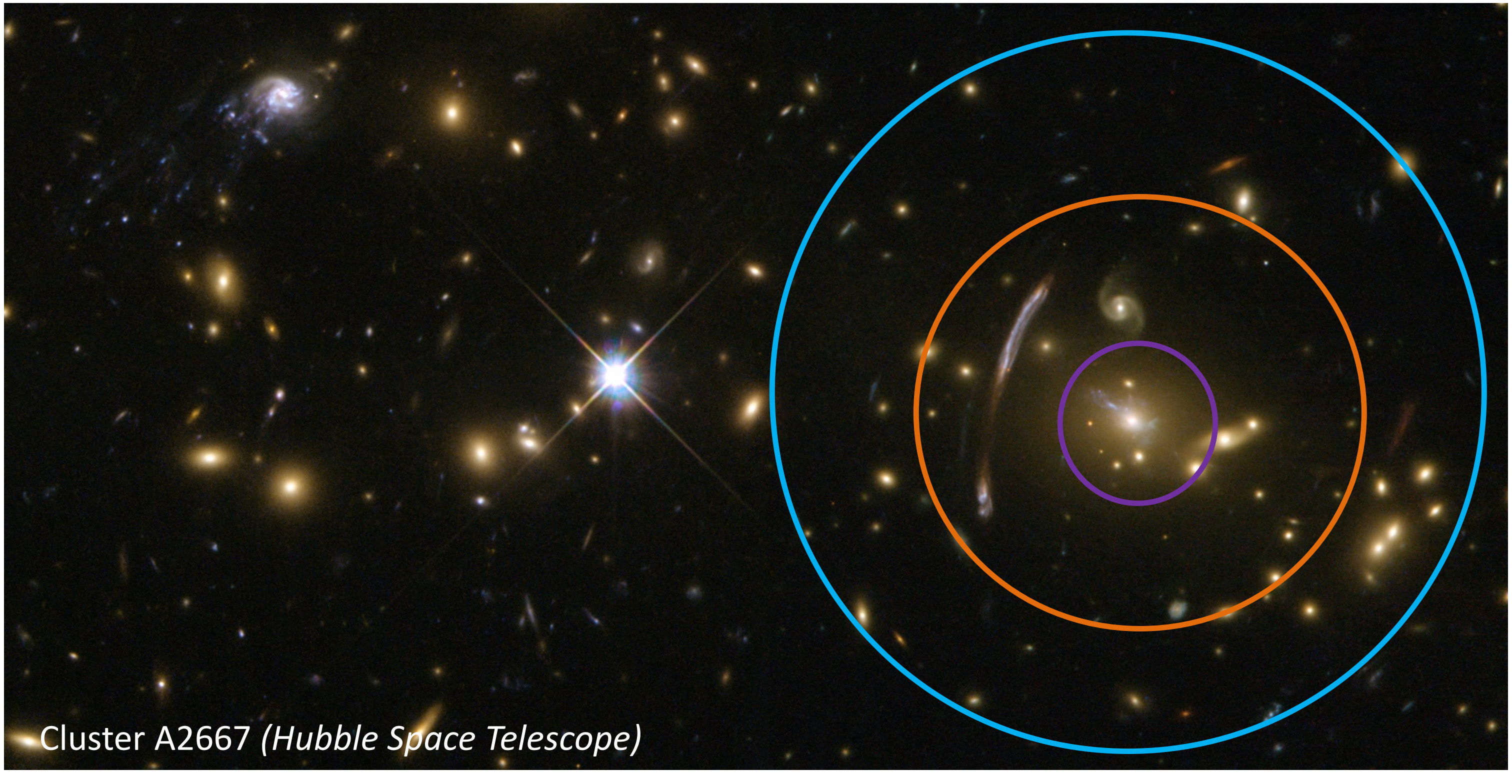
Kuzio de Naray et al (2007); Kuzio de Naray & Spekkens (2011)

1. Cores in clusters



Cluster A2667 *(Hubble Space Telescope)*

1. Cores in clusters


Cluster A2667 *(Hubble Space Telescope)*

Use multiple measurements to study dark matter halo

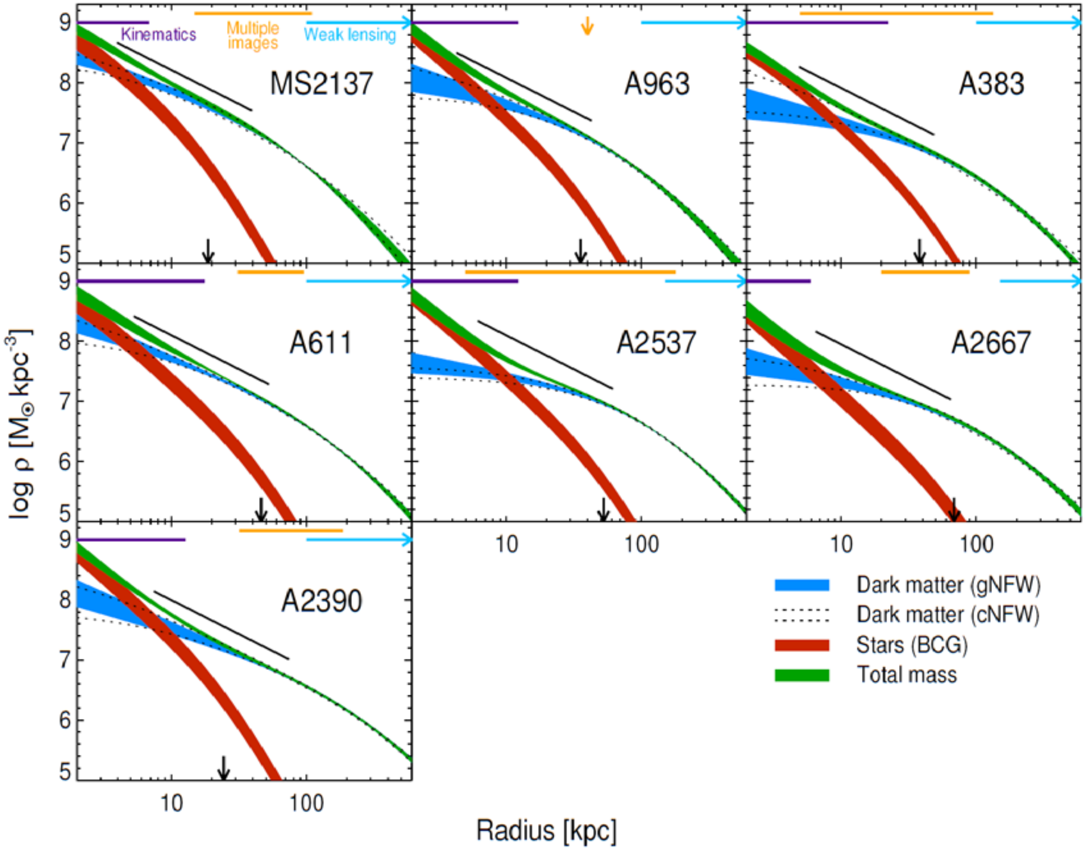
Newman et al (2012)

Weak gravitational lensing at large distance

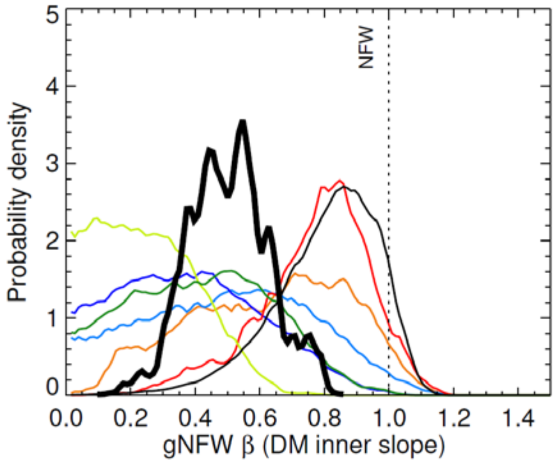
Gravitational lensing arcs (strong lensing) at medium distance

Stellar kinematics for the cluster center

1. Cores in clusters



Newman et al (2012)



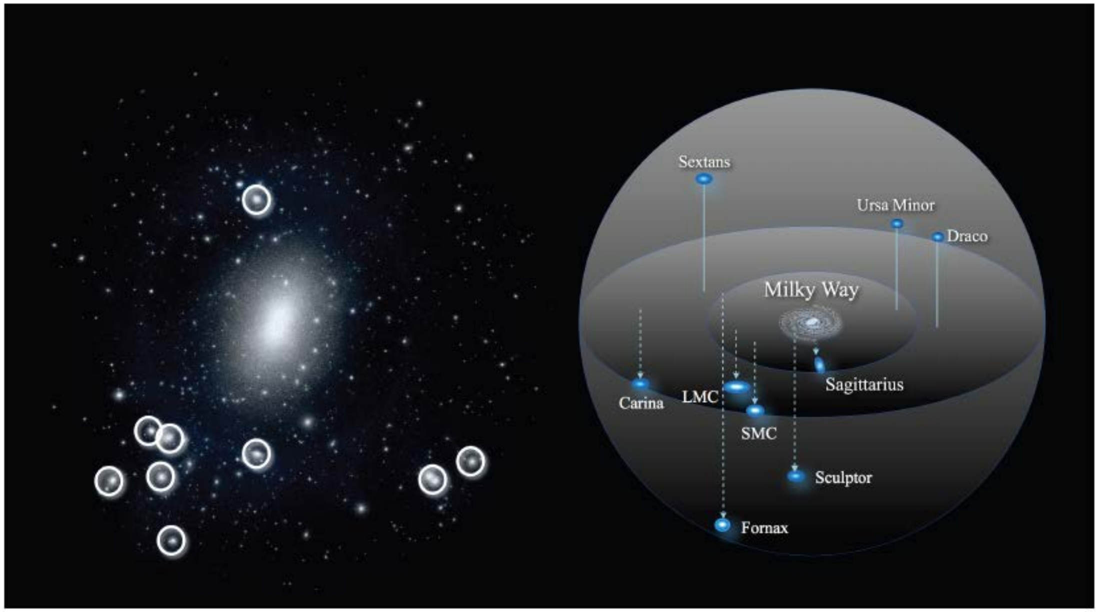
gNFW fit:

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

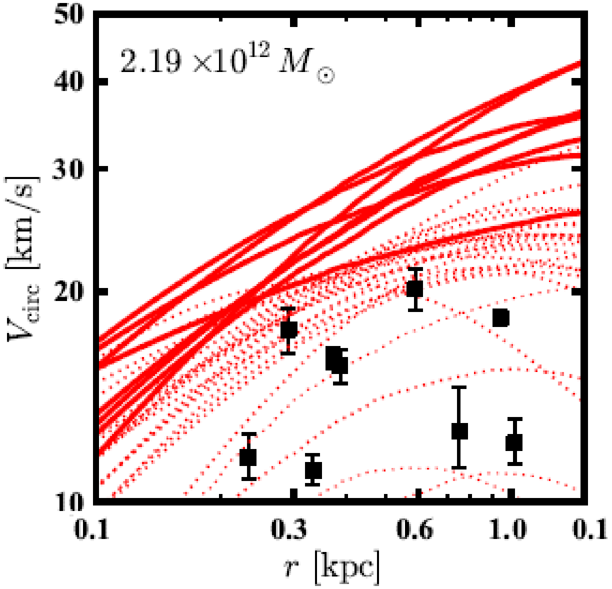
2. Too-big-to-fail problem

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

MW galaxy should have O(10) satellite galaxies which are more massive than the most massive (classical) dwarf spheroidals

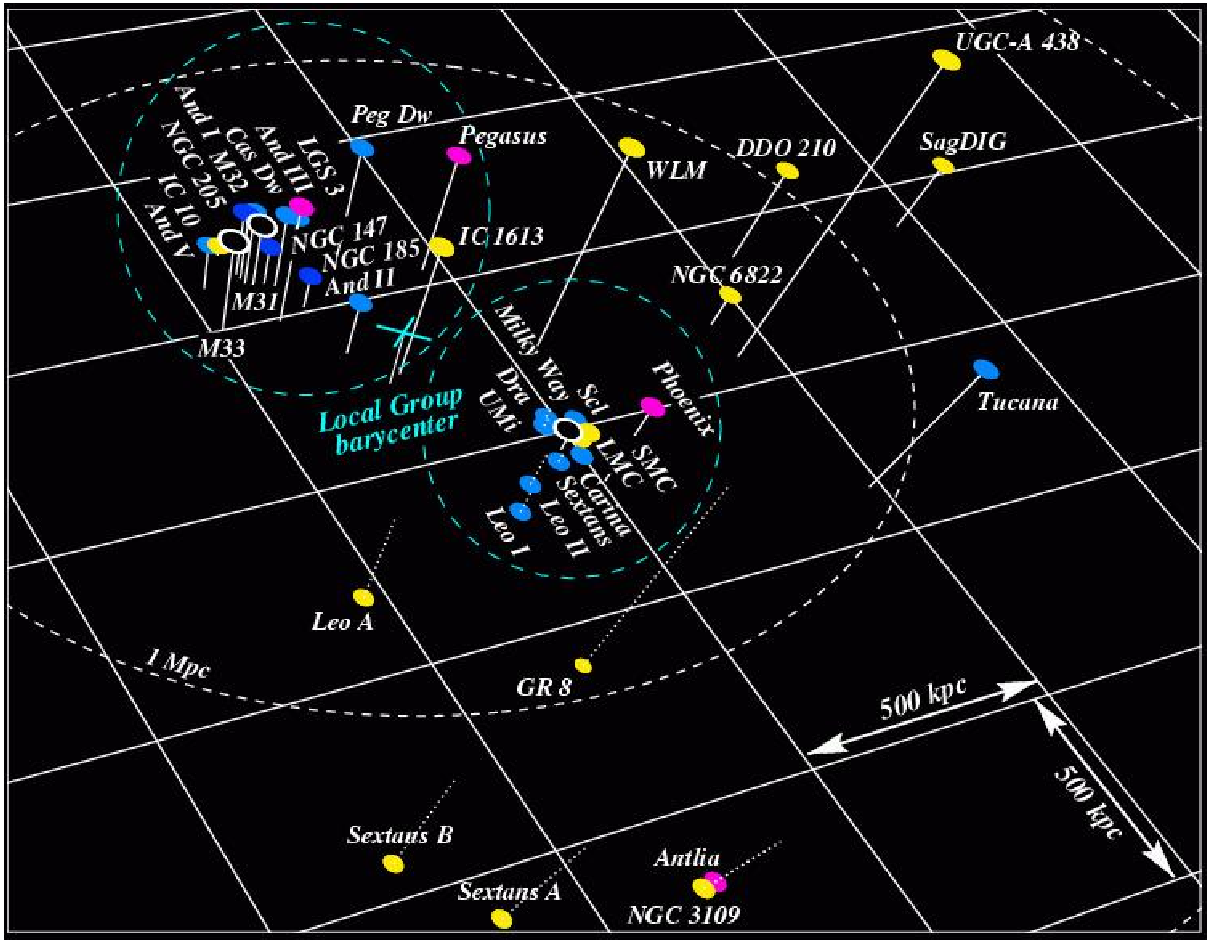


From Weinberg, Bullock, Governato, Kuzio de Naray, Peter (2013)



2. Too-big-to-fail problem

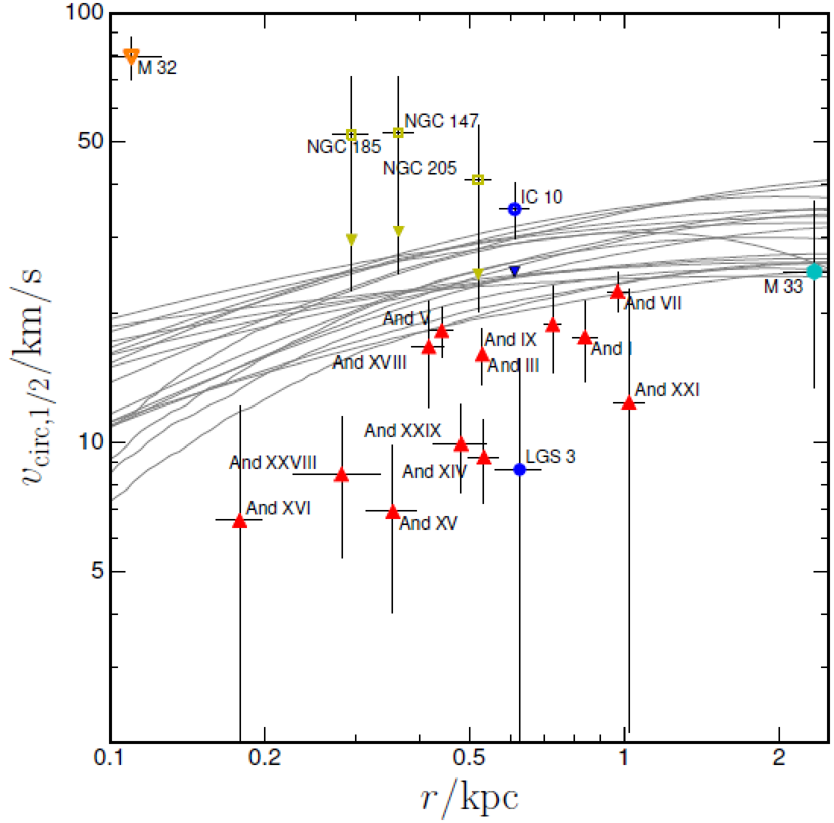
Is there a problem beyond the Milky Way?



2. Too-big-to-fail problem

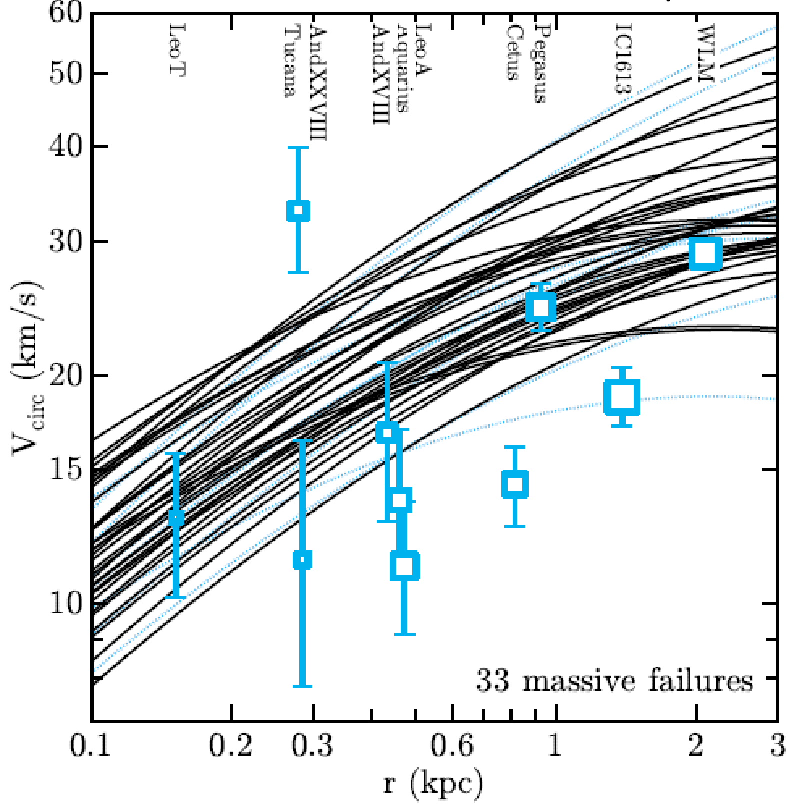
Is there a problem beyond the Milky Way?

Satellites of the Andromeda galaxy (M31)



Tollerud et al. (2014)

Field dwarfs in the Local Group



Garrison-Kimmel et al. (2014)

CDM Problems

- Problem with our interpretation of observations
  - Can’t use DM-only simulations to model real DM+baryons Universe
  - Astrophysical observations not being modeled correctly
  - Other systematic/statistical uncertainties

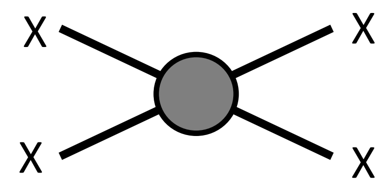
- Dark matter may not be CDM

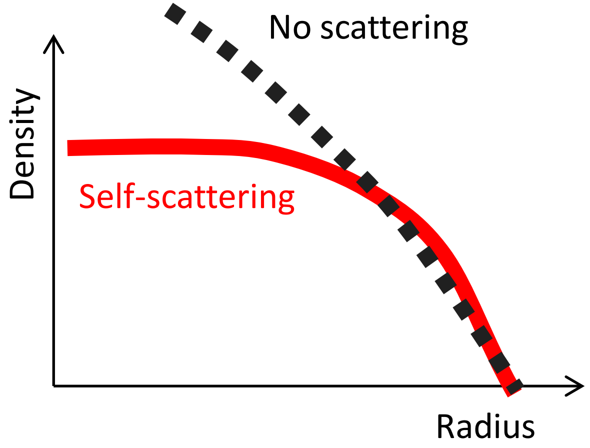
Self-interacting dark matter

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)*

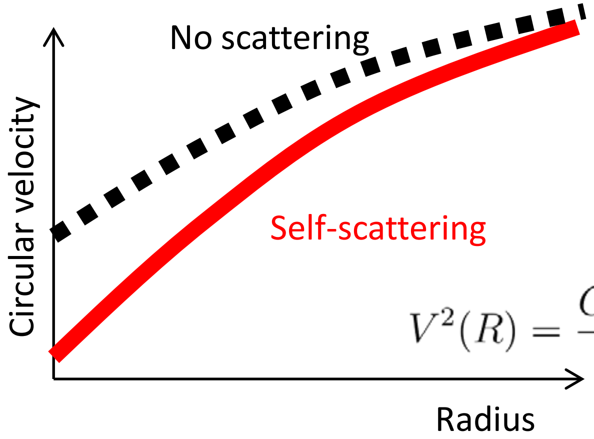
Dark matter self-scattering





Self-interactions solve core-vs-cusp

Particles get scattered out of dense halo centers



$$V^2(R) = \frac{G M_{\rm encl}(R)}{R}$$

Self-interactions solve too-big-to-fail

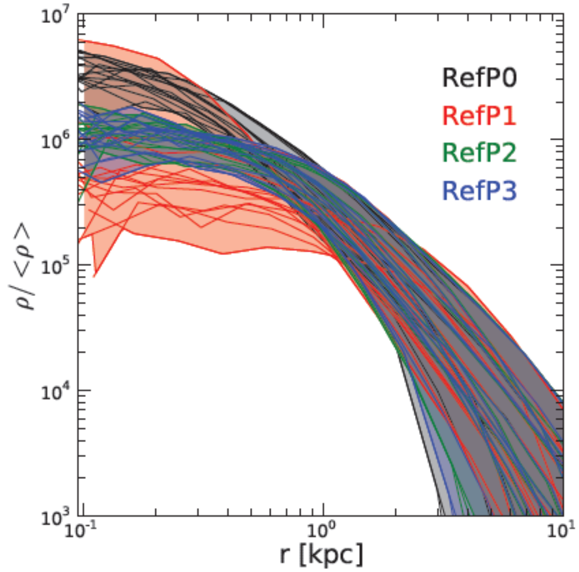
Rotation curves reduced (less enclosed mass)

Simulated satellites matched to observations

N-body simulations for SIDM

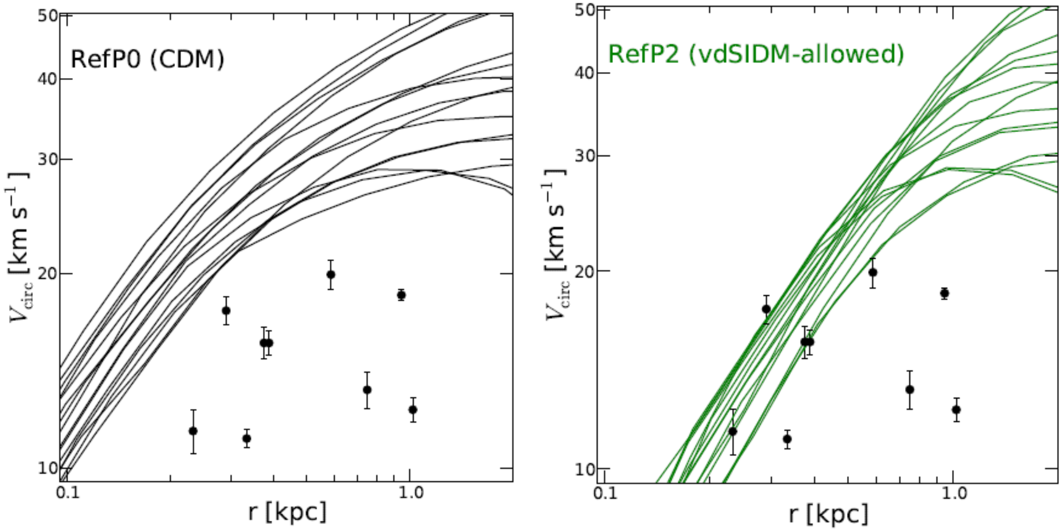
Vogelsberger, Zavala, Loeb (2012); see also Rocha et al, Peter et al (2012)

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 does this tell us about the underlying particle physics theory of the dark sector?

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

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

Self-interacting dark matter

- What does this tell us about the underlying particle physics theory of the dark sector?
- History of SIDM

1. Contact interaction proposed to solve small-scale structure issues σ=const *Spergel & Steinhardt (2000), Dave et al (2000)*
2. Large enough cross section excluded on cluster scales
   - Velocity dependent cross section ($\sigma \sim 1/v$) *Yoshida et al (2000)*
   - SIDM disfavored
3. Improved SIDM simulations *Vogelsberger, Zavala, Loeb (2012); Rocha et al, Peter et al (2012)*
4. Improved SIDM particle physics models

Ackerman et al (2008), Feng et al (2009), Buckley & Fox (2009), Loeb & Weiner (2010), ST, Yu, Zurek (2012 + 2013), Cyr-Racine et al (2013), Fan et al (2013), Cline et al (2013), Boddy et al (2014), …

Constraints on DM self-interactions

Constraints from large scales weaker than previously thought

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

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

Halo shape constraints from elliptical galaxy

Buote et al. (2002); Feng et al. (2010)

Weaker than previously thought due to baryonic contribution to the potential *Kaplinghat et al (2014)*

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

Randall et al. (2007)

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

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

Particle physics lessons for SIDM

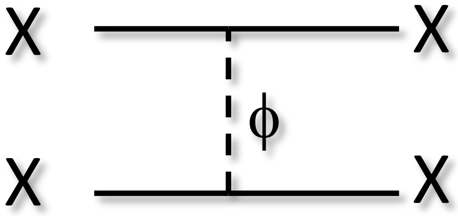
Large self-interaction cross section required

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

Typical WIMP: $\sigma \sim 1$ pb, $m_\chi \sim 100$ GeV

$$\sigma/m_\chi \sim 10^{-14}\ \mathrm{barns/GeV}$$

Simplest model: new mediator ϕ lighter than weak scale

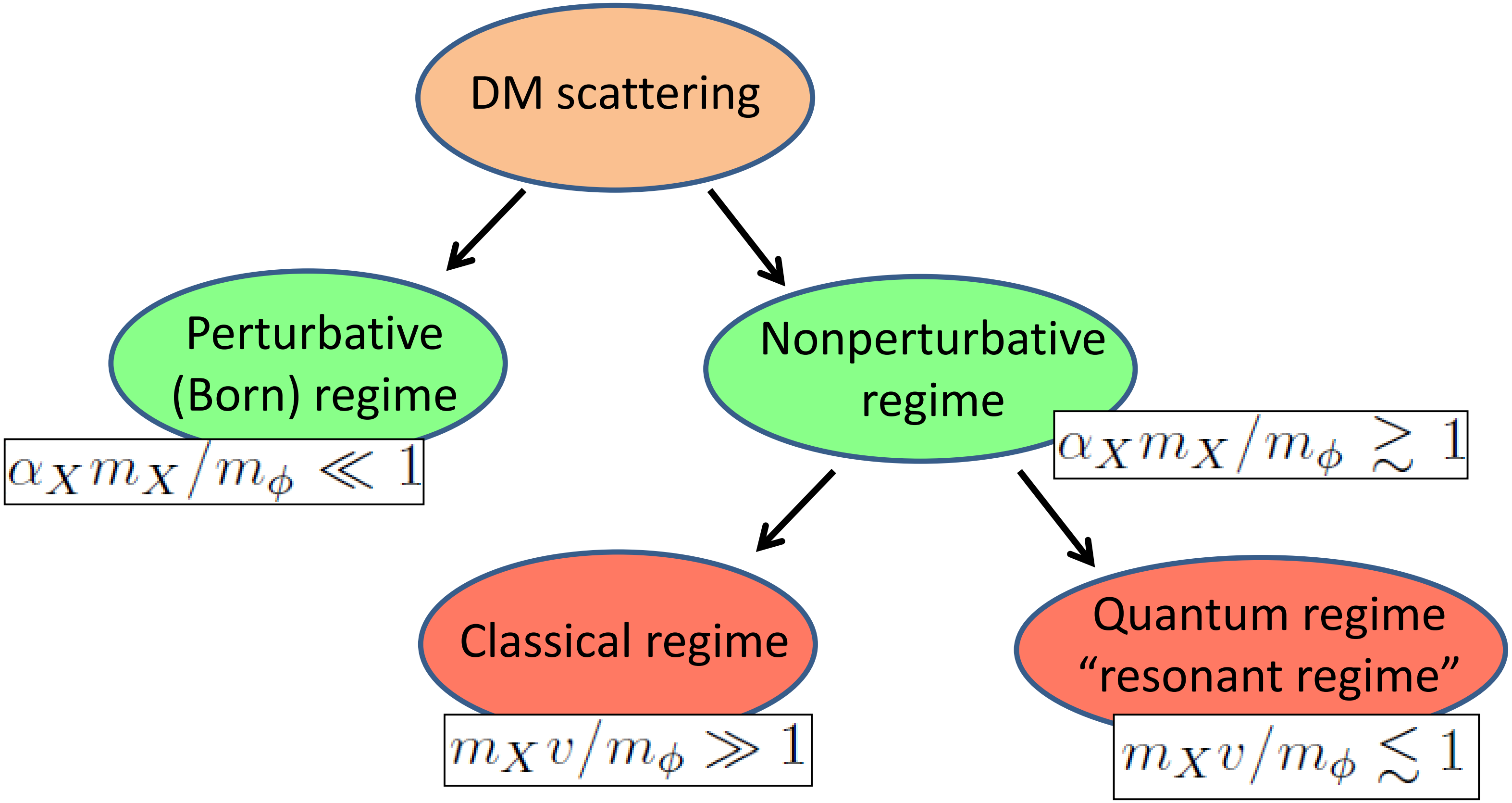


self-interaction

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

DM self-interaction cross section

$$\mathscr{L}_{\text{int}} = \begin{cases} g_\chi \bar{\chi}\gamma^\mu \chi \phi_\mu & \text{vector mediator} \\ g_\chi \bar{\chi}\chi\phi & \text{scalar mediator} \end{cases} \qquad \alpha_X = g_X^2/(4\pi)$$



DM scattering

Perturbative (Born) regime

$\boxed{\alpha_X m_X/m_\phi \ll 1}$

Nonperturbative regime

$\boxed{\alpha_X m_X/m_\phi \gtrsim 1}$

Classical regime

$\boxed{m_X v/m_\phi \gg 1}$

Quantum regime “resonant regime”

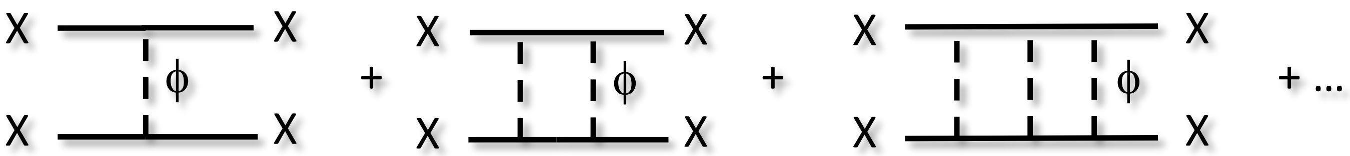
$\boxed{m_X v/m_\phi \lesssim 1}$

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)

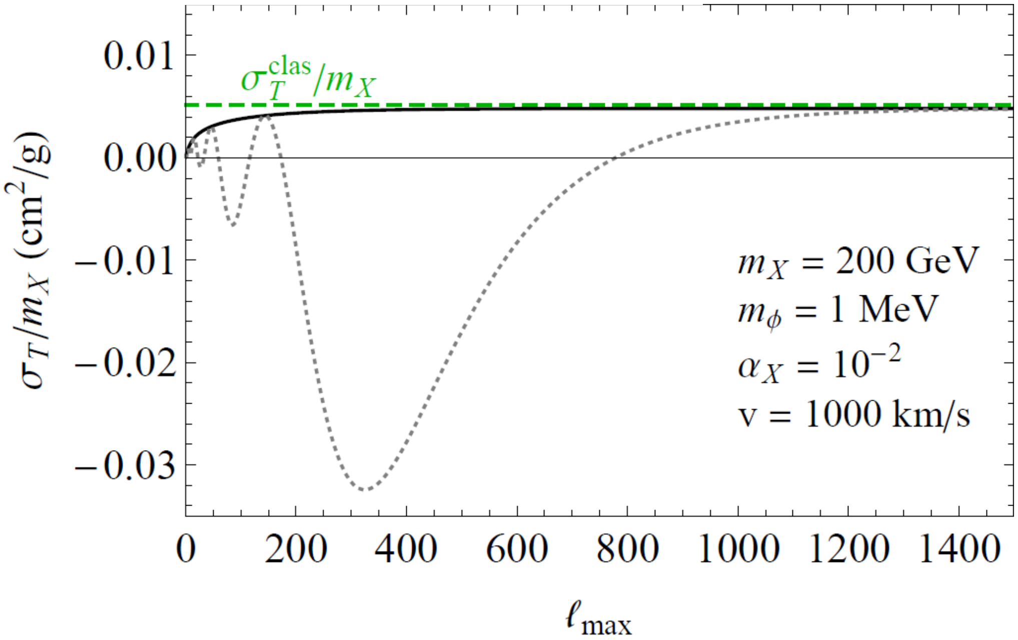
1. More efficient method for matching onto asymptotic solution of Bessel functions, not sines (B&F had $\ell_{\text{max}} = 5$)
2. More efficient formula for summing partial waves

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

Buckley & Fox 2009

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

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

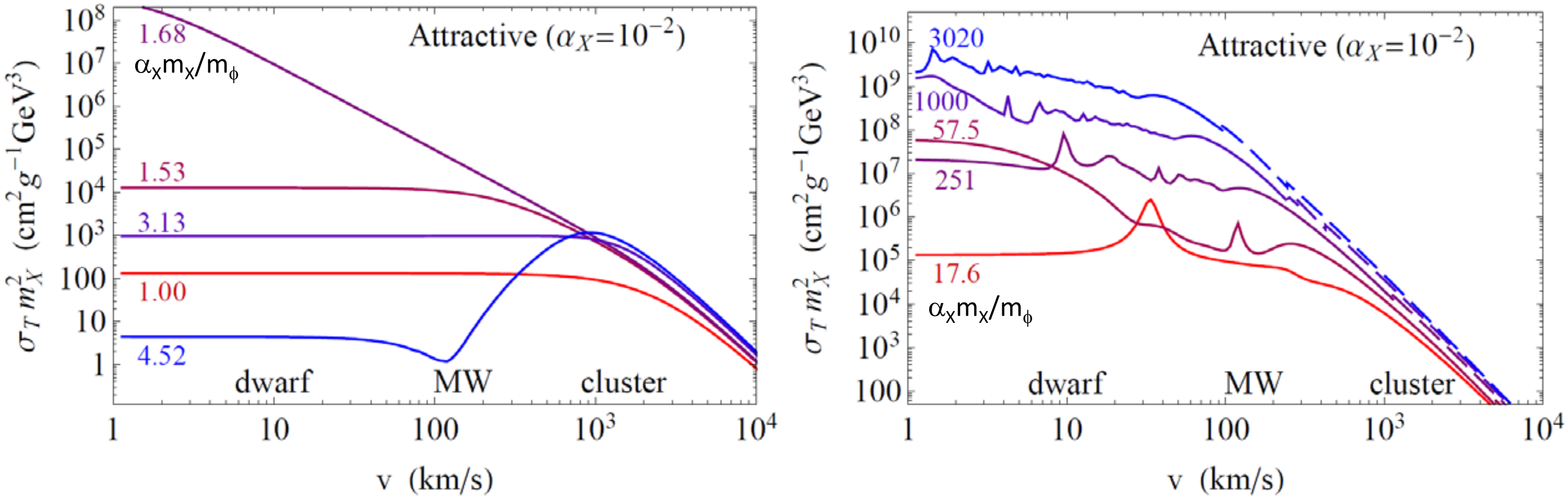


Particle physics lessons for SIDM

Light mediator implies velocity-dependent cross section

- Not a contact interaction in general
- Want to consider $\sigma(v)$, rather than σ as a fixed number

ST, Yu, Zurek (2013)



Example of cross section vs velocity for vector mediator ϕ model

Parameters: α_X, m_X, m_ϕ

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

Different halos have different velocities

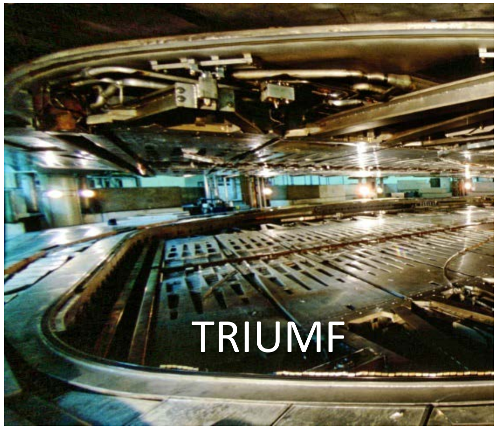
Cores in different systems are probing self-interactions at different energies

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

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

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

Each galaxy and cluster is like a different particle physics collider with a different beam energy



Dark matter halos as colliders

- Goal: Particle physics from observations of cores in dwarfs, LSBs, and clusters

- Caveat: assuming no baryonic feedback to generate cores (background)

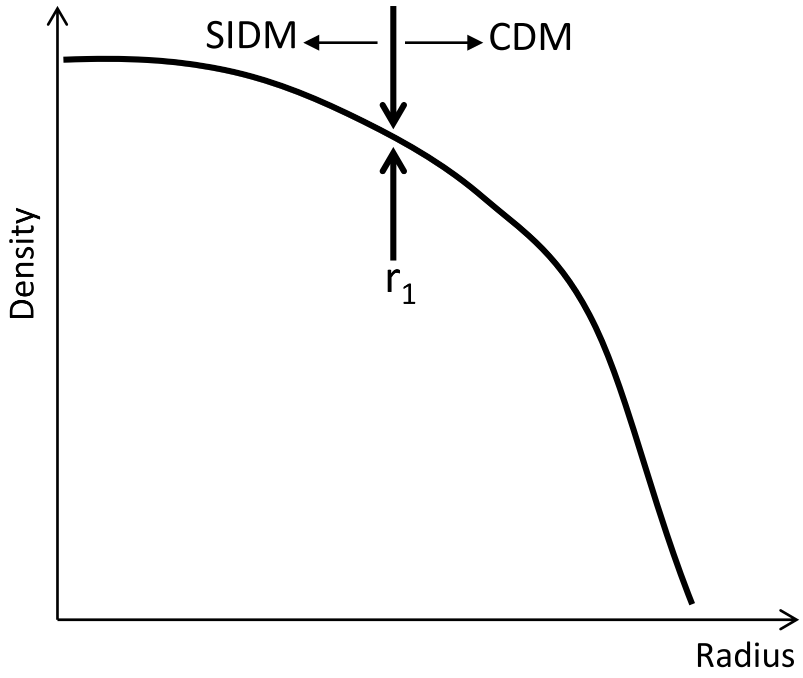
- 2nd caveat: all very preliminary

Kaplinghat, ST, Yu (in preparation)

Particle physics from astrophysics

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

Kaplinghat et al (2014)



Inner halo ($r < r_1$): expect DM to be pseudo-isothermal profile

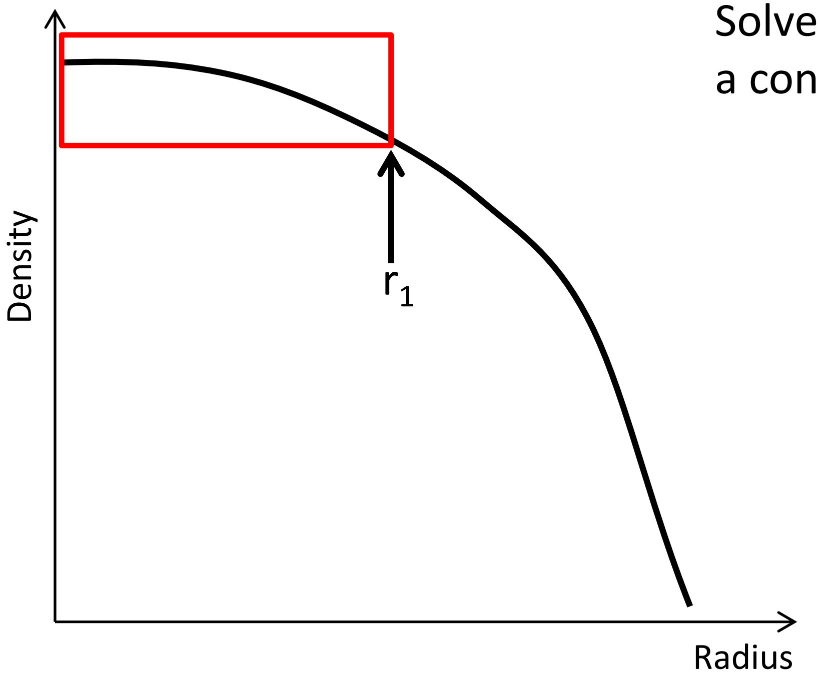
$$N_{scat} \sim \langle \sigma v \rangle / m \, \rho \, t_{age} > 1$$

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

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

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

Particle physics from astrophysics



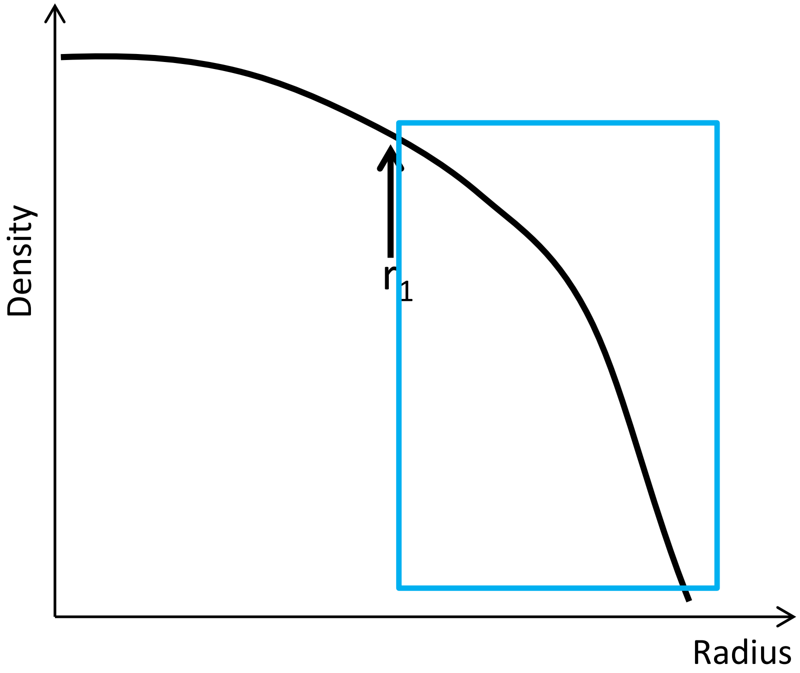
Solve inner region using the Jeans equation with a constant isotropic dispersion

$$\frac{1}{\rho}\frac{d\rho}{dr}\sigma_0^2 = -\frac{d\Phi}{dr}$$

σ_0 is DM velocity dispersion
Φ is total potential (DM + baryons)

Choose σ_0, $\rho(0)$.
Solve $\rho(r)$ for $0 < r < r_1$.

Particle physics from astrophysics



Match the outer region onto NFW solution

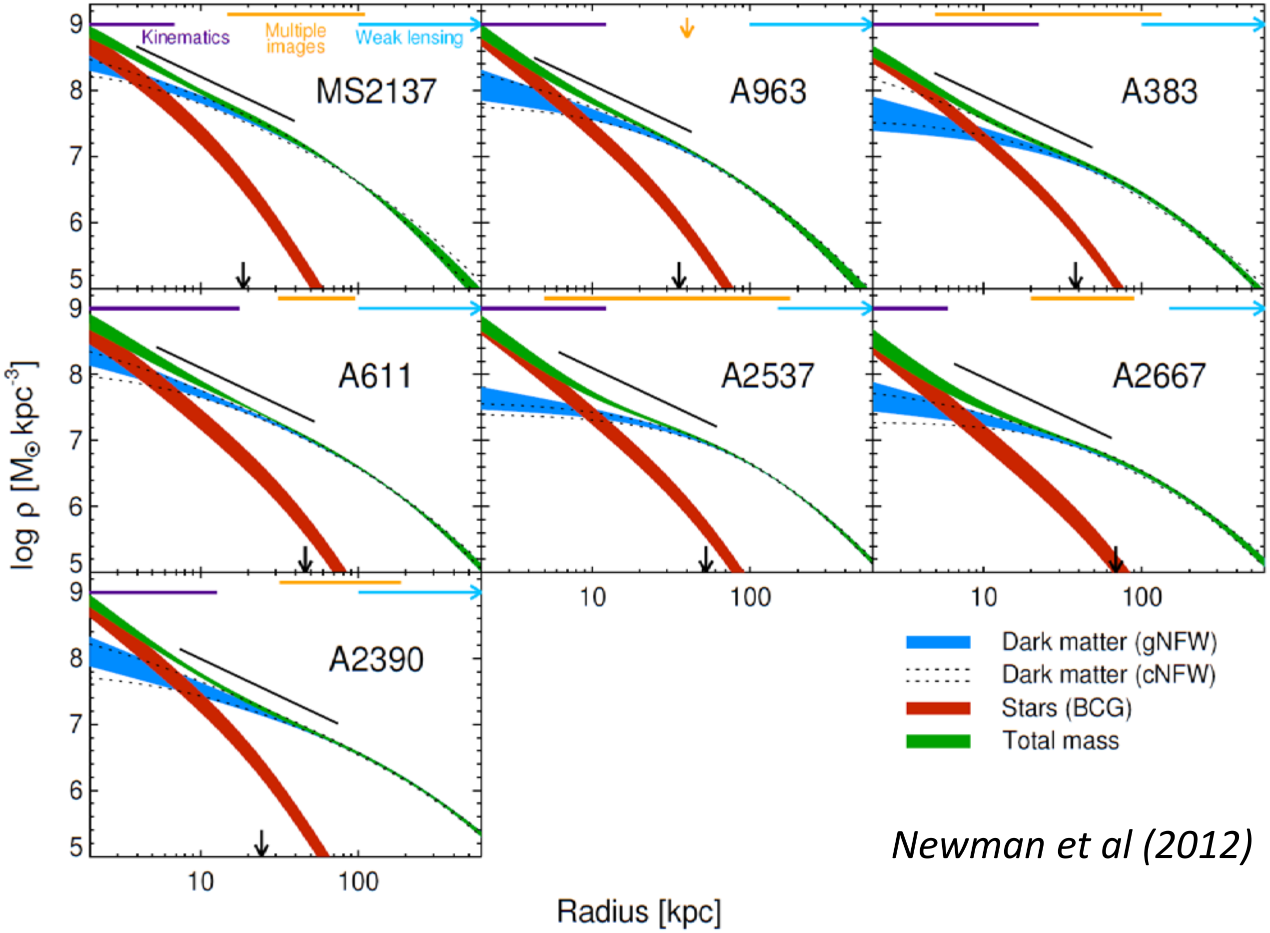
Require $\rho(r)$ and $M_{encl}(r)$ are continuous at $r = r_1$.

In practice, r_1 is unknown.
Need to scan over r_1 to find best fit to both SIDM and CDM regions.

Clusters

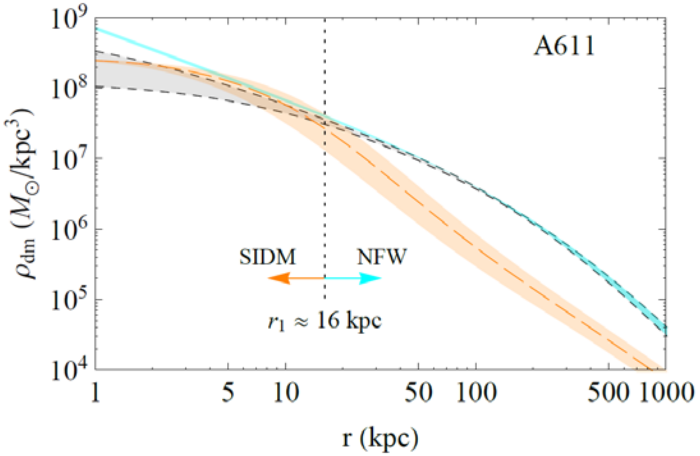
Fantastic data for fitting SIDM:

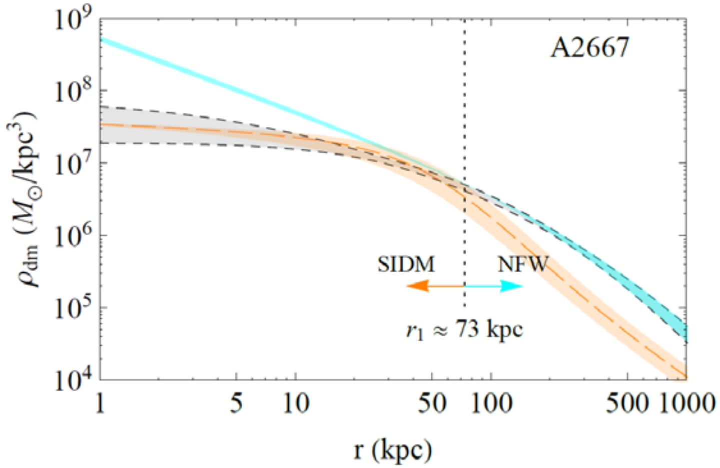
1. Dark matter density obtained for large range of radius (spanning $r > r_1$ and $r < r_1$)
2. Baryon density is easy to include in Φ

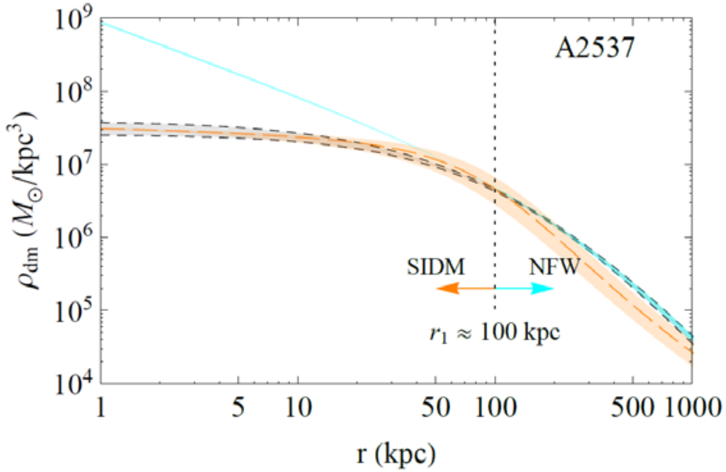


Newman et al (2012)

Cluster fits by eye







Gray dashed contours = Newman et al results for DM density

Cyan = NFW fits obtained by matching large radius DM density (fitting V_{max}, R_{max})

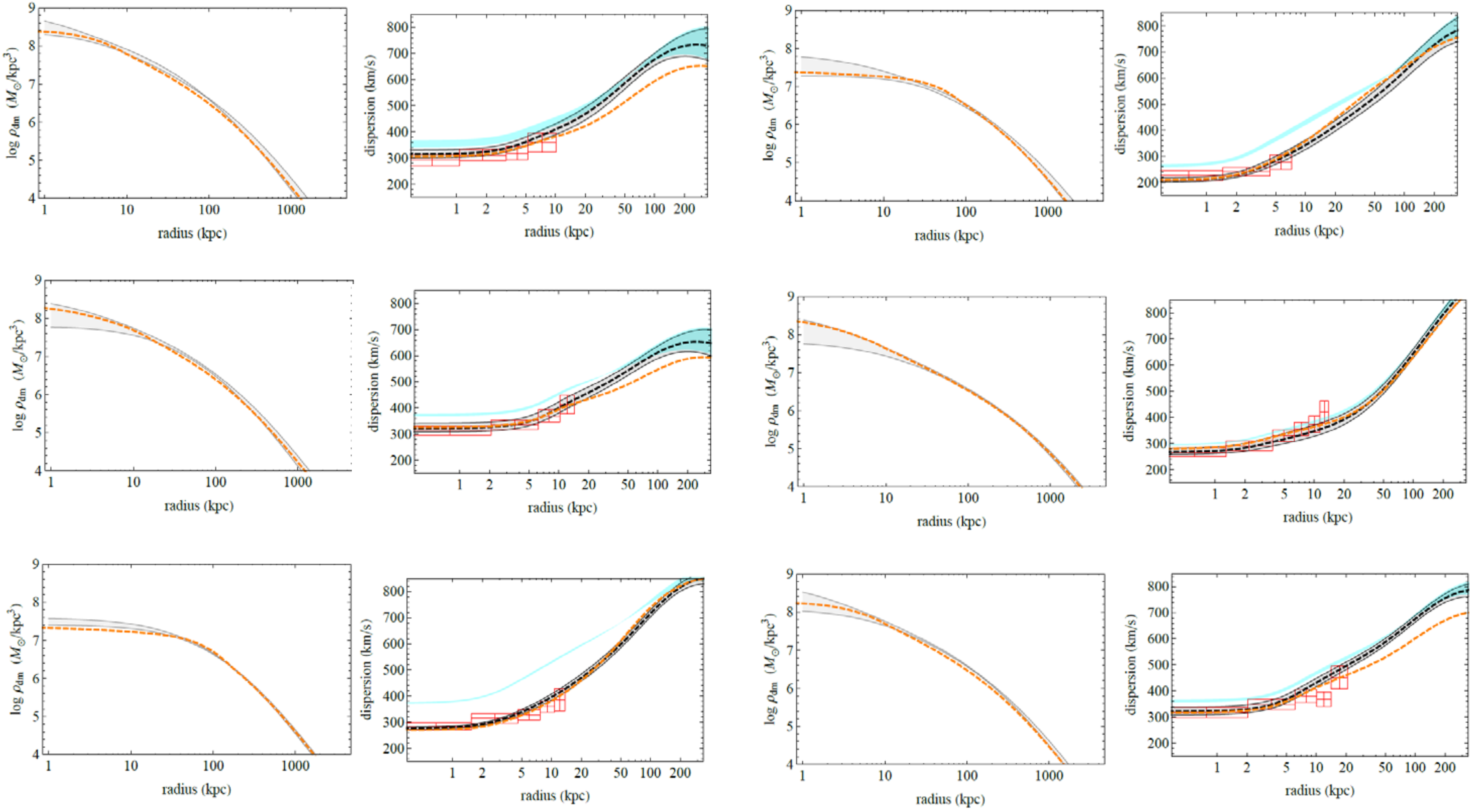
Orange = SIDM fits taken by eye

Cluster fits by MCMC scan

Scan over (σ_0, $\rho(0)$, r_1) and fit to:

- Stellar kinematics data for central galaxy in the cluster (small r)
- Fit to NFW obtained by (V_{max}, R_{max}) at large r.
- Continuity between SIDM and NFW at $r = r_1$.

Cluster fits by MCMC scan



Cluster fits by MCMC scan

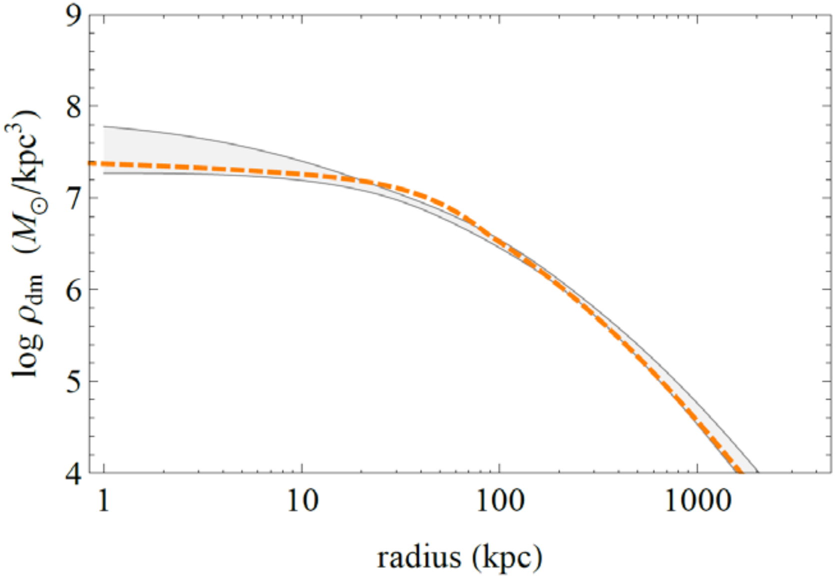
Gray = DM density by Newman et al

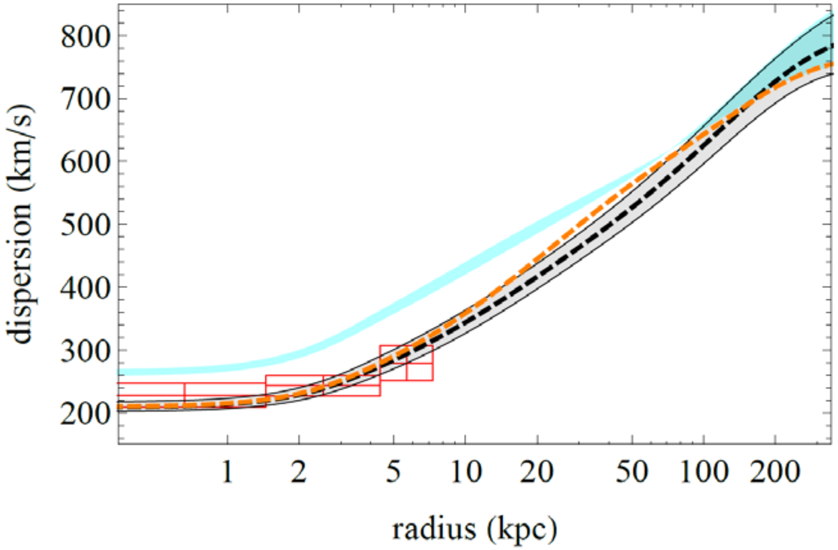
Orange = best fit SIDM point (no error band included yet)

Cyan = NFW

Red = Stellar kinematics data


Cluster A2667 *(Hubble Space Telescope)*

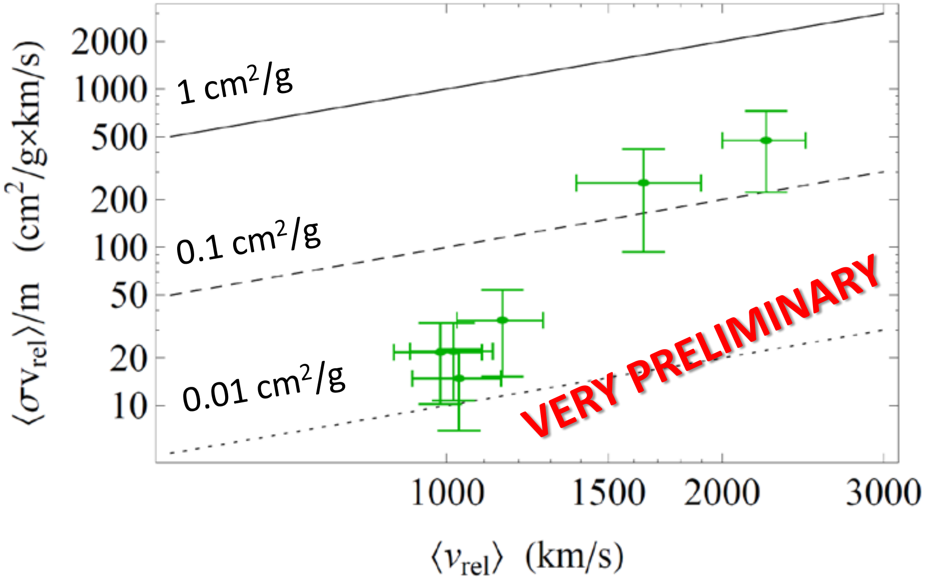




Cross section data from clusters

Instead of σ/m vs v, better to think of $\langle\sigma v\rangle/m$ vs $\langle v\rangle$

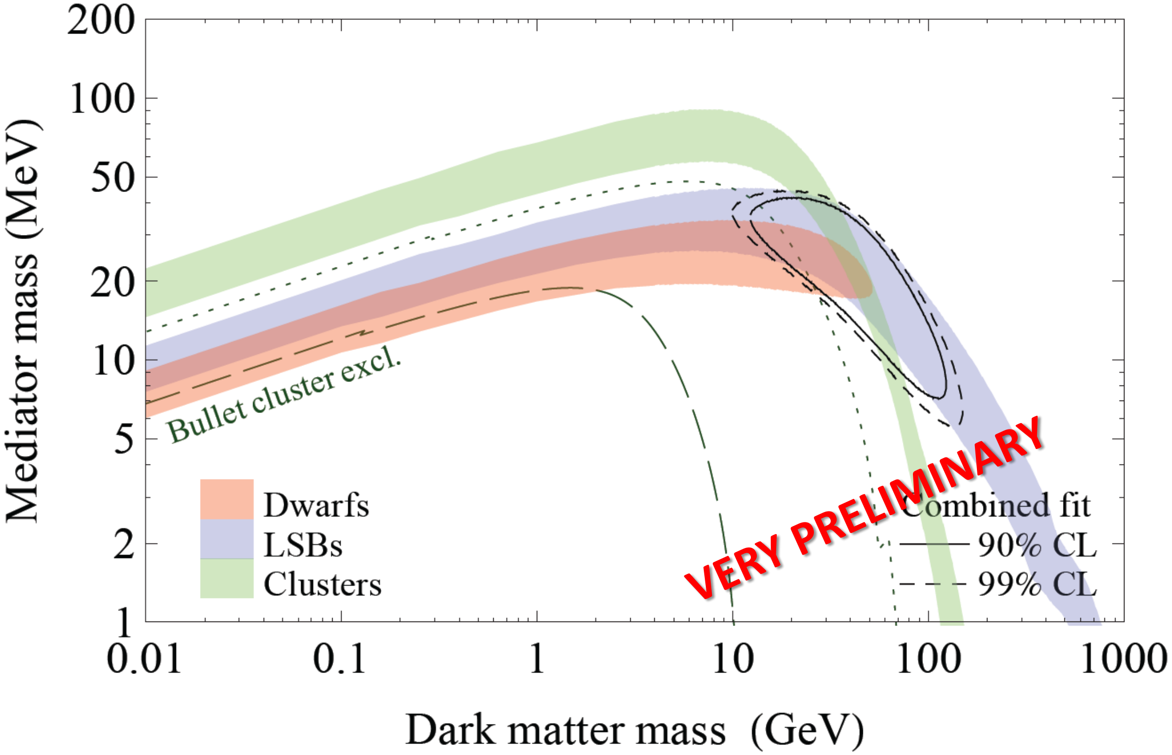
- $\langle\sigma v\rangle/m = 1/\rho(r_1)\, t_{age}$ from rate equation
- $\langle v\rangle = 4\sigma_0/\sqrt{\pi}$ is average (relative) velocity in the thermalized inner halo



Fitting a particle model

Dwarfs and LSBs favor $\sigma/m \sim 1$ cm^2/g (or larger)
Clusters favor $\sigma/m \sim 0.1$ cm^2/g

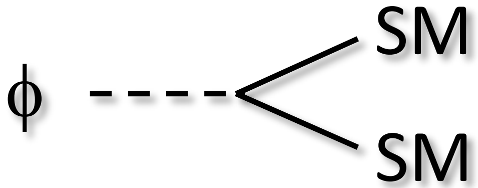
Joint fit to vector mediator ϕ model with $\alpha_X = 10^{-2}$.



Complementary with traditional DM searches

Mediators likely to couple to SM at some level

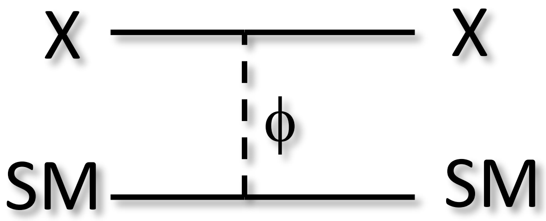
- EFT framework: all renormalizable operators should arise unless forbidden by symmetry
- Coupling to SM allow decays before BBN



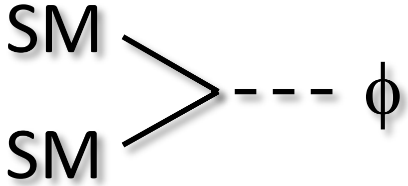
decay

Minimal setup with no new particles:
ϕ decays to SM fermions before BBN

- Mediator provides a portal between SM and dark sector

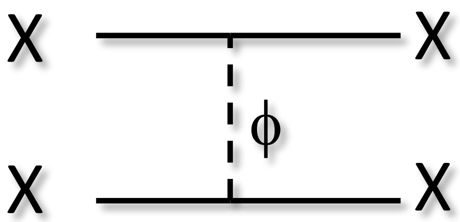


Direct detection

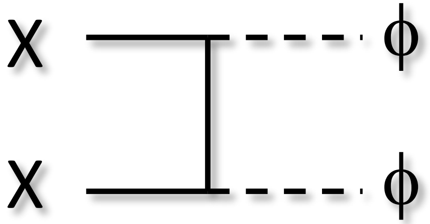


Direct production

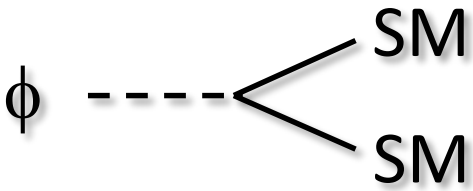
Phenomenology of SIDM



Self-interactions
Astrophysical observations of structure

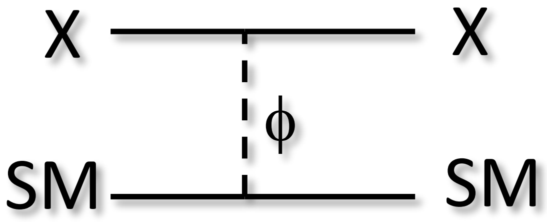


Annihilation

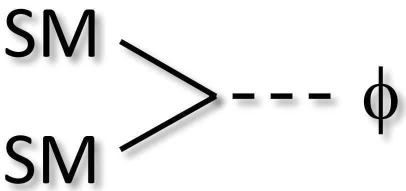


Decay

Relic density
Indirect detection



Direct detection

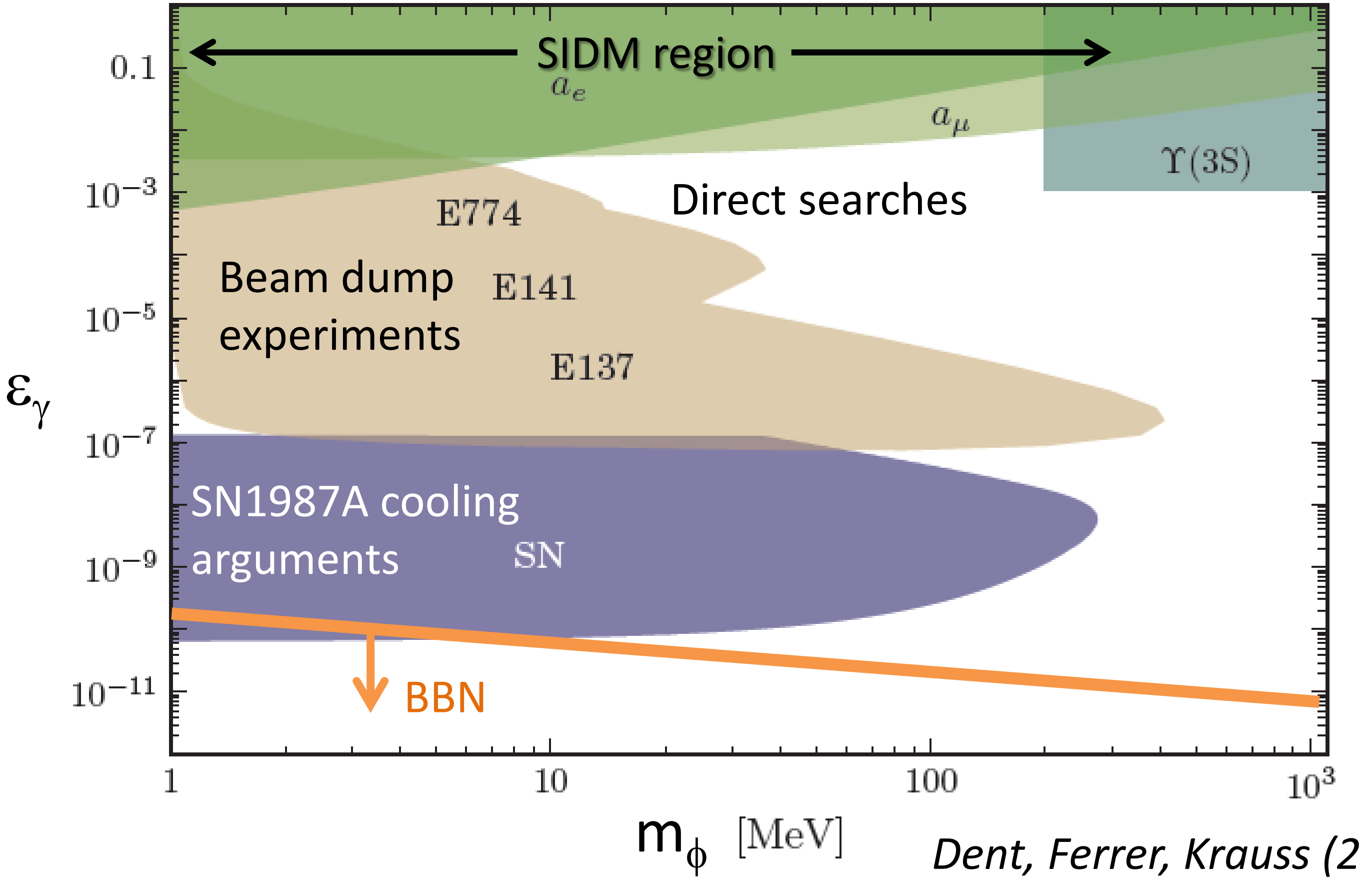


Direct production
Intermediate energy colliders

Dark force coupled via kinetic mixing

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

Holdom (1984); Pospelov et al (2007);
Arkani-Hamed et al (2009) …



Post BBN decays
Entropy dilution of
baryon density
between BBN and CMB

Coupling can be very
weak ~ 10^{-10}

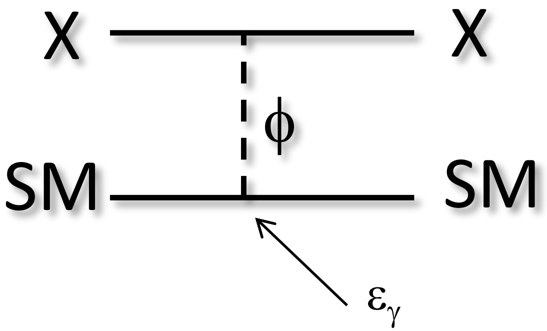
Dent, Ferrer, Krauss (2012)

Dark force coupled via kinetic mixing

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

Holdom (1984); Pospelov et al (2007); Arkani-Hamed et al (2009) …

Direct detection



$$\sigma^{\rm SI}_{\chi n} = \frac{16\pi\alpha_\chi\alpha_{\rm em}\mu^2_{\chi n}\epsilon^2_{\rm eff}}{m^4_\phi} \approx 10^{-24}\ {\rm cm}^2 \times \epsilon^2_{\rm eff}\left(\frac{\alpha_\chi}{10^{-2}}\right)\left(\frac{30\ {\rm MeV}}{m_\phi}\right)^4$$

$\varepsilon_{\rm eff} = \varepsilon_\gamma\ (Z/A)$

Direct detection limits ($\sim 10^{-45}$ cm^2) can probe down to 10^{-10}

Direct detection rate

Kaplinghat, ST, Yu (2013)

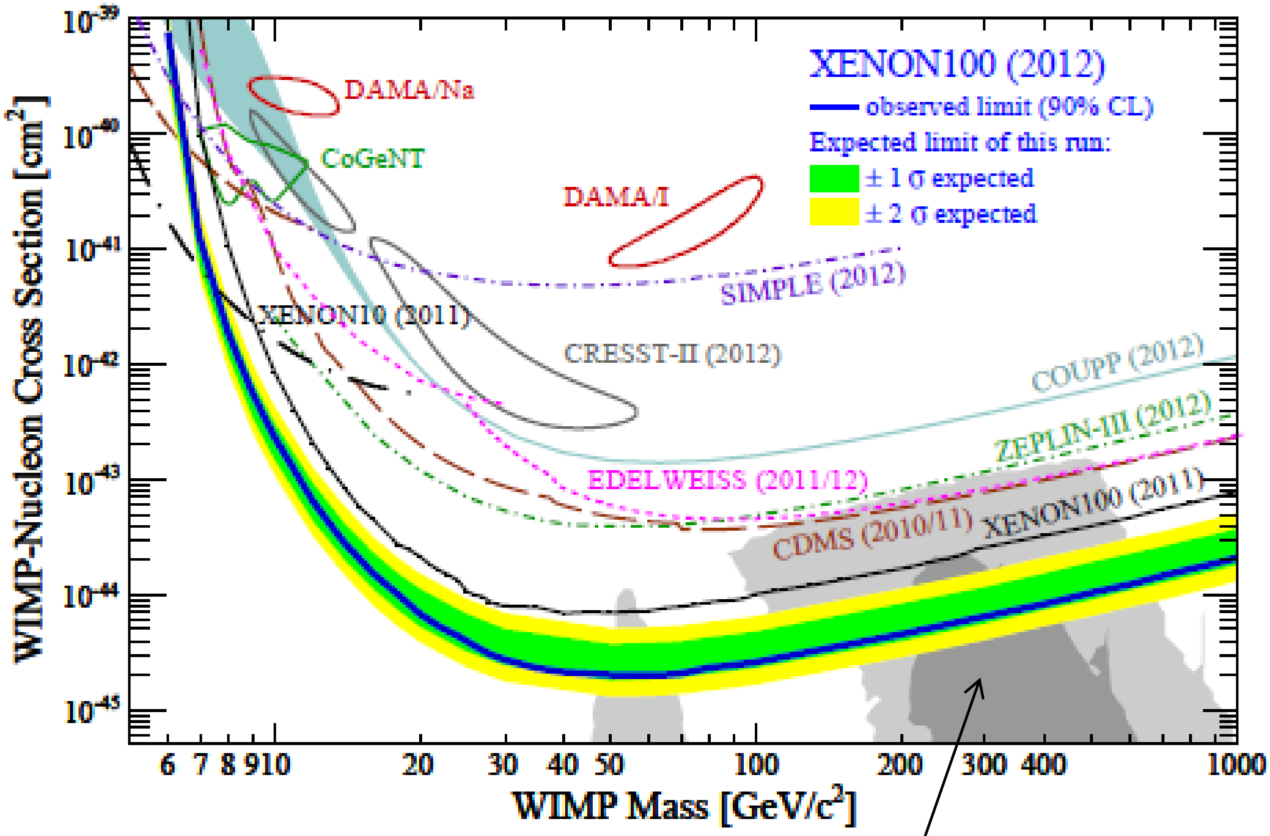
Direct detection has dependence on momentum transfer (not a contact interaction)

$$\begin{aligned} \frac{dR}{dE_R} &= \frac{\rho_{\rm DM}}{m_X} \int_{v_{\rm min}} d^3v \, v \, f(\vec{v}) \, \frac{d\sigma^{\rm SI}_{XN}(v, E_R)}{dE_R} \\ &= \frac{\rho_{\rm DM}}{m_X} \int_{v_{\rm min}} d^3v \, v \, f(\vec{v}) \left(\frac{d\sigma^{\rm SI}_{XN}(v, E_R)}{dE_R} \right)_{q^2=0} \times \frac{m_\phi^4}{(m_\phi^2 + q^2)^2} \end{aligned}$$

Momentum transfer $q = \sqrt{2 m_N E_R}$ ~ 50 MeV ~ m_ϕ

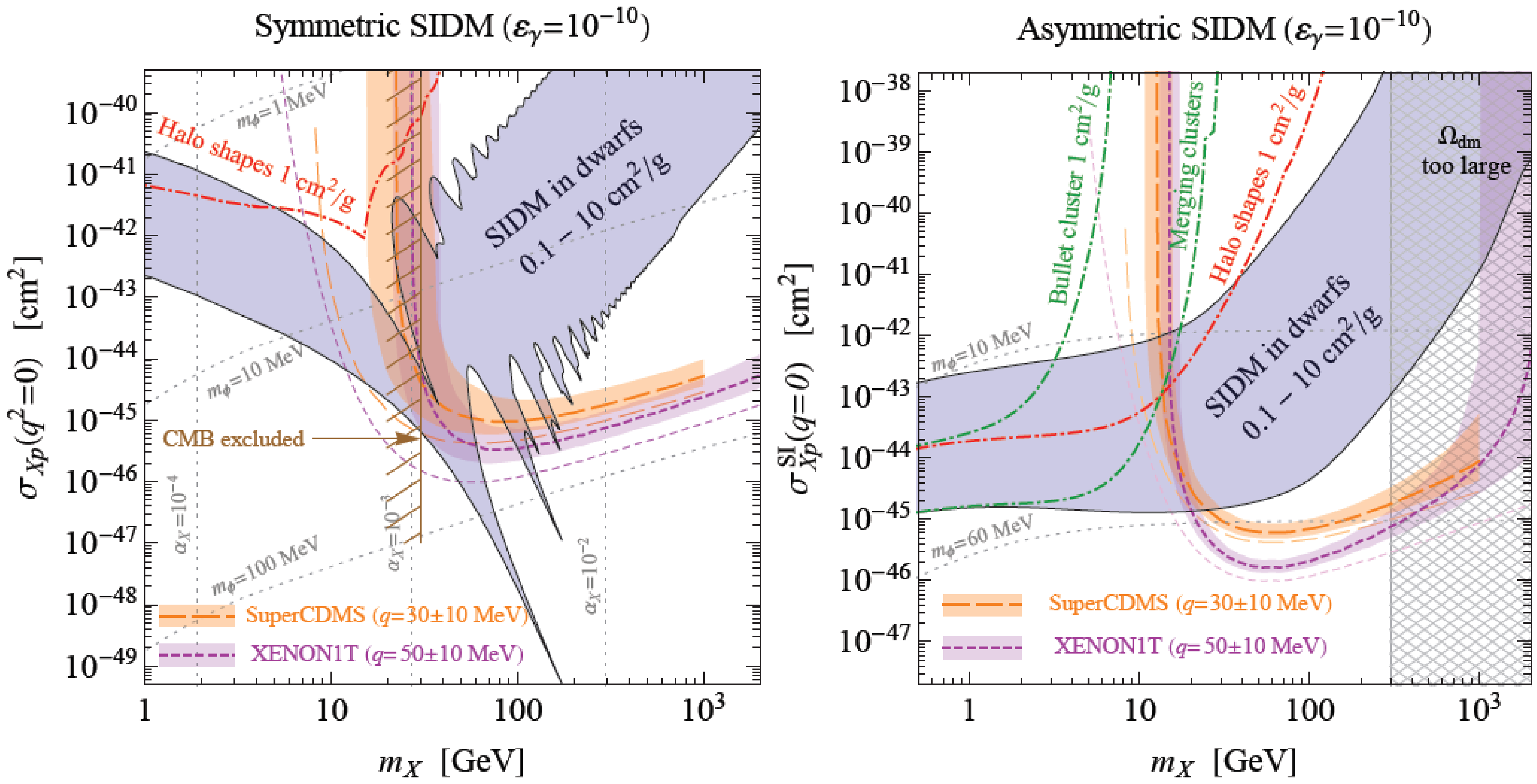
- Low energy threshold and lighter nuclei better for SIDM
- Heuristic approach: take fixed q and rescale direct detection sensitivity by this form factor

Direct detection



Benchmarks from SUSY
Why should SUSY get all the attention?

SIDM benchmarks for direct detection



Kaplinghat, ST, Yu (2013)

Conclusions

- Astrophysical observations of structure offer possibility to explore dark matter interactions beyond WIMP paradigm and may be hidden from visible sector

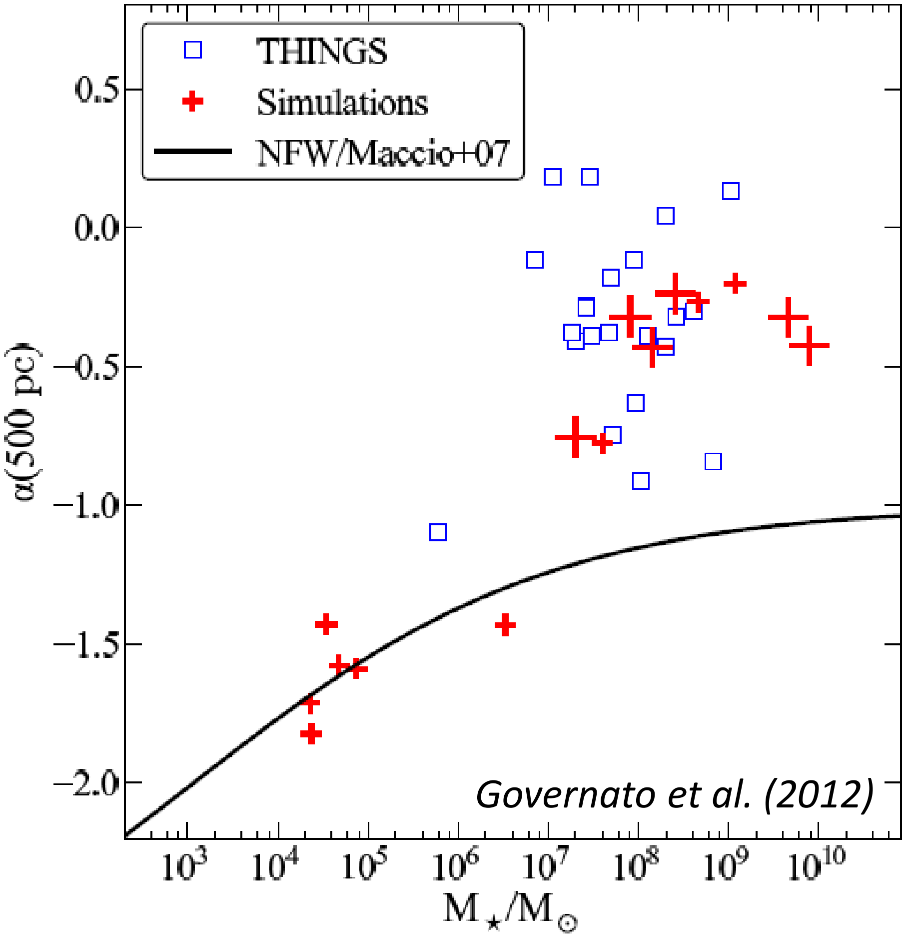
- Long-standing issues for CDM and structure, but jury still out

- Galaxies and clusters offer huge complementary power for exploring particle physics of SIDM (but need to understand the backgrounds), as well as other DM searches.

Backup slides

1. Cores in field dwarfs

CDM-only simulations poor representation of DM+baryon Universe



Governato et al. (2012)

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

Requires bursty star formation history

Depends on implementation sub-grid physics

1. Cores in MW satellites

CDM-only simulations poor representation of DM+baryon Universe

- Supernova feedback mechanism insufficient (not enough baryons)

  Garrison-Kimmel, et al (2013)

- Environmental effect from MW baryonic disk can form DM cores

  Zolotov et al (2012)

1. Cores in MW satellites

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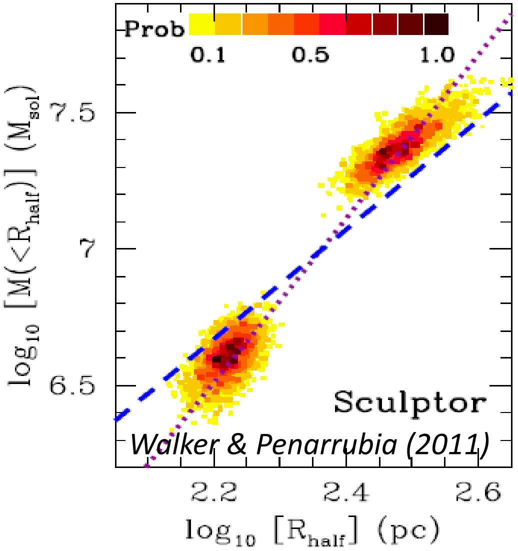
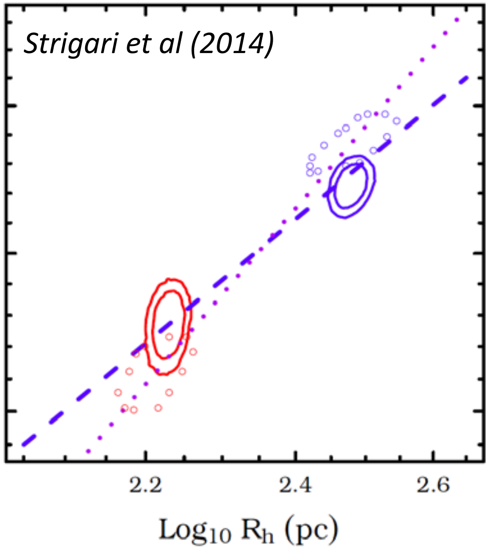
Systematic uncertainty in astrophysical interpretation



Walker & Penarrubia (2011)



Strigari et al (2014)

No cores in MW satellites?

Conclusions depend on assumptions for stellar kinematic distribution

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

But also arguments from existence of old globular clusters

1. Cores in LSBs

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

1. Cores in clusters

CDM-only simulations poor representation of DM+baryon Universe

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

Systematic uncertainty in astrophysical interpretation

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

Schaller et al (2014)

2. Too-big-to-fail problem

Caveats:

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

Purcell & Zentner (2012)

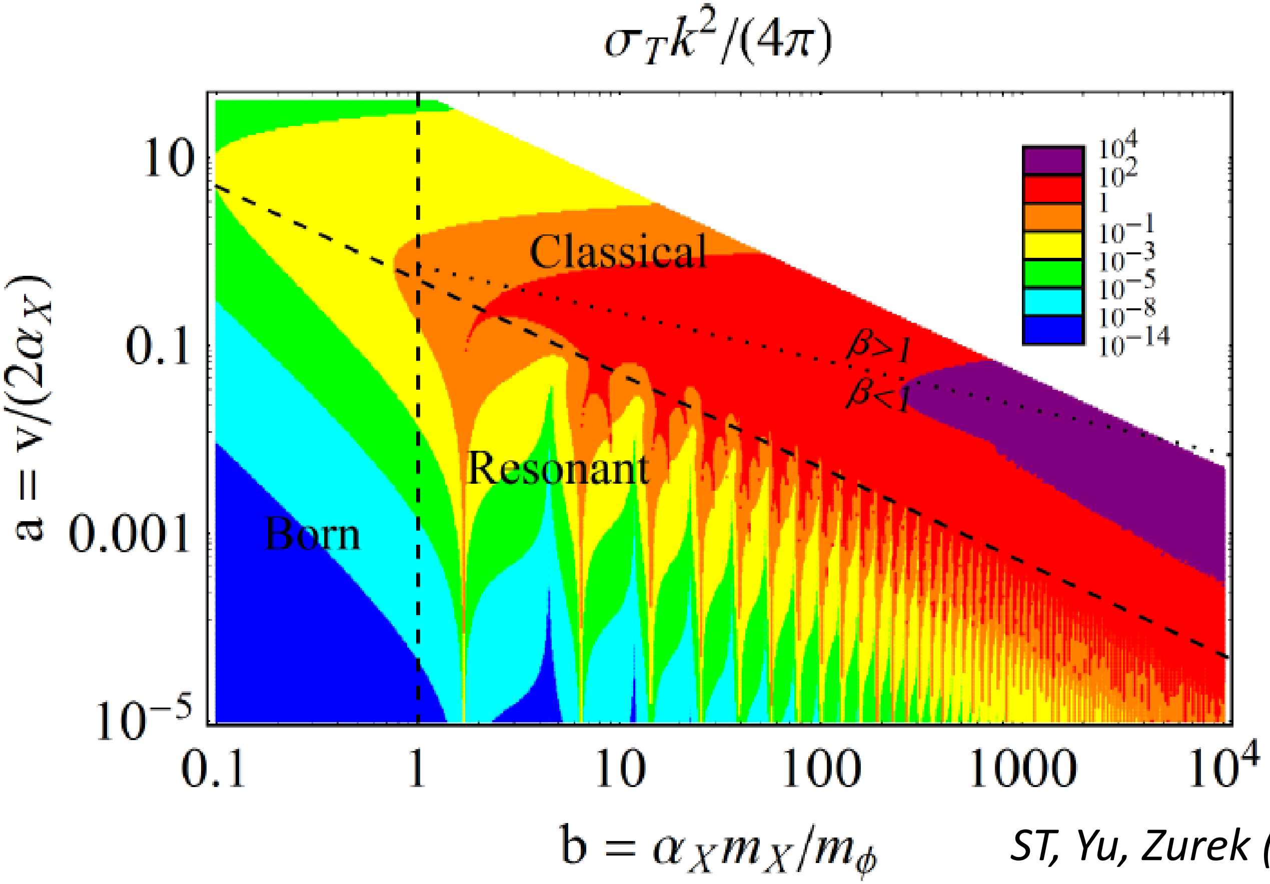
MW mass might be smaller (but combined mass of MW+M31 is relatively well constrained) *Tollerud et al. (2014)*

Baryons are important

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

Parameter space for SIDM

- Scan over SIDM parameters (v, m_χ, m_ϕ, α_χ)

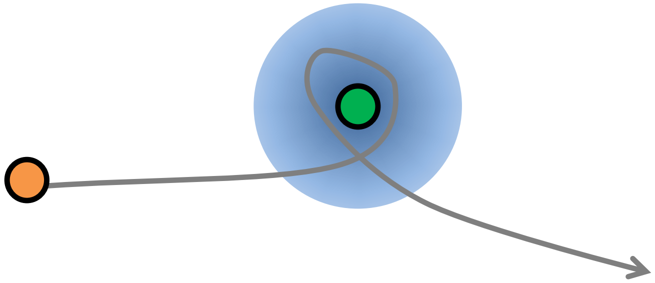


ST, Yu, Zurek (2013)

Classical self-scattering

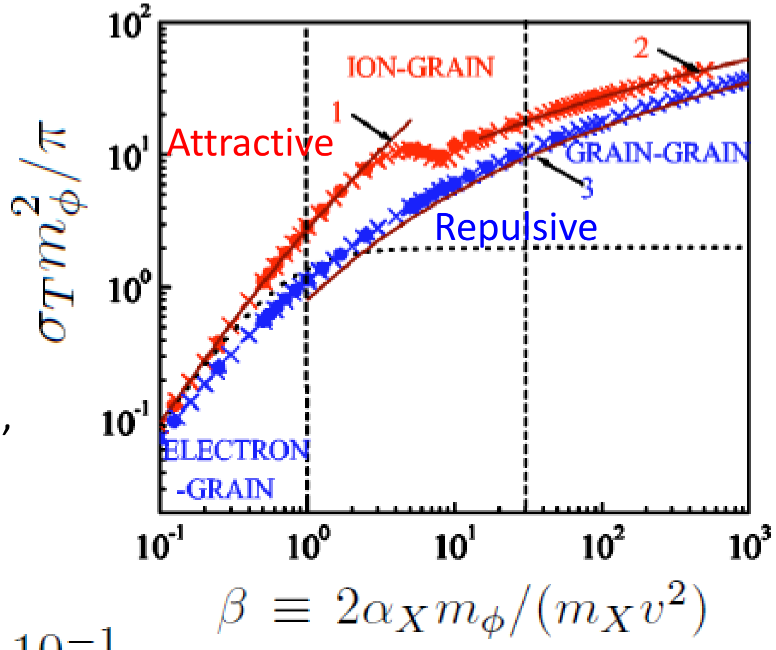
- Classical approximation for σ_T from plasma physics

Classical scattering in potential



$$V(r) = \mp \frac{\alpha_X}{r} e^{-m_\phi r}$$

m_ϕ = Debye mass,
α = EM coupling



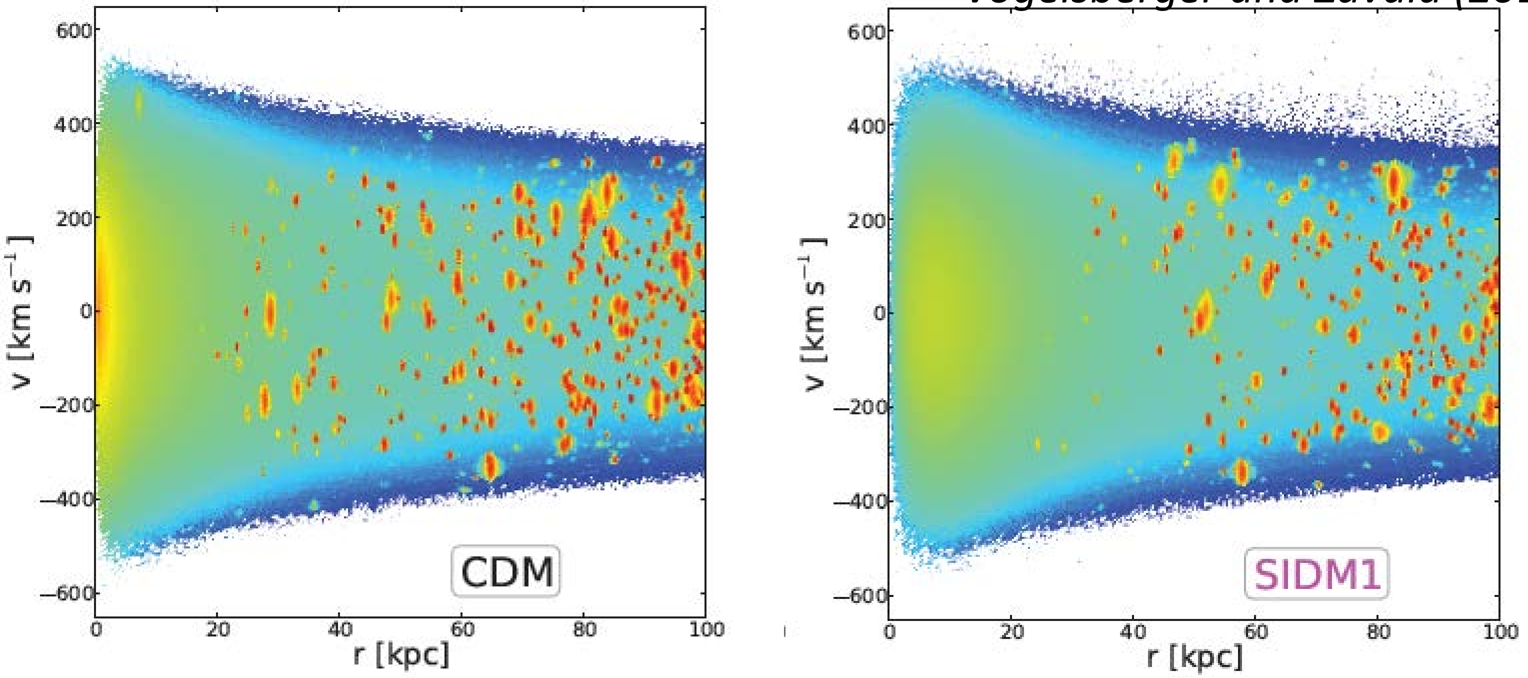
$$\sigma_T^{\rm clas} \approx \begin{cases} \frac{4\pi}{m_\phi^2}\beta^2 \ln\left(1+\beta^{-1}\right) & \beta \lesssim 10^{-1} \\ \frac{8\pi}{m_\phi^2}\beta^2/\left(1+1.5\beta^{1.65}\right) & 10^{-1} \lesssim \beta \lesssim 10^3 \\ \frac{\pi}{m_\phi^2}\left(\ln\beta + 1 - \frac{1}{2}\ln^{-1}\beta\right)^2 & \beta \gtrsim 10^3 \end{cases}$$

Khrapak et al (2004)

SIDM and direct detection

Self-interactions change phase space distribution of DM halo

Vogelsberger and Zavala (2012)



O(10%) effect on DM recoil rate in direct detection experiments
Also effect annnual modulation amplitude and phase

Three portals to the dark sector

1. Vector mediator (ϕ mixes with Z or γ)
   - Kinetic mixing with photon

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

Holdom (1984); Pospelov et al (2007);
Arkani-Hamed et al (2009);
Lin et al (2011) …

   - Z mass mixing (ε_Z is Z-ϕ mixing angle):

$$\mathscr{L}_{\text{mix}} = \varepsilon_Z m_Z^2\,\phi_\mu Z^\mu$$

Babu et al (1997);
Davoudiasl et al (2012) …

2. Scalar mediator
   - Higgs mixing (ε_h is h-ϕ mixing angle)

$$\mathscr{L}_{\text{mix}} = -\varepsilon_h m_h^2\,\phi h$$

Patt & Wilczek (2006), …

(Assume $\varepsilon \ll 1$, $m_\phi \sim 1 - 100$ MeV $\ll m_Z$)

Three portals to the dark sector

- Limits from BBN (want lifetime < second)
  - Kinetic mixing

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

$$\text{BR}(\phi \to e^+e^-) \approx 1$$

  - Z mixing

$$\tau_\phi \approx 1 \text{ second} \times \left(\frac{\varepsilon_Z}{10^{-10}}\right)^{-2} \left(\frac{m_\phi}{10 \text{ MeV}}\right)^{-1}$$

$$\text{BR}(\phi \to \nu\bar{\nu}) \approx 6/7 \text{ and } \text{BR}(\phi \to e^+e^-) \approx 1/7$$

  - Higgs mixing

$$\tau_\phi \approx 4 \text{ seconds} \times \left(\frac{\varepsilon_h}{10^{-5}}\right)^{-2} \left(\frac{m_\phi}{10 \text{ MeV}}\right)^{-1}$$

$$\text{BR}(\phi \to e^+e^-) \approx 1$$