# Beyond Collisionless DM

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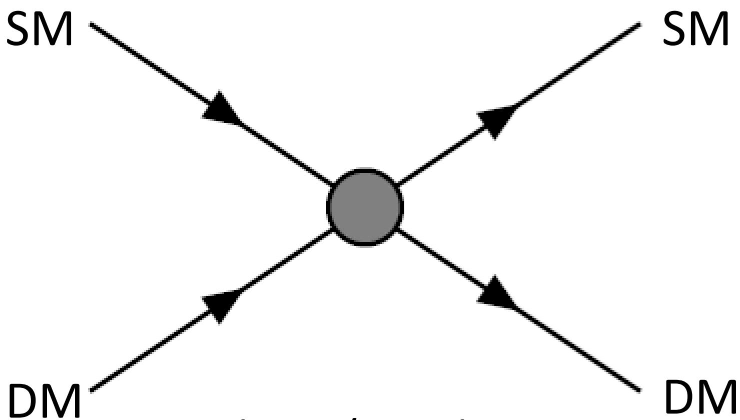
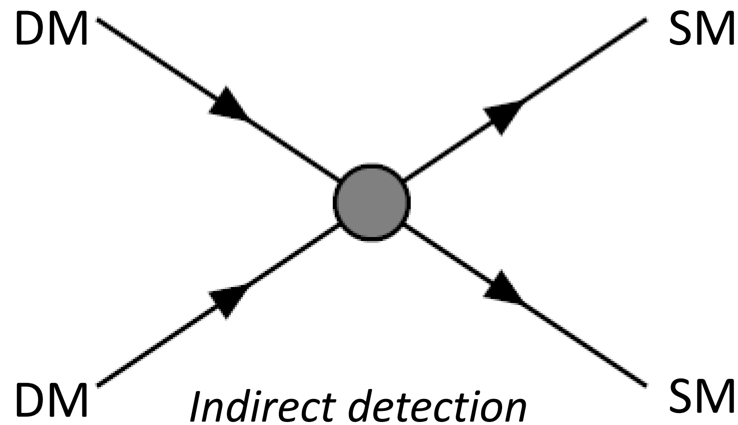
Based on: ST, Haibo Yu, Kathryn Zurek (1210.0900 + 1302.3898)
Manoj Kaplinghat, ST, Haibo Yu (1308.0618 + 13xx.xxxx)

# Exploring the dark sector



*Direct detection*



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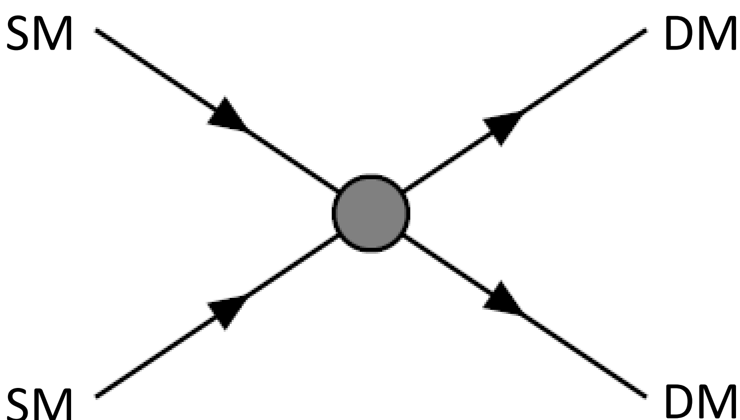
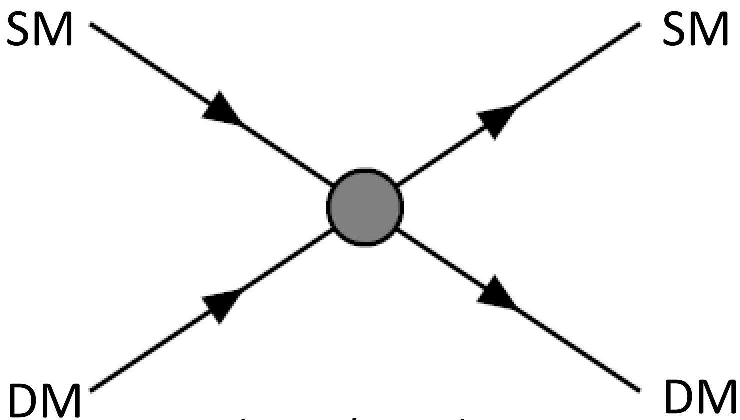


*Colliders*

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

# Exploring the dark sector

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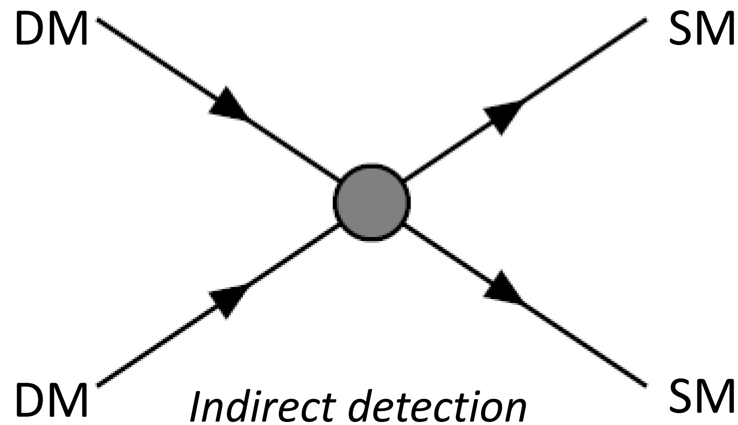
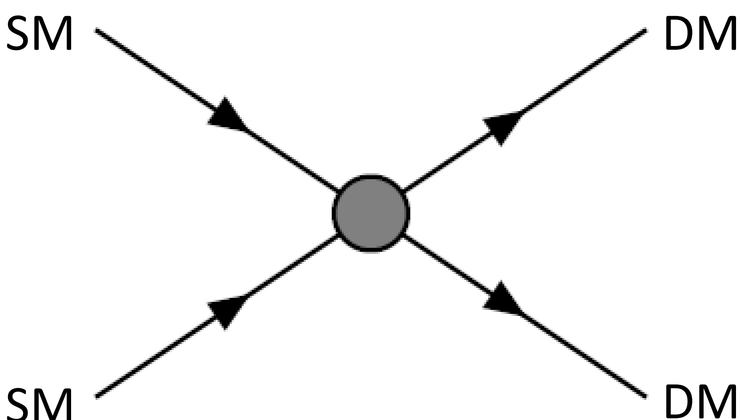



*Indirect detection*

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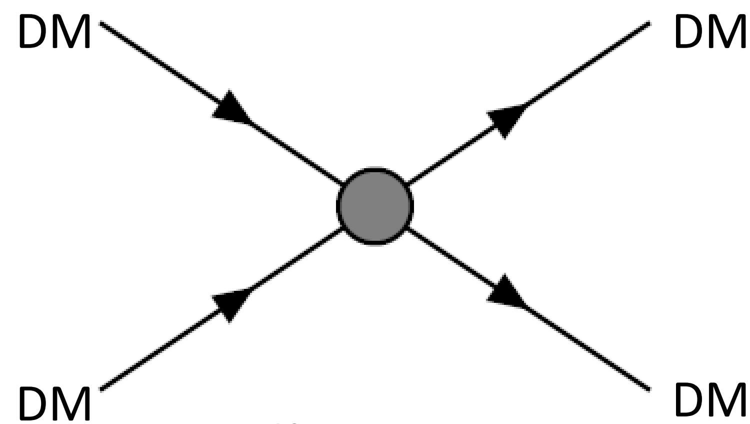



*Self-interactions*

# Outline

- Cold collisionless DM paradigm in trouble (??)
  - Discrepancy between N-body simulations and astrophysical observations on smallest scales
  - Dwarf galaxies: laboratories for studying DM
- DM may have self-interactions
  - Particle physics implications of self-interacting DM

# CDM in trouble

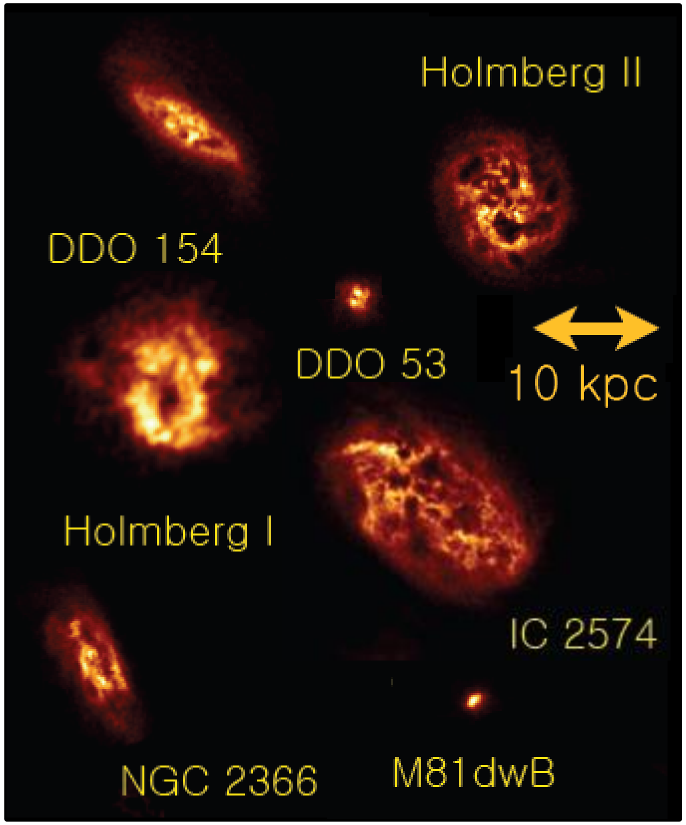
1. Core-vs-cusp problem *Moore (1994), Flores & Primack (1994)*
   – Central densities of dwarf halos exhibit cores

     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

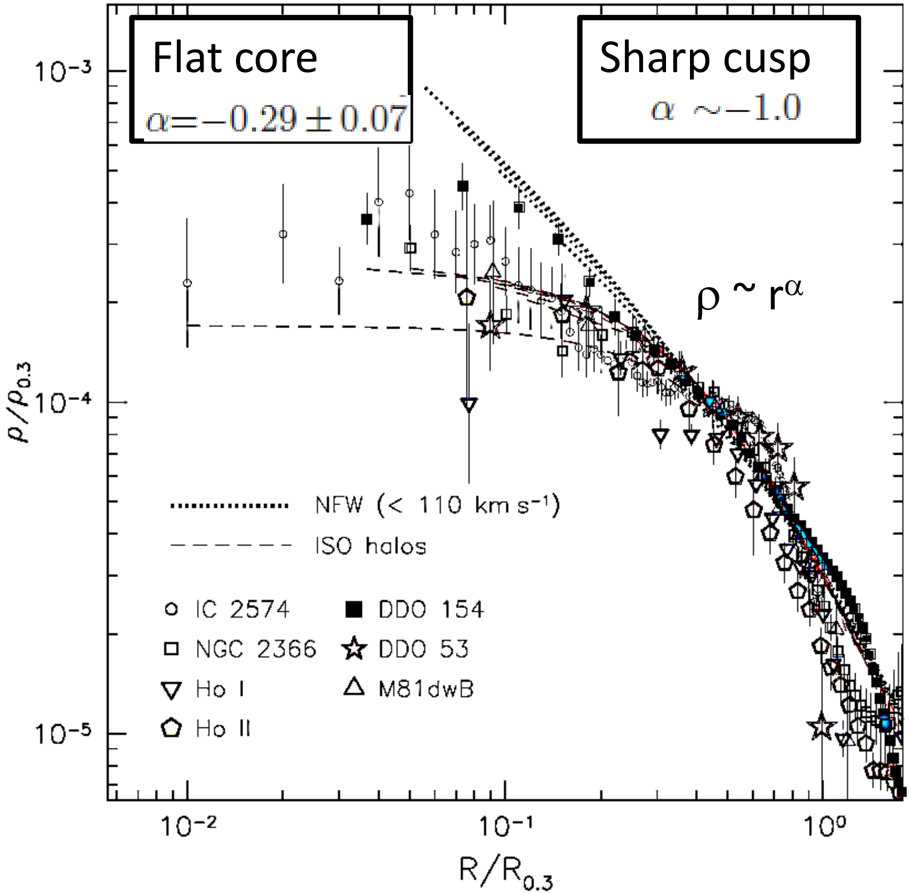
# 1. Core-vs-cusp problem

Cores in dwarf galaxies outside the MW halo

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



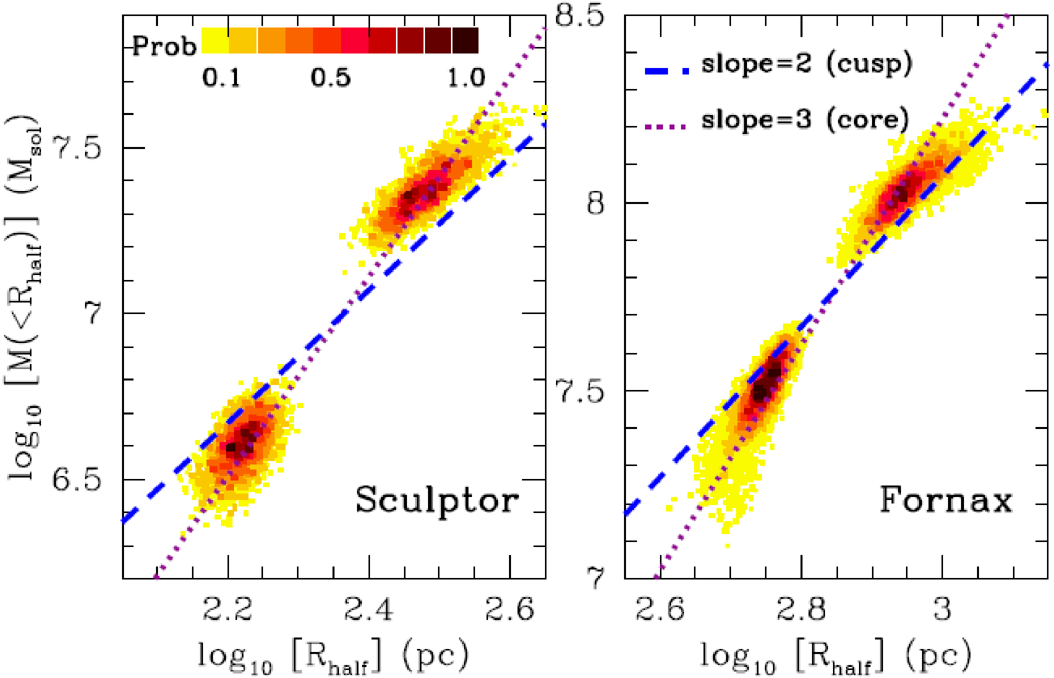

THINGS (dwarf galaxy survey) - Oh et al. (2011)




Baryonic feedback from supernovae may flatten central cusps (*Governato et al 2012*)

# 1. Core-vs-cusp problem

Cores in MW dwarf spheroidals (dSphs)




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

*Walker & Penarrubia (2011)*

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

Not enough baryonic feedback from supernovae *(Garrison-Kimmel et al 2013)*

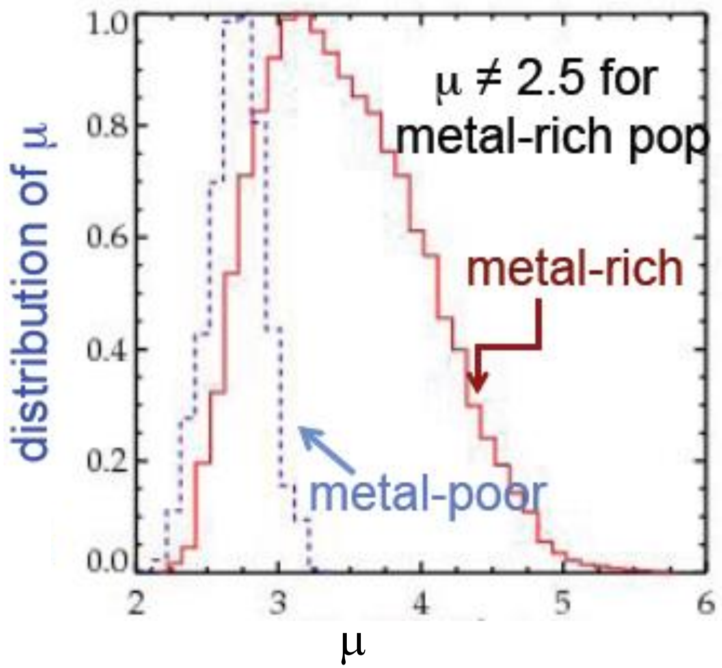
Estimate enclosed mass from line-of-sight dispersion: $M(<r) = \mu\, r \langle\sigma_{los}^2\rangle/G$ $\mu=2.5$

# 1. Core-vs-cusp problem

Cores in MW dwarf spheroidals (dSphs)

*Frenk, Strigari, White (2013) [C. Frenk's Aspen talk]*

MW dSphs can be consistent with NFW profiles due to uncertainty in $\mu$

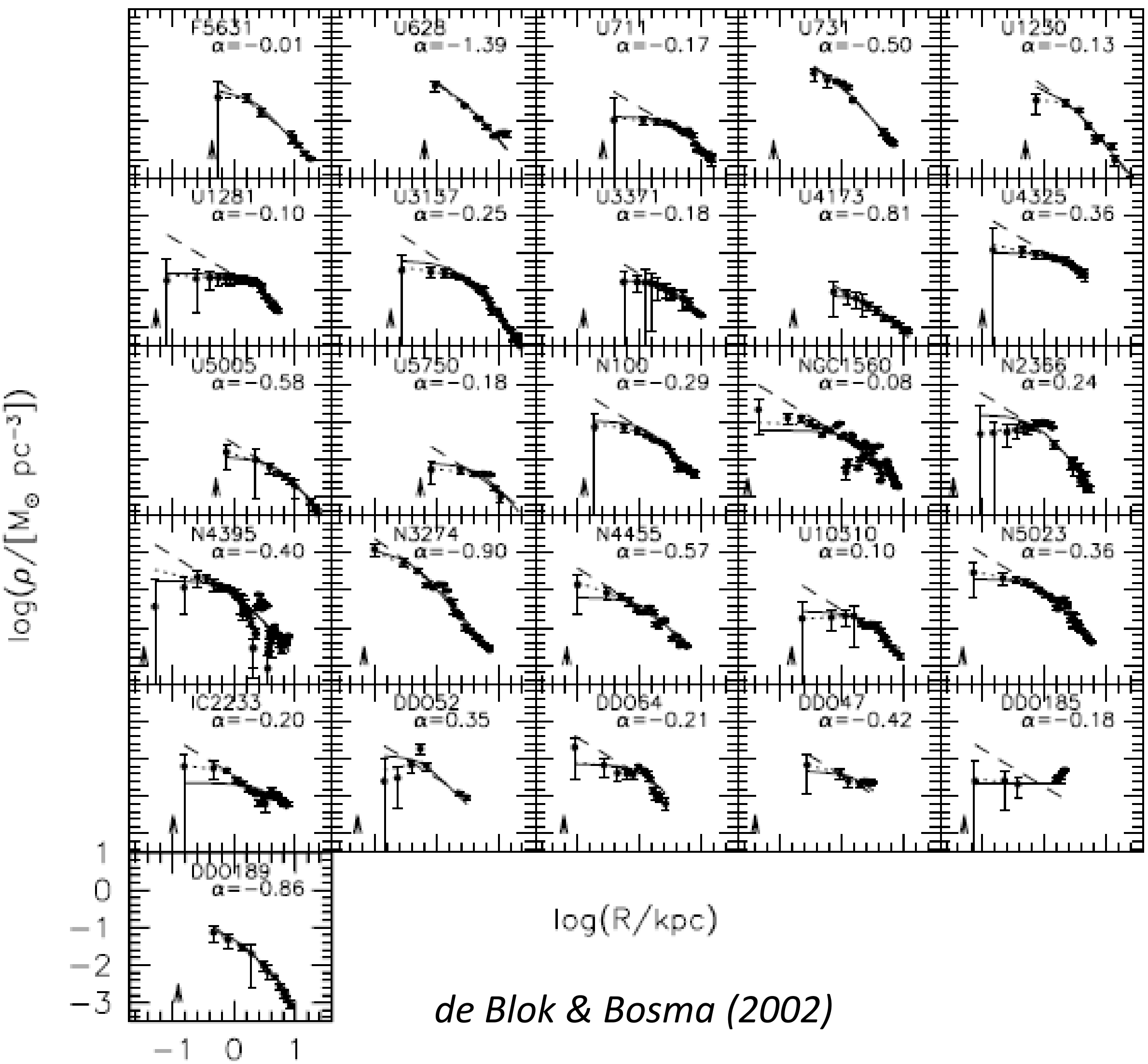



Cores in MW dSphs favored from longevity of ~10 Gyr old globular clusters

Cusps lead to inspiral of GCs on ~ few Gyr timescale by dynamical friction, cores do not

*Sanchez-Salcedo et al (2006), Goerdt et al (2006)*

# 1. Core-vs-cusp problem




*de Blok & Bosma (2002)*

Cores in low surface brightness galaxies (LSBs)

Metal-poor galaxies with limited star formation history (more pristine)

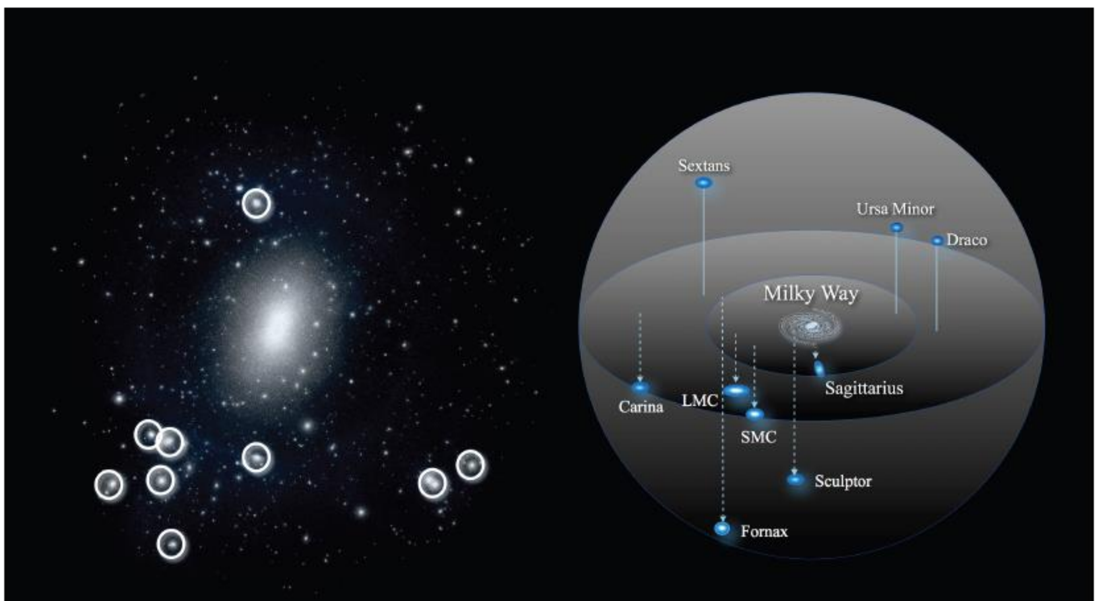
Not enough baryonic feedback to affect DM cusps

*Kuzio de Naray & Spekkens (2011)*

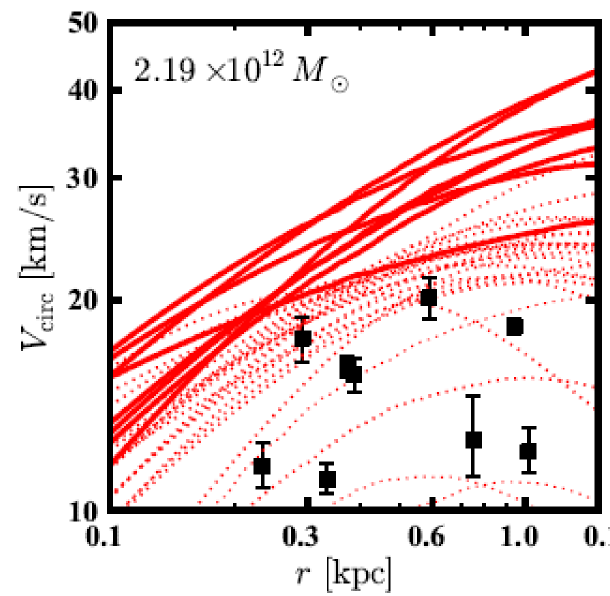
# 2. Too-big-to-fail problem

*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

*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

- Variation in number of satellites (~10% "tuning")

  *Purcell & Zentner (2012)*

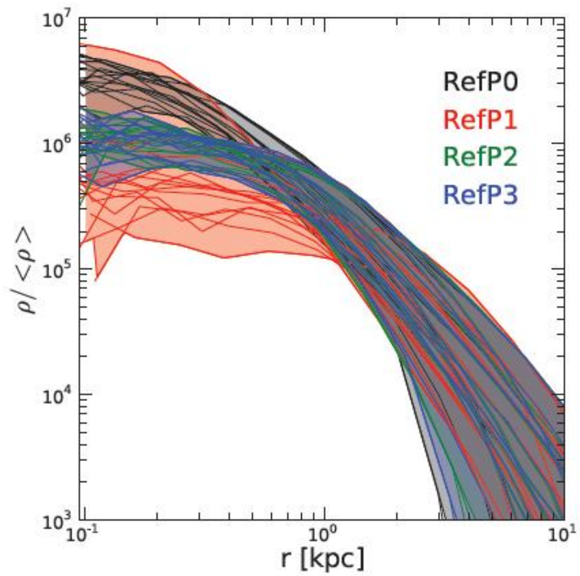
- Uncertainty in MW halo mass

# Self-interactions

- Self-interactions can solve small scale structure problems

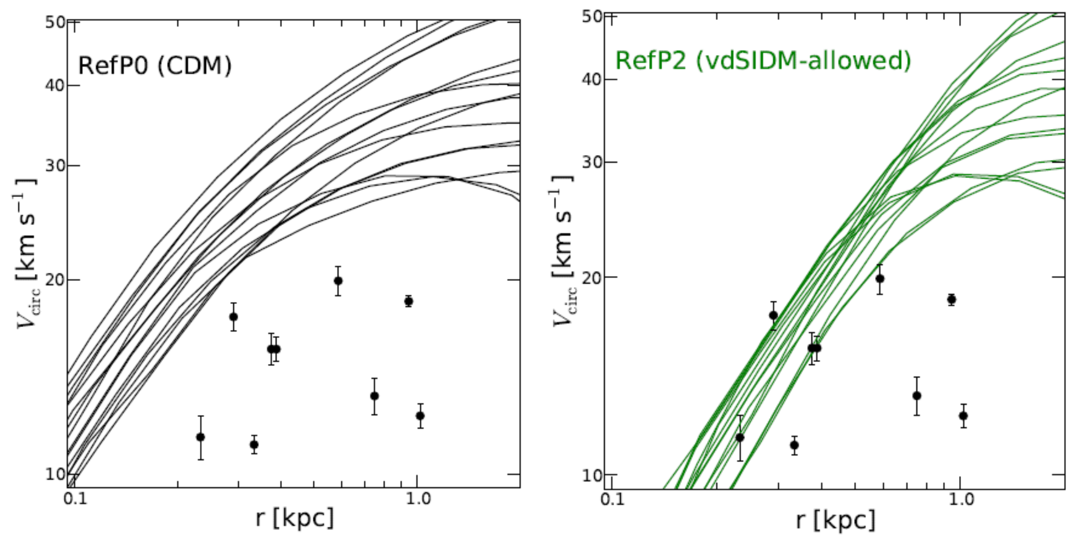
*Vogelsberger, Zavala, Loeb (2012); see also Rocha et al, Peter et al (2012)*

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?

# Self-interacting dark matter

- What does this tell us about the underlying particle physics theory of the dark sector?
- History of particle physics models for SIDM
  1. $\sigma$=const *Spergel & Steinhardt (2000), Dave et al (2000)*
  2. $\sigma \sim 1/v$ *Yoshida et al (2000)*
  3. $\sigma \sim 1/v^4$ (massless mediator) *Ackerman et al (2008)*
  4. Scattering with a finite mass mediator

*Buckley & Fox (2009), Feng, Kaplinghat, Yu (2009), Loeb & Weiner (2010), ST, Yu, Zurek (2012 + 2013)*

# Five particle physics lessons for SIDM

# Five particle physics lessons for SIDM

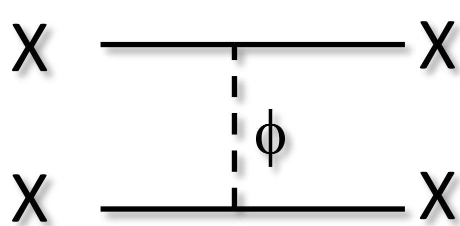
1. Large self-interaction cross section required

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

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

– New mediator $\phi$ much lighter than weak scale



self-interaction

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

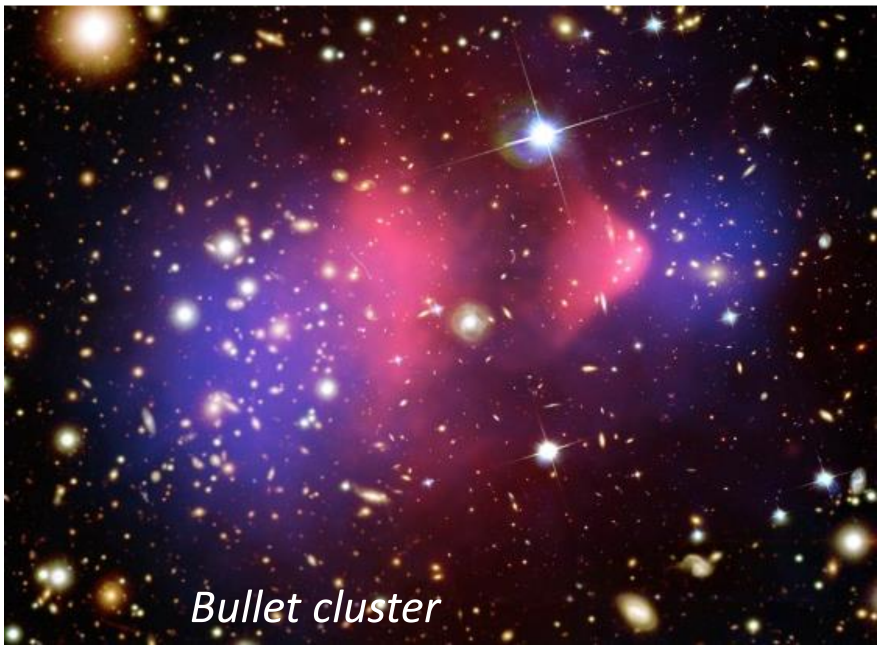
# Five particle physics lessons for SIDM

2. Light mediator implies velocity-dependent self-interaction cross section

$\sigma/m_X$ enhanced at low velocity, suppressed at high velocity (like Rutherford scattering)

# Five particle physics lessons for SIDM

## 3. Different size DM halos have different velocities




*Randall et al. (2007)*


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

DM appears collisionless on larger scales

# Five particle physics lessons for SIDM

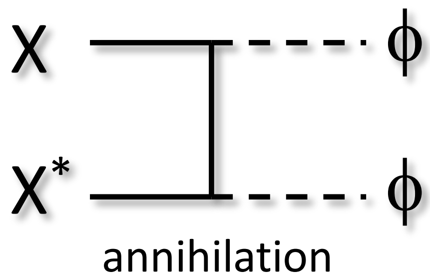
3. Different size DM halos have different velocities

| | | |
|---|---|---|
| Dwarfs | v ~ 30 km/s | SIDM |
| LSBs | v ~ 100 km/s | SIDM |
| MW-sized halos | v ~ 200 km/s | Collisionless DM |
| Clusters | v ~ 1000 km/s | Collisionless DM |

Natural for self-interactions to manifest in smaller halos

# Five particle physics lessons for SIDM

## 4. Annihilation channel for the DM relic density

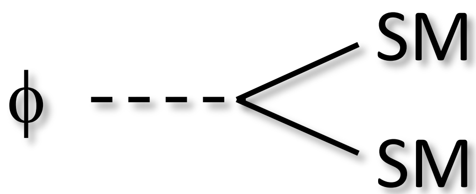



– Preserves WIMP miracle

$$\Omega_{\rm dm} \sim 0.2 \times \left( \frac{6 \times 10^{-26}\ {\rm cm^3/s}}{\langle \sigma v \rangle_{\rm ann}} \right) \sim 0.2 \times \left( \frac{\alpha_X}{10^{-2}} \right)^{-2} \times \begin{cases} (m_X/300\ {\rm GeV})^2 & \text{vector} \\ (m_X/100\ {\rm GeV})^2 & \text{scalar} \end{cases}$$

# Five particle physics lessons for SIDM

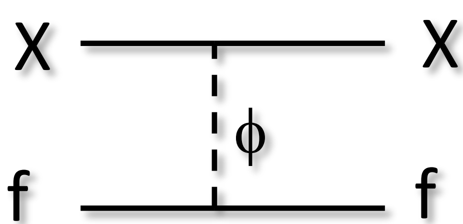
## 5. Mediator particles should decay before BBN




decay

Minimal setup with no new particles: $\phi$ decays to SM fermions before BBN

– Upper bound on $\phi$ lifetime implies lower bound on direct detection cross section



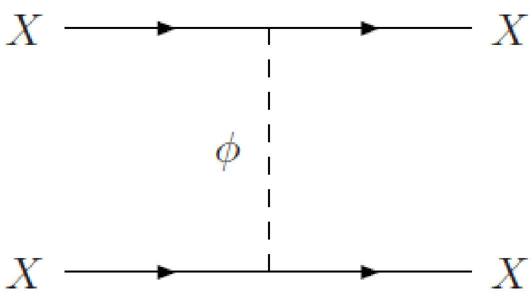

Direct detection

Direct detection constraints rule out large parameter region for SIDM

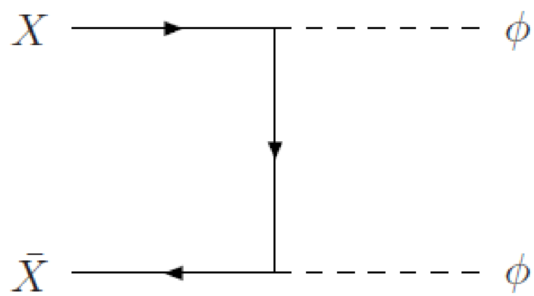
# Simplified models for SIDM

- DM particle X + light mediator ϕ

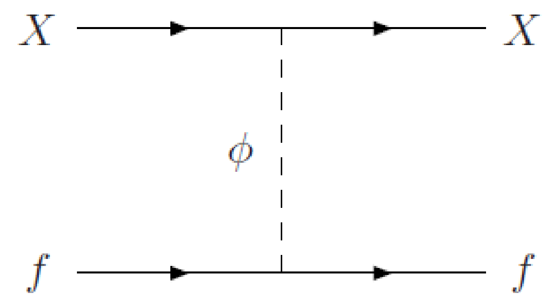
$$\mathscr{L}_{\rm int} = \begin{cases} g_\chi \bar{\chi}\gamma^\mu \chi \phi_\mu & \text{vector mediator} \\ g_\chi \bar{\chi}\chi\phi & \text{scalar mediator} \end{cases} \qquad \alpha_X = g_X^2/(4\pi)$$




DM self-interactions




DM annihilation




Direct detection

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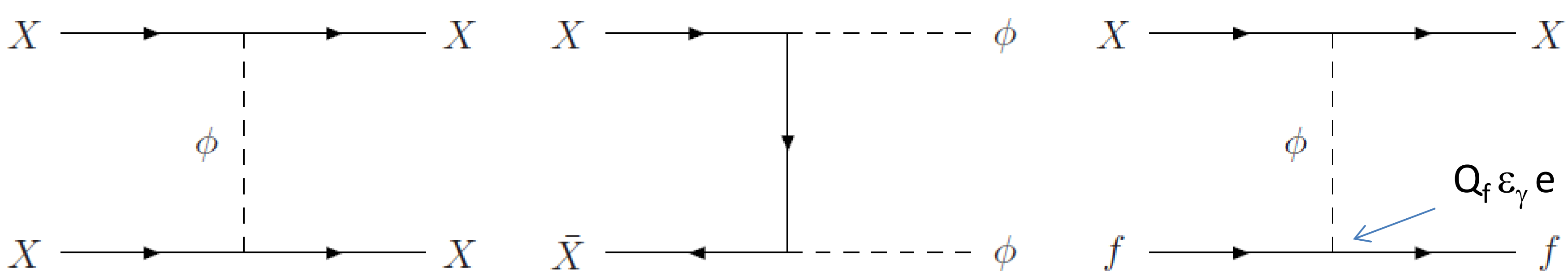


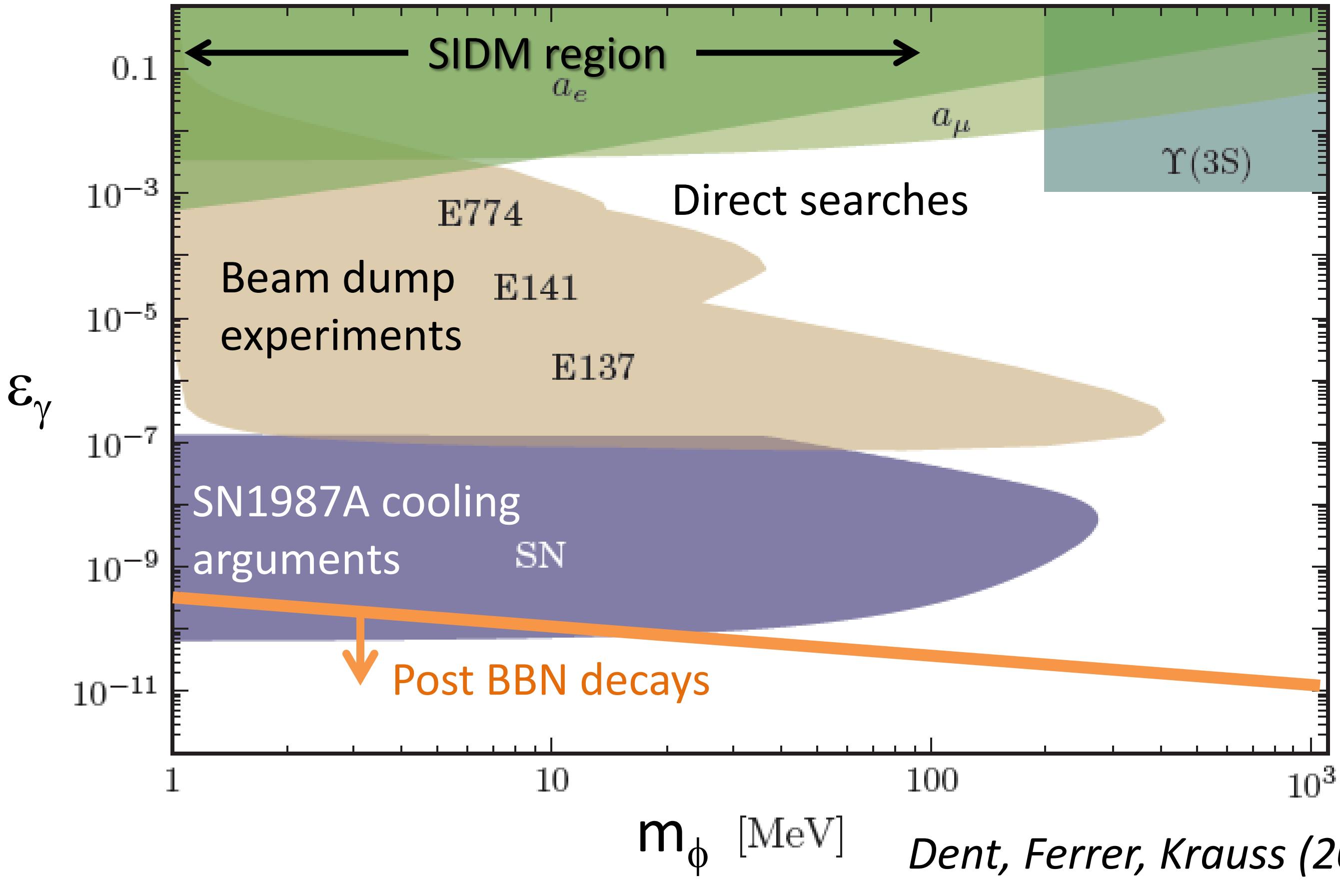

DM self-interactions　　DM annihilation　　Direct detection

Portals for direct detection: 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); Lin et al (2011) …*

ϕ lifetime: $1/\Gamma_\phi \approx 2.7\ \text{second} \times \left(\frac{\varepsilon_\gamma}{10^{-10}}\right)^{-2}\left(\frac{m_\phi}{10\ \text{MeV}}\right)^{-1}$

# Constraints on kinetic mixing




*Dent, Ferrer, Krauss (2012)*

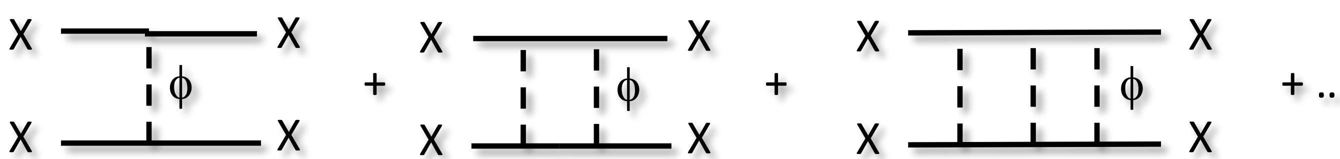
Kinetic mixing case very constrained for SIDM: $\varepsilon_\gamma \sim 10^{-10}$ (!)

# DM self-interaction cross section

- Nonperturbative calculation

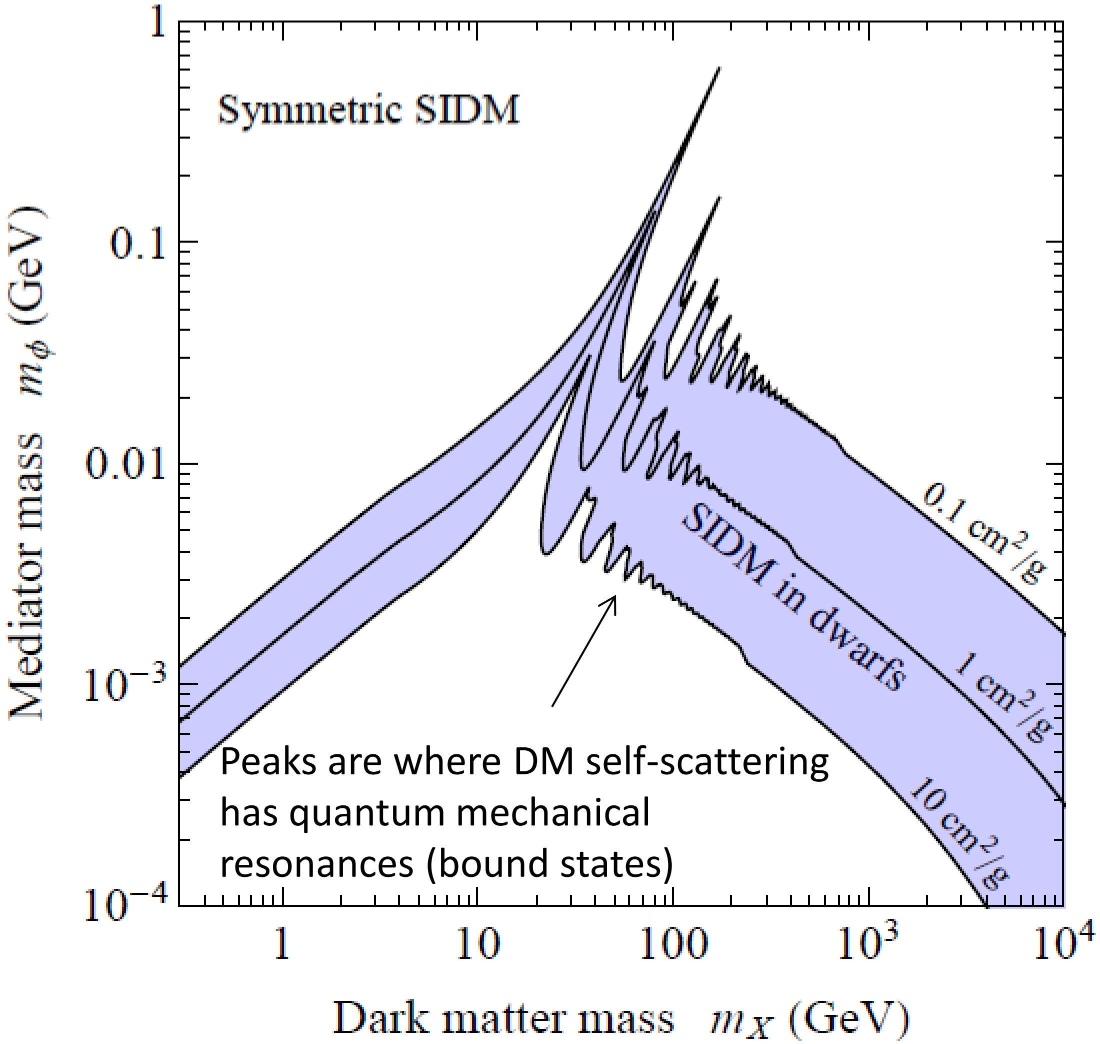
*Buckley & Fox (2009),*
*ST, H.-B. Yu, K. Zurek (2012 + 2013)*

  - 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 $\sigma_T \equiv \int d\Omega\, (1 - \cos\theta)\, d\sigma / d\Omega$

# Parameter space for symmetric SIDM

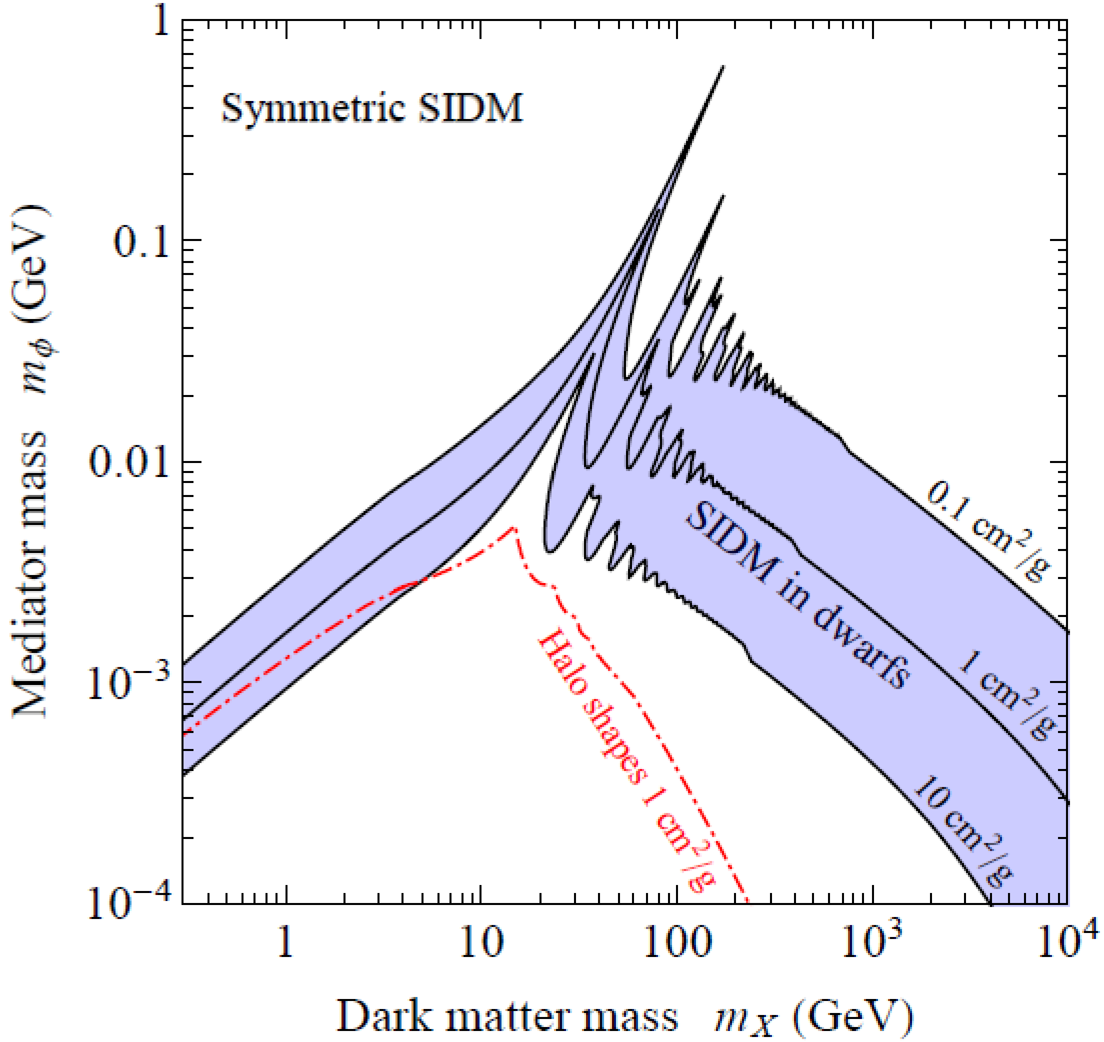



SIDM region for solving dwarf anomalies

Wide range of DM mass
Mediator ~ 1 – 100 MeV

Assume dwarf halos with characteristic velocity 30 km/s

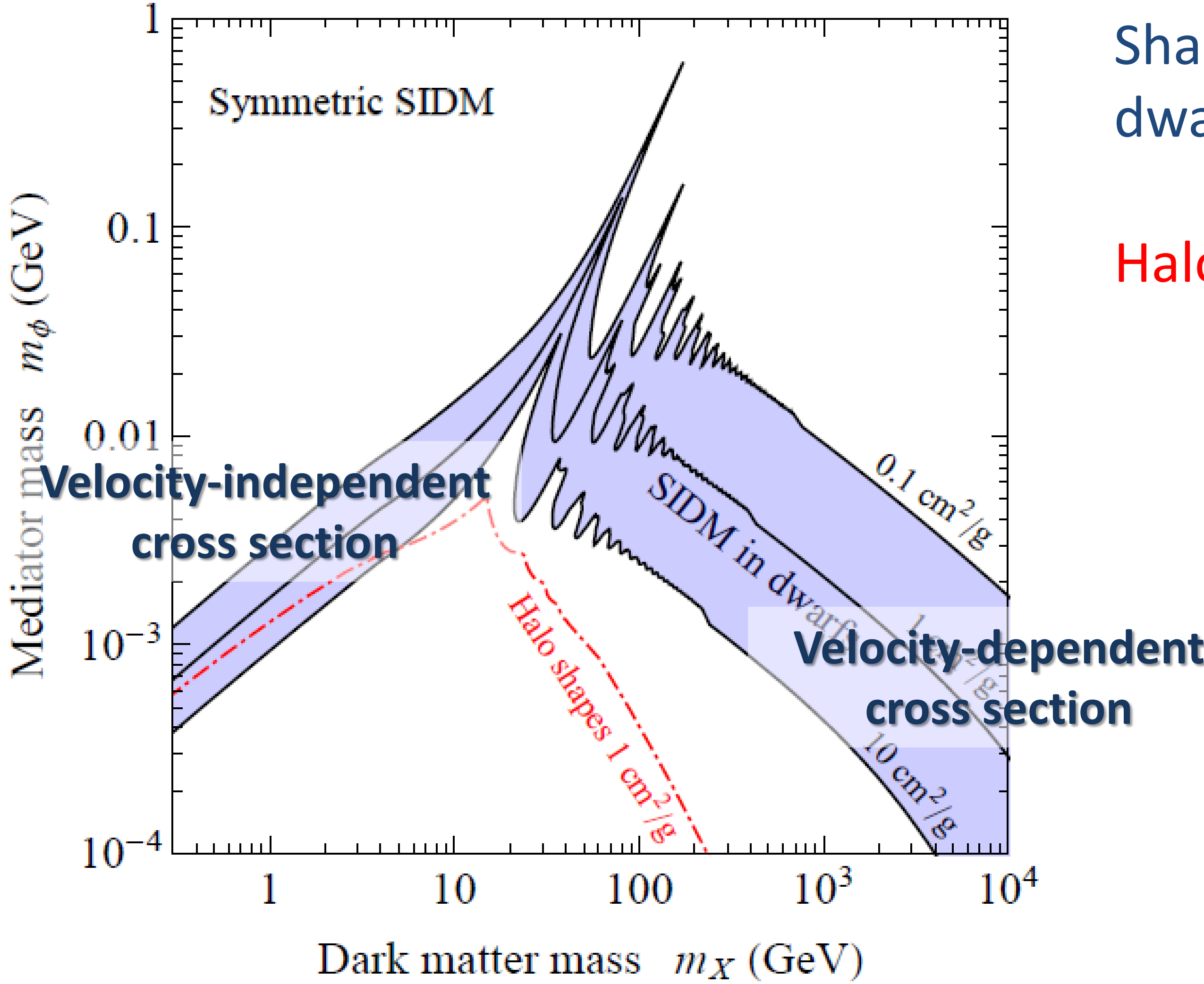
# Parameter space for symmetric SIDM




Shaded region: solve dwarf anomalies

Halo shape bound

# Parameter space for symmetric SIDM

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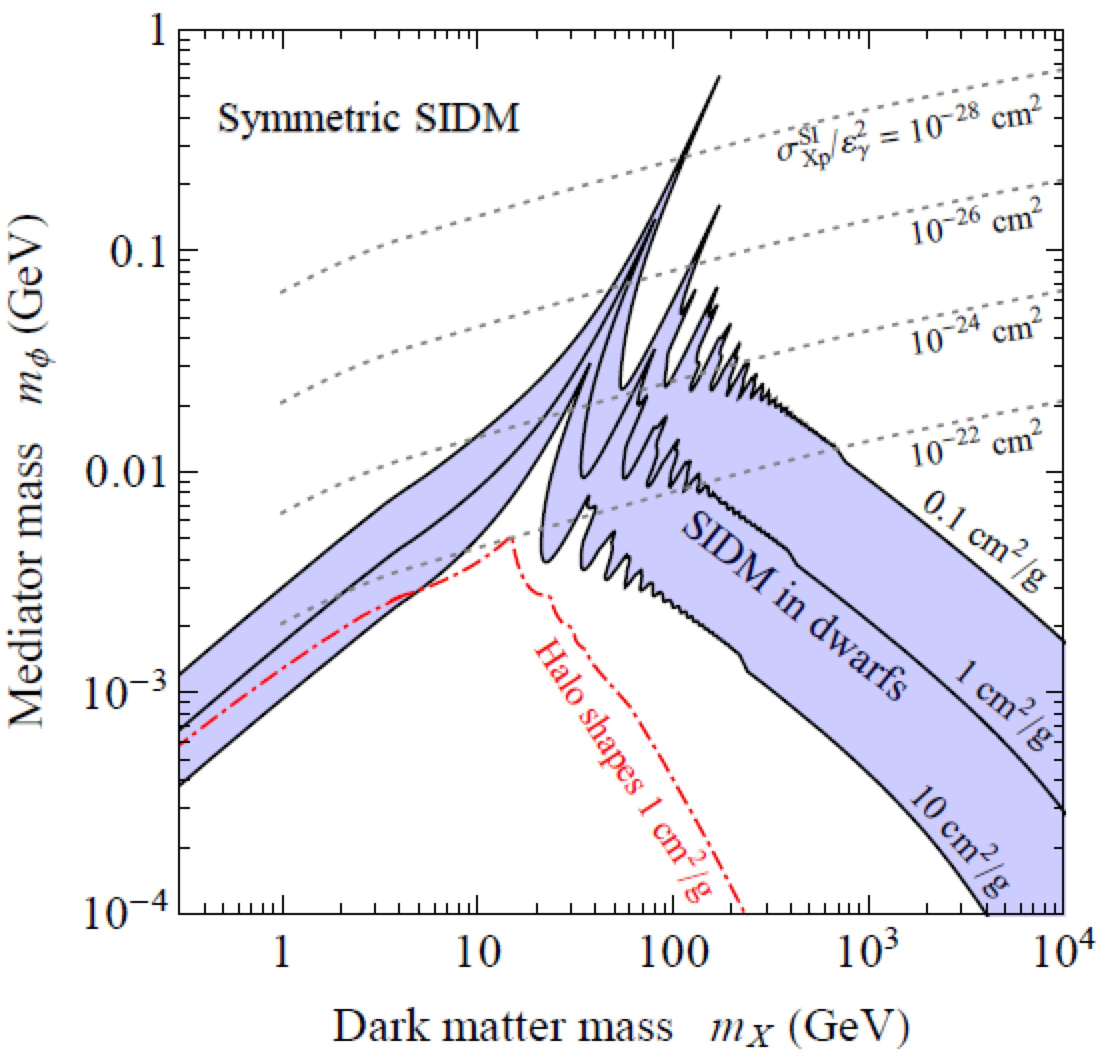


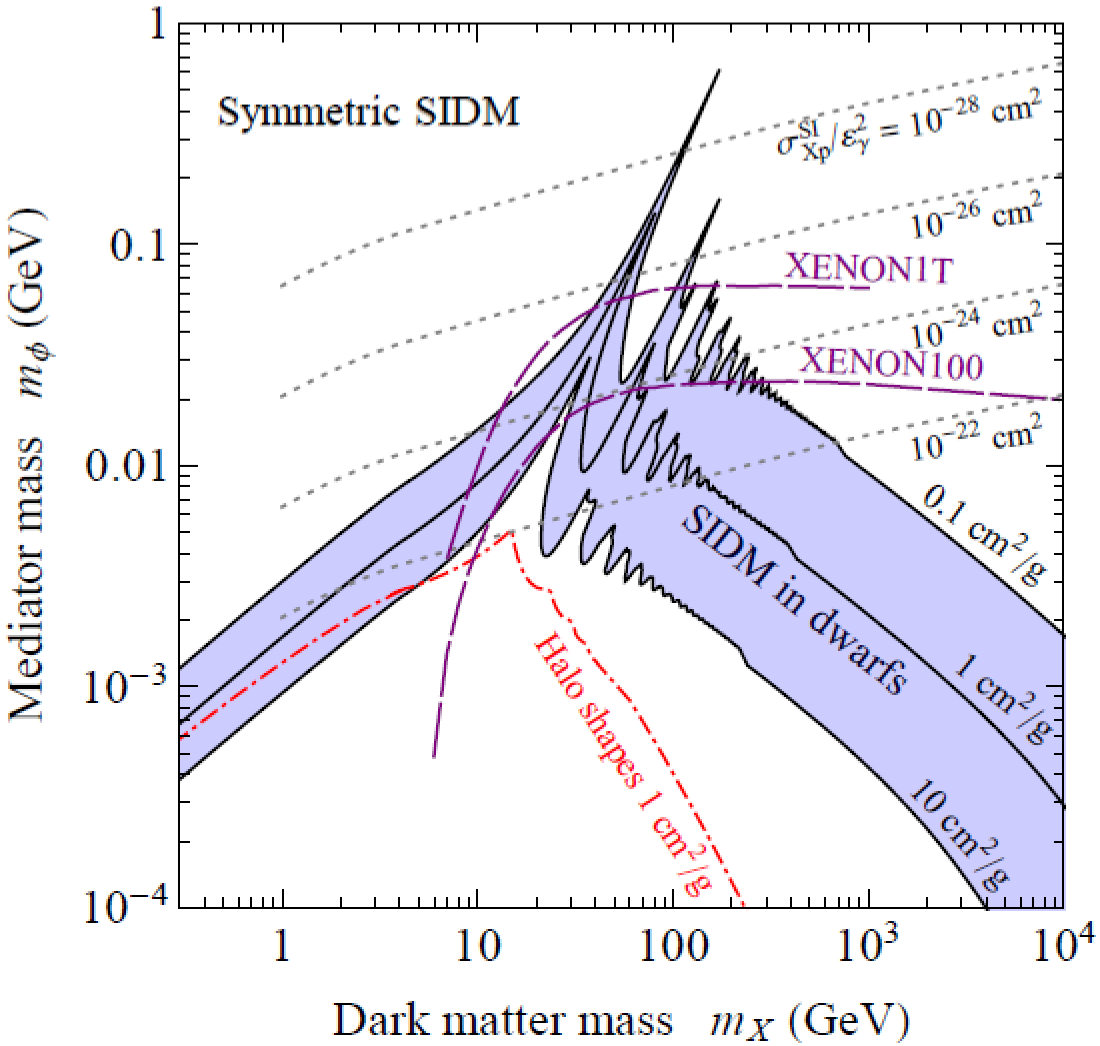

Shaded region: solve dwarf anomalies

Halo shape bound

Direct detection via kinetic mixing

$$\sigma^{SI}_{Xp} \approx 1.5 \times 10^{-24} \text{ cm}^2 \times \varepsilon^2_\gamma \times \left(\frac{\alpha_X}{10^{-2}}\right)\left(\frac{m_\phi}{30 \text{ MeV}}\right)^{-4}$$

# Parameter space for symmetric SIDM



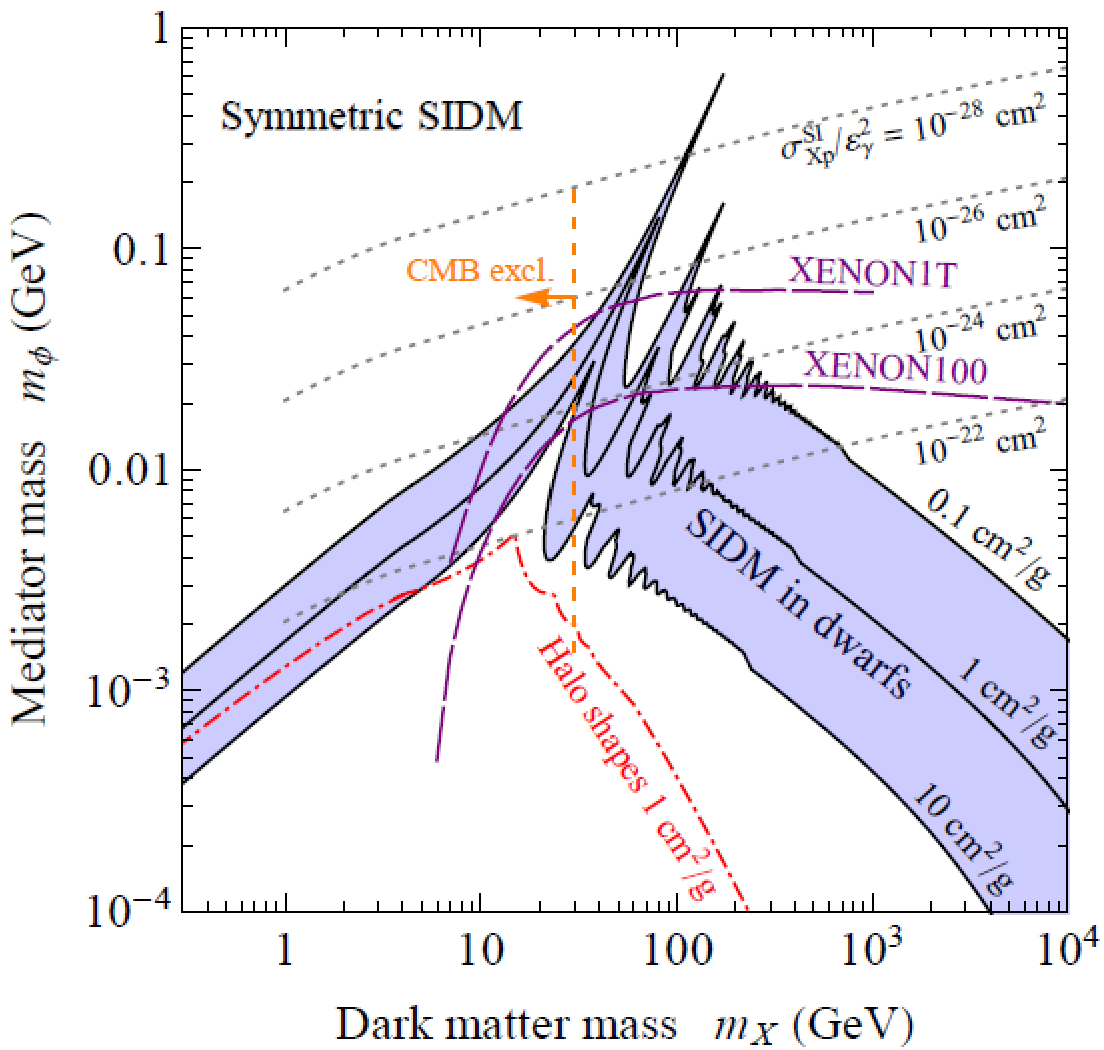

Shaded region: solve dwarf anomalies

Halo shape bound

Direct detection via kinetic mixing

XENON bounds with mixing parameter $\varepsilon_\gamma = 10^{-10}$

# Parameter space for symmetric SIDM




Shaded region: solve dwarf anomalies

Halo shape bound

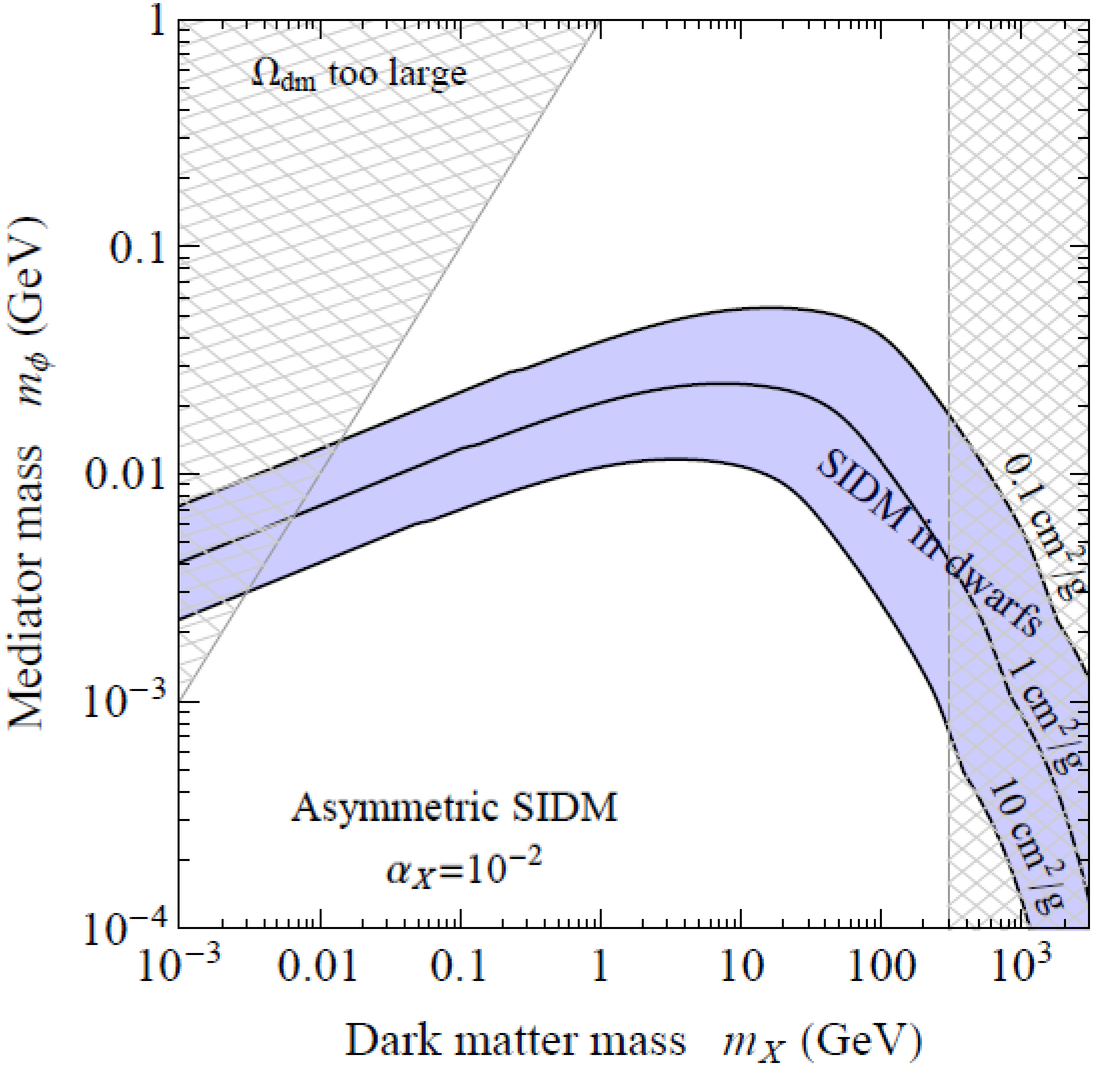
Direct detection via kinetic mixing

XENON bounds with mixing parameter $\varepsilon_\gamma = 10^{-10}$

CMB bound

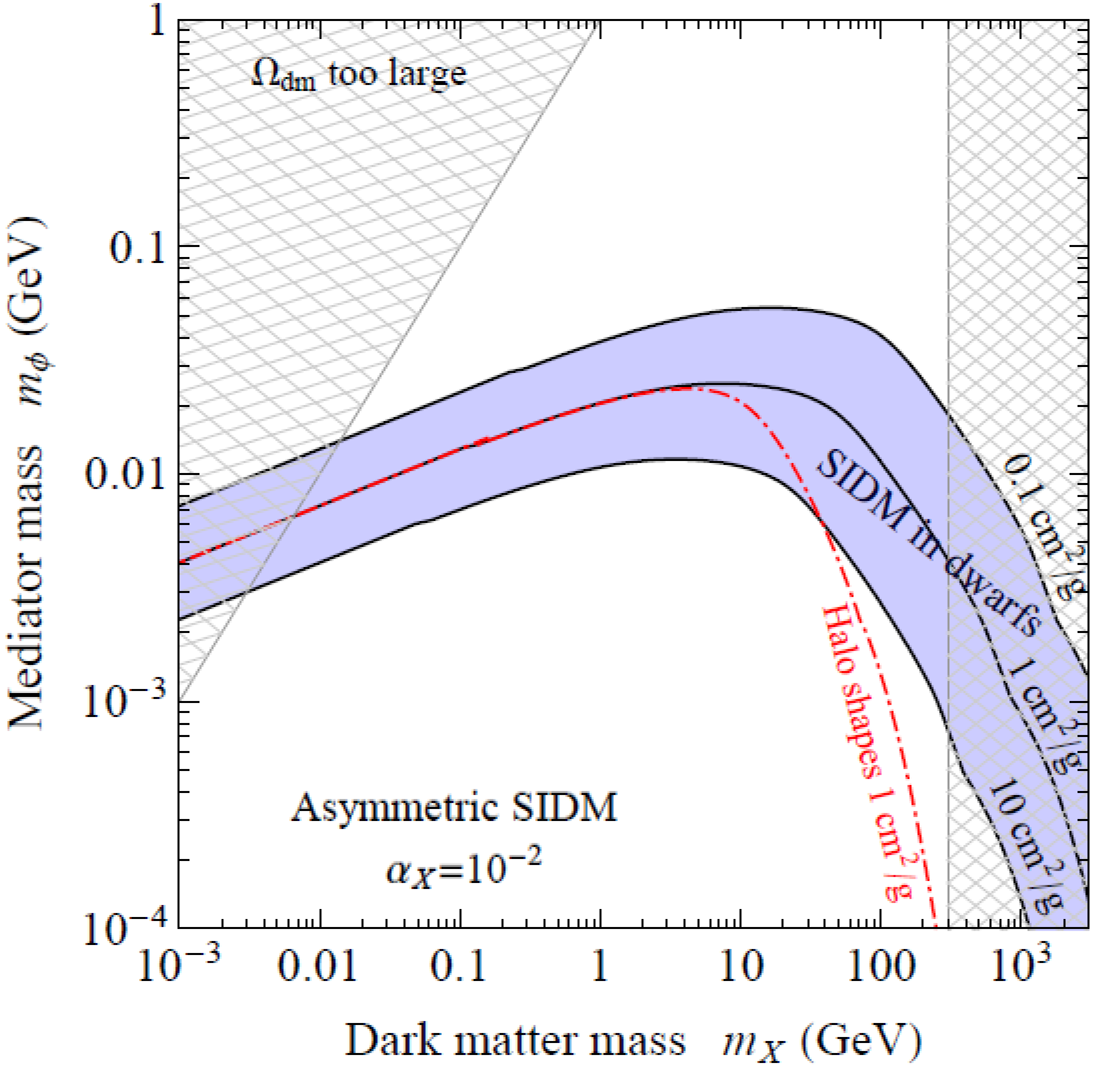
*Lopez-Honorez et al (2013)*

# Parameter space for asymmetric SIDM




Shaded region: solve dwarf anomalies

# Parameter space for asymmetric SIDM




Shaded region: solve dwarf anomalies

Halo shape bound

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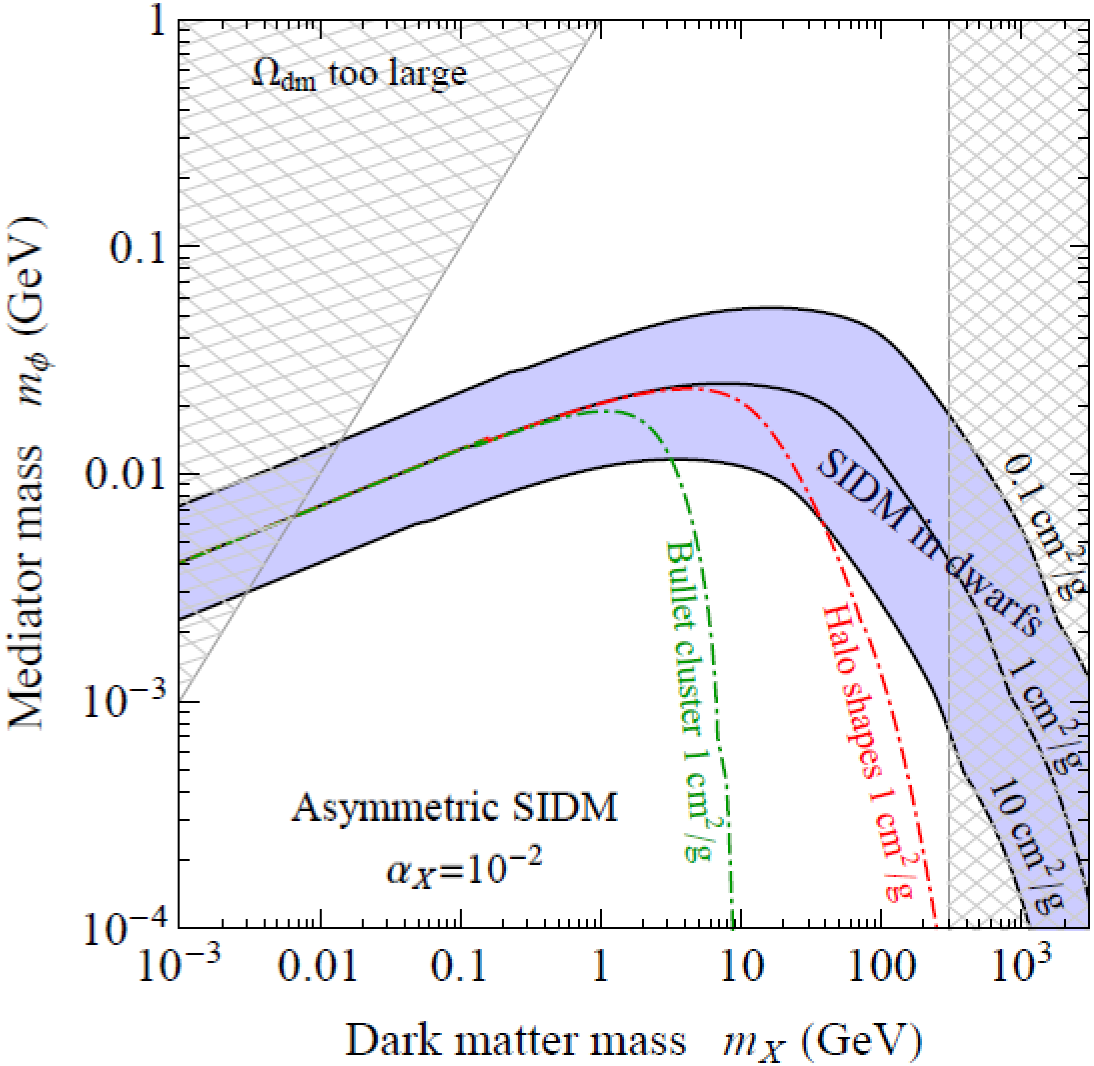
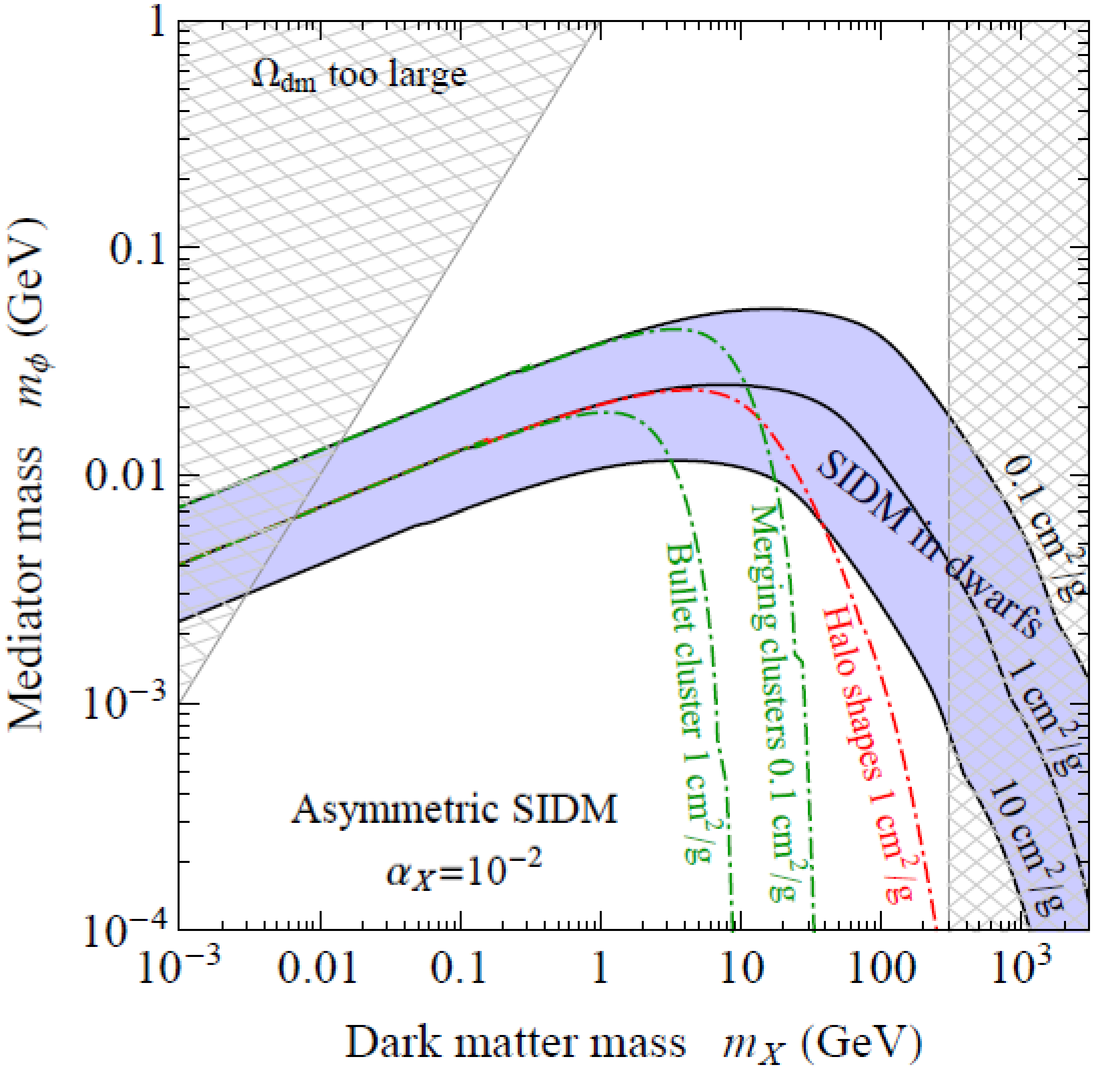



Shaded region: solve dwarf anomalies

Halo shape bound

Bullet cluster

# Parameter space for asymmetric SIDM



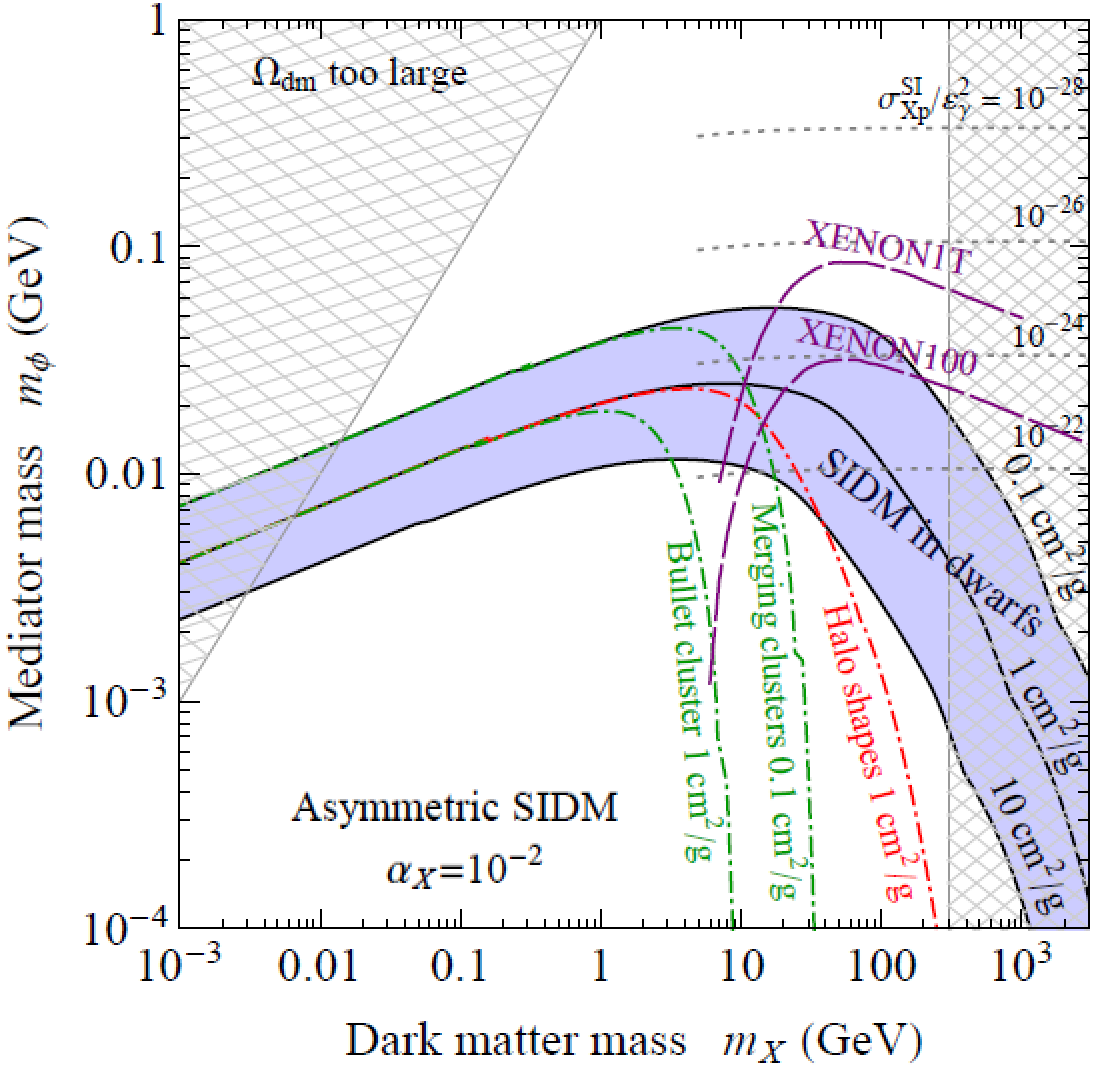

Shaded region: solve dwarf anomalies

Halo shape bound

Bullet cluster

Future merging clusters bound (??)

# Parameter space for asymmetric SIDM




Shaded region: solve dwarf anomalies

Halo shape bound

Bullet cluster

Direct detection with $\varepsilon_\gamma = 10^{-10}$

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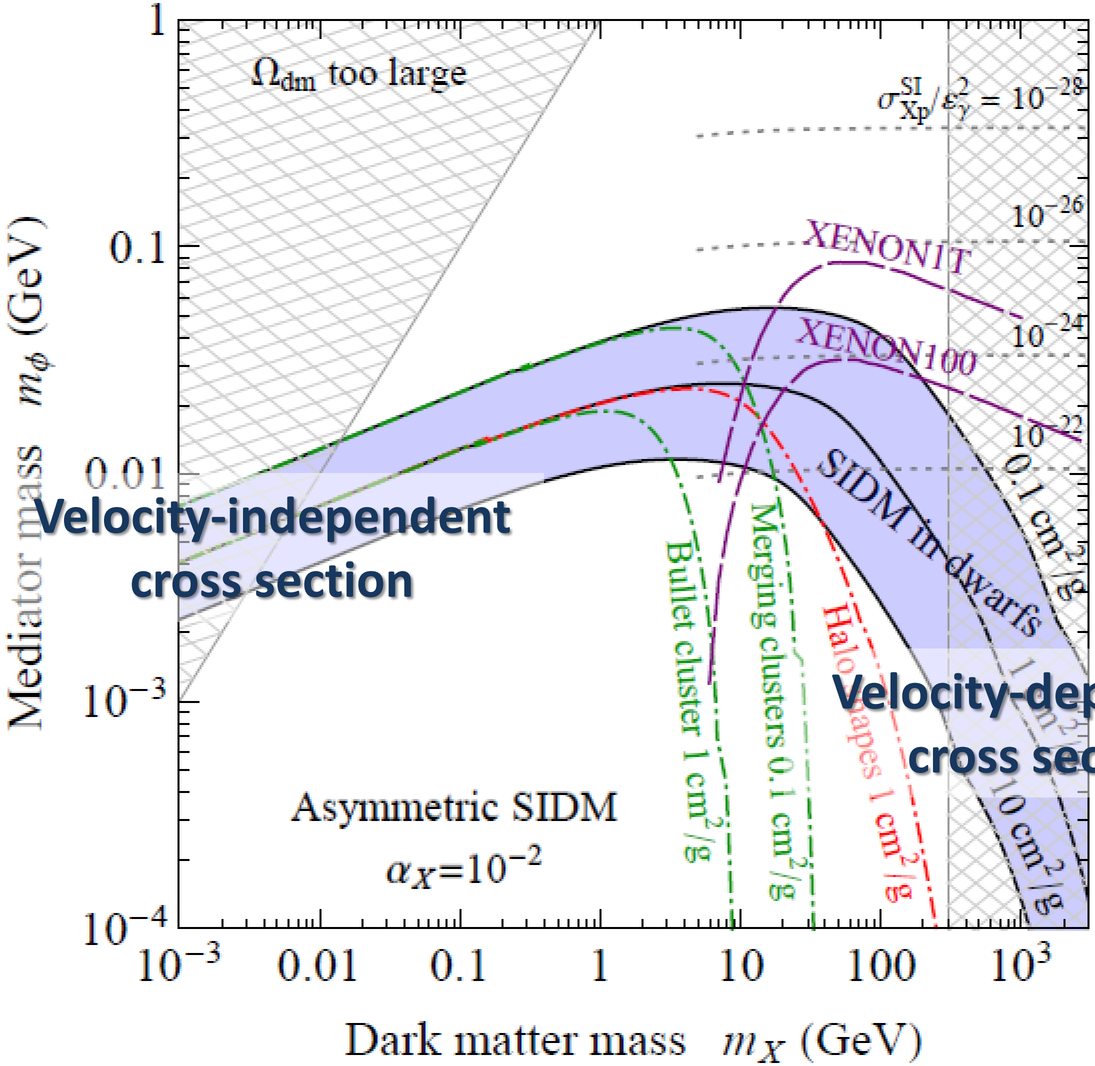


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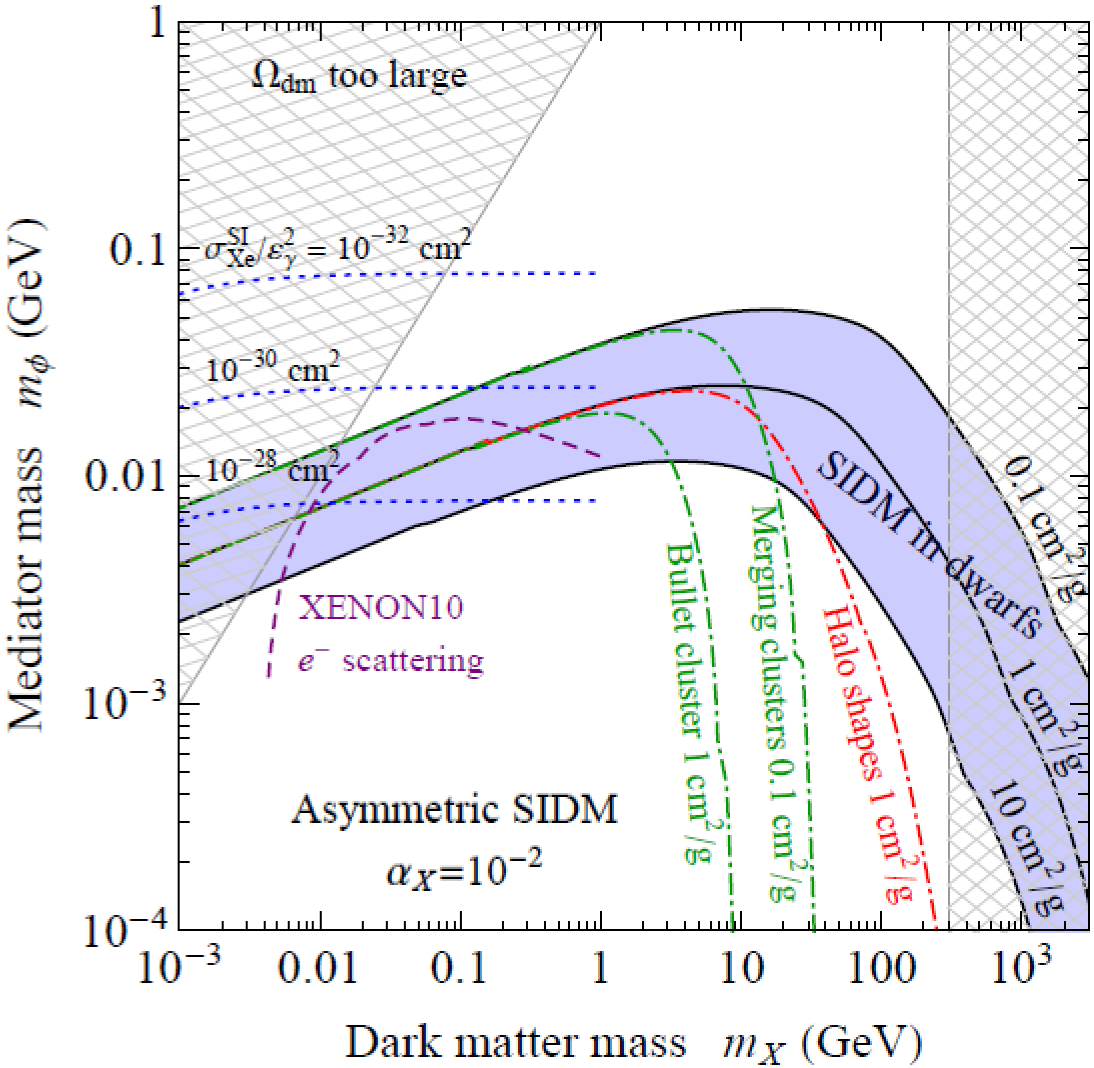



Shaded region: solve dwarf anomalies

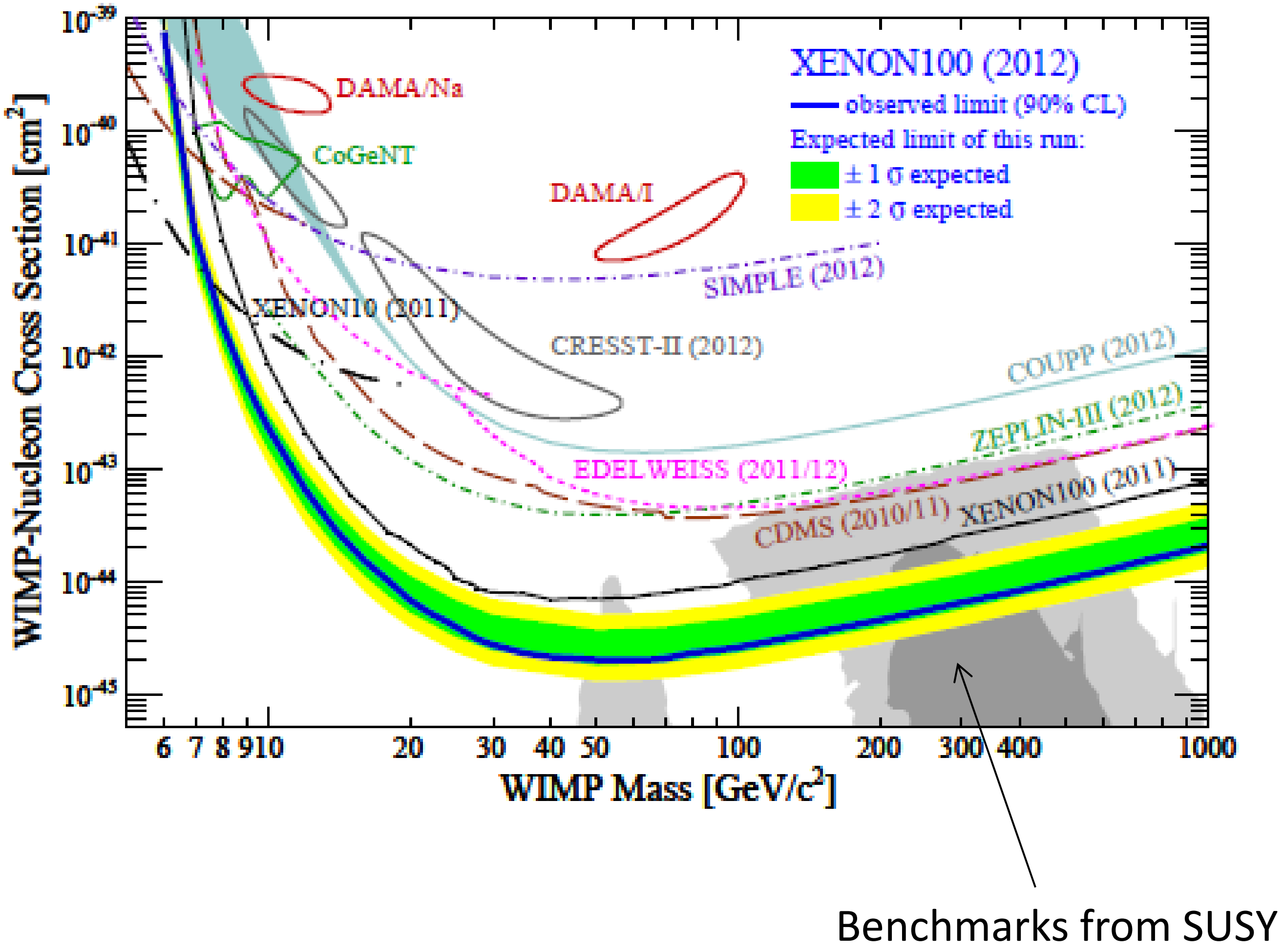
Halo shape bound

Bullet cluster

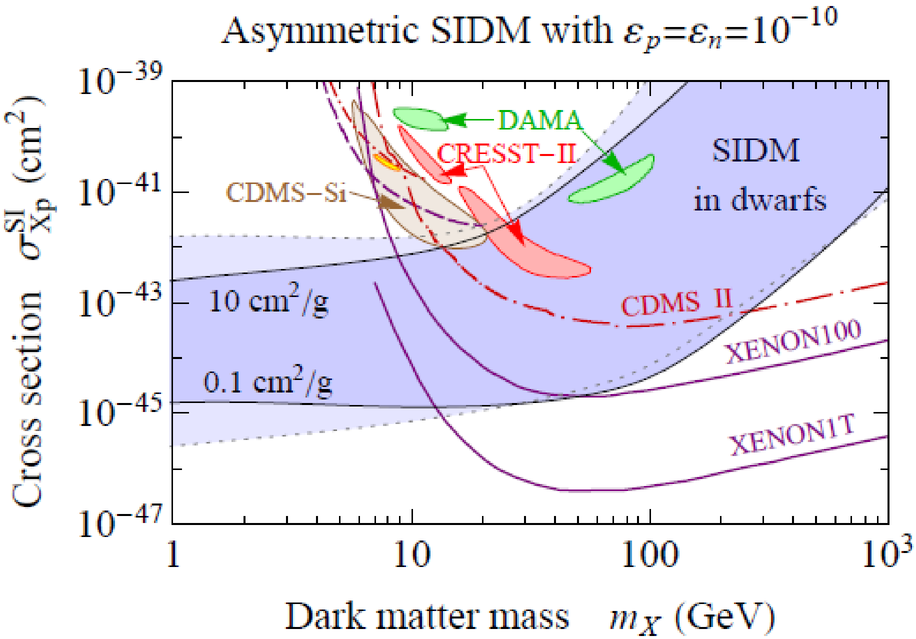
Direct detection from scattering on electrons with $\varepsilon_\gamma = 10^{-4}$

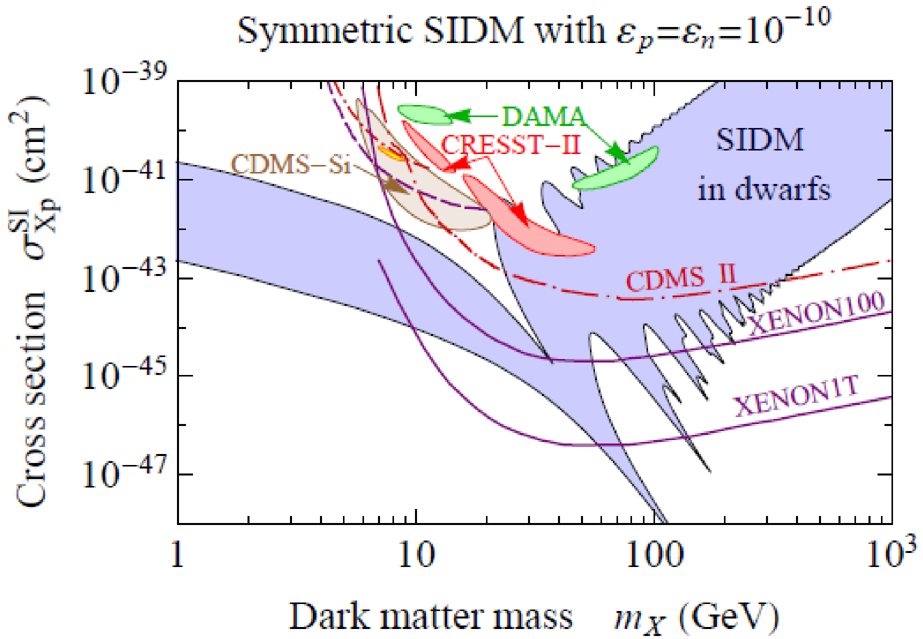
*Essig et al (2011+2012)*

# Direct detection



# SIDM benchmarks for direct detection



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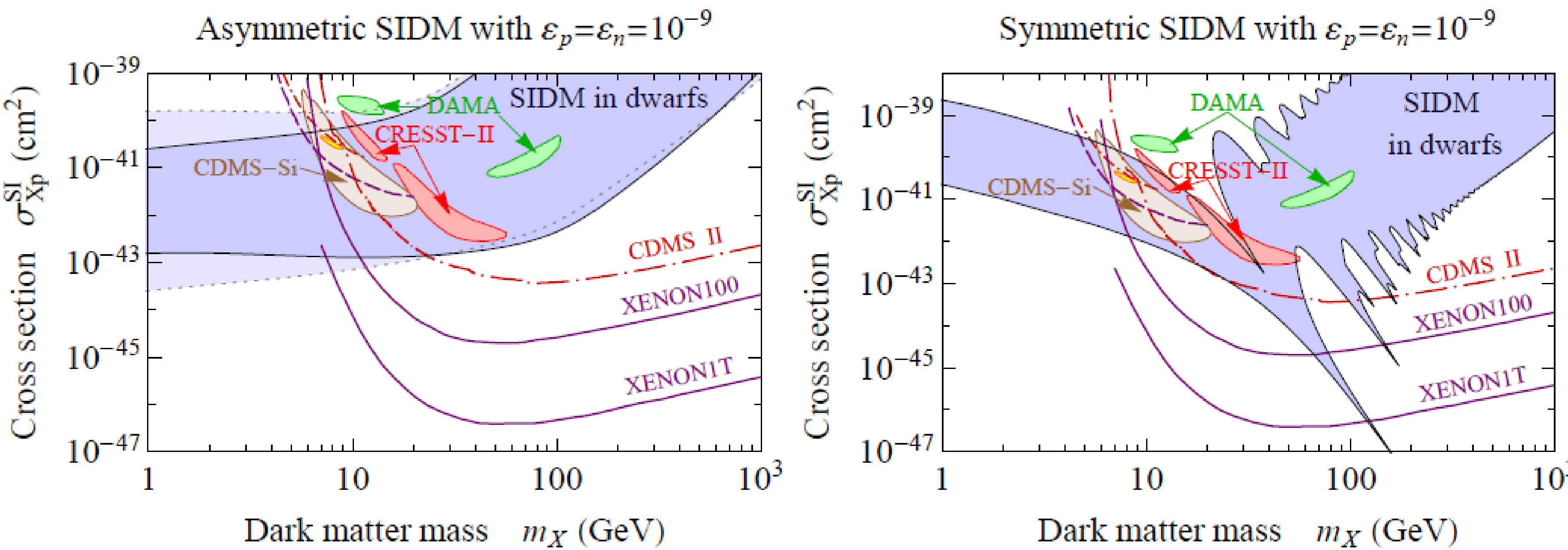


# Conclusions (part 1)

- Simplified model: DM $\chi$ + mediator $\phi$
- Anomalies on dwarf scales: $m_\phi \sim 1 - 100$ MeV
- Although SIDM may be decoupled from direct detection, expect DM-SM coupling at some level
- Light mediator means direct detection sensitive to **very** small DM-SM couplings
- Current & future direct detection exploring “BBN parameter region” ($\phi \rightarrow$ SM before BBN)

# Conclusions (part 2)

- Direct detection complementary to astrophysics
  - Constraints on large scales (e.g. Bullet Cluster) constrain SIDM at low DM mass (constant $\sigma$)
  - Direct detection constrain SIDM at WIMP-scale masses (corresponding to v-dependent $\sigma$)

# Backup

# Comparison to previous work

*M. Buckley & P. Fox (2009)*

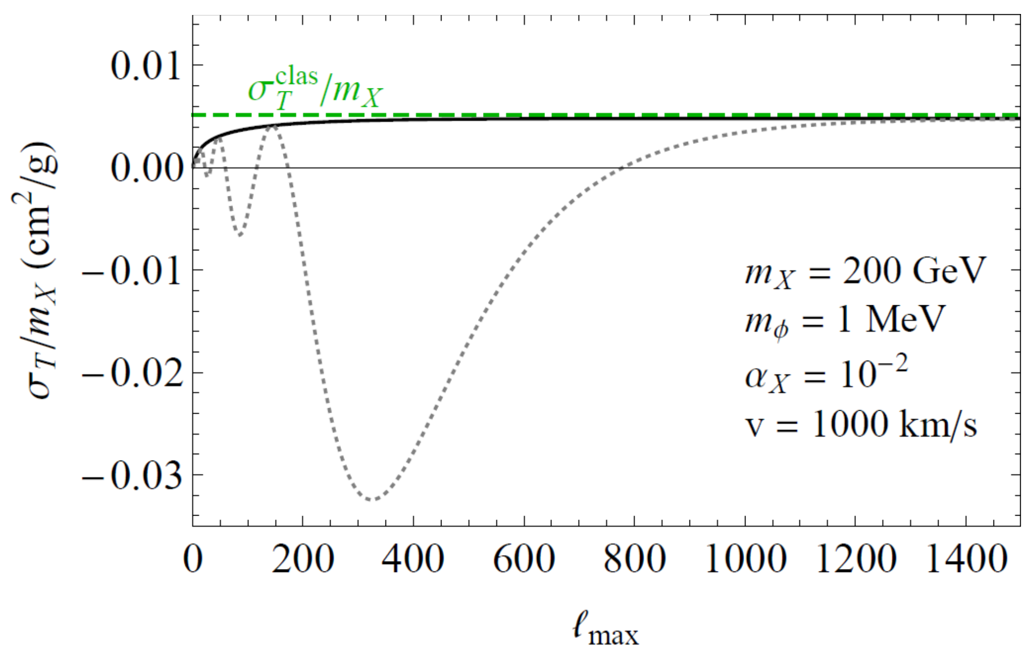
1. More efficient method for matching onto asymptotic solution of Bessel functions, not sines (B&F had $\ell_{max} = 5$)
2. More efficient formula for summing partial waves

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

*Buckley & Fox 2009*

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

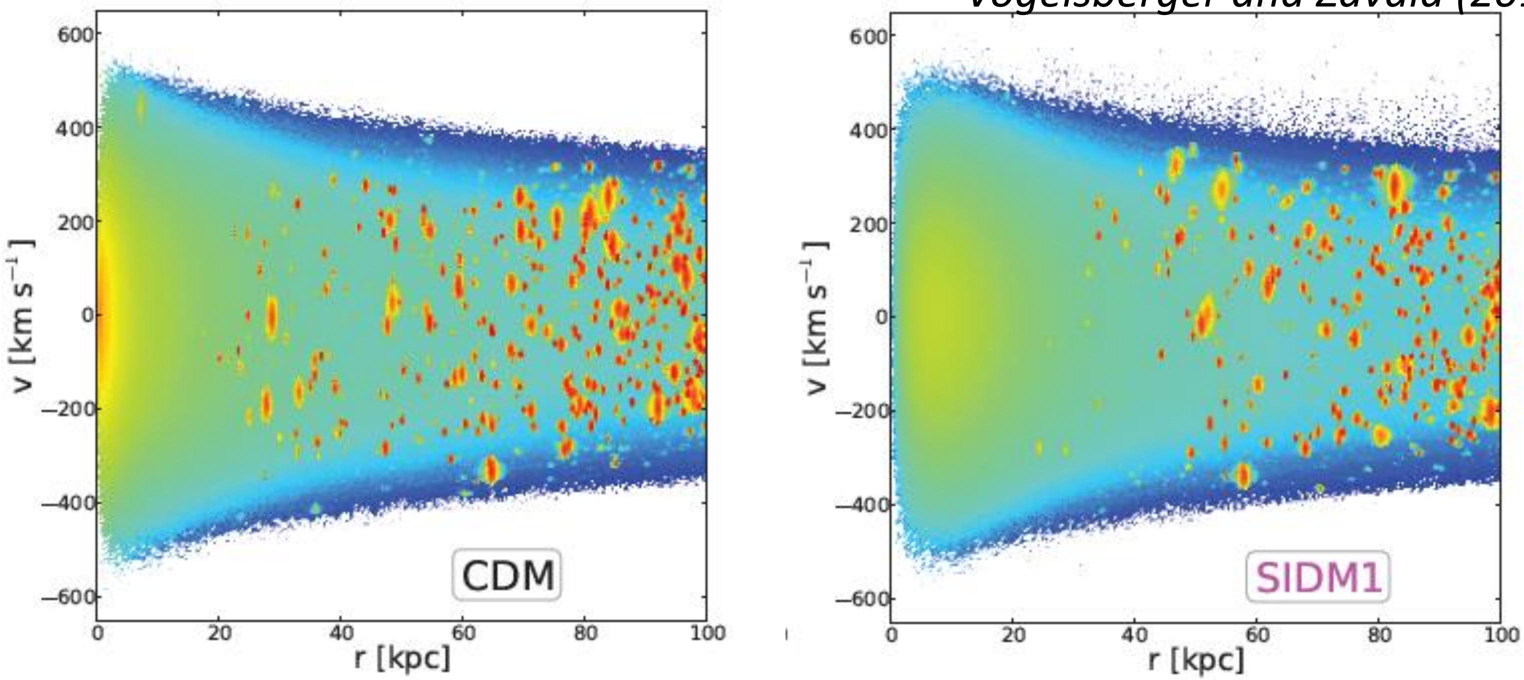
ST, H.-B. Yu, K. Zurek (2013)



# 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

# Portals to the dark sector

1. Vector mediator ($\phi$ mixes with Z or $\gamma$)
   - 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); Lin et al (2011) …*

   - Z mass mixing ($\varepsilon_Z$ is Z-$\phi$ mixing angle):

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

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

2. Scalar mediator
   - Higgs mixing ($\varepsilon_h$ is h-$\phi$ mixing angle)

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

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