Direct detection of SIDM

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[1308.0618 + *in progress*]

Particle physics of SIDM

- Dwarf scale anomalies point toward large cross section for DM particle χ

$$\sigma/m_\chi \sim 1 \text{ cm}^2/\text{g} \; \approx \; 2 \text{ barns/GeV}$$

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

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

- Suggests dark force mediator ϕ much lighter than weak scale

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

Particle physics of SIDM

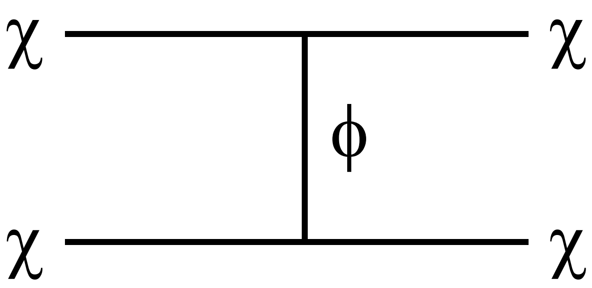
- Light mediator gives efficient annihilation channel for relic density: $\chi\bar{\chi} \rightarrow \phi\phi$
  - Symmetric or asymmetric DM

$$\langle \sigma v \rangle_{\rm ann} \gtrsim 6 \times 10^{-26}\ {\rm cm}^3/{\rm s}$$

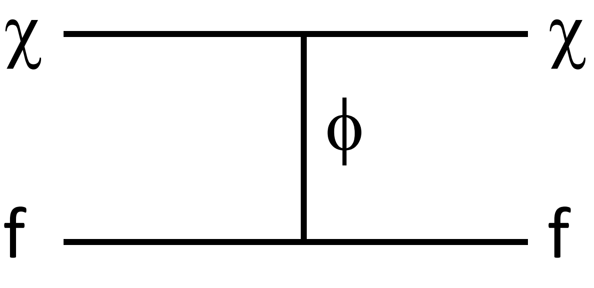
- Light mediator means self-interaction is velocity dependent (like Rutherford scattering)
  - Self-interacting DM in dwarf halos (v ~ 30 km/s)
  - Collisionless DM in larger halos (e.g. v ~ 3000 km/s for Bullet Cluster)

Light mediators in the dark sector

What do self-interactions have to do with direct detection?



DM self-scattering



DM direct detection

What happens to the light mediator ϕ?

– Assume decays to SM particles before BBN
– Simplest scenario (doesn't affect cosmology)

Light mediators in the dark sector

Decay $\phi \rightarrow$ SM fermions before BBN

- Maximum lifetime for ϕ to decay $\sim$ 1 second
- Minimal coupling between dark sector and SM
- *Lower bound* on direct detection cross section

Direct detection cross section

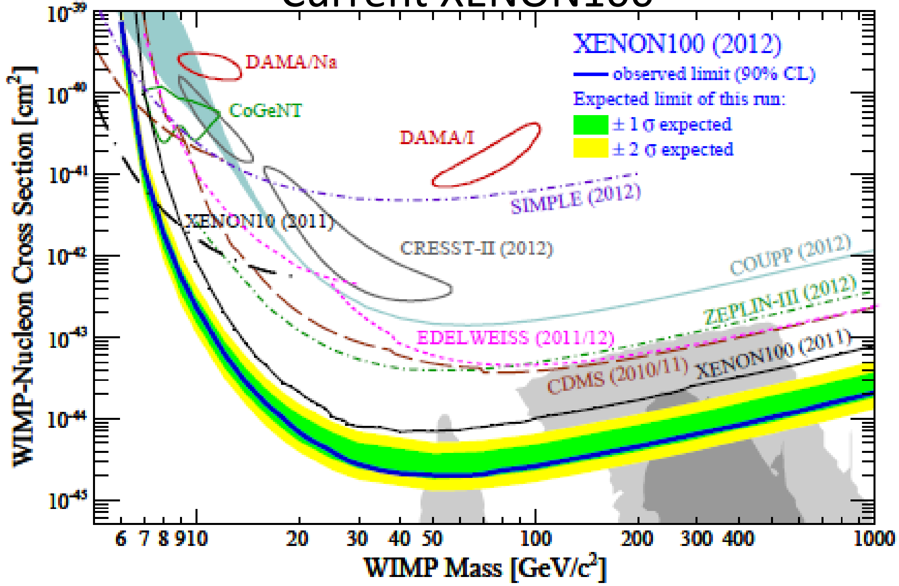
- Suppressed by tiny coupling (long ϕ lifetime)
- Enhanced by light mediator mass $\sim 1 - 100$ MeV

Generically expect ϕ coupled to SM

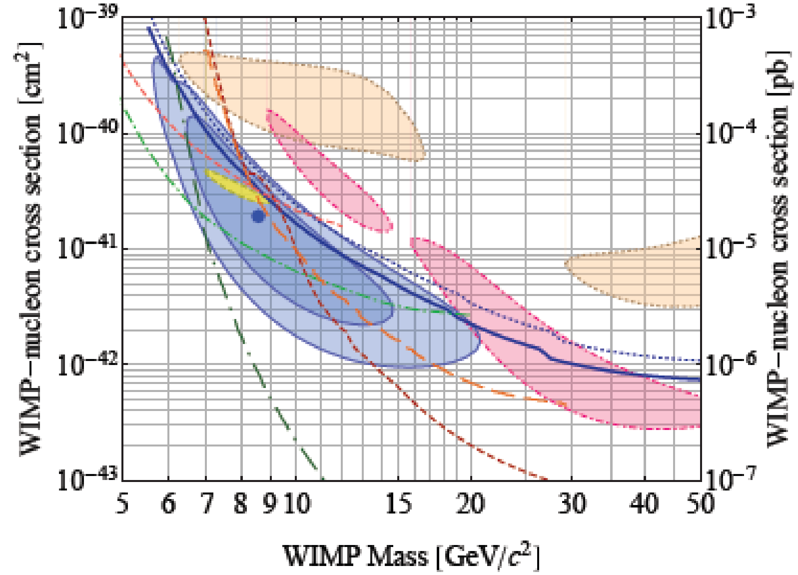
What is the reach of direct detection for SIDM?

Direct detection

Current XENON100



Recent CDMS-Si (3 events)



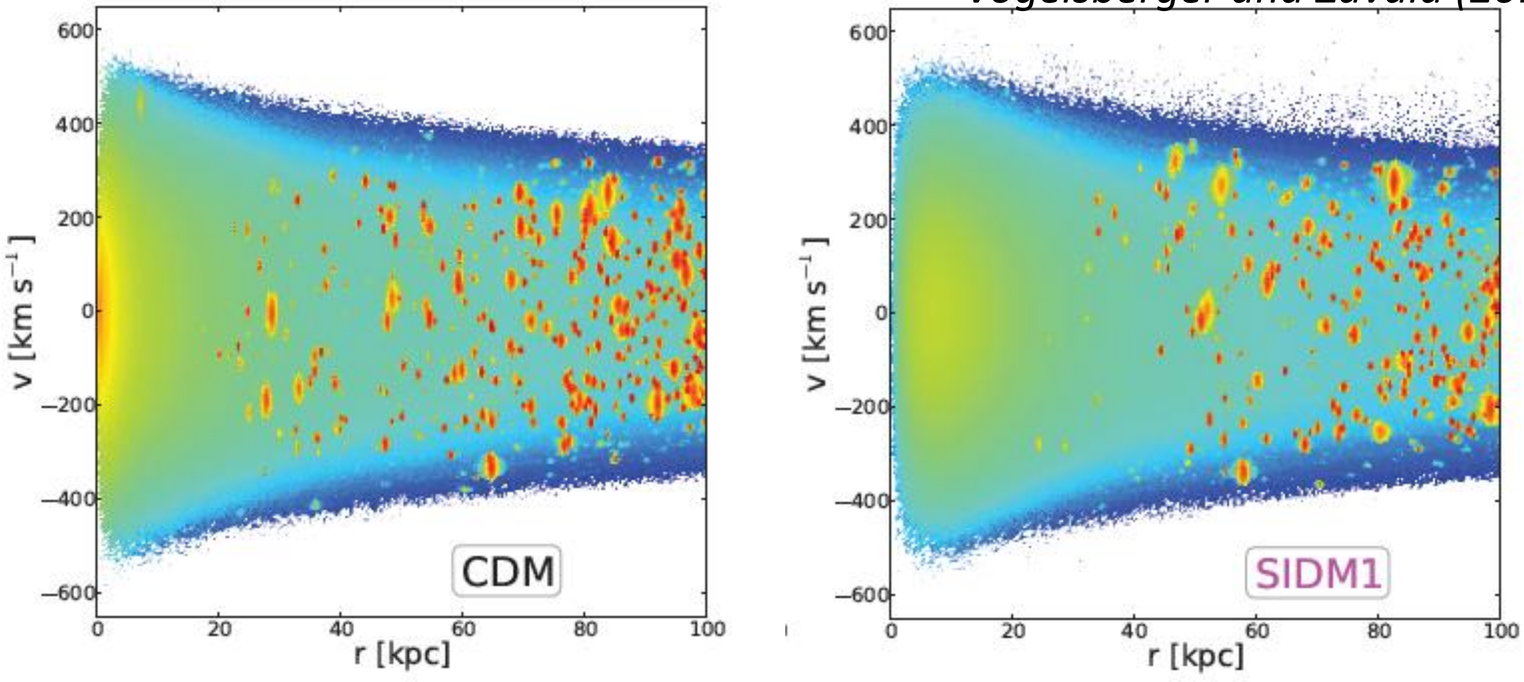
Exciting/confusing time!

Future limits: XENON1T, LUX, CDMS-lite, SuperCDMS, PandaX, …

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

Simplified models for SIDM

- DM χ is a Dirac fermion
- Mediator ϕ is a real scalar or vector

$$\mathscr{L}_{\rm int} = \begin{cases} g_\chi \bar{\chi}\gamma^\mu \chi \phi_\mu & \text{vector mediator} \\ g_\chi \bar{\chi}\chi\phi & \text{scalar mediator} \end{cases}$$

See also Bellazzini, Cliche, Tanedo (2013)

- Self-interactions through a Yukawa potential

$$V(r) = \pm \frac{\alpha_\chi}{r} e^{-m_\phi r} \; , \text{ where } \; \alpha_\chi = g_\chi^2/(4\pi)$$

- Calculate parameter space for SIDM vs α_χ, m_χ, m_ϕ, and v (relative velocity)

ST, H.-B. Yu, K. Zurek (2012 + 2013); see also Buckley & Fox (2010)

Portals to the dark sector

1. Vector mediator (ϕ mixes with Z or γ)
   - 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 (ε_Z is Z-ϕ 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 (ε_h is h-ϕ mixing angle)

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

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

Portals to the dark sector

- Kinetic mixing with photon
  - No photon mass
  - No coupling of photon to DM (no millicharged DM)
  - Couple mediator ϕ to SM fermions with EM charge

- Mixing with Z boson
  - Couple mediator ϕ to weak neutral current

Portals to the dark sector

Want ϕ to decay before BBN time ~ 1 second

Focus on vector mediator only *(work in progress)*

Lifetime (similar for both kinetic and Z mixing):

$$1/\Gamma_\phi \sim 1 \text{ second} \times \left(\frac{10^{-10}}{\varepsilon_{\gamma,Z}}\right)^2 \left(\frac{10 \text{ MeV}}{m_\phi}\right)$$

Final states:

- Kinetic mixing: ϕ decays to all e^+e^-

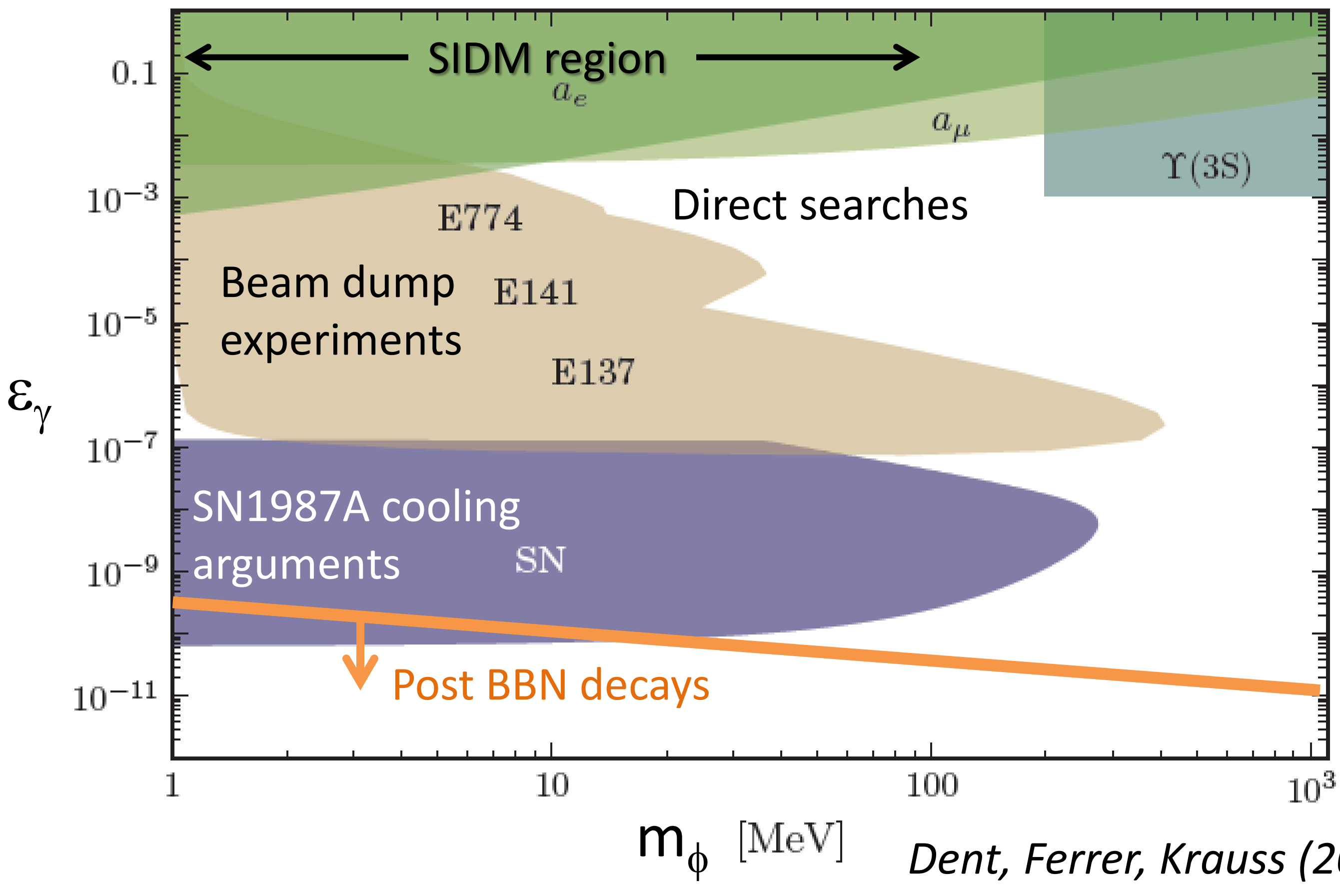
$$\mathrm{BR}(\phi \to e\bar{e}) \approx 1,\ \mathrm{BR}(\phi \to \nu\bar{\nu}) = 0$$

- Z mixing: ϕ decays mostly to neutrinos

$$\mathrm{BR}(\phi \to e\bar{e}) \approx 1/7,\ \mathrm{BR}(\phi \to \nu\bar{\nu}) \approx 6/7$$

(Neutrino-rich indirect detection signals)

Constraints on kinetic mixing



Dent, Ferrer, Krauss (2012)

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

Different (weaker?) constraints for Z mixing case

Direct detection

Parameterize ϕ-nucleon coupling as: $e\varepsilon_{\text{eff}}$

Spin-dependent DM-nucleon direct detection cross section (*$q^2 = 0$* limit):

$$\sigma_{\chi n}^{\text{SI}} = \frac{16\pi\alpha_\chi\alpha_{\text{em}}\mu_{\chi n}^2\epsilon_{\text{eff}}^2}{m_\phi^4} \approx 10^{-24}\ \text{cm}^2 \times \epsilon_{\text{eff}}^2 \left(\frac{\alpha_\chi}{10^{-2}}\right)\left(\frac{30\ \text{MeV}}{m_\phi}\right)^4$$

Interaction portal with SM governed by ε_{eff}

- Kinetic mixing: $\varepsilon_{\text{eff}} = \varepsilon_\gamma\ (Z/A)$
- Z mixing: $\varepsilon_{\text{eff}} = 0.35\ \varepsilon_Z\ (N/A)$

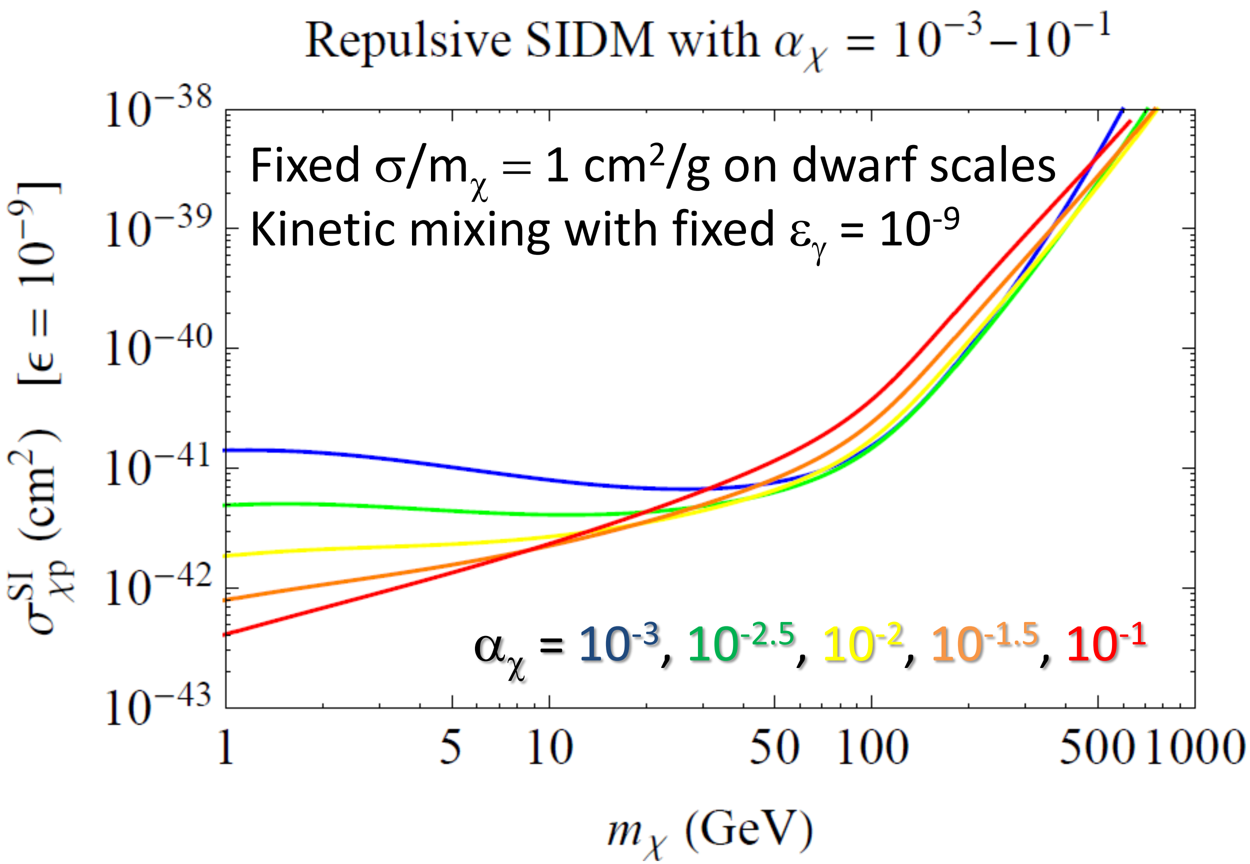
Note: two cases are isospin-violating
Frandsen et al (2011)

XENON100 limits approaching 10^{-45} cm^2

Sensitivity to $\varepsilon_{\text{eff}} \sim 10^{-10}$ (Interesting for BBN limit!)

Direct detection implications for SIDM

Solving small scale anomalies puts a constraint on direct detection.



m_ϕ and α_χ fixed by self-interactions

Smaller α_χ compensated by smaller m_ϕ

Parameter space for symmetric SIDM

- Three parameters: $(\alpha_\chi, m_\chi, m_\phi)$
- Relic density determined by usual freeze-out (fixes α_χ)

$$\chi\bar{\chi} \to \phi\phi \qquad \alpha_\chi \approx 4 \times 10^{-5}(m_\chi/\mathrm{GeV})$$

- CMB constraint on DM annihilation $\chi\bar{\chi} \to \phi\phi \to e^+e^-e^+e^-$

$m_\chi > 30$ GeV*BR($\phi \to e^+e^-$) *Galli et al (2009); Slatyer et al (2009); Lopez-Honorez et al (2013)*

- Self-interactions in dwarfs to solve small scale anomalies

$$0.1 \lesssim \sigma/m_\chi \lesssim 10\ \mathrm{cm}^2/\mathrm{s}$$ for v ~ 30 km/s

Vogelsberger et al (2012); Rocha et al (2012)

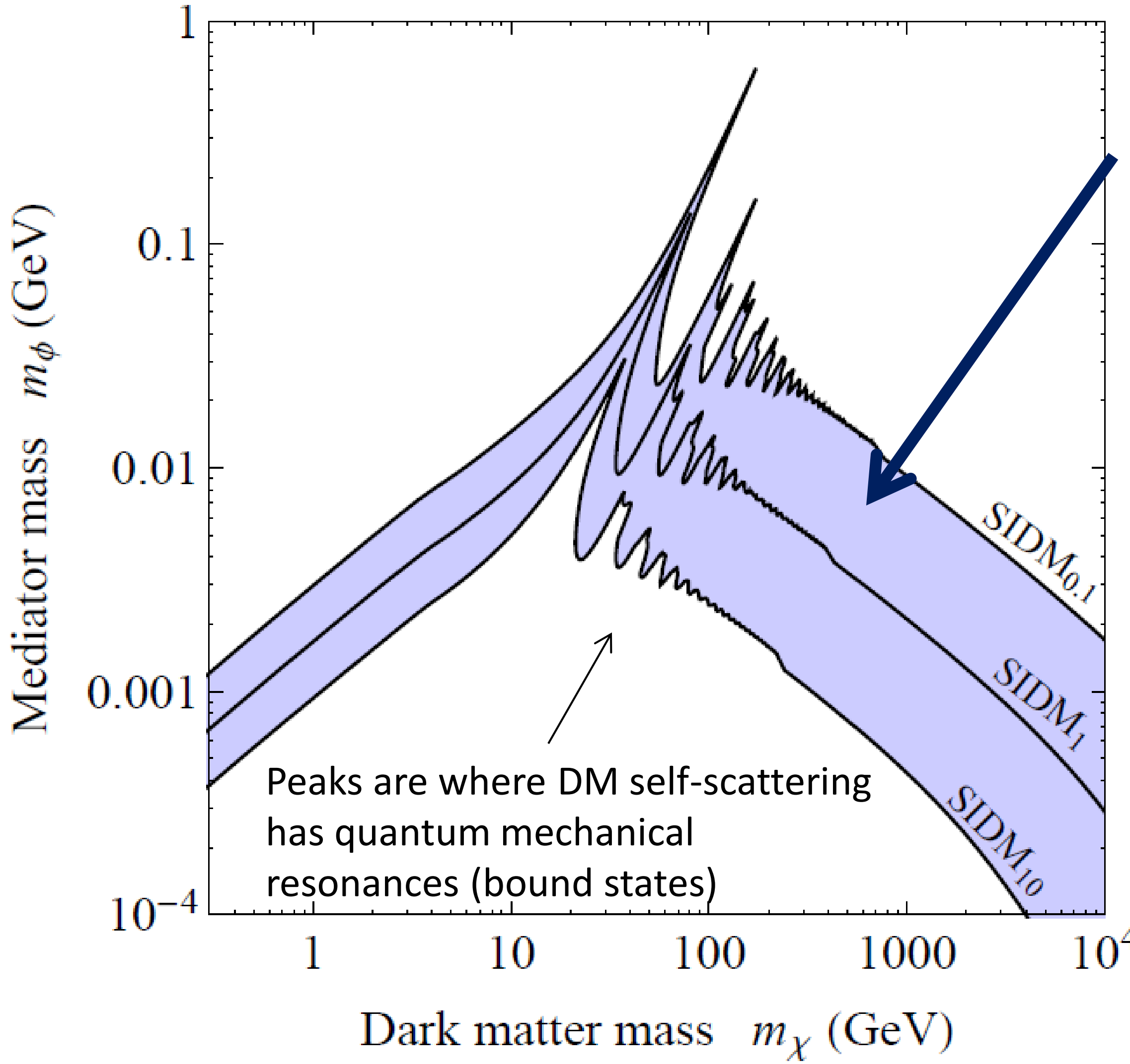
- Constraints from halo shapes (ellipticity of group halos)

$$\sigma/m_\chi \lesssim 1\ \mathrm{cm}^2/\mathrm{s}$$ for v ~ 300 km/s *Peter et al (2012)*

- Bullet cluster constraint

$$\sigma/m_\chi \lesssim 1\ \mathrm{cm}^2/\mathrm{s}$$ for v ~ 3000 km/s *Randall et al (2007)*

Parameter space for symmetric SIDM

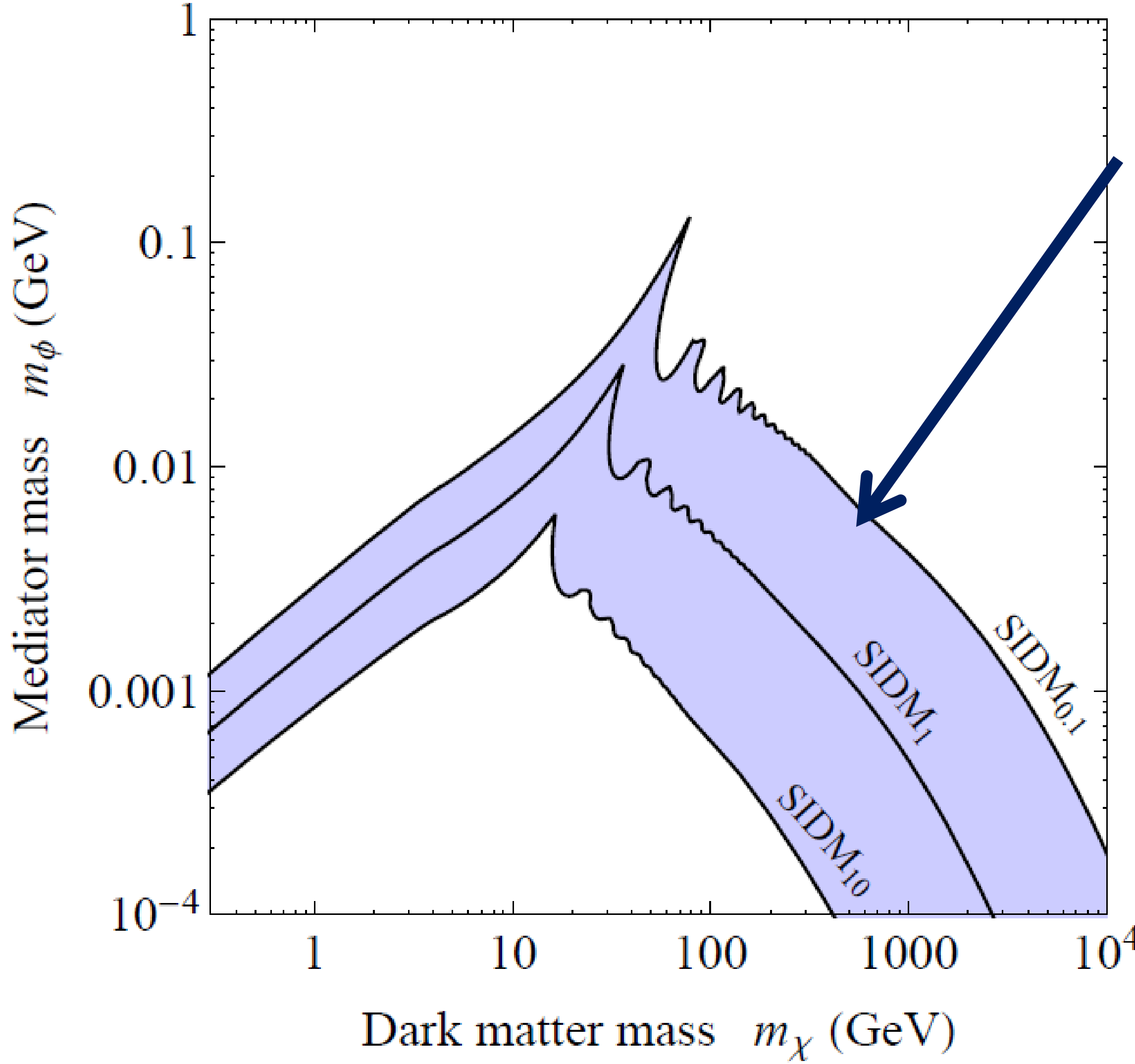


SIDM region for solving dwarf anomalies

Wide range of DM mass
Mediator ~ 1 – 100 MeV

Assume dwarf halos with characteristic velocity v_0 = 30 km/s

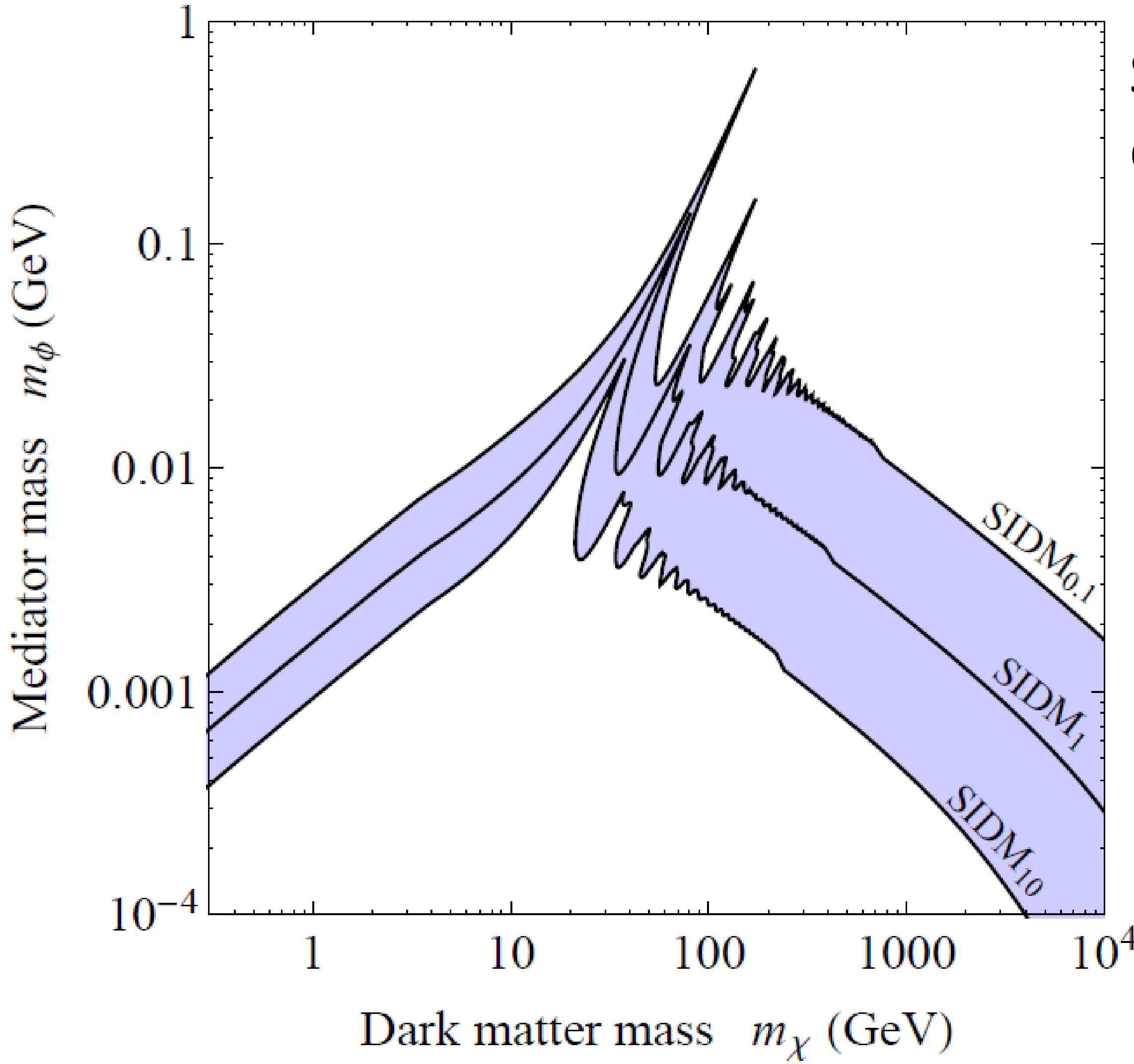
Parameter space for symmetric SIDM



SIDM region for solving dwarf anomalies

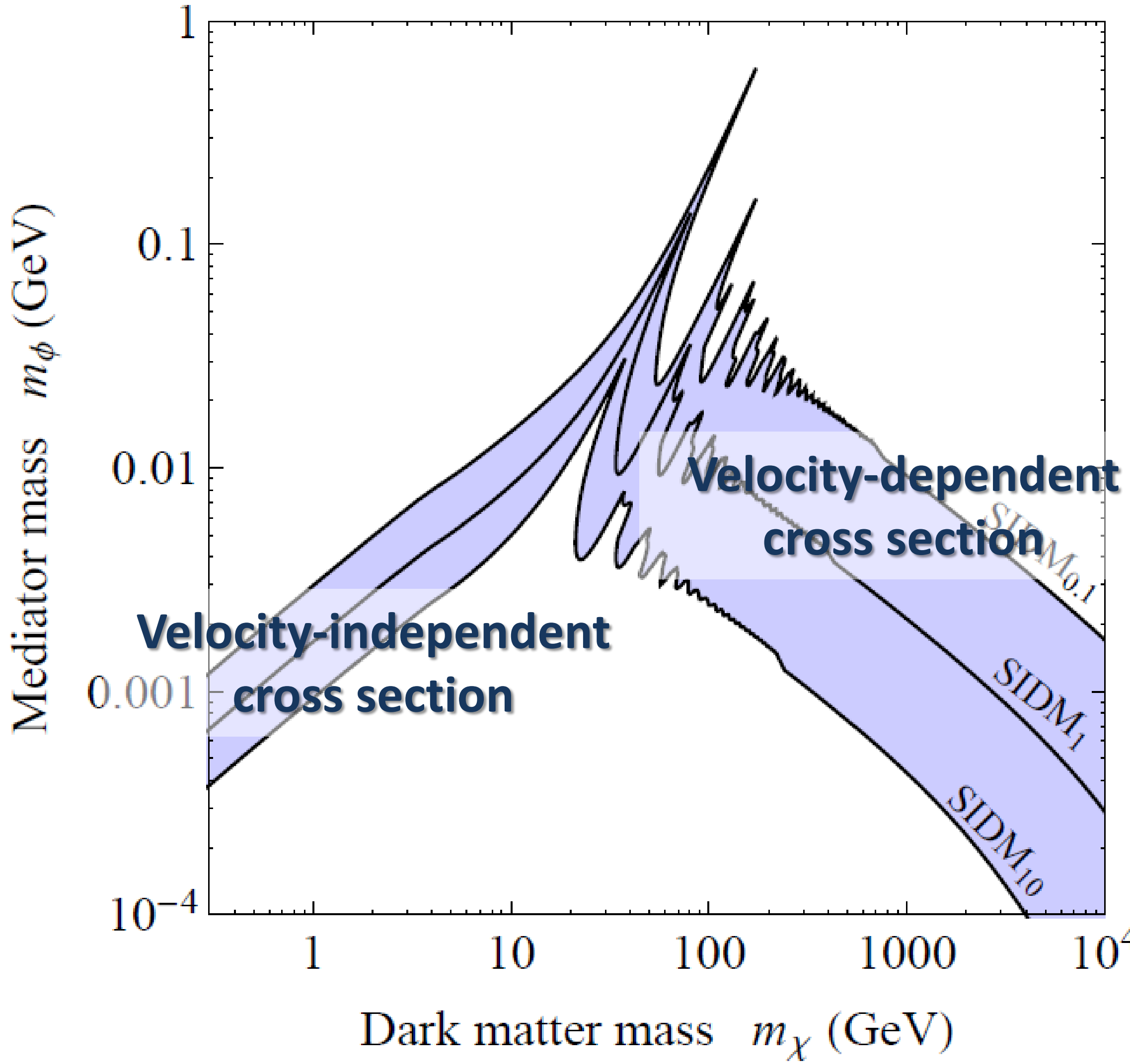
Assume dwarf halos with characteristic velocity v_0 = 100 km/s i.e. LSB's

Parameter space for symmetric SIDM



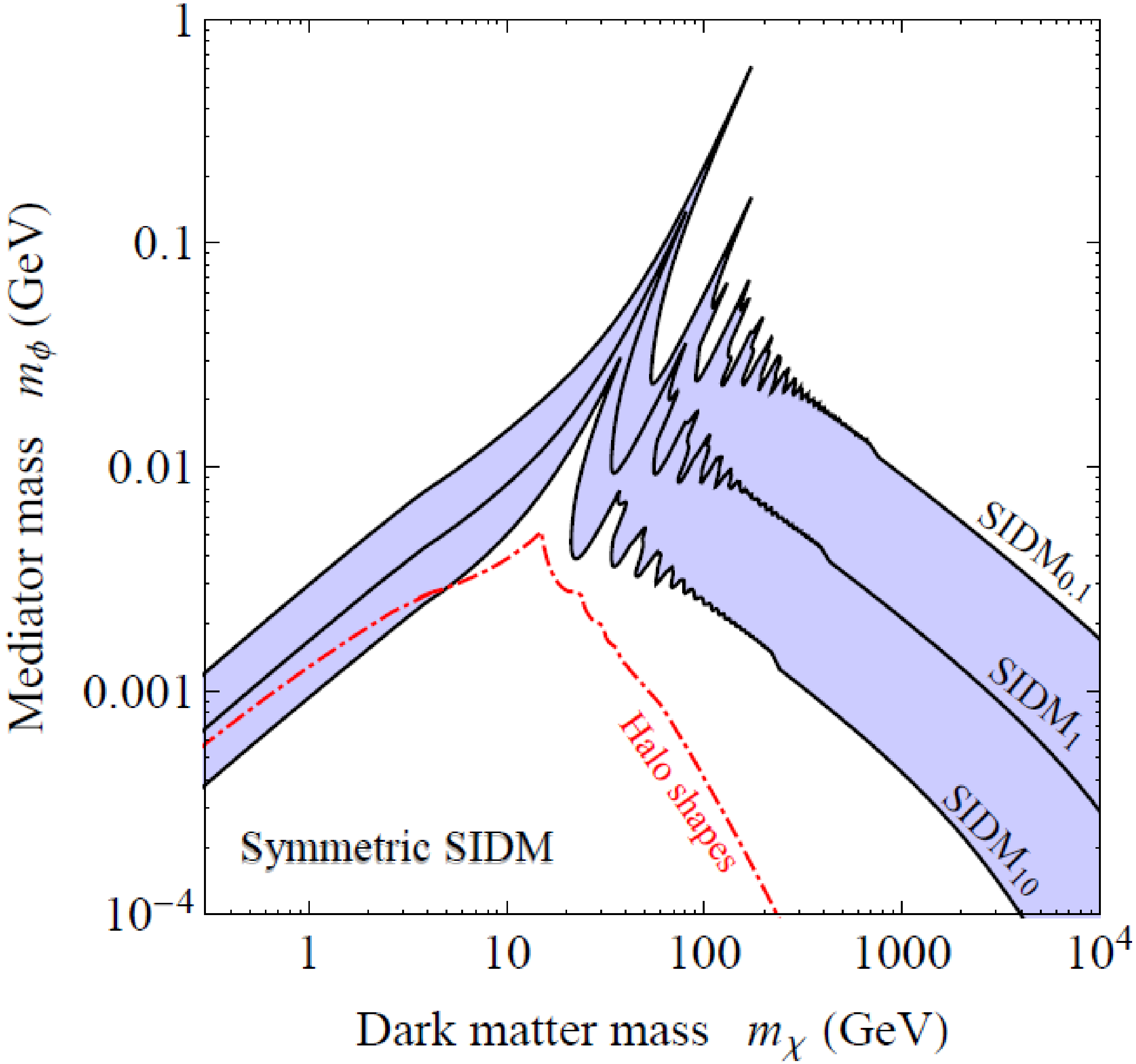
SIDM region for solving dwarf anomalies

Parameter space for symmetric SIDM



SIDM region for solving dwarf anomalies

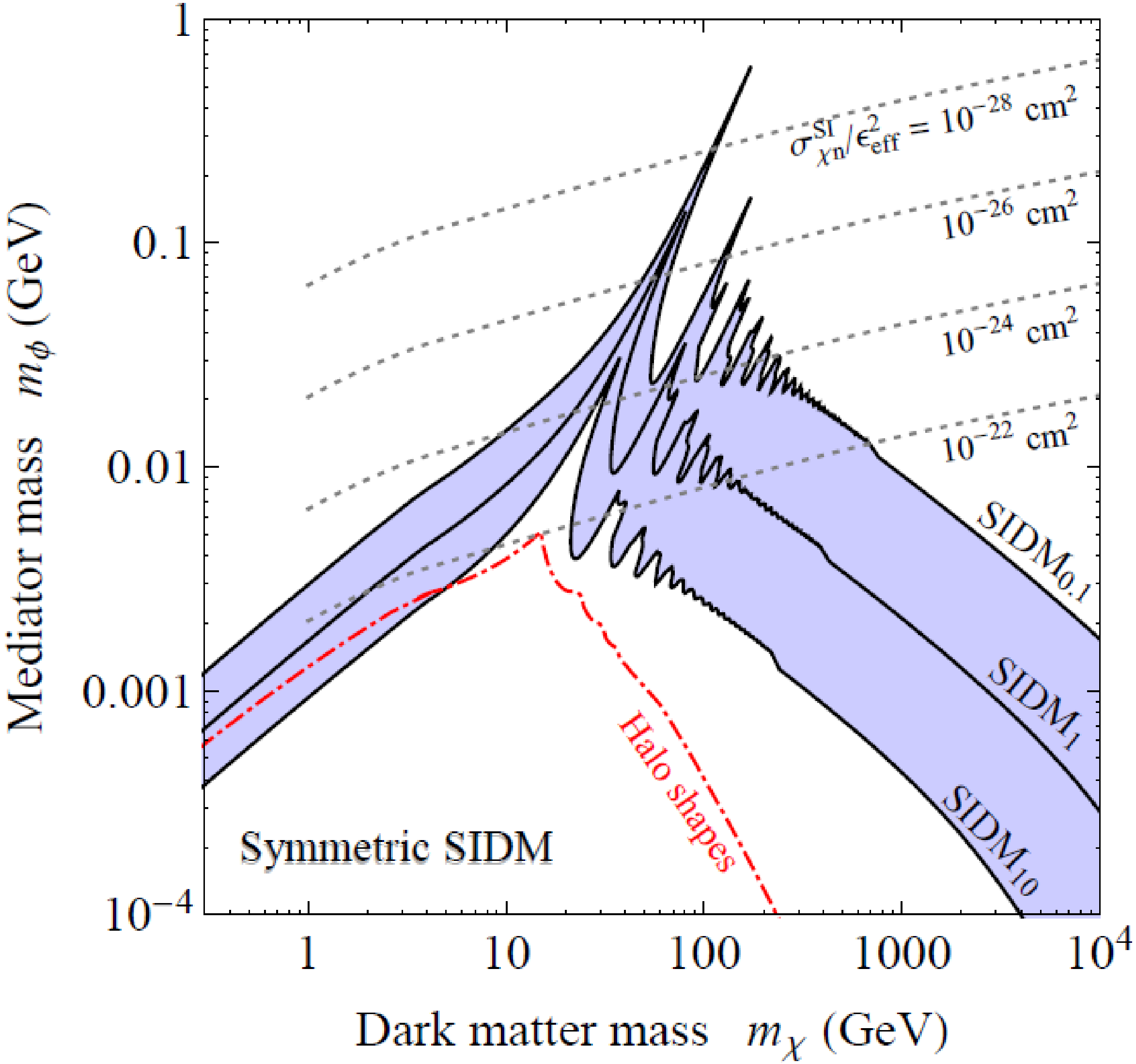
Parameter space for symmetric SIDM



Shaded region: solve dwarf anomalies

Halo shape bound

Parameter space for symmetric SIDM



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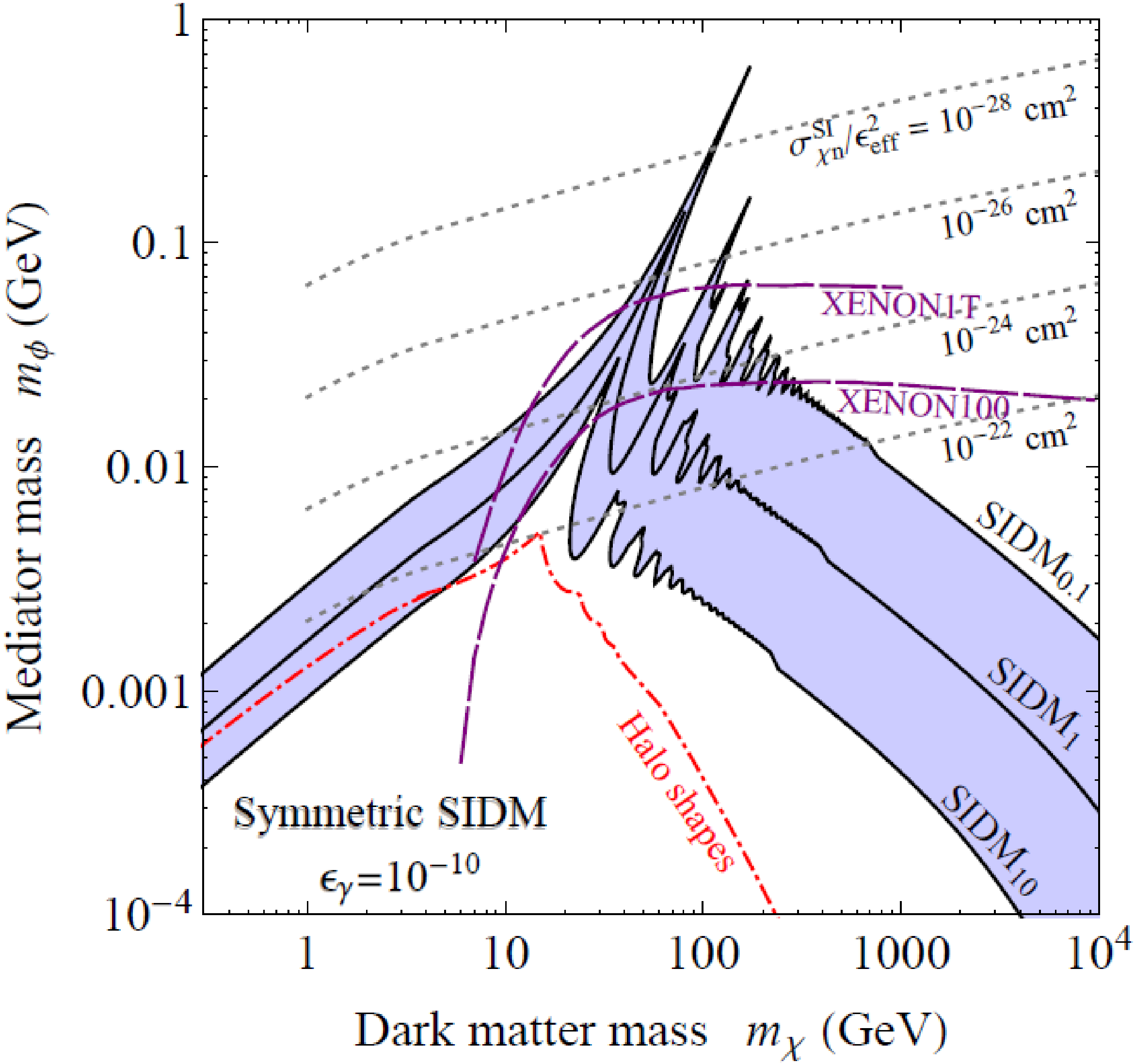
Halo shape bound

Direct detection

Parameter space for symmetric SIDM



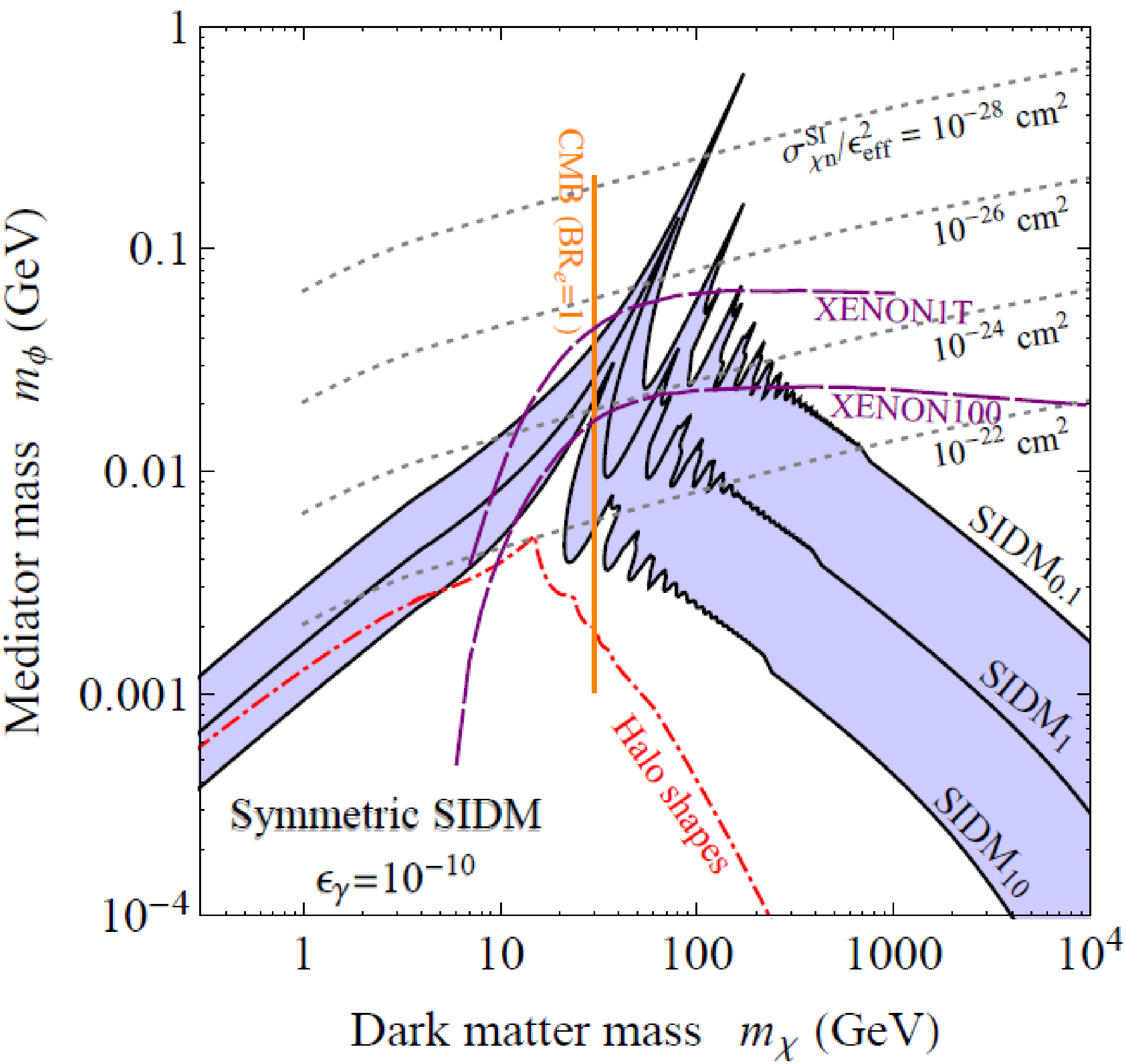
SIDM coupled via kinetic mixing

Shaded region: solve dwarf anomalies

Halo shape bound

Direct detection

Parameter space for symmetric SIDM



SIDM coupled via kinetic mixing

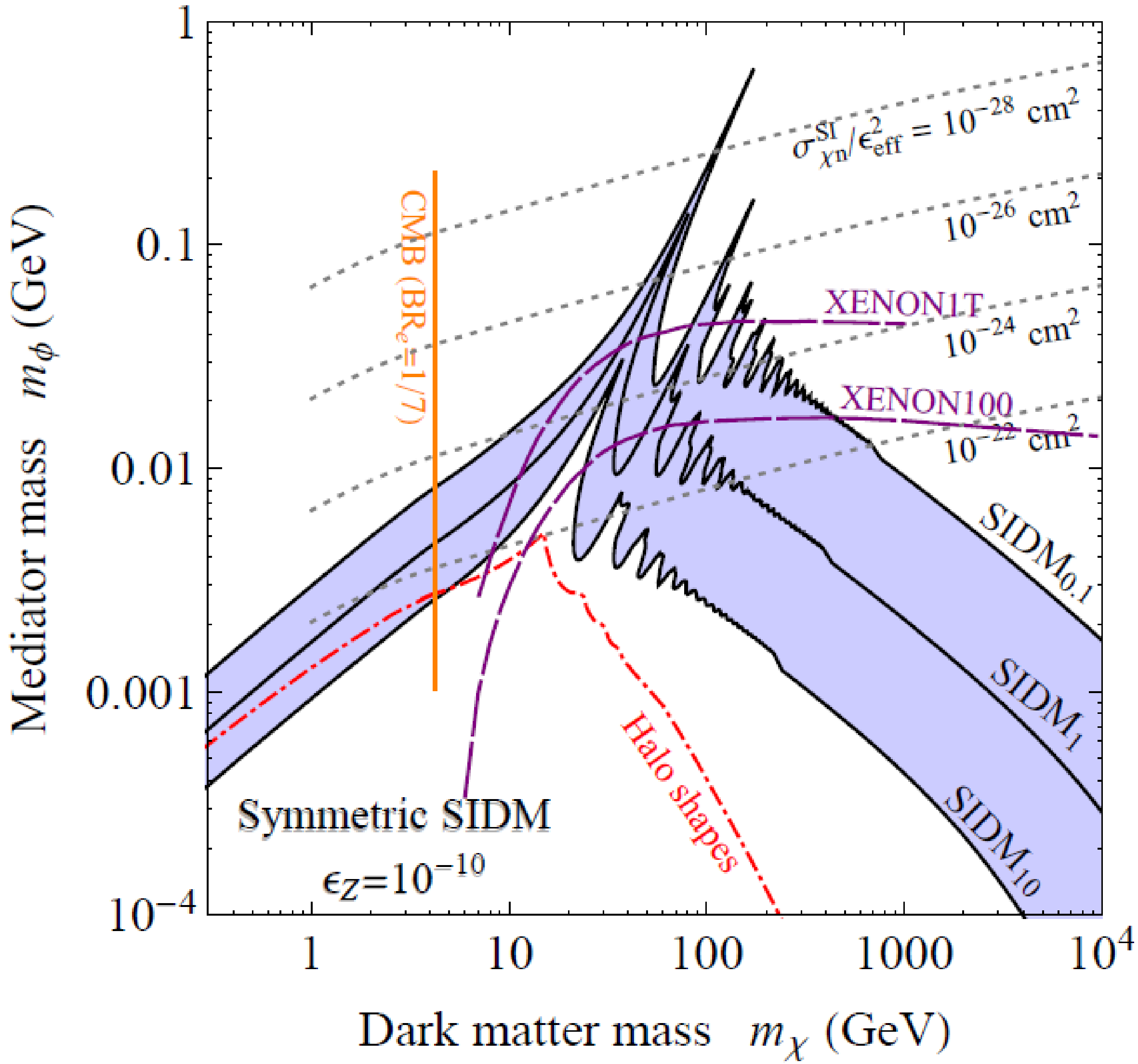
Shaded region: solve dwarf anomalies

Halo shape bound

Direct detection

CMB constraint

Parameter space for symmetric SIDM



SIDM coupled via Z mixing

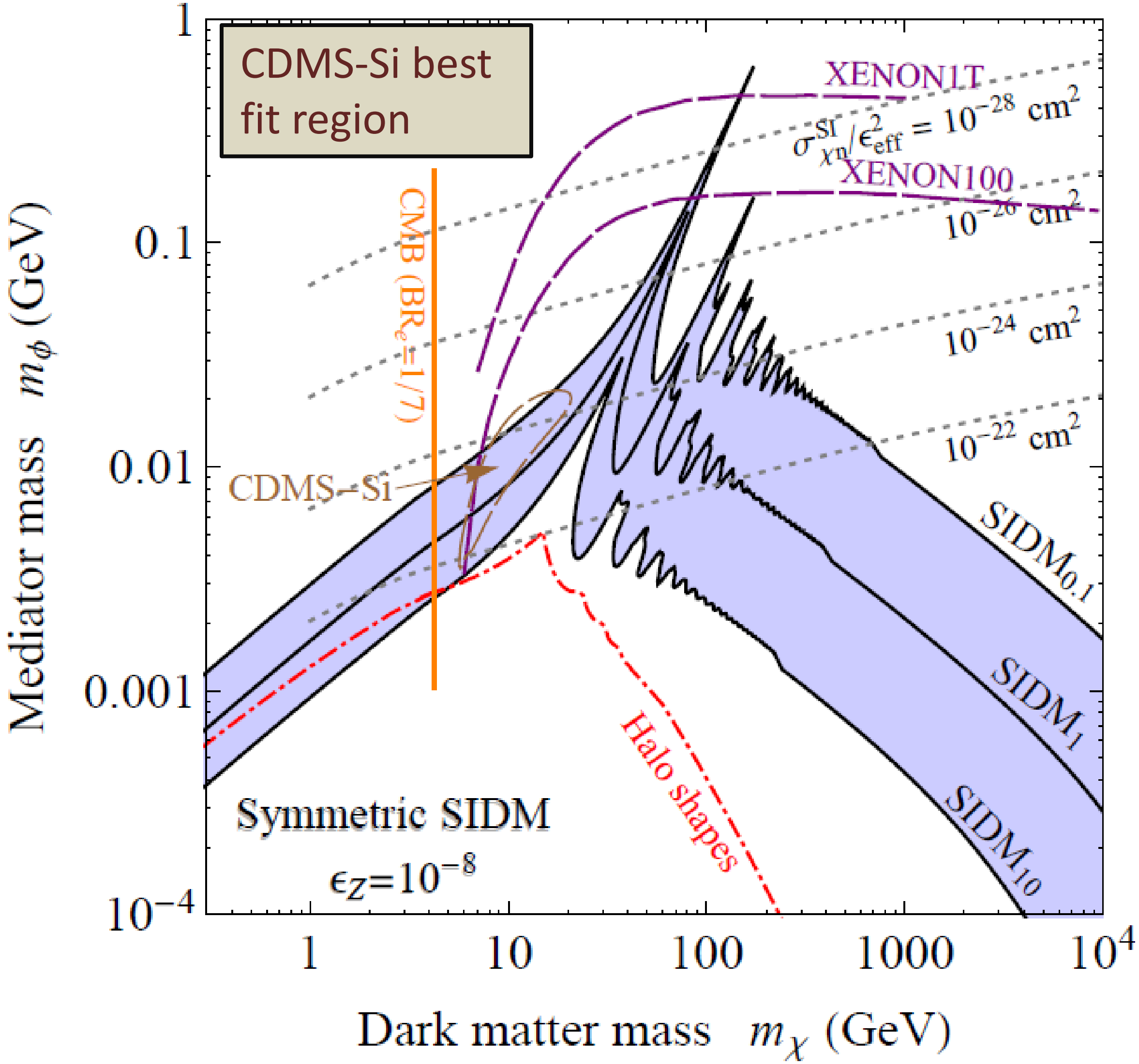
Shaded region: solve dwarf anomalies

Halo shape bound

Direct detection

CMB constraint

Parameter space for symmetric SIDM



SIDM coupled via Z mixing

Shaded region: solve dwarf anomalies

CMB constraint

Halo shape bound

Direct detection

Parameter space for asymmetric SIDM

- Three parameters: $(\alpha_\chi, m_\chi, m_\phi)$
- Require sufficient annihilation for fixed α_χ

$$\alpha_X \gtrsim 4 \times 10^{-5} (m_X / \mathrm{GeV})$$

- No constraints on annihilation (only χ present after freezeout)

- Self-interactions in dwarfs to solve small scale anomalies

$$0.1 \lesssim \sigma / m_\chi \lesssim 10 \ \mathrm{cm}^2/\mathrm{s}$$ for v ~ 30 km/s

Vogelsberger et al (2012); Rocha et al (2012)

- Constraints from halo shapes (ellipticity of group halos)

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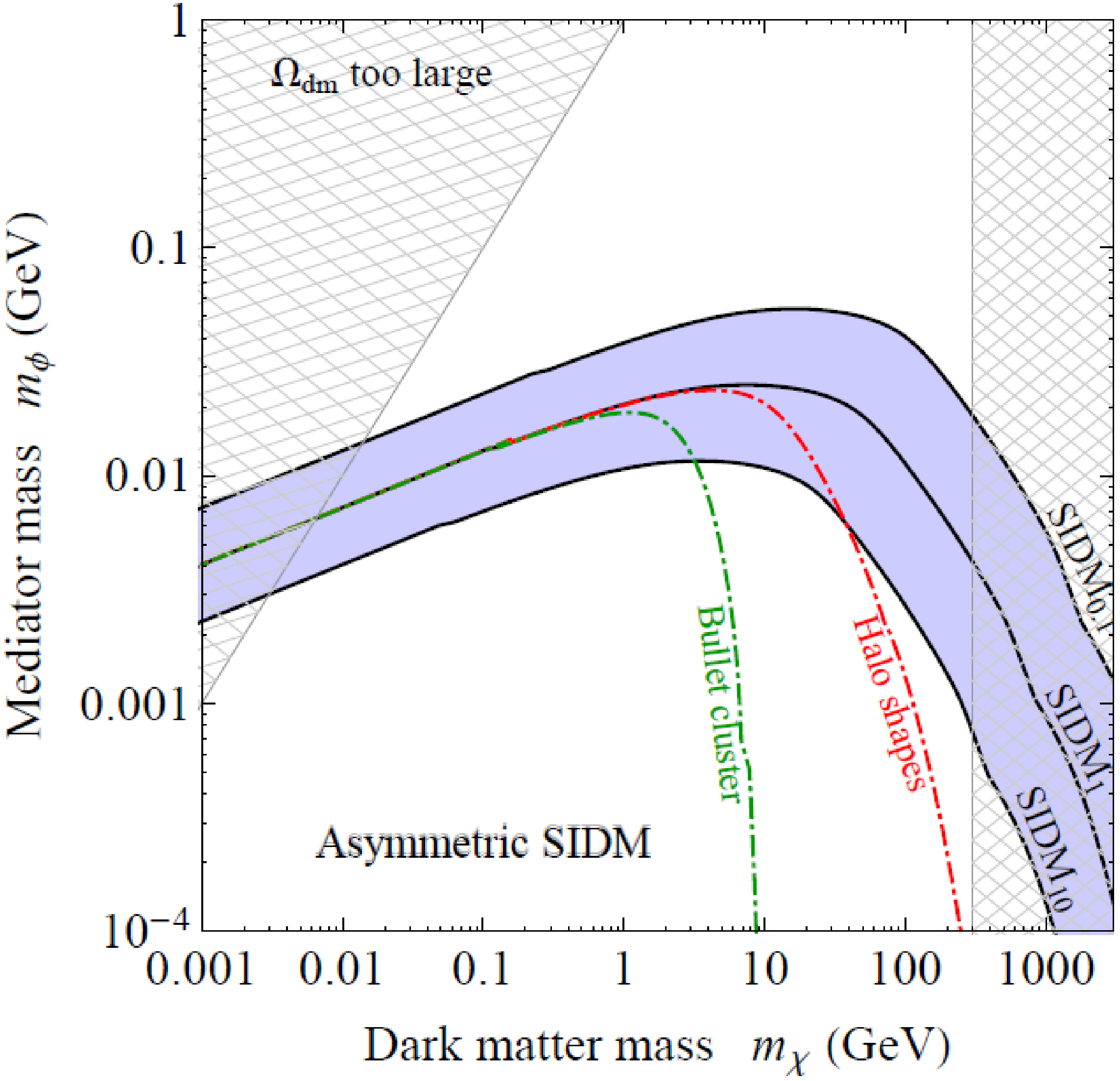
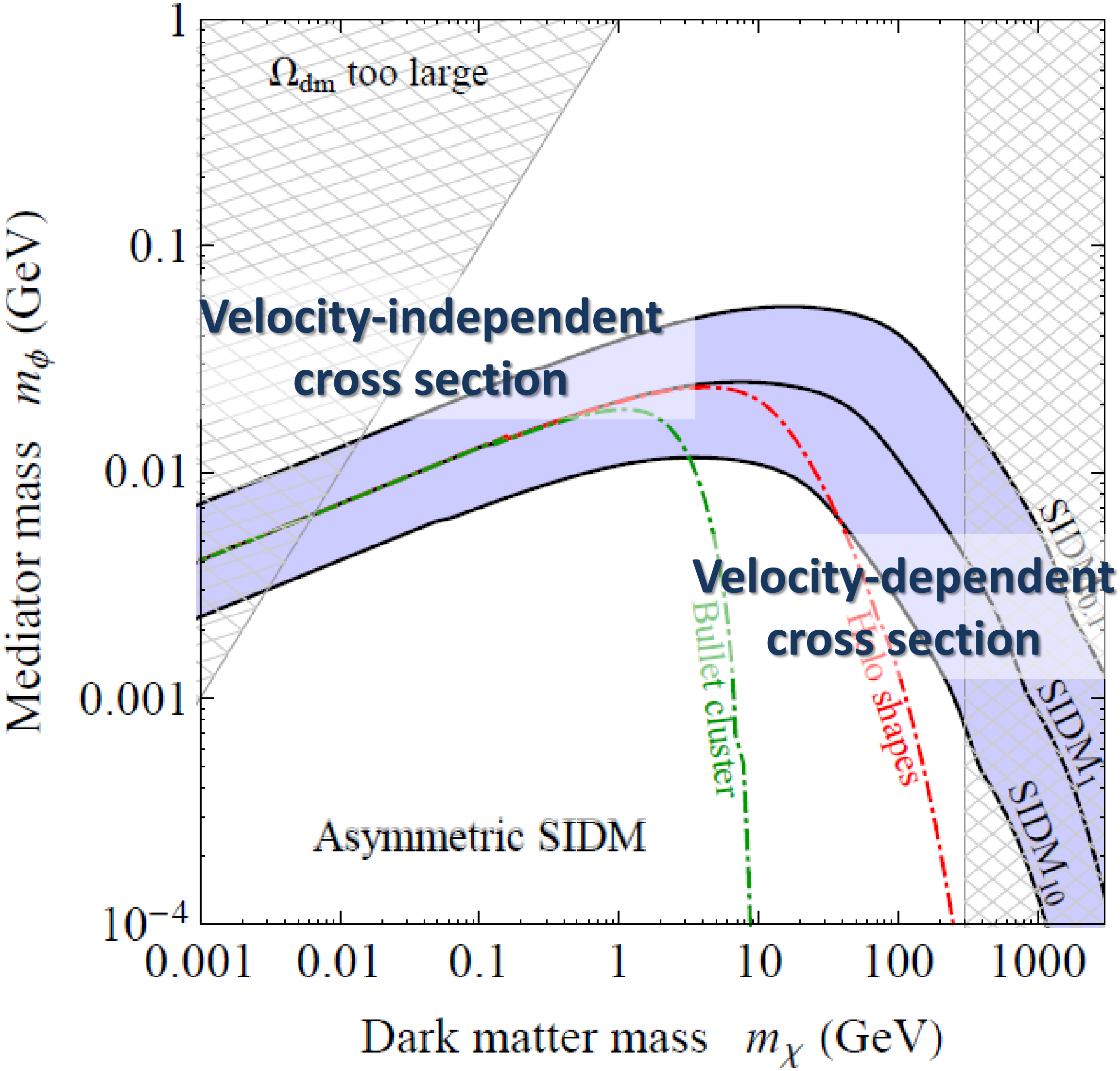


Shaded region: solve dwarf anomalies

Halo shape bound

Bullet cluster

Parameter space for asymmetric SIDM



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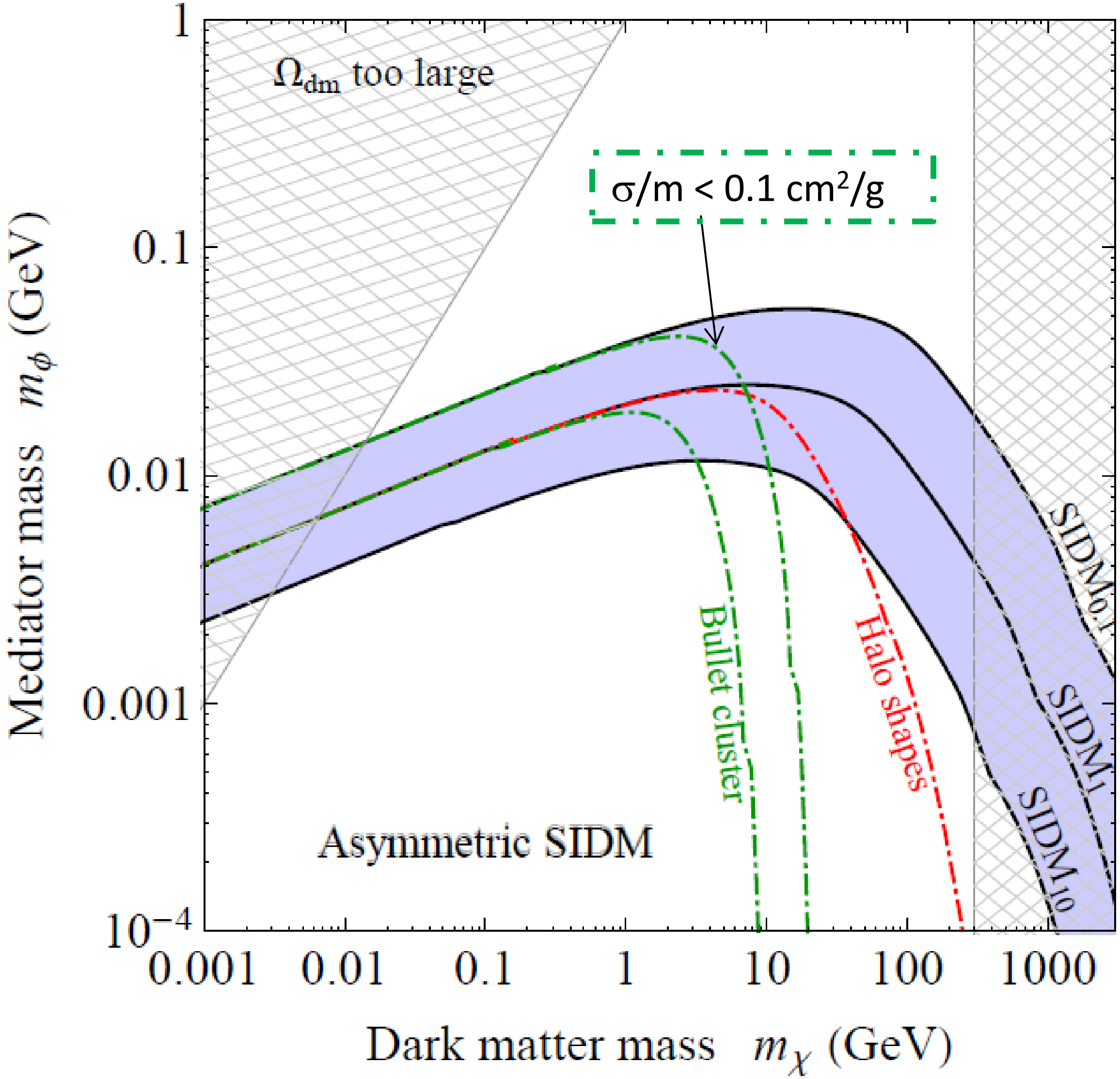

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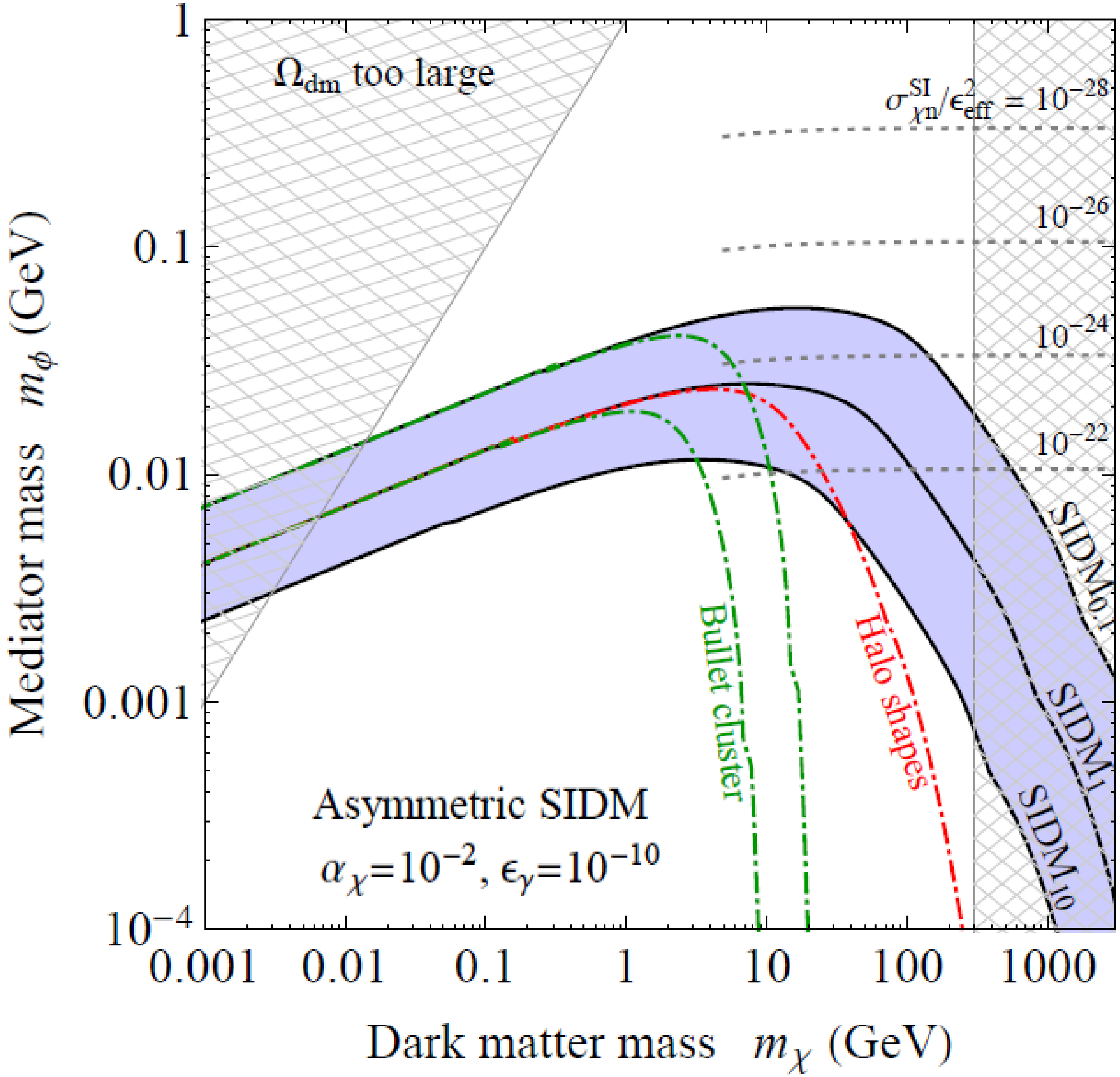
Parameter space for asymmetric SIDM

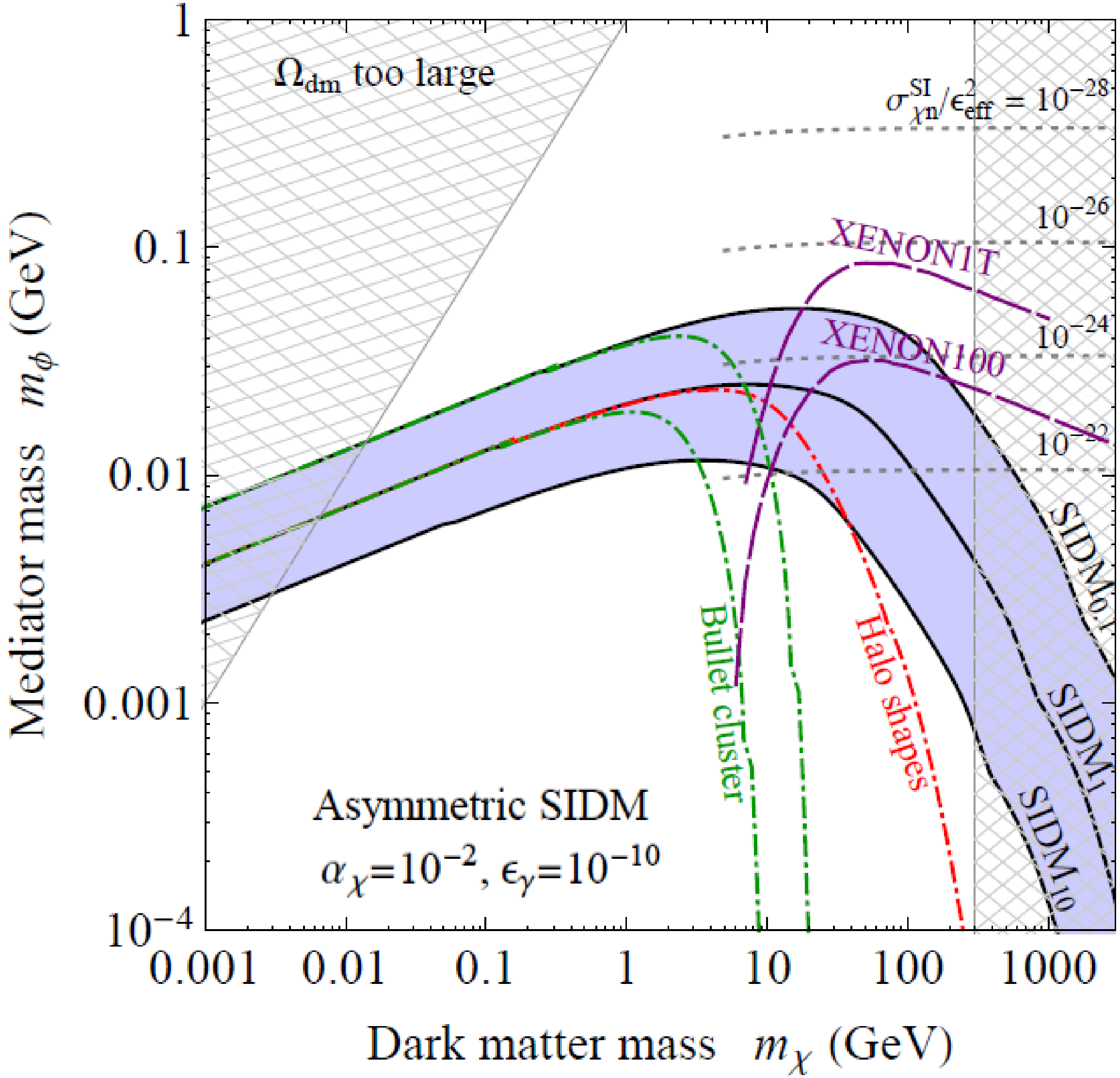


Shaded region: solve dwarf anomalies

Halo shape bound

Bullet cluster

Parameter space for asymmetric SIDM



SIDM coupled via kinetic mixing

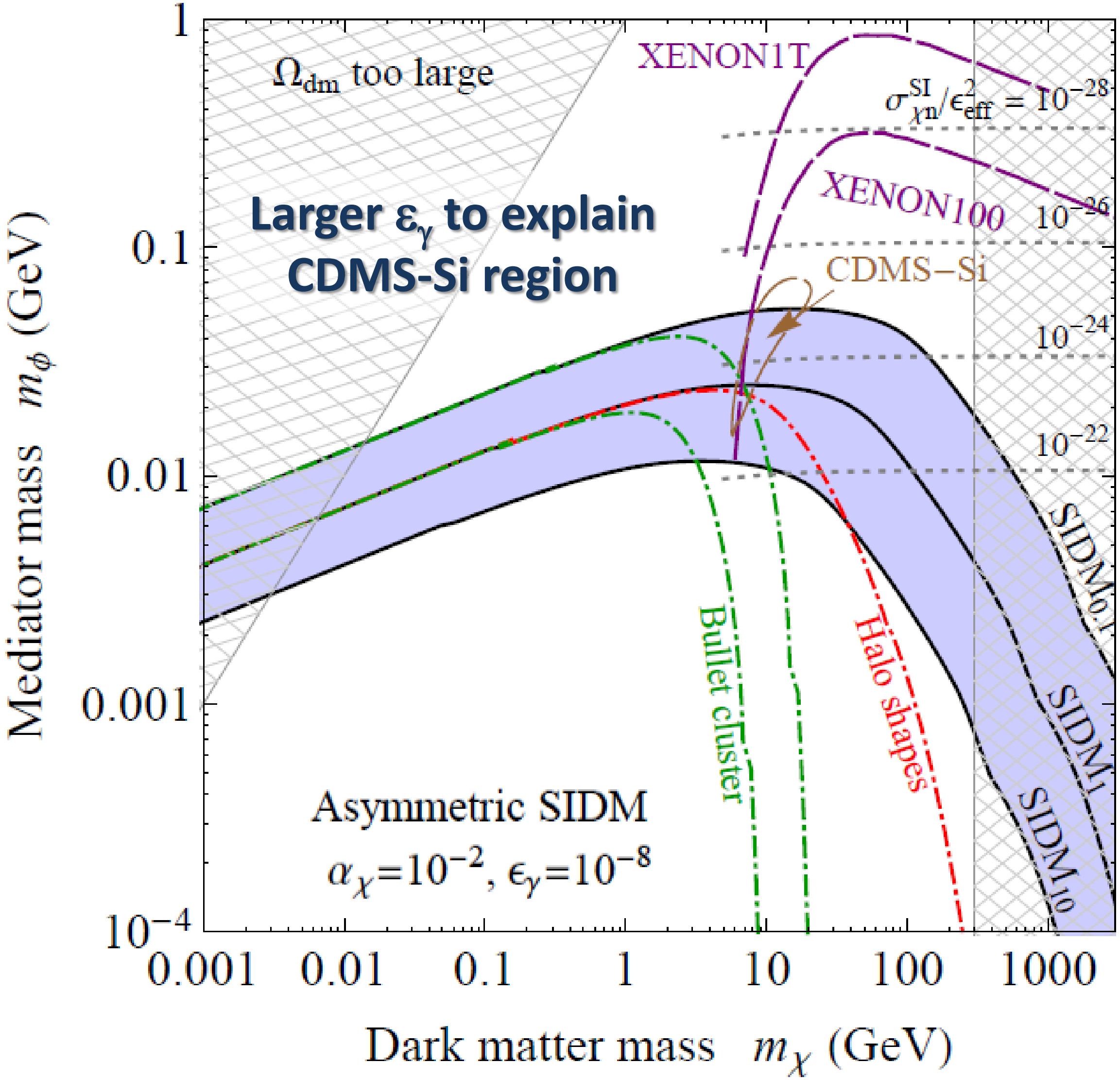
Shaded region: solve dwarf anomalies

Halo shape bound

Bullet cluster

Direct detection

Parameter space for asymmetric SIDM



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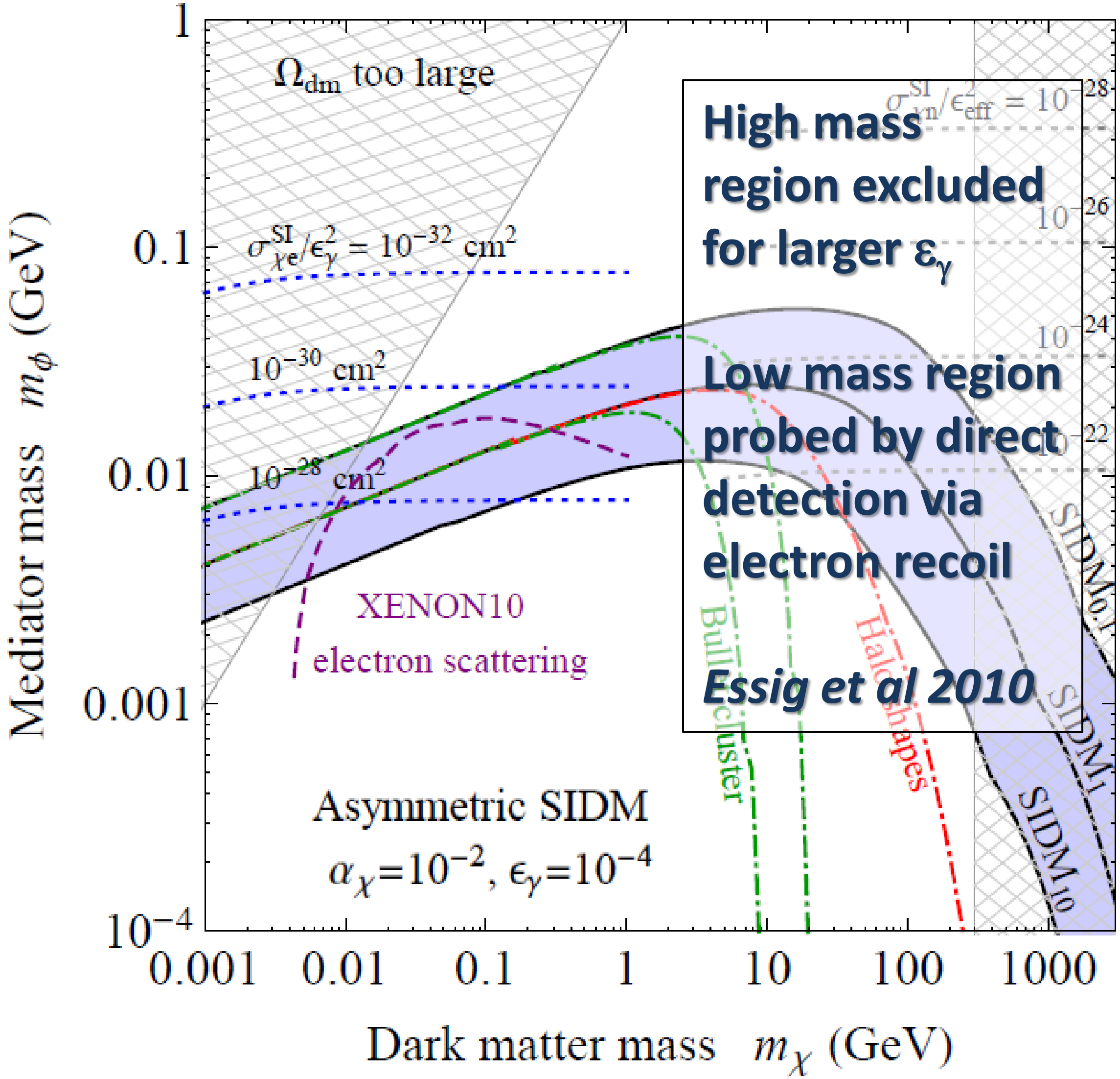

SIDM coupled via kinetic mixing

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Halo shape bound

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Conclusions (part 1)

- Simplified model: DM χ + vector mediator ϕ
- 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 σ)
  - Direct detection constrain SIDM at WIMP-scale masses (corresponding to v-dependent σ)