Self-interacting Dark Matter and Muon g-2 in a gauged $U(1)_{L_\mu - L_\tau}$ model

Keisuke Yanagi

(University of Tokyo)

A. Kamada, K. Kaneta, KY, H. Yu

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What do we know about dark matter?

Dark Matter: an evidence of physics beyond the Standard Model!

$$\mathscr{L}_{\rm DM} = \textbf{?}$$

- Large scale: $\Omega_{\rm DM} h^2 \simeq 0.12$
- **Small scale: Astrophysical observations have tensions with CDM paradigm**

[e.g., Tulin & Yu, 2017]

missing satellite

Rotation curve diversity

Core vs. cusp

Too big to fail

related to DM density profile

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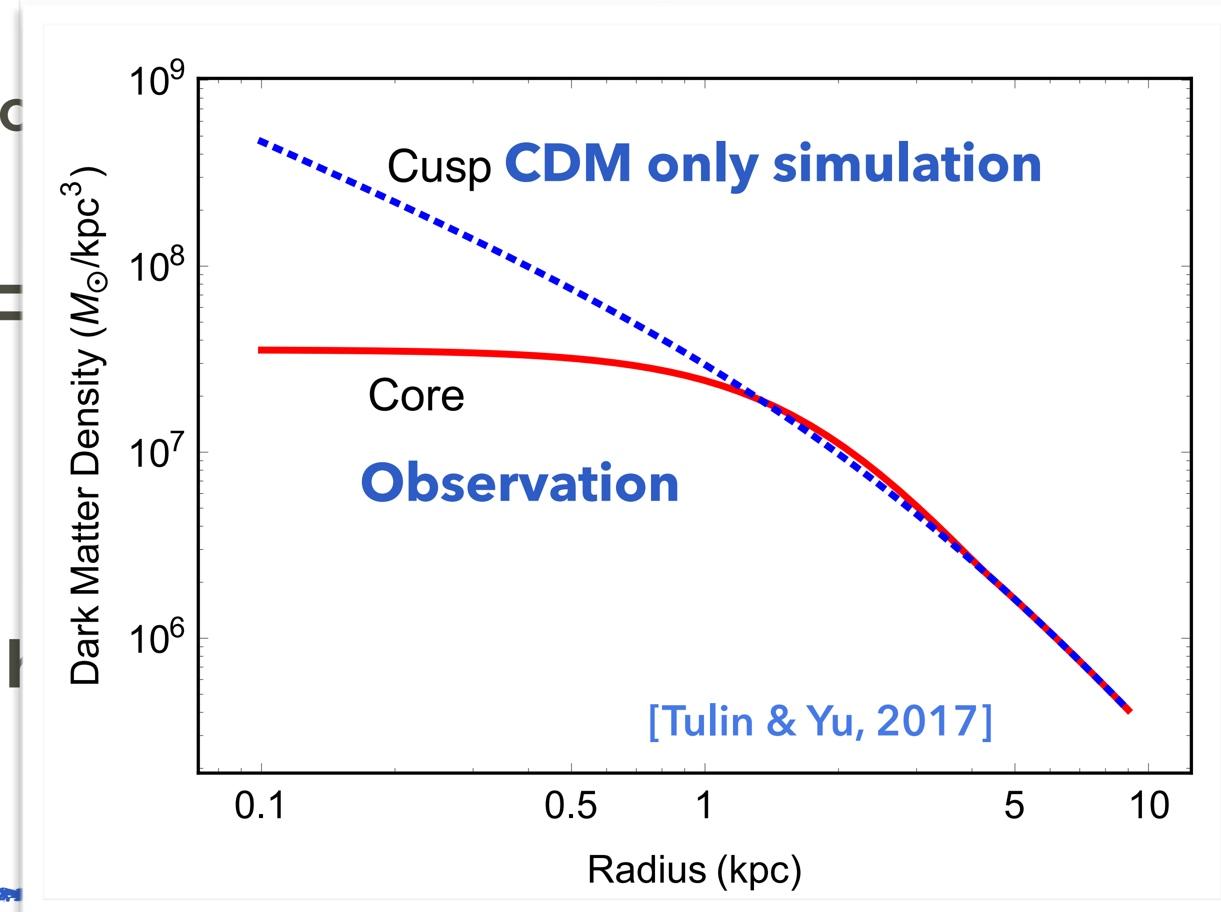

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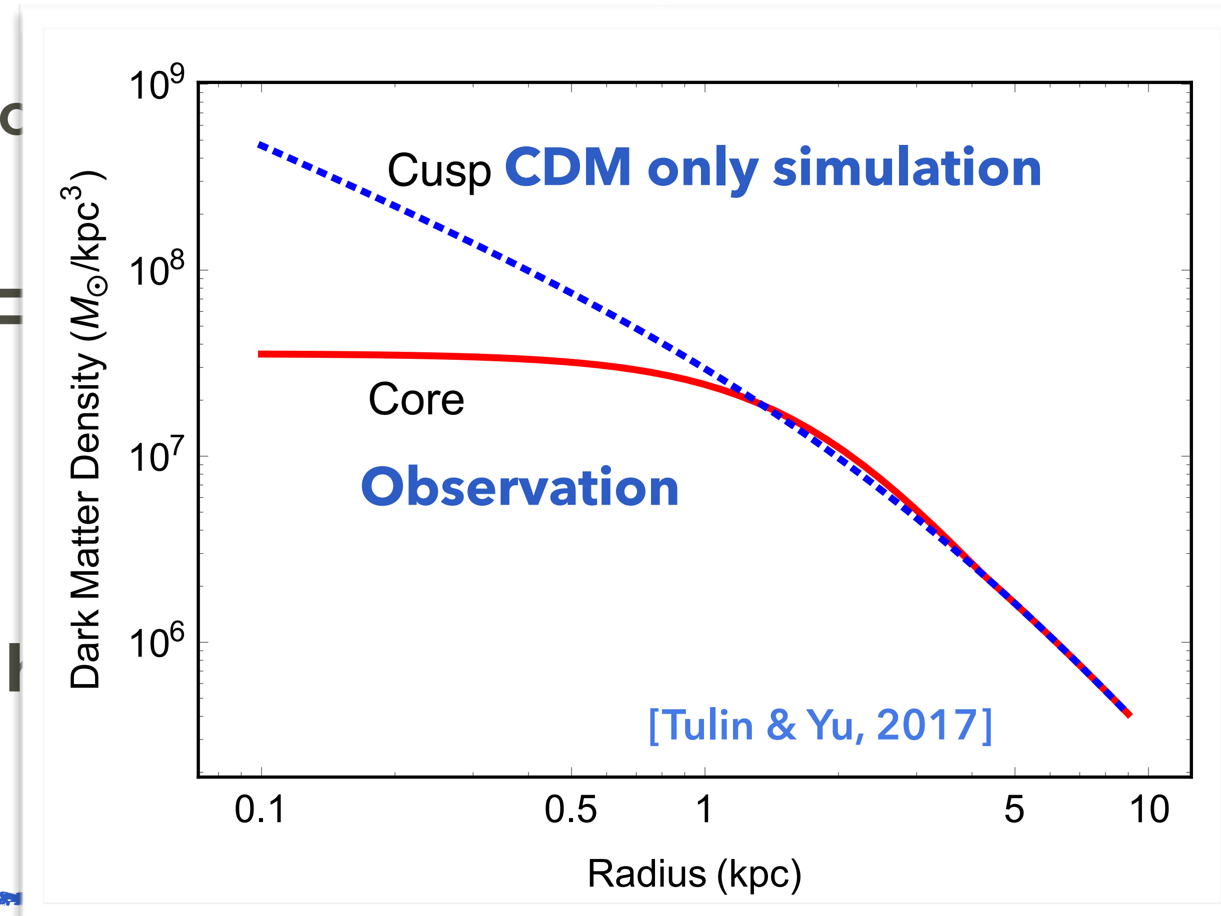

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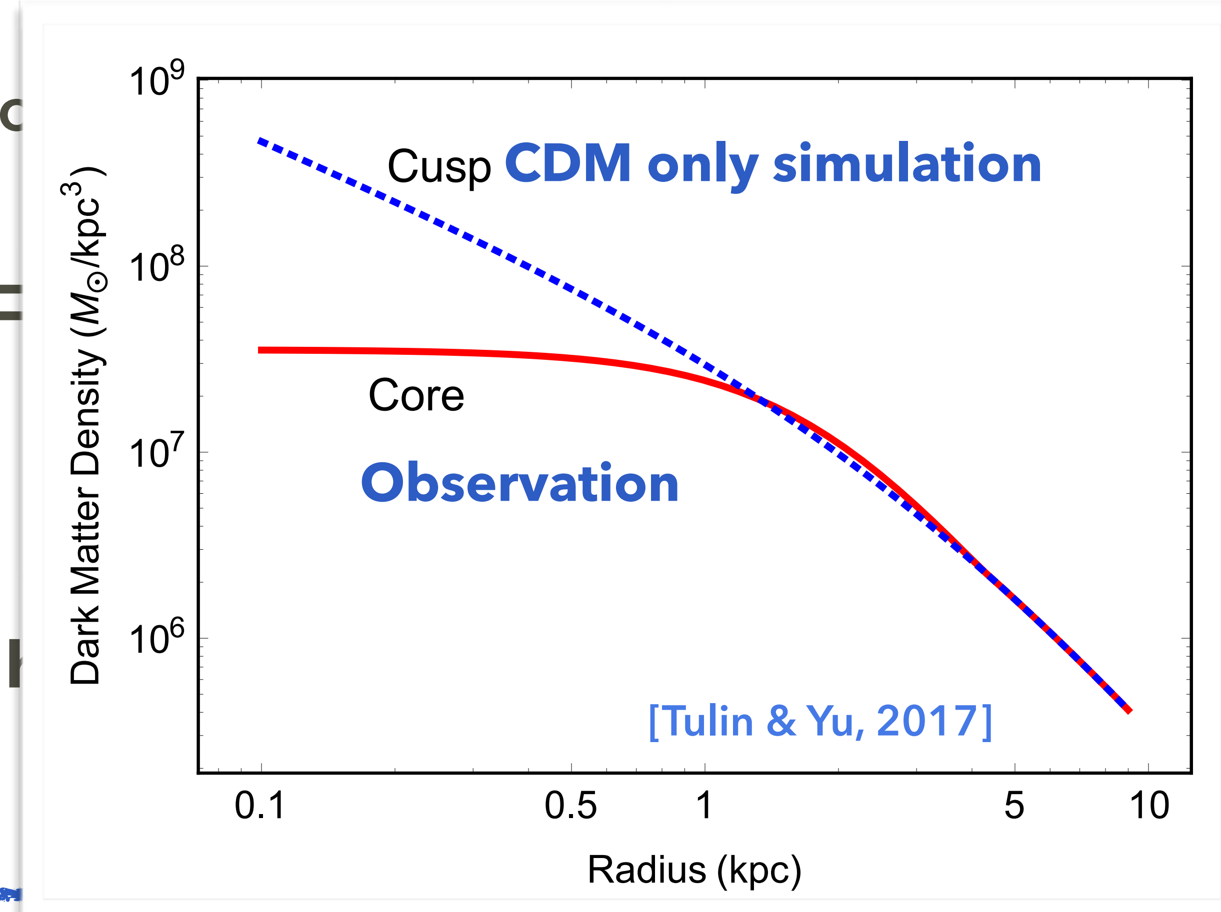

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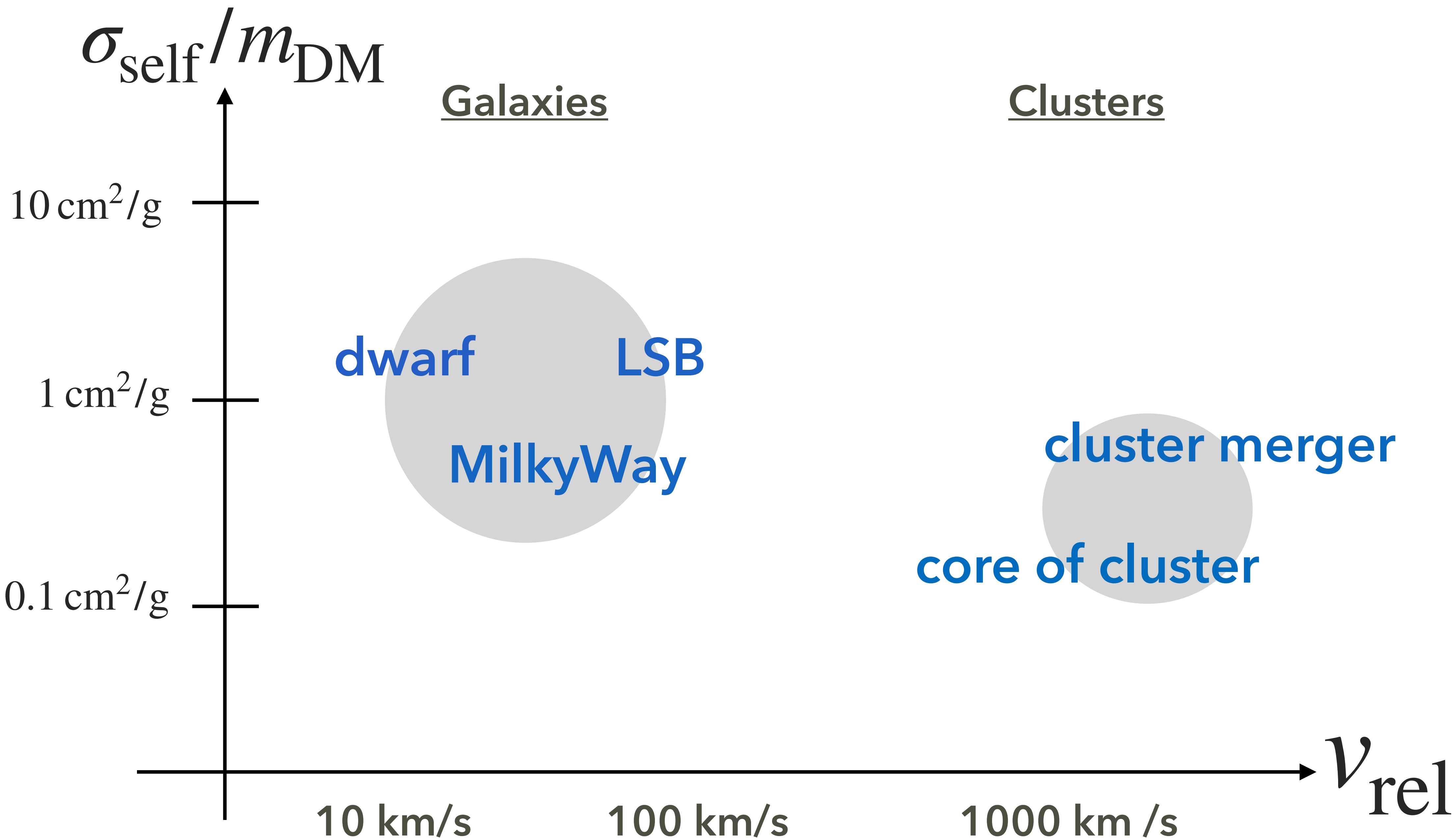
Dark matter self-interaction! (this talk)

- Velocity distribution is more Maxwell-Boltzmann like
- Halo central density is reduced

Small scale issues suggests DM self-interaction

Small scale issues **favor** sizable self-scattering at **galaxy** and **cluster** scales



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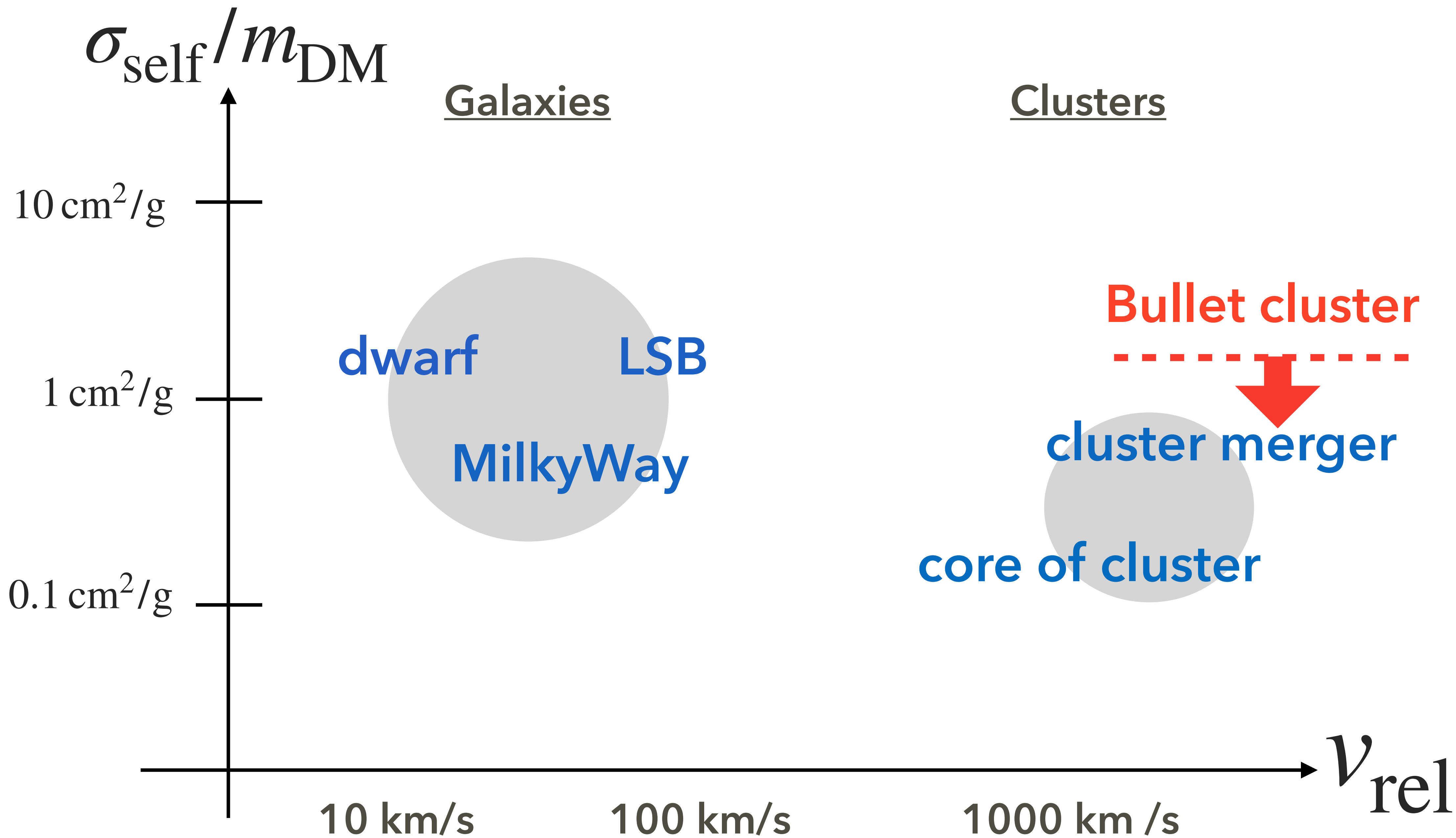
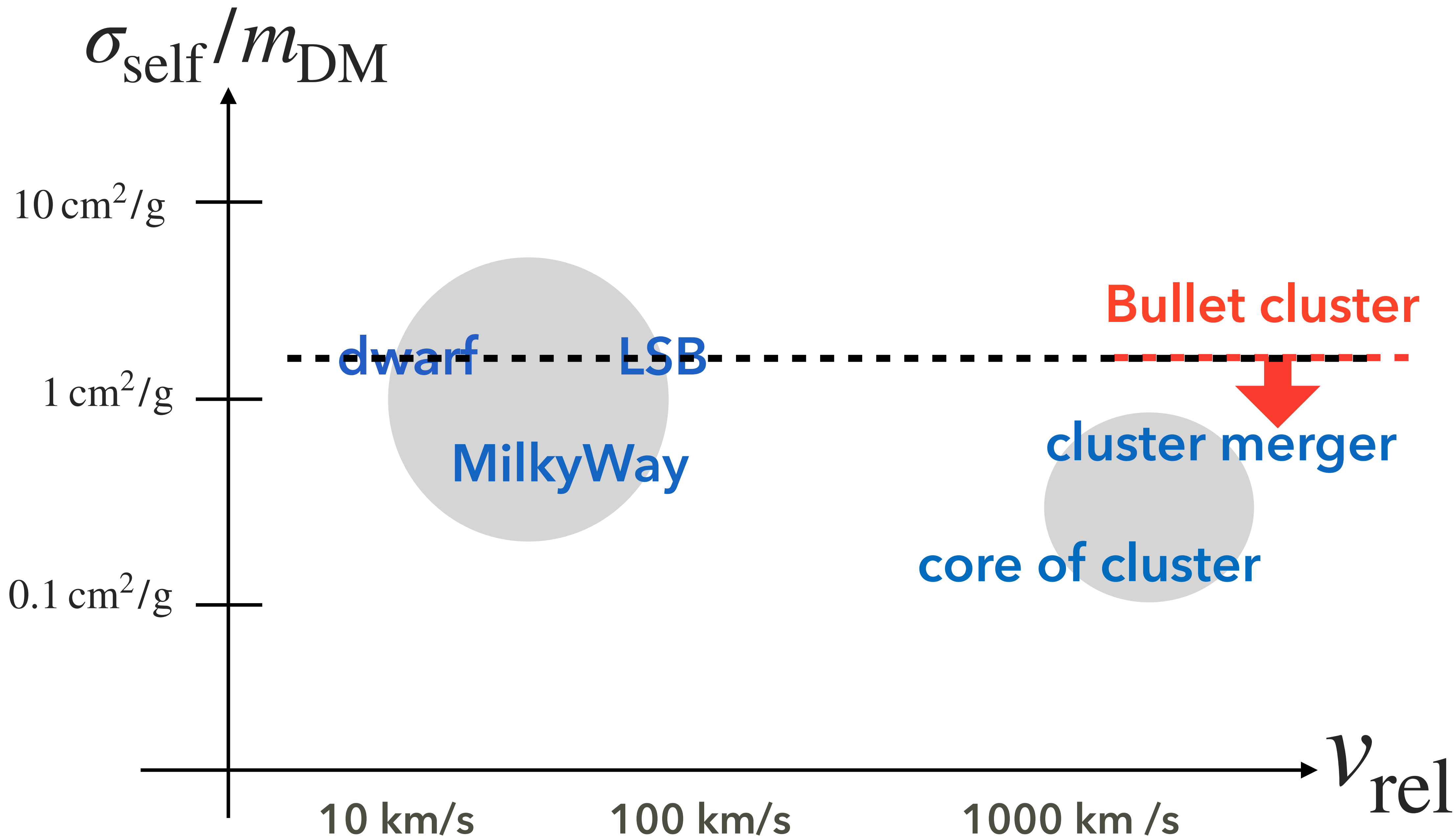
Small scale issues **favor** sizable self-scattering at **galaxy** and **cluster** scales

There is also an **upper bound** on self-scattering from Bullet cluster



Implication on particle physics

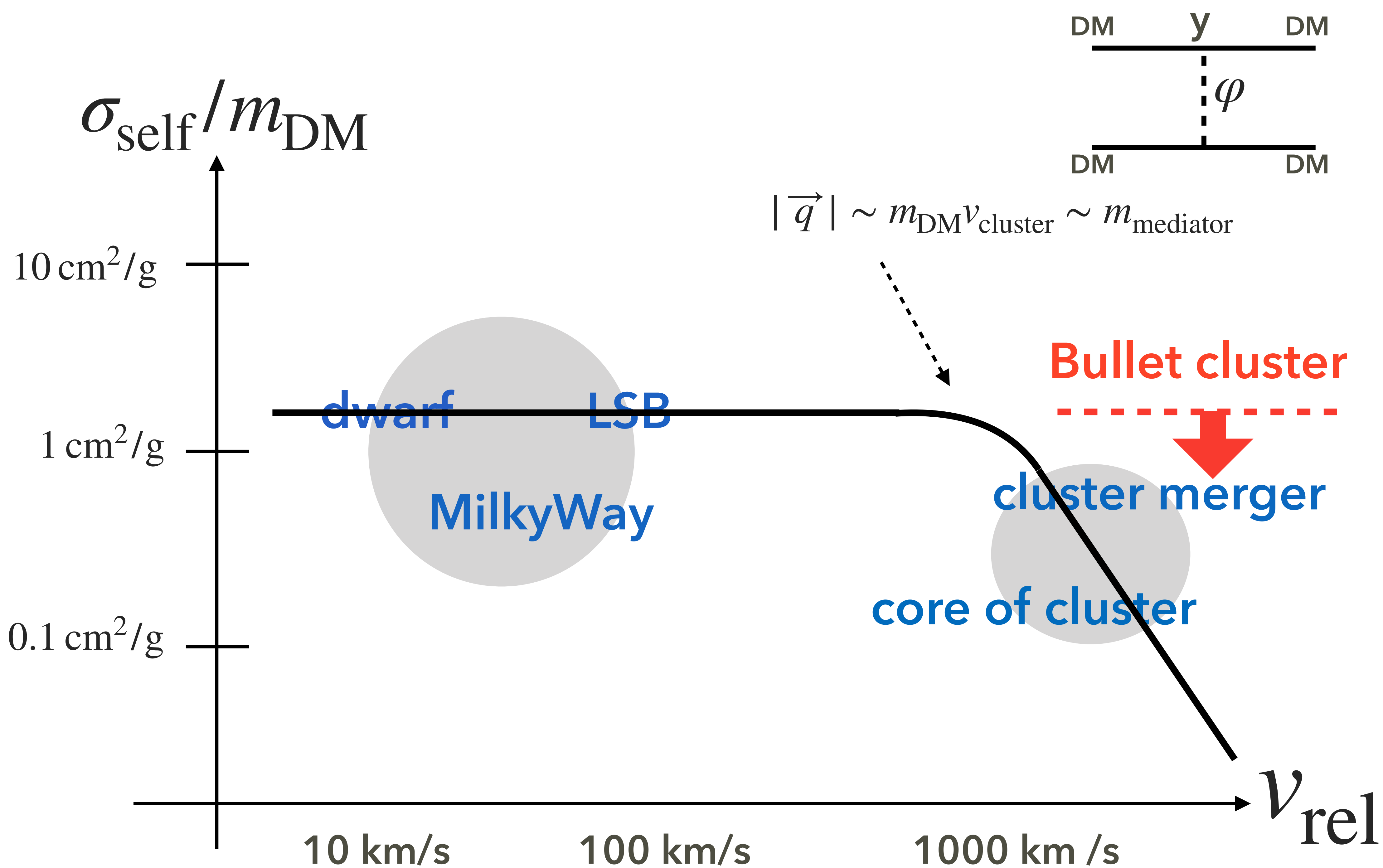
A constant cross section may not be consistent with the bullet cluster



Implication on particle physics

A constant cross section may not be consistent with the bullet cluster

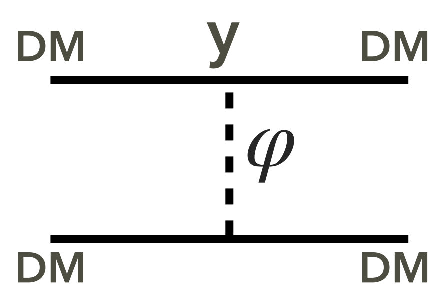
Velocity-dependent cross section is favored!



Weak scale DM + MeV mediator suggested!

Can we build a model of such self-interacting DM?

A simplified model: scalar or vector mediator



$$\mathcal{M} \sim \frac{y^2}{q^2 - m_{\text{mediator}}^2}$$

We want

$$\sigma \sim 1\,\text{cm}^2\,(m/\text{g}) \sim 2 \times 10^{-24}\,\text{cm}^2\,(m/\text{GeV}) \quad \& \quad |\vec{q}\,| \sim m_{\text{DM}} v_{\text{cluster}} \sim m_{\text{mediator}}$$

~ 1000 km/s

Roughly…

$$\sigma \sim \frac{y^4}{4\pi}\frac{m_{\text{DM}}^2}{m_\varphi^4} = 3 \times 10^{-23}\,\text{cm}^2 \left(\frac{y}{0.1}\right)^4 \left(\frac{m_{\text{DM}}}{10\,\text{GeV}}\right)^2 \left(\frac{m_\varphi}{10\,\text{MeV}}\right)^{-4}$$

$$v \sim \frac{m_\varphi}{m_{\text{DM}}} \sim 300\,\text{km/s} \left(\frac{m_{\text{DM}}}{10\,\text{GeV}}\right)^{-1} \left(\frac{m_\varphi}{10\,\text{MeV}}\right)$$

Weak scale DM + MeV mediator

DM - mediator interaction: $\mathcal{L} = y\varphi\bar{X}X$ or $yZ'_\mu\bar{X}\gamma^\mu X$

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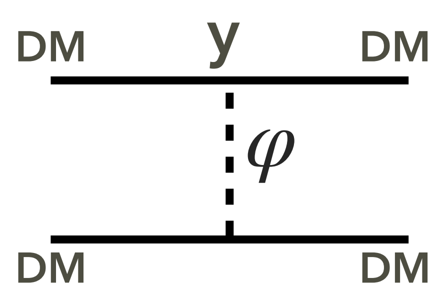

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Weak scale DM + MeV mediator

DM - mediator interaction: $\mathscr{L} = y\varphi\bar{X}X$ or $yZ'_\mu\bar{X}\gamma^\mu X$

This is not the end of the story !

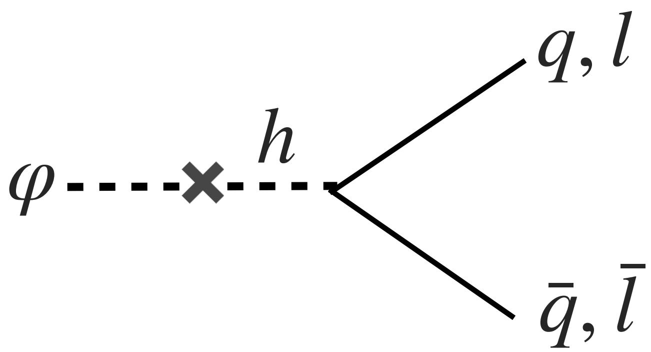
Challenges in model building

Mediators must decay before the BBN

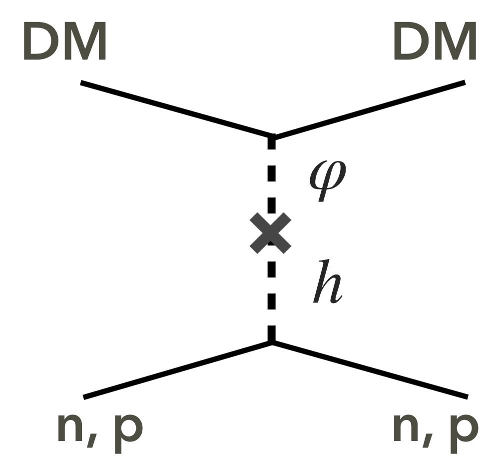
If it decays via portal coupling with SM,

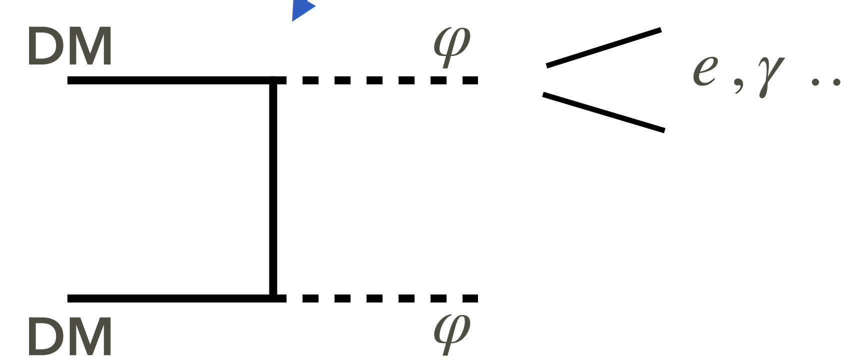
$$\mathscr{L} = \lambda_{\Phi H}|H|^2|\Phi|^2 \quad \text{or} \quad \mathscr{L} = \epsilon Z'_{\mu\nu}B^{\mu\nu}$$

Mediator - SM particles couplings



Large cross section for direct/indirect searches





Previous works:

If one introduces mixing with SM, **direct/indirect/CMB exclude most of the parameter space** favored by the small scale issues [Kaplinghat, Tulin, Yu, 2013] [Bringmann, et.al., 2016]

A simplified model does not work…

U(1) $L_\mu - L_\tau$ extension solves the difficulties

Our work: we propose a SIDM model based on **a gauged U(1)$_{L_\mu - L_\tau}$ extension**

Model:

fermion, complex scalar

	N	$\bar{N}$	Φ	$\mu_{L,R}, \nu_\mu$	$\tau_{L,R}, \nu_\tau$
$\mathrm{U}(1)_{L_\mu - L_\tau}$	1/2	-1/2	-1	1	-1
Z_2	-1	-1	1	1	1

$\Phi = (v_\Phi + \varphi)/\sqrt{2}$

SIDM mediator

DM (stable)

(Fermion: 2-component)

Lagrangian

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \underline{g' Z'_\mu \left(L_2^\dagger \bar{\sigma}^\mu L_2 - L_3^\dagger \bar{\sigma}^\mu L_3 - \bar{\mu}^\dagger \bar{\sigma}^\mu \bar{\mu} + \bar{\tau}^\dagger \bar{\sigma}^\mu \bar{\tau} \right)}$$

couplings only with mu/tau leptons/neutrinos

➡ **constraints are automatically weak**

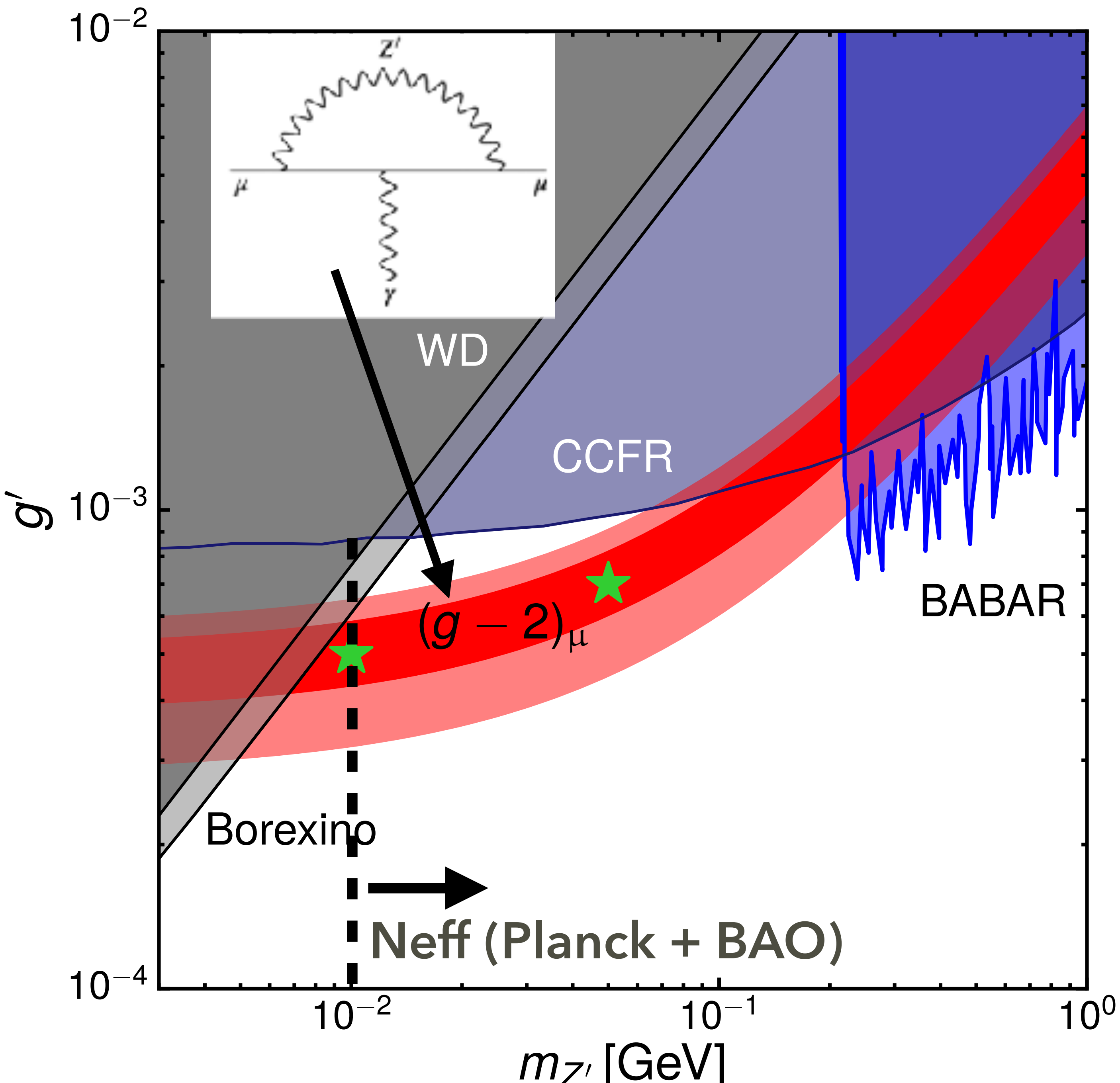
$$-\frac{1}{4} Z'_{\mu\nu} Z'^{\mu\nu} - \frac{1}{2} \epsilon Z'_{\mu\nu} B^{\mu\nu} + (D_\mu \Phi)^\dagger D^\mu \Phi + m_\Phi^2 |\Phi|^2 - \frac{1}{4} \lambda_\Phi |\Phi|^4 - \lambda_{\Phi H} |H|^2 |\Phi|^2$$

$\epsilon \to 0$, $\lambda_{\Phi H} \to 0$

assume no tree-level mixing

$$+ i N^\dagger \bar{\sigma}^\mu D_\mu N + i \bar{N}^\dagger \bar{\sigma}^\mu D_\mu \bar{N} - m_N N \bar{N} - \frac{1}{2} y_N \Phi N N - \frac{1}{2} y_{\bar{N}} \Phi^* \bar{N} \bar{N} + \mathrm{h.c.}$$

$U(1)_{L_\mu - L_\tau}$ Parameter space



Bonus: we can explain muon g-2!

$$a_\mu^{\rm exp} - a_\mu^{\rm SM} = (26.1 \pm 8.0) \times 10^{-10}$$

[Hagiwara, et. al, 2011]

The favored parameters:

$$g' \sim 5 \times 10^{-4}$$

$$m_{Z'} = g' v_\Phi \sim 10 - 100\,{\rm MeV}$$

Neff constraints:

$$m_{Z'} \gtrsim 10\,{\rm MeV} \quad \text{for} \quad g' = 5 \times 10^{-4}$$

Other constraints

- White dwarf: cooling by plasmon decay through off-shell Z' [Dreiner, et. al, 2013]
- Borexino: $\nu - e$ scat. from $^7{\rm Be}$ solar neutrino
- CCFR: neutrino trident $\nu N \to \nu N \mu \bar{\mu}$ [Altmannshofer, et. al, 2014]
- BABAR: $e\bar{e} \to \mu\bar{\mu} Z', Z' \to \mu\bar{\mu}$ [BABAR collaboration, 2016]

DM sector consists of two Majorana fermions

DM mass terms:

$$-\mathscr{L}_{\text{mass}} = m_N N\bar{N} + \frac{1}{2} y_N \Phi N N + \frac{1}{2} y_{\bar{N}} \Phi^* \bar{N}\bar{N} + \text{h.c.}$$

+1/2 -1/2 -1

$\langle \Phi \rangle : \mathrm{U}(1)_{L_\mu - L_\tau} \to Z_2$

$$-\mathscr{L}_{\text{mass}} = \frac{1}{2} M_1 N_1 N_1 + \frac{1}{2} M_2 N_2 N_2 + \text{h.c.} \quad (M_1 < M_2)$$

DM

Two Majorana fermions

DM interaction:

$$\mathscr{L} \supset -\frac{y}{2\sqrt{2}} \varphi \left(-\overline{N}_1 N_1 + \overline{N}_2 N_2 \right) + i g' Q_N Z'_\mu \overline{N}_2 \gamma^\mu N_1 \, .$$

- relic density $y \sim 0.1$
- self-scattering

$g' \simeq 5 \times 10^{-4}$

does not affect DM phenomenology

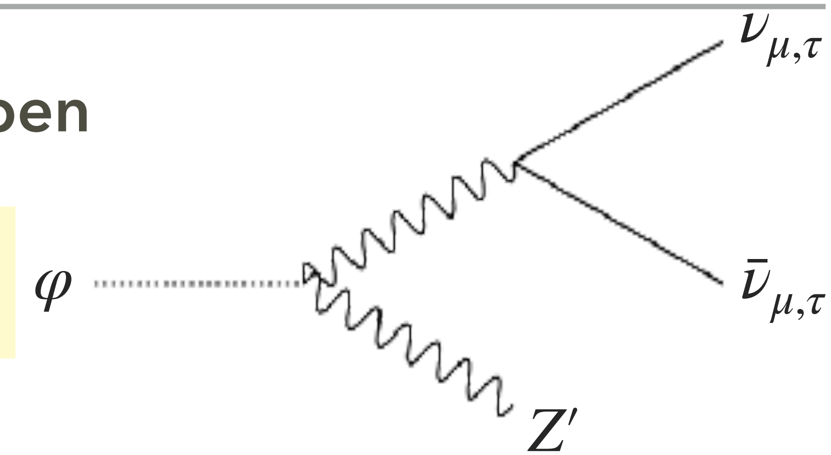
Note: we take $m_N \gg y_N v_\Phi, y_{\bar{N}} v_\Phi$ and $y_N = y_{\bar{N}} \equiv y > 0$

$N_1 = (N - \bar{N})/\sqrt{2} i \quad N_2 = (N + \bar{N})/\sqrt{2} \quad M_2 - M_1 \simeq \sqrt{2} y v_\Phi \quad M_1 \sim m_N$

How to evade constraints?

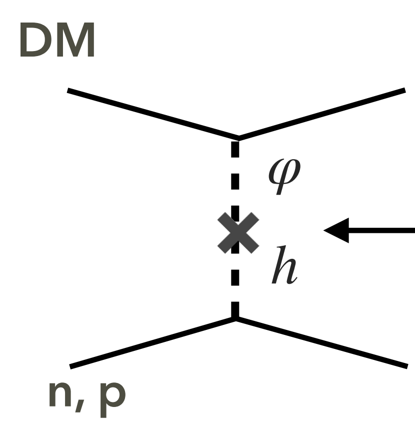
- The lifetime of mediator φ is < 1sec if 3-body decay is open

$$m_\varphi \gtrsim m_{Z'} \gtrsim 10\,\mathrm{MeV}$$



Higgs portal $\lambda_{\Phi H}|H|^2|\Phi|^2$ **is not necessary** for the decay of mediators

No bound from direct detection



very small (if absent at tree, arises at 2-loop)

- Late time annihilation (T << 1 GeV) is **p-wave dominant**

$$N_1 N_1 \to \varphi\varphi\,, Z'Z' \to \nu_{\mu,\tau}\text{'s}$$

We choose $m_\varphi\,, m_{Z'} < m_\mu$, then Z′ and φ decay to neutrinos

Indirect detection constraints are weak

SIDM parameter space

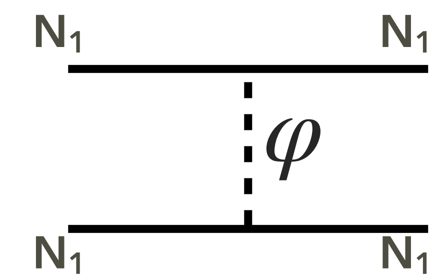
5 model parameters: $m_{Z'}\,,\,g'\,,\,y\,,\,m_\varphi\,,\,M_1$

3 for DM phenomenology

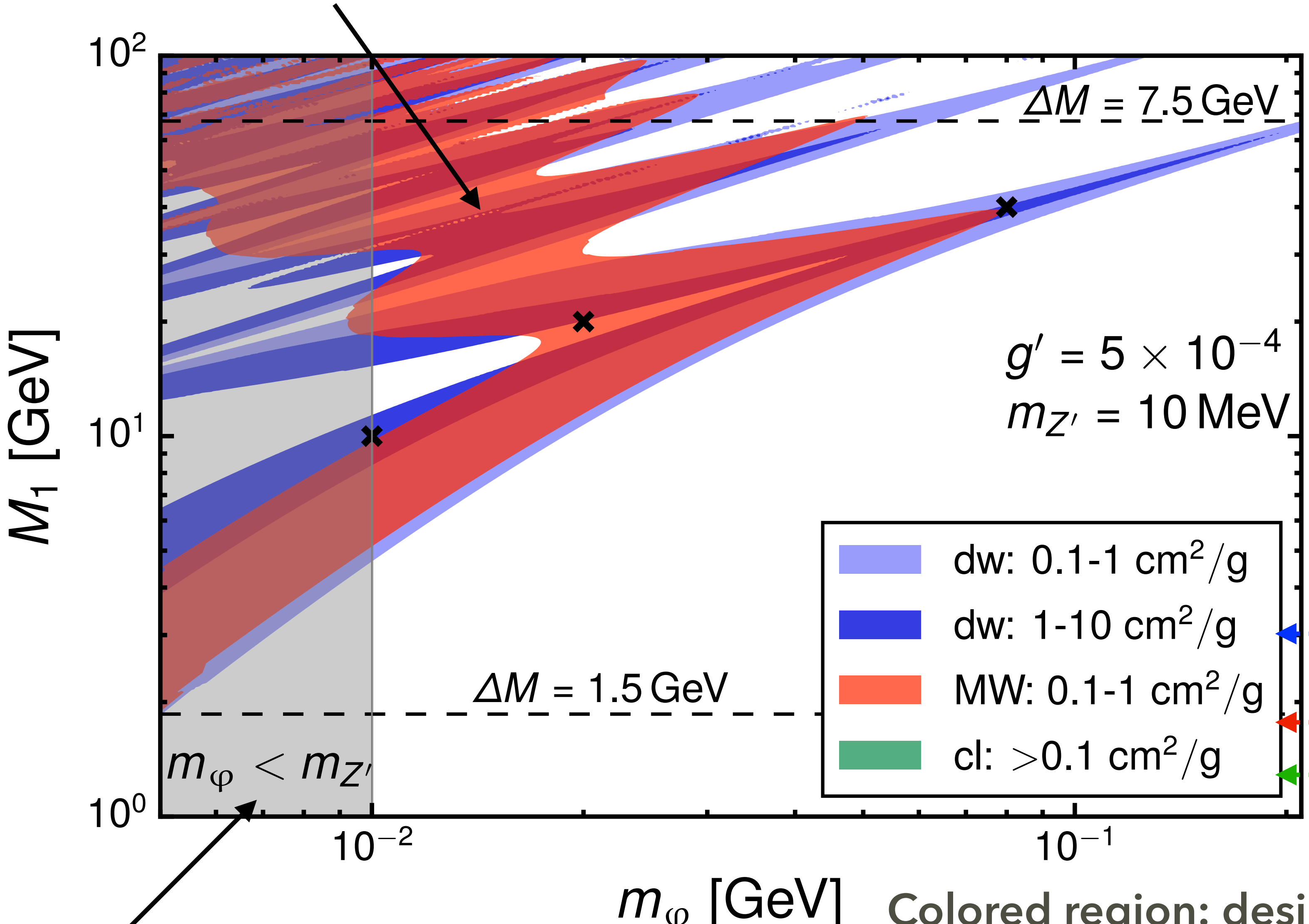
Fixed by muon g-2 ($m_{Z'}$)

determined by DM abundance (g')

Scan ($y\,,\,m_\varphi\,,\,M_1$)



solves small scale issues at dwarfs and MW



φ Lifetime > 1 sec

v_{rel} = 30 km/s

v_{rel} = 200 km/s

v_{rel} = 3000 km/s

$$\mathscr{L} \supset \frac{y}{2\sqrt{2}}\varphi\bar{N}_1 N_1 \;\rightarrow\; V(r) = -\frac{y^2}{4\pi r}e^{-m_\varphi r}$$

Transfer cross section

$$\sigma_T = 4\pi\int_0^1 d\cos\theta\,(1-\cos\theta)\frac{d\sigma}{d\Omega}$$

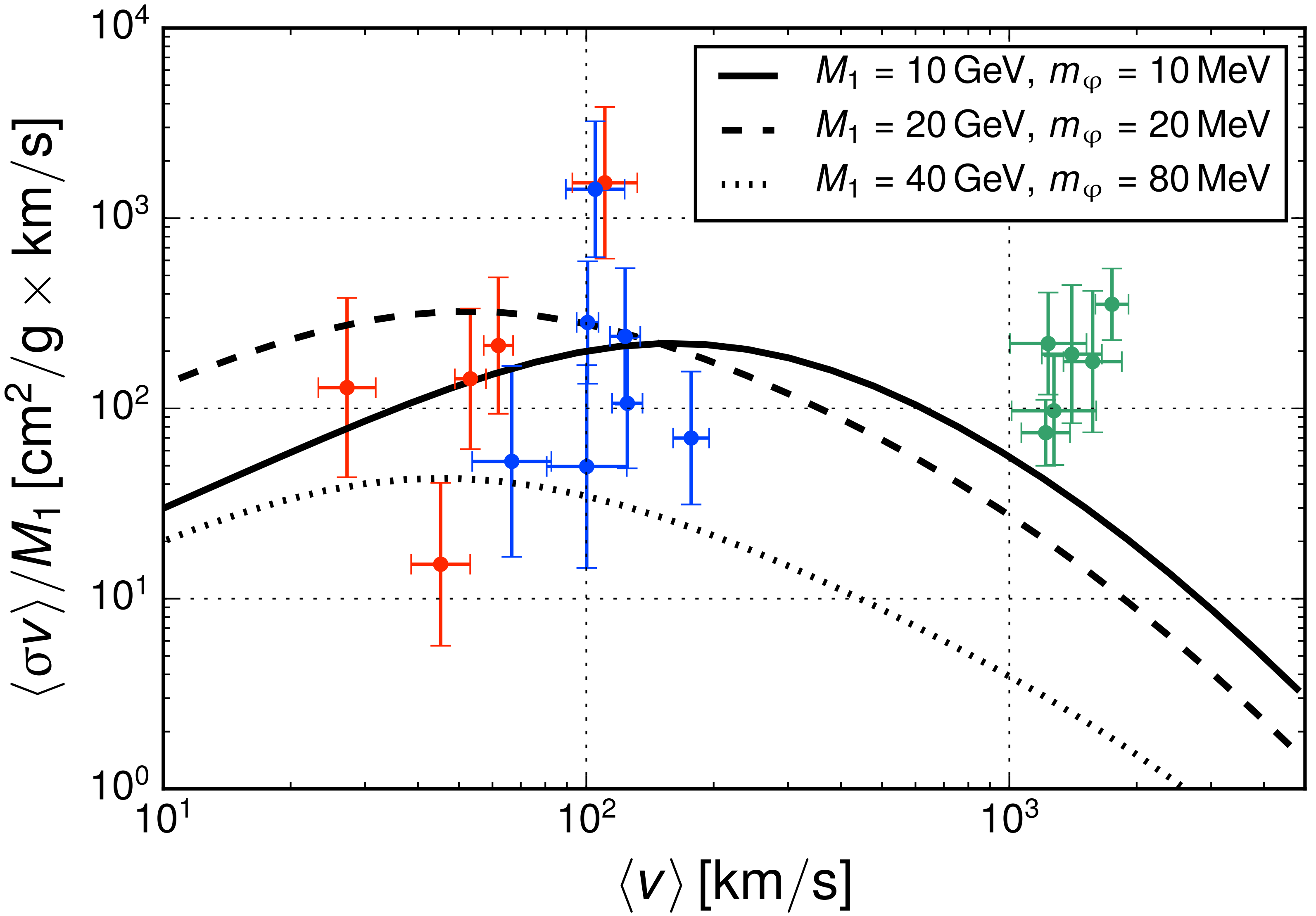
Colored region: desired self-scattering cross section σ_T/M_1

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

Closer look at self-scattering cross section

Velocity averaged cross section for three benchmark points

Maxwell velocity distribution is assumed



Points are inferred self-scattering cross section to explain the small scale anomalies at

- Red: dwarf galaxies
- Blue: low surface brightness galaxies
- Green: galaxy clusters

[Kaplinghat, Tulin, Yu, 2015]

Summary

- Gauged U(1) $L_\mu - L_\tau$ symmetry is very useful to realize velocity-dependent DM self-scattering
- The model evades the tight constraints from direct/indirect searches
- As a bonus, our model can explain the muon g-2 discrepancy
- We also updated the lower bound of $L_\mu - L_\tau$ Z′ mass; $m_{Z'} \gtrsim 10\,\mathrm{MeV}$ for $g' = 5 \times 10^{-4}$

Backup

DM phenomenology

DM sector: we focus on the pseudo-Dirac DM scenario

DM mass terms: $$\mathscr{L} \supset m_N N\bar{N} - \frac{1}{2} y_N \Phi N N - \frac{1}{2} y_{\bar{N}} \Phi^* \bar{N}\bar{N} + \mathrm{h.c.}$$

$$\xrightarrow{\langle\Phi\rangle = \frac{1}{\sqrt{2}} v_\Phi} \begin{pmatrix} y_N \frac{v_\Phi}{\sqrt{2}} & m_N \\ m_N & y_{\bar{N}} \frac{v_\Phi}{\sqrt{2}} \end{pmatrix}$$

Pseudo-Dirac DM $m_N \gg y_N v_\Phi, y_{\bar{N}} v_\Phi$ SIDM and $(g\text{-}2)_\mu$ not simultaneously realized if $m_N \ll y_N v_\Phi, y_{\bar{N}} v_\Phi$

Focus on the case $y_N = y_{\bar{N}} \equiv y > 0$ $\longleftarrow$ $\left(\begin{array}{lll} C_{L_\mu - L_\tau} & : N \leftrightarrow \bar{N} & \Phi \leftrightarrow \Phi^* \\ \text{Parity} & : N \to i\bar{N}^\dagger & \bar{N} \to i N^\dagger \end{array}\right)$

Two nearly degenerate Majorana fermions

DM $N_1 = \dfrac{N - \bar{N}}{\sqrt{2} i}$ $\left(M_1 = m_N - \dfrac{y v_\Phi}{\sqrt{2}} \right)$

$N_2 = \dfrac{N + \bar{N}}{\sqrt{2}}$ $\left(M_2 = m_N + \dfrac{y v_\Phi}{\sqrt{2}} \right)$

DM annihilation

DM (co-)annihilation $$\mathscr{L} \supset -\frac{y}{2\sqrt{2}}\varphi\left(-\overline{N}_1 N_1 + \overline{N}_2 N_2\right) + ig' Q_N Z'_\mu \overline{N}_2 \gamma^\mu N_1 \,.$$

Channel	Cross section $x = M_1/T$
• $N_i N_i \to \varphi\varphi\,, Z'Z'\,(i=1,2)$	$\langle \sigma_{\rm ann} v_{\rm rel} \rangle_{11} = \langle \sigma_{\rm ann} v_{\rm rel} \rangle_{22} \simeq \frac{9y^4}{64\pi m_N^2} x^{-1}$
• $N_1 N_2 \to \varphi Z'$	$\langle \sigma_{\rm ann} v_{\rm rel} \rangle_{12} \simeq \frac{y^4}{64\pi m_N^2} - \frac{9y^4}{256\pi m_N^2} x^{-1}$

$g' \simeq 5 \times 10^{-4}$ neglected

- For a given $m_N \sim 1 - 100\,\mathrm{GeV}$, DM relic density fixes y

  $M_2 - M_1 = \sqrt{2} y v_\Phi \sim 1\,\mathrm{GeV}$, annihilation in the early universe is s-wave dominant

- Late time annihilation (T << 1 GeV) is p-wave dominant

$$N_1 N_1 \to \varphi\varphi\,, Z'Z'$$

our choice: $m_\varphi\,, m_{Z'} < m_\mu$, Z' and φ decays to neutrinos,

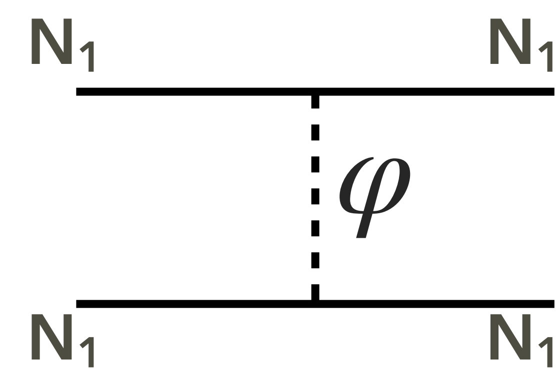
→ Indirect detection constraints are weak

DM self-scattering

Self-scattering through Yukawa potential

We solve the non-relativistic Schrodinger equation

$$\mathscr{L} \supset \frac{y}{2\sqrt{2}}\varphi \overline{N}_1 N_1 \quad \Longrightarrow \quad V(r) = -\frac{y^2}{4\pi r}e^{-m_\varphi r}$$



N_1 is a Majorana fermion (indistinguishable)

The cross section is sum of the spin singlet and triplet

unpolarized

$$\frac{d\sigma}{d\Omega} = \frac{1}{2} \times \left[\frac{1}{4}|f(\theta) + f(\pi - \theta)|^2 + \frac{3}{4}|f(\theta) - f(\pi - \theta)|^2\right]$$

Transfer cross section is used to see the effects on the DM distribution

$$\sigma_T = 4\pi \int_0^1 d\cos\theta\,(1 - \cos\theta)\frac{d\sigma}{d\Omega}$$

regulate forward and backward scattering

Constraints from Z′ energy injection

After neutrino decoupling $T \lesssim 1.5\,\mathrm{MeV}$, three independent thermal bath

$$\begin{array}{ccc} (\gamma, e) & (\nu_e) & (\nu_\mu, \nu_\tau, Z') \\ T & T_\nu & T' \end{array}$$

Z′ affects N_{eff} in two ways:

1. Decay of ~MeV Z′ injects energy into ν_μ, ν_τ
2. Via 1-loop A - Z′ mixing, Z′ ⇄ ee transfers heat between (γ, e) & (ν_μ, ν_τ, Z')

We solve the evolution of entropy

$$\frac{1}{a^3}\frac{d}{dt}[s_\gamma(T)a^3 + 2s_e(T)a^3] = \frac{1}{T}\Gamma_{Z'\to e\bar{e}}\,[\rho_{Z'}(T') - \rho_{Z'}(T)]$$

$$\frac{1}{a^3}\frac{d}{dt}[2s_{\nu_\mu}(T')a^3 + 2s_{\nu_\tau}(T')a^3 + s_{Z'}(T')a^3] = -\frac{1}{T'}\Gamma_{Z'\to e\bar{e}}\,[\rho_{Z'}(T') - \rho_{Z'}(T)]$$

$$\frac{1}{a^3}\frac{d}{dt}[2s_{\nu_e}(T_\nu)a^3] = 0 \qquad \left(dS = \frac{dQ}{T}\right)$$

Effects of φ is very small if $m_\varphi \gtrsim m_{Z'}$