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

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Introduction

Dark Matter Self Interaction

We have no DM signal from direct, indirect and collider searches…

Let's see the hints from astrophysics!

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Small scale issues: astrophysical observations have tensions with CDM paradigm

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

missing satellite

Rotation curve diversity

Too big to fail

Core vs. cusp

related to DM density profile

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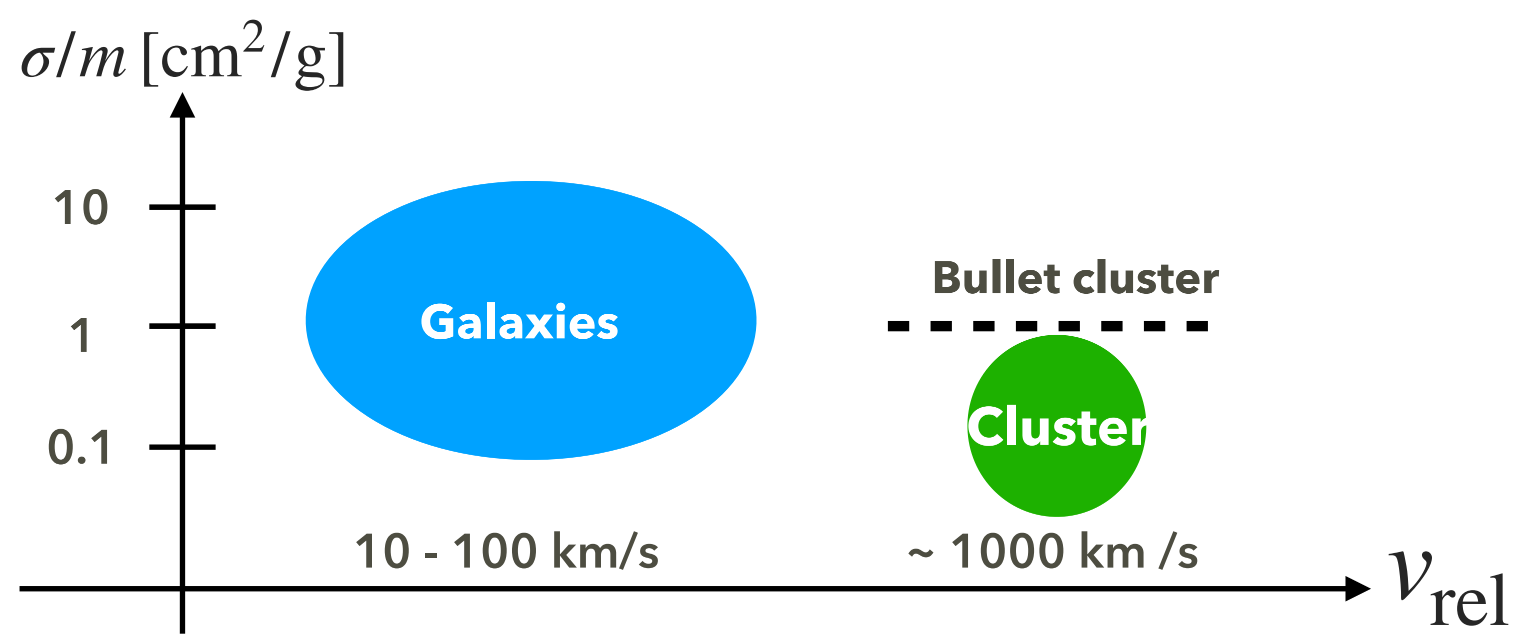
Dark matter self-interaction!

- $\sigma/m \sim 0.1 - 10\,\mathrm{cm}^2/\mathrm{g}$ is favored at **galaxy** and **galaxy cluster** scale
- **Bullet cluster** constraint $\sigma/m \lesssim 1\mathrm{cm}^2/\mathrm{g}$



Implication on particle physics

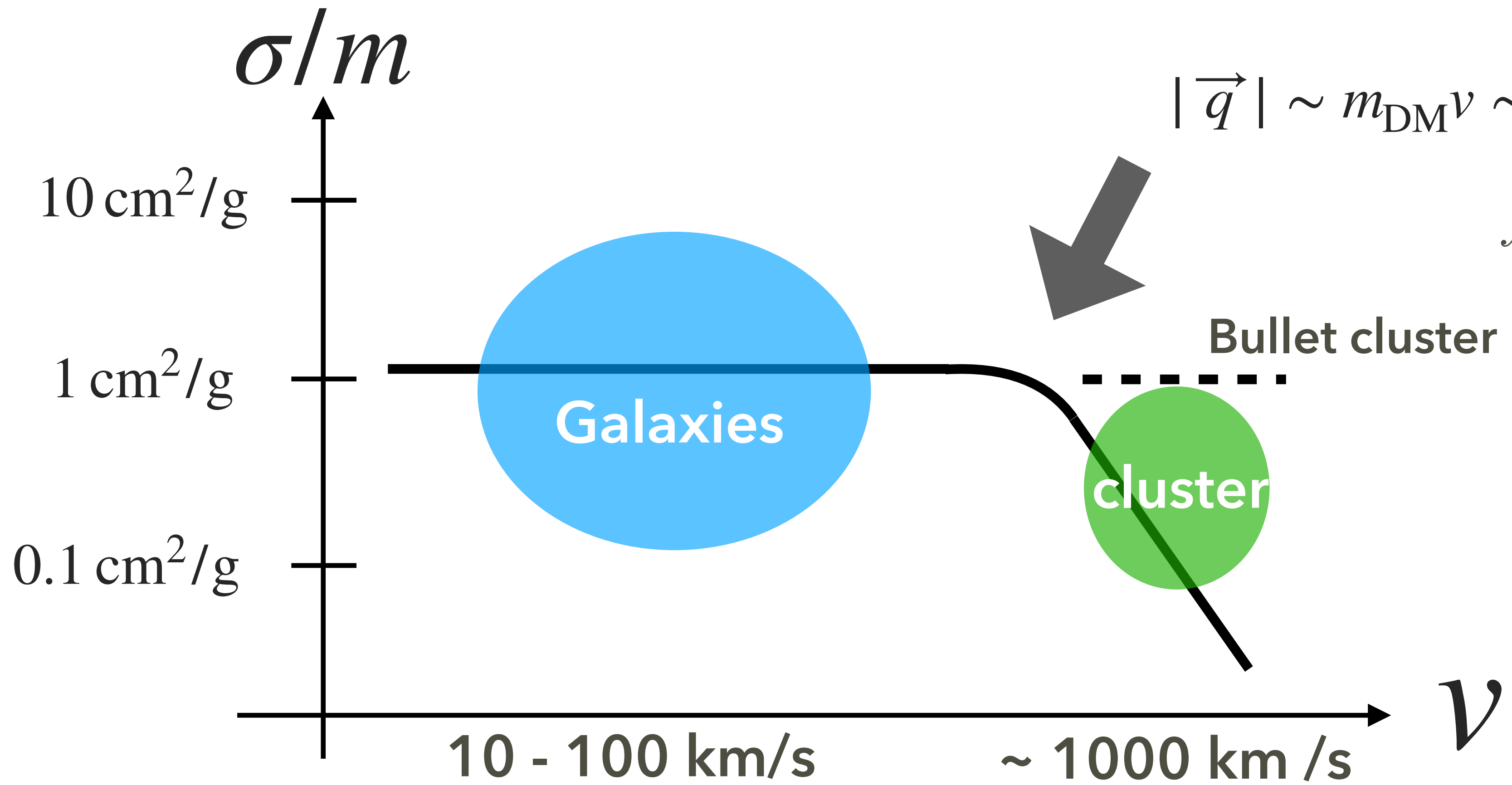
Very strong self-interaction! $\sigma \sim 1\,\mathrm{cm}^2\,(m/\mathrm{g}) \sim 2 \times 10^{-24}\,\mathrm{cm}^2\,(m/\mathrm{GeV})$

nuclear scale!

Velocity-dependent cross section is favored

$|\vec{q}\,| \sim m_{\mathrm{DM}} v \sim m_{\mathrm{mediator}}$

$$\mathscr{M} \sim \frac{1}{q^2 - m_{\mathrm{mediator}}^2}$$



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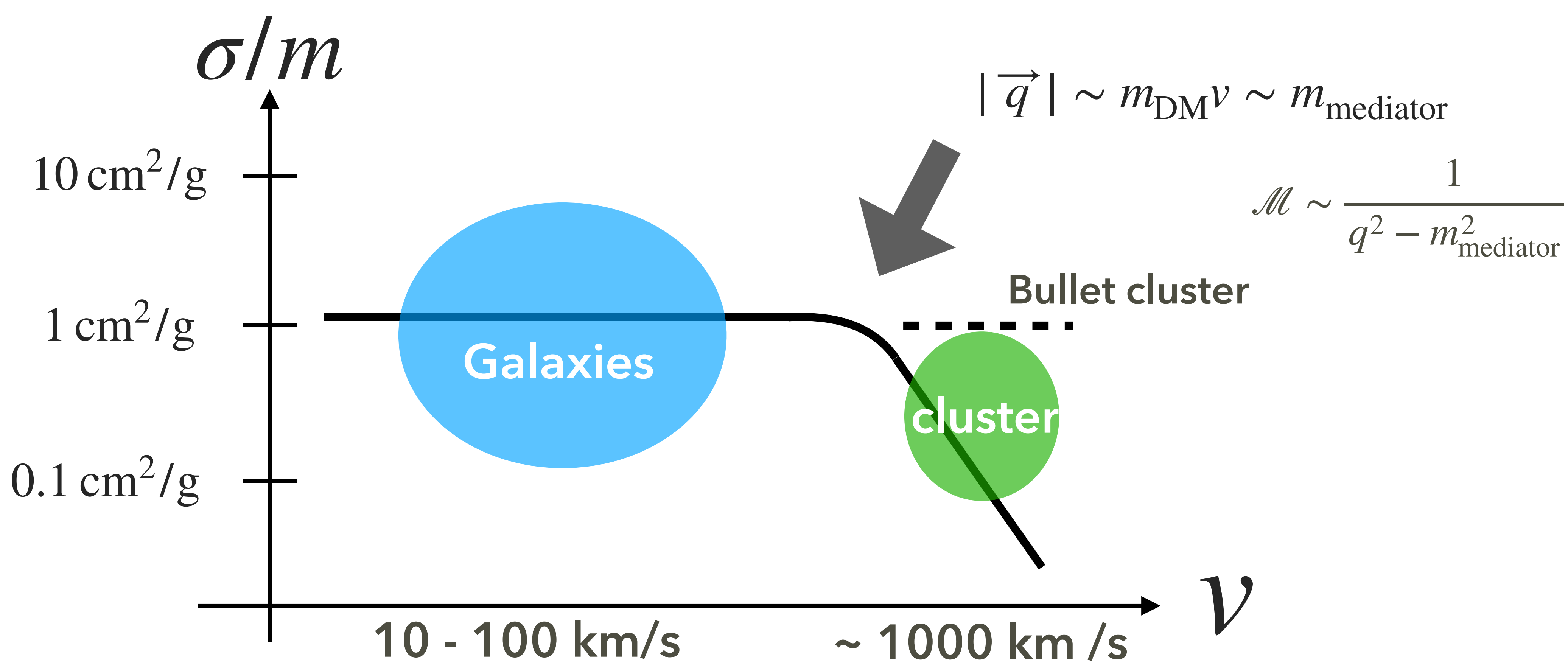


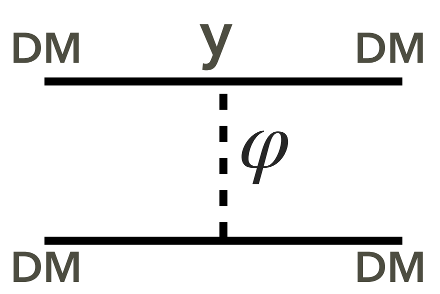
1 - 100 MeV mediator for **1 - 100 GeV DM** realizes such situation [Tulin, Yu, Zurek, 2013]

- Efficient self-scattering at galaxy scale (v ~ 10 - 100 km/s)
- Collisionless at cluster scale (v ~ 3000km/s)

Challenges in model building

A SIDM model is severely constrained by DM direct and indirect bounds

Simplified setup: 4 model parameters: $\underbrace{m_{\mathrm{DM}}, m_{\varphi}, y}_{\textbf{DM phenomenology}}, \varepsilon$



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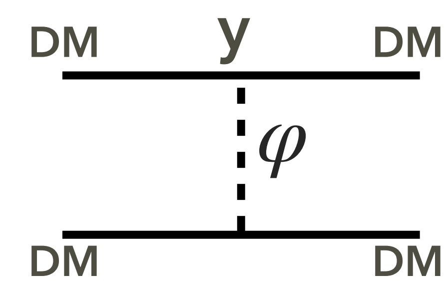
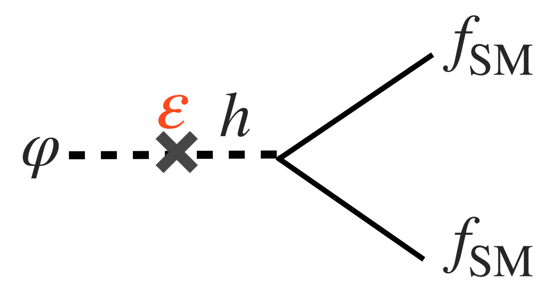


- We need mixing parameter ε
  - to produce DM from the SM plasma
  - **For the mediator decay** (not to dominate the energy density, not to affect the BBN)



- **Higgs portal** (scalar mediator)
- **Kinetic mixing** (vector mediator)

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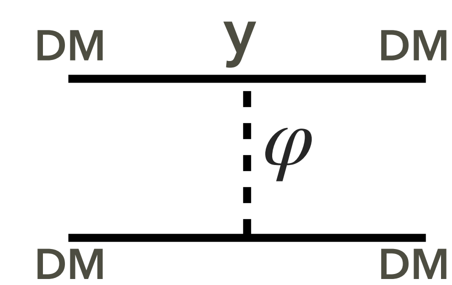

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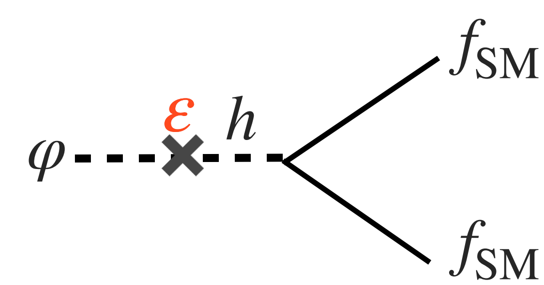
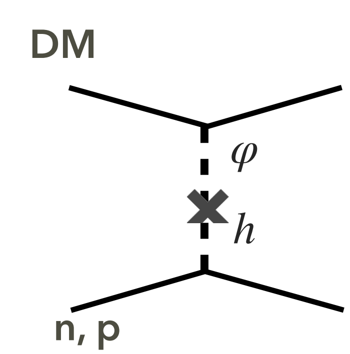


- **Higgs portal** (scalar mediator)
- **Kinetic mixing** (vector mediator)

- To evade the BBN bound, **we need large mixing, which leads to very large direct detection cross section**

➡ **Much of the parameter space is excluded by XENON1T**

[Kaplinghat, Tulin, Yu, 2013]



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A SIDM model is severely constrained by DM direct and indirect bounds

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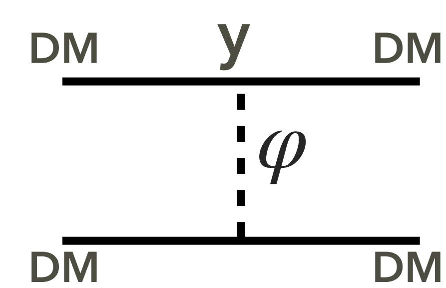
DM phenomenology



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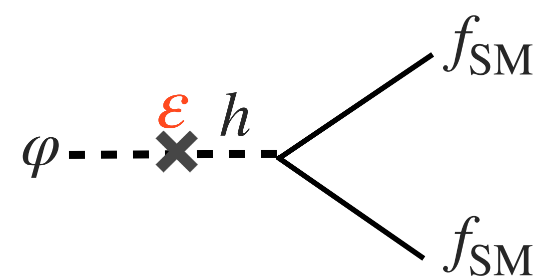

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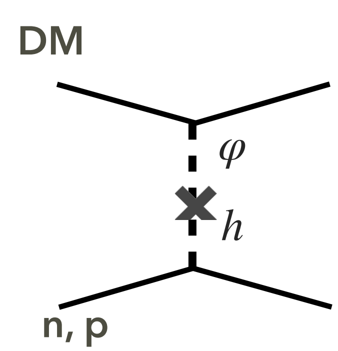


- DM DM -> SM particles are constrained by CMB or indirect search

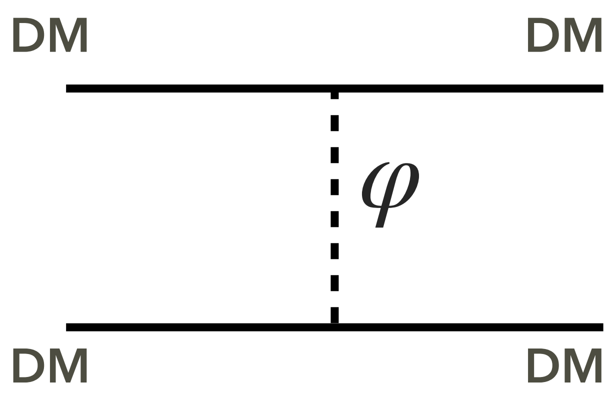
➡ **If DM annihilation is s-wave, most of the parameter space is excluded**

[Bringmann, et.al., 2016]

Our Idea

Gauged U(1) $_{L_\mu - L_\tau}$ solves the difficulty

- Anomaly free extension of the SM
- A new gauge boson Z′ associated with U(1)$_{L_\mu - L_\tau}$
- We add SM singlets $N, \bar{N}, \Phi$



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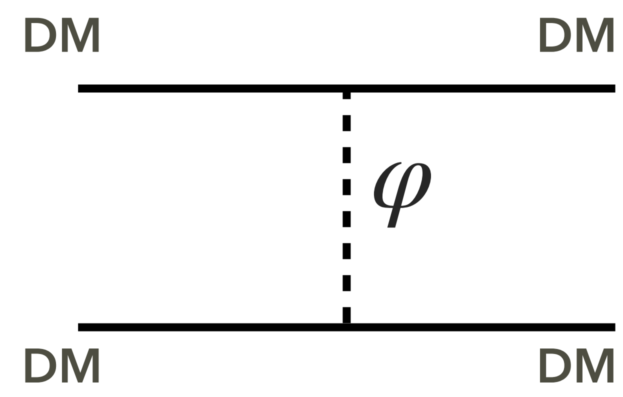

Vector-like fermion

complex scalar

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

DM (stable)

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

SIDM mediator

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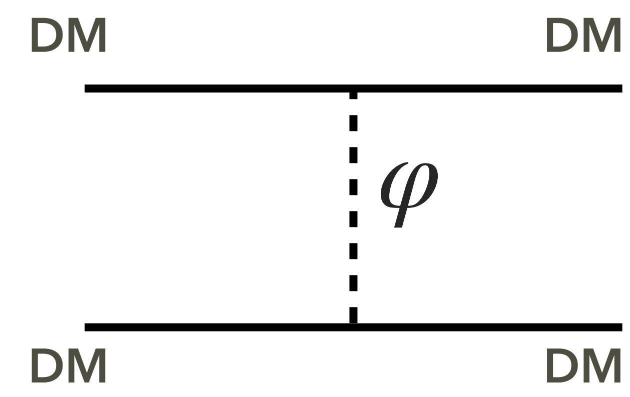

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$\Phi = (v_\Phi + \varphi)/\sqrt{2}$

SIDM mediator

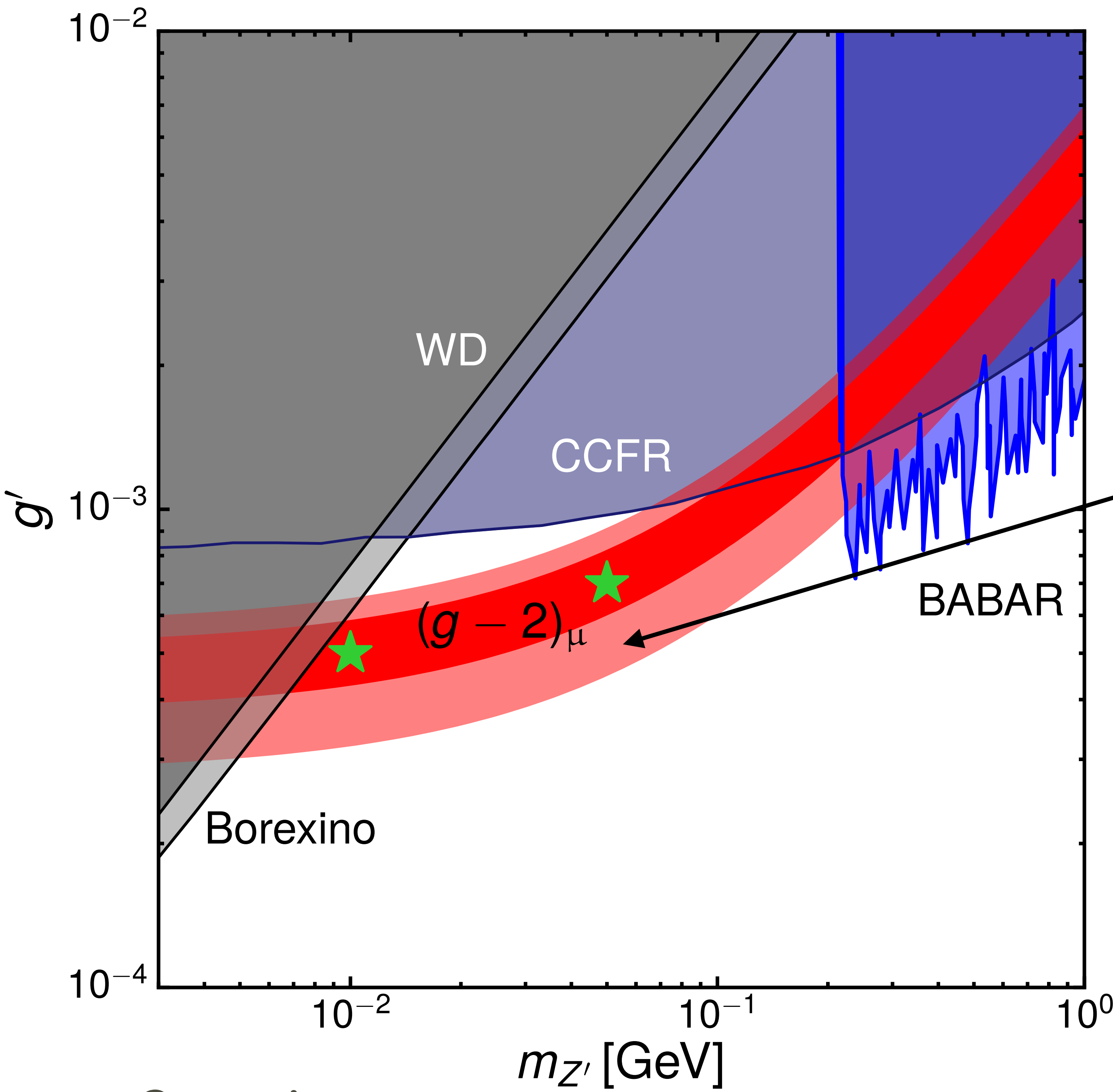
DM (stable)

We choose $m_\varphi, m_{Z'} < m_\mu$

Under this symmetry, **φ and Z′ decay only to neutrinos**, so astrophysical and cosmological constraints are weak

SIDM in a gauged U(1)$_{L_\mu - L_\tau}$ model

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

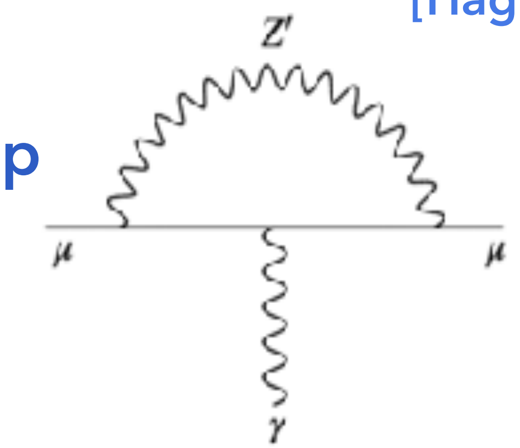


As a bonus, **we can explain muon g-2!**

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

[Hagiwara, et. al, 2011]

Z′ 1 loop



The favored parameters are

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

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

$$\Rightarrow \quad v_\Phi \sim 100\,\mathrm{GeV}$$

Constraints

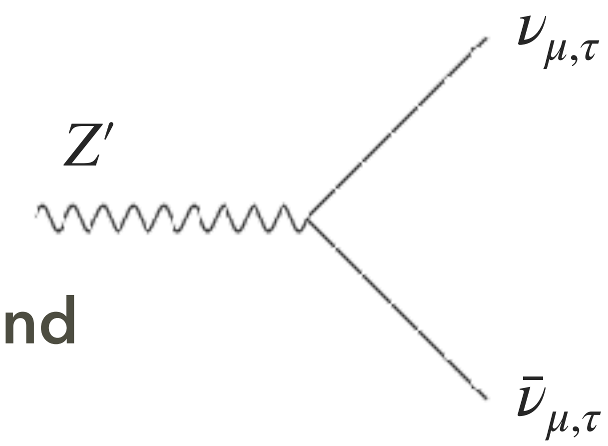
- White dwarf: cooling by plasmon decay through off-shell Z′ [Dreiner, et. al, 2013]
- Borexino: $\nu - e$ scat. from $^7\mathrm{Be}$ solar neutrino
- CCFR: neutrino trident $\nu N \to \nu N \mu \bar{\mu}$ [Altmannshofer, et. al, 2014]
- BABAR: $e\bar{e} \to \mu\bar{\mu} Z'\,, Z' \to \mu\bar{\mu}$ [BABAR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

Fate of Z′ and the mediator φ

- Z′ is in chemical equilibrium with neutrinos

  If $m_{Z'} \sim T_{\rm BBN} \sim 1\,{\rm MeV}$, energy injection increases $N_{\rm eff}$

  Evaluating entropy evolution, for Planck bound $N_{\rm eff} < 3.5$, we found



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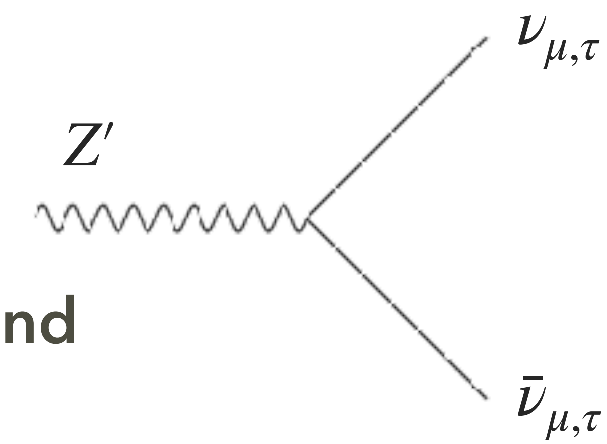

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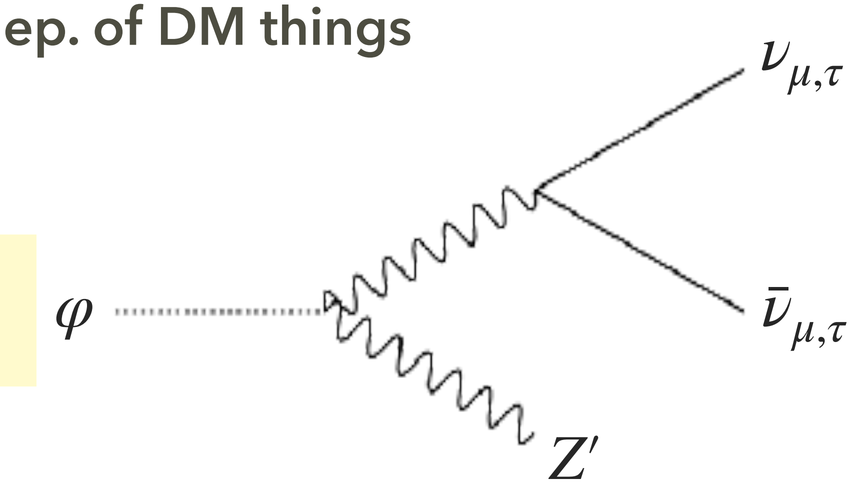
$$m_\varphi \gtrsim m_{Z'} \gtrsim 10\,{\rm MeV}$$



Fate of Z′ and the mediator φ

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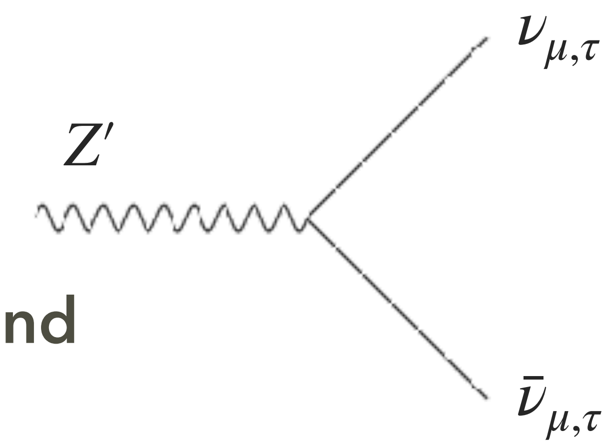

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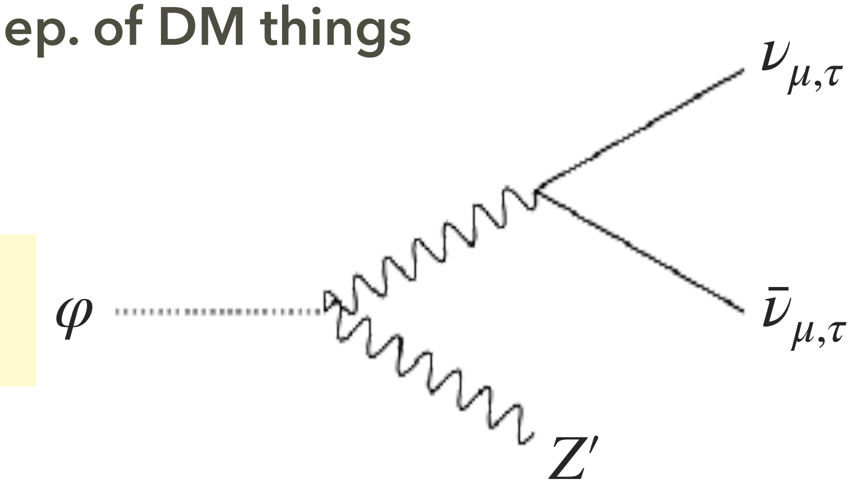
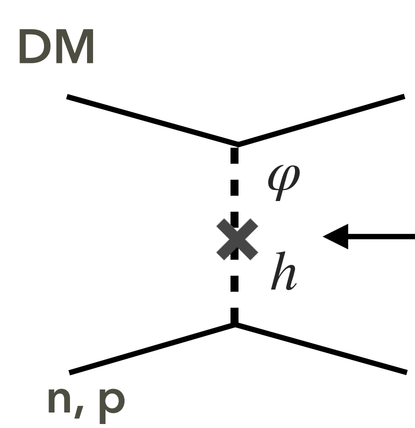


Higgs portal $\lambda_{\Phi H}|H|^2|\Phi|^2$ is not necessary for the decay of mediators

No bound from direct detection



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

DM phenomenology

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

+1/2 -1/2 -1

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

→ **Two Majorana fermions** N_1 N_2 $(M_1 < M_2)$

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- DM interaction (we take $m_N \gg y_N v_\Phi, y_{\bar{N}} v_\Phi$ and $y_N = y_{\bar{N}} \equiv y > 0$)

$N_1 = (N - \bar{N})/\sqrt{2}i$

$N_2 = (N + \bar{N})/\sqrt{2}$

$M_1 \sim m_N$

$M_2 - M_1 \simeq \sqrt{2} y v_\Phi$

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

relic density $y \sim 0.1$

self-scattering

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

does not affect DM phenomenology

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relic density $y \sim 0.1$

self-scattering

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does not affect DM phenomenology

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

$$N_1 N_1 \to \varphi\varphi\,, Z'Z' \qquad \left\langle \sigma_{\mathrm{ann}} v_{\mathrm{rel}} \right\rangle_{11} \simeq \frac{9y^4}{64\pi m_N^2}\frac{T}{M_1}$$

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

→ **Indirect detection constraints are weak**

SIDM parameter space

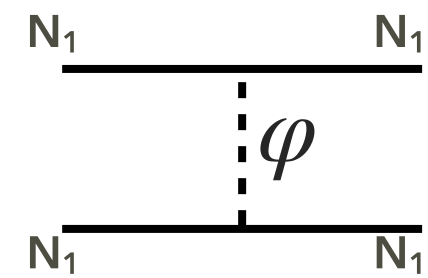
5 model parameters: $m_{Z'}, g', y, m_\varphi, M_1$

3 for DM phenomenology

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

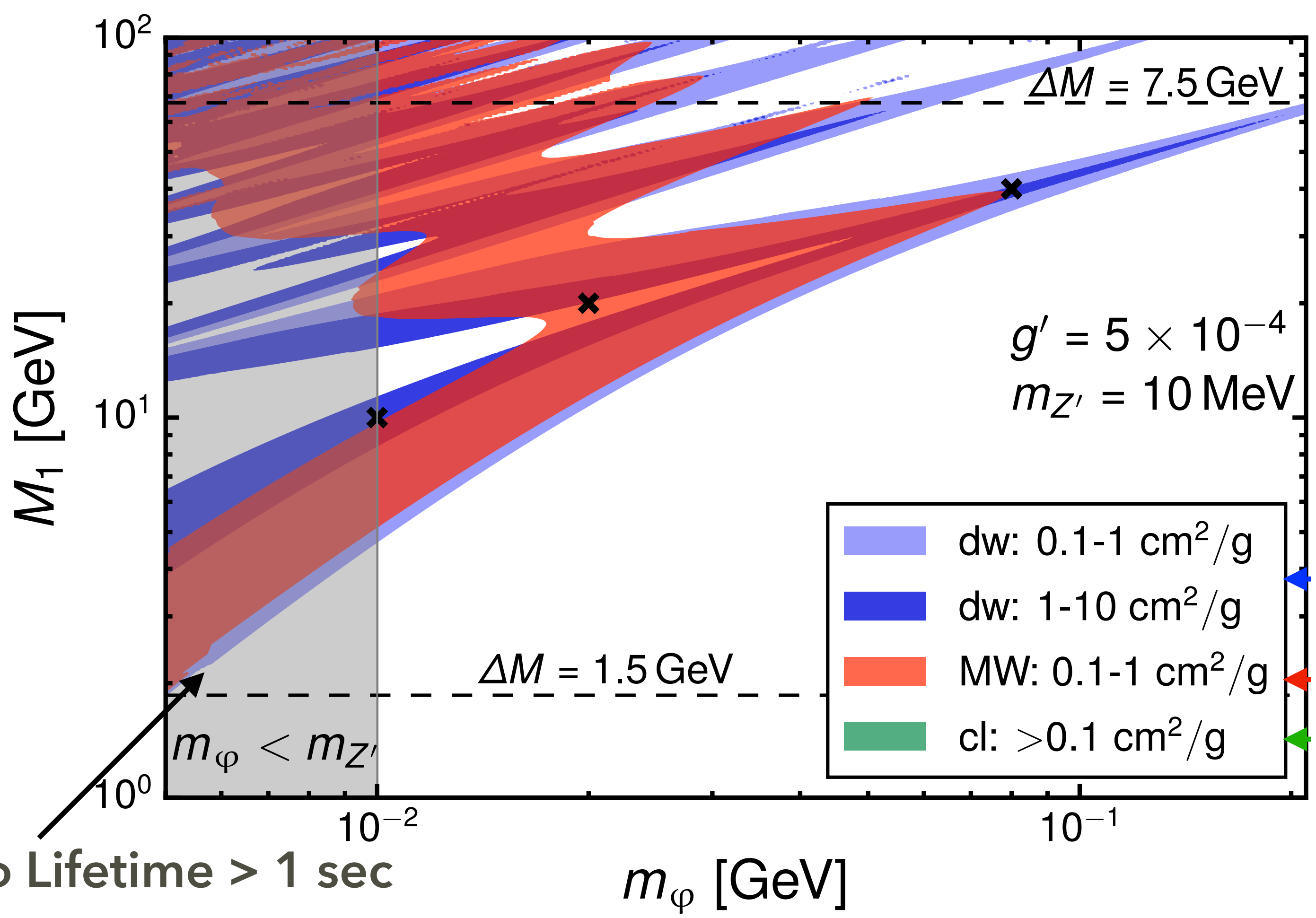
determined by DM abundance (y)

Scan (m_φ, M_1)



- Our model can solve the small scale issues in dwarf and MW galaxies
- Bullet cluster constraint is safely evaded; $\sigma_T/M_1 < 0.1\,\mathrm{cm}^2/\mathrm{g}$ in the whole region

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



φ Lifetime > 1 sec

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

Transfer cross section

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

v_{rel} = 30 km/s

v_{rel} = 200 km/s

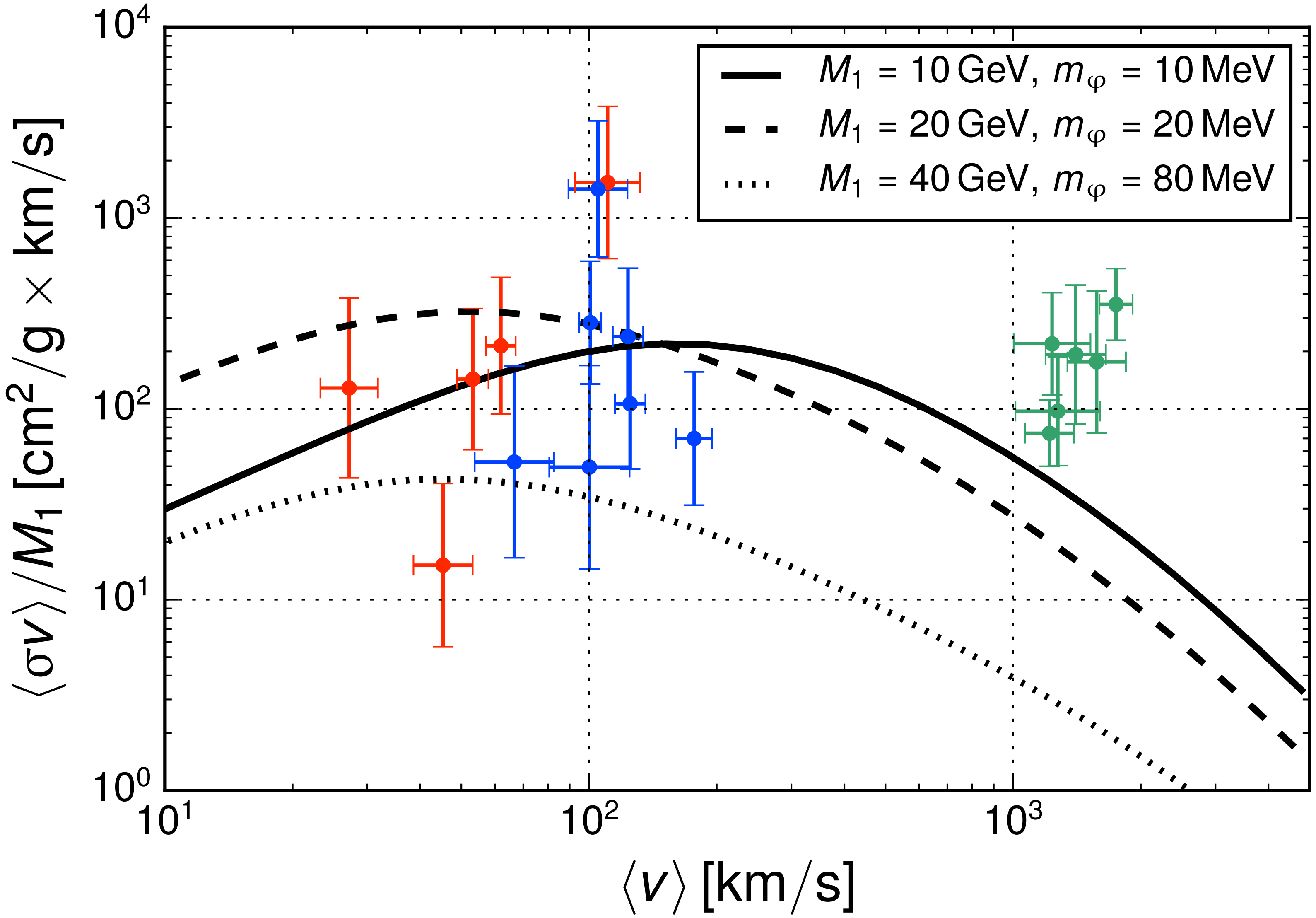
v_{rel} = 3000 km/s

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

- We have found a gauged U(1)$_{L_\mu - L_\tau}$ symmetry resolves the difficulties of SIDM model building
- The new gauge boson Z′ solves the muon g-2 problem
- The U(1)$_{L_\mu - L_\tau}$ Higgs φ mediates DM self-interaction with a velocity-dependent manner
- The model can resolve the small scale issues of galaxy scale, while consistent with the bullet cluster constraint
- We also updated the lower bound of 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: $$\mathscr{L} \supset m_N N\bar{N} - \frac{1}{2}y_N \Phi NN - \frac{1}{2}y_{\bar{N}}\Phi^* \bar{N}\bar{N} + \mathrm{h.c.}$$

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

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

Focus on the case $y_N = y_{\bar{N}} \equiv y > 0$ $\longleftarrow$ $\begin{pmatrix} C_{L_\mu - L_\tau} : N \leftrightarrow \bar{N} & \Phi \leftrightarrow \Phi^* \\ \text{Parity} : N \rightarrow i\bar{N}^\dagger & \bar{N} \rightarrow iN^\dagger \end{pmatrix}$

Two nearly degenerate Majorana fermions

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

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

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

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

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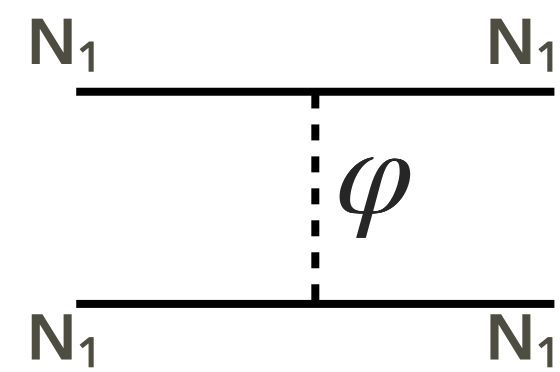
DM self-scattering

Self-scattering through Yukawa potential

We solve the non-relativistic Schrodinger equation

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



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 $m_\varphi \gtrsim m_{Z'}$