Muonphilic Dark Matter explanation of gamma-ray galactic center excess

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09/05/2023

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1. Motivation
2. The simplified muonphilic DM models
3. The global fitting with GCE, DM relic density, DM direct detection and muon g-2 excess
4. Conclusion

Content

1. **Motivation**
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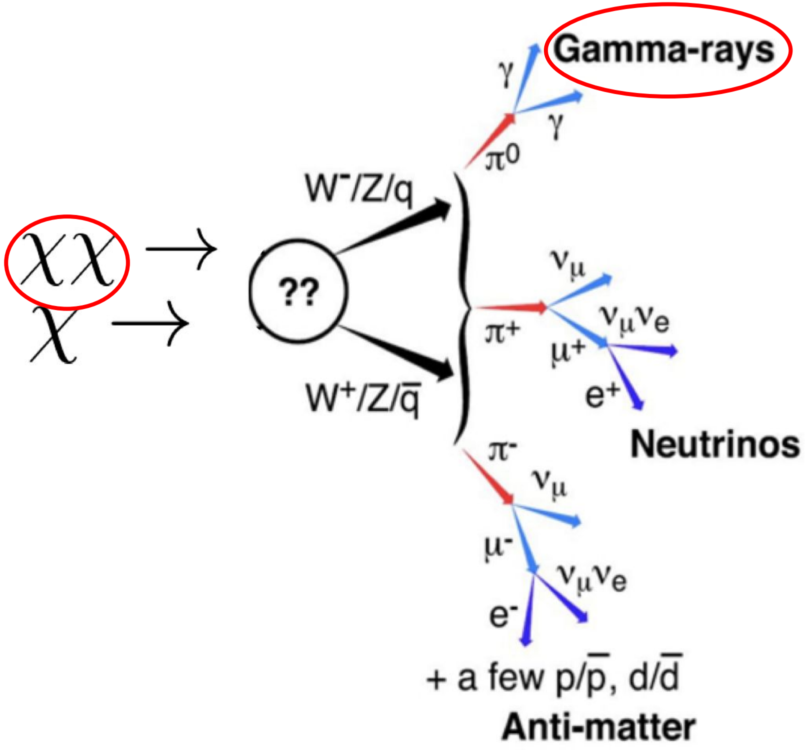
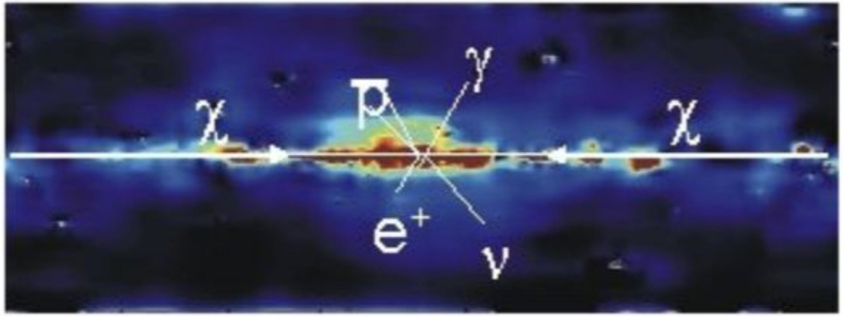
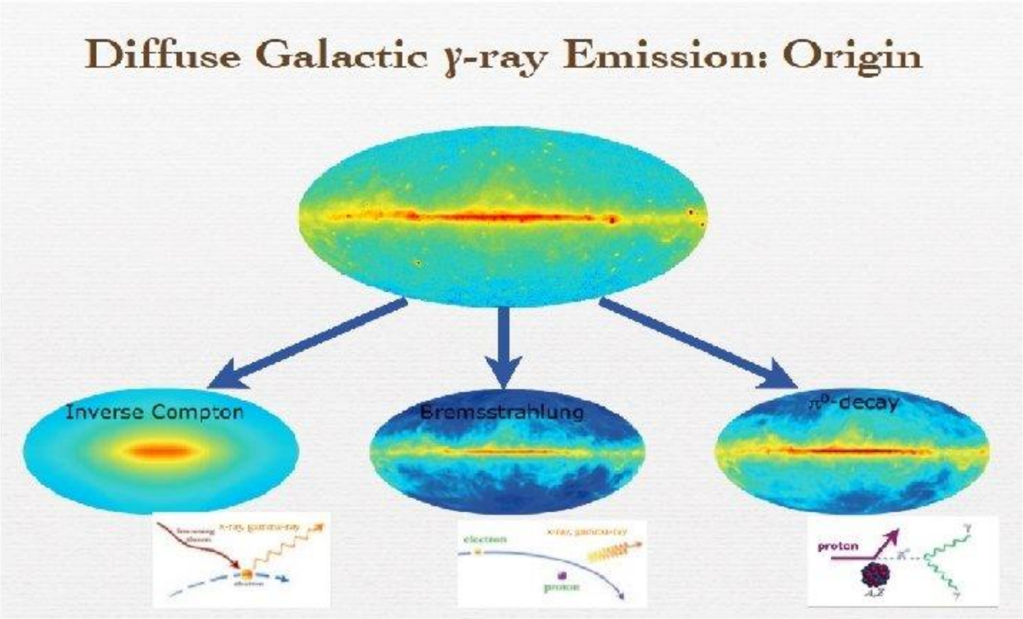
Dark matter indirect detection





Pamela ,ATIC, Fermi,
HESS, AMS02, DAMPE
and so on

Fermi LAT gamma-rays can provide good test of the DM models



Other explanations :

(1) From some undetected point sources (pulsars) in the inner Galaxy

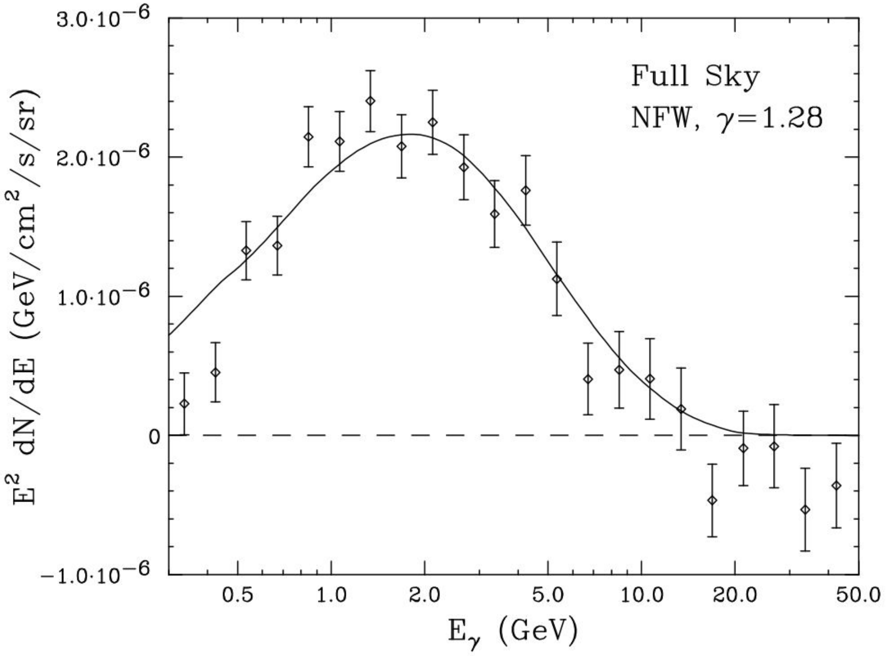
(2) The stellar origin in the Galactic bulge

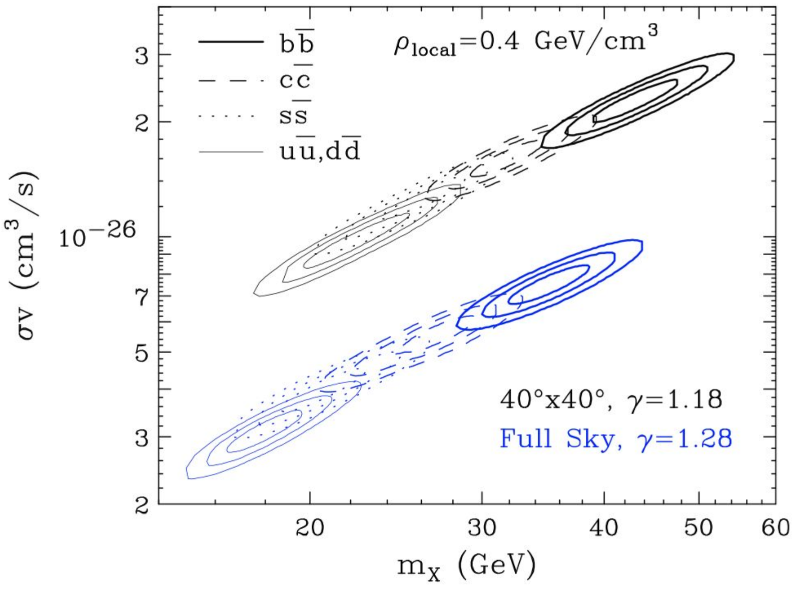
Leane 2019/2020,
Macias 2018/2019,
Bartels 2018

The GeV excess

Phys.Dark Univ. 12 (2016) 1-23 e-Print: 1402.6703 [astro-ph.HE]

Tansu Daylan, Douglas P. Finkbeiner, Dan Hooper, Tim Linden, Stephen K. N. Portillo, Nicholas L. Rodd, Tracy R. Slatyer



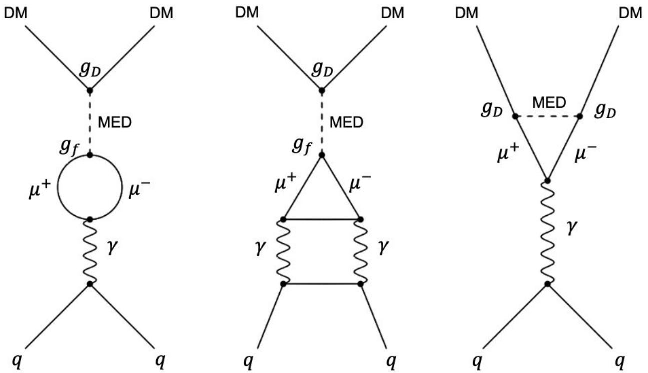


a 36.6 GeV dark matter particle annihilating to $b\bar{b}$

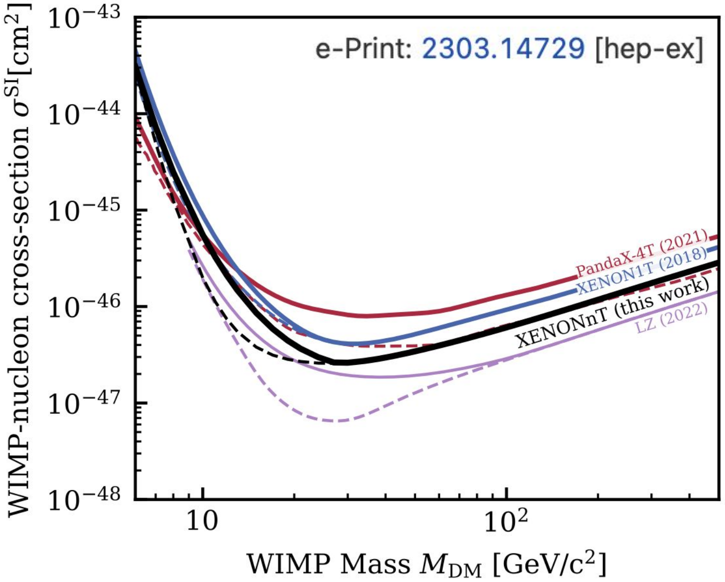
with a cross section of $\sigma v = 0.75 \times 10^{-26}\ \mathrm{cm}^3/\mathrm{s}\ \times [(0.4\,\mathrm{GeV}/\mathrm{cm}^3)/\rho_{\mathrm{local}}]^2$.

Why do we consider the muonphilic DM to explain GCE excess ?

- If DM would only couple to muon, it naturally generates a loop-suppressed DM-nucleon scattering cross section.

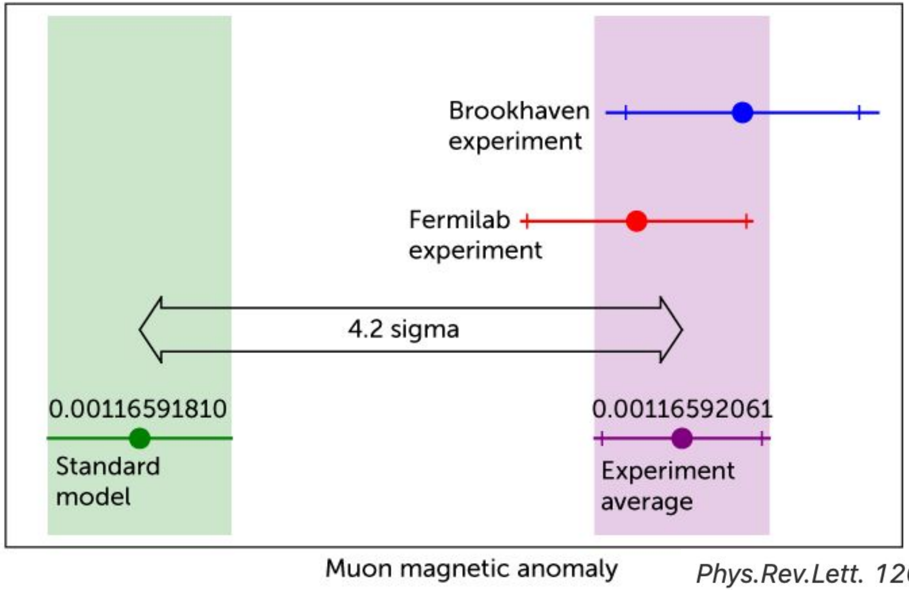


Z₂ even 1 loop diagram   Z₂ even 2 loop diagram   Z₂ odd 1 loop diagram



Why do we consider the muonphilic DM to explain GCE excess ?

- The excess of the muon g − 2 measurement by the FermiLab E989 experiment.



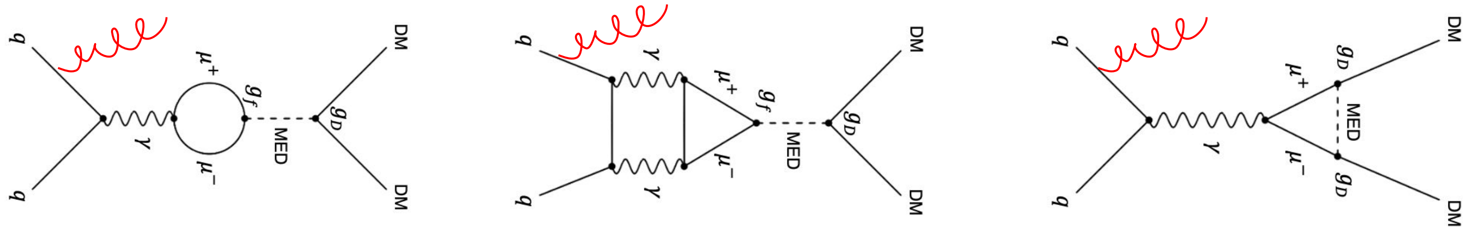
Phys.Rev.Lett. 126 (2021) 14, 141801

Why do we consider the muonphilic DM to explain GCE excess ?

- The relic density measurement with the thermal DM paradigm can further narrow down the parameter space.

$$\langle \sigma v \rangle \simeq a + b v_{\text{rel.}}^2$$

- The muonphilic DM models with Z2-even mediators can easily escape the mono-photon and mono-jet constraints from LEP and LHC such that the electroweak scale DM is still allowed.

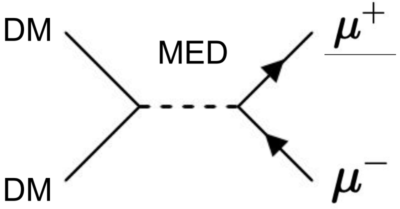


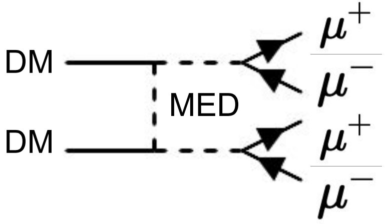
The muonphilic DM explanation to the GCE

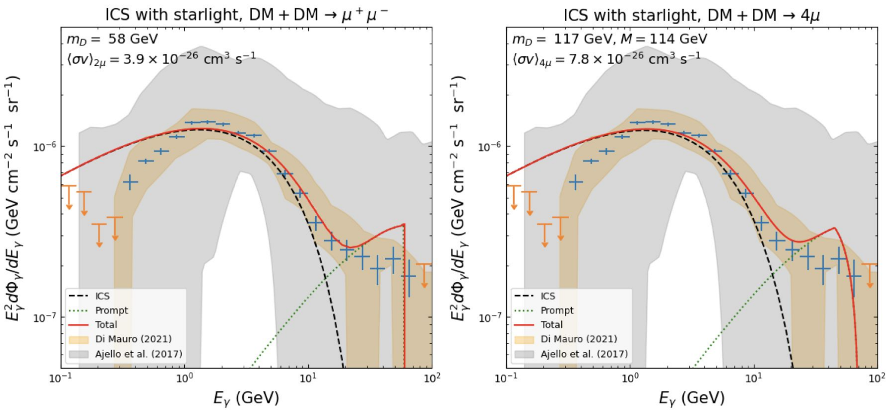
1. The favoured annihilation cross sections (μ+μ− final state) and DM masses are

$$\langle \sigma v \rangle_{2\mu} = 3.9^{+0.5}_{-0.6} \times 10^{-26}\ \mathrm{cm}^3 s^{-1}, \quad \text{and } m_D = 58^{+11}_{-9}\,\mathrm{GeV}.$$

2. If requiring the same ICS gamma ray fluxes to explain GCE, a twice higher annihilation cross section is needed for 4μ final state. Therefore, it will be difficult to explain the <u>GCE</u> and <u>relic density</u> measurement simultaneously in the sceanrio of DM + DM → MED + MED.





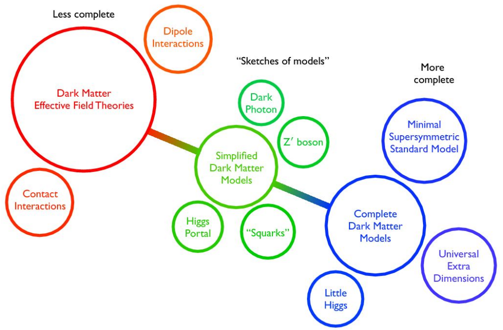


Motivation of this work

Based on the above reasons, the muonphilic DM is a nice choice to explain the GCE and satisfy other relevant constraints.

The next question is what kind of interactions can explain GCE and also satisfy the relic density, DM direct detection, collider constraints and (maybe) muon g-2 excess.

We start from the simplified muonphilic DM models and do a comprehensive study.



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The simplified muonphilic DM models

We restrict ourselves to only concern SM singlet DM and MED with

spin-0 (real/complex), ½ (Majorana/Dirac), 1(real/complex) DM candidates

(1) Z2 even meidator : spin-0(real), 1(real)

(2) Z2 odd mediator : spin-0 (complex), ½ (Dirac), 1(complex)

	Scalar	Fermion	Vector
Dark Matter	S	χ	X^μ
Mediator	ϕ	ψ	V^μ

The simplified muonphilic DM models

s-channel

Z_2 even mediator

types	Lagrangian	$\langle \sigma v \rangle_{2\mu} \simeq a + bv^2$	$\langle \sigma v \rangle_{4\mu} \simeq a + bv^2$
χ and ϕ	$\mathcal{L}_1 = (g_D \bar{\chi}\chi + g_f \bar{f} f)\phi$	$a = 0$	$a = 0$
	$\mathcal{L}_2 = (g_D \bar{\chi}\chi + g_f \bar{f} i\gamma^5 f)\phi$	$a = 0$	$a = 0$
	$\mathcal{L}_3 = (g_D \bar{\chi} i\gamma^5 \chi + g_f \bar{f} f)\phi$	**Case (i)**	$a = 0$
	$\mathcal{L}_4 = (g_D \bar{\chi} i\gamma^5 \chi + g_f \bar{f} i\gamma^5 f)\phi$	**Case (i)**	$a = 0$
χ and V_μ	$\mathcal{L}_5 = (g_D \bar{\chi}\gamma^\mu\gamma^5 \chi + g_f \bar{f}\gamma^\mu f)V_\mu$	$a = 0$	**Case (A)**
	$\mathcal{L}_6 = (g_D \bar{\chi}\gamma^\mu\gamma^5 \chi + g_f \bar{f}\gamma^\mu\gamma^5 f)V_\mu$	**Case (ii)**	**Case (A)**
	$\mathcal{L}_7 = (g_D \bar{\chi}\gamma^\mu \chi + g_f \bar{f}\gamma^\mu f)V_\mu$	**Case (i)**	**Case (C)**
	$\mathcal{L}_8 = (g_D \bar{\chi}\gamma^\mu \chi + g_f \bar{f}\gamma^\mu\gamma^5 f)V_\mu$	**Case (i)**	**Case (C)**
S and ϕ	$\mathcal{L}_9 = (M_{D\phi} S^\dagger S + g_f \bar{f} f)\phi$	**Case (i)**	**Case (B)**
	$\mathcal{L}_{10} = (M_{D\phi} S^\dagger S + g_f \bar{f} i\gamma^5 f)\phi$	**Case (i)**	**Case (B)**
	$\mathcal{L}_{9'} = (g_D S^\dagger S\phi + g_f \bar{f} f)\phi$	—	$b = 0$
	$\mathcal{L}_{10'} = (g_D S^\dagger S\phi + g_f \bar{f} i\gamma^5 f)\phi$	—	$b = 0$

S and V_μ	$\mathcal{L}_{11} = (ig_D S^\dagger \overleftrightarrow{\partial}_\mu S + g_D^2 S^\dagger S V_\mu + g_f \bar{f}\gamma_\mu f)V^\mu$	$a = 0$	**Case (C)**
	$\mathcal{L}_{12} = (ig_D S^\dagger \overleftrightarrow{\partial}_\mu S + g_D^2 S^\dagger S V_\mu + g_f \bar{f}\gamma_\mu\gamma^5 f)V^\mu$	$a = 0$	**Case (C)**
X_μ and ϕ	$\mathcal{L}_{13} = (M_{D\phi} X^\mu X_\mu^\dagger + g_f \bar{f} f)\phi$	**Case (i)**	**Case (D)**
	$\mathcal{L}_{14} = (M_{D\phi} X^\mu X_\mu^\dagger + g_f \bar{f} i\gamma^5 f)\phi$	**Case (i)**	**Case (D)**
	$\mathcal{L}_{13'} = (g_D X^\mu X_\mu^\dagger \phi + g_f \bar{f} f)\phi$	—	$b = 0$
	$\mathcal{L}_{14'} = (g_D X^\mu X_\mu^\dagger \phi + g_f \bar{f} i\gamma^5 f)\phi$	—	$b = 0$
X_μ and V_μ	$\mathcal{L}_{15} = ig_D\{X^{\mu\nu} X_\mu^\dagger V_\nu - X^{\mu\nu\dagger} X_\mu V_\nu + X_\mu X_\nu^\dagger V^{\mu\nu}\}$ $+ g_D^2\{X_\mu^\dagger X^\mu V_\nu V^\nu - X_\mu^\dagger V^\mu X_\nu V^\nu\} + g_f \bar{f}\gamma^\mu f V_\mu$	$a = 0$	**Case (C)**
	$\mathcal{L}_{16} = ig_D\{X^{\mu\nu} X_\mu^\dagger V_\nu - X^{\mu\nu\dagger} X_\mu V_\nu + X_\mu X_\nu^\dagger V^{\mu\nu}\}$ $+ g_D^2\{X_\mu^\dagger X^\mu V_\nu V^\nu - X_\mu^\dagger V^\mu X_\nu V^\nu\} + g_f \bar{f}\gamma^\mu\gamma^5 f V_\mu$	$a = 0$	**Case (C)**

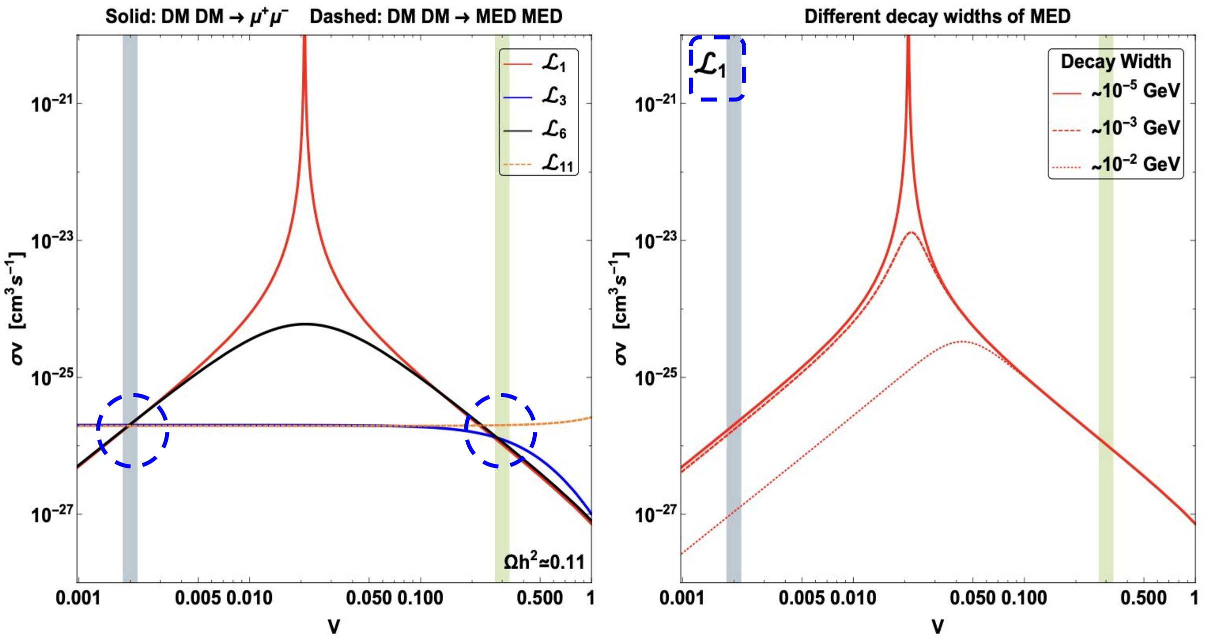
The simplified muonphilic DM models

First, for 2μ final state, we can simplify the analytical expressions of σv [39] near resonance as

$$\sigma v \propto \frac{C_0}{(4R - R^2)^2} \left(\mathcal{C}_1 - \frac{\mathcal{C}_2}{4R - R^2} v^2 \right) , \tag{12}$$

where C_0 (in GeV^{-2}) and $\mathcal{C}_{1,2}$ are positive coefficients. The resonance parameter R is defined as $R \equiv (2m_D - M)/m_D$. The conditions $\mathcal{C}_2 v^2 \leq \mathcal{C}_1(4R - R^2)$ is to be kinematics allowed and $R \leq 2$ is for a physical mass M.

The simplified muonphilic DM models



$\mathcal{L}_{1,3,6}$ are $m_D/\,\mathrm{GeV} = (72.99, 73.11, 73.02)$, $M/\,\mathrm{GeV} = (146.0, 143.5, 146.0)$, $g_D g_f \times 10^3 = (3.319, 2.494, 3.030)$

For $\mathcal{L}_{11}$, $(m_D, M, g_D) = (68.64\ \mathrm{GeV}, 5.85\ \mathrm{GeV}, 8.53 \times 10^{-3})$.

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The likelihoods

$$\chi^2_{\rm tot} = \chi^2_{\rm GCE} + \chi^2_{\Omega h^2} + \chi^2_{\rm DD}.$$

1. Fermi GCE:

$$\chi^2_{\rm GCE} = \sum_{i=1}^{19} \left(\frac{dN}{dE_i} - \frac{dN_0}{dE_i} \right)^2 / 19\sigma_i^2,$$

2. PLANCK Relic density:

$$\Omega h^2 = 0.1186 \pm 0.002.$$

$$\chi^2_{\Omega h^2} = \left(\frac{\mu_t - \mu_0}{\sqrt{\sigma^2_{\rm theo} + \sigma^2_{\rm exp}}} \right)^2,$$

$$\sigma_{\rm theo} = \tau \mu_t.$$

$$\tau = 10\%$$

3. PandaX-4T:

$$\chi^2_{\rm DD} = \left(\frac{\sigma^{\rm SI}_{\chi p}}{\sigma^{\rm SI,90\%}_{\chi p}/1.64} \right)^2,$$ 1.64 is the unit of 90% confidence level.

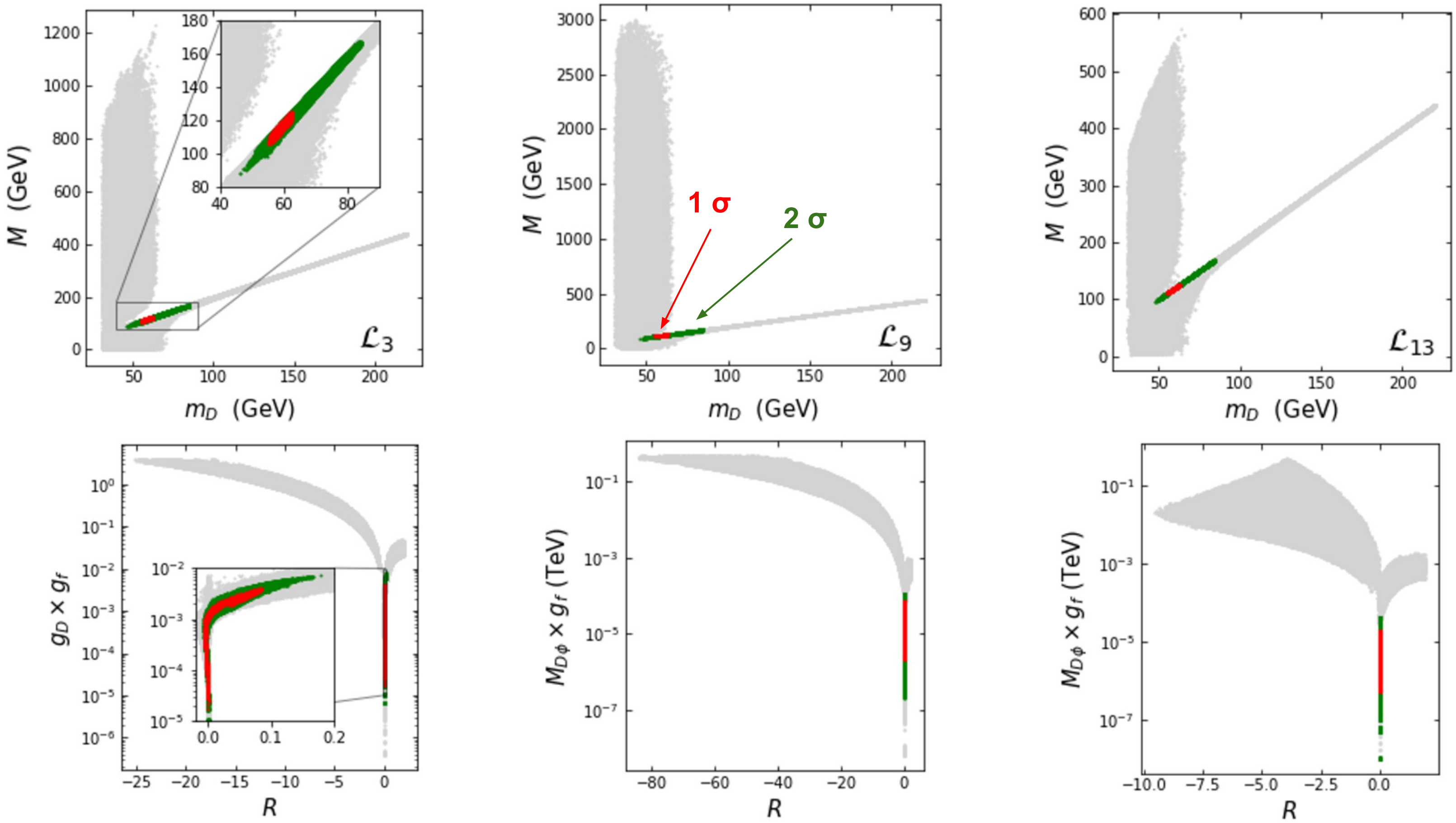
The range for the scaned parameters in s-channel models

For each model, we perform several MCMC scans individually to optimize the coverage and the parameters are scanned in the following range

$$
\begin{aligned}
&20\,\mathrm{GeV} < m_D < 300\,\mathrm{GeV},\ 10^{-4}\,\mathrm{GeV} < M < 3000\,\mathrm{GeV},\\
&10^{-6} < g_f < 2,\ 10^{-6} < g_D < 2,\ 10^{-6}\,\mathrm{GeV} < M_{D\phi} < 1000\,\mathrm{GeV}.
\end{aligned}
$$

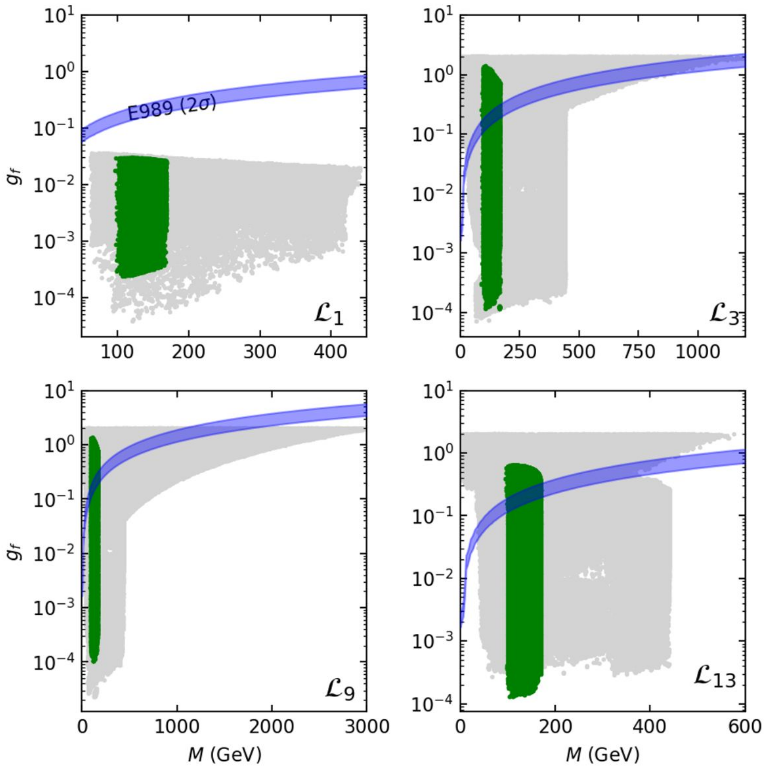
Resonance parameter : $R \equiv (2m_D - M)/m_D$

Only focus on the parameter space of L_3, L_9, L_13 in this talk !

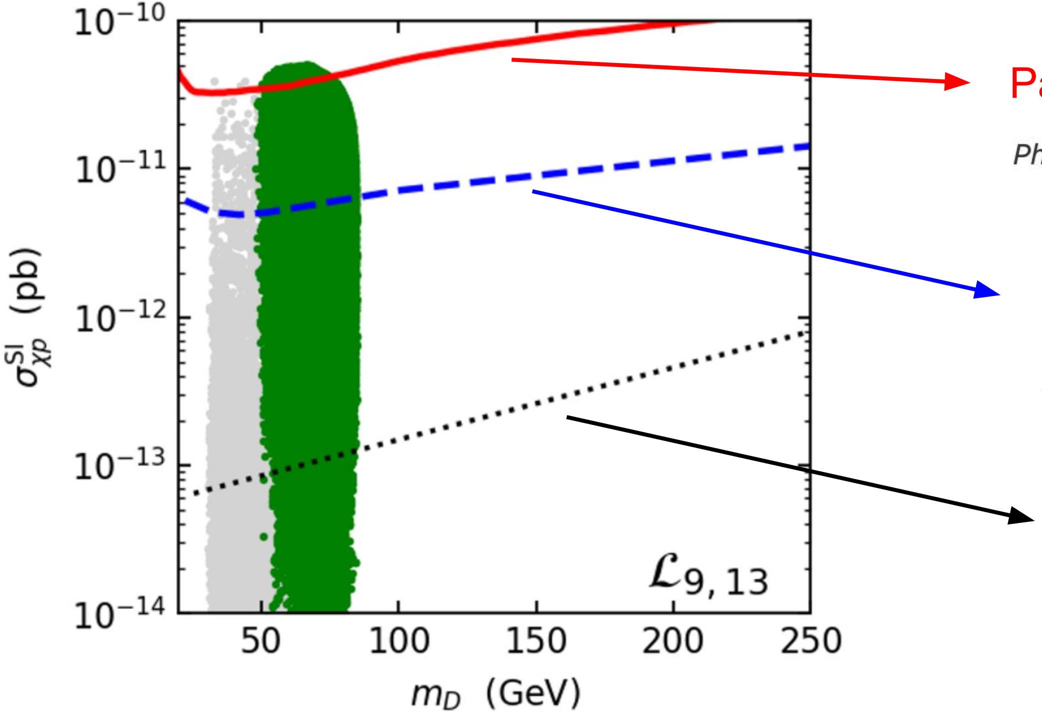


M (GeV)
m_D (GeV)
$\mathcal{L}_3$
$\mathcal{L}_9$
$\mathcal{L}_{13}$
1 σ
2 σ
$g_D \times g_f$
$M_{D\phi} \times g_f$ (TeV)
R

The muon g − 2 excess



Discussion of the DM direct detection



PandaX-4T (Current)

Phys.Rev.Lett. 127 (2021) 26, 261802

PandaX-4T (Projected)

Sci.China Phys.Mech.Astron. 62 (2019) 3, 31011

Neutrino floor

Nucl.Phys.B 804 (2008) 144-159

Content

Conclusion

1. We perform a comprehensive analysis for the muonphilic DM from the particle physics point of view. For scenario with Z2-even mediators, the favoured regions show an interesting feature that only the narrow phase spaces of resonances are remained to accommodate both GCE and DM relic density.
2. Although the muonphlic DM can only scatter with proton via loop contributions, the current DM direct detection for σ^{SI} upper limit is still sensitive to this kind of models.
3. If muon g − 2 excess can be confirmed, only the scalar mediator is allowed and the possible interaction types are L_3 (fermionic DM), L_9 (scalar DM) and L_13 (vector DM). Among these three models, only L_3 cannot be tested by future DD experiments.
4. The future muon colliders are sensitive to explore these muonphilic DM models.

Thank you

for your attention

Back-up

Gamma-ray galactic center excess

The systematic uncertainties of these GCE analyses are still unclear. It can be a challenge to discover or exclude the DM origin by only using GCE Fermi data.

However,

with the help from other astrophysical data, such as Fermi-LAT observations of dwarf spheroidal galaxies (dSphs) and AMS-02 cosmic-ray data, we can abandon the DM explanation of GCE if all the above data do not support DM annihilation.

→ The strategy in Di Mauro and Winkle (2021)

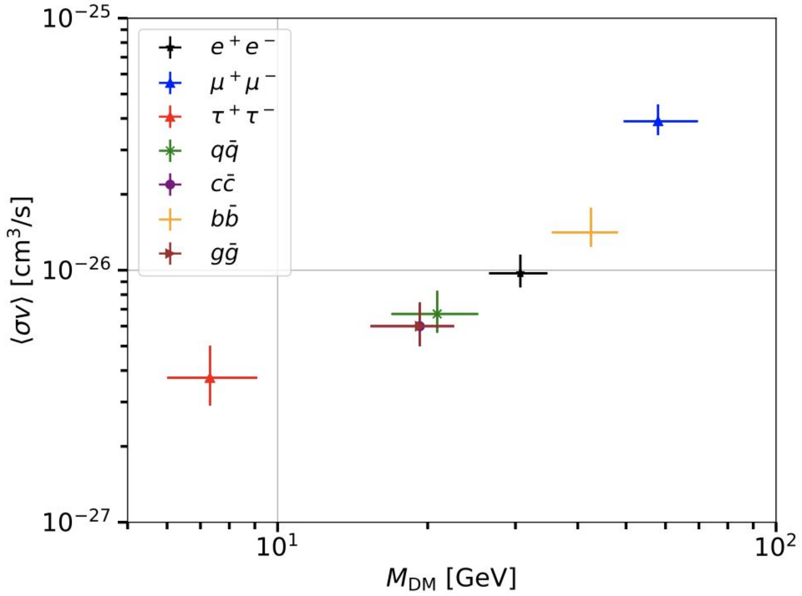
"Multimessenger constraints on the dark matter interpretation of the Fermi-LAT Galactic center excess"

Gamma-ray galactic center excess

“However, we find that the GCE DM signal is excluded by the AMS-02 anti-proton flux data for all hadronic and semi-hadronic annihilation channels unless the vertical size of the diffusion halo is smaller than 2 kpc -- which is in tension with radioactive cosmic ray fluxes and radio data. Furthermore, AMS-02 e+ data rule out pure or mixed channels with a component of e+ e-. The only DM candidate that fits the GCE spectrum and is compatible with constraints obtained with the combined dSphs analysis and the AMS-02 anti-proton and e+ data annihilates purely into $\mu^+ \mu^-$, has a mass of 60 GeV and roughly a thermal cross section.”

→ Di Mauro and Winkle (2021)

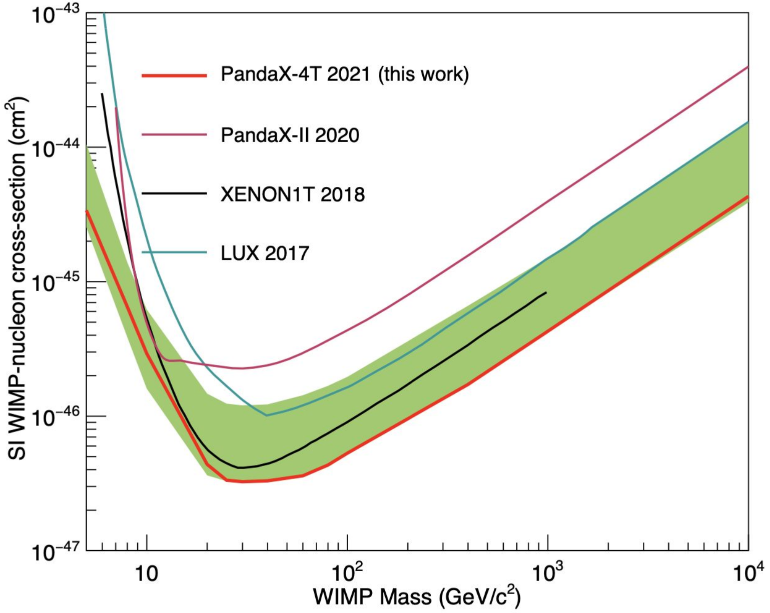
The GCE fitting results from Di Mauro and Winkle (2021)



Channel	M_{DM} [GeV]	$\langle \sigma v \rangle$ [$\times 10^{-26}$ cm^3/s]	$\chi^2(\tilde{\chi}^2)$
e^+e^-	30^{+4}_{-4}	$1.13^{+0.21}_{-0.12}$	161.61 (5.39)
$\mu^+\mu^-$	58^{+11}_{-9}	$3.9^{+0.5}_{-0.6}$	164.12 (5.47)
$\tau^+\tau^-$	$7.2^{+1.9}_{-1.2}$	$0.43^{+0.15}_{-0.10}$	1178.40 (39.3)
$q\bar{q}$	21^{+4}_{-4}	$0.77^{+0.19}_{-0.12}$	208.89 (6.96)
$c\bar{c}$	20^{+3}_{-5}	$0.70^{+0.16}_{-0.11}$	214.11 (7.14)
$b\bar{b}$	42^{+6}_{-7}	$1.41^{+0.35}_{-0.18}$	176.47 (5.88)
gg	19^{+3}_{-4}	$0.70^{+0.16}_{-0.11}$	214.14 (7.14)

PandaX-4T

a stringent limit to the dark matter-nucleon spin-independent interactions, with a lowest excluded cross section (90% C.L.) of $3.3 \times 10^{-47}\text{cm}^2$ at a dark matter mass of 30 GeV/c^2.



Phys.Rev.Lett. 127 (2021) 26, 261802

The simplified muonphilic DM models

t-channel

	Z_2 odd mediator			
	types	Lagrangian	$\langle \sigma v \rangle_{2\mu}$	DM field
	χ and ϕ	$\mathcal{L}_{17} = g_D \bar{\chi} P_R f \phi$+h.c.	s	Dirac
	χ and V_μ	$\mathcal{L}_{18} = g_D \bar{\chi} \gamma^\mu P_R f V_\mu$+h.c.	s	Dirac
✗	χ and ϕ	$\mathcal{L}_{19} = g_D \bar{\chi} P_R f \phi$+h.c.	p	Majorana
✗	χ and V_μ	$\mathcal{L}_{20} = g_D \bar{\chi} \gamma^\mu P_R f V_\mu$+h.c.	p	Majorana
	S and ψ	$\mathcal{L}_{21} = g_D \bar{\psi} P_R f S$+h.c.	**Case (i)**	Real
✗	S and ψ	$\mathcal{L}_{22} = g_D \bar{\psi} P_R f S$+h.c.	p	Complex
	X_μ and ψ	$\mathcal{L}_{23} = g_D \bar{\psi} \gamma^\mu P_R f X_\mu^\dagger$+h.c.	s	Real/Complex

The simplified muonphilic DM models

Compared with the Z2-even mediator case, there is no resonance enhancement in t-channel models.

Thus, we are safe to exclude the p-wave interactions L_19, L_20, L_22 because they are not able to simultaneously generate the correct relic density and the DM annihilation cross section required by GCE.

The charged mediator such as slepton suffers from the stringent lower mass limit 103.5 GeV from LEP.

Therefore, we foucs on L_21 only with the following scaned parameters :

$$20\,\mathrm{GeV} < m_D < 200\,\mathrm{GeV},\ m_D < M < 1000\,\mathrm{GeV},\ 10^{-6} < g_D < 2.$$

DISCUSSION OF DM DIRECT DETECTION

1. For the simplified muonphilic DM models, there is no tree level DM-nuclei elastic scattering.
2. First, we consider the Z2-even mediator case and define the general lepton current as $\bar{l}\Gamma_l l$. The one loop contributions are nonzero only for vector and tensor lepton currents, namely $\Gamma_l = \gamma_\mu, \sigma_{\mu\nu}$ Therefore, only L_5, L_7, L_11, L_15 can generate one loop contributions to the DM-nuclei elastic scattering.
3. For the scalar lepton current, $\Gamma_l = 1$, the one loop contribution vanishes since a scalar current cannot couple to a vector current. The DM-quark interaction can only be induced at two loop level for L_1, L_3, L_9, L_13.
4. For pseudo-scalar and axial vector lepton currents $\Gamma_l = \gamma_5, \gamma_\mu\gamma_5$, the diagrams vanish to all loop orders. The interaction with γ_5 gives either zero or a fully anti-symmetric tensor $\epsilon^{\alpha\beta\mu\nu}$. Since there are only three independent momenta in the 2 → 2 scattering process, two indices can be contracted with the same momentum and return a zero amplitude square. Therefore, we can ignore the DM-nuclei elastic scattering for L_2, L_4, L_6, L_8, L_10, L_12, L_14, L_16.

DISCUSSION OF DM DIRECT DETECTION

1. For the Z2-odd mediator case, the DM-nuclei scattering cross sections are suppressed for the self-conjugate DM, namely real scalar, Majorana fermion, and real vector, since the self-conjugate DM couples to a single photon in t-channel simplified models only through the anapole moment. This leads to that DM-quark scattering amplitude is suppressed in the non-relativistic limit as for L_19, L_20, L_21, L_23.
2. On the other hand, if the muonphilic DM are complex scalar, Dirac fermion and complex vector, the one-loop induced DM-quark interactions cannot be ignored.

THE MUON g − 2 EXCESS

A deviation $\delta a_\mu = (2.51 \pm 0.59) \times 10^{-9}$ with 4.2σ significance deviating from the value of the SM prediction.

(1) The contribution from pseudo-scalar and axial-vector mediator are negative at one loop level.
(2) For the contributions from vector mediator, δa_μ is too small to reach 2σ region.
(3) Thus, only the contributions form scalar mediators are considered.

Therefore, as long as the E989 result can be confirmed in the near future, only L_3 (fermionic DM), L_9 (scalar DM) and L_{13} (vector DM) are allowed to explain the correct DM relic density, GCE and muon g − 2 excess simultaneously.