P^2EAK 2026 @ Kuju, Oita

Taming Lepton-Portal DM by a Non-Invertible Selection Rule

Working in Progress

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Outline

1. Lepton Portal DM
2. How to tame LPDM
3. Phenomenological tests
4. Summary

DM zoo

there are now hundreds of dark matter species

generated by ChatGPT

Among them, WIMP is an attractive candidate due to the **WIMP miracle**

Lepton portal DM 1402.6696 Y. Bai, J. Berger

A **real scalar X** couples to **SM leptons** through Yukawa couplings λ_L, λ_E

$$-\mathcal{L}_{portal} = \lambda_L \, \boldsymbol{X} \, \bar{L} \, P_L \ell_{\mathrm{SM}} + \lambda_E \, \boldsymbol{X} \, \bar{e}_{\mathrm{SM}} P_L E + h.c.$$

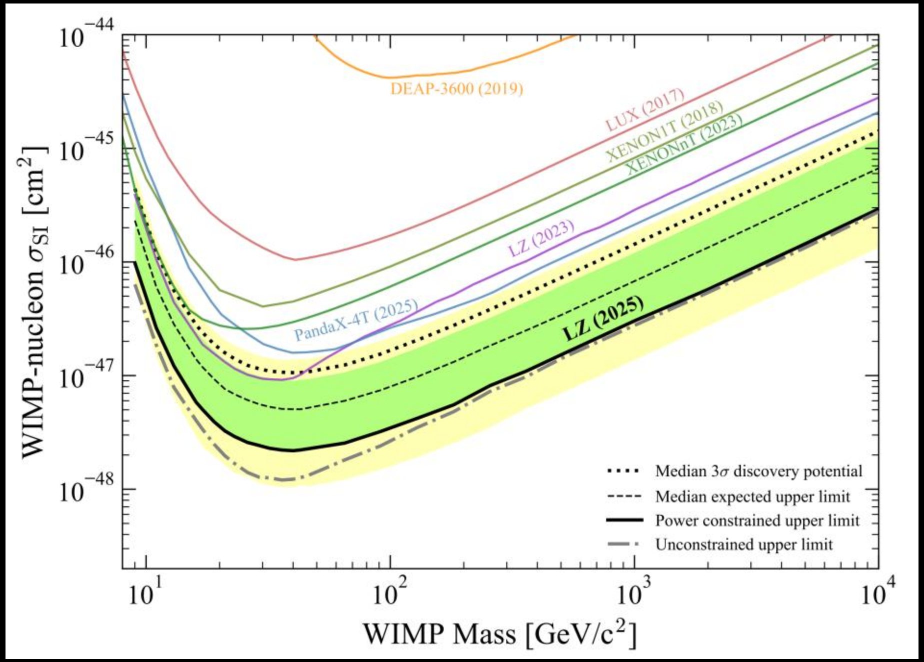
➢ Mediator leptons

- In addition to the **DM**, there are vector-like leptons (**VLLs**) as a mediator
- We assume Z_2 symmetry where the DM and VLLs are odd, for DM stability

Why Lepton portal DM ?

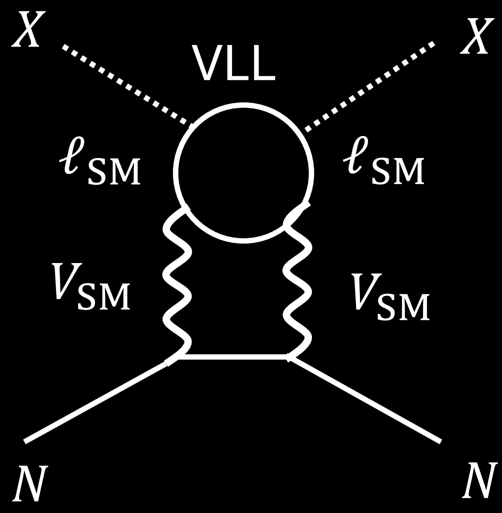
In general, WIMPs are severely constrained **by direct-detection** experiments

- Upper limits on $\sigma_{SI}(XN \to XN)$



LZ collab., 2410.17036

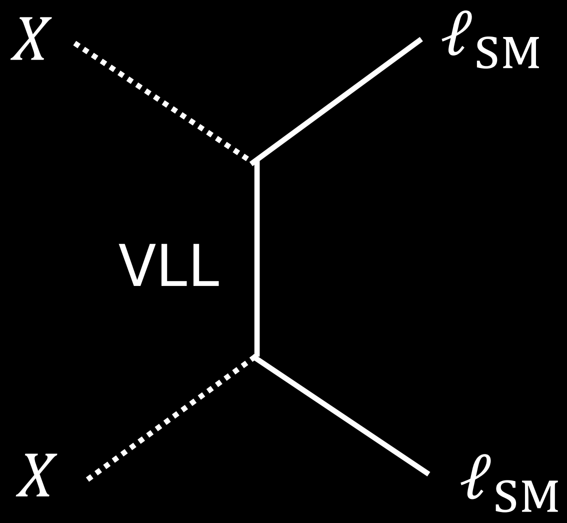
- Case of LPDM



σ_{SI} is **below the neutrino floor** since it is 2-loop

Annihilation of LPDM

DM $\boldsymbol{X}$ annihilates through t-channel exchange of VLLs



$$-\mathcal{L}_{portal} = \lambda_L \, \boldsymbol{X} \, \overline{L} \, P_L \ell_{\rm SM} + \lambda_E \, \boldsymbol{X} \, \overline{e}_{\rm SM} P_L E + h.c.$$

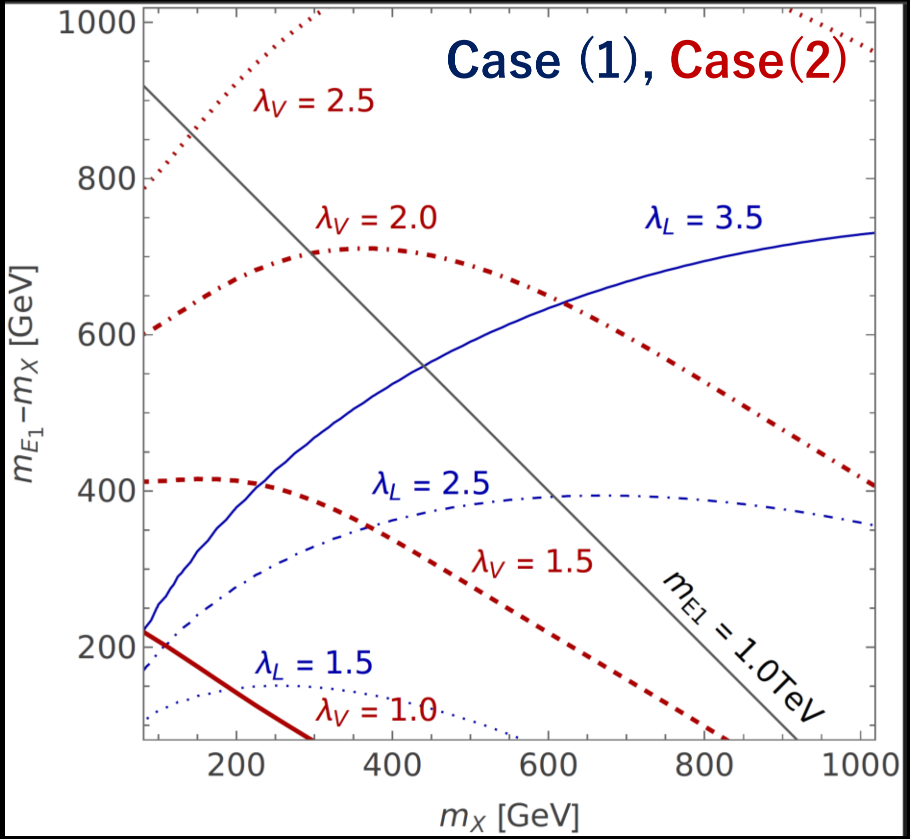
$$\downarrow$$

$$\sigma v_{\rm rel} \sim \underbrace{\frac{1}{\pi}\left|\sum_{a=1,2} \lambda_L^a \lambda_E^a \frac{m_{E_a}}{m_X^2 + m_{E_a}^2}\right|^2}_{\text{s-wave}} + \underbrace{\frac{m_X^2}{60\pi}\left(\frac{|\lambda_L|^4}{(m_X^2 + m_L^2)^2} + \frac{|\lambda_E|^4}{(m_X^2 + m_E^2)^2}\right) v_{\rm rel}^4}_{\text{d-wave}}$$

- **If $\boldsymbol{\lambda_L \lambda_E \neq 0}$**, s-wave dominates the annihilation
- Otherwise, cross section is **d-wave dominant**

Relic density

We consider two cases: **(1)** $\boldsymbol{\lambda_E = 0}$ and **(2)** $\boldsymbol{\lambda_V \coloneqq \lambda_L = \lambda_E}$



$m_{E_2} = m_{E_1} + 100$ GeV, $s_L = s_R = 0.1$

- Solve the Boltzmann eq. for the number density n_X

$$\dot{n}_X + 3Hn_X = -\langle \sigma v \rangle (n_X^2 - n_{X,\mathrm{eq}}^2)$$

- determine λ_L to reproduce $\Omega_X h^2 = 0.12$

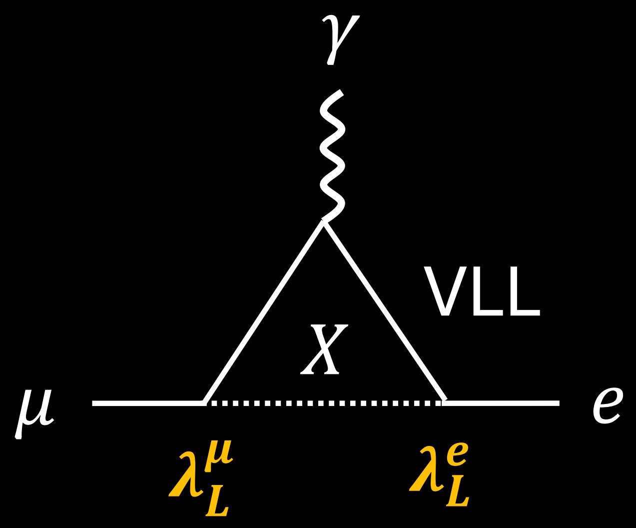
$\longrightarrow$ $\mathcal{O}(1)$ portal coupling λ_L is necessary

Lepton flavor violation

SM leptons carry flavor indices $i = e, \mu, \tau$

$$-\mathcal{L}_{portal} = \boldsymbol{\lambda_L^i}\, \boldsymbol{X}\, \bar{L}\, P_L \boldsymbol{\ell_i} + \boldsymbol{\lambda_E^i}\, \boldsymbol{X}\, \boldsymbol{\bar{e}_i} P_L E + h.c.$$

→

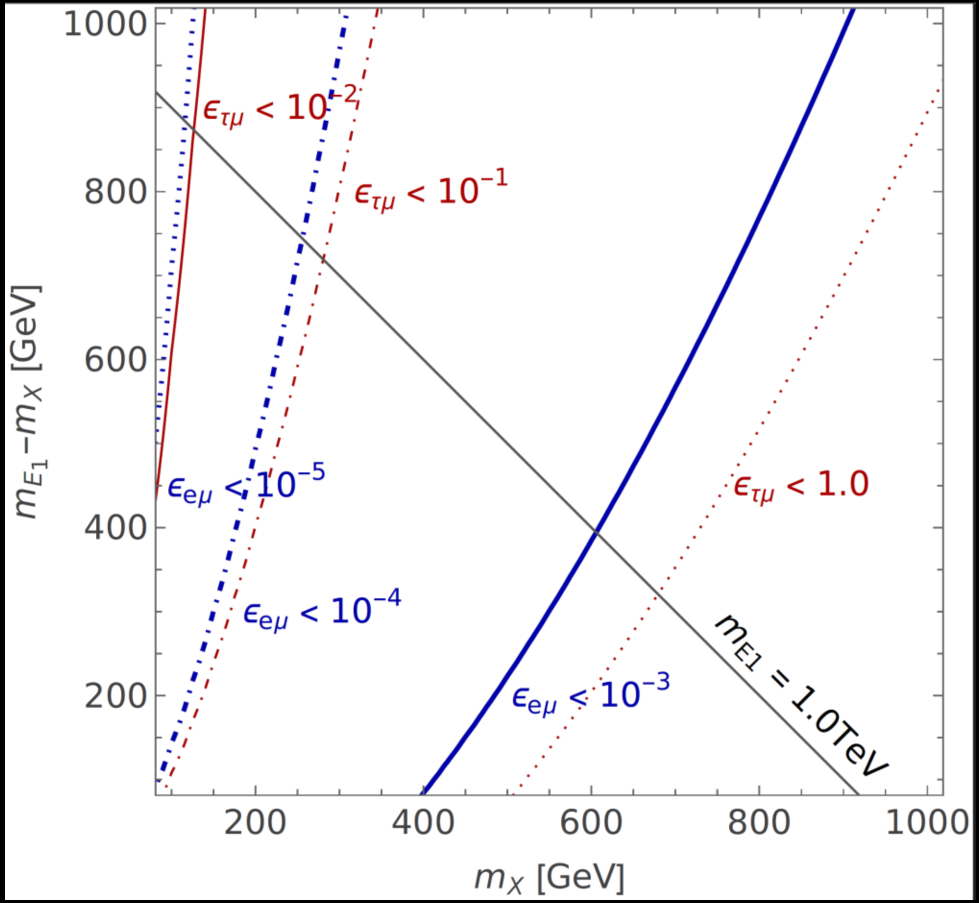


$$\mathrm{Br}(\mu \to e\gamma) = \frac{\alpha_e m_\mu^5 \left|\lambda_L^e \lambda_L^\mu\right|^2}{1024\pi^4 m_X^4 \Gamma_\mu} F\left(\frac{m_E^2}{m_X^2}\right) < 4.2 \times 10^{-13}$$

Flavor violation is induced by the portal interactions

Upper bounds on LFV couplings

We assume that LFV arises only from λ_L



$m_{E_2} = m_{E_1} + 100$ GeV, $s_L = s_R = 0.1$

Upper bounds from $\mu \to e\gamma, \tau \to \mu\gamma$

- Electron-philic

$$\epsilon_{e\mu} = \frac{\lambda_L^\mu}{\lambda_L^e}, \qquad \epsilon_{\tau\mu} = \frac{\lambda_L^\mu \lambda_L^\tau}{(\lambda_L^e)^2}$$

- Muon-philic

$$\epsilon_{e\mu} = \frac{\lambda_L^e}{\lambda_L^\mu}, \qquad \epsilon_{\tau\mu} = \frac{\lambda_L^\tau}{\lambda_L^\mu}$$

- Tau-philic

$$\epsilon_{e\mu} = \frac{\lambda_L^e \lambda_L^\mu}{(\lambda_L^\tau)^2}, \qquad \epsilon_{\tau\mu} = \frac{\lambda_L^\mu}{\lambda_L^\tau}$$

Summary of LPDM

Lepton-Portal DM (LPDM) is a WIMP candidate with the portal interactions:

$$-\mathcal{L}_{portal} = \lambda_L^i \, X \, \overline{L} \, P_L \ell_i + \lambda_E^i \, X \, \overline{e}_i P_L E + h.c.$$

- a viable DM candidate with a suppressed direct detection rate
- Flavor violation can **easily become dangerous**

How to tame LPDM ?

generated by ChatGPT

Outline

1. Lepton Portal DM
2. How to tame LPDM
3. Phenomenological tests
4. Summary

Portal coupling and PMNS mixing

In addition to DM, **lepton masses and mixing** must also be reproduced

- SM lepton mass and mixing

$$-\mathcal{L}_{SM} = y_e^{ij}\ \bar{e}_i\, P_L \ell_j H + \frac{c_n^{ij}}{\Lambda}\,(\bar{\ell}^{ci} H)\, P_L(\ell^j H) + h.c$$

$v_H = \langle H^0 \rangle$

$\rightarrow$ $v_H V_L^\dagger\, y_e V_R = \mathrm{diag}(m_e, m_\mu, m_\tau)$ $\frac{v_H^2}{\Lambda} U_n^T\, c_n U_n = \mathrm{diag}(m_{\nu_1}, m_{\nu_2}, m_{\nu_3})$

$$U_{\mathrm{PMNS}} = V_L^\dagger\, U_n \sim \begin{pmatrix} 0.82 & 0.55 & 0.15 \\ 0.28 & 0.61 & 0.74 \\ 0.50 & 0.57 & 0.66 \end{pmatrix}$$ has **sizable mixing angles**

Case of Abelian Z_2 symmetry

For simplicity, let's consider 2-flavor case with Z_2 symmetry

$$-\mathcal{L}_{SM+port.} = y_e^{ij}\ \bar{e}_i\, P_L \ell_j H + \frac{c_n^{ij}}{\Lambda}\,(\overline{\ell^{ci}} H)\, P_L(\ell^j H) + \lambda_L^i\, X\, \bar{L}\, P_L \ell_i + \lambda_E^i\, X\, \bar{e}_i P_L E + h.c.$$

Step 1: impose the absence of LFV

$\ell = (+,-)$ **and/or** $e = (+,-)$ $\rightarrow$ $\lambda_L = (✓, 0)$ and/or $\lambda_E = (✓, 0)$

Step 2: require massive leptons

$\ell = (+,-)$ **and** $e = (+,-)$ $\rightarrow$ $y_e = \begin{pmatrix} ✓ & 0 \\ 0 & ✓ \end{pmatrix}$ otherwise $y_e = \begin{pmatrix} ✓ & ✓ \\ 0 & 0 \end{pmatrix}$

However, then $c_n = \begin{pmatrix} ✓ & 0 \\ 0 & ✓ \end{pmatrix}$ $\rightarrow$ $U_{\text{PMNS}} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$, thus **no mixing**

Non-invertible symmetry

We can generalize the discussion to 3-flavor with a Z_N symmetry

→ An ordinary symmetry may be **too restrictive** to tame LPDM

- **Non-invertible selection rule** e.g. S. Schafer-Nameki 2305.18296, J. Kaidi 2603.08798

Assign **conjugacy classes,** rather than representations, to the fields

→ It can control the couplings while imposing **weaker constraints**

see Otsuka-san's talk for backgrounds

Z_2 gauging of Z_3 2409.05270 Kobayashi, Otsuka, Tanimoto

ordinary Z_3 has 3 elements $g^0, g^1, g^2 = g^{-1}$ with $g^a g^b = g^{a+b}$ mod 3

- Z_2 gauging

consider Z_2 consisting of two elements e and r, which act on the Z_3 elements as

$$e\, g^a\, e = g^a, \qquad r g^a r = g^{-a}$$

→ After gauging the Z_2, the Z_3 elements form **2 classes** $[g^0] = \{g^0\}$, $[g^1] = \{g^1, g^{-1}\}$

- Fusion rule

$* \; g^1 g^1 = g^2 = r g^1 r \sim g^1$

$$[g^0][g^a] = [g^a]\,,\ [g^1][g^1] = [g^0] \oplus [\boldsymbol{g^1}]$$

$[g^1]$ does not have an inverse whose fusion returns **only** $[g^0]$, so **non-invertible**

Non-invertible selection rule of $Z_3//Z_2$

an interaction is allowed if the product **contains $[\boldsymbol{g}^0]$**

- Example: 2-flavor model

$$X = E = [g^0]\,,\ L = \boldsymbol{H} = [\boldsymbol{g}^1], \ell = ([g^1],[g^0]), e = ([g^0],[g^1])$$

portal coupling $X\,\bar{L}\,\ell = \left([\boldsymbol{g}^0] \oplus [g^1], [g^1]\right) \sim (\checkmark,\ 0) \sim X\,\bar{e}\,E$

$\rightarrow$ Yukawa coupling $H\,\bar{e}\,\ell = \begin{pmatrix} [g^0]\oplus[g^1] & [g^1] \\ [g^0]\oplus[g^1] & [g^0]\oplus[g^1] \end{pmatrix} \sim \begin{pmatrix} \checkmark & 0 \\ \checkmark & \checkmark \end{pmatrix}$

neutrino mass $(H\ell)^2 = \begin{pmatrix} [g^0]\oplus[g^1] & [g^0]\oplus[g^1] \\ [g^0]\oplus[g^1] & [g^0]\oplus[g^1] \end{pmatrix} \sim \begin{pmatrix} \checkmark & \checkmark \\ \checkmark & \checkmark \end{pmatrix}$

$$\hat{\lambda}_L = V_L^\dagger \lambda \neq (\boldsymbol{\checkmark}, \boldsymbol{0})$$

Full-rank lepton mass matrices and PMNS mixing, but LFV remains **after diagonalization**

Z_2 gauging of Z_5 2409.05270 Kobayashi, Otsuka, Tanimoto

ordinary Z_5 has 5 elements $g^0, g^{\pm 1}, g^{\pm 2}$ with $g^a g^b = g^{a+b}$ mod 5

- after gauging the Z_2

$$[g^0] = \{g^0\}\ ,\ [g^1] = \{g^1, g^{-1}\}, [g^2] = \{g^2, g^{-2}\}$$

- Fusion rule

$$[g^0][g^a] = [g^a], \quad [g^1][g^1] = [g^0] \oplus [g^2], \quad [g^2][g^2] = [g^0] \oplus [g^1]$$
$$[g^1][g^2] = [g^1] \oplus [g^2]$$

We assign $[g^0], [g^1], [g^2]$ to the fields in the LPDM model

Non-invertible selection rule of $Z_5//Z_2$

- Example: 2-flavor model

$$X = [g^0]\,,\ L = [g^1],\ E = H = [g^2], \ell = ([g^1],[g^2]), e = ([g^2],[g^0])$$

portal coupling $X\,\bar{L}\,\ell = \left([g^0] \oplus [g^2], [g^1] \oplus [g^2]\right) \sim (\checkmark,\ 0) \sim X\,\bar{e}\,E$

$\rightarrow$ Yukawa coupling $H\,\bar{e}\,\ell = \begin{pmatrix} [g^0] \oplus [g^1] \oplus [g^2] & [g^1] \oplus [g^2] \\ [g^1] \oplus [g^2] & [g^0] \oplus [g^1] \end{pmatrix} \sim \begin{pmatrix} \checkmark & 0 \\ 0 & \checkmark \end{pmatrix}$

neutrino mass $(H\ell)^2 = \begin{pmatrix} [g^0] \oplus [g^1] \oplus [g^2] & [g^0] \oplus [g^1] \oplus [g^2] \\ [g^0] \oplus [g^1] \oplus [g^2] & [g^0] \oplus [g^1] \oplus [g^2] \end{pmatrix} \sim \begin{pmatrix} \checkmark & \checkmark \\ \checkmark & \checkmark \end{pmatrix}$

$$\hat{\lambda}_L = \lambda = (\checkmark, \mathbf{0})$$

full-rank lepton masses and PMNS mixing from U_n, while portal **LFV is absent**

LPDM model with $Z_5//Z_2$

- 3-flavor model

$$X = [g^0]\,,\ L = [g^1],\ E = H = [g^2],\ \ell = ([g^1],[g^2],[g^2]),\, e = ([g^2],[g^0],[g^0])$$

portal coupling: $X\,\bar{L}\,\ell \sim X\,\bar{e}\,E \sim (\checkmark,\ 0,\ 0)$ (or $X\,\bar{e}\,E \sim (0,\ 0,\ 0)$ **if $\boldsymbol{E = [g^0]}$**)

no FLV

$\rightarrow$

Yukawa coupling: $H\,\bar{e}\,\ell \sim \begin{pmatrix} \checkmark & 0 & 0 \\ 0 & \checkmark & \checkmark \\ 0 & \checkmark & \checkmark \end{pmatrix}$ neutrino mass: $(H\ell)^2 \sim \begin{pmatrix} \checkmark & \checkmark & \checkmark \\ \checkmark & \checkmark & \checkmark \\ \checkmark & \checkmark & \checkmark \end{pmatrix}$

full-rank charged lepton masses

neutrino masses and PMNS matrix

the NISR from $Z_5//Z_2$ can tame LPDM

Summary of non-invertible selection rule

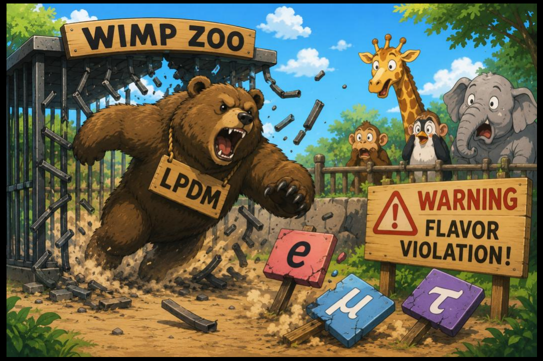
NISR can tame LPDM consistently with the PMNS matrix

symmetry

generated by ChatGPT

Outline

1. Lepton Portal DM
2. How to tame LPDM
3. **Phenomenological tests**
4. Summary

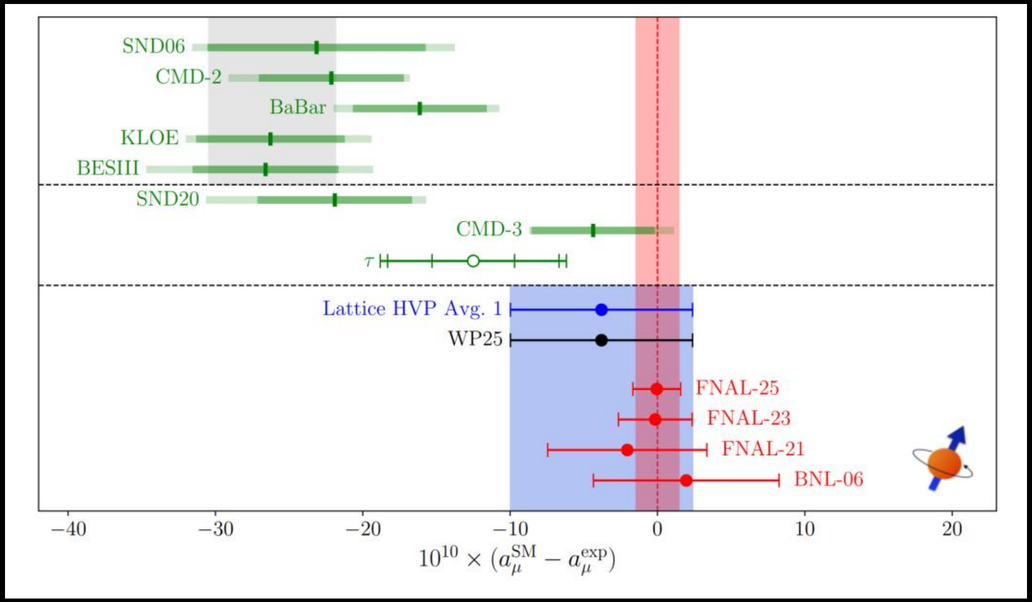


Magnetic dipole moment

The anomalous MDM a_ℓ is one of the most precisely measured observables

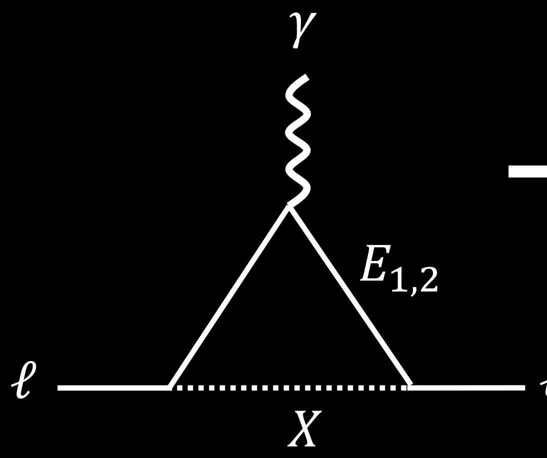
- muon g-2

FNAL, 2505.21476



$$|\Delta a_\mu| < \mathcal{O}(10^{-9}), \qquad |\Delta a_e| < \mathcal{O}(10^{-12})$$

- LPDM case



$$\rightarrow \frac{e\, a_\ell}{4 m_\ell} \bar{\psi}_\ell \sigma^{\mu\nu} \psi_\ell F_{\mu\nu}$$

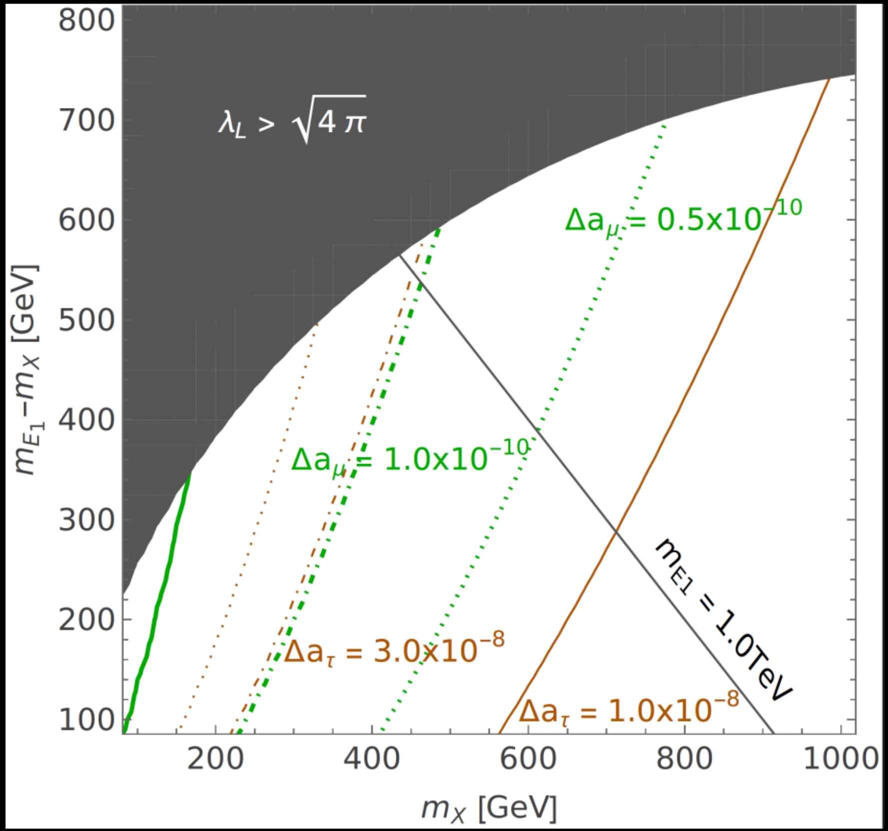
$$\Delta a_\ell \sim \frac{m_\ell^2}{8\pi^2 m_X^2}\left((|\lambda_L|^4 + |\lambda_E|^4) F\left(\frac{m_E^2}{m_X^2}\right) + \boldsymbol{\frac{m_E}{m_\ell} Re(\lambda_L^* \lambda_E)} G\left(\frac{m_E^2}{m_X^2}\right)\right)$$

chirality enhancement for $\lambda_L \lambda_E \neq 0$

Magnetic dipole moment

$m_{E_2} = m_{E_1} + 100$ GeV, $s_L = s_R = 0.1, \Omega h^2 = 0.12$

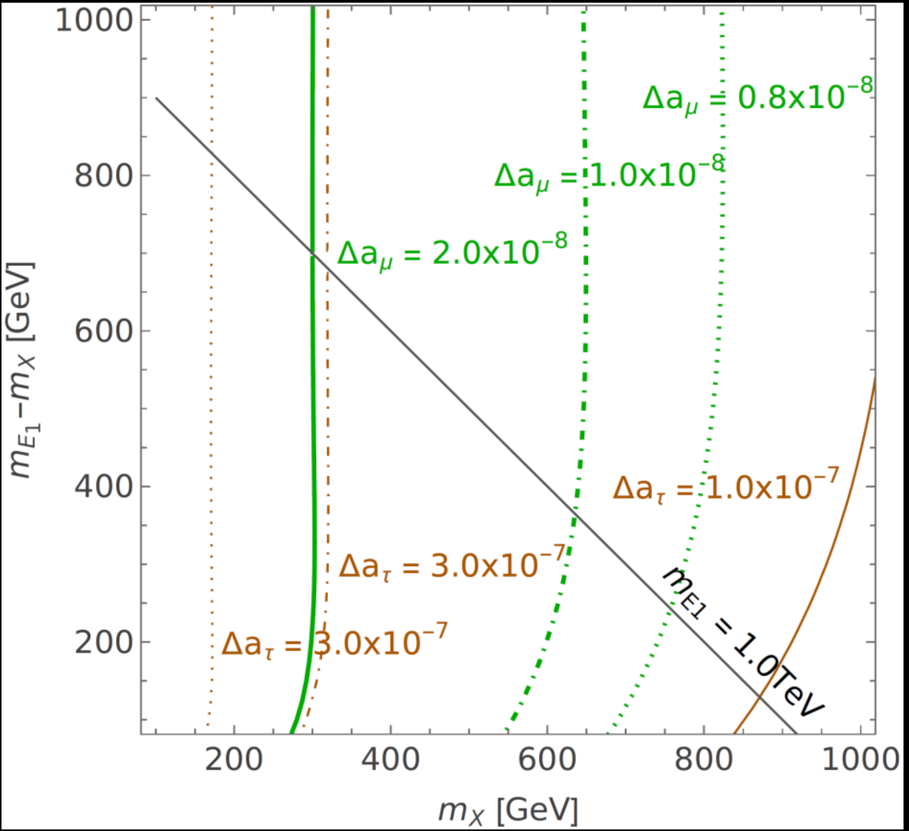
- $\lambda_L \neq 0, \lambda_E = 0$



all cases are within the constraints

- $\lambda_L = \lambda_E \neq 0$

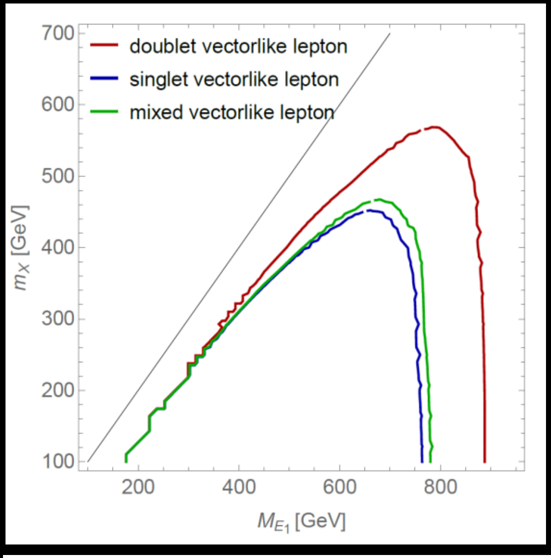
c.f. $\Delta a_\tau < \mathcal{O}(10^{-3})$



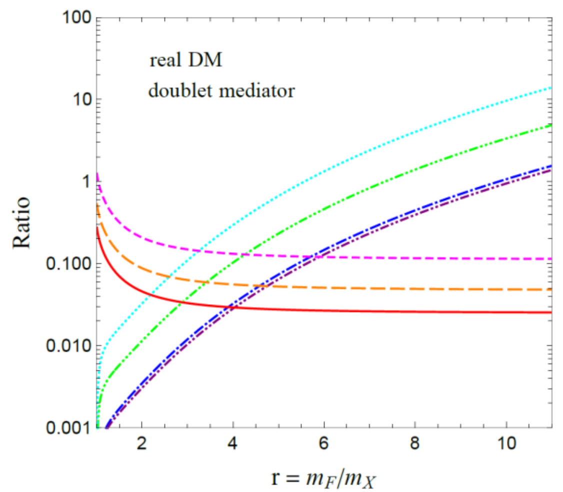
The e and μ-philic cases are excluded

Comment on other tests

2002.12534 JK, S.Okawa, Y. Omura



- LHC limits
  - $2\ell + E_T^{miss}$ slepton searches place bounds
  - $<$ 1 TeV may be probed with the full Run 3 data
- Indirect detection
  - at low velocities, 1-loop $XX \to VV'$ may be dominant
  - H.E.S.S., Fermi-LAT, AMS, CTA are sensitive



$$\frac{\sigma(XX \to VV')}{\sigma(XX \to \ell\ell)}$$

$$\frac{\sigma(XX \to \ell\ell V)}{\sigma(XX \to \ell\ell)}$$

- Lepton flavor universality working in progress...
  - flavor-specific couplings violate lepton flavor universality

Flavor leakage in type-I seesaw

The NISR is not an ordinary invertible symmetry and may be more fragile

- type-I seesaw a UV completion of the neutrino masses

$$-\mathcal{L}_{\text{type1}} = y_n^{ij}\ \overline{n}_i\, P_L \ell_j H + \frac{1}{2} M_n^{ij}\, \overline{n}\, P_L\, n^{cj} + h.c$$

integrating out n_i

$$\rightarrow \quad -\mathcal{L}_{eff} = \frac{c_n^{ij}}{\Lambda}\, (\overline{\ell}^{ci} H)\, P_L (\ell^j H) + h.c \qquad \text{where} \quad \frac{c_n^{ij}}{\Lambda} = y_n^{ai} (M_n^{-1})_{ab} y_n^{bj}$$

If $n = ([g^1], [g^1], [g^1])$, all elements of y_n, M_n, and hence c_n, can be non-zero

Flavor leakage in type-I seesaw

The NISR is not an ordinary invertible symmetry and may be more fragile

- RGE of portal couplings

$$16\pi^2\beta_{\lambda_L} \sim \left(3\lambda_L\lambda_L^\dagger + \frac{1}{2}y_e^T y_e^* + \frac{1}{2}\boldsymbol{y_n^T y_n^*} + \cdots\right)\lambda_L$$

$$16\pi^2\beta_{\lambda_E} \sim \left(3\lambda_E\lambda_E^\dagger + y_e y_e^\dagger + \cdots\right)\lambda_E$$

The neutrino Yukawa couplings y_n can induce LFV in the portal coupling λ_L

$$\rightarrow \quad \lambda_L(\mu) \sim \lambda_L^0\left(1 + \frac{y_n^T y_n^*}{32\pi^2}\log\frac{\mu}{\Lambda_{NISR}}\right)$$

Λ_{NISR} : scale at which the NISR is imposed

LFV at low-energy may be induced by y_n in type-I seesaw

Summary and discussion

NISR can tame LPDM consistently with the PMNS matrix

➢ Phenomenological tests

- e and μ-philic cases are excluded by g-2 if $\lambda_L \lambda_E \neq 0$
- LHC and indirect detection are also important
- lepton flavor non-universality may also be a good test
- LFV can be correlated with the UV completion of the lepton sector