Lepton-flavoured scalar dark matter

Monika Blanke

Karlsruher Institut für Technologie

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Two major puzzles of matter

Flavour puzzle

- Why does visible matter come in three generations?
- Why are their masses so hierarchical?
- Why is flavour violation so small?

Dark matter puzzle

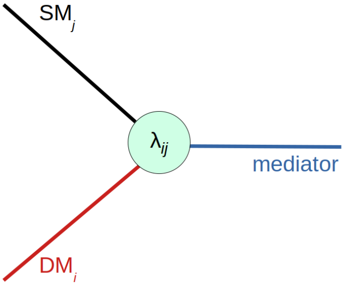
- What is the dark matter of the universe made of?
- How was it created?
- How does it couple to ordinary matter?

potential link: **flavoured dark matter**

What is flavoured dark matter?

Minimal assumptions

- dark matter comes in three generations
- dark flavour triplet couples to SM flavour triplet via new mediator field
- new flavour-violating coupling matrix λ



The flavoured DM model space

Model-building choices

- the nature of DM
  - scalar or fermion
  - real or complex representation

  ➢ 4 options

- the SM fermion portal
  - quarks or leptons
  - left- or right-handed...

  ➢ 5 options

- the flavour structure
  - Minimal Flavour Violation (MFV) or beyond

In this talk
complex scalar flavoured DM coupled to right-handed charged leptons

In Jan's talk
Majorana fermion flavoured DM coupled to right-handed up-type quarks

In both talks
Dark Minimal Flavour Violation (DMFV)

- dark flavour symmetry $U(3)$ or $O(3)$
- broken only by new coupling matrix λ

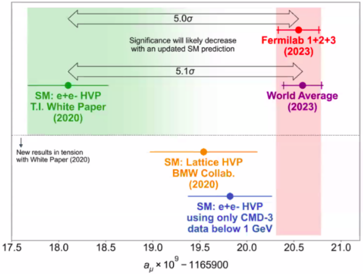
➢ minimal step beyond MFV

Why lepton-flavoured DM?

Advantages of lepton-flavoured DM

- possible link between SM flavour structure and dark sector
- richer phenomenology than simple non-flavoured models
- possibility to reconcile WIMP hypothesis with non-observation constraints
  - ➢ *in this talk:* thermal freeze-out
- less constrained by direct detection and LHC searches than quark-flavoured DM
- potential connection to $(g-2)_\mu$ puzzle

New physics in $(g-2)_\mu$?



- using data-driven SM prediction: 5.1σ tension with data
- using lattice QCD input: tension reduced to 1.6σ

Lepton-flavoured complex scalar DM – the model

The model

Acaroğlu, Agrawal, MB (2022)

$$\mathcal{L}_{\text{dark}} = (\partial_\mu \phi)^\dagger (\partial^\mu \phi) - M_\phi^2 \phi^\dagger \phi - \bar{\psi}(i\not{D} - m_\psi)\psi - (\lambda_{ij} \bar{\ell}_{Ri} \psi \phi_j + \text{h.c.})$$
$$+ \Lambda_H H^\dagger H \phi^\dagger \phi + \Lambda_\phi \left(\phi^\dagger \phi\right)^2$$

- complex scalar field ϕ: gauge singlet, triplet under new flavour symmetry $U(3)_\phi$
- Dirac fermion ψ: hypercharge $Y = -1$, mediates DM coupling to right-handed leptons
- flavour-violating coupling matrix λ
- flavoured Higgs-portal interaction Λ_H Acaroğlu, MB, Tabet (2023)

Mass spectrum

- mass spectrum convention: $m_{\phi_1} > m_{\phi_2} > m_{\phi_3}$; assumption: $m_\psi > m_{\phi_3}$
- ϕ and ψ odd under new $\mathbb{Z}_2$ symmetry ➢ ϕ_3 stable, forms DM
- Dark Minimal Flavour Violation (DMFV)

More on Dark Minimal Flavour Violation (DMFV)

DMFV principle

Agrawal, MB, Gemmler (2014)

- extend concept of Minimal Flavour Violation, where all flavour violation originates from SM Yukawas
- DMFV: one new source of flavour violation – coupling matrix λ
- other flavourful interactions can be expanded in powers of λ

$$M_\phi^2 = m_\phi^2 \left[\mathbb{1} + \eta \lambda^\dagger \lambda + \mathcal{O}(\lambda^4)\right] \qquad \Lambda_H = \lambda_H \left[\mathbb{1} + \eta_H \lambda^\dagger \lambda + \mathcal{O}(\lambda^4)\right]$$

- parametrization of λ in terms of physical parameters

$$\lambda = UD$$

U: unitary matrix with three mixing angles θ_{ij} and three complex phases δ_{ij}
D: diagonal matrix with positive entries $D_{1,2,3}$

Initial study

Initial analysis ACAROĞLU, AGRAWAL, MB (2022)

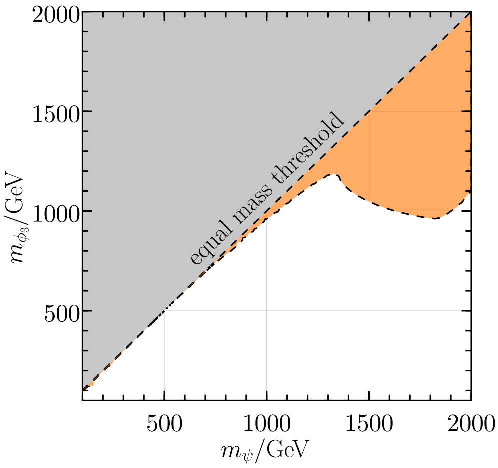
- case with $\lambda_H = 0$ and $\eta < 0$
- constraints from LFV decays, relic density and DM detection experiments

➢ too heavy NP to resolve $(g-2)_\mu$ puzzle

Possible solution ACAROĞLU, AGRAWAL, MB (2022 II)

- introduce second fermionic mediator
- couple DM also to left-handed leptons
- lift chirality suppression of $(g-2)_\mu$

➢ large NP contribution to $(g-2)_\mu$ possible, but at the cost of many new parameters

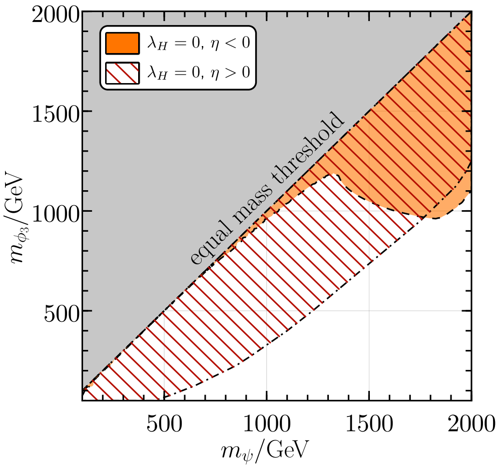


ACAROĞLU, MB, TABET (2023)

Opportunities within the minimal model

1.) invert hierarchy of DM couplings ($\eta > 0$)

- ϕ_3 couples with $\min(D_1, D_2, D_3)$
- DM relic density dominantly produced by freeze-out of heavy flavours $\phi_{1,2}$
- small ϕ_3 couplings evade strong direct detection bounds

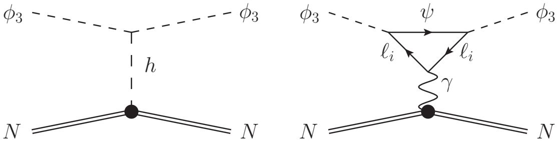


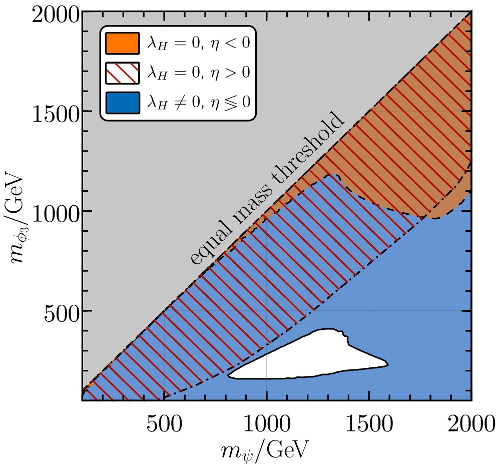
Acaroğlu, MB, Tabet (2023)

Opportunities within the minimal model

2.) open Higgs portal ($\lambda_H \neq 0$)

- additional DM annihilation channels
- new DM–nucleon scattering process
- potential destructive interference in σ_{SI}^N



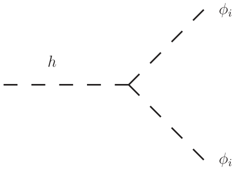


➢ **both options render $m_\psi \sim 100$ GeV viable**

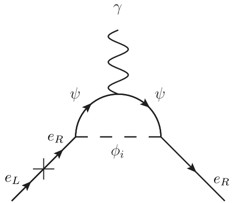
Acaroğlu, MB, Tabet (2023)

Additional constraints

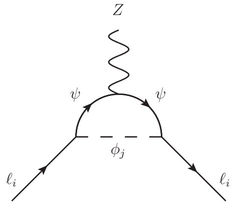
However, small NP scales come at the cost of additional constraints:



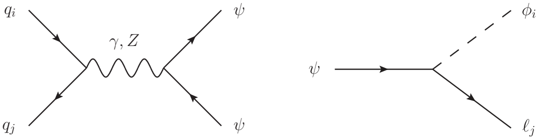
(a) invisible Higgs decays



(b) electron MDM $(g-2)_e$



(c) Z–ℓ vertex corrections



(d) collider searches

Global analysis setup

Few technical details

- minimise χ^2-function

$$\chi^2 = \left(\vec{\mathcal{O}}_{\text{th}}(\xi_i) - \vec{\mathcal{O}}_{\text{exp}}\right)^T C^{-1} \left(\vec{\mathcal{O}}_{\text{th}}(\xi_i) - \vec{\mathcal{O}}_{\text{exp}}\right)$$

- constraints from collider searches, observed DM relic density, detection experiments, the electron MDM, invisible Higgs decays and Z–ℓ vertex corrections
- flavour-conserving case with $\theta_{ij} = 0$, i.e. no relevant limits from LFV decays

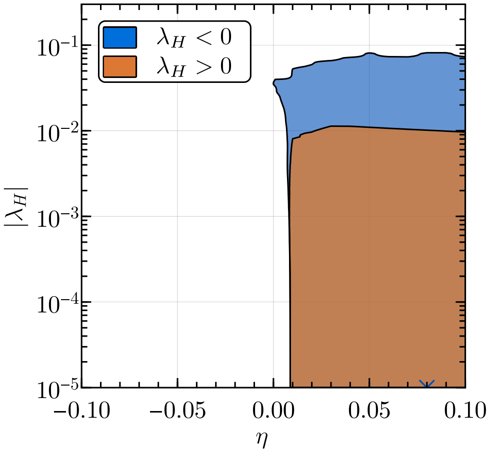
Two benchmark cases for $(g-2)_\mu$

1. it exhibits a 5.1σ anomaly, i.e. $\Delta a_\mu^{\text{exp,dat}} = (2.49 \pm 0.48) \times 10^{-9}$
2. it is SM-like at 1.6σ, i.e $\Delta a_\mu^{\text{exp,lat}} = (1.05 \pm 0.62) \times 10^{-9}$

Results

Anomaly scenario

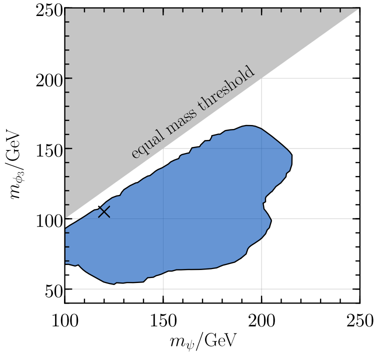
- destructive interference in σ_{SI}^N for $\lambda_H < 0$: λ_H may grow as large as 10^{-1}
- opening the Higgs portal alone not sufficient, $\eta > 0$ necessary to fit $(g-2)_\mu$
- overall goodness of fit indicates resolution of $(g-2)_\mu$ puzzle



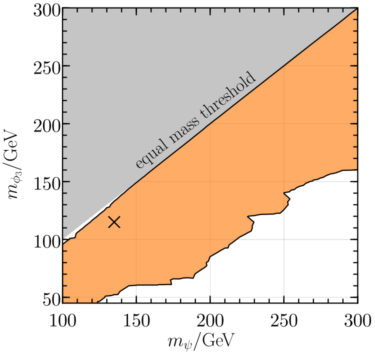
Acaroğlu, MB, Tabet (2023)

Comparison of $(g-2)_\mu$ benchmarks

$(g-2)_\mu$ anomaly scenario



SM-like $(g-2)_\mu$ scenario



- both scenarios describe experimental data equally well at low scales: $\chi^2/\text{ndf} \simeq 6/7$
- larger DM and mediator masses possible in SM-like $(g-2)_\mu$ scenario

Summary

Flavoured dark matter

- elegant and potent connection between dark sector and SM flavour structure
- reconciliation of WIMP hypothesis with the absence of signal
- very rich phenomenology

Lepton-flavoured scalar dark matter

- can be realised at the EW scale and is thus in the reach of LHC searches
- Higgs portal interactions severely alter the phenomenology
- NP resolution of $(g-2)_\mu$ puzzle possible, but SM-like $(g-2)_\mu$ equally consistent with low DM and mediator masses