Flavoured Majorana Dark Matter: From Freeze-Out to the LHC

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Collaborative Research Center TRR 257
Particle Physics Phenomenology after the Higgs Discovery

The Flavour Path to New Physics
Zurich – June 7, 2024

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 (DM) 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?

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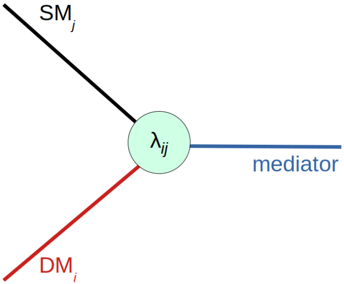
Assumptions

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



Simplified models as tools to approach big puzzles

Fundamental UV-complete theory

- theoretical description up to high energy scales, based on fundamental symmetries
- addresses fundamental puzzles
- phenomenologically challenging: non-trivial connection to observables

Simplified models

- contain minimal set of relevant particles and interactions
- useful tool for efficient phenomenological studies
- constraints on classes of UV-complete theories

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

- Majorana fermion flavoured DM coupled to right-handed up-type quarks
- Dark Minimal Flavour Violation (DMFV)

  Agrawal, MB, Gemmler (2014)
  - dark flavour symmetry $O(3)$
  - broken only by new coupling matrix λ
- ➢ minimal step beyond MFV

talk based on:

Acaroğlu, MB (2021)
Acaroğlu, MB, Heisig, Krämer, Rathmann (2023)
illustrations: Heisig @ MoriondEW 2024

The model

Model basics

The model

ACAROĞLU, MB (2021)

$$\mathcal{L}_{\text{dark}} = \frac{1}{2}\left(i\bar{\chi}\not{\partial}\chi - M_\chi\bar{\chi}\chi\right) - \left(\lambda_{ij}\bar{u}_{Ri}\chi_j\phi + \text{h.c.}\right) + (D_\mu\phi)^\dagger(D^\mu\phi) - m_\phi^2\phi^\dagger\phi - V(\phi, H)$$

- Majorana fermion χ: gauge singlet, triplet under new approx. flavour symmetry $O(3)_\chi$
- complex scalar ϕ: colour & hypercharge, couples DM to right-handed up-type quarks
- flavour-violating coupling matrix λ with 15 parameters

$$\lambda = UDOd$$

U: unitary, O: orthogonal, d: Majorana phases, $D = \text{diag}(D_1, D_2, D_3)$ diagonal

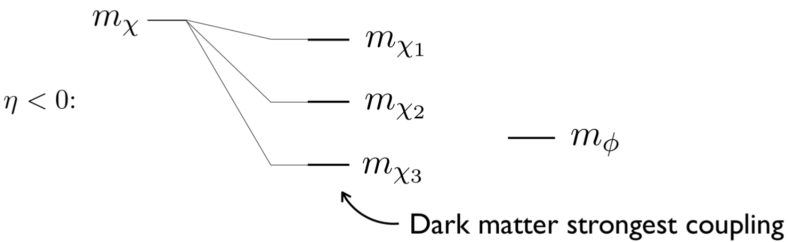
- $\mathbb{Z}_2$ symmetry: χ and ϕ odd to stabilise DM

DMFV and the mass spectrum

DMFV ansatz ties DM mass spectrum to coupling strength via spurion expansion

$$m_{\chi_i} = m_\chi(\mathbb{1} + \eta\,\mathrm{Re}(\lambda^\dagger\lambda) + \dots)_{ii} \simeq m_\chi\left[1 + \eta\, D_i^2\right]$$

Standard hierarchy



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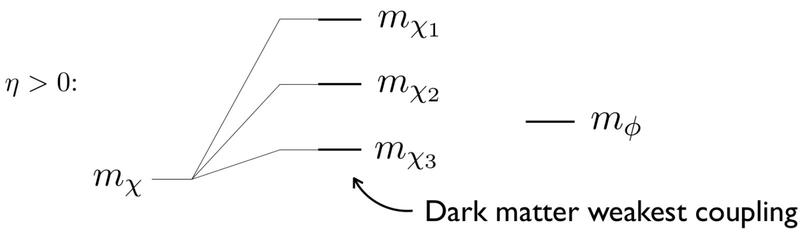
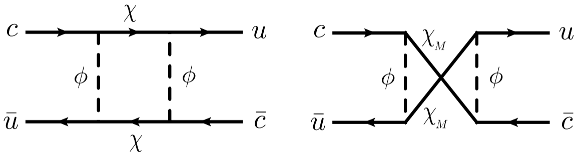
Inverse hierarchy



Experimental constraints

Acaroğlu, MB (2021)

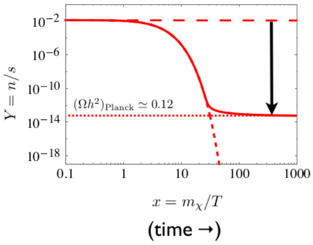
- **flavour constraints:** neutral D meson mixing

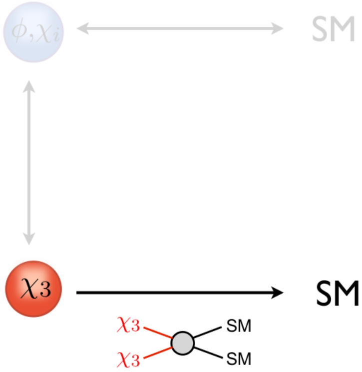


- **direct detection limits:** latest results from LZ experiment
- **indirect detection constraints:** cosmic-ray antiproton flux from AMS-02
- **DM relic density:** different possible freeze-out scenarios
- **LHC searches:** depending on dark spectrum

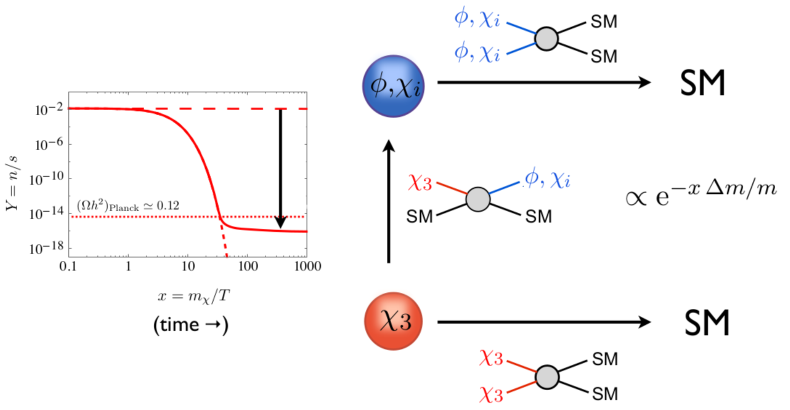
Freeze-out

DM freeze-out scenarios I: standard WIMP freeze-out



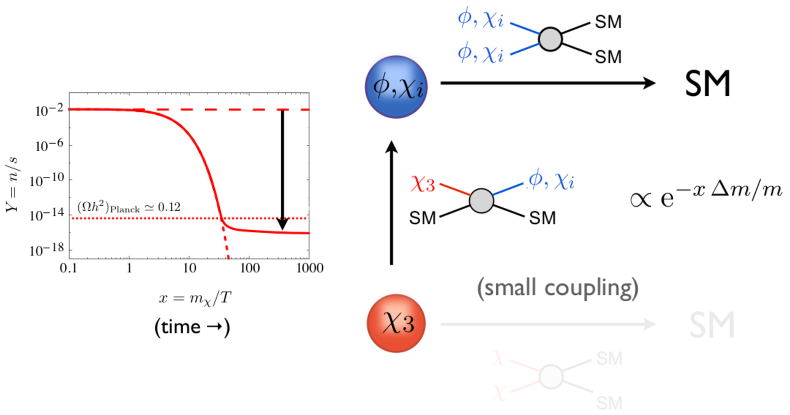


DM freeze-out scenarios II: coannihilation



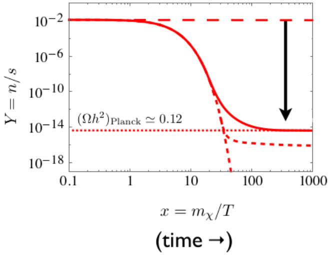
Griest, Seckel (1991); Bell, Cai, Medina (2013)

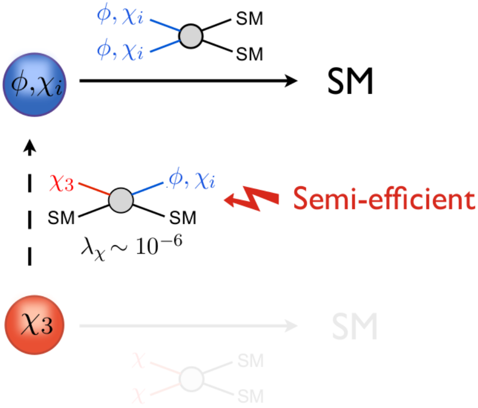
DM freeze-out scenarios II: coannihilation



Griest, Seckel (1991); Bell, Cai, Medina (2013)

DM freeze-out scenarios III: conversion-driven





Garny, Heisig, Lülf, Vogl (2017); D'Agnolo, Pappadopulo, Ruderman (2017)

Canonical freeze-out

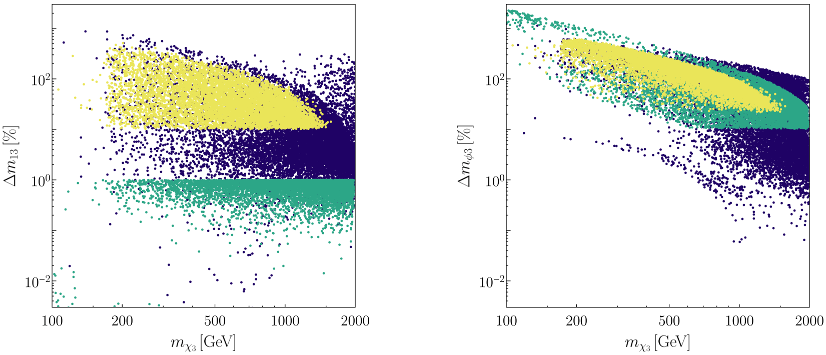
large couplings: efficient conversions between all $\mathbb{Z}_2$-odd particles ➢ thermal equlibrium

Scenarios

Acaroğlu, MB (2021); Acaroğlu, MB, Heisig, Krämer, Rathmann (2023)

- Single Flavour Freeze-Out (SFF)
  - significant mass splitting $(> 10\%)$ between χ_3 and other odd particles
  - standard WIMP scenario, coannihilations irrelevant
- Quasi-Degenerate Freeze-Out (QDF)
  - small mass splitting $(< 1\%)$ between χ_i flavours
  - all flavours contribute equally to freeze-out, according to their couplings
- Generic Canonical Freeze-Out (GCF)
  - no constraint on mass spectrum
  - captures relevant coannihilation effects

Canonical freeze-out scenarios – viable parameter space



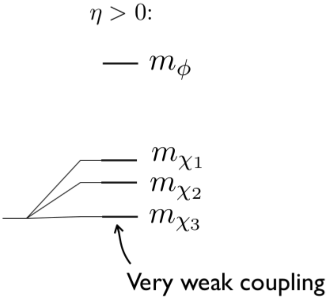
- coannihilation effects open up significant region of parameter space
- quasi-degenerate mediator ϕ dilutes relic abundance due to QCD annihilations

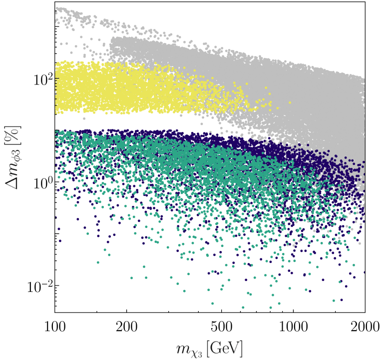
Acaroğlu, MB, Heisig, Krämer, Rathmann (2023)

Conversion-driven freeze-out

Scenarios

- $\chi_2\chi_3$-conversion ($C_\chi 1_u$)



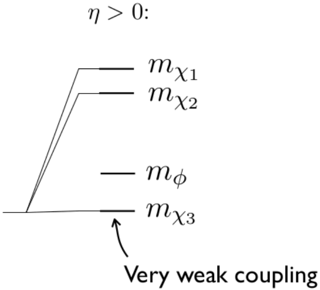


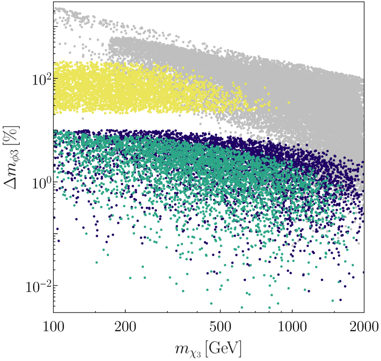
Acaroğlu, MB, Heisig, Krämer, Rathmann (2023)

Conversion-driven freeze-out

Scenarios

- $\chi_2\chi_3$-conversion ($C_\chi 1_u$)
- $\chi_3\phi$-conversion ($C_\phi 1_u$)





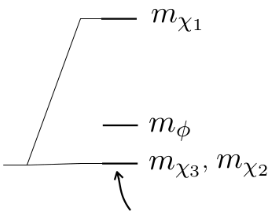
Acaroğlu, MB, Heisig, Krämer, Rathmann (2023)

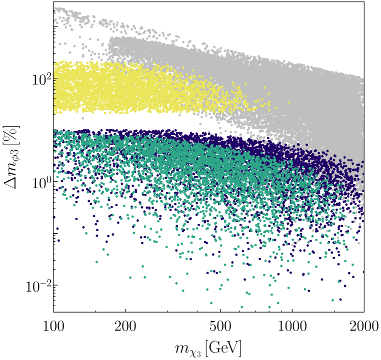
Conversion-driven freeze-out

Scenarios

- $\chi_2\chi_3$-conversion ($C_\chi 1_u$)
- $\chi_3\phi$-conversion ($C_\phi 1_u$)
- $\chi_{2,3}\phi$-conversion ($C_\phi 2_u$)

$\eta > 0$:





Acaroğlu, MB, Heisig, Krämer, Rathmann (2023)

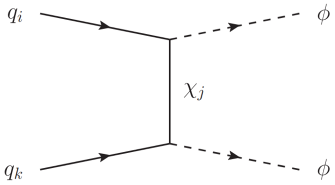
LHC signatures

Relevant LHC processes

Mediator pair-production

- QCD interactions (c.f. SUSY squarks)
- t-channel exchange of χ
- same-sign production due to Majorana nature of χ ➢ **enhanced** for $uu \to \phi\phi$

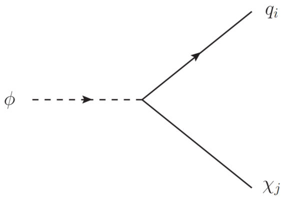
see also Garny, Ibarra, Pato, Vogl (2013)



Acaroğlu, MB (2021)
Acaroğlu, MB, Heisig, Krämer, Rathmann (2023)

Mediator decay

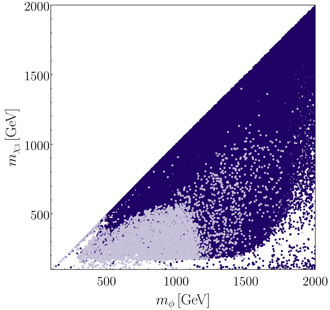
- determined by flavour structure of λ



- final states involving u, c, t and $\not{E}_T$
- chain decays via intermediate $\chi_{1,2}$ states
- soft and long-lived signatures for quasi-degenerate spectrum and/or small couplings

Current constraints – using SModels v2

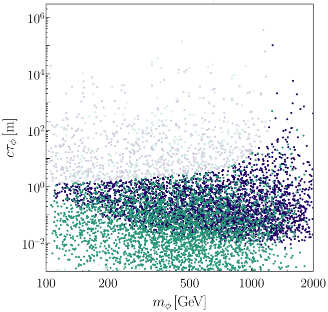
Canonical freeze-out



- relevant searches: jets+$\not{E}_T$, tops+$\not{E}_T$
- increased reach due to same-sign channel

Acaroğlu, MB, Heisig, Krämer, Rathmann (2023)

Conversion-driven freeze-out (C_ϕ)



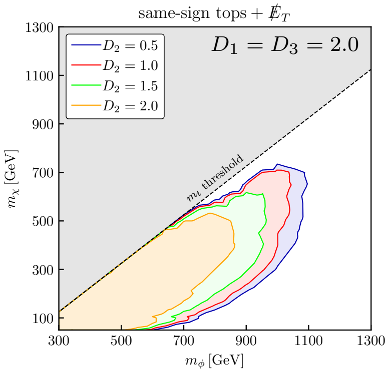
- relevant limit: stable R-hadrons
- intermediate lifetimes not constrained
  ➢ **opportunity** for future LLP searches

Majorana-specific signatures I: same-sign tops

Same-sign top signature ACAROĞLU, MB (2021)

$$pp \to \phi\phi \to tt + \not{E}_T$$

- top charges accessible in dilepton final states
- cross-section in the fb regime



Naive reach estimate using CMS $ttjj + \not{E}_T$ search

- different kinematics ➢ not fully applicable
- highest reach for non-zero DM mass
- rate suppressed by BR$(t \to b\ell\nu)^2 \sim 0.05$ and requirement of extra jets

➢ **not competitive** (?) **with jets+$\not{E}_T$**

ACAROĞLU, MB, HEISIG, KRÄMER, RATHMANN (2023)

Majorana-specific signatures II: single-top charge asymmetry

Single-top signature and charge asymmetry

- flavoured DM ➢ flavour-violating LHC final states

  MB, Kast (2017)

- proposed $tj + \not{E}_T$ search with significant reach

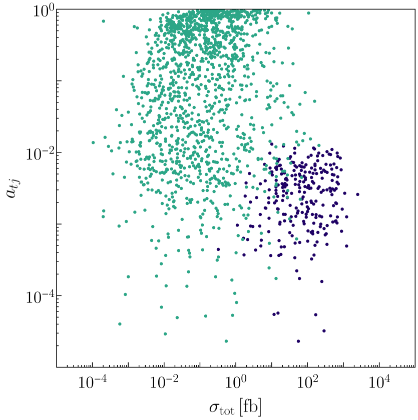
  MB, Pani, Polesello, Rovedi (2020)

- consider single-top charge asymmetry

$$a_{tj} = \frac{\sigma(tj + \not{E}_T) - \sigma(\bar{t}j + \not{E}_T)}{\sigma(tj + \not{E}_T) + \sigma(\bar{t}j + \not{E}_T)}$$

- $a_{tj} > 0$ only for Majorana flavoured DM

➢ **highly promising smoking gun signature!**



Acaroğlu, MB, Heisig, Krämer, Rathmann (2023)

Conclusions

Flavored Majorana dark matter

- potential link between flavour and dark matter puzzles
- rich phenomenology in direct & indirect detection, flavour and collider physics
- large regions of viable parameter space

Dark matter freeze-out scenarios

- canonical
  - standard WIMP
  - coannihilation
- conversion-driven
  - different possibilities depending on flavour structure

LHC signatures

- current gaps in LHC searches
  - complex decay chains, esp. with soft final states
  - long-lived particles (intermediate lifetimes)
  - flavour-violating final states
- Majorana-specific signatures
  - same-sign tops suffer from small BR$(t \to b\ell\nu)$
  - single-top charge asymmetry promising