# Flavored Dark Matter

## Freeze-out scenarios and LHC signatures

*based on 2312.09274*
*in collaboration with H. Acaroğlu, M. Blanke, M. Krämer, L. Rathmann*

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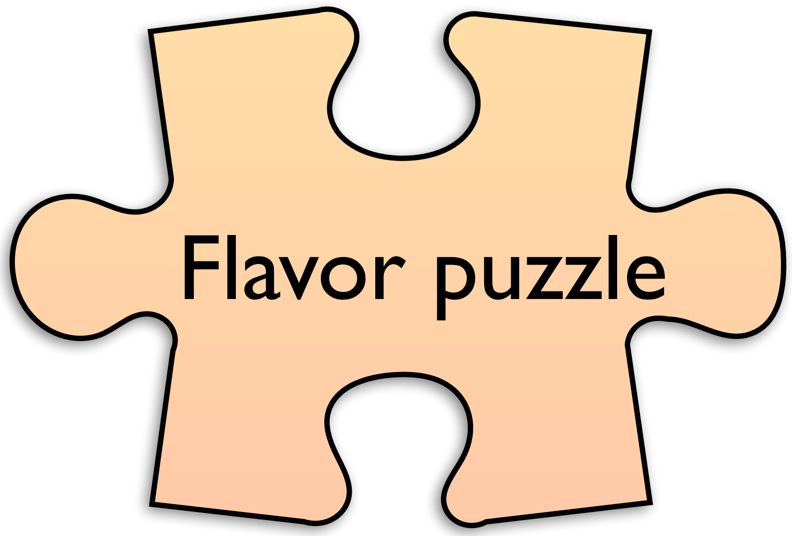
Institute for Theoretical Particle Physics and Cosmology | RWTH AACHEN UNIVERSITY

Alexander von HUMBOLDT STIFTUNG

*Moriond EW 2024*
*March 24 - 31, 2024*

# What’s the underlying principle of matter?



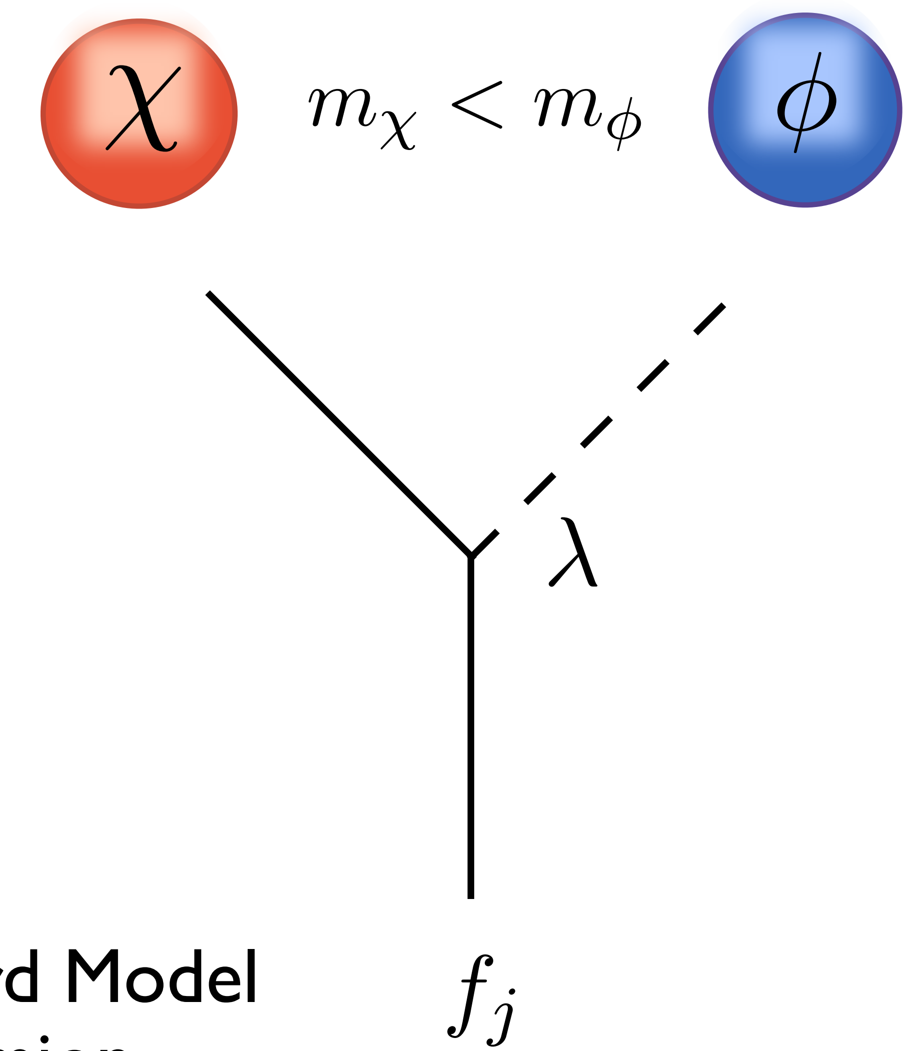


## Flavored Dark Matter

- Framework to study their links
- Reconcile WIMP hypothesis
- Rich phenomenology

# $t$-channel mediator Dark Matter

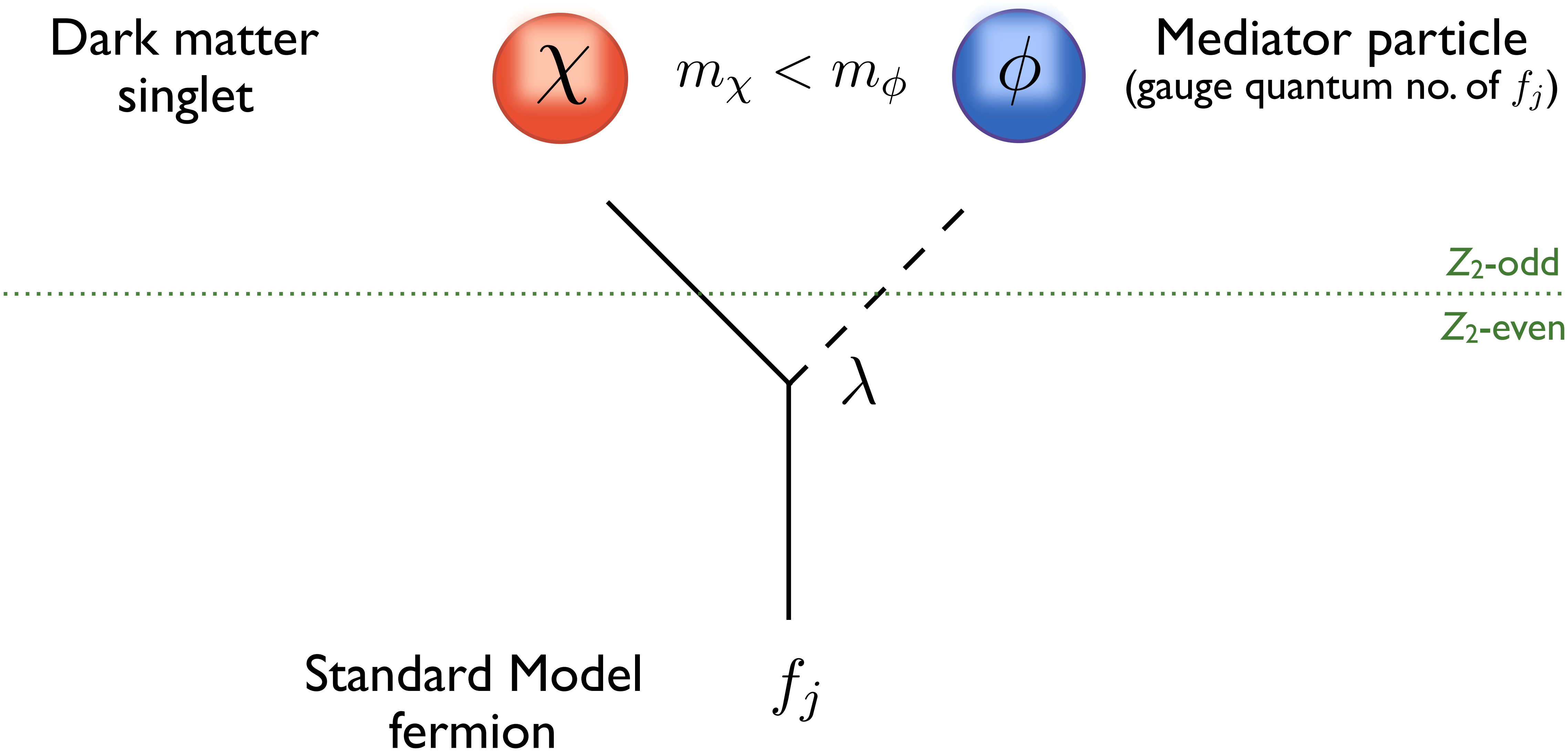
Dark matter singlet



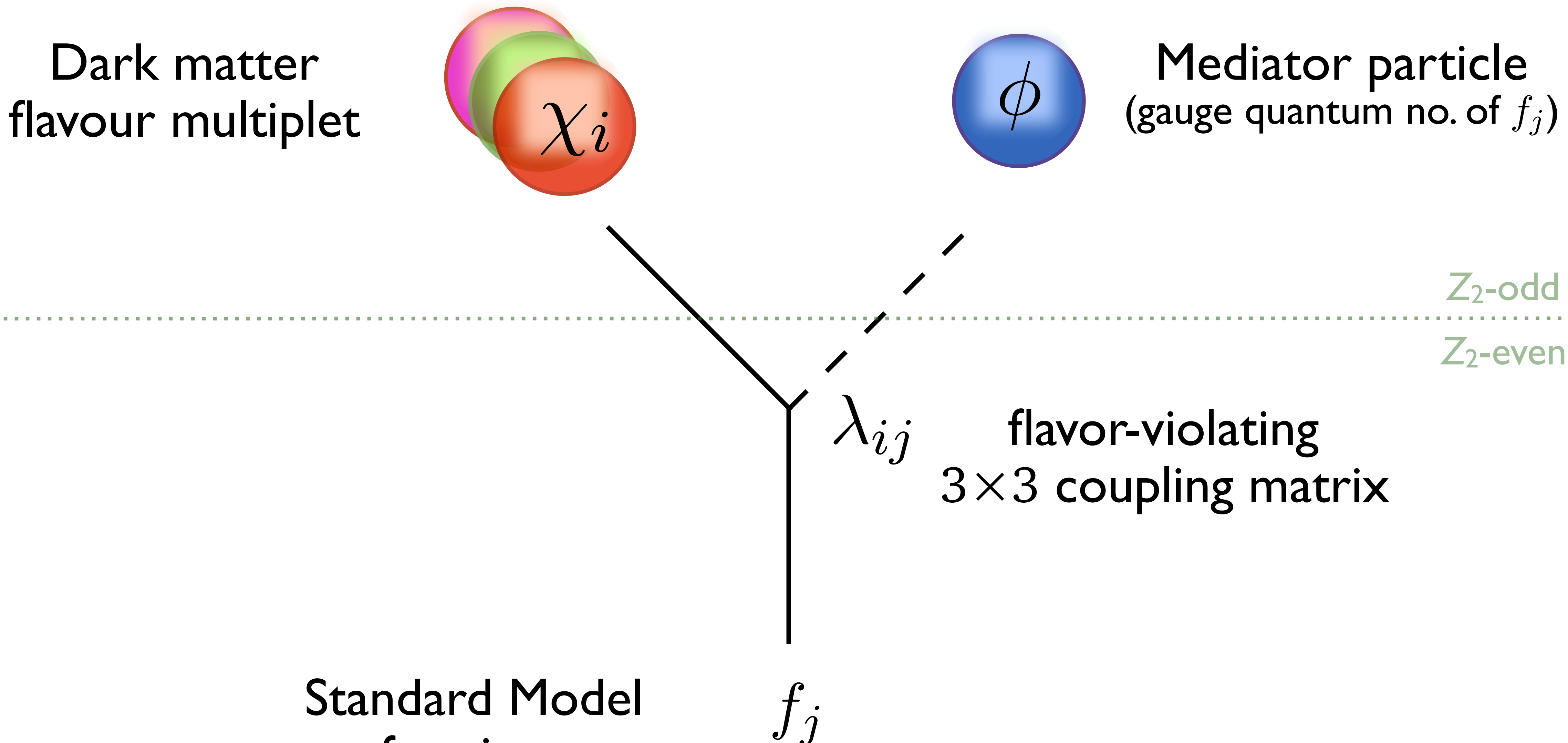

Mediator particle
(gauge quantum no. of $f_j$)

Standard Model fermion

# *t*-channel mediator Dark Matter



# Flavored Dark Matter



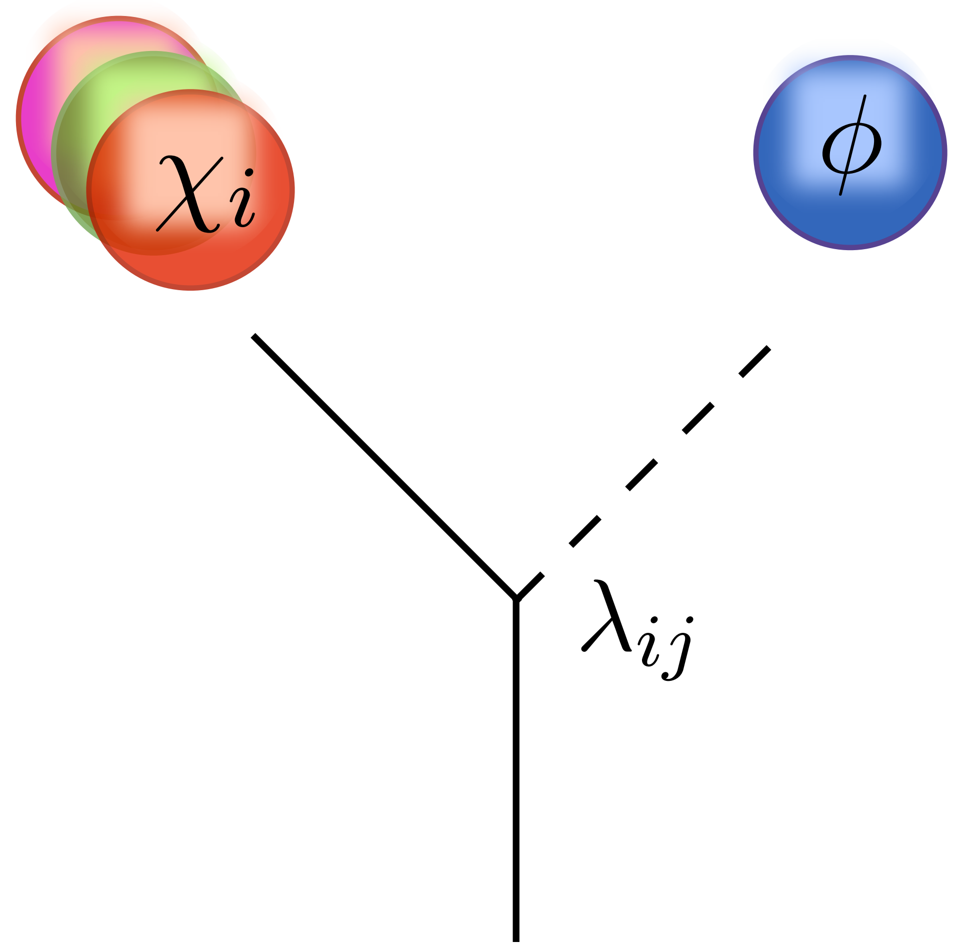

[*early accounts on the subject:* J. Kile, A. Soni 2011; B. Batell, J. Pradler, M. Spannowsky 2011; J. F. Kamenik, J. Zupan 2011; P. Agrawal, S. Blanchet, Z. Chacko, C. Kilic 2011; A. Kumar, S. Tulin 2013; B. Batell, T. Lin, L.-T. Wang 2013]

# Flavored Dark Matter

Dark matter
flavour multiplet

*Fermion/Scalar*

*Dirac/Majorana*




Mediator particle
(gauge quantum no. of $f_j$)

*Scalar/Fermion*

Standard Model
fermions

$u_j, d_j, Q_j, e_j, L_j$

➔ Total of 20 cases

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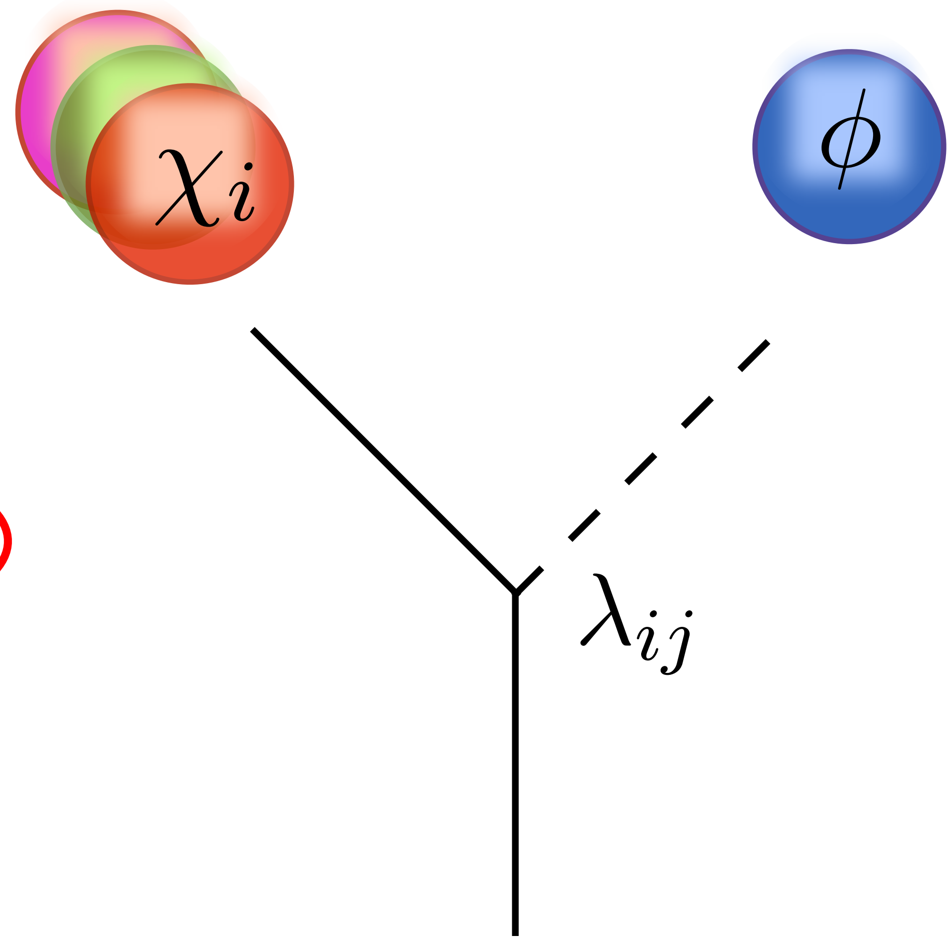


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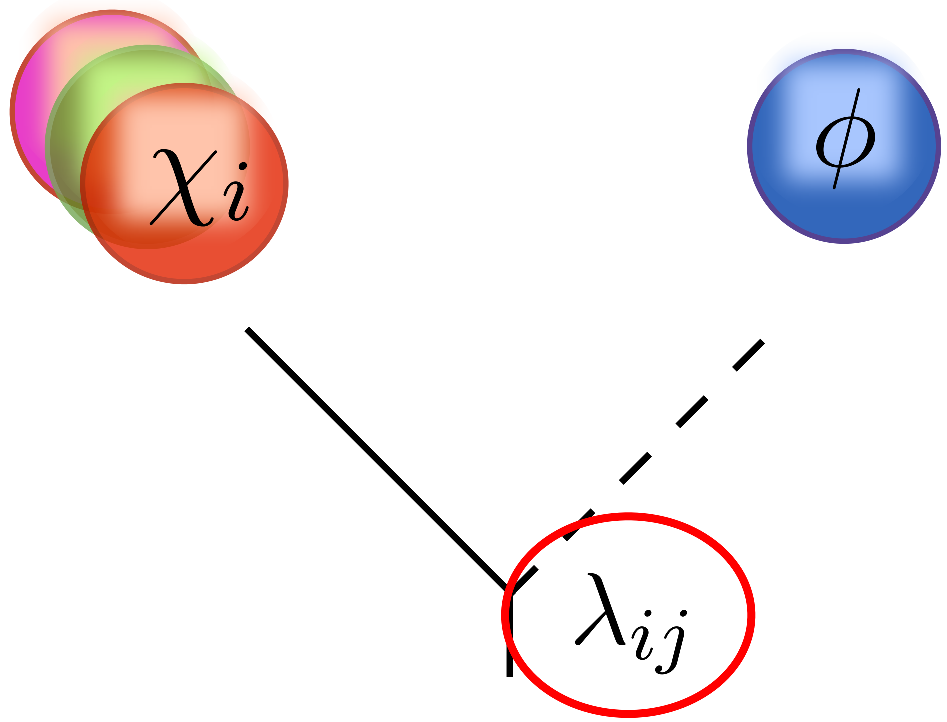


Mediator particle
(gauge quantum no. of $f_j$)

## Dark Minimal Flavor Violation (DMFV):

[Agrawal, Blanke, Gemmler 1405.6709]

- Step beyond Minimal Flavor Violation (MFV)
- Dark flavor symmetry:
  $U(3)$ (Dirac), $O(3)$ (Majorana)

# Model Lagrangian

$$\mathcal{L} \supset -\left(\lambda_{ij}\bar{u}_{Ri}\chi_j\phi + \text{h.c.}\right) + \left|D_\mu\phi\right|^2$$

$$-\frac{M_\chi}{2}\bar{\chi}\chi - m_\phi^2\left|\phi\right|^2 + \lambda_{H\phi}\phi^\dagger\phi H^\dagger H$$

# Particle spectrum

$$\mathcal{L} \supset -\left(\lambda_{ij}\bar{u}_{Ri}\chi_j\phi + \text{h.c.}\right) + |D_\mu\phi|^2$$

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DMFV

$$M_\chi = m_\chi\left[\mathbb{1} + \eta\,\text{Re}(\lambda^\dagger\lambda) + \mathcal{O}(\lambda^4)\right] = \text{diag}(m_{\chi_1}, m_{\chi_2}, m_{\chi_3})$$

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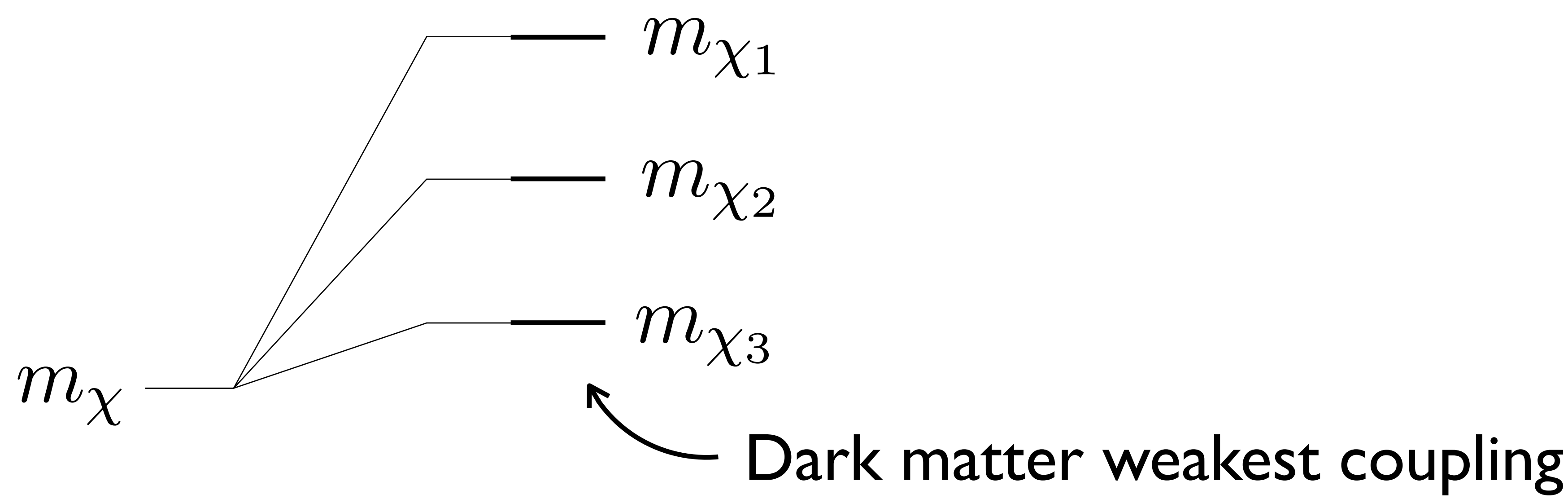
$\eta > 0$:



# Particle spectrum

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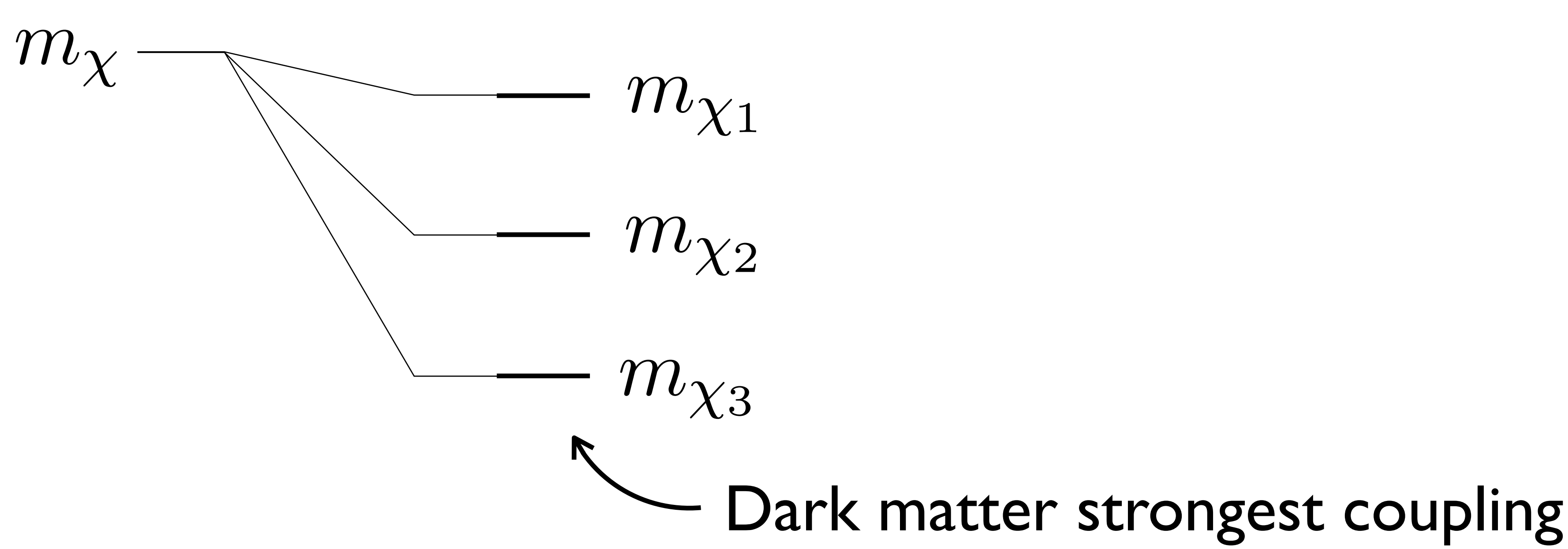
$\eta < 0$:



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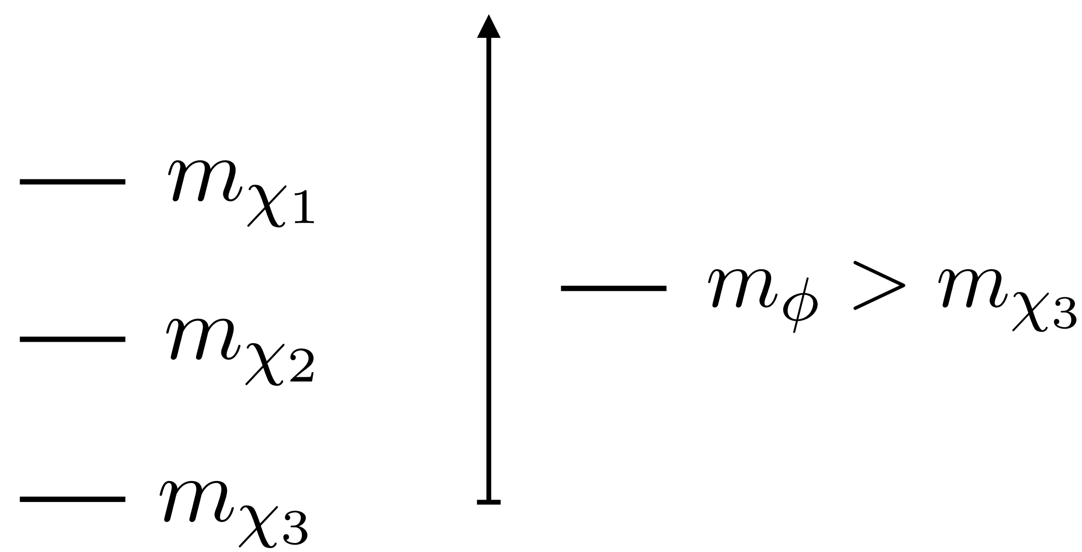
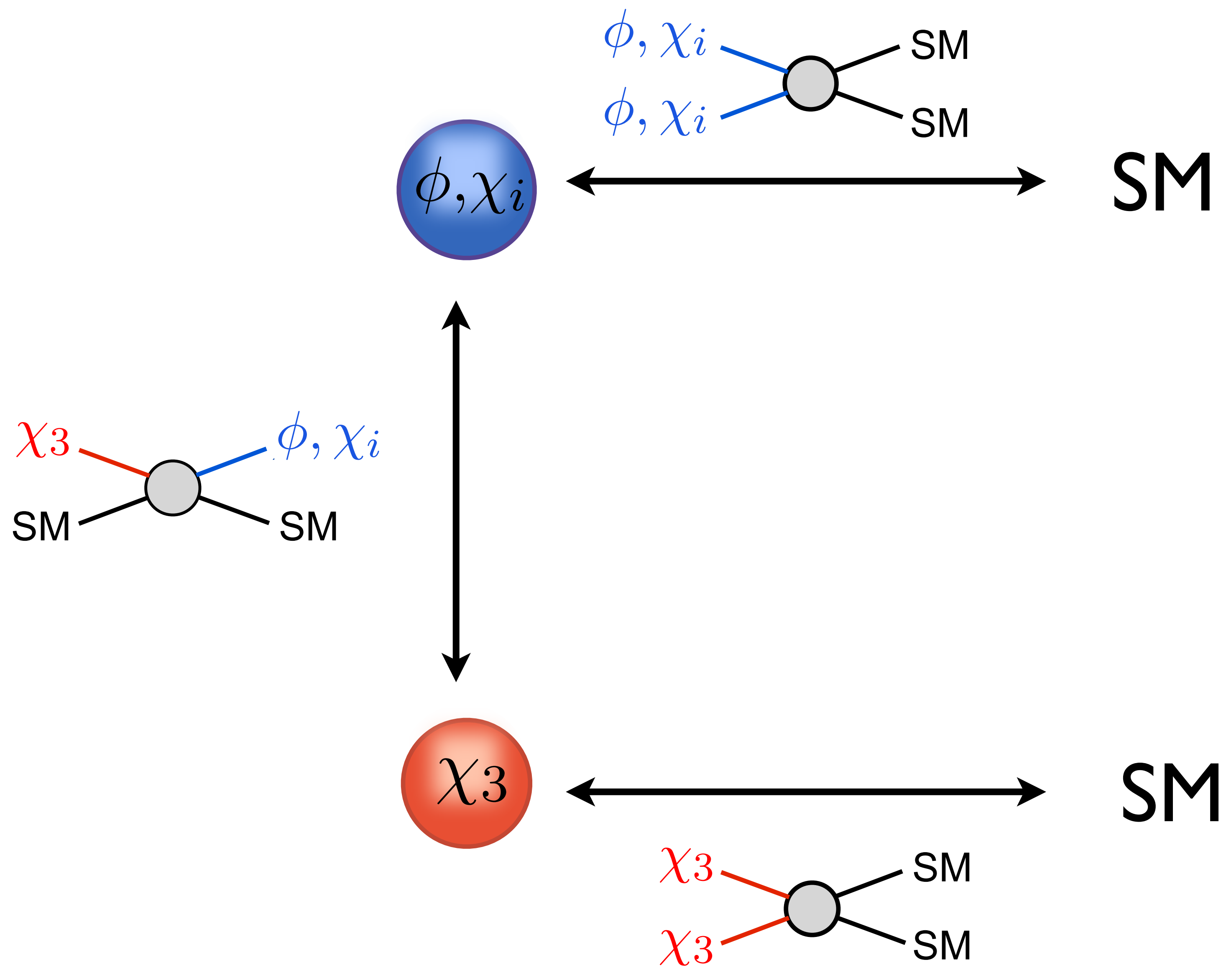
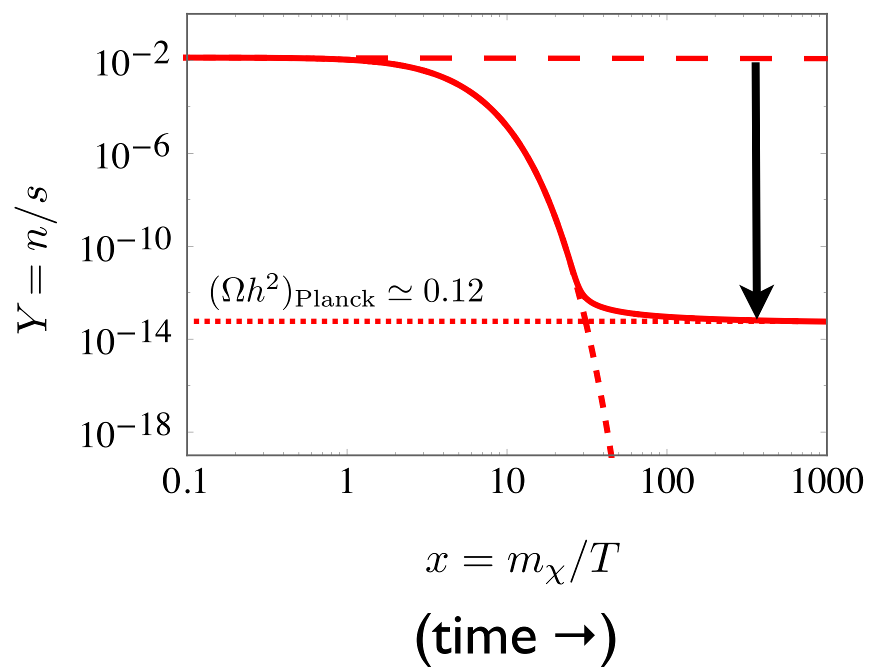


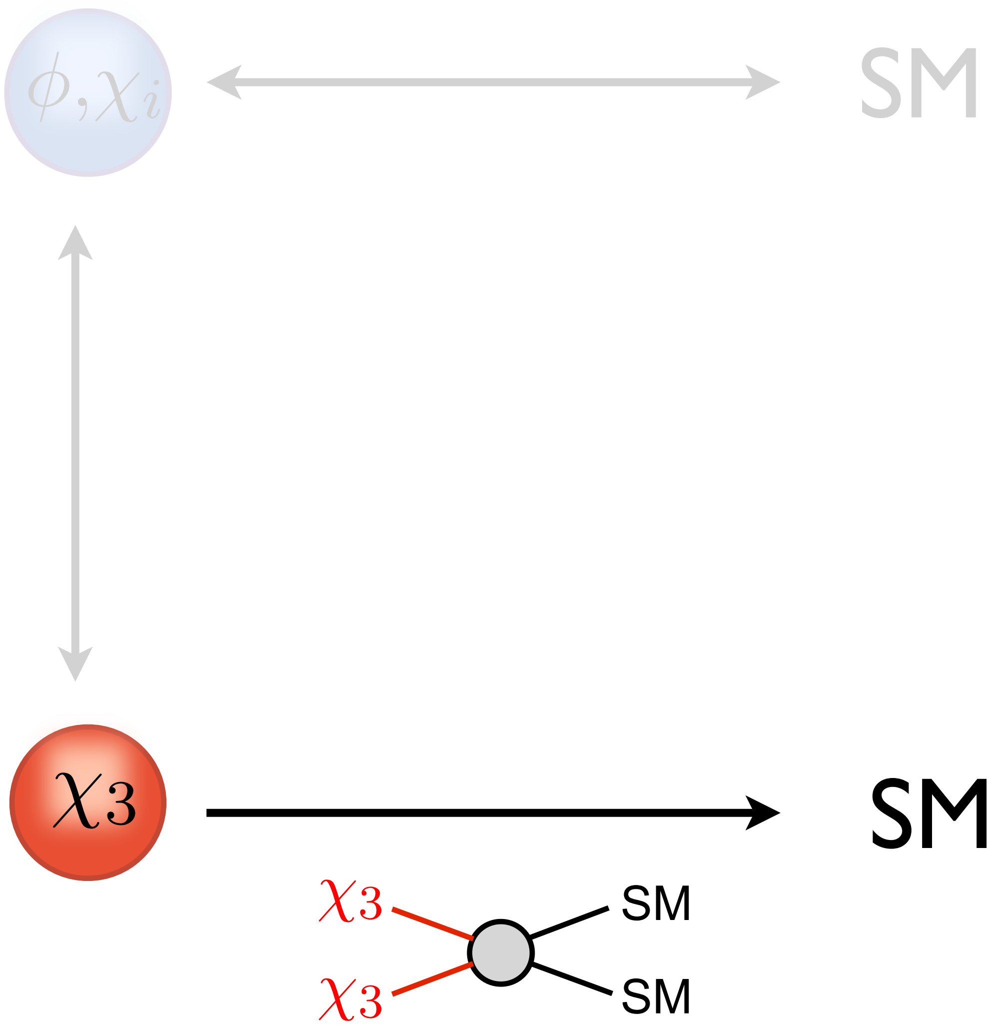
# Freeze-out scenarios

# Thermal processes

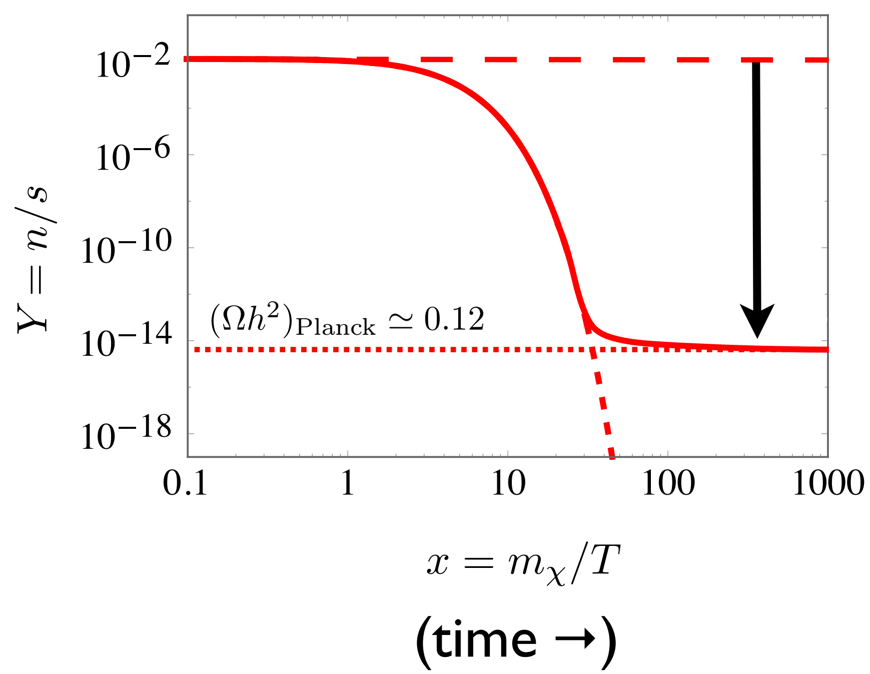


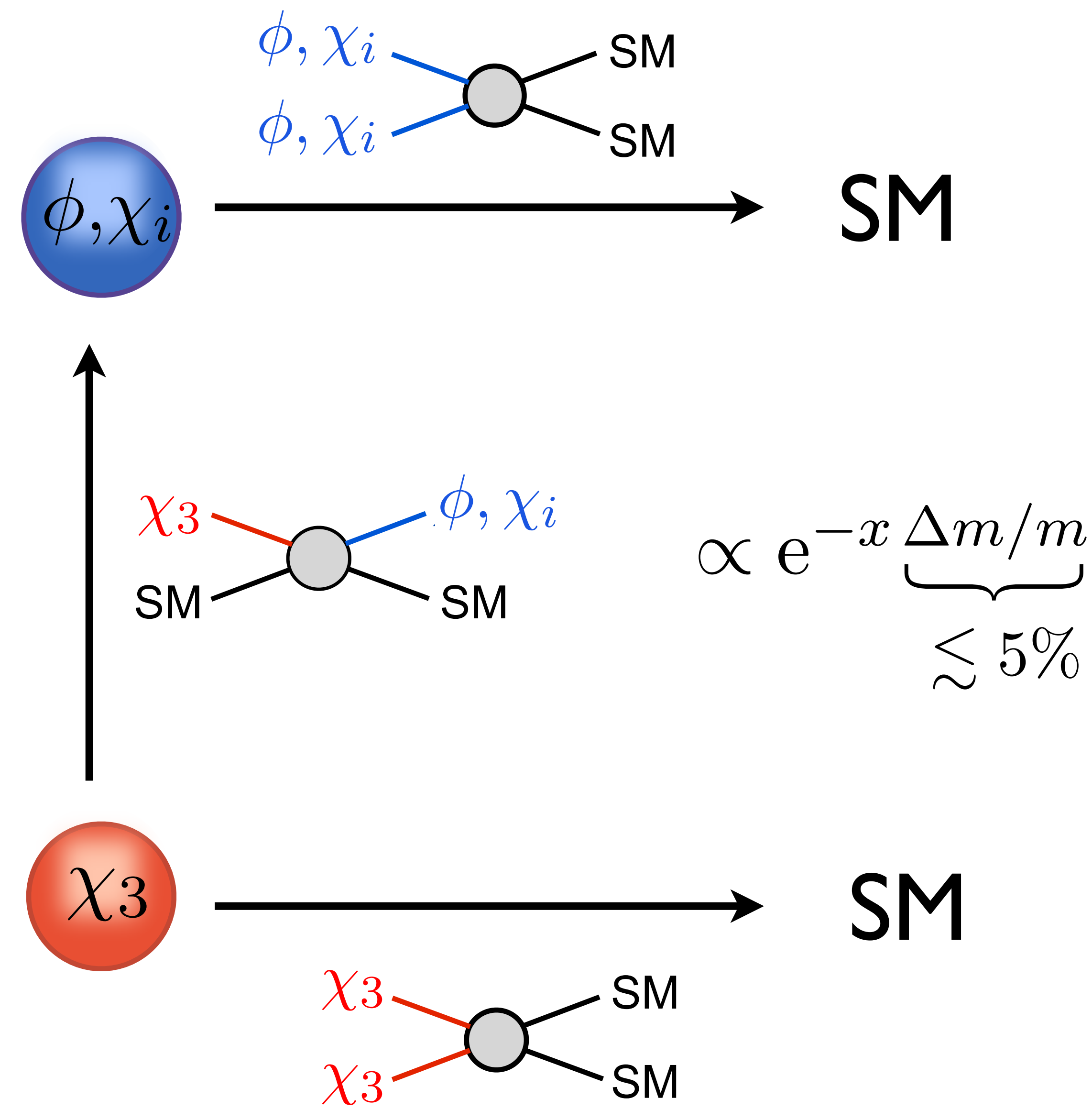
# WIMP freeze-out



# Coannihilation



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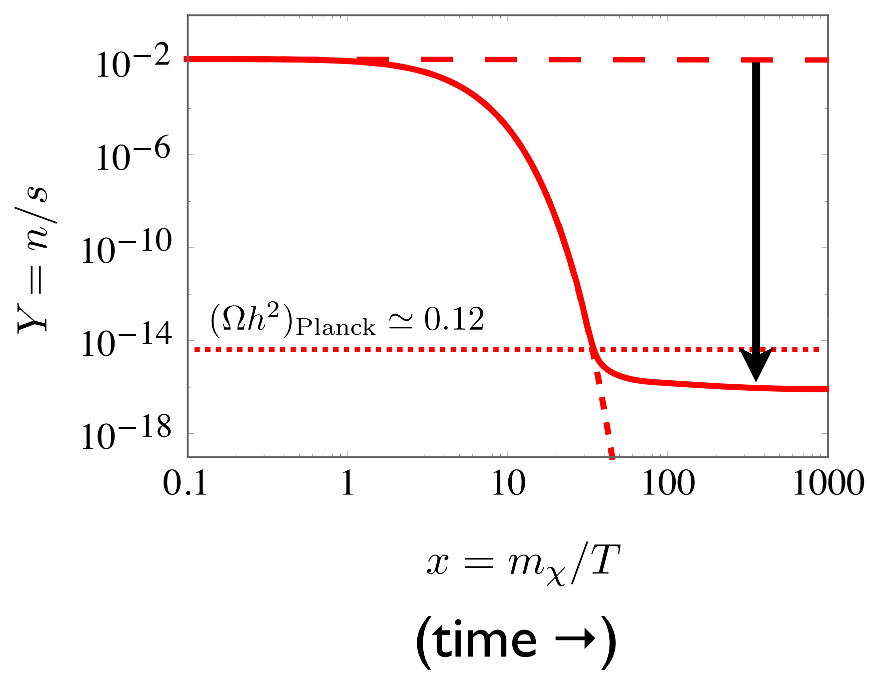


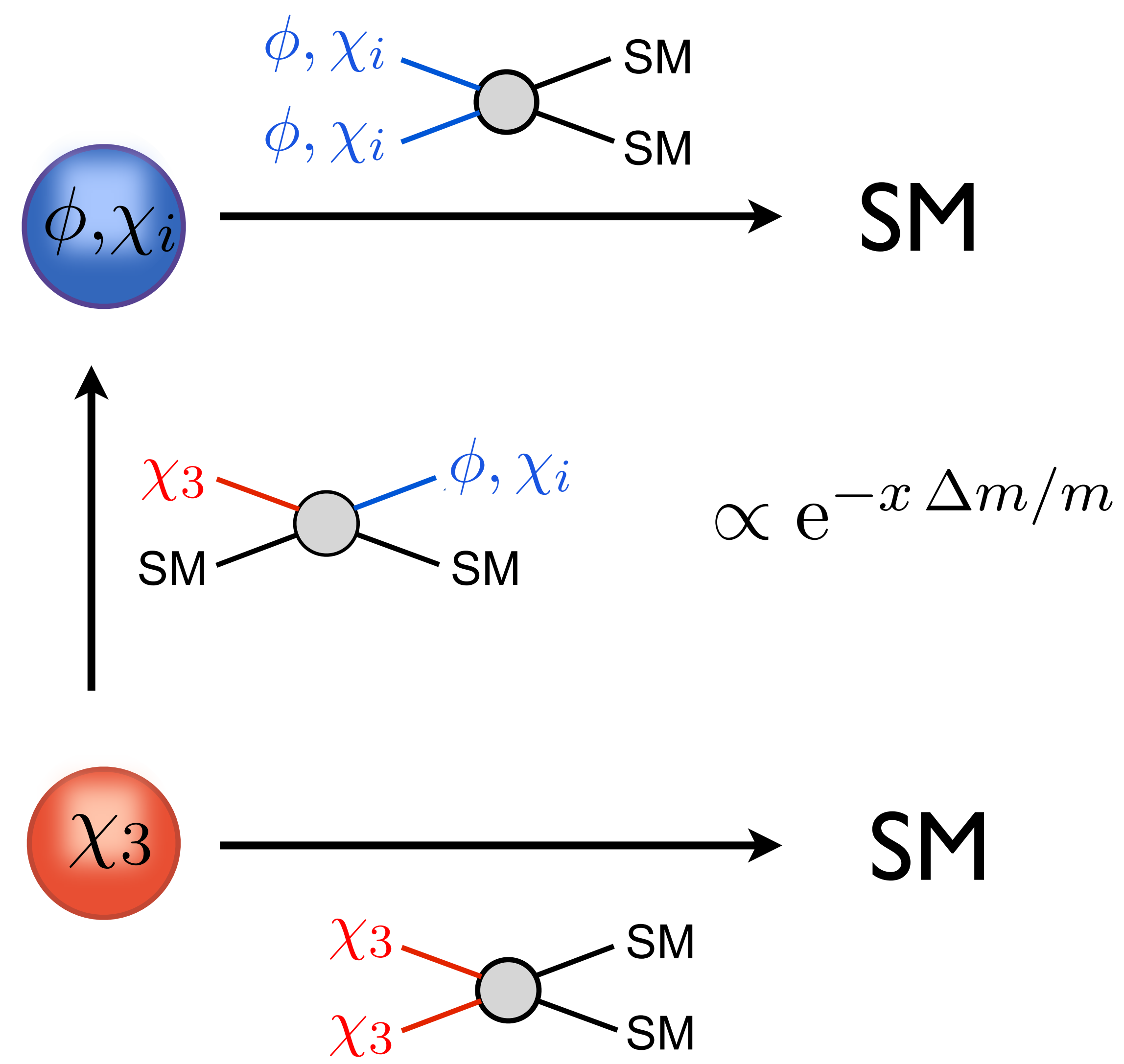

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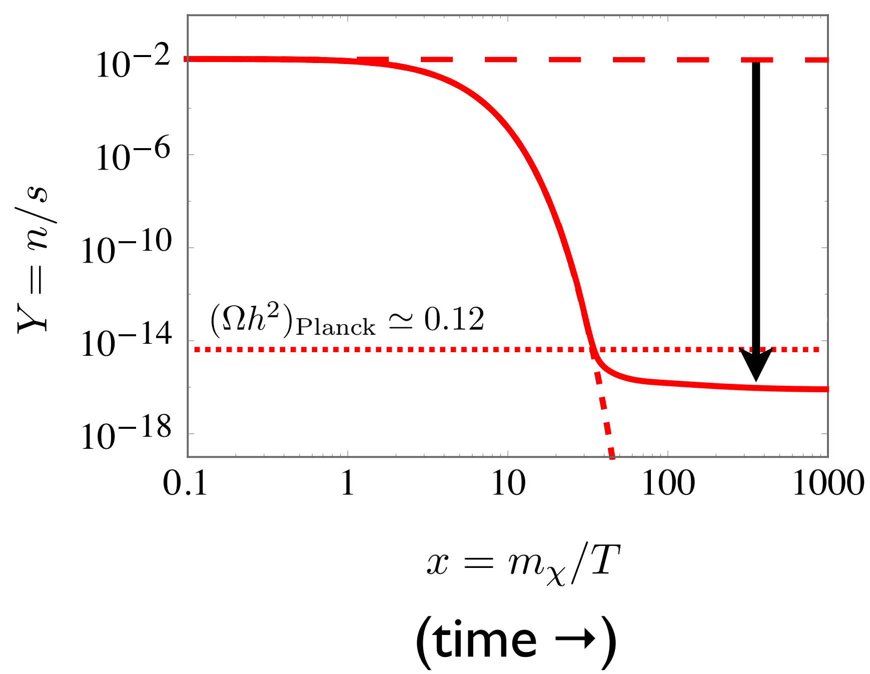
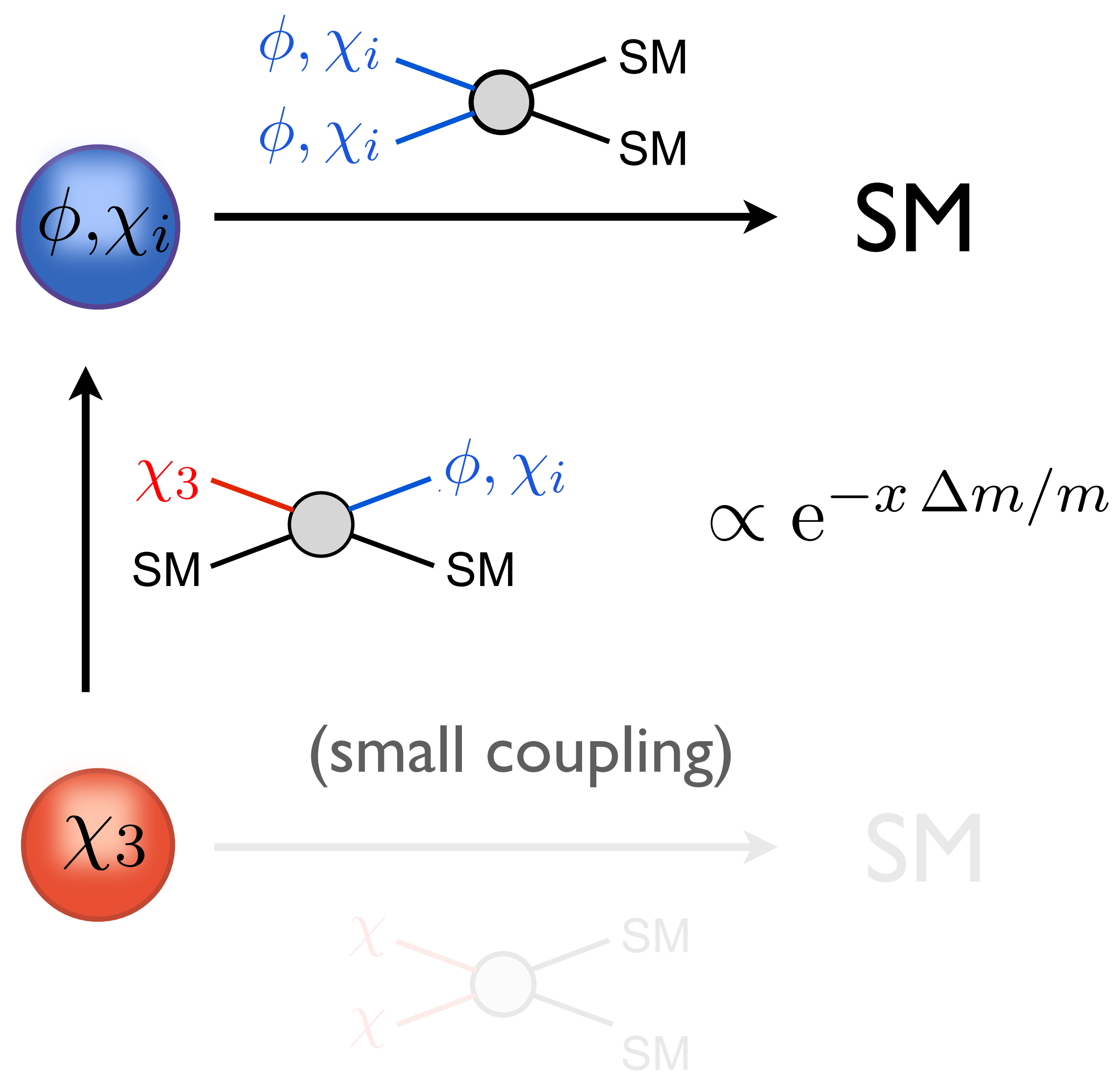
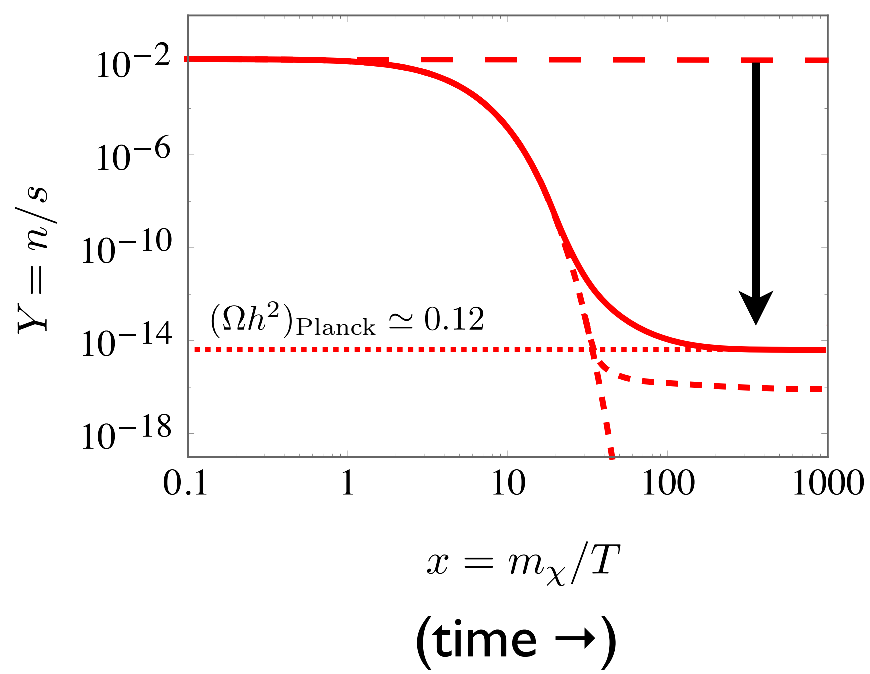
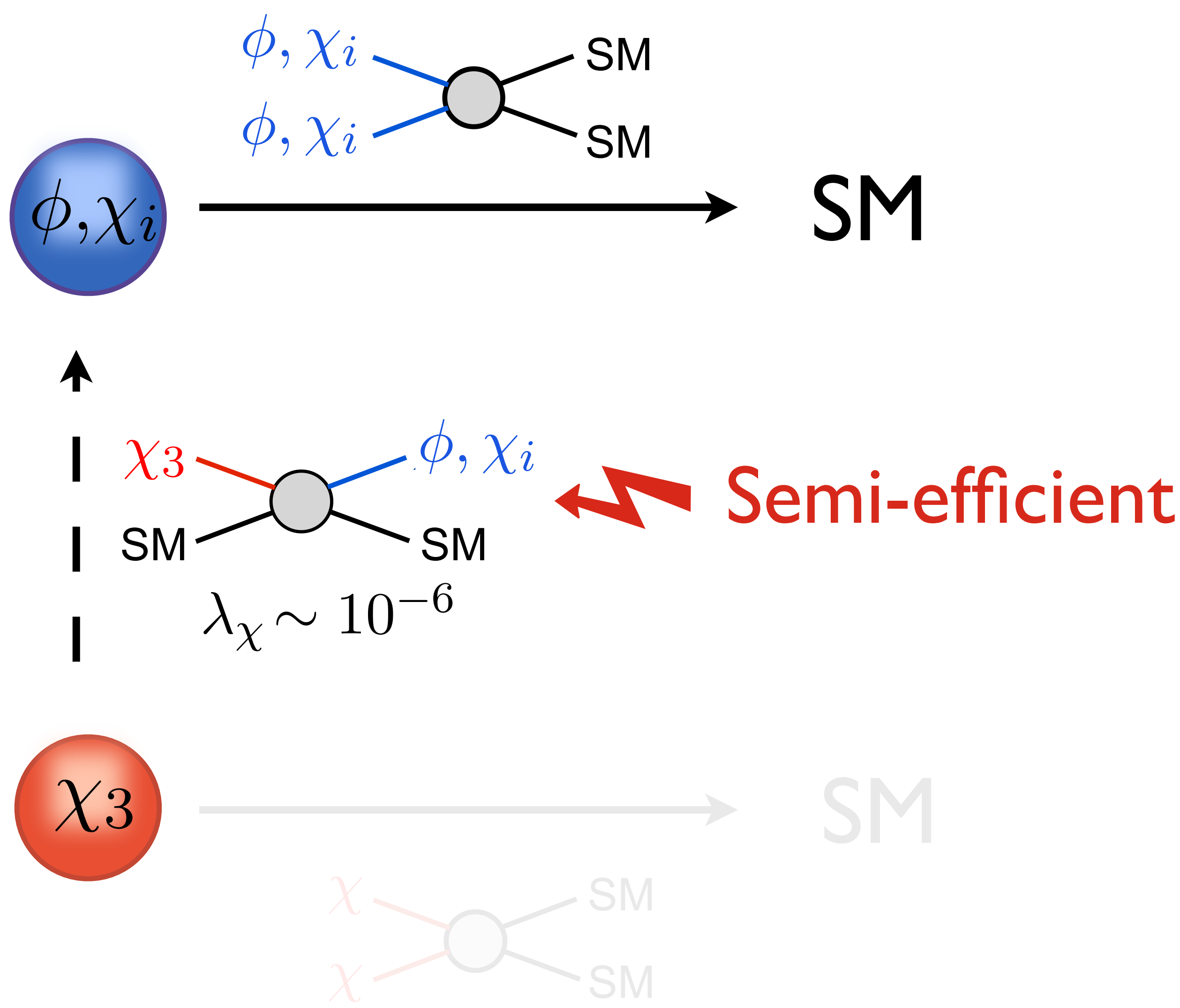


# Conversion-driven freeze-out / coscattering

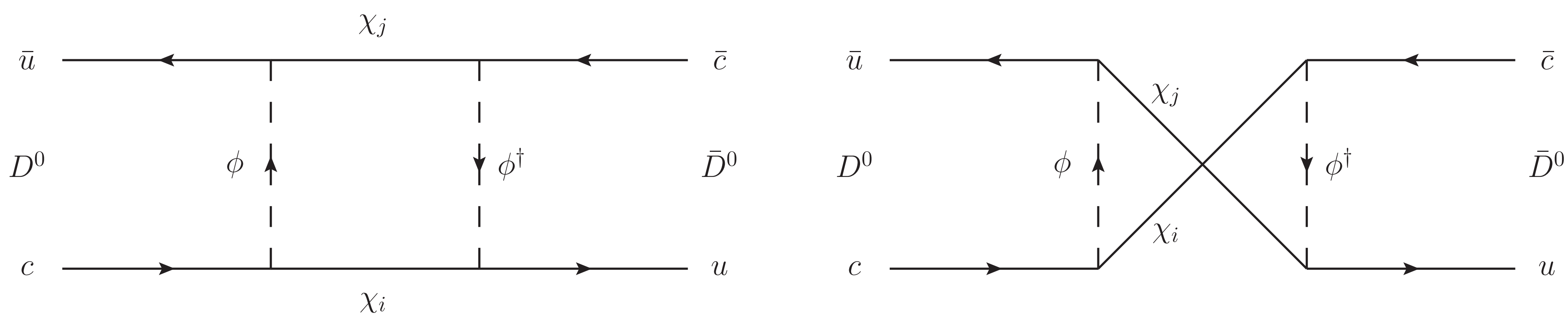
[Garny, JH, Lülf, Vogl 1705.09292; D'Agnolo, Pappadopulo, Ruderman 1705.08450]



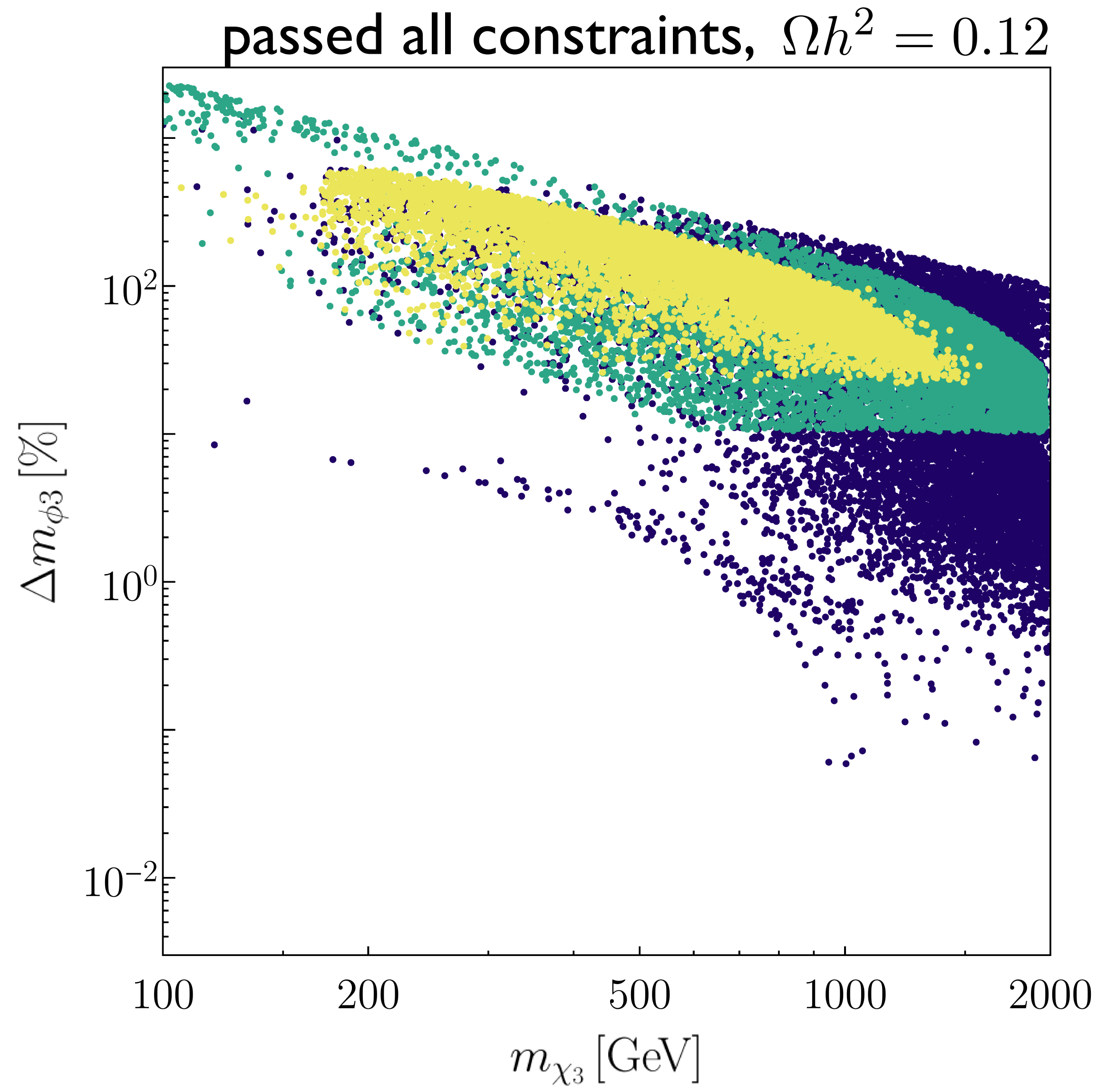
# Viable parameter space

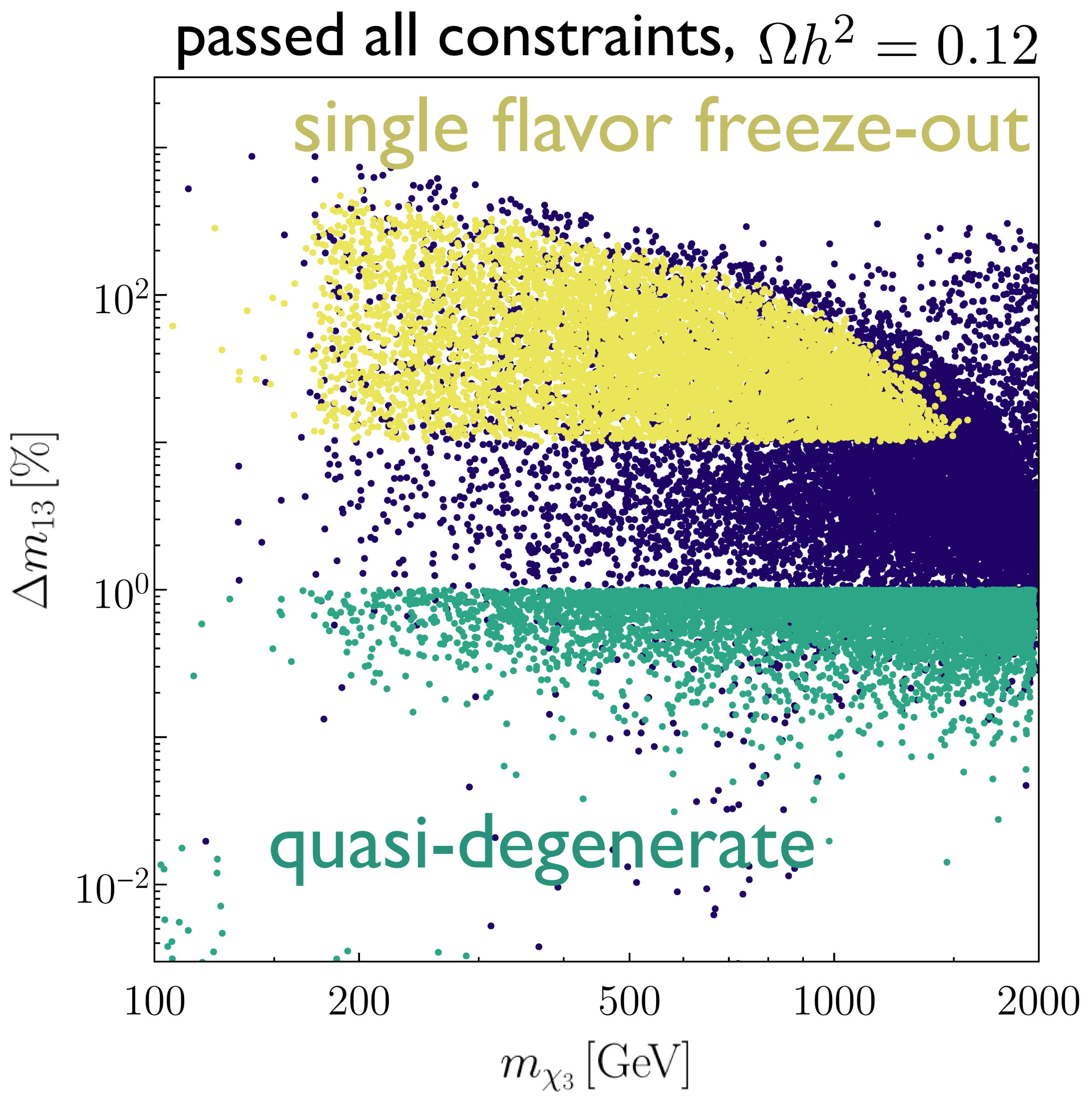
- Flavor constraints from D-meson mixing:
  [HFLAV, *see also* 2109.10357]




- Direct detection constraints from LZ
  [2207.03764]
- Indirect detection from AMS-02 cosmic-ray antiprotons
  [1711.05274]
- Relic density $\Omega h^2 = 0.12$
  [1807.06209]

# Canonical freeze-out



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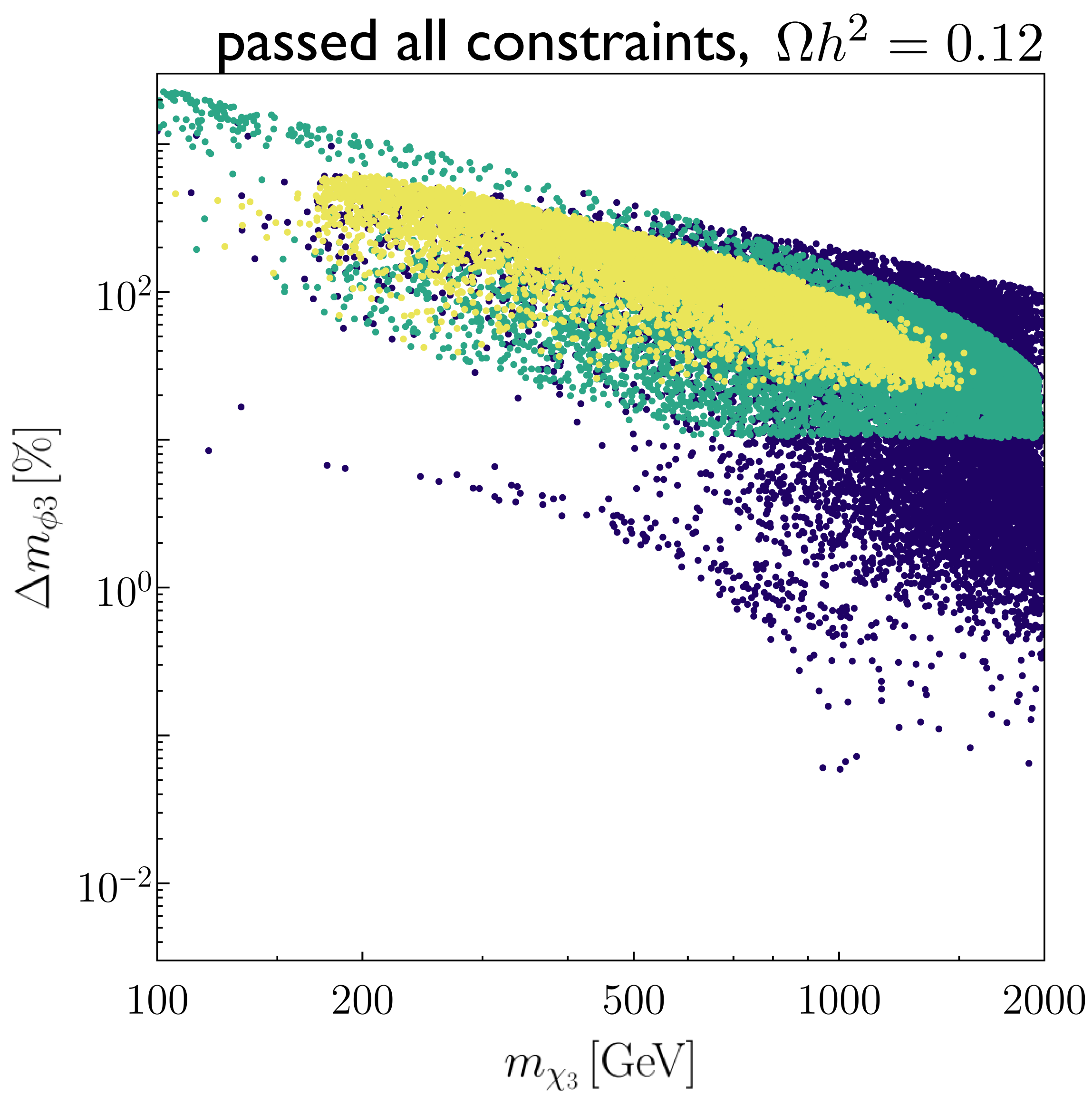
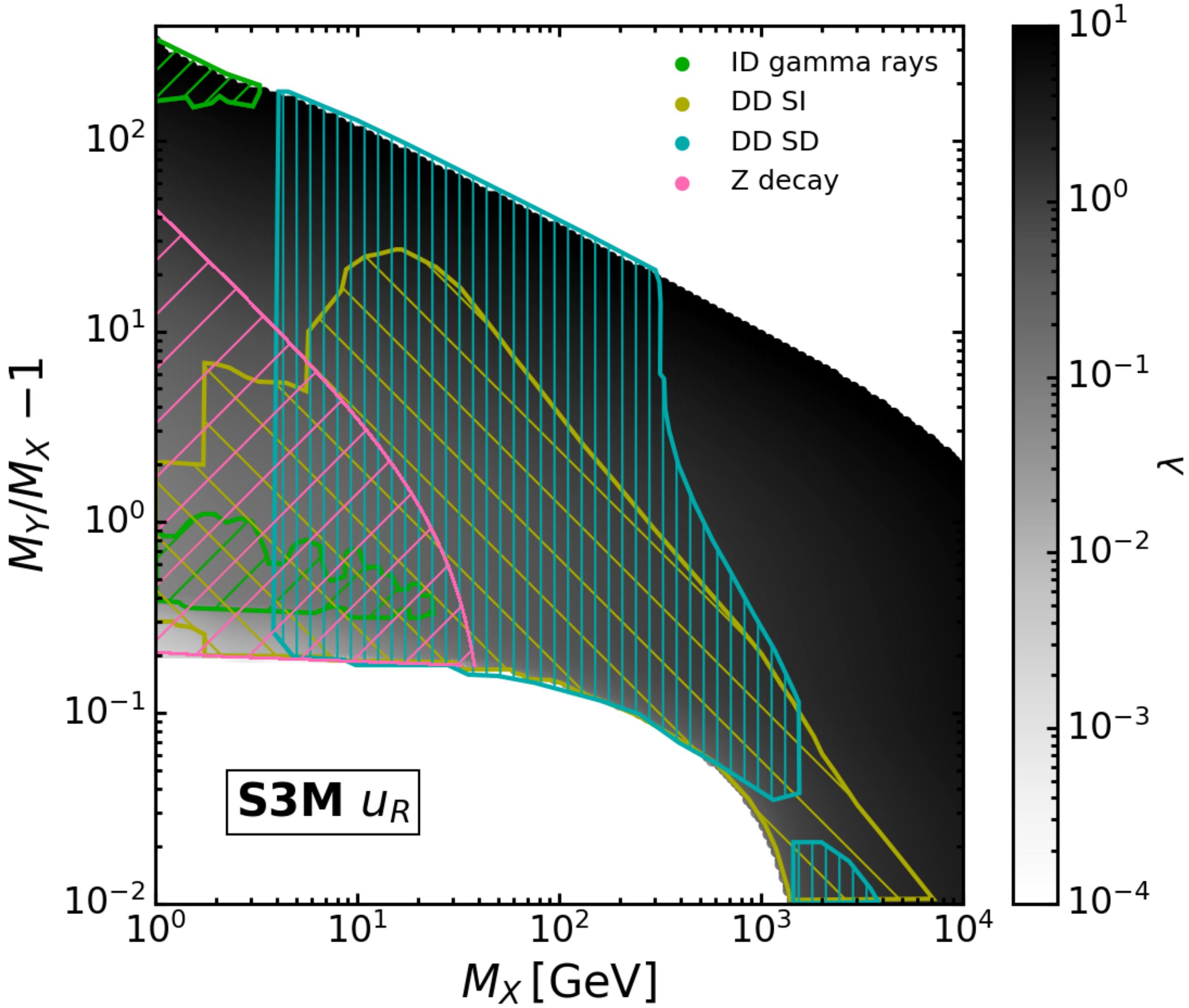



[Arina, Fuks, JH, Krämer *et al.* 2307.10367]



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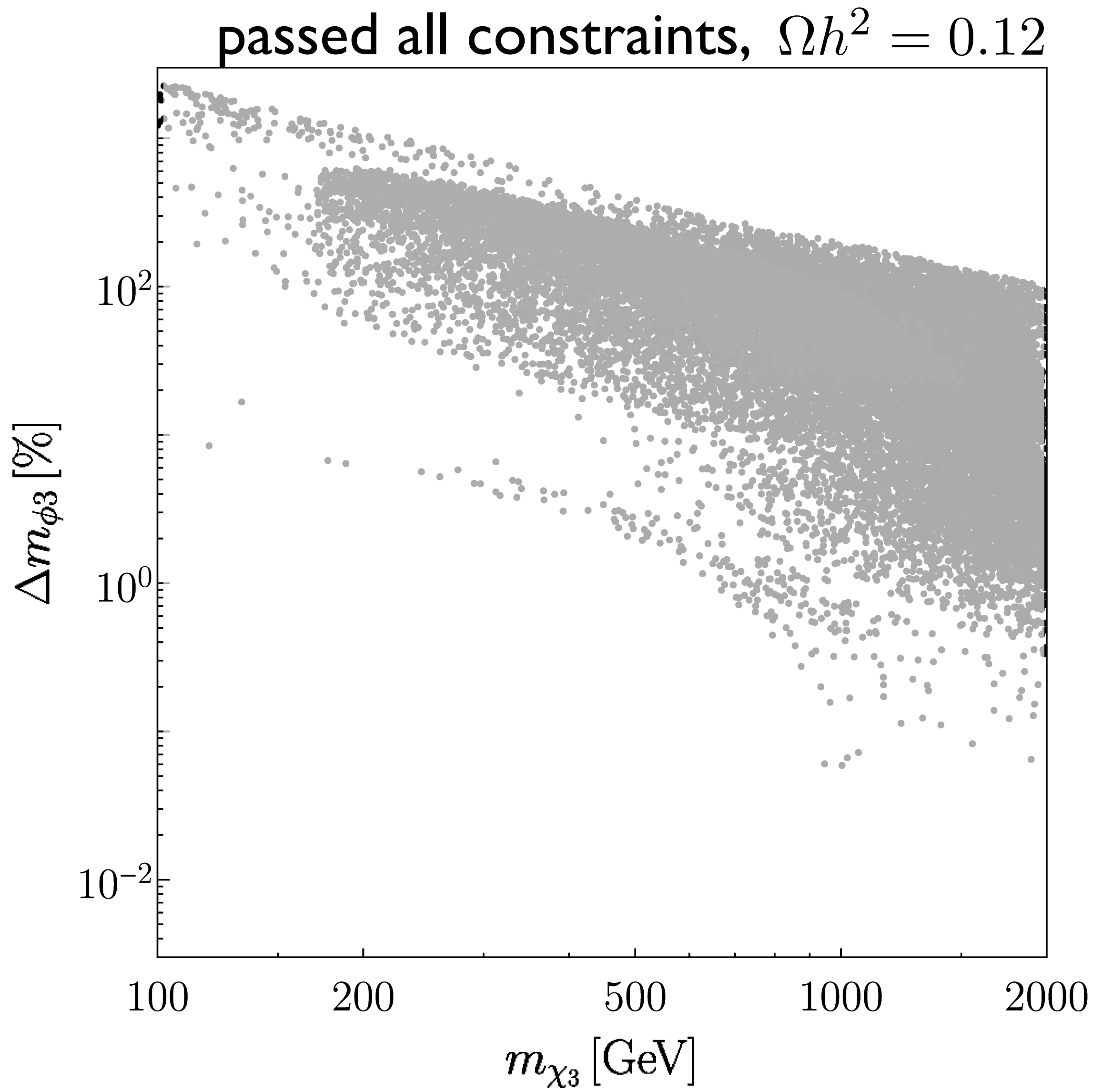

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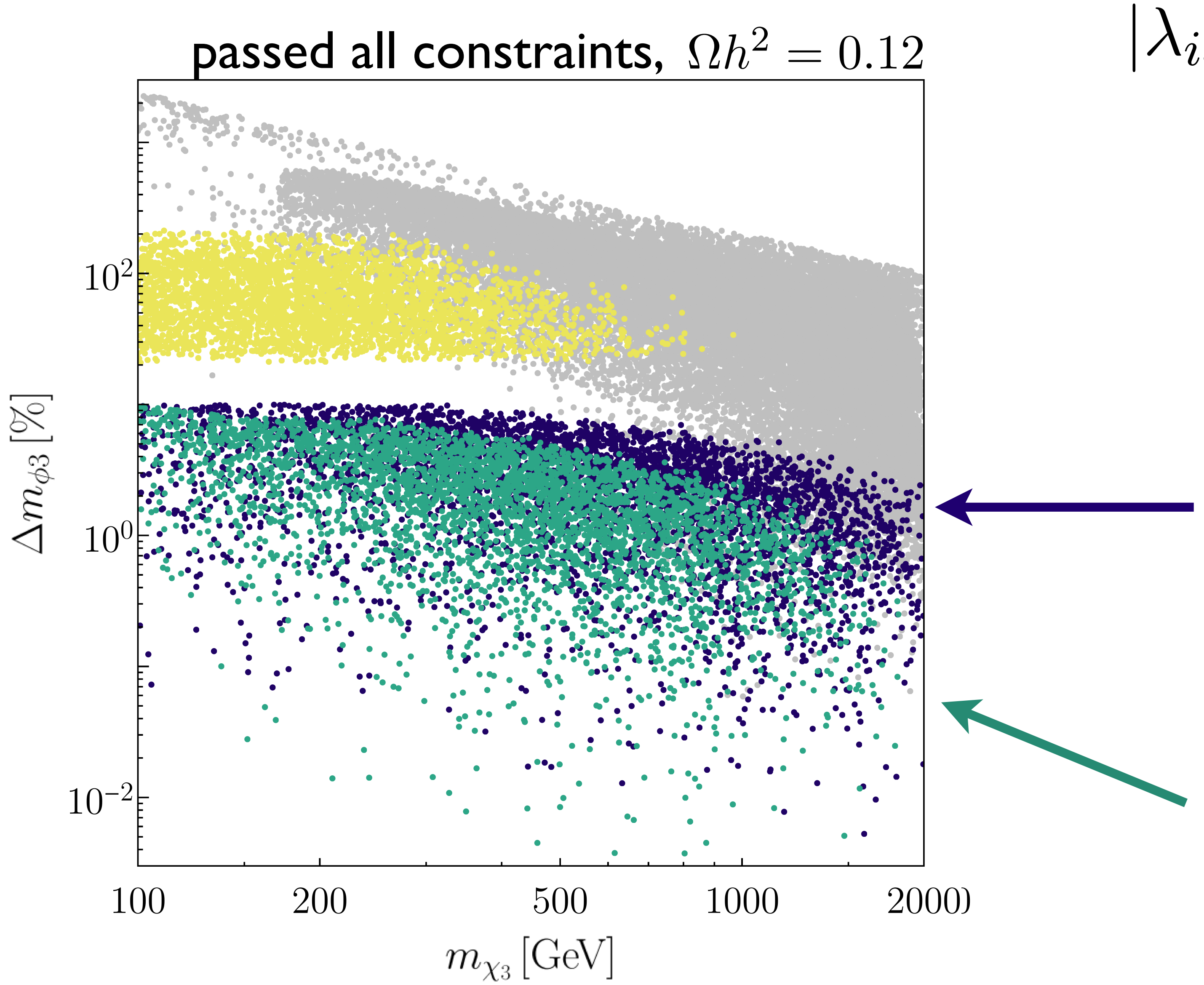
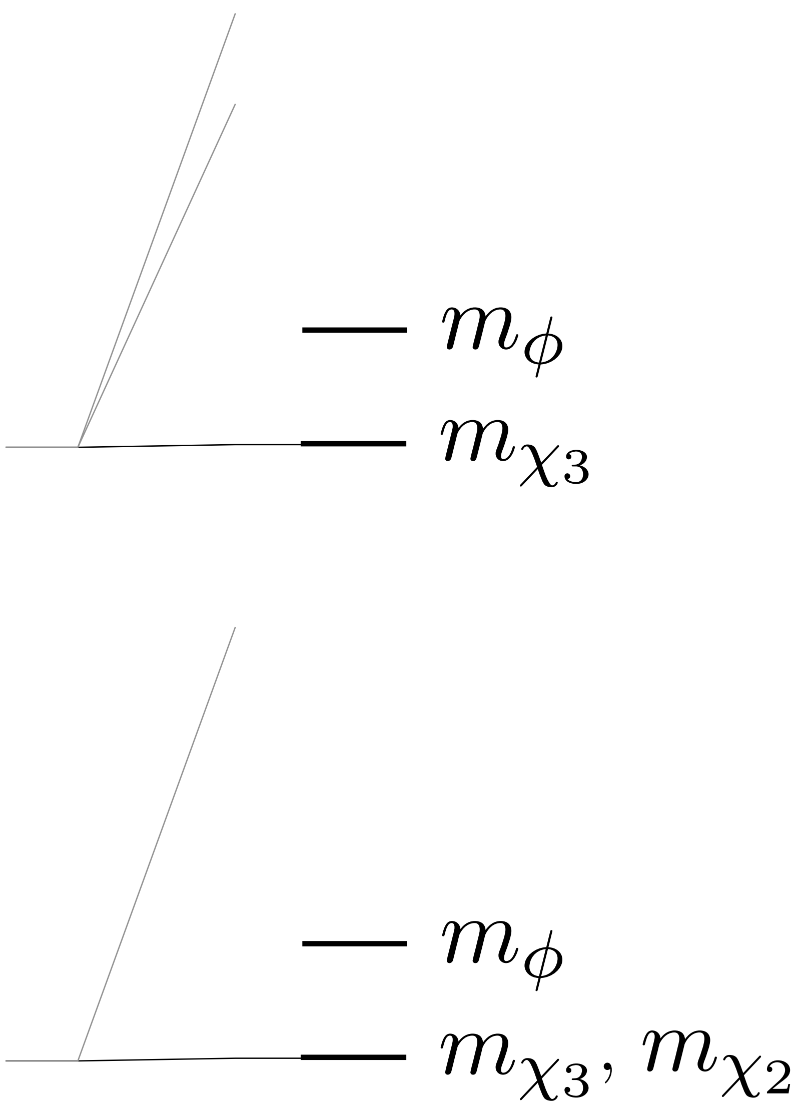


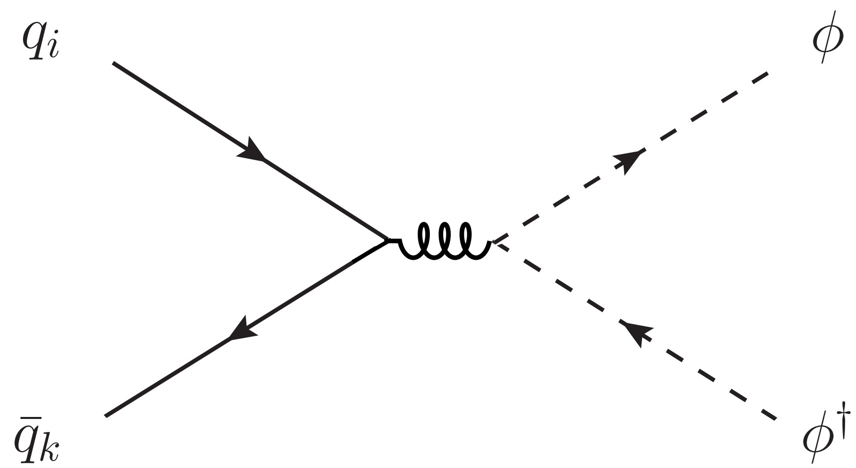

$|\lambda_{i3}| \sim 10^{-6},\ \eta > 0$:

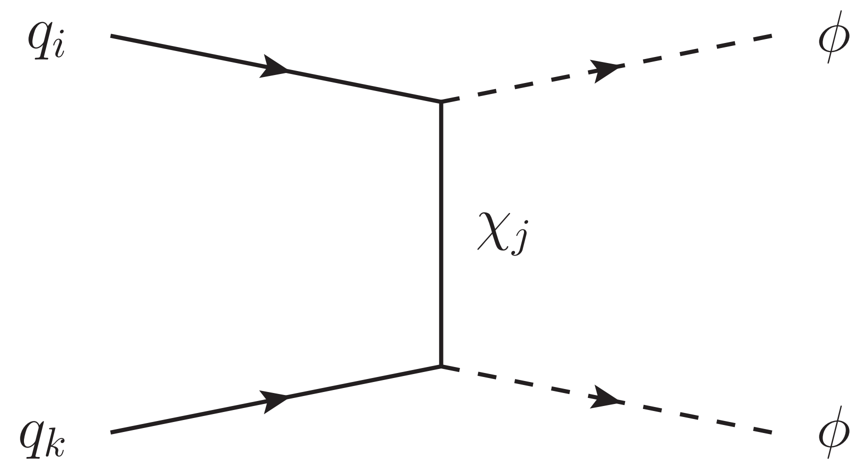


# LHC signatures

# LHC signatures

Production:

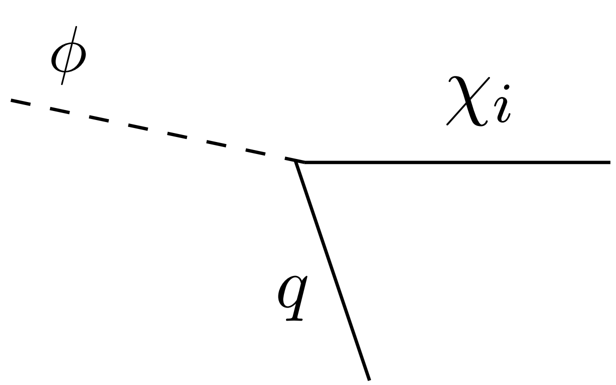



$uu \to \phi\phi$ large cross section

[see *also* e.g. M. Garny, A. Ibarra, M. Pato, S. Vogl, 1306.6342]

Decay:



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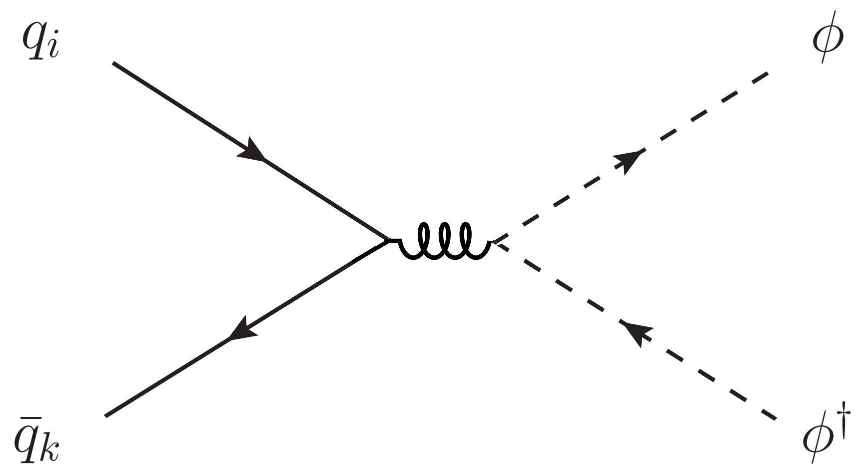


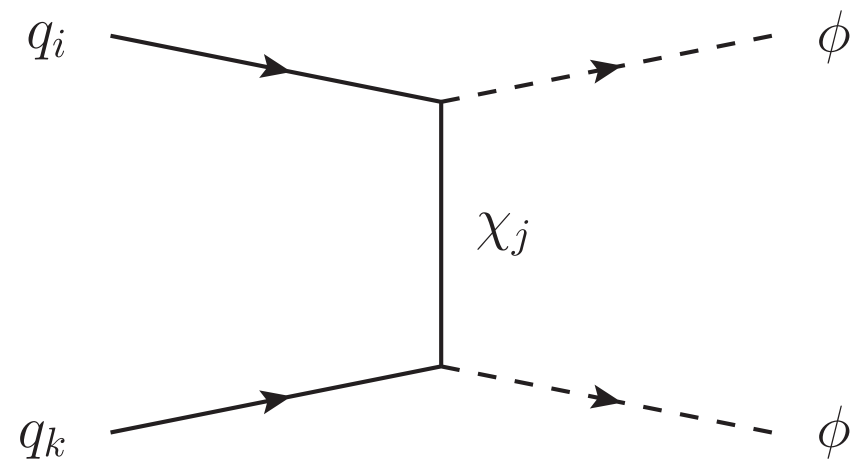


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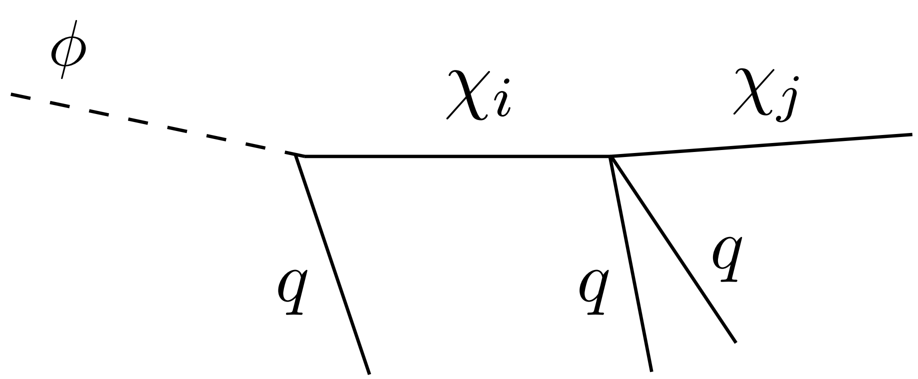

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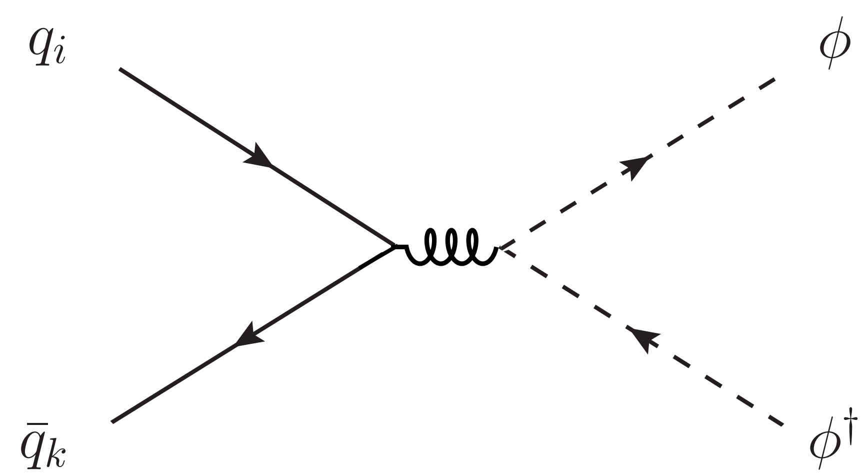


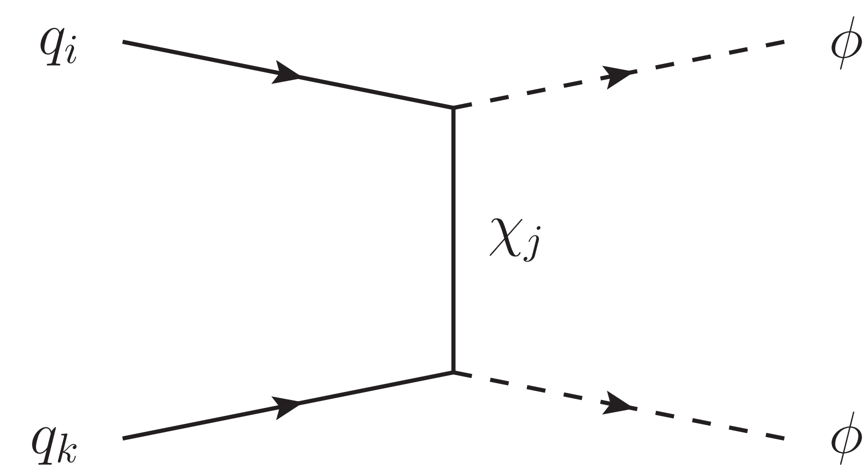


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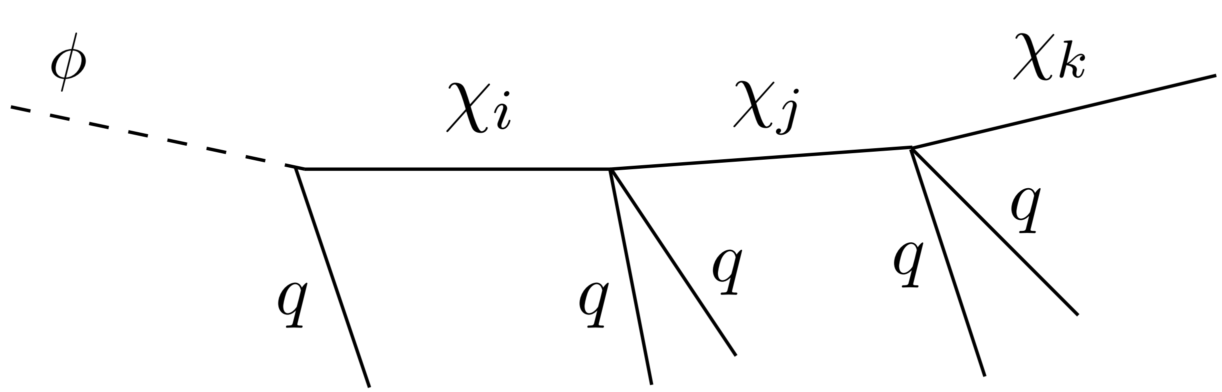
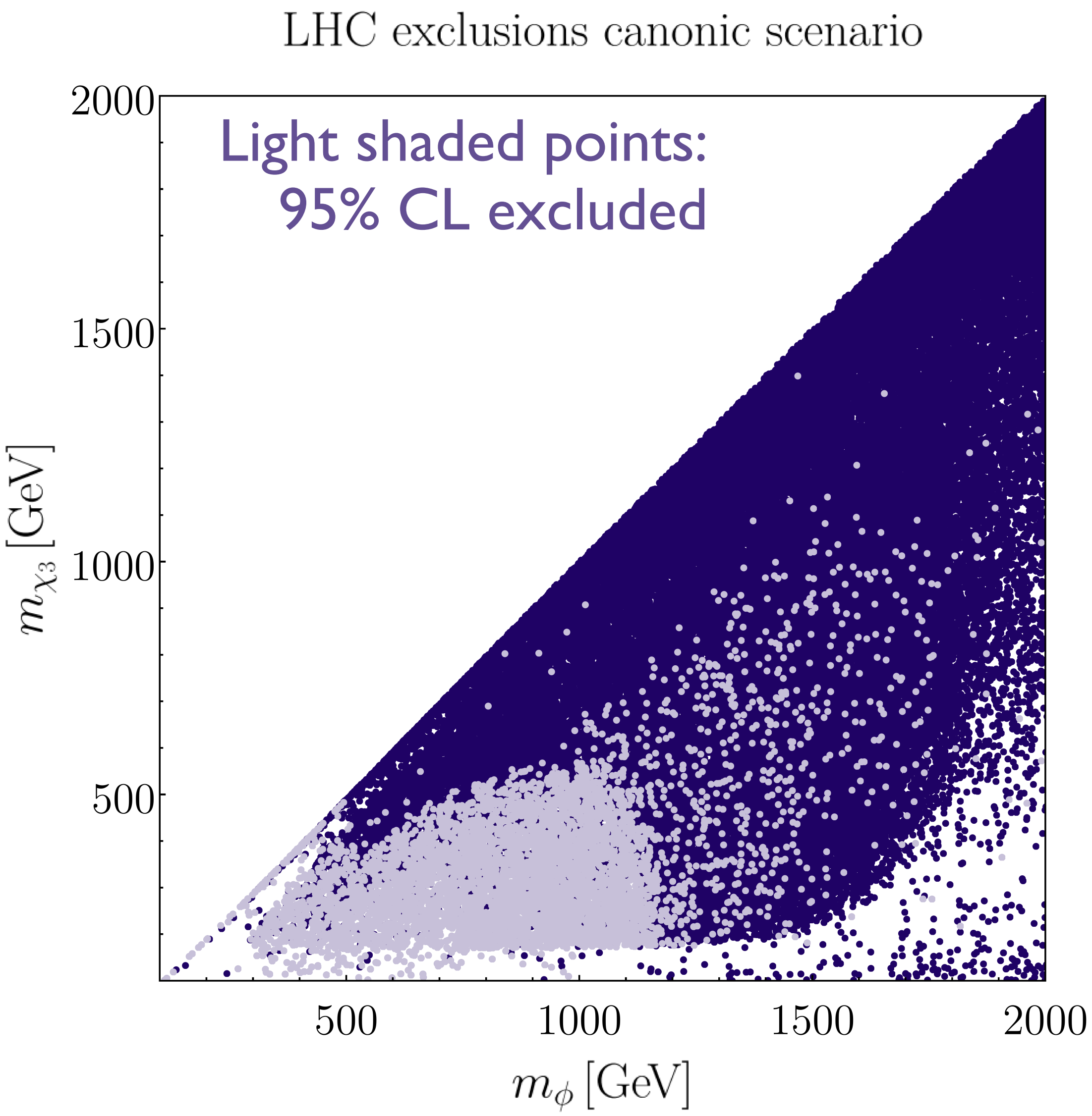


# Current constraints: canonical freeze-out




Using SModelS 2

[G. Alguero, JH, C. K. Khosa, S. Kraml *et al.* 2112.00769]

| search | $\sqrt{s}$ | signatures |
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| ATLAS-SUSY-2013-02 [49] | 8 TeV | jets+$\not{E}_T$ |
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| CMS-SUS-16-036 [55] | 13 TeV | jets+$\not{E}_T$ |
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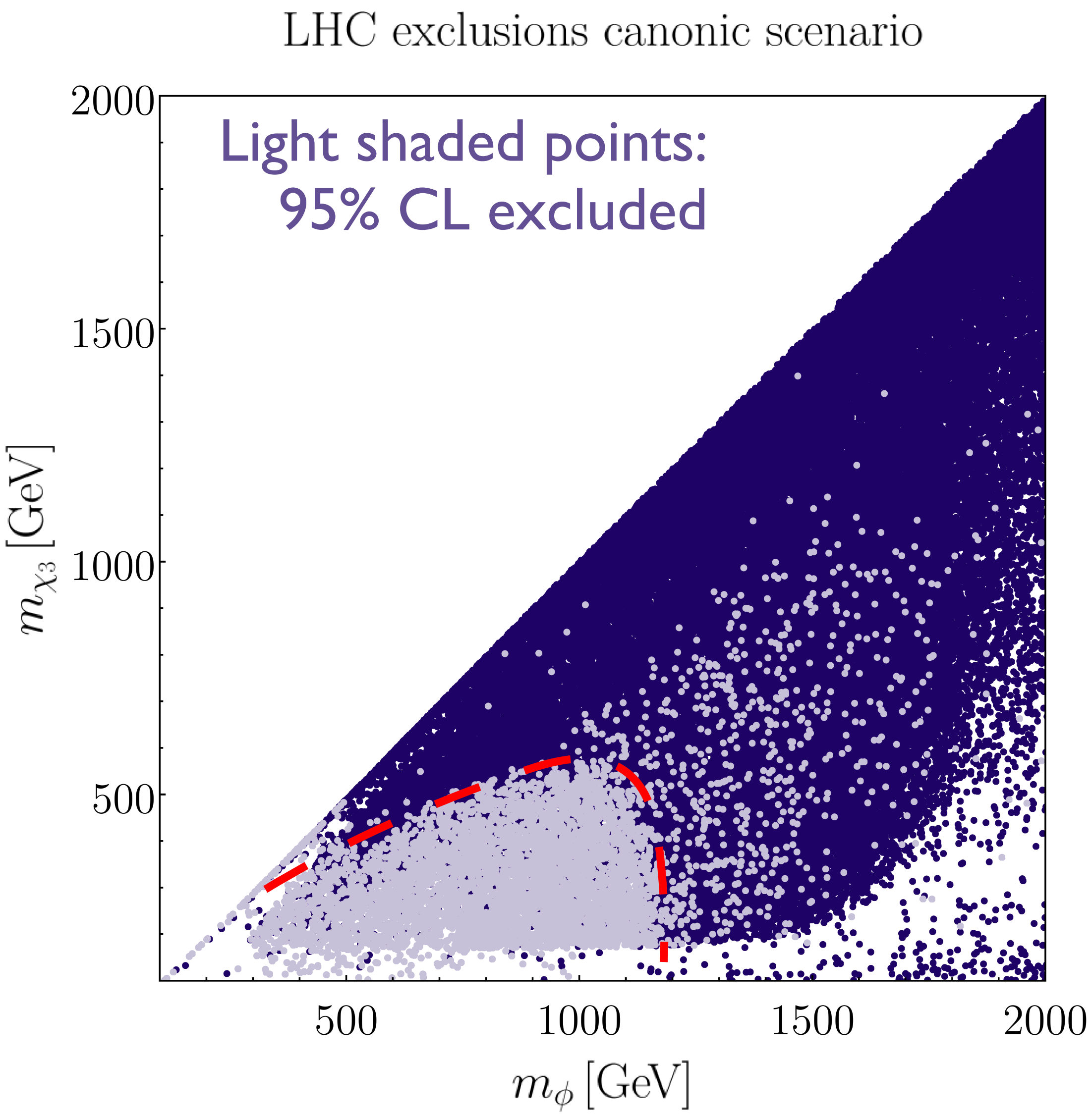


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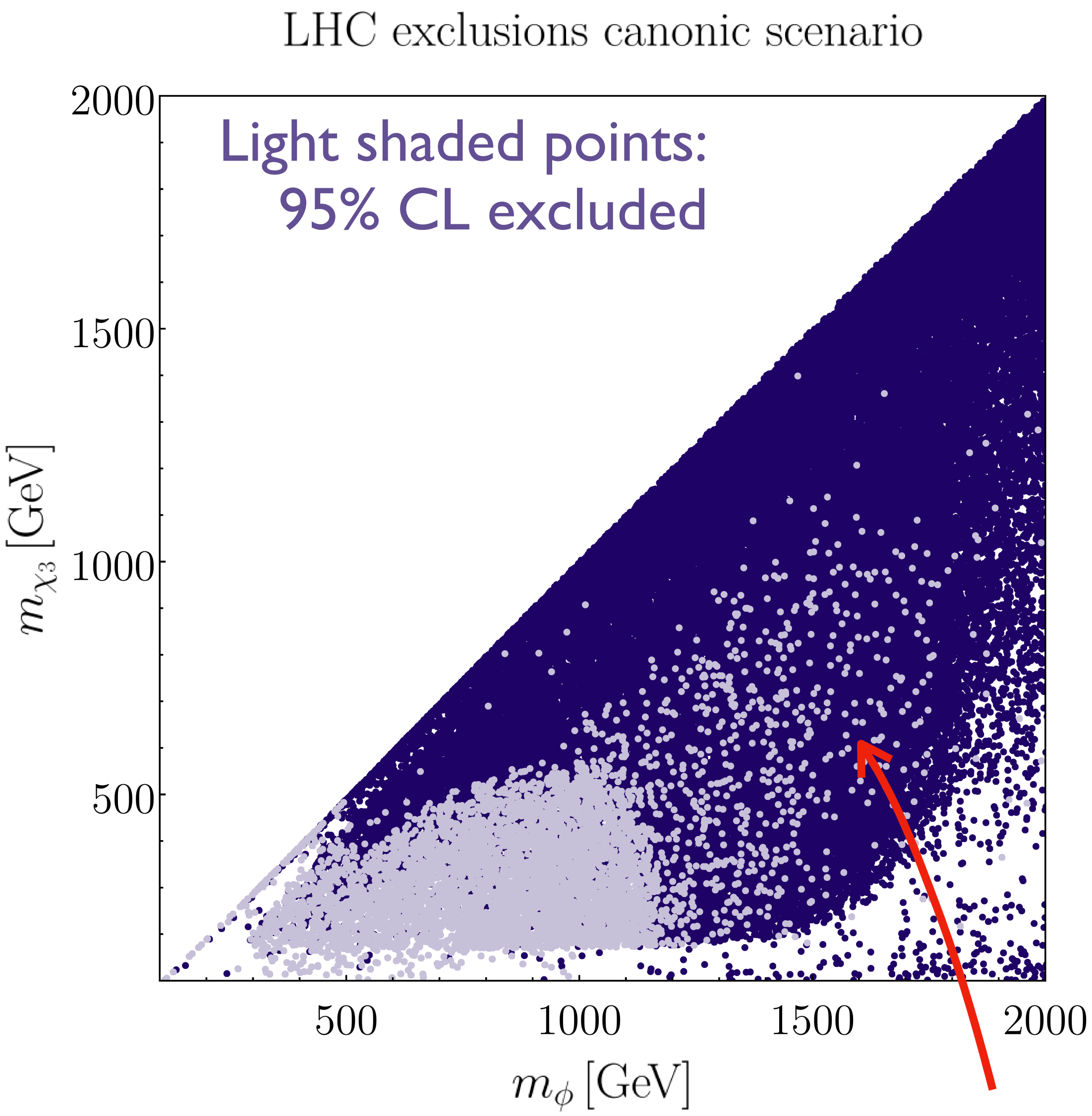


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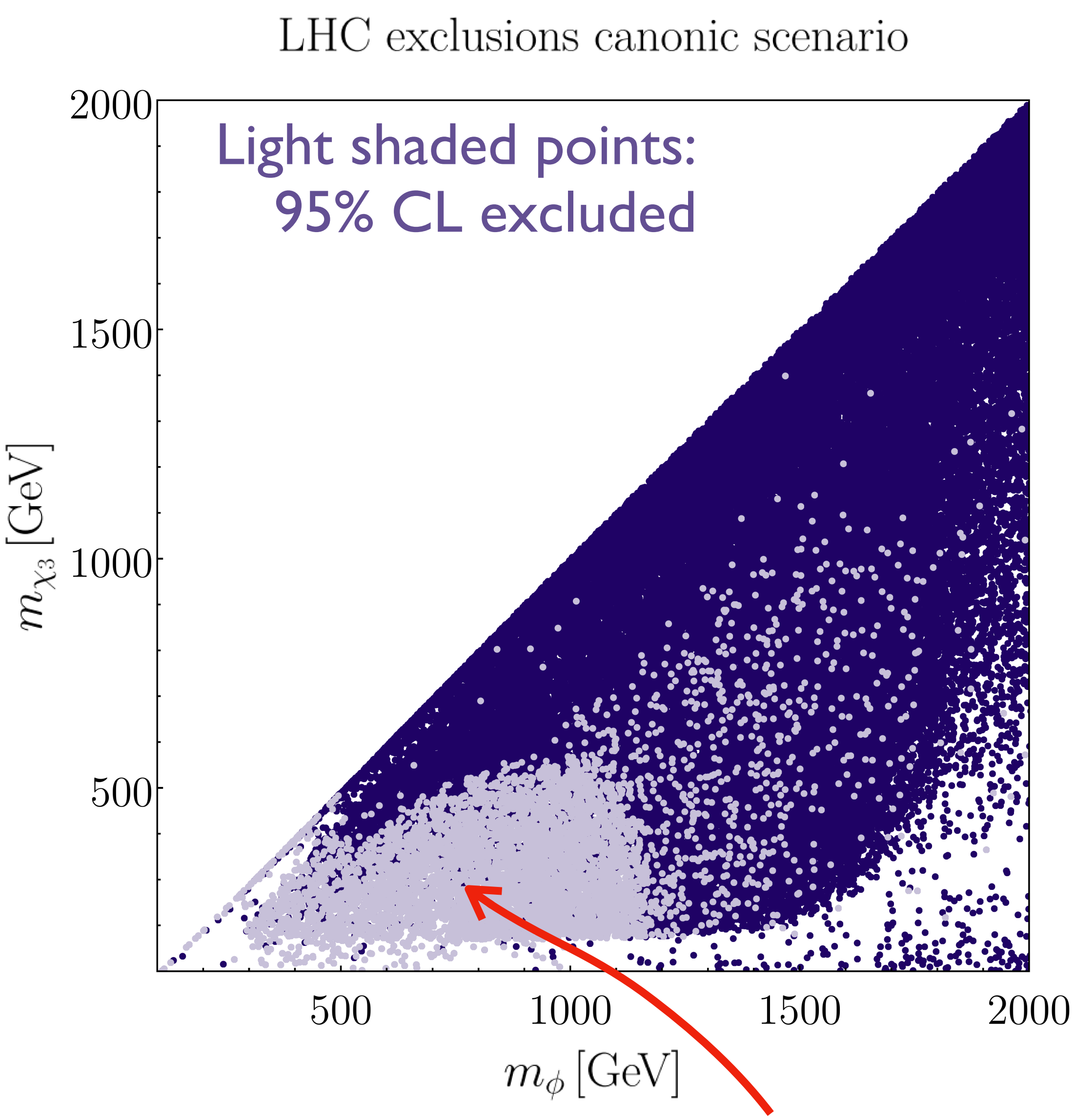
Excluded points: enhanced *t*-channel mediator production

# Current constraints: canonical freeze-out

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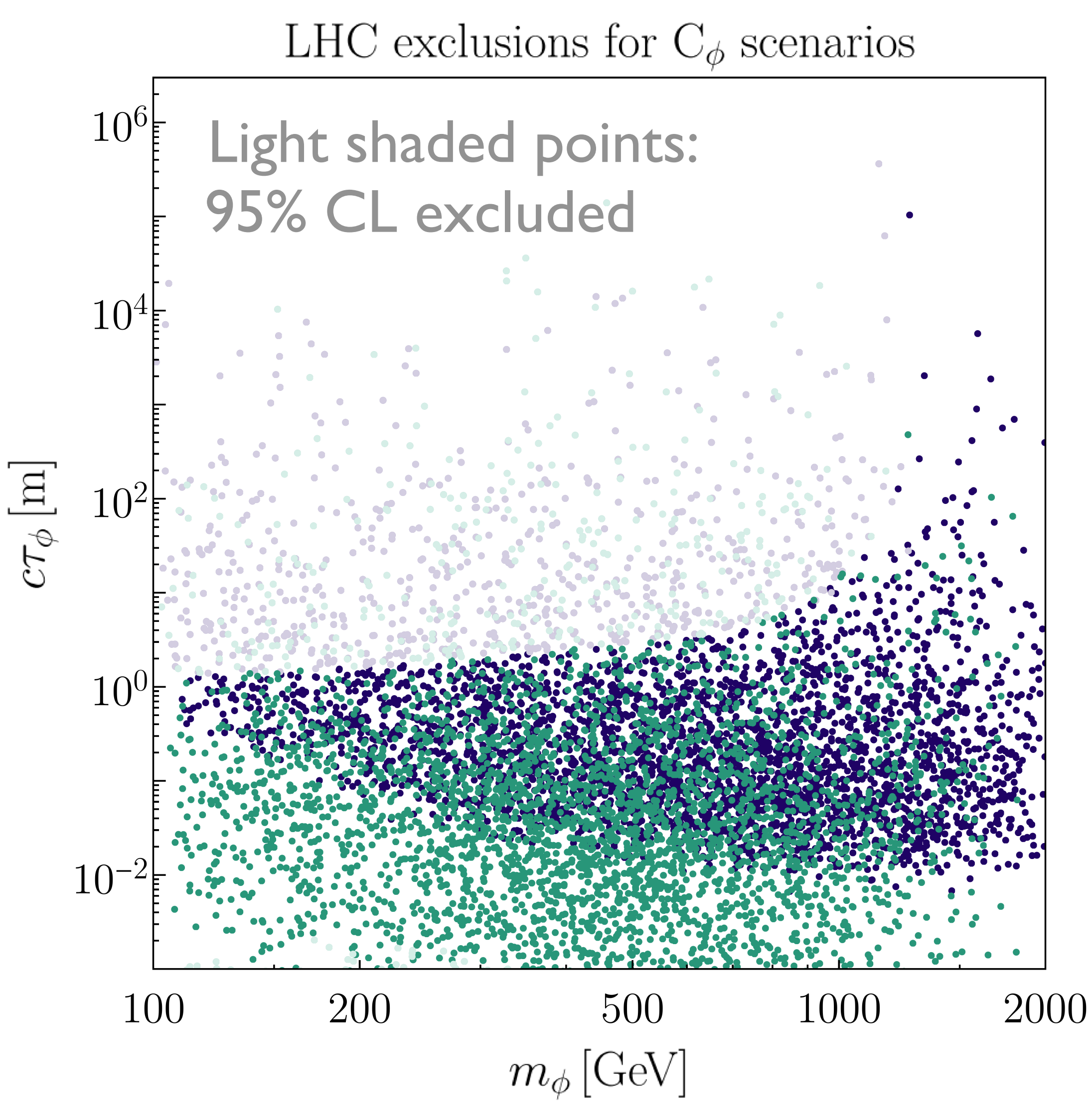
Allowed points: complex decay patterns/non-prompt decays

# Constraints: conversion-driven freeze-out

- Small DM coupling: long-lived particles

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[G. Alguero, JH, C. K. Khosa, S. Kraml *et al.* 2112.00769]

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|---|---|---|
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| CMS-PAS-EXO-16-036 [63] | 13 TeV | stable R-hadron |
| CMS-SUS-16-032 [64] | 13 TeV | $cc + \not{E}_T$ |
| CMS-SUS-16-036 [55] | 13 TeV | jets+$\not{E}_T$ |
| CMS-SUS-16-049 [61] | 13 TeV | tops+$\not{E}_T$ |

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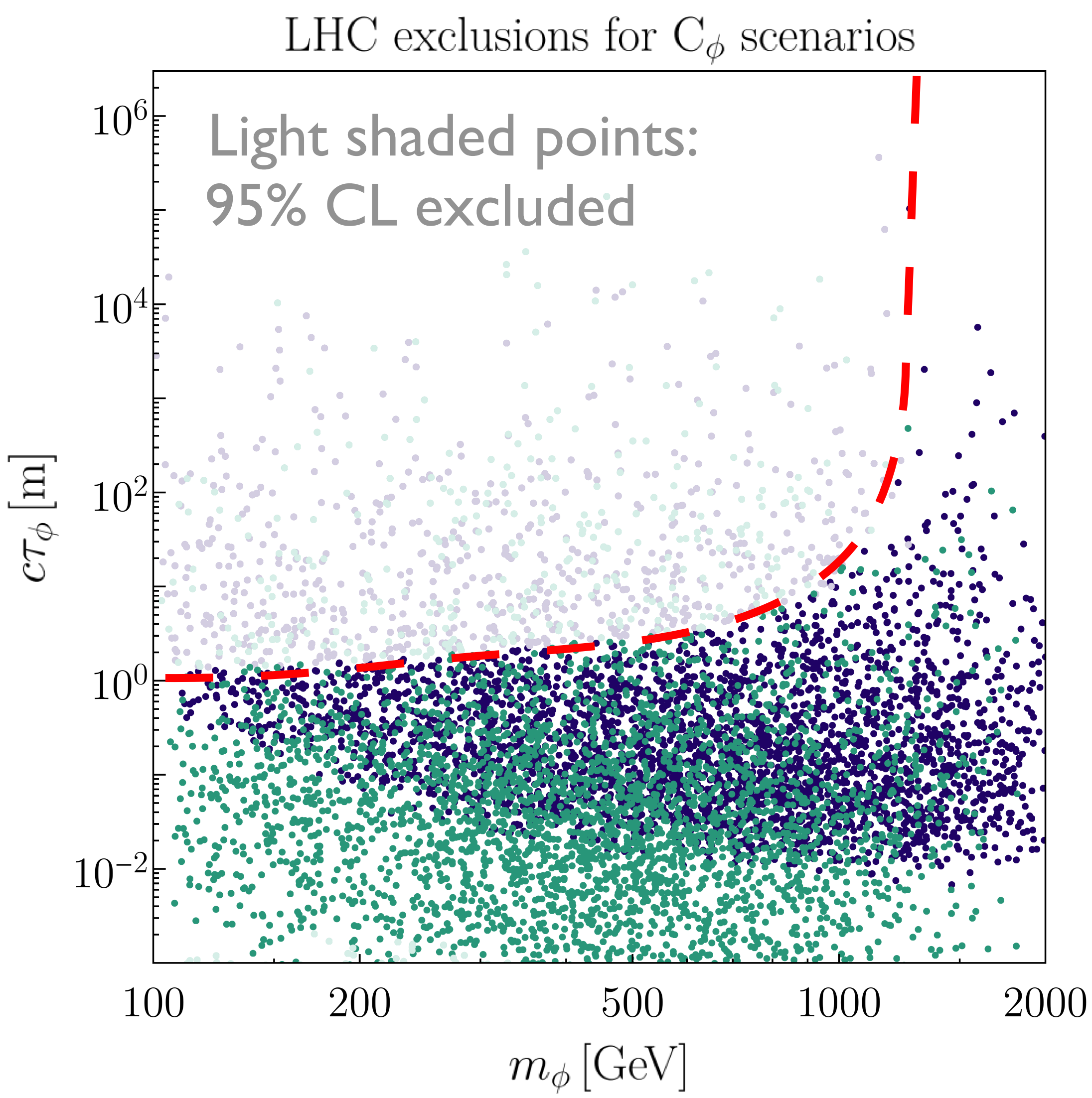


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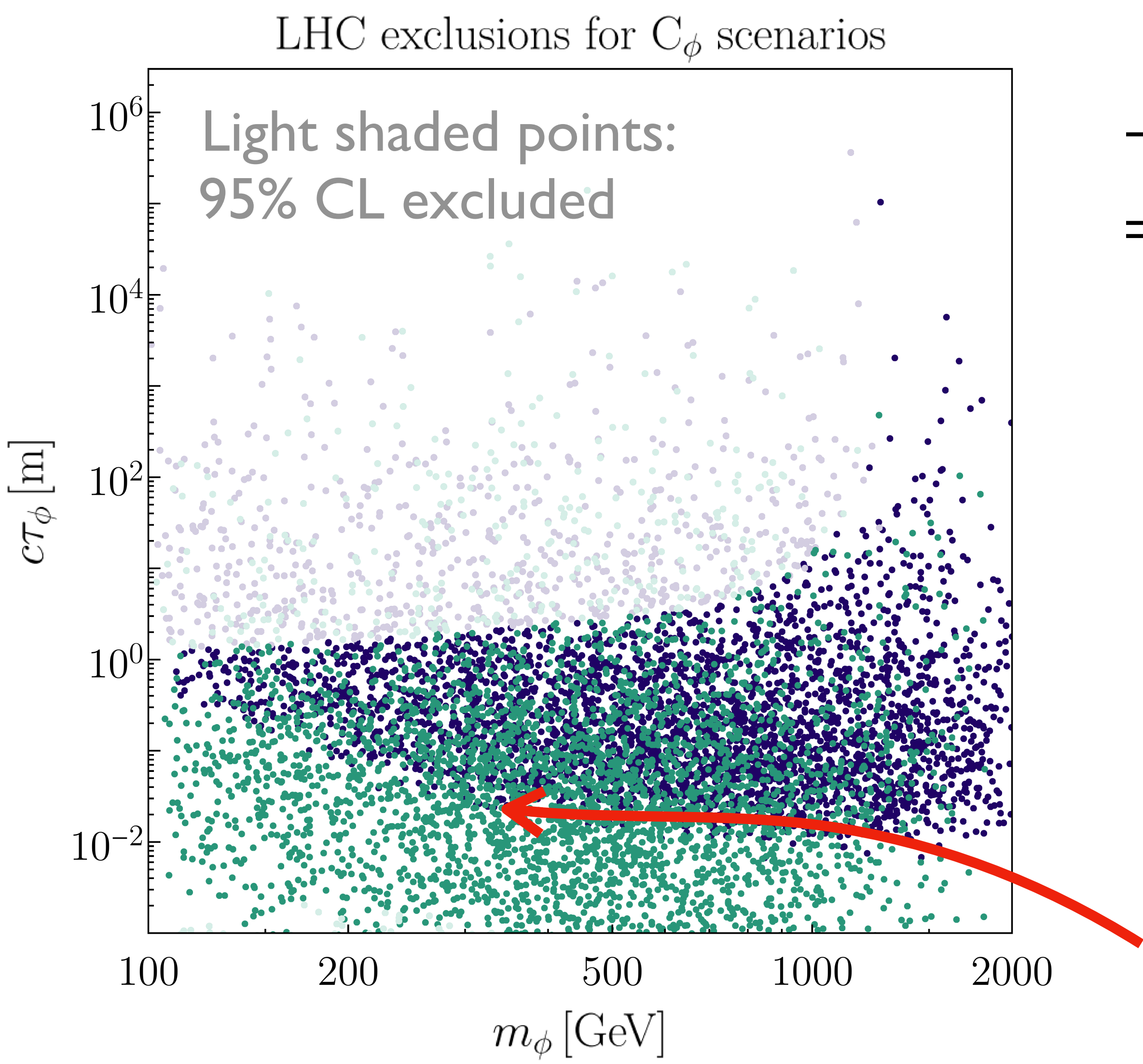
| CMS-PAS-EXO-16-036 [63] | 13 TeV | stable R-hadron |
| CMS-SUS-16-032 [64] | 13 TeV | $cc + \not{E}_T$ |
| CMS-SUS-16-036 [55] | 13 TeV | jets+$\not{E}_T$ |
| CMS-SUS-16-049 [61] | 13 TeV | tops+$\not{E}_T$ |

# Constraints: conversion-driven freeze-out

- Small DM coupling: long-lived particles




Using SModelS 2

[G. Alguero, JH, C. K. Khosa, S. Kraml *et al.* 2112.00769]

| search | $\sqrt{s}$ | signatures |
|---|---|---|
| ATLAS-SUSY-2016-32 [62] | 13 TeV | stable R-hadron |
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Intermediate lifetimes (mm–m): great potential, current searches do not apply

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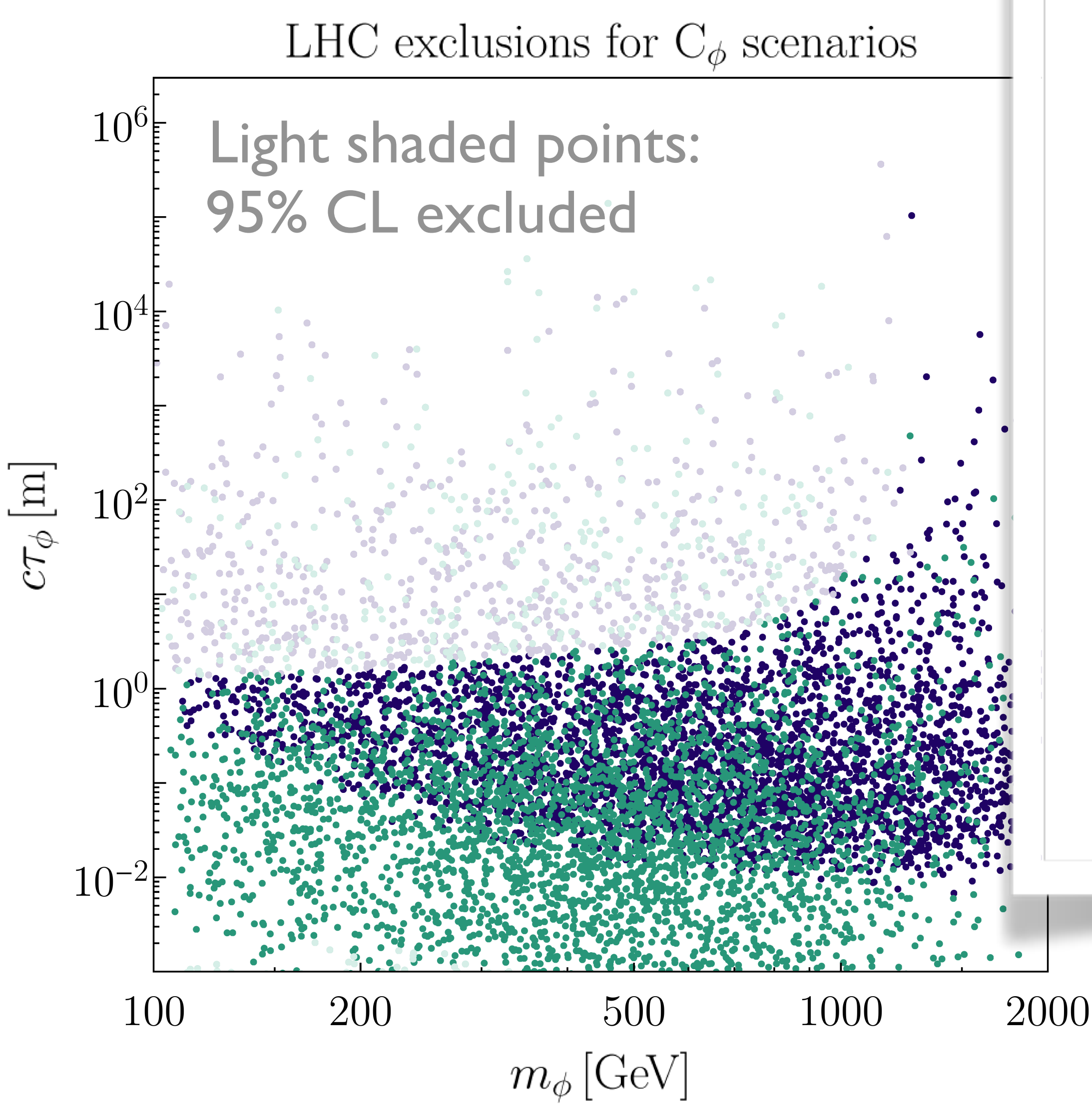
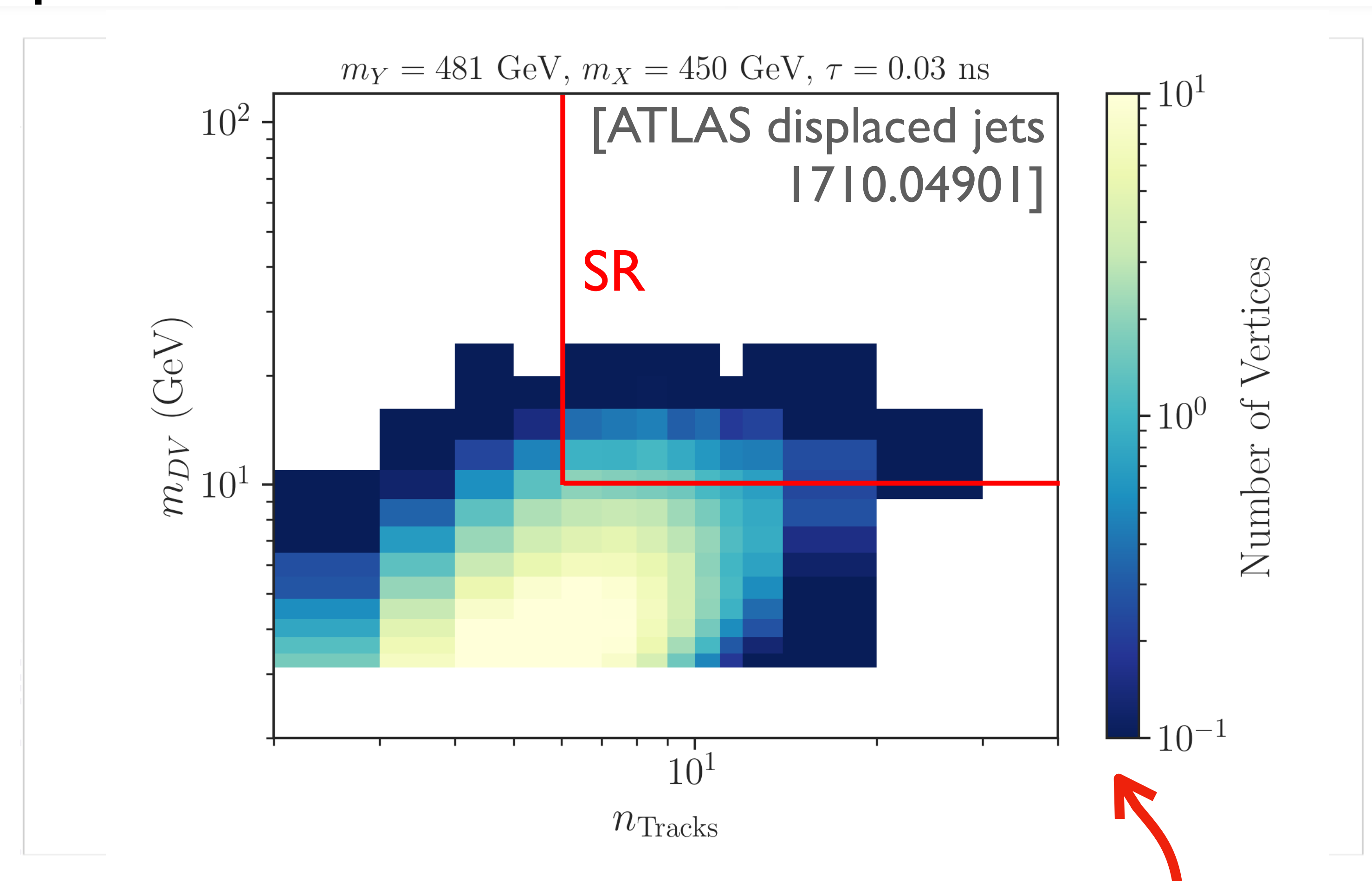
[JH, Lessa, Magno Dantas Ramos]

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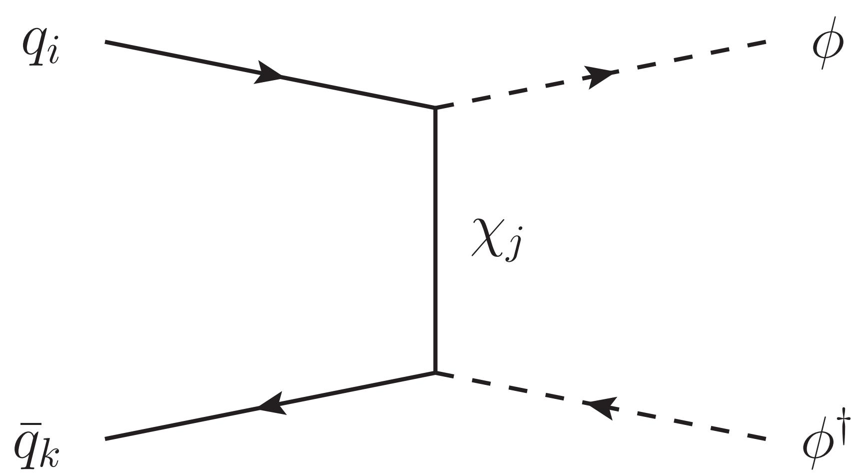
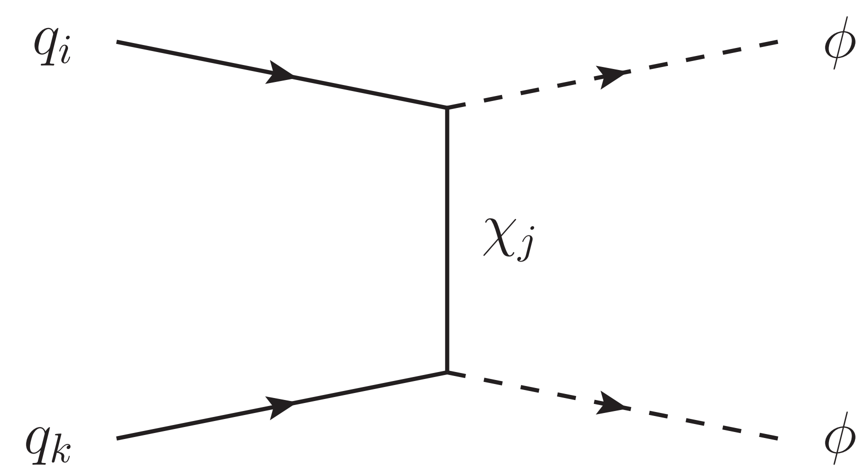
# Majorana-specific signatures




$uu \to \phi\phi$ large cross section

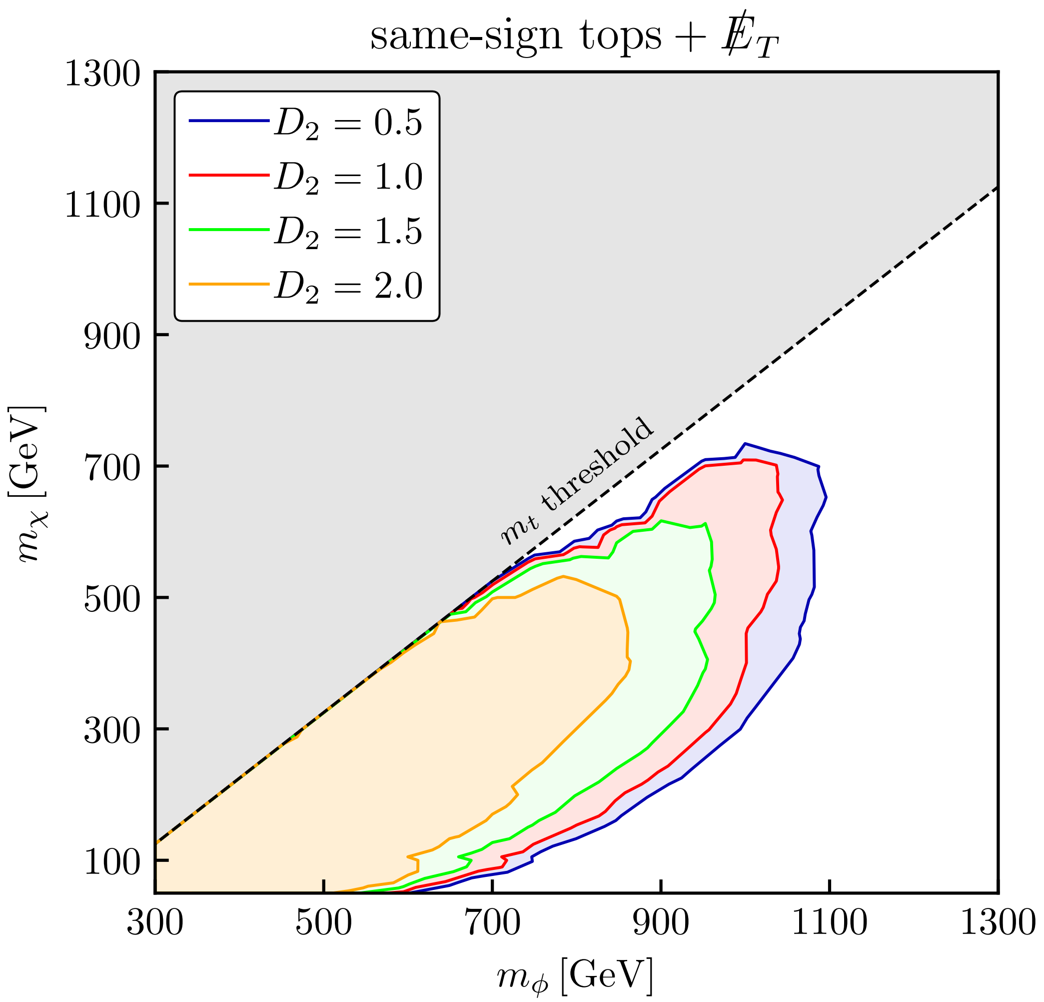
[*see also e.g.* M. Garny, A. Ibarra, M. Pato, S. Vogl, 1306.6342]

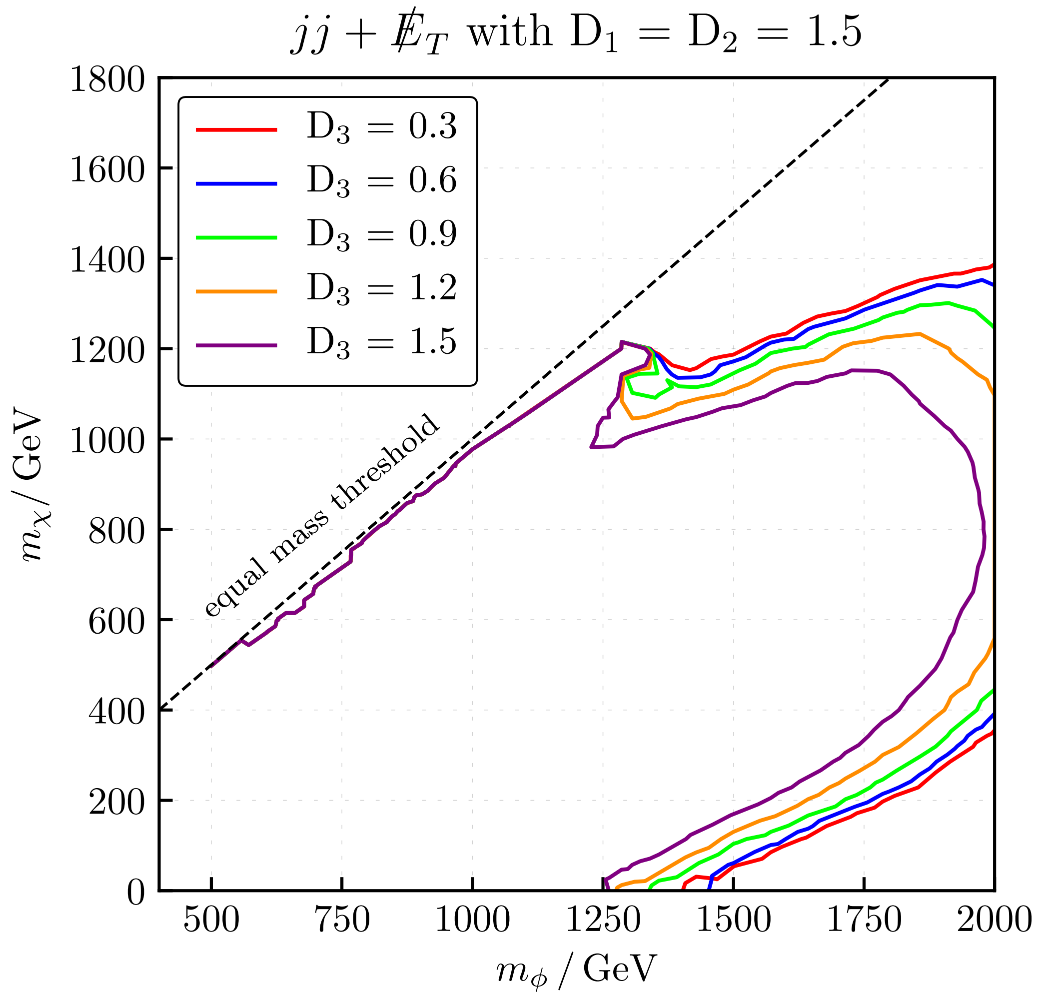
➔ Same-sign quark searches promising

# Majorana-specific signatures

Same-sign top searches in SUSY $ttjj + \not{E}_T$ and $\overline{tt}jj + \not{E}_T$

CMS-SUS-19-008 [2001.10086]




[Acaroğlu, Blanke 2109.10357
using CMS-SUS-19-006]

# Single-top charge asymmetry

$$\sigma_{\mathrm{Dirac}}(tj + \not{E}_T) = \sigma_{\mathrm{Dirac}}(\bar{t}j + \not{E}_T)$$

For Majorana, $\phi\phi$ production present and enhanced compared to $\phi^\dagger\phi^\dagger$ (due to valence up-quark content in $p$)

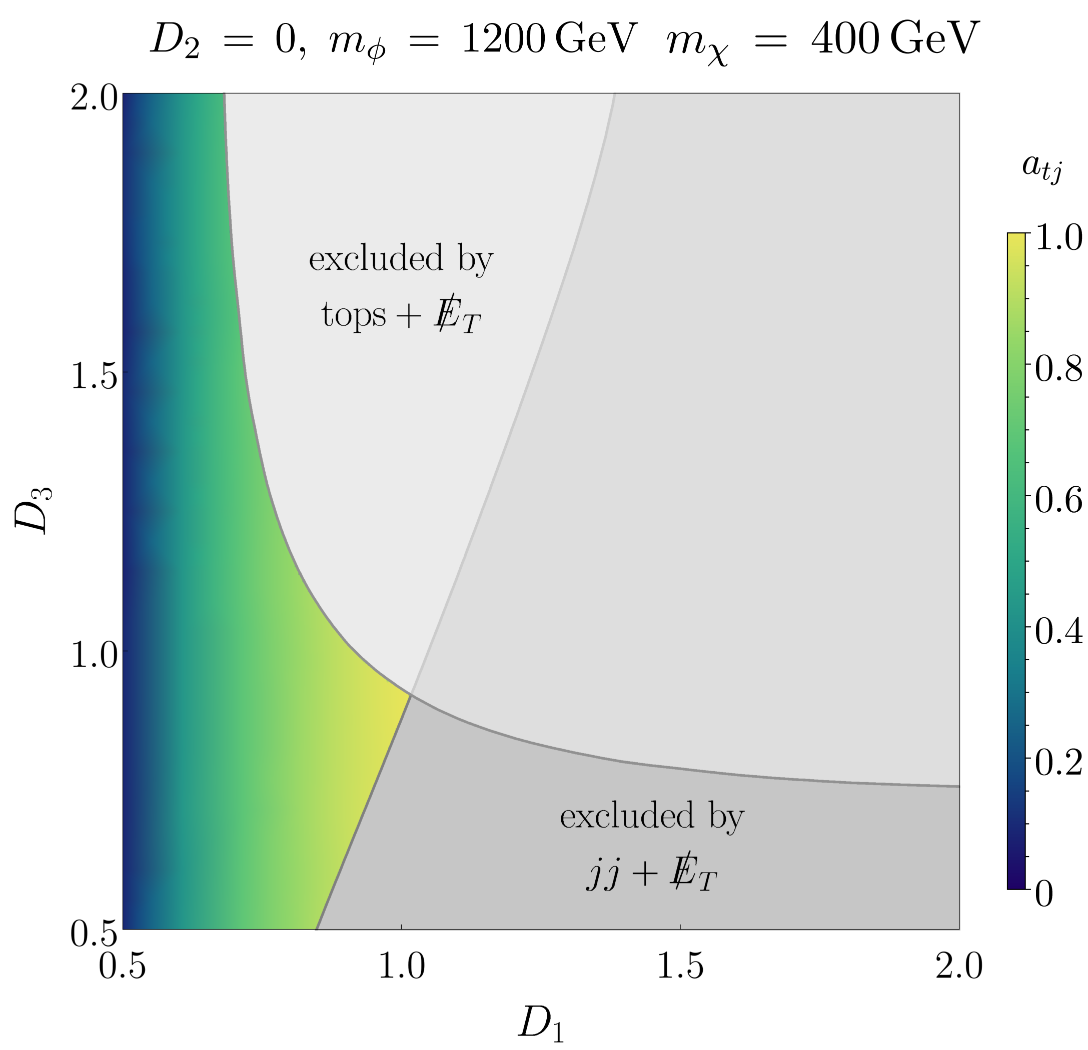
$$\sigma_{\mathrm{Majorana}}(tj + \not{E}_T) > \sigma_{\mathrm{Majorana}}(\bar{t}j + \not{E}_T)$$

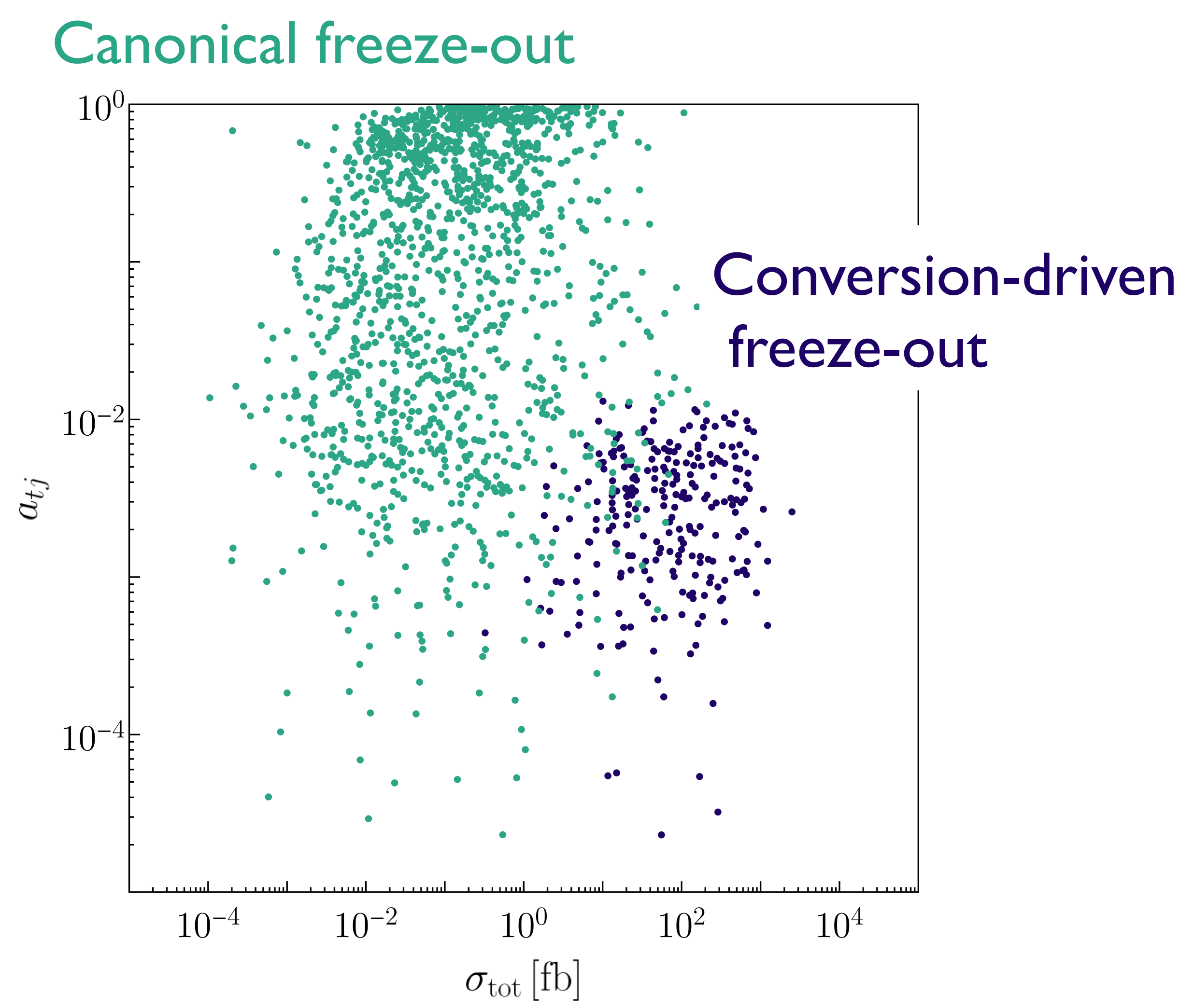
Consider charge asymmetry:

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

$$\begin{aligned} \text{Dirac DM} \quad &\Rightarrow \quad a_{tj} \simeq 0 \\ \text{Majorana DM} \quad &\Rightarrow \quad a_{tj} > 0 \end{aligned}$$

# Single-top charge asymmetry



# Summary

- Flavored Majorana Dark Matter:
  Large regions of viable parameter space
- Canonical and conversion-driven freeze-out
- Current gaps in LHC searches:
  - Complex decay chains
  - Long-lived particles (intermediate lifetimes)
- Majorana-specific signatures
  - Same-sign tops suffer from extra jets required
  - Single-top charge asymmetry