Flavoured Majorana dark matter

from freeze-out scenarios to LHC signatures

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

Jan Heisig

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Alexander von HUMBOLDT STIFTUNG

Annual Meeting of the CRC TRR 257
Particle Physics Phenomenology after the Higgs Discovery
KIT, March 12, 2024

The model

$$\mathcal{L} \;=\; \mathcal{L}_{\mathrm{SM}} + \frac{1}{2}\left(i\bar{\chi}\partial\!\!\!/\chi - M_\chi\bar{\chi}\chi\right) - \left(\lambda_{ij}\bar{u}_{Ri}\chi_j\phi + \mathrm{h.c.}\right)$$
$$+(D_\mu\phi)^\dagger(D^\mu\phi) - m_\phi^2\phi^\dagger\phi + \lambda_{H\phi}\phi^\dagger\phi H^\dagger H + \lambda_{\phi\phi}\left(\phi^\dagger\phi\right)^2$$

λ_{ij}: Complex 3×3 matrix

- 18 parameters reduced to 15 by $O(3)_\chi$ symmetry (Dirac: $U(3)_\chi$)
- Parametrization:

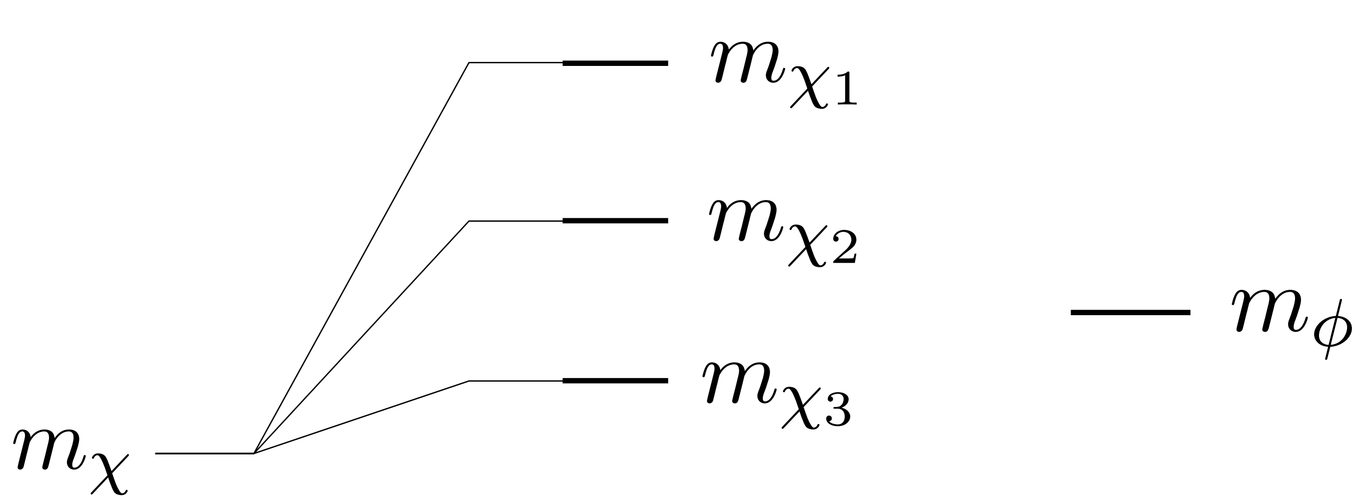
$$\lambda = U\,D\,O\,d$$

where $\theta_{23},\,\theta_{13},\,\theta_{12},\,\phi_{23},\,\phi_{13},\,\phi_{12}$ are mixing angles,
$\delta_{23},\,\delta_{13},\,\delta_{12},\,\gamma_1,\,\gamma_2,\,\gamma_3$ are complex phases, and
$D=\mathrm{diag}(D_1,D_2,D_3)$ parametrizes the coupling strengths

Particle spectrum

$$\begin{aligned}\mathcal{L} &= \mathcal{L}_{\rm SM} + \frac{1}{2}\left(i\bar{\chi}\partial\!\!\!/\chi - M_\chi\bar{\chi}\chi\right) - \left(\lambda_{ij}\bar{u}_{Ri}\chi_j\phi + \text{h.c.}\right)\\ &\quad + (D_\mu\phi)^\dagger(D^\mu\phi) - m_\phi^2\phi^\dagger\phi + \lambda_{H\phi}\phi^\dagger\phi H^\dagger H + \lambda_{\phi\phi}\left(\phi^\dagger\phi\right)^2\end{aligned}$$

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



Particle spectrum

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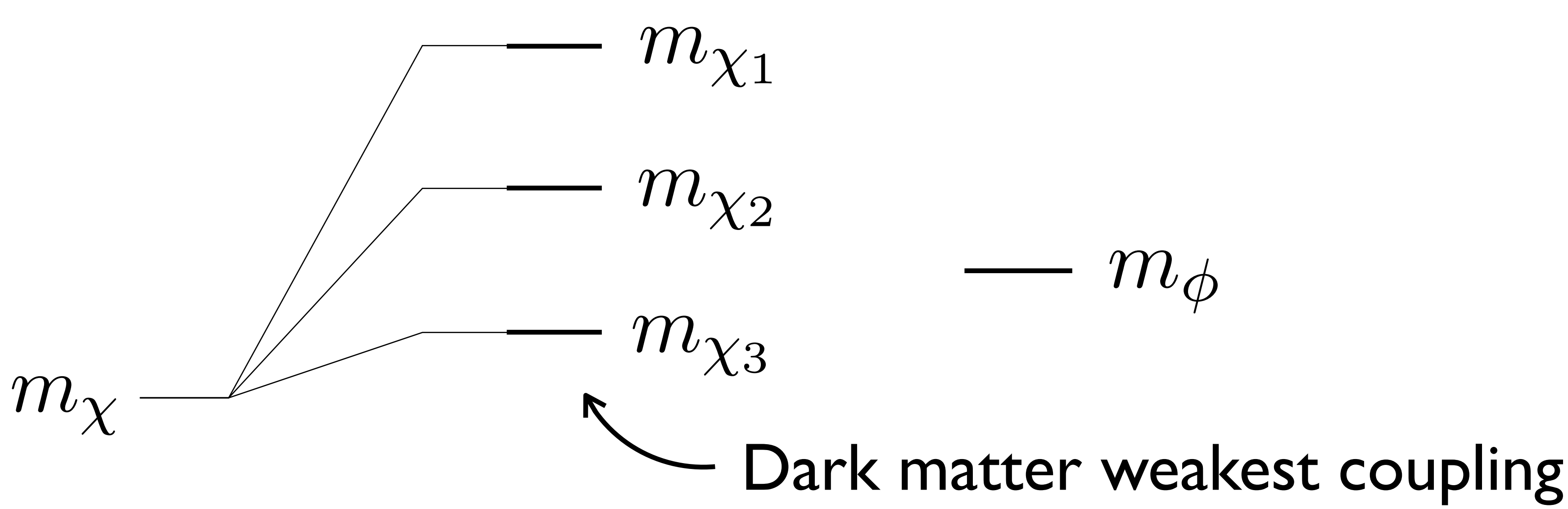
$\eta > 0$:



Particle spectrum

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\mathcal{L} \;&=\; \mathcal{L}_{\rm SM} + \frac{1}{2}\left(i\bar{\chi}\partial\!\!\!/\chi - M_\chi \bar{\chi}\chi\right) - \left(\lambda_{ij}\bar{u}_{Ri}\chi_j\phi + \text{h.c.}\right) \\
&\quad + (D_\mu\phi)^\dagger(D^\mu\phi) - m_\phi^2\phi^\dagger\phi + \lambda_{H\phi}\phi^\dagger\phi H^\dagger H + \lambda_{\phi\phi}\left(\phi^\dagger\phi\right)^2
\end{aligned}
$$

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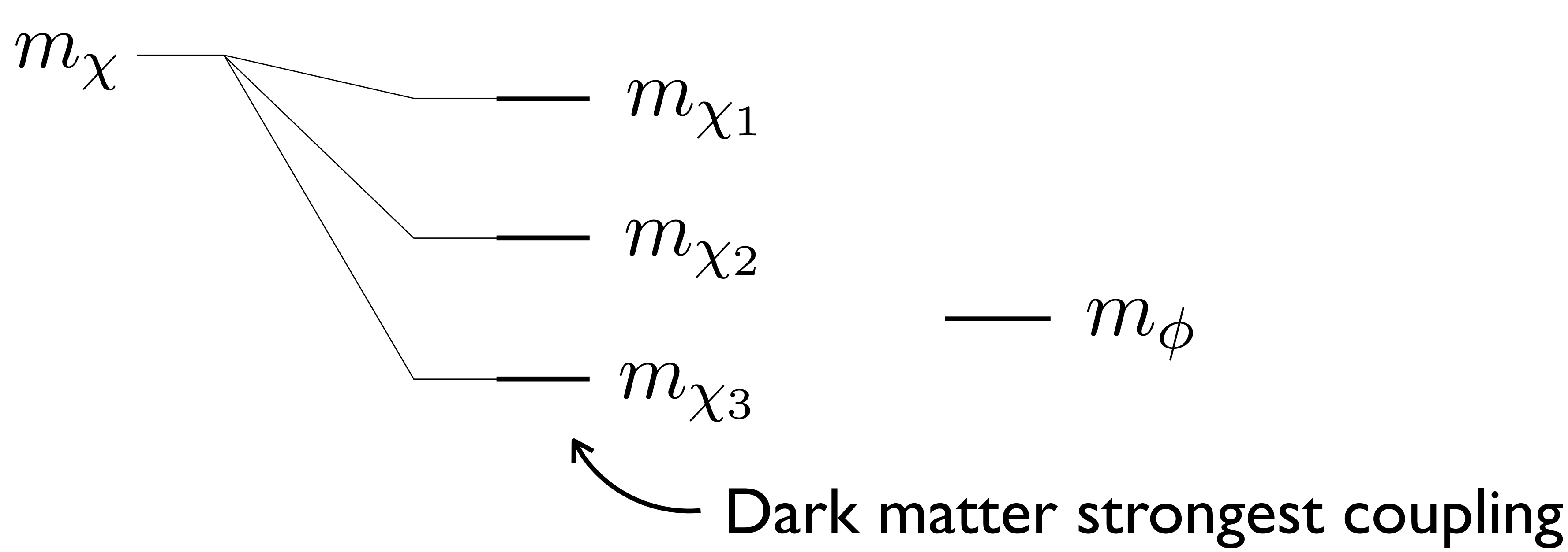
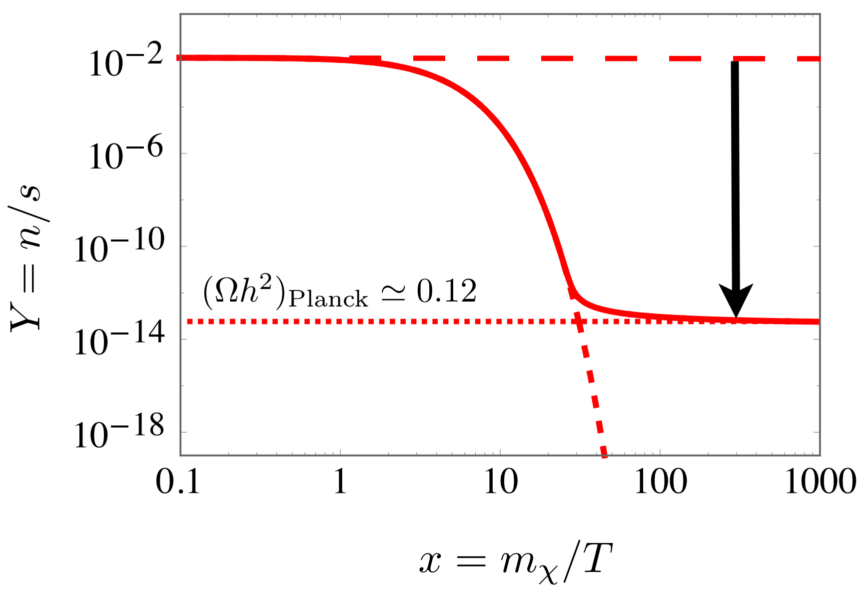
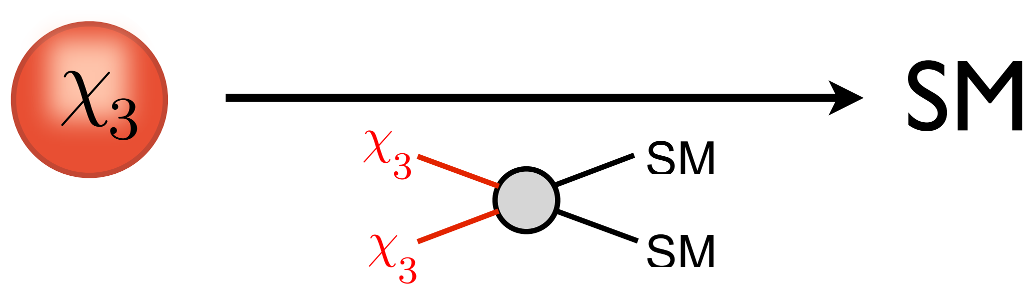


Freeze-out scenarios

Dark matter freeze-out



(time →)



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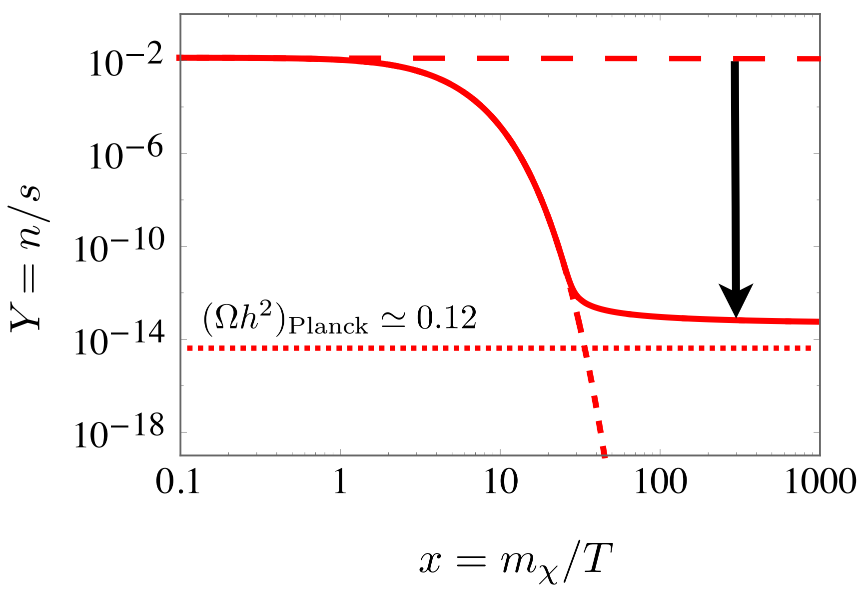

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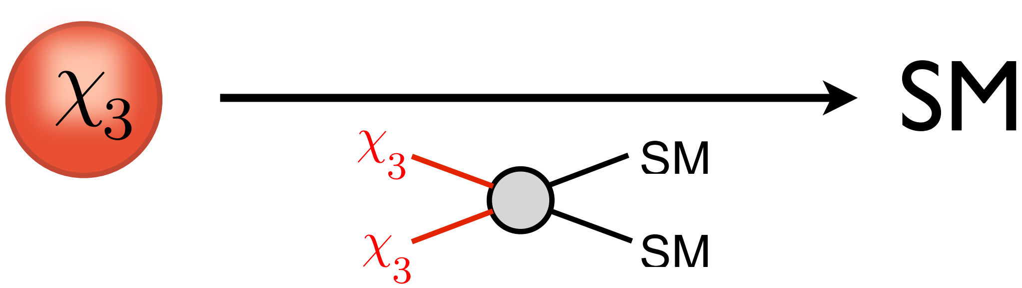
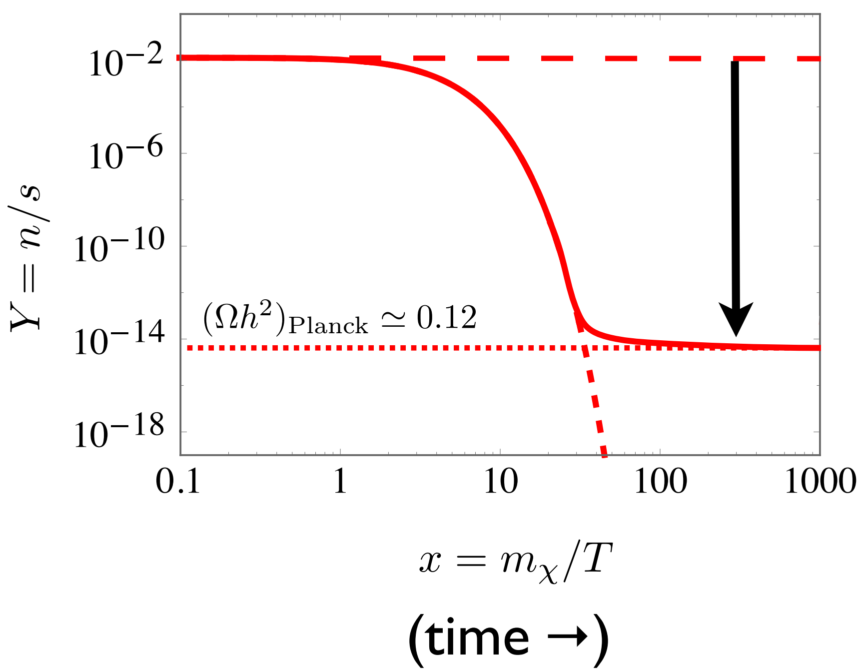
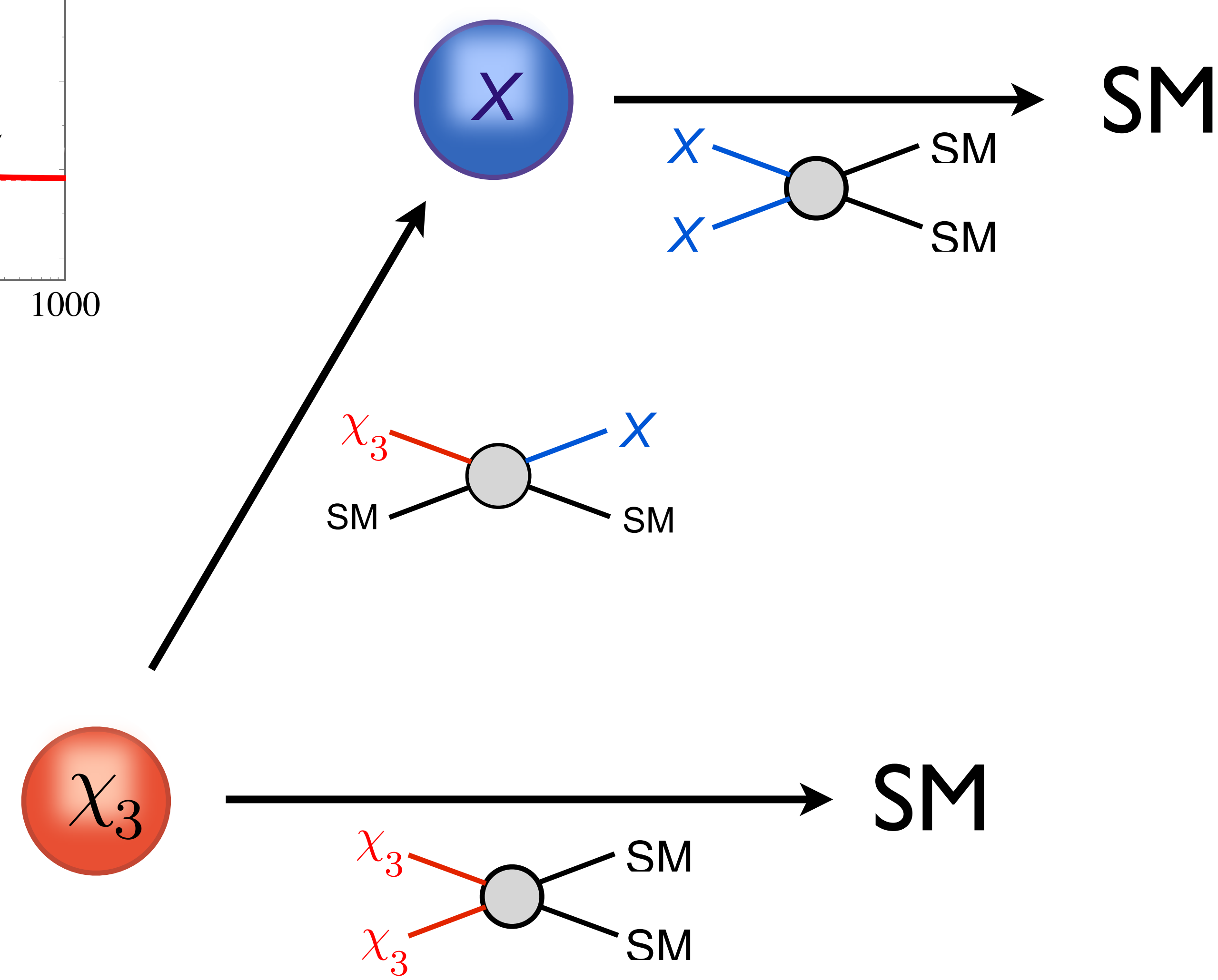


Dark matter freeze-out: coannihilation





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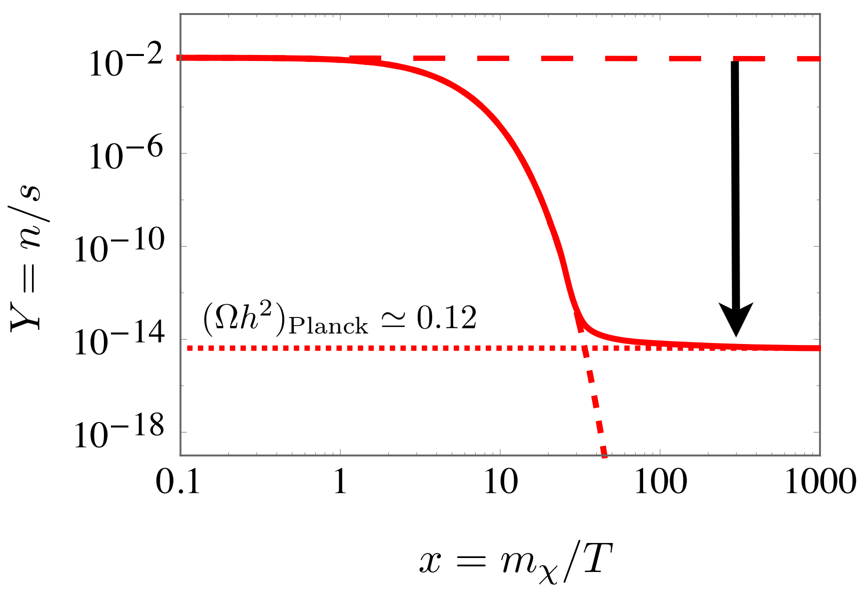

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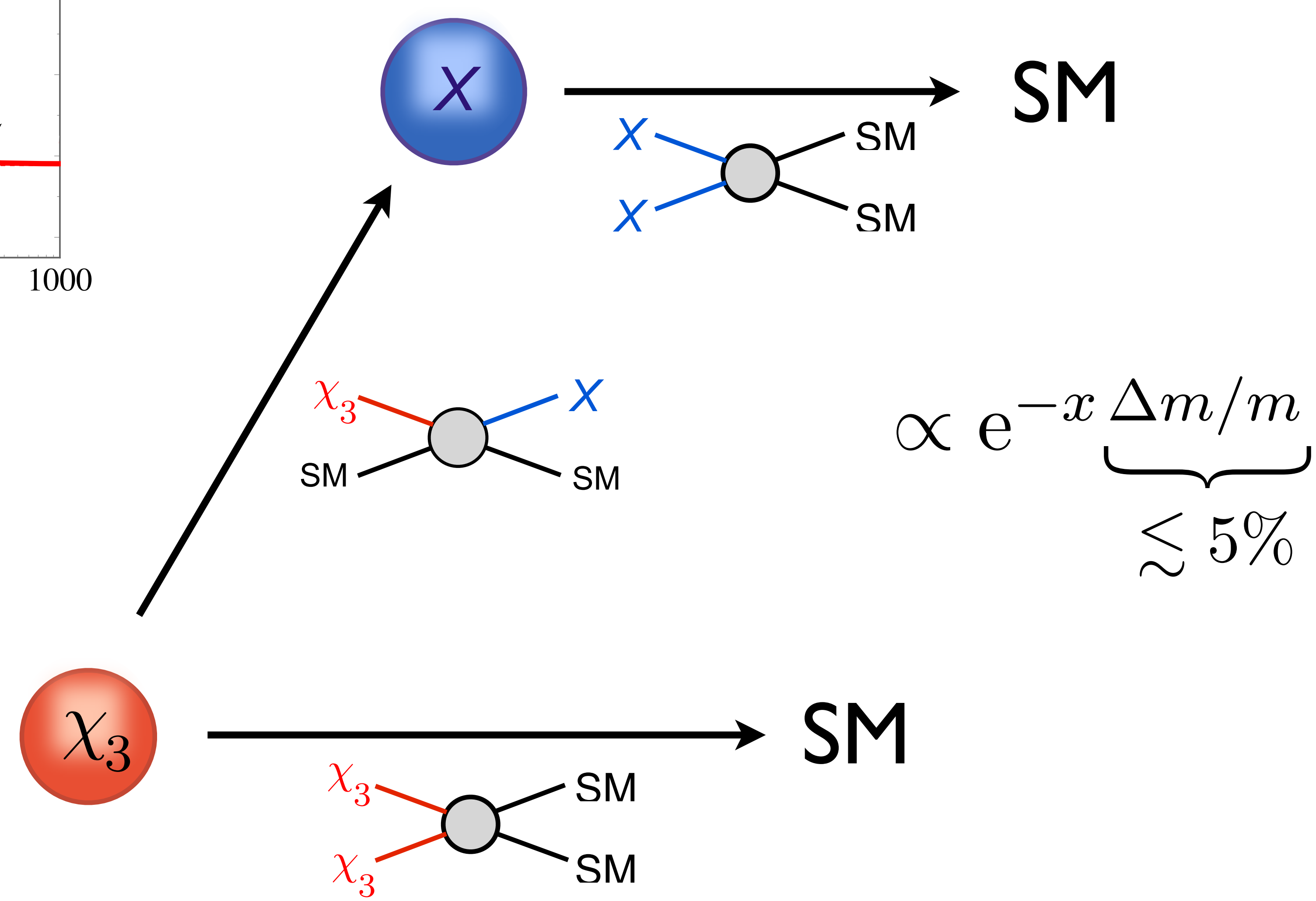

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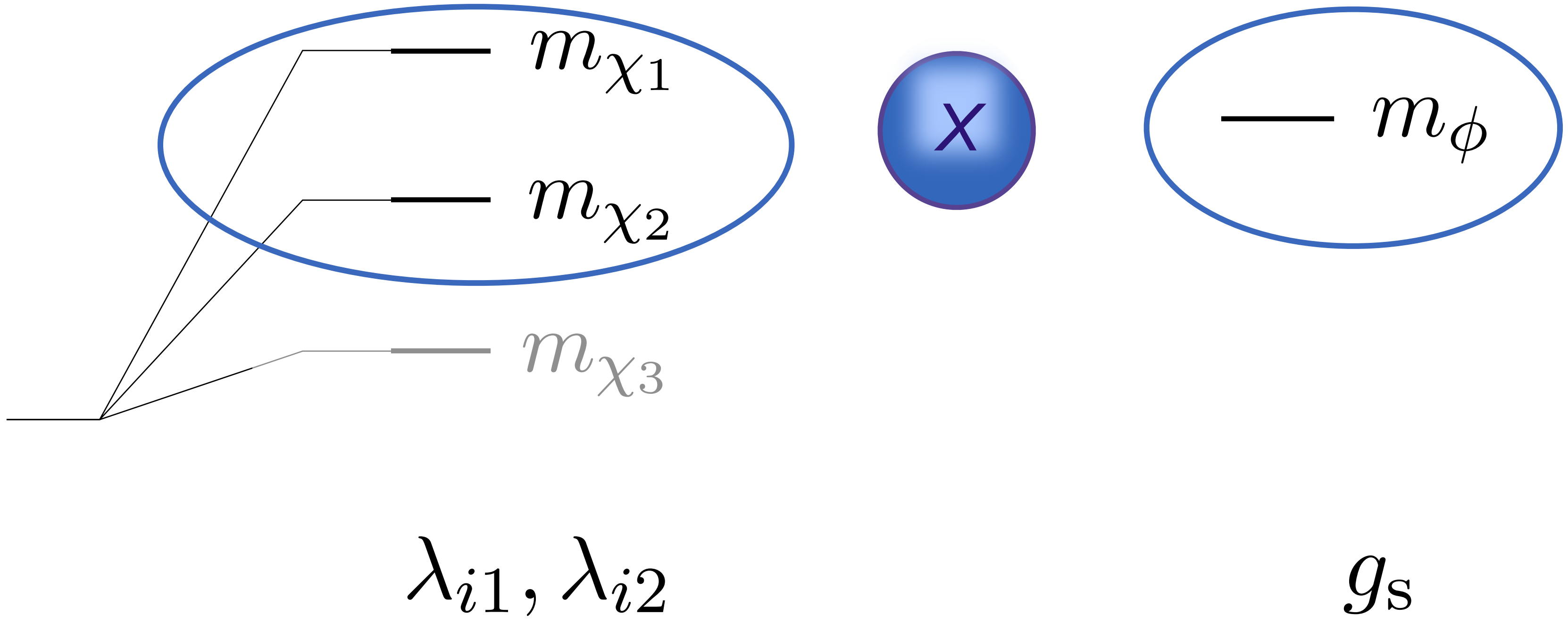

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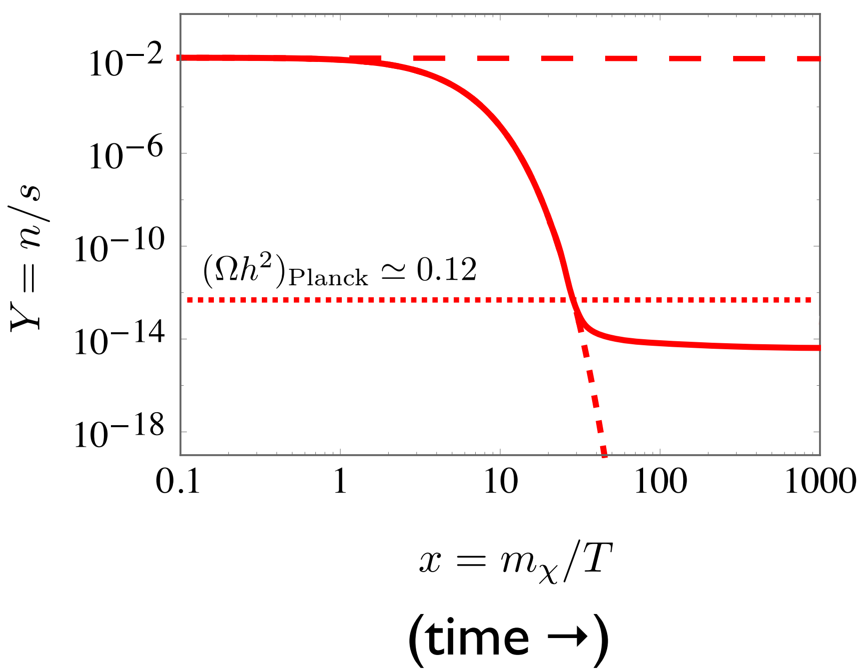
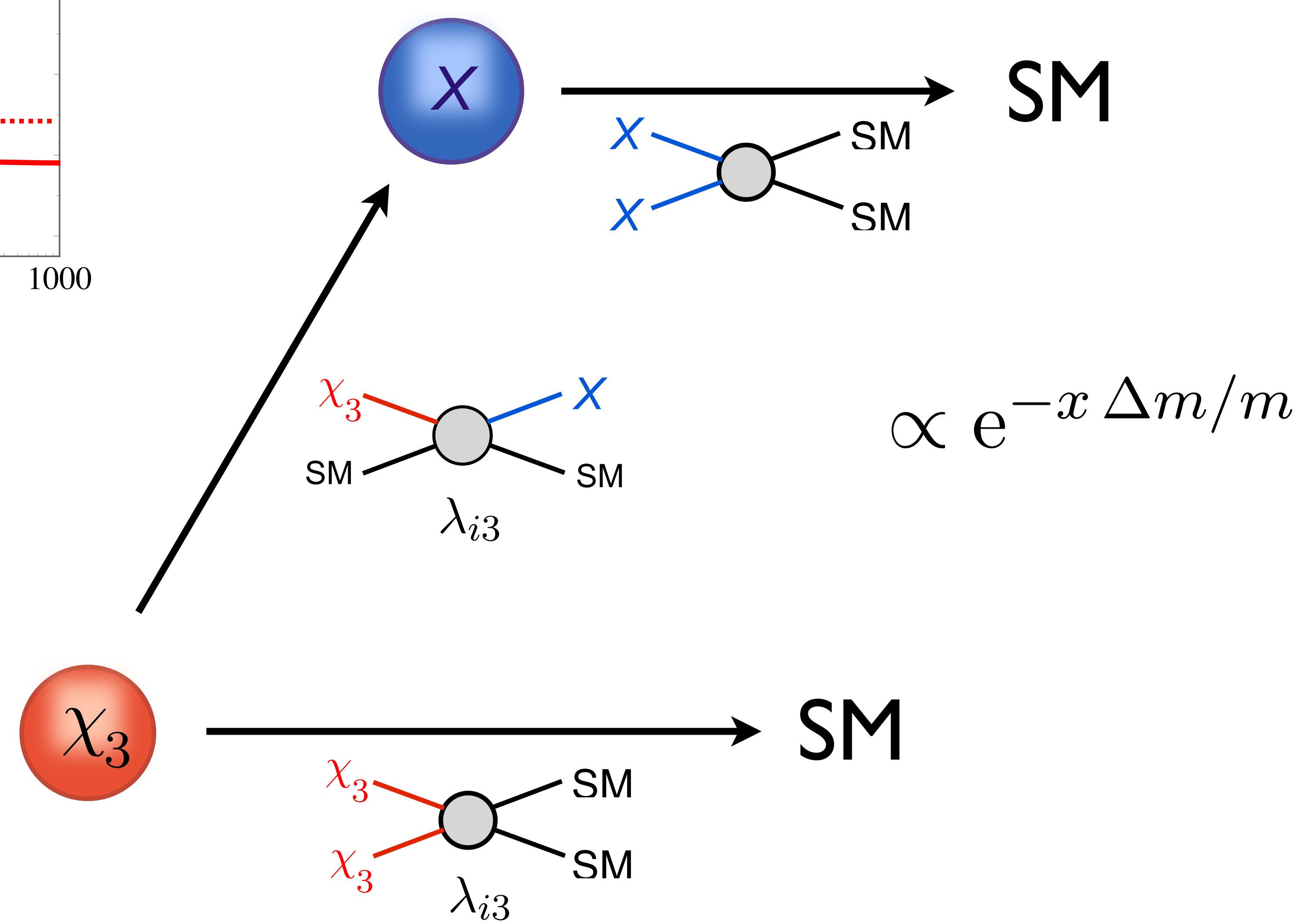
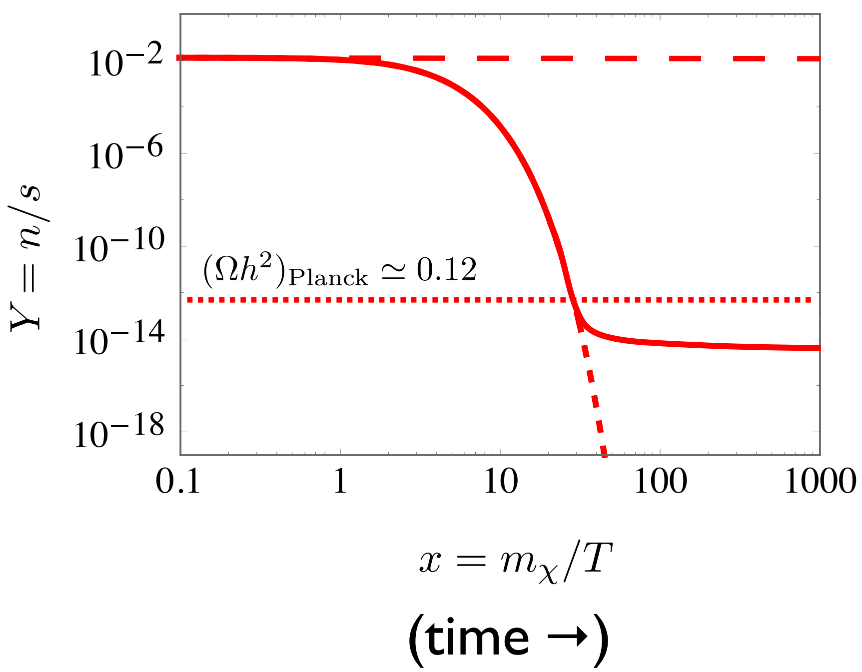
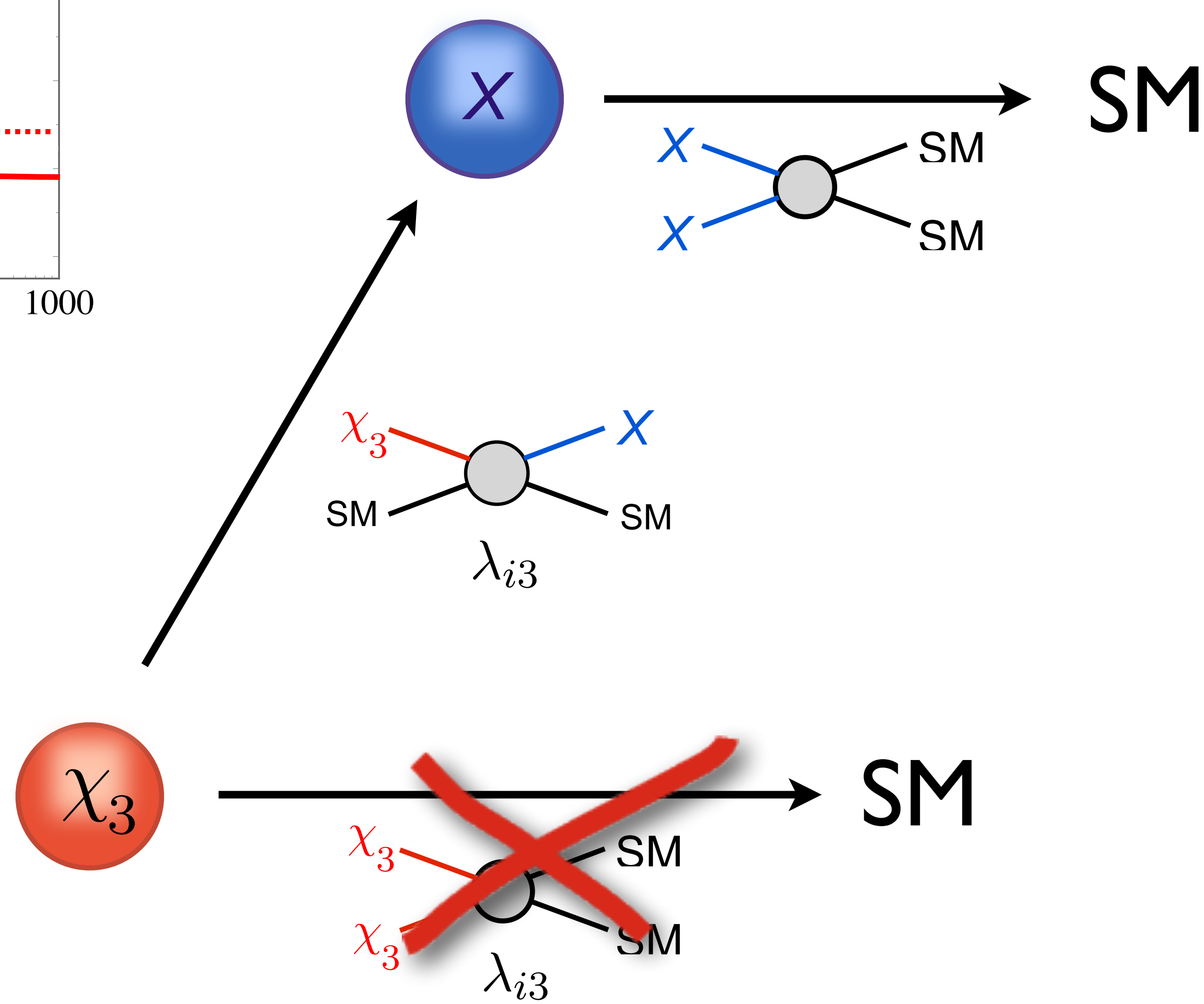


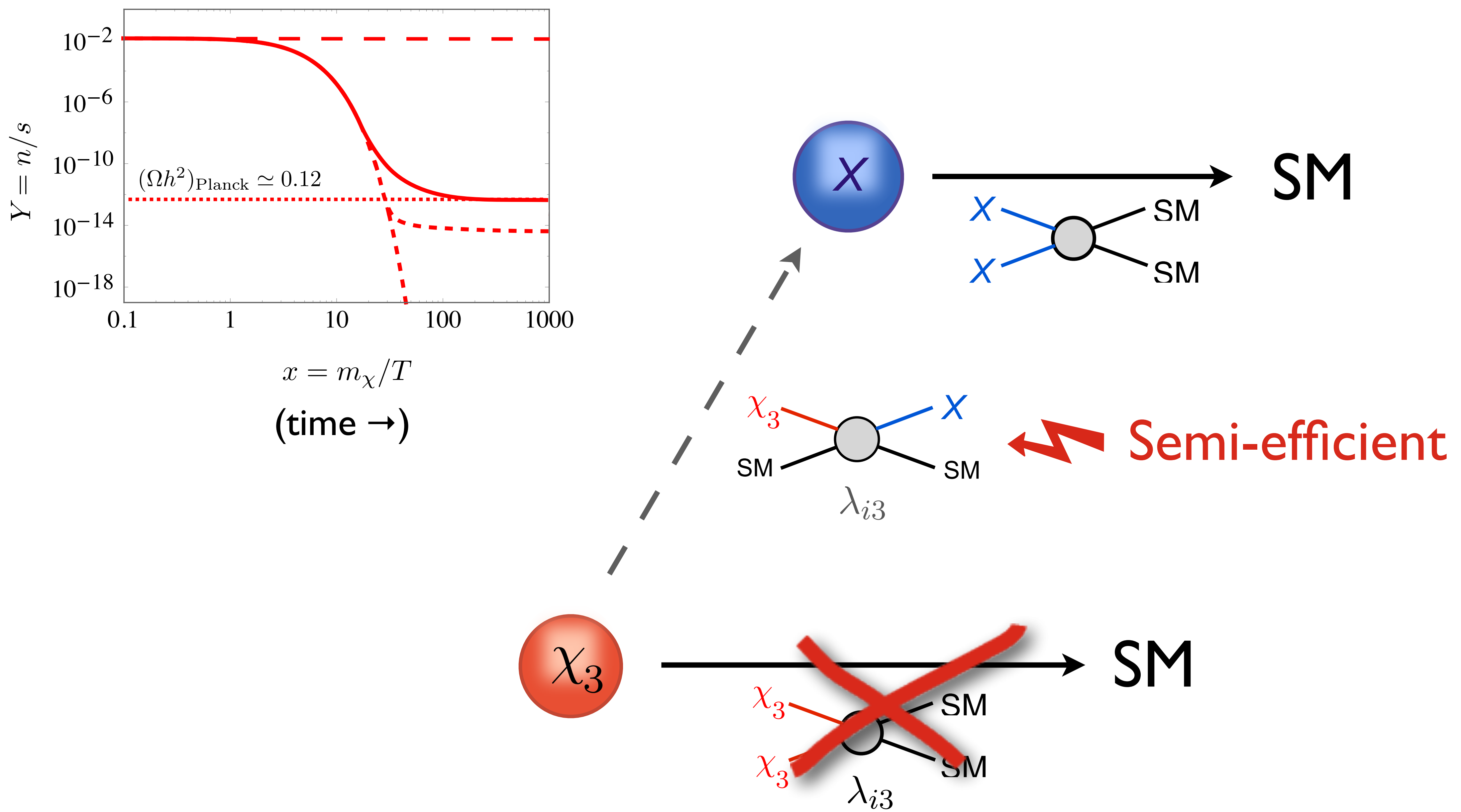


Dark matter freeze-out: small λ_{i3}





Dark matter freeze-out: very small λ_{i3}



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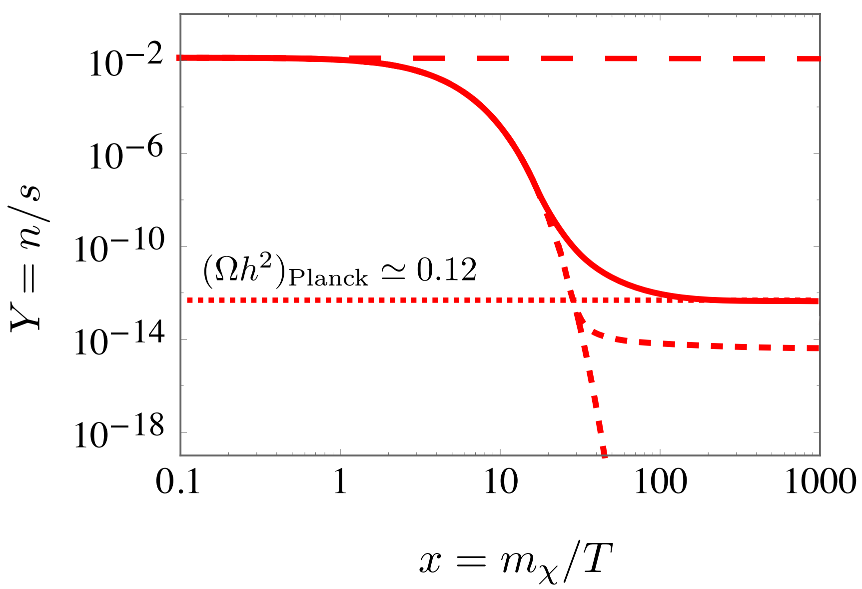

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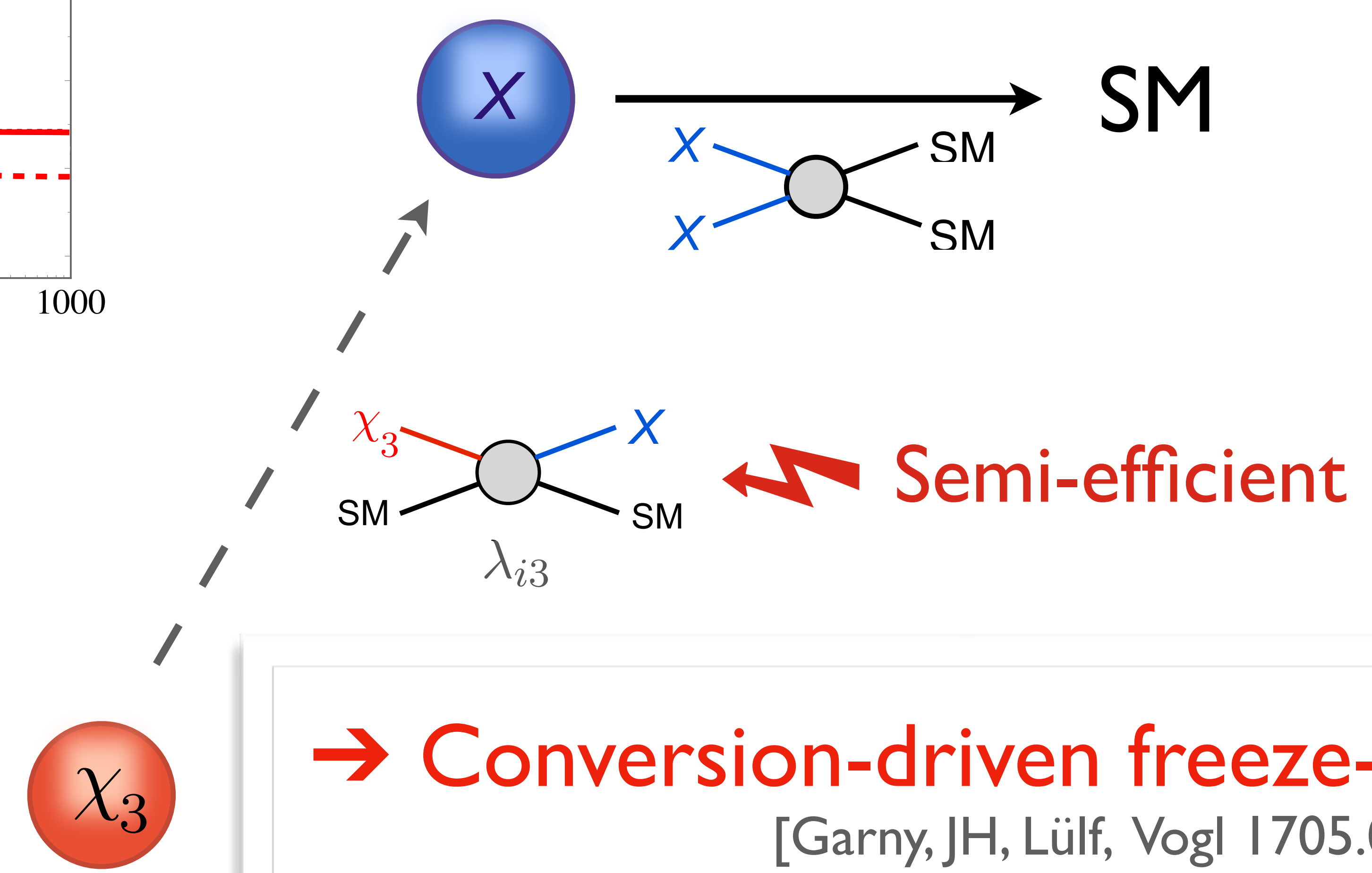


→ Conversion-driven freeze-out

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

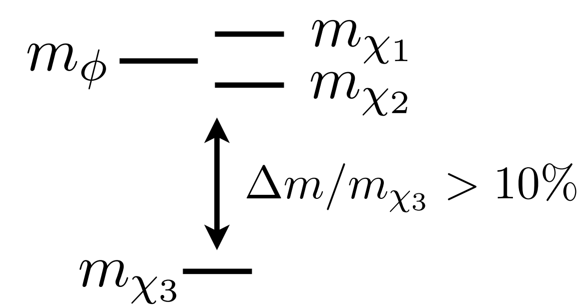
Flavored dark matter: freeze-out scenarios

- `Canonical' freeze-out (with or w/o coannihilation)

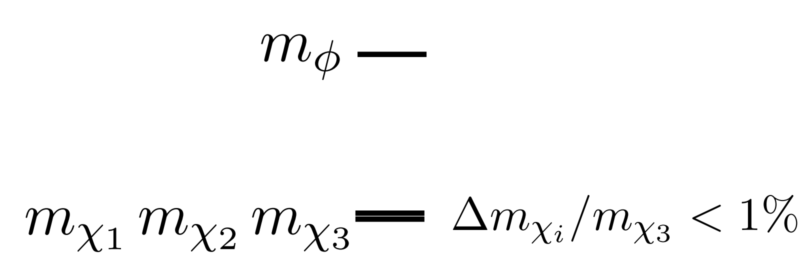
- Conversion-driven freeze-out

Flavored dark matter: freeze-out scenarios

- `Canonical' freeze-out
  - Single Flavour Freeze-Out (SFF):



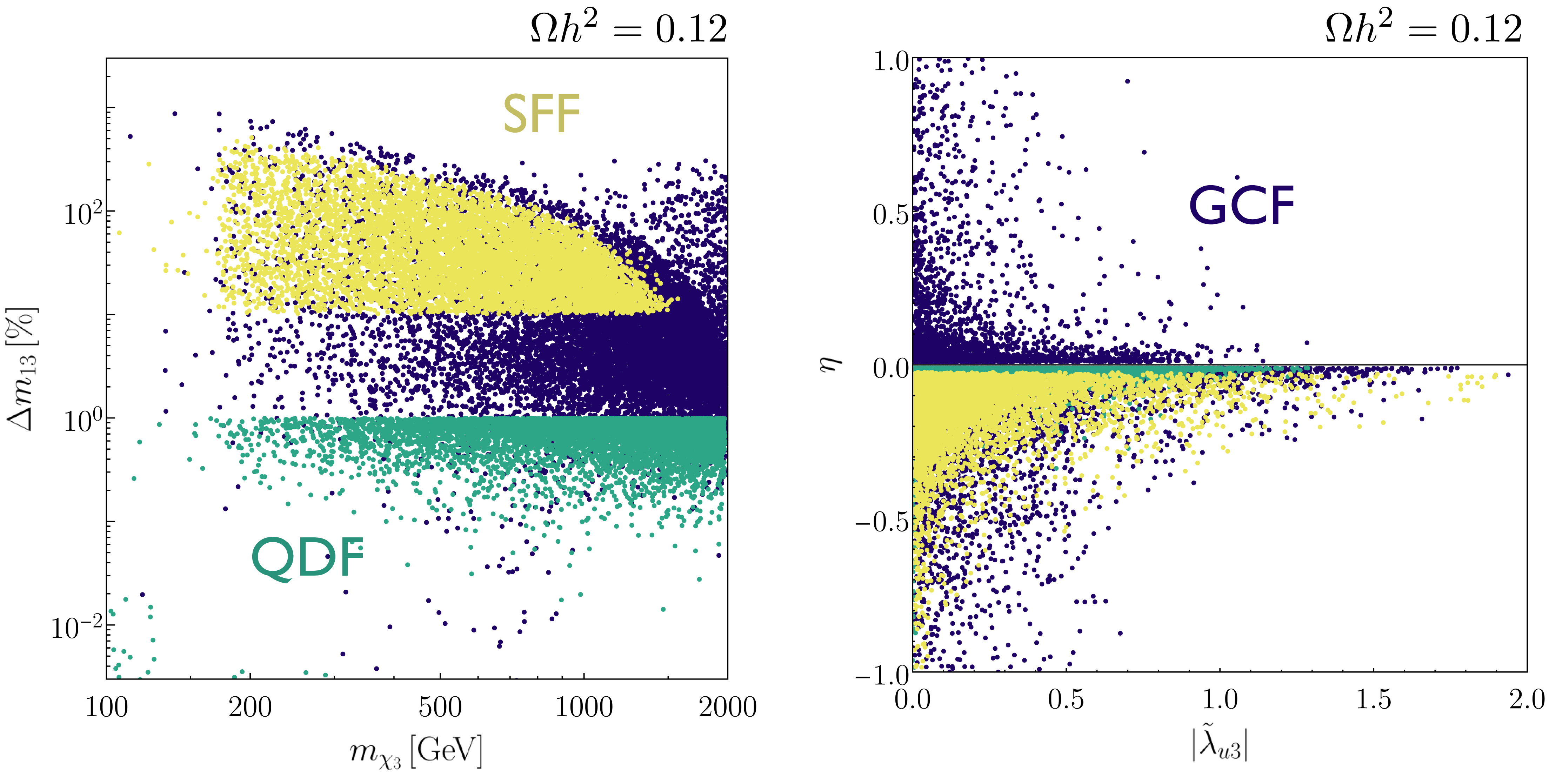
  - Quasi-Degenerate Freeze-Out (QDF):



  - Generic Canonical Freeze-Out (GCF)

Canonical freeze-out

- Flavor constraints from D-meson mixing
- Direct detection constraints from LZ
- Indirect detection from cosmic-ray antiprotons



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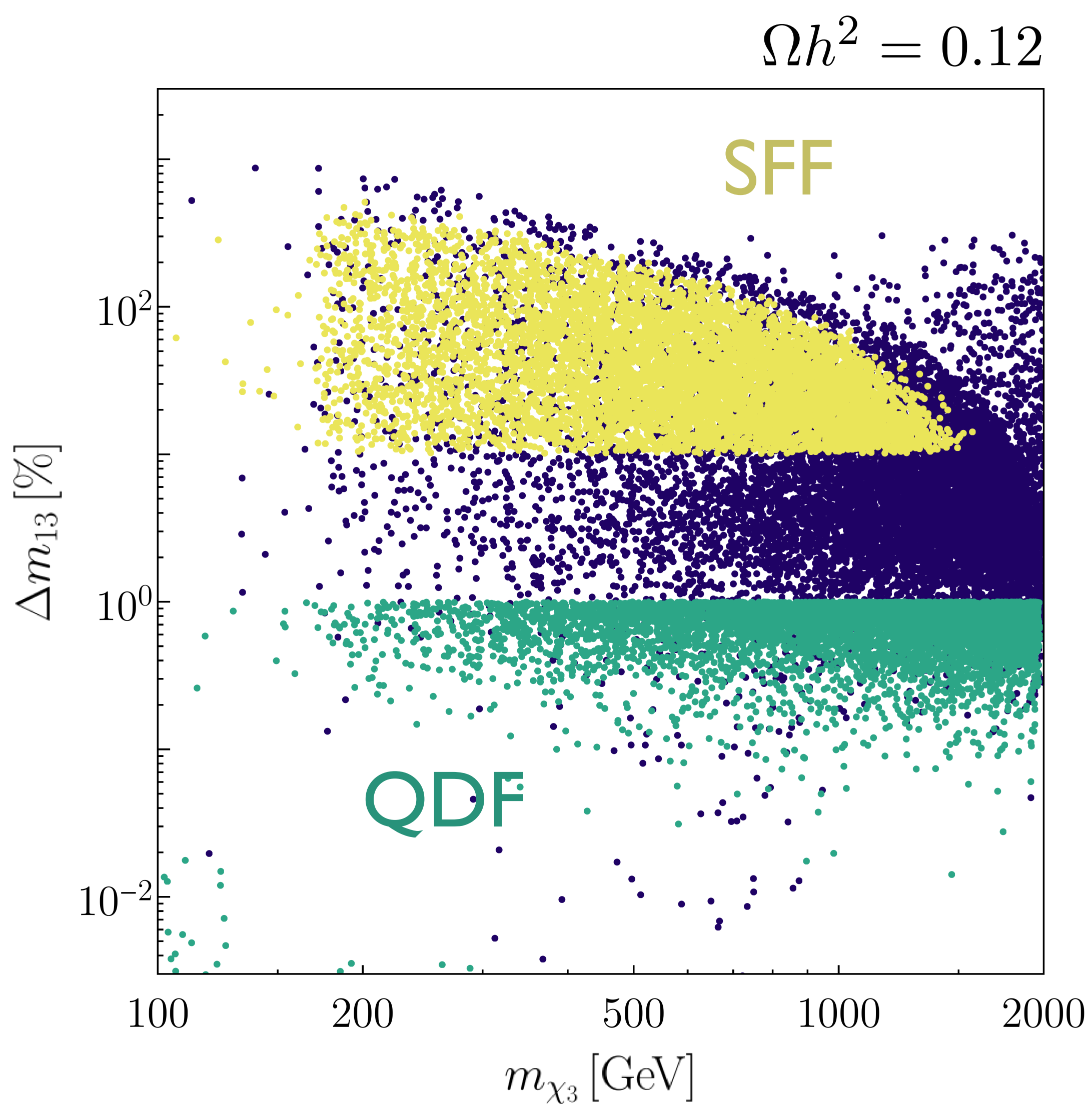

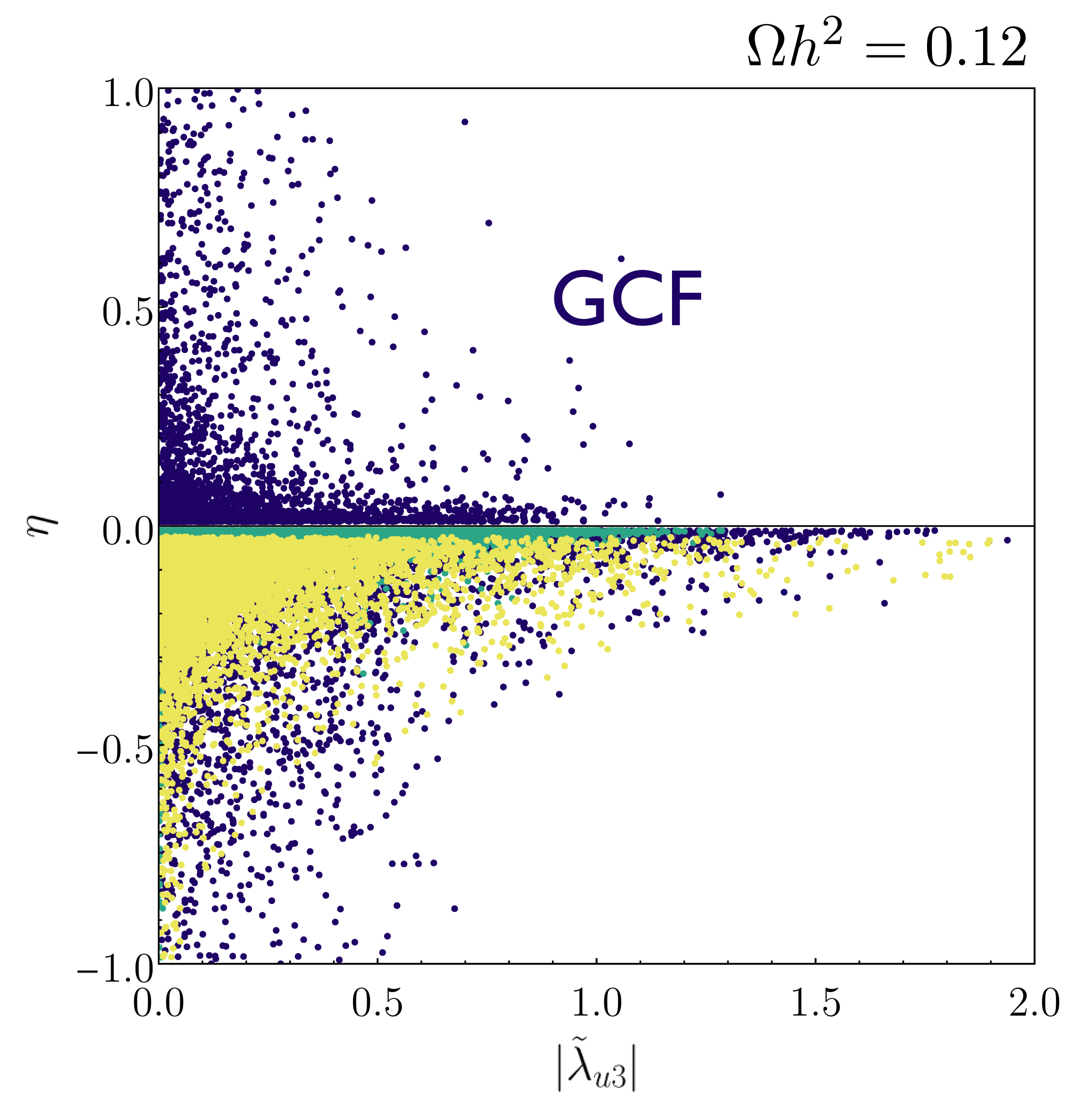

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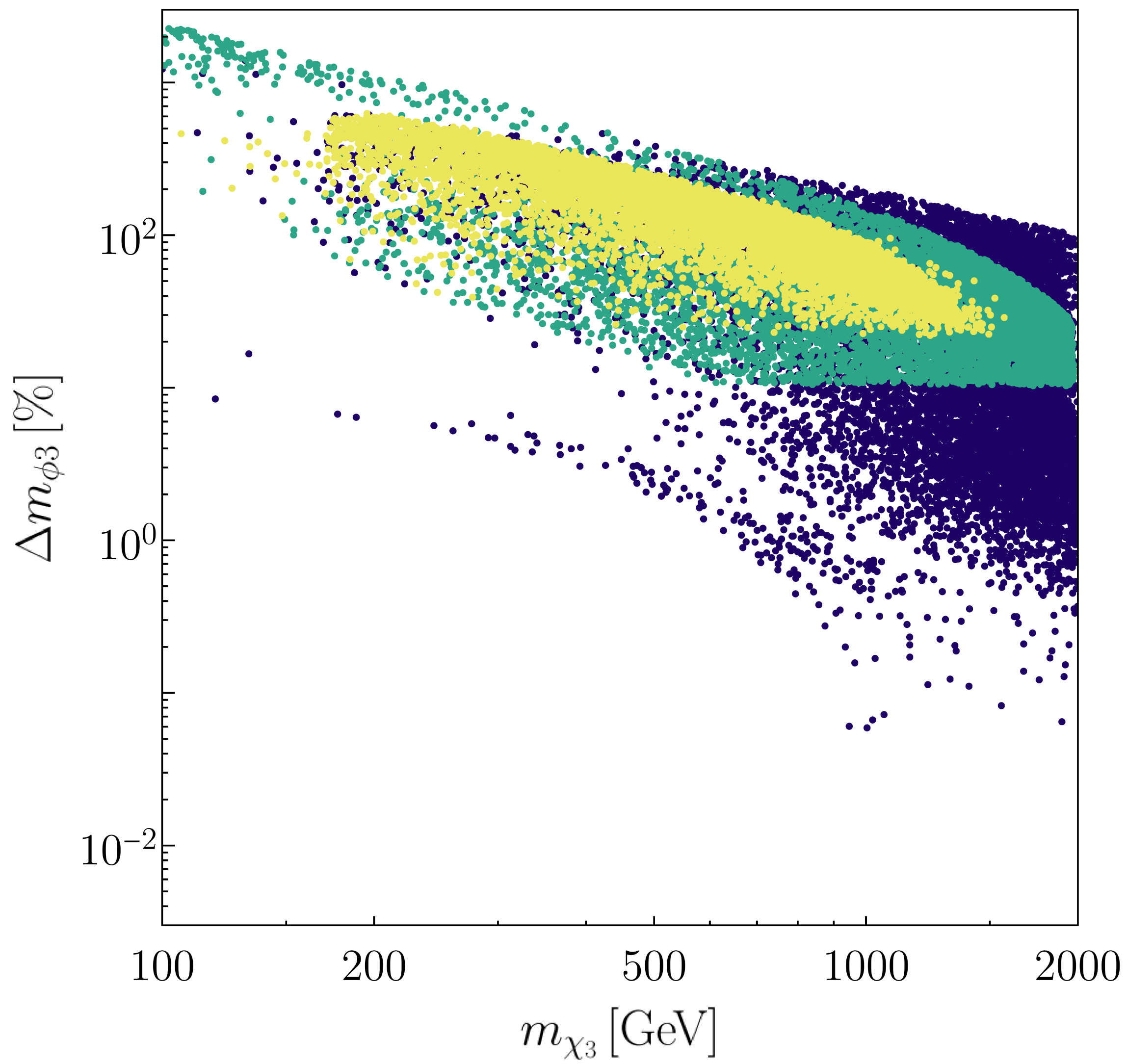
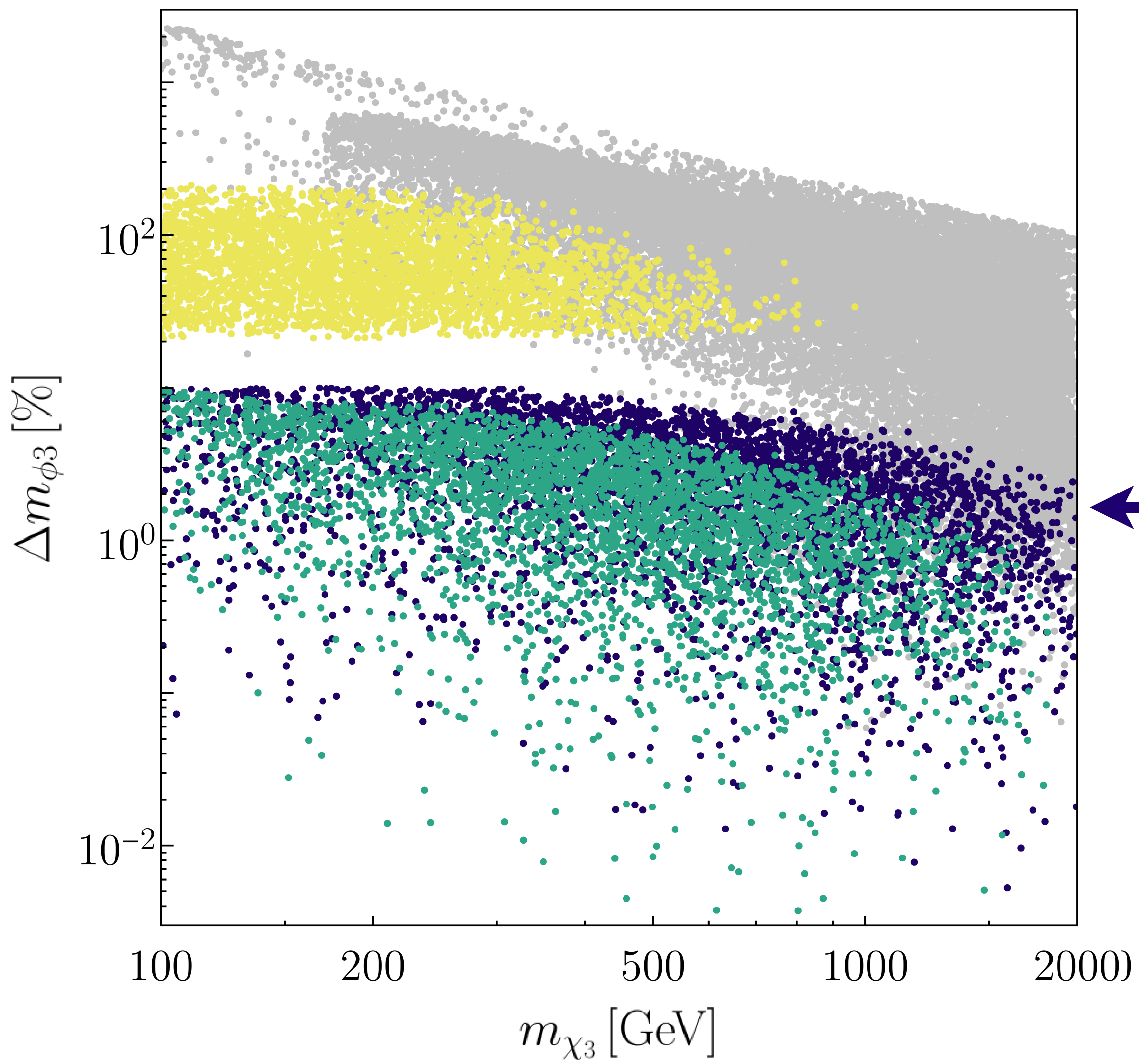
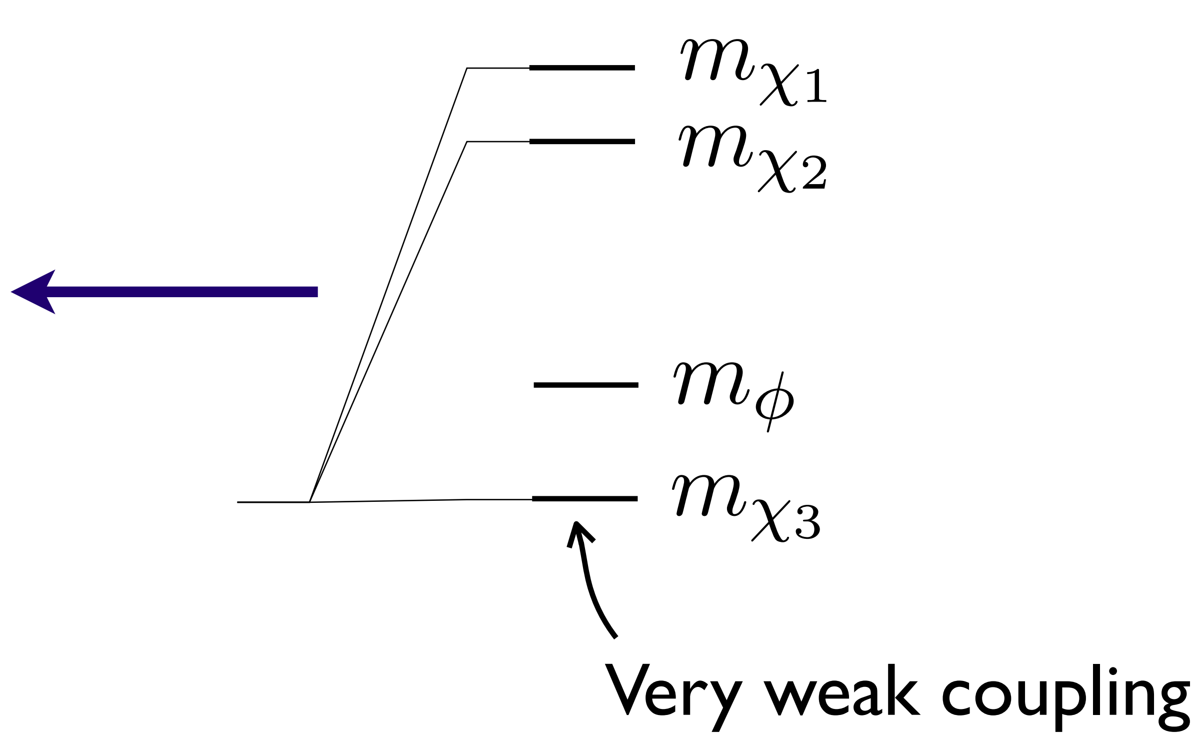


Conversion-driven freeze-out



$\eta > 0$:



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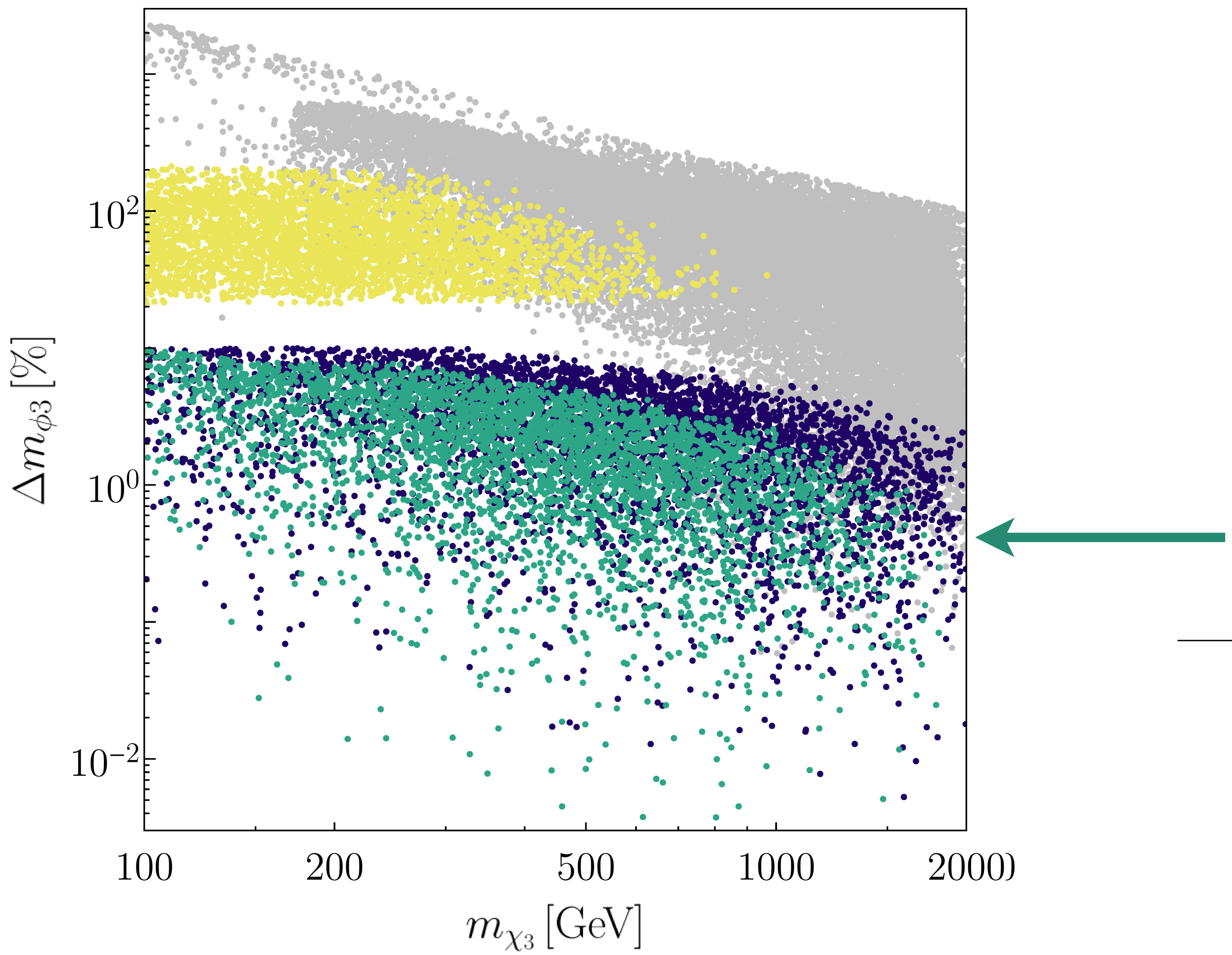

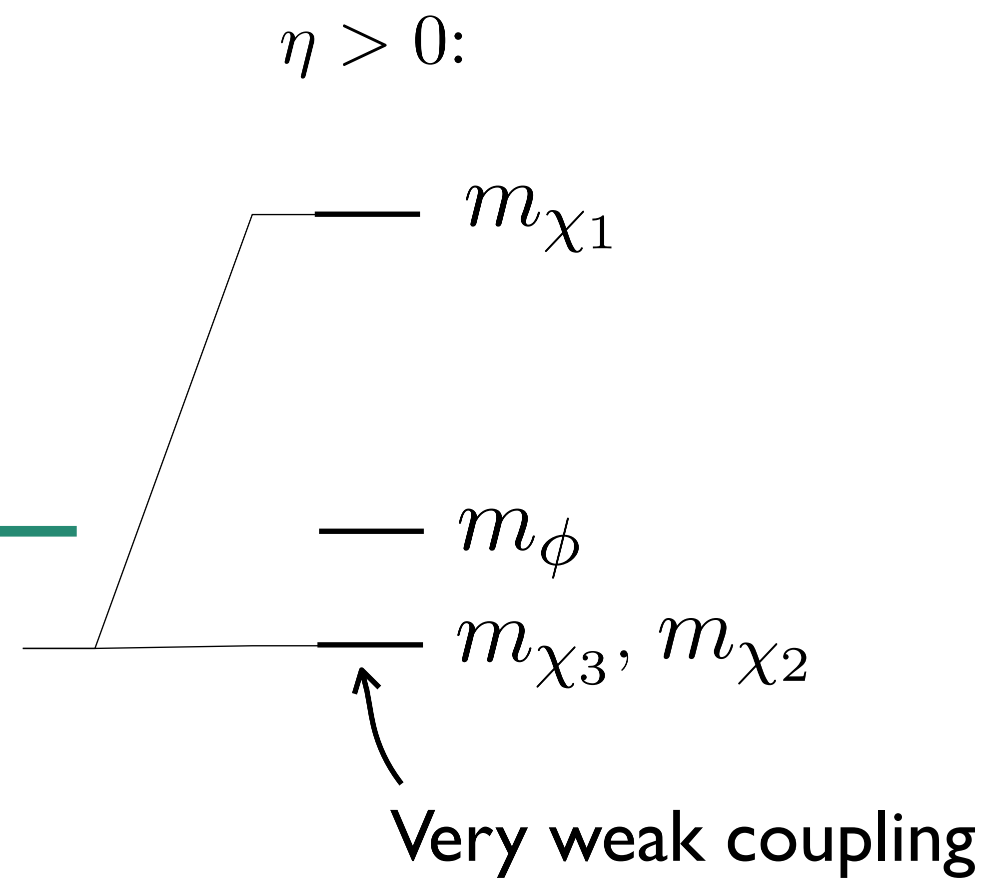

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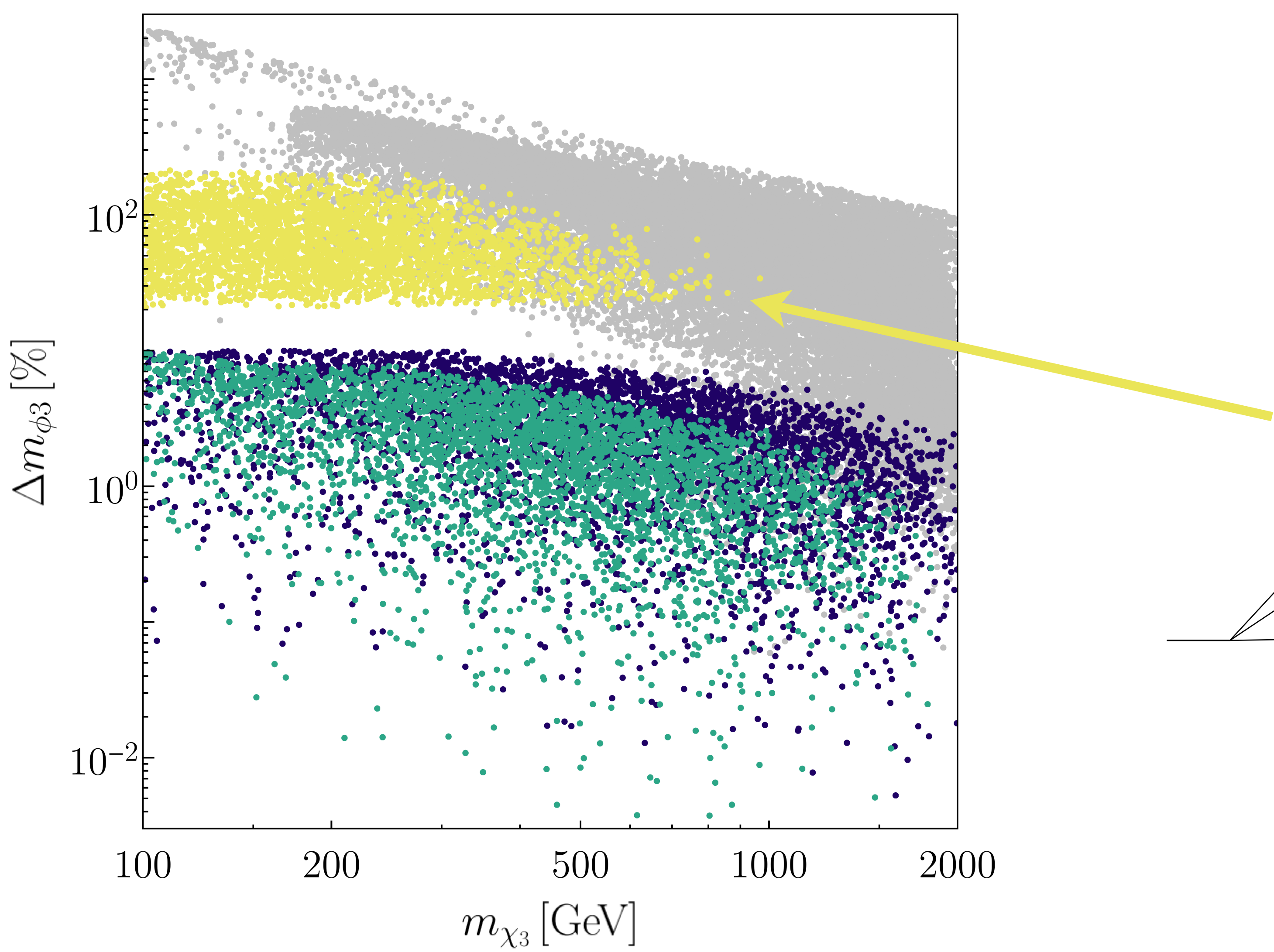

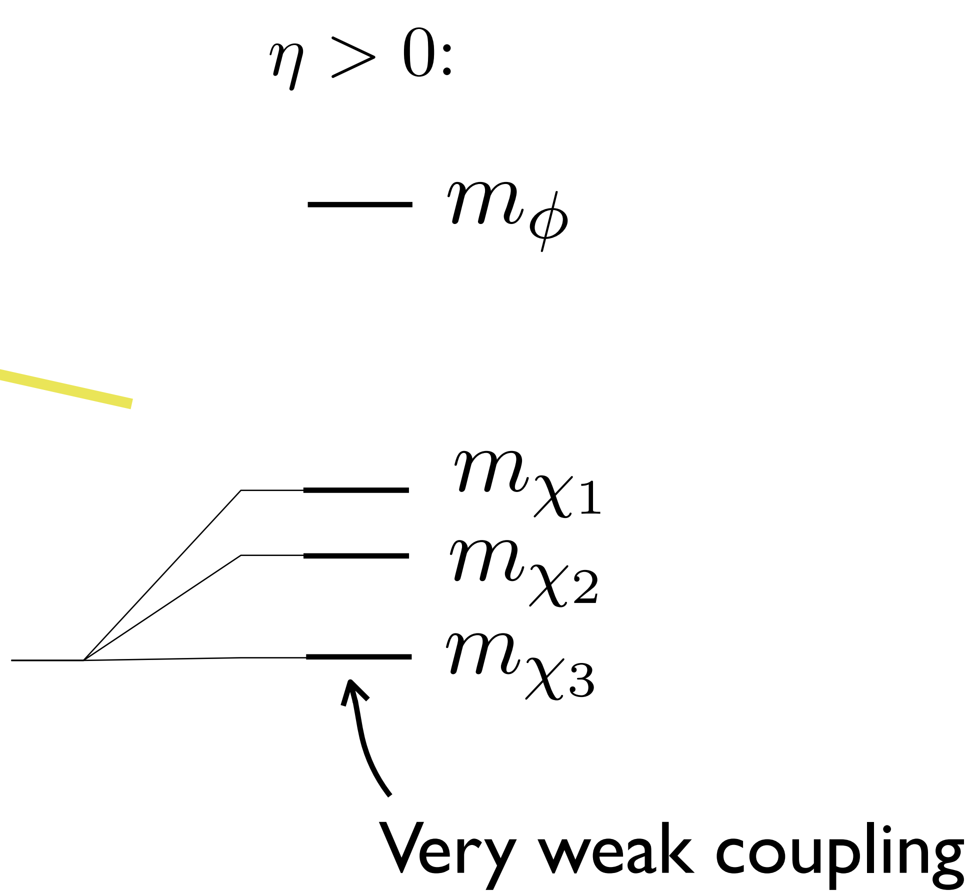

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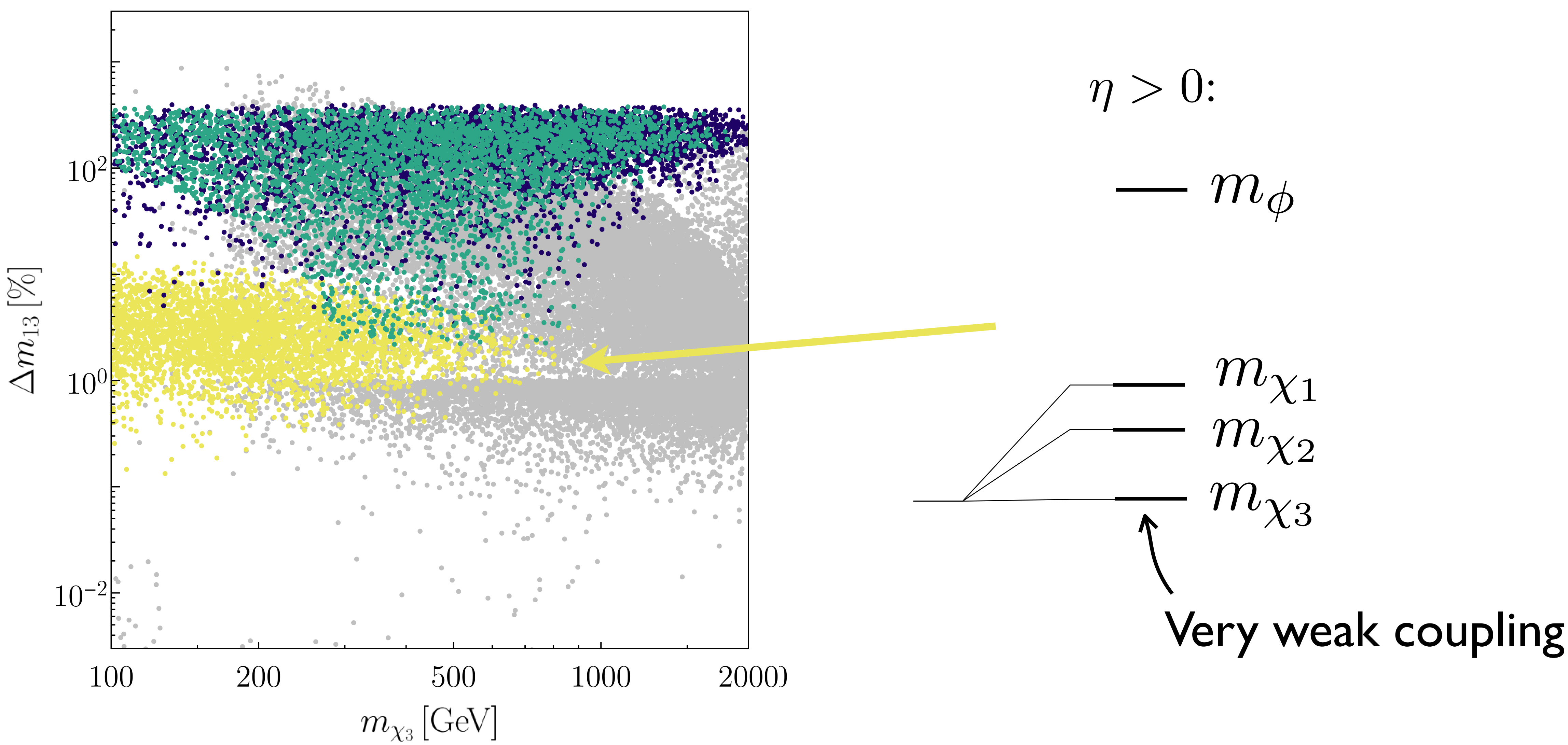
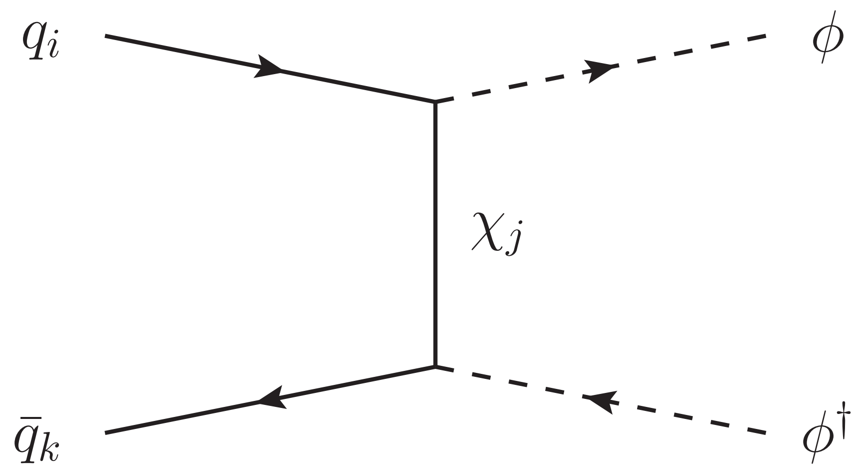
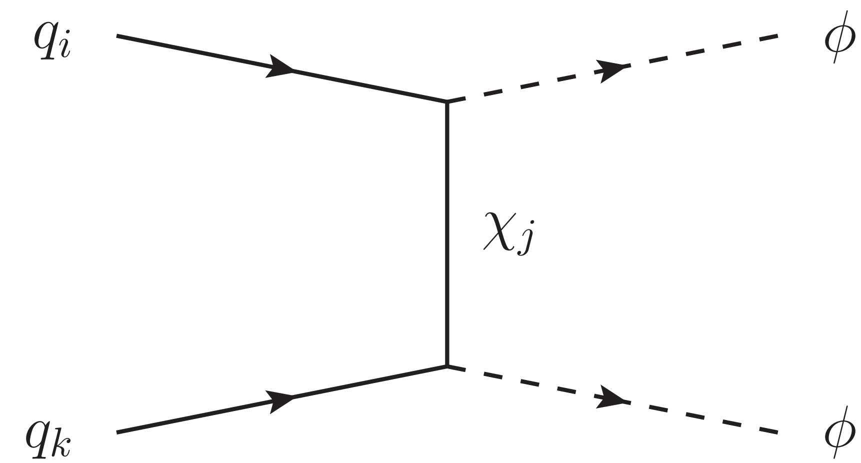


LHC signatures

LHC signatures

Production:

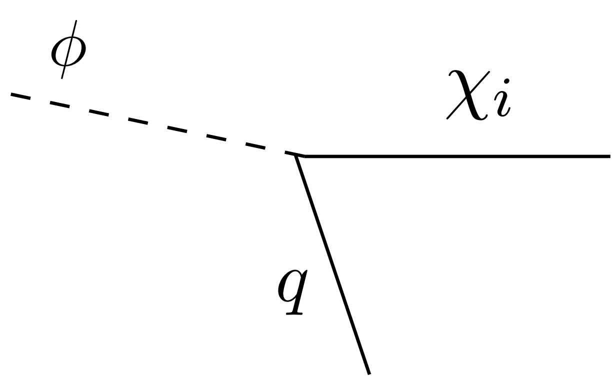




$uu \to \phi\phi$ large cross section

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

Decay:



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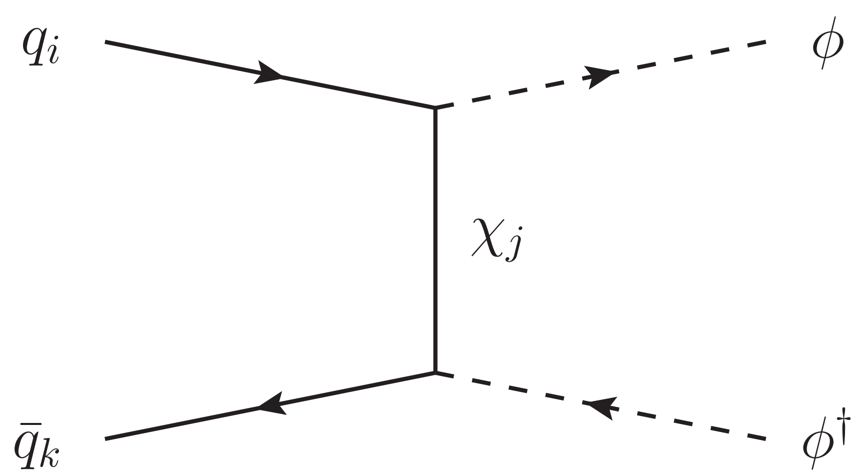

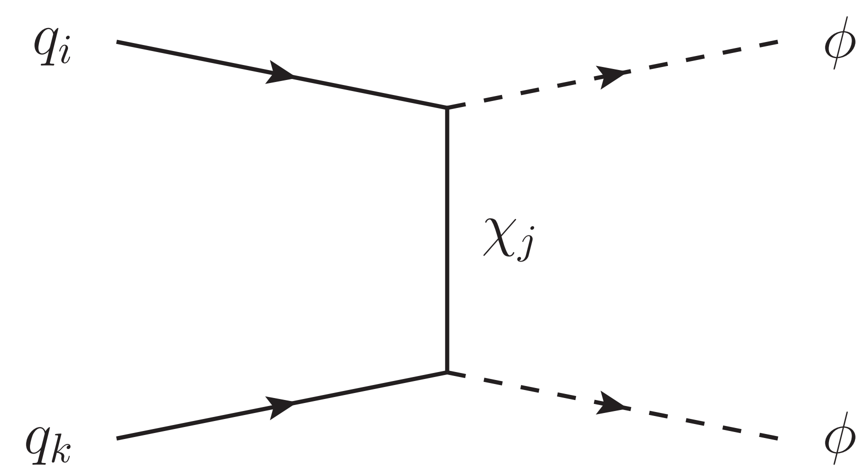

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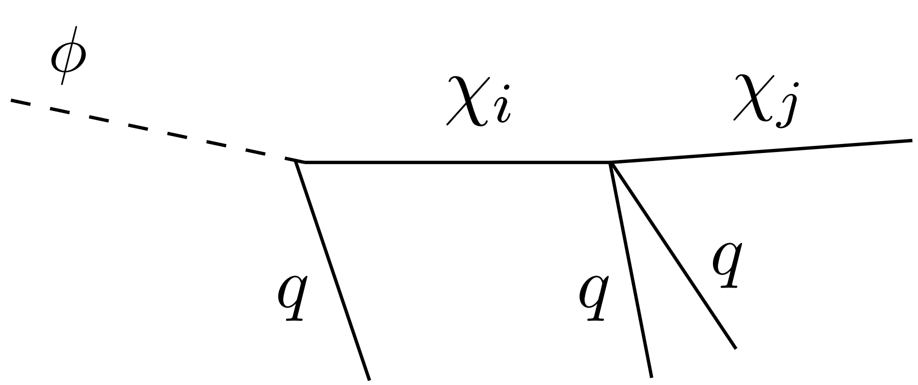

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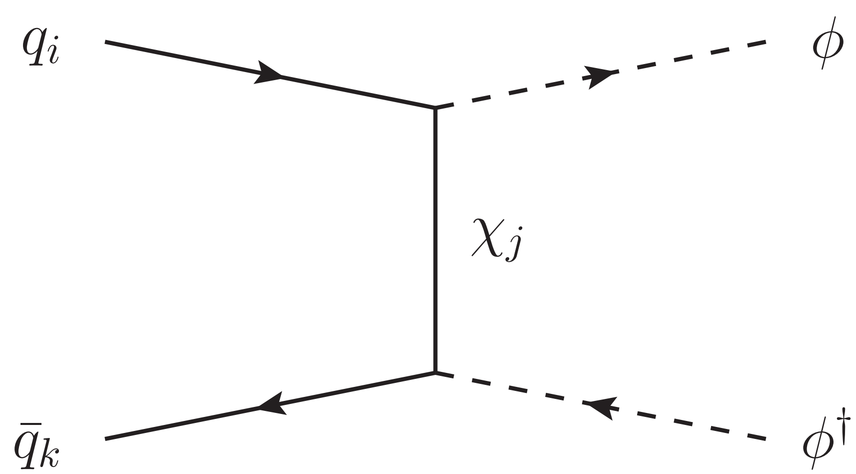

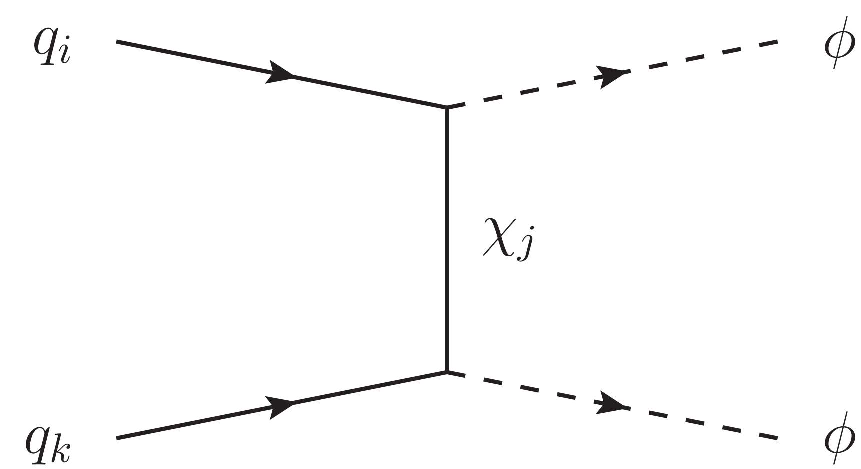

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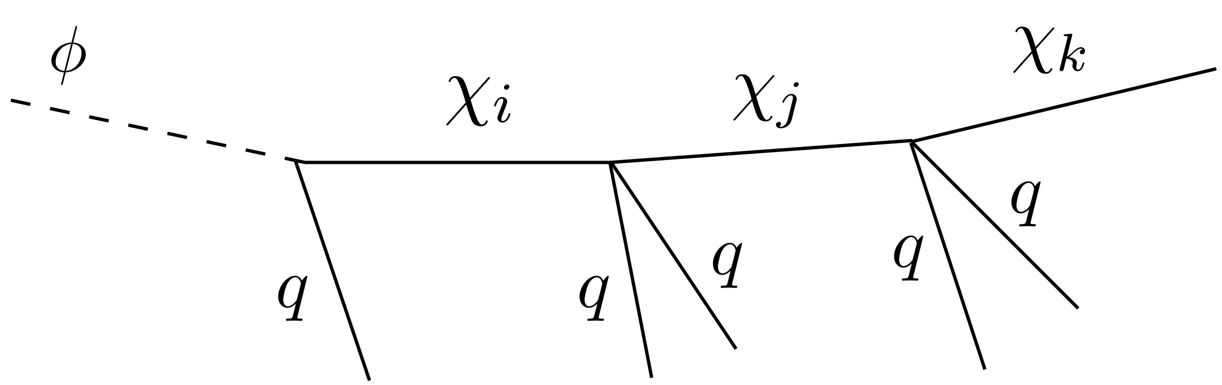
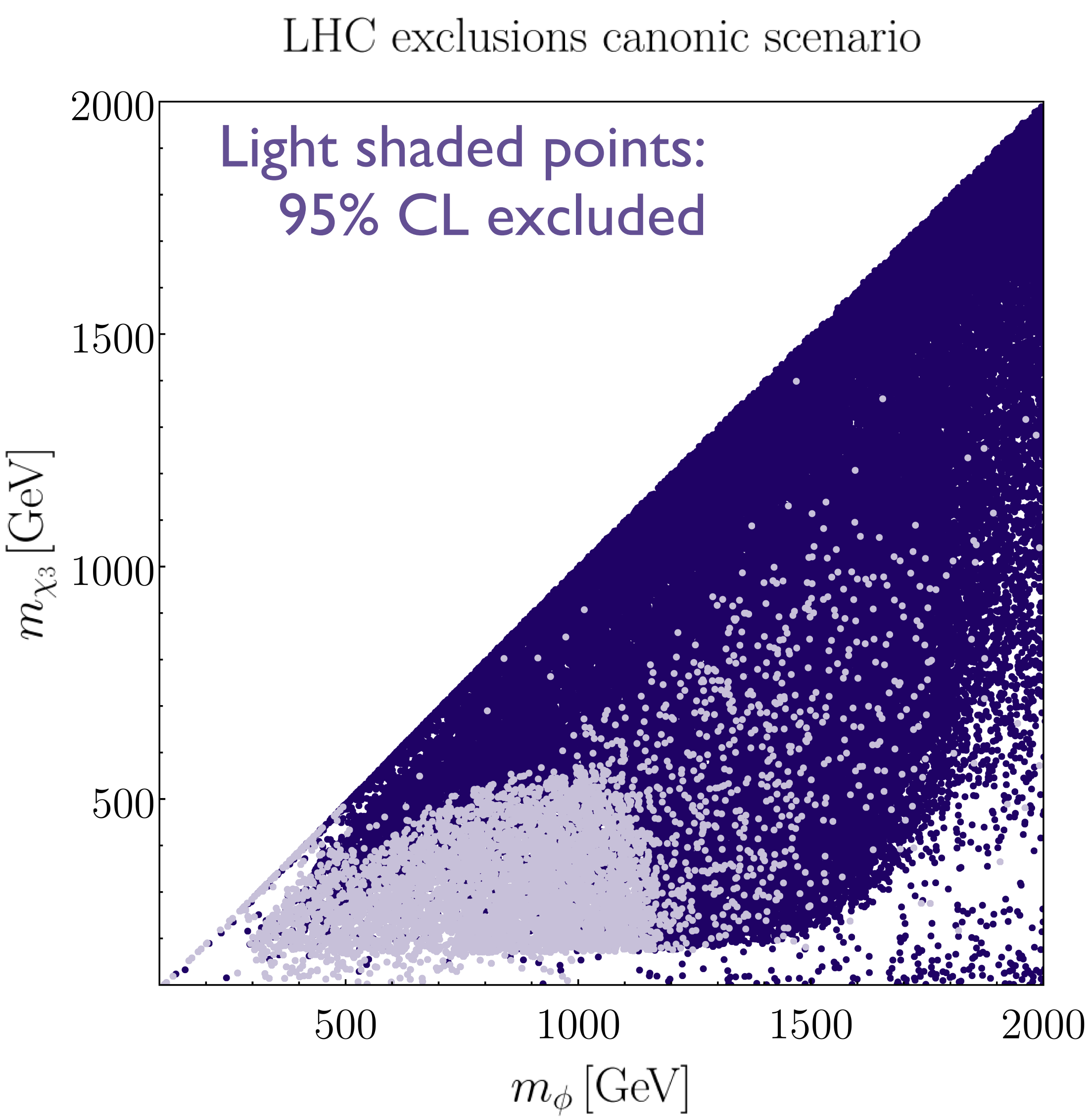


Current constraints: canonical freeze-out



Using SModelS 2

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

search	$\sqrt{s}$	signatures
ATLAS-SUSY-2013-02 [49]	8 TeV	jets+$\not{E}_T$
ATLAS-SUSY-2016-07 [50]	13 TeV	jets+$\not{E}_T$
ATLAS-SUSY-2016-15 [51]	13 TeV	tops+$\not{E}_T$
ATLAS-SUSY-2018-12 [52]	13 TeV	tops+$\not{E}_T$
ATLAS-SUSY-2018-22 [53]	13 TeV	jets+$\not{E}_T$
CMS-SUS-16-033 [54]	13 TeV	jets+$\not{E}_T$
CMS-SUS-16-036 [55]	13 TeV	jets+$\not{E}_T$
CMS-SUS-19-006 [45]	13 TeV	jets+$\not{E}_T$
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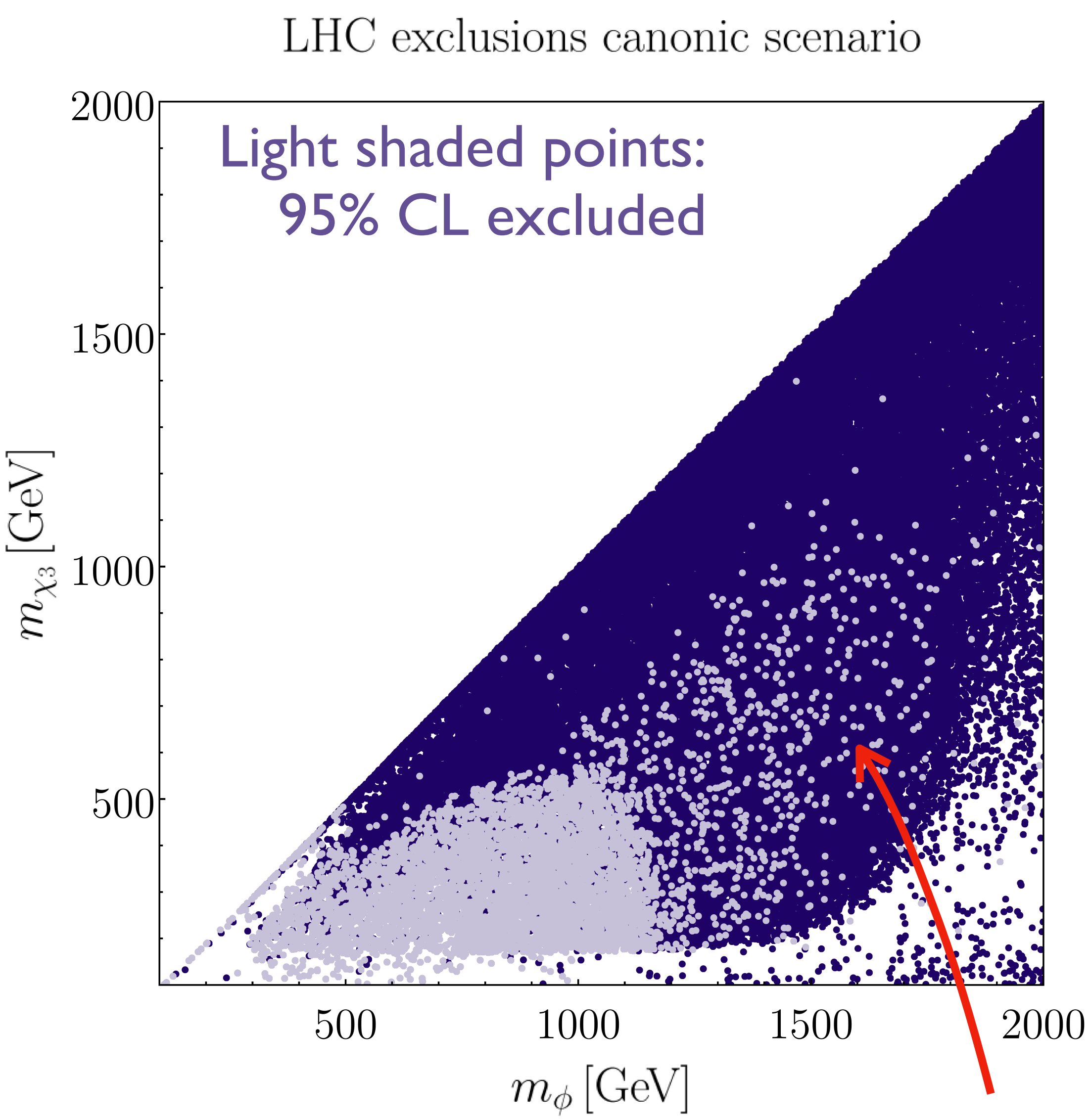

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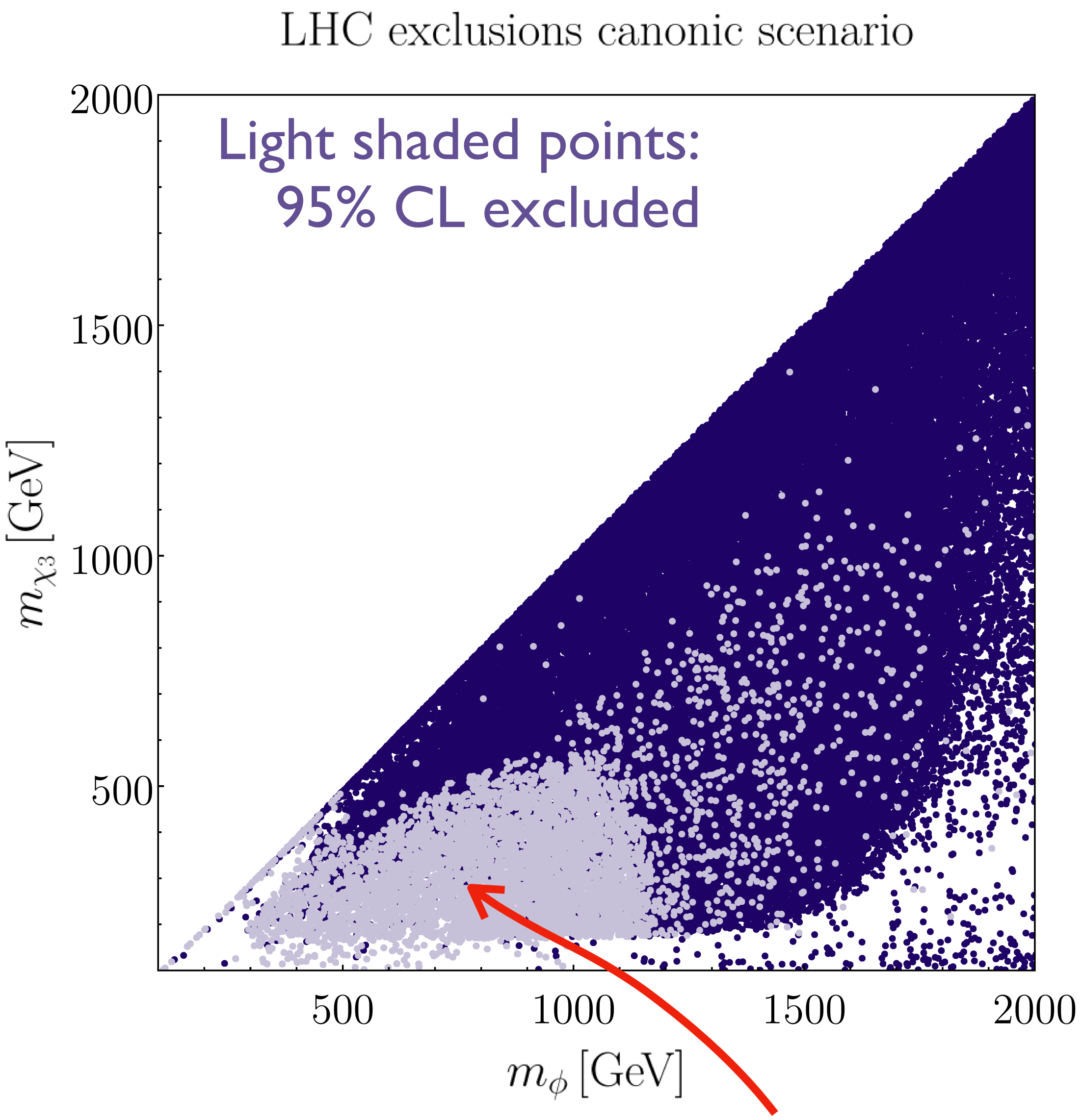
Excluded points: enhanced *t*-channel mediator production

Current constraints: canonical freeze-out



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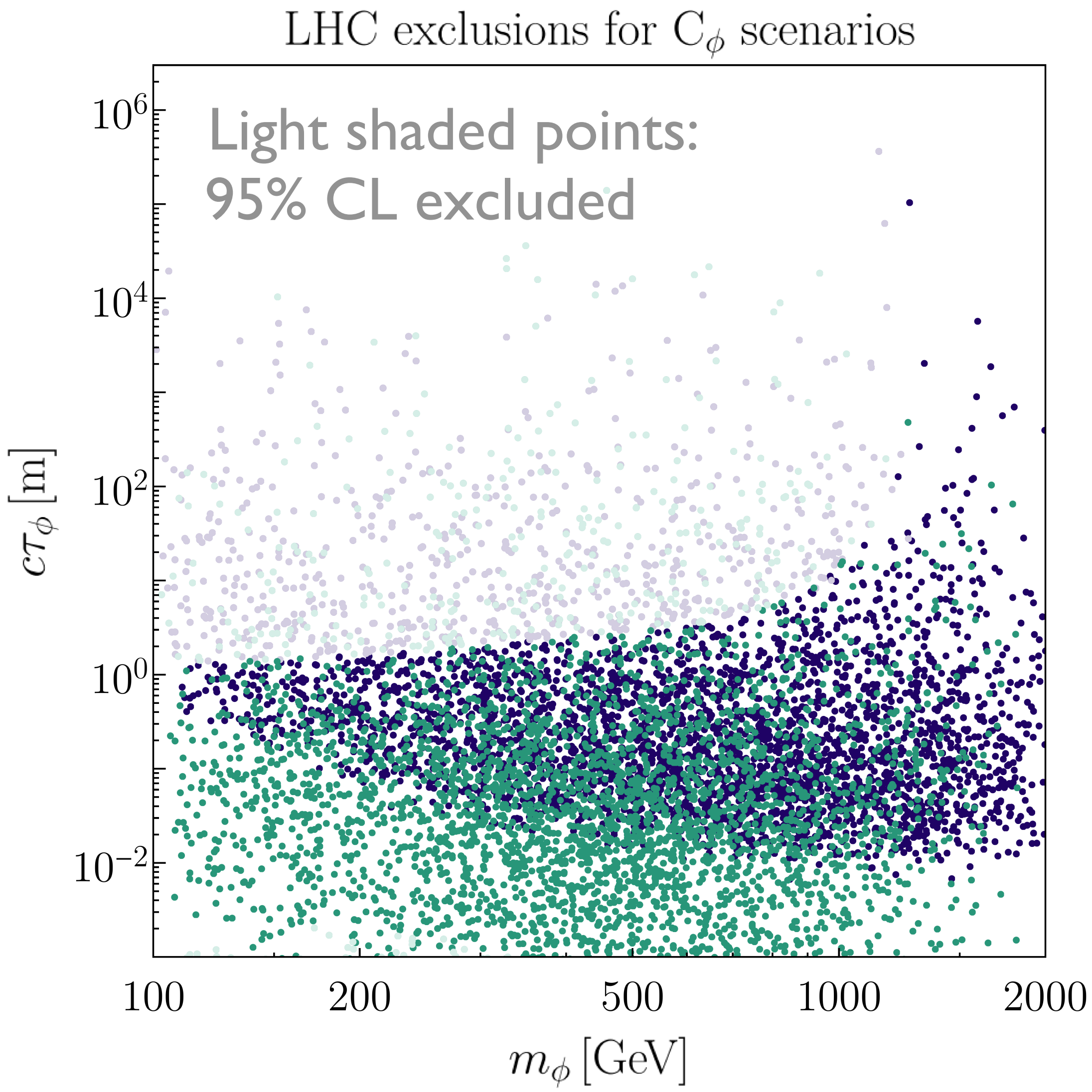
Allowed points: complex decay patterns/non-prompt decays

Constraints: conversion-driven freeze-out

- Small DM coupling: long-lived particles



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
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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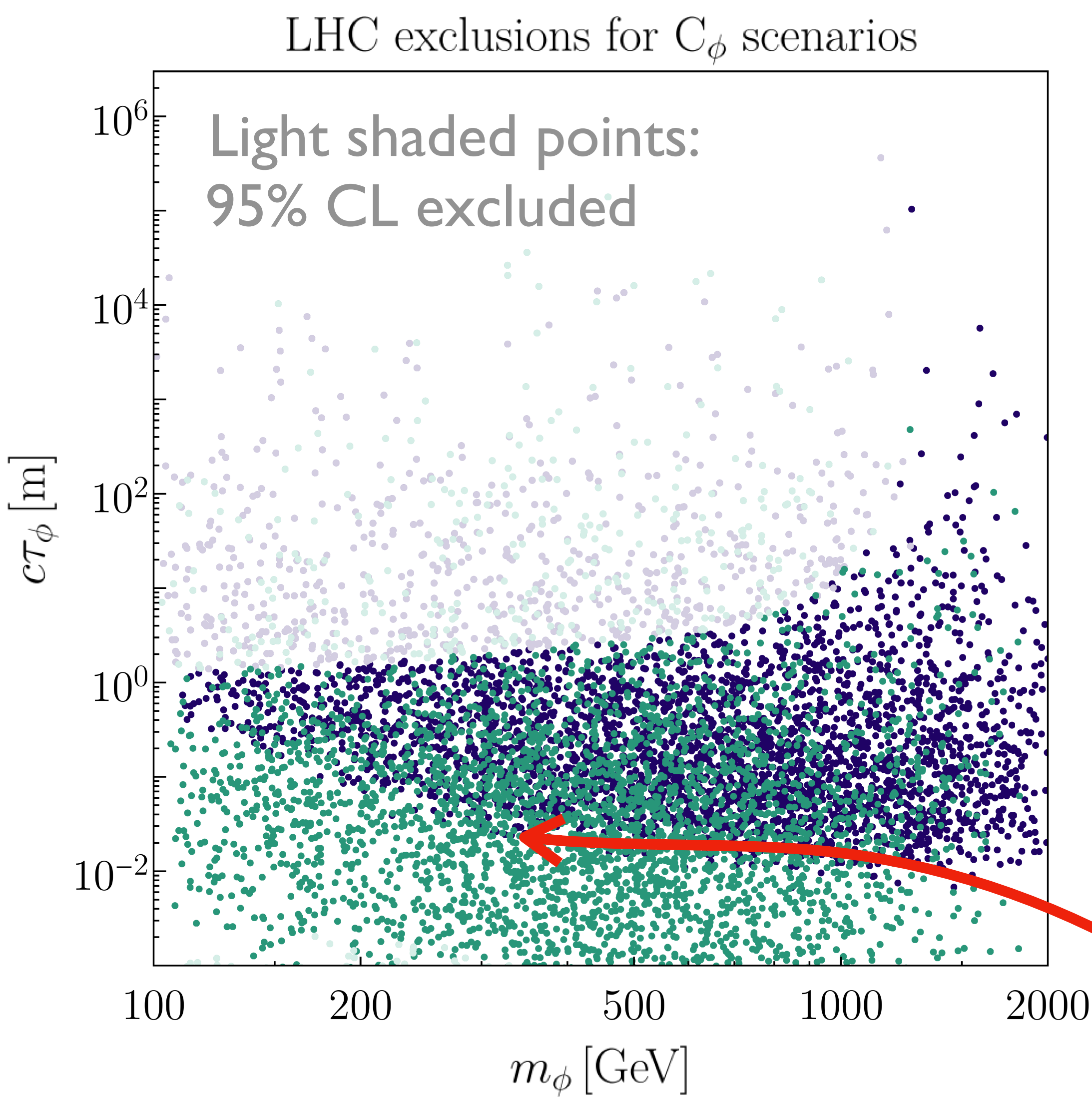

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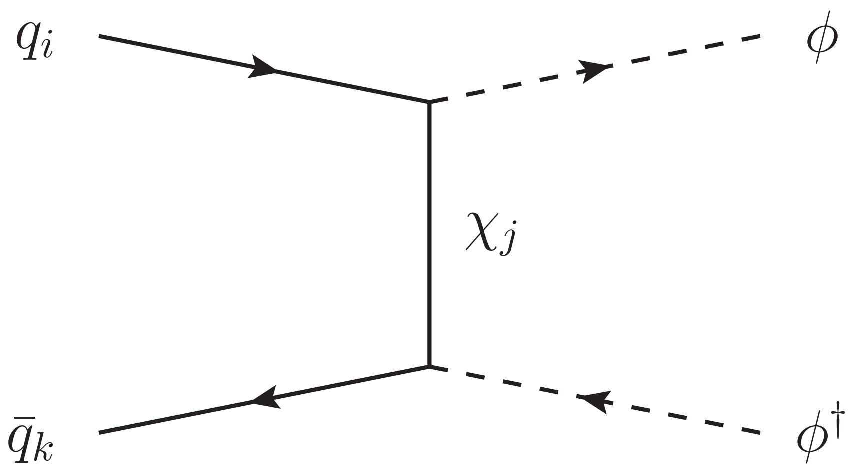
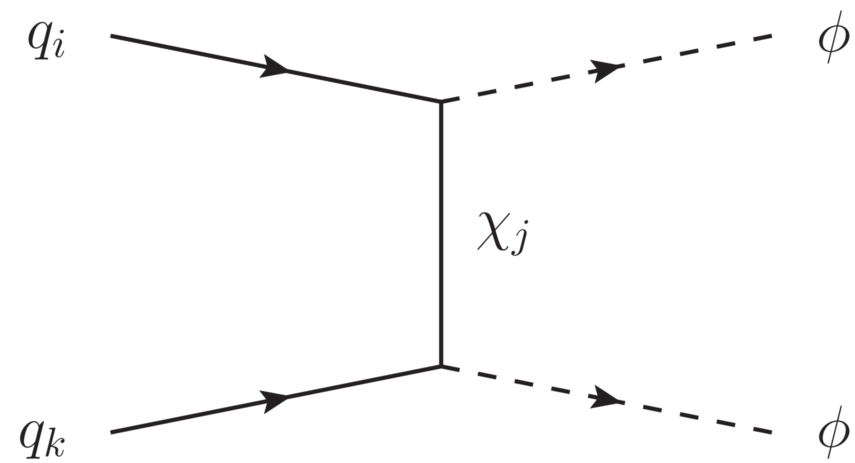
Intermediate lifetimes (mm–m): great potential, current searches do not apply

Majorana-specific signatures





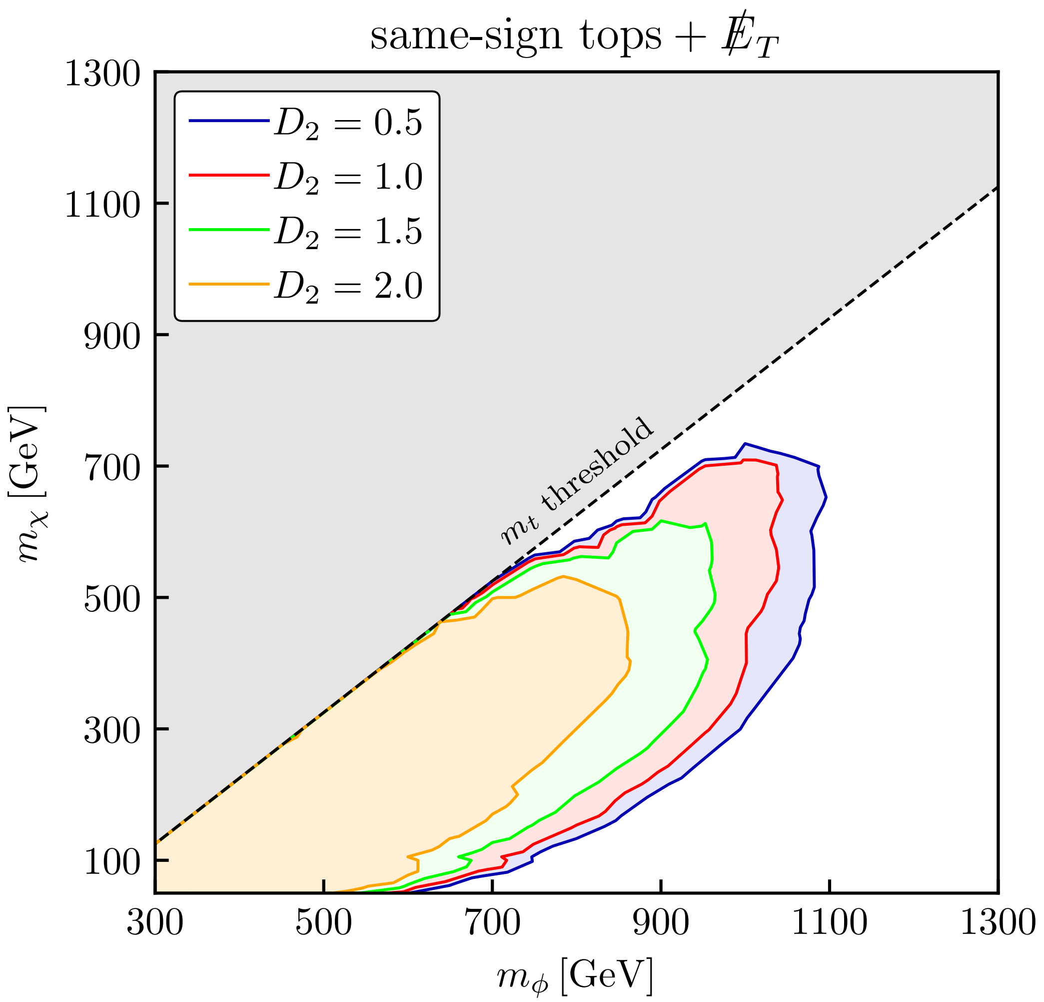
$uu \to \phi\phi$ large cross section
[*see also e.g.* M. Garny, A. Ibarra, M. Pato, S. Vogl, 1306.6342]

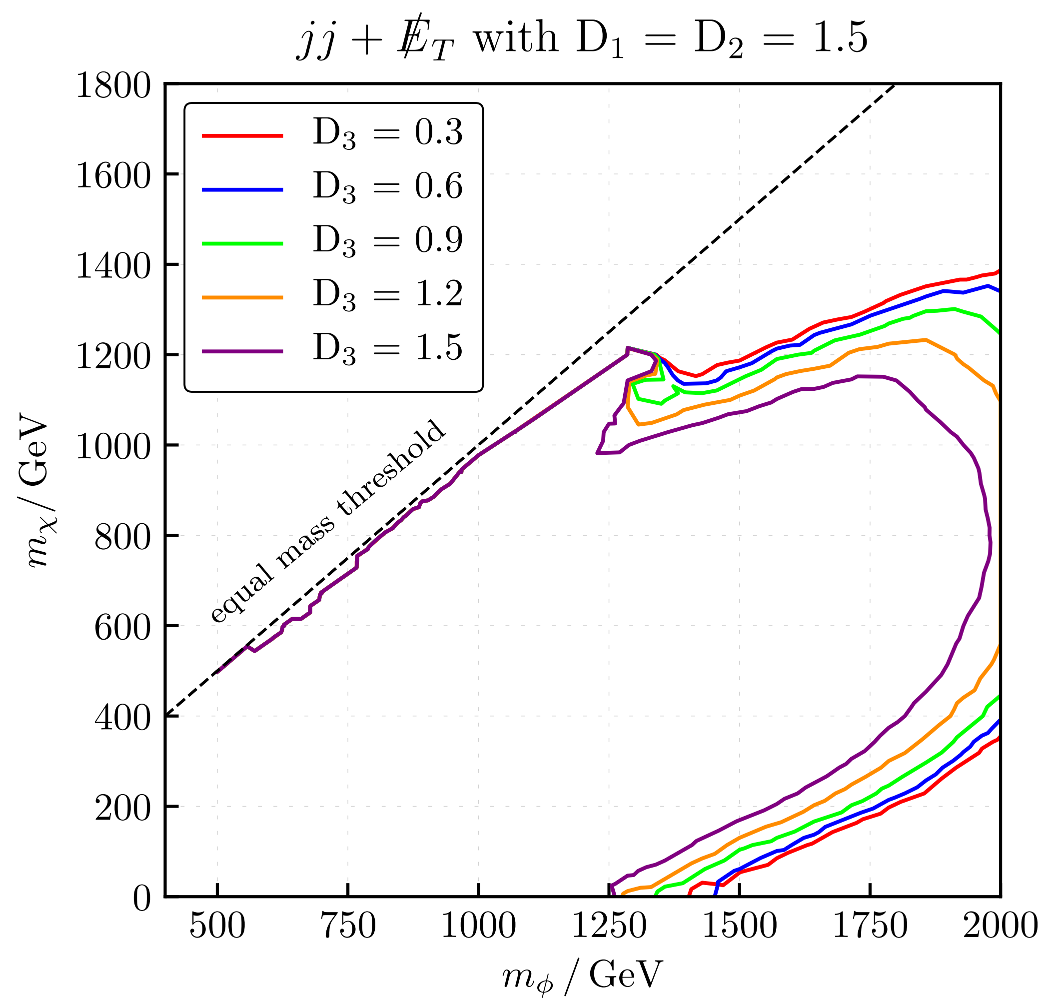
➔ Same-sign quark searches promising

Majorana-specific signatures

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

CMS-SUS-19-008 [2001.10086]





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

Single-top charge asymmetry

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

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

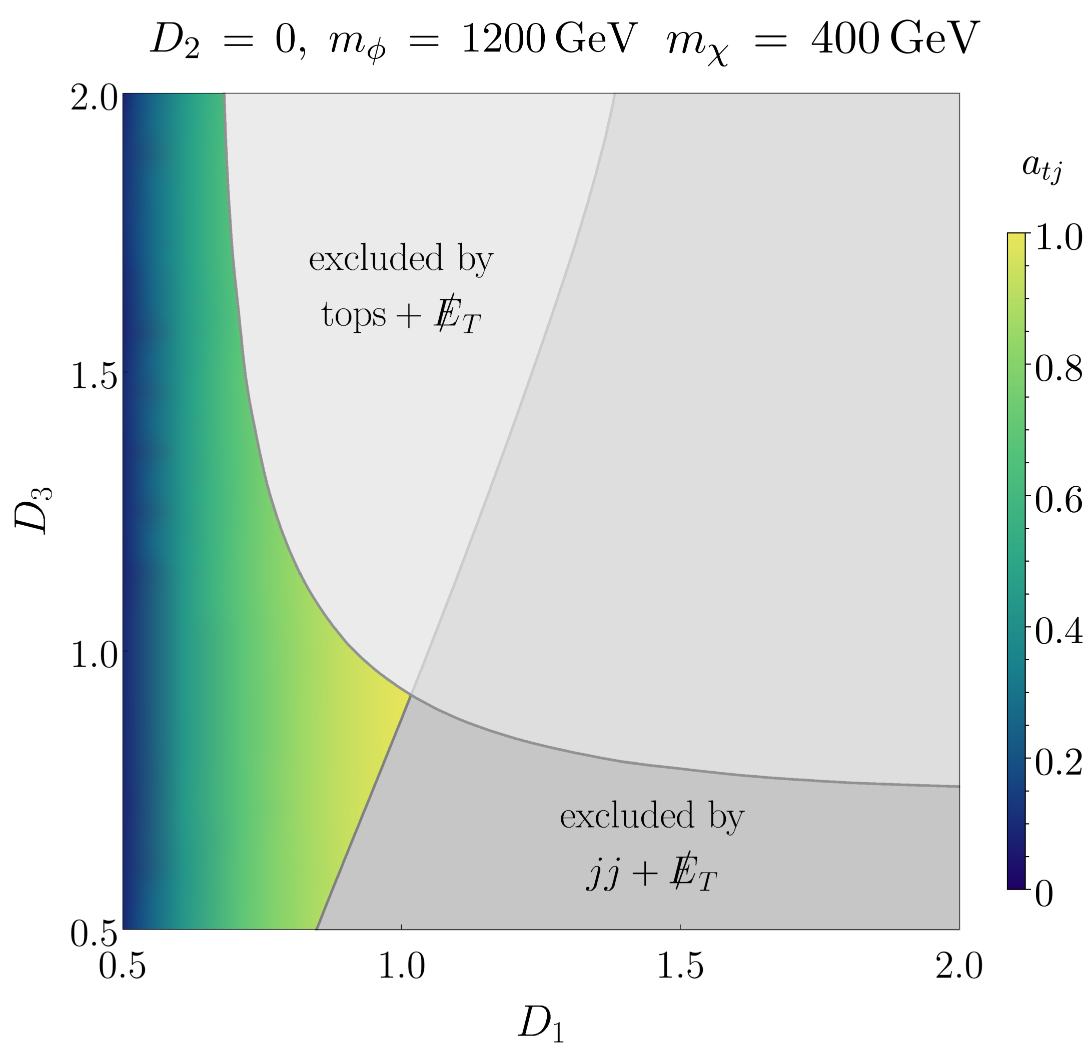
$$\sigma_{\text{Majorana}}(tj + \not{E}_T) > \sigma_{\text{Majorana}}(\bar{t}j + \not{E}_T)$$

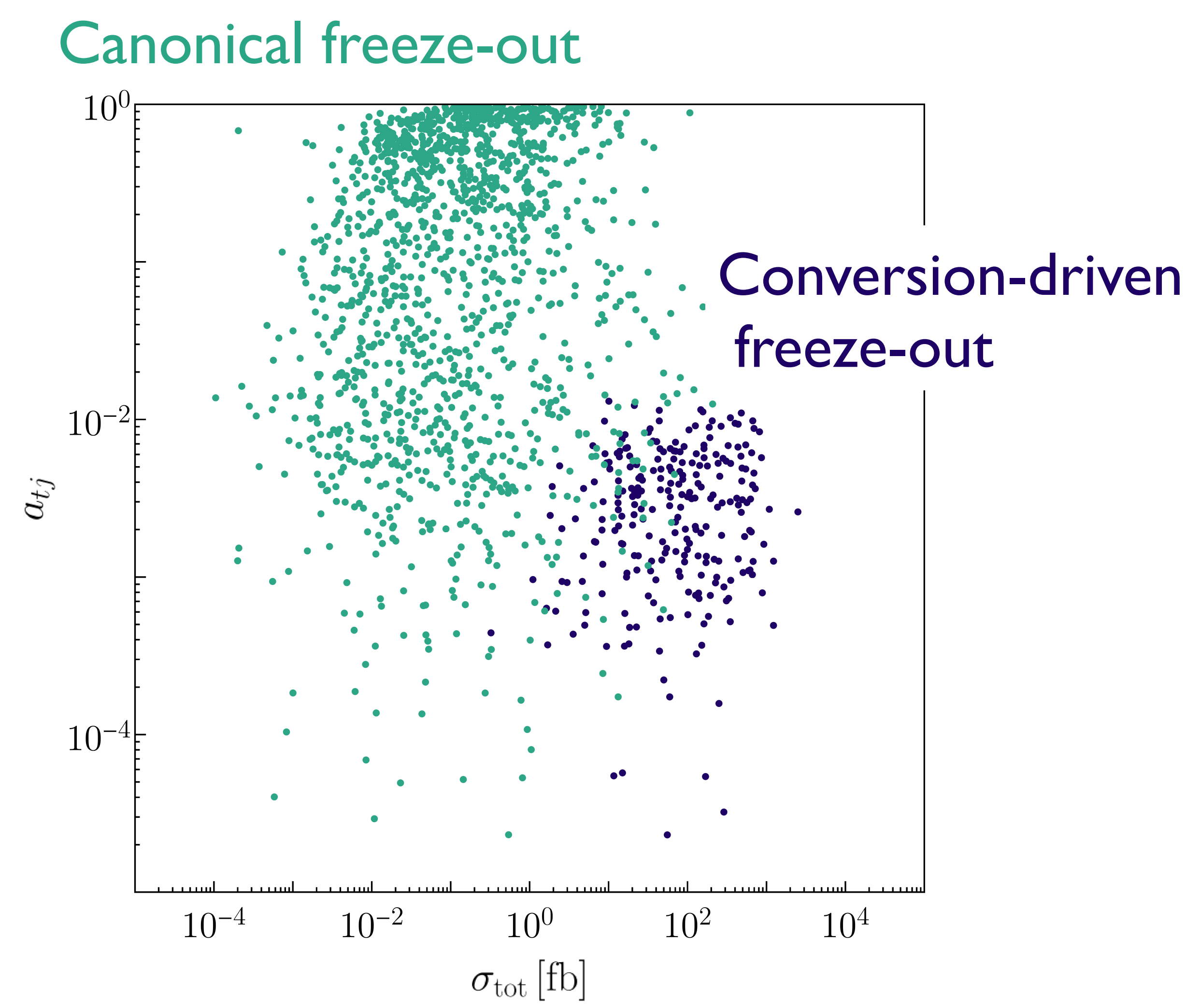
Consider charge asymmetry:

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

$$\text{Dirac DM} \quad \Rightarrow \quad a_{tj} \simeq 0$$
$$\text{Majorana DM} \quad \Rightarrow \quad a_{tj} > 0$$

Single-top charge asymmetry



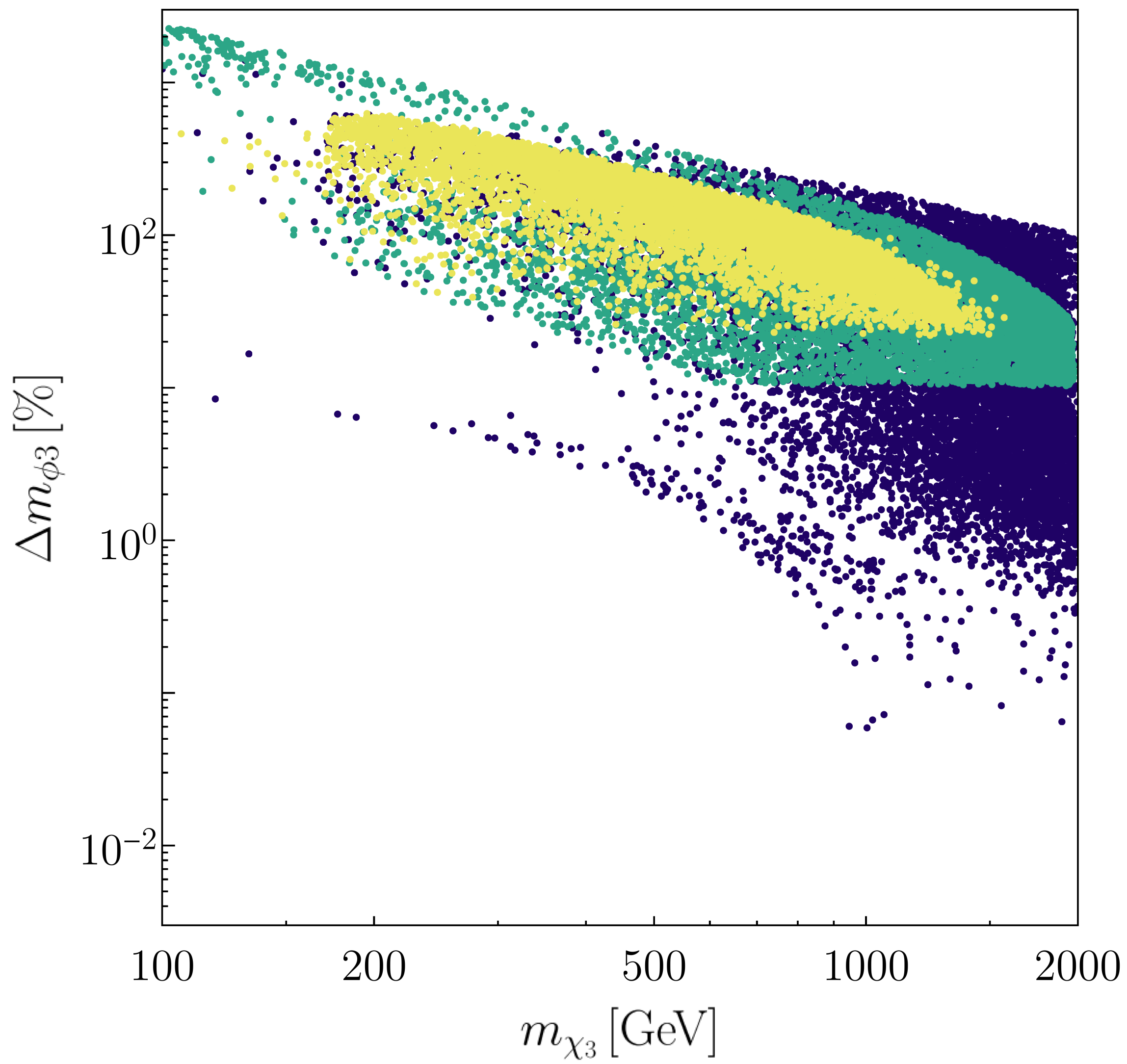


Summary

- 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

Backup

Flavored dark matter vs simple t-channel model



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