

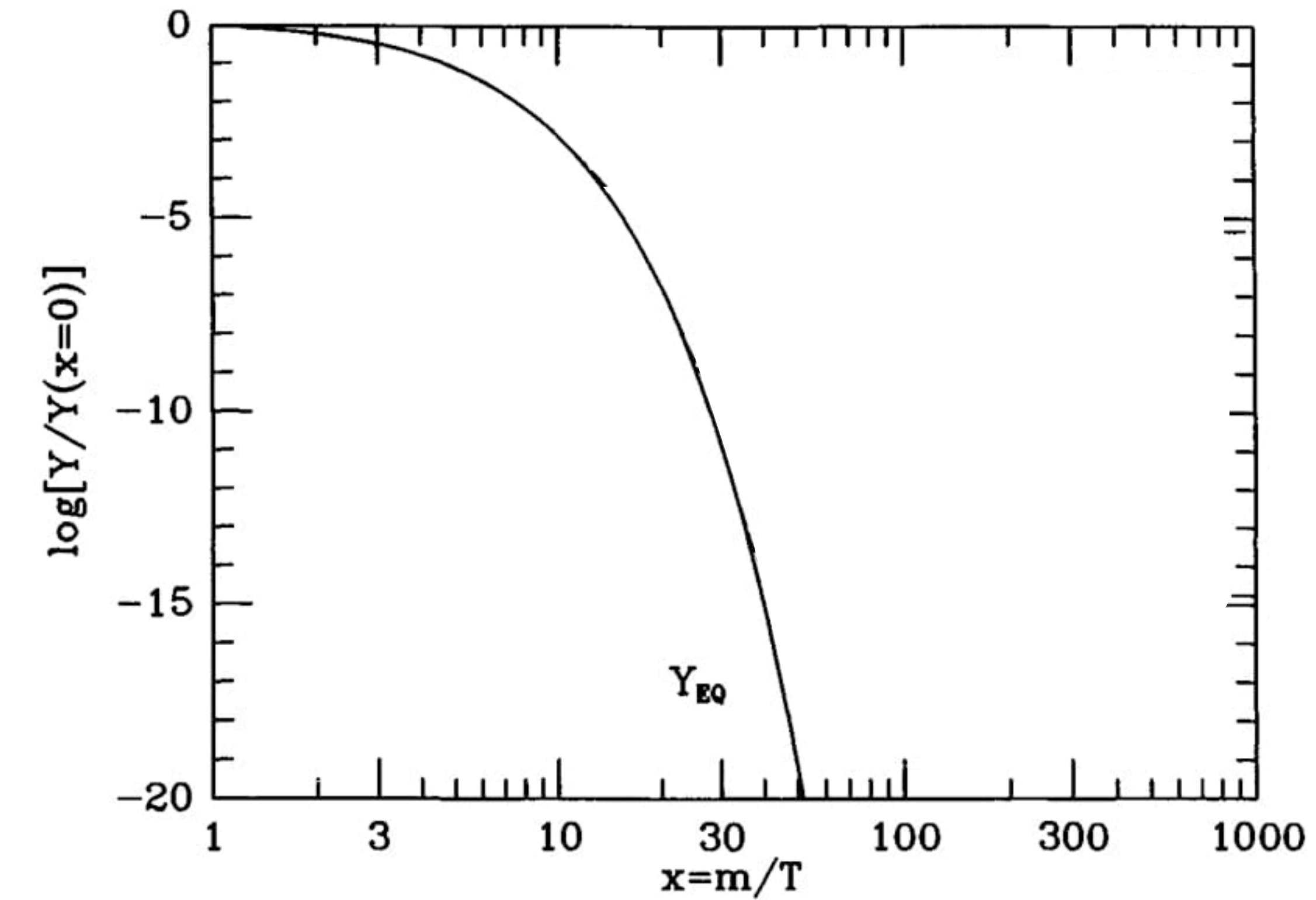
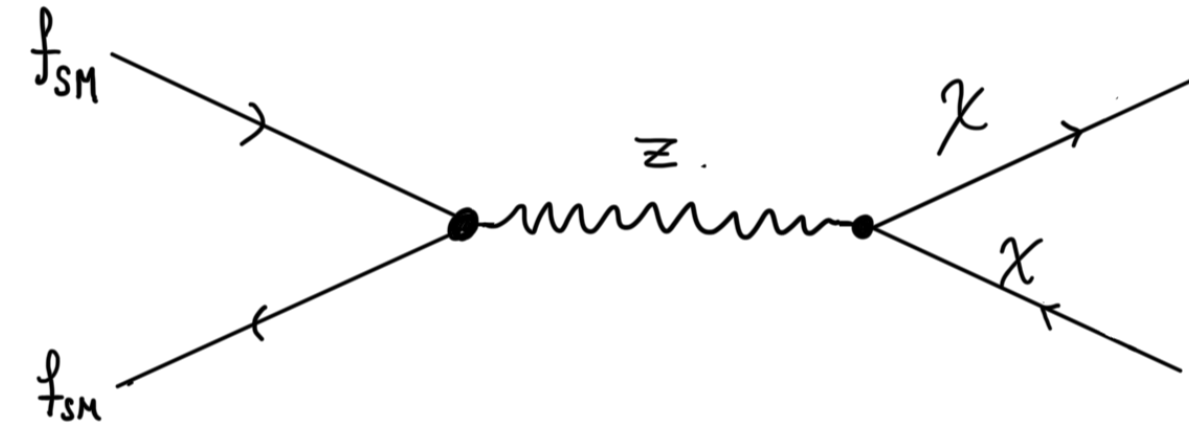
What can Flavour Tell us about Dark Matter?

Xavier Ponce Díaz

with Admir Greljo, Simone Biondini and Alessandro Valenti
[arXiv:2601.07921](#), published in [Phys. Rev. D 113, 095021](#)

The WIMP *miracle*

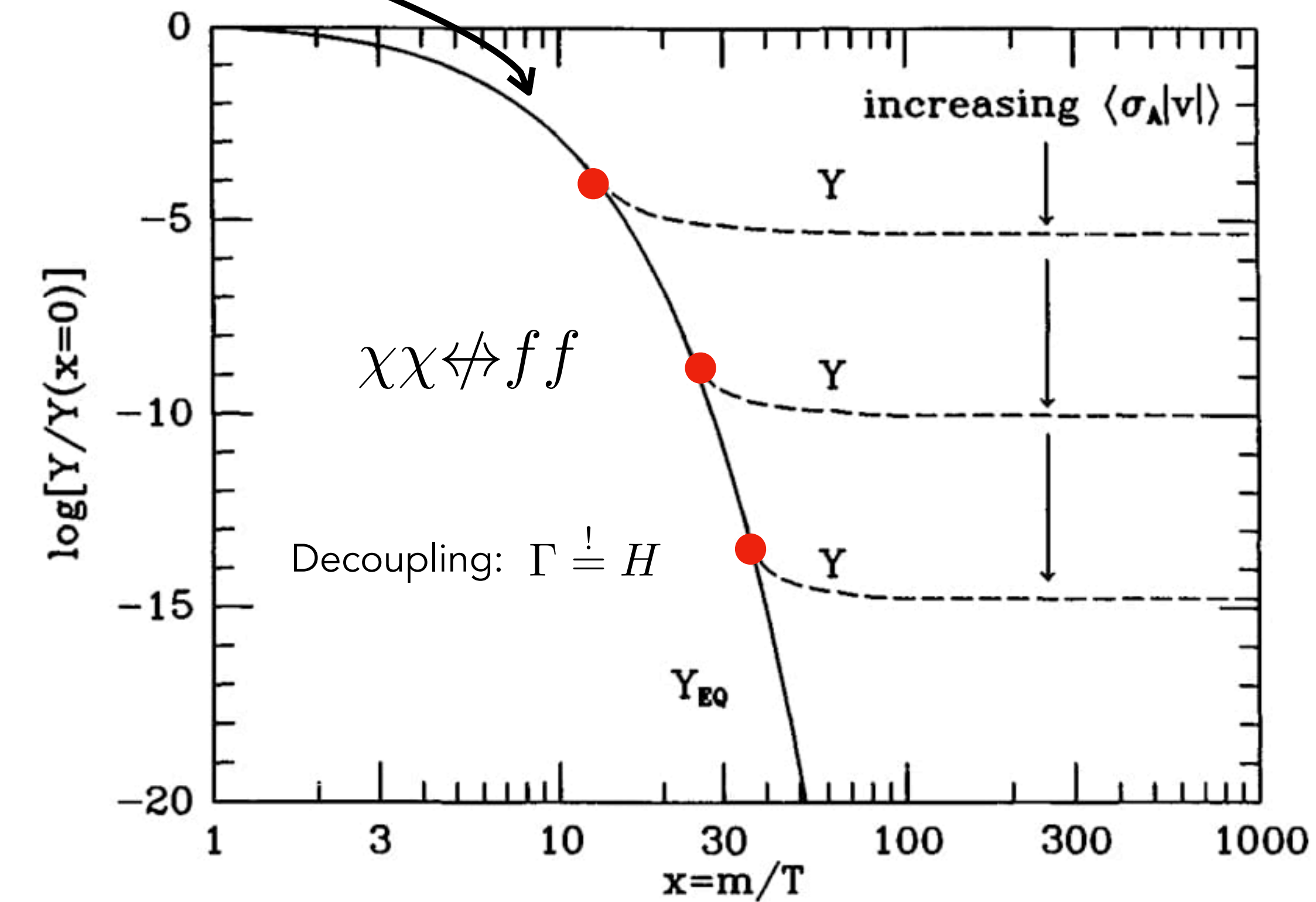
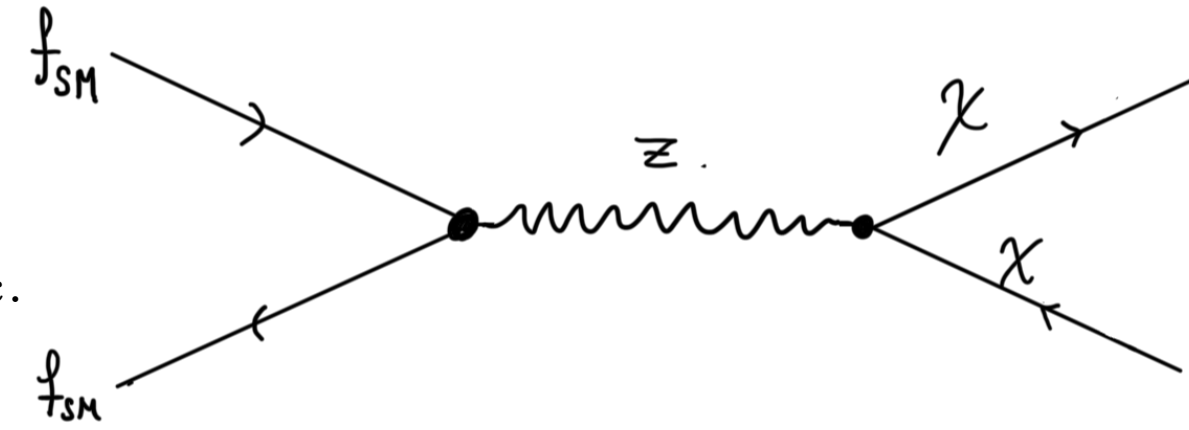
$$\chi\chi \leftrightarrow f\bar{f}$$



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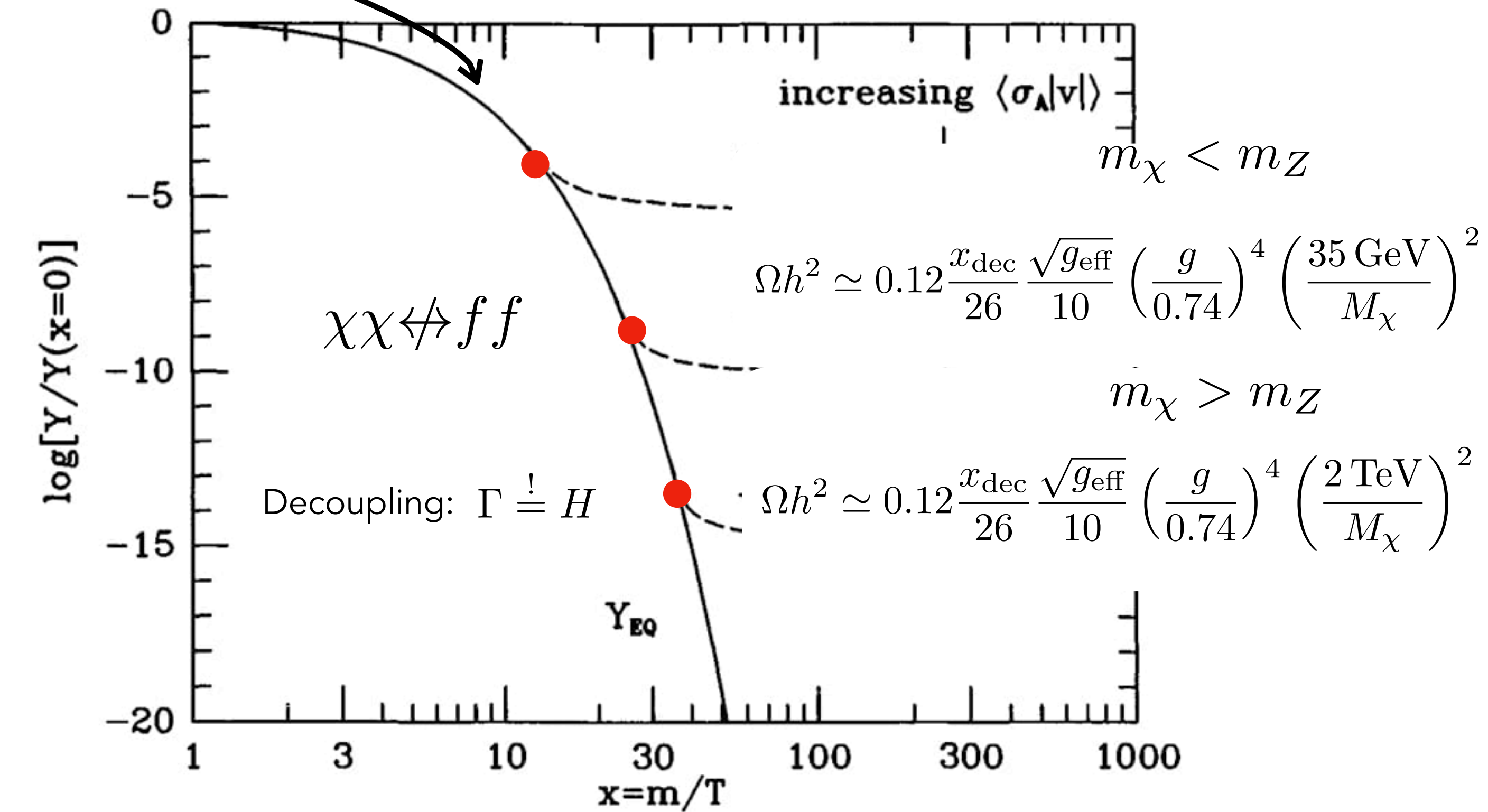
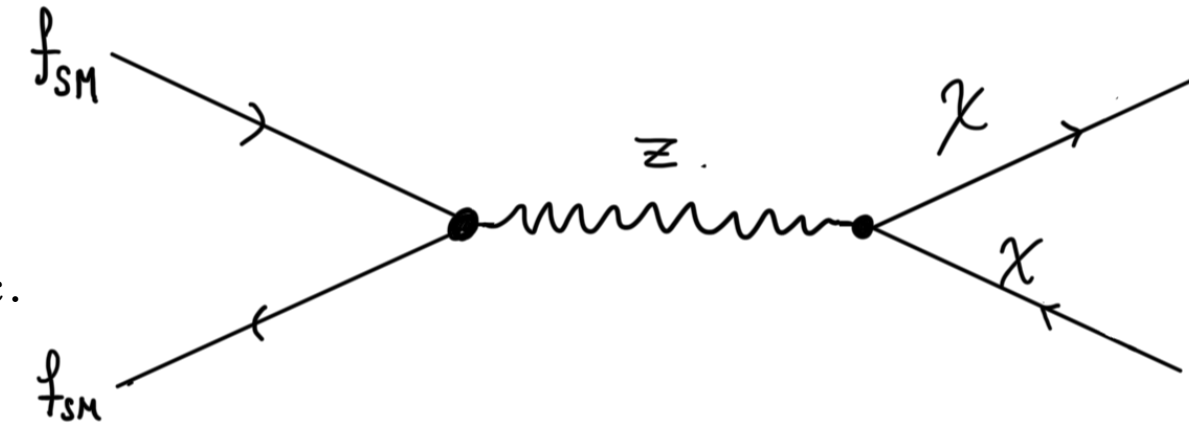
$$\Gamma = \sigma_{\chi\chi} v n_{\chi}^{\text{eq.}} \sim e^{-M_{\chi}/T_{\text{dec.}}}$$



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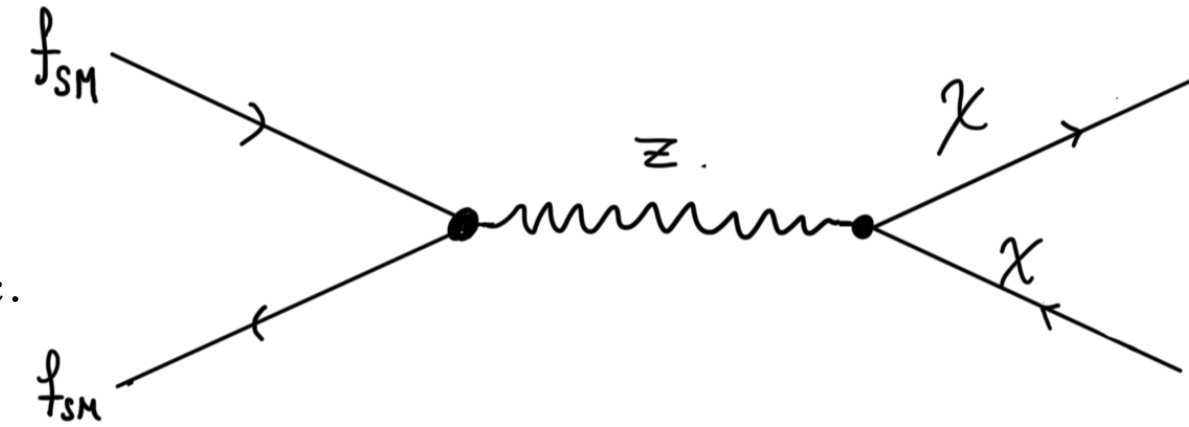
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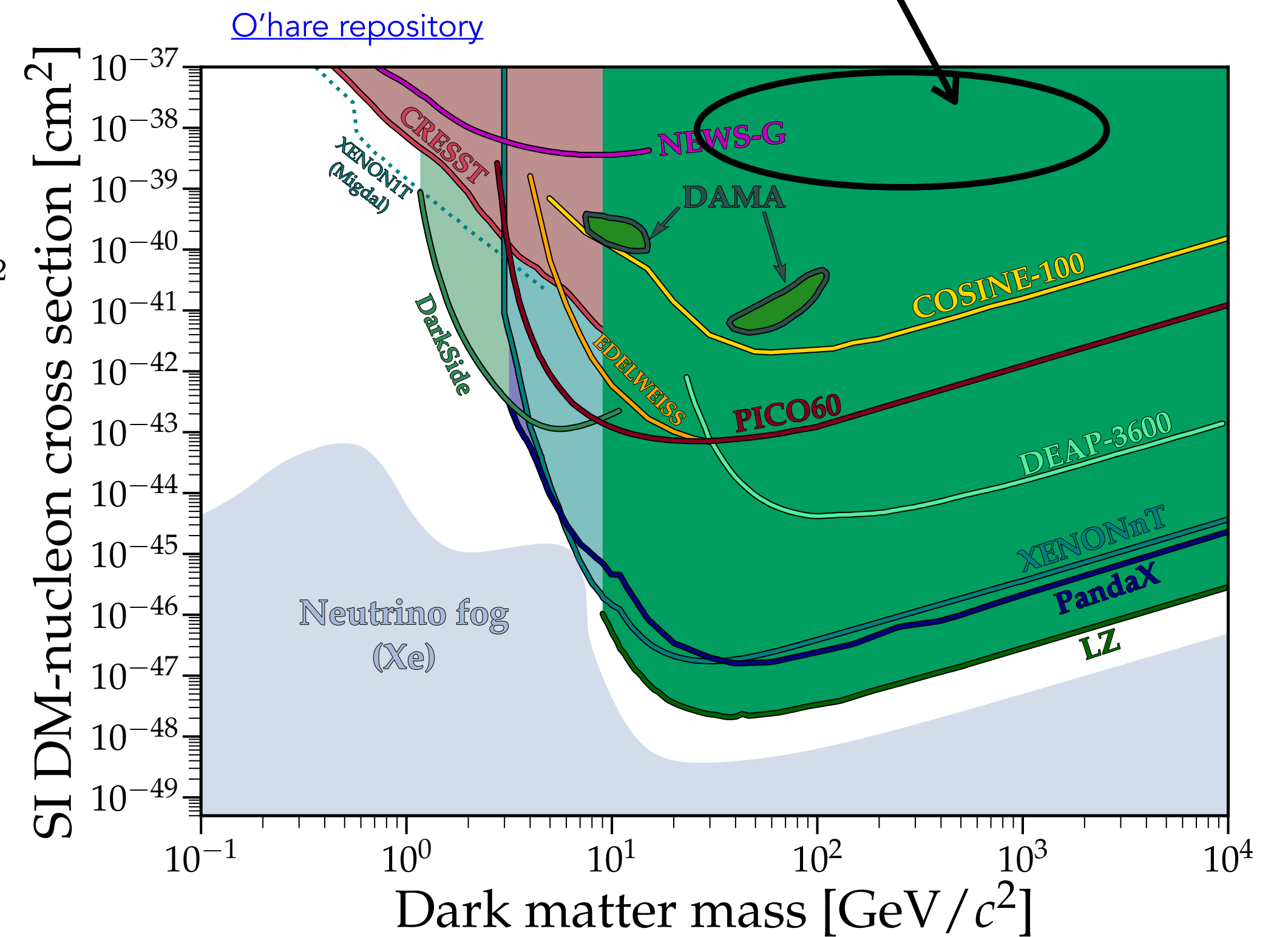
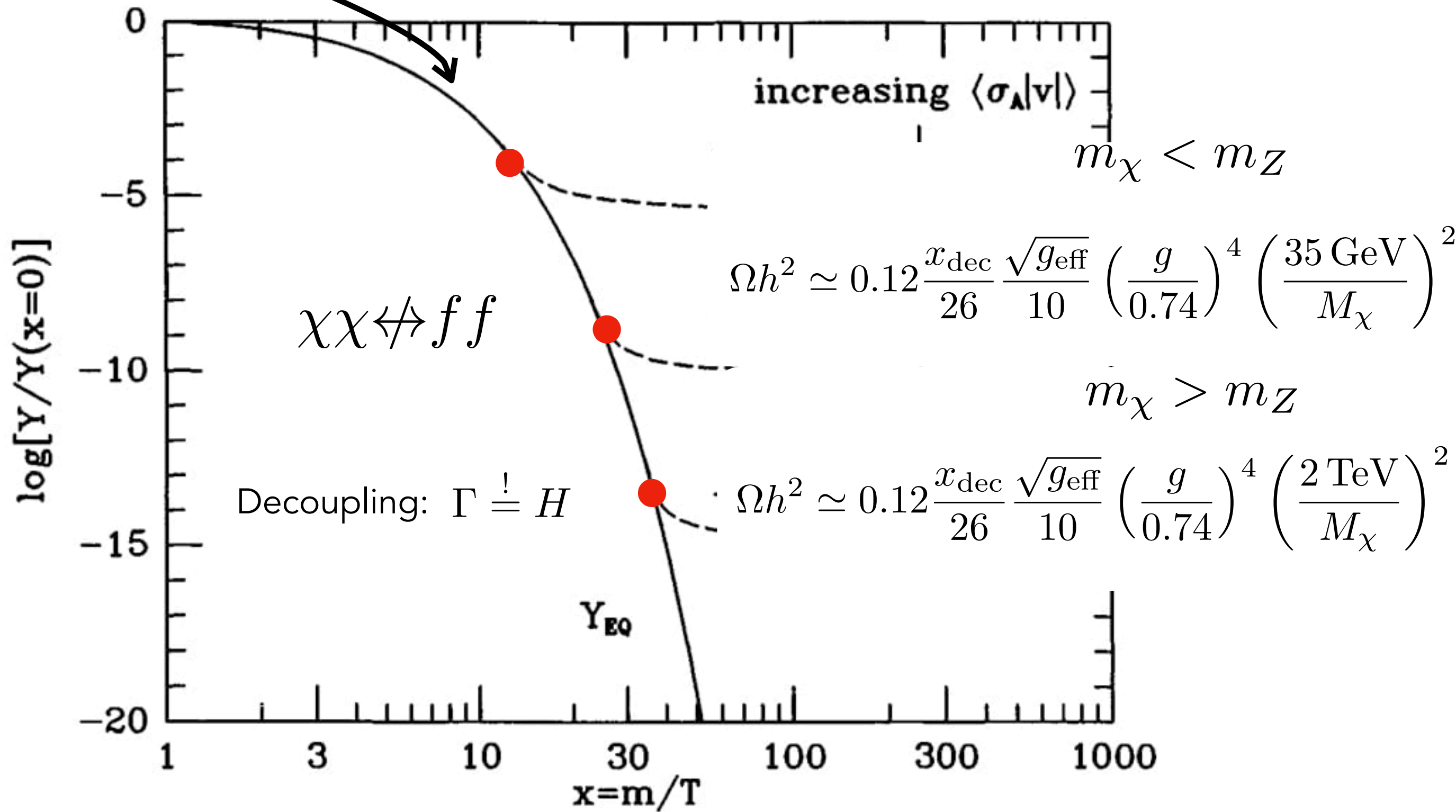
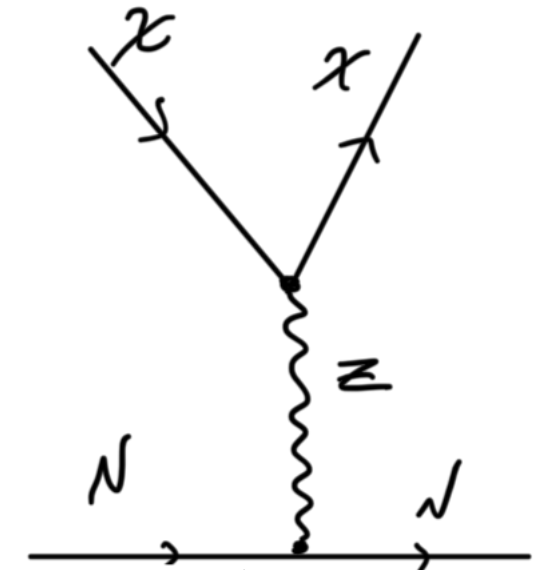
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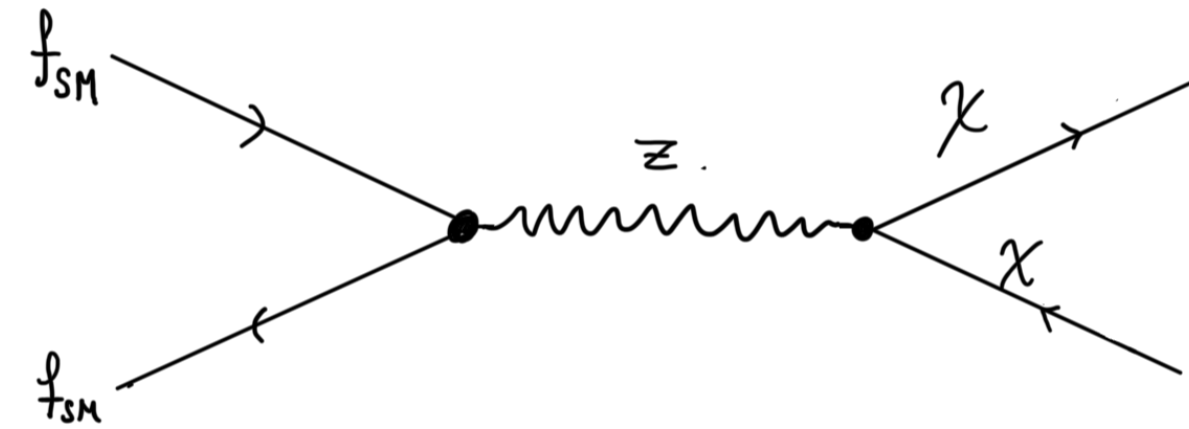


Z-mediated Dark matter

$$\chi f \leftrightarrow f \chi$$

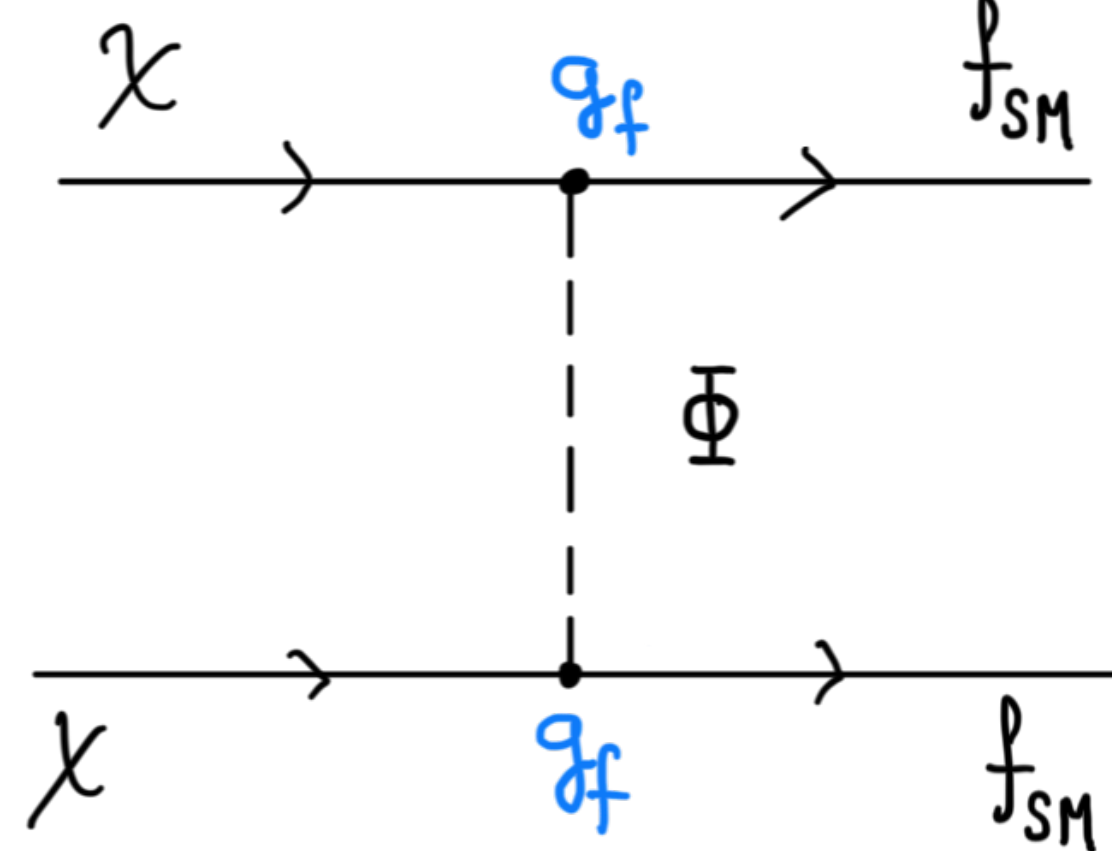


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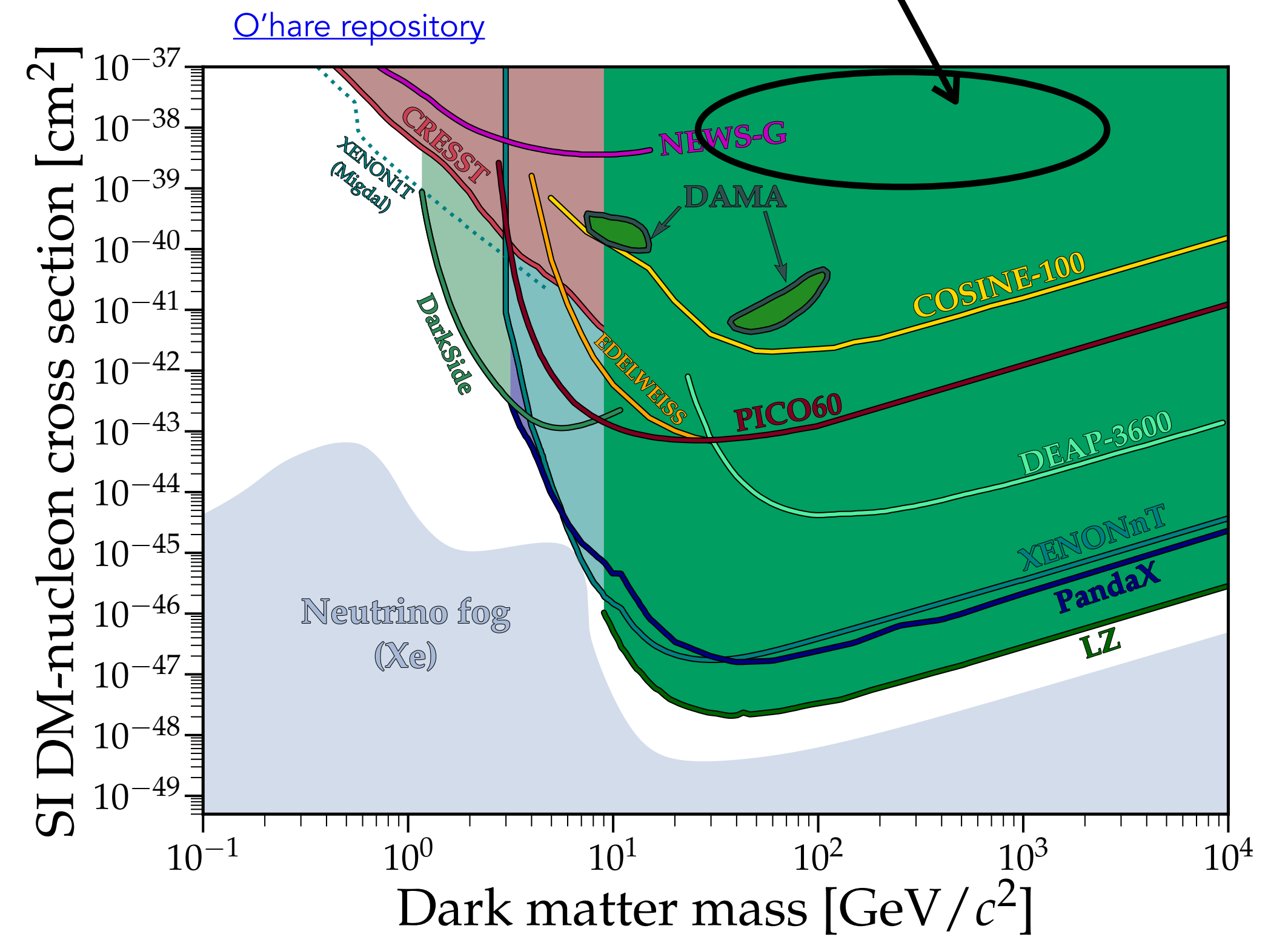
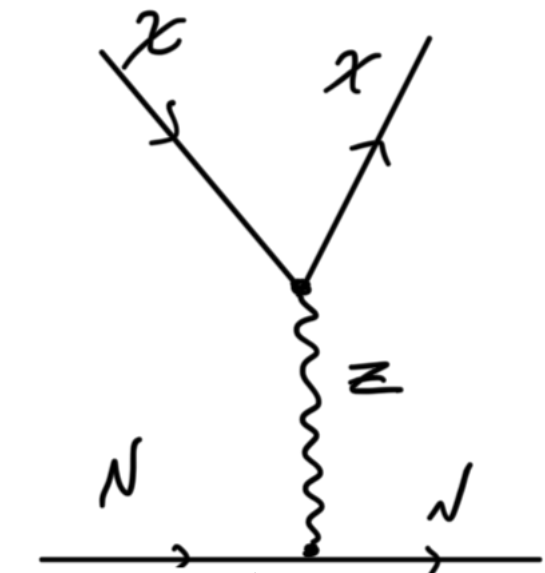
A way around...

Add new forces: t-channel DM



Z-mediated Dark matter

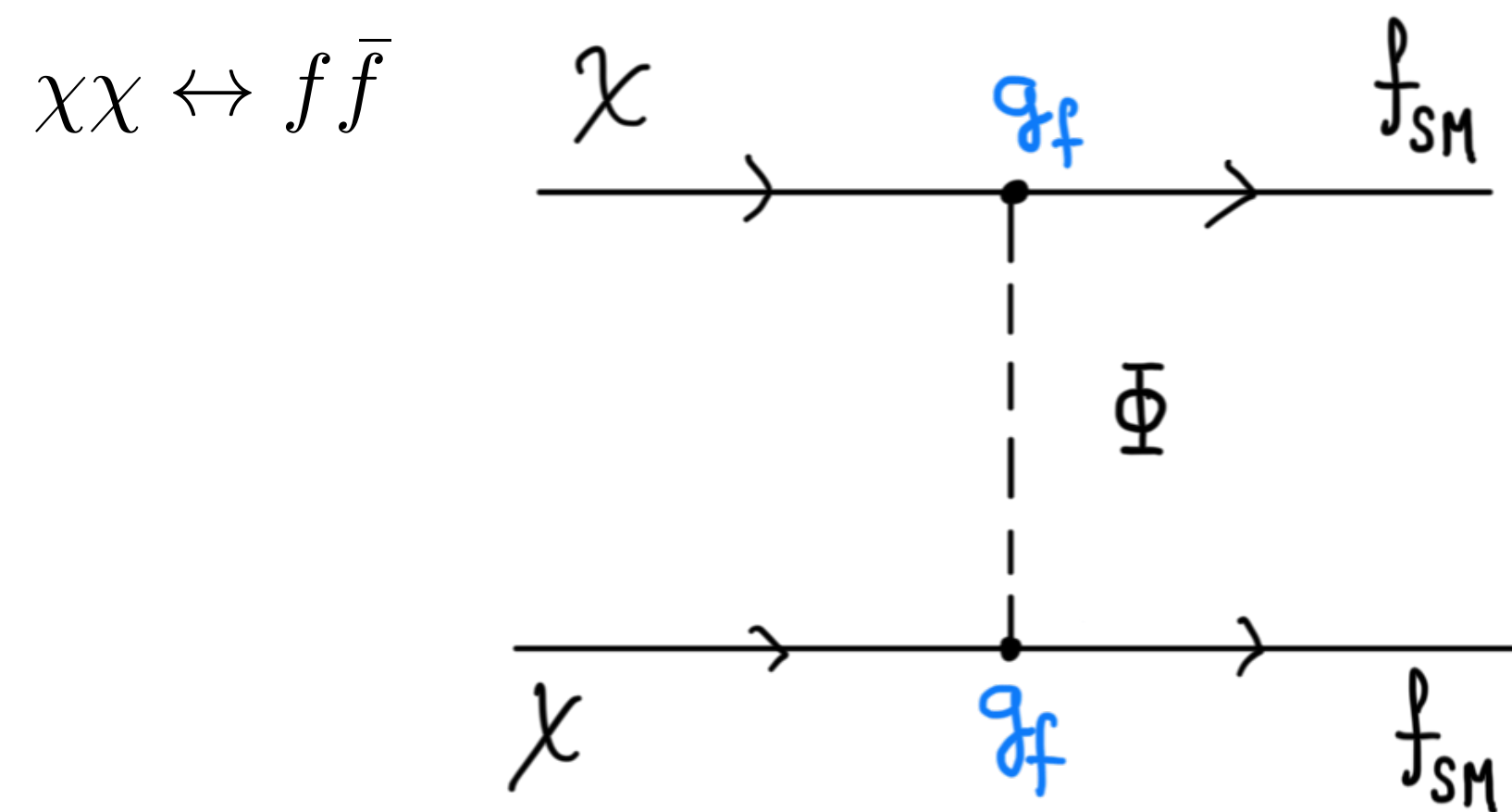
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The WIMP *miracle* and the Flavour *problem*



"With great power comes with great responsibility..."



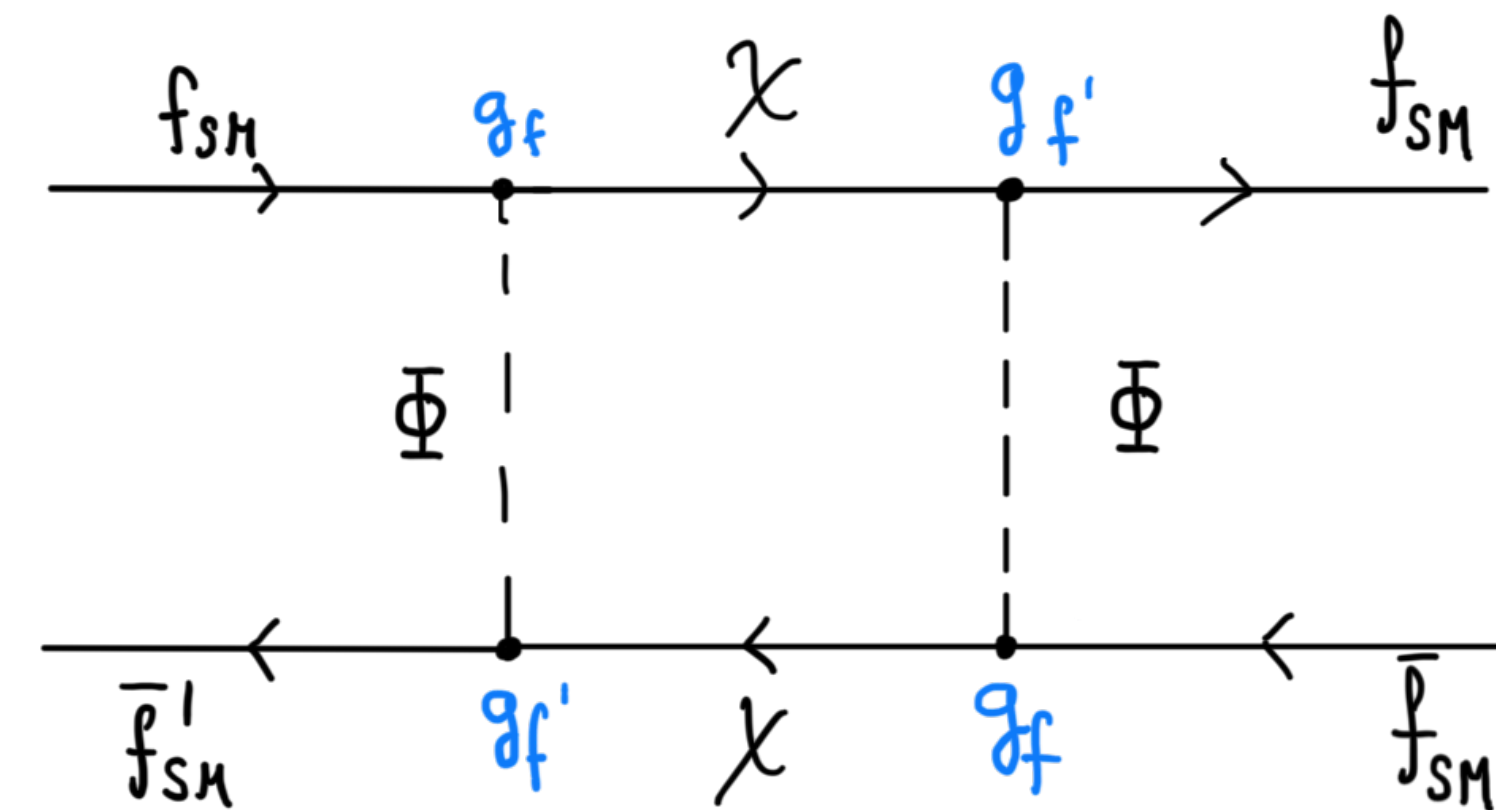
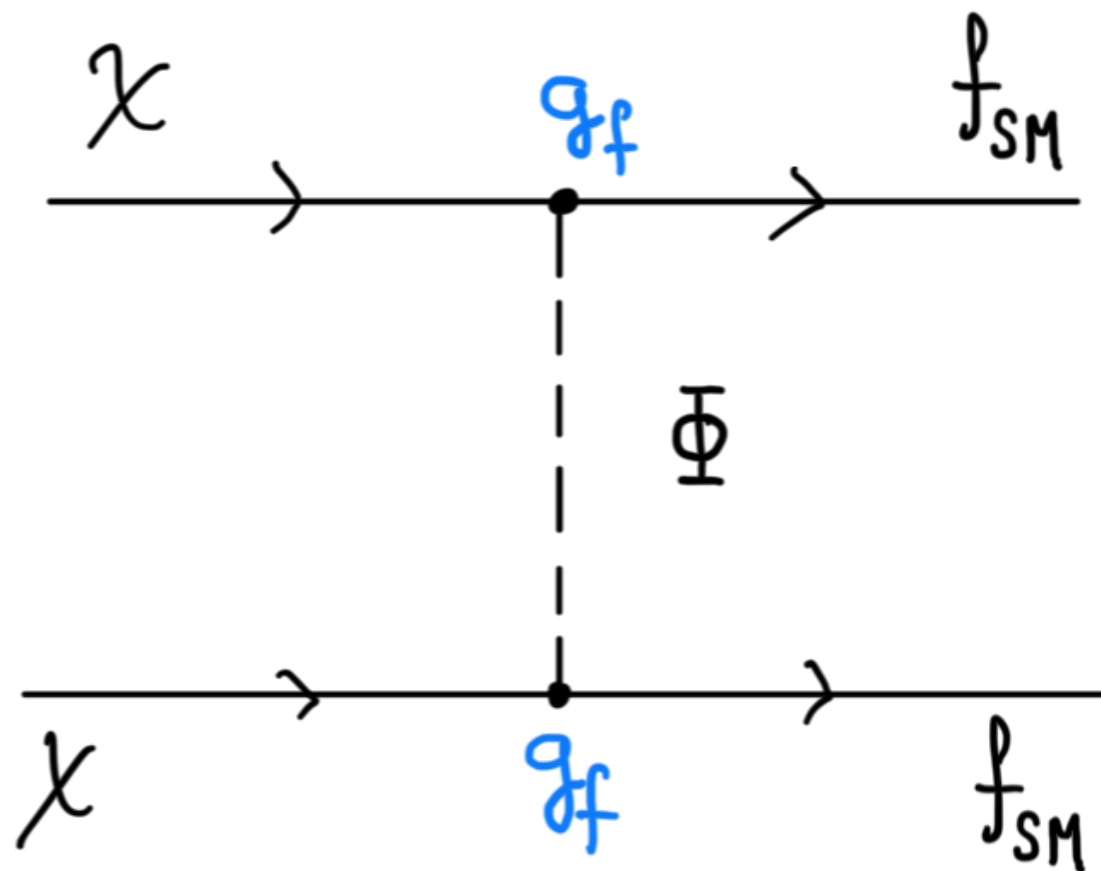
$$\Omega h^2 \simeq 0.12 \frac{x_{\text{dec}}}{26} \frac{\sqrt{g_{\text{eff}}}}{10} \left(\frac{g}{0.74} \right)^4 \left(\frac{2 \text{ TeV}}{M_\chi} \right)^2$$

The WIMP *miracle* and the Flavour *problem*



“With great power comes with great responsibility and **New Physics** with **non-trivial flavour structure** leads to unsuppressed FCNCs”.

$\chi\chi \leftrightarrow f\bar{f}$



$$M_\chi \gtrsim \frac{g_d g_s}{0.74^2} 150 \text{ TeV}$$

$$f_{\text{SM}} = s, f'_{\text{SM}} = d \rightarrow \Delta m_K$$

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New-physics flavour problem applied to freeze-out DM

The WIMP *miracle* and the Flavour *problem*

Solutions? Use of flavour symmetries: $G_{\text{flav.}}^{\text{SM}} \simeq U(3)^5 \longrightarrow$ approximate symmetry broken by the Yukawas

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Rules of the game:

1) Approximate symmetry of the SM $U(2)^5$

$$Y_u = \left(\overbrace{\begin{pmatrix} \text{[light blue box]} & \text{[light blue box]} & \vdots & 0.003 \\ < 0.01 & & \vdots & 0.04 \\ \dots & & \vdots & 1 \end{pmatrix}}^{U(2)_u} \right) U(2)_q$$

The WIMP *miracle* and the Flavour *problem*

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- 2) Promote Yukawa to **spurion fields** to formally **restore** the **symmetry**.

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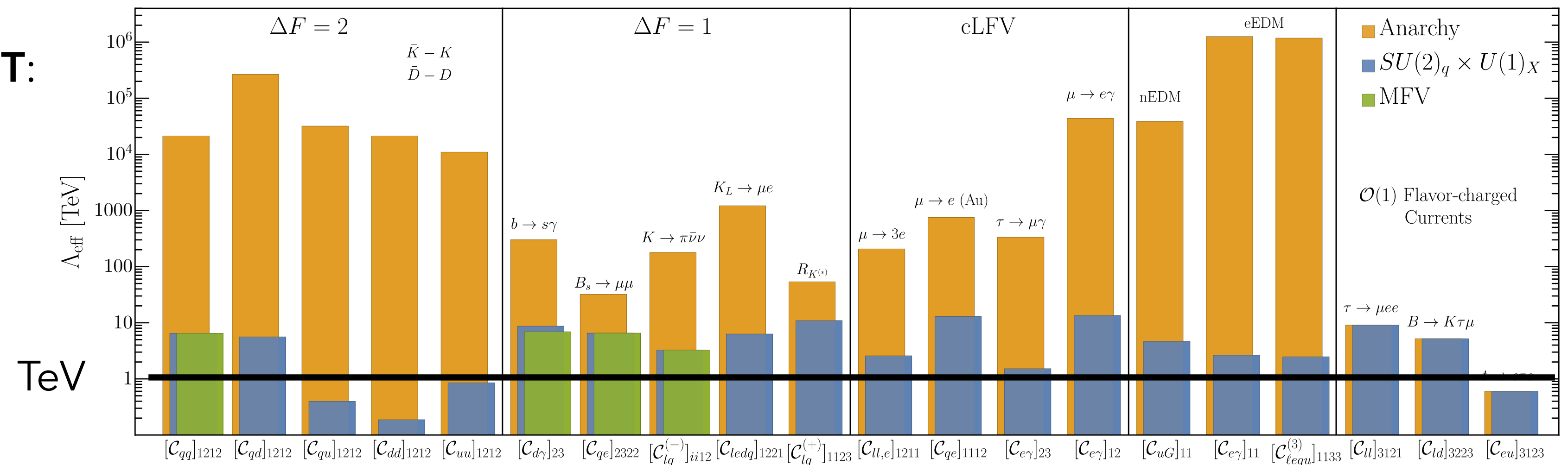
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[Greljo, Palavrić, Stefaneč '25](#)

3) Use **spurions** in the **SMEFT**:

The pattern of flavour transitions aligns to SM and bounds are drastically reduced.



The WIMP *miracle* and the Flavour *problem*

Use of flavour symmetries: $G_{\text{flav.}} \equiv G_{\text{SM}} \times G_{\text{DS}} \quad \chi \rightarrow U_{\text{flav}} \chi$

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The Yukawas are the MFV spurions in the Standard Model

Minimal Flavour Violation (**MFV**): $U(3)_q \times U(3)_u \times U(3)_d \times U(3)_\ell \times U(3)_e \quad Y_u \sim (\mathbf{3}_q, \bar{\mathbf{3}}_u), \quad Y_d \sim (\mathbf{3}_q, \bar{\mathbf{3}}_d), \quad Y_e \sim (\mathbf{3}_\ell, \bar{\mathbf{3}}_e),$

[D'Ambrosio, Giudice, Isidori, Strumia '02](#)

[Batell, Pradler, Spannowsky '11](#)

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Dark MFV: $\text{MFV} \times U(3)_\chi$

[Agrawal, Blanke, Gemmler '14](#) $U(3)_\chi \times U(3)_d$

Dirac: [Blanke, Kast '17](#)
Majorana: [Acaroğlu, Blanke '21](#) $U(3)_\chi \times U(3)_u$

Fermion: [Chen, Huang, Takhistov '15](#) $U(3)_\chi \times U(3)_e$

Scalar: [Acaroğlu, Agrawal, Blanke '22](#)

Lots of model building with a rich dark sector:

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Flavour analyses **mostly focused** on the **MFV** scenario.

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Lots of model building with a rich dark sector:

our work & this talk

[Greljo, Biondini, XP, Valenti '26](#)

The goal of this work:

- Generalise previous works to smaller flavour groups.
- Show qualitatively the flavour symmetric limits, and give a quantitative answer to how close one must be to these limits, with present and future bounds.
- Interplay Direct Detection and Flavour observables

in this direction see also:

EFT analysis on third family WIMP [Demetriou, Isidori, Piazza, Pinsard '25](#)

t-channel Dark Matter models and flavour violation

from [Olgoso, Paradisi, Selimović](#)

Mediator	DM spin $\frac{1}{2}$: χ	DM spin 0: ϕ
spin $\frac{1}{2}$: Ψ	$\chi \Psi H$	$f_{\text{SM}} \phi \Psi$
spin 0: Φ	$f_{\text{SM}} \chi \Phi$	$\phi \Phi H$

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Non-trivial flavour structure!

Dark matter: stable and dark

- stability with $\mathbb{Z}_2$ discrete symmetry
- Dark:
 - Φ same SM gauge charges as f_{SM} : fermion $\text{DM} \rightarrow \chi$
 - Ψ same SM gauge charges as f_{SM} : scalar $\text{DM} \rightarrow \phi$

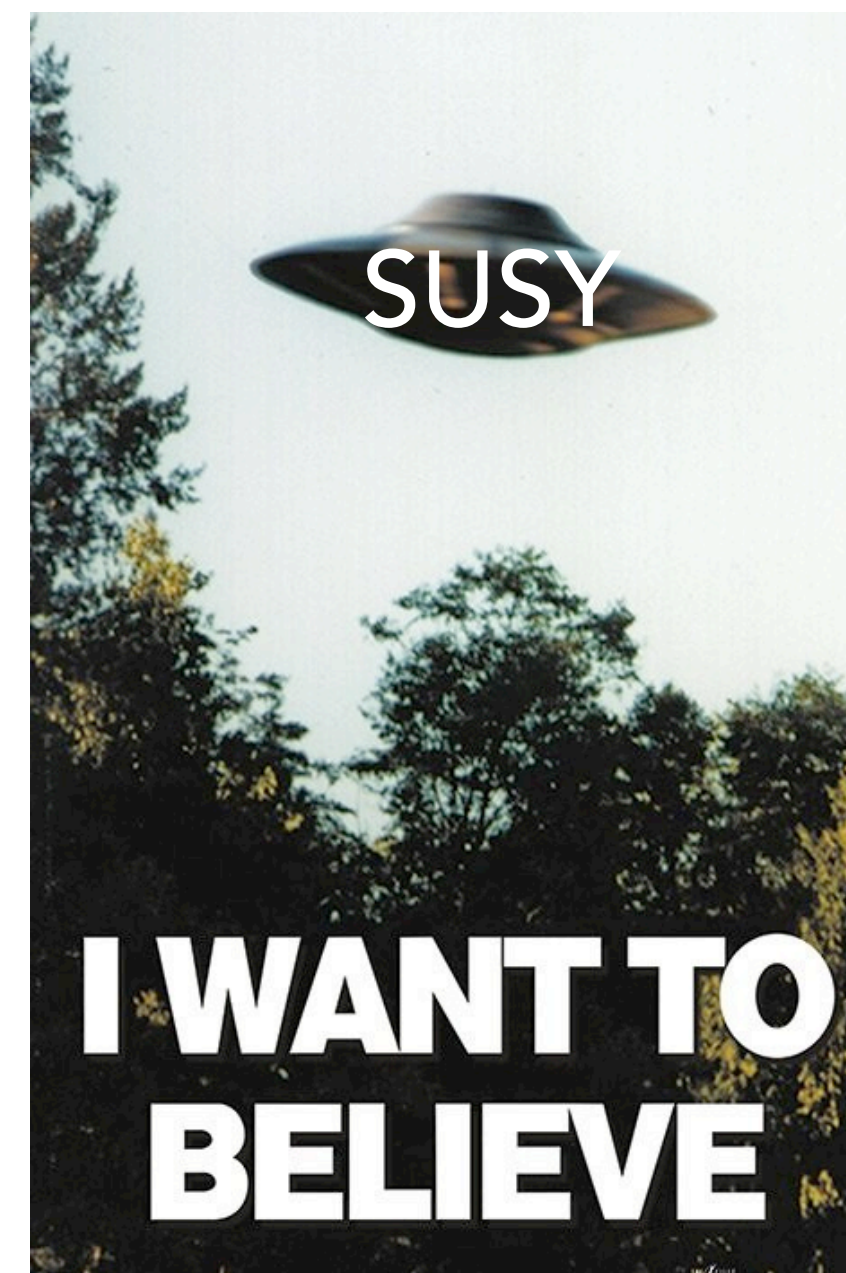
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motivated by



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Φ : SUSY-partner "sfermion"

χ : Lightest Supersymmetric Particle

$$\mathcal{L} \supset y \bar{f}_{\text{SM}} \chi \Phi + \text{h.c.}$$

+ 2 options: Majorana or Dirac

Two benchmarks: rank-1 flavour violation

Leptophilic Dark Matter:

$$\mathcal{L} \supset -y_i \bar{e}_{R,i} \chi \Phi + \text{h.c.}$$

Quarkphilic Dark Matter:

$$\mathcal{L} \supset -y_i \bar{q}_{L,i} \chi \Phi + \text{h.c.}$$

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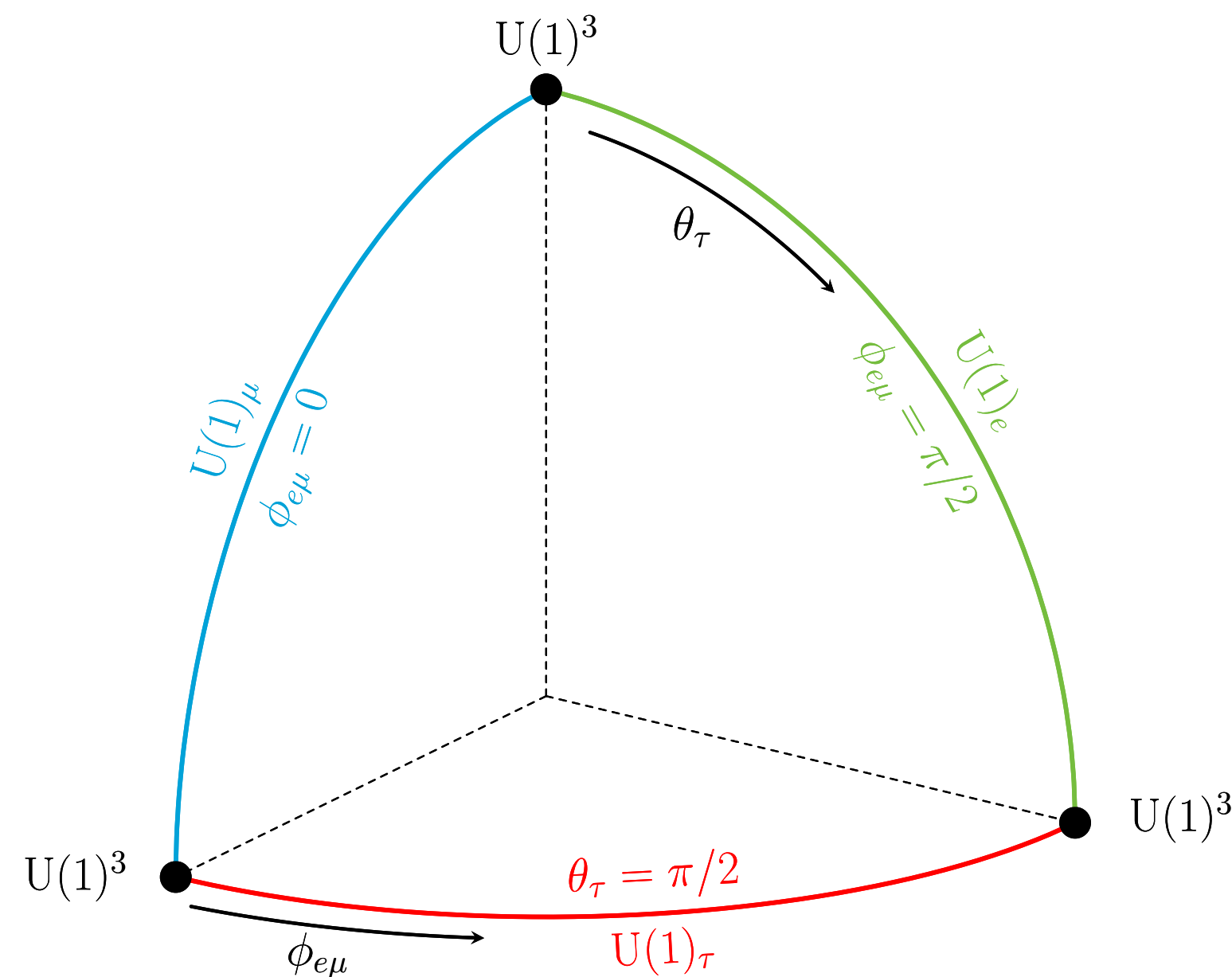
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No CP-violation for leptons: can be removed by U(1) rotations

$$\mathbf{y} = \begin{pmatrix} y_e & y_\mu & y_\tau \end{pmatrix}$$

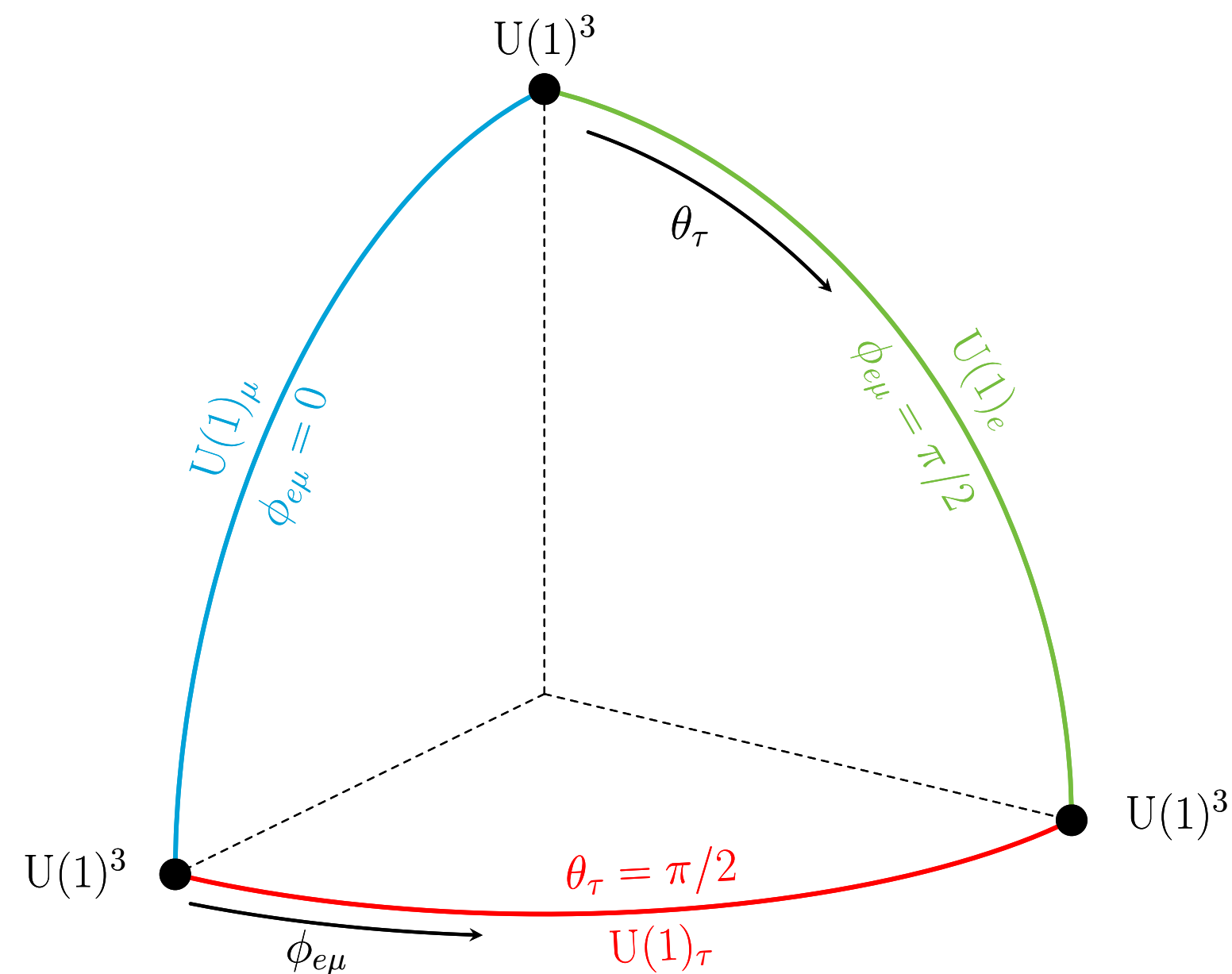
$$= y_e \begin{pmatrix} \cos \phi_{e\mu} \sin \theta_\tau & \sin \phi_{e\mu} \sin \theta_\tau & \cos \theta_\tau \end{pmatrix} \quad \text{this reduces the parameter space to a sphere octant}$$



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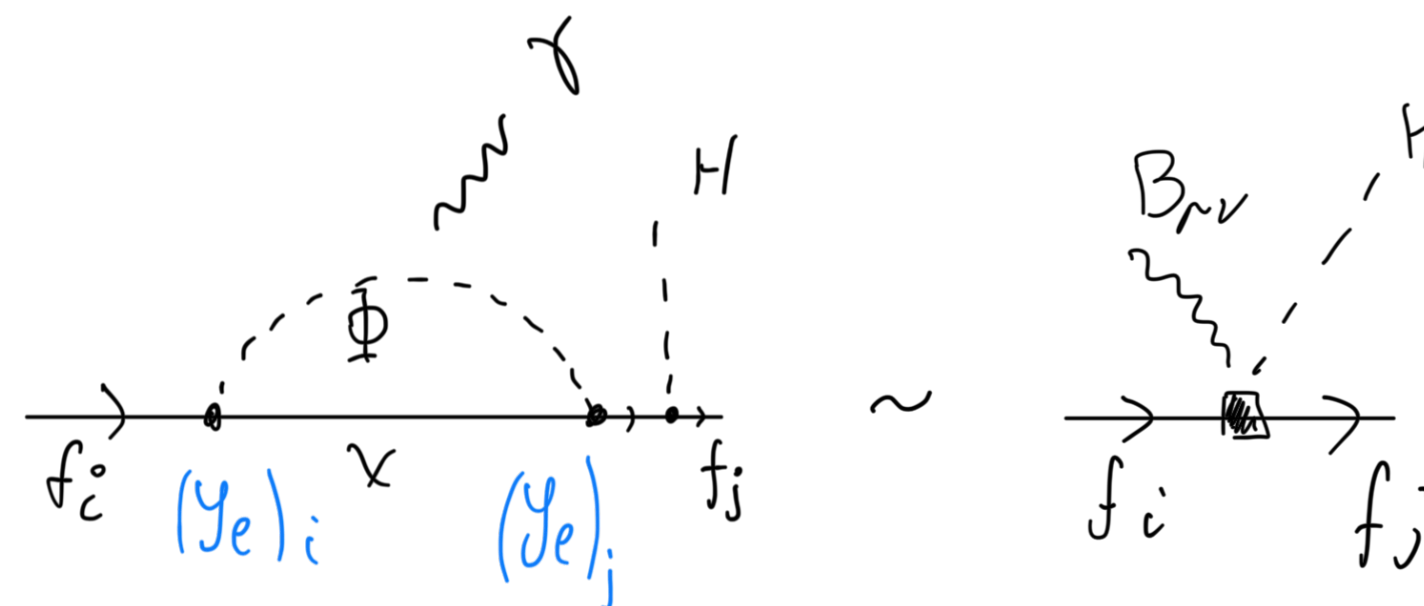
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"Rank-1" flavour violation: at low scales the flavour structure is made by one vector

[Gherardi, Marzocca, Nardecchia, Romanino '19](#)

[Marzocca, Nardecchia, Stanzione, Toni '24](#)



$$\frac{[C_{eB}]_{ij}}{\Lambda^2} \sim \frac{[\mathbf{y}_e \mathbf{y}_e^T]_{ij}}{M_\Phi^2}$$

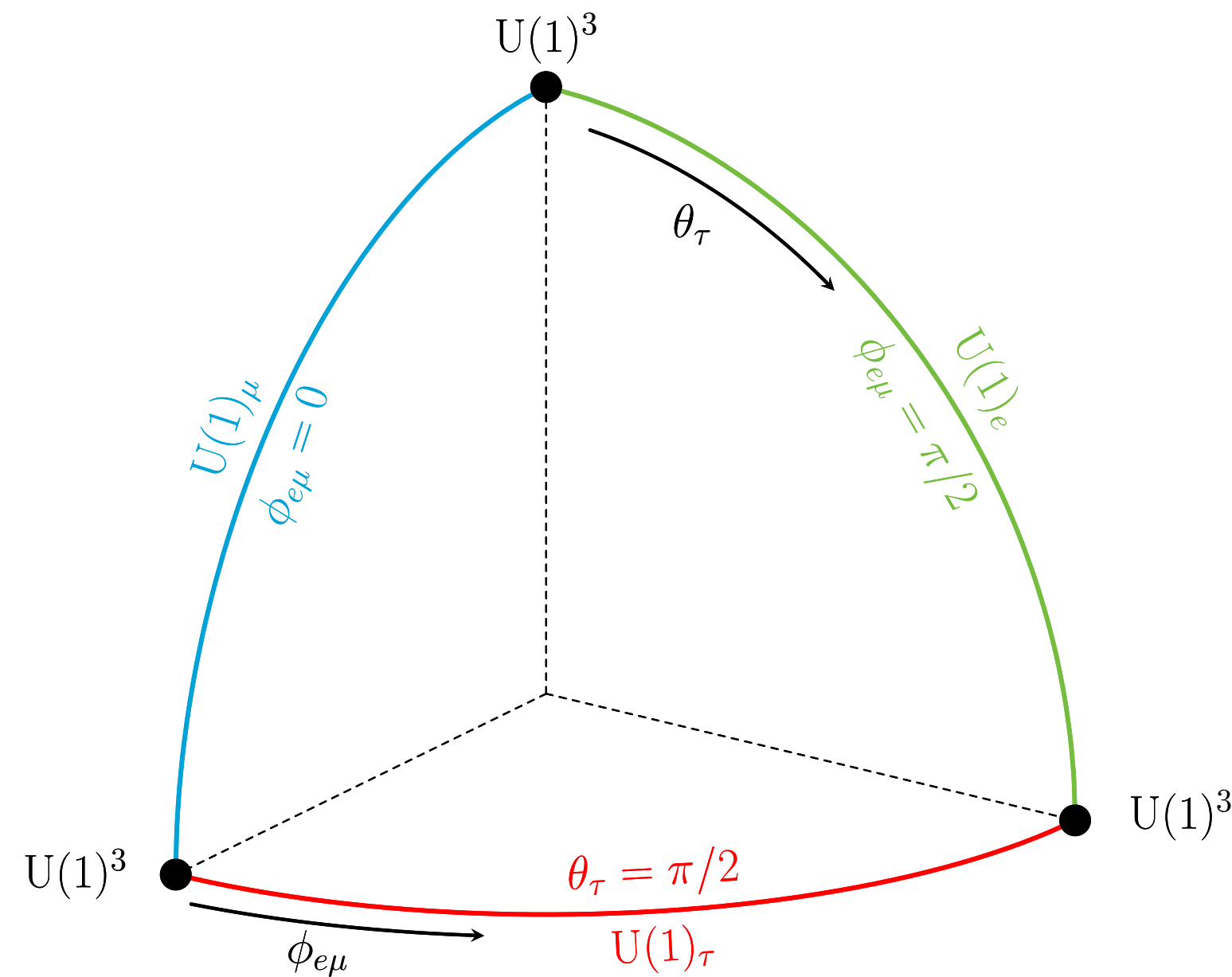
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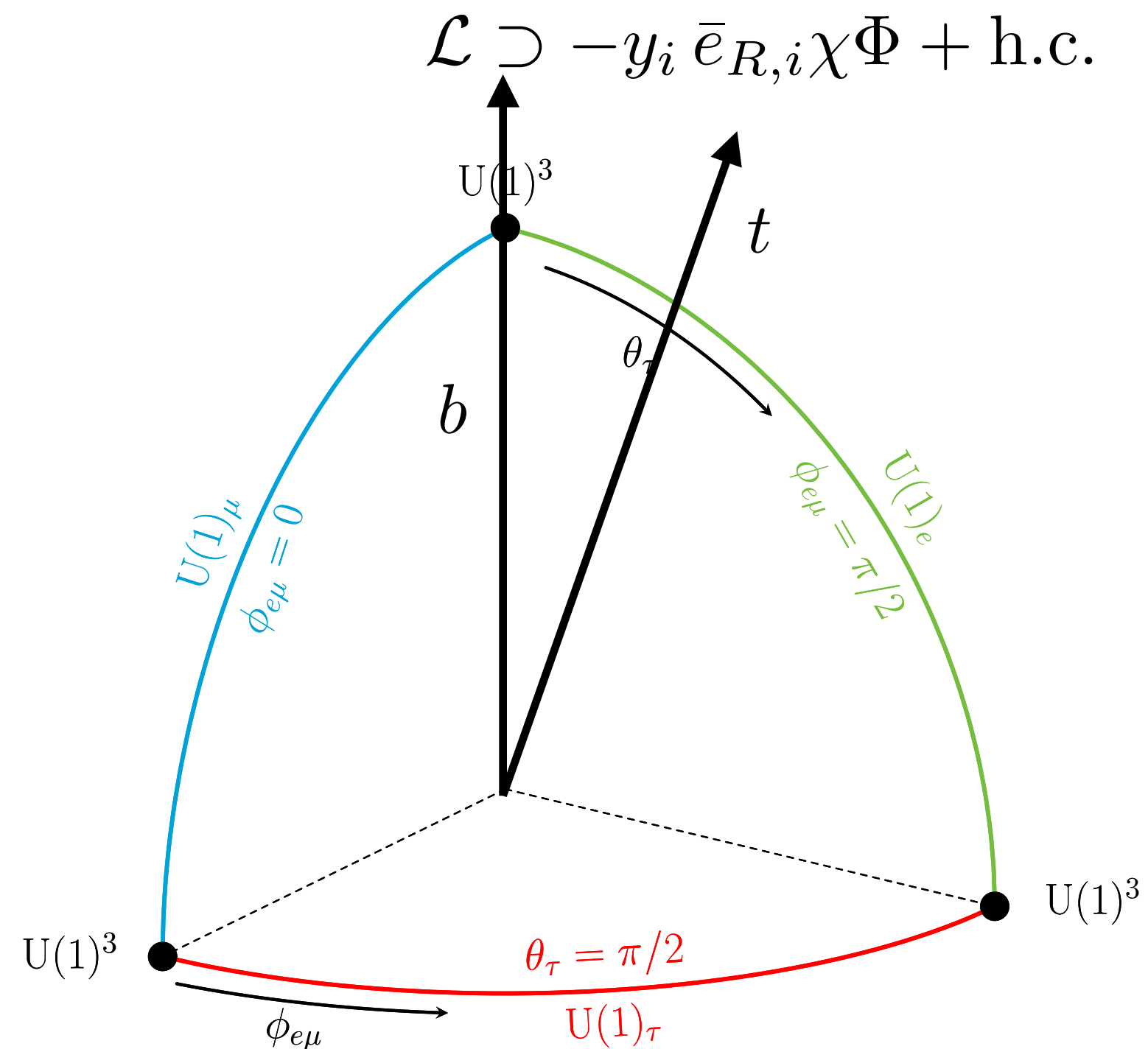
$$\begin{aligned} \mathbf{y} &= (y_e \quad y_\mu \quad y_\tau) \\ &= y_e (\cos \phi_{e\mu} \sin \theta_\tau \quad \sin \phi_{e\mu} \sin \theta_\tau \quad \cos \theta_\tau) \end{aligned} \quad \text{this reduces the parameter space to a sphere octant}$$

For LH quarks, CP-violating phases cannot be removed

$$\begin{aligned} \mathbf{y} &= (y_{q1} \quad y_{q2} \quad y_{q3}) \\ &= y_q (\sin \theta \cos \phi e^{i\alpha_1} \quad \sin \theta \sin \phi e^{i\alpha_2} \quad \cos \theta) \end{aligned}$$

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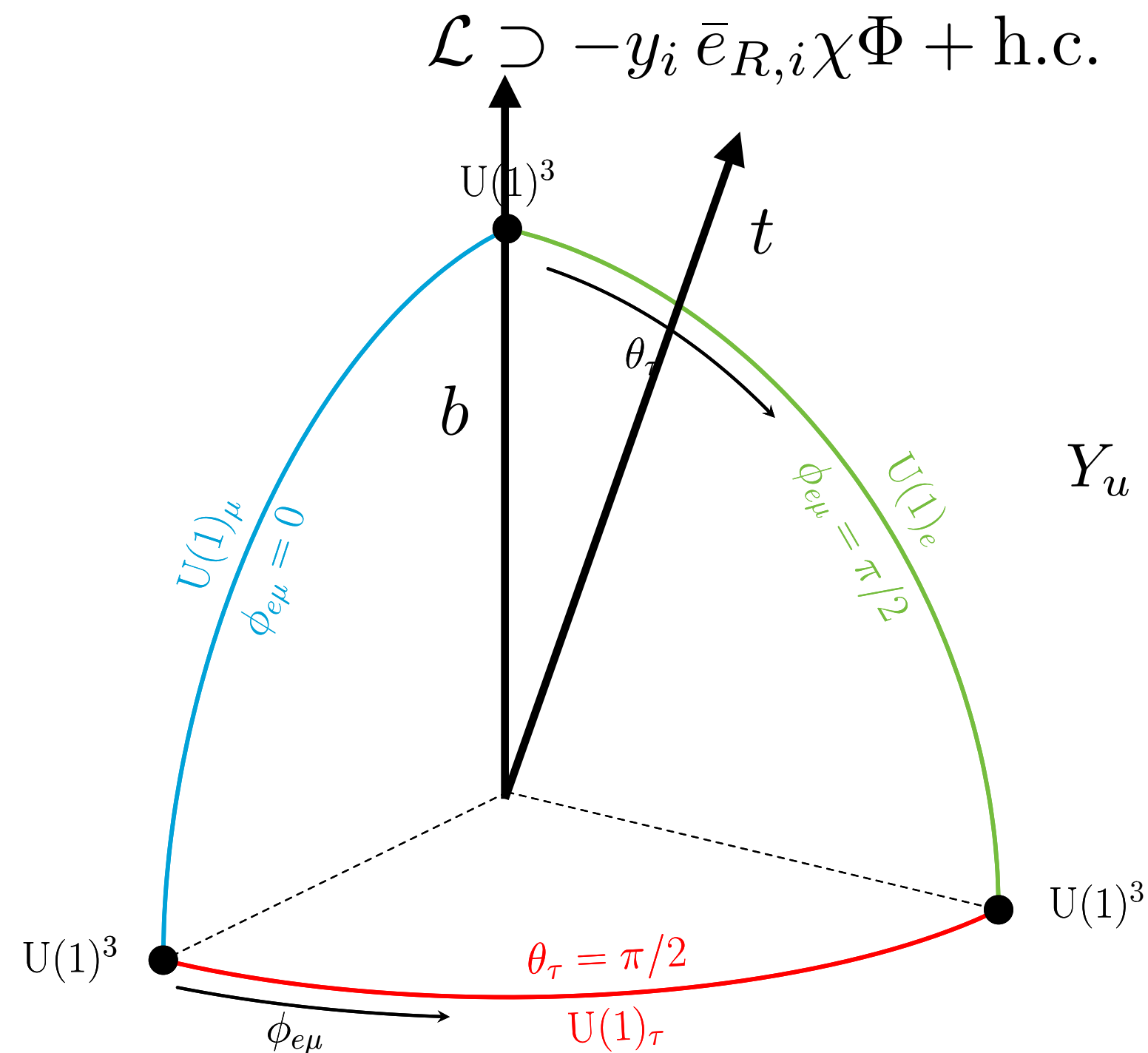
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At low energies: $\mathbf{y} \equiv \mathbf{y}_d = V_{\text{CKM}}^\dagger \cdot \mathbf{y}_u$

We **cannot simultaneously align** to a specific generation for **up-** and **down-**quarks

Two benchmarks: rank-1 flavour violation

Leptophilic Dark Matter:



Quarkphilic Dark Matter:

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No MFV spurions allowed in these frameworks but $U(3)^5 \supset U(2)^5$

$$Y_u = \left(\begin{array}{c|c} \Delta_u & V_q \\ \hline 0 & y_t \end{array} \right), \quad Y_d = \left(\begin{array}{c|c} \Delta_d & V_q \\ \hline 0 & y_b \end{array} \right), \quad \Delta_u \sim (\mathbf{2}_q, \bar{\mathbf{2}}_u), \quad \Delta_d \sim (\mathbf{2}_q, \bar{\mathbf{2}}_d),$$

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$$\mathbf{y} = y_q \begin{pmatrix} \sin \theta \cos \phi e^{i\alpha_1} & \sin \theta \sin \phi e^{i\alpha_2} & \cos \theta \end{pmatrix} \sim \begin{pmatrix} a V_q & b \end{pmatrix}$$

$U(2)_q$ $2 \oplus 1$ With a and b order one parameters

Two benchmarks: rank-1 flavour violation

Leptophilic Dark Matter:

$$\mathcal{L} \supset -y_i \bar{e}_{R,i} \chi \Phi + \text{h.c.}$$

1. Relic Density
2. Collider Searches
3. Direct Detection
4. Flavour bounds

$$\text{U}(1)_e \oplus \text{U}(1)_\mu \oplus \text{U}(1)_\tau$$

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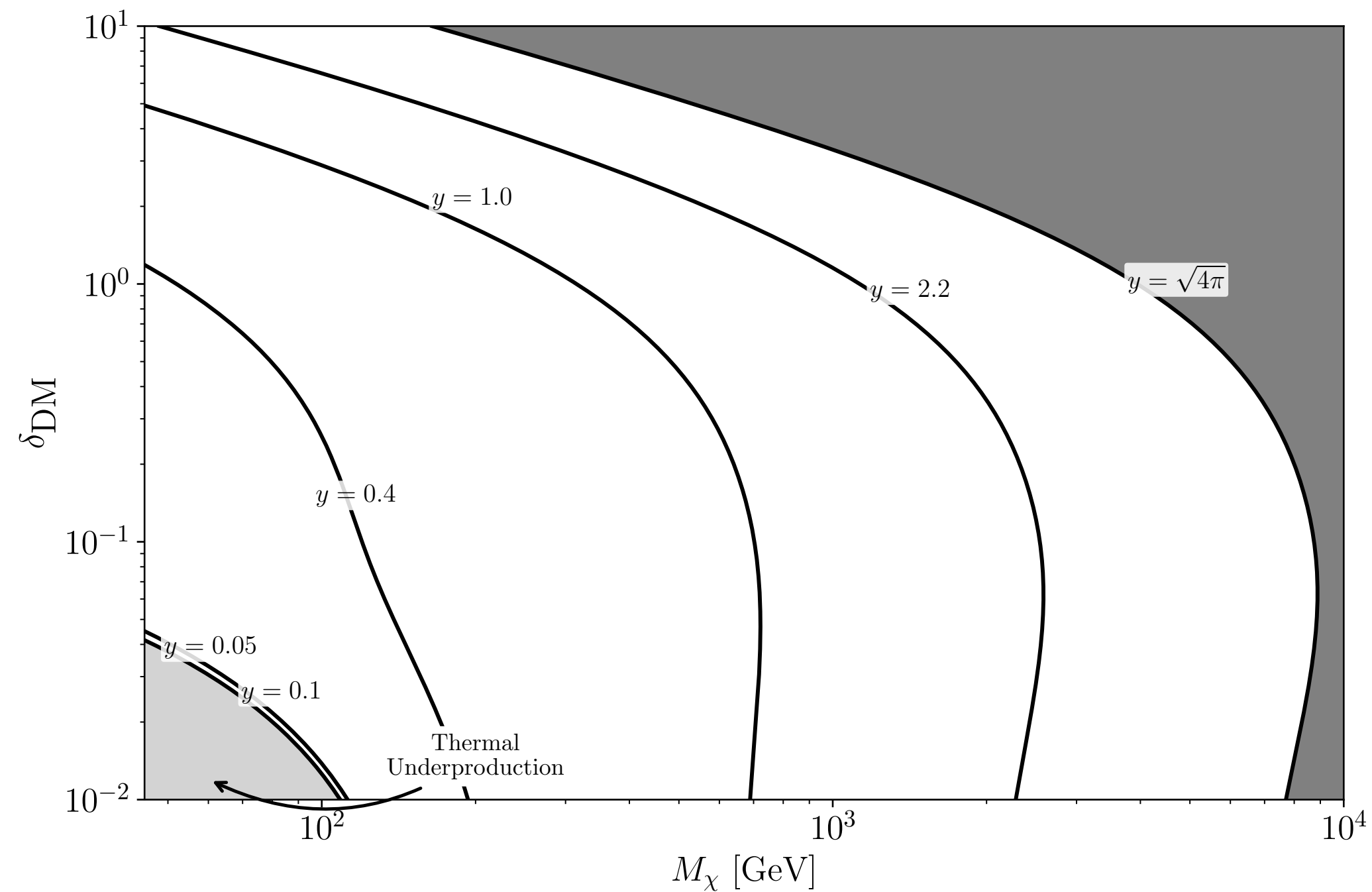
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$$\text{U}(2)_q$$

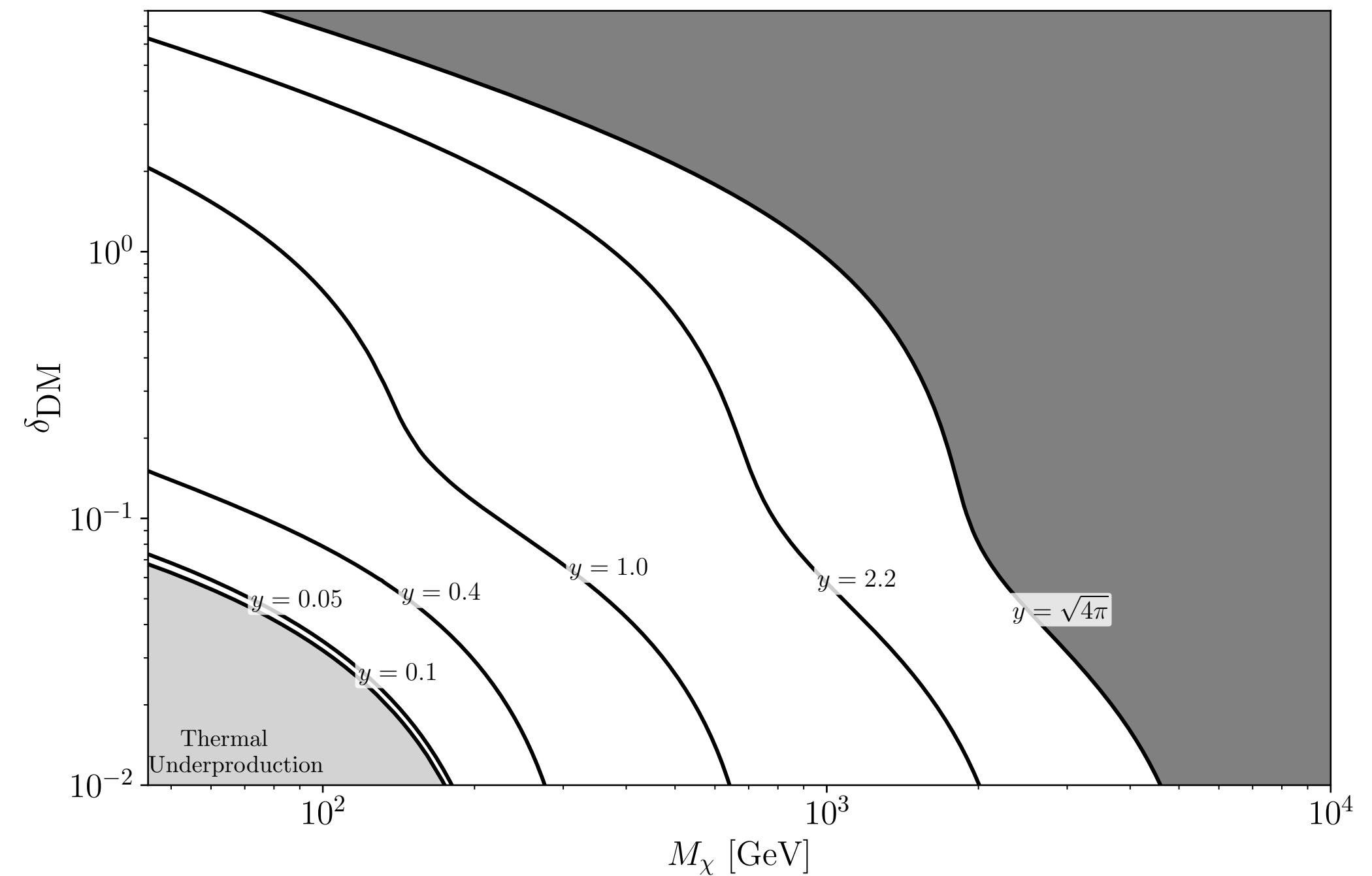
Leptophilic Dark Matter: production

$$\delta_{\text{DM}} = \frac{M_{\Phi} - M_{\chi}}{M_{\chi}}$$

Dirac

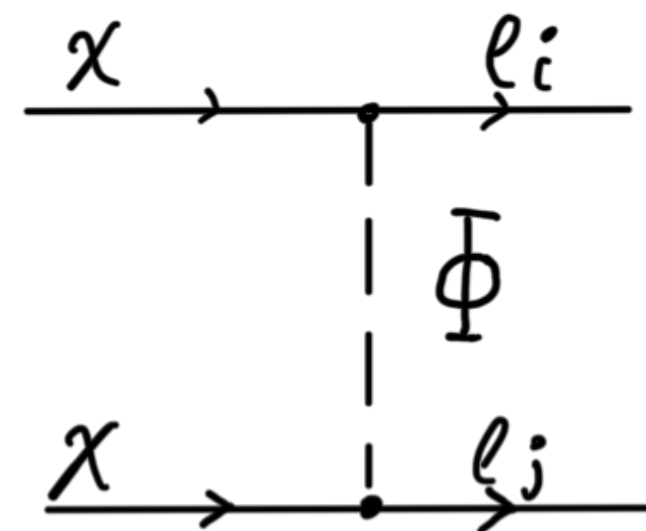


Majorana



solve Boltzmann equation:

$$\dot{n} = -\langle \sigma_{\text{eff}} v_{\text{rel}} \rangle (n^2 - n_{\text{eq}}^2)$$

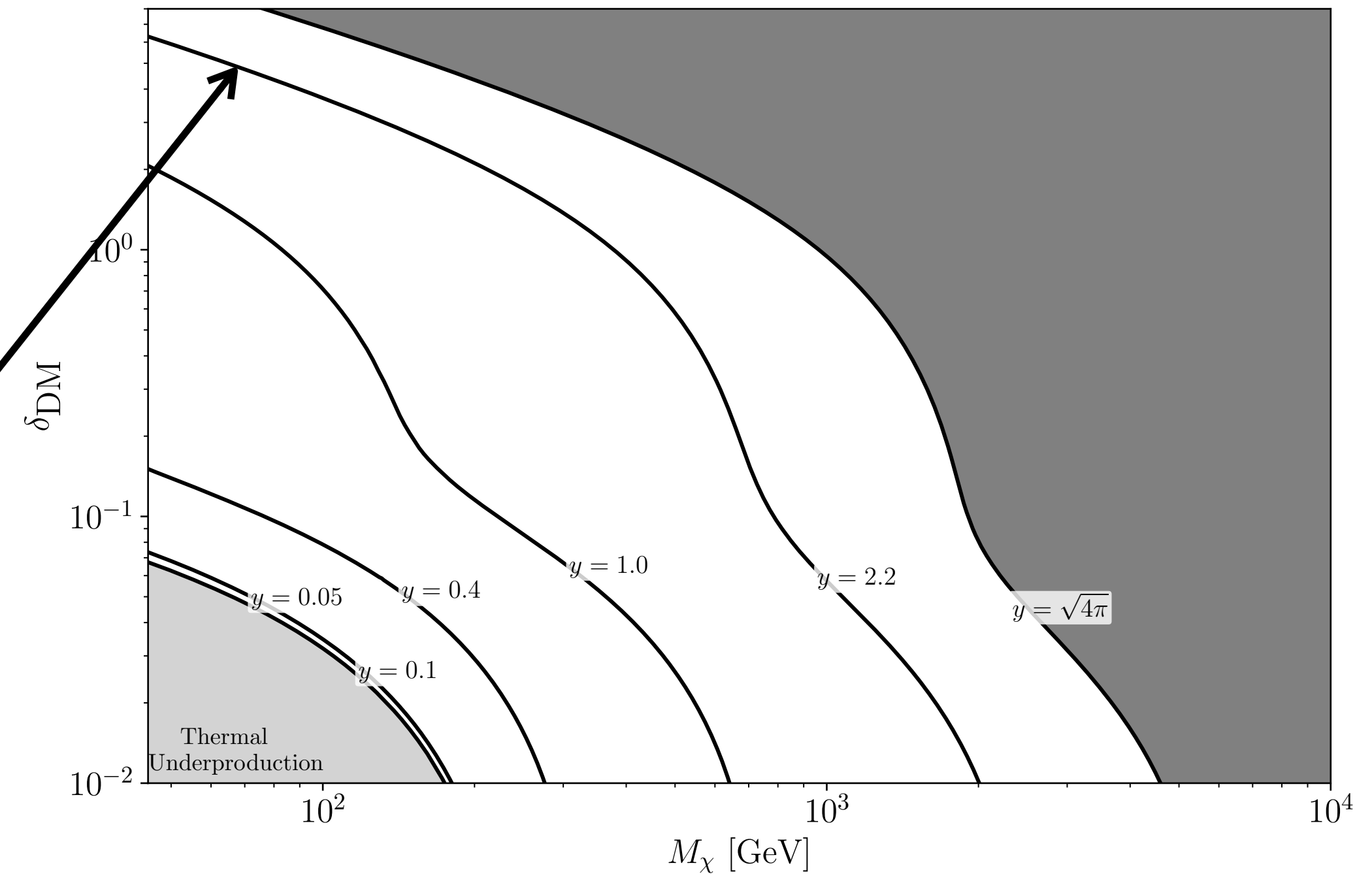
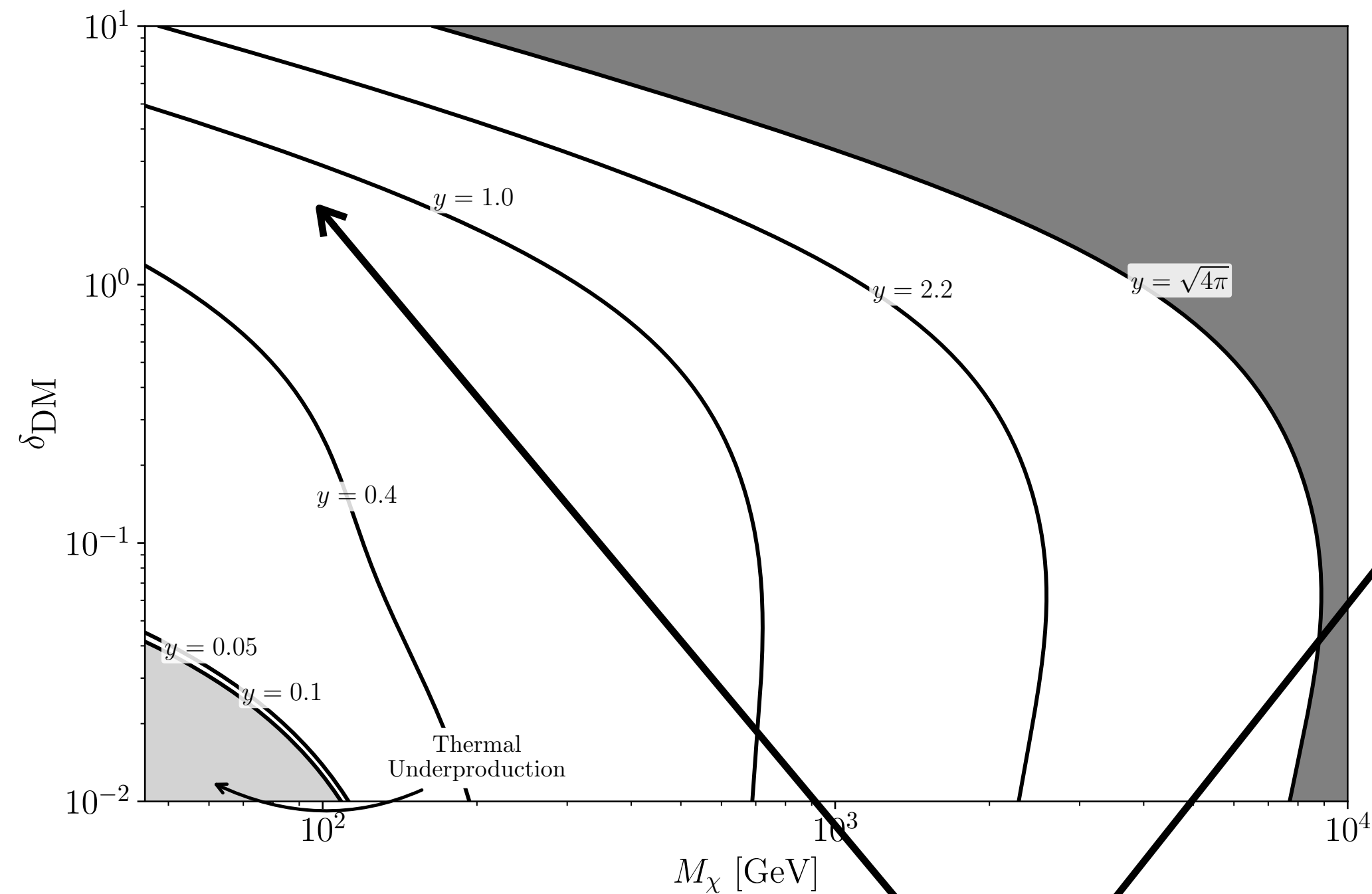


Leptophilic Dark Matter: production

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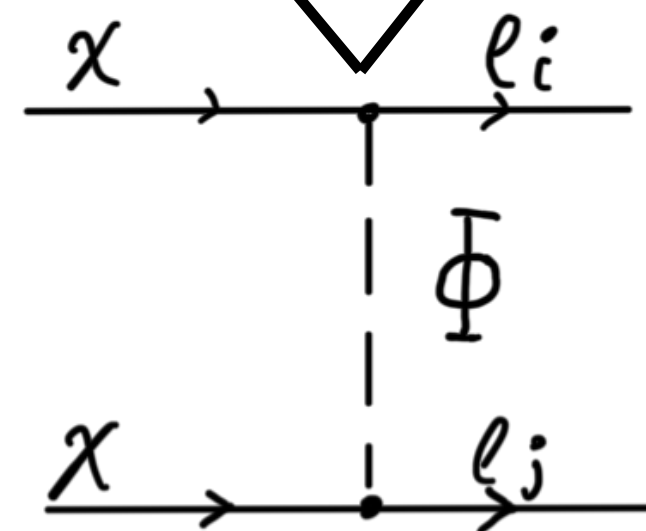
Dirac

Majorana



solve Boltzmann equation:

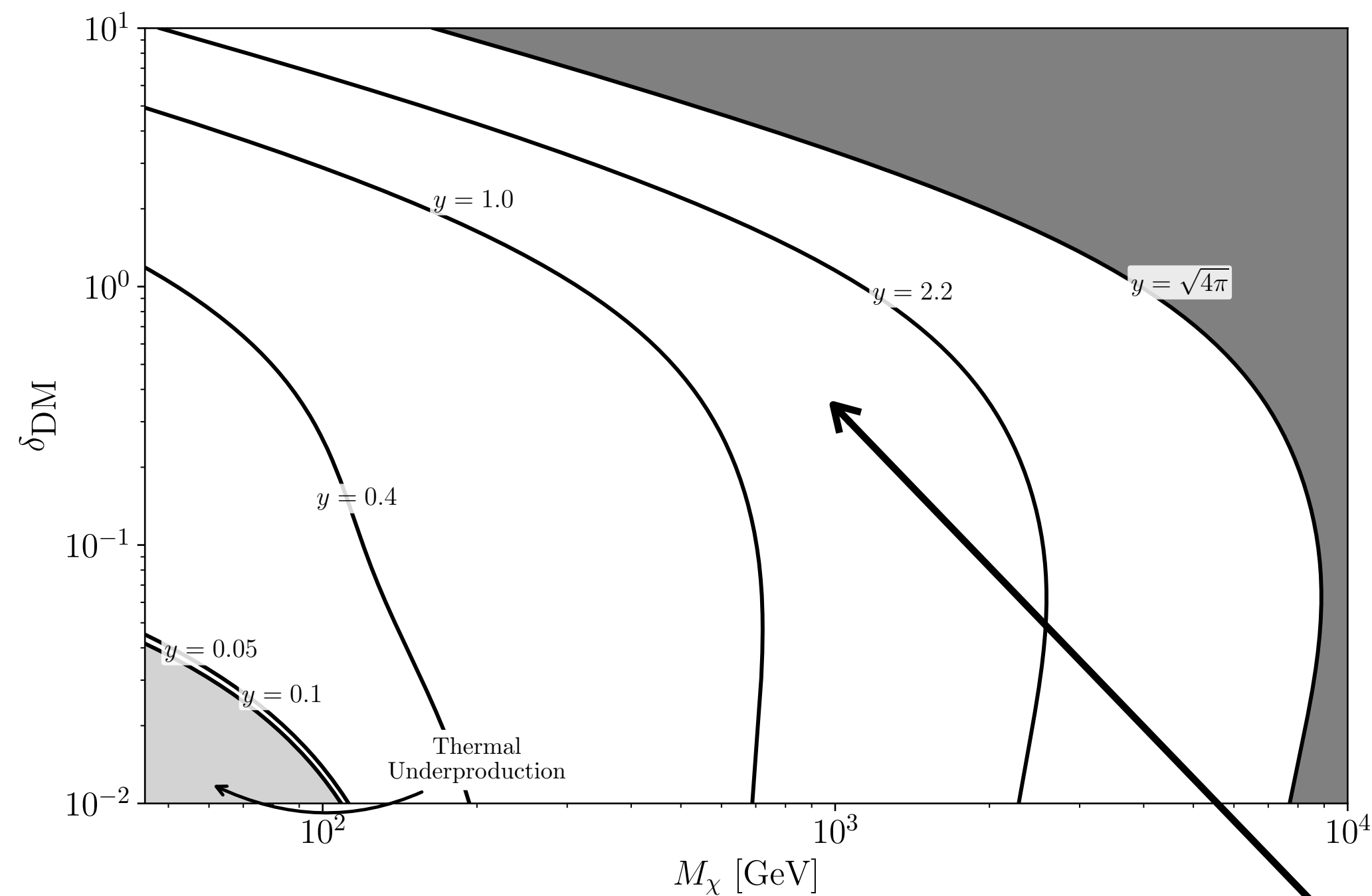
$$\dot{n} = -\langle \sigma_{\text{eff}} v_{\text{rel}} \rangle (n^2 - n_{\text{eq}}^2)$$



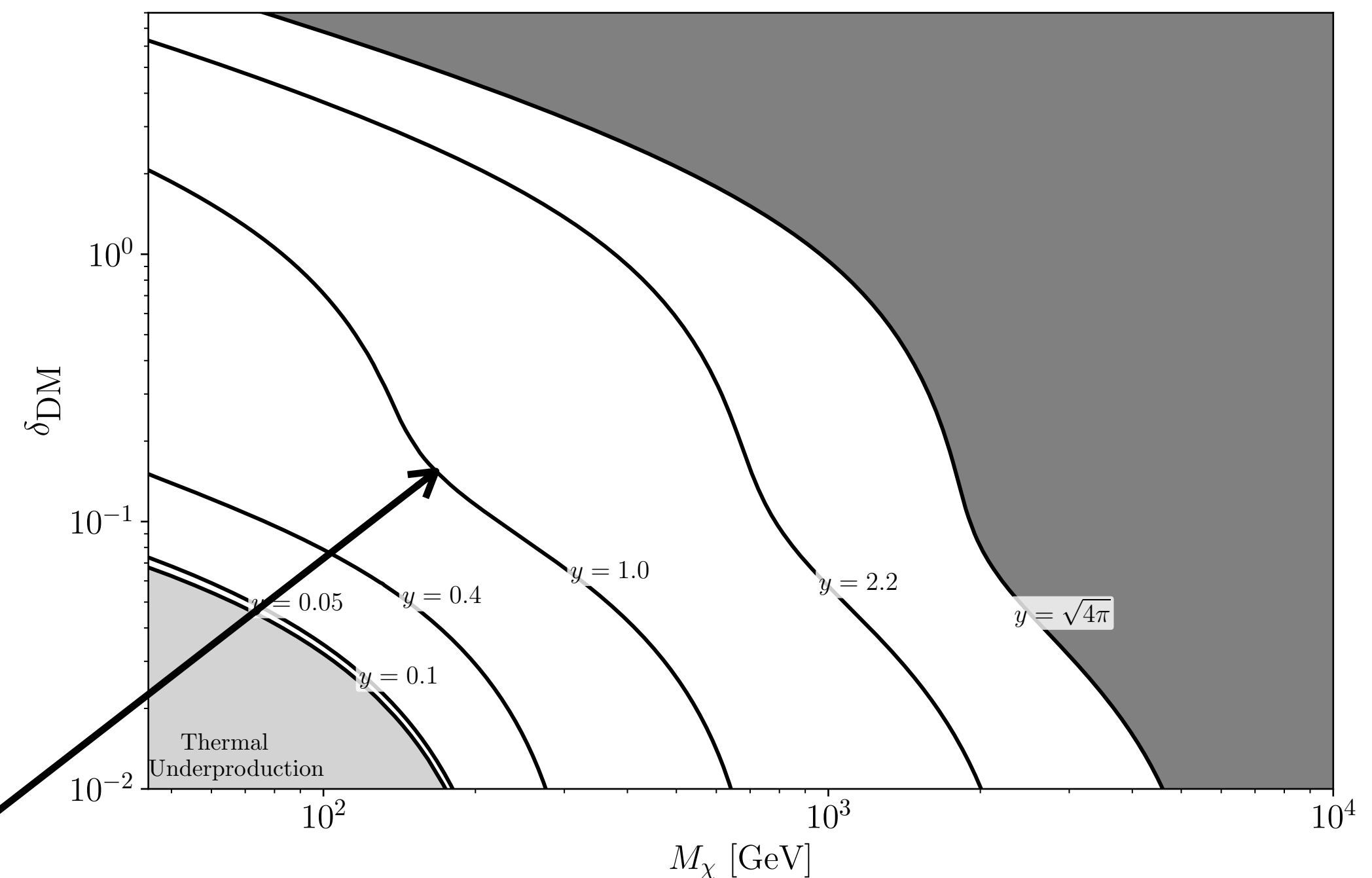
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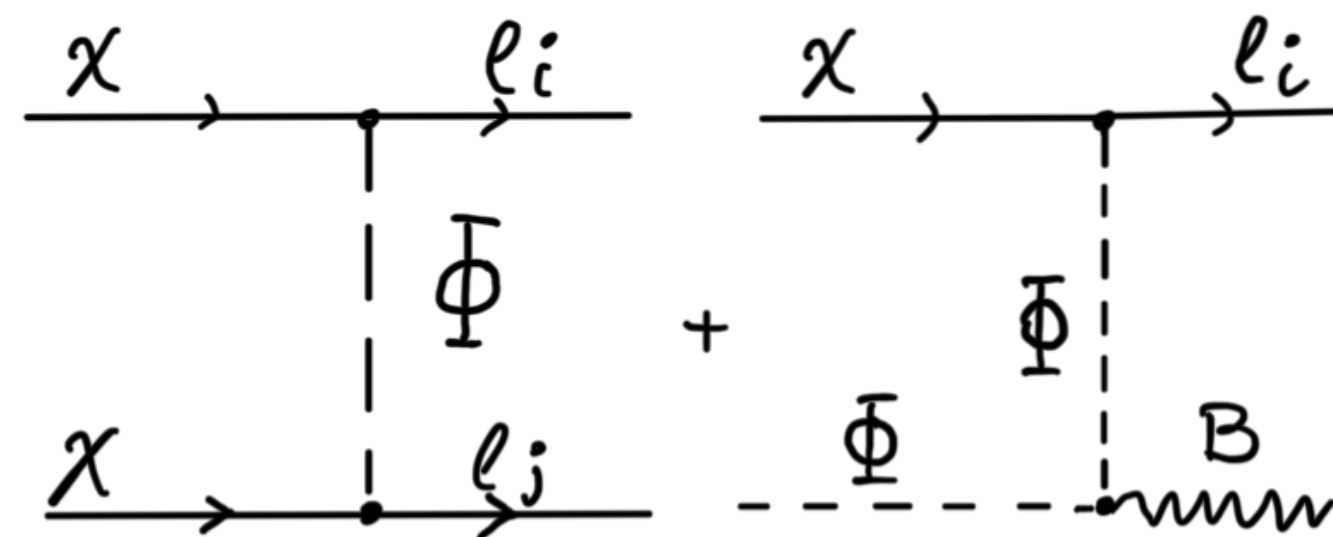
Dirac



Majorana



Majorana DM s-wave suppression, velocity-suppressed **p-wave** **dominates**. Coannihilations matter more for Majorana!



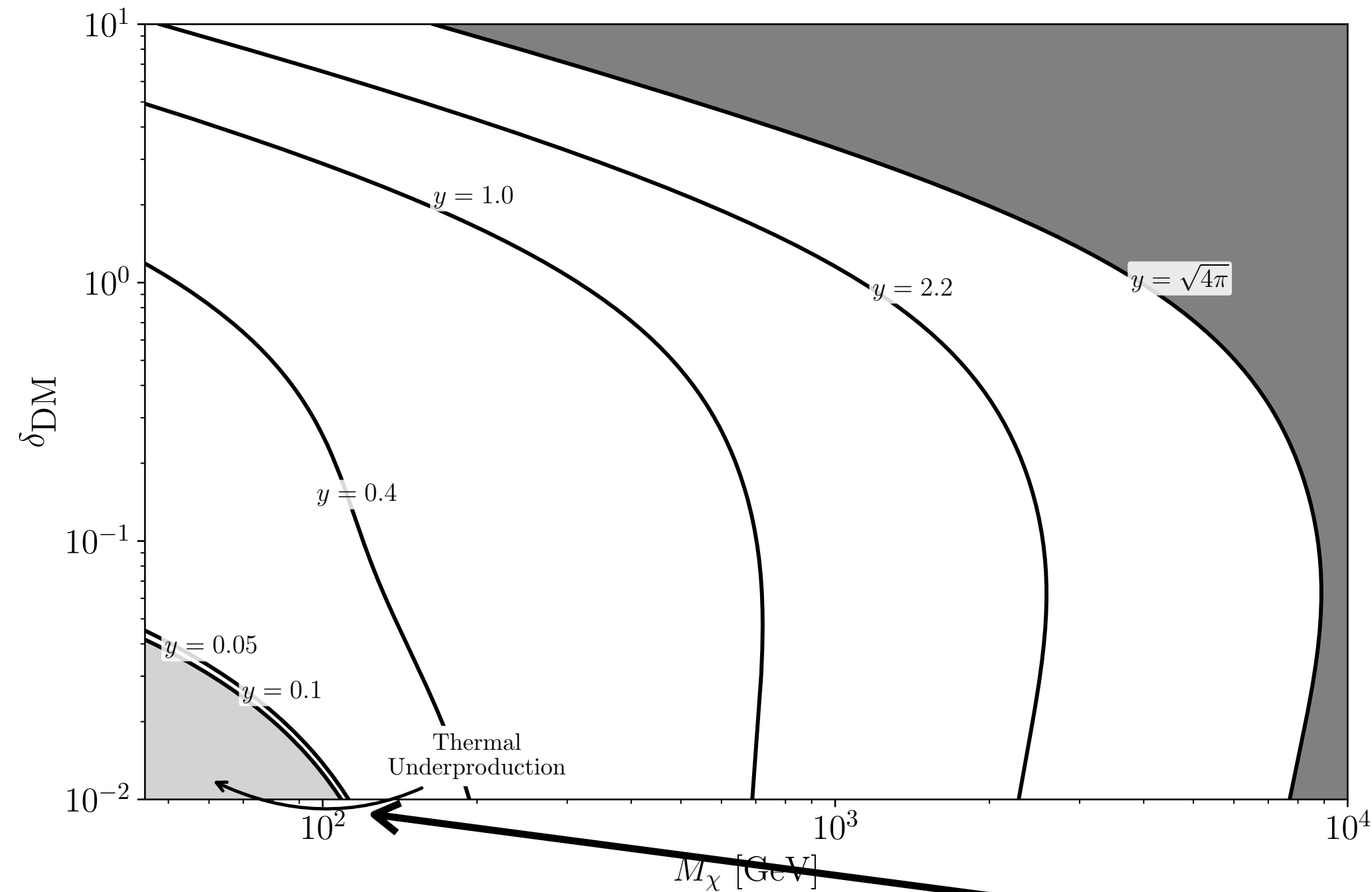
$$\delta_{\text{DM}} = \frac{M_{\Phi} - M_{\chi}}{M_{\chi}} \ll 1$$

Importance of **coannihilation** channels

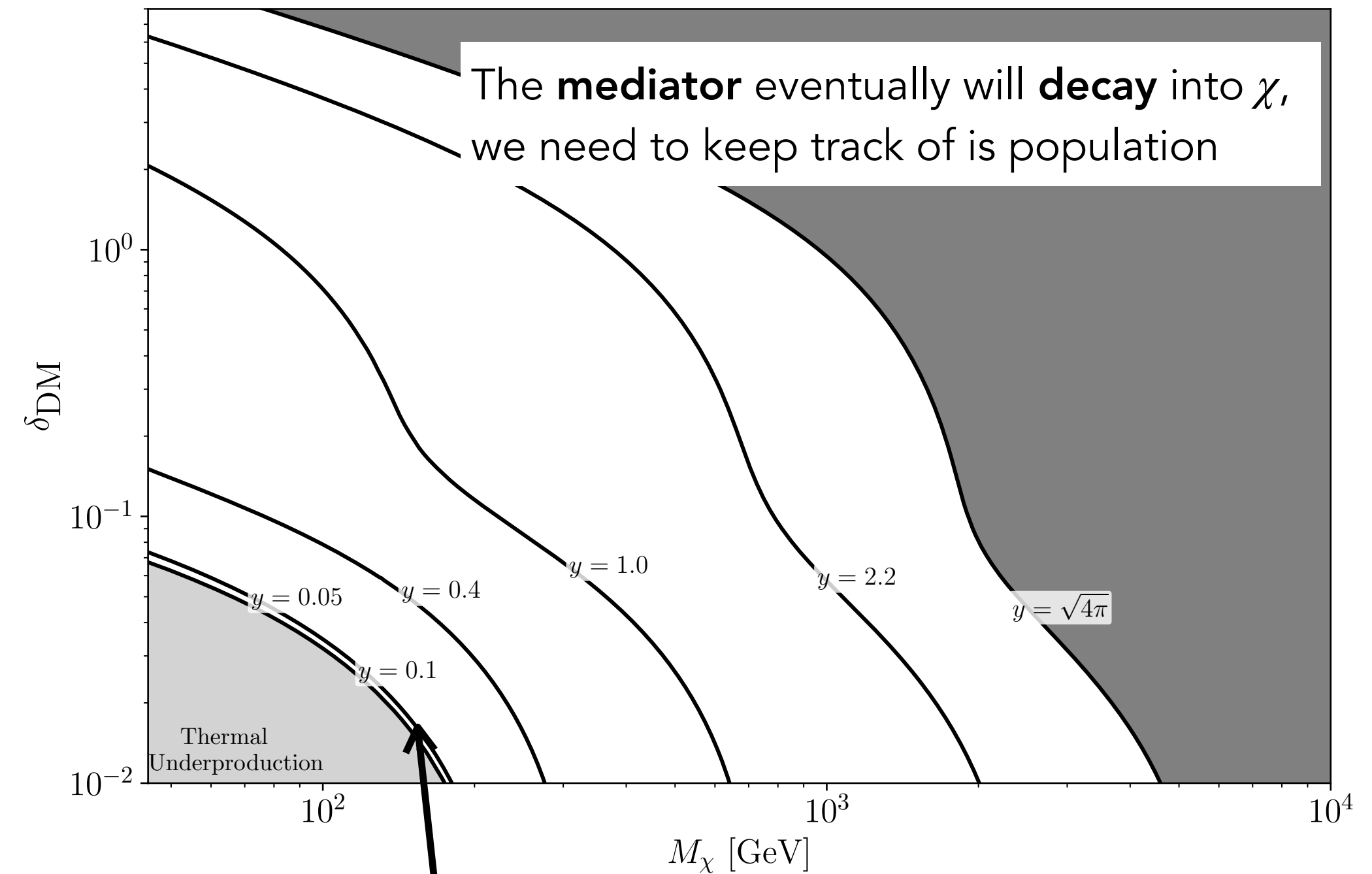
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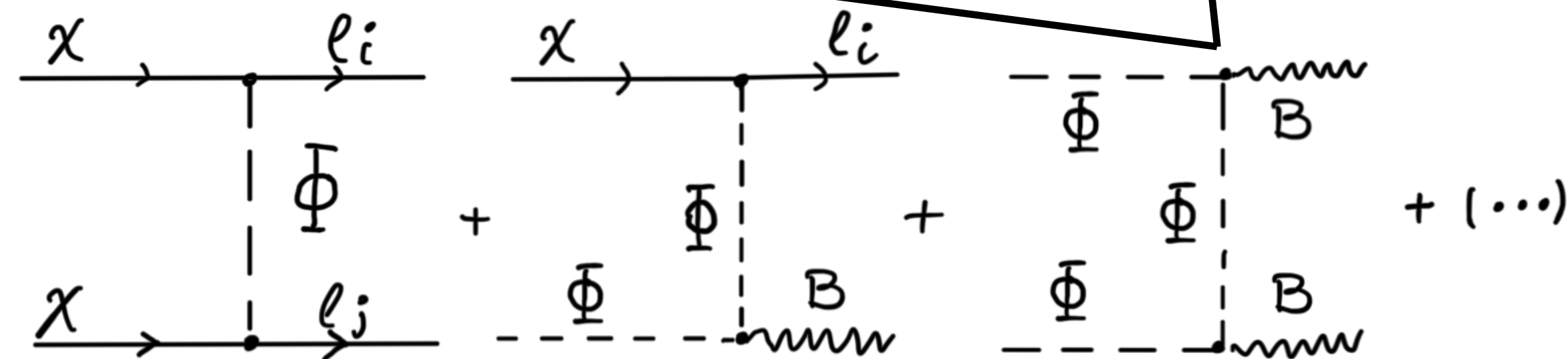
Dirac



Majorana

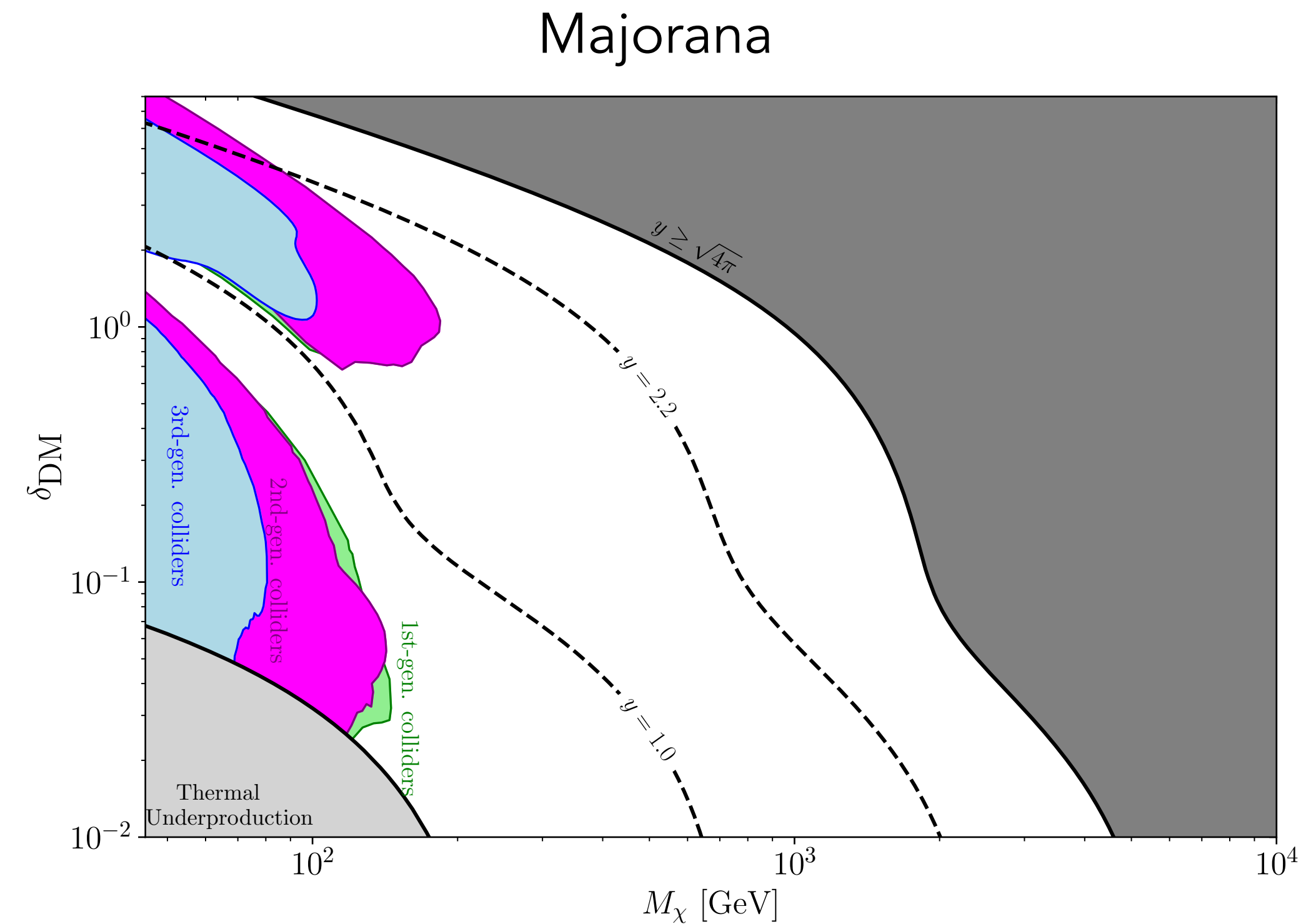
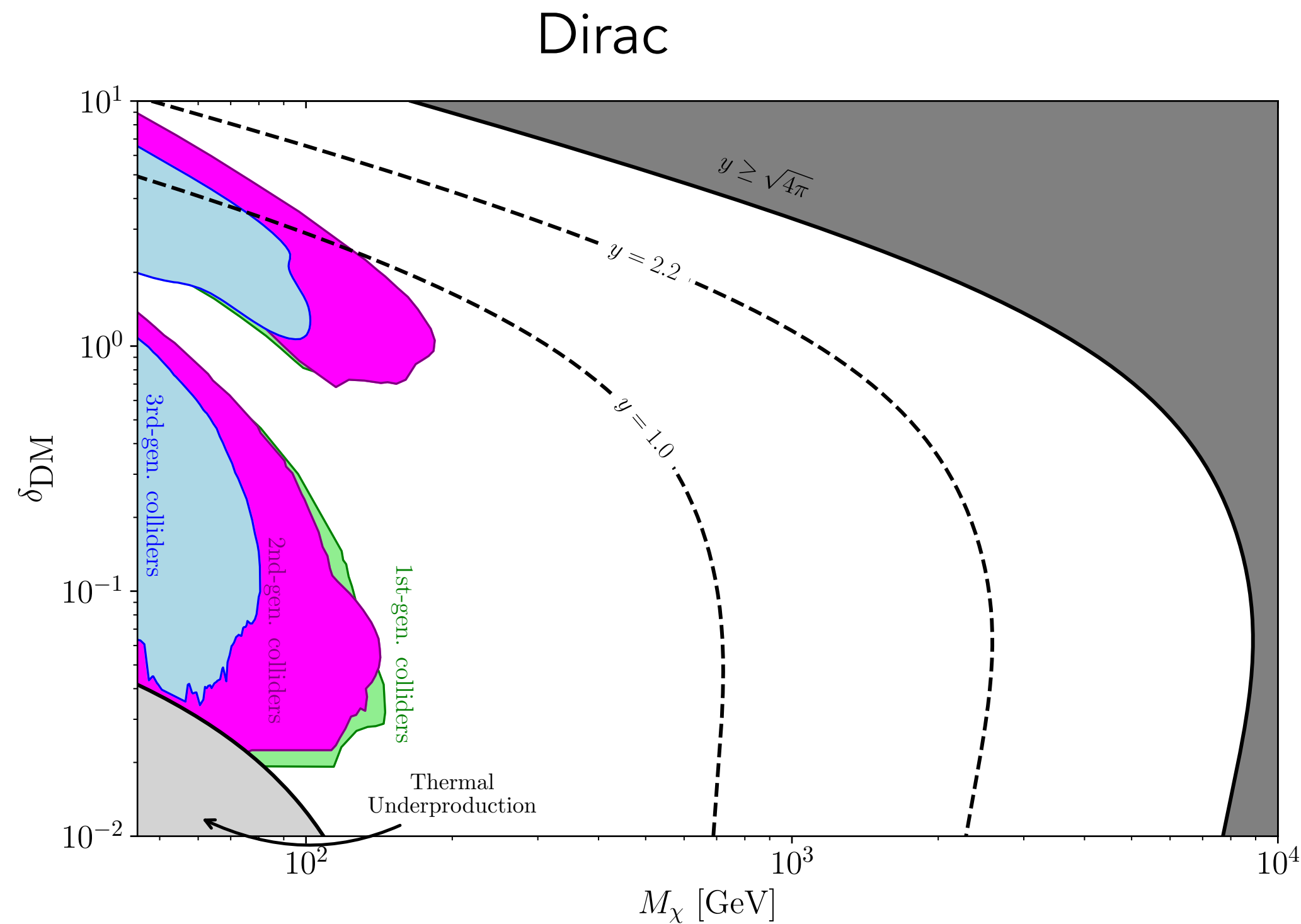


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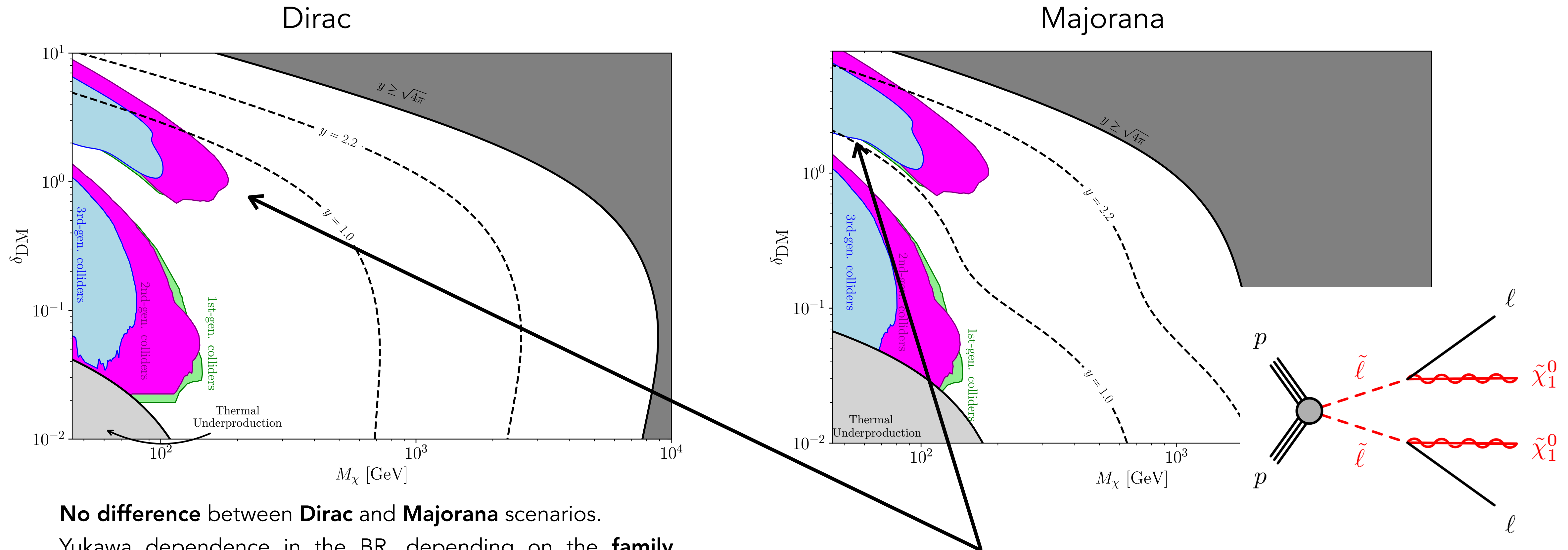
Mediator is charged under SM gauge group → **Irreducible** diagrams with gauge bosons can keep Φ in **equilibrium**.

Leptophilic Dark Matter: collider searches



No difference between **Dirac** and **Majorana** scenarios.
Yukawa dependence in the BR, depending on the **family alignment** one needs to **interpolate** on the different bounds.

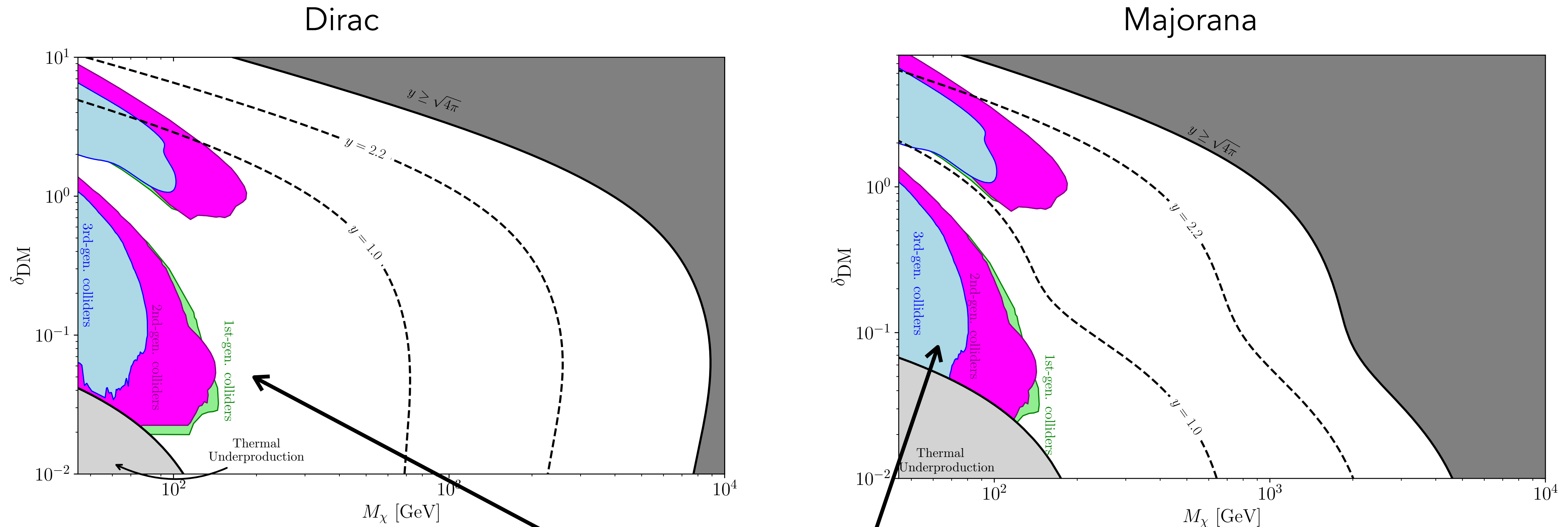
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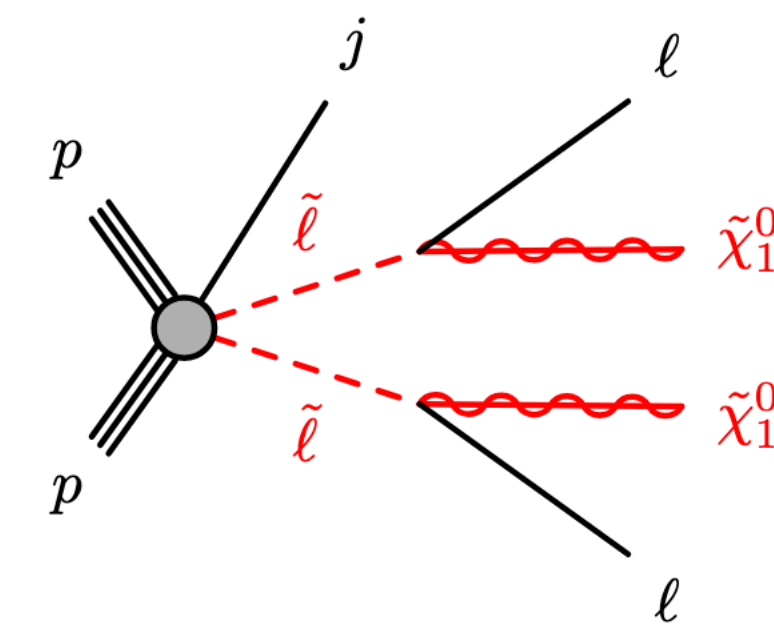
ATLAS + CMS uncompressed SUSY spectrum, light sleptons better tested than 3rd family.

Leptophilic Dark Matter: collider searches



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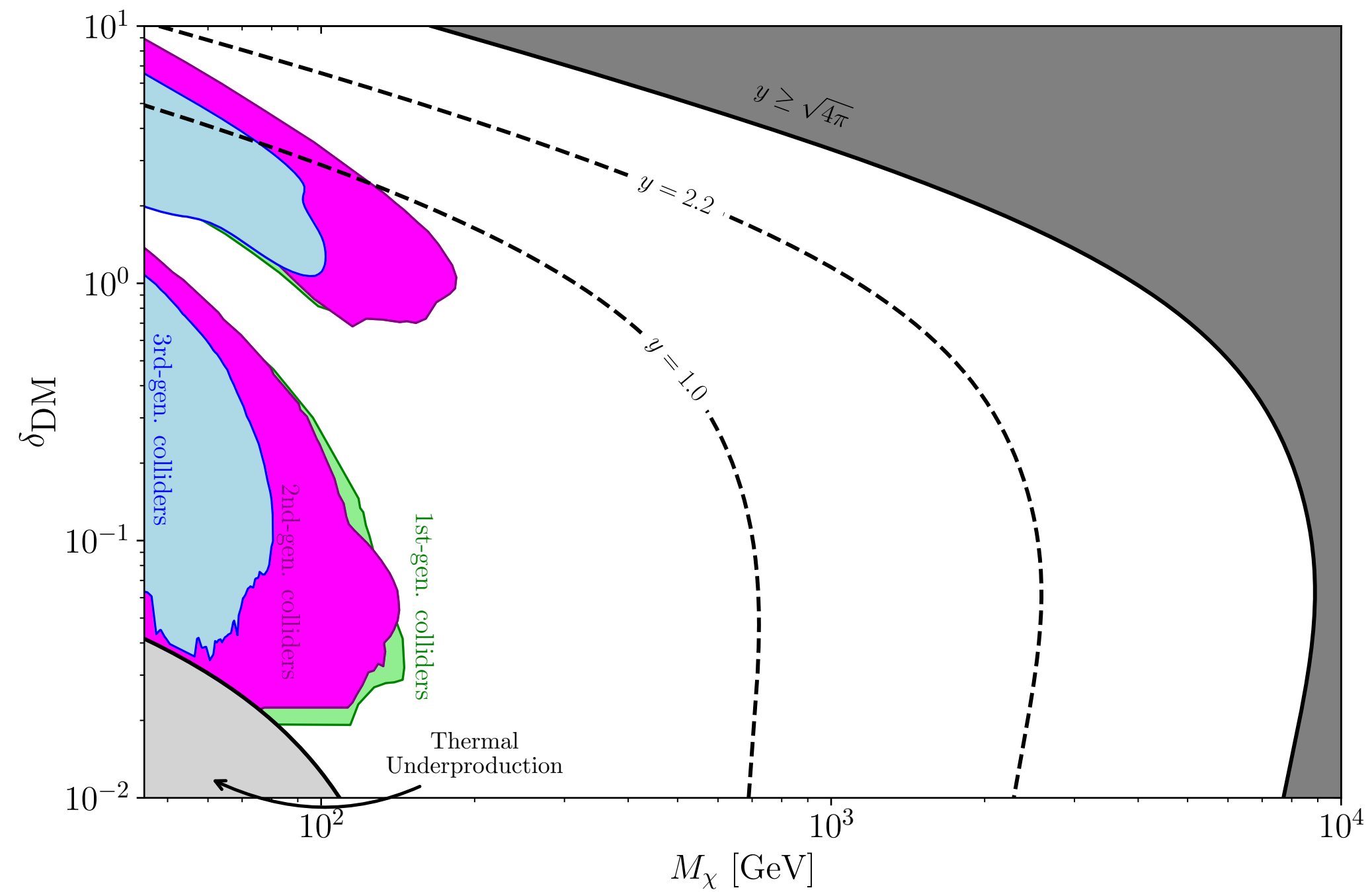
Compressed searches **CMS+ATLAS** for light leptons
Stau-searches from **LEP**



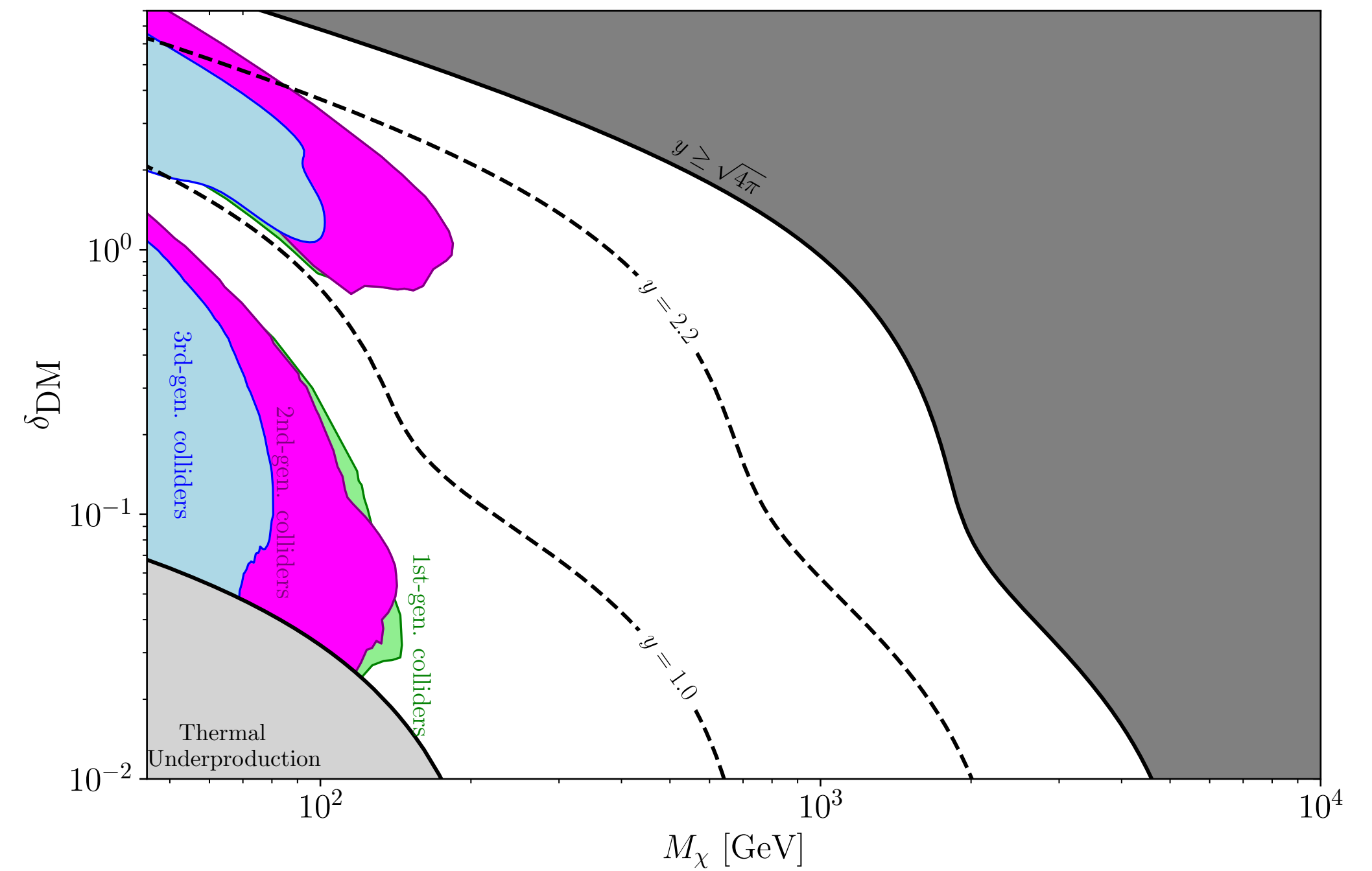
Indirect FCC-ee constraints: [Olgoso, Paradisi, Selimović](#)

Leptophilic Dark Matter: Direct Detection

Dirac

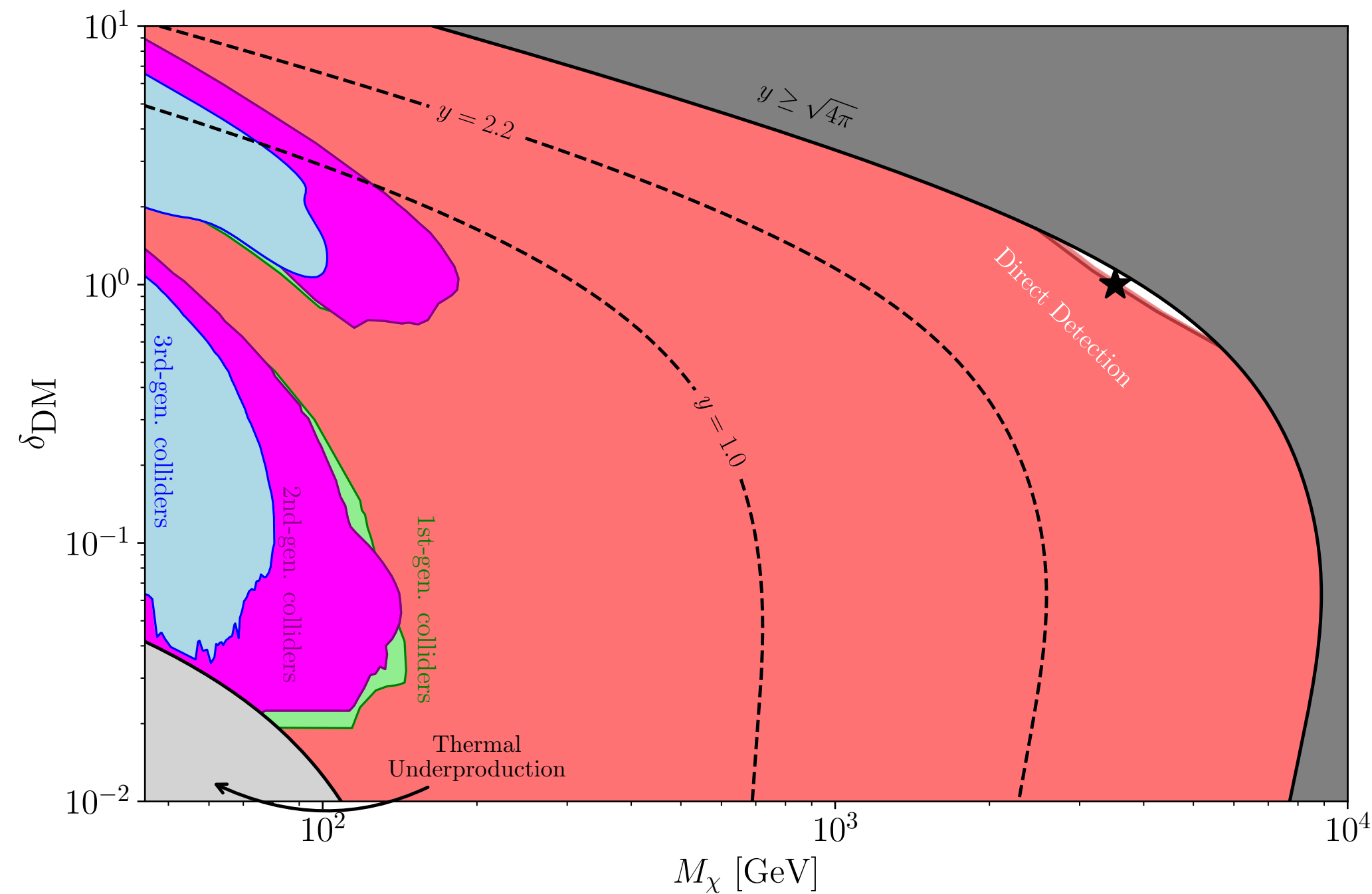


Majorana



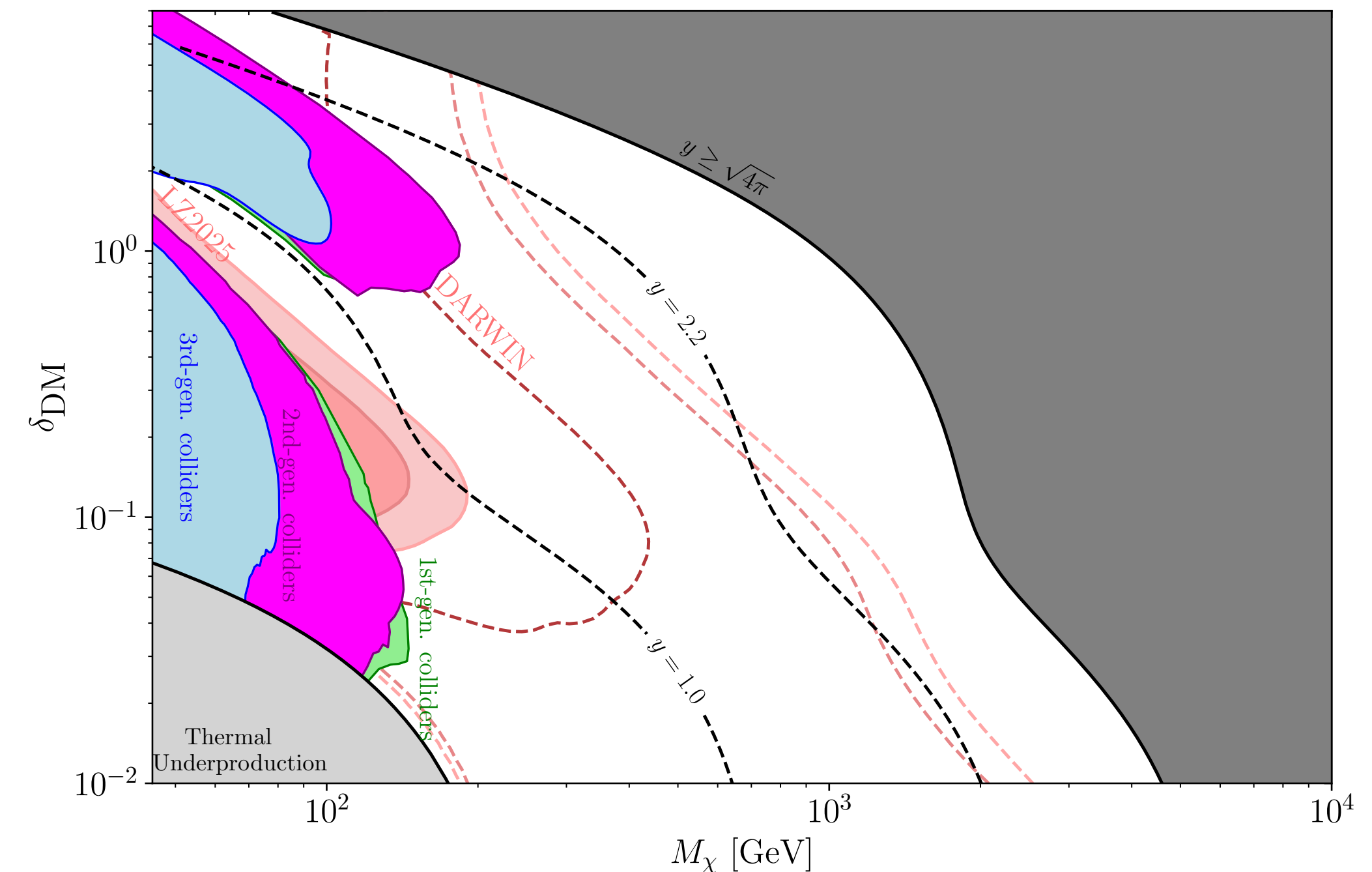
Leptophilic Dark Matter: Direct Detection

Dirac

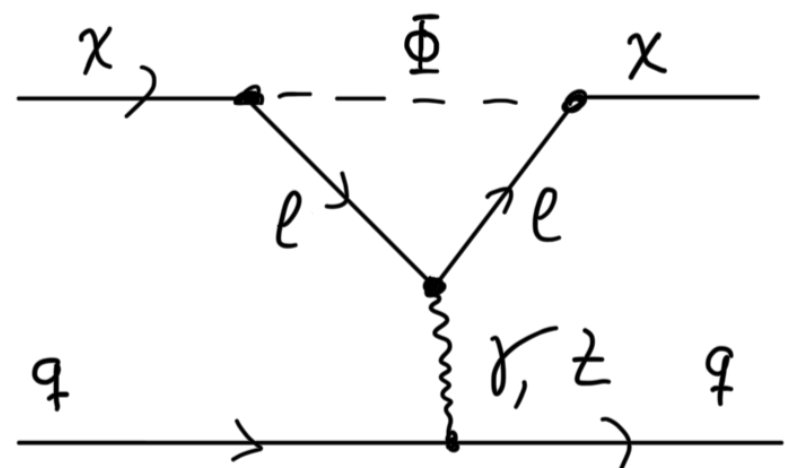


Lighter **shades** of red correspond to **lighter** fermions.

Majorana



Yukawas are **fixed** to reproduce the relic abundance at each point

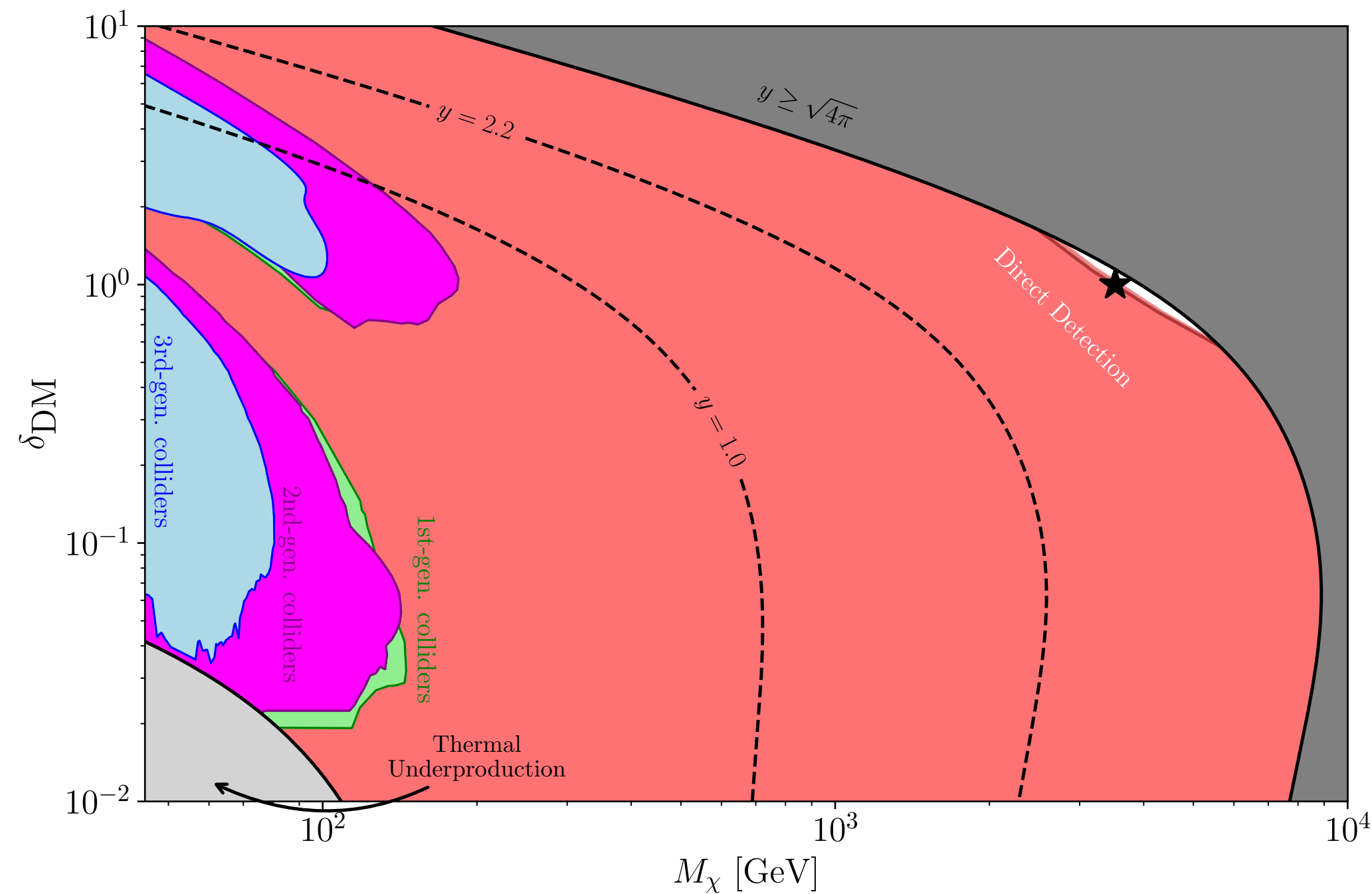


magnetic dipole charge radius

$$\mathcal{L}_{\text{eff}} = \frac{\mu_\chi}{2} \bar{\chi} \sigma^{\mu\nu} \chi F_{\mu\nu} + b_\chi \bar{\chi} \gamma^\mu \chi \partial^\nu F_{\mu\nu}$$

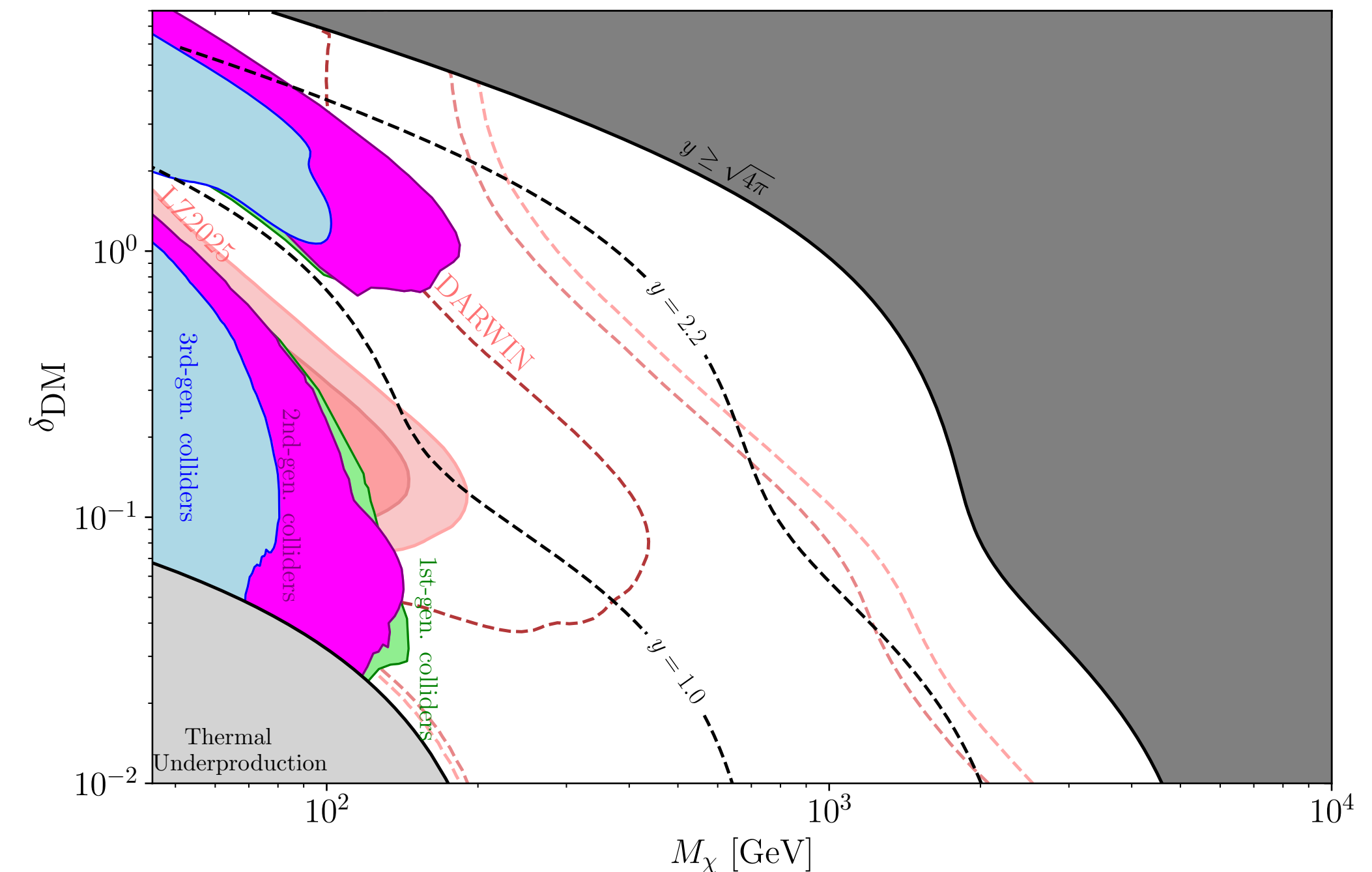
Leptophilic Dark Matter: Direct Detection

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[Kopp, Michaels, Smirnov '14](#)

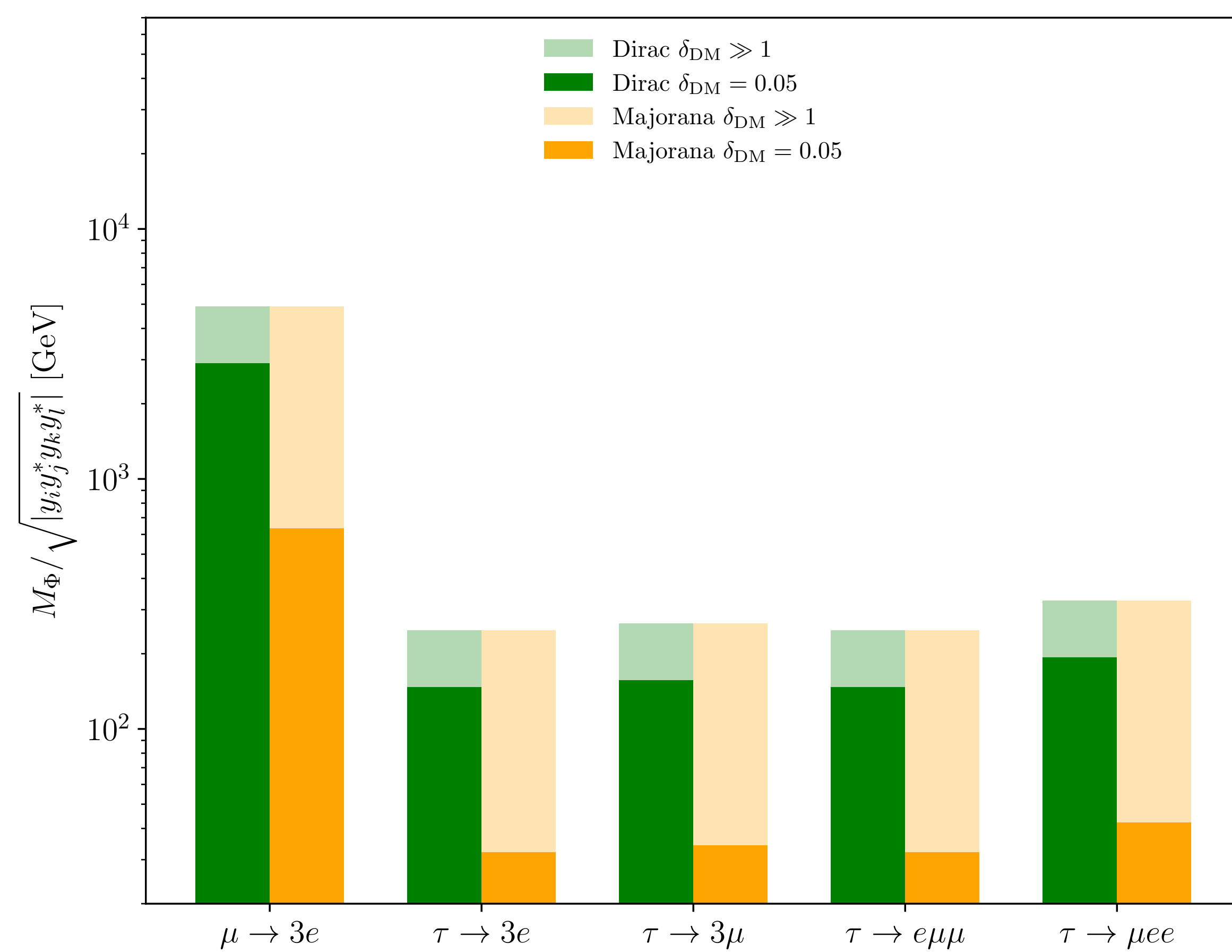
Next important operator, the **anapole**, appears at dimension six.

$$(C^\dagger \Gamma C)^T = -\Gamma \longrightarrow \bar{\chi} \Gamma \chi = -\bar{\chi} \Gamma \chi = 0$$

$$C^\dagger \gamma^\mu C = -(\gamma^\mu)^T, \quad C^\dagger \sigma^{\mu\nu} C = -(\sigma^{\mu\nu})^T,$$

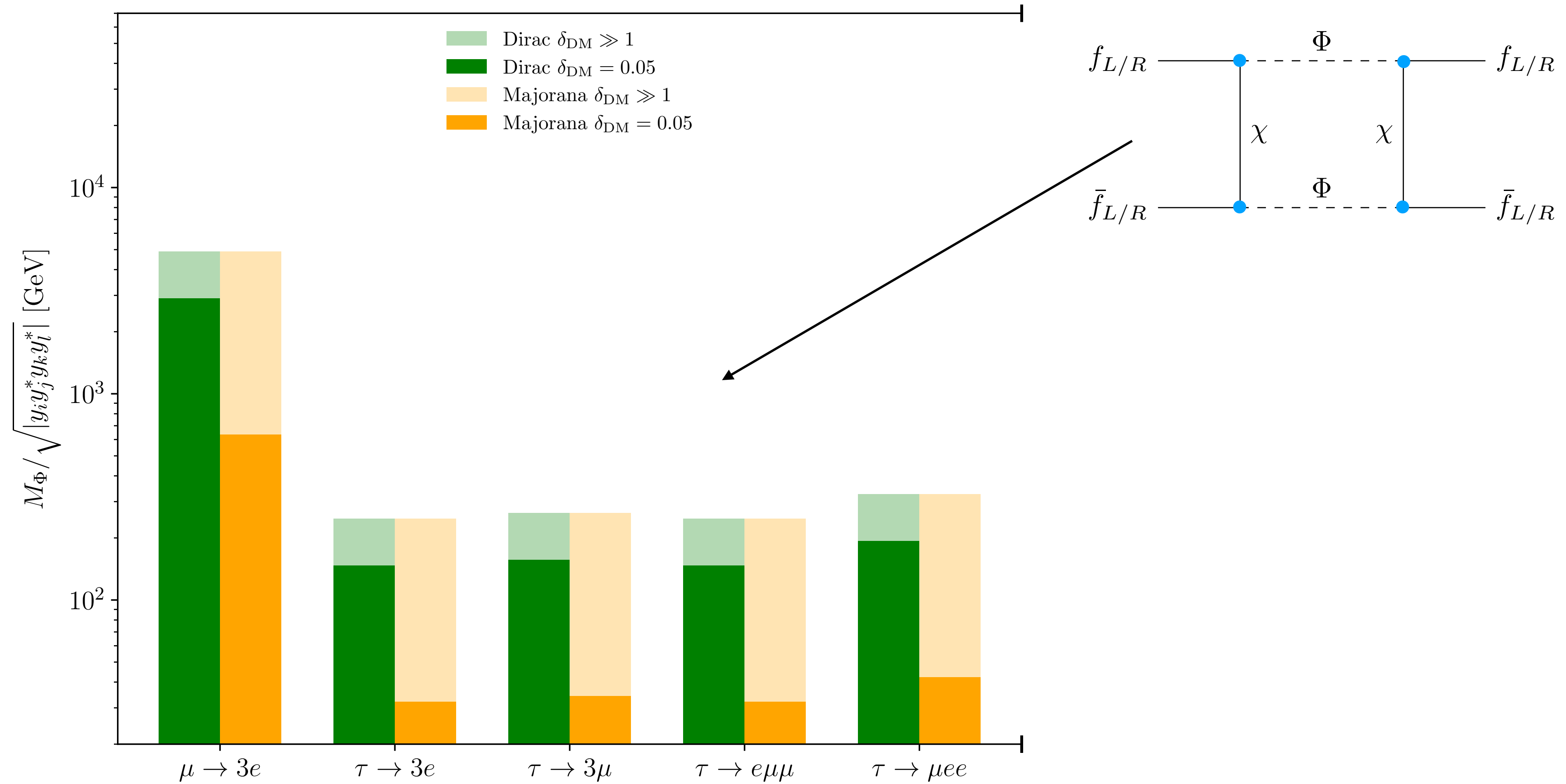
$$\mathcal{L}_{\text{eff}} = \frac{\mu_\chi}{2} \bar{\chi} \cancel{\sigma^{\mu\nu}} \chi F_{\mu\nu} + b_\chi \bar{\chi} \cancel{\gamma^\mu} \chi \partial^\nu F_{\mu\nu} + \mathcal{A} \bar{\chi} \gamma_\mu \gamma_5 \chi \partial^\nu F_{\mu\nu}$$

Overview of LFV bounds



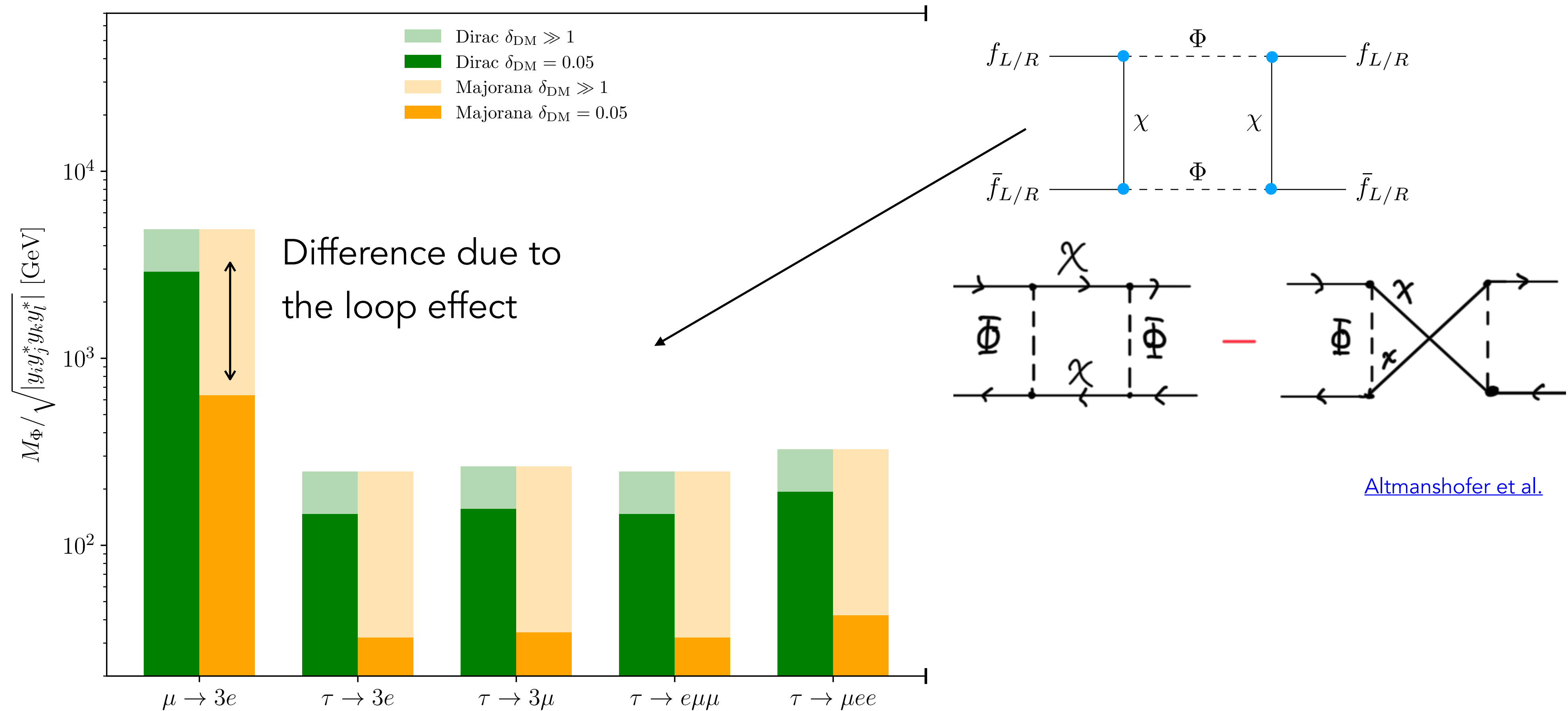
For LFV bounds see
[Fernández-Martínez, Marcano, Naredo-Tuero](#)

Overview of LFV bounds



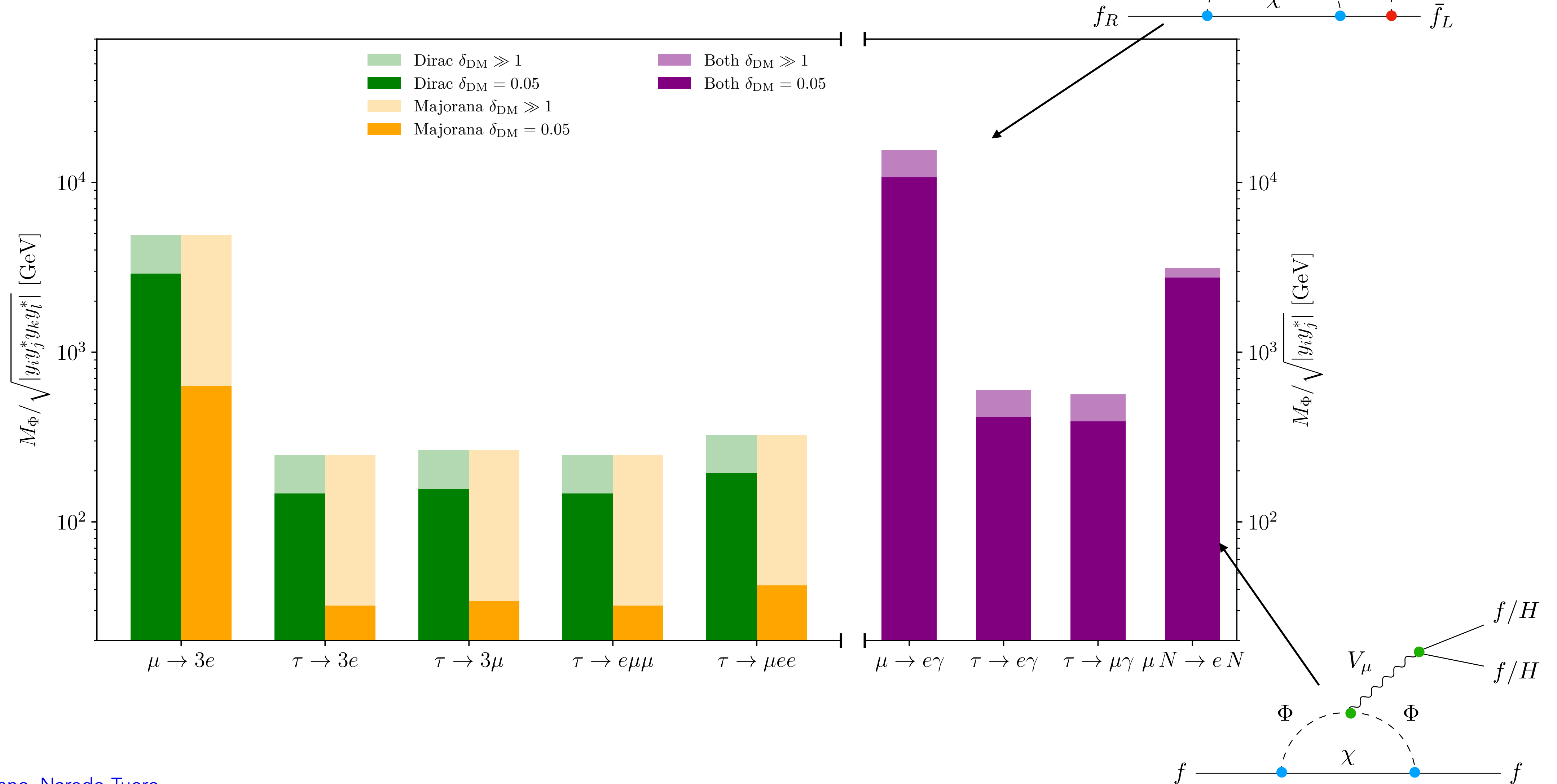
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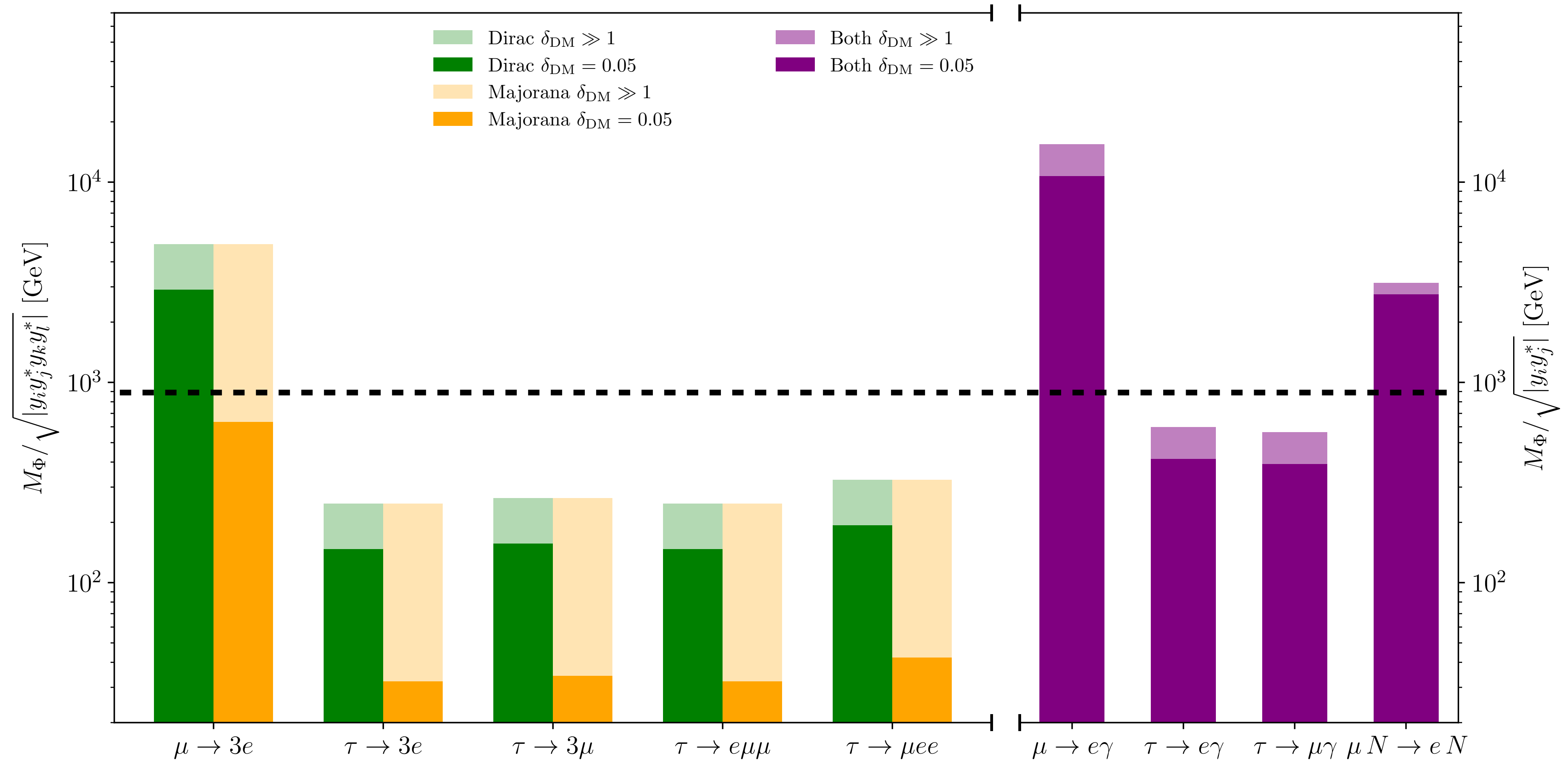
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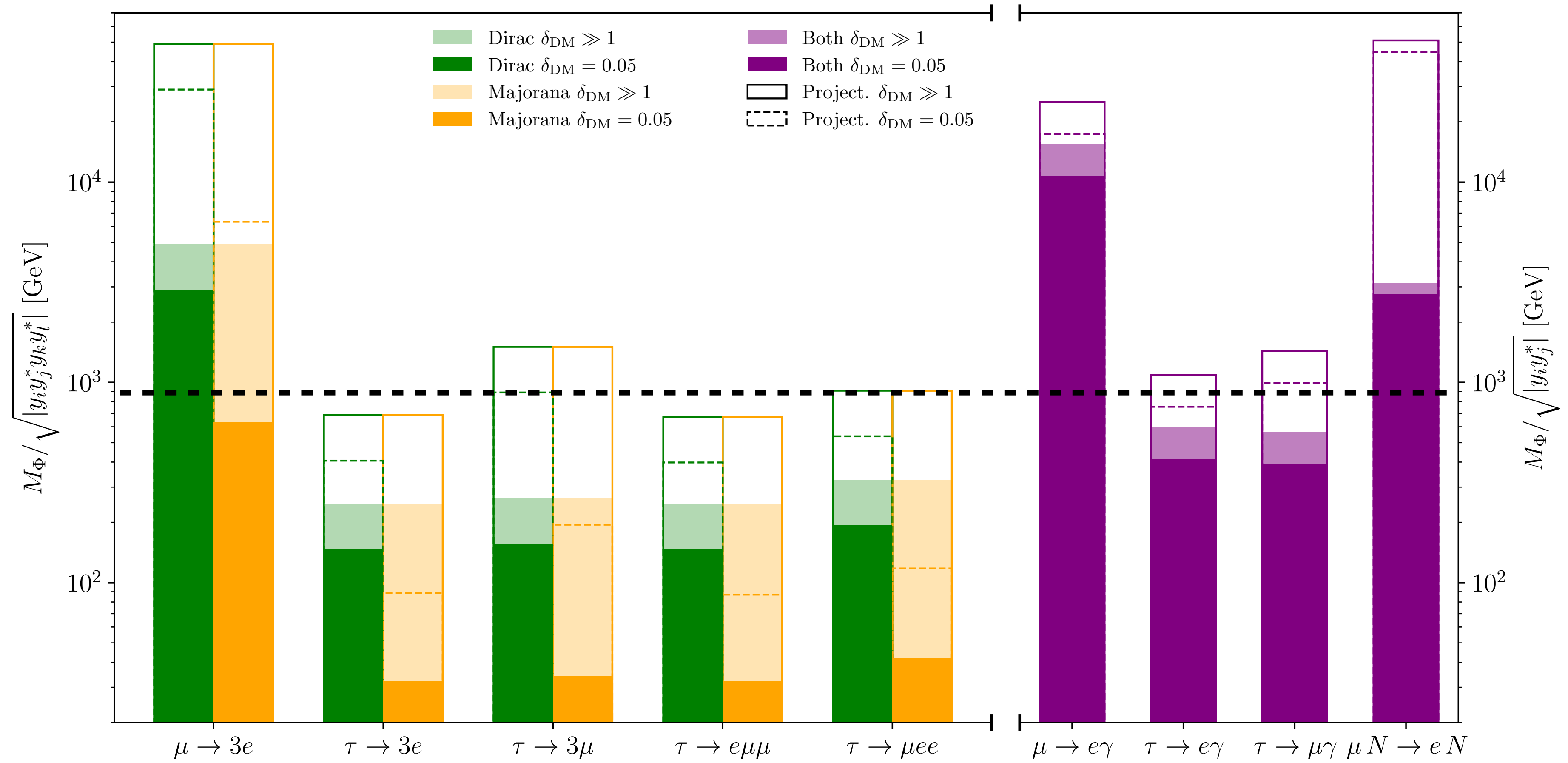
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We must avoid $\mu - e$ direction

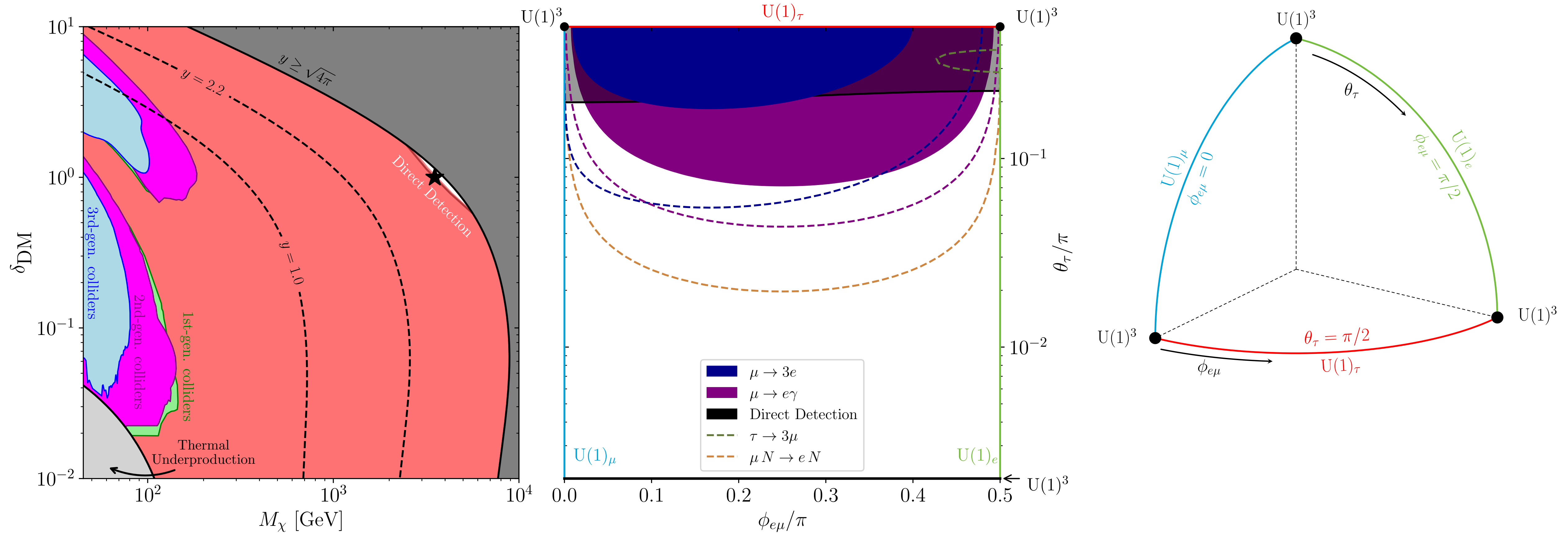
Overview of LFV bounds



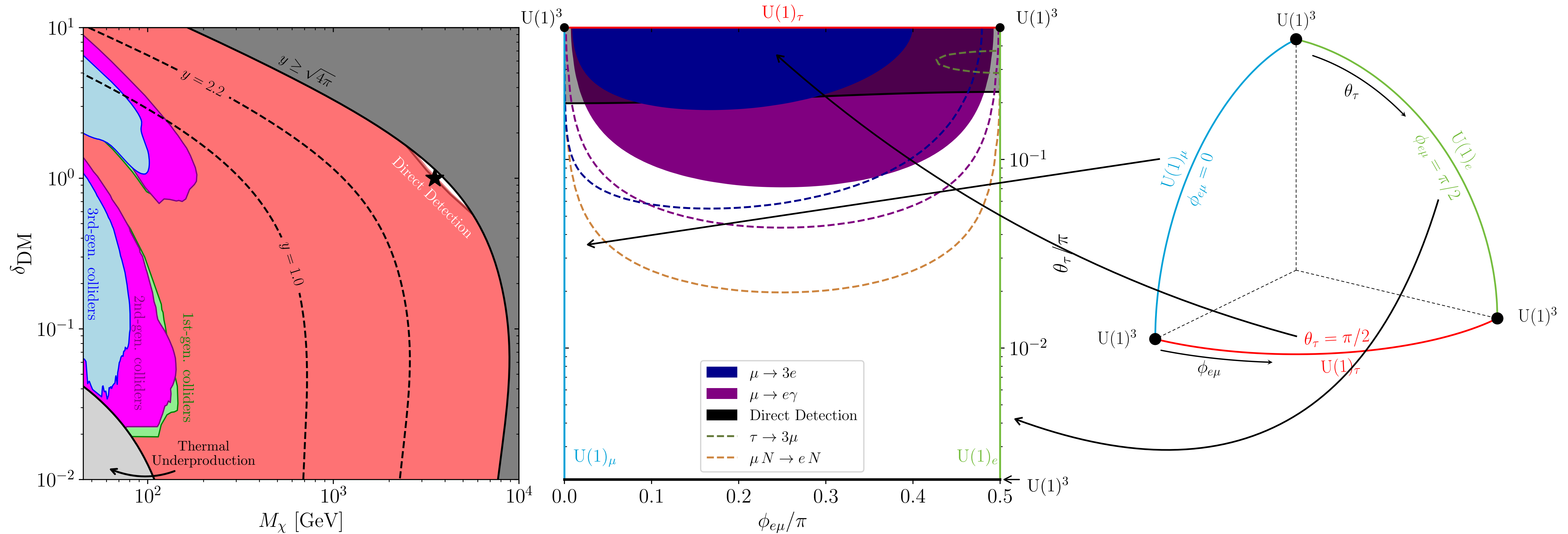
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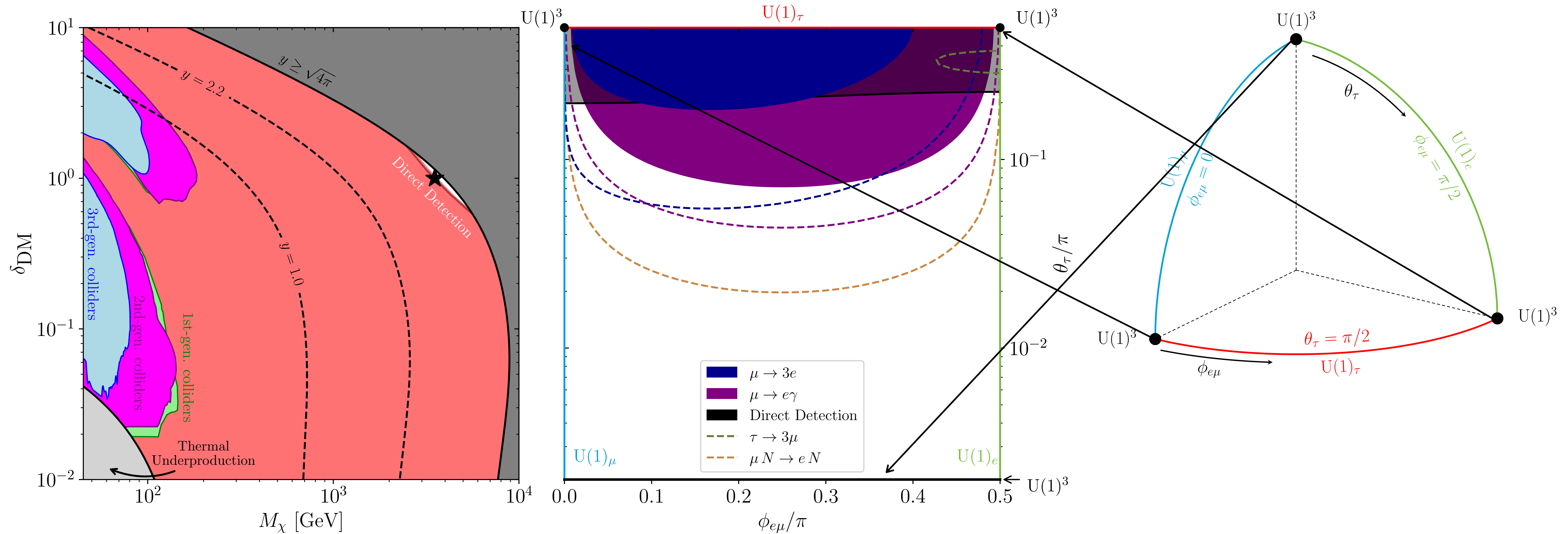
Leptophilic Dark Matter: Dirac



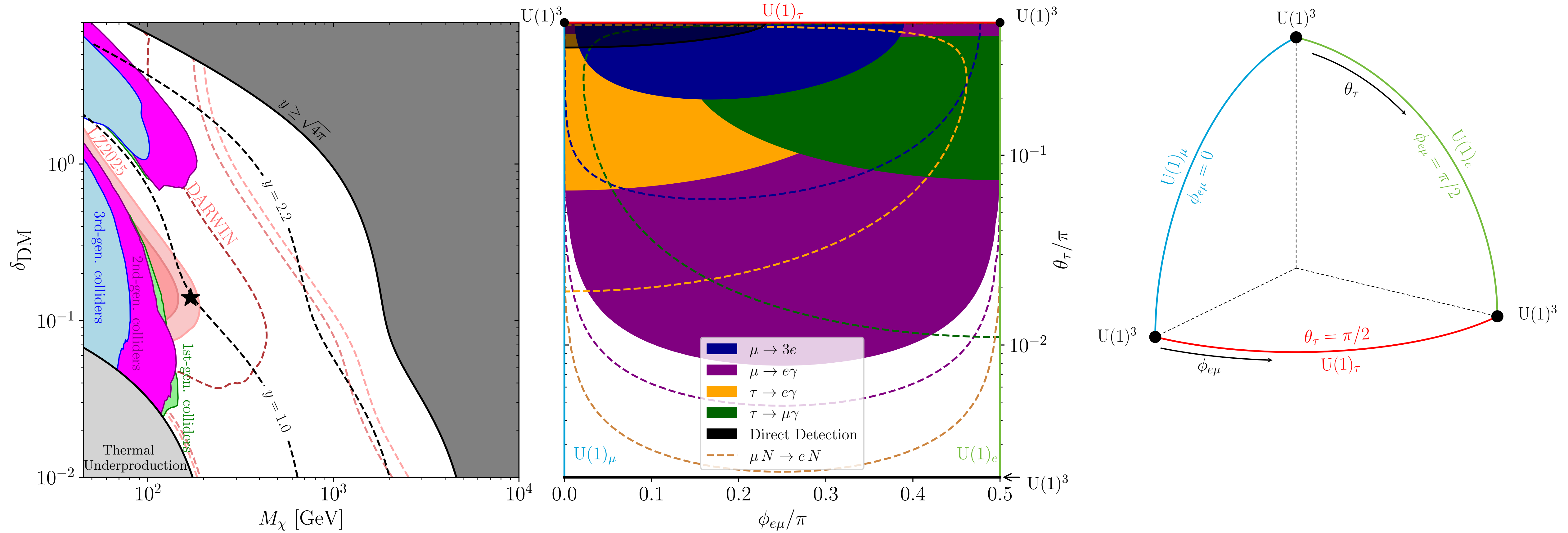
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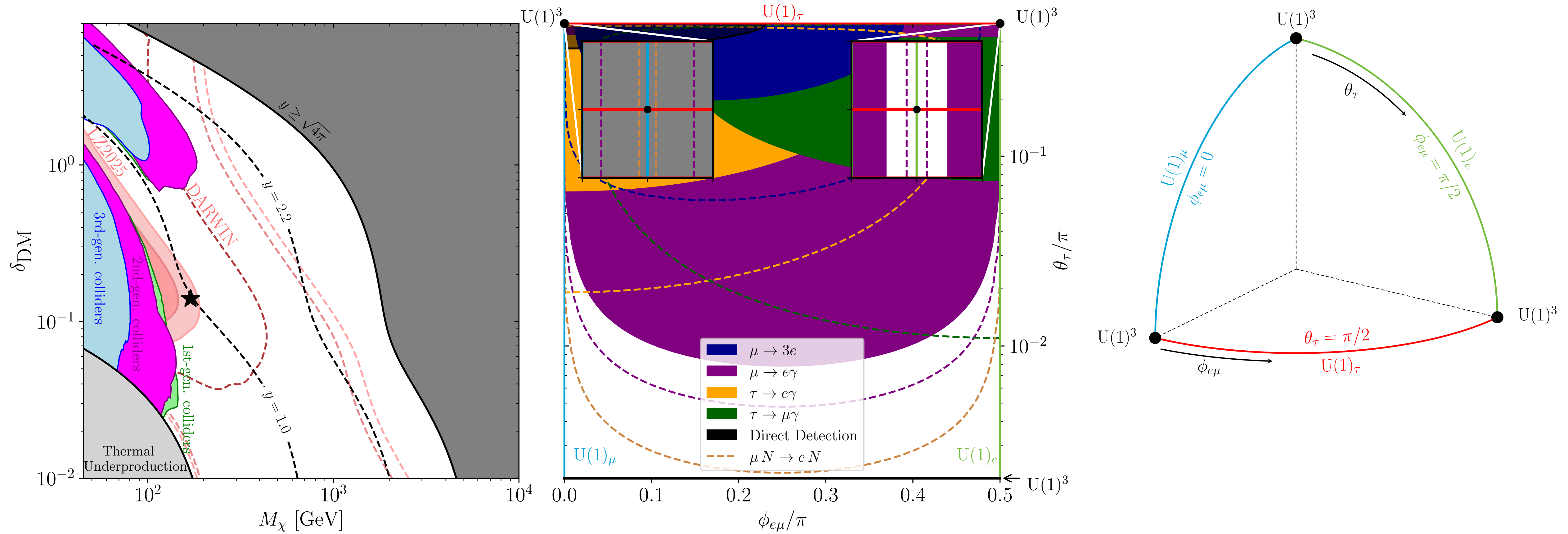
Leptophilic Dark Matter: Dirac



Leptophilic Dark Matter: Majorana



Leptophilic Dark Matter: Majorana



Two benchmarks: rank-1 flavour violation

Leptophilic Dark Matter:

$$\mathcal{L} \supset -y_i \bar{e}_{R,i} \chi \Phi + \text{h.c.}$$

1. Relic Density
2. Collider Searches
3. Direct Detection
4. Flavour bounds

$$U(1)_e \oplus U(1)_\mu \oplus U(1)_\tau$$

Quarkphilic Dark Matter:

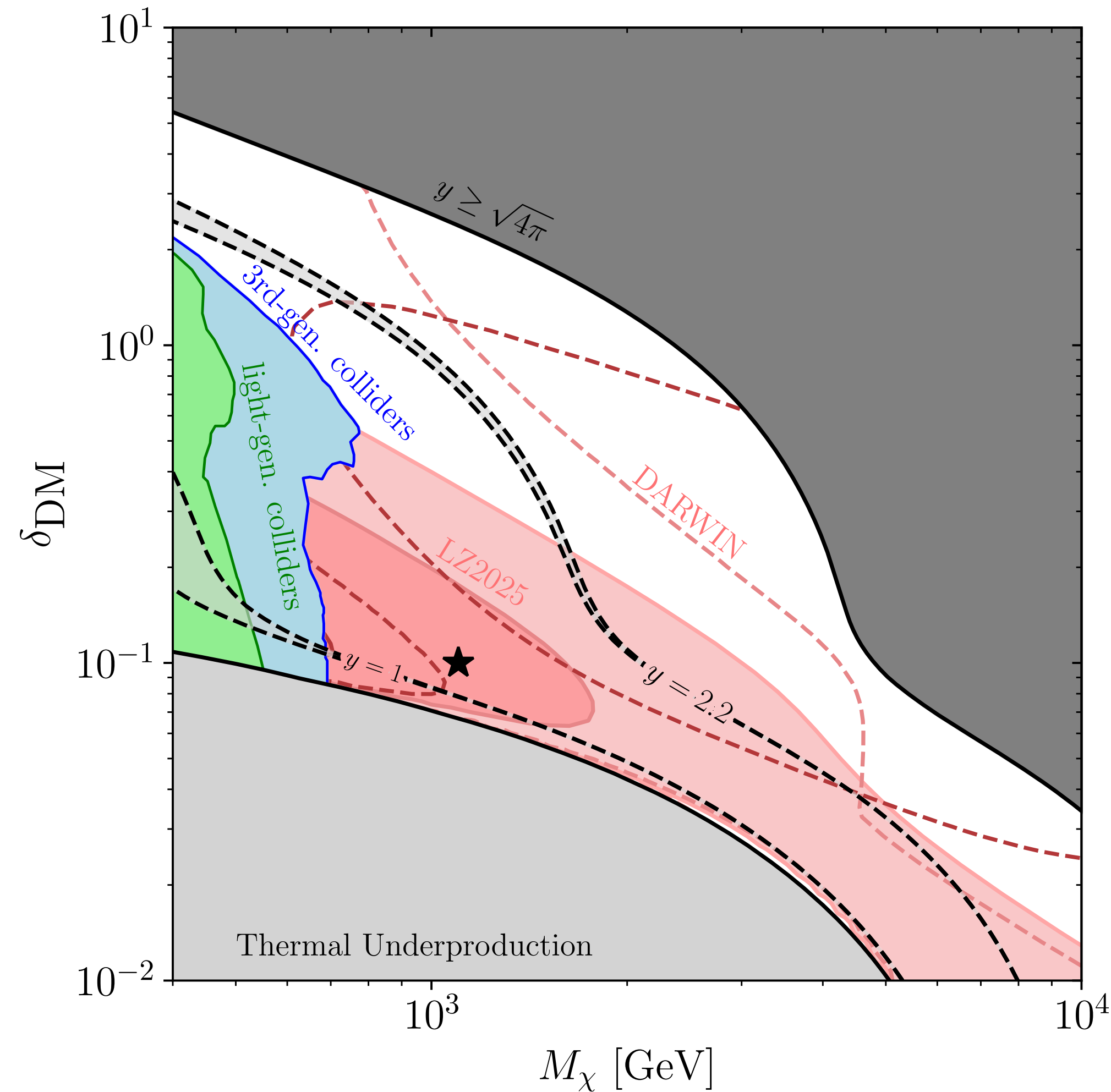
$$\mathcal{L} \supset -y_i \bar{q}_{L,i} \chi \Phi + \text{h.c.}$$

- ~~1. Relic Density~~
- ~~2. Collider Searches~~ Ask me later
- ~~3. Direct Detection~~
4. Flavour bounds

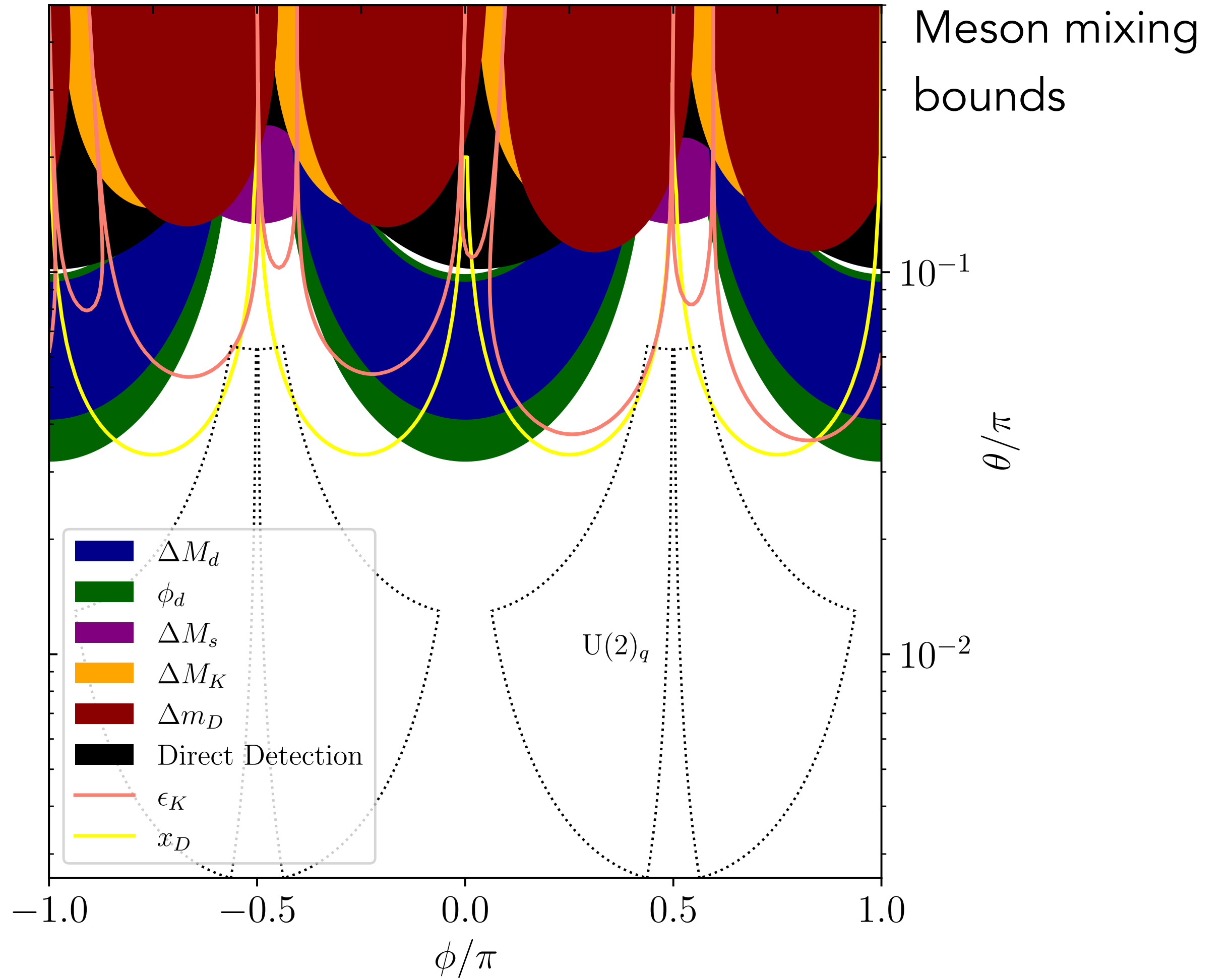
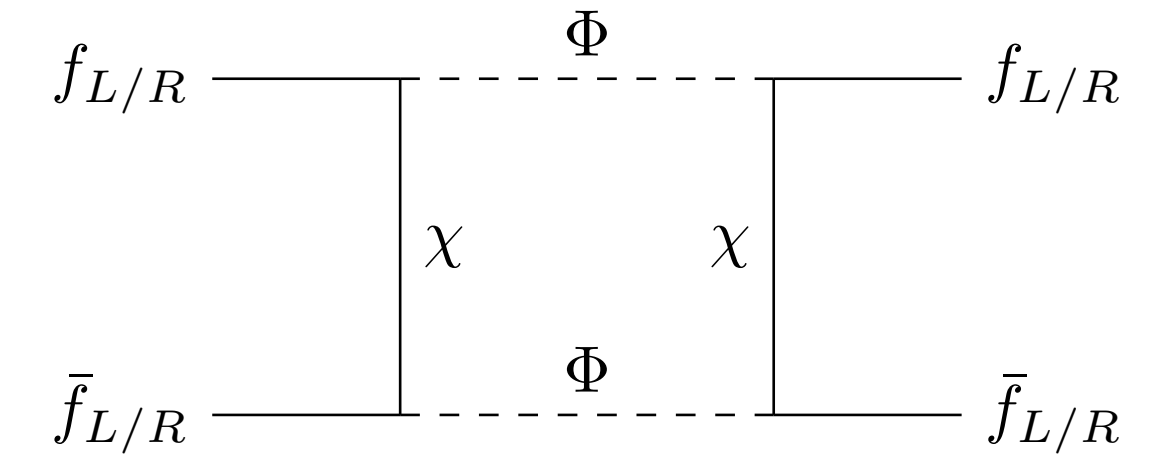
$$U(2)_q$$

Quarkphilic Dark Matter

Majorana:

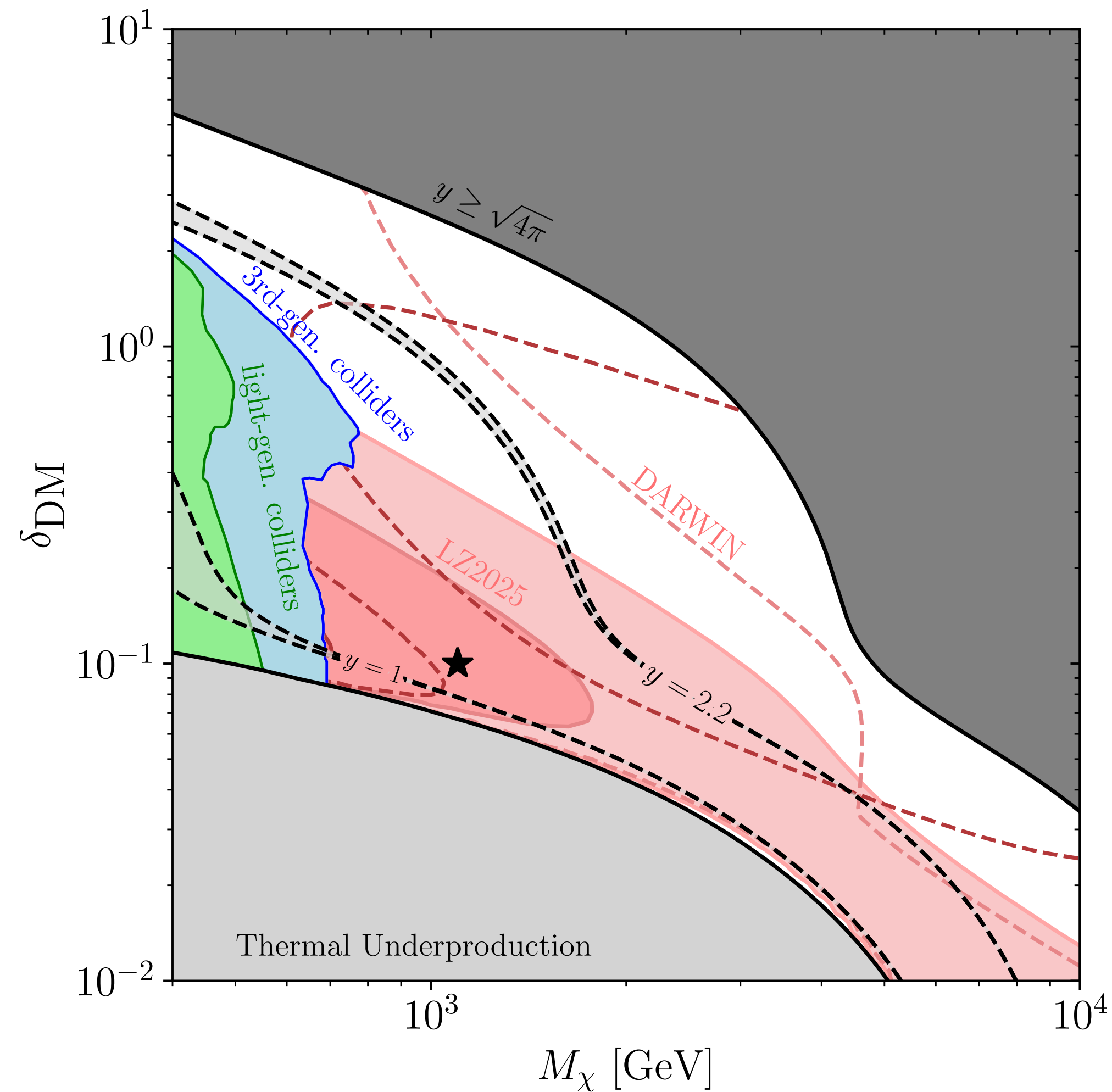


TeV DM still allow in the $U(2)_q$ symmetric limit! (Even with order-one CP!)



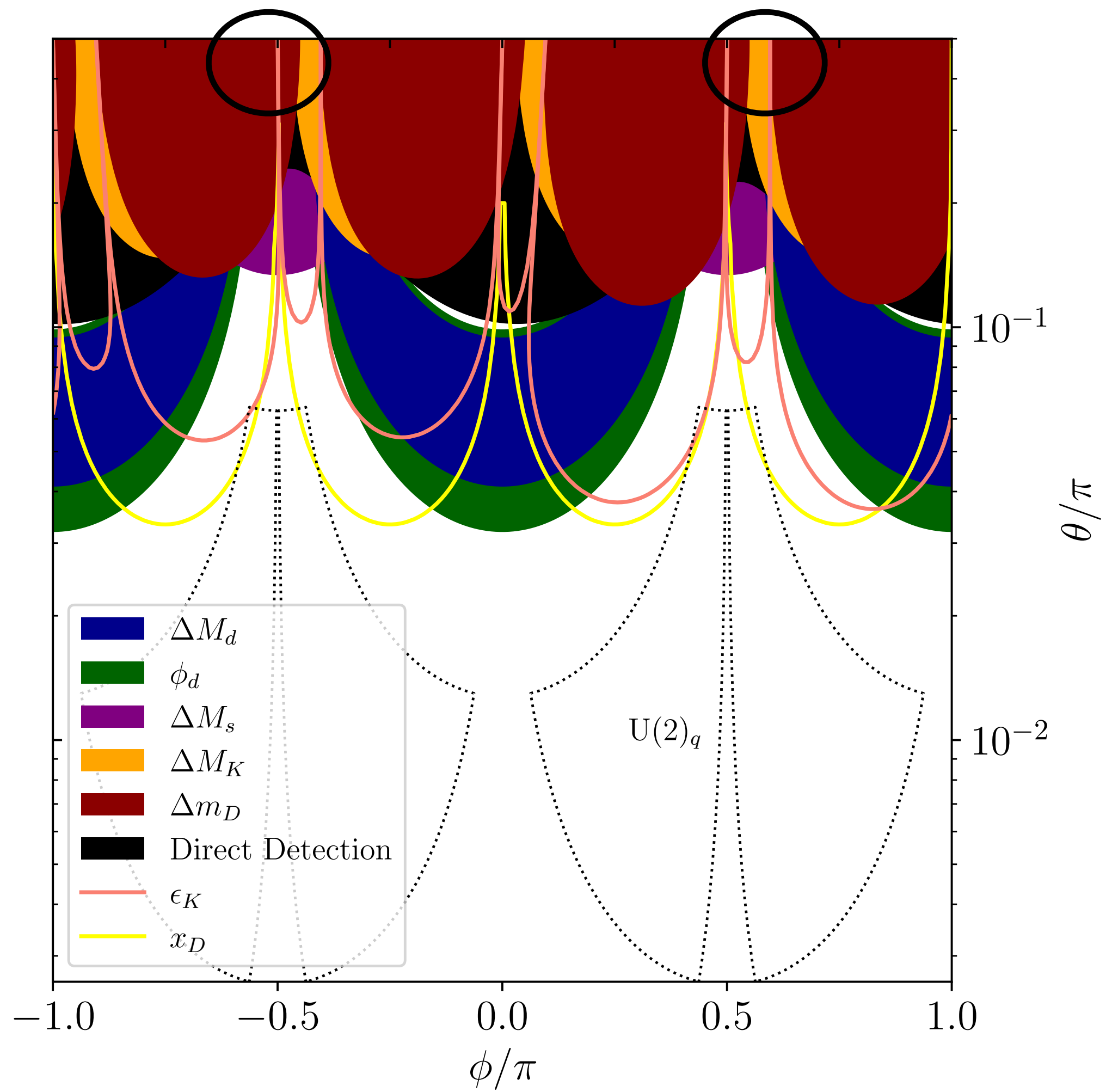
Quarkphilic Dark Matter

Majorana:



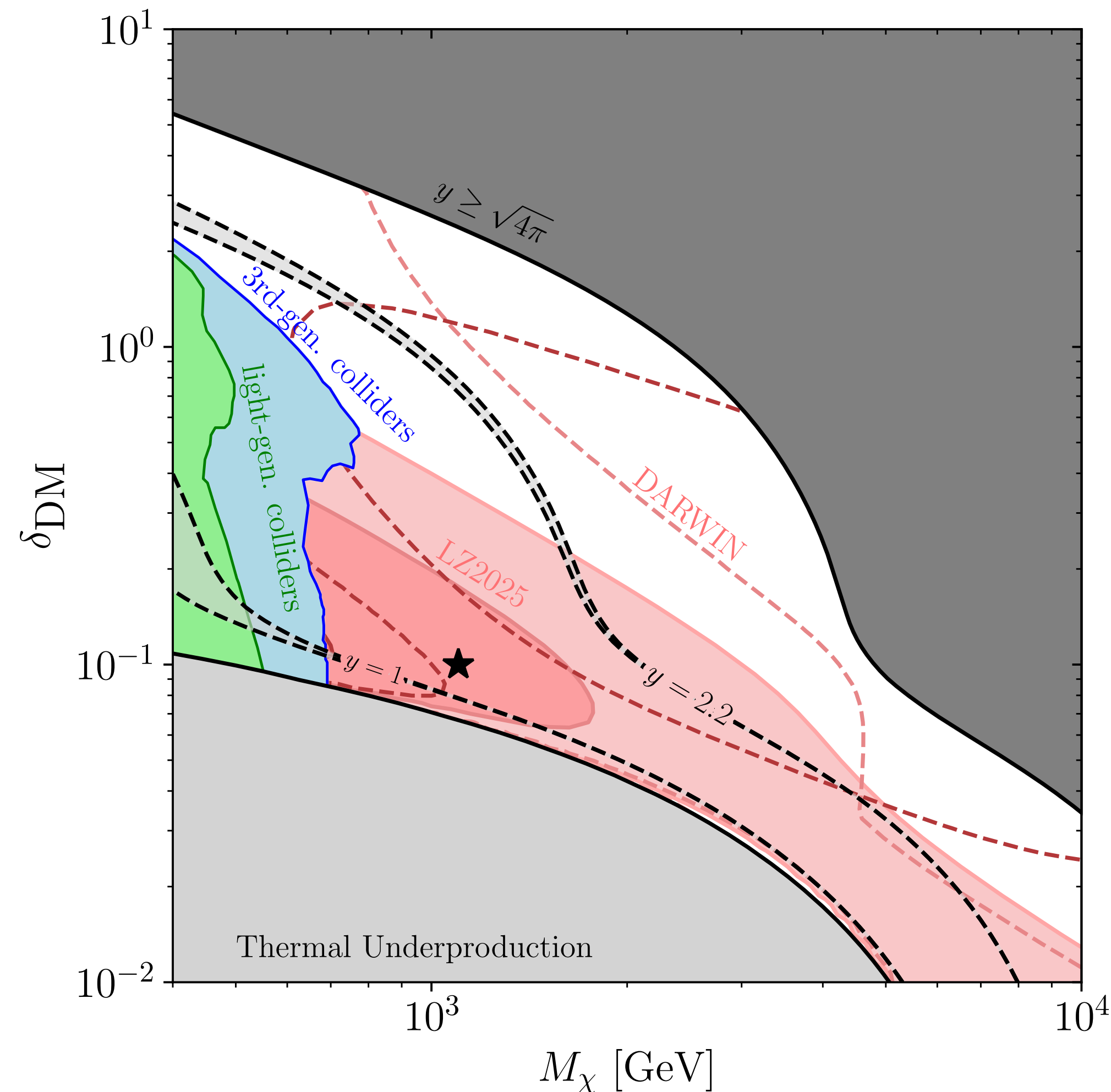
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no longer $U(1)$ symmetric points!



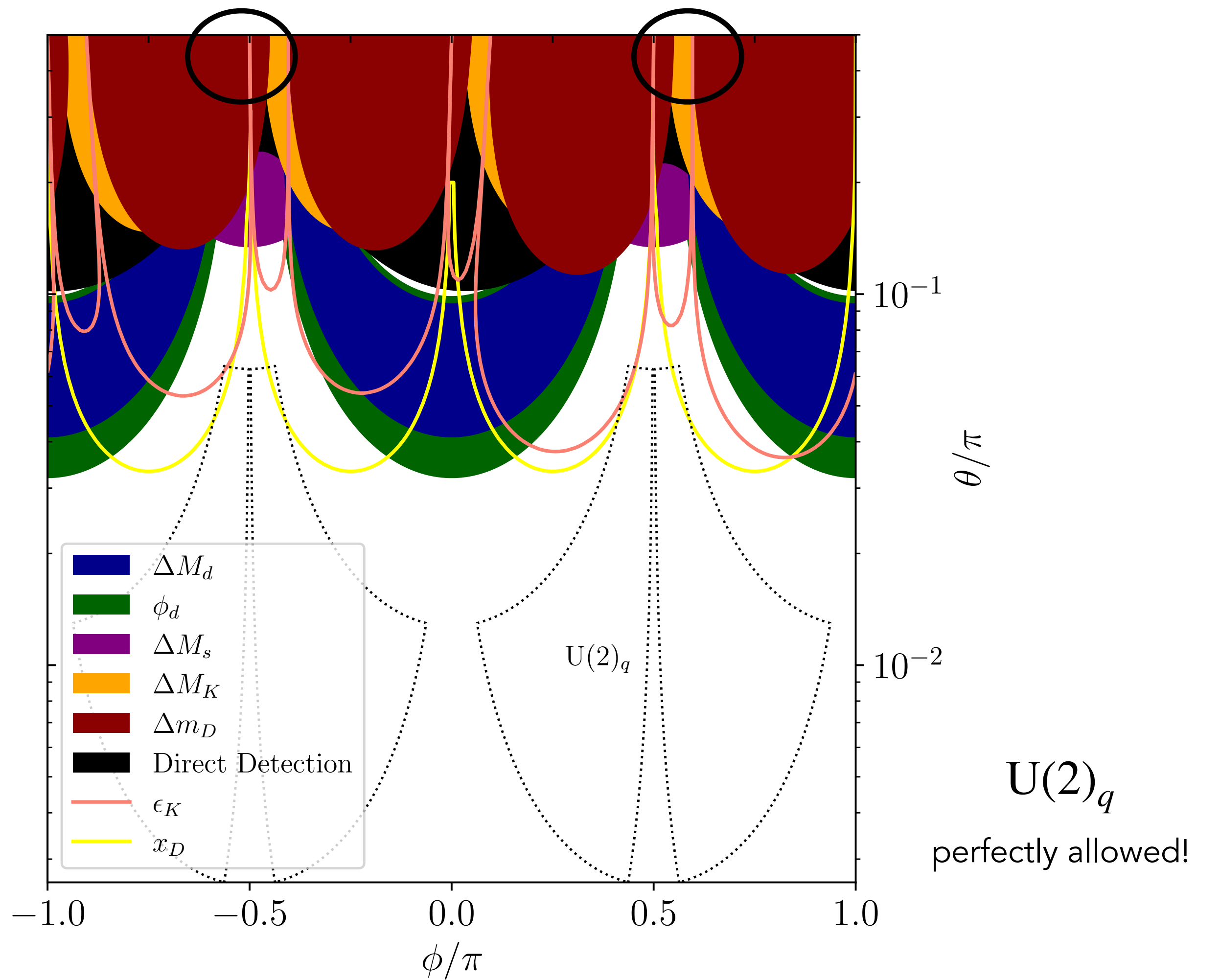
Quarkphilic Dark Matter

Majorana:



TeV DM still allow in the $U(2)_q$ symmetric limit! (Even with order-one CP!)

no longer $U(1)$ symmetric points!



$$\mathbf{y} = y_q \begin{pmatrix} \sin \theta \cos \phi e^{i\alpha_1} & \sin \theta \sin \phi e^{i\alpha_2} & \cos \theta \end{pmatrix} \sim \begin{pmatrix} aV_q & b \end{pmatrix}$$

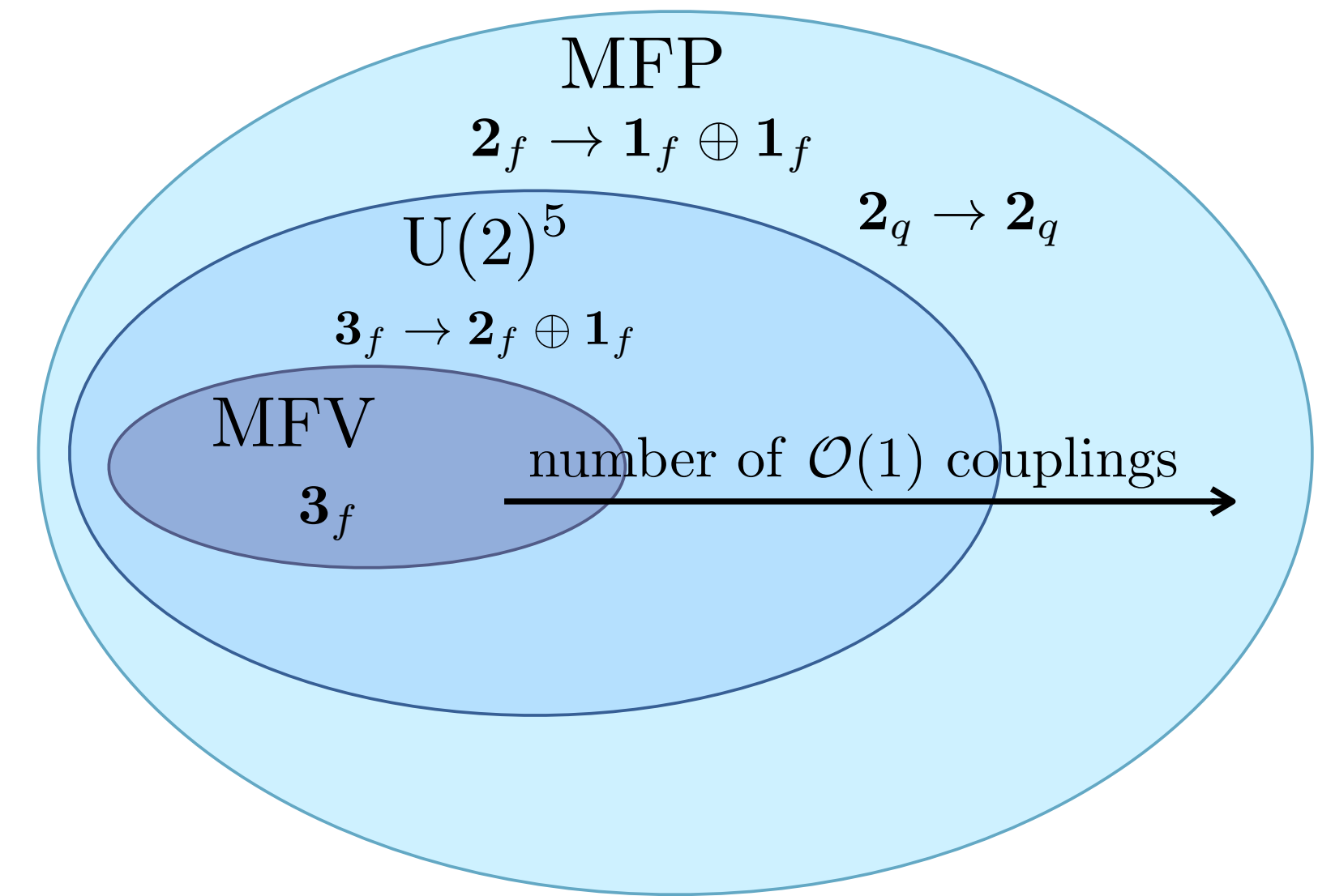
Conclusions

1. Generalise previous analysis to smaller groups:

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Proving that there is a **large landscape of symmetries** that could be used to protect DM fermion structure



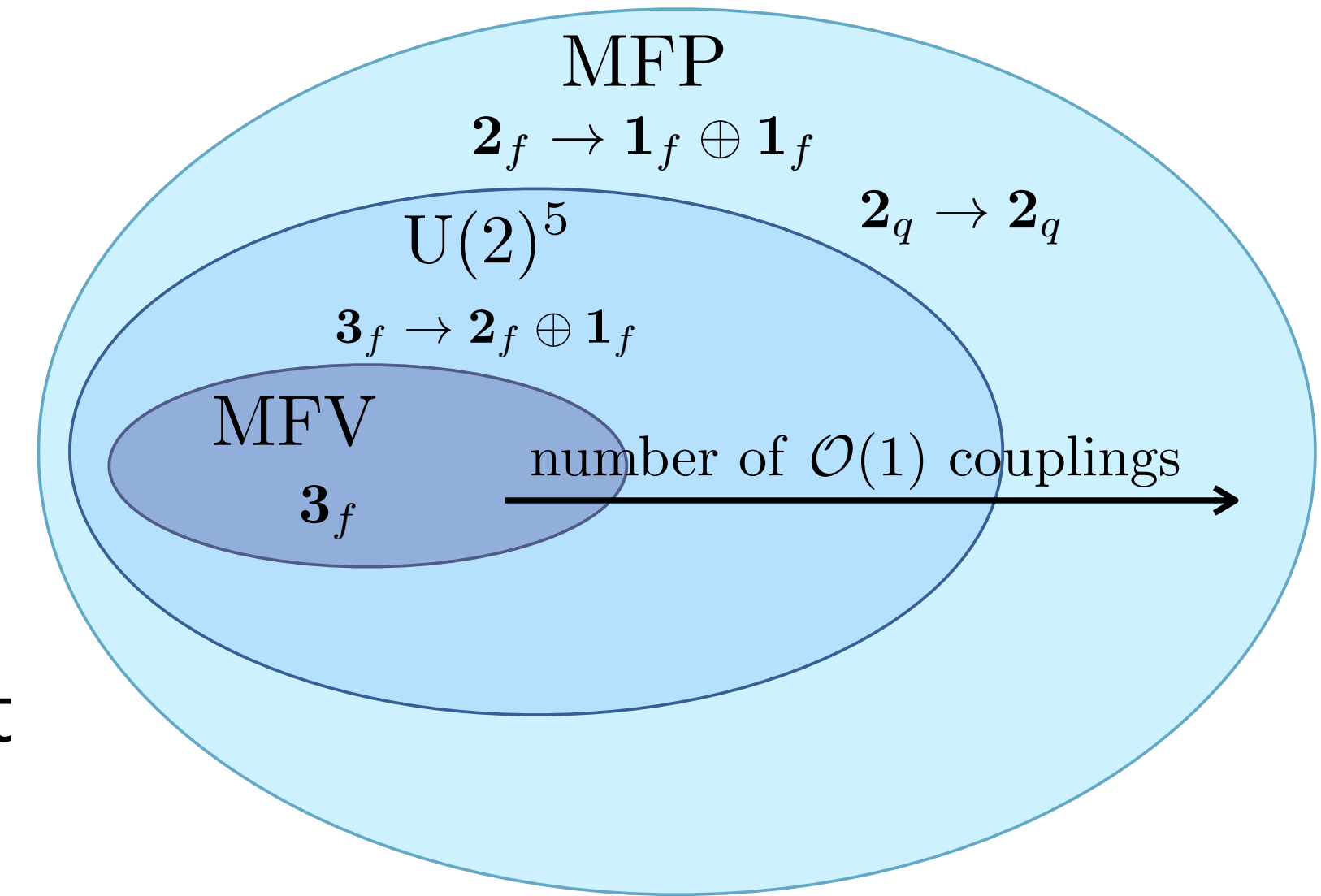
Conclusions

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2. We have explored qualitatively/quantitatively different **flavour limits** for two particular minimal benchmarks

$$U(2)_q \oplus U(1)_e \oplus U(1)_\mu \oplus U(1)_\tau$$



Conclusions

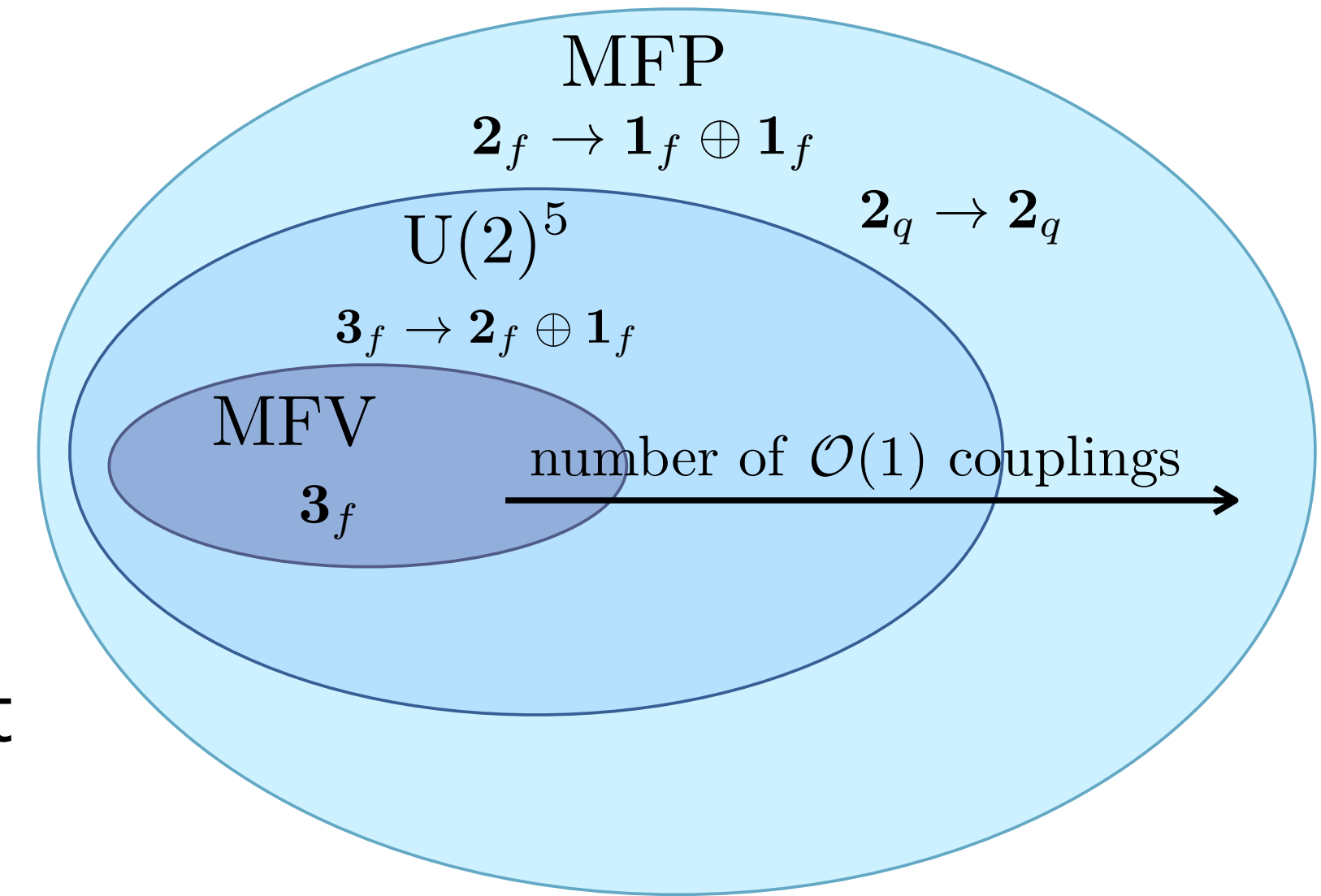
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$$U(2)_q \oplus U(1)_e \oplus U(1)_\mu \oplus U(1)_\tau$$

3. **Interplay**: Different flavour-symmetric limits can be tested with Direct Detection → testing non-universality.



$$C_{ij} \sim \begin{pmatrix} \text{red} & \text{blue} & \text{light blue} \\ \text{blue} & \text{red} & \text{light blue} \\ \text{light blue} & \text{light blue} & \text{red} \end{pmatrix}$$

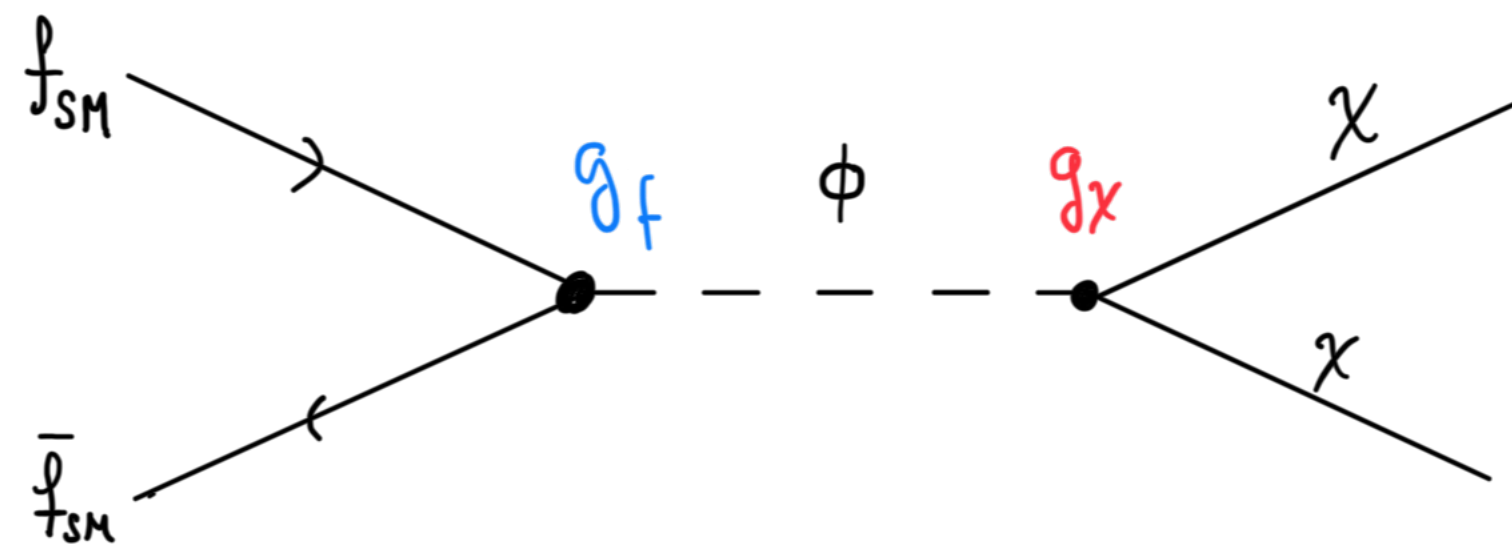
■ tested in flavour ■ tested in direct detection

Thanks for your attention!

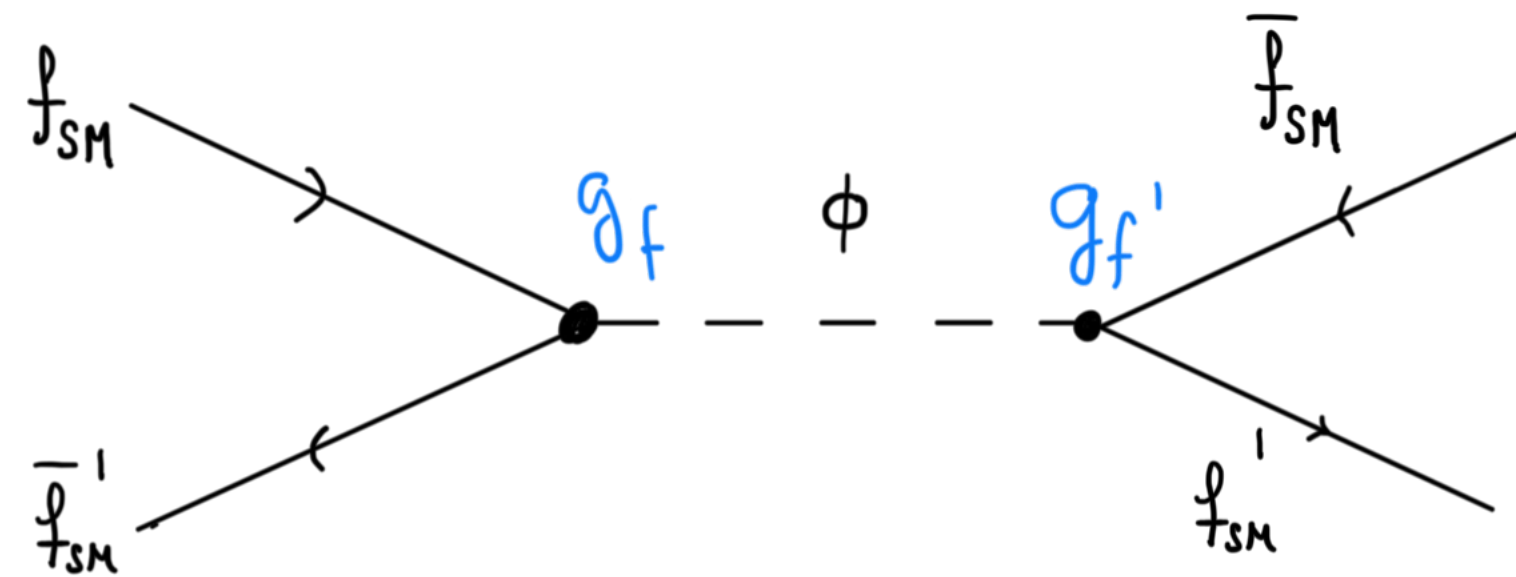
Back Up

s-channel vs t-channel

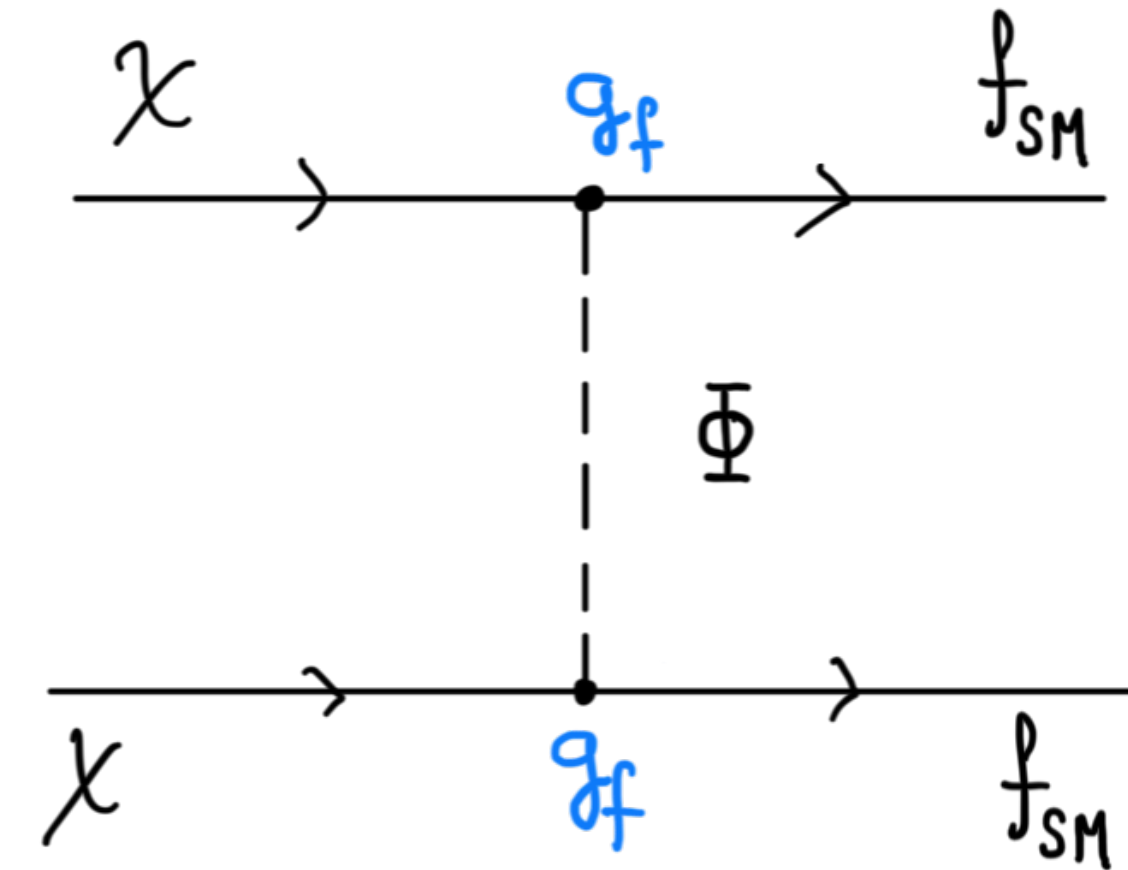
S-channel $\longrightarrow$ linear extensions of the SM [de Blas et al. '17](#)



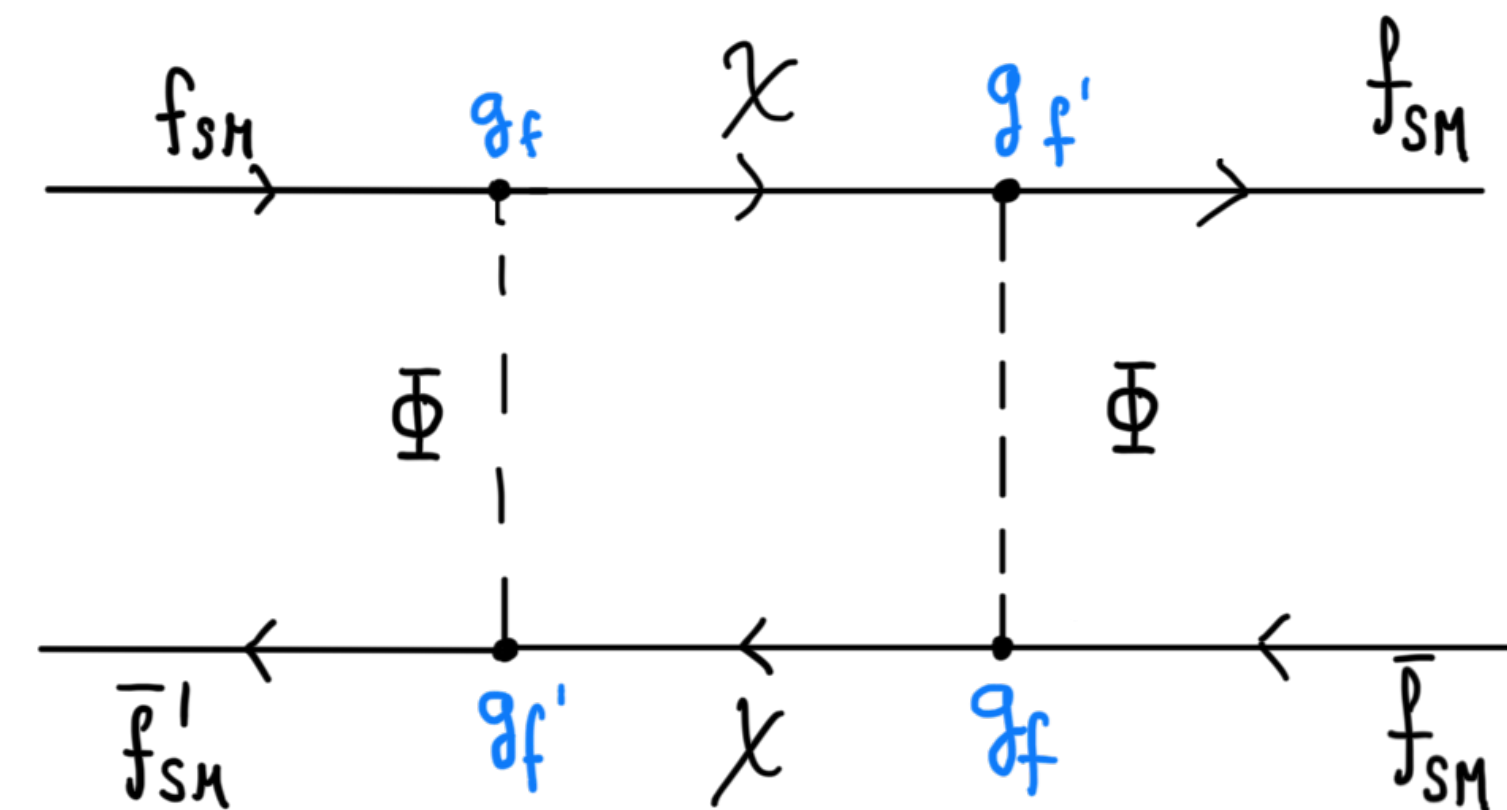
The flavour structure is in the mediator, the Dark Matter field knows nothing about it.



Flavour structure of linear extensions of the SM: e.g. [Greljo, Palavrić '23](#)



In t-channel DM the flavour structure is directly related to the DM production



t-channel Dark Matter models and flavour violation

from [Olgoso, Paradisi, Selimović](#)

Mediator	DM spin $\frac{1}{2}$: χ	DM spin 0: ϕ
spin $\frac{1}{2}$: Ψ	$\chi \Psi H$	$f_{\text{SM}} \phi \Psi$
spin 0: Φ	$f_{\text{SM}} \chi \Phi$	$\phi \Phi H$

Non-trivial flavour structure!

Use spurions for classification:

$$\mathcal{L} \supset \bar{f}_{\text{SM}} y X + \text{h.c.} \quad X \equiv (\chi \Phi) \quad \text{or} \quad X \equiv (\Psi \phi)$$

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Non-trivial flavour structure!

$$f_{\text{SM}} \rightarrow U_f f_{\text{SM}}$$

Use spurions for classification:

$$\mathcal{L} \supset \bar{f}_{\text{SM}} y X + \text{h.c.} \quad X \equiv (\chi \Phi) \quad \text{or} \quad X \equiv (\Psi \phi)$$

$$G_{\text{flavour}} = \text{MFV}$$

The Yukawas are the MFV spurions in the Standard Model

$$Y_u \sim (\mathbf{3}_q, \bar{\mathbf{3}}_u), \quad Y_d \sim (\mathbf{3}_q, \bar{\mathbf{3}}_d), \quad Y_e \sim (\mathbf{3}_\ell, \bar{\mathbf{3}}_e),$$

Green entries: $y_t \sim 1$ yellow entries: $y_{b,\tau} \sim 10^{-2}$

$$X \rightarrow U_X X$$

$X \setminus \bar{f}_{\text{SM}}$	$\bar{\mathbf{3}}_q$	$\bar{\mathbf{3}}_u$	$\bar{\mathbf{3}}_d$	$\bar{\mathbf{3}}_\ell$	$\bar{\mathbf{3}}_e$
1	$\mathbf{3}_q$	$\mathbf{3}_u$	$\mathbf{3}_d$	$\mathbf{3}_\ell$	$\mathbf{3}_e$
$\mathbf{3}_q$	$\mathbf{1} \oplus \mathbf{8}_q$	$(\mathbf{3}_u, \bar{\mathbf{3}}_q)$	$(\mathbf{3}_d, \bar{\mathbf{3}}_q)$	$(\mathbf{3}_\ell, \bar{\mathbf{3}}_q)$	$(\mathbf{3}_e, \bar{\mathbf{3}}_q)$
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$\mathbf{3}_u$	$(\mathbf{3}_q, \bar{\mathbf{3}}_u)$	$\mathbf{1} \oplus \mathbf{8}_u$	$(\mathbf{3}_d, \bar{\mathbf{3}}_u)$	$(\mathbf{3}_\ell, \bar{\mathbf{3}}_u)$	$(\mathbf{3}_e, \bar{\mathbf{3}}_u)$
$\bar{\mathbf{3}}_u$	$(\mathbf{3}_q, \mathbf{3}_u)$	$\bar{\mathbf{3}}_u \oplus \mathbf{6}_u$	$(\mathbf{3}_d, \mathbf{3}_u)$	$(\mathbf{3}_\ell, \mathbf{3}_u)$	$(\mathbf{3}_e, \mathbf{3}_u)$
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$\mathbf{3}_\ell$	$(\mathbf{3}_q, \bar{\mathbf{3}}_\ell)$	$(\mathbf{3}_u, \bar{\mathbf{3}}_\ell)$	$(\mathbf{3}_d, \bar{\mathbf{3}}_\ell)$	$\mathbf{1} \oplus \mathbf{8}_\ell$	$(\mathbf{3}_e, \bar{\mathbf{3}}_\ell)$
$\bar{\mathbf{3}}_\ell$	$(\mathbf{3}_q, \mathbf{3}_\ell)$	$(\mathbf{3}_u, \mathbf{3}_\ell)$	$(\mathbf{3}_d, \mathbf{3}_\ell)$	$\bar{\mathbf{3}}_\ell \oplus \mathbf{6}_\ell$	$(\mathbf{3}_e, \mathbf{3}_\ell)$
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$\bar{\mathbf{3}}_e$	$(\mathbf{3}_q, \mathbf{3}_e)$	$(\mathbf{3}_u, \mathbf{3}_e)$	$(\mathbf{3}_d, \mathbf{3}_e)$	$(\mathbf{3}_\ell, \mathbf{3}_e)$	$\bar{\mathbf{3}}_e \oplus \mathbf{6}_e$
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$

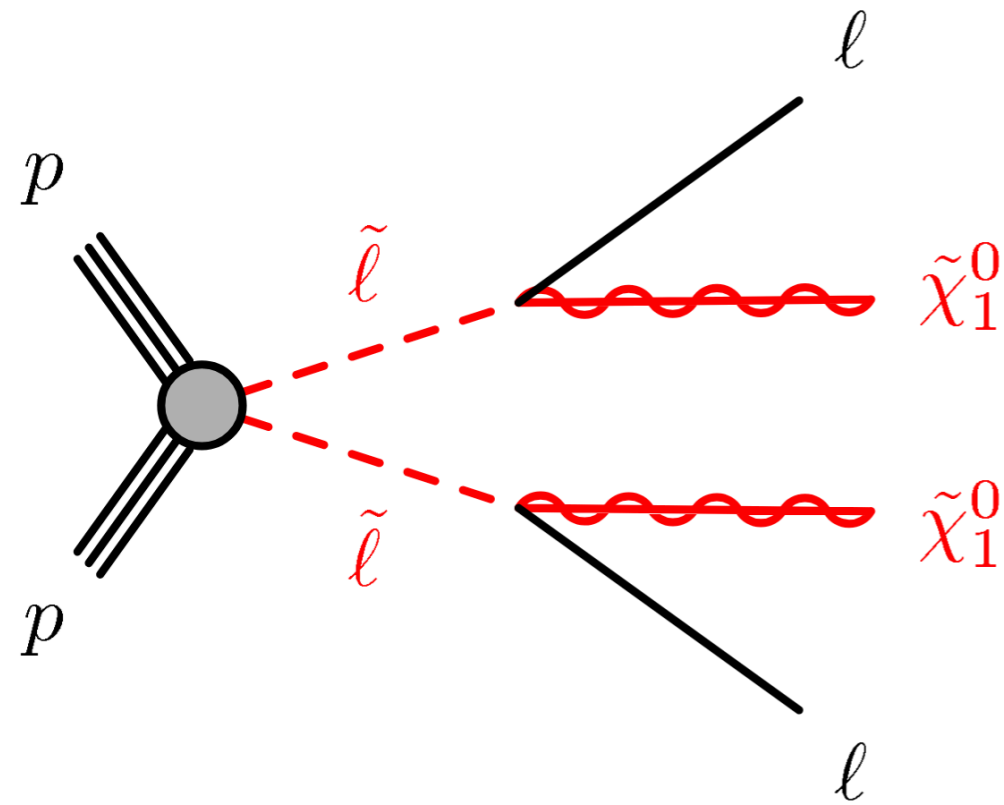
Leptophilic Dark Matter: collider searches

Collider searches for SUSY sleptons can be used:

- Main production channel of the “slepton” in LEP and LHC is EW Drell-Yann

LHC

in our notation $\tilde{\ell} = \Phi$, $\chi = \tilde{\chi}_1^0$



When the splitting between Φ and χ is large the decay is prompt $\rightarrow$ mild Yukawa dependence.

$$pp \rightarrow \ell^+ \ell^- + \cancel{E}$$

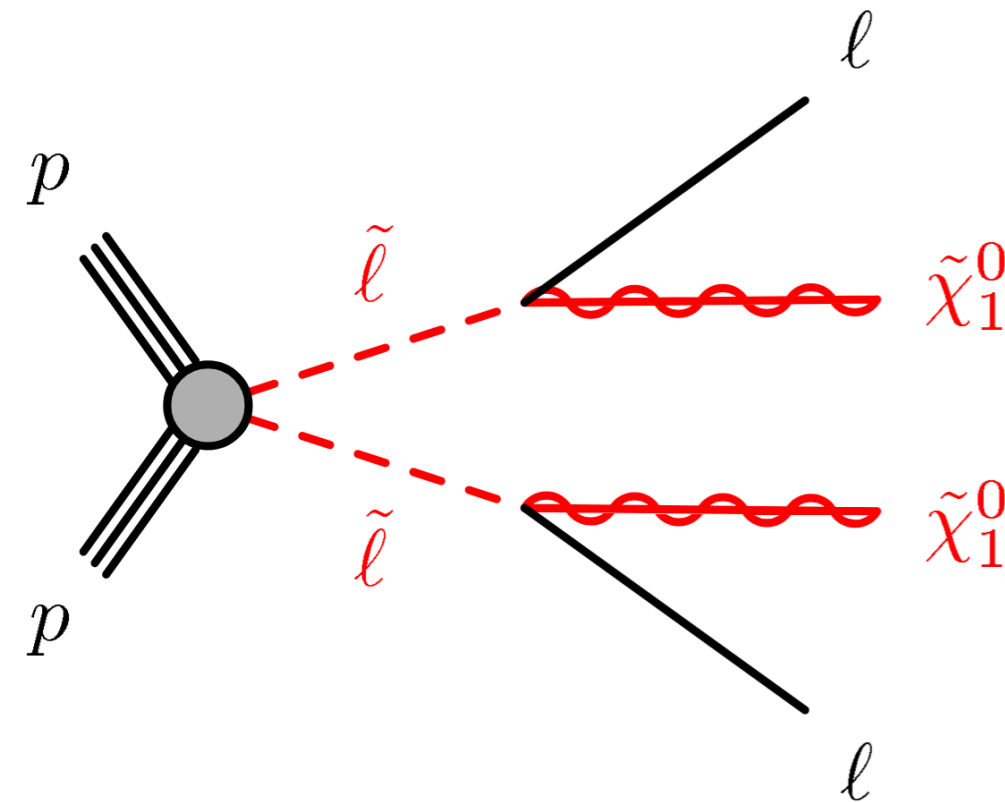
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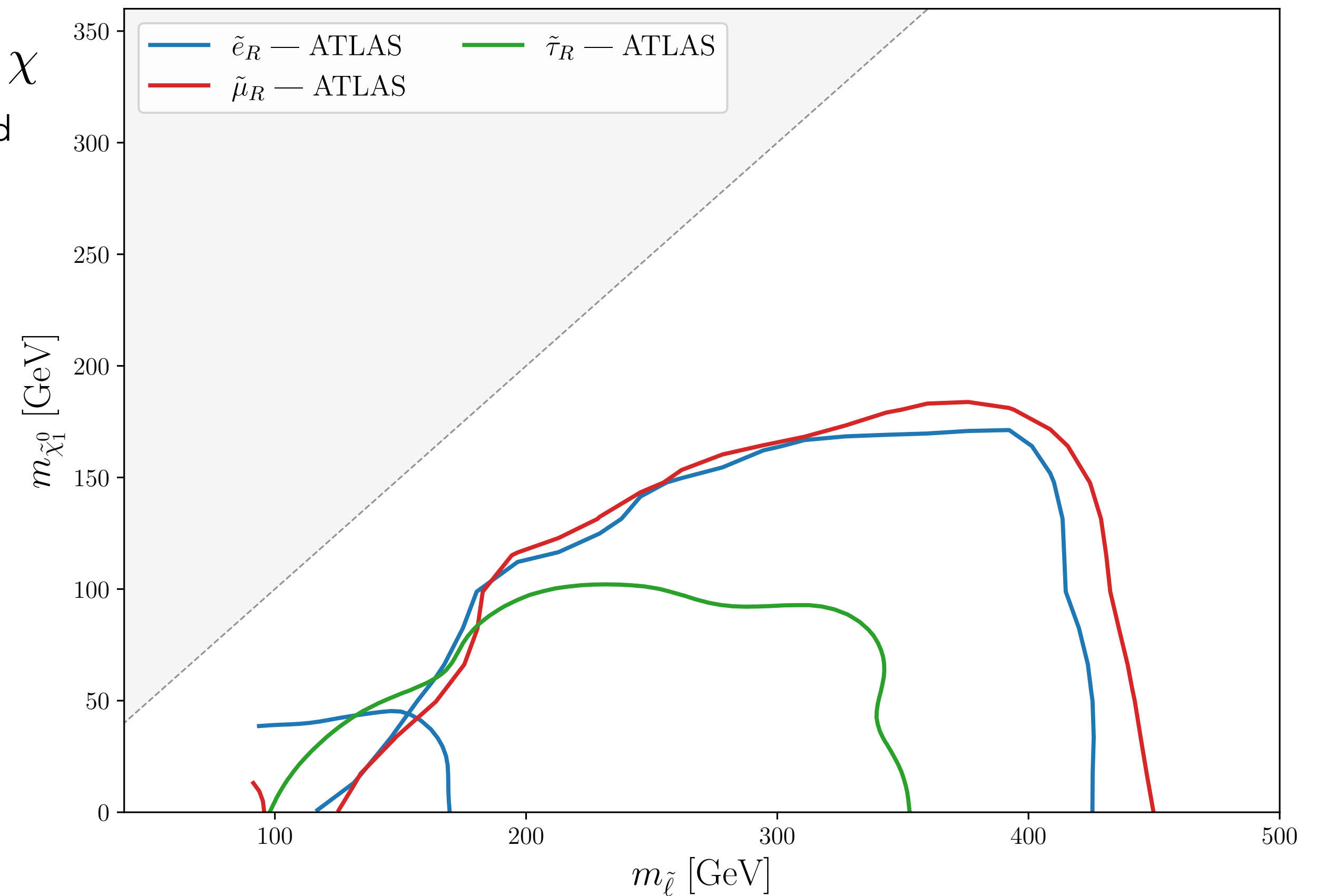
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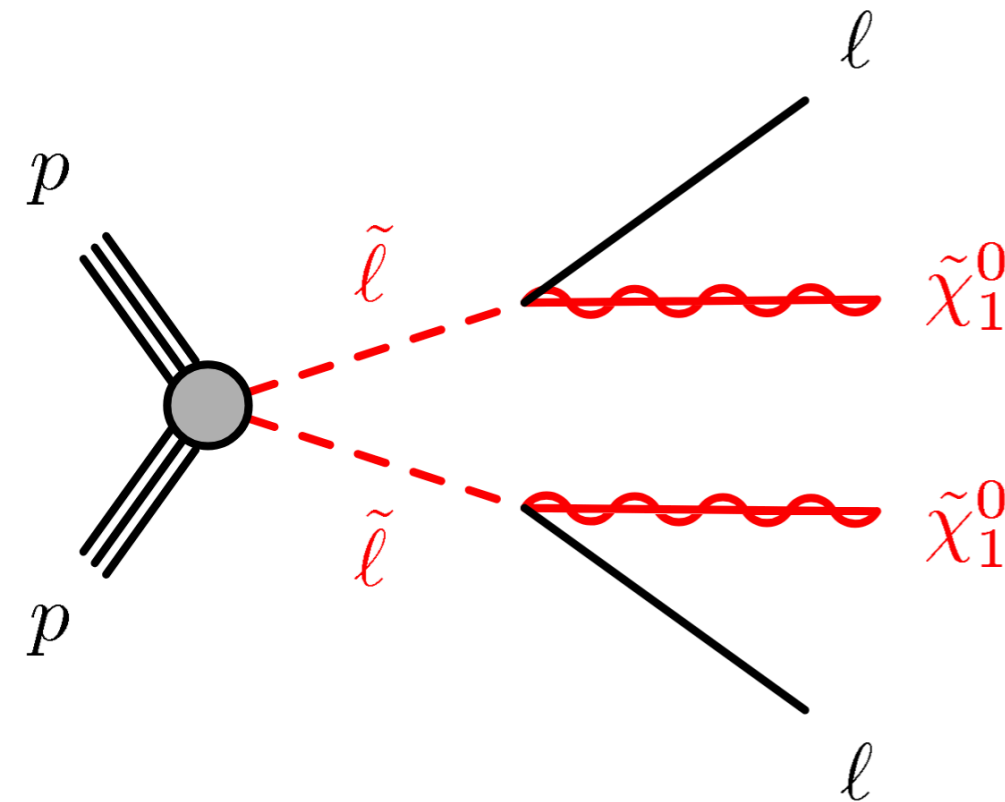
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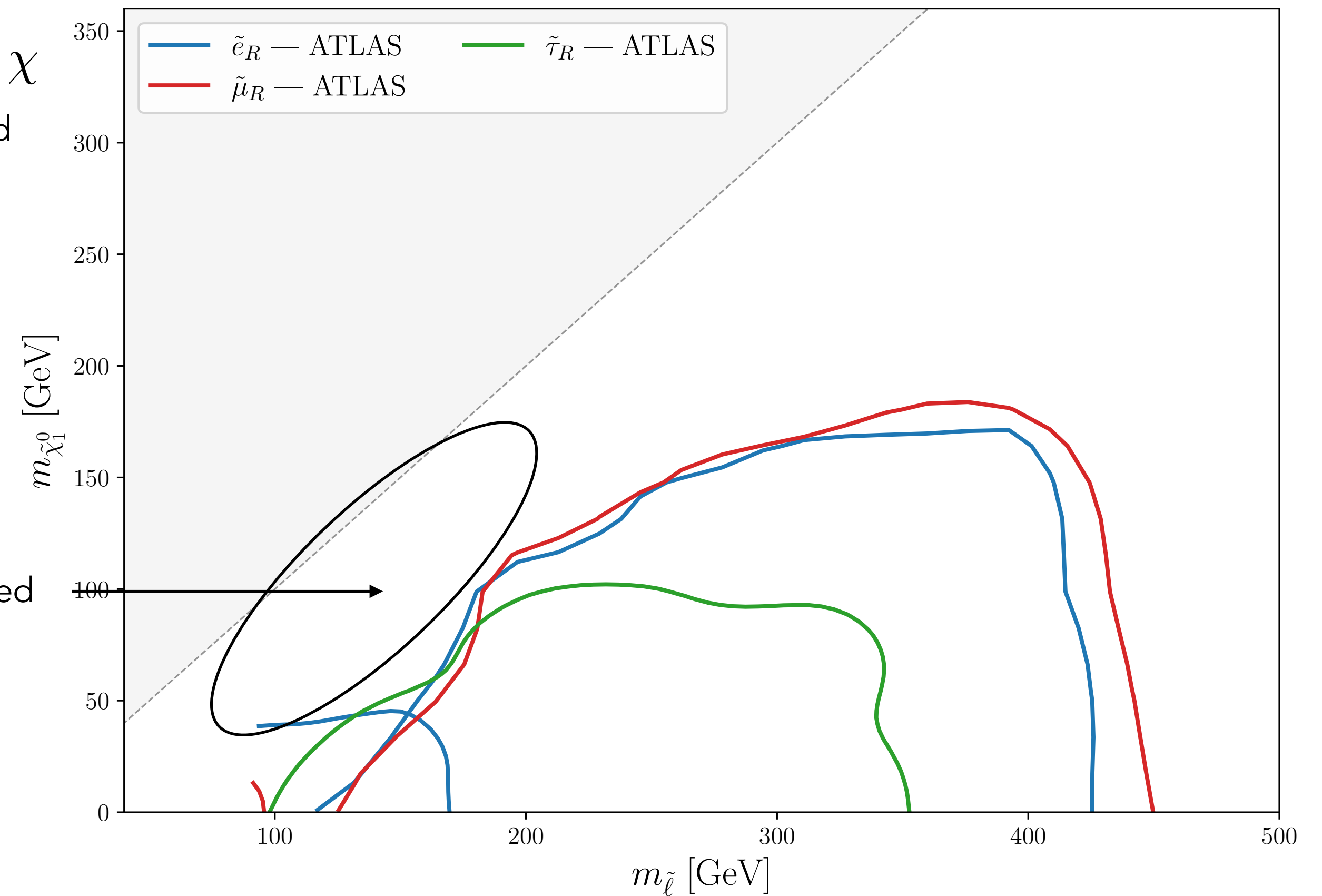
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When the splitting between Φ and χ is large the decay is prompt $\rightarrow$ mild Yukawa dependence.

Loses sensitivity in the “compressed SUSY” spectrum: **soft leptons**



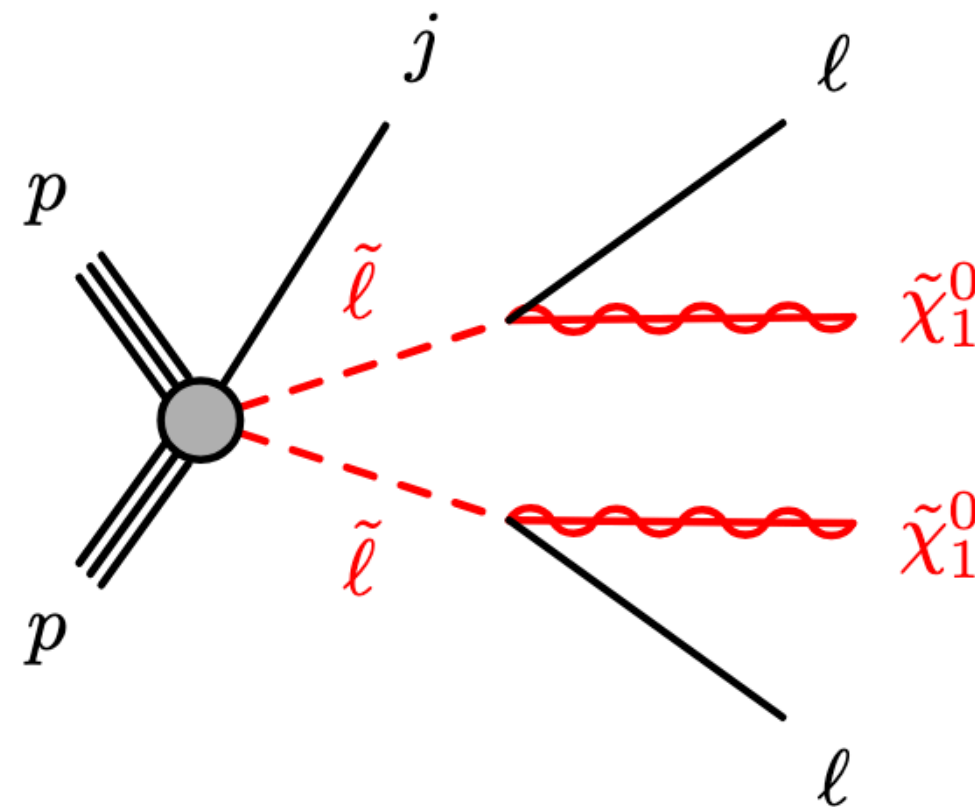
Leptophilic Dark Matter: collider searches

Collider searches for SUSY sleptons can be used:

- Main production channel of the “slepton” in LEP and LHC is EW Drell-Yann

LHC

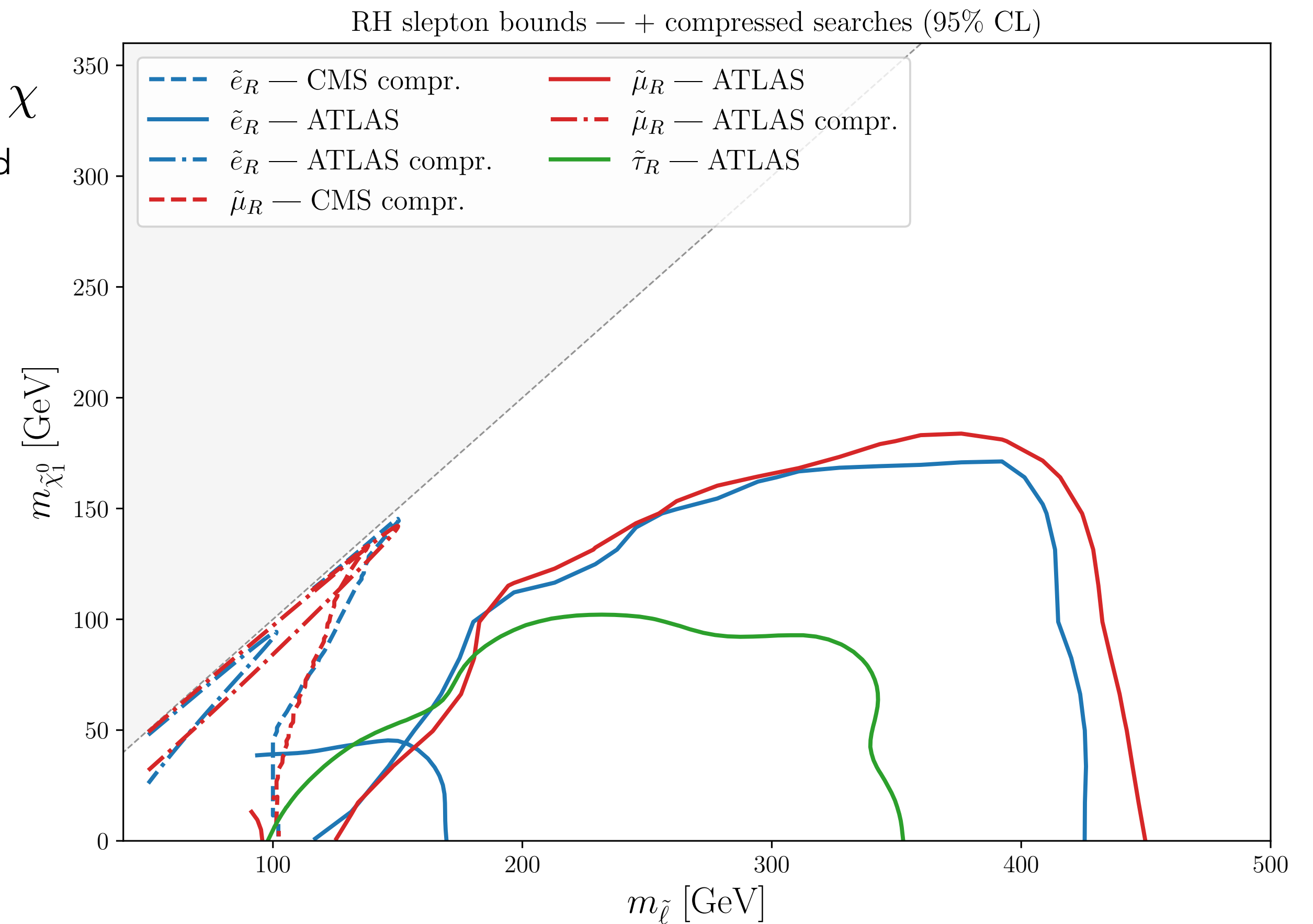
in our notation $\tilde{\ell} = \Phi$, $\chi = \tilde{\chi}_1^0$



$$pp \rightarrow \ell^+ \ell^- + \cancel{E} + j$$

When the splitting between Φ and χ is large the decay is prompt $\rightarrow$ mild Yukawa dependence.

Initial State Radiation can be used to generate a larger p_T and make the event “triggerable”.



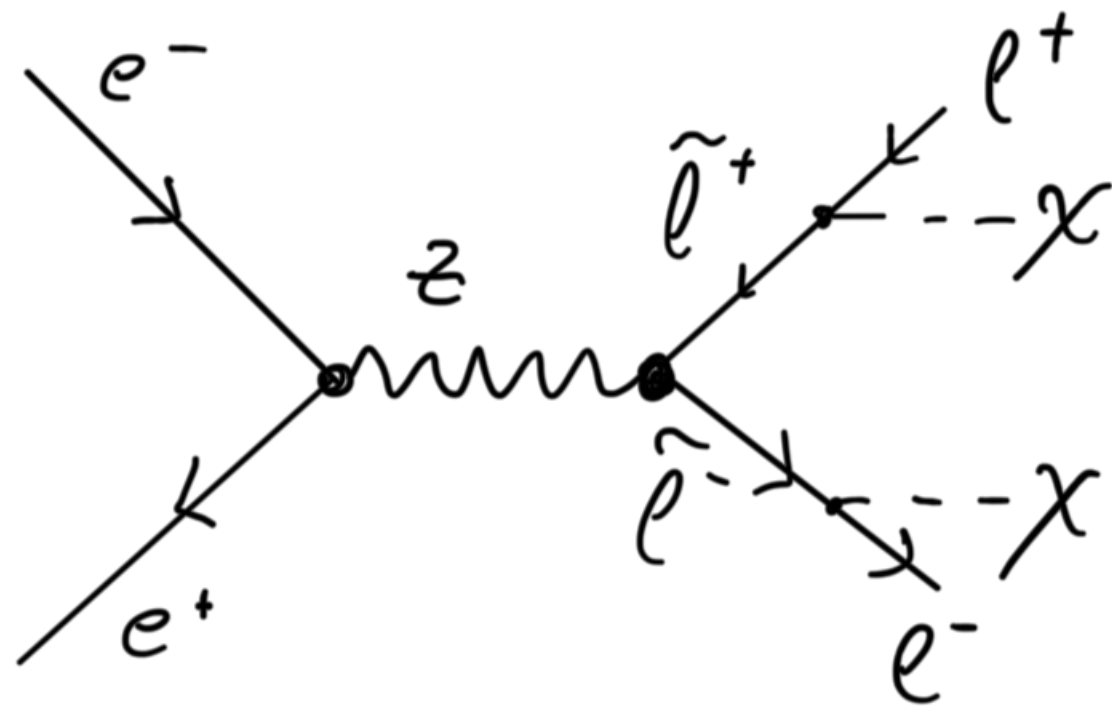
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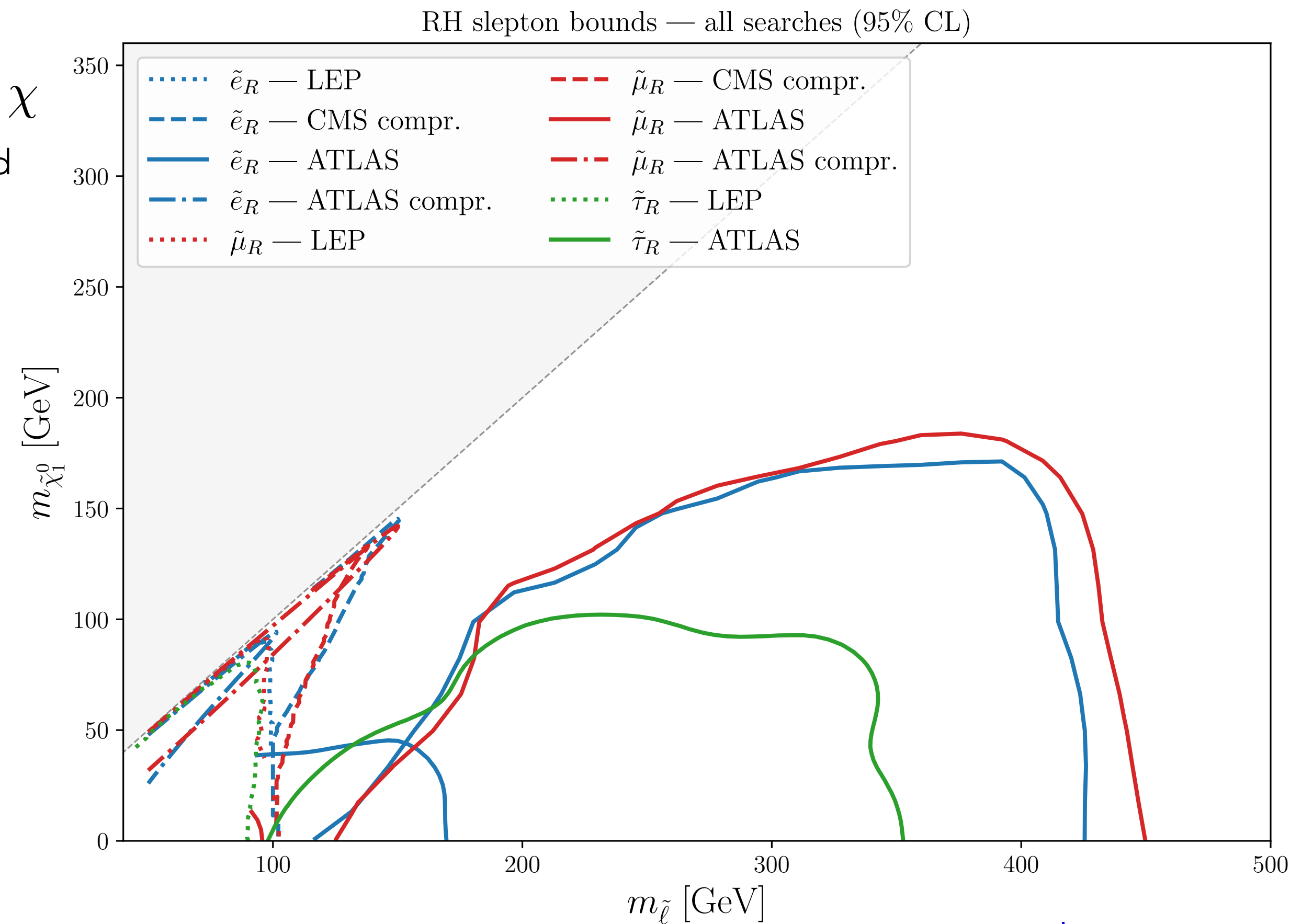


$$e^- e^+ \rightarrow \ell^+ \ell^- + \cancel{E} + (\gamma)$$

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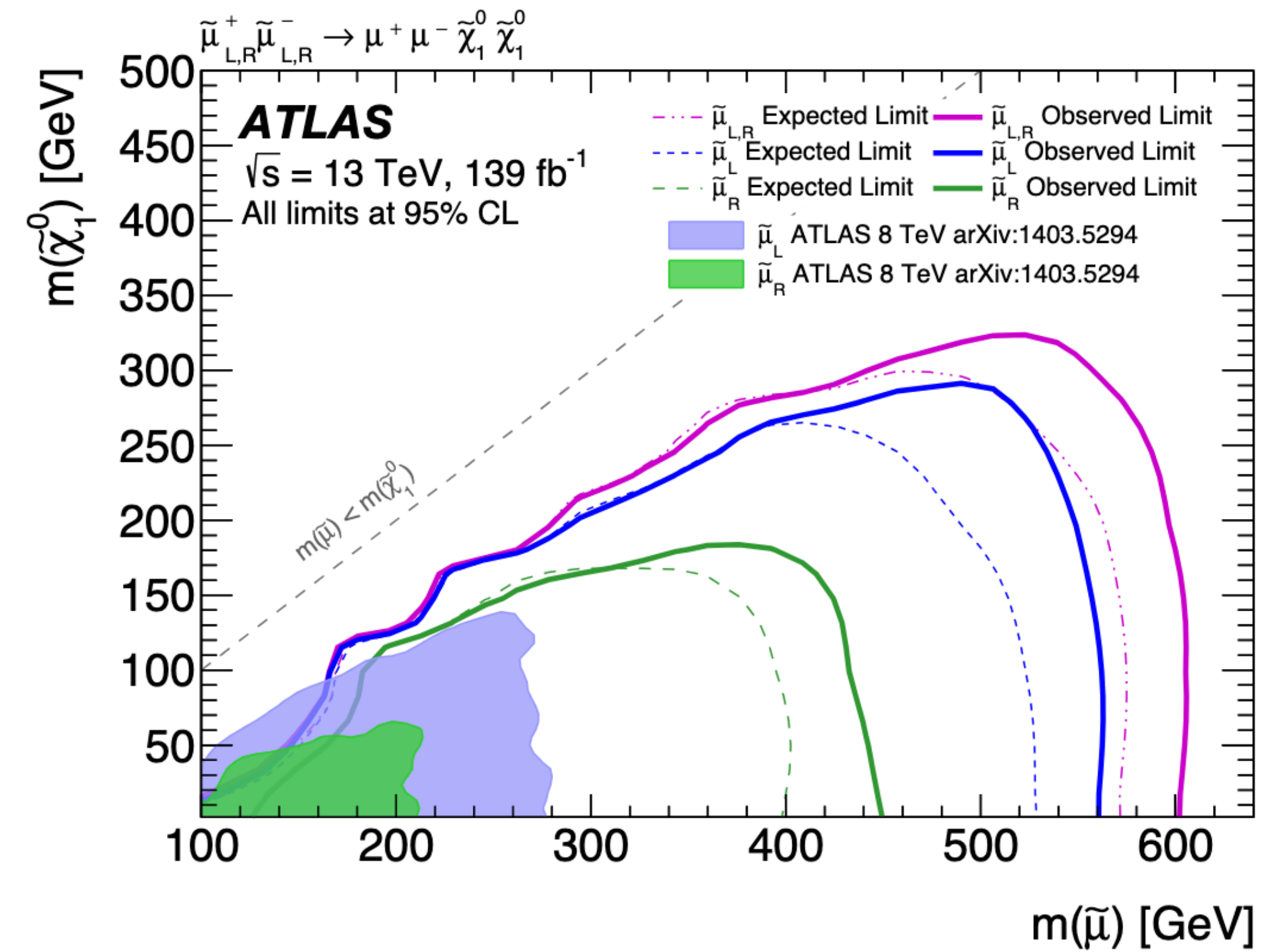
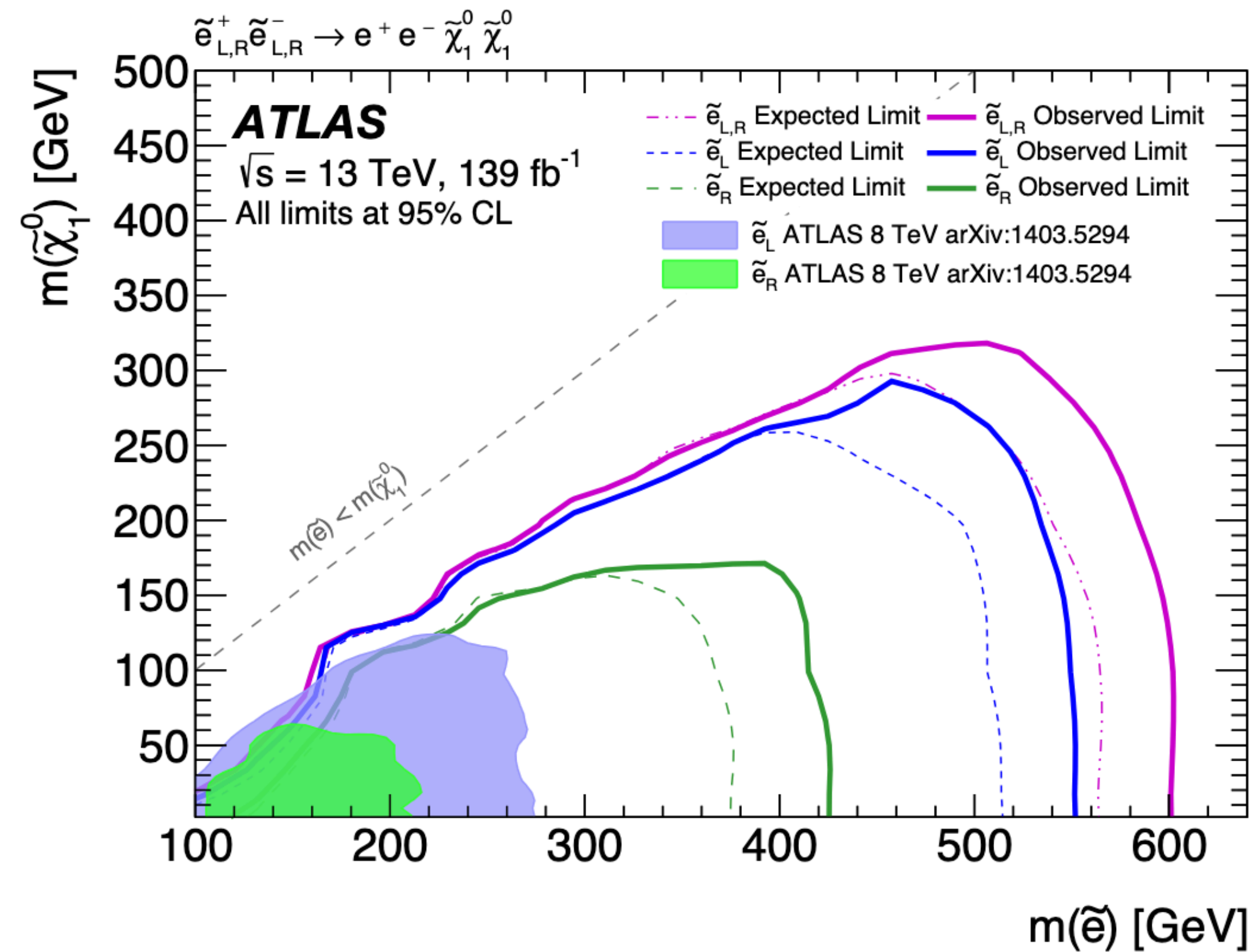
Initial State Radiation can be used to generate a larger p_T and make the event “triggerable”.

t-channel also possible at LEP, induces a Yukawa dependence, only s-channel as a conservative assumption.



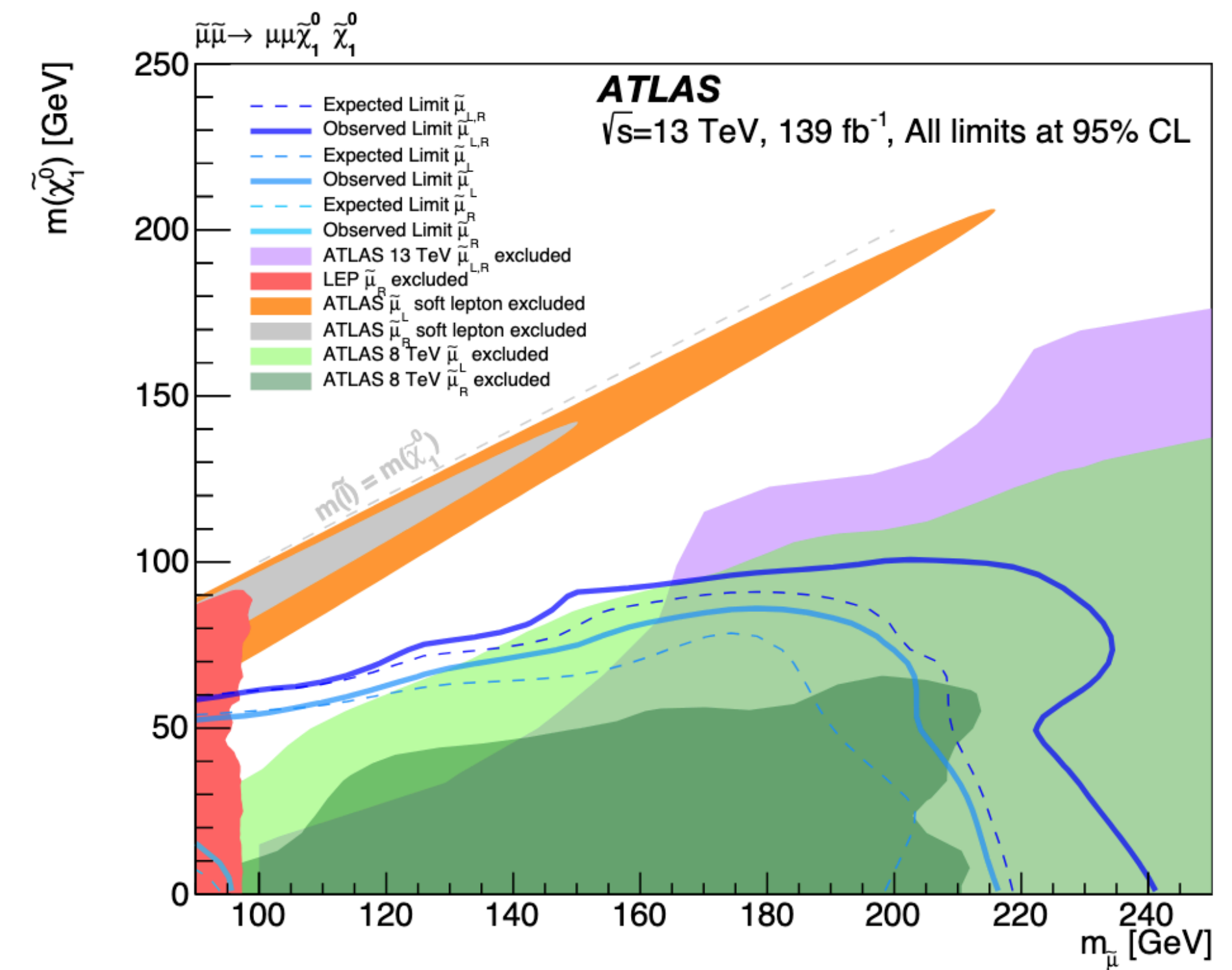
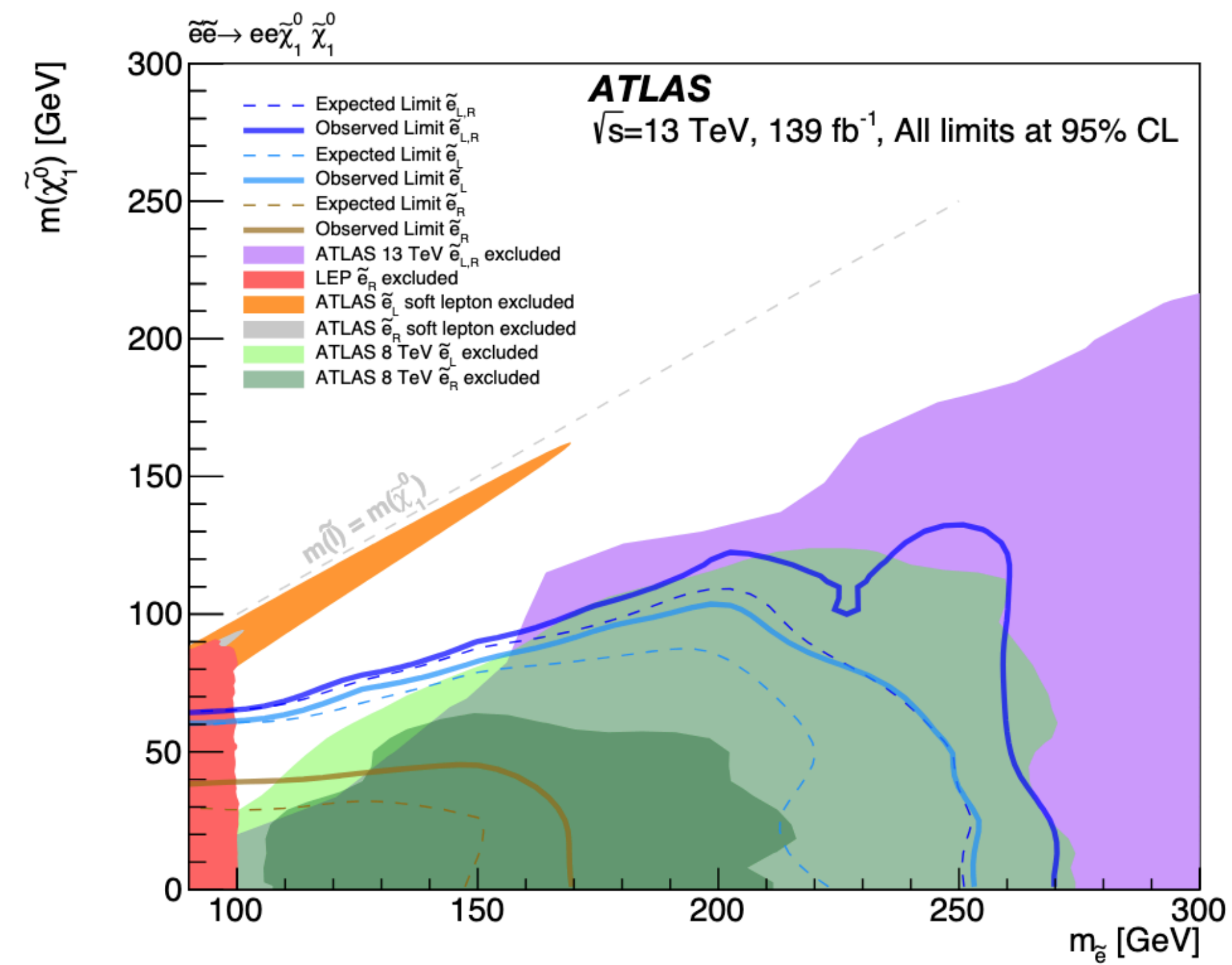
[see also](#)

SUSY searches in ATLAS: sleptons

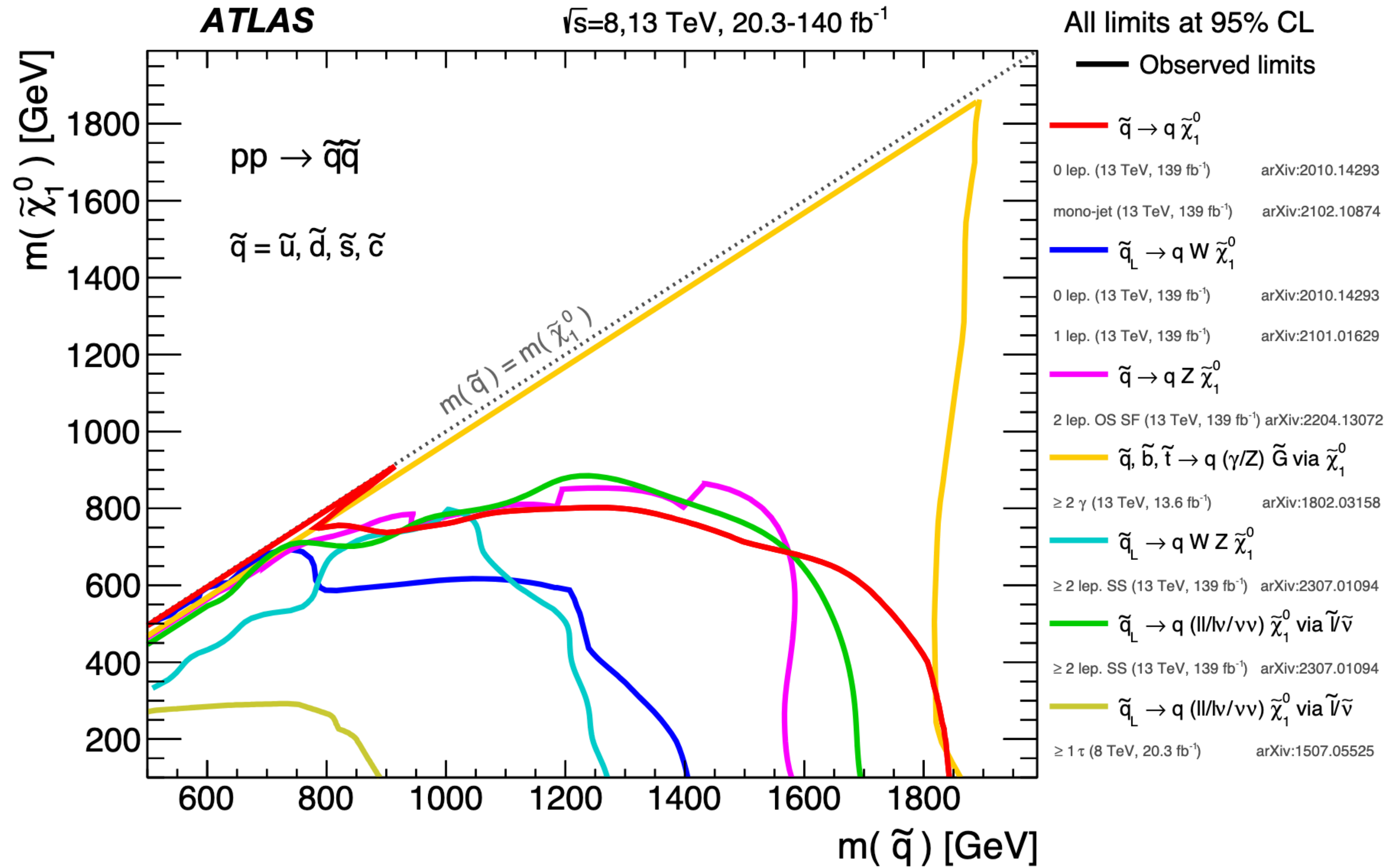


back to summary slide

SUSY searches in ATLAS: sleptons

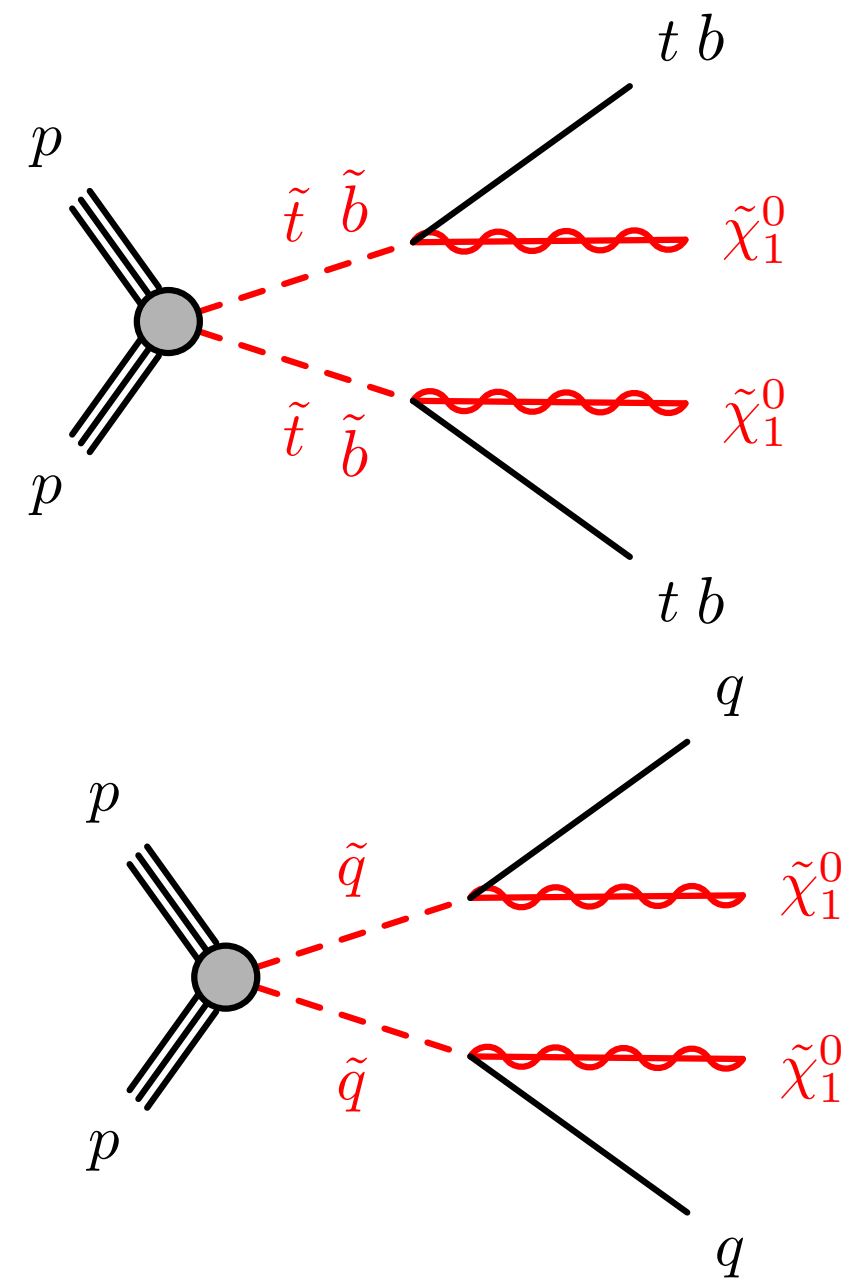


SUSY searches in ATLAS: squarks

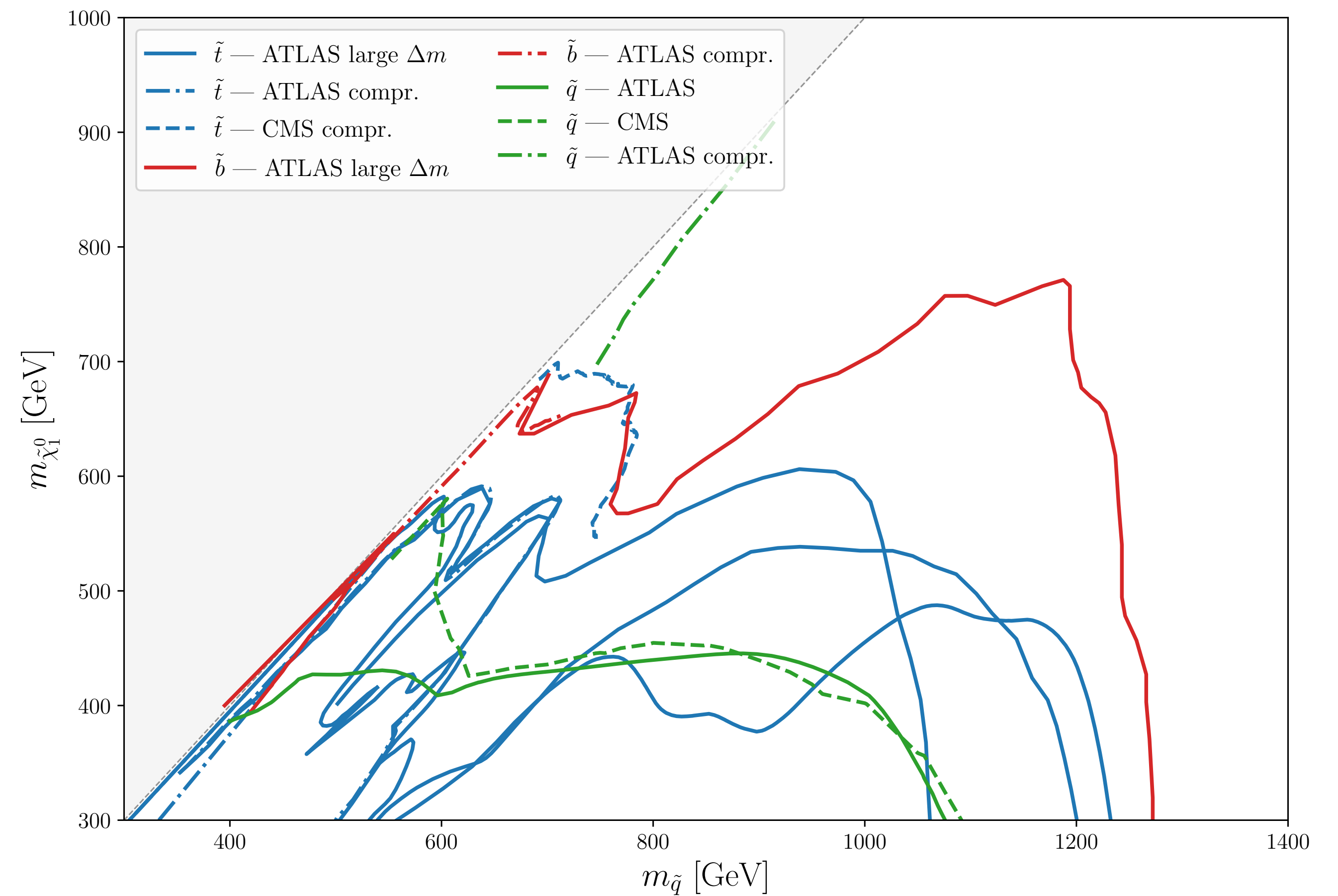


Quarkphilic Dark Matter: collider searches

Same type of diagrams: look for tops and bottoms or light jets

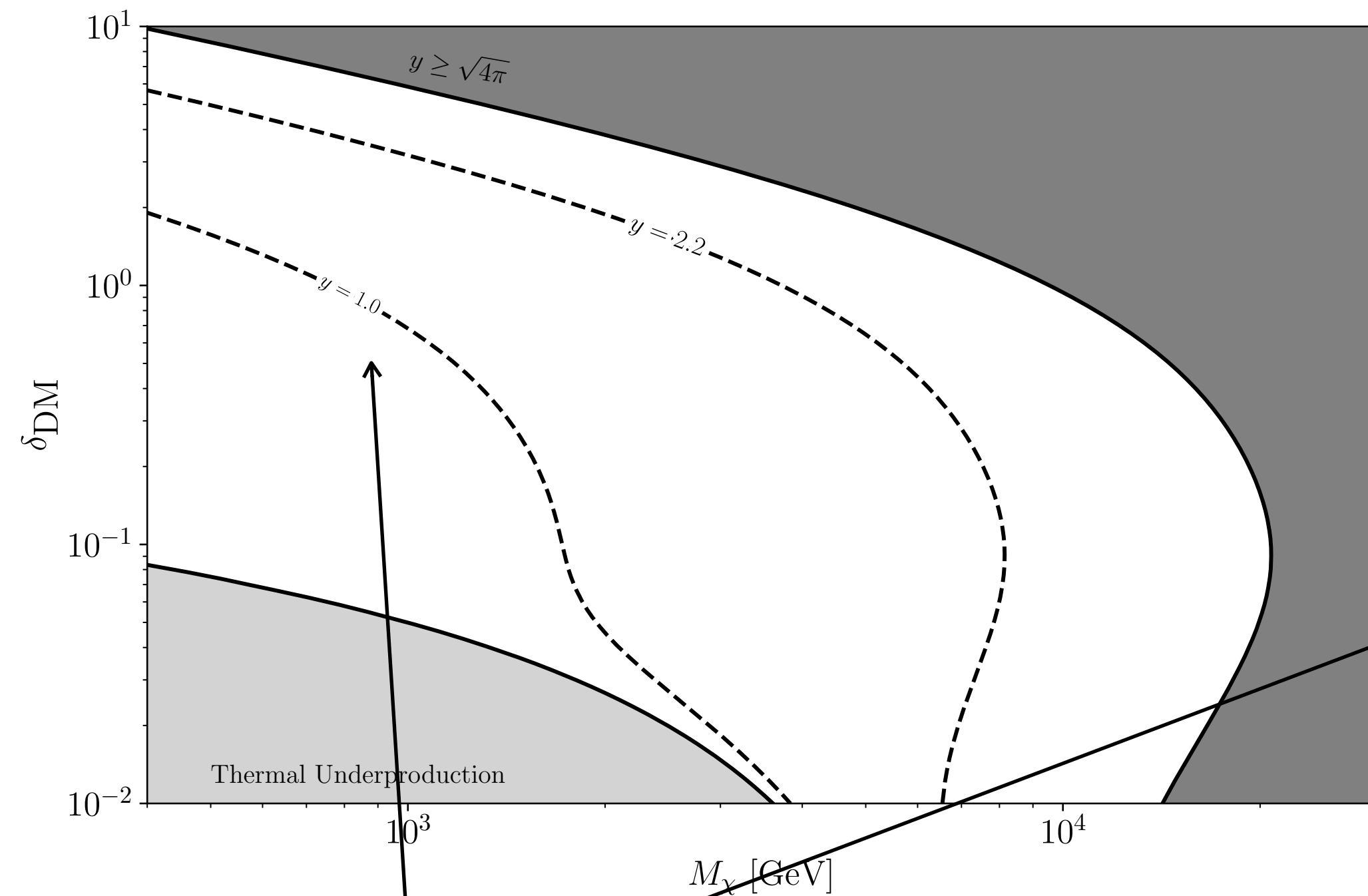


Also using ISR of jets for compressed SUSY searches

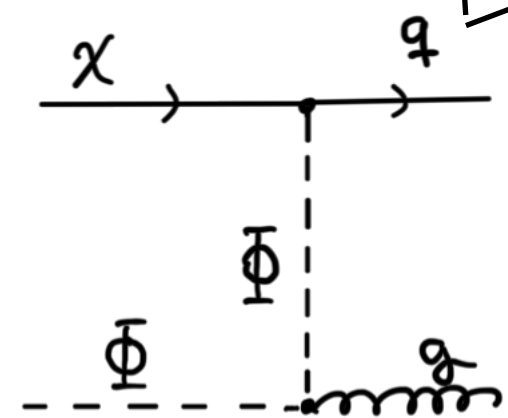
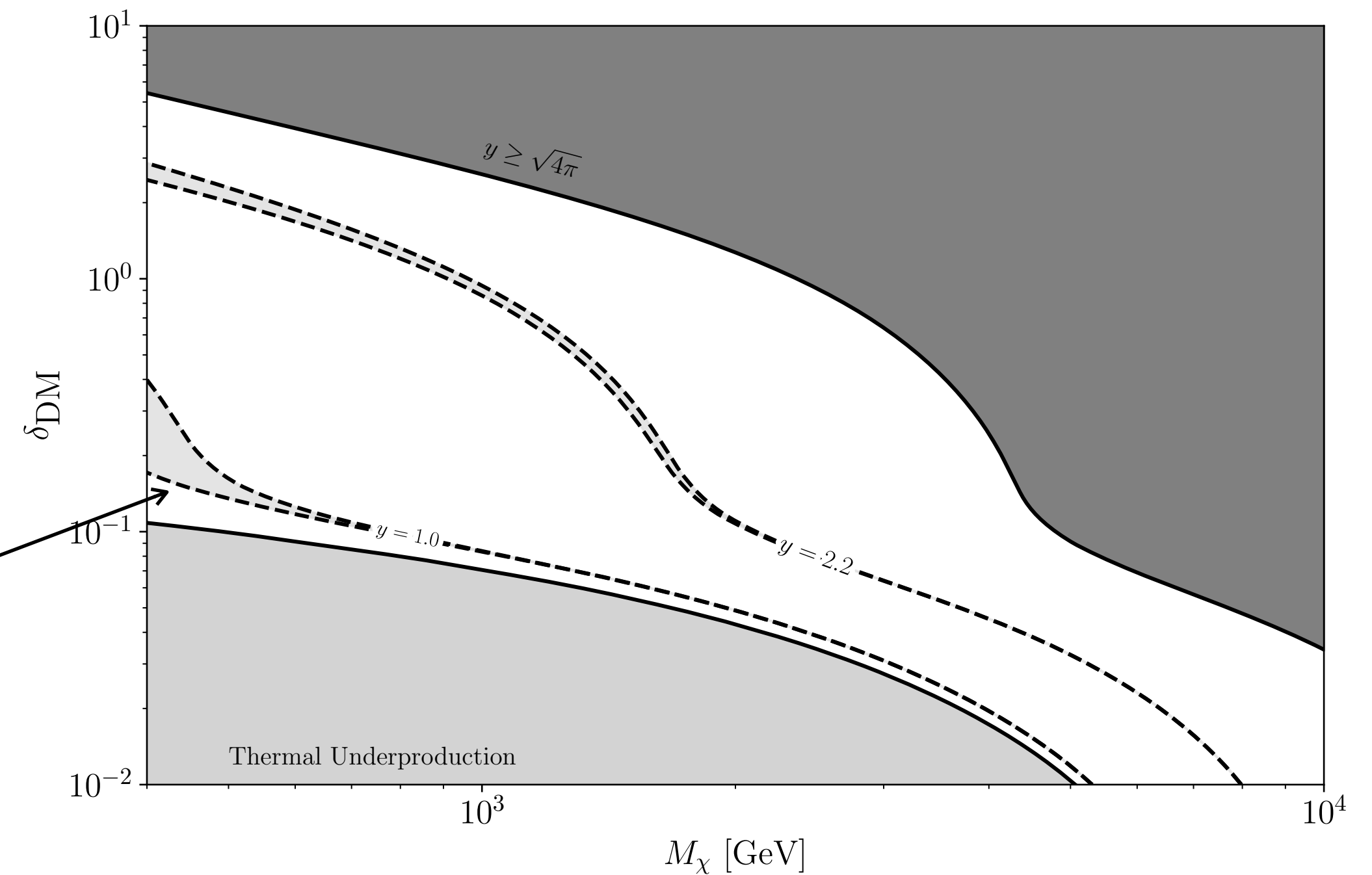


Quarkphilic Dark Matter: Production

Dirac



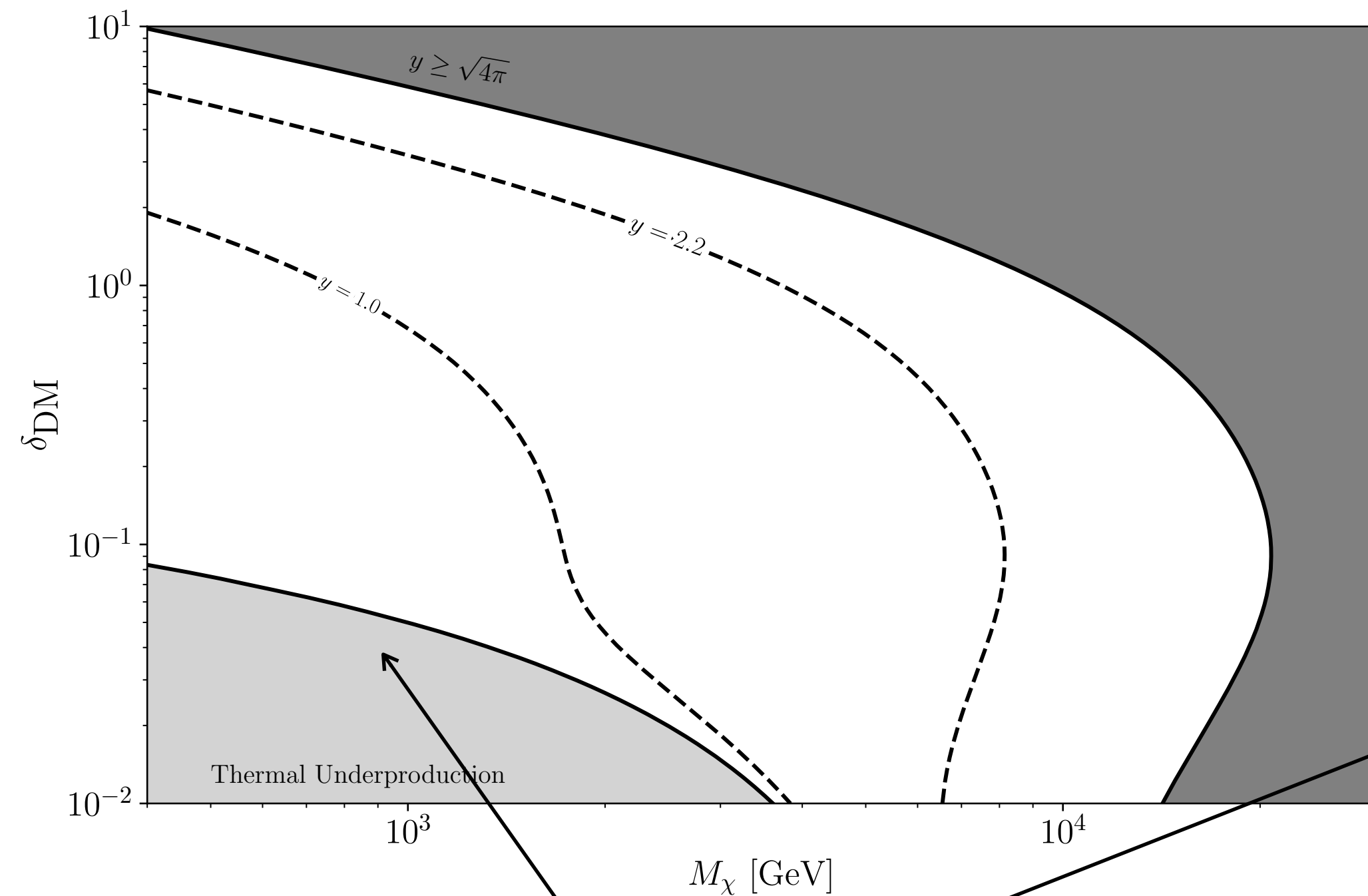
Majorana



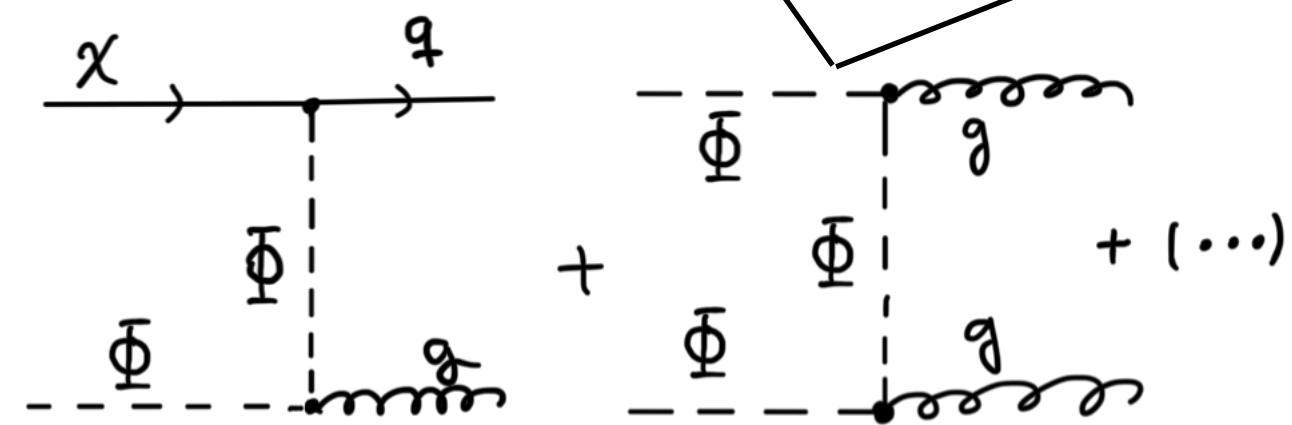
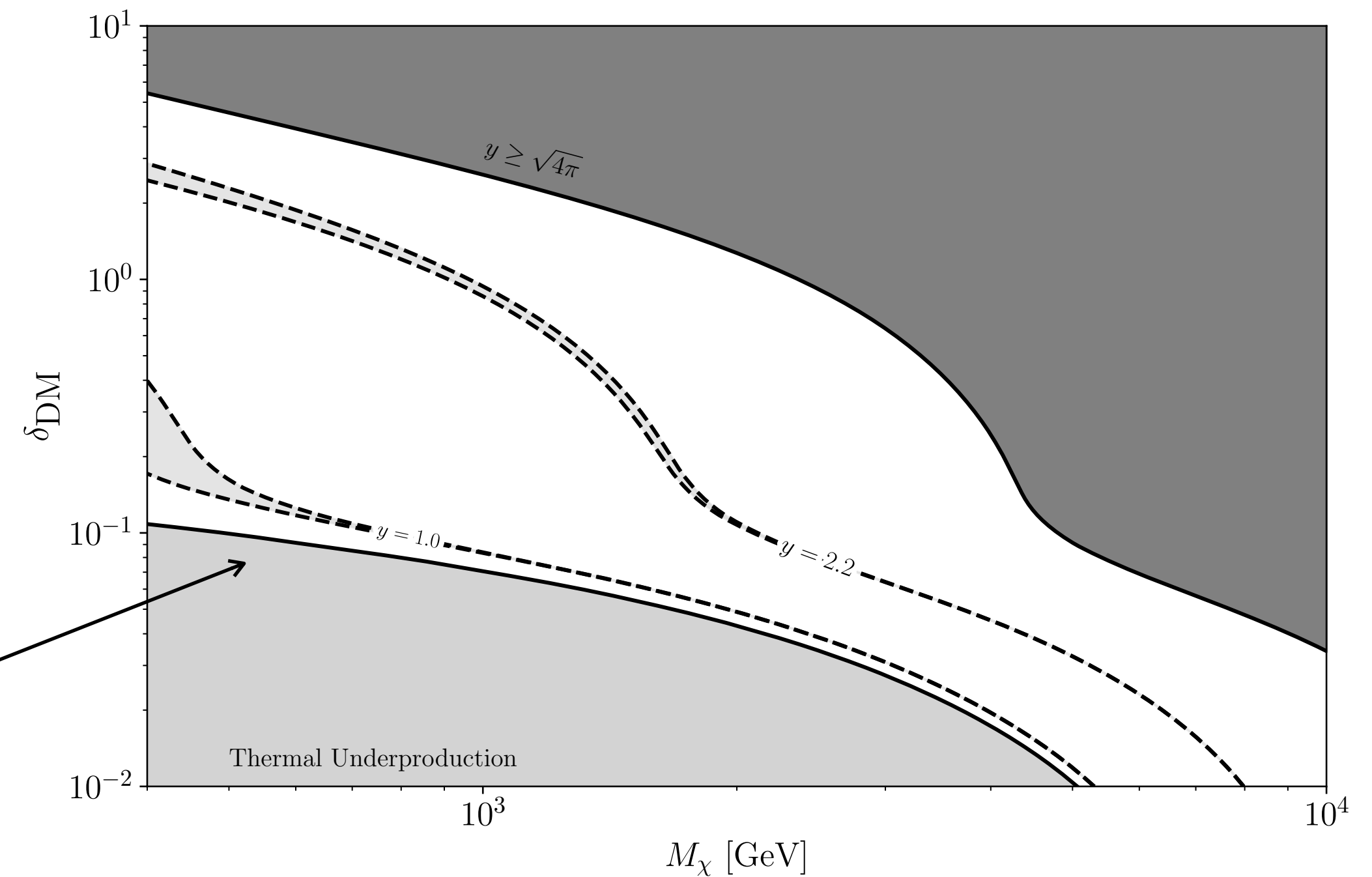
Coannihilations kick-in earlier,
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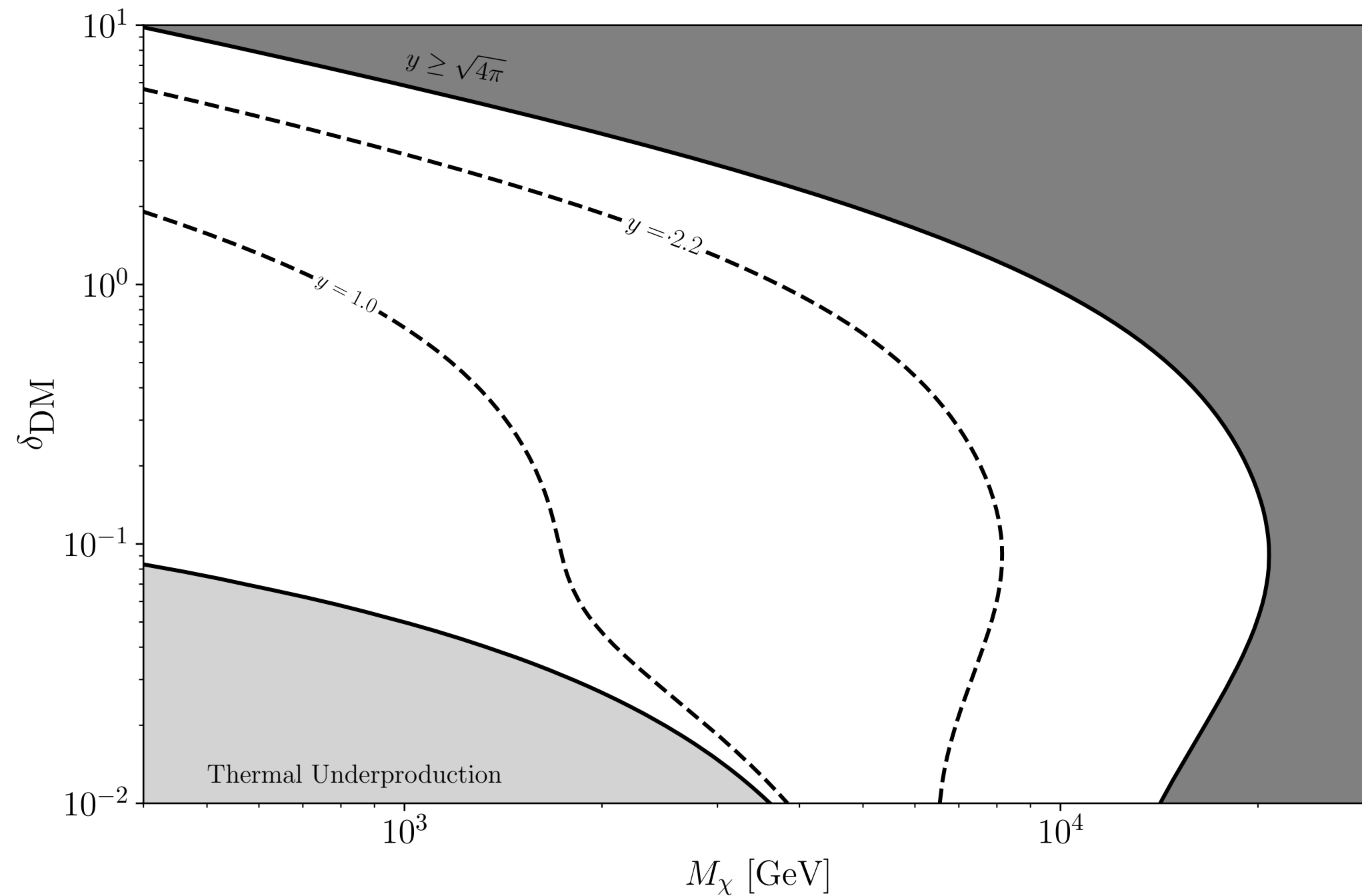


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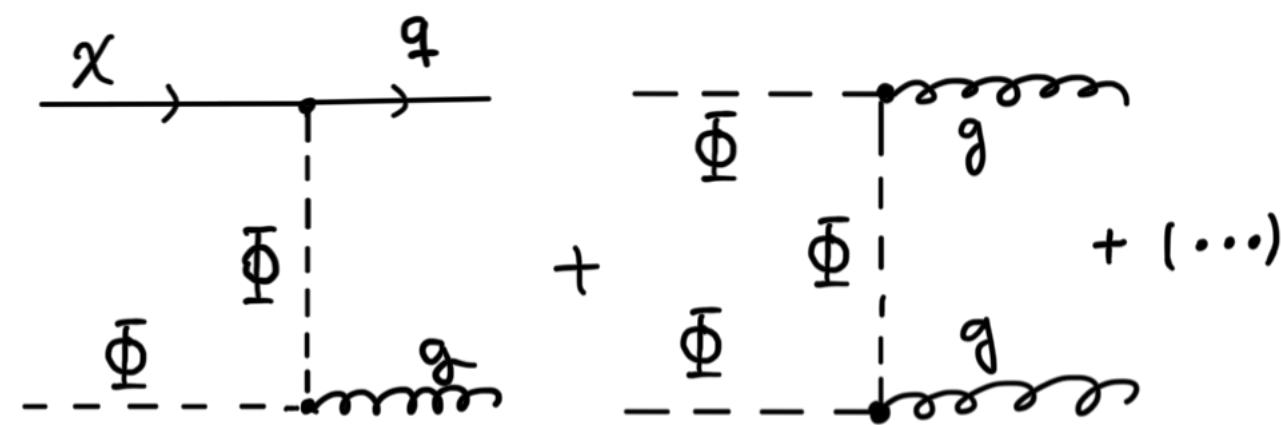
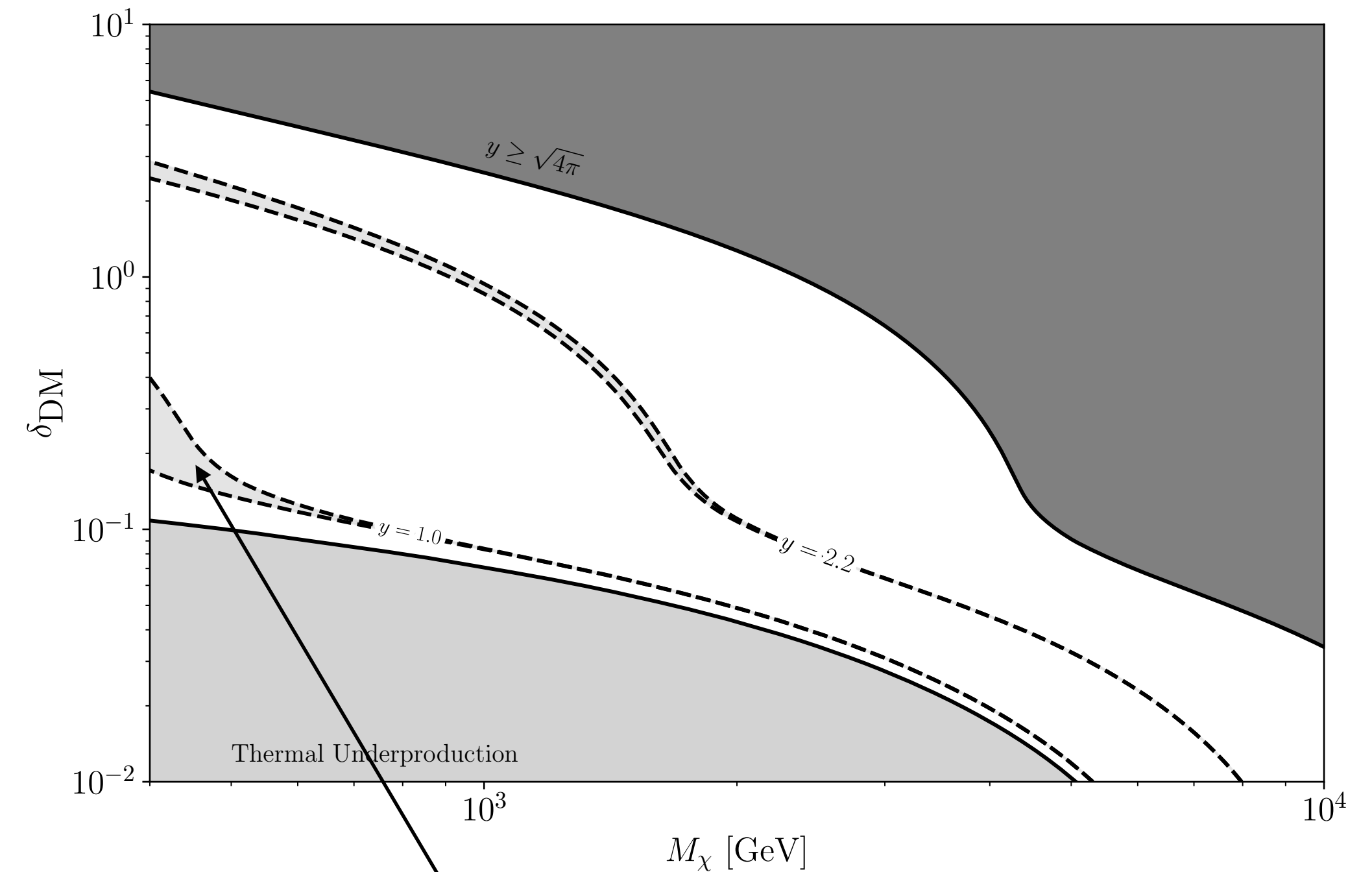
The $\sigma_{\Phi\Phi}$ contributions are also stronger

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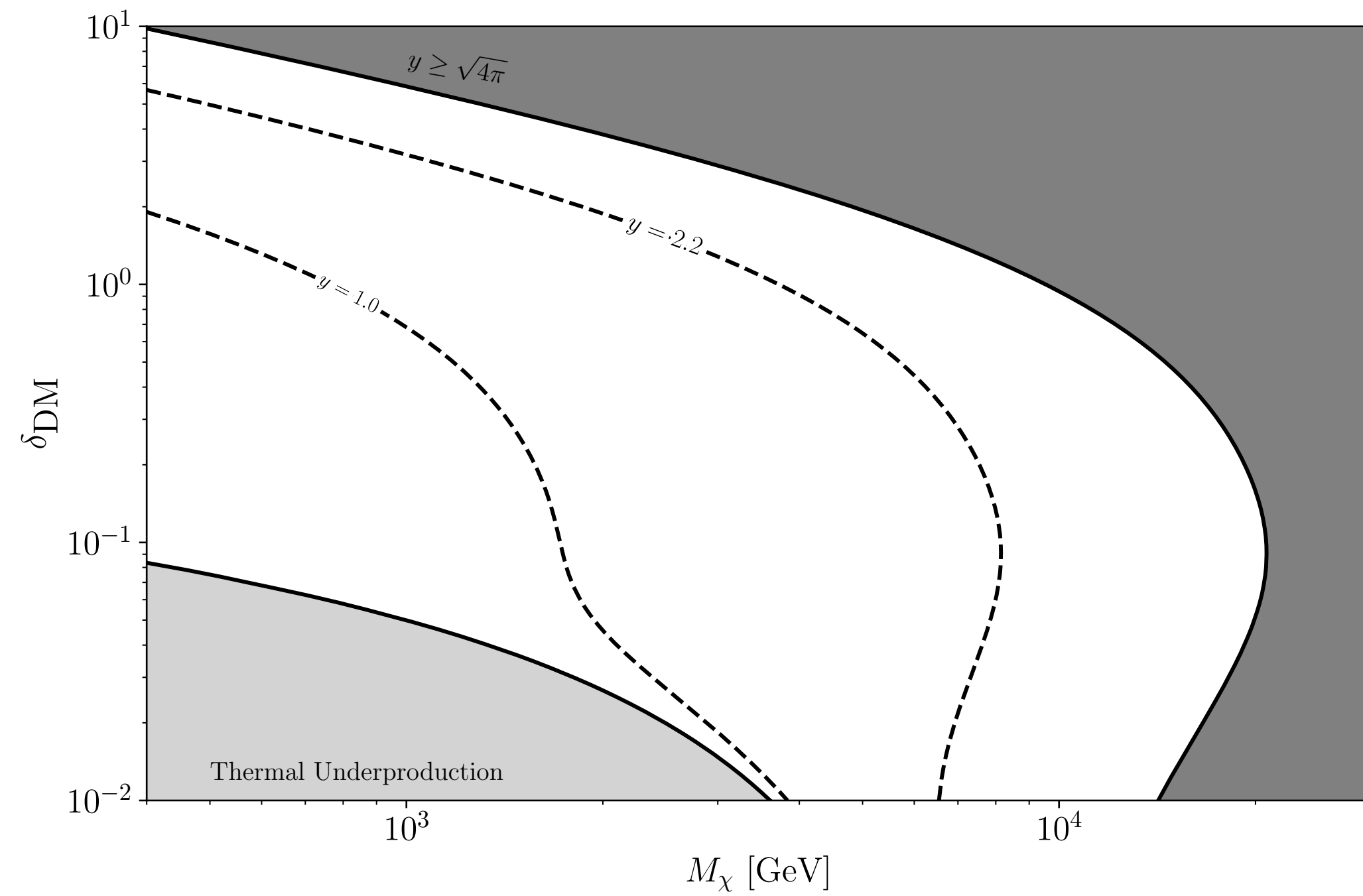
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top-quark effects important for lower m_χ

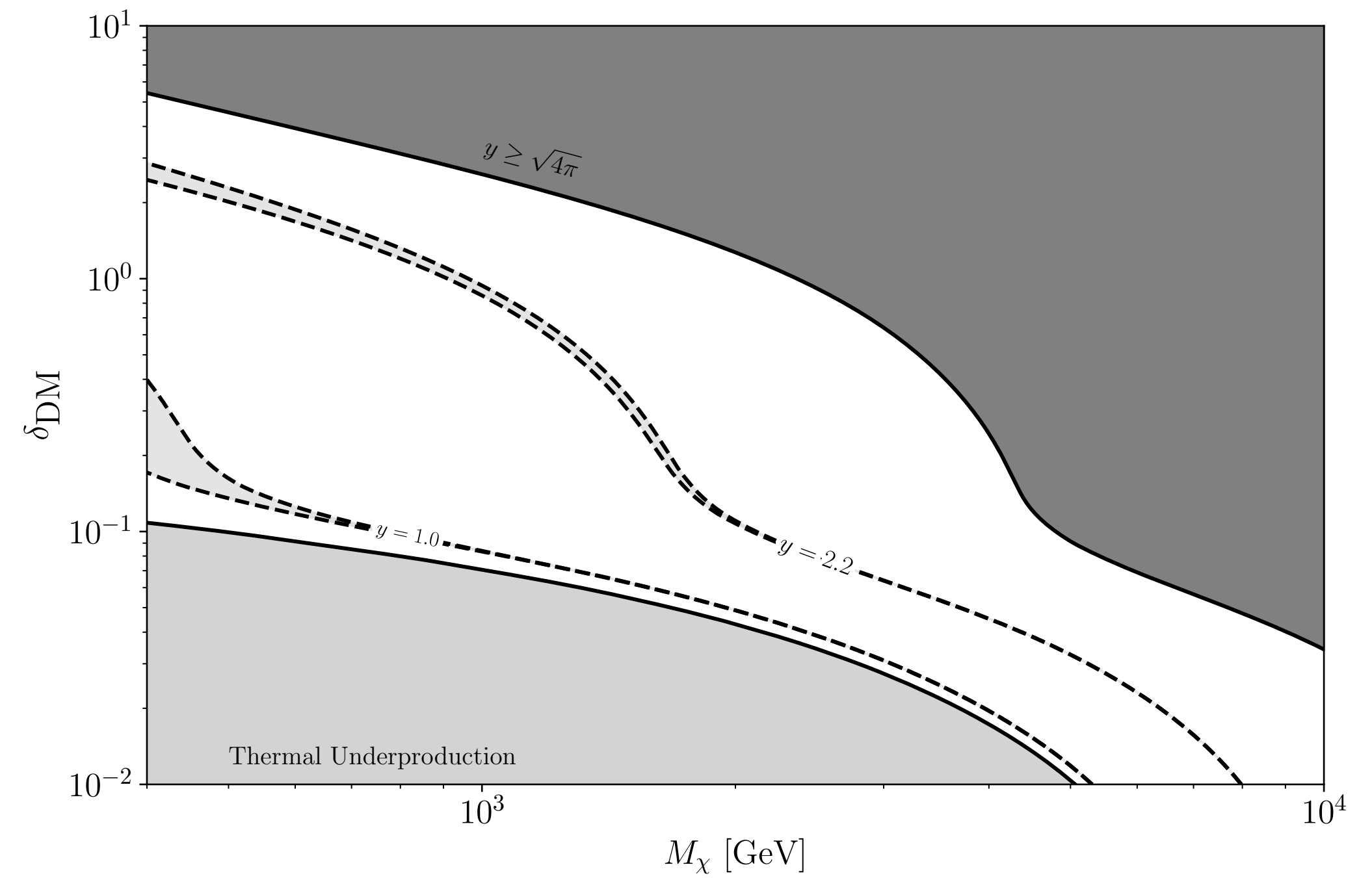
$$\sum_{i,j=1}^3 \sigma v_{\text{rel}}(\chi\chi \rightarrow q_i \bar{q}_j) = 2 \sin^4 \theta \sigma_{\chi\chi}^{m_q=0} v_{\text{rel}} \\ + 2 \cos^2 \theta \sin^2 \theta (\sigma_{\chi\chi}^{m_q=0} v_{\text{rel}} + \sigma_{\chi\chi}^{m_q} v_{\text{rel}}) \\ + \cos^4 \theta (\sigma_{\chi\chi}^{m_q=0} v_{\text{rel}} + \sigma_{\chi\chi}^{2m_q} v_{\text{rel}}) .$$

Quarkphilic Dark Matter: Production

Dirac

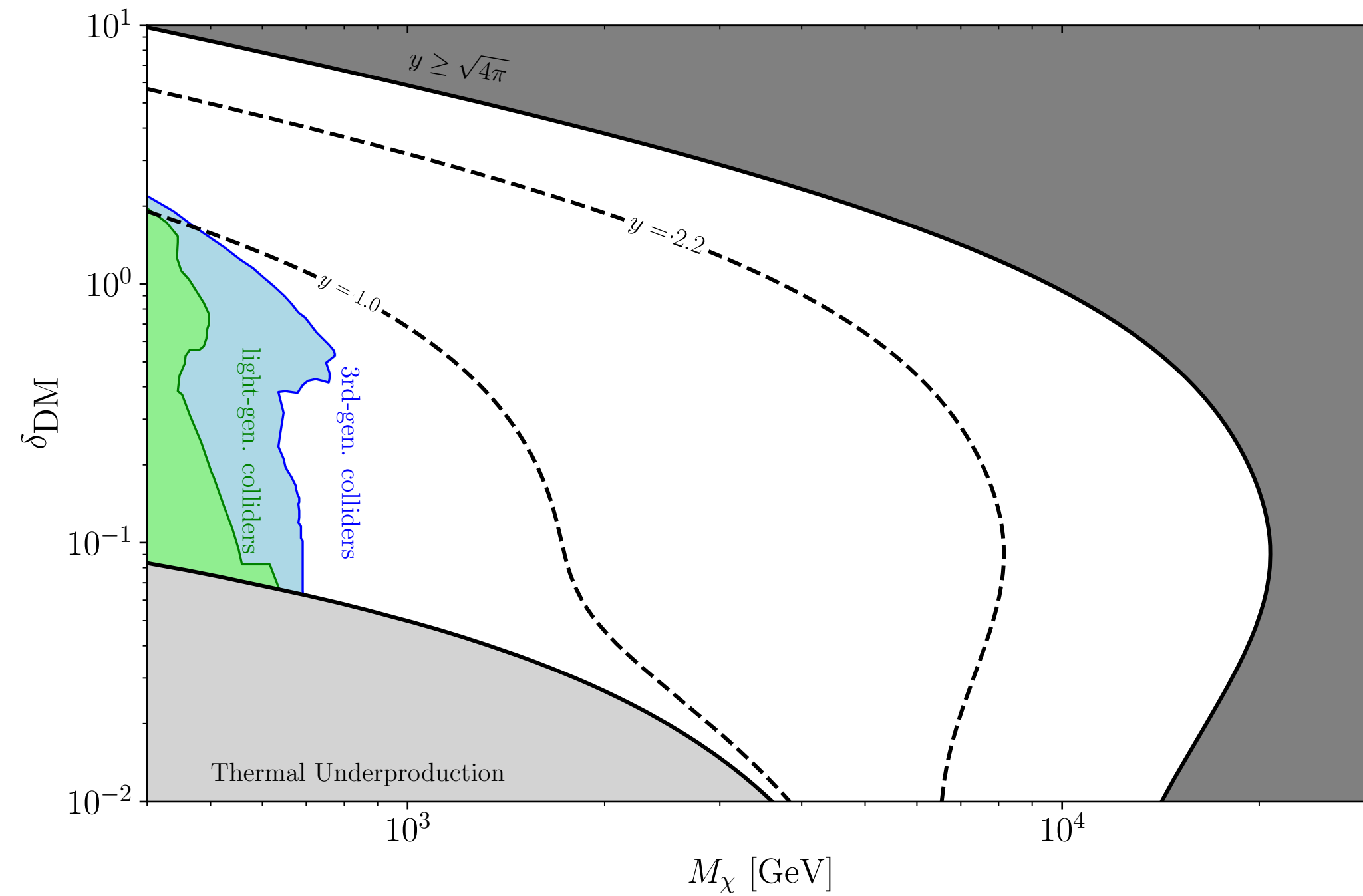


Majorana

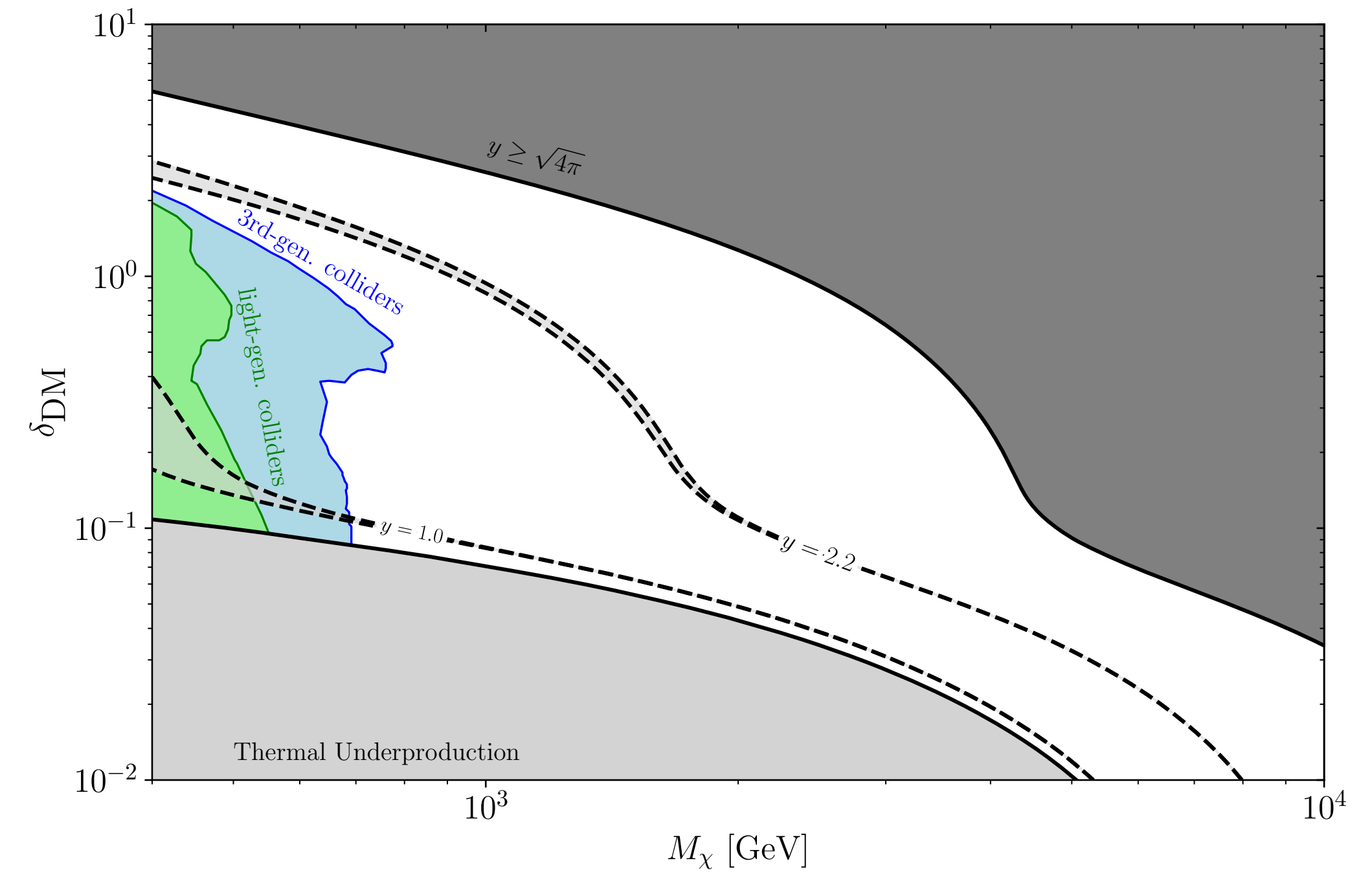


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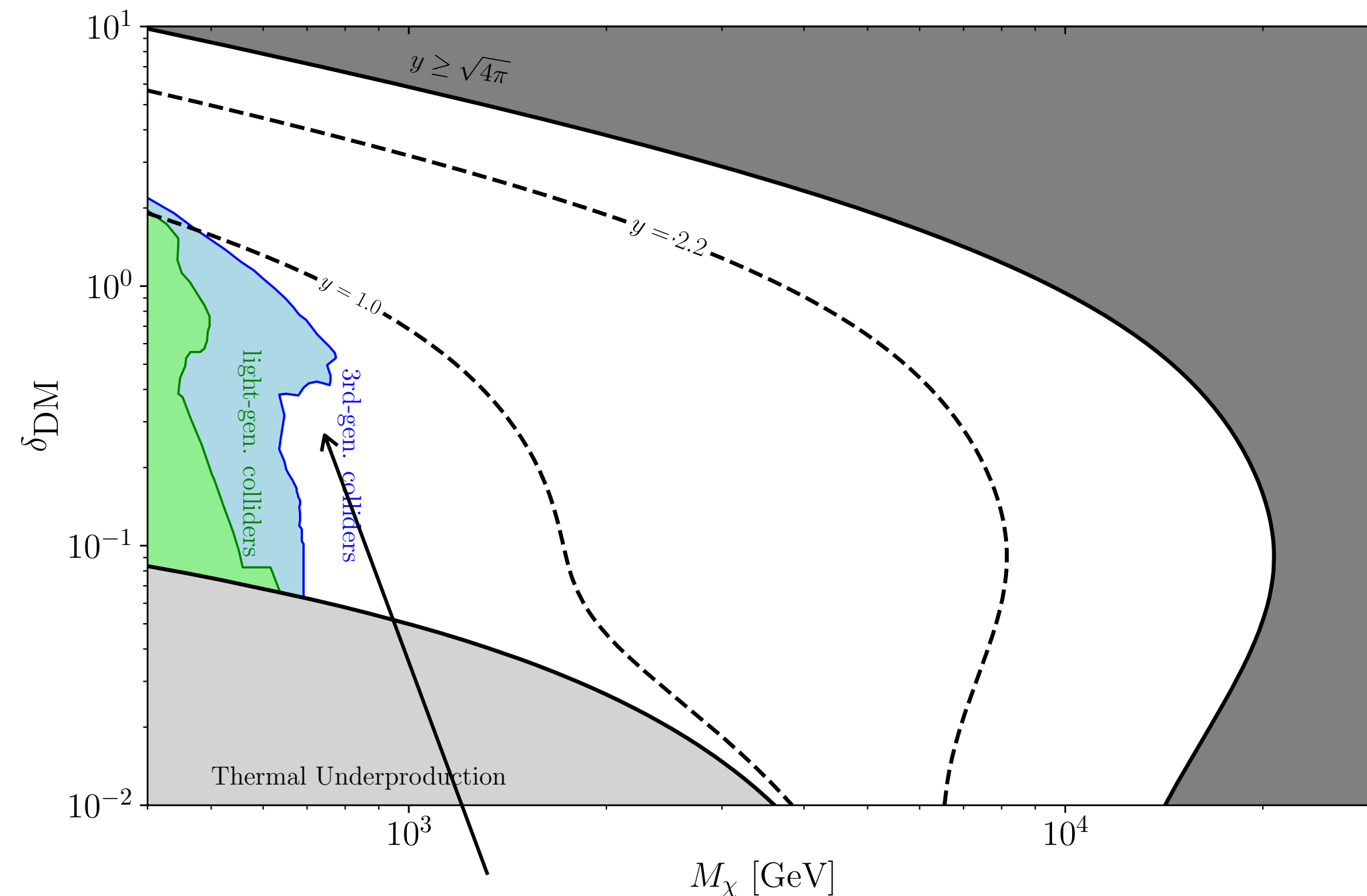


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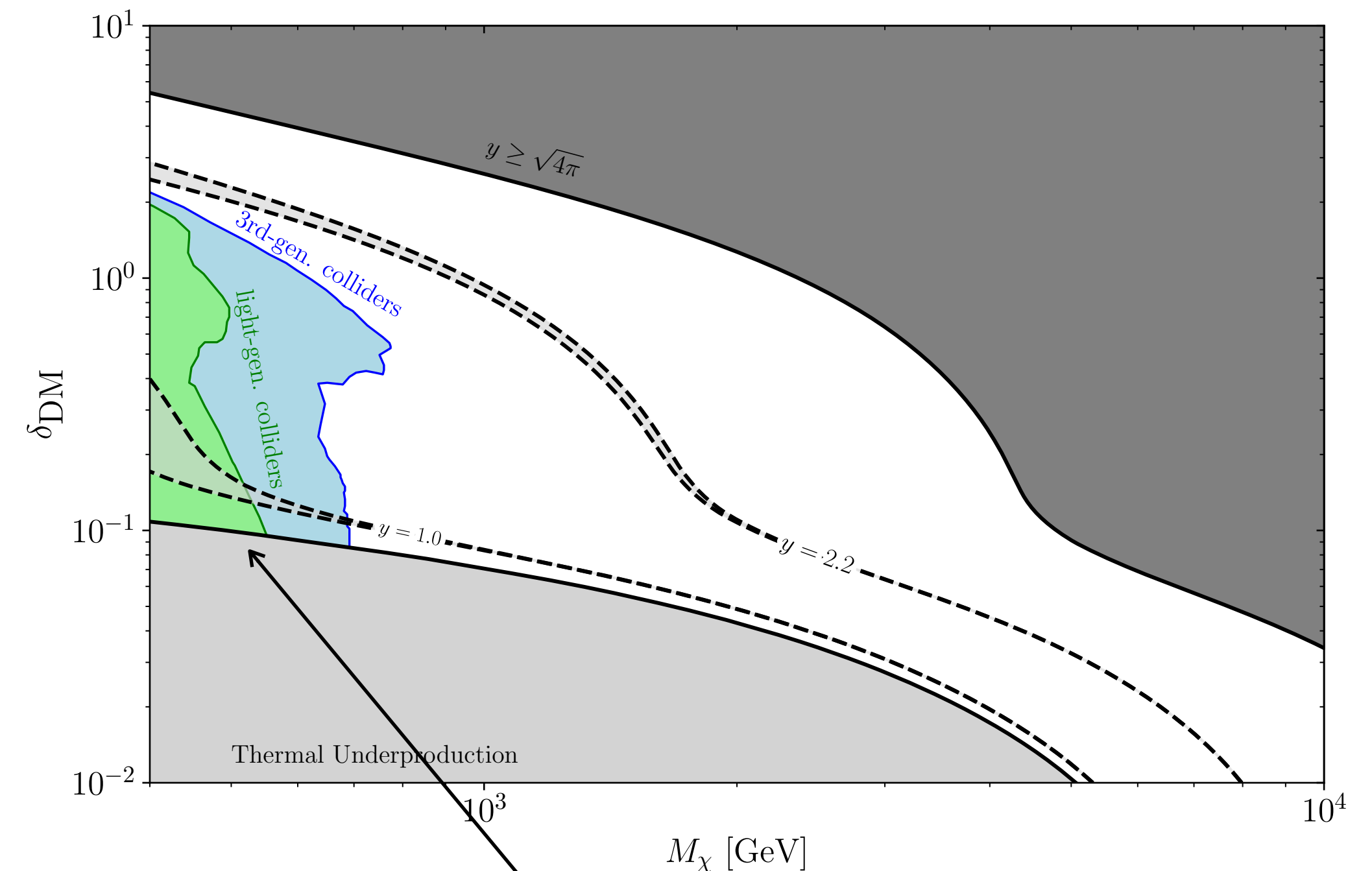
Quarkphilic Dark Matter: Production

Dirac



Mainly sbottom searches

Majorana

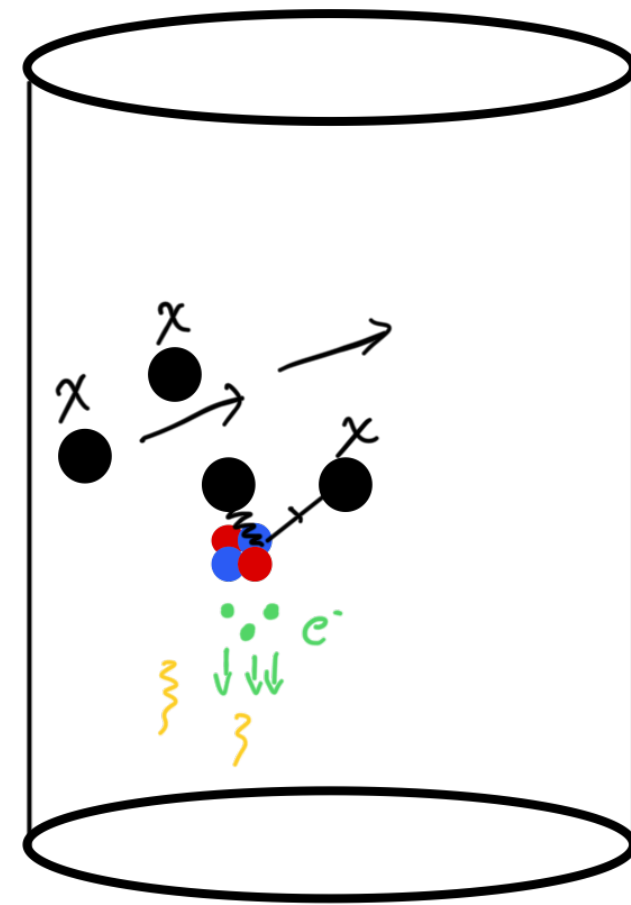


Compressed searches below the thermal underproduction limit

* Note that we are working with $q_L = \begin{pmatrix} u \\ d \end{pmatrix}$ benchmark. For u_R & d_R benchmarks these stop and sbottom searches constrain differently.

Leptophilic Dark Matter: Direct Detection

DM in the halo can collide with **nuclei** of the detector **depositing** some **energy** that is detected as scintillation and/or electrons



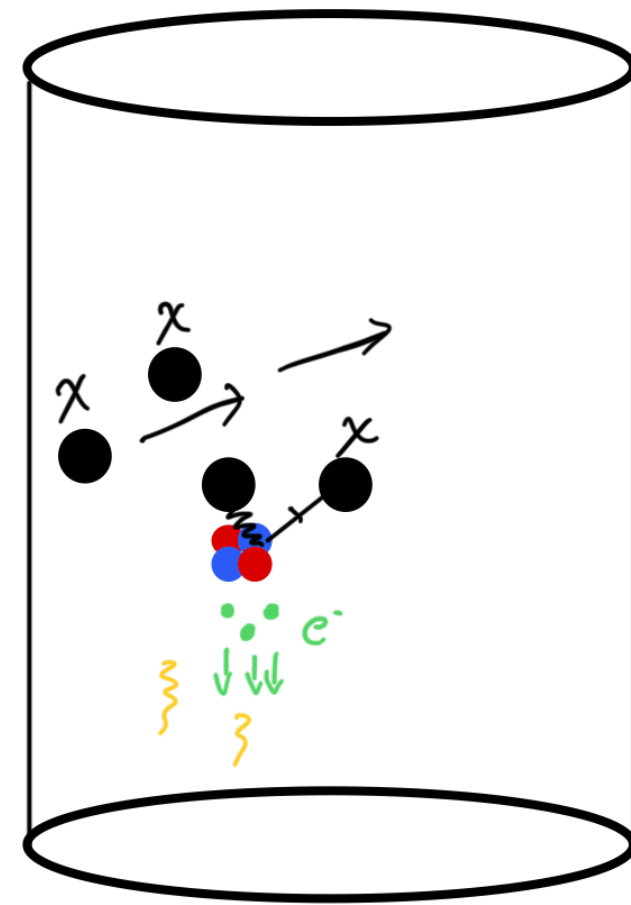
$$\mathcal{L}_{UV} = -y_i \bar{e}_{R,i} \chi \Phi + \text{h.c.}$$

1. Need to find relevant interactions with **quarks**, **gluons** and **photons**

$$\mathcal{L}_{\text{eff}}(\chi, q, g, \gamma)$$

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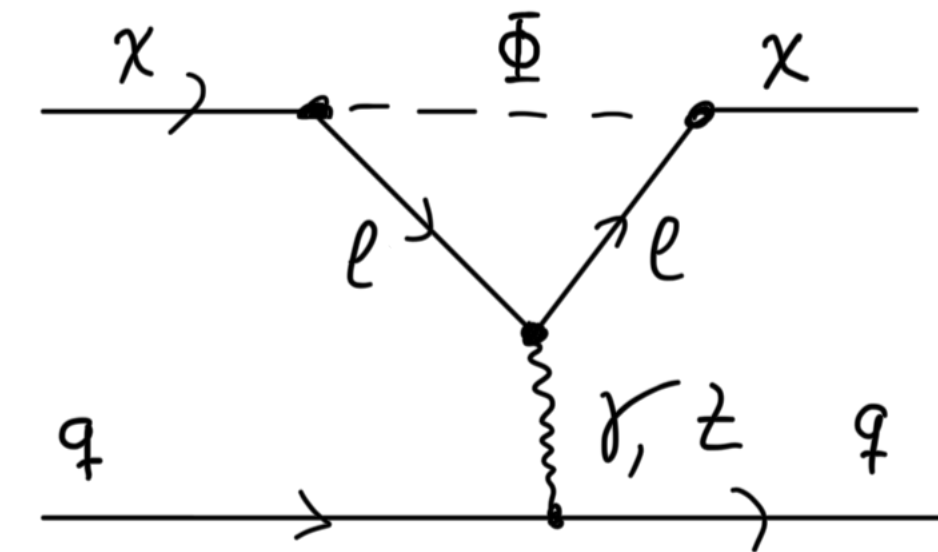
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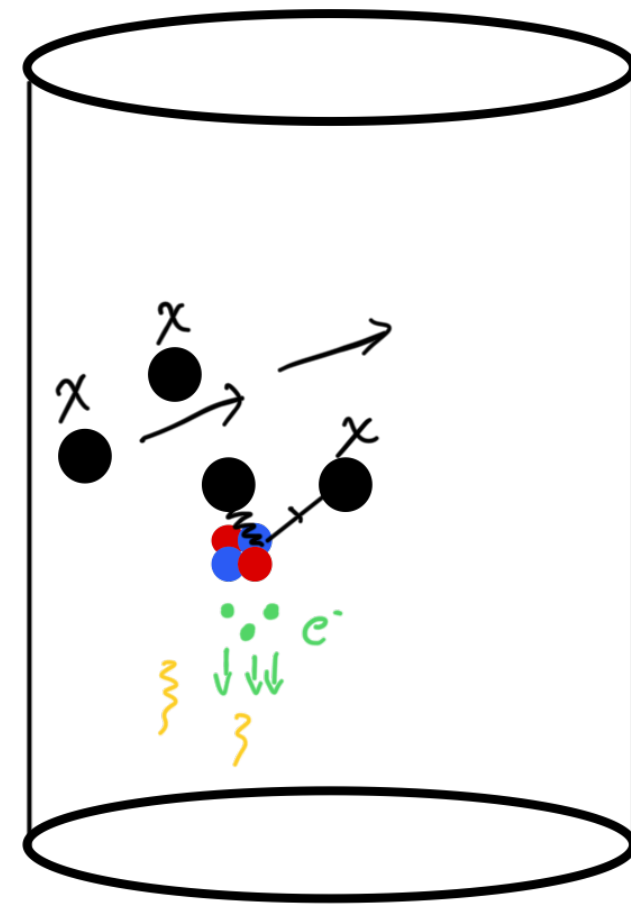
magnetic dipole charge radius

$$\mathcal{L}_{\text{eff}} = \frac{\mu_\chi}{2} \bar{\chi} \sigma^{\mu\nu} \chi F_{\mu\nu} + b_\chi \bar{\chi} \gamma^\mu \chi \partial^\nu F_{\mu\nu}$$



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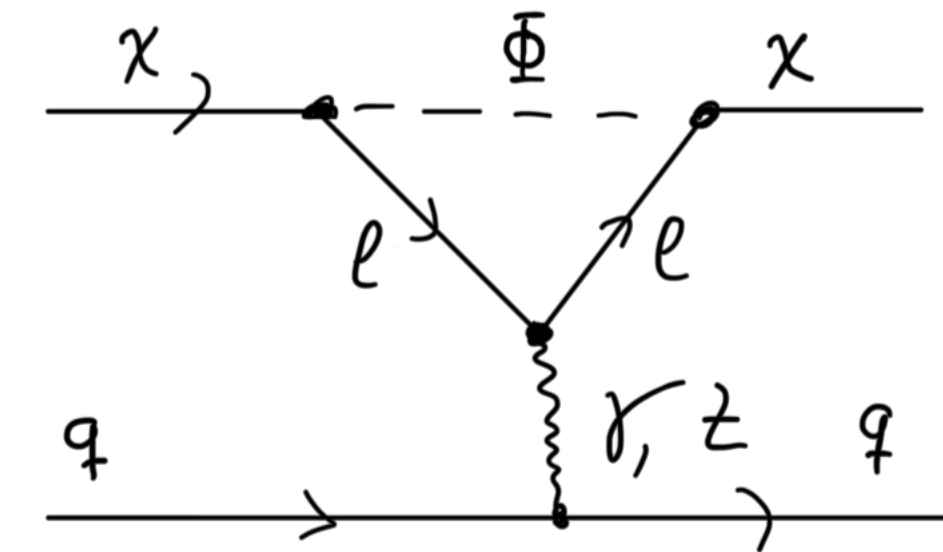
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2. Interactions need to be matched to their effective Lagrangian with nuclei

$$\mathcal{L}_{\text{eff}}(\chi, N) = \sum_{N=p,n} f_S^{(N)} \bar{\chi} \chi \bar{N} N + f_V^{(N)} \bar{\chi} \gamma^\mu \chi \bar{N} \gamma_\mu N + f_A^{(N)} \bar{\chi} \gamma^\mu \gamma_5 \chi \bar{N} \gamma_\mu \gamma_5 N + \dots$$

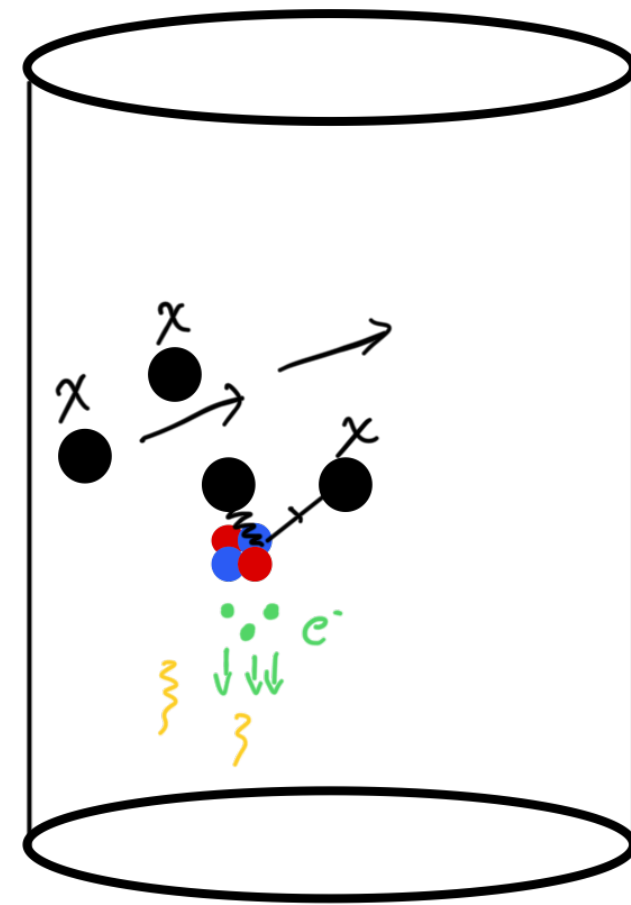
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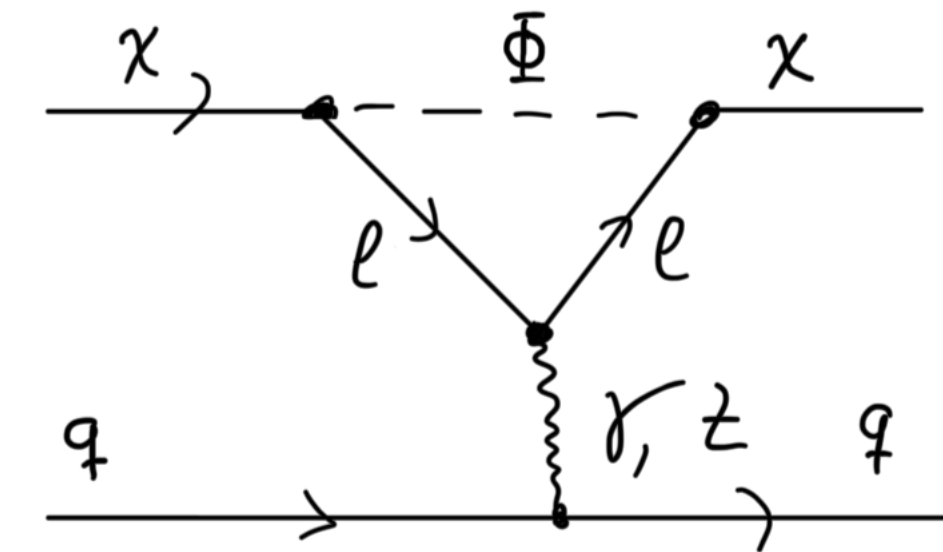
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3. Finally, since the DM halo is non-relativistic we compute in the non-relativistic effective theory $\frac{|q|}{m_N} \sim v \sim 10^{-3}$

$$\mathcal{L}_{\text{eff}}^{\text{NR}}(\chi, N) = \sum_{N=p,n} \sum_i c_i \mathcal{O}_i = \sum_N c_0^{(N)} \mathcal{O}_0 + c_2^{(N)} q^2 \mathcal{O}_2 + \dots$$

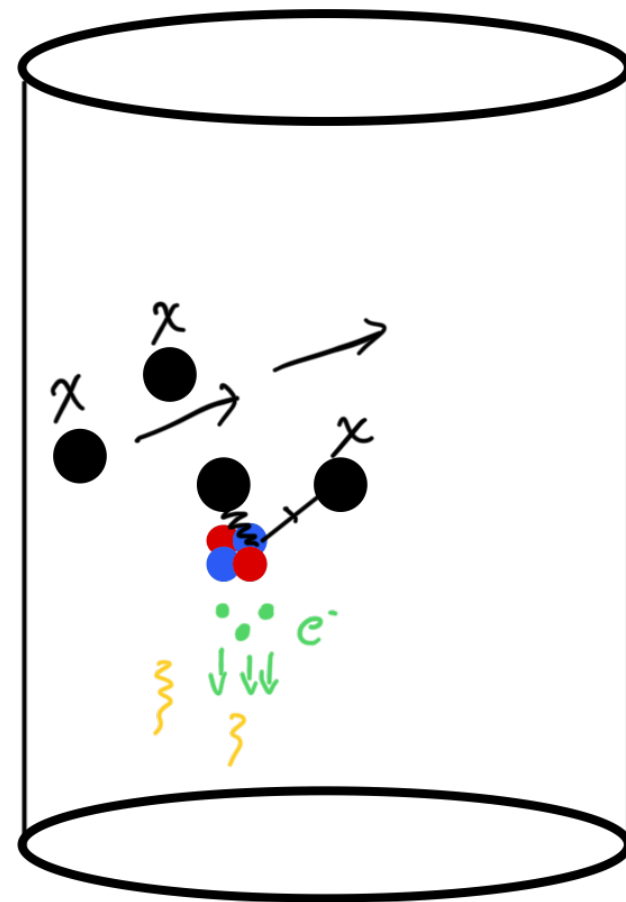
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Spin-independent:

$$\bar{\chi} \chi \bar{N} N \rightarrow 4m_\chi m_N \mathbf{1}_\chi \mathbf{1}_N$$

Coherent interaction with the nuclei

$$\sigma_{\text{SI}} \sim A^2$$

Spin-dependent:

$$\bar{\chi} \gamma_\mu \gamma_5 \chi \bar{N} \gamma^\mu \gamma_5 N \rightarrow -16m_\chi m_N \mathbf{S}_\chi \cdot \mathbf{S}_N$$

Non-coherent scattering

$$\sigma_{\text{SD}} \sim J(J+1)$$

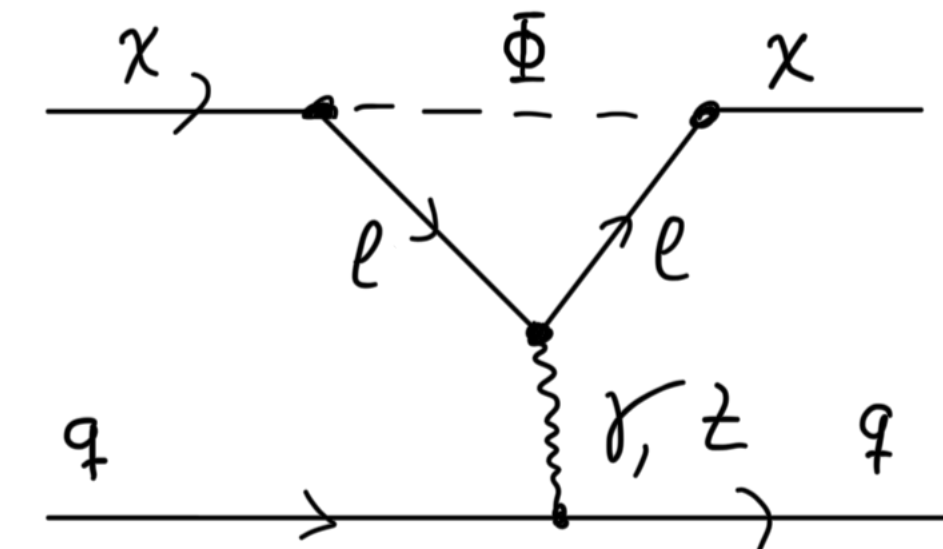
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Leptophilic Dark Matter: Direct Detection

Dirac leptophilic DM direct detection:

Nuclear form factors

[Ibarra, Wild '15](#)

$$\frac{d\sigma}{dE_R} = \alpha_{\text{em}} \mu_{\chi}^2 Z^2 \left(\frac{1}{E_R} - \frac{m_A}{2\mu_{\text{red}}^2 v^2} \right) [F_{\text{SI}}(E_R)]^2 + \frac{\mu_A^2 \mu_{\chi}^2 m_A}{\pi v^2} \frac{J_A + 1}{3J_A} [F_{\text{dipole}}(E_R)]^2 + \frac{m_A}{2\pi v^2} (f^{(A)})^2 [F_{\text{SI}}(E_R)]^2$$

$$f^{(A)} = -eZ \left(b_{\chi} + \frac{\mu_{\chi}}{2M_{\chi}} \right)$$

Leptophilic Dark Matter: Direct Detection

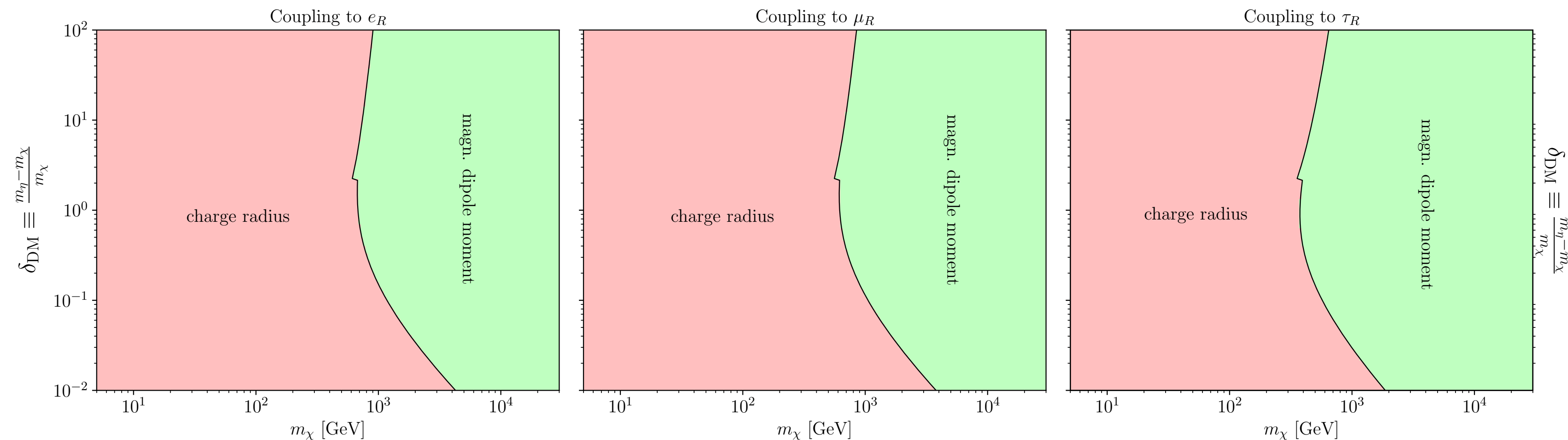
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Very small dependence on the fermion mass

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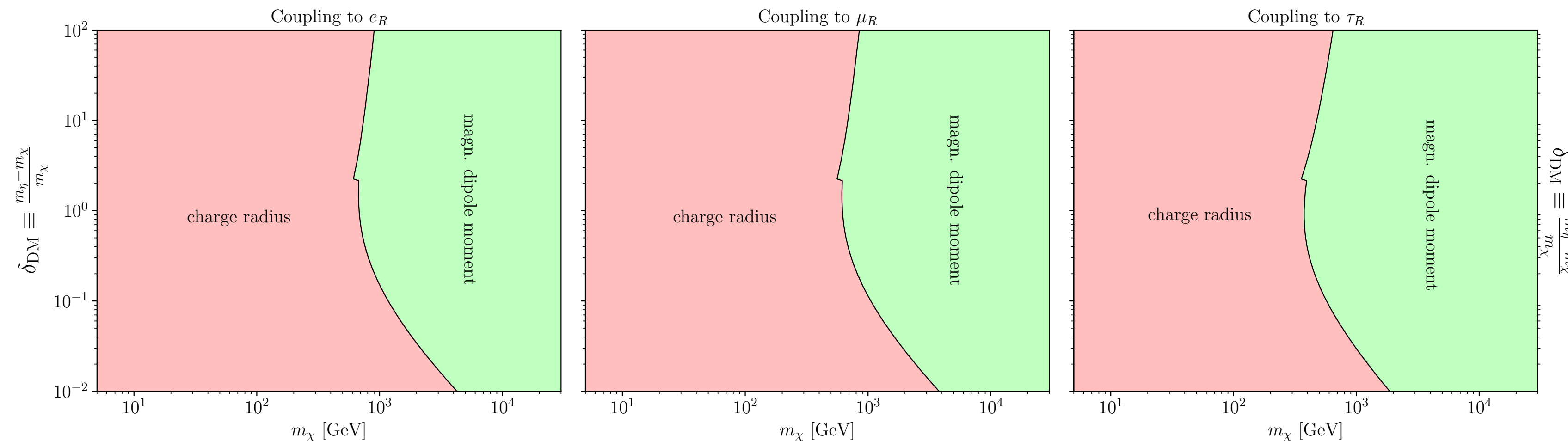
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Dependence on the recoil-energy.



Very small dependence on the fermion mass

One cannot directly extract bounds from σ_{SI} for two reasons:

- large isospin violation: photon dipoles only interact with **protons**
- large **dependence** with **recoil-energies**

$$\longrightarrow R \propto \oint_n dS_1 \text{Gauss}(S_1|n) \otimes \text{Pois}(n|\nu(E_R)) \otimes \frac{d\sigma}{dE_R}$$

Leptophilic Dark Matter: Direct Detection

Majorana leptophilic DM direct detection:

Majorana particles fulfil $\chi = \chi^c$ $\bar{\chi} \Gamma \chi = \bar{\chi}^c \Gamma \chi^c = \bar{\chi} (C^\dagger \Gamma C)^T \chi$

$$(C^\dagger \Gamma C)^T = -\Gamma \longrightarrow \bar{\chi} \Gamma \chi = -\bar{\chi} \Gamma \chi = 0$$

$$C^\dagger \gamma^\mu C = -(\gamma^\mu)^T, \quad C^\dagger \sigma^{\mu\nu} C = -(\sigma^{\mu\nu})^T,$$

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Next important operator, the **anapole**,
appears at dimension six.

$$\bar{\chi} \gamma_5 \gamma^\mu \chi \partial^\nu F_{\mu\nu} = - \sum_{q=u,d,s} e Q_q \mathcal{O}_{2,q}^{(6)} - \sum_{\ell=e,\mu,\tau} e Q_\ell \mathcal{O}_{2,\ell}^{(6)}, \quad \mathcal{O}_{2,q}^{(6)} = (\bar{\chi} \gamma_\mu \gamma_5 \chi) (\bar{q} \gamma^\mu q),$$

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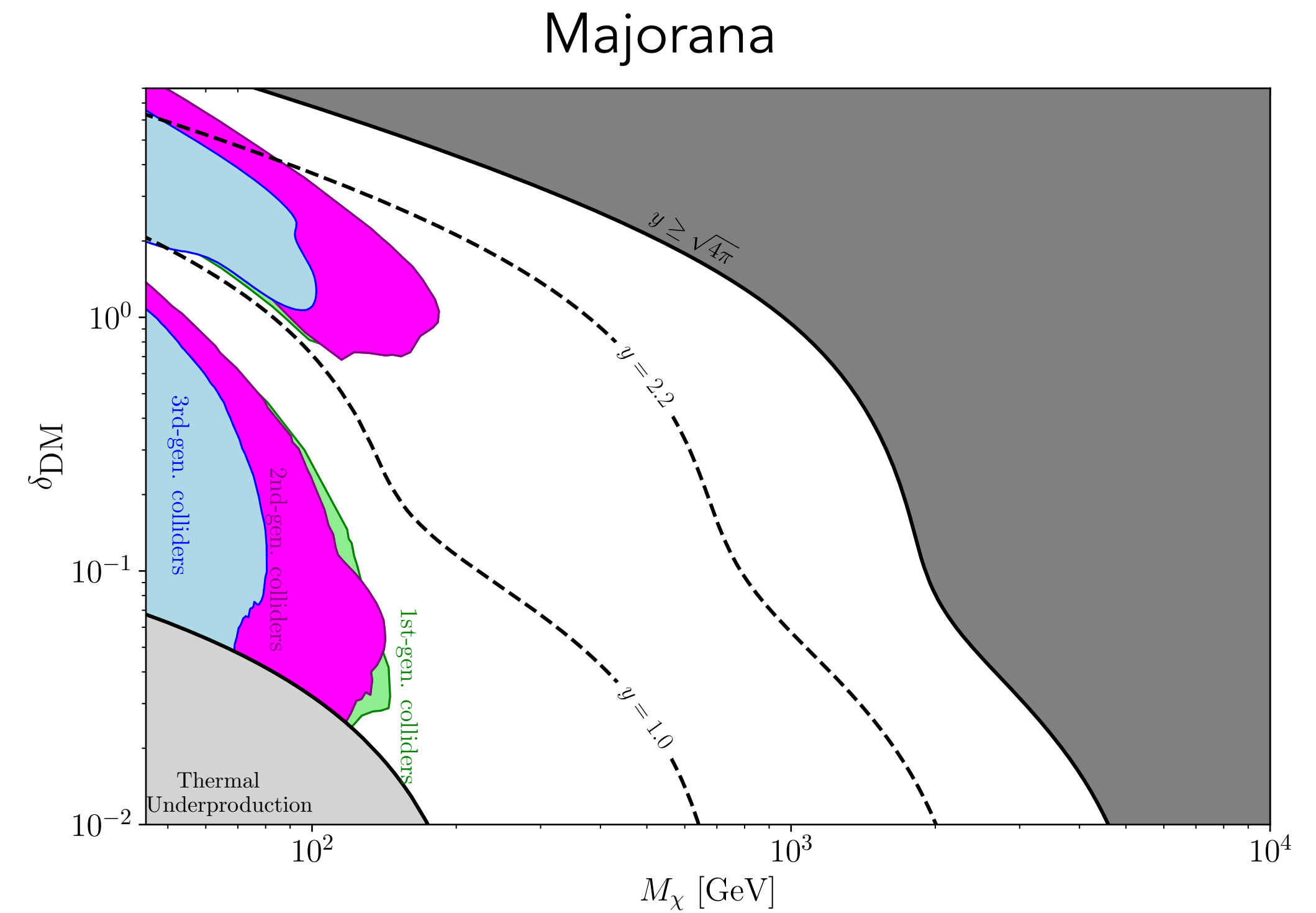
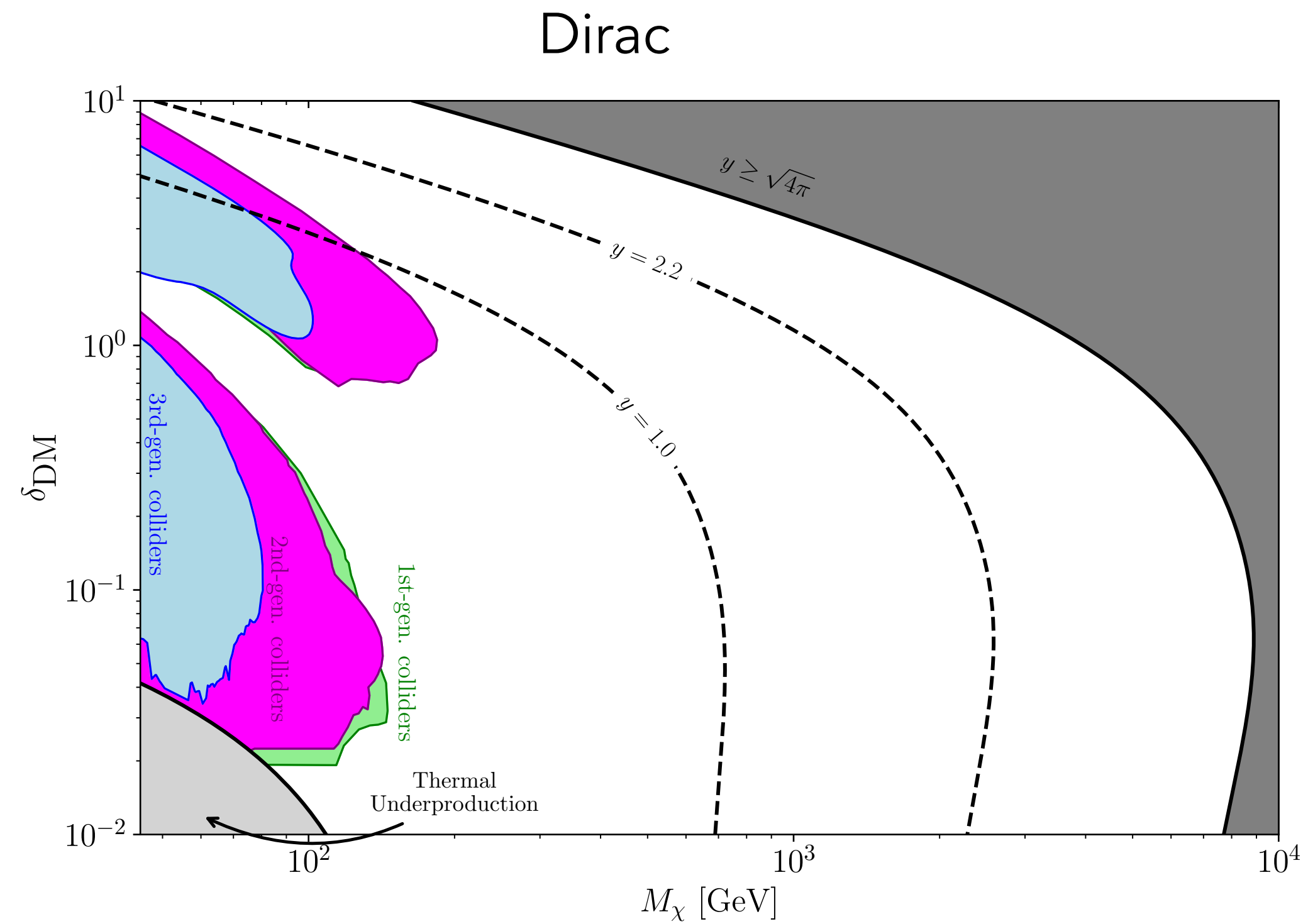
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$$\frac{d\sigma_{\chi N}^{\text{anapole}}}{dE_R} = 4\alpha_{\text{em}} \mathcal{A}^2 Z^2 [F_Z(E_R)]^2 \left[2m_N - \left(1 + \frac{m_N}{m_\chi} \right)^2 \frac{E_R}{v^2} \right] + 4\mathcal{A}^2 d_A^2 [F_s(E_R)]^2 \left(\frac{J+1}{3J} \right) \frac{2E_R m_N^2}{\pi v^2}$$

different scaling with recoil energy
coming from the matching to the NR effective theory

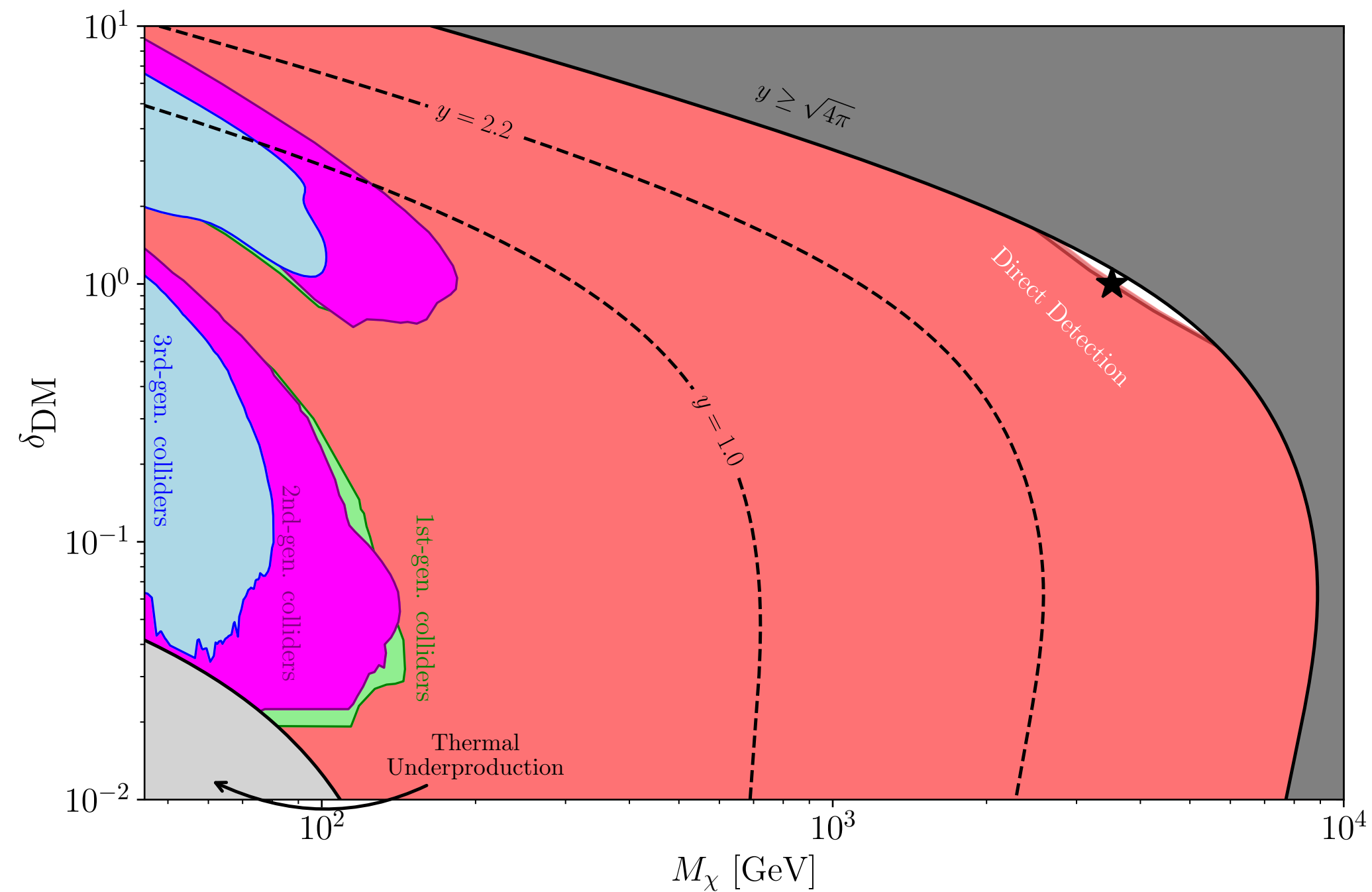
[Kopp, Michaels, Smirnov '14](#)

Leptophilic Dark Matter: Direct Detection



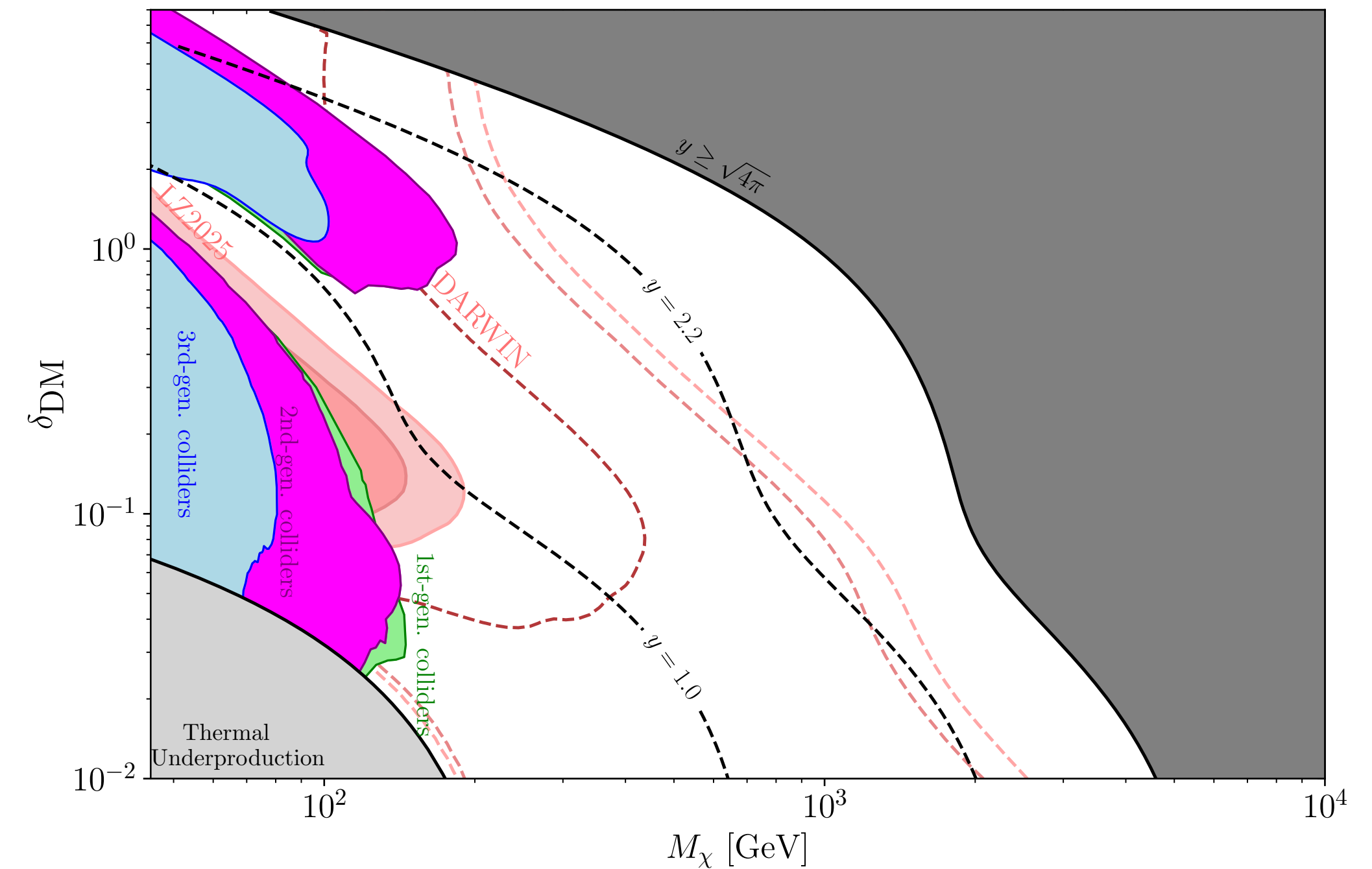
Leptophilic Dark Matter: Direct Detection

Dirac



Lighter **shades** of red correspond to **lighter** fermions.

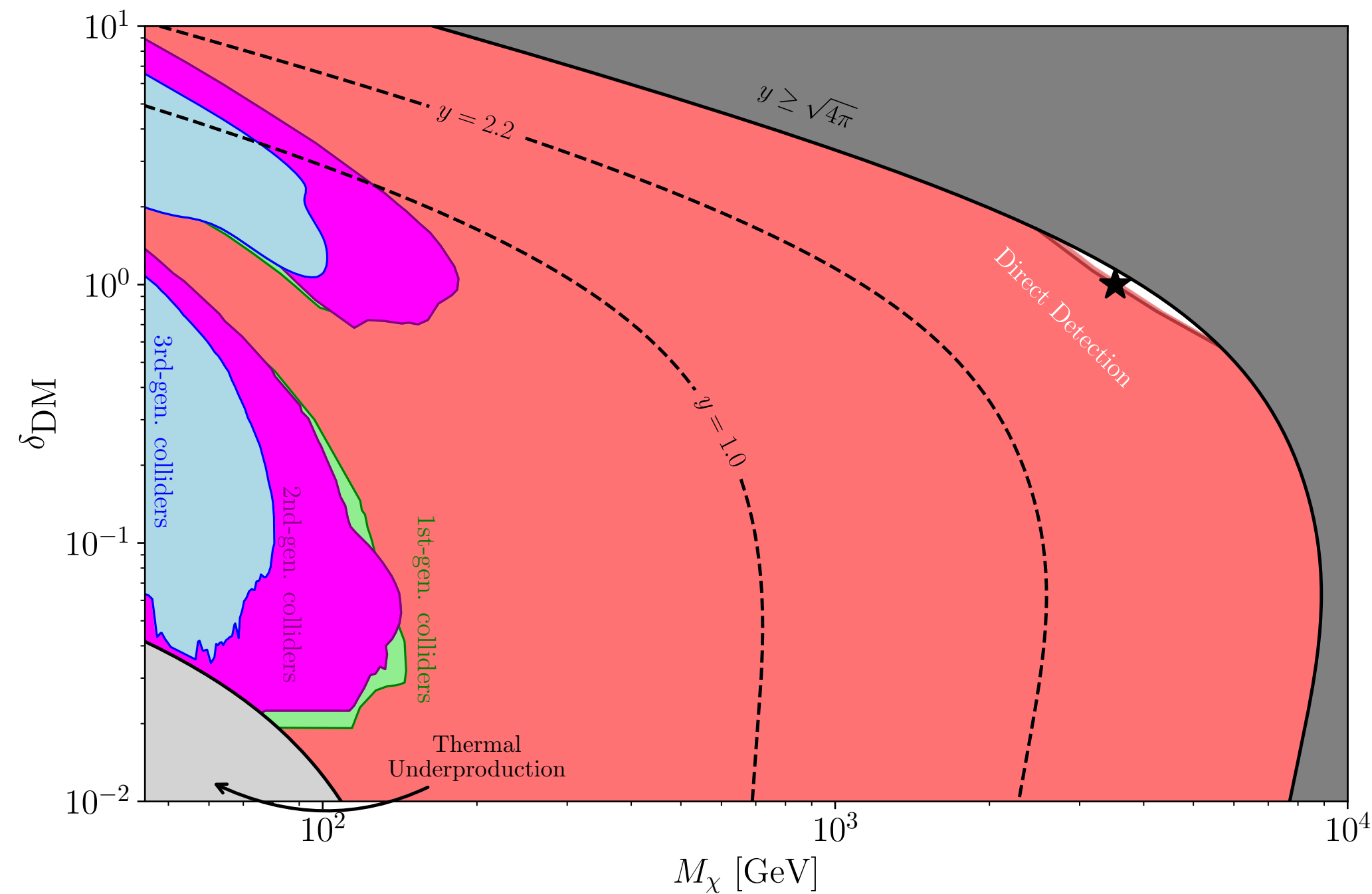
Majorana



Yukawas are **fixed** to reproduce the relic abundance at each point

Leptophilic Dark Matter: Direct Detection

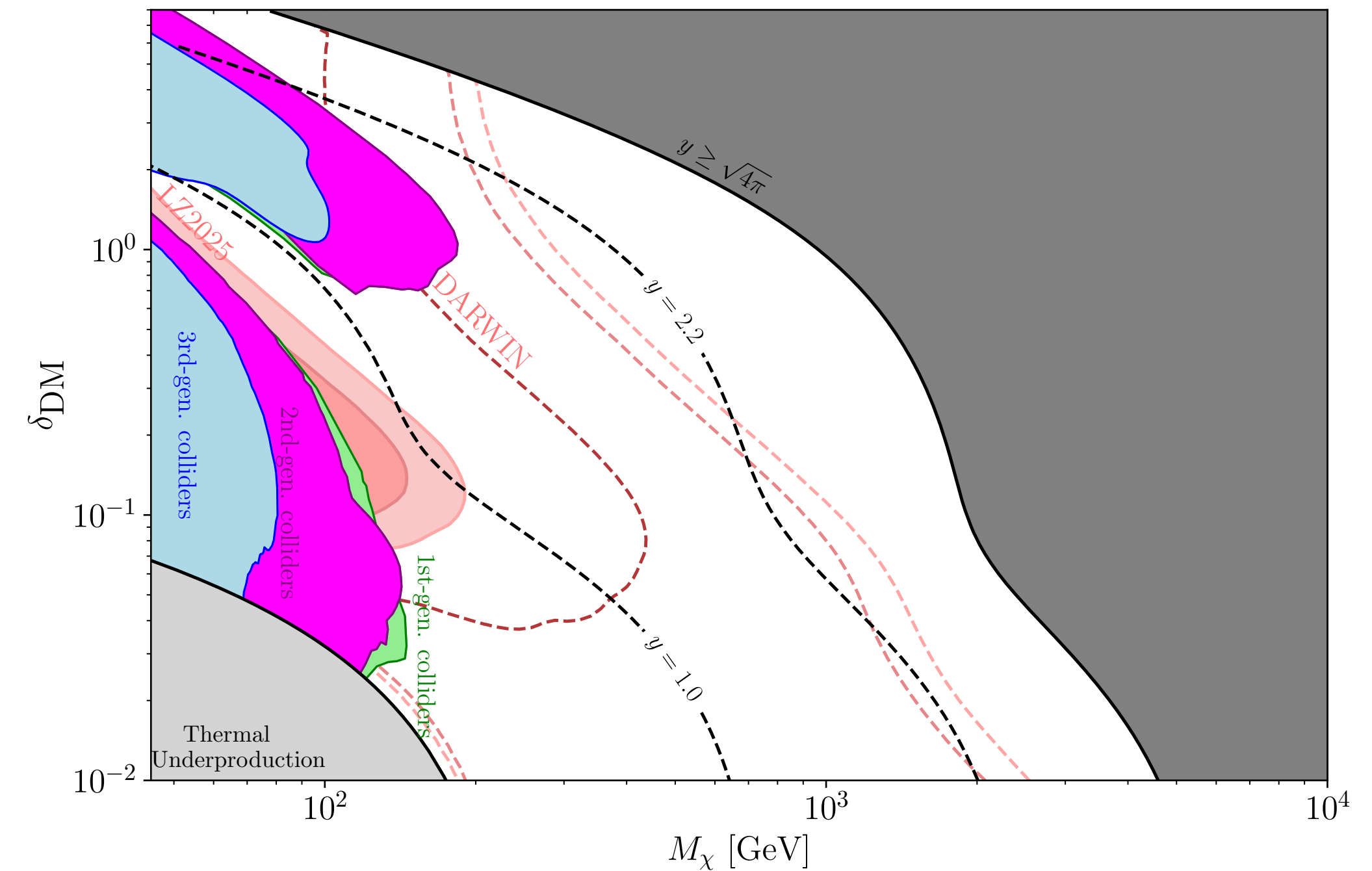
Dirac



Lighter **shades** of red correspond to **lighter** fermions.

Almost no dependence on the fermion mass for the Dirac case, dipole is almost no-sensitive.

Majorana

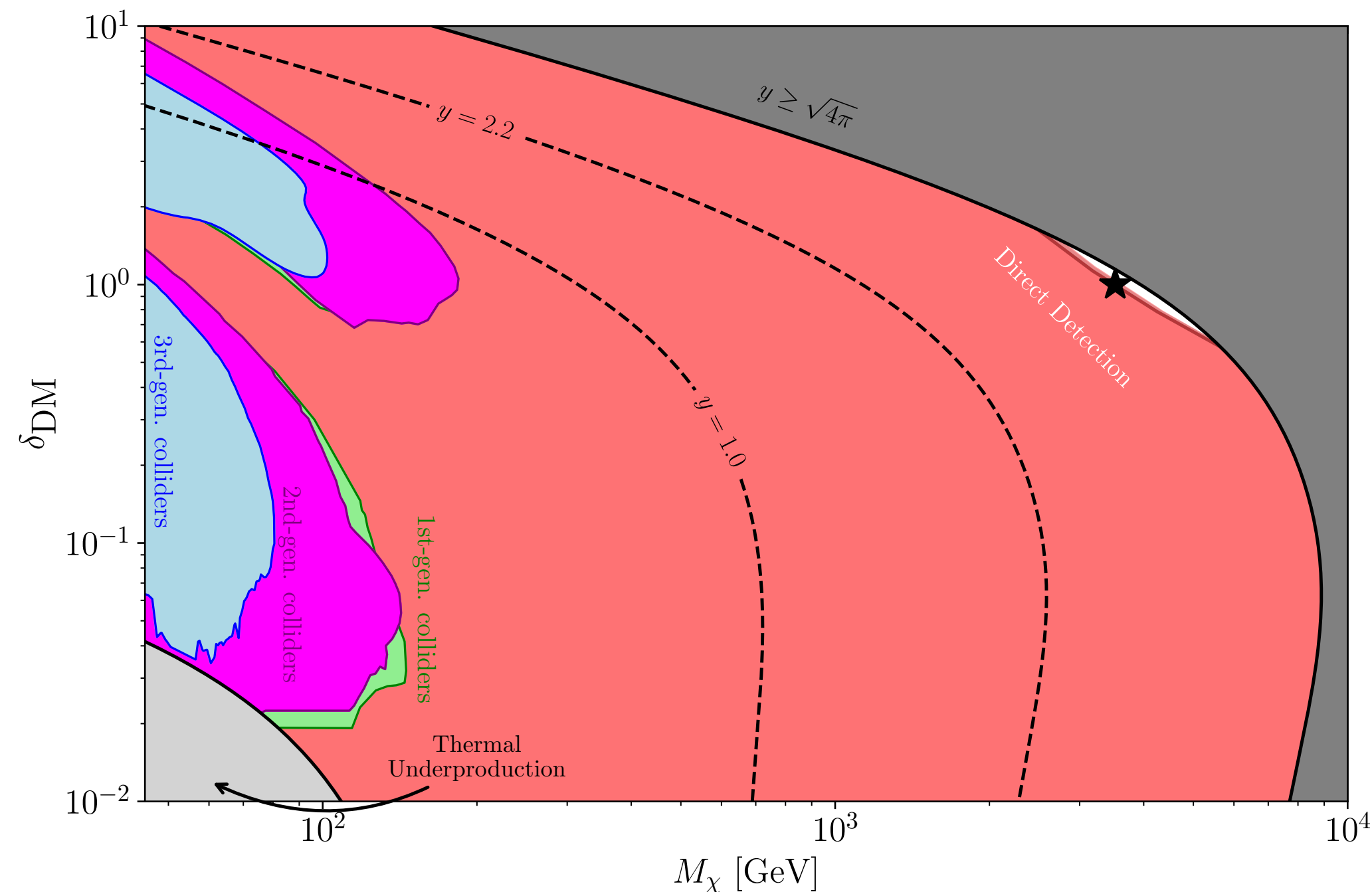


Yukawas are **fixed** to reproduce the relic abundance at each point

Anapole loop function is very dependent on the lepton mass, also larger in the degenerate limit.

Leptophilic Dark Matter: Direct Detection

Dirac



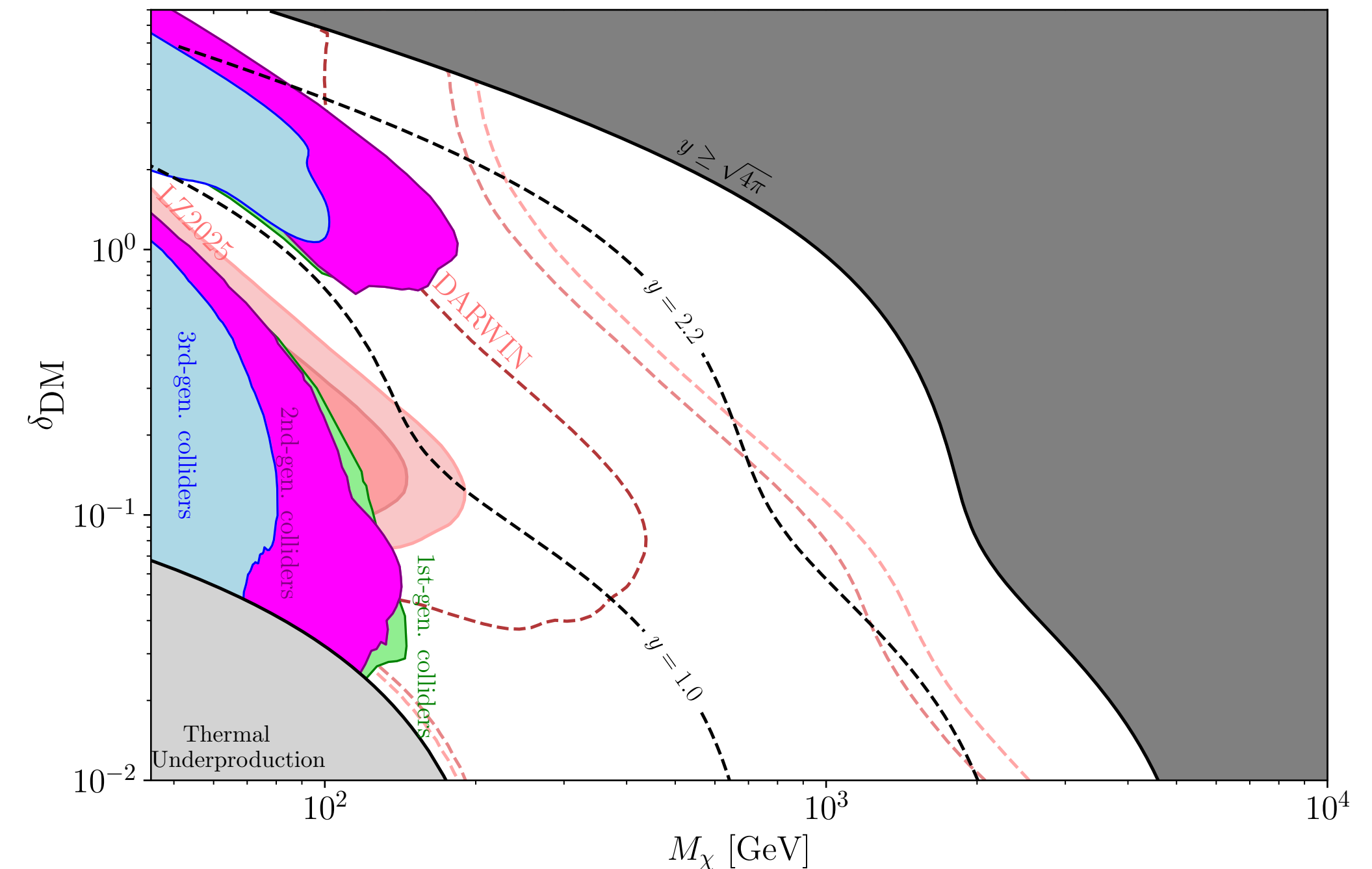
Lighter **shades** of red correspond to **lighter** fermions.

Almost no dependence on the fermion mass for the Dirac case, dipole is almost no-sensitive.

Anapoles are weaker than dipoles in general:

$$\frac{\mathcal{A}}{\mu_\chi} \sim \frac{1}{m_\chi} \quad \frac{d\sigma^{\text{anap.}}}{dE_R} / \frac{d\sigma^{\text{dip.}}}{dE_R} \sim \frac{m_N E_R}{m_\chi^2}$$

Majorana

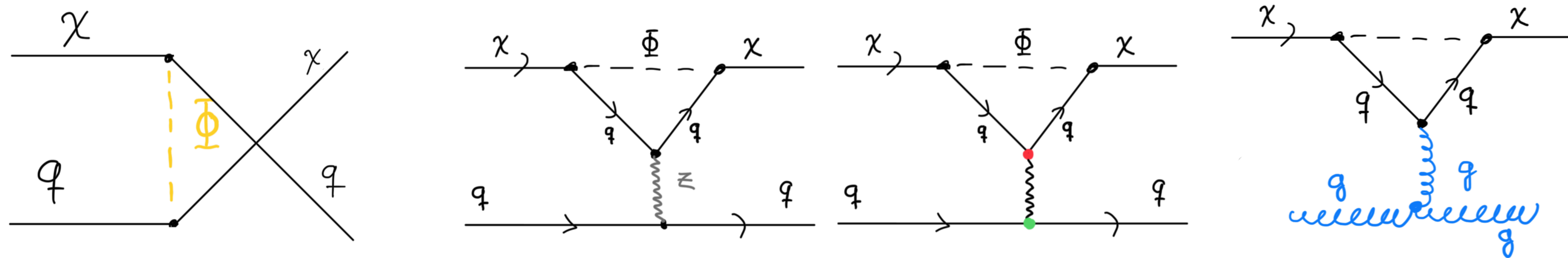


Yukawas are **fixed** to reproduce the relic abundance at each point

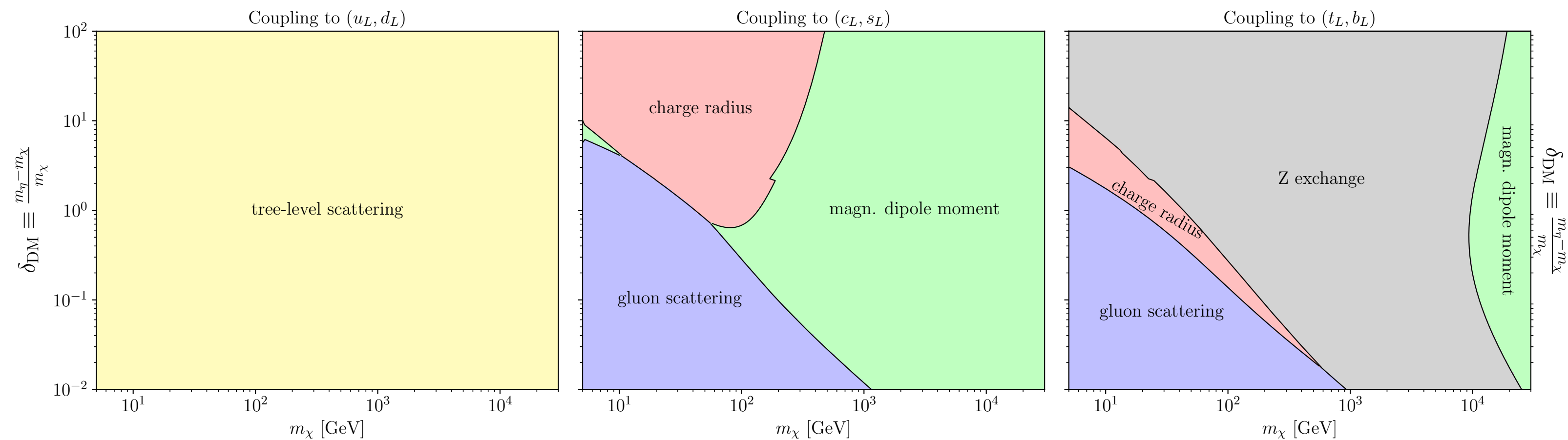
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Quarkphilic Dark Matter: Direct Detection

Dirac:



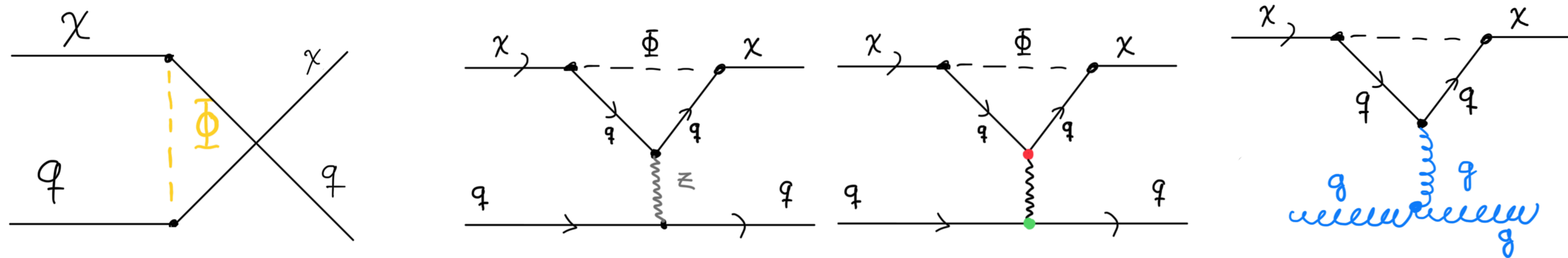
$$\mathcal{L} \supset (f_{V,Z}^{(N)} + f_{\text{tree}}^{(N)}) \bar{\chi} \gamma_\nu \chi \bar{N} \gamma_\nu N + b_\chi \bar{\chi} \gamma_\mu \chi \partial_\nu F^{\mu\nu} + \frac{\mu_\chi}{2} \bar{\chi} \sigma_{\mu\nu} \chi F^{\mu\nu} + f_{S,g}^{(N)} \bar{\chi} \chi \bar{N} N$$



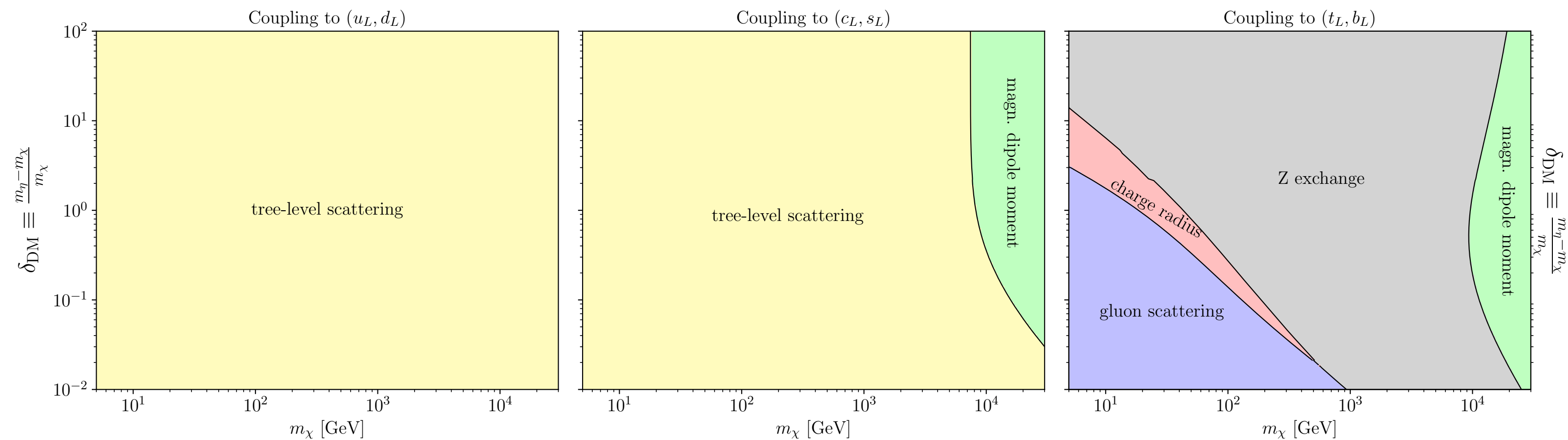
plots adapted from
[Ibarra, Wild '15](#)

Quarkphilic Dark Matter: Direct Detection

Dirac:



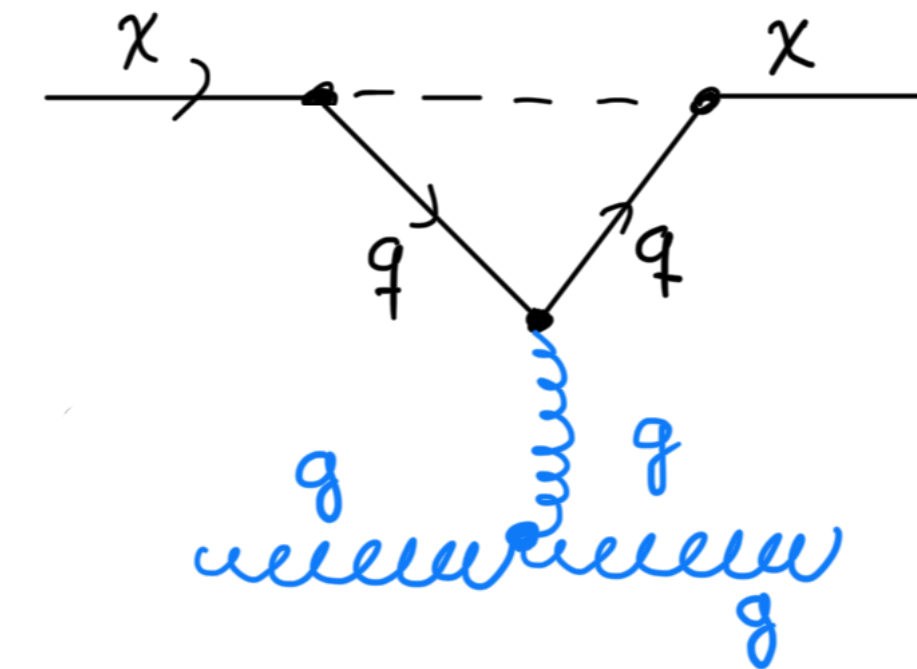
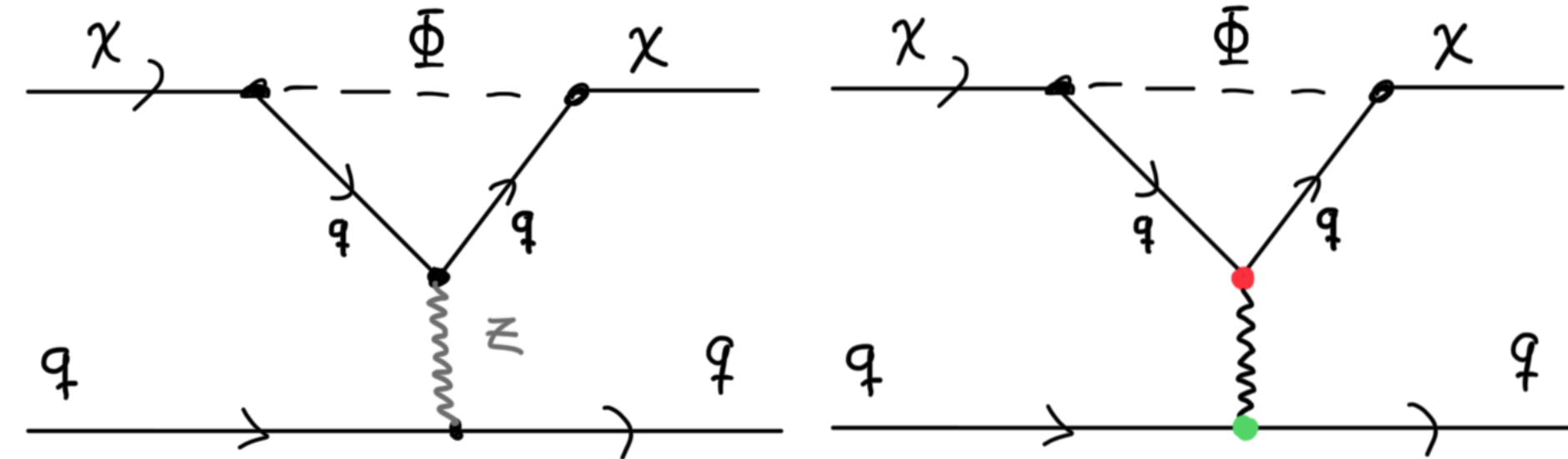
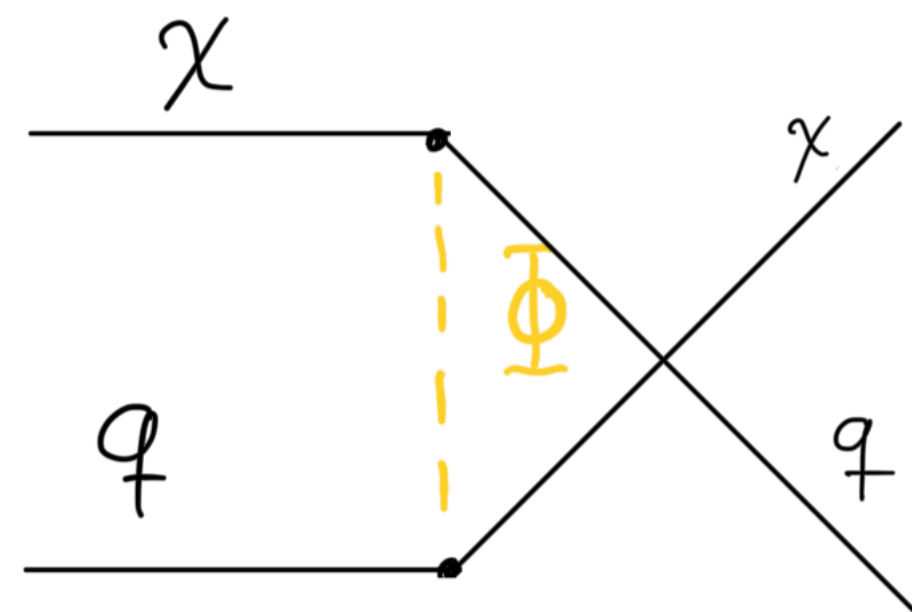
$$\mathcal{L} \supset (f_{V,Z}^{(N)} + f_{\text{tree}}^{(N)}) \bar{\chi} \gamma_\nu \chi \bar{N} \gamma_\nu N + b_\chi \bar{\chi} \gamma_\mu \chi \partial_\nu F^{\mu\nu} + \frac{\mu_\chi}{2} \bar{\chi} \sigma_{\mu\nu} \chi F^{\mu\nu} + f_{S,g}^{(N)} \bar{\chi} \chi \bar{N} N$$



plots adapted from
[Ibarra, Wild '15](#)

Quarkphilic Dark Matter: Direct Detection

Majorana:



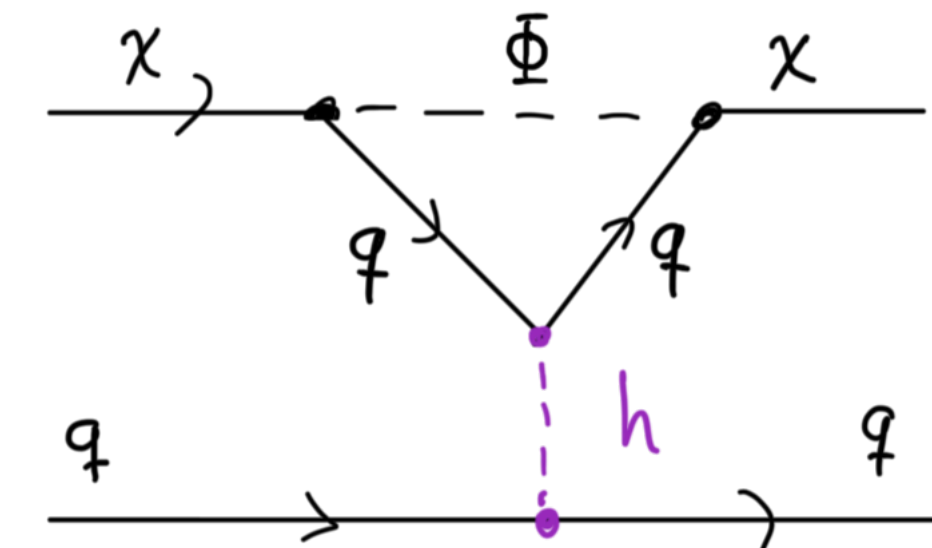
$$\mathcal{L} \supset (f_{V,Z}^{(N)} + f_{\text{tree}}^{(N)}) \bar{\chi} \gamma_\nu \chi \partial_\nu N + b_\chi \bar{\chi} \chi \partial_\nu F^{\mu\nu} + \frac{\mu_\chi}{2} \bar{\chi} \chi F^{\mu\nu} + f_{S,g}^{(N)} \bar{\chi} \chi \bar{N} N$$

$$\mathcal{L} \supset c_{d=8} \bar{\chi} \gamma_\mu D_\nu \chi \bar{q} \gamma^\mu D^\nu q + c_A \bar{\chi} \gamma_\mu \gamma_5 \chi \bar{q} \gamma^\mu \gamma_5 q + (f_{S,g}^{(N)} + f_{S,H}^{(N)}) \bar{\chi} \chi \bar{N} N$$

First contribution to the spin independent appears at dimension-8

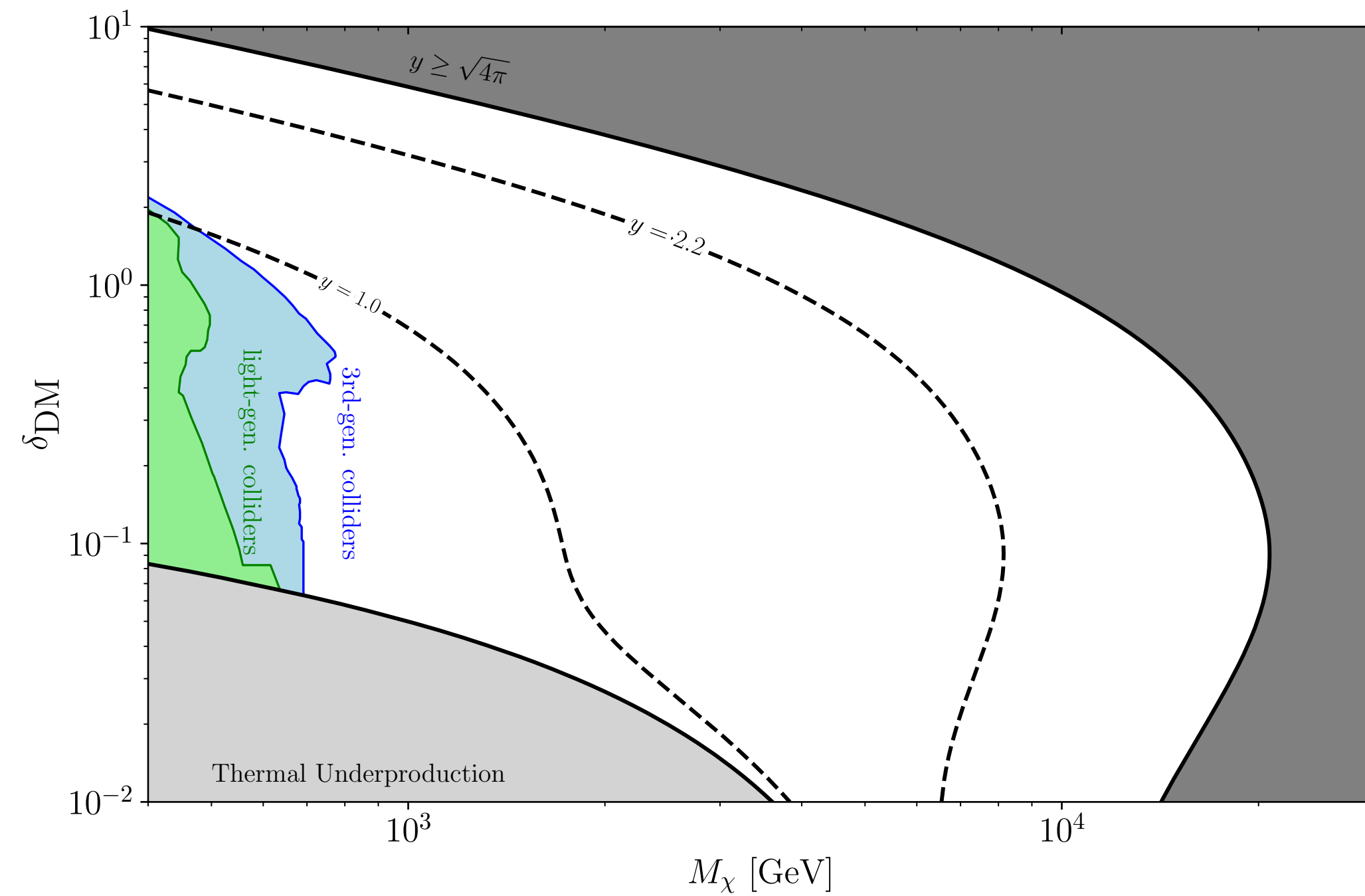
Dimension-6 spin-dependent contribution

Higgs contribution can be important for top-coupling at large masses

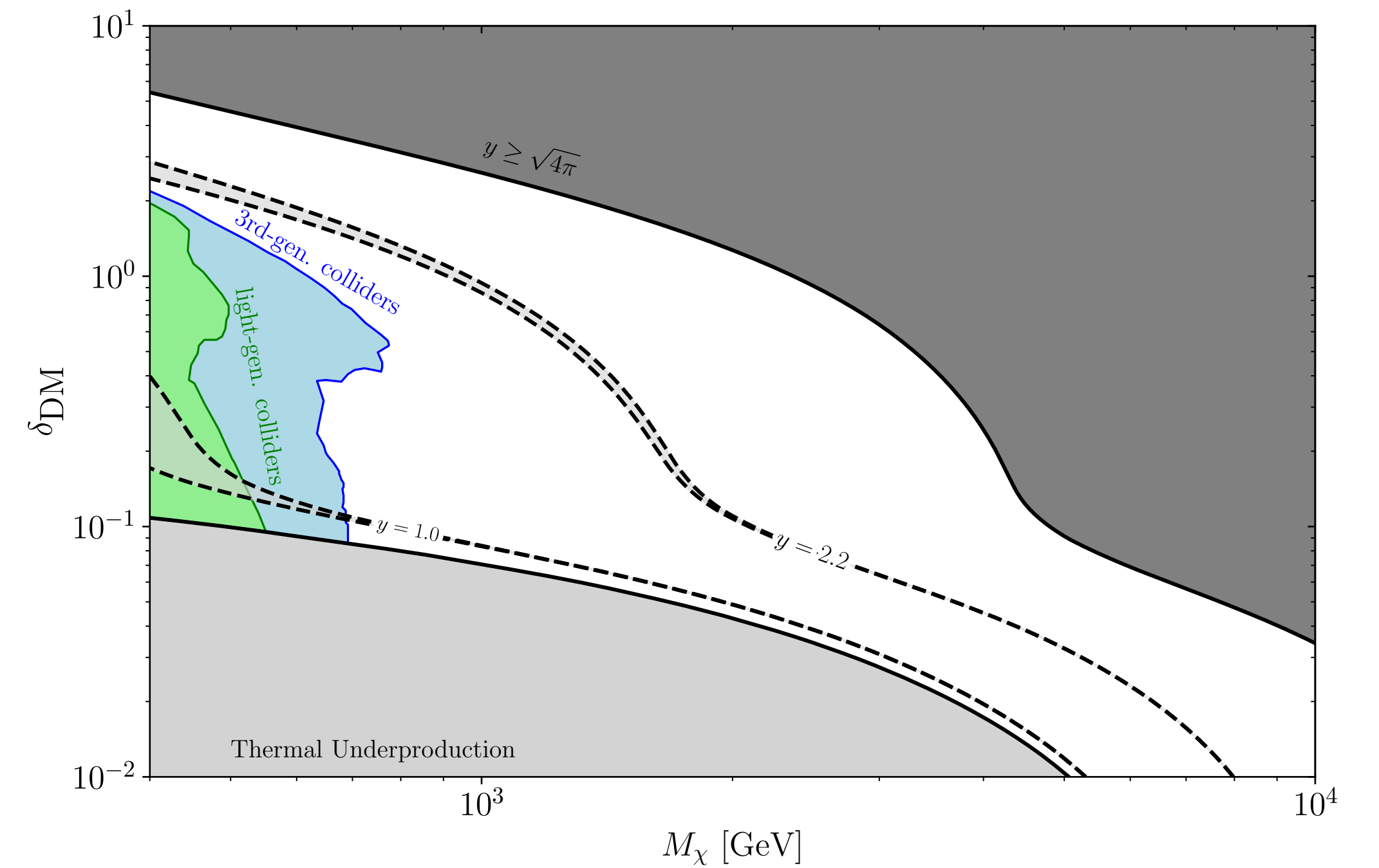


Quarkphilic Dark Matter: Direct Detection

Dirac

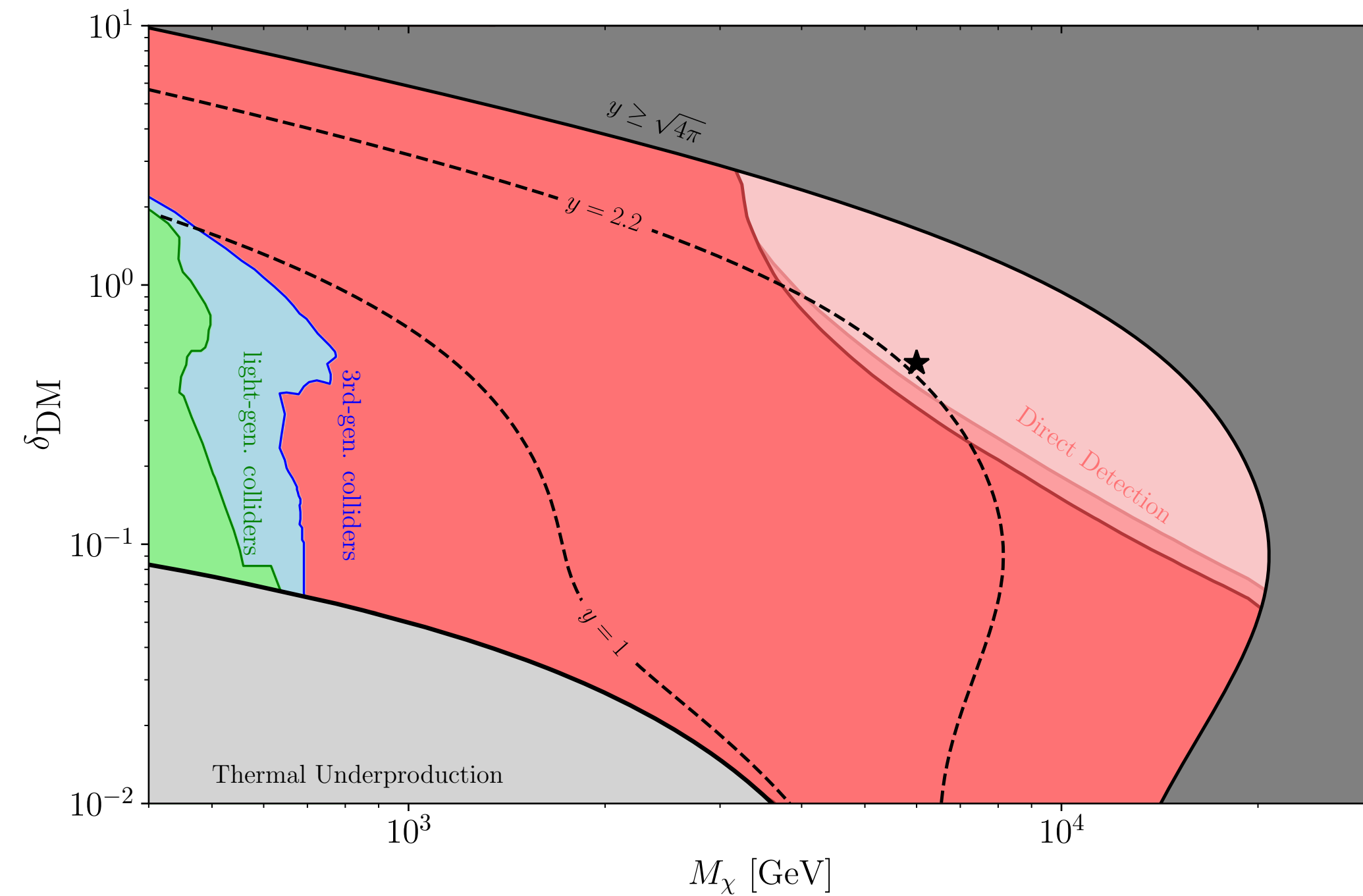


Majorana

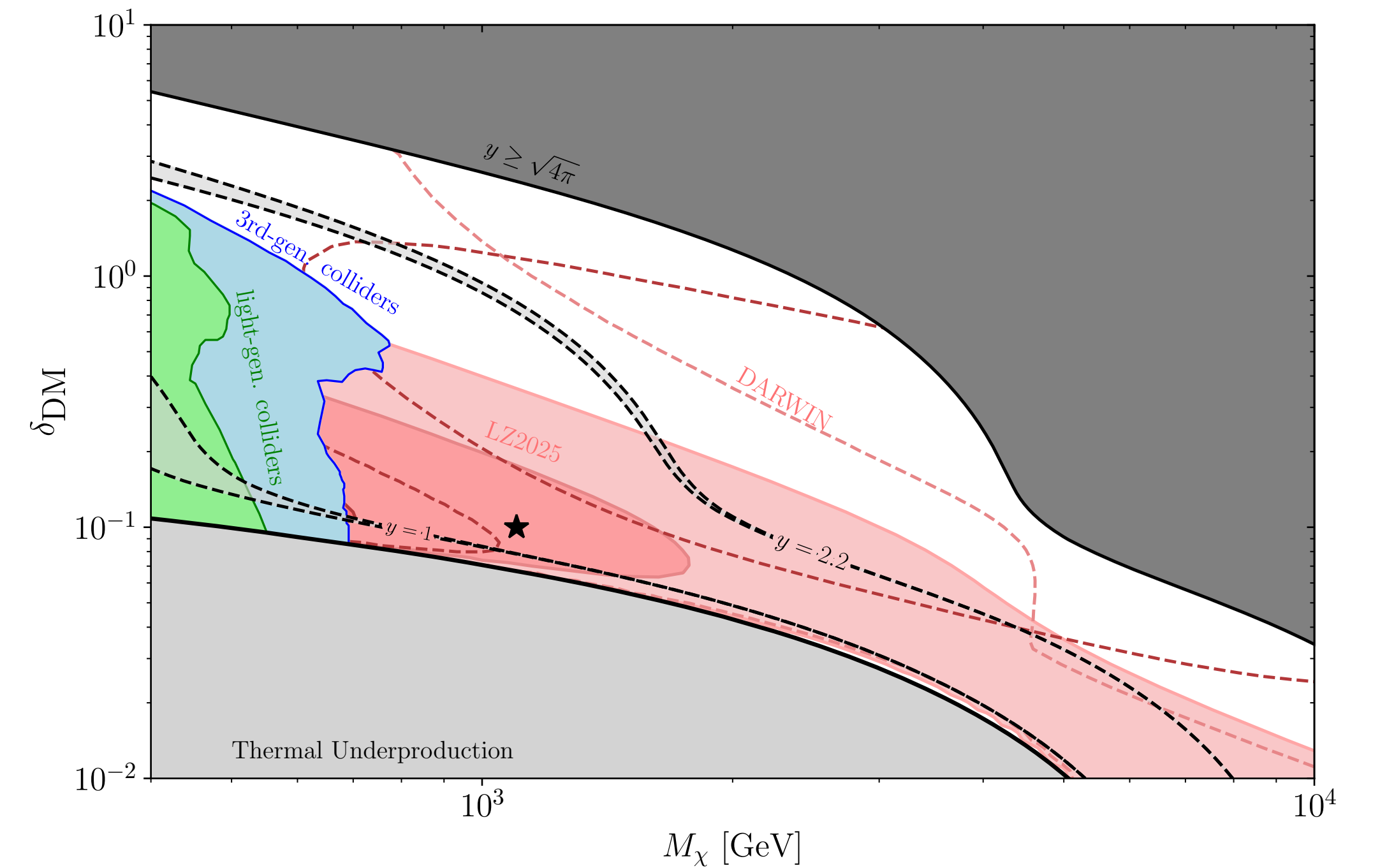


Quarkphilic Dark Matter: Direct Detection

Dirac

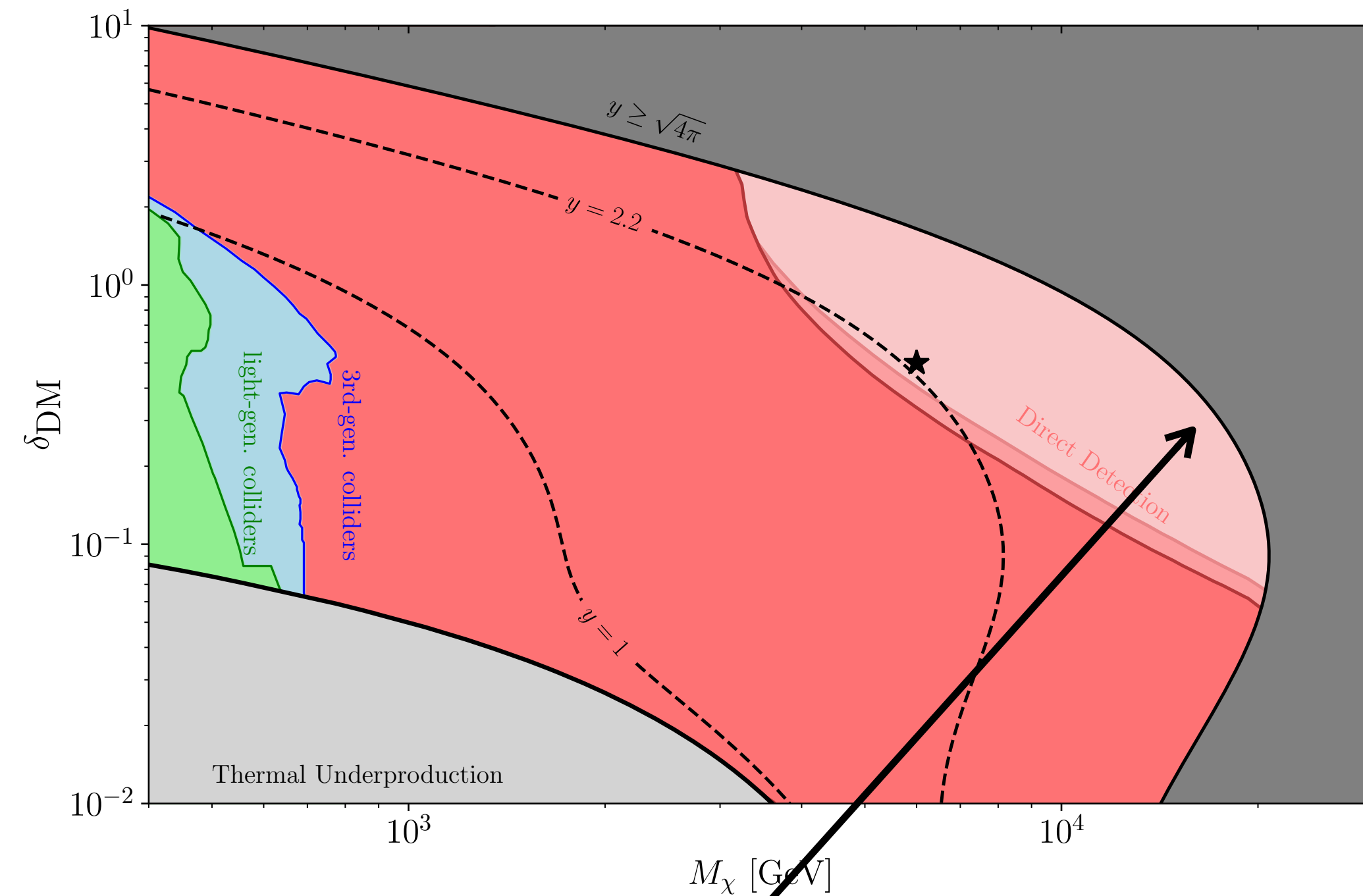


Majorana

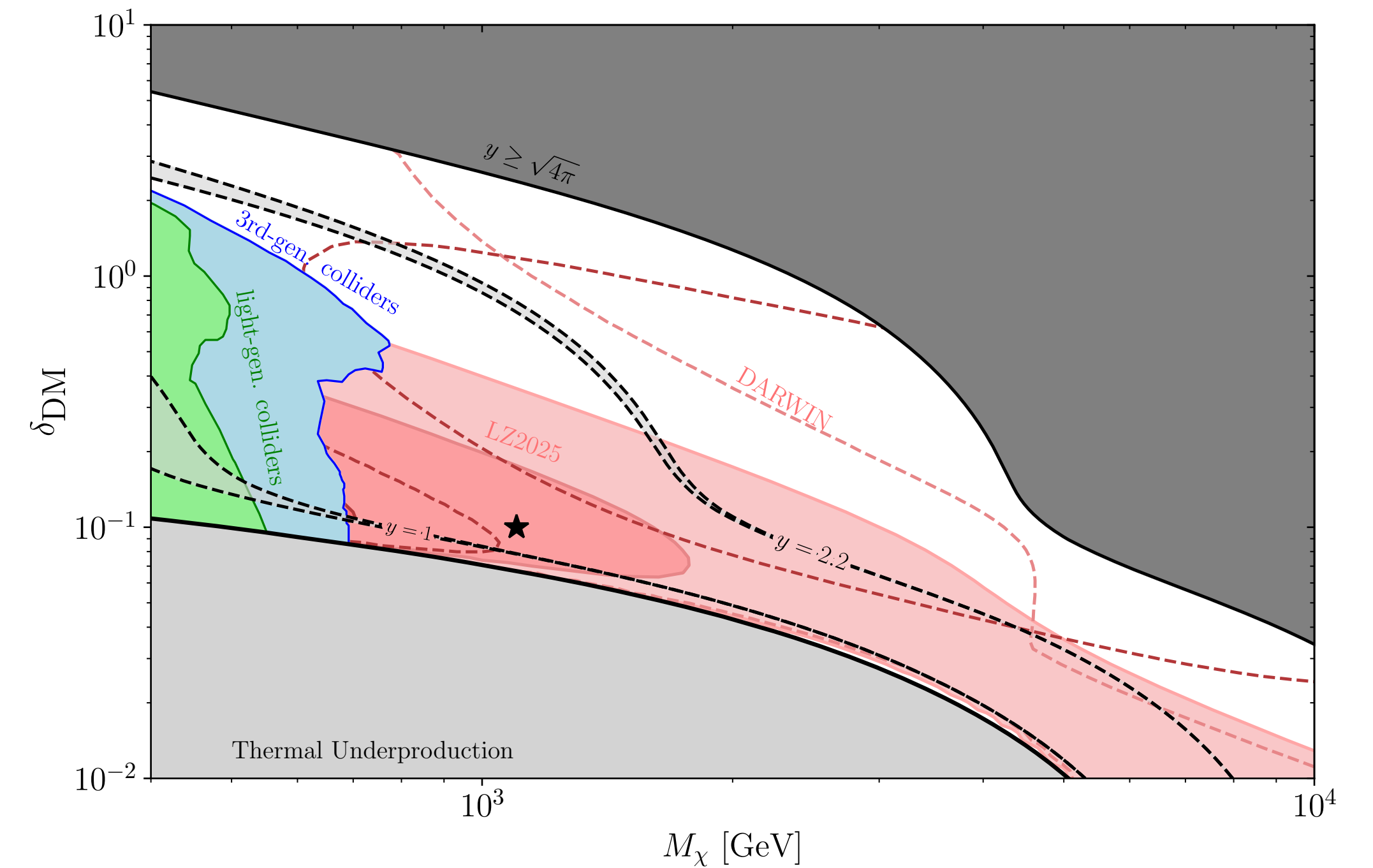


Quarkphilic Dark Matter: Direct Detection

Dirac



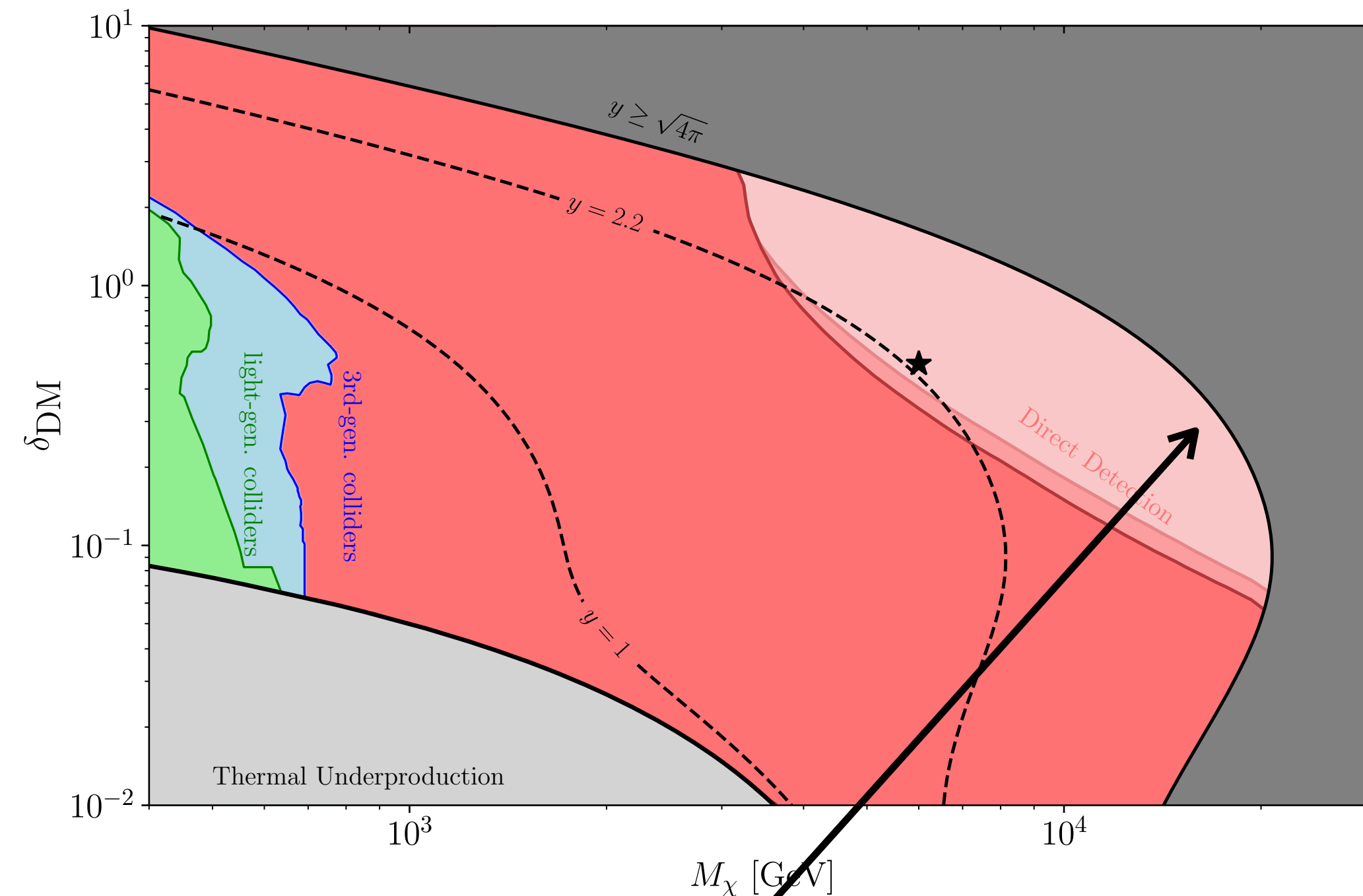
Majorana



For first family, tree-level exchange is completely ruled out in the Dirac case

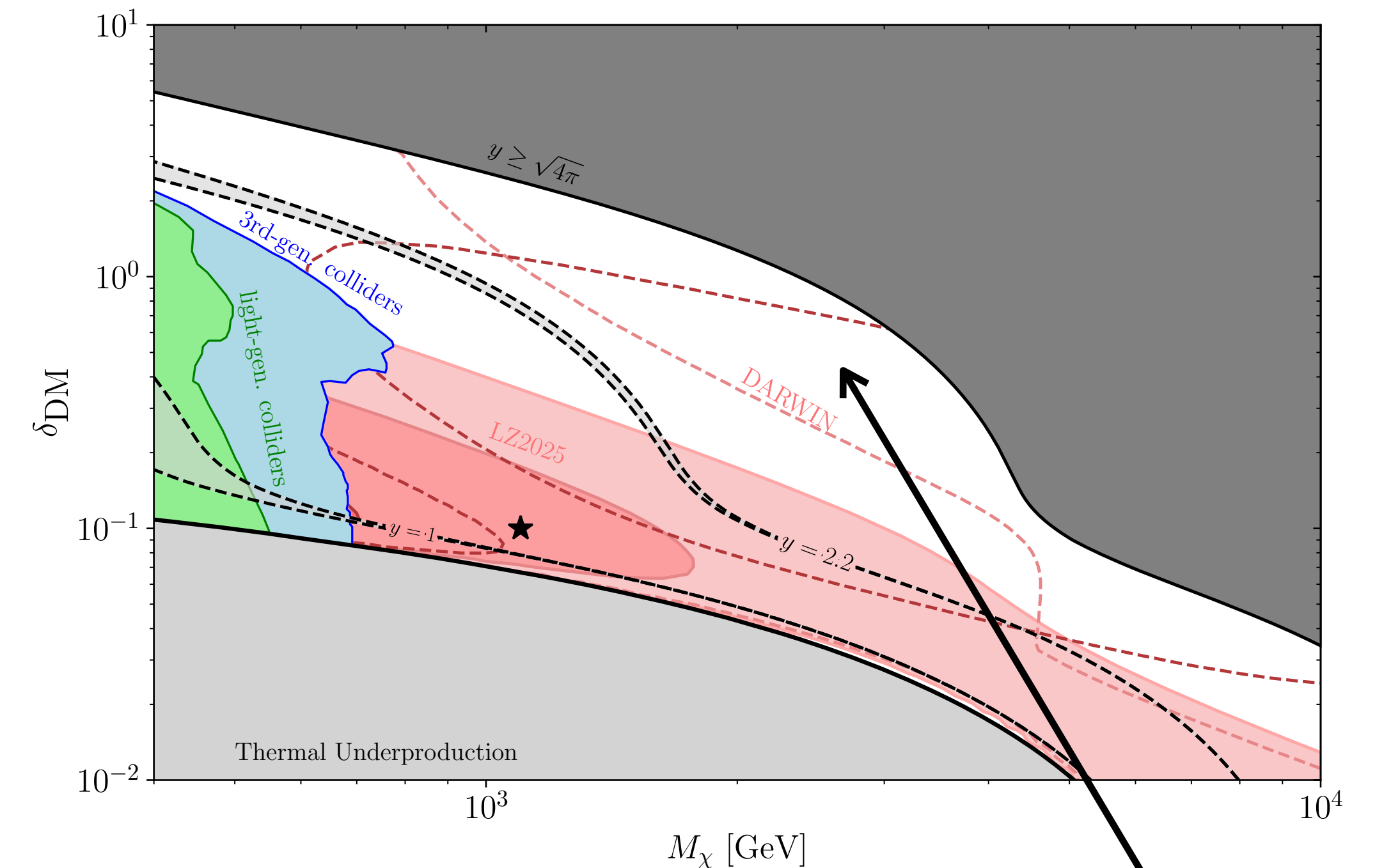
Quarkphilic Dark Matter: Direct Detection

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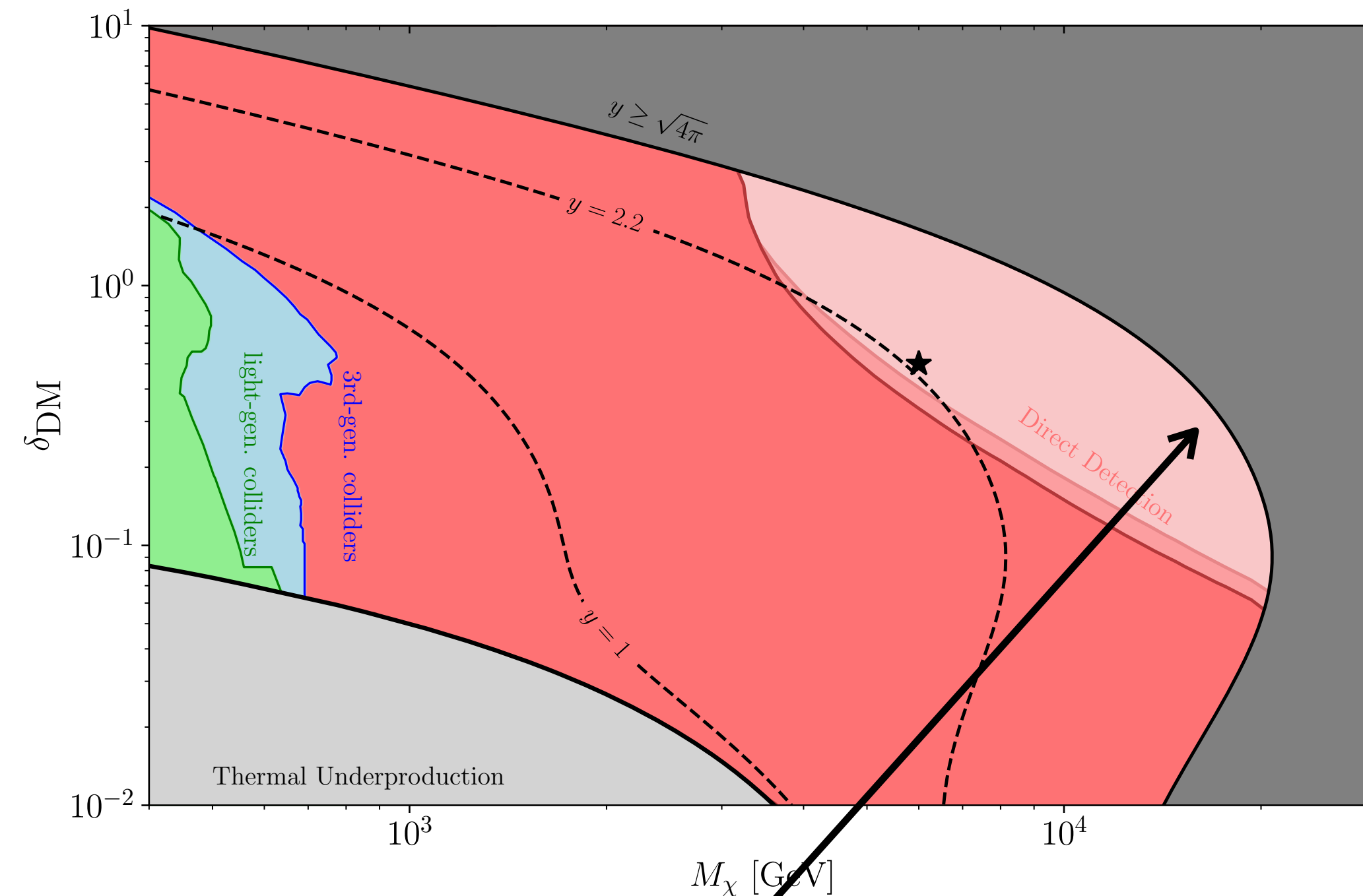
Majorana



Higgs diagram, relevant most relevant for the top coupling

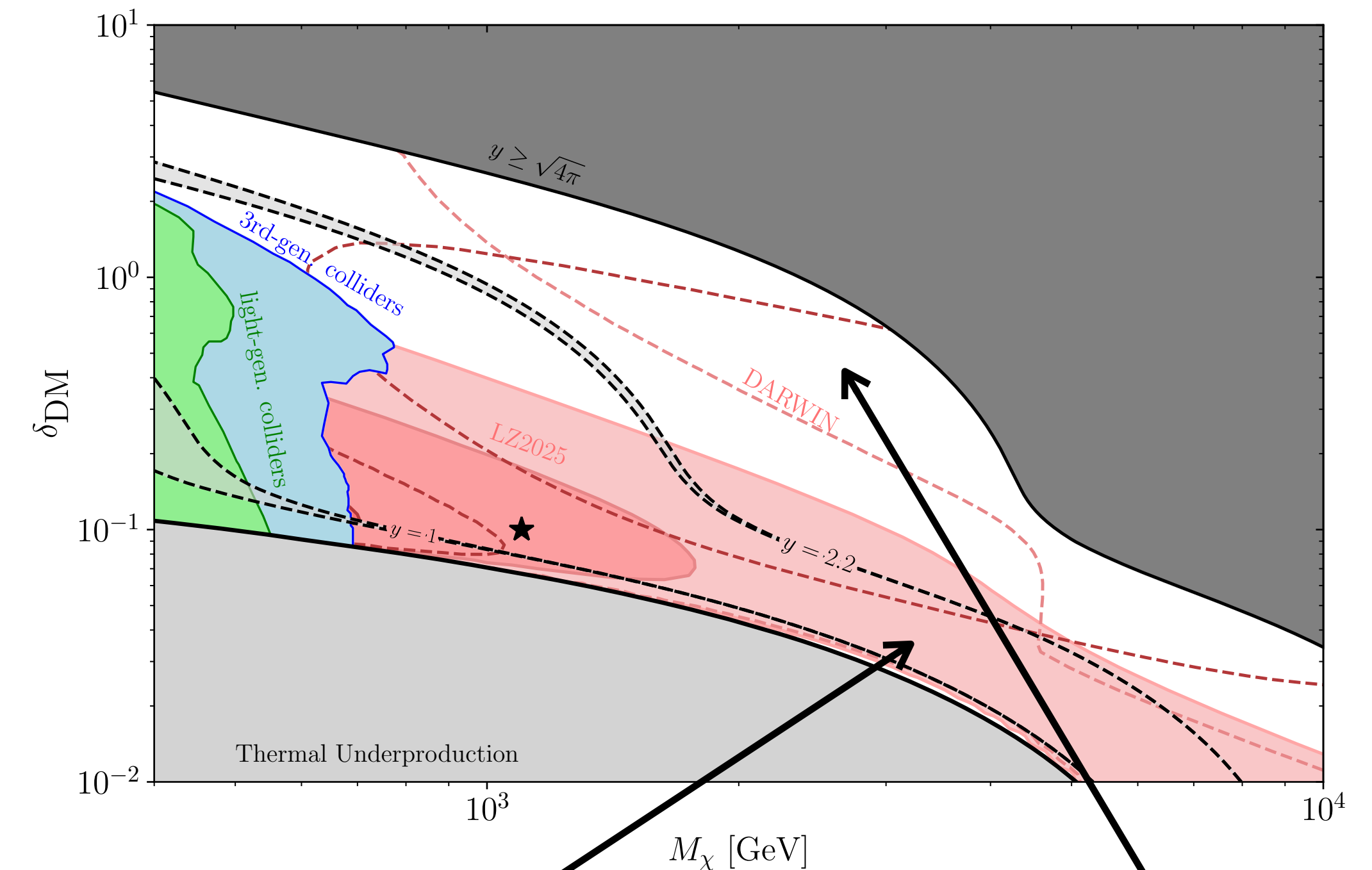
Quarkphilic Dark Matter: Direct Detection

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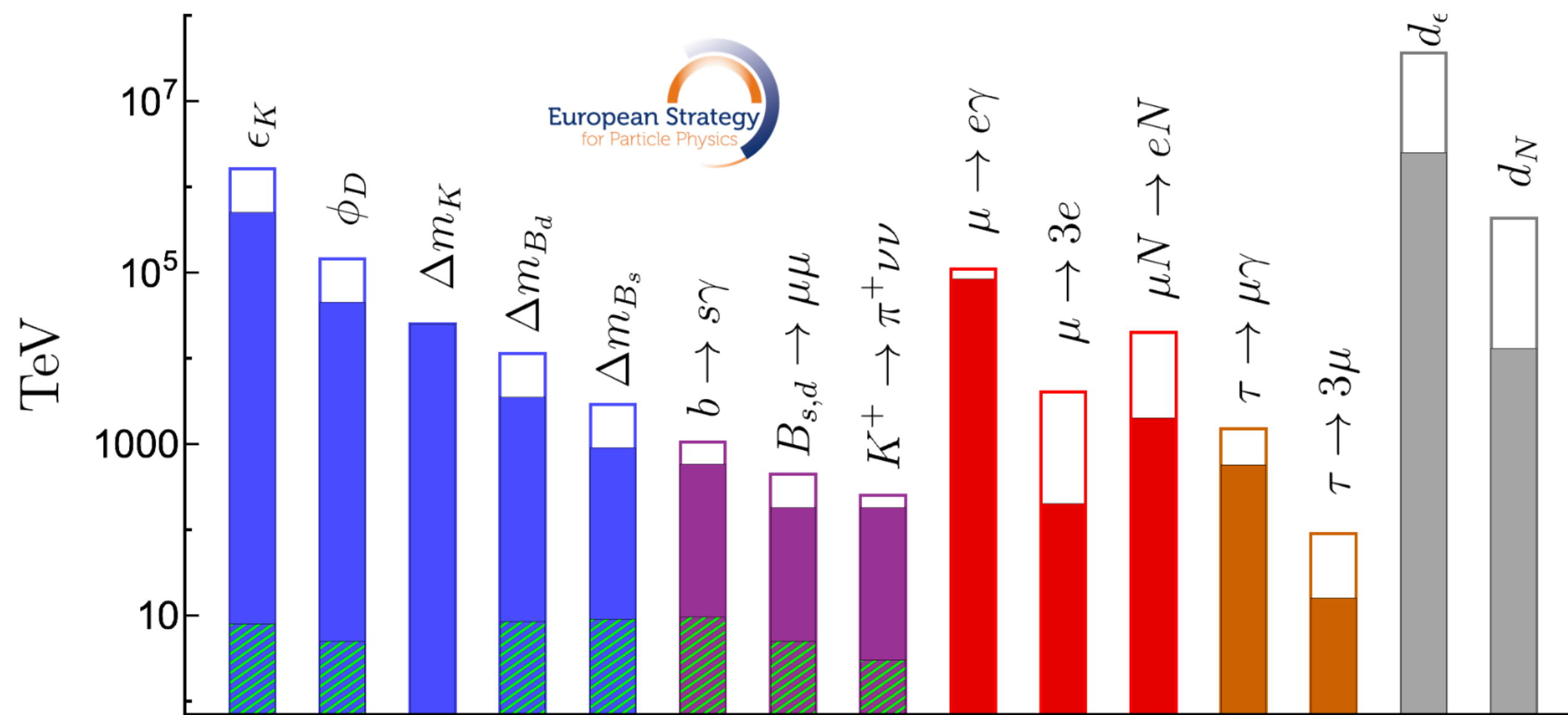


Tree-level exchange is enhanced for small splittings. The SI cross-section constrains smaller splittings. At larger splittings, SD cross-section sets the strongest bounds.

Higgs diagram, relevant most relevant for the top coupling

Leptophilic Dark Matter: Flavour Bounds

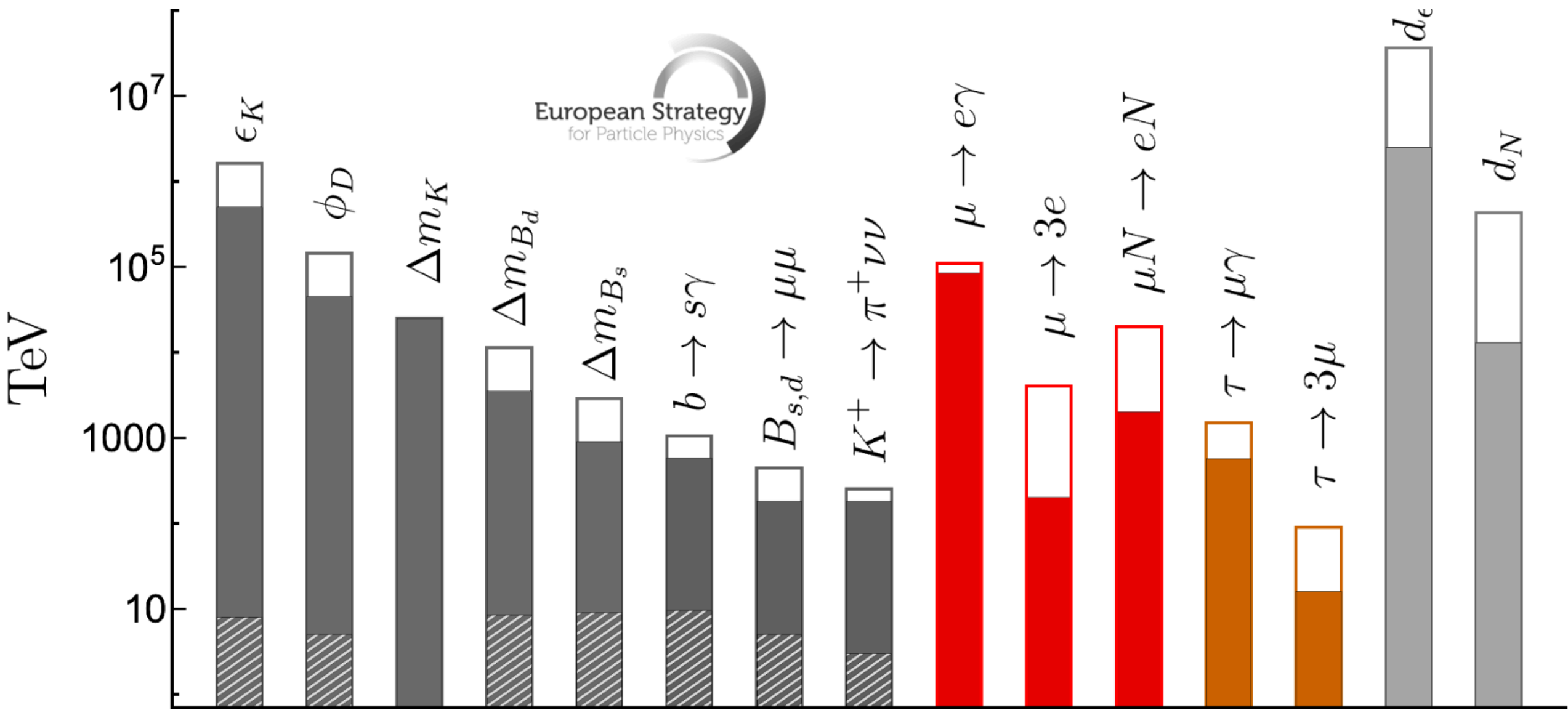
Present and future of the “most important” flavour observable:



from [Physics Briefing book 25](#)

Leptophilic Dark Matter: Flavour Bounds

Present and future of the “most important” flavour observable:



Big landscape of present and future experiments in the sector of Lepton observables.

Observable	Present	Future
$\text{BR}(\mu \rightarrow e\gamma)$	4.2×10^{-13} MEG	6×10^{-14} Meg-II
$\text{BR}(\mu \rightarrow 3e)$	10^{-12} SINDRUM	10^{-16} Mu3e
$\text{CR}(\mu N \rightarrow eN)$	7×10^{-13} SINDRUM II	$10^{-16} - 10^{-17}$ COMET/Mu2e
$\text{BR}(\tau \rightarrow \mu\gamma)$	4.8×10^{-8} Belle	10^{-9} FCC-ee
$\text{BR}(\tau \rightarrow e\gamma)$	3.3×10^{-8} Belle(LHCb)	9×10^{-9} Belle-II
$\text{BR}(\tau \rightarrow 3\mu)$	2.1×10^{-8} belle-II	2×10^{-11} FCC-ee
$d_e [e \cdot \text{cm}]$	5×10^{-30} HfF+	$10^{-31} - 10^{-32}$ Several Exp.

from [Physics Briefing book 25](#)

Leptophilic Dark Matter: Observables

from [Fernández-Martínez, Marcano, Naredo-Tuero](#)

Most important LFV observables $\mu \ll v_{ew}$,
we must match into the Low-energy EFT

3-body decays: $\ell_i \rightarrow \ell_j \ell_k \bar{\ell}_k$

$$\text{BR}(\ell_i \rightarrow \ell_j \ell_k \bar{\ell}_k) = \frac{N_c m_{\ell_i}^5}{3(16\pi)^3 \Gamma_{\ell_i}} \left\{ 8|C^{VRR}|^2 + 8|C^{VLR}|^2 + 8|C^{VRL}|^2 \right. \\ \left. + \frac{256e^2}{m_{\ell_i}^2} \left(\log \frac{m_{\ell_i}^2}{m_{\ell_k}^2} - 3 \right) (|C_{\gamma}^{ji}|^2 + |C_{\gamma}^{ij}|^2) \right. \\ \left. - \frac{64e}{m_{\ell_i}} \text{Re} \left[C^{VLR} C_{\gamma}^{ji*} + (C^{VRR} + C^{VRL}) C_{\gamma}^{ij} \right] \right\},$$

$N_c = 1/2, j=k$

$$C^{VRR} = 2s_w^2 C_{He}^{ji} + C_{ee}^{jikk},$$

$$C^{VLR} = C_{le}^{jikk},$$

$$C^{VRL} = (2s_w^2 - 1) C_{He}^{ji} + C_{le}^{kkji},$$

$$C_{\gamma}^{ij} = \frac{v}{\sqrt{2}} c_w C_{eB}^{ij}$$

Degenerate limit
suppressed for Majorana

Radiative-decays: $\ell_i \rightarrow \ell_j \gamma$

$$\text{BR}(\ell_i \rightarrow \ell_j \gamma) = \frac{m_{\ell_i}^3 c_w^2 v^2}{8\pi \Gamma_{\ell_i}} \left(|[C_{eB}]_{ji}|^2 + |[C_{eB}]_{ij}|^2 \right),$$

$\mu \rightarrow e$ conversion:

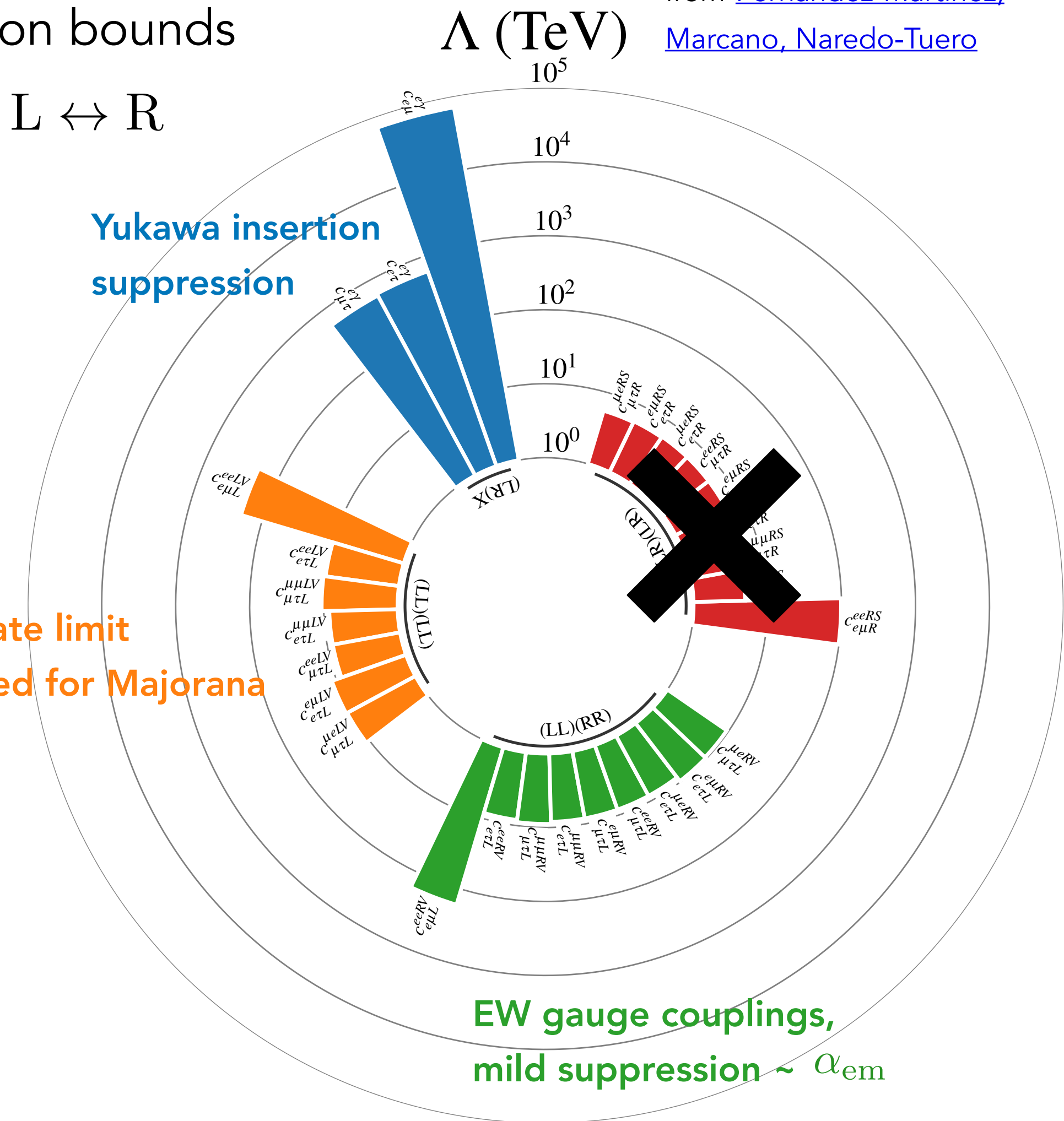
$$\Gamma_{\mu \rightarrow e} = \frac{m_{\mu}^5}{4} \left| \tilde{C}_{VR}^p 4V_{Au}^p \right|^2 + L \leftrightarrow R$$

$$\tilde{C}_{VR}^p = 4(1 - s_w^2) [C_{eH}]_{\mu e}$$

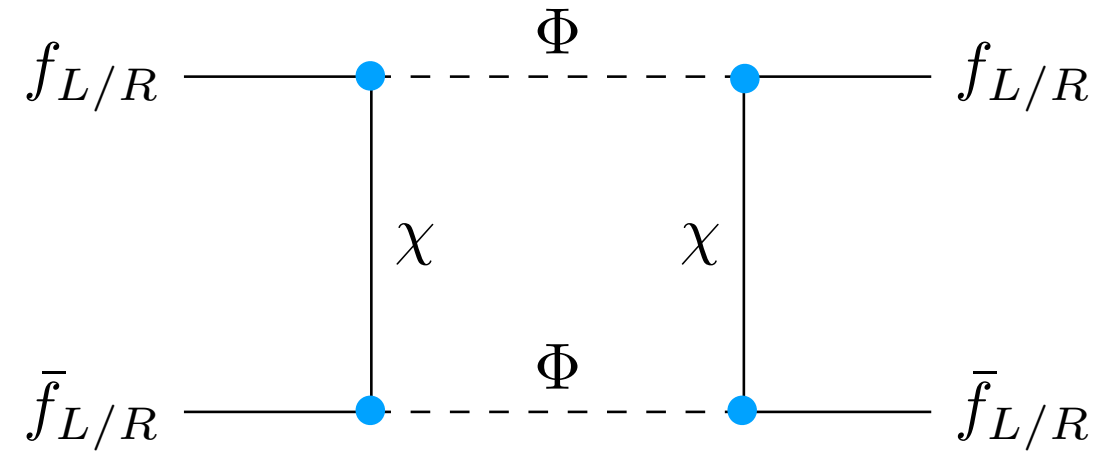
lepton bounds

$L \leftrightarrow R$

Yukawa insertion
suppression

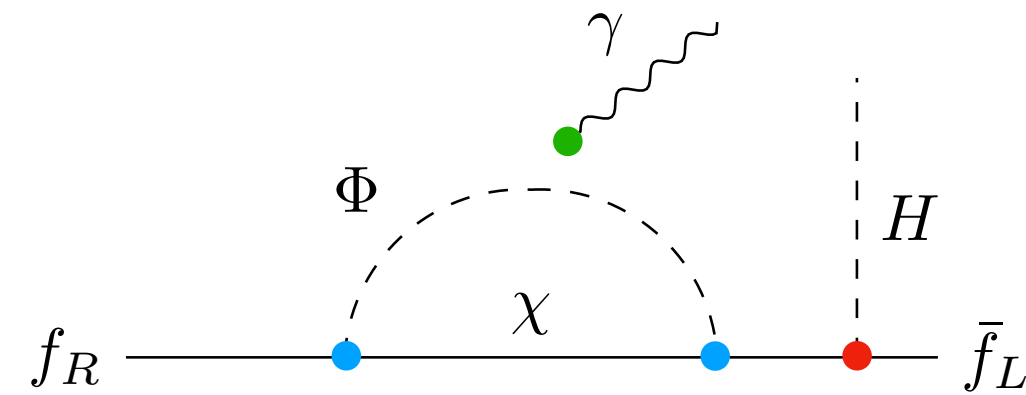


Leptophilic Dark Matter



- Four-fermion operators: $\mathcal{L}_{\text{EFT}}^e \supset [\mathcal{C}_{ee}]_{ijkl} \bar{e}_i \gamma^\mu e_j \bar{e}_k \gamma_\mu e_l$

$$[C_{ee}]_{ijkl} = \frac{1}{64\pi^2 M_\Phi^2} - \frac{1}{2} y_i y_j^* y_k y_l^* F(x_\Phi)$$

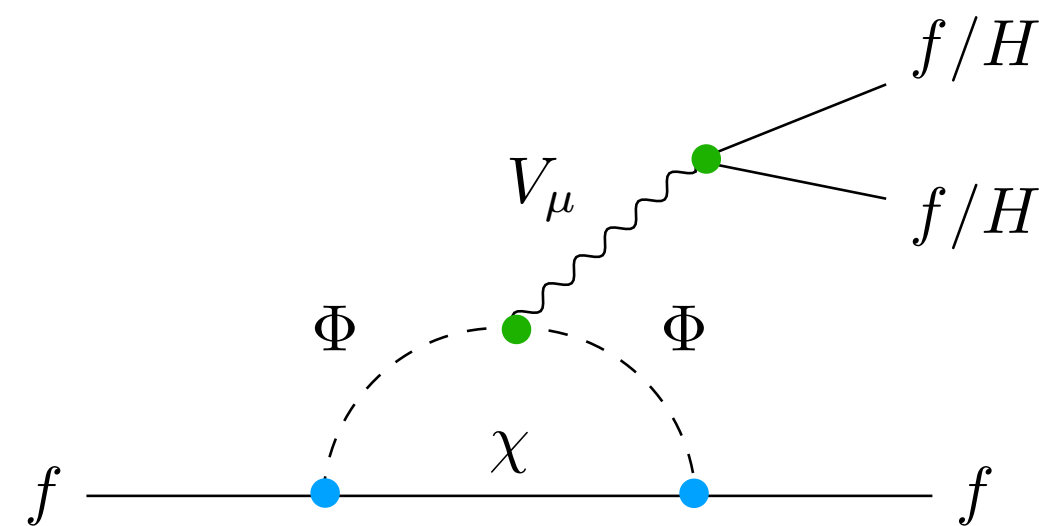


- Dipole operators: $\mathcal{L}_{\text{EFT}}^e \supset [\mathcal{C}_{eB}]_{ij} \bar{\ell}_i H \sigma_{\mu\nu} e_j B^{\mu\nu}$

Needs to pick up a Yukawa insertion from the SM

$$[C_{eB}]_{ij} = \frac{g'}{384\pi^2 M_\Phi^2} y_i y_k^* Y_{kj} G(x_\Phi),$$

$\mathcal{Y}_X$: hypercharges

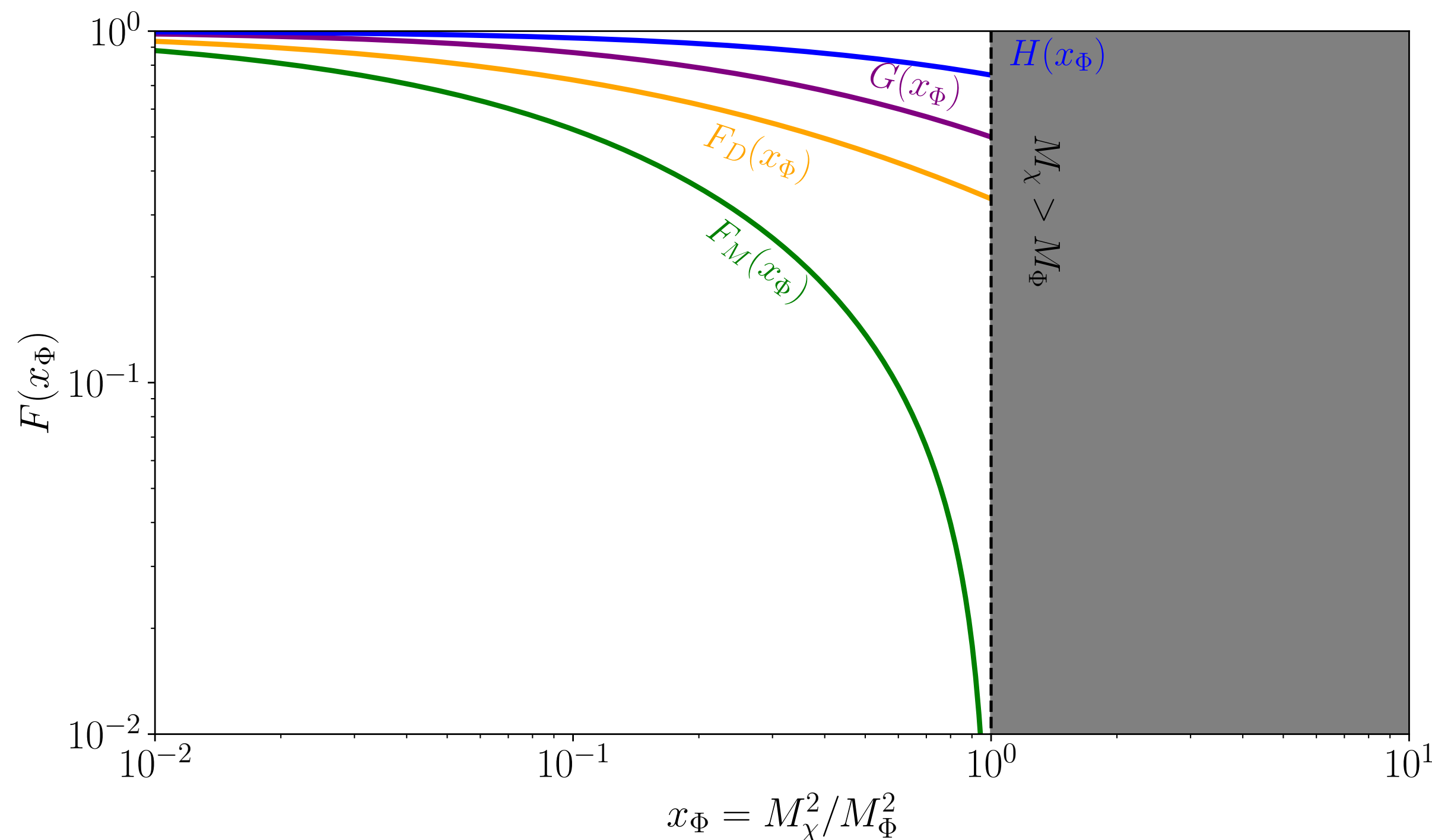


- Penguin-like diagrams: $\sim \bar{e}_R \gamma_\mu e_R \partial_\nu B^{\nu\mu} = \bar{e}_R \gamma_\mu e_R \left(\sum_f \mathcal{Y}_f \bar{f} \gamma^\mu f + \mathcal{Y}_H H^\dagger D^\mu H \right)$

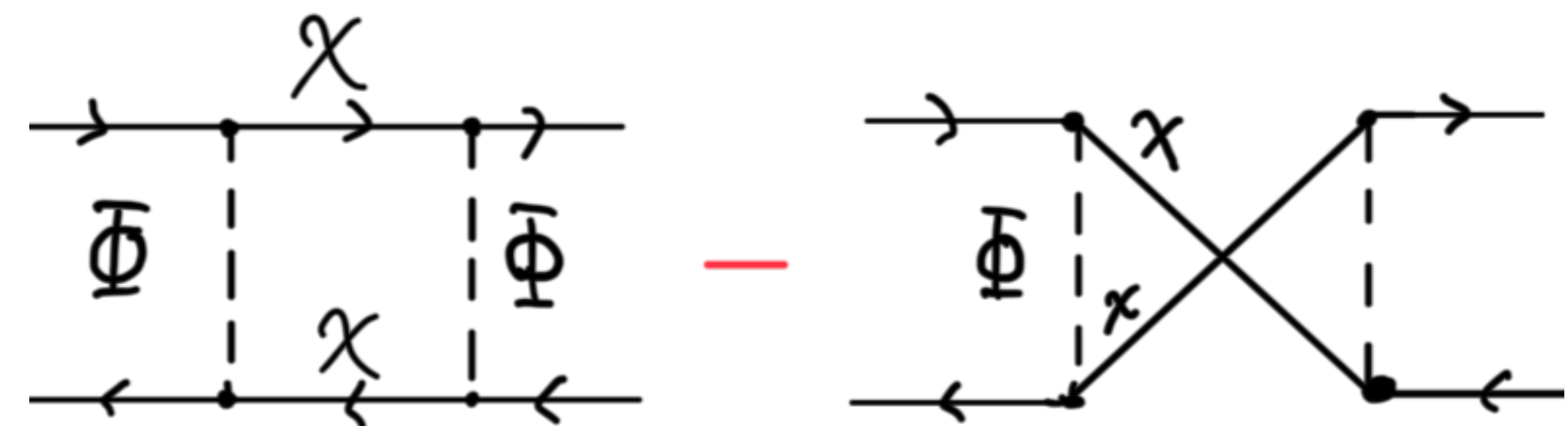
$$[C_{He}]_{ij} = -[C_{\ell e}]_{ijkl} = 3[C_{qe}]_{ijkl} = \frac{3}{4}[C_{eu}]_{ijkl} = -\frac{3}{2}[C_{ed}]_{ijkl} = -\frac{g'^2}{576\pi^2 M_\Phi^2} y_i y_j^* H(x_\Phi)$$

Leptophilic Dark Matter

$$\begin{aligned}
 [C_{ee}]_{ijkl} &= \frac{1}{64\pi^2 M_\Phi^2} \left[-\frac{1}{2} y_i y_j^* y_k y_l^* F_{M,D}(x_\Phi) + \frac{g'^2}{9} (\delta_{ij} y_k y_l^* + \delta_{il} y_j^* y_k) H(x_\Phi) \right] \\
 [C_{eB}]_{ij} &= \frac{g'}{384\pi^2 M_\Phi^2} y_i y_k^* Y_{kj} G(x_\Phi), \\
 [C_{He}]_{ij} &= -[C_{\ell e}]_{ijkl} = \frac{1}{3} [C_{qe}]_{ijkl} = \frac{4}{3} [C_{eu}]_{ijkl} = -\frac{2}{3} [C_{ed}]_{ijkl} = -\frac{g'^2}{576\pi^2 M_\Phi^2} y_i y_j^* H(x_\Phi)
 \end{aligned}
 \quad x_\Phi \equiv \frac{M_\chi^2}{M_\Phi^2}
 \quad \left. \begin{array}{l} \text{Different loop functions} \\ F_{M,D}(x_\Phi), G(x_\Phi), H(x_\Phi) \\ \text{Boxes} \quad \text{Dipoles} \quad \text{Penguins} \end{array} \right\}$$



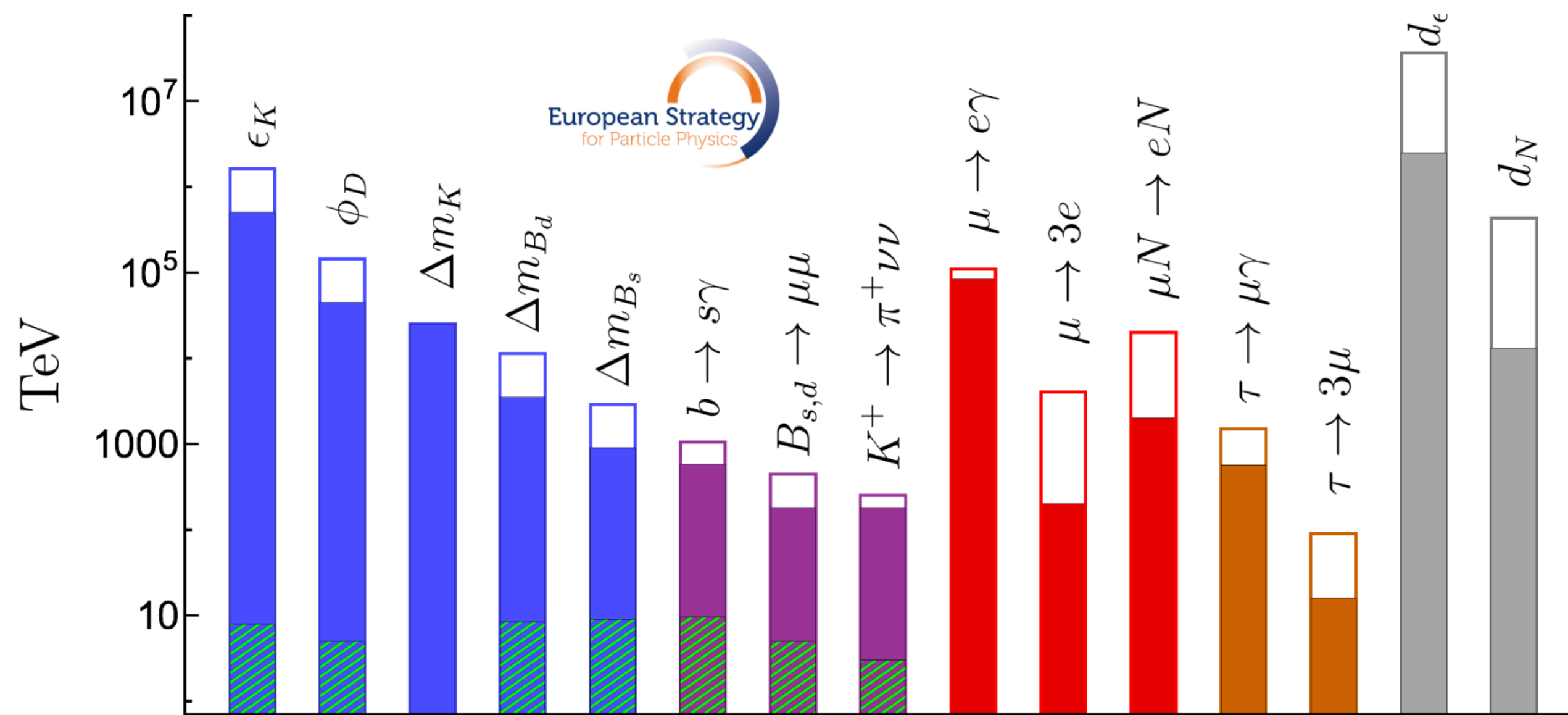
Most important difference: suppression of box diagrams for Majorana DM in the degenerate limit.



[Altmanshofer et al. '12](#)

Quarkphilic Dark Matter: Flavour Bounds

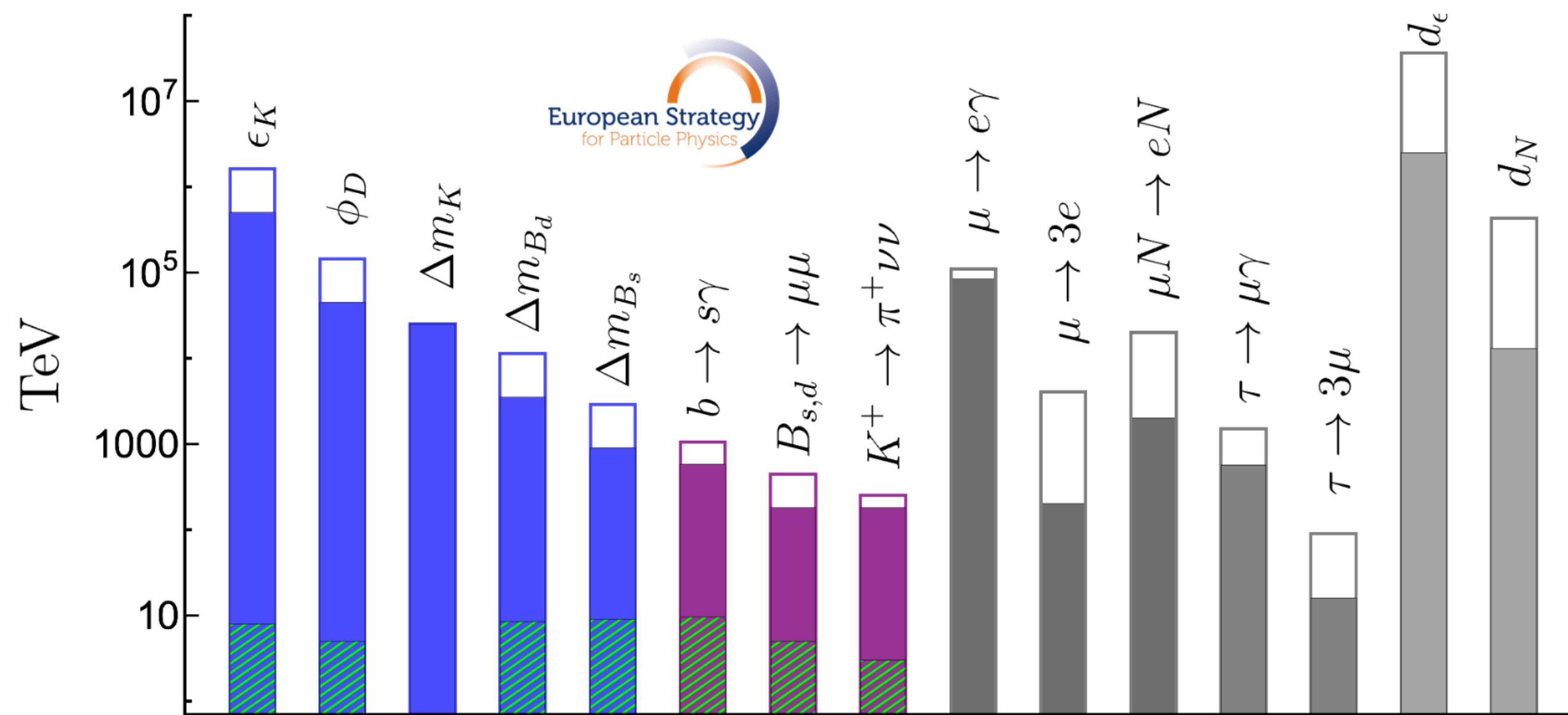
Present and future of the “most important” flavour observable:



from [Physics Briefing book 25](#)

Quarkphilic Dark Matter: Flavour Bounds

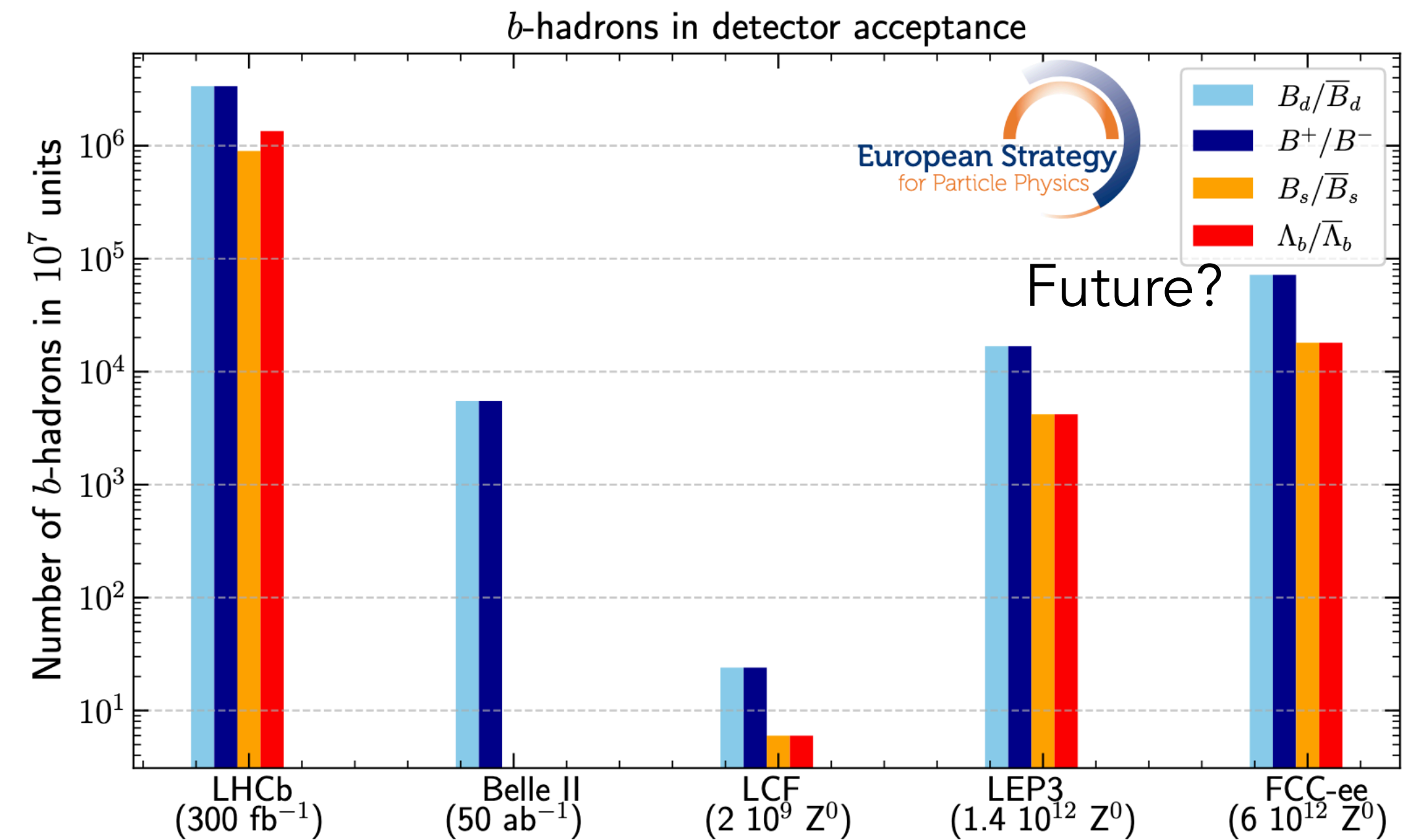
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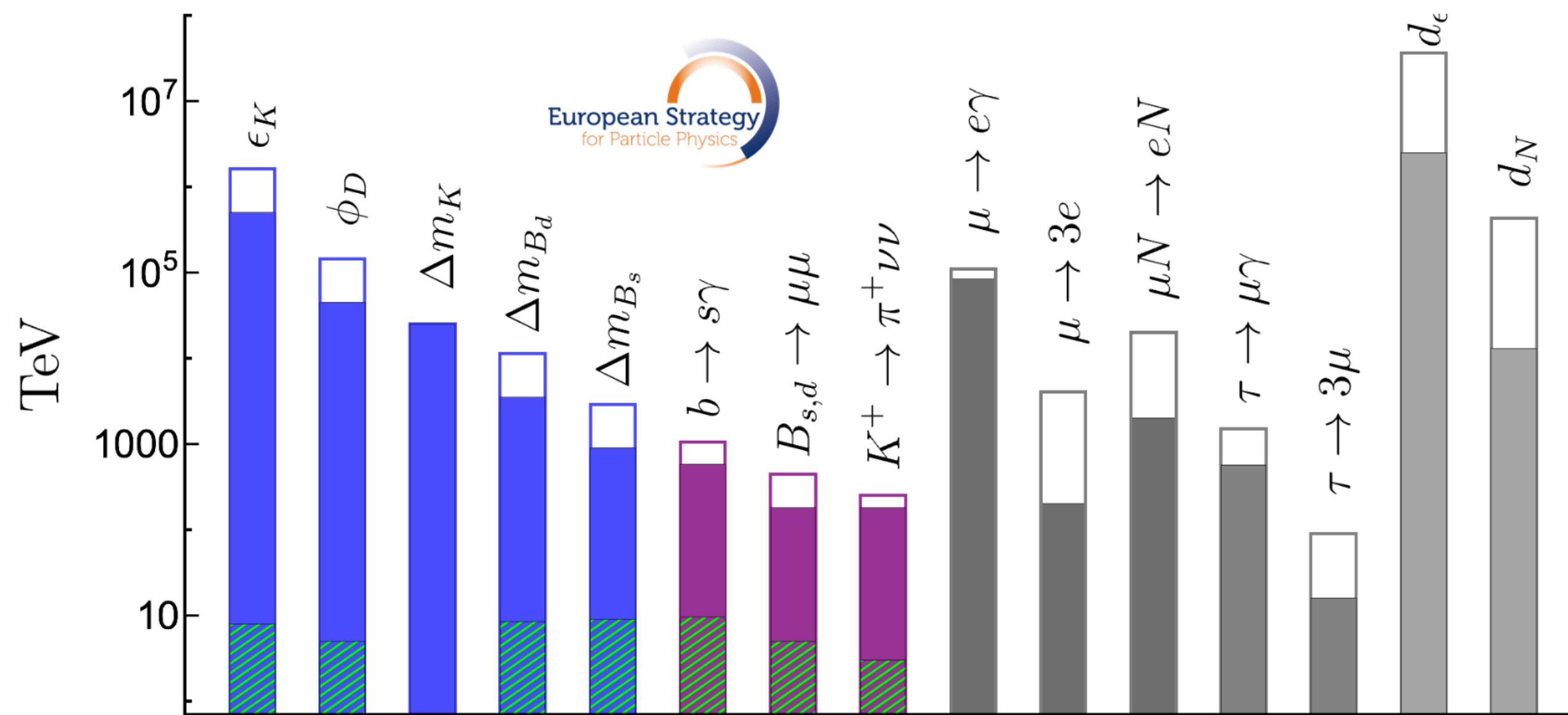
*CMS also doing good in flavour physics, [CMS '22](#)

Also a big landscape of experiments:



Quarkphilic Dark Matter: Flavour Bounds

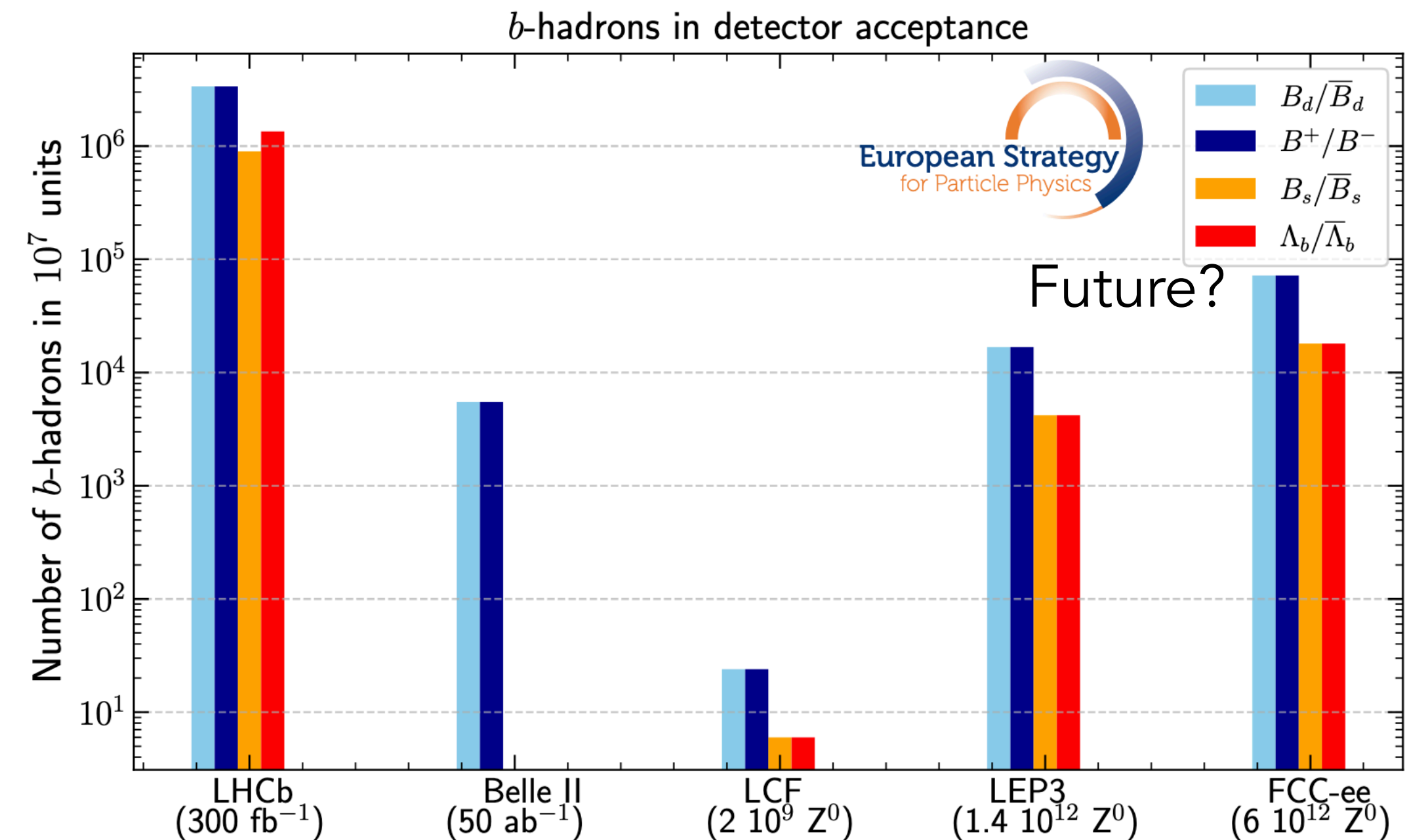
Present and future of the “most important” flavour observable:



from [Physics Briefing book 25](#)

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Also a big landscape of experiments:



Currently some of the strongest flavour observables are **theory-error dominated**: e.g. QCD/lattice errors, CKM determination ...

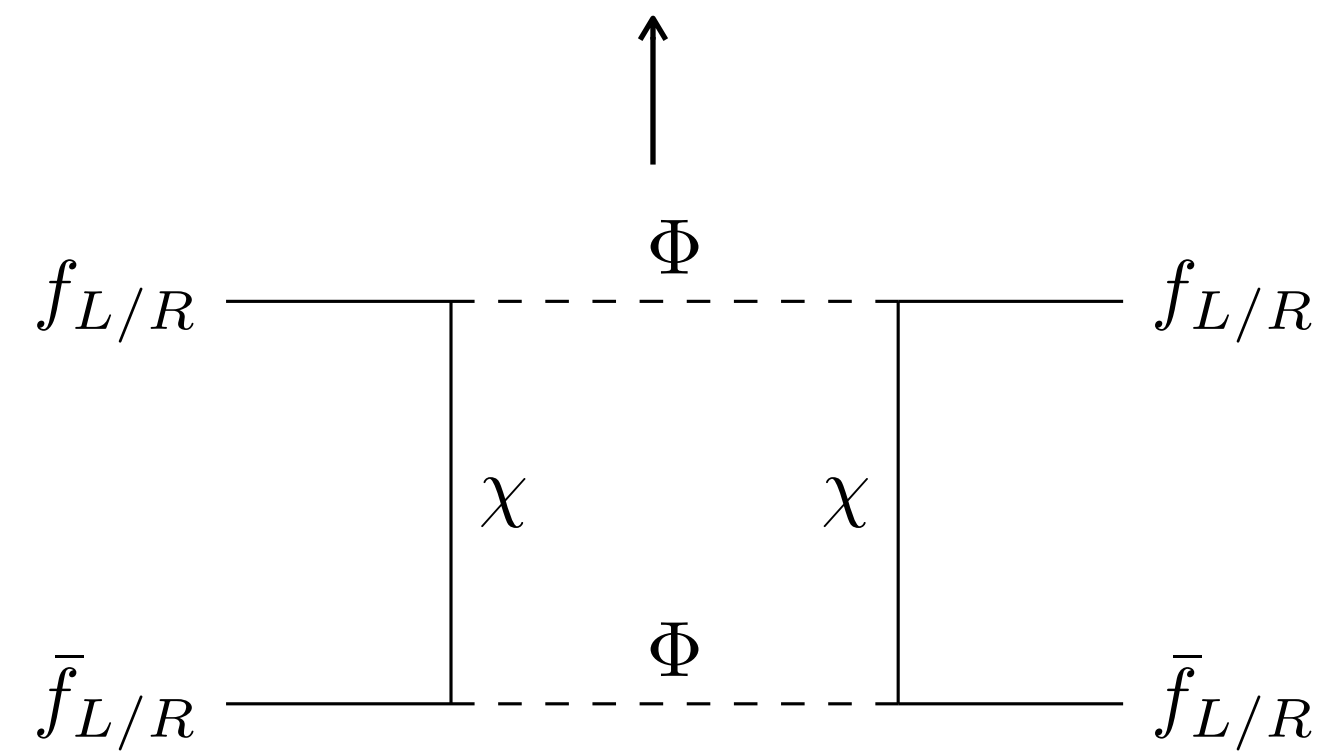
Developments on the theory side could make future bounds even larger.

Quarkphilic Dark Matter

Analogously to the lepton sector, quark flavour observables are dominated by boxes and dipole operators

$$\mathcal{L}_{\text{EFT}}^q = [\mathcal{C}_{qq}]_{ijkl} \bar{q}_i \gamma^\mu q_j \bar{q}_k \gamma_\mu q_l + [\mathcal{C}_{d(u)B}]_{ij} \bar{q}_i H \sigma_{\mu\nu} d_j B^{\mu\nu} + [\mathcal{C}_{d(u)W}]_{ij} \bar{q}_i H \sigma_{\mu\nu} \tau^a d_j W^{a\mu\nu} + [\mathcal{C}_{d(u)G}]_{ij} \bar{q}_i H \sigma_{\mu\nu} T^A d_j G^{A\mu\nu}$$

Meson mixing:
 $\Delta M_K, \epsilon_K, \Delta M_B$

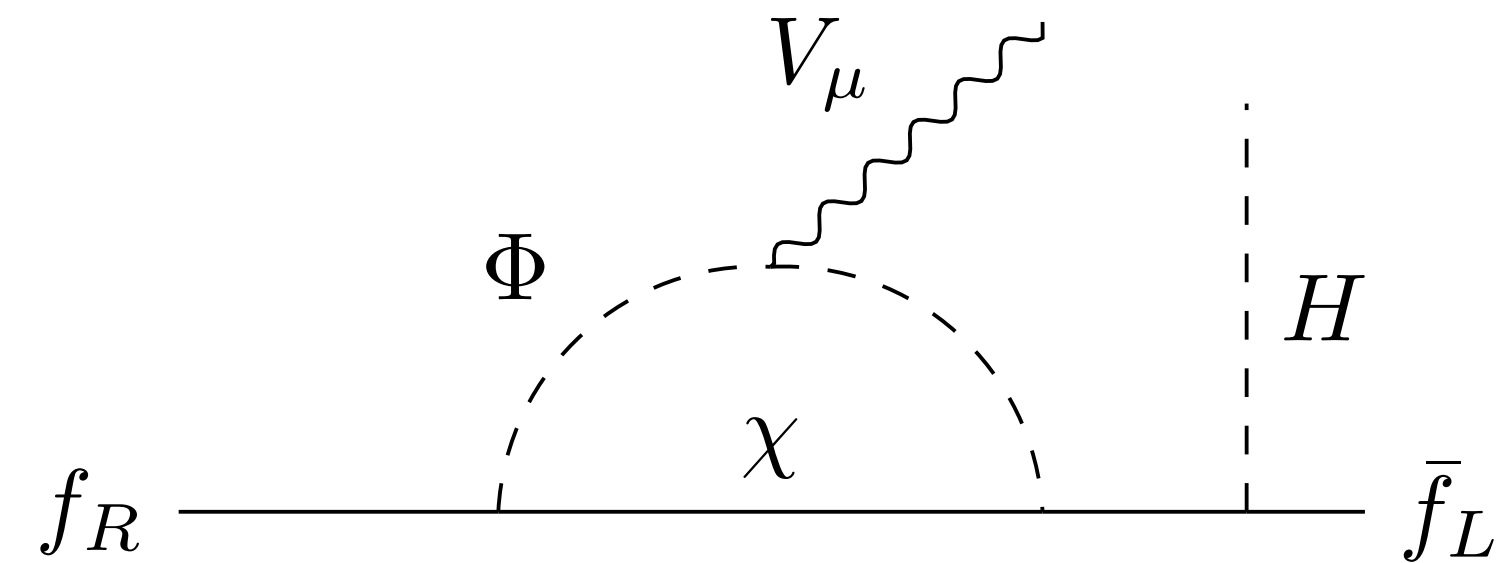
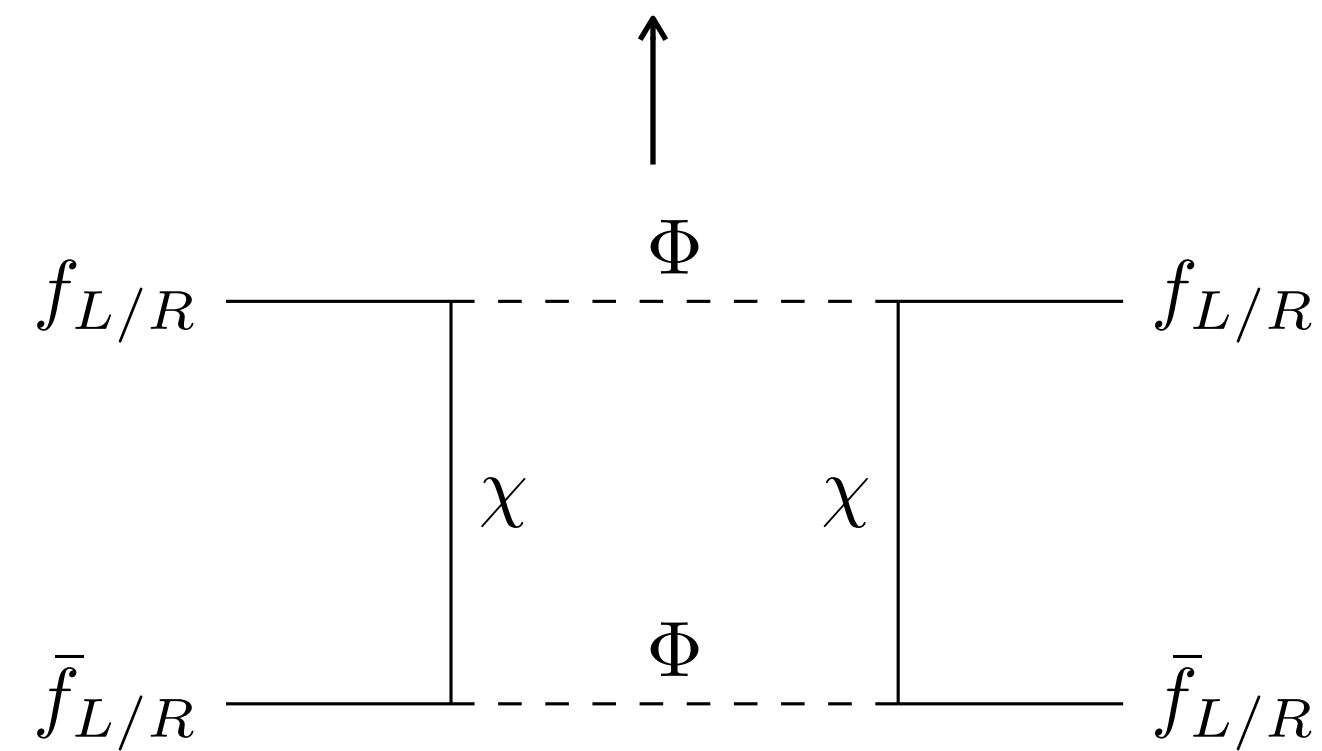


Quarkphilic Dark Matter

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Meson mixing:
 $\Delta M_K, \epsilon_K, \Delta M_B$



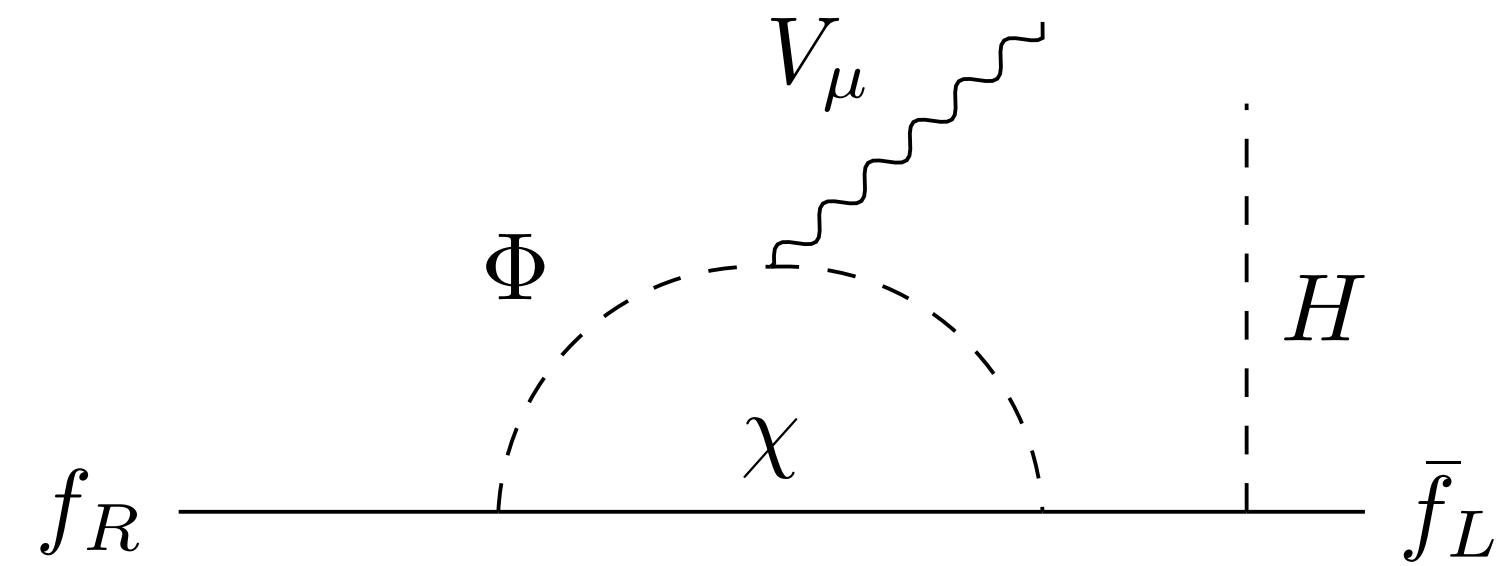
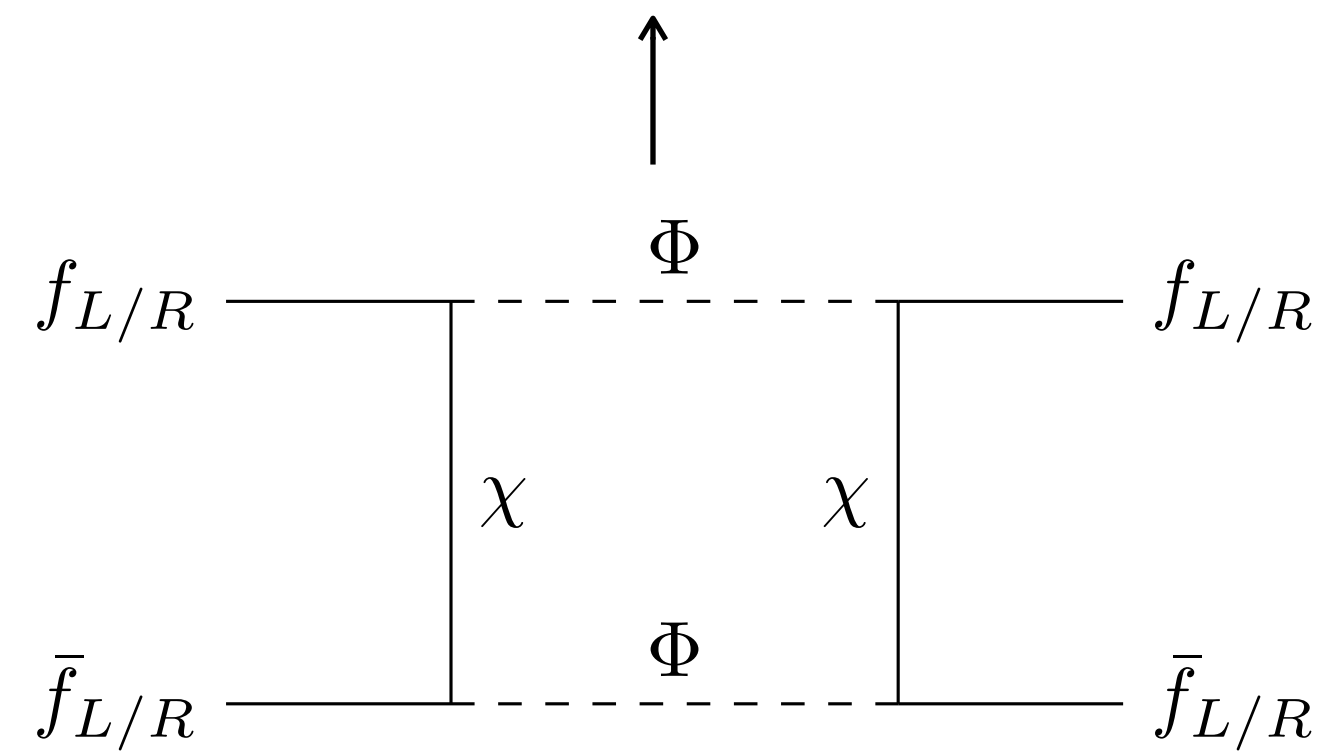
Dipoles:
 d_N
 $b \rightarrow s\gamma$

Quarkphilic Dark Matter

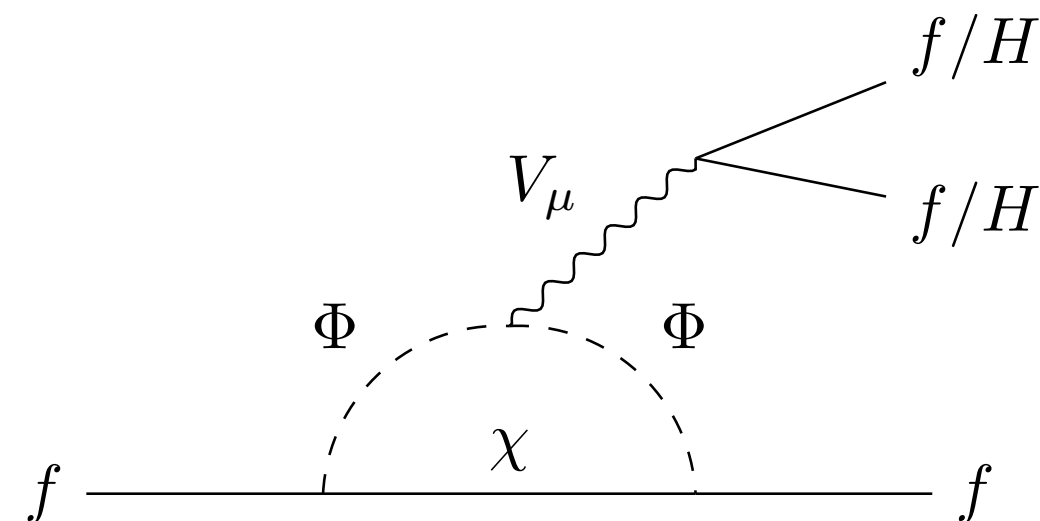
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Meson mixing:
 $\Delta M_K, \epsilon_K, \Delta M_B$



Dipoles:
 d_N
 $b \rightarrow s\gamma$



Leptonic decays:

$B_{s,d} \rightarrow \mu\mu, K_L \rightarrow \mu\mu$

$$\bar{q} \gamma_\mu q \partial_\nu B^{\nu\mu}, \bar{q} \gamma_\mu q \partial_\nu W^{\nu\mu} \longrightarrow \mathcal{O}_{Hq}^{(1,3)}, \mathcal{O}_{qe}, \mathcal{O}_{q\ell}^{(1,3)}, \dots$$

Quarkphilic Dark Matter: Observables

Meson mixing:

[Buras, Stangl '24](#)

SM prediction very dependent on lattice and CKM inputs

$$\epsilon_K = e^{i\phi_\epsilon} \sin \phi_\epsilon \left(\frac{\text{Im } M_{12}}{\Delta m_K} + \xi \right)$$

$$\Delta m_K \simeq 2\text{Re}(M_{12}^{\text{SM}} + M_{12}^{\text{NP}})$$

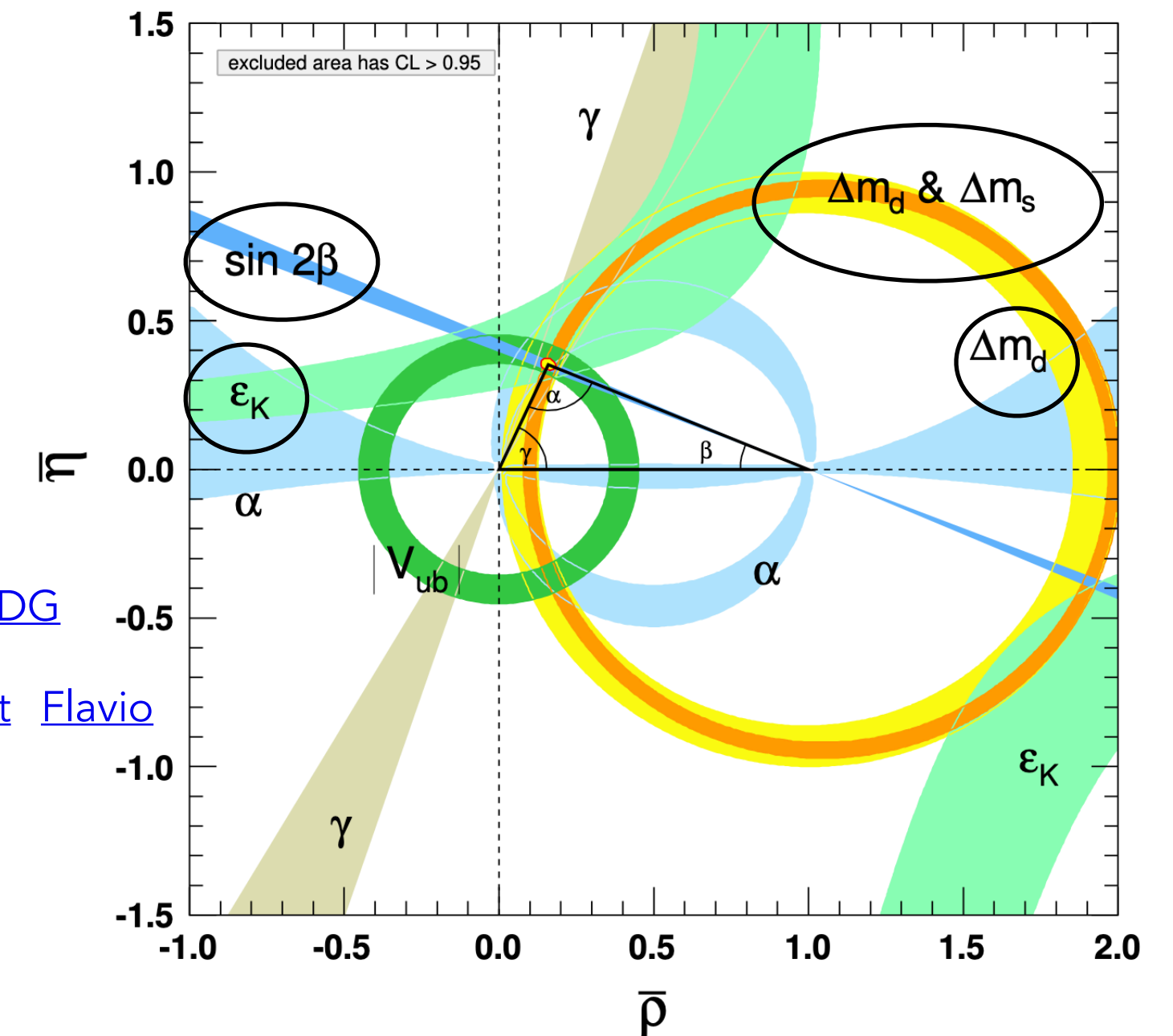
Important: CKM-element is determined using meson mixing

$$\Delta m_{B_q} \simeq 2 \left| M_{12}^{\text{SM},q} + M_{12}^{\text{NP},q} \right|$$

$$\phi_q = \arg \left(M_{12}^{\text{SM},q} + M_{12}^{\text{NP},q} \right)$$

Options:

1. **Tree-level CKM determination** [PDG](#)
2. Simultaneous fit CKM+BSM [UTFit](#) [Flavio](#)



Quarkphilic Dark Matter: Observables

Meson mixing:

[Buras, Stangl '24](#)

SM prediction very dependent on lattice and CKM inputs

$$\epsilon_K = e^{i\phi_\epsilon} \sin \phi_\epsilon \left(\frac{\text{Im } M_{12}}{\Delta m_K} + \xi \right)$$

$$\Delta m_K \simeq 2\text{Re}(M_{12}^{\text{SM}} + M_{12}^{\text{NP}})$$

Leptonic meson decays:

$$\frac{\text{BR}(B_i \rightarrow \mu^+ \mu^-)}{\text{BR}(B_i \rightarrow \mu^+ \mu^-)_{\text{SM}}} = \left| 1 + \frac{\Delta C_{10,i}^\mu}{C_{10}^{\text{SM}}} \right|^2$$

$$\Delta C_{10} = \frac{4\pi^2}{e^2 \lambda_{ts}} \frac{v^2}{\Lambda^2} \left(C_{qe} - C_{\ell q}^{(1)} + C_{Hq}^{(1)} + C_{Hq}^{(3)} - C_{\ell q}^{(3)} \right)$$

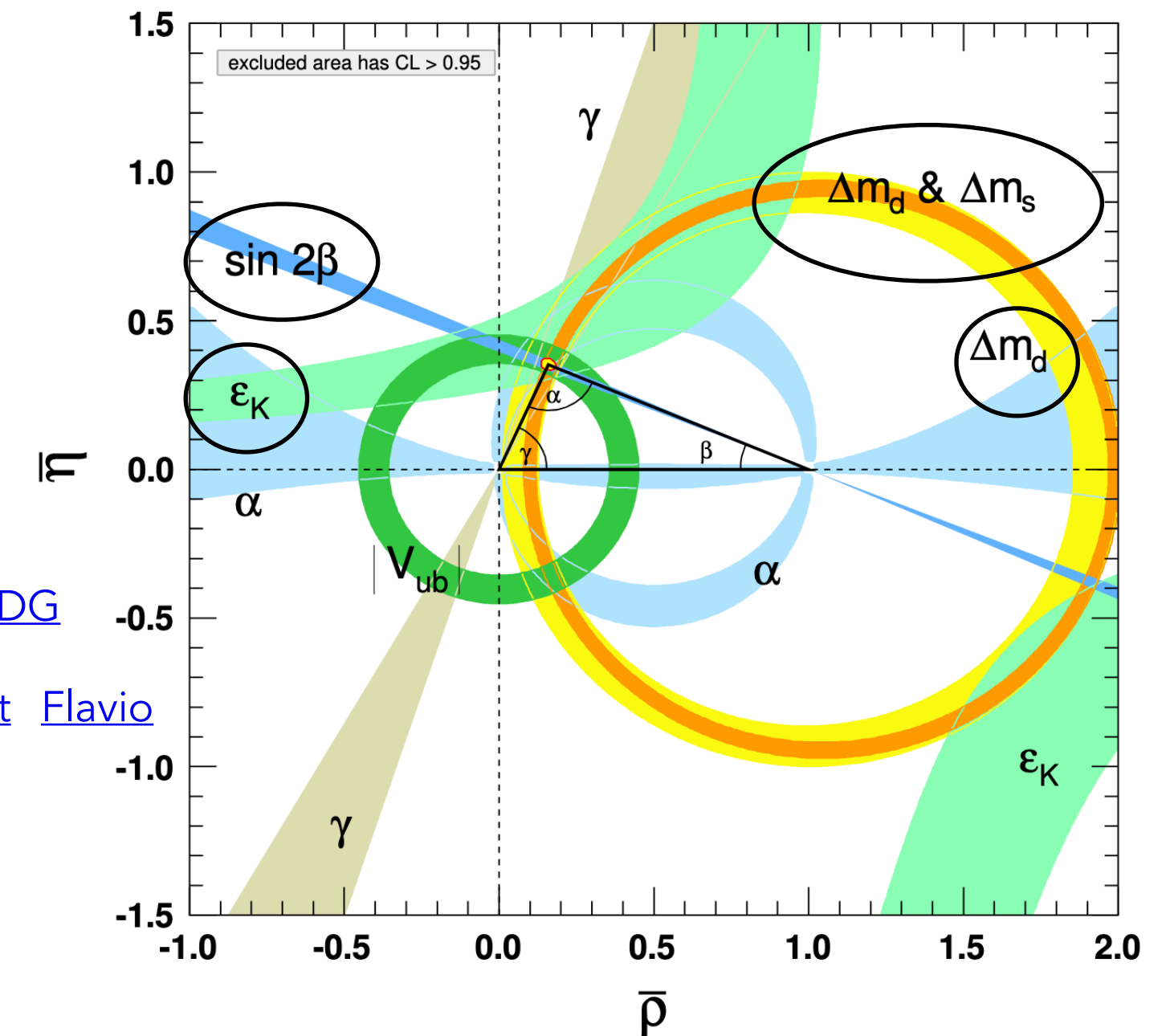
Important: CKM-element is determined using meson mixing

$$\Delta m_{B_q} \simeq 2 \left| M_{12}^{\text{SM},q} + M_{12}^{\text{NP},q} \right|$$

$$\phi_q = \arg \left(M_{12}^{\text{SM},q} + M_{12}^{\text{NP},q} \right)$$

Options:

1. Tree-level CKM determination [PDG](#)
2. Simultaneous fit CKM+BSM [UTFit](#) [Flavio](#)



Quarkphilic Dark Matter: Observables

Meson mixing:

[Buras, Stangl '24](#)

SM prediction very dependent on lattice and CKM inputs

$$\epsilon_K = e^{i\phi_\epsilon} \sin \phi_\epsilon \left(\frac{\text{Im } M_{12}}{\Delta m_K} + \xi \right)$$

$$\Delta m_K \simeq 2\text{Re}(M_{12}^{\text{SM}} + M_{12}^{\text{NP}})$$

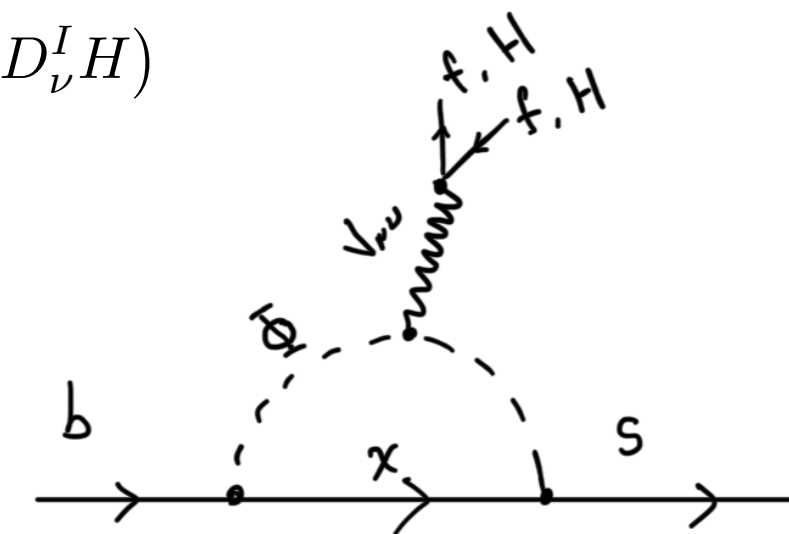
Leptonic meson decays:

$$\frac{\text{BR}(B_i \rightarrow \mu^+ \mu^-)}{\text{BR}(B_i \rightarrow \mu^+ \mu^-)_{\text{SM}}} = \left| 1 + \frac{\Delta C_{10,i}^\mu}{C_{10}^{\text{SM}}} \right|^2$$

$$\partial^\mu B_{\mu\nu} = \left(-\frac{1}{2} \bar{\ell} \gamma_\nu \ell - \bar{e} \gamma_\nu e + \frac{1}{2} H^\dagger D_\nu H \right)$$

$$\Delta C_{10} = \frac{4\pi^2}{e^2 \lambda_{ts}} \frac{v^2}{\Lambda^2} \left(C_{qe} - C_{\ell q}^{(1)} + C_{Hq}^{(1)} + C_{Hq}^{(3)} - C_{\ell q}^{(3)} \right)$$

$$\partial^\mu W_{\mu\nu}^I \sim (\bar{\ell} \sigma^I \gamma_\nu \ell + H^\dagger D_\nu^I H)$$



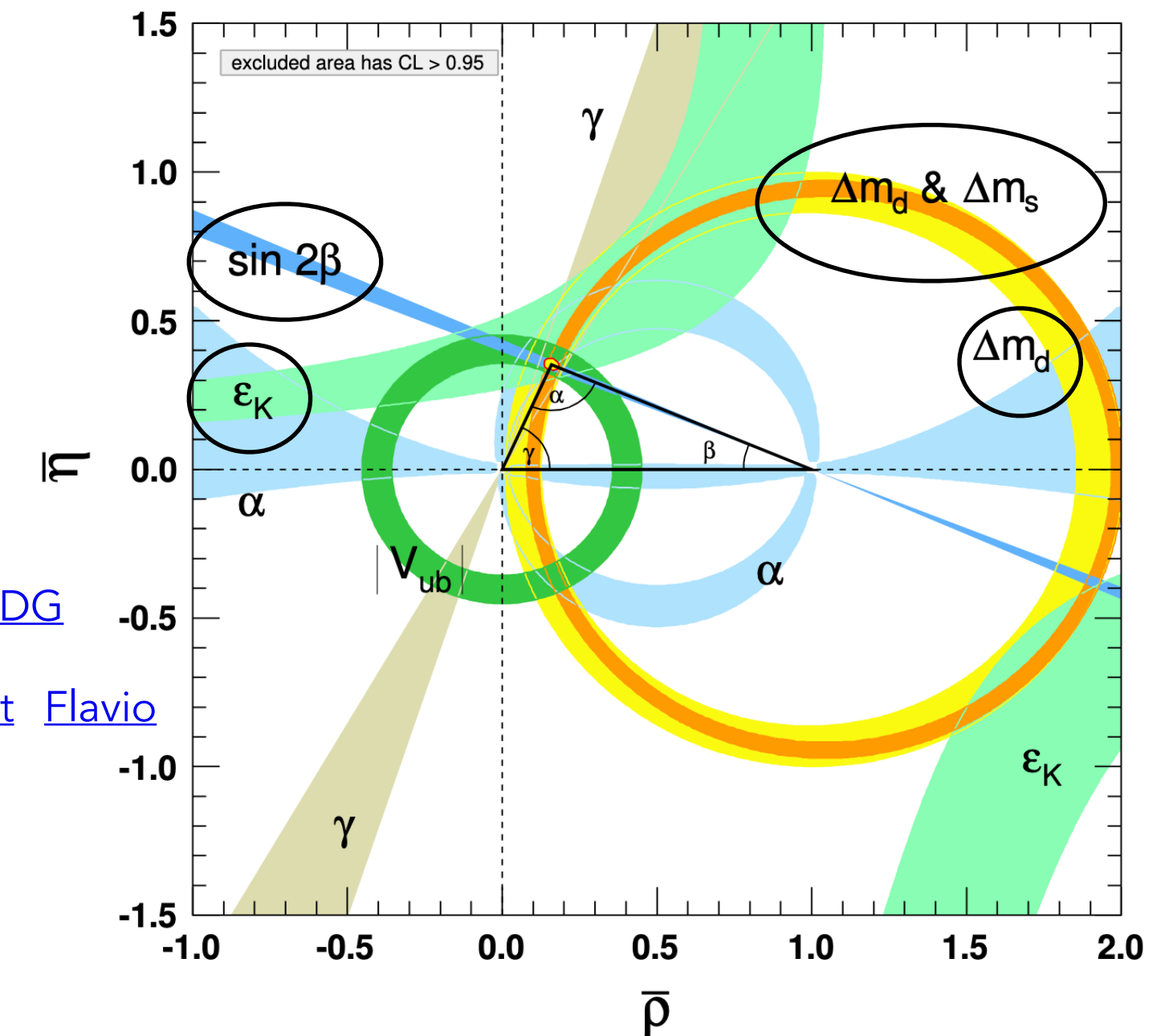
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Options:

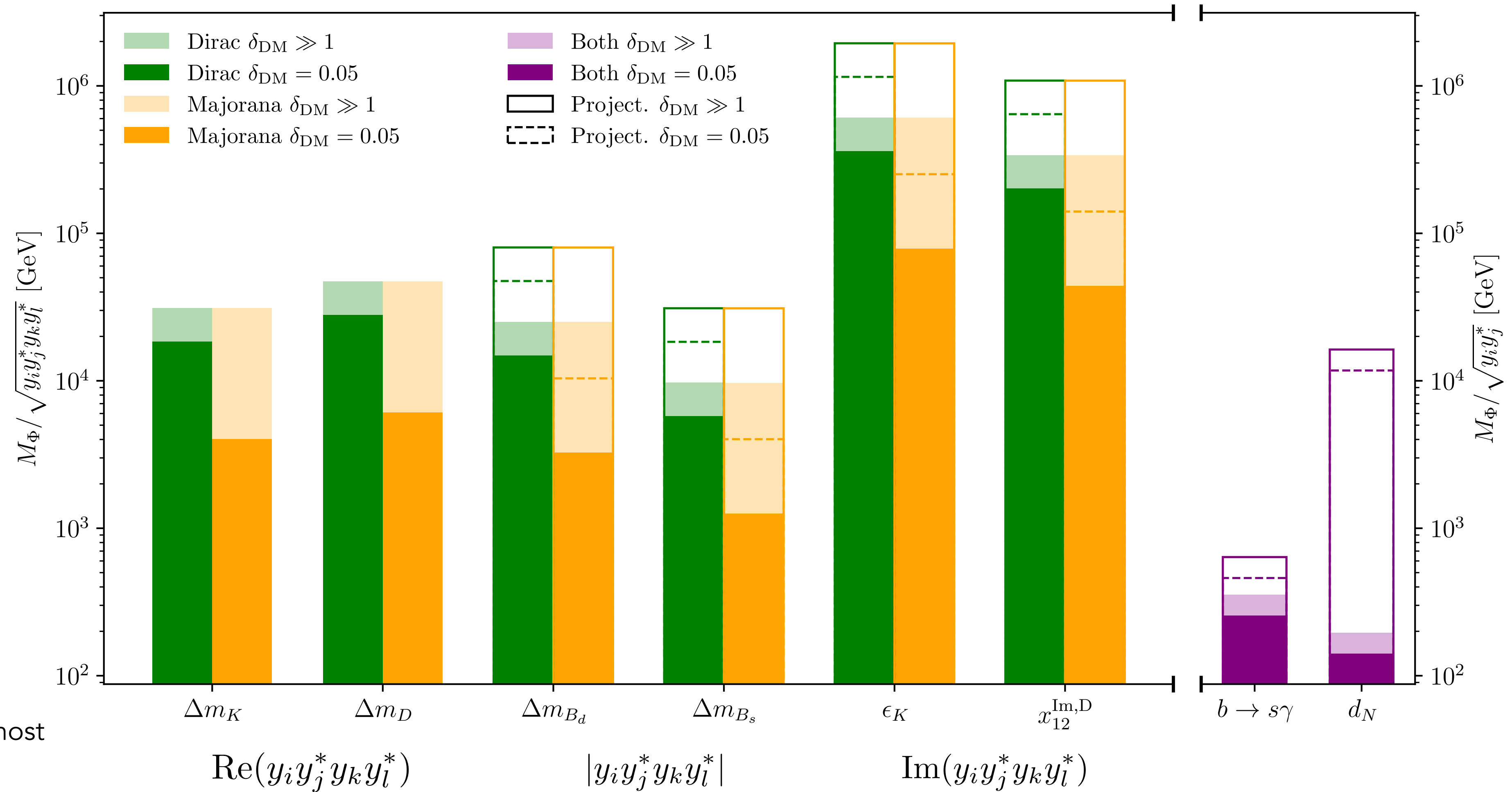
1. Tree-level CKM determination [PDG](#)
2. Simultaneous fit CKM+BSM [UTFit](#) [Flavio](#)



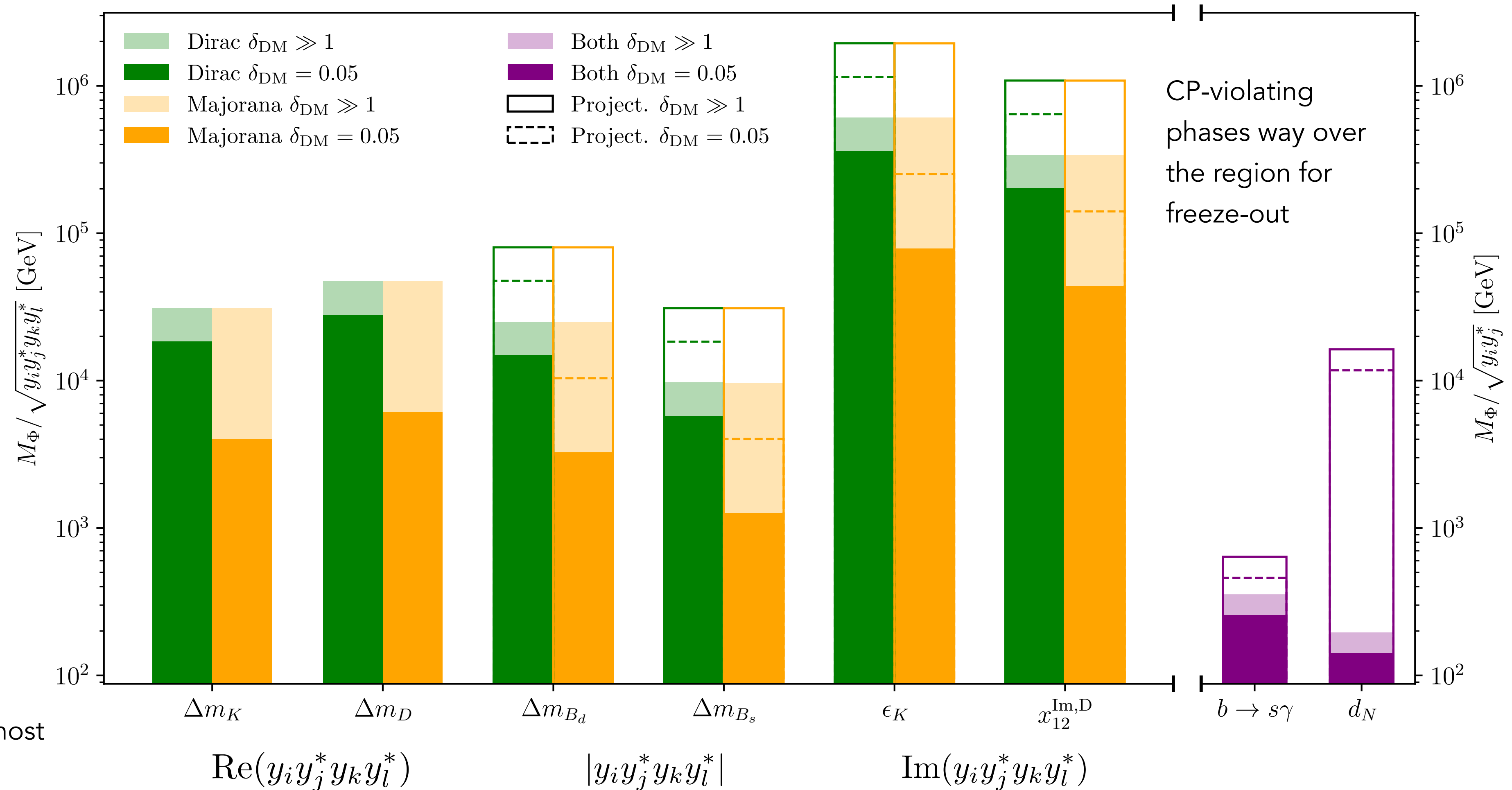
No leptonic meson decays!

Similar to [Davighi, Stefanek '23](#)

Quarkphilic Dark Matter: Flavour Observables

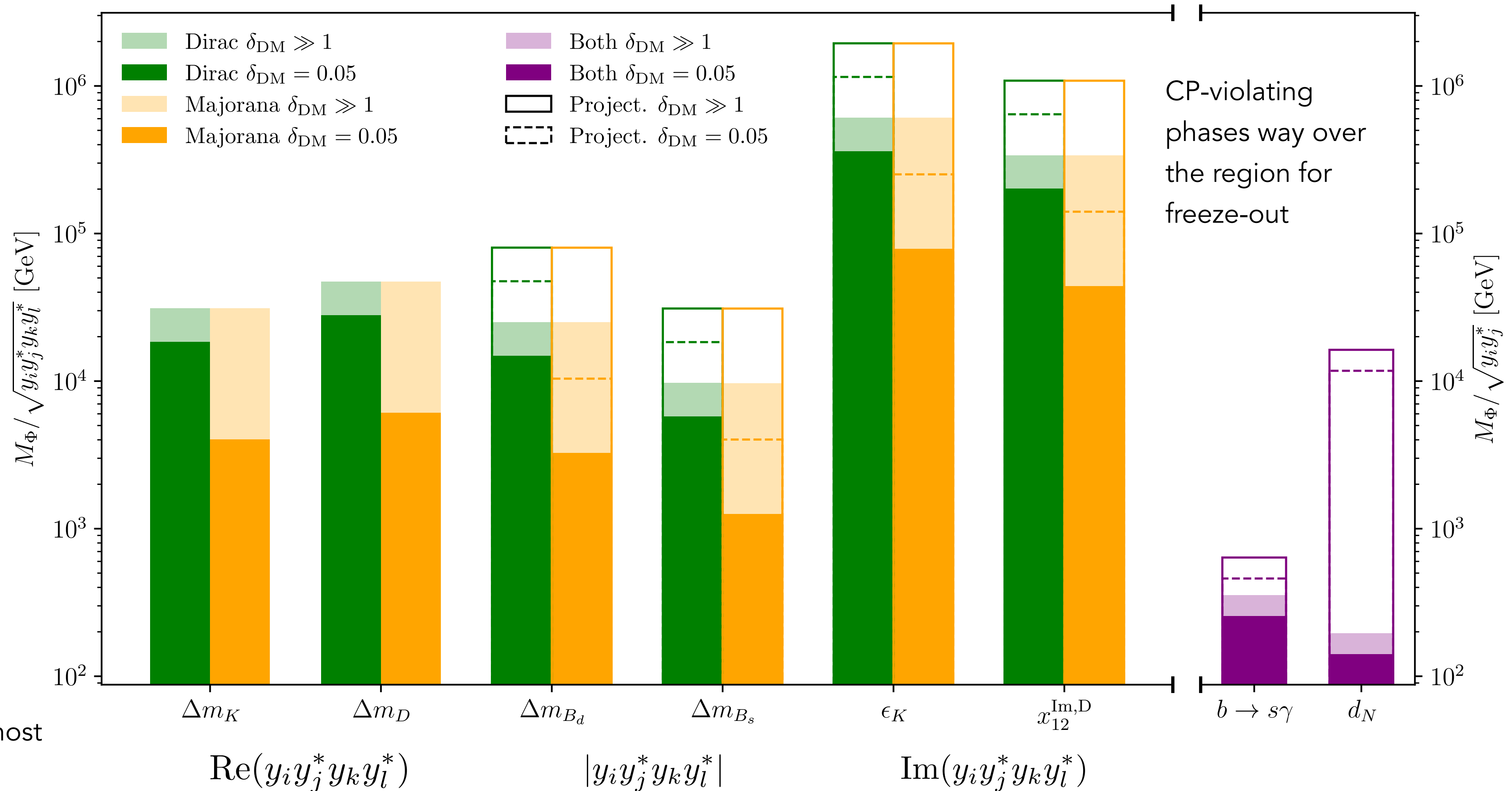


Quarkphilic Dark Matter: Flavour Observables



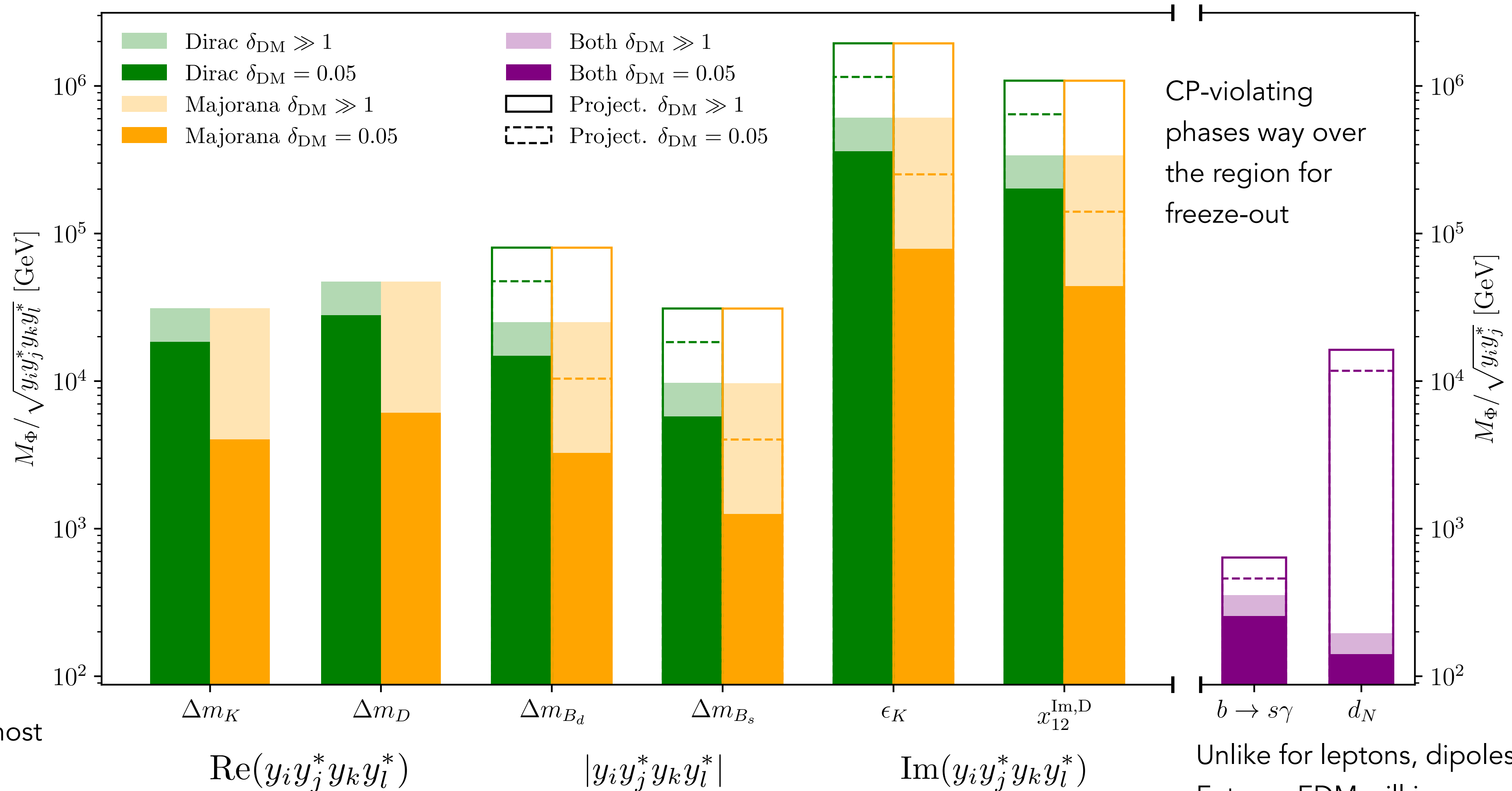
Quarkphilic Dark Matter: Flavour Observables

Except in the degenerate limit for Majorana, all flavour bounds are above 10 TeV, need to avoid these transitions.



Quarkphilic Dark Matter: Flavour Observables

Except in the degenerate limit for Majorana, all flavour bounds are above 10 TeV, need to avoid these transitions.



Each observable is most sensitive to different parts of the couplings:

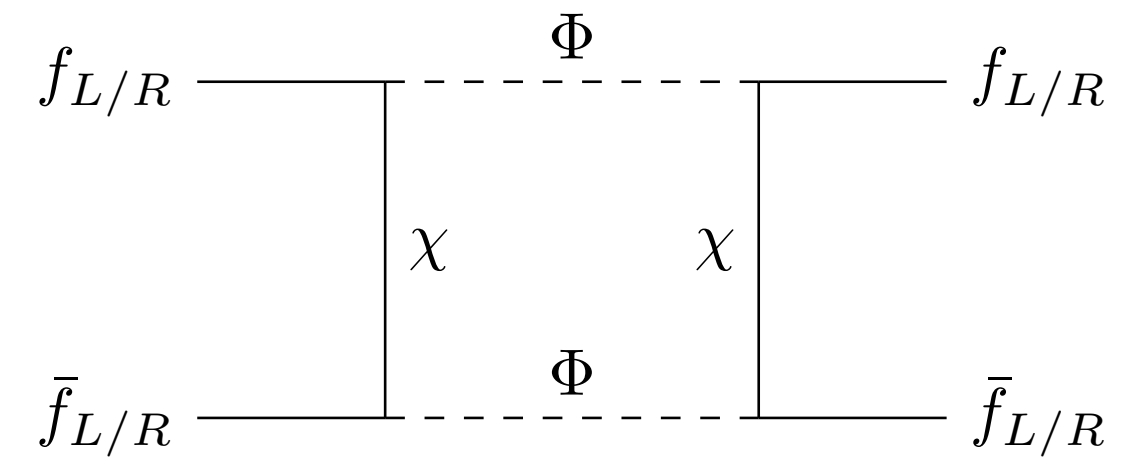
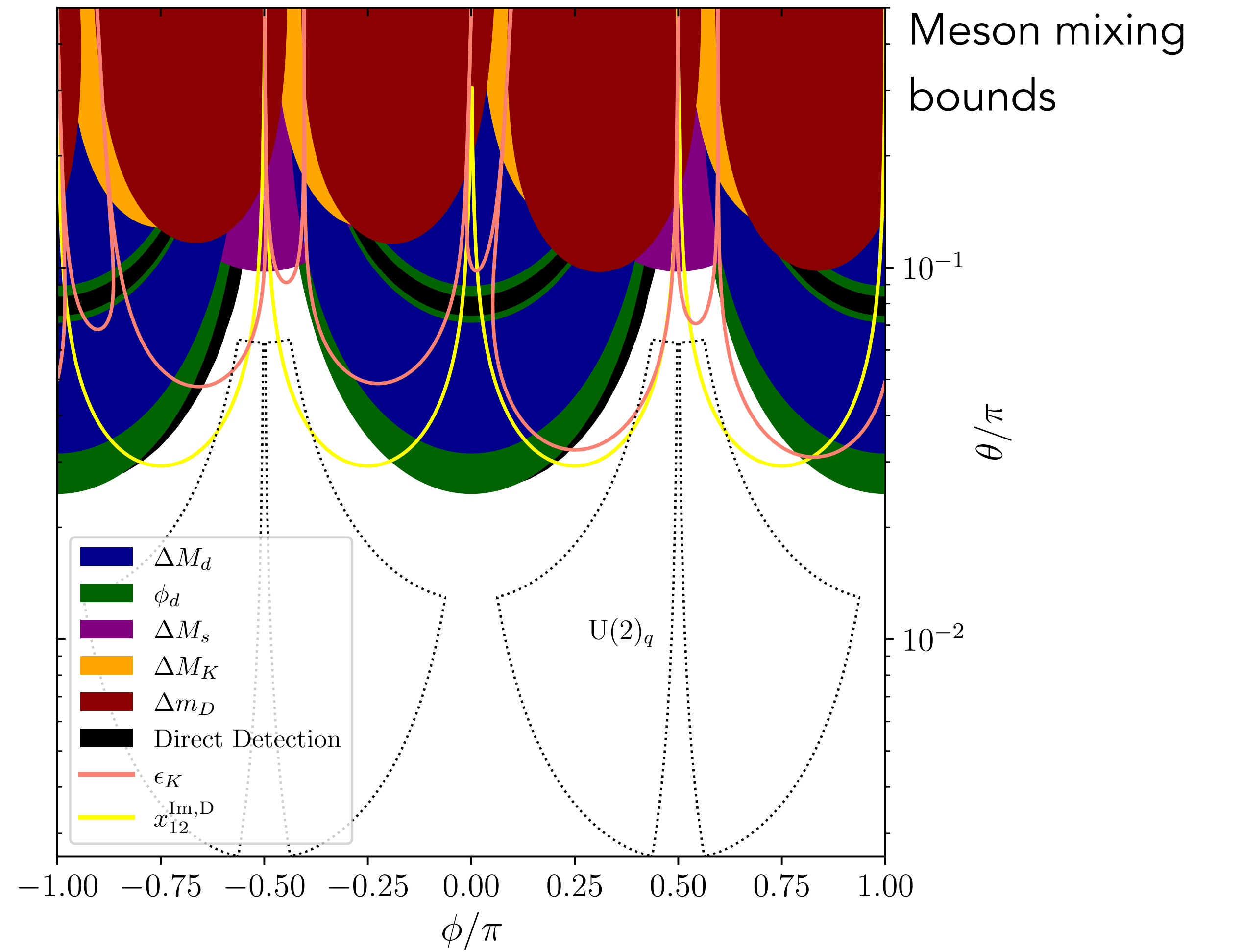
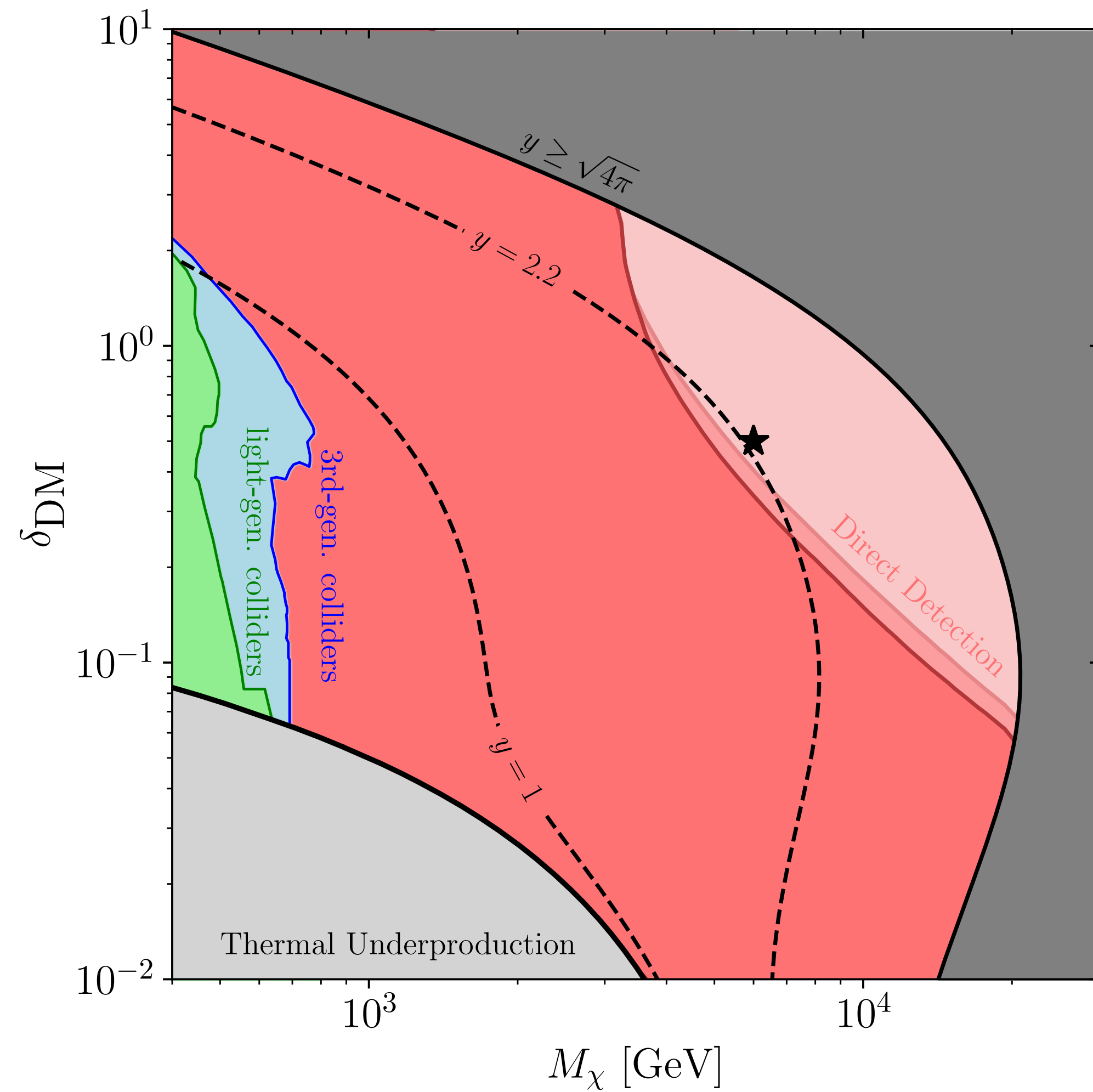
$$\text{Re}(y_i y_j^* y_k y_l^*)$$

$$|y_i y_j^* y_k y_l^*|$$

$$\text{Im}(y_i y_j^* y_k y_l^*)$$

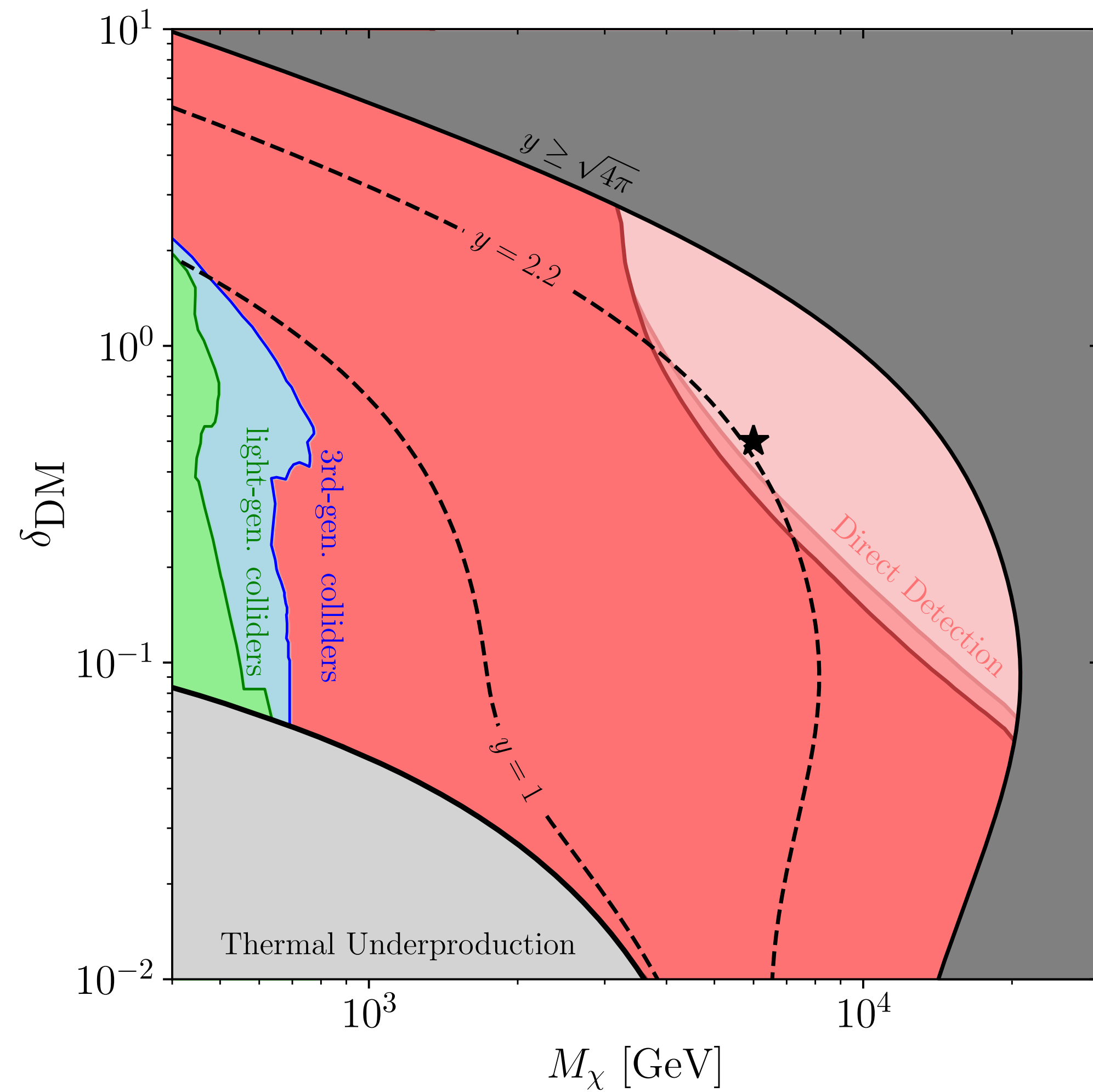
Quarkphilic Dark Matter

Dirac:

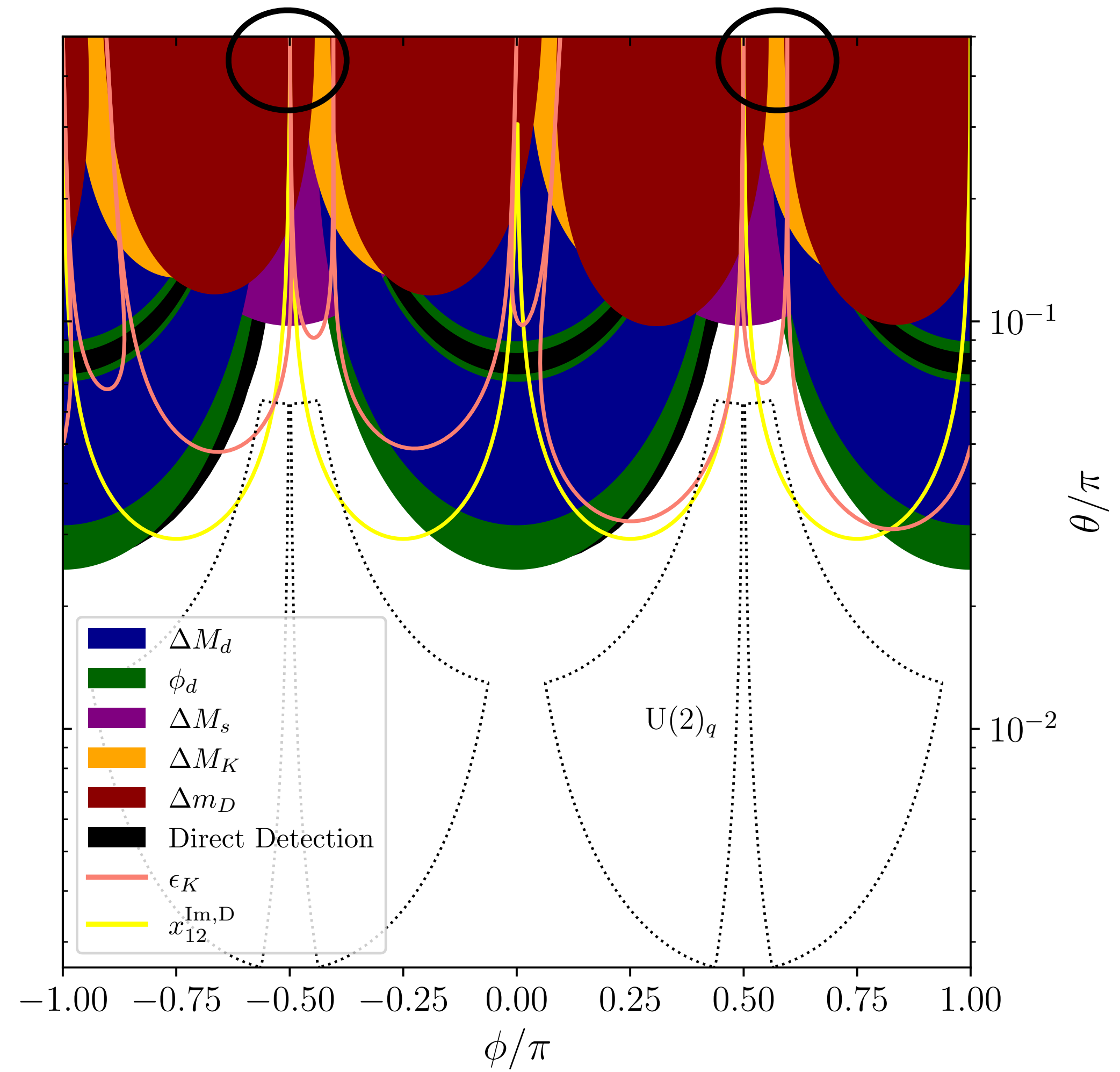


Quarkphilic Dark Matter

Dirac:

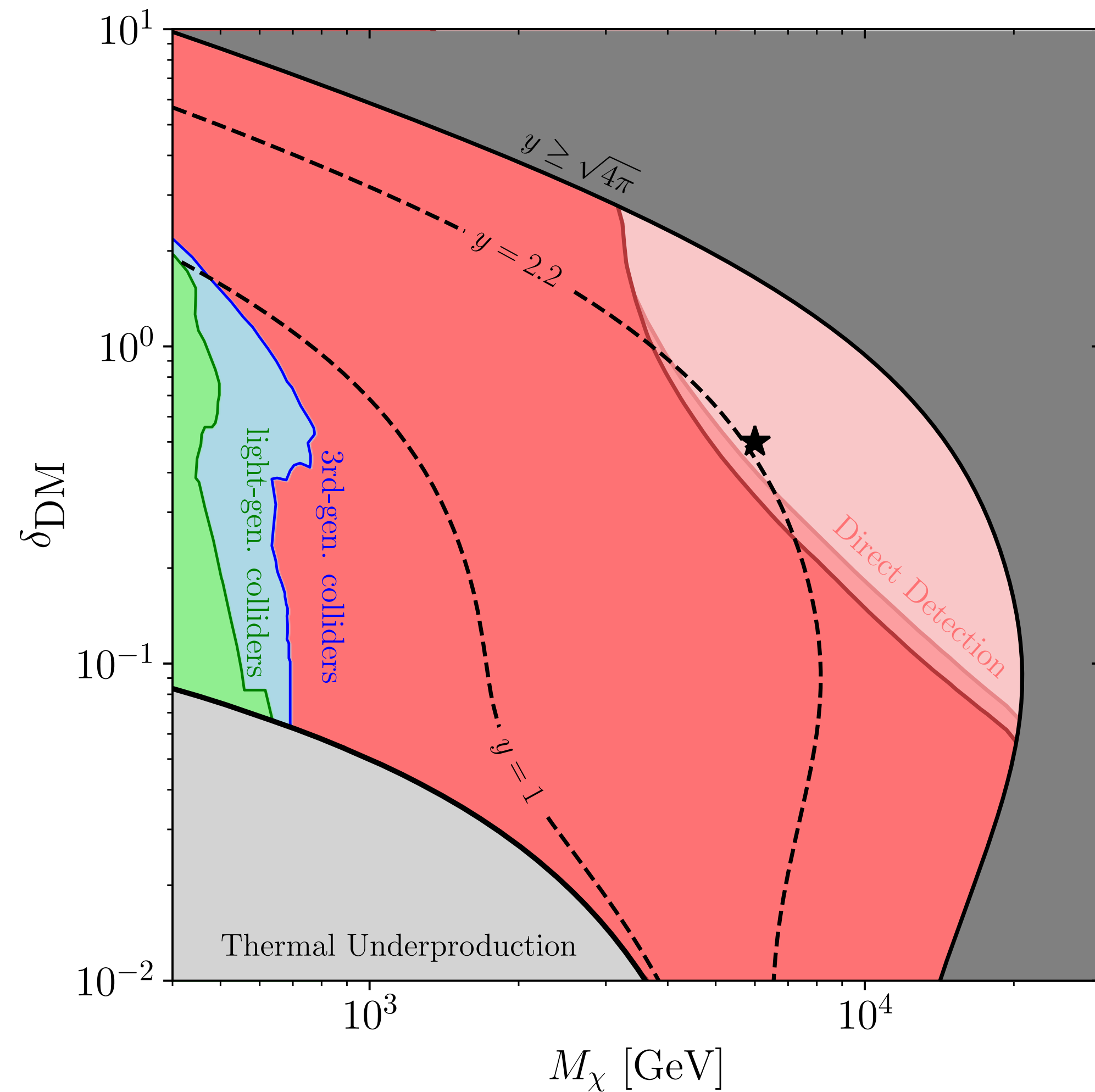


no longer $U(1)$ symmetric points!

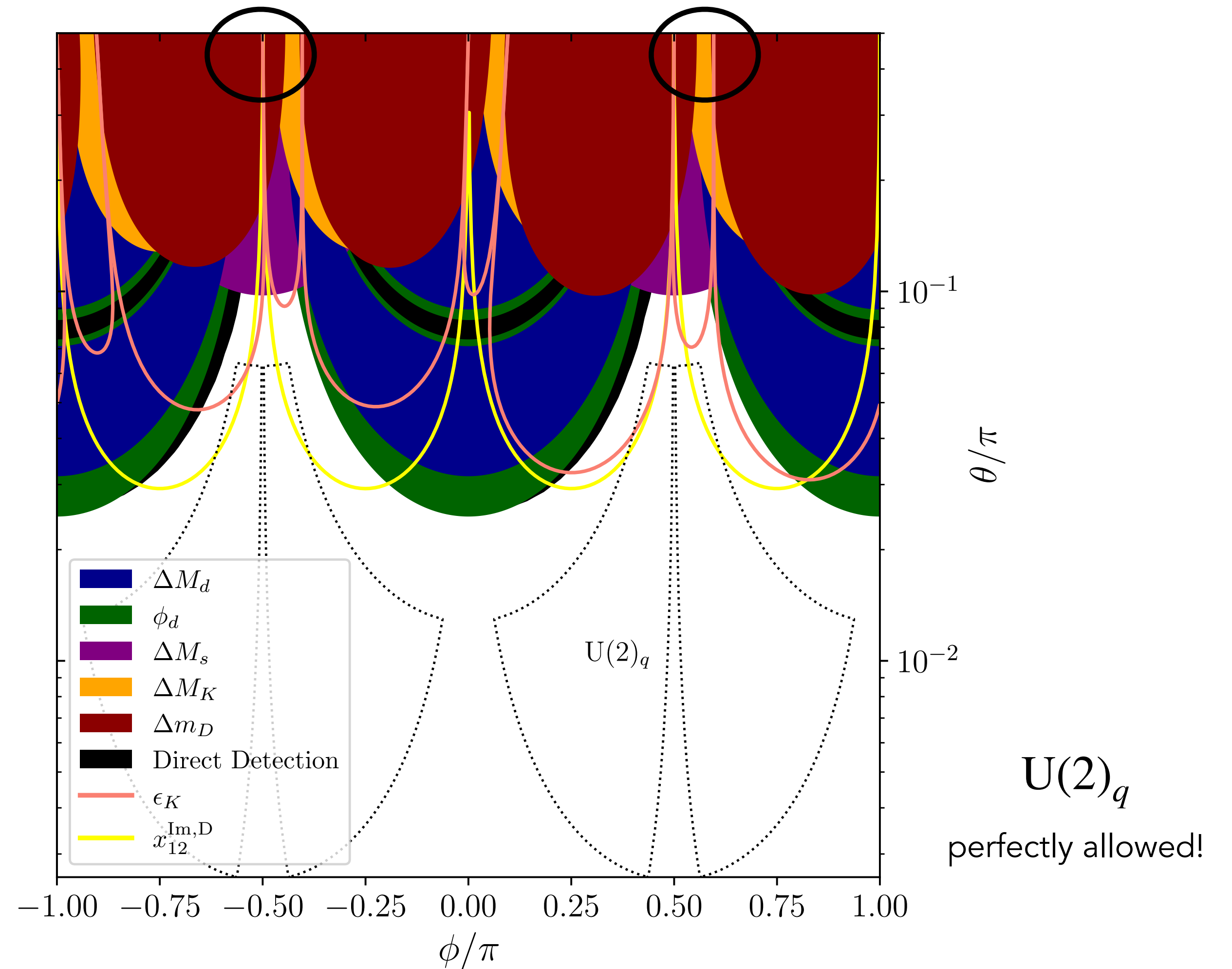


Quarkphilic Dark Matter

Dirac:



no longer U(1) symmetric points!



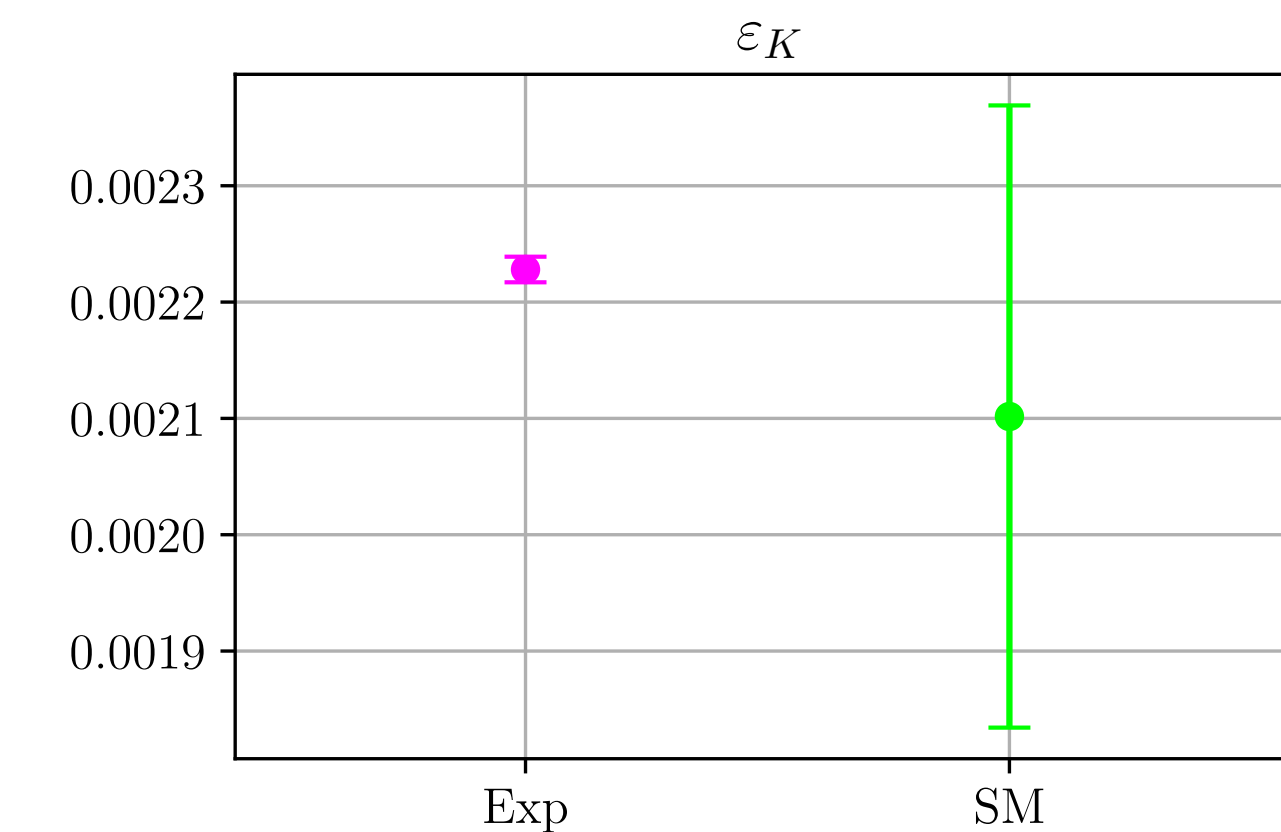
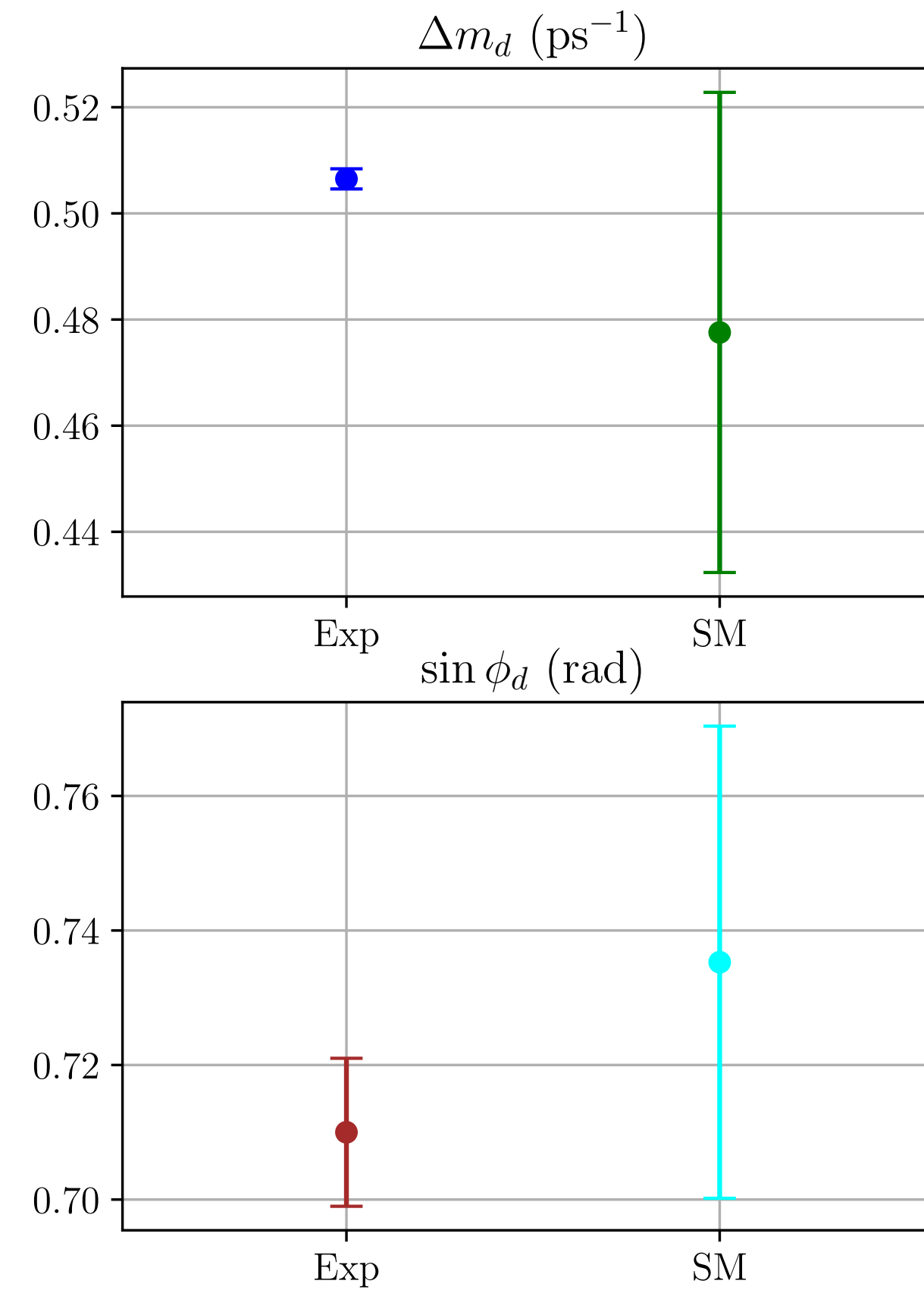
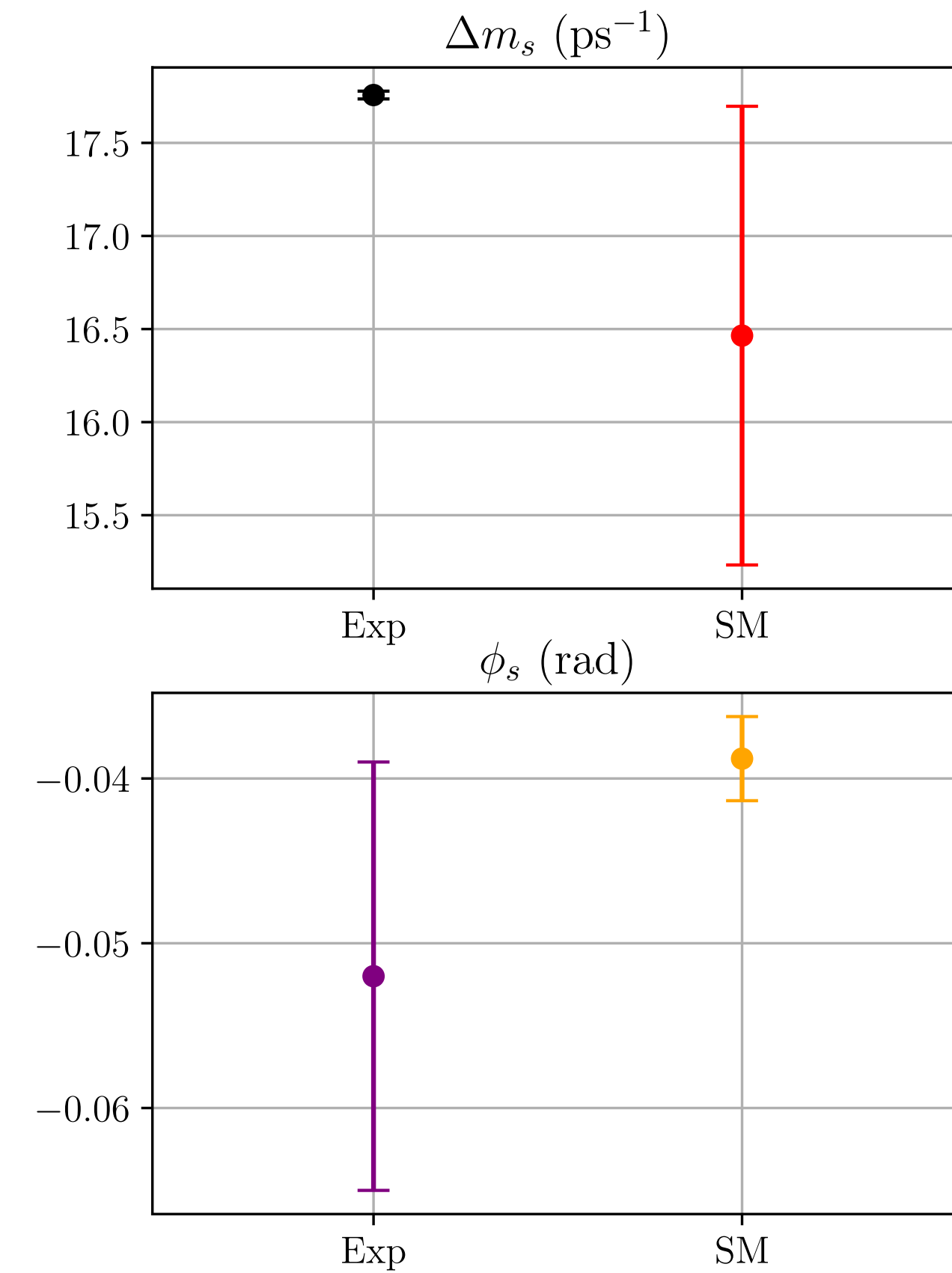
$$\mathbf{y} = y_q \begin{pmatrix} \sin \theta \cos \phi e^{i\alpha_1} & \sin \theta \sin \phi e^{i\alpha_2} & \cos \theta \end{pmatrix} \sim \begin{pmatrix} aV_q & b \end{pmatrix}$$

Flavour Observables SM predictions

Tree-level determination of the CKM

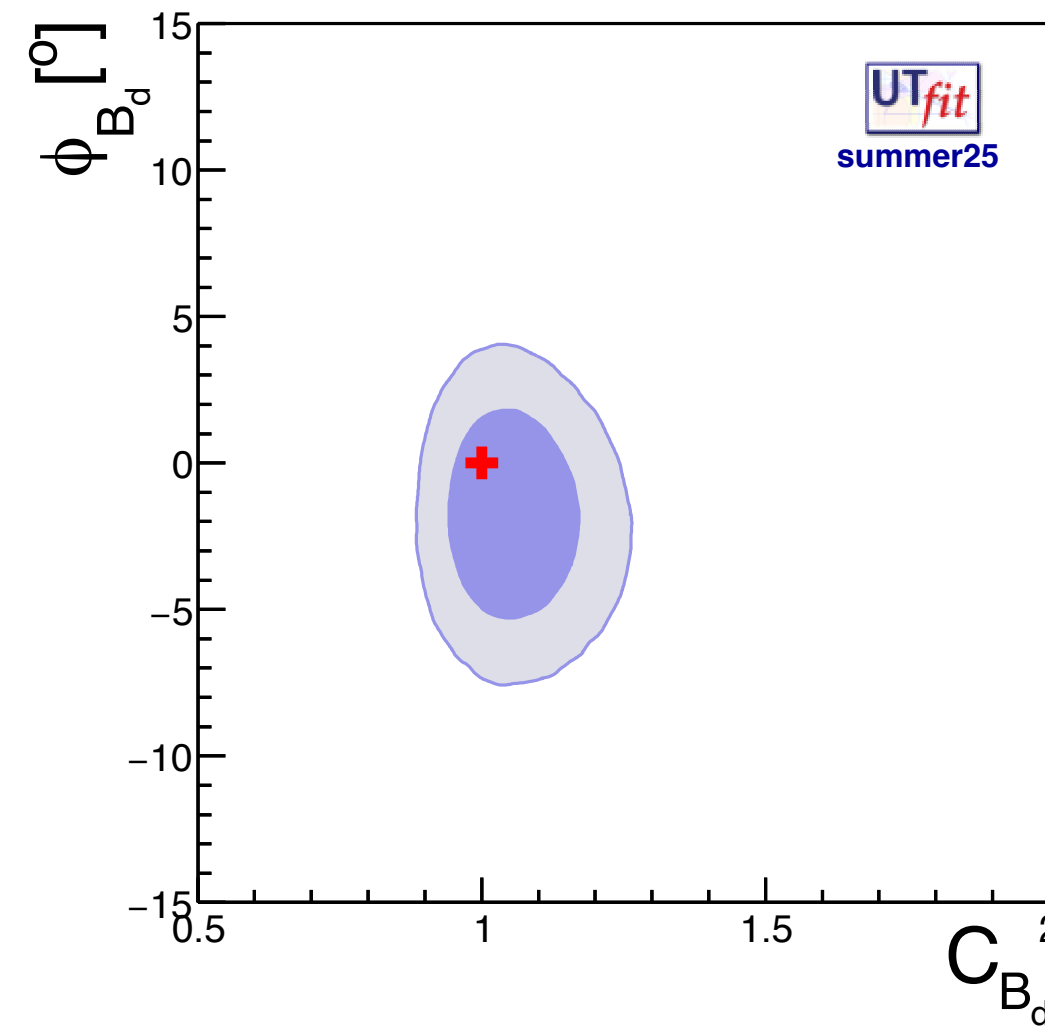
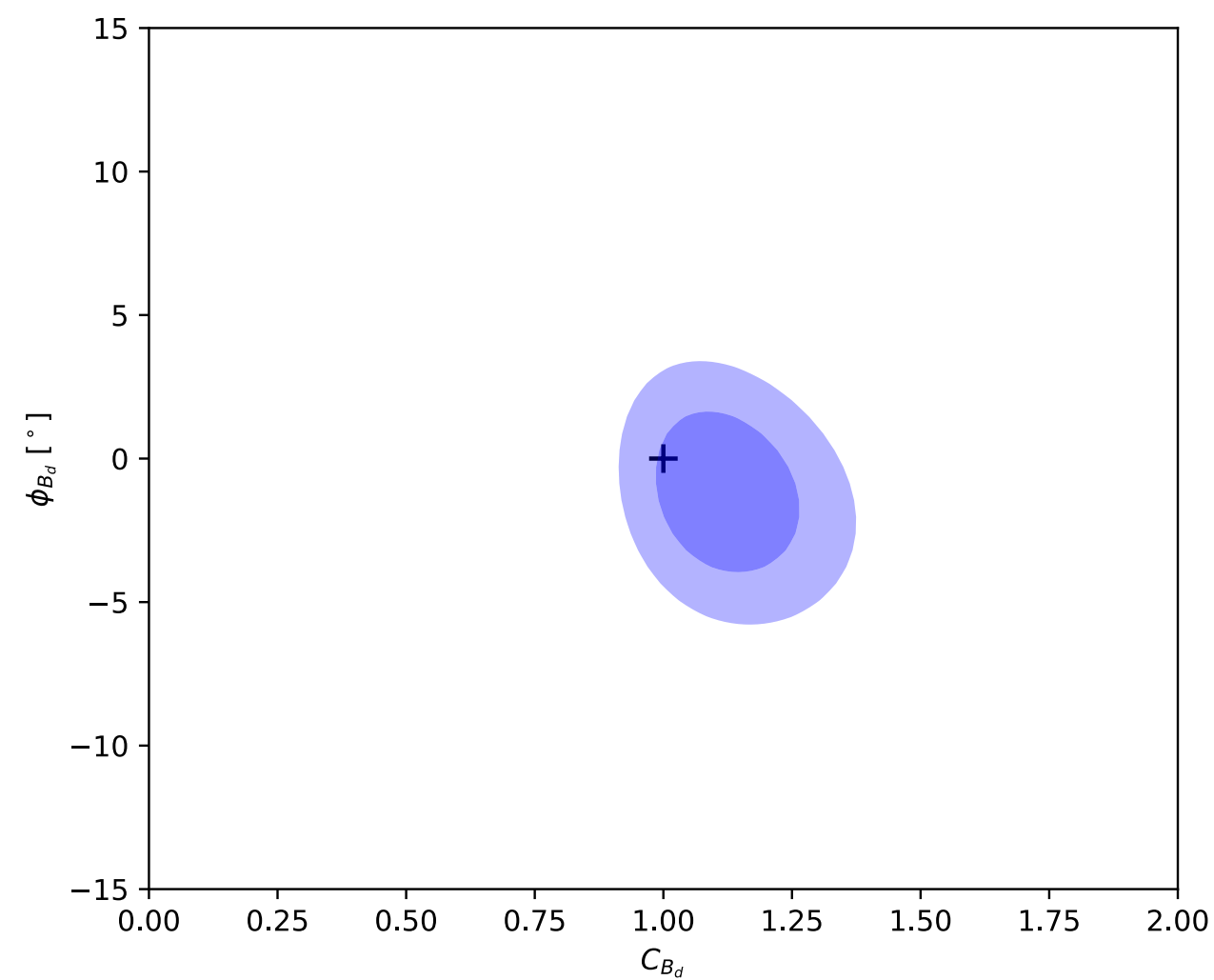
$$V_{us} = 0.22431 \pm 0.00085, V_{ub} = 0.00382 \pm 0.00020$$

$$V_{cb} = 0.0433 \pm 0.002, \gamma = 66.4 \pm 0.3^\circ$$

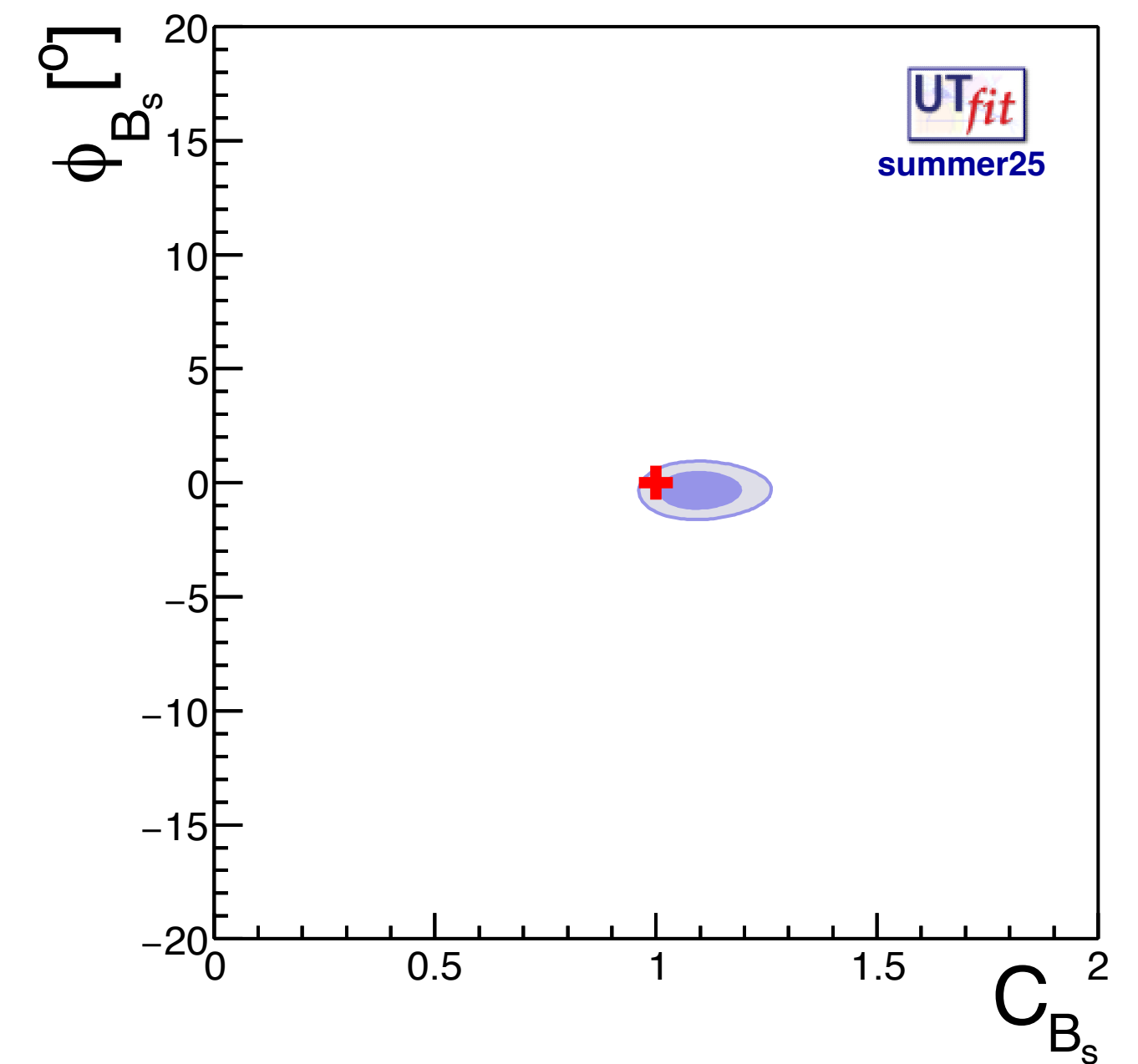
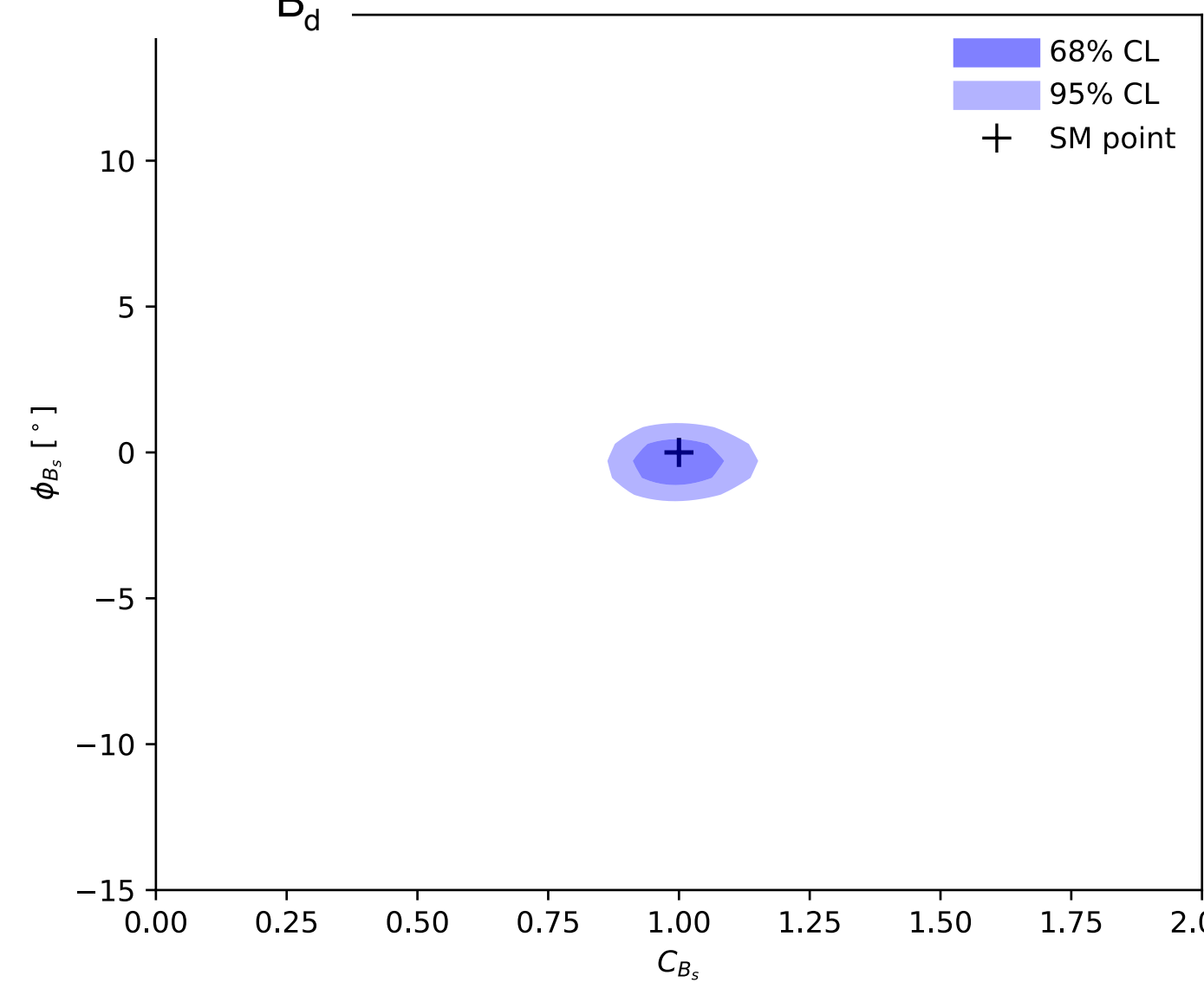


for ϵ_K we follow [Brod, Gorbahn, Stamou '19](#)

Fitting BSM + CKM

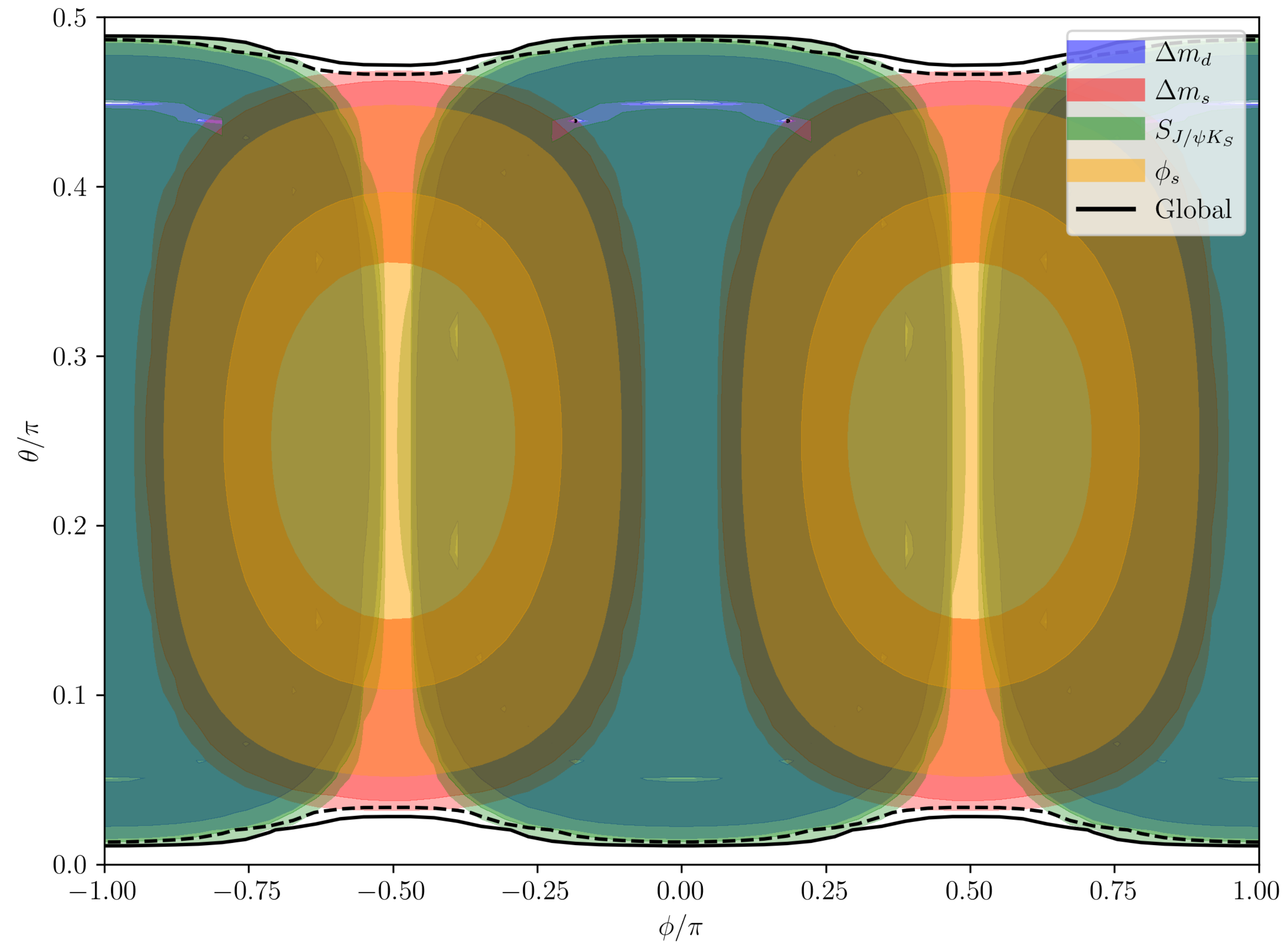


$$C_{B_q} e^{2i\phi_{B_q}} = \frac{\langle B_q^0 | H_{\text{eff}}^{\text{full}} | \bar{B}_q^0 \rangle}{\langle B_q^0 | H_{\text{eff}}^{\text{SM}} | \bar{B}_q^0 \rangle}, \quad (q = d, s)$$



Not too bad :)

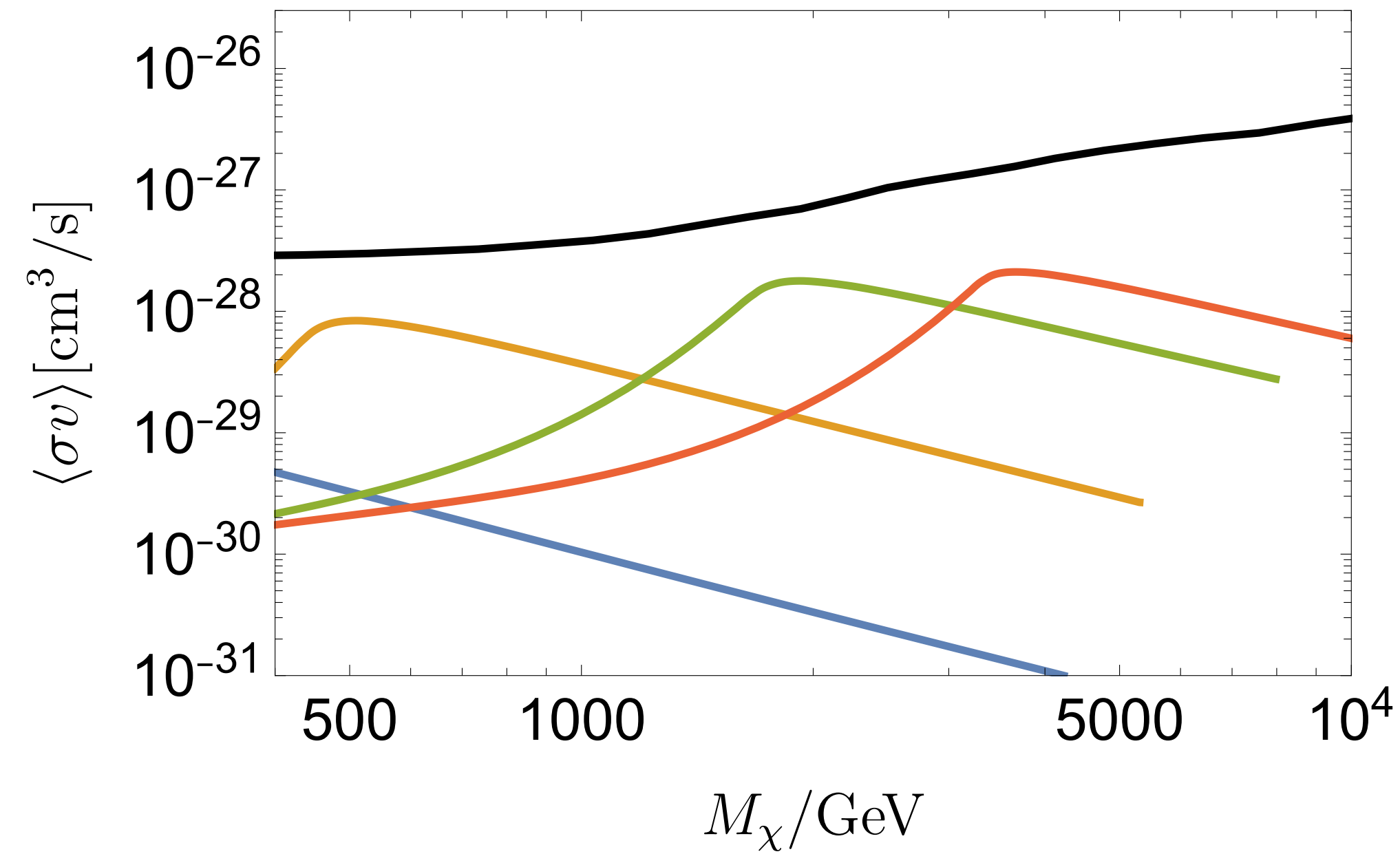
Results using a combined fit



Results mainly
unchanged, just slower.

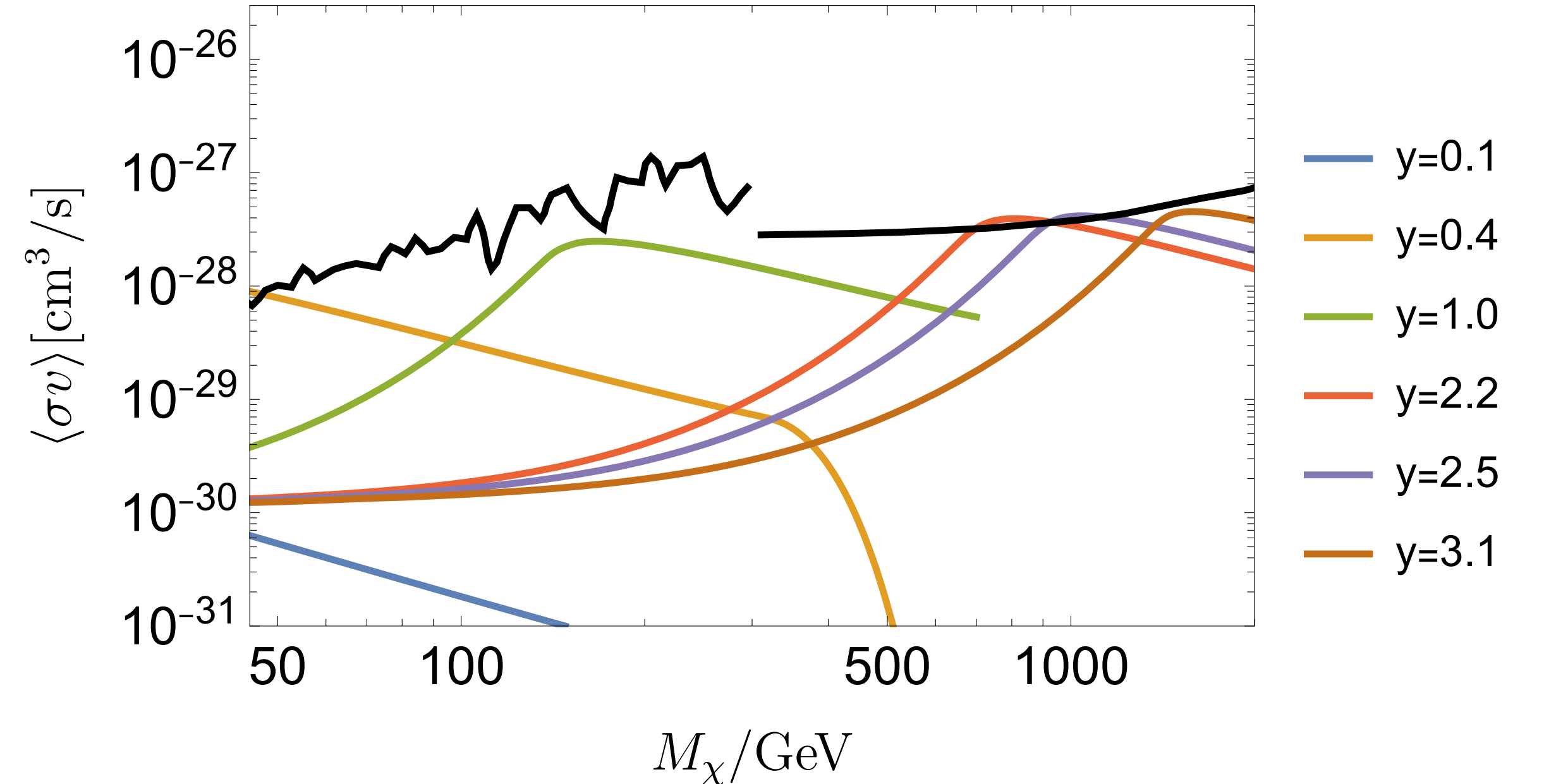
Indirect detection

Majorana, q_L



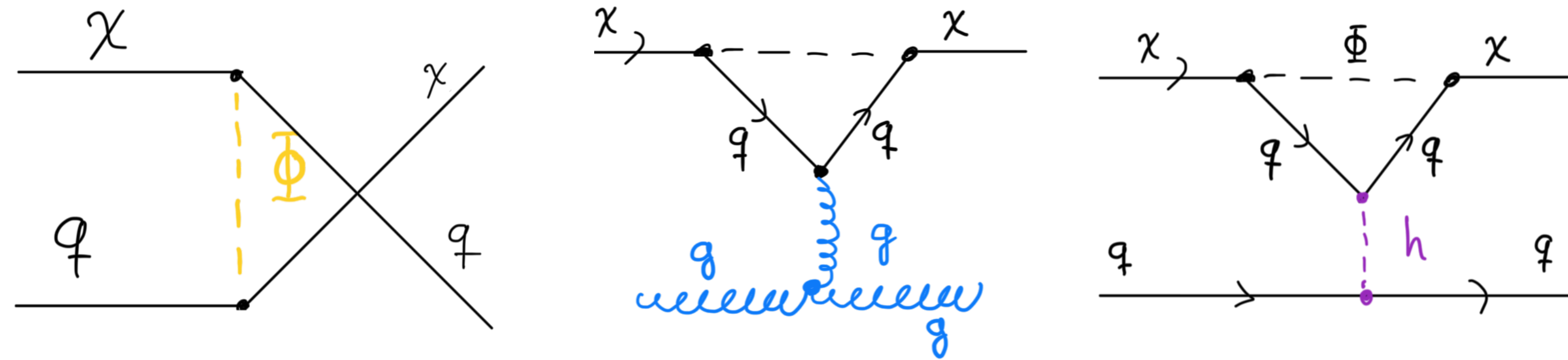
- $y=0.1$
- $y=1.0$
- $y=2.2$
- $y=3.1$

Majorana, e_R



- $y=0.1$
- $y=0.4$
- $y=1.0$
- $y=2.2$
- $y=2.5$
- $y=3.1$

Majorona Quarkphilic DD



$$\mathcal{L} \supset c_{d=8} \bar{\chi} \gamma_\mu D_\nu \chi \bar{q} \gamma^\mu D^\nu q + c_A \bar{\chi} \gamma_\mu \gamma_5 \chi \bar{q} \gamma^\mu \gamma_5 q + (f_{S,g}^{(N)} + f_{S,H}^{(N)}) \bar{\chi} \chi \bar{N} N$$

