WIMP dark matter in the parity solution to strong CP problem

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Based on the work (arXiv:1812.07004)

with J. Kawamura (*Ohio State U.*), S. Okawa (*U. of Victoria*), Y. Tang (*U. of Tokyo*).

Introduction

SM succeeds in many experiments,
but still we cannot be satisfied because of

a lot of "why", e.g.

Why is Higgs mass tachyonic and O(100) GeV?

Why are there three generations?

Why is the gauge symmetry like that?

Why is parity broken?

Why is θ-term so small? (strong CP problem)

cosmological observation

dark matter, Baryogenesis, etc.

Introduction

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Why is Higgs mass tachyonic and O(100) GeV?

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Why is the gauge symmetry like that?

My proposal

Why is parity broken?

Why is θ-term so small? (strong CP problem)

→ **parity symmetric model**

cosmological observation

dark matter, Baryogenesis, etc.

→ **WIMP DM**

What is strong CP problem?

CP is explicitly broken in the SM, so that namely θ -term is allowed.

$$\theta \frac{g_s^2}{32\pi^2} F^a_{\mu\nu} \tilde{F}^{a\mu\nu}$$

To avoid the experimental bound, θ should be tiny:

$$|\theta| \lesssim 10^{-10}$$

Why is it so small?

well-known solutions

$$\theta \frac{g_s^2}{32\pi^2} F^a_{\mu\nu} \tilde{F}^{a\mu\nu}$$

global U(1)$_{PQ}$ symmetry

$$a(x) \frac{g_s^2}{32\pi^2} F^a_{\mu\nu} \tilde{F}^{a\mu\nu}$$

axion

Peccei, Quinn ’77; Weinberg ’77; Wilczek ’77

parity is respected

θ-term is forbidden

Babu, Mohapatra ’90; etc.

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My talk

Point of the model building

- The SM gauge symmetry is

SU(3)$_C$×SU(2)$_L$×U(1)$_Y$

$$Q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix} \qquad \begin{matrix} u_R \\ d_R \end{matrix}$$

We have to extend or introduce extra symmetries and matters, in order to respect parity.

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・The SM gauge symmetry is

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We have to extend or introduce extra symmetries and matters, in order to respect parity.

・We may need more fields to avoid conflict with experimental results.

There are so many fields, but some of extra fields could be good DM candidates.

Content

- Setup
- Introduction of DM
- Phenomenology
- Summary

Setup

Parity transformation

For Dirac fermion (q),

$$P\, q(t,x)\, P = \gamma_0\, q(t,-x) \quad \Leftrightarrow \quad \begin{pmatrix} q_R(t,x) \\ q_L(t,x) \end{pmatrix} \to \begin{pmatrix} q_L(t,-x) \\ q_R(t,-x) \end{pmatrix}$$

LR exchanging

Parity transformation

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LR exchanging

In the SM

SU(2)$_L$ doublet	SU(2)$_L$ singlet
$Q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$	$u_R \qquad d_R$

need extra something to make parity symmetric

Our extension to realize LR exchanging

SU(2)L doublet

$$Q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$$

SU(2)L singlet

u_R d_R

parity transformation

extra something

SU(2)R doublet

$$Q'_R = \begin{pmatrix} u'_R \\ d'_R \end{pmatrix}$$

SU(2)R singlet

u'_L d'_L

gauge symmetry

$SU(3)_C \times SU(2)_L \times U(1)_L \quad \times SU(2)_R \times U(1)_R$

A_L^{μ} ⟷ $A_{R\,\mu}$

parity transformation

gauge symmetry

SU(3)c×SU(2)L×U(1)L ×SU(2)R×U(1)R

A_L^μ ⟷ $A_{R\,\mu}$

parity transformation

Higgs fields

H_L ⟷ H_R

parity transformation

matter content

"SM side"

Fields	spin	$\mathrm{SU}(3)_c$	$\mathrm{SU}(2)_L$	$\mathrm{SU}(2)_R$	$\mathrm{U}(1)_R$	$\mathrm{U}(1)_L$
Q^i_L	$1/2$	$\mathbf{3}$	$\mathbf{2}$	$\mathbf{1}$	0	$1/6$
u^i_R	$1/2$	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$	0	$2/3$
d^i_R	$1/2$	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$	0	$-1/3$
l^i_L	$1/2$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$	0	$-1/2$
e^i_R	$1/2$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	0	-1
H_L	0	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$	0	$1/2$

"Mirror side"

parity transformation

Fields	spin	$\mathrm{SU}(3)_c$	$\mathrm{SU}(2)_L$	$\mathrm{SU}(2)_R$	$\mathrm{U}(1)_R$	$\mathrm{U}(1)_L$
Q'^i_R	$1/2$	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{2}$	$1/6$	0
u'^i_L	$1/2$	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$	$2/3$	0
d'^i_L	$1/2$	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$	$-1/3$	0
l'^i_R	$1/2$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$-1/2$	0
e'^i_L	$1/2$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	-1	0
H_R	0	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$1/2$	0

Yukawa couplings

$$\mathcal{L}_Y = -Y_d^{ij}\overline{Q_L^i}H_L d_R^j - Y_u^{ij}\overline{Q_L^i}\widetilde{H}_L u_R^j - Y_e^{ij}\overline{l_L^i}H_L e_R^j + h.c.$$

$$-Y_d^{ij}\overline{Q'^i_R}H_R d'^j_L - Y_u^{ij}\overline{Q'^i_R}\widetilde{H}_R u'^j_L - Y_e^{ij}\overline{l'^i_R}H_R e'^j_L + h.c.$$

Yukawa couplings

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problem 1

Mirror fermions should be heavy $\rightarrow \langle H_L \rangle \ll \langle H_R \rangle$

Yukawa couplings

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problem 1

Mirror fermions should be heavy $\rightarrow \langle H_L \rangle \ll \langle H_R \rangle$

problem 2

Stable colored particles appear

$\rightarrow$ *introduce extra scalars,* X_b *and* X_l *with*

$$\lambda_u^{ij}\, X_b\, \overline{u_R^i}\, u'^j_L + \lambda_e^{ij}\, X_l\, \overline{e_R^i}\, e'^j_L$$

The detail of X_b and X_l

charge assignment

Fields	spin	$U(1)_R$	$U(1)_L$
X_b	0	$-2/3$	$2/3$
X_l	0	1	-1

They are not charged under the other symmetries.

Coupling with quarks and electrons

$$\lambda_u^{ij}\, X_b\, \overline{u_R^i}\, u_L^{\prime\, j} + \lambda_e^{ij}\, X_l\, \overline{e_R^i}\, e_L^{\prime\, j}$$

Mirror quarks decay through these couplings:

$$u_j' \to u_i\, X_b,\ \ e_j' \to e_i\, X_l$$

We can consider two cases:

$$(I)\ \langle X_b \rangle = 0\ and\ \langle X_l \rangle \neq 0$$

$$(II)\ \langle X_b \rangle \neq 0\ and\ \langle X_l \rangle = 0$$

For instance

$$(I)\ \langle X_b \rangle = 0\ and\ \langle X_l \rangle \neq 0$$

- $SU(3)_C \times SU(2)_L \times U(1)_L \times SU(2)_R \times U(1)_R$

$\rightarrow SU(3)_C \times SU(2)_L \times U(1)_L \times U(1)' \rightarrow SU(3)_C \times SU(2)_L \times U(1)_Y$

$\langle H_R \rangle \neq 0$ $\qquad\qquad$ $\langle X_l \rangle \neq 0$

For instance

$$(I)\ \langle X_b\rangle = 0\ and\ \langle X_l\rangle \neq 0$$

- $SU(3)_c \times SU(2)_L \times U(1)_L \times SU(2)_R \times U(1)_R$

$\rightarrow SU(3)_c \times SU(2)_L \times U(1)_L \times U(1)' \rightarrow SU(3)_c \times SU(2)_L \times U(1)_Y$

$\langle H_R\rangle \neq 0$ $\langle X_l\rangle \neq 0$

- X_b is neutral under the SM gauge symmetry and stable because of the remnant discrete symmetry.

X_b is a good DM candidate that couples to up-type quarks

"baryonic DM"

For instance

$$(II)\ \langle X_b \rangle \neq 0\ and\ \langle X_l \rangle = 0$$

- $SU(3)_C \times SU(2)_L \times U(1)_L \times SU(2)_R \times U(1)_R$

  $\rightarrow SU(3)_C \times SU(2)_L \times U(1)_L \times U(1)' \rightarrow SU(3)_C \times SU(2)_L \times U(1)_Y$

  $\langle H_R \rangle \neq 0$ $\quad$ $\langle X_b \rangle \neq 0$

- X_l is neutral under the SM gauge symmetry and stable because of the remnant discrete symmetry.

X_l is a good DM candidate that couples to leptons

"leptonic DM"

Phenomenology

We can explicitly calculate most parts.
The relevant free parameters are the Yukawa couplings:

$$\lambda_u^{ij}\, X_b\, \overline{u_R^i}\, u_L'^{\,j} + \lambda_e^{ij}\, X_l\, \overline{e_R^i}\, e_L'^{\,j}$$

These couplings contribute to

flavor physics (*D*-$\bar{D}$ *mixing*, $t \to qV$, $\mu \to e\gamma$, etc.)

LHC physics (*pp*→*jj*+*missing*, *ll*+*missing*, *etc.*)

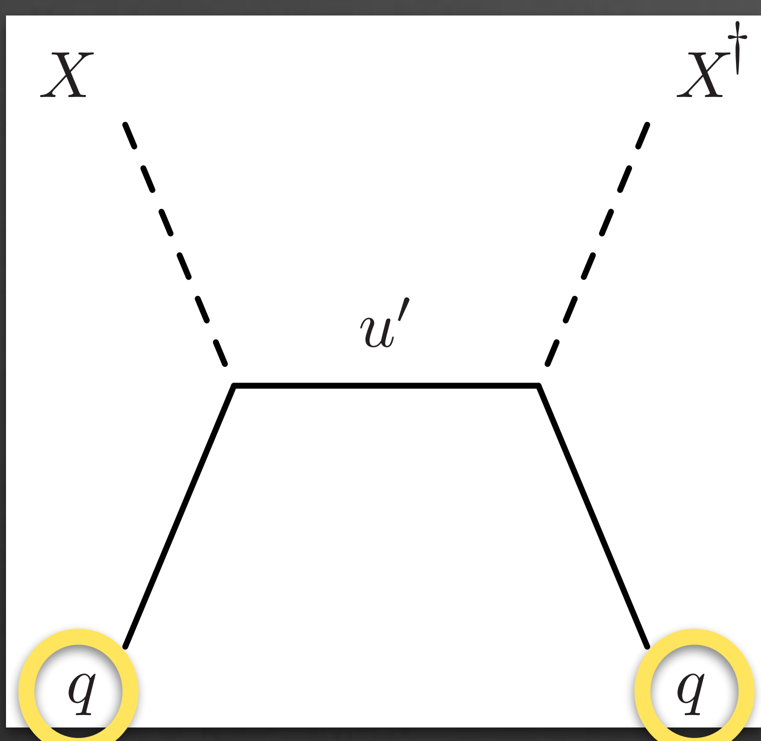
dark matter physics

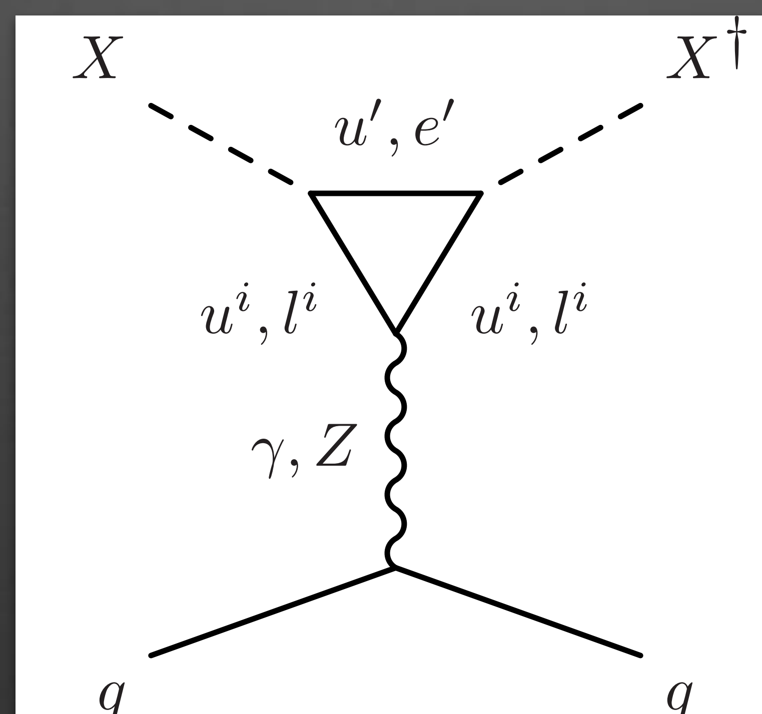
In particular, DM physics strongly constrains this setup.

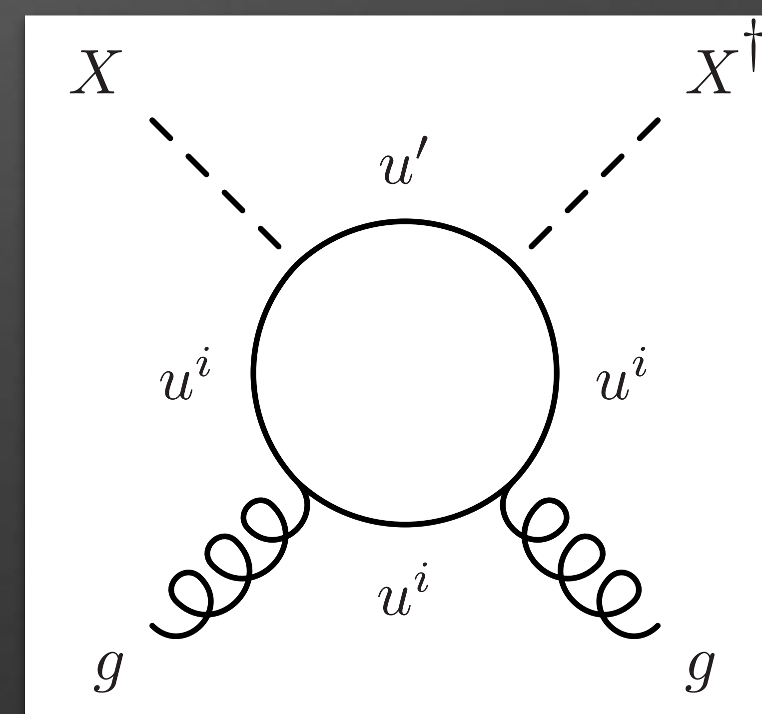
Dark Matter Physics

$$\lambda_u^{ij}\, X_b\, \overline{u_R^i}\, u_L'^{\,j} + \lambda_e^{ij}\, X_l\, \overline{e_R^i}\, e_L'^{\,j}$$

contribute to annihilation and direct detection:





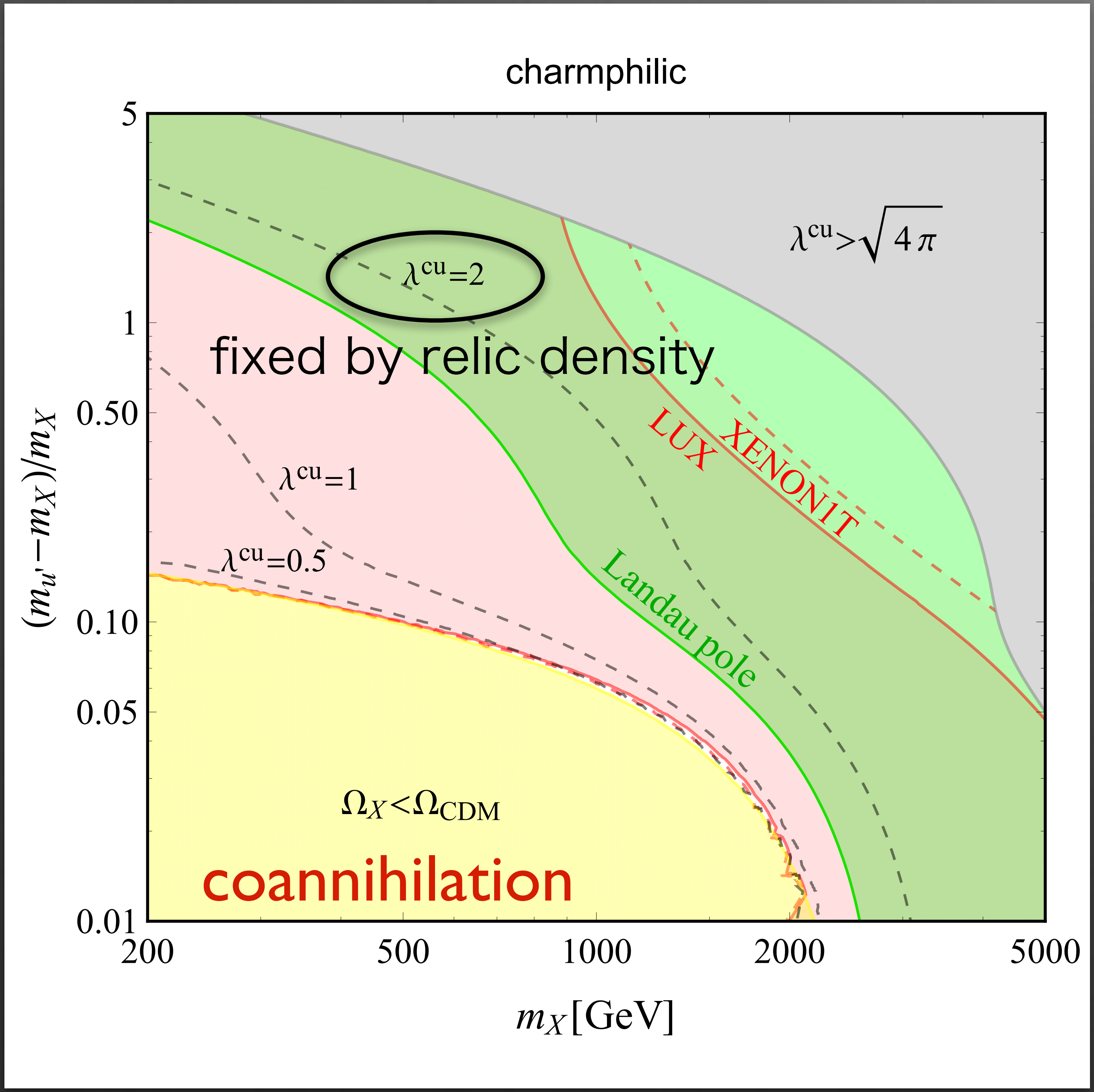


flavor depends on the Yukawa alignment, λ_u

Allowed region in baryonic DM (X_b)

(1) Assume DM dominantly couples to **charm quark** and mirror up quark

$(u' \to c\, X_b)$



1812.07004, Kawamura, Okawa, YO, Tang

Allowed region in baryonic DM (Xb)

(1) Assume DM dominantly couples to **charm quark** and mirror up quark

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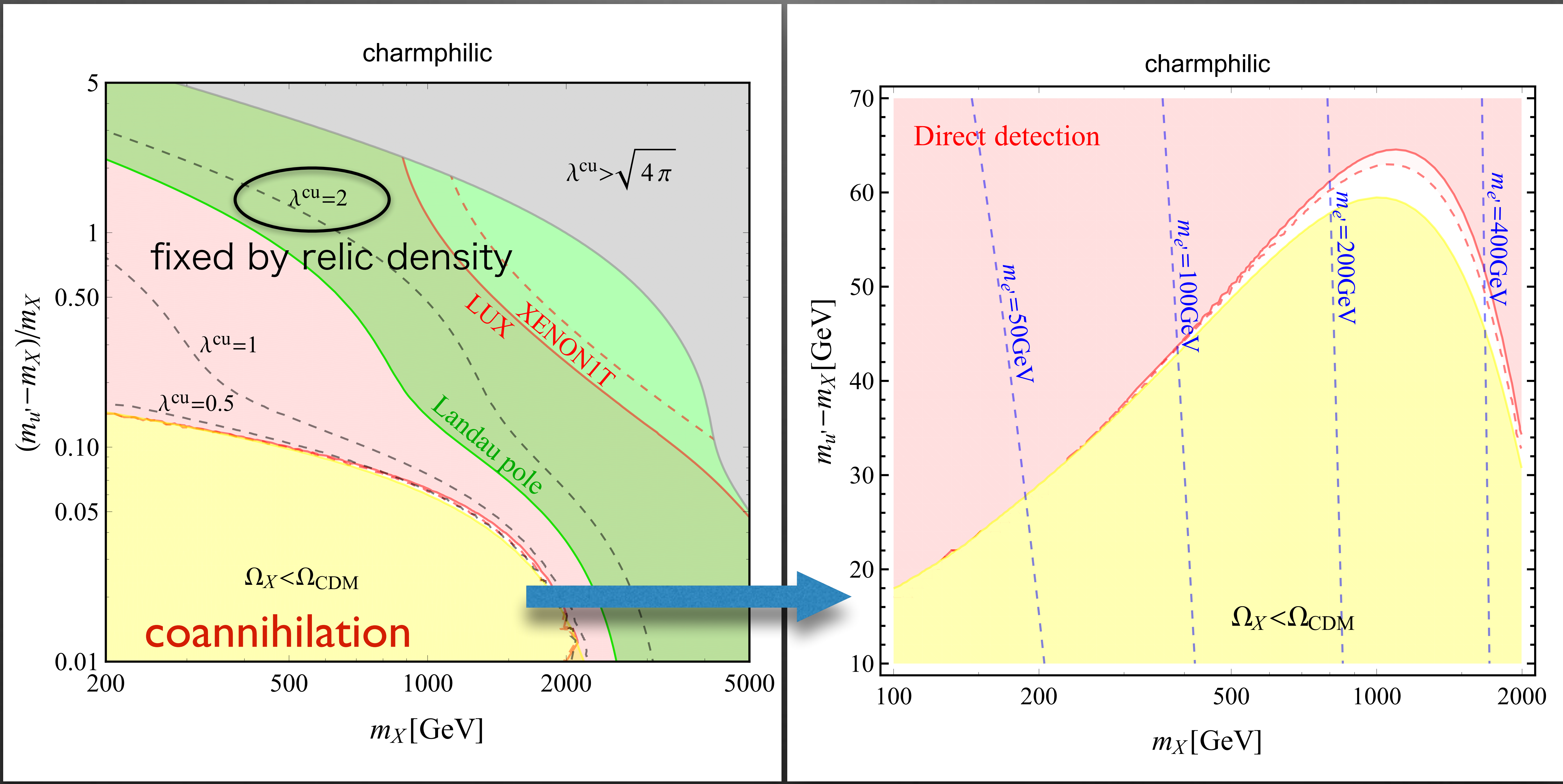

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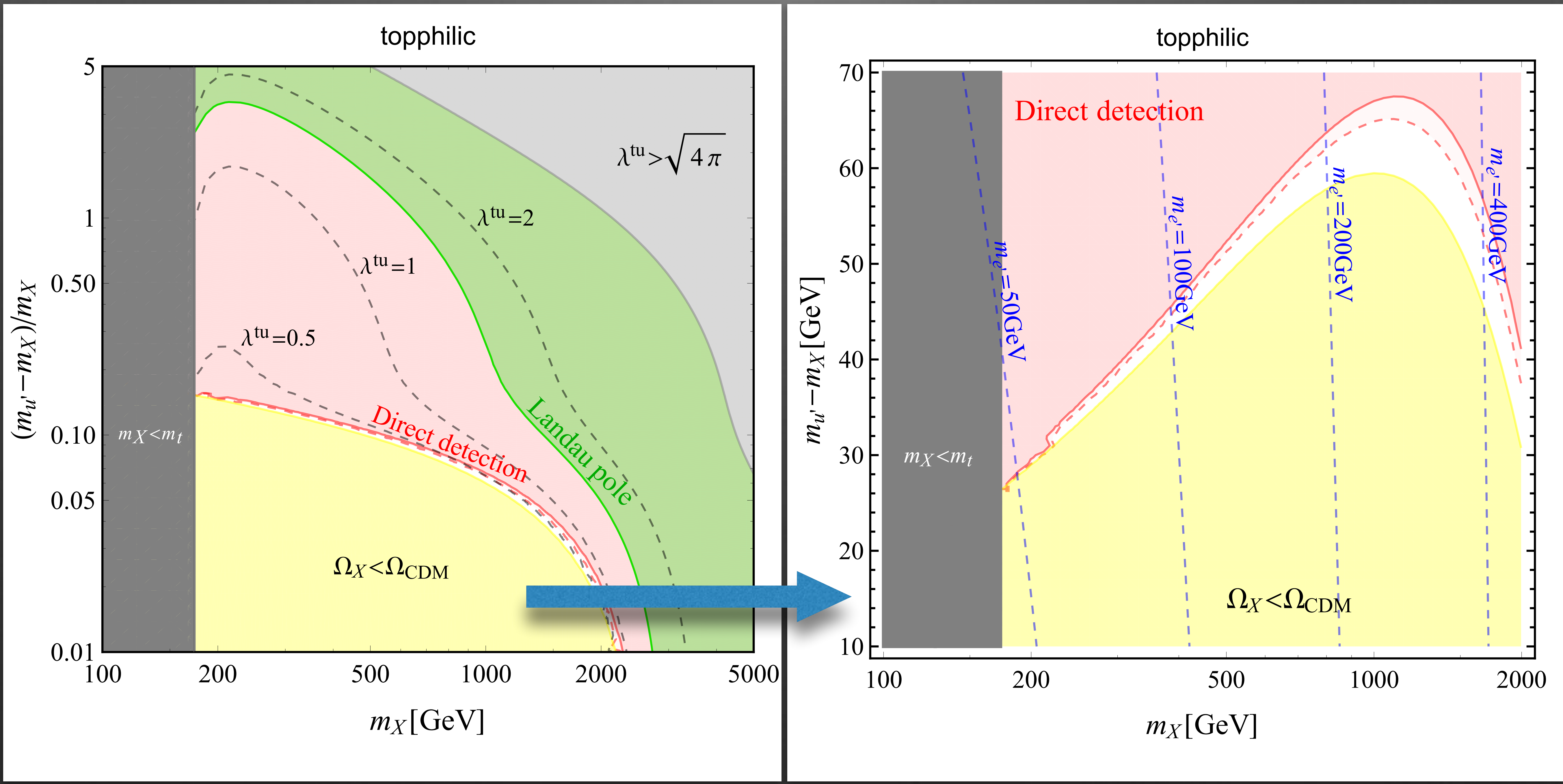
Allowed region in baryonic DM (Xb)

(2) DM dominantly couples to **top quark** and mirror up quark

$(u' \to t\, X_b)$



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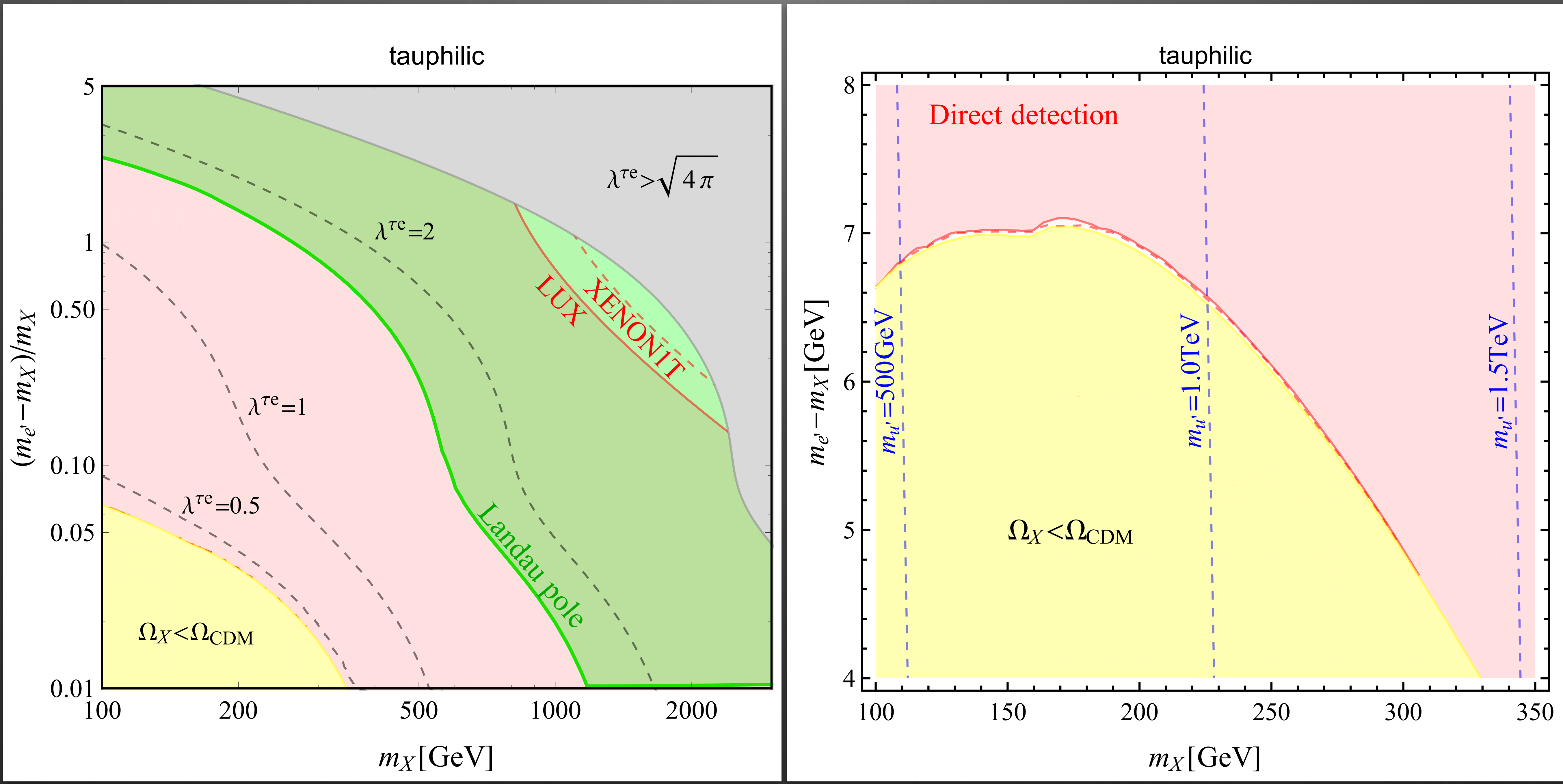
Allowed region in leptonic DM (Xl)

(3) DM dominantly couples to τ and mirror electron



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Summary

- We propose one model with parity symmetry, motivated by *the strong CP problem*.

One well-known simple setup

$SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

$$Q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix} \qquad Q_R = \begin{pmatrix} u_R \\ d_R \end{pmatrix}$$

Babu, Mohapatra, '89

We have to discuss how to construct the realistic fermion mass spectrum and how to avoid avoid the tree-level FCNC.

- We propose one model with parity symmetry introducing the mirror sector, motivated by *the strong CP problem*.

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- Yukawa couplings are the same as the SM.
- Some mirror (colored) charged particles become stable, so we introduce extra scalars, X_b and X_l.
- X_b/X_l is a baryonic/leptonic DM candidate.
- DM physics strongly constrains this model, as far as DM is thermally produced.
- LHC physics is also important ($pp \to e'^{+}e'^{-} \to l^{+}l^{-}$ *missing etc.*).
- Neutrino physics would have rich phenomenology.

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and work in progress

END