WIMP dark matter expected in the parity solution to strong CP problem

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Based on the work (arXiv:1812.*****)

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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My proposal

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.

well-known solutions

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

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My talk

Content

- Setup
- Introduction of DM
- Phenomenology
- Summary

Setup

Parity transformation

For Dirac fermion (q),

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

Parity transformation

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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

P. H. Gu, '11;etc.

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

parity transformation

extra something

SU(2)R doublet	SU(2)R singlet
$Q'_R = \begin{pmatrix} u'_R \\ d'_R \end{pmatrix}$	u'_L $\quad$ d'_L

symmetry

SU(3)$_C$×SU(2)$_L$×U(1)$_L$ ×SU(2)$_R$×U(1)$_R$

$A_L^\mu \longleftrightarrow A_{R\,\mu}$

parity transformation

symmetry

SU(3)$_C$×SU(2)$_L$×U(1)$_L$ ×SU(2)$_R$×U(1)$_R$

$$A_L^{\mu} \longleftrightarrow A_{R\,\mu}$$

parity transformation

Higgs fields

$$H_L \longleftrightarrow H_R$$

parity transformation

matter content

"original side"

Fields	spin	$\mathrm{SU}(3)_c$	$\mathrm{SU}(2)_L$	$\mathrm{SU}(2)_R$	$\mathrm{U}(1)_R$	$\mathrm{U}(1)_L$
Q_L^i	$1/2$	$\mathbf{3}$	$\mathbf{2}$	$\mathbf{1}$	0	$1/6$
u_R^i	$1/2$	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$	0	$2/3$
d_R^i	$1/2$	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$	0	$-1/3$
l_L^i	$1/2$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$	0	$-1/2$
e_R^i	$1/2$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	0	-1
H_L	0	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$	0	$1/2$

parity transformation

"Mirror side"

Fields	spin	$\mathrm{SU}(3)_c$	$\mathrm{SU}(2)_L$	$\mathrm{SU}(2)_R$	$\mathrm{U}(1)_R$	$\mathrm{U}(1)_L$
$Q'^{\,i}_R$	$1/2$	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{2}$	$1/6$	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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$$-Y_d^{ij}\overline{Q'^i_R}H_R d'^j_L - Y_u^{ij}\overline{Q'^i_R}\widetilde{H}_R u'^j_L - Y_e^{ij}\overline{l'^i_R}H_R e'^j_L + h.c.$$

problem 1

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

Yukawa couplings

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

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

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 Xb and Xl

charge assignment

Fields	spin	$\mathrm{U}(1)_R$	$\mathrm{U}(1)_L$
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

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

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

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

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

$$\xrightarrow[\langle H_R \rangle \neq 0]{} SU(3)_C \times SU(2)_L \times U(1)_L \times U(1)' \xrightarrow[\langle X_l \rangle \neq 0]{} SU(3)_C \times SU(2)_L \times U(1)_Y$$

For instance

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

$\xrightarrow[\langle H_R \rangle \neq 0]{}$ $SU(3)_C \times SU(2)_L \times U(1)_L \times U(1)'$ $\xrightarrow[\langle X_l \rangle \neq 0]{}$ $SU(3)_C \times SU(2)_L \times U(1)_Y$

- 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"

Phenomenology (dark matter physics)

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 (*$pp \to jj$+missing, ll+missing, etc.*)

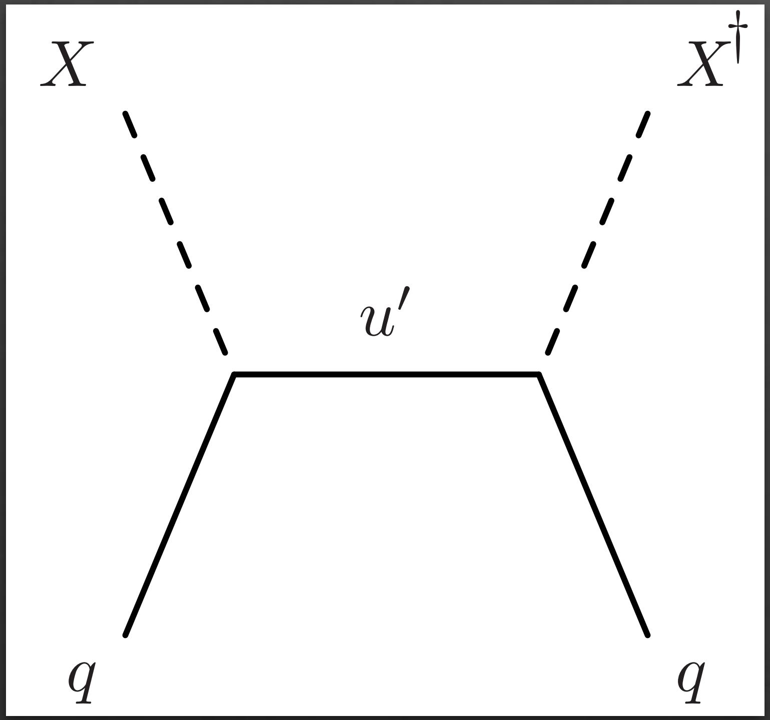
dark matter physics

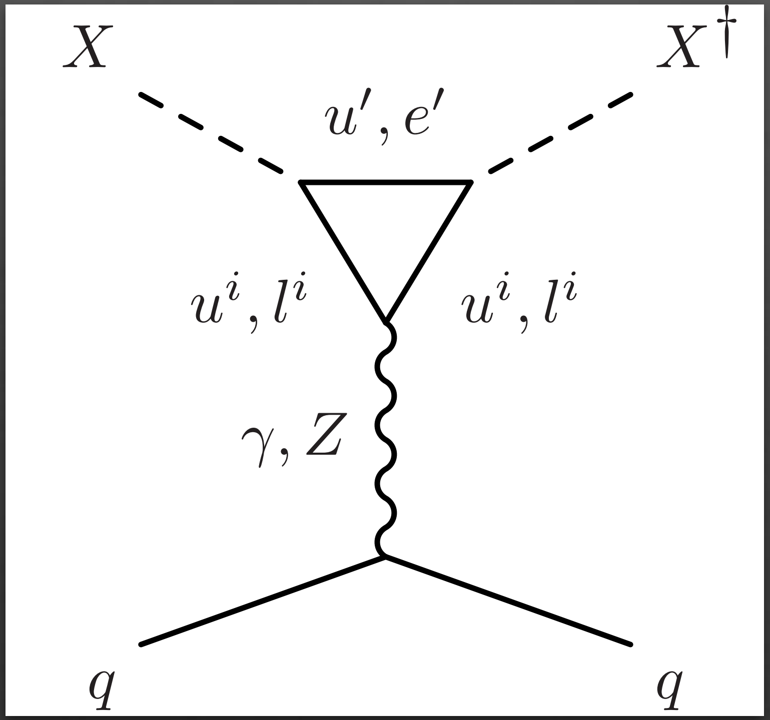
In particular, DM physics strongly constrains this setup.

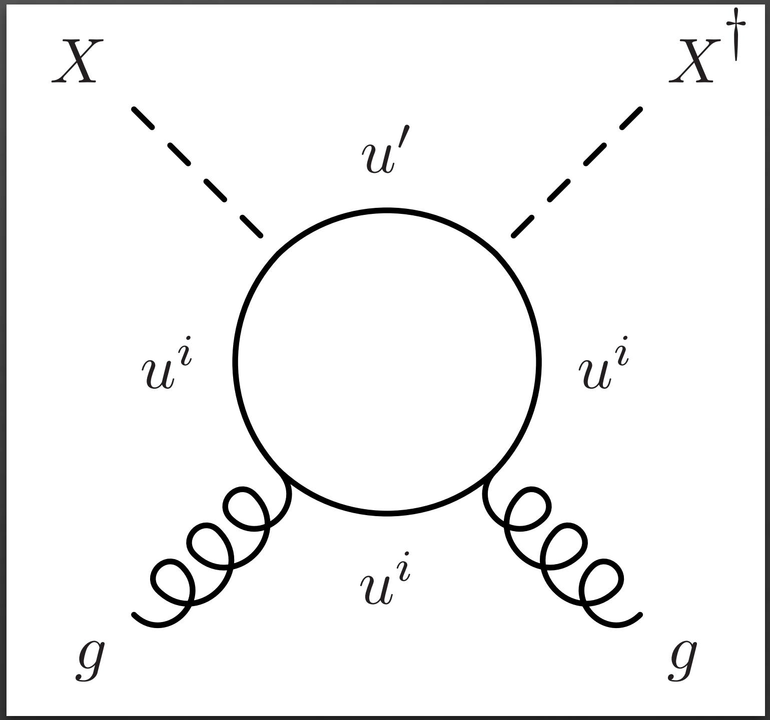
Dark Matter Physics

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

contribute to annihilation and direct detection:



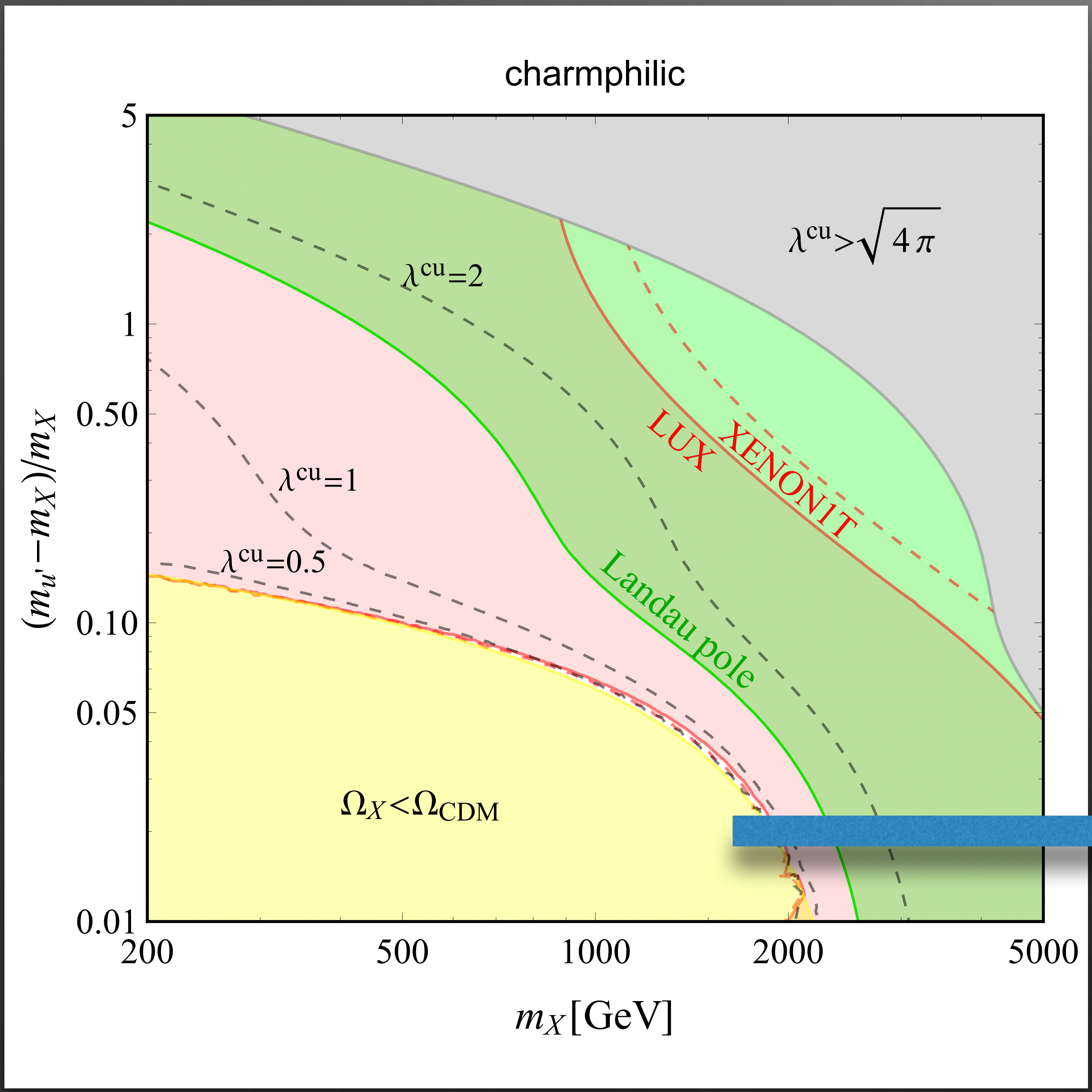


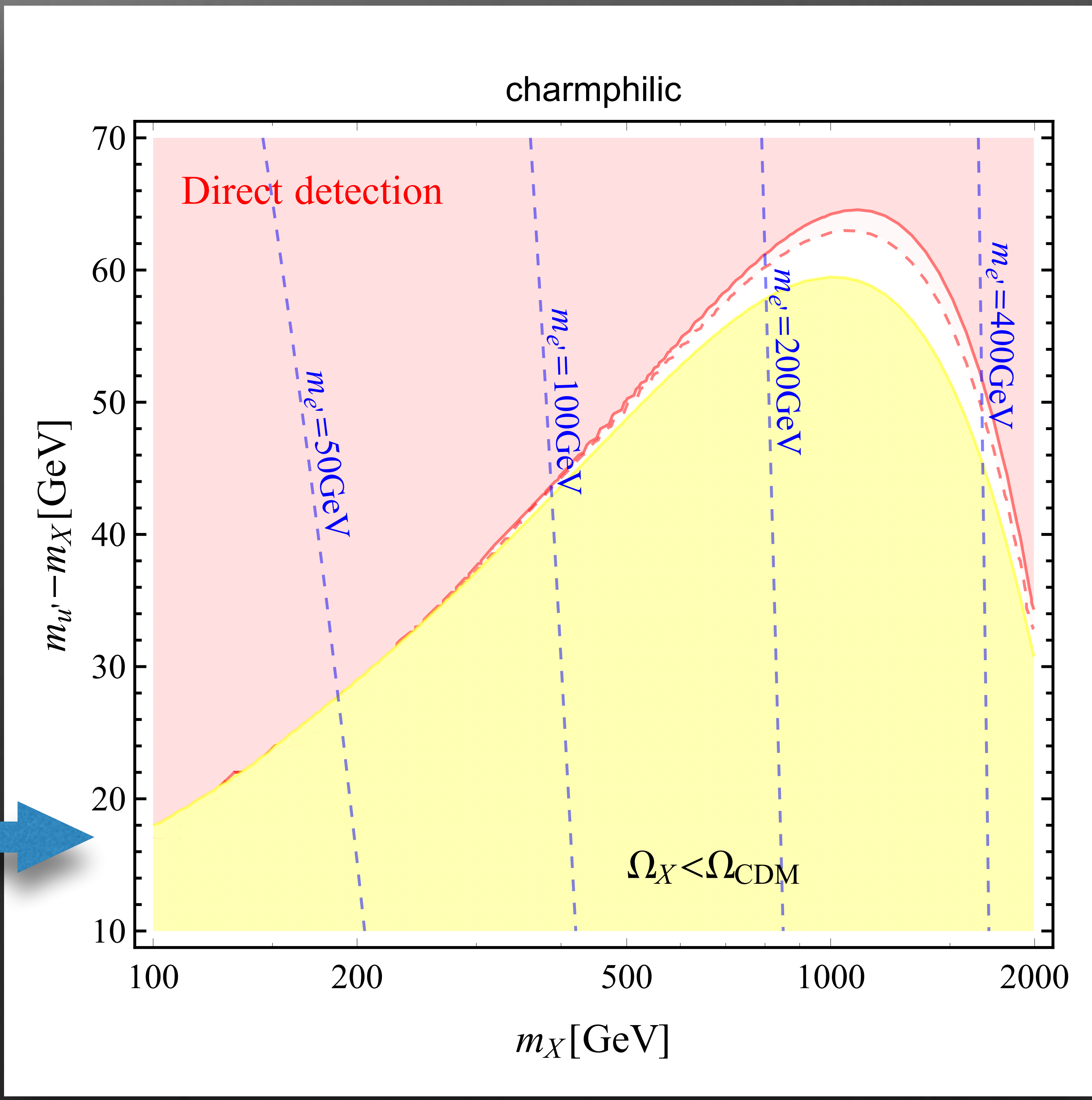


Allowed region in baryonic DM (Xb)

(I) DM dominantly couples to charm quark and mirror up quark

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

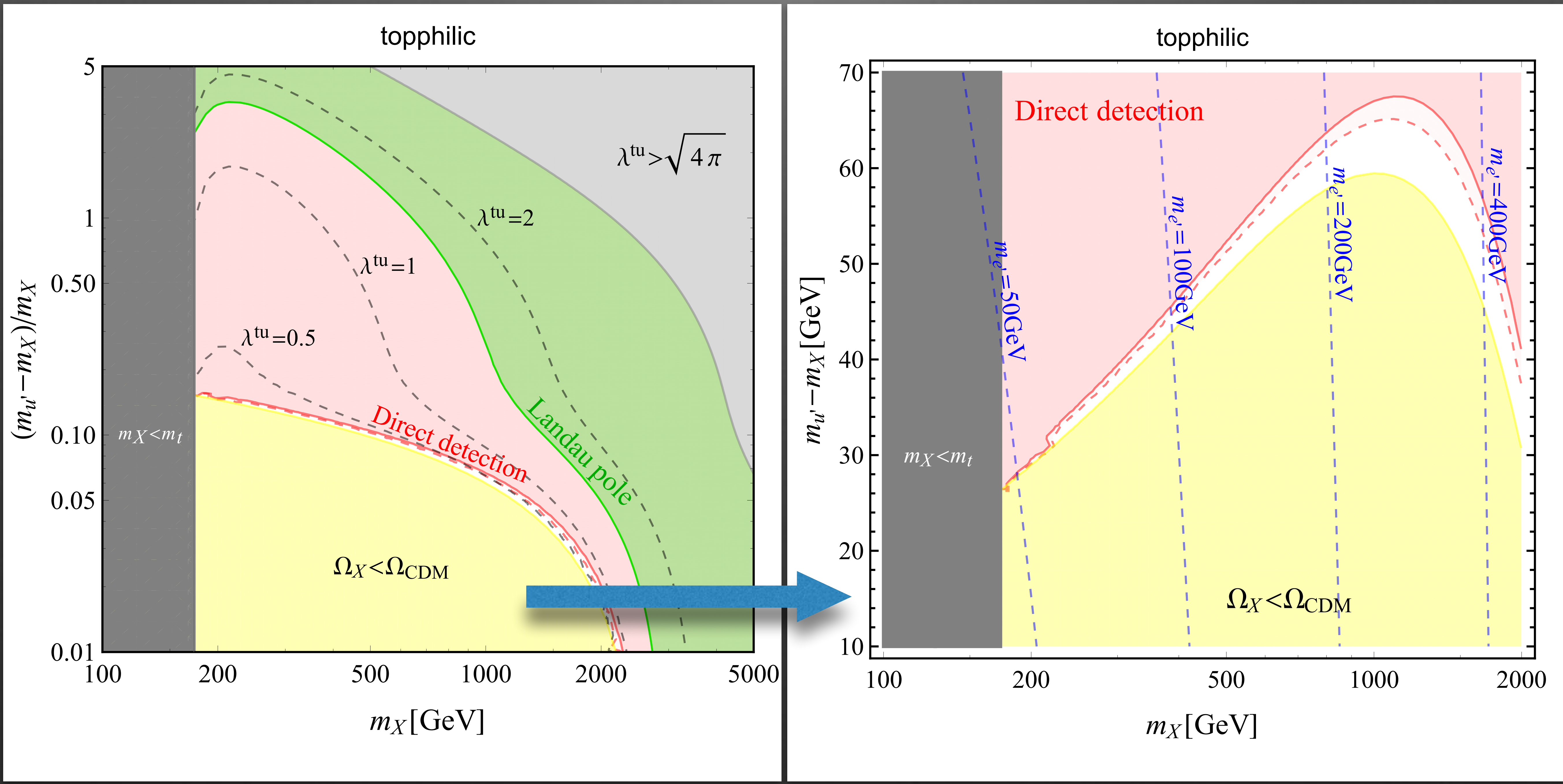




Allowed region in baryonic DM (Xb)

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

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



Summary

- We propose one model with parity symmetry introducing the mirror sector, motivated by *the strong CP problem*.
- 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.
- LHC physics would be relevant ($pp \to e'_+ e'_- \to l_+ l_-$ *missing*).
- *Our paper will appear on arXiv this month.*

END

We consider two cases:

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

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

  $\xrightarrow{\langle H_R \rangle \neq 0} SU(3)_C \times SU(2)_L \times U(1)_L \times U(1)' \xrightarrow{\langle X_b \rangle \neq 0} SU(3)_C \times SU(2)_L \times U(1)_Y$

- 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"

Allowed region in leptonic DM (Xl)

(3) DM dominantly couples to τ and mirror electron