

WIMP dark matter in the parity solution to strong CP problem

Yuji Omura
(*Kindai Univ.*)

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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Our work

motivated by

What is strong CP problem?

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

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

To avoid the experimental bound, θ should be tiny:

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

Why is it so small?

well-known solutions

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


The diagram shows a central theta term equation at the top. Two blue arrows point downwards from this equation to two separate blue boxes. The left box contains the axion solution, and the right box contains the parity-respecting solution.

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

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

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

Content

- Setup
- Introduction of DM
- Phenomenology
- Summary

Setup

Parity transformation

For Dirac fermion (q),

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

LR exchanging

Parity transformation

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LR exchanging

In the SM

SU(2)_L doublet

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

SU(2)_L singlet

$$u_R \quad d_R$$

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

$$u_R \quad d_R$$



parity transformation



extra something

SU(2)_R doublet

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

SU(2)_R singlet

$$u'_L \quad d'_L$$

gauge symmetry

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

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

parity transformation

Higgs fields

$$H_L \quad \longleftrightarrow \quad H_R$$

parity transformation

matter content

“SM side”

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

“Mirror side”

parity transformation



Fields	spin	$SU(3)_c$	$SU(2)_L$	$SU(2)_R$	$U(1)_R$	$U(1)_L$
$Q_R'^i$	1/2	3	1	2	1/6	0
$u_L'^i$	1/2	3	1	1	2/3	0
$d_L'^i$	1/2	3	1	1	-1/3	0
$l_R'^i$	1/2	1	1	2	-1/2	0
$e_L'^i$	1/2	1	1	1	-1	0
H_R	0	1	1	2	1/2	0

Yukawa couplings

$$\begin{aligned}\mathcal{L}_Y = & -Y_d^{ij} \overline{Q_L^i} H_L d_R^j - Y_u^{ij} \overline{Q_L^i} \tilde{H}_L u_R^j - Y_e^{ij} \overline{l_L^i} H_L e_R^j + h.c. \\ & -Y_d^{ij} \overline{Q_R'^i} H_R d_L'^j - Y_u^{ij} \overline{Q_R'^i} \tilde{H}_R u_L'^j - Y_e^{ij} \overline{l_R'^i} H_R e_L'^j + h.c.\end{aligned}$$

Yukawa couplings

$$\begin{aligned}\mathcal{L}_Y = & -Y_d^{ij} \overline{Q}_L^i H_L d_R^j - Y_u^{ij} \overline{Q}_L^i \tilde{H}_L u_R^j - Y_e^{ij} \overline{l}_L^i H_L e_R^j + h.c. \\ & -Y_d^{ij} \overline{Q}_R'^i H_R d_L'^j - Y_u^{ij} \overline{Q}_R'^i \tilde{H}_R u_L'^j - Y_e^{ij} \overline{l}_R'^i H_R e_L'^j + h.c.\end{aligned}$$

problem I

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

Yukawa couplings

$$\mathcal{L}_Y = -Y_d^{ij} \overline{Q}_L^i H_L d_R^j - Y_u^{ij} \overline{Q}_L^i \tilde{H}_L u_R^j - Y_e^{ij} \overline{l}_L^i H_L e_R^j + h.c.$$
$$-Y_d^{ij} \overline{Q}_R'^i H_R d_L'^j - Y_u^{ij} \overline{Q}_R'^i \tilde{H}_R u_L'^j - Y_e^{ij} \overline{l}_R'^i H_R e_L'^j + h.c.$$

problem 1

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

problem 2

Stable (colored) charged particles appear

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

$$\lambda_u^{ij} X_b \overline{u}_R^i u_L'^j + \lambda_e^{ij} X_l \overline{e}_R^i e_L'^j$$

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

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

Mirror quarks decay through these couplings:

$$u_j' \rightarrow u_i X_b, \quad e_j' \rightarrow e_i X_l$$

We can consider two cases:

$$(I) \quad \langle X_b \rangle = 0 \text{ and } \langle X_l \rangle \neq 0$$

$$(II) \quad \langle X_b \rangle \neq 0 \text{ and } \langle X_l \rangle = 0$$

For instance

$$(I) \quad \langle X_b \rangle = 0 \text{ and } \langle X_l \rangle \neq 0$$

$$\cdot \text{SU}(3)_c \times \text{SU}(2)_L \times \text{U}(1)_L \times \text{SU}(2)_R \times \text{U}(1)_R$$

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

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

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

For instance

$$(I) \quad \langle X_b \rangle = 0 \text{ and } \langle X_l \rangle \neq 0$$

$$\bullet \text{ SU}(3)_c \times \text{SU}(2)_L \times \text{U}(1)_L \times \text{SU}(2)_R \times \text{U}(1)_R$$

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

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

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

- 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”

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, $t \rightarrow qV$, $\mu \rightarrow e \gamma$, etc.)

LHC physics ($pp \rightarrow jj + \text{missing}$, $ll + \text{missing}$, etc.)

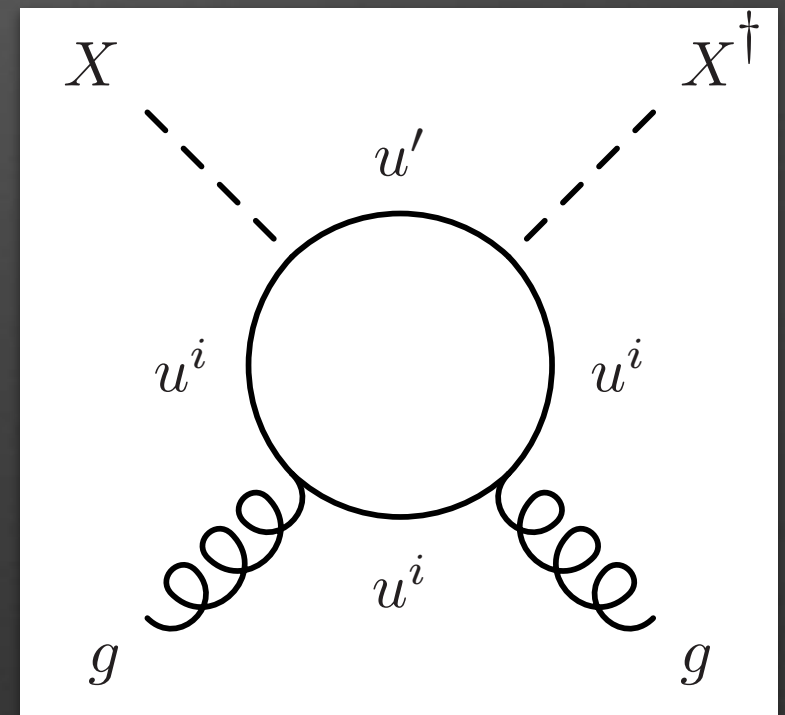
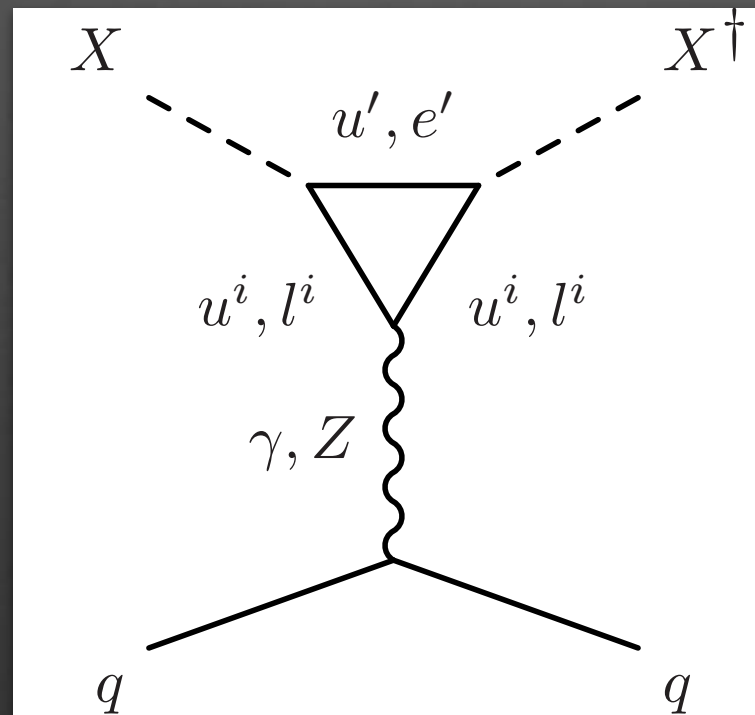
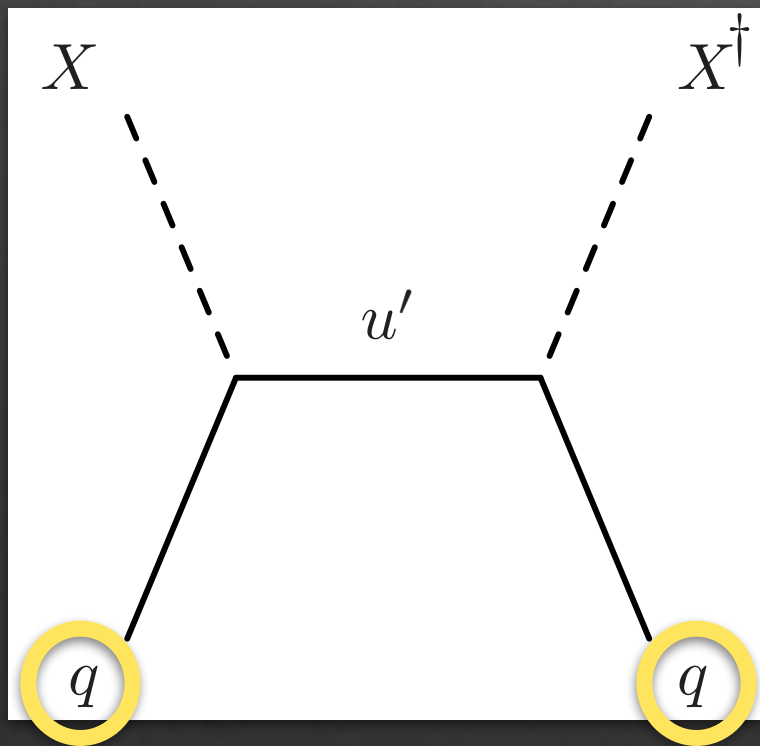
dark matter physics

In particular, DM physics strongly constrains this setup.

Dark Matter Physics

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

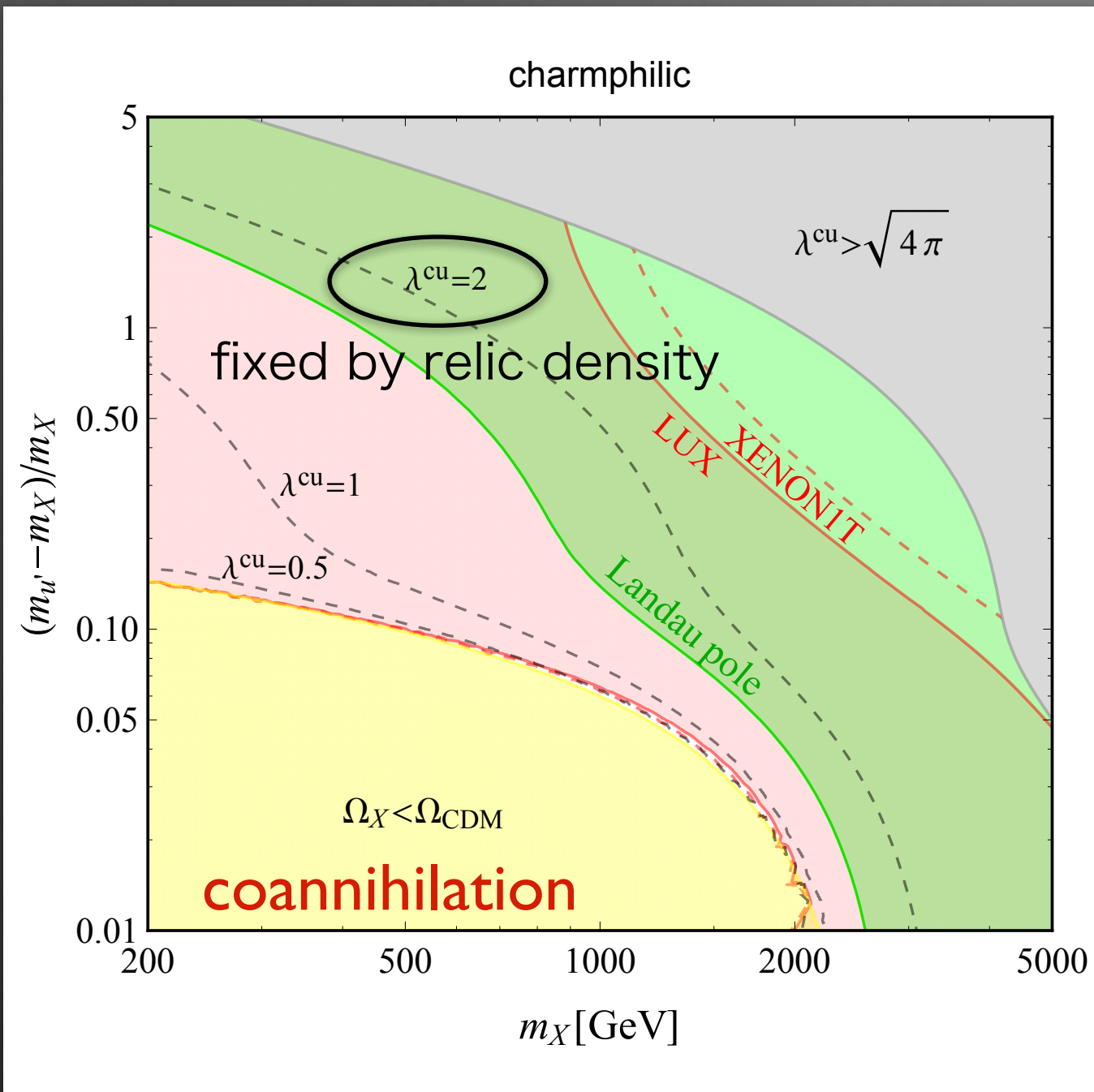
contribute to annihilation and direct detection:



flavor depends on the Yukawa alignment, λ_u

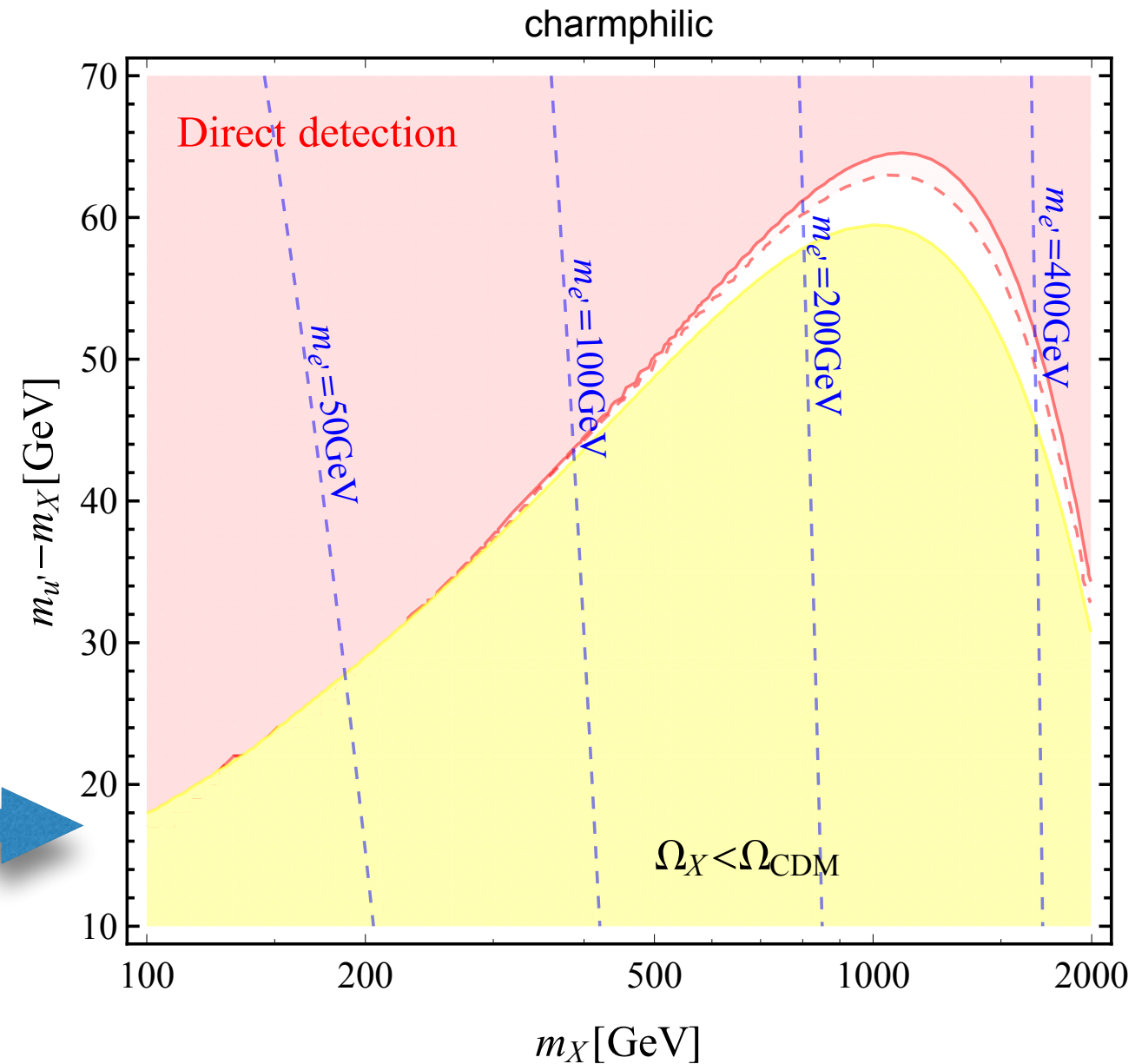
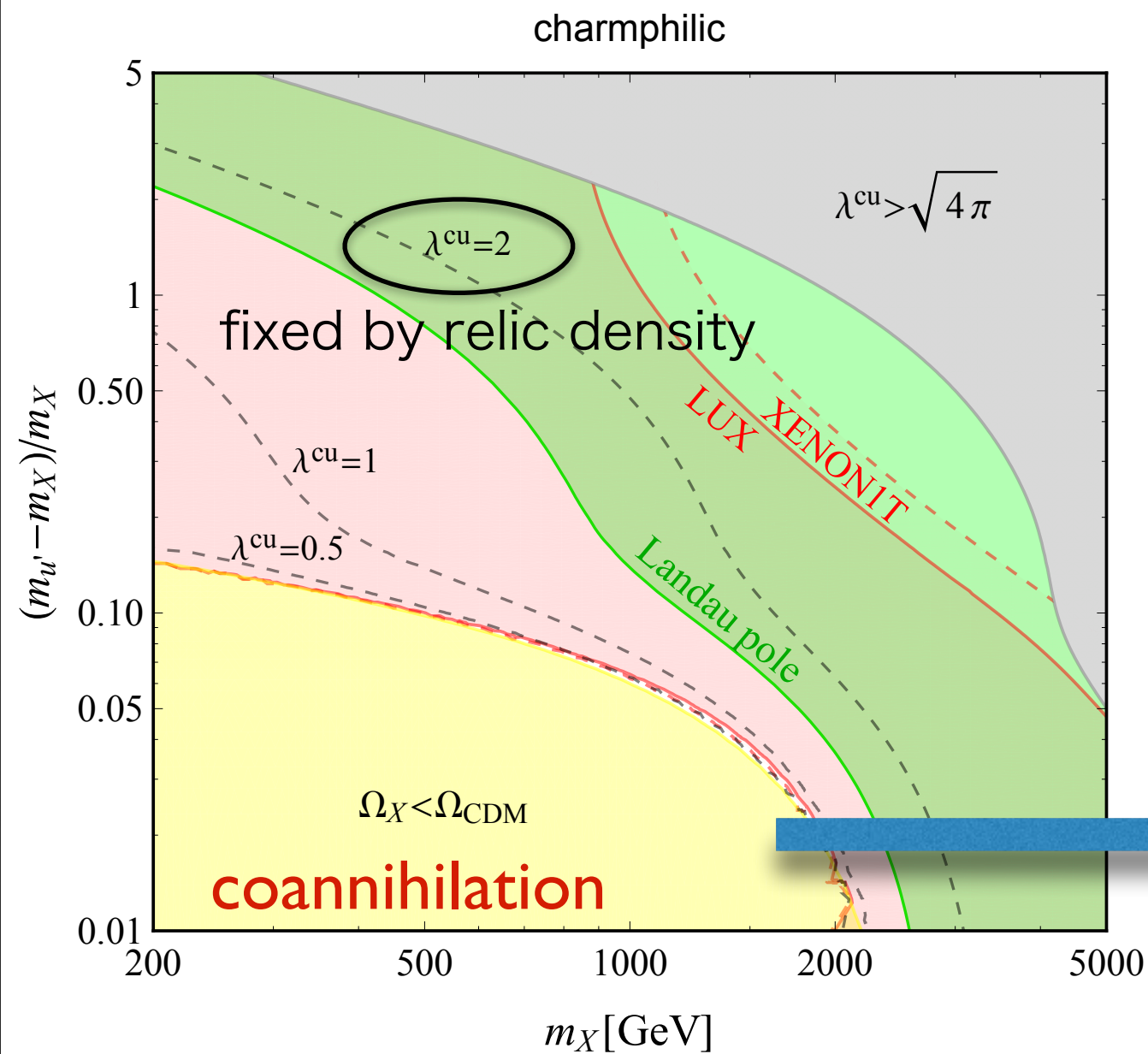
Allowed region in baryonic DM (X_b)

(I) Assume DM dominantly couples to **charm quark** and mirror up quark
($u' \rightarrow c X_b$)



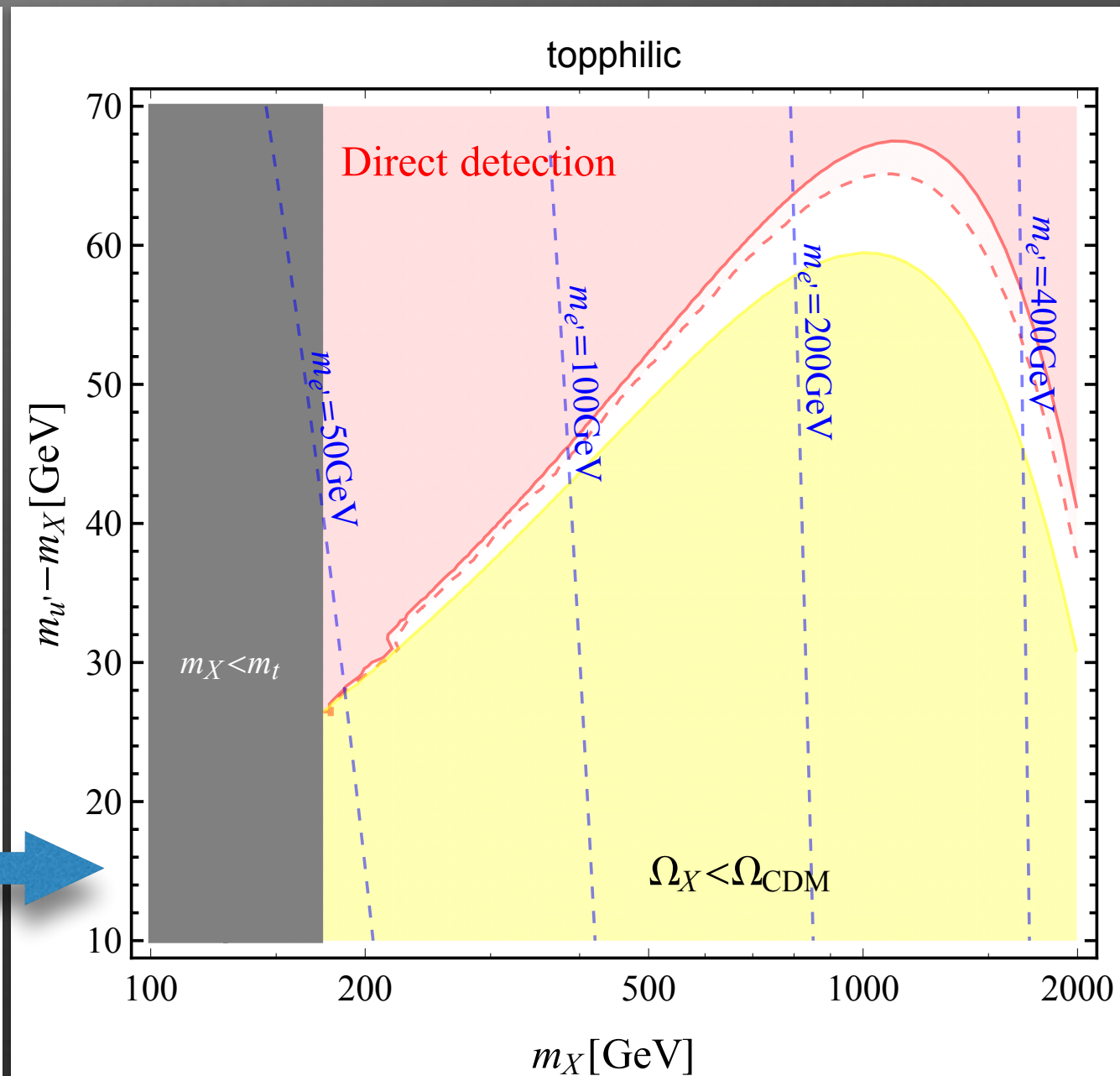
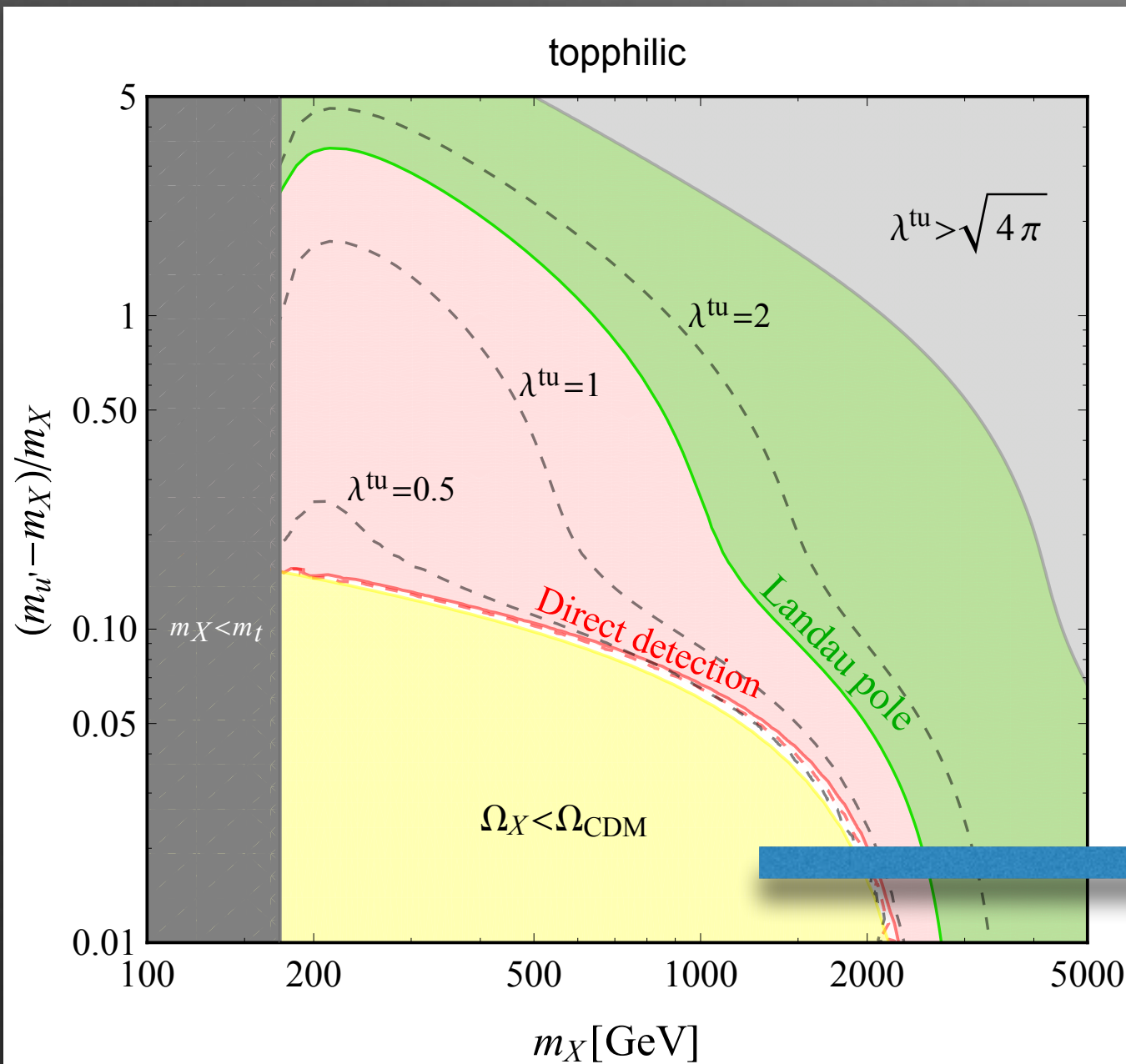
Allowed region in baryonic DM (X_b)

(I) Assume DM dominantly couples to **charm quark** and mirror up quark
 $(u' \rightarrow c X_b)$



Allowed region in baryonic DM (X_b)

(2) DM dominantly couples to **top quark** and mirror up quark
 $(u' \rightarrow t X_b)$



Summary

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

One well-known simple setup

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

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

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*.
1812.07004, Kawamura, Okawa, YO, Tang
- 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 ($pp \rightarrow e'_+ e'_- \rightarrow l_+ l_-$ missing etc.).
- Neutrino physics would have rich phenomenology.

1812.07004, Kawamura, Okawa, YO, Tang
and work in progress

END