Effect of CP violation
in the singlet-doublet dark matter model

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based on
PLB 771 (2017) 125-130 (arXiv:1702.07236)

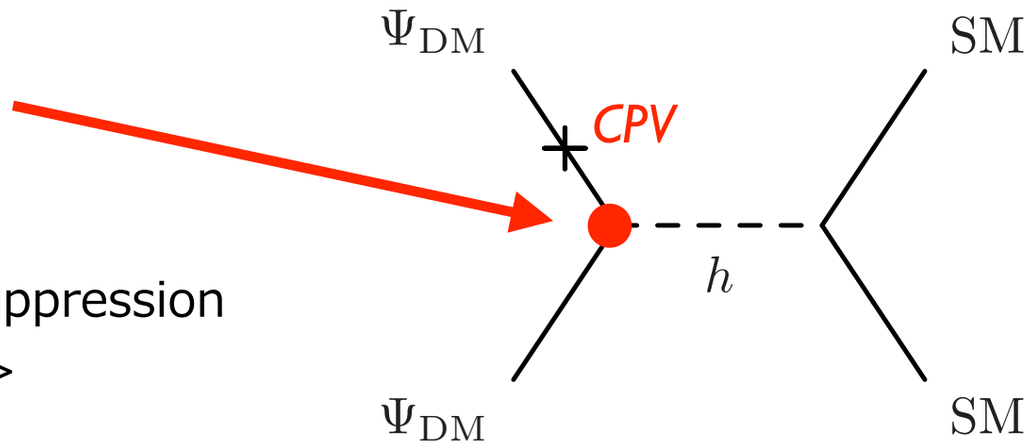
A reason why CP violation in dark sector

To avoid strong constraint from DM direct detection

- ⋆ take advantage of the pseudo-scalar interaction
- ⋆ the interaction can be there if CPV in dark sector

pseudo-scalar interaction

$$\bar{\Psi}_{\rm DM} i\gamma^5 \Psi_{\rm DM} h$$



- $\sigma_{SI} \sim 0$ thanks to the velocity suppression
- s-wave contributions to $\langle \sigma_{ann.} v \rangle$

→ ★ constraints from direct detection is avoidable
★ DM is thermal relic

Singlet-doublet DM model

Mahbubani, Senatore [hep-ph/0510064]
D'Eramo [0705.4493]
Enberg et.al. [arXiv:0706.0918]
…

New particles (three Z_2 odd Weyl fermions)

	$\mathrm{SU}(3)_c$	$\mathrm{SU}(2)_L$	$\mathrm{U}(1)_Y$	Z_2
ω	$\mathbf{1}$	$\mathbf{1}$	0	-1
η	$\mathbf{1}$	$\mathbf{2}$	$1/2$	-1
$\xi^\dagger$	$\mathbf{1}$	$\mathbf{2}$	$1/2$	-1

Mass terms and Yukawa interactions with the SM Higgs

$$\mathcal{L}_{int.} = -\frac{M_1}{2}\omega\omega - M_2\xi\eta - y\omega H^\dagger\eta - y'\xi H\omega + (h.c.)$$

There is a CP phase naturally

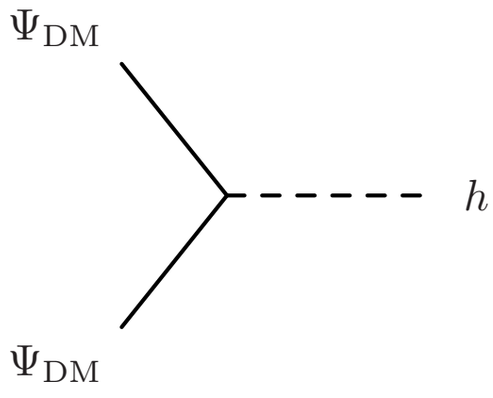
- four complex parameters
- three phases are unphysical, eliminated by the rotation of the three Weyl fermions

→ five parameters: $(|M_1|, |M_2|, |y|, |y'|, \phi)$ $\qquad \phi = \mathrm{Arg}(M_1^* M_2^* y y')$

Mixing Majorana fermion with Dirac fermions

→ three neutral Majorana fermions + one charged Dirac fermion

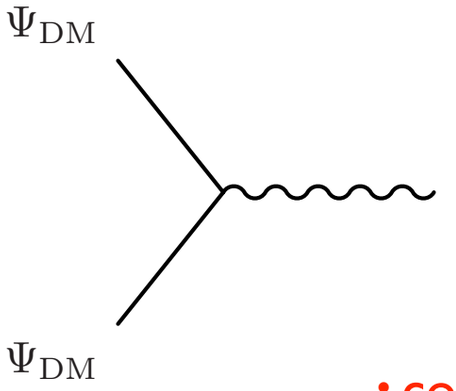
Three important couplings



$$= -i\left(c_{h\chi_1\chi_1} - i\gamma^5 c^P_{h\chi_1\chi_1}\right)$$

- does not contribute to direct detection
- becomes zero if no CPV phase in dark sector
- contributes to direct detection (σ_{SI})
- can be zero by parameter choice (blind spot)

Cohen, Kearney, Pierce and Tucker-Smith [1109.2604]
Cheung, Hall, Pinner and Ruderman [1211.4873]
Cheung and Sanford [1311.5896]



$$= i\gamma^\mu\gamma^5 c_{Z\chi_1\chi_1}$$

- contributes to direct detection (σ_{SD})
- becomes zero if **y = y'**

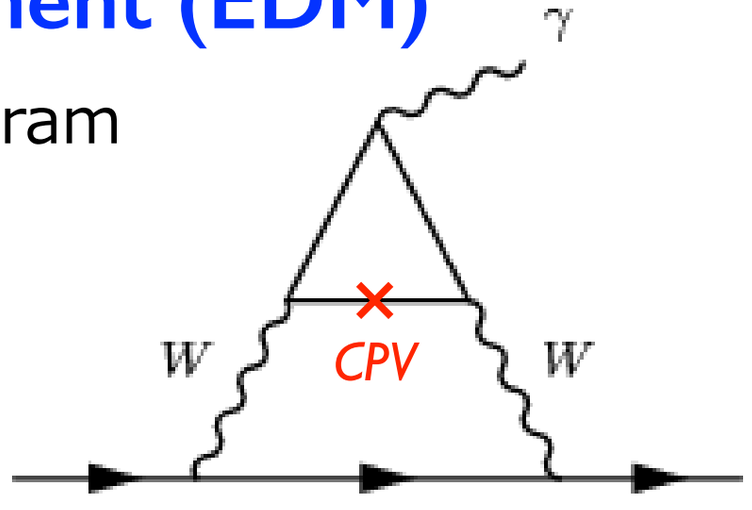
$$\mathcal{L}_{int.} = -\frac{M_1}{2}\omega\omega - M_2 e^{-i\phi}\xi\eta - y\omega H^\dagger\eta - y'\xi H\omega + (h.c.).$$

We can avoid the direct detection constraints
if $c_{ZXX} = c_{hXX} = 0$ and $c_{hXX}^P \neq 0$.

Another effect of CP violation in this model

prediction of the electric dipole moment (EDM)

- ⋆ EDM is predicted via Barr-Zee type diagram
- ⋆ nice complement to direct detection



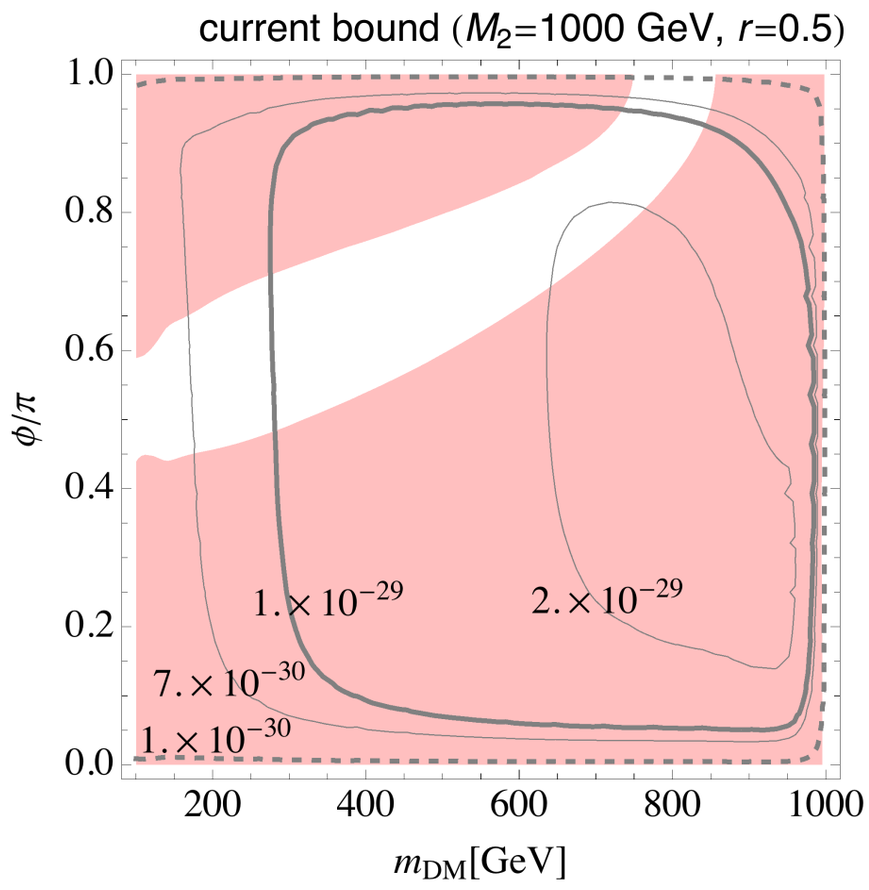
nice complement to direct detection

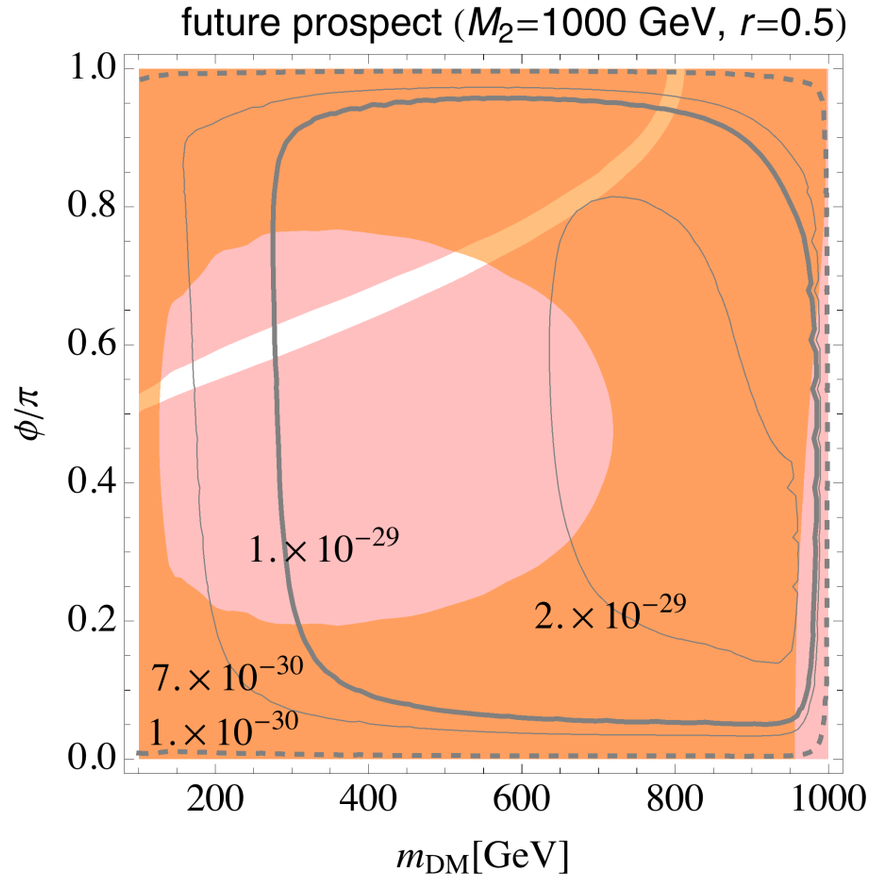
- ⋆ In large CPV case, σ_{SI} is small, EDM is large
- ⋆ In small CPV case, σ_{SI} is large, EDM is small
- ⋆ EDM helps to test this model in the region where direct detection signal is not expected

Result 1 : all couplings exist case

$c_{hXX} \neq 0$, $c_{ZXX} \neq 0$, $c_{hXX}^{P} \neq 0$ (M_2 = 1000GeV, y/y' = 0.5)

[prospects for LZ is given in 1310.8327]





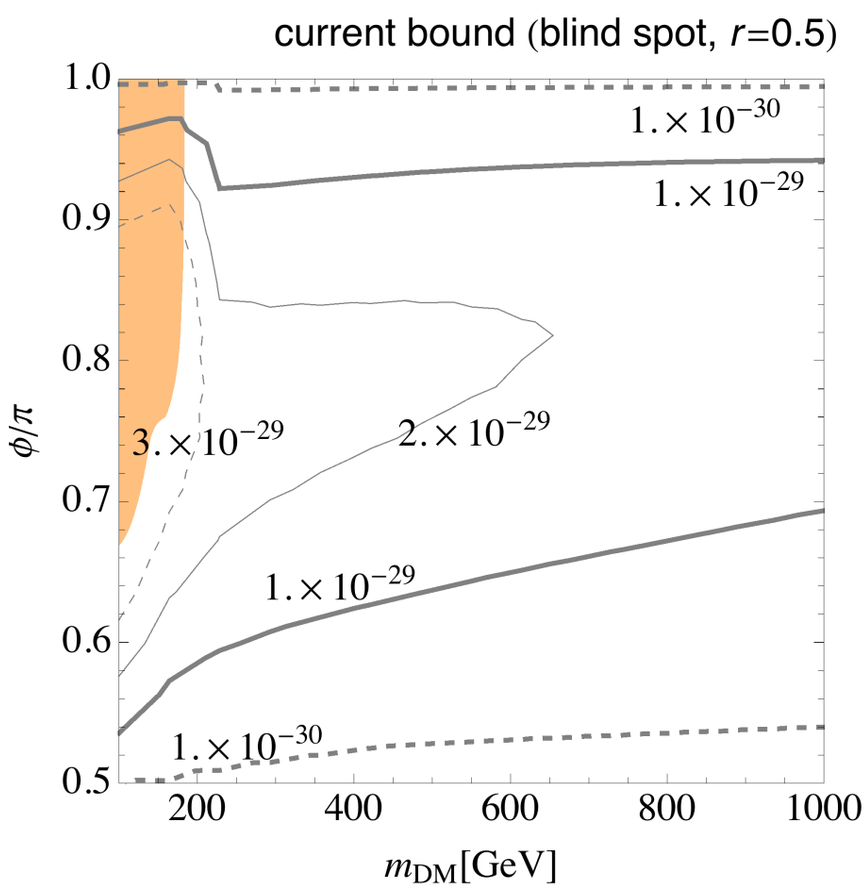
pink **:** excluded by σ_{SI}
orange **:** excluded by σ_{SD}
***contours*:** electron EDM

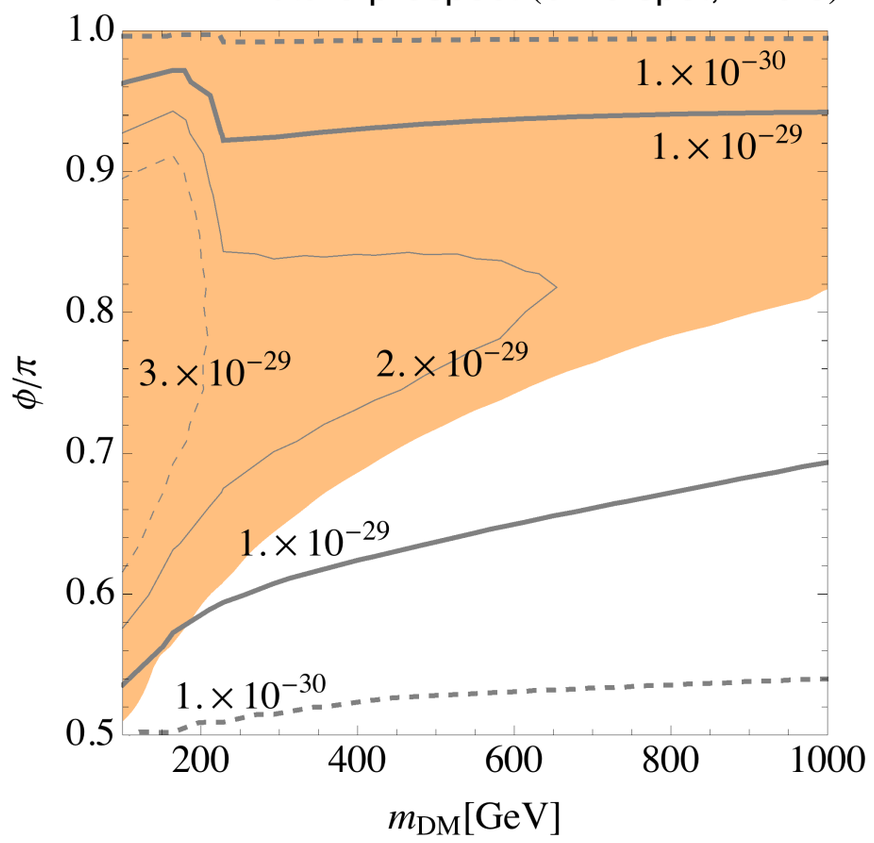
electron EDM (d_e)

- ★ ***current bound*** : $|d_e| < 8.7 \times 10^{-29}$ e cm
  ACME experiment [1310.7534]
- ★ ***future prospect*:** $|d_e| < O(10^{-30})$ e cm
  [1208.4507, 1502.04317, …]

Result 2 : c_{hXX} = 0 case

$c_{hXX} = 0$, $c_{ZXX} \neq 0$, $c_{hXX}^{P} \neq 0$ (y/y' = 0.5)





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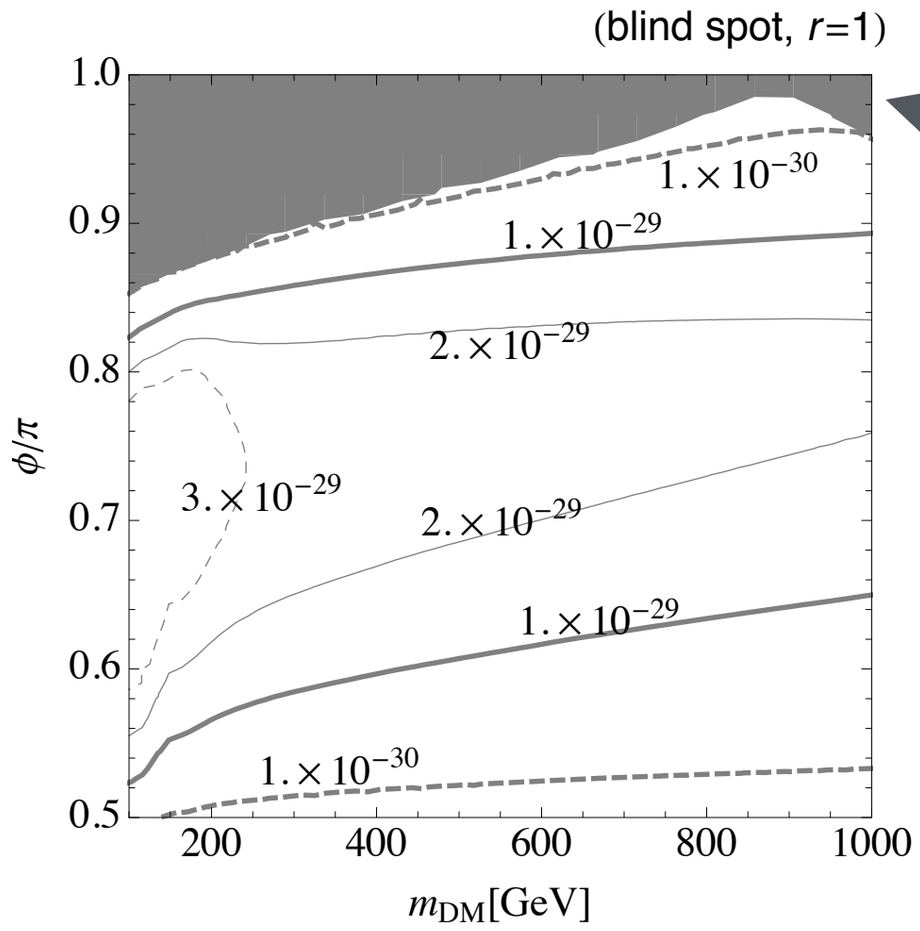
Result 3 : only pseudo-scalar coupling case

$c_{hXX} = 0$, $c_{ZXX} = 0$, $c_{hXX}^{P} \neq 0$ $(y/y' = 1)$



In the gray region, the dark matter density cannot be the measured value.

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Summary

Effect of CP violation

- ⋆ generate pseudo-scalar interaction
- ⋆ avoid strong constraints from direct detection
- ⋆ keep DM annihilation cross section

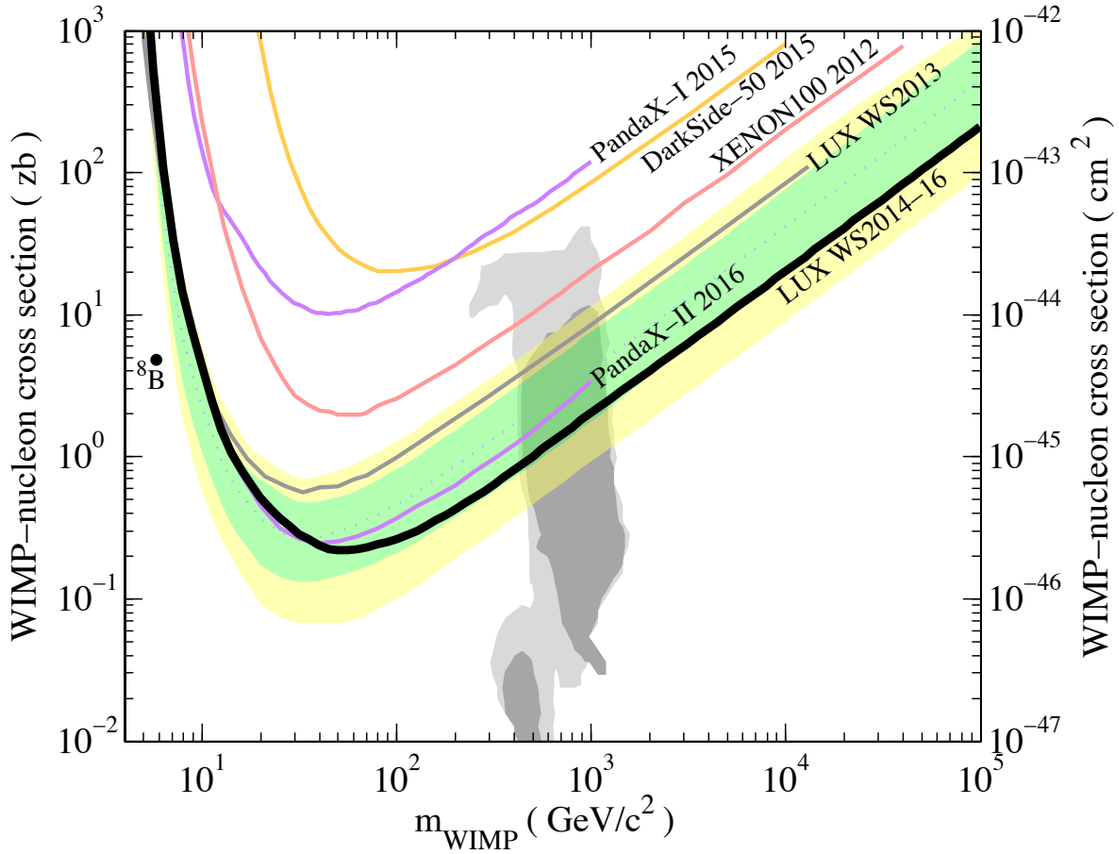
CPV in singlet-doublet DM model

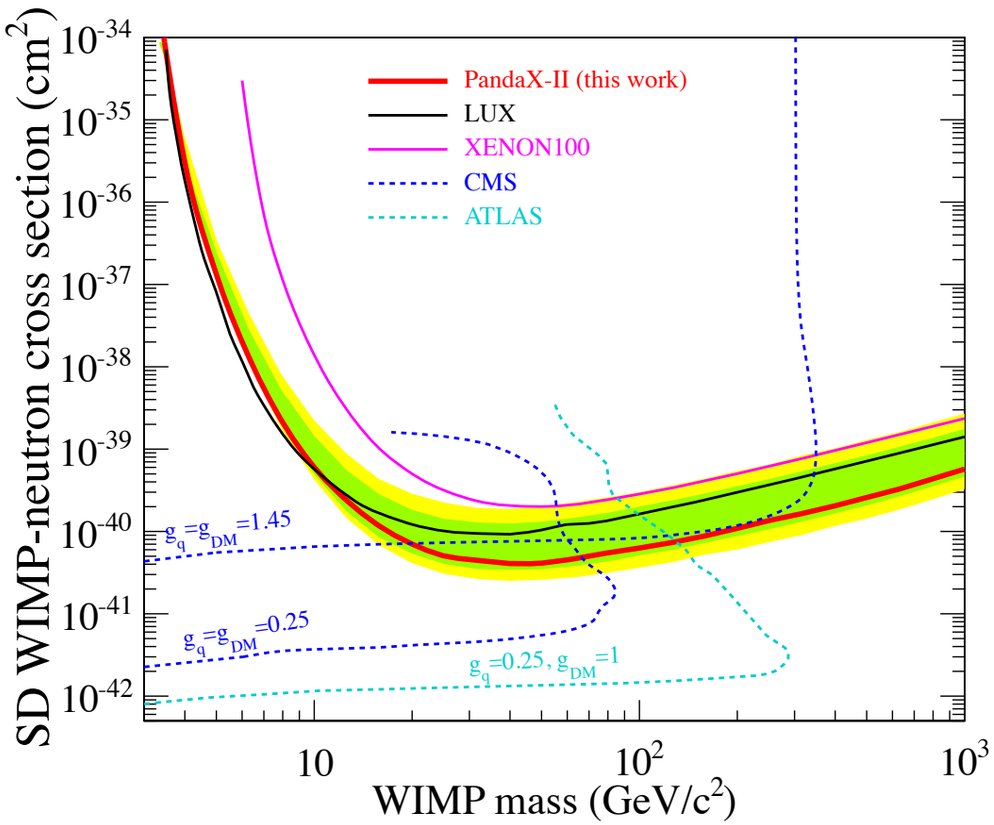
- ⋆ CP violation naturally arises
- ⋆ constraints from direct detection is avoidable
- ⋆ prediction of EDM > 10^{-30} [e cm], within future prospect
- ⋆ direct detection and EDM complement to each other

Backup slides

Introduction

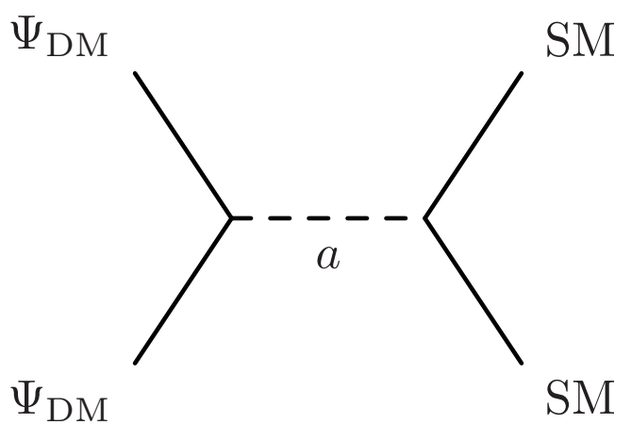
Motivation: Escape from strong constraints from DM direct detection





two simple realizations of the pseudo-scalar interaction

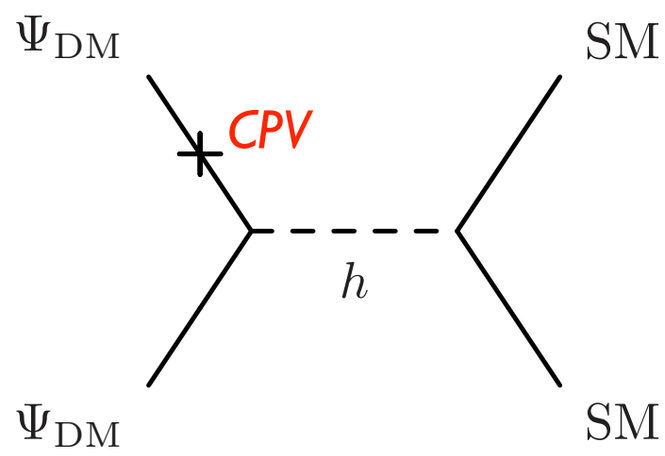
add pseudo-scalar mediator that couple both to DM and SM



- SM + dark sector + pseudo-scalar boson

Boehm et.al 1401.6458, Berlin et.al 1502.06000, …
Ghorbani 1408.4929, Baek, Ko, Liu 1701.04131, Bauer Haisch Kahlhoefer 1701.07427, …

use the Higgs as a mediator with **CP violation** in dark sector



- SM + dark sector + CPV
- new scalars are not necessary

yukawa and M_2 values in blind spot