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CP Violation Beyond SM: Dark Photon and GB Frameworks

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Work with Xiao-Gang He, Michael J. Ramsey-Musolf, Eung Jin Chun, Cheng-Wei Chiang
Wei Liu, Seokhoon Yun, Minxi He, Tae Hyun Jung, Suruj Jyoti Das, Yu Cheng

Workshop on Physics BSM, Nanjing University of Science and Technology, 23/11/25

Research logic

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CP violation

↓

New sources from BSM

↙ ↘

Dark photon | **Goldstone boson**

Dark photon:
- (Non)-Abelian Kinetic mixing
- Mass mixing

Goldstone boson:
- DFSZ, ALP
- Majoron

↓

phenomenology

EW bounds, DM, FCNC, EDM, baryon asym

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Introduction

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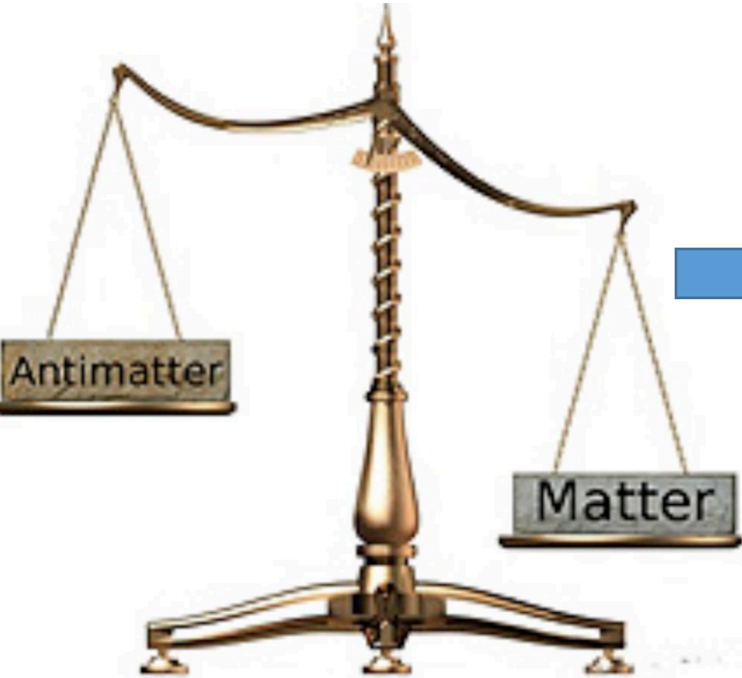
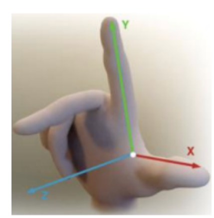


Sakharov conditions

1. **Baryon number violation**
2. **C and CP violation**
3. **Out of thermal equilibrium**

What is CP violation: Charge-parity

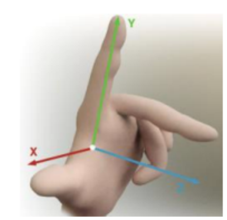
$$p \xrightarrow{C} \bar{p}$$



$$(x, y, z) \xrightarrow{P} (-x, -y, -z)$$

Right-Handed

Left-Handed



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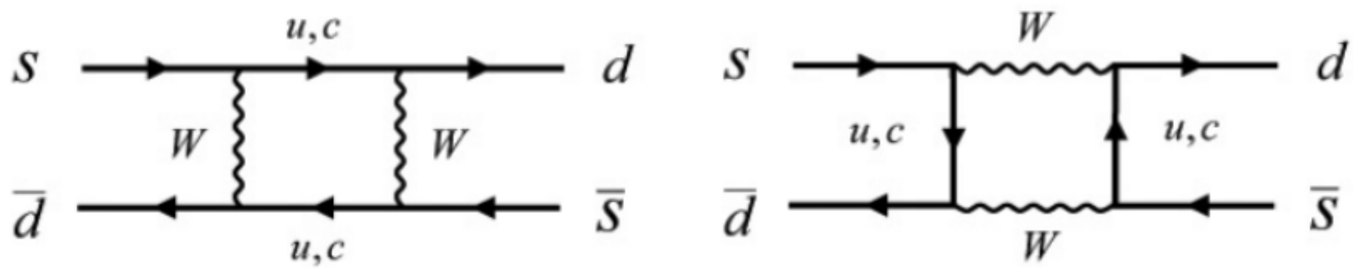
Discovery of CP violation



$K^0 - \bar{K}^0$ oscillation

Mass eigenstates

$$|K_1\rangle \equiv \frac{1}{\sqrt{2}}(|K^0\rangle + |\bar{K}^0\rangle)$$

$$|K_2\rangle \equiv \frac{1}{\sqrt{2}}(|K^0\rangle - |\bar{K}^0\rangle)$$

CP eigenstates

$CP|K_1\rangle = +|K_1\rangle$ (CP-even state)

$CP|K_2\rangle = -|K_2\rangle$ (CP-odd state)

$CP|\pi\pi\rangle = +|\pi\pi\rangle$ (CP-even state)

$CP|\pi\pi\pi\rangle = -|\pi\pi\pi\rangle$ (CP-odd state)

Observe $K_2 \rightarrow 2\pi$ means CP violation

1964: Fitch-Cronin Experiment

First CPV evidence in neutral kaon decays

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Types of CP Violation

1. $\boxed{\text{Direct CP violation via decay}}$
2. CP violation in mixing
3. interference of decay and mixing

Baryon system

$\Lambda_b \to p\pi^+\pi^-K^-$

Meson system

CP violation in SM

$$V_{CKM} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

$n_B/s \sim 8.8 \times 10^{-11}$

Identify new CPV source

SM: Baryon sector

BSM: dark photon, axion…

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2 **CPV in Dark photon**

3 **CPV in Goldstone boson**

4 **Conclusion**

Dark photon

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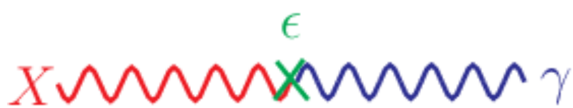
1. A new U(1) gauge boson acting like photon $Q_f A'_\mu \bar{f}\gamma^\mu f$
2. Dark: No charge under SM gauge groups
3. SM particle without charge under new U(1)

No direct interaction with SM particle $U(1)_Y \times U(1)_X$

1. Abelian kinetic mixing 

$-\frac{\epsilon}{2}\tilde{X}'_{\mu\nu}\tilde{Y}'^{\mu\nu}$
2. Non-abelian kinetic mixing $W^a_{\mu\nu}X^{\mu\nu}\Sigma^a$
3. Mass mixing effects $\sigma = \frac{1}{\sigma}\frac{2g_X}{g'}\frac{v_2^2}{v^2}$

$\phi_1 : (1,2,1/2)(0),\ \phi_2 : (1,2,1/2)(1),\ \phi_d : (1,1,0)(1)$

These mixing effects enlighten dark photon

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Transformation

$$\begin{pmatrix} \tilde{A}' \\ \tilde{Z}' \\ \tilde{X}' \end{pmatrix} = \begin{pmatrix} 1 & -s_\theta \frac{\sigma c_W}{\sqrt{1-\sigma^2}} & -c_\theta \frac{\sigma c_W}{\sqrt{1-\sigma^2}} \\ 0 & c_\theta + s_\theta \frac{\sigma s_W}{\sqrt{1-\sigma^2}} & -s_\theta + c_\theta \frac{\sigma s_W}{\sqrt{1-\sigma^2}} \\ 0 & s_\theta \frac{1}{\sqrt{1-\sigma^2}} & c_\theta \frac{1}{\sqrt{1-\sigma^2}} \end{pmatrix} \begin{pmatrix} A \\ Z \\ X \end{pmatrix}$$

Kinetic + mass mixing

$$\tan(2\theta) \approx \frac{2\sigma s_W(1-\epsilon)}{1-\tilde{r}^2}$$

$$\mathcal{L} = -\frac{1}{4} X_{\mu\nu} X^{\mu\nu} - \frac{1}{4} A_{\mu\nu} A^{\mu\nu} - \frac{1}{4} Z_{\mu\nu} Z^{\mu\nu}$$

Z interaction

X interaction

$$+ j^\mu_{em} \left(A_\mu \boxed{- s_\theta \frac{\sigma c_W}{\sqrt{1-\sigma^2}} Z_\mu} - \boxed{c_\theta \frac{\sigma c_W}{\sqrt{1-\sigma^2}} X_\mu} \right)$$

$$+ j^\mu_Z \left(\boxed{\left(c_\theta + s_\theta \frac{\sigma s_W}{\sqrt{1-\sigma^2}} \right) Z_\mu} + \boxed{\left(-s_\theta + c_\theta \frac{\sigma s_W}{\sqrt{1-\sigma^2}} \right) X^\mu} \right)$$

$$\boxed{+ j^\mu_X \left(s_\theta \frac{1}{\sqrt{1-\sigma^2}} Z_\mu + c_\theta \frac{1}{\sqrt{1-\sigma^2}} X_\mu \right)} . \qquad (13$$

Existing limits for Dark photon

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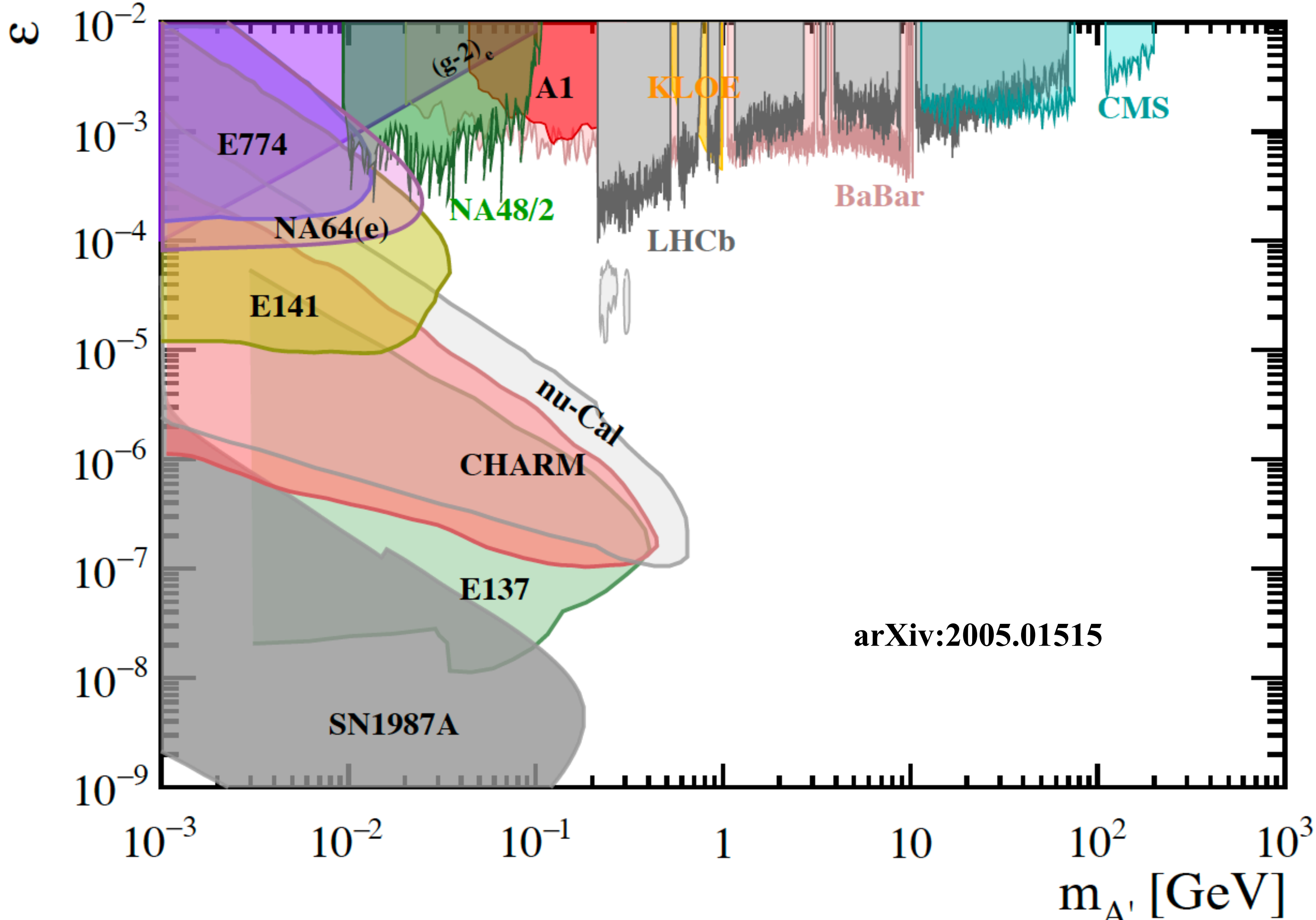

CP violation

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1. Abelian

- **CP conserving** $X_{\mu\nu}Y^{\mu\nu}$
- **CP violating** $Y^{\mu\nu}\tilde{X}_{\mu\nu} = -\frac{\epsilon_{\mu\nu\alpha\beta}}{2}\partial^{\alpha}(Y^{\mu\nu}X^{\beta})$

2. Non-Abelian

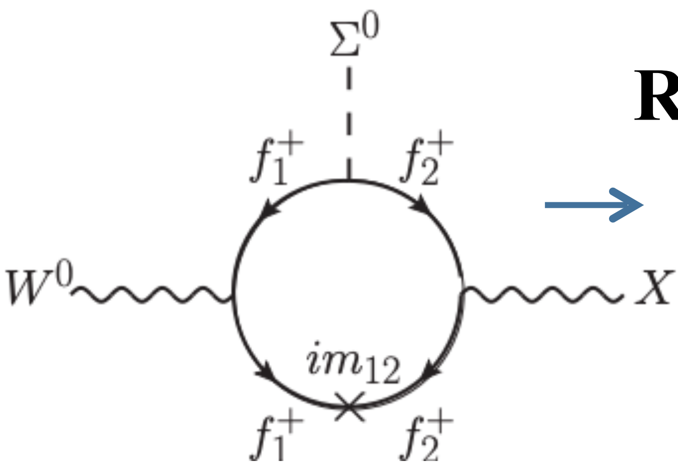
$$\mathcal{L}_X = -\frac{\beta_X}{\Lambda}Tr(W_{\mu\nu}\Sigma)X^{\mu\nu} - \frac{\tilde{\beta}_X}{\Lambda}Tr(W_{\mu\nu}\Sigma)\tilde{X}^{\mu\nu}$$

$$\downarrow$$

$$-\frac{\beta_X}{2\Lambda}X^{\mu\nu}\left(s_W F_{\mu\nu} + c_W Z_{\mu\nu} + ig(W^-_\mu W^+_\nu - W^+_\mu W^-_\nu)\right)(v_\Sigma + \Sigma^0)$$
$$-\frac{\tilde{\beta}_X}{2\Lambda}\tilde{X}^{\mu\nu}\left[(s_W F_{\mu\nu} + c_W Z_{\mu\nu})\Sigma^0 + ig(W^-_\mu W^+_\nu - W^+_\mu W^-_\nu)(v_\Sigma + \Sigma^0)\right]$$

CP violating non-Abelian kinetic mixing

Fuyuto, He, Li, Michael, 2019vfe,



Renormalizable theory

$\rightarrow$ $\mathrm{Tr}(W_{\mu\nu}\Sigma)\tilde{X}^{\mu\nu}$ $\rightarrow$ **Type-III seesaw**

$$f = \begin{pmatrix} \frac{\Sigma^0}{\sqrt{2}} & \Sigma^+ \\ \Sigma^- & -\frac{\Sigma^0}{\sqrt{2}} \end{pmatrix}$$

$$f_1 = (1,3,0)(x_f),$$
$$f_2 = (1,3,0)(-x_f),$$

EDM constraints

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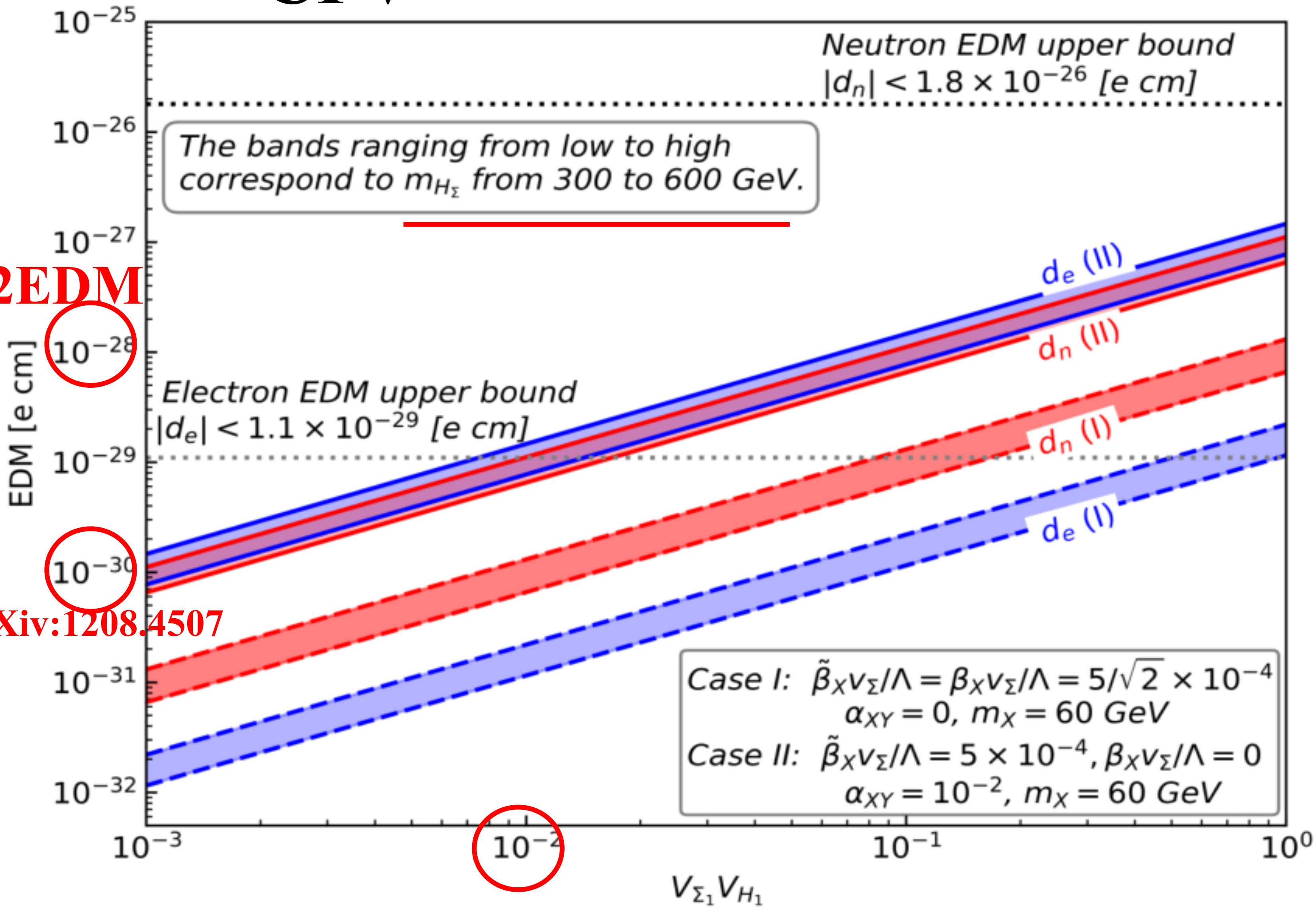
CPV → EDM

n2EDM



arXiv:1208.4507

Global fits for EW fits

2310.06526

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Observable	Experimental data	Our work $(m_X > m_Z)$
g_V^τ	-0.0366 ± 0.0010	-0.03814 ± 0.00022
g_V^μ	-0.0367 ± 0.0023	
g_V^e	-0.03817 ± 0.00047	
g_A^τ	-0.50204 ± 0.00064	-0.499784 ± 0.000084
g_A^μ	-0.50120 ± 0.00054	
g_A^e	-0.50111 ± 0.00035	
g_V^u	0.266 ± 0.034	0.19106 ± 0.00026
g_A^u	$0.519^{+0.028}_{-0.033}$	0.499784 ± 0.000084
g_V^d	$-0.38^{+0.04}_{-0.05}$	-0.34629 ± 0.00017
g_A^d	$-0.527^{+0.040}_{-0.028}$	-0.499784 ± 0.000084
$\mathrm{Br}_{\tau^+\tau^-}$	$(3.3658 \pm 0.0023)\%$	$(3.38080 \pm 0.00091)\%$
$Br_{\mu^+\mu^-}$	$(3.3662 \pm 0.0066)\%$	$(3.39090 \pm 0.00091)\%$
$Br_{e^+e^-}$	$(3.3632 \pm 0.0042)\%$	$(3.39094 \pm 0.00091)\%$
$Br_{c\bar{c}}$	$(12.03 \pm 0.21)\%$	$(11.5862 \pm 0.0074)\%$
$Br_{b\bar{b}}$	$(15.12 \pm 0.05)\%$	$(14.8783 \pm 0.0015)\%$
$Br_{(c\bar{c}+u\bar{u})/2}$	$(11.6 \pm 0.6)\%$	$(11.5891 \pm 0.0074)\%$
$Br_{(d\bar{d}+s\bar{s}+b\bar{b})/3}$	$(15.6 \pm 0.4)\%$	$(14.9390 \pm 0.0015)\%$
P_τ	-0.144 ± 0.015	-0.15176 ± 0.00090
P_μ	-0.142 ± 0.015	
P_e	-0.1515 ± 0.0019	
P_s	-0.90 ± 0.09	-0.93627 ± 0.00022
P_b	-0.923 ± 0.020	
P_c	-0.670 ± 0.027	-0.66708 ± 0.00059
$m_W(\mathrm{GeV})$	80.4028 ± 0.0067	80.408 ± 0.019
ρ	1.00038 ± 0.00020	1.00003 ± 0.00015

$$j_Z^\mu = -\frac{e}{2s_W c_W}\bar{f}\gamma^\mu(\tilde{g}_V^f - \tilde{g}_A^f\gamma_5)f$$

$$\tilde{g}_V^f = I_3^f - 2Q_f s_W^2, \tilde{g}_A^f = I_3^f$$

$$g_V^f \approx \tilde{g}_V^f\left[1 + \sigma^2\tilde{s}_W^2\left(\frac{1-\epsilon}{1-\tilde{r}^2} - \frac{(1-\epsilon)^2}{2(1-\tilde{r}^2)^2}\right)\right]$$

$$g_A^f \approx \tilde{g}_A^f\left[1 + \sigma^2 s_W^2\left(-\frac{(1-\epsilon)^2}{2(1-\tilde{r}^2)^2} + \frac{1-\epsilon}{1-\tilde{r}^2}\right)\right]$$

Fit results

ϵ	σ	m_X
-1.37 ± 0.46	0.074 ± 0.021	275 ± 39
1	0.583	-0.045
	1	0.488
		1

$\chi^2/\mathrm{d.o.f} = 19.75/16 = 1.23$

Dark matter [2503.21083]

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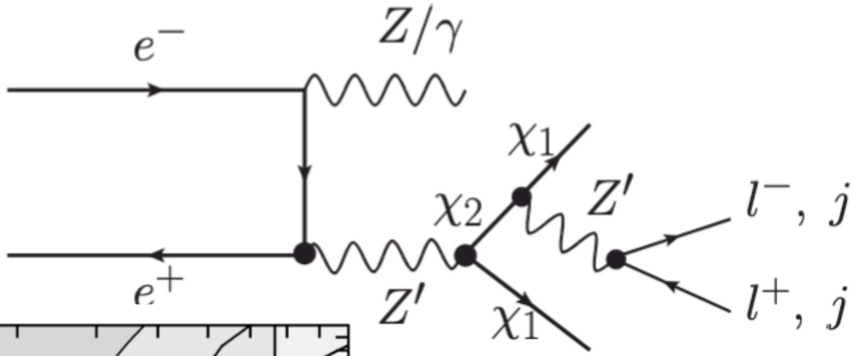
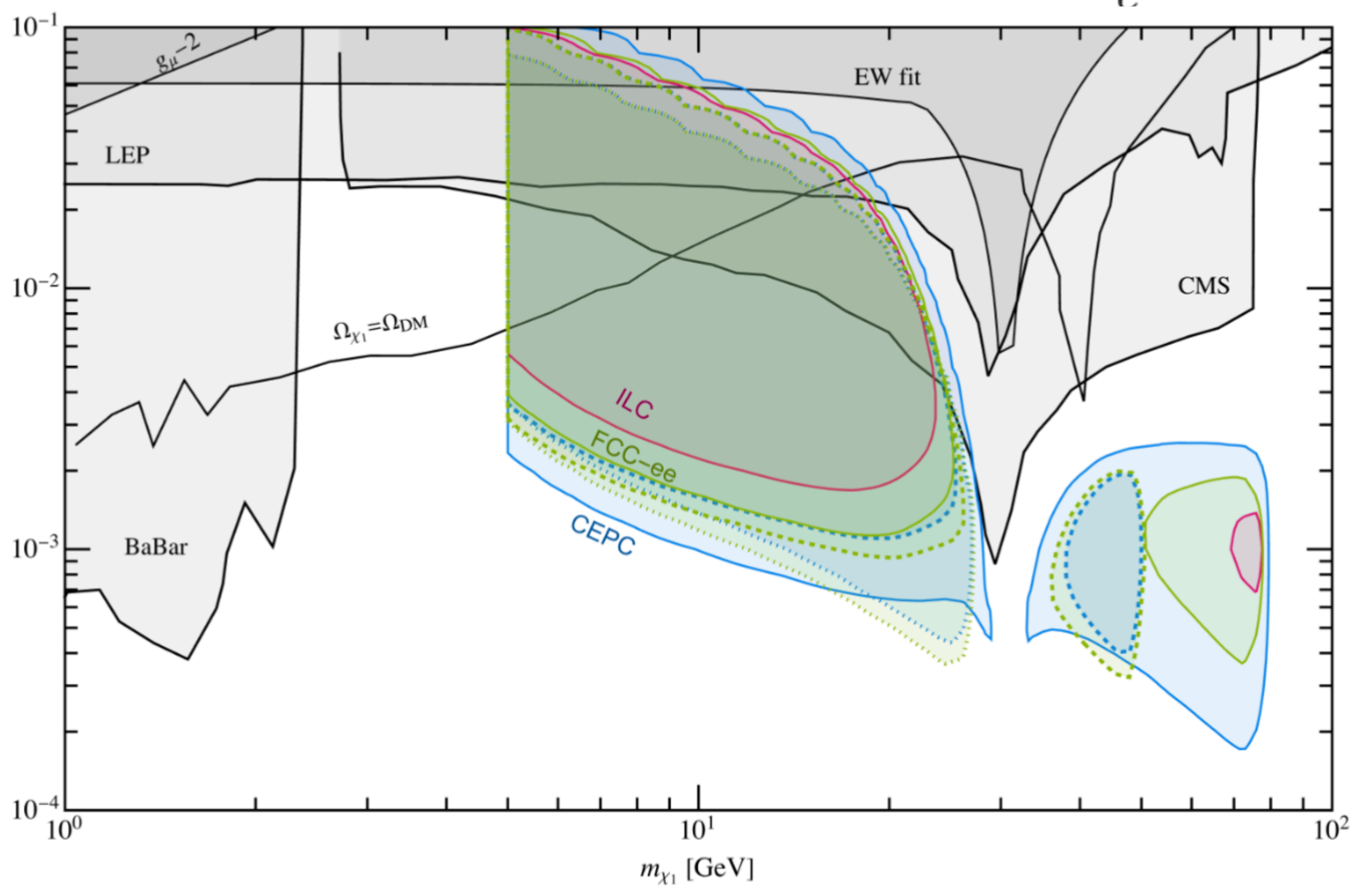
inelastic dark model

$$j^\mu_{Z'} = -i\frac{g_D}{2}(\overline{\chi_2}\gamma^\mu\chi_1 - \overline{\chi_1}\gamma^\mu\chi_2)$$





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CP violating QCD term

$\theta < 10^{-10}$

$$\mathscr{L}_{CP} = \theta \frac{\alpha_s}{8\pi} G \cdot \tilde{G}$$

Axion $\theta \rightarrow a/f_a$

1. **Coupling with gluon** $aG \cdot \tilde{G}\alpha_s/8\pi f_a$
2. **Coupling with photon** $g_{a\gamma} aF \cdot \tilde{F}/4$
3. **Coupling with fermions** $\partial_\mu a a \bar{\Psi}\gamma^\mu \gamma^5 \Psi/2f_a$

DFSZ axion : SM quarks charged under PQ (2HDM)

Standard version: $H_{1,2}$, S

$$Q_L:\ 0,\ U_R:\ X_u = X_1,\ D_R:\ X_d = -X_2,\ L_L:\ 0,\ E_R:\ X_e = -X_{2,1}\ .$$

$$L_Y = -\bar{Q}_L Y_u \tilde{H}_1 U_R - \bar{Q}_L Y_d H_2 D_R - \bar{L}_L Y_e H_{1,2} E_R + H.C.$$

Variant version: new H_3 $H_{1,2}: (1,2,-1/2)(+X), H_3: (1,2,-1/2)(-X)$

$$L_Y = -\bar{Q}_L Y_u H_3 U_R - \bar{Q}_L (Y_{d1}\tilde{H}_1 + Y_{d_2}\tilde{H}_2) D_R - \bar{L}_L (Y_{e1}\tilde{H}_1 + Y_{e_2}\tilde{H}_2) E_R + H.C..$$

FCNC

Existing limits for axion

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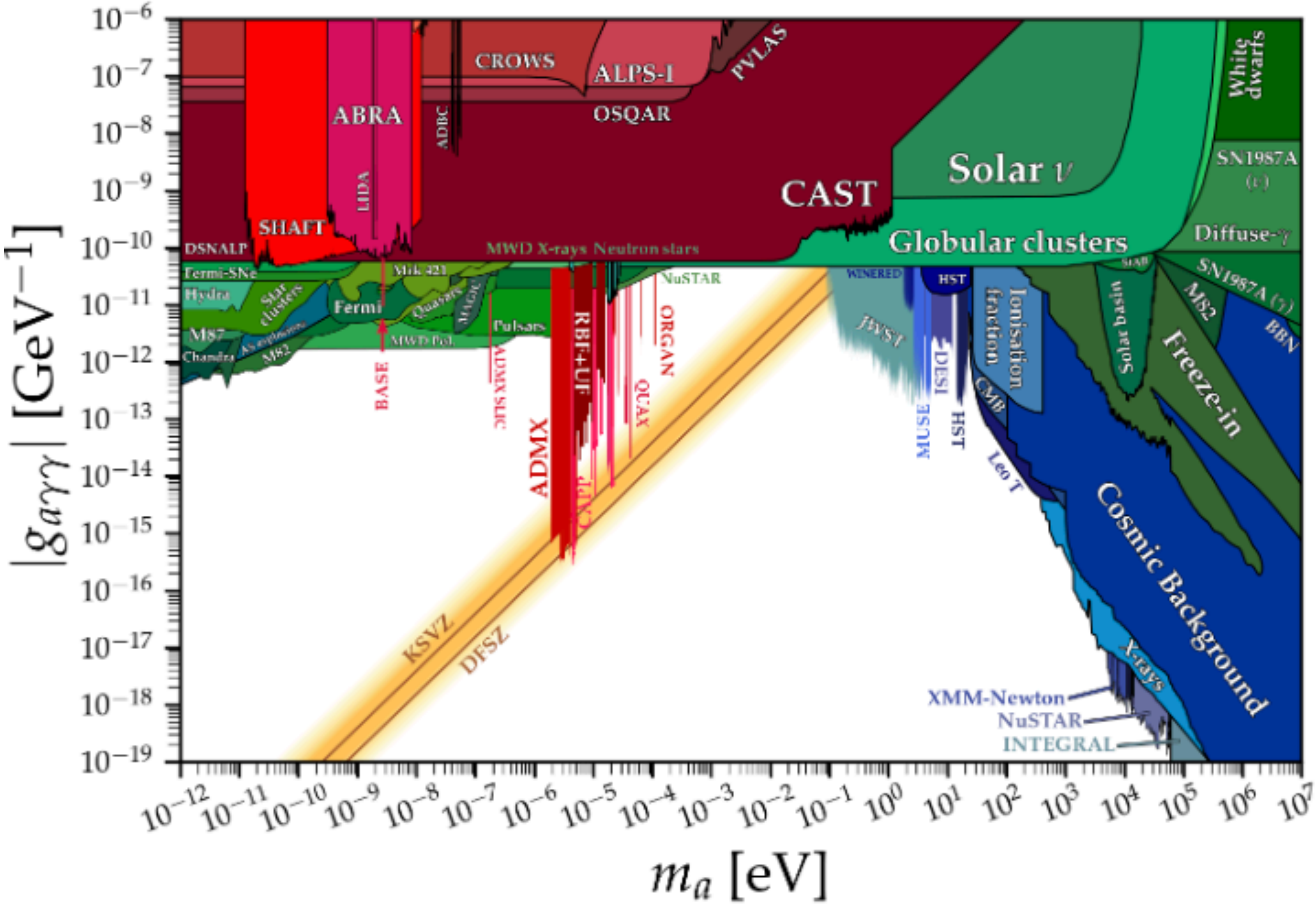

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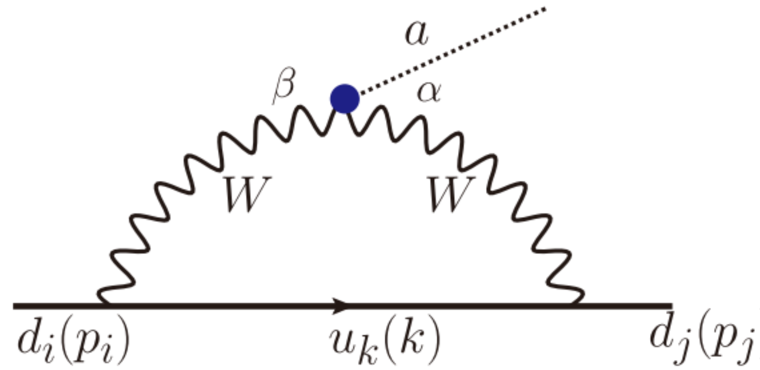
ALP

Coupling with EW gauge bosons

$$\mathcal{L}_{EW} = -\frac{g_{aW}}{4} a W^a_{\mu\nu} \tilde{W}^{a\mu\nu} - \frac{g_{aB}}{4} a B_{\mu\nu} \tilde{B}^{\mu\nu}$$

photophobic

$$g_{a\gamma\gamma} = g_{aW} s_W^2 + g_{aB} c_W^2 = 0$$



Flavor-changing ALP

$$\mathcal{L}_{d_i \to d_j} \supset -g_{ad_id_j} (\partial_\mu a) \bar{d}_j \gamma^\mu \mathcal{P}_L d_i + \mathrm{H.c.},$$

$$g_{ad_id_j} \equiv -\frac{3\sqrt{2} G_F m_W^2 g_{aW}}{16\pi^2} \sum_{\alpha \in u,c,t} V_{\alpha i} V^*_{\alpha j} f(m_\alpha^2/m_W^2), f(x) \equiv \frac{x[1 + x(\log x - 1)]}{(1-x)^2}$$

$$g_{aFF} = \frac{3\alpha^2}{4} \left[\frac{3}{4 s_W^4} \frac{g_{aW}}{g^2} + \frac{(Y_{F_L}^2 + Y_{F_R}^2)}{c_W^4} \frac{g_{aB}}{g'^2} \right] \log \frac{\Lambda^2}{m_W^2} + \frac{3}{2} Q_F^2 \frac{\alpha}{4\pi} g_{a\gamma\gamma} \log \frac{m_W^2}{m_F^2}$$

Axion-like particle

ALP

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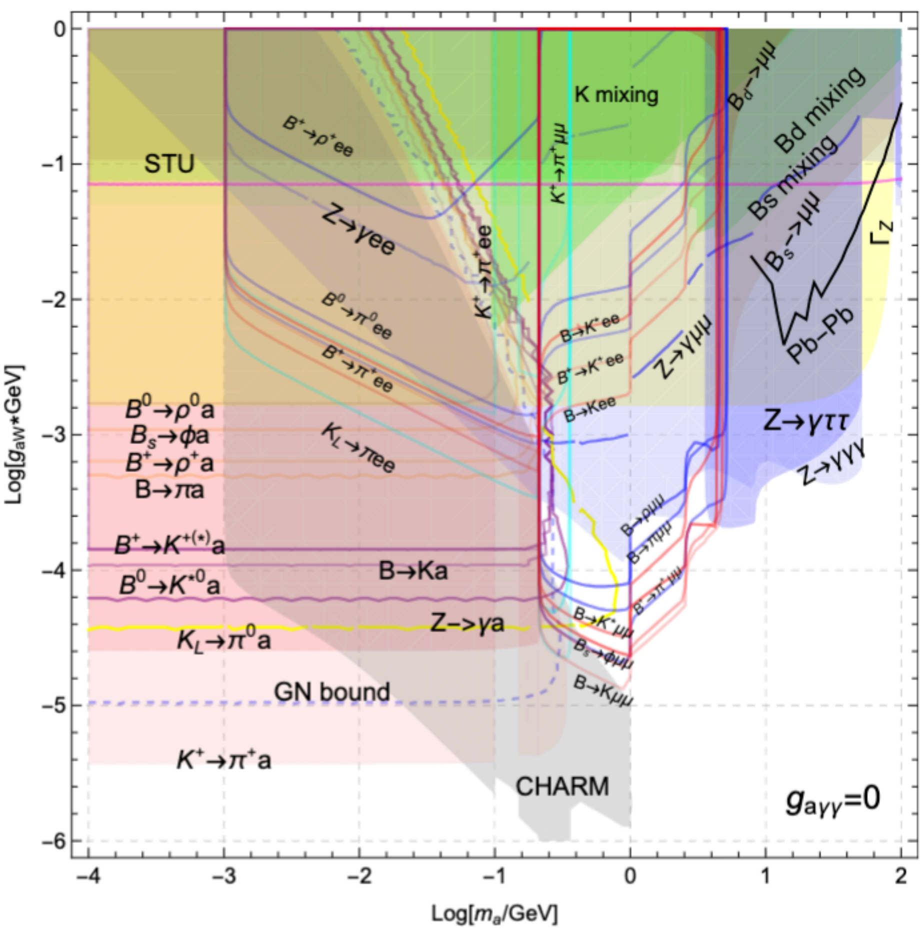
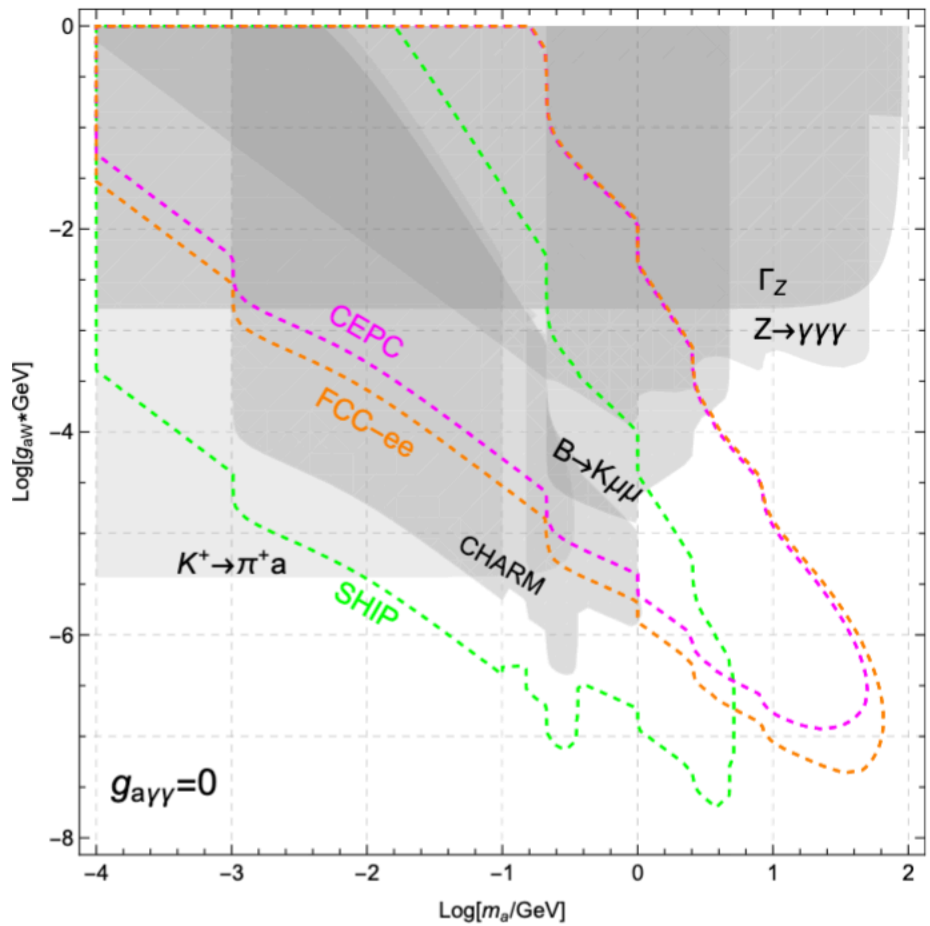
Current bounds



Future sensitivity



Majoron

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Extend SM with singlet to break $U(1)_L$ $\xrightarrow{\text{arise}}$ **Majoron**

Use Type-III seesaw to realize flavor-changing Majoron

$$\Sigma_R = \begin{pmatrix} \frac{\Sigma_L^{0\,c}}{\sqrt{2}} & \Sigma_L^{-\,c} \\ \Sigma_L^{+\,c} & -\frac{\Sigma_L^{0\,c}}{\sqrt{2}} \end{pmatrix}$$

$$S = (1/\sqrt{2})(v_s + h_s + iI_s) : (1,1,0,-2)$$

$$J = I_s$$

$$-\frac{1}{2}\left(\overline{\nu_L}, \overline{\nu_R^c}\right) M_\nu \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix} - (\overline{E_L}, \overline{\psi_L}) M_c \begin{pmatrix} E_R \\ \psi_R \end{pmatrix}$$

$$- i\frac{J}{2f_J}\left(\overline{\nu_R^c} M_R \nu_R - 2\overline{\psi_L} M_R \psi_R\right) + \text{H.c.}$$

Mass matrix diagonalization

$$\frac{\partial_\mu J}{2f_J}\Big\{\Big[\overline{\nu_L}(V^\nu_{LL}V^\nu_{LL}{}^\dagger - V^\nu_{LR}V^\nu_{LR}{}^\dagger)\gamma^\mu\nu_L + \overline{\nu_R^c}(V^\nu_{RL}V^\nu_{RL}{}^\dagger - V^\nu_{RR}V^\nu_{RR}{}^\dagger)\gamma^\mu\nu_R^c$$
$$+\overline{\nu_L}(V^\nu_{LL}V^\nu_{RL}{}^\dagger - V^\nu_{LR}V^\nu_{RR}{}^\dagger)\gamma^\mu\nu_R^c + \text{H.c.}\Big]$$

no unitary

$$-2\Big[\overline{E_L}\gamma^\mu \underline{V^{e\,L}_{LR}V^{e\,L}_{LR}{}^\dagger} E_L + \overline{\psi_L}\gamma^\mu V^{e\,L}_{RR}V^{e\,L}_{LR}{}^\dagger E_L$$

Flavor-changing

Majoron constraints

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$$\frac{\partial_\mu J}{2f_J}\left[\overline{E_j}\gamma^\mu(c_V^{e\,ji}+c_A^{e\,ji}\gamma_5)E_i+\overline{\nu_{Lj}}\gamma^\mu c_L^{\nu\,ji}\nu_{Li}\right]$$

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Process	Experimental input	Bound (in units of f_J/TeV)
$M\to\overline{M}$	$\mathrm{P}<8.3\times10^{-11}/S_B(B_0)$ [15] $S_B(B_0)_{SS}=0.50$ $S_B(B_0)_{PP}=0.9$ $S_B(B_0)_{(S\pm P)(S\pm P)}=0.35$	$\lvert c_V^{\mu e}\rvert<0.407$ $\lvert c_A^{\mu e}\rvert<0.351$ $\lvert c_{V/A}^{\mu e}\rvert<0.444$
$\mu\to eJ$	$\mathrm{Br}<2.6\times10^{-6}$ (90% CL) [16]	$\lvert c_{V/A}^{e\mu}\rvert<3.64\times10^{-7}$
$\tau\to\mu J$	$\mathrm{Br}<5.7\times10^{-3}$ (95% CL) [17]	$\lvert c_{V/A}^{\mu\tau}\rvert<6.87\times10^{-4}$
$\tau\to eJ$	$\mathrm{Br}<3.2\times10^{-3}$ (95% CL) [17]	$\lvert c_{V/A}^{e\tau}\rvert<5.11\times10^{-4}$
$\tau\to\mu e\bar{\mu}$	$\mathrm{Br}<2.7\times10^{-8}$ (90% CL) [18]	$\sqrt{\lvert c_{V/A}^{\mu\tau}\rvert\lvert c_{V/A}^{e\mu}\rvert}<0.379-0.405$
$\tau\to\mu e\bar{e}$	$\mathrm{Br}<1.8\times10^{-8}$ (90% CL) [18]	$\sqrt{\lvert c_{V/A}^{e\tau}\rvert\lvert c_{V/A}^{\mu e}\rvert}<0.353-0.355$
$\tau\to\mu\mu\bar{e}$	$\mathrm{Br}<1.7\times10^{-8}$ (90% CL) [18]	$\sqrt{\lvert c_{V/A}^{\mu\tau}\rvert\lvert c_{V/A}^{\mu e}\rvert}<0.346-0.349$
$\tau\to ee\bar{\mu}$	$\mathrm{Br}<1.5\times10^{-8}$ (90% CL) [18]	$\sqrt{\lvert c_{V/A}^{e\tau}\rvert\lvert c_{V/A}^{e\mu}\rvert}<0.346-0.347$
$(g-2)_e$	$-(0.88\pm0.36)\times10^{-12}$ [19]	$\lvert C_A^{e\mu}\rvert<3.21,\ \lvert C_A^{e\tau}\rvert<0.782$
$(g-2)_\mu$	$(28.02\pm7.37)\times10^{-10}$ [19]	$\lvert C_V^{\mu\tau}\rvert<3.07$
$\mu\to e\gamma$	$\mathrm{Br}<4.2\times10^{-13}$ (90% CL) [20]	$\sqrt{\lvert C_{V/A}^{e\tau}\rvert\lvert C_{V/A}^{\tau\mu}\rvert}<0.011$
$\tau\to\mu\gamma$	$\mathrm{Br}<4.4\times10^{-8}$ (90% CL) [21]	$\sqrt{\lvert C_{V/A}^{\mu e}\rvert\lvert C_{V/A}^{e\tau}\rvert}<5.14$
$\tau\to e\gamma$	$\mathrm{Br}<3.3\times10^{-8}$ (90% CL) [21]	$\sqrt{\lvert C_{V/A}^{e\mu}\rvert\lvert C_{V/A}^{\mu\tau}\rvert}<4.78$

0.4

strongest

0.4

small

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Final-state lepton polarization to determine chiral nature

Helicity-conserving decay $E_{i,j} \gg m_{i,j}$

$$\Gamma_{LL,RR} = \frac{m_i m_j}{64\pi E_i}\left[\left(|g_{e1}^{ji}|^2 - |g_{e2}^{ji}|^2\right)\left(2 - \frac{2}{x_{ij}^2}\right)\right.$$
$$+\left(|g_{e1}^{ji}|^2 + |g_{e2}^{ji}|^2\right)\left(\frac{2}{x_{ij}}\ln x_{ij} + \frac{x_{ij}}{2} - \frac{1}{2x_{ij}^3}\right)$$
$$\left.\pm \mathrm{Re}(g_{e1}^{ji} g_{e2}^{ji*})\left(x_{ij} - \frac{1}{x_{ij}^3} - \frac{4}{x_{ij}}\ln x_{ij}\right)\right]$$

Helicity-flipping decay Suppressed

$$\Gamma_{LR,RL} = \frac{m_i m_j}{64\pi E_i}\left[|g_{e1}^{ji}|^2 + |g_{e2}^{ji}|^2 \mp 2\mathrm{Re}(g_{e1}^{ji} g_{e2}^{ji*})\right]$$
$$\times\left(\frac{x_{ij}}{2} - \frac{1}{2x_{12}^3} - \frac{2}{x_{ij}}\ln x_{ij}\right)$$

$x_{ij} \equiv m_i / m_j$

$$A \equiv \frac{\Gamma_{LL}+\Gamma_{RL}-\Gamma_{LR}-\Gamma_{RR}}{\Gamma_{LL}+\Gamma_{RL}+\Gamma_{LR}+\Gamma_{RR}} = -2\frac{\mathrm{Re}(c_V^{ji} c_A^{ji*})}{|c_V^{ji}|^2+|c_A^{ji}|^2} \times \frac{1-\frac{1}{x^2}-\frac{1}{x^4}+\frac{1}{x^6}-\frac{4\ln x}{x^2}+\frac{4\ln x}{x^4}}{1-\frac{3}{x^2}+\frac{3}{x^4}-\frac{1}{x^6}}$$

lepton mass gives small negligibly deviation to 1

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Spontaneous baryongenesis

Baryon Asymmetry (from BBN and CMB):

$$Y_B = \frac{n_B - n_{\bar{B}}}{s} = 8.7 \times 10^{-11}$$

Cogenesi

Dark Matter abundance(from CMB):

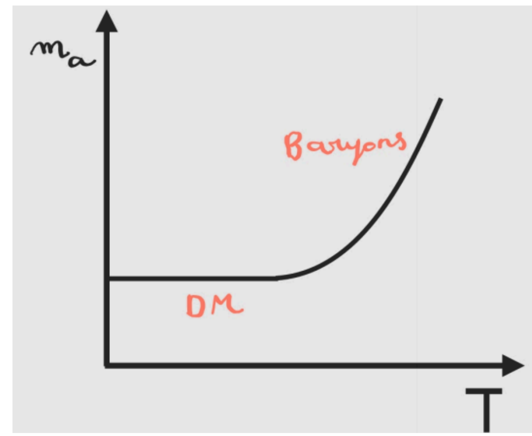
$$\Omega_{DM} h^2 = \frac{\rho_{DM}}{\rho_{total}} h^2 = 0.12$$

Thermal potential

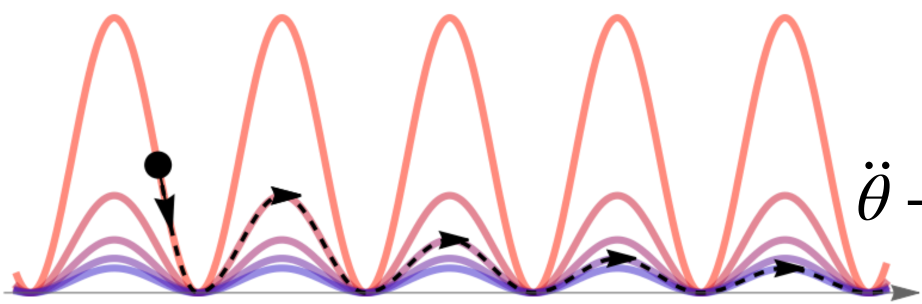
$$c_\lambda \simeq \lambda_{mix}/3\lambda_\phi$$

$$V_T(\phi) \simeq \frac{\lambda_\phi}{4}\phi^4 - \frac{1}{2}(m_\phi^2 + c\,T^2)\phi^2 \Rightarrow \langle \sqrt{2}\phi \rangle_T = f_a(T) = \sqrt{f_a^{(0)^2} + c_\lambda T^2}$$

$$\frac{\Phi^n}{\Lambda^{n-4}} + \mathrm{H.c.} \Rightarrow V_a(a) = \frac{f_a^n}{2^{\frac{n}{2}-1}\Lambda^{n-4}}\left(1 - \cos\left(\frac{na}{f_a}\right)\right)$$



Temperature dependent



$$\ddot{\theta} + \left(3H + \boxed{2\frac{\dot{f}_a}{f_a}}\right)\dot{\theta} = -\frac{1}{n}\boxed{m_a^2(T)}\sin(n\theta)$$

Parameter regions

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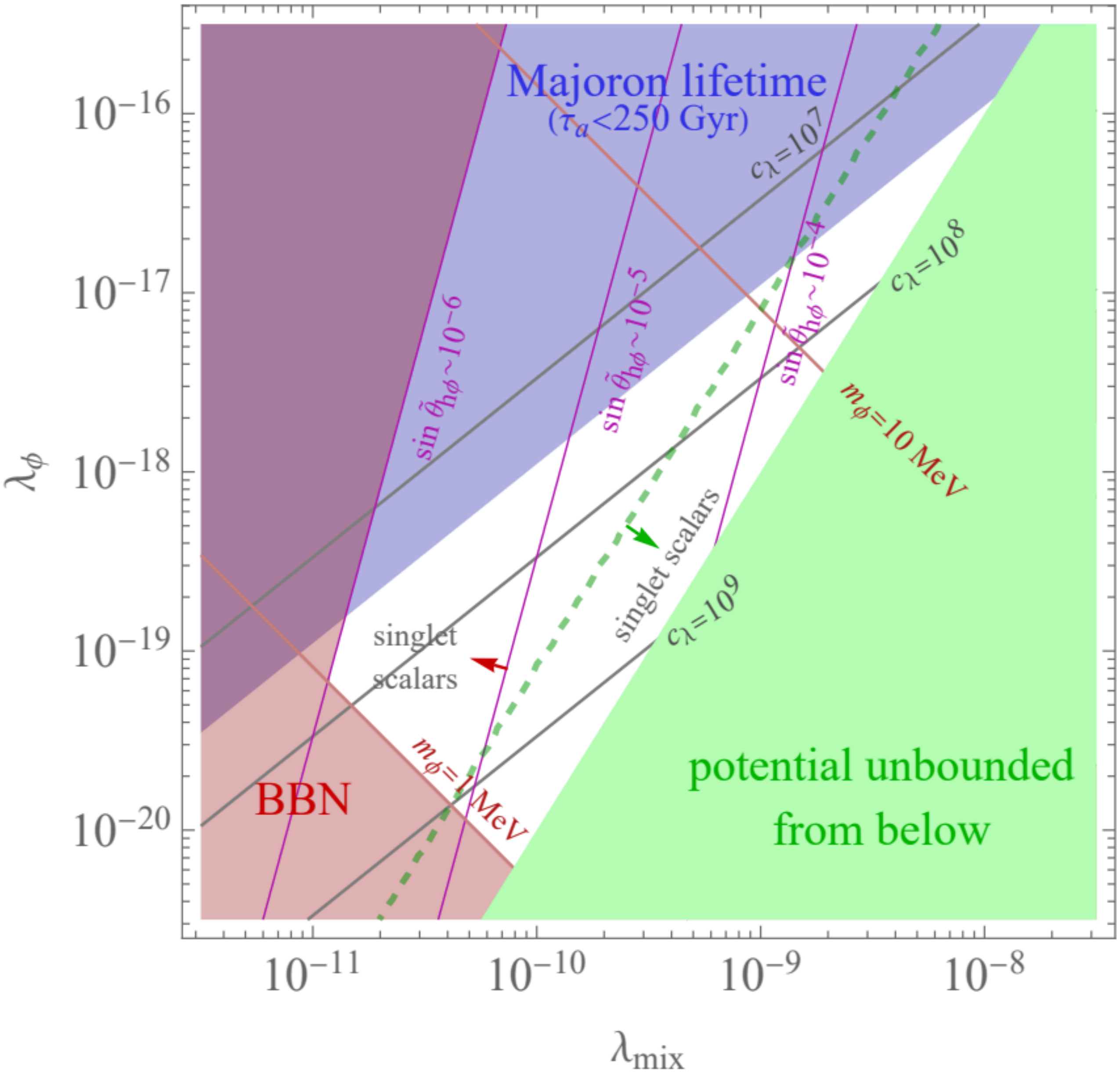

$$MeV < m_\phi < 20\ MeV$$

$$10^{-6} < \sin\theta_{h\phi} < 10^{-4}$$

$$100\ GeV < M_N < 400\ GeV$$

$$10^7 < c_\lambda < 10^9$$

$$m_a^0 \sim eV$$

$$f_a^0 \sim 10^6 GeV$$

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1 Introduction

2 CPV in Dark photon

3 CPV in Goldstone boson

4 Conclusion

Summary

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1. **CP violation serves to both probe the origins of matter-antimatter asymmetry and stringently test the SM, where the deficit requires new CP source.**

2. **Various CP violation mechanisms—such as dark photon, Axion—can occur in BSM.**

3. **CP violation is explored in conjunction with relevant phenomenological implications, including DM, EWPT, FCNC, baryon asym…**

Thanks!

谢谢

Type-III seesaw

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$$H'_{1,2} : (1, 2, -1/2)(\mp x_f)$$

$$-\bar{L}_L Y_{fL1} H'_1 f_{R\,1} - \bar{L}_L Y_{fL2} H'_2 f_{R\,2}$$

$$\mathcal{L}_m = -\frac{1}{2}(\bar{\nu}_L, \bar{\nu}^c_R) \begin{pmatrix} 0 & M_D \\ M_D^T & M_R \end{pmatrix} \begin{pmatrix} \nu^c_L \\ \nu_R \end{pmatrix}$$

$$-(\bar{E}_L, \bar{f}_L) \begin{pmatrix} m_e & \sqrt{2} M_D \\ 0 & M_R \end{pmatrix} \begin{pmatrix} E_R \\ f_R \end{pmatrix}$$

$$M_D = \begin{pmatrix} \frac{Y_{fL11} v'_1}{\sqrt{2}} & \frac{Y_{fL12} v'_2}{\sqrt{2}} & \frac{Y_{fL13} v}{\sqrt{2}} \\ \frac{Y_{fL21} v'_1}{\sqrt{2}} & \frac{Y_{fL22} v'_2}{\sqrt{2}} & \frac{Y_{fL23} v}{\sqrt{2}} \\ \frac{Y_{fL31} v'_1}{\sqrt{2}} & \frac{Y_{fL32} v'_2}{\sqrt{2}} & \frac{Y_{fL33} v}{\sqrt{2}} \end{pmatrix} \quad M_R = \begin{pmatrix} \frac{Y_{fs1} v_s}{\sqrt{2}} & m_{12} & 0 \\ m_{12} & \frac{Y_{fs2} v_s}{\sqrt{2}} & 0 \\ 0 & 0 & m_{33} \end{pmatrix}$$

Renormalizable CP violation

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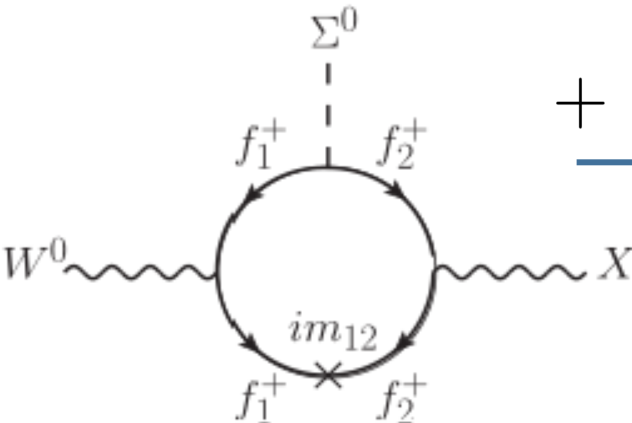
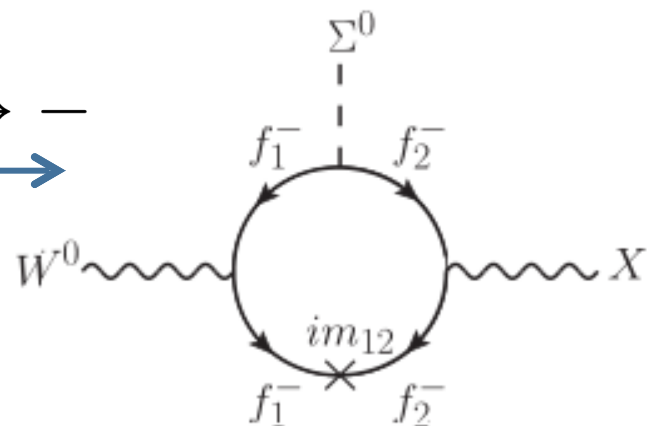
$$f_1 = (1,3,0)(x_f), \quad f_2 = (1,3,0)(-x_f),$$



(a)

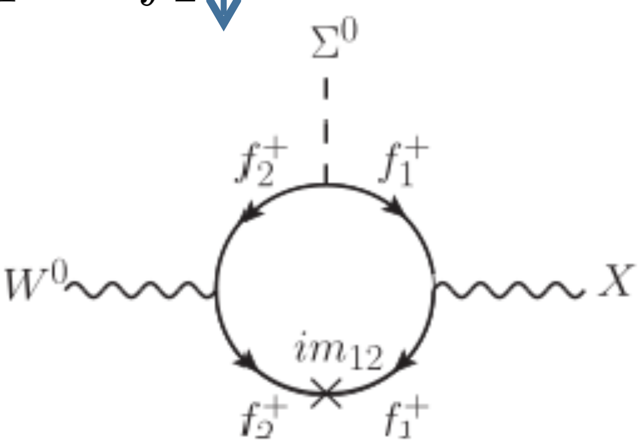
$+ \to -$



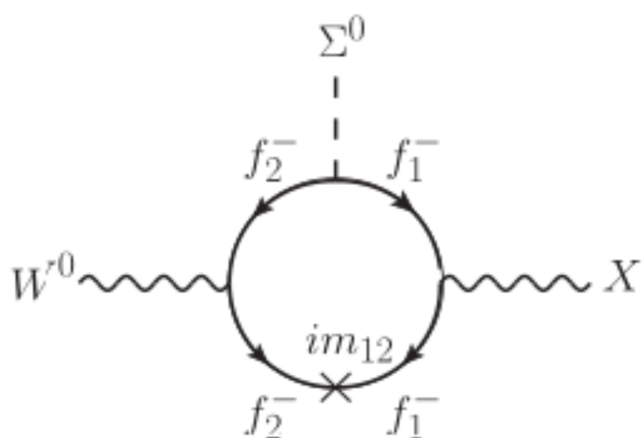
(b)

$f_1 \leftrightarrow f_2$

$$\longrightarrow \mathrm{Tr}(W_{\mu\nu}\Sigma)\tilde{X}^{\mu\nu}$$



(c)



(d)

CPC and CPV kinetic mixing

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$$\mathcal{L}_X \to -\frac{\tilde{\beta}_X}{2\Lambda}\tilde{X}^{\mu\nu}\left[(s_W F_{\mu\nu} + c_W Z_{\mu\nu})\right](v_\Sigma + \Sigma^0)$$

$$2\epsilon^{\mu\nu\alpha\beta} p_{X\alpha} p_{W\beta} \epsilon_{W\mu} \epsilon^*_{X\nu} \to -\tilde{X}^{\mu\nu} W^0_{\mu\nu}$$

CP conserving

$$\frac{\beta_X}{\Lambda} = \frac{1}{2\pi^2} g g_X x_f \mathrm{Re}(m_{12} Y^*_{f\sigma}) \times \left[f(m_1, m_2, p_W, p_X) + f(m_2, m_1, p_W, p_X)\right]$$

CP violating

$$\frac{\tilde{\beta}_X}{\Lambda} = \frac{1}{2\pi^2} g g_X x_f \mathrm{Im}(m_{12} Y^*_{f\sigma}) \times \left[f(m_1, m_2, p_W, p_X) + f(m_2, m_1, p_W, p_X)\right]$$

$$m_1 \approx m_2 \approx |m_{12}| \approx m$$

$$\tilde{\beta}_X/\Lambda \approx g g_X x_f |Y^*_{f\sigma}| \sin\delta / 6\pi^2 m < 5 \sin\delta \times 10^{-4}$$

SM fermion EDM

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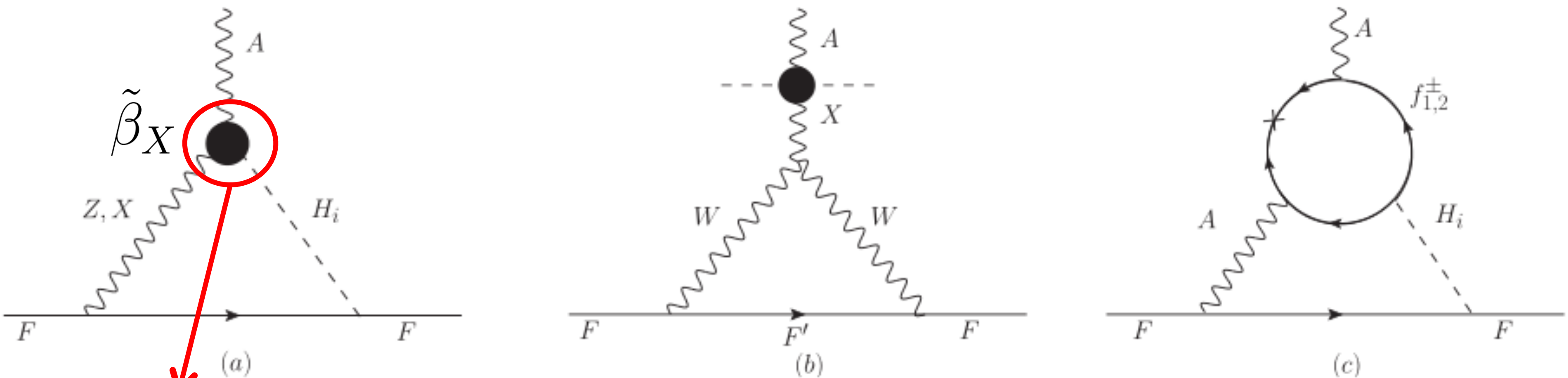
CPV → EDM



at one loop level | **No Z-X mixing** | **Barr-Zee**

$$\begin{pmatrix} A \\ Z \\ X \end{pmatrix} = \begin{pmatrix} 1 & 0 & -\epsilon_{AX} \\ 0 & 1 & -\xi - \epsilon_{ZX} \\ 0 & \xi & 1 \end{pmatrix} \begin{pmatrix} A^m \\ Z^m \\ X^m \end{pmatrix}$$

↓ **Two loop(dominant)**

↓ $d_q \approx 0$

↓ **Cancel**