Dark GMSB

(Dark gauge-mediated supersymmetry breaking)

based on JHEP 05 (2025) 052, with Brian Batell, Yechan Kim, Jiheon Lee

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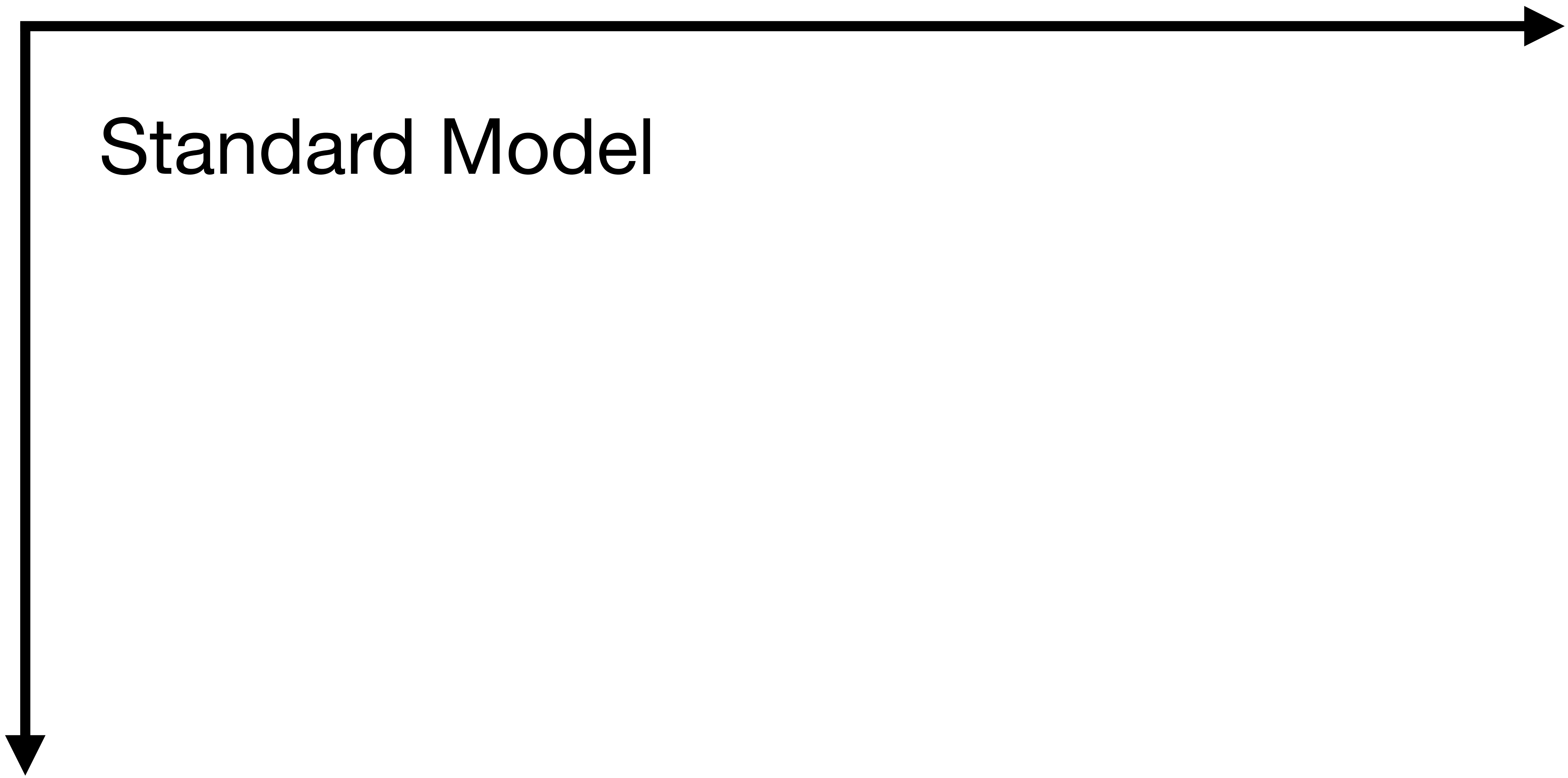
Phenomenology Before and After the Standard Model
Madison, Wisconsin / June 5, 2025

KAIST

Extension of the Standard Model



Extension of the Standard Model

Standard Model

+ New heavy particles
(Supersymmetry, …)

+ New light particles
(Dark photon, …)

Supersymmetry + Dark photon

Many studies on the dark photon in the Supersymmetry framework.

Yet, focus was on the small kinetic mixing (ϵ) scenario.

$$-\frac{\epsilon}{2}\mathbb{B}_{\mu\nu}\mathbb{X}^{\mu\nu}$$

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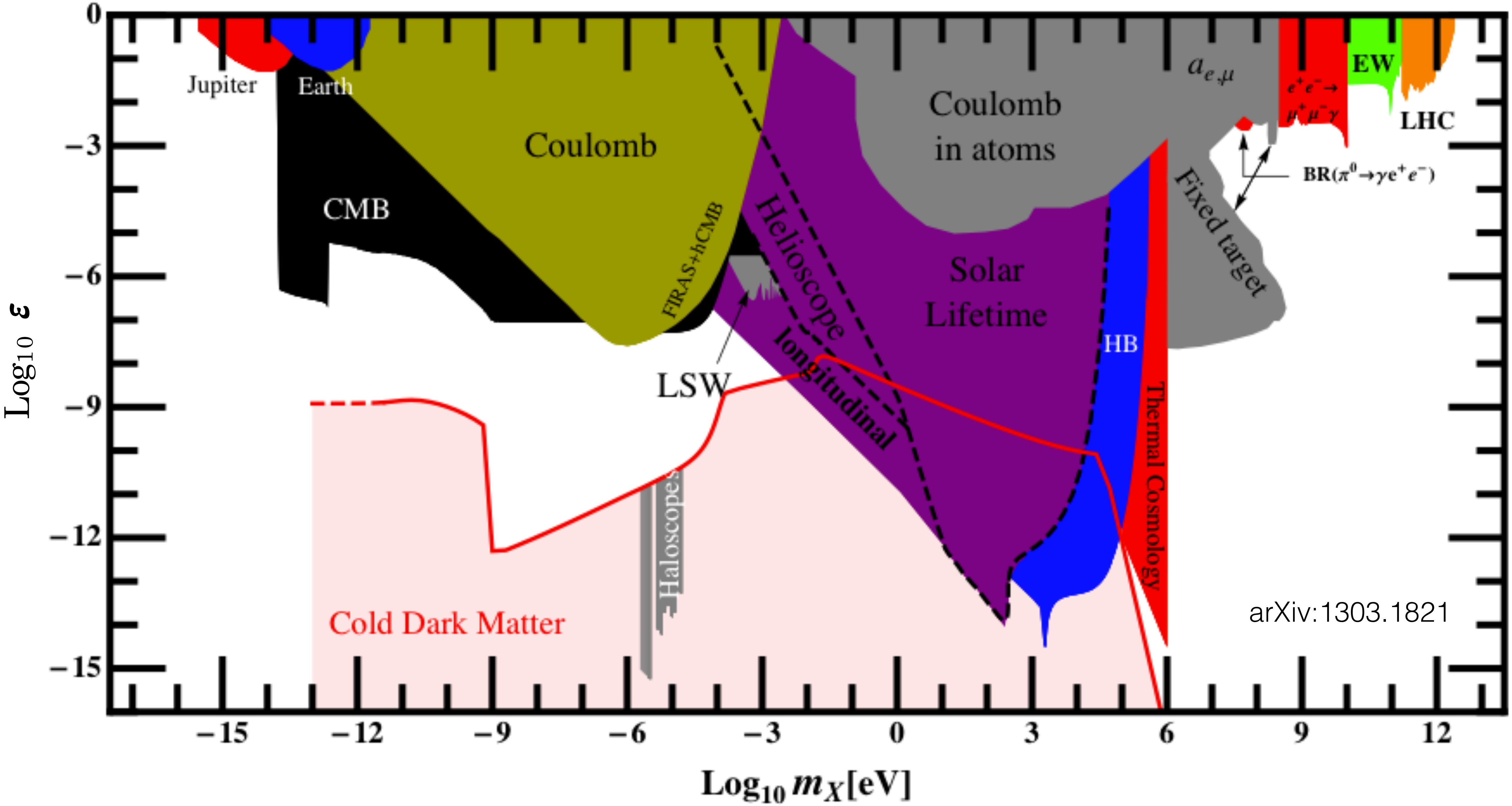
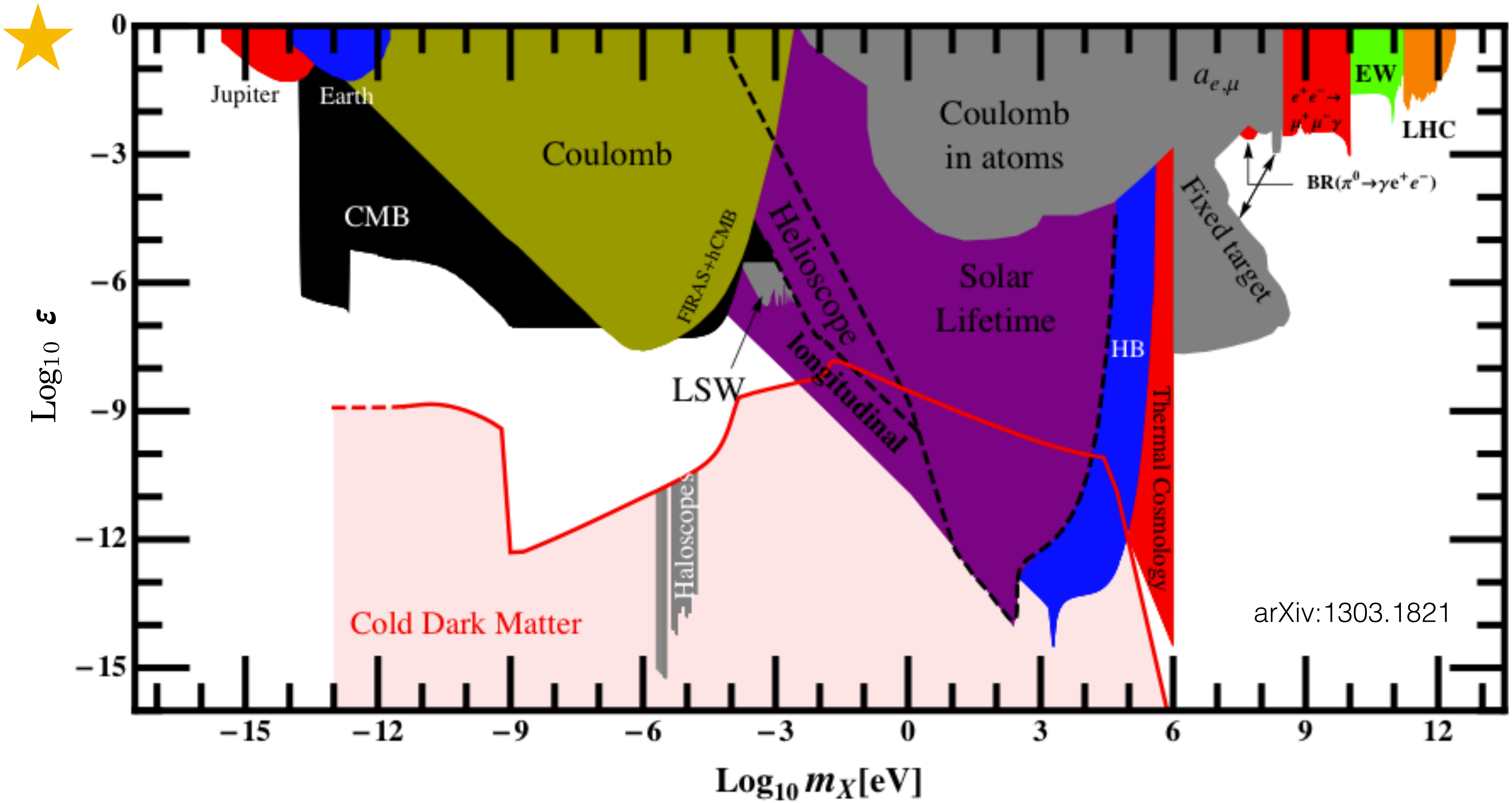
Dark photon parameter space



Kinetic mixing ϵ is severely constrained by many experiments.
Dark photon effects in the supersymmetry were somewhat limited.

Dark photon parameter space



In the massless limit, ϵ is unconstrained unless there are dark sector particles with induced (milli) electric charges. The kinetic mixing can be rotated away by field redefinitions, without mass mixing.

This work:

GMSB scenario extended by U(1) dark gauge symmetry
with large kinetic mixing allowed by the massless dark photon

My PhD thesis in Madison (2005): “Phenomenology of the $U(1)'$-extended MSSM”

Massless dark photon in SUSY

Supersymmetric kinetic mixing of $U(1)_B$ and $U(1)_{\text{dark}}$

$$
\mathcal{L} \supset \int d^2\theta \left(\frac{1}{4} \hat{\mathcal{W}}_{\mathbb{B}} \hat{\mathcal{W}}_{\mathbb{B}} + \frac{1}{4} \hat{\mathcal{W}}_{\mathbb{X}} \hat{\mathcal{W}}_{\mathbb{X}} + \frac{\epsilon}{2} \hat{\mathcal{W}}_{\mathbb{B}} \hat{\mathcal{W}}_{\mathbb{X}} \right) + h.c.
$$

$$
\begin{aligned}
&= -\frac{1}{4}\mathbb{B}_{\mu\nu}\mathbb{B}^{\mu\nu} - \frac{1}{4}\mathbb{X}_{\mu\nu}\mathbb{X}^{\mu\nu} - \frac{\epsilon}{2}\mathbb{B}_{\mu\nu}\mathbb{X}^{\mu\nu} \\
&\quad + i\tilde{\mathbb{B}}^\dagger \sigma^\mu \partial_\mu \tilde{\mathbb{B}} + i\tilde{\mathbb{X}}^\dagger \sigma^\mu \partial_\mu \tilde{\mathbb{X}} + (i\epsilon \tilde{\mathbb{B}}^\dagger \sigma^\mu \partial_\mu \tilde{\mathbb{X}} + h.c.) \\
&\quad + \frac{1}{2} D_{\mathbb{B}}^2 + \frac{1}{2} D_{\mathbb{X}}^2 + \epsilon D_{\mathbb{B}} D_{\mathbb{X}},
\end{aligned}
$$

Massless dark photon in SUSY

Supersymmetric kinetic mixing of $U(1)_B$ and $U(1)_{\text{dark}}$

$$
\begin{aligned}
\mathcal{L} \supset & \int d^2\theta \left(\frac{1}{4}\hat{\mathcal{W}}_{\mathbb{B}}\hat{\mathcal{W}}_{\mathbb{B}} + \frac{1}{4}\hat{\mathcal{W}}_{\mathbb{X}}\hat{\mathcal{W}}_{\mathbb{X}} + \frac{\epsilon}{2}\hat{\mathcal{W}}_{\mathbb{B}}\hat{\mathcal{W}}_{\mathbb{X}} \right) + h.c. \\
= & -\frac{1}{4}\mathbb{B}_{\mu\nu}\mathbb{B}^{\mu\nu} - \frac{1}{4}\mathbb{X}_{\mu\nu}\mathbb{X}^{\mu\nu} - \frac{\epsilon}{2}\mathbb{B}_{\mu\nu}\mathbb{X}^{\mu\nu} \\
& + i\tilde{\mathbb{B}}^\dagger\sigma^\mu\partial_\mu\tilde{\mathbb{B}} + i\tilde{\mathbb{X}}^\dagger\sigma^\mu\partial_\mu\tilde{\mathbb{X}} + (i\epsilon\tilde{\mathbb{B}}^\dagger\sigma^\mu\partial_\mu\tilde{\mathbb{X}} + h.c.) \\
& + \frac{1}{2}D_{\mathbb{B}}^2 + \frac{1}{2}D_{\mathbb{X}}^2 + \epsilon D_{\mathbb{B}}D_{\mathbb{X}},
\end{aligned}
$$

Gauge interaction after kinetic diagonalization

$$\begin{pmatrix} \hat{\mathbb{X}} \\ \hat{\mathbb{B}} \end{pmatrix} = \begin{pmatrix} 1 & -\frac{\epsilon}{\sqrt{1-\epsilon^2}} \\ 0 & \frac{1}{\sqrt{1-\epsilon^2}} \end{pmatrix} \begin{pmatrix} \hat{X} \\ \hat{B} \end{pmatrix}$$

(our basis)

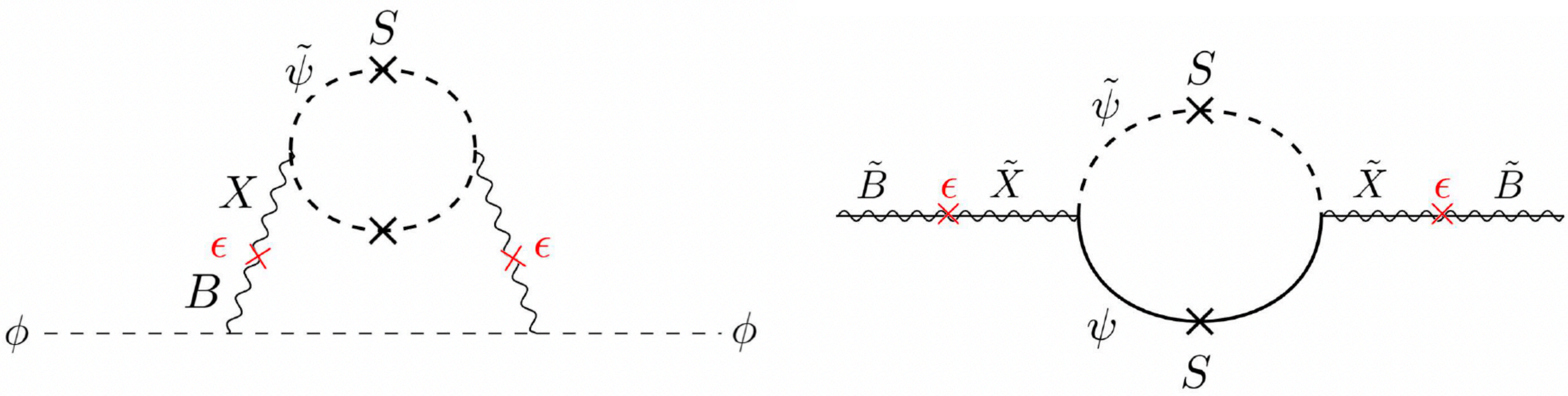
Gauge interaction terms

$$\begin{aligned} \mathcal{L} &\supset g'_Y Y J^\mu_Y \mathbb{B}_\mu + g_D D J^\mu_D \mathbb{X}_\mu \\ &= \left[-\frac{g_D \epsilon}{\sqrt{1-\epsilon^2}} D J^\mu_D + g_Y Y J^\mu_Y \right] B_\mu + g_D D J^\mu_D X_\mu, \end{aligned}$$

$$Y_{\rm eff} = Y - \frac{g_D}{g_Y} \frac{\epsilon}{\sqrt{1-\epsilon^2}} D.$$

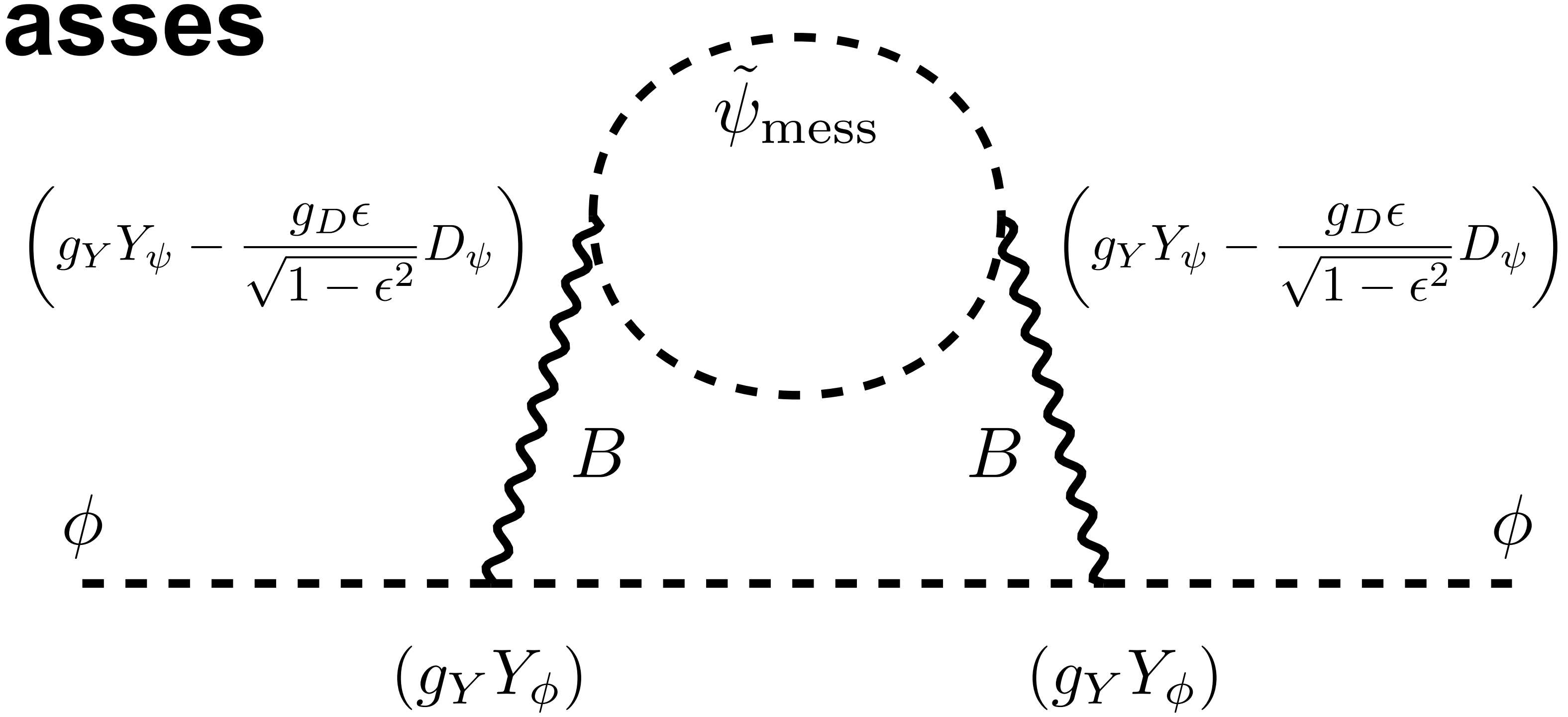
Hypercharge is effectively modified by the kinetic mixing.

Soft mass terms in Dark GMSB



The messengers (ψ, $\tilde{\psi}$) are charged under the SM and dark gauge symmetries. They couple to the dark photon (X) and dark photino ($\tilde{X}$), which mix with B and $\tilde{B}$ with large kinetic mixing, giving additional contribution to scalar masses and neutralino masses.

Scalar masses



$$(g_Y Y_\phi)^2 (g_Y Y_\Psi)^2 \to (g_Y Y_\phi)^2 \left(g_Y Y_\Psi - \frac{g_D \epsilon D_\Psi}{\sqrt{1-\epsilon^2}}\right)^2$$

The effect of ϵ appears as the hypercharge shift for the messenger fields.

$$m^2_{H_i}(g_D, \epsilon) = \sum_\Psi \tilde{M}^2_{\rm mess,1} \left[N_{\rm SU(2)} \frac{3 g_2^4}{8} + N_{\rm U(1)} g_Y^2 Y_{H_i}^2 \left(g_Y Y_\Psi - \frac{g_D \epsilon D_\Psi}{\sqrt{1-\epsilon^2}} \right)^2 \right].$$

$$m^2_{\tilde{q}_L}(g_D, \epsilon) = \sum_\Psi \tilde{M}^2_{\rm mess,1} \left[N_{\rm SU(3)} \frac{2 g_3^4}{3} + N_{\rm SU(2)} \frac{3 g_2^4}{8} + N_{\rm U(1)} g_Y^2 Y_{\tilde{q}_L}^2 \left(g_Y Y_\Psi - \frac{g_D \epsilon D_\Psi}{\sqrt{1-\epsilon^2}} \right)^2 \right],$$

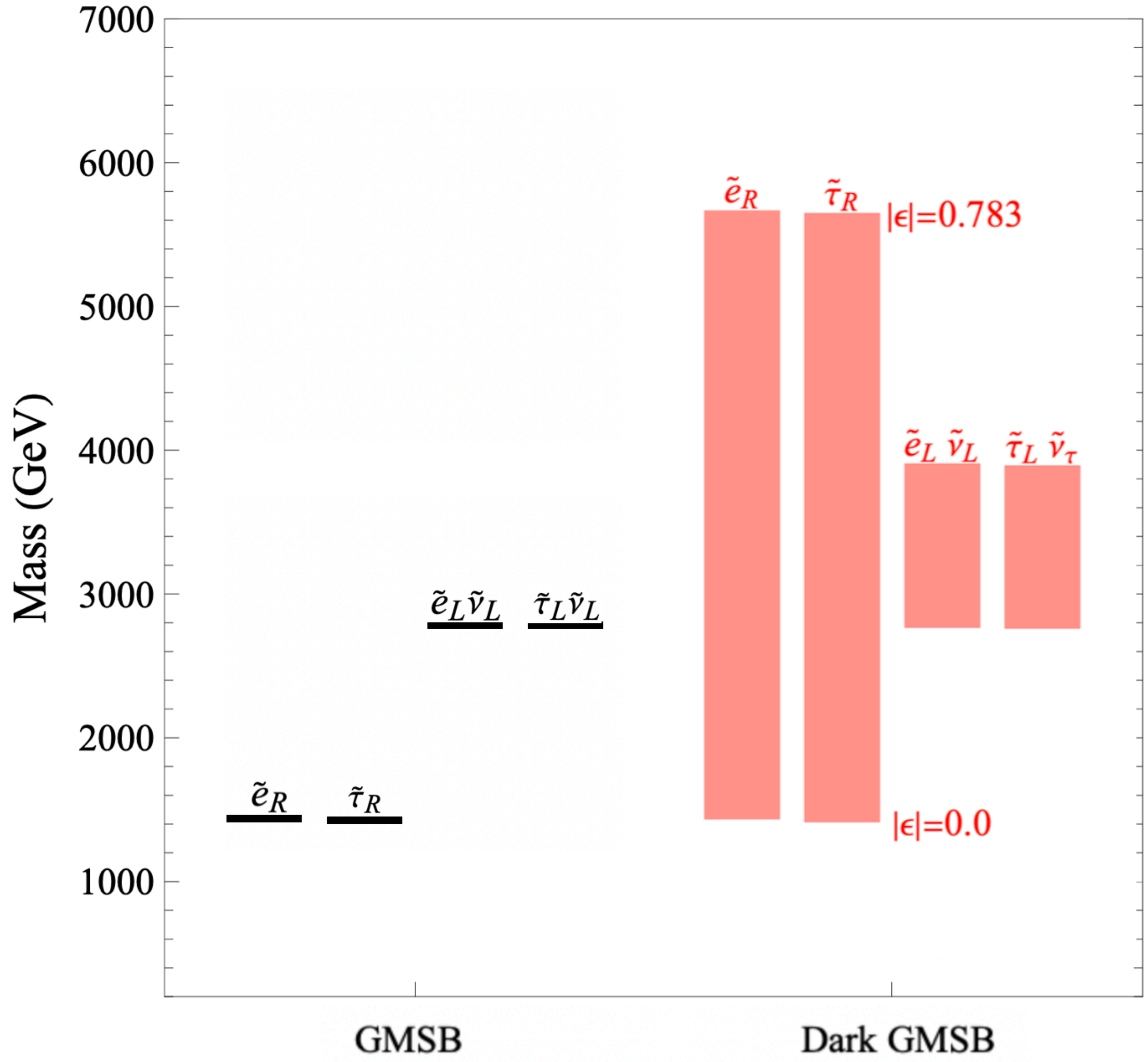
$$m^2_{\tilde{u}_R}(g_D, \epsilon) = \sum_\Psi \tilde{M}^2_{\rm mess,1} \left[N_{\rm SU(3)} \frac{2 g_3^4}{3} + N_{\rm U(1)} g_Y^2 Y_{\tilde{u}_R}^2 \left(g_Y Y_\Psi - \frac{g_D \epsilon D_\Psi}{\sqrt{1-\epsilon^2}} \right)^2 \right],$$

$$m^2_{\tilde{d}_R}(g_D, \epsilon) = \sum_\Psi \tilde{M}^2_{\rm mess,1} \left[N_{\rm SU(3)} \frac{2 g_3^4}{3} + N_{\rm U(1)} g_Y^2 Y_{\tilde{d}_R}^2 \left(g_Y Y_\Psi - \frac{g_D \epsilon D_\Psi}{\sqrt{1-\epsilon^2}} \right)^2 \right],$$

$$m^2_{\tilde{\ell}_L}(g_D, \epsilon) = \sum_\Psi \tilde{M}^2_{\rm mess,1} \left[N_{\rm SU(2)} \frac{3 g_2^4}{8} + N_{\rm U(1)} g_Y^2 Y_{\tilde{\ell}_L}^2 \left(g_Y Y_\Psi - \frac{g_D \epsilon D_\Psi}{\sqrt{1-\epsilon^2}} \right)^2 \right],$$

$$m^2_{\tilde{e}_R}(g_D, \epsilon) = \sum_\Psi \tilde{M}^2_{\rm mess,1} \left[N_{\rm U(1)} g_Y^2 Y_{\tilde{e}_R}^2 \left(g_Y Y_\Psi - \frac{g_D \epsilon D_\Psi}{\sqrt{1-\epsilon^2}} \right)^2 \right].$$

Slepton spectrum



$Y_L = -1/2, \ Y_{e_R} = -1$

$$m^2_{\tilde{\ell}_L}(g_D, \epsilon) = \sum_{\Psi} \tilde{M}^2_{\text{mess},1} \left[N_{\text{SU}(2)} \frac{3g_2^4}{8} + N_{\text{U}(1)} g_Y^2 Y_{\tilde{\ell}_L}^2 \left(g_Y Y_\Psi - \frac{g_D \epsilon D_\Psi}{\sqrt{1-\epsilon^2}} \right)^2 \right]$$

$$m^2_{\tilde{e}_R}(g_D, \epsilon) = \sum_{\Psi} \tilde{M}^2_{\text{mess},1} \left[N_{\text{U}(1)} g_Y^2 Y_{\tilde{e}_R}^2 \left(g_Y Y_\Psi - \frac{g_D \epsilon D_\Psi}{\sqrt{1-\epsilon^2}} \right)^2 \right].$$

EWSB

The scalar potential of neural Higgs fields

$$V(H_u^0, H_d^0) = \sum_{i=u,d} \left(|\mu|^2 + m_{H_i}^2\right) |H_i^0|^2 - \left(b_\mu H_u^0 H_d^0 + \text{h.c.}\right)$$
$$+ \frac{1}{8}(g_Y^2 + g_2^2) \left(|H_u^0|^2 - |H_d^0|^2\right)^2 .$$

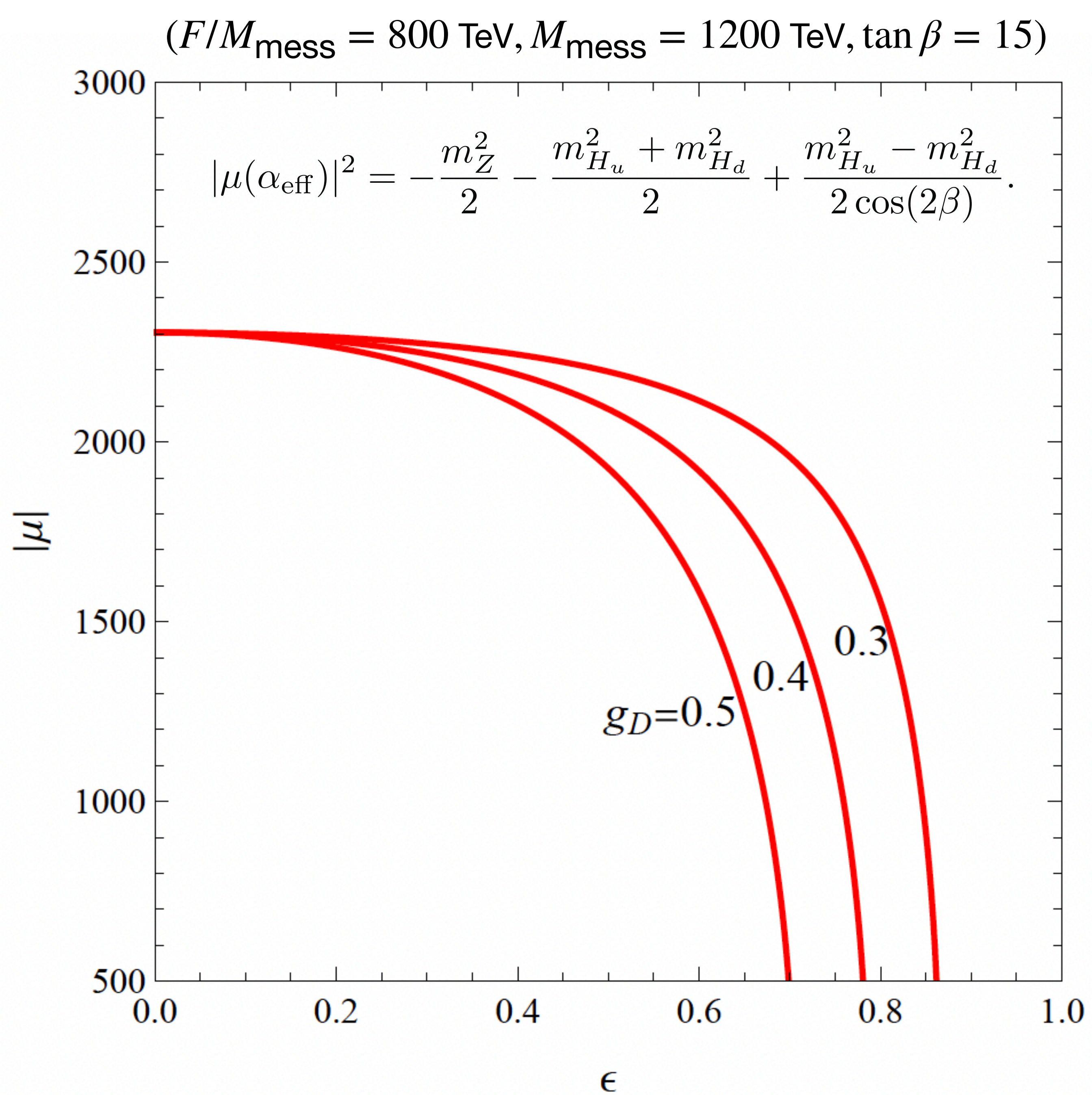
At the potential minimum, EWSB dictates

$$b_\mu = \frac{\sin(2\beta)}{2} \left[2|\mu|^2 + m_{H_u}^2 + m_{H_d}^2\right] ,$$
$$|\mu|^2 = -\frac{m_Z^2}{2} - \frac{m_{H_u}^2 + m_{H_d}^2}{2} + \frac{m_{H_u}^2 - m_{H_d}^2}{2\cos(2\beta)} .$$

$m_{H_u}^2$ and $m_{H_d}^2$ are also altered in Dark GMSB.

$$m_{H_i}^2(g_D, \epsilon) = \sum_{\Psi} \tilde{M}_{\text{mess},1}^2 \left[N_{\text{SU}(2)} \frac{3g_2^4}{8} + N_{\text{U}(1)} g_Y^2 Y_{H_i}^2 \left(g_Y Y_\Psi - \frac{g_D \epsilon D_\Psi}{\sqrt{1-\epsilon^2}}\right)^2\right]$$

μ parameter

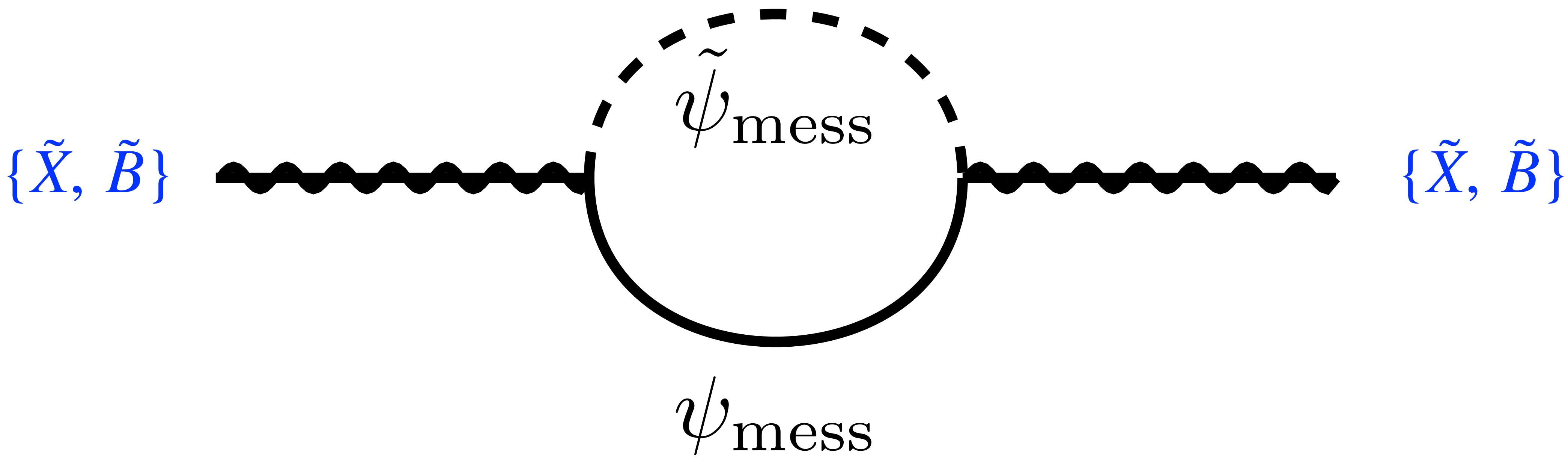


In Dark GMSB, required $|\mu|$ values for the EWSB depends on ϵ.

Thus, ϵ is constrained by the EWSB condition (from $|\mu|^2 > 0$).

(It does not solve the μ-problem.)

Dark photino ($\tilde{X}$) / Bino ($\tilde{B}$) masses



Hypercharge shift for the messenger fields

$$(g_Y Y_\Psi)^2 \rightarrow \left(g_Y Y_\Psi - \frac{g_D \epsilon D_\Psi}{\sqrt{1-\epsilon^2}}\right)^2$$

$$\mathbf{M}^{2\times 2}_{\tilde{N}} = \begin{pmatrix} M_D & M_K \\ M_K & M_1 \end{pmatrix}$$

$\{\tilde{X} \quad \tilde{B}\}$

$$M_D(g_D) = \sum_\Psi N_{\rm U(1)} g_D^2 D_\Psi^2 \tilde{M}_{{\rm mess},2},$$

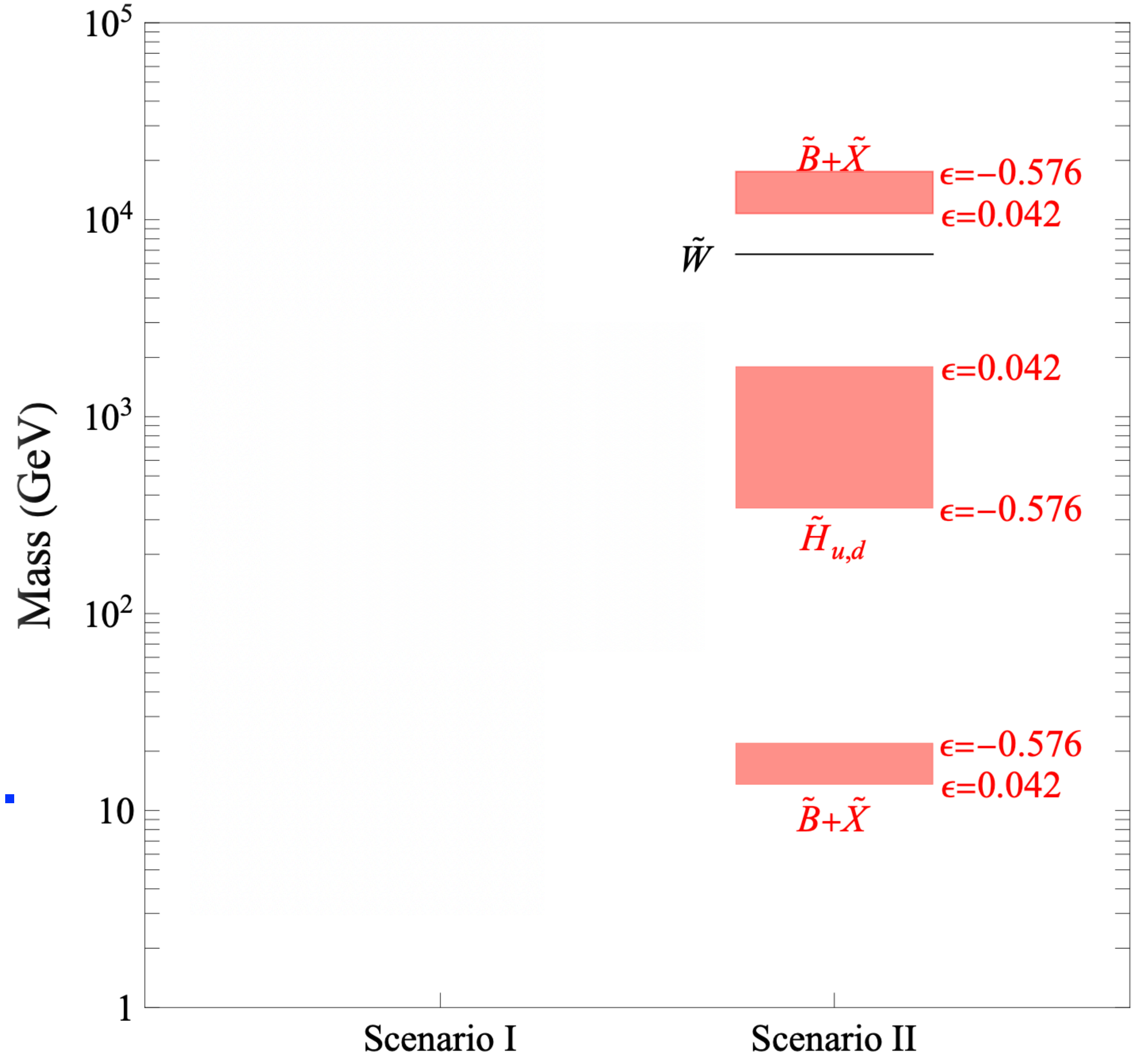
$$M_K(g_D, \epsilon) = \sum_\Psi N_{\rm U(1)} g_D D_\Psi \left(g_Y Y_\Psi - \frac{g_D \epsilon D_\Psi}{\sqrt{1-\epsilon^2}}\right) \tilde{M}_{{\rm mess},2},$$

$$M_1(g_D, \epsilon) = \sum_\Psi N_{\rm U(1)} \left(g_Y Y_\Psi - \frac{g_D \epsilon D_\Psi}{\sqrt{1-\epsilon^2}}\right)^2 \tilde{M}_{{\rm mess},2},$$

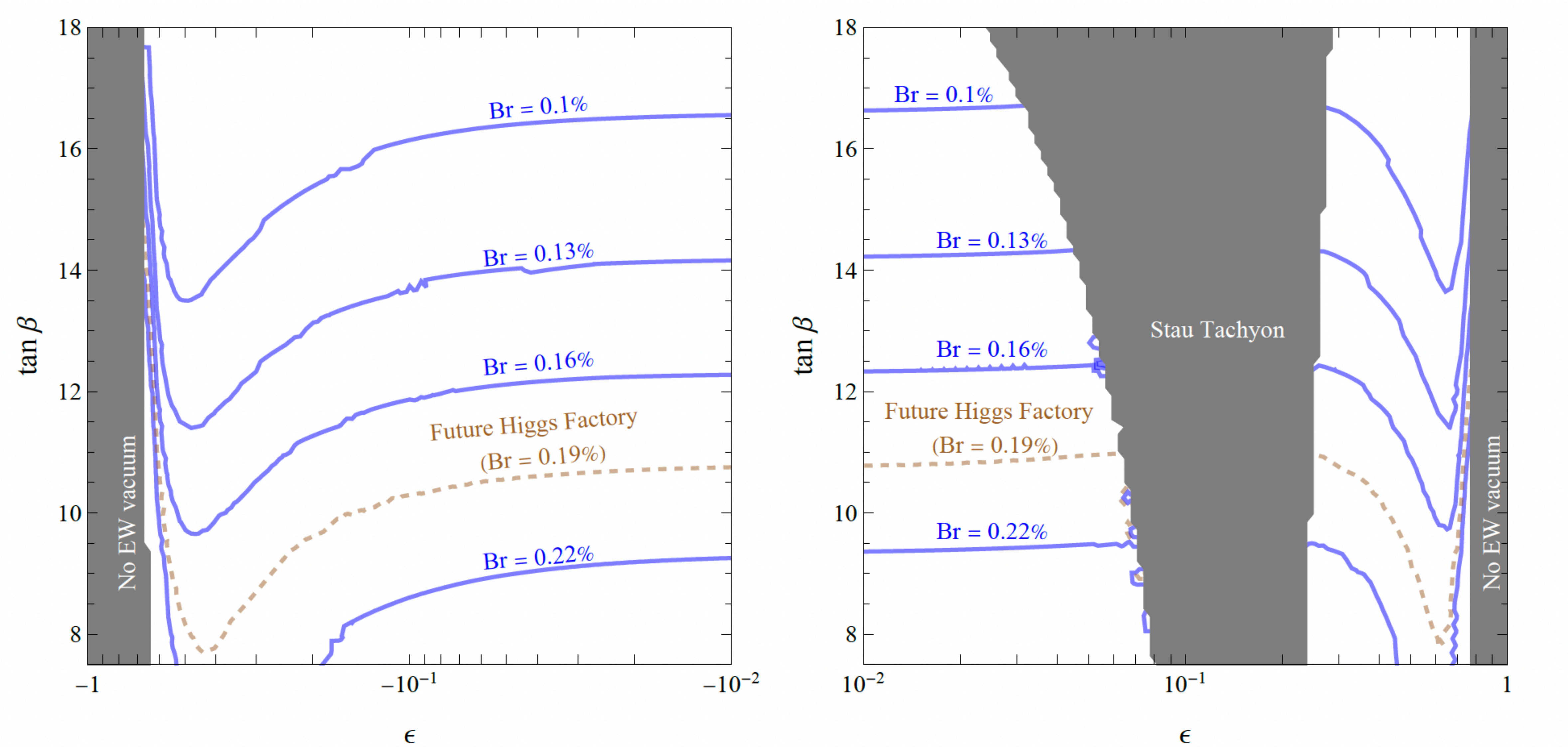
Neutralino mass matrix

$$\mathbf{M}_{\tilde{N}} = \begin{pmatrix} M_D & M_K & 0 & 0 & 0 \\ M_K & M_1 & 0 & -c_\beta s_W m_Z & s_\beta s_W m_Z \\ 0 & 0 & M_2 & c_\beta c_W m_Z & -s_\beta c_W m_Z \\ 0 & -c_\beta s_W m_Z & c_\beta c_W m_Z & 0 & -\mu \\ 0 & s_\beta s_W m_Z & -s_\beta c_W m_Z & -\mu & 0 \end{pmatrix}$$

$\tilde{N}_0$ can be very light (e.g. 10-20 GeV).

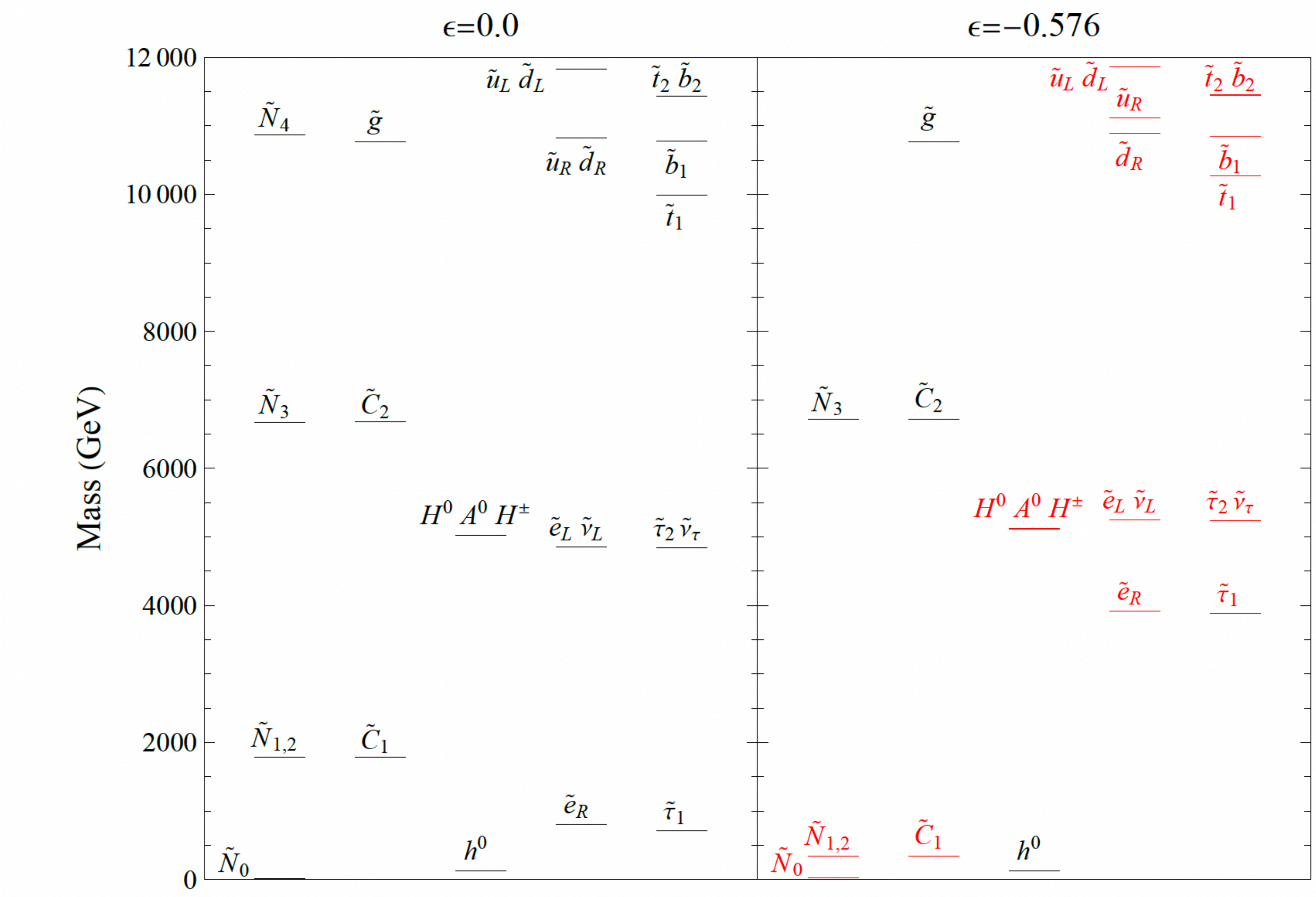


Exotic Higgs decay



The invisible $h(125) \to \tilde{N}_0 \tilde{N}_0$ decay signal could be probed in future Higgs factory (e.g. ILC).

Summary



Supersymmetry + U(1) is always an interesting extension of the SM.

Dark GMSB with large kinetic mixing, allowed by a massless dark photon leads to significant changes in the superpartner spectrum from conventional GMSB.

- Thank you -

back-up

Massless dark photon

$$\begin{pmatrix} \hat{\mathbb{X}} \\ \hat{\mathbb{B}} \end{pmatrix} = \begin{pmatrix} 1 & -\frac{\epsilon}{\sqrt{1-\epsilon^2}} \\ 0 & \frac{1}{\sqrt{1-\epsilon^2}} \end{pmatrix} \begin{pmatrix} \cos\omega & -\sin\omega \\ \sin\omega & \cos\omega \end{pmatrix} \begin{pmatrix} \hat{X} \\ \hat{B} \end{pmatrix},$$

For massless X case, ω is free to choose.

For massive X case, $\sin\omega = -\epsilon$ is determined to keep B massless.

$$\text{(Our basis)} \quad \sin\omega = 0, \quad \cos\omega = 1.$$

$$\begin{aligned} \mathcal{L} &\supset g'_Y Y J^\mu_Y \mathbb{B}_\mu + g_D D J^\mu_D \mathbb{X}_\mu \\ &= \left[-\frac{g_D \epsilon}{\sqrt{1-\epsilon^2}} D J^\mu_D + g_Y Y J^\mu_Y \right] B_\mu + g_D D J^\mu_D X_\mu, \end{aligned}$$

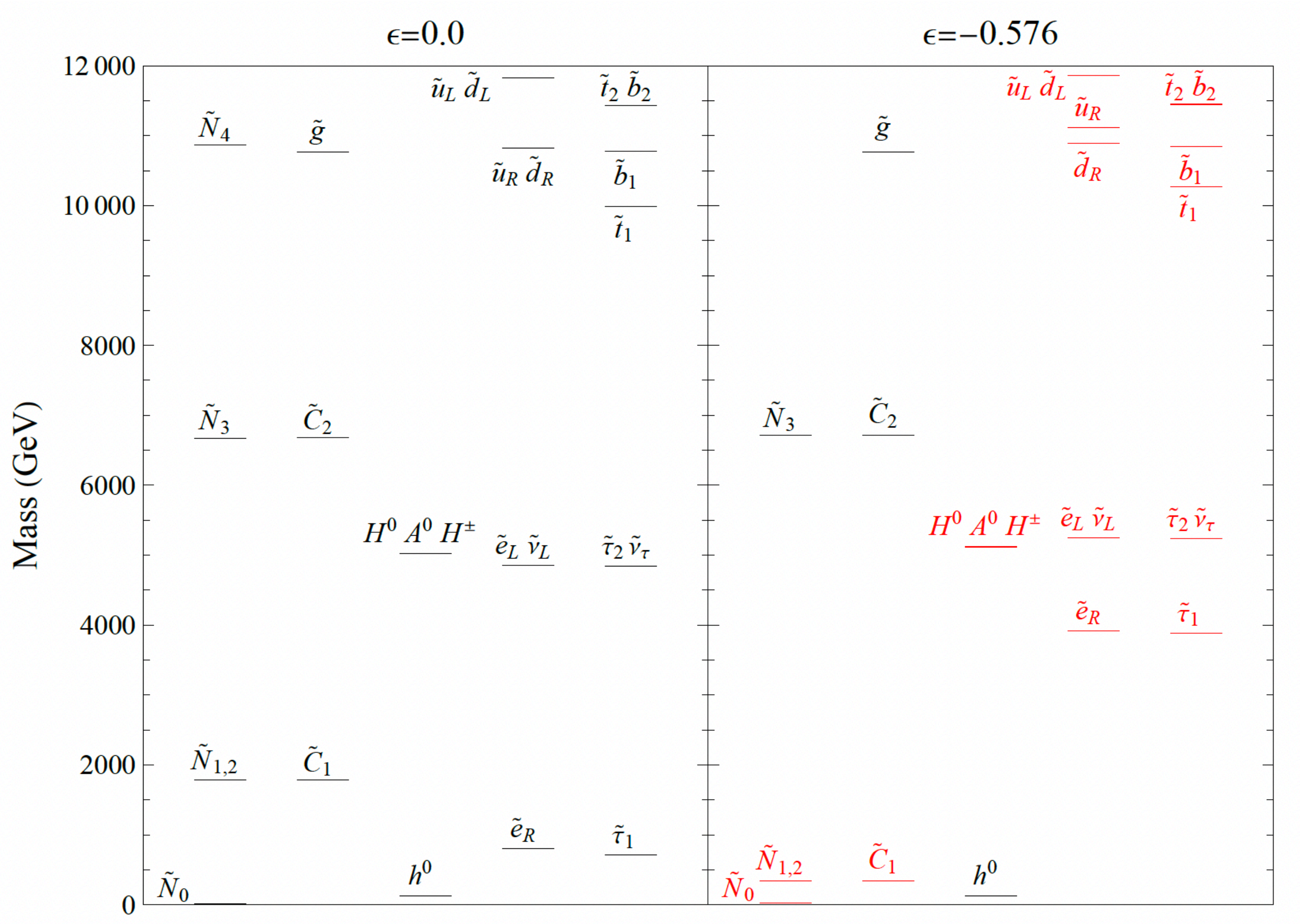
Scenario	Superfield	Component fields	Representation
I	$\hat{\Psi}_1$	$\psi_1, \tilde{\psi}_1$	$(\mathbf{3}, 1, -1/3, D_\Psi)$
	$\hat{\bar{\Psi}}_1$	$\bar{\psi}_1, \tilde{\bar{\psi}}_1$	$(\bar{\mathbf{3}}, 1, 1/3, -D_\Psi)$
	$\hat{\Psi}_2$	$\psi_2, \tilde{\psi}_2$	$(1, \mathbf{2}, 1/2, D_\Psi)$
	$\hat{\bar{\Psi}}_2$	$\bar{\psi}_2, \tilde{\bar{\psi}}_2$	$(1, \mathbf{2}, -1/2, -D_\Psi)$
II	$\hat{\Psi}$	$\psi, \tilde{\psi}$	$(\mathbf{3}, \mathbf{2}, 1/6, D_\Psi)$
	$\hat{\bar{\Psi}}$	$\bar{\psi}, \tilde{\bar{\psi}}$	$(\bar{\mathbf{3}}, \mathbf{2}, -1/6, -D_\Psi)$

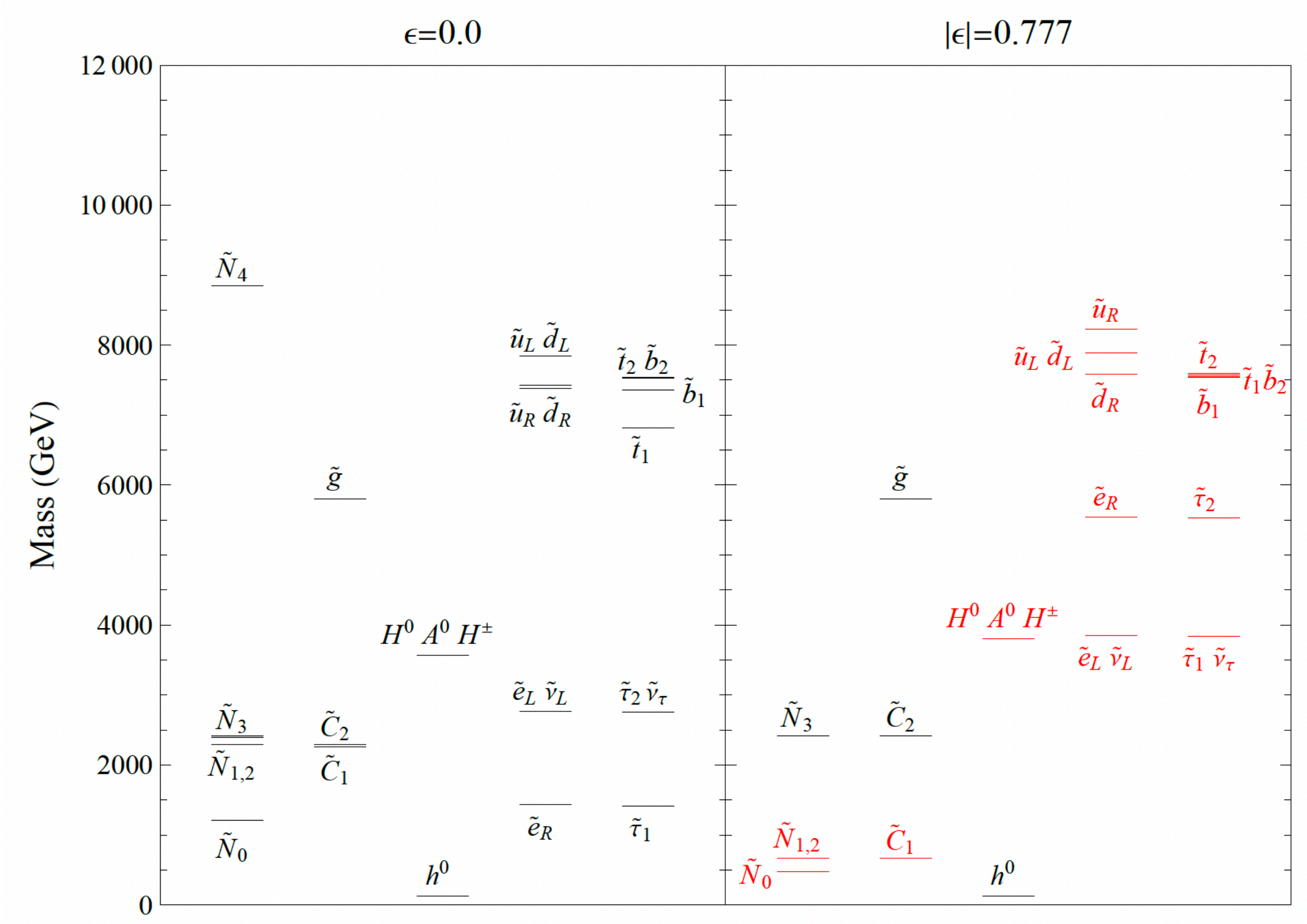
Table 1. Messenger representations for two distinct scenarios, which we will discuss in this paper. We denote the representation as $(SU(3)_C, SU(2)_L, U(1)_Y, U(1)_D)$. We assume the messenger fields are in a vector-like representation to avoid the gauge anomaly. Scenario I employs a $SU(5)$ complete representation (the fundamental $\mathbf{5}+\bar{\mathbf{5}}$), whereas Scenario II utilizes a $SU(5)$ incomplete representation. For concreteness, we fix $D_\Psi = 1$.

$F/M_{\rm mess}$	$M_{\rm mess}$	g_D	$\tan\beta$	$F/M_{\rm mess}^2$
800 TeV	1200 TeV	0.4	15	2/3

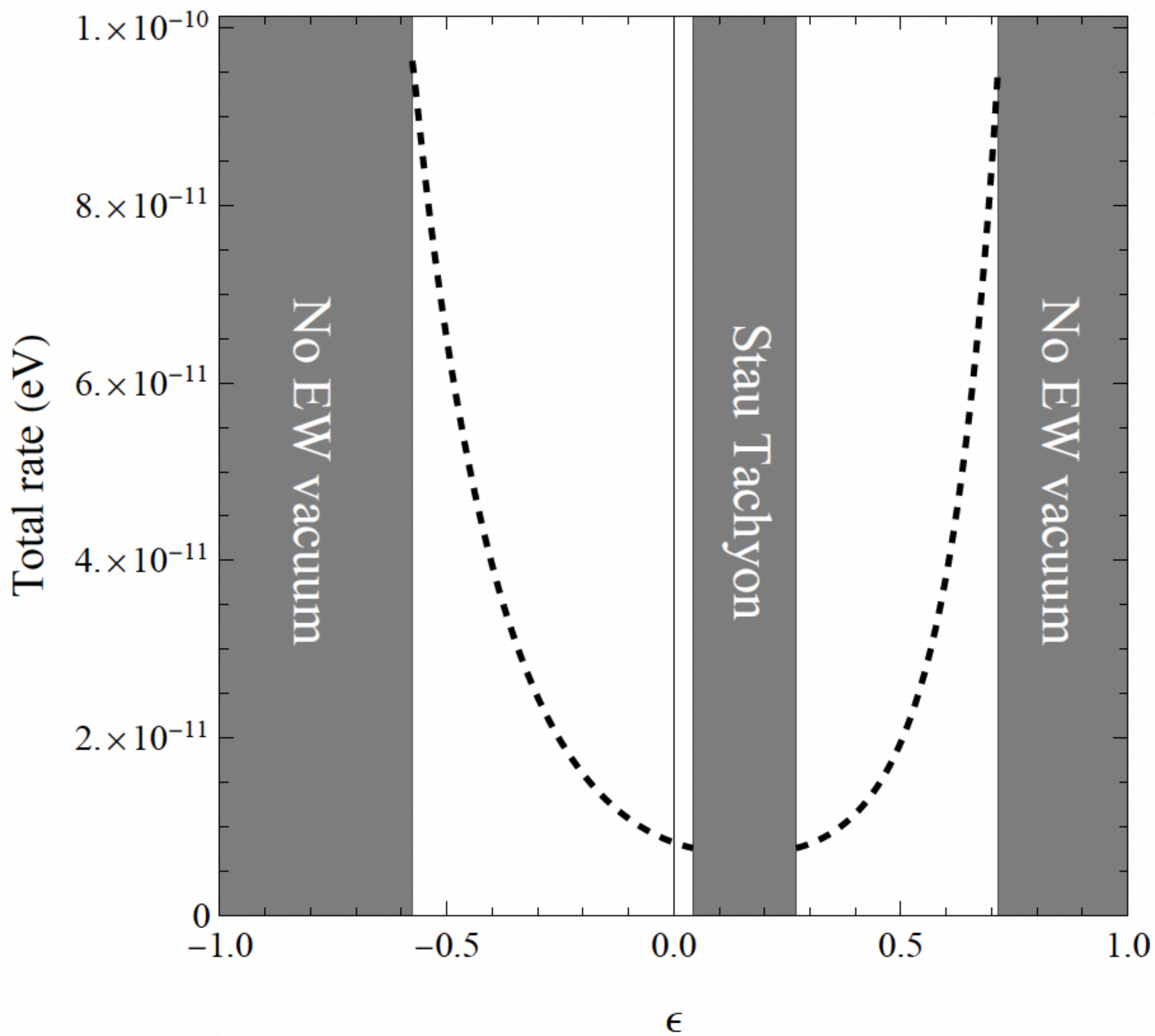
Table 2. The parameters listed in this table are utilized for illustrations unless specifically stated otherwise. This parameters setup is fit to obtain the observed SM-like Higgs mass of $m_{h^0} = 125\,\text{GeV}$.

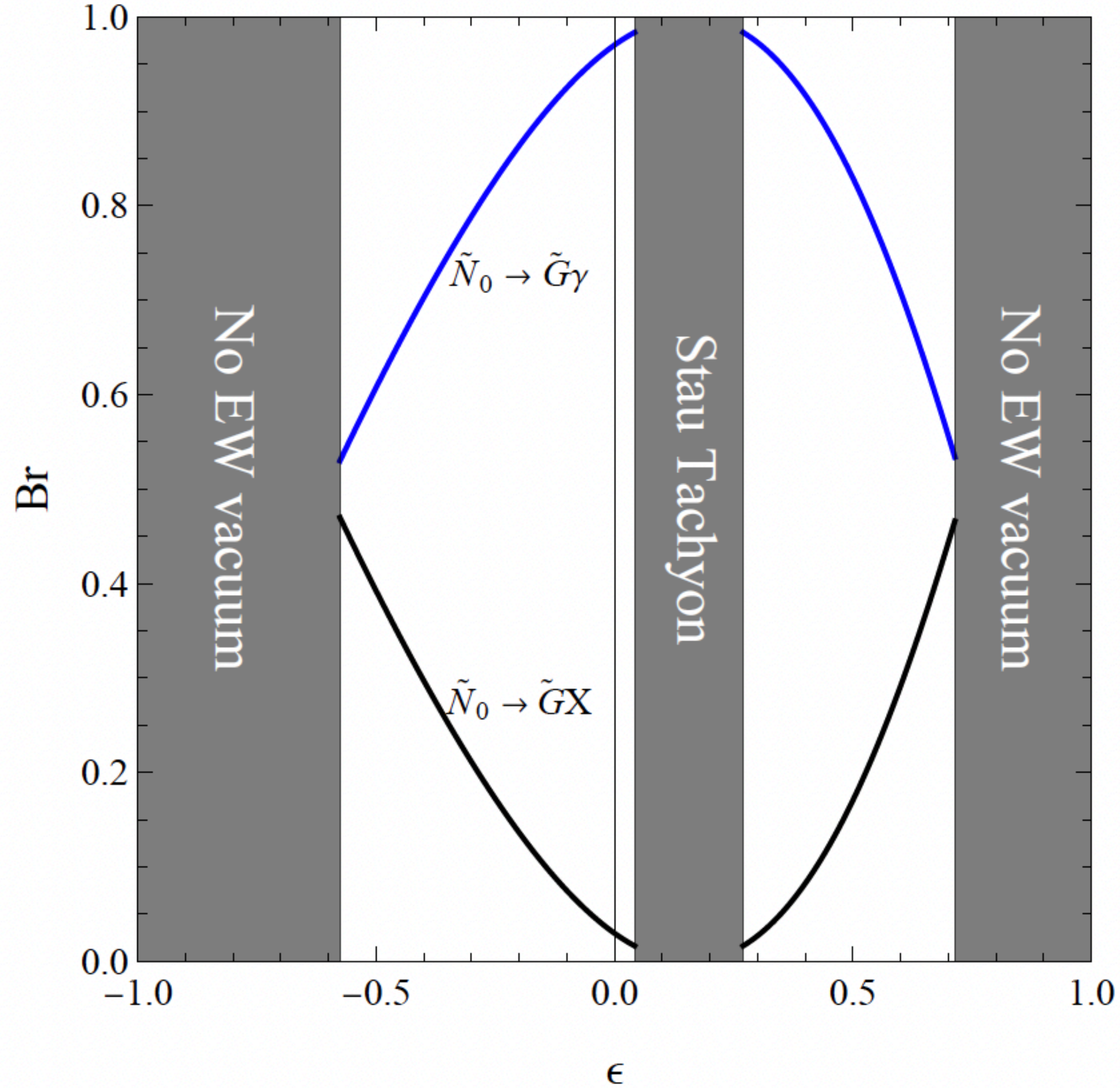
Dark GMSB Spectrums





NLSP ($\tilde{N}_0$) decay rate

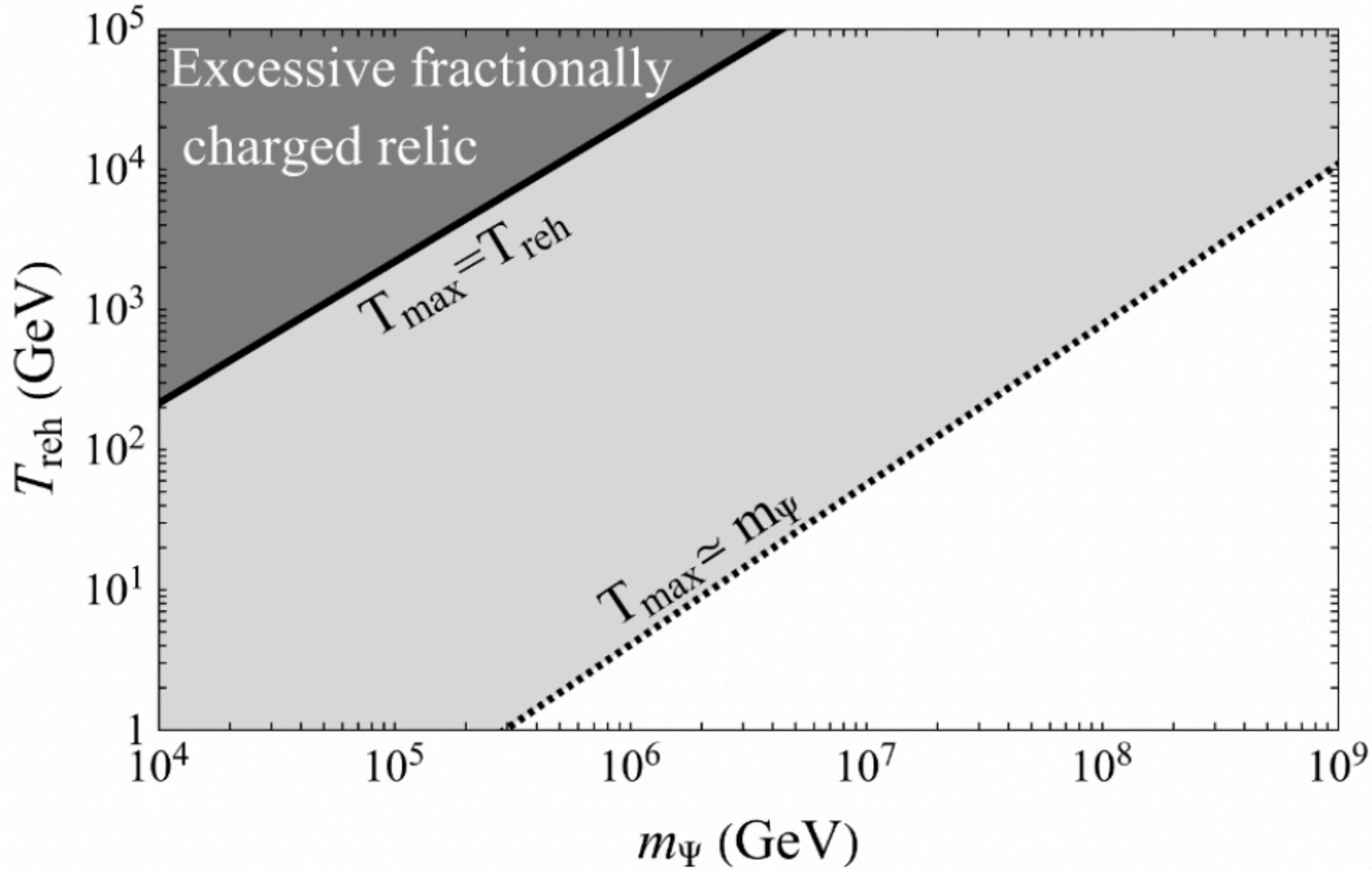




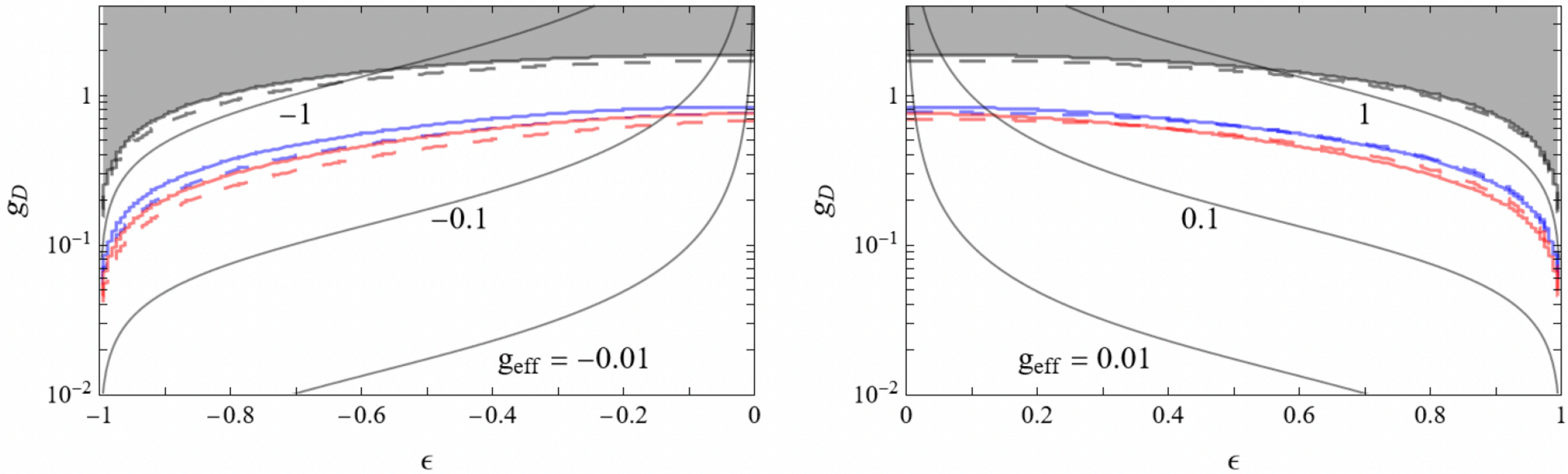
$$\Gamma(\tilde{N}_0 \to \tilde{G}X) = \frac{m^5_{\tilde{N}_0}}{16\pi F^2}|N_{0\tilde{X}}|^2,$$

$$\Gamma(\tilde{N}_0 \to \tilde{G}\gamma) = \frac{m^5_{\tilde{N}_0}}{16\pi F^2}|N_{0\tilde{B}}\cos\theta_W + N_{0\tilde{W}}\sin\theta_W|^2,$$

Reheating temperature vs lightest messenger mass



Landau poles constraints

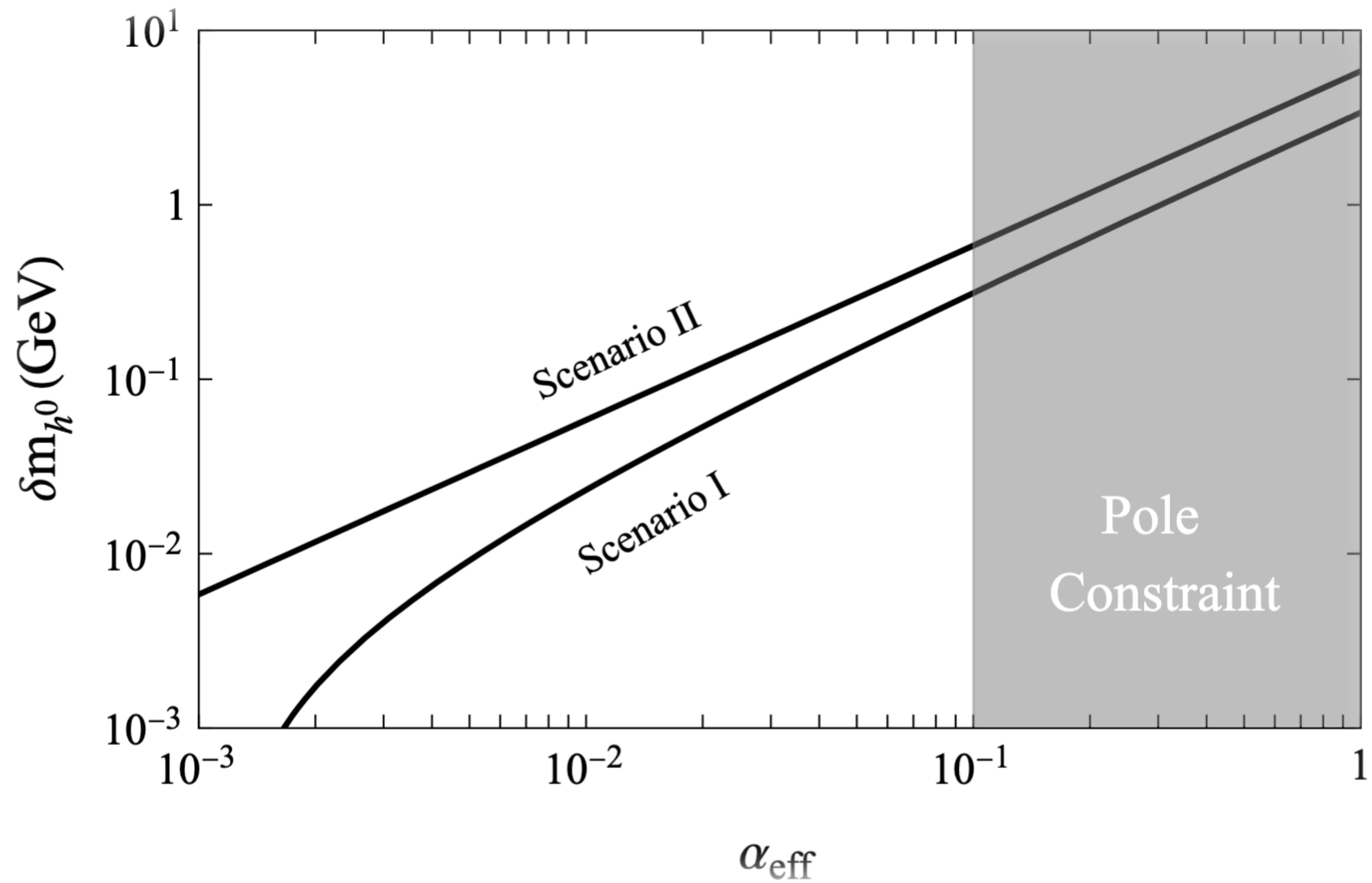


In the grey region, the Landau poles appear below 100 M_{mess}.

$$g_{\text{eff}} = g_D \epsilon / \sqrt{(1 - \epsilon^2)}.$$

Higgs mass

$$\delta m^2_{h^0}(g_{\rm eff}) \simeq \frac{17 m_t^4}{32\pi^2 v^2} \frac{\sum_\Psi N_{\rm U(1)} g_Y^2 g_{\rm eff} D_\Psi \left(-2 g_Y Y_\Psi + g_{\rm eff} D_\Psi\right)}{\sum_\Psi N_{\rm SU(3)} g_3^4}.$$



In the dark GMSB, light Higgs mass variation is less than O(0.1) GeV when considering constraints on g_D and ϵ from EWSB.