Dark Gauge-Mediated SUSY Breaking
with a Massless Dark Photon
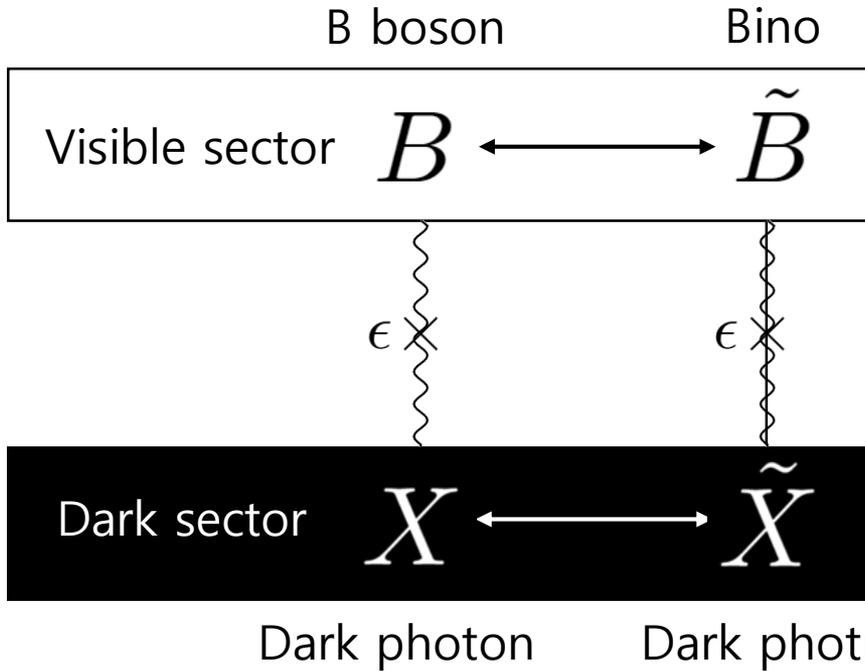
Yechan Kim
KAIST

Based on [arXiv:2412.17777]

Collaborated with Brian Batell[1], Hye-Sung Lee[2], Jiheon Lee[2]
[1]*University of Pittsburgh,* [2]*KAIST*

2025 CAU-IBS Beyond the Standard Model Workshop (Feb. 2025)

Kinetic mixing & SUSY

B boson   Bino

Visible sector $B \longleftrightarrow \tilde{B}$

$\epsilon \times$ $\epsilon \times$

Dark sector $X \longleftrightarrow \tilde{X}$

Dark photon   Dark photino

$$\mathcal{L} \supset \int d^2\theta \left(\frac{1}{4}\hat{\mathcal{W}}_B\hat{\mathcal{W}}_B + \frac{1}{4}\hat{\mathcal{W}}_X\hat{\mathcal{W}}_X + \frac{\epsilon}{2}\hat{\mathcal{W}}_B\hat{\mathcal{W}}_X \right)$$

$$= -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} - \frac{\epsilon}{2}B_{\mu\nu}X^{\mu\nu}$$

$$+ i\tilde{B}^\dagger\sigma^\mu\partial_\mu\tilde{B} + i\tilde{X}^\dagger\sigma^\mu\partial_\mu\tilde{X} + i\epsilon\tilde{B}^\dagger\sigma^\mu\partial_\mu\tilde{X}$$

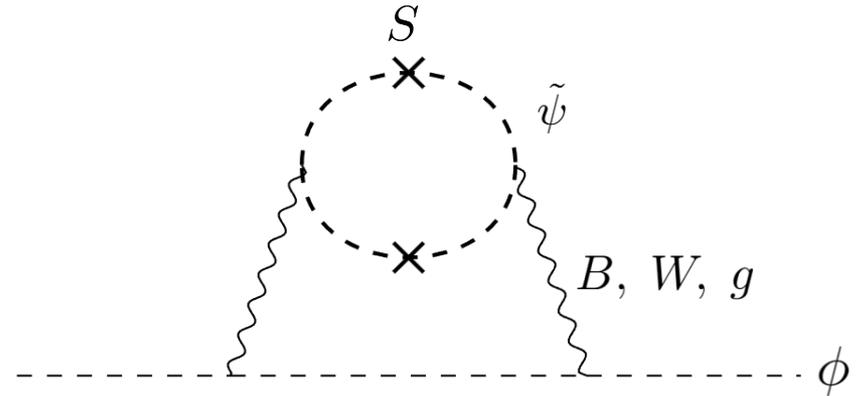**SUSY Kinetic mixing**

**Kinetic mixing
for SUSY breaking
transfer**

+

GMSB
(**G**auge-**M**ediated
SUSY **B**reaking)

=

"Dark GMSB"

GMSB vs Dark GMSB

(1) S (2) $\psi, \tilde{\psi}$ $U(1)_Y$, $SU(2)_L$, $SU(3)_C$ (3) $\tilde{B}, \tilde{W}, \tilde{g}, \phi$

| (1) SUSY sector | (2) Messenger | (3) Visible sector |

$\langle S \rangle = M + \theta^2 F$ $W = y\hat{S}\hat{\tilde{\Psi}}\hat{\Psi}$ SM charged

$$M_a \simeq \frac{g_a^2}{16\pi^2}\frac{F}{M}$$
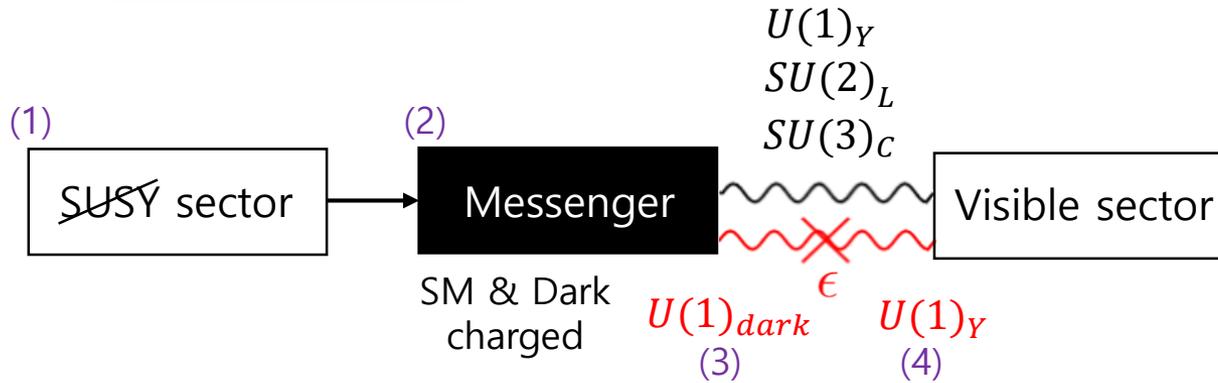
Gaugino soft mass

$$m_\phi^2 \simeq \sum_a \left(\frac{g_a^2}{16\pi^2}\right)^2 \left(\frac{F}{M}\right)^2$$

Scalar soft mass

3

GMSB vs Dark GMSB

$U(1)_Y$
$SU(2)_L$
$SU(3)_C$

(1)

| SUSY sector |

(2)

| Messenger |

SM & Dark charged

$U(1)_{dark}$
(3)

ϵ

$U(1)_Y$
(4)

| Visible sector |

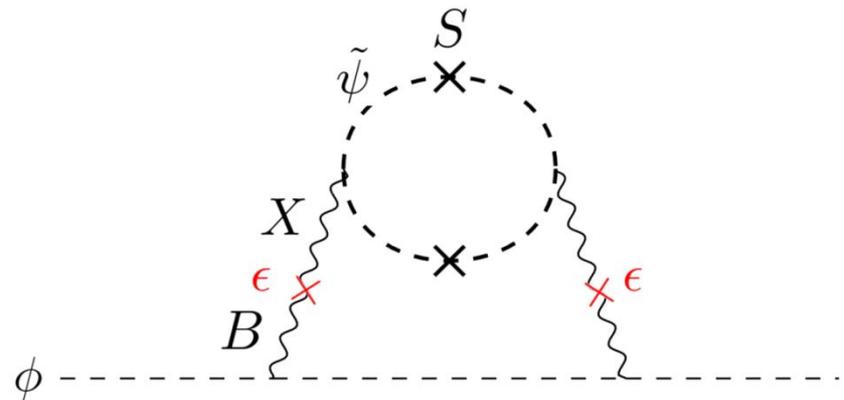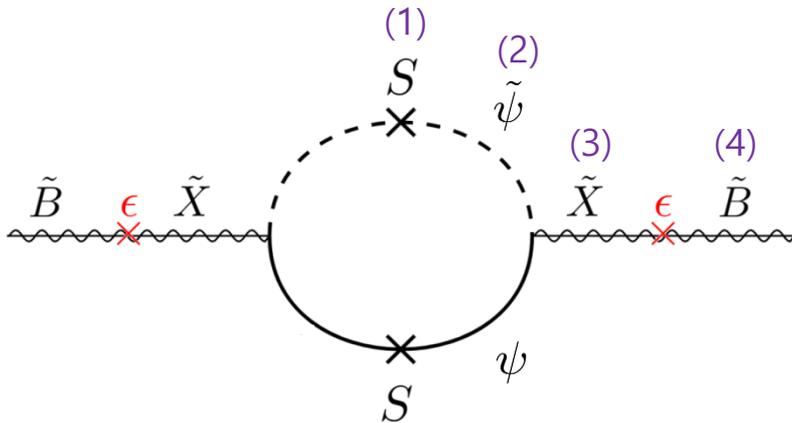Ex) $\hat{\Psi}_1 : (\mathbf{3}, 1, -1/3, D_\Psi)$

$\hat{\Psi}_2 : (1, \mathbf{2}, 1/2, D_\Psi)$

or

$\hat{\Psi} : (\mathbf{3}, \mathbf{2}, 1/6, D_\Psi)$

$$m_{\text{soft}}(\epsilon) \simeq \frac{g_{\text{eff}}^2(\epsilon)}{16\pi^2} \frac{F}{M}$$

ϵ-**dependent soft mass**

(1)   (2)   (3)   (4)

S $\tilde{\psi}$ $\tilde{X}$ $\tilde{B}$

$\tilde{B}$ ϵ $\tilde{X}$ ψ S

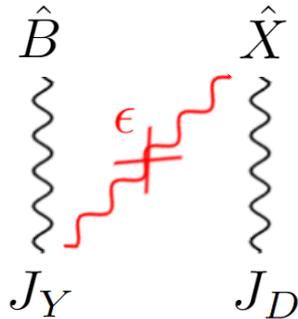$\tilde{\psi}$ S X ϵ B ϕ ϵ

Soft mass in Dark GMSB - Effective coupling

$$\mathcal{L}_{\text{kin}} \supset \int d^2\theta \left(\frac{1}{4}\hat{\mathcal{W}}_B \hat{\mathcal{W}}_B + \frac{1}{4}\hat{\mathcal{W}}_X \hat{\mathcal{W}}_X + \frac{\epsilon}{2}\hat{\mathcal{W}}_B \hat{\mathcal{W}}_X \right)$$
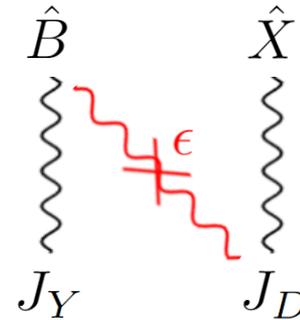
$$\rightarrow \int d^2\theta \left(\frac{1}{4}\hat{\mathcal{W}}_B \hat{\mathcal{W}}_B + \frac{1}{4}\hat{\mathcal{W}}_X \hat{\mathcal{W}}_X \right)$$

Kinetic term diagonalization by GL(2) transformation

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

Massive dark photon

Visible current   Dark current

Massless dark photon
(for large kinetic mixing)

$$\sin\omega = \epsilon, \quad \cos\omega = \sqrt{1-\epsilon^2}.$$

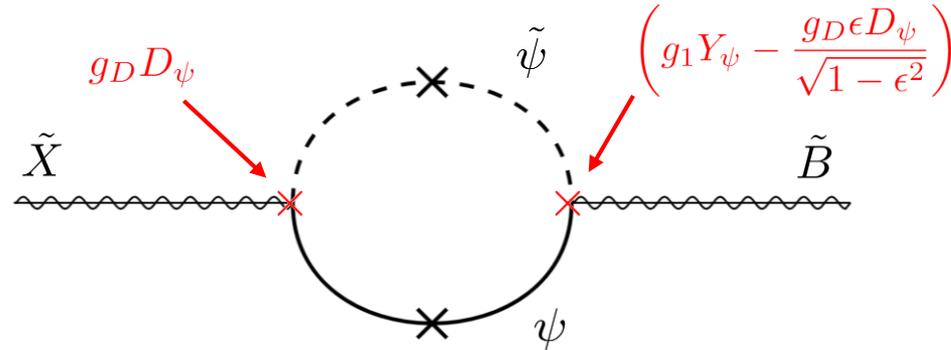$$\mathcal{L}_{\text{int}} \supset g_Y Y J_Y B + g_D D J_D X$$

$$\rightarrow \left[g_1 Y J_Y - \frac{g_D \epsilon}{\sqrt{1-\epsilon^2}} D J_D \right] B + g_D D J_D X$$

where $g_1 = g_Y / \sqrt{1-\epsilon^2}$

Soft mass in Dark GMSB - (1) Gaugino mass

$$\mathcal{L}_{\mathrm{int}} \supset \left[g_1 Y J_Y - \frac{g_D \epsilon}{\sqrt{1-\epsilon^2}} D J_D \right] B + g_D D J_D X$$
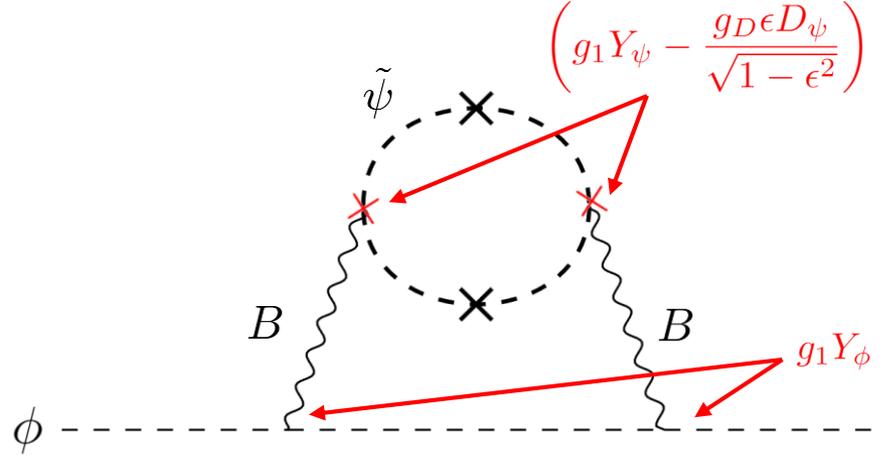

$$\mathcal{L} \supset M_D \tilde{X}\tilde{X} + 2 M_K \tilde{X}\tilde{B} + M_1 \tilde{B}\tilde{B}$$

$$M_D \simeq \frac{1}{16\pi^2} \frac{F}{M} g_D^2 D_\Psi^2$$

$$M_K \simeq \frac{1}{16\pi^2} \frac{F}{M} g_D D_\Psi \left(g_1 Y_\Psi - \frac{g_D \epsilon D_\Psi}{\sqrt{1-\epsilon^2}} \right)$$

$$M_1 \simeq \frac{1}{16\pi^2} \frac{F}{M} \left(g_1 Y_\Psi - \frac{g_D \epsilon D_\Psi}{\sqrt{1-\epsilon^2}} \right)^2$$

Soft mass in Dark GMSB - (2) Scalar soft mass

$$m_{\tilde{q}_L}^2 \simeq \left(\frac{1}{16\pi^2} \frac{F}{M} \right)^2 \left[\frac{2g_3^4}{3} + \frac{3g_2^4}{8} + g_1^2 Y_{\tilde{q}_L}^2 \left(g_1 Y_\Psi - \frac{g_D \epsilon D_\Psi}{\sqrt{1-\epsilon^2}} \right)^2 \right]$$

$$m_{\tilde{u}_R}^2 \simeq \left(\frac{1}{16\pi^2} \frac{F}{M} \right)^2 \left[\frac{2g_3^4}{3} + g_1^2 Y_{\tilde{u}_R}^2 \left(g_1 Y_\Psi - \frac{g_D \epsilon D_\Psi}{\sqrt{1-\epsilon^2}} \right)^2 \right]$$

$$m_{\tilde{d}_R}^2 \simeq \left(\frac{1}{16\pi^2} \frac{F}{M} \right)^2 \left[\frac{2g_3^4}{3} + g_1^2 Y_{\tilde{d}_R}^2 \left(g_1 Y_\Psi - \frac{g_D \epsilon D_\Psi}{\sqrt{1-\epsilon^2}} \right)^2 \right]$$

$$m_{H_i}^2 = m_{\tilde{\ell}_L}^2 \simeq \left(\frac{1}{16\pi^2} \frac{F}{M} \right)^2 \left[\frac{3g_2^4}{8} + g_1^2 Y_{\tilde{\ell}_L}^2 \left(g_1 Y_\Psi - \frac{g_D \epsilon D_\Psi}{\sqrt{1-\epsilon^2}} \right)^2 \right]$$

$$m_{\tilde{e}_R}^2 \simeq \left(\frac{1}{16\pi^2} \frac{F}{M} \right)^2 \left[g_1^2 Y_{\tilde{e}_R}^2 \left(g_1 Y_\Psi - \frac{g_D \epsilon D_\Psi}{\sqrt{1-\epsilon^2}} \right)^2 \right]$$

Soft mass in Dark GMSB - (3) Tachyonic sfermion for some ϵ

$$m_{\tilde{e}_R}^2 \simeq \left(\frac{1}{16\pi^2}\frac{F}{M}\right)^2 \left[g_1^2 Y_{\tilde{e}_R}^2 \boxed{\left(g_1 Y_\Psi - \frac{g_D \epsilon D_\Psi}{\sqrt{1-\epsilon^2}}\right)^2}\right]$$

Effective coupling

Scenario I - GUT complete representation

$$\hat{\Psi}_1 : (\mathbf{3}, 1, -1/3, D_\Psi)$$
$$\hat{\Psi}_2 : (1, \mathbf{2}, 1/2, D_\Psi)$$

Linear term of ϵ is canceled out
→ **Symmetric under $\epsilon \to -\epsilon$**

$$\frac{d}{dQ}X = \frac{1}{16\pi^2}\beta_X^{(1)} + \frac{1}{(16\pi^2)^2}\beta_X^{(2)}$$

$$\beta_{m_e^2}^{(1)} = (4m_{H_d}^2 + 2\mathbf{m}_e^2)\mathbf{Y}_e\mathbf{Y}_e^\dagger + 4\mathbf{Y}_e\mathbf{m}_L^2\mathbf{Y}_e^\dagger + 2\mathbf{Y}_e\mathbf{Y}_e^\dagger\mathbf{m}_e^2 + 4\mathbf{h}_e\mathbf{h}_e^\dagger$$
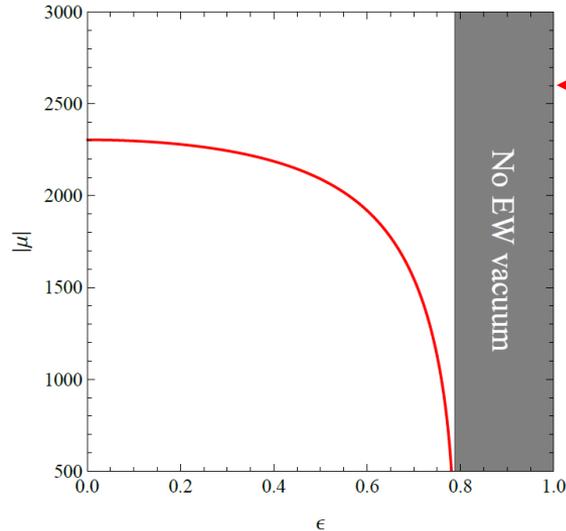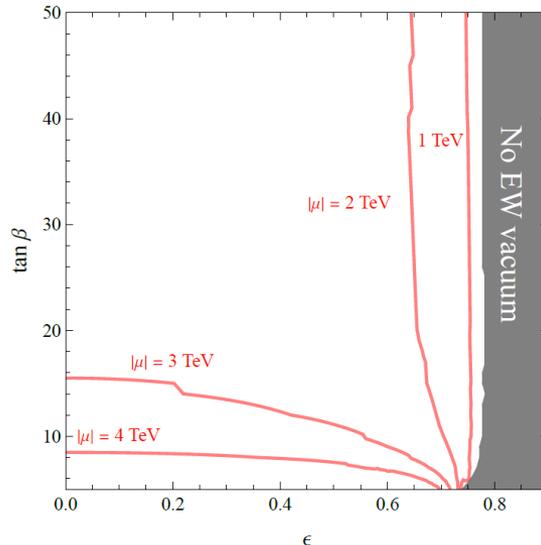
$$+ \frac{6g_1^2\mathcal{S}}{5} - \frac{24g_1^2}{5}(|M_1|^2 + |M_K|^2)$$

$$\mathcal{S} \equiv m_{H_u}^2 - m_{H_d}^2 + \mathrm{Tr}[\mathbf{m}_Q^2 - 2\mathbf{m}_u^2 + \mathbf{m}_d^2 - \mathbf{m}_L^2 + \mathbf{m}_e^2]$$

Scenario II - GUT incomplete representation
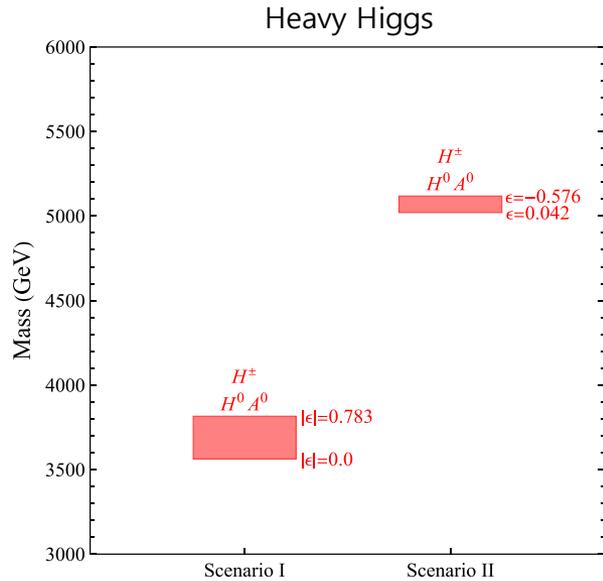
$$\hat{\Psi} : (\mathbf{3}, \mathbf{2}, 1/6, D_\Psi)$$

Linear term of ϵ is remained
→ **Effective coupling vanishes at specific ϵ**

RG running

RH slepton (like stau) can be tachyon around specific value of ϵ

Soft mass in Dark GMSB - (4) No EWSB for large ϵ

$M_1(\epsilon), M_K(\epsilon)$ effect in RG beta function

$$m_{H_i}^2 \simeq \left(\frac{1}{16\pi^2}\frac{F}{M}\right)^2 \left[\frac{3g_2^4}{8} + g_1^2 Y_{\tilde{\ell}_L}^2 \left(g_1 Y_\Psi - \frac{g_D \epsilon D_\Psi}{\sqrt{1-\epsilon^2}}\right)^2\right]$$

$$\beta_{m_{H_u}^2}^{(1)} = 6\mathrm{Tr}[(m_{H_u}^2 + \mathbf{m}_Q^2)\mathbf{Y}_u^\dagger \mathbf{Y}_u + \mathbf{Y}_u^\dagger \mathbf{m}_u^2 \mathbf{Y}_u + \mathbf{h}_u^\dagger \mathbf{h}_u] - 6g_2^2|M_2|^2$$

$$+ \frac{3g_1^2 \mathcal{S}}{5} - \frac{6g_1^2}{5}(|M_1|^2 + |M_K|^2)$$

$$\mathcal{S} \equiv m_{H_u}^2 - m_{H_d}^2 + \mathrm{Tr}[\mathbf{m}_Q^2 - 2\mathbf{m}_u^2 + \mathbf{m}_d^2 - \mathbf{m}_L^2 + \mathbf{m}_e^2]$$

RG running

$$|\mu(\epsilon)|^2 = -\frac{m_Z^2}{2} - \frac{m_{H_u}^2(\epsilon) + m_{H_d}^2(\epsilon)}{2} + \frac{m_{H_u}^2(\epsilon) - m_{H_d}^2(\epsilon)}{2\cos(2\beta)}$$

μ-term has ϵ-dependence to satisfy EWSB condition.

For large ϵ, EWSB condition cannot be satisfied

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

9

Soft mass in Dark GMSB - **Comparison between Scenarios I/II**

Scenario I - GUT complete representation

$$\hat{\Psi}_1 : (\mathbf{3}, 1, -1/3, D_\Psi)$$
$$\hat{\Psi}_2 : (1, \mathbf{2}, 1/2, D_\Psi)$$

Symmetric under $\epsilon \to -\epsilon$

$$\tilde{e}_R < \tilde{e}_L \qquad \tilde{e}_R > \tilde{e}_L$$

More sensitive to ϵ for large hypercharge $\longrightarrow$ RH/LH sfermion mass hierarchy can be swapped

$$Y_{\tilde{\ell}_L} < Y_{\tilde{e}_R}$$

Scenario II - GUT incomplete representation

$$\hat{\Psi} : (\mathbf{3}, \mathbf{2}, 1/6, D_\Psi)$$

Maximum at $\epsilon = -0.576$

Stau tachyon for some ϵ
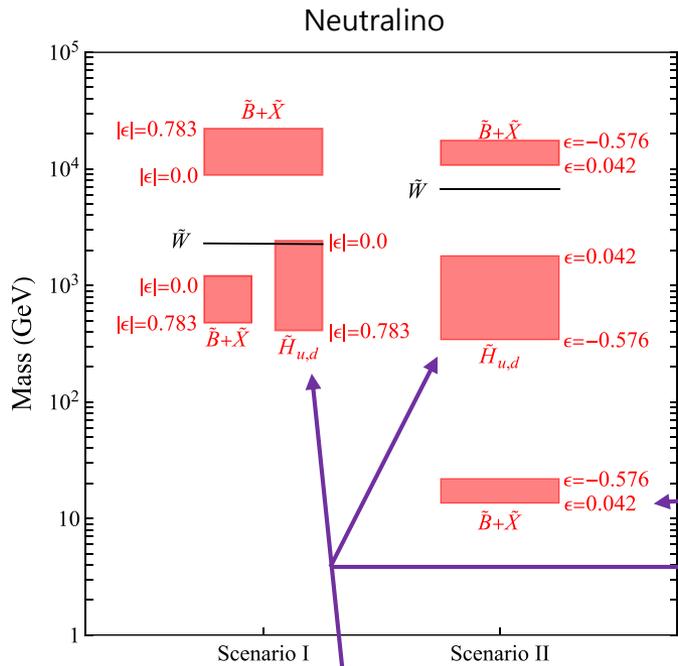

Minimum at $\epsilon = 0.042$

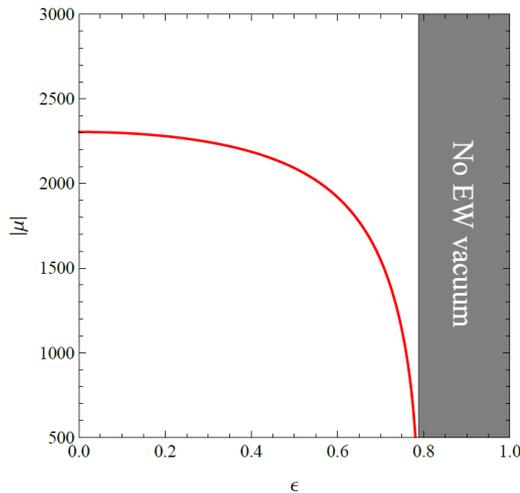# Mass spectrum - (1) Higgs & Sfermion sectors

More sensitive to ϵ
for large hypercharge

$$Y_{\tilde{q}_L} < Y_{\tilde{d}_R} < Y_{\tilde{\ell}_L} = Y_H < Y_{\tilde{u}_R} < Y_{\tilde{e}_R}$$

11

Mass spectrum - **(2) Neutralino & Chargino sectors**

Neutralino

Chargino

ϵ-dependent Higgsino

Dark photino-Bino submatrix
has zero determinant in Scenario II

$$\mathbf{M}_{\tilde{N}} = \begin{pmatrix} M_D & M_K(\epsilon) & 0 & 0 & 0 \\ M_K(\epsilon) & M_1(\epsilon) & 0 & -c_\beta s_W m_Z & s_\beta s_W m_Z \\ 0 & 0 & M_2 & c_\beta c_W m_Z & -s_\beta c_W m_Z \\ 0 & -c_\beta s_W m_Z & c_\beta c_W m_Z & 0 & -\mu \\ 0 & s_\beta s_W m_Z & -s_\beta c_W m_Z & -\mu & 0 \end{pmatrix}$$
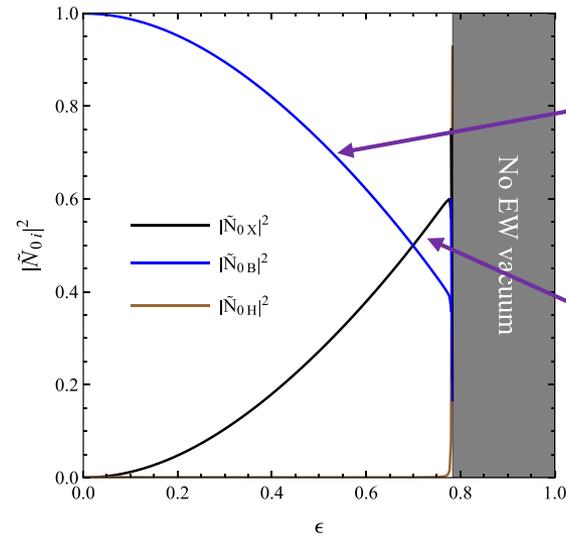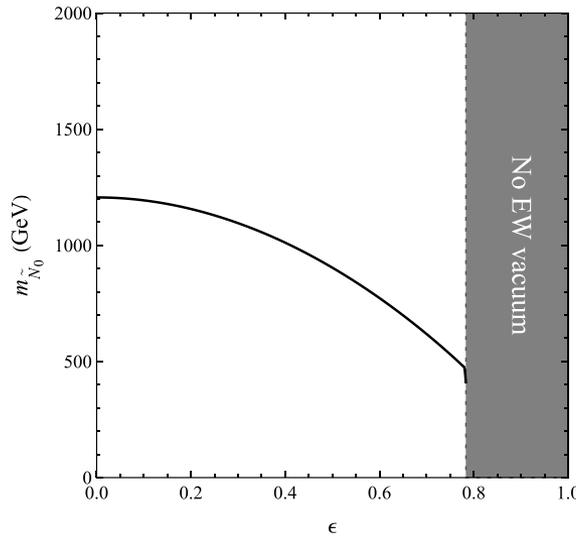
12

Mass spectrum - The lightest neutralino

Scenario I

Scenario II

$\tilde{B} + \tilde{X}$
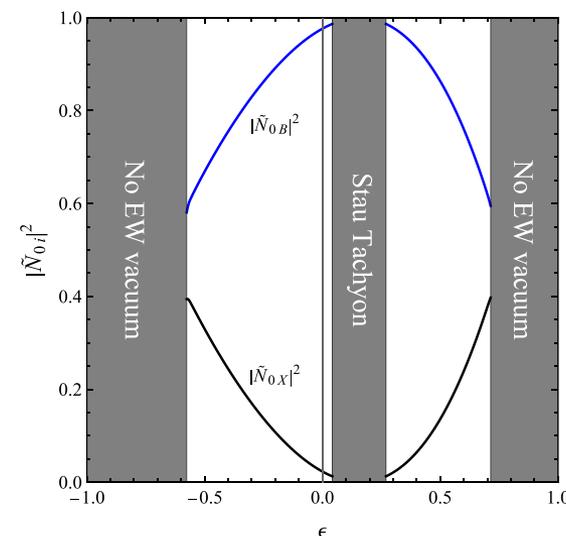
$\tilde{N}_0$

Bino-dominant

Dark photino-dominant

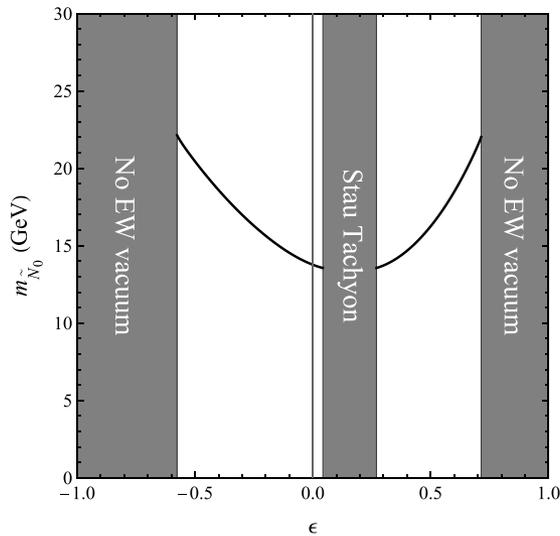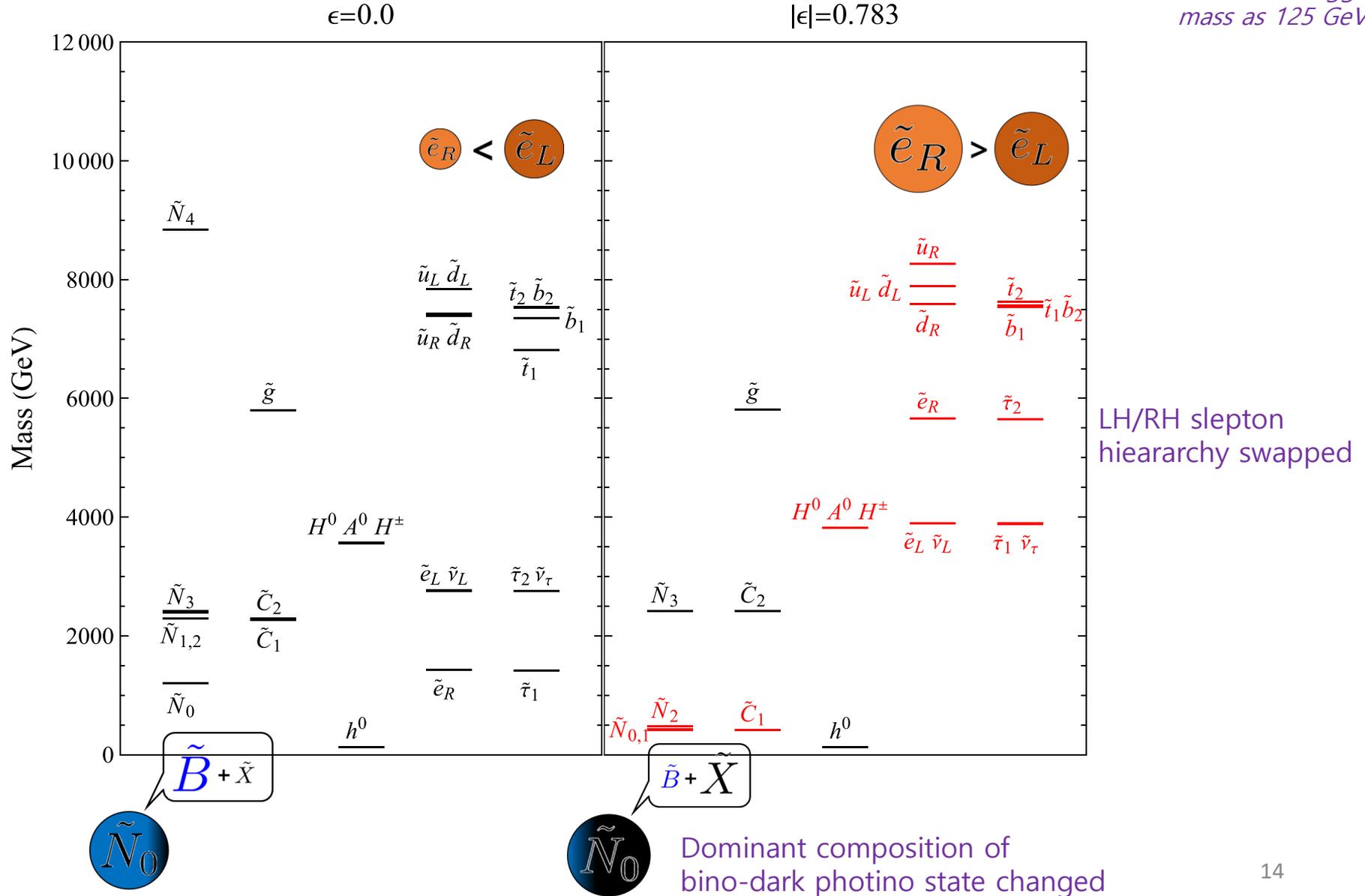$\tilde{B} + \tilde{X}$

$\tilde{\tilde{N}}_0$

$$|\tilde{N}_{0X}| : |\tilde{N}_{0B}| \simeq |M_K(\epsilon)| : |M_D| = \left| g_1 Y_\Psi - \frac{g_D \epsilon D_\Psi}{\sqrt{1-\epsilon^2}} \right| : |g_D D_\Psi|$$

Neutralino composition depends on ϵ

13

Mass spectrum - **Complete representation**

Parameters to fit SM-Higgs mass as 125 GeV

$\epsilon=0.0$

$|\epsilon|=0.783$

$\tilde{e}_R < \tilde{e}_L$

$\tilde{e}_R > \tilde{e}_L$

Mass (GeV)

LH/RH slepton hieararchy swapped

Dominant composition of bino-dark photino state changed

14

Mass spectrum - **Incomplete representation**

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

Parameters to fit SM-Higgs mass as 125 GeV

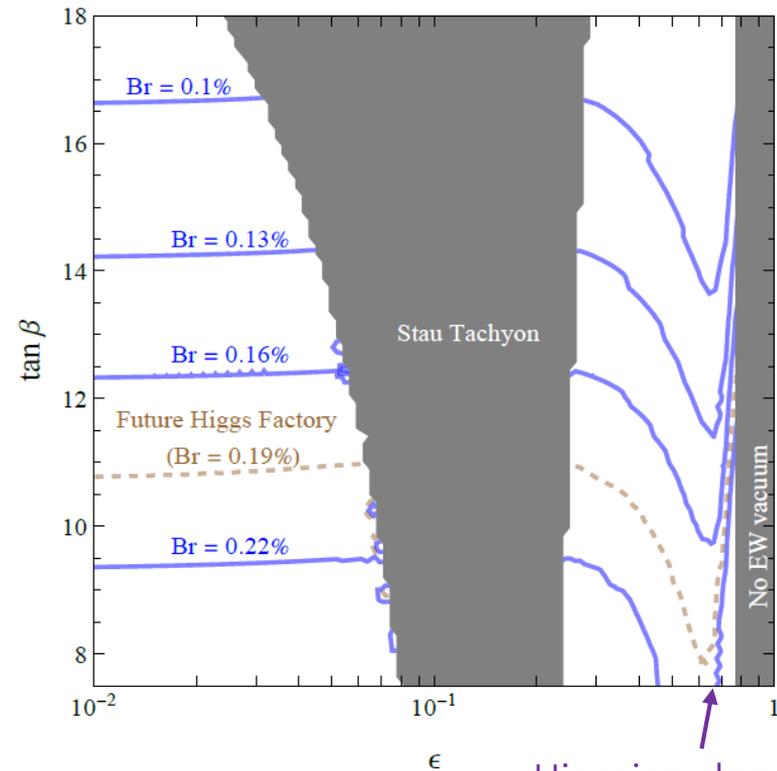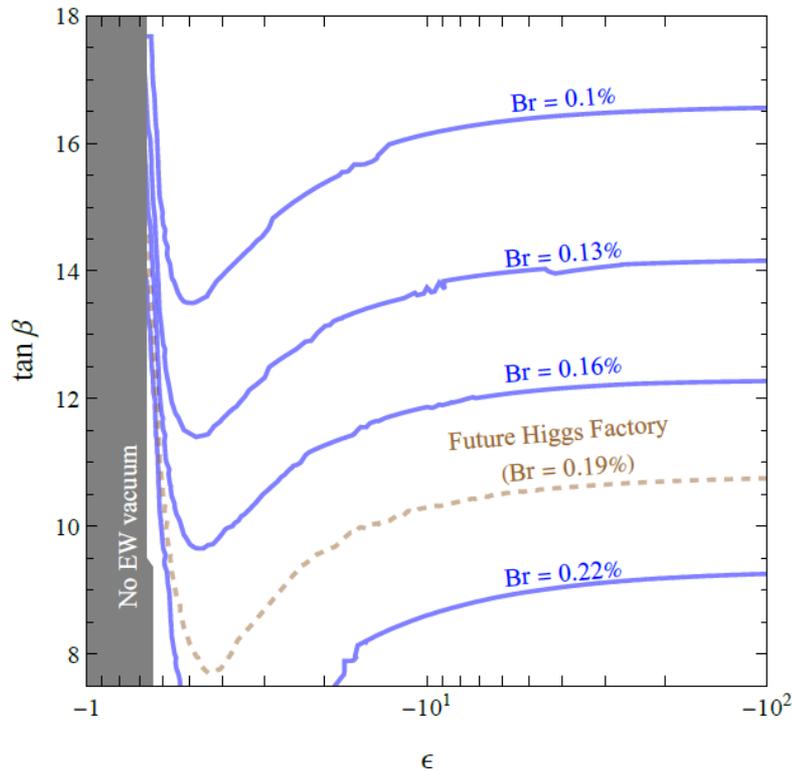The lightest neutralino
(bino-dark photino mixture)
w/ suppressed mass

Phenomenology - **Higgs decay**

This may contributes
the invisible Higgs decay width!

$h^0 \to \tilde{N}_0 \tilde{N}_0$ in Scenario II with suppressed mass of the lightest neutralino

$$\Gamma(h^0 \to \tilde{N}_0 \tilde{N}_0) = \frac{g_2^2 m_{h^0}}{16\pi} \left(1 - \frac{4m_{\tilde{N}_0}^2}{m_{h_0}^2}\right)^{3/2} \left|(\tilde{N}_{0W} - \tilde{N}_{0B}\tan\theta_W)(\underline{\tilde{N}_{0H_u}\cos\alpha + \tilde{N}_{0H_d}\sin\alpha})\right|^2$$

This term is large
For small tan β

Higgsino-dominant
for large $|\epsilon|$

16

Phenomenology - NLSP decay to Gravitino $\quad m_{3/2} \simeq \dfrac{F}{\sqrt{3}M_{\rm Pl}} \quad \sim$ few eV

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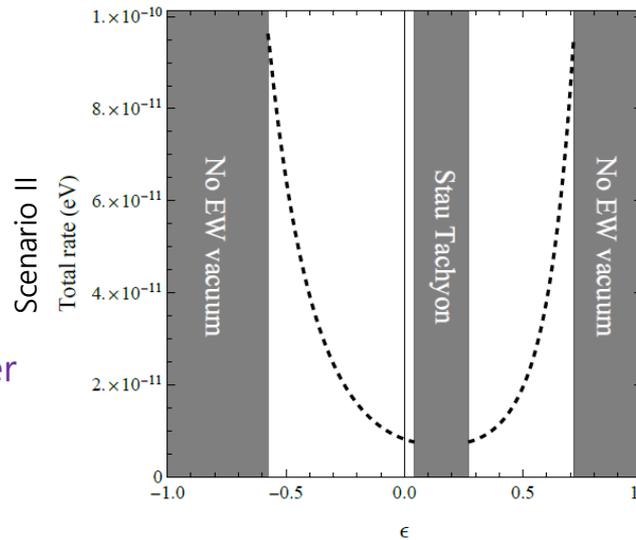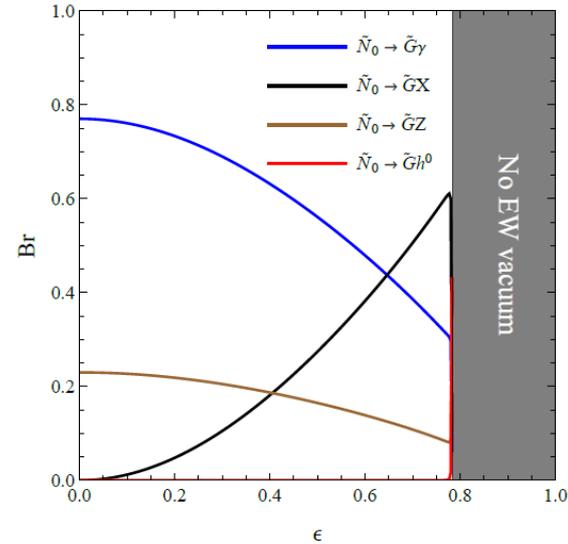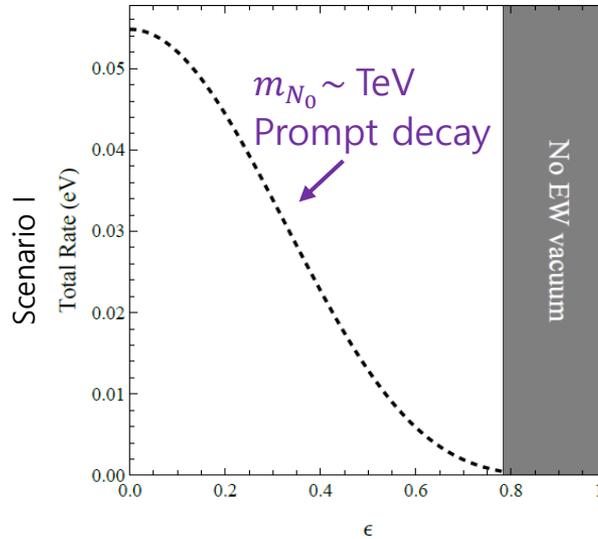
$$\Gamma(\tilde{N}_0 \to \tilde{G}X) = \frac{m_{\tilde{N}_0}^5}{16\pi F^2} |N_{0\tilde{X}}|^2,$$

$$\Gamma(\tilde{N}_0 \to \tilde{G}Z) = \frac{m_{\tilde{N}_0}^5}{16\pi F^2}\left(1 - \frac{m_Z^2}{m_{\tilde{N}_0}^2}\right)^4$$
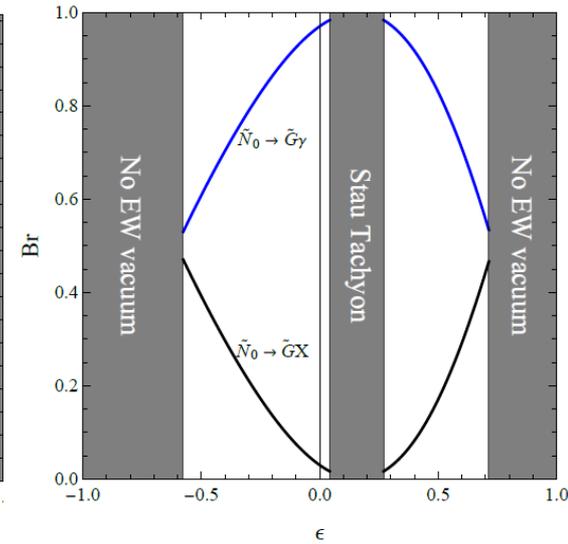$$\times\left(|N_{0\tilde{B}}\sin\theta_W - N_{0\tilde{W}}\cos\theta_W|^2\right.$$
$$\left. + \frac{1}{2}|N_{0\tilde{H}_d}\cos\beta - N_{0\tilde{H}_u}\sin\beta|^2\right)$$

$$\Gamma(\tilde{N}_0 \to \tilde{G}h^0) = \frac{m_{\tilde{N}_0}^5}{32\pi F^2}\left(1 - \frac{m_{h^0}^2}{m_{\tilde{N}_0}^2}\right)^4$$
$$\times |N_{0\tilde{H}_d}\sin\alpha - N_{0\tilde{H}_u}\cos\alpha|^2.$$

$m_{N_0} \sim$ TeV
Prompt decay

$m_{N_0} \sim$ GeV
Out-of-collider decay

17

Remarks - Cosmology

Possible DM candidates are…

(1) Gravitino

Gravitino problem with over-abundance still exists in dark GMSB like typical scenario.

Low reheating temperature (~ TeV) or dilution process is required.
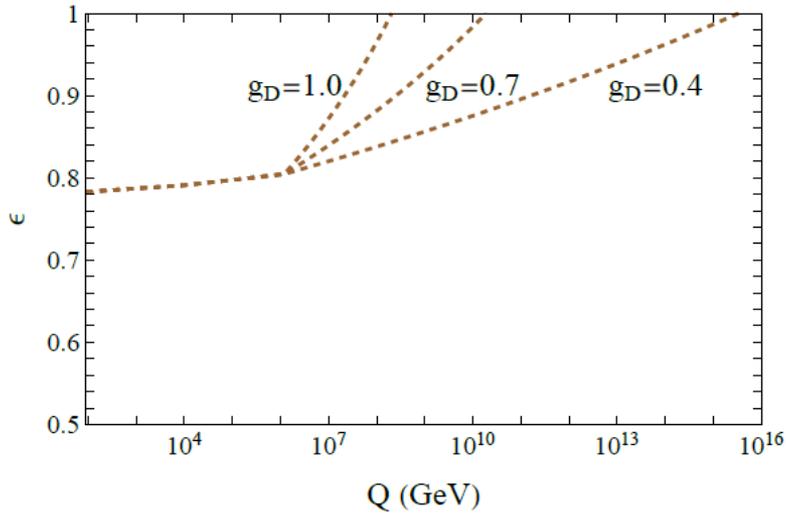
(2) Messenger

The lightest messenger particle charged under dark gauge is stable.

It may get the fractionally charge particle constraint (also low reheat temperature required).
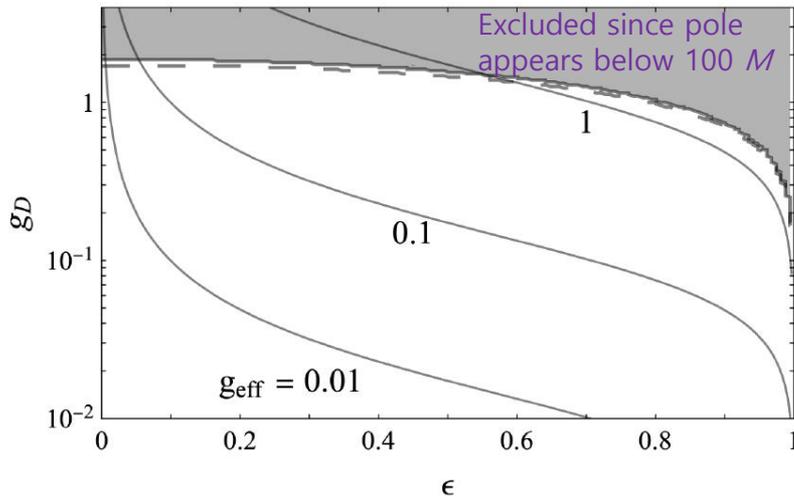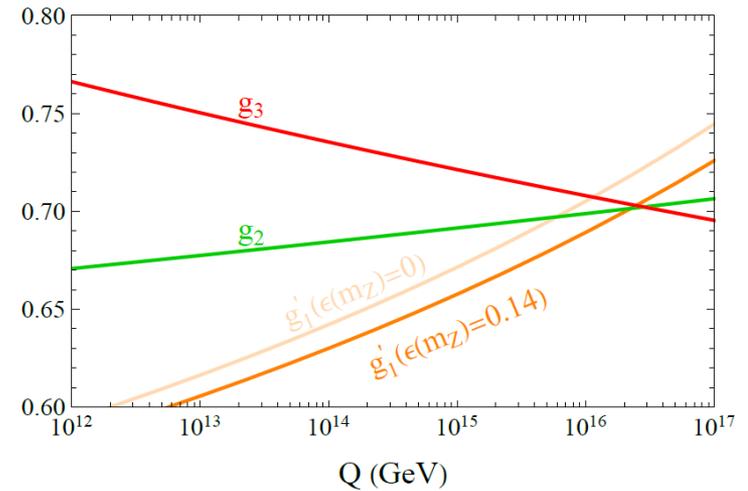
(3) Dark photon

Massless dark photon is isolated from the visible sector (only interact with messenger).

For low reheating temperature or heavy messenger, the production is suppressed.

As a result, the dark photon does not contribute N_{eff} almost.

Remarks - RG running

Too large g_D, ϵ may induce pole

$g_D=1.0$ $g_D=0.7$ $g_D=0.4$

ϵ

Q (GeV)

ϵ may help gauge coupling unification

g_3

g_2

$g_1'(\epsilon(m_Z)=0)$

$g_1'(\epsilon(m_Z)=0.14)$

Q (GeV)
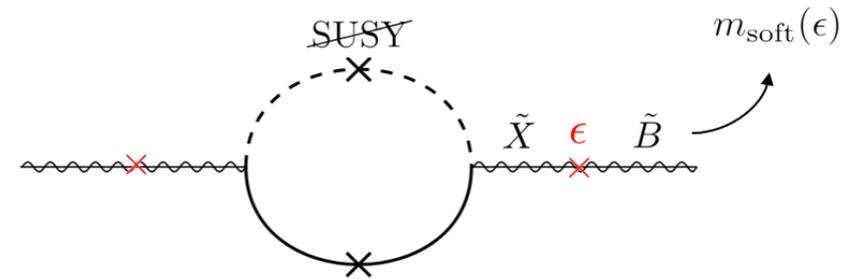

Excluded since pole appears below 100 M

1

0.1

$g_{eff} = 0.01$

g_D

ϵ

- ➤ RG running evaluation by SOFTSUSY 4.1.20 with modification/addition of beta function from new dark sector parameters.

Summary

"Dark GMSB"

➢ Supersymmetric kinetic mixing can be a new method of SUSY breaking transfer. As a result, the mass spectrum get the dependence on the new variables (g_D and ϵ) of dark sector. We call this **"Dark GMSB"**.

➢ EWSB condition cannot be satisfied in large ϵ due to the modified RG beta function. Besides, stau can become tachyonic if the effective coupling vanishes around specific value of ϵ.

➢ Scalar particle mass is more sensitive to ϵ if it has large hypercharge, so the mass hierarchy between LH/RH sfermion can be swapped.

➢ Dominant composition of dark photino-bino mixture neutralino state is swapped at the critical value of ϵ.

➢ The Higgs can decay to the lightest neutralino with suppressed mass, and this can be tested by the future Higgs factory.