Syndetic Extension of B and L Numbers

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Exploration of Particle Physics and Cosmology with Neutrinos Workshop

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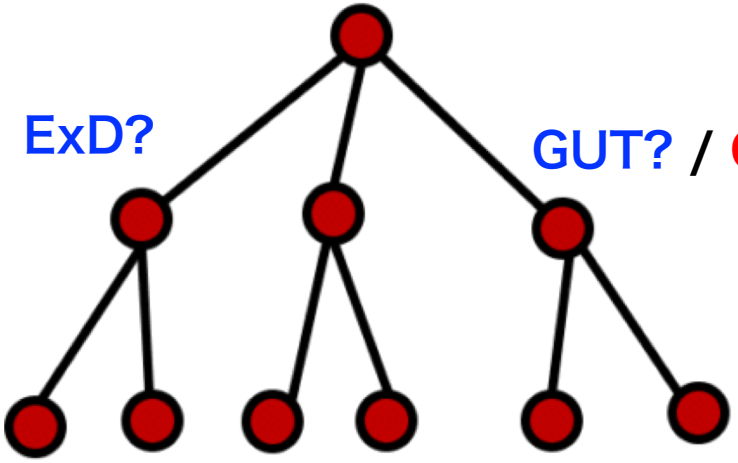
*"Syndetic Extension of Baryon and Lepton Numbers: **Proton Decay** and Long-Lived Dark Matter"*

E. Ma, K. Tsumura, Phys. Rev. D98, 035037 (2018), arXiv:1805.05056 [hep-ph]

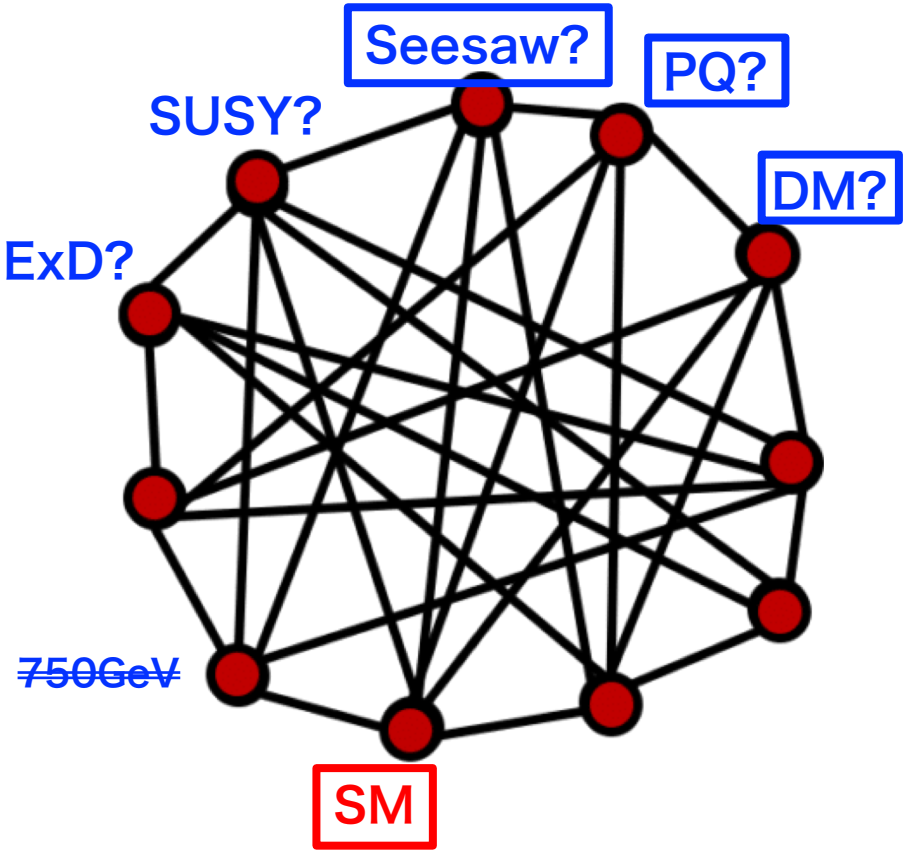
Top-down / Bottom-up

String Th. / Quantum Gravity



"Top-down"

Philosophical ➔ Big Picture



"Bottom-up"

Practical ➔ Exp. Friendly

Symmetries of SM (BSM)

Symmetries of SM

- Renormalizable level :

$$\mathcal{L}_{\rm SM} = \mathcal{L}_{\rm quark} + \mathcal{L}_{\rm lepton} + \cdots$$

Symmetries : B# (Baryon Number), L# (Lepton Number)

$$\begin{cases} Q \to e^{i\theta_{\rm B}/3} Q \\ u_R \to e^{i\theta_{\rm B}/3} u_R \\ d_R \to e^{i\theta_{\rm B}/3} d_R \end{cases} \qquad \begin{cases} L \to e^{i\theta_{\rm L}} L \\ e_R \to e^{i\theta_{\rm L}} e_R \end{cases}$$

- Quantum level : “B-L” (~~B#~~, ~~L#~~)
- Non-renormalizable level ? (BSM effect)

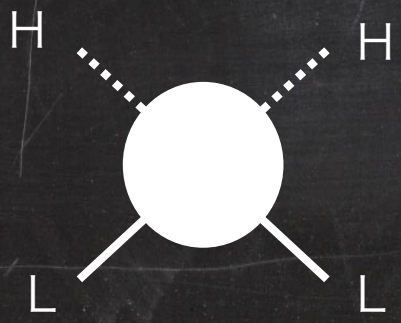
L#V operator

Non-renormalizable ops. after integrating heavy d.o.f.

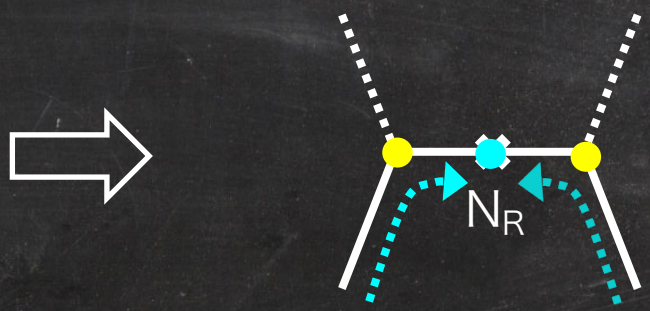
$$\mathcal{O}_5 = \overset{(1,2)_{-1/2}}{L}\,L\,H\,\overset{(1,2)_{+1/2}}{H}$$

L#V (Lepton Number Violation)

Unknown UV completion



Well known example of UV completion



$$\mathcal{L} = Y_N \overline{L}\widetilde{\Phi} N_R + \frac{1}{2} M_N \overline{N}^c_R N_R + \text{H.c}$$

Define L# of N_R **L#V by M_N**

L#V operator

Non-renormalizable ops. after integrating heavy d.o.f.

$$\mathcal{O}_5 = LLHH$$

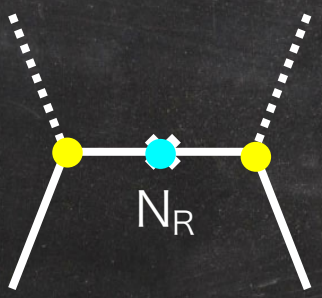
$$M_\nu = \frac{1}{\Lambda} v_{\rm EW}^2 = \frac{Y_N^2}{M_N} v_{\rm EW}^2$$

Seesaw Scale : Λ = $10^{9\sim13}$ GeV

$$\mathcal{L} = \frac{1}{\Lambda}\mathcal{O}_5$$

$$\Rightarrow \mathcal{L}_{\rm eff} = \frac{1}{2} M_\nu \overline{\nu_L^c} \nu_L$$

Type- I Seesaw



Unknow NP predicts
L#V Mass of Majorana ν

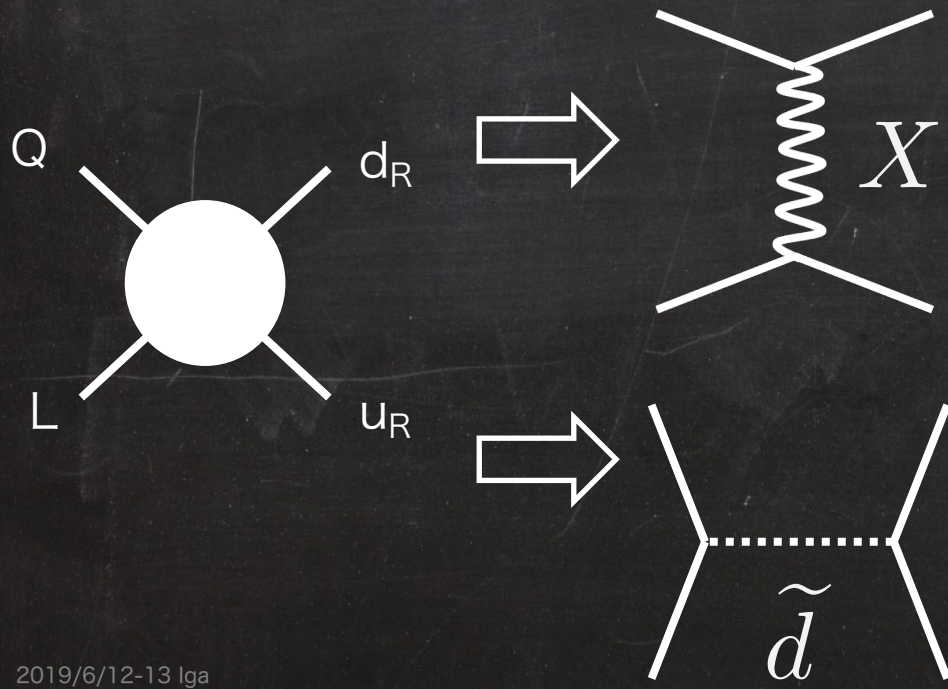
$$\mathcal{L} = Y_N \overline{L}\widetilde{\Phi} N_R + \frac{1}{2} M_N \overline{N}_R^c N_R + \text{H.c}$$

B#V and L#V operators

Non-renormalizable ops. after integrating heavy d.o.f.

$$\mathcal{O}_6 = \overline{u_R^c}\,\overline{d_R^c}\,Q L, \cdots$$

$(3,1)_{+2/3}$ $(3,2)_{+1/6}$ $(3,1)_{-1/3}$



Grand Unified Theory

R-parity violating SUSY

Symmetries of BSM

Non-renormalizable ops. after integrating heavy d.o.f.

	L#	B#
$\mathcal{O}_5 = LLHH$	× 2	○
$\mathcal{O}_6 = \overline{u_R^c}\,\overline{d_R^c} Q L, \cdots$	× 1	× 1
$\mathcal{O}_7 = u_R d_R d_R L^c H^c, \cdots$	× -1	× 1

BSM breaks B# and L# in general

→ B# and L# are accidental symmetries in the SM

Symmetries of BSM

Non-renormalizable ops. after integrating heavy d.o.f.

$$\mathcal{O}_5 = LLHH$$

"B" conservation

"L" violation

$$\mathcal{O}_6 = \overline{u_R^c}\,\overline{d_R^c} Q L, \cdots$$

"B-L" conservation

"B" and "L" violation

$$\mathcal{O}_7 = u_R d_R d_R L^c H^c, \cdots$$

"B+L" conservation

"B" and "L" violation

BSM still respects symmetries

Signal of BSM

⇨ 0ν2β (M_ν)

$$\mathcal{O}_5 = LLHH$$

"B" conservation

"L" violation

$$\mathcal{O}_6 = \overline{u_R^c d_R^c} QL, \cdots$$

"B-L" conservation

"B" and "L" violation

⇨ Proton decay

$$\mathcal{O}_7 = u_R d_R d_R L^c H^c, \cdots$$

"B+L" conservation

"B" and "L" violation

⇨ Proton decay

Proton decays

B-L conserving

$$-\frac{1}{\Lambda^2}(\overline{u^c}\,\gamma^\mu\,Q)(\overline{d^c}\,\gamma_\mu\,L)$$

Effective Int.

$$p \to \pi^0 e^+$$

$$p \to \pi^+ \bar{\nu}$$

Decay modes

$$\tau_p \simeq \frac{\Lambda^4}{m_p^5}$$

Life time

$\propto \Lambda^4$, $\Lambda > 10^{15}$GeV

B+L conserving

$$\frac{1}{\Lambda^3}(\overline{u^c}\,\gamma^\mu\,u)(\overline{d^c}\,\gamma_\mu\,L^c)H$$

$$p \to \pi^+ \nu$$

No charged lepton mode

$$\tau_p \simeq \frac{\Lambda^6}{v^2\,m_p^5}$$

$\propto \Lambda^6$, longer life time by Λ^2/v^2

or Lower New Physics Scale :
(roughly) $\Lambda > 10^{10}$GeV

A Model of B+L conserving proton decay

B-L conserving

$$-\frac{1}{\Lambda^2}(\overline{u^c}\,\gamma^\mu\,Q)(\overline{d^c}\,\gamma_\mu\,L)$$

$$p \to \pi^0 e^+$$

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$$\tau_p \simeq \frac{\Lambda^4}{m_p^5}$$

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Effective Int.

Decay modes

Life time

B+L conserving

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PQ symmetry and B#

Strong CP problem can be solved by PQ sym.

PQ scale > 10^{12} GeV

(Ambiguity in B# assignment for new particles)

Strong CP Problem

Why does QCD conserve CP ?

$$\mathcal{L}_{\rm QCD} = -\frac{1}{4} G_a^{\mu\nu} G^a_{\mu\nu} - \theta \, \frac{\alpha_s}{8\pi} \, G_a^{\mu\nu} \tilde{G}^a_{\mu\nu}$$

CP violation allowed

$$+ \sum_q \bar{q} \left(i \not{D} - M_q e^{i \gamma_5} \right) q$$

$$\bar{\theta} = \theta - \sum_q \theta_q \qquad \begin{cases} q_L \to e^{-i\,\theta_q/2}\, q_L \\ q_R \to e^{i\,\theta_q/2}\, q_R \end{cases}$$

Unnaturally small :

$$d_n/e \sim 10^{-15}\, \bar{\theta} < 1.9 \times 10^{-26} \qquad (\bar{\theta} \lesssim 10^{-11})$$

PQ symmetry

Why does QCD conserve CP ?

$$\mathcal{L}_{\rm QCD} = -\frac{1}{4} G_a^{\mu\nu} G^a_{\mu\nu} - \theta \frac{\alpha_s}{8\pi} G_a^{\mu\nu} \tilde{G}^a_{\mu\nu}$$

CP violation allowed

$$+ \sum_q \bar{q} \left(i \not{D} - Y \phi \, e^{i\theta_q} \right) q$$

$$\phi \to e^{-i\,\theta_q} \phi \qquad \begin{cases} q_L \to e^{-i\,\theta_q/2}\, q_L \\ q_R \to e^{i\,\theta_q/2}\, q_R \end{cases}$$

Mass M is replaced by complex scalar

→ Enhanced Chiral Symmetry

PQ symmetry

Solution to Strong CP

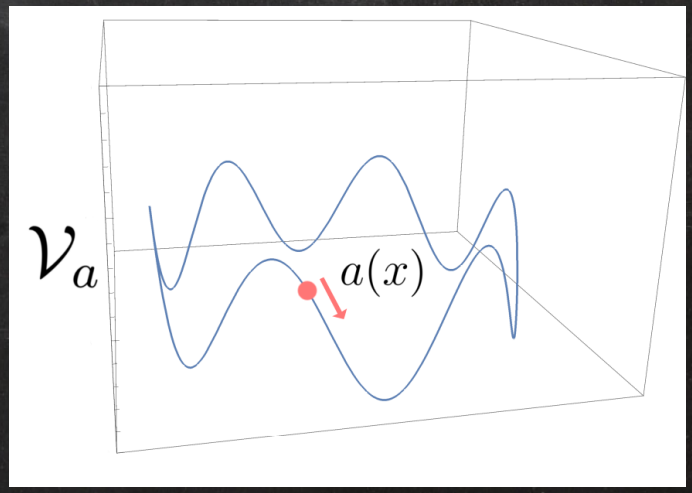
Dynamical fine-tuning by pNGB (axion)

$$\phi(x) = \left(f_a + \sigma(x) \right) e^{i\, a(x)/f_a}$$

Effective Lagrangian

$$\mathcal{L}_a = -\frac{1}{2}\partial_\mu a\, \partial^\mu a - \left(\overline{\theta} - a/f_a\right) \frac{\alpha_s}{8\pi} G_a^{\mu\nu} \widetilde{G}^a_{\mu\nu} + f_a^2 m_a^2 \left[1 - \cos\left(\overline{\theta} - a/f_a\right)\right]$$

$$\langle a \rangle / f_a = \overline{\theta}$$



Symmetry breaking scale

$f_a > 10^{12}$ GeV (stellar cooling)

KSVZ and B#

$$+\sum_q \bar{q}\,(i\not{D} - Y\phi\, e^{i\theta_q})\,q$$

Invisible Axion : PQ mech. in non-SM sector

$$S_\Psi^*\,\overline{\Psi_L}\Psi_R$$

$$\begin{cases} \Psi_L \to e^{-i\,\theta_{\rm PQ}}\Psi_L \\ \Psi_R \to e^{i\,\theta_{\rm PQ}}\Psi_R \\ S_\Psi \to e^{2\,i\,\theta_{\rm PQ}} S_\Psi \end{cases}$$

PQ symmetry

$$\begin{cases} \Psi_L \to e^{i\,\theta_\Psi}\Psi_L \\ \Psi_R \to e^{i\,\theta_\Psi}\Psi_R \end{cases}$$

Ψ# symmetry

We still don't know the charges (B#) of Ψ

B# of Ψ is defined by the connection with SM sector

Ex. $M\overline{\Psi_L} d_R \quad \to \quad B(\Psi_L) = 1/3$

$$PQ = L\#$$

Unification of Scales

Different Physics imply similar **High Scale**

Seesaw Scale $M_N \simeq F_a$ **PQ Scale**

$M_N = 10^{9\sim13}$GeV $\quad$ $F_a > 10^{12}$GeV

➡ **L# symmetry = PQ symmetry ?**

L# and B# of New Particles (N_R, Ψ, S) ambiguous

➔ **Goal : Construct "B+L" conserving theory**

$$\mathcal{O}_7 = u_R d_R d_R L^c H^c, \cdots$$

B# and L# of New Particles

Seesaw : $\overline{L}\widetilde{H}N_R,\ S_N\overline{N_R^c}N_R$ **PQ :** $S_\Psi\overline{\Psi_L}\Psi_R$

$$\begin{cases} L(N_R)=1 \\ B(N_R)=0 \end{cases} \quad \begin{cases} L(S_N)=-2 \\ B(S_N)=0 \end{cases} \quad \begin{cases} L(*)=? \\ B(*)=? \end{cases}$$

Artificial connection

$$y_L\zeta^*\overline{Q}(i\tau_2)Q^c,\ y_R\zeta\overline{d_R^c}u_R,\ y_\zeta\zeta^*\overline{N_R^c}\Psi_R$$

Diquark[ζ]

$$\begin{cases} L(\Psi_R)=-1 \\ B(\Psi_R)=-2/3 \end{cases}$$

$$\begin{cases} L(\zeta)=0 \\ B(\zeta)=-2/3 \end{cases}$$

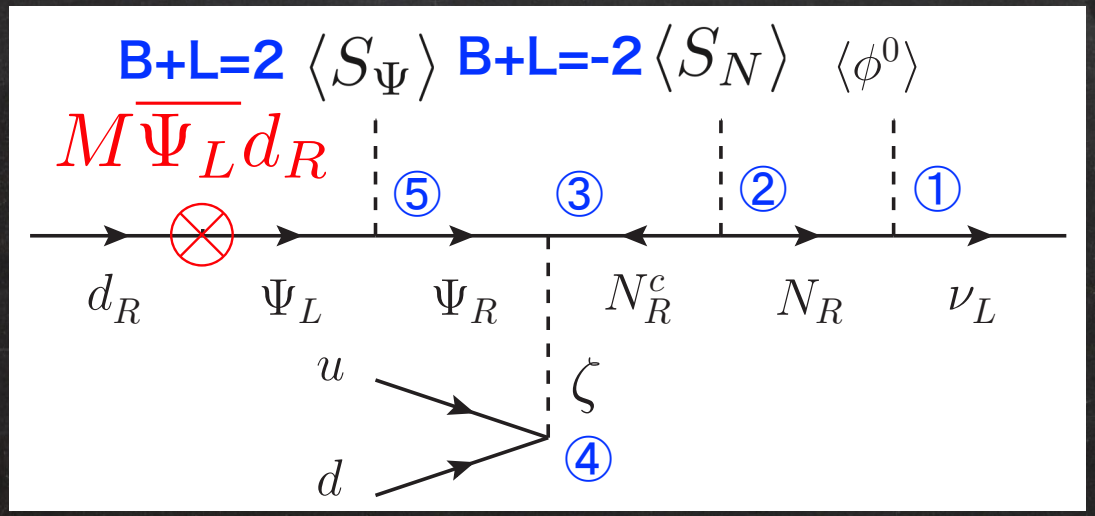
cf. $\overline{Q}H\Psi_R$ $\begin{cases} L(\Psi_R)=0 \\ B(\Psi_R)=1/3 \end{cases}$

B+L conserving operator

Seesaw : $\overset{①}{\overline{L}}\widetilde{H}N_R,\ \overset{②}{S_N}\overline{N_R^c}N_R$ **PQ :** $\overset{⑤}{S_\Psi}\overline{\Psi_L}\Psi_R$

Artificial connection

$$y_L\zeta^*\overline{Q}(i\tau_2)Q^c,\ \overset{④}{y_R}\zeta\overline{d_R^c}u_R,\ \overset{③}{y_\zeta}\zeta^*\overline{N_R^c}\Psi_R$$



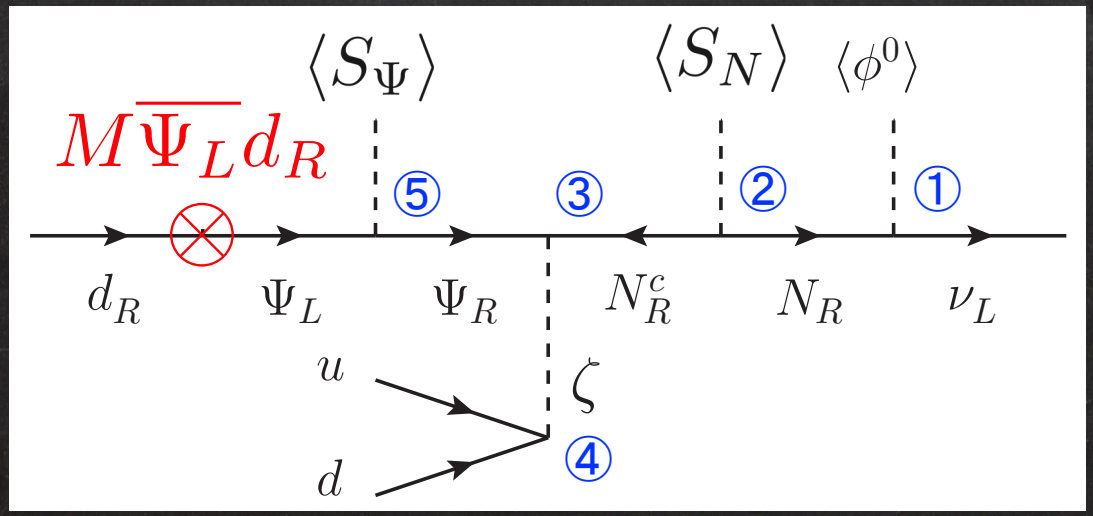
$$\begin{cases} L(\Psi_L) = 0 \\ B(\Psi_L) = 1/3 \end{cases}$$

$$\begin{cases} L(S_\Psi) = 1 \\ B(S_\Psi) = 1 \end{cases}$$

B+L conserving Proton Decay

Proton decay probes Seesaw and PQ scales

$$\frac{1}{\Lambda^3}(\overline{u^c}\,\gamma^\mu\,u)(\overline{d^c}\,\gamma_\mu\,L^c)H \qquad \frac{1}{\Lambda^3} \sim \frac{M}{M_\zeta^2 M_N M_\Psi}$$



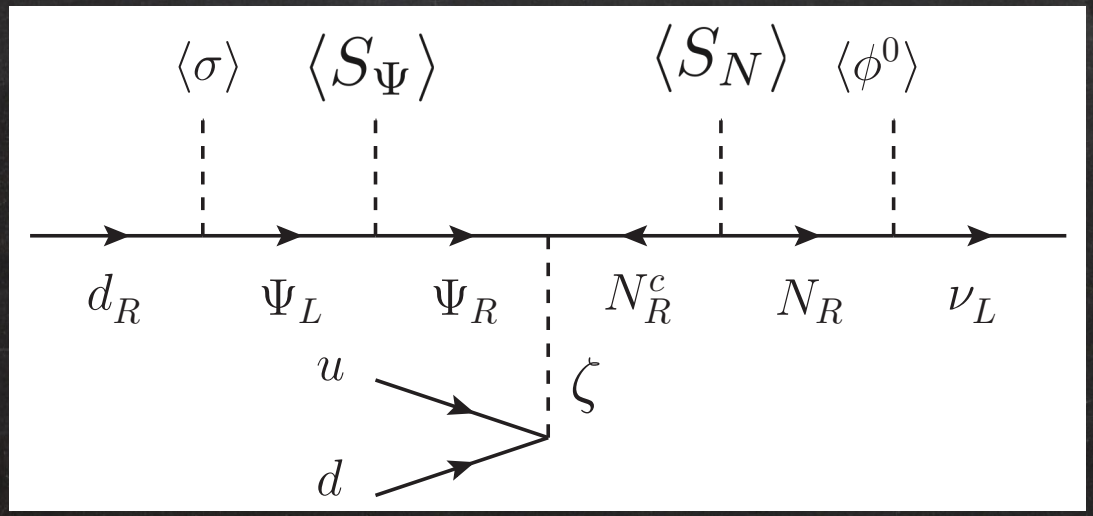
$$\tau_p \simeq \frac{\Lambda^6}{v^2\, m_p^5}$$

$\Lambda > 10^{10}$GeV

DM connection

pNGB $S = \mathrm{Im}(\sigma)$ of B#V can be long-lived DM

$$\frac{1}{\Lambda^3}(\overline{u^c}\,\gamma^\mu\,u)(\overline{d^c}\,\gamma_\mu\,L^c)H \qquad \frac{1}{\Lambda^3} \sim \frac{M}{M_\zeta^2 M_N M_\Psi}$$



$$\tau_p \simeq \frac{\Lambda^6}{v^2\, m_p^5}$$

$\Lambda > 10^{10}$GeV

Longevity of Matter and DM are linked

They are controlled by the same SSB scale

Matter longevity :

$$\Gamma(p \to \pi^+ \nu) \sim \frac{m_p}{32\pi}\left(\sum_{X=L,R} \frac{y_X}{M_\zeta^2} \frac{y_\zeta (y_\sigma \langle\sigma\rangle) m_D}{M_N M_\Psi} \langle \pi^+ | (ud)_X d_R | p \rangle \right)^2$$

$$\tau_p \simeq 8 \times 10^{32}\,\mathrm{yr} \times \left(\frac{M_\zeta}{3\,\mathrm{TeV}}\right)^4 \left(\frac{M_\Psi}{10^{10}\mathrm{GeV}} \frac{20\mathrm{GeV}}{v_\sigma}\right)^2 \left(\frac{M_N}{10^{10}\mathrm{GeV}} \frac{10^{-10}\mathrm{GeV}}{m_\nu}\right)$$
$$\times \left(\frac{0.05}{y_\zeta} \frac{6.5\times 10^{-3}}{y_\sigma}\right)^2 \left(\frac{y_L}{10^{-2}} \frac{\langle \pi^+ | (ud)_L d_R | p \rangle}{0.18} + 2\frac{y_R}{10^{-2}} \frac{\langle \pi^+ | (ud)_R d_R | p \rangle}{0.18}\right)^{-2}$$

DM longevity :

$$\Gamma(S \to d\bar{d}) \sim \frac{m_S}{16\pi}\left(\frac{y_\sigma^2 m_d \langle\sigma\rangle}{M_\Psi}\right)^2$$

$$\tau_S \simeq 10^{27}\mathrm{sec} \times \left(\frac{M_\Psi}{10^{10}\,\mathrm{GeV}} \frac{6.5\times 10^{-3}}{y_\sigma^d}\right)^4 \left(\frac{4.7\,\mathrm{MeV}}{m_d} \frac{20\,\mathrm{GeV}}{v_\sigma}\right)^2 \left(\frac{20\,\mathrm{GeV}}{m_S}\right)$$

Summary

BSM breaks L# and B# in general.

- Dim 5 : B# conserving (L# violating)
- Dim 6 : B-L conserving
- Dim 7 : B+L conserving

➔ (新学術 friendly signals) 0v2b, **p decay**

Proton decay can probe many BSMs.

GUT, RpV SUSY, Seesaw, PQ

Longevity of M and DM maybe related.

Fin.

The Concrete Model

Particle	$SU(3)_C \times SU(2)_L \times U(1)_Y$	B	L
$q_L = (V_{\rm CKM}^\dagger u, d)_L$	$(3, 2, 1/6)$	$1/3$	0
u_R	$(3, 1, 2/3)$	$1/3$	0
d_R	$(3, 1, -1/3)$	$1/3$	0
Ψ_L	$(3, 1, -1/3)$	$-2/3$	0
Ψ_R	$(3, 1, -1/3)$	$-2/3$	-1
$\ell_L = (\nu, e)_L$	$(1, 2, -1/2)$	0	1
e_R	$(1, 1, -1)$	0	1
N_R	$(1, 1, 0)$	0	1
$\Phi = (\phi^+, \phi^0)$	$(1, 2, 1/2)$	0	0
S_1	$(1, 1, 0)$	0	-1
S_2	$(1, 1, 0)$	0	-2
ζ	$(3, 1, -1/3)$	$-2/3$	0
σ	$(1, 1, 0)$	1	0

Lagrangian

$$-\mathcal{L}_S = +y_\Psi\, S_1^\star \overline{\Psi_L} \Psi_R + \frac{1}{2} y_N^i\, S_2 \overline{N_{iR}^c} N_{iR} + \kappa\, S_2^\star (S_1)^2 + \text{H.c.}$$

$$-\mathcal{L}_\zeta = +y_L^{ij}\, \zeta^\star\, \overline{q_{iL}}\, i\tau^2 q_{jL}^c + y_R^{ij}\, \zeta\, \overline{d_{iR}^c} u_{jR} + y_\zeta^i\, \zeta^\star\, \overline{N_{iR}^c} \Psi_R + \text{H.c.}$$

$$-\mathcal{L}_\sigma = +y_\sigma^i\, \sigma^\star\, \overline{\Psi_L} d_{iR} + \text{H.c.}$$

$$\mathcal{L}_D = -y_D^{\ell j} \overline{L}_\ell \widetilde{\Phi} N_{jR} + \text{H.c.}$$

$$V_{\text{soft}} = -\frac{\mu^2}{2}\sigma^2 + \text{H.c.}$$

Soft B# violation ➔ Sakharon mass

$(-1)^{3B}$ conserving soft B#V

Scalar Potential

$$
\begin{aligned}
V = &-\mu_\Phi^2 \Phi^\dagger \Phi - \mu_1^2 |S_1|^2 - \mu_2^2 |S_2|^2 - \mu_\sigma^2 |\sigma|^2 - \frac{\mu^2}{2}(\sigma^2 + \text{H.c.}) - \kappa\left(S_2^\star (S_1)^2 + \text{H.c.}\right) \\
&+ \frac{\lambda_\Phi}{2}(\Phi^\dagger \Phi)^2 + \frac{\lambda_1}{2}|S_1|^4 + \frac{\lambda_2}{2}|S_2|^4 + \frac{\lambda_\sigma}{2}|\sigma|^4 + \lambda_{12}|S_1|^2 |S_2|^2 \\
&+ (\lambda_{1\Phi}|S_1|^2 + \lambda_{2\Phi}|S_2|^2 + \lambda_{\Phi\sigma}|\sigma|^2)(\Phi^\dagger \Phi) + (\lambda_{1\sigma}|S_1|^2 + \lambda_{2\sigma}|S_2|^2)|\sigma|^2 .
\end{aligned}
$$

$$
\Phi = \begin{pmatrix} i\,\eta^+ \\ v + \frac{\rho + i\,\eta}{\sqrt{2}} \end{pmatrix}, \; S_1 = f_1 + \frac{\rho_1 + i\,\eta_1}{\sqrt{2}}, \; S_2 = f_2 + \frac{\rho_2 + i\,\eta_2}{\sqrt{2}}, \; \sigma = v_\sigma + \frac{\rho_\sigma + i\,\eta_\sigma}{\sqrt{2}}.
$$

$$
\begin{pmatrix} h_{125} \\ h_\sigma \end{pmatrix} = \begin{pmatrix} \cos\theta_h & \sin\theta_h \\ -\sin\theta_h & \cos\theta_h \end{pmatrix} \begin{pmatrix} \rho \\ \rho_\sigma \end{pmatrix}
$$

$$
\begin{pmatrix} J \\ K \end{pmatrix} = \begin{pmatrix} f_1/f & 2f_2/f \\ -2f_2/f & f_1/f \end{pmatrix} \begin{pmatrix} \eta_1 \\ \eta_2 \end{pmatrix}
$$

Higher Dimensional Operators

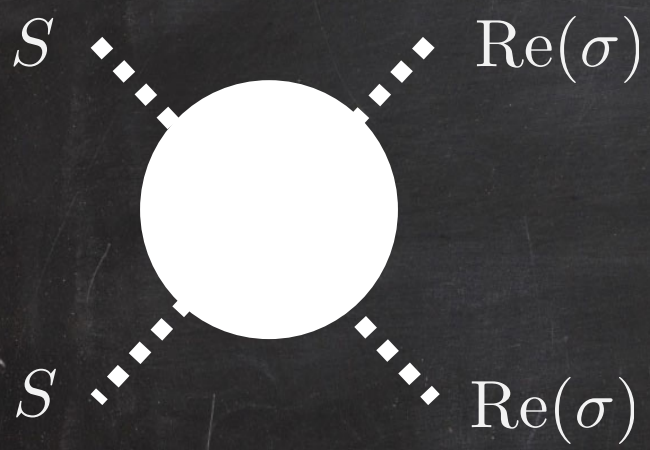
$$\mathcal{L}^{\rm eff}_{\rm dim6} = \frac{2}{M_\zeta^2}\left| + y_L^{ij}\,\overline{q_{iL}}\,i\tau^2 q^c_{Lj} + y_R^{ij\star}\,\overline{u_{jR}} d^c_{iR}\right|^2,$$

$$\mathcal{L}^{\rm eff}_{\rm dim7} = \frac{1}{M_\zeta^2}\frac{y^i_\zeta (y^i_\sigma v_\sigma) y^{\ell i}_D}{M^i_N M_\Psi}\overline{\ell_L}\widetilde{\Phi} d_{iR}\left(+ y_L^{ij\star}\,\overline{q^c_{iL}}\,i\tau^2 q_{Lj} + y_R^{ij}\,\overline{u^c_{jR}} d_{iR}\right) + \text{H.c.}$$

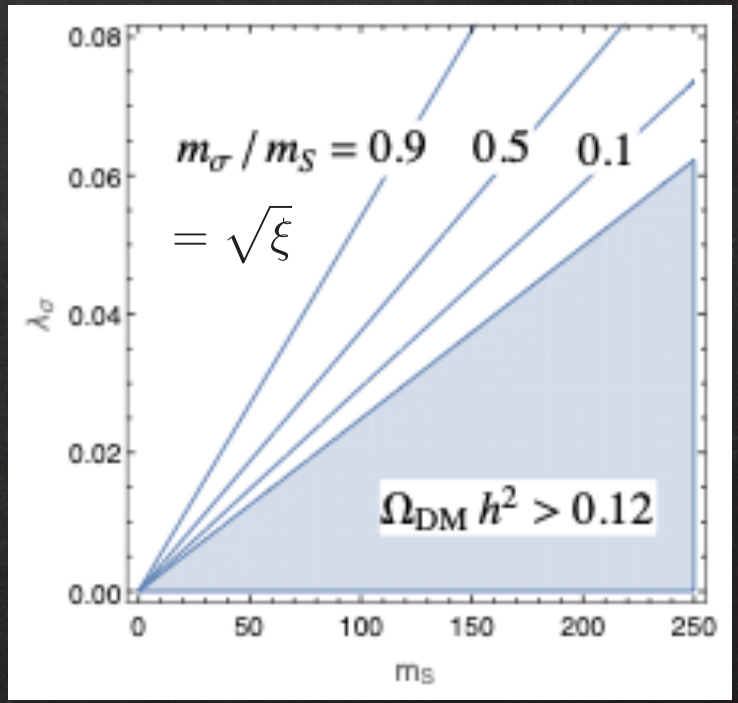
$$\mathcal{L}^{\rm eff}_{\rm dim8} = \frac{2}{M_\zeta^2}\left|\frac{y^i_\zeta (y^i_\sigma v_\sigma) y^{\ell i}_D}{M^i_N M_\Psi}\overline{\ell_L}\widetilde{\Phi} d_{iR}\right|^2.$$

DM relic abundance

Controlled by Scalar 4pt interaction $\frac{\lambda}{2}|\sigma|^4$



$$\sigma v_{\rm rel} \approx \frac{1}{2!}\frac{\lambda_\sigma^2}{32\pi m_S^2}\left(1-\frac{3\,\xi}{4-\xi}+\frac{\xi}{2-\xi}\right)^2\sqrt{1-\xi}$$



If $S_N = S_\psi$

Rapid Sakharon decays into Majoron (axion)

$S \rightarrow Re(\sigma)+J$ **Longevity of DM is violated**