Baryon   Lepton

Theory of B and L Number Violation

Koji Tsumura (Kyushu U.)

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Baryon number non-conservation as Peccei-Quinn mechanism

T. Ohata, K. Takeuchi, K. Tsumura

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The goal of this talk is to set the stage for the following presentations.

Contents

- Standard Model (SM) & Accidental Symmetries
- Strong CP problem and PQ mechanism
- Lepton Number Violation (L#V)
- Baryon Number Violation (B#V)
- Summary

SM and Accidental Symmetries

SM and Global symmetries

- **Renormalizable Level (Tree)：** $\mathcal{L}_{\rm SM} = \underbrace{\mathcal{L}_{\rm quarks} + \mathcal{L}_{\rm leptons} + \cdots}_{\text{(up to d=4)}}$

As for Accidental Symmetry：B# (baryon number)，L# (lepton number)

$$\begin{cases} Q \to e^{i\theta_B/3} Q \\ u_R \to e^{i\theta_B/3} u_R \\ d_R \to e^{i\theta_B/3} d_R \end{cases} \qquad \begin{cases} L \to e^{i\theta_L} L \\ e_R \to e^{i\theta_L} e_R \end{cases}$$

- **Non-Renormalizable Level（higher dim operators）：**

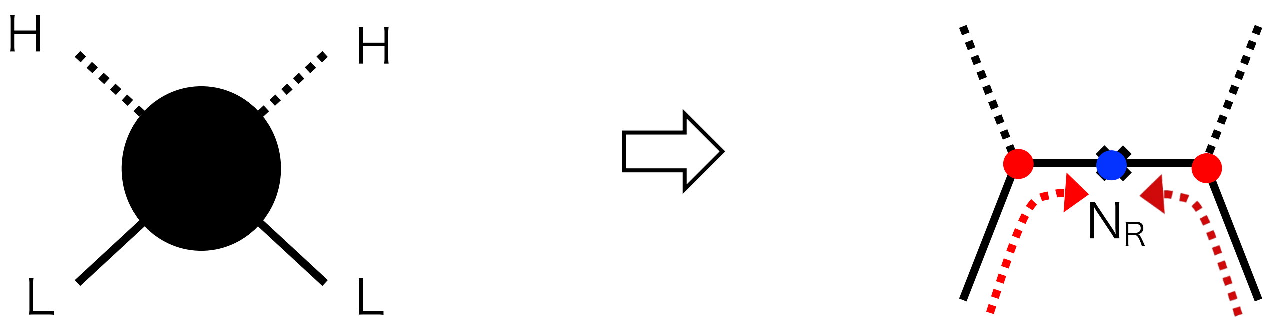
$$\mathcal{L}_{\rm eff} = + \frac{1}{\Lambda}\mathcal{O}_5 + \frac{1}{\Lambda^2}\mathcal{O}_6 + \frac{1}{\Lambda^3}\mathcal{O}_7 + \cdots$$

Suppressed by Unknown New Physics scale

➔ Reflect symmetries of BSM (UV theory)

L#V and higher dim operator

- **Higher d Operators written in terms of SM fields**



UV independent description — **UV complete example**

$$\mathcal{O}_5 = LLHH$$ L# violating dim 5 op.

L: $(1,2)_{-1/2}$ H: $(1,2)_{+1/2}$

(after the integration of heavy d.o.f.)

Heavy N_R

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

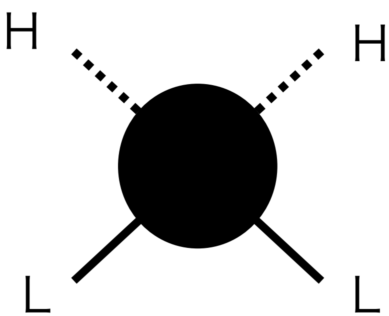
Detemine L# — Explicit L#V (UV theory break L#)

L#V and Neutrino Mass

- **Unknown New Physics (NP) imply Majorana Neutrino**

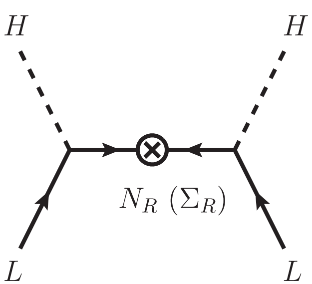
$$\mathcal{L}_{\rm eff} = \frac{1}{\Lambda}\mathcal{O}_5 + {\rm H.c.} \quad \Rightarrow \quad \frac{1}{2}M_\nu\, \overline{\nu_L^c}\nu_L + {\rm H.c.}$$

Higher d operators characterize NP without specifying details of NP

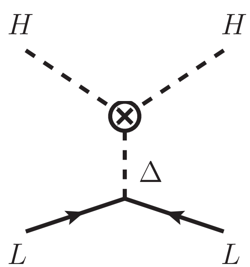


UV completions :

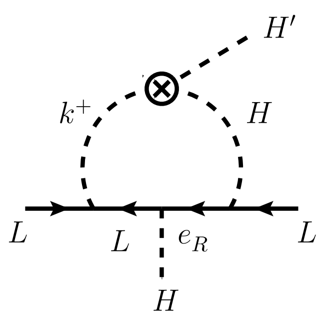
- ✓ UV model can be obtained by decomposition of diagram
- ✓ 3 types of (tree level) seesaw mechanism
- ✓ Many variants of (loop level) radiative seesaw mech.
- ✓ (Dark Matter may be mediated in loops)



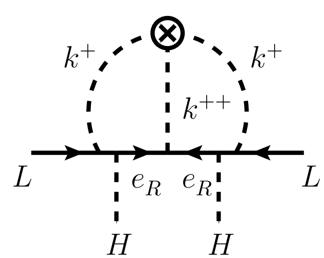
Type I (III)



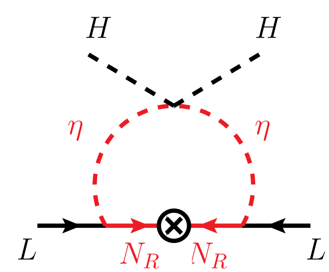
Type II



Zee type



Zee-Babu type



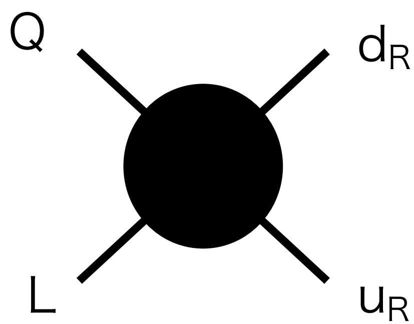
Scotogenic type

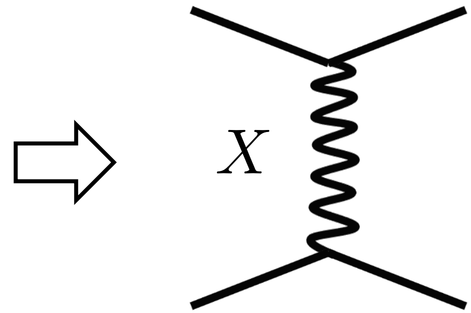
B#V and higher dim operator

- **Higher d Operators written in terms of SM fields**

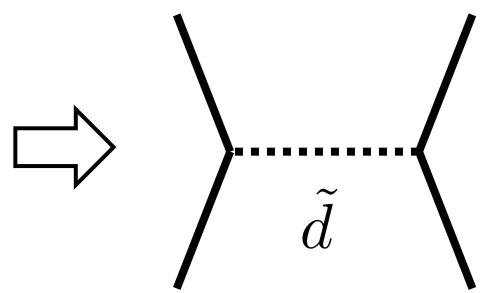
$$\mathcal{O}_6 = u_R d_R Q L, \cdots$$ B# violating d=6 operator

u_R: $(3,1)_{-2/3}$, d_R: $(3,1)_{+2/3}$, Q: $(3,2)_{+1/6}$





GUT



RpV SUSY

New Physics and Symmetries

- Higher d Operators

	L#	B#	BSM symmetry
$\mathcal{O}_5 = LLHH$	$\times_2$	○	"B" conservation
$\mathcal{O}_6 = u_R d_R Q L, \cdots$	$\times_1$	$\times_1$	"B-L" conservation
$\mathcal{O}_7 = u_R d_R d_R L^c H^c, \cdots$	$\times_{-1}$	$\times_1$	"B+L" conservation

BSM Signal ➔ $0\nu 2\beta$ (M_ν) (for $\mathcal{O}_5$)

➔ Nucleon decays (for $\mathcal{O}_6$)

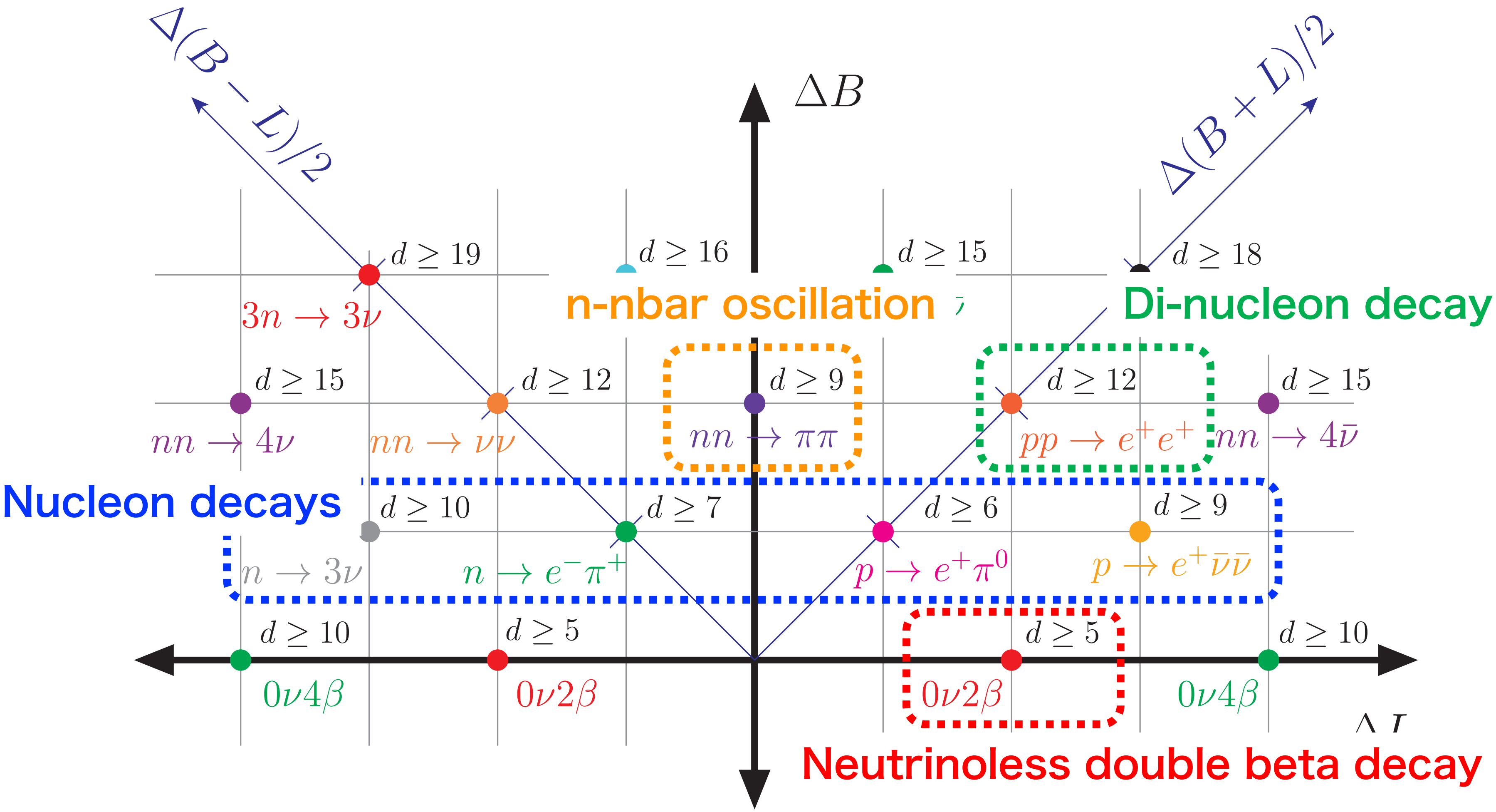
In general, BSM does not hold L# & B#. (Accidental sym in minimal SM)

➔ Nucleon decays   Controlled by BSM sym

Can we construct physically motivated models based on L# & B# ?

BSM symmetry and Signal

Heeck, Takhistov (19)



Strong CP problem and PQ sym

't Hooft (76)

Strong CP Problem

- **QCD breaks CP in General**

$$\mathcal{L}_{\rm QCD} = -\frac{1}{4} G_a^{\mu\nu} G^a_{\mu\nu} - \theta \frac{\alpha_s}{8\pi} G_a^{\mu\nu} \widetilde{G}^a_{\mu\nu} + \sum_q \bar{q}(i \not{D} - M_q e^{i\theta_q}) q$$

When we redefine phases of left- and right-handed field (chiral transf)

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

✓ Chiral sym. is broken by quark mass → Remove phase in quark mass by chiral transf

✓ On the other hand, θ term shifts by chiral transf

✓ Quark mass matrix is complex in general → KM phase **→ CP violation is natural**

However, from the neutron EDM measurement

$$d_n/e \sim 10^{-15}\bar{\theta} < 1.8 \times 10^{-26} \quad (\bar{\theta} \lesssim 10^{-11})$$

Extremely small !! New physics may exist in the behind

PQ symmetry

Peccei-Quinn (77)

- Restore the chiral sym. by introducing new scalar ϕ

$$\mathcal{L}_{\rm PQ} = -\frac{1}{4}G_a^{\mu\nu}G^a_{\mu\nu} - \theta\,\frac{\alpha_s}{8\pi}G_a^{\mu\nu}\widetilde{G}^a_{\mu\nu} + \sum_q \left\{\bar{q}i\not{D}q - \left(y\,\bar{q}_L\phi\,q_R + {\rm H.c.}\right)\right\}$$

Remove θ by chiral transf., and the phase in quark sector is absorbed by complex scalar

$(q \to e^{-i\gamma_5\theta_q}q)$

θ is unphysical since it is removed by field redefinition

PQ sym $\begin{cases} q_L \to e^{-i\theta_q/2}q_L \\ q_R \to e^{+i\theta_q/2}q_R \\ \phi \to e^{-i\theta_q}\phi \end{cases}$

✓ Left-handed and right-handed fields transforms differently
✓ Dirac Lagrangian holds (vector-like) baryon number
→ Chiral transf. = Axial vector transformation

- Effective Lagrangian $\phi(x) = (f_a + \sigma(x))\,e^{i\,a(x)/f_a}$ — axion (NGB)

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm QCD} + \frac{1}{2}(\partial_\mu a)^2 + (\theta - a/f_a)\frac{\alpha_s}{8\pi}G\widetilde{G} + \cdots$$

NGB does not have a potential ⇔ NGB has shift symmetry

Detergent
(Washout Strong CP problem)

Kim (79), Shifman-Vainshtein-Zakharov (80)

Invisible (KSVZ) axion

- An simple realization of invisible axion
  - ✓ PQ sym is broken only by SM singlet S : $S = \frac{f_a + \sigma}{\sqrt{2}} e^{i\, a(x)/f_a}$
  - ✓ Assume chiral sym for new colored fermion

$$\mathcal{L}_{\rm KSVZ} = Y_\Psi\, S\, \overline{\Psi}_L \Psi_R + \text{H.c.}$$

All particles in QCD are replaced by new particles

$$\begin{cases} \Psi \to e^{-i\gamma_5 \alpha}\, \Psi \\ S \to e^{-2i\alpha}\, S \end{cases}$$

L# and B# of new particles have <u>not yet defined!!</u>

	S	Ψ_L	Ψ_R
$\mathrm{SU}(3)_C$	$\mathbf{1}$	$\mathbf{3}\,(\mathbf{6},\mathbf{8},\cdots)$	$\mathbf{3}\,(\mathbf{6},\mathbf{8},\cdots)$
$\mathrm{SU}(2)_L$	$\mathbf{1}$	$\mathbf{1}\,(\mathbf{2},\mathbf{3},\cdots)$	$\mathbf{1}\,(\mathbf{2},\mathbf{3},\cdots)$
$\mathrm{U}(1)_Y$	0	$-$	$-$
$\mathrm{U}(1)_{\rm PQ}$	-2	-1	$+1$
$\mathrm{U}(1)_\Psi$	0	$+1$	$+1$
$\mathrm{U}(1)_L$	$-$	$-$	$-$
$\mathrm{U}(1)_B$	$-$	$-$	$-$

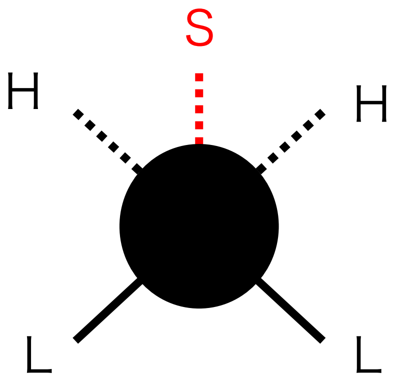
Chiral sym for new fermion

New fermion numbers for new fermions
(similarly to B# for ordinary quarks)

$$\alpha\, Q_{\rm PQ} + \beta\, Q_\Psi$$

Arbitrary linear combinations also holds sym
Non-zero charges of S and of $\Psi_{L/R}$ are key ingredient

PQ symmetry and L#V



PQ = L#

Shin (87)

- **Define L# through Seesaw model**

$$M_N \to y_N S$$

Promote a mass to a complex scalar

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

Determine L# L#V

→ Identify PQ sym and L# sym : Majoraxion (Majoron = Axion)

NGB of L#V

Both PQ mech and Seesaw mech require the relatively high energy scale (~10^{12}GeV)

Unification of these two scale might be interesting (but not necessary)

	S	Ψ_L	Ψ_R
$\mathrm{SU}(3)_C$	$\mathbf{1}$	$\mathbf{3}\,(\mathbf{6},\mathbf{8},\cdots)$	$\mathbf{3}\,(\mathbf{6},\mathbf{8},\cdots)$
$\mathrm{SU}(2)_L$	$\mathbf{1}$	$\mathbf{1}\,(\mathbf{2},\mathbf{3},\cdots)$	$\mathbf{1}\,(\mathbf{2},\mathbf{3},\cdots)$
$\mathrm{U}(1)_Y$	0	$-$	$-$
$\mathrm{U}(1)_{\mathrm{PQ}}$	-2	-1	$+1$
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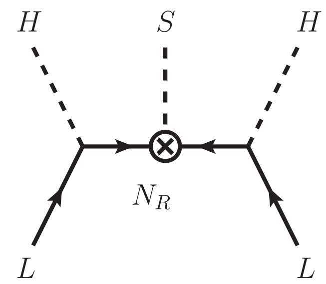
$\mathrm{U}(1)_L$	-2	$-$	$-$
$\mathrm{U}(1)_B$	$-$	$-$	$-$



Take the same charge as PQ charge w/o loss of generality

PQ = L#

Shin (87)

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$$M_N \to y_N S$$

Promote a mass to a complex scalar

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

Determine L#   L#V

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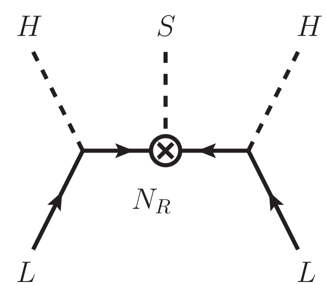
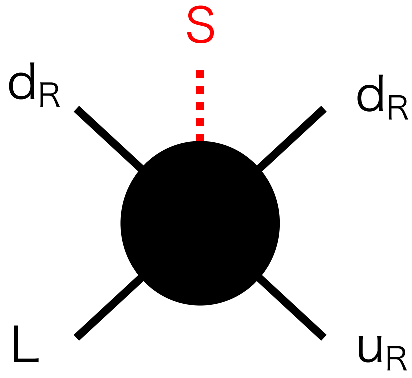
$\mathrm{SU}(2)_L$	$\mathbf{1}$	$\mathbf{1}\,(\mathbf{2},\mathbf{3},\cdots)$	$\mathbf{1}\,(\mathbf{2},\mathbf{3},\cdots)$
$\mathrm{U}(1)_Y$	0	$-$	$-$
$\mathrm{U}(1)_{\mathrm{PQ}}$	-2	-1	$+1$
$\mathrm{U}(1)_\Psi$	0	$+1$	$+1$
$\mathrm{U}(1)_L$	-2	-1 (0)	+1 (+2)
$\mathrm{U}(1)_B$	$-$	$-$	

$\mathrm{U}(1)_{L\text{-}\Psi}$



Take the same charge as PQ charge w/o loss of generality

PQ symmetry and B#V



Lepton parity is also broken in this example

B# in KSVZ axion models

- Need to make a connection btw SM and new fermion Ψ

$$\begin{cases} \text{none} & (3,1)_0 \\ \mu_d\,\overline{\Psi}_L d_R & (3,1)_{-1/3} \\ \mu_u\,\overline{\Psi}_L u_R & (3,1)_{+2/3} \\ \mu_Q\,\overline{Q}\,\Psi_R & (3,2)_{+1/6} \\ y\,\overline{\Psi}_L \widetilde{H} d_R & (3,2)_{+5/6} \\ y\,\overline{\Psi}_L \widetilde{H} u_R & (3,2)_{+7/6} \\ \vdots & \vdots \end{cases}$$

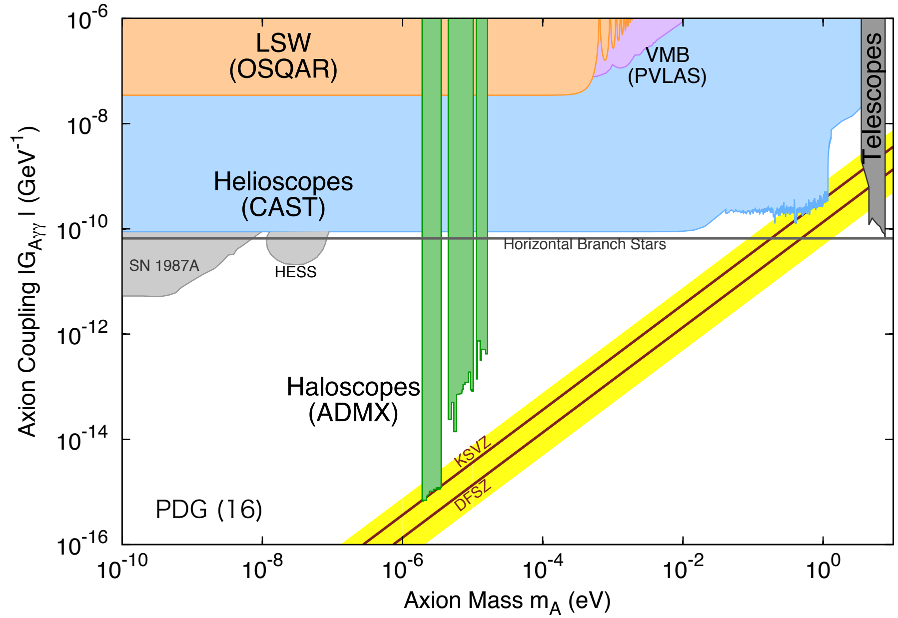
Original model : (colored) Ψ is stable → Need to washout (by inflation etc)

B# depends on the way of connections

Besides original model, all others predict B# = +1/3 (= Ψ#)

Different prediction on pheno.

$$\mathcal{L}_{a\gamma\gamma} \simeq \frac{\alpha}{8\pi}\frac{N}{f_a}\left(\frac{E}{N} - 1.92\right) a\,F\tilde{F}$$



PQ = B# ?

- PQ should be axial(-vector) sym, while Ψ# is vector sym

  ➔ Impossible to take B# = Ψ# (B# ≠ Ψ# is necessary)

- A PQ-Seesaw model based on lepton parity L_p and B#

Relation from Seesaw sector

$$Y_N \overline{L}\widetilde{H} N_R, \;\; M_N \overline{N_R^c} N_R \;\; \Rightarrow \;\; \begin{cases} L_p(N_R) = - \\ B(N_R) = 0 \end{cases}$$

Up to here we may take L_p odd for H in principle.
However, it is incompatible with quark Yukawa. → L_p of N_R should be odd

Relation from PQ sector

$$Y_\Psi \, S \, \overline{\Psi_L} \Psi_R, \;\; \mu_d \, \overline{\Psi_L} d_R \;\; \Rightarrow \;\; \begin{cases} L_p(\Psi_L) = * \\ B(\Psi_L) = +1/3 \end{cases}$$

an example

PQ sector does not define L_p.

$$B(\Psi_R) \neq +1/3$$

Any other relation can be used to determine B# ?

PQ = B#

$(3,1)_{+1/3}$ or $(\underline{6},1)_{+1/3}$

- Introduce new scalar (diquark) with well-defined B#

$$\mathcal{L}_\zeta = -y_L\, \zeta\, \overline{Q}(i\sigma_2)Q^c + y_R\, \zeta\, \overline{d^c_R} u_R + \text{H.c.} \;\Rightarrow\; \begin{cases} L_p(\zeta) = + \\ B(\zeta) = -2/3 \end{cases}$$

- Relation completed with Diquark

$$y_\zeta\, \zeta^*\, \overline{N^c_R}\Psi_R \;\Rightarrow\; \begin{cases} L_p(\Psi_R) = - \\ B(\Psi_R) = -2/3 \end{cases}$$

Also fixes pending part
$L_p(\Psi_L) = +$

- Summary

	S	Ψ_L	Ψ_R	N_R	ζ
$\mathrm{SU}(3)_C$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{3}\,(\mathbf{6})$
$\mathrm{SU}(2)_L$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
$\mathrm{U}(1)_Y$	0	$-1/3$	$-1/3$	0	$-1/3$
$\mathrm{U}(1)_{\mathrm{PQ}}$	-2	-1	$+1$	0	$*$
$\mathrm{U}(1)_\Psi$	0	$+1$	$+1$	0	0
L_p	$-$	$+$	$-$	$-$	$+$
$\mathrm{U}(1)_B$	$+1$	$+1/3$	$-2/3$	0	$-2/3$

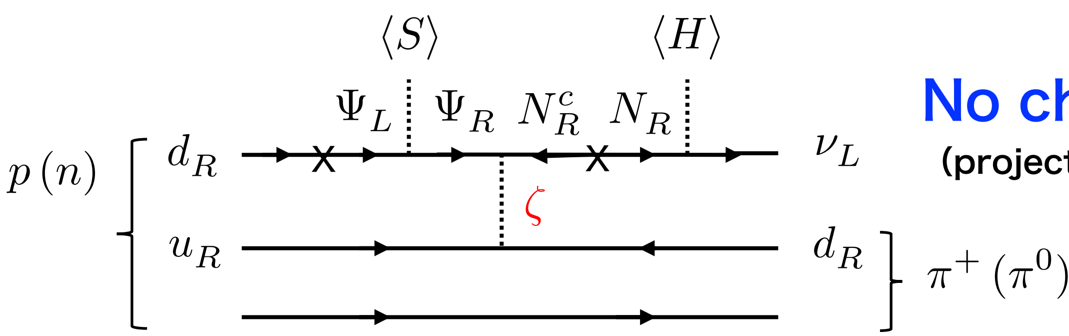
$$Q_{\mathrm{PQ}} = -2\,Q_{\mathrm{B}} - \frac{1}{3}\,Q_\Psi$$

→ Identify PQ sym and B# sym : Sakhaxion (Sakharon = Axion)

NGB of B#V

(Non-GUT) Nucleon decay

- d=7 operator : $\mathcal{L}_{\rm eff} \sim \frac{\mu_d}{M_\zeta^2 M_\Psi M_N} u_R d_R d_R L^c H^*$ "B+L" conserving



No charged lepton mode
(project out by Higgs VEV)

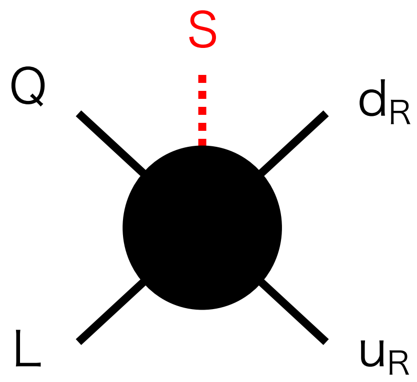
- Obtained constraint on New Physics scale

$$\tau \simeq \left(\frac{\Lambda^3}{v}\right)^2 \frac{1}{m_N^5} \gtrsim \tau_{\rm exp} \quad \Rightarrow \quad \Lambda \gtrsim 10^{10}{\rm GeV}$$

$$\Rightarrow \quad M_\zeta \gtrsim \sqrt{\frac{\mu_d}{\rm GeV}\frac{10^{12}{\rm GeV}}{M_\Psi}\frac{10^{12}{\rm GeV}}{M_N}} \times {\rm TeV}$$

Nucleon decay also constrain theories other than GUTs

PQ symmetry and L#V/B#V



L# is also broken in this example

Spontaneous breaking of B and L

- **Assume Yukawa int among S and KSVZ quarks**

$$\mathcal{L}_{\rm KSVZ} = Y_\Psi \, S \, \overline{\Psi}_L \Psi_R + {\rm H.c.}$$

- **Determine L# and B# of S by higher d operators**

$$\mathcal{L}_{\rm eff} = \kappa \, S^* u_R d_R Q L + {\rm H.c.}$$ (In this stage, **B#** and **L#** syms are assumed)

- **When S acquire VEV** $U(1)_{\rm B} \times U(1)_{\rm L} = U(1)_{\rm B+L} \times U(1)_{\rm B-L} \rightarrow U(1)_{\rm B-L}$

	S	Ψ_L	Ψ_R
$\mathrm{SU}(3)_C$	$\mathbf{1}$	$\mathbf{3}\,(\mathbf{6},\mathbf{8},\cdots)$	$\mathbf{3}\,(\mathbf{6},\mathbf{8},\cdots)$
$\mathrm{SU}(2)_L$	$\mathbf{1}$	$\mathbf{1}\,(\mathbf{2},\mathbf{3},\cdots)$	$\mathbf{1}\,(\mathbf{2},\mathbf{3},\cdots)$
$\mathrm{U}(1)_Y$	0	$-$	$-$
$\mathrm{U}(1)_{\rm PQ}$	-2	-1	$+1$
$\mathrm{U}(1)_\Psi$	0	$+1$	$+1$
$\mathrm{U}(1)_L$	$+1$	$-$	$-$
$\mathrm{U}(1)_B$	$+1$	$-$	$-$

NGB of B+L breaking becomes axion

Prescription to define B and L

- Determine L# and B# of KSVZ quarks

$$\mathcal{O}'_{\rm mix} = \{\overline{Q}\widetilde{H}\Psi^U_R, \overline{\Psi^U_L}u_R, \overline{Q}H\Psi^D_R, \overline{\Psi^D_L}d_R\}$$ Choose 1 of these ops

- L# and B# of the rest KSVZ quark (w/ different chirality) are also fixed through the KSVZ Yukawa int

	S	Ψ_L	Ψ_R
$\mathrm{SU}(3)_C$	$\mathbf{1}$	$\mathbf{3}\,(\mathbf{6},\mathbf{8},\cdots)$	$\mathbf{3}\,(\mathbf{6},\mathbf{8},\cdots)$
$\mathrm{SU}(2)_L$	$\mathbf{1}$	$\mathbf{1}\,(\mathbf{2},\mathbf{3},\cdots)$	$\mathbf{1}\,(\mathbf{2},\mathbf{3},\cdots)$
$\mathrm{U}(1)_Y$	0	$-$	$-$
$\mathrm{U}(1)_{\rm PQ}$	-2	-1	$+1$
$\mathrm{U}(1)_\Psi$	0	$+1$	$+1$
$\mathrm{U}(1)_L$	$+1$	0	-1
$\mathrm{U}(1)_B$	$+1$	$+1/3$	$-2/3$

example

$\mathbf{B}(\Psi^U_R) = -2/3, \mathbf{L}(\Psi^U_R) = -1$

$$\mathcal{L} = -\,y_\Psi\, S\, \overline{\Psi^{Ua}_L}\Psi^{Ua}_R + \kappa\, S^* u_R d_R Q L - \mu^i_U\, \overline{\Psi^{Ua}_L} u^a_{iR} + \mathrm{H.c.}$$

$\mathbf{B}(\Psi^U_L) = +1/3, \mathbf{L}(\Psi^U_L) = 0$

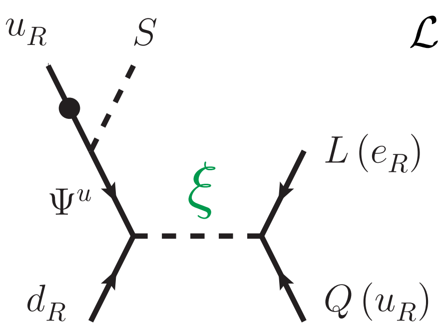
$\mathbf{B}(S) = +1, \mathbf{L}(S) = +1$

UV completion : PQ = B+L

- d=6 operator is decomposed to renormalizable int

  As explained in Majoraxion model, there are many variants (tree, loop)

  - Add one additional scalar (charges can be read from the Feynman diagram)



$$\mathcal{L} = -\, y_\Psi\, S\, \overline{\Psi^{Ua}_L} \Psi^{Ua}_R - \mu^i_U\, \overline{\Psi^{Ua}_L} u^a_{iR} - y^i_{\Psi D}\, \epsilon_{abc} \xi^a \overline{(\Psi^{Ub}_R)^C} d^c_{iR}$$
$$- \left[+ y^{ij}_{QL} \overline{(Q^a_i)^C} (i\sigma_2) L_j + y^{ij}_{UE}\, \overline{(u^a_{iR})^C} e_{Rj} \right] (\xi^a)^* + \text{H.c.}$$

Leptoquark

- Predict proton decay $\mathcal{L}_{\text{eff}} = \kappa\, \langle S^* \rangle u_R d_R Q L + \text{H.c}$

B-L conserving

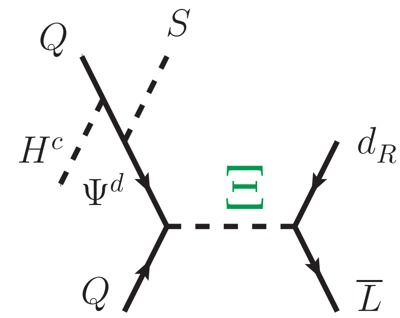
$$\kappa = -\frac{\mu_U y_{\Psi D} y_{QL}}{M_\Psi M_\xi^2}$$

$$\tau_{p\to\pi^0 e^+} \simeq (2.4 \times 10^{34}\,\text{yrs}) \times \left(\frac{0.2}{\mu_U/M_\Psi}\right)^2 \left(\frac{1}{|y_{\Psi D}|}\right)^2 \left(\frac{1}{|y_{q\ell}|}\right)^2 \left(\frac{M_\xi}{2.0 \times 10^{15}\text{GeV}}\right)^4$$

Normalized by SK bound

✓ Many uncertainties with model parameters
✓ Typical LQ mas should be much larger than PQ scale

UV completion : PQ = B-L



- **Let us start with d=7 operator**

$$\mathcal{O}_8 = S^* \mathcal{O}'_7 = S^* (d_R Q Q \overline{L} H^*)$$ This operator conserves B# and L#

■ **Add one additional scalar**

$$\mathcal{L} = -\, y_\Psi\, S^* \overline{\Psi^{Da}_L} \Psi^{Da}_R - y'^{i}_{D} \overline{Q^a_i} H \Psi^{Da}_R - y^i_{\Psi Q}\, \epsilon_{abc}\, \Xi^a \overline{(\Psi^{Db}_L)^C} Q^c_i - y^{ij}_{\overline{L}D} (\Xi^a)^* \overline{L_i} d^a_{jR} + \text{H.c.}$$

Leptoquark

B+L conserving

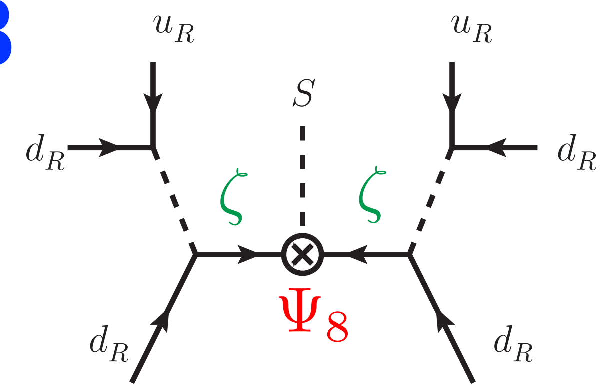
- **Predict "different" proton decay**

$$\tau_{p \to K^+ \nu_i} \simeq (6.6 \times 10^{33}\,\text{yrs}) \times \left(\frac{10^{-9}}{\frac{y'_D v_{\text{EW}}}{\sqrt{2}} / M_\Psi} \right)^2 \left(\frac{1}{|y_{\Psi Q}|} \right)^2 \left(\frac{1}{|y_{\overline{L}D}|} \right)^2 \left(\frac{M_\Xi}{8.5 \times 10^{10}\text{GeV}} \right)^4$$

Normalized by SK bound

✓ No charged lepton mode
✓ Constraint from Kaon is stronger than that from π
✓ Reaction rate suppressed by Higgs VEV insertion
✓ Typical LQ mas should be much larger than PQ scale

UV completion : PQ = B



- Let us start with d=9 operator

ΔB=2 op

  - Introduce one color octet fermion

c.f. Ma 07, gluino-axion

  - Add one additional scalar diquark

$$\mathcal{L} = -\frac{1}{2} y_8 S^* \overline{(\Psi_{8L}^A)^C} \Psi_{8L}^A - y_\zeta^{ij} \epsilon_{abc} (\zeta_a)^* \overline{(u_{iR}^b)^C} d_{jR}^c - y_{8D}^i \zeta_a (T^A)^a{}_b \overline{\Psi_{8L}^A} d_{iR}^b + \text{H.c.}$$

- Predict n-nbar oscillation

$$\mathcal{L}_{\text{eff}}^{\Delta B=2} = \frac{y_\zeta^{ij} y_\zeta^{kl} y_{8D}^m y_{8D}^n}{12 M_\zeta^4 M_8} \overline{(u_{iR}^a)^C} d_{jR}^b \overline{(u_{kR}^c)^C} d_{lR}^d \overline{(d_{mR}^e)^C} d_{nR}^f + \text{H.c.}$$

$$\tau_{n\bar{n}} = {\Gamma_{n\bar{n}}}^{-1} = (7 \times 10^8\,\text{s}) \times \left(\frac{M_\zeta}{400\,\text{TeV}}\right)^4 \left(\frac{M_8}{400\,\text{TeV}}\right) \left(\frac{1}{|y_\zeta^{11}|}\right)^2 \left(\frac{1}{|y_{8d}^1|}\right)^2$$

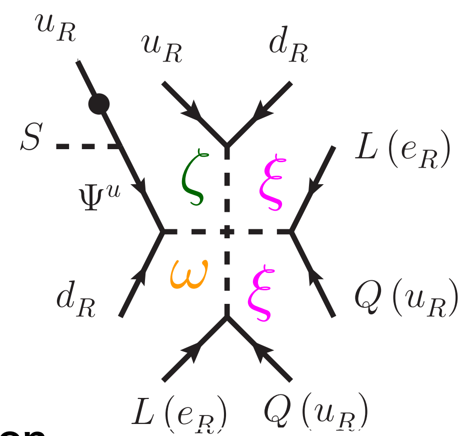
SK bound : > 4.7 x 10^8 s

✓ Typical new particle masses are much smaller than PQ scale

✓ Though, it is challenging at collider exp

✓ Competitive w/ flavor exp (Yukawa structure constrained)

UV completion : PQ = B-L



- **Let us start with d=12 operator**

  ΔB=ΔL=2

  - Since <S> breaks different B# & L#, LQξ and DQζ do not generate proton decay and also n-nbar oscillation
  - UV completion complete with tetraquark

$$\mathcal{L} = -\, y_\Psi S\, \overline{\Psi^{Ua}_L}\Psi^{Ua}_R - \mu^i_U \overline{\Psi^{Ua}_L} u^a_{iR} - \left[y^{ij}_{QL}\overline{(Q^a_i)^C}(i\sigma_2)L_j + y^{ij}_{UE}\overline{(u^a_{iR})^C} e_{jR}\right](\xi^a)^*$$
$$- \epsilon_{abc}\left[y^{ij}_{QQ}\overline{(Q^b_i)^C}(i\sigma_2)Q^c_j + y^{ij}_{UD}\overline{(u^b_{iR})^C} d^c_{jR}\right](\zeta_a)^* - y^i_{\Psi D}\epsilon_{abc}\overline{(\Psi^{Ua}_R)^C} d^b_{iR}\,\omega^c$$
$$- \lambda'\, \xi^a \xi^b \zeta_a (\omega^b)^* + \text{H.c.}$$

- **Predict di-nucleon decay** (No proton decay, while deuteron decays)

$$\tau_{pp\to e^+e^+} = \Gamma^{-1}_{pp\to e^+e^+} \simeq (5\times 10^{33}\,\text{yrs}) \times \left(\frac{M_\omega}{2\,\text{TeV}}\right)^4 \left(\frac{M_\zeta}{2\,\text{TeV}}\right)^4 \left(\frac{M_\xi}{2\,\text{TeV}}\right)^8$$
$$\times \left(\frac{0.2}{\mu^1_U/M_\Psi}\right)^2 \left(\frac{1}{|\lambda'|}\right)^2 \left(\frac{1}{|y^{11}_{UD}|}\right)^2 \left(\frac{1}{|y^{11}_{UE}|}\right)^4 \left(\frac{1}{|y^{1}_{\Psi D}|}\right)^2$$

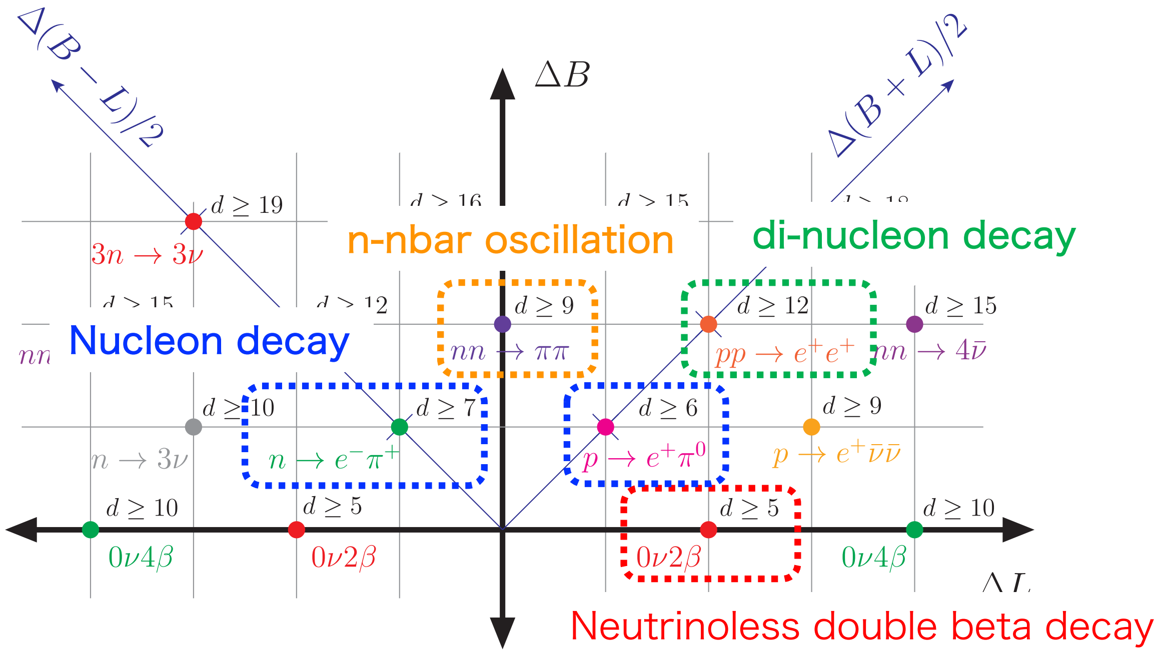
SK bound： > 4.2 x 10^{33} s

✓ Within the collider reach

✓ Severe constraint from flavor exp

Summary

- Established a method to construct a model w/ PQ = αB+βL
- Model w/ **B and L symmetry** might be interesting



Thank you

B#V and L#V are good probe for uncovering New Physics !!

Backup

PQWW axion

Weinberg (78), Wilczek (78)

- Higgs doublet in the SM is a complex scalar
  - ✓ 3 NGBs (from EW sym breaking) are absorbed by W/Z bosons

    → No NGB for PQ mechanism
  - ✓ 2HDM (2 Higgs doublet model) with global sym : axion = CP-odd Higgs

    → PQ mech works!! PQ sym breaking scale = EW scale $f_a = \sqrt{v_u^2 + v_d^2}$

$$\mathcal{L}_{\rm 2HDM} = +\overline{Q} Y_u H_u u_R + \overline{Q} Y_d H_d d_R - V(H_u, H_d) \leftarrow +\cancel{\lambda_5 (H_u^\dagger H_d)}^2$$

- Prediction : $\mathcal{B}(K^+ \to \pi^+ a) \approx \frac{f_\pi^2}{f_a^2} \times \mathcal{B}(K^+ \to \pi^+ \pi^0) \sim 10^{-5}$ Ruled out!!

- Invisible (DFSZ) Axion (introduce additional scalar singlet S)

$$H_u^T (i\sigma_2) H_d (S^*)^2 \quad \Rightarrow \quad f_a = \sqrt{v_S^2 + v_u^2 v_d^2 / v_S^2}$$ Large VEV → suppressed int

Zhitnitsky (80), Dine-Fischier-Srednicki (81)

Determination of B#

- **Assume Yukawa int among S and KSVZ quarks**

$$\mathcal{L}_{\rm KSVZ} = Y_\Psi \, S \, \overline{\Psi}_L \Psi_R + {\rm H.c.}$$

- **Determine L# and B# of S by higher d operators**

$$\mathcal{L}_{\rm eff} = \kappa \, S^* u_R d_R Q L + {\rm H.c.}$$

(In this stage, **B#** and **L#** syms are assumed)

- **When S acquire VEV** $U(1)_{\rm B} \times U(1)_{\rm L} \rightarrow U(1)_{\rm B-L}$

NGB of B+L breaking becomes axion

	S	Ψ_L	Ψ_R
$\mathrm{SU}(3)_C$	$\mathbf{1}$	$\mathbf{3}\,(\mathbf{6},\mathbf{8},\cdots)$	$\mathbf{3}\,(\mathbf{6},\mathbf{8},\cdots)$
$\mathrm{SU}(2)_L$	$\mathbf{1}$	$\mathbf{1}\,(\mathbf{2},\mathbf{3},\cdots)$	$\mathbf{1}\,(\mathbf{2},\mathbf{3},\cdots)$
$\mathrm{U}(1)_Y$	0	$-$	$-$
$\mathrm{U}(1)_{\rm PQ}$	-2	-1	$+1$
$\mathrm{U}(1)_\Psi$	0	$+1$	$+1$
$\mathrm{U}(1)_L$	$+1$	$-$	$-$
$\mathrm{U}(1)_B$	$+1$	$-$	$-$

Previous example :

L# may be broken from the beginning

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

In this case, PQ = B#

Sakhaxion (Axion = Sakharon)