2025.8.26 TWENTY-SECOND LOMONOSOV CONFERENCE
ON ELEMENTARY PARTICLE PHYSICS

Spontaneous CP violation, sterile neutrino dark matter and leptogenesis

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Jiang, **NY**, Phys.Lett.B 862 (2025) 139331

Strong CP problem

- The QCD vacuum state, which is an eigenstate of the both small and large gauge transformations, is parametrized by theta-term

$$\mathcal{L} \ni \frac{g_s^2 \bar{\theta}}{16\pi^2} \mathrm{tr}(G_{\mu\nu}\tilde{G}^{\mu\nu}) \qquad \bar{\theta} = \theta_0 + \arg\det(M_u) + \arg\det(M_d)$$

Non-zero $\bar{\theta}$ induces neutron EDM $(\propto \bar{\theta})$ $\quad |d_n| < 1.8 \times 10^{-26}\, e\,\mathrm{cm}$ (from experiment)

[Phys.Rev.Lett. 124 (2020) 8, 081803]

Constraint: $\bar{\theta} \lesssim 10^{-10}$ ⟷ Expectation: $\bar{\theta} \sim 1$

tension

No anthropic reason

[Ubaldi, Phys.Rev.D 81 (2010) 025011]

Spontaneous CP violation (SCPV)

- The CP is an exact symmetry of the Lagrangian but the ground state breaks it
- The theta-term is absent and all the couplings are real
- The CP symmetry is spontaneously broken and the CKM phase is generated, keeping $\arg\det(M_q) \approx 0$

$\bar{\theta} < 10^{-10}$

Challenges:

- To keep $\arg\det(M_q) < O(10^{-10})$
- To generate the baryon asymmetry of the universe (no CPV in the Lagrangian, c.f. Sakharov 3 conditions)
- Unlike axion solution, dark matter is not included

The minimal model (Bento-Branco-Parada)

- A pair of vector-like heavy quarks (down-type) and a new scalar that has a complex VEV are introduced
- The new scalar couples to down-type quarks to explain the CPV phase in CKM
- 4 x 4 matrix takes a from such that $\arg\det(M_d) \approx 0$

The mass term: $\overline{d'_L} M_d d'_R + h.c.$

4x4 matrix

$$M_d = \begin{pmatrix} m_{d,ij} & 0 \\ B_{d,k} & \mu_D \end{pmatrix}$$

$$\arg\det(M_d) = 0$$

$$V^\dagger_{d_L} M_d U_{d_R} = \mathrm{diag}(m_d, m_s, m_b, m_D \sim \mu_D)$$

$$B_{d,k} \sim \mu_D \ (\text{required})$$

complex elements that lead to the CKM phase

[Bento, Branco, Parada, Phys. Lett. B267 (1991), 95-99]

More details

- Extended down-quark mass matrix

SM Yukawa interaction

$$y_{d,ij}\overline{Q_L}Hd_{j,R} + h.c.$$

$$+\left[\underbrace{(k_i S + k_i' S^*)}_{B_{d,i}}\overline{D_L}d_{i,R} + \mu_D \overline{D_L}D_R'\right] + h.c.$$

The complex mass parameters, after $S \to \langle S \rangle$

- Introduction of a discrete symmetry to obtain the VEV with a complex phase (the phase direction has to be fixed)

$$S \to -S,\ D_L \to -D_L,\ D_R' \to -D_R'$$

- Because of Z_2 symmetry, there are two degenerated (and discrete) vacua, for $\langle S \rangle = \pm C$

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- Because of Z_2 symmetry, there are two degenerated (and discrete) vacua, for $\langle S \rangle = \pm C$

This causes **the cosmological domain wall problem** if $T_{max} > |\langle S \rangle|$

Dangerous operators

The solution can be easily spoiled by higher dimensional operators

$$M_d = \begin{pmatrix} m_{d,ij} & 0 \\ B_{d,k} & \mu_D \end{pmatrix} + \delta M_d \qquad \delta M_d = \begin{pmatrix} \delta a & \delta b \\ 0 & \delta c \end{pmatrix}$$

For instance,

$$\delta b \ni \frac{c_b \langle S \rangle + c_b' \langle S \rangle^*}{M_*} \overline{Q_L} H D_R'$$ allowed by the symmetry

$$\theta < \mathcal{O}(10^{-10})$$ ➡ $|\langle S \rangle| < 10^8 \text{ GeV}$ for $M_* = M_{\rm PL}$

The symmetries alone are difficult to suppress the dangerous operators

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$$\theta < \mathcal{O}(10^{-10}) \qquad T_{max} < \; |\langle S \rangle| < 10^8 \ \text{GeV} \quad \text{for} \quad M_* = M_{\text{PL}}$$

The symmetries alone are difficult to suppress the dangerous operators

Challenges

- Because of the domain wall problem, $T_R < S < 10^8$ GeV
- Tension with leptogenesis (T_R and no CPV parameters in the Lagrangian)
- No dark matter candidate
- Lack of explanation of neutrino masses and oscillations

We look for a simple model that addresses the above issues

Setup of our model in 5D

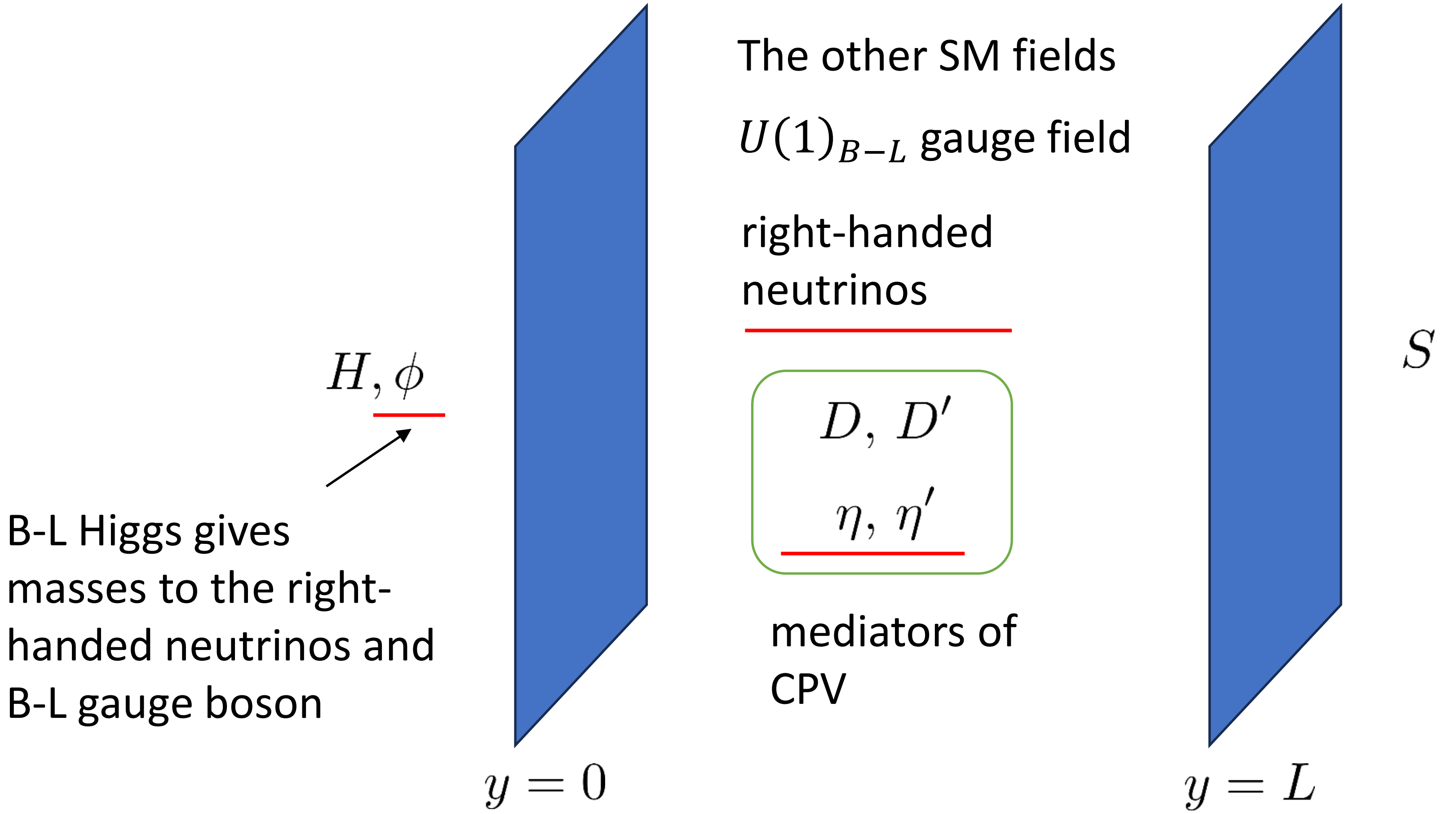
- Gauged $U(1)_{B-L}$ and introduce *B-L* Higgs and right-handed neutrinos
- Introduce the fifth-dimension
- We have another way to control the Lagrangian, geometry
- Introduce a pair of mediator to generate leptonic CP violating phases

$$ds^2 = (dx^0)^2 - \sum_{i=1}^{3}(dx^i)^2 - dy^2$$

Setup of our model in 5D

$G_{SM} \otimes U(1)_{B-L}$

$G_{SM} = SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$

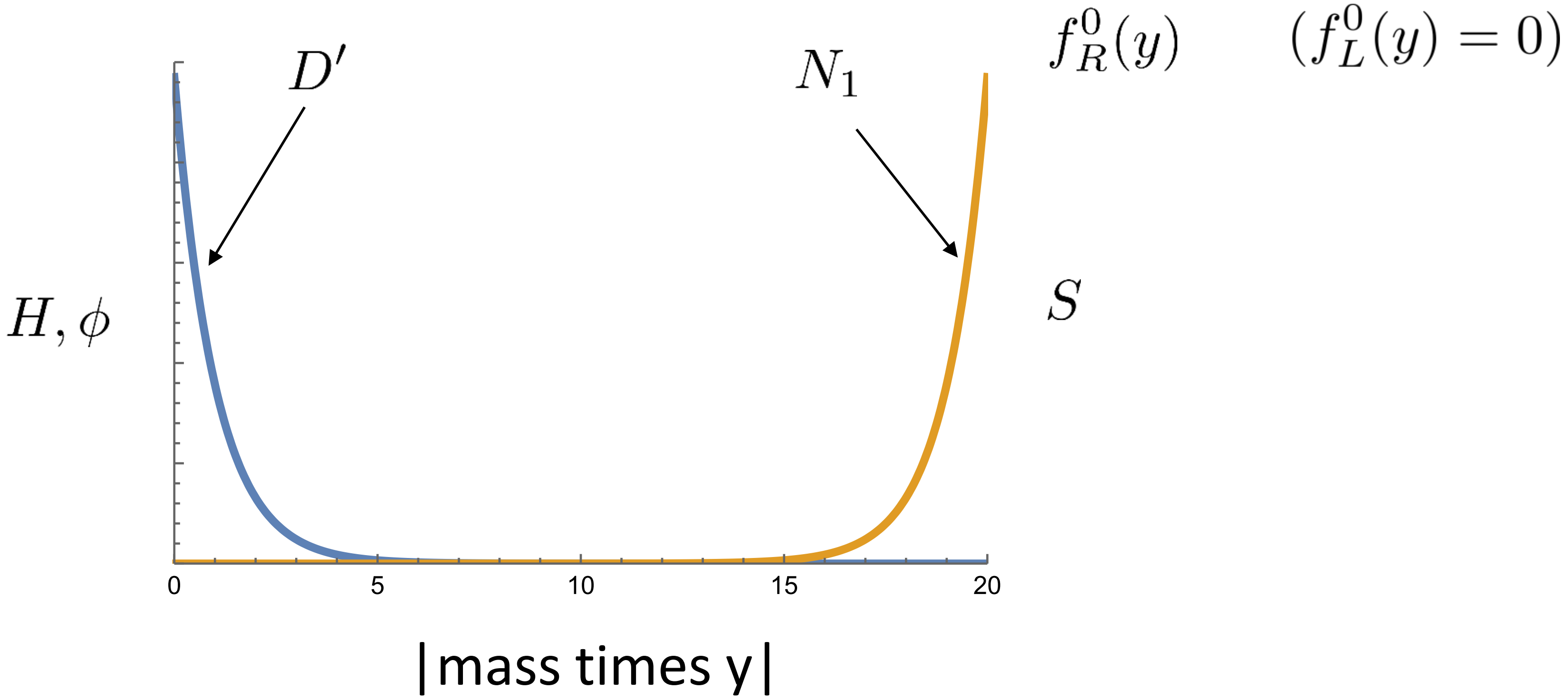


With orbifolding

S_1/Z_2

With a bulk mass term, zero-mode has an exponentially localized wave-function in the *y*-direction

$$\mathcal{L}_{\text{bulk}} \ni +m_b \overline{N}_1 N_1 - m_b' \overline{D'} D'$$

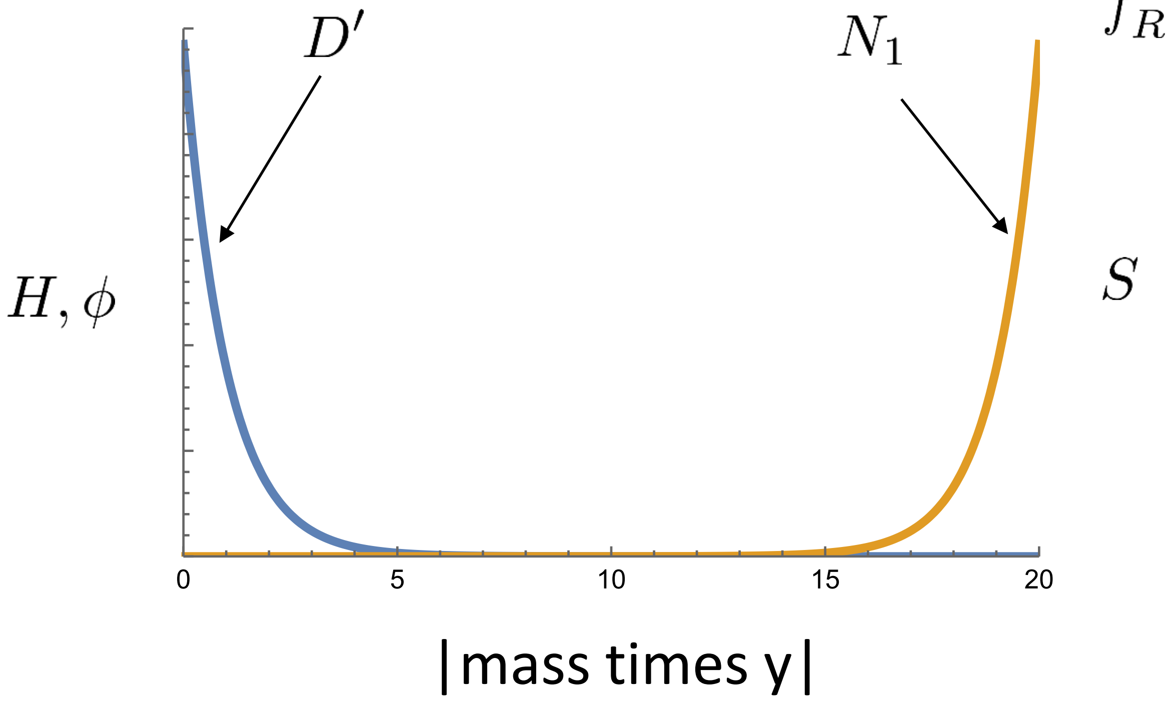


$$\psi_R(x,y) = \frac{1}{\sqrt{L}} \sum_n f_R^n(y) \psi_R^n(x)$$

With a bulk mass term, zero-mode has an exponentially localized wave-function in the *y*-direction

$$\mathcal{L}_{\text{bulk}} \ni +m_b \overline{N}_1 N_1 - m_b' \overline{D'} D'$$

$f_R^0(y) \qquad (f_L^0(y) = 0)$



Dangerous operators are suppressed exponentially: $\langle S \rangle$ and T_R can be larger

$$\frac{c_{i,a} S^2 + c'_{i,a} S^{*\,2}}{M_*^2} \overline{Q_L} H d_{i,R} \qquad \frac{c_b S + c_b' S^*}{M_*} \overline{Q_L} H D'_R \qquad \frac{c_c S^2 + c_c' S^{2\,*}}{M_*^2} \overline{D_L} D'_R$$

With a bulk mass term, zero-mode has an exponentially localized wave-function in the *y*-direction

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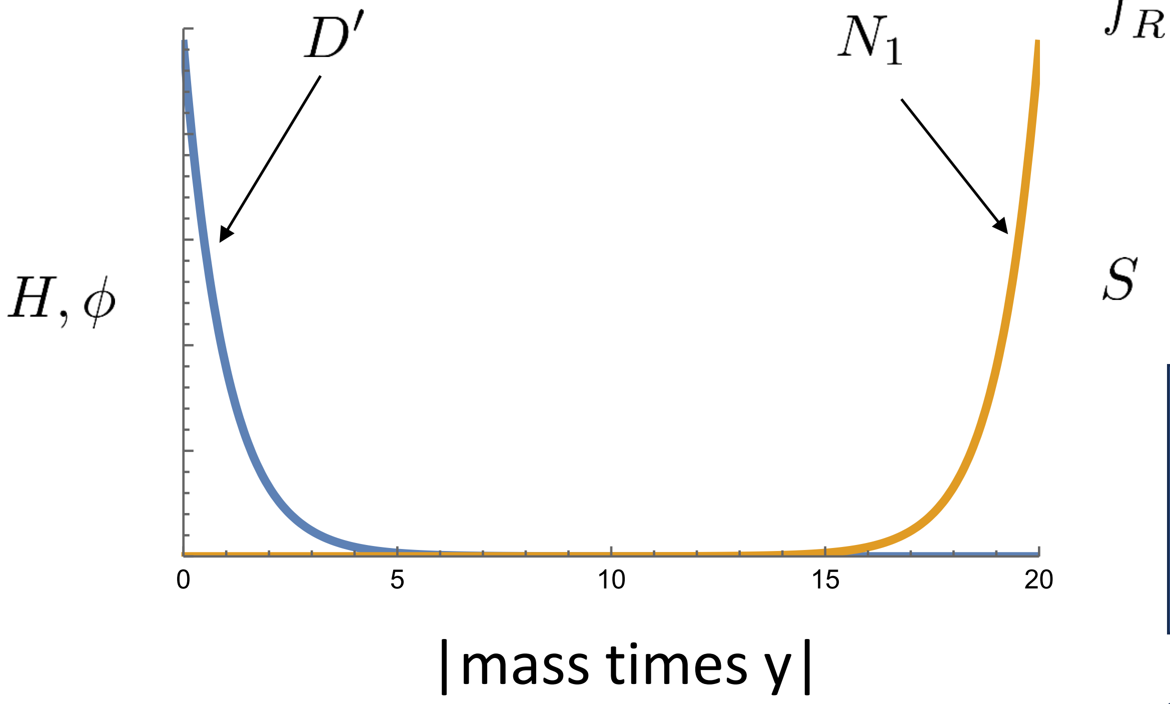


This is essential for $N_{R,1}$ being dark matter

The coupling and mass for the zero mode is exponentially suppressed

$$y_{\nu,i1} \overline{L}_i H N_{R,1}, \ \frac{1}{2} M_{N,1} \overline{(N_{R,1})^c} N_{R,1} \quad \Rightarrow \quad \frac{y_{\nu,i1}}{L} e^{-m_b L} \overline{L_i^0} H N_{R,1}^0, \ \frac{1}{2} \frac{M_{N,1}}{L} e^{-2m_b L} \overline{(N_{R,1}^0)^c} N_{R,1}^0$$

- (Exponential) localization allows us to suppress the dangerous operators
- Localization naturally makes the lightest right-handed neutrino a dark matter candidate (with extremely small mixing and mass)

- These features cannot be achieved by symmetries alone.

Sterile neutrino dark matter

- The right-handed neutrino with a mass of $O(10-100)$ keV can be dark matter

(From now on, we focus on the zero-modes and suppress the index 0)

Sterile neutrino dark matter

- The right-handed neutrino with a mass of $O(10-100)$ keV can be dark matter

$$\frac{y_{\nu,i1}}{L} e^{-m_b L} \overline{L}_i H N_{R,1}, \quad \frac{1}{2} \frac{M_{N,1}}{L} e^{-2m_b L} \overline{(N_{R,1})^c} N_{R,1}$$

$$m_b L = 20 \Rightarrow \exp(-20) \approx 2.1 \times 10^{-9}$$

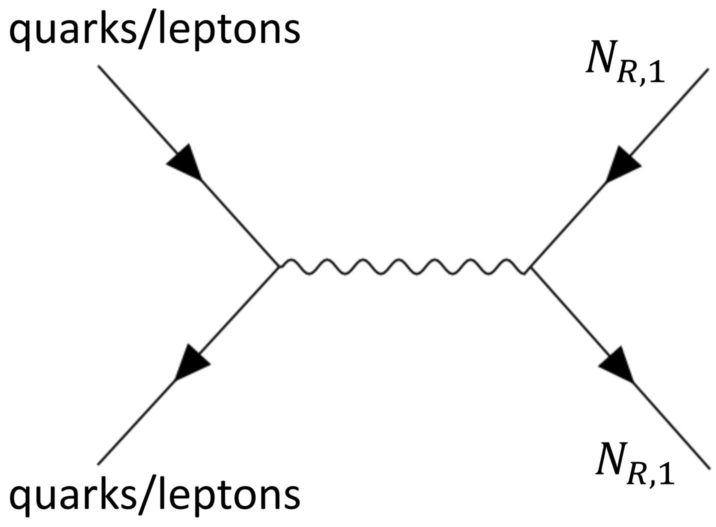
$$\frac{M_{N,1}}{L} e^{-2m_b L} \sim 10\text{keV}$$ **is natural**

- The Yukawa coupling and mass are highly suppressed
- This is important to avoid the gamma ray constraint

$N_{R,1} \to \gamma + \nu_i$ (one-loop)

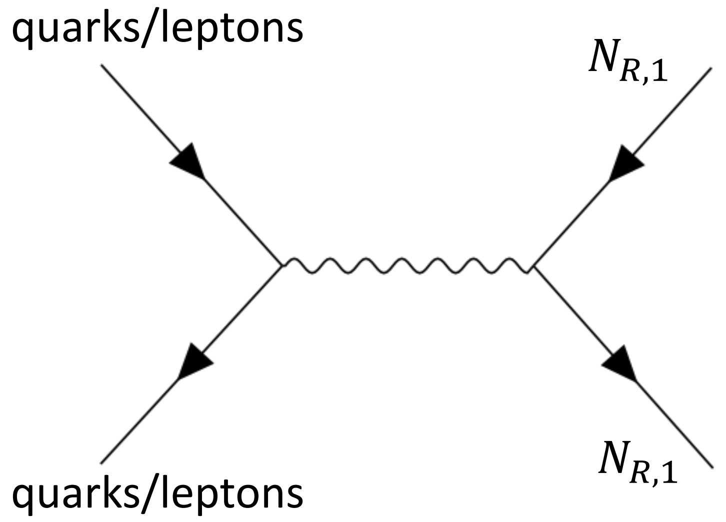
Production of the sterile neutrino dark matter

- Because of extremely small Yukawa coupling, the Yukawa interaction is essentially negligible for production
- The main production is through $U(1)_{B-L}$ gauge interaction
- No viable solution is found when the sterile neutrino DM is thermalized (it can not fit to the oscillation data)



Non-thermalized case

- Even in this case, $N_{R,1}$ is created from SM particles (SM particles are in the thermal bath)
- For the largest temperature, the production is most efficient



It can explain 100% of dark matter

$$\Omega_{N_1} \approx 0.26 \times \left(\frac{M_1}{50\,\mathrm{keV}}\right)\left(\frac{T_R}{10^{10}\mathrm{GeV}}\right)^3\left(\frac{3\times 10^{12}\,\mathrm{GeV}}{v_{B-L}}\right)^4$$

Leptogenesis

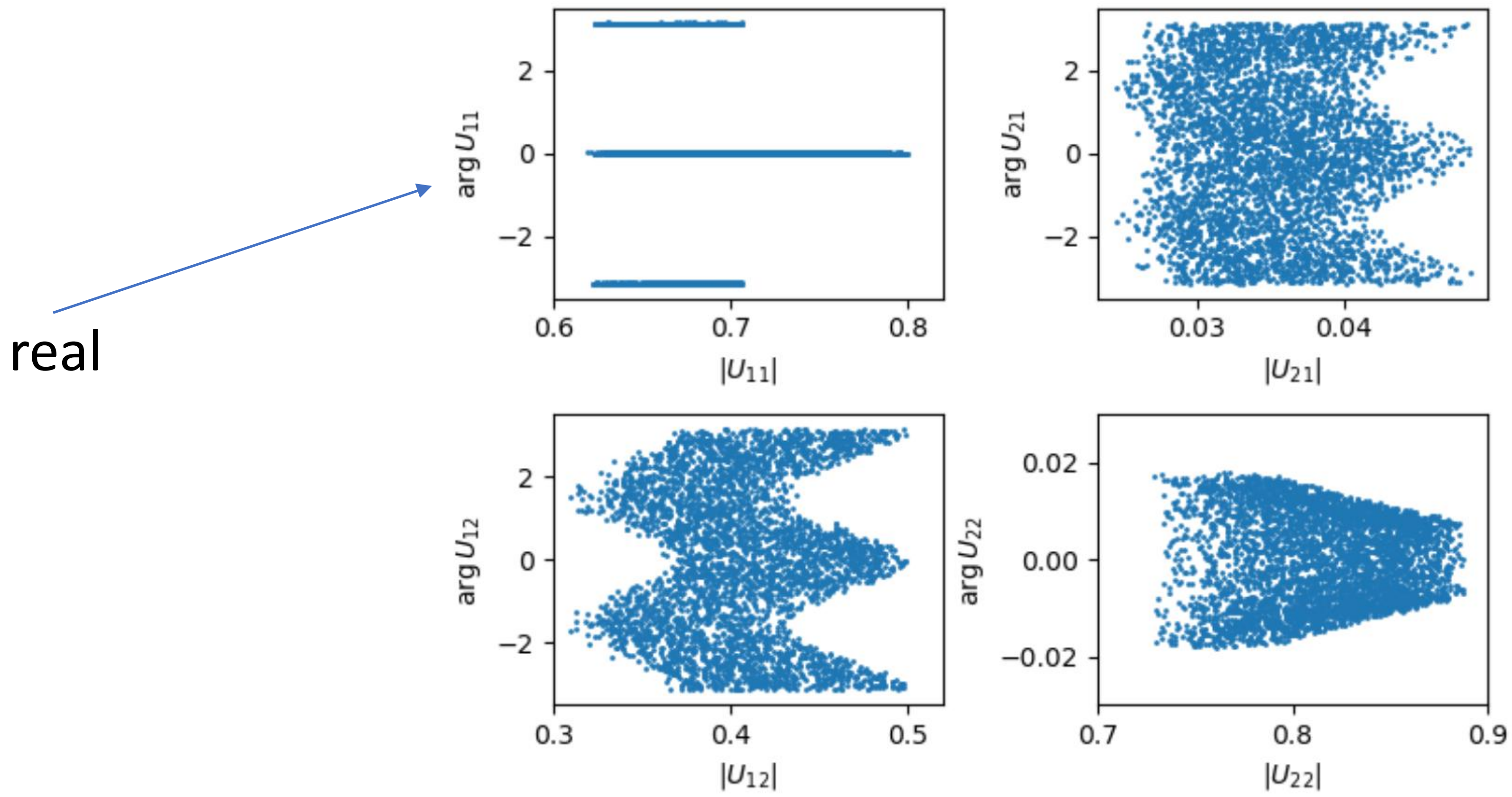
- The next to lightest right-handed neutrino is responsible for leptogenesis
- The heaviest one is important through loops as well

The relevant effective Lagrangian for zero-modes is

$$\begin{aligned} -\mathcal{L} &\ni \overline{\eta_L}(C_2 N_{2,R} + C_3 N_{3,R} + \mu_\eta \eta'_R) + h.c. \\ &+ \sum_{i=2,3} \frac{1}{2} M_{N,i} \overline{(N_{i,R})^c} N_{i,R} + h.c., \end{aligned}$$

C_2 and C_3 are complex parameter coming from

$$S \ni \int d^4x dy \mathcal{L}_2 \delta(y-L), \quad \mathcal{L}_2 \ni -(l_j S + l'_j S^*)\overline{\eta_L} N_{R,j} + h.c.$$



$M_{N,2}/\mu_\eta = 10^{-2}$ and $M_{N,3}/\mu_\eta = 10^{-1}$,

$|C_2/\mu_\eta| = [0.8, 1.2],\ |C_3/\mu_\eta| = [0.8, 1.2],$
$\arg(C_2) = [-\pi, \pi],\ \arg(C_3) = [-\pi, \pi].$

- There are O(1) complex phases required for leptogenesis
- Dark matter and baryon asymmetry of the universe are explained for e.g.

$$M_{N,2} = 2 \times 10^{10}\,\text{GeV} \qquad v_{B-L} = \mathcal{O}(10^{12})\,\text{GeV}$$

with the hierarchy $v_{B-L} > \langle S \rangle > T_R > M_{N,2}$

Conclusion

- 5D model can suppress the dangerous operators which are not forbidden solely from the symmetries
- It is easy to avoid the domain wall problem, and the cosmology will be more flexible
- The lightest right-handed neutrino is dark matter, the required small parameters are naturally explained in 5D
- The baryon asymmetry of the universe is explained by the other two right-handed neutrinos
- The gamma ray constraint is severe. In other words, the gamma ray originated from the sterile neutrino DM may be observed in future