Phenomenology of a Supersymmetric Pati-Salam Model

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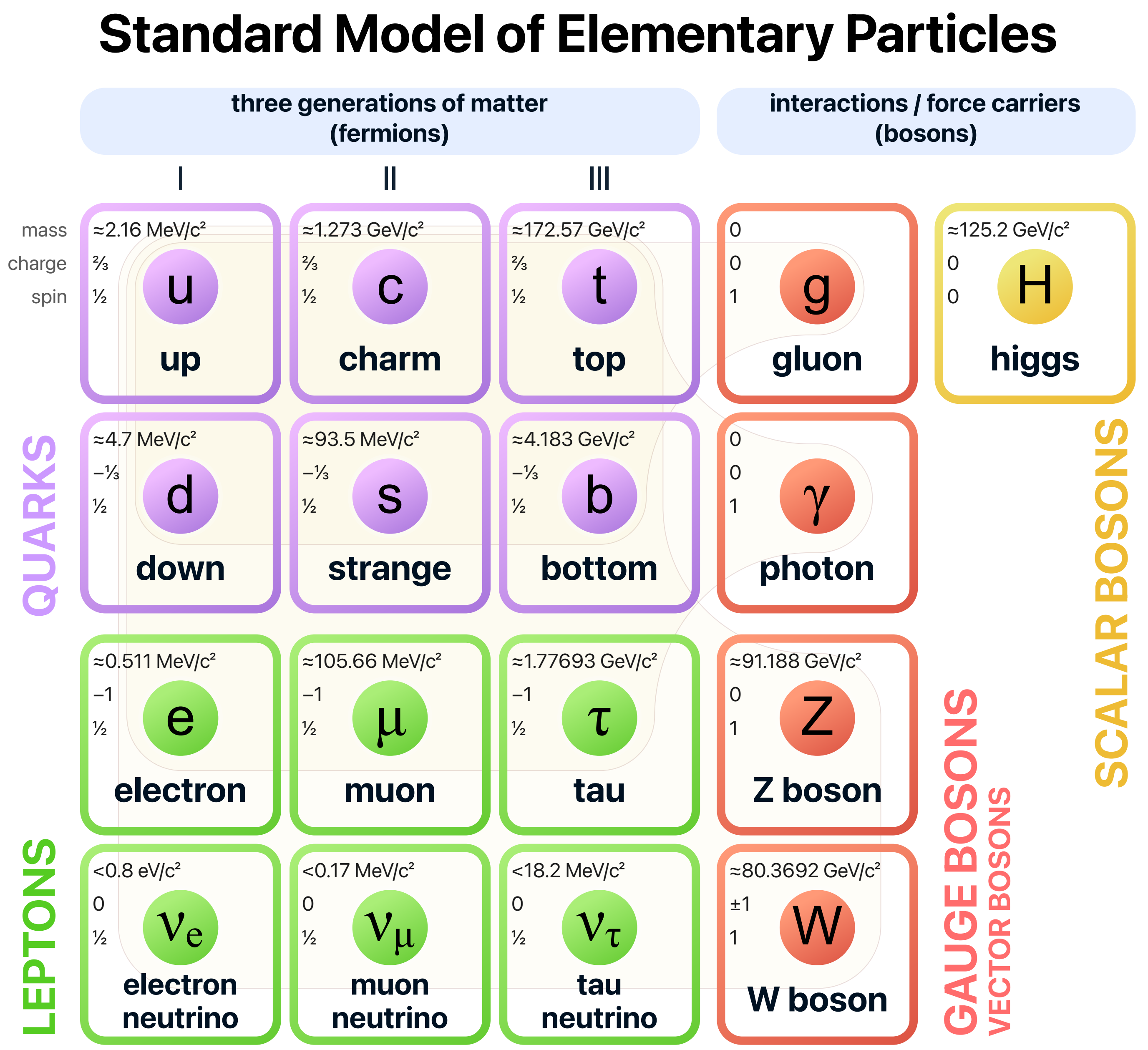
Based on 2502.15614 (G. Leontaris, RO & Y.L. Zhou)

1. Introduction

Introduction



- Left-handed fermions: $F_L = (4,2,1)$

$$= \left(u_L^{c_1}, d_L^{c_1}, u_L^{c_2}, d_L^{c_2}, u_L^{c_3}, d_L^{c_3}, \ell_L, \nu_L^{\ell}\right)$$

- Right-handed fermions: $\bar{F}_R = (\bar{4},1,2)$

$$= \left(u_R^{c_1}, d_R^{c_1}, u_R^{c_2}, d_R^{c_2}, u_R^{c_3}, d_R^{c_3}, \ell_R, \nu_R^{\ell}\right)$$

- Three generations of quarks and leptons are embedded into five representations

$$(\mathbf{3},\mathbf{2})_{1/6} + (\bar{\mathbf{3}},\mathbf{1})_{-2/3} + (\bar{\mathbf{3}},\mathbf{1})_{1/3} + (\mathbf{1},\mathbf{2})_{-1/2} + (\mathbf{1},\mathbf{1})_{1}\,.$$

transforming under the gauge group

$$\mathscr{G}_{\mathrm{SM}} = \mathrm{SU}(3)_C \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y\,,$$

- The SM is not complete: it is an effective field theory (EFT) valid below a cutoff scale Λ.

- The Pati-Salam (PS) model is based on the $\mathrm{SU}(4)_C \times \mathrm{SU}(2)_L \times \mathrm{SU}(2)_R$ gauge symmetry, with the quarks and leptons of each generation grouped together in the representations $F_L + \bar{F}_R = (4,2,1) + (\bar{4},1,2)$.

- The PS gauge group is one of the simplest extensions of the SM, which also arises as an intermediate step between a fully unified theory such as SO(10) or E6 and the SM gauge group.

Pati-Salam Model

Basic building blocks of Pati Salam model:

- Gauge symmetry: $\mathrm{SU}(4)_C \times \mathrm{SU}(2)_L \times \mathrm{SU}(2)_R$;
- SM fermions + right-handed neutrinos: $F_L^i + \bar{F}_R^i = (4,2,1) + (\bar{4},1,2)\ (i = 1,2,3)$;
- Higgs fields: $h^a = (1,2,2)$, $\Sigma = (15,2,2)$, $\Delta = (10,1,3)$, … (Depending on SSB pattern).

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Large representations is necessarily introduced in the traditional PS approach!

Problems

However, large representations can be problematic in the following senses:

- It results in large beta coefficients of gauge couplings, making them rapidly growing into non-perturbative regime or even Landau pole beyond the GUT scale.

- It introduces many new degrees of freedom which stay heavy at the GUT scale, which requires certain fine-tuning to obtain light fields when the large representation is decomposed. This is similar to the Doublet-triplet splitting (DTS) problem in SU(5). The extended survival hypothesis is often applied to avoid the problem.
[Georgi '79; del Aguila & Ibanez '81;Mohapatra & Senjanovic '83; Dimopoulos & Georgi '84]

- It makes scalar potential and the corresponding vacuum structure very complicated. In particular it may be hard to realize a desired good vacuum.
[Dev, Mohapatra, Rodejohann & Xu '18]

- In several appealing string-derived constructions such as the heterotic string models, large representations, especially the adjoints, are not available.
[Leontaris & Rizos '99]

Motivation

The question we ask: can we only use small representations to construct a GUT model that is consistent with a string theory completion?

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The question we ask: can we only use small representations to construct a GUT model that is consistent with a string theory completion?

- We introduce supersymmetry so that the PS model could be UV completed to some string models.
- However, without the adjoints, the PS model predicts a tree-level mass relation $M_d = M_e$ for all three generations at PS scale, because all masses of the chiral fermions arise from a single term, namely $F_L \bar{F}_R h$.
- Therefore, we try to look for higher order corrections to find possible ways to split the mass relation.

2. Model details

SUSY-PS Model

In the supersymmetric Pati Salam model, the building blocks are generalized to: [Antoniadis & Leontaris ’89]

- Gauge symmetry: $\mathrm{SU}(4)_C \times \mathrm{SU}(2)_L \times \mathrm{SU}(2)_R$;
- Global symmetry: supersymmetry, $U(1)_R$ symmetry, $\mathbb{Z}_n$ symmetry;
- SM fermions + right-handed neutrinos: $F_L^i + \bar{F}_R^i = (4{,}2{,}1) + (\bar{4}{,}1{,}2)\ (i = 1{,}2{,}3)$;
- Higgs fields: $h^a = (1{,}2{,}2)$, $H_R = (4{,}1{,}2)$, $\bar{H}_R = (\bar{4}{,}1{,}2)$, …;
- Sextets mediating the higher-order corrections: $T = (6{,}1{,}1)$, $D = (6{,}1{,}1)$;
- Singlets: $\phi = (1{,}1{,}1)$, $\psi^m = (1{,}1{,}1)$.

- The smallest possible representations to break the $SU(4)_C \times SU(2)_R$ symmetry are the bi-fundamentals $(4,1,2)+(\bar{4},1,2)$ (Antoniadis & Leontaris '89).
- We observed that adding the Higgses in the bi-fundamentals $H_L + \bar{H}_L = (4,2,1)+(\bar{4},2,1)$ generate sizable quantum corrections to split masses of down quarks with leptons.
- Singlets $(1,1,1)$ and sextets $(6,1,1)$ are naturally present due to the fusion rules $4 \times \bar{4} = 1$ and $4 \times 4 = 6 + 10$. They usually comes in pairs with distinct R-charges in string derived models.

Notations	Superfields	PS reps	$U(1)_R$	$\mathbb{Z}_3$ charge
SM fields	$F_L^{i=1,2,3}$	$(4,2,1)$	1	0
	$\bar{F}_R^{j=1,2,3}$	$(\bar{4},1,2)$	1	0
	$h^{a=1,2}$	$(1,2,2)$	0	0
Sextets	T	$(6,1,1)$	1	1
	D	$(6,1,1)$	0	2
Higgs 4-plets	H_L	$(4,2,1)$	0	2
	$\bar{H}_R$	$(\bar{4},1,2)$	0	2
	$\bar{H}_L$	$(\bar{4},2,1)$	0	2
	H_R	$(4,1,2)$	0	2
Singlets	ϕ	$(1,1,1)$	0	1
	$\psi^{m=1,\ldots,N_\psi}$	$(1,1,1)$	1	1

The minimal spectrum

[Leontaris, RO & Zhou '25]

- The model introduces $U(1)_R$ symmetry to constrain the superpotential.

- The gauge singlets ϕ, once introduced, must be non-trivially charged under a discrete symmetry, which is assumed to be a typical $\mathbb{Z}_3$, to avoid having massless Goldston bosons after spontaneous symmetry breaking, otherwise it will gives a universal large mass to every neutral pairs by the vev v_ϕ.

- The vev of ϕ implies the existence of an intermediate scale $\langle\phi\rangle \equiv v_\phi < v_R$ that is crucial to the generation of hierarchies, and it is convenient to parametrize the ratio of scales by $r \equiv v_\phi/v_R \ll 1$ (in our analysis, we adopt $r < 10^{-1}$ for concreteness.)

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SM fields	$F_L^{i=1,2,3}$	$(4,2,1)$	1	0
	$\bar{F}_R^{j=1,2,3}$	$(\bar{4},1,2)$	1	0
	$h^{a=1,2}$	$(1,2,2)$	0	0
Sextets	T	$(6,1,1)$	1	1
	D	$(6,1,1)$	0	2
Higgs 4-plets	H_L	$(4,2,1)$	0	2
	$\bar{H}_R$	$(\bar{4},1,2)$	0	2
	$\bar{H}_L$	$(\bar{4},2,1)$	0	2
	H_R	$(4,1,2)$	0	2
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The minimal spectrum

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Superpotential

- The most general superpotential consists of 4 parts: $W = W_F + W_D + W_\phi + W_h$;

$$\begin{aligned} W_F &= y_a^{ij} F_L^i \bar{F}_R^j h^a + y_L^i F_L^i H_L T + y_R^j \bar{F}_R^j \bar{H}_R T + y_\psi^{jm} \bar{F}_R^j H_R \psi^m + \lambda_\psi^{im} F_L \bar{H}_L \psi^m \\ W_D &= \lambda_{H_L} D H_L H_L + \lambda_{\bar{H}_L} D \bar{H}_L \bar{H}_L + \lambda_{H_R} D H_R H_R + \lambda_{\bar{H}_R} D \bar{H}_R \bar{H}_R \,, \\ W_\phi &= y_\phi^{mn} \psi^m \psi^n \phi + y_T T T \phi + \lambda_\phi \phi^3 \,, \\ W_h &= \mu_1 h_1^2 + \mu_2 h_2^2 + \mu_{12} h_1 h_2 \,. \end{aligned}$$

- SM quarks and leptons become massive by the first operator in W_F after EW Higgs h acquiring vevs. The second and third terms in W_F generates sizable corrections to masses of down quarks after integrating out heavy sextet mediator T.

- The tree-level $b - \tau$ mass relation $m_b = m_\tau$ will be deformed by the effective operator:

$$(y_L M_T^{-1} y_R^T)^{ij} (F_L^i H_L)(\bar{F}_R^j \bar{H}_R) \to (y_L M_T^{-1} y_R^T)^{ij} v_L \bar{v}_R (d_i d_j^c).$$

- Light neutrinos are predicted when double seesaw mechanism are triggered by the forth term, while the fifth term contribute to neutrino masses via linear seesaw mechanism.

Mass Matrices

- The most general superpotential consists of 4 parts: $W = W_F + W_D + W_\phi + W_h$;

$$W_F \;=\; y_a^{ij} F_L^i \bar{F}_R^j h^a + y_L^i F_L^i H_L T + y_R^j \bar{F}_R^j \bar{H}_R T + y_\psi^{jm} \bar{F}_R^j H_R \psi^m + \lambda_\psi^{im} F_L \bar{H}_L \psi^m$$

- The mass matrices for quark and lepton are now:

$$\begin{aligned} m_u^{ij} &= y_1^{ij} v_u^1 + y_2^{ij} v_u^2 \,, \\ m_d^{ij} &= y_1^{ij} v_d^1 + y_2^{ij} v_d^2 - (y_L M_T^{-1} y_R^T)^{ij} v_L \bar{v}_R \,, \\ m_e^{ij} &= y_1^{ij} v_d^1 + y_2^{ij} v_d^2 \,, \\ m_{\nu_D}^{ij} &= y_1^{ij} v_u^1 + y_2^{ij} v_u^2 \,. \end{aligned}$$

- The mass matrix of neutrinos in the basis (ν, ν^c, ψ) is given by:

$$\begin{pmatrix} 0 & m_{\nu_D}^{ij} & \lambda_\psi^{im} \bar{v}_L \\ m_{\nu_D}^{ji} & 0 & y_\psi^{jm} v_R \\ \lambda_\psi^{mi} \bar{v}_L & y_\psi^{mj} v_R & y_\phi^{mn} v_\phi \end{pmatrix} \equiv \begin{pmatrix} 0 & m_u^{ij} & m_L^{im} \\ m_u^{ji} & 0 & m_R^{jm} \\ m_L^{mi} & m_R^{mj} & m_\psi^{mn} \end{pmatrix} ,$$

and thus,

$$m_\nu = m_u (m_R^T)^{-1} m_\psi (m_R)^{-1} m_u^T - m_L (m_R)^{-1} m_u^T - m_u (m_R^T)^{-1} m_L^T \,.$$

Color triplets

- The second part of the superpotential is important for generating masses for the color triplets:

$$W_D = \lambda_{H_L} D H_L H_L + \lambda_{\bar{H}_L} D \bar{H}_L \bar{H}_L + \lambda_{H_R} D H_R H_R + \lambda_{\bar{H}_R} D \bar{H}_R \bar{H}_R \,,$$

- Decomposing the superfields under the SM gauge symmetry, we have:

$$D \to D_3(3,1,-\frac{1}{3}) + \bar{D}_3(\bar{3},1,\frac{1}{3}), \quad H_R \to \bar{u}^c_{H_R}(3,1,\frac{2}{3}) + \bar{d}^c_{H_R}(3,1,-\frac{1}{3}) + \bar{e}^c_{H_R}(1,1,-1) + \bar{\nu}^c_{H_R}(1,1,0), \quad \ldots$$

- When the $SU(4)_C$ gauge symmetry is broken , $\bar{u}^c_{H_R}$ and $\bar{e}^c_{H_R}$ fields, etc, are "eaten" by the Higgs mechanism, leaving only color triplets $d^c_{H_R}$ and $\bar{d}^c_{H_R}$ as "uneaten" fields. The superpotential produces mixings between color triplet states $\bar{d}^c_{H_R}$, $d^c_{H_R}$ and $\bar{D}_3$, D_3 correspondingly:

$$\lambda_{H_R} H_R H_R D + \lambda_{\bar{H}_R} \bar{H}_R \bar{H}_R D \to \lambda_{H_R} v_R \bar{d}^c_{H_R} \bar{D}_3 + \lambda_{\bar{H}_R} \bar{v}_R d^c_{H_R} D_3 \,.$$

- And similarly:

$$\lambda_{H_L} H_L H_L D + \lambda_{\bar{H}_L} \bar{H}_L \bar{H}_L D \to \lambda_{H_L} v_L d_{H_L} \bar{D}_3 + \lambda_{\bar{H}_L} \bar{v}_L \bar{d}_{H_L} D_3$$

Color triplets

- The higher order corrections are also important to generating a subleasing contributions to the mass matrices:

$$\frac{c_{H_R}}{\Lambda} H_R \bar{H}_R \phi^2 \to \frac{c_{H_R} v_\phi^2}{\Lambda} d^c_{H_R} \bar{d}^c_{H_R} ,$$
$$\frac{c_{H_L}}{\Lambda} H_L \bar{H}_L \phi^2 \to \frac{c_{H_L} v_\phi^2}{\Lambda} d_{H_L} \bar{d}_{H_L} .$$

- The mass matrices of color triplets under the basis $(d_{H_L}, \bar{d}^c_{H_R}, D_3)$ is

$$\begin{pmatrix} c_{H_L} r v_\phi & 0 & \lambda_{H_L} v_L \\ 0 & c_{H_R} r v_\phi & \lambda_{H_R} v_R \\ \lambda_{\bar{H}_L} \bar{v}_L & \lambda_{\bar{H}_R} \bar{v}_R & c_D r v_\phi \end{pmatrix} ,$$

whose eigenvalues are approximately given by (when $r \simeq 0$):

$$m_{H_L} = c_{H_L} r v_\phi + \mathcal{O}(r^3) , \quad m_{H_R,D} = \pm \sqrt{\lambda_{H_R} \lambda_{\bar{H}_R} v_R \bar{v}_R} + \mathcal{O}(r) .$$

- Therefore, lighter color triplets in H_L and $\bar{H}_L$ might reside just a few orders of magnitude below the intermediate scale v_ϕ, while heavier color triplets in H_R and $\bar{H}_R$ obtain masses at the PS scale v_R.

EW Higgs doublets

- Similar decoupling mechanism works for the heavy Higgs doublets.

- The mass matrices of Higgs doublets under basis $(h_d^1, h_d^2, \ell_{H_L})$ is:

$$\begin{pmatrix} c_{h1} r^2 v_\phi & c_{h12} r^2 v_\phi & c_2 r v_\phi \\ c_{h12} r^2 v_\phi & c_{h2} r^2 v_\phi & c_2 r v_\phi \\ c_1 r v_\phi & c_1 r v_\phi & c_{H_L} r v_\phi \end{pmatrix},$$

- whose eigenvalues are given by

$$m_{h_1} \simeq \frac{1}{2}(c_{h1} + c_{h2} - 2c_{h12}) r^2 v_\phi + \mathcal{O}(r^3)\,,$$

$$m_{h_2, \ell_{H_L}} \simeq \pm\sqrt{2c_1 c_2}\, r v_\phi + \frac{1}{4}(2c_{H_L} + c_{h1} r + c_{h2} r + 2c_{h12} r) r v_\phi + \mathcal{O}(r^2)\,.$$

- In conclusion, only one pair of Higgs doublets remains light at the EW scale set by the scale of μ term. The other two pairs of Higgs doublets will acquire masses near the intermediate scale v_ϕ.

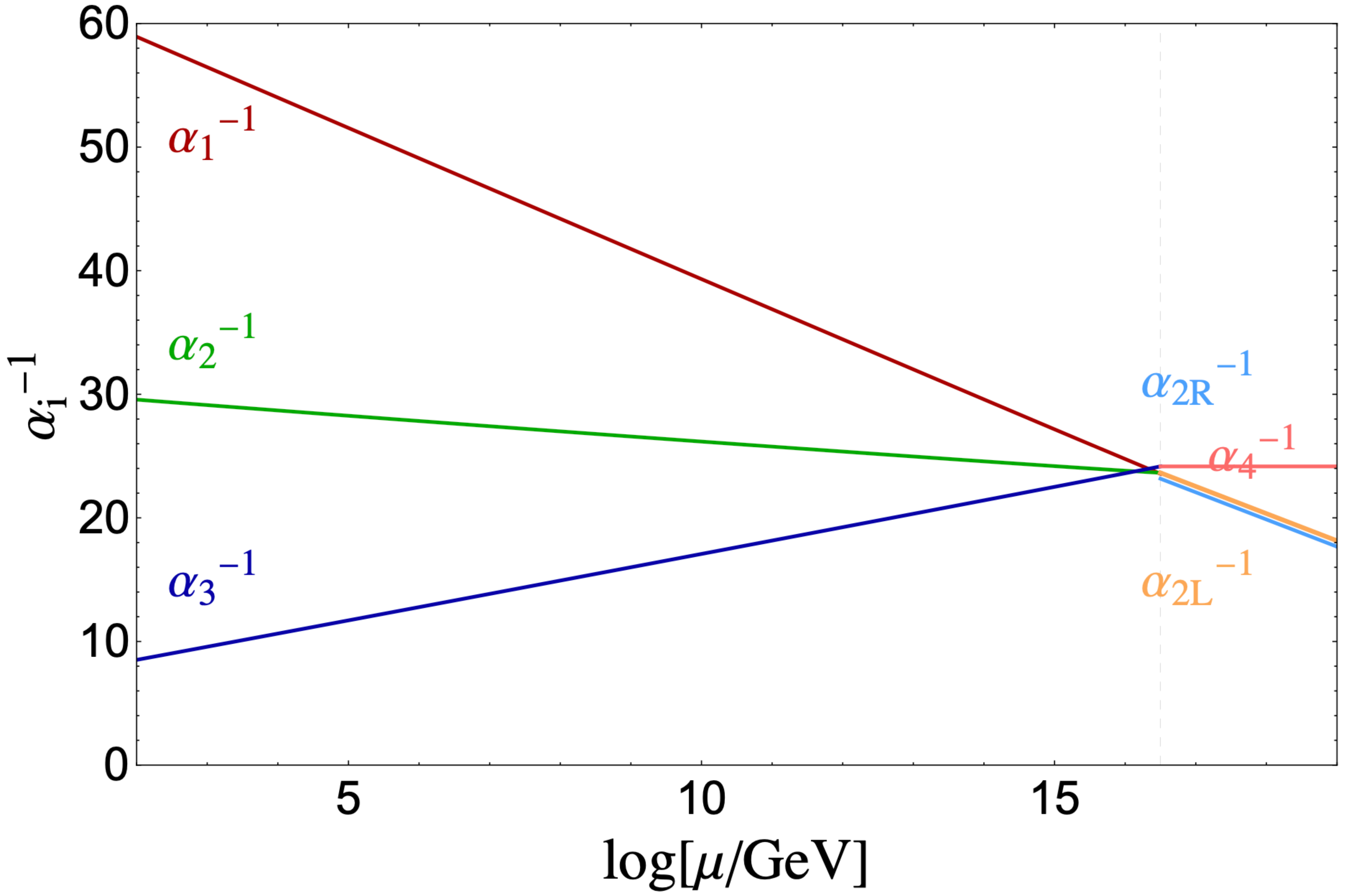
3. Phenomenological Implications

Running of couplings

- We found that the $SU(4)_C$ gauge couplings becomes near-conformal above the PS scale ($b_4 = 0$), implying the existence of a UV fixed point at one-loop level.

- It is noted that there will be no Landau pole from the PS scale to the Planck scale.

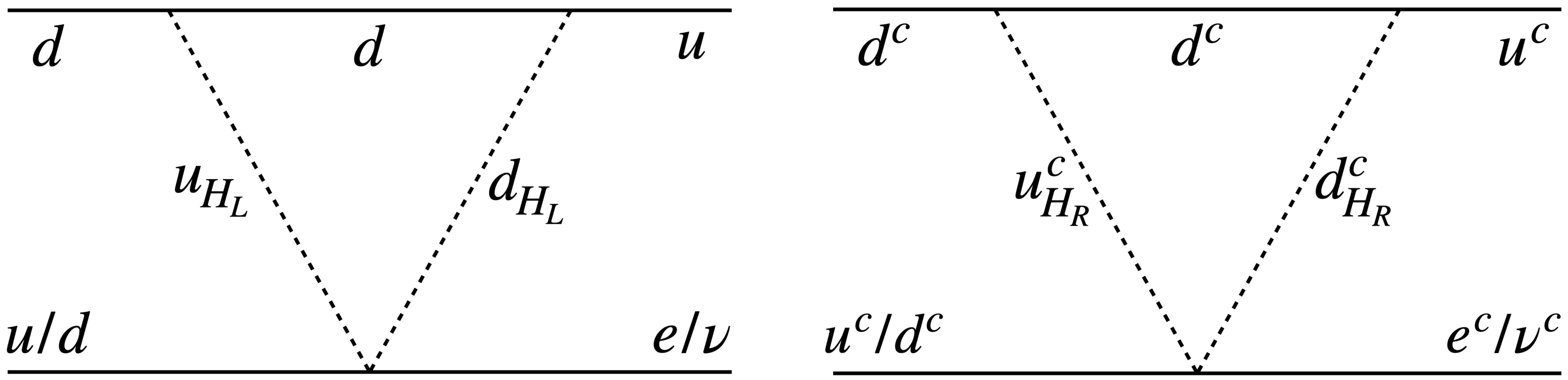
- If the model can be ultimately unified into a string theory or a quantum theory of gravity, there could be large threshold corrections near the quantum gravity scale, such as the KK towers from compactification of extra dimensions or string towers. Without string thresholds, the gauge couplings are safe and the model is still consistent at the far UV scale.



$$b_i = -3C_2(G_i) + \sum_R S(R)$$

Proton decay

- In the proposed model, the dominant baryon-number violating operators with $\Delta B = 1$ arises from the superpotential couplings with the heavy sextets T. Integrating out T generates the dimension-5 effective operators $\frac{y_L^2}{M_T}(F_L H_L)(F_L H_L)$ and $\frac{y_R^2}{M_T}(\bar{F}_R \bar{H}_R)(\bar{F}_R \bar{H}_R)$ that violate the baryon number conservation.



- Our calculation shows that the amplitude of proton decay are naturally suppressed due to heavy mediators.

- The suppression for proton decay in the proposed model is not surprising, after all, the PS gauge symmetry and the supersymmetry are both very restrictive in limiting the possible baryon-number violating operators. A similar mechanism that suppresses proton decay mediated by the color-triplet Higgsino is also observed in SUSY-SO(10) [Babu & Barr '93], where a doublet–triplet splitting by the adjoint Higgs converts those dimension 5 operators effectively into dimension 6, resulting in a natural suppression of proton decay. The difference is that, in our approach, the color triplets become massive due to the vevs of bifundamentals instead of the adjoint.

Z3 Domain Walls

- In this model, the PS symmetry breaking at the GUT scale would generate superheavy magnetic monopoles, while the subsequent breaking of the discrete $\mathbb{Z}_3$ symmetry at an intermediate scale v_ϕ produces domain walls.

- However, if the defects form before or during inflation, their energy density is exponentially diluted by the inflationary expansion, rendering them unobservable. To preserve observable signatures, such as gravitational waves from collapsing domain walls, in the present study we assume that the $\mathbb{Z}_3$-breaking scale v_ϕ is of the order of 10^{11} GeV.

- At lower energy, after integrating out the F-term, the corresponding renormalizable potential for singlet ϕ is:

$$V(\phi) = m_\phi^2 |\phi|^2 + (A m_\phi \lambda_\phi \phi^3 + \mathrm{h.c.}) + |\lambda_\phi \phi^2|^2 ,$$

- where A is a numerical coefficient and $|A| > 1$ which has to be determined by solving the full action involving the Kähler potential. Taking λ_ϕ real and parameterizing $\phi = v_0 e^{i\varphi}$, the potential simplifies to:

$$V(v_0, \varphi) = m_\phi^2 v_0^2 + 2A m_\phi \lambda \ \cos 3\varphi \ v_0^3 + \lambda_\phi^2 v_0^4$$

- which exhibits three degenerate minima at: $$v_0 = \frac{m_\phi}{4\lambda_\phi}\left(3|A| + \sqrt{9A^2 - 8}\right), \quad \varphi = 0, \pm\frac{2\pi}{3} \ (A\lambda_\phi < 0) .$$

Z3 Domain Walls

- However, an exactly $\mathbb{Z}_3$-symmetric potential produces long-lived domain walls that dominate the energy density in the early universe which drives an accelerating expansion that is inconsistent with current observations. A common way to avoid this problem is to introduce an explicit $\mathbb{Z}_3$-breaking term so that the domain walls start collapsing, which can be conveniently parametrized as: [Wu, Xie & Zhou, '22]

$$V_{\mathbb{Z}_3-\text{breaking}} = \frac{2e^{i\alpha}}{3\sqrt{3}}\epsilon\phi\left(\frac{1}{4}\phi^3 - v_0^3\right) + \text{h.c.}$$

- where $\epsilon \ll 1$ parametrizes the breaking strength, and α is a free parameter.

- The domain walls collapse when the vacuum pressure caused by the energy bias dominates over their tension-driven surface pressure $p_T \sim \mathcal{A}\sigma/t$. the resulting gravitational wave spectra are characterized by a peak frequency f_{peak} and energy density Ω_{GW}:

$$f_{\text{peak}} = 1.1 \times 10^{-7}\text{Hz} \times \left(\frac{g_*(T_{\text{ann}})}{10}\right)^{1/2}\left(\frac{10}{g_{*S}(T_{\text{ann}})}\right)^{1/3}\left(\frac{T_{\text{ann}}}{\text{GeV}}\right),$$

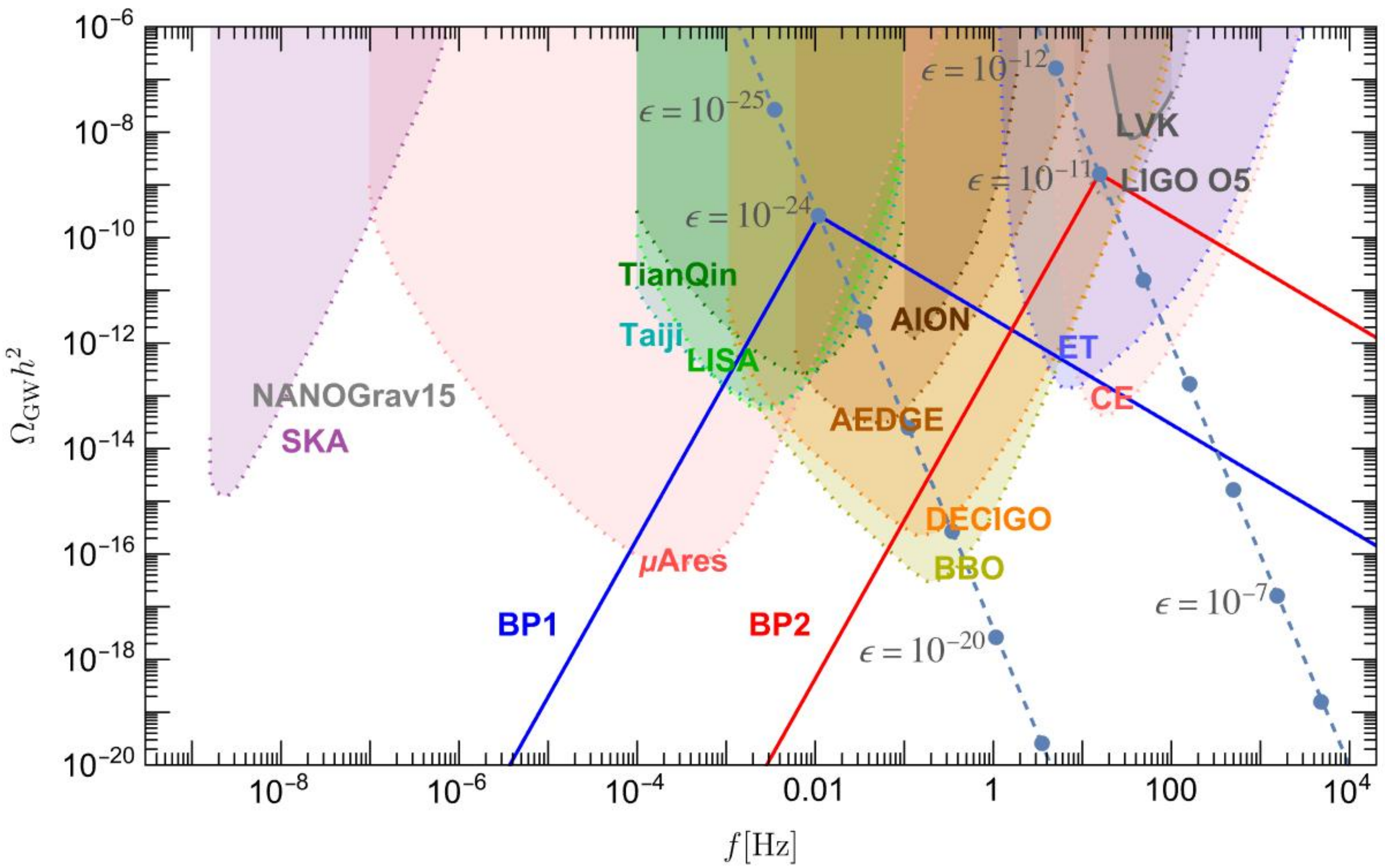
$$\Omega_{\text{GW}}(f_{\text{peak}})h^2 = 7.2 \times 10^{-26} \times \tilde{\epsilon}_{\text{GW}}\mathcal{A}^2 \times \left(\frac{10}{g_*(T_{\text{ann}})}\right)^{4/3}\left(\frac{\sigma^{1/3}}{\text{TeV}}\right)^6\left(\frac{\text{GeV}}{T_{\text{ann}}}\right)^4,$$

- where T_{ann} is the temperature at wall annihilation:

$$T_{\text{ann}} = 3.41 \times 10^4\ \text{GeV} \times C_{\text{ann}}^{-1/2}\mathcal{A}^{-1/2} \times \left(\frac{10}{g_*(T_{\text{ann}})}\right)^{1/4}\left(\frac{\text{TeV}}{\sigma^{1/3}}\right)^{3/2}\left(\frac{V_{\text{bias}}^{1/4}}{\text{GeV}}\right)^2.$$

Z3 Domain Walls

- With the parameters $\alpha = 2\pi/9$, $\mathscr{A} = 1.10 \pm 0.20$, $C_{\rm ann} = 5.02 \pm 0.44$, and $\tilde{\epsilon}_{\rm GW} \simeq 0.7 \pm 0.4$, the GW spectrum is approximately $\Omega_{\rm GW}h^2 \propto f^3$ below $f_{\rm peak}$ and $\propto f^{-1}$ above it [Hiramatsu, et al. '14; Kitajima, et al. '24], though some recent studies show deviations at high frequencies [Ferreira, et al. '24; Dankovsky, et al. '24]:



[Leontaris, RO & Zhou, '25]

Summary

- Motivation: use small representations to construct realistic string-inspired GUT models.
- The SUSY-PS model has an elegant superpotential incorporating mechanisms giving mass to light SM fields and neutrinos, while ensuring that all the other fields are heavy, and it can be further UV-completed into string theory.
- It has rich phenomenology below the GUT scale. There are more EW doublets and color triplets lying a few order of magnitude below the intermediate scale which could potentially affect the low energy observables in B-physics or flavor physics experiments.
- The $SU(4)_C$ coupling shows a near-conformal behavior in the UV.
- Proton decay are naturally suppressed in the model due to the fact that all baryon-number violating operators are suppressed by heavy mediators T and the loop factor involving Higgs propagator at the GUT scale.
- The spontaneous breaking of $\mathbb{Z}_3$ implies the existence of domain walls that are successfully addressed.

Future prospect

- It is promising to derive the spectrum in string theory based on intersecting D-brane constructions [e.g. Cvetic, Shiu, Uranga ’01; Anastasopoulos, Leontaris, Vlachos ’10; Ibanez, Schellekens, Uranga ’12; Leontaris, Shafi ’18.]
- Realistic realizations based on F-theory approach [Heckman & Vafa ’08; Cvetic, Klevers, Penã, Oehlmann, Reuter, ’15] are still absent in literature.
- Explore more GUT phenomenological predictions, like phase transitions, inflations…

Mass mechanism

- Mass splitting between down quarks and charged leptons: $y_L^i F_L^i H_L T + y_R^j \bar{F}_R^j \bar{H}_R T \to y_L^i \langle \nu_{H_L} \rangle (d_i \bar{T}_3) + y_R^j \langle \nu_{H_R}^c \rangle (d_j^c T_3)$.
- Color triplets in H_R and $\bar{H}_R$ acquire large masses: $\lambda_{H_R} H_R H_R D + \lambda_{\bar{H}_R} \bar{H}_R \bar{H}_R D \to \lambda_{H_R} v_R \bar{d}_{H_R}^c \bar{D}_3 + \lambda_{\bar{H}_R} \bar{v}_R d_{H_R}^c D_3$.
- Color triplets in H_L and $\bar{H}_L$ are heavy due to higher-order corrections: $\frac{c_{H_L}}{\Lambda} H_L \bar{H}_L \phi^2 \to \frac{c_{H_L} v_\phi^2}{\Lambda} d_{H_L} \bar{d}_{H_L}$.
- EW doublets in H_L and $\bar{H}_L$ are heavy due to dimension-6 operators: $$\frac{c_1}{\Lambda^2} H_L \bar{H}_R h \phi^2 \to \frac{c_1}{\Lambda^2} \bar{v}_R v_\phi^2 h_u^a \ell_{H_L} ;$$ $$\frac{c_2}{\Lambda^2} \bar{H}_L H_R h \phi^2 \to \frac{c_2}{\Lambda^2} v_R v_\phi^2 h_d^a \bar{\ell}_{H_L} .$$
- Electroweak μ-term are generated at a lower scale: $\frac{c_h}{\Lambda^2} h^2 \phi^3 \to \frac{c_h}{\Lambda^2} v_\phi^3 h^2 \to \mu h^2$.
- Three intrinsic scales satisfying: $v_L \lesssim v_{EW}$, $v_{EW} < v_\phi < v_R$, $v_R \simeq \Lambda_{GUT} \simeq 10^{16}$ GeV.