A Pyramid Scheme for Particle Physics

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Outline

Cosmological SUSY Breaking

- Cosmological constant an input parameter Banks
- LEFT $\Lambda = 0$ limit
  - Super-Poincaré symmetry
  - Discrete R-symmetry $\Rightarrow \Lambda = 0$
- LEFT $\Lambda \neq 0$ limit $\Rightarrow$ R-breaking operators
  - UV/IR mixing effect
  - Metastable SUSY violating state with $m_{3/2} = K\Lambda^{1/4}$, $K = \mathcal{O}(10)$
  - Constant term in superpotential such that $\text{c.c.} = \Lambda$
  - Tunneling probability of order $\mathcal{O}(e^{-\pi(RM_P)^2})$

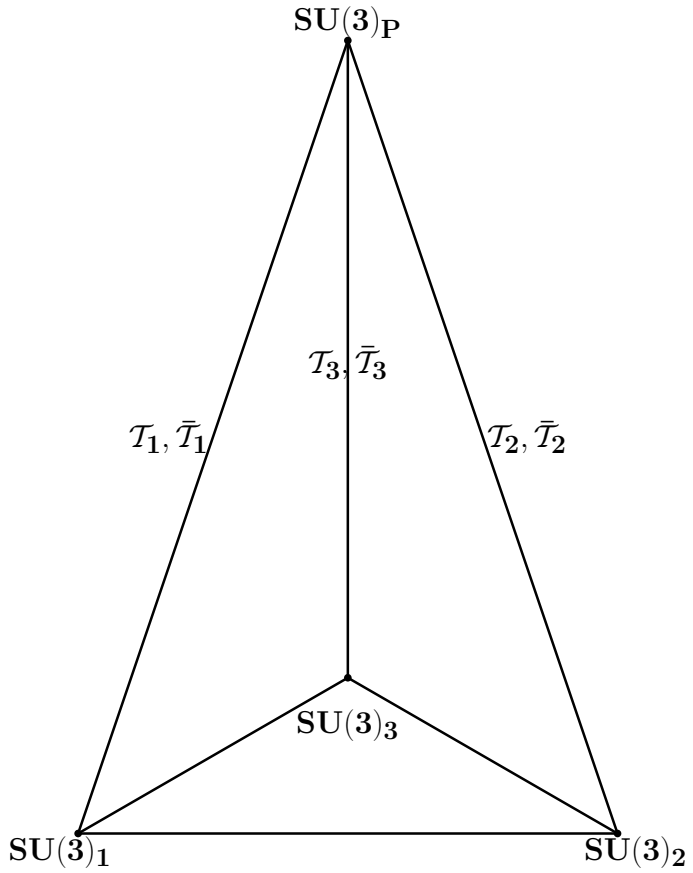
$\Rightarrow$ Constraints on LEFT

Metastable DSB

- Metastable dynamical SUSY breaking
  - DSB $\Rightarrow$ Natural hierarchy of scales $M_{SUSY} \ll M_P$ Witten
  - More generic than DSB in stable states Intriligator, Seiberg, Shih
- Direct gauge mediation and MSSM $\Rightarrow$ $G \times SU(1,2,3)$
  - No messenger sector
  - Solution of SUSY flavor problem
  - One loop gauge coupling unification
- SM gauge couplings in perturbative regime

Trinification and Pyramid scheme

- Trinification Glashow
  - $SU(3)^3 \rtimes Z_3$
  - Gauge bosons in $(8,1,1) \oplus \cdots$
    2 Higgs and 3 families in
    $(3,\bar{3},1) \oplus (\bar{3},1,3) \oplus (1,3,\bar{3})$
- Pyramid scheme
  - Extra $SU(3)_P$
  - Extra matter (trianons)
    $\mathcal{T}_1 + \bar{\mathcal{T}}_1 = (3,1,1,\bar{3}) \oplus (\bar{3},1,1,3)$
    $\mathcal{T}_2 + \bar{\mathcal{T}}_2 = (1,3,1,\bar{3}) \oplus (1,\bar{3},1,3)$
    $\mathcal{T}_3 + \bar{\mathcal{T}}_3 = (1,1,3,\bar{3}) \oplus (1,1,\bar{3},3)$
  - One singlet $S \Rightarrow \mu$-problem



GUT $SU(3)_P \times SU(3)^3 \rtimes Z_3 \rightarrow$ LEFT $SU(3)_P \times SU(1,2,3)$

Discrete R-symmetry

- Non-anomalous
- Yukawa terms, Higgs terms and trianon terms allowed
- Dimension 4 and 5 B and L violating terms forbidden (apart from neutrino seesaw operator)

$$W = \sum_{i=1}^{3}(m_i + y_i S)\mathcal{T}_i\bar{\mathcal{T}}_i + \text{GUT terms} + g_\mu S H_u H_d$$
$$+ \lambda_u H_u Q \bar{U} + \lambda_d H_d Q \bar{D} + \lambda_L H_d L \bar{E} + \frac{\lambda_\nu}{M}(L H_u)^2 + W_0$$

$SU(3)_P$ with $N_F = 9$ flavors $\Rightarrow$ IR free

- Without ISS mass terms
  - Free theory with SUSY
  - Forbidden by CSB $\Rightarrow$ Dynamical metastable SUSY violating state with $m_{3/2} = K\Lambda^{1/4}$
- With ISS mass terms
  - Two heavy masses $\Rightarrow$ Assumed SUSY and R-symmetry breaking metastable state

Phenomenology suggests heavy $m_{1,3} > \Lambda_3$ with $m_2 \approx \Lambda_3$

$$\text{Mass hierarchy } \Lambda_3 \approx m_2 \lesssim m_3 \ll m_1$$

Spectrum

$$W = X(\det M/\Lambda_3 - P\bar{P} - \Lambda_3^2) + \text{trianon terms} + \cdots$$

- Two kinds of messengers
  - $N_F = N_C = 3$ theory moduli
    $M = Z_a \lambda^a$, $P = i\Lambda_3 e^{(q+p)/\Lambda_3}$ and $\bar{P} = i\Lambda_3 e^{(q-p)/\Lambda_3}$
  - Heavy trianons
- SUSY breaking vacuum $\Rightarrow \langle P \rangle = \langle \bar{P} \rangle \neq 0$
- R-symmetry breaking vacuum $\Rightarrow \langle M \rangle \propto \mathrm{Id}$

$\Rightarrow V_{\text{non-SUSY}} \approx K^{-1}_{M^\dagger M} |m_2 \Lambda_3|^2$

M messengers

$$\begin{aligned} m_{3/2} &= X_g \frac{m_2 \Lambda_3}{m_P} = K \Lambda^{1/4} \\ m^i_{1/2} &= 3 X_i \frac{\alpha_i}{4\pi} m_2 \end{aligned}$$

- M field quartic scalar couplings of order $\mathcal{O}(m_2^2/\Lambda_3^2) \Rightarrow m_2 < \sqrt{4\pi}\Lambda_3$
- Chargino mass bound of 160 GeV $\Rightarrow X_2 \frac{m_2}{\mathrm{TeV}} > 19.7$

$\Rightarrow$ Example:

- Assumption: $m_2 = 1.7\Lambda_3$ such that $\frac{m_2^2}{4\pi\Lambda_3^2} \approx \frac{1}{4}$
- $X_2 > 4.2\sqrt{X_g/K} \Rightarrow \Lambda_3 = 5.1$ TeV and $m_2 = 8.6$ TeV

$\mathcal{T}_{1,3}$ messengers

- $m_3 \gg \Lambda_3$
  - Gluino effective couplings $\int d^2\theta \, (W_\alpha^3)^2 f(M/m_3, P/m_3, \bar{P}/m_3)$
- $m_3 \gtrsim \Lambda_3$ due to gluino constraint
  - CW approximation breaks down
  - Chiral perturbation theory not suitable

$\Rightarrow$ Gluino/chargino and squark/slepton mass ratios suppressed compared to usual gauge mediation

- No large contributions to Higgs potential $\Rightarrow$ Good for little hierarchy problem

Cosmology

- Gauge mediation $\Rightarrow$ LSP gravitino thus no WIMP dark matter candidate
- Hidden baryon-like states as dark matter Banks, Mason, O'Neil
- Pyramid scheme $\Rightarrow$ 3 accidental baryon number-like symmetries
  - 2 unbroken $U_{\mathcal{B}_{1,3}}$ $\Rightarrow$ Observed DM density without asymmetry through non-thermal production with $T_{\rm reh} < \Lambda_3$
  - 1 spontaneously broken $U_{\mathcal{B}_2}$

Assumption: Negligible primordial asymmetries with low $T_{\rm reh}$

- $U_{\mathcal{B}_3}$-charged particles as DM
  - QCD-like interactions with dynamical scale Λ_3
  - Energy-independent annihilation cross section of order $\mathcal{O}(\Lambda_3^{-2})$
  - Annihilation to PNGB of spontaneously broken $U_{\mathcal{B}_2}$ with high multiplicity

- PNGB of spontaneously broken $U_{\mathcal{B}_2}$ (pyrmion)
  - Leading $U_{\mathcal{B}_2}$ breaking operator $\int d^2\theta\, S(\det \mathcal{T}_2)/M_{\rm GUT} \Rightarrow$ Light (MeV range)
  - Stellar cooling rates bound satisfied
  - Colorless constituents

  $\Rightarrow$ Decay to e^+e^-, photons and neutrinos from operators like $\alpha_2^2 \partial_\mu p J^\mu/\Lambda_3 \sim \alpha_2^2 m_e p e^+ e^-/\Lambda_3$

$\Rightarrow$ Positron excess with DM annihilation cross section $\sigma_0 = A/\Lambda_3^2$

Features and problems

Features

- Based on trinification $\Rightarrow$ No Landau poles
- Heavy trianons needed for metastable SUSY violating state $\Rightarrow$ colored sparticle mass suppression
- 2 unbroken baryon number-like symmetries $\Rightarrow$ Non-thermal DM candidate compatible with experiments
- Pyrmion mass $\Rightarrow$ Not produced in ordinary stars and positron excess compatible with experiments

Problems

- Existence of metastable SUSY breaking state $\Rightarrow$ Non-zero meson VEV