The Pyramid Scheme for TeV Scale Physics

Tom Banks

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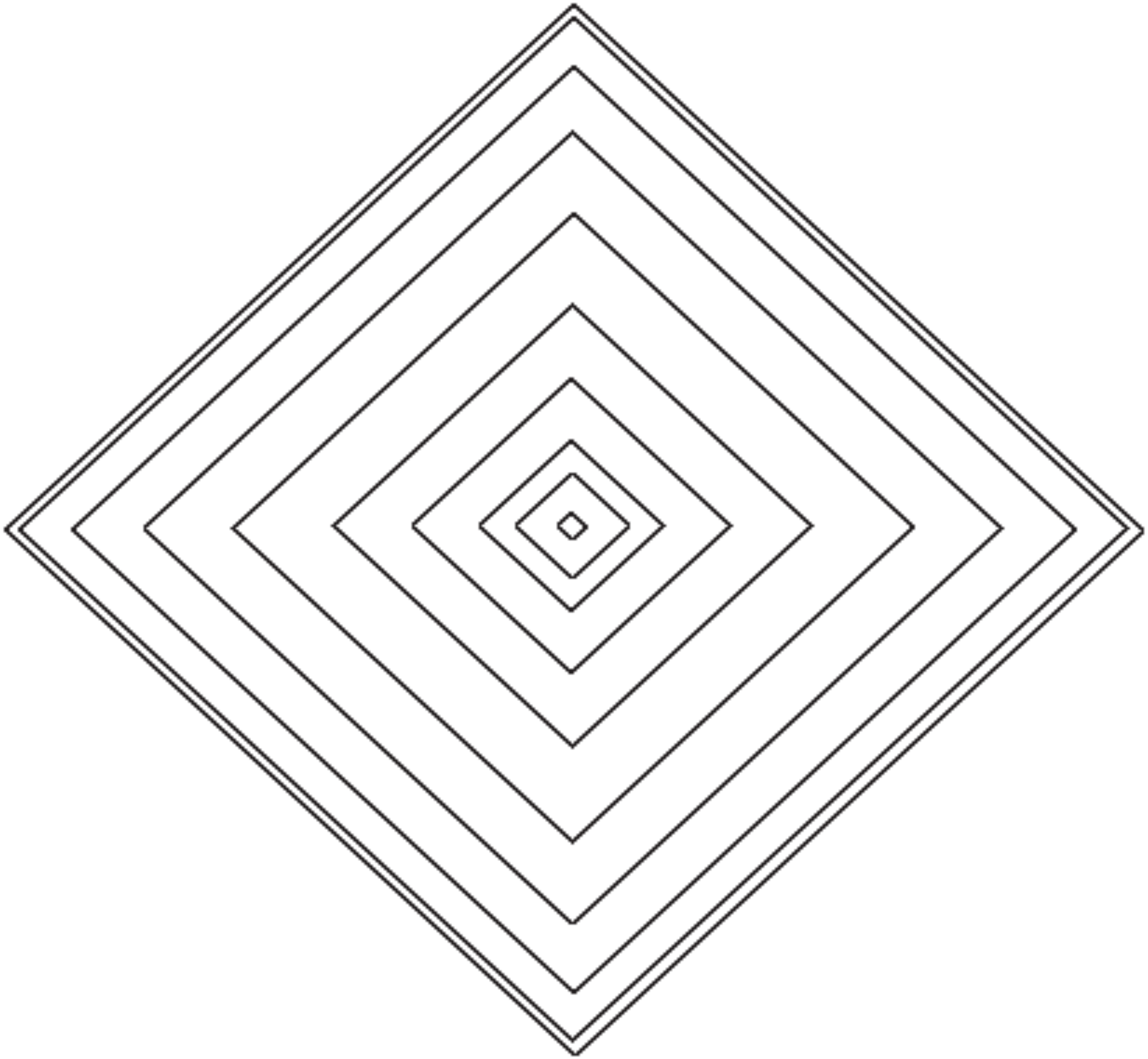
Holographic Space-time

- Time Dependent Hamiltonian $H_{in}(t) + H_{out}(t)$ Acts on Hilbert Space of Nested Causal Diamonds (Proper Time Intervals) Along a Trajectory.



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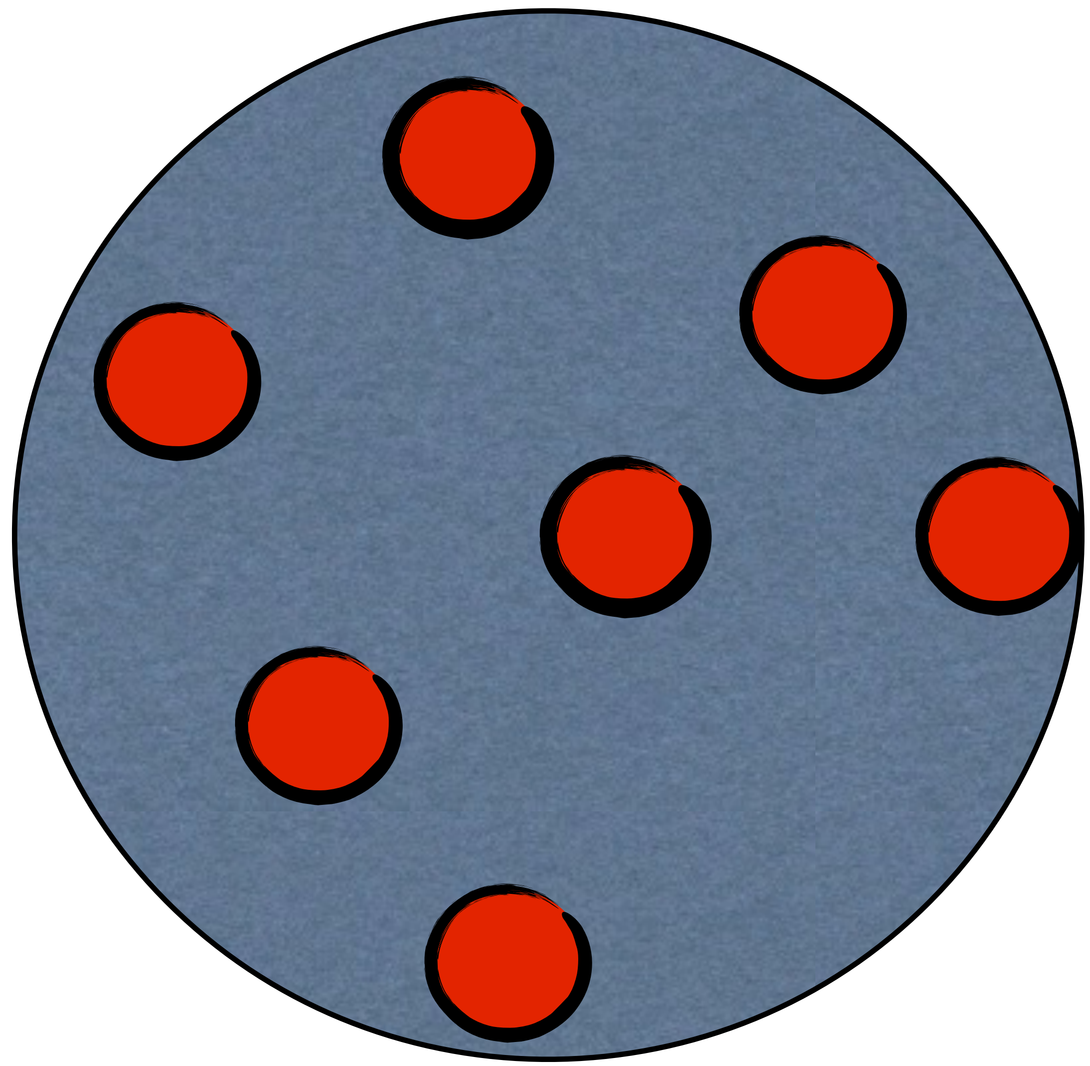
- Similar Algebra for $P \rightarrow \tilde{P}$ If There Are Massive Particles .

Properties of HST

- All of DOF are at $P = 0$ (boundary gauge modes) . Non-zero P DEFINED by constraints on states of $P = 0$ DOF (Exclusive Sterman-Weinberg Jets)



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- Overlap conditions on shared density matrix for Synchronized pairs of diamonds knit trajectories together into Space-time. Quantum Principle of General Relativity.

Cosmological SUSY Breaking

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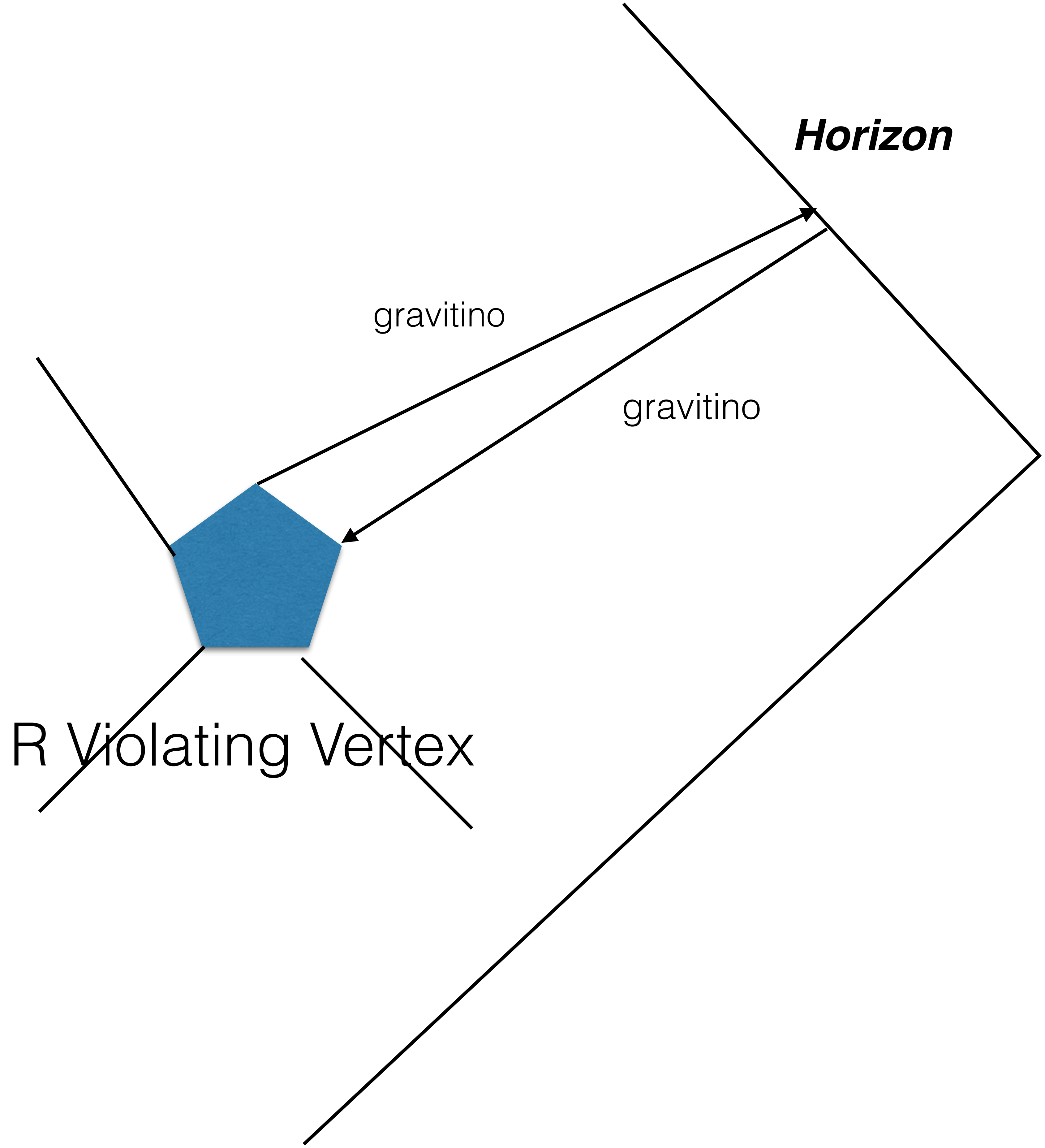
Horizon
gravitino
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R Violating Vertex

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$$\Delta\mathcal{L} \sim e^{-2m_{3/2}R} e^{M_P^2 A}.$$

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- $F = \frac{M_P m_{3/2}}{\sqrt{8\pi}} = [(c)^{1/4} 2.75 \times 10^4 \mathrm{GeV}]^2$.

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- Goldstino + MSSM not enough: $\mathcal{L}_{\Delta R} = \int d^2\theta \, [G(aH_uH_d - F) + W_0 + o(1/M_U)]$. Need new strongly coupled (Pyramid) sector with $\Lambda_P \sim \sqrt{F}$ (Why?) and fields with Std. Model charges, to communicate SUSY breaking to Std. Model.

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- This might cause a problem with perturbative unification.

The Pyramid Scheme

- Investigated models with SU(5) unification: all fail at two loop level.

In addition to the gauge and matter content summarized in the quiver diagram of Fig. 1, the model contains gauge singlets S_i, which are essential for implementing SUSY breaking. The minimal number is 3 and we will work with that minimal content in this paper.

The origin of the name Pyramid Scheme is evident in the quiver diagram of Fig. 1, where standard model generations run around the base of the pyramid and additional field content is given by:

	$SU_1(3)$	$SU_2(3)$	$SU_3(3)$	$SU_P(3)$
S_i	1	1	1	1
$\mathcal{T}_1$	$\square$	1	1	$\bar{\square}$
$\bar{\mathcal{T}}_1$	$\bar{\square}$	1	1	$\square$
$\mathcal{T}_2$	1	$\square$	1	$\bar{\square}$
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$\mathcal{T}_3$	1	1	$\square$	$\bar{\square}$
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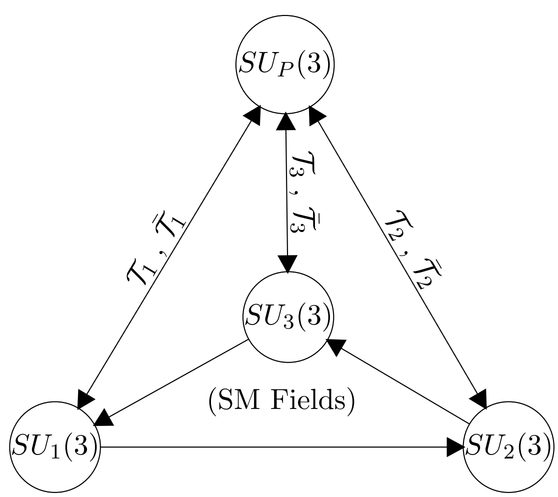
Here the $\mathcal{T}_i$ are fields which transform in the bifundamental of $SU_i(3) \times SU_P(3)$ which we call "trianons," and the $\bar{\mathcal{T}}_i$ are the conjugates of the $\mathcal{T}_i$.

FIG. 1. The quiver diagram of the pyramid scheme has a pyramidal shape with the base of the pyramid containing SM fields which arise from trinification, and the top of the pyramid arising from the extension of the gauge group to include $SU_P(3)$.



Though $SU_P(3)$ must be strongly coupled at the TeV scale, it is not asymptotically free at high energies. $SU_P(3)$ does become asymptotically free below the highest trianon mass scale, and thus we seek to look at effective field theories below this scale such that at low

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- Need 3 New Singlets S_i to make model with SUSY Breaking. Origin of S_i, H_u, H_d at M_U left unspecified.

The R Symmetry

- R symmetry forbids all B and L violating terms up to dimension 5 except LH_uLH_d. Discrete Symmetry commuting with SUSY forbids S^3 Terms. R also Forbids Relevant Terms like $\mu H_u H_d$, Trianon Masses, Bilinears in and Linears in S_i. Also implies Accidental $U(1)_{PQ}$.

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- R Violating Diagrams With 2 Gravitino Lines going to horizon have UV cutoff $\sqrt{m_{3/2}M_U} \sim 1$ TeV, so induced B and L violating terms are highly suppressed.
- Gravitino-Horizon Interactions Are At Very High Temperature $\sim M_U$ so If CP Violation is Spontaneous, at Low Enough Scale Then R Violating Terms Do Not Have CP Violating Phases. **Novel Solution to the Strong CP Problem**. Would Be PQ Axion Gets TeV scale Mass Without Uncontrollable CP Phases.

The R Symmetry

- For $SU_P(3)$ The R Symmetry Group Z_8 Does the Job

The vanishing of the 't Hooft operators implies the vanishing of the following equations

$$\begin{aligned} SU_P(3)^2 U_R(1) &\Rightarrow 2\cdot 3 + 3(\mathcal{T}_1 + \bar{\mathcal{T}}_1 + \mathcal{T}_2 + \bar{\mathcal{T}}_2 + \mathcal{T}_3 + \bar{\mathcal{T}}_3 - 6) = 6 - 9S \\ SU_C(3)^2 U_R(1) &\Rightarrow 2\cdot 3 + 6(Q-1) + 3(\bar{U} + \bar{D} - 2) + 3(\mathcal{T}_3 + \bar{\mathcal{T}}_3 - 2) = 0 \\ SU_L(2)^2 U_R(1) &\Rightarrow 2\cdot 2 + (H_u + H_d - 2) + 9(Q-1) + 3(L-1) \\ &\qquad +3(\mathcal{T}_2 + \bar{\mathcal{T}}_2 - 2) = 3(3Q+L) - 4(2-S). \end{aligned}$$

The vanishing of the 't Hooft operator coming from $SU_C(3)$ standard model instantons does not constraint the R-charges. The remaining equations lead to $S = 22 - 6(3Q+L)$ with the 't Hooft constraints $27(3Q+L) - 96 = 0$.

The forbidden (non-B and non-L violating) renormalizable superpotential terms can be combined into 4 groups,

$$\begin{aligned} G_1^{(\mathrm{ren})} = \{\mathrm{tr}(\mathcal{T}_i\bar{\mathcal{T}}_i),\ H_u H_d\} &\Rightarrow S \\ G_2^{(\mathrm{ren})} = \{S\} &\Rightarrow S-2 \\ G_3^{(\mathrm{ren})} = \{S^2\} &\Rightarrow 2S-2 \\ G_4^{(\mathrm{ren})} = \{S^3\} &\Rightarrow 3S-2. \end{aligned}$$

Moreover, the dangerous renormalizable and higher-dimensional B and L violating superpotential and Kähler potential terms can be combined into 9 groups,

$$\begin{aligned} G_1^{(\not B\,\mathrm{or}\,\not L)} = \{LL\bar{E},\ LQ\bar{D},\ SLH_u\} &\Rightarrow L - H_d \\ G_2^{(\not B\,\mathrm{or}\,\not L)} = \{\bar{U}\bar{D}\bar{D}\} &\Rightarrow 3Q + H_d - S - 2 \\ G_3^{(\not B\,\mathrm{or}\,\not L)} = \{LH_u,\ Q\bar{U}\bar{E}H_d,\ \bar{U}\bar{D}^*\bar{E},\ H_u^* H_d \bar{E},\ Q\bar{U}L^*\} &\Rightarrow L - H_d - S \\ G_4^{(\not B\,\mathrm{or}\,\not L)} = \{QQQL\} &\Rightarrow 3Q + L - 2 \\ G_5^{(\not B\,\mathrm{or}\,\not L)} = \{QQQH_d,\ QQ\bar{D}^*\} &\Rightarrow 3Q + H_d - 2 \\ G_6^{(\not B\,\mathrm{or}\,\not L)} = \{\bar{U}\bar{U}\bar{D}\bar{E}\} &\Rightarrow 3Q + L - 2S - 2 \\ G_7^{(\not B\,\mathrm{or}\,\not L)} = \{LH_uH_dH_u\} &\Rightarrow L - H_d - 2S + 2 \\ G_8^{(\not B\,\mathrm{or}\,\not L)} = \{SLL\bar{E},\ SLQ\bar{D},\ S^2LH_u\} &\Rightarrow L - H_d + S \\ G_9^{(\not B\,\mathrm{or}\,\not L)} = \{S\bar{U}\bar{D}\bar{D}\} &\Rightarrow 3Q + H_d - 2S - 2. \end{aligned}$$

All operators belonging to the same group share the same R-charge.

Taking into account all the relations and constraints, it is possible to engineer the following superpotential of the low energy effective theory in the zero c.c. limit,

$$\begin{aligned} W_{\Lambda=0} = \sum_{i,j} y_{ij} S_i \mathrm{tr}(\mathcal{T}_j\bar{\mathcal{T}}_j) + \sum_i \left[u_i \det(\mathcal{T}_i) + \bar{u}_i \det(\bar{\mathcal{T}}_i) + \beta_i S_i H_u H_d\right] \\ + \lambda_u H_u Q\bar{U} + \lambda_d H_d Q\bar{D} + \lambda_L H_d L\bar{E} + \frac{\lambda_\nu}{m_P}(LH_u)^2 \end{aligned} \tag{2.1}$$

where all allowed renormalizable terms are present and all dangerous terms are forbidden by a discrete Z_8 R-symmetry with $S_i = \mathcal{T}_i = \bar{\mathcal{T}}_i = 6$, $Q = 5$, $L = 1$ and $H_d = 0$. Notice

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- We'll stick with $SU_P(3)$ for these lectures. Need Exploration of $N = 4$ models.

Dark Matter and the Λ_P, F Coincidence

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- $SU_P(4)$ Model Has SCFT and Automatic Pyrma-Baryon number conservation. Not all Pyrma Baryons are SM Singlets. Possible Forbidden Relics.

Two Loop RG With One $g_i = 0$

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- If $g_3 \neq 0$, SM coupling unification could be spoiled at two loop level. In RGE neglecting various threshold effects, could be as much as 15%, but not a complete calculation. One loop is OK and SM perturbative up to M_U.

The Ordering of The Trianon Masses Strongly Affects Phenomenology

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- Effective Theory Below $4\pi\Lambda_P$ scale: Colored ([1] + [8]) Pyrmesons and Singlet Pyrmabaryon plus S_i fields plus SSM. Will Give Only Highlights of the Analysis.

Gaugino Mixing with Trianon Composites

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- Other Gauginos get seesaw Dirac mass contributions from mixing with Electroweak adjoint pyrmesons. Harder to calculate, but nominally $\sim 16\pi^2$ larger than gauge mediated masses. Implies NLSP a right handed slepton or Higgsino.

SUSY Breaking, Higgs Potential, Little Hierarchy

- $W_{eff} = \alpha^i S_i + (\beta^i S_i + \mu) HuHd + (\gamma^i S_i + m) TrM + g_{P1} B + g_{P2} \tilde{B} + X(detM \Lambda_P^3 - B\tilde{B}\Lambda_P^3 - \Lambda_P^6)$

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- Minimizing potential non-trivial and can only be done numerically and invoking unjustified approximations. Robust results: Color and Electromagnetism Unbroken. SUSY and (probably) $SU(2)$ broken in stable (not meta-stable) vacuum. $|H_u| = |H_d|$ at tree level. Top/stop loops can allow $\tan\beta > 1.7$. Can easily accommodate Observed Higgs mass with large enough β^i. Landau poles in those couplings hard to estimate because of interactions with strongly coupled sector.

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- All of this needs to be redone, taking into account Dirac gaugino masses.

Dark Matter and Baryogenesis

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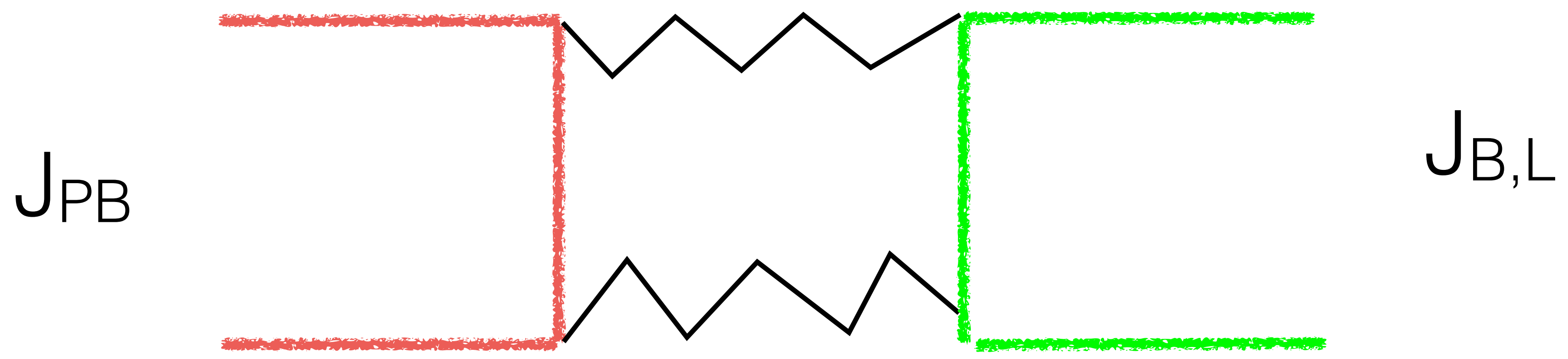
- Non-thermal population from late decay of NLSP?



Could Be Any Std Model Gauge Boson Exchange
But C Conservation Forbids Color Till Two Loops

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- One Asymmetry Provides Chemical Potential For the Other: Spontaneous (pyrma) baryogenesis. Can match both DM density and baryon asymmetry with this mechanism using electroweak baryon violation.

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