Towards a complete A4 X SU(5) SUSY GUT

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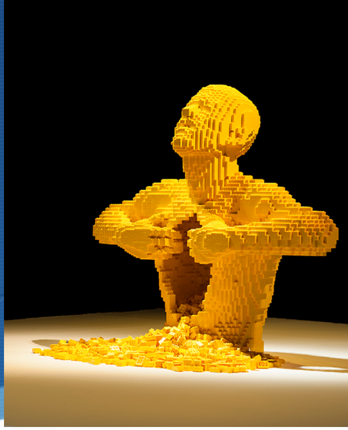
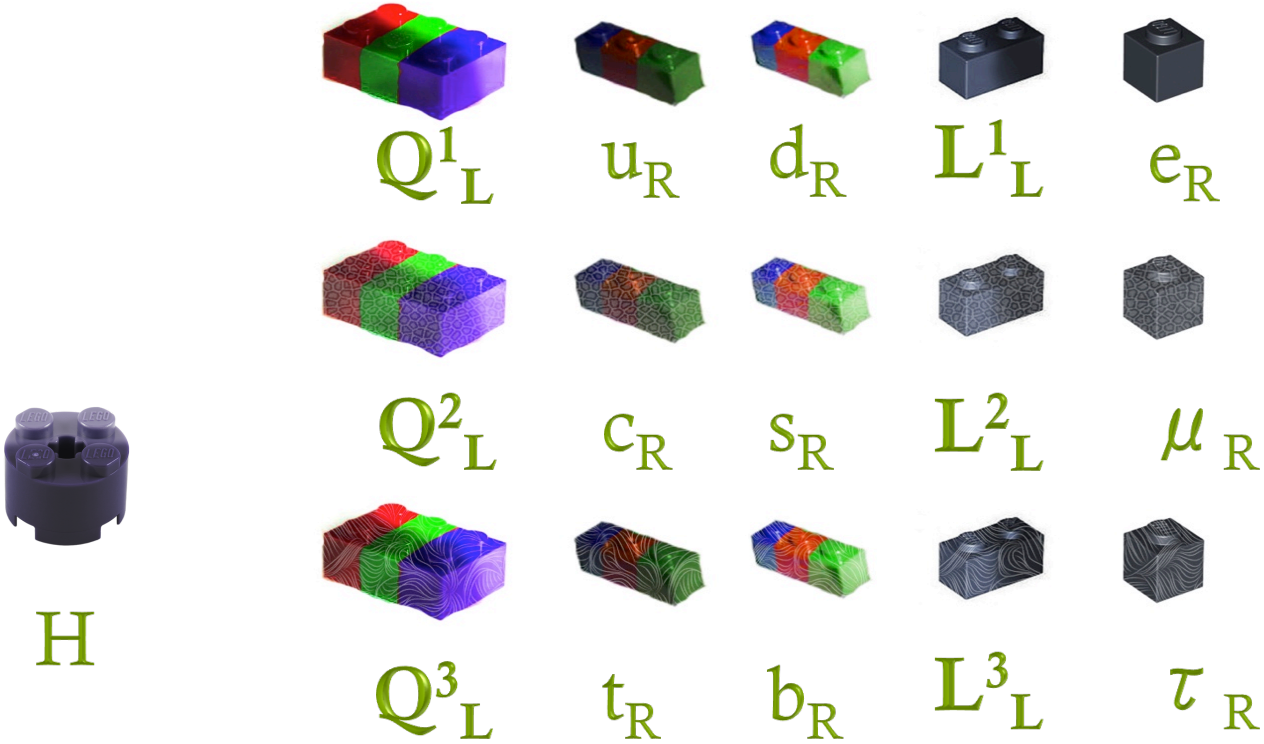
Standard Model



Gauge theory

$SU(3)_C \times SU(2)_L \times U(1)_Y$



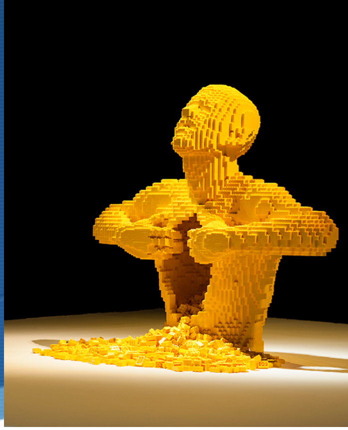
Q^1_L u_R d_R L^1_L e_R

Q^2_L c_R s_R L^2_L μ_R

Q^3_L t_R b_R L^3_L τ_R

H

Standard Model



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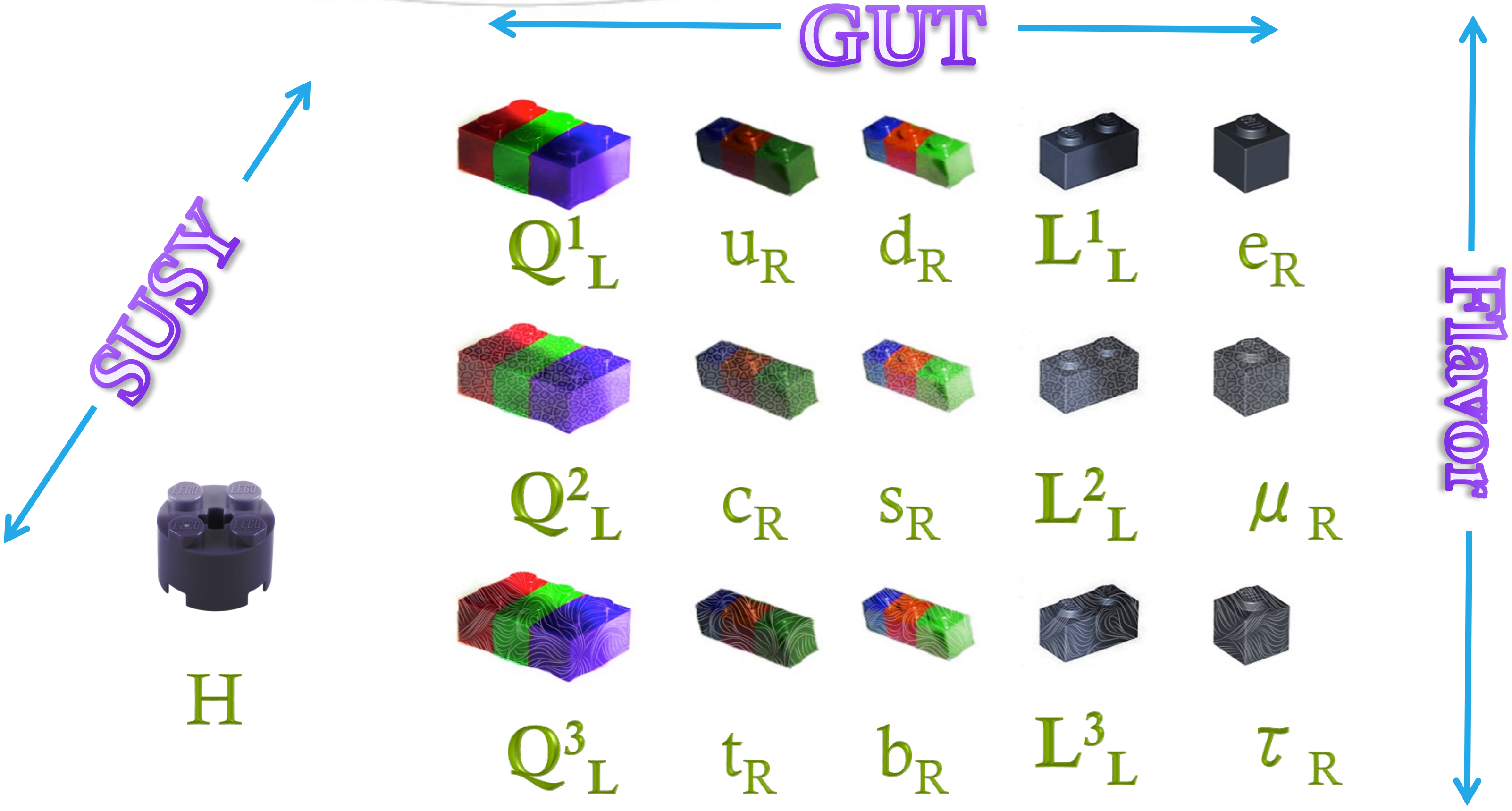

SM: Problems to solve

- Free gauge couplings.
- Free masses and mixings.
- Hierarchy problem.
- Not enough baryon asymmetry.
- Arbitrary charge quantization.
- No dark matter.
- No neutrino mass mechanism.
- Strong CP problem.

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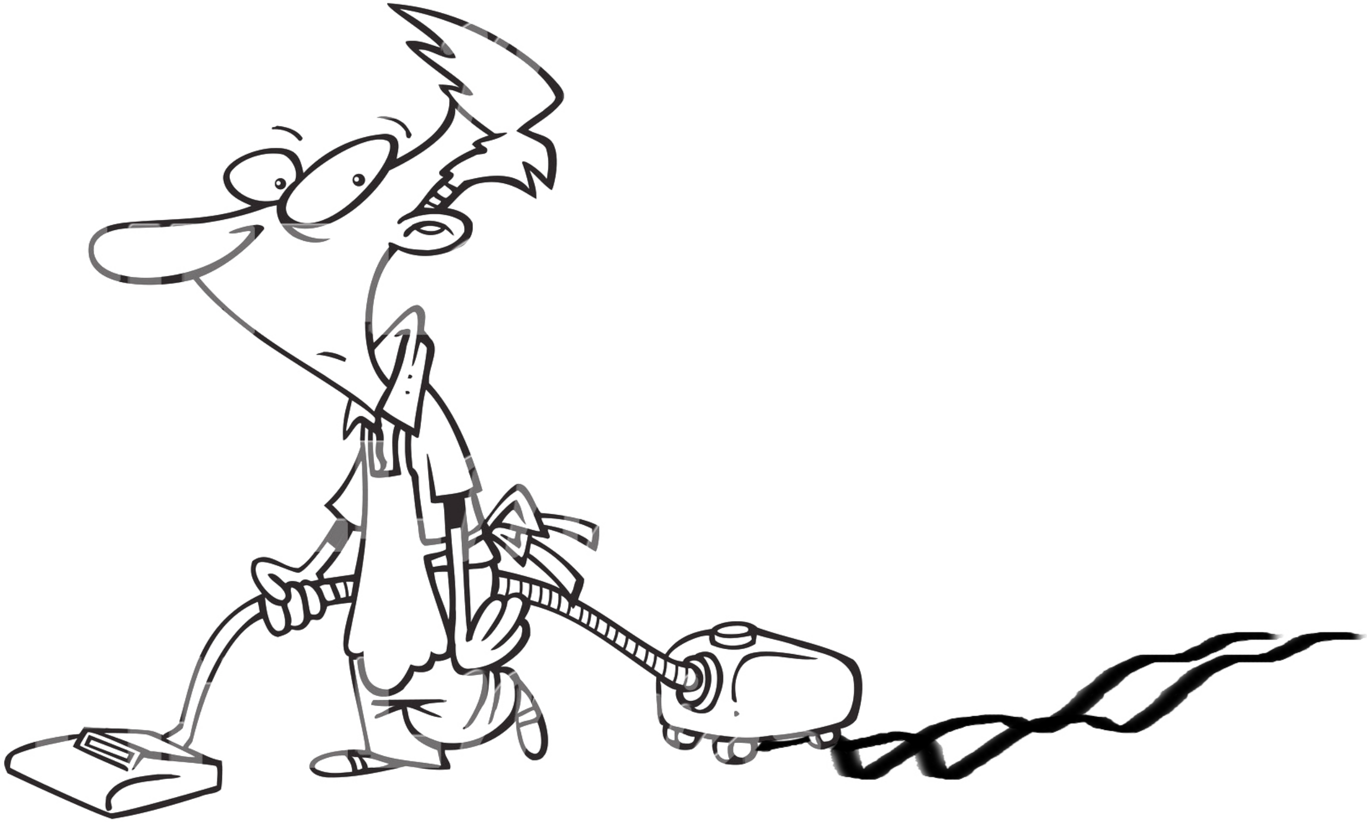
SUSY
GUT
FLAVOR

New problems



New problems

- GUT breaking mechanism.
- Flavor symmetry breaking mechanism (alignment).
- FCNCs.
- Missing new particles (heavy masses, doublet-triplet splitting).
- SUSY breaking.
- μ problem.
- Proton decay.
- Harder to obtain correct masses.

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How to fix them now?

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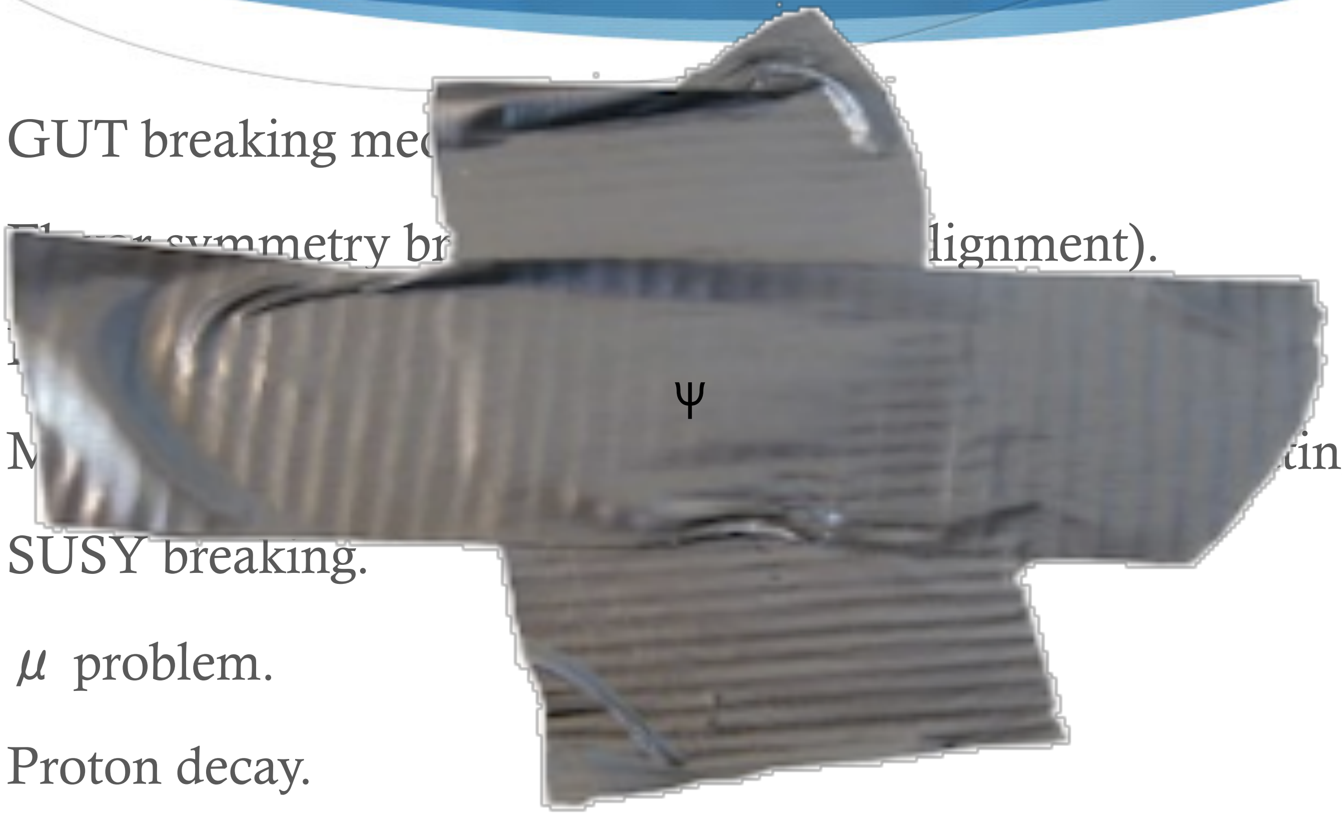

There. It's fixed.

New problems

A_4 X SU(5) based theory

- No doublet-triplet splitting, μ problem nor proton decay.
- CP spontaneosly broken and no strong CP violation.
- Renormalizable at GUT scale.
- Correct baryon asymmetry.
- Neutrino mass mechanism (with right handed neutrinos).
- Reduces to MSSM at low energies (with R parity to have DM and no FCNC).
- All O(1) free parameters.
- Explicit GUT breaking.
- Explicit flavor breaking and alignment.

$A_4 \times SU(5) \times Z_9 \times Z_6 \times Z_4^R$

Flavor symmetry

GUT symmetry

Shaping/Flavor symmetry

Shaping symmetry (for flavons)

R symmetry (breaks into R parity)

A_4 X SU(5) X Z_9 X Z_6 X Z_4^R

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- Superfields containing MSSM superfields (EW scale masses).
- Symmetry breaking superfields (masses around the GUT scale).
- Messenger superfields (renormalizable masses).

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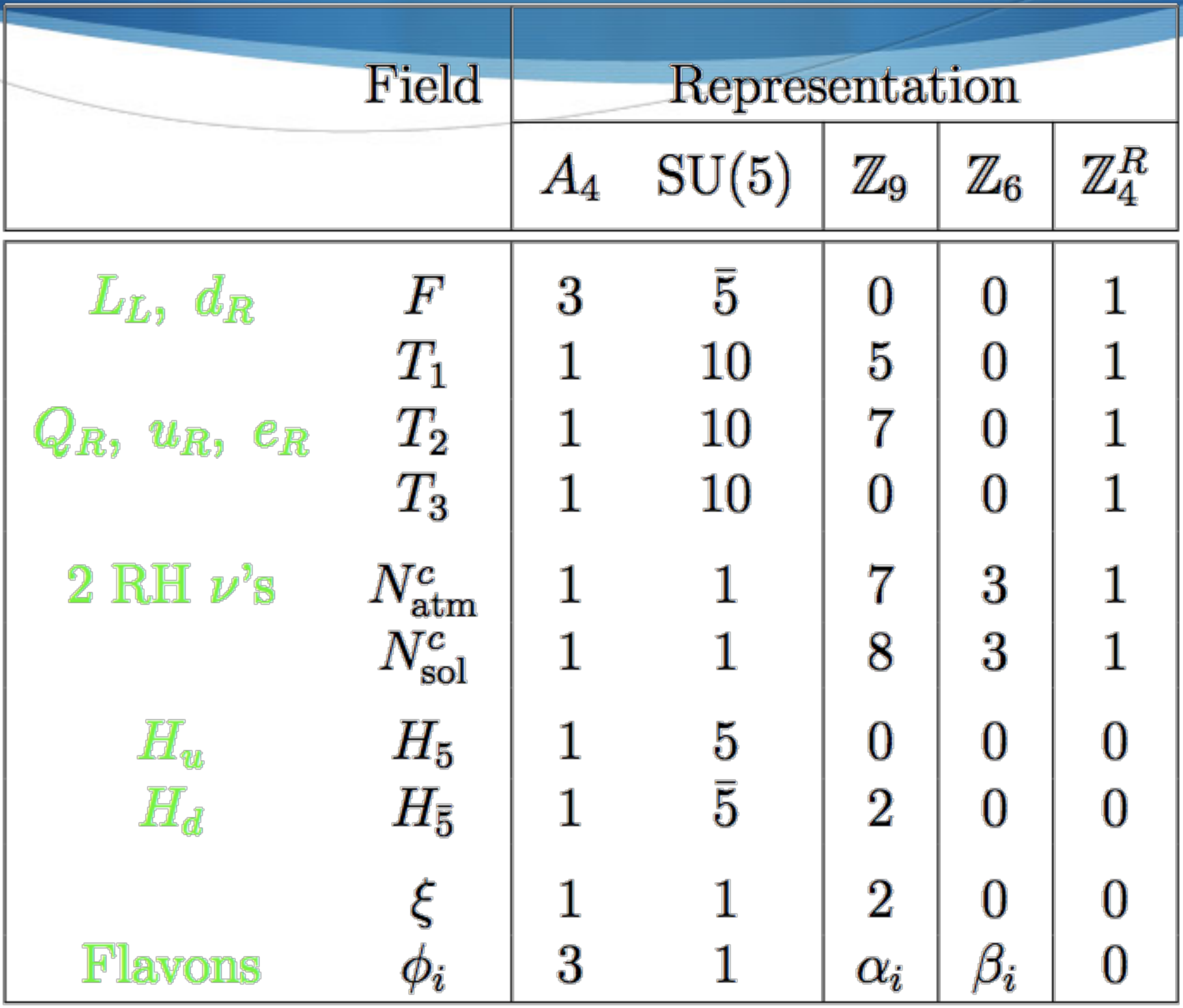
102 superfields in total.

MSSM containing superfields



	Field	Representation				
		A_4	SU(5)	$\mathbb{Z}_9$	$\mathbb{Z}_6$	$\mathbb{Z}_4^R$
L_L, d_R	F	3	$\bar{5}$	0	0	1
	T_1	1	10	5	0	1
Q_R, u_R, e_R	T_2	1	10	7	0	1
	T_3	1	10	0	0	1
2 RH ν's	N^c_{atm}	1	1	7	3	1
	N^c_{sol}	1	1	8	3	1
H_u	H_5	1	5	0	0	0
H_d	$H_{\bar{5}}$	1	$\bar{5}$	2	0	0
	ξ	1	1	2	0	0
Flavons	ϕ_i	3	1	α_i	β_i	0

Flavon VEV alignment

New superfields A's (A_4 triplets) and O's (A_4 singlets) whose **F term** determine the flavon VEV alignment.

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$$W \sim A\phi_a\phi_a$$

$$\phi_a^1\phi_a^2 = 0$$

$$\phi_a^2\phi_a^3 = 0$$

$$\phi_a^3\phi_a^1 = 0$$

2 components must vanish.

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2 components must vanish.

$$W \sim O\phi_a\phi_b$$

$$\phi_a \cdot \phi_b = 0$$

They must be orthogonal.

Flavon VEV alignment

New superfields A's (A_4 triplets) and O's (A_4 singlets) whose **F term** determine the flavon VEV alignment.

$$
\begin{aligned}
W_{\text{align}} \sim\; & A_\mu \phi_\mu \phi_\mu + A_\tau \phi_\tau \phi_\tau + A_2(\phi_2\phi_2 + \phi_2\theta_1) \\
& + O_{e\mu}\phi_e\phi_\mu + O_{e\tau}\phi_e\phi_\tau + O_{\mu\tau}\phi_\mu\phi_\tau \\
& + O_{e3}\phi_e\phi_3 + O_{23}\phi_2\phi_3 + O_{12}\phi_1\phi_2 + O_{13}\phi_1\phi_3 \\
& + O_{\mu 5}\phi_\mu\phi_5 + O_{25}\phi_2\phi_5 + O_{\mu 6}\phi_\mu\phi_6 + O_{56}\phi_5\phi_6 \\
& + O_{64}\phi_6\phi_4 + O_{14}\phi_1\phi_4 .
\end{aligned}
$$

Flavon VEV alignment

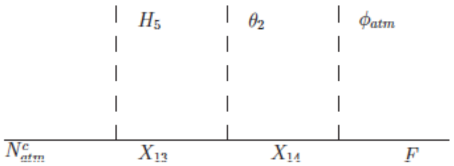
Completely fixed flavon VEV alignments:

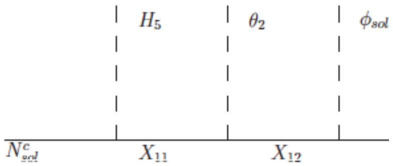
$$\langle\phi_e\rangle = v_e\begin{pmatrix}1\\0\\0\end{pmatrix} \qquad \langle\phi_\mu\rangle = v_\mu\begin{pmatrix}0\\1\\0\end{pmatrix} \qquad \langle\phi_\tau\rangle = v_\tau\begin{pmatrix}0\\0\\1\end{pmatrix}$$

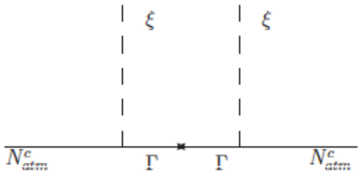
$$\langle\phi_{\rm atm}\rangle = v_{\rm atm}\begin{pmatrix}0\\1\\1\end{pmatrix} \qquad \langle\phi_{\rm sol}\rangle = v_{\rm sol}\begin{pmatrix}1\\3\\1\end{pmatrix}$$

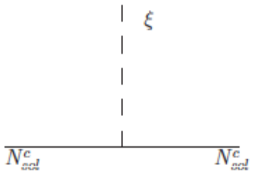
CSD(3) alignment for neutrinos

$$W_\nu = y_1 H_5 F \frac{\phi_{\rm atm}}{\langle\theta_2\rangle} N^c_{\rm atm} + y_2 H_5 F \frac{\phi_{\rm sol}}{\langle\theta_2\rangle} N^c_{\rm sol} + y_3 \frac{\xi^2}{M} N^c_{\rm atm} N^c_{\rm atm} + y_4 \xi N^c_{\rm sol} N^c_{\rm sol}.$$









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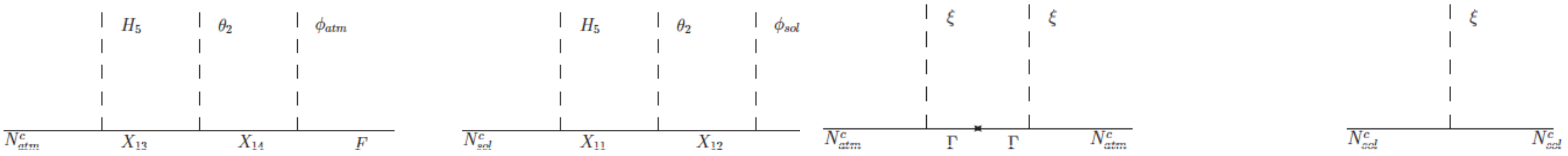
- 2 right handed neutrinos with $M_{atm} << M_{sol}$.
- Seesaw mechanism.
- Normal hierachy with one massless neutrino.

Dirac mass matrix:

$$\lambda^\nu = \begin{pmatrix} 0 & b \\ a & 3b \\ a & b \end{pmatrix}$$

Diagonal RH ν mass matrix.



Neutrino masses

$$m^\nu = m_a \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 1 \\ 0 & 1 & 1 \end{pmatrix} + m_b e^{i\eta} \begin{pmatrix} 1 & 3 & 1 \\ 3 & 9 & 3 \\ 1 & 3 & 1 \end{pmatrix}$$

$\eta = \frac{2\pi n}{9}$, with $n \in \mathbb{Z}$,
due to the $\mathbb{Z}_9$ symmetry.
We choose $\eta = 2\pi/3$

We fit the Δm^2 and choose
the phase η (1 in 9)
and the PMNS matrix
is completely fixed.

(Negligible contributions from charged lepons)

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	Experimental	Theory
θ^l_{12} (°)	$33.48\ ^{+0.78}_{-0.75}$	34.3
θ^l_{23} (°)	$42.3\ ^{+3.0}_{-1.6}$	45.8
θ^l_{13} (°)	$8.5\ ^{+0.20}_{-0.21}$	8.67
δ^l (°)	$-54\ ^{+39}_{-70}$	-86.7

Leptogenesis

- Baryon asymtery of the universe due to CP violation in leptons.
- Generated through decays of N_{atm} (lightests RH neutrino).
- Decay violates lepton number and CP in this model.

arXiv:1505.05504

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- Generated through decays of N_{atm} (lightests RH neutrino).
- Decay violates lepton number and CP in this model.
- To obtain correct BAU we fix **M_{atm} = 4 X 10^{10} GeV**.

$$M_{\rm atm} = y_3 \frac{\langle \xi \rangle^2}{M}$$

Taking $M \to M_P$ fixes $y_3 \simeq 0.3$.

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Up-quark masses

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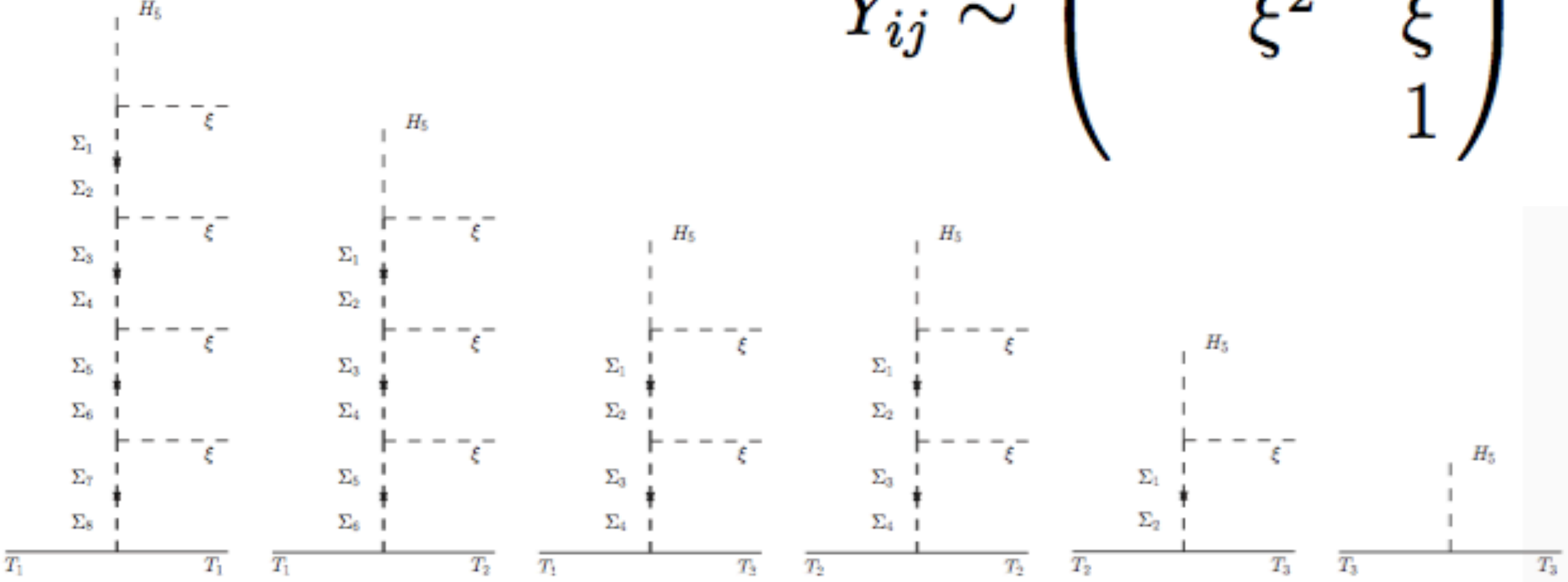
$$\tilde{\xi} = \frac{\langle \xi \rangle}{M} \simeq 0.06$$

$$Y_{ij} \sim \begin{pmatrix} \tilde{\xi}^4 & \tilde{\xi}^3 & \tilde{\xi}^2 \\ & \tilde{\xi}^2 & \tilde{\xi} \\ & & 1 \end{pmatrix}$$



Down-quarks and charged leptons masses

$$W_{dl} = Y_{ij} H T_i \phi_j F$$

They come from the same terms so we need Georgi-Jarlskog relations (from a 45 and 24)

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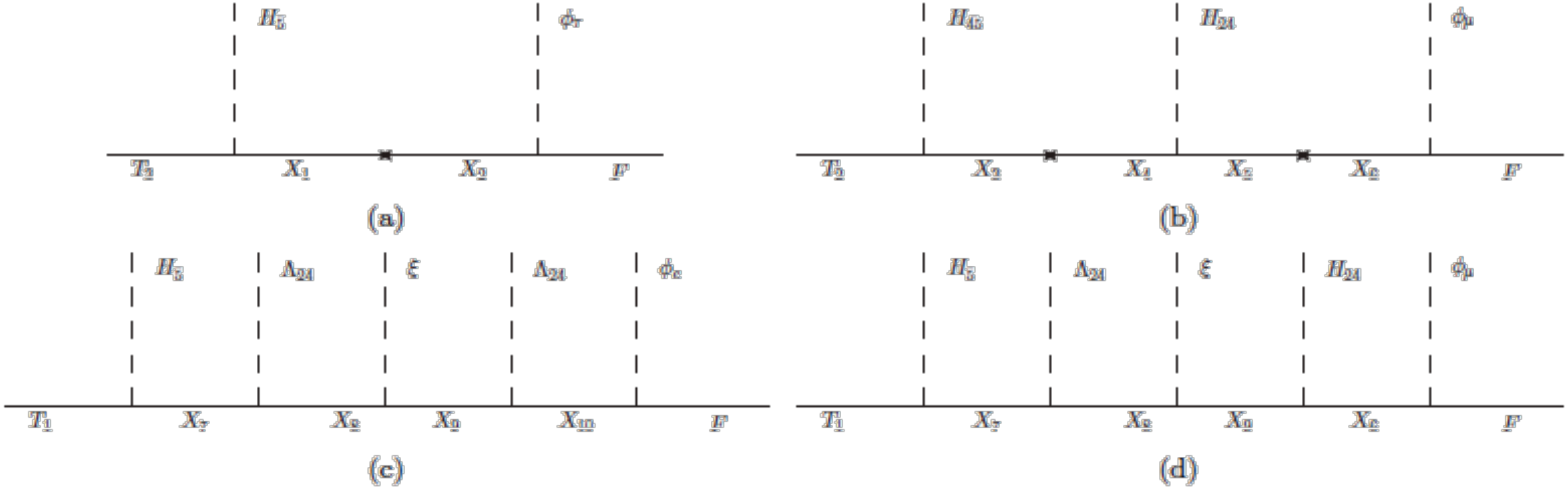

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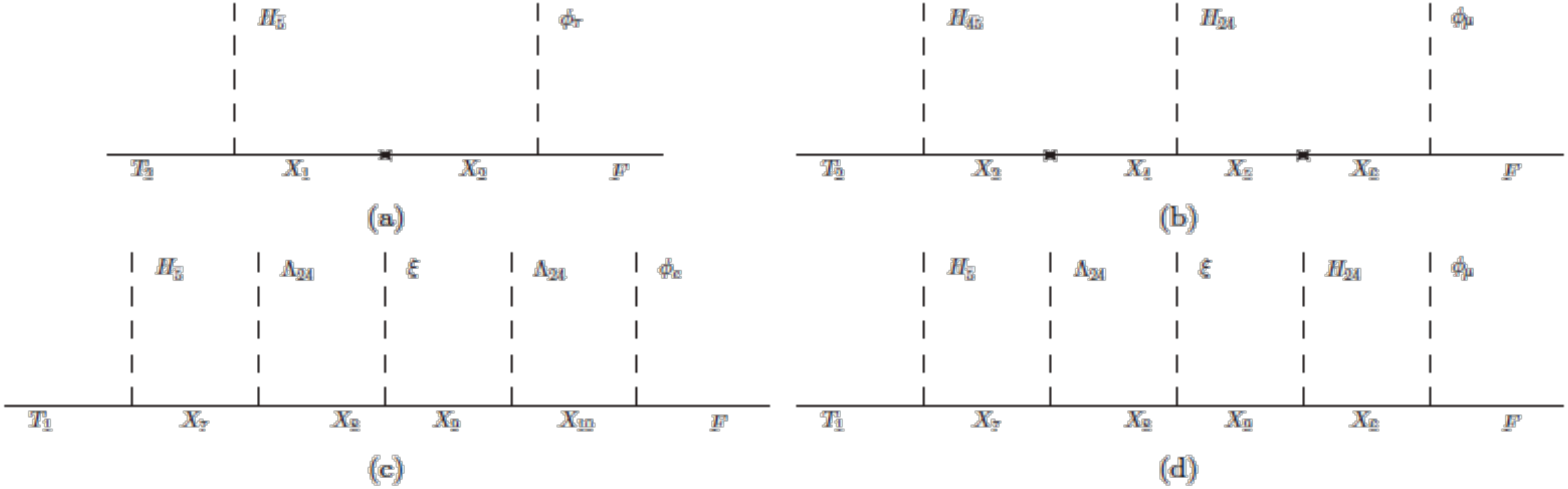

Experimental (at GUT and no threshold c.)

$$\frac{y_\mu}{y_s} \approx 4.36 \pm 0.23, \quad \frac{y_e}{y_d} \approx 0.41 \pm 0.06$$

Our model

$$\frac{y^e_{22}}{y^d_{22}} = \frac{9}{2} = 4.5, \quad \frac{y^e_{11}}{y^d_{11}} = \frac{4}{9} \approx 0.44$$

Strong CP

CP is only spontaneously broken

$$\theta = \arg\det(Y^u Y^d)$$

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$$Y^u \in \mathbb{R} \qquad Y^d_{LR} \sim \begin{pmatrix} * & *\, e^{i\zeta} & 0 \\ 0 & * & 0 \\ 0 & 0 & * \end{pmatrix}$$

No strong CP violation: Nelson-Barr mechanism

Parameter fit

18 parameters surviving at low energies.

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All dimensionless parameters $y \in [0.32,\ 3.12]$

$$\chi^2 = \sum_{i=1}^{N} \left(\frac{P_i(\{x\}) - \mu_i}{\sigma_i} \right)^2 = 7.98$$

More facts

- Doublet-triplet splitting due to the Missing Partner Mechanism.

Adding a 75 with a SM singlet VEV.

Adding a 50 with SU(3) triplets but no SU(2) doublets.

$$W_{DT} \sim H_{\bar{5}}\Omega_{50}\Pi_{75}$$

More facts

- Doublet-triplet splitting due to the Missing Partner Mechanism.
- Higgs mixing generates μ term.

$$W_\mu \sim M_{GUT} \begin{array}{ccc} \mathbf{2}(H_{\bar{5}}) & \mathbf{2}(H_{\overline{45}}) & \\ 0 & 1 & \mathbf{2}(H_5) \\ \tilde{\xi}^8 & 1 & \mathbf{2}(H_{45}) \end{array}$$

$$\mu \sim \tilde{\xi}^8 M_{GUT} \sim 10^{-10} M_{GUT}$$

More facts

- Doublet-triplet splitting due to the Missing Partner Mechanism.
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$$\mu \sim \tilde{\xi}^8 M_{GUT} \sim 10^{-10} M_{GUT}$$

- No dangerous (TTF) proton decay terms allowed.
- There's an explicit symmetry breaking potential.

Not shown, too large :-P

Conclusion

- SUSY Flavor-GUT based on A_4 X SU(5) X Z_9 X Z_6 X Z_4^R.
- Reduces to MSSM at LE (Everything has GUT scale masses).
- Fixed PMNS matrix with great precision.
- Gives hierarchy to quark masses and G-J relations.
- Fits quarks and lepton masses and CKM with O(1) parameters.
- Generates BAU through leptogenesis.
- No strong CP violation and controled proton decay.
- Generates doublet-triplet splitting and small μ term.

Conclusion