A flavor of string theory

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In collaboration with B. Carballo-Pérez & E. Peinado: arXiv:1607.06812

Our goal

Flavor

Symmetries

The need for discrete flavor symmetries

Discrete symetries in (quantum) field theories may explain

- Mass hierarchies of elementary particles

$$
\begin{aligned}
m_e^i &\sim (0.000511, 0.106, 1.777)\ \text{GeV}\,,\\
m_u^i &\sim (0.002, 1.3, 173)\ \text{GeV}\,,\\
m_d^i &\sim (0.005, 0.1, 4.2)\ \text{GeV}\,,
\end{aligned}
$$

- Quark mixing

$$
|V_{CKM}| = \begin{pmatrix} 0.97 & 0.22 & 0.004 \\ 0.23 & 1.02 & 0.04 \\ 0.01 & 0.04 & 0.88 \end{pmatrix}
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- Neutrino mixing

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|V_{PMNS}| = \begin{pmatrix} 0.82 & 0.55 & 0.15 \\ 0.36 & 0.70 & 0.62 \\ 0.44 & 0.46 & 0.77 \end{pmatrix}
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- Mass hierarchies of elementary particles

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\begin{aligned}
|Y_u^{\mathsf{diag}}| &\sim \mathrm{diag}(10^{-5}, 0.01, 1)\,, \\
|Y_d^{\mathsf{diag}}| &\sim \mathrm{diag}(5\cdot 10^{-5}, 10^{-3}, 0.01)\,, \\
|Y_e^{\mathsf{diag}}| &\sim \mathrm{diag}(10^{-6}, 10^{-3}, 0.01)\,.
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  Observation: $\quad \mathbb{Z}_3, S_3, \Delta(27), \Delta(54) \subset \mathrm{SU}(3)$
- Spontaneous breakdown of $G \longrightarrow$ phenomenology (predictions?)

Flavor symmetries: bottom–up

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geometry $\rightarrow$ symmetry

Discrete non-Abelian flavor symmetries can arise from the geometric structure of string compactifications! ☺

Strings

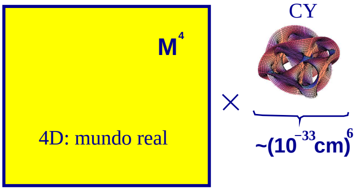
Compactifying string theories

- compactifications:

$$\mathcal{M}^{9,1} = \mathcal{M}^{3,1} \otimes X_6 \qquad \text{vol}(X_6) \sim \ell_{Pl}^6, \quad \mathcal{N} = 1$$

1. X_6: Calabi-Yau threefolds

Candelas,Horowitz,Strominger,Witten (1985)



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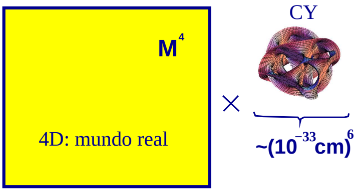
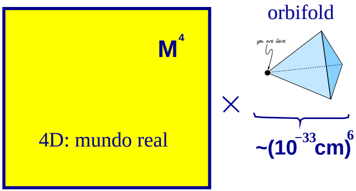


2. X_6: orbifolds

Dixon,Harvey,Vafa,Witten (1985)



Framework: toroidal orbifolds

Orbifold:

$$\mathcal{O} = \frac{\text{compact manifold } \mathcal{M}}{\text{discrete group of isometries } I}$$

Toroidal Orbifold:

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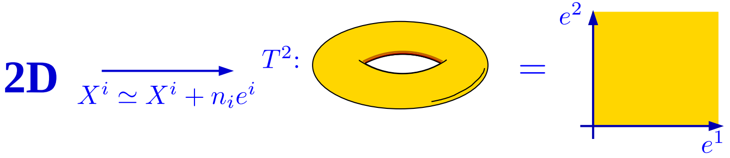
E.g. 2D torus T^2



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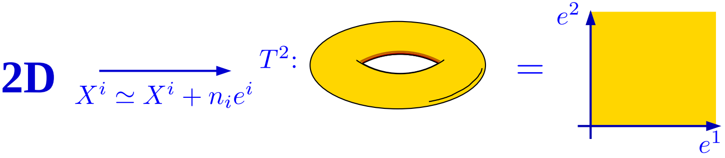
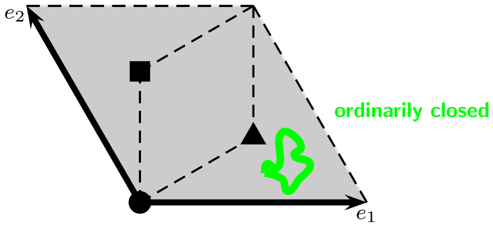


$$\text{then, divide by } I = \begin{cases} \text{Abelian, e.g. } \mathbb{Z}_2, \mathbb{Z}_3, \mathbb{Z}_3 \times \mathbb{Z}_3 \\ \text{non-Abelian} \end{cases}$$

Possible closed strings on the orbifold $T^2/\mathbb{Z}_3$

Three types of *closed strings*:

ordinarily closed, closed on the torus, closed under the orbifold



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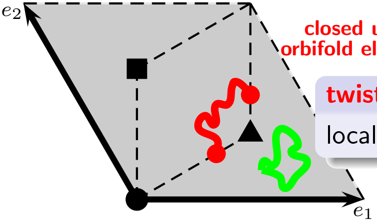

twisted string

localized at fixed point

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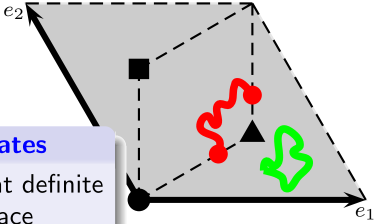

localized twisted states

LEEF states appear at definite points in compact space

Twisted strings located at fixed points $\longrightarrow$ LEEF states localized

Selection rules: localization (*space group*)

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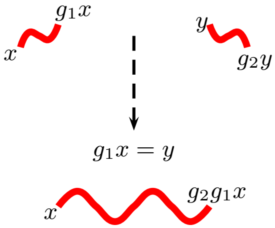

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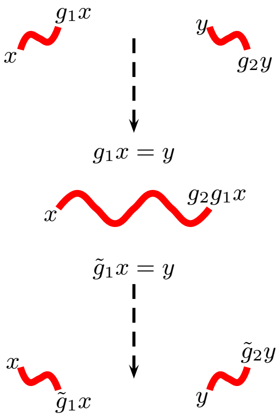

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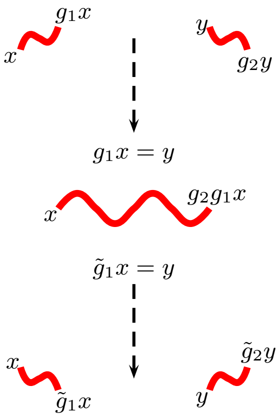
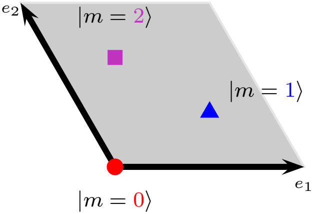


space group selection rule:

Rules telling when strings can interact/mix due to their localization in compact dimensions

Flavor symmetry for $T^2/\mathbb{Z}_3$, $\vartheta = e^{2\pi i/3}$

space group rule



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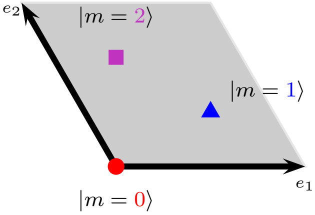

$\Rightarrow$ 2 $\mathbb{Z}_3$'s acting on p, m charges:

$$\sum_j p^{(j)} \overset{!}{=} 0 \mod 3$$
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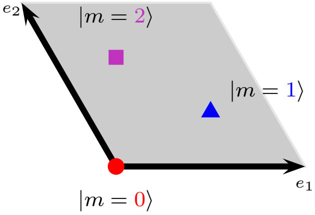

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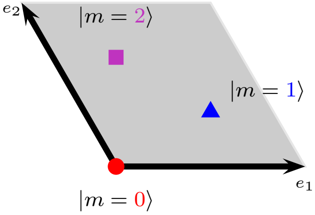

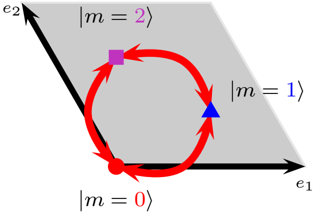

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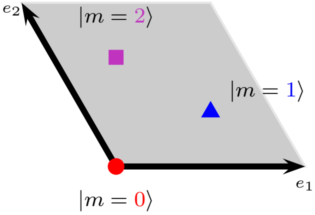
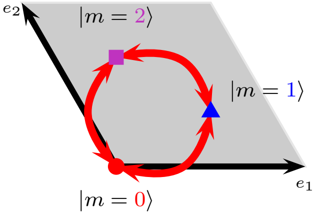


relabeling



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$\Downarrow$

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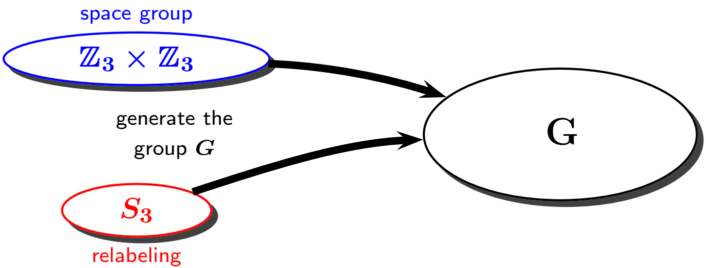
relabeling symmetry:

S_3

Construction of the full flavor symmetry group

- Invariance of couplings under:



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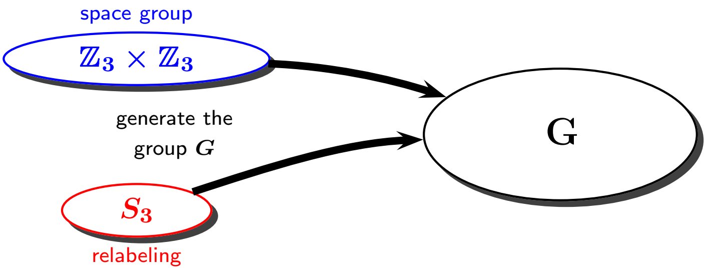

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- There is a *normal subgroup* $N = \mathbb{Z}_3 \times \mathbb{Z}_3 \subset G$

$$G = S_3 \ltimes (\mathbb{Z}_3 \times \mathbb{Z}_3) = \Delta(54)$$

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   - 4D gauge group $= \mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \times G_{hidden}$
   - 3 generations of quarks and leptons + a pair H_u, H_d
   - $\sin^2\theta_w(M_{GUT}) = 3/8$
   - only SM-vectorlike extra matter

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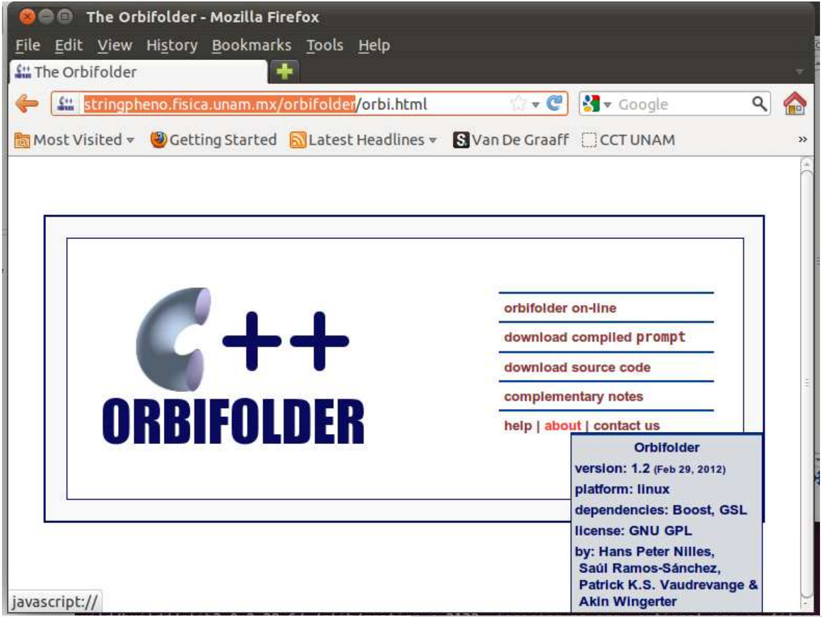
6. Allow for spontaneous breakdown of $\Delta(54)$ flavor symmetry
7. Study the low-energy consequences for quarks and leptons

$\rightarrow$ predictions?

Orbifolder needed as a tool (Nilles, SR-S, Vaudrevange, Wingerter, 2011)



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* Numbers compatible with Nilles,Vaudrevange (2014), but we find many more models ☺

$\Delta(54)$ stringy EXAMPLE

- From superpotential, obtain quark and charged-lepton Lagrangian

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\begin{aligned}
\mathcal{L}_Y^f &= y_1^f \left[F_1 H \bar{f}_1 \phi_1 + F_2 H \bar{f}_2 \phi_2 + F_3 H \bar{f}_3 \phi_3\right] \\
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- Impose now the mass invariants (m_i^f: measured fermion masses)
- Take the hierarchical sol: $r^f \approx (m_2^f - m_1^f)/m_3^f \ll 1\,,\ (a^f)^2 \approx m_1^f m_2^f\,,\ b^f \approx m_3^f$

$$
M_f^D \approx \begin{pmatrix} 0 & \sqrt{m_1^f m_2^f} & \frac{m_2^f - m_1^f}{m_3^f}\sqrt{m_1^f m_2^f} \\ \sqrt{m_1^f m_2^f} & m_2^f - m_1^f & 0 \\ \frac{m_2^f - m_1^f}{m_3^f}\sqrt{m_1^f m_2^f} & 0 & m_3^f \end{pmatrix},
$$

$\Delta(54)$ stringy EXAMPLE

- From superpotential, obtain quark and charged-lepton Lagrangian

$$\begin{aligned}\mathcal{L}_Y^f &= y_1^f\left[F_1 H\bar{f}_1\phi_1 + F_2 H\bar{f}_2\phi_2 + F_3 H\bar{f}_3\phi_3\right]\\ &+ y_2^f\left[(F_1 H\bar{f}_2 + F_2 H\bar{f}_1)\phi_3 + (F_3 H\bar{f}_1 + F_1 H\bar{f}_3)\phi_2 + (F_2 H\bar{f}_3 + F_3 H\bar{f}_2)\phi_1\right] + h.c.\,,\end{aligned}$$

F_i : LH fermion, f_i : RH fermion, H : Higgs, ϕ_i : flavon scalar

- Assume a flavon alignment in D sector: $\langle\phi^f\rangle = v_\phi^f(0, r^f, 1)$
- Impose now the mass invariants (m_i^f: measured fermion masses)
- Take the hierarchical sol: $r^f \approx (m_2^f - m_1^f)/m_3^f \ll 1\,,\ (a^f)^2 \approx m_1^f m_2^f\,,\ b^f \approx m_3^f$

$$M_f^D \approx \begin{pmatrix} 0 & \sqrt{m_1^f m_2^f} & \frac{m_2^f - m_1^f}{m_3^f}\sqrt{m_1^f m_2^f} \\ \sqrt{m_1^f m_2^f} & m_2^f - m_1^f & 0 \\ \frac{m_2^f - m_1^f}{m_3^f}\sqrt{m_1^f m_2^f} & 0 & m_3^f \end{pmatrix},$$

For down-quarks

$$\Rightarrow \quad \tan\theta_C \approx \frac{(M_d^D)_{12}}{(M_d^D)_{22}} \approx \sqrt{\frac{m_d}{m_s}}$$ Gatto-Sartori-Tonin ☺

$\Delta(54)$ stringy phenomenology: down sector

Down-quark and charged-lepton sectors are symmetric

$$\Rightarrow \quad \tan\theta_C^e \approx \frac{(M_e^D)_{12}}{(M_e^D)_{22}} \approx \sqrt{\frac{m_e}{m_\mu}} \qquad \text{leptonic Gatto-Sartori-Tonin} \quad ☺$$

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BUT all other quark and charged-lepton mixing angles are smaller than observed ☹

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Additional novel consequence

$$\frac{m_s - m_d}{m_b} \overset{!}{=} \frac{m_\mu - m_e}{m_\tau}.$$

more stringent than $b - \tau$ unification ☹

$\Delta(54)$ stringy phenomenology: neutrino sector

Además, renormalizable neutrino Lagrangian is

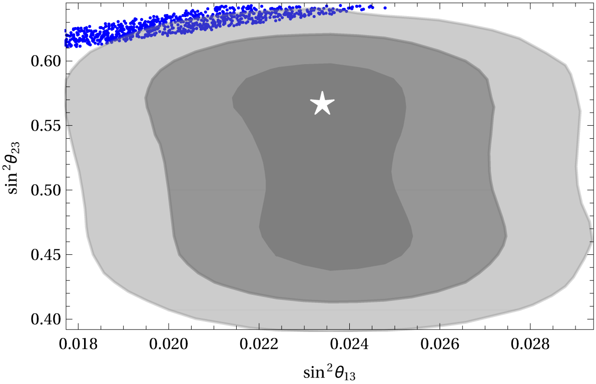
$$
\begin{aligned}
\mathcal{L}_Y^\nu &= y_1^\nu \left[L_1 H_u \bar\nu_1 + L_2 H_u \bar\nu_2 + L_3 H_u \bar\nu_3\right] \\
&+ \lambda_1 \left[\bar\nu_1 \bar\nu_1 \bar\phi_1^\nu + \bar\nu_2 \bar\nu_2 \bar\phi_2^\nu + \bar\nu_3 \bar\nu_3 \bar\phi_3^\nu\right] \\
&+ \lambda_2 \left[2\bar\nu_1 \bar\nu_2 \bar\phi_3^\nu + 2\bar\nu_1 \bar\nu_3 \bar\phi_2^\nu + 2\bar\nu_2 \bar\nu_3 \bar\phi_1^\nu\right]
\end{aligned}
$$

$\Rightarrow$ type I see-saw possible!! ☺

$\Delta(54)$ stringy phenomenology: neutrino sector

Correlation atmospheric–reactor mixing angles compatible with best fit

Forero, Tortola, Valle (2014)



- atmospheric mixing angle: $51.3^o \lesssim \theta_{23} \lesssim 53.1^o$ (second octant) ☺
- reactor mixing angle: $7.8^o \lesssim \theta_{12} \lesssim 8.9^o$ ☺
- $6meV \lesssim m_{\nu_1} \lesssim 6.8meV\,,\quad 65meV \lesssim \sum m_\nu \lesssim 70meV$ ☺

$\Delta(54)$ stringy phenomenology: neutrino sector

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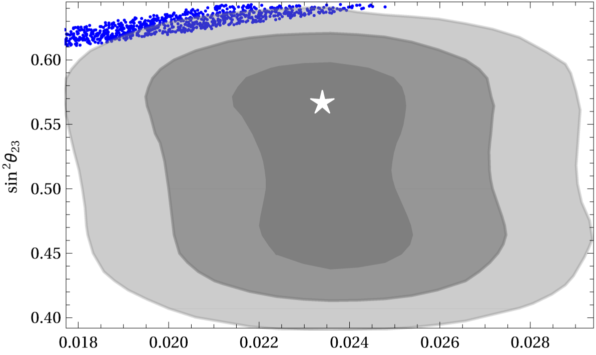


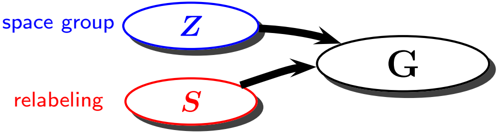
- atmospheric … cond octant) ☺
- reactor mixin…
- $6meV \lesssim m_{\nu_1}$ … eV ☺

Advantages of model:

Compatible with T2K (2016)
only normal hierarchy admissible
Falsifiable soon

Conclusions

- $\Delta(54)$ (and other) flavor symmetries from compactification geometry:



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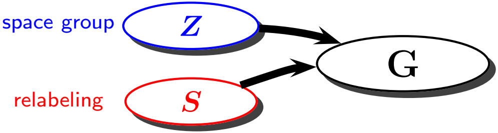

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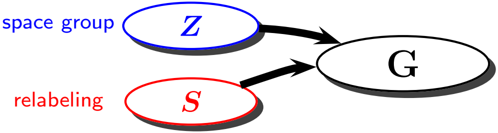

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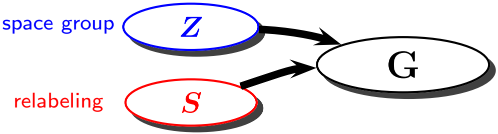

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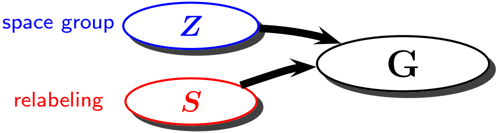

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- Leading to
  1. $6meV \lesssim m_{\nu_1} \lesssim 6.8meV, \quad 65meV \lesssim \sum m_\nu \lesssim 70meV$ ☺
  2. correct masses for quarks and leptons
  3. Gatto-Sartori-Tonin in down-sector
  4. funny unification mass relation ☹
  5. normal hierarchy for neutrino masses
  6. "predict" neutrino mixing angles ☺

Conclusions

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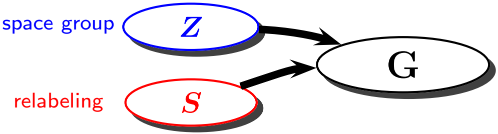

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BUT

- bad quark mixing angles
- proton decay
- unjustified vacuum alignments
- SUSY breaking not understood