F-theory, GUTs and the Weak Scale

Based on:

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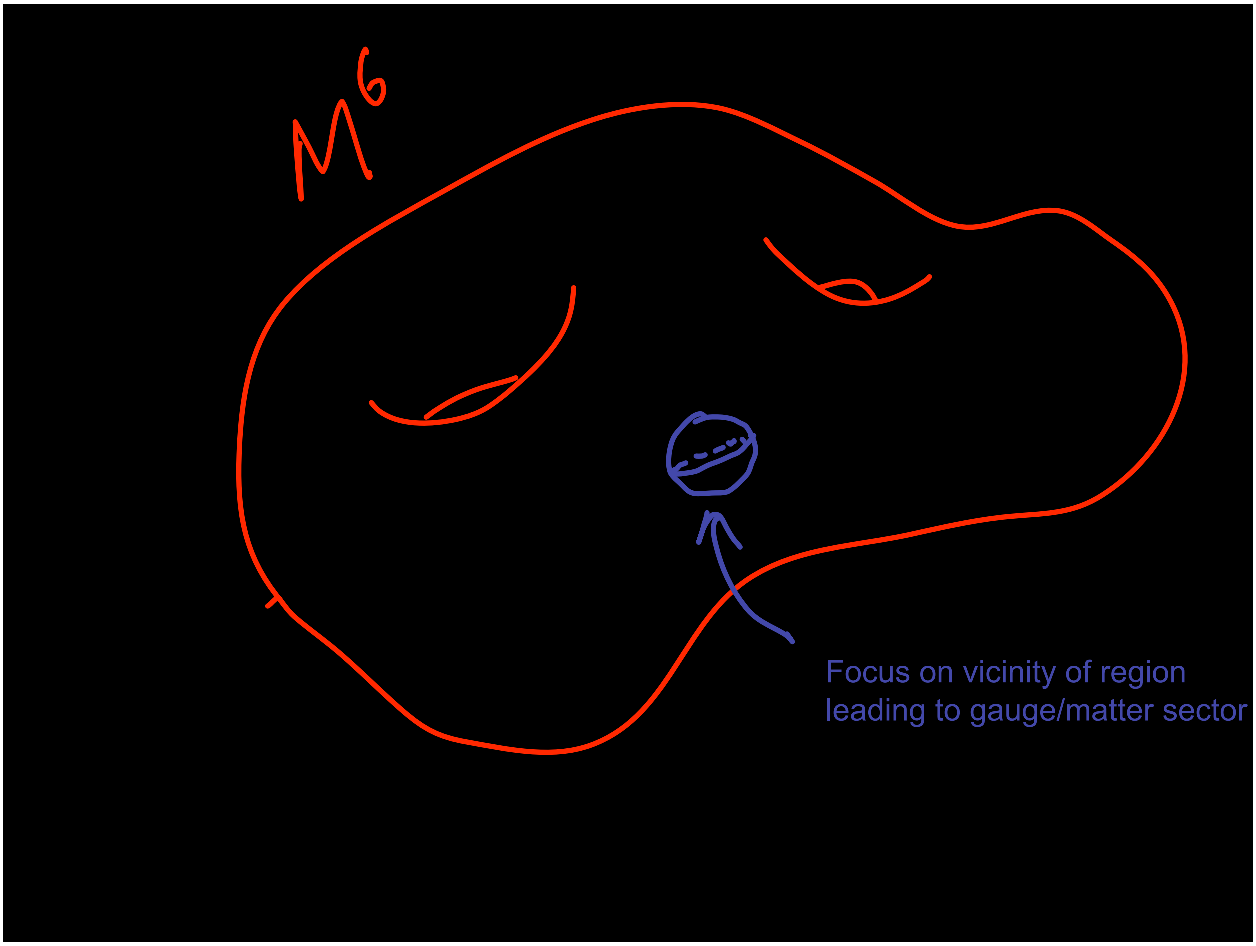
F-theory, GUTS and the Weak Scale, to appear

Most of the effort in string phenomenology has been directed to finding the precise vacuum which leads to a more or less realistic phenomenology. However a precise matching with phenomenology is most often lacking. There is a 'cure' proposed for this: The fact that the string vacuum has so many parameters to adjust, have led some to suggest that one can obtain more or less any phenomenology one aims for! If this were indeed true, it would be very unfortunate for string theory as we would lose predictive power specially for `low energy' experiments such as the ones being currently undertaken here at the LHC.

The aim of the present talk is to argue that if we add some rather mild assumptions we can trim down the open string landscape, dealing with gauge and matter sector, while not affecting the closed string landscape, reserving it for solution to issues involving gravity, such as the cosmological constant problem. This restores predictability of low energy physics coming from string theory. In particular we concentrate not on the full internal compactification geometry of string, but rather focus on the vicinity of the region leading to gauge theory and matter. We build up the internal manifold near this region using the known experimental data and see how much freedom we have. The lack of total freedom simply translates to predictions! This approach has been called local model building.

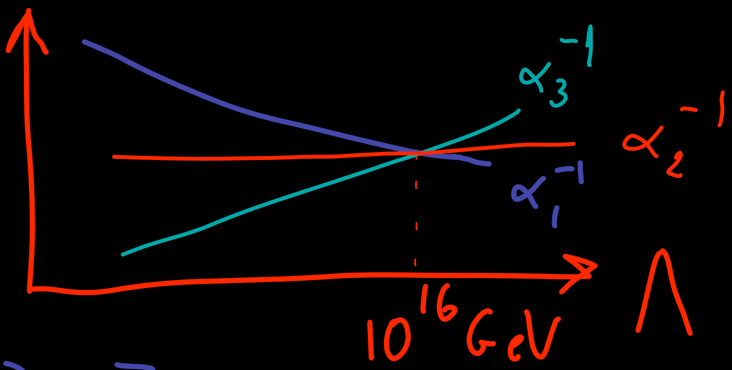


Assumptions

1-Gravitational dynamics decouples from gauge dynamics. This in particular means that we could in principle have taken Planck mass to infinity while keeping the particle masses fixed. This would not have been possible if the matter spectrum was not asymptotically free. The fact that GUTs typically involve asymptotically free theory supports this assumption. In particular this means that if gauge theory is supported on a brane, the internal worldvolume of the brane should be contractible, i.e. be on `vanishing cycle'. This is the strongest assumption we will make, and naturally fits with the idea of local model building on the contractible cycle.

In the context of branes wrapping internal geometries this assumption still leaves us with various choices: We can have p+3 branes wrapping a p-dimensional internal vanishing cycle. The choices for p, compatible with such vanishing cycles inside a CY (or G_2) are p=2,3,4. Clearly the higher the dimension of the brane the more flexibility we will have in building phenomenological models.
We will thus concentrate on the case of p=4, i.e., 7-branes wrapping vanishing 4-cycles. This naturally lands us on type IIB strings. Even for 7-branes wrapping internal 4-cycles we find that it is just barely possible to satisfy the various constraints placed by phenomenology.

2- We assume a SUSY GUT gauge group at a scale of about 10^{16} GeV. Evidence for GUTs is not just limited to the unification of the coupling constants at this scale (which also hints/requires SUSY preserved down to around the weak scale) but perhaps even more importantly also the elegant unification of matter multiplets:



$SU(5): \bar{5}+10+1$ or $SO(10): 16$

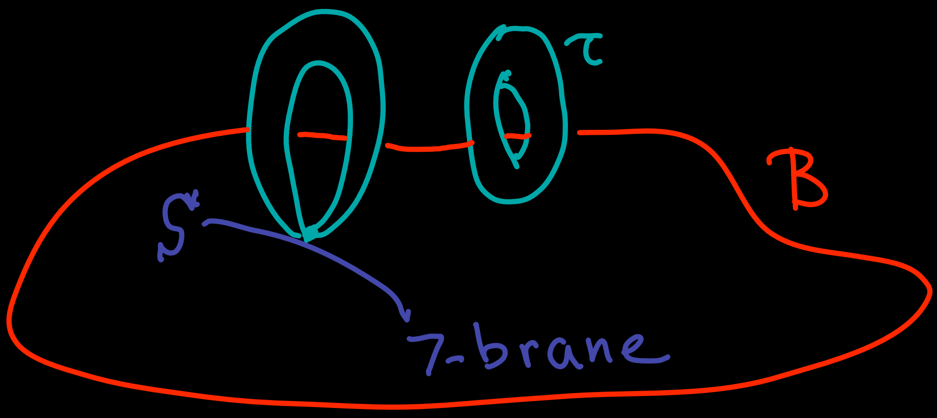
SU(5) and SO(10) gauge symmetries can be easily obtained: In peturbative IIB these can be a stack of D7 branes or their orientifold. However the matter structure of SO(10), the spinor, cannot be obtained in pertrubative IIB. The 5* and 10 of SU(5) are easy to obtain by intersections with other 7-branes and their orientifold in perturbative IIB. But the interaction

5(Higgs) . 10 (Matter) . 10 (Matter)

necessary for top quark mass is not possible (violates U(1)) in pertubative IIB. We are thus naturally led to the non-perturbative completion of IIB via F-theory where we can obtain both spinor of SO(10) as well as the above interaction for SU(5), as we will now discuss.

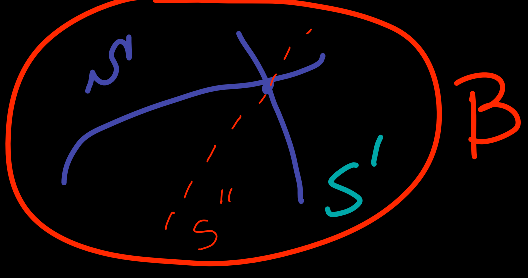
F-theory Gauge fields, Matter and Interactions

F-theory compactification involves elliptic CY 4-folds where the elliptic fiber varies over the complex 3d base B. The base B is interpreted as the geometry of IIB compactification and the modulus of the torus interpreted as the coupling constant of IIB.

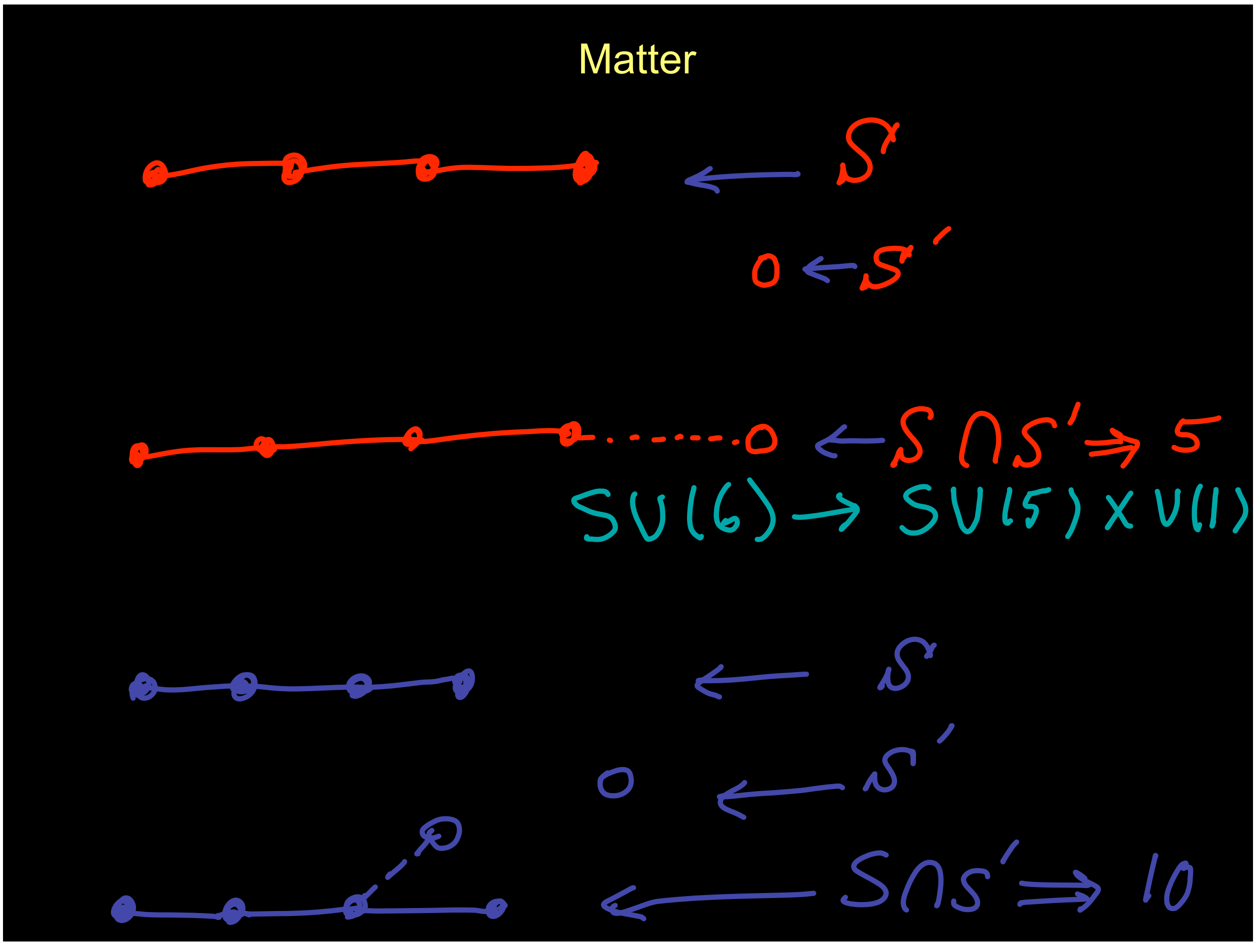


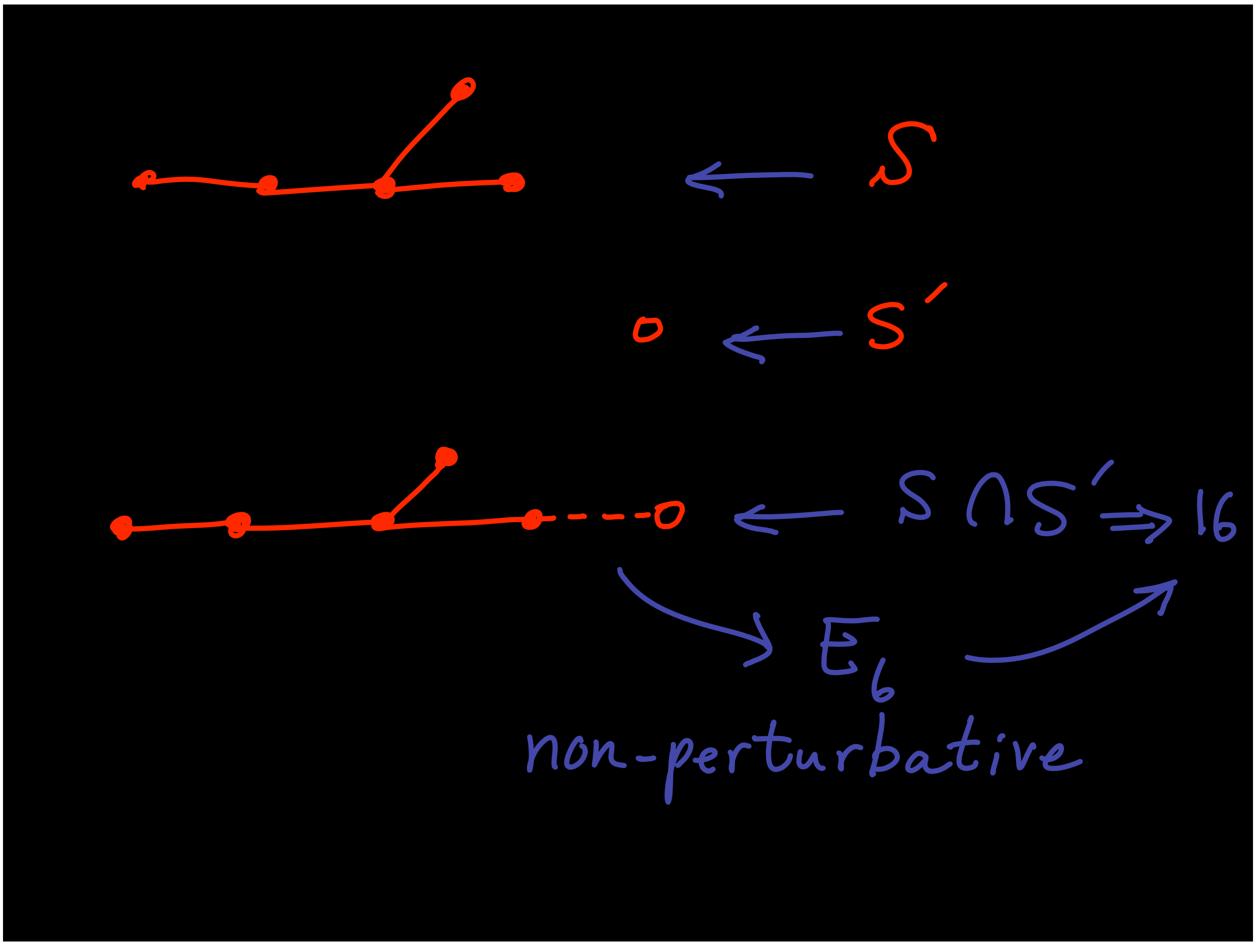
In F-theory various structures separate evenly in dimensions:

Gravity: 10d B
Gauge Fields: 8d (on 7-branes) S
Matter Fields: 6d (intersection of two 7-branes) $S \cap S'$
Interactions: 4d (triple intersection of 7-branes) $S \cap S' \cap S''$

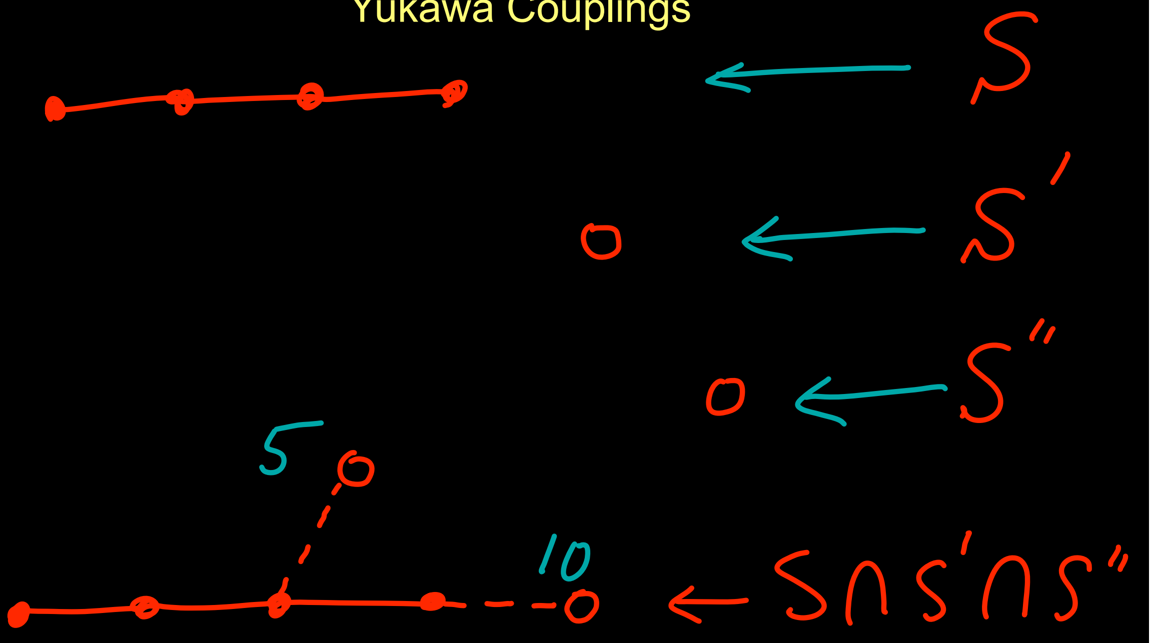


Moreover both the matter and the interactions are determined by singularity enhancement at intersections:


Matter
S
S'
S ∩ S' ⇒ 5
SU(6) → SU(5) x U(1)
S
S'
S ∩ S' ⇒ 10


S
S'
S ∩ S' ⇒ 16
E6
non-perturbative

Yukawa Couplings



$$E_6 \to f_{ijk} \to 5 \cdot 10 \cdot 10$$

non-perturbative

We are interested in 4d particle spectrum. To obtain this from the higher dimensional fields we have to look at the relevant zero modes.

--Gauge fields 8→4 can be partially broken by turning on fields on internal 7-brane (F = *F).

$$G \supset G'$$

--Chiral matter field 6→4 can be obtained by looking at the zero modes of the Dirac operator on the Riemann surface (intersection of two 7-branes) coupled to the gauge fields on the corresponding 7-branes:

$$\not{D}_{A+A'}\Psi = 0$$

The assumption that the 7-brane wraps a vanishing 4-cycle implies that the 4-cycle is a del Pezzo surface (which is unique up to changes of moduli including blow downs). The fundamental group of del Pezzo is trivial. The gauge group on the 7-brane should contain at least an SU(5). For a minimal GUT let us assume it is an SU(5). How to break it to the standard model gauge group? If we had a Higgs in the adjoint, we could give it a vev, but for rigid cycles all such fields have GUT scale mass. Moreover since the fundamental group of del Pezzo is trivial we cannot break it using Wilson lines. The only way to break it is by turning on F of hypercharge: (often Higgses U(1) in the heterotic strings, but OK here)

$SU(5) \to SU(3)\times SU(2)\times U(1)$: $F \neq 0$

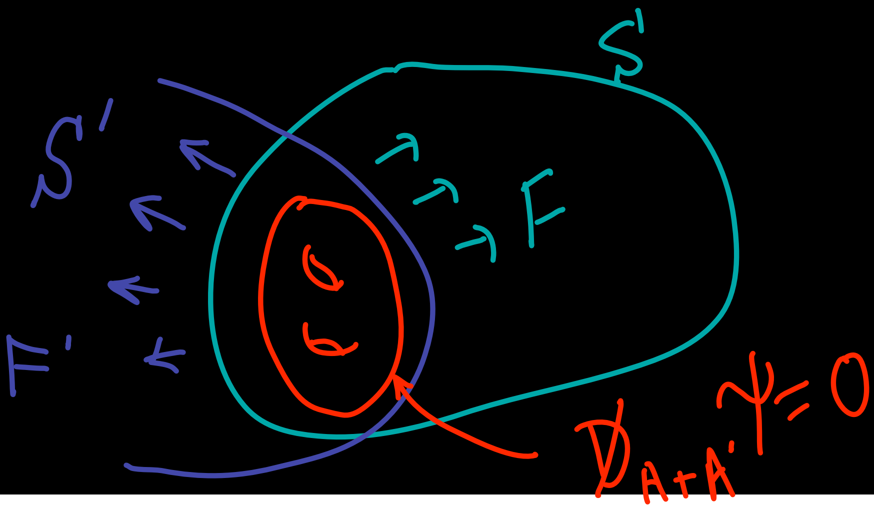
The choice of the flux is unique. In particular to avoid exotic charged particles from reduction of gauge field on the del Pezzo surface S, completely fixes the flux:

$$F \in H^2(S) = \Gamma_{E_8} \oplus \mathbb{Z}$$

$$\Gamma_{E_8} = \text{root lattice of } E_8$$

$$F = \text{a root of } E_8 \, !$$

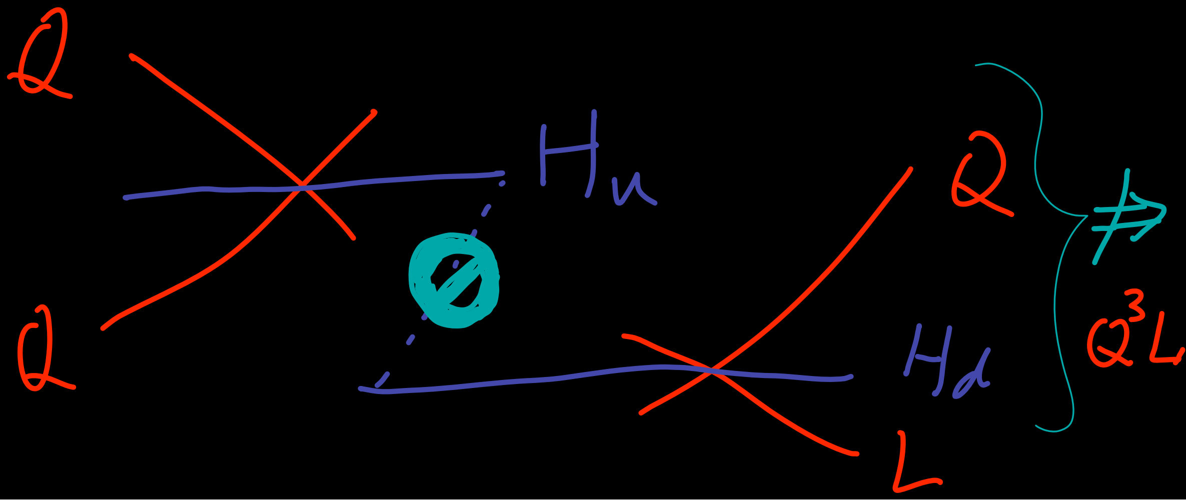
For the matter spectrum all we have to do is simply make sure that we get the right types of intersecting 7-branes, to give us 10's and 5's and turn on appropriate flux on the 7-branes, so that the spectrum of the Dirac field on the intersection gives rise to the appropriate number of matter fields.



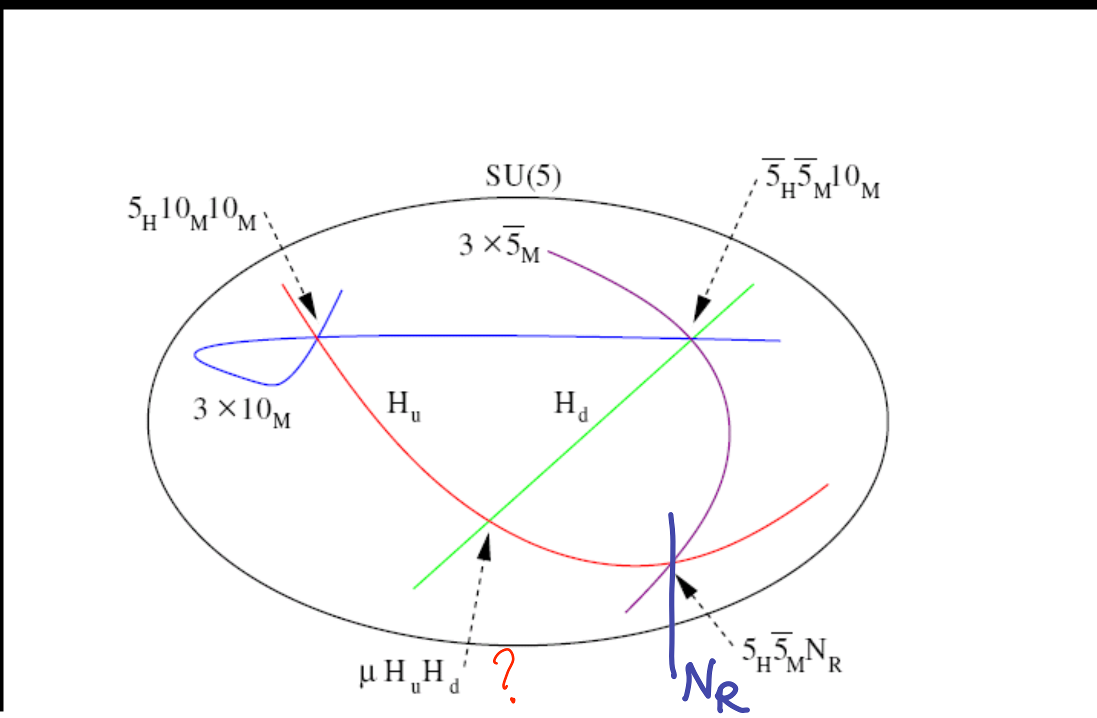
Note that depending on whether the total hypercharge flux F, on the Riemann surface is zero or not, the 4d matter that we would get forms GUT multiplets or not. This is a natural mechanism to solve the doublet-triplet splitting problem: The Higgs fields come from Riemann surface with net hyperflux, and so the triplet can be missing, whereas the matter multiplets come from Riemann srufaces with no net hyperflux, thus forming complete SU(5) reps:

$$\int_{\Sigma_{Higgs}} F \neq 0 \ ; \quad \int_{\Sigma_{matter}} F = 0$$

Moreover the H_u and H_d must come from separate Riemann surfaces (5 versus 5* have opposite sign index for Dirac operator). This ends up naturally solving the dangerous superpotential quartic terms violating baryon number (due to the missing partner mechanism).



Of course we also need to have the appropriate Yukawa couplings, and this is guaranteed by having suitable intersections of the matter and Higgs curves:



This framework is quite predictive and leads to specific predictions for various quantities of phenomenological interest. In particular one finds, assuming a Majorana component for neutrino mass that (slightly different from the prediction coming from seesaw mechanism):

$$\Rightarrow \begin{cases} m_\nu^{light} \approx 0.2 \times 10^{\pm 1.5}\ eV \\ m_\nu^{heavy} \approx 3 \times 10^{12 \pm 1.5}\ GeV \end{cases}$$

Weak Scale and SUSY Breaking

So far we have not dealt with SUSY breaking. This is crucial to understand, especially if we wish to make predictions at the weak scale: The breaking of SUSY naturally triggers the breaking of the electroweak symmetry. It turns out that our setup leads to a very specific region of the soft Lagrangian which can be potentially tested at the LHC! Moreover this leads to several novel theoretical ideas related to how SUSY breaking takes place and how it gets communicated to the MSSM as I will now explain. Let me first review some of the basics of SUSY breaking in connection with phenomenology.

The first basic distinction we need to make is whether the SUSY breaking is gauge or gravity mediated. Let X be the Goldstino chiral superfield:

$$X = x + \theta^2 F$$

gravity mediation $\quad F \gtrsim 10^{20}\,(\mathrm{GeV})^2$

gauge mediation $\quad F \lesssim 10^{18}\,(\mathrm{GeV})^2$

$$m_{3/2} \sim \frac{F}{\sqrt{3}\,M_{pl}}$$

The approach we find very natural for F-theory is gauge mediation for communicating supersymmetry. We have messenger fields Y,Y' (say in the 5 and 5* of SU(5)) coupled to the Goldstino field X :

$$X(\theta) = x + \theta^2 F$$

$$\langle x \rangle \neq 0$$

$$\langle F \rangle \neq 0$$

$$\int d^2\theta\, X Y Y' \longrightarrow \langle x \rangle = M_{mess}$$

Integrating the messenger fields out leads to SUSY breaking in the visible sector. Mass splitting scale in the visible sector, both for the gauge and matter sector is set by

$$\Lambda = \frac{F}{X} \sim 10^5 \text{ GeV}$$

e.g. $\quad m_i = \frac{\alpha_i}{4\pi} \Lambda$

for gluino masses

The main challenge in gauge mediation is to generate a μ term, while not generating too large a $B\mu$ term. In particular the following will not work:

$$\int d^2\theta \; X \cdot H_u H_d$$

$$\downarrow$$

$$X + \theta^2 F \rightarrow \begin{cases} \mu = X \\ B\mu = F \end{cases}$$

$$\Rightarrow B = \frac{F}{X} \sim 10^5 \text{ GeV}$$

too large

Instead it is natural to implement the generation of μ term using a Giudice-Masiero mechanism, as in gravity mediation, which involves the term

$$\int d^4\theta \, \frac{X^\dagger H_u H_d}{M_X}$$

$$\mu = \frac{F}{M_X} \qquad B\mu = 0$$

This leads to large $\tan\beta = \frac{\langle H_u \rangle}{\langle H_d \rangle}$ which is favored.

Note that we have three scales to fix

$$X, \; F, \; M_X$$

In fact given one of these three scales, and requiring

$$\Lambda = \frac{F}{X} = 10^5 \text{ GeV}$$

$$\mu = \frac{F}{M_X} = 10^{2-3} \text{ GeV}$$

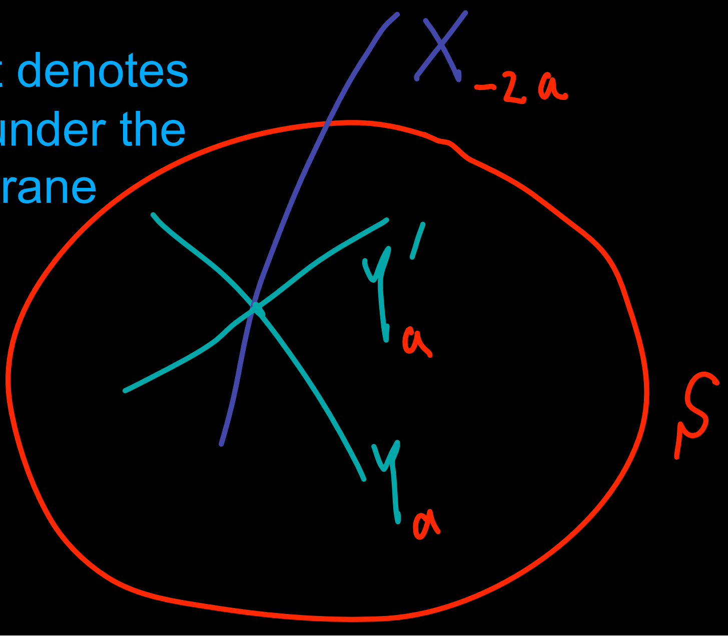
fixes all three

F-theory Realization of Gauge Mediation

We need fields Y,Y' and X together with a Yukawa coupling between them. This can be arranged:

The subscript denotes U(1) charge under the intersecting brane

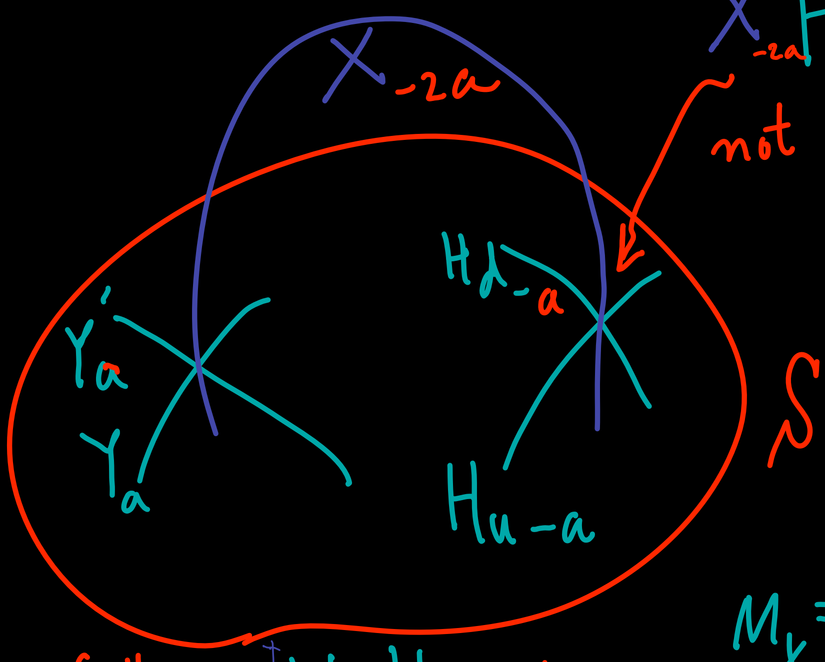
$$X_{-2a} Y_a Y'_a$$



We also need to obtain the Giudice-Masiero term:

$$X_{-2a} H_{u_{-a}} H_{d_{-a}}$$

not allowed



$$M_X = 10^{15}\ \mathrm{GeV}$$

generates $\int d^4\theta\, X^\dagger_{2a} H_{u_{-a}} H_{d_{-a}} / M_X$

This forces us to the parameter choices:

$$X \simeq 10^{12}\ \mathrm{GeV} = M_{mess}$$

$$F \simeq 10^{17}\ (\mathrm{GeV})^2$$

$$M_X \simeq 10^{15}\ \mathrm{GeV}$$

Moreover the U(1) gauge symmetry on the orthogonal 7-brane can be identified with gauging the Peccei-Quinn symmetry (as the Higgs are charged under it). Indeed this Peccei-Quinn 7-brane is responsible for SUSY breaking!

SUSY breaking occurs due to existence of 8d-gauge instantons (`stringy instantons') on the PQ brane
(Heckman,Marsano,Saulina, Schafer-Nameki, Vafa, arXiv:0808.1286)

$$W = q \cdot X$$

$$q = M_*^2 e^{-V_4} \sim \text{small}$$

On the other hand the PQ gauge symmetry is anomalous and there is a D-term which leads to Higgsing PQ (Green-Schwarz mechanism):

$$V = \ldots + \left(|X|^2 + \ldots - \xi\right)^2$$

$\uparrow$ FI-term

$$\Rightarrow \langle |X| \rangle \sim \sqrt{\xi} \quad \sim 10^{12}\,\text{GeV} \leftarrow \text{B.P.}$$

$$F = \frac{\partial W}{\partial X} \sim M_*^2\, q \neq 0$$

$\sim 10^{17}\,\text{GeV}^2$ naturally small (instanton)

Thus this leads to SUSY breaking via a stringy hybrid of Fayet and Polonyi models!

The expectation value <X> Higgses the PQ gauge symmetry. However there are two competing Goldstone bosons: One is the phase of X and the other is the 3-brane potential corresponding to the PQ brane. A combination of them (which is mostly the latter) gets eaten by the gauge boson. The other combination, which is mostly the phase of X remains massless, all the way to the QCD scale. Since integrating the messenger fields generates

$$\underbrace{\ln X}_{\text{axion}}\; F \wedge F$$

$\Rightarrow$ phase of X is QCD axion!

The decay constant of this axion is |X|

$$X = |X| e^{i\theta}$$

$$\int |D_\mu X|^2 \rightarrow \int |X|^2 (\partial\theta)^2$$

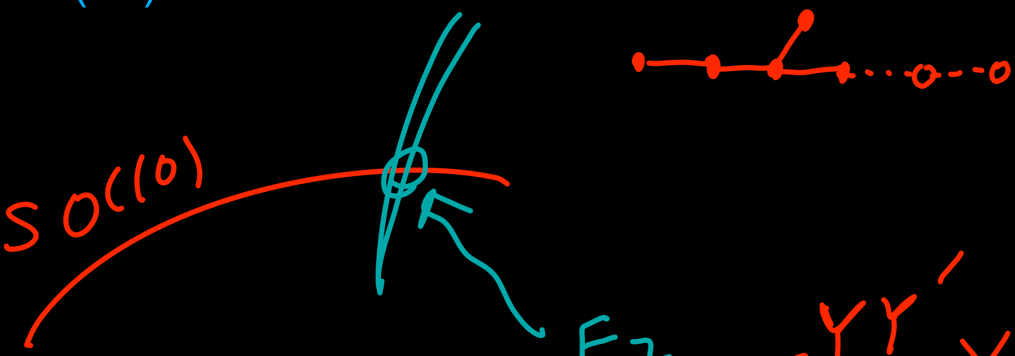
$$f_a = |X| \simeq 10^{12}\,\mathrm{GeV}!$$

$$10^9 \lesssim f_a \lesssim 10^{12} \text{ : bound } \checkmark$$

Note that this identification of QCD axion not only solves the usual difficulty string theory has in getting a low enough axion decay constant, but also correlates its value with GUT scale, gluino scale Λ and the μ term.

$$f_a \sim M_{GUT} \cdot \frac{\mu}{\Lambda} \cdot O(1)$$

It may appear that the charge assignments for the messenger fields and the X fields and the Higgs fields for the PQ symmetry is somewhat unnatural. It turns out it is very natural in the context of an SO(10) unification:



$Y, Y' \quad X$

$E_7 \supset E_6 \supset SO(10) \times U(1)_{PQ}$

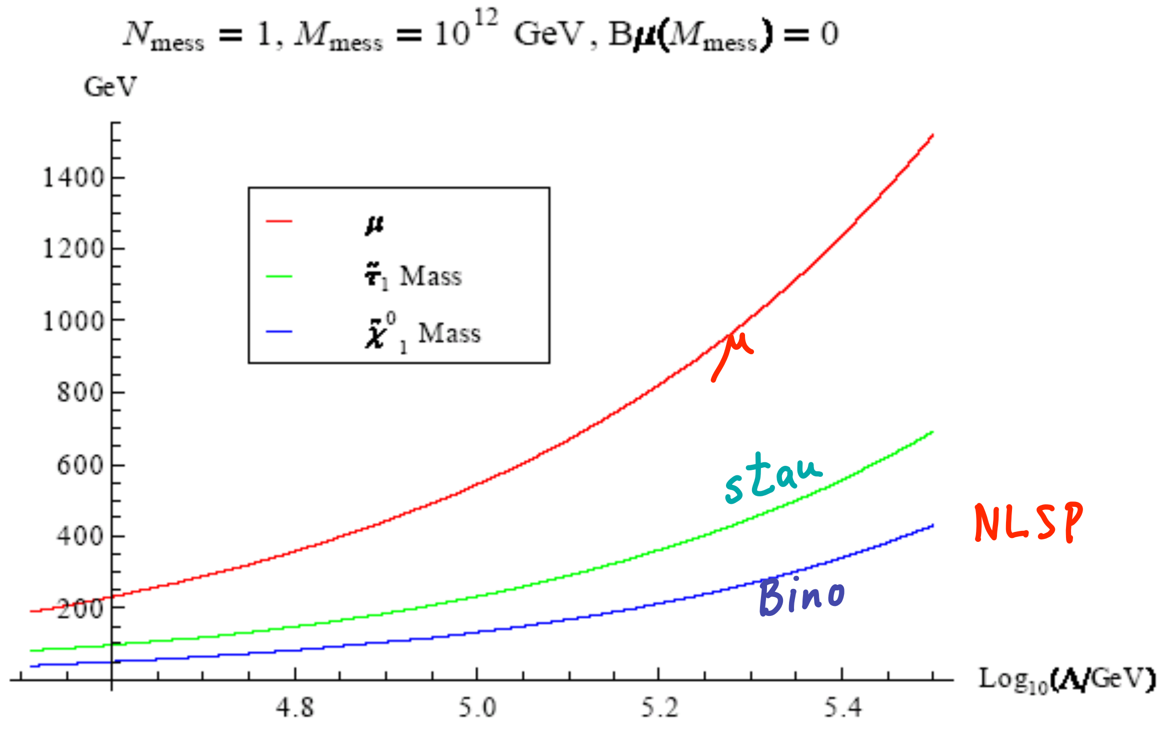
$27 \to 16_{-1} + 10_{+2} + 1_{-4}$

Also in this context the Higgsing of the U(1) Peccei-Quinn symmetry leave a discrete Z_4 symmetry, which contains the Z_2 R-parity needed to avoid unwanted cubic superpotential terms!

$$U(1)_{PQ} \overset{\langle X \rangle}{\supset} Z_4 \supset Z_2^{\text{R-parity}}$$

Experimental Predictions for LHC

Given the relatively robust boundary conditions we have, we can start with them at the messenger scale and run it down to the weak scale and require that proper electroweak breaking occurs. In this way we find a very narrow range of allowed values for quantities of interest at the weak scale. We thus find a very predictive structure:



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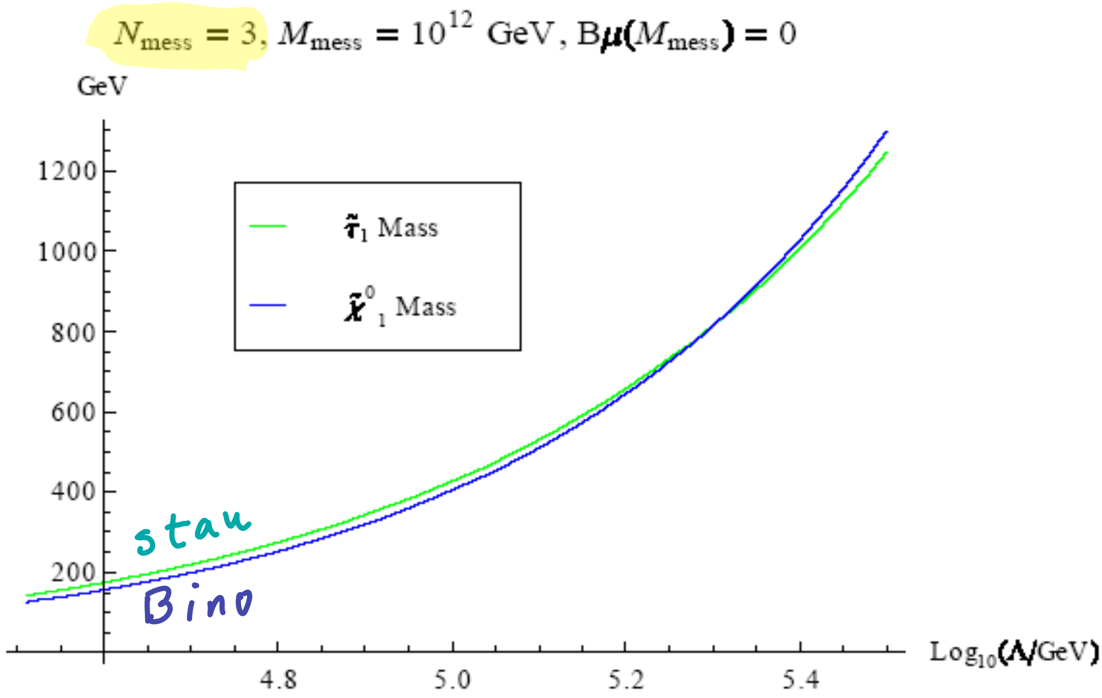

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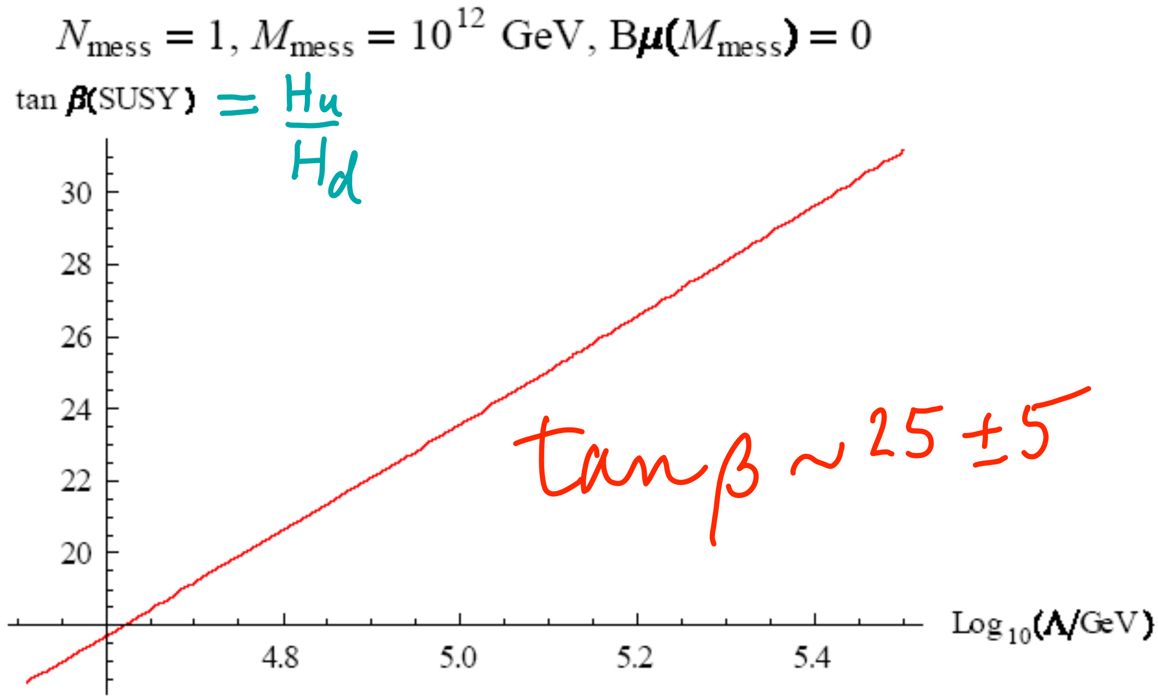

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A Deformation of Gauge Mediation

Since the U(1) PQ gauge symmetry directly couples to Higgs and matter fields, it leads to additional soft mass terms:

$$\propto \int d^4\theta \, \frac{X^\dagger X \, \phi^\dagger \phi}{M_{PQ}^2}$$

If $M_{PQ} \gg M_X$ then this is negligible. But apriori this can be similar in scale. Thus we can consider a one parameter extension of the usual gauge mediation by the choice of M_{PQ}.