

A Landscape solution to SUSY flavor and CP problems.

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Based on *arXiv* : 1910.00090 with Howard Baer and Vernon Barger

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Overview

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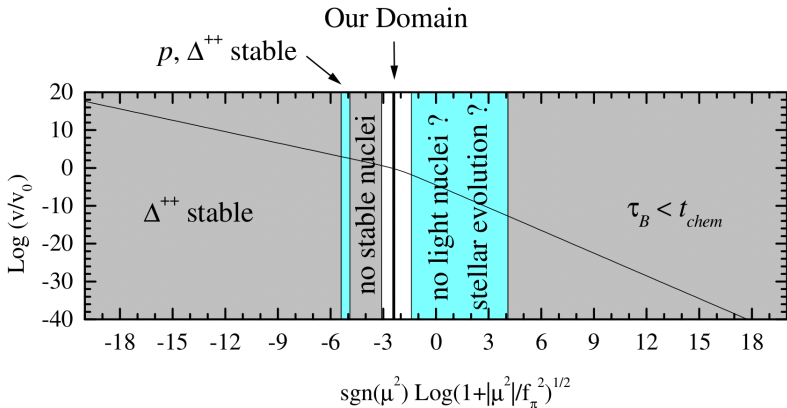
Landscape from the Multiverse

- Why is the cosmological constant (CC) Λ so tiny when there is no known symmetry to suppress its magnitude? Naively, one would expect $\Lambda \simeq m_P^4$ whereas experiments suggest $\Lambda \simeq 10^{-120} m_P^4$.
- Assuming a multiverse with a huge assortment of vacua states with cosmological constant uniformly distributed, then those pocket universes with Λ somewhat larger than our measured value would lead to such rapid expansion that galaxies wouldn't condense, and presumably observers wouldn't arise. Weinberg used such reasoning (anthropic principle) to predict the value of Λ to within a factor of several well before it was experimentally measured.

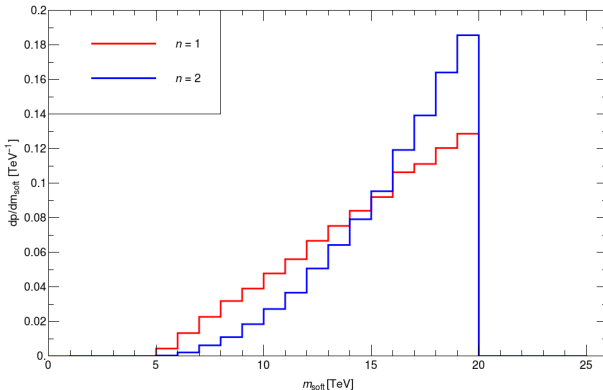
Landscape from the Multiverse

- Given the success of the landscape in predicting Λ , can multiverse arguments also be used to predict the scale of SUSY breaking in a fertile patch of string landscape which has MSSM as the EFT ?
- For this, Douglas suggest a power-law statistical selection of soft breaking terms (m_{soft}^n where $n = 2n_F + n_D - 1$ with n_F the number of hidden sector F-SUSY breaking fields and n_D the number of hidden sector D-SUSY breaking fields)
- The statistical draw towards large soft terms must be tempered by requiring an appropriate breakdown of electroweak (EW) symmetry with no contributions to the weak scale larger than a factor 2-5 of its measured value, lest one violates the (anthropic) atomic principle. For a fixed natural value of μ , this translates to $\Delta_{EW} < 30$.

arXiv : hep-ph/9801253 by Agrawal et al.



[For details on stringy naturalness please see Talk by Howard Baer (Monday 3 pm; SUSY) and Shadman Salam (Tuesday 2 pm; Theoretical Developments and Extra Dimensions)]



These soft terms with non-uniform distribution at the GUT scale are used to generate masses of particles at the weak scale through RGE running and an upper bound is obtained by requiring appropriate EWSB (no CCB vacua) and $m_{\text{weak}}^{PU} < 4 \times m_{\text{weak}}^{OU}$.

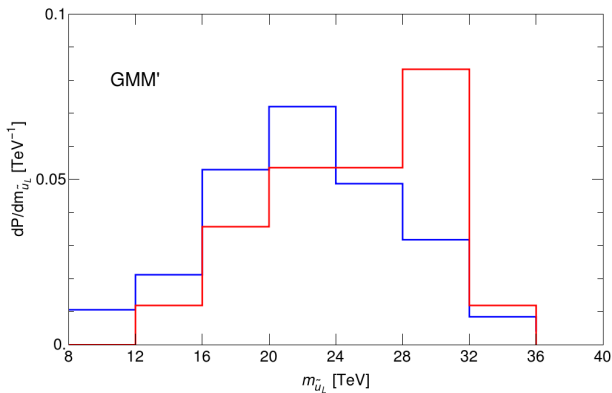
By scanning over SUSY models with soft terms generated according to m_{soft}^n for $n = 1$ and 2 , along with the anthropic vetos from $m_{weak}^{PU} < 4 \times m_{weak}^{OU}$, then the following features were found:

- A statistical peak was found at $m_h \simeq 125 \pm 2$ GeV.
- The probability distribution $dP/dm_{\tilde{g}}$ yields a value $m_{\tilde{g}} \sim 4 \pm 2$ TeV, safely above LHC2 limits.
- The light top squark is lifted to $m_{\tilde{t}_1} \sim 1.5 \pm 0.5$ TeV, also safely above LHC Run 2 limits.



- Light higgsinos $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_{1,2}^0$ with mass $\sim \mu \sim 200 \pm 100$ GeV. The mass gap is $m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} \sim 7 \pm 3$ GeV. Thus, higgsino pair production signals should ultimately show up at LHC14 via $pp \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_2^0$ production followed by $\tilde{\chi}_2^0 \rightarrow \ell^+ \ell^- \tilde{\chi}_1^0$ decay with $m(\ell^+ \ell^-) < (7 \pm 3)$ GeV once sufficient luminosity is gained.
- First and second generation matter scalars (squarks and sleptons) are pulled up to $m(\tilde{q}, \tilde{\ell}) \sim 30 \pm 10$ TeV.

Here, we focus on the last point. Apparently, with first and second generation matter scalars being pulled up to the tens of TeV regime, then one is also being pulled up to a potential decoupling solution to the SUSY flavor and CP problems. **The question is: how does this decoupling arise, and is it enough to actually solve these two SUSY issues?**



Probability distribution $dP/dm_{\tilde{u}_L}$ vs $m_{\tilde{u}_L}$ from general scan for $n_{1/2} = 1$ but for $n_0 = 1$ (Blue) and $n_0 = 2$ (Red).

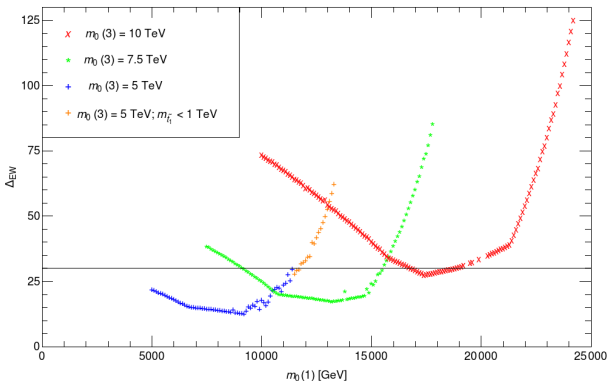
Living dangerously with heavy sfermions

- Here, we concern ourselves with the upper bound on matter sfermion masses for the first two generations, which we label according to high-scale soft term values $m_0(1)$ and $m_0(2)$.
- The model considered here is NUHM4 allowing for splittings between first and second generation masses (as well as the third) *i.e.* $m_0(1) \neq m_0(2) \neq m_0(3)$. The presence of off-diagonal soft term masses are also allowed.
- From a scan over NUHM3 parameter space in *arXiv* : [1712.01399](#) by Baer *et al.* it was found that the statistical distribution of first/second generation sfermion masses for $n = 1$ or 2 was peaked around $m_{\tilde{f}} \sim 20$ TeV but with tails extending as far as 40 TeV.

Living dangerously with heavy sfermions

- The upper bound on first/second generation matter sfermions arises from two-loop RG contributions to third generation soft masses which actually push these values to small, even tachyonic values.
- In the string landscape picture, this is yet another example of *living dangerously*, wherein soft terms are pulled to large values which actually *increases the naturalness of the theory* until huge first/second generation sfermion masses drive third generation masses tachyonic leading to CCB vacua.

Living dangerously with heavy sfermions



$m_{1/2} = 1200$ GeV, $A_0 = -1.6m_0(3)$ and $\tan \beta = 10$ with $\mu = 200$ GeV and $m_A = 2000$ GeV.

The SUSY flavor problem

In the SM, a fourth quark, charm, was posited in order to suppress flavor changing neutral current (FCNC) processes, for which there were strict limits. In a successful application of practical naturalness, Gaillard and Lee required the charm-quark box diagram contribution to the $m_{K_L} - m_{K_S} \equiv \Delta m_K$ mass difference to be less than the measured value of Δm_K itself: this led to the successful prediction that $1 \text{ GeV} < m_c < 2 \text{ GeV}$ shortly before the charm quark discovery.

By supersymmetrizing the SM into the MSSM, then many new parameters are introduced, mainly in the soft SUSY breaking sector. These include sfermion mass matrices

$$\mathcal{L}_{soft} \ni -\tilde{f}_i^\dagger (\mathbf{m}_{\tilde{\mathbf{f}}}^2)_{ij} \tilde{f}_j \quad (1)$$

The SUSY flavor problem

In the superCKM basis, the 6×6 sfermion mass matrices are built out of 3×3 LL , RR , LR and RL sub-matrices which have the form e.g.

$$(\mathbf{m}_{\tilde{f}}^2)_{LL} = \begin{pmatrix} (m_{f1}^2)_{LL} & (\Delta_{12}^f)_{LL} & (\Delta_{13}^f)_{LL} \\ (\Delta_{21}^f)_{LL} & (m_{f2}^2)_{LL} & (\Delta_{23}^f)_{LL} \\ (\Delta_{31}^f)_{LL} & (\Delta_{32}^f)_{LL} & (m_{f3}^2)_{LL} \end{pmatrix} \quad (2)$$

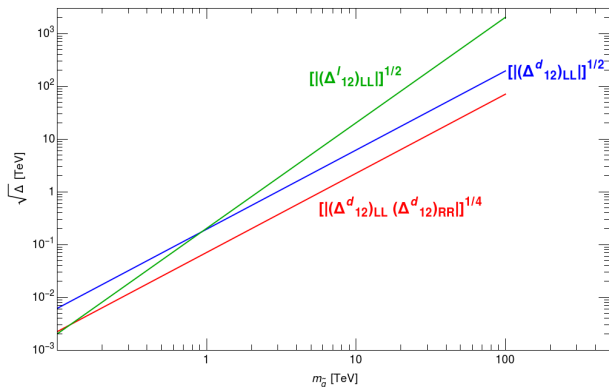
with $(m_{\tilde{U}}^2)_{LL} = V_L^u \mathbf{m}_Q^2 V_L^{u\dagger}$, $(m_{\tilde{U}}^2)_{RR} = V_R^u \mathbf{m}_U^{2T} V_R^{u\dagger}$ and $(m_{\tilde{U}}^2)_{LR} = -\frac{v \sin \beta}{\sqrt{2}} V_L^u \mathbf{a}_U^* V_R^{u\dagger}$ etc. and where the CKM matrix is given by $V_{KM} = V_L^u V_L^{d\dagger}$.

The SUSY flavor problem

Since the transformation that diagonalizes the quark mass matrices does not simultaneously diagonalize the corresponding squark mass squared matrices, then the **off-diagonal mass matrix contributions** Δ_{ij}^f may contribute to FCNC processes via mass insertions, and furthermore, **non-degenerate diagonal terms** can also lead to FCNC effects.

In the following figure, the most restrictive limits on several Δ_{ij} quantities arising from Δm_K constraint and also from updated branching fraction limits on $\mu \rightarrow e\gamma$ decay:
 $BF(\mu \rightarrow e\gamma) < 4.2 \times 10^{-13}$ at 90% CL are shown .

A Landscape Solution to the SUSY flavor problem



Upper limits on off-diagonal squark mass terms from Δm_K constraints (blue and red) and off-diagonal slepton masses from $BF(\mu \rightarrow e\gamma)$ (green).

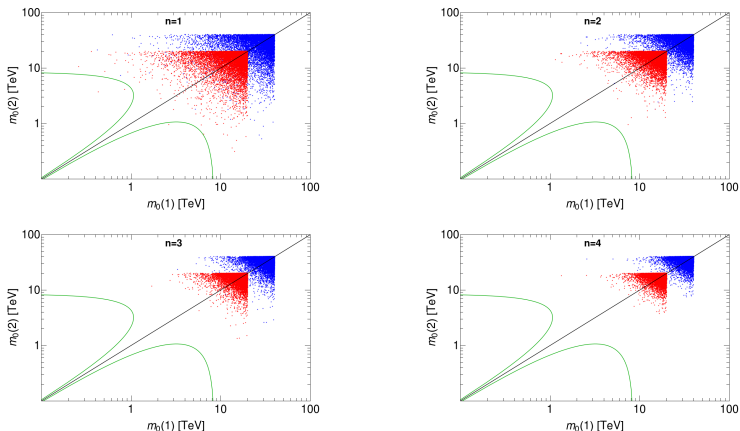
A Landscape Solution to the SUSY flavor problem

Along with limits on off-diagonal mass matrix terms, to suppress FCNC effects and hence solve SUSY flavor problem one needs **degeneracy on the diagonal**. Limits on degeneracy have been computed by Misiak *et al.* in *arXiv : hep-ph/9703442*. From the Δm_K constraint, for the first two generations of squarks these amount to

$$|m_{\tilde{q}1} - m_{\tilde{q}2}| \leq 2m_c m_{\tilde{q}}^2 / m_W^2 \quad (3)$$

for both up and down squarks. Thus, for sparticle masses of order m_W , splittings of only a few GeV are allowed and we must be in a state of near degeneracy. As $m_{\tilde{q}}$ increases, then these bounds become much weaker, as can be seen in the following figure.

A Landscape Solution to the SUSY flavor problem



The values of $m_0(2)$ vs. $m_0(1)$ from an *a*) $n = 1$, *b*) $n = 2$, *c*) $n = 3$ and *d*) $n = 4$, statistical selection of first and second generation matter scalar soft terms. The lower-left of green curves is excluded while red points denote soft terms scanned up to 20 TeV while blue points show points scanned up to 40 TeV.

A Landscape Solution to the SUSY flavor problem

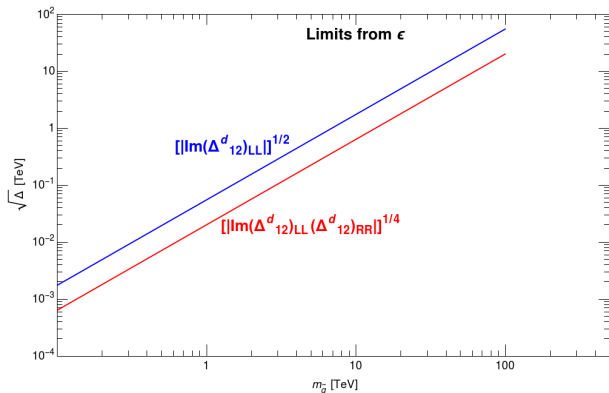
- As already mentioned earlier, it was found in *arXiv : 1712.01399* that landscape pull with $n = 1$ or 2 results in $m_{\tilde{f}} = 20$ TeV to be the most probable value with some non-zero probability for $m_{\tilde{f}} = 40$ TeV. This results in [decoupling](#). Because of this decoupling, limits on off-diagonal terms can float as high as tens of TeV, comparable to the tens of TeV for diagonal terms.
- Since this upper bound depends only on gauge quantum numbers, so it is same for both first and second generation. With strong enough pull, this results in [quasi-degeneracy](#), thereby, suppressing FCNC effects.
- This quasi-degeneracy, along with decoupling, helps in solving the SUSY flavor problem.

The SUSY CP violation problem

Limits can also be placed on complex valued soft terms due to their inducement of CP violating effects on ϵ and ϵ'/ϵ in the kaon system and also from neutron (d_n) and electron (d_e) electric dipole moments (EDMs). The latter contribute only to LR mixing terms and are suppressed by Yukawa couplings for the first two generations so we concentrate on the former kaon constraints.

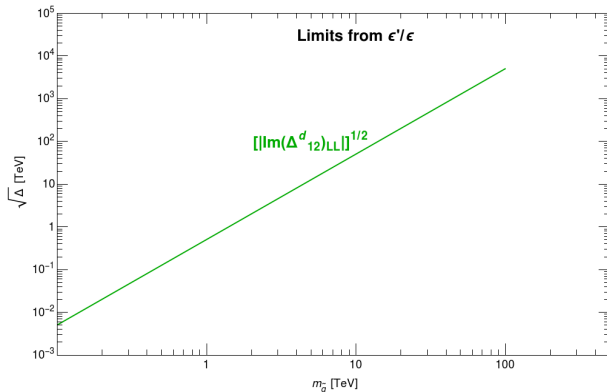
In the following figure, we show the **constraints on the Imaginary part** $[|Im(\Delta_{12}^d)_{LL}|]^{1/2}$ and $[|Im(\Delta_{12}^d)_{LL}(\Delta_{12}^d)_{RR}|]^{1/4}$ from requiring contributions to the ϵ **parameter** to be below its measured value followed by constrain on $[|Im(\Delta_{12}^d)_{LL}|]^{1/2}$ from the measured value of ϵ'/ϵ .

A Landscape Solution to the SUSY CP problem



Upper limits on $[Im|(\Delta^d_{12})_{LL}|]^{1/2}$ (blue) and $[Im|(\Delta^d_{12})_{LL}(\Delta^d_{12})_{RR}|]^{1/4}$ (red) from kaon system ϵ constraints.

A Landscape Solution to the SUSY CP problem



Upper limits on Imaginary part of off-diagonal squark mass terms from Kaon system ϵ'/ϵ constraints.

Example

Quantity	Upper bound	Source
$[\ (\Delta_{12}^d)_{LL}(\Delta_{12}^d)_{RR}\]^{1/4}$	$< 12 \text{ TeV}$	Δm_K
$[\ (\Delta_{12}^d)_{LL}\]^{1/2}$	$< 30 \text{ TeV}$	Δm_K
$[\ (\Delta_{12}^\ell)_{LL}\]^{1/2}$	$< 200 \text{ TeV}$	$BF(\mu \rightarrow e\gamma)$
$ m_{\tilde{q}1} - m_{\tilde{q}2} $	unbounded	Δm_K
$[\ Im(\Delta_{12}^d)_{LL}\]^{1/2}$	$< 10 \text{ TeV}$	ϵ
$[\ Im(\Delta_{12}^d)_{LL}(\Delta_{12}^d)_{RR}\]^{1/4}$	$< 3 \text{ TeV}$	ϵ
$[\ Im(\Delta_{12}^d)_{LL}\]^{1/2}$	$< 500 \text{ TeV}$	ϵ'/ϵ

Table: Upper bounds on various flavor changing and CP violating quantities considered for average sfermion mass $m_{\tilde{f}} = 30 \text{ TeV}$ from various measurements.

Summary

- Here, the focus has been on the landscape pull on first/second generation sfermion masses to the multi-TeV regime towards a flavor-independent upper bound.
- Their upper bound arises from two-loop RG contributions to third generation soft masses which actually push these values to small, even tachyonic values.
- After evaluating FCNC and CP-violating constraints, it can be safely concluded that the string landscape picture offers a compelling picture of at best only mild constraints on off-diagonal flavor changing soft terms and CP-violating masses via a **mixed decoupling/quasi-degeneracy solution to the SUSY flavor problem** and **a decoupling solution to the SUSY CP problem**.

Thank You

Questions ?

Back Up Slides

$$\Delta_{EW}, \Delta_{HS}, \Delta_{BG}$$

$$\mathcal{O} = \mathcal{O} + b - b$$

When evaluating fine-tuning, it is not permissible to claim fine-tuning of dependent quantities one against another.

The Electroweak Measure Δ_{EW}

$$\frac{m_Z^2}{2} = \frac{(m_{H_d}^2 + \Sigma_d^d) - (m_{H_u}^2 + \Sigma_u^u)\tan^2\beta}{(\tan^2\beta - 1)} - \mu^2 \quad (4)$$

$$\approx -m_{H_u}^2 - \mu^2 - \Sigma_u^u(\tilde{t}_{1,2}) \quad (5)$$

Sensitivity to High Scale Parameters Δ_{BG}

$$m_Z^2 \approx -2m_{H_u}^2 - 2\mu^2 \quad (6)$$

The Large Log Measure Δ_{HS}

$$m_h^2 \approx \mu^2 + m_{H_u}^2(\Lambda) + \delta m_{H_u}^2 \quad (7)$$

where Λ is a high energy scale up to which MSSM is valid. Λ can be as high as m_{GUT} or even m_P .

A simple fix for Δ_{HS} is to regroup the dependent terms as follows :

$$m_h^2 \approx \mu^2 + (m_{H_u}^2(\Lambda) + \delta m_{H_u}^2) \quad (8)$$

This regrouping now leads back to Δ_{EW} measure because now $(m_{H_u}^2(\Lambda) + \delta m_{H_u}^2) = m_{H_u}^2(Weak)$.

Stringy Naturalness

Here, naturalness is replaced by stringy naturalness wherein observable \mathcal{O}_2 is more natural than observable \mathcal{O}_1 if more *phenomenologically viable* vacua lead to \mathcal{O}_2 than to \mathcal{O}_1 .

The key phrase “phenomenologically viable” can be used here in an anthropic sense, as in the case of the cosmological constant, in that such vacua lead to pocket universes that can admit life as we understand it.

Specifically, we might write the distribution of vacua as

$$dN_{vac}[m_{hidden}^2, m_{weak}, \Lambda] = f_{SUSY}(m_{hidden}^2) \cdot f_{EWSB} \cdot f_{CC} \cdot dm_{hidden}^2 \quad (9)$$

- For the prior distribution f_{SUSY} , Douglas proposed on rather general grounds a power law ansatz

$$f_{SUSY}(m_{hidden}^2) \sim (m_{hidden}^2)^{2n_F+n_D-1} \quad (10)$$

- Following Douglas, $f_{CC} \sim \Lambda/m_{string}^4$.
- The function f_{EWSB} contains any anthropic requirements. For the case of SUSY, it also depends on the anticipated solution to the SUSY μ problem: why is the SUSY conserving μ parameter of order the weak scale rather than the Planck scale.

- Several solutions has been reviewed in *arXiv : 1902.10748* to account for the generation of $\mu \sim m_{weak}$.
- For a fixed natural value of μ , vetoing any vacua with $m_Z^{PU} > 4 \times m_Z^{OU}$ (since Agrawal et al. have computed that if the weak scale is increased by a factor of 2-5 beyond its measured value, then nuclear physics is modified in ways that are unlikely to lead to a livable universe.) corresponds to vetoing pocket universes with $\Delta_{EW} > 30$.
- Thus, we implement

$$f_{EWSB} = \Theta(30 - \Delta_{EW}). \quad (11)$$