Hierarchies from fluxless G_2 vacua

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Outline

- Motivation
- M theory on G_2 manifolds (a very brief intro)
- Kahler potential
- Moduli stabilization and SUSY breaking
- Axiverse and strong CP
- Soft SUSY breaking parameters
- Electroweak scale spectrum
- Conclusions

Motivation

Why do we study 4-dim String/M theory vacua?

- Non-Abelian gauge symmetry
- Chiral fermions
- Hierarchical Yukawa couplings
- Dynamical supersymmetry breaking
- Gauge coupling unification

Great! But can we make genuine predictions even in principle?

• By compactifying to 4D, we obtain a multitude of scalar fields – moduli, parameterizing internal metric deformations, brane positions, etc.

• Their masses must be large enough to be compatible with observations (BBN => $M_{mod} > O(10)TeV$)

• Subtlety:

$$f_{QCD} = \frac{4\pi}{g_3^2(M)} + i\frac{\theta_{QCD}(M)}{2\pi}$$

heavy light

• In String/M theory all masses and couplings are functions of the moduli vevs

• Once the moduli are stabilized, all couplings are completely fixed and are computable in principle

• Can we stabilize all moduli so that we can make predictions?

• In particular, can String/M theory *naturally* explain the hierarchy between the electroweak scale $M_Z = 90\ GeV$ and Planck scale $M_{Pl} \sim 10^{19}\ GeV$?

Strong hints in favor of low scale SUSY from bottom up:

✓ Stabilizes the hierarchy between the EW scale and M_{Pl}

✓ Radiative Electroweak Symmetry Breaking naturally occurs in the MSSM (large top Yukawa drives $m_{H_u}^2 < 0$)

✓ MSSM gauge coupling unification

✓ LSP is a dark matter candidate (maybe)

• However, while supersymmetry alone can stabilize the hierarchy, it still does not explain it!

Standard lore in mid 80s: strong hidden sector gauge dynamics may generate a potential for the moduli and break supersymmetry at a small scale (Witten 1981)

• Fluxless G_2 compactifications of M theory may *naturally* implement this good old idea from top down

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• In fact, in this corner of the landscape, the gauge hierarchy $M_Z << M_{Planck}$,Yukawa hierarchies and the axion mass hierarchies (Axiverse) have the same origin!

Disclaimer:

• We have not constructed an explicit realistic global G_2 compactification (none exists thus far). Rather, we utilize known properties of G_2 moduli space metrics and make some assumptions that may ultimately be implemented in explicit models.

• Modulo those assumptions, our construction is still very general and may represent a large sample of possible G_2 vacua (this is not a toy model!)

M theory on G_2 manifolds

• Consider M theory compactifications on singular 7-dim manifolds X with G_2 holonomy (required for $\mathcal{N}$=1 SUSY)

• The Riemannian metric $g(X)$ can be expressed in terms of the associative 3-form Φ as

$$g_{ij} = (\det s)^{-\frac{1}{9}} s_{ij},$$

where $$s_{ij} = \frac{1}{144}\Phi_{ikn}\Phi_{jlm}\Phi_{rst}\varepsilon^{knlmrst}, \quad \varepsilon^{12\ldots 7} = +1$$

• Expand Φ in terms of basis harmonic 3-forms

$$\Phi = \sum_{i=1}^{N} s_i \phi_i, \quad \phi_{\mathrm{i}} \in H^3(X, Z), \; N = b^3(X)$$

• Unlike CY, there is only one type of geometric moduli:

$$z_i = t_i + is_i, \quad i = 1,\ldots,N; \quad N = b_3(X)$$

Axions
(periods of the 3-form C_3,
transform under a shift symmetry)

periods of the associative 3-form Φ
(fluctuations of the metric)

• This PQ-type shift symmetry guarantees that in the absence of fluxes the entire superpotential is purely non-perturbative => exponential hierarchies are natually expected!

• Non-Abelian gauge fields are localized on three-dimensional submanifolds $Q \in X$ along which there is an orbifold singularity. Acharya. hep-th/9812205, hep-th/0011089

• Example: locally, M-theory on $R^{3,1} \times \overbrace{Q \times (C_2 / Z_N)}^{X}$ is the 11-dim SUGRA coupled to a 7-dim SU(N) gauge theory on $R^{3,1} \times Q$.

associative (supersymmetric) 3-cycle

• Chiral fermions are localized at point-like isolated singularities $p \in X$. Atiyah-Witten. hep-th/0107177, Acharya-Witten. hep-th/0109152

• A particle localized at p will be charged under the gauge group supported along the associative three-cycle Q if $p \in Q$

Bulk Kahler potential

Beasley-Witten: hep-th/0203061; Acharya, Denef, Valandro: hep-th/0502060

$$K = -3\ln(4\pi^{1/3}V_7)$$

• We know that the 7-dim volume V_7 is a homogeneous function of the moduli s_i of degree 7/3

$$\sum_{i=1}^{N} s_j \frac{\partial V_7}{\partial s_i} = \frac{7}{3} \quad \Rightarrow \quad \sum_{i=1}^{N} s_j \frac{\partial K}{\partial s_i} = -7; \quad \sum_{i,j=1}^{N} s_i s_j \frac{\partial^2 K}{\partial s_i \partial s_j} = 7$$

• These properties and everything that follows from them are all we use! In particular, no specific choice of the 7-dim volume needs to be made in order to compute the soft SUSY breaking terms!

• In earlier work

B. Acharya, KB, G. Kane, P. Kumar and J. Shao, hep-ph/0801.0478
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we assumed a specific N-parameter family of the 7-dim volumes consistent with G_2 holonomy

$$V_7 = \prod_{i=1}^{N} s_i^{n_i}, \text{where } \sum_{i=1}^{N} n_i = \frac{7}{3}$$

• We then also assumed a canonical Kahler potential for charged chiral matter

$$\tilde{K} = \bar{\phi}\phi$$

• In B. Acharya, KB hep-th/0810.3285, presented here, we redid the entire analysis with no such assumptions

Kahler potential for matter fields

- Because charged chiral matter is localized at points in the seven extra dimensions, we expect that the corresponding kinetic terms should be "largely independent of bulk moduli fields"

- A single conical singularity gives only N of $SU(N)$ which gives a trivial superpotential

- When $W=0$ there is a one-to one correspondence between holomorphic gauge-invariant operators (HGIO) and D-flat directions Taylor, Luty, hep-th/9506098

- One cannot construct any HGIO from a single N => no D-flat directions => no local moduli

Matter Kahler metric from dim reduction

- The physics of a conical singularity in M-theory does not involve any new scale, aside from the 11d Planck scale so the natural frame is the 11d Einstein frame.
- Lagrangian density in 11d frame

$$L \sim M_{11}^{9}\sqrt{g_{11}}R + \delta_7 \wedge \partial_M \bar{\phi}\,\partial_N \phi\, g^{MN}\kappa(s_i)\sqrt{g_{11}} + \ldots$$

Peaked at the position of the matter multiplet

where $$\sum_{i=1}^{N} s_i \frac{\partial \kappa}{\partial s_i} = 0$$

Kinetic term is "largely independent of bulk moduli"

- Integrating over X gives

$$L \sim V_7 M_{11}^{9}\sqrt{g_4}R + \kappa(s_i) g^{\mu\nu}\partial_\mu \bar{\phi}\,\partial_\nu \phi\sqrt{g_4} + \ldots$$

• Weil rescaling into the 4d Einstein frame gives

$$L \sim m_p^2 \sqrt{g_E} R_E + \frac{\kappa(s_i)}{V_7} g_E^{\mu\nu} \partial_\mu \overline{\phi} \partial_\nu \phi \sqrt{g_E} + \ldots$$

• The kinetic term is non-trivial in the 4d Einstein frame – the standard frame in which we define the Kahler potential.

• Read off the Kahler potential from the kinetic term

$$\tilde{K} = \kappa(s_i) \frac{\overline{\phi}\phi}{V_7}$$

Matter Kahler metric from the finiteness of the physical (normalized) Yukawa couplings

- In $\mathcal{N}$=1 D=4 supergravity

$$|Y_{\alpha\beta\gamma}| = e^{K/2}\,|Y'_{\alpha\beta\gamma}|\left(\tilde{K}_\alpha \tilde{K}_\beta \tilde{K}_\gamma\right)^{-1/2} \sim |Y'_{\alpha\beta\gamma}|\left(V_7^3 \tilde{K}_\alpha \tilde{K}_\beta \tilde{K}_\gamma\right)^{-1/2}$$

where (in M-theory on G_2) the superpotential Yukawa is

$$|Y'_{\alpha\beta\gamma}| \sim e^{-2\pi V_{\alpha\beta\gamma}}, V_{\alpha\beta\gamma} = \sum_{i=1}^{N} m_i^{\alpha\beta\gamma} s_i$$

- There are well-defined local models where manifold X is non-compact , i.e. $V_7 \to \infty \Rightarrow m_{pl}/M_{11} \to \infty$

$$Y_{\alpha\beta\gamma} \text{ is finite } \Rightarrow K_\alpha \sim K_\beta \sim K_\beta \sim \frac{1}{V_7}$$

• Expand the fundamental associative three-form Φ in a basis of harmonic three-forms $\{\phi_i\}$

$$\Phi = \sum_{i=1}^{b_3(X)} s_i \phi_i, \quad \phi_i \in H^3(X, Z)$$

• Choose the basis of $\{\phi_i\}$ such that for all Poincare dual four-cycles $\{\beta_i\}$ the periods of $*\Phi$ are positive definite

$$\int_{\beta_i} *\Phi > 0, \quad \forall \beta_i, \text{ where } PD_X(\phi_i) = \beta_i \in H_4(X)$$

Then, we can ensure that all four-cycle volumes are positive because

$$\mathrm{Vol}(\beta_i) \geq \int_{\beta_i} *\Phi > 0$$

• Consider an associative three-cycle Q

$$\mathrm{Vol}(Q) = \int_Q \Phi = \sum_{i=1}^{b_3(X)} s_i \int_Q \phi_i = \sum_{i=1}^{b_3(X)} s_i N_i$$

• <u>Key point</u>: we implicitly assume that we study any G_2 manifold X containing an associative three-cycle Q supporting a non-Abelian gauge theory, such that in the above basis of harmonic three-forms $\{\phi_i\}$ the integers specifying the homology of Q are all positive definite

$$N_i = \int_Q \phi_i > 0$$

Moduli stabilization and SUSY breaking

• Consider a hidden sector supersymmetric QCD with $SU(N+M)$ gauge group along a three-cycle Q that also contains two separate co-dimension seven singularities supporting the fundamental N+M and the conjugate

• Assume that Q has a non-trivial fundamental group so $SU(N+M)$ can be broken by a discrete Wilson line

$$SU(N+M) \to SU(N) \times SU(M) \times U(1)$$

$$\mathrm{N}+\mathrm{M} \to (\mathrm{N},1)+(1,\mathrm{M});\ \left(\mathrm{N}+\mathrm{M}\right)^{*} \to (\tilde{\mathrm{N}},1)+(1,\tilde{\mathrm{M}})$$

• Alternatively we may consider

$$SO(2(N+M)) \to SU(N) \times SU(M) \times U(1) \times U(1)$$

$$2(\mathrm{N}+\mathrm{M}) \to (\mathrm{N},1)+(1,\mathrm{M})+(\tilde{\mathrm{N}},1)+(1,\tilde{\mathrm{M}})$$

• Superpotential is generated by strong dynamics in the hidden sectors (PQ symmetry => W is non-perturbative)

$$W = A_1 \phi_1^{-\frac{2}{N-1}} e^{i\frac{2\pi}{N-1}f} + A_2 \phi_2^{-\frac{2}{M-1}} e^{i\frac{2\pi}{M-1}f} + \ldots$$

where the gauge kinetic function is $f = \sum_{i=1}^{N} N_i z_i$

Integers specifying the homology of the hidden sector 3-cycle

Effective "meson" fields

$$\phi_1 \equiv \sqrt{2\mathrm{N}\tilde{\mathrm{N}}}; \ \phi_2 \equiv \sqrt{2\mathrm{M}\tilde{\mathrm{M}}}$$

Kahler potential

$$K = -3\ln V_7 + \frac{\kappa_1(s_i)}{V_7}\phi_1\bar{\phi}_1 + \frac{\kappa_2(s_i)}{V_7}\phi_2\bar{\phi}_2$$

where we used

$$\langle \mathrm{N} \rangle = e^{i\theta_1}\langle \tilde{\mathrm{N}} \rangle; \ \langle \mathrm{M} \rangle = e^{i\theta_2}\langle \tilde{\mathrm{M}} \rangle \text{ along the D-flat directions}$$

- F-terms (first consider a simplified case $\kappa_1(s_i) = \kappa_2(s_i)=1$)

$$F_{\phi_1} = -\frac{2}{N-1} A_1 \phi_1^{-\frac{2}{N-1}-1} e^{i\frac{2\pi}{N-1}f} + \frac{\bar{\phi}_1 W}{V_7}$$

$$\tau_i = \frac{1}{3}\int_{\beta_i} * \Phi$$

$$F_{\phi_2} = -\frac{2}{M-1} A_2 \phi_2^{-\frac{2}{M-1}-1} e^{i\frac{2\pi}{M-1}f} + \frac{\bar{\phi}_2 W}{V_7}$$

$$F_{z_i} = iN_i\left(\frac{2\pi}{N-1} A_1 \phi_1^{-\frac{2}{N-1}} e^{i\frac{2\pi}{N-1}f} + \frac{2\pi}{M-1} A_2 \phi_2^{-\frac{2}{M-1}} e^{i\frac{2\pi}{M-1}f}\right) + i\frac{3\tau_i}{2V_7}\left(1+\frac{\phi_1\bar{\phi}_1}{3V_7}+\frac{\phi_2\bar{\phi}_2}{3V_7}\right)W$$

$$F_{\phi_1} = 0;\ F_{\phi_2} = 0 \Rightarrow F_{z_i} = iN_i\left(\phi_1\bar{\phi}_1 + \phi_2\bar{\phi}_2\right)\frac{\pi W}{V_7} + i\frac{3\tau_i}{2V_7}\left(1+\frac{\phi_1\bar{\phi}_1}{3V_7}+\frac{\phi_2\bar{\phi}_2}{3V_7}\right)W$$

$F_{z_i} \neq 0;\ \Rightarrow$ SUSY is broken!

Minimize the full scalar potential => minima exist when $|N\text{-}M| \geq 3$

$$N \geq M+3 \Rightarrow F_{\phi_2} >> F_{\phi_1} \approx 0, F_{z_i} \approx 0$$

$$M \geq N+3 \Rightarrow F_{\phi_1} >> F_{\phi_2} \approx 0, F_{z_i} \approx 0$$

• For concreteness we shall consider the case

$$M \geq N+3 \Rightarrow \quad F_{\phi_1} >> F_{\phi_2} \approx 0, F_{z_i} \approx 0$$

$$W = A_1 \phi^a e^{ib_1 f} + A_2 e^{ib_2 f} + \ldots$$

Most economical way to fix moduli and get dS vacua !
All F-terms will have the same phase as W. Important for CP!

• An effective meson field $\phi \equiv \sqrt{2\mathrm{N}\tilde{\mathrm{N}}} = \phi_0 e^{i\theta}$

• For *SU(N)* and *SU(M)* hidden sector gauge groups and $N_f = 1$ flavor:

$$b_1 = \frac{2\pi}{P}, \quad b_2 = \frac{2\pi}{M}, \quad a = -\frac{2}{P}, \quad \text{where} \quad P = N-1, \text{and } M-P \geq 3$$

• Inverse Kahler metric (first consider $\kappa(s_i)=1$):

$$K^{i\bar{j}} = \frac{4 s_i s_{\bar{j}}}{3 a_{\bar{j}}} \frac{(\Delta^{-1})^{i\bar{j}}}{1+\frac{\phi_0^2}{3V_7}}; K^{i\bar{\phi}} = i\frac{2}{3}\frac{s_i \bar{\phi}}{1+\frac{\phi_0^2}{3V_7}}; K^{\phi\bar{\phi}} = V_7\left(1+\frac{7}{3}\frac{1}{1+\frac{\phi_0^2}{3V_7}}\frac{\phi_0^2}{3V_7}\right)$$

"angular" (scale-invariant) coordinates on the moduli space

$\downarrow$

$$a_i \equiv -\frac{1}{3} s_i \frac{\partial K}{\partial s_i} \qquad \sum_{i=1}^{N} a_i = \frac{7}{3} \qquad \sum_{\bar{j}=1}^{N} (\Delta^{-1})^{i\bar{j}} a_{\bar{j}} = a_i \qquad \sum_{i=1}^{N} (\Delta^{-1})^{i\bar{j}} = 1$$

These contraction properties are completely general and are crucial for our ability to minimize the scalar potential and perform explicit computations of the soft terms!

$\mathcal{N}$=1 D=4 SUGRA scalar potential

$$
\begin{aligned}
V = \frac{e^{\frac{\phi_0^2}{V_7}}}{64\pi V_7^3}\Bigg[& \frac{4}{3}\sum_{i=1}^{N}\sum_{\bar{j}=1}^{N}\frac{s_i s_{\bar{j}} N_i N_{\bar{j}}}{a_{\bar{j}}}\frac{(\Delta^{-1})^{i\bar{j}}}{1+\frac{\phi_0^2}{3V_7}}(b_1 A_1\phi_0^a e^{-b_1\vec{N}\cdot\vec{s}} - b_2 A_2\phi_0^a e^{-b_2\vec{N}\cdot\vec{s}})^2 \\
& + 4\vec{N}\cdot\vec{s}(b_1 A_1\phi_0^a e^{-b_1\vec{N}\cdot\vec{s}} - b_2 A_2\phi_0^a e^{-b_2\vec{N}\cdot\vec{s}})(A_1\phi_0^a e^{-b_1\vec{N}\cdot\vec{s}} - A_2\phi_0^a e^{-b_2\vec{N}\cdot\vec{s}}) \\
& + 7(b_1 A_1\phi_0^a e^{-b_1\vec{N}\cdot\vec{s}} - b_2 A_2\phi_0^a e^{-b_2\vec{N}\cdot\vec{s}})^2\left(1+\frac{\phi_0^2}{3V_7}\right) - 3(A_1\phi_0^a e^{-b_1\vec{N}\cdot\vec{s}} - A_2\phi_0^a e^{-b_2\vec{N}\cdot\vec{s}})^2 \\
& - \frac{4}{3}\left(\frac{(b_1 A_1\phi_0^a e^{-b_1\vec{N}\cdot\vec{s}} - b_2 A_2\phi_0^a e^{-b_2\vec{N}\cdot\vec{s}})}{1+\frac{\phi_0^2}{3V_7}}\vec{N}\cdot\vec{s} + \frac{7}{2}(A_1\phi_0^a e^{-b_1\vec{N}\cdot\vec{s}} - A_2\phi_0^a e^{-b_2\vec{N}\cdot\vec{s}})\right) \\
& \times\left(aA_1\phi_0^a e^{-b_1\vec{N}\cdot\vec{s}} + \frac{\phi_0^2}{V_7}(A_1\phi_0^a e^{-b_1\vec{N}\cdot\vec{s}} - A_2\phi_0^a e^{-b_2\vec{N}\cdot\vec{s}})\right) \\
& + \frac{V_7}{\phi_0^2}\left(1+\frac{7}{3}\frac{1}{1+\frac{\phi_0^2}{3V_7}}\frac{\phi_0^2}{3V_7}\right)\left(aA_1\phi_0^a e^{-b_1\vec{N}\cdot\vec{s}} + \frac{\phi_0^2}{V_7}(A_1\phi_0^a e^{-b_1\vec{N}\cdot\vec{s}} - A_2\phi_0^a e^{-b_2\vec{N}\cdot\vec{s}})\right)^2\Bigg]
\end{aligned}
$$

• Minimize the potential with respect to the moduli and the meson to obtain a system of N+1 coupled equations

• Solve in the limit when the volume V_Q of the hidden sector associative cycle Q is large

• Moduli vevs: $s_i = \frac{a_i}{N_i}\frac{3}{7}V_Q$ where $V_Q \approx \frac{1}{2\pi}\frac{PM}{M-P}\ln\left(\frac{MA_1\phi_0^a}{PA_2}\right)$

• Parameters a_i satisfy a system of N equations: $\left.\frac{\partial K}{\partial s_i}\right|_{s_i=\frac{a_i}{N_i}} + 3N_i = 0$

Integers specifying the homology of the hidden sector 3-cycle Q

• 7-dim volume is fixed at: $V_7 = V_Q^{7/3}\left(\frac{3}{7}\right)^{7/3} \times V_7(s_i)\Big|_{s_i=\frac{a_i}{N_i}}$

- Alternatively, introducing a basis of dual variables

$$\tau_i \equiv \frac{\partial V_7}{\partial s_i} = \frac{1}{3}\int_X \phi_i \wedge *\Phi = \frac{1}{3}\int_{\beta_i} *\Phi$$

- We find upon minimizing the scalar potential

$$\tau_i = N_i \frac{7V_7}{3V_Q} > 0, \quad \Leftrightarrow \quad *\Phi = \alpha \cdot PD_X(Q), \quad 0 < \alpha \in R$$

Fixed by the supergravity scalar potential

The co-associative four-form $*\Phi$ is dynamically fixed by the homology of Q!

- Recasting the volume V_7 in terms of τ_i we can express:

$$s_i = \frac{4V_Q}{7}\frac{\partial}{\partial \tau_i}\ln V_7(\tau_k)\Big|_{\tau_k = N_k}$$

Integers specifying the homology of the hidden sector 3-cycle Q

- In Type IIB even more explicit: $\tau_i = \frac{\tau_D}{3}\frac{\partial}{\partial n_i}\ln \sum d_{ljk} n_l n_j n_k$

K.B, V. Braun, P. Kumar and S. Raby: hep-th 1003.1982

• In Type IIB K.B, V. Braun, P. Kumar and S. Raby: hep-th/1003.1982

$$t_i = \frac{n_i \tau_D^{1/2}}{\sqrt{3\sum d_{ijk} n_i n_j n_k}}, \quad \tau_i = \frac{\tau_D}{3} \frac{\partial}{\partial n_i} \ln \sum d_{ljk} n_l n_j n_k, \quad V_{CY} = \frac{\tau_D^{3/2}}{3\sqrt{3\sum d_{ijk} n_i n_j n_k}}$$

• Explicit three-parameter example (hep-th/1003.1982)

$$\tau_1 = \frac{6}{30}\tau_D, \quad \tau_2 = \frac{11}{30}\tau_D, \quad \tau_3 = \frac{13}{30}\tau_D, \quad t_1 = t_2 = t_3 = \frac{\tau_D^{1/2}}{3\sqrt{5}}, \quad V_{CY} = \frac{\tau_D^{3/2}}{9\sqrt{5}}$$

• At the minimum all Kahler moduli are controlled by a single parameter τ_D ! In G_2 this is true for all moduli!

• This approach to moduli fixing is highly constraining and therefore potentially predictive. For example:

$$\alpha_{GUT}^{-1} \approx 25$$

$$\alpha_{GUT}^{-1} = \sum_{i=1}^{h_{11}^+} n_i^{vis} \tau_i \quad \Rightarrow \quad \tau_D = 3\left(\sum_{i=1}^{h_{11}^+} n_i^{vis} \frac{\partial}{\partial n_i} \ln \sum d_{ljk} n_l n_j n_k \right)^{-1} \times \alpha_{GUT}^{-1}$$

• Potential at the minimum in the leading order as a function of the meson vev

$$V_0 \approx \left[\left(\frac{2}{M-P}+\frac{\phi_0^2}{V_7}\right)^2+\frac{14}{P_{eff}}\left(1-\frac{2}{3(M-P)}\right)\left(\frac{2}{M-P}+\frac{\phi_0^2}{V_7}\right)-3\frac{\phi_0^2}{V_7}\right]\frac{V_7}{\phi_0^2}m_{3/2}^2$$

$$\frac{\partial V_0}{\partial \phi_0^2}=0\,\&\,V_0=0 \quad \Rightarrow \quad \frac{\phi_0^2}{V_7}\approx\frac{2}{M-P}+\frac{7}{P_{eff}}\left(1-\frac{2}{3(M-P)}\right)+O\left(\frac{1}{P_{eff}^2}\right)$$

$$V_0=0 \quad \Rightarrow \quad P_{eff}\approx\frac{14(3(M-P)-2)}{9(M-P)-6\sqrt{6(M-P)}}$$

where $P_{eff}\equiv P\ln\left(\frac{MA_1\phi_0^a}{PA_2}\right)$ such that $V_Q\approx\frac{1}{2\pi}\frac{P_{eff}M}{M-P}$

$$V_Q>0\,\&\,M>P\Rightarrow P_{eff}>0\Rightarrow M-P\geq 3$$

Generalizing to the case when $\kappa(s_i) \neq const$

- The main difference is in the moduli vevs

$$s_i \approx \frac{1}{N_i}\left(a_i + c_i \frac{\phi_c^2}{3} r\right)\frac{3}{7}V_Q$$

where, $r \approx \frac{3}{2}$ and the vev of the canonically normalized meson $\phi_c^2 \equiv \frac{\kappa(s_i)}{V_7}\phi_0^2 \approx \frac{2}{M-P} + \frac{7}{P_{eff}}\left(1 - \frac{2}{3(M-P)}\right)$ is the same as when $\kappa(s_i)=1$. Parameters a_i , c_i can be found from

$$s_i \left.\frac{\partial K}{\partial s_i}\right|_{s_i = \frac{1}{N_i}\left(a_i + c_i \frac{\phi_c^2}{3} r\right)} + 3a_i = 0; \quad s_i \left.\frac{\partial \ln \kappa}{\partial s_i}\right|_{s_i = \frac{1}{N_i}\left(a_i + c_i \frac{\phi_c^2}{3} r\right)} - c_i = 0$$

- For $M - P = 3$: $P_{eff} \approx 61.65;\ \phi_c^2 \approx 0.75;\ s_i \approx 1.4 \dfrac{a_i + 0.37 c_i}{N_i} \times M$

- Can we actually tune $P_{eff} \equiv P \ln\left(\dfrac{M A_1 \phi_0^a}{P A_2}\right) \approx 62$?

- Recall $A_1 = \tilde{C} P e^{-\frac{S_1'}{2P}};\ A_2 = \tilde{C} M e^{-\frac{S_2'}{2M}}$

Ray-Singer torsions

- When the 3-cycle is a lens space S^3/Z_q, the KK thresholds

are: $S'_{SU(N)} = -2N \ln q + 2(N-2) \ln\left(4 \sin^2(4\pi m w / q)\right)$

$$\Rightarrow \qquad P_{eff} \approx P \ln\left(\frac{\left(4\sin^2(4\pi n l / q)\right)^{\frac{M-2}{M}}}{\left(4\sin^2(4\pi m w / q)\right)^{\frac{P-1}{P}}}\right)$$

P_{eff}	P	M	q	l	w	n	m
61.3	10	13	99	12	25	1	1
61.9	20	23	17	6	4	1	1
64.2	27	30	11	3	5	1/2	1/2

- Perturbative corrections may help fine tune the CC

$$\delta V_0^{1-loop} = \frac{1}{32\pi^2}\sum_i (-1)^{2J_i}(2J_i+1)m_i^2 M_{11}^2 + \ldots$$

- From non-Abelian *SU(N)* and *U(1)* gauginos:

$$\delta V_0^{SU(N_i)} = -\frac{1}{16\pi^2} N_i^2 \lambda_i^2(N_i, w_i) m_{3/2}^2 M_{11}^2, \quad \delta V_0^{U(1)} = -\frac{1}{16\pi^2}\lambda_i^2(\vec{w}_i) m_{3/2}^2 M_{11}^2$$

discrete Wilson line winding numbers

- Vary discrete Wilson lines to scan over all N_i and w_i

in all hidden sectors => Fluxless discretuum !

• When M-P=3 and the CC is tuned $P_{eff} \approx 60$, the volume of the hidden sector cycle is

$$V_Q = \mathrm{Im}\, f = \sum_{i=1}^{N} N_i s_i = \frac{MP_{eff}}{6\pi} \approx \frac{10M}{\pi}$$

the contributions of the leading condensates are fixed!

$$\delta W_0 \sim e^{-\frac{2\pi}{M} V_Q} \approx e^{-20}$$

• Consider another rigid 3-cycle Y, supporting an SU(M`) gauge group. Its volume is also proportional to M !

$$V_Y = \sum_{i=1}^{N} N_i' s_i = \frac{3}{7} V_Q \sum_{i=1}^{N} \frac{N_i' a_i}{N_i} = M \times O(1)$$

• The extra contributions to the superpotential can be suppressed relative to the leading ones when $M >> M$`

$$\delta W_{extra} \sim e^{-\frac{2\pi}{M'} V_Y} \approx e^{-2\pi \frac{M}{M'} \times O(1)} << \delta W_0$$

- Gravitino mass is fixed once coarse tuning is done

$$m_{3/2} = m_{pl} e^{\frac{\phi_0^2}{2V_7}} \frac{|P-M| C_2}{8\sqrt{\pi} V_7^{3/2}} e^{-\frac{P_{eff}}{M-P}} \approx 9\times 10^5 (TeV) \frac{C_2}{V_7^{3/2}}$$

- Extract V_7 from $\frac{1}{8\pi m_{pl}^2} = \frac{\alpha_{GUT}^3 V_{Q_{vis}}^{7/3} L(Q_{vis})^{2/3}}{32\pi^2 M_{GUT}^2 V_7}$ Friedmann and Witten, hep-th/0211269

- For typical values $\alpha_{GUT}^{-1} = V_{Q_{vis}} \approx 25,\ M_{GUT} \approx 2\times 10^{16} GeV$

- Obtain $V_7 \approx 137.4 \times L(Q_{vis})^{2/3}$, where $L(Q_{vis}) = 4\sin^2(5\pi w/q)$

q	2	3	4	4	6	6	6
w	1	1, 2	1, 3	2	1, 5	2, 4	3
V_7	549.6	594.5	549.6	872.4	453.7	943.7	1143.2
$m_{3/2}/C_2$	70 TeV	62 TeV	70 TeV	35 TeV	93 TeV	31 TeV	23 TeV

• Moduli: $M_1 \approx O(200-300)\times m_{3/2}, \quad m_i \approx O(1)\times m_{3/2} < 2\times m_{3/2}$

• $m_{3/2}$ ~$O(10)TeV$ => moduli are heavy enough to decay before BBN.

• Non-standard cosmology: large entropy production at late times, but before BBN; dark matter is generated non-thermally.

• When the LSP is mostly Wino => relic density is compatible with observation

Acharya, et.al, hep-ph/0804.0863, astro-ph/0908.2430

Axiverse and Strong CP

• To fix all axions we must include the truncated non-perturbative contributions B. Acharya, KB, P. Kumar: hep-th/1004.5138

$$W = A_1 \phi^a e^{ib_1 f} + A_2 e^{ib_2 f} + \sum_{k>2} A_k e^{ib_k f_k}$$

• The leading contributions freeze the geometric moduli s_i and a single linear combination of axions

$$\cos((b_1 - b_2)\vec{N} \cdot \vec{t} + a\theta) = -1$$

• Effective scalar potential after including the remaining non-perturbative terms and freezing all s_i

$$V \approx V_0 - m_{3/2} m_{pl}^3 e^{K/2} \sum_{j>2} D_k e^{-b_j V_j} \cos(\chi_1 - \chi_j)$$

$$\chi_j = b_j \vec{N}_j \cdot \vec{t}; \qquad \chi_1 = b_1 \vec{N} \cdot \vec{t} + a\theta$$

• The axion mass spectrum before the QCD effects

$$m_1 \approx O(200-300)\times m_{3/2}, \quad m_i^2 \approx O(1)\frac{m_{pl}^3 m_{3/2}}{f_i^2} e^{K/2} e^{-b_i V_i}, \; i = 2,\ldots,N+1$$

where

$$V_j = \frac{3}{7} V_Q \sum_k \frac{N_j^k}{N^k} a_k$$

• Consider $b_i = 2\pi$, $m_{3/2} \sim 10$ TeV, $V_7 = 1000$, $f_i = 10^{16}$GeV

$$15 < V_j < 40 \;\Rightarrow\; 10^{-33} eV < m_i < 1 eV$$

• In generic G_2 compactifications $N = b_3(X) \sim O(100)$

$\Rightarrow$ String Axiverse with a multitude of light axions

Arvanitaki et. al hep-th/0905.4720, hep-th/1004.3558

• From QCD instantons $\delta V_{QCD} = \Lambda_{QCD}^4 \left(1 - \cos\theta_{QCD}\right)$

where

$$\theta_{QCD} = 2\pi \sum_{i=1}^{N} N_i^{vis} t_i = \sum_{K=1}^{N+1} \frac{\psi_K}{\tilde{f}_K}; \qquad \frac{1}{\tilde{f}_L} \equiv \sum_{i=1}^{N} \sum_{K=1}^{N+1} N_i^{vis} U_{iK} \frac{2\pi}{f_K} \tilde{U}_{KL}$$

• The QCD instanton mass matrix is rank one =>

$$\left(m_K^2\right)_{QCD} = 0, \ \forall K = 1,\ldots,N; \ \left(m_{N+1}^2\right)_{QCD} \approx \Lambda_{QCD}^4 \sum_{L=1}^{N+1} \frac{1}{\tilde{f}_L^2}$$

• QCD effects give mass to the lightest mass eigenstate ψ_K inside the linear combination representing θ_{QCD}

• Can easily achieve $|\theta_{QCD}| << 10^{-10}$, as long as at least one of the mass eigenstates inside θ_{QCD} is lighter than

$$m_{\exp}^2 \approx 10^{-10} \left(m_{N+1}^2\right)_{QCD} \approx \left(10^{-14} eV\right)^2$$

• Pre BBN cosmological history is non-thermal so the standard estimates on the axion relic density do not apply. The mass of the QCD axion is such that it starts coherent oscillations during moduli dominated era. For all axions whose masses are greater then

$$\Gamma_{X_0} \approx O(1)\frac{m_{X_0}^3}{m_{pl}^2} \sim 10^{-14} eV; \quad m_{X_0} \approx 50 TeV$$

the relic abundance is independent of their mass

$$\Omega_k h^2 = O(10)\left(\frac{f_k}{2\times 10^{16} GeV}\right)^2 \left(\frac{T_{RH}^{X_0}}{1 MeV}\right)\left\langle \theta_{I_k}^2 \right\rangle \chi$$

Fox, Pierce, Thomas hep-th:0409059

$$\Omega_{DM} h^2 \le 0.11 \Rightarrow \left\langle \theta_{I_k}^2 \right\rangle \le 10^{-2}$$

• Modest fine tuning of the misalignment angle. The entropy dilution due to late time moduli decays allows decay constants f_k much closer to the GUT scale

Kahler potential for the visible sector matter

• For the visible sector matter fields, the Kahler potential may generally include a tree-level interaction term with the hidden sector

$$\tilde{K} = \tilde{K}_{\alpha\bar{\beta}} Q^{\alpha} \overline{Q}^{\bar{\beta}} = \frac{\kappa_{\alpha\bar{\beta}}(s_i) Q^{\alpha} \overline{Q}^{\bar{\beta}}}{V_7} \left(1 + c(s_i) \frac{\phi\bar{\phi}}{3V_7} \right)$$

• In the above we assumed that the flavor structure of $\tilde{K}_{\alpha\bar{\beta}}$ is completely determined by the matrix $\kappa_{\alpha\bar{\beta}}(s_i)$. Here this form is motivated by the suppression of the FCNCs from the bottom up. Another way to suppress FCNCs is to assume that $c(s_i) \approx 0$.

•<u>Key point</u>:

To find the soft supersymmetry breaking parametrs we do not need to know the explicit values of a_i and s_i ! The following general contraction properties are all we need to know!

$$\sum_{i=1}^{N} a_i = \frac{7}{3}, \qquad \sum_{\bar{j}=1}^{N} (\Delta^{-1})^{i\bar{j}} a_{\bar{j}} = a_i, \qquad \sum_{i=1}^{N} (\Delta^{-1})^{i\bar{j}} = 1$$

Computing soft SUSY breaking terms

- Use the general contraction rules to obtain

$$e^{K/2}F^k \approx -i2s_k \frac{1}{P_{eff}}\left(1+\frac{2}{\phi_c^2(M-P)}+O\left(\frac{1}{P_{eff}}\right)\right)\times m_{3/2}m_{pl}$$

$$e^{K/2}F^\phi \approx \phi\left(1-\frac{7}{3P_{eff}}\right)\left(1+\frac{2}{\phi_c^2(M-P)}+O\left(\frac{1}{P_{eff}}\right)\right)\times m_{3/2}m_{pl}$$

- Notice two key properties of the F-terms:

$$F^i \approx s_i \times const, \quad \text{and} \quad F^i << F^\phi$$

- When computing the soft terms use homogeneity:

$$\sum_i F^i \partial_i \frac{\kappa_{\alpha\beta}}{V_7} \approx const \times \sum_i s_i \partial_i \frac{\kappa_{\alpha\beta}}{V_7} = -\frac{7}{3}\frac{\kappa_{\alpha\beta}}{V_7}\times const$$

Summary of the soft SUSY breaking terms

$$m_{1/2}^{tree} \approx -\frac{1}{P_{eff}}\left(1+\frac{2}{\phi_c^2(M-P)}+\frac{\delta}{P_{eff}}\right)\times m_{3/2} << m_{3/2}, \text{ since } P_{eff} \approx 60$$

$$m_{1/2}^{1-loop} \approx \frac{\alpha_{GUT}}{4\pi}\left(\left(3C_a-\sum_\alpha C_a^\alpha\right)K_1+\frac{2}{3}K_2\sum_\alpha C_a^\alpha\right)\times m_{3/2}$$

$$A_{\alpha\beta\gamma}^{tree} \approx \left(K_2+\frac{4\pi}{P_{eff}}\left(1+\frac{2}{\phi_c^2(M-P)}\right)V_{Q_{\alpha\beta\gamma}}\right)\times m_{3/2}$$

$$A_a^{1-loop} \approx -\frac{1}{16\pi^2}\gamma_a K_1\times m_{3/2}$$

$$m_\alpha^2 \approx (1-c)\left(m_{3/2}^2-\frac{7}{3}\left(m_{1/2}^{tree}\right)^2\right)$$

Volume of the cycle $Q_{\alpha\beta\gamma}$ that connects three co-dimension seven singularities supporting charged chiral matter

$$K_1 \equiv 1-\frac{1}{3}\left(1+\frac{2}{\phi_c^2(M-P)}\right)\left(\phi_c^2+\frac{7}{P_{eff}}\right), \quad K_2 \equiv \left(1+\frac{2}{\phi_c^2(M-P)}\right)(1-c)\phi_c^2$$

GUT-scale soft SUSY breaking terms after setting *M-P=3* and P_{eff}=*61.65*

- Express $c = 1 - \left(\frac{m_\alpha}{m_{3/2}}\right)^2$. GUT scale input: $m_{3/2}, m_\alpha, \eta, \delta, \tan\beta$

  Can set $\eta = 1$

- Recast the soft terms as

$$M_1 \approx e^{-i\gamma_w} m_{3/2}\left(-(0.031 + 0.00026\times\delta)\eta + \alpha_{GUT}\left(-0.225 + 0.523(m_\alpha / m_{3/2})^2\right)\right)$$

$$M_2 \approx e^{-i\gamma_w} m_{3/2}\left(-(0.031 + 0.00026\times\delta)\eta + \alpha_{GUT}\left(-0.034 + 0.555(m_\alpha / m_{3/2})^2\right)\right)$$

$$M_3 \approx e^{-i\gamma_w} m_{3/2}\left(-(0.031 + 0.00026\times\delta)\eta + \alpha_{GUT}\left(0.102 + 0.476(m_\alpha / m_{3/2})^2\right)\right)$$

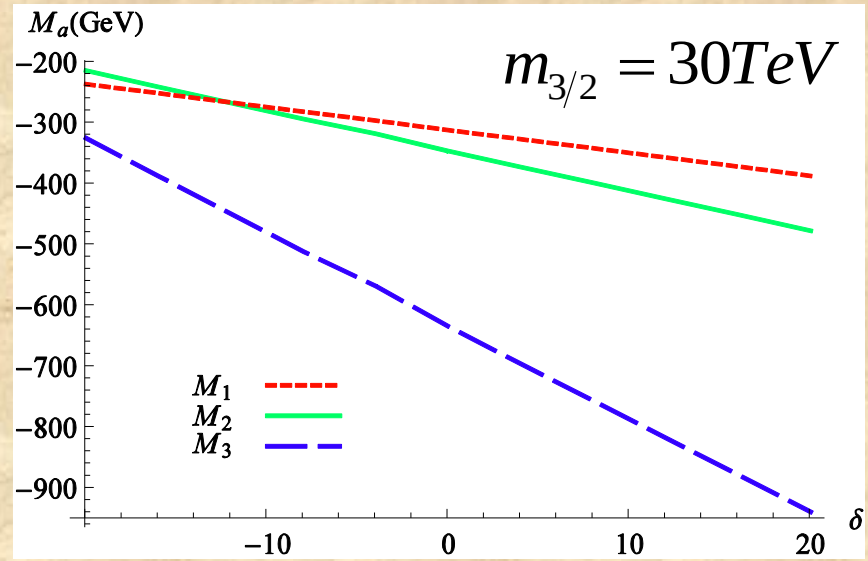
$$\tilde{A}_t \approx e^{-i\gamma_w} m_{3/2}\left(1.5(m_\alpha / m_{3/2})^2 - 0.003(-(46/5)g_{GUT}^2 + 6Y_t^2 + Y_b^2)\right)$$

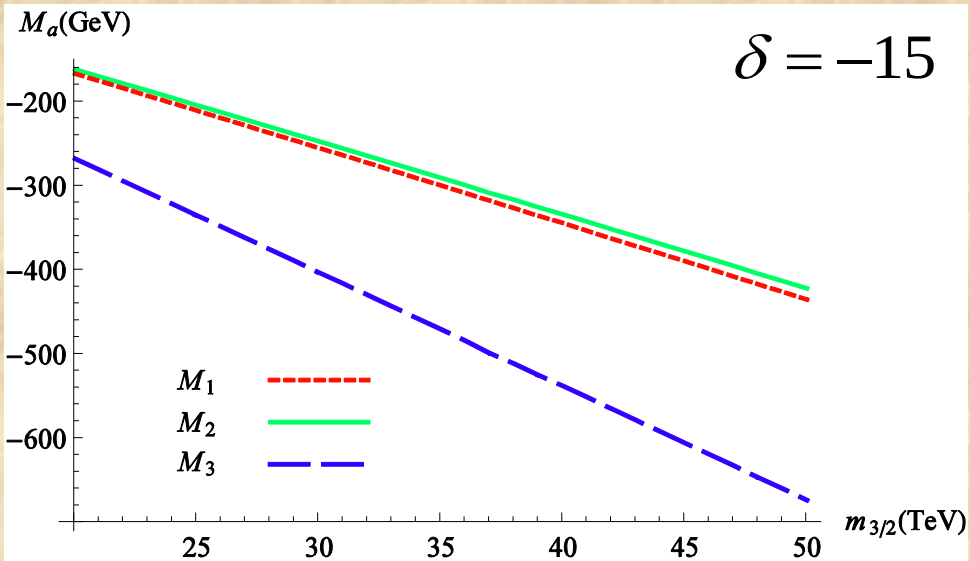
$$\tilde{A}_b \approx e^{-i\gamma_w} m_{3/2}\left(1.5(m_\alpha / m_{3/2})^2 - 0.003(-(44/5)g_{GUT}^2 + Y_t^2 + 6Y_b^2 + Y_\tau^2)\right)$$

$$\tilde{A}_\tau \approx e^{-i\gamma_w} m_{3/2}\left(1.5(m_\alpha / m_{3/2})^2 - 0.003(-(24/5)g_{GUT}^2 + 3Y_b^2 + 4Y_\tau^2)\right)$$

- Used SOFTSUSY to get the EW scale spectrum

Gaugino masses at the EW scale
(generated by SOFTSUSY package)





$$\tan\beta = 2.5, c = 0, \mu < 0, \eta = 1$$

- Pure Wino LSP is rapidly excluded as δ is increased
- For typical values $0 < c < 1$ get pure Bino LSP

Benchmark spectra (masses are in GeV)

GUT scale input

$m_{3/2}$	20000	20000	20000	20000	30000	50000	30000
δ	-15	-12	0	-15	15	-15	-15
C	0	0	0	0.1	0.5	0	0
$\tan\beta$	3	2.65	2.65	3	3	2.5	3
μ	-11943	-13377	-13537	-10969	-10490	-34019	+17486
LSP	Wino	Wino	Bino	Bino	Bino	Wino	Bino
M_1	165	173	203	181	484	434	252
M_2	158	173	225	189	662	421	242
M_3	262	297	423	328	1328	673	395
$m_{\tilde{g}}$	401	449	622	492	1784	1001	597
$m_{\tilde{\chi}_1^0}$	145.1	155.6	189	170	473	373.4	271
$m_{\tilde{\chi}_2^0}$	153	159	214.3	181.5	702.4	397	334.2
$m_{\chi_1^\pm}$	145.2	155.8	214.5	181.7	702.6	373.6	334.2
$m_{\tilde{t}_1}$	9130	8779	8662	8928	11151	22887	14264
$m_{\tilde{b}_1}$	15342	15250	15224	14635	16783	38473	23236
m_h	116.4	114.3	114.6	116.0	115.9	115.1	114.6

Computation of soft SUSY breaking terms

- Since we stabilized the moduli we can compute the terms in the soft-breaking lagrangian

Nilles: Phys. Rept. 110 (1984) 1, Brignole et.al.: hep-th/9707209

- Tree-level gaugino masses

$$M_{1/2} = m_p \frac{e^{\hat{K}/2} F^n \partial_n f_{sm}}{2i \,\mathrm{Im}\, f_{sm}}$$

where the SM gauge kinetic function

$$f_{sm} = \sum_{i=1}^{N} N_i^{sm} z_i$$

Integers specifying the homology of the visible sector 3-cycle

• Use the expressions for the F-terms to compute

$$M_{1/2} \approx -\frac{e^{-i\gamma_W}}{P_{eff}}\left(1+\frac{2}{\phi_c^2\left(M-P\right)}+\frac{\delta}{P_{eff}}\right)\times m_{3/2}$$

• The tree-level gaugino mass is always suppressed for the entire class of dS vacua obtained in our model

$$V_0 = 0 \,\&\, M - P = 3 \Rightarrow P_{eff} \approx 61.65$$

$$\Rightarrow M_{1/2} \approx -e^{-i\gamma_W}(0.031+0.00026\times\delta)\times m_{3/2}$$

• Depending on N_i^{sm} we find typically $|\delta| \leq O(1-10)$

• Vary $61 \leq P_{eff} \leq 62 \Rightarrow -O(m_{3/2}m_{pl})^2 < V_0 < +O(m_{3/2}m_{pl})^2$

• However, $M_{1/2}$ stays virtually inert!

- Anomaly mediated gaugino masses:

Gaillard et. al.: hep-th/09905122, Bagger et. al.: hep-th/9911029

$$(M)_a^{am} = -\frac{g_a^2}{16\pi^2}\left[-\left(3C_a - \sum_\alpha C_a^\alpha\right)e^{\hat{K}/2}\overline{W} + \left(C_a - \sum_\alpha C_a^\alpha\right)e^{\hat{K}/2}F^m K_m + 2\sum_\alpha C_a^\alpha e^{\hat{K}/2}F^m \partial_m \ln \tilde{K}_\alpha\right]$$

- Use $\ln \tilde{K}_\alpha \approx \frac{1}{3}\hat{K} + (c-1)\kappa(s_i)\frac{\phi\bar{\phi}}{3V_7} + const$

$$(M)_a^{am} \approx -\frac{\alpha_{GUT}}{4\pi}\left[-\left(3C_a - \sum_\alpha C_a^\alpha\right)\left(1 - \frac{1}{3}\left(1 + \frac{2}{(M-P)\phi_c^2}\right)\left(\phi_c^2 + \frac{7}{P_{eff}}\right)\right)\right.$$

$$\left. + (c-1)\left(1 + \frac{2}{(M-P)\phi_c^2}\right)\frac{2\phi_c^2}{3}\sum_\alpha C_a^\alpha\right]e^{-i\gamma_w} \times m_{3/2}$$

- In the limit $c \to 1$ Konishi anomaly contribution vanishes. In this case we obtain a particular example of mirage pattern for gaugino masses

- Assume a SUSY GUT broken to MSSM
- Require zero CC at tree-level and $M - P = 3$ to obtain tree-level plus anomaly gaugino masses:

$$M_1 \approx e^{-i\gamma_w}\left(-(0.031 + 0.00026 \times \delta)\eta + \alpha_{GUT}\left(-0.225 + 0.523(1-c)\right)\right) \times m_{3/2}$$

$$M_2 \approx e^{-i\gamma_w}\left(-(0.031 + 0.00026 \times \delta)\eta + \alpha_{GUT}\left(-0.034 + 0.555(1-c)\right)\right) \times m_{3/2}$$

$$M_3 \approx e^{-i\gamma_w}\left(-(0.031 + 0.00026 \times \delta)\eta + \alpha_{GUT}\left(0.102 + 0.476(1-c)\right)\right) \times m_{3/2}$$

- From KK threshold corrections $\eta = 1 - \frac{5 g_{GUT}^2}{8\pi^2}\tau_\omega$

  Friedmann and Witten, hep-th/0211269
- Ray-Singer torsion $\tau_\omega = \ln(4\sin^2(5\pi w/q))$
- $\alpha_{GUT} \approx 1/25$ is fixed from gauge coupling unification
- For the case when *c=0*, the Konishi anomaly is large such that the tree-level and anomaly partially cancel

• μ - problem

in superpotential

from Kahler potential (Giudice-Masiero)

physical

$$\mu = \left(\frac{\overline{W}}{|W|} e^{\hat{K}/2} \mu' + \overbrace{m_{3/2} Z - e^{\hat{K}/2} F^{\overline{m}} \partial_{\overline{m}} Z} \right) (\tilde{K}_{H_u} \tilde{K}_{H_d})^{-1/2}$$

Invariant under **F**

where $Z(z_i, \bar{z}_i, \phi, \bar{\phi})$ originates from $\delta\tilde{K} = \overbrace{Z(z_i, \bar{z}_i, \phi, \bar{\phi}) H_u H_d} + h.c.$

• μ` -parameter can vanish if the G_2 manifold has a discrete symmetry **F**. Also used to solve the doublet-triplet splitting problem

Witten, hep-ph/0201018

• Since $Z(z_i, \bar{z}_i, \phi, \bar{\phi})$ is unknown $\mu \equiv Z^1_{eff} m_{3/2}, B\mu \equiv Z^2_{eff} m^2_{3/2}$

• If $Z^{1,2}_{eff} \sim O(1)$ then typically expect $\mu \sim O(m_{3/2})$

• Heavy higgsinos and $\tan\beta \sim O(1)$

From Higgs-Higgsino loops, at the weak scale get an extra contribution to M_1 and M_2.

Pierce, et.al, hep-ph/9606211; Gherghetta et.al, hep-ph/9904378; Arkani-Hamed, et.al hep-ph/0601041

$$\Delta M_{1,2} \approx \frac{\alpha_{1,2}}{4\pi} \frac{\mu \sin(2\beta)}{\left(1 - \frac{\mu^2}{m_A^2}\right)} \ln \frac{\mu^2}{m_A^2} \approx \frac{\alpha_{1,2}}{4\pi} \mu = \frac{\alpha_{1,2}}{4\pi} Z_{eff}^1 m_{3/2}$$

used that $\tan\beta \approx O(1)$ and $\frac{\mu^2}{m_A^2} \approx 1$

When $\mu \sim O(1) m_{3/2}$, such contributions can change the type of the LSP, depending on the sign of μ !

- In $\mathcal{N}$=1 D=4 sugra, the unnormalized scalar masses:

$$m'^2_{\alpha\bar{\beta}} \approx \tilde{K}_{\alpha\bar{\beta}}(m^2_{3/2}+V_0) - e^{\hat{K}} F^n \bar{F}^{\bar{m}} (\partial_n \partial_{\bar{m}} \tilde{K}_{\alpha\bar{\beta}} - \partial_n \tilde{K}_{\alpha\bar{\gamma}} \tilde{K}^{\bar{\gamma}\delta} \partial_{\bar{m}} \tilde{K}_{\delta\bar{\beta}})$$

- In our construction we obtain (using homogeneity)

$$m'^2_{\alpha\bar{\beta}} \approx (1-c)\left(m^2_{3/2} - \frac{7}{3}\left(m^{tree}_{1/2}\right)^2 \right)\tilde{K}_{\alpha\bar{\beta}} \Rightarrow m_\alpha \approx (1-c)^{1/2} m_{3/2}$$

- For generic values of c the scalars are very heavy

- Tree-level mass vanishes in the limit $c=1$ – get tachyons in the scalar spectrum.

- We restrict our analysis to the values of c when

$$\frac{1}{16\pi^2} << \frac{m_\alpha}{m_{3/2}}$$

- Trilinear couplings:

$$A^{tree}_{\alpha\beta\gamma} = \frac{\overline{W}}{|W|} e^{\hat{K}/2} F^m \left(K_m Y'_{\alpha\beta\gamma} + \partial_m Y'_{\alpha\beta\gamma} - \left(\tilde{K}^{\delta\bar{\rho}} \partial_m \tilde{K}_{\bar{\rho}\alpha} Y'_{\delta\beta\gamma} + (\alpha \leftrightarrow \beta) + (\alpha \leftrightarrow \gamma) \right) \right)$$

$$Y'_{\alpha\beta\gamma} = C_{\alpha\beta\gamma} e^{i2\pi \sum_{i=1}^{N} m_i^{\alpha\beta\gamma} z_i}$$

Membrane instanton volume: $V_{Q^{\alpha\beta\gamma}} = \sum_{i=1}^{N} m_i^{\alpha\beta\gamma} s_i$

$$\tilde{A}^{tree}_{\alpha\beta\gamma} \equiv \frac{A^{tree}_{\alpha\beta\gamma}}{Y'_{\alpha\beta\gamma}} \approx m_{3/2} e^{-i\gamma_W} \left(1 + \frac{2}{(M-P)\phi_c^2} \right) \left((1-c)\phi_c^2 + \frac{4\pi}{P_{eff}} V_{Q^{\alpha\beta\gamma}} \right)$$

Anomaly: $$\tilde{A}^{AM}_a = -\frac{1}{16\pi^2} \gamma_a \left(e^{\hat{K}/2} \overline{W} - \frac{1}{3} e^{\hat{K}/2} F^n K_n \right) + \frac{(1-c)}{16\pi^2} X_a m_{3/2}$$

Gaillard-Nelson. hep-th/0004170

$$\tilde{A}^{AM}_t \approx -\frac{e^{-i\gamma_w}}{16\pi^2} \left(-\frac{46}{5} g^2_{GUT} + 6Y_t^2 + Y_b^2 \right) \left(1 - \frac{1}{3} \left(1 + \frac{2}{(M-P)\phi_c^2} \right) \left(\phi_c^2 + \frac{7}{P_{eff}} \right) \right) m_{3/2}$$

$$\tilde{A}^{AM}_b \approx -\frac{e^{-i\gamma_w}}{16\pi^2} \left(-\frac{44}{5} g^2_{GUT} + Y_t^2 + 6Y_b^2 + Y_\tau^2 \right) \left(1 - \frac{1}{3} \left(1 + \frac{2}{(M-P)\phi_c^2} \right) \left(\phi_c^2 + \frac{7}{P_{eff}} \right) \right) m_{3/2}$$

$$\tilde{A}^{AM}_\tau \approx -\frac{e^{-i\gamma_w}}{16\pi^2} \left(-\frac{24}{5} g^2_{GUT} + 3Y_b^2 + 4Y_\tau^2 \right) \left(1 - \frac{1}{3} \left(1 + \frac{2}{(M-P)\phi_c^2} \right) \left(\phi_c^2 + \frac{7}{P_{eff}} \right) \right) m_{3/2}$$

• Total trilinear couplings for *M-P=3* and zero CC:

$$\tilde{A}_t \approx e^{-i\gamma_w}\left(1.5(1-c)-0.003\left(-\frac{46}{5}g_{GUT}^2+6Y_t^2+Y_b^2\right)\right)\times m_{3/2}$$

$$\tilde{A}_b \approx e^{-i\gamma_w}\left(1.5(1-c)-0.003\left(-\frac{44}{5}g_{GUT}^2+Y_t^2+6Y_b^2+Y_\tau^2\right)\right)\times m_{3/2}$$

$$\tilde{A}_\tau \approx e^{-i\gamma_w}\left(1.5(1-c)-0.003\left(-\frac{24}{5}g_{GUT}^2+3Y_b^2+4Y_\tau^2\right)\right)\times m_{3/2}$$

• We assumed that the third generation Yukawas arise from colliding singularities and thus dropped the volume terms

Friedmann and Witten, hep-th/0211269
Atiyah-Witten. hep-th/0107177

• For generic values of *0<c<1*: $\tilde{A}_{t,b,\tau} \sim O(1)\times m_{3/2}$

Electroweak Symmetry Breaking

- In most models REWSB is accommodated but not predicted, i.e. one picks $\tan\beta$ and then finds μ, which give the experimental value of M_Z
- Recall $\mu \equiv Z_{eff}^{1} m_{3/2}, B\mu \equiv Z_{eff}^{2} m_{3/2}^{2}$
- Radiative EWSB is generic in our construction for a large range of values $0.1 < Z_{eff}^{1,2} < 3$
- However, generically get $M_Z \sim O(m_{3/2})$
- Getting $M_Z \approx 91 GeV$ requires fine tuning up to 0.01% level

Conclusions

• Generalized the previous construction by relying only on the most basic property of the bulk Kahler potential

• Presented a very general form of the Kahler potential for chiral matter and used it in the construction

• All moduli are stabilized by the potential generated by the strong gauge dynamics in the hidden sector. The superpotential is very simple, contains only two terms!

• Supersymmetry is broken spontaneously via F-terms (no antibranes are needed for uplifting)

- Constrained $m_{3/2} \sim O(10)\ TeV$ from CC=0
- Demonstrated via explicit computations that the soft breaking terms are independent of the detailed microscopic structure of the Kahler potential
- Gauginos are always light: $M_{1,2,3} \sim O(100\text{-}1000)\ GeV$
- Gauge coupling unification and REWSB are generic
- The little hierarchy problem leads to 0.01% tuning
- Typical spectrum: light gauginos and heavy scalars and higgsinos, Bino LSP is generic but can be Wino

Related work

• Found a robust solution to the Strong CP problem and realization of the String Axiverse
(K.B. with Bobby Acharya and Piyush Kumar; hep-th/1004.5138)

• Constructed a new class of compactifications in Type IIB on CY orientifolds, completely analogous to the M-theory models described here. Found explicit CY examples that implement the idea. (K.B with Volker Braun, Piyush Kumar and Stuart Raby: hep-th 1003.1982)

Things to do in the future

• Baryogenesis (AD mechanism is a good candidate)

• Yukawa couplings and neutrino masses

• Inflation (probably need to know the details of $V_7(s_i)$)