Moduli stabilization and supersymmetry breaking for string phenomenology

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(DESY)

Based on works with
Hiroyuki Abe, Ryuichiro Kitano, Tatsuo Kobayashi, Yuji Omura and Osamu Seto

■ Why moduli?

Superstring theory:

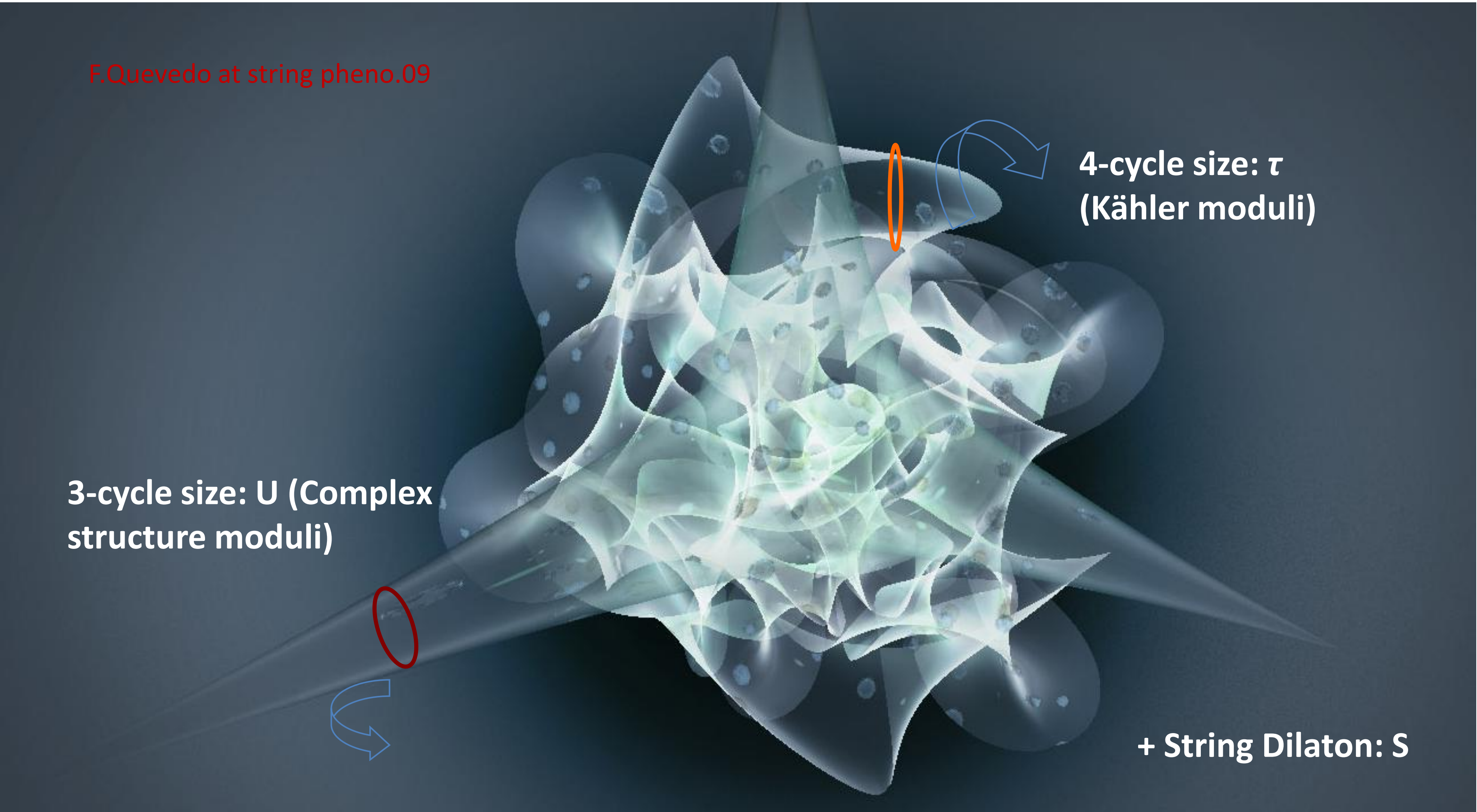
Unified theory including quantum gravity.

If the world we observe (4D) is described by superstring theory (10D), the theory will be

compactified on $\mathbb{R}^{1,3} \times \mathcal{M}_6$

$\mathcal{M}_6$: A six dimensional compact space
e.g. Calabi-Yau (CY) 3-fold, 6-dim. torus.

Closed string moduli = dynamical volumes and shapes.



They always exist in string vacua!

- Moduli coupling to our sector (gauge field) localized on the D(3+n)-brane wrapping on Σ_n , where Σ_n is an n-cycle in $\mathcal{M}_6$

$$\mathcal{L} = \int_{\Sigma_n} d^n y \sqrt{g} (F_{\mu\nu})^2 \equiv \underline{\mathrm{Vol}(\Sigma_n)} (F_{\mu\nu})^2 = \frac{1}{g^2} (F_{\mu\nu})^2.$$

↕ SUSY

$$\mathcal{L}_{\mathrm{gaugino}} = F \lambda^\alpha \lambda_\alpha = \underline{(D_{\mathrm{moduli}} W)} \lambda^\alpha \lambda_\alpha = M_{1/2} \lambda^\alpha \lambda_\alpha.$$

The moduli vevs = physical parameters!

■ Moduli stabilization: global (bulk) issues

•Scales, couplings: GUT scale, gauge/Yukawas , ν_R mass, μ...

Kaplunovsky et al; Conlon et al; Strominger; Font et al; Cremades et al...

•Cosmology: Cosmological constant, inflation, CMP...

Kachru et al.; Conlon et al.; Cicoli et al. ...

•SUSY breaking: moduli mediation, i.e. $m_{3/2} \geqq 1$TeV, for new physics (plus other mediations)

Kaplunovsky et al; Brignole et al.;
Choi et al.; Endo et al.; Falskowski et al; Conlon et al....

Without the stabilization, a fifth force would be found ...

■ Moduli stabilization: global (bulk) issues

•Scales, coupl

•Stabilizing hierarchy problem
•Gauge coupling unification (GUT)
•Dark matter candidate with R-parity
•Discovery at the LHC?

•Cosmology

…a et al.; Conlon et al.; Cicoli et al. …

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Without the stabilization, a fifth force would be found …

■ Issue of the stabilization?

SUSY moduli posses perturbative Peccei-Quinn symmetries:

$$\Phi \to \Phi + i \cdot \text{const.}$$

$$\Phi = \text{Vol} + ia : \ \text{moduli complex scalar.}$$

∵ Axions {a} come from tensor fields with gauge sym.

$$C_{\mu_1\mu_2\cdots\mu_p} \to C_{\mu_1\mu_2\cdots\mu_p} + \partial_{[\mu_1}\Lambda_{\mu_2\cdots\mu_p]}.$$

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Moduli multipets = axion ones.

$Re(\Phi)$: moduli = saxion that determines its decay const.

Universe with many light axions = string axiverse.

Arvanitaki et al.

How are they stabilized?

- Background closed string flux:

$$W_{flux} = f_{ij}\,\Phi^i\Phi^j + \ \ldots$$

Typically ignored in low energy

→ Heavier moduli: $m_\Phi \leq M_{GUT}$.

- Gaugino condensations (GCs), instantons:

SUSY is important for analyzing strong dynamics.

$$W_{\text{inst./GC}} \sim e^{-1/g^2} \sim e^{-\text{Vol(brane)}} \sim e^{-\Phi}.$$

→ Heavy moduli: $m_\Phi \geq m_{3/2}$.

- SUSY breaking; $m_\Phi \leq m_{3/2}$.

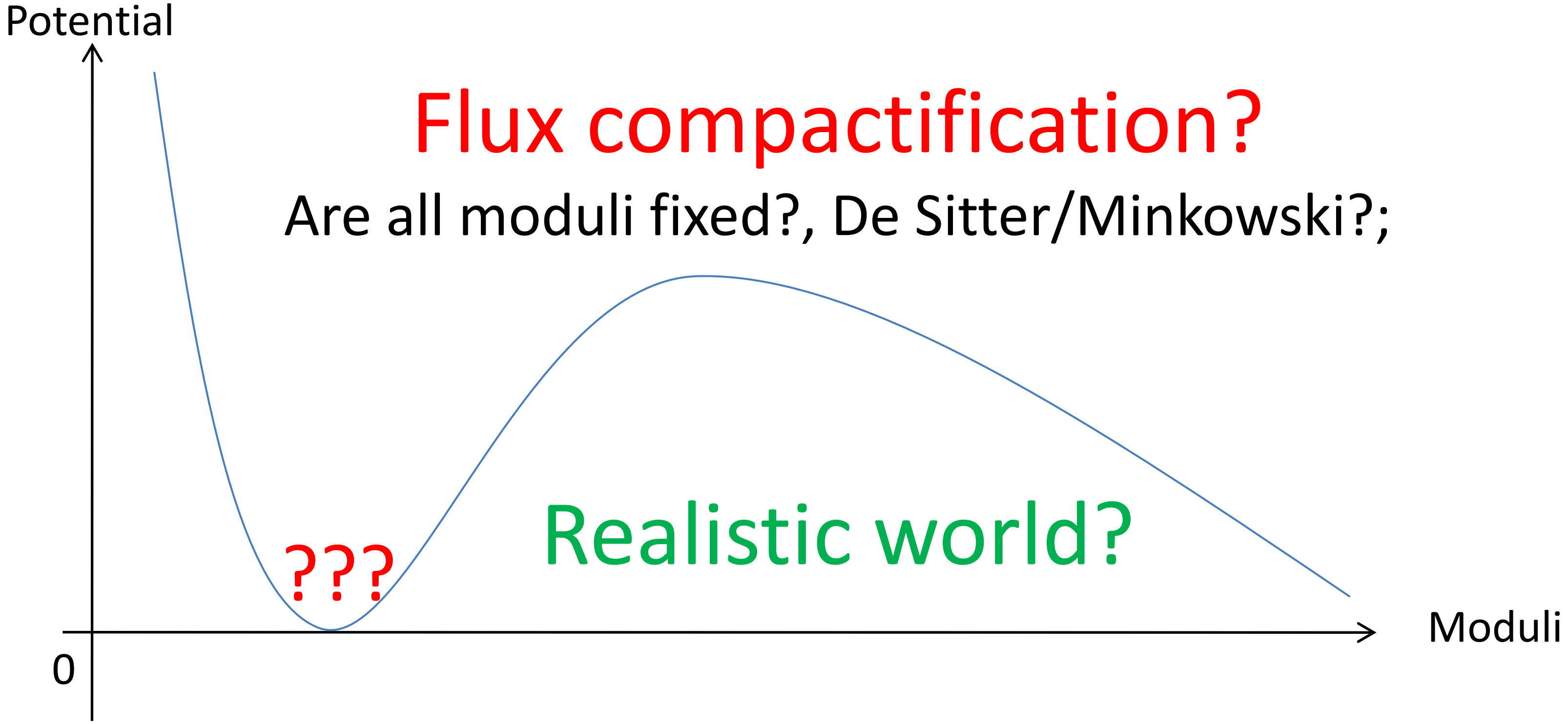
Moduli stabilization before KKLT:

- Relevant interactions of moduli: $1/M_{\text{string}} \sim 1/M_{\text{Pl}}$.

(TeV or intermediate string without moduli stabilizations.)

- Mass scales of moduli mass, soft SUSY mass: $\sim m_{3/2}$.

(also general but highly model dependent issue)



Moduli stabilization after KKLT:

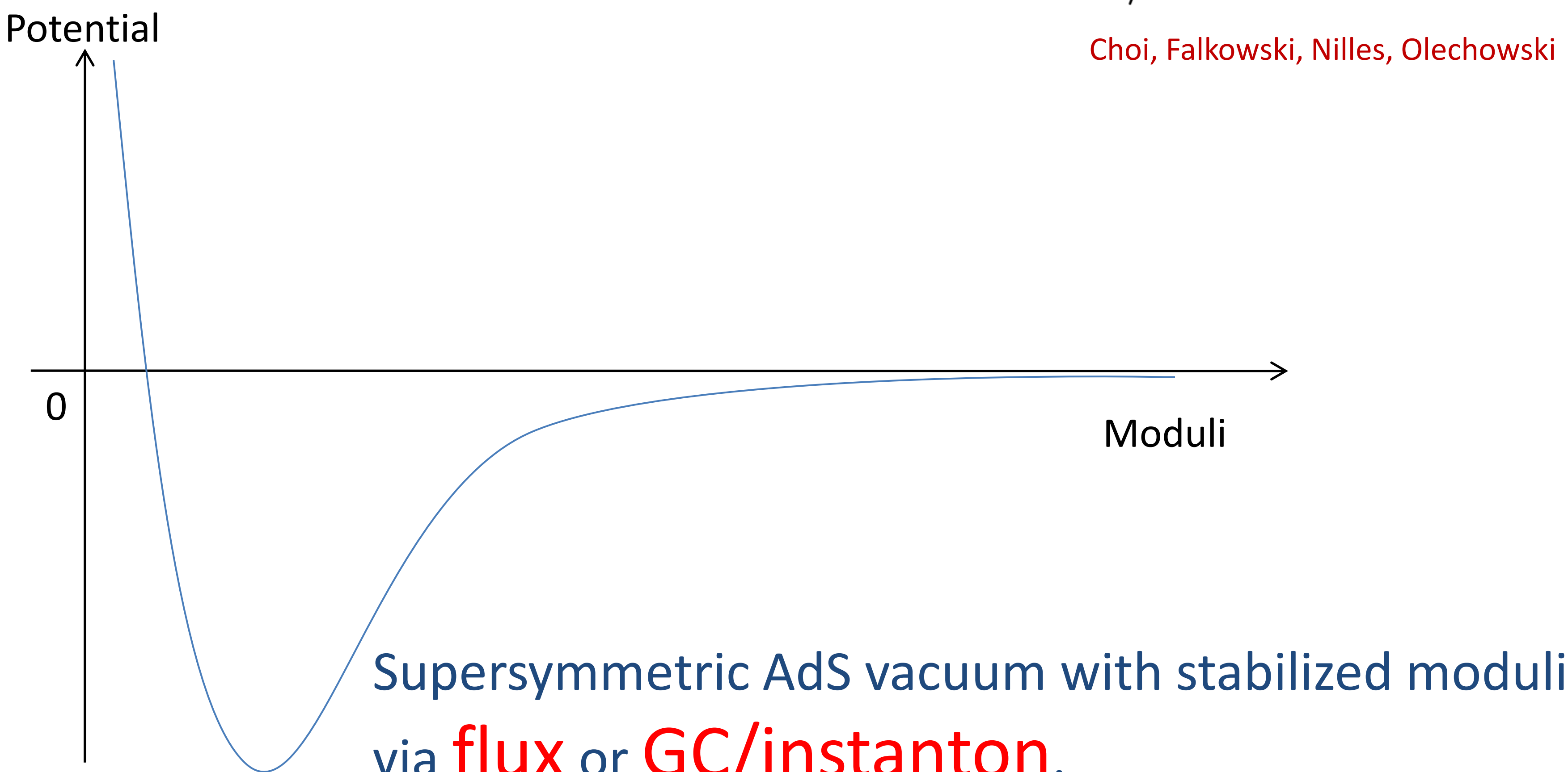
Kachru, Kallosh, Linde, Trivedi

- Stronger interaction than the gravitational force.

Conlon and Quevedo

- moduli mass much larger than $m_{3/2}$, and soft mass much smaller than $m_{3/2}$.

Choi, Falkowski, Nilles, Olechowski



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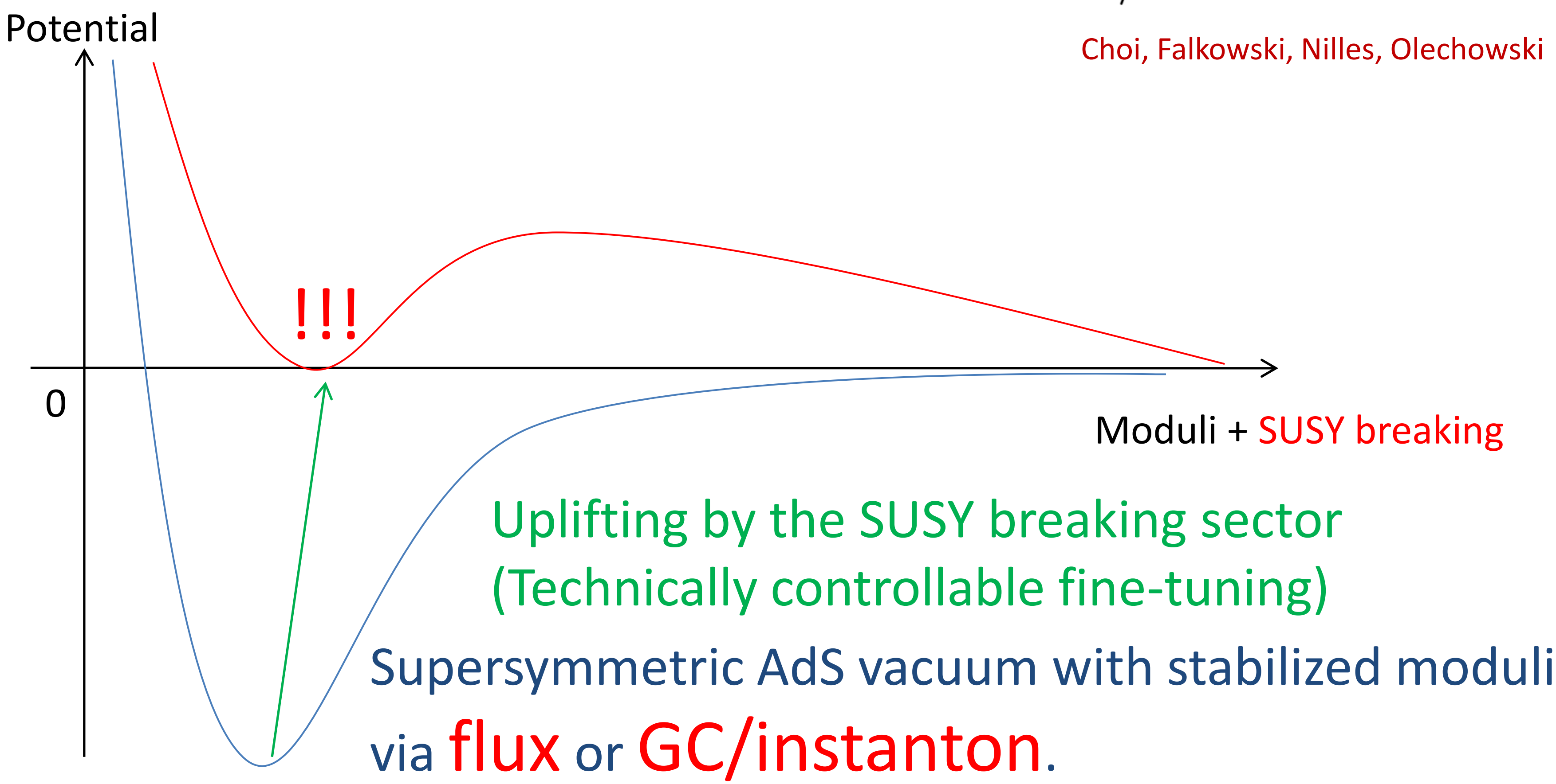


Semi-realistic models can be gained

→ Explicit computations are motivated!

Two comments…

■ Remark: Model dependent problems

- CMP (moduli-dominated universe)

Coughlan et al; Banks et al; Carlos et al.

- Gravitino overproduction

Endo et al; Nakamura et al; Kawasaki et al.; Asaka et al.

- Overshooting or destabilization by T_{emp} or inflation

Brustein et al; Buchmüller et al; Kallosh et al.

Low H_{inf} (< m_{moduli}), very heavy moduli, late time entropy production (n_B/s), low cutt-off, change DM, high H for stabilization, low H_{inf} (< $m_{3/2}$), moduli inflation, low or very high temperature, negative exponent, no SUSY…

Dine et al; Fan et al; Lyth et al; Kawasaki et al; Nagai et al; Choi et al; Conlon et al; Nakamura et al; Kaloper et al; Brustein et al; Conlon et al; Lalak et al; Abe, TH, Kobayashi+Seto…

- Open string moduli stabilization

Branes on the rigid cycle e.g. dP, flux, non-perturbative effect...

Camara et al; Baumann et al…

■ Local model building: local (brane) issue

Aldazabal et al.; Heckman et al.; Donagi et al.; Watari et al.
Marsano et al. and many authors.

•Realization of the SM:

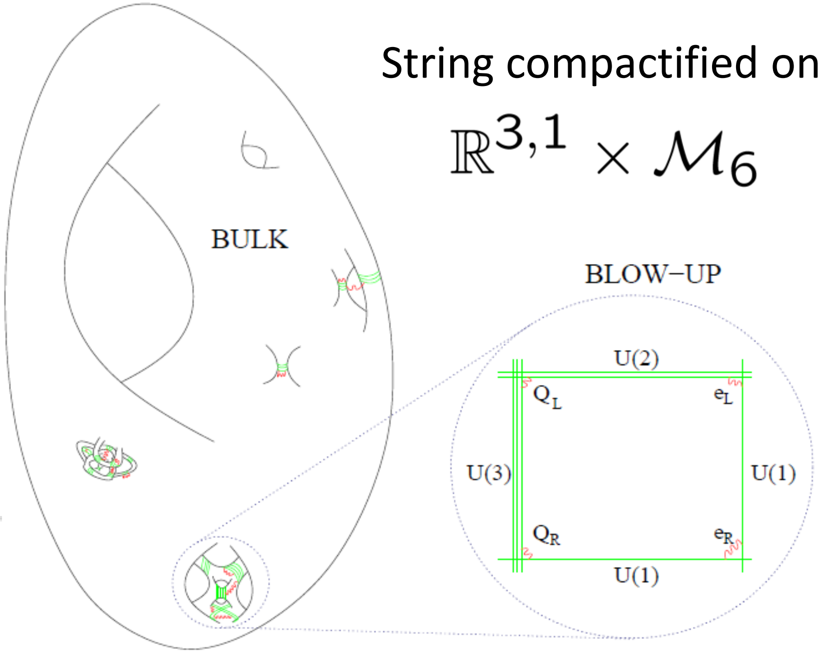
chiral mass spectra, gauge group, gauge/Yukawa couplings, flavor symmetries, stable proton, open moduli stabilization...

•SUSY breaking: gauge mediation (smaller $m_{3/2}$)

Often moduli stabilization is ignored since it will demand hidden, e.g. strong coupling, sectors. Our talk will be another aspects (or limit against) in local model building.

String compactified on

$$\mathbb{R}^{3,1} \times \mathcal{M}_6$$



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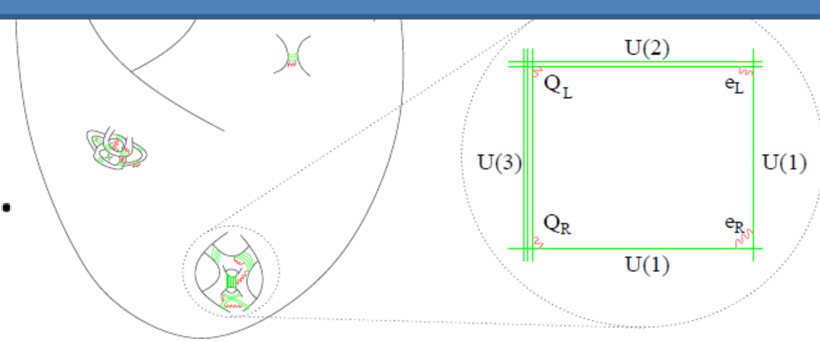
•Realization of the SM:

We must not forget
moduli stabilization
besides the tadpole condition
(global issue).

another aspects (or limit against) in local model building.



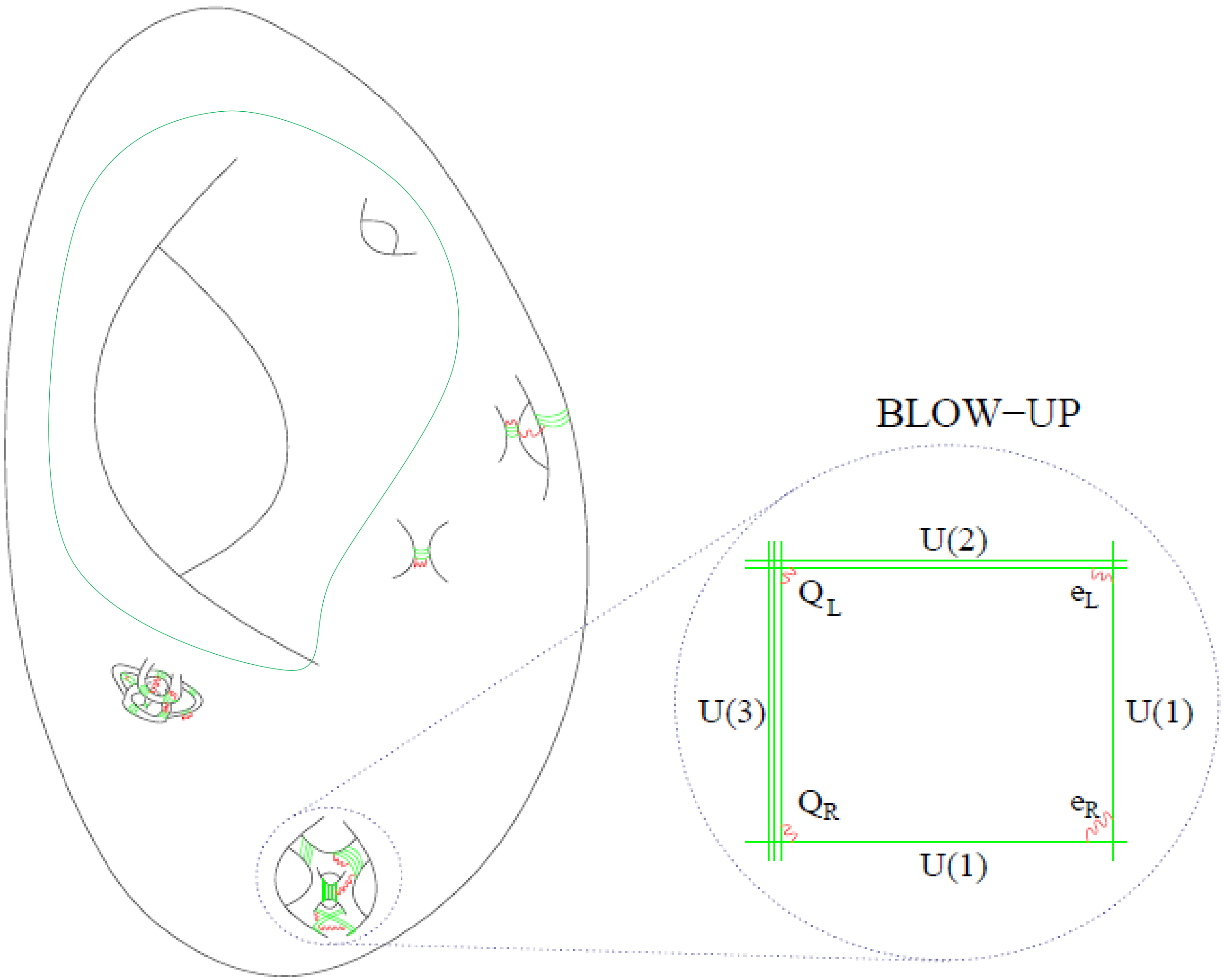
Plan of Talk

1. Introduction
2. Kachru-Kallosh-Linde-Trivedi model
3. Almost SUSY stabilization
4. SUSY breaking field and moduli
5. Non-QCD axion mass

2.Kachru-Kallosh-Linde-Trivedi (KKLT) model

■ KKLT vacuum

Kachru, Kallosh, Linde, Trivedi



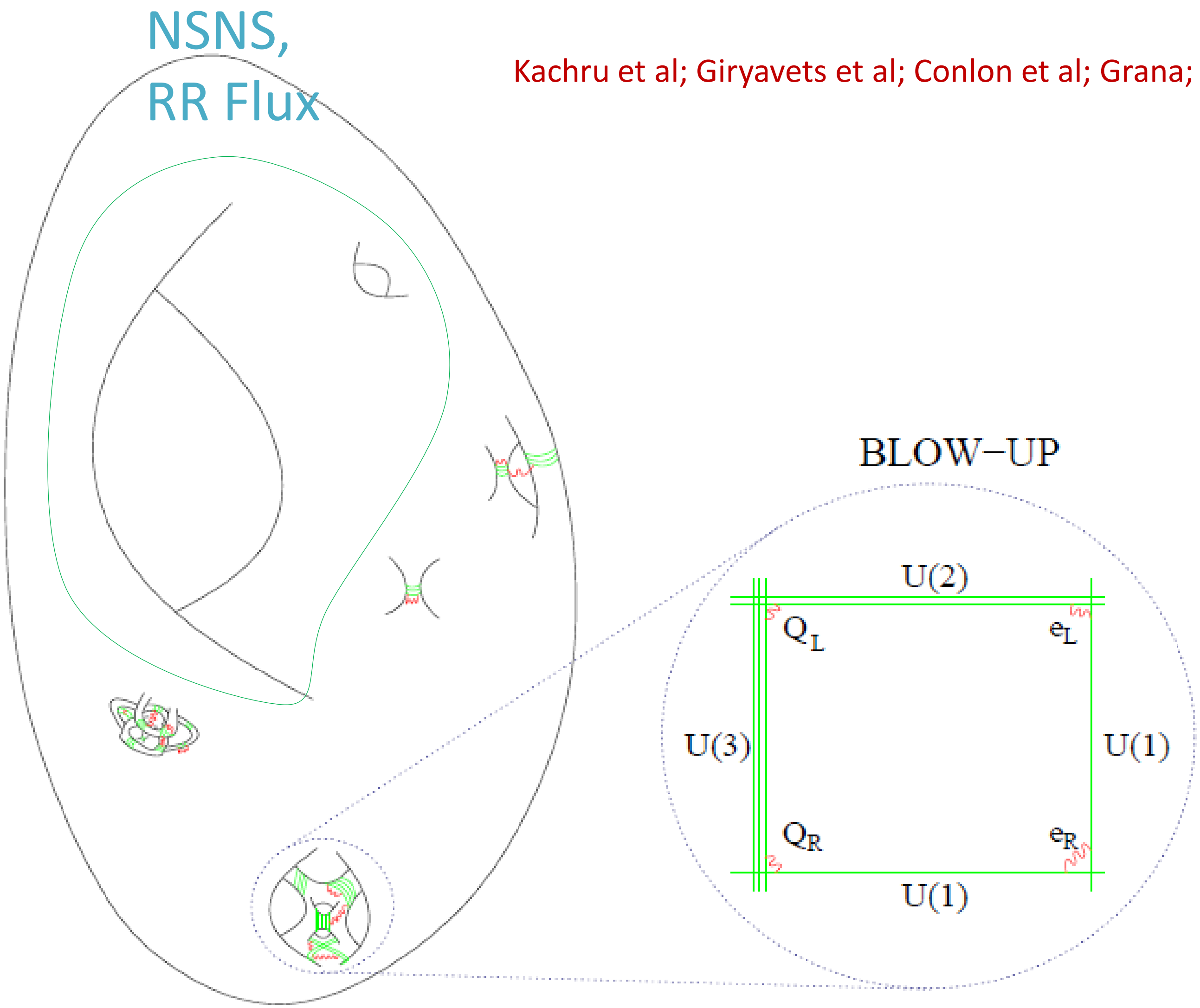
The Standard Model sector

■ KKLT vacuum

Kachru, Kallosh, Linde, Trivedi

Flux: fixing many moduli, e.g. shape moduli.

Kachru et al; Giryavets et al; Conlon et al; Grana; Douglas et al and many authors



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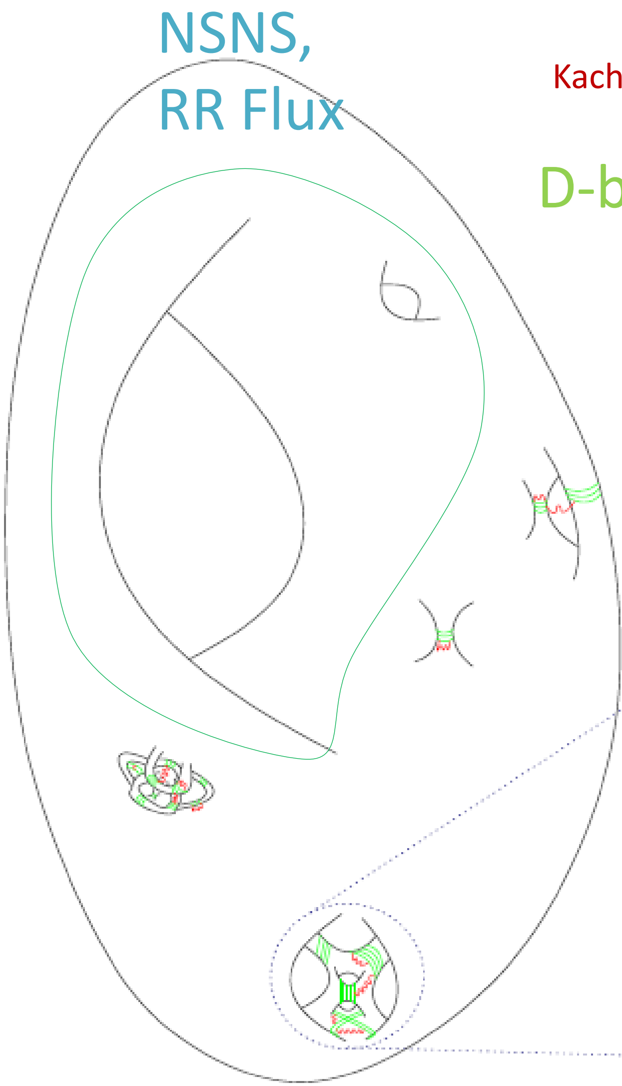
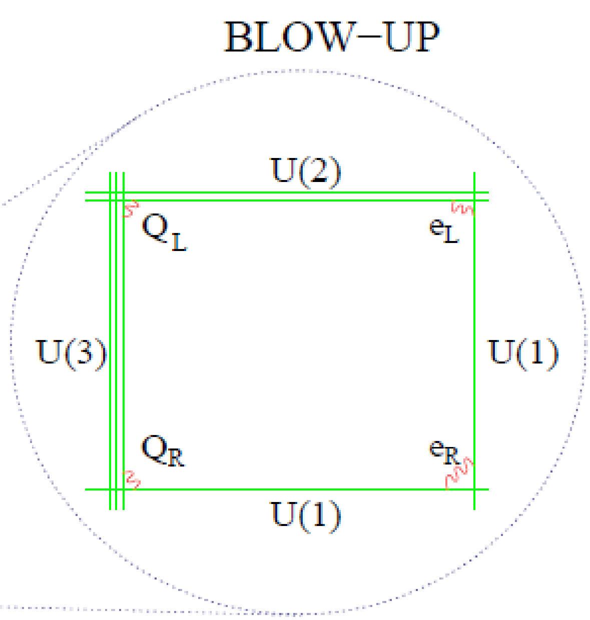
D-branes: fixing the remaining (volume) moduli.

The visible sector





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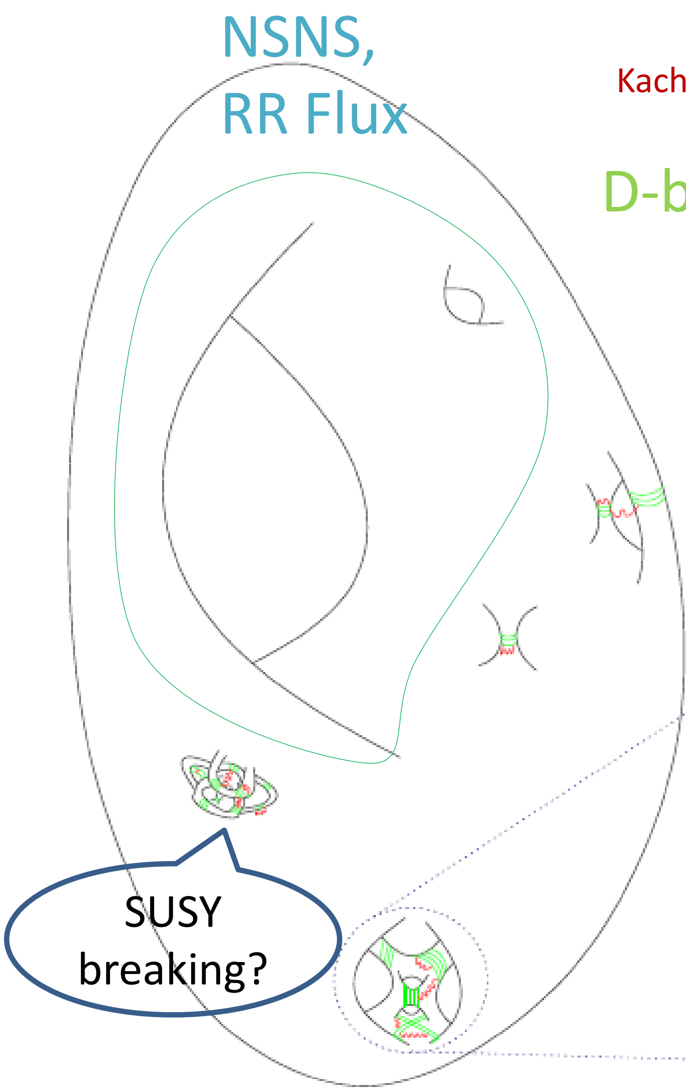
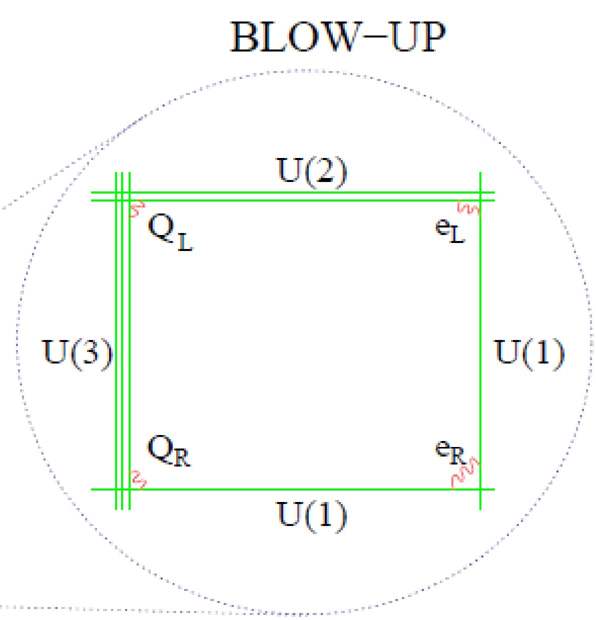
D-branes: fixing the remaining (volume) moduli.
The visible sector and SUSY breaking effects.

→ <V> = 0





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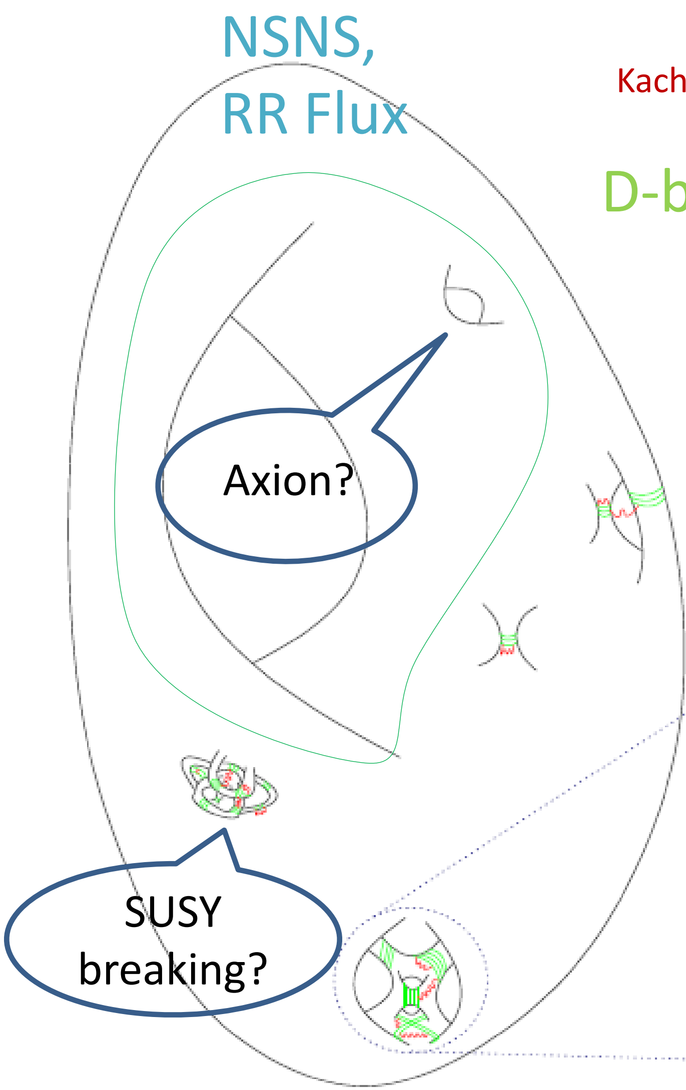

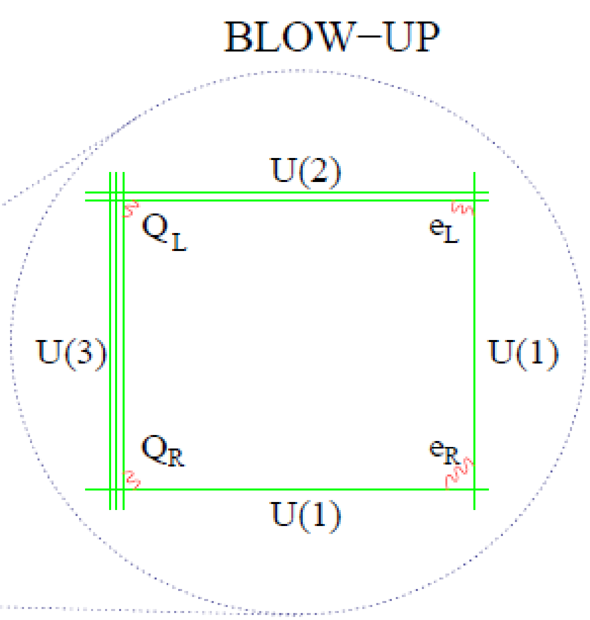

The Standard Model sector

- Effective 4d N=1 supergravity:

$$V = e^K[DW \cdot \overline{DW} - 3W\overline{W}],$$
$$= e^G[\partial G \cdot \overline{\partial G} - 3]. \qquad e^{G/2} \equiv m_{3/2}.$$

$$DW = e^{-K}\partial(e^K W), \quad G = K + \log(W\bar{W}), \quad F \sim e^{G/2}\partial G.$$

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Type IIB CY orientifold models with SUSY breaking

Grimm, Louis

$$K = -2\log[\mathcal{V}] + \hat{K}_{\cancel{\text{SUSY}}} + \cdots,$$

$$W = W_{\text{flux}} + \sum_{i} e^{-a_i \Phi^i} + \hat{W}_{\cancel{\text{SUSY}}}.$$

Polonyi etc.

$$\mathcal{V} = \text{Vol}(CY), \quad \frac{\partial \text{Vol}(CY)}{\partial t^i} = \text{Re}(\Phi^i), \quad J = t^i \omega_i^{+}$$

KKLT model with one modulus T (up to SUSY sector)

$$K = -3\log(T+\bar{T}), \qquad W = W_0 + Ae^{-aT}.$$

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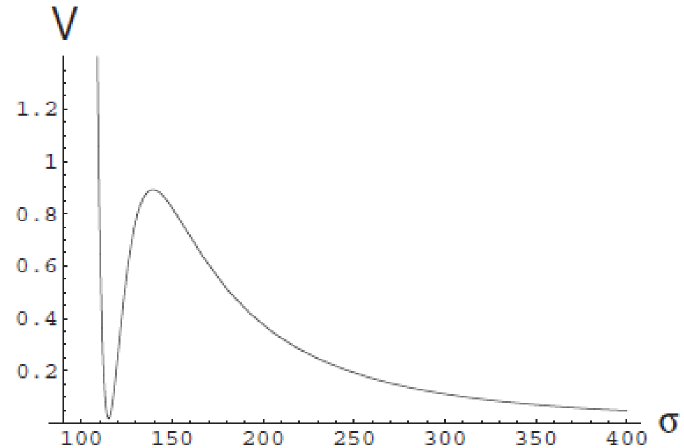

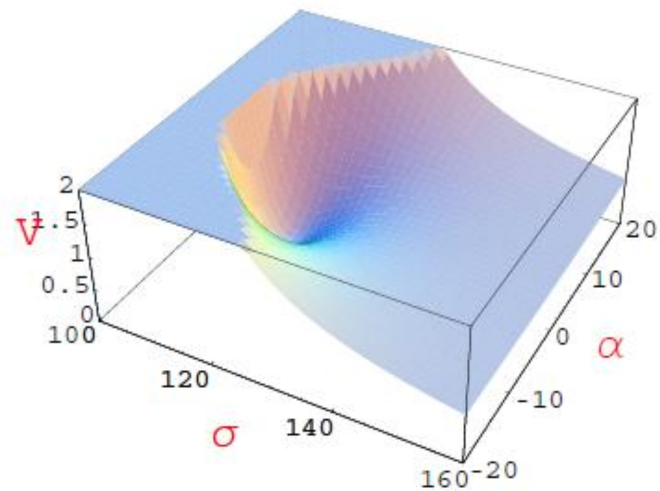

$$V = \frac{aAe^{-a\sigma}}{2\sigma^2}\left[A\left(1+\frac{a\sigma}{3}\right)e^{-a\sigma} + W_0\cos(a\alpha)\right] + \frac{D_{SB}}{\sigma^n}$$

n=2: sequestered SUSY breaking, n=3: non-sequestered SUSY breaking.

$$W_0 \sim 10^{-13}, \quad A \sim 1, \quad a = \frac{8\pi^2}{N} = O(10), \quad T = \sigma + i\alpha.$$

for low scale SUSY breaking phenomenology.

■ Properties of KKLT vacuum

Choi, Falkowski, Nilles, Olechowski
Choi, Jeong, Okumura;
Endo, Yoshioka, Yasmaguchi

- Supersymmetric stabilization of moduli

$$D_T W \sim 0$$

$$\to a < T > \sim -\log(W_0) \sim \log(M_{Pl}/m_{3/2}) \sim 4\pi^2.$$

- Mass hierarchy between m_T, $m_{3/2}$ and m_{soft}

$$m_T \sim 4\pi^2 m_{3/2} \sim (4\pi^2)^2 m_{soft}.$$

i.e. m_{soft} = 1TeV, $m_{3/2}$= 30TeV, m_T =1000TeV.

Note that anomaly mediated SUSY breaking $m_{AMSB} \sim \frac{m_{3/2}}{4\pi^2}$ contributes to m_{soft}; we could obtain degenerate masses.

LSP = bino (+ higgsino).

Why is (was) KKLT viable?

■ Standard procedure of modern moduli stabilization

- IIB moduli stabilization on CY (KKLT, KL on SUSY vac.)

All moduli can be fixed via 3-form flux + GCs/instantons on 4-cycles

$$W = \int G_3 \wedge \Omega + \sum_i A_i e^{-a_i \sum_A n_A T^A}$$
$$= U^2 + SU + T^2(a^2 e^{-aT}) + \cdots .$$

(+ D-term stabilization via <F_{ij}> or SUSY breaking)

Uplifting (SUSY breaking) is necessary in many cases.

But… <W_{flux}> =O(1) + α' corrections

Westphal et al.

-> de Sitter vacuum without uplifting?

■ Standard procedure of modern moduli stabilization

- IIA moduli stabilization on (non-)CY

All moduli can be fixed via flux compactifications.

(There are both even and odd-form fluxes. CY; ∃ axions, AdS as KKLT)

Uplifting will not be necessary.

$$W = \int e^{J_c} \wedge F + \int (H_3 + dJ_c) \wedge \Omega_c$$

$$= T^2 + TS + TU + \cdots, F = \sum_{p=0}^{3} F_{2p}$$

➢ Gaugino condensation would be viable

$$W_{GC} \sim e^{-S-U} + \text{uplifting}$$

in addition to D-term stabilization and SUSY breaking.

■ Standard procedure of modern moduli stabilization

- Heterotic moduli stabilization on (non-)CY?

  Extra dimension is mathematically complicated with 3-form flux compactifications.
  Strominger; Becker et al.; Yau et al…

  Instead, 2-from flux and GCs/world sheet instanton on CY space viable?
  Anderson, Gray, Lukas, Ovrut

$$W = \int (H_3 + dJ_c) \wedge \Omega$$

↓

$$W = \int \omega_3^{\mathrm{YM}}(F) \wedge \Omega(U) + \sum_i A_i e^{-a_i(n^i S - \beta^i_A T^A)}$$

(+ D-term stabilization and SUSY breaking)

3. Other variant models based on supersymmetric stabilization

Recent SUSY pheno. models via moduli stabilization

- KKLT + string theoretic axion
- Minimal LARGE volume scenario
- G2 MSSM + string theoretic axions (no flux)

Mass hierarchy: $m_{\rm moduli} \gg m_{3/2} \gg m_{\rm soft}.$

e.g.

$$\frac{m_{\rm moduli}}{m_{3/2}} \simeq \frac{m_{3/2}}{m_{\rm soft}} \simeq \log(M_{\rm Pl}/m_{3/2}) \simeq 4\pi^2.$$

■ KKLT model + axion

Conlon; Choi, Jeong

$$K = -\frac{3}{2}\log(T_1 + \bar{T}_1) - \frac{3}{2}\log(T_2 + \bar{T}_2), \quad W = W_0 + Ae^{-a(T_1+T_2)}.$$

T_1-T_2 is absent from W; the direction becomes light axion.

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This model can be rewritten as

$$K = -\frac{3}{2}\log(\mathrm{Re}(\Phi + u)) - \frac{3}{2}\log(\mathrm{Re}(\Phi - u)), \quad W = W_0 + Ae^{-a\Phi}.$$

$$\Phi = T_1 + T_2, \quad u = T_1 - T_2.$$

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$$\Phi = T_1 + T_2, \quad u = T_1 - T_2.$$

$$D_\Phi W,\ \partial_u K \sim 0 \ \rightarrow \ \Phi \sim \text{KKLT sol.},\ u \sim 0.$$

$$m_\Phi \sim \text{KKLT}, \quad m_u \simeq 2m_{3/2},\ F^\Phi \sim \frac{K^{\Phi\bar{\Phi}}}{K^{\Phi\bar{u}}} F^u \sim m_{3/2}\frac{m_{3/2}}{m_\Phi}.$$

Sequestered anti D3-brane: $V_{\text{lift}} = e^{2K/3}\epsilon \ \rightarrow \ m_u \simeq \sqrt{2}m_{3/2}$.

■ Minimal LARGE volume scenario (LVS)

Balasubramanian, Berglund, Conlon, Quevedo ;
Conlon, Quevedo, Suruliz

$$K = -2\log(\mathcal{V} + \hat{\xi}), \quad \mathcal{V} = (T + \bar{T})^{3/2} - (\Phi + \bar{\Phi})^{3/2}$$

$$W = W_0 + Ae^{-a\Phi}, \qquad W_0 = O(1).$$

$$V \simeq \frac{2\sqrt{2}\sqrt{\phi}a^2A^2e^{-2a\phi}}{3\mathcal{V}} - \frac{4\phi a A e^{-a\phi}W_0}{\mathcal{V}^2} + \frac{3W_0^2\hat{\xi}}{2\mathcal{V}^3}$$

$$\mathrm{Re}(T) = \tau, \quad \mathrm{Re}(\Phi) = \phi.$$

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$$\mathrm{Re}(T) = \tau, \quad \mathrm{Re}(\Phi) = \phi.$$

$$\mathcal{V} \sim \tau^{3/2} \sim e^{a\phi} \sim 10^{13}, \quad \phi \sim \hat{\xi}^{2/3} = O(1),$$

$$m_{3/2} \sim \mathcal{V}^{-1} \ll 1, \quad m_\tau \sim m_{3/2}(\frac{m_{3/2}}{M_{\rm Pl}})^{1/2}, \quad m_\Phi \sim a\phi m_{3/2},$$

$$F^T \sim m_{3/2}, \quad F^\Phi \sim m_{3/2}\frac{m_{3/2}}{m_\Phi} \sim m_{soft}$$

LSP = bino

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$$\mathrm{Re}(T) = \tau, \quad \mathrm{Re}(\Phi) = \phi.$$

$M_{string} \sim 10^{11}$ GeV

$$\mathcal{V} \sim \tau^{3/2} \sim e^{a\phi} \sim 10^{13}, \quad \phi \sim \hat{\xi}^{2/3} = O(1),$$

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$$F^T \sim m_{3/2}, \quad F^\Phi \sim m_{3/2}\frac{m_{3/2}}{m_\Phi} \sim m_{soft}$$

O(10) TeV

LSP = bino

■ G2 MSSM (M-theory on G2 space without flux)

$$K = -3\log V_{G_2} + \bar{X}X, \quad W = Ae^{-af}X^{-c} + Be^{-bf},$$

$$f = \sum_i z_i N^i, \quad N^i\text{: integer},$$

$$V_{G_2} = \prod_i Re(z_i)^{d_i}, \quad \frac{7}{3} = \sum_i d_i.$$

ADS superpotential with one meson X

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ADS superpotential with one meson X

$$D_f W \sim 0 : \text{racetrack sol.}, \quad K_z \sim 0, \quad X < O(1),$$

$$m_f = m_{r.t.} \sim 10^3 m_{3/2}, \quad m_X \sim m_z \simeq 2m_{3/2}$$

$$M_{1/2} \sim F^{f,z} + m_{AMSB} \sim 10^{-2}m_{3/2}, \quad m_0 \sim A_0 \sim F^X \sim m_{3/2}$$

Axions

Non-sequestered

LSP = Wino.

3. Almost SUSY moduli stabilization: Generic result

Main points of recent models: $V_{\mathrm{SUGRA}} = V_F$

- No-scale moduli Kähler potential at the tree level (common property);

Calabi-Yau, torus,

For instance, Grimm et al.

(would-be) T-dual of Calabi-Yau or torus with flux.

$$\mathcal{K}_{\hat{i}}\mathcal{K}^{\hat{i}\bar{\hat{j}}}\mathcal{K}_{\bar{\hat{j}}} = -(\phi^{\hat{i}} + \bar{\phi}^{\bar{\hat{i}}})\mathcal{K}_{\hat{i}} = \mathrm{const.}$$

$$\phi^{\hat{i}} = (u^{\alpha}, \Phi^{i})$$

{Φ}: heavy moduli, {u}: saxion-axion multiplets

- Almost relevant moduli are stabilized near the supersymmetric location via instantons or gaugino condensations (GCs) in the Minkowski vacuum.

E.g. KKLT proposal.

W = W(Φ)

$$(\partial_\Phi \mathcal{K})W + \partial_\Phi \mathcal{W} \sim 0, \qquad \partial_u \mathcal{K} \sim 0.$$

$$\rightarrow \quad m_{\Phi^i} \gg m_{3/2}. \qquad \frac{\partial_i \partial_j \mathcal{W}}{W} \equiv \mathcal{K}_{i\bar{j}} \frac{m_{\Phi^i}}{m_{3/2}}.$$

$$F^X \simeq -\sqrt{3} m_{3/2}.$$

{X}: SUSY breaking and uplifting to the de Sitter/Minkowski vacuum.

One finds … (up to $\frac{m_{3/2}}{m_\Phi}$ factors)

Choi, Jeong

- SUSY breaking F-term vevs (up to 1/2Re[Φ]):

$$F^{\Phi^i} \sim -K_{\alpha\bar{\beta}}(K_{\bar{\beta}i})^{-1}F^{\alpha} \sim 3m_{3/2}\frac{m_{3/2}}{m_{\Phi^i}}.$$

$F^u \sim \text{max.}[F^{\Phi^i}]$; If moduli masses are degenerate, universal F-terms are obtained.

- Vev shifts from SUSY solution:

$$\delta\Phi^i \sim \delta u^{\alpha} \sim \left(\frac{m_{3/2}}{m_{\Phi^i}}\right)^2 \ll 1.$$

- Saxion masses (degenerate): “<V>=0” is important.

$$m_{\rm sax} \simeq 2m_{3/2} \quad \text{or} \quad \simeq \sqrt{2}m_{3/2}.$$

For $V_{\rm lift} \propto$ Exp[K] or $V_{\rm lift} \propto$ Exp[2K/3].

No decay into gravitino pair from these saxions.

- Axino masses (degenerate):

$$m_{\tilde{a}} \simeq m_{3/2}.$$

SUSY breaking axion multiplet: $\mathcal{R}$

Let us consider a simple case of small mixing

$$K = \hat{K}(\bar{X}, X) + \tilde{K}(\mathcal{R} + \bar{\mathcal{R}}) + \mathcal{K}(\Phi + \bar{\Phi}; u + \bar{u}), \quad W = \hat{W}(X) + \mathcal{W}(\Phi).$$

We will parameterize the metric as

$$\tilde{K}_{\mathcal{R}\bar{\mathcal{R}}} \equiv n \frac{[1 + \Delta(\mathcal{R} + \overline{\mathcal{R}})]}{(\mathcal{R} + \overline{\mathcal{R}})^2}.$$

$$\Delta \lesssim O(1)$$

g_s, α'-correction or choice of linear comb. etc.

One finds in the Minkowski vacuum…

- SUSY breaking F-term vevs except for {Φ,u}:

$$F^X \simeq -\sqrt{(3-n)+O(\Delta)}m_{3/2}, \quad \frac{F^{\mathcal{R}}}{\mathcal{R}+\overline{\mathcal{R}}} \simeq m_{3/2}$$

- Saxion (r) mass:

$$m_r^2 \sim \Delta m_{3/2}^2.$$

- Axino mass for n≠3 (for n=3 goldstino):

$$(m_{\tilde{a}})_{\mathcal{R}\mathcal{R}} \simeq m_{3/2}\left[-1+\frac{n}{3}+O(\Delta)\right].$$

4. SUSY breaking field and Moduli

GC/instanton for particle physics other than moduli stabilization:

$$W_{\mathrm{inst./GC}} = \mathcal{O} e^{-\Phi} \quad \text{or} \quad e^{-\Phi + \log(\mathcal{O})}.$$

- SUSY breaking model, e.g. Polonyi — Aharony et al; Camara et al; Acharya et al; Abe, TH, Kobayashi; Choi et al....
- Gauge theory-like ones, i.e. ADS superpotential. — Akerbolm et al....
- Majorana neutrino masses — Blumenhagen et al; Ibanez et al...
- Yukawa couplings — Blumenhagen et al; Marchesano et al...

(backreaction from moduli stabilization, C.f. brane inflation.)

- μ-term (Higgsino mass) — Casas el al; Choi et al.; Ibanez et al...

In string theories, SUSY breaking parameter also should be moduli, e.g. it should be promoted as

$$\hat{W}(X) = \mu^2 X \ \rightarrow \ \hat{W}(X,\Phi) = e^{-a_i^X \Phi^i_X} X.$$

Therefore we should consider a model like

$$W = \hat{W}(X,\Phi) + \sum_k A_k e^{-\sum_i a_i^{(k)} \Phi^i_X}.$$

If $a_i^X \sim a_i$, one would find in the minimum

(a_i is the most effective (smallest) one to the mass in $a_i^{(k)}$.)

$$F^{\Phi^i_X} \sim a_i^X m_{3/2} \frac{m_{3/2}}{m_{\Phi^i_X}}.$$

Abe, TH, Kobayashi;
Acharya, Bobokov, Kane, Kumar, Shao.

$F^u \sim$ max.$[F^{\Phi^X}, F^{\Phi^i}]$ via mixing.

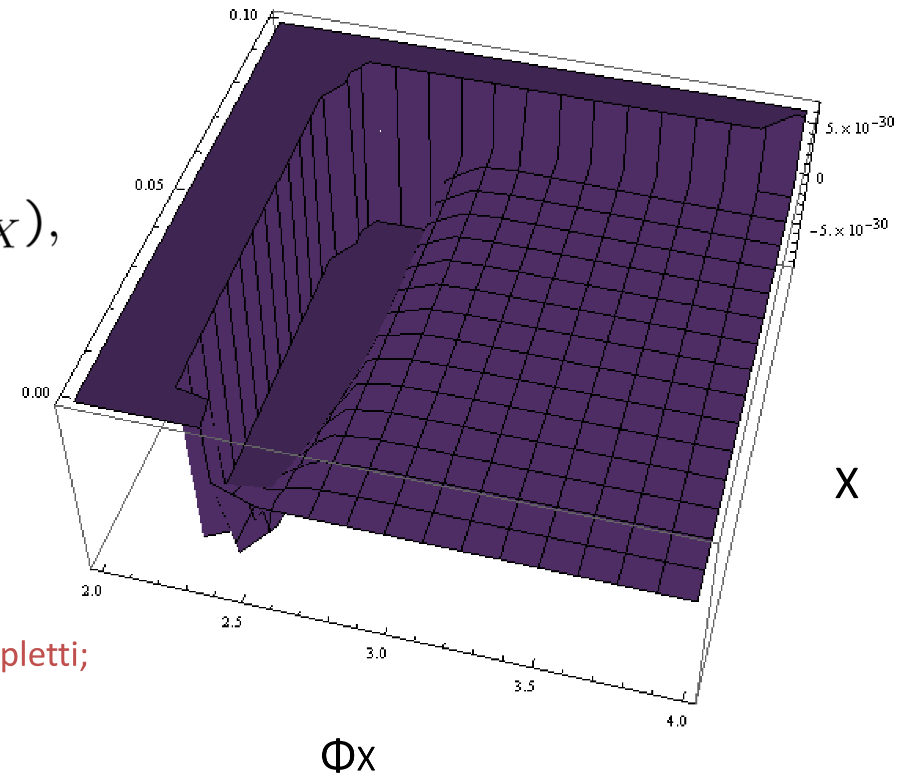
Assuming Φx has a KKLT-type mass, one obtains

$$F^{\Phi_X} \sim m_{3/2} \gg F^{\mathrm{KKLT}} \quad ?$$

This will mean KKLT stabilization of Φx in the SUSY breaking Minkowski vacuum is unstable.
The vacuum runs away to AdS vacuum consequently.

$$K = \bar{X}X - \frac{(\bar{X}X)^2}{\Lambda^2} - 3\log(\Phi_X + \bar{\Phi}_X),$$

$$W = e^{-a\Phi_X}X + W_0.$$



Dudas, Mambrini, Pokorski, Romagnoni (Two papers)+ Trapletti;
Krippendorf, Quevedo

Hence moduli ΦX should be stabilized to be

$$m_{\Phi_X} \gg (a\Phi_X) m_{3/2}.$$

•Possibilities in string theories:

- Racetrack: $m_{\Phi_X} \geq (a\Phi_X)^2 m_{3/2}$

- (non-geometric) closed string flux:

$$m_{\Phi_X} \leq M_{GUT} \quad \text{if } M_{GUT} \leq M_{string}.$$

- D-term: $m_{\Phi_X} \sim M_{string}$ via $\partial_{\Phi_X} K \sim 0.$

mΦX from Kähler potential

$$F^{\Phi_X} \sim \delta_{GS} m_{3/2} \sim 10^{-2} m_{3/2}.$$

Heckman , Vafa;
Choi, Jeong, Okumura, Yamaguchi

- Kähler potential coupling to X?: $m_{\Phi_X} \gg m_{KKLT}$ TH, Kitano

6. Non-QCD axion mass

Consider a deformation of W by δW breaking PQ

$$W = \mathcal{W}(\Phi^i) + \delta W(\Phi^i, u) \ , \quad \langle \mathcal{W} \rangle \gg \langle \delta W \rangle$$

Then light axion mass will be given by

$$(m_a^2)_{\alpha\alpha} \simeq 3\frac{e^K |W|^2}{K_{\alpha\bar{\alpha}}} \mathrm{Re}\left(\frac{\delta W_{\alpha\alpha}}{W}\right) \simeq 3\frac{b_\alpha^2}{f_\alpha^2} m_{3/2}^2 \left(\frac{m_{3/2}}{M_{\mathrm{Pl}}}\right)^{r_\alpha - 1}$$

Acharya, Bobokov, Kumar

$$b_\alpha = \frac{8\pi^2}{M_\alpha}, \quad f_\alpha = O\left(\frac{M_{\mathrm{string}}}{M_{\mathrm{Pl}}}\right), \quad \frac{b^2}{f^2} \gtrsim 10^4.$$

$$\delta W_{\alpha\alpha} \equiv b_\alpha^2 (\delta W)_\alpha, \quad (\delta W)_\alpha \equiv W \left(\frac{m_{3/2}}{M_{\mathrm{Pl}}}\right)^{r_\alpha - 1}, \quad K_{\alpha\alpha} \equiv f_\alpha^2.$$

Only u^α dependence besides {Φ}

Kähler potential correction:

$$m_a^2 \sim 3\frac{e^K |W|^2}{f^2}\left[-\delta K_{\alpha\bar{\beta}} + \mathrm{Re}(\delta K_{\alpha\beta})\right].$$

Example:
SU(N+M) × SU(M) gaugino condensations

$$W = W_0 + e^{-a\Phi} + e^{-b(u+\Phi)}, \quad a = \frac{8\pi^2}{N+M}, \quad b = \frac{8\pi^2}{M}, \quad N \gg M,$$

$$m_a^2 \sim 3\frac{b^2}{f^2} m_{3/2}^2 \left(\frac{m_{3/2}}{M_{\rm Pl}}\right)^{\frac{N}{M}}. \quad r_\alpha - 1 = \frac{N}{M}.$$

r_α	3	5	7	9
m_a for $m_{3/2} = 1$ TeV	10^{-4} eV	10^{-19} eV	10^{-34} eV	10^{-50} eV
m_a for $m_{3/2} = 10$ TeV	10^{-2} eV	10^{-16} eV	10^{-30} eV	10^{-45} eV
m_a for $m_{3/2} = 100$ TeV	1 eV	10^{-13} eV	10^{-26} eV	10^{-40} eV

Table 1: Axion masses up to b_α^2/f_α^2.

String theoretic R-axion mass would be on the order of 1MeV – 1GeV: $\delta W \sim \mathcal{W}^2$ (r=2)

A lot of axions with mass range

$$m_a \gtrsim H_0 \sim 10^{-33}\ \mathrm{eV}$$

will affect observations of CMB fluc. by e.g. their isocurvature fluctuation generated during inflation.

→ Constraint on Moduli stabilization models?

The axiverse would be falsified by the observation of tensor mode connected with inflation via the PLANCK;

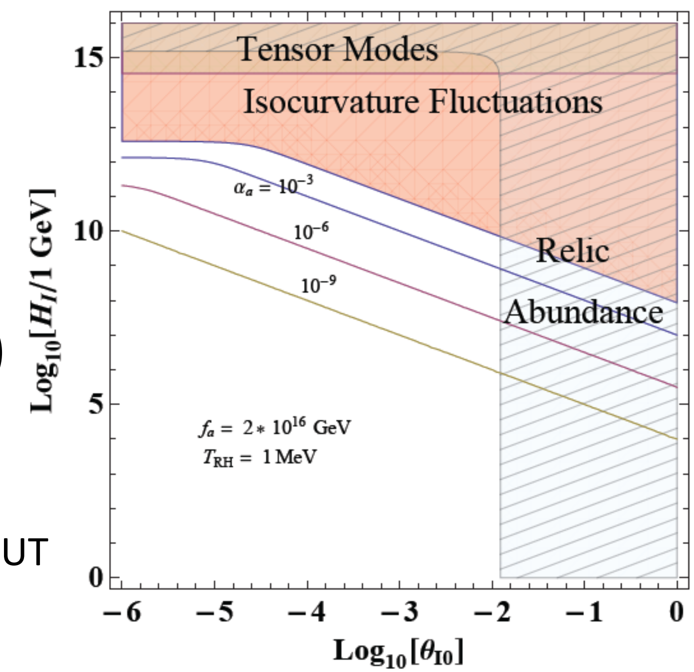
$H_{\rm inf} \lesssim 3 \times 10^{12}$ GeV by the isocurvature constraint in the axiverse. (overshooting?)

$N_{\rm axion}$ = O(10) for a right picture.

Acharya, Bobokov, Kumar

$N_{\rm axion}$ = 1: string theoretic QCD axion with f≧ $M_{\rm GUT}$

$H_{\rm inf} \lesssim 10^{13}$ GeV. Fox, Pierce, Thomas



Conclusion

- Moduli are always present in string vacua and responsible for physical parameters.
- In special, supersymmetric moduli stabilization via gaugino condensatons in flux vacua is viable and interesting for particle physics models because of the SUSY breaking effect.
- Mass of moduli coupling to the SUSY breaking sector should be heavier than mass from KKLT stabilization.
- String axiverse will be possible in the string vacua.
- Controllable stabilization = choosing a fine (local) geometry?

3. Other variant models based on supersymmetric stabilization

■ KKLT model + axion

Conlon; Choi, Jeong

$$K = -\frac{3}{2}\log(T_1 + \bar{T}_1) - \frac{3}{2}\log(T_2 + \bar{T}_2), \quad W = W_0 + Ae^{-a(T_1+T_2)}.$$

T_1-T_2 is absent from W; the direction becomes light axion.

KKLT model + axion

Conlon; Choi, Jeong

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T_1-T_2 is absent from W; the direction becomes light axion.

This model can be rewritten as

$$K = -\frac{3}{2}\log(\mathrm{Re}(\Phi + u)) - \frac{3}{2}\log(\mathrm{Re}(\Phi - u)), \quad W = W_0 + Ae^{-a\Phi}.$$

$$\Phi = T_1 + T_2, \quad u = T_1 - T_2.$$

KKLT model + axion

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$$K = -\frac{3}{2}\log(\mathrm{Re}(\Phi + u)) - \frac{3}{2}\log(\mathrm{Re}(\Phi - u)), \quad W = W_0 + Ae^{-a\Phi}.$$

$$\Phi = T_1 + T_2, \quad u = T_1 - T_2.$$

$$D_\Phi W, \ \partial_u K \sim 0 \ \rightarrow \ \Phi \sim \text{KKLT sol.}, \ u \sim 0.$$

$$m_\Phi \sim \text{KKLT}, \quad m_u \simeq 2m_{3/2}, \ F^\Phi \sim \frac{K^{\Phi\bar{\Phi}}}{K^{\Phi\bar{u}}} F^u \sim m_{3/2}\frac{m_{3/2}}{m_\Phi}.$$

Sequestered anti D3-brane: $V_{\text{lift}} = e^{2K/3}\epsilon \ \rightarrow \ m_u \simeq \sqrt{2}m_{3/2}$.

■ Minimal LARGE volume scenario (LVS)

Balasubramanian, Berglund, Conlon, Quevedo ;
Conlon, Quevedo, Suruliz

$$K = -2\log(\mathcal{V} + \hat{\xi}), \quad \mathcal{V} = (T + \bar{T})^{3/2} - (\Phi + \bar{\Phi})^{3/2}$$

$$W = W_0 + Ae^{-a\Phi}, \qquad W_0 = O(1).$$

$$V \simeq \frac{2\sqrt{2}\sqrt{\phi}a^2A^2e^{-2a\phi}}{3\mathcal{V}} - \frac{4\phi a A e^{-a\phi}W_0}{\mathcal{V}^2} + \frac{3W_0^2\hat{\xi}}{2\mathcal{V}^3}$$

$$\mathrm{Re}(T) = \tau, \quad \mathrm{Re}(\Phi) = \phi.$$

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$$\mathrm{Re}(T) = \tau, \quad \mathrm{Re}(\Phi) = \phi.$$

$$\mathcal{V} \sim \tau^{3/2} \sim e^{a\phi} \sim 10^{13}, \quad \phi \sim \hat{\xi}^{2/3} = O(1),$$

$$m_{3/2} \sim \mathcal{V}^{-1} \ll 1, \quad m_T \sim m_{3/2}(\frac{m_{3/2}}{M_{Pl}})^{1/2}, \quad m_\Phi \sim a\phi m_{3/2},$$

$$F^T \sim m_{3/2}, \quad F^\Phi \sim m_{3/2}\frac{m_{3/2}}{m_\Phi} \sim m_{soft}$$

LSP = bino

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Balasubramanian, Berglund, Conlon, Quevedo ; Conlon, Quevedo, Suruliz

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$$\mathrm{Re}(T) = \tau, \quad \mathrm{Re}(\Phi) = \phi.$$

$M_{string} \sim 10^{11}$ GeV

$$\mathcal{V} \sim \tau^{3/2} \sim e^{a\phi} \sim 10^{13}, \quad \phi \sim \hat{\xi}^{2/3} = O(1),$$

$$m_{3/2} \sim \mathcal{V}^{-1} \ll 1, \quad m_\tau \sim m_{3/2}\left(\frac{m_{3/2}}{M_{\mathrm{Pl}}}\right)^{1/2}, \quad m_\Phi \sim a\phi m_{3/2},$$

$$F^T \sim m_{3/2}, \quad F^\Phi \sim m_{3/2}\frac{m_{3/2}}{m_\Phi} \sim m_{soft}$$

O(10) TeV

LSP = bino

■ Racetrack model

Krasnikov; Dixon; Taylor; Carlos, Casas, Munoz; Kallosh, Linde; Denef, Douglas, Florea.

$$K = -3\log(T+\bar{T}), \quad W = W_0 + Ae^{-aT} + Be^{-bT}.$$

$$D_T W \sim 0 \rightarrow \langle\sigma\rangle \sim \frac{1}{a-b}\log\left(\frac{aA}{bB}\right).$$

$$m_T \sim ab\sigma^2 m_{3/2} \gg m_T^{\mathrm{KKLT}}, \quad F^T \sim m_{3/2}\frac{m_{3/2}}{m_T}, \quad m_{3/2} \sim W_0 \ll 1.$$

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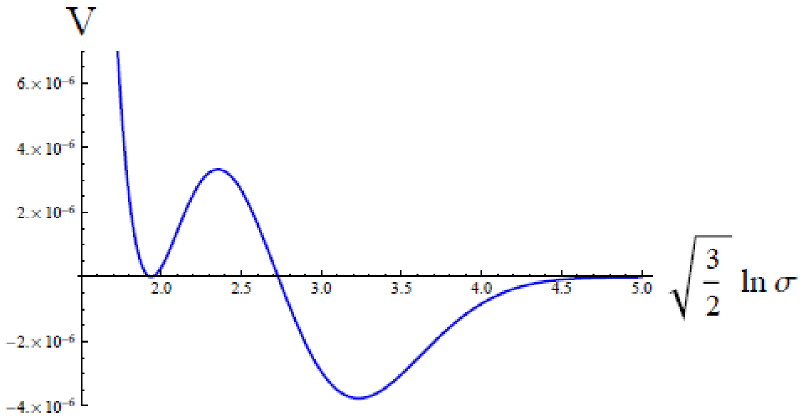
$$m_T \sim ab\sigma^2 m_{3/2} \gg m_T^{\rm KKLT}, \quad F^T \sim m_{3/2}\frac{m_{3/2}}{m_T}, \quad m_{3/2} \sim W_0 \ll 1.$$

With a fine-tuning of W_0, we get further larger modulus mass .



AMSB is dominant:

$$m_{soft} \sim m_{AMSB} \sim \frac{m_{3/2}}{4\pi^2}$$

■ G2 MSSM (M-theory on G2 space without flux)

$$K = -3\log V_{G_2} + \bar{X}X, \quad W = Ae^{-af}X^{-c} + Be^{-bf},$$

$$f = \sum_i z_i N^i, \quad N^i: \text{integer},$$

$$V_{G_2} = \prod_i Re(z_i)^{d_i}, \quad \frac{7}{3} = \sum_i d_i.$$

ADS superpotential
with one meson X

■ G2 MSSM (M-theory on G2 space without flux)

$$K = -3\log V_{G_2} + \bar{X}X, \quad W = Ae^{-af}X^{-c} + Be^{-bf},$$

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$$V_{G_2} = \prod_i Re(z_i)^{d_i}, \quad \frac{7}{3} = \sum_i d_i.$$

ADS superpotential with one meson X

$$D_f W \sim 0 : \text{racetrack sol.}, \quad K_z \sim 0, \quad X < O(1),$$

$$m_f = m_{r.t.} \sim 10^3 m_{3/2}, \quad m_X \sim m_z \simeq 2m_{3/2}$$

$$M_{1/2} \sim F^{f,z} + m_{AMSB} \sim 10^{-2} m_{3/2}, \quad m_0 \sim A_0 \sim F^X \sim m_{3/2}$$

Axions

Non-sequestered

LSP = Wino.

Conclusion

- We formulated no-scale and almost supersymmetric moduli stabilization in the non-SUSY Minkowski vacuum:

$$F^{\Phi^i} \sim -K_{\alpha\bar{\beta}}(K_{\bar{\beta}i})^{-1}F^{\alpha} \sim 3m_{3/2}\frac{m_{3/2}}{m_{\Phi^i}} \quad \text{for} \quad m_{\Phi^i} \gg m_{3/2}.$$

$$F^u \sim \text{max.}[F^{\Phi^i}]$$

$$m_{\text{sax}} \simeq 2m_{3/2} \quad \text{or} \quad \simeq \sqrt{2}m_{3/2}, \quad m_{\tilde{a}} \simeq m_{3/2}.$$

$$m_r^2 \sim \Delta m_{3/2}^2 \lesssim m_{3/2}^2, \quad m_{\tilde{a}_{\mathcal{R}}} \leq m_{3/2}, \quad \frac{F^{\mathcal{R}}}{\mathcal{R}+\bar{\mathcal{R}}} \simeq m_{3/2}.$$

Explicit models were not used!

•Moduli {ΦX} which are coupled to the SUSY breaking sector should be heavier than KKLT-type mass.

$$m_{\Phi_X} \gg m_{\mathrm{KKLT}} = (a\Phi_X) m_{3/2}.$$

They should be stabilized via racetrack, flux, D-term etc.

$$F^{\Phi^i_X} \sim a_i^X m_{3/2} \frac{m_{3/2}}{m_{\Phi^i_X}} \quad \text{or} \quad \sim 10^{-2} m_{3/2} \quad \text{for} \quad m_{\Phi X} \gg m_{\mathrm{KKLT}}.$$

$$F^u \sim \text{max.}[F^{\Phi X}, F^{\Phi^i}]$$

D-term stabilization

•String theoretic axion masses have been given.

Open questions and future directions: Model building

- Model dependent issues: is LVS OK? (flux-stabilized moduli?, a lot of axions in LVS?)

$$\frac{F^S}{S+\bar{S}} \sim \mathcal{V}^{-2}$$

- D-term potential: moduli have PQ U(1) shift charges.

  Is a concrete example necessary? (X also can be charged)
- Coupling to the (local model) visible sector:

  Choi, Jeong; Acharya, Bobokov, Kane, Kumar, Shao + Watson.

  String theoretic QCD axion in {u}? (δW=0 or lightest axion)

  Advantages for dilution of harmful particles by {u}?

$$\mathcal{L}_{\mathsf{SSM}} = \int d^2\theta f(\Phi, u) W^\alpha W_\alpha \qquad m_a^{\mathsf{QCD}} \sim \frac{\Lambda^2_{\mathsf{QCD}}}{f_a}.$$

- Axiverse phenomenology? Etc.

Remark 1:
There would be cosmological problems.

- CMP: moduli-dominated universe

  (or axion dominated universe) -> BBN?, Ω_{matter}?...

- Gravitino overproduction from moduli

  gravitino decay -> BBN?, Ω_{matter} ?...

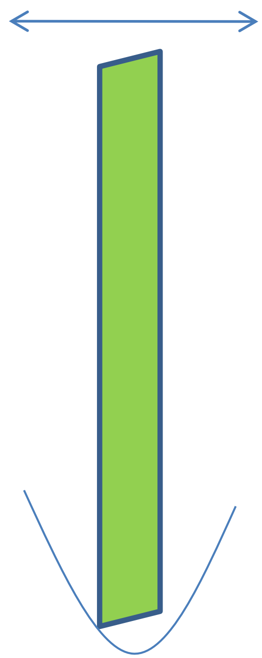
- Overshooting or destabilization

  by initial condition, inflaton potential or temperature.

Solutions: late time entropy production (n_B/s?),
very heavy moduli, change DM, high H, low H_{inf} ($< m_{3/2}$),
low temperature, no SUSY...

Remark 2: Open string moduli

D-brane's position and Wilson line modes (adj. rep.) often prevent GC, instanton or realistic models (= no strong coupling); they will get heavy via the feature of the rigid cycle in $\mathcal{M}_6$.



E.g. Consider type IIB CY orientifold.
For D7-brane wrapping on the 4-cycle (ample divisor),

$$h^{0,1}(\Sigma_4) = h^{0,2}(\Sigma_4) = 0.$$

$h^{0,2} \neq 0$ would be OK.

No D3-brane or (fractional) D3-branes on the dP singularity, e.g. $\mathbb{C}^3/\mathbb{Z}_3$. (If not, D3 position enters in G.C.)

Other constraints for small H_{inf} ?

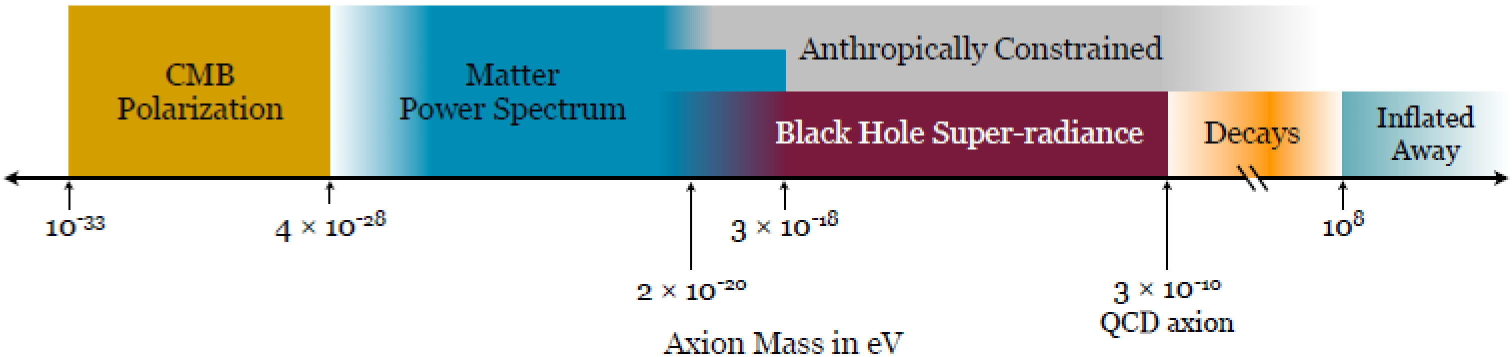


Figure 1: **Map of the Axiverse:** The signatures of axions as a function of their mass, assuming $f_a \approx M_{GUT}$ and $H_{inf} \sim 10^8$ eV. We also show the regions for which the axion initial angles are anthropically constrained not to over-close the Universe, and axions diluted away by inflation. For the same value of f_a we give the QCD axion mass. The beginning of the anthropic mass region (2×10^{-20} eV) as well as that of the region probed by density perturbations (4×10^{-28} eV) are blurred as they depend on the details of the axion cosmological evolution (see Section 2.3). 3×10^{-18} eV is the ultimate reach of density perturbation measurements with 21 cm line observations. The lower reach from black hole super-radiance is also blurred as it depends on the details of the axion instability evolution (see Section 2.5). The region marked as "Decays", outlines very roughly the mass range within which we expect bounds or signatures from axions decaying to photons, if they couple to $\vec{E} \cdot \vec{B}$. We will discuss axion decays in detail in a companion paper.

Please check it since I will study them.

CMB rotation by light axion: $\Delta\beta\, \vec{E} \cdot \vec{B}$

$$\Delta\beta = \sqrt{N} 10^{-3} < 3.5 \times 10^{-2}\ .$$

By PLANCK: $\Delta\beta > 10^{-3}$ (expectation)

By CMBPol (Boomerang experiment): $\Delta\beta > 10^{-5}$ (expectation)

And so on from power spectrum and B.H.

■ Recent moduli stabilizations

By flux compactifications and KKLT proposal with GCs/instantons, techniques have been developed.

Kachru, Kallosh, Linde, Trivedi

- all moduli can be fixed definitely.
- de Sitter or Minkowski vacua with SUSY breaking are obtained in string vacua.

They are technically under control.

→ semi-realistic models can be gained!
→ explicit computations are motivated!

■ Soft mass at TeV scale

Choi, Jeong, Okumura

$M_{U(1)} : M_{SU(2)} : M_{SU(3)}$ = (1 + 0.66α) : (2 + 0.2α) : (6 − 1.8α)

For 1st and 2nd generation with $^\forall n_i = 0$,

$$m^2_{\tilde{Q}} : m^2_{\tilde{D}} : m^2_{\tilde{L}} : m^2_{\tilde{E}} = (6.0 - 3.6\alpha + 0.51\alpha^2) : (5.5 - 3.3\alpha + 0.52\alpha^2) : (1.49 - 0.23\alpha - 0.015\alpha^2) : (1.15 - 0.046\alpha - 0.016\alpha^2)$$

$m_{\rm soft}$ unifies at $\mu_{\rm mirage} = M_{GUT}\left(\frac{m_{3/2}}{M_{\rm Pl}}\right)^{\alpha/2}$, $\alpha = \frac{m_{3/2}}{4\pi^2 M_{1/2}(T)}$.

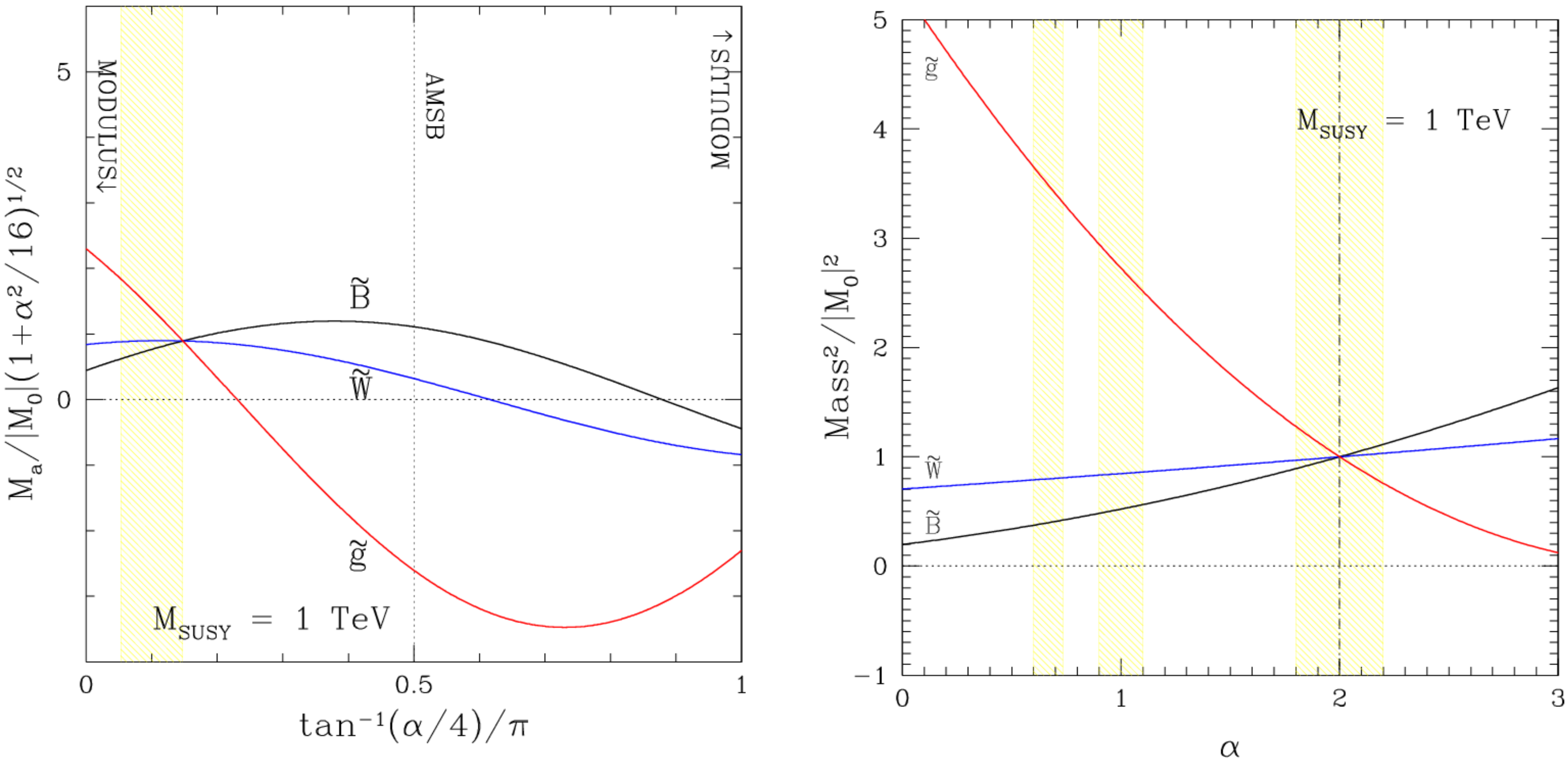
α depends on also the vev of heavy string dilaton S and world volume flux on the visible/hidden sector brane; $\frac{\langle S\rangle}{\langle T\rangle}\int \mathcal{F}^2$.

Abe, TH, Kobayashi

- Gaugino masses at TeV scale for given α: $\alpha = \frac{m_{3/2}}{4\pi^2 M_{1/2}(T)}$

m_{soft} unifies at $\mu_m = M_{GUT}(\frac{m_{3/2}}{M_{Pl}})^{\alpha/2}$.

Choi, Jeong, Okumura

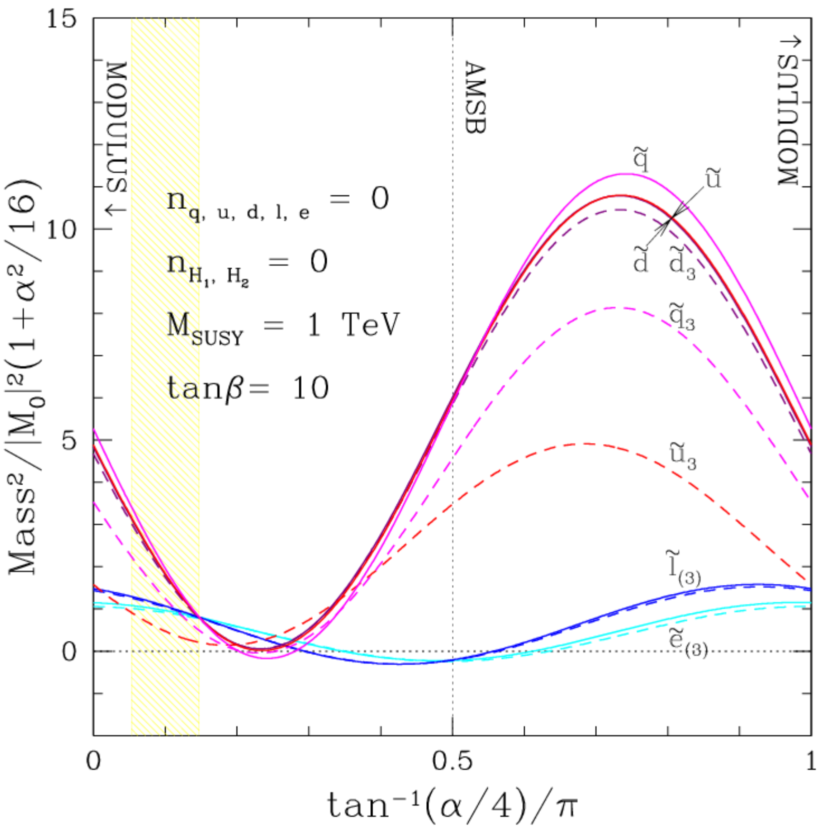


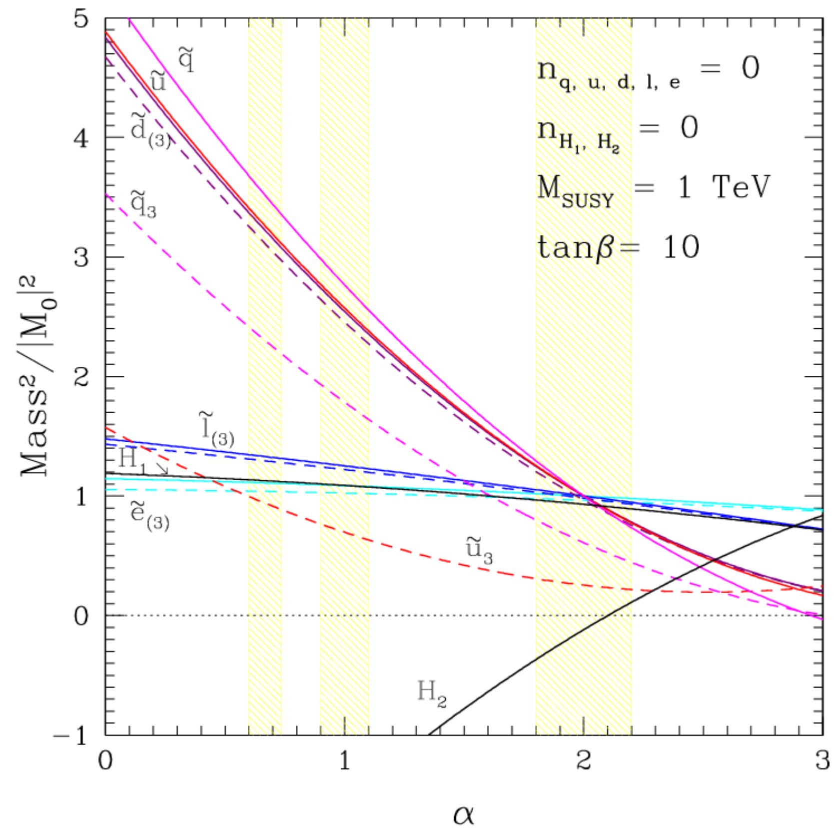
$M_{U(1)} : M_{SU(2)} : M_{SU(3)}$ = (1 + 0.66α) : (2 + 0.2α) : (6 − 1.8α)

α depends on also the vev of heavy string dilaton S and world volume flux; $\frac{<S>}{<T>} \int F^2$.

Abe, TH, Kobayashi

- Sfermion masses at TeV scale for given α:





For 1st and 2nd generation with $\forall n_i = 0$,

$$m_{\tilde{Q}}^2 : m_{\tilde{D}}^2 : m_{\tilde{L}}^2 : m_{\tilde{E}}^2 = (6.0 - 3.6\alpha + 0.51\alpha^2) : (5.5 - 3.3\alpha + 0.52\alpha^2) : (1.49 - 0.23\alpha - 0.015\alpha^2) : (1.15 - 0.046\alpha - 0.016\alpha^2)$$

Let {Φ} be heavy moduli, {u} saxion-axion multiplets, and {X} SUSY breaking, uplifting to Minkowski vacuum.

$$K = \hat{K}(X, \overline{X}) + \mathcal{K}(\Phi + \overline{\Phi}, u + \overline{u}), \quad W = \hat{W}(X) + \mathcal{W}(\Phi).$$

No "u".

Assumption of the potential: Let $\phi^{\hat{i}} = (u^{\alpha}, \Phi^{i})$.

- No scale: $\mathcal{K}_{\hat{i}}\mathcal{K}^{\hat{i}\bar{\hat{j}}}\mathcal{K}_{\bar{\hat{j}}} = -(\phi^{\hat{i}} + \bar{\phi}^{\bar{\hat{i}}})\mathcal{K}_{\hat{i}} = \text{const.}$
- Non-pert. W: $\mathcal{W} = W_0 + \sum_i A_i \exp(-\sum_k a_i^{(k)} \Phi^k).$
- E.g., X is Polonyi: $\hat{K} = \bar{X}X - \frac{(\bar{X}X)^2}{\Lambda^2}, \quad \hat{W} = \mu^2 X.$ Polonyi

Combination against moduli stabilizaion: Endo, Hamaguchi, Takahashi; Lebedev, Nilles, Ratz; Dine, Kitano, Morisse, Shirman; Dudas, Papineau, Pokorski; Abe, TH, Kobayashi, Omura; Kallosh, Linde

Assumption: {Φ, u} are stabilized supersymmetrically,
{X} are the main source of SUSY breaking

Endo, Hamaguchi, Takahashi

- $(\partial_\Phi \mathcal{K})W + \partial_\Phi \mathcal{W} \sim 0, \qquad \partial_u \mathcal{K} \sim 0.$

$\rightarrow \quad m_{\Phi^i} \gg m_{3/2}. \qquad \frac{\partial_i \partial_j \mathcal{W}}{W} \equiv \mathcal{K}_{i\bar{j}} \frac{m_{\Phi^i}}{m_{3/2}}.$

Then $\partial G \cdot \overline{\partial G}|_X \simeq 3 \quad \gg \quad \partial G \cdot \overline{\partial G}|_{\Phi,u}.$

This means

$F^X \simeq -\sqrt{3} m_{3/2}.$ E.g., $V_{\rm lift} = e^{\mathcal{K}} \mu^4 \simeq 3 e^{\mathcal{K}} |\langle \mathcal{W} \rangle|^2.$

The stationary condition for X: $\nabla_X G_X \simeq -1.$

$G_{X\bar{X}} = 1$