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Phenomenology of KKLT flux compactification

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Outline:

1. KKLT compactification scheme
2. Soft terms
3. Phenomenology

based on:
Kachru, Kallosh, Linde, Trivedi (2003)
Choi, ~~ⒶⒶ~~, Nilles, Olechowski (2005)
~~ⒶⒶ~~, Lebedev, Mambrini (2005)

Type IIB String Theory

Starting point: type IIB string compactified on Calabi-Yau three-fold ($h_{1,1} = 1$).

Moduli

- Dilaton S (related to string coupling)
- T (related to volume of CY)
- $h_{2,1}$ complex structure moduli Z_i (related to shape of CY)

Low energy supergravity description:

$$K = -\log(S + \overline{S}) - 3\log(T + \overline{T}) - \log i \int \Omega \wedge \Omega^\dagger$$

$\Omega(Z_i) \rightarrow$ the holomorphic $(3,0)$-form of CY. All moduli flat directions so far

KKLT stabilization prescription:

1. Stabilize dilaton and complex structure moduli by fluxes
2. Stabilize T by gaugino condensation on D7 branes
3. Adjust correct vacuum energy by introducing anti-D3 branes

KKLT Compactification (1)

Step 1: Flux stabilization Giddings, Kachru, Polchinski (2001)

- Superpotential due to fluxes of NS and RR forms over 3-cycles:

$$W = A(Z_i) + SB(Z_i)$$

- CSM and dilaton stabilized at string scale. Below string scale:

$$K_{eff} = -3\log(T + \overline{T}) \qquad W_{eff} = w_0$$

- By fine-tuning fluxes w_0 can be made small $\sim 10^{-13}$

KKLT COMPACTIFICATION (2)

Step 2: Nonperturbative stabilization of T

- Gaugino condensation on D7 branes (where $f = T$) modifies superpotential

$$W_{eff} \to w_0 - Ce^{-aT}$$

- T is stabilized close to SUSY scale with vev

$$a \, \mathrm{Re}\, T \sim \log \frac{M_{Pl}}{m_{3/2}} \sim 25$$

- This is a supersymmetric AdS$_4$ minimum: $F_T = 0$, $V_0 \approx -3M_p^2 m_{3/2}^2$.

Alternative: large volume compactification Balasubramanian, Berglund, Conlon, Quevedo (2005)

KKLT COMPACTIFICATION (3)

Step 3: Adjusting vacuum energy with $\bar{D}3$

- Anti-D3 branes placed in highly warped region of CY (Klebanov-Strassler throat)
- Additional non-susy contribution to scalar potential

  $$\Delta V = \frac{D}{(T+\overline{T})^n}$$

  with $n = 2$ for anti-D3 branes
- Main effect: vacuum energy can be fine-tuned to zero (or tiny positive) value for $D \sim M_{Pl}^2 m_{3/2}^2$
- Side effect: vev of T slightly shifted so that F_T no longer vanishes

  $$\frac{F_T}{T+\overline{T}} \approx \frac{1}{a\,\mathrm{Re}\,T} m_{3/2}$$

Summary of KKLT compactification

- All moduli are stabilized
- Dilaton and CSM do not play role at low energies
- Low scale SUSY breaking ($m_{3/2} \ll M_{Pl}$) achieved by fine-tuning fluxes
- Vanishing cosmological constant achieved by fine-tuning anti-D3 brane tension

Phenomenology affected by appearance of moderataly large parameter

$$a\,\mathrm{Re}\,T \sim \log \frac{M_{Pl}}{m_{3/2}} \sim 25$$

- T modulus mass enhanced wrt gravitino mass

$$m_T \sim 2(a\,\mathrm{Re}\,T)m_{3/2}$$

- T modulus F-term suppressed wrt gravitino mass

$$\frac{F_T}{T+\overline{T}} \approx \frac{1}{a\,\mathrm{Re}\,T} m_{3/2}$$

Moduli and gravitino problems absent in KKLT scenario!

Supersymmetry breaking

Three potential sources of supersymmetry breaking mediation to visible sector

1. Explicit supersymmetry breaking by anti-D3 branes
   in Choi, , Nilles, Olechowski (2005) argued to be suppressed by warping
2. Moduli mediation by T multiplet that develops non-zero F_T
   operating when MSSM matter lives on D7 branes
3. Mediation by super-Weyl anomaly
   important in models with $m_{3/2} \gg F$

Soft terms with mixed modulus-anomaly mediation

Supergravity action for matter fields:

$$\mathcal{L} = \int d^4\theta \, \Phi^\dagger \Phi Y_i(T_n, T_n^\dagger) Q_i^\dagger Q_i + \left\{ \int d^2\theta \left(\tfrac{1}{4} f_a(T_n) W^{a\alpha} W_\alpha^a + \Phi^3 \lambda_{ijk}(T_n) Q_i Q_j Q_k \right) + \text{h.c.} \right\}$$

Gaugino masses:

$$M_a = \frac{1}{f_a + \overline{f}_a} \frac{\partial f_a}{\partial T_n} F_{T_n} + \frac{1}{16\pi^2} b_a g_a^2 F_\Phi$$

Scalar masses:

$$m_i^2 = -\frac{\partial^2 \log Y_i}{\partial T_n \partial T_m^\dagger} F_{T_n} F_{T_m}^\dagger - \dot{\gamma}_i \frac{1}{(16\pi^2)^2} |F_\Phi|^2 + \left(\frac{\partial \gamma_i}{\partial T_n^\dagger} \frac{1}{16\pi^2} F_\Phi F_{T_n}^\dagger + \text{h.c.} \right)$$

Soft trilinear terms

$$A_{ijk} = -\frac{\partial}{\partial T_n} \log\left(\frac{\lambda_{ijk}}{Y_i Y_j Y_k} \right) F_{T_n} - (\gamma_i + \gamma_j + \gamma_k) \frac{1}{16\pi^2} F_\Phi$$

where $F_\Phi = m_{3/2} + \frac{\partial K}{\partial T_n} F_{T_n}$

KKLT D7 MODEL (1)

MSSM matter on D7 brane: $Y_i = (T + \overline{T})^{n_i}$, $f_a = T$ where $n_i = (1, 1/2, 0)$.
For $n_i = 1$:

- Tree-level moduli mediated soft terms are present
- Since $F_T \equiv \tilde{\alpha} M_s \sim F_\Phi / 16\pi^2$ soft spectrum gets comparable contributions from moduli and anomaly mediation

$$M_a = M_s \left[\tilde{\alpha} + b_a g_a^2\right]$$
$$m_i^2 = M_s^2 \left[\tilde{\alpha}^2 - \dot{\gamma}_i + 2\tilde{\alpha}(T + \overline{T})\partial_T \gamma_i\right]$$
$$A_{ijk} = M_s \left[3\tilde{\alpha} - \gamma_i - \gamma_j - \gamma_k\right]$$

- For original KKLT model $\tilde{\alpha} \approx 5 \div 6$
- Absence of tachyons yields lower bound $\tilde{\alpha} > 4$

KKLT D7 MODEL - CONSTRAINTS

Some phenomenological and cosmological consequences studied first by Choi, Jeong, Okumura (2005); Endo, Yamaguchi, Yoshioka (2005)
, Lebedev, Mambrini (2005): Full study of constraints on parameter space

Collider constraints

1. Lightest Higgs boson mass: $m_h > 114\,\mathrm{GeV}$
2. Chargino mass $m_{\chi^+} > 103.5\,\mathrm{GeV}$
3. $2.33 \times 10^{-4} \le BR(b \to s\gamma) \le 4.15 \times 10^{-4}$.
4. $\mathrm{BR}(B_s \to \mu^+\mu^-) < 2.9 \times 10^{-7}$

Theoretical constraints

1. Electroweak breaking: $\mu^2 \approx -m_{H_2}^2 - \frac{1}{2}M_Z^2$
2. Neutralino dark matter: $0.094 < \Omega_{DM}h^2 < 0.129$
3. No color and charge breaking minima

KKLT D7 model - gluino mass

Importance of GUT scale gluino mass for electroweak breaking

$m_{H_u}^2(\,\mathrm{TeV}) \approx 0.6 m_{H_u}^2 - 0.4 m_{Q3}^2 - 0.4 m_{U3}^2 - 2M_3^2 + 0.05 M_2^2 - 0.01 M_1^2 - 0.05 A_0^2 + \ldots$

Modulus and anomaly mediated gluino mass partially cancel

$$M_3 = M_s(\tilde{\alpha} + b_3 g^2) \approx M_s(\tilde{\alpha} - 3/2)$$

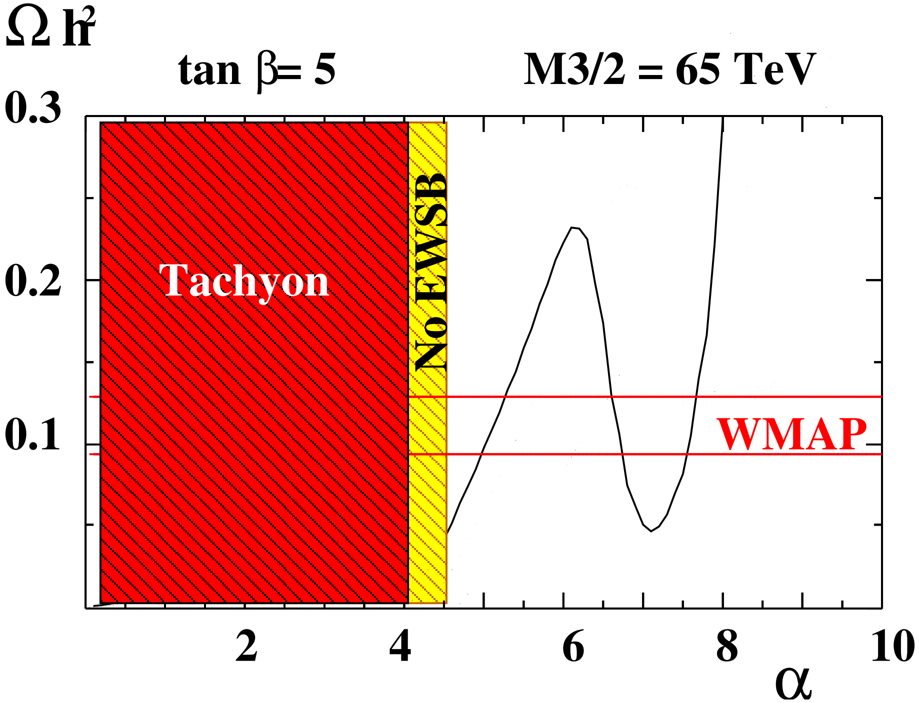
For not too large $\tilde{\alpha}$ soft masses heavier than μ

$$\mu^2(\,\mathrm{TeV}) \approx -m_{H_u}^2(\,\mathrm{TeV}) < M_a^2 \sim m_i^2$$

Strong constraints on parameter space from electroweak breaking: $\tilde{\alpha} > 4.5$

KKLT D7 MODEL - LSP

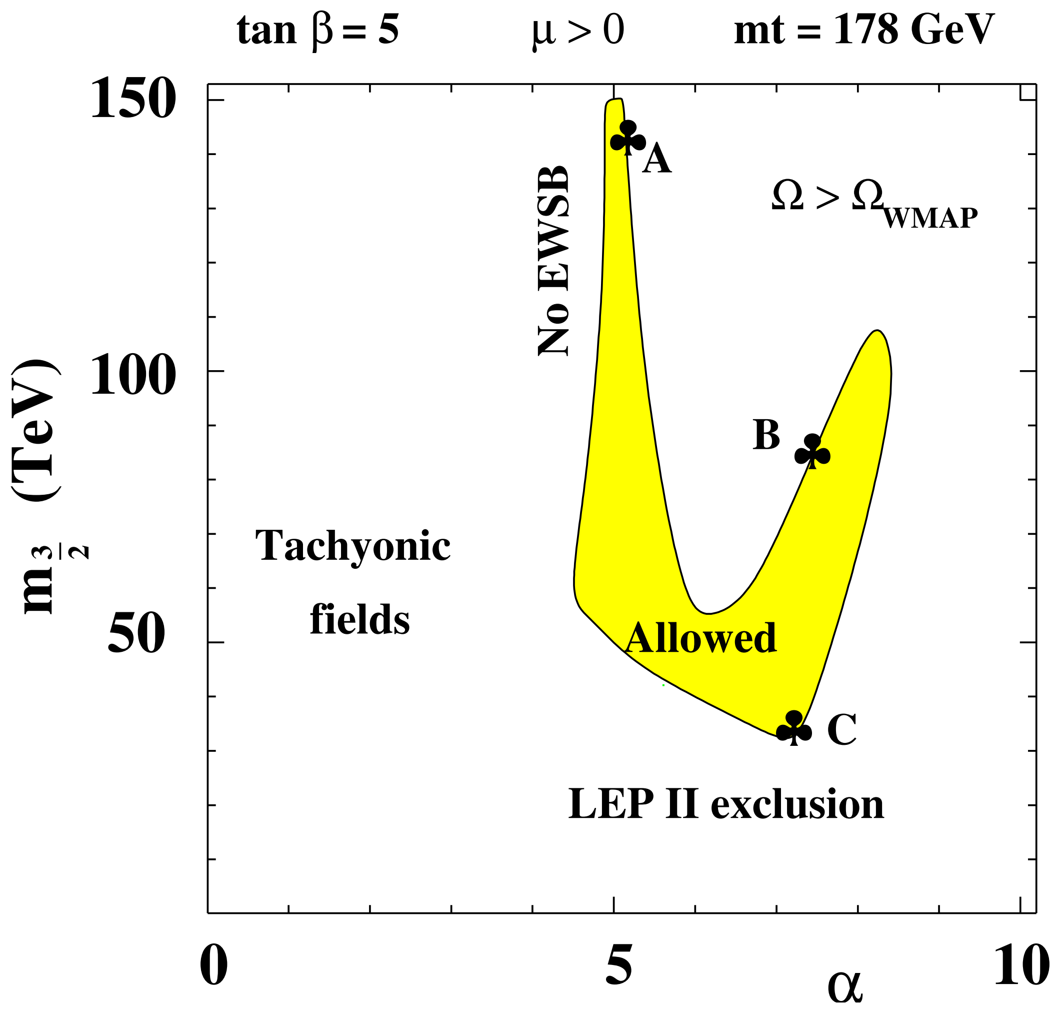
- In non-tachyonic region $M_1(\text{TeV}) < M_2(\text{TeV}) < M_3(\text{TeV})$: bino is lightest gaugino
- Bino mass is enhanced by anomaly mediation: $M_1 \approx M_s(\tilde{\alpha} + 3.3)$
- For $\tilde{\alpha} < 8$, $\mu < M_1(\text{TeV})$ and LSP is higgsino-like
- Higgsino-like LSP annihilates efficiently via Z-boson exchange and does not overclose universe even when LSP is quite heavy



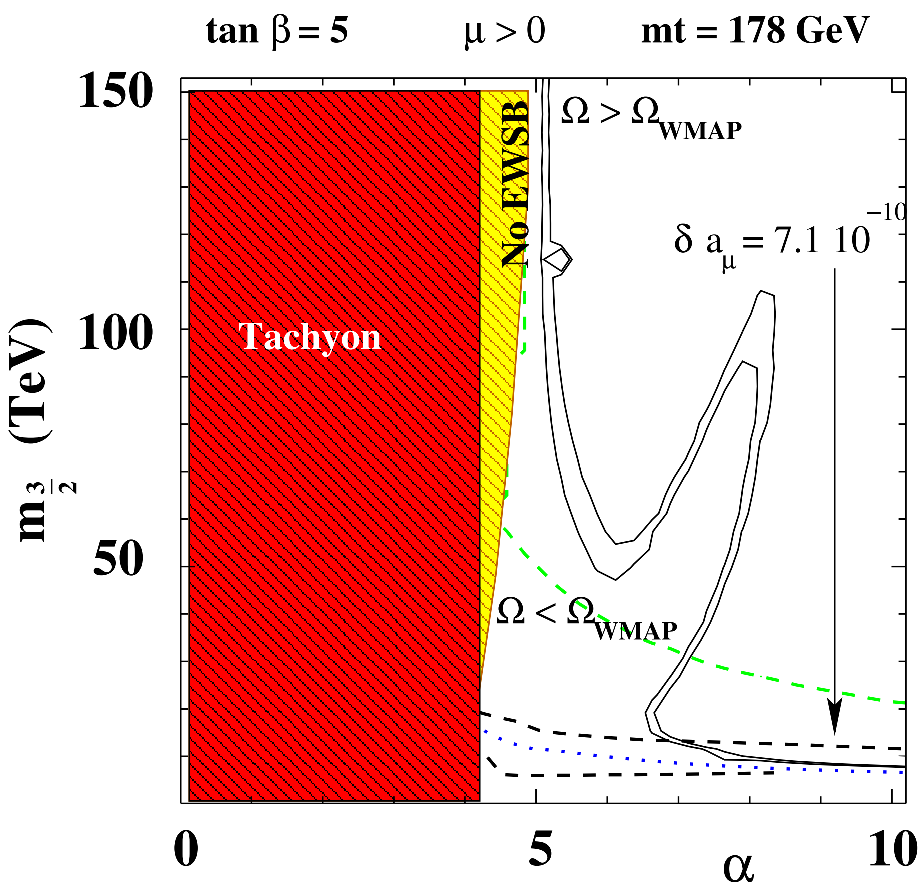
KKLT D7 model - Constraints from color breaking minima

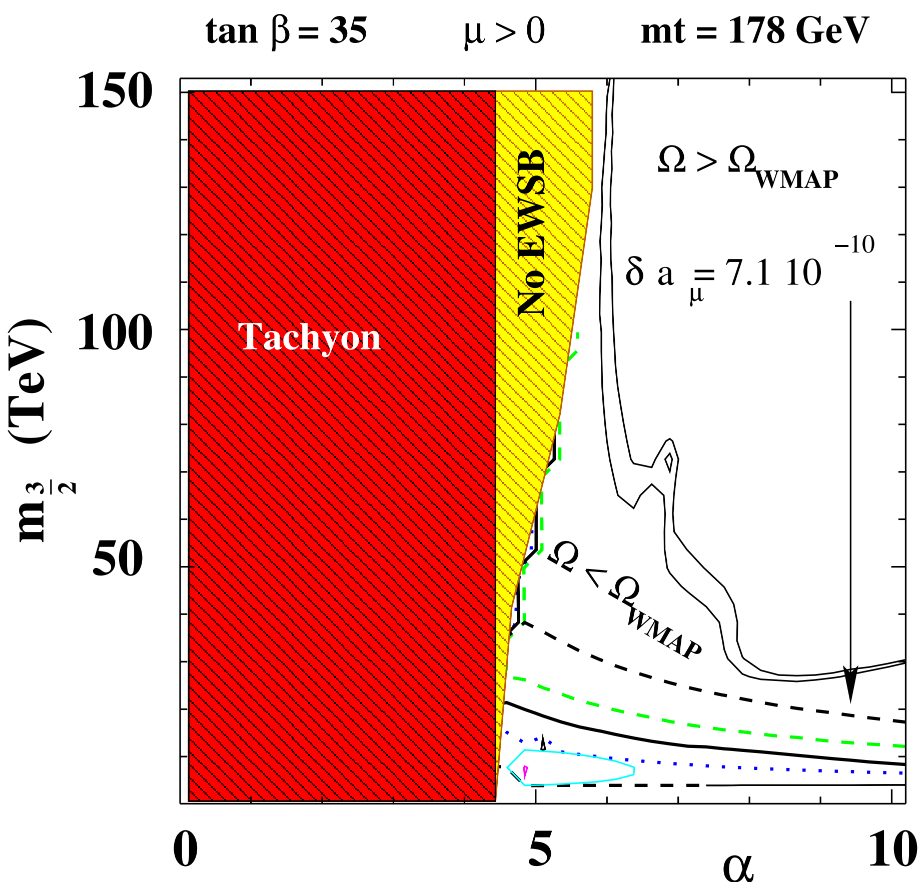
- CCB and UFB directions in MSSM field space classified by Casas, Lleyda, Munoz (1995)
- Typically most dangerous UFB-3 when $m_{H_2}^2 + m_L^2 < 0$
- E.g. in dilaton domination scenario whole parameter space is excluded by CCB
- In KKLT $-m_{H_2}^2 \approx \mu^2 < m_L^2$ and CCB constraints do not affect allowed parameter space

KKLT D7 model - Example of allowed parameter space



KKLT D7 model - Constraints on parameter space





Summary

- KKLT offers a consistent scenario of flux compactification of string theory, in which all moduli are stabilized and the vacuum energy has the correct value
- When fluxes are fine-tuned to achieve weak scale supersymmetry, the set-up leads to a very characteristic pattern of soft terms that acquire comparable contributions from moduli and anomaly mediation
- There are considerable regions of parameter space consistent with all theoretical and experimental constraints including correct amount of dark matter