Quasi-realistic heterotic-string models with vanishing one-loop cosmological constant and perturbatively broken supersymmetry?

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Outline

- Supersymmetry breaking in string theory and in quantum field theory
- Free fermionic heterotic string models with minimal Higgs spectrum
- Flat directions
    - F and D-flat constraints
    - stringent and general f-flatness
    - basis of flat directions
- Conclusions

QFT: **Supersymmetry preserved at the classical level** →
no supersymmetry breaking in perturbation theory
(supersymmetry breaking only by non perturbative effects)

String Theory (Free-Fermionic Models):

The presence of $U(1)_A$ gives rise to a FY D-term

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breaking of Susy at one-loop level

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Susy restored by imposing F and D-flatness on the vacuum

Can susy be broken at perturbative level ?

Models with minimal Higgs spectrum

- Asymmetric boundary conditions on the compact space coordinates reduce the Higgs spectrum to a pair of untwisted doublets (hep-th/0504016) .

- A consequence is the projection of untwisted singlet fields (hep-th/0610118) .

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If flat directions are not found supersymmetric moduli are fixed!!!

D and F flatness constraints in free fermionic models

- **$\langle D_A \rangle = \langle D_\alpha \rangle = 0$; $\langle F_i = \partial W / \partial \chi_i \rangle = 0$;**
- $D_A = \sum Q^k{}_A | \chi_k |^2 + \xi$;
- $D_\alpha = \sum Q^k{}_\alpha | \chi_k |^2$, $\alpha \neq A$;

$$\xi = g^2 (\mathrm{Tr}\, Q_A) M^2_{Pl} / 192\, \pi^2$$

General results so far….

- In free fermionic models solutions to F and D-flatness contraints have always been found.
- In general there is a moduli space of solutions (supersymmetric and degenerate)
- Solutions can be given by
  - non-Abelian singlets (type 1 solutions)
  - non-Abelian fields (type 2 solutions)
- The analysis and classification of flat directions is performed by a systematic method.

Stringent flat directions

- F-flatness of a vev direction in the low energy spectrum may be proven to a given order by cancellation of F-term components but this flatness is lost if there is no cancellation at the next higher order

- Stringent F-flatness requires that each component has vanishing vacuum expectation value, for ex.:

$$W= ..+ \overline{\Phi}_{45}(\overline{\Phi}_{46}\,\overline{\Phi}'_{56} + \overline{\Phi}'_{46}\,\overline{\Phi}_{56})+ \Phi_{45}(\Phi_{46}\,\Phi'_{56} + \Phi'_{46}\,\Phi_{56})+\ldots$$

$$F_{\Phi_{45}} = \overline{\Phi}_{46}\,\overline{\Phi}'_{56} + \overline{\Phi}'_{46}\,\overline{\Phi}_{56}$$

usual condition

$$\langle F_{\Phi_{45}} \rangle = 0$$

stringent flatness condition

$$\langle \overline{\Phi}_{46}\,\overline{\Phi}'_{56} \rangle = 0\ ;\ \langle \overline{\Phi}'_{46}\,\overline{\Phi}_{56} \rangle = 0$$

Why do we look for stringent F-flatness?

- Can be proved to all orders:
  the analysis is restricted to a finite set of possible dangerous superpotential terms (SVD method)
- It makes easier the classification of flat directions
- It is a stronger constraint which gives less fine-tuned solutions

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<u>if none of these terms survive</u>
<u>F-flatness safe to all orders!!</u>

A specific model

- **NAHE set** {1,S,b_1,b_2,b_3}
- One-loop **GSO projection coefficients**
- **Additional boundary condition basis vectors**

	ψ^μ	χ^{12}	χ^{34}	χ^{56}	$\bar{\psi}^{1,\ldots,5}$	$\bar{\eta}^1$	$\bar{\eta}^2$	$\bar{\eta}^3$	$\bar{\phi}^{1,\ldots,8}$
α	0	0	0	0	1 1 1 0 0	1	0	0	1 1 0 0 0 0 0 0
β	0	0	0	0	1 1 1 0 0	0	1	0	0 0 1 1 0 0 0 0
γ	0	0	0	0	$\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	0 0 0 0 $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$

	y^3y^6	$y^4\bar{y}^4$	$y^5\bar{y}^5$	$\bar{y}^3\bar{y}^6$	$y^1\omega^5$	$y^2\bar{y}^2$	$\omega^6\bar{\omega}^6$	$\bar{y}^1\bar{\omega}^5$	$\omega^2\omega^4$	$\omega^1\bar{\omega}^1$	$\omega^3\bar{\omega}^3$	$\bar{\omega}^2\bar{\omega}^4$
α	1	0	0	1	0	0	1	1	0	0	1	1
β	0	0	1	1	1	0	0	1	0	1	0	1
γ	0	1	0	0	0	1	0	0	1	0	0	0

continued…

- Observable gauge group → $SU(3)_C \times SU(2)_L \times U(1)_C \times U(1)_L \times U(1)_{1,2,3} \times U(1)_{4,5,6}$
- Hidden gauge group → $SU(2)_{1,2,3,4} \times SU(4)_{H_1} \times U(1)_{H_1}$
- Anomalous U(1) → $U_A = -2U_1 - 2U_2 + 2U_3 - U_4 + U_5 - U_6, \quad \mathrm{Tr}Q_A = 180.$
- Anomaly free combinations for all U(1)s →

$$\begin{aligned} U'_1 &= U_1 - U_2 \quad , \quad U'_2 = U_1 + U_2 + 2U_3, \\ U'_3 &= U_4 + U_5 \quad , \quad U'_4 = U_4 - U_5 - 2U_6, \\ U'_5 &= U_1 + U_2 - U_3 - 2U_4 + 2U_5 - 2U_6. \end{aligned}$$

D-flat maximally orthogonal basis of Vevs

- **Each direction is uniquely identified by a particular VeV**
- **Each direction can have positive,negative or zero anomalous charge**
- **A physical D-flat direction has anomalous charge with sign opposite to ξ and is given by**

$$D_{\text{phys}} = \sum_{\text{i}=1}^{\#\ \text{basis dirs.}} a_i D_i$$

Directions with only non-Abelian singlets

FD	$\frac{Q_A}{15}$	Φ_{46} / $\bar{\Phi}_{56}$	Φ'_{45} / e_1^c	$\bar{\Phi}'_{56}$ / e_2^c	V_3 / e_3^c	V_2 / H_7	V_6 / H_6	V_5 / H_5	V_9	V_8	N_1^c	N_2^c	N_3^c	Φ'_{46}	Φ_{45}
$\mathcal{D}'_1$	1	1	-2	1	0	0	0	0	0	3	0	0	0	0	0
		0	0	0	3	2	2	2							
$\mathcal{D}'_2$	2	2	-1	-1	0	6	0	0	0	0	0	0	0	0	0
		0	0	0	6	1	4	7							
$\mathcal{D}'_3$	2	-1	-1	2	0	0	0	6	0	0	0	0	0	0	0
		0	0	0	6	1	7	4							
$\mathcal{D}'_4$	0	1	-1	0	0	0	0	0	0	0	0	0	0	0	0
		0	0	2	-2	1	-1	0							
$\mathcal{D}'_5$	0	-1	1	0	0	0	0	0	0	0	0	2	-2	0	0
		0	0	0	0	1	-1	0							
$\mathcal{D}'_6$	0	0	-1	1	0	0	0	0	0	0	0	0	0	0	0
		0	2	0	-2	1	0	-1							
$\mathcal{D}'_7$	0	1	0	-1	0	0	0	0	0	0	0	0	0	0	1
		0	0	0	0	0	0	0							
$\mathcal{D}'_8$	0	1	-1	0	0	0	0	0	0	0	0	0	0	0	0
		1	0	0	0	0	0	0							
$\mathcal{D}'_9$	0	0	-1	1	0	0	0	0	0	0	0	0	0	1	0
		0	0	0	0	0	0	0							
$\mathcal{D}'_{10}$	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
		0	0	0	-1	0	-1	-1							
$\mathcal{D}'_{11}$	0	0	1	-1	0	0	0	0	0	0	2	0	-2	0	0
		0	0	0	0	1	0	-1							
$\mathcal{D}'_{12}$	0	-1	1	0	0	0	2	0	0	0	0	0	0	0	0
		0	0	0	-2	-1	-1	-2							
$\mathcal{D}'_{13}$	0	0	1	-1	2	0	0	0	0	0	0	0	0	0	0
		0	0	0	-2	-1	-2	-1							

do not carry negative charge!!

do not have vector-like partner fields!!

No physical D-flat directions!!

…including non-Abelian charged fields…

Set of *50 maximally orthogonal* D-flat *basis directions*; among them

- negative, positive and zero anomalous charged directions
- many of the fields have vector-like partners

Constraints on the coefficients to get physical D-flat directions

- Negative anomalous charge

$$-2\sum_{i=1}^{2} a_i - \sum_{i=3}^{9} a_i + \sum_{i=30}^{44} a_i + 2\sum_{i=45}^{50} a_i < 0$$

- Non-negative norm square vev for non-vector like components (ex. e_3^c)

$$-6\sum_{i=1}^{2} a_i - 3a_3 - 6\sum_{i=4}^{6} a_i - 2a_7 - 6\sum_{i=8}^{9} a_i - 2\sum_{i=18}^{19} a_i - a_{20} + a_{21}$$
$$-2\sum_{i=23}^{24} a_i - a_{25} - 2a_{26} + 2a_{27} - 2a_{28} + 2a_{29} + 6a_{30} + 6a_{32} + a_{38}$$
$$+3\sum_{i=39}^{40} a_i + 6a_{42} + 6\sum_{i=45}^{47} a_i + 2\sum_{i=48}^{49} a_i + 6a_{50} \geq 0.$$

- For the set of non-vector like fields

$$a_i \geq 0$$

F-flatness constraints on the coefficients

Each superpotential term induces several stringent F-term constraints on the coefficients a_i of physical flat directions

For non-Abelian singlets ⟶ two or more singlets with no vevs
For non-Abelian fields ⟶

W=.. $+ \ \Phi_{45}(\bar{\Phi}_{46}\bar{\Phi}'_{56} + \bar{\Phi}'_{46}\bar{\Phi}_{56}) + \bar{\Phi}_{45}(\Phi_{46}\Phi'_{56} + \Phi'_{46}\Phi_{56})$
$+ \ \Phi'_{45}(\bar{\Phi}_{46}\Phi_{56} + \bar{\Phi}'_{46}\Phi'_{56}) + \bar{\Phi}'_{45}(\Phi_{46}\bar{\Phi}_{56} + \Phi'_{46}\bar{\Phi}'_{56})$ ..+..

Ex.:

$$< \Phi_{45} >, < \Phi'_{45} >, < \bar{\Phi}_{45} >, < \bar{\Phi}'_{45} > \ \neq 0, \quad \text{or}$$
$$< \bar{\Phi}_{46} >, < \bar{\Phi}'_{46} >, < \Phi_{46} >, < \Phi'_{46} > \ \neq 0, \quad \text{or}$$
$$< \bar{\Phi}'_{56} >, < \bar{\Phi}_{56} >, < \Phi'_{56} >, < \Phi_{56} > \ \neq 0.$$

Systematic investigation performed

- Physical D-flat directions which are linear combinations of only up to 6 basis elements
- Assume all the Vevs to be of the same order of magnitude
- Fix the range where the coefficients can vary
- Impose the Anomalous D-flat constraints
- Applying the SVD method we test stringent F-flatness to all order
- Check F-flatness to eight order superpotential terms

But… No physical D-flat directions satisfying stringent F-costraints have been found to all order!!! No F-flat to eight order!!

We can enlarge the set of D-flat directions

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Increase the number of ai coefficients

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Increase the number of unique Vevs associated to each direction

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The probability to satisfy stringent F-flatness constraints decreases

Conclusion

- Is supersymmetry breaking in string theory the same mechanism as in quantum field theory?
- Heterotic free fermionic models with minimal untwisted Higgs spectrum reveal interesting phenomenology.
- Analysis of flat directions in a systematic way
- **Existence of a supersymmetric model at the classical level with perturbatively broken supersymmetry ?**