Supersymmetry Breaking in String Theory: An Overview

F. Quevedo ICTP/Cambridge Bonn Workshop on SUSY tools May 2013

Plan of the Discussion

- Importance of Stringy studies of SUSY Breaking
- Gravity vs Gauge vs Anomaly vs ... mediation
- General Moduli Mediation
- Status of Moduli Stabilisation
- Constraints from Cosmology
- Heterotic vs IIB vs F-theory vs M-theory vs
 Scenarios
- Concrete String Inspired Scenarios

Importance of Stringy SUSY

- UV completion of low-energy effects.
- Concrete case where UV effects relevant (gravity+anomaly mediation but also gauge mediation)
- Potential to determine dynamically the relevant scales M_{GUT} and M_{SUSY}.
- Explore fundamental SUSY and mediation mechanisms.

Key: Moduli Stabilisation (MS)

• Relevant Physical Scales (in Planck units)

M _{GUT}	M _{SVSY}	M _{soft}	M _{EW}	M _{cc} ⁴=∧
10-3	>10 ⁻¹⁵	>10 ⁻¹⁵	10 ⁻¹⁵	10 ⁻¹²⁰

 Note: in MSSM M_{GUT}=10⁻³=10¹⁶GeV, M_{soft}= 1TeV are put in by hand, in string theory should be output.

MODULI STABILISATION

4-cycle size: *τ* (Kahler moduli)

3-cycle size: U (Complex structure moduli)

Warning on Λ

• In MSSM: Leave the cc problem to some 'other mechanism'. Weakest point of MSSM!

- In String Theory (even worst)
 - * Λ is an outcome
 - * Cannot rely on 'other mechanism'
 - * If for a scenario there is an 'yet unknown mechanism', it most probably select very ungeneric models
 - * For IIB there is a mechanism: The Landscape.

The Landscape

• Good: It allows for the first time to trust calculations for low-energy SUSY breaking.

 Bad: missed opportunity to have new physics at low energies from small Λ.

• Ugly: It allows not to use SUSY to address the hierarchy problem (Split SUSY, High-energy SUSY)

Cosmological Constraints

- Cosmological Moduli Problem (CMP) M_{LMP} > 10 Tev or a 2nd stage of inflation?
- Gravitino (or gravitino induced CMP)
- Overshooting (after inflation, large reheating T,...)
- Dark Radiation (Neff ≥ 3.04)

General SUSY Scenarios

 Moduli Stabilisation with SUSY, <F_M>≠0 Moduli (gravity) mediation: M_{soft}≈ M_{3/2} Problems: flavour, CMP, ...

 Moduli Stabilisation with SUSY, <F_M>=0
 Two steps, suitable for gauge mediation
 Problems: μ-problem, light gravitino and moduli (CMP),
 complicated in string theory,...(no concrete realistaion)

Effective Field Theory

$$V = e^{K} \left(K^{i\overline{j}} D_{i} W D_{\overline{j}} \overline{W} - 3|W|^{2} \right) + \text{D-terms}$$

$$W = \hat{W}(\Phi) + \mu(\Phi)H_1H_2 + \frac{1}{6}Y_{\alpha\beta\gamma}(\Phi)C^{\alpha}C^{\beta}C^{\gamma} + \dots,$$

$$K = \hat{K}(\Phi,\bar{\Phi}) + \tilde{K}_{\alpha\bar{\beta}}(\Phi,\bar{\Phi})C^{\alpha}C^{\bar{\beta}} + \left[Z(\Phi,\bar{\Phi})H_1H_2 + h.c.\right] + \dots,$$

$$f_a = f_a(\Phi).$$



$$F^m = e^{\hat{K}/2} \hat{K}^{m\bar{n}} D_{\bar{n}} \bar{\hat{W}}.$$

Gaugini Masses:

$$M_a = \frac{1}{2} \frac{F^m \partial_m f_a}{\operatorname{Re} f_a}.$$

Scalars ('sfermions') masses:

$$\tilde{m}_{\alpha\bar{\beta}}^2 = (m_{3/2}^2 + V_0)\tilde{K}_{\alpha\bar{\beta}} - \bar{F}^{\bar{m}}F^n \left(\partial_{\bar{m}}\partial_n\tilde{K}_{\alpha\bar{\beta}} - (\partial_{\bar{m}}\tilde{K}_{\alpha\bar{\gamma}})\tilde{K}^{\bar{\gamma}\delta}(\partial_n\tilde{K}_{\delta\bar{\beta}})\right)$$

A-Terms:

$$A'_{\alpha\beta\gamma} = e^{\hat{K}/2} F^m \Big[\hat{K}_m Y_{\alpha\beta\gamma} + \partial_m Y_{\alpha\beta\gamma} \\ - \Big((\partial_m \tilde{K}_{\alpha\bar{\rho}}) \tilde{K}^{\bar{\rho}\delta} Y_{\delta\beta\gamma} + (\alpha \leftrightarrow \beta) + (\alpha \leftrightarrow \gamma) \Big) \Big].$$

Bµ-Terms:

$$B\hat{\mu} = (\tilde{K}_{H_{1}}\tilde{K}_{H_{2}})^{-\frac{1}{2}} \Biggl\{ e^{\hat{K}/2}\mu \left(F^{m} \left[\hat{K}_{m} + \partial_{m}\log\mu - \partial_{m}\log(\tilde{K}_{H_{1}}\tilde{K}_{H_{2}}) \right] - m_{3/2} \right) + \left(2m_{3/2}^{2} + V_{0} \right) Z - m_{3/2}\bar{F}^{\bar{m}}\partial_{\bar{m}}Z + m_{3/2}F^{m} \left[\partial_{m}Z - Z\partial_{m}\log(\tilde{K}_{H_{1}}\tilde{K}_{H_{2}}) \right] \\ \bar{F}^{\bar{m}}F^{n} \left[\partial_{m}\partial_{n}Z - (\partial_{\bar{m}}Z)\partial_{n}\log(\tilde{K}_{H_{1}}\tilde{K}_{H_{2}}) \right] \Biggr\}.$$

Explicit Scenarios

- General moduli: S, T, U
- Need to chose a string theory: Heterotic (smooth or singular) IIA IIB/F-theory (smooth or singular) M-theory

• Ingredients for MS: Fluxes, perturbative and nonperturbative effects,...

IIB Scenarios

KKLT (Mirage mediation) LVS (LARGE Volume Scenarios) F-theory Gauge Mediation models

KKLT

 $W=W_0+Ae^{-aT}$ with $W_0 \approx 10^{-13}$ Source of SUSY breaking: anti D3 uplifting to de Sitter.

Mirage Mediation

Soft terms $\approx M_{3/2}/\ln(M_{planck}/M_{3/2})$ may need to combine with Anomaly mediation \rightarrow Mirage mediation.

Bunched spectrum +

 $M_1: M_2: \dot{M}_3 \simeq (1+0.66\alpha): (2+0.2\alpha): (6-1.8\alpha),$

LARGE Volume Scenarios (LVS)

U,S stabilised by fluxes. Not need to tune W₀

$$\mathcal{V} \sim e^{a_s \tau_s} \gg 1 \text{ with } \tau_s \sim \frac{\xi^{2/3}}{g_s}.$$

- * SUSY broken by fluxes $\langle F_T \rangle \neq 0$
- * No scale structure broken in a control way. Leading order in 1/volume keeps no-scale.

Relevant Scales

- String scale Ms=M_P/V^{1/2}
- Kaluza-Klein scale $M_{KK}=M_P/V^{2/3}$
- Gravitino mass $m_{3/2} = W_0 M_P / V$
- Volume modulus mass

$$M_{v} = M_{p} / V^{3/2}$$

Lighter (fibre) moduli

Original Scenarios

- $M_{\text{String}} = M_{\text{GUT}} \sim 10^{16} \text{ GeV} (V \sim 10^5)$
- $W_0 \sim 10^{-11} <<1$ to get TeV soft terms, or $W_0 \sim 1$ and 10^{10} GeV soft terms ?
- Fits with coupling unification
- Natural scale of most string inflation models.
- Axi-volume quintessence scale (w=-0.999....)

•
$$M_{\text{String}} = M_{\text{int.}} \sim 10^{12} \text{ GeV} (V \sim 10^{15})$$

- W₀~1
- m_{3/2}~1 TeV (solves hierarchy problem!!!)
- QCD axion scale
- neutrino masses LLHH

- W₀~1
- Most exciting, 5th Force OK m~10⁻³ eV, if SM non SUSY. Back reaction?

SUSY Breaking

- Approximate Universality
- $\Psi \iff \text{K\"ahler moduli}, \qquad \Phi = \Psi_{\text{susy-breaking}} \oplus \chi_{\text{flavour}}.$ $\chi \iff \text{Complex structure moduli}.$

- Cases:
- F_{SM}≠0 soft terms~m_{3/2} Ms~10¹² GeV

 F_{SM}=0 soft terms <<m_{3/2} or~m_{3/2} (loops)



Where is the Standard Model?

Visible or Hidden Sectors

D3 Brane or D7 Brane

CHIRAL MATTER ON D7 BRANES SOFT SUSY BREAKING TERMS

$$M_{i} = \frac{F^{s}}{2\tau_{s}},$$

$$m_{\alpha} = \sqrt{\lambda}M_{i},$$

$$A_{\alpha\beta\gamma} = -3\lambda M_{i},$$

$$B = -(\lambda + 1) M_{i}.$$

Simplest case λ=1/3

$$m_{soft} = \frac{m_{3/2}}{\ln(M_P/m_{3/2})}.$$

- Approximate Universality
- No extra CP violation
- $M_i = m_{3/2} / \log (Mp/m_{3/2})$
- String scale 10¹¹ GeV ??
- Solves hierarchy problem!

$$M_1: M_2: M_3 = (1.5 \rightarrow 2): 2:6$$

But: Local/Global Mixing

- Standard Model in small cycle
- SM cycle usually NOT fixed by nonperturbative effects:

• SM chiral implies:
$$W_{np} = \left(\prod_{i} \Phi_{hidden,i}\right) \left(\prod_{j} \Phi_{MSSM,j}\right) e^{-aT_{MSSM}}$$
.

Blumenhagen et al.2007

$$D_a \sim \sum_i (|\Phi|^2 - \xi)^2, \quad \xi = (\partial_{V_a} K)|_{V_a = 0}$$

MSSM: $<\Phi>=0$, so $W_{np}=0$, $\xi = 0$. (singularity)? Or $<|\Phi|^2>=\xi$

SM Cycle does not break SUSY

'Fayet-Iliopoulos' →0

$$K_{T_a} = 0$$
 $\tau_a \to 0$
 $F_a = e^{K/2} (W_{T_a} + WK_{T_a})$
 $F^a = 0$

'Sequestered moduli/gravity mediated SUSY Breaking'

$$|F^{T_b}| \sim \frac{M_P^2}{\mathcal{V}}, \qquad |F^{T_s}| \sim \frac{M_P^2}{\mathcal{V}^{3/2}}, \qquad |F^S| \sim \frac{M_P^2}{\mathcal{V}^2}$$
No-scale (vanishing soft terms) Suppressed !

Sequestered Scenario

$$egin{aligned} M_P &\equiv 2.4 imes 10^{18}\,{
m GeV},\ M_{string} &\sim M_P/\sqrt{\mathcal{V}},\ m_{ au_{s,i}} &\sim m_{a_{s,i}} &\sim M_P\ln\mathcal{V}/\mathcal{V},\ m_{3/2} &\sim m_U \sim m_S &\sim M_P/\mathcal{V},\ m_{ au_b} &\sim M_P/\mathcal{V}^{3/2},\ m_{a_b} &\lesssim M_P\,e^{-2\pi\mathcal{V}^{2/3}} \sim 0\,. \ {
m Model \ independent \ !} \end{aligned}$$

$$\begin{split} M_{soft} \sim \frac{M_P}{\mathcal{V}^2} \ll m_{\tau_b} \sim \frac{M_P}{\mathcal{V}^{3/2}} \,. \\ M_{soft} \sim 1 \,\mathrm{TeV} \qquad \qquad m_{\tau_b} \sim 3 \times 10^6 \,\mathrm{GeV} \,. \end{split}$$

*No CMP, *No gravitino induced moduli problem, *Volume reheating

Different Scenarios

- Scalars 1/V^{3/2}, others 1/V²
- All a/V^{3/2}
- All 1/V² (No CMP, unification, inflation !!!)
- Loop corrections ~ b/V^{5/3}
- M_{string}~10¹³-10¹⁵ GeV
- Field redefinitions at loop order: soft terms 1/V except 'ultra-local' SM at D3
- Controversy on AMSB→ino-AMSB!

F-Theory Models

- Compact models not well understood yet
- EFT similar to IIB
- Local models: assume a version of gauge mediation with a larger breaking scale
- Phenomenology explored

Heterotic Scenarios

Heterotic Orbifold Models and M-Theory Models

Heterotic Orbifold Models

• Moduli Stabilisation less understood.

• Version of mirage mediation

• Natural SUSY (light stops,...)

M-Theory Models

• Not explicit models

Moduli stabilisation (even) less understood

• A version of 'Mini-split'

Conclusions

- Rich structure of soft terms from string models
- Moduli stabilisation is the key
- All relevant energy scales should be outcomes (strong constraints)
- Several concrete string inspired scenarios that can be put to test (mirage,inoAMSB,Mtheory, F-Theory, LVSn, Natural, mini-split,...)
- Open questions before a controlled scenario (loop corrections to matter K, flavour issues,...)