Large Volume String Compactifications

F. Quevedo, Cambridge. UKBSM Liverpool 2007
(J. Conlon, K. Suruliz, D. Cremades, S. Abdussalam, B. Allanach, S. Kom, V.Balasubramanian, P. Berglund, …)

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OUTLINE

- Moduli Stabilisation and the String Landscape
- Exponentially Large Volumes
- SUSY Breaking (LHC Phenomenology)
- Cosmology (Inflation, CMP,…)
- Conclusions

Moduli Stabilisation and the String Landscape

The Problem

- String/M-Theory unique but has many solutions or vacua. Moduli:

  Dilaton S,
  Kähler T
  Complex structure U
  Wilson lines W, Brane separation Y

- Some solutions resemble the Standard Model and MSSM but moduli unrealistic.

- Degeneracy : Discrete + Continuous (SUSY) .

- Outstanding Problems: SUSY breaking + Vacuum degeneracy.

KKLT Scenario

- Type IIB String on Calabi-Yau
- Turn on Fluxes

$$\int_a F_3 = n_a \qquad \int_b H_3 = m_b$$

Size of cycle a = U_a

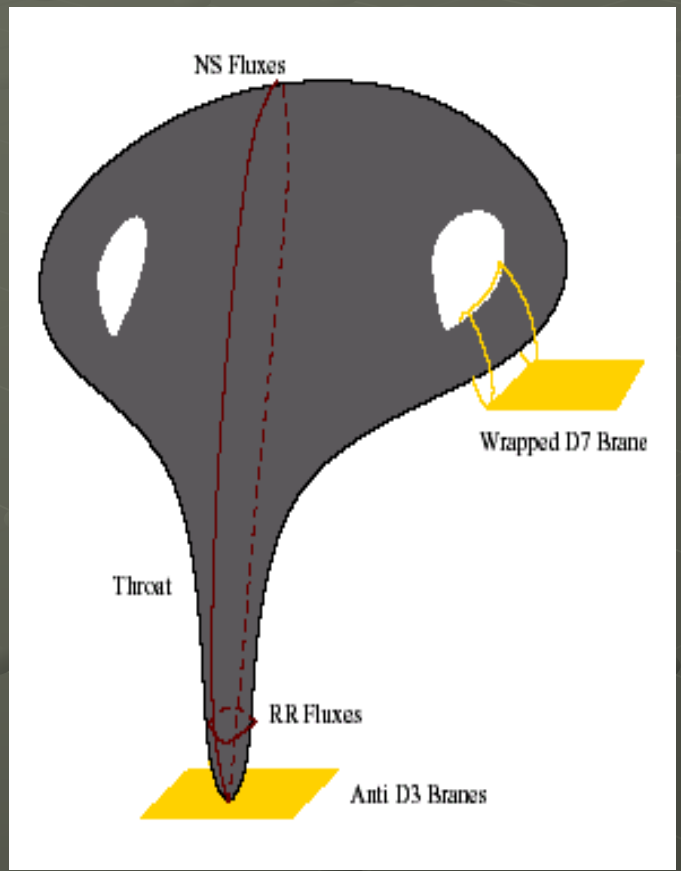
Superpotential $W = \int G_3 \wedge \Omega, \qquad G_3 = F_3 - iS\,H_3$

Scalar Potential: $V = e^K \, |D_a W|^2$

→ Minimum $D_a W = 0$ Fixes U_a and S
T moduli unfixed: No-Scale models

GKP

- To fix Kähler moduli: Non-perturbative D7 effects



Fluxes

Non-perturbative

$$W = W_0 + \sum_i A_i e^{-a_i T_i},$$

Volume

$$K = -2\log[\mathcal{V}]$$

SUSY AdS minimum

$$V = e^K \left[G^{i\bar{j}} D_i W \bar{D}_{\bar{j}} \bar{W} - 3|W|^2 \right],$$

$$D_i W \equiv \frac{\partial W}{\partial T_i} + W \frac{\partial K}{\partial T_i} = 0.$$

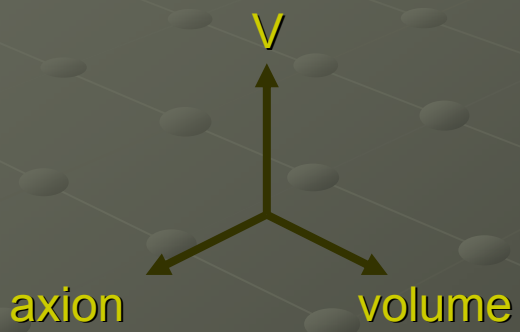
($W_0 << 1$)

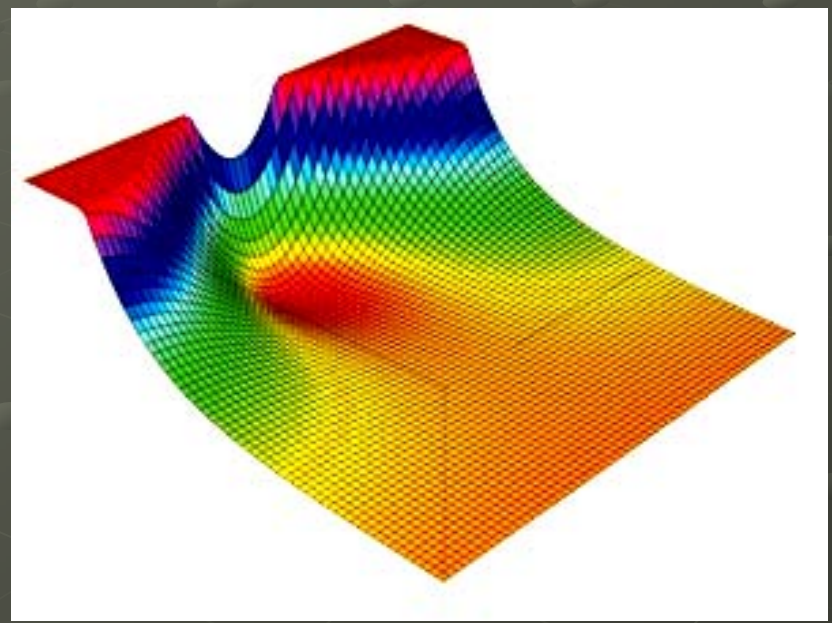
- Lifting to de Sitter (add anti D3 branes, D-terms, etc.)

KKLT, BKQ, SS,…

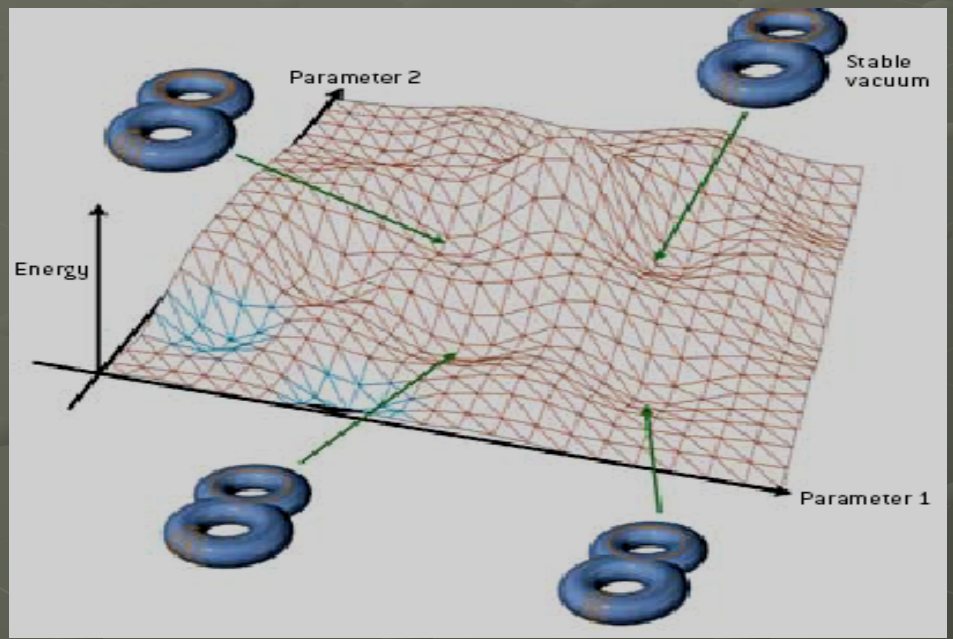
SUSY breaking term

$$V = V_F + \delta V \ .$$





The Landscape



- Huge number of discrete vacua $>10^{500}$
- Statistics AD, DD, GKTT,CQ,BGHLW
- Randall-Sundrum warping from strings! GKP
- Non SUSY de Sitter
- Dark energy? BP

Exponentially Large Volumes

Exponentially Large Volumes

BBCQ, CQS

- At least two Kähler moduli ($h_{21}>h_{11}>1$)
- Perturbative corrections to K

Example :

$$\mathcal{K} = \mathcal{K}_{cs} - 2\ln\left(\mathcal{V} + \frac{\xi}{2}\right), \qquad \mathcal{V} = \frac{1}{9\sqrt{2}}\left(\tau_5^{\frac{3}{2}} - \tau_4^{\frac{3}{2}}\right)$$

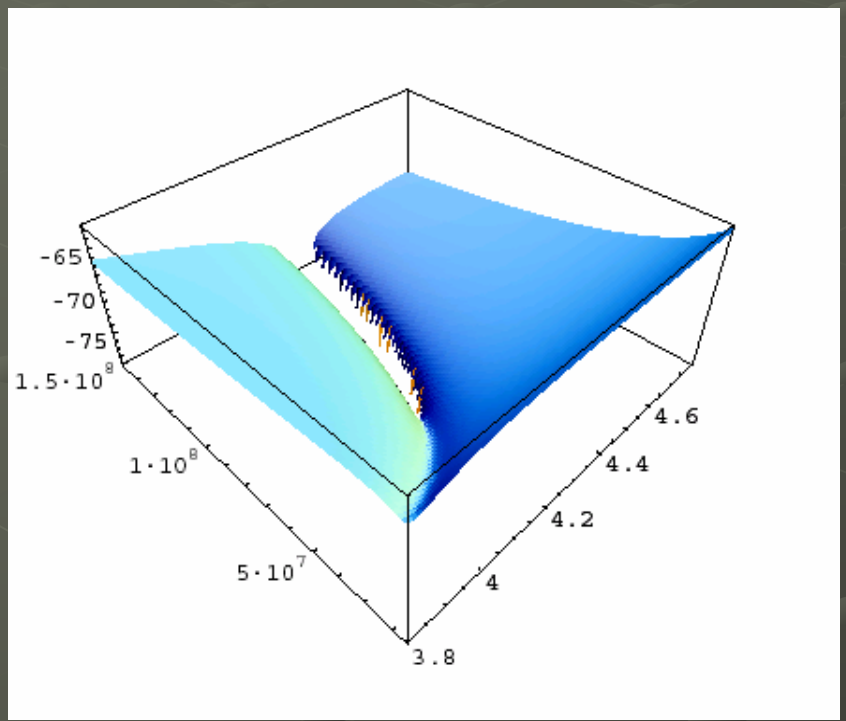
$$W = W_0 + A_4 e^{-\frac{a_4}{g_s}T_4} + A_5 e^{-\frac{a_5}{g_s}T_5}.$$

$$\tau_4 \propto \xi^{\frac{2}{3}} \quad \text{and} \quad \langle\mathcal{V}\rangle \propto W_0 e^{\frac{a_4\tau_4}{g_s}}.$$

Exponentially large !

Non SUSY AdS

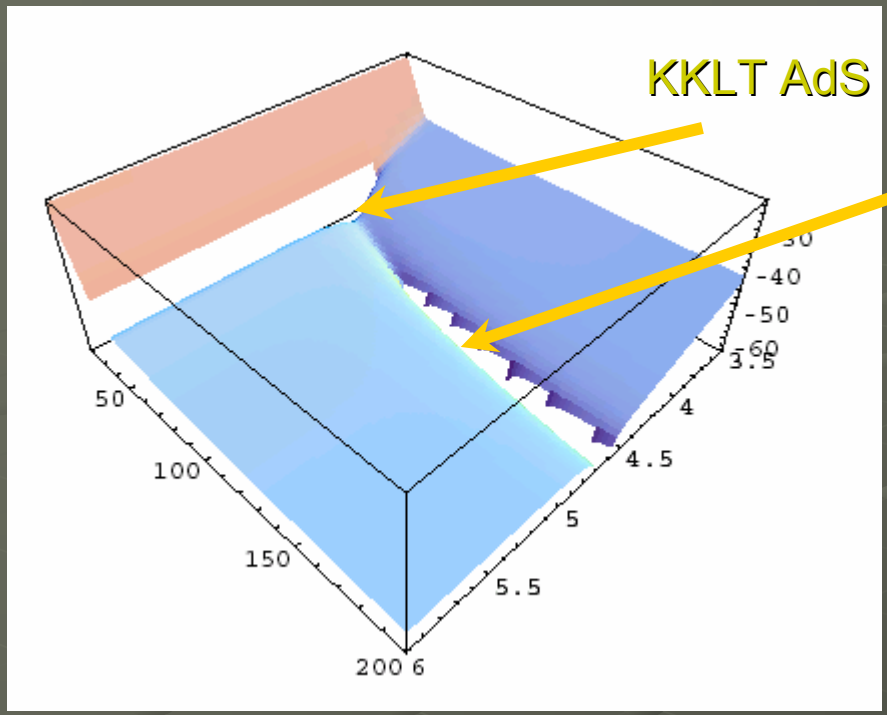
$$V = \sum_{\Phi=S,U} \frac{\mathcal{K}^{\Phi\bar{\Phi}} D_\Phi W \bar{D}_{\bar{\Phi}} \bar{W}}{\mathcal{V}^2} + \frac{(a_s A_s)^2 e^{-2a_s\tau_s}}{\mathcal{V}} - \frac{W_0 a_s A_s e^{-a_s\tau_s}}{\mathcal{V}^2} + \frac{\xi |W_0|^2}{g_s^{3/2}\mathcal{V}^3}.$$



W_0~1-10

String scale: $Ms^2=Mp^2/V$

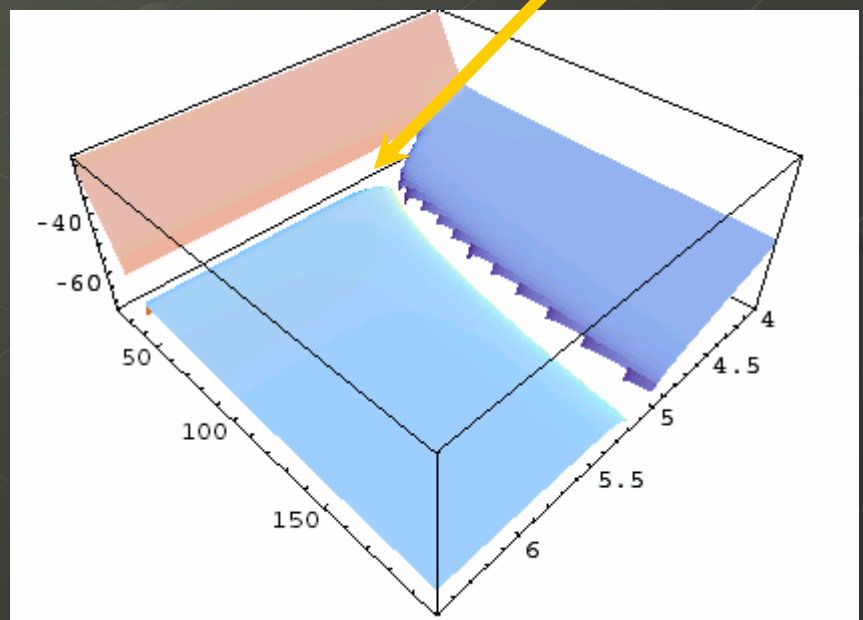
Scale	$\mathcal{V}_s$	g_sN	N if $g_s = 0.1$
GUT	4600	2.25	22
Intermediate	4.6×10^9	0.85	9
TeV	4.6×10^{27}	0.30	3



$W_0 \sim 10^{-10}$

Both minima merge

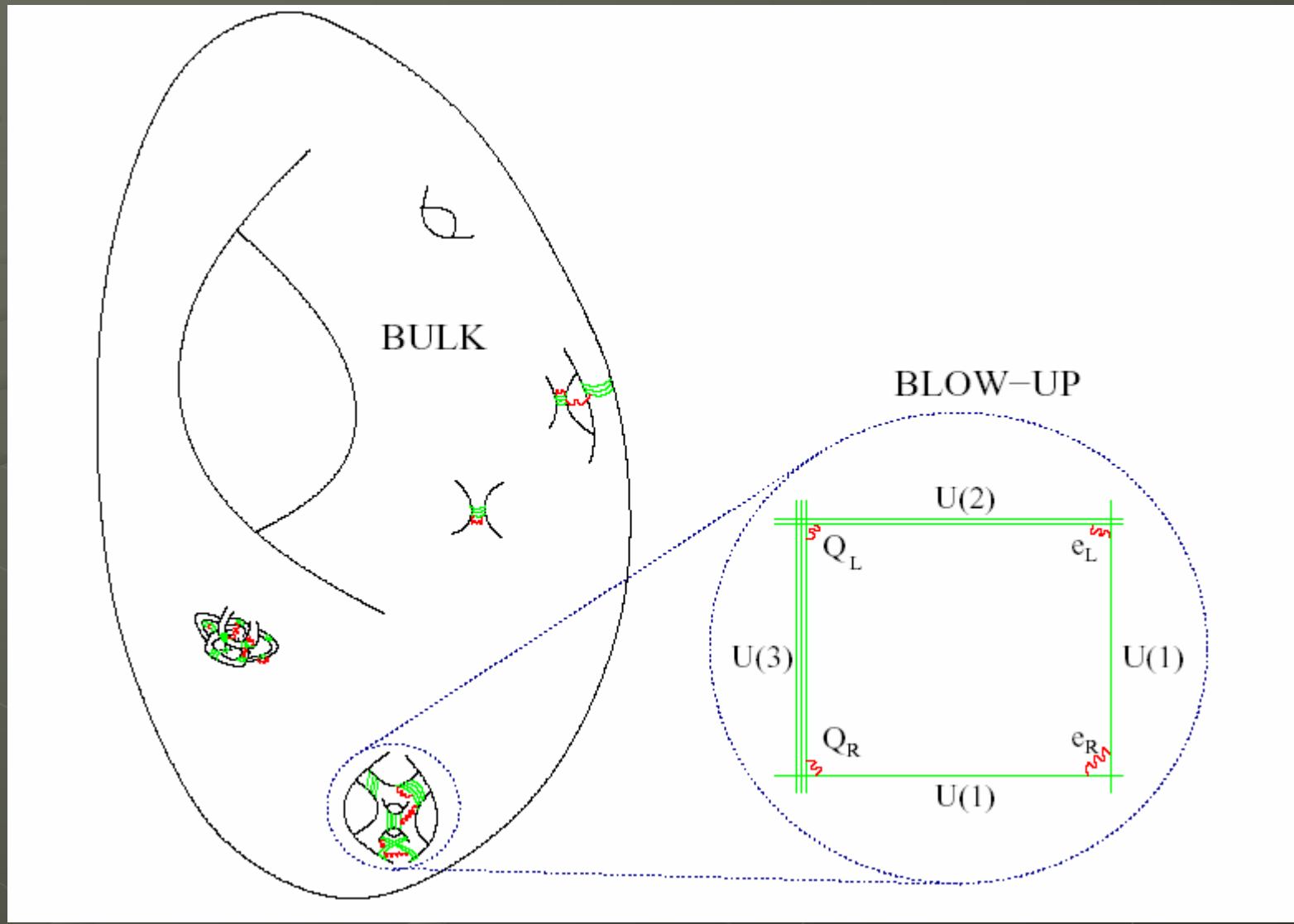
$W_0 < 10^{-11}$



SUSY Breaking

(LHC Signatures)

The Standard Model in the CY



4D effective Action

$$\hat{K}(\Phi,\bar{\Phi}) = -2\ln\left(\mathcal{V}+\frac{\hat{\xi}}{2g_s^{3/2}}\right) - \ln\left(i\int\Omega\wedge\bar{\Omega}\right) - \ln(S+\bar{S}).$$

$$\hat{W}(\Phi) = \int G_3\wedge\Omega + \sum_i A_i e^{-a_i T_i}.$$

Φ moduli, C matter, H Higgs

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

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

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

$$\tilde{K}_{\alpha\bar{\beta}} = \frac{\tau_s^\lambda}{\mathcal{V}^{2/3}}k_{\alpha\bar{\beta}}(\phi).$$

New!

Chiral matter in CY

Conlon, Cremades, FQ

Soft SUSY Breaking

- Large Volume (SM on D3 brane)

CQS, AQS

Scale	Mass	GUT	Intermediate	TeV
Scalars m_i	$\frac{g_s^2}{(\mathcal{V}_s^0)^{7/6}} W_0 M_P$	3.6×10^{11} GeV	3.6×10^{4}GeV	3.6×10^{-17}GeV
Gauginos M_{D3}	$\frac{g_s^2}{(\mathcal{V}_s^0)^{2}} W_0 M_P$	3.6×10^{9}GeV	3.6×10^{-3}GeV	3.6×10^{-39} GeV
A-term A	$\frac{g_s^2}{(\mathcal{V}_s^0)^{4/3}} W_0 M_P$	3.2×10^{11}GeV	3.2×10^{3} GeV	3.2×10^{-21}GeV
μ-term $\hat{\mu}$	$\frac{g_s^2}{(\mathcal{V}_s^0)^{4/3}} W_0 M_P$	3.2×10^{11}GeV	3.2×10^{3} GeV	3.2×10^{-21}GeV
B term $\hat{\mu} B$	$\frac{g_s^2}{(\mathcal{V}_s^0)^{7/6}} W_0 M_P$	3.6×10^{11} GeV	3.6×10^{4}GeV	3.6×10^{-17}GeV

Matter on D3

Ms~10^{13} GeV Gaugino masses ~ 10^{2} GeV, scalars m ~ 10^{7} GeV

Ms=M_{GUT} viable if warping,

Ms=Tev `viable' if SM anti D-brane (but 5th force and cmp?)

Standard Model on D3 Brane
Two General Scenarios

- Intermediate Scale Split SUSY

  SM on D3 brane, $M_s = 10^{12}$ Gev

- Stringy mSUGRA

  SM on D3 brane, $M_s = 10^{17}$ Gev

Do not solve hierarchy problem(?)

Standard Model on D7 Branes

- Solve hierarchy problem $M_{string} = 10^{11}$ GeV!
- $W_0 \sim 1$ (no fine tuning)
- Kahler potential for *chiral* matter computed

Conlon, Cremades, FQ

Chiral Matter on D7 Branes

Soft SUSY Breaking terms

$$
\begin{aligned}
M_i &= \frac{F^s}{2\tau_s}, \\
m_\alpha &= \frac{1}{\sqrt{3}} M_i, \\
A_{\alpha\beta\gamma} &= -M_i, \\
B &= -\frac{4}{3} M_i.
\end{aligned}
$$

Simplest case

Conlon et al.

- Universality!
- No extra CP violation!
- $M_i = m_{3/2} / \log (Mp/m_{3/2})$
- String scale 10^{11} GeV
- Solves hierarchy problem!

$$
\begin{aligned}
M_i &= \frac{F^s}{2\tau_s}, \\
m_\alpha &= \sqrt{\lambda} M_i, \\
A_{\alpha\beta\gamma} &= -3\lambda M_i, \\
B &= -(\lambda + 1) M_i.
\end{aligned}
$$

More general case

Stringy source of universality

(approximate)

$$\Phi = \Psi_{\text{susy-breaking}} \oplus \chi_{\text{flavour}}.$$

$$\Psi \Longleftrightarrow \text{Kähler moduli},$$
$$\chi \Longleftrightarrow \text{Complex structure moduli}.$$

CP Violation

$$\phi_A = \{\arg\left(\frac{A_{\alpha\beta\gamma}}{Y_{\alpha\beta\gamma}}\right)\},\ \phi_B = \{\arg B\},\ \phi_C = \{\arg(M_a)\}.$$

Physical phases $\phi = \{\phi_A - \phi_C, \phi_B - \phi_C\}$ vanish !

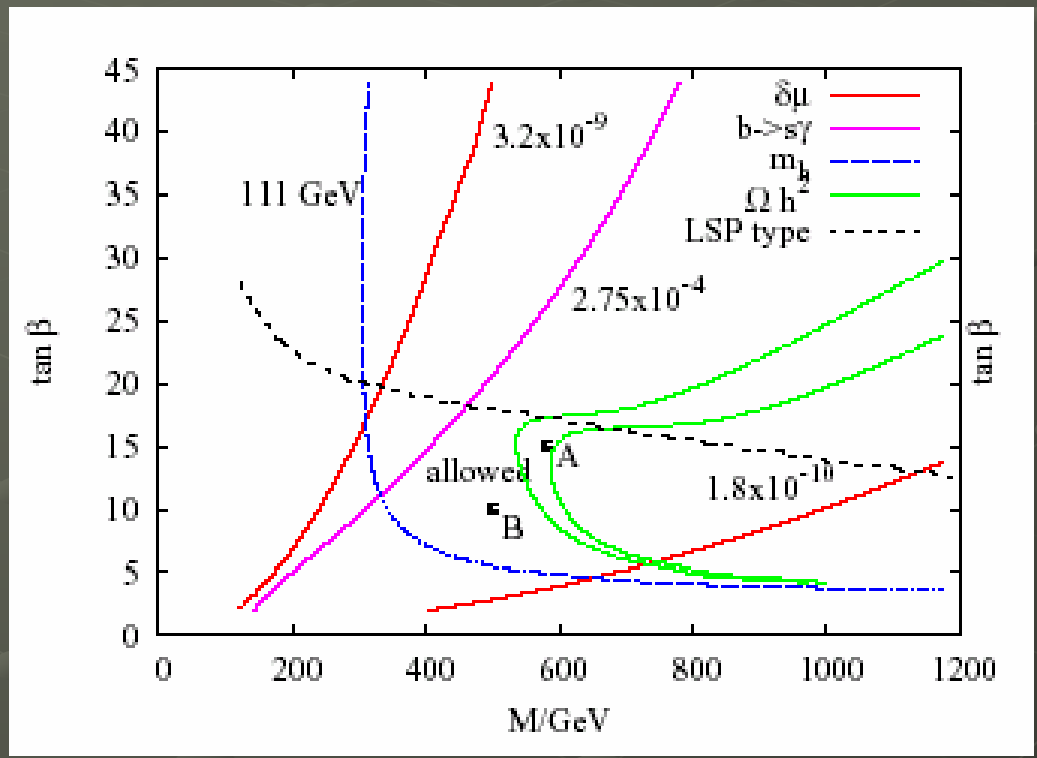
Also: Anomaly mediation suppressed !

From Strings to LHC data

- Stabilise Moduli
- SUSY broken with hierarchy
- “Realistic” Observable sector
- Soft SUSY Breaking terms@Ms
- RG-Running of Soft terms to TeV (softsusy)
- Event Generators (PYTHIA-Herwig)
- Detector Simulators (PGS, GEANT)
- Data Analysis (Root)
- Estimate overall uncertainty

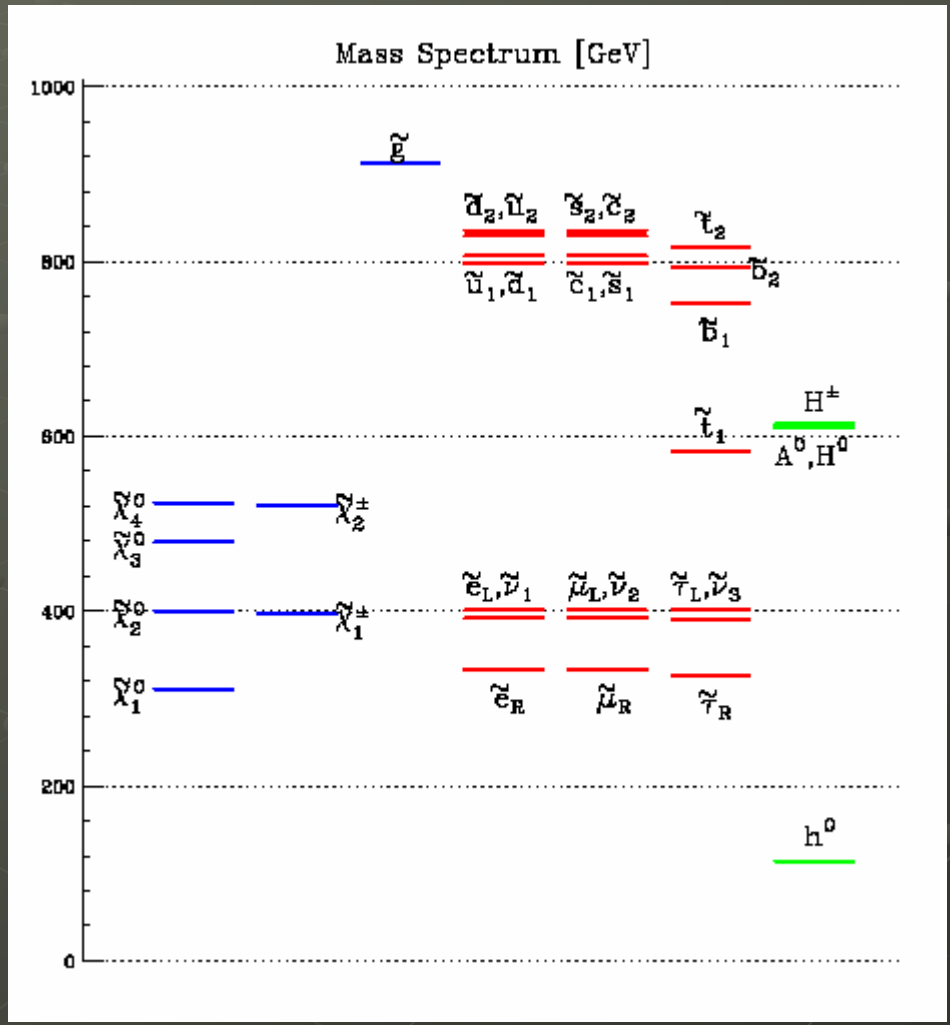
Renormalisation group run

Allowed Regions

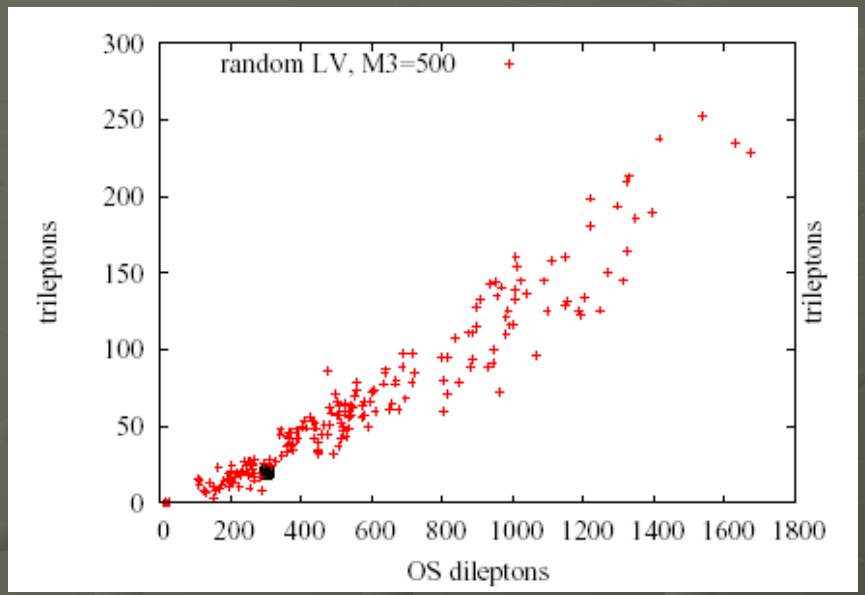


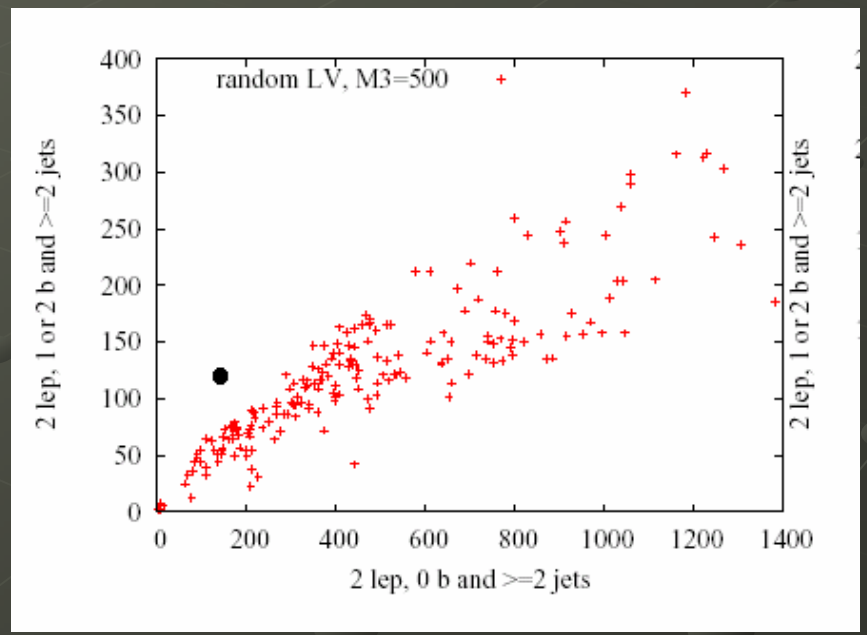
Low energy spectrum

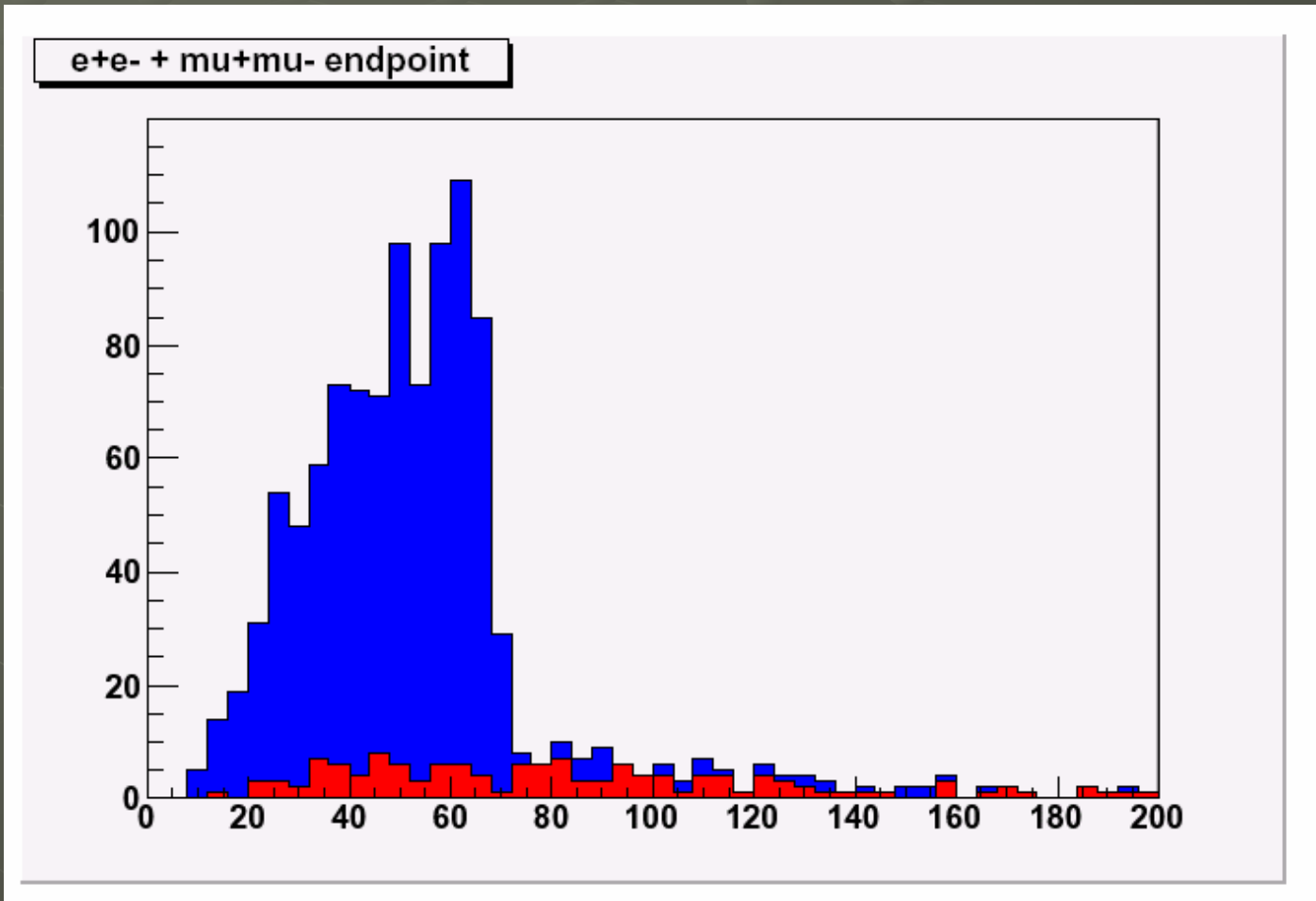
	A	B	C
m_s	10^{11}	10^{11}	10^{11}
$\tan\beta$	15	10	23
M	580	500	1000
sgnμ	+	+	-
$\tilde{e}_L, \tilde{\mu}_L$	464	401	792
$\tilde{e}_R, \tilde{\mu}_R$	386	333	661
$\tilde{\tau}_L$	463	402	779
$\tilde{\tau}_R$	369	326	618
$\tilde{u}_1, \tilde{c}_1$	924	806	1527
$\tilde{u}_2, \tilde{c}_2$	951	829	1580
$\tilde{t}_1$	679	582	1166
$\tilde{t}_2$	958	815	1448
$\tilde{d}_1, \tilde{s}_1$	915	798	1512
$\tilde{d}_2, \tilde{s}_2$	958	835	1585
$\tilde{b}_1$	859	752	1405
$\tilde{b}_2$	903	792	1455
χ_1^0	364	311	643
χ_2^0	469	400	822
χ_3^0	541	479	862
χ_4^0	587	524	927
$\chi_1^\pm$	467	397	821
$\chi_2^\pm$	584	521	924
A_0, H_0	679	610	1042
$H^\pm$	684	614	1046
$\tilde{g}$	1048	913	1745
$\tilde{\nu}_{1,2}$	456	392	789
$\tilde{\nu}_3$	451	390	771
h	116	114	118
$B(b \to s\gamma)/10^{-4}$	3.3	3.4	4.42
$\delta a_\mu/10^{-10}$	7.9	7.0	-4.3
Ωh^2	0.12	0.01	—



Some observables






e+e- + mu+mu- endpoint
100
80
60
40
20
0
0
20
40
60
80
100
120
140
160
180
200

Sources of uncertainty

- Gaugino masses

1. Dilute flux limit

$$f_{SU(3)} = \frac{T_s}{2\pi},$$
$$f_{SU(2)} = \frac{T_s}{2\pi},$$
$$f_{U(1)_Y} = k_Y \frac{T_s}{2\pi}.$$

2. Physical case

$$f_{SU(3)} = \frac{T_s}{2\pi} + h_{SU(3)}(F)S,$$
$$f_{SU(2)} = \frac{T_s}{2\pi} + h_{SU(2)}(F)S,$$
$$f_{U(1)_Y} = k_Y \left(\frac{T_s}{2\pi} + h_{U(1)}(F)S \right).$$

1. Dilute flux limit

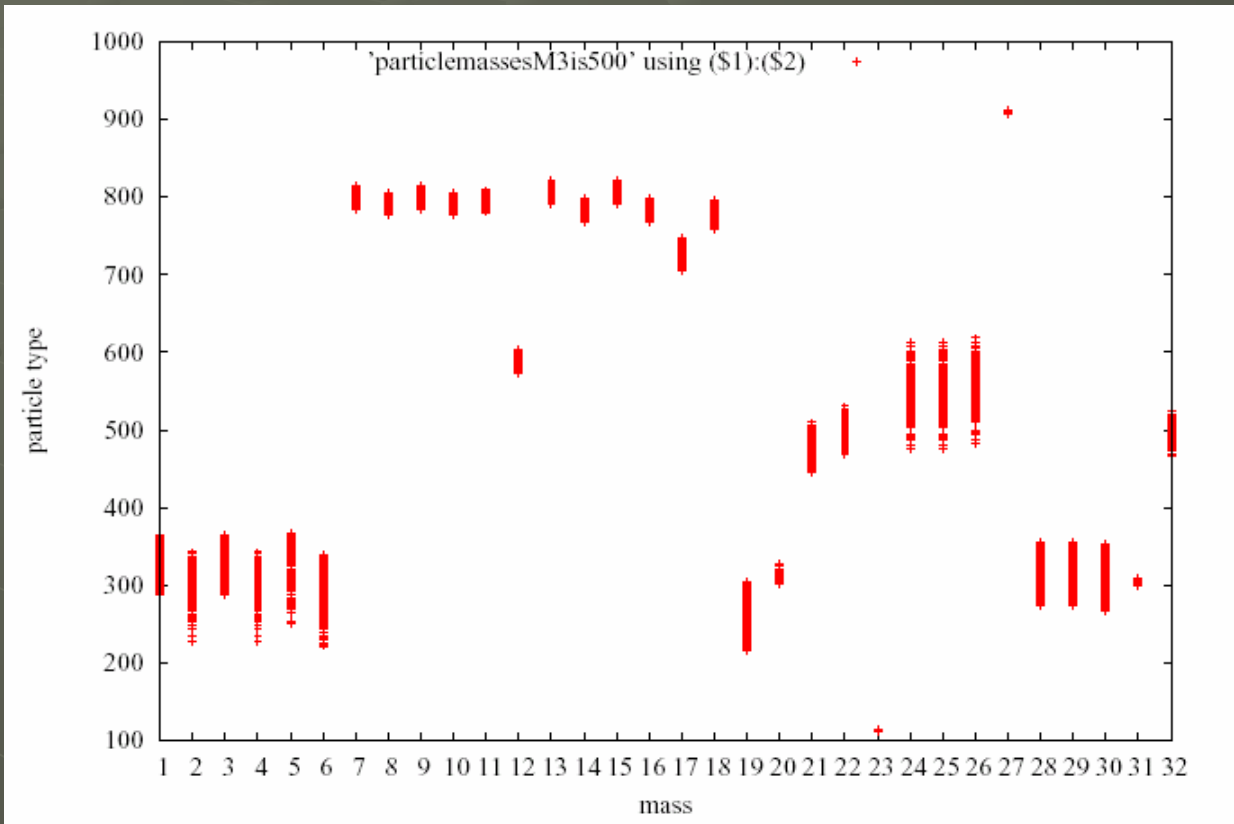
$$M_1 = M_2 = M_3 = \frac{F^s}{2\tau_s} \equiv M.$$

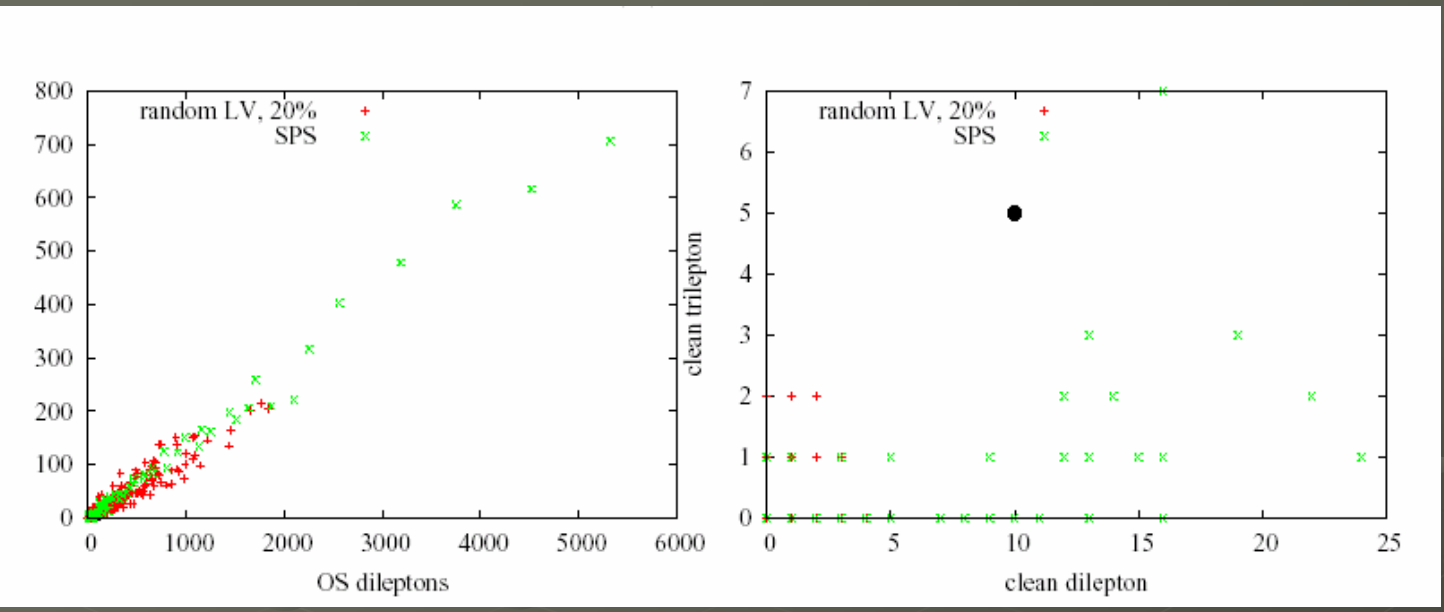
2. Physical case

$$M_1 = \frac{F^s}{2(\tau_s + 2\pi h_1(F)\mathrm{Re}(S))},$$
$$M_2 = \frac{F^s}{2(\tau_s + 2\pi h_2(F)\mathrm{Re}(S))},$$
$$M_3 = \frac{F^s}{2(\tau_s + 2\pi h_3(F)\mathrm{Re}(S))}.$$

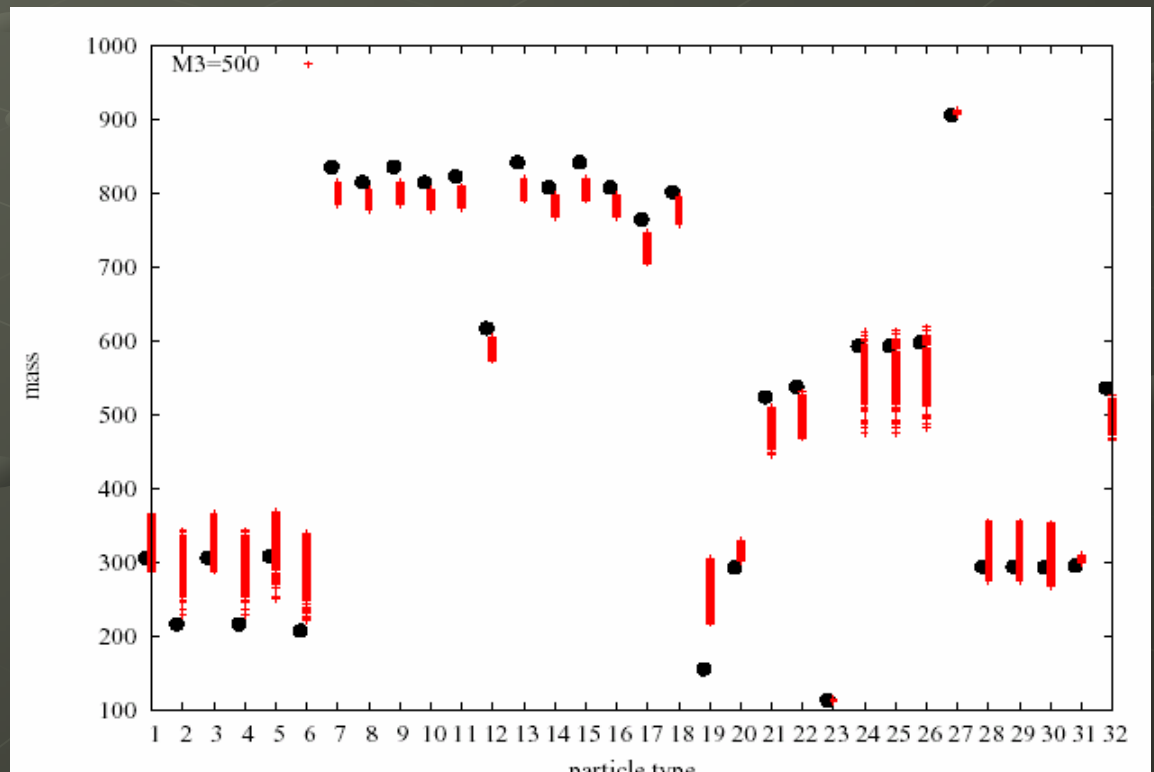
- Spectrum Beyond MSSM

Spectrum uncertainty





Comparison with MSUGRA



Smoking gun?

- Gaugino masses

$$(M_3 : M_2 : M_1)\Big|_{M_Z} = \left(g_3^2 : g_2^2 : k_Y g_1^2\right)\Big|_{M_Z} \sim 6 : 2 : (1.5 \to 2).$$

Large volume

$$(M_3 : M_2 : M_1)\Big|_{M_Z} = \left(g_3^2 : g_2^2 : g_1^2\right)\Big|_{M_Z} \sim 6 : 2 : 1.$$

MSUGRA

- Scalar masses (focus)

$$\frac{d}{dt}\left(\frac{M_3^2}{m_{\tilde{q}}^2}\right) = -3\left(\frac{M_3^2}{m_{\tilde{q}^2}}\right)\left(\frac{g_3^2}{4\pi}\right) + \frac{8}{3}\left(\frac{g_3^2}{4\pi}\right)\left(\frac{M_3^2}{m_{\tilde{q}}^2}\right)^2.$$

Intermediate vs GUT scale !

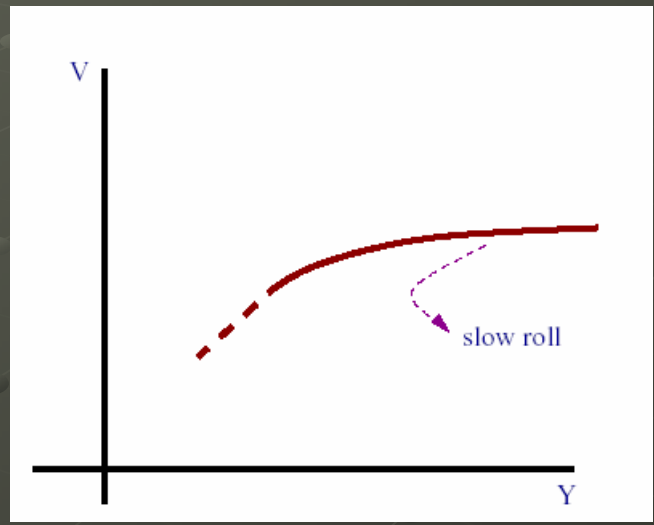
Cosmology

(Inflation, Cosmological moduli problem, etc.)

Inflation

- Need to compute scalar potential from String theory satisfying slow-roll conditions:

$$\epsilon \equiv \frac{M_{Planck}^2}{2}\left(\frac{V'}{V}\right)^2 \ll 1\,,$$
$$\eta \equiv M_{Planck}^2\,\frac{V''}{V} \ll 1\,.$$



Number of e-folds N>60

$$N(t) \equiv \int_{t_{init}}^{t_{end}} H(t')dt' = \int_{\psi_{init}}^{\psi_{end}} \frac{H}{\dot{\psi}}d\psi = \frac{1}{M_{Planck}^2}\int_{\psi_{end}}^{\psi_{init}} \frac{V}{V'}d\psi\,.$$

Density perturbations

$$\delta_H = \frac{2}{5}\mathcal{P}_{\mathcal{R}}^{1/2} = \frac{1}{5\pi\sqrt{3}}\frac{V^{3/2}}{M_p^3\,V'} = 1.91\times10^{-5},$$

$$n-1 = \frac{\partial \ln \mathcal{P}_{\mathcal{R}}}{\partial \ln k} \simeq 2\eta - 6\epsilon\,, \qquad \frac{dn}{d\ln k} \simeq 24\epsilon^2 - 16\epsilon\eta + 2\xi^2\,.$$

$$n_{grav} = \frac{d\ln \mathcal{P}_{grav}(k)}{d\ln k} = -2\epsilon\,.$$

Inflation and Moduli Stabilisation

- Brane-antibrane inflation (also DBI)

- Racetrack inflation

First explicit inflation realisations in string theory

Fine tuning 1/1000 or large fluxes ?

Kähler Moduli Inflation

Conlon-FQ

Bond-Kofman-Prokushkin

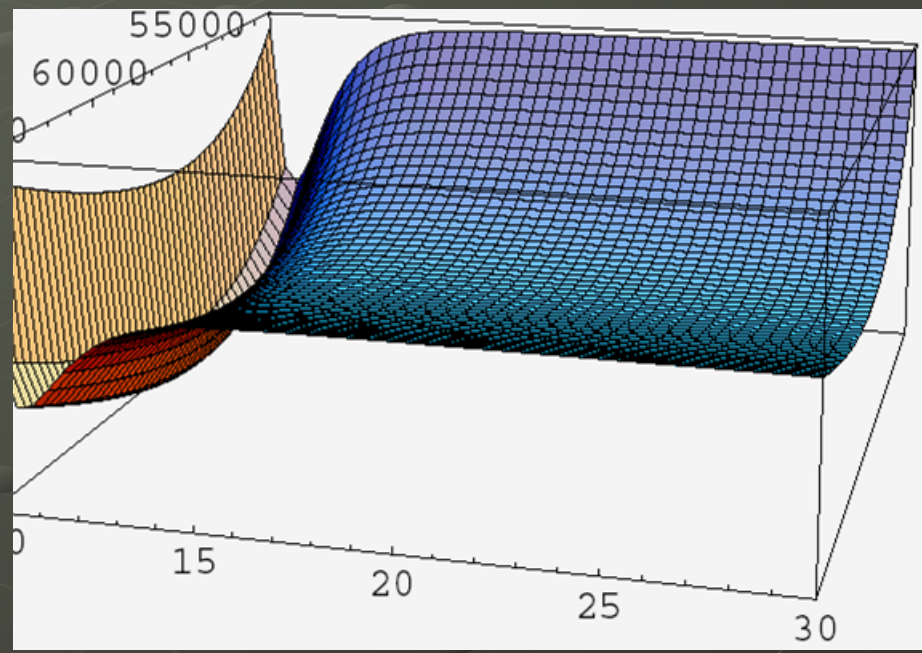
Calabi-Yau:

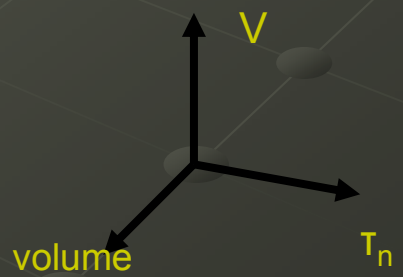
$h_{21}>h_{11}>2$

$$W = W_0 + \sum_{i=2}^{n} A_i e^{-a_i T_i},$$

$$\mathcal{K} = \mathcal{K}_{cs} - 2\ln\left[\alpha\left(\tau_1^{3/2} - \sum_{i=2}^{n}\lambda_i\tau_i^{3/2}\right) + \frac{\xi}{2}\right],$$

$$V = \sum_i \frac{8(a_i A_i)^2\sqrt{\tau_i}}{3\mathcal{V}\lambda_i\alpha}e^{-2a_i\tau_i} - \sum_i 4\frac{a_i A_i}{\mathcal{V}^2}W_0\tau_i e^{-a_i\tau_i} + \frac{3\xi W_0^2}{4\mathcal{V}^3}.$$





Small field inflation

No fine-tuning!!

0.960<n<0.967

GUT scale Ms?, Loops?

Other Cosmological Implications

- Cosmological moduli problem

U,S: trapped at their minimum

T: except for volume, heavy ad decay fast ! (No CMP nor gravitino overproduction)

Volume: (mass MeV) CMP (thermal inflation?). Dark matter?

- Observational implications of light volume modulus?

X-rays, Gamma rays, e^+-e^- (511 KeV?)

CONCLUSIONS

- Exciting times for string phenomenology!
- Soft terms calculable for first time ➡ rich phenomenology
- Intermediate scale strings: hierarchy, QCD axions, neutrino masses (Conlon, Conlon+Cremades)
- Concrete models of inflation
- Model independent light modulus
- Many open questions (A fully realistic model?)

(String Vacuum Project (SVP)?)