String Theory Scenarios Confront Experiments

F. Quevedo, Cambridge.   Strings 2007. Madrid
(J. Conlon, K. Suruliz, D. Cremades, S. Abdussalam,
B. Allanach, S. Kom, M. Cicoli)

hep-th/0609180, 0704.3403[hep-ph], hep-ph/0512081, 0705.3460[hep-ph], to appear

Related work: Choi et al., Acharya et al.

Moduli Stabilisation and Supersymmetry Breaking

Moduli stabilisation and supersymmetry breaking

You all wanted me
to catch him!

Now what should I do with him?

Exponentially Large Volumes

Exponentially Large Volumes

BBCQ, CQS (2005)

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

$\mathbb{P}^4_{[1,1,1,6,9]}$,

$$\mathcal{K} = -2\ln\left(\frac{1}{9\sqrt{2}}\left(\tau_b^{3/2} - \tau_s^{3/2}\right) + \frac{\xi}{2g_s^{3/2}}\right)$$

$$W = W_0 + A_s e^{-a_s T_s}.$$

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

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

$a_s \sim 2\pi/g_s N$

Exponentially large volumen !!!

Scale	$\mathcal{V}_s$	$g_s N$	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

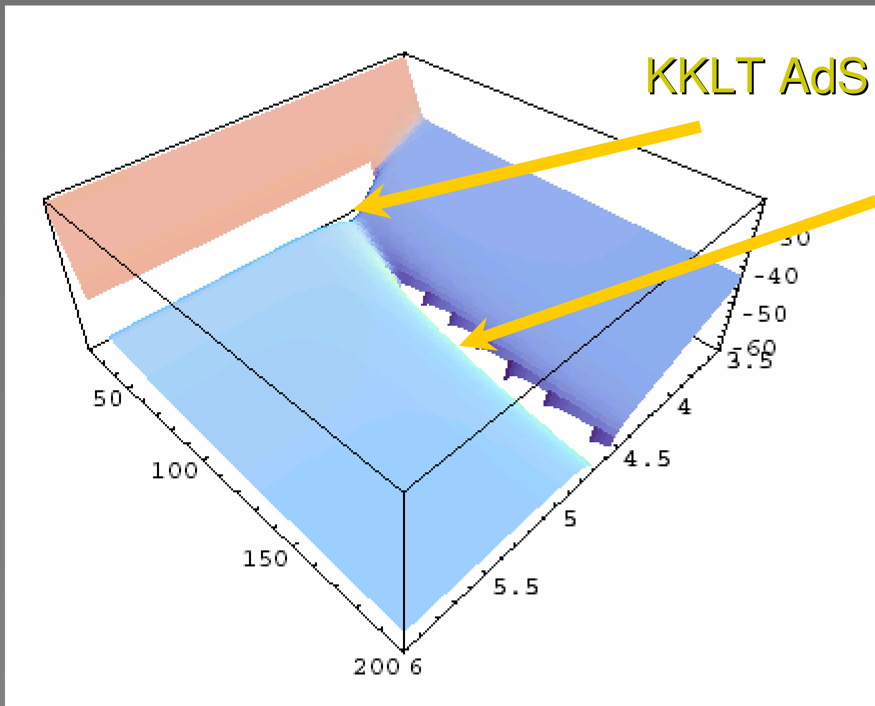
String scale: $M_s^2 = M^2_{Planck}/V$

$W_0 \sim 1\text{-}10$

Robustness: CQS, C (2005), BHKP (2007)

KKLT AdS

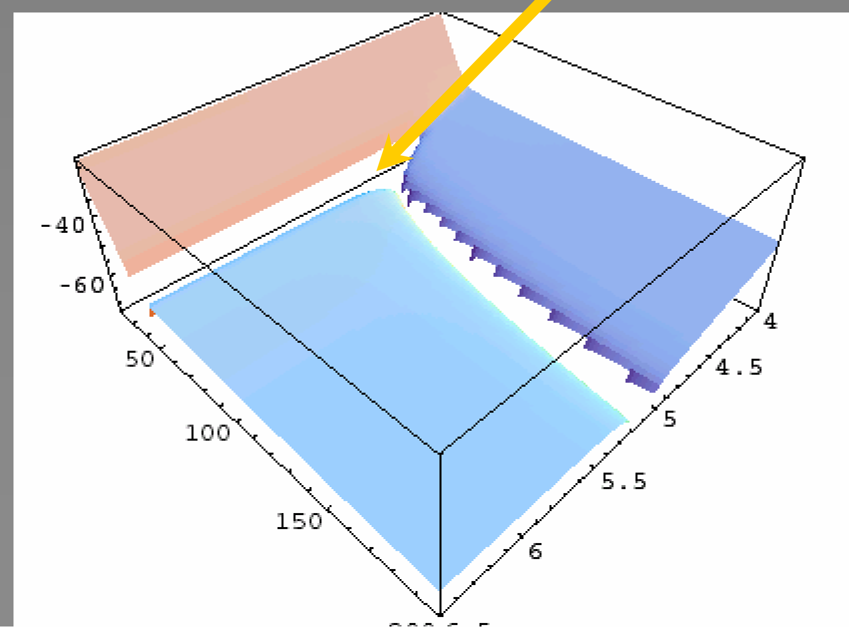
Non SUSY AdS



$W_0 \sim 10^{-10}$

Both minima close

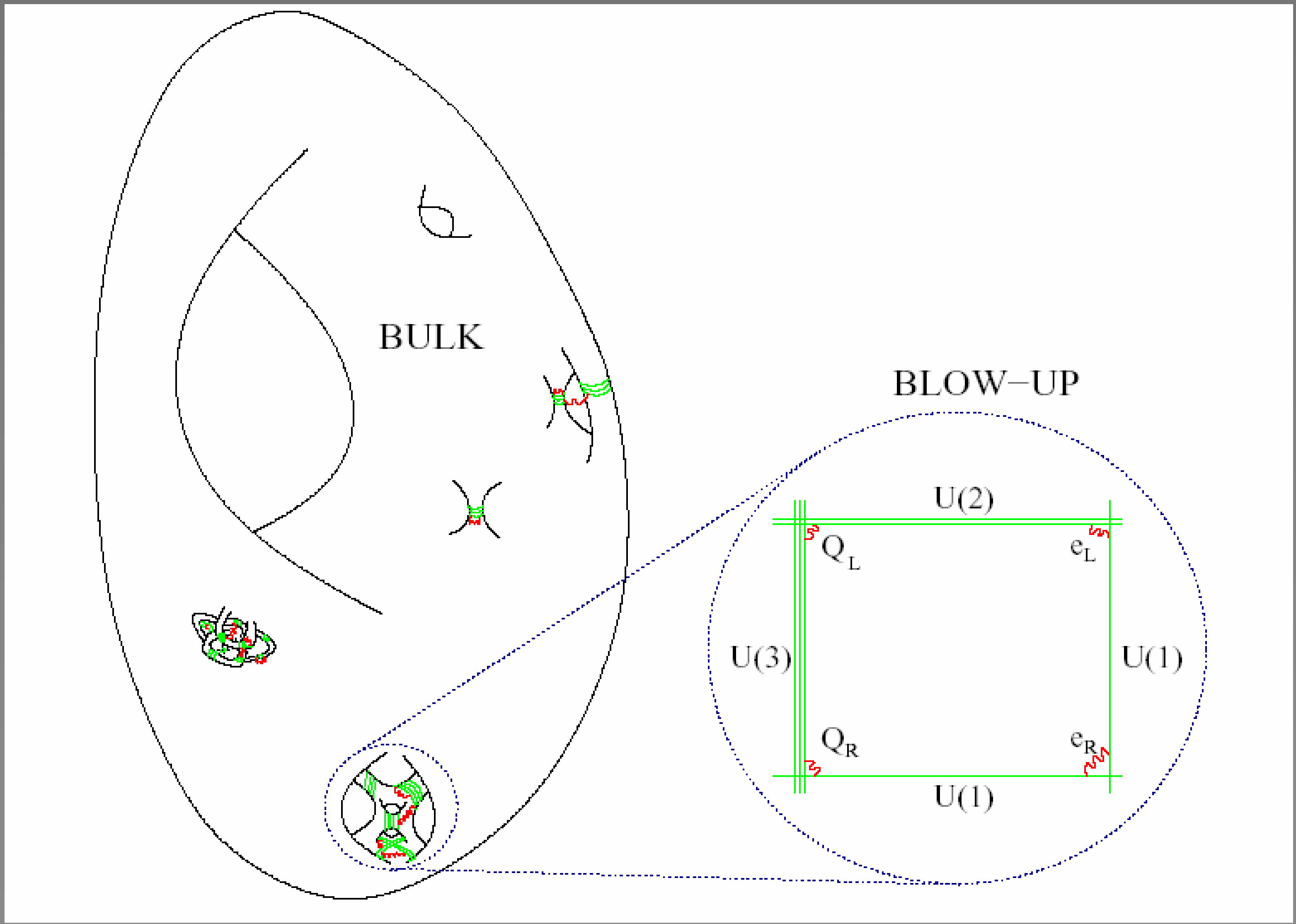
$W_0 < 10^{-11}$



Modular Model Building

(Bottom up approach)

The Standard Model in the CY



Bottom-up Approach

Aldazabal,Ibanez, FQ, Uranga 2000

Verlinde,Wijnholt 2006

Local (brane) Properties

- Gauge group
- Chiral spectrum
- Yukawa couplings
- Gauge unification
- Proton stability
- Baryogenesis
- Reheating

Global (bulk) Properties

- Moduli Stabilisation
- SUSY Breaking
- Soft terms
- Cosmological constant
- Inflation

PHENOMENOLOGY

(From Strings to LHC)

Standard Model on D3 Brane Two General Scenarios

- Intermediate Scale Split SUSY

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

- Stringy mSUGRA

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

Do not solve hierarchy problem(?)

Standard Model on D7 Branes

- Solve hierarchy problem $M_{string} = 10^{11}$ GeV!

$$m_s \sim \frac{M_P}{\sqrt{\mathcal{V}}}, \qquad m_{3/2} \sim \frac{M_P}{\mathcal{V}} W_0.$$

- W_0~1 (no fine tuning)

- Kahler potential for *chiral* matter computed

Conlon, Cremades, FQ (2006)

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

$$W = \hat{W}(\Phi) + \mu(\Phi) H_1 H_2 + \frac{1}{6} Y_{\alpha\beta\gamma}(\Phi) C^\alpha C^\beta C^\gamma + \ldots,$$

$$K = \hat{K}(\Phi, \bar{\Phi}) + \tilde{K}_{\alpha\bar{\beta}}(\Phi, \bar{\Phi}) C^\alpha C^{\bar{\beta}} + \left[Z(\Phi, \bar{\Phi}) H_1 H_2 + h.c.\right] + \ldots,$$

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

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

New!

Chiral matter in CY

Conlon, Cremades, FQ

Chiral Matter on D7 Branes
Soft SUSY Breaking terms

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

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

Simplest case
$\lambda=1/3$

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

Stringy source of universality
(approximate)

$\Psi \Longleftrightarrow$ Kähler moduli,

$\chi \Longleftrightarrow$ Complex structure moduli.

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

Approximate no-scale + locality

Also: Anomaly mediation suppressed !!!

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 !

From Strings to LHC data

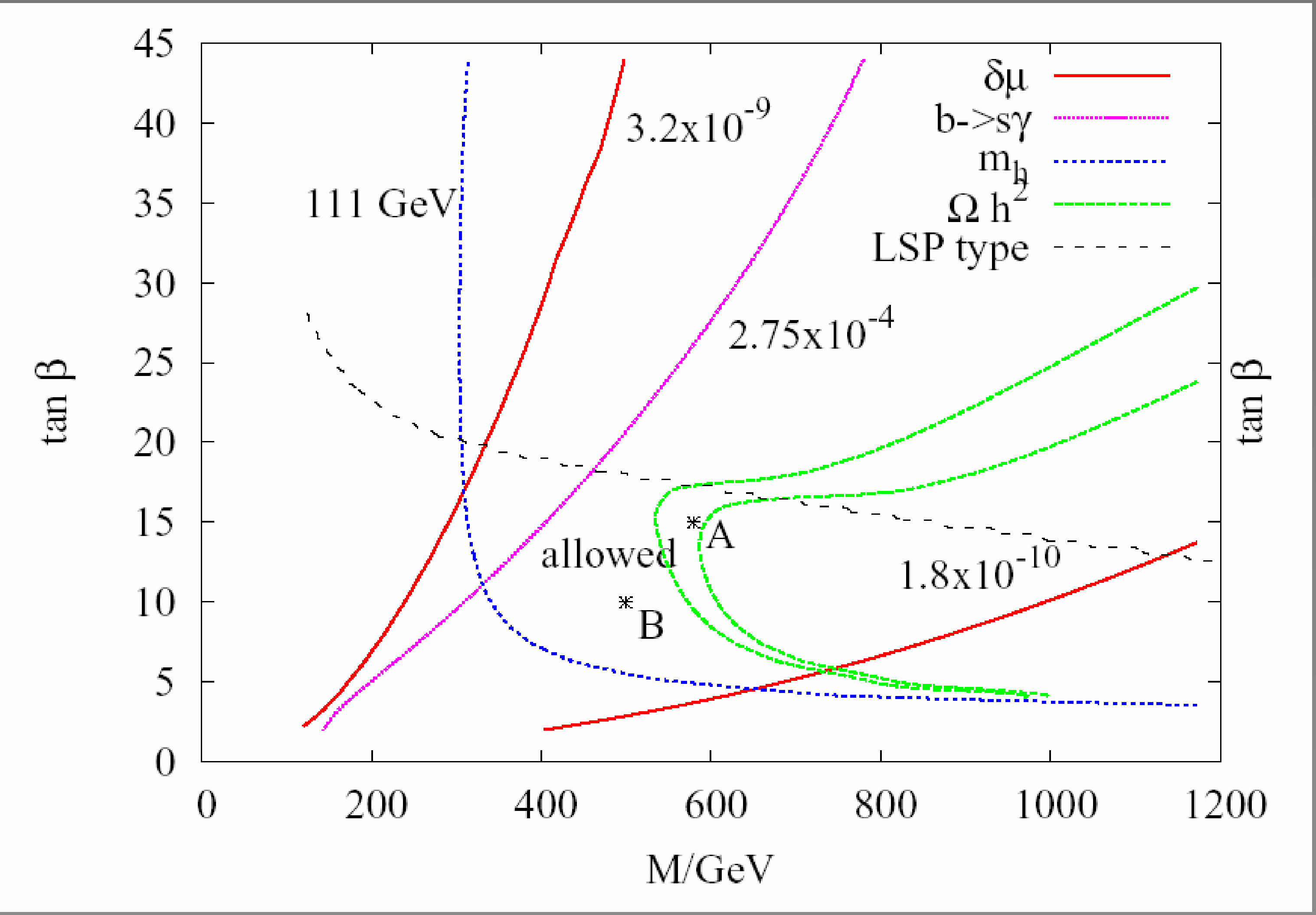
CKSAQ 0705.3460[hep-ph],

- 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, ATLASFAST) 10^{-1} fb
- Data Analysis and reconstruction (Root) 100^{-1} fb
- Estimate overall uncertainty

Thanks: CAMGRID !

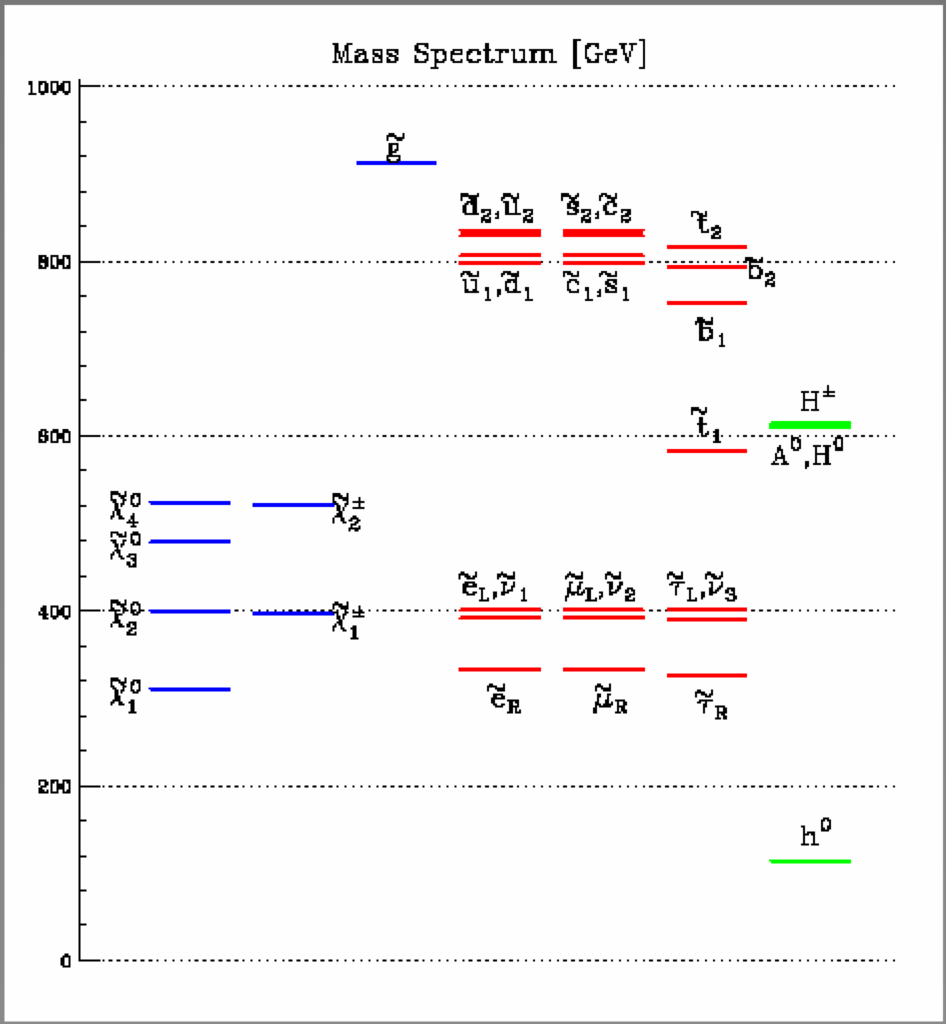
Renormalisation group running

Allowed Regions



	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	—

Low energy spectrum



Sources of uncertainty

- Gaugino masses

Dilute flux limit

$$f_{SU(3)} = \frac{T_s}{4\pi},$$
$$f_{SU(2)} = \frac{T_s}{4\pi},$$
$$f_{U(1)_Y} = k_Y \frac{T_s}{4\pi}.$$

Physical case

$$f_{SU(3)} = \frac{T_s}{4\pi} + h_{SU(3)}(F)S,$$
$$f_{SU(2)} = \frac{T_s}{4\pi} + h_{SU(2)}(F)S,$$
$$f_{U(1)_Y} = k_Y \left(\frac{T_s}{4\pi} + h_{U(1)}(F)S\right).$$

Dilute flux limit

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

Physical case

$$M_1 = \frac{F^s}{2(\tau_s + 4\pi h_1(F)\mathrm{Re}(S))},$$
$$M_2 = \frac{F^s}{2(\tau_s + 4\pi h_2(F)\mathrm{Re}(S))},$$
$$M_3 = \frac{F^s}{2(\tau_s + 4\pi h_3(F)\mathrm{Re}(S))},$$

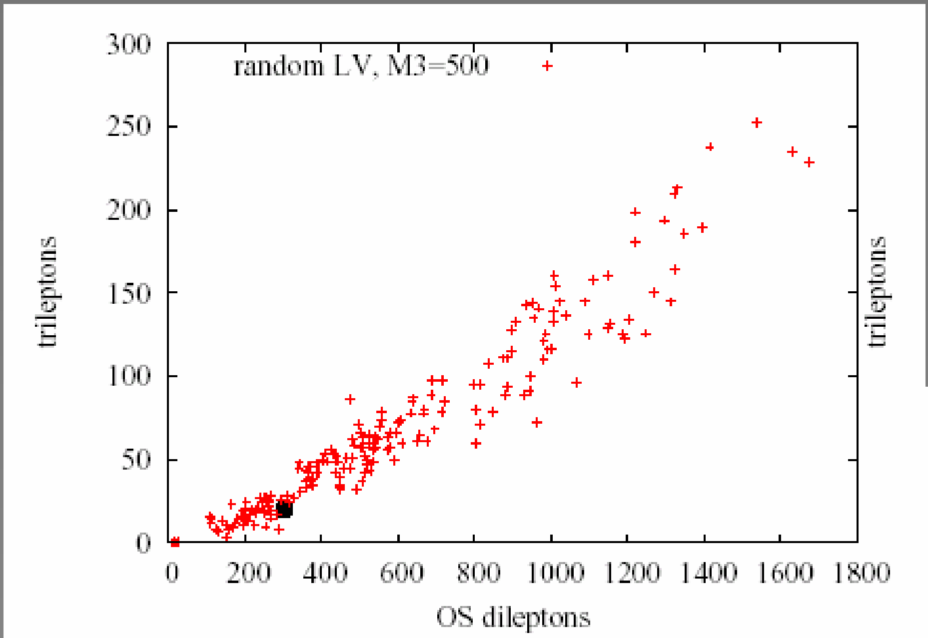
- Scalar soft terms

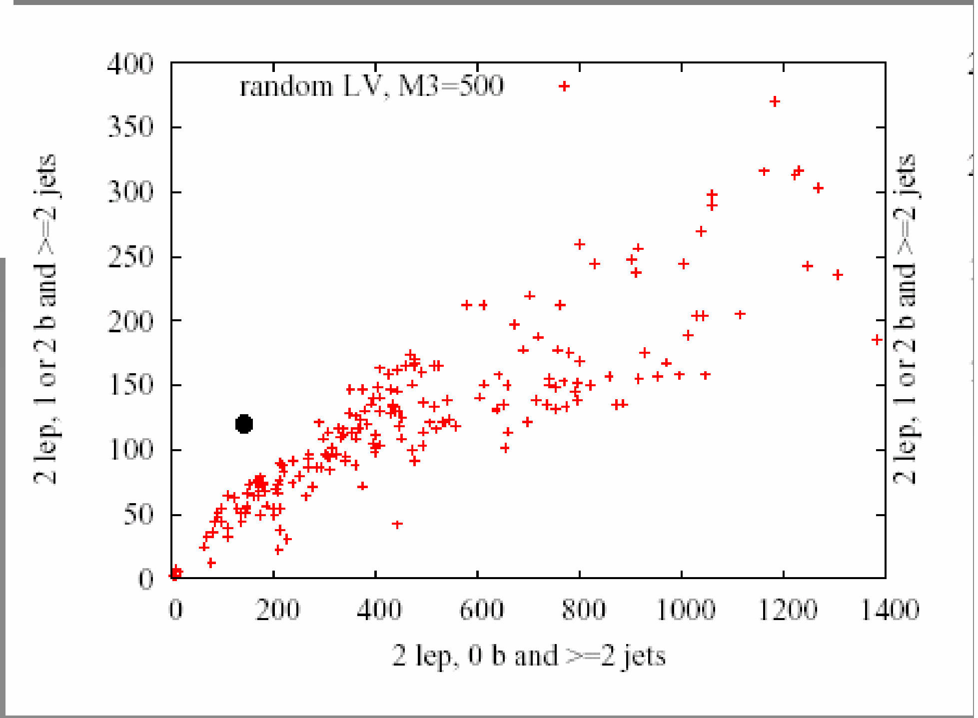
$$\tilde{K}_\alpha = \frac{(\tau_s + \epsilon_\alpha(F))^{1/3}}{\mathcal{V}^{2/3}}.$$

$$m_\alpha = \frac{1}{\sqrt{3}} \frac{F^s}{2(\tau_s + \epsilon_\alpha(F))},$$
$$A_{\alpha\beta\gamma} = -\frac{1}{\sqrt{3}}(m_\alpha + m_\beta + m_\gamma).$$

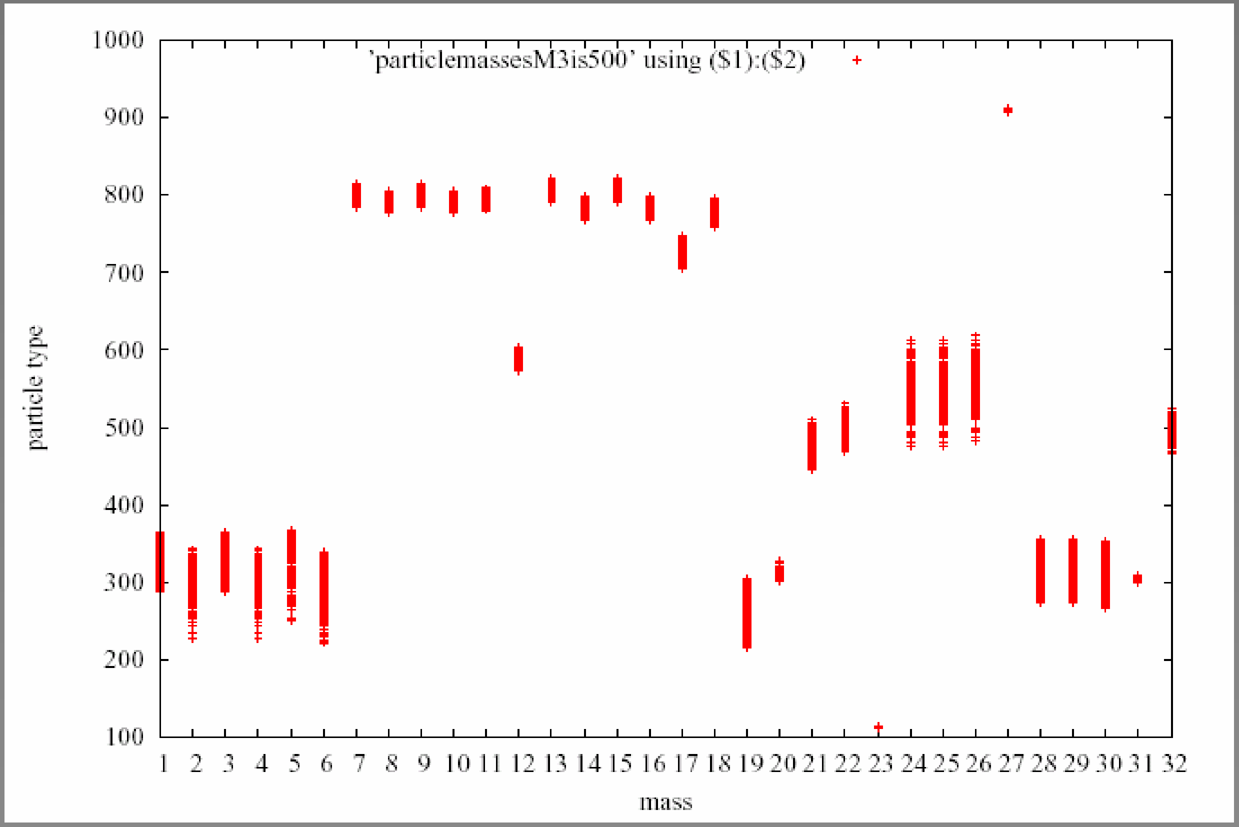
- Spectrum Beyond MSSM

Some observables

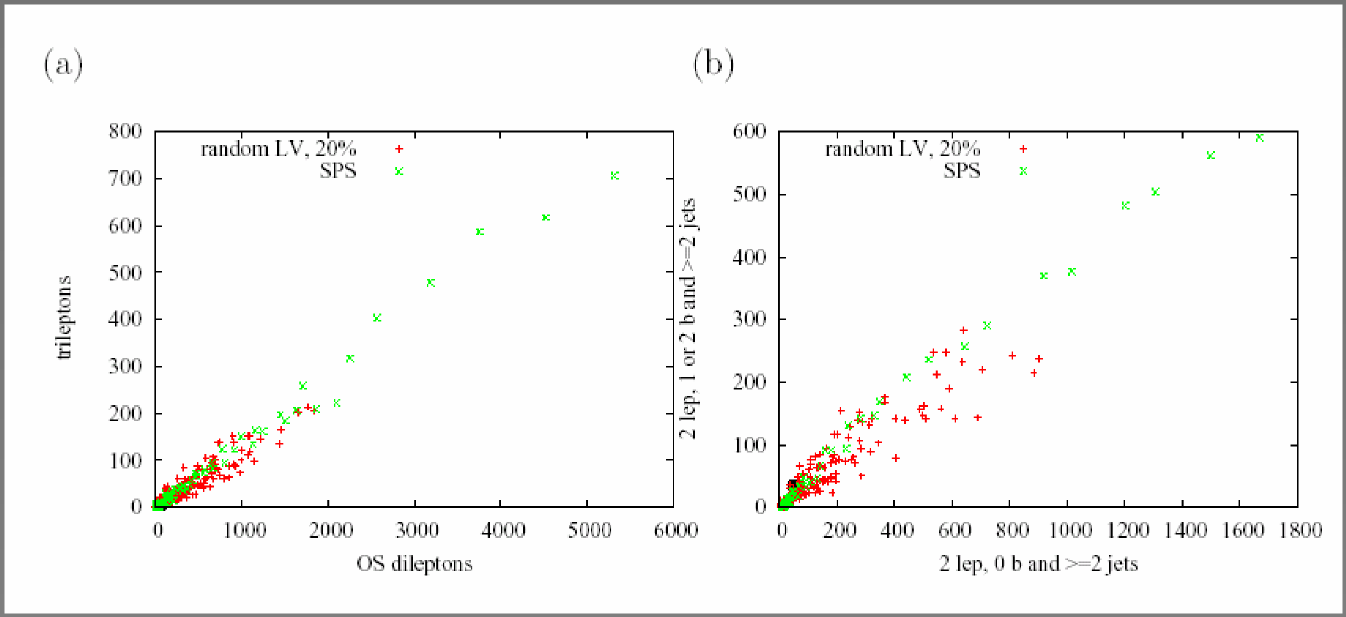


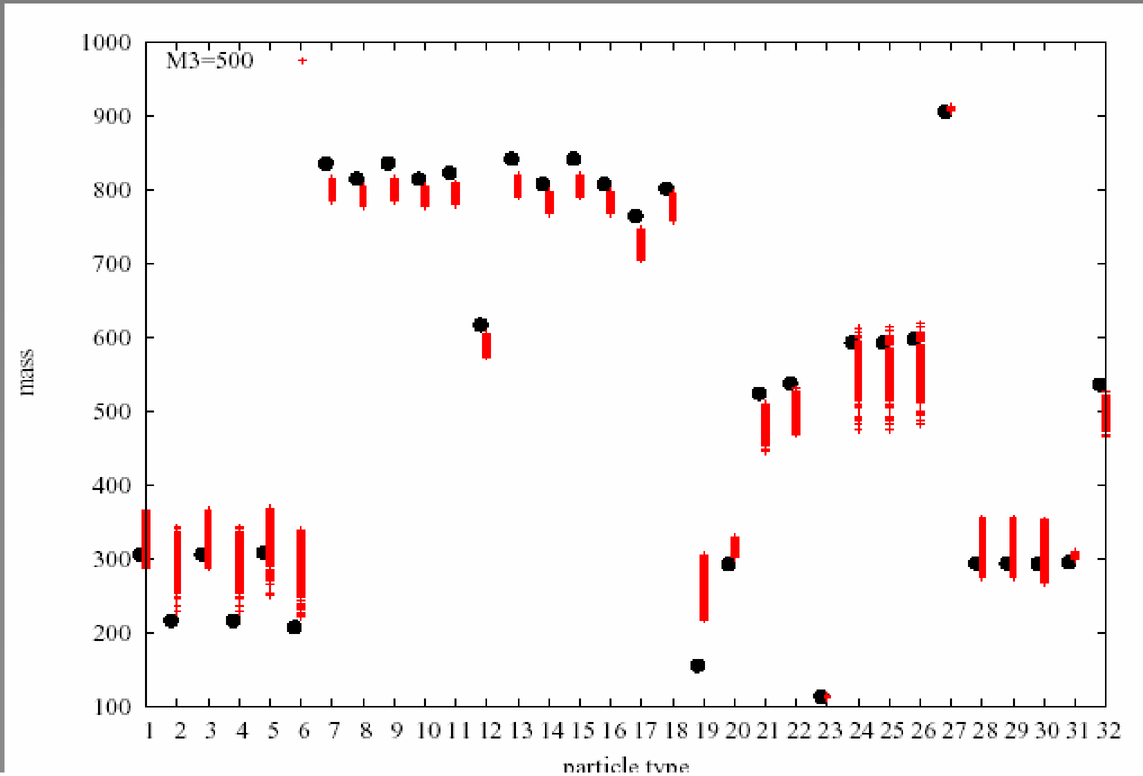


Spectrum uncertainty



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

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

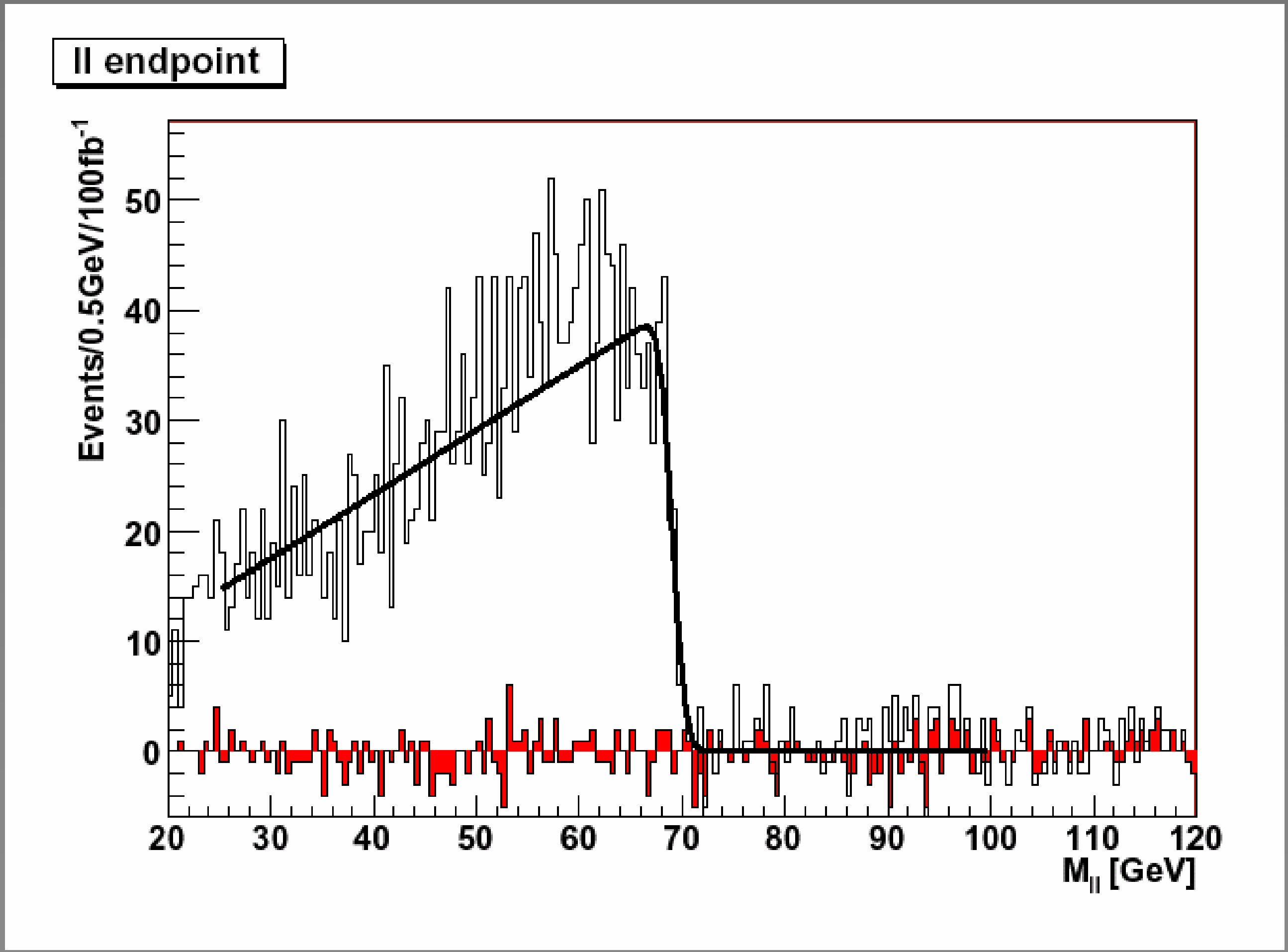
MSUGRA

- 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 !

Reconstruction?



$\tilde{\chi}_2^0 \to \tilde{l}^{\pm} l^{\mp} \to \tilde{\chi}_1^0 l^{\pm} l^{\mp}$

$$(m_{\tilde{q}_L} - m_{\tilde{\chi}_1^0})/(m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0}) = 8.09 \pm 0.38.$$

Cosmology

(Inflation, Cosmological moduli problem, etc.)

Kähler Moduli Inflation

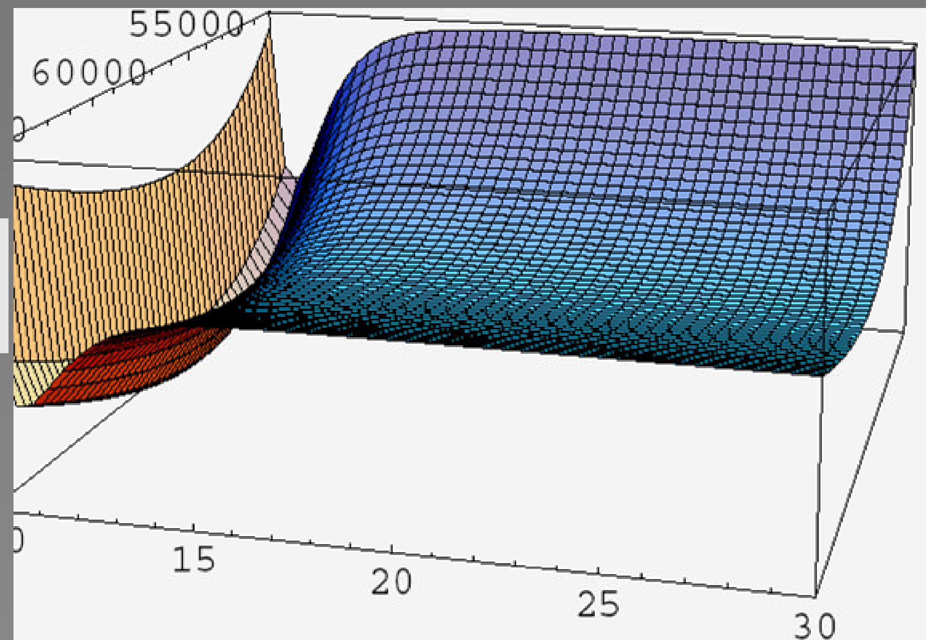
Conlon-FQ

Bond-Kofman-Prokushkin

Calabi-Yau:

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

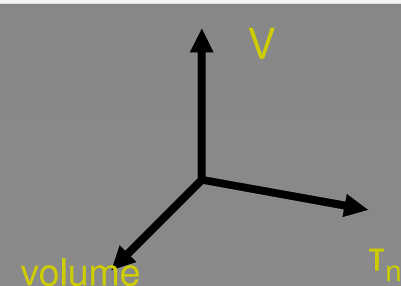
$$V=\sum_i \frac{8(a_iA_i)^2\sqrt{\tau_i}}{3\mathcal{V}\lambda_i\alpha}e^{-2a_i\tau_i}-\sum_i 4\frac{a_iA_i}{\mathcal{V}^2}W_0\tau_i e^{-a_i\tau_i}+\frac{3\xi W_0^2}{4\mathcal{V}^3}.$$



Small field inflation

No fine-tuning!!

$0.960<n<0.967$



GUT scale Ms?, Loops?

See Andrei + Renata’s talks

Physics of Moduli Fields

Moduli masses:

- Dilaton and Complex Structure

$$m_{3/2} \sim \frac{M_P}{\mathcal{V}}, \qquad m_s \sim \frac{M_P}{\sqrt{\mathcal{V}}}.$$

- Small (heavy) Kahler moduli

$$m_{\tau_s} \sim \frac{M_P \ln(M_P/m_{3/2})}{\mathcal{V}}.$$

- Large (light) Kahler modulus

$$m_{\tau_b} \sim \frac{M_P}{\mathcal{V}^{3/2}},$$

Physical Fields

$$\delta\tau_b = \left(\sqrt{6}\langle\tau_b\rangle^{1/4}\langle\tau_s\rangle^{3/4}(1-2\epsilon)\right)\frac{\Phi}{\sqrt{2}} + \left(\sqrt{\frac{4}{3}}\langle\tau_b\rangle\right)\frac{\chi}{\sqrt{2}} \sim \mathcal{O}\left(\mathcal{V}^{1/6}\right)\Phi + \mathcal{O}\left(\mathcal{V}^{2/3}\right)\chi$$

$$(3.7)$$

$$\delta\tau_s = \left(\frac{2\sqrt{6}}{3}\langle\tau_b\rangle^{3/4}\langle\tau_s\rangle^{1/4}\right)\frac{\Phi}{\sqrt{2}} + \left(\frac{\sqrt{3}}{a_s}(1-2\epsilon)\right)\frac{\chi}{\sqrt{2}} \sim \mathcal{O}\left(\mathcal{V}^{1/2}\right)\Phi + \mathcal{O}(1)\,\chi$$

Decay Rates

$$\lambda_{\chi\gamma\gamma} = \frac{\sqrt{6}}{2M_P \ln\left(M_P/m_{3/2}\right)},$$

$$\delta\mathcal{L}_{\chi ee} \sim \left(1 + \frac{1}{a\langle\tau_s\rangle}\right)\frac{1}{\sqrt{6}}\frac{\chi}{M_P}m_e\bar{e}e.$$

$$\lambda_{\Phi\gamma\gamma} \sim \left(\frac{2}{\sqrt{3}}\frac{\langle\tau_b\rangle^{3/4}}{\langle\tau_s\rangle^{3/4}M_P}\right) \sim \frac{\sqrt{\mathcal{V}}}{M_P} \sim \frac{1}{m_s}.$$

$$\delta\mathcal{L}_{\Phi ee} \sim \frac{\sqrt{\mathcal{V}}\chi}{M_P}m_e\bar{e}e \sim \frac{\chi}{m_s}m_e\bar{e}e.$$

Summary

	Light modulus χ	Heavy Modulus Φ
Mass	$\sim m_{3/2}\left(\frac{m_{3/2}}{M_P}\right)^{\frac{1}{2}} \sim 2\text{MeV}$	$2\ m_{3/2}\ln(M_p/M_{3/2}) \sim 1200\text{TeV}$
Matter Couplings	M_P^{-1} (electrons) $\left(M_P \ln\left(\frac{M_P}{m_{3/2}}\right)\right)^{-1}$ (photons)	m_s^{-1}
Decay Modes		
$\gamma\gamma$	$\text{Br} \sim 0.025,\quad \tau \sim 6.5 \times 10^{25}\text{s}$	$\text{Br} \sim \mathcal{O}(1),\quad \tau \sim 10^{-17}\text{s}$
e^+e^-	$\text{Br} \sim 0.975,\quad \tau \sim 1.7 \times 10^{24}\text{s}$	$\text{Br} \sim \mathcal{O}(1),\quad \tau \sim 10^{-17}\text{s}$
$q\bar{q}$	inaccessible	$\text{Br} \sim \mathcal{O}(1),\quad \tau \sim 10^{-17}\text{s}$
$\psi_{3/2}\psi_{3/2}$	inaccessible	$\text{Br} \sim 10^{-30},\quad \tau \sim 10^{13}\text{s}$

Other Cosmological Implications

J.Conlon, FQ

- Cosmological moduli problem

DCQR, BKN

U,S: trapped at their minimum

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

Volume: (mass MeV) CMP

- Observational implications of light volume modulus?

Gamma rays, e^{+}-e^{-}

Solution of CMP?

Thermal Inflation

Lyth+Stewart (1995)

$$V = V_0 + (T^2 - m_\sigma^2)\,\sigma^2 + \cdots$$

$$\langle \sigma \rangle \equiv M_* \gg m_\sigma .$$

$$m_\sigma \sim 1 \text{ TeV and } M_* \sim 10^{11} \text{ GeV}$$

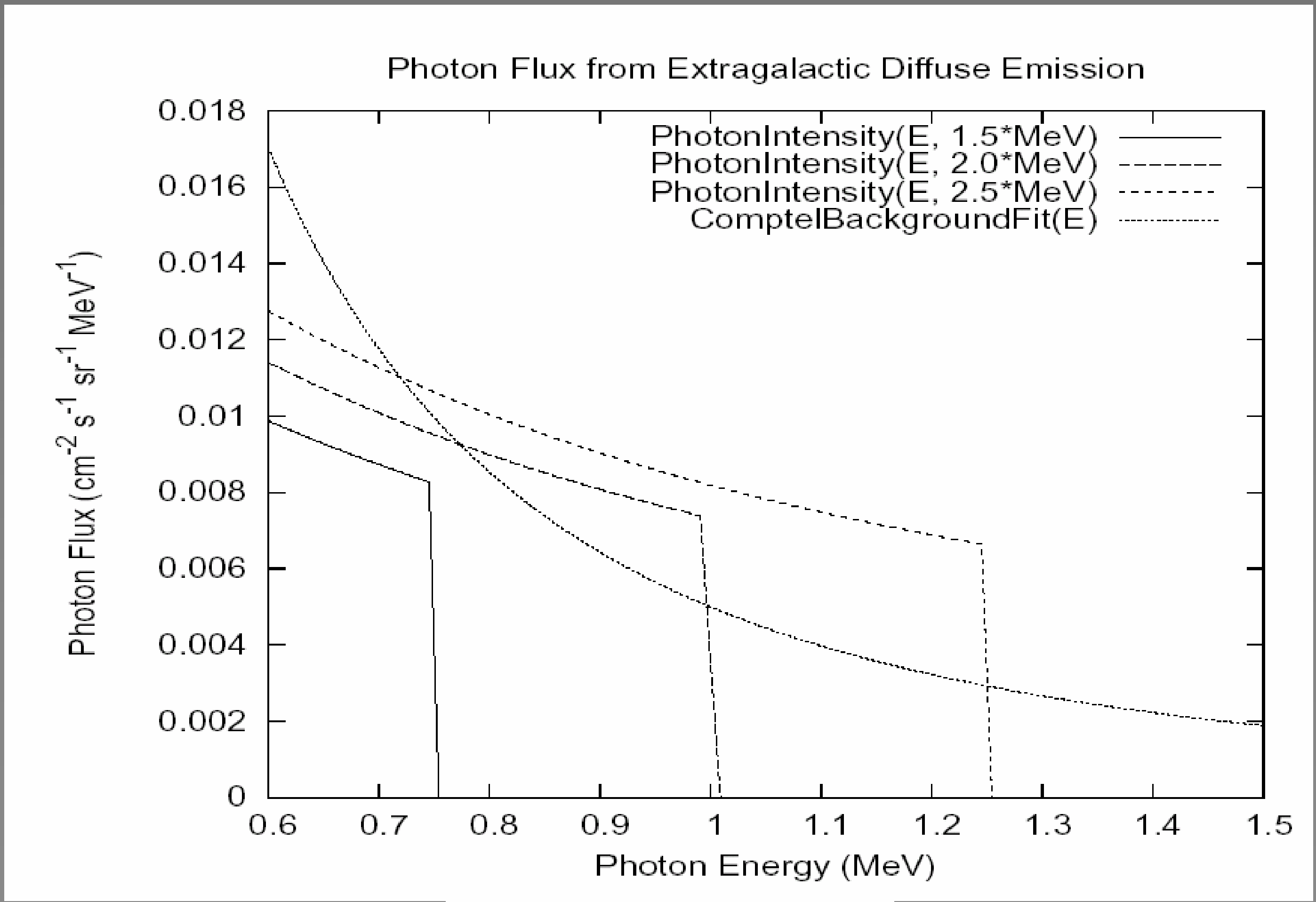
Number of e-folds

$$N \sim \log\left(V_0^{1/4}/T_c\right) \sim \log\,(M_*/m_\sigma)^{1/2}$$

N~10 dilutes moduli !!

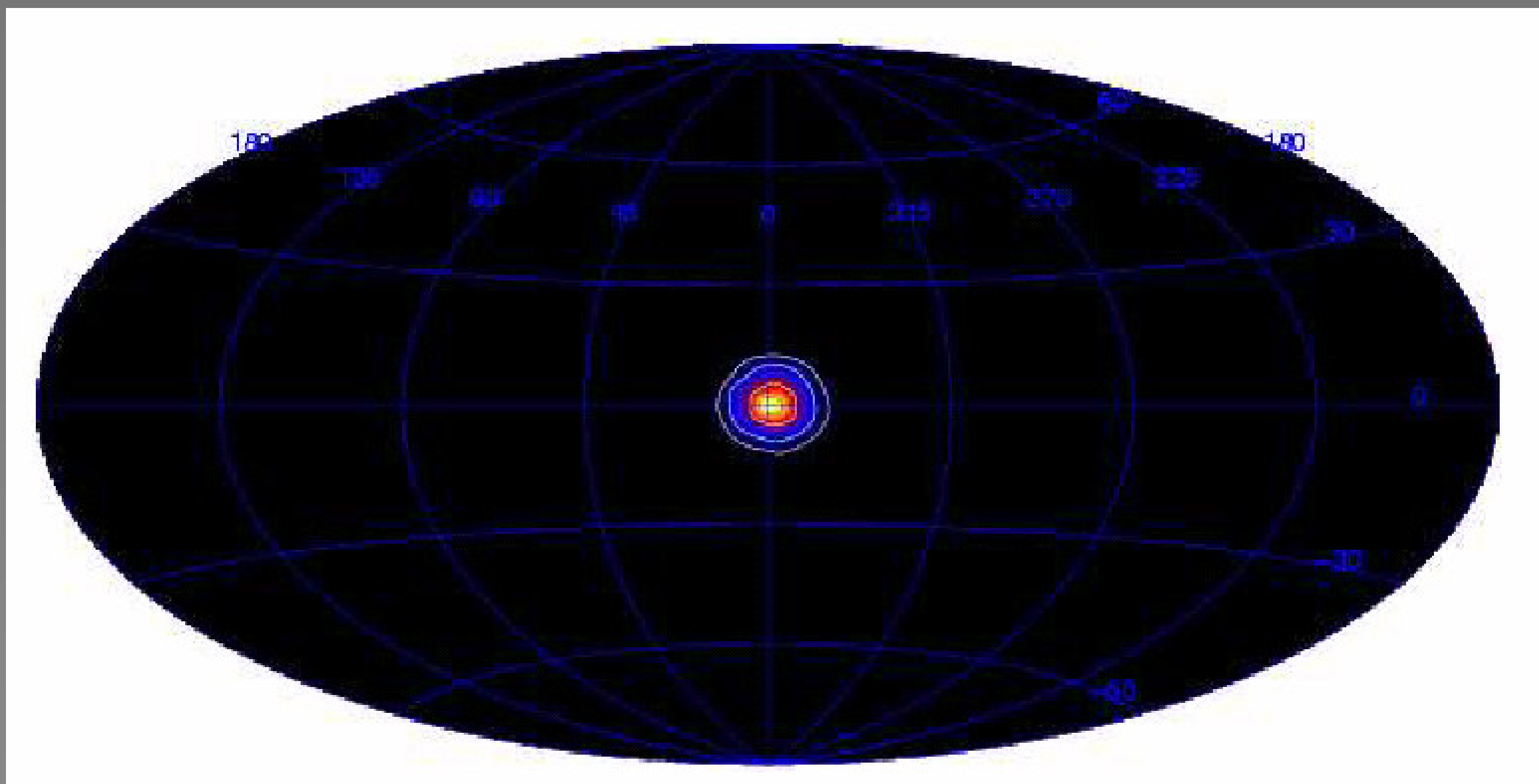
Late time implications:

Diffuse Gamma Ray Background

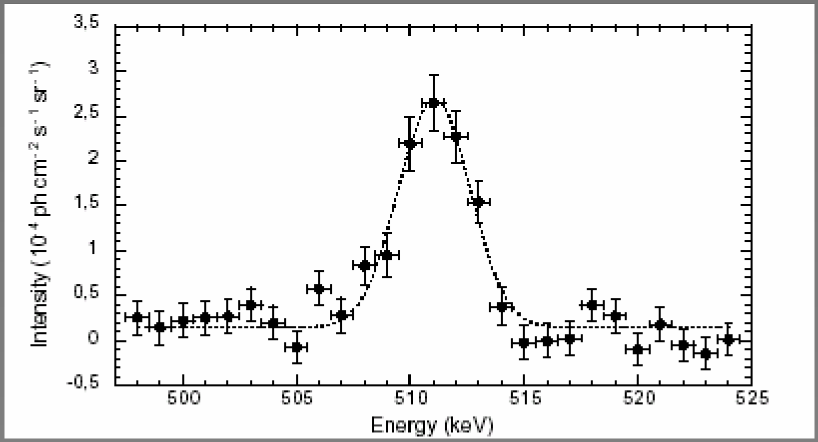


$$\frac{\Omega_\chi}{\Omega_m} \lesssim \left(\frac{1\mathrm{MeV}}{m_\chi}\right)^{3.5} .$$

The 511 keV Line



INTEGRAL/ SPI 511 keV line

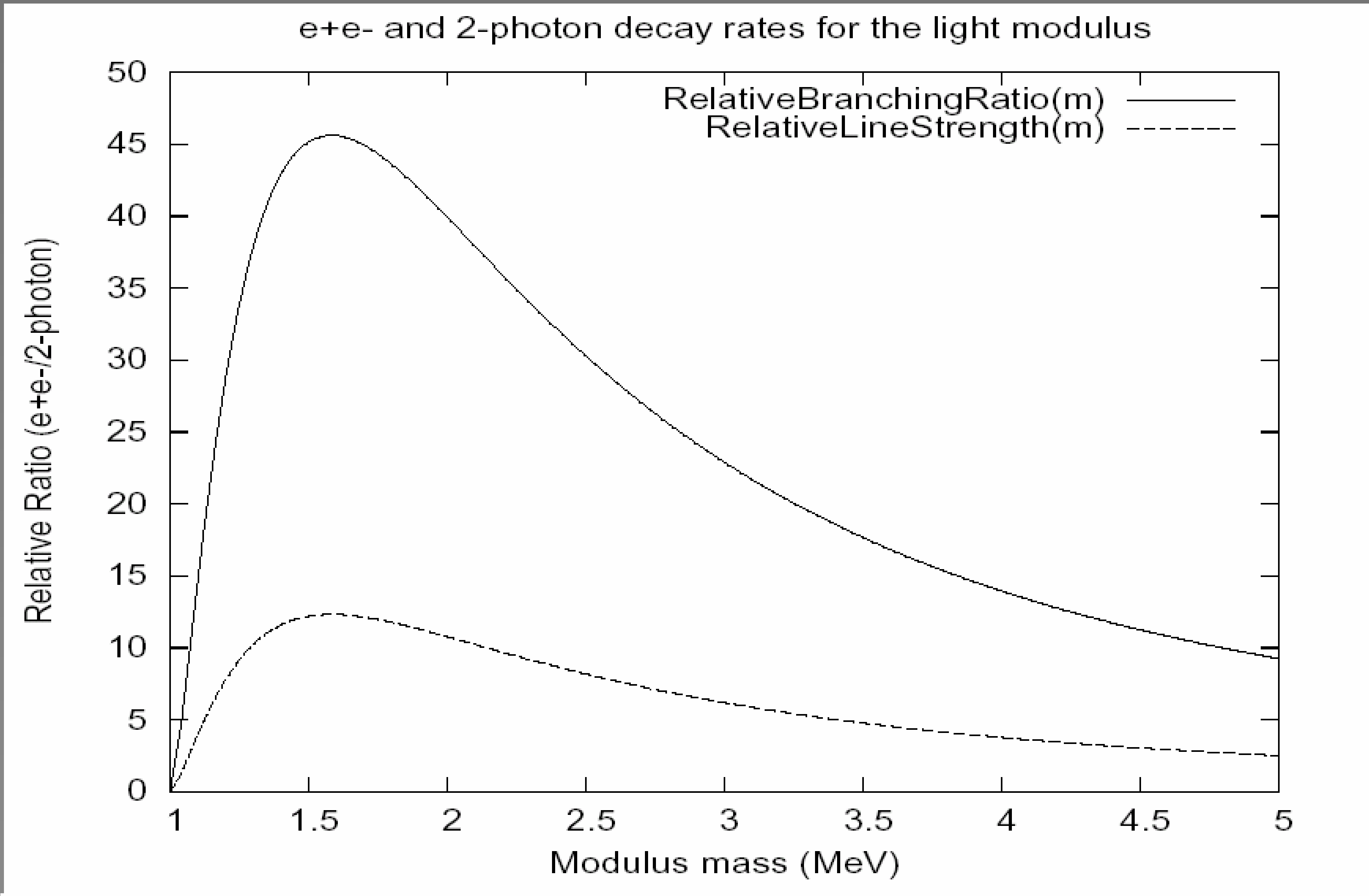


Light Modulus χ: Dark matter?

Mass 1MeV, coupling to electrons dominant

511 keV from volume modulus decay?

Prediction! Monochromatic line at $m_\chi/2$)



$$\frac{\Omega_\chi}{\Omega_{dm}} \lesssim 10^{-3} \left(\frac{2\mathrm{MeV}}{m_\chi}\right)^2.$$

Intensity $\sim 8 \times 10^{-5}\mathrm{photons\ cm^{-2}s^{-1}}$

INTEGRAL $\lesssim 5 \times 10^{-5}\mathrm{photons\ cm^{-2}s^{-1}}$

CONCLUSIONS

- Exciting times for string phenomenology!
- Soft terms calculable → rich phenomenology
- Intermediate scale strings: hierarchy, QCD axions, neutrino masses (Conlon, Conlon+Cremades)
- Distinctive moduli cosmology
- Concrete models of inflation
- Model independent light modulus → (CMP, 511 keV? Prediction!)
- Many open questions

M_{GUT} vs 10^{11} GeV scales?

Fully realistic model?...