Cosmological and Astrophysical Implications of Large Volume String Models

F. Quevedo, Cambridge. String Cosmology Phenomenologyy, Stockholm 2007

(J. Conlon + FQ hep-th/050912, 0705.3460[hep-ph],+…+ to appear)

Moduli Stabilisation

Moduli Stabilisation

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

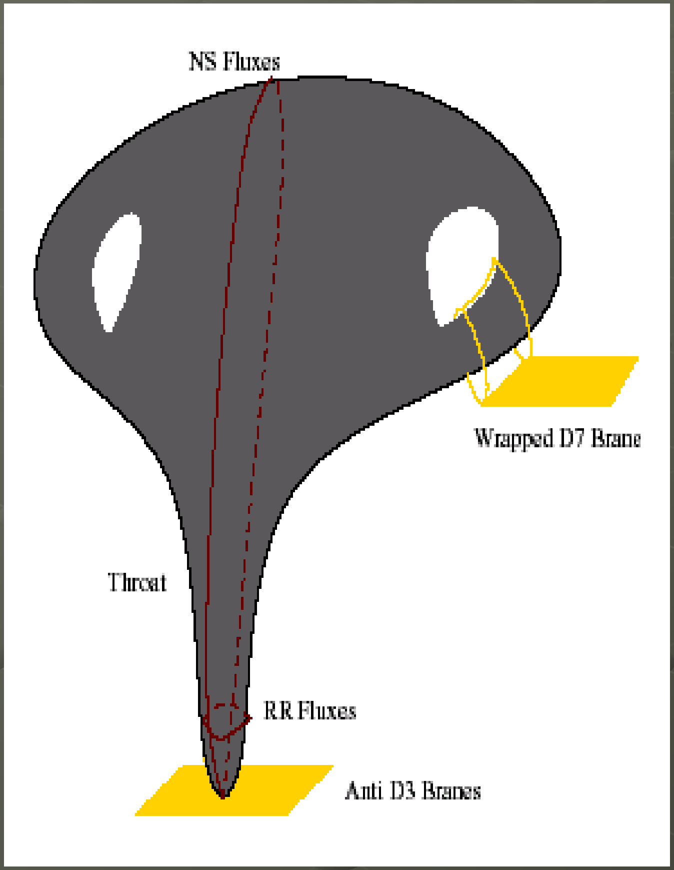
Scalar Potential: $V = e^K \, |D_a W|^2$

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

GKP

Kähler moduli: Non-perturbative D7 effects

KKLT



Fluxes

Non-perturbative

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

Volume

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

SUSY AdS minimum

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

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

($W_0 << 1$)

Exponentially Large Volumes

Exponentially Large Volumes

BBCQ, CQS

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

Example :

$$\mathcal{K} = \mathcal{K}_{cs} - 2\ln\left(\mathcal{V} + \frac{\xi}{2}\right)$$

$$\mathcal{V} = \frac{1}{9\sqrt{2}}\left(\tau_5^{\frac{3}{2}} - \tau_4^{\frac{3}{2}}\right)$$

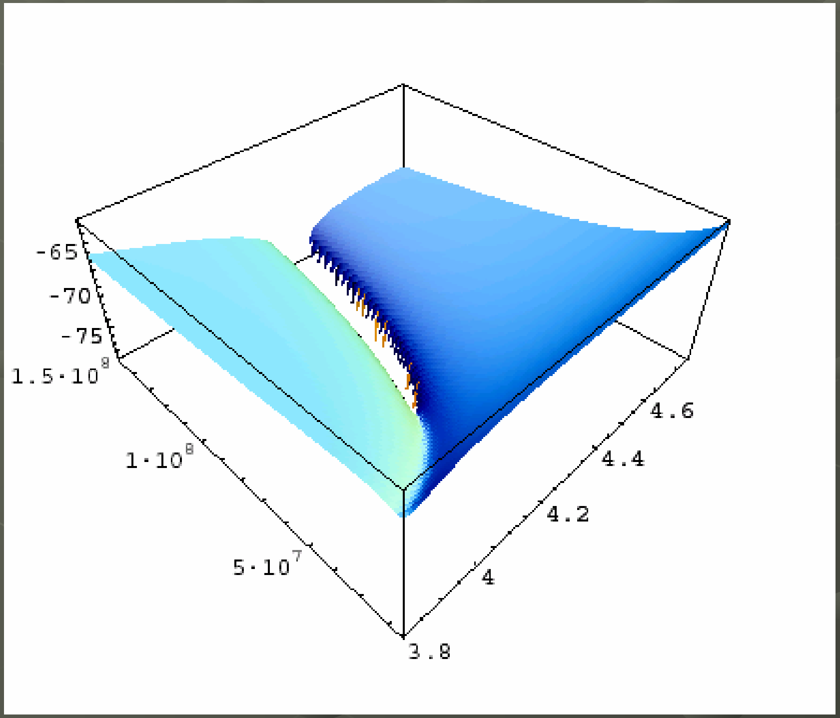
$$W = W_0 + A_4 e^{-\frac{a_4}{g_s}T_4} + A_5 e^{-\frac{a_5}{g_s}T_5}.$$

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

Exponentially large !

Non SUSY AdS

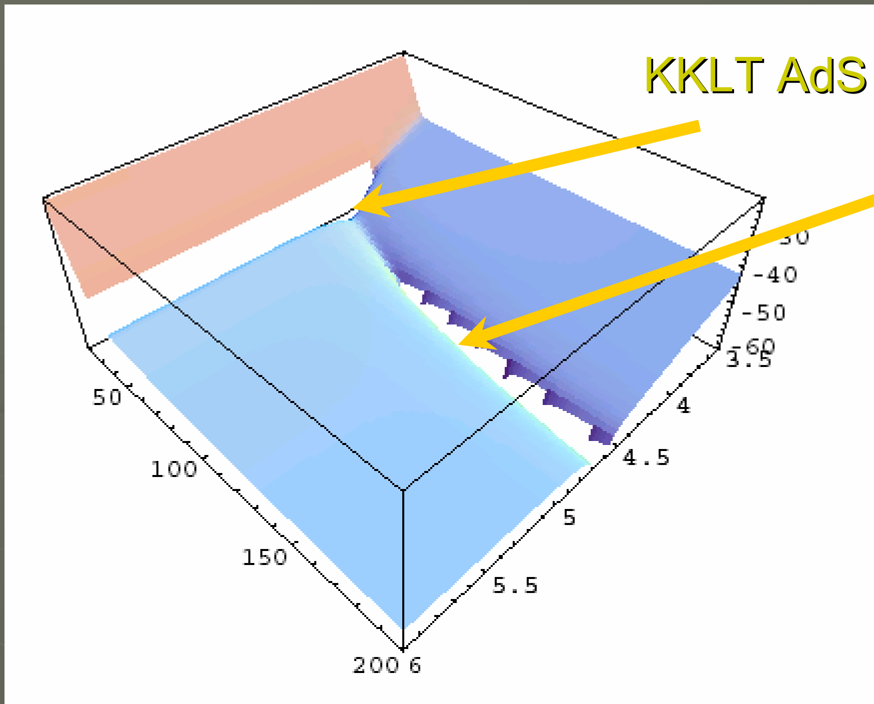
$$V = \sum_{\Phi=S,U} \frac{\mathcal{K}^{\Phi\bar{\Phi}} D_\Phi W \bar{D}_{\bar{\Phi}} \bar{W}}{\mathcal{V}^2} + \frac{(a_s A_s)^2 e^{-2a_s\tau_s}}{\mathcal{V}} - \frac{W_0 a_s A_s e^{-a_s\tau_s}}{\mathcal{V}^2} + \frac{\xi |W_0|^2}{g_s^{3/2}\mathcal{V}^3}.$$



W_0~1-10

String scale: $M_s^2 = M_p^2/V$

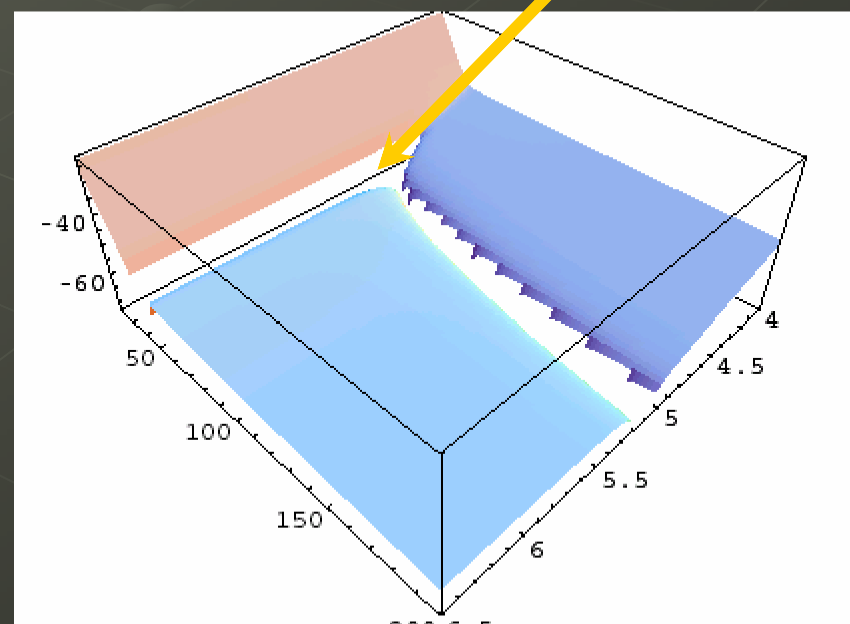
Scale	$\mathcal{V}_s$	$g_s N$	N if $g_s = 0.1$
GUT	4600	2.25	22
Intermediate	4.6×10^9	0.85	9
TeV	4.6×10^{27}	0.30	3



Non SUSY AdS

$W_0 \sim 10^{-10}$

Both minima close

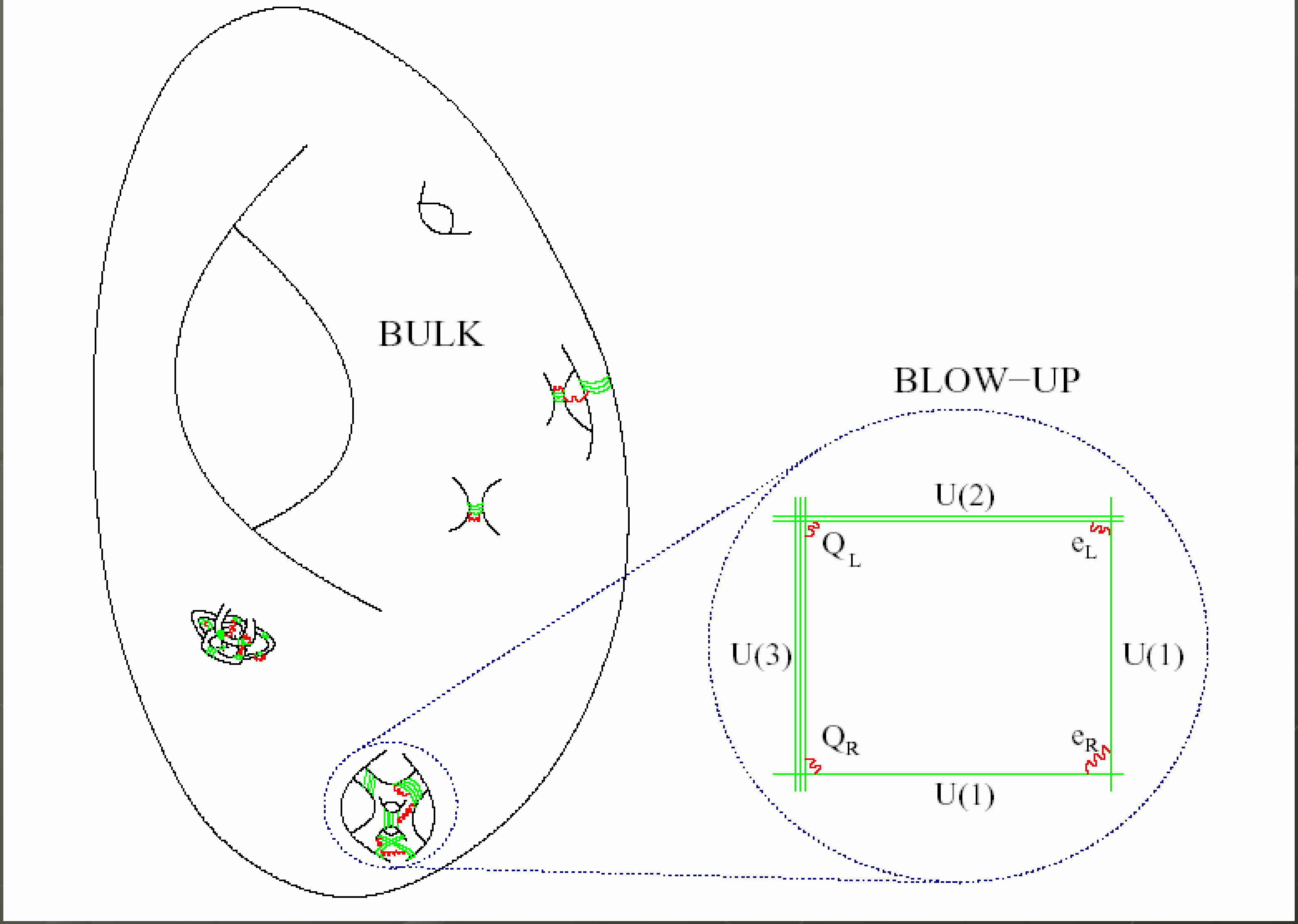


$W_0 < 10^{-11}$

Modular Model Building

(Bottom up approach)

The Standard Model in the CY



Bottom up Approach

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

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

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

Chiral Matter on D7 Branes
Soft SUSY Breaking terms

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

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

Simplest case

Conlon et al.

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

More general case

- 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)

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

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

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 !

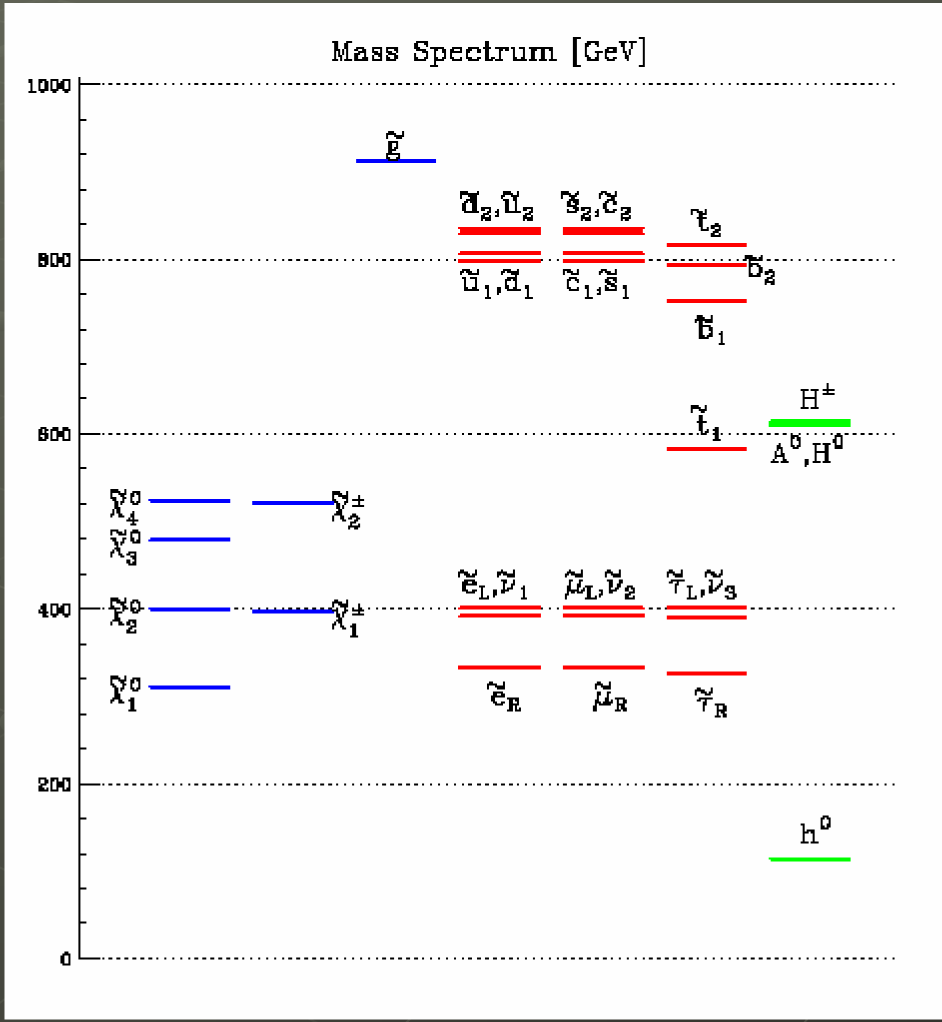
From Strings to LHC data

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

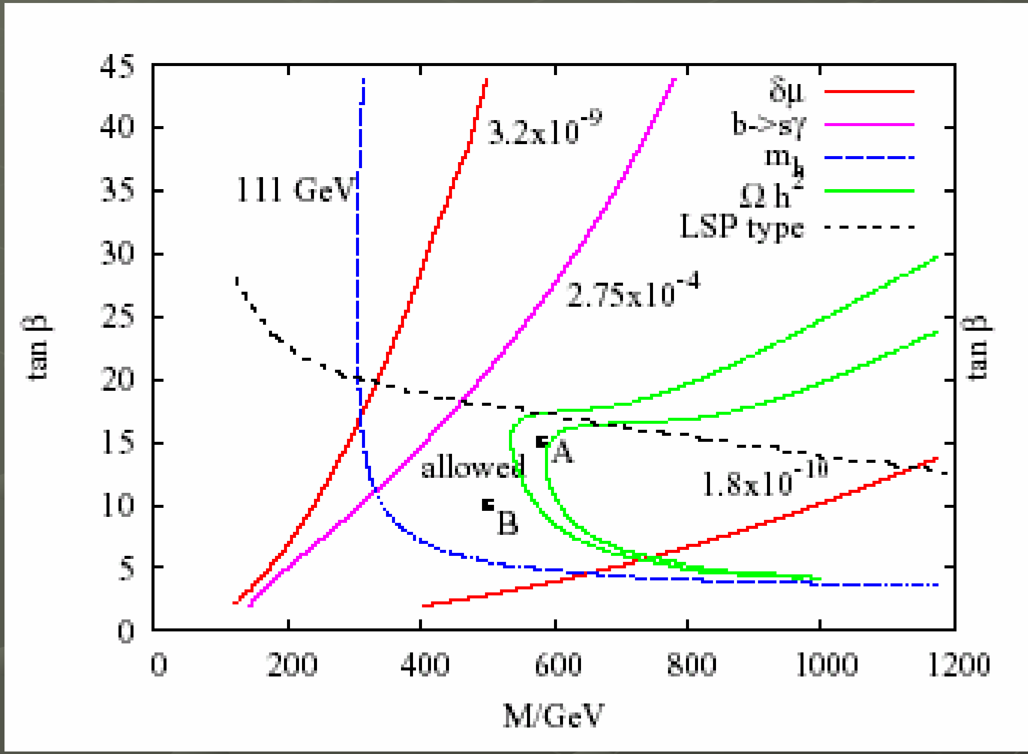
Low energy spectrum

	A	B	C
m_s	10^{11}	10^{11}	10^{11}
$\tan\beta$	15	10	23
M	580	500	1000
$\mathrm{sgn}\mu$	+	+	-
$\tilde{e}_L, \tilde{\mu}_L$	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	—



Renormalisation group run

Allowed Regions



Cosmology

(Inflation, Cosmological moduli problem, etc.)

Kähler Moduli Inflation

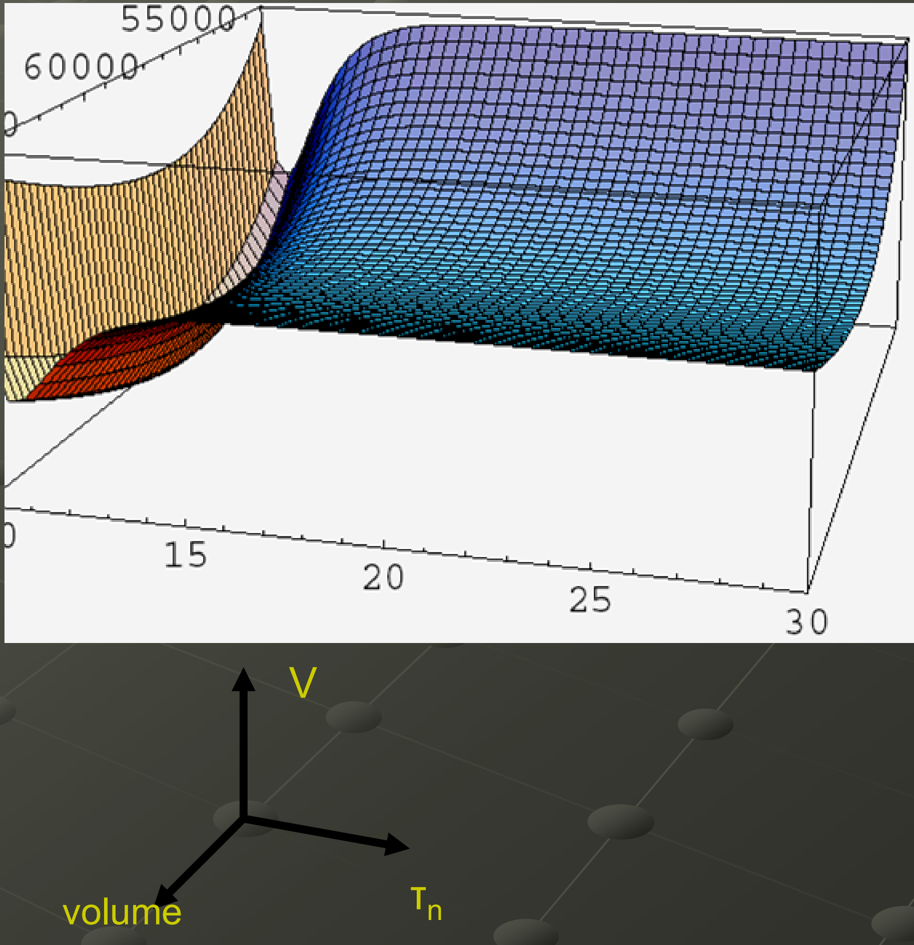
Conlon-FQ

Bond-Kofman-Prokushkin

Calabi-Yau:

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

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



Small field inflation

No fine-tuning!!

$0.960 < n < 0.967$

GUT scale Ms?, Loops?

See Andrei + Renata's talks

Physics of Moduli Fields

- Dilaton and Complex Structure

  Moduli masses:

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

- Small (heavy) Kahler moduli

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

- Large (light) Kahler modulus

$$m_{\tau_b} \sim \frac{M_P}{\mathcal{V}^{3/2}} \sim M_P \left(\frac{m_{3/2}}{M_P}\right)^{3/2}.$$

Physical Fields

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

$$\delta\tau_s = \left(\frac{2\sqrt{6}}{3}\langle\tau_b\rangle^{3/4}\langle\tau_s\rangle^{1/4}\right)\frac{\Phi}{\sqrt{2}} + \left(\frac{\sqrt{3}}{a_s}(1-2\epsilon)\right)\frac{\chi}{\sqrt{2}} \sim \mathcal{O}\left(\mathcal{V}^{1/2}\right)\Phi + \mathcal{O}(1)\chi \quad (3.7)$$

Decay Rates

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

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

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

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

	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}	m_s^{-1}
Decay Modes		
$\gamma\gamma$	$\text{Br} \sim 0.025$, $\tau \sim 6.5\times10^{25}\text{s}$	$\tau \sim 10^{-17}\text{s}$
e^+e^-	$\text{Br} \sim 0.975$, $\tau \sim 1.7\times10^{24}\text{s}$	$\tau \sim 10^{-17}\text{s}$
$\psi_{3/2}\psi_{3/2}$	inaccessible	$\text{Br} \sim 10^{-30}$, $\tau \sim 10^{-2}\text{s}$

Other Cosmological Implications

J.Conlon, FQ

- Cosmological moduli problem

DCQR, BKN

U,S: trapped at their minimum

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

Volume: (mass MeV) CMP

- Observational implications of light volume modulus?

X-rays,Gamma rays, e^+-e^-

Solution of CMP?

Thermal Inflation

Lyth+Stewart (1995)

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

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

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

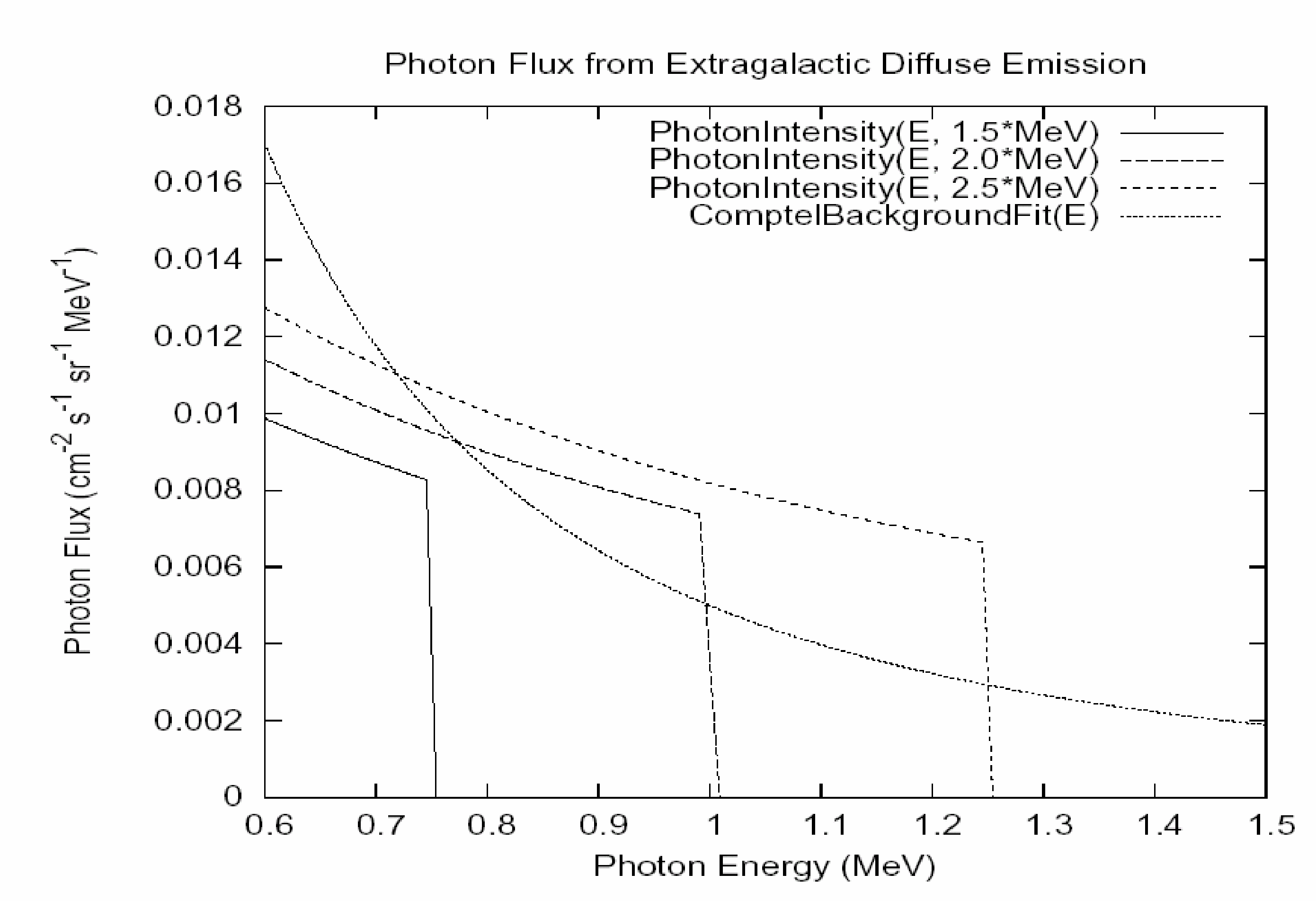
Number of e-folds

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

N~10 dilutes moduli

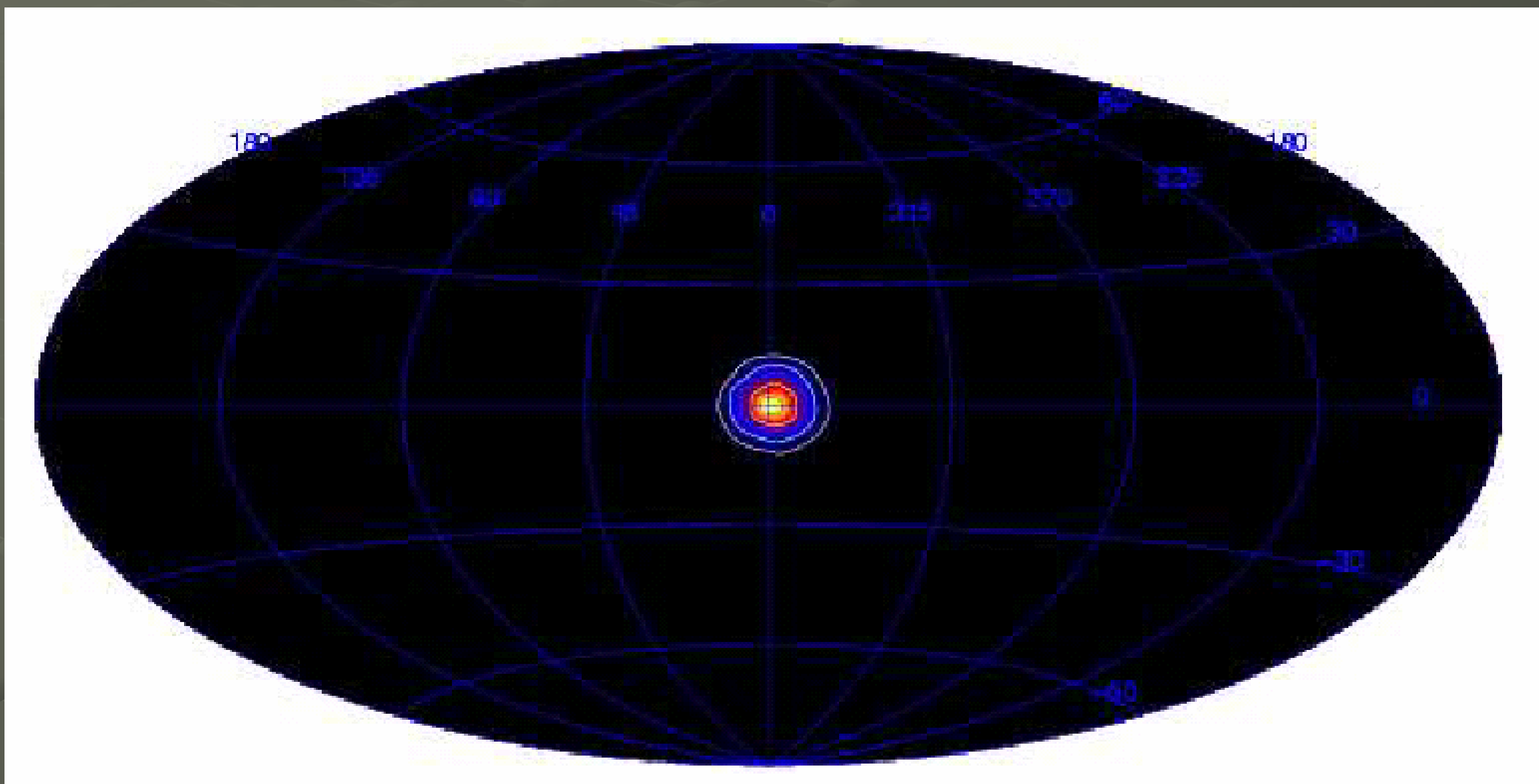
Late time implications:

Diffuse Gamma Ray Background

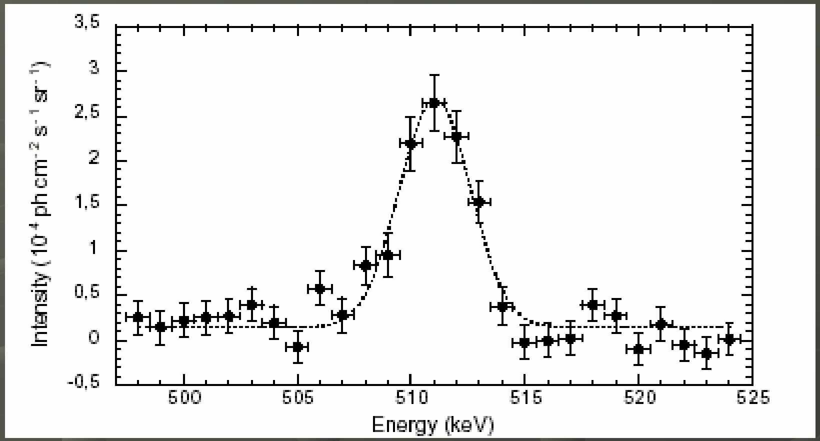


$$\frac{\Omega_\chi}{\Omega_m} \lesssim \left(\frac{1\mathrm{MeV}}{m_\chi}\right)^{3.5}.$$

The 511 keV Line



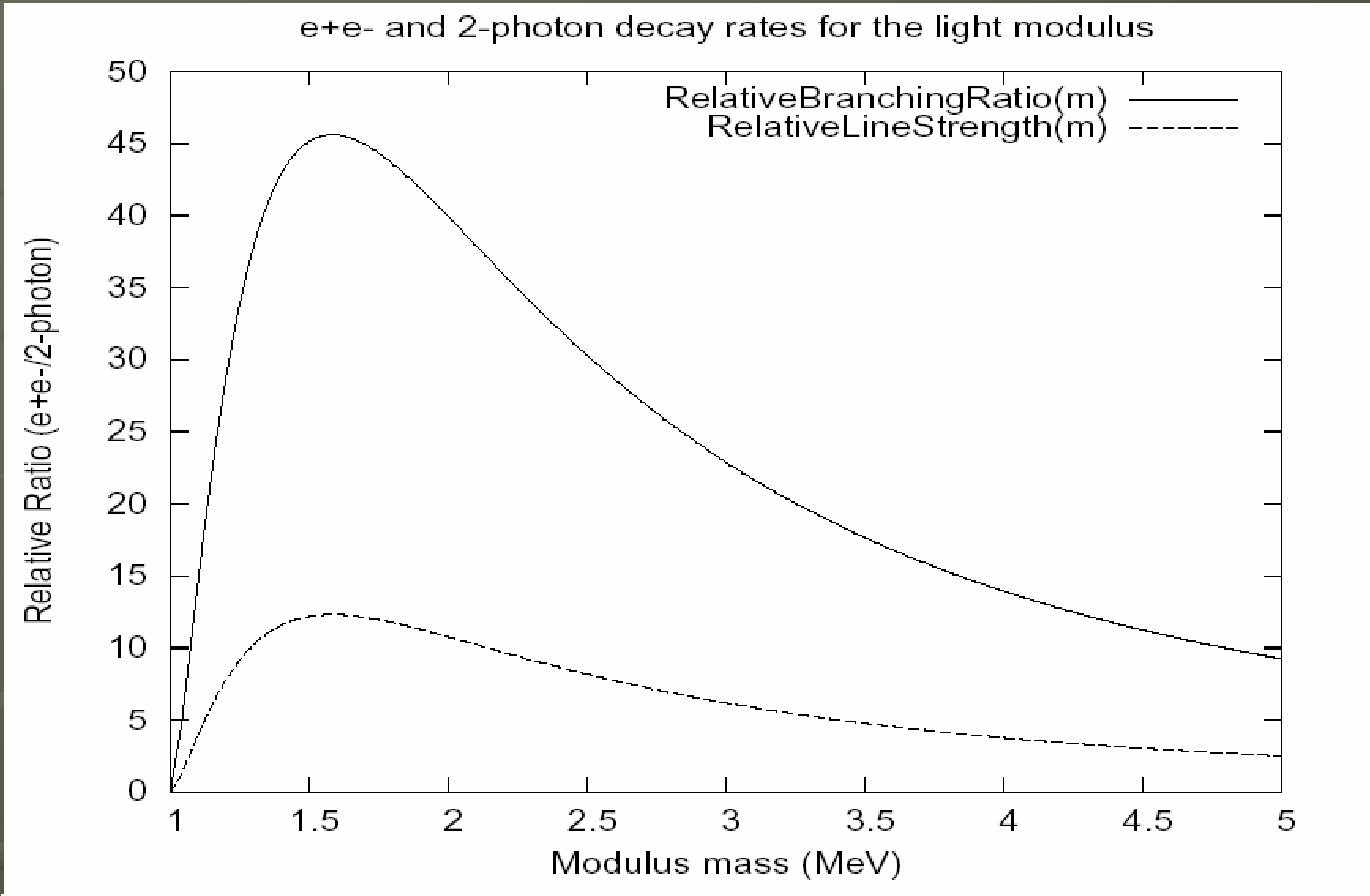
INTEGRAL/ SPI 511 keV line



Light Modulus χ: Dark matter?

Mass 1MeV, coupling to electrons dominant

511 keV from volume modulus decay? (prediction!)



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

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

CONCLUSIONS

- Exciting times for string phenomenology!
- Soft terms calculable ➡ rich phenomenology
- 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?...