Title: Cosmological Implications of LARGE Volume String Compactifications

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Abstract:

Cosmological Implications of LARGE Volume String Scenarios

F. Quevedo, Cambridge. PASCOS 2008.

M. Cicoli, J. Conlon, FQ, 0708.1873 [hep-th] + 0805.1029[hep-th]
J. Conlon, R. Kallosh, A. Linde, FQ, to appear
C.B. Burgess, M. Cicoli, J. Conlon, L.-Y Hung, S. Kom, A. Maharana, **arXiv:0805.4037** [hep-th] and in progress.

String Phenomenology

(as opposed to `String Noumenology')

- **Explicit Realistic Models**

  (SU(3)xSU(2)xU(1), 3 families, etc.)

- **4D Effective Actions**

  (Explicit form of K, W, f. For N=1 compactifications)

- **Model Independent Issues**

  (axions, no-global symmetries,…,SUSY breaking, moduli stabilisation,…)

- **Cosmology** (Inflation, etc.)

Why LARGE volume?

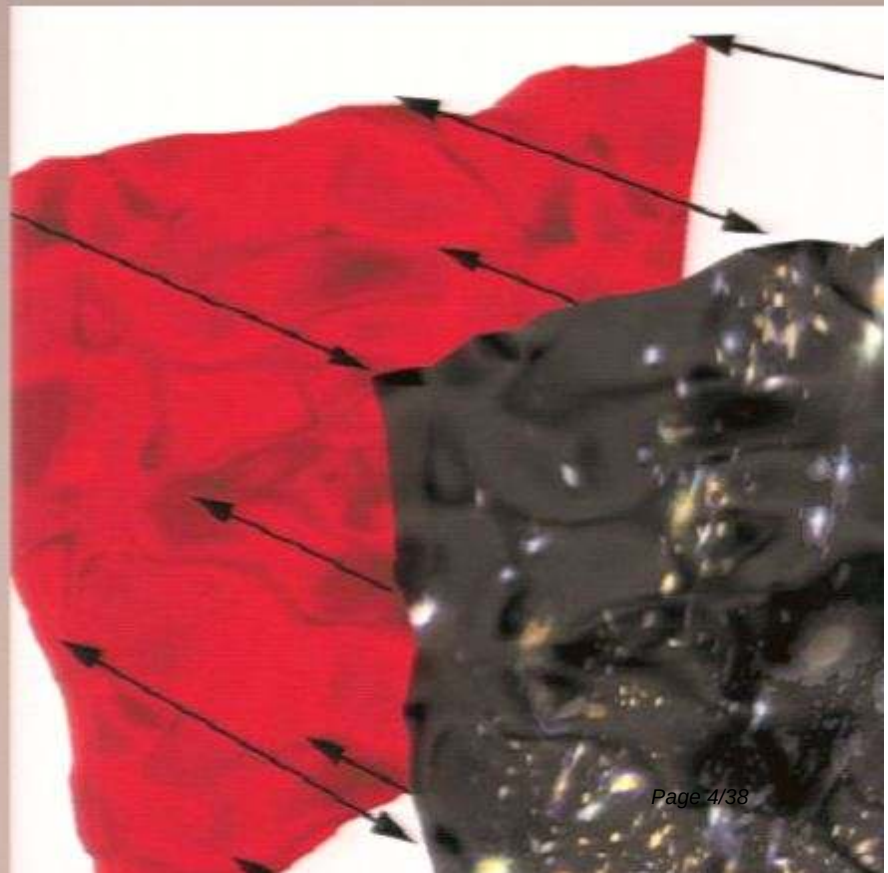
- Effective field theory robust
- Phenomenology $M^2_{Planck} = M^2_{string}\, V$

$V = 10^4 \rightarrow M_{string} = M_{GUT} = 10^{17}$ GeV

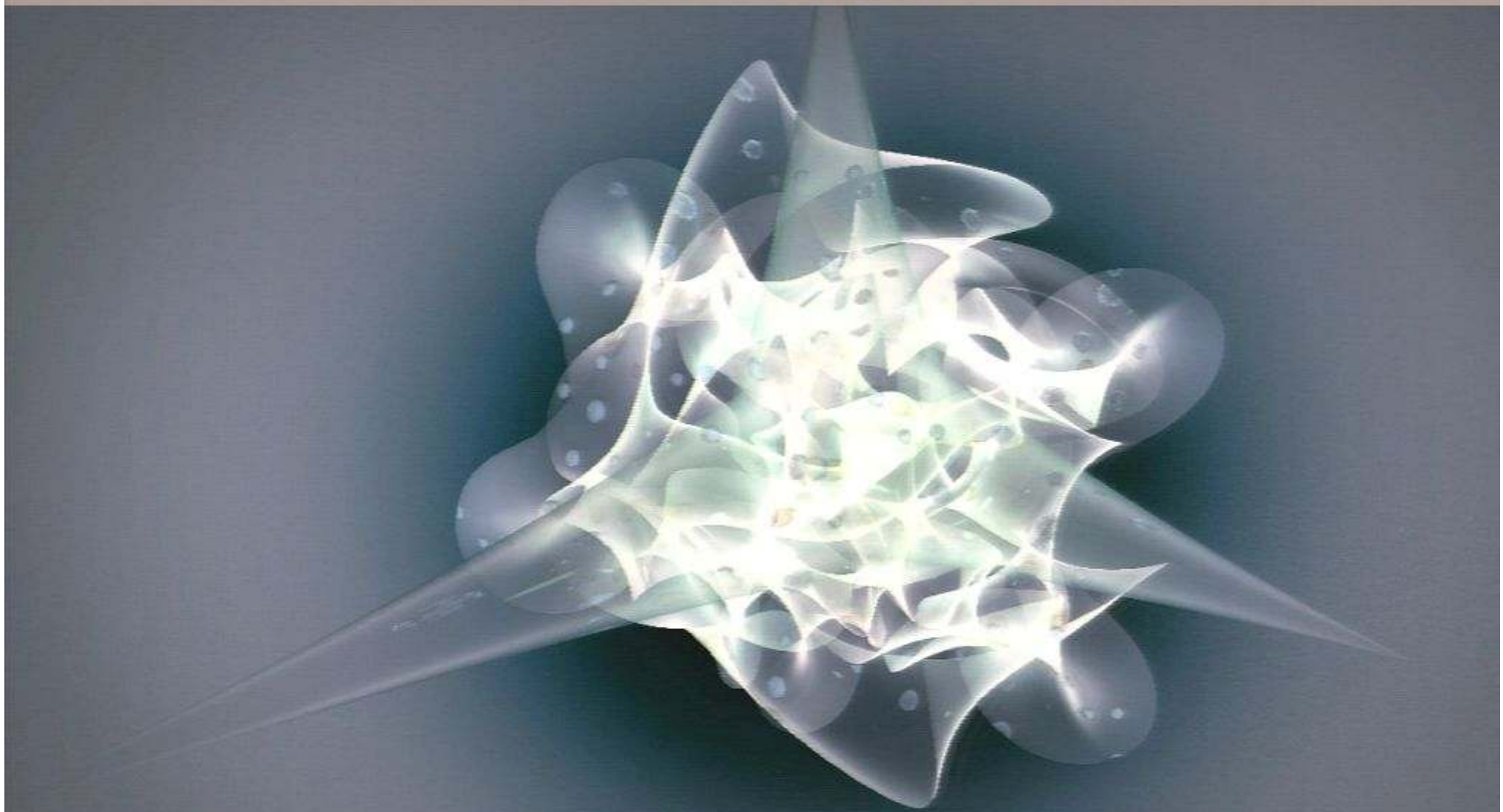
$V = 10^{30} \rightarrow M_{string} = 1$ TeV

$V = 10^{15} \rightarrow M_{string} = 10^{11}$ GeV

(Also RS warping !)



MODULI STABILISATION?



Exponentially Large Volumes in IIB

(Fluxes + nonperturbative effects)

For IIA see Palti et al

Perturbative vs Non perturbative :

- **In general:**

$$\begin{aligned} K &= K_0 + K_p + K_{np} \approx K_0 + J, \\ W &= W_0 + W_{np} \approx W_0 + \Omega. \end{aligned}$$

- **Then:**

$$V = V_0 + V_J + V_\Omega + \cdots,$$

$$V_0 \sim W_0^2, \quad V_J \sim J W_0^2, \quad V_\Omega \sim \Omega^2 + W_0 \Omega.$$

- **Usually V_0 dominates but V_0=0 (no-scale $G^{-1}_{ik} K_i K_k = 3$)**
- **Dominant term is V_J unless W_0<<1 (KKLT)**

Exponentially Large Volumes

BBCQ, CQS (2005)

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

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

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

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

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

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

$a_s \sim 2\pi/g_s N$

Exponentially large volumen !!!

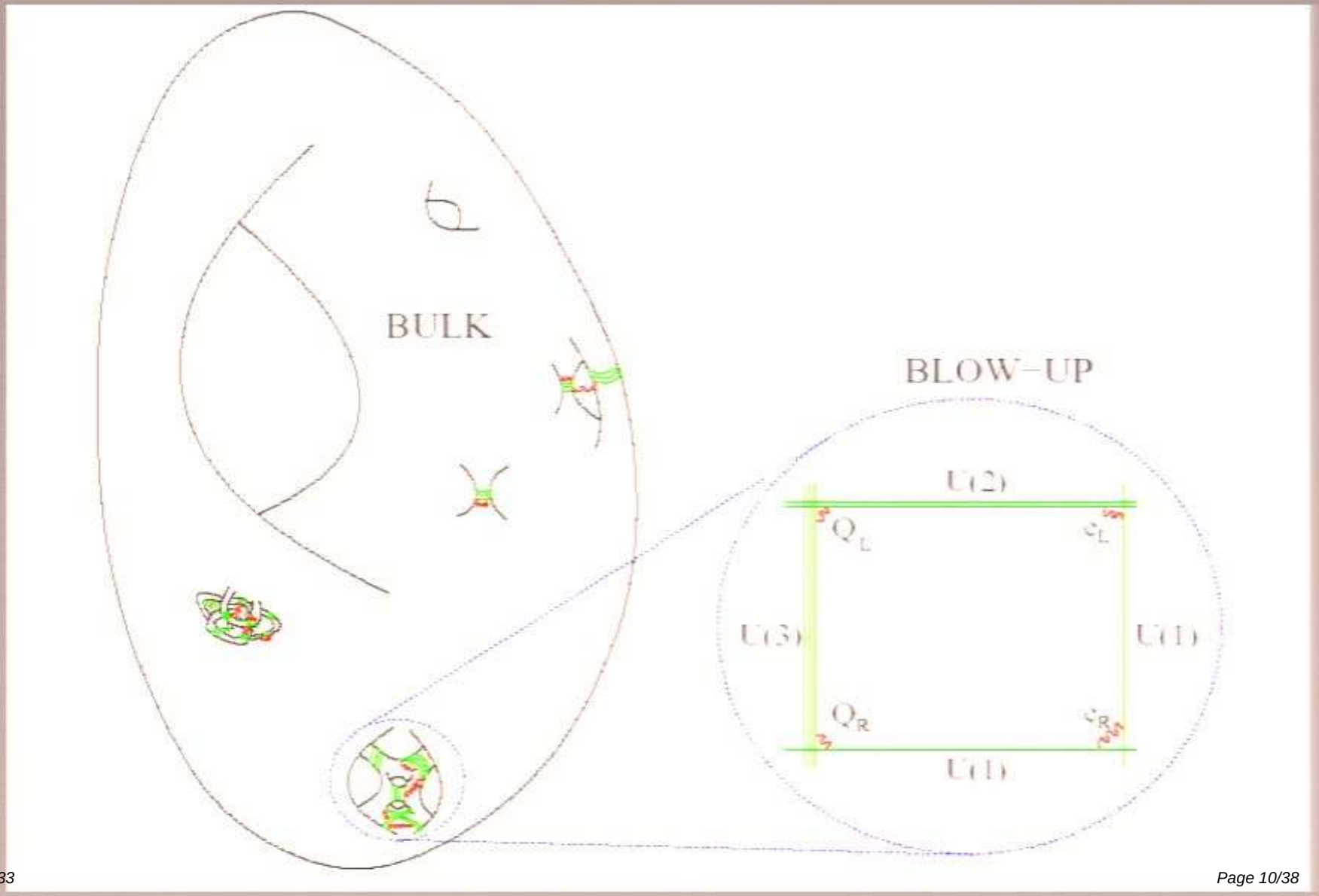
Scale	$\mathcal{V}_s$	$g_s \mathcal{V}$
GUT	4600	2.25
Intermediate	4.6×10^9	0.85
TeV	4.6×10^{27}	0.30

String scale: $M_s^2 = M_{Planck}^2/\mathcal{V}$

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

$M_s = 1$ TeV problematic from 5th force

The Standard Model in the CY



General Conditions for LARGE Volume

- $h_{12} > h_{11} > 1$
- At least one blow-up mode (point-like singularity)
- Blow-up mode fixed by non-perturbative effects, volume by alpha' corrections
- For N_{small} blow-up modes, there are $L=h_{11}-N_{small}-1$ flat directions at tree-level
- These directions are usually lifted by perturbative effects

L moduli lighter than volume!

String Loop Corrections

$$\delta K^{KK}_{(g_s)} \sim \frac{\sqrt{\tau}}{\mathcal{V}}.$$

$$\delta K^{W}_{(g_s)} \sim \frac{1}{\mathcal{V}\sqrt{\tau}}.$$

Berg-Haack-Kors

Berg-Haack-Pajer

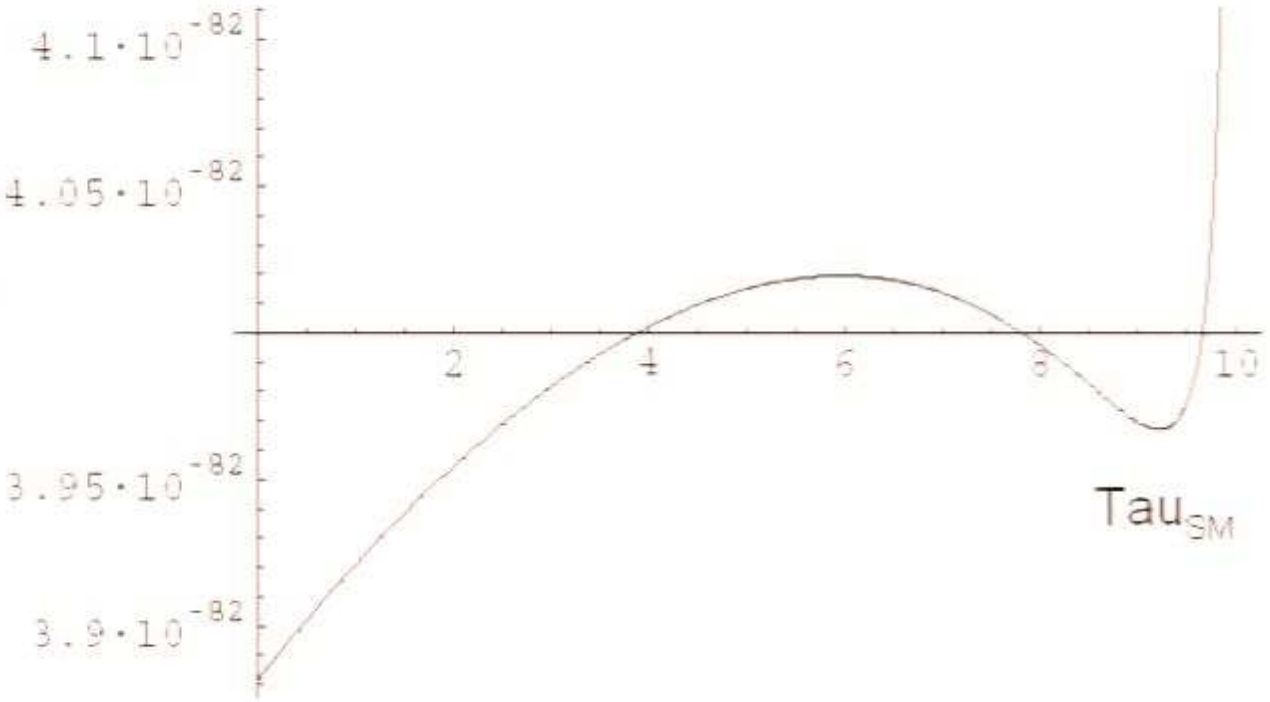
$$\delta V^{KK}_{(g_s)} \sim \left(0 \cdot \frac{\partial K_0}{\partial \tau} + \frac{\partial^2 K_0}{\partial \tau^2}\right) \frac{1}{\mathcal{V}^2} \sim 0 \cdot \frac{\sqrt{\tau}}{\mathcal{V}^3} + \frac{1}{\mathcal{V}^3\sqrt{\tau}}.$$

Leading order correction for V is alpha' but string loops relevant to fix other moduli

Example 1

The multiple-hole Swiss cheese: $\mathbb{C}P^1_{[1,3,3,3]}$

$$\Gamma - \delta\Gamma_{(g_s)} = \frac{\lambda_1\left(\sqrt{5\,(2\tau_{E3}-\tau_{SM})}-\sqrt{\tau_{E3}-\tau_{SM}}\right)e^{-4\pi\tau_{E3}}}{\mathcal{V}} - \frac{3\lambda_2\tau_{E3}e^{-2\pi\tau_{E3}}}{\mathcal{V}^2}$$
$$-\frac{\lambda_3}{\mathcal{V}^3} - \left(\frac{\lambda_1}{\sqrt{\tau_{E3}-\tau_{SM}}} - \frac{\lambda_7}{\sqrt{2\tau_{E3}-\tau_{SM}}}\right)\frac{1}{\mathcal{V}^3}.$$



Addresses the Blumenhagen et al problem.

Example 2: K3 Fibrations

- K3 Fibration with 2 Kahler moduli [1,1,2,2,6] model

$$\mathcal{V} = t_1 t_2^2 + \frac{2}{3} t_2^3 = \frac{1}{2}\sqrt{\tau_1}\left(\tau_2 - \frac{2}{3}\tau_1\right).$$

$$V_{np} + V_{(\alpha')} = \frac{1}{\mathcal{V}^2}\left[a_1 A_1^2 \tau_1 (a_1\tau_1 + 1) e^{-2a_1\tau_1} - a_1 A_1 \tau_1 W_0 e^{-a_1\tau_1}\right]$$
$$+ \frac{3}{4}\frac{\xi}{\mathcal{V}^3}\left(W_0^2 + A_1^2 e^{-2a_1\tau_1} - 2A_1 W_0 e^{-a_1\tau_1}\right).$$

- No LARGE volume

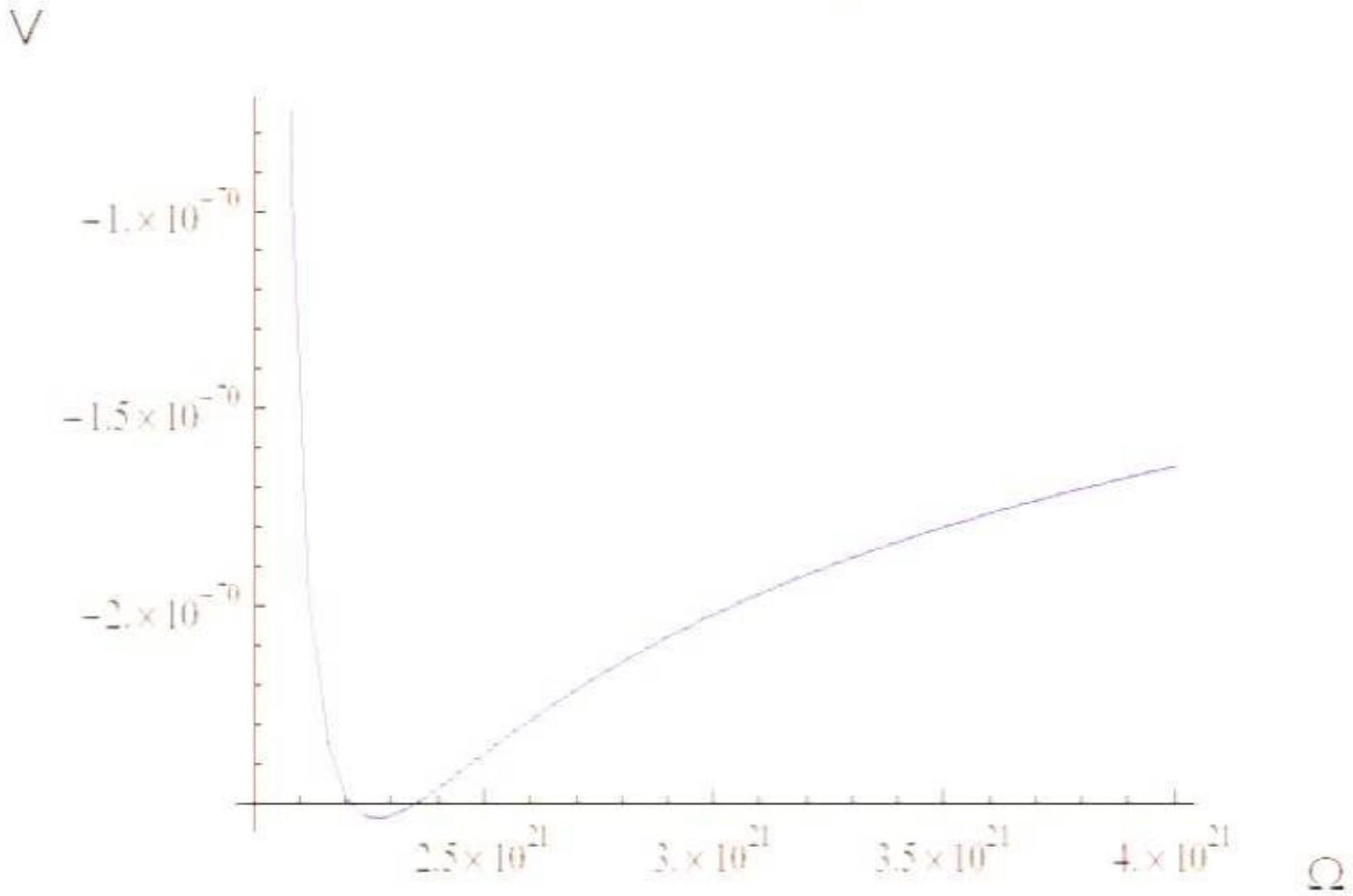
- K3 Fibration with 3 Kahler moduli (one blow- up)

$$\mathcal{V} = \alpha \left[\sqrt{\tau_1}(\tau_2 - \beta\tau_1) - \gamma\tau_3^{3/2} \right].$$

$$\delta V_{(g_s)\tau_1} - \delta V_{(g_s)\tau_2} = \frac{A}{\tau_1^2 \mathcal{V}^2} - \frac{B\sqrt{\tau_1}}{(\tau_2 - 2\tau_1)\mathcal{V}^3} - \frac{C}{\sqrt{\tau_1}\mathcal{V}^3} - \frac{D\tau_1}{\mathcal{V}^4}.$$

- Tau 3 small, tau 1 and tau 2 LARGE

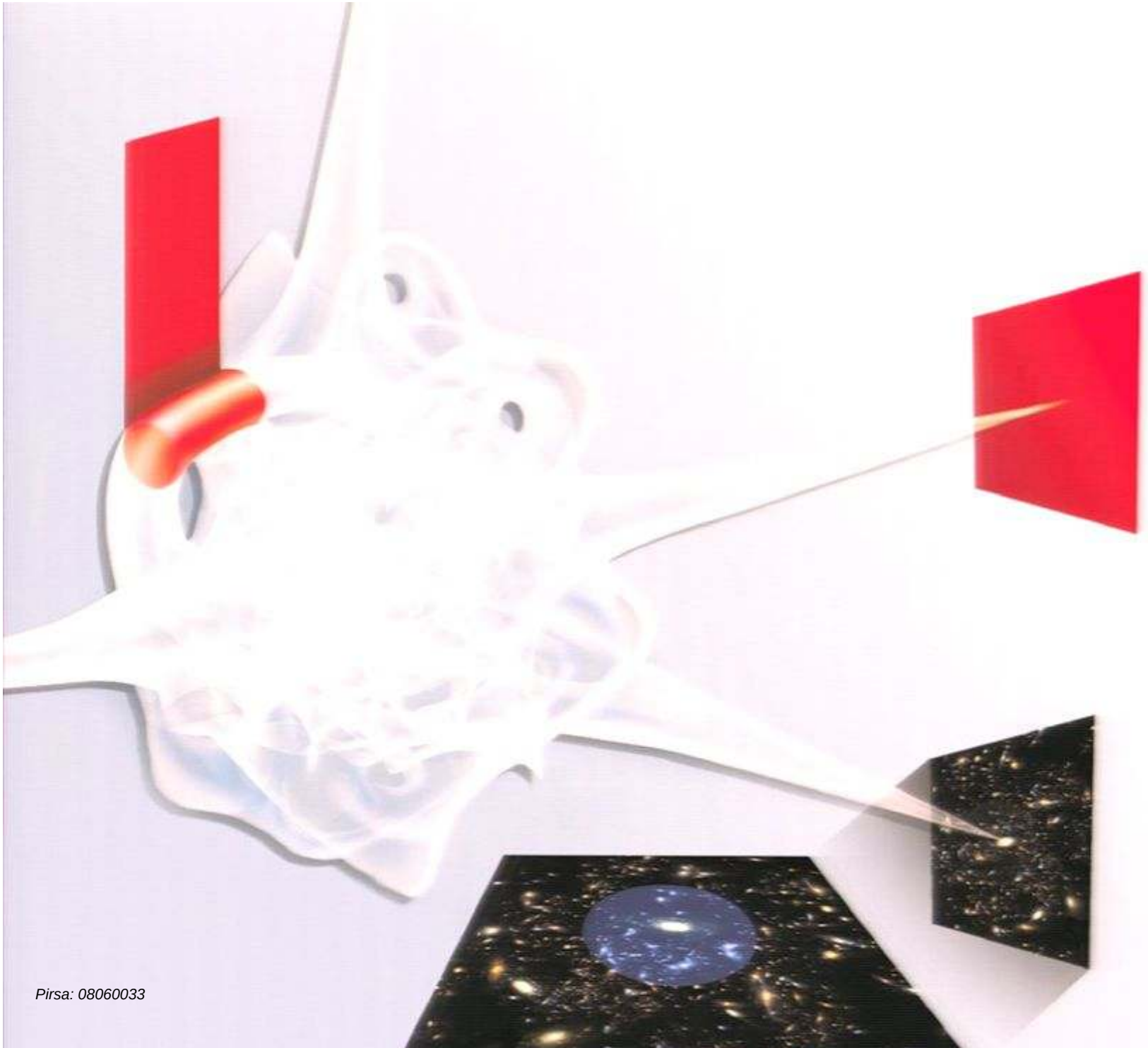
$$(\tau_1, \tau_2) \quad \longrightarrow \quad (\mathcal{V}, \Omega) : \qquad \begin{cases} \mathcal{V} \simeq a \left[\sqrt{\tau_1} (\tau_2 - i\tau_1) \right] \\ \Omega = a \left[\sqrt{\tau_1} (\tau_2 - i\tau_1) \right] \end{cases}$$



$m^2 = 1/\mathcal{V}^3, \ 1/\mathcal{V}^{10/3}, \ldots$

Volume, Ω

Intermediate Scale String Scenario



Univers

D3 Bran

or

D7 Bran

Standard Model on D7 Branes

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

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

- $W_0 \sim 1$ (no fine tuning)

- Kahler potential for *chiral* matter computed

Conlon, Cremades, FQ (2006)

Chiral Matter on D7 Branes
Soft SUSY Breaking terms

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

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

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

Simplest case
λ=1/3

COSMOLOGY

(Inflation, Cosmological moduli problem, etc.)

Continuous Global Symmetries

- No exact global symmetries in string theory

(Flavour, Topological Textures, semilocal strings, ruled out?)

- Extend to Open strings (just closed string sector)
- Two known exceptions: Peccei-Quinn + anomalous U(1)'s
- Approximate Global symmetries: Non-abelian "isometries" of localised Geometry (flavour!) + Hyper-weak "hidden brane" interactions
- Interesting mixing (minicharged particles, ...)

KAHLER MODULI INFLATION

Candidate Inflatons:
Closed string modes

- **Kahler Moduli (size/axion)**
- **Small modulus inflaton**

Kähler Moduli Inflation

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

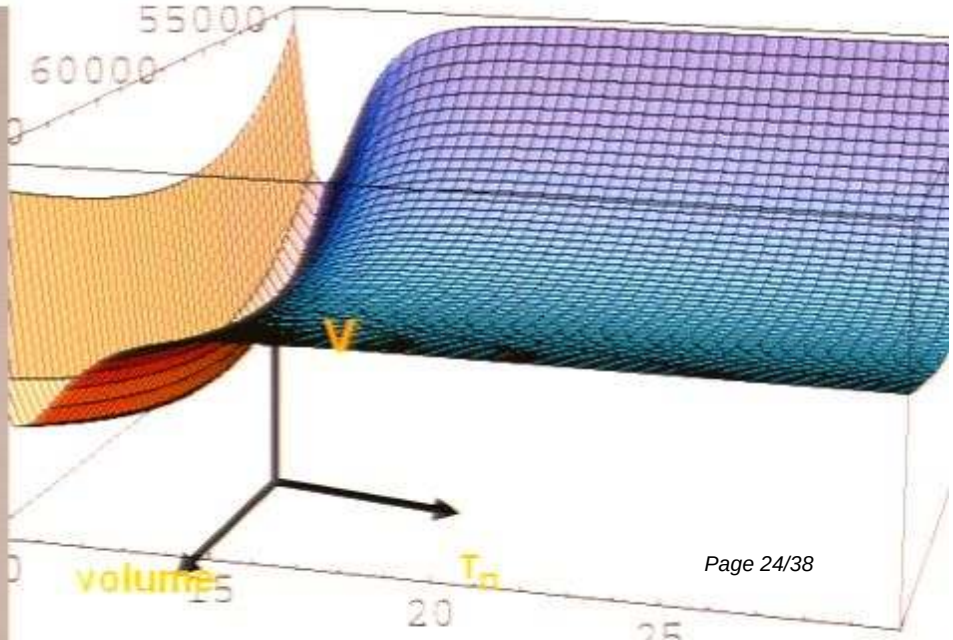
Conlon-FQ

Bond et al.

...

$$V \cong V_0 - \frac{4W_0 a_n A_n}{\mathcal{V}^2}\left(\frac{3\mathcal{V}}{4\lambda}\right)^{2/3}(\tau_n^c)^{1/3}\exp\left[-a_n\left(\frac{3\mathcal{V}}{4\lambda}\right)^{2/3}(\tau_n^c)^{1/3}\right].$$

Calabi-Yau: $h_{21} > h_{11} > 2$



Small field inflation

No fine-tuning!!

$0.960 < n_s < 0.967$

Open Questions

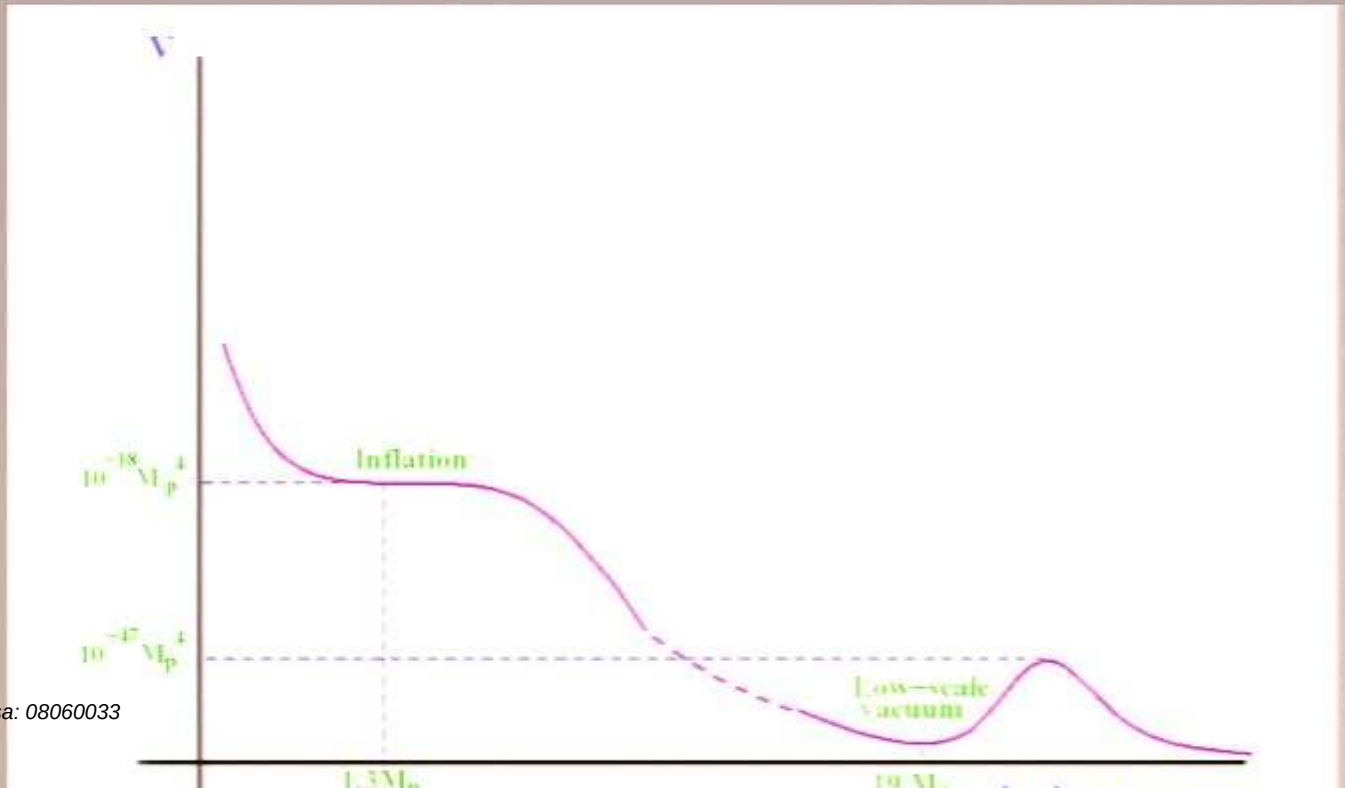
- Loop effects tend to spoil flatness
- Non tensor perturbations (r=T/S<<<1)?
- Tension phenomenology vs cosmology

Gravitino mass 1 TeV/Gravitino mass >> 1 TeV ??

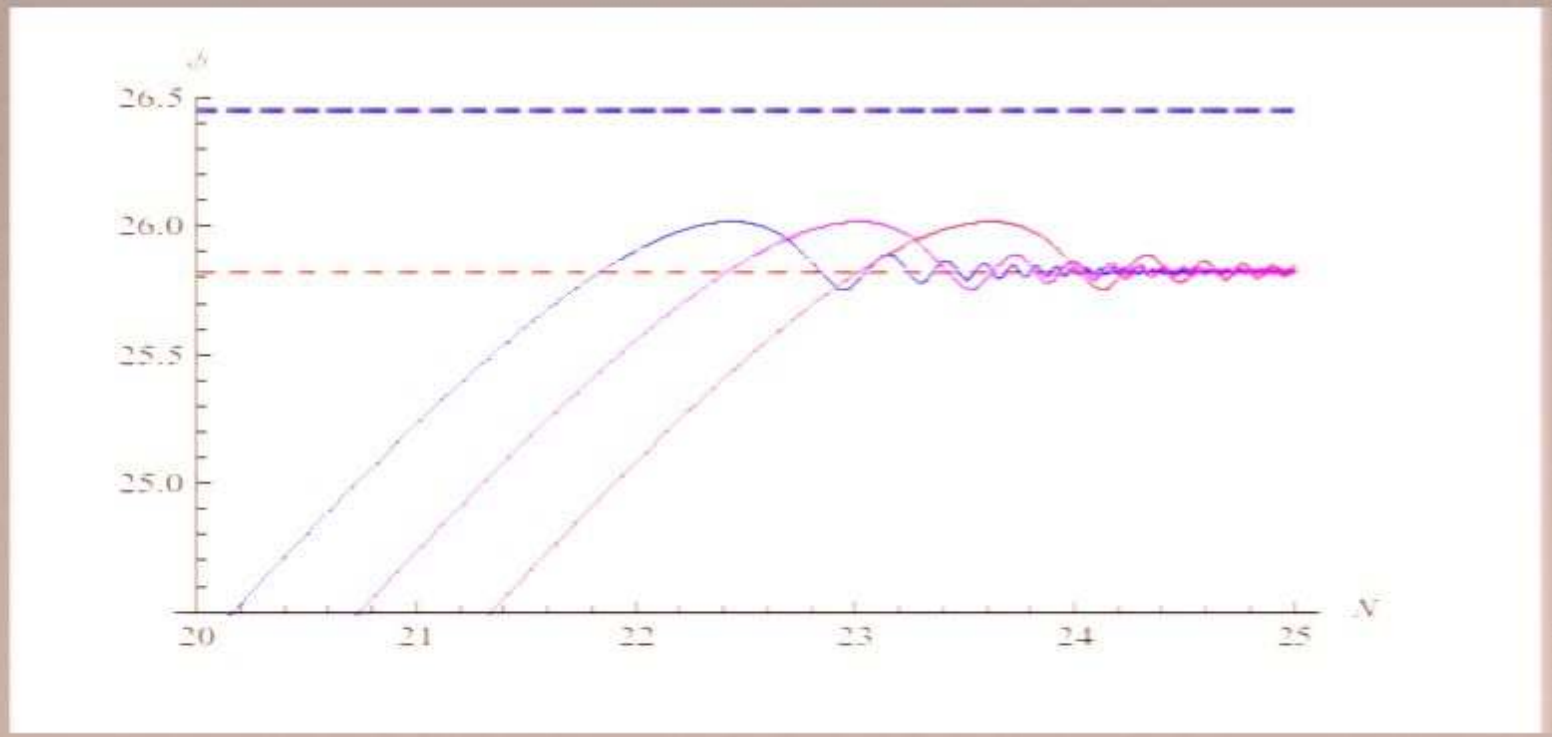
(string scale 10^{11} GeV/ string scale ~ GUT scale)

Low Energy SUSY vs Inflation

- Low scale inflation? Ross et al, …
- Runaway before reheating? Conlon, Kallosh, Linde, F



No Overshooting problem!!!



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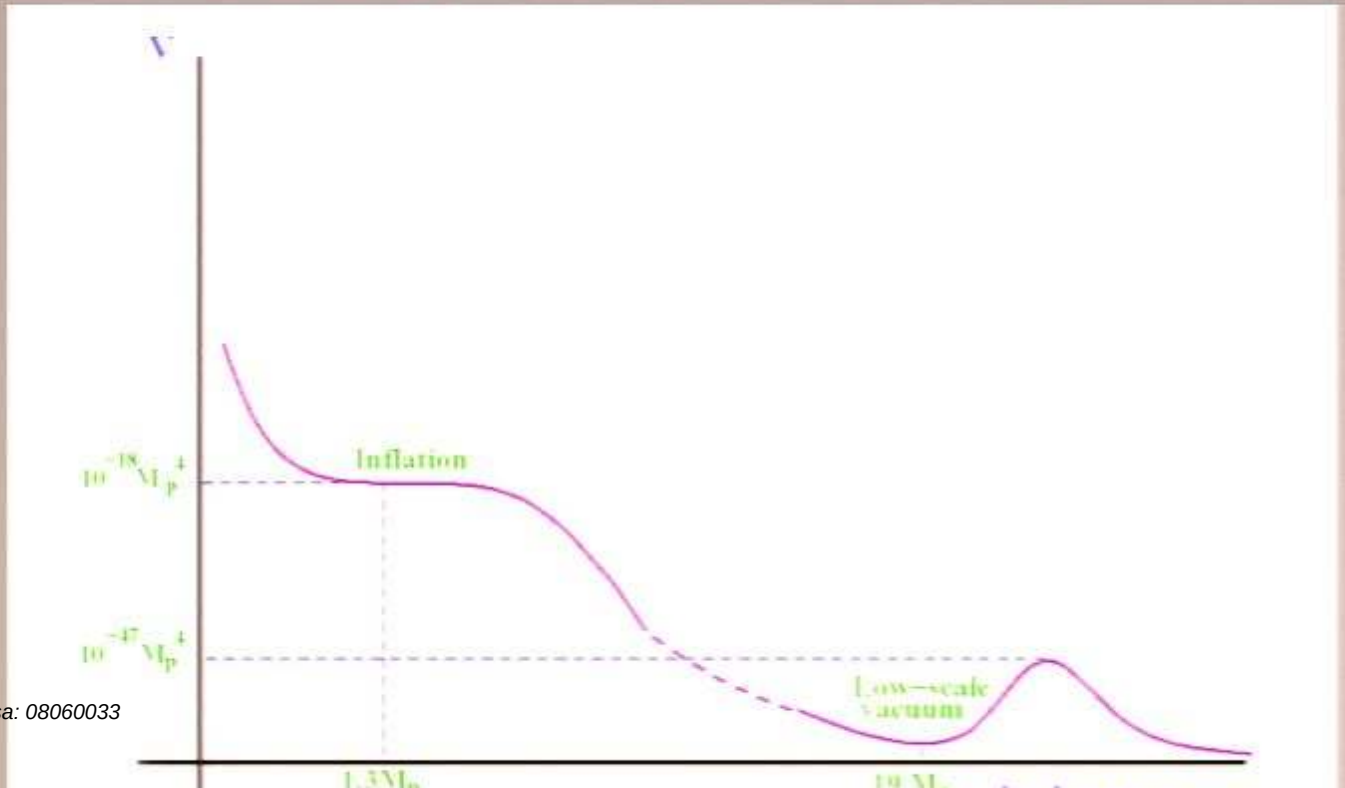


New Candidate Inflatons

- $L=h_{11}-N_{small}-1$ `almost' flat directions are light
- $Mass=V^{-5/3}<$ Volume modulus mass
  $m=V^{-3/2}\sim H$
- Recall $\eta \sim mass^2/H^2$

(Large field inflation $V\sim V_0-A\, e^{-2\varphi/\sqrt{3}}$, $r\sim 0.01$!)

(in progress) Cicoli et al.

Other Cosmological Implications

J.Conlon, FQ

- **Cosmological moduli problem**

DCQR, BKN

U,S: trapped at their minimum

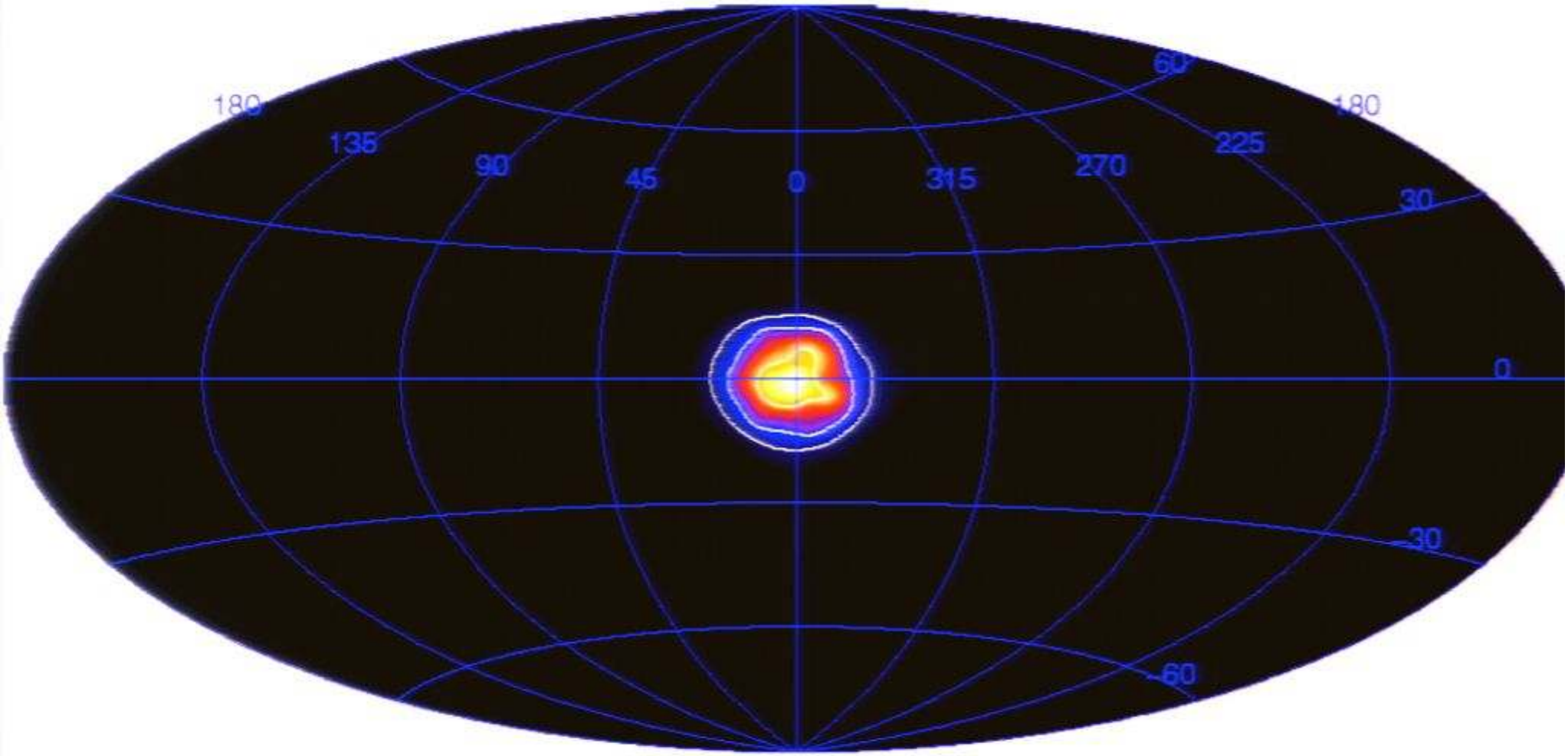
T: except for volume, heavy and decay fast ! (No CMP nor gravitino overproduction)

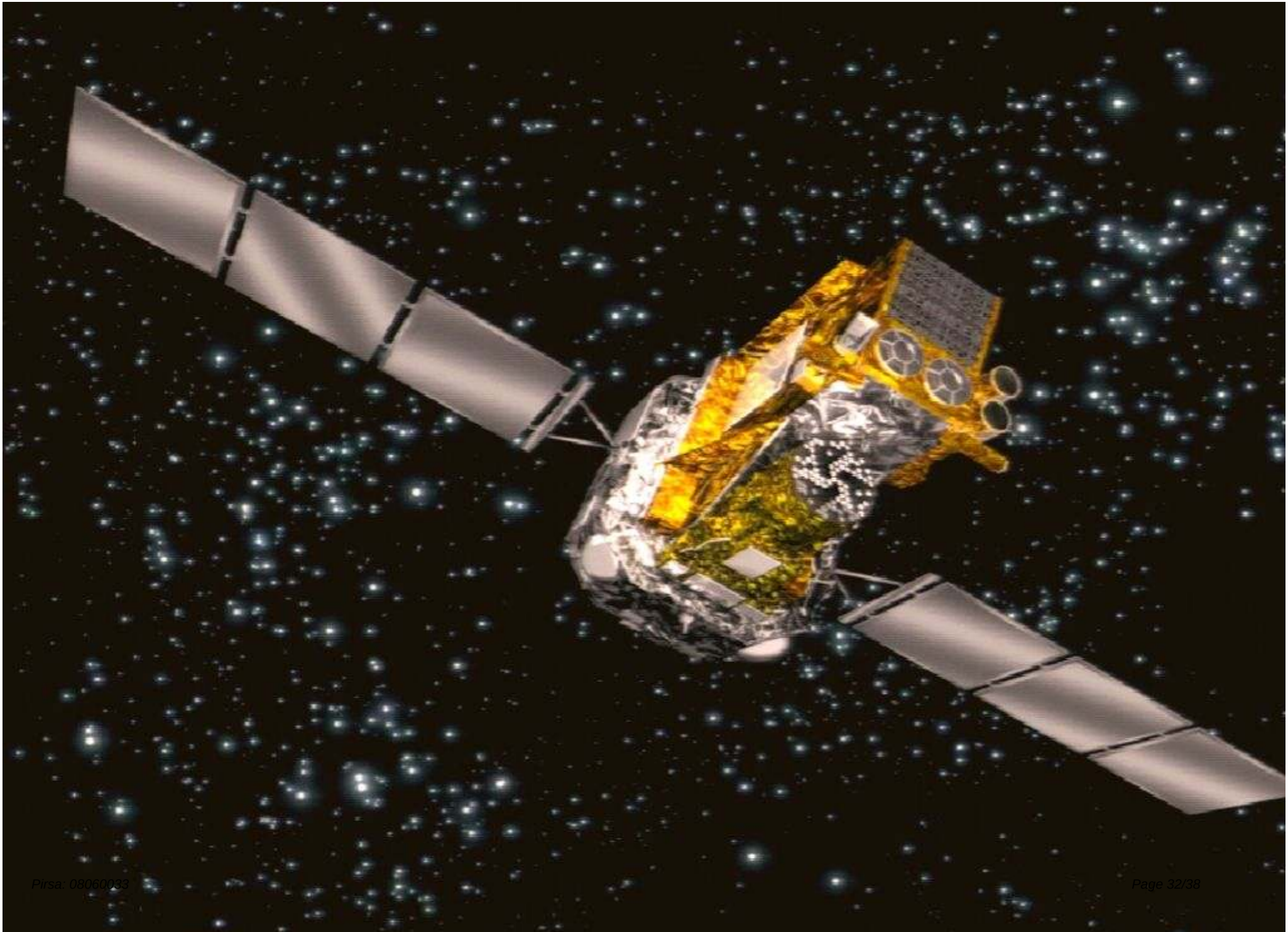
Volume: (mass MeV) CMP

- **Observational implications of light volume modulus?**

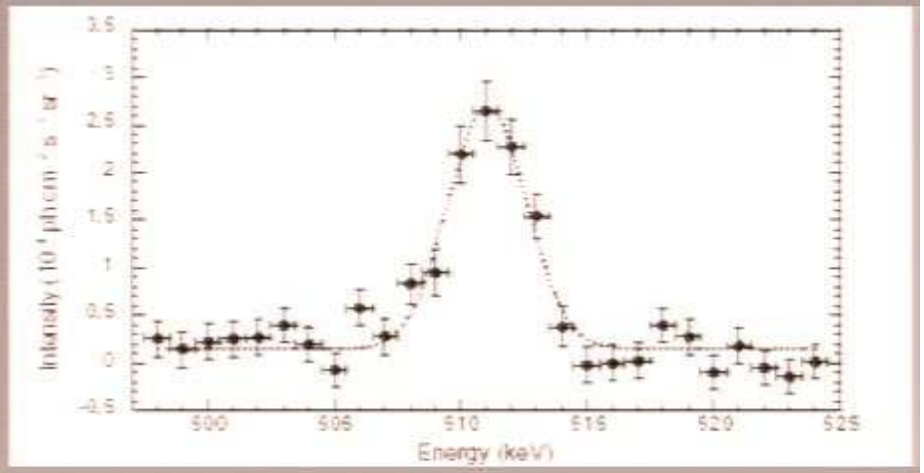
Gamma rays, e^+-e^-

The 511 keV Line





INTEGRAL/ SPI 511 keV line



Light Modulus χ: Dark matter?

Mass ~ 2MeV, coupling to electrons dominant:

X → e+ e- → 511 keV gammas (dominant)

X → ½ M χ gammas (prediction!)

BUT observed 511 keV line lopsided?

We have found a number of weak (with the significance $3-4\sigma$) lines in the background-subtracted spectrum of SPI. These lines cancel by worse than 90% when subtracting OFF dataset (see Section 4). Apart from it we have found in the background-subtracted spectrum two lines with high significance – known lines at 511 keV and at 1809 keV. Any of these lines can in principle be a DM decay line. We analyzed each of them, by considering the profile of their intensity over the sky. Our analysis shows that none of these lines could be *pure* DM line (as their dependence on the off-GC angle does not show any clear trend to decrease towards the anti-center). The possibility that some of these lines are the superposition of instrumental and DM lines remains open. Quantitative analysis of the amount of DM flux admissible in a given line depends strongly on the model of the DM distribution in the Milky Way halo. Therefore it was not conducted here.

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Pirsa: 08060033

arXiv:0710.4922v1 [astro-ph]

General Picture

- N_{small} heavy Kahler moduli (cosmological harmless)
- Volume modulus (CMP + 511 keV line+ predicted monochromatic line!) (see Boyarsky et al)
- $L=h_{11}-N_{small}-1$ lighter moduli (candidate inflatons, CMP, new monochromatic lines!! (observable?))
- CMP (late low energy inflation?)

GUT String Scale Scenarios

GUT String Scale Scenario

- GUT Scale
- Inflation Scale
- Standard Model Scale from $W_0 \ll 1$ or warping (warping + Large Volume!)
- No Cosmological Moduli Problem
- Candidate for quintessence: volume axion ($w \simeq -0.99\ldots$)
- Dark matter?
- Contact with realistic RS models
- Low-energy SUSY or No Low-Energy SUSY!!

Conclusions

- Non-perturbative effects fix only a fraction of Kahler moduli (N_{small})
- Alpha' effects fix volume to exponentially large values
  (Both LARGE volume and large warping in the same class of models!?)
- Loop corrections needed to fix the rest of Kahler moduli
- Abelian+Nonabelian Global Symmetries (approximate)
- Interesting Phenomenology/Cosmology
- GUT vs Intermediate Scale
- New large field inflation r~0.01
- Astrophysics (forest of monochromatic lines?)
- CMP? Reheating?
- Fully realistic model?