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 $M^2_{Planck} = M^2_{string} V$

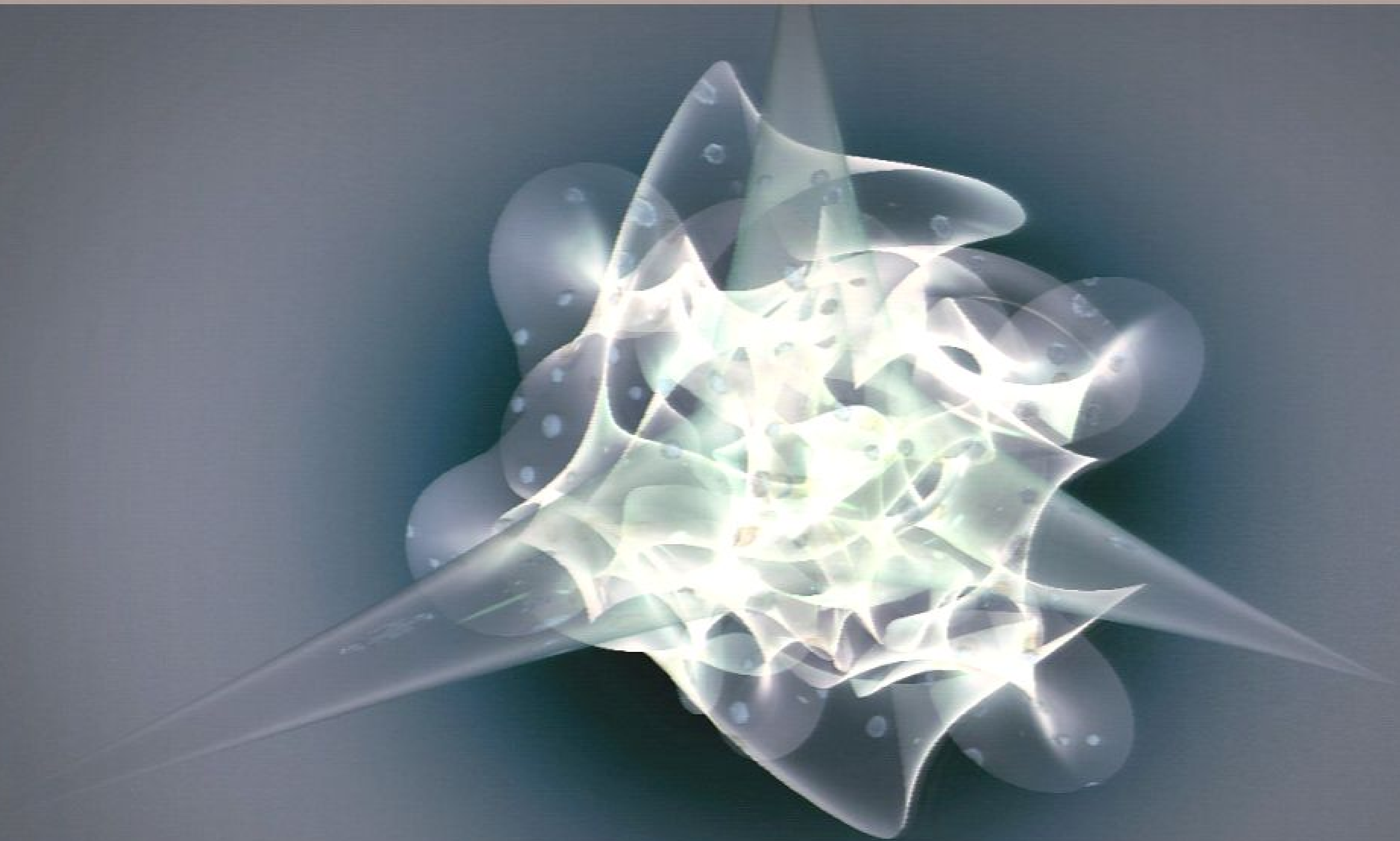
$V = 10^4 \rightarrow M_{string} = M_{GUT} = 10^{17}$ GeV

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

$$\mathcal{K} = \mathcal{K}_0 + \mathcal{K}_p + \mathcal{K}_{np} \approx \mathcal{K}_0 + J.$$
$$W = W_0 + W_{np} \approx W_0 + \Omega.$$

- 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 $G^{-1}_{i\bar{k}} \mathcal{K}_i \mathcal{K}_{\bar{k}} = 3$)
- Dominant term is V_J unless $W_0 \ll 1$ (KKLT)

Exponentially Large Volumes

BBCQ, CQS (2005)

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

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

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

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

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

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

Exponentially large volumen !!!

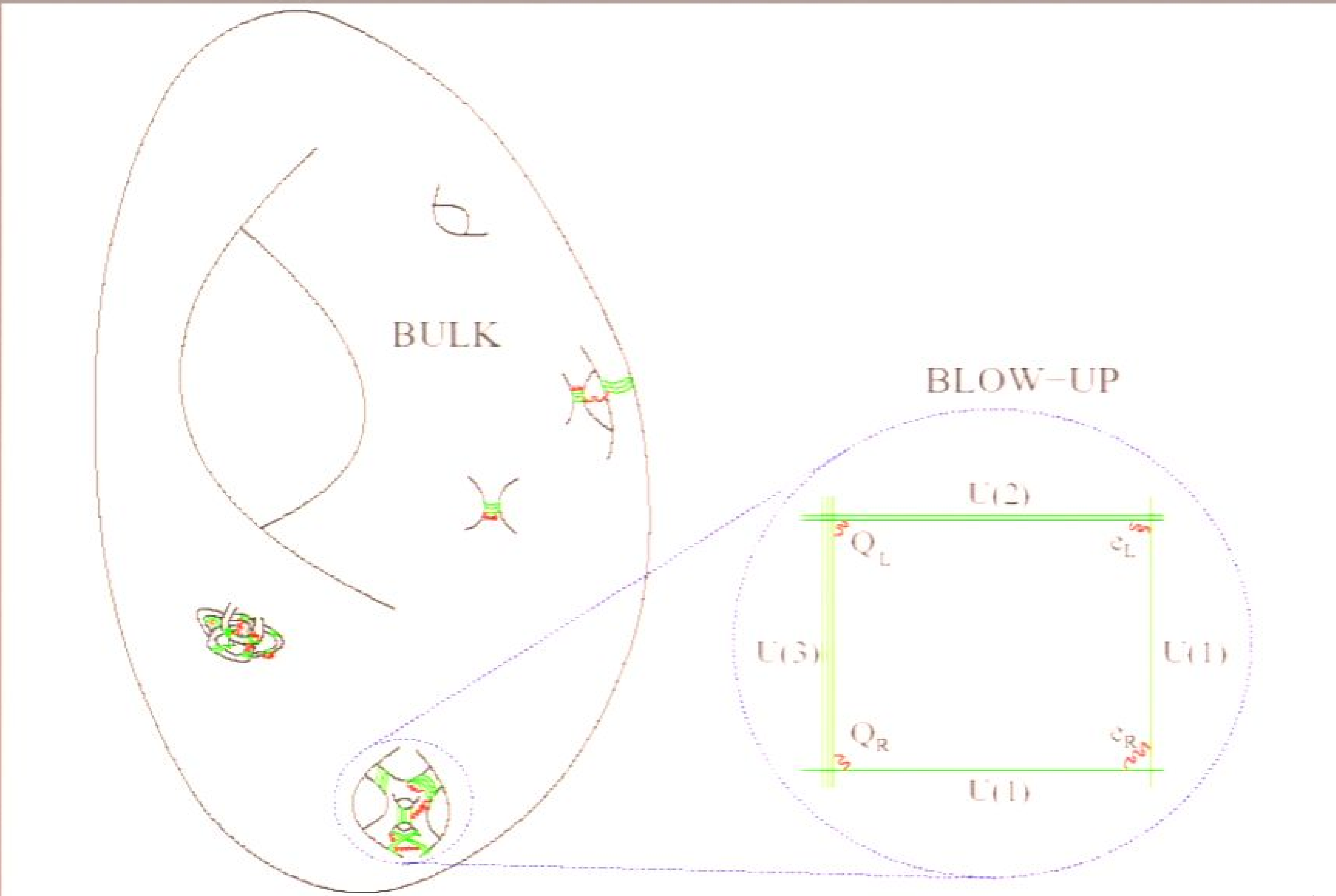
Scale	$\mathcal{V}_s$	$g_s N$
GUT	4600	2.25
Intermediate	4.6×10^9	0.85
TeV	4.6×10^{27}	0.30

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

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

Ms=1 TeV problematic from 5[th] 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

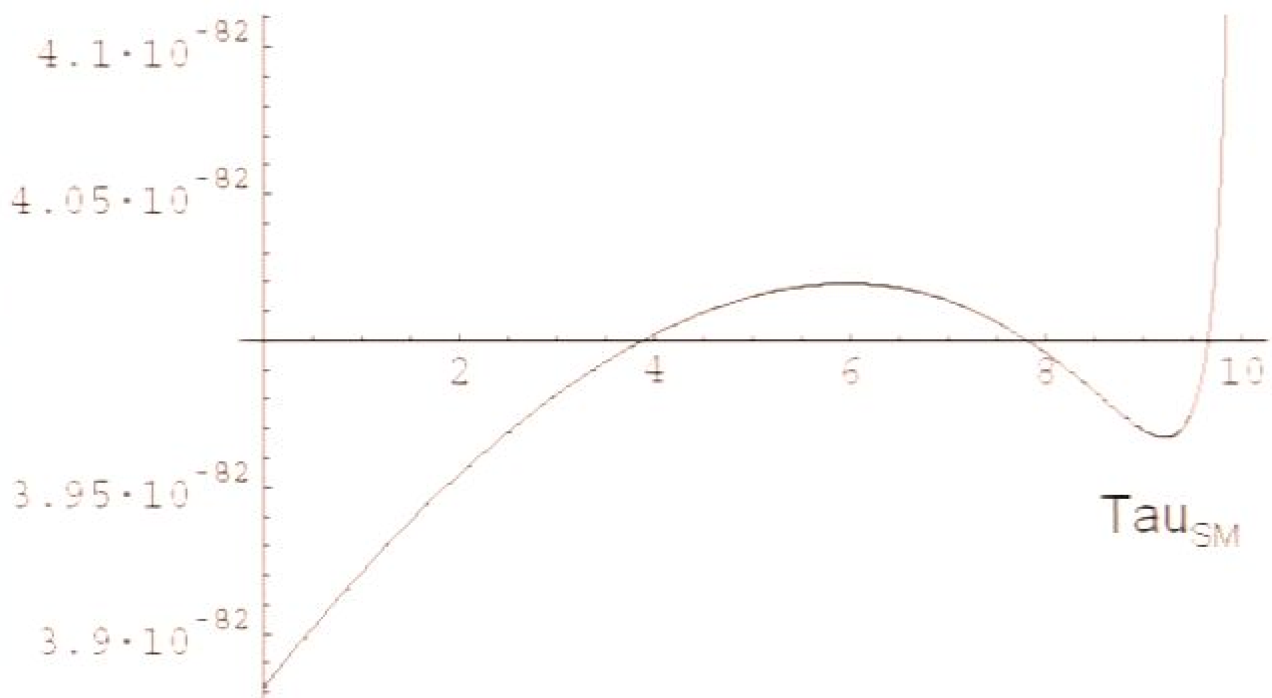
$$\delta V^{KK}_{(g_s)} \sim \left(0 \cdot \frac{\partial K_0}{\partial \tau} + \frac{\partial^2 K_0}{\partial \tau^2}\right)\frac{1}{\mathcal{V}^2} \sim 0 \cdot \frac{\sqrt{\tau}}{\mathcal{V}^3} + \frac{1}{\mathcal{V}^3\sqrt{\tau}}.$$

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

Example 1

The multiple-hole Swiss cheese: $\mathbb{C}P^4_{[1,3,3,3,5]}$

$$V + \delta V_{(g_s)} = \frac{\lambda_1 \left(\sqrt{5\,(2\tau_{E3} + \tau_{SM})} - \sqrt{\tau_{E3} - \tau_{SM}}\right) e^{-4\pi\tau_{E3}}}{\mathcal{V}} - \frac{3\lambda_2 \tau_{E3} e^{-2\pi\tau_{E3}}}{\mathcal{V}^2}$$
$$+ \frac{\lambda_3}{\mathcal{V}^3} + \left(\frac{\lambda_4}{\sqrt{\tau_{E3} - \tau_{SM}}} + \frac{\lambda_5}{\sqrt{2\tau_{E3} - \tau_{SM}}}\right) \frac{1}{\mathcal{V}^3}.$$



Addresses the Blumenhagen et al problem.

Example 2: K3 Fibrations

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

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

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

- No LARGE volume

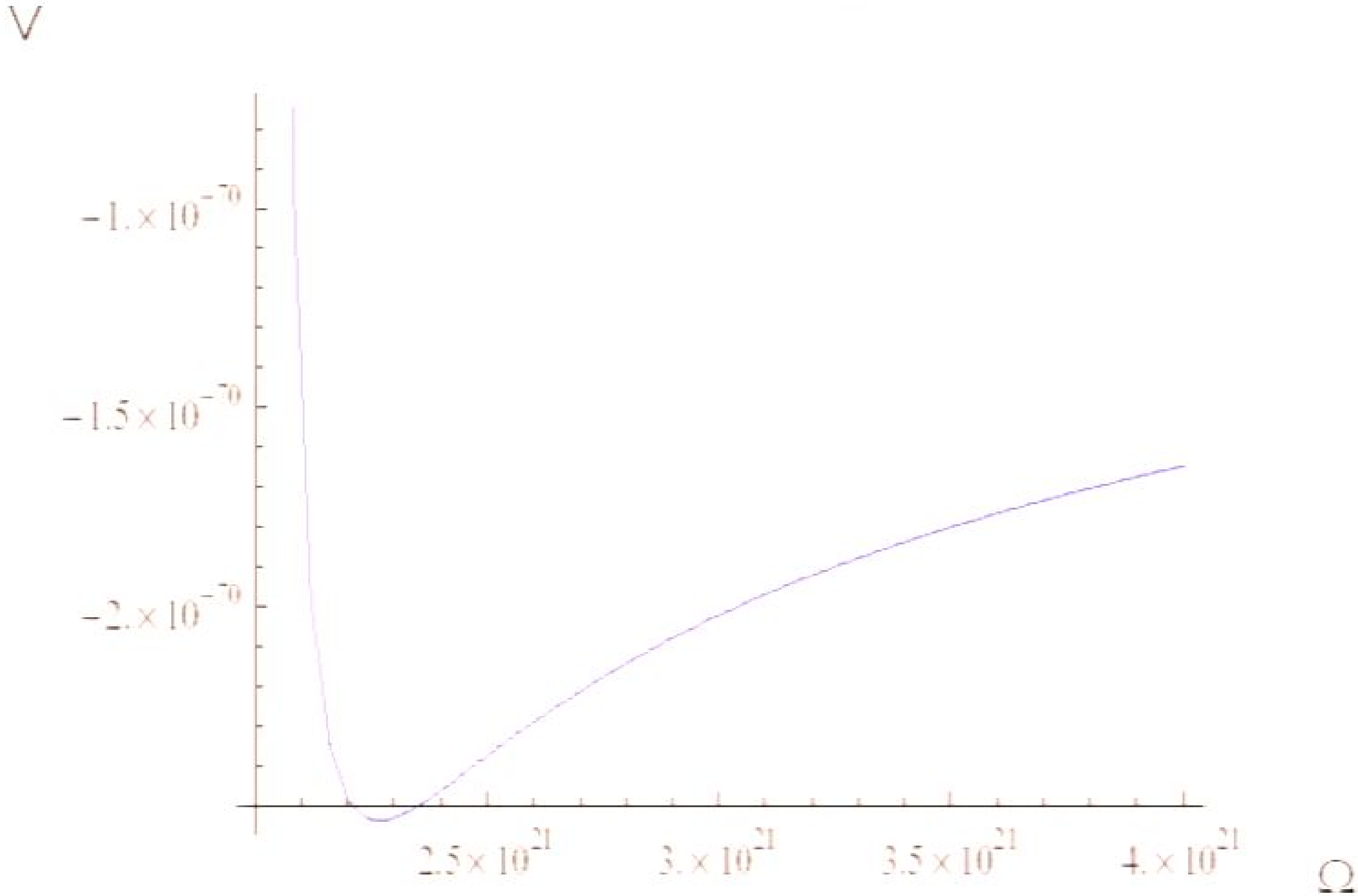
- K3 Fibration with 3 Kahler moduli (one blow- up)

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

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

- Tau 3 small, tau 1 and tau 2 LARGE

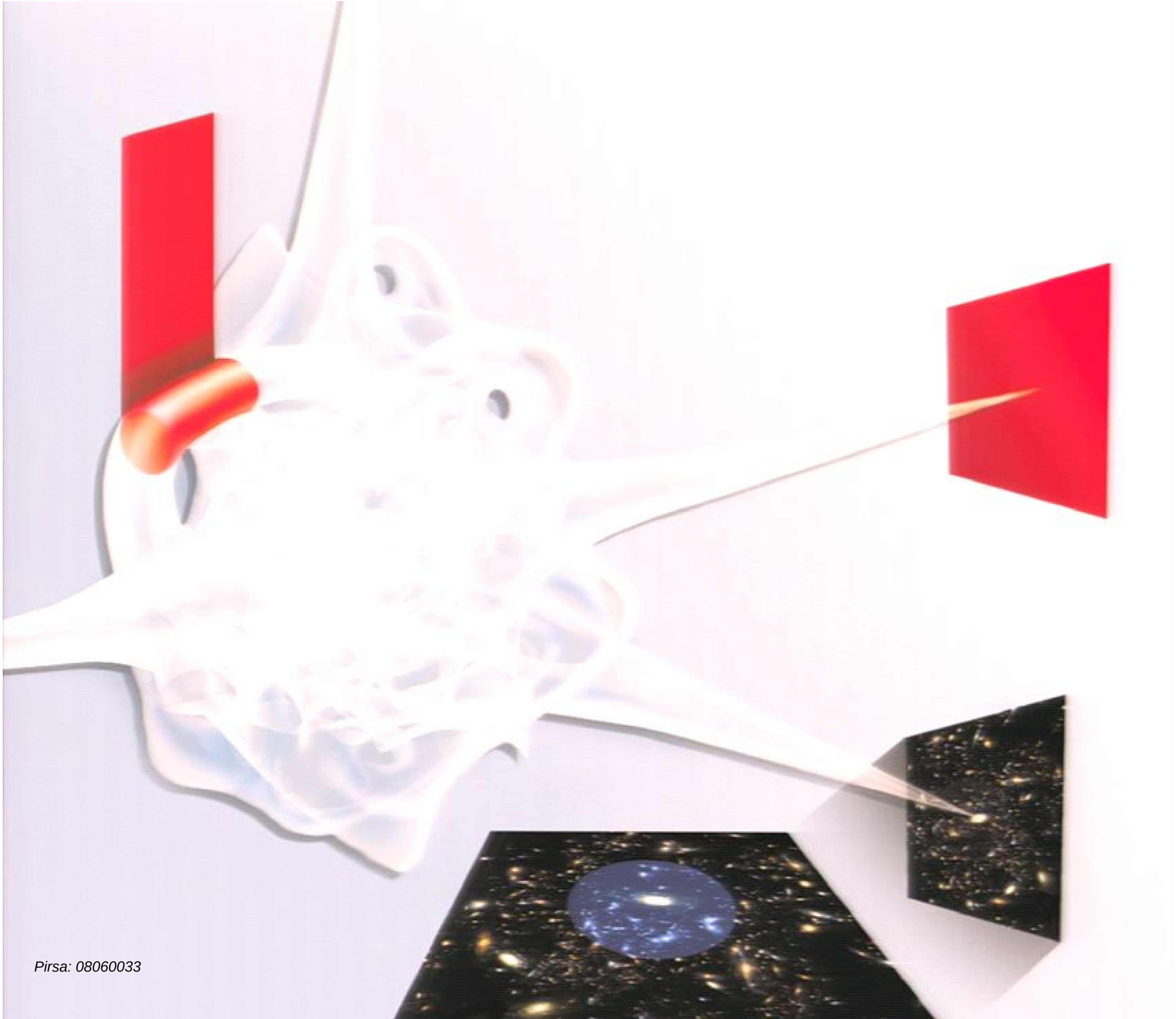
$$(\tau_1, \tau_2) \longrightarrow (\mathcal{V}, \Omega): \qquad \begin{cases} \mathcal{V} \simeq \alpha \left[\sqrt{\tau_1}\,(\tau_2 - 3\tau_1)\right] \\ \Omega = \alpha \left[\sqrt{\tau_1}\,(\tau_2 + 3\tau_1)\right] \end{cases}$$



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

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

$\lambda=1/3$

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

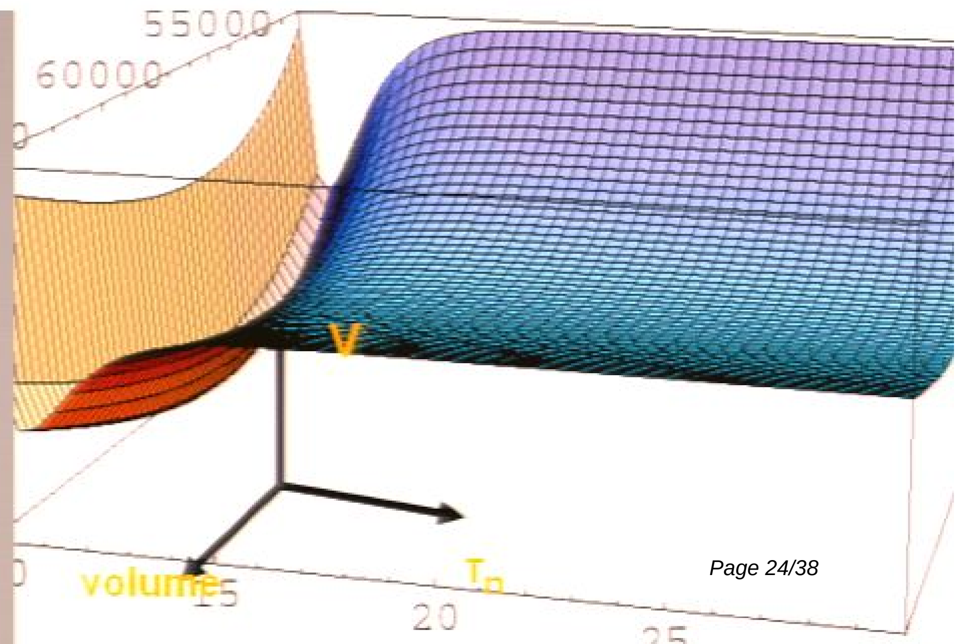
$$V=\sum_i \frac{8(a_iA_i)^2\sqrt{\tau_i}}{3\mathcal{V}\lambda_i\alpha}e^{-2a_i\tau_i}-\sum_i 4\frac{a_iA_i}{\mathcal{V}^2}W_0\tau_i e^{-a_i\tau_i}+\frac{3\xi W_0^2}{4\mathcal{V}^3}.$$

Conlon-FQ
Bond et al.
...

$$V\cong V_0-\frac{4W_0a_nA_n}{\mathcal{V}^2}\left(\frac{3\mathcal{V}}{4\lambda}\right)^{2/3}(\tau_n^c)^{4/3}\exp\left[-a_n\left(\frac{3\mathcal{V}}{4\lambda}\right)^{2/3}(\tau_n^c)^{4/3}\right].$$

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

Small field inflation
No fine-tuning!!
0.960<n<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)

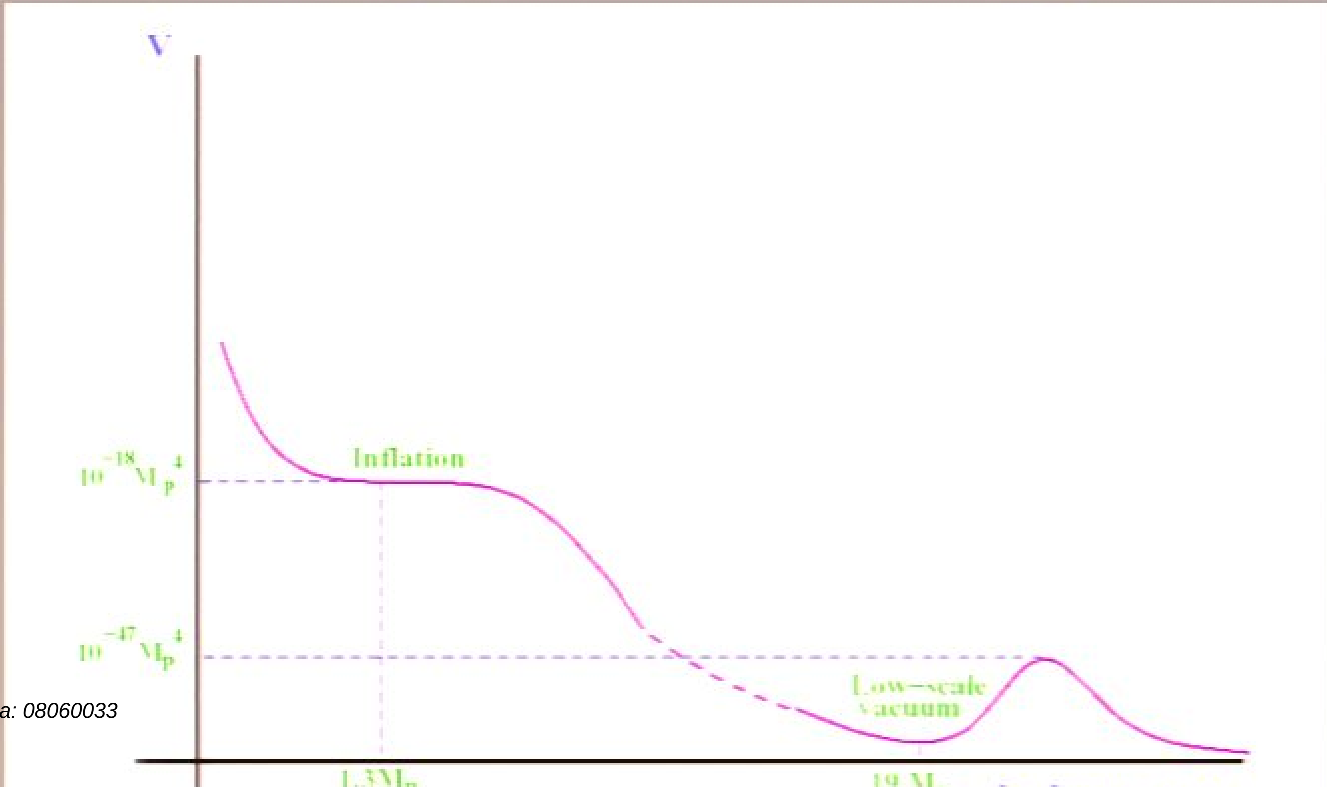
Low Energy SUSY vs Inflation

- Low scale inflation?

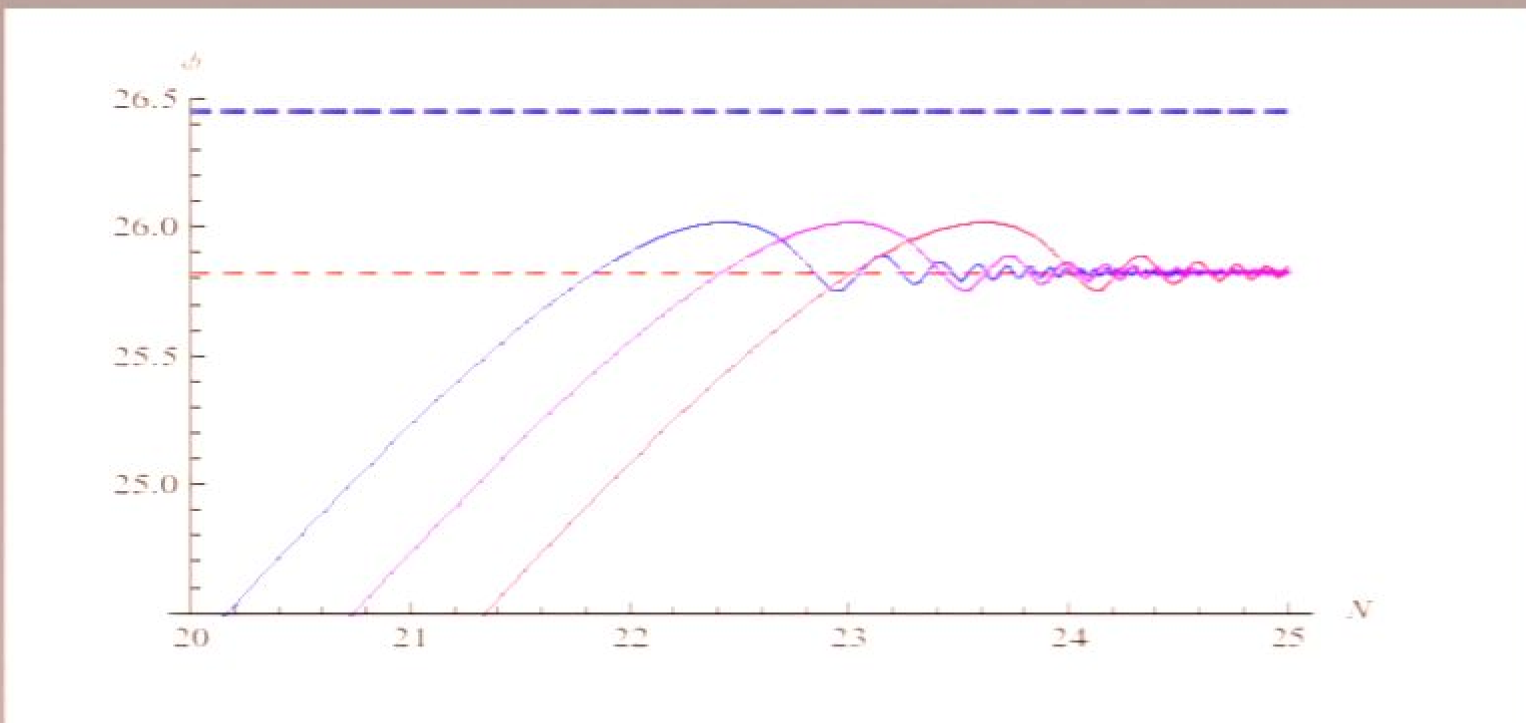
Ross et al, …

- Runaway before reheating?

Conlon, Kallosh, Linde, F



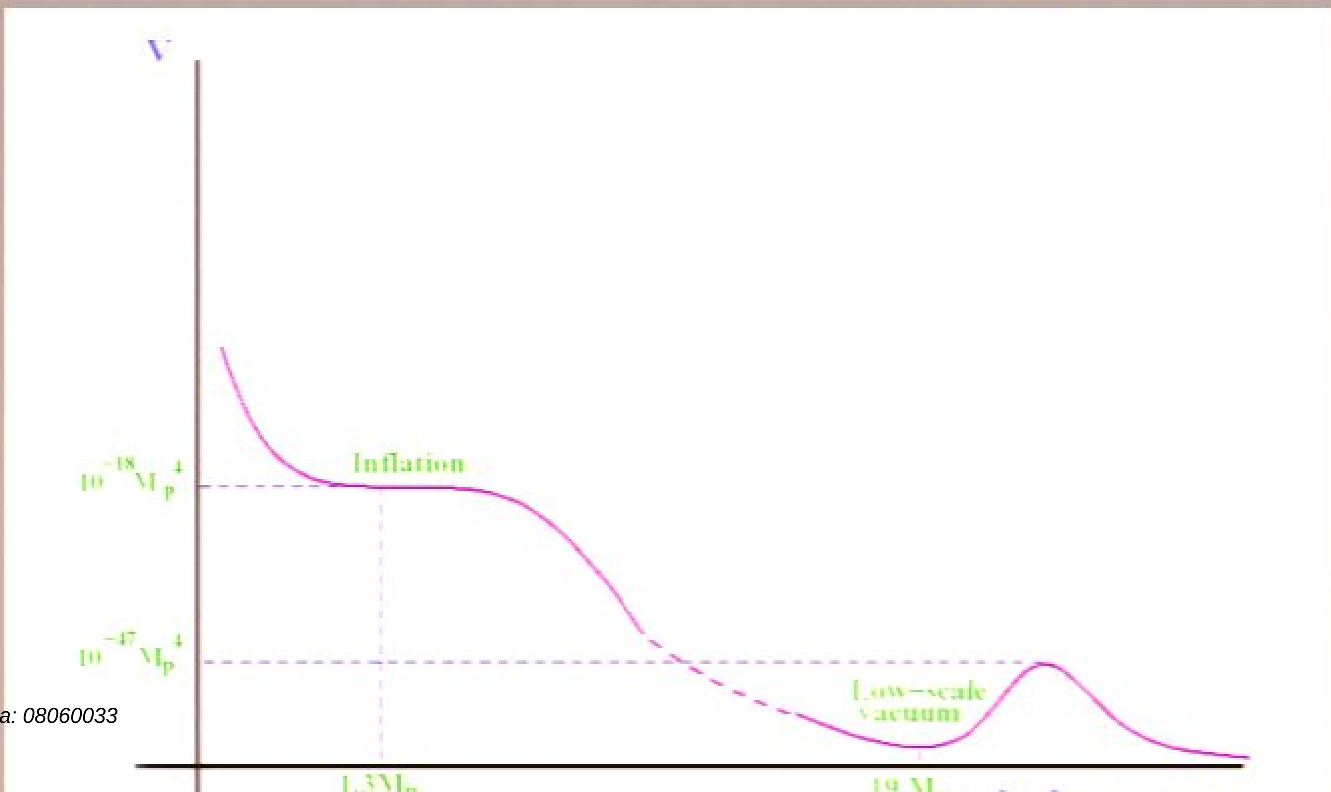
No Overshooting problem!!!



Low Energy SUSY vs Inflation

- Low scale inflation? Ross et al, …

- Runaway before reheating? Conlon, Kallosh, Linde, F



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

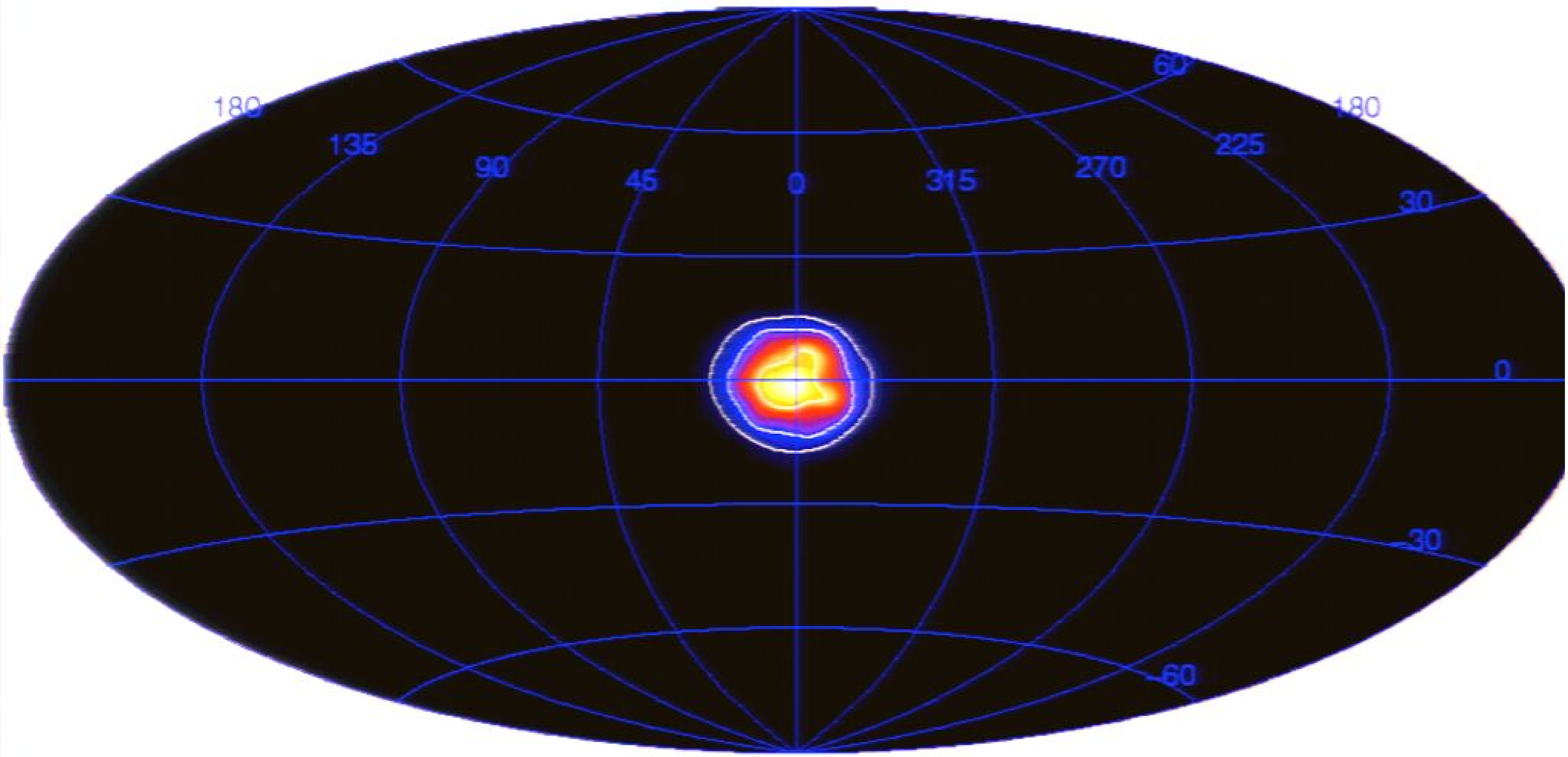
T: except for volume, heavy and decay fast ! (No CMP nor gravitino overproduction)

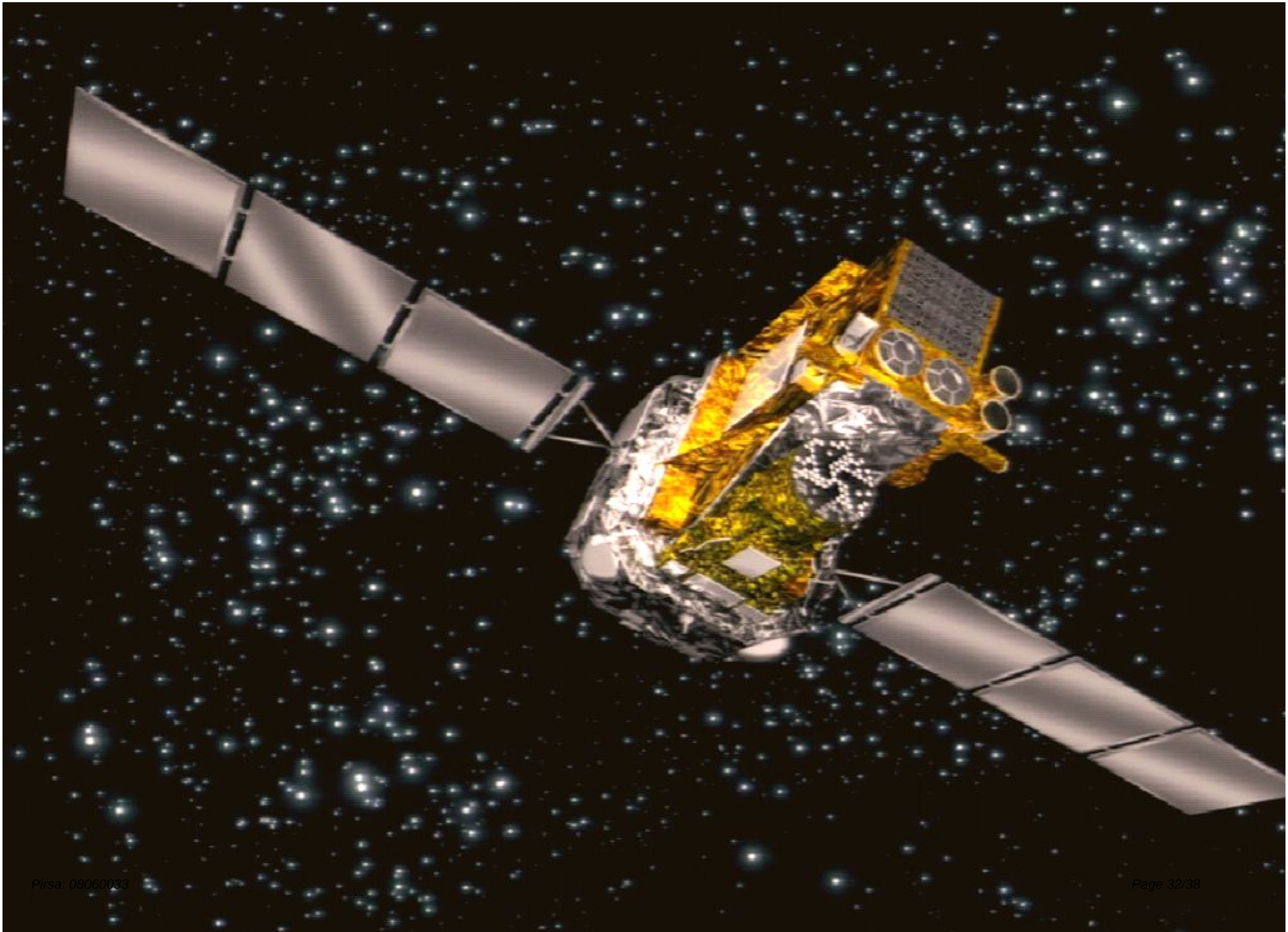
Volume: (mass MeV) CMP

- Observational implications of light volume modulus?

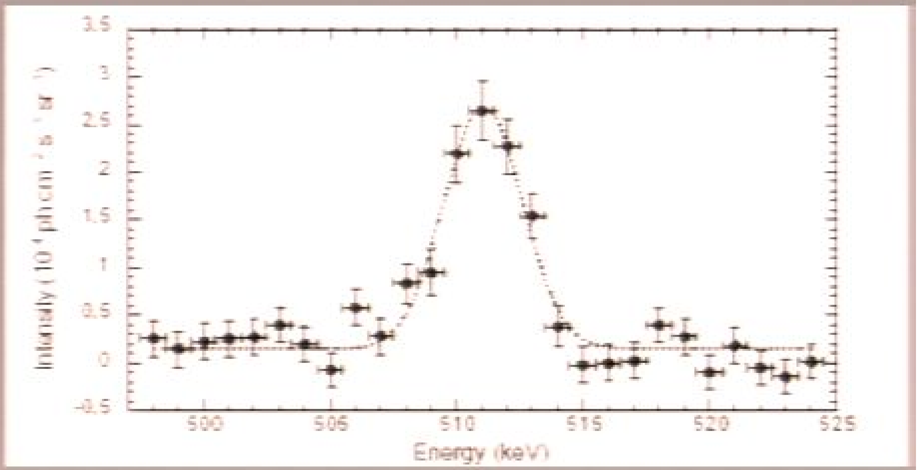
Gamma rays, e^+-e^-

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 $_{\chi}$ 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.

Alexey Boyarsky[1,*], Denys Malyshev[2,3], Andrey Neronov[4,*], Oleg Ruchayskiy[5]

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<<1 or warping (warping + Large Volume!)
- No Cosmological Moduli Problem
- Candidate for quintessence: volume axion (w=-0.99...)
- 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?