Slaying the Hydra of Dark Radiation

Arthur Hebecker (Heidelberg)

based on work with **Michele Cicoli, Joerg Jaeckel and Manueal Wittner '22**

(to appear in JHEP)

Outline

- Realizing a phenomenologically/cosmologically favourable QCD axion in the string-theoretic 'Large Volume Scenario'.
- Naturally avoiding the Dark Radiation problem due to a strong coupling of volume modulus and Higgs.
- Need for an explicit inflation model:
  Kahler inflation & reheating → Dark Radiation abundance.
- Key result: Small but potentially observable amount of Dark Radiation from reheating after Kahler inflation.

QCD axion:

$$\mathcal{L} \supset \theta F_{QCD} \tilde{F}_{QCD} + \frac{1}{2} f^2 (\partial\theta)^2 + \Lambda_{QCD}^4 \cos(\theta) .$$

(QCD-induced potential dominates θ-dynamics, driving it to zero.)

Axion origins:

(1) Field-theoretic: $\varphi = \langle\varphi\rangle e^{i\theta}$

Needs model building; in general faces ‘quality problem’.

(2) Fundamental (stringy or *p*-form) axion: $\theta \sim \int C_p / B_2$

Axion arises as *p*-form gauge field in 10d, integrated over cycle of Calabi-Yau. $\Rightarrow$ Perturbatively flat potential by gauge symmetry.

$\Rightarrow$ Excellent quality for free.

Finally, the SUSY structure $\mathcal{L} \supset T W_\alpha W^\alpha |_{F-term}$; $T = \tau + i\theta$

automatically leads to the desired coupling $\mathcal{L} \supset \theta F \tilde{F}$.

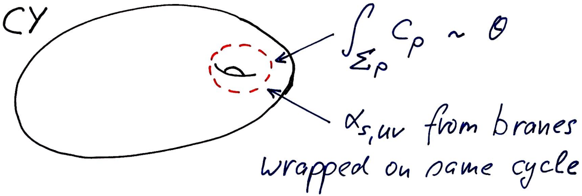
Personal conclusion:

Option **(2)** of a *p*-form axion is much preferred.

Known problem / challenge in this context:

Conlon, Svrcek/Witten '06

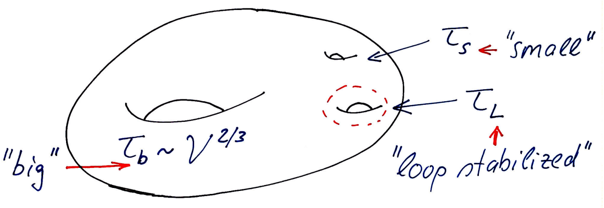
Non-trivial to realize the preferred value $f \ll M_P$.
Leading approach: Large compactification volume.



$$\Rightarrow \quad \frac{f_{min}^2}{M_P^2} \sim \frac{\alpha_{s,\,UV}}{\sqrt{g_s}\,\mathcal{V}} \qquad \left(\text{In LVS: } \frac{f_{min}^2}{M_P^2} \sim \frac{3\gamma_L}{16\pi^2\sqrt{\tau_L}\,\mathcal{V}} \right).$$

Large Volume Scenario (LVS) with loop-stabilized cycle

- The only (more or less...) controlled way of getting the required large volume $\mathcal{V}$ above is the ‘LVS’.
- It is based on CYs with a big and a small 4-cycle. (In our case with a further cycle ‘τ_L’ stabilized by loop effects.)



- Supergravity description:

$$K = -2\ln(\mathcal{V} + \xi/g_s^{3/2}) \;; \qquad \mathcal{V} = \tau_b - \gamma_s\tau_s^{3/2} - \gamma_L\tau_L^{3/2} \;;$$

$$W = W_0 + e^{-\tau_s} \qquad \Rightarrow \qquad \boxed{\mathcal{V} \sim e^{\tau_s} \sim e^{1/g_s}} \,.$$

Key cosmological bounds

DM: $\Omega_{DM} \gtrsim 0.2 \left(\frac{f}{10^{12}\mathrm{GeV}} \right)^{7/6} \theta_i^2$ (with 'i' for initial)

Isocurvature perturbations: $H_I \lesssim 1.4 \cdot 10^5 \; f \, \theta_i$

Using also $f \sim \frac{1}{\sqrt{\mathcal{V}}}$ and $\theta_i \lesssim \left(\frac{10^{12}\mathrm{GeV}}{f} \right)^{7/12}$, one finds

$$\Rightarrow \quad \boxed{H_I \lesssim \frac{10^9\mathrm{GeV}}{\mathcal{V}^{5/24}}}$$

Combining $H_I \lesssim (10^9 \text{GeV}/\mathcal{V}^{5/24})$

with the general expectation $H_I^2 \sim V_{LVS}/M_P^2 \sim (W_0^2/\mathcal{V}^3)M_P^2$,

one finally has:

$$\Rightarrow \quad \boxed{\mathcal{V} \gtrsim 10^7} \quad ,$$

i.e. we are deeply in the ‘LVS regime’. Must face

Dark radiation problem of LVS

Cicoli/Conlon/Quevedo, Higaki/Takashi ’12
AH/Mangat/Rompineve/Witkowski ’14

- ‘Volume modulus’ τ_b is lightest field
- It oscillates late and decays to – its own axion θ_b
  – the (MS)SM Higgs particles.

The coupling to the Higgs originates in the Kahler potential

$$K \supset -3 \ln \left(T_b + \overline{T}_b + \frac{1}{3}(H_u \overline{H}_u + H_d \overline{H}_d + z H_u H_d + \text{h.c.}) \right)$$

$$\Rightarrow \qquad \mathcal{L} \supset z H_u H_d \, \partial^2 (\ln \tau_b) \, .$$

This is comparable to the standard, Kahler-potential-based coupling of τ_b to its own axion θ_b, such that:

$$\Rightarrow \qquad \Gamma_{\tau_b \to \text{SM or } \theta_b \theta_b} \sim \frac{m_{\tau_b}^3}{M_P^2} \qquad \Rightarrow \qquad \Delta N_{eff} \gtrsim \mathcal{O}(1) \, .$$

(Recall: observationally, $\Delta N_{eff} \lesssim 0.2 \cdots 0.4$.)

Crucial new point: This will change for high-scale ~~SUSY~~.

Volume modulus decay for high-scale ~~SUSY~~

- Dominant effect now due to mass term: $\mathcal{L} \supset -m_h^2(\mathcal{V})\, h^2\,.$

$$m_h^2(\mathcal{V}) \;\sim\; m_{3/2}^2 \left[c_0 + c_{loop}\, \ln\left(\frac{m_{KK}}{m_{3/2}}\right)\right]$$

- This is the famously fine-tuned small eigenvalue of the MSSM Higgs mass matrix.

- The running of its loop correction is governed by:

$$m_{KK} \equiv m_{KK,\tau_s} \sim M_P/\sqrt{\mathcal{V}} \quad ; \qquad m_{3/2} \sim M_P \cdot W_0/\mathcal{V}\,.$$

- Using $\mathcal{V} \sim \tau_b^{3/2}$ this gives

$$\boxed{\mathcal{L} \;\supset\; m_{3/2}^2\, c_{loop}\; h^2\, \delta(\ln \tau_b)\,.}$$

Volume modulus decay for high-scale ~~SUSY~~ (continued)

- The resulting rate is governed by the pre-fine-tuning scale $m_{3/2}^2$ of the Higgs mass term:

$$\Gamma_{\tau_b \to hh} \sim \frac{m_{3/2}^4 c_{loop}^2}{m_{\tau_b} M_P^2} \sim (c_{loop}\mathcal{V})^2 \frac{m_{\tau_b}^3}{M_P^2} \gg \Gamma_{\tau_b \to \theta_b \theta_b} \,.$$

(Head one of the Hydra is gone.)

- Does this solve the DR problem? Not necessarily since
  - τ_b now decays too fast.
  - It loses its role of the particle reheating the universe.
  - Instead, one expects this task to fall to the inflaton, potentially re-introducing a DR issue.

(This is head two, to be dealt with montarily....)

⇒ We need the details of

String inflation in the LVS

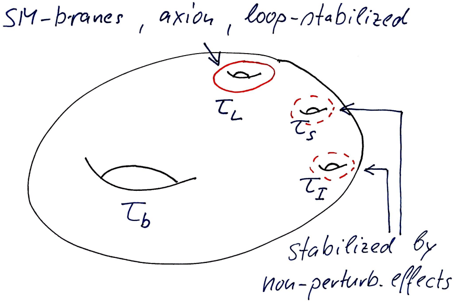
- The leading candidates are Blowup and Fibre inflaton.

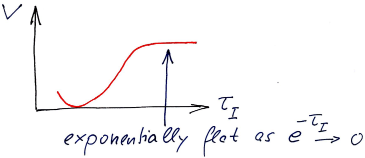
  Conlon/Quevedo/Burgess/Cicoli '05/08'

- Blowup is preferred due to its low value of H_I.

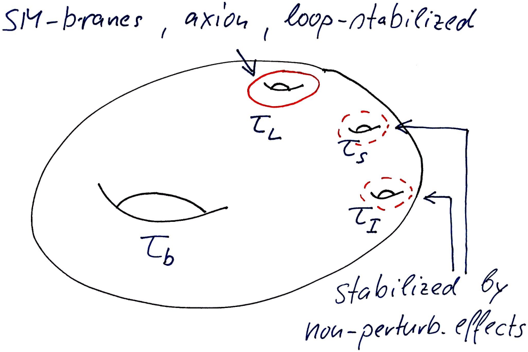
- At the technical level, one introduces a 4th blowup-cycle 'τ_I':

$$K = -2\ln\mathcal{V} = -2\ln(\tau_b^{3/2} - \tau_s^{3/2} - \tau_I^{3/2} - \tau_L^{3/2})$$





String inflation in the LVS and reheating



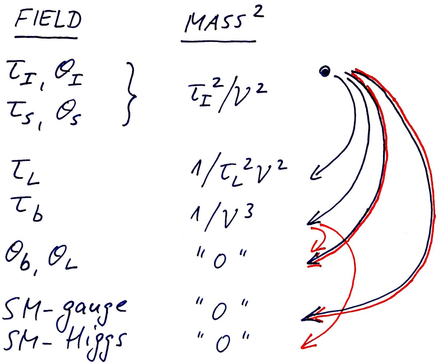
- The hierarchy of cycles is $\tau_b \gg \tau_L \gg \tau_s, \tau_I$
- for the loop-stabilization of τ_L we use the ansatz

Cicoli/Goodsell/Ringwald

$$V_{loop} = \left(\frac{\mu_1}{\sqrt{\tau_L}} - \frac{\mu_2}{\sqrt{\tau_L} - \mu_3} \right) \frac{W_0^2 M_P^4}{\mathcal{V}^3}$$

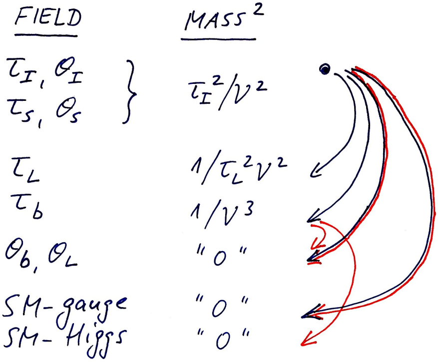
- The detailed analysis of decay rates in this setting shows that kinetic-term-induced decays dominate.
(cf. our 20-page Appendix following Cicoli/Mazumdar '10)

- Mass hierarchy:



FIELD	MASS^2
τ_I, θ_I τ_s, θ_s	$\tau_I^2/\mathcal{V}^2$
τ_L	$1/\tau_L^2\mathcal{V}^2$
τ_b	$1/\mathcal{V}^3$
θ_b, θ_L	"0"
SM-gauge	"0"
SM-Higgs	"0"

- Key point made before: The decay of τ_b to the SM Higgs is fast and dominates over the decay to its axion.



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- The decay rates of τ_I shown above are all parametrically of the order of $$\Gamma_1 \sim \frac{(\ln \mathcal{V})^{9/2}}{\mathcal{V}^4} M_P \, .$$
- The crucial numerical ratios are specified by

$$\frac{\Gamma_{\tau_I \to \tau_b \tau_b \,/\, \theta_b \theta_b}}{\Gamma_1} = 1 \, , \qquad \frac{\Gamma_{\tau_I \to \tau_L \tau_L \,/\, \theta_L \theta_L}}{\Gamma_1} = 4 \, , \qquad \frac{\Gamma_{\tau_I \to \text{SM gauge}}}{\Gamma_1} = 8 N_g \, .$$

- The crucial large rate to gauge bosons arises because τ_l mixes with τ_L, and the latter directly governs the SM gauge coupling.

- Eventually, DR branching ratio and abundance are:

$$BR(\tau_l \to \text{DR}) \simeq \frac{5}{8N_g} = \frac{5}{8\cdot 12} \simeq 0.05\,.$$

$$\Delta N_{\rm eff} \simeq 6.1\left(\frac{11}{g_*}\right)^{1/3} BR(\tau_l \to \mathrm{DR}) \simeq 2.8\,BR \simeq 0.14\,.$$

- This is a rather specific prediction and an interesting target for future CMB observations.

- The relative smallness originates in $N_g = 12 \gg 1$.

Sweet-spot cosmology (high-temperature regime)

- The lowest allowed volume (without excessive tuning) is

$$\mathcal{V} \sim 10^7 .$$

- This implies

$$f \sim 10^{14}\,\mathrm{GeV}\,, \qquad m_{3/2} \sim 10^{11}\,\mathrm{GeV}\,, \qquad m_{\tau_b} \sim 10^{7}\,\mathrm{GeV}.$$

- Resulting inflation scale and reheating temperature (based on the decay rates above):

$$H_I \sim 10^7\,\mathrm{GeV}\,, \qquad T_R \sim 10^6\,\mathrm{GeV}.$$

- In summary, this is a fairly standard cosmology, with some tension concerning the (potentially low) CMB-normalization.
  $\Rightarrow$ More work on blowup-inflation pheno needed.

Cosmology: low-temperature regime

- It would be interesting to explore larger volumes (up to $\mathcal{V} \sim 10^{10}$ and hence $T_R \sim 100\,\mathrm{GeV}$.)
- Then $m_{\tau_b} \sim m_h$, possibly leading to interesting effects in the $\tau_b - SM$ transition.
- But: The relevant H_I becomes very low, strongly clashing with normalization of CMB perturbations.

Summary/Conclusions

- Due to its p-form fields, string models have very natural high-quality axion candidates – let us take them seriously!
- Cosmological bounds on f_a enforce large $\mathcal{V}$ and hence LVS.
- Since SM must be on D7-brane, we have $m_{3/2} \gg$ TeV.
- The fine-tuned Higgs mass operator induces strong coupling $\tau_b\, hh$ and solves 'conventional' DR problem.
- But now the inflaton (of blowup-inflation) becomes the longest-lived particle and again creates (too much?) DR.
- But, fortunately, the mixing $\tau_{inf} - \tau_L$ is large enough to produce so many SM gauge bosons that we land at a non-excluded but discoverable amount of DR! ($\Delta N_{eff} \simeq 0.14$)