Dark radiation
in the non-sequestered Large Volume scenario

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Outline

- Dark radiation – observational hints/bounds
- Dark radiation in the sequestered LVS
- . . . and in the non-sequestered LVS
- . . . and in the LVS with flavor-branes
- Summary/Conclusions

Introduction

- conventional variable: N_{eff}

  (effective number of neutrino species; $N_{eff}^{SM} = 3.046$)

- Plank + WMAP + highL + BAO:

$$N_{eff} = 3.3 \pm 0.5 \quad (95\%\ \mathrm{CL})$$

- Including also H_0:

$$N_{eff} = 3.5 \pm 0.5 \quad (95\%\ \mathrm{CL})$$

- $\Rightarrow$ mild preference for $\Delta N_{eff} \neq 0$;
  Here: View this as a bound on dark radiation

- Crucial: Significant improvement expected in the future;
  Potential to exclude models with $\Delta N_{eff} \neq 0$

Introduction - continued

- Conventional picture of cosmological evolution with some extra light d.o.f. (DR) :

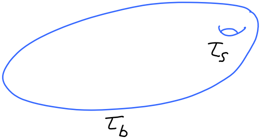
$$\text{Inflaton} \longrightarrow (\text{Modulus } \Phi) \longrightarrow \text{SM} + \text{DR}$$

$$\Delta N_{eff} = \frac{43}{7}\left(\frac{10.75}{g_*(T_d)}\right)^{1/3} \frac{\rho_{DR}}{\rho_{SM}}\bigg|_{T_d}$$

- Here T_d is the decay temperature of Φ and

$$\frac{\rho_{DR}}{\rho_{SM}}\bigg|_{T_d} = \frac{\Gamma_{\Phi \to DR}}{\Gamma_{\Phi \to SM}}$$

Dark radiation in the Large Volume scenario



- Notation: $T_b = \tau_b + ia_b$; $T_s = \tau_s + ia_s$

$$K = -2\ln \mathcal{V} = -2\ln\left((T_b + \overline{T}_b)^{3/2} - (T_s + \overline{T}_s)^{3/2}\right)$$

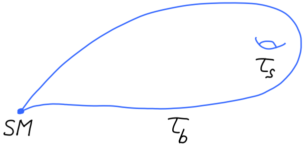
- Crucial point:
  α'-corrections + non-pert. effects lead to stabilization at exponentially large volume

$$\tau_b \sim \exp(\tau_s) \sim \exp(\chi)$$

- Classical shift symmetry $a_b \to a_b +$ const. is only broken non-perturbatively; $m_a = 0$ for all practical purposes.

Dark radiation in the sequestered Large Volume scenario

Cicoli, Conlon, Quevedo '12
Higaki, Nakayama, Takahashi '12...'13



- SM on fract. D3s at singularity of type-IIB CY-orientifold
- gauge-kinetic function $f = f(S)$
- sequestered Kähler potential:

$$K = -3\ln\left(T_b + \overline{T}_b - \frac{1}{3}\left[C^i\overline{C}^i + H_u\overline{H}_u + \{zH_uH_d + \text{h.c.}\} + \cdots\right]\right)$$

see e.g. Blumenhagen, Conlon, Krippendorf, Moster, Quevedo, '09

- A straightforward analysis gives:

$$\Gamma_{\Phi \to a_b a_b} = \frac{1}{48\pi} \frac{m_\Phi^3}{M_P^2}$$

$$\Gamma_{\Phi \to H_u H_d} = \frac{2z^2}{48\pi} \frac{m_\Phi^3}{M_P^2}$$

- Conclusion: Need either $z > 2$ or $n_H > 4$.

  (Here n_H counts pairs of Higgs doublets
  and one assumes the bound $N_{eff} < 4$.)

- Comment: Shift symmetry singles out $z = 1$,

$$K_H \sim |H_u + \overline{H}_d|^2 \,.$$

  (It is unclear how to realize $z \gg 1$ at a fundamental level.
  Note that the Kähler metric becomes singular in this limit.)

Dark radiation in the non-sequestered Large Volume scenario

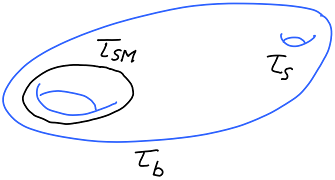
- The non-sequestered case been discussed before (with SM on non-perturbatively stablized cycles)

  Higaki, Kamada, Takahashi '12

- It is claimed that axions are not an issue at all, but stringy realizability of this specific setting is unclear

- We focus on the (in our opinion more standard) D-term stabilization of 4-cycle ratios

- We assume that τ_{SM}/τ_b is stabilized by $V_D = 0$.



- Due to SUSY, we the have $T_{SM} = \alpha T_b$, with $\alpha \ll 1$ to be realized by the tuning of gauge fluxes.

- Now $m_{soft} \sim 1/\mathcal{V}$, while $m_{\tau_b} \sim 1/\mathcal{V}^{3/2}$.

  (Thus, low-scale SUSY is difficult to realize cosmologically. But this may actually be OK nowadays...)

- The gauge kinetic function reads

$$f \;=\; T_{SM} + hS \;=\; \alpha T_b + hS$$

- Again, a straightforward analysis gives:

$$\Gamma_{\Phi \to a_b a_b} = \frac{1}{48\pi} \frac{m_\Phi^3}{M_P^2}$$

$$\Gamma_{\Phi \to hh} = \frac{z^2 \sin^2(2\beta)}{192\pi} \frac{m_\Phi^3}{M_P^2}$$

$$\Gamma_{\Phi \to AA} = \frac{N_g \gamma^2}{96\pi} \frac{m_\Phi^3}{M_P^2}$$

where

$$\gamma = \frac{\tau_{SM}}{\tau_{SM} + h\,\mathrm{Re}S}$$

- The branching ratio to axions is

$$B_a = \frac{\Gamma_{aa}}{\Gamma_{aa} + \Gamma_{hh} + \Gamma_{AA}} = \frac{1}{1 + \frac{\sin^2(2\beta)}{4} z^2 + \frac{N_g}{2}\gamma^2}$$

- This gives

$$\Delta N_{eff} = \frac{43}{7}\left(\frac{10.75}{g_*(T_d)}\right)^{1/3} \frac{B_a}{1 - B_a}$$

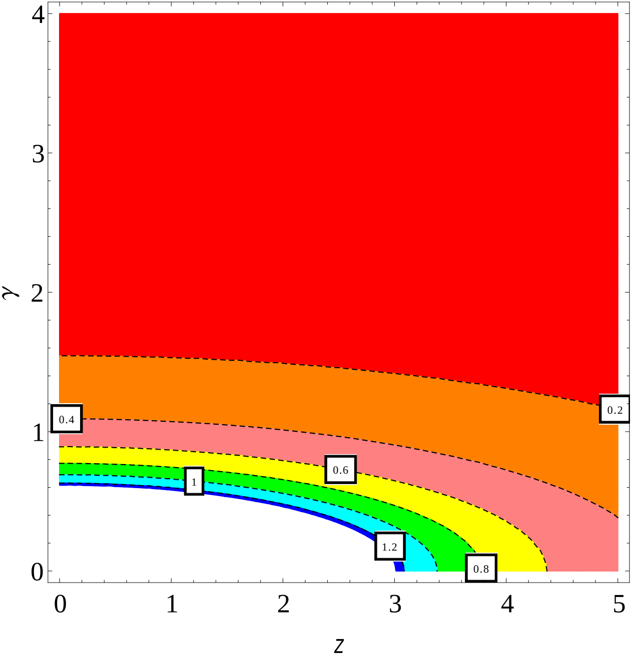
- Thus, assuming $\tan\beta = 1$ and $z \lesssim 1$
  and taking $N_g = 12$ (SM),
  our only option for lowering B_a is to increase γ.

ΔN_{eff}

in

non-sequestered

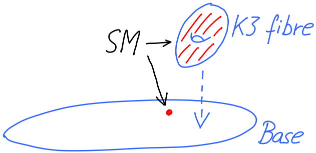
LVS



Non-sequestered LVS, stabilization by loop corrections

- Known possibility: fibre inflation

Cicoli, Burgess, Quevedo '08



$$\mathcal{V} = \sqrt{\tau_1}\tau_2 - \tau_s^{3/2}$$

- Here $\mathcal{V}_{K3} = \tau_1$; $\quad \mathcal{V}_{Base} = \frac{\tau_2}{\sqrt{\tau_1}}$
- Loops and standard LVS naturally stabilize $\tau_2 \gg \tau_1 \gg \tau_s$.

- Here, the overall volume $\mathcal{V}$ is not the lightest modulus
- This role is taken over by the ratio τ_2/τ_1.
- Advantage: $\tau_{SM} \sim \tau_1$ is naturally much smaller than the typical volume size.
- Now we have two axions (from T_1 and T_2).

$$B_a = \frac{1}{1 + \frac{1}{5} z^2 + \frac{24}{5} \gamma^2}$$

(for $\tan\beta = 1$ and $N_g = 12$)

- Numerical results are similar to the 'D-term case' above

Fundamental problem:

- In both case, unavoidably $\mathcal{L} \supset T_{light}\, W^{SM}_{\alpha} W^{SM,\alpha}\Big|_{\theta^2}$
- Our light axion is also the QCD axion
- Way out: Increase V
(But this lowers $T_{reh.}$ and makes baryogenesis difficult)
- Way out: Accept fine-tuning $a_{initial} \ll a_{typical}$
(This can be justified e.g. if ρ_{DM} is anthropically bounded)

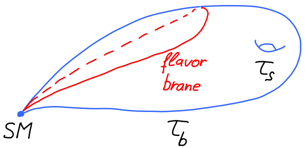
see e.g. Hertzberg, Tegmark, Wilczek '08; Freivogel '08

- Way out: Add a field-theoretic (open-string) QCD axion, with a decay constant which is set by some field-theory VEV ($\ll$ string scale)

Yet another possibility:

"sequestered" (or "de-sequestered") LVS with flavor branes

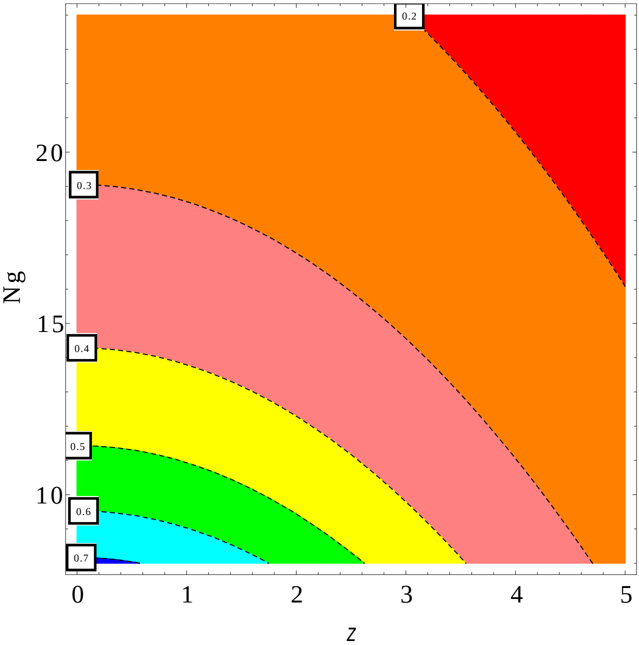
...appearing in Aldazabal, Ibanez, Quevedo, Uranga '00



- The SM is again at a singularity, but an extra weakly coupled gauge theory lives on a stack of flavor branes.
- This gauge theory must be spontaneously broken (Z' bounds apply)
- Cosmology: $\Phi \to DR + A'_\mu$; Subsequently $A'_\mu \to SM$
- Second decay is fast; The analysis is (essentially) as before

ΔN_{eff}

in LVS
with
flavor-branes



Conclusions / Summary

- Interpreting present 'dark radiation data' as bounds, the sequestered LVS may already be in trouble

  (Although this depends on $T_{reh.}$)

- The 'non-sequestered' or 'de-sequestered' (through flavor branes) LVS provides a natural way out

- Nevertheless, discovery of dark radiation is expected in the foreseeable future

- Otherwise, there is the potential of ruling out the LVS altogether

  (Unless one is prepared to accept an anthropically unmotivated tuning)