# Dark Radiation in Fibred LARGE Volume Compactifications

Stephen Angus

based on arXiv:1403:6473 (SA)

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# Outline

1. **Motivation**
   - Experimental hints
   - Theoretical perspective
2. **Dark radiation in the LARGE Volume Scenario**
   - The minimal model: one axion
   - Fibred scenario: two axions
3. **Dark Radiation in Fibred LVS models**
   - The decay modes
   - Predictions for $\Delta N_{\rm eff}$

# Why dark radiation?

- Dark radiation: hidden relativistic matter that contributes to the energy density of the universe.
- At CMB temperatures,

$$\rho_{\text{radiation}} = \rho_\gamma + \rho_\nu + \rho_{\text{hidden}} \, .$$

- Conventionally parametrised in terms of the "excess effective number of neutrino species", $\Delta N_{\text{eff}} = N_{\text{eff}} - 3.046$:

$$\rho_{\text{radiation}} = \rho_\gamma \left( 1 + \frac{7}{8} \left( \frac{4}{11} \right)^{4/3} N_{\text{eff}} \right) \, .$$

NOTE: Not necessarily extra $\nu$s; $N_{\text{eff}}$ can be non-integer valued!

# Why dark radiation?

Experimental hints:

- Planck+WP+highL+BAO+$H_0$ results:
  $N_{\text{eff}} = 3.52^{+0.48}_{-0.45}$,with $H_0 = 67.3 \pm 1.2\,\text{km}\,\text{s}^{-1}\,\text{Mpc}^{-1}$.
  (arXiv:1303.5076, Planck Collaboration)
- One BBN-only study: $N_{\text{eff}} = 3.50 \pm 0.20$ (arXiv:1308.3240).
- [BICEP2: $r > 0$. Having more DR can reduce tension with Planck.
  $N_{\text{eff}}^{(r=0.2)} = 4.00 \pm 0.41$ (Planck+WP+BICEP2) (arXiv:1403.4852).]

Can we trust these values?

- Results may favour a small DR contribution.
- Need to wait until the dust settles!

# Why dark radiation?

**Disclaimer**

In this talk: axion $\equiv$ axion-like particle (ALP).

String theory perspective:

- Generically $\mathcal{O}(100)$ gravitationally-coupled moduli (scalars), each with associated axions (ALPs), many of which can be massless.
- After inflation, universe reheated by decays of the lightest moduli.
- Any non-zero branching ratio to light hidden states is a source of dark radiation!

General considerations:

- Simple and natural extension of $\Lambda$CDM — if DM, why not DR?
- No a-priori reason why $N_{\rm eff} = 3.046$ (eg. not symmetry-protected).

Harder to argue why dark radiation should *not* exist!
(Conversely, if $N_{\rm eff} = 3.046$, string theory models must explain why.)

# Reheating

What happens after inflation?

- Any gravitationally-coupled scalar particles (eg. moduli in string theory) have generically acquired large non-zero VEVs.
- Begin to oscillate coherently about their final vacuum.
- Redshift as matter, $\rho_{\mathrm{M}} \sim a^{-3}$; any radiation redshifts as $\rho_{\mathrm{R}} \sim a^{-4}$.
- Moduli come to dominate the energy density of the universe; reheating is driven by the last modulus to decay.
- Final modulus $\Phi$ decays into visible and hidden-sector particles, with comparable decay rates,

$$\Gamma \sim \frac{m_{\Phi}^3}{M_{\mathrm{P}}^2}\,.$$

Take-home message: the *lightest* modulus is *last* to decay.

# Cosmic Axion Background

- Decay to axions can occur via an interaction Lagrangian

$$\mathcal{L} \supset \frac{2}{\sqrt{6} M_P} \Phi \partial_\mu a \partial^\mu a .$$

- This produces pairs of axions, each with energies $E_a = m_\Phi / 2$.
- These axions are highly relativistic and stream freely.
- Present day: would form a Cosmic Axion Background 1305.3603 (Conlon, Marsh).
- Can test CAB hypothesis via:
  - CMB, $N_{\rm eff}$ (that's us!);
  - axion-photon conversion in galaxy cluster B-fields (see talk by M.Rummel);
  - 3.5 keV line: DM $\rightarrow a \rightarrow \gamma$ in clusters/galaxies (other talk by M.Rummel).

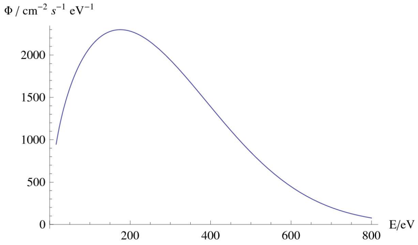



**Figure:** CAB, for $N_{\rm eff} = 3.62$.

# LARGE Volume Scenario — overview

- Compactification of type IIB string theory where the Calabi-Yau volume $\mathcal{V}$ is stabilized to be exponentially large.
- Field content always includes:
  - the volume modulus, $\Phi$, whose large VEV fixes the volume;
  - its axion partner, the volume axion $a_b$.
- Realise (MS)SM on D3 branes at a singularity $\Rightarrow$ sequestering of soft masses:

$$M_{\text{soft}} \sim m_0 \sim m_{1/2} \sim \frac{M_{\text{P}}}{\mathcal{V}^2} \,.$$

Some reasons to have a sequestered visible sector:

- makes $\Phi \to$ visible kinematically viable;
- avoids Cosmological Moduli Problem (light moduli spoil BBN) for TeV-scale soft terms $\Rightarrow m_\Phi \sim 5 \times 10^6$ GeV.

Alternatively: D7s on fibre cycle (Hebecker *et al*, arXiv:1403.6810).

# LARGE Volume Scenario — mass hierarchy

**Hierarchy of scales:**

$$\begin{aligned} M_{\text{string}} &\sim \frac{M_P}{\mathcal{V}^{1/2}} \\ m_\Phi &\sim \frac{M_P}{\mathcal{V}^{3/2}} \\ M_{\text{soft}} &\sim \frac{M_P}{\mathcal{V}^2} \\ m_{a_b} &\lesssim M_P\, e^{-2\pi\mathcal{V}^{2/3}} \sim 0\,. \end{aligned}$$

- Note that the volume axion $a_b$ is effectively massless $\Rightarrow$ candidate for dark radiation.
- The leading decay modes of $\Phi$ are:
  - $\Phi \to a_b a_b$ (hidden);
  - $\Phi \to H_u H_d$ (visible).
- Other hidden sector channels possible (won't discuss here).
- Shift symmetry in Higgs sector $\Rightarrow Z = 1$ at the string scale.

Interaction Lagrangian:

$$\mathcal{L} \supset \frac{2}{\sqrt{6}M_P}(\partial_\mu a_b)^2\,\Phi + \frac{1}{\sqrt{6}M_P}\left[Z H_u H_d \Box \Phi + \text{h.c.}\right].$$

# Results for the one-axion model

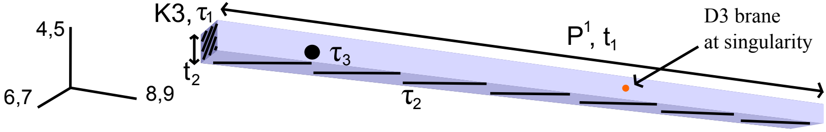
- Minimal LVS: MSSM spectrum; Giudice-Masiero coupling $Z = 1$.
- Tree-level result: $\Delta N_{\text{eff}} \simeq 1.7$, in conflict with observation arXiv:1208.3562 (Cicoli, Conlon, Quevedo), 1208.3563 (Higaki, Takahashi).
- Include loop corrections $\Rightarrow$ lower bound of

$$\Delta N_{\text{eff}} \gtrsim 1.4 \, ,$$

  which is not much better than the tree-level result! arXiv:1305.4128 (SA, Conlon, Haisch, Powell)
- Exhibits the "moduli-induced axion problem": too much DR arXiv:1304.7987 (Higaki, Nakayama, Takahashi).

# Fibred scenario: two axions

- The minimal scenario appears to be ruled out!
- Need to look for alternative scenarios...
- Simple extension: fibred LVS compactifications (e.g. K3 or $T^4$ fibrations over a $\mathbb{P}^1$ base).
- Now two bulk moduli, each with associated axions.
- Visible sector on D3 branes at a singularity $\Rightarrow$ sequestering.
- Bulk volume takes the form $\mathcal{V} \simeq \sqrt{\tau_1}\tau_2$ .




- $\tau_3$: small local cycle wrapped by ED3s; gives LARGE volume $\mathcal{V}$.

# Fibred LVS — mass hierarchy

**New hierarchy of states:**

$$\begin{aligned} M_{\text{string}} &\sim \frac{M_P}{\mathcal{V}^{1/2}} \\ m_{\Phi_{\mathcal{V}}} &\sim \frac{M_P}{\mathcal{V}^{3/2}} \\ m_{\Phi_\Omega} &\sim \frac{M_P}{\mathcal{V}^{3/2}\tau_1^{1/4}} \\ M_{\text{soft}} &\sim \frac{M_P}{\mathcal{V}^2} \\ m_{a_1,a_2} &\lesssim M_P\, e^{-2\pi\mathcal{V}^{2/3}} \sim 0\,. \end{aligned}$$

- One linear combination of moduli corresponds to the large bulk volume $\mathcal{V} \simeq \sqrt{\tau_1}\tau_2$.
- Flat transverse direction $\Omega$, lifted by string loop corrections (from D7 branes on $\tau_1$ and $\tau_2$) $\Rightarrow$ transverse combination $\Phi_\Omega$ is now the lightest modulus!
- Predictions of this scenario different from minimal LVS.
- Assume $\tau_1/\tau_2 \sim 10^{\pm \text{only a few}}$ $\Rightarrow$ ensures $m_{\Phi_{\mathcal{V}}} \gg m_{\Phi_\Omega}$.

# Decay to axions

- Kähler potential for bulk moduli & axions ($T_i \equiv \tau_i + i a_i$):

$$K = -2\ln\mathcal{V} \sim -\ln(T_1 + \bar{T}_1) - 2\ln(T_2 + \bar{T}_2)\,.$$

- Normalise $\Phi_1 = \frac{1}{\sqrt{2}}\ln\tau_1$, $\Phi_2 = \ln\tau_2$; rotate to mass eigenbasis (Burgess *et al*, arXiv:1005.4840)

$$\Phi_{\mathcal{V}} \equiv \sqrt{\frac{2}{3}}\Phi_2 + \sqrt{\frac{1}{3}}\Phi_1\,, \qquad \Phi_\Omega \equiv \sqrt{\frac{1}{3}}\Phi_2 - \sqrt{\frac{2}{3}}\Phi_1\,.$$

- Kinetic terms give interaction Lagrangian

$$\mathcal{L}_{\Phi_\Omega \to aa} = \frac{1}{\sqrt{3}M_P}\Phi_\Omega\left(2\partial_\mu a_1 \partial^\mu a_1 - \partial_\mu a_2 \partial^\mu a_2\right)\,.$$

**Resulting decay rate to axions:**

$$\Gamma_{\Phi_\Omega \to aa} = \frac{5}{96\pi}\frac{m_{\Phi_\Omega}^3}{M_P^2}\,.$$

# Decays to visible matter

- Decay to Higgs bosons: Kähler potential for vector-like matter is

$$K = -2\ln\mathcal{V} + \left\{ \frac{H_u\bar{H}_u + H_d\bar{H}_d + (Z H_u H_d + \mathrm{h.c.})}{\left(T_1+\bar{T}_1\right)^{1/3}\left(T_2+\bar{T}_2\right)^{2/3}} \right\} .$$

- Relevant terms in the Lagrangian are

$$\mathcal{L} \supset -\frac{1}{\sqrt{6}M_P}\Phi_{\mathcal{V}}\left[H_u\Box\bar{H}_u + H_d\Box\bar{H}_d + \mathrm{h.c.}\right]$$
$$-\frac{1}{\sqrt{6}M_P}\left[Z H_u H_d\Box\Phi_{\mathcal{V}} + \mathrm{h.c.}\right] .$$

  - 1st line: present for all matter scalars.
  - 2nd line: present for only vector-like matter.

- No longer any tree-level coupling to $\Phi_\Omega$!

# Decays to visible matter

Other visible sector decays:

- matter scalars — similarly no tree-level coupling to $\Phi_\Omega$;
- fermions — interactions chirality-suppressed, decays at loop level;
- gauge bosons — axions in the bulk, SM localised
  $\Rightarrow$ coupling $\mathcal{V}$-suppressed, also appears at loop level;
- other vector-like states — same story as for the Higgs bosons.

**Conclusion:**

NO tree-level decays of lightest modulus $\Phi_\Omega$ to visible matter!

# Consequences for $\Delta N_{\rm eff}$

- Amount of dark radiation fixed by the ratio of branching ratios,

$$\kappa \equiv \frac{\mathrm{Br(hidden)}}{\mathrm{Br(visible)}} = \frac{\mathrm{Br}(\Phi_\Omega \to aa)}{\mathrm{Br}(\Phi_\Omega \to \text{visible})} \, .$$

- Estimate decay rate to visible sector:

$$\Gamma_{1-\mathrm{loop}} \sim \left(\frac{\alpha_{\rm SM}}{4\pi}\right)^2 \frac{m_{\Phi_\Omega}^3}{M_P^2} \, ,$$

so

$$\kappa \equiv \frac{\mathrm{Br(hidden)}}{\mathrm{Br(visible)}} \sim \frac{5\pi}{6}\frac{1}{\alpha_{\rm SM}^2} \sim 10^2 \, .$$

**Result:**

$\Delta N_{\rm eff} \gtrsim 3\kappa$, so $\Delta N_{\rm eff} \gtrsim 300 \Rightarrow$ completely excluded!

# Alternative scenario

Alternatively:

- Visible sector on D7s wrapping the fibre cycle $\tau_1$ arXiv:1403.6810 (Hebecker, Mangat, Rompineve, Witkowski).
- Gauge kinetic function $f_{\rm vis} = T_1 + hS$, $\mathrm{Re}(f) \sim 1/g_{\rm SM}^2$, for $g_{\rm SM} \sim \mathcal{O}(1)$ consider limit where $\tau_2 \gg \tau_1$ ("anisotropic limit").
- Decay to Higgs restored; also decay to gauge bosons,

$$\Gamma = \frac{N_g}{48\pi} \gamma^2 \frac{m_{\Phi_\Omega}^3}{M_{\rm P}^2} \quad , \quad \gamma = \frac{\tau_1}{\tau_1 + h\mathrm{Re}(S)} \, .$$

- With $Z = 1$ and $\gamma = 1$ find a dark radiation abundance

$$\Delta N_{\rm eff} \simeq 0.6 \, .$$

- Natural parameter values allowed by data!

# Summary

- Dark radiation is a well-motivated addition to $\Lambda$CDM.
- The LARGE Volume Scenario in IIB String Theory is a good framework for building and testing models of the early universe.
- Constraints on $N_{\rm eff}$ provide a powerful test of such models.
- Minimal LVS is in tension with Planck data, so need to look at more complicated scenarios; fibred models qualitatively different.
- In the fibred sequestered scenario, $\Delta N_{\rm eff} \gtrsim 300$ (c.f. $\Delta N_{\rm eff} \simeq 0.5$) $\Rightarrow$ fibred sequestered models ruled out.
- D7s on the fibre cycle $\Rightarrow$ $\Delta N_{\rm eff} \simeq 0.6$, consistent with data.

However…

- If BICEP2 were to be confirmed, $\Delta N_{\rm eff} \simeq 1.0 \pm 0.4$ at 68% c.l. $\Rightarrow$ consistent with minimal LVS, where $\Delta N_{\rm eff} \gtrsim 1.4$.
- Watch this parameter space!