Loop corrections to dark radiation production in large volume models

Stephen Angus
in collaboration with
Joseph P. Conlon, Ulrich Haisch, Andrew J. Powell
University of Oxford

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Outline

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   - Theoretical perspective
2. **Dark radiation in the Minimal LARGE Volume Scenario (MLVS)**
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   - Outlook for MLVS

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 this is 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 νs; N_{eff} can be non-integer valued!

Why dark radiation?

Experimental hints:

- Planck+WP+highL+BAO results:
  $N_{\mathrm{eff}} = 3.30^{+0.54}_{-0.51}$, with $H_0 = 67.3 \pm 1.2\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$.
- Important fact: Planck does not measure H_0 directly!
- N_{eff} and H_0 are degenerate parameters — increasing one increases the other.

From Planck results, regarding H_0:

"We emphasise here that the CMB estimates are *highly model dependent*. It is important therefore to compare with astrophysical measurements of H_0, since any discrepancies could be a pointer to new physics."
— Planck 2013 results. XVI. Cosmological Parameters (1303.5076)

Why dark radiation?

Experimental hints (cont.):

- When combined with astrophysical measurements of H_0, now get $N_{\rm eff} = 3.52^{+0.48}_{-0.45}$ (Planck+WP+highL+BAO+H_0).
- A recent BBN-only study (arXiv:1308.3240) suggests that

$$N_{\rm eff} = 3.57 \pm 0.18 \, .$$

- This corresponds to a significance of 2.9σ!

Can we trust these values?

- Results may favour a small DR contribution.
- Need to wait until the dust settles, or for better constraints on H_0.

Why dark radiation?

String theory perspective:

- Generically $\mathcal{O}(100)$ gravitationally-coupled moduli (scalars), each with associated axions, many of which can remain 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 ΛCDM — 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.)

LARGE Volume Scenario — key features

- 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, Φ, whose large VEV fixes the volume;
  - its axion partner, the volume axion a_b.
- Hierarchy of scales:

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

- Note that the volume axion a_b is effectively massless $\Rightarrow$ candidate for dark radiation.

Reheating and dark radiation

$$M_{\text{string}} \sim \frac{M_P}{\mathcal{V}^{1/2}} \quad \gg \quad m_\Phi \sim \frac{M_P}{\mathcal{V}^{3/2}} \quad \gg \quad m_{a_b} \lesssim M_P\, e^{-2\pi\mathcal{V}^{2/3}} \sim 0\,.$$

- Decay rate, $\Gamma \sim m^3/M_P^2$, so Φ is the longest-living modulus (all others have masses $m \sim M_{\text{string}}$).
- Reheating is driven by coherent oscillations of Φ.
- Dark radiation arises (non-thermally) via the decay $\Phi \to a_b\, a_b$.
- Assume sequestering of soft scalar masses, such that

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

Consequently it turns out there is only one competitive visible sector decay mode: $\Phi \to H_{\text{u}}\, H_{\text{d}}$.

Reheating and dark radiation

- The leading decay modes are $\Phi \to a_b a_b$ and $\Phi \to H_u H_d$ (assuming there are no additional hidden-sector decay modes).
- Fraction of dark radiation produced is just the ratio of branching ratios,

$$\kappa \equiv \frac{\mathrm{Br}(\text{hidden})}{\mathrm{Br}(\text{visible})} = \frac{\mathrm{Br}(\Phi \to a_b a_b)}{\mathrm{Br}(\Phi \to H_u H_d)} = \frac{1}{2Z^2} \, .$$

- This tree-level result depends on the Giudice-Masiero coupling Z associated with the process $\Phi \to H_u H_d$.
- Normally Z is $\mathcal{O}(1)$, however a shift symmetry in the Higgs sector at the string scale would fix $Z = 1$.

Tree-level result

- Define Minimal LARGE Volume Scenario (MLVS) as:
  - $Z = 1$ at the string scale;
  - pure MSSM matter content;
  - no additional hidden-sector decay modes.
- The MLVS is completely defined and predictive.
- arXiv:1208.3562 (Cicoli, Conlon, Quevedo) and 1208.3563 (Higaki, Takahashi) found that $\Delta N_{\text{eff}} \simeq 3.3\,\kappa$.
- For $Z = 1$ ($\kappa = 1/2$) this gives $\Delta N_{\text{eff}} \simeq 1.7$, in conflict with observation ($\Delta N_{\text{eff}} \simeq 0.6$).
- Exhibits the "moduli-induced axion problem": too much DR (see 1304.7987 (Higaki, Nakayama, Takahashi)).

- The minimal scenario appears to be ruled out!
- However, the decay rate has been evaluated at the string scale.
- For TeV-scale soft terms, need $\mathcal{V} \sim 3 \times 10^7$, which implies

$$M_{\text{string}} \sim \frac{M_P}{\mathcal{V}^{1/2}} \sim 10^{15}\,\text{GeV}\ .$$

- What we really need is the decay rate at the scale of the modulus mass,

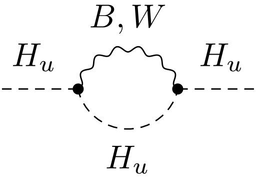
$$m_\Phi \sim \frac{M_P}{\mathcal{V}^{3/2}} \sim 3 \times 10^6\,\text{GeV}\ .$$

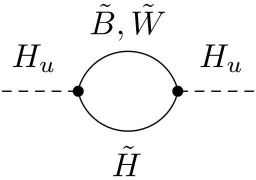
- Hence Z may receive large quantum corrections due to RG running... need to renormalize!

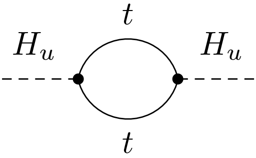
Our aim: to compute the Renormalization Group running of the coupling Z to determine its value at m_Φ, the scale of reheating.

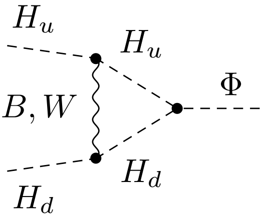
See arXiv:1305.4128 (SA, Conlon, Haisch, Powell).

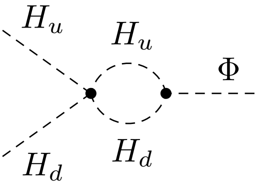
Loop diagrams



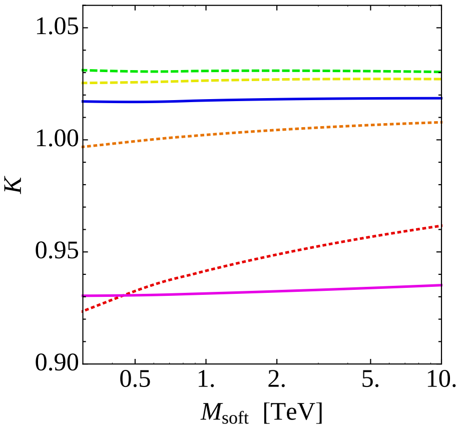








RG evolution — results



- Here are the results for $K \equiv Z(m_\Phi)/Z(M_{\mathrm{string}})$ using $M_{\mathrm{soft}} \equiv \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$.
- The dotted red, dotted orange, dashed yellow, dashed green, solid blue and solid magenta lines correspond to different choices of the Higgs VEV ratio, $\tan\beta = 2, 3, 5, 15, 25$ and 50, respectively.

What do we learn from this?

- For intermediate tan β the coupling is enhanced, whereas it is suppressed for large/small tan β.
- For tan $\beta \simeq 10$ the enhancement saturates at $K \simeq 1.03$.
- This leads to a lower bound of

  $$\Delta N_{\text{eff}} \gtrsim 3.1/2K^2 \simeq 1.4 \ ,$$

  which is not much better than the tree-level result!
- Measured value is $\Delta N_{\text{eff}} \simeq 0.57 \pm 0.25$ (Planck+H_0), corresponding to a tension of 3–4σ between theory and experiment.
- Minimal LVS ruled out!

Summary

- Dark radiation is a well-motivated addition to ΛCDM.
- We have considered radiative corrections to the branching fraction of dark radiation in the Minimal LARGE Volume Scenario ($Z = 1$ and MSSM matter content).
- Lower bound of $\Delta N_{\mathrm{eff}} \gtrsim 1.4$, which is too large to be compatible with observations ($\Delta N_{\mathrm{eff}} \simeq 0.57 \pm 0.25$)
  $\Rightarrow$ minimal model ruled out.