Loop corrections to ΔN_{eff} in large volume models

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Outline

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”, $\Delta N_{\text{eff}} = N_{\text{eff}} - 3.046$:

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

Why dark radiation?

Experimental hints:

- Important fact: Planck does not measure H_0 directly!
- N_{eff} and H_0 are degenerate parameters — increasing one increases the other.
- When combined with astrophysical measurements of H_0, the Planck, ACT, SPT and BAO measurements give consistently high values of N_{eff}, centred around $N_{\mathrm{eff}} \simeq 3.6$.
- A recent BBN-only study (arXiv:1308.3240) suggests that

$$N_{\mathrm{eff}} = 3.57 \pm 0.18\ .$$

- This corresponds to a significance of 2.9σ!

Why dark radiation?

Cosmology perspective:

- Simple and natural extension of ΛCDM
- After inflation, universe reheated by decays of a scalar field
- Any non-zero branching ratio to light hidden states is a source of dark radiation

String theory perspective:

- Generically $\mathcal{O}(100)$ moduli and associated light axions
- In principle, many hidden-sector particles that could behave as dark radiation

Harder to argue why dark radiation should *not* exist!

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

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

- 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 via the decay $\Phi \rightarrow a_b a_b$.
- 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: $\Phi \rightarrow H_{\text{u}} H_{\text{d}}$.

Reheating and dark radiation

- Fraction of dark radiation produced is just the ratio of branching ratios,

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

- This tree-level result depends on the Giudice-Masiero coupling Z associated with the process $\Phi \to H_\mathrm{u} H_\mathrm{d}$.
- Normally Z is $\mathcal{O}(1)$, however a shift symmetry in the Higgs sector at the string scale would fix $Z = 1$.
- Define Minimal LARGE Volume Scenario (MLVS) as:
  - $Z = 1$ at the string scale;
  - pure MSSM matter content.

Tree-level result

- The MLVS is now 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 dark radiation (see 1304.7987, talk by Nakayama).
- However, Z may receive large logarithmic corrections... 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).

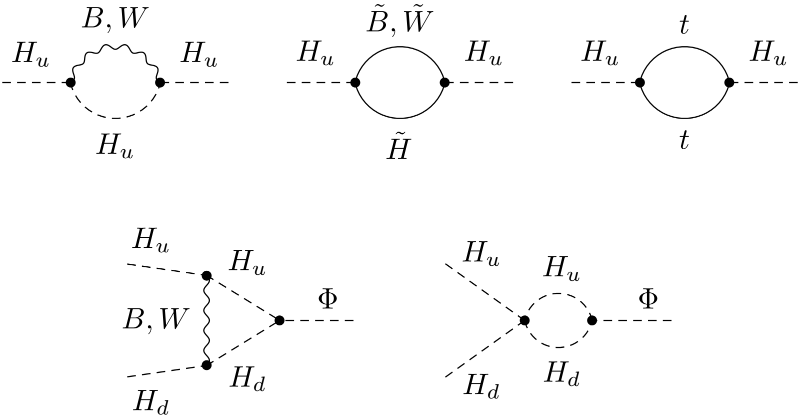
One-loop corrections

- The tree-level decay $\Phi \to H_u H_d$ is governed by the Lagrangian

$$\mathcal{L} \supset \frac{1}{\sqrt{6} M_P} \left[Z H_u H_d \Box \Phi + \text{h.c.} \right] .$$

- We computed the one-loop corrections in $\overline{\text{DR}}$ scheme, using an arbitrary R_ξ gauge within Wess-Zumino gauge.
- Loop corrections arise due to
  - vertex renormalization;
  - $H_{u,d}$ wavefunction renormalization.
- Corrections to the Φ wavefunction and to the $\Phi \to a_b a_b$ decay are Planck-suppressed and therefore not included.

Loop diagrams



One-loop anomalous dimension

- The running of Z is governed by the anomalous dimension, defined by

$$\frac{d}{d\ln\mu} Z = \gamma_Z Z\,.$$

- The one-loop result is

$$\gamma_Z^{(1)} = \frac{1}{(4\pi)^2}\left[-\frac{3g_1^2}{5} - 3g_2^2 + 3|y_t|^2 + 3|y_b|^2 + |y_\tau|^2\right]\,,$$

where $g_1 = \sqrt{5/3}\,g'$ and $g_2 = g$ respectively.

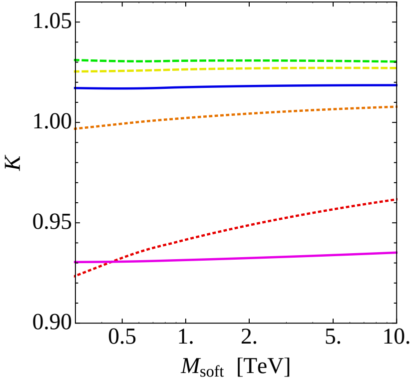
- This is just the sum of Higgs superfield anomalous dimensions given in the literature,

$$\gamma_Z^{(1)} = \gamma_{H_u}^{(1)} + \gamma_{H_d}^{(1)}\,.$$

RG evolution

- We computed the RG running of Z using SoftSusy 3.3.7.
- Included running of gauge couplings and Yukawas.
- Couplings fixed by their values at the Z-boson mass, m_Z.
- Procedure:
    - SM running from m_Z to $M_{\text{soft}} \sim \mathcal{O}(1\,\text{TeV})$;
    - MSSM running between M_{soft} and M_{string};
    - MSUGRA boundary conditions and $Z = 1$ fixed at M_{string};
    - Z evaluated at $m_\Phi \sim 10^6\,\text{GeV}$.
- Two-loop effects were included, however these turned out to be negligible.

RG evolution — results



- Here are the results for $K \equiv Z(m_\Phi)/Z(M_{\text{string}})$ using $M_{\text{soft}} \equiv \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$.
- 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 $\tan\beta$ the coupling is enhanced, whereas it is suppressed for large/small $\tan\beta$.
- For $\tan\beta \simeq 10$ the enhancement saturates at $K \simeq 1.03$.
- This leads to a lower bound of

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

  which is not much better than the tree-level result!
- Measured value is $\Delta N_{\rm eff} \simeq 0.57 \pm 0.25$ (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 $\Delta N_{\rm eff} \gtrsim 1.4$, which is too large to be compatible with observations ($\Delta N_{\rm eff} \simeq 0.57 \pm 0.25$)
$\Rightarrow$ minimal model ruled out.