

Loop corrections to ΔN_{eff} in large volume models

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Outline

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- 2 Dark radiation in the Minimal LARGE Volume Scenario (MLVS)
 - An overview of dark radiation in LVS
 - The minimal model
- 3 Loop corrections
 - The leading contributions
 - The effects of RG running

Why dark radiation?

- Dark radiation: hidden relativistic matter that contributes to the energy density of the universe.
- Measured in terms of the excess effective number of neutrino species, $\Delta N_{\text{eff}} = N_{\text{eff}} - 3.046$.
- When combined with direct measurements of H_0 , the Planck, ACT, SPT and BAO measurements currently suggest values around $N_{\text{eff}} \simeq 3.6$, allowing for the presence of extra hidden-sector radiation.

Why dark radiation?

Cosmology perspective:

- Simple and natural extension of Λ CDM
- 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

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

This ensures that $\Phi \rightarrow H_u H_d$ is the only competitive visible sector decay mode.

Reheating and dark radiation

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

$$\kappa \equiv \frac{\text{Br}(\text{hidden})}{\text{Br}(\text{visible})} = \frac{\text{Br}(\phi \rightarrow a_b a_b)}{\text{Br}(\phi \rightarrow H_u H_d)} = \frac{1}{2Z^2}.$$

- This tree-level result depends on the Giudice-Masiero coupling Z associated with the process $\phi \rightarrow H_u H_d$.
- Normally Z is hard to determine, however a shift symmetry in the Higgs sector at the string scale would imply $Z = 1$.
- 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 ($\Delta N_{\text{eff}} \simeq 0.6$).
- 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 (Angus, Conlon, Haisch, Powell).

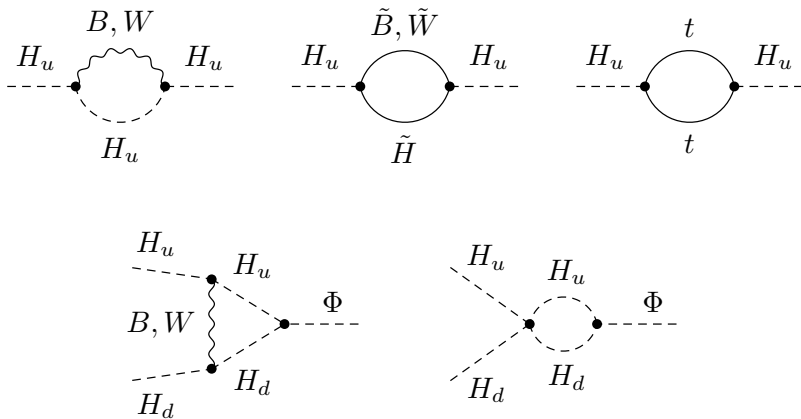
One-loop corrections

- The tree-level decay $\phi \rightarrow H_u H_d$ is governed by the Lagrangian

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

- 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.
- Wavefunction corrections to ϕ 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.

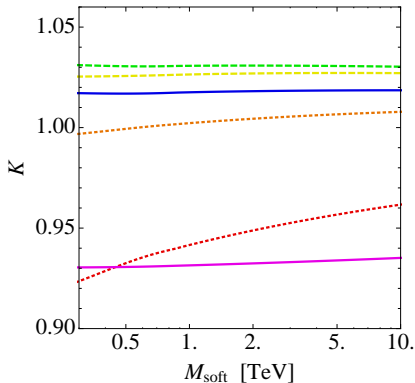
- This is just the sum of Higgs superfield anomalous dimensions given in the literature,

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

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 m_Z .
- Procedure:
 - SM running from the Z -boson mass 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 $M_{\text{soft}} \equiv \sqrt{m_{t_1} m_{t_2}}$.
- 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

$$\Delta N_{\text{eff}} \gtrsim 3.3/2K^2 \simeq 1.4 ,$$

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 3–4 σ between theory and experiment.
- **Minimal LVS ruled out!**

Summary

- Dark radiation is a well-motivated addition to Λ CDM.
- 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 $\Delta N_{\text{eff}} \gtrsim 1.4$, which is too large to be compatible with observations ($\Delta N_{\text{eff}} \simeq 0.57 \pm 0.25$)
 \Rightarrow MLVS ruled out.