Dark Radiation in LARGE Volume Models

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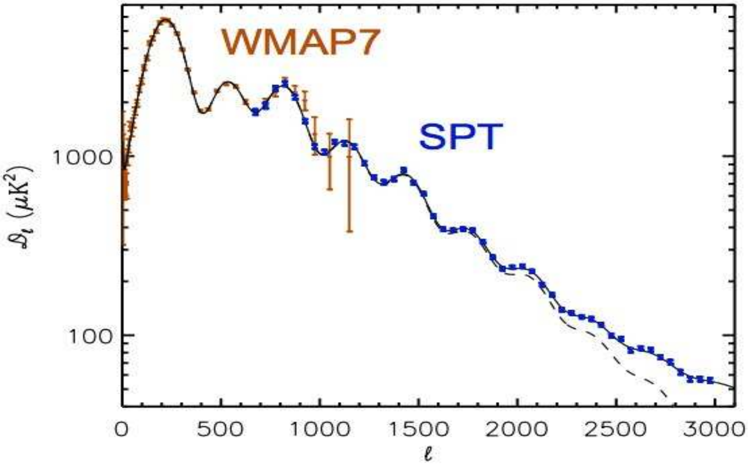
Based on 1208.3562 Cicoli JC Quevedo
(also see 1208.3563 Higaki Takahashi)

Motivation

This is the age of precision cosmology.



Motivation

This is the age of precision cosmology.

- 80% of the non-relativistic matter content of the universe does not come from the Standard Model.

  This implies the existence of new non-relativistic species not present in the Standard Model.

- ?? % of the relativistic radiation content of the universe does not come from the Standard Model ($0 <?? \lesssim 10$)

  If dark matter, why not dark radiation?

  What new non-Standard Model relativistic species exist?

Reheating and N_{eff}

The observable sensitive to non-Standard Model radiation is N_{eff}.

N_{eff} measures the 'effective number of neutrino species' at BBN/CMB: in effect, any hidden radiation decoupled from photon plasma.

At CMB times,

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

Dark radiation refers to additional radiation decoupled from SM thermal bath.

Reheating and N_{eff}

What physics measures N_{eff}?

BBN:

- BBN predictions depend on the expansion rate as a function of temperature.
- This relationship is modified by additional non-SM radiation.

CMB:

- The CMB has peaks due to baryon acoustic oscillations.
- The CMB tail is damped due to photon freestreaming.
- The ratio of the damping scale to the sound horizon is sensitive to additional non-SM radiation.

Reheating and N_{eff}

Observation has tended to hint at the $1 \to 2\sigma$ level for $N_{eff} - N_{eff,SM} > 0$.

Various measurements:

- BBN
  - 3.71 ± 0.45 (BBN Y_p, 1208.0032)
  - 3.9 ± 0.44 (CMB + BBN + D/H, 1112.2683)
- CMB
  - 3.26 ± 0.35 (WMAP9 + eCMB + BAO + H0, 1212.5226)
  - 3.71 ± 0.35 (SPT + CMB + BAO + H0, 1212.6267)
  - 3.52 ± 0.39 (WMAP7 + ACT + BAO+ H0, 1301.0824)

Light Particles

Dark radiation requires a particle relativistic at CMB times - $m \lesssim 10\text{eV}$.

We know three good ways of keeping particles light.

- Chirality - charged chiral fermions cannot acquire a mass term without symmetry breaking.
- Gauge symmetries - unbroken $U(1)_{em}$ explains why $m_\gamma \simeq 0$.
- Shift symmetries and axions - the symmetry $a \rightarrow a + \epsilon$ forbids perturbative mass terms

$$\frac{1}{2} m_a^2 a^2 \in \mathcal{L}$$

Axions

Axions are

- Generic in string compactifications - may easily be $\mathcal{O}(100)$ in number
- Naturally light - the shift symmetry $a \rightarrow a + 2\pi f_a$ forbids a perturbative mass term.
- Not part of the Standard Model - uncharged under SM gauge group

Axions are a outstanding and well motivated candidate for dark radiation.

This talk explores this in one well-motivated string model.

The Big Picture

The Accepted Big Picture of the early universe is

1. Inflation
2. End of inflation and inflaton oscillation
3. Inflaton decay
4. Reheating of SM and recovery of Hot Big Bang

Any hidden sector decays of the inflaton generate dark radiation.

Visible/hidden inflaton branching ratio sets magnitude of dark radiation.

The Big Picture

However - whatever the inflaton is -

Matter redshifts slower than radiation, and reheating is dominated by the last particle to decay.

Gravitationally coupled scalars - moduli - live a long time and decay late.

For direct couplings $\frac{\Phi}{4M_P}F_{\mu\nu}F^{\mu\nu}$ the 'typical' moduli decay rate is

$$\Gamma \sim \frac{1}{16\pi}\frac{m_\phi^3}{M_P^2}$$

with a lifetime

$$\tau \sim \left(\frac{40\text{TeV}}{m_\phi}\right)^3 1\text{ s}.$$

Reheating and N_{eff} in LVS

General string/UV-complete models have lots of moduli.

Calabi-Yaus give rise to $\mathcal{O}(100)$ moduli, which may all have comparable masses and decay widths.

This makes a systematic analysis of reheating very hard.

- Which moduli dominate the energy density?
- Which moduli decay last?
- What are their branching ratios?
- How do you treat a coupled system of $\mathcal{O}(100)$ particles?

LARGE Volume Models

LARGE Volume Scenario (Balasubramanian, Berglund, Conlon, Quevedo hep-th/0502058) : stabilises volume at exponentially large values in 'Swiss cheese' geometry

$$\mathcal{V} \sim |W| e^{c/g_s}, \qquad \tau_s \sim \ln \mathcal{V}.$$

The minimum is at exponentially large volume and non-supersymmetric.

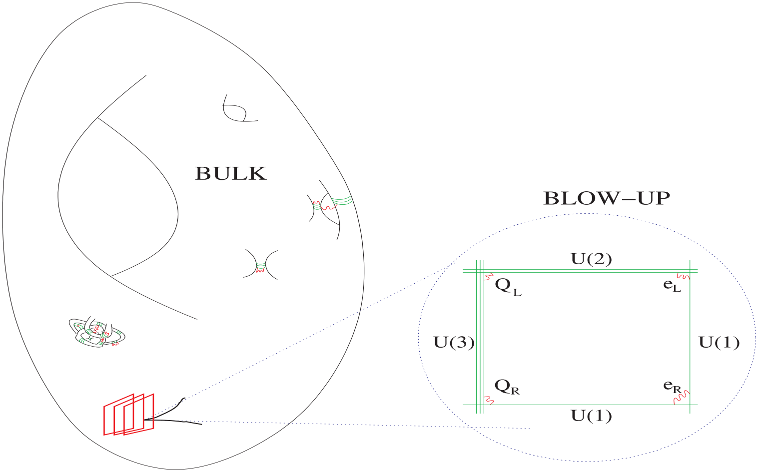
The large volume lowers the string scale and supersymmetry scale through

$$m_{string} \sim \frac{M_P}{\sqrt{\mathcal{V}}}, \qquad m_{3/2} \sim \frac{M_P}{\mathcal{V}}.$$

An appropriate choice of volume generates TeV scale soft terms and allow a supersymmetric solution of the hierarchy problem.

LARGE Volume Models

SM at local singularity:



LARGE Volume Models

The basic mass scales present (in sequestered scenario) are

Planck scale:	M_P	$2.4 \times 10^{18}\,\mathrm{GeV}.$
String scale:	M_S	$M_P \times \mathcal{V}^{-\frac{1}{2}}.$
KK scale	M_{KK}	$M_P \times \mathcal{V}^{-2/3}.$
Gravitino mass	$m_{3/2}$	$M_P \times \mathcal{V}^{-1}.$
Small modulus	m_{τ_s}	$M_P \times \mathcal{V}^{-1} \times \ln \mathcal{V}.$
Complex structure moduli	m_U	$M_P \times \mathcal{V}^{-1}.$
Volume modulus	m_{τ_b}	$M_P \times \mathcal{V}^{-3/2}.$
Soft terms	M_{soft}	$M_P \times \mathcal{V}^{-2}.$
Volume axion	m_{a_b}	$M_P \times e^{-\mathcal{V}^{2/3}}.$

LARGE Volume Models

The key points are:

- There is a distinguished lightest modulus (the overall volume modulus).
- All other moduli are much heavier than the volume modulus.
- There is also a single universal massless axion (the volume axion) that is effectively massless.

Bulk volume modulus outlives all other moduli by at least a factor $\sqrt{\mathcal{V}}(\ln \mathcal{V})^3 \gg 1$.

Therefore volume modulus τ_b comes to dominate energy density of universe independent of post-inflationary initial conditions.

Reheating comes from decays of τ_b.

Reheating and N_{eff} in LVS

In LVS reheating is driven by decay modes of τ_b.

We can quantify dark radiation through hidden/visible sector decays of τ_b.

As the lightest modulus is the overall volume modulus, couplings are model-independent.

One guaranteed contribution to dark radiation:

bulk volume axion $\text{Im}(T_b)$ which is massless up to effects exponential in $\mathcal{V}^{2/3} \gg 1$.

Reheating and N_{eff} in LVS

Decay to bulk axion is induced by $K = -3\ln(T + \bar{T})$. This induces a Lagrangian

$$\mathcal{L} = \frac{3}{4\tau^2}\partial_\mu \tau \partial^\mu \tau + \frac{3}{4\tau^2}\partial_\mu a \partial^\mu a$$

For canonically normalised fields, this gives

$$\mathcal{L} = \frac{1}{2}\partial_\mu \Phi \partial^\mu \Phi + \frac{1}{2}\partial_\mu a \partial^\mu a - \sqrt{\frac{8}{3}}\frac{\Phi}{M_P}\frac{\partial_\mu a \partial^\mu a}{2}$$

This gives

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

Reheating and N_{eff} in LVS

Decay to Higgs fields are induced by Giudice-Masiero term:

$$K = -3\ln(T+\bar{T}) + \frac{H_u H_u^*}{(T+\bar{T})} + \frac{H_d H_d^*}{(T+\bar{T})} + \frac{Z H_u H_d}{(T+\bar{T})} + \frac{Z H_u^* H_d^*}{(T+\bar{T})}$$

Effective coupling is

$$\frac{Z}{2}\sqrt{\frac{2}{3}}\left(H_u H_d \frac{\partial_\mu \partial^\mu \Phi}{M_P} + H_u^* H_d^* \frac{\partial_\mu \partial^\mu \Phi}{M_P}\right)$$

This gives

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

Reheating and N_{eff} in LVS

Other decays:

- Decays to SM gauge bosons are loop suppressed and so negligible, $\Gamma \sim \left(\frac{\alpha}{4\pi}\right)^2 \frac{m_\phi^3}{M_P^2}$
- Decays to SM fermions are chirality suppressed and so negligible, $\Gamma \sim \frac{m_f^2 m_\phi}{M_P^2}$
- Decays to MSSM scalars are mass suppressed and so negligible, $\Gamma \sim \frac{m_{\tilde{Q}}^2 m_\phi}{M_P^2}$.
- Decays to RR U(1) gauge fields are volume suppressed and negligible $\Gamma \sim \frac{m_\phi^3}{\mathcal{V}^2 M_P^2}$.
- Decays to bulk gauge bosons are not suppressed but are model dependent.
- Decays to other axions are not suppressed but are model dependent.

Reheating and N_{eff} in LVS

Important points are:

- The only non-suppressed decay modes to Standard Model matter are to the Higgs fields via the Giudice-Masiero term.
- There is always a hidden radiation component from the bulk axion.
- Both rates are roughly comparable and unsuppressed.

Reheating and N_{eff} in LVS

Assuming $Z = 1$ (as in shift-symmetric Higgs) and just volume axion gives

$$BR(\Phi \to \text{hidden}) = \frac{1}{3}$$

Volume axion remains massless and is entirely decoupled from Standard Model.

This branching ratio corresponds to $N_{eff} \sim 4.7$.

This is a tree level result - there are large logs at loop level which need to be included (Angus)

Conclusions

- Axions are excellent candidates for dark radiation
- Relativistic hidden sector axions are produced by decay of the inflaton
- LVS allows relatively calculable and predictive framework
- Progressively improving experimental sensitivity....