Dark Radiation in the LARGE Volume Scenario

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

Plan

Plan of talk:

1. In The Beginning...
2. The LARGE Volume Scenario
3. Scales and Moduli Decays
4. Dark radiation and N_{eff} in LVS

Once Upon A Time....

In the beginning, the energy density of the universe was dominantly in relativistic Standard Model degrees of freedom.

Not in hidden sectors, not in vacuum energy, not in dark matter, but in the SM.

How did this come about?

Reheating and N_{eff}

Focus on one particular observable: N_{eff}.

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

At BBN times,

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

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.
- These peaks originate from photon-baryon coupling.
- The interpretation of these - specifically the ratio of the damping scale to the sound horizon - are modified by excess non-SM radiation.

Reheating and N_{eff}

The Standard Model value is $N_{eff} = 3$ (technically 3.04 at CMB times).

However observation has a consistent preference at $1 \to 2\sigma$ level for $N_{eff} - N_{eff,SM} \sim 1$.

Various measurements:

- BBN
  - 3.7 ± 0.75 (BBN Y_p)
  - 3.9 ± 0.44 (BBN, D/H)
- CMB
  - 4.34 ± 0.85 (WMAP 7 year, BAO)
  - 4.6 ± 0.8 (Atacama, BAO)
  - 3.86 ± 0.42 (South Pole Telescope, BAO)

Reheating and N_{eff}

PLANCK and also SPT will sharpen errors considerably.

If this holds up, this will be a detection of BSM physics.

As it involves gravitational physics and a new ultralight particle, it is a good target for string cosmology/string phenomenology.

Is this calculable?

LARGE Volume Models

Balasubramanian Berglund JC Quevedo 2005

Consider IIB flux compactifications.

The leading order 4-dimensional supergravity theory is

$$K = -2\ln(\mathcal{V}) - \ln\left(i\int \Omega \wedge \bar{\Omega}\right) - \ln\left(S + \bar{S}\right),$$
$$W = \int G_3 \wedge \Omega.$$

This fixes dilaton and complex structure but is no-scale with respect to the Kähler moduli.

No-scale models have

- Vanishing cosmological constant
- Broken supersymmetry
- Unfixed flat directions

Moduli Stabilisation: Fluxes

- The effective supergravity theory is

$$
\begin{aligned}
K &= -2\ln(\mathcal{V}) - \ln\left(i\int \Omega \wedge \bar{\Omega}\right) - \ln(S+\bar{S}) \\
W &= \int (F_3 + iSH_3)\wedge \Omega \equiv \int G_3 \wedge \Omega.
\end{aligned}
$$

- This stabilises the dilaton and complex structure moduli.

$$D_S W = D_U W = 0.$$

$$W = \int G_3 \wedge \Omega = W_0.$$

Moduli Stabilisation: Fluxes

The theory has an important no-scale property.

$$\hat{K} = -2\ln\left(\mathcal{V}(T+\bar{T})\right) - \ln\left(i\int \Omega \wedge \bar{\Omega}(U)\right) - \ln\left(S+\bar{S}\right),$$

$$W = \int G_3 \wedge \Omega\,(S,U).$$

$$V = e^{\hat{K}}\left(\sum_{U,S}\hat{K}^{\alpha\bar{\beta}}D_\alpha W D_{\bar{\beta}}\bar{W} + \sum_{T}\hat{K}^{i\bar{j}}D_i W D_{\bar{j}}\bar{W} - 3|W|^2\right)$$

$$= e^{\hat{K}}\left(\sum_{U,S}\hat{K}^{\alpha\bar{\beta}}D_\alpha W D_{\bar{\beta}}\bar{W}\right) = 0.$$

Moduli Stabilisation: Fluxes

$$
\begin{aligned}
\hat{K} &= -2\ln\left(\mathcal{V}(T_i + \bar{T}_i)\right), \\
W &= W_0 \, . \\
V &= e^{\hat{K}}\left(\sum_T \hat{K}^{i\bar{j}} D_i W D_{\bar{j}} \bar{W} - 3|W|^2\right) \\
&= 0
\end{aligned}
$$

No-scale model :

- vanishing vacuum energy
- broken susy
- T unstabilised

No-scale is broken perturbatively and non-pertubatively.

Moduli Stabilisation: KKLT

$$\hat{K} = -2\ln(\mathcal{V}) - \ln\left(i\int \Omega \wedge \bar{\Omega}\right) - \ln\left(S + \bar{S}\right),$$

$$W = \int G_3 \wedge \Omega + \sum_i A_i e^{-a_i T_i}.$$

Non-perturbative effects (D3-instantons / gaugino condensation) allow the T-moduli to be stabilised by solving $D_T W = 0$.

For consistency, this requires

$$W_0 = \left\langle \int G_3 \wedge \Omega \right\rangle \ll 1.$$

Moduli Stabilisation: KKLT

$$\hat{K} = -2\ln(\mathcal{V}),$$
$$W = W_0 + \sum_i A_i e^{-a_i T_i}.$$

Solving $D_T W = \partial_T W + (\partial_T K) W = 0$ gives

$$\text{Re}(T) \sim \frac{1}{a}\ln(W_0)$$

For $\text{Re}(T)$ to be large, W_0 must be *enormously* small.

LARGE Volume Models

Going beyond no-scale the appropriate 4-dimensional supergravity theory is

$$K = -2\ln\left(\mathcal{V} + \frac{\xi}{g_s^{3/2}}\right) - \ln\left(i\int \Omega \wedge \bar{\Omega}\right) - \ln\left(S + \bar{S}\right),$$

$$W = \int G_3 \wedge \Omega + \sum_i A_i e^{-a_i T_i}.$$

Key ingredients are:

(1) the inclusion of stringy α' corrections to the Kähler potential
(2) nonperturbative instanton corrections in the superpotential.

LARGE Volume Models

The simplest model (the Calabi-Yau $\mathbb{P}^4_{[1,1,1,6,9]}$) has two moduli and a 'Swiss-cheese' structure:

$$\mathcal{V} = \left(\tau_b^{3/2} - \tau_s^{3/2} \right).$$

Computing the moduli scalar potential, we get for $\mathcal{V} \gg 1$,

$$V = \frac{\sqrt{\tau_s} a_s^2 |A_s|^2 e^{-2a_s\tau_s}}{\mathcal{V}} - \frac{a_s |A_s W| \tau_s e^{-a_s\tau_s}}{\mathcal{V}^2} + \frac{\xi |W|^2}{g_s^{3/2} \mathcal{V}^3}.$$

The minimum of this potential can be found analytically.

Moduli Stabilisation: LARGE Volume

$$V = \underbrace{\frac{\sqrt{\tau_s} a_s^2 |A_s|^2 e^{-2a_s\tau_s}}{\mathcal{V}} - \frac{a_s |A_s W_0| \tau_s e^{-a_s\tau_s}}{\mathcal{V}^2}}_{\text{Integrate out heavy mode } \tau_s} + \frac{\xi |W_0|^2}{g_s^{3/2}\mathcal{V}^3}.$$

$$V = -\frac{|W_0|^2 (\ln \mathcal{V})^{3/2}}{\mathcal{V}^3} + \frac{\xi |W_0|^2}{g_s^{3/2}\mathcal{V}^3}.$$

A minimum exists at

$$\mathcal{V} \sim |W_0| e^{a_s\tau_s}, \qquad \tau_s \sim \frac{\xi^{2/3}}{g_s}.$$

This minimum is non-supersymmetric AdS and at exponentially large volume.

LARGE Volume Models

The locus of the minimum satisfies

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

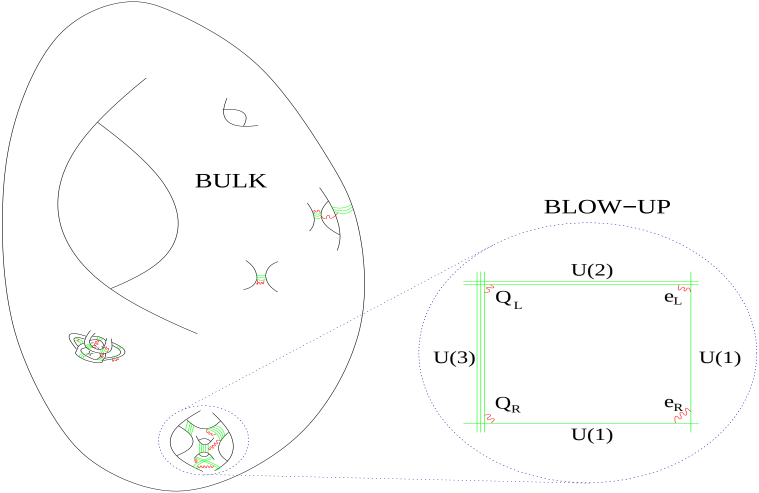
The minimum is at exponentially large volume and non-supersymmetric.

The large volume lowers the string scale and supersymmetry scale through

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

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

LARGE Volume Models



Moduli Stabilisation: LARGE Volume

Question: LVS uses an α' correction to the effective action.

If some α' corrections are important, won't all be?

Truncation is self-consistent because minimum exists at exponentially large volumes.

The inverse volume is the expansion parameter and so it is consistent to only include the leading α' corections.

Moduli Stabilisation: LARGE Volume

Higher α' corrections are suppressed by more powers of volume.

Example:

$$\begin{array}{rcl} \int d^{10}x\sqrt{g}\mathcal{G}_3^2\mathcal{R}^3 & : & \int d^{10}x\sqrt{g}\mathcal{R}^4 \\ \int d^4x\sqrt{g_4}\left(\int d^6x\sqrt{g_6}\mathcal{G}_3^2\mathcal{R}^3\right) & : & \int d^4x\sqrt{g_4}\left(\int d^6x\sqrt{g_6}\mathcal{R}^4\right) \\ \int d^4x\sqrt{g_4}\left(\mathcal{V}\times\mathcal{V}^{-1}\times\mathcal{V}^{-1}\right) & : & \int d^4x\sqrt{g_4}\left(\mathcal{V}\times\mathcal{V}^{-4/3}\right) \\ \int d^4x\sqrt{g_4}\left(\mathcal{V}^{-1}\right) & : & \int d^4x\sqrt{g_4}\left(\mathcal{V}^{-1/3}\right) \end{array}$$

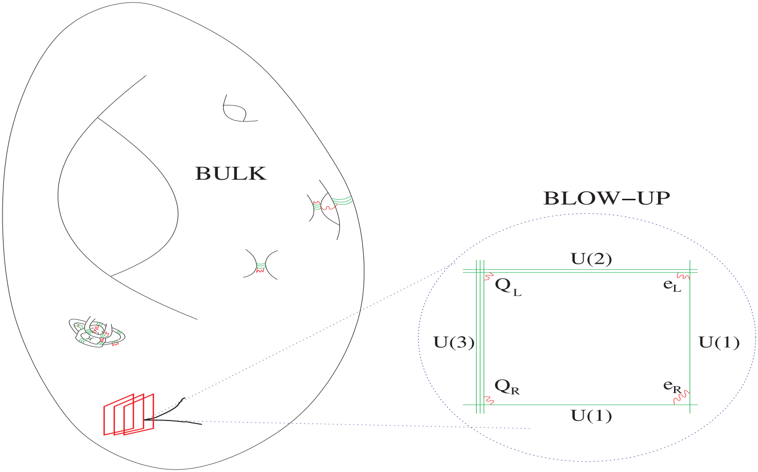
LARGE Volume Models

The basic closed string mass scales present are

Planck scale:	M_P	$2.4 \times 10^{18}\text{GeV}.$
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}	$M_P \times \mathcal{V}^{-3/2}.$
Volume axion	m_{a_b}	$M_P \times e^{-\mathcal{V}^{2/3}}.$

Moduli Stabilisation: LARGE Volume

SM at local singularity:



LARGE Volume: Soft Terms

In any string construction an important general question is the scale of the soft terms.

The standard moduli cosmology and moduli problems follow from:

$$m_{moduli} \sim m_{3/2} \sim m_{soft} \sim 1\text{TeV}$$

and

$$V_{typical} \sim m_{3/2}^2 M_P^2$$

In LVS the second relation is false and the first subtle.

LARGE Volume: Soft Terms

The leading susy breaking structure is essentially that of no-scale models:

$$
\begin{aligned}
W &= W_0 \\
K &= -3\ln(T_b + \bar{T}_b) + \frac{C\bar{C}}{(T_b + \bar{T}_b)}
\end{aligned}
$$

The gauge kinetic function is independent of the volume modulus T_b.

No-scale has many remarkable properties and cancellations.

LARGE Volume: Soft Terms

No-scale has many remarkable properties and cancellations.

1. Gaugino mass vanishes as f_a does not depend on volume modulus.
2. Anomaly-mediated gaugino mass also vanishes.

$$
\begin{aligned}
m_{1/2} &= -\frac{g^2}{16\pi^2}\Big[(3T_G - T_R)\, m_{3/2} - (T_G - T_R)\, K_i F^i \\
&\quad - \frac{2T_R}{d_R} F^i \partial_i \left(\ln \det Z\right) + 2T_G F^I \partial_I \ln\left(\frac{1}{g_0^2}\right)\Big] \\
&= 0.
\end{aligned}
$$

LARGE Volume: Soft Terms

No-scale has many remarkable properties and cancellations.

1. Leading order scalar mass vanishes.

$$m^2_{\tilde{Q}} = m^2_{3/2} - F^i F^{\bar{j}} \partial_i \partial_{\bar{j}} \ln \tilde{K} = 0.$$

2. In that the calculation exists, anomaly mediated scalar masses also vanish.

The upshot is that soft terms are suppressed significantly below the gravitino mass scale.

This violates one 'genericity' assumption $m_{soft} \sim m_{3/2}$.

LARGE Volume: Soft Terms

At what order do soft terms arise?

As

$$f_a = S + \lambda_a T_i,$$

gaugino masses are set by $F^S, F^{T_i} \sim \mathcal{V}^{-2}$.

These generate gaugino masses of

$$M_{gaugino} \sim \frac{M_P}{\mathcal{V}^2}$$

One potential exception to these cases is if field redefinitions occur at the singularity, which may lead to $m_{soft} \sim m_{3/2}$. The conditions for, and effects of, these are poorly understood at the moment.

LARGE Volume: Soft Terms

Scalar masses are more subtle.

Cancellations in scalar mass formulae persist to the extent that physical Yukawas are independent of the bulk volume.

Calculation pushes scalar masses to

$$m^2_{scalar} \lesssim \frac{M_P^2}{\mathcal{V}^3}$$

A full analysis of whether a further suppression of soft terms exists requires α' corrections to the matter kinetic terms that have not been computed.

We shall assume the most appealing case with $m_{\tilde{Q}} \sim M_a \sim \frac{M_P}{\mathcal{V}}$.

Moduli Stabilisation: LARGE Volume

The mass scales present are then (for $\mathcal{V} \sim 3 \times 10^7 l_s^6$)

Planck scale:	$M_P = 2.4 \times 10^{18} \text{GeV}.$
String scale:	$M_S \sim \frac{M_P}{\sqrt{\mathcal{V}}} \sim 10^{15} \text{GeV}.$
KK scale	$M_{KK} \sim \frac{M_P}{\mathcal{V}^{2/3}} \sim 10^{14} \text{GeV}.$
Gravitino mass	$m_{3/2} \sim \frac{M_P}{\mathcal{V}} \sim 10^{11} \text{GeV}.$
Small modulus	$m_{\tau_s} \sim m_{3/2} \ln\left(\frac{M_P}{m_{3/2}}\right) \sim 10^{12} \text{GeV}.$
Complex structure moduli	$m_U \sim m_{3/2} \sim 10^{11} \text{GeV}.$
Volume modulus	$m_{\tau_b} \sim \frac{M_P}{\mathcal{V}^{3/2}} \sim 4 \times 10^6 \text{GeV}.$
Soft terms	$M_{soft} \sim \frac{M_P}{\mathcal{V}^2} \sim 10^3 \text{GeV}.$

We now examine cosmological consequences of this moduli spectrum.

Cosmological Moduli Problem

Review: Moduli are assumed to displace from their minimum after inflation.

Neglecting anharmonicities their equation of motion is

$$\ddot{\phi} + 3H\dot{\phi} + m_\phi^2 \phi = 0$$

and so oscillations start at $3H \sim m$.

Moduli redshift as matter and come to dominate universe energy density.

Hot Big Bang is recovered after moduli decay and reheat Standard Model.

Cosmological Moduli Problem

Moduli can decay via 2-body processes, e.g. $\Phi \to gg$, $\Phi \to qq$, etc

For direct couplings such as

$$\frac{\Phi}{4M_P} F_{\mu\nu} F^{\mu\nu} \qquad \text{or} \qquad \frac{\Phi}{2M_P} \partial_\mu C \partial^\mu C$$

the 'typical' moduli decay rate is

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

with a lifetime

$$\tau \sim \left(\frac{40\text{TeV}}{m_\phi} \right)^3 1 \text{ s} \equiv \left(\frac{4 \times 10^6 \text{GeV}}{m_\phi} \right)^3 10^{-6} s$$

LARGE Volume Models

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Volume axion	m_{a_b}	$M_P \times e^{-\mathcal{V}^{2/3}}.$

Cosmological Moduli Problem in LVS

In sequestered scenario ($\mathcal{V} \sim 3 \times 10^7$):

String scale:	$M_S \sim \frac{M_P}{\sqrt{\mathcal{V}}} \sim 10^{15}\text{GeV}.$
Gravitino mass	$m_{3/2} \sim \frac{M_P}{\mathcal{V}} \sim 10^{11}\text{GeV}.$
Small modulus	$m_{\tau_s} \sim m_{3/2} \ln\left(\frac{M_P}{m_{3/2}}\right) \sim 10^{12}\text{GeV}.$
Complex structure moduli	$m_U \sim m_{3/2} \sim 10^{11}\text{GeV}.$
Volume modulus	$m_{\tau_b} \sim \frac{M_P}{\mathcal{V}^{3/2}} \sim 4 \times 10^6\text{GeV}.$
Soft terms	$M_{soft} \sim \frac{M_P}{\mathcal{V}^2} \sim 10^3\text{GeV}.$

$$V_{decay}^{1/4} = \left(3H_{decay}^2 M_P^2\right)^{1/4} = (1\text{GeV})\left(\frac{m_\phi}{4 \times 10^6\text{GeV}}\right)^{3/2}$$

Cosmological Moduli Problem in LVS

Moduli decays occur at

$$V_{decay}^{1/4} = \left(3H_{decay}^2 M_P^2\right)^{1/4} = (1\text{GeV}) \left(\frac{m_\phi}{4 \times 10^6 \text{GeV}}\right)^{3/2}$$

This is well above BBN and so solves cosmological moduli problem.

Note that the sequestered LVS scenario is crucial here. If $m_{soft} \sim m_{3/2}$, then volume modulus has $m_\tau \sim 1\text{MeV}$ and $\tau_{decay} > 10^{11}$ years.

Suppression of soft terms with relation to $m_{3/2}$ is what allows the volume modulus to avoid the cosmological moduli problem.

Reheating and N_{eff} in LVS

Cicoli, Conlon, Quevedo 1208.3562

Higaki, Takahashi, 1208.3563

Normally a systematic analysis of reheating in string models is very hard.

Calabi-Yaus have $\mathcal{O}(100)$ moduli and generic models have many moduli with comparable masses and decay widths - need to perform a coupled analysis.

LVS has the single light volume modulus with a parametrically light small mass.

Reasonable to expect - independent of initial conditions - modulus τ_b to dominate the energy density of universe and be sole driver of reheating.

Reheating and N_{eff} in LVS

In LVS reheating is driven by decay modes of τ_b.

Any decays of τ_b to hidden radiation contribute to $N_{eff} - N_{eff,SM}$.

To be hidden *radiation*, a field must remain relativistic up to CMB decoupling.

This requires $m \lesssim 10\text{eV}$: axions/hidden phtotons are ideal candidates for such light and protected masses.

For reheating by volume modulus decays, LVS has one guaranteed contribution to hidden radiation: bulk volume axion $\text{Im}(T_b)$ which is massless up to effects exponential in $\mathcal{V}^{2/3} \gg 1$.

Also many hidden RR photons which are dark radiation candidates.

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

What about RR photons?

These have a gauge kinetic term depending only on complex structure moduli

$$\mathcal{L} = f(U) F_{\mu\nu,RR} F^{\mu\nu,RR}$$

Coupling of volume modulus $\Phi F_{\mu\nu} F^{\mu\nu}$ set by mixing of Kähler modulus Φ into complex structure moduli.

However - this is volume suppressed in LVS, due to factorised Kähler potential

$$K = -2 \ln \mathcal{V}(T) - \ln \left(\int \Omega \wedge \bar{\Omega} \right) (U)$$

Effective interaction strength is $\frac{1}{M_P \sqrt{\mathcal{V}}}$ and negligible.

What about visible fermions?

These couplings are chirality suppressed. The Lagrangian is

$$\mathcal{L} = \frac{\Phi}{M_P}\bar{\psi}\gamma^\mu\partial_\mu\psi \equiv m_\psi \frac{\Phi}{M_P}\bar{\psi}\psi$$

The resulting branching ratio is

$$\Gamma_{\Phi\to\psi\psi} \simeq \frac{m_\psi^2 m_\phi}{M_P^2} \ll \frac{m_\phi^3}{M_P^2}$$

Reheating and N_{eff} in LVS

What about visible scalars?

These are again mass suppressed. Taking all terms contibuting, the resulting Lagrangian is

$$\mathcal{L} = \frac{\Phi}{M_P} \phi^* \partial_\mu \partial^\mu \phi \simeq \frac{m_\phi^2}{M_P} \Phi \phi^* \phi$$

This again has a negligible decay width.

What about visible gauge bosons?

These decays are absent at tree-level.

They are expected to be generated radiatively through fermion loops, inducing an effective coupling

$$\frac{\alpha}{4\pi}\frac{\Phi}{M_P}F_{\mu\nu,a}F^{\mu\nu,a}$$

The induced branching ratio is

$$\Gamma_{\Phi\to gg}\simeq\left(\frac{\alpha}{4\pi}\right)^2\frac{m_\Phi^3}{M_P^2}\ll\frac{m_\Phi^3}{M_P^2}$$

and is again negligible.

What about Higgs fields?

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

Overall:

- 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 axion is unsuppressed.
- Decay to Higgs field is unsuppressed.

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

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

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

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

This is approximately the right order if observational hints of dark radiation persist.

Note hidden radiation also follows only from volume modulus couplings - it does *not* assume TeV-scale susy.

Generalities

Dark radiation is a strong probe of string models.

String models have many hidden sectors - moduli decays must reheat only the Standard Model.

A moduli spectrum with $m_\Phi \gtrsim 40$TeV does not guarantee a safe cosmology.

If the spectrum is known, the fraction of dark radiation is calculable.

Conclusions

- Dark radiation is a possible extension of the Standard Model.
- The LARGE Volume Scenario is an attractive scenario of moduli stabilisation which generates hierarchies.
- Decays of lightest modulus give dark radiation consistent with experimental hints.
- Experimental situation will clarify soon...