Dark Radiation in LARGE Volume Models

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

Plan

Plan of talk:

1. Dark Radiation and N_{eff}
2. Moduli spectrum in LVS
3. Cosmological evolution and moduli problem
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 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 interpretation of these are modified by excess non-SM radiation.

Reheating and N_{eff}

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

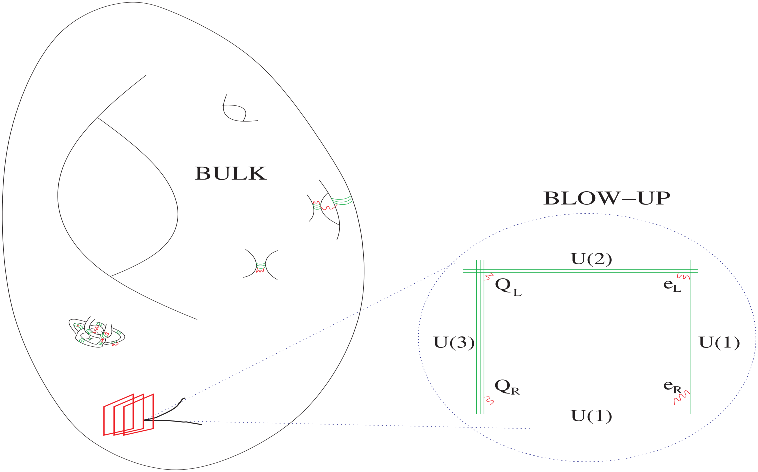
Various measurements:

- 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)

PLANCK will sharpen errors considerably.

LARGE Volume Models

SM at local singularity:



LARGE Volume Models

LARGE Volume Scenario : 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

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

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

LARGE Volume Models

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}	$M_P \times e^{-\mathcal{V}^{2/3}}$.

LARGE Volume Models

$\mathcal{V}$ fixed by scale of soft terms:

Standard Model via branes at singularities motivates sequestered scenario with $m_{soft} \sim \frac{M_P}{\mathcal{V}^2}$: with $\mathcal{V} \sim 3 \times 10^7 l_s^6$ we have

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	$M_{soft} \sim \frac{M_P}{\mathcal{V}^2} \sim 10^3\,\text{GeV}.$

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

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

Cosmological Moduli Problem

The corresponding Hubble scale at decay is

$$H_{decay} \sim 3 \times 10^{-10}\text{eV} \left(\frac{m_\phi}{4 \times 10^6 \text{GeV}} \right)^3$$

and so

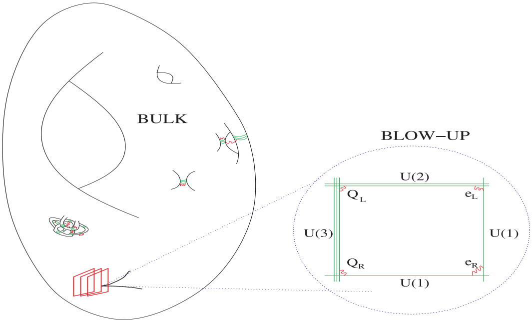
$$V_{decay}^{1/4} = \left(3H_{decay}^2 M_P^2\right)^{1/4} = (1\text{GeV}) \left(\frac{m_\phi}{4 \times 10^6 \text{GeV}} \right)^{3/2}$$

For masses less than ~ 40TeV, the reheating temperature is too cool to allow for BBN.

Even for heavier moduli, the reheating temperature is relatively low.

Coupling of Moduli in LVS

The decay widths of moduli are determined by the strengths of their couplings to matter.



Distinguish between local ('small') and global ('bulk') moduli and local and global matter.

Coupling of Moduli in LVS

Couplings are

$$\begin{aligned}
\text{Local moduli to local matter on same cycle} \quad & \sim \frac{1}{M_s} \sim \frac{\sqrt{\mathcal{V}}}{M_P} \gg \frac{1}{M_P} \\
\text{Local moduli to bulk/ distant matter} \quad & \sim \frac{1}{\sqrt{\mathcal{V}} M_P} \\
\text{Bulk moduli to bulk matter} \quad & \sim \frac{1}{M_P} \\
\text{Bulk moduli to local matter} \quad & \sim \frac{1}{M_P}
\end{aligned}$$

These couplings determine the decay widths and moduli lifetimes.

Coupling of Moduli in LVS

Moduli lifetimes are then

$$\begin{aligned} \Gamma_{\tau_s} &\sim \frac{M_P (\ln \mathcal{V})^3}{\mathcal{V}^2} \text{ or } \frac{M_P (\ln \mathcal{V})^3}{\mathcal{V}^4} \\ \Gamma_{U,S} &\sim \frac{M_P}{\mathcal{V}^3} \\ \Gamma_{\tau_b} &\sim \frac{M_P}{\mathcal{V}^{9/2}} \end{aligned}$$

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

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

Cosmological Moduli Problem in LVS

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

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

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

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 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 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 $\mathcal{V}^{2/3} \gg 1$.

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 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 $m_\Phi \gtrsim 40\text{TeV}$ does not guarantee a safe cosmology.

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

Conclusions

- String cosmology requires the study of moduli
- 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...

Job Advert

- Two ERC-funded postdocs soon to be advertised at Oxford for October 2013
- One position 2+2 years
- One position 2 years
- Postdocs will be appointed within project area of ERC grant, ‘Supersymmetry Breaking In String Theory’

WhyStringTheory.com