LARGE Volume Models and Superstring Cosmophysics

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Plan

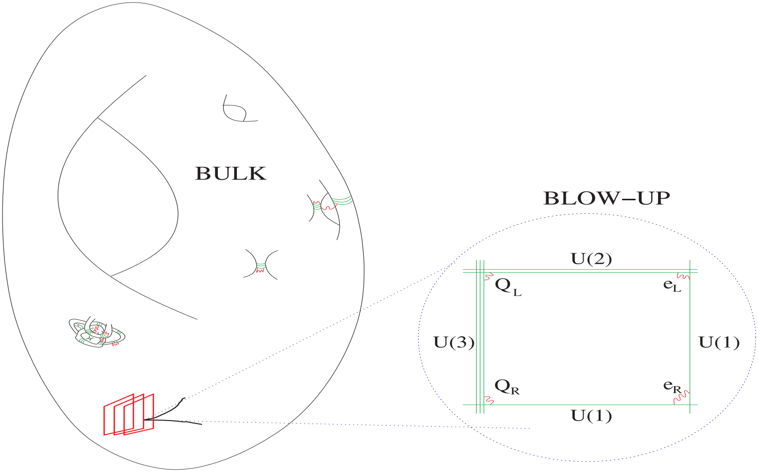
Plan of these two lectures:

1. The LARGE volume scenario (last time)
2. Applications to cosmology
   - Cosmological moduli problem
   - Dark radiation and N_{eff}
   - Inflation/susy tension

   - Quantum Gravity Constraints on Inflation

Moduli Stabilisation: LARGE Volume

SM at local singularity:



Moduli Stabilisation: LARGE Volume

The basic mass scales present are (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	$M_{soft} \sim \frac{M_P}{\mathcal{V}^2} \sim 10^3\text{GeV}.$

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

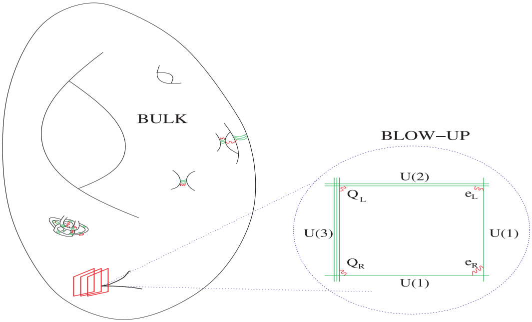
$$V_{decay}^{1/4} = \left(3H_{decay}^2 M_P^2\right)^{1/4} = (1\text{GeV}) \left(\frac{m_\phi}{4 \times 10^6 \text{GeV}} \right)^{3/2}$$

For masses less than $\sim$ 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

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

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:	$M_S \sim \frac{M_P}{\sqrt{\mathcal{V}}} \sim 10^{15}\text{GeV}.$
Gravitino mass	$m_{3/2} \sim \frac{M_P}{\mathcal{V}} \sim 10^{11}\text{GeV}.$
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$$V_{decay}^{1/4} = \left(3H_{decay}^2 M_P^2\right)^{1/4} = (1\text{GeV})\left(\frac{m_\phi}{4 \times 10^6\text{GeV}}\right)^{3/2}$$

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.xxxx

Higaki, Takahashi, 1208.xxxx

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

Calabi-Yaus have $\mathcal{O}(100)$ moduli and generic models of 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

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.

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} in LVS

We aim to study 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 $Z = 1$ 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.

Inflation/Supersymmetry Tension

'Kallosh-Linde problem'

There is a general tension that afflicts models attempting to combine inflation with low energy supersymmetry.

As

$$V = e^K \left[K^{i\bar{j}} D_i W D_{\bar{j}} W - 3|W|^2 \right],$$

the characteristic scale of a typical supergravity potential is $V \sim m_{3/2}^2 M_P^2$.

Absent fine-tuning or special features, the potential has structure at this scale $\sim m_{3/2}^2 M_P^2$.

For $m_{3/2} \sim 1\text{TeV}$, the scale of the potential is $V \sim (10^{11}\text{GeV})^4$.

As the inflationary ϵ parameter is $\epsilon \sim \left(\frac{V}{3\times 10^{16}\text{GeV}}\right)^4$, this requires an inflationary model with $\epsilon \lll 1$

Inflation/Supersymmetry Tension

Another way of putting this:

- The construction of string-theoretic inflation models normally gives $10^{13}\text{GeV} \lesssim V_{inf}^{1/4} \lesssim 10^{16}\text{GeV}$.
- This is not a theorem; just an observation on models that people attempt to construct.
- However potentials that naturally give inflation at these scales do not naturally have vacua with $m_{3/2} \sim 1\text{TeV}$.
- There is a tension of scales between models with moduli potentials with $10^{13}\text{GeV} \lesssim V_{inf}^{1/4} \lesssim 10^{16}\text{GeV}$ and models with $m_{3/2} \sim 1\text{TeV}$.

Inflation/Susy Tension in LVS

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

$$\begin{array}{cc} \text{Planck scale:} & M_P = 2.4 \times 10^{18}\text{GeV}. \\ \text{String scale:} & M_S \sim \frac{M_P}{\sqrt{\mathcal{V}}} \sim 10^{15}\text{GeV}. \\ \text{Gravitino mass} & m_{3/2} \sim \frac{M_P}{\mathcal{V}} \sim 10^{11}\text{GeV}. \\ \text{Volume modulus} & m_{\tau_b} \sim \frac{M_P}{\mathcal{V}^{3/2}} \sim 4 \times 10^{6}\text{GeV}. \end{array}$$

The LVS potential is at $V \sim m_{3/2}^3 M_P$.

This gives $V \sim \left(10^{13}\text{GeV}\right)^4$ for sequestered scenario.

This significantly ameliorates the tension.

Further improvements are possible if the volume (and hence characteristic gravitino mass scale) changes during inflation.

Quantum Gravity Constraints on Inflation

Based on 1203.5476 JC

- A different topic: intrinsic constraints on inflation.
- Inflation is a promising theory of the early universe
- Inflation involves a period where the universe is approximate de Sitter (up to slow roll)
- Inflationary model building is field theoretic: can there be gravitational constraints on what is allowed?

  We will focus particularly on the N-flation proposal of N axions with field range f_a to obtain a transPlanckian field range $N\sqrt{f_a} \gg M_P$.

Quantum Gravity Constraints on Inflation

Why is this reasonable?

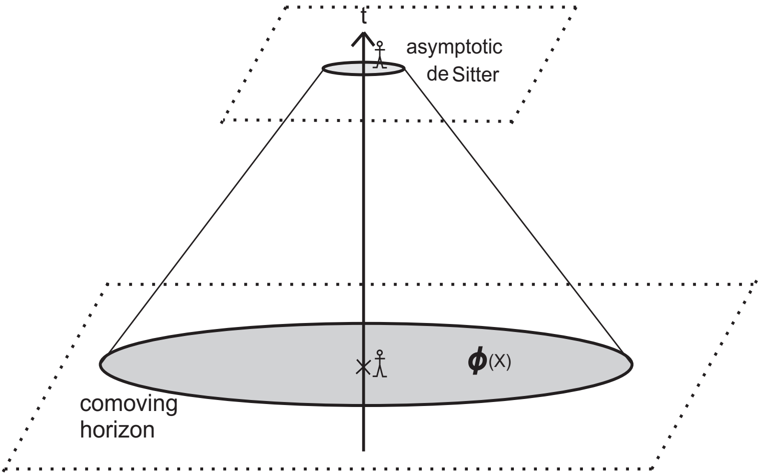
de Sitter space is a quantum gravitational object in the same way that a black hole is.

Why? Like a black hole it has

- A horizon, at a distance $r = H_{dS}^{-1}$
- An entropy $S = \frac{8\pi^2 M_P^2}{H_{dS}^2}$
- A temperature $T_{dS} = \frac{H_{dS}}{2\pi}$

As de Sitter is a quantum gravitational object, there may be quantum gravitational constraints on permitted realisations invisible to purely field theoretical treatments.

Basic structure of de Sitter space:



Quantum Gravity Constraints on Inflation

Basic idea:

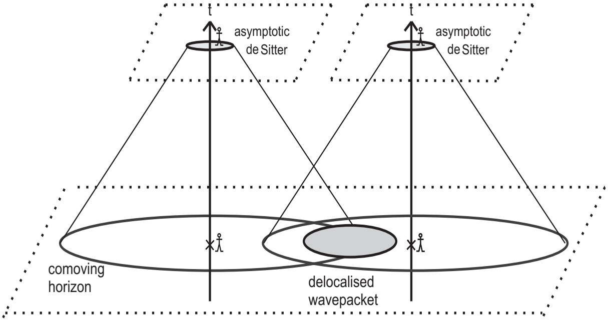
- de Sitter space has a finite entropy

$$S_{dS} = \frac{8\pi^2 M_P^2}{H^2}$$

- A field theoretic inflationary model has N fields with field range f_a.
- We can associate an entropy to the field theory model, which heuristically should increase with N and f_a.
- For sufficiently many fields with sufficiently large field range, the entropy of the field theory will exceed the de Sitter entropy.

In pure de Sitter, inflation prevents us knowing what is behind the horizon.

In our aymptotic future, we only learn about within our (observer-dependent) horizon.



Quantum Gravity Constraints on Inflation

Entropy associated with discarding super-horizon degrees of freedom.

There is a natural field theory entropy that does this: entanglement entropy. What is this?

- Take the density matrix $|0><0|$ for the vacuum of a free scalar field $|0>$
- Define a closed surface Σ
- Trace over all degrees of freedom outside Σ:

$$|0><0| \to \sum_i \lambda_i |i>_{in}<i|_{in}$$

- Take the entropy of the final mixed state

$$S_{entanglement} = -\sum_i \lambda_i \ln \lambda_i$$

Quantum Gravity Constraints on Inflation

The entanglement entropy of a field theory with cutoff Λ is

$$S_{ent} \sim \Lambda^2 \mathcal{A}$$

where A is a area of the entangling surface.

If A is the de Sitter horizon, $A \sim H^{-2}$, and

$$S_{ent} \sim \frac{\Lambda^2}{H^2}$$

For an axionic field, field range f_a and cutoff Λ are identical:

$$S_{ent} \sim \frac{f_a^2}{H^2}$$

Quantum Gravity Constraints on Inflation

To an inflationary model consisting of one axion with field range f_a we can associate an entropy

$$S_{model} \sim \frac{f_a^2}{H^2}$$

Entropy is additive: to an inflationary model of N axions with field range f_a we can associate an entropy

$$S_{model} \sim \frac{N f_a^2}{H^2}$$

Therefore we (parametrically) exceed the de Sitter entropy when

$$N f_a^2 >> M_P^2$$

Quantum Gravity Constraints on Inflation

The condition

$$Nf_a^2 >> M_P^2$$

which violates the de Sitter entropy bound is precisely the condition in N-flation to obtain transPlanckian field range.

This suggests that the point at which such models become most interesting is the point at which such models become inconsistent in quantum gravity.

Consistent in inflatonary field theory $\neq$ Consistent in quantum gravity

Conclusions

- String cosmology requires the study of moduli
- The LARGE Volume Scenario is an attractive scenario of moduli stabilisation which generates hierarchies.
- A sequestered matter sector gives an attractive cosmology including
  - Solution to the cosmological moduli problem
  - A natural source of dark radiation at reheating
  - An amelioration of tension between inflationary models and low-scale supersymmetry.
- We have also discussed gravitational constraints on inflationary model building

The End

どうもありがとうございました