Nflation in IIB flux compactifications

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Outline

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- Review of LVS moduli stabilisation; axions in LVS
- Nflation
- Scenario for moduli stabilisation; implications for microscopic parameters
- Phenomenological aspects
- Challenges
- Future Directions and Conclusions

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Introduction/Motivation

- From the perspective of the Planck scale physicist inflation is a low energy phenomenon and hence can be described by a low energy effective theory. Yet, the dynamics of inflation is sensitive to higher dimensional operators e.g. slow roll inflation

$$\epsilon \equiv \frac{1}{2} M_{\rm Pl}^2 \left(\frac{V'(\varphi)}{V(\varphi)} \right)^2 \ll 1, \qquad \eta \equiv M_{\rm Pl}^2 \left(\frac{V''(\varphi)}{V(\varphi)} \right) \ll 1$$

- This implies that models of inflation are sensitive to the ultraviolet completion; obtaining models of inflation can be considered as a challenge for theories of quantum gravity.
- In string theory, at tree level moduli fields have a flat potential - can serve as candidate inflatons. Particularly interesting candidates are axions - the shift symmetry guarantees that that the potential remains flat to all orders in perturbation theory.
- Inflationary models need to be constructed in unison with model stabilisation;

$$m_\varphi^2 \ll H^2 \ll m_{\rm mod}^2$$

this has proven to be non-trivial. Address in the context of Nflation.

II B flux compactifications, Large Volume Scenario

- IIB flux compactifications; complex structure moduli are fixed by background fluxes.
- Kahler moduli
$$T_i = \frac{1}{2}\int_{\Sigma_i} J \wedge J + i\int_{\Sigma_i} C_4 \equiv \tau_i + i\theta_i$$
remain massless at tree level.
- In the four dimensional effective field theory has
$$K = -2\log(\mathcal{V}); \qquad W = W_0$$
with $\mathcal{V}$ (the volume of the Calabi Yau) a homogeneous function of degree 3/2 of the T_i. This has the "no scale structure"
$$K^{i\bar{j}}K_i K_{\bar{j}} = 3;$$
which will play an important role later.
- Simplest realisation of LVS, two Kahler moduli
$$\mathcal{V} = \tau_b^{3/2} - \tau_s^{3/2}$$

- Since the potential is flat at leading order; subleading effects need to be considered. Non-perturbative effects for the super potential

$$W = W_0 + A_s e^{-a_s T_s} + A_b e^{-a_b T_b}$$

leading α' effect for the Kahler potential

$$K = -2 \log (\mathcal{V} + \xi/2)$$

- Bottom line: With these effects working self consistent in the limit $\tau_b \gg \tau_s$; the moduli fixed.
- In fact the non-perturbative effect $A_s e^{-a_s T_s}$ generates a potential for

$$\tau_s, \theta_s \text{ and } \tau_b$$

This effect does not break the shift symmetry associated with θ_b.
- Hence the axion θ_b acquires a mass as due the non-perturbative effect $A_b e^{-a_b T_b}$. It strength is minute given the hierarchy $\tau_b \gg \tau_s$.

- Note that since both the constituents of T_s (τ_s and θ_s) acquire a mass due to the same ingredient in the effective action; hence acquire masses of the same order – it is difficult to decouple their dynamics.
- The situation is different for T_b; $m_{\theta_b} \ll m_{\tau_b}$ It is possible to decouple the dynamics from that of the geometric modulus.
- Of course it is not possible to drive inflation by just the axion θ_b.
    - As for an axionic field

$$V(\theta) = \Lambda^4 \cos(2\pi\theta/f) \quad 0 < \theta < f; \qquad \Lambda^4 \propto e^{-S_{\rm inst}}.$$

$$\epsilon, \eta \propto \frac{M_{\rm Pl}^2}{f^2}$$

    - Generic arguments in string theory for $f < M_{\rm Pl}$,
      Dine, Fox, Gorbatov '03; Svrcek and Witten '06
      Grimm '14; Blumenhagen, Plauschinn '14

- Explicitly computation (Kallosh, Sivanandam and Soroush '07)

$$f \approx M_{\rm kk} \approx \frac{M_{\rm pl}}{\mathcal{V}^{2/3}}$$

- Various possibilities around this issue
  - Alligned Natural Inflation: Kim, Nilles, and Peloso '04
  - Axion Monodromy; Siverstein, Westphal: McAllister, Silverstein, Westphal 08
  - N-flation: Dimopoulos, Kachru, McGreevy and Wacker '05
- In its simplest realisation N axions with equal decay constant and masses. Inflation is driven by a collective mode

$$\rho^2 = \sum_{A=1}^{N} \theta_A^2$$

At onset of inflation $\theta_A \approx f$; $\rho \approx \sqrt{N} f$. Effective field range enhanced

$$\epsilon = \eta = \frac{2}{N}\left(\frac{M_{\rm Pl}}{f}\right)^2 \ll 1 \quad \text{for} \quad N \gg 1.$$

Microscopic Parameters essentially determined from observational constraints

- After using the spectral tilt to fix ϵ

$$N \approx 240\left(\frac{f}{M_{\rm Pl}}\right)^2$$

- Requiring the density perturbations of the right magnitude

$$m \approx 3 \times 10^{14}{\rm Gev}$$

Tensor to scalar ratio

$$r \approx 0.13$$

Makes model highly predictive. Adds to the motivation to explore in detail.

- Result generalises when the decay constants and masses are unequal but are in a sharp distribution.

Obtain a scenario, with these microscopic parameters – with moduli stabilisation such that the axions are the lightest moduli

- Our construction will involve Calabi Yaus whose volume ($\mathcal{V}$) can be expressed in terms of the volume of four cycles as

$$\mathcal{V} = f(\tau_A) - \gamma \tau_s^{3/2}$$

$A = 1 \ . \ . \ N$; $f(\tau^A)$ is a homogeneous function of degree $3/2$ of τ_A and is independent of τ_s. Explicit analysis of moduli stabilisation for general N, similar analysis for small number of Kahler moduli Cicolo, Conlon, Quevedo '07.

- This is the form that the volume takes when τ_s corresponds to the resolution of a point like singularity by a blow up. The volume cycle s can be smoothly taken to zero without affecting the volume of the compactification.
- It will be useful to think of $f(\tau_A)$ as giving the volume of a fictitious manifold (the one in the limit in which the blow up mode is absent). Thus we will write

$$\mathcal{V} = \hat{\mathcal{V}} - \gamma \tau_s^{3/2}; \quad \hat{K} = -2\log(\hat{\mathcal{V}});$$

- We will stabilise in a regime in which $\hat{\mathcal{V}}$ is exponentially large in τ_s.

- Strategy is to work self consistently in the limit $\hat{\mathcal{V}} \gg 1$; we begin by looking at the dominant effects
  - The non-pertubative effect associated with the cycle τ_s
  - The leading α' correction

$$W = W_0 + A_s e^{-a_s T_s} \quad K = -2\log(\mathcal{V} + \xi/2) = -2\log(\hat{\mathcal{V}} - \gamma\tau_s^{3/2} + \xi/2)$$

- With this compute the potential in the limit $\hat{\mathcal{V}} \gg 1$.

$$V = D\frac{\sqrt{\tau_s}\, e^{-2a_s\tau_s}}{\hat{\mathcal{V}}(\tau_A)} - E\cos(a_s\theta_s - \psi_s)\frac{|W_0|\tau_s\, e^{-a_s\tau_s}}{\hat{\mathcal{V}}^2(\tau_A)} + F\frac{|W_0|^2}{\hat{\mathcal{V}}^3(\tau_A)}\,.$$

D,E and F are positive constants; ψ_s is defined by the equation $A_s W_0^* = -|A_s W_0| e^{i\psi_s}$

- Note that the potential depends on τ_s, θ_s and the combination of the moduli τ_A corresponding to $\hat{\mathcal{V}}(\tau_A)$ and is independent of the other moduli.
- This is a consequence of the identity

$$K^{B\bar{s}}\partial_B K = -2\tau_s \hat{K}^{B\bar{D}}\partial_{\bar{D}}\hat{K}\partial_B \hat{K} = -6\tau_s$$

  closely related to $K^{i\bar{j}}\partial_i K \partial_{\bar{j}} K = 3$
- There are two no scale structures one of the Calabi Yau and other of the fictitious manifold – are important to arrive at the result that the potential of τ_s and the combination corresponding to $\hat{\mathcal{V}}$.
- This fixes τ_s, θ_s and $\mathcal{V}(\hat{\tau_A})$ - the combination of τ_A which corresponds to the volume $\hat{\mathcal{V}}$.

- Next consider the loop effects. These have dependence on all the geometric moduli. The fact that the overall volume has been fixed prevents a behaviour runaway. Thus a potential is developed for these moduli.
- The axions θ_A are still massless as the associated shift symmetry is unbroken. These are protected by a shift symmetry broken by the non-perturbative effect $e^{-a_A T_A}$.

$$V_{\mathrm{np}_b}(\hat{\theta}_{b_i}) = \frac{4|W_0|}{\mathcal{V}^2} \sum_{i,j=1}^{N} a_{b_i} \tau_{b_i} |A_{b_i}| e^{-a_{b_i} \tau_{b_i}} \cos\left(a_{b_i} S_{ij} \hat{\theta}_{b_j} + \psi_{b_i} \right)$$

where the S_{ij} is the matrix that diagonalises the Kahler metric $\hat{K}_{i\bar{j}}$
- We follow the approach of R. Easther and L. McAllister '06 taking $K_{i\bar{j}}$ to be a random matrix.
- Qualitatively the answer same as N axions with

$$f \approx \frac{1}{\mathcal{V}^{2/3}} \qquad m \approx e^{-a\mathcal{V}^{2/3}}$$

Combining with the earlier discussion on microscopic parameters

- After using the spectral tilt to fix ϵ

$$N \approx 240\left(\frac{f}{M_{\mathrm{Pl}}}\right)^2$$

- Requiring the density perturbations of the right magnitude

$$m \approx 3 \times 10^{14}\mathrm{Gev}$$

We get

$$\mathcal{V} \approx 200 \text{ and } N \approx 10^5$$

Some phenomenology

- Susy is broken in the background. The gravitino mass

$$m_{3/2} \approx 10^{15}\mathrm{Gev}$$

  Susy not relevant for hierarchy problem. In keeping with general arguments - for e.g. Ibanez and Valenzuela '14
- Reheating: Matter fields on D7 branes wrapping bulk cycles. Since standard model degrees of freedom not localised one can hope that reheating is efficient. Dominant mode of decay is to gauge bosons. The reheating temperature

$$T_{\mathrm{rh}} = \frac{m}{f}\sqrt{N_\gamma m M_{\mathrm{Pl}}} \approx 10^{14}\mathrm{GeV}$$

  is independent of N.
- By making an appropriate change in the parameter one can also obtain a model of quintessence (Kaloper and Sorbo '05). This requires $m \sim 10^{-30} meV$

$$\mathcal{V} \approx 10^5 \ \text{and} \ N \approx 10^6$$

Challenges

- Challenges for Nflation -
  - Moduli stabilisation
  - Renormalisation of Planck mass.
- Expectation from effective field theory that the Planck mass receives a correction proportional to N. Such a correction will destroy the parametric suppression in N obtained for the slow roll parameters.
- To address the above problem a complete understanding of α' and g_s is necessary; are there class backgrounds which exhibit behaviour which is non-generic from the effective field theory perspective.
- Our addition to this part of the story the values of the microscopic parameters

$$\mathcal{V} \approx 200 \text{ and } N \approx 10^5$$

- This also brings out a new challenge. So far, explicit example of Calabi Yau with $N = 10^5$.

Conclusions/Future Directions

- Usually any ingredient that gives masses to the moduli will also contribute to the inflaton mass unless there is some kind of symmetry reason. In our case, the Nflationary axions have their own shift symmetry have can be parametrically lighter than other moduli
- Calabi Yau with

$$\mathcal{V} = f(\tau_A) - \gamma \tau_s^{3/2}$$

- Have developed an understanding of the moduli potential for general N (N number of Kahler moduli). Study the N dependence of various quantities. Can this be used as a parameter to generate hierarchies.
- Can we make any general statements about inflation driven by the geometric (Kahler moduli) – based on generic properties of the Kahler potential (just as we did here for moduli stabilisation) ?
- Better understanding of IIB axiverse.