Ultraviolet Fingerprints of the Early Universe

A Review of Inflation in String Theory and Field Theory

Daniel Baumann Institute for Advanced Study

Madrid, December 2010















Inflation is sensitive to Planck-scale physics!

Outline

Eta problem

1. UV Sensitivity of Inflation \rightarrow Gravitational waves

Non-Gaussianity

2. Inflation in String Theory

Case study: warped D-brane inflation

3. Inflation in Field Theory

A new solution to the eta problem

UV Sensitivity of Inflation

Eta problem Gravitational waves Non-Gaussianity

 $\ll 1$

Slow-Roll Inflation

$$\mathcal{L} = \frac{1}{2} \partial_{\mu} \phi \partial^{\mu} \phi - V(\phi)$$
 -

60 e-folds of quasi-de Sitter requires:

 $\varepsilon = \frac{M_{\rm pl}^2}{2} \left(\frac{V'}{V}\right)^2 \ll 1$

 $\eta = M_{\rm pl}^2 \frac{V''}{V}$

measure of the inflaton mass

 $\eta \approx \frac{m_\phi^2}{H^2}$



Linde (1982), Albrecht and Steinhardt (1982)



The Eta Problem

Given a potential $V(\phi)$ with $\eta = M_{\rm pl}^2 \frac{V''}{V} \ll 1$

add Planck-scale corrections



Inflation is sensitive to **dimension 5 and 6 Planck-suppressed operators** Every model of inflation has to address the eta problem.

Some classes of models have observational signatures that dramatically enhance the UV sensitivity:



Gravitational Waves

Non-Gaussianity

Gravitational Waves

Measuring the background of gravitational waves predicted by inflation is the holy grail of observational cosmology.



DB et al. (2009), Probing Inflation with CMB Polarization

The signal will be observed within the next decade IF:





Observable gravitational waves require super-Planckian field variation.



This makes an effective field theorist nervous and a string theorist curious!

Gravitational Waves



Gravitational Waves



= Fantastic Opportunity for String Inflation!

Are super-Planckian field variations UV-completable?

see Silverstein et al.



slow-roll inflation



with Dymarsky, Kachru, Klebanov, Maldacena and McAllister

Case Study: Warped D-brane Inflation Dvali & Tye (1996), Kachru et al. (2003) a toy model Ψ bulk explicit local geometry $AdS_5 \times X_5$ - generic in flux compactifications - high degree of **computability** dual gauge theory - RG filtering of UV corrections $SU(N) \times SU(N)$

Case Study: Warped D-brane Inflation

a toy model

Dvali & Tye (1996), Kachru et al. (2003)



Case Study: Warped D-brane Inflation

a toy model

Eta Problem

addressed by explicit computation

Gravity Waves

constrained by geometry

Non-Gaussianity

controlled by symmetry



Gravitational Waves

no-go for warped brane inflation DB and McAllister

size of the compact space

volume of the compact space

 $M_{\rm pl}^2 \propto L^6$

 $\frac{\Delta \phi^2}{M_{\rm pl}^2} \propto \frac{1}{L^4}$

inversely proportional to the size of the compact space!



B-flux

Silverstein et al.

D5-brane



axion monodromy inflation

• axions e.g. type IIB string theory

$$b \equiv \int_{\Sigma_2} B$$

<u>classical:</u> flat potential

protected by a continuous shift symmetry.

<u>quantum:</u> periodic potential \leftarrow from non-perturbative instanton effects protected by a discrete shift symmetry.

axions + wrapped branes

<u>monodromy:</u> potential energy is *not* a periodic function of the axion

$$V(b) \propto \sqrt{1+b^2} \sim b$$



axion monodromy inflation

axions explore a super-Planckian range on the "covering space"



Why is the inflaton light?

Integrating out massive moduli can give large corrections to inflaton mass.

In warped brane inflation this requires careful treatment of:

D3-brane backreaction, interactions with moduli-stabilizing ingredients, and compactification effects.

Why is the inflaton light?

A brane and an anti-brane in a warped background interact via an exponentially small Coulomb force KKLMMT (2003)



Does this mean that the system can source inflation with exponentially flat potential ?

D3-brane backreaction



D3-brane backreaction



 $\mathcal{V}_6(\phi) \neq \mathcal{V}_6$

overall volume depends on the D3-brane position

even if the inflaton potential is flat in string frame it will not be flat in **Einstein frame**

$$V_{\rm E}(\phi) = rac{1}{\mathcal{V}_6^2(\phi)} \cdot V_{
m str}(\phi)$$





Non-perturbative effects













Inflection point inflation

inflation can occur, but only near an approximate *inflection point*

 $V(\phi) = V_0 \left[1 + c_1 \, \phi^1 + c_{3/2} \, \phi^{3/2} + c_2 \, \phi^2 + \dots \right]$

Eta Problem

AdS/CFT and fluxes



DB, Dymarsky, Kachru, Klebanov, and McAllister D3-brane Potentials from Fluxes in AdS/CFT

Non-Gaussianity

How to control large inflaton interactions?

Sources of large non-Gaussianity: • higher-derivative interactions of the inflaton • couplings of the inflaton to other fields

Both are rather natural in string inflation.

Non-Gaussianity

DBI inflation

<u>Relativistic</u> D-brane motion produces large non-Gaussianity. Silverstein and Tong

> D3-brane action in a warped background $\mathcal{L} = -f^{-1}(\phi)\sqrt{1 - f(\phi)(\partial\phi)^2} - V(\phi)$ cf. relativistic point particle $\mathcal{L} = -m\sqrt{1 - \dot{x}^2}$ protected by 5d boost symmetry derivative interactions are under control

Inflation in Field Theory

with Daniel Green

The Eta Problem

Can we forbid corrections with a symmetry ?

all dangerous corrections are forbidden if the inflaton respects a **shift symmetry**

 $\varphi \rightarrow \varphi + const.$

arise naturally in theories with **spontaneous breaking of global symmetries**

Inflaton = Pseudo-Nambu Goldstone Boson

 $\phi = \rho \, e^{i\varphi/f}$

spontaneously broken global U(1)



III. Baryon Inflation

Proton Decay in the SM

experimental fact:

the proton has a very long lifetime

"I can feel it in my bones."

Wigner (1943)

imagine we didn't know about quarks and treated the proton as fundamental :

induce rapid proton decay

 $\frac{p\mathcal{O}}{M_{\rm pl}} \longrightarrow \Gamma \sim \frac{m_p^3}{M_{\rm pl}^2} \sim 10^{-13} \,\mathrm{s}^{-1}$

dimension 5 Plancksuppressed operators:

Proton Decay in the SM

experimental fact: the proton has a very long lifetime

explanation:

the Standard Model has an "accidental" baryon number symmetry

i.e. given the gauge symmetries and the particle content of the SM, there are no renormalizable interactions that violate baryon number

leading operators are dimension 6

in fact, there are **no** dimension 5 operators



consistent with experiments.

III. Baryon Inflation

Can we solve the eta problem in a similar way?

A New Solution to the Eta Problem

Find a theory with an accidental global symmetry because its gauge symmetries and field content forbid symmetry breaking operators with dimensions less than 7

existence proof:

baryons in SUSY QCD

see DB and Daniel Green (2010)

baryon

$$\mathcal{B} = qq\cdots q$$

quarks

no dangerous Kähler and superpotential corrections !!

Conclusions



inflaton mass

Inflation is sensitive to Planck-scale physics!

gravitational waves

 $\Delta \phi \gg M_{\rm pl}$

non-Gaussianity

 $(\partial \phi)^2 \sim M_{\rm pl}^4$

Gracias por su atencion y feliz navidad!

and thanks to my collaborators:

Liam McAllister, Anatoly Dymarsky, Igor Klebanov, Shamit Kachru, Juan Maldacena, Paul Steinhardt, Arvind Murugan and Daniel Green

III. Baryon Inflation

$$\begin{aligned} & {\displaystyle {\displaystyle \operatorname{Supergravity}}\; \operatorname{Eta}\; \operatorname{Problem}}\\ & V \,=\, e^{K/M_{\mathrm{pl}}^2} \left[K^{\Phi\bar\Phi} D_{\Phi} W \overline{D_{\Phi} W} - \frac{3}{M_{\mathrm{pl}}^2} |W|^2 \right] \end{aligned}$$

F-term vacuum energy drives inflation: $D_X W = \mu^2$

$$V = \mu^4 \left[1 + \frac{K}{M_{\rm pl}^2} + \cdots \right]$$

 $K = \Phi^{\dagger} \Phi \qquad \longrightarrow \qquad \eta = 1 + \cdots$ tied to kinetic term extra terms from $W(\Phi)$ can lead to (fine-tuned) cancellations *cf.* brane inflation

III. Baryon Inflation

no mass for

PNGBs in SUGRA

 $\Phi = f e^{\phi} \longrightarrow K = \Phi^{\dagger} \Phi = f^2 e^{\phi + \phi^{\dagger}} \longrightarrow \varphi \equiv f \operatorname{Im}(\phi)$

i.e. "a Goldstone boson coupled to gravity is a Goldstone boson"

mass is only generated by explicit symmetry breaking





A Simple Model

Pseudo Natural Inflation Arkani-Hamed et al.

$$W = X\mu^2 + S(\Phi\tilde{\Phi} - f^2)$$

III. Baryon Inflation

Planck-Scale Corrections

Pseudo Natural Inflation Arkani-Hamed et al.

$$W = X\mu^2 + S(\Phi\tilde{\Phi} - f^2)$$

Dimension 5:
$$c \frac{\Phi}{M_{\rm pl}} X^{\dagger} X \longrightarrow \eta = c \frac{M_{\rm pl}}{f} \gg 1$$

Dimension 6:
$$(c_0 \Phi^{\dagger} \tilde{\Phi} + c_1 \Phi^2 + c_2 \tilde{\Phi}^2) \frac{X^{\dagger} X}{M_{\rm pl}^2}$$

 $\eta = c_i \sim 1$

many dangerous corrections.

 ΛK

 ΔW

Goal: Construct a model of inflation that is insensitive to Planck-scale corrections.

SUSY QCD

Consider $SU(N_c)$ with $N_f > 3N_c$ flavors of quarks $(q_i)_a$ (IR free) and anti-quarks $(\tilde{q}_i)^a$ gauge index flavor index two types of composite operators: mesons $\mathcal{M}_{ij} = (q_i)_a (\tilde{q}_j)^a$

mesons $\mathcal{M}_{ij} = (q_i)_a (q_j)^a$ inflaton baryons $\mathcal{B}_{i..k} = \epsilon^{a..d} (q_i)_a ... (q_k)_d \sim f^{N_c} e^{i\frac{\varphi}{f}}$

Baryon Symmetry				
$U(1)_B$	$F \rightarrow e^{iQ_B \alpha} F$			
			Q_B	Δ
	quarks	q_i	+1	1
		\widetilde{q}_i	-1	1
	mesons	\mathcal{M}_{ij}	0	2
	baryons	${\mathcal B}_{ik}$	$+N_c$	N_c
		$ ilde{\mathcal{B}}_{ik}$	$-N_c$	N_c

 $N_c \ge 3$

all baryon symmetry violating operators are irrelevant !

III. Baryon Inflation

use the phase of a baryon as the inflaton

vacuum energy spontaneous symmetry breaking $W = X\mu^2 + S^{mn}(q_m\tilde{q}_n - f^2\delta_{mn})$ flavor indices $m, n = 1..N_{c}$ $F_X = \mu^2$ $F_S = 0$ $V_0 = \mu^4$ $(q_m)_a = f e^{i\frac{\varphi}{f}} \delta_{m,a}$ $(\tilde{q}_n)^a = f e^{-i\frac{\varphi}{f}} \delta_n^a$

III. Baryon Inflation

 $M_{\rm pl}$

 μ

Absence of the Eta Problem

Kähler Corrections

$$\Delta K = \frac{\mathcal{B}}{M_{\rm pl}^{N_c}} X^{\dagger} X \longrightarrow \Delta \eta = \left(\frac{f}{M_{\rm pl}}\right)^{N_c - 2}$$

$$N_c \ge 3 \qquad \text{no Kähler corrections } !!$$

Superpotential Corrections

$$\Delta W = \frac{\mathcal{B}}{M_{\rm pl}^{N_c - 2}} X \longrightarrow \Delta \eta = \left(\frac{f}{M_{\rm pl}}\right)^{N_c - 4} \frac{f^2}{\mu^2}$$

$$N_c \ge 5 \quad \text{everything suppressed !!}$$