Dante's Inferno

based on Berg, E.P. & Sjörs, arXiv:0912.1341 (hep-th)

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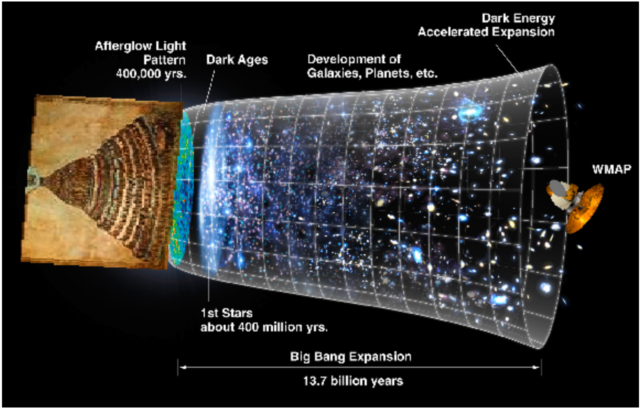

Outline

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1. Motivations
2. Dante's Inferno: the EFT story
3. Dante's Inferno: the string theory story
4. Conclusions

Tensor modes and the Lyth bound

- The detection of tensor modes would fix the scale of inflation close to the GUT scale.
- Measuring tensor modes puts a lower bound on the range of variation of the inflaton [Lyth 98]

$$\frac{d\phi}{M_{pl}} = dN\sqrt{2\epsilon} \simeq dN\sqrt{\frac{r}{8}}$$

$$\frac{\Delta\phi}{M_{pl}} > \sqrt{\frac{r}{0.01}}\,\frac{N_{CMB}}{30}$$

- $\Delta\phi$ above the cutoff makes the use of EFT suspicious
- This is the main motivation to consider axion monodromy inflation

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Schematically

Tensor modes $\Rightarrow$ High scale $\Rightarrow$ Large field $\Rightarrow$ more UV-sensitive

UV-sensitivity

- EFT approach: learn about higher scales studying UV-sensitive observables.
- Inflation is a UV-sensitive mechanism. Schematically

$$V(\phi) = \frac{1}{2}m^2\phi^2 + \sum_n \lambda_n \frac{\phi^n}{M_{pl}^{n-4}}$$

- Within string theory and supergravity many models suffer from an η-problem.
- We need to invoke a symmetry, e.g. shift symmetry.
- Then we need a fundamental theory (UV-finite) to ask if, how and where the symmetry is broken.

Axions in field theory and string theory

- Axions are scalars with only derivative couplings.
- Arise from breaking of a $U(1)$ [Peccei & Quinn 77] or in dimensional reduction integrating p-forms on p-cycles

$$c(x) = \int_{\Sigma_p} C_p \, , \qquad b(x) = \int_{\Sigma_2} B_2$$

- Continuous shift symmetry at all orders in perturbation theory $\phi \to \phi + \text{const}$
- Shift symmetry is broken to a discrete shift symmetry by non-perturbative effects

$$\mathcal{L} \supset \frac{1}{2}(\partial\phi)^2 + \Lambda^4 \cos\left(\frac{\phi}{f}\right) \Rightarrow \phi(x) \to \phi(x) + 2\pi f$$

where f is the axion decay constant and $\Lambda \sim e^{-1/g}$.

Axion inflation

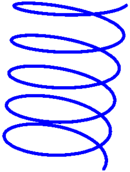
- Natural inflation [Freese et at. 90]

$$V(\phi) = \Lambda^4 \left[1 + \cos\left(\frac{\phi}{f}\right)\right] \,,$$

- Very hard to achieve in string theory [Banks et al. 03, Kallosh et al. 95]
- Axion monodromy [(Silverstein & Westphal)(1+McAllister) 08]

$$V(\phi) = W(\phi) + \Lambda^4 \cos\left(\frac{\phi}{f}\right)$$

- Can be constructed in string theory
- The hardest part is to control the large vev (e.g. backreaction on the geometry and lighter KK modes)

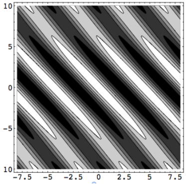


Inflation with more than one axion

- Two axion model [Peloso et al. 04]

$$V = \Lambda_1^4 \left[1 + \cos\left(\frac{\theta}{f_1} + \frac{r}{g_1}\right)\right] + \Lambda_2^4 \left[1 + \cos\left(\frac{\theta}{f_2} + \frac{r}{g_2}\right)\right]$$

- subplanckian axion decay constants lead to large field inflation



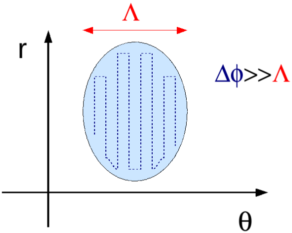
- N-flation [Dimopoulos et al. 05] : assisted mechanism with N axions.
- The vev is reduced by $\sqrt{N}$, equivalently f is enhanced by $\sqrt{N}$

Outline

Back to the Lyth bound

There is a dichotomy which becomes evident with more than one inflaton.

- The bound is on the effective inflaton $\phi_{\rm eff}$, i.e. the length of the inflationary trajectory $\Delta\phi_{\rm eff} \equiv \int d\phi_{\rm eff}$
- Quantum corrections grow with the vev's of fundamental fields.



The Lyth bound

The consequences of the Lyth bound are generically different in multi-field inflation

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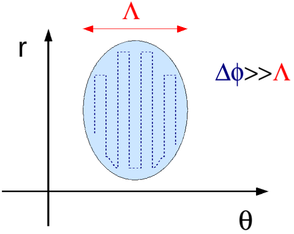


The Lyth bound

The consequences of the Lyth bound are generically different in multi-field inflation

How complicate a potential can provide this classical trajectories?

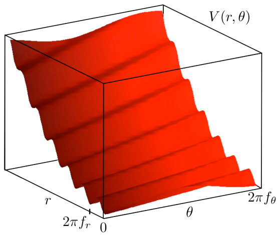
The potential is as simple as this:

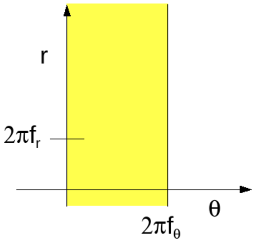
$$V(r(x),\theta(x)) \;=\; W(r) + \Lambda^4\left[1-\cos\left(\frac{r}{f_r}-\frac{\theta}{f_\theta}\right)\right]$$

- Two canonically normalized axions $\{r, \theta\}$, with respective axion decay constants $\{f_r, f_\theta\}$.
- The shift symmetry of r is broken by a monodromy term $W(r)$. This could be anything. For illustration $W(r) = m^2 r^2/2$.
- A non-perturbative effect involves a linear combination of r and θ.
- θ enjoys a shift symmetry to all order in perturbation theory broken only by non-perturbative effects to $\theta \to \theta + 2\pi f_\theta$.

The infernal potential

The potential on the two-field space





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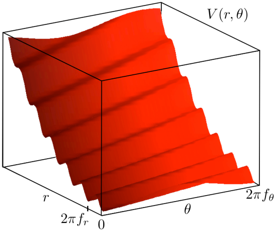
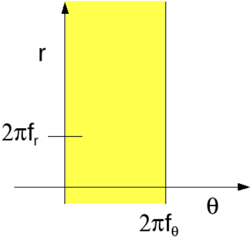
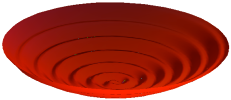
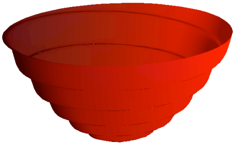
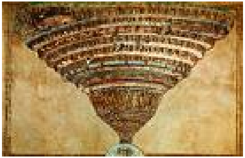




The periodicity in θ is evident in polar coordinates.







Hence the name...

Solution of the infernal dynamics

In the regime

A. $f_r \ll f_\theta \ll M_{pl}$,

B. $\Lambda^4 \gg f_r m^2 r_0$,

r can be integrated out ($m_r > H$), i.e. $r = r(\theta)$:

$$V_{eff}(\phi_{\rm eff}) = \frac{1}{2}\, m_{\rm eff}^2\, \phi_{\rm eff}^2 \ , \quad m_{\rm eff} \equiv m\, \frac{f_r}{f_\theta}$$

where $\phi_{\rm eff} \simeq \cos(f_r/f_\theta)\theta + \sin(f_r/f_\theta) r$.

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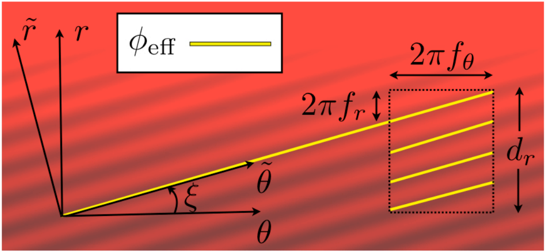
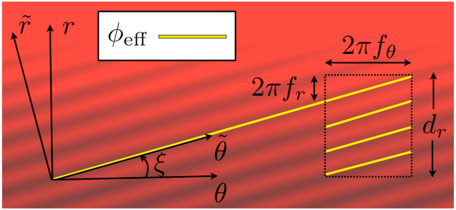


The extra dial and the η-problem

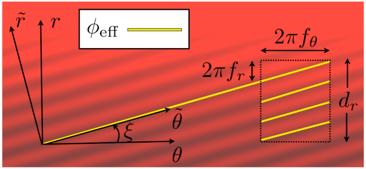


The η-problem is alleviated

Since $m_{\mathrm{eff}} = m(f_r/f_\theta)$,

- even if $m \sim H$ and hence r would have an η-problem, a mild hierachy $f_r/f_\theta \sim \mathcal{O}(.1)$ gives slow-roll inflation.
- Intuitively ϕ_{eff} is mostly θ which has a shift symmetry.

The extra dial and the field range



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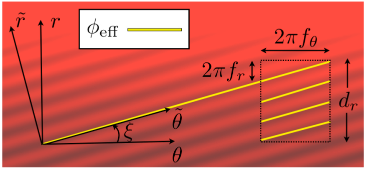

What about the field range?

- $\Delta\phi_{\text{eff}} \simeq 15 M_{pl}$, but...
- whole inflationary dynamics takes place inside

$$0 < \theta < 2\pi f_\theta \,, \qquad 0 < r < 15 M_{pl} \frac{f_r}{f_\theta}$$

- Provided $f_r / f_\theta \sim \mathcal{O}(10^{-1} - 10^{-2})$, chaotic inflation takes place in a region subplanckian in size.

Summary of the effective model

Phenomenology:

- Observable tensor modes
- Oscillations in correlation functions (model dependent)
  [Raphael's talk]
- Inverse decay non-Gaussianity (model dependent)
  [Marco and Neil's talks]

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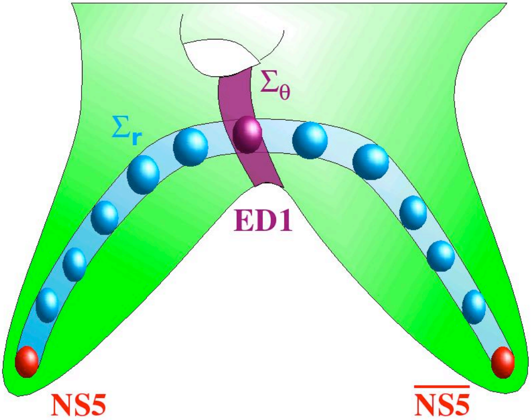
Theoretical considerations:

- The inflaton is mostly an axion with a shift symmetry (only non-perturbative corrections) which alleviates the η-problem.
- The whole large-field inflationary dynamics takes place within a region subplanckian in size.
- Issues related to the large vev's of the axions are alleviated

Outline

A cartoon of Dante's Inferno

- Two axions:
  two-cycles Σ_r and Σ_θ
- Monodromy:
  NS5-branes
- Non-perturbative term:
  Euclidean D1-brane



The setup [McAllister et al. 08]

- Type IIB orientifolds.
- Moduli stabilization á la KKLT does not spoil the shift symmetry.
- Non-perturbative effects (e.g. ED1) and the monodromy term (5-brane) can wrap two overlapping but non-identiacal two-cycles.
- We can choose a basis of two-cycles such that only one axion has a monodromy, say r

$$V(r(x), \theta(x)) \quad = \quad W(r) + \Lambda^4 \left[1 - \cos\left(\frac{r}{f_r} - \frac{\theta}{f_\theta}\right)\right]$$

- Even if W is steep, inflation works provided $f_r \ll f_\theta$.

The axion decay constant

Using $N = 1$ 4D data and dimensional reduction one finds

$$\frac{f^2}{M_{pl}^2} = \frac{g_s}{8\pi^2}\frac{c_{\alpha--}v^\alpha}{\mathcal{V}_E} \propto \frac{g_s}{\mathcal{V}_4} \ll 1$$

The ratio f_r/f_θ depends on the geometry

$$\frac{f_r}{f_\theta} = \frac{c_{\alpha rr}v^\alpha}{c_{\beta\theta\theta}v^\beta}$$

Easily $\mathcal{O}(10)$ or more

Axion decay constant in string theory

In controlled setups $g_s \ll 1$ and $L \gg \alpha'$, hence $f \ll M_{pl}$. [Banks et al. 03]

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- Dante's inferno is a robust string theory model of large field inflation
- UV symmetries protect the flatness of the potential
- The infernal dynamics ensures small vevs
- Observable tensor modes (plus model dependent signals) make it a falsifiable model

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