Chain Inflation in the Landscape

James T. Liu

12 December 2006

Katie Freese and Doug Spolyar, hep-ph/0412145
Katie Freese, JTL and Doug Spolyar, hep-ph/0502177, hep-th/0612056

KITP

Outline

- Introduction – the string landscape
- Fast tunneling in the landscape
- Chain inflation
- Issues
- Other models of rapid tunneling

The string landscape

- Long been recognized – string vacua are not unique

  the vacuum selection problem

- Consider e.g. strings on Calabi-Yau with fluxes

  Bousso and Polchinski "discretuum"; KKLT

- Degeneracy arises from

  different possible Calabi-Yau manifolds

  quanta of fluxes on each cycle

- Rough estimates can yield 10^{100} – 10^{500}

  can expect large numbers of cycles

The string landscape

- Given the 'reality' of the landscape, it is natural to discuss both the cosmological constant problem and inflation in the context of the landscape

– The cosmological constant problem

statistical properties/statistical description

dynamical selection

(anthropic)

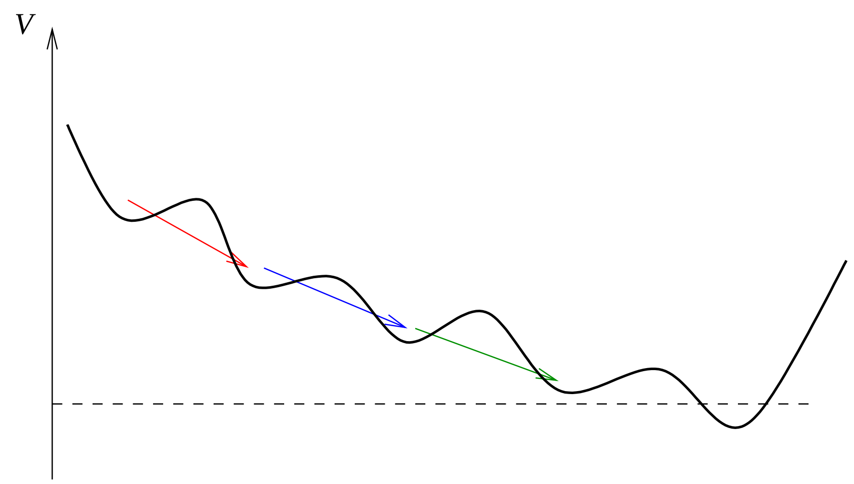
– Inflation

General perception: long lived metastable states connected by membrane instantons $\Rightarrow$ slow tunneling and eternal inflation

However, can fast tunneling occur? $\Rightarrow$ chain inflation

Chain inflation

- Inflation proceeds via a rapid sequence of tunneling events



- The universe expands a fraction of an e-fold in each metastable state
- We demand a total of 60 or so e-folds

  more than 200 tunneling events in the course of inflation

Fast tunneling in the landscape

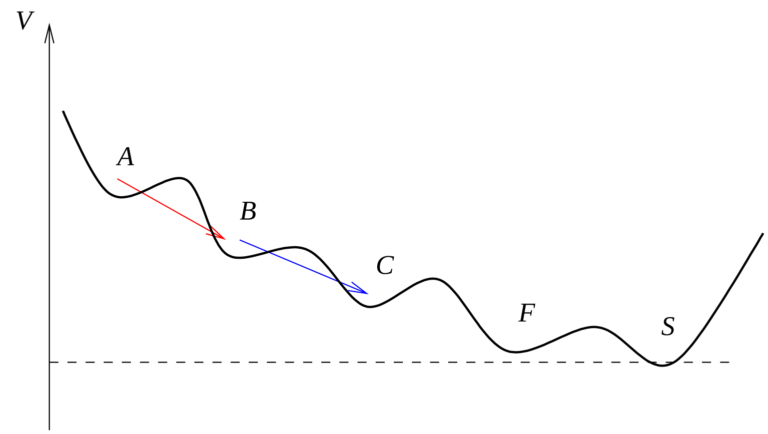
- Resonant tunneling [Henry Tye, hep-th/0611148]
- Quantum effects in the landscape
  [Kane, Perry and Zytkow, hep-th/0311152]
  [Davoudiasl, Sarangi and Shiu, hep-th/0611232]
- Take a closer look at the instanton action

  we consider a Bousso-Polchinski [hep-th/0004134] example

As long as there is at least one fast channel for vacuum decay,
that is all that is needed

Resonant tunneling

- Resonant quantum effects may lead to $A \rightarrow B \rightarrow C$ of order unity if resonance condition satisfied



- All that is required is for one chain $A \rightarrow B_i \rightarrow C_i$ to be on resonance

  Large Λ: large # of next nearest neighbors $\Rightarrow$ fast (resonant) tunneling

  Small Λ: fewer adjacent vacua $\Rightarrow$ tunneling stops at $\Lambda \approx 0$

Quantum superposition in the landscape

- Kane, Perry and Zytkow, hep-th/0311152

  The landscape does not consist of a set of discrete metastable minima, but is instead in a quantum superposition state

  Bloch wave picture: lowest point in the band has $\Lambda \approx 0$

  Large quantum superpositions $\Rightarrow$ can have fast transitions between states (similar to fast tunneling)

  Exploited by Watson, Perry, Kane and Adams, hep-th/0610054 for inflation

- Davoudiasl, Sarangi and Shiu, hep-th/0611232

  Quantum sampling and Bloch waves over part of the landscape during inflation

Tunneling in Bousso-Polchinski

- Extension of the Brown-Teitelboim mechanism
  Phys. Lett. B 19, 177 (1987); Nucl. Phys. B 297, 787 (1988).
- Make Λ dynamical: $\Lambda \rightarrow F_{(4)}$ (in four dimensions) where $F_{(4)}$ may arise from string/M-theory fluxes on cycles

$$F_{\mu\nu\rho\sigma} = nq\epsilon_{\mu\nu\rho\sigma}, \qquad n \in \mathbb{Z}$$

$$\Lambda = \Lambda_{\rm bare} + \tfrac{1}{2}n^2q^2$$

- This flux is reduced by the nucleation of membrane (wrapped p-brane) instantons
  $n \rightarrow n-1$ gives an energy drop $\epsilon = -(n-\tfrac{1}{2})q^2$

Tunneling in Bousso-Polchinski

- A simple estimate of the tunneling rate

$$\Gamma \sim e^{-S_E} \qquad S_E = \frac{27\pi^2}{2}\frac{\tau^4}{|\epsilon|^3}$$

$\epsilon =$ energy drop, $\qquad \tau =$ brane tension

(thin-wall instanton action ignoring gravity)

- Can S_E be of order 1?

Expectation: $\tau \sim$ large, $\epsilon \sim$ small $\Rightarrow$ slow tunneling

- But adjacent vacua are separated by a discrete jump in flux

$n \rightarrow n-1$ does not necessarily give small ϵ

Another look at the bounce action

- For tunneling from $n \to n-1$, we estimate

$$S_E \approx \frac{27\pi^2}{2n^3}\frac{\tau^4}{q^6}$$

so we are interested in the ratio τ^4/q^6

- For string/M-theory branes, we may use the BPS condition $\tau = m_{\rm pl} q/\sqrt{2}$ to obtain

$$S_E \approx \frac{27\pi^2}{16n^3}\left(\frac{m_{\rm pl}^3}{\tau}\right)^2$$

(we expect $\tau/m_{\rm pl}^3 < 1$)

- So long as $\tau/m_{\rm pl}^3$ is not too small, we can compensate by taking n moderately large, and thus end up with reasonably fast tunneling

Example: wrapped M5-branes in BP

- Consider M-theory compactified on a 7-manifold with many 3-cycles
- Wrapped M5-branes have an effective 4-dimensional tension

$$\tau = 2\pi M_{11}^3 (V_3 M_{11}^3)$$

- Taking $M_{11} \sim 10^{-3}\, m_{\rm pl},\ V_3 M_{11}^3 \sim 10^3$ gives

$$\tau \sim 2\pi \times 10^{-6}\, m_{\rm pl}^3$$

- Then $n \sim (\text{few}) \times 10^3$ gives $S_E \sim \mathcal{O}(10\text{–}100)$
- Not all decay channels are fast — but you only need one

Inflation and chain inflation

- Requirements on inflation
  - sufficient inflation (about 60 e-folds) for horizon, flatness, monopoles, etc.
  - "graceful exit" (reheating)
  - generate observed density perturbations

  . . .

- Generally two types of models
  - tunneling models (first order phase transition)

  "old inflation" – inflate in a false vacuum, then nucleate bubbles of true vacuum
  - rolling models

The problem with old inflation

- Cannot inflate for 60 e-foldings and also reheat
  [Guth and Weinberg, Nucl. Phys. B 212, 321 (1983)]

- Define

$$\beta \equiv \frac{\Gamma}{H^4} = \text{volume fraction of space occupied by bubbles nucleated over a Hubble time}$$

  where $\Gamma \sim e^{-S_E}$ is the bubble nucleation rate per unit volume

- Requirements:

  $\beta \ll 1$ to inflate 60 e-folds

  $\beta > 9/4\pi$ to percolate and reheat

- Both conditions cannot be satisfied simultaneously for constant β

Variations on tunneling

- Make β variable during the course of inflation

  $\beta < 10^{-4}$ initially small from limits on "big bubbles"

  $\beta > 9/4\pi$ at late time to exit inflation

- Still highly constrained – how to make this transition without producing bad big bubbles?

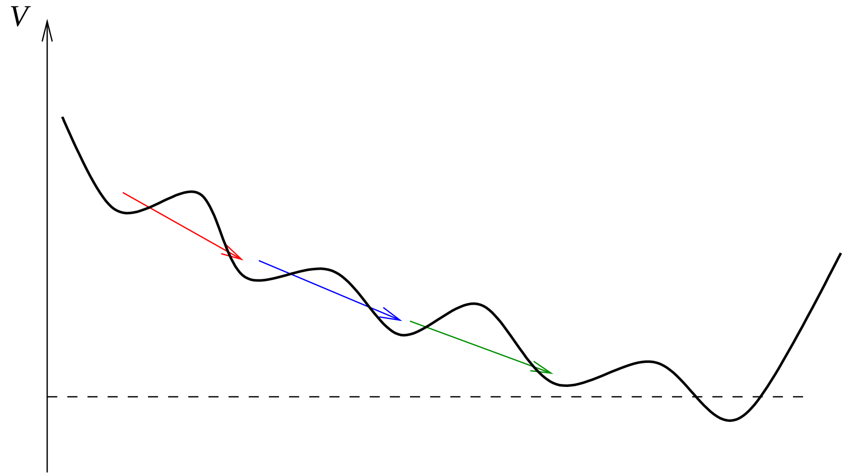
  Turner, Weinberg and Widrow, Phys. Rev. D 46, 2384 (1992)]

- But why not tunnel and percolate all the way down?

  $\Rightarrow$ Chain inflation

Chain inflation

- Inflation proceeds by a sequence of rapid tunnelings
- Bubbles constantly percolate
- Total of 60 or so e-folds



Requirements on chain inflation

- The percolation requirement

$$\beta > \frac{9}{4\pi} \qquad \text{at each stage of the chain}$$

- The total number of e-foldings

The number of e-foldings for a single tunneling event is estimated by $\chi = \int H\,dt \approx H\tau$ where τ is the lifetime of the false vacuum, $\tau = 3/4\pi\beta H$

This gives

$$\chi \approx \frac{3}{4\pi\beta} < \frac{1}{3}$$

For $N_{\rm tot} > 60$ we need a chain of more than 180 tunnelings

Back to the wrapped M5-brane example

- For

$$\tau \sim 2\pi \times 10^{-6}\, m_{\rm pl}^3 \qquad n \sim \text{(few)} \times 10^3$$

each tunneling event drops the vacuum energy by

$$\epsilon \sim nq^2 = 2n\frac{\tau^2}{m_{\rm pl}^2} \sim 10^{-7}\, m_{\rm pl}^4$$

- We suppose inflation starts at $\Lambda_{\rm initial} \sim 10^{-4}\, m_{\rm pl}^4$ and ends at $\Lambda_{\rm final} \sim 10^{-8}\, m_{\rm pl}^4$

  We actually want $\Lambda_{\rm final} \approx 0$, however here we do not address the cosmological constant problem, so we assume $\Lambda_{\rm final}$ is of the order of ϵ

Back to the wrapped M5-brane example

- Using

$$\beta = \frac{\Gamma}{H^4} = 9\left(\frac{\Lambda}{m_{\rm pl}^4}\right)^{-2} e^{-S_E} \quad \text{where} \quad S_E \approx \frac{27\pi^2}{16n^3}\left(\frac{m_{\rm pl}^3}{\tau}\right)^2$$

the fast tunneling (percolation) requirement $\beta > 9/4\pi$ demands

$$n_{\rm initial} > 2735, \qquad n_{\rm final} > 2210$$

- Note that we need about 1000 tunneling events to reduce $\Lambda_{\rm initial}$

  These tunnelings can occur on different cycles

Issues

- Are large units of flux $n \sim 1000$ realistic?

  have to worry about backreaction and possibly the tadpole constraint

- How does inflation end without getting stuck in a long lived metastable state?

  may still end up with eternal inflation

- Can chain inflation be tied in to a solution to the Λ problem?

- Is the supergravity/effective field theory estimate for S_E to be trusted?

  de Alwis, hep-th/0605184: no supergravity solution for the membrane instanton

More to be done

- Better understand and characterize fast tunneling in the landscape
- What are the signatures of chain inflation?

  density perturbations, tensor modes, etc.

- Go beyond the thin-wall approximation
- Chain inflation can occur in other models of rapid tunneling

  Inflating with the QCD axion [hep-th/0502177]

  QCD instantons along with softly broken $U(1)_{PQ}$ gives a 'tilted cosine' potential for the axion

Other models of rapid tunneling

- Although we assume rapid tunneling, we still envision the landscape to consist of a set of metastable de Sitter minima separated by barriers
- In the limit where tunneling is unsuppressed, the individual minima may be better described as a quantum superposition state (Bloch waves)
- The entire landscape as a quantum superposition [Kane, Perry and Zytkow, hep-th/0311152; Watson, Perry, Kane and Adams, hep-th/0610054]

  The universe starts at (or near) the top of the band, and inflates as it decays towards the bottom

- During inflation, light fields develop fluctuations, and may coherently sample multiple adjacent vacua [Davoudiasl, Sarangi and Shiu, hep-th/0611232]

  Can end up with domain walls after inflation (devaluation?)

Other models of rapid tunneling

- Can various inflation models in the landscape be connected?

(slow tunneling) → (fast tunneling)

eternal inflation   chain inflation   quantum superposition

- Different regions of the landscape may favor different models
- Inflation and the cosmological constant may be closely tied together in the string landscape