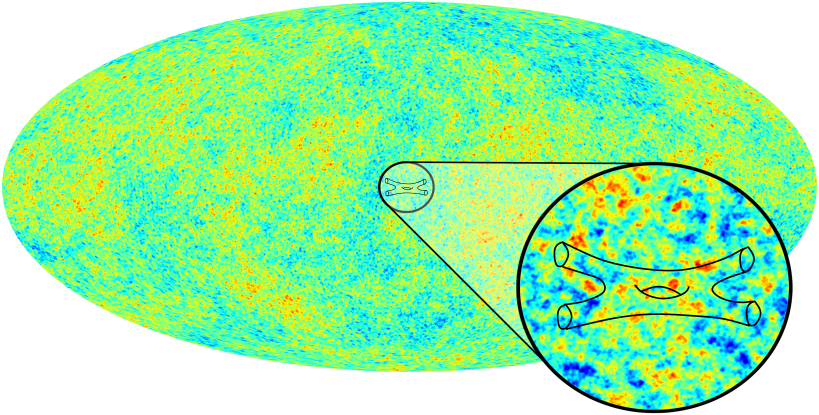
Recent Progress in String-Theoretic Models of Cosmological Inflation



Background Image: Planck Collaboration and ESA

Recent Progress in String-Theoretic Models of Cosmological Inflation

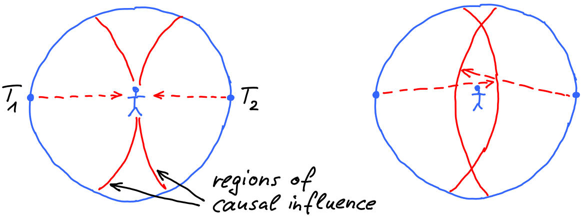
Arthur Hebecker (Heidelberg)

Outline

- Preliminaries: The need for inflation
- Inflation in field theory
- Why look for inflation in string theory
- The (flux-) landscape, eternal inflation and the multiverse
- Problems with large-field inflation in string theory
- Axion monodromy - early models and recent progress

The need for inflation

- Inflation has become the dominant paradigm for early cosmology
- One of the reasons is the ‘Horizon Problem’
- In short, the problem is that:
  We observe homogeneity between regions which have never been in causal contact with each other



- Crucial: The extra time between zero and decoupling is very small (cf. right-hand picture)

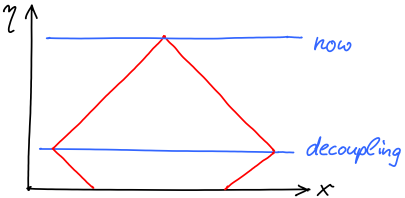
The need for inflation (continued)

- To be more precise, start from the Freedman-Robertson-Walker metric:

$$ds^2 = dt^2 - a^2(t)d\vec{x}^2 \qquad , \qquad a(t) \sim t^{2/3}$$

- Change coordinates accoring to $d\eta = dt/a(t)$ (conformal time):

$$ds^2 = a^2(\eta)\left[d\eta^2 - d\vec{x}^2\right]$$



- The plot makes the 'shortness' of the time before $\eta_{decoupling}$ manifest

Comment

- Of course, at $t = 0$ (or at $\eta = 0$), the whole universe is just a point
- Thus, one could say that at this 'big-bang singularity' everything is in causal contact anyway
- But to make this quantitative, one needs to be able to calculate at Planck-scale energy-densities
- Such attempts have indeed been made, but they depend on even conceptually unknown physics

Inflation solves the horizon problem

- Inflation introduces an early period in cosmology dominated by $\Lambda_{cosm.} = V(\varphi)$

- During this period, the universe expands exponentially: $a(t) \sim e^{Ht}$, where $H \sim \sqrt{\Lambda}/M_P$

- This expansion is so fast, that even tiny regions (where everything is in causal contact) are blown up to sizes much bigger than the whole observable universe

- To check this quantitatively, just redo the previous plot with $a \sim e^{Ht}$

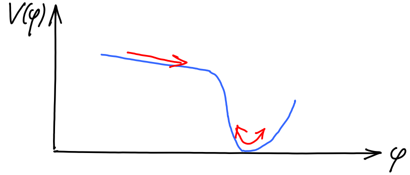
Starobinsky '80
Guth '81
Linde '82

Inflation in field theory

- The simplest relevant action is (from now on $M_P = 1$)

$$S = \int d^4x \sqrt{g} \left[\frac{1}{2} R[g_{\mu\nu}] + \frac{1}{2}(\partial\varphi)^2 - V(\varphi) \right]$$

- We can realise inflation if $V(\varphi)$ has a sufficiently flat region

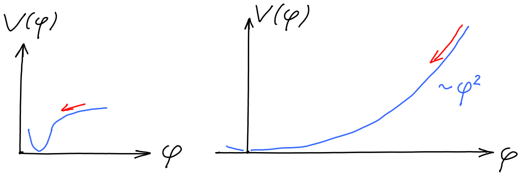


(More quantitatively, we need $V'/V \ll 1$ and $V''/V \ll 1$)

- In the end, φ oscillates and decays to SM particles
('reheating' $\equiv$ 'big bang')

Inflation in field theory (continued)

- If we allow ourselves to draw $V(\varphi)$ 'by hand', we can make some part of it very flat
- In this case, φ rolls very slowly, i.e. we get enough inflation (number of e-foldings) with $\Delta\varphi \ll 1$
- Such models are called 'small field' models



- Alternatively, one can use 'generic' potentials (e.g. $V(\varphi) \sim \varphi^2$)
- In such large field models, one needs $\Delta\varphi \gg 1$
  (We will see that this is a challenge in string theory)

Why look for inflation in string theory?

- Different types of questions have different sensitivity to the UV-completion / quantum gravity effects / string theory
- I want to argue that inflation is very sensitive to the UV
- Key point: In field-theory + quantum gravity we generically have higher-dimension operators $\sim \varphi^6/M_P^2 \equiv \varphi^6$ etc.
- Such effects may endanger the extreme flatness at $\varphi \ll 1$ or be completely fatal at $\varphi \gg 1$

A small warning / disclaimer:

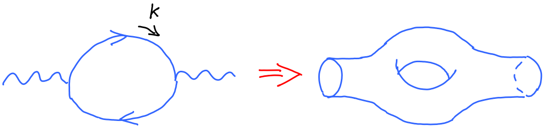
- It is not impossible to ensure flatness (i.e. control higher -dimension operators) just in low-energy effective field theory
- The most promising tools are shift symmetry ($\varphi \to \varphi + c$) and SUSY
- Nevertheless, one needs to make assumptions about tree-level values of and loop corrections to operator coefficients....

$$\mathcal{L} \supset \alpha_6 \varphi^6 + \alpha_8 \varphi^8 + \cdots$$

- By contrast, in string theory such corrections are calculable
- Furthermore, if start from string theory as *the* candidate quantum gravity theory, then for the above reasons inflation is *the* canonical way of testing it

String theory: 'to know is to love'

- String theory solves the problems (of QFT and, in particular, of perturbative quantum gravity) in 10 dimensions:

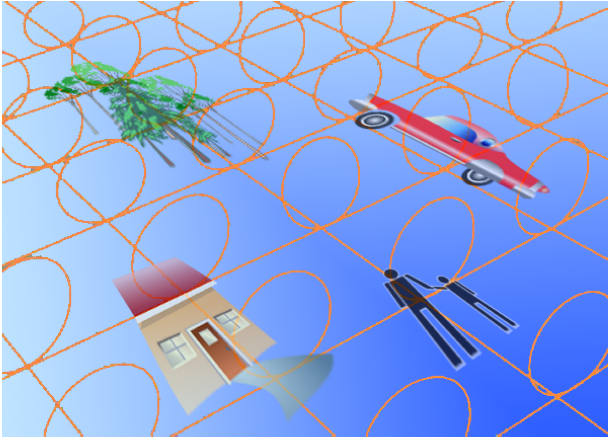


- The divergences at $k \to \infty$ are now removed
- Thus, in 10 dimensions but at low energy ($E \ll 1/l_{string}$), we get an (essentially) unique 10d QFT:

$$\mathcal{L} = R[g_{\mu\nu}] + F_{\mu\nu\rho}F^{\mu\nu\rho} + H_{\mu\nu\rho}H^{\mu\nu\rho} + \cdots$$

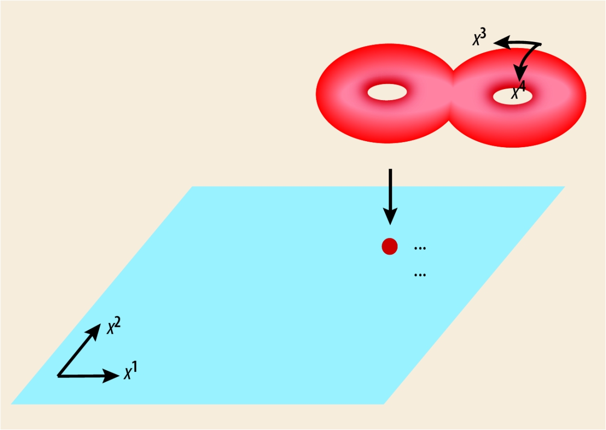
We need to 'compactify' 6 dimensions, going from 10d to 4d

- Quite analogously, we can compactify on S^1 from 3d to 2d, i.e. using $\mathbb{R}^2 \times S^1$ as our space:



'Compactification' continued

- We can compactify on Riemann surfaces from 4d to 2d:



Closer to reality:

- To go from 10d to 4d, i.e. we need 6d compact spaces
- We also want these spaces to solve Einstein's equations ($R_{\mu\nu} = 0$)
- Such geometries are called 'Calabi-Yau spaces' and $\sim 10^4$ of them are known (finiteness is conjectured but not established)

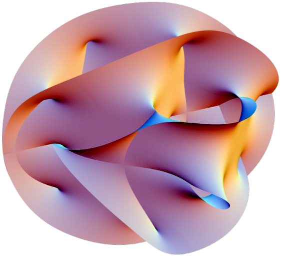
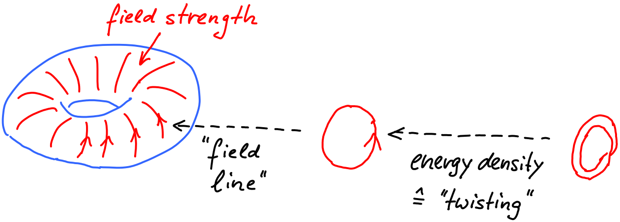


Image by J.F. Colonna

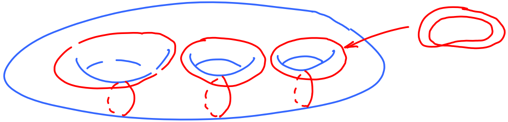
Next crucial ingredient: Fluxes

- Fluxes are field strengths of (higher-dimensional analogues) of gauge fields, such as $F_{\mu\nu\rho}$, $H_{\mu\nu\rho}$
- They are crucial for the landscape since they stabilize the geometry and lead to $\sim 10^{500}$ possibilites
- Simplest version of an explanation:

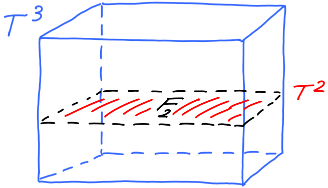


- This illustrates a flux wrapped on a 1-cycle of the torus

- Quite generally, fluxes ‘live’ on cycles of the compact space
- Example: several 1-cycles in 2d space



- Crucial: Higher-dimensional cycles (with fluxes) exist in higher-dimensional spaces
- Example: a 2-cycle in T^3



The string theory landscape

- Typcial CYs have $\mathcal{O}(300)$ 3-cycles
- Each can carry some integer number of flux of $F_{\mu\nu\rho}$, $H_{\mu\nu\rho}$
- With, for example, $N_{flux} \in \{-10, \ldots, 10\}$ on gets

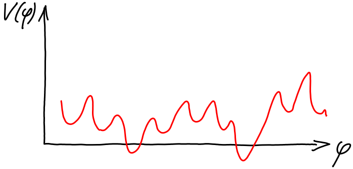
$$(2 \times 20)^{300} \;\sim\; 10^{500} \text{ possibilities}$$

- This is the string theory landscape!
- To appreciate the complexity, recall that there are only $\sim 10^{80}$ atoms in our universe

The string theory landscape (continued)

- Each of these geometries corresponds to a solution ('vacuum') of the same, unique fundamental theory

- Each solution has a different vacuum energy

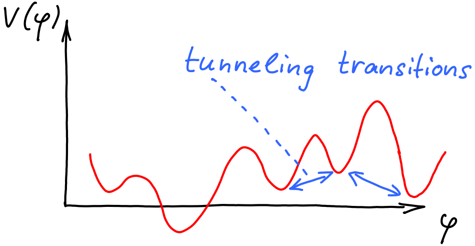


Here φ corresponds to $\{\varphi_1, \ldots, \varphi_n\}$, parametrizing the shape of the CY

Weinberg '87
Bousso/Polchinski '00
Giddings/Kachru/Polchinski '01 (GKP)
Kachru/Kallosh/Linde/Trivedi '03 (KKLT)
Denef/Douglas '04

Populating the landscape

- Any vacuum with $\Lambda > 0$ gives classically an eternally expanding (de Sitter) universe
- However, by a quantum fluctuation, a bubble of a different vacuum can form, which then also expands
- .... just like bubble nucleation in first order phase transitions



Bubbles within bubbles within bubbles ....

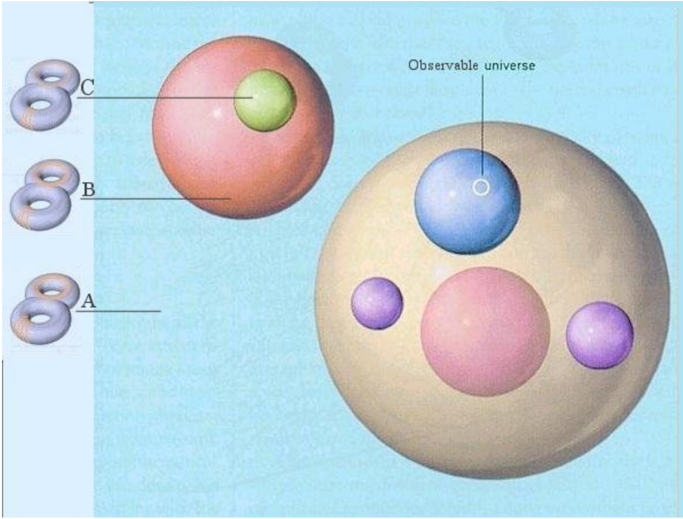
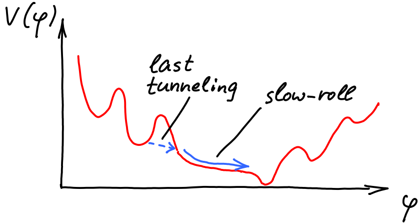


image from "universe-review.ca"

Slow-roll inflation in the landscape

- To make our universe flat, we need a period of slow-roll inflation after the last tunneling event
  (...as we also argued initially purely in fiel theory)



- This last period of slow-roll inflation is what we observe on the CMB-sky (Cosmic Microwave Background)

  (quantum fluctuations of φ transform into density perturbations transform into temperature fluctuations)

Mukhanov/Chibisov '81

Slow-roll inflation in the string theory landscape

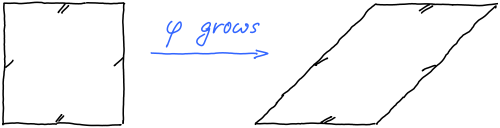
- As explained earlier, the flat piece could be short and very flat or generic, but long ($\Delta\varphi \gg 1$)

- Only this last option describes 'primordial gravity waves' as recently 'suggested' (???) by BICEP

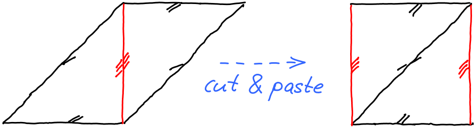
- As we will now see, this feature of '$\Delta\varphi \gg 1$' is extremely hard to get in string theory (chance of ruling our the landscape?)

Why is $\Delta\varphi \gg 1$ problematic?

- The field φ generically corresponds to some geometric feature of the CY, e.g. the shape of a torus

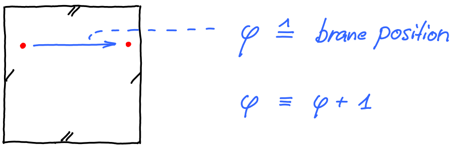


- However, after the angle of a torus has grown to 45°, it is secretly the same torus



- The problem is that this applies (more or less) to all 4d fields of a string compactification
- Another, even more obvious example arises if φ is a brane position. Clearly, this field is also periodic and the field space is hence limited:

Dvali/Tye '98



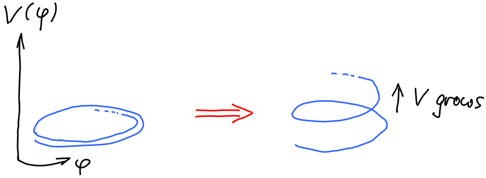
- One needs a new idea!

Monodromy inflation

- One relatively recent such idea is to introduce a monodromy

  Silverstein/Westphal '08

- A monodromy is a change in the potential, weakly breaking the periodicity in φ



- Various concrete realizations have been discussed, especially since BICEP

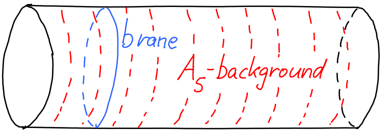
  see e.g. Palti/Weigand '14
  Hassler/Lüst/Massai '14

  (An alternative but related proposal is that of **'Kim/Nilles/Peloso-type models'**, not to be discussed here)

  see e.g. Grimm '14

Monodromy inflation - early models

- I will only explain a toy-model analogy to early constructions
- Let the periodic field be a Wilson line: $\varphi = \int A_5$
- The potential is exactly flat as a result of gauge symmetry, $A_5 \to A_5 + \partial_5 \chi$
- Flatness is broken by the presence of a brain, in the action of which A_5 enters directly (rather than just F_{MN}).



- Note: Actually, one uses not A_M but a 2-form potential C_{MN}

Monodromy inflation - early models

- One needs anti-branes, complicated non-Calabi-Yau geometries...

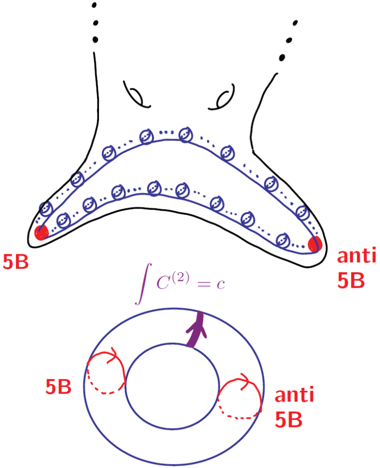


figure from McAllister/Silverstein/Westphal '08

F-term axion inflation

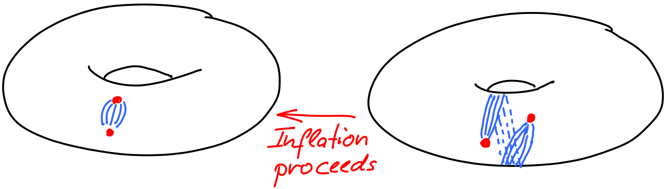
- Very recently, the first suggestions have emerged how this could be realized in a quantitatively controlled way

  (i.e. in a 4d supergravity description, with a stabilized compact space)

  Marchesano/Shiu/Uranga '14
  Blumenhagen/Plauschinn '14
  AH/Kraus/Witkowski '14

- In particular, in our suggestion inflation corresponds to brane-motion

- The monodromy arises from a flux sourced by the brane



F-term axion inflation (continued)

- The strong point of these constructions is the manifest supergravity description (SUSY is broken only spontaneously, the basic geometry is still approximately Calabi-Yau, explicit calculations are feasible)

- The weak point is the required fine-tuning to make the monodromy-effect weak

- Implementing this fine tuning is subject of an ongoing debate

  Blumenhagen, Herschmann, Plauschinn '14
  AH, Mangat, Rompineve, Witkowski '14

F-term axion inflation (for the 'insiders')

- The Kahler potential is shift-symmetric (and periodic):

$$K = K(\Phi - \overline{\Phi})$$

- This situation arises e.g. in the 'large complex structure limit'
- The flux-induced superpotential breaks this symmetry (induces a monodromy):

$$W = W_0 + a\,\Phi$$

- The challenge is to ensure that a is sufficiently small

Reminder of Outline

- The need for inflation / Inflation in field theory
- Why look for inflation in string theory
- The (flux-) landscape, eternal inflation and the multiverse
- Problems with large-field inflation in string theory
- Axion monodromy - early models and recent progress

'Conclusion'

- Inflation is developing into an interesting, quantitative playground for string theory!

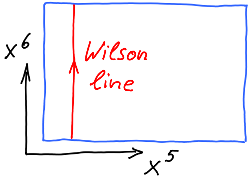
Backup slides:

Next-simplest version:

(For those who know about quantization
of magnetic monopole charges.)

- Consider magnetic monopole in $\mathbb{R}^3$
- For reasons of quantum mechanical consistency, the charge is quantized in units of the electron charge
- In fact, this can be seen focussing only on the field strength on an S^2 surrounding this monople
- The field strength on this S^2 is 'twisted' in analogy to the Moebius strip on the previous slide
- Here, we are dealing with an $F_{\mu\nu}$-flux on a 2-cycle (the S^2)

Next-simplest version, but for $S^2 \rightarrow T^2$



- With $A_6 = \alpha x^5$ we have $F_{56} = \alpha$
- The 'Wilson line' $w = \int dx^6 \, A_6$ induces a phase $\exp(iw)$ of the electron wave function
- In our case $w = w(x^5)$, which is only OK if

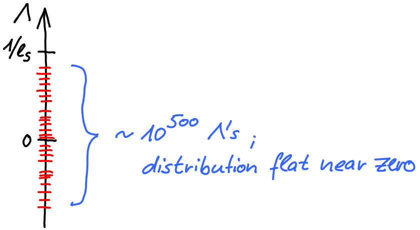
$$w(0) = w(1) + 2\pi N$$

$\Rightarrow$ Flux quantization

The cosmological constant in the landscape

- Crucially, at least for part of the landscape, the statistical distriution of $\Lambda = V(\varphi_{\text{min}})$ can be calculated.

  It is 'flat' in the region near $\Lambda = 0$

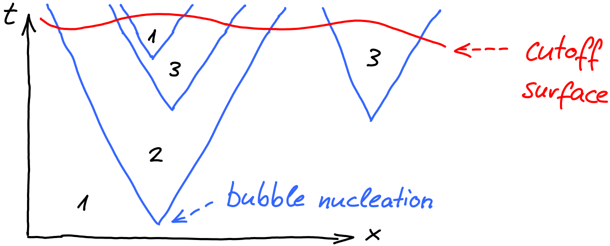


- Thus, while having $\Lambda \sim 10^{-120}$ (as is measured) is extremely unlikely, it is known that such vacua do exist

- One can appeal to anthropic arguments to explain why we find ourselves in such an 'rare' vacuum

Bubbles within bubbles within bubbles ....

- More scientific but less pretty: A cartoon of eternal inflation in 2 dimensions



- The arbitrariness of the 'cutoff surface' is one of the faces of the measure problem – we don't know how to count and thus how to make even just statistical predictions