Axion Monodromy Inflation

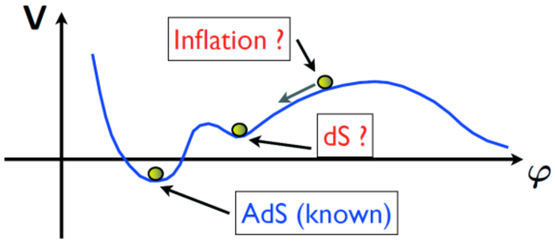
Timm Wrase

IPMU August 6, 2014

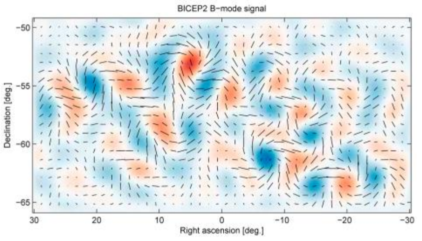
Based on: Liam McAllister, Eva Silverstein, Alexander Westphal, TW 1405.3652

Outline

- Why string cosmology



- Axion monodromy inflation:



  - BICEP2 as motivation
  - New constructions in string theory

- Conclusion

Why string cosmology?

There are (at least) three reasons:

1. Extrapolating backwards in time using GR we hit a singularity

2. The cosmological constant in the current universe seems to be very small and non-zero

3. Inflation is UV sensitive

Why string cosmology?

1. **Extrapolating backwards in time using GR we hit a singularity**

- String theory is a UV complete theory of quantum gravity
- We know how string theory can resolve time-like singularities
- The cosmic singularity is much more complicated

see for example H. Liu, G. Moore and N. Seiberg arxiv:gr-qc/0301001

$\Longrightarrow$ long term goal

Why string cosmology?

2. **The cosmological constant in the current universe seems to be very small and non-zero**

- Compactifications of string theory give rise to dS vacua

KKLT, LVS, …

- There seem to be so many string vacua (10^{500}) that a very small cosmological constant (as observed in our universe) can plausible arise $\Longrightarrow$ landscape

- Our understanding of dS vacua is still very basic

$=$ work in progress

Why string cosmology?

3. Inflation is UV sensitive

- The energy scale of inflation is below the Planck scale, so that we can use GR + QFT (bottom-up)

- However, higher dimensional operators lead to the eta-problem

$$V(\phi_0) = V_0\left(1 + \sum_{n\geq 1} c_n \left(\frac{\phi - \phi_0}{M_{pl}}\right)^n\right) \quad \Rightarrow \quad \eta = M_{pl}^2 \frac{V''}{V} = \sum_{n\geq 2} n(n-1)\, c_n \left(\frac{\phi - \phi_0}{M_{pl}}\right)^{n-2}$$

- If ϕ-$\phi_0 \ll M_{pl}$ then we need to control c_2

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- If ϕ-$\phi_0 \geq M_{pl}$ then we need to control **all c_n**

Why string cosmology?

- The size of these higher dimensional operators can often be checked in string theory models of inflation
- String theory might tell us what is (and is not) possible in a theory of quantum gravity
- String theory compactifications can lead to new ideas for inflationary models

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$\Longrightarrow$ Bottom-up (QFT+GR) and top-down (string theory) approaches complement each other

Goals of string cosmology

Description of the early universe cosmology in a UV complete theory of quantum gravity

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Description of the early universe cosmology in a UV complete theory of quantum gravity

Not a simple task:

- String theory has several extra dimensions that we need to compactify
- The simplest compactifications give rise to 4D theories with many massless scalar fields ϕ^I

$\Longrightarrow$ Moduli Problem

Goals of string cosmology

Description of the early universe cosmology in a UV complete theory of quantum gravity

Not a simple task:

- We can generate a potential for these scalar fields
- However, to describe our universe we need: $V\left(\phi^I\right)\Big|_{\min} \approx 10^{-120} M_{Pl}^4$ but m_{ϕ^I} much larger, a period of inflation ending in this dS vacuum, a reheating mechanism, a standard model sector, dark matter ....

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Currently too complicated!

Goals of string cosmology

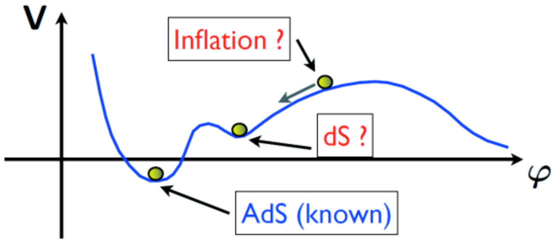
Description of the early universe cosmology in a UV complete theory of quantum gravity

Break the problem down into pieces:

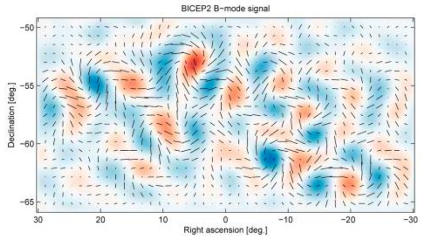
- Try to generate a potential that allows for a period of inflation that ends in a dS vacuum
- In explicit models it is often possible to do more (like discussing a reheating mechanism or adding an SM sector)

Outline

- Why string cosmology



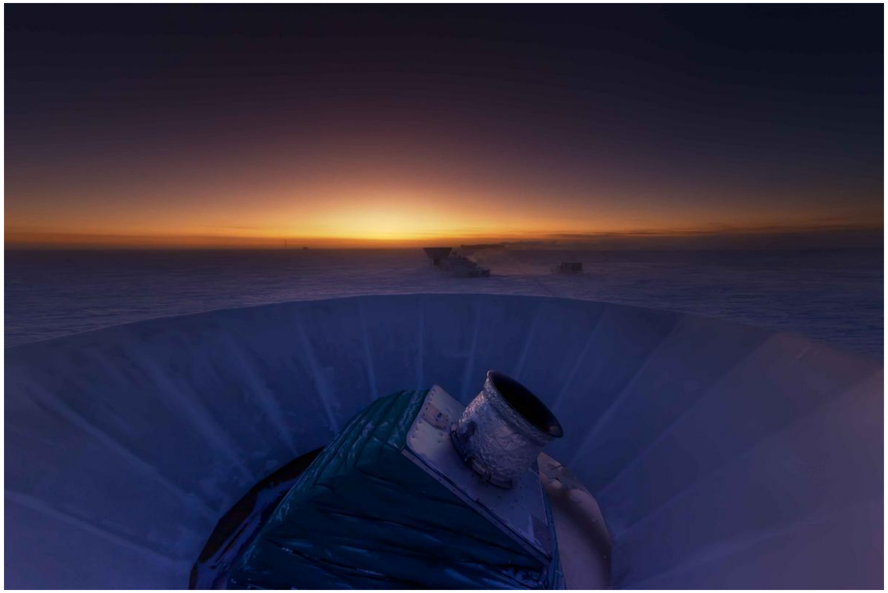
- **Axion monodromy inflation:**
  - BICEP2 as motivation
  - New constructions in string theory



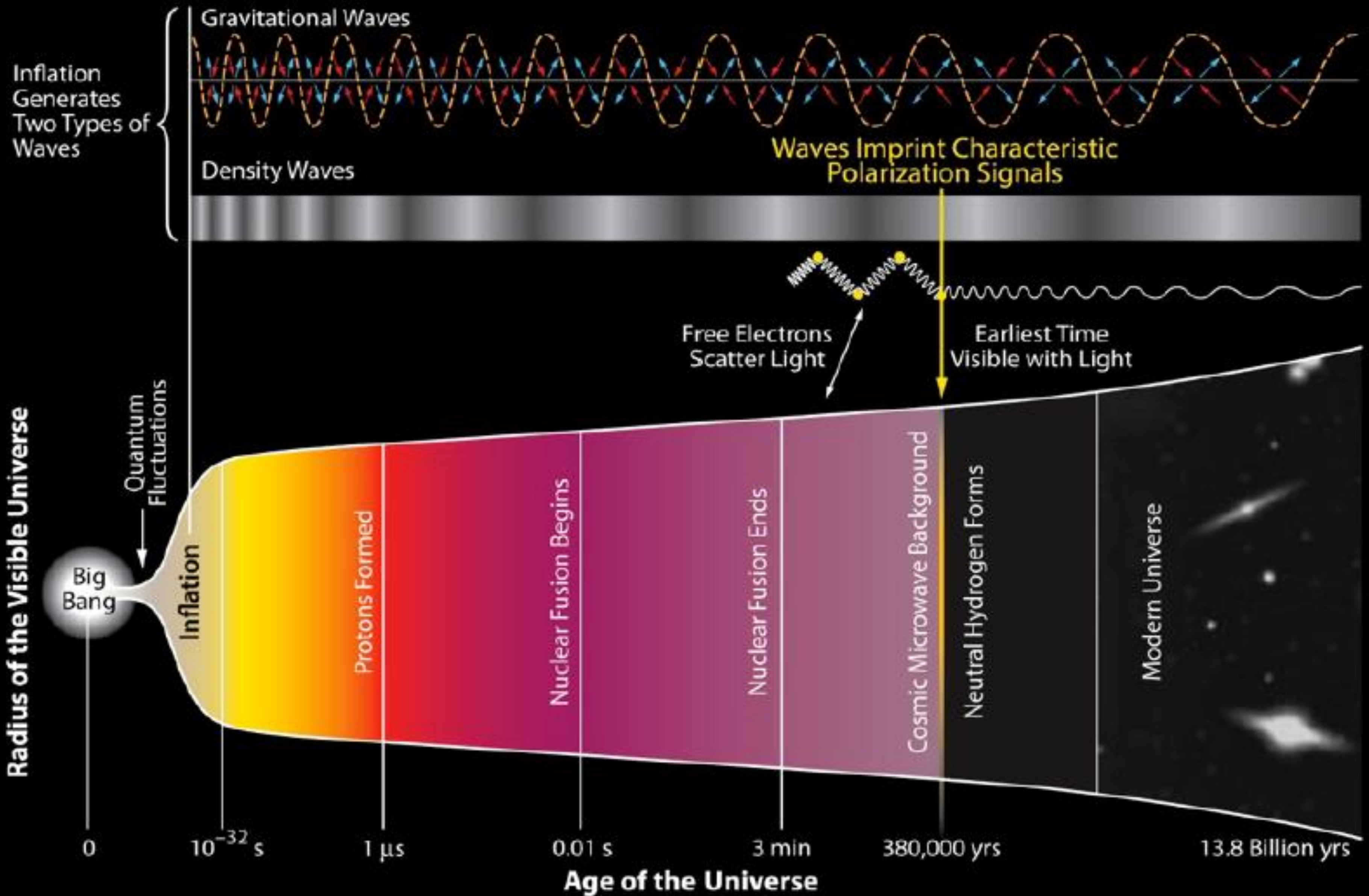
- Conclusion

BICEP2 result

A small telescope at the south pole with the primary goal of measuring the very faint polarization of the cosmic microwave background (CMB).

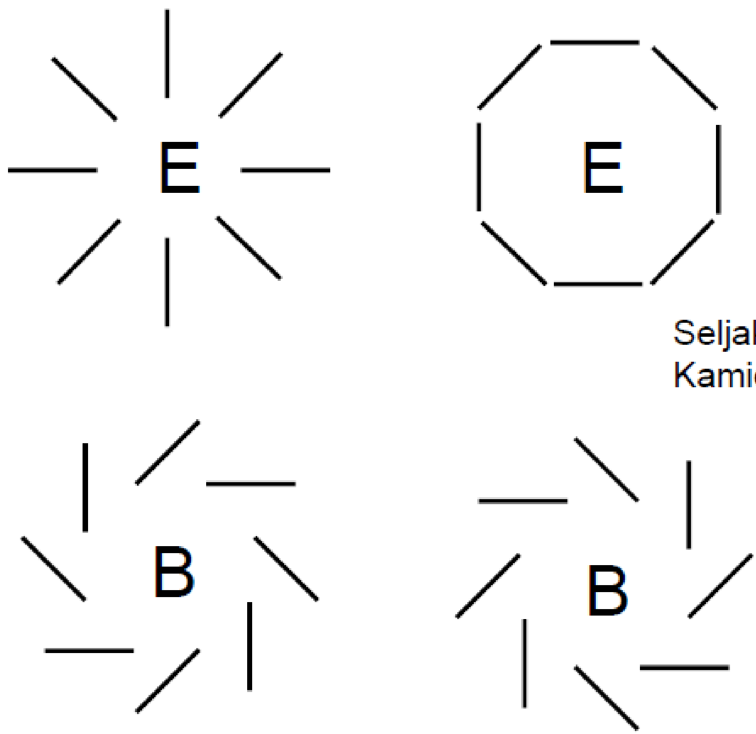


History of the Universe



BICEP2 result

Only gravitational waves can generate B-modes in the CMB



curl-free

Seljak & Zaldarriaga '97
Kamionkowski, Kosowsky, Stebbins '97

div-free

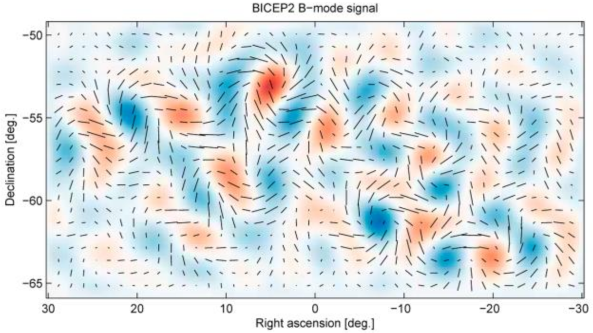
BICEP2 result

March 2014 data release after *three long nights*: 2010-2012

BICEP2 I: Detection Of B-mode Polarization at Degree Angular Scales

Abstract:

- We find an excess of B-mode power over the base lensed-LCDM expectation in the range 30<l<150, inconsistent with the null hypothesis at a significance of >5σ.
- The observed B-mode power spectrum is well-fit by a lensed-LCDM + tensor theoretical model with tensor/scalar ratio r=0.20+0.07−0.05, with r=0 disfavored at 7.0σ.



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Primordial B-modes can tell us the energy scale of inflation:

$$\Delta_t^2 \approx \frac{2}{3\pi^2}\frac{V}{M_{Pl}^4}$$

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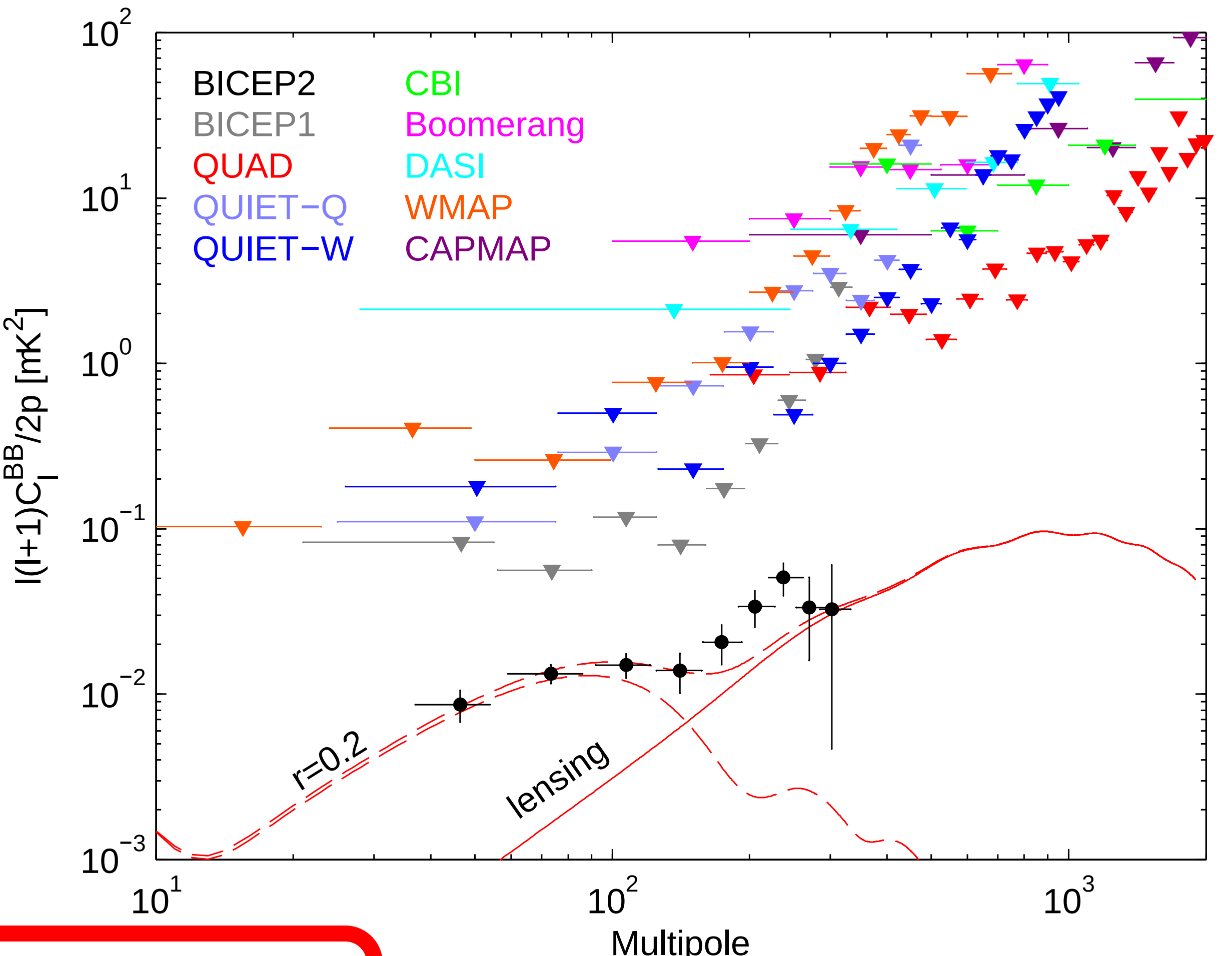
$$r = \frac{\Delta_t^2}{\Delta_s^2} = .2 \quad \Rightarrow \quad \left(V_{\inf}\right)^{1/4} \approx 2\times10^{16}\,\mathrm{GeV}\left(\frac{r}{0.1}\right)^{\frac{1}{4}} \approx 2\times10^{16}\,\mathrm{GeV}$$


“Can you say it again?”

BICEP2 result



$$(V_{\inf})^{1/4} \approx 2\times10^{16}\,GeV$$

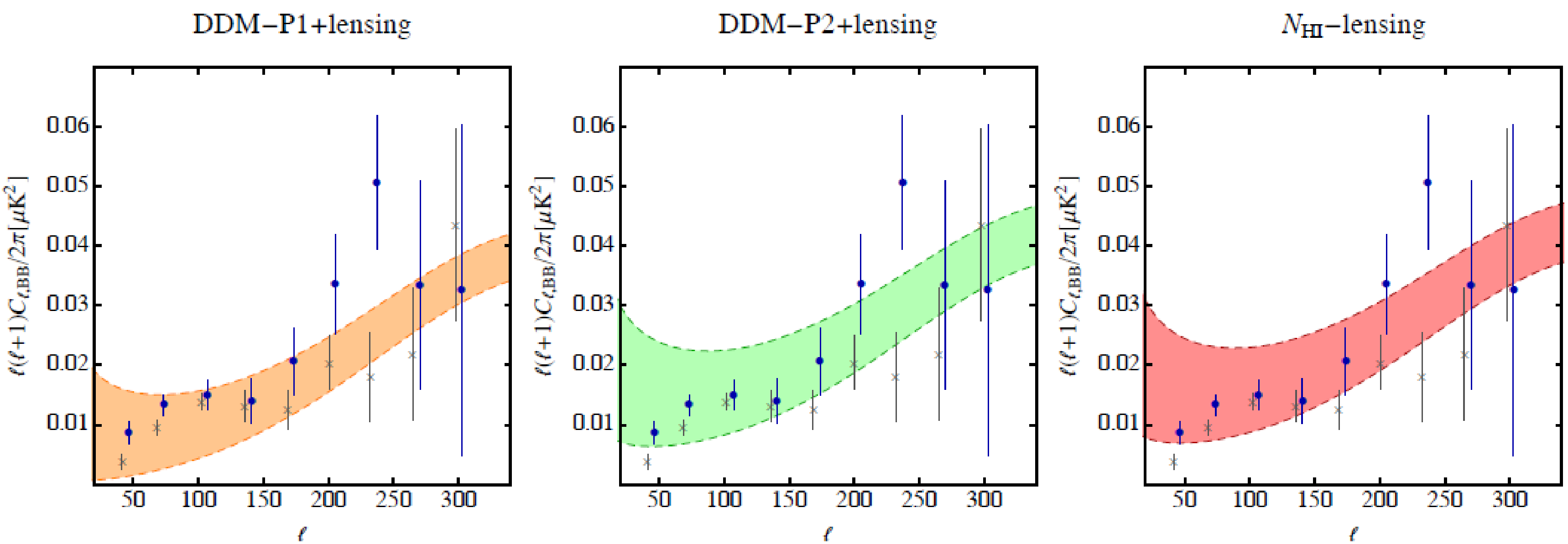
12 orders of magnitude larger than LHC!!!!

BICEP2 result

Alan Guth and Andrei Linde are very happy!!!

BICEP2 result

A word of caution: Flauger, Hill, Spergel 1405.7351



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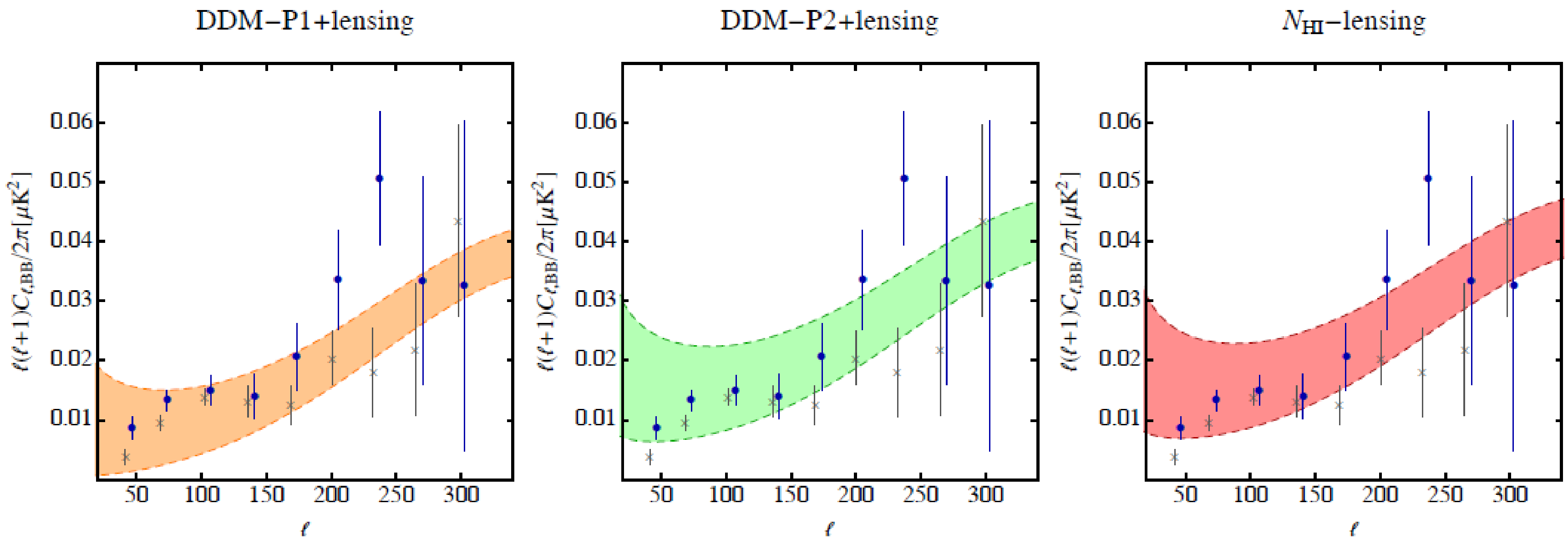
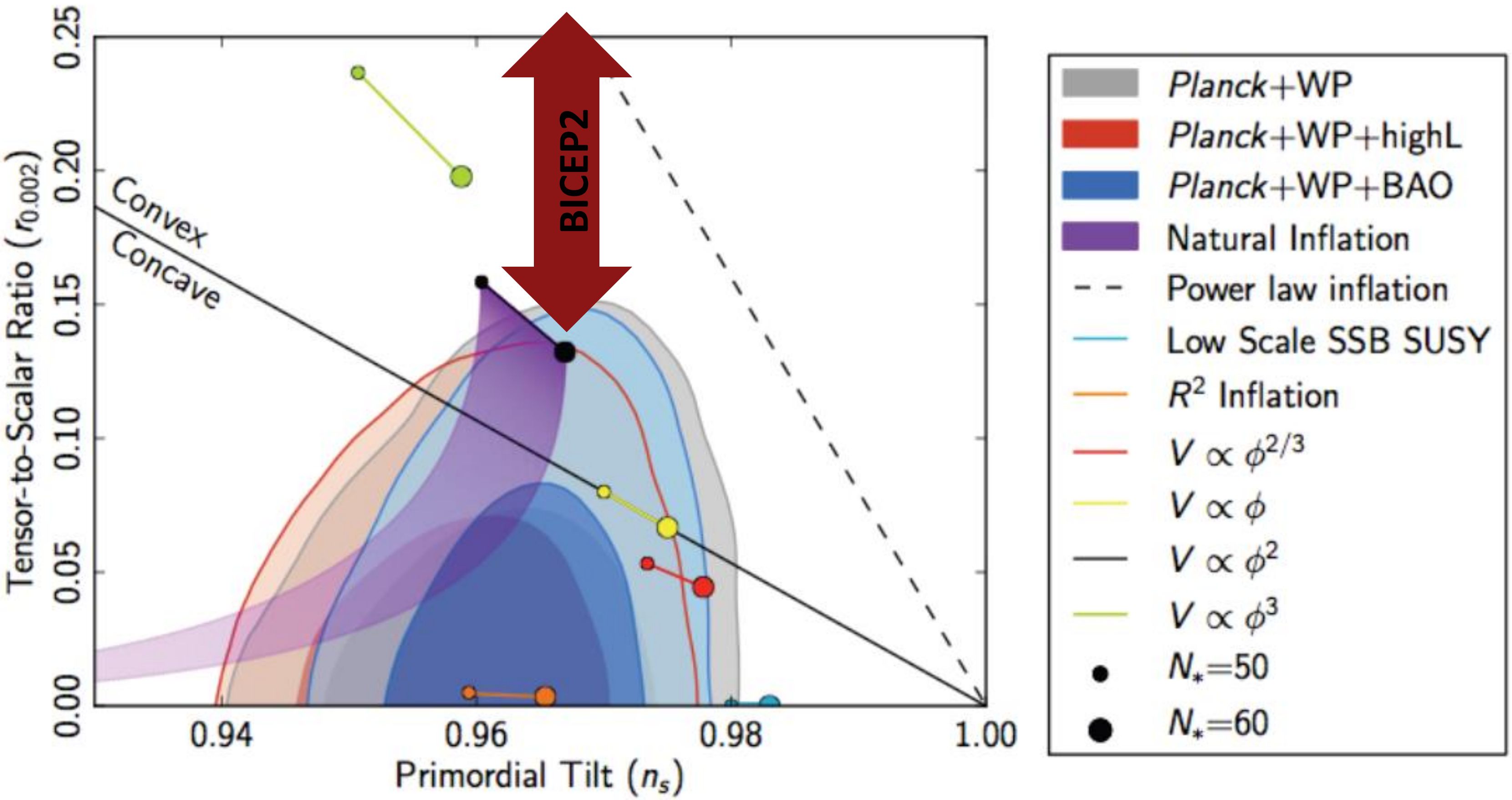


We have to wait for Planck

(and probably many more experiments)

BICEP2 result

Simple potentials favored: $V(\phi) = \phi^p,\ p \leq 4$



Lyth bound

David Lyth hep-ph/9606387:

A large value of the scalar to tensor ratio leads to large field range, so called large-field inflation:

$$\frac{\Delta\phi}{M_{Pl}} \geq 2\sqrt{\frac{r}{.01}} \approx 10$$

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How can we trust a low energy expansion?

$$V(\phi) = V(\phi_0)\left(1 + \sum_{n\geq 1} c_n \left(\frac{\phi - \phi_0}{M_{Pl}}\right)^n\right)$$

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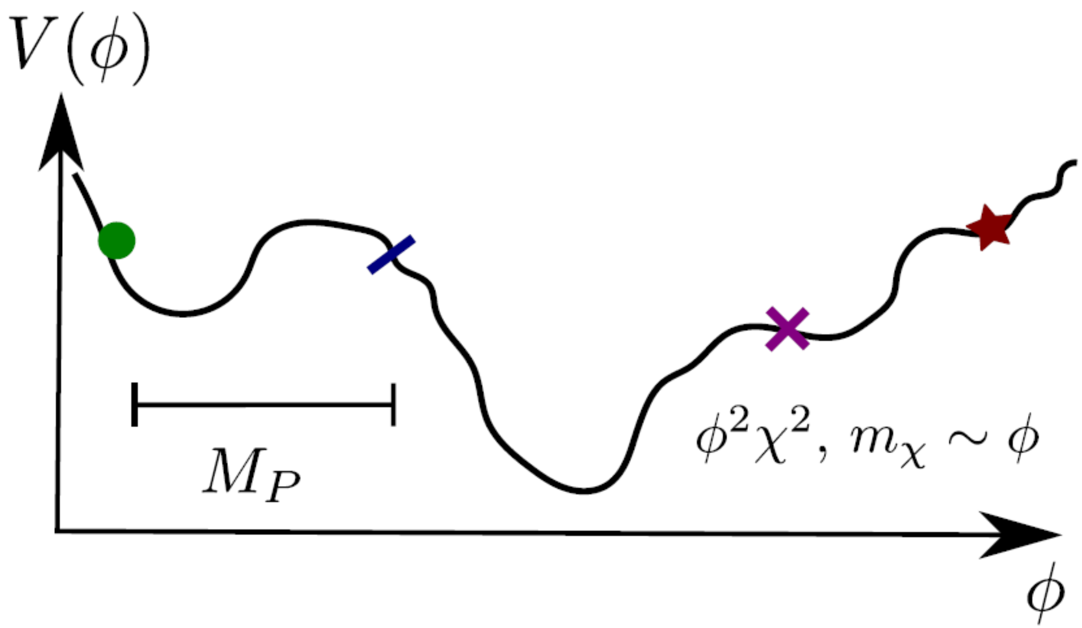
$\Longrightarrow$ String theory very useful

Axion monodromy inflation

Having a UV complete theory of quantum gravity seems very useful, but this is not enough:

Usually we expect to have new features in the potential whenever we move by one Planck distance



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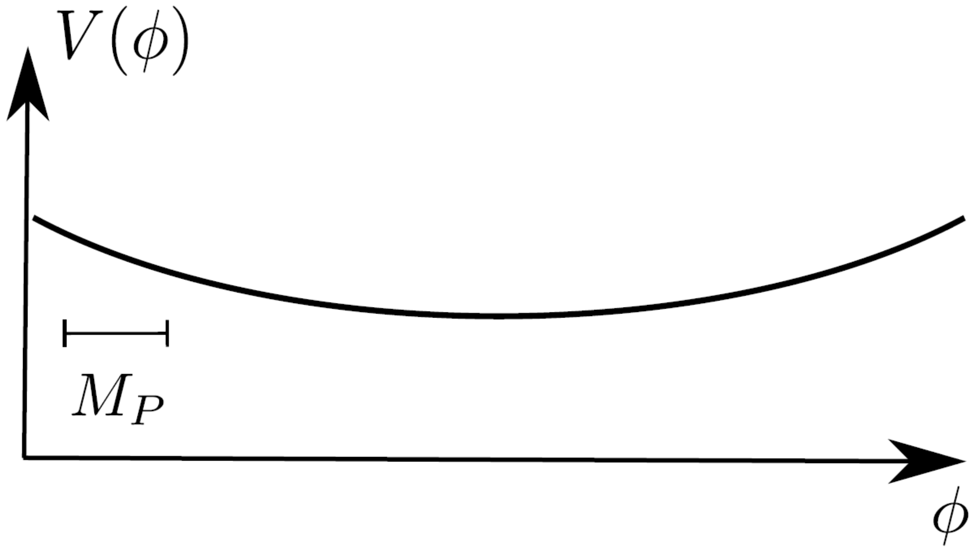
For inflation we need



Axion monodromy inflation

- String compactification usually have 100-1000 scalar fields
- We want to move one field over 10 Planck distances without disturbing the other fields (too much)
- The best approach seems to use a field with a (broken) shift symmetry as inflaton

Axion monodromy inflation

- In string compactification we find many axion fields

- These axion fields have only derivative couplings in the 4D effective theory

$$S = \int d^4x \, \partial_\mu a \cdot (\ldots)^\mu$$

- This leads to a shift symmetry for these axion fields

$$a \to a + c, \quad c \in \mathbb{R}$$

Axion monodromy inflation

Side note:

Usual lore:

There are no continuous global symmetries
in a theory of quantum gravity

Axion monodromy inflation

Side note:

Usual lore:

There are no continuous global symmetries

in a theory of quantum gravity

- This seems to be true in string theory
- The continuous shift symmetry of axions is broken by non-perturbative effects to a discrete symmetry

$$a \to a + f_a n, \quad n \in \mathrm{Z}$$

The discrete shift symmetry still forbids many corrections!

Axion monodromy inflation

Side note:

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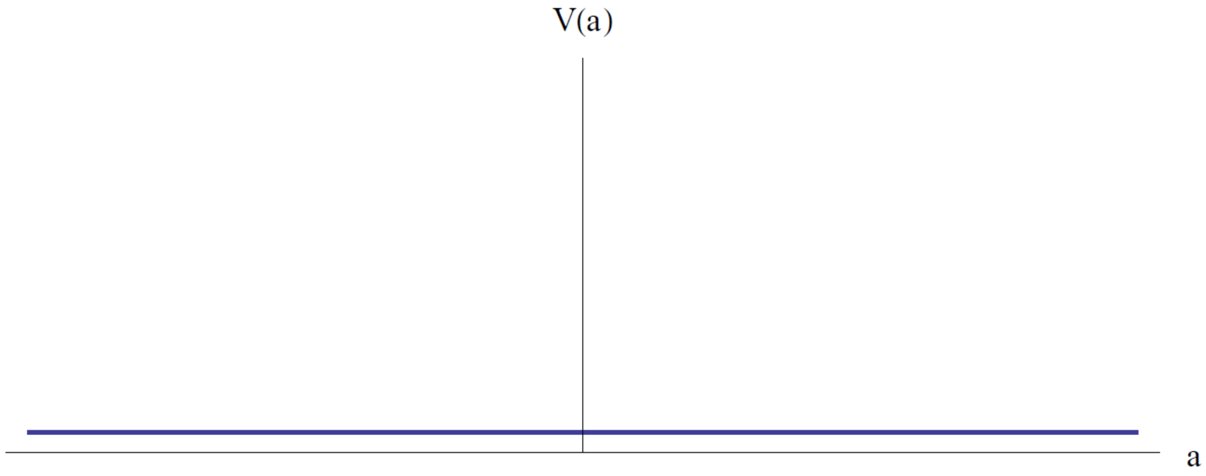
A continuous shift symmetry:



Axion monodromy inflation

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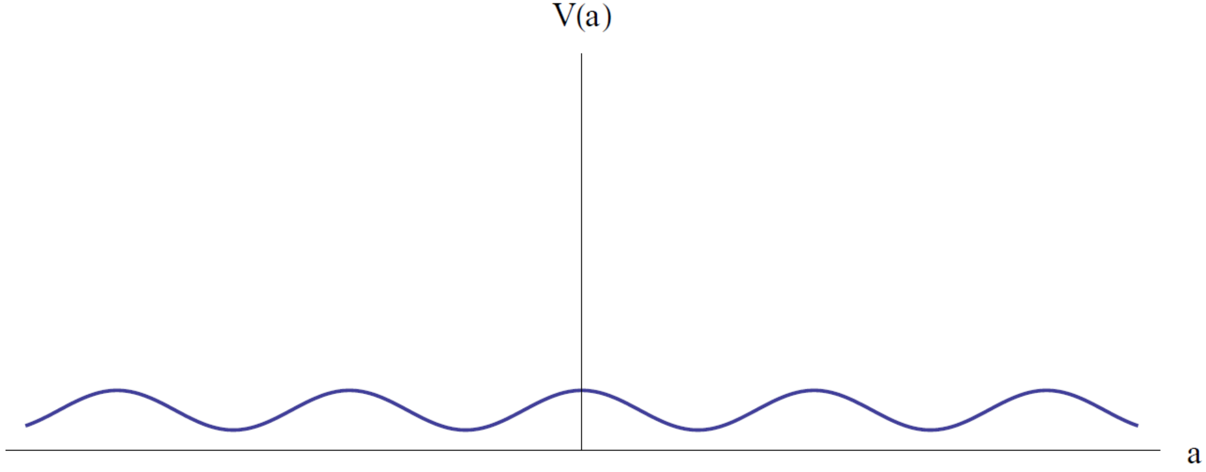

Axion monodromy inflation

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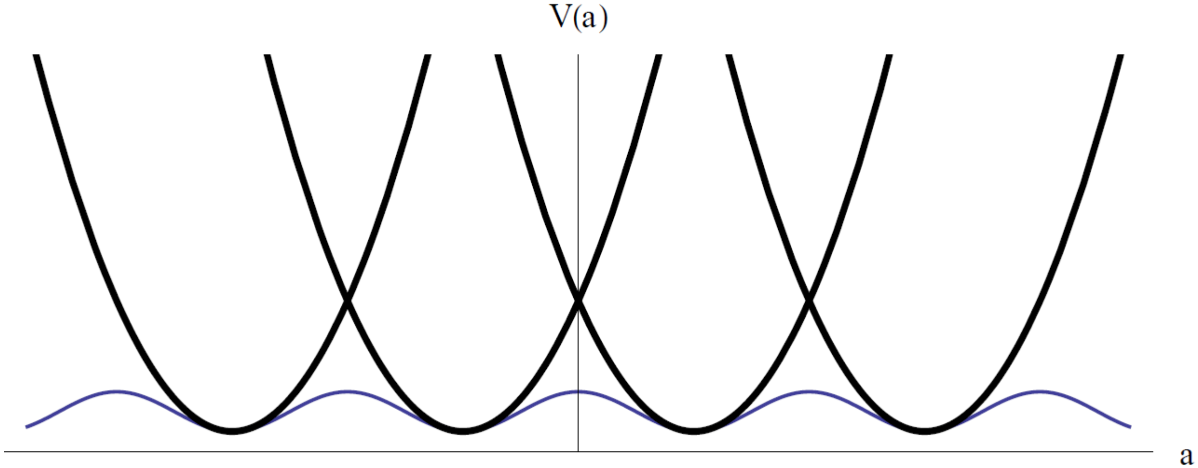
The axion potential after breaking the symmetry:



Axion monodromy inflation

Liam McAllister, Eva Silverstein, Alexander Westphal, TW   1405.3652

- String theory has higher dimensional generalizations of gauge fields: B_2 and C_p

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- String theory has higher dimensional generalizations of gauge fields: B_2 and C_p
- Their gauge invariance gives rise to the shift symmetry of the 4D axions after compactification

E&M: $A_M(X^M)dX^M = A_\mu(x^\mu)dx^\mu + a(x^\mu)dy + \ldots, \quad a(x^\mu) = A_y(x^\mu)$

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$$A(X^M) \to A(X^M) + d(c \cdot y) = A(X^M) + c\,dy$$

$$\Rightarrow \quad a(x^\mu) = a(x^\mu) + c, \quad c \in \mathbb{R}$$

Axion monodromy inflation

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Axion monodromy inflation

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- String theory has higher dimensional generalizations of gauge fields: B_2 and C_p
- Their gauge invariance gives rise to the shift symmetry of the 4D axions after compactification
- In compactifications of critical string theory half of the light fields are axions
- Turning on background fluxes in the internal dimension breaks this shift symmetry and generates a polynomial potential for the axions

Axion monodromy inflation

- We focus on compactification of the 10D type IIA/B string theory and axions arising from B_2
- The 10D low energy action contains terms of the form

$$S = -\frac{1}{\alpha'^4} \int_M d^{10}x \sqrt{-G} \left\{ \frac{1}{g_s^2} \left| dB_2 \right|^2 + \sum_p \left| \tilde{F}_p \right|^2 \right\}$$

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- For type IIA with $F_0 = Q_0$ or type IIB with $F_1 = Q_0$ we find

$$S = -\frac{1}{\alpha'^4}\int_M d^{10}x\sqrt{-G}\left\{\frac{1}{g_s^2}\left|dB_2\right|^2 + \left|Q_0 B_2\right|^2 + \left|Q_0 B_2 B_2\right|^2 + \ldots\right\}$$

$$\tilde{F}_3 = dC_2 + F_1 B_2 \qquad \tilde{F}_5 = dC_4 + F_1 B_2 + \frac{1}{2}F_1 B_2 B_2$$

Axion monodromy inflation

- Upon reduction to 4D, B will give rise to an axion

Potential: $V(b) = c_0 + c_2\, b^2 + c_4\, b^4$

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Kinetic term
for axion *b*

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- What about Planck suppressed operators?
- We turn on $\left|\tilde{F}\right|^2 \supset \left|Q_0 B_2 B_2\right|^2$. What about $\left|\tilde{F}\right|^4 \supset \left|Q_0 B_2 B_2\right|^4$?
- Can we break the shift symmetry by only turning on the operator $\left|\tilde{F}\right|^2 \supset \left|Q_0 B_2 B_2\right|^2$?

Axion monodromy inflation

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- Can we break the shift symmetry by only turning on the operator $\left|\tilde{F}\right|^2 \supset \left|Q_0 B_2 B_2\right|^2$? NO!

Axion monodromy inflation

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- What about Planck suppressed operators?
- In this setup all the operators $\left|\tilde{F}\right|^{2n} \supset \left|Q_0 B_2 B_2\right|^{2n}$ appear, but they are all suppressed by the string coupling:

$$\ldots \supset g_s^{\;2(n-1)}\left|\tilde{F}\right|^{2n} \supset g_s^{\;2(n-1)}\left|Q_0 B_2 B_2\right|^{2n} << \left|Q_0 B_2 B_2\right|^2 \quad \text{for } \; g_s << 1$$

Axion monodromy inflation

- We see that in string compactifications axions arise naturally with a variety of exponents
- We can suppress the infinite number of dangerous irrelevant operators
- Can we build explicit models in which these axions serve as inflaton?

Axion monodromy inflation

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- Can we build explicit models in which these axions serve as inflaton?

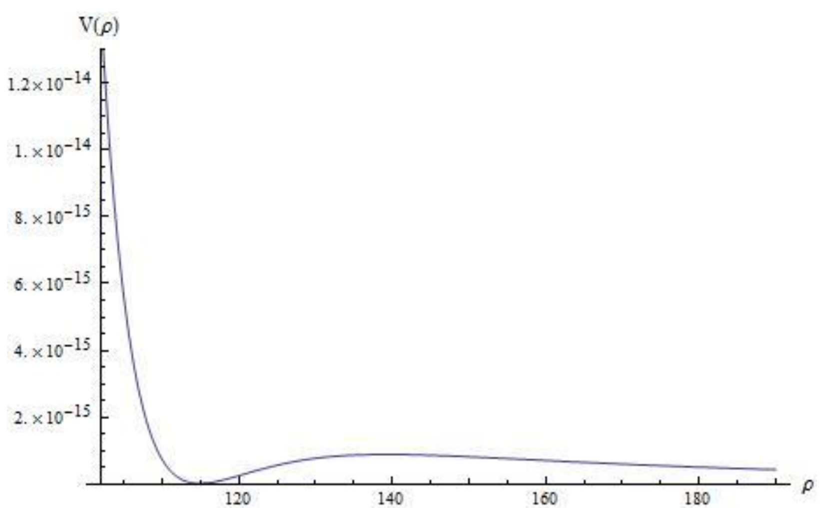
1. This requires us to stabilize all moduli in a dS vacuum
2. Then we have to ensure that moving the B-axion a lot does not destabilize our construction

Axion monodromy inflation

Stabilizing all fields in a dS vacuum:

- A variety of constructions exist like KKLT, LVS etc.
- Most of these use perturbative and non-perturbative ingredients

$\Longrightarrow$ Generically small barriers towards a runaway direction



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- String theory has 10D flat Minkowski space as its solution so all dS vacua are metastable but barriers can be high

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- A variety of constructions exist like KKLT, LVS etc.
- Most of these use perturbative and non-perturbative ingredients

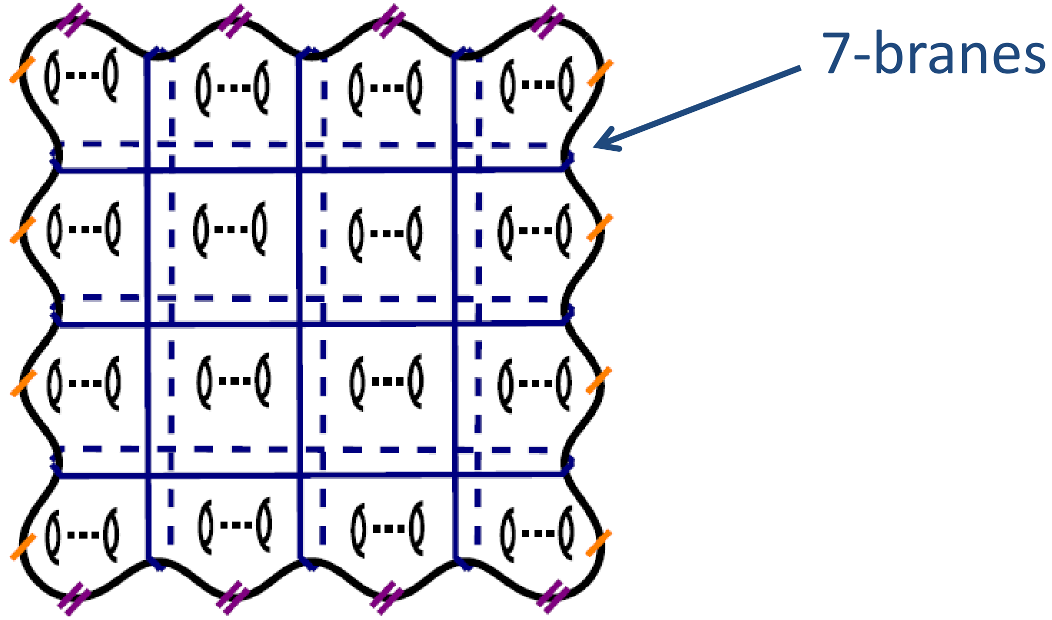
$\Longrightarrow$ Generically small barriers towards a runaway direction

- We use the dS vacua construction of Saltman and Silverstein hep-th/0411271 that breaks supersymmetry at the compactification scale and has high barriers

Axion monodromy inflation

We compactify type IIB string theory on the product of three Riemann surfaces $\Sigma_1 x \Sigma_2 x \Sigma_3$ and add 7-branes and fluxes

Σ_i:



Axion monodromy inflation

- In four dimensions this leads to a slightly complicated potential $V(\phi^I)$

- We can usually not keep all other fields fixed at their minimum value while the axion moves over many Planck distance

$\Longrightarrow$ Flattening of the potential

Axion monodromy inflation

flux quanta (can be chosen)

Example:

$$V \sim M_{pl}^{4} \frac{g_s^4}{L^{12}} \left(\frac{Q_1^2}{u^3} + \frac{Q_2^2}{L^4} u\, b^4 + Q_3^2 u^3 \right)$$

one extra scalar field

axion = inflaton

Axion monodromy inflation

<u>Example:</u>

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$$\Longrightarrow \quad u = \frac{3^{1/4} L}{b} \sqrt{\frac{Q_1}{Q_2}} \propto \frac{1}{b}$$

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Flattening: $V \propto b^4 \quad \rightarrow \quad V \propto b^3$

Axion monodromy inflation

Generic feature in our models:

- One or more fields adjust their value during inflation and thereby flatten the scalar potential

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- Other nice ideas with fractional power:
  - F. Takahashi 1006.2801
  - K. Harigaya, M. Ibe, K. Schmitz, T. T. Yanagida 1211.6241, 1403.4536, 1407.3084

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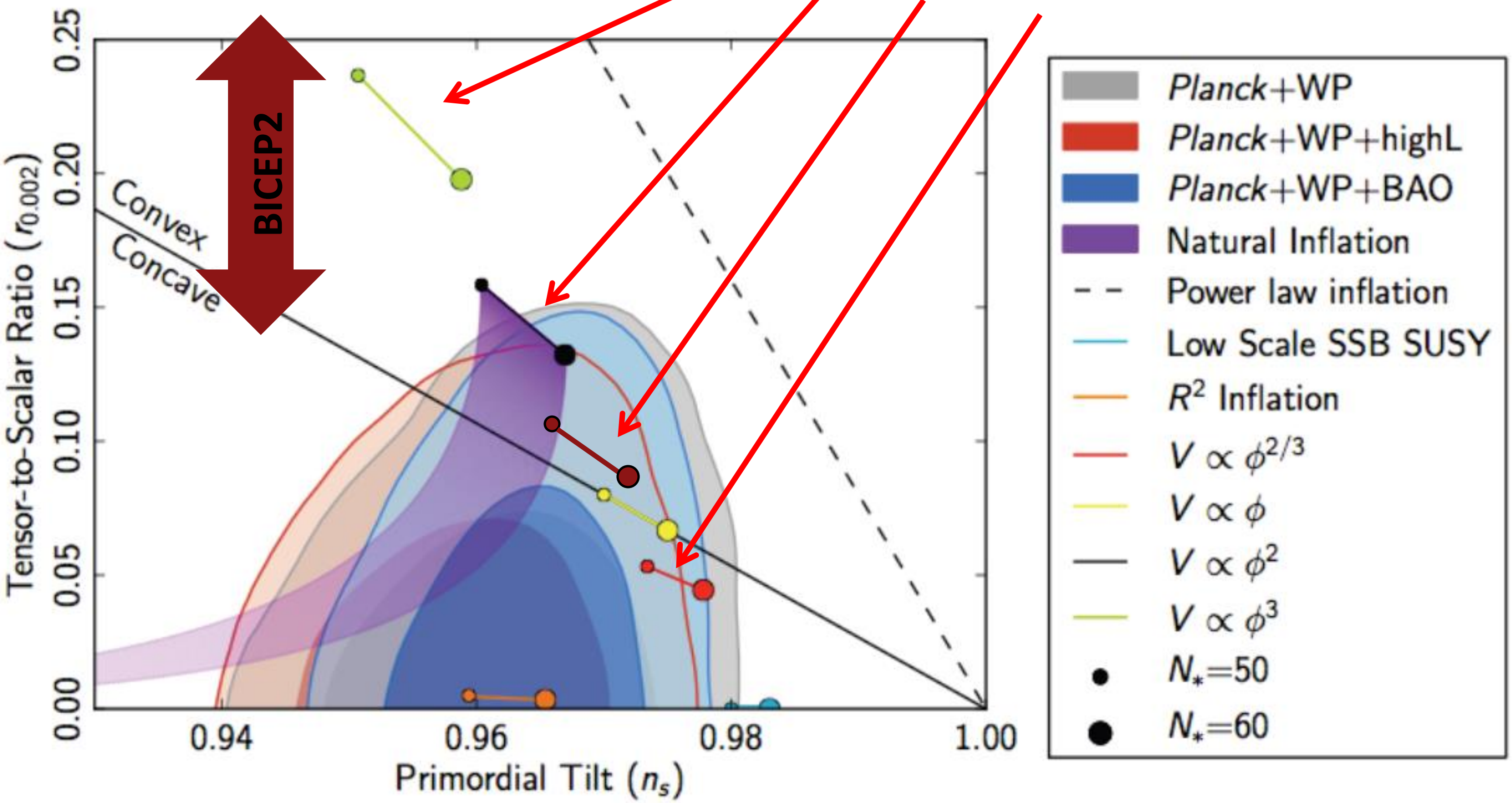
- There is some freedom in choosing fluxes to control the flattening
- We find p = 3, 2, 4/3, 2/3 (previously only $p \leq 2$)

Axion monodromy inflation

We find $V(\phi) = \phi^p, \ p \approx 3, 2, \frac{4}{3}, \frac{2}{3}$



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We will be able to distinguish between these different models!

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  - we have an unprecedented window on quantum gravity!
- We are in the golden era of (string) cosmology, in which our models are confronted with ever improving data

THANK YOU!