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CSIC
CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

erc European Research Council
SPLE Advanced Grant

D6-branes and axion monodromy inflation

Based on:
D. Escobar, A.L., F. Marchesano, D. Regalado
[1505.07871] and [1511.XXXXX]

IV Postgraduate Meeting, Madrid
November, 19th

Aitor Landete

Overview

- Introduction
  - Inflation
  - String Theory
  - String Theory & Inflation
- Inflation from D-branes
  - Setup of our model
  - Moduli stabilization
  - Masses analysis
- Results
  - Single-field inflation scenario
  - Consistency with Planck bounds

Pointing in what field I am working on

Presenting my model… a little bit technical (you can sleep here)

Wake up! After all the details we see that our model is correct after all.

Motivation

Big Bang Theory

the BIG BANG THEORY

Based on

- General Relativity
- Universe Expansion
- Light element abundance
- Cosmic Microwave Background

Problems

- Horizon Problem
- Flatness Problem
- Origin of Universe structure
- Origin of Matter and Radiation

**Our whole Universe was in a hot dense state,
Then nearly fourteen billion years ago
expansion started, wait…**

Motivation

Inflation

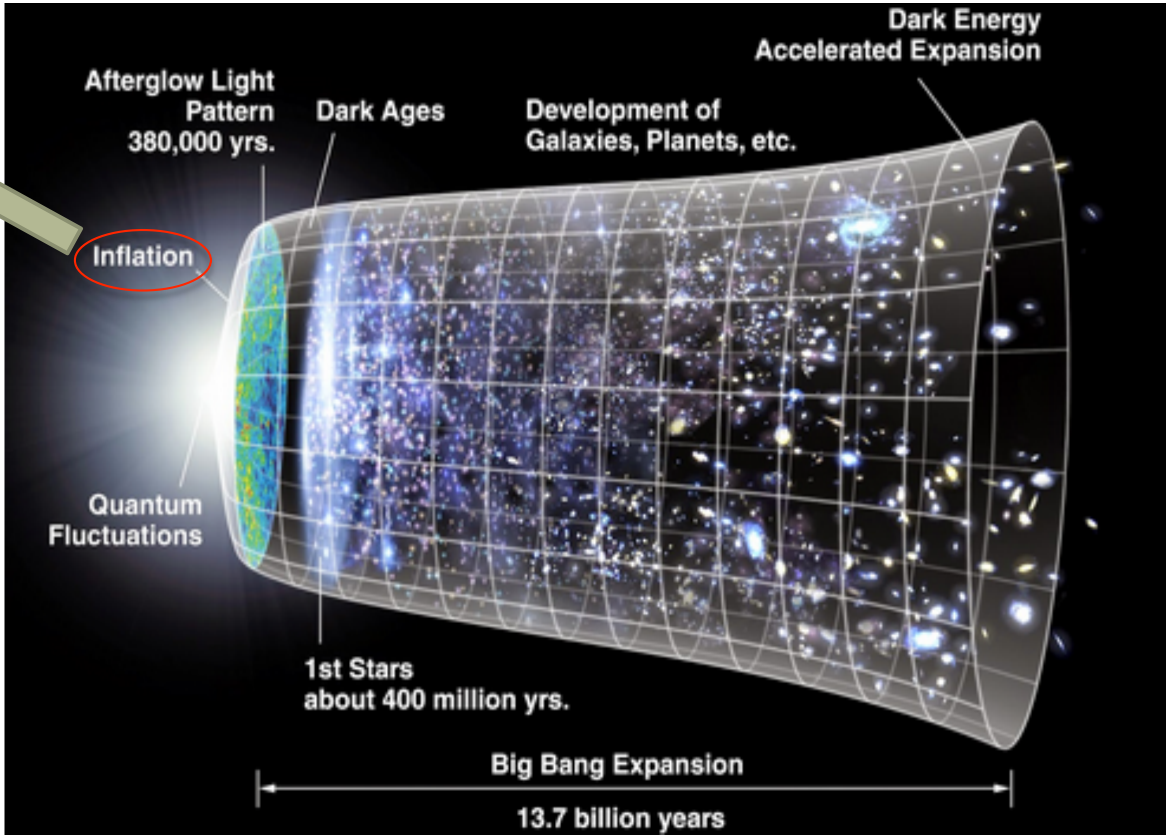
Exponential accelerated period of the universe due to a vacuum constant (scalar field inflation)

Proposed by

Alan Guth

Andrei Linde

Alexei Starobinsky



Inflation

Models

- As a result, trying to solve all the above problems arose lots of different inflationary models

- Power law $$V(\phi) = V_0 e^{-\beta\kappa\phi}$$
- Cahotic $$V(\phi) = \frac{1}{2} m^2 \phi^2$$ $$V(\phi) = \frac{1}{4} \lambda \phi^4$$
- Natural $$V(\phi) = M^2 f^2 \left(1 - \cos\frac{\phi}{f}\right)$$
- Starobinsky $$V(\phi) = \frac{R^2}{12^2 M^2}\left(1 - \frac{R}{2M^2}\right)^{-2}$$
- Hybrid $$V(\phi, \chi) = \frac{\lambda}{4}(\chi^2 - v^2)^2 + \frac{1}{2} g^2 \phi^2 \chi^2 + \frac{1}{2} m^2 \phi^2$$

Inflation

Data & Constraints

- Can we embed all this different theories in string theory?

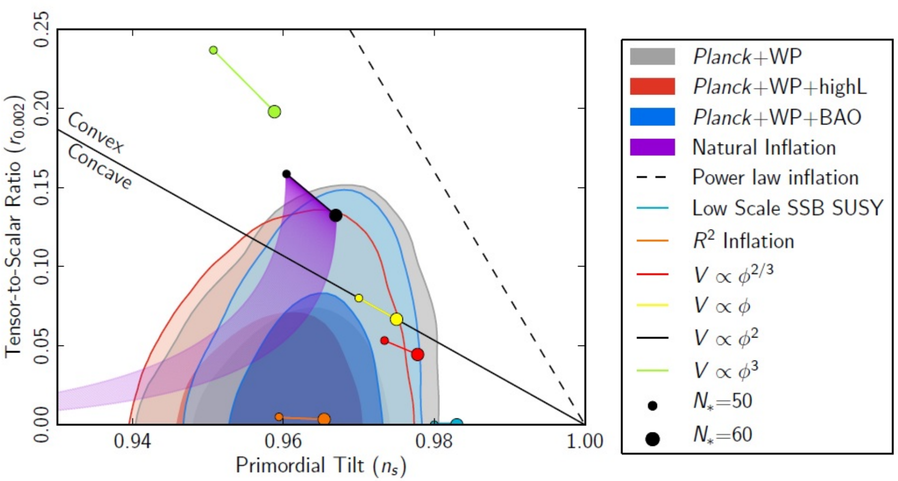
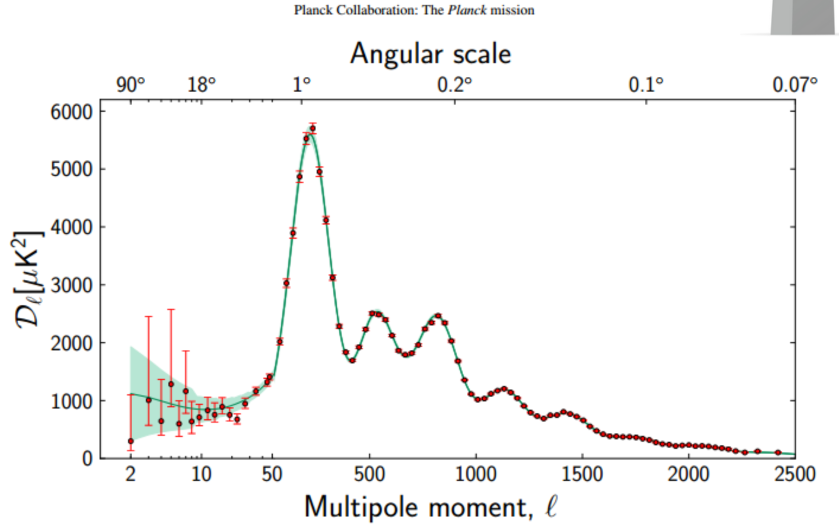


Fig. 1. Marginalized joint 68% and 95% CL regions for n_s and $r_{0.002}$ from *Planck* in combination with other data sets compared to the theoretical predictions of selected inflationary models.



$$n_s = 0.9603 \pm .0073 \qquad \ln 10^{10} A_S^2 = 3.089 \pm 0.027$$

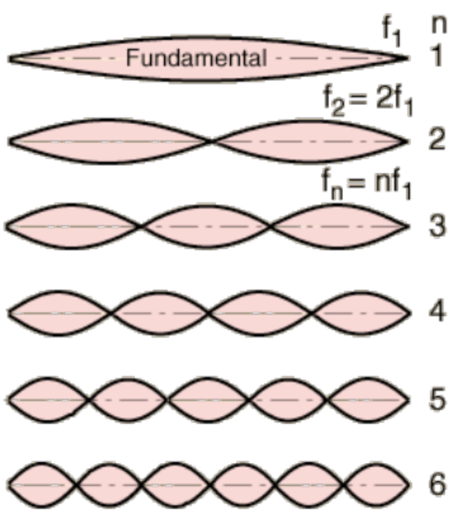
String Theory

What is a String

What we understand by elementary particles are not point-like but vibrating strings

graviton

Gauge boson



Quarks, leptons, etc.

There are two kinds of strings

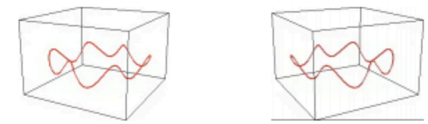
Massive excitations.

and depending how vibrates it could be one particle or other…

String Theory

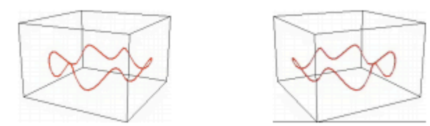
Theories

- In superstring theory appear different theories that apparently are different…
- Type IIA
  - Closed strings
  - Lev. and Dex. modes are differente



ψ_s ψ_c

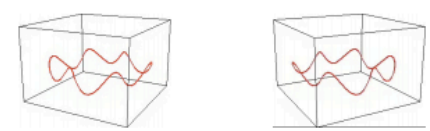
- Type IIB
  - Closed strings
  - Lev. and Dex. modes are the same



ψ_s ψ_s

- Type I
  - Open and closed strings (non orientable)

- Heterotic
  - Closed strings
  - One mode is fermionic and the other bosonic



ψ_s X

String Theory

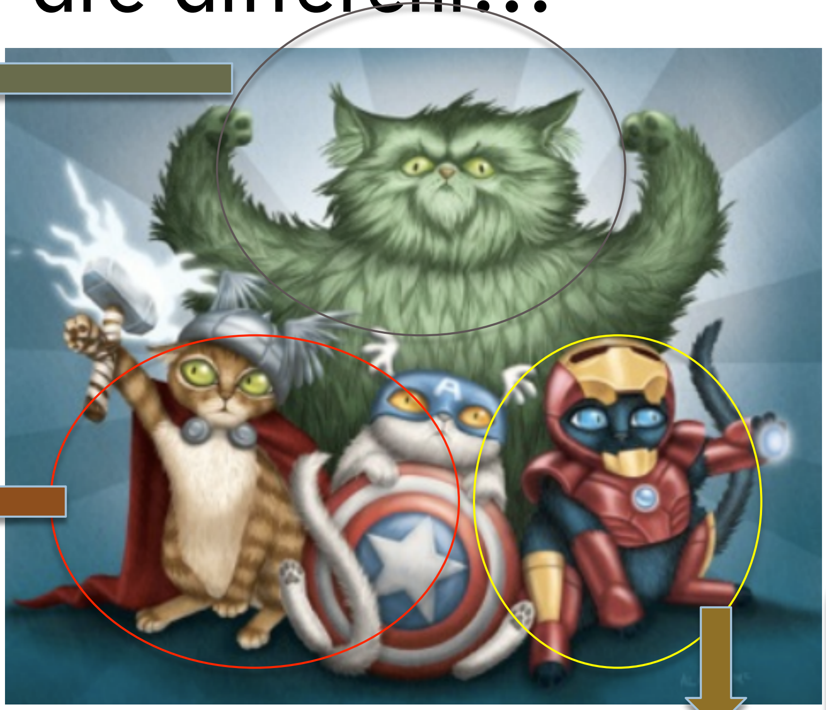
Theories

- In superstring theory appear different theories that apparently are different…

Heterotic
N = 1 SUSY

Type HO
SO(32)

Type HE
E8xE8



Type II
N = 2 SUSY

Type IIA
Both gravitinos are different

Type IIB
Both gravitinos are equal

Type I
N = 1 SUSY

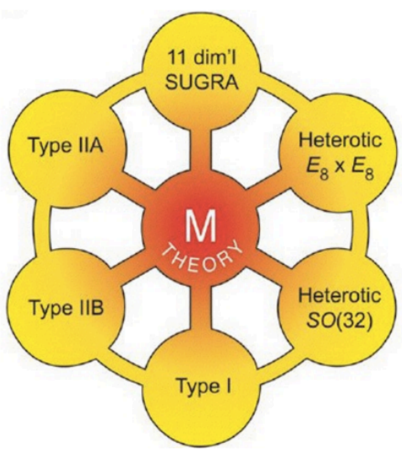
Contains gauge interactions SO(N)

String Theory

2nd Revolution

- In superstring theory appear different theories that apparently are different…

But if you know them closer



All are equivalent!

The chosen one is type IIA

String Theory

Compactification

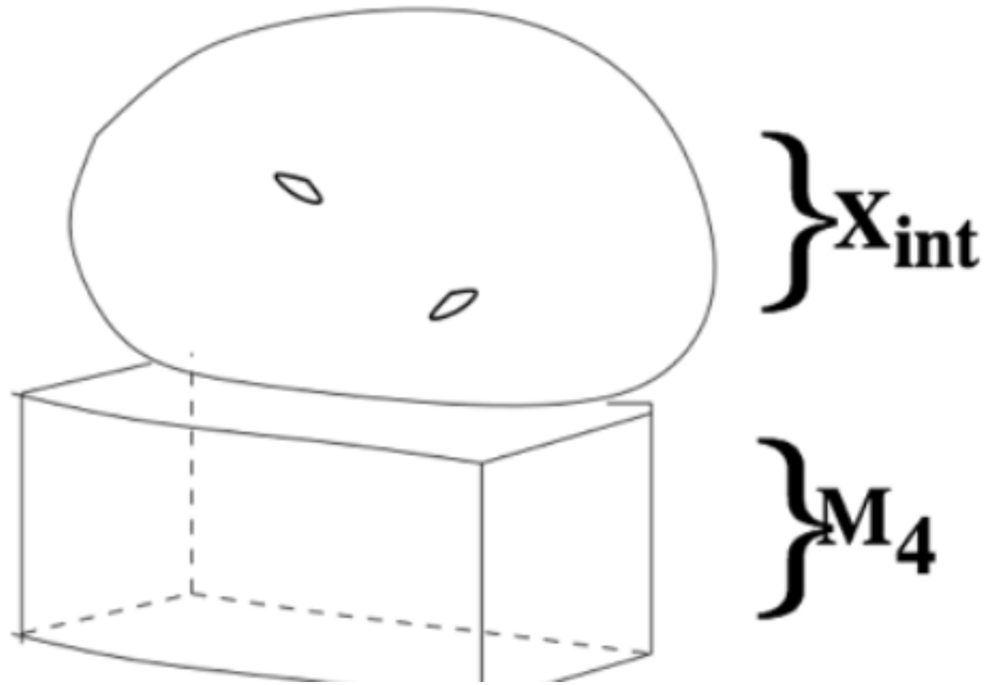
- In order to achieve a 4d theory we have to compatify the extra dimensions

Calabi-Yau Manifolds

Gravity in 4d

Gauge interaction 4d

SUSY in 4d



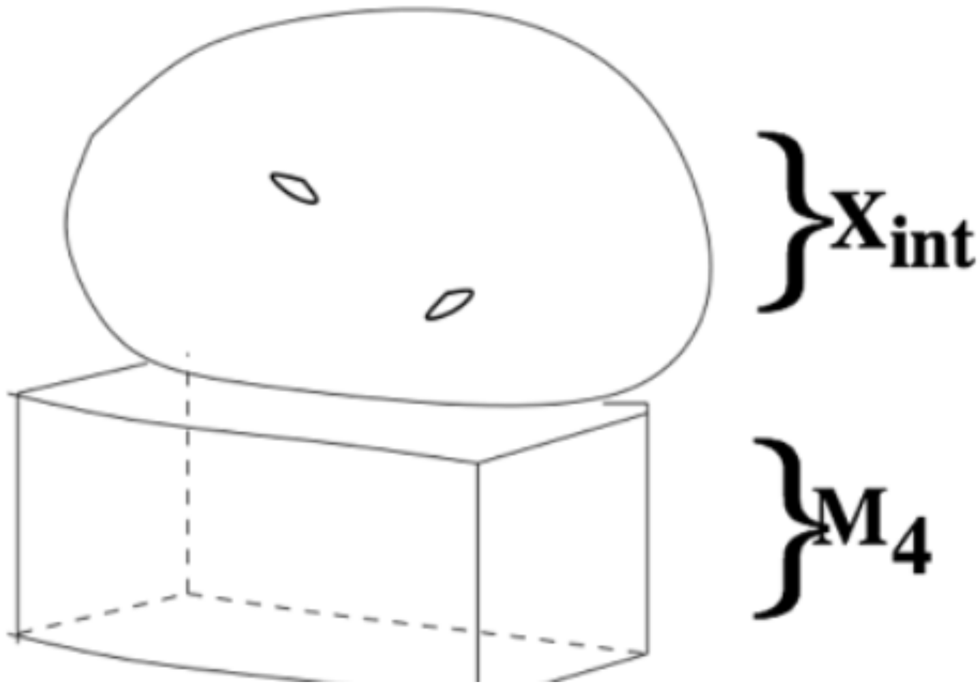
String Theory

Compactification

- In order to achieve a 4d theory we have to compatify the extra dimensions

Calabi-Yau Manifolds

Moreover the process of compactification gives us moduli, which we have to fix



String Theory

Moduli

- In order to achieve a 4d theory we have to compatify the extra dimensions

Calabi-Yau Manifolds

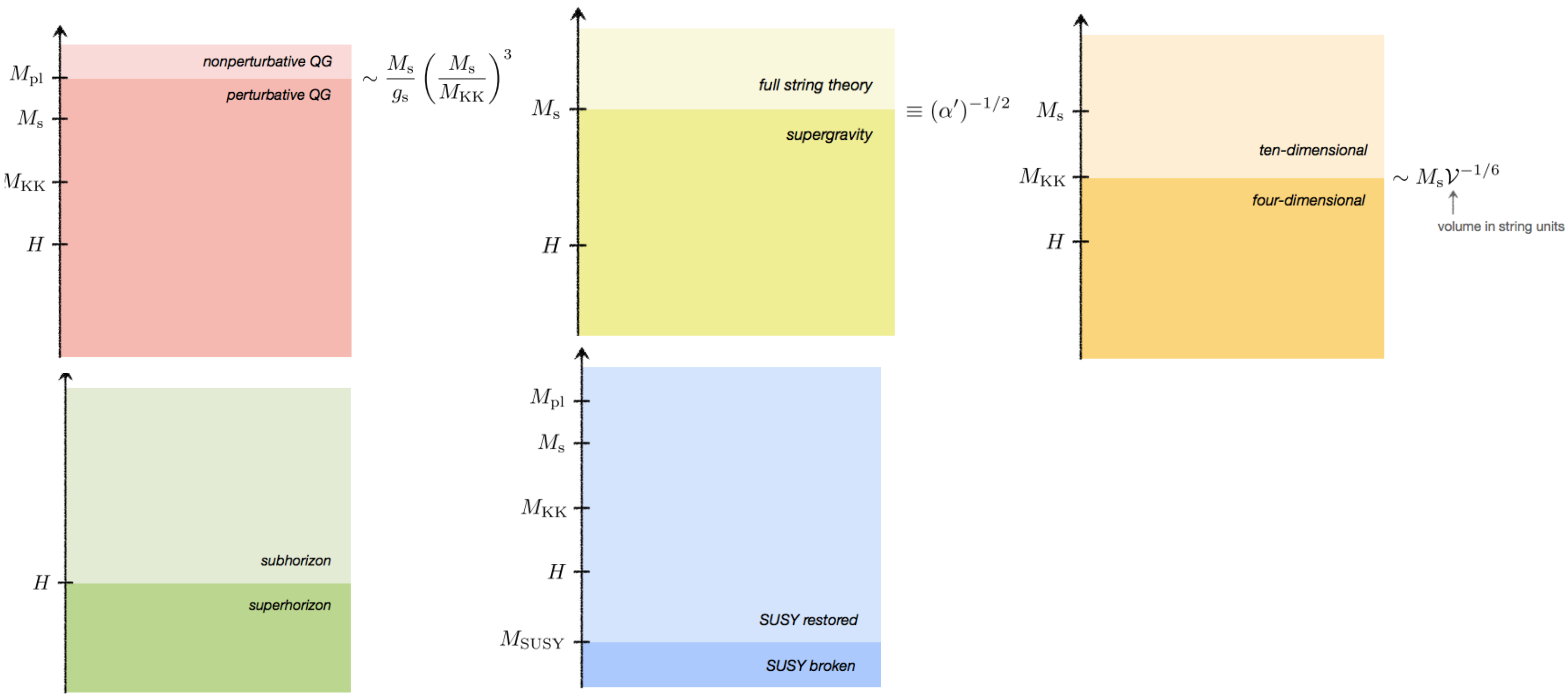
Moreover the process of compactification gives us moduli, which we have to fix

modulus	name	
$S \ = s + ic$	axio-dilaton	
$U^i = v^i + iu^i$	complex structure	$\rightarrow$ shape deformations
$T_\alpha = \tau_\alpha + i\rho_\alpha + \ldots$	Kähler	$\rightarrow$ size deformations
$G^a = Sb^a + ic^a$	axionic odd	

ST & Inflation

Hierarchy

- We should stablish a mass hierarchy to the moduli in order to inflate with one scalar field



ST & Inflation

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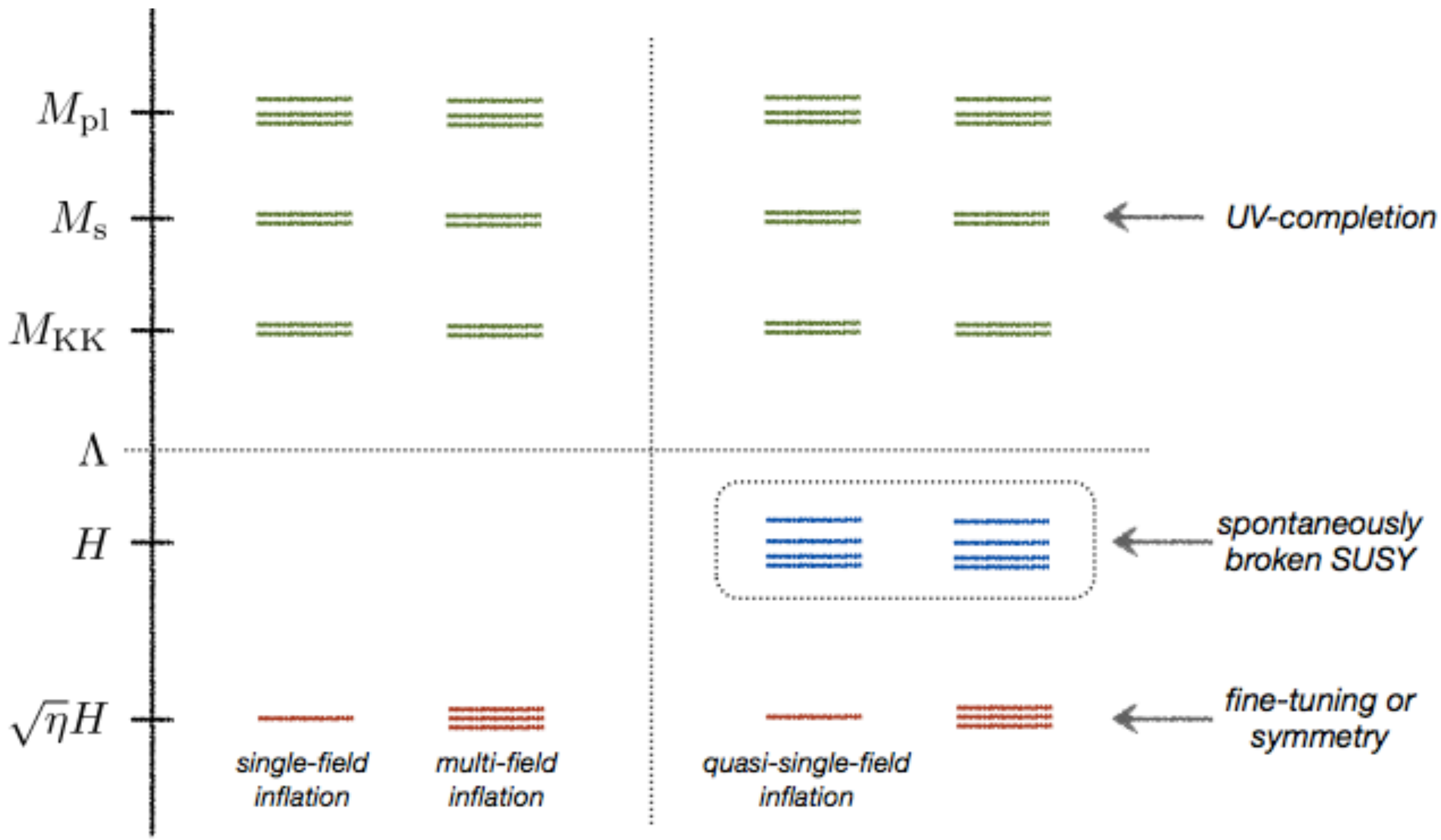
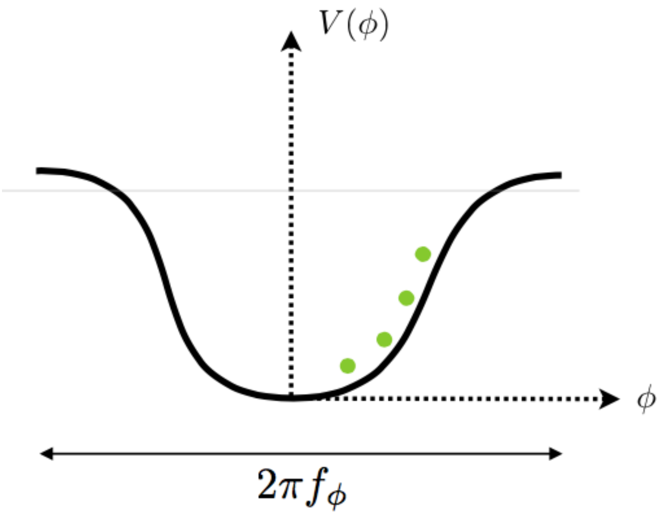


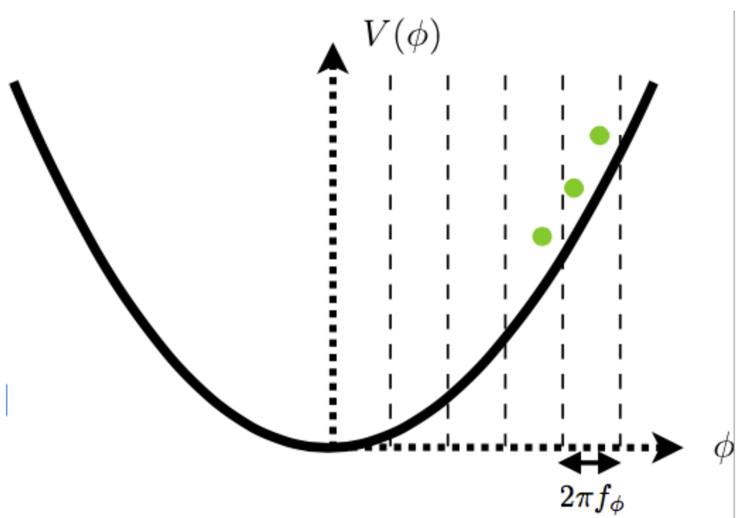
ST & Inflation

Axion monodromy

String axions are promising inflaton candidates. Equipped with **a continuous shift symmetry to all orders in perturbation theory,** the axion potential is stable against radiative corrections



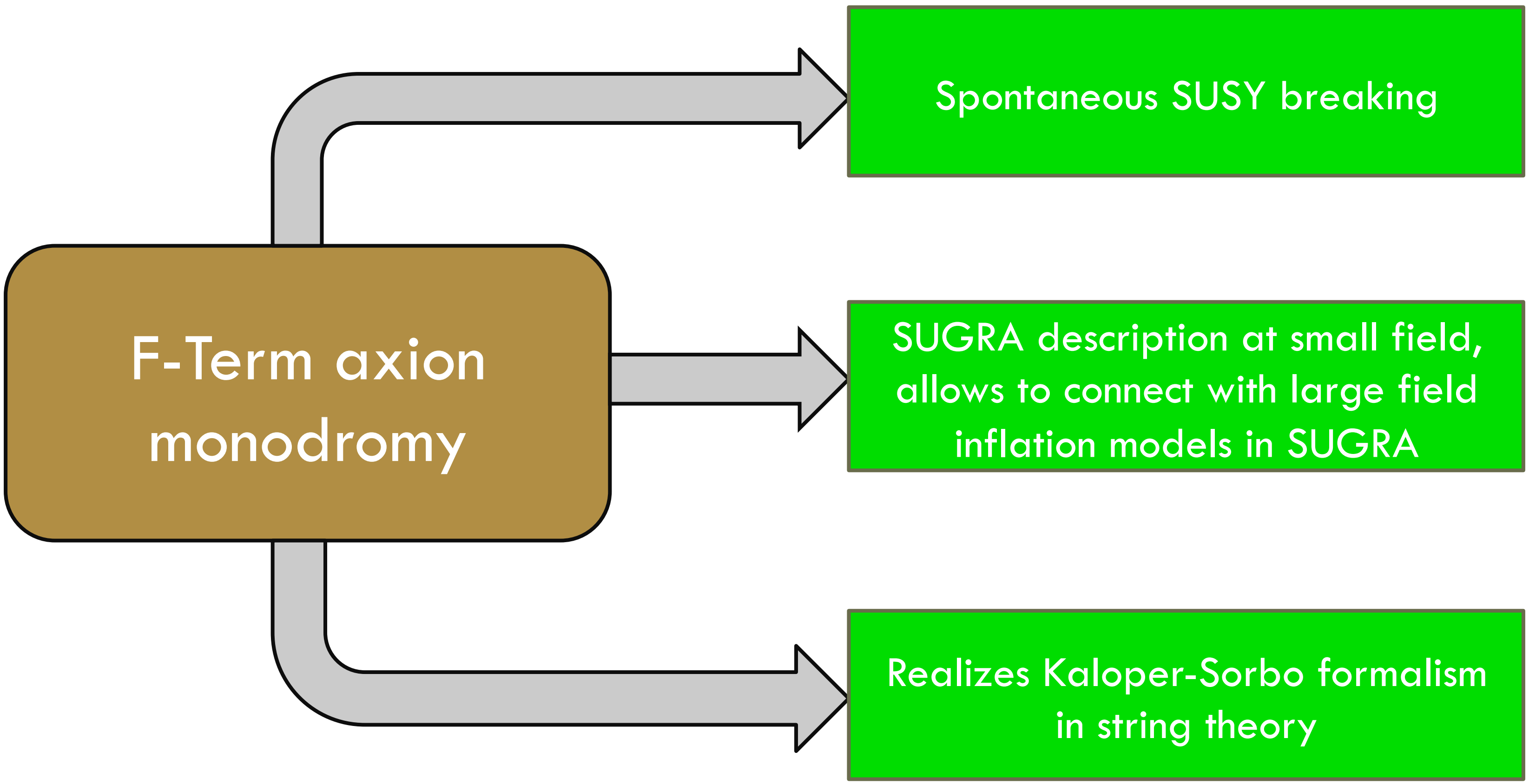
The basic idea of monodromy
Inflation is that inflation can persist through many cycles around the
configuration space. **The effective field range is then much larger than the fundamental period,** but the axion shift symmetry protects the structure of
the potential over each individual cycle



Silverstein & Westphal '08

ST & Inflation

F-term axion monodromy



Marchesano, Shiu & Uranga '14

Motivation

F-term axion monodromy

F-Term axion monodromy

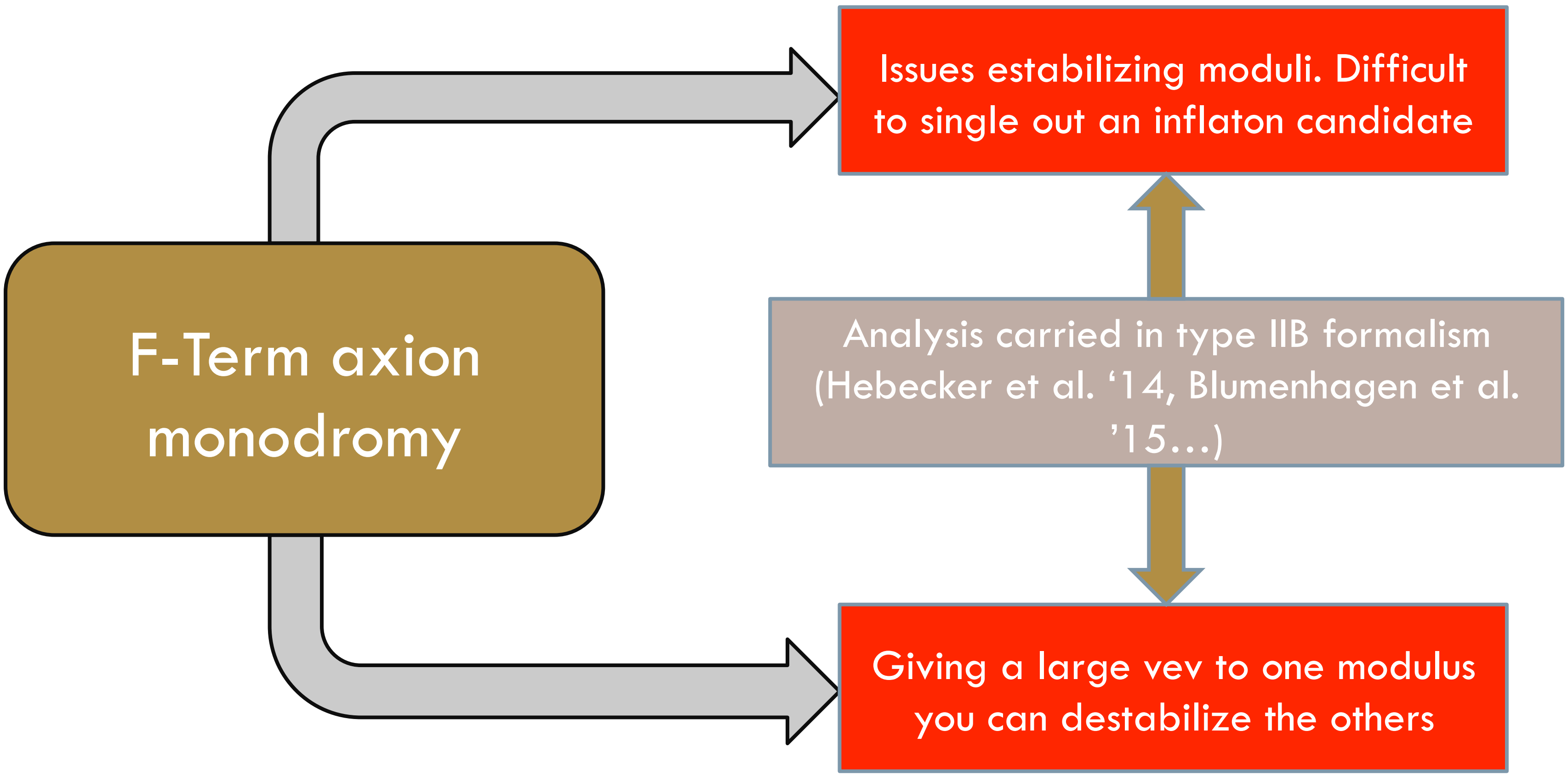
Issues estabilizing moduli. Difficult to single out an inflaton candidate

Giving a large vev to one modulus you can destabilize the others

Marchesano, Shiu & Uranga '14

Motivation

F-term axion monodromy



Marchesano, Shiu & Uranga '14

Inflation from D-branes

Setup

4d **type IIA** compactifications with O6-planes and background fluxes

D6-brane wrapping a special lagrangian 3-cycle Π_3 of the compactification manifold such that

$$b_1(\Pi_3) = 1$$

$$J_c = B + iJ$$

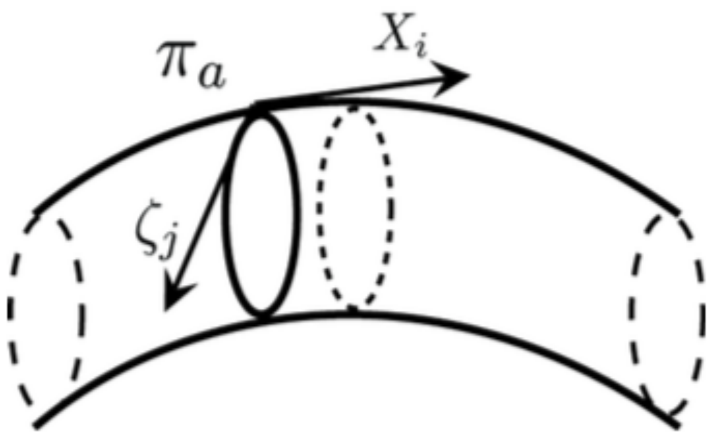
Complexified brane position modulus

$$A + [\iota_X J_c]_{\Pi_3} = \Phi\zeta$$

$$b_1(\Pi_3) = 1$$

$[\Pi_2]$ non trivial in the homology of M_6

$$\int_{\Pi_2} J_c = \sum_a n_a T^a = T$$



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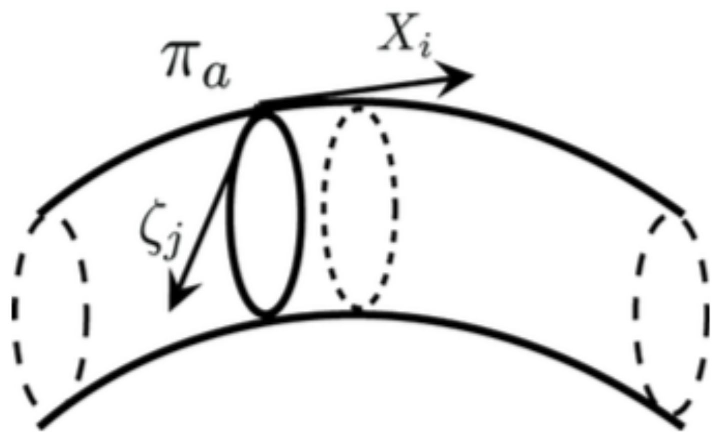
$$\int_{\Pi_2} J_c = \sum_a n_a T^a = T$$

$$W_{\mathrm{inf}} = a\,\Phi\,T$$



Marchesano, Regalado & Zoccarato '14

Motivation

Inflation & SUGRA

- Chaotic inflation is builded in SUGRA using the following setup

Stabilizer field

$$W = Sf(X)$$

$$K = K\left(S, \bar{S}, X, \bar{X}\right)$$

The Kähler potential is invariant under

$$S \to -S$$

$$X \to \bar{X}$$

$$X \to X + a \in \mathbb{R}$$

$$V = e^K\left(K^{\alpha\bar{\beta}} D_\alpha W D_{\bar{\beta}} \bar{W} - 3|W|^2\right)$$

$$S = 0 = \mathrm{Im}\left(\Phi\right)$$

$$V = f^2\left(\frac{X}{\sqrt{2}}\right)$$

Kawasaki, Yamaguchi & Yanagida '00

Kallosh, Linde & Rube '10

Inflation from D-branes

Setup

$$V = e^K \left(K^{\alpha\bar{\beta}} D_\alpha W D_{\bar{\beta}} \bar{W} - 3|W|^2 \right)$$

$$K_K = -\log\left(\frac{i}{6}\mathcal{K}_{abc}(T^a - \bar{T}^a)(T^b - \bar{T}^b)(T^c - \bar{T}^c)\right)$$

$$K_Q = -2\log\left(\frac{1}{2i}\mathcal{F}_{\hat{K}\hat{L}}\left[N^{\hat{K}} - \bar{N}^{\hat{K}} + \frac{i}{4}Q^{\hat{K}}\Phi\bar{\Phi}\right]\cdot\left[N^{\hat{L}} - \bar{N}^{\hat{L}} + \frac{i}{4}Q^{\hat{L}}\Phi\bar{\Phi}\right]\right)$$

Satisfies the conditions imposed in SUGRA

$$W_{\text{mod}} = W_{\text{flux}} + W_{\text{D2}} + W_{\text{WS}}$$

$$W = W_{\text{mod}} + \Phi T$$

$$W = S f(X)$$

$$\Phi \to -\Phi$$

$$T \to \bar{T}$$

$$T \to T + a \in \mathbb{R}$$

We want to understand the interplay between the inflationary potential and the moduli stabilization

We identify

Φ stabilizer

$$J_c = B + iJ$$

Re T
Inflaton candidate

$$\int_{\Pi_2} J_c = \sum_a n_a T^a = T$$

$$b = \int_{\Pi_2} B$$

Inflation from D-branes

Setup

$$V = e^K \left(K^{\alpha\bar{\beta}} D_\alpha W D_{\bar{\beta}} \bar{W} - 3|W|^2 \right)$$

$$K_K = -\log\left(\frac{i}{6}\mathcal{K}_{abc}(T^a - \bar{T}^a)(T^b - \bar{T}^b)(T^c - \bar{T}^c)\right)$$

$$K'_Q = -2\log\left(\frac{1}{16i}\mathcal{F}_{KL}\left[N^K - \bar{N}^K - \frac{i}{8}Q^K(\Phi - \bar{\Phi})^2\right]\cdot\left[N^L - \bar{N}^L - \frac{i}{8}Q^L(\Phi - \bar{\Phi})^2\right]\right)$$

5

$$W_{\text{mod}} = W_{\text{flux}} + W_{\text{D2}} + W_{\text{WS}}$$

$$W = W_{\text{mod}} + \Phi T$$

$$W = Sf(X)$$

Satisfies the conditions imposed in SUGRA

$$T \to -T$$
$$\Phi \to \bar{\Phi}$$
$$\Phi \to \Phi + a \in \mathbb{R}$$

We identify

T stabilizer

$$T = T^1 - T^2$$

Re Φ
Inflaton candidate

We want to understand the interplay between the inflationary potential and the moduli stabilization

Does not require any two-cycle of M_6 shrinking to vanishing size

Inflation from D-branes

Mod. Stabil

$$V = e^K \left(K^{\alpha\bar{\beta}} D_\alpha W D_{\bar{\beta}} \bar{W} - 3|W|^2 \right)$$

$$\begin{aligned} K_K &= -\log\left(\frac{i}{6}\mathcal{K}_{abc}(T^a - \bar{T}^a)(T^b - \bar{T}^b)(T^c - \bar{T}^c)\right) \\ K_Q &= -2\log\left(\frac{1}{2i}\mathcal{F}_{\hat{K}\hat{L}}\left[N^{\hat{K}} - \bar{N}^{\hat{K}} + \frac{i}{4}Q^{\hat{K}}\Phi\bar{\Phi}\right]\cdot\left[N^{\hat{L}} - \bar{N}^{\hat{L}} + \frac{i}{4}Q^{\hat{L}}\Phi\bar{\Phi}\right]\right) \\ K'_Q &= -2\log\left(\frac{1}{16i}\mathcal{F}_{KL}\left[N^K - \bar{N}^K - \frac{i}{8}Q^K(\Phi - \bar{\Phi})^2\right]\cdot\left[N^L - \bar{N}^L - \frac{i}{8}Q^L(\Phi - \bar{\Phi})^2\right]\right) \end{aligned}$$

$$W_{\rm mod} = W_{\rm flux} + W_{\rm D2} + W_{\rm WS}$$

We assume

W_{mod} **does not depend** on T and Φ

Axion is a flat direction

F-terms vanish and almost all moduli are stabilized with a very small or vanishing value of W^0

Inflation from D-branes

Mod. Stabil

$$V = e^K \left(K^{\alpha\bar\beta} D_\alpha W D_{\bar\beta} \bar W - 3|W|^2 \right)$$

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Switch on $W_{\rm inf}$

$$V = V_Q + V_K - 3e^K|W|^2$$

$$W_{\rm mod} = W_{\rm flux} + W_{\rm D2} + W_{\rm WS}$$

We assume

$W_{\rm mod}$ does not depend on T

Axion is a flat direction

F-terms vanish and almost all moduli are stabilized with a very small or vanishing value of W^0
We have **concrete examples**

$$\begin{aligned} D_N W_{\rm mod} &= 0 \\ D_{T^a} W_{\rm mod} &= 0 \end{aligned}$$

Scalar potential during inflation

Inflation from D-branes

Mod. Stabil

$$V \;=\; e^K \left(K^{\Phi\bar\Phi}\,|\partial_\Phi W_{\rm inf}|^2 + (K^{T\bar T} + 4({\rm Re}\,T)^2)|\partial_T W_{\rm inf}|^2\right) + \mathcal{O}(|W^0_{\rm mod}|)$$

$\mathrm{ReT} \neq 0,\ \mathrm{ImT} = 0,\ \Phi = 0$

Inflating with B-field

$$V|_{\rm Traj} \;=\; \frac{e^K}{\kappa_4^2}\frac{K^{\Phi\bar\Phi}}{K_{T\bar T}}|a|^2\,\tilde b^2$$

Cuadratic potential

$$V|_{\rm Traj} \;=\; \frac{e^K}{\kappa_4^2}\frac{K^{T\bar T}}{K_{\Phi\bar\Phi}}|a|^2\,\theta^2$$

Inflating with Wilson Line

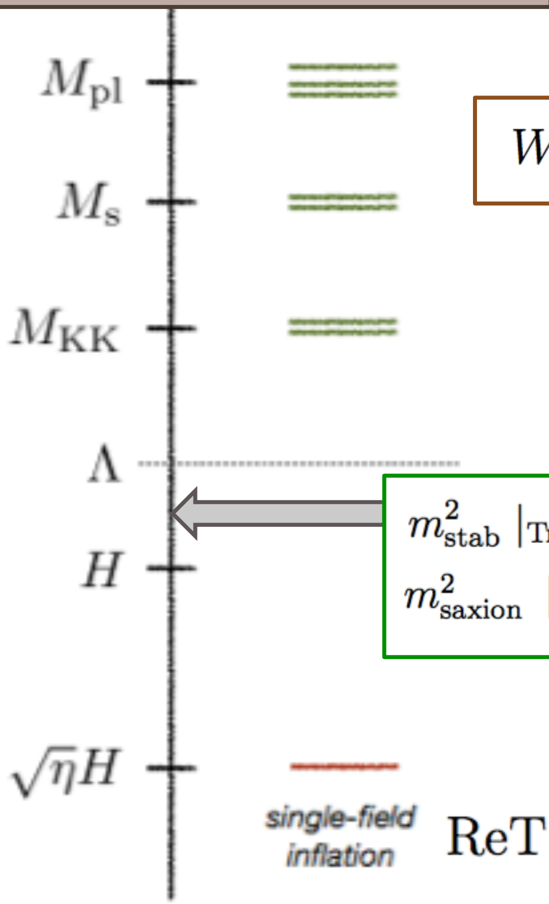
${\rm Re}\,\Phi \neq 0\ ,\ {\rm Im}\,\Phi = 0\ ,\ T = 0$

$$V = e^K \left(K^{\Phi\bar\Phi}\,|\partial_\Phi W_{\rm inf}|^2 + K^{T\bar T}|\partial_T W_{\rm inf} + 2TW^0_2|^2 + 4|a|^2({\rm Re}\,T)^2({\rm Re}\,\Phi)^2\right) + \mathcal{O}(W^0_{\rm mod})$$

Inflation from D-branes

Mass Hierarc.

Inflating with B-field



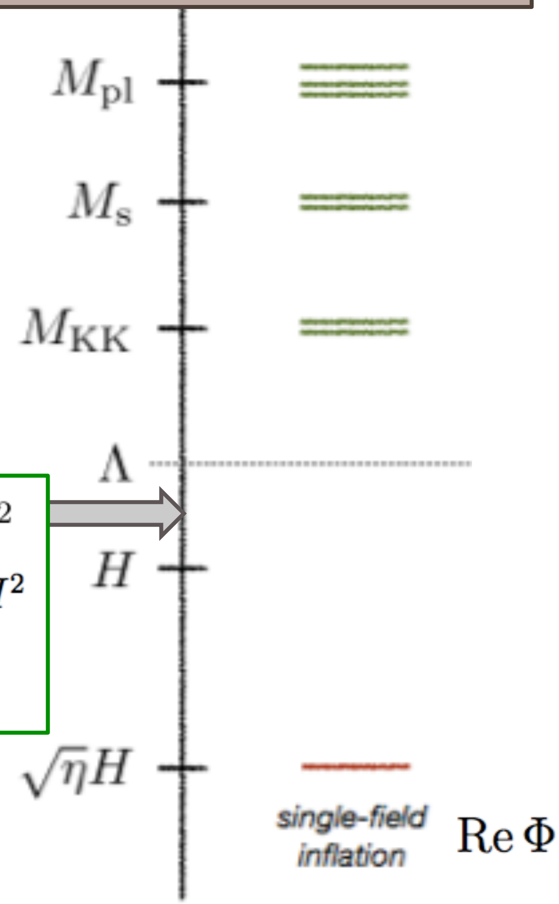
$$W_{\rm mod} = W_{\rm flux} + W_{\rm D2} + W_{\rm WS}$$

$$N^K, T^a$$

$$m^2_{\rm stab}\,|_{\rm Traj} \simeq 15H^2$$
$$m^2_{\rm saxion}\,|_{\rm Traj} \simeq 6H^2$$

$$m^2_{s_1}|_{\rm Traj} \simeq 12H^2$$
$$m^2_{\rm saxion}\,|_{\rm Traj} \simeq 6H^2$$
$$m^2_{s_2}|_{\rm Traj} \simeq 6H^2$$

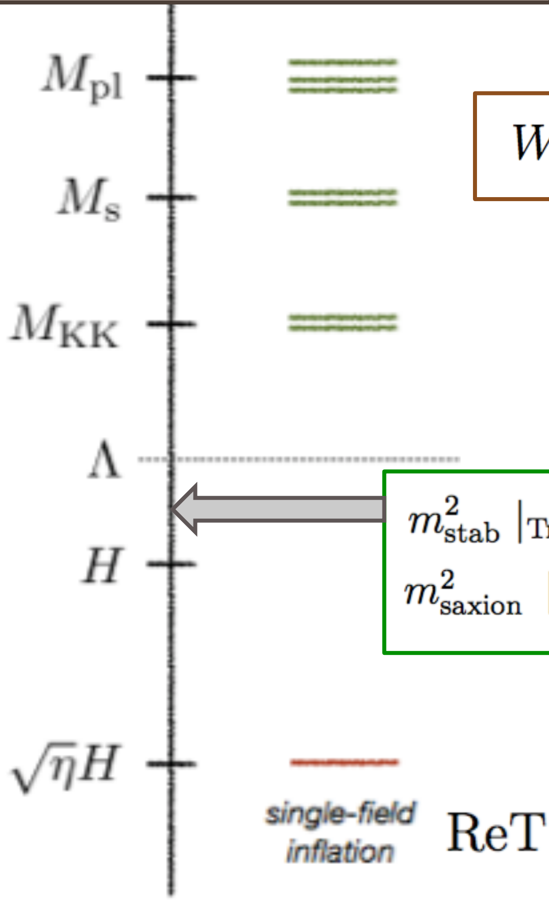
Inflating with Wilson Line



Inflation from D-branes

Mass Hierarc.

Inflating with B-field



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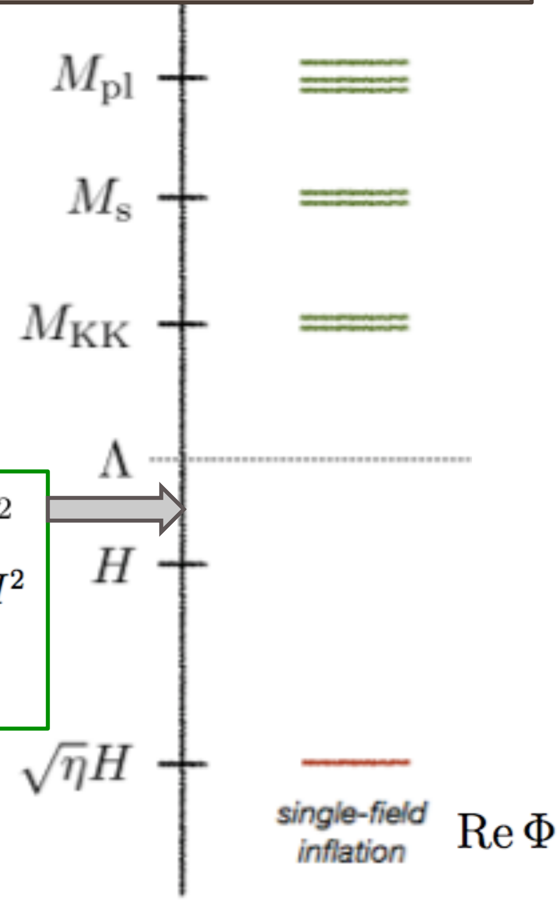
Inflating with Wilson Line



Our model has a mass hierarchy that allows single-field inflation

Inflation from D-branes DBI reduction

The inflaton will take **trans-Plankian vacuum expectation value** at the beginning of inflation

It is **necessary to take into account Planck supressed corrections** to the quadratic potential given by SUGRA

Dimensional reduction of the DBI action which sumes over all α' corrections to the potential

$$V = c\frac{\sqrt{1 + a\left(\frac{b^2+j^2}{M_p^2}\right)} - 1}{A_0 - A_2 j^2}$$

Inflation from D-branes

Masses

How to supress the inflaton mass with respect the other closed string moduli?

Decrease the value of respect K^{TT}

Set the D6-brane in a **warped region**

Enhance the constants Q^K

$$\Delta V = e^K K^{\Phi\bar{\Phi}}|T|^2$$

$$\mathcal{V}_{\mathcal{M}_6} \sim 10^3$$
$$\mathcal{V}_{\Pi_3} \sim 10$$
$$g_s^2 \sim 0.1$$

$$m_{\rm inf} \sim Z_{\rm D6}^{-1/2} 10^{-4} M_{\rm pl}$$

$Z \sim 100$

Gives a realistic inflaton mass

Inflation from D-branes

Masses

How to supress the inflaton mass with respect the other closed string moduli?

Decrease the value of respect K^{TT}

Set the D6-brane in a **warped region**

Enhance the constants Q^K

$$\Delta V = e^K K^{\Phi\bar{\Phi}} |T|^2$$

$$m_{\rm inf} \sim Z_{\rm D6}^{-1/2} 10^{-4} M_{\rm pl}$$

What about the **saxionic partner?**

$$m^2_{\rm sax}|_{trj} = 3H^2 \left(\frac{2}{1+\frac{1}{\sqrt{1+a\frac{b^2}{M_p^2}}}}\epsilon + 2 \right)$$

$$m^2_{\rm sax}|_{trj}] \approx 6H^2$$

Single-Field Inflation

Inflation from D-branes DBI reduction

$$c \sim 10^{-2} g_s^3 \frac{\mathcal{V}_{\Pi_3}}{\mathcal{V}_{\mathcal{M}_6}}$$

$$a^{-1} \sim g_s^{-1} K_{\Phi\bar{\Phi}} K_{T\bar{T}} \mathcal{V}_{\Pi_3} \mathcal{V}_{\mathcal{M}_6}$$

$$a \sim 10^{-1} - 10^{-3}$$

$$\mathcal{V}_{\mathcal{M}_6} \sim 10^3$$

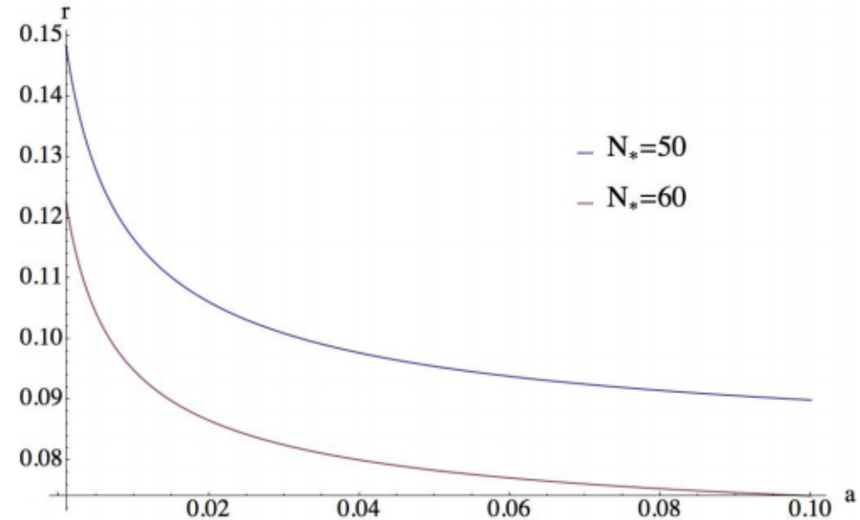
$$\mathcal{V}_{\Pi_3} \sim 10$$

$$g_s^2 \sim 0.1$$

Typical mass of the inflaton with these scales and also we satisfy Planck bounds

$$V = c\left(\sqrt{1 + a\left(\frac{\phi_b}{M_{\rm pl}}\right)^2} - 1\right) M_{\rm pl}^4$$

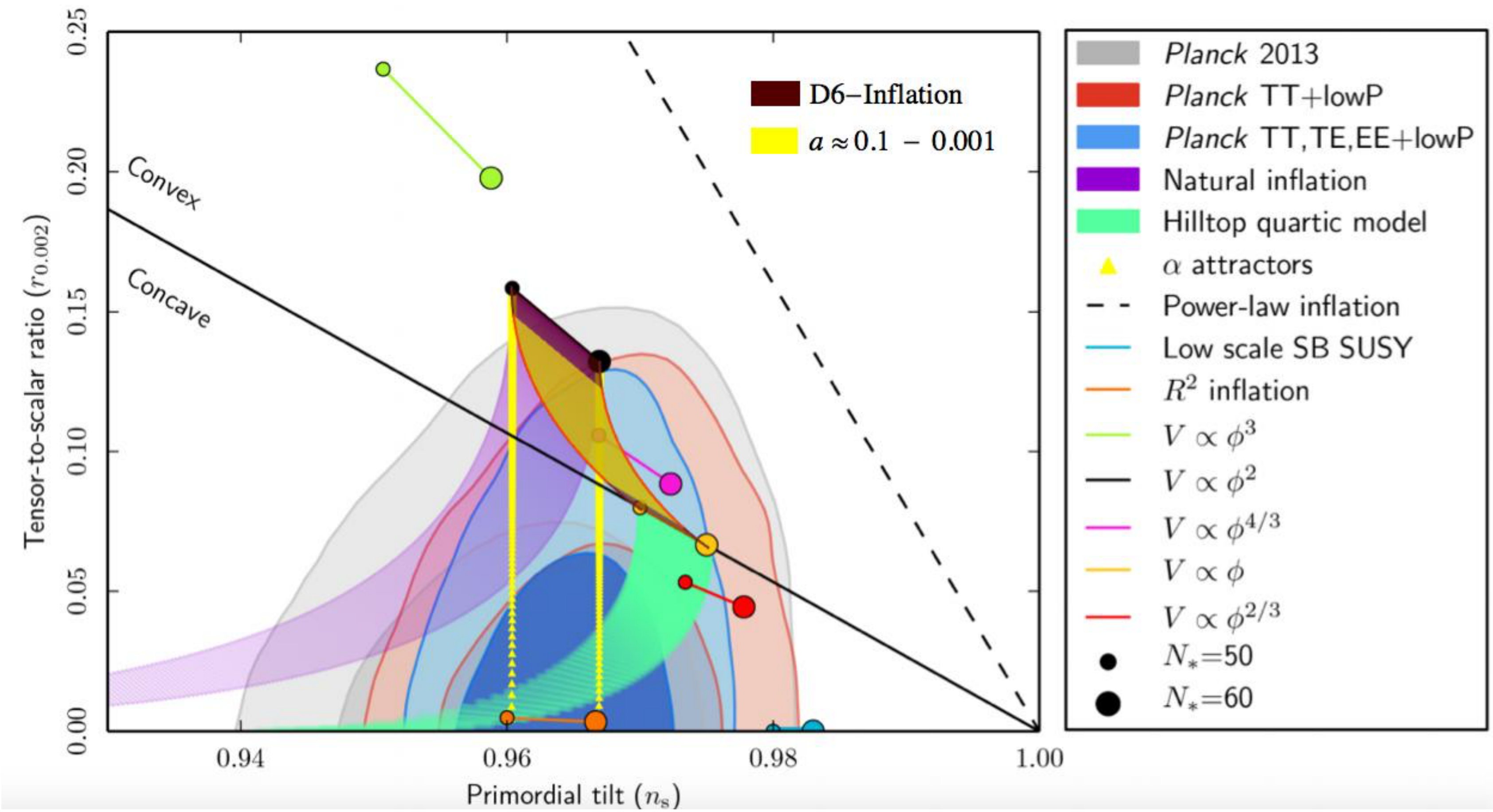
Single-Field case



Our model interpolates between quadratic chaotic inflation ($a \approx 10^{-3}$) and linear chaotic inflation ($a \approx 10^{-1}$)

Inflation from D-branes

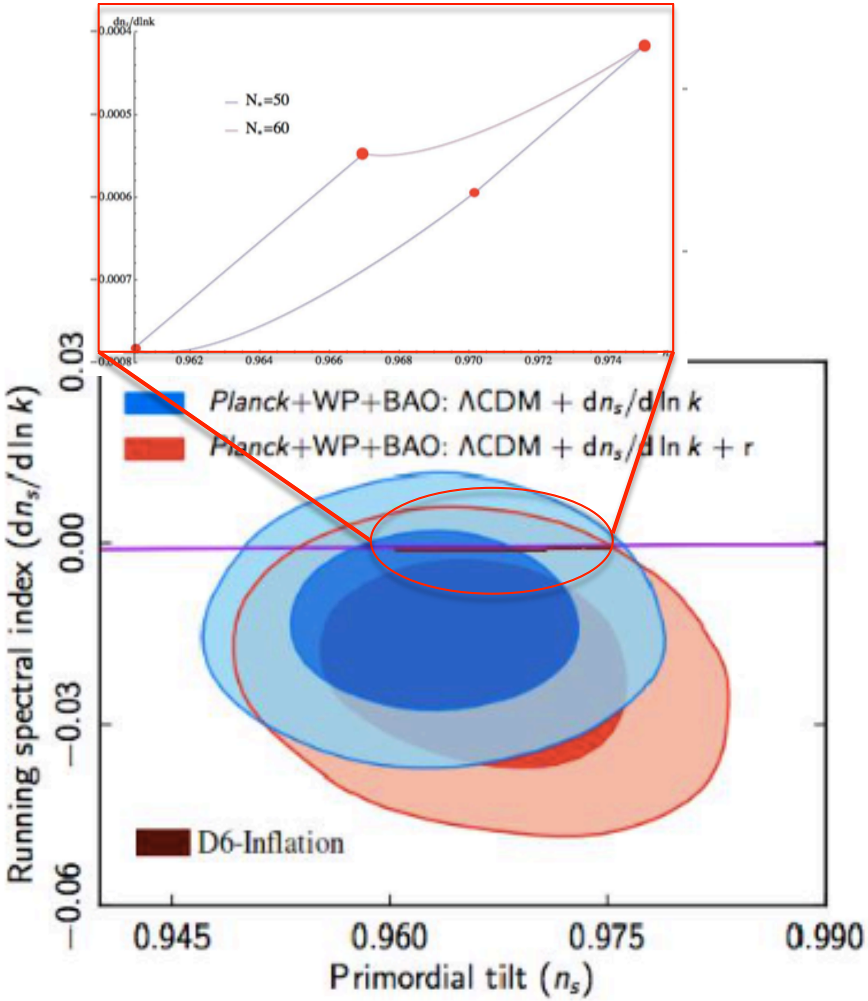
Results

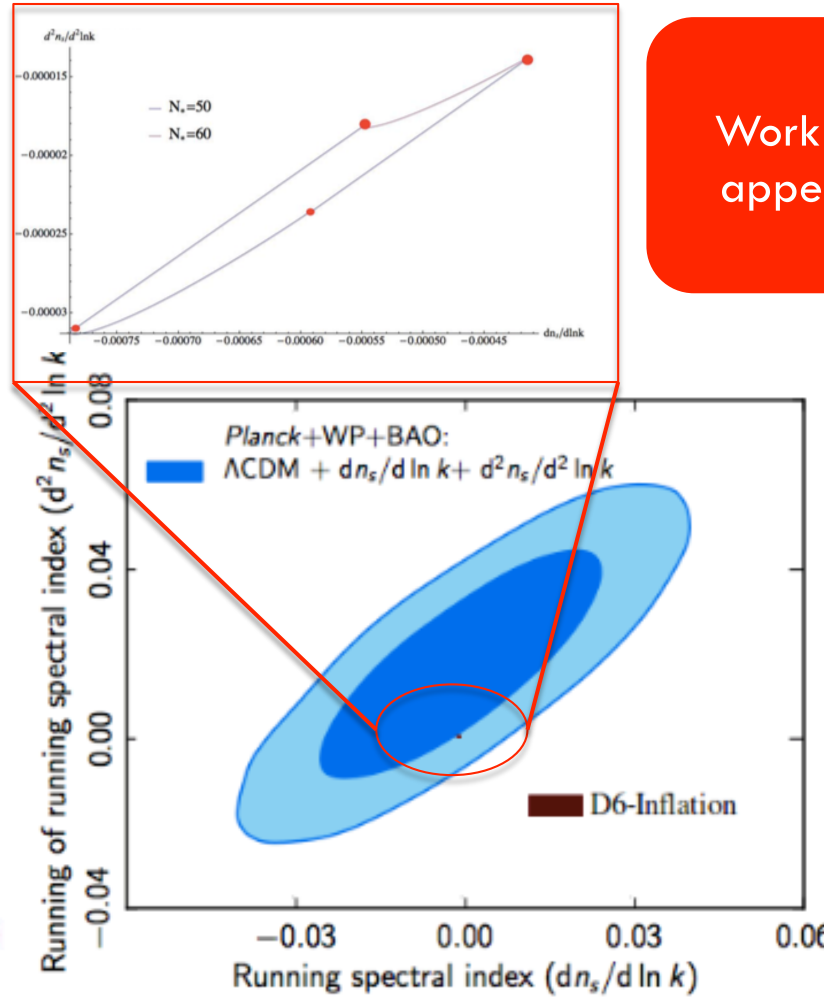


Escobar, A.L. , Marchesano & Regalado '15

Inflation from D-branes

Results





Work to appear

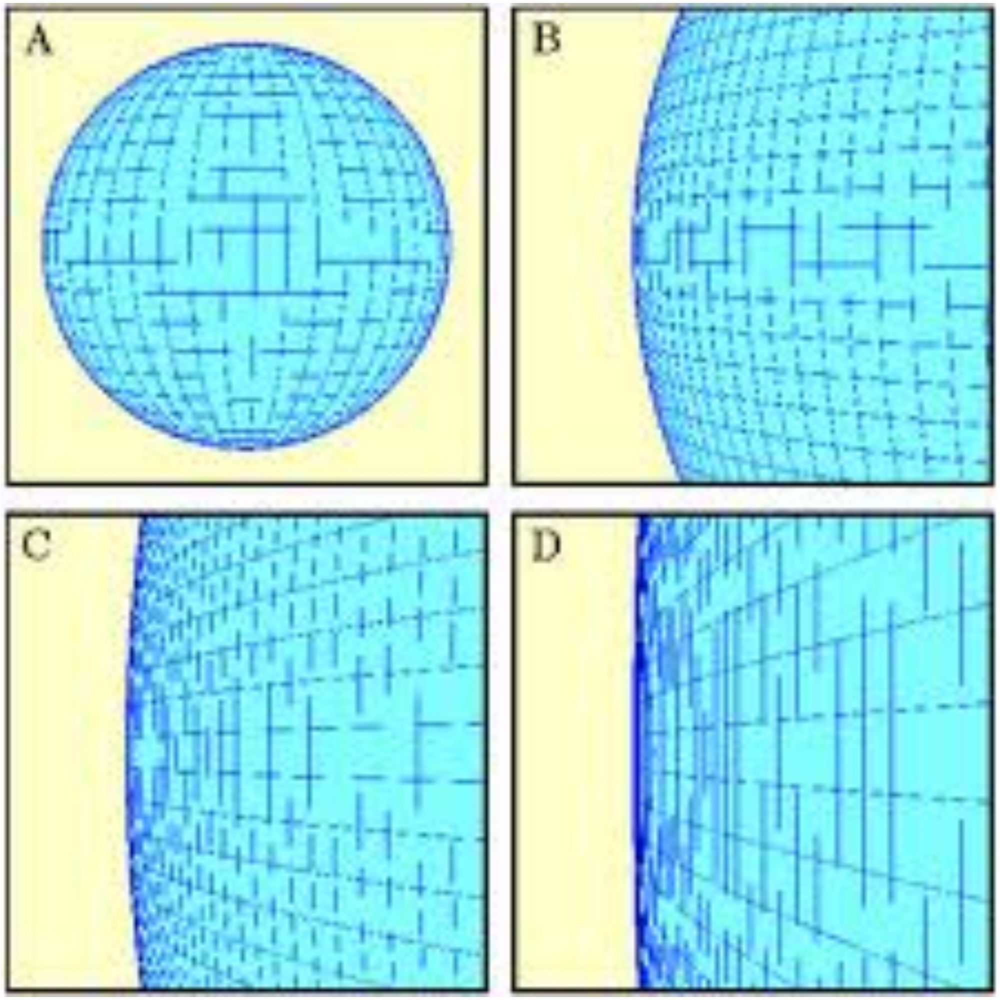
Conclusions

- We have been able to develop a model in type IIA with O6-planes and background fluxes which interpolates between quadratic chaotic inflation and linear chaotic inflation.
- We see that our model satisfies, in the single-field scenario, all the bounds stablished by the Planck collaboration.
- Our model matches with well-stablished models of inflation in N=1 SUGRA in the small field regime.
- We have been able to carry out the building of a mass hierarchy through flux compactification which is consistent with a single field inflationary secenario.

Thank you for your attention!

Inflation

Flatness problem

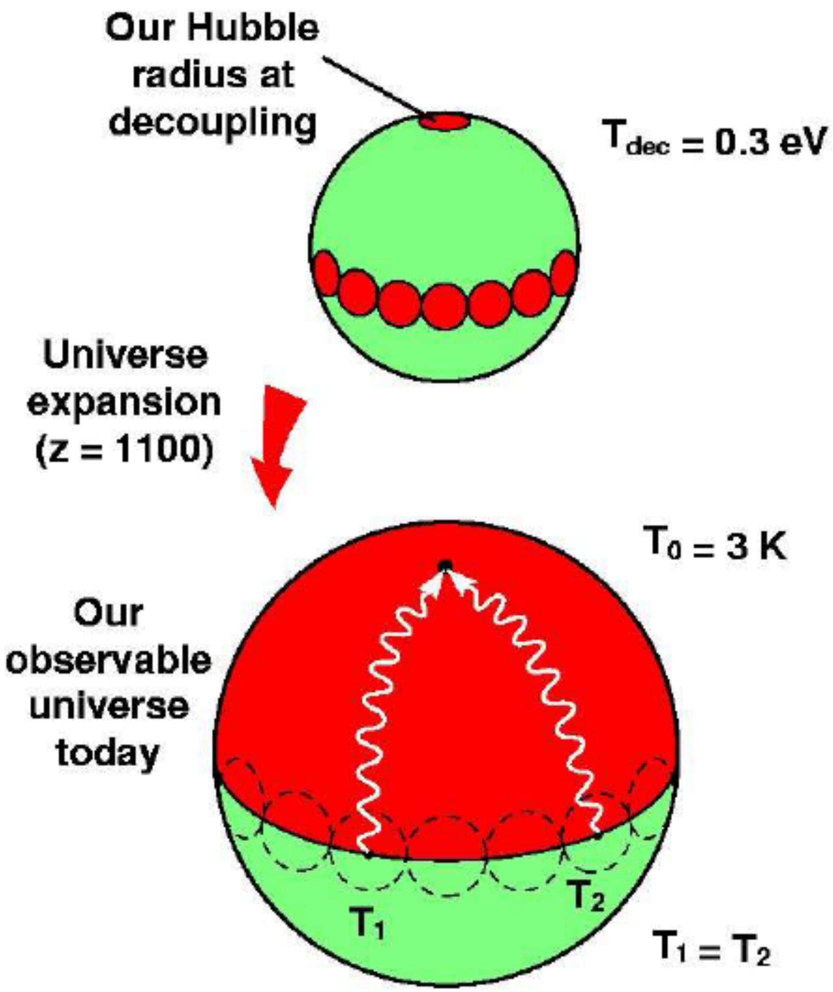


For the universe to be nearly flat today it must have been extremely flat at nucleosynthesis.

This extreme fine tuning of initial conditions is explained by the exponential expansion.
It explains how a region much greater than our observable universe could have become smooth and flat.

HorizonProblem

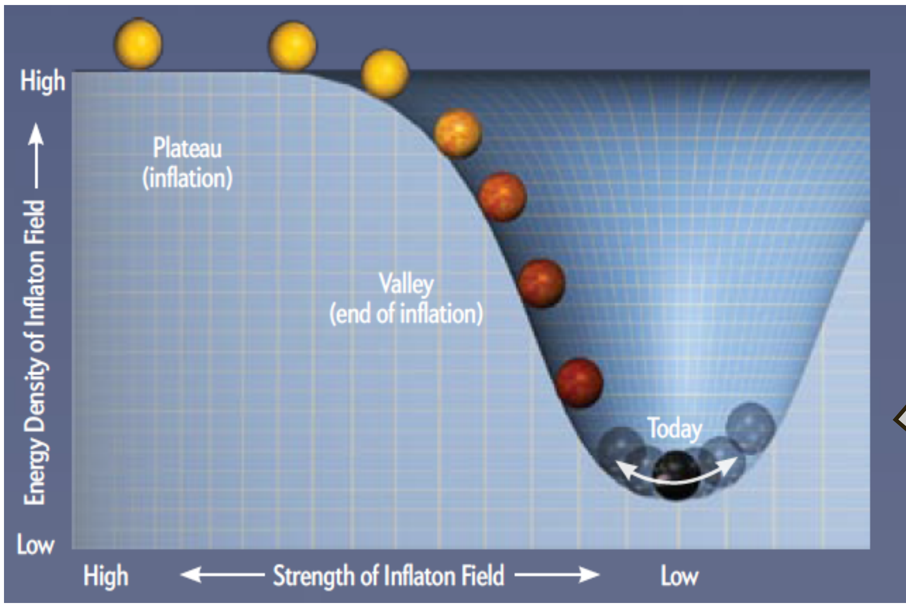
Horizon problem



Regions separated today by more than 1 degree in the sky were in causal
contact before inflation,
but were stretched to
cosmological distances by the
exponential expansion

Inflation

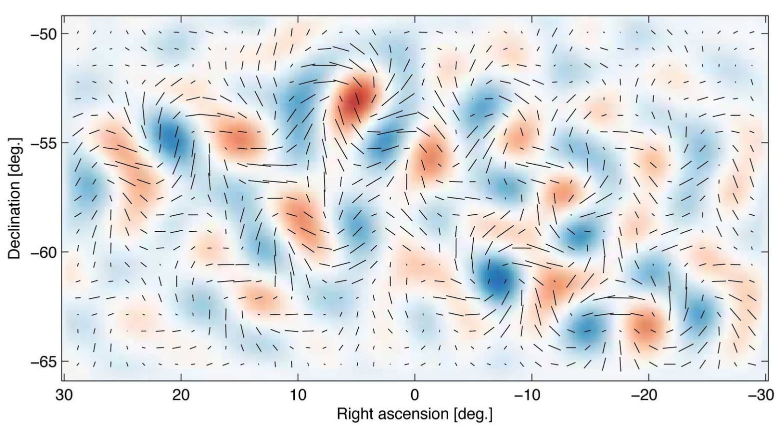
Radiation and matter origin



During inflation the universe was empty

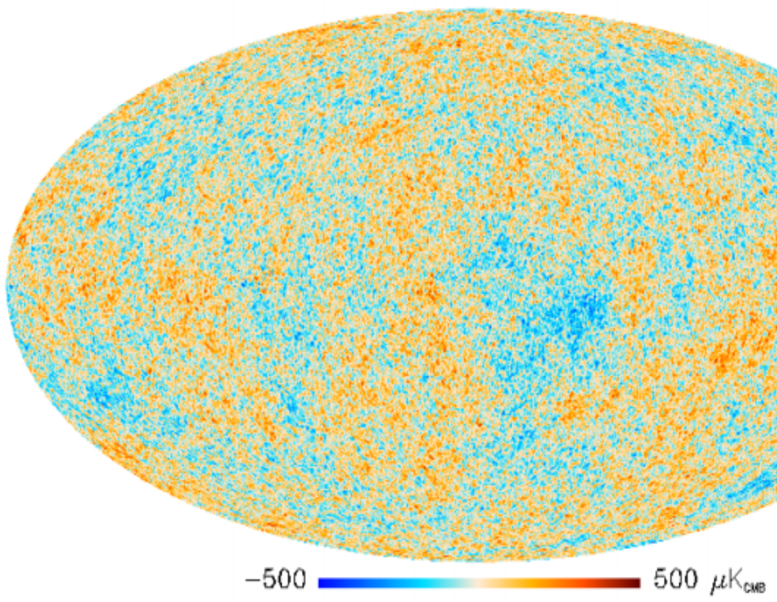
When the accelerated expansion ended all the potential energy of the inflaton turned into matter and kinetic energy

Gravitational Wave background



Inflation

Origin of Structure



Any inhomogeneities present before the tremendous expansion would be washed out

The inflaton is a quantum field, so it has its own inhomogeneities. These inhomogeneities growed with the expansion and were the seeds for the great structures that we observe today.