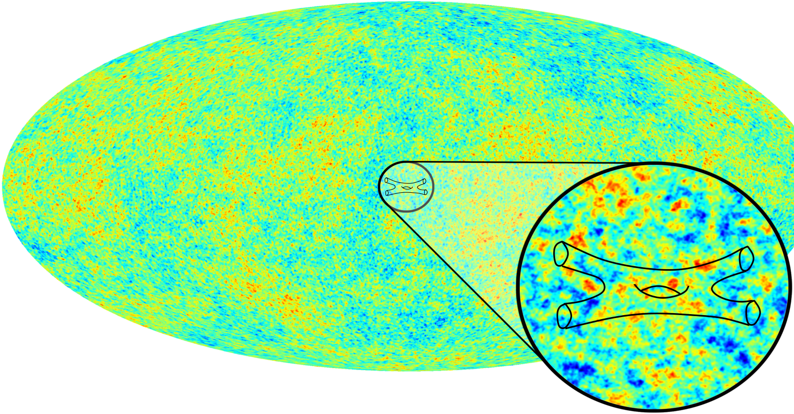
# Quantum Gravity Constraints on Large-Field Inflation?



Background Image: Planck Collaboration and ESA

# Quantum Gravity Constraints on Large-Field Inflation?

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(based on work with P. Mangat, F. Rompineve, L. Witkowski)

## Outline

- The interest in large-field models of inflation
- Fundamental obstructions to large-field inflation
- Problems with large-field inflation in string theory
- Axion alignement and Axion monodromy:
  Early models and recent progress

## Fundamentals of inflation

- The simplest relevant action is ($M_P \equiv 1$ here and below)

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

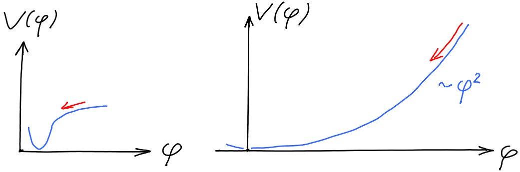
- Inflation is realized if $V(\varphi)$ has a sufficiently flat region

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

Starobinsky '80; Guth '81
Mukhanov/Chibisov '81; Linde '82

# Fundamentals of inflation (continued)

- If $V(\varphi)$ has some very flat region, 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 may be a problem in quantum gravity)

I will now focus on large-field models for two reasons....

## 1) Observations

- The amount of primordial gravity waves is measured by the tensor-to-scalar ratio:

$$r = \frac{\Delta_T^2}{\Delta_R^2} \simeq 8 \left| \frac{d\varphi}{dN} \right|^2 \quad \Rightarrow \quad \Delta\varphi \simeq 20\sqrt{r}$$

- Thus, even though the BICEP 'discovery' of $r \simeq 0.15$ went away, the need to consider large-field models may return

- Note: The new Planck/BICEP analysis still sees a ($\sim 1.8\sigma$) hint for $r \simeq 0.05$

- Much better values/bounds are expected soon

...reasons for interest in large-field models...

## 2) Fundamental

- On the one hand, large-field models are more 'robust'
- On the other hand, there are generic arguments against large-field models in consistent quantum gravity theories

  see e.g. Arkani-Hamed/Motl/Nicolis/Vafa '06 .... Conlon '12

- This goes hand in hand with certain problems in constructing large-field models in (the known part of) the string theory landscape

## ‘Fundamental reasoning’ continued...

- However, triggered by BICEP, new promising classes of stringy large-field have been constructed (e.g. $F$-term axion monodromy)

  Kim/Nilles/Peloso ’07
  McAllister, Silverstein, Westphal ’08
  .....
  Marchesano/Shiu/Uranga ’14
  Blumenhagen/Plauschinn ’14
  AH/Kraus/Witkowski ’14

- At the same time, there are ongoing efforts to sharpen the ‘no-go arguments’ as well as to refute them

  Rudelius ’14...’15
  Montero, Uranga, Valenzuela ’15
  Brown, Cottrell, Shiu, Soler ’15
  AH/Mangat/Rompineve/Witkowski ’15
  ...

- I will try to explain some aspects of this debate....

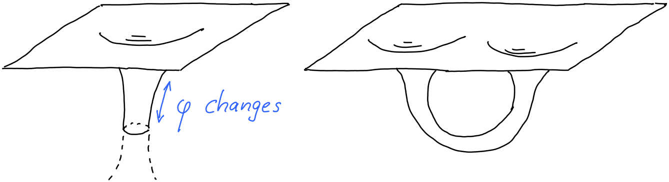
## No-go argument I: (Gravitational) instantons

- One of the leading inflaton candidates is a shift-symmetric, periodic scalar (axion)

  Freese/Frieman/Olinto '90
  Kawasaki/Yamaguchi/Yanagida '00

- In Euclidean Einstein gravity, supplemented with an axionic scalar $\varphi$ ($\varphi \equiv \varphi + f$), instantonic solutions exist:

  Giddings/Strominger '88
  ...




- The 'throat' is supported by the kinetic energy of $\varphi$, hence the large field range is essential

## Caveats:

- a) Euclidean quantum gravity has its own fundamental problems
- b) It is not completely clear 'where the throat should connect' (our world, another world, 'crunch', 'baby universe' ......)
- Hence the interpetation of these instanton solutions still has issues...

## Gravitational instantons (continued)

- Their Euclidean action is

$$S \sim n/f \qquad \text{(with } n \text{ the instanton number)}$$

- Their maximal curvature scale is $f/n$, which should not exceed the UV cutoff:

$$f/n < \Lambda$$

- This fixes the lowest $n$ that we can trust and hence the minimal size of the instanton correction to the potential $V(\varphi)$:

$$\boxed{\delta V \sim e^{-S} \sim e^{-n/f} \sim e^{-1/\Lambda}}$$

## Gravitational instantons (continued)

- For gravitational instantons not to prevent inflation, the relative correction must remain small:

$$\frac{\delta V}{V} \sim \frac{e^{-1/\Lambda}}{H^2} \ll 1$$

- For a Planck-scale cutoff, $\Lambda \sim 1$, this is never possible
- However, the UV cutoff can in principle be as low as $H$
- Then, if also $H \ll 1$, everything might be fine....

$$\frac{\delta V}{V} \sim \frac{e^{-1/H}}{H^2}$$

## Gravitational instantons (continued)

- Now, most string models of inflation do indeed have a low cutoff (e.g. compactification scale)
- However, it may be too naive to assume that 'uncalculable' gravitational instantons can simply be ignored
- They may find their 'continuation' in the gauge or D-brane instantons of the concrete string model
- Whether this is generically the case and whether such effects always spoil inflation is under debate ....

## No-go argument II: Weak gravity conjecture

Arkani-Hamed/Motl/Nicolis/Vafa '06

- Roughly speaking: 'Gravity is always the weakest force.'

- More concretely (mild form):

  For any U(1) gauge theory there exits a charged particle with

  $$\boxed{q/m > 1\,.}$$

- Strong form:

  The above relation holds for the lightest charged particle.

## Weak gravity conjecture (continued)

- One supporting argument:

  Quantum gravity forbids global symmetries. We should not be able to take the limit of small gauge couplings.

  The WGC quantifies this on the basis of stringy examples.

- Another supporting argument:

  In the absence of sufficiently light, charged particles, extremal BHs are stable. Such remnants are believed to cause inconsistencies.

  see e.g. Susskind '95

  The boundary of stability of extremal black holes is precisely $q/m = 1$ for the decay products

## Generalizations of the weak gravity conjecture

- The basic lagrangian underlying the above is

$$S \;\sim\; \int (F_2)^2 \;+\; m \int_{1-dim.} d\ell \;+\; q \int_{1-dim.} A_1$$

- This generalizes to charged strings, domain walls etc. Crucially, the degree of the corresponding form-field (gauge-field) changes:

$$S \;\sim\; \int (F_{p+1})^2 \;+\; m \int_{p-dim.} dV \;+\; q \int_{p-dim.} A_p$$

with

$$F_{p+1} = dA_p$$

## Generalizations to instantons

- One can also lower the dimension of the charged object, making it a point a in space-time:

$$S \sim \int (d\varphi)^2 + m + q\,\varphi(x_{inst.})$$

- One easily recognizes that this is just a more general way of talking about instantons and axions:

$$m \Leftrightarrow S_{inst.} \quad , \quad q\,\varphi(x_{inst.}) \Leftrightarrow \frac{1}{f}\int \varphi F\tilde{F}$$

## WGC for instantons and inflation

- The consequences for inflation are easy to derive
- First, recall that the instantons induce a potential (after the redefinition $\varphi \to \varphi/f$ to normalize the kin. term)

$$V(\varphi) \;\sim\; e^{-m}\cos(\varphi/f)$$

- Since, for instantons, $q \equiv 1/f$, we have

$$q/m > 1 \qquad \Rightarrow \qquad \boxed{\,m\,f < 1\,}$$

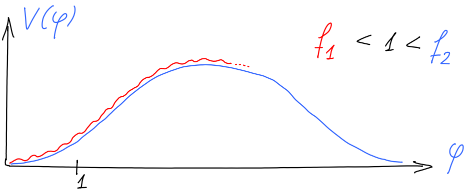
- Theoretical control (dilute instanton gas) requires $m > 1$
- This implies $f < 1$ and hence large-field 'natural' inflation is in trouble

# A Loophole

Rudelius '15

- Suppose that only the mild form of the WGC holds

- In this case, we can have one 'sub-planckian' instanton maintaining the WGC, together with a lighter 'super-planckian' instanton realizing inflation:



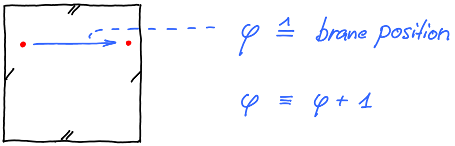

For other arguments and loopholes see e.g.
de la Fuente, Saraswat, Sundrum '14
Bachlechner, Long, McAllister '15
Heidenreich, Reece, Rudelius '15

## What do explicit string constructions have to say about $\Delta\varphi \gg 1$ ?

- The problem is that (more or less) all 4d fields $\varphi$ (moduli) have a small field range.

- An obvious example arises if $\varphi$ is a brane position. Clearly, this field is periodic and the field space is hence limited:

Dvali/Tye '98




- Note: Thus, we naturally get the axionic scalars discussed earlier. But their periodicity is always too short.

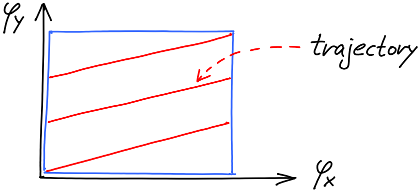
Banks, Dine, Fox, Gorbatov '03

One needs ideas!

# (I) Winding inflation / KNP

Kim/Nilles/Peloso '04; Berg/Pajer/Sjors '09; Ben-Dayan/Pedro/Westphal '14

- One such idea is to realize a 'winding' trajectory on a 2d periodic field space:




- Clearly, such a trajectory can be much longer than the (naive) field range

- The technical challenge is the realization of the required potential in concrete string models

# Winding inflation (continued)

- The fields $\varphi_x$ and $\varphi_y$ are two 'string theory axions', both with $f < 1$ (obeying the WGC)
- They are also moduli. Hence, fluxes (e.g. $\langle F_3 \rangle \neq 0$ on the compact space) can be used to stabilize them
- A judicious choice of fluxes allows for stabilizing just one linear combination, forcing the remaining light field on the winding trajectory:

$$V \supset (\varphi_x - N\varphi_y)^2 + e^{-M}\cos(\varphi_x/f) + e^{-m}\cos(\varphi_y/F)$$

with $N \gg 1$

- This realizes inflation and avoids the WGC!

AH/Mangat/Rompineve/Witkowski '15

## Winding inflation (continued)

- To be more precise, let's change variables:

$$\varphi \equiv \varphi_x \,, \qquad \psi \equiv \varphi_x - N\varphi_y$$

- While $\psi$ is 'frozen', our inflaton $\varphi$ 'sees' both the instantons belonging to $\varphi_x$ as well as those belonging to $\varphi_y$:

$$V \;\supset\; \psi^2 \;+\; e^{-M}\cos(\varphi/f) \;+\; e^{-m}\cos[(\varphi-\psi)/NF]$$

- Crucially, in our proposal the quantities $M$ and $m$ are precisely the type of variables that can be tuned in the landscape (like the vacuum energy)

  ....thus, getting a largish $M$ is not a problem

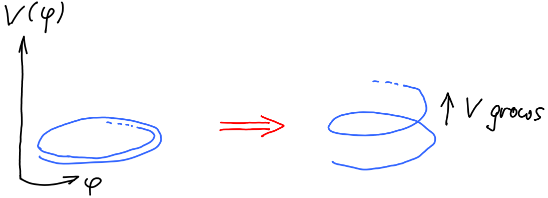
- Stabilizing all the other moduli appears possible, but the details are more complicated than naively expected...

  Buchmüller, Dudas, Heurtier, Westphal, Wieck, Winkler '15

## (II) Monodromy inflation

Silverstein/Westphal/McAllister '08

- We start with a single, periodic inflaton $\varphi$
- The periodicity is then weakly broken by the scalar potential



## *F*-term axion monodromy

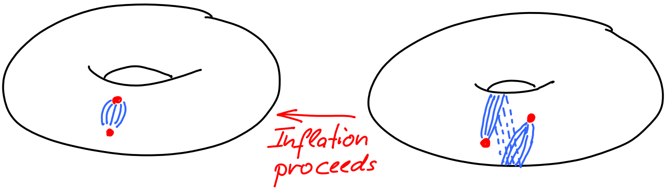
- Very recently, the first suggestions have emerged how this could be realized in a quantitatively controlled way

  (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



## Summary/Conclusions

- Quantum gravity (Instantons / Weak gravity conjecture) may be constraining large-field inflation at a very fundamental level
- Concrete problems with large-field inflation in string theory reflect these fundamental 'issues'
- Progress is being made both in understanding the generic constraints as well as in constructing counterexamples (i.e. models)

In primordial gravity waves / large-field inflation, fundamental quantum gravity problems may meet reality!