

New Ideas on Inflation

(... on Large-Field Inflation in Strings / Quantum Gravity)

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(including work with P. Henkenjohann, S. Kraus, D. Lüst, P. Mangat, J. Moritz,
F. Rompineve, P. Soler, S. Theisen, A. Westphal, L. Witkowski, ...)

Outline

- Why this subtopic?
- Large-field inflation: Issues in quantum gravity / strings

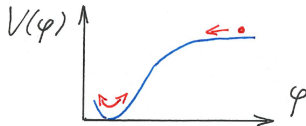
In particular: Weak Gravity Conjecture;
Gravitational instantons;
The Landscape / Swampland paradigm

Single-field slow-roll inflation

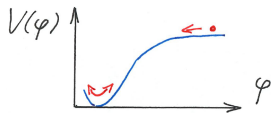
Starobinsky '80; Guth '81

Mukhanov/Chibisov '81; Linde '82

- ... is, in view of the present (e.g. CMB) data, an amazing intellectual achievement.
- Yet, it is also very simply and (embarassingly) versatile
- All you need is $\frac{1}{2}(\partial\varphi)^2 + V(\varphi)$:
- Indeed, virtually any desired potential can be packaged into a reasonable (e.g. technically natural) EQFT model
- Even in supergravity, still, almost anything goes ...



Single-field slow-roll inflation (continued)



- One reason for this freedom is (weakly broken) **shift symmetry**

Freese/Frieman/Olinto '90

- Another is the possibility to **separate** inflationary and reheating regimes (as e.g. in hybrid inflation)

Linde '91; Dvali/Shafi/Schaefer; Copeland et al. '94

- Thus, connections to particle physics (such as GUTs or the Higgs) are needed to make progress

Dvali/Shafi/Schaefer; Copeland et al. '94

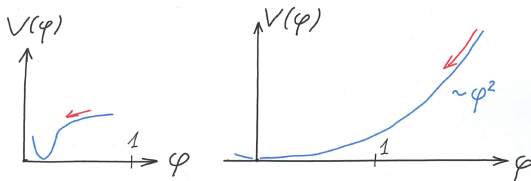
Bezrukov/Shaposhnikov '07

..., Antusch, Covi, Domcke, Buchmüller, ...

- However, one also has to be lucky since such connections are by no means guaranteed...

Inflation and Strings / Small- and Large-Field Models

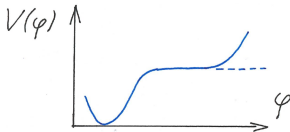
- A possible reaction is to turn to more fundamental constraints & challenges (e.g. from quantum gravity).
- Those look very different for **small** and **large** field models:



- Small field: $V(\phi)$ has some tuned **very flat** region.
 - Large field: '**Generic**' potentials work!
- But: problems with quantum gravity → **most of this talk.**

Small-Field Models (very briefly)

- Recently, the 'Starobinsky' model or, more generally, α -attractor models have received much attention
Starobinsky '80; Kallosh/Linde/Roest '13
- They fit the data well and string theory has a well-known class of models resembling them closely (Fibre Inflation)
Cicoli/Burgess/Quevedo '08; Kallosh/Linde/Roest/Westphal/Yamada '17



- A problem is the multitude of other similar models in the landscape, and the generally rather significant tuning / model-building-complexity

Let us now focus on

Large-Field Models in Quantum Gravity

and discuss the reasons for this choice in more detail:

1) Observations

- Recall the relation of tensor-to-scalar ratio and field-range:

$$r \equiv \frac{\Delta_T^2}{\Delta_R^2} = 16\epsilon \quad \Leftrightarrow \quad \Delta\varphi \simeq 20\sqrt{r} \quad \text{Lyth '96}$$

- The Planck/BICEP bounds are now somewhere near $r \simeq 0.1$.
- This will improve and we will see the discovery or demise of large-field models.
cf. talk by R. Flauger
- If we manage (see below) to show that string theory forbids $\Delta\varphi > 1$, we can hope to rule out string theory!

...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

.....

Kaloper/Kleban/Lawrence/Sloth '15

- This goes hand in hand with persistent problems in constructing large-field models in string theory.

- However, triggered by BICEP and building on earlier proposals

Kim, Nilles, Peloso '07

McAllister, Silverstein, Westphal '08

new promising classes of stringy large-field models have been constructed (e.g. F -term axion monodromy)

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, Reece, Heidenreich '14...'15

Ibanez, Montero, Uranga, Valenzuela '15

Brown, Cottrell, Shiu, Soler '15

AH, Mangat, Rompineve, Witkowski '15

...

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

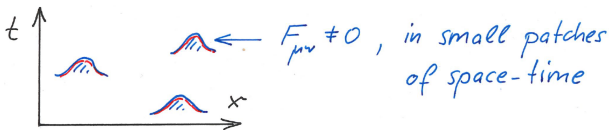
Natural (axionic) inflation in string theory

Freese/Frieman/Olinto '90

- In 4d effective theories of string compactifications, **axion-like fields** are abundant:

$$\mathcal{L} \supset -\frac{1}{2}(\partial\varphi)^2 - \frac{1}{32\pi^2} \left(\frac{\varphi}{f}\right) \text{tr}(F\tilde{F}).$$

- The shift symmetry is generically broken by **instantons**:



$$\Rightarrow V_{\text{eff}} \sim \cos(\varphi/f), \quad \varphi \equiv \varphi + 2\pi f.$$

- I will focus on two ideas for **enlarging the axionic field range** without losing calculational control:

(a) KNP Kim/Nilles/Peloso '04

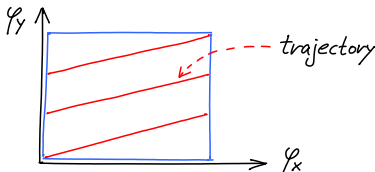
(b) Axion-Monodromy McAllister/Silverstein/Westphal '08

- The **No-Go arguments** alluded to earlier challenge these possibilities.

(a) KNP / Winding inflation

Kim/Nilles/Peloso '04; Berg/Pajer/Sjors '09; Ben-Dayan/Pedro/Westphal '14
(cf. also Choi/Im, Kaplan/Rattazzi '15)

- Consider a 'winding' trajectory on a 2d periodic field space:



- Clearly, such a trajectory can be much longer than the (naive) field range
- But: It is hard to realize the required potential in concrete string models
- Thus, even getting only an effective trans-planckian axion appears to be difficult. Is there a fundamental reason?

No-go argument I: Weak gravity conjecture

Arkani-Hamed/Motl/Nicolis/Vafa '06

- Some recent papers developing this in (more or less close) relation to large-field inflation:

Cheung/Remmen; de la Fuente/Saraswat/Sundrum ... '14

Rudelius; Ibanez/Montero/Uranga/Valenzuela; Brown/Cottrell/Shiu/Soler;

Bachlechner/Long/McAllister; AH/Mangat/Rompineve/Witkowski;

Junghans; Heidenreich/Reece/Rudelius; Kooner/Parameswaran/Zavala;

Harlow; AH/Rompineve/Westphal; ... '15

Ooguri/Vafa, Conlon/Krippendorf ... '16

Dolan/Draper/Kozaczuk/Patel; AH/Henkenjohann/Witkowski/Soler ... '17

Weak gravity conjecture

- Roughly speaking: 'Gravity is always the weakest force.'
- More concretely (mild form):
For any U(1) gauge theory there exists a charged particle with

$$q/m > 1.$$

- Strong form:
The above relation holds for the lightest charged particle.

Weak gravity conjecture (continued)

- The historical 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

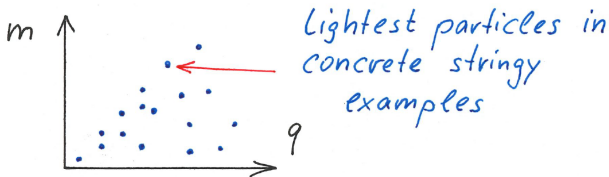
The boundary of stability of extremal black holes is precisely $q/m = 1$ for the decay products.

Weak gravity conjecture (continued)

- Another (possibly stronger?) 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.



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

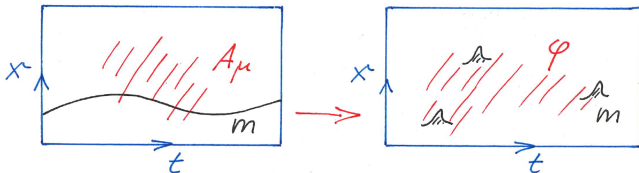
- One can also **lower** the dimension of the charged object, making it a point in space-time:

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

This should be compared with

$$\text{cf. } S \sim \int (d\varphi)^2 + \int \text{tr}(F^2) + \int \left(\frac{\varphi}{f}\right) \text{tr}(F\tilde{F}),$$

$$\text{where } \int \text{tr}(F^2) \sim S_{inst.} \sim m.$$



WGC for instantons and inflation

- The consequences for inflation are easy to derive.
- First, recall that the instantons induce a potential

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

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

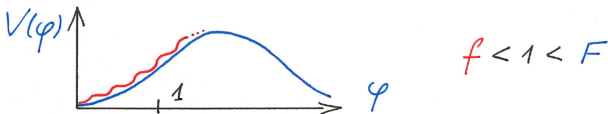
$$q/m > 1 \quad \Rightarrow \quad mf < 1.$$

- 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.
- We can have one **heavy** instanton (large F , large M) for the WGC, and one **light** instanton (small f , small m) for inflation.



- In a recent string-theoretic model ('Winding Inflation') of natural inflation **precisely** this loophole is automatically realized.

AH/Mangat/Rompineve/Witkowski '15

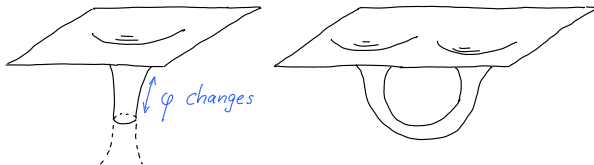
For other arguments and loopholes see e.g.
de la Fuente, Saraswat, Sundrum '14
Bachlechner, Long, McAllister '15.

No-go argument II: (Gravitational) instantons

- In Euclidean Einstein gravity, supplemented with an axionic scalar φ , instantonic solutions exist:

Giddings/Strominger '88

...



- The 'throat' is supported by the kinetic energy of $\varphi = \varphi(r)$, with r the radial coordinate of the throat/instanton.
- The relevance for inflation arises through the induced instanton-potential for the originally **shift-symmetric** field φ .

Montero/Uranga/Valenzuela '15

(cf. also Bachlechner/Long/McAllister; Heidenreich/Reece/Rudelius '15

Gravitational instantons (continued)

- These objects come with instanton number $n = 1, 2, \dots$ and action $S \sim n/f$.
- Their maximal curvature scale is $\sqrt{f/n}$, which should not exceed the UV cutoff:

$$f/n < \Lambda^2$$

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

$$\delta V \sim e^{-S} \sim e^{-n/f} \sim e^{-1/\Lambda^2}$$

- It is easy to convince oneself that, in low-cutoff models, natural inflation can not be ruled out.

Can one at least obtain reasonably model-independent bounds in high-cutoff models ?

AH/Mangat/Theisen/Witkowski '16

- Look at the case where we expect the strongest bound:
A string model with $g_s = 1$ on T^6 at **self-dual** radius.
- Need to decide when to trust a wormhole / extremal instanton
(i.e., what is the smallest allowed S^3 -radius r_c)

The following two choices appear 'natural':

$$2\pi^2 r_c^3 = \mathcal{V}_{\text{self-dual}}^{1/2} \quad \text{and} \quad 2\pi r_c = \mathcal{V}_{\text{self-dual}}^{1/6}$$

- One finds:

First case: $r_c M_p \simeq 1.3$

Second case: $r_c M_p \simeq 0.56$

- The crucial numerical effect comes from the π 's in the instanton action:

$$S_{inst.} = 3\pi^3 (r_c M_p)^2$$

- The correction to the potential is suppressed as

First case: $e^{-S} \simeq 10^{-68}$

First case: $e^{-S} \lesssim 10^{-13}.$

- Thus, one needs to look into the quantum-gravity regime of gravitational instantons.
- For recent work on bounds from gravitational instantons in the **small- f regime**, see

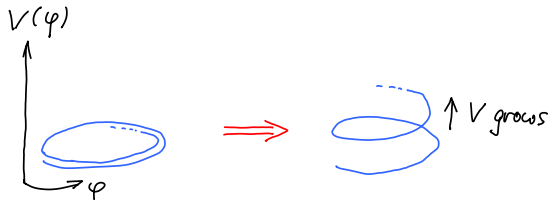
Alonso/Urbano '17

(c) Monodromy inflation

Silverstein/Westphal/McAllister '08

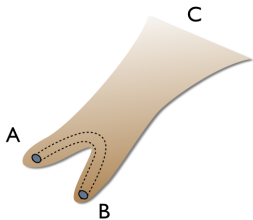
Very general but simple-minded definition:

- Start with a single, shift-symmetric, periodic inflaton φ
- Break the periodicity **weakly** by the scalar potential



The 'classical' model ...

$$S_{\text{NS5}} \sim \int \sqrt{-\det(g_{\mu\nu} + F_{\mu\nu} + C_{\mu\nu})}$$



Bifid throat with shared 2-cycle
(figure from Retolaza et al. '15)

... has issues with the explicit geometry and quantitative control.

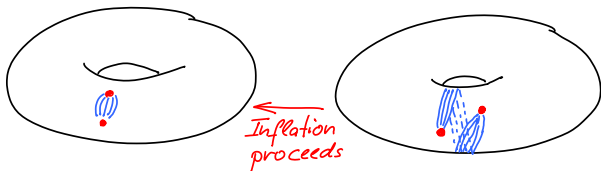
For recent progress see e.g. McAllister/Silverstein/Westphal/Wrase '14
...
Retolaza/Uranga/Westphal '15

F-term axion monodromy

- More recently, classes of monodromy models with 4d supergravity description and stabilized compact space have emerged.

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

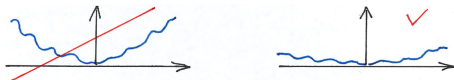
- One option is that inflation corresponds to **brane-motion**
Dvali/Tye '98....Dasgupta et al. '02....Lüst et al. '11
- The monodromy arises from a flux sourced by the brane



Challenges in axion monodromy

- It remains controversial whether one can (e.g by tuning) make the monodromy as **small** as necessary for moduli stabilization

cf. recent work by Blumenhagen, Valenzuela, Palti, Marchesano,... (and by our group)



- The WGC applies only indirectly (in its domain-wall version), but the constraints are not strong enough for inflation

Brown/Cottrell/Shiu/Soler, Ibanez/Montero/Uranga/Valenzuela, AH/Rompineve/Westphal '15

- It has been attempted to use the **Swampland Conjecture** to argue against axion monodromy inflation

Baume/Palti, Klaewer/Palti '15 ... '16

The Landscape/Swampland paradigm and the Size of Moduli Spaces

- The idea is to ask **which subset of effective theories** can be UV-completed in Strings (or Quantum Gravity in general)

Vafa '05, Ooguri/Vafa '06

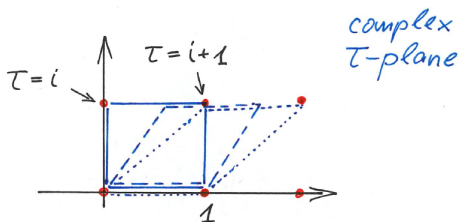
- The WGC may be viewed as **one particular instance** of this
- One suggested criterium is that, “**as we move a distance L in moduli space, the cutoff must come down as $\exp(-L)$.**”

In the present context, see especially Palti et al.

- I will try to explain this using the toy model of a **torus moduli space** and make some new observations

AH/Henkenjohann/Witkowski 1708.06761

- Recall that a torus can be viewed as a lattice in $\mathbb{C}$ and its shape is parametrized by $\tau \in \mathbb{C}$.



- There are many identifications (e.g. $\tau = i$ and $\tau = i + 1$ correspond to the same torus)
- Moreover, the metric in the τ -plane (both in math in the 4d EFT with a complex modulus field τ) reads

$$ds^2 = \frac{d\tau d\bar{\tau}}{4(\text{Im}\tau)^2} \quad \text{'Hyperbolic plane'}$$

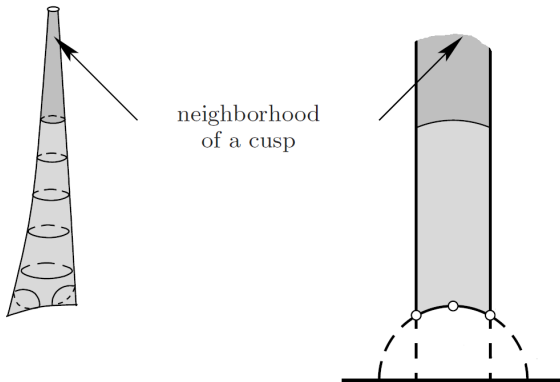


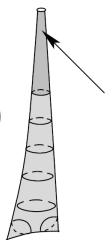
Fig. from A. Zorich, 'Flat surfaces'

- The fundamental domain is an infinitely long, vertical strip with $i \times \infty$ corresponding to a very thin torus.

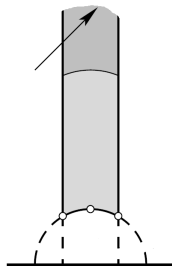


- The modulus space has an **infinite extension**, but the cutoff comes down exponentially fast if one goes there (due to light winding strings).

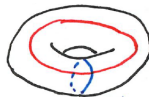
- The 'axionic' horizontal direction is at most $\mathcal{O}(1)$ in size ($f \lesssim M_p$)



neighborhood
of a cusp

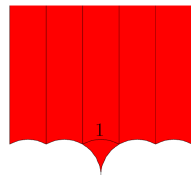
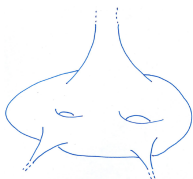


- Now, if the torus carries **flux** (think of rubber bands marking the cycles), the picture changes.

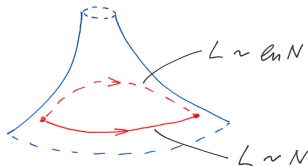


- Some of the identifications are lost and the **fundamental domain increases** ($\rightarrow$ fund. domain of congruence subgroups of $SL(2, \mathbb{Z})$).

- The cusp or 'throat' becomes much wider (super-planckian f),



...but the geodesic distances remain short ($\sim \ln(1/\text{cutoff})$)



- We formulate this in a '**moduli space size conjecture**' which tries to unify axionic WGC and Swampland Conjecture
- The implications for inflation require further work....

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!