Axionic Field Ranges, Weak Gravity, and Euclidean Wormholes

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including work with

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and work in progress with P. Soler and T. Mikhail

Outline – Part I

- Extending axionic field ranges by gauging
- Interplay with the Swampland (Distance) Conjecture

Outline – Part I

- Conjecture-independent constraints from gravitational instantons / wormholes ?
- General importance of wormholes (a reminder)

Motivation

- Inflation (and cosmology more generally) might produce evidence for large field displacements: $\Delta\varphi \gg M_P$.

- This is hard to realize in string theory and may be constrained by general no-go theorems in quantum gravity ...

  Banks, Dine, Fox, Gorbatov '03

  The swampland conjecture

  Vafa '05, Ooguri/Vafa '06

  The weak gravity conjecture

  Arkani-Hamed/Motl/Nicolis/Vafa '06

- However, even accepting (certain forms of) these conjectures, the implications for large $\Delta\varphi$ are far from clear

- A unique opportunity to confront quantum gravity and reality!

Introduction: Weak Gravity Conjecture

- Roughly speaking: 'Gravity is always the weakest force.'
- More technically: As a 4d $U(1)$ gauge coupling goes to zero, $g \to 0$, the low-energy EFT develops a global symmetry.
- This should be censored. The censoring occurs by new physics at the scale $\Lambda \sim gM_P$, which also goes to zero.

  (It could involve one or many charged particles, a cutoff, ...
  $\to$ different forms of the conjecture.)

cf. talks by Rudelius, Ibanez, Shiu, Cottrell, ...

Introduction: Weak Gravity Conjecture for axions

- For axions, the charged 'particles' are the instantons:

$$S \sim \int f^2 \, (\partial\varphi)^2 \; + S_{inst} + i\varphi(x_{inst.})\,.$$

- With the substitution $g \to 1/f$ and $m \to S_{inst}$ one finds

$$m < gM_P \qquad \Rightarrow \qquad S < M_P/f \;.$$

Thus, for $f > M_P$, the instanton-induced potential

$$V(\varphi) \;\sim\; e^{-S_{inst}} \cos(\varphi) + e^{-2S_{inst}} \cos(2\varphi) + \cdots$$

becomes uncontrolled and large f appears to be censored.

Introduction: The Swampland Conjecture

- Roughly speaking: 'If one moves a long distance in field space, the cutoff comes down exponentially.'

- Here, the relation to inflation (not axionic but rather modulus-inflation) is immediate.

- Note however that, phenomenologically, $H \ll M_P$, so the above is not necessarily a problem.

  For recent work developing

  Vafa '05, Ooguri/Vafa '06

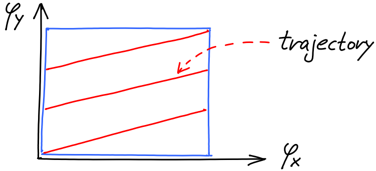
  see, e.g.

  Palti/Baume, Palti/Klaewer '16, Blumenhagen/Valenzuela/Wolf, AH/Henkenjohann/Witkowski '17, Heidenreich/Reece/Rudelius, Grimm/Palti/Valenzueala '18

Winding Inflation

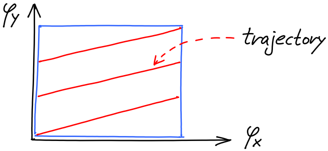
- Now, let us see how far one gets in terms of 'counterexamples':
- Even in a small field space a long trajectory can be realized if the potential is appropriate.

Kim/Nilles/Peloso '04



- However, getting such an 'instantonic' potential is hard and may in particular be forbidden by the WGC.

Winding Inflation (continued)



- But there is a simple, perturbative way of enforcing the desired trajectory: By gauging à la Dvali.

- We will refer to this as 'Winding Inflation'.

AH/Mangat/Rompineve/Witkowski '14

$$|F_0|^2 \quad \to \quad |F_0 + \varphi_x + N\varphi_y|^2$$

- This is can be realized very explicitly in the flux landscape, with N being the flux number.

Concrete realization at (partially) large complex stucture

- Let $z_1, \cdots, z_n, u, v$ be complex structure moduli of a type-IIB orientifold, let $\mathrm{Im}(u) \gg \mathrm{Im}(v) \gg 1$.

$$K = -\log\left(\mathcal{A}(z, \overline{z}, u - \overline{u}, v - \overline{v}) + \cdots e^{2\pi i v} + \mathrm{c.c.}\right)$$

$$W = w(z) + f(z)(u - Nv) + \cdots e^{2\pi i v}$$

- Without exponential terms, it is clear that W leaves one of the originally shift-symmetric directions $\mathrm{Re}(u)$ and $\mathrm{Re}(v)$ flat
- In supergravity, generically: fluxes $\leftrightarrow$ gauging
- Remarkably, the subleading cosine-potentials 'conspire' to fulfil at least the so called 'mild form' of the WGC

An Aside:

- Recently, the same gauging idea has been discussed as a way to evade the WGC for 1-forms.

  Saraswat '16

- My personal feeling is that

  (a) This is very interesting to explore further.

  (b) It may fail since the UV theory may not permit $N \gg 1$ together with $\Lambda \sim M_P$, as required.

- The technical reason might be as follows:

$$N \gg 1 \;\Rightarrow\; \text{Ratio of certain radii is large (e.g. } R_A/R_B \gg 1\text{)}$$
$$\Rightarrow\; \Lambda \ll M_P .$$

(This logic is not applicable in the axionic case since Λ does not enter. See, however, below....)

A simple, torus-based model for transplanckian axions

(toy-model for winding inflation)

- Type IIB on $T^6/\mathbb{Z}_2$ with 64 O3 planes.
- Using standard technology, we can generate

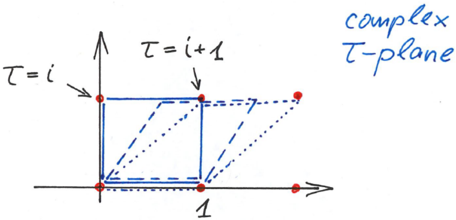
  $W = (M\tau_1 - N\tau_2)(\tau - \tau_3)$

  Kachru/Schulz/Trivedi '02
  Gomis/Marchesano/Mateos '05
  ...

  (The explicit F_3/H_3 is easy to state.)

- In the interests of time, the rest will be described in pictures...

- 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

$$ds^2 = \frac{d\tau\, d\overline{\tau}}{4\,(\mathrm{Im}\tau)^2}$$

'Hyperbolic plane'

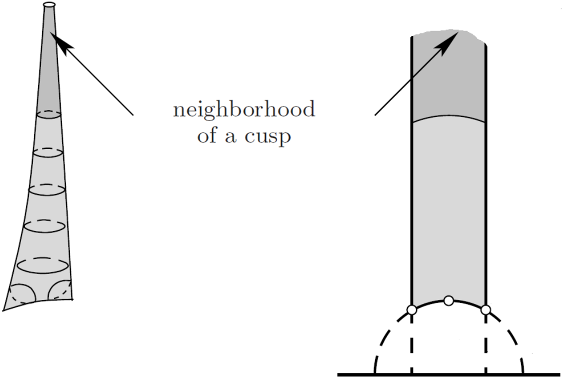
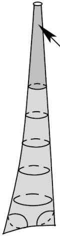
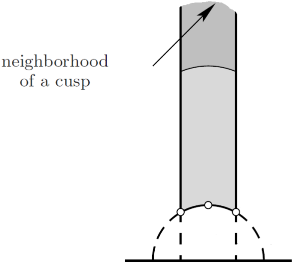


Fig. from A. Zorich, 'Flat surfaces'

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

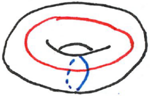
- The modulus space has an infinite extension, but the cutoff comes down exponentially fast if one goes there (due to light winding strings).





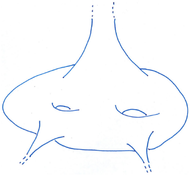
- The 'axionic' horizontal direction is at most $\mathcal{O}(1)$ in size ($f \lesssim M_p$)

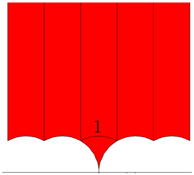
- Now, if the torus carries flux (think of rubber bands marking the cycles), the picture changes.



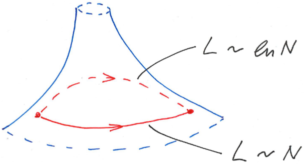
- Some of the identifications are lost and the fundamental domain increases ($\equiv$ fund. domain of congruence subgroups of $SL(2,\mathbb{Z})$).

- 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 the axionic WGC and Swampland Conjecture

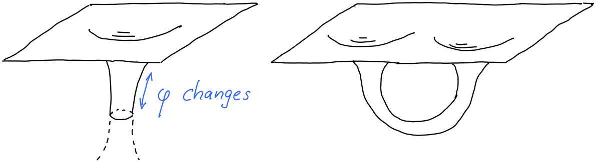
Intermediate summary / transition to part II

- It appears that the swampland conjecture extends in a non-trival way to axions.
- This extension does not preclude transplanckian f.
- Implications for large-field inflation are not a priori negative.
- One needs more detailed explicit stringy models and/or finer conjectures (work in Progress Palti, Junghans, Schachner...)
- In the meantime, let us return to 'generic quantum gravity' and how it breaks shift symmetry in a 'conjecture-independent' way ....

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

Gravitational instantons (continued)

- The underlying lagrangian is simply

$$\mathcal{L} \sim \mathcal{R} + f^2 |d\varphi|^2 \,, \quad \text{now with} \quad \varphi \equiv \varphi + 2\pi \,.$$

- This can be dualized $(dB_2 \equiv f^2 * d\varphi)$ to give

$$\mathcal{L} \sim \mathcal{R} + \frac{1}{f^2} |dB_2|^2 \,.$$

- The 'throat' exists due the compensation of these two terms. Reinstating M_P, allowing n units of flux (of $H_3 = dB_2$) on the transverse S^3, and calling the typical radius R, we have

$$M_P^2 \, R^{-2} \sim \frac{n^2}{f^2} R^{-6} \quad \Rightarrow \quad M_P \, R^2 \sim \frac{n}{f} \,.$$

Gravitational instantons (continued)

- Returning to units with $M_P = 1$, their instanton action is

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

- 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 $V(\varphi)$:

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

Gravitational instantons (continued)

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

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

- 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....

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

AH, Mangat, Rompineve, Witkowski '15

- At least for high-cutoff models:

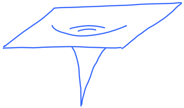
  Can one obtain a reasonably model-independent bound from gravitational instantons?

AH/Mangat/Theisen/Witkowski '16

Note:

- Our analysis also includes the closely related issue of (singular) 'cored instantons', which have been brought up by

Heidenreich, Reece, Rudelius '15



- For recent work on the emedding in string theory see...

Hertog/Trigiante/Van Riet '17

Very rough summary of results

- 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':

$$2\pi^2 r_c^3 = \mathcal{V}_{self-dual}^{1/2} \quad \Rightarrow \quad r_c M_P \simeq 1.3 \quad \Rightarrow \quad e^{-S} \simeq 10^{-68}$$

$$2\pi r_c = \mathcal{V}_{self-dual}^{1/6} \quad \Rightarrow \quad r_c M_P = \simeq 0.56 \quad \Rightarrow \quad e^{-S} \simeq 10^{-13}$$

Surprisingly weak bounds!

...However, beyond inflation, wormholes remain very interesting, both conceptually and phenomenologically

Gravitational instantons - Small-f axions

see e.g. Alonso/Urbano '17

- For example, for a QCD axion with (relatively) high f, the wormhole effect might be relevant:

$$V(\varphi) = \Lambda_{QCD}^4 \cos(\varphi) + r_c^{-4} e^{-S_w/2} \cos(\varphi + \delta) \, .$$

- It turns out that for $f \gtrsim 10^{16}$ GeV the solution to the strong CP problem is lost.

- Interesting positive observational consequences exits in the context of black-hole superradiance and ultralight dark matter.

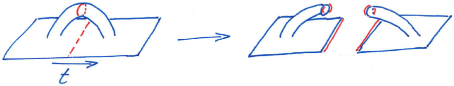
Gravitational instantons / wormholes - conceptual issues

- Motivated by the above, it is worthwhile revisiting some very fundamental conceptual issues of (euclidean) wormholes.

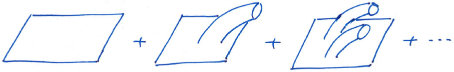
  Hawking '78..'88, Coleman '88, Preskill '89
  Giddings/Strominger/Lee/Klebanov/Susskind/Rubakov/Kaplunovsky/..
  Fischler/Susskind/...

  Review by AH, P. Soler, T. Mikhail, ...to appear...

- First, once one allows for wormholes, one has to allow for baby universes.

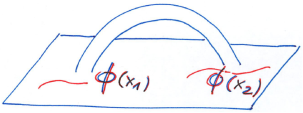


- Second, with baby universes comes a 'baby universe state' (α vacuum) encoding information on top of our 4d geometry.



Conceptual issues (continued)

- Crucially, α-parameters remove the disastrous-looking bilocal interaction.



$$\exp\left(\int_{x_1}\int_{x_2}\Phi(x_1)\Phi(x_2)\right) \quad \rightarrow \quad \int_\alpha \exp\left(-\frac{1}{2}\alpha^2+\alpha\int_x\Phi(x)\right)$$

- In our concrete (single-axion) case, an α parameter now governs the naively calculable $e^{-S}\cos(\varphi/f)$-term.
- But, what is worse, all coupling constants are 'renormalized' by α parameters are hence not predictable in principle.

Conceptual issues (continued)

- Most naively, 4d measurements collapse some of the many α parameters to known constants.

- But in a global perspective, both different 4d geomtries and α parameters have to be integrated over.

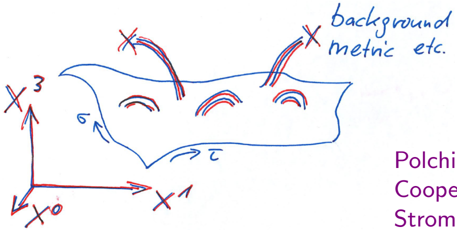
- But this leads to the
  'Fischler-Susskind-Kaplunovsky catastrophy'.

- The problem is that, through certain higher operators, high densities of even very large wormholes are rewarded;
  $\rightarrow$ exponential suppression overcome.

- Finally, just integrating over the α parameters is clearly not sufficient - one needs to consider their full quantum dynamics.

Conceptual issues (continued)

- Indeed, consider the case of 1+1 dimensions with a number of scalar fields (in addition to gravity).
- This is, of course, well known as string theory and the α parameters characterize the geometry the target space.



Polchinski, Banks/Lykken/O'Loughlin, Cooper/Susskind/Thorlacius, Strominger '89...'92

- The latter has a quantum dynamics of its own, the analogue of which in case of 3+1 dimensions is completely unknown.
- All this raises so many complicated issues, that one might want to dismiss wormholes altogether.

Conceptual issues (continued)

- But this is not easy, for example because we know that in string theory wormholes correspond to string loops and are a necessary part of the theory.

- Thus, forbidding for example topology change in general does not appear warranted.

- Is there a good reason to forbid topology change just in $d > 2$?

- Arguments have been given that the euclidean Giddings-Strominger solution has negative modes and should hence be dismissed.

  Rubakov/Shvedov '96, Maldacena/Maoz '04, see however Alonso/Urbano '17, ...

- But, while this is even technically still an open issues, it does not appear to be a strong enough objection ....

Conceptual issues (continued)

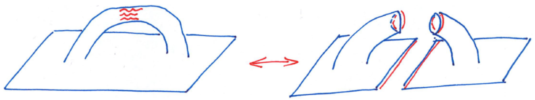
- Indeed, once a non-zero amplitude

$$\text{universe} \;\rightarrow\; \text{universe} \;+\; \text{baby-universe}$$

  is accepted, the reverse process is hard to forbid.

- As a result, one gets all the wormhole effects.

- The negative mode issue may be saying:
  'Giddings-Strominger' does not approximate the amplitude well.



- ..hard to see, how it would dispose of the problem altogether..

For further problems (and possible resolutions) see e.g.
Bergshoeff/Collinucci/Gran/Roest/Vandoren/Van Riet '04,
Arkani-Hamed/Orgera/Polchinski '07, Hertog/Trigiante/Van Riet '17

Summary/Conclusions

- Axionic directions may be extended in fluxed geometries, violating a possible 'subplanckian f conjecture'

- But the corresponding moduli-space-size does not grow faster than logarithmic. Consequences for inflation remain open....

- Euclidean wormholes are the universal, semiclassical counterpart of instantons

- They do not constrain inflation strongly, but may have other pheno applications 'at small f'

- They come at the price of α vacua (and other disasters)

- Worthwhile reviving this fundamental unresolved issue?