Constraints on Axion Inflation from the Weak Gravity Conjecture

Tom Rudelius

T.R., 1409.5793/hep-th, 1503.00795/hep-th
Ben Heidenreich, Matt Reece, T.R., 1506.03447/hep-th
+ Work in Progress

Department of Physics
Harvard University

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Outline

Section 1

Inflation

The CMB

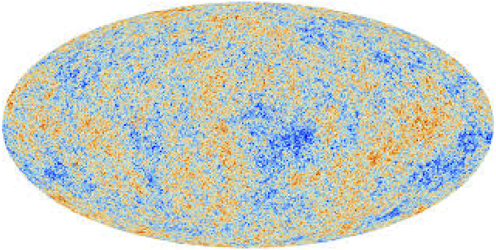


Figure 1 : The CMB, measured by the *Planck* collaboration [Ade '13].

- Image of last scattering surface, remnant of $t = 380,000$ years.
- Note large-scale homogeneity, large-scale correlations.

Inflation

Problem: Why is the universe so flat and homogenous?

Solution: Inflation.

(Period of quasi-exponential growth $a(t) \approx e^{Ht}$ in the early universe.)

Slow-Roll Inflation

- Inflation can be thought of as the theory of a ball rolling down a hill with friction.

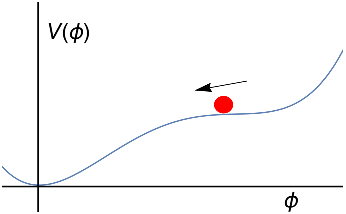


Figure 2 : The inflaton rolling down its potential.

- Slow roll parameters encode relevant features of potential:

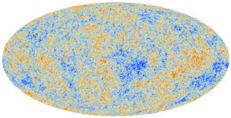
$$\epsilon_V = \frac{M_p^2}{2}\left(\frac{V'(\phi)}{V(\phi)}\right)^2, \quad \eta_V = M_p^2 \frac{V''(\phi)}{V(\phi)}. \tag{1}$$

Slow-Roll Inflation

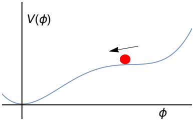
- Measurable quantities are determined by the slow-roll parameters,

$$r_* \approx 16\epsilon_V^* \quad (2)$$

$$n_s^* - 1 \approx 2\eta_V^* - 6\epsilon_V^*. \quad (3)$$



Experiment



Theory

Planck and BICEP2 Data

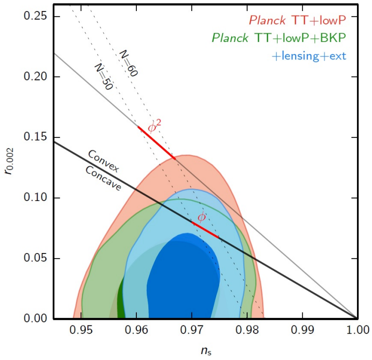


Figure 3 : *Planck* and BICEP2 measurements give a best fit value of $r_* = 0.05$. $r_* < 0.075$ at 95% CI when lensing + ΛCDM+noise+dust are taken into account. $r_* > 0$ at 92% CI [Ade '15a, Ade '15b].

Implications of a Large r_*

- A large r_* implies a large first derivative of the potential, and hence a fast-moving inflaton.
- Distance $=$ Rate $\times$ Time $\Rightarrow$ r_* is thus related to the distance traveled by the inflaton via the 'Lyth bound' [Lyth1996],

$$\Delta\phi \gtrsim \left(\frac{r_*}{0.01}\right)^{1/2} M_p. \tag{4}$$

- **A detectable tensor-to-scalar ratio implies a trans-Planckian traversal of the inflaton during the course of its slow-roll.**

EFT of Inflation

- EFT for inflaton [Cheung '07]:

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_l(\phi) + \sum_i c_i \frac{\phi^{\delta_i}}{\Lambda^{\delta_i - 4}} + \ldots . \tag{5}$$

- When ϕ is of order M_p, higher dimension terms cannot be neglected. One expects large corrections to the potential on scales M_p, destroying the flatness needed for slow-roll inflation.
- Solution: impose a shift symmetry $\phi \to \phi + a$, potential vanishes.

Possible Solution: Axions

- Shift symmetry broken to discrete subgroup by instanton effects,

$$V(\phi) = \Lambda^4(1 - \cos\frac{\phi}{f}) + (\Lambda^{(2)})^4(1 - \cos\frac{2\phi}{f}) + ... \quad (6)$$

- Higher harmonics can typically be neglected.

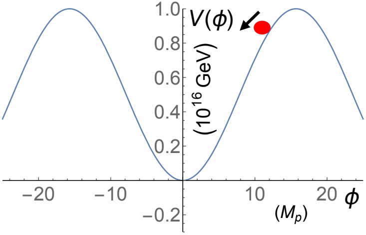


Figure 4 : Axion potential with $f = 4M_p$.

Axions in String Theory

- Axions are ubiquitous in string compactifications, arising from *p*-forms integrated over *p*-cycles.
- But...axion decay constants in string theory are constrained to be $\mathcal{O}(M_p)$ or smaller [Banks '03], making them unsuitable for inflation.

Three Popular Solutions:

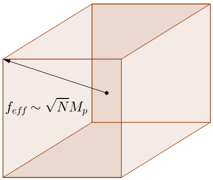


Figure 5 : *N*-flation [Dimopoulos '05]

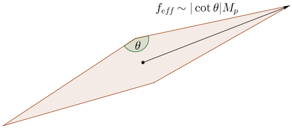


Figure 6 : Decay Constant Alignment [Kim '04]

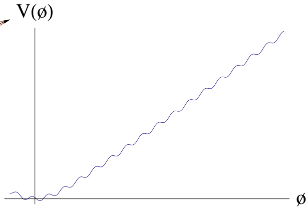


Figure 7 : Axion Monodromy [McAllister '08, Silverstein '08, Flauger '09]

Section 2

The Weak Gravity Conjecture

The Weak Gravity Conjecture

The (Mild) Weak Gravity Conjecture [Arkani-Hamed '06]

Any consistent theory with a $U(1)$ gauge field admitting a UV completion with gravity must contain a state with charge to mass ratio greater than that of an extremal black hole:

$$\frac{q}{m} \geq \frac{Q}{M}\Big|_{\text{extremal BH}} \tag{7}$$

The Strong Weak Gravity Conjecture [Arkani-Hamed '06]

The particle satisfying (7) must be the lightest charged particle in the spectrum.

Why Should the Weak Gravity Conjecture Be True?

- If not, extremal black holes will be unable to decay $\Rightarrow$ BH remnants.

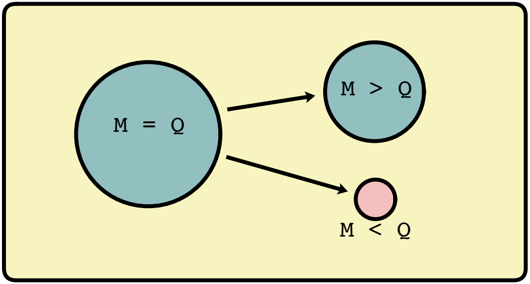


Figure 8 : Charged black hole decay.

Why Should the Weak Gravity Conjecture Be True?

- Many examples in string theory obey the WGC [Arkani-Hamed '06].

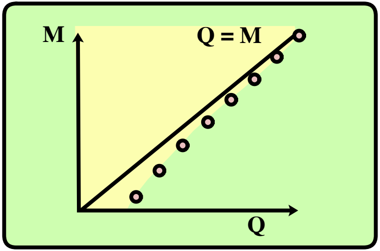


Figure 9 : Charged black hole decay.

- No counterexamples to the mild or strong form (see however [Heidenreich, to appear]).

The Generalized Weak Gravity Conjecture

- We have so far dealt with 1-form gauge fields in 4d. It is natural to generalize this to arbitrary p-forms and d spacetime dimensions.

The Generalized Weak Gravity Conjecture

Consider a p-form Abelian gauge field in any number of dimensions d. Then, there exists an electrically charged $p-1$ dimensional object with tension,

$$T_{el} \lesssim \left(\frac{g^2}{G_N}\right)^{1/2}$$

- The “strong form” holds that this should be the charged object of smallest tension.

Axions and the Weak Gravity Conjecture

- Consider the case of a 0-form ϕ (i.e. an axion) in 4d. The generalized WGC then says that there must exist a -1-dimensional object (instanton) with tension,

$$T \lesssim \frac{M_p}{f}. \tag{8}$$

- But, this T is just the instanton action S. If we impose $S > 1$, we find

$$1 < S \lesssim \frac{M_p}{f} \Rightarrow f < M_p. \tag{9}$$

- Thus,

The Generalized WGC $+$Instanton Action > 1	$\Rightarrow$	Decay constants larger than M_p are forbidden!

The N-Species Weak Gravity Conjecture

- Suppose we have not 1, but N 1-form gauge fields.
- The N-species weak gravity conjecture holds that the convex hull of the charge-to-mass vectors $\pm\vec{z}_i = \pm\frac{\vec{q}_i}{m_i}M_p$ must contain the N-dimensional unit ball.

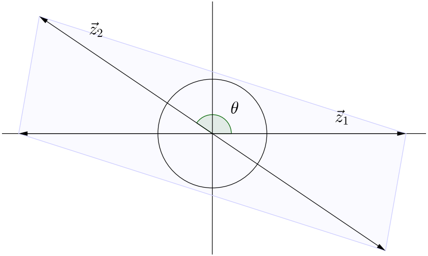


Figure 10 : The convex hull condition.

Section 3

WGC Constraints on Axion Inflation

The N-Species Axion WGC

- So far, we have seen two extensions of the WGC:
  - The "generalized" WGC for p-form gauge fields.
  - The "N-species" WGC for multiple gauge fields.
- It is natural to consider: what happens when we put these two together?

Axion Inflation Models and the WGC

The Main Point

"Vanilla" models of N-flation and decay constant alignment are both ruled out by the WGC.

WGC Implications for Inflation:

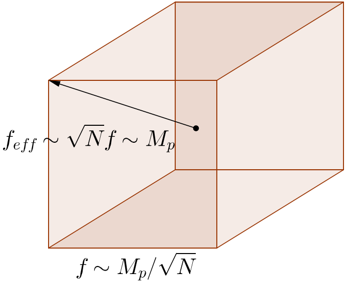


Figure 11 : *N*-flation

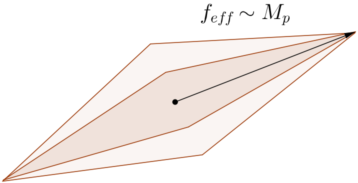


Figure 12 : Decay Constant Alignment

Section 4

Loopholes

Loopholes in the WGC

- Our derivation of the bound on axion moduli spaces relied crucially on two assumptions:
  1. Instanton actions larger than 1 $\Rightarrow$ the "small action loophole."
  2. No additional instantons satisfying the bound $\Rightarrow$ the "extra particle loophole."

The Extra Particle Loophole

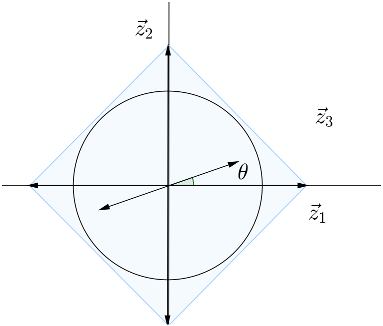


Figure 13 : A model with three charge vectors and two axions. Although the generalized weak gravity conjecture still constrains the size of moduli space, one could achieve a large inflaton traversal as long as the potential contributions from $\vec{z}_3$ dominate those from $\vec{z}_2$.

Closing the Extra Particle Loophole

- A "strong" form of the WGC holds that the particles of minimal action should satisfy the convex hull condition, which would close the loophole (but is it true?).
- This loophole can also sometimes be closed by the magnetic WGC [de la Fuente '14, Heidenreich '15].

Section 5

Conclusions and Directions for Future Research

Conclusions

- The WGC rules out vanilla models of N-flation and axion decay constant alignment.
- Evidence for this conjecture comes from arguments regarding black holes and examples in string theory.
- There are loopholes which would allow natural inflation consistent with the WGC, and there are (unverified) conjectures that would close these loopholes.

Outstanding Questions

- Is the mild WGC necessarily true in any consistent theory of quantum gravity?
  - If so, is the strong WGC true?
  - If not, what else could explain the sub-Planckian decay constants of string theory?
- Does the mild WGC place important constraints on realistic models in string theory, or are the aforementioned loopholes readily exploited?
- Can one place similar constraints on axion monodromy inflation?
- Is the WGC pointing us toward something even more fundamental about quantum gravity?

For Further Reading I

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