THRAXIONS:

ULTRALIGHT THROAT AXIONS

based on [1512.04463] with Arthur Hebecker, Alexander Westphal and Lukas T. Witkowski

and [1812.03999] with A. Hebecker, Sascha Leonhardt and A. Westphal

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MOTIVATION

▶ Is large field inflation possible in string theory?
▶ Pheno’ interest: Observable primordial tensor modes require super-Planckian inflationary trajectories in field space:

\[ \Delta \phi \gtrsim \left( \frac{r}{0.01} \right)^{1/2} M_p \]

[Lyth ’96]

▶ Moreover: We learn lessons about global properties of string moduli spaces, and scalar potentials.

[Ooguri, Vafa’06; Rudelius’15; Brown, Cottrell, Shiu, Soler’15; Bachlechner, Long, McAllister’15; Klaewer, Palti’16; Blumenhagen, Valenzuela, Wolf’17; Grimm, Palti, Valenzuela’18; Heidenreich, Reece, Rudelius’18; Blumenhagen, Klaewer, Schlechter, Wolf’18; Lee, Lerche, Weigand’18, Grimm, Li, Palti’18; Buratti, Calderón, Uranga’18]
Basic requirement: Scalar potential has to be kept small over large range of inflaton.

\[ V(\phi) \]

\[ \phi \rightarrow \phi + \text{const.} \]

\[ \Rightarrow \text{axions} \]
(STRINGY) AXIONS

- Crucial property: Shift symmetric "in perturbation theory".
- Non-perturbatively, there remains a **gauged and discrete** shift symmetry

\[ \phi \rightarrow \phi + 2\pi f \]

- **Stringy** axions seem to satisfy \( f < M_P \). \([\text{Banks,Dine,Gorbatov'03}]\)
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(see however: [Kim,Nilles,Peloso’05],[Dimopoulos,Kachru,McGreevy,Wacker’05]
and the discussion surrounding the **weak gravity conjecture** for axions

[Arkani-Hamed,Nicolis,Motl,Vafa’05;Rudelius’15;Montero,Uranga,Valenzuela’15;
Brown,Cottrell,Shiu,Soler’15;Bachlechner, Long,McAllister’15;Long,McAllister,Stout’17…]}
One possibility: Break the discrete shift symmetry \textit{spontaneously} and \textit{weakly}:

\[
\phi \rightarrow \phi + 2\pi f,
\]

\[
V \rightarrow V + \Delta V
\]

\[\text{[Silverstein, Westphal '08; McAllister, Silverstein, Westphal'08; Kaloper, Sorbo'08]}
\]

\[\text{[Marchesano, Shiu, Uranga'14; Blumenhagen, Plauschinn'14; Hebecker, Kraus, Witkowski'14]}\]
AN AXION CANDIDATE

- type IIB string theory contains the RR/NS 2-forms $C_2$ and $B_2$, with gauge symmetry

$$C_2 \rightarrow C_2 + d\Lambda_1$$

- For each non-trivial 2-cycle $\Sigma_2$ one obtains a complex massless axion in four dimensions:

$$\mathcal{G} \sim \int_{\Sigma_2} C_2 - \tau \int_{\Sigma_2} B_2$$

We want to give it a (computable) potential.
THE SETUP

- Consider a type IIB Calabi-Yau flux compactification, with a **double throat**.
- Such configurations arise when a CY is stabilized near a conifold transition locus by fluxes.

\[\text{References: } \text{Candelas, de la Ossa'89; Candelas, Green, Hübsch'89; Greene, Morrison, Strominger'95;...},\]
\[\text{Klebanov, Strassler'00; Giddings, Kachru, Polchinski'01}\]
THE SETUP  (continued)

- The **throats** are 10d realizations of the Randall-Sundrum scenario with gravitational red-shift

\[
\omega_{IR} \sim \exp\left(-\frac{K}{g_s M}\right) \ll 1.
\]

\[K, M \in \mathbb{Z}, \quad g_s = \text{string coupling}\]

[Randall,Sundrum'99;KS'00;GKP'01]
THE THRAXION

- We consider the 4d field

\[ G \equiv c - \tau b = \int_{\Sigma_2} (C_2 - \tau B_2), \quad \tau = \text{frozen dilaton} \]

where \( \Sigma_2 \) is the "equatorial" \( S^2 \) between the two throats.

- It is the boundary of a "hemisphere" three-chain that reaches into either throat.
THE THRAXION (continued)

- By Stokes theorem an axion excursion generates RR/NS flux/anti-flux pairs \( \sim \pm G \) at the ends of the throats.
- From a 10d analysis one may deduce the scalar potential:

\[
V(G, z_1, z_2) \propto w_{IR1}^4 \left| M \log(z_1) - 2\pi i \tau K/2 - iG \right|^2 \\
+ w_{IR1}^4 \left| M \log(z_2) - 2\pi i \tau K/2 + iG \right|^2 \\
+ |z_1 - z_2|^2
\]

fluxes in first throat

fluxes in second throat

bulk potential

\( z_1, z_2 \leftrightarrow \) orientation and length of two throats.
Note that only the locus $z_1 = z_2$ is part of complex structure moduli space.
THE THRAXION  (continued)

▶ For $g_s M < K$ there is a very flat valley parametrized by

$$z_{1,2} = e^{2\pi i \frac{K}{2M}} \times \exp(\pm i G) \sim w_{IR}^3 \ll 1$$

We can integrate out $z_{1,2}$ and obtain

$$V_{\text{eff}}(G) \propto w_{IR}^6 |\sin(G/M)|^2$$

▶ We have,

$$m_G \sim w_{IR}^3, \quad m_{z_{1,2}} \sim w_{IR}$$

▶ Intermediate conclusion:

$M$-fold (and thus finite) axion monodromy
There is a new light field $G$ ("thraxion") that controls the relative length and orientation of the two throats.

$$f = c - e b$$
COMMENTS and RESULTS (continued)

- Natural 4d supergravity proposal ($T=\text{Kähler modulus}$):
  \[
  K(\text{Re}(T), \text{Im}(G)) = -3 \log(\text{Re}(T) - \text{const} \times \text{Im}(G)^2),
  \]
  \[
  W(G) = \text{const} \times (1 - \sin(G/M)) + \text{const}.
  \]

- Note: The $M$-fold axion monodromy can also be understood to arise from gaugino condensation in the 4d (KS) gauge theories dual to the throats.
In examples with more than two throats the effective axion decay constant can be parametrically large, but potential oscillates on sub-Planckian distances:

\[ V(c) \]

\[ c = \text{Re}(G) \]
VIOLATING THE AXION WEAK GRAVITY CONJECTURE

Such a behavior would in principle be compatible with the strong form of the weak gravity conjecture.

Recall that it demands existence of an instanton of charge $q$ and euclidean action $S_E^{(q)}$ s.t. 

\[ S_E^{(q)} \lesssim q \frac{M_P}{f} \]

But in our case, 

\[ S_E \lesssim \left( q \frac{M_P}{f} \right)^2 \]

for the dominant effective instanton.
CONCLUSIONS

- We have found a new type of axion with mass of order the third power of the warp factor of warped throats.
- It is the relevant light degree of freedom that governs the global stabilization of CY’s near a conifold transition in moduli space.
- It serves as an example for violating the WGC for axions while generically there are still dominant sub-Planckian modulations in the potential.
- It is remarkably light:

\[
\frac{m_c}{M_P} \sim e^{-S_E} \gtrsim e^{-\mathcal{O}(1) \left( \frac{M_P}{f} \right)^2}
\]
CONCLUSIONS (continued)

- It is also a model of axion monodromy. Showing finiteness of the monodromy required "leaving" complex structure moduli space.

- **Open questions:**
  1. Is axion monodromy always finite?
  2. What are the universal constraints for axion-models of general multi-throat systems?
  3. In what way does our scheme of backreaction carry over to the complicated proposals of five-brane axion monodromy?
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THANK YOU!
Backup 1: Multi-throat systems

Consider case of $n$ shrinking cycles, $m$ homology relations among them: $\sum_{i=1}^{n} p_i^l [A^i] = 0$, $l = 1, \ldots, m$.

Periods are known near conifold point, \cite{GreeneMorrisonStrominger95}.

The flux superpotential reads

$$W(z) = \sum_{i=1}^{n} W_{cfd} \left( z_i; \left( \frac{M_i}{-\tau K^i} \right) \right) + \sum_{i=1}^{n} \sum_{l=1}^{m} \frac{G_l}{2\pi} p_i^l z_i + \text{const.}$$

$$= \sum_{i=1}^{n} W_{cfd} \left( z_i; \left( \sum_{l=1}^{m} \frac{G_l}{2\pi} p_i^l - \tau K^i \right) \right) + \text{const.}$$

with $\sum_{i=1}^{n} p_i^l M_i^i = 0$.

Now there are $m$ Lagrange multipliers that are promoted to dynamical axions. These correspond to the $m$ additional massless axions on the other side of the conifold transition.
Backup 2: Concrete example: Thraxions on the quintic

- Consider the quintic three-fold near its "canonical" conifold transition point.

- At this point, $n = 16$ three-cycles shrink and there is $m = 1$ homology relation among them.

- It follows that there is one complex axion $G$. Its superpotential depends on the choice of flux quanta.

- Example 1: $M_i = (-1)^{i+1} M$, $K^i = (-1)^{i+1} K$
  $\rightarrow$ same superpotential as $n = 2$, $m = 1$.

- Example 2:
  
  $M_1 = M$, $M_2 = M + 1$, $M_3 = -M$, $M_4 = -(M + 1)$,
  and $M_{i+4} = M_i$, $K^i \equiv K$, with $K/g_s M \gg 1$. Now

  \[ W_{\text{eff}}(G) \approx M \sin \frac{G}{M} + (M + 1) \sin \frac{G}{M + 1} \]

Long periodicity with sub-Planckian modulations
Backup 3: Gauge/Gravity

- The throat solution is believed to be dual to a certain $SU(N + M) \times SU(N)$ gauge theory. [Klebanov, Tseytlin’00; Klebanov, Strassler’00]
- Can we recover the same superpotential from a gauge theory calculation? Yes we can! [Biden, Obama’08]
- Gauge coupling of first group factor can be identified with axion $G$. [Klevanov, Witten’98]
- There are "cascades" of Seiberg dualities [Klevanov, Strassler]. Last remaining group: $SU(M) \times \{1\}$.
- Gaugino condensation superpotential [Veneziano, Yankielowicz’82]:

$$W_{\text{eff}}(G) = M\Lambda^3 \sim M\mu^3_{\text{IR}} \exp\left(2\pi i \frac{\tau}{M}\right)$$

$$\sim M\mu^3_{\text{UV}} \exp\left(\frac{2\pi i}{M} \left(\tau K + \frac{G}{2\pi}\right)\right)$$
Backup 4: Swampland Distance Conjecture & the $B_2$-axion

[$Ooguri,Vafa’06;Klaewer,Palti’16;Blumenhagen,Valenzuela,Wolf’17;Grimm,Palti,Valenzuela’18;
Heidenreich,Reece,Rudelius’18;Blumenhagen,Klaewer,Schlechter,Wolf’18;
Lee,Lerche,Weigand’18,Buratti,Calderón,Uranga’18,...$]

▶ What about the $B_2$ - "axion"?
▶ The superpotential completely breaks the shift symmetry $b \rightarrow b + \text{const}$.
▶ However, the scalar potential grows exponentially.
▶ In our case, as $b \gg M$, warped KK-scale comes down exponentially:

$$\Lambda_{wKK}/m_c \sim w_{IR}^{-2} e^{-\frac{4b}{3M}} \leq w_{IR}^{-2} \exp\left(-\frac{\phi_b}{M_P}\right)$$

$$\Lambda_{wKK}/M_P \sim w_{IR} e^{-\frac{b}{3M}} \leq w_{IR} \exp\left(-\frac{\phi_b}{M_P}\right)$$
Backup 4: SDC & the $B_2$-axion (continued)

- This happens because the $B_2$-axion controls the relative amount of $H_3$ fluxes that are distributed on the two throats.
- The local $H_3$ fluxes set the D3-brane charge, length and exponential hierarchy of the KS throat, so the IR-warp factor depends on $b$.
- One arrives at the following picture: