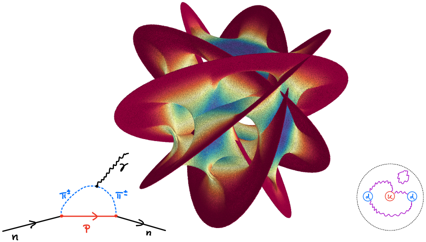
PQ AXIVERSE



Calabi-Yau image by Geoff Fatin

based on [2204.06566] with Mehmet Demirtas, Naomi Gendler, Cody Long, and Liam McAllister

07/08/2022 at String Phenomenology 2022

Jakob Moritz (Cornell)

GENERAL REMARKS

Our common goal: make string theory predictions accessible to low-energy observers (such as us).

Obviously difficult due to $\frac{m_Z}{M_P} \sim 10^{-17} \ll 1$.

Instead of tackling QG feature directly, study the landscape of low-energy theories arising in string theory.

One of the most ubiquitous features of string compactifications:

promising candidate: inflaton, dark matter, ...,
solution to strong CP problem

KEY TAKE AWAYS

We study the Peccei-Quinn mechanism and its quality problem in a vast landscape of type IIB models on Calabi-Yau hypersurfaces in toric varieties.

We find that the quality problem is generically absent for $N \gtrsim 20$ axions, in the geometric regime.

Hierarchical large-N structures of divisor volumes appear to solve the quality problem.

PLAN

1. Strong CP problem, PQ-Axion solution, PQ quality problem and all that.
2. Evading a quality problem from small QCD instantons.
3. Evading a quality problem from stringy instantons.
4. Conclusions

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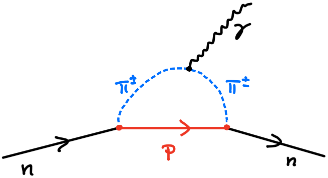
STRONG CP PROBLEM

Strong CP problem is a tuning problem of the standard model:

$$S_{QCD} \supset \frac{1}{8\pi}\int \frac{\theta}{2\pi}\mathrm{Tr}\left(G \wedge G\right) \quad \text{breaks CP.}$$

Gives electric dipole moment to neutron:



$\propto \theta$

STRONG CP PROBLEM (continued)

Experiment constrains neutron EDM, leading to sharp bound:

$$\theta \lesssim 10^{-10}$$

Strong CP problem:

Why is the neutron so incredibly neutral?!

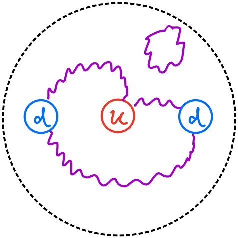


figure adapted from [Hook'18]

THE PQ MECHANISM

Axion-solution [Peccei,Quinn'77]: θ is vev of dynamical pseudo-scalar:

$$\mathcal{L} \supset -\frac{f_\theta^2}{2}(\partial\theta)^2$$

As θ-dependent non-perturbative potential induced by renormalizable QCD has $\theta = 0$ as its minimum [Vafa,Witten'84],

$$V_{QCD}(\theta) = \frac{1}{2}\frac{m_u m_d}{(m_u + m_d)^2}\Lambda_{QCD}^4\theta^2 + \mathcal{O}(\theta^4)$$

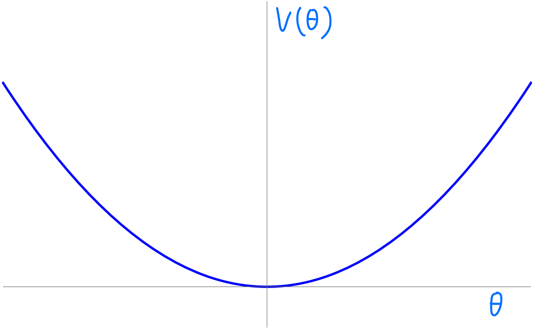
axion will relax dynamically to

$$\langle\theta\rangle = 0$$

THE PQ QUALITY PROBLEM

The axion solution comes with its own problem: one has to assume that the "pre-QCD" axion-potential is very small:

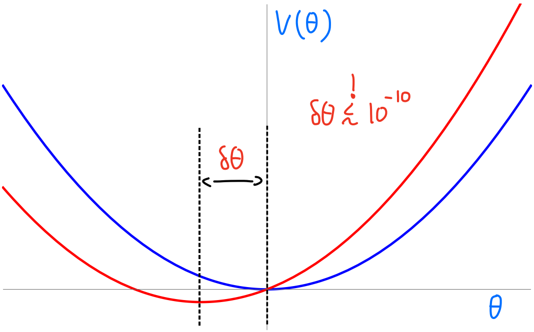
$$V(\theta) = V_{QCD}(\theta) \qquad\qquad ,$$



THE PQ QUALITY PROBLEM

The axion solution comes with its own problem: one has to assume that the “pre-QCD" axion-potential is very small:

$$V(\theta) = V_{QCD}(\theta) + V_{hidden}(\theta)\,,$$



THE PQ QUALITY PROBLEM

$$V_{hidden}(\theta) \overset{!}{\lesssim} 10^{-10}\Lambda_{QCD}^4 \sim e^{-200}M_P^4$$

or highly CP preserving, (or a combination of both).

At first glance, this looks just as bad as the original strong CP problem...

STRING THEORY TO THE RESCUE ?

In string theory, dynamical axions coupling to non-abelian gauge groups are ubiquitous.

Under mild restrictions axion shift symmetries are broken only non-perturbatively, thus abating the PQ quality problem

[Dine'86; Conlon'06; Svrcek, Witten'06;...]

But: Need to check that this actually works!

Goal for the rest of this talk:

Show that PQ quality problem is often (or even generically) evaded in type IIB Calabi-Yau orientifold models, with QCD hosted on stacks of seven-branes.

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STRING THEORY TO THE RESCUE ?

PQ quality problem can come from two (related) sources:

1. UV limit of QCD gauge instanton. Rather model-independent, i.e. can study without explicit reference to string compactifications.
2. Stringy instantons. Meaningful analysis requires string theory.

$\longrightarrow$ will study both in turn.

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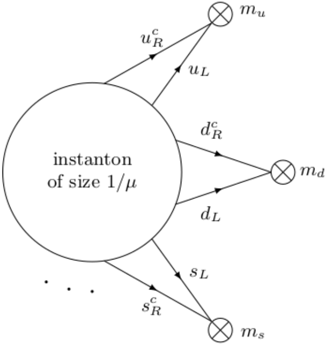
A QUALITY PROBLEM FROM QCD ITSELF ?

Gauge-instantons in renormalizable QCD induce potential

$$V_{QCD}(\theta) = \int \frac{d\mu}{\mu} I_{inst}(\mu, \theta) + c.c.$$

$$I_{inst}(\mu, \theta) =$$



$$\sim \mu^4 \frac{\det(m)}{\mu^6} e^{-\frac{8\pi^2}{g^2(\mu)} - i\theta}$$

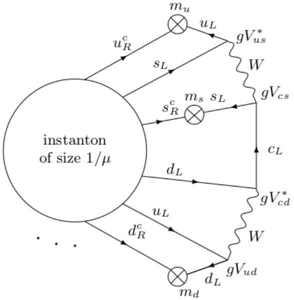
and this is minimized at $\theta = 0$:

A QUALITY PROBLEM FROM QCD ITSELF ?

But QCD as an EFT below weak scale is not renormalizable.

CP breaking in the weak interactions already shifts the θ-minimum,

$$I_{inst}^{weak}(\mu, \theta) =$$



Happily, this is within the allowed region: $\langle\theta\rangle \to 10^{-19} \ll 10^{-10}$

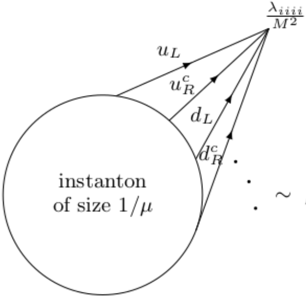
[Georgi,Randall'86]

A QUALITY PROBLEM FROM QCD ITSELF ?

Viewing the SM as an EFT with cutoff M we are allowed to consider further sources of CP breaking from dimension six operators, e.g.

$$S_{eff} \supset \int d^4x \frac{\lambda_{ijkl}}{M^2} \mathcal{O}_6^{ijkl} + c.c.\,, \quad \mathcal{O}_6^{ijkl} = \epsilon_{ab} D^i Q^{j,a} U^k Q^{l,b}$$

$$I_{inst}^{BSM}(\mu, \theta) =$$



$$\sim \mu^4 \prod_{i=1}^{3} \frac{\mu^2 \lambda_{iiii}}{M^2} e^{-\frac{8\pi}{g^2(\mu)} - i\theta}$$

Whether or not this generates a sufficiently small $V_{hidden}(\theta)$ depends on the UV!

THE UV QCD POTENTIAL

Let us make the following (mild?) assumptions:

1. The standard model is supersymmetrically completed at some scale M_{SUSY}. No further light states charged under QCD.
2. $4d$ EFT breaks down at some UV scale M, where CP becomes fully broken.

"SUSY-desert scenario"

Following the (one-loop) RG flow we find

[Demirtas,Gendler,Long,McAllister,JM'21]

$$\delta V_{hidden}(\theta) \sim 10^{-12} \left(\frac{1\,\text{TeV}}{M_{SUSY}}\right)^3 \Lambda_{QCD}^4 \left(1 - \cos(\theta + \phi_0)\right)$$

(up to factor logarithmic in M/m_Z)

THE UV QCD POTENTIAL (continued)

Some upshots:

- Generic CP breaking in the deep UV almost spoils the PQ mechanism for low SUSY breaking scale!
- High SUSY breaking scale suppresses the effects of small instantons because the QCD coupling runs faster without SUSY.
- Adding light vector-like pairs endangers the PQ solution more, and can spoil it.

In SUSY-desert scenario small instantons do not lead to a quality problem.

Rest of talk: Assume this scenario, and inquire about stringy instantons in the type IIB landscape.

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A STRINGY SETUP

To fully assess PQ quality, need to restrict to a workable part of the string landscape:

- Consider type IIB O3/O7 orientifolds of Calabi-Yau threefolds X, with QCD realized on stack of seven-branes wrapping divisor D, at large volume:

$$\mathrm{Vol}(D) > 1$$

- Chern-Simons action of D-branes implies that

$$\theta = 2\pi \int_D C_4, ,$$

  so presence of QCD axion is automatic.
- In general, θ is linear combination of $h^{1,1}(X)$ independent axions $\theta = \sum_{A=1}^{h^{1,1}} q_A \xi^A$.
- $V_{hidden}(\xi)$ is generated by euclidean D3-branes wrapped on divisors (this includes the UV-limit of the QCD instanton).

A DISCLAIMER

In general, the PQ quality problem can be made arbitrarily severe (in string theory)

Example: consider QCD realized on D3 branes, in general three-form flux background (axion monodromy):

$$\left\langle \frac{\theta}{2\pi} \right\rangle = \langle C_0 \rangle = \mathrm{Re}\left[\frac{\int_X F_3 \wedge \Omega}{\int_X H_3 \wedge \Omega}\right] = \mathcal{O}(1) \quad \text{generically.}$$ [cf Conlon'06]

In contrast: even in such a scenario $\langle \theta \rangle = 0$ is not hard to find.

$\rightarrow$ e.g. solutions [Cecotti, Vafa'18], [Demirtas,Kim,McAllister,JM'19,...]
& general analysis: [Bönisch, Elmi, Kashani-Poor, Klemm'22]

But: type IIB orientifold/F-theory models with QCD on seven-branes is extremely rich and promising landscape with light axions: $\rightarrow$ important to assess status of PQ mechanism.

This is non-trivial:

1. Large volume limit $\mathcal{V} \rightarrow \infty$ not accessible as $\alpha_{QCD} \rightarrow 0$.
2. Control constraint $\mathrm{Vol}(D) > 1$ in no obvious way enough to sufficiently suppress stringy instantons.

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STRATEGY

- Consider the Kreuzer-Skarke dataset of Calabi-Yau hypersurfaces X in toric fourfolds V.
- For each CY scan over distinct choices of QCD-divisors D in set of $h^{1,1}(X) + 4$ toric divisors intersecting hypersurface.
- In principle: compute all instanton actions and demand that they do not collectively spoil $\langle \theta \rangle \lesssim 10^{-10}$.

Problems:

1. Most moduli-vev's will not reproduce correct QCD coupling at low energies.
2. Computing all instanton actions is out of reach
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AN UPDATED STRATEGY

Dilate overall volume $\mathcal{V}$ to get correct QCD coupling at low energies. (1. ✓)

Instanton actions become large as $\mathcal{V}$ grows (weak coupling limit), so the PQ mechanism is endangered most when $\mathcal{V}$ is smallest.

Correct overall dilation of $\mathcal{V}$ depends on M_{SUSY}, and is smallest when $M_{SUSY} = 1$ TeV. For this choice, the PQ mechanism is endangered most.

So let us set $M_{SUSY} = 1$ TeV.

AN UPDATED STRATEGY (continued)

For such low SUSY breaking scale, expect BPS-instantons to dominate over non-BPS instantons:

$$\delta V_{BPS}(\xi) \propto M_{SUSY} M_P^3 e^{-S} \quad \text{vs} \quad \delta V_{non-BPS}(\xi) \propto M_{SUSY}^2 M_P^2 e^{-S}$$

We can compute BPS instanton actions: (2. ✓)

$$S_D = 2\pi \int_D \frac{1}{2} J \wedge J \,, \quad \text{with} \quad D \text{ effective}$$

Only need to enumerate smallest effective divisors, and consider

$$V(\xi) = V_0 + \sum_{D \text{ eff.}} \Lambda_D^4 \left(1 - \cos(\vec{\xi} \cdot \vec{q}_D + \phi_D)\right) \,,$$

with non-perturbative scales $\Lambda_D^4 \approx \frac{4 M_{SUSY} S_D}{\mathcal{V}} \mathcal{A}_D e^{-S_D}$

(we set unknown Pfaffians to one: $\mathcal{A}_D = 1$)

SAMPLING RAYS IN THE KAHLER CONE

Finally, need to select points in Kahler cones of Calabi-Yau's.

It turns out that results are rather insensitive to particular choice of points.

Intuitively, this is because Kahler cones are narrow:

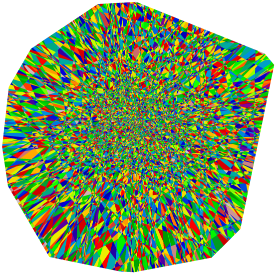


Figure adapted from [Demirtas,McAllister,Rios-Tascon'20]

Thus, fair sampling of Calabi-Yau's appears to be enough.
(fair sampling algorithm [Demirtas,McAllister,Rios-Tascon'20])

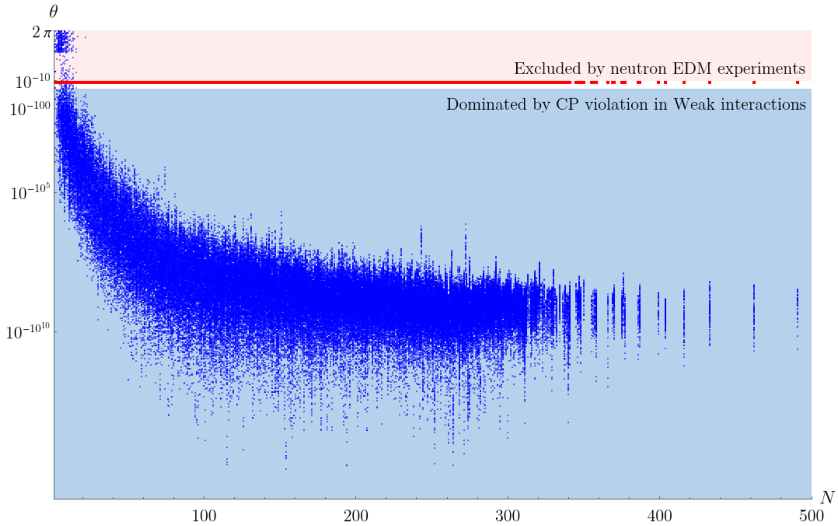
OUR ENSEMBLE OF GEOMETRIES

With above scheme we studied:

- $32,040$ CY's with $2 \leq h^{1,1} \leq 491$.
- up to 10 polytopes per $h^{1,1}$, up to 10 triangulations per CY.
- up to 5 choices of QCD divisor.

Total ensemble size: $136,659$ distinct models.

RESULTS



No PQ quality problem for $h^{1,1} \gtrsim 20$: $\delta\theta_{\text{stringy}} \sim e^{-1.8\times(h^{1,1})^4}$

COMMENTS

Why does the PQ mechanism work so well at large $h^{1,1}$?

- Generating a quality problem in a many-axion theory requires existence of instantons with charges $q_1, \ldots, q_n$, all more relevant than UV-QCD gauge instanton, and such that $q_{QCD} \in \text{span}(q_1, \ldots, q_n)$.
- This does happen sometimes, even at large $h^{1,1}$, but once this occurs the smallest divisor volume is very small, thus outside of regime of computational control.

Absence of quality problem explained by hierarchical structures found in Calabi-Yau's at large $h^{1,1}$!

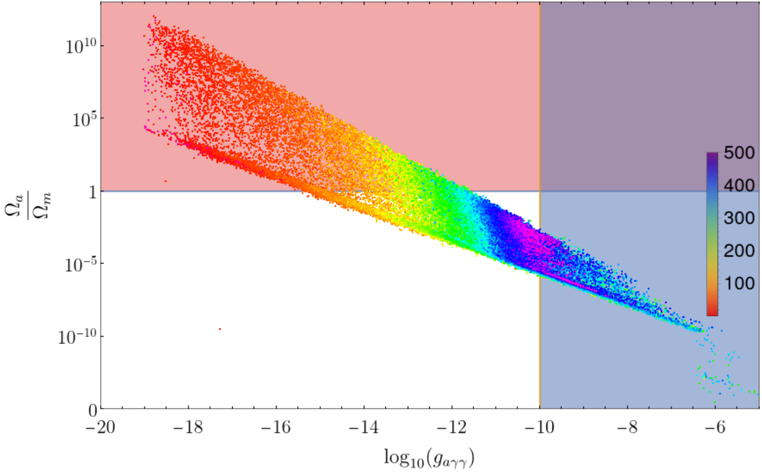
CONCLUSIONS

- Studied the Peccei-Quinn mechanism and its potential quality problem in type IIB landscape.
- PQ quality is endangered most for low SUSY breaking scale. For $M_{SUSY} = 1$ TeV, expect $\theta_{QCD} \sim 10^{-12}$ due to small gauge instantons.
- For $N \gtrsim 20$ axions stringy instantons are negligible and thus do not lead to a quality problem.
- Aside: Many models appear to be consistent with both dark matter and astrophysical exclusion bounds.

THANKS !

COSMO AND ASTROBOUNDS

Aside: In our ensemble we have also computed dark matter relic abundances, and checked astrophysical constraints (CAST):



Many models appear not ruled out by either!

VECTORLIKE PAIRS

More generally, consider adding n vector-like pairs in $3 + \overline{3}$.
Then, small instantons can lead to a quality problem: