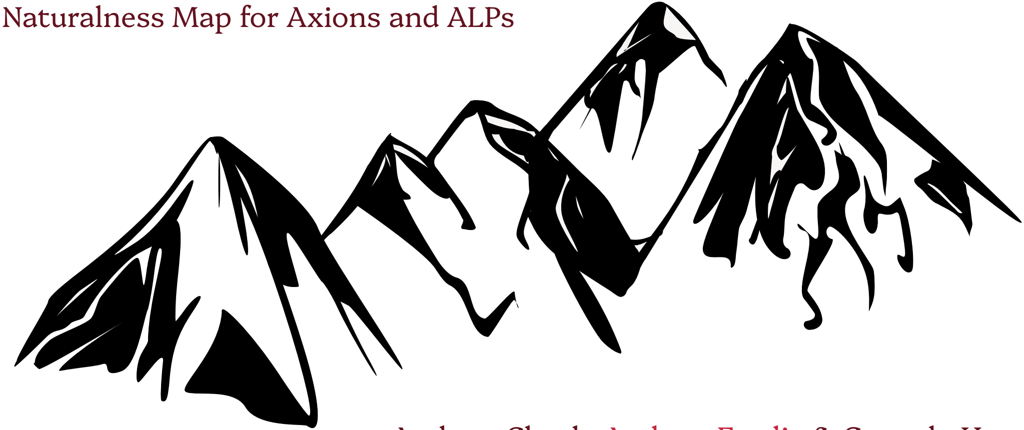
Mapping the ALPs

A Naturalness Map for Axions and ALPs



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10 June 2026

Mapping the ALPs

Message

- Planck-suppressed PQ-breaking operators can spoil the strong CP solution and destabilise light ALPs
- Axion and ALP parameter space should be mapped by mass, couplings, experimental reach and *PQ quality*
- We quantify this using Bayesian naturalness and map ALP quality

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Section 1

The strong CP problem

QCD parameters

- QCD can be written schematically as (see e.g., Dine (2000))

$$\boxed{\mathcal{L} \sim \frac{1}{\alpha_S} GG + \bar{q} i \not{D} q - \bar{q} M q}$$

- Described by a coupling, α_S, and the quark mass matrix
- What about the CP-violating

$$\boxed{G\tilde{G}?}$$

- That's a **total derivative**; can be written as $G\tilde{G} = \partial_\mu K^\mu$

Wait, there's another parameter

- We can ignore total derivatives, right?
- Not quite. It cannot be neglected because of **finite-action instantons**
- Thus, must consider

$$\boxed{\mathcal{L} \sim \frac{1}{\alpha_S} GG + \bar{q} i \not{D} q - \bar{q} M q + \theta_C \, G\tilde{G}}$$

- A new parameter, θ_C? Can it be shifted away?
- After chiral rotations and shifts in CP-violating phases, physically invariant parameter remains:

$$\boxed{\bar{\theta} = \theta_C - \theta_Y \quad \text{where} \quad \theta_Y = \arg\det M}$$

Electric dipole moments

- Electric dipole moments (EDMs) violate CP;

$$\boxed{H = -\vec{d} \cdot \vec{E}}$$

- For the neutron, the relevant low-energy operator is $\bar{n}\gamma_5\sigma_{\mu\nu}n\,F^{\mu\nu}$
- The contribution from $\bar{\theta}$ to the neutron EDM

$$\boxed{|d_n| = 3.6 \times 10^{-16}\,\bar{\theta}\,e\,\mathrm{cm}}$$

- The CKM phase contribution is about $10^{-32}\,e\,\mathrm{cm}$
- Constraints on neutron EDM (Abel *et al.*, 2020) imply that

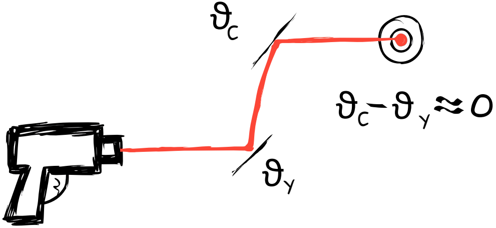
$$\boxed{|\bar{\theta}| \lesssim 10^{-10}}$$

Why is the QCD angle so small?

- We almost forgot about $\bar{\theta}$. Turns out it must be tiny anyway. **Weird**
- The effective angle was a sum of two contributions

$$\boxed{\bar{\theta} = \theta_C - \theta_Y}$$

- Why are phases from separate sectors so precisely aligned?
- This is the *strong CP problem*



Section 2

Axions and ALPs

The QCD vacuum

- Relaxing $\bar{\theta} \to 0$ is natural because Vafa and Witten (1984) theorem tells us that minimum energy state at $\bar{\theta} = 0$
- However, $\bar{\theta}$ is a parameter, so it cannot relax to that minimum
- We need to **promote** it to a **dynamical** field to relax it — the axion and the Peccei-Quinn mechanism (Peccei and Quinn, 1977; Weinberg, 1978; Wilczek, 1978)

The QCD axion

- Add a compact pseudo-scalar field, a and by effective-field theory rules, write down

$$\boxed{\mathcal{L} \supset \left(\bar{\theta} + \frac{a}{f_a}\right) G\tilde{G}}$$

- Treating $\bar{\theta}$ as a spurion, the Lagrangian possesses a global PQ shift symmetry

$$\boxed{\bar{\theta} \to \bar{\theta} - \alpha \ \text{ and } \ a \to a + \alpha f_a}$$

- In a UV model, the axion and the shift symmetry can arise from a spontaneously broken global $U(1)_{\mathrm{PQ}}$

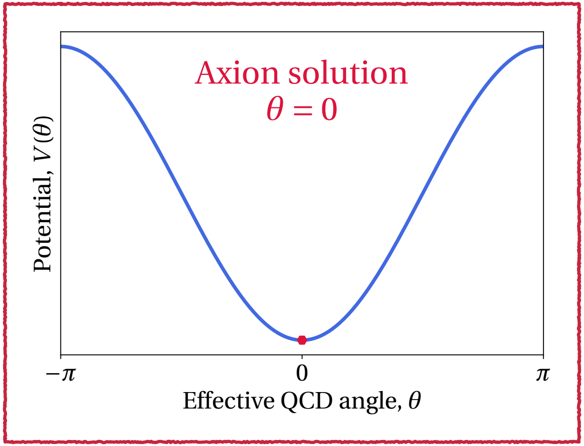
The PQ mechanism

- By the PQ symmetry, anywhere we had $\bar{\theta}$, we now write $a/f_a + \bar{\theta}$
- Contributions to EDM $\propto a/f_a + \bar{\theta}$
- The PQ symmetry is **anomalous** under QCD
- By Vafa and Witten (1984) theorem, the ground state now at $a/f_a + \bar{\theta} = 0$. The non-perturbative potential approximately equals

$$\boxed{V_{\mathrm{IR}} = -m_\pi^2 f_\pi^2 \cos\left(\frac{a}{f_a} + \bar{\theta}\right)}$$

- Minimum at $a/f_a + \bar{\theta} = 0$; thus dynamical axion field **relaxes** effective QCD angle to zero

QCD axion potential

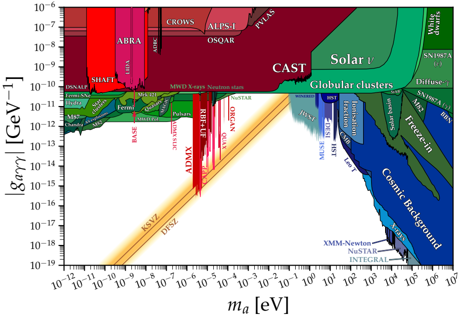


Axion-like particles

- Pseudo-scalar fields are interesting — forget about QCD and generalise it

$$V_{\rm IR} = -m_{\rm IR}^2 f_a^2 \cos\left(\frac{a}{f_a} + \phi\right)$$

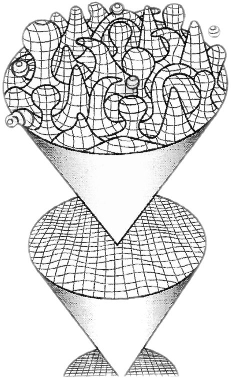
- No assumed relationship between mass and couplings
- Rich phenomenology and it could play role of DM. Search for it (O'Hare, 2020)!



Section 3

Quantum gravity

All that glisters is not gold



Quantum gravity breaks all global symmetries

- *Maybe*. Folk theorem but no one actually knows
- What happens to global charge thrown into a black hole? or global charge thrown down a wormhole? See e.g. Kallosh *et al.* (1995)
- Thus, there are gravitational corrections to the axion potential that break the shift symmetry (Ghigna *et al.*, 1992; Kamionkowski and March-Russell, 1992; Barr and Seckel, 1992)

Quantum gravity operators

- Assume that the axion originates as a component of a complex scalar that is charged under the $U(1)_{\mathrm{PQ}}$ symmetry

$$\boxed{\Phi(x) = \frac{1}{\sqrt{2}}\left(f_a + \rho(x)\right) e^{ia(x)/f_a}}$$

- We describe PQ breaking quantum gravitational corrections using effective field theory

$$\boxed{\mathcal{L}_{\mathrm{UV}} = \sum_{d=5}^{\infty}\sum_{k=1}^{d} c_{kd}\frac{|\Phi|^{d-k}\,\Phi^k}{M_{\mathrm{Pl}}^{d-4}} + \text{h.c.}}$$

- The Wilson coefficients are *unknown* to us

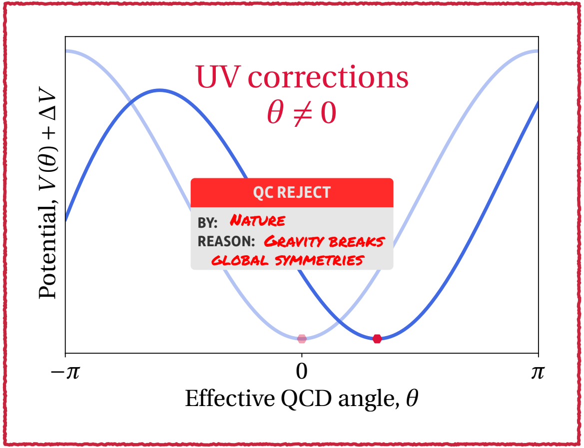
Planck-suppressed corrections to the potential

- When PQ breaks spontaneously, these PQ-violating operators generate a potential
- Integrating out the radial mode,

$$\boxed{V_{\mathrm{UV}} = -2M_{\mathrm{Pl}}^4 \sum_{d=5}^{\infty} \sum_{k=1}^{d} |c_{kd}| \left(\frac{f_a}{\sqrt{2}M_{\mathrm{Pl}}} \right)^d \cos\left(\frac{ka}{f_a} + \phi_{kd} \right)}$$

- The terms are suppressed by operator dimension d and break PQ symmetry by k units
- The CP violating phases ϕ_{kd} of the Wilson coefficients are unrelated to $\bar{\theta}$
- Even if quantum gravity breaks PQ but respects CP, i.e. $\phi_{kd} = 0$, the misalignment can still spoil the PQ mechanism; we need $\phi_{kd} = \bar{\theta}$

Potential with gravity turned on



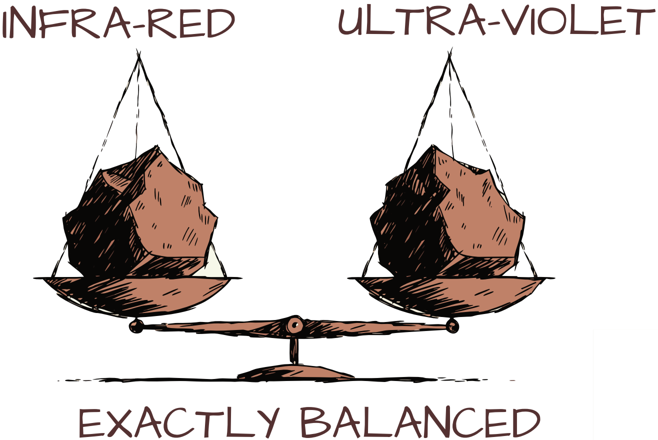
Quality problem

- This is the quality problem — the PQ symmetry isn't protected from gravity
- The axion no longer relaxes to $a/f_a + \bar{\theta} \to 0$
- Instead, there is a residual CP-violating phase

$$\boxed{\theta_{\text{eff}} \simeq -\sum_{d=5}^{\infty} \frac{|c_{1d}| f_a^{d-2} \sin(\phi_{1d} - \bar{\theta})}{2^{d/2-1} M_{\text{Pl}}^{d-4} m_{\text{IR}}^2}}$$

- We need a *quality* PQ symmetry to forbid these operators
- We need an *anomalous* PQ symmetry to generate a pseudo-Goldstone axion and the IR potential

Quantum gravity



What about ALPs?

- The ALP mass receives IR and UV contributions,

$$\boxed{m_a^2 = \left\langle \frac{\partial^2 V_{\mathrm{IR}}}{\partial a^2} \right\rangle + m_{\mathrm{UV}}^2 \quad \text{with} \quad m_{\mathrm{UV}}^2 \equiv \left\langle \frac{\partial^2 V_{\mathrm{UV}}}{\partial a^2} \right\rangle}$$

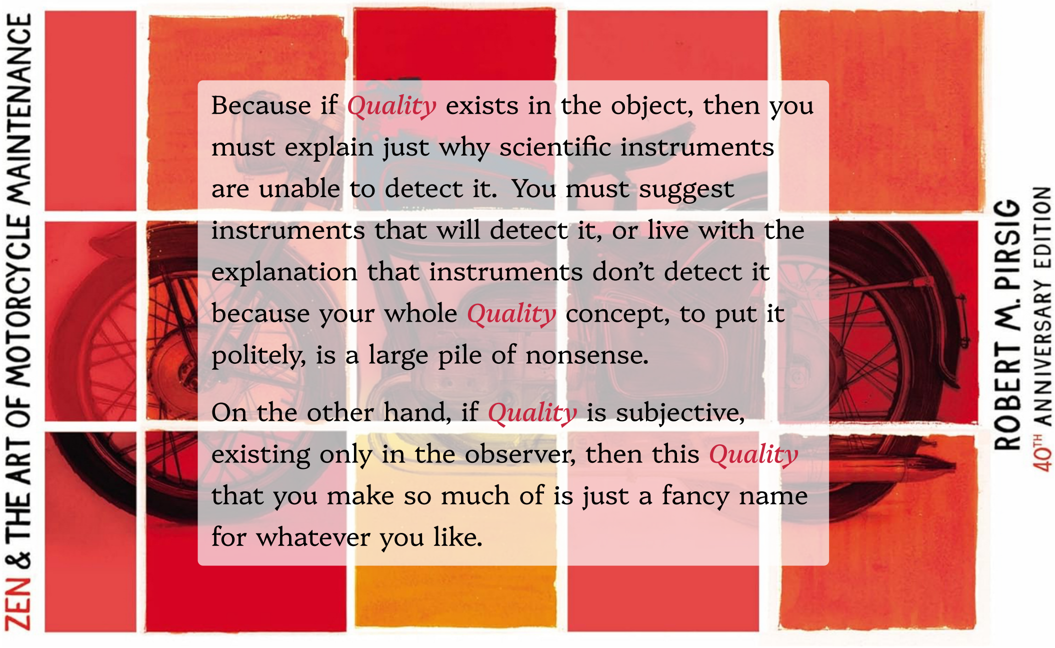
- Reminiscent of the hierarchy problem, this requires fine-tuning to maintain $m_a^2 \ll |m_{\mathrm{UV}}^2|$
- Treating the gravitational corrections as a perturbation,

$$\boxed{\frac{m_{\mathrm{UV}}^2}{m_{\mathrm{IR}}^2} \simeq \sum_{d=5}^{\infty} \frac{|c_{1d}| f_a^{d-2} \cos(\phi_{1d} - \bar{\theta})}{2^{d/2-1} M_{\mathrm{Pl}}^{d-4} m_{\mathrm{IR}}^2}}$$

- ALPs are often assumed to be light; ALPs need *quality* as well

Section 4

Mapping the ALPs using quality



Because if *Quality* exists in the object, then you must explain just why scientific instruments are unable to detect it. You must suggest instruments that will detect it, or live with the explanation that instruments don't detect it because your whole *Quality* concept, to put it politely, is a large pile of nonsense.

On the other hand, if *Quality* is subjective, existing only in the observer, then this *Quality* that you make so much of is just a fancy name for whatever you like.

Quality

Pirsig didn't know Bayes — quality is subjective, but it's not quite whatever you like

- Fine-tuned models are penalised for making *poor predictions*
- Penalty is automatic, and often, though not always, aligns with intuition about Occam's razor and naturalness
- Under mild assumptions, traditional fine-tuning measures appear in Bayesian approach (Fowlie and Herrera, 2025)
- Results depend on choices of priors for unknown parameters

Quantifying axion quality

1. Plausibility of agreement with nEDM bound

$$\boxed{\text{Quality} \sim P(|\theta_{\text{eff}}| < 10^{-10})}$$

2. Ability to predict a desired ALP mass, quantified by a Barbieri-Giudice measure

$$\boxed{\text{Quality} \sim \Delta \equiv \left| \frac{m_{\text{IR}}^2}{m_a^2} \frac{\partial m_a^2}{\partial m_{\text{IR}}^2} \right|}$$

3. Degree of UV protection required

$$\boxed{\text{Quality} \sim \text{Operator dimension } D}$$

below which gravitational corrections must be forbidden

Treatment of unknown parameters

- We treat the unknown axion mass and decay constant as *coordinates*
- We *average* over the unknown Wilson coefficients
- This needs a choice of prior; our baseline assumption

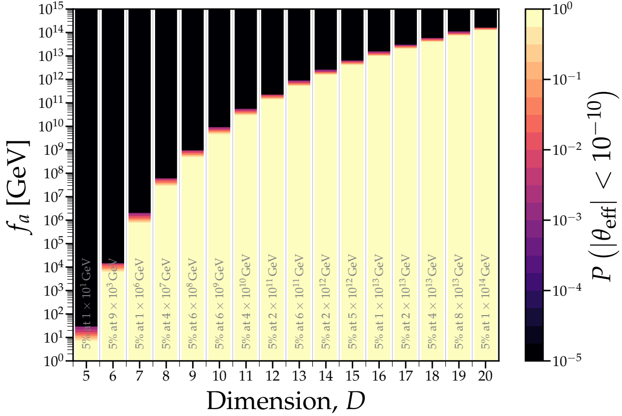
$$\boxed{\phi_{kd} \sim \mathcal{U}(-\pi, \pi) \quad \text{and} \quad |c_{kd}| \sim \text{Rayleigh}(1).}$$

- Phases are uniformly random: no assumed alignment
- Magnitudes are unsuppressed and generically $\mathcal{O}(1)$

  $\rightsquigarrow$ *Rayleigh distribution — length of 2d vector with normally distributed components*
- Smaller variance would already assume a UV suppression mechanism; larger variance would make the quality problem worse

QCD axion

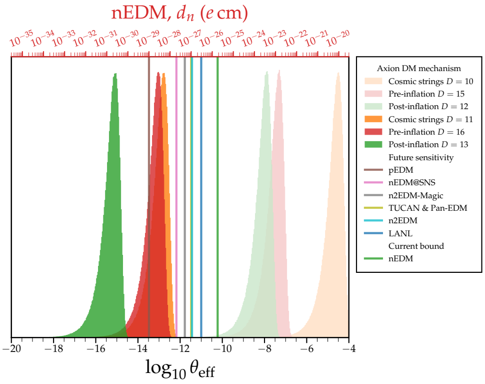
- Probability that $|\theta_{\rm eff}| > 10^{-10}$ arises from sampling over unknown $\mathcal{O}(1)$ Wilson coefficients
- Depends on dimension D where UV corrections are switched on
- Desire for at least 5% bounds the axion decay constant



Takeaway: QCD axion models require protection from quantum gravity

Prediction for nEDM

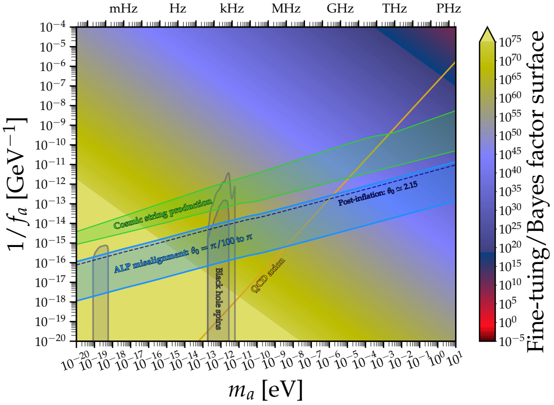
- Residual phase could be measurable in upcoming nEDM experiments
- We take f_a such that QCD axion plays role of DM in three scenarios
    1. Pre-inflation misalignment
    2. Post-inflation misalignment
    3. Cosmic strings
- Pick D such that we satisfy existing constraint



Takeaway: Detection of residual CP-violating phase requires *next-next-generation* facilities

Mapping the ALPs

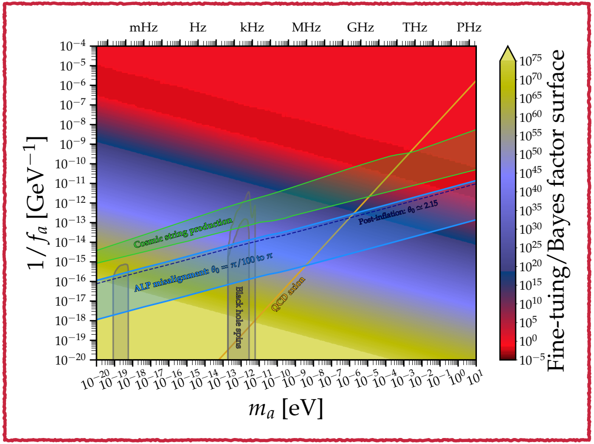
- Assume that UV corrections start at $D = 5$
- Marginalise Wilson coefficients; treat $(m_a, 1/f_a)$ as coordinates
- For ALP mass $m_a \ll 1\,\text{GeV}$, potential dominated by gravitational corrections



Takeaway: Without protection, ALPs are fine-tuned everywhere on $(m_a, 1/f_a)$ plane

Adding protection

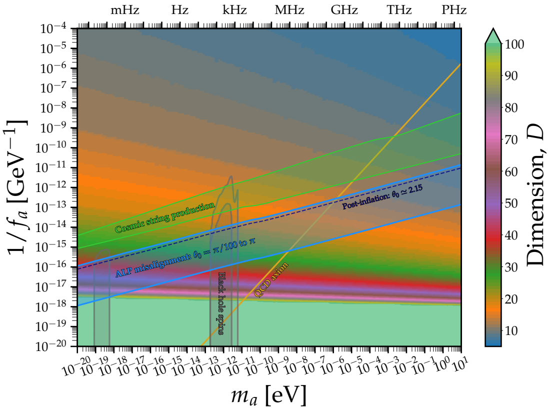
- Assume that UV corrections start at $D = 10$
- Triangle of untuned parameter space where UV corrections are small
- Natural band where UV corrections predict required axion mass



Takeaway: Even with protection to $D = 10$, ALPs are often fine-tuned

Quantifying UV protection

- What dimension D is required to avoid fine-tuning $\Delta > 100$?
- **Quality pushes up from bottom; complementary to experimental measurements**
- $f_a \gtrsim 10^{16}$ GeV needs UV completion that protects quality to $D \gtrsim 50$



Takeaway: ALPs need protection, often far beyond operator dimension $D \gg 10$

Conclusions

- **We can map PQ quality**: axion parameter space should be characterised by mass, couplings, experimental reach, *and PQ quality*
- **For the QCD axion**, these operators can ruin the PQ mechanism; DM benchmarks required protection up to operator dimension $D \gtrsim 11$–16 to satisfy current nEDM bounds
- **For ALPs**, the same UV corrections cause a mass naturalness problem; ALPs require high-dimensional PQ protection, often far beyond $D \gtrsim 10$
- **Future neutron/proton EDM searches** probe CP violation *and PQ quality*

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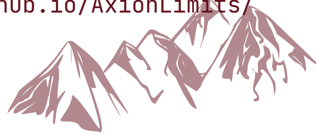

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