A Theory Perspective on Axions

Matt Reece
Harvard University
at the BREAD Collaboration Meeting, Jan. 14, 2026

Outline

Key things to know about axions and Strong CP

- Demystifying theta terms
- Strong CP problem and axion solutions
- What is the right experimental target?

Axion theory at Harvard

- Brief summary: what my students and I are up to

The θ Parameter in SU(n) Gauge Theory

Gauge theories have a θ **parameter.** There are formulas for it:

Lagrangian viewpoint:

$$S_\theta = S_0 + \frac{\theta}{8\pi^2}\int \mathrm{tr}(F\wedge F) = S_0 + \frac{\theta}{64\pi^2}\int d^4x\,\epsilon^{\mu\nu\rho\sigma}F^a_{\mu\nu}F^a_{\rho\sigma}\,.$$

Hamiltonian viewpoint, Weyl gauge ($A_0 = 0$):

$$H_\theta = g^2\left(\mathrm{i}\frac{\delta}{\delta A^a_i} - \frac{\theta}{4\pi^2}B^a_i\right)^2 + \frac{1}{g^2}(B^a_i)^2 \quad \text{where} \quad B^a_i = (\nabla\times A^a)_i - \frac{1}{2}f^{abc}(A^b\times A^c)_i$$

Facts About the θ Parameter

Physical quantities depend on the value of θ.

All physics is 2π periodic in the value of θ. More precisely,

$$H_{\theta+2\pi} = U H_\theta U^\dagger$$

where U is a unitary operator (the "Chern-Simons operator").

If θ is *not* an integer multiple of π, then **CP** (equivalently, **T**) symmetry is explicitly violated.

The θ term is "topological": $\frac{1}{8\pi^2}\int \mathrm{tr}(F \wedge F) \in \mathbb{Z}$ when integrating over a closed spacetime. (Mathematically, related to the 2π-periodicity.)

Facts About the θ Parameter

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Theorists like to emphasize this bit about the topological nature of the term, but people often get confused about it.

In particular, the other facts that I told you are **all true even if you study QFT in topological trivial spacetime (like Minkowski spacetime).**

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Aside: Advice About the θ Parameter

If you ever get confused about the θ parameter (many of us do, sometimes), there is a simple system with all the key properties.

This is a *free* quantum particle on a ring (or circle), with coordinate $\varphi \cong \varphi + 2\pi$, and action

$$S = \int \mathrm{d}t \left(\frac{I}{2}\dot{\varphi}^2 + \frac{\theta}{2\pi}\dot{\varphi} \right)$$

It has Hamiltonian

$$H = \frac{1}{2I}\left(\frac{\mathrm{d}}{\mathrm{d}\varphi} - \frac{\theta}{2\pi} \right)^2$$

and θ-dependent energy eigenvalues $E_n = \frac{1}{2I}\left(n - \frac{\theta}{2\pi} \right)^2, \quad n \in \mathbb{Z}$.

Any surprising claim about θ terms can be evaluated in this context.

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For *any* QFT with *any* parameter y, you can make up a kind of “super-QFT”* with states $|\psi, y\rangle$ and matrix elements

$$\langle \psi', y' | O | \psi, y \rangle = \delta_{yy'} \left(\langle \psi' | O | \psi \rangle \right)_{\text{QFT with param } y}$$

* The correct technical term is “direct sum of QFTs.”

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You *can* do this, but it's usually a silly thing to do.

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When people talk about “θ vacua,” they are making up such a “super-QFT.”

Oddly, people only do this for θ; you never hear about, say, “electron Yukawa vacua,” but the super-QFT works there too.

People often say we do this because the “θ vacua” are linear combinations of something else called “n vacua,” but those make *less* sense.

What happened here is that a few very smart and influential people were confused in 1976, and other people have been repeating their confusion ever since.

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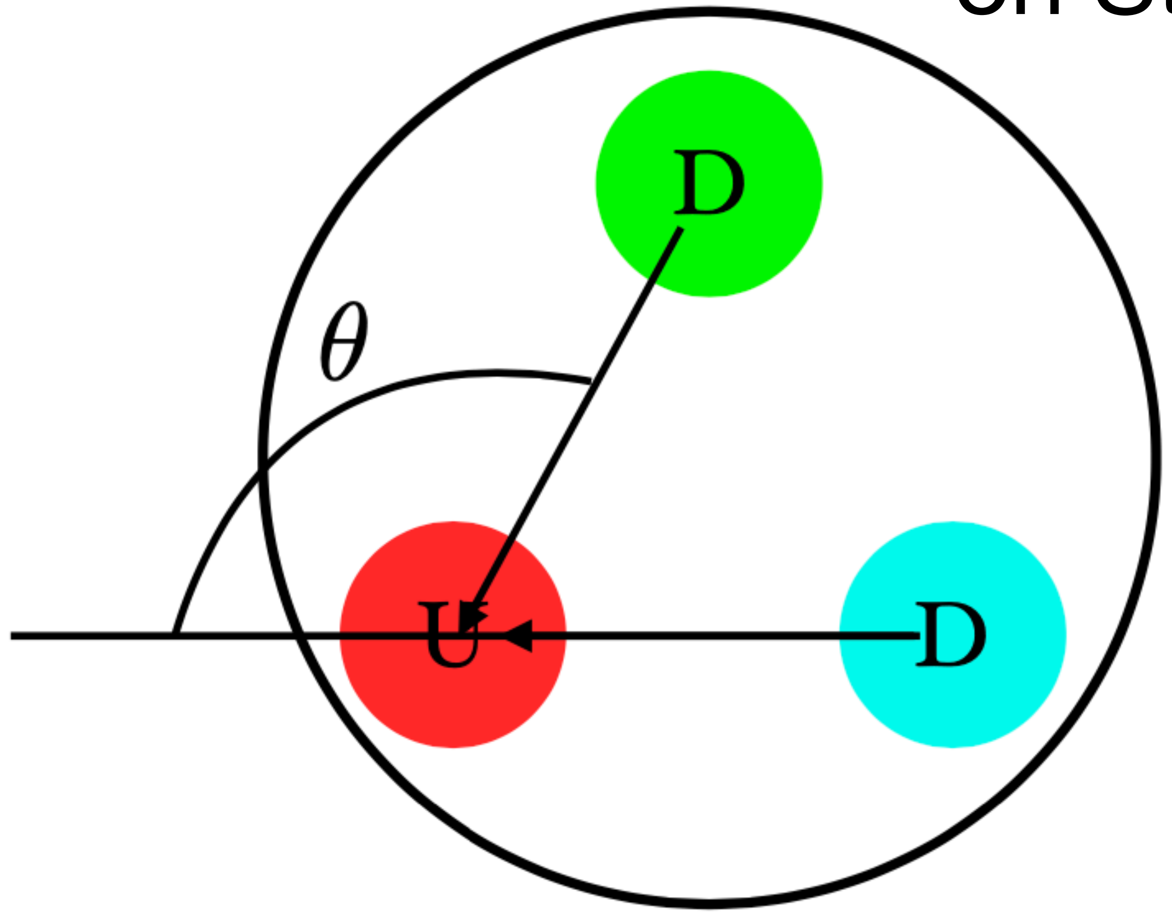
Fifty years have passed. We should stop repeating them.
θ is ***just*** a parameter in the Lagrangian (or Hamiltonian).
Don't mystify it.

Neutron EDM and Strong CP Puzzle

Smaller than geometric cartoon expectation by factor $m_u/\Lambda_{\rm QCD} \sim 10^{-3}$. (Chiral anomaly)

Fig. from Anson Hook, TASI Lectures on Strong CP



The Strong CP phase $\bar{\theta}$ gives rise directly to a CP-odd pion-proton-neutron interaction.

This in turn feeds into the neutron EDM at one loop:

$$d_n \approx \frac{e\bar{\theta} g_A c_+ m_u m_d}{8\pi^2 (m_u + m_d) f_\pi} \log \frac{m_\rho^2}{m_\pi^2} \sim 3 \times 10^{-16}\, \bar{\theta}\, e\, \text{cm} \quad \Rightarrow \quad |\bar{\theta}| \lesssim 10^{-10} \quad (!)$$

Crewther, di Vecchia, Veneziano, Witten 1979

But: CP is not a symmetry of nature! Why so small?

Axions

Promote θ to a **dynamical field,** $\theta(x)$, interacting with gluons.

$$\mathscr{L} = \frac{1}{2} f^2 (\partial\theta)^2 + \frac{1}{64\pi^2} \theta(x) G^a_{\mu\nu} \tilde{G}^{a\mu\nu}(x)$$

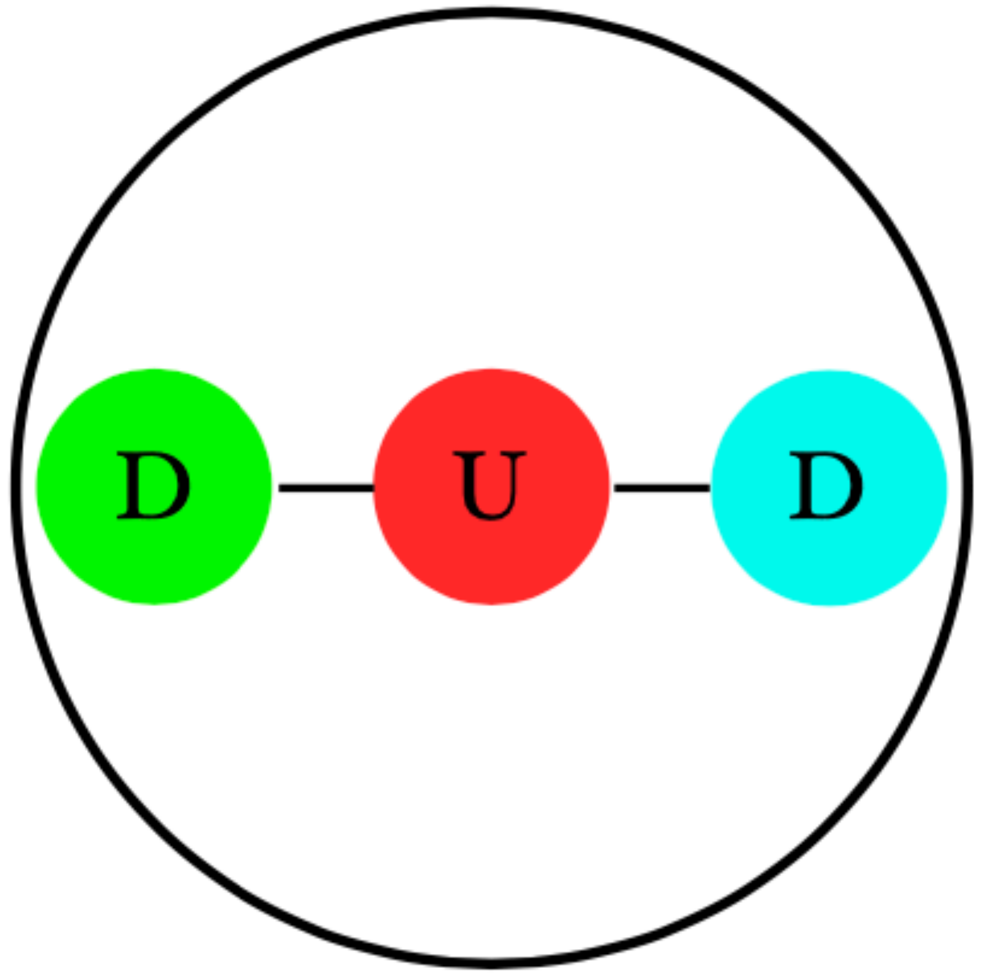
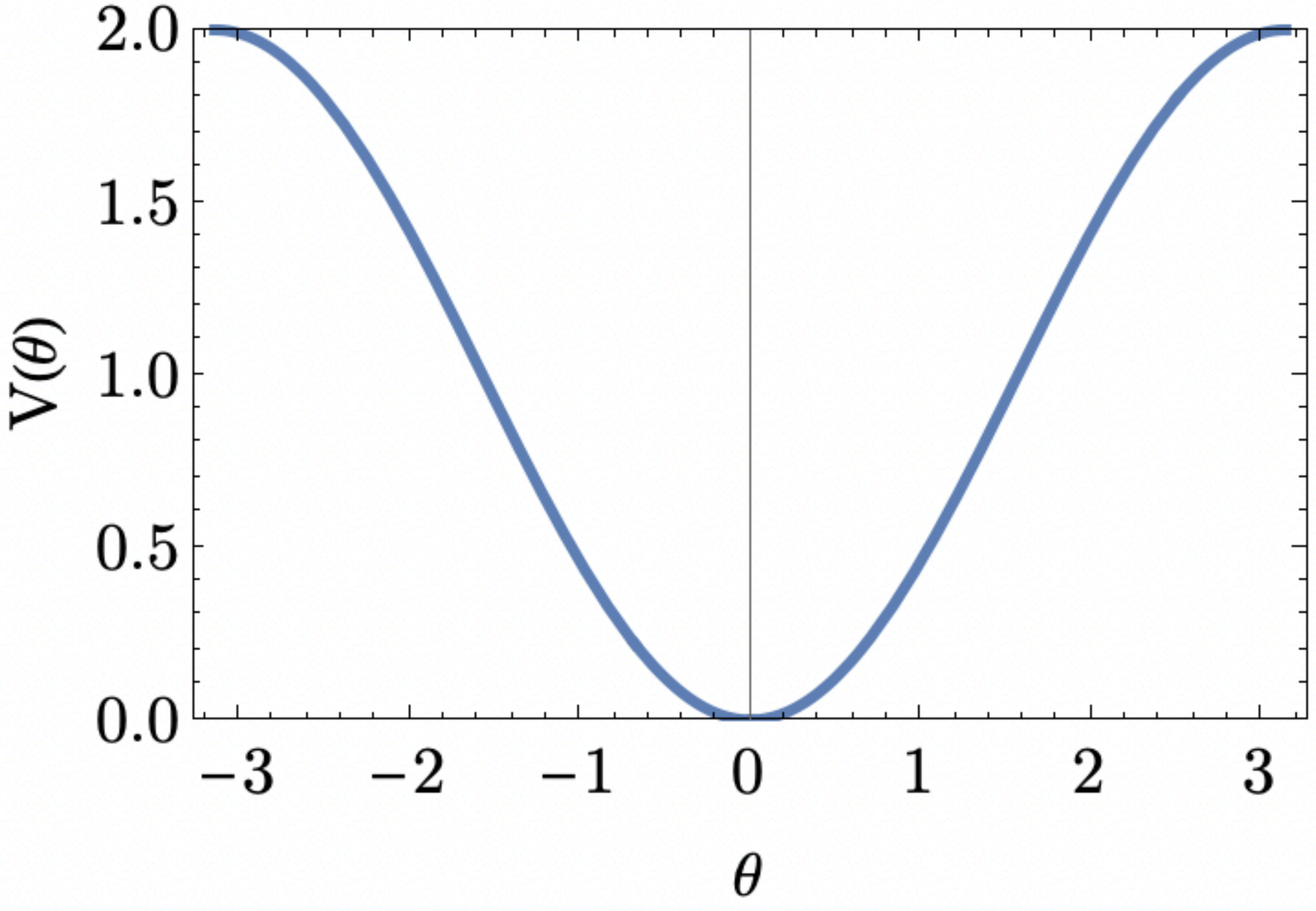


Fig. from Anson Hook, TASI Lectures on Strong CP

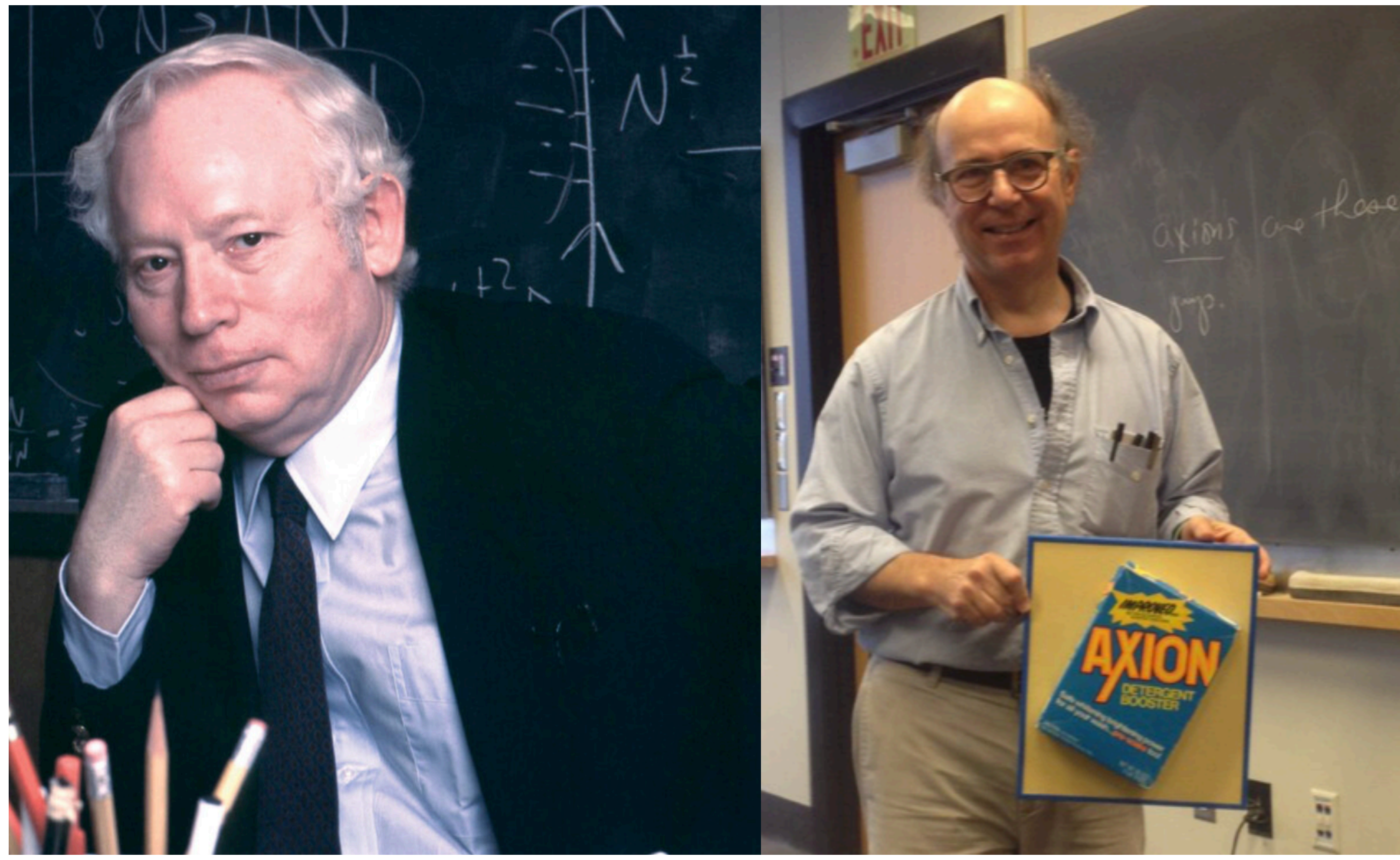
Roberto Peccei, Helen Quinn
(photo: Ryan Schude, Quanta Magazine)



Strong dynamics ⇒

Axion relaxes to CP-conserving value.

$$m_a \sim \frac{m_\pi f_\pi}{f} \sim \frac{10^{-5}\,\mathrm{eV}}{f/(10^{12}\,\mathrm{GeV})}$$

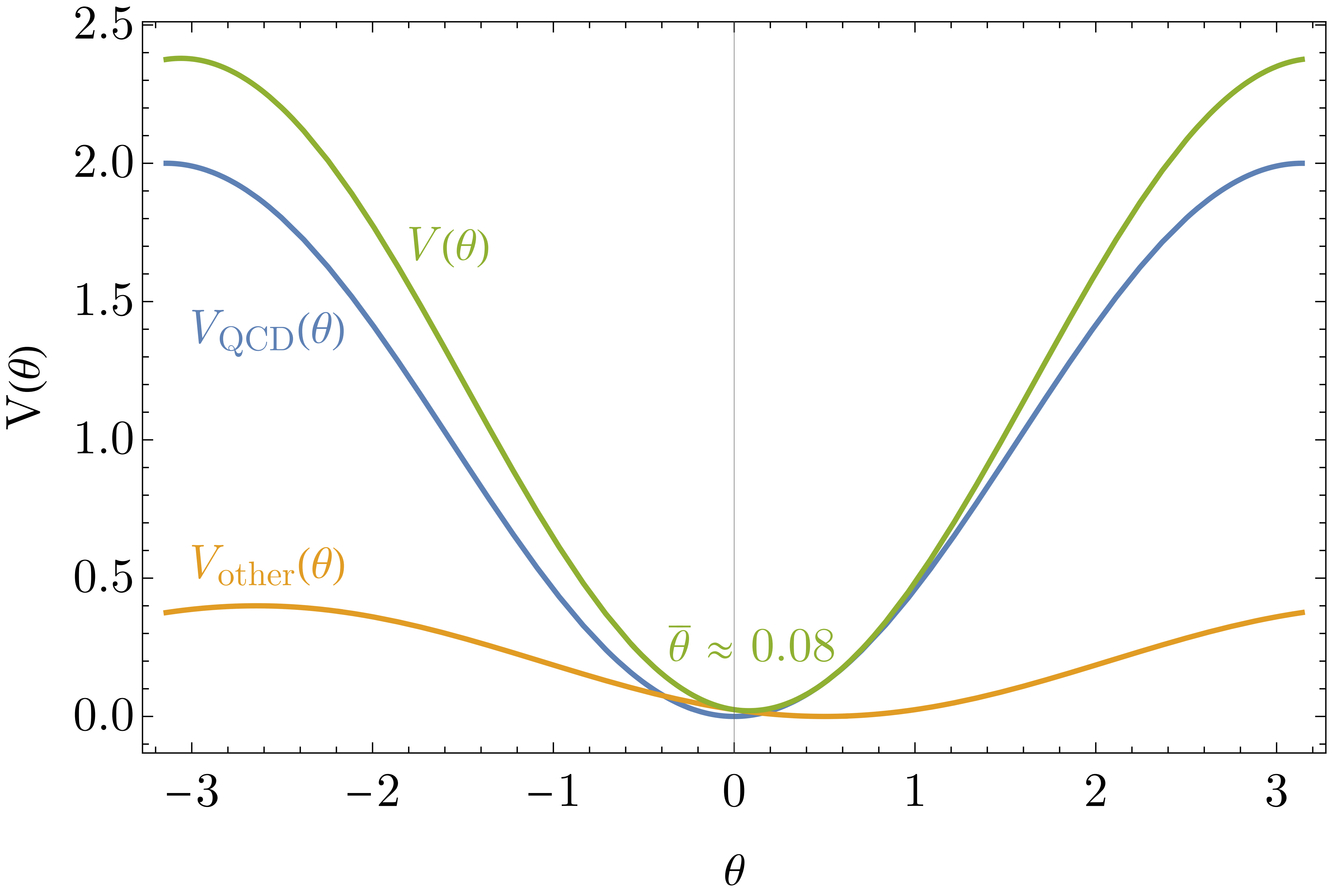


Steven Weinberg, Frank Wilczek

The Axion "Quality Problem"

The Peccei/Quinn (and KSVZ, DFSZ) "solution" wasn't really. $V_{\rm QCD}(\theta)$ is minimized at $\theta = 0$, but we could add all kinds of other terms that have a minimum elsewhere.

To explain $|\bar{\theta}| < 10^{-10}$ we need to assume $V_{\rm other}(\theta)$ to be tiny — but then why not just assume small $\bar{\theta}$ to start?



(Georgi, Hall, Wise '81; Lazarides, Panagiotakopoulos, Shafi '86; Casas, Ross '87; Kamionkowski, March-Russell '92; Holman, Hsu, Kephart, Kolb, Watkins, Widrow '92; Barr, Seckel '92; Ghigna, Lusignoli, Roncadelli '92; …)

Axion Theories: 4d ("Peccei-Quinn") vs. Extra-Dimensional

Familiar 4d axion theories (e.g., KSVZ-like, DFSZ-like): the axion is a **pseudo-Nambu-Goldstone boson,** the phase of a complex field Φ. Quality problem from terms like $\frac{\lambda}{M_{\rm Pl}^{n-4}}\Phi^n + {\rm c.c.}$ in the Lagrangian, which must be suppressed all the way up to $n \sim 14$. **New gauge symmetries** can do that.

Extra-dimensional axion theories: the axion is **not** a Goldstone boson. Arises as gauge field **integrated over extra dimension(s):** $\theta = \int A$. Gauge invariance forbids terms like A^n, allows terms involving $F = {\rm d}A$ hence ${\rm d}\theta$.

Experimentally: hard to tell the difference. (Maybe best hope is cosmology.)

Some Good News

For **extra-dimensional axions,** the quality problem is mild. Every dangerous term $V_{\text{other}}(\theta)$ is proportional to an exponential like $\exp(-M^d L^d)$ where M is a fundamental mass scale and L a length scale of extra dimensions.

Axion-gluon coupling from a "Chern-Simons" coupling $\frac{1}{8\pi^2}\int A \wedge \mathrm{tr}(G \wedge G)$.

Not *guaranteed* to solve the Strong CP problem, but often will.

Furthermore, **extra-dimensional axions** are a **prediction** of string theory. They are probably the single most promising way we might connect quantum gravity with realistic experiments in the foreseeable future.

(This all goes back to a 1984 paper of Edward Witten; see also 2006 work of Joe Conlon and of Peter Svrcek & Edward Witten.)

Axion Models at a Glance

	Pseudo-Nambu-Goldstone for 4d $U(1)_{PQ}$	Zero mode of gauge field in higher dimensions
"Pre-inflation" scenario	Quality problem Isocurvature problem	(Quality problem) Isocurvature problem **UV insights**
Post-inflation PQ transition	Quality problem Domain wall problem Stable relic problem	**Not possible** (no linearly realized PQ symmetry to break) (maybe similar late-time physics from other initial conditions?)

Axion interactions with gluons & photons

Fundamental axion interactions:

$$\int \left(\frac{k_G}{8\pi^2}\theta(x)\,\mathrm{tr}(G\wedge G) + \frac{k_F}{8\pi^2}\theta(x)\,F\wedge F \right)$$

(gluons) (photons)

The interactions are **quantized**. If no fractionally charged particles:

$$k_G \in \mathbb{Z}, \quad \frac{2}{3}k_G + k_F \in \mathbb{Z}$$

(MR '23; Choi, Forslund, Lam, Shao '23; Córdova, Hong, Wang '23)

Low-energy axion-photon coupling: $g_{a\gamma\gamma} = \dfrac{\alpha}{2\pi f/k_G}\left(\dfrac{2k_F}{k_G} - 1.92(4)\right)$

Axion interactions with gluons & photons

Constrained by quantization

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From mixing with pions

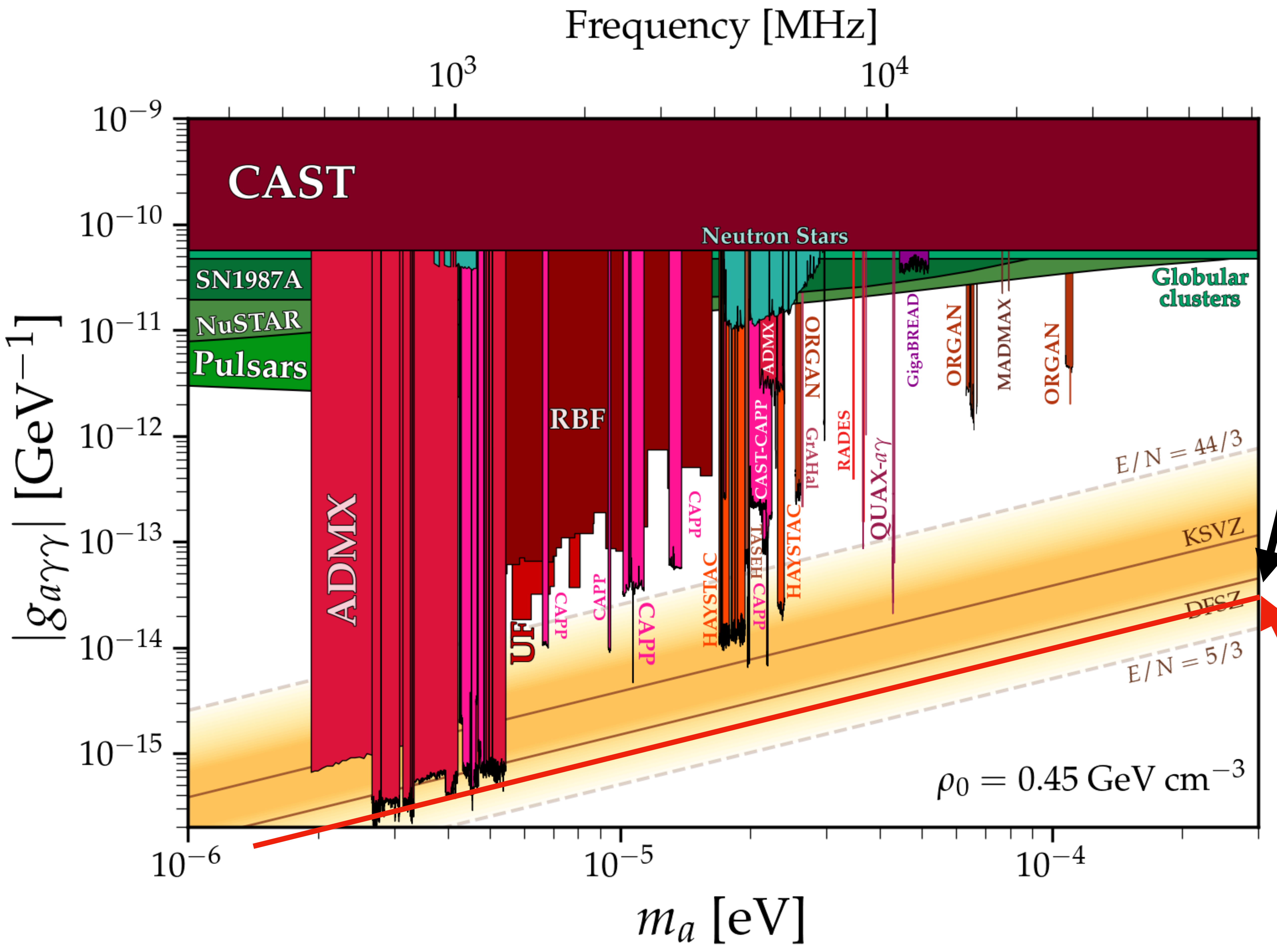
A minimal $|k_G| = 1$ is often theoretically favored (e.g., domain wall problem).

Then the **smallest** $g_{a\gamma\gamma}$ **is when**

$$\frac{2k_F}{k_G} \equiv \frac{E}{N} = \frac{8}{3}.$$

a.k.a. "DFSZ target" but **not** linked to DFSZ model

Experimental Target



Source: Ciaran O'Hare, github

Experiments measure $\rho_0 \, | \, g_{a\gamma\gamma} \, |^2$.

"DFSZ line" $E/N = 8/3$ ***with*** $\rho_0 = 0.45 \, \mathrm{GeV/cm^3}$ **dark matter density.**

Credible estimates have large error bars (e.g., de Salas & Widmark '20), often centered at **smaller** ρ_0, so need to reach ***lower*** in the plot.

My nightmare scenario is we stop looking because "it's already ruled out" at **wrong** ρ_0.

Some Ongoing Research Directions

Reducing axion isocurvature for an extra-dimensional, pre-inflation axion: axion properties different today than during inflation.

Time-dependent mass, first-order phase transition, gravitational waves, ….

w/ Prish Chakraborty, Junyi Cheng, Zekai Wang
arXiv:2507.12519 and ongoing work

Time-dependent decay constant, moduli dynamics, reheating, …

w/ Chandrika Chandrashekar (ongoing work)

And: chiral fermions $\Rightarrow$ existence of light axions in string theory

Brief Advertisement

Local students in the audience, please consider taking my class:

Axion Physics

PHYSICS 253DR Matthew Reece ▾

2026 Spring
Full Term
1/26/2026 to 4/29/2026

S	M	T	W	Th	F	S

1:30pm - 2:45pm
Location:TBA3

Class Number: 17222 **Course ID:** 226491 **Consent:** No Consent **Class Capacity:** No Limit

View: Description Q Scores/Course Evaluations

Theory and phenomenology of axion fields. First, we review the QFT toolkit needed to understand the Strong CP problem and axions (e.g., instantons, theta terms, Chern-Simons terms, the chiral anomaly, the chiral Lagrangian). We will discuss axion models with an emphasis on the axion quality problem and extra-dimensional axions; phenomenological aspects of axion physics (axion cosmology, axion dark matter, laboratory searches, astrophysical constraints); and theoretical developments related to axions (anomaly inflow, generalized symmetries).

Recommended Prep: Familiarity with quantum field theory and the Standard Model (e.g., Physics 253a, 253b and/or 254) is necessary. Some familiarity with cosmology would be useful, but we will review the basics.

Thank You!