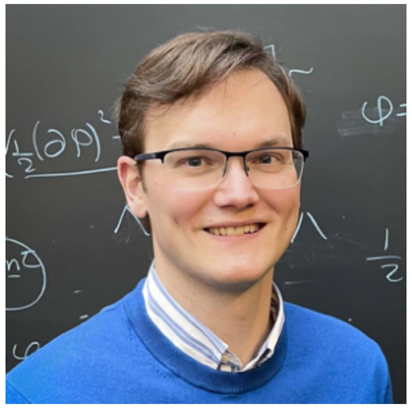
The Strong CP Problem and Axions

Pheno 2026

Prateek Agrawal
UC Santa Barbara

Vazha Loladze

Michael Nee



Arthur Platschorre

Mario Reig

Take Aways

The Strong CP problem has been revisited recently, questioning standard lore in several different ways

- Is it even a problem?
- Can discrete symmetries solve the problem?
- Can axion couplings be modified due to duality?

I will argue that the standard lore is correct

The axion is a very compelling solution to the strong CP problem

- Dark matter candidate
- Ubiquitous in string compactifications
- Accessible in ongoing experiments

Finding the axion will give us new fundamental information

The Strong CP Problem

The QCD Lagrangian

$$\mathscr{L}_{\text{QCD}} \sim -\frac{1}{4}G_{\mu\nu}G^{\mu\nu} + \theta\frac{\alpha_s}{32\pi^2}G_{\mu\nu}\tilde{G}^{\mu\nu} + y_u Q H u^c + y_d Q \tilde{H} d^c$$

Two CP violating phases

$$\delta_{\text{CKM}} \propto \text{im}\det[y_u y_u^\dagger, y_d y_d^\dagger] \sim O(1)$$

$$\bar{\theta} = \theta - \arg\det y_u y_d \leq 10^{-10} \qquad \text{[neutron EDM]}$$

One of the few unmeasured parameters within the Standard Model

The Strong CP Problem Discontents

- Order of limits in instanton calculations
  - Infinite volume before summing over instantons
  - Gapped theory: finite volume perfectly fine

Ai, Cruz, Garbrecht, Tamarit [2001.07152]
Ai, Garbrecht, Tamarit [2403.00747]

- No discrete symmetry solution
  - Symmetry does not forbid a θ term
  - Definition of symmetry, Gauged P / CP, heavy axions

Dvali [hep-th/0510053]
Kaplan, Melia, Rajendran [2505.08358]

- Chiral gauge theory on a 5D lattice
  - Boundary chiral fermion proposal to get SM on lattice
  - Non-locality?

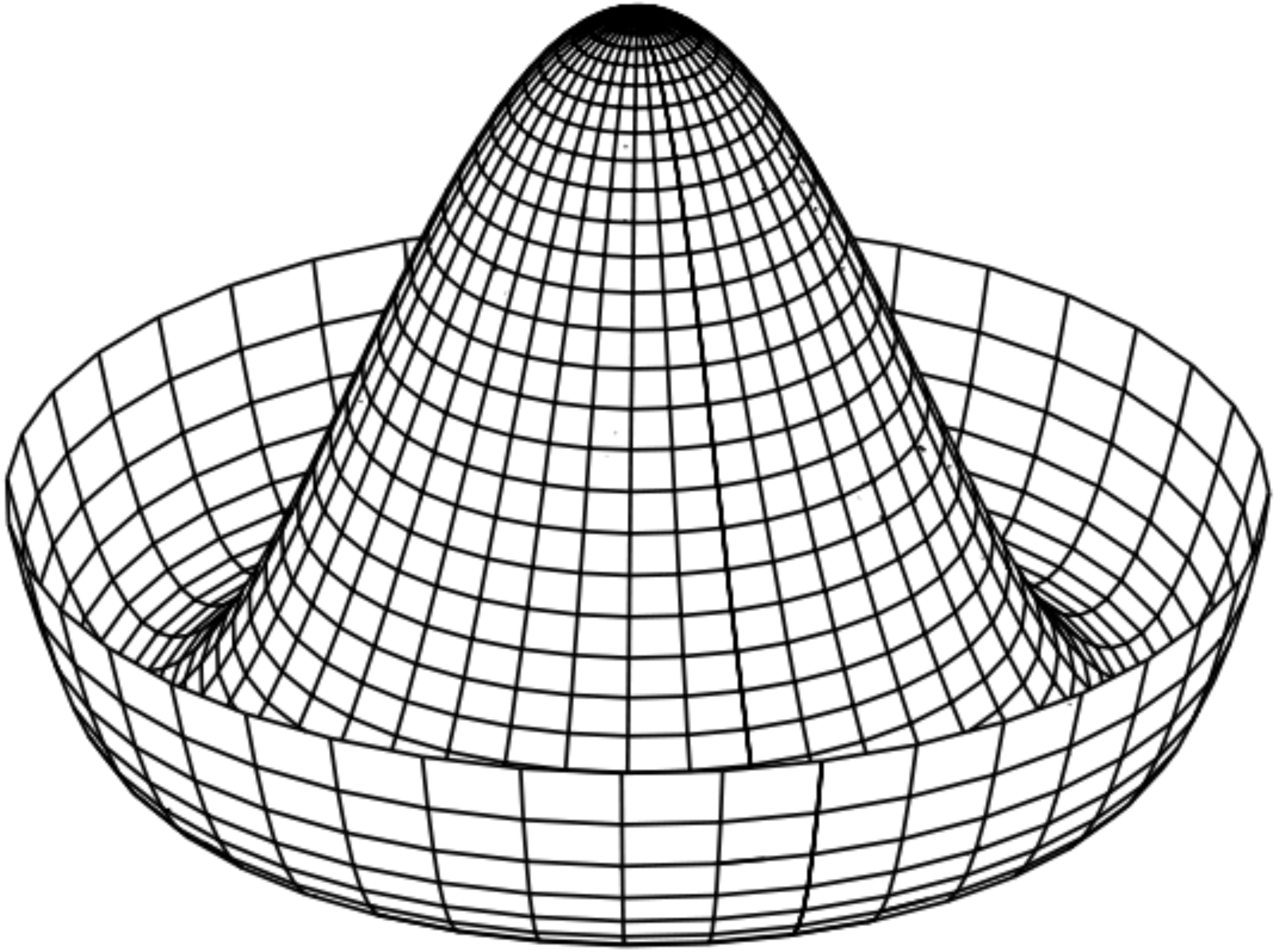
Kaplan, Sen [2412.02024]

- Electromagnetic duality and the axion-photon coupling
  - PQ quarks can be magnetically charged
  - In the SM, the electron would have a tower

Ringwald, Sokolov [2303.10170, 2205.02605]
Heidenreich, McNamara, Reece [2309.07951]
Csáki, Ovadia, Ruhdorfer, Telem, Terning [2411.15312]

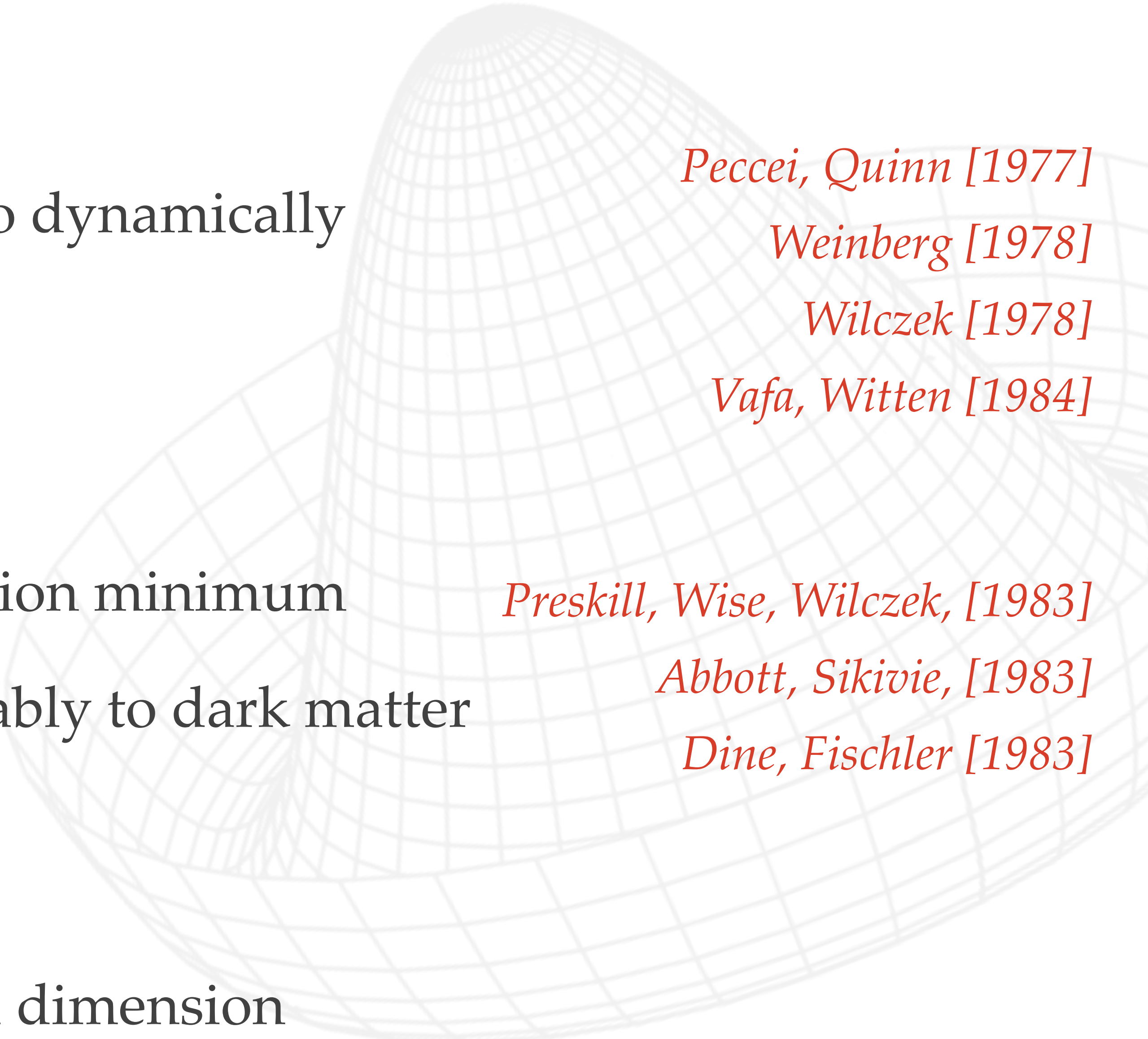
See also: Rapid Response Workshop on the Strong CP Problem [https://indico.cern.ch/event/1617813/]

Introducing the Axion



A compact scalar field $a \cong a + 2\pi f$

Compelling Candidates for New Physics



The strong-CP problem

If $\bar{\theta}$ made dynamical, QCD drives it to zero dynamically

Peccei, Quinn [1977]
Weinberg [1978]
Wilczek [1978]
Vafa, Witten [1984]

Dark matter candidate

Energy density in oscillations about the axion minimum

QCD axion inevitably contributes appreciably to dark matter

Preskill, Wise, Wilczek, [1983]
Abbott, Sikivie, [1983]
Dine, Fischler [1983]

Ubiquitous in string compactifications

Toy example: Gauge theory with one extra dimension

$$A_M \equiv (A_\mu, A_5)$$

Axion is the Aharanov-Bohm phase around the extra dimension

$$a(x) \sim \oint dx_5 \, A_5$$

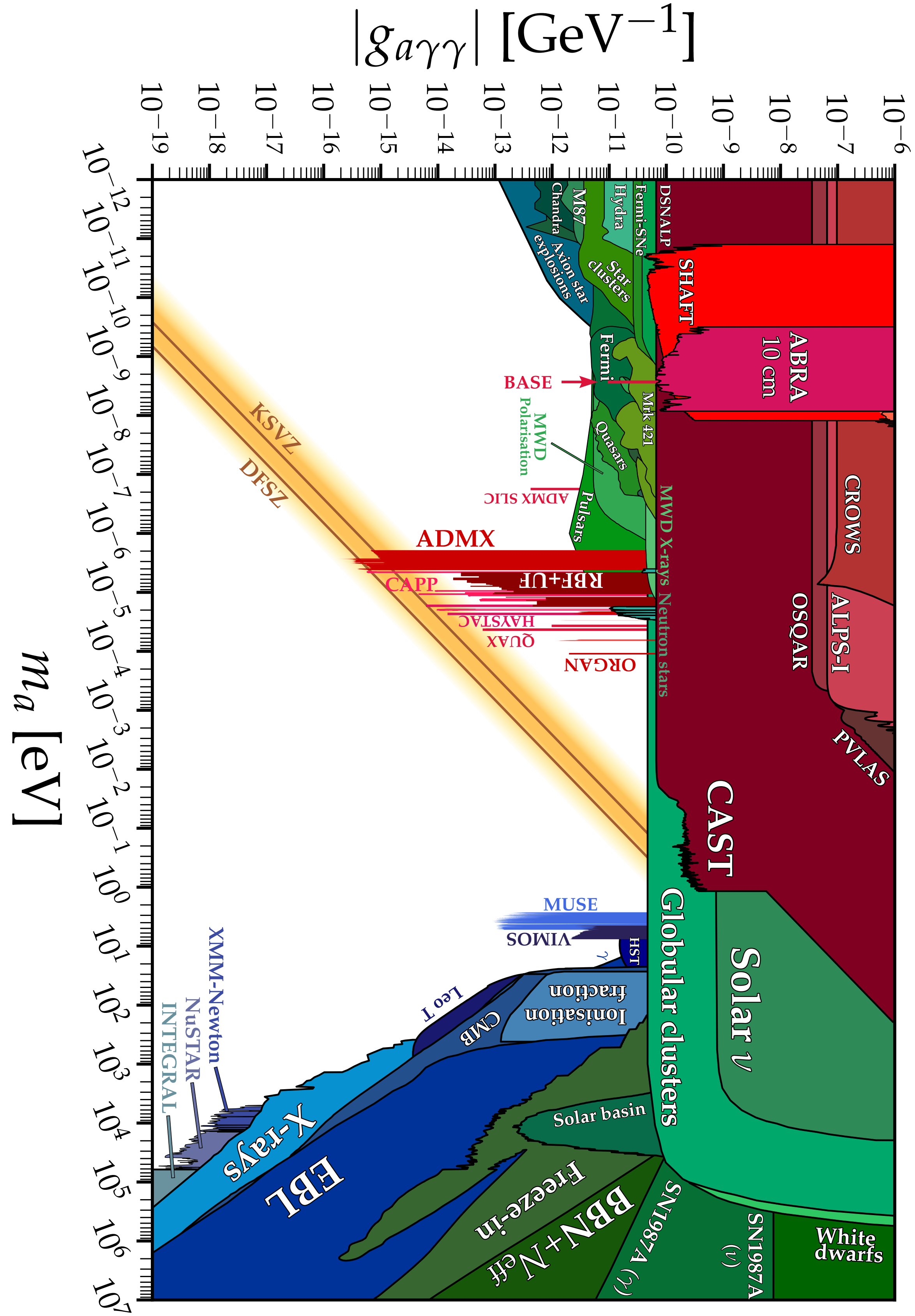
“hundreds of axions, some of them massless”

Arvanitaki, Dimopoulos,
Dubovsky, Kaloper, March-Russell
[0905.4720]

Demirtas, Long, McAllister, Stillman
[1808.01282]

Rich Phenomenology

Cosmology,
astrophysics,
tabletop experiments



[github: Axion Limits, Ciaran O'Hare]

The Axion Quality Problem

Axion solution to the strong CP problem relies on a pristine symmetry

Global symmetries are expected to be violated by quantum gravity

For axions from complex scalar fields $\Phi \sim f_a e^{ia}$, operators

$$\mathcal{O} \sim \frac{c\Phi^N}{M_{\text{pl}}^N}$$

up to $N = 12$ need to be disallowed for $f_a \sim 10^{11}$ GeV and $c \sim O(1)$

A $\mathbb{Z}_{12}$ discrete gauge symmetry?

Babu, Gogoladze, Wang [hep-ph/0212339]
Lee et al [1102.3595]
Harigaya, Ibe, Schmitz, Yanagida [1308.1227]

Composite axion models can be given additional structure to protect axion quality

Randall [1992]
Gherghetta, Murayama, Quílez [2505.08866]
Gherghetta, Murayama, Noether, Quílez,[2508.21813]

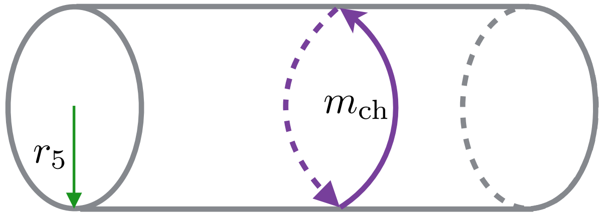
Simple solution: Use $U(1)_{\text{Baryon}}$ in supersymmetric QCD

Lillard, Tait [1707.04261]
PA, Hook, Loladze, Reig [2510.07366]
Choi, Gherghetta [2512.15666]

Axions from Extra Dimensions

High quality axions arise from gauge theory on a compact extra dimension

$$S = \oint \int d^4x \left[-\frac{1}{4} F_{\mu\nu}F^{\mu\nu} - \frac{1}{4} V_{\mu\nu}V^{\mu\nu} + \epsilon^{\mu\nu\alpha\beta\sigma} V_{\sigma} F_{\mu\nu} F_{\alpha\beta} \right]$$



The axion is the Wilson line around the circle $a = \oint V$

$$\int d^4x \oint V \wedge F \wedge F \to \int d^4x \, aF \wedge F$$

The *large gauge transformation* of V becomes the axion discrete gauge symmetry

The *1-form global symmetry* of the field V becomes the axion continuous shift symmetry

In 5D, the 1-form symmetry cannot be broken by local operators in the Lagrangian

Charged particle loops around the S_1 appear as instantons in 4D, generate a suppressed axion potential

$$V(a) \sim \exp(-m_{\rm ch} r_5) \cos(a/F_a)$$

Reece [2406.08543]
Craig, Kongsore [2408.10295]

See talks by Chandrika Chandrasekhar, Arthur Platschorre

Axion as a Gauge Theory

The periodicity of the axion is a discrete gauge symmetry

$$a \cong a + 2\pi F_a$$

Useful to think of axion as a 0-form gauge field

Gauge invariant operators: $\partial_\mu a,\ e^{ia/F_a}$

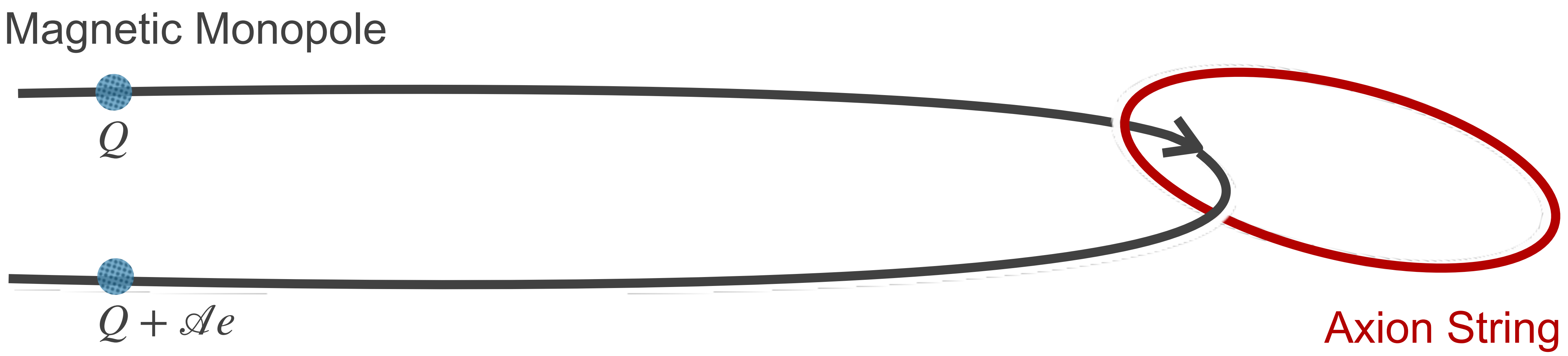
Analogous to the EM field, $F_{\mu\nu}$ and the Wilson loop $e^{\oint iA_\mu dx^\mu}$

The axion - photon coupling has a topological character

$$\mathscr{A}\frac{\alpha_{\text{em}}}{4\pi F_a} a F_{\mu\nu}\widetilde{F}^{\mu\nu}$$

Ideal setting for connecting BSM pheno with generalized symmetries

Axion Strings and Monopoles



Sikivie
[Phys.Lett.B 137 (1984) 353-356]

The monopole experiences $\Delta\theta = \mathscr{A}\dfrac{\Delta a}{F_a} = 2\pi\mathscr{A}$

Picks up an extra electric charge $\Delta Q = e\mathscr{A}$ due to the Witten effect

Charge flows on to the axion string through the Goldstone-Wilczek current
Anomaly inflow ⇒ charge flow!

Dirac-Schwinger-Zwanziger Quantization ⇒ $\mathscr{A} \in \mathbb{Z}$

The monodromic axion-photon coupling

Puzzle: Lagrangian for the QCD axion is parametrized as

$$\mathscr{L} = \frac{a}{f_a}\frac{\alpha_s}{8\pi} G^a_{\mathrm{QCD},\mu\nu}\widetilde{G}^{a,\mu\nu}_{\mathrm{QCD}} + \frac{1}{4} g_{a\gamma\gamma}\, a F_{\mathrm{em},\mu\nu}\widetilde{F}^{\mu\nu}_{\mathrm{em}}$$

$$g_{a\gamma\gamma} = \frac{\alpha_{\mathrm{em}}}{\pi f_a}\left(\frac{E}{N} \underbrace{- \frac{5}{3} - \frac{1-z}{1+z}}_{=-1.92}\right) \qquad z = \frac{m_u}{m_d}$$

The coupling is non-linear $\dfrac{g(a/f_a)}{8\pi} F_{\mu\nu}F^{\mu\nu}$

$$g(\theta) = \frac{E}{N} - \frac{5}{3} - \arctan\left(\frac{1-z}{1+z}\tan N\theta\right) - \pi\sum_{k=1}^{2N}\Theta\left(\theta - (2k-1)\frac{\pi}{2N}\right)$$

PA, Fan, Reece, Wang [1709.06085]
Fraser, Reece [1910.11349]
PA, Platschorre [2309.03934]
Reece [2309.03939]
Choi, Forslund, Lam, Shao [2309.03937]
Córdova, Hong, Wang [2309.05636]

$g(\theta)$ has integer monodromy

$$g(a + 2\pi) = g(a) + 2\pi n$$

ALPs are GUT probes

If SM is UV completed to a simple GUT, and $U(1)_{\rm PQ}$ commutes with the GUT

$$\partial^\mu J_\mu^{\rm PQ} = \mathscr{A}\frac{\alpha_{\rm GUT}}{8\pi}\,\mathscr{G}^{\alpha\beta}\widetilde{\mathscr{G}}_{\alpha\beta} = \frac{\mathscr{A}}{8\pi}\left[\alpha_s G^{\alpha\beta}\widetilde{G}_{\alpha\beta} + \alpha_w W^{\alpha\beta}\widetilde{W}_{\alpha\beta} + \alpha_Y B^{\alpha\beta}\widetilde{B}_{\alpha\beta} + \ldots\right]$$

If PQ symmetry does not commute with GUT, gauging of GUT breaks PQ

e.g. $\pi^\pm$ gets mass from $U(1)_{\rm em}$ which does not commute with $SU(2)_L \times SU(2)_R$

If multiple $U(1)_{\rm PQ}$, one linear combination saturates the anomaly

e.g. $U(1)_B \times U(1)_L \to U(1)_{B-L} \times U(1)_{B+L}$

One axion couples to QCD <u>and</u> EM; all other axions are decoupled

PA, Nee, Reig [2206.07053]

Discovery of an "axion-like particle" can rule out simple Grand Unified Theories

Grand Unification and Axions

Other axions can couple to the SM gauge bosons through mixing effects

$$V(a_1, a_2) = \left(\frac{a_1}{f_1} + \frac{a_2}{f_2}\right) \mathcal{G}\widetilde{\mathcal{G}} + \frac{1}{2} m_2^2 a_2^2$$

$f_1 = f_2 = f$ for illustration

An explicit mass for a_1 will spoil the solution to strong-CP

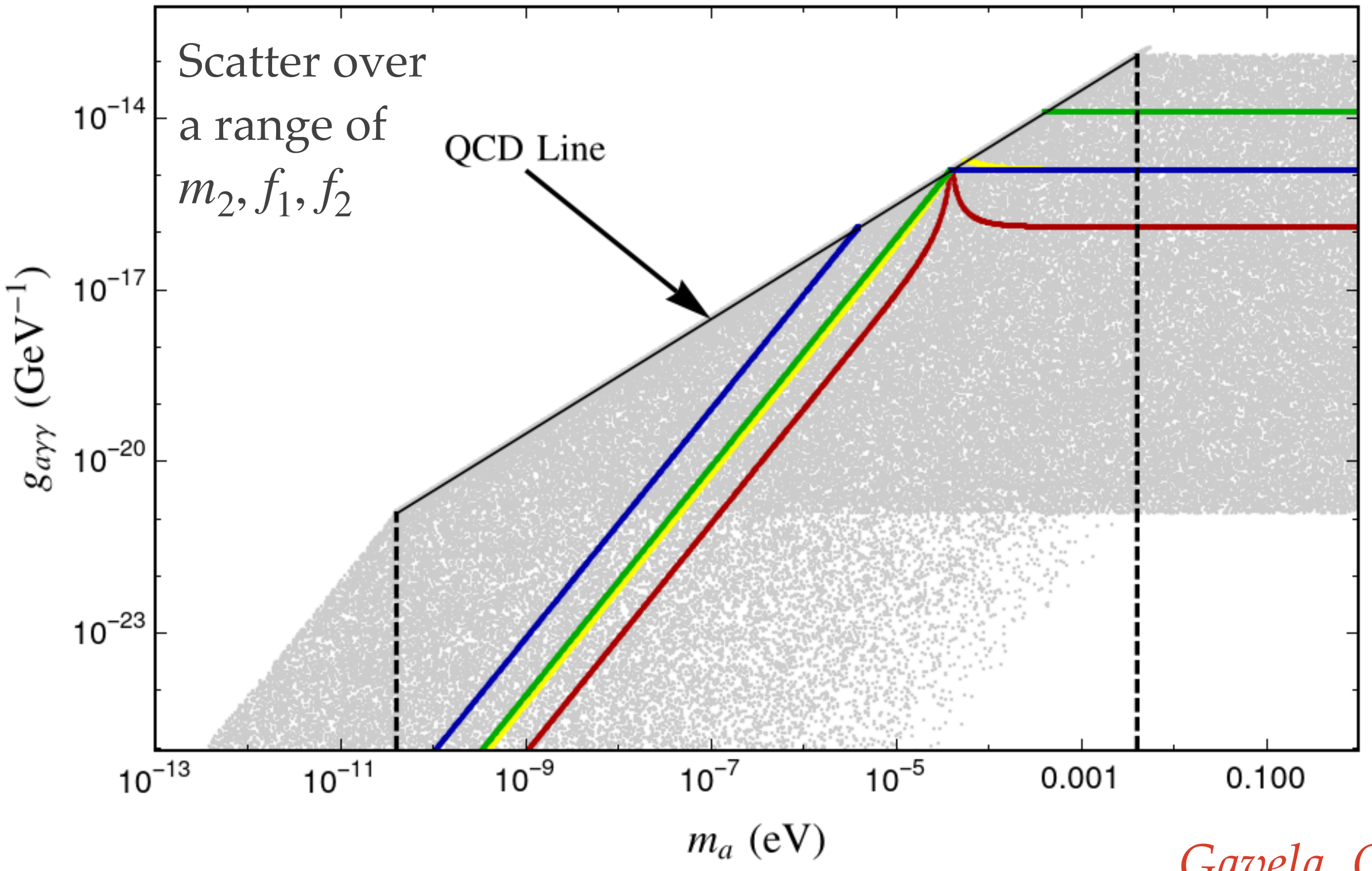
Since a_2 decouples as $m_2 \to 0$, its couplings are suppressed when $m_2 \ll m_a$

$$m_2 \ll \frac{f_\pi m_\pi}{f}$$

$$a \sim a_1 + a_2$$

$$m_b \ll m_a$$

$$g_{b\gamma\gamma} \propto \frac{m_b^2 f^2}{f_\pi^2 m_\pi^2}$$



$$m_2 \gg \frac{f_\pi m_\pi}{f}$$

$$a \simeq a_1,\ b \simeq a_2$$

$$g_{b\gamma\gamma} \sim g_{a\gamma\gamma}$$

$$m_b \gg m_a$$

PA, Nee, Reig [2206.07053]

Gavela, Quílez, Ramos [2305.15465]

Axions in Heterotic String Theory

Heterotic string theory has a very well defined starting point in 10d

$$S_{10} = \frac{1}{2\kappa_{10}^2}\int e^{-2\phi}\left[d^{10}x\sqrt{-g_{10}}R + 4d\phi\wedge\star d\phi - \frac{l_s^4}{2}H\wedge\star H - \frac{\alpha'}{4}\mathrm{tr}(\mathcal{F}\wedge\star\mathcal{F})\right] + \frac{1}{768\pi^3}\int B\wedge X_8$$

Gauge bosons come from a unified structure, $SO(32)$ or $E_8\times E_8$

There are many 4d axion candidates, arising from the 2-form B field

$$a = 2\pi\int_K B_6, \quad b_i = 2\pi\int_{C_i} B, \quad \phi_j = f_{c_j}e^{iq_{c_j}c_j(x)}$$

Axion-photon coupling found by matching anomalies in 10d to 4d

For almost all realistic compactifications in E8 x E8

SM is embedded in one of the E8 factors

A single QCD axion, others decoupled

Svrcek, Witten [hep-th/0605206]
PA, Nee, Reig [2410.03820]
Reig, Weigand [2509.08042]
Benabou, Dainelli, Reig, Safdi [2605.04142]

Discovery of an “axion-like particle” can rule out a large part of the heterotic string landscape

Conclusions

The strong CP problem remains a compelling indicator of new physics beyond the Standard Model

The discovery of the axion will not just be the discovery of a particle — it will also give us deep information about fundamental physics.

Thank You