Why we should believe in axions

Theoretical motivations and dark matter

INFN
PADOVA

Philip Sørensen
Dark Matter Accross All Scales, SDU,
11.05.2026

UNIVERSITÀ
DEGLI STUDI
DI PADOVA

My plan for this talk

Why should we believe in axions at all?

- Why the QCD axion?
- Why axion-like-particles?

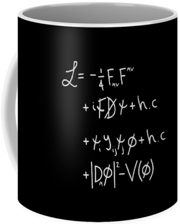
Why should we believe in axions as *dark matter*?

- Axion dark matter from misalignment
- Axion dark matter from topological defects
- Axion dark matter from alternative mechanisms

Part 1: Why the QCD axion?

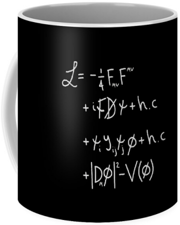
The Strong CP Problem

Philosophy of the standard model:
Define symmetries and write all consistent terms



The Strong CP Problem

Philosophy of the standard model:
Define symmetries and write all consistent terms

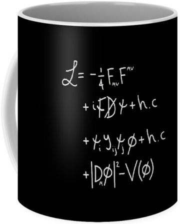


$$+ \quad \tilde{\theta}_{\text{QCD}} \frac{g_s^2}{32\pi^2} G\tilde{G}$$

Allowed by symmetries, but break CP in QCD

The Strong CP Problem

Philosophy of the standard model:
Define symmetries and write all consistent terms



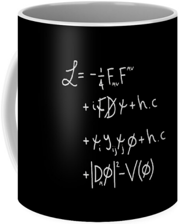
$$+ \quad \tilde{\theta}_{\text{QCD}} \frac{g_s^2}{32\pi^2} G\tilde{G}$$

Allowed by symmetries, but break CP in QCD

- Quark masses can be made real with $q \to e^{i\theta_q\gamma_5/2}q$
- Anomalous path integral measure shifts $\tilde{\theta}_{\text{QCD}} \to \tilde{\theta}_{\text{QCD}} + \theta_q$
- One physical parameter: $\theta_{\text{QCD}} = \tilde{q}_{\text{QCD}} + \theta_q$

The Strong CP Problem

Philosophy of the standard model:
Define symmetries and write all consistent terms



$$+ \qquad \tilde{\theta}_{\text{QCD}} \frac{g_s^2}{32\pi^2} G\tilde{G} \quad + \quad m e^{i\theta_q \gamma_5} \overline{q} q$$

Allowed by symmetries, but break CP in QCD (1 quark for simplicity)

- Quark masses can be made real with $q \rightarrow e^{i\theta_q \gamma_5 / 2} q$
- Anomalous path integral measure shifts $\tilde{\theta}_{\text{QCD}} \rightarrow \tilde{\theta}_{\text{QCD}} + \theta_q$
- One physical parameter: $\theta_{\text{QCD}} = \tilde{q}_{\text{QCD}} + \theta_q$

The Strong CP Problem

Key CP violating observable: Neutron electric dipole moment (nEDM):

$$H = -d_n \overrightarrow{E} \cdot \overrightarrow{S}$$

where $|d_n| \sim \theta_{\text{QCD}} \times 10^{-16}$ e cm

Observational bound of $|d_n| \lesssim 10^{-26}$ e cm demands (Pendlebury, et al. 15), arXiv:1509.04411

$$\theta_{\text{QCD}} \lesssim 10^{-10}$$

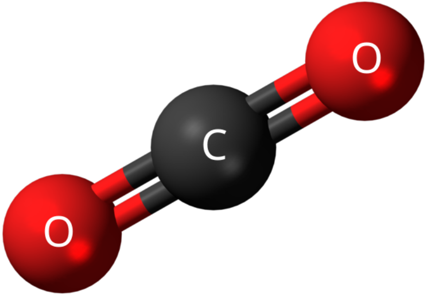
$\boxed{\text{Strong CP problem: Why is } \theta_{\text{QCD}} \text{ so small?}}$

How can we explain a zero?

Let us take inspiration from nature

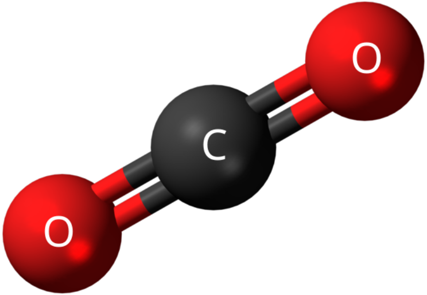
How can we explain a zero?

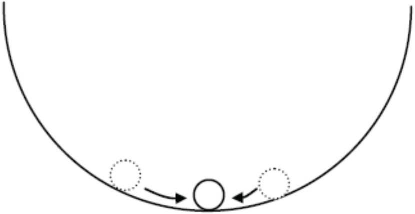
Let us take inspiration from nature



How can we explain a zero?

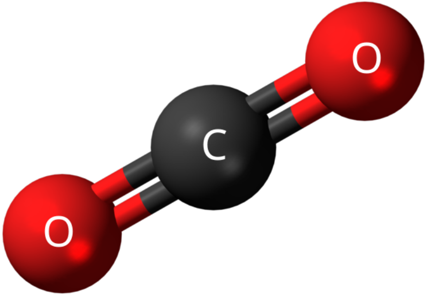
Let us take inspiration from nature

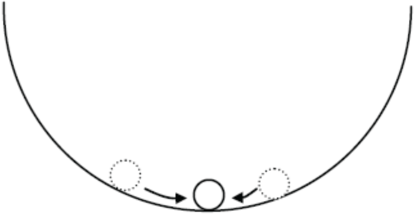




How can we explain a zero?

Let us take inspiration from nature





- Dynamical relaxation: Turn θ_{QCD} dynamic!

A dynamic solution: The axion

- Introduce complex scalar

$$\phi = \frac{1}{\sqrt{2}} f_a e^{i\theta}$$

- Impose global PQ symmetry, broken spontaneously

$$U(1)_{\text{PQ}} \to \theta + \theta'$$

- Make PQ symmetry anomalous under QCD

KSVZ example: $\mathcal{L} \supset \phi \overline{\chi}_L \chi_R \xrightarrow[\text{QCD anomaly}]{} \theta \frac{g_s^2}{32\pi^2} G\tilde{G}$

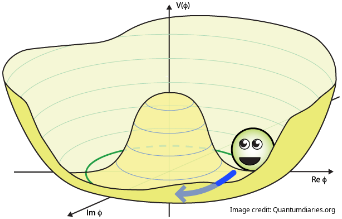


Image credit: Quantumdiaries.org

(Classical literature by Pecci, Quinn, Weinberg, and Wilcezk)

A dynamic solution: The axion

Result: The constant parameter θ_{QCD} replaced with the dynamic *axion* field θ

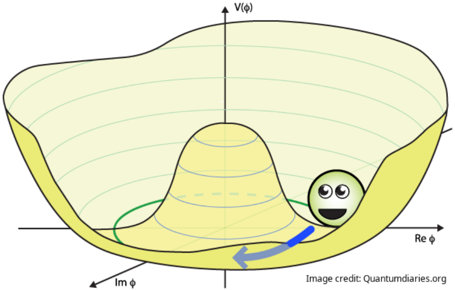
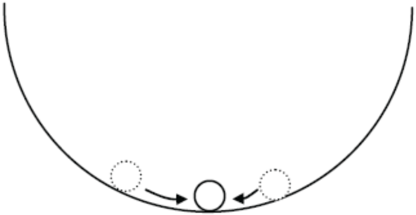


Image credit: Quantumdiaries.org



The axion can roll to the minimum of it's potential, explaining $\theta \ll 1$ in a natural way.

QCD axion properties

- Naturally light, with a potential generated non-perturbatively by QCD:

$$m_a = \frac{1}{f_a}\sqrt{\chi_{\text{QCD}}},$$

suppressed as $m_a(T) \propto T^{-3.92}$ above $T_{\text{QCD}} \approx 150$ MeV (Lattice fit: Borsanyi et al. 2016)

- Suppressed couplings, which are of the form

$$g_{a,\text{SM}} \sim \mathcal{O}(1)\frac{a}{f_a} \ll 1$$

Any QCD axion receives a model-independent (KSVZ-like) contribution from $aG\tilde{G}$.

Part 2: Why ALPs?

UNIVERSITÀ
DEGLI STUDI
DI PADOVA

pNGB's are axion-like

The phenomenologically defining features,

- Pseudoscalar
- Light mass $m \sim \sqrt{\Lambda}/f \ll \Lambda$,
- Weak coupling $g = C(a/f)$,

arose because the QCD axion is a pseudo Nambu–Goldstone boson of $U(a)_{\text{PQ}}$.

pNGB’s with axion-like properties can arise from any spontaneous breaking of global symmetry.

Example of a pNGB ALP: The majoron

Neutrino masses can be explained from the seesaw Lagrangian:

$$\mathcal{L}_{\text{Seesaw}} = -\frac{1}{2} \begin{pmatrix} \bar{\nu}_L & \bar{\nu}_R^C \end{pmatrix} \begin{pmatrix} 0 & m_D \\ m_D^T & m_M \end{pmatrix} \begin{pmatrix} \nu_L^C \\ \nu_R \end{pmatrix} + \text{h.c.},$$

which yields $m_l \sim 10^{-2}$ eV for $m_D \sim \mathcal{O}(m_w)$, $m_M \gg m_D$.
Where does the majorana mass m_M come from?

$$m_M \bar{\nu}_R^c \nu_R \to y \Phi \nu_R^c \nu_R, \quad \text{with SSB} \quad \Phi \to \frac{1}{\sqrt{2}} f e^{iJ/f}$$

The majoron J is then a pNGB of $U(1)_l$, similar to the QCD axion. (Chikashige, Mohapatra, Peccei 80)

- Example of an axion-like-particle
- Generic for spontaneously broken global symmetries

Axions from string theory

Psudoscalar fields ALP-like properties arise in string compactifications.

Consider a 5D gauge field:

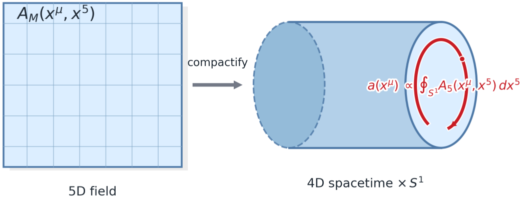
$$A^M(x^\mu, x^5),\ M = 0, 1, 2, 3, 5$$

After the compactificaiton:

$$A^\mu = \text{Regular QED}$$

$$a \sim \int_0^{2\pi R} \mathrm{d}x^5\, A_5$$

Compact field with $f = 1/R$



(Original graphics, example stolen from talk by B. Safdi)

Whats better than a single axion?

Realistic string theories have complex compactification topology.

- The exact spectrum is difficult to sample
- Predicts between $\mathcal{O}(1)$ to $\mathcal{O}(100)$ ALP

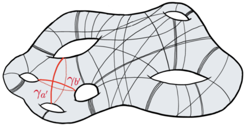


Image source: Petrossian-Byrne and Villadoro 25

Expected properties:

- m: widely distributed in log space
- f: often assumed large, i.e. GUT scale

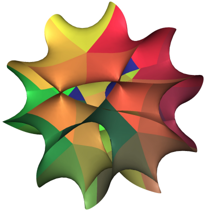
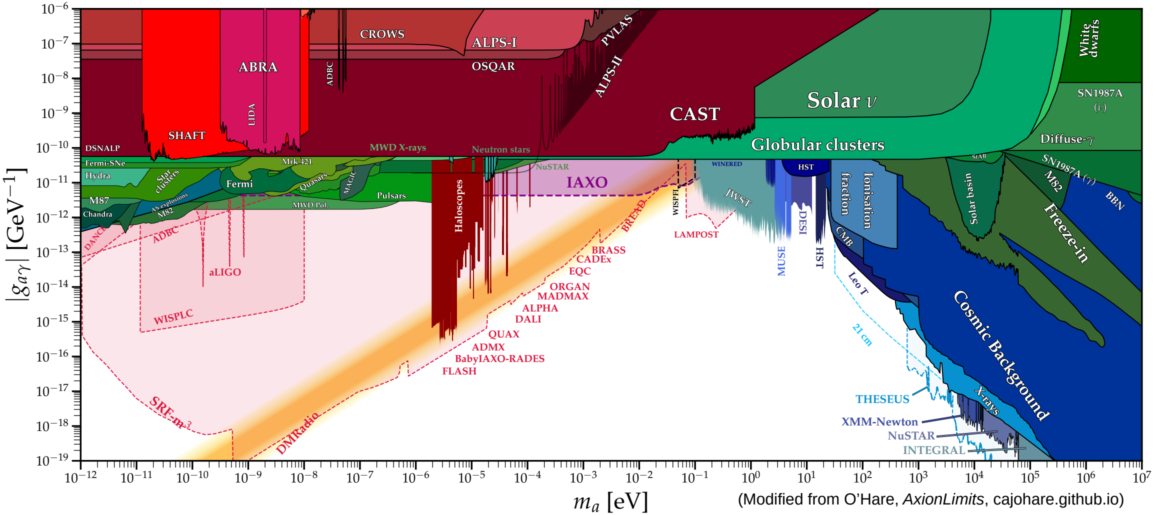


Image source: Wikipedia

Known as the *axiverse*

(Avinataki, Dimopoulos, Dubovsky, Kaloper, March-Russel 09, arXiv:0274.5090)

The axion parameter space



(Modified from O’Hare, *AxionLimits*, cajohare.github.io)

Part 1: Why axions as dark matter?

UNIVERSITÀ
DEGLI STUDI
DI PADOVA

The axion as dark matter: Misalignment

Consider a massive ALP with a (potentially T-dependent) mass:

$$\mathcal{L} \supset \frac{f_a^2}{2}\partial_\mu\theta\partial^\mu\theta - \frac{1}{2}m_a^2(T)f_a^2\theta^2$$

The axion as dark matter: Misalignment

Consider a massive ALP with a (potentially T-dependent) mass:

$$\mathcal{L} \supset \frac{f_a^2}{2}\partial_\mu\theta\partial^\mu\theta - \frac{1}{2}m_a^2(T)f_a^2\theta^2$$

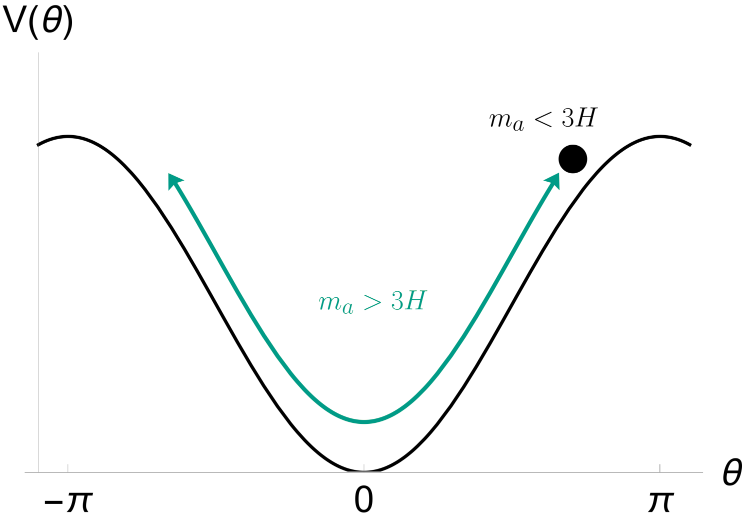
Equation of motion in an expanding spacetime:

$$(\underbrace{\nabla^2}_{\text{CD}} + m^2)\theta = 0 \quad \rightarrow \quad \ddot{\theta} + \underbrace{3H\dot{\theta}}_{\text{friction}} + m_a^2(T)\theta = 0$$

Two regimes:

- $m_a(T) \ll 3H \iff \rho_a \propto a^0$ (Frozen)
- $m_a(T) \gg 3H \iff \rho_a \propto a^{-3}$ (Oscillating)

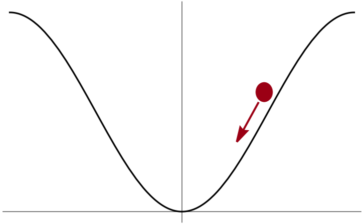
The axion as dark matter: Misalignment



The axion as dark matter: Misalignment

Present day DM relic:

$$\rho_{a,\,\text{today}} \approx \frac{1}{2} m_a^2 f_a^2 \theta_{\text{ini}}^2 \frac{m_a(T_{\text{osc}})}{m_a} \frac{g_{*s}(T_0)}{g_{*s}(T_{\text{osc}})} \left(\frac{T_0}{T_{\text{osc}}}\right)^3$$

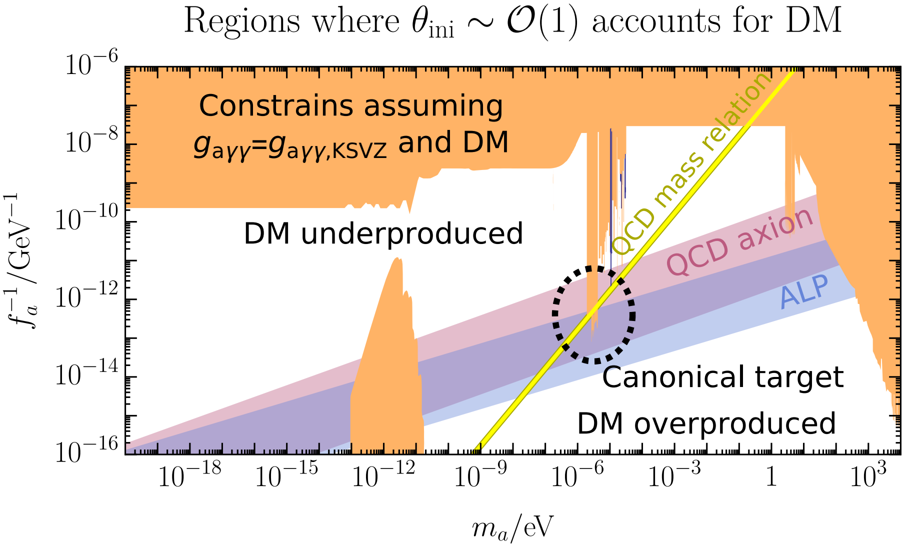


For a QCD axion:

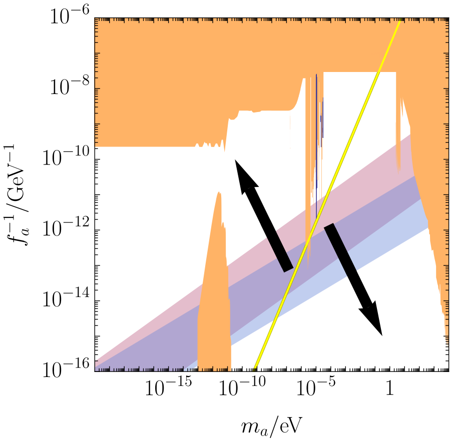
- $m_a^2 f_a^2 = \chi_{\text{QCD}} \approx (76\ \text{MeV})^4$
- Matches the observed DM relic only for a unique oscillation temperature:

$$T_{\text{osc}} \approx 950\ \text{MeV} \left(\frac{\rho_{a,\,\text{today}}}{\rho_{\text{DM,today}}}\right)^{-1/7} \theta_{\text{ini}}^{2/7}.$$

Misalignment dark matter parameter space



Pushing misalignment bounds



Push to higher masses:

- Restricted by $|\theta_{\text{ini}}| \leq \pi$
- $\theta_{\text{ini}} \rightarrow \pi$ implies $\cos(\theta) \rightarrow$ flat, enhancing relic
- Limited by your willingness to tune and instabilities (Arvanitaki et al. 2019, arXiv:1909.11665)

Push to lower masses:

- Limited by isocurvature contribution,
- $\theta_{\text{ini}}^2 \gg \delta\theta_{\text{iso}}^2 \approx \frac{H_I}{2\pi f_a}$ (Hertzberg, Tegmark, Wilczek 08, arXiv:0807.1726)

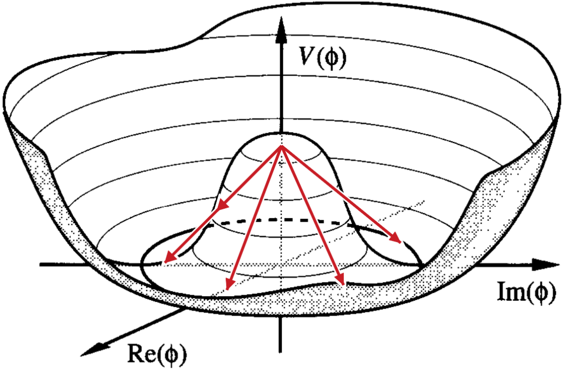
Pre- and post-inflationary axions

- PQ broken during/before inflation
  - θ_{ini} form a single inflated patch
  - $\theta_{\text{ini}}(x) = \theta_{\text{ini}} \sim \mathcal{O}(1)$
  - θ_{ini} is a free parameter

- PQ broken after inflation:
  - Each Hubble patch chooses $\theta_{\text{ini}}(x) \in [-\pi, \pi)$ independently.
  - Predictable average: $\langle|\theta_{\text{ini}}|\rangle = \pi/\sqrt{3}$
  - Fully determined, *but not calculable*

Cosmic strings

PQ breaking leads to topological defects:



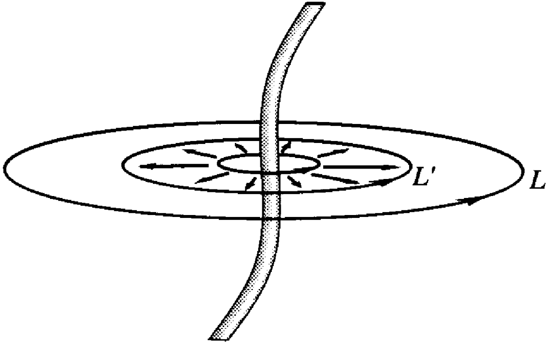
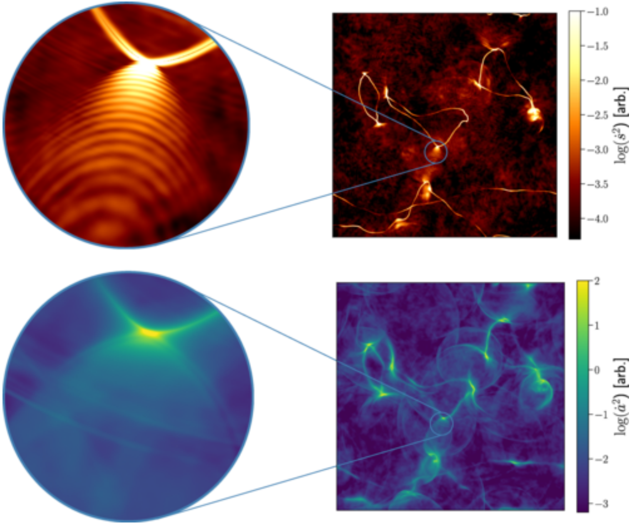


Illustration taken and modified from the classic textbook *Cosmic strings and other topological defects*, by Vilenkin and Shellard.

Cosmic string simulations



Benabou et al., arXiv:2308.01334

Summary of dark matter predictions

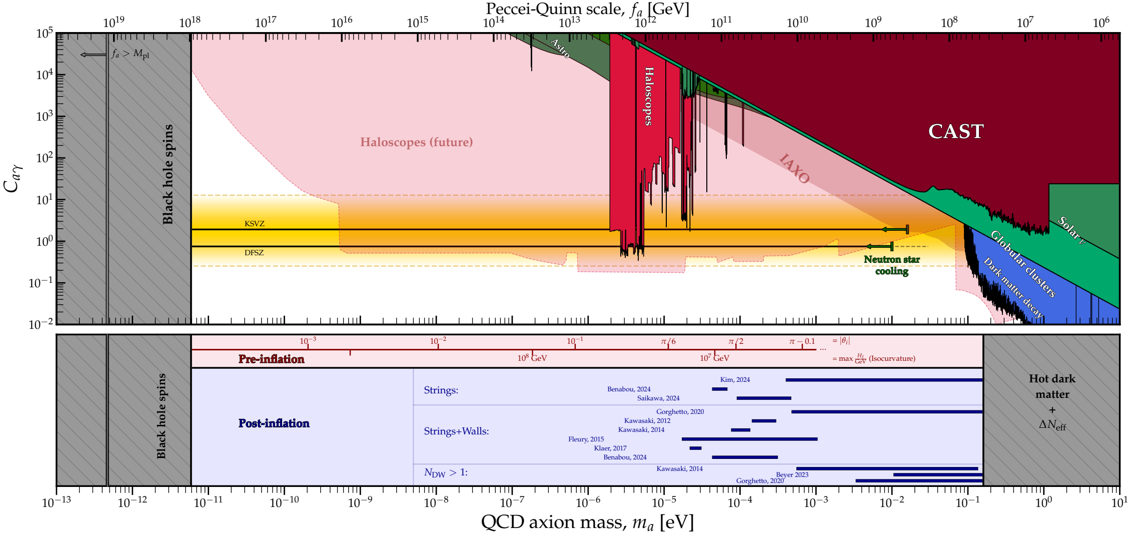


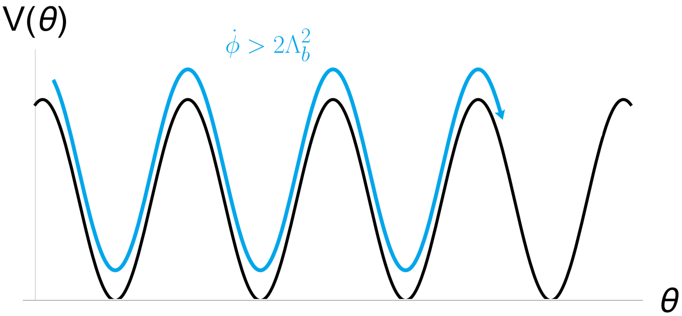
Illustration taken and modified from the *Axion Limits*, cajohare.github.io, by Ciaran O'Hare.

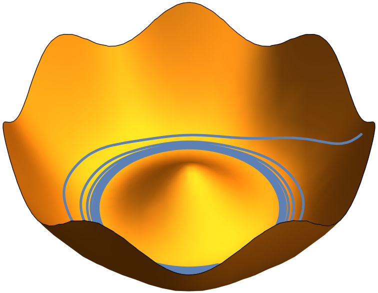
Part 5: Alternative mechanisms

Università degli Studi di Padova

Kinetic misalignment

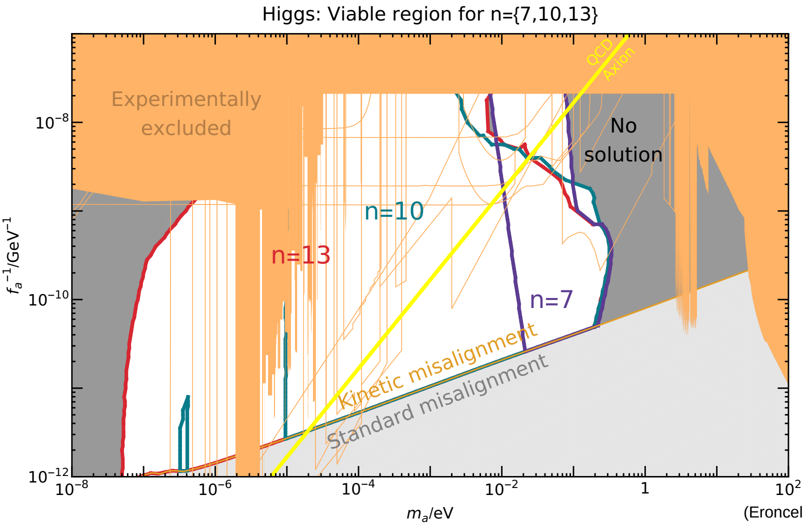
Assume initial kinetic energy, $\frac{\dot{\phi}}{\Lambda^2} \gg 1$ to delay oscillations by spinning.





(Co, Hall, Harigaya 19)
(Co et al. 20a), (Co et al. 20b)
(Eroncel, Sato, Servant, **PS** 22)
(Eroncel, Sato, Servant, **PS** 24)
...

Kinetic misalignment



(Eroncel, Sato, Servant, **PS** 24)

Trapped misalignment

To improve: Temperature-dependent potentials:

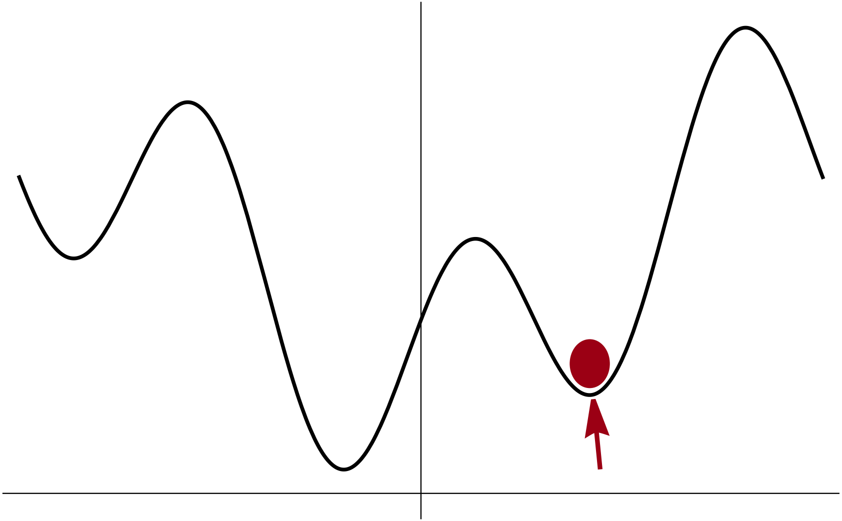
$$V_{\text{th}} = -\Lambda^4_{\cancel{PQ}}(T) \times \cos\big(n\theta + \delta_{\cancel{PQ}}\big)$$

Y. Zhang (2305.15495) proposed to generate such potentials from

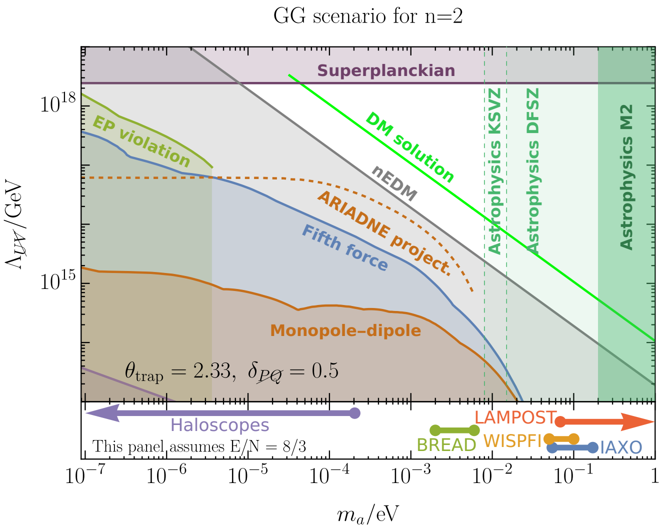
$$\mathcal{L} \supset \left(\frac{\phi}{\Lambda_{\text{UV}}}\right)^n \times \mathcal{O}_{\text{SM}}$$

- Proposed as a solution to DW problem
- Zhang considered only $n = 1$
- We (Di Luzio, **PS** 24) generalize to $n > 1$, update constraints, and evaluate DM

Trapped misalignment



Parameter space: Testable with nEDM



Summary

Take-away points:

- The QCD axion is a well-motived extension to the standard model:
  - Build to solve the Strong CP problem
  - Ideal dark matter candidate with ”build-in” production mechanism

- Particles with similar phenomenological properties are common in theory
  - pNGB’s are generically axion-like-particle’s
  - String theory predicts large numbers of ALP coexisting

- ALPs can be produced as dark matter in several ways
  - Post-inflationary: Cosmic strings
  - Pre-inflationary: Misalignment
  - Many variations exist

Thank you!

Discussion!

Contact
Philip Sørensen
0000-0003-4780-9088
University of Padova / INFN Padova
philip.soerensen@pd.infn.it
+4530897153