PLANCK 2024:
A minimal solution to the axion isocurvature problem from a non-minimal coupling

based on **2404.06441**

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06.06.2024

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Financiado por la Unión Europea NextGenerationEU
Gobierno de España
Plan de Recuperación, Transformación y Resiliencia

Peccei-Quinn mechanism & QCD Axion

Neutron EDM: $\overline{\theta} \equiv \theta_{\text{QCD}} + \text{Arg}[\det(m_q)] < 10^{-10}$

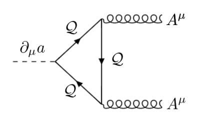
Promote $\overline{\theta}$ to field, relax strong CP violation [Peccei, Quinn 1977]

$$\frac{g_3^2}{32\pi^2}\frac{a}{f_a}\text{Tr}\left(G_{\mu\nu}\tilde{G}^{\mu\nu}\right) \quad \text{with} \quad \left\langle \frac{a}{f_a} \right\rangle \simeq 0$$

Global $U(1)_{PQ}$ w. $U(1)_{PQ} \otimes SU(3)_c^2$ anomaly

$$\sigma = \frac{\rho + f_a}{\sqrt{2}} e^{i\frac{a}{f_a}}$$

a QCD Axion [Weinberg, Wilczek 1977]



source: [2105.01406]

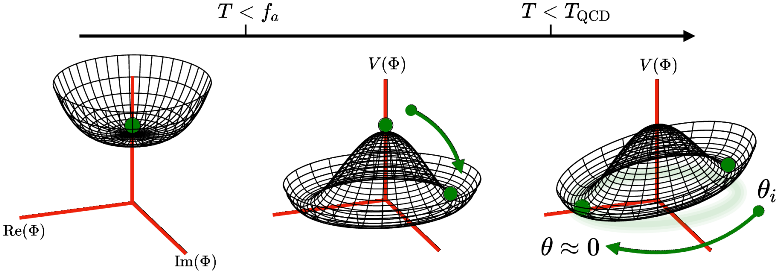
source: Amazon

Peccei-Quinn mechanism & QCD Axion

QCD instantons induce potential for PNGB

$$m_a = 5.7\,\mu\text{eV}\left(\frac{10^{12}\text{ GeV}}{f_a}\right)$$

Vacuum realignment of $\theta \equiv a/f_a$ can explain cold dark matter
[Abbott, Sikivie; Dine, Fischler; Preskill, Wise, Wilczek 1983]



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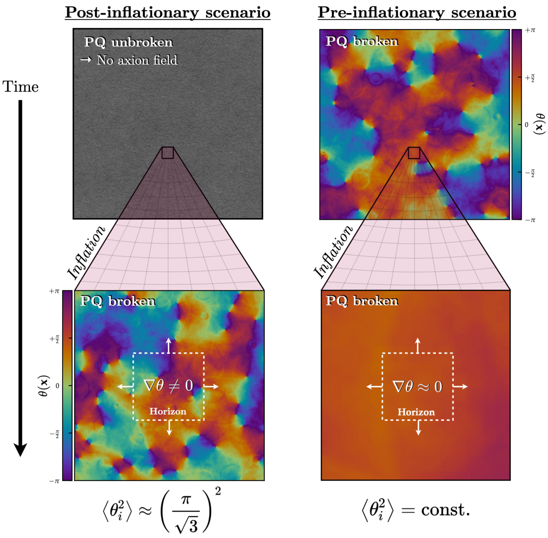
Axion Cosmology: Impact of Inflation



source: [2403.17697]

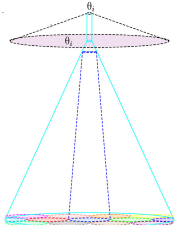
Post-Inflationary PQ breaking

Breaking **after** (visible) Inflation & Reheating

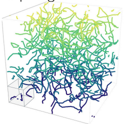
$$f_a < \mathrm{Max}\left[\frac{H_I}{2\pi}, T_{\mathrm{RH}}, T_{\mathrm{max}}\right]$$

- different θ_i in each patch $\left(\sqrt{\langle\theta_i^2\rangle} \simeq \pi/\sqrt{3}\right)$
  $\Rightarrow$ DWs at $T < \mathcal{O}(100\ \mathrm{MeV})$
- Defects: string-wall-network
  (unstable for $N_{\mathrm{DW}} = 1$)
- $h^2\Omega_a$: misalignment **and** defects

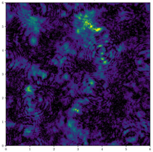
$$3 \times 10^{10}\ \mathrm{GeV} \lesssim f_a \lesssim 4.8 \times 10^{11}\ \mathrm{GeV}$$
$$(14\ \mu\mathrm{eV} \lesssim m_a \lesssim 200\ \mu\mathrm{eV})$$



Topological defects

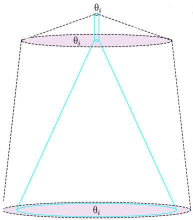


Nonlinear dynamics

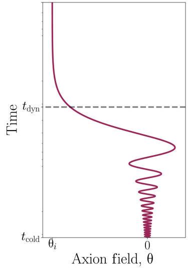


[2105.01406]

Pre-Inflationary PQ breaking



Harmonic motion



[2105.01406]

Breaking **before** (visible) Inflation & Reheating

$$f_a > \text{Max}\left[\frac{H_I}{2\pi}, T_{\rm RH}, T_{\rm max}\right]$$

- θ_i smoothed out $\Rightarrow$ no DWs!!!!
- cosmic strings diluted by inflation
- $h^2\Omega_a$ from misalignment **only**

$$\Omega_a h^2 \simeq 0.12 \left(\frac{\theta_i}{1}\right)^2 \left(\frac{f_a}{8.7\times 10^{11}\,\text{GeV}}\right)^{\frac{7}{6}}$$

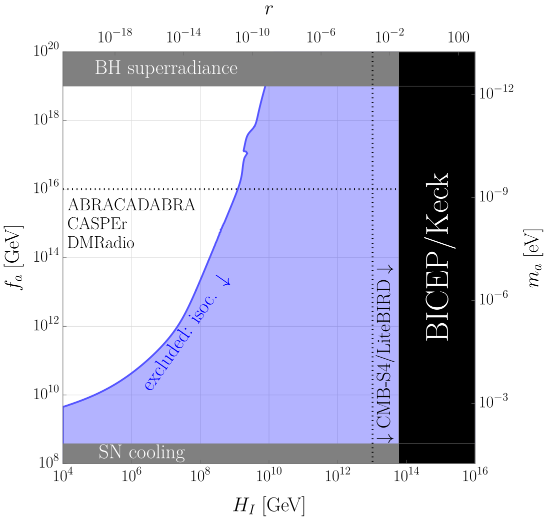
Axion isocurvature problem

Breaking before (visible) Inflation

- axion: **massless** during inflation ($H_I \gg T_{\mathrm{QCD}} \simeq \mathcal{O}(100\,\mathrm{MeV})$)
- quantum fluct. $\delta\theta = \frac{H_I}{2\pi f_a}$ $\Rightarrow$ **scale-invariant** CDM isocurv.
- CMB: **only curvature** perturbations observed [Planck 2018]

$$\Delta_a^2(k_*) \simeq \left(\frac{H_I}{f_a \pi \theta_i}\right)^2 < \frac{\beta_{\mathrm{iso}}}{1-\beta_{\mathrm{iso}}}\Delta_\zeta^2(k_*) \simeq 8.7 \times 10^{-11}$$

Axion isocurvature problem



$f_a > \frac{H_I}{2\pi}$ **incompatible** w. obervable inflationary GWs ($H_I \simeq 10^{13}$ GeV)

Quality problem

$U(1)_{PQ}$: global symmetry violated by quantum gravity (wormholes)

$$V_{P\!\!\!/Q} = c_d e^{-S_E} \sigma^d M_{\rm Pl.}^{4-d} + \text{h.c.}$$

This shifts the minimum of the axion from $\langle a/f_a \rangle \simeq 0$ to

$$\left\langle \frac{a}{f_a} \right\rangle > 10^{-10}$$

With $S_E \ll 1, |c_d|, \mathrm{Arg}(c_d) \simeq \mathcal{O}(1)$ this is avoided for

$$d > 8\ (10) \quad \text{for} \quad f_a = 10^8\ \text{GeV}\ (10^{10}\ \text{GeV})$$

Needs mechanism to select large enough d or S_E!

Proceed with caution

The mechanism

Assume PQ symmetry is **softly** broken by gravity ($R = -12H_I^2$)

$$V(\sigma) \supset \xi_\sigma R \sigma^2 + \text{h.c.} = |\xi_\sigma| R \rho^2 \cos(2\theta - \theta_R)$$

Hubble dependent mass during inflation

$$M_a^2 = 48 |\xi_\sigma| \cos(\theta_R) H_I^2$$

The mechanism

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Hubble dependent mass during inflation

$$\underbrace{m_\rho^2}_{\text{for well-defined PNGB}} \quad > \quad 48\,|\xi_\sigma| \cos(\theta_R) H_I^2 \quad > \quad \underbrace{\left(\frac{3}{2} H_I\right)^2}_{\text{no quant. fluctuations}}$$

The mechanism

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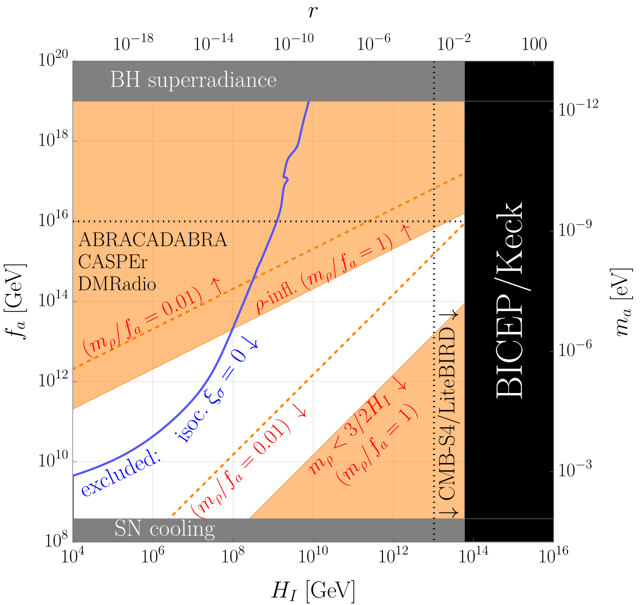
$$m_\rho^2 \quad > \quad 48 |\xi_\sigma| \cos(\theta_R) H_I^2 \quad > \quad \left(\frac{3}{2} H_I\right)^2$$

Power spectrum **suppressed** on CMB scales ($k_* = 0.05\ \text{Mpc}^{-1}$)

$$\Delta_a^2(k_*) \simeq \left(\frac{H_I}{f_a \pi \theta_i}\right)^2 \frac{H_I}{M_a} \underbrace{\left(\frac{k_*}{a_{\text{end}} H_I}\right)^3}_{e^{-3N_*} = 7\times 10^{-66}}$$

Enlarged Parameter space



Quality problem?

How much is the axion minimum $\theta_0 \simeq 0$ shifted?

$$V(a) = m_a^2 f_a^2 (1 - \cos(\theta)) + 12 \left|\xi_\sigma\right| H_0^2 f_a^2 \cos(2\theta - \theta_R)$$

Correction to the axion potential suppressed due to **tiny** Hubble rate today

$$H_0 \simeq 10^{-33}\ \text{eV}$$

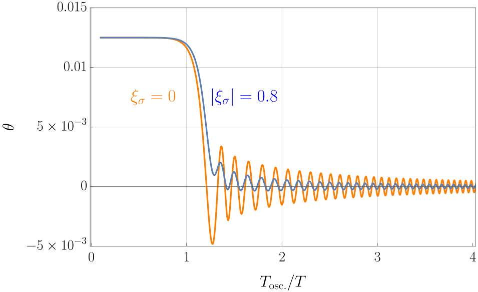
Does **not** lead to any relevant constraints

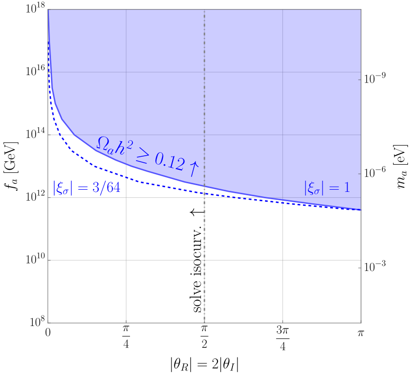
$$\theta_0 \simeq 10^{-26} \left|\xi_\sigma\right| \sin(\theta_R) \left(\frac{f_a}{10^{16}\ \text{GeV}}\right)^2 \left(\frac{H_0}{70 \frac{\text{km}}{\text{s}} \text{Mpc}^{-1}}\right)^2$$

Impact on Misalignment

Adiabatic Relaxation:

[Linde 1996, Takahashi et al. 2015-20]





- RD: $R \neq 0$ because of QCD
- $M_a/H(T) \sim \alpha_S(T)$
- starts from $\theta_I = \theta_R/2 < \pi/4$
- θ_I larger by $\mathcal{O}(1)$ factor

Summary

- grav. PQ breaking $\begin{cases}\text{suppressed isoc. fluct. on CMB scales} \\ \text{negligible correction to } \theta_0\end{cases}$

- IC θ_i replaced by parameter $\theta_R/2$

- $h^2\Omega_a$ slightly reduced

- **Smoking Gun:** $\begin{cases}\text{GUT scale axion at ABRA.../CASPEr/DMRadio} \\ \text{GWs at LiteBIRD}\end{cases}$

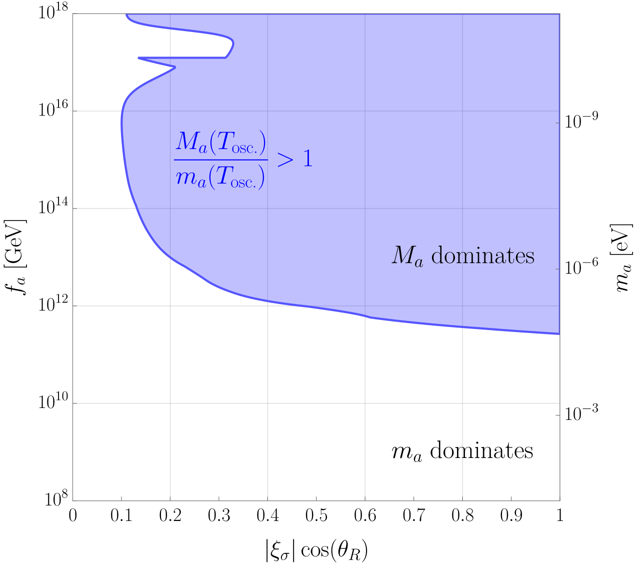
Outro

Thank you for your time and attention!

Appendix

Here be dragons

Impact on Misalignment (2)



DM from fluctuations

- during **inflation**: [1807.09785, 1905.09836]
  $|\xi_\sigma| < 1$ and $H_I \simeq 10^{13}$ GeV needs $m_a \simeq 1\,\text{keV}$
  ($m_a \uparrow$ for $|\xi_\sigma| \uparrow$ or $H_I \downarrow$)

- during **reheating**: [hep-ph/0602144, 1512.07288]
  oscillating inflaton $\leftrightarrow$ oscillating R a la geometric preheating
  needs $m_a \gtrsim 10\,\text{GeV}$ or $|\xi_\sigma| > 1$
  - oscillating R (or epoch of kination) could destabilize $\theta_I = \theta_R/2$

- non-adiabat. **transition** inflation to reheating: [1506.04065]
  $\delta\theta \simeq \frac{2.2\times 10^{-4}}{(|\xi_\sigma|\cos(\theta_R))^{\frac{1}{4}}} \left(\frac{H_e}{10^{13}\ \text{GeV}}\right) \left(\frac{10^{16}\ \text{GeV}}{f_a}\right) \ll \theta_I \simeq 1.7\times 10^{-2}$ for $\Omega_a h^2$
  (produced 50-60 e-folds after CMB modes left horizon)

Established solutions to axion iscocurvature problem

1. Larger decay constant [Linde 1991]
   - quant. fluct. or couplings like $R|\sigma|^2$, $\frac{V(\varphi)}{M_{\text{Pl}}^2}|\sigma|^2$
   - field displacement $S_i \gg f_a$
   - bound on H_I relaxed by S_i/f_a

2. Restore PQ symmetry
   - couplings like $-R|\sigma|^2$, $\frac{V(\varphi)}{M_{\text{Pl}}^2}|\sigma|^2$, $\frac{\partial_\mu\varphi\partial^\mu\varphi}{M_{\text{Pl}}^2}|\sigma|^2$ or **PR**
   - $\mu_\sigma^2 > 0$ during inflation
   - breaking **during** visible inflation [Redi, Tesi 2023]
     $\Rightarrow$ fluctuations at lager scales e.g. Lyman-α

3. Heavy QCD axion [Dvali 1995]
   - early QCD confinement, add. gauge groups, magnetic monopoles,
   - OR kinetic term modified by gravity