Effects of PQ symmetry breaking on the axion cosmological production through misalignment

Upcoming work with Luca di Luzio

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Background

The QCD axion potential and VEV

- Axion T-dependence: QCD generates a potential of the form (Lattice fit: Borsanyi et al. 2016)

$$V_{\text{QCD}} \approx -m_a^2(T) f_a^2 \cos\left(\frac{a}{f_a}\right) \quad \text{where} \quad m_a^2(T) \approx m_a^2 \max\left[\left(\frac{T}{T_{\text{QCD}}}\right)^{-2b}, 1\right]$$

$$\text{where} \quad b \approx 3.92 \quad \text{and} \quad T_{\text{QCD}} \approx 150 \text{ MeV}$$

- PQV sensitivity: QCD preserves PQ - ensured by Vafa-Witten
  Other contributions in general violate it:

$$V(\theta) \approx \underbrace{\Lambda^4_{\cancel{PQ}}\theta}_{\sim\text{anything else}} + \frac{1}{2}\underbrace{\Lambda^4_{\text{PQ}}\theta^2_{\text{eff}}}_{\supset\text{QCD}} + \mathcal{O}(\theta^3)$$

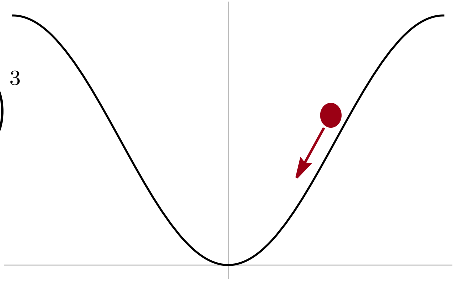
The VEV must be small today:

$$\theta_{\text{eff}} \simeq -\frac{\Lambda^4_{\cancel{PQ}}}{\Lambda^4_{\text{PQ}}} \lesssim 10^{-10} \quad \text{from nEDM}$$

Dark matter from misalignment

- Axion initially frozen at a random $\theta_{\text{ini}} \in -\pi, \pi$
- Field starts oscillating when $m_a(T) > 3H(T)$
- Generates a DM relic density:

$$\rho_{a,\,\text{today}} \approx \frac{1}{2} \underbrace{m_a^2 f_a^2}_{\approx (0.75\ \text{MeV})^4} \theta_{\text{ini}}^2 \frac{m_a(T_{\text{osc}})}{m_a} \frac{g_{*s}(T_0)}{g_{*s}(T_{\text{osc}})} \left(\frac{T_0}{T_{\text{osc}}}\right)^3$$



- Matches the observed DM relic only for a unique oscillation temperature:

$$T_{\text{osc}} \approx 900\ \text{MeV} \left(\frac{\rho_{a,\,\text{today}}}{\rho_{\text{DM,today}}}\right)^{-1/7} \theta_{\text{ini}}^{2/7}.$$

PQ violation at higher temperatures?

Large hierarchy at T_{osc}:

$$\frac{V_{\text{QCD}}(900\text{ MeV})}{V_{\text{QCD}}} \sim 8 \times 10^{-7}$$

- PQ violation more competitive at higher temp.
- However, constant temperature PQV can't dominate at $T_{\text{osc}} \approx 900$ MeV
- Higher $m_a \to$ higher $T_{\text{osc}} \to$ possibility of PQV domination:

$$V_{\cancel{PQ}} \gtrsim V_{\text{QCD}}(T_{\text{osc}}) \quad \text{possible for} \quad m_a \gtrsim 5 \times 10^{-3}\text{ eV}$$

Some hope of interesting phenomenology?

Constant temperature PQ violation

Constant temperature PQ violation

Possible origins:

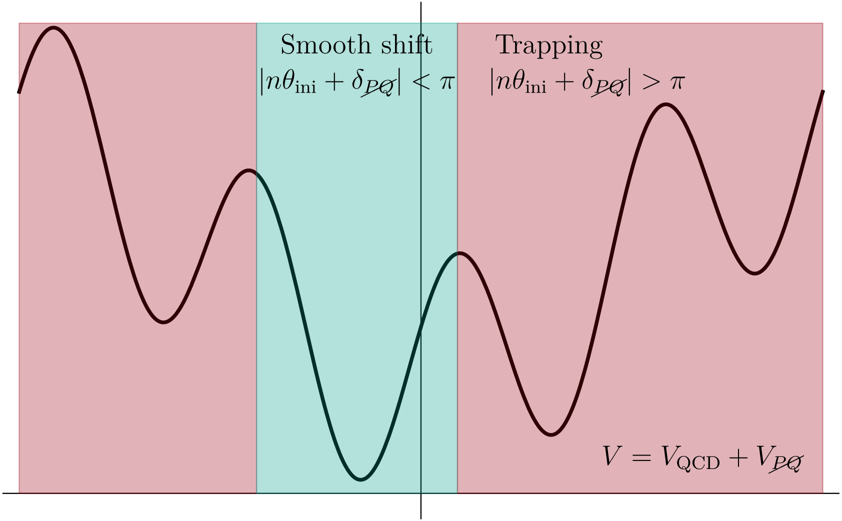
- Planck suppressed operators
- Any BSM physics far above $T \sim 1$ GeV

General form:

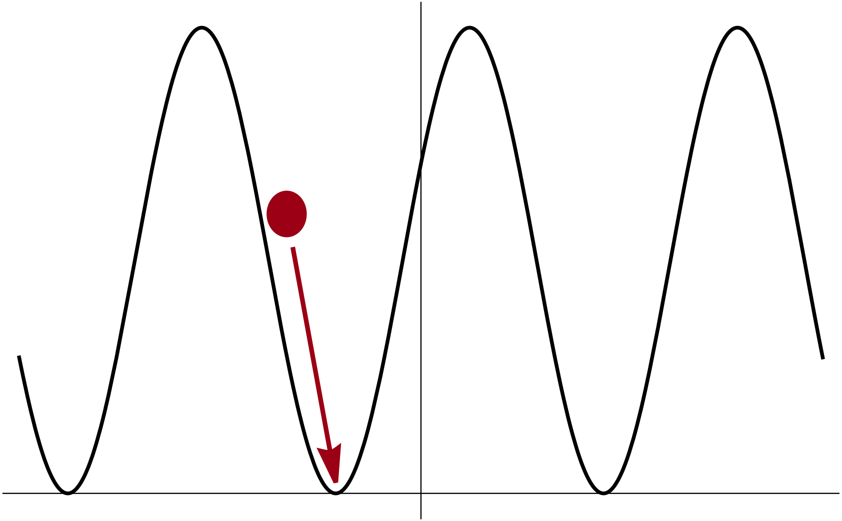
$$V_{\cancel{PQ}} = -\Lambda^4_{\cancel{PQ}} \cos\left(n\theta + \delta_{\cancel{PQ}}\right)$$

- Already studied in litterature: (Jeong, Matsukawa, Nakagawa, Takahashi, 2022)
- Two distinct regimes

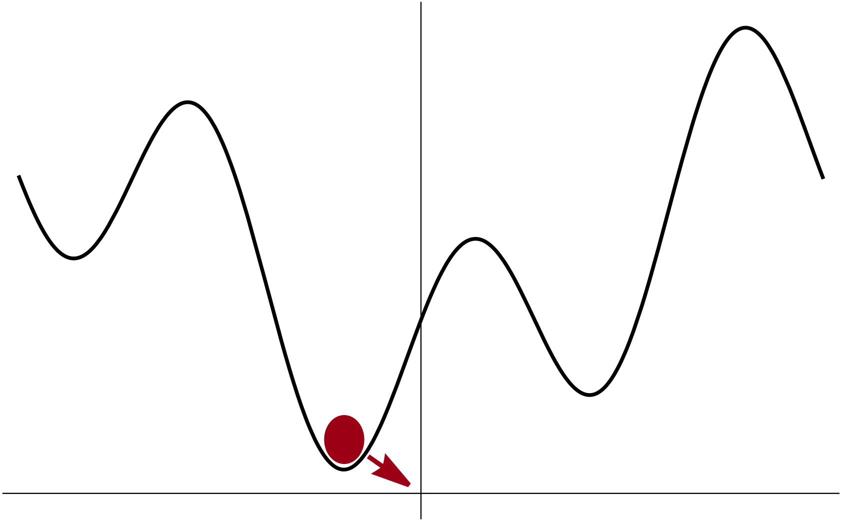
The two regimes identified by Jeong et al.



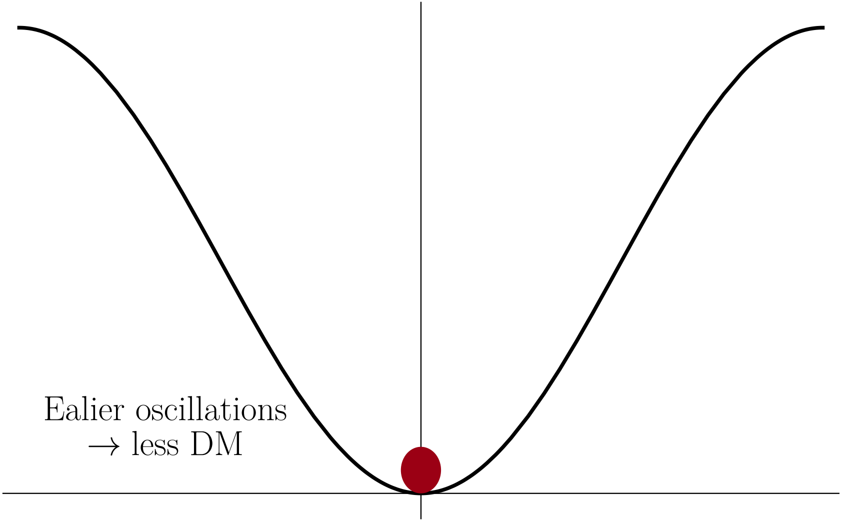
Smooth shift regime



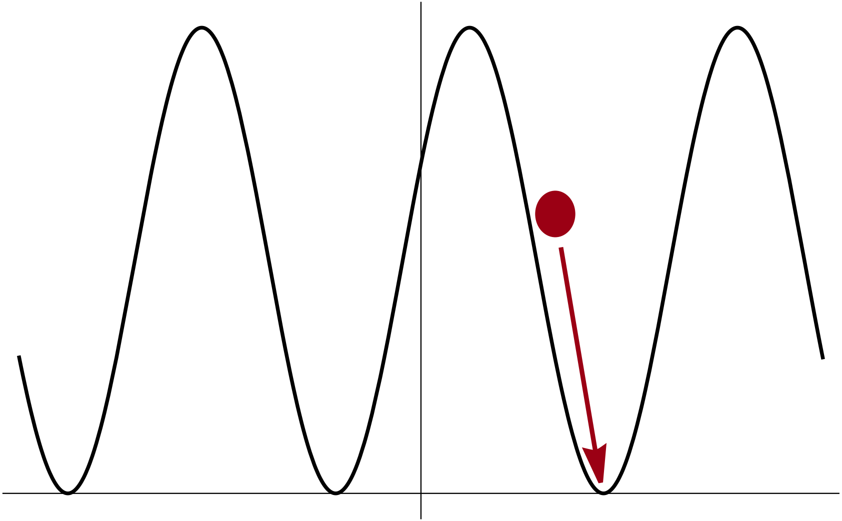
Smooth shift regime



Smooth shift regime



Trapping regime



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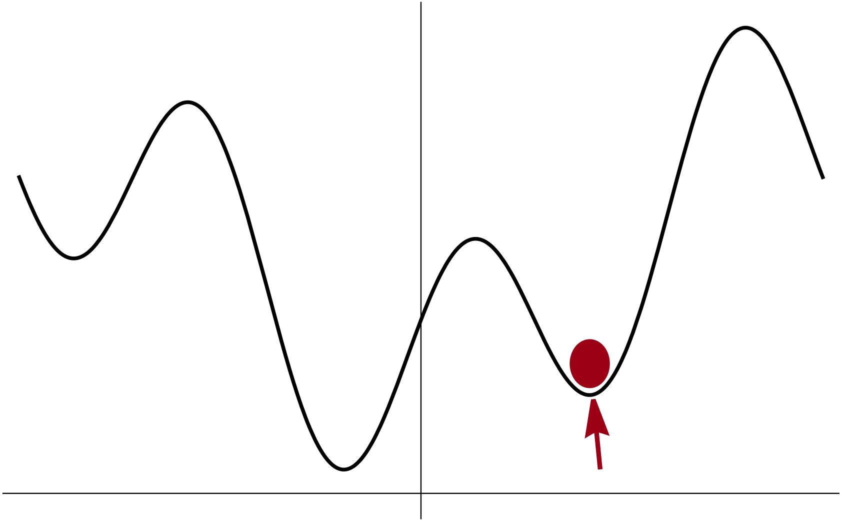

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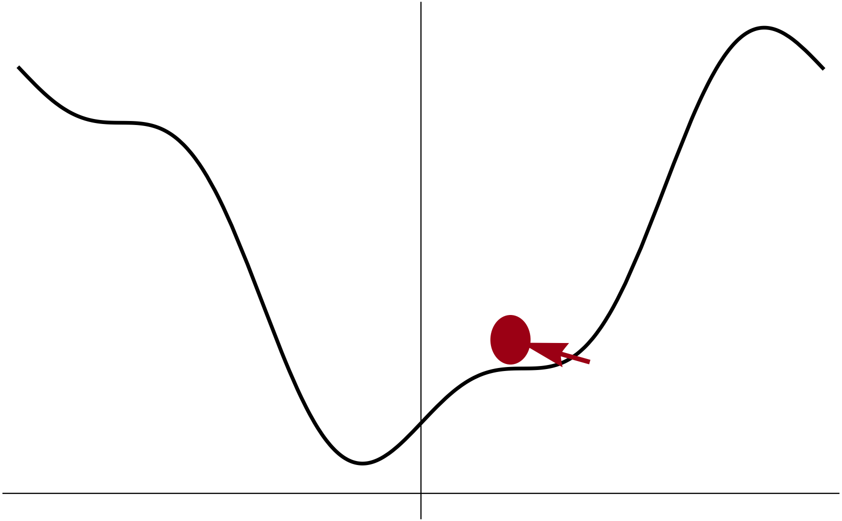

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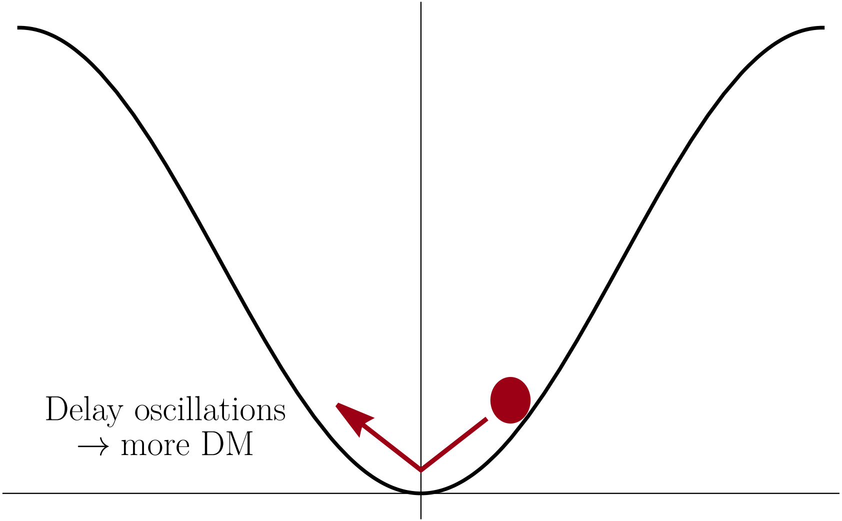
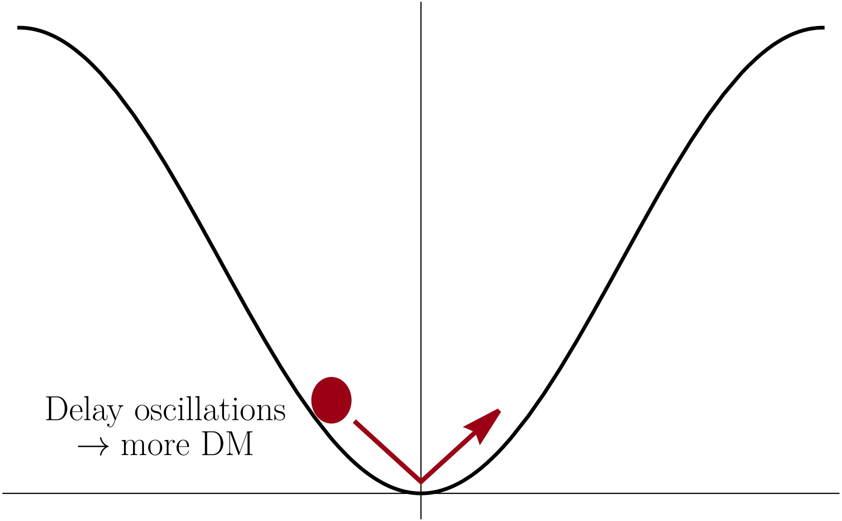


Trapping regime



Trapped misalignment - analytic solution

- General arguments: $m_a > 5 \times 10^{-3}$ eV
- DM under-production $\rightarrow$ Trapped misalignment more interesting
- Trapped misalignment release condition:

$$\frac{\partial V}{\partial \theta} = 0 \quad \text{and} \quad \frac{\partial^2 V}{\partial \theta^2} = 0,$$

Simplifies to

$$\tan \theta_{\text{trap}} = \frac{1}{n} \tan\left(n\theta_{\text{trap}} + \delta_{\cancel{PQ}}\right) \quad \rightarrow \quad (n-1) \;\; \mathcal{O}(1) \text{ release angles}$$

$$T_{\text{trap}} \approx 1.3 \text{ GeV} \left(\frac{n\Lambda_{\cancel{PQ}}}{10^{-3} \text{ GeV}}\right)^{-0.13}.$$

- Freedom to choose T_{trap} $\rightarrow$ choose DM relic!

Constraints from nEDM

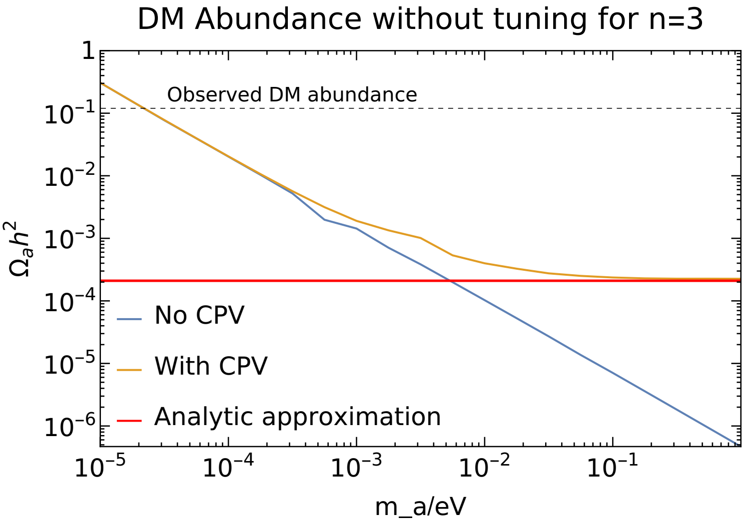
VEV constrained by nEDM:

$$|\theta_{\text{eff}}| \approx \frac{n\Lambda^4_{\cancel{PQ}}}{m_a^2 f_a^2} \sin \delta_{\cancel{PQ}}, \quad \text{must satisfy} \quad |\theta_{\text{eff}}| < 10^{-10}$$

Saturating the nEDM bounds yields best-case DM relic:

$$\frac{\rho_{a,\text{today}}}{\rho_{\text{DM,today}}} \lesssim 5 \times 10^{-4} \frac{\theta^2_{\text{ini}}}{\sin^{0.88}(\delta_{\cancel{PQ}})}, \quad \text{for} \quad m_a \gg 10^{-3}$$

Trapped misalignment - numeric solution



Trapped misalignment - tuned regime

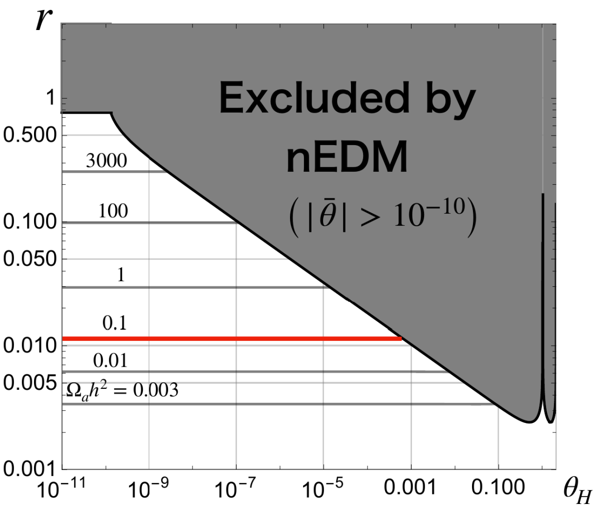
- Results in the tuned regime from Jeong, Matsukawa. Nakagawa, Takahashi, 2022:
- Notation:

$$\theta_H = \delta_{\cancel{PQ}}$$

$$r = \frac{\Lambda^4_{\cancel{PQ}}}{m_a^2 f_a^2}$$

- 100% DM requires tuning:

$$\delta_{\cancel{PQ}} < 10^{-3}$$



Temperature-dependent PQ violation

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Temperature-dependent PQ violation

To improve, we now go to temperature-dependent potentials:

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

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

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

- Proposed as a solution to DW problem
- Zhang considered only $n = 1$
- We generalize to $n > 1$, update constraints, and evaluate DM

Which SM fields can we couple to?

- Relevant temperature: $T \gtrsim$ GeV: After EWSB, before QCD phase transition
- Only fields with $m \lesssim$ GeV
- Candidate fermion fields: e, μ, u, d, s:

$$V_{\text{th,f}} \approx -\frac{n_{\text{col}}}{6}\left(\frac{\frac{1}{\sqrt{2}}f_a}{\Lambda_{\cancel{PQ}}}\right)^n m_f^2 T^2 \cos\left(n\theta + \delta_{\cancel{PQ}}\right) \quad \text{for} \quad T < v_{\text{EW}}$$

- Gauge boson candidates: Gluons and photons:

$$V_{\text{th,GG}} \approx \text{loop factor} \times 2\pi\alpha_s^2 \left(\frac{\frac{1}{\sqrt{2}}f_a}{\Lambda_{\cancel{PQ}}}\right)^n T^4 \cos\left(n\theta + \delta_{\cancel{PQ}}\right)$$

What about photons? See our paper!

Misalignment impact of T-dependent PQV

Previous solutions can be straight-forward generalized:

$$\Lambda_{\cancel{PQ}}^4 \to \Lambda_{\cancel{PQ}}^4(T) = \lambda_{\cancel{PQ}}^4 \left(\frac{\frac{1}{\sqrt{2}} f_a}{\Lambda_{\cancel{PQ}}} \right)^n T^q$$

General solution:

$$T_{\text{trap}} \approx \left(2^{\frac{n}{4b}} n^{-\frac{1}{2b}} \lambda_{\cancel{PQ}}^{-2/b} m_a^{1/b} f_a^{-\frac{n-2}{2b}} T_{\text{QCD}} \Lambda_{\cancel{PQ}}^{\frac{n}{2b}} \right)^{\frac{2b}{2b+q}}$$

Fix to target of $T_{\text{trap}} \approx 900$ MeV $\to$ DM solution for $\Lambda_{\cancel{PQ}}$

Understanding the evolution

The evolution can be understood with effective masses:

$$m_{a,\text{th}}^2 \equiv \frac{1}{a}\frac{\partial V_\text{th}}{\partial a}\Big|_\text{min}$$

Allows for easier interpretation of evolution:

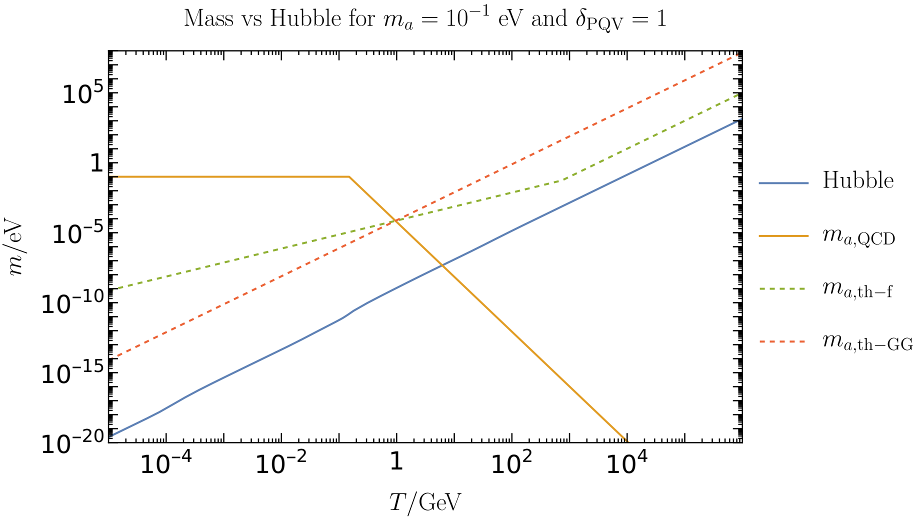
- Release condition:

$$m_a(T_\text{trap}) \approx m_{a,\text{th}}$$

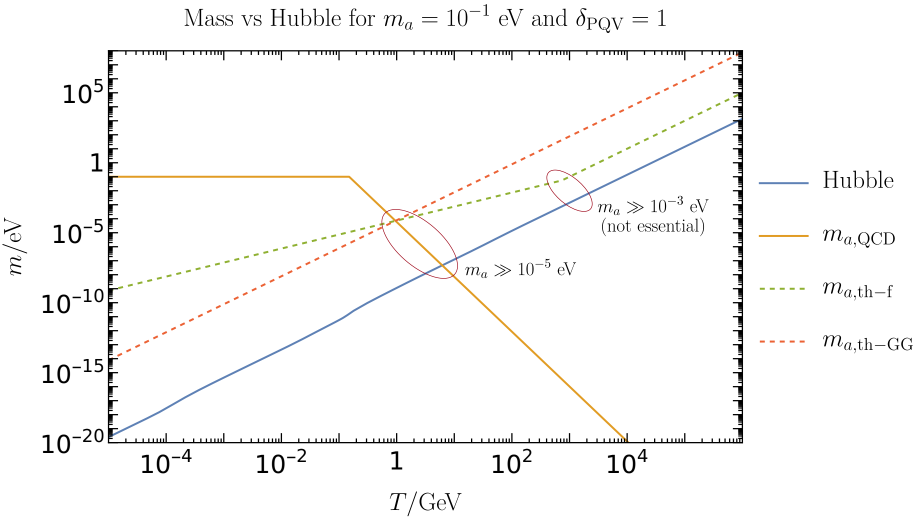
- Hubble domination:

$$m_{a,\text{th}} > 3H$$

Understanding the evolution



Understanding the evolution



Constraints on Fermion Yukawas

The scenario to a number of constraints, investigated by Zhang (2209.09429).

- Coleman-weinberg driven VEV:

$$\theta_{\text{eff}} \approx \frac{n n_{\text{col}}}{4\pi^2} \frac{m_f^4}{m_a^2 f_a^2} \left(\frac{f_a}{\sqrt{2}\Lambda_{\cancel{PQ}}} \right)^n \left[\ln\left(\frac{m_f^2}{\mu^2} \right) - 1 \right] \sin \delta_{\cancel{PQ}} \ll 10^{-10}$$

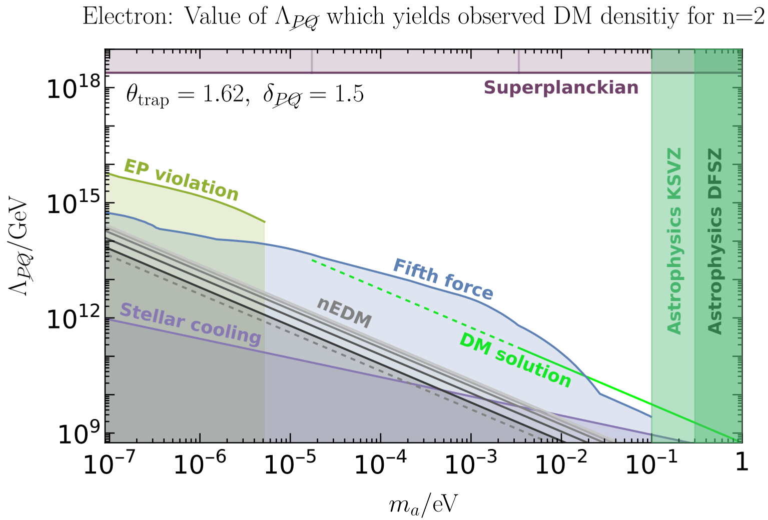
- Long range interactions:

$$\mathcal{L} \supset g_{a\bar{f}f} a \bar{f} f \quad \text{where} \quad g_{a\bar{f}f} = \frac{m_f}{f_a} \left(\frac{f_a}{\sqrt{2}\Lambda_{\cancel{PQ}}} \right)^n \sin \delta_{\cancel{PQ}}$$

$$\rightarrow V_{\text{Yukawa}} = -g_{a\bar{f}f}^2 \frac{e^{-m_a r}}{4\pi r}$$

- Stellar cooling bound on $g_{a\bar{f}f}$

Example solution: Testable with fifth force



Constraints on gluon interactions

- For GG, The VEV $\langle GG \rangle$ dominates generates a zero-temperature PQV potential:

$$V_{\langle GG \rangle} = -2\alpha_s \langle GG \rangle \left(\frac{f_a}{\sqrt{2}\Lambda_{\cancel{PQ}}} \right)^n \cos\left(n\theta + \delta_{\cancel{PQ}}\right) \quad \text{where} \quad \left\langle \frac{\alpha_s}{\pi} GG \right\rangle \approx (330\ \text{MeV})^4$$

- As before, $V_{\langle GG \rangle} \to \theta_{\text{eff}} \to$ upper bound on $\Lambda_{\cancel{PQ}} \leftarrow$ dominates long range forces
- Viable solutions for $m_a > 10^{-5}$ eV: Example:

$$\frac{\text{DM solution for } \Lambda_{\cancel{PQ}}}{\text{Upper bound on } \Lambda_{\cancel{PQ}}} \approx 1.5 \times \left(\frac{10^{-10}}{\theta_{\text{eff}}} \right)^{1/2} \quad \text{for} \quad \delta_{\cancel{PQ}} = 3,\ n = 2$$

- All non-tuned solutions are close to this nEDM bound
- Warning! Assumes free QCD close to Λ_{QCD}!

Summary

- We expanded on existing literature by considering misalignment impact of temperature-dependent PQ violating potentials
- Take-away points:
  - PQ-violating potentials can impact misalignment without violating nEDM
  - If $V_{\cancel{PQ}}$ is constant in T near $T \sim$ GeV, and there is no tuning, then
    - $V_{\cancel{PQ}}$ can have an impact for $m_a \gg 10^{-3}$ eV
    - $\frac{\rho_{a,\,\text{today}}}{\rho_{\text{DM,today}}}$ cannot be raised further than few $\times 10^{-4}$
  - If $V_{\cancel{PQ}}$ is T-dependent, is generated by $(\phi/\Lambda_{\text{QCD}})^n \times \mathcal{O}_{\text{SM}}$, and there is no tuning, then
    - axion DM can motivated by trapped misalignment across the $m_a \sim 10^{-5}$ eV $\to 10^{-1}$ eV range
    - all DM solutions found here have clear signals in either fifth-force or nEDM
- What to expect from our paper: Better overview of viable parameters, monopole-dipole forces, and conclusions on FF.

Thank you!

Questions?

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