No Quantum Breaking for Cosmic Axions

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[1] G. Dvali and S. Zell, *Classicality and Quantum Break-Time for Cosmic Axions*, to appear

Outline

1. QCD axion
   - ▷ Solution to strong CP-problem
   - ▷ Dark matter candidate

2. Is classical description still valid today? → **Yes**
   - ▷ Theoretical importance: quantum break-time[2]
   - ▷ Practical importance: experiments
   - ▷ Differing statements[3]

[2] G. Dvali, D. Flassig, C. Gomez, A. Pritzel, and N. Wintergerst, *Scrambling in the Black Hole Portrait*, arXiv:1307.3458 [hep-th].

[3] P. Sikivie and Q. Yang, *Bose-Einstein Condensation of Dark Matter Axions*, arXiv:0901.1106 [hep-ph].

The Strong CP-Problem

- Allowed in QCD:

$$\mathcal{L} \supset \theta G_{\mu\nu} \tilde{G}^{\mu\nu}$$

- Experiment: $\theta \lesssim 10^{-9}$
- Possible axion solution: $\theta \to a/f_a$:[4]

$$\mathcal{L} \supset \frac{1}{2}(\partial_\mu a)^2 + \frac{a}{f_a} G_{\mu\nu} \tilde{G}^{\mu\nu}$$

[4] R. D. Peccei and H. R. Quinn, *CP conservation in the presence of pseudoparticles*, Phys. Rev. Lett. **38** (1977).

Cosmic History

- Massless before QCD phase transition: $A_i := \langle\langle a \rangle\rangle_i \approx f_a$
- Effective low-energy potential

$$V_{\text{eff}} \approx \Lambda_{QCD}^4 \left(1 - \cos\left(\frac{a}{f_a}\right)\right)$$

- Cosmic expansion dilutes axions:

$$\lambda := \frac{A}{f_a} \ll 1$$

- CP violation vanishes dynamically

Properties of the Axion

- Weakly interacting and non-relativistic

$$\lambda \ll 1 \qquad v \ll 1$$

- Candidate for cold dark matter
- Constraints: $10^9\,\text{GeV} < f_a < 10^{12}\,\text{GeV}$

Classical Description

- Approximate: $\hat{a} \to a_{\text{cl}}$
- Potential

$$V_{\text{eff}} = \Lambda_{QCD}^4 \left(1 - \cos\left(\frac{a_{\text{cl}}}{f_a}\right)\right) = \frac{1}{2} \underbrace{\frac{\Lambda_{QCD}^4}{f_a^2}}_{m_{\text{cl}}^2} a_{\text{cl}}^2 + \ldots$$

- Classical solution

$$a_{\text{cl}} = A\cos(m_{\text{cl}} t) \quad + \quad \underbrace{\sum_{n=1}^{\infty} \lambda^n f_n}_{\text{Classical nonlinearities}}$$

- No $\hbar$

Quantum Picture

- Quantum field

$$V_{\text{eff}} = \frac{1}{2} \underset{m_{\text{q}} = \hbar m_{\text{cl}}}{\overset{[1/t]}{\overset{\uparrow}{(m_{\text{cl}})}}}^2 \hat{a}^2 - \frac{1}{4!} \underset{\alpha_{\text{q}} = \hbar \alpha_{\text{cl}}}{\overset{[1/(Et)]}{\overset{\uparrow}{\alpha_{\text{cl}}}}} \hat{a}^4 + \dots$$

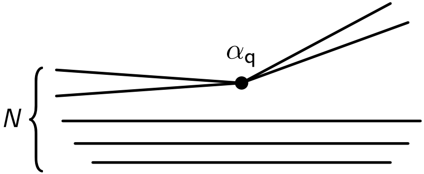
- Quantum state

$$N = \frac{E_{\text{cl}}}{m_{\text{q}}} \gg 1$$

- Collective coupling

$$\lambda = \alpha_{\text{q}} N \sim \hbar^0$$

Leading Quantum Effect



- Rate of $2 \to 2$-scattering

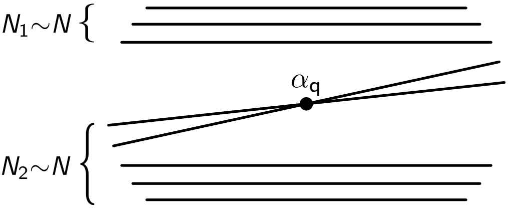
$$\Gamma \lesssim m_{\mathrm{cl}} \alpha_{\mathrm{q}}^2 N^2$$

- Quantum break-time

$$t_{\mathrm{q}} \gtrsim N\Gamma^{-1} = m_{\mathrm{cl}}^{-1} \frac{N}{\lambda^2} \gg t_{\mathrm{universe}}$$

- Quantum effect too weak

Collective Interaction



- Enhanced scattering rate

$$\Gamma_{col} = N\Gamma$$

- Time-scale

$$t_{col} = N^{-1} t_q = m_{cl}^{-1} \frac{1}{\lambda^2}$$

- Has classical description

Summary

- Cosmic QCD axion
  - Quantum effects very weak
  - Can be described classically
- Generic system[5]
  - Quantum break-time: $t_{\mathsf{q}} \propto N^k$
  - Classical nonlinearities: $\lambda = \alpha_{\mathsf{q}} N$

[5] G. Dvali, C. Gomez, and S. Zell, *Quantum Break-Time of de Sitter*, arXiv:1701.08776 [hep-th].