Quantum Breaking for Cosmic Axions, de Sitter and Others

Sebastian Zell

Based on work[1] with Gia Dvali and Cesar Gomez

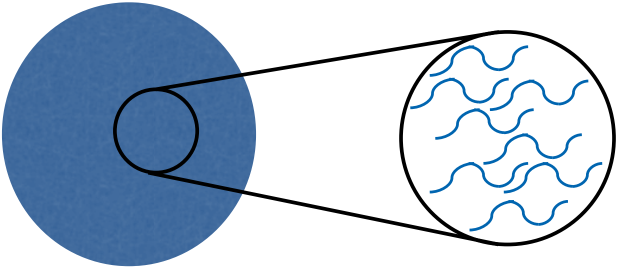
Max-Planck-Institute for Physics & LMU Munich

9^{th} November 2018

[1] G. D., C. G., S. Z., *Quantum Break-Time of de Sitter*, JCAP **1706** (2017) 028, arXiv:1701.08776.
G. D., S. Z., *Classicality and Quantum Break-Time for Cosmic Axions*, JCAP **1807** (2018) 064, arXiv:1710.00835.
G. D., C. G., S. Z., *Quantum Breaking Bound on de Sitter and Swampland* arXiv:1810.11002;
Discrete Symmetries Excluded by Quantum Breaking, arXiv:1811.03077;
A Proof of the Axion?, arXiv:1811.03079.

The World is Fundamentally Quantum

Classical solution:		Fundamental description:
approximation	$\longrightarrow$	quantum
Φ		$\langle N \| \hat{\Phi} \| N \rangle$



Quantum Break-Time[2]

How long is classical description valid?

1. Scalar Field
2. Cosmic Axions
3. De Sitter
4. Constraints for Model Building

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

Classical Solution

- Classical theory

$$\mathcal{L} = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}m_{\text{cl}}^2\phi^2 - \frac{1}{4}\alpha_{\text{cl}}\phi^4$$

- Solution

$$\phi_{\text{cl}}(t) = A\cos(m_{\text{cl}}t) \quad + \sum_{n=1}^{\infty}\Bigg(\underbrace{\alpha_{\text{cl}}\frac{A^2}{m_{\text{cl}}^2}}_{=:\,\lambda}\Bigg)^n f_n(t)$$

- Classical nonlinearities

$$t_{\text{cl}} = \frac{m_{\text{cl}}^{-1}}{\lambda}$$

- Goal: Find $|N\rangle$ s.t.

$$\langle N|\,\hat{\phi}\,|N\rangle = \phi_{\text{cl}}$$

Quantum Description

- Quantum field

$$\hat{\mathcal{L}} = \frac{1}{2}\partial_\mu \hat{\phi}\partial^\mu \hat{\phi} \quad -\frac{1}{2\hbar^2}\,(m_{\mathrm{q}})^2\,\hat{\phi}^2 \quad -\frac{1}{4!\hbar}\,\alpha_{\mathrm{q}}\,\hat{\phi}^4$$

$$m_{\mathrm{q}} = \hbar m_{\mathrm{cl}} \qquad \alpha_{\mathrm{q}} = \hbar \alpha_{\mathrm{cl}}$$

$$\hat{\phi} \sim \int \mathrm{d}^3\vec{k}\,\sqrt{\frac{\hbar}{\omega_{\vec{k}}}}\left(\hat{c}^\dagger_{\vec{k}}\,\mathrm{e}^{i\hbar^{-1}kx} + \hat{c}_{\vec{k}}\,\mathrm{e}^{-i\hbar^{-1}kx}\right)$$

- Coherent state

$$|N\rangle = \mathrm{e}^{-\frac{1}{2}N + \sqrt{N}\hat{c}^\dagger_0}\,|0\rangle$$

Quantum Description

- Fix N

$$\langle N | \hat{\phi} | N \rangle \overset{!}{=} \phi_{\text{cl}}^{(0)} \qquad \Rightarrow \qquad N = \frac{A^2}{\hbar m_{\text{cl}}^2}$$

- Matches classical energy

$$E_{\text{cl}} = N m_{\text{q}}$$

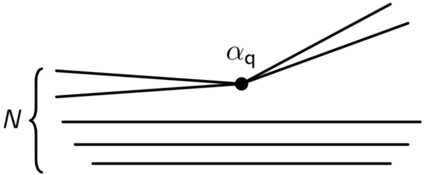
- Scaling in classical limit

$$N \sim \hbar^{-1} \qquad \alpha_{\text{q}} \sim \hbar$$

- Collective coupling

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

New Quantum Effect



- Rate

$$\Gamma \lesssim m_{cl} \alpha_q^2 N^2$$

- Time-scale

$$t_q \gtrsim N\Gamma^{-1} = m_{cl}^{-1} \frac{1}{\alpha_q \lambda} \sim \hbar^{-1}$$

- Quantum break-time

Generic System

- Control parameters

$$\alpha_q$$

Quantum effects

$$\lambda = \alpha_q N$$

Classical effects

- Quantum break-time

$$t_q = m_{cl}^{-1} \frac{1}{\alpha_q \lambda^{\beta}}$$

Outline

1. Scalar Field
2. Cosmic Axions[3]
3. De Sitter
4. Constraints for Model Building

[3] G. Dvali, S. Z., *Classicality and Quantum Break-Time for Cosmic Axions*, arXiv:1710.00835.

The Strong CP-Problem

- Allowed in QCD:

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

- Experiment: $\theta \lesssim 10^{-10}$
- Possible axion solution:[4] $\theta \to \phi/f_a$
- Dark matter candidate

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

Effective Theory

- After QCD phase transition

$$\mathcal{L} = \frac{1}{2}(\partial_\mu \phi)^2 - \Lambda_{QCD}^4 \left(1 - \cos\left(\frac{\phi}{f_a}\right)\right)$$

- CP violation vanishes dynamically
- Expand

$$V_{\text{eff}} = \frac{1}{2}\underbrace{\left(\frac{\Lambda_{QCD}^2}{f_a}\right)}_{m_{\text{cl}}}^2 \phi^2 - \frac{1}{4!}\underbrace{\frac{\Lambda_{QCD}^4}{f_a^4}}_{\alpha_{\text{cl}}} \phi^4 + \dots$$

- Energy

$$N = \frac{E_{\text{cl}}}{m_{\text{q}}} \sim \rho_{\text{dm}}$$

Phenomenological Implications

- Quantum break-time

$$t_{\text{q}} = m_{\text{cl}}^{-1} \frac{1}{\alpha_{\text{q}} \lambda} \gg t_{\text{universe}}$$

- Quantum effects negligible
- Important for experimental axion searches

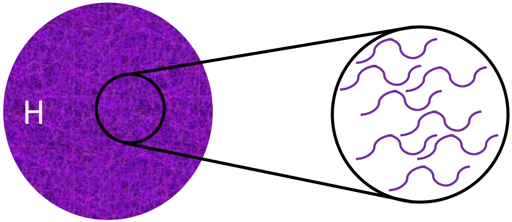
Outline

1. Scalar Field
2. Cosmic Axions
3. De Sitter[5]
4. Constraints for Model Building

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

Application to Gravity

- Is de Sitter a state on top of Minkowski?[6]
- Does classical metric $h_{\mu\nu}$ have underlying quantum description?



[6] G. Dvali, C. Gomez, *Quantum Compositeness of Gravity: Black Holes, AdS and Inflation*, arXiv:1312.4795.

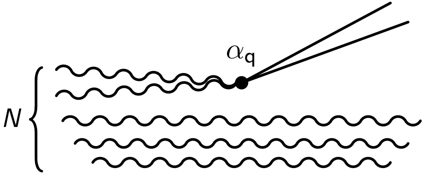
Quantum Description

- Goal: obtain de Sitter as collective multi-graviton effect
- Ansatz: model constituent gravitons by Fierz-Pauli
- Parameters

$$m_{\mathrm{q}} = \hbar H$$
$$\alpha_{\mathrm{q}} = \hbar G H^2$$
$$N = \frac{E_{\mathrm{cl}}}{m_{\mathrm{q}}} = \frac{1}{\hbar G H^2}$$

$$\boxed{\langle N | \hat{h}_{\mu\nu} | N \rangle = h_{\mu\nu}}$$

New Quantum Effect



- Quantum break-time

$$t_q = m_{cl}^{-1} \frac{1}{\alpha_q \lambda} = \frac{1}{\hbar G H^3}$$

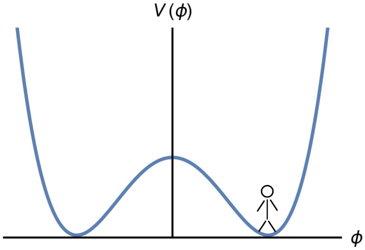
- Two options for final state
  1. Metric replaced by quantum description
  2. **Quantum picture inconsistent**

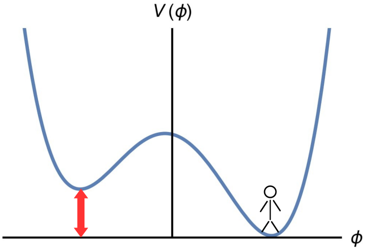
Implications of Consistency Requirement

- Exclusion of any theory with metastable de Sitter vacuum
- Present dark energy cannot be constant
- New class of constraints for model building

Outline

Exclusion of Spontaneously-Broken Discrete Symmetries[7]





$\Downarrow$

Domain wall problem[8]

$\Downarrow$

Inconsistent de Sitter minimum

[7] G. Dvali, C. Gomez, S. Z., *Discrete Symmetries Excluded by Quantum Breaking*, `arXiv:1811.03077`.

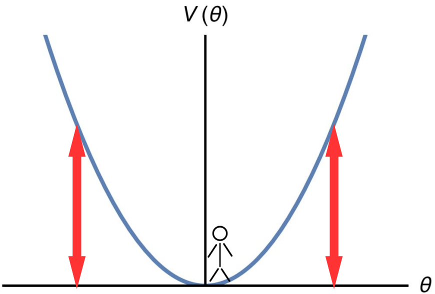
[8] Ya. Zeldovich, I. Kobzarev, L. Okun, *Cosmological consequences of a spontaneous breakdown of a discrete symmetry*, JETP 40 (1974) 1.

Exclusion of Spontaneously-Broken Discrete Symmetries[7]

- Need symmetry breaking before inflation
  (or other solution to domain wall problem)
- Excludes well-motivated models
  - NMSSM
  - Spontaneous CP-violation
  - . . .

[7] G. Dvali, C. Gomez, S. Z., *Discrete Symmetries Excluded by Quantum Breaking*, arXiv:1811.03077.

Existence of Axion Mandatory[9]



- θ-vacua: consistency problem instead of naturalness question
- Only way out: axion to make θ unphysical

[9] G. Dvali, C. Gomez, S. Z., *A Proof of the Axion?*, arXiv:1811.03079.

Outlook: Other Systems

- Inflation: exclude regime of self-reproduction[10]
- Black holes:[10] quantum breaking after half-evaporation
- String theory:[11] de Sitter swampland conjectures as consequence of quantum breaking?

[10] G. Dvali, C. Gomez, *Quantum Compositeness of Gravity: Black Holes, AdS and Inflation*, arXiv:1312.4795.

[11] G. Dvali, C. Gomez, *On Exclusion of Positive Cosmological Constant*, arXiv:1806.10877.
G. Dvali, C. Gomez, S. Z., *Quantum Breaking Bound on de Sitter and Swampland*, arXiv:1810.11002.

Summary

- Quantum break-time

$$t_{\mathrm{q}} = m_{\mathrm{cl}}^{-1} \frac{1}{\alpha_{\mathrm{q}} \lambda^{\beta}}$$

- Axions: classical approximation justified
- De Sitter: inconsistent on quantum level?
- New class of constraints for model building