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MAX-PLANCK-INSTITUT FÜR PHYSIK

Cosmic Strings and Domain Walls of the QCD Condensate with and without a hidden Axion

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INTRODUCTION

- Axion solves strong CP problem
- Chiral anomaly of $U(1)_{PQ} \rightarrow$ Explicit breaking by instanton effects 't Hooft; **'76**
- Possible topological defects

  $\rightarrow$ Important for Cosmology and Astrophysics

THE η' MESON AS A POOR QUALITY AXION

QCD with 1 Light Quark - Massless Case

	PQ Axion	η' Meson
Relevant fermion	heavy quark Ψ	light quark ψ
Chiral Symmetry	$U(1)_{PQ}$	flavor $U(1)_A$
SSB	PQ field $\langle \Phi \rangle = f_\phi$	QCD Condensate $\langle \bar{\psi}\psi \rangle = \Lambda^3_{QCD}$
Goldstone	Axion phase $\theta_\phi \equiv \phi/\sqrt{2}f_\phi$	η' phase $\theta_\eta = \eta'/\sqrt{2}f_\eta$
Instanton induced potential	$V(\theta_\phi) = \Lambda^4_{QCD}\cos(\theta_\phi - \bar{\theta})$	$V(\theta_\eta) = \Lambda^4_{QCD}\cos(\theta_\eta - \bar{\theta})$

$\Rightarrow$ dynamical relaxation of vacuum angle

$\Rightarrow$ **η' is an axion** Dvali; **'05**

THE η' MESON AS A POOR QUALITY AXION

QCD with 1 Light Quark - Massive Case

- Quark mass explicitly breaks flavor symmetry
- Additional Contribution to effective potential

$$\simeq m_\psi \Lambda_{QCD}^3 \cos(\theta_\eta)$$

$$\downarrow$$

$$\theta_{\text{eff}} \sim \frac{m_\psi}{\Lambda_{QCD}} \bar{\theta}$$

$\Rightarrow \eta'$ **is no viable axion**

AXION-η' COUPLED SYSTEM

Massless Light Quark

$$\theta_\eta \equiv \eta/\sqrt{2}f_\eta$$
$$\theta_\phi \equiv \phi/\sqrt{2}f_\phi$$
$$\downarrow$$
$$a_\eta/\sqrt{2}\tilde{f}_\eta = \theta_\phi + \theta_\eta$$

- light quark ψ + PQ scalar Φ + heavy quark Ψ
- Anomaly-free $U(1)_V$: $\psi \to e^{+i\frac{\alpha}{2}\gamma_5}\psi$, $\Psi \to e^{-i\frac{\alpha}{2}\gamma_5}\Psi$
- Anomalous $U(1)_A$: $\psi \to e^{+i\frac{\alpha}{2}\gamma_5}\psi$, $\Psi \to e^{+i\frac{\alpha}{2}\gamma_5}\Psi$
- $U(1)_A$ explicitly broken → Effective potential for θ_η & θ_ϕ

$$V(\theta_\eta, \theta_\phi) = \Lambda_{QCD}^4 \cos(\theta_\phi + \theta_\eta - \bar{\theta})$$

→ massive state $a_\eta \simeq \eta' \to$ **axion**

→ massless state $a_\phi \simeq \phi$

AXION-η' COUPLED SYSTEM

Massive Light Quark

- Light Quark mass $\rightarrow U(1)_V$ explicitly broken
- Additional Contribution $\simeq m_\psi \Lambda_{QCD}^3 \cos(\theta_\eta)$
- a_ϕ gets mass $\sim \sqrt{m_\psi \Lambda^3 / f_\phi} \rightarrow$ **becomes axion**

AXION-η' MIXED DEFECTS

Massless Light Quark

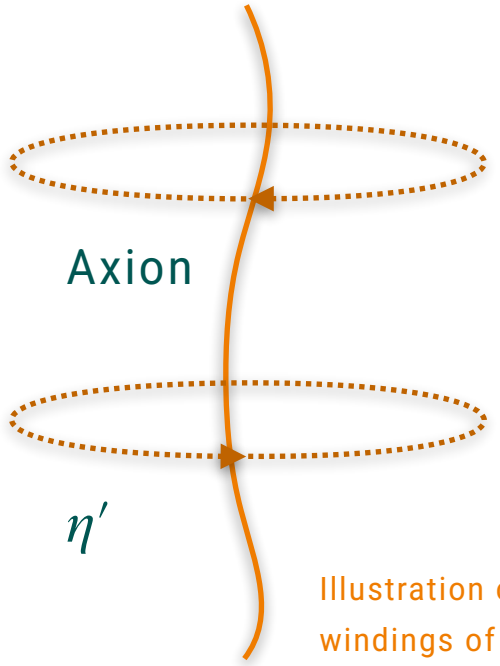


Illustration of a global string, involving windings of the axion and the η'

- $U(1)_V$ spontaneously broken → Cosmic Strings
- Opposite winding $\theta_\eta = -\theta_\phi = -n_\phi \varphi$ far from core
- Winding in only one phase → Domain walls due to $V(\eta', \phi)$

AXION-η' MIXED DEFECTS

Massive Light Quark

- $m_\psi \neq 0 \rightarrow$. $U(1)_V$ explicitly broken
- Opposite winding remains energetically favorable
- Winding restricted to arches of fixed length
- Optimal winding length $L_\phi = L_\eta \simeq 1/m_\phi$

$\rightarrow$ Strings become string-wall systems

Illustration of the String-Wall system formed by breaking the $U(1)_V$ symmetry

$\rightarrow$ **η' is involved in Axionic defects**

PURE η' DEFECTS

$$V(\theta_\eta, \theta_\phi) = \Lambda_{QCD}^4 \cos(\theta_\phi + \theta_\eta - \bar{\theta})$$

- $U(1)_A$ always explicitly broken
- Potential allows String-Wall systems
- Equal winding $\theta_\eta = \theta_\phi$ unfavorable, tension $\sigma \sim \Lambda^2 f_\phi$
- To lowest order: only winding in η', $\sigma \sim \Lambda^2 f_\eta$

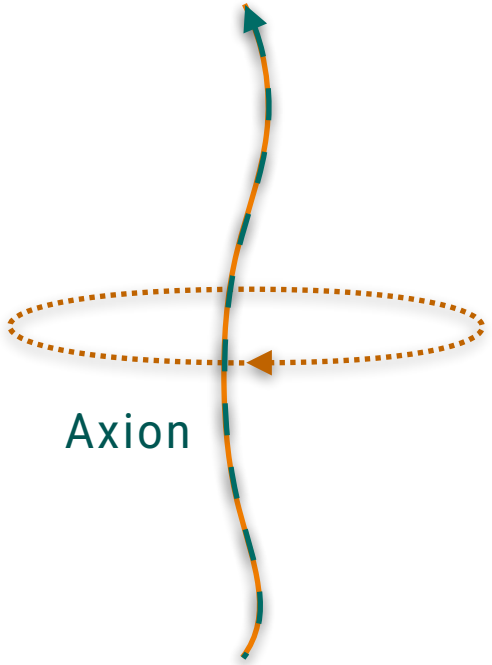
→ **Pure η' defects possible**

PHYSICAL PROPERTIES

Pure Axion Strings

- Ψ deposits chiral zero mode on string Jackiw, Rossi; **'81**
- Electric charge induces superconducting current Witten; **'85**
- Anomalous symmetry in bulk → gauge anomaly on world-sheet

  → cancelled by anomaly inflow Callan, Harvey; **'85**



Axion String with chiral Fermion zero mode

PHYSICAL PROPERTIES

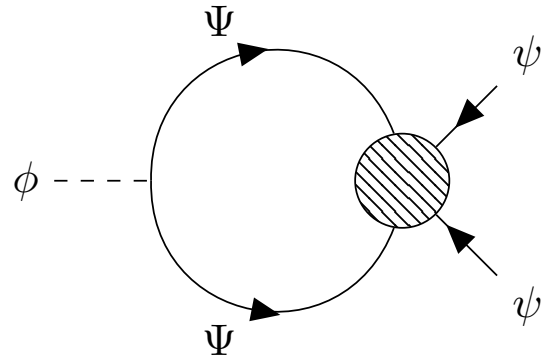
Axion-η' Strings

- 't Hooft vertex induces ψ coupling to Φ

  → induces oppositely charged zero mode

  → world-sheet anomaly-free

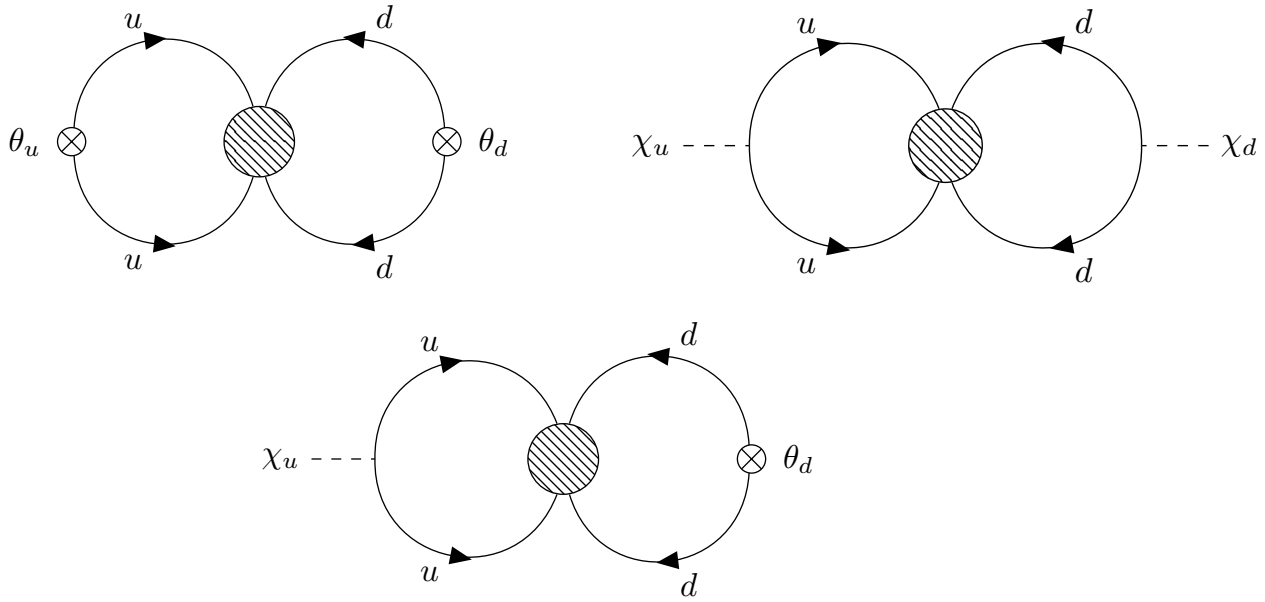
→ **Light quarks influence zero-mode structure**



Yukawa coupling of the light quark, induced by the 't Hooft vertex

DFSZ TYPE MODEL

- 2 EW Higgs doublets H_u, H_d coupled to u & d quarks
- PQ field coupled to H_u & $H_d \rightarrow \mu \Phi H_u H_d + \mathrm{h.c.}$
- Effective potential terms generated by 't Hooft vertex



Terms of the effective potential generated by the 't Hooft vertex

DFSZ TYPE MODEL

Topological Defects

- Anomaly-free $U(1)_V \rightarrow$ Global Strings for $m_u = 0$

  $\rightarrow m_u \neq 0$ induces domain walls

- Winding of PQ phase compensated by Higgs phase

- Higgs + quark fields carry Z charge Dvali, Senjanovic; **'93**

  $\rightarrow$ Strings can carry Z flux

  $\rightarrow$ Higgs phase winding can induce quark phase winding

  $\rightarrow \pi^0$ can wind in String-Wall systems

$$\mu \Phi H_u H_d + \mathrm{h.c.}$$

COSMOLOGICAL IMPLICATIONS

- Usual Assumption: $f_\phi \gg \Lambda_{QCD}$ in early universe
- Inflation can affect gauge coupling & PQ scale Dvali; **'95**

→ **Hierarchy between f_ϕ and Λ_{QCD} can be different**

→ **QCD Condensate can dominate defect dynamics**

→ Source for Gravitational Waves

$$\mathcal{U}\left(\frac{\Sigma}{M}\right)\Phi^*\Phi$$

$$\mathcal{W}\left(\frac{\Sigma}{M}\right)\mathrm{Tr}\,G^{\mu\nu}G_{\mu\nu}$$

Schematic Coupling of the Inflaton to the PQ field Φ and the gluons

SUMMARY

- QCD Condensate relevant for Axion Defects

  → Affects Physical Properties

- Pure QCD Defects Possible

- QCD Defects can Dominate in the Early Universe

REFERENCES

[1] G. Dvali, L. Komisel, A. Stuhlfauth, *Cosmic strings and domain walls of the QCD quark condensate with and without a hidden axion*, arXiv: 2505.03542 [hep-ph], **2025** and references therein

[2] G. 't Hooft, *Symmetry breaking through Bell-Jackiw Anomalies*, Phys. Rev. Lett. 37, **1976**; G. 't Hooft, *Computation of the Quantum Effects due to a Four-Dimensional Pseudoparticle*, Physics. Rev. D 14, **1976**

[3] G. Dvali, *Three-form gauging of axion symmetries and gravity*, arXiv: hep-th/0507215, **2005**

[4] R. Jackiw, P. Rossi, *Zero-Modes of the Vortex-Fermion system*, Nucl. Phys. B 190, **1981**

[5] E. Witten, *Superconducting Strings*, Nucl. Phys, B 249, **1985**

[6] C.G. Callan Jr., J.A. Harvey, *Anomalies and Fermion Zero Modes on Strings and Domain Walls*, Nucl. Phys. B 250, **1985**

[7] G. Dvali, G. Senjanovic, *Topologically stable electroweak flux tubes*, Phys. Rev. Lett. 71, **1993**

[8] G. Dvali, *Removing the cosmological bound on the axion scale*, arXiv: hep-ph/9505253, **1995**