Axion superconducting string
Cosmic axion Background

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2021 Chung-Ang University BSM Workshop
February 1, 2021

Hajime Fukuda, Aneesh Manohar, HM, Ofri Telem, 2010.02763
Jeff Dror, HM, Nick Rodd, 2101.09287
An old puzzle: Why doesn’t strong interaction violate CP?
periodic in $\theta \rightarrow \theta + 2\pi$
leads to $H_{\text{eff}} = d_e \bar{s}_n \cdot \vec{E}$
$\theta < 10^{-10}$
$\theta < 10^{-10}$

$$d_e \approx \frac{e m_u \sin \theta}{m^2_{\text{constituent}}} < 2.9 \times 10^{-26} \text{e cm}$$

blow up neutron to Earth size:
allowed separation of electric charge $< 3 \mu$
QCD axion

- Promote $\theta$-parameter to a dynamical field

$$\mathcal{L}_{\text{eff}} = \frac{1}{64\pi^2} \left( \theta_0 + \frac{a}{f_a} \right) \epsilon^{\mu\nu\rho\sigma} G_\mu^a G_\rho^a$$

- Effect on pion Lagrangian in low energy:

$$\mathcal{L}_\chi = f_\pi^2 \text{tr} \partial U^\dagger \partial U + \mu^3 \text{tr} M e^{i(\theta_0 + a/f_a)} U + \text{c.c.}$$

- Potential for axion (U=1)

$$V = -m_\pi^2 f_\pi^2 \cos \left( \theta_0 + \frac{a}{f_a} \right)$$

- It settles $a = -\theta_0 f_a$, canceling $\theta_0$

- No CP violation at the minimum!

$$m_a = \frac{m_\pi f_\pi}{f_a}$$
axion

- motivated by strong CP problem
- moduli/dilaton in string theory
- could be dark matter
- consider generically axion-like particle
- couplings: $aF\tilde{F}$, $aG\tilde{G}$
Cosmic axion Background (CaB)

Jeff Dror, HM, Nick Rodd, 2101.09287
relativistic axion

- sources of relativistic axions
- thermal axions
- decay of dark matter into axions today
- decay of topological defect e.g. string, wall
thermal axion

for QCD axion, decoupling temperature is typically $T_d > 10\text{TeV}$ due to SN1987A constraint

regard free parameter potentially addresses $H_0$ tension

$$\Omega_a(\omega) = \frac{1}{\rho_c} \frac{d\rho_a}{d \ln \omega}$$

axion energy $E = \hbar \omega$
dark matter decay

- consider scalar dark matter $\chi \rightarrow a a$

- decay in galactic halo gives monochromatic peak

- decays in other galaxies add up to continuum due to redshifts
relied on simulation for QCD strings by M. Gorghetto, E. Hardy, G. Villadoro, 1806.04677, 2007.04990

depends on decoupling temperature

assumed PMF=0
Can we detect CaB?

- Assume $aF \tilde{F}$
- Dark matter $\nu \sim 10^{-3}$ with narrow frequency distribution $E = \hbar \omega = m_a c^2 + m_a v^2 / 2$
- Axion experiments focus on very narrow frequency range and scan
- Relativistic axion spread out in frequencies
- Interactions need to be worked out without assuming non-relativistic
frequency spectrum

- Dark-Matter Axion
- CaB Gaussian ($\sigma = \bar{\omega}$)
- CaB Cosmic String
Maxwell equations

\[ \nabla \cdot \mathbf{E} = \rho - g_{\alpha \gamma \gamma} \mathbf{B} \cdot \nabla a \]
\[ \nabla \cdot \mathbf{B} = 0 \]
\[ \nabla \times \mathbf{E} = -\partial_t \mathbf{B} \]
\[ \nabla \times \mathbf{B} = \partial_t \mathbf{E} + \mathbf{J} + g_{\alpha \gamma \gamma} (\mathbf{B} \partial_t a - \mathbf{E} \times \nabla a) \]

\[ (\Box + m_a^2) a = g_{\alpha \gamma \gamma} \mathbf{E} \cdot \mathbf{B} \]

\[ \rho = -g_{\alpha \gamma \gamma} \mathbf{B} \cdot \nabla a \]
\[ \mathbf{J} = g_{\alpha \gamma \gamma} (\mathbf{B} \partial_t a - \mathbf{E} \times \nabla a) \]
QCD axion

\[ m_a = \frac{m_\pi f_\pi}{f_A} \] [eV]

Axion Mass \( m_A \) (eV)

- Dark Matter (pre-inflation PQ phase transition)
- Dark Matter (post-inflation PQ phase transition)
- LUX \((g_{Aee},\text{DFSZ})\)
- Hot-DM / CMB / BBN
- Telescope/EBL
- Beam Dump
- SN1987A \((g_{A_{\epsilon\epsilon}},\text{KSVZ})\)
- Burst Duration
- Counts in SuperK
- RGs in GCs \((g_{A_{ee},\text{DFSZ}})\)
- WDLF \((g_{A_{ee},\text{DFSZ}})\)
- HB Stars in GCs \((G_{A_{\gamma\gamma},\text{DFSZ}})\)
- ADMX
- KSVZ
- CAST

June 5, 2018 20:09

\[ f_A \text{ (GeV)} \]

\[ 10^{17} 10^{16} 10^{15} 10^{14} 10^{13} 10^{12} 10^{11} 10^{10} 10^9 10^8 10^7 10^6 10^5 10^4 10^3 10^2 10^1 10^0 \]

\[ 10^{-11} 10^{-10} 10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^0 10^1 10^2 10^3 10^4 10^5 10^6 \]
Use the effective coupling

$$\mathcal{L}_{\text{eff}} \sim \frac{e^2}{4\pi^2} \frac{a}{f_a} \vec{E} \cdot \vec{B}$$
The axion mass, would be created in the early universe making it an excellent candidate for dark matter. The properties of the axion and the mechanism by which it was proposed to be created led to the prediction of a light pseudoscalar. Peccei and Quinn proposed a solution by which the axial Ward identity of quantum chromodynamics (QCD) is saturated, implying the existence of a light pseudoscalar. This effect is known as the axion axion-photon coupling that appears in the axion-photon Lagrangian is a D-parity (CP)-conserving minimum of the effective potential. The standard model of particle physics includes a term proportional to the product of the electric and magnetic fields of the photon and an axion, which gives rise to a coupling constant of order $\rho_g a^3$. This coupling is consistent with experimental bounds and can help resolve the strong CP problem.

For axions with mass $\lesssim 10^{-2}$ eV, the natural conversion rate is very low. For it to be detectable on a reasonable time-scale, this conversion must be enhanced. One scheme based on the axion-photon conversion is to couple an axion to a light pseudoscalar that can interact with the photon. In this way, a factor of 2.7 above the benchmark KSVZ model over the mass range $0.01$ eV to $1$ eV is obtained. This enhancement can be achieved by operating at a temperature $T < h a/\kappa$, where $h$ is Planck's constant, $a$ is the axion mass, and $\kappa$ is the loaded cavity quality factor. For $\kappa = 10^8$, the natural conversion rate is enhanced by a factor of 2.7 above the benchmark KSVZ model.

Results from phase 1 of the HAYSTAC microwave cavity axion experiment


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FIG. 4. Our exclusion limit at 90% confidence. Green represents this work combined with our previous results presented in Ref. [15]. Red represents previous cavity limits from ADMX [21–24], pink represents results from Brookhaven [25], and blue represents results from the University of Florida [26]. The axion model band is shown in yellow [27]. The KSVZ [11,12] and DSVZ [28,29] couplings are plotted as dashed lines.
\[ H_{\text{eff}}(t) = -\vec{\mu} \cdot \vec{B} - \frac{m_u}{m_{\text{const}}} \sin(m_a t) \times \vec{s}_n \cdot \vec{E} \]

\[ a(t) = a_0 \sin m_a t \]

resonance @ \( \mu B = m_a \)

SQUID pickup loop

Budker et al
arXiv:1306.6089

\[ g_d \] (GeV^2)

mass (eV)
An Axion In a Magnetic Field

- Modification to Ampere’s law (MQS approximation)

\[ \nabla \times \mathbf{B} = g_{a\gamma\gamma} \frac{\partial a}{\partial t} \mathbf{B} \]

- An oscillating axion field creates an “effective current” in the presence of a magnetic field

\[ \mathbf{J}_{\text{eff}} = g_{a\gamma\gamma} \frac{\partial a}{\partial t} \mathbf{B} \]
A Broadband/Resonant Approach to Cosmic Axion Detection with an Amplifying B-Field Ring Apparatus

- Start with a toroidal magnet with a fixed magnetic field $B_0$
- ADM generates an oscillating effective current around the ring (MQS approx: $\lambda \gg R$)
- ... this generates an oscillating magnetic field through the center of the toroid
- Insert a pickup loop in the center and measure the induced current in the loop read out by a SQUID based readout

$$\Phi(t) = g_{a\gamma\gamma} B_{\text{max}} \sqrt{2 \rho_{\text{DM}}} \cos(m_a t) G_V V$$
dark matter decay

Present $\Gamma[\chi \to aa]$ Sensitivity
$g_{\alpha\gamma\gamma} = 0.66 \times 10^{-10}$ GeV$^{-1}$

Future $\Gamma[\chi \to aa]$ Sensitivity
- ADMX ($g_{\alpha\gamma\gamma}^{\text{lim}}/10$)
- HAYSTAC ($g_{\alpha\gamma\gamma}^{\text{lim}}/100$)
- DMRadio ($m^3 + \text{GUT}$)

$H_0$ Excluded
daily modulation

detection rate depends on the incident angle

e.g. ADMX

dark matter concentrated in galactic center

expect daily modulation
string

Cosmic String
ABRA 100 m³
$g_{\alpha\gamma\gamma} = 3.6 \times 10^{-12}$ GeV$^{-1}$

$H_I > 6 \times 10^{13}$ GeV

$\Delta N_{\text{eff}} > 1$

$H_0$ Preferred

$T_d$ [GeV]

$10^7$ $10^8$ $10^9$ $10^{10}$ $10^{11}$ $10^{12}$ $10^{13}$ $10^{14}$ $10^{15}$ $10^{16}$

$f_a$ [GeV]

$10^{14}$ $10^{15}$ $10^{16}$
CaB Landscape

\( g_{a\gamma\gamma} = g_{a\gamma\gamma}^{\mathrm{SE}} \)

\( m_a < 1 \) neV

\( g_{a\gamma\gamma} \neq a(a) \)
Conclusions

- CaB detection is not easy
- we’ve not detected CνB either!
- possible for
  - dark matter decay
  - string
- requires different analysis strategy
- potential daily modulation
axion string is superconducting

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QCD axion string

- Axion is Nambu-Goldstone boson of spontaneously broken $U(1)_{PQ}$ symmetry.
- If broken after inflation, creates cosmic string by Kibble-Zurek mechanism.
- $U(1)_{PQ}$ anomalous, strings ultimately unstable.
- If there is an exact (non-anomalous) $Z_N$ subgroup of $U(1)_{PQ}$ also domain walls.
- Dominates the universe, disaster.
- Not possible for DFSZ. Assume KSVZ.
- Consider minimal PQ fermions: one triplet.
scaling behavior

\[ \phi(\theta) = f_a e^{i\theta} \]

\[ \phi = f_a e^{i\alpha} / f_a \]

\[ \alpha = f_a \theta \]
axion vs GW

\[ \Omega_{GW} h^2 \]

\[ \Omega_{\text{Gold}} h^2 \]

\[ \int d(\ln f) \Omega h^2 \]

Chang, Cui, 1910.04781
KSVZ axion

$$\mathcal{L}_{UV} = \lambda (\phi^* \phi - f_a^2)^2 - y_Q (\phi \bar{Q}_L Q_R + \text{c.c.})$$

- integrate out massive $Q$

$$\mathcal{L}_{\text{eff}} = \frac{g_s^2}{16\pi^2 f_a} a \text{Tr} G \tilde{G} + \frac{N_C q_Q^2 e^2}{16\pi^2 f_a} a F \tilde{F}$$

- new contribution to the EM current

$$j^\mu = - \frac{\mathcal{L}_{\text{eff}}}{\delta A_\mu} = - \frac{N_C q_Q^2 e^2}{4\pi^2 f_a} \tilde{F}^{\mu\nu} \partial_\nu a$$

- EM current not conserved??

$$\partial_\mu j^\mu = - \frac{\mathcal{L}_{\text{eff}}}{\delta A_\mu} = - \frac{N_C q_Q^2 e^2}{4\pi^2 f_a} \tilde{F}^{\mu\nu} \partial_\mu \partial_\nu a$$

$$= - \frac{N_C q_Q^2 e^2}{4\pi^2 f_a} \tilde{F}^{12} \partial_\mu 2\pi f_a \delta^2 (x) = - \frac{N_C q_Q^2 e^2}{2\pi} F^{03} \delta^2 (x) \neq 0$$

$$a = f_a \theta$$
KSVZ axion

\[ \mathcal{L}_{UV} = \lambda (\phi^* \phi - f_a^2)^2 - y_Q (\phi \bar{Q}_L Q_R + c.c.) \]

\[
\partial_\mu j^\mu = - \frac{\mathcal{L}_{\text{eff}}}{\delta A_\mu} = - \frac{N_C q_Q^2 e^2}{4\pi^2 f_a} \tilde{F}^{\mu \nu} \partial_\mu \partial_\nu a
\]

\[ a = f_a \theta \]

then not gauge-invariant??

implies massless chiral fermion on the string that cancels the anomaly

similar to edge state in FQHE

in the UV description, it is the zero mode of PQ fermion Q on the string

Witten, Callan, Goldstone-Wilczek, ...
superconducting string

- chiral massless fermion on the string
  \[ \partial_{\mu} j^{\mu} = \frac{N_C q^2 e^2}{2\pi} E_z \neq 0 \]
- translational invariance along the \( z \) direction
  \[ \partial_t \rho = \partial_t j_z = \frac{N_C q^2 e^2}{2\pi} E_z \neq 0 \]
  \[ \rho = j = \frac{N_C q^2 e^2}{2\pi} E_z t \]
- build-up of charge and current: London eq
- superconducting!
current dissipation

\[ \mathcal{L}_{UV} = \lambda (\phi^* \phi - f_a^2)^2 - y_Q (\phi \bar{Q}_L Q_R + \text{c.c.}) - y_q \bar{Q}_R q_L H_0 \]

- heavy Q would overclose the Universe
- Q needs to decay to SM
- H or q_R hitting the string and knocking out the zero mode of Q from the string
- dissipation stops below the temperature

\[ T_X = (3.8 \times 10^2 \text{ GeV}) \frac{1}{y} \left( \frac{f_a}{10^{10} \text{ GeV}} \right)^4 \left( \frac{10^{10} \text{ GeV}}{I/(N_c e_\psi)} \right)^2 \left( \frac{y^2 \phi g^1/2}{h_*} \right) \]
primordial magnetic field

- the origin of intergalactic magnetic field $B \approx 10 \mu G$ is not understood
- possible primordial magnetic field from phase transition
- string moves in the magnetic field
- string sees the electric field
- leads to build up of charge
Once string charged, friction in plasma string does not move freely to simplify its network does not reach scaling, disappears much more slowly leads to denser network leads to much more axions

\[ B_0 = 10^{-13} \text{G} \]
\[ T_{\text{init}} = 10^3 \text{ GeV} \]
\[ \alpha = 1/3 \]
axion abundance

- normally dark matter
- axion from misalignment
  \[ f_a > 10^{12} \text{ GeV} \]

Here, \( f_a \approx 10^7 \text{ GeV} \)

- tension with astrophysical bounds \( f_a \approx 10^9 \text{ GeV} \)

- needs simulation for more detailed study
If $T_{\text{init}} < 100$ GeV or so, higher $f_a$ allowed

Challenge to models of PMF generation

Diagram:

- $T_{\text{init}}$ vs. $f_a$ plot
- Lines represent different values of $\Omega_{\text{ax}}/\Omega_{\text{DM}}$
- $B_0 = 10^{-13}$ G
- $\alpha = 1/3$
Conclusion

- Axion string is superconducting (generic for all axion-like particles with $aF\tilde{F}$ coupling)
- QCD axion string needs minimal KSVZ model
- With PMF, charge builds up, creates friction in string motion, enhances axion abundance
- Other consequences?