Production of axion CDM from strings and domain-walls

Toyokazu Sekiguchi (IBS-CTPU)

References:

• T. Hiramatsu, M. Kawasaki, TS, M. Yamaguchi & J. Yokoyama [arXiv:1012.550]
• T. Hiramatsu, M. Kawasaki, K. Saikawa, & TS [arXiv:1202.5851,1207.3166]
• M. Kawasaki, K. Saikawa, & TS [arXiv:1412.0789]
• M. Kawasaki, TS, M. Yamaguchi, & J. Yokoyama, in prep.
Outline

• Introduction: axion strings and domain walls (DWs)

• Field-theoretic simulation of axion topological defects

• Abundance of axion CDM from defects

• Current project: upgrading simulation

• Summary
Axion

Strong CP problem in QCD

\[ \frac{\theta}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{a\mu\nu} \in \mathcal{L} \rightarrow \text{CP violation} \]

- Experimental bound: \( \theta \lesssim 10^{-10} \); Why so small?

Solution: Peccei-Quinn mechanism Peccei & Quinn (1977)

- Anomalous \( U(1)_{\text{PQ}} \) spontaneously broken at \( \sim f_a \)

\[ \theta(x) = \theta - \frac{a(x)}{f_a} \]

- Pseudo-NG boson \( a(x) \): axion \( \rightarrow \) candidate of CDM

\[ m_a(x) \simeq 6 \mu\text{eV} \left( \frac{f_a}{10^{12}\text{[GeV]}} \right)^{-1} \]
Axion cosmology

Two possibilities:

- **U(1)$_{\text{PQ}}$ is broken before inflation**
  - (Almost) homogeneous $\theta_{\text{ini}} = a_{\text{ini}}/f_a \sim \pi$
  - CDM axions from coherent oscillation

\[ \Omega_{\text{axion}} \simeq 1.2 \times \theta_{\text{ini}}^2 \left( \frac{f_a}{10^{12} \text{GeV}} \right)^{1.2} \rightarrow f_a < 1.5 \times 10^{11} \text{GeV} \]

- CDM isocurvature perturbations is generated $\rightarrow$ bound on $H_{\text{inf}}$

- **U(1)$_{\text{PQ}}$ is restored during or after inflation ($\max[H_{\text{inf}}, T] > f_a$)**
  - Random $a_{\text{ini}}$. Global strings and DWs form.
  - CDM axions are also produced from these topological defects.
Formation of axionic defects

- $T > f_a : U(1)_{PQ}$ is restored

- $T = f_a : U(1)_{PQ}$ breaks down
  - Random distribution of phase: $\text{unif}(-\pi, \pi)$
  - Formation of axion strings (≈vortex)
  - Axions are radiated from strings

- $T = \Lambda_{QCD} : \text{QCD phase transition}$
  - Axion acquires potential $\sim \Lambda_{QCD}^4 \cos \left( \frac{a}{f_a} \right)$
  - Formation of DWs

  DWs have boundary edged by strings for $N_{DW}=1$ (e.g. hadronic axion model Kim ’79; Shifman, Vainshtein & Zakharov ’80)
  → DW-string system collapses into axion radiation within a few Hubble time
Evolution of defect network

Thermodynamics: scaling solution

- Number of topological defects in a horizon is constant of $O(1)$.
- Attractor solution: more(less) strings $\rightarrow$ more(less) inter-commutation
- Existence of scaling solution allows extrapolation of simulation results wrt parameters (to be discussed later)
Abundance of axion CDM

Energy density of axion CDM at present

$$\bar{\rho}_{\text{axion}}(t_0) = m_{\text{axion}} \bar{n}_{\text{axion}}(t_0)$$

Number density of axions radiated from topological defects

Estimated from simulations

Evolution of density of defects

Spectrum of radiated axions

(Energy loss of string-DW system)

(Mean energy of radiated axions)
Lattice simulation

PQ scalar on the lattice $\Phi(x_i, y_j, z_k)$

$$\dddot{\phi}_i + 2\mathcal{H}\dot{\phi}_i - \nabla^2\phi_i = \frac{\partial V}{\partial \phi_i}$$

$$V[\Phi] = \frac{\lambda}{4}(|\Phi|^2 - f_a^2)^2 + \frac{\lambda}{6}T^2|\Phi|^2 - m_a^2(T)f_a^2 \left(\frac{\text{Re} \Phi}{f_a}\right)$$

$$m_a(T)^2 f_a^2 \sim \begin{cases} 10^{-7} \Lambda_{\text{QCD}}^4 \left(\frac{T}{\Lambda_{\text{QCD}}}\right)^{-6.7} & (T \gtrsim \Lambda_{\text{QCD}}) \\ 10^{-3} \Lambda_{\text{QCD}}^4 & (T \lessgtr \Lambda_{\text{QCD}}) \end{cases}$$

Field theoretic simulation: first principles calculation ($\leftrightarrow$ string based action)

Drawback: unphysical parameters

(Box size $L$) \(\gg\) (Horizon $1/\mathcal{H}$) \(\gg\) (defect width $d$) \(\gg\) (lattice spacing=$L/N_{\text{grid}}\sim O(10^{-3})L$)

- Simulations with unphysical parameters & extrapolation to physics point

$f_a/M_{\text{pl}} \sim 10^{-3}, \Lambda_{\text{QCD}}/f_a \sim 0.1$

$f_a/M_{\text{pl}} \sim 10^{-8}, \Lambda_{\text{QCD}}/f_a \sim 10^{-12}$

$a(\tau) \propto \tau = 1/\mathcal{H}$ in RD epoch

$\Phi = \frac{\phi_1 + i\phi_2}{\sqrt{2}}$
String network

Kawasaki, TS, Yamaguchi & Yokoyama in prep
String-DW system ($N_{DW}=1$)
Scaling solution

\[ \kappa = \frac{\Lambda_{\text{QCD}}}{F_a} \]

- # of strings in a horizon (\(=\xi\)) is constant → **scaling solution is realized**
- \(\xi\) is close to 1
  - long-range force/dissipation process
cf. \(\xi\sim10\) for local strings (i.e. Abelian Higgs)

- DWs also scale at first
- Then quickly decay after energy of DWs dominates over strings.
Spectrum estimation

Hiramatsu, Kawasaki, TS, Yamaguchi & Yokoyama (2011)

Energy spectrum of radiated axions

\[ P(k) = |\dot{a}(\vec{k})|^2 \]

Need to remove contamination from defects

\[ \dot{a}(\vec{x}) = \dot{a}_{\text{free}}(\vec{x}) + \text{(string-DW contribution)} \]

Statistical reconstruction of spectrum (\sim\text{CMB analysis})

- Masking

\[ \tilde{a}(\vec{x}) = W(x)\dot{a}(\vec{x}) \quad \text{with window function} \quad W(\vec{x}) = \begin{cases} 0 & \text{(near defects)} \\ 1 & \text{(elsewhere)} \end{cases} \]

\[ \rightarrow \text{convolved power spectrum} \quad \tilde{P}(k) = \int \frac{d\vec{k}}{4\pi} \left| \tilde{a}(\vec{k}) \right|^2 \]

- Deconvolution

\[ \hat{P}_{\text{free}}(k) \approx \int dk M^{-1}(k, k') \tilde{P}(k') \quad \text{with} \quad M(k, k') = \int \frac{d\vec{k}}{4\pi} \frac{d\vec{k}'}{4\pi} \left| W(\vec{k} - \vec{k}') \right|^2 \]
Axion radiation spectrum

**Spectrum** of axions from strings

**Mean energy** of axions from DWs

Typical momentum $\sim 1/(\text{horizon size})$

- **strings:** $\langle \omega \rangle = (4.0 \pm 0.7) \times 2\pi H$
- **DWs:** $\langle \omega \rangle = (3.2 \pm 0.2) \times m_a$

Smooth dissipation of strings/DWs energy into radiation;
No evidence for turbulence generating high $k$ radiation
Abundance of axion CDM

Energy density of axion CDM at present

$$\bar{\rho}_{\text{axion}}(t_0) = m_{\text{axion}} \bar{n}_{\text{axion}}(t_0)$$

Number density of axions radiated from topological defects

- (Energy loss of string-DW system)
- (Mean energy of radiated axions)

Evolution of density of defects
Spectrum of radiated axions
Estimated from simulations
Axion abundance
when $U(1)_{\text{PQ}}$ is restored during or after inflation

Three sources:

- Strings (before DW-domination)
  \[
  [\Omega_{\text{axion}} h^2]_{\text{strings}} = (1.7 \pm 0.9) \times \left( \frac{f_a}{10^{12}\text{GeV}} \right)^{1.2}
  \]

- String-DW (after DW-domination)
  \[
  [\Omega_{\text{axion}} h^2]_{\text{DWs}} = (0.9 \pm 0.3) \times \left( \frac{f_a}{10^{12}\text{GeV}} \right)^{1.2}
  \]

- Coherent oscillation
  \[
  [\Omega_{\text{axion}} h^2]_{\text{osc}} = 1.1 \times \left( \frac{f_a}{10^{12}\text{GeV}} \right)^{1.2}
  \]

Contributions of defects are dominant

Constraint on axion decay constant: $f_a \leq (4.6 - 7.2) \times 10^{10}\text{GeV}$
Allowed mass range of axion (when $U(1)_{\text{PQ}}$ is restored)

$10^{-4} \text{ eV} < m_a (< 10^{-2} \text{ eV})$

Upper bound from astrophysics (white dwarfs, SN1987A, etc.)

So far the mass range is left untouched by direct detection (e.g. ADMX, CAST), but many future projects are being planned to probe the mass range:

- Microwave cavity at high frequency
  \textit{ADMX HF, IBS-CAPP}

- Nuclear Magnetic Resonance
  \textit{ARIADNE} [arXiv:1403.1290]

- Dielectric haloscope
  \textit{MADMAX} [arXiv:1611.04549]
Current project

M. Kawasaki, TS, M. Yamaguchi & J. Yokoyama in prep

Pinning down $f_a$ and $m_a$ in scenario where $U(1)_{PQ}$ is restored

- cf. dependence on initial misalignment $\theta_{ini}$ when $U(1)_{PQ}$ is not restored after inflation
  → Target mass for direct detection

Our prediction heavily lies on **scaling behaviour**

- Existence seems ubiquitous.
- However, relevant parameters characterising the scaling (e.g. $\xi$) cannot be predicted.
- Mild (~logarithmic) parameter dependences etc. may exist?
  → potential source of major uncertainties

Current project:

- Updating our simulations from $N_{grid}=512^3$ to $4096^3$
- Simulations with a range of parameters will be available
- Testing & improving one-scale model [Kibble 1985,…] w/ significant dissipation processes.
Scrutinizing scaling solution

- infinite strings
- loops
- axion radiation

$d\rho_{\infty}/dt = -2H(1 + v^2)\rho_{\infty} - \frac{\zeta}{L_{\infty}}\rho_{\infty}$

$d\rho_l/dt = -2H\rho_l$

$d\rho_{NG}/dt = -4H\rho_{NG}$

$\kappa \left[ \frac{\rho_{\infty}}{L_{\infty}} + \frac{\rho_l}{L_l} \right]$ cosmic expansion

loop production

One-scale model

$\tau_{cr} = 9.5 \left( \frac{g_{cr}}{\eta M} \right)^{3/2}$

string # density

string velocity

energy radiation rate

loop fraction

axion emission

preliminary

production

axion radiation parameter

loop momentum

preliminary

preliminary

preliminary

$\zeta = 30 \left( \frac{g_{cr}}{\eta M} \right)^{3/2} \tau_{cr}$

$\zeta = 25 \left( \frac{g_{cr}}{\eta M} \right)^{3/2} \tau_{cr}$

$\zeta = 15 \left( \frac{g_{cr}}{\eta M} \right)^{3/2} \tau_{cr}$

$\zeta = 9.5 \left( \frac{g_{cr}}{\eta M} \right)^{3/2} \tau_{cr}$
Summary

We investigated a scenario where

• $(1)_{PQ}$ is restored in the early Universe
• axions CDM are produced from axion strings and domain-walls

However, there have been lots of controversies e.g. on

• scaling evolution of the network of these defects
• radiation spectrum of axions from them

Performing field theoretic simulations, we confirmed

• average # of strings per horizon is $\sim1$
• mean wave length of radiated axions is around horizon size

We estimated the abundance of CDM axions from defects, that leads to a bound $f_a \lesssim (4.6 - 7.2) \times 10^{10} \text{GeV}$. Direct detection experiments will probe the mass range in the near future.

We are now upgrading our simulations ($N_{\text{grid}}=4096^3$). Critical test of scaling evolution of strings will be focused.