5.2.2 Topological defects

So far: Assumed homogeneous value for axion field in early Universe.

\( \rightarrow \) Justified if \( a > A_i \) scale of inflation.

If \( a < A_i \), a can take different values in different regions of space.

At high \( T \):

\[ \uparrow \rightarrow \uparrow \downarrow \text{ where } \rightarrow: \theta_0 = 0 \]
\[ \rightarrow \rightarrow \rightarrow \uparrow \text{ or } \rightarrow: \theta_0 = \frac{\pi}{2} \text{ etc.} \]

At small \( T \):

Field moves to low-energy configuration (like ferromagnet).

\[ \rightarrow \rightarrow \rightarrow \rightarrow \text{ (homogeneous value)} \]
Sometimes this is not possible

E.g.

```
↑ ↑ → → ↓
↑ ↑ . ↓ ↓
↑ ↓ ← ↓
```

"Cosmological string"

or the axion approaches different values in different regions of space:

```
↑ ↑ ↑ ↑ →
↑ ↑ ↑ → →
↑ → → → →
```

"Domain wall"

⇒ Axion field becomes trapped in high-energy configuration

\[ L, \text{ very large contribution} \]

to \( \Omega_a \ h^2 \)

Topological defects are usually unstable & decay to axions

\[ \Omega_a \ (\text{strings & walls}) \approx 0.4 \left( \frac{f_a}{10^{10} \text{ GeV}} \right)^{7/6} \]
5.3 Axion phenomenology

\[ L = \frac{1}{32\pi^2} \frac{a}{f_a} \left( \bar{G}^\mu \gamma^\nu G_{\mu\nu} \right) \]

- \( a \): spin-0, CP-odd
- \( \Rightarrow \) same quantum numbers as \( \pi^0 \)
- \( \Rightarrow \) axions and pions can mix

Any process that produces a pion can produce an axion with probability

\[ p \sim \frac{f_\pi^2}{f_a^2} \]

Example: \( K_s \rightarrow \pi^0 \pi^0 \) (BR \( \sim 30\% \))

\( \Rightarrow \) Prediction

\( K_s \rightarrow \pi^0 a \)

\( \Rightarrow \) invisible

\( \Rightarrow \) Used to exclude Weinberg-Wilczek axion

But for \( f_a \sim 10^{12} \text{ GeV} \): \( p \sim 10^{-25} \)

\( \Rightarrow \) Impossible to produce QCD axions in the lab

Need to rely on cosmological axions!
5.3.1 Hologscopes

Most interesting mass range:

\[ 1 \text{ meV} \leq m_a \leq 1 \text{ meV} \]

⇒ Corresponds to

\[ \lambda_a = \frac{2\pi}{m_a} \approx 1 \text{ mm} \rightarrow 1 \text{ mm} \]

Is comparable to size of typical experiment

Basic idea: Build resonant cavity of size \( \lambda_a \) to convert axions into photons

In addition to axion-gluon coupling, there is also an axion-photon coupling

\[ L = -\frac{\lambda_a}{4} \epsilon \mathcal{F}_{\mu \nu} \tilde{\mathcal{F}}_{\mu \nu} \]

⇒ Produced generated via axion-pion mixing and via fermion loops

\[ g_T = \frac{\Gamma}{2\pi p_a} \left( -1.55 + \frac{E}{\Gamma} \right) \]

\[ \text{model-independent} \rightarrow \text{model-dependent} \]
Well-known examples:

DFSZ axions: \( \frac{E}{N} = \frac{g}{3} \)

KS VZ axions: \( \frac{E}{N} = 0 \)

First consequence: \( a \rightarrow \gamma f \) decay

\[
\Gamma = \frac{g_{a\gamma}^2 m_a}{64 \pi}
\]

\[\Rightarrow \tau \approx 10^{24} \text{ s} \left( \frac{1 \text{ eV}}{m_a} \right)^5 \gg \text{t universe} \]

QCD axions are effectively stable if \( m_a \lesssim 20 \text{ eV} \)

More interesting: \( F_{\mu\nu} \tilde{F}_{\mu\nu} = -4 E \cdot B \)

\( \Rightarrow \) In a transverse magnetic field, axions can convert into photons
\[ E_\theta = m_a \left( + \frac{1}{2} m_a v^2 \right) \]

Power \( \propto g_a^2 \frac{B^2 V}{\text{volume}} \)

At first sight: Power of converted axion energy too small to be observable

Trick: Resonant conversion

\( \Rightarrow \) Set up a resonator tuned to frequency \( f_a = \frac{m_a}{2\pi} \Rightarrow \Delta a = \frac{2\pi}{m_a} \)

\( \Rightarrow \) Conversion probability enhanced by factor \( Q \)

\( Q \approx 10^5 \text{ possible} \)

\( \Rightarrow \) Conversion feasible

Problem: We don't know \( m_a \)

\( \Rightarrow \) Need to time cavity to scan over axion mass
Very slow progress

But if we hit right $x_0$, discovery possible within a day!

Strategy stops working for $x_0 \leq 10 \text{cm}$

$\Rightarrow$ Applicable only in narrow $x_0$ range

5.3.2 Light shining through walls

Can we use atom-photon conversion to produce axions in the lab?

[Diagram: Laser, magnetic field, wall, resonant cavities, Detector]

Cavity stores light injected by Laser

$\Rightarrow$ Power increased by

$$F_p = \frac{2}{\ell} \mathcal{Q}$$

$\ell$: wavelength

$\mathcal{Q}$: length of cavity

$\mathcal{Q}$: quality factor of cavity

Transverse $B$-field can convert photons to axions
\[ \text{Pay} \sim B^2 C^2 q^2 F(q, E) \]

- \( B \): magnetic field
- \( q \): momentum transfer \( (q = \frac{\mu_{a2}^2}{2Ea}) \)

\[ F(q, E) = \frac{2(1 - \cos q_E)}{(q_E)^2} \]

\( \rightarrow \) loss of coherence due to finite axion mass

\[ F(q, E) = 1 \quad \text{for} \quad q_E \ll 1 \]

\[ \Rightarrow \quad \frac{\mu_{a2}^2 E}{4\pi} \ll 1 \]

Typically \( 2 \sim 1 \text{m}, \theta \sim 10 \text{m} \)

\[ \Rightarrow \text{Can search for any axion with} \quad \mu_{a2} \ll 1 \text{meV} \]

If photon is converted to axion, it will travel through the wall and can be converted back on the other side.

\( \Rightarrow \) Second cavity has same mode & phase

\[ \Rightarrow \text{reconversion probability enhanced by} \quad F_2 \]
\[
Pr \rightarrow a \rightarrow 5 = 10^{-37} \ F_p \ F_r \\
\times \left( \frac{a_r}{10^{-10} \text{ GeV}^{-1}} \right)^4 \left( \frac{B}{1T} \right)^4 \left( \frac{E}{10^4} \right)^4
\]

**ALPS:** Current sensitivity: \( g_{ap} \sim 10^{-8} \text{ GeV}^{-1} \)

**Future plans:** \( g_{ap} \sim 10^{-11} \text{ GeV}^{-1} \)

\( \Rightarrow \) Not enough to reach QCD axions

5.3.3 Novel ideas

5.3.3.1 Dielectric haloscopes

To explore \( m_a \approx 10 \text{ meV} \)

need to enhance conversion probability for axions with very small \( 2a \)

Idea: Axion conversion at dielectric interface

\( \Rightarrow \) Place large number of dielectric disks in magnetic field

For \( d \sim 2a \): Constructive interference
Very new idea: MADMAX

R&D contribution from RWTH!

5.3.3.2 Nuclear magnetic resonance

Idea: Axions solve strong CP problem by setting $\varphi_{\text{eff}} \rightarrow 0$

$\Rightarrow$ no neutron EDM

But according to misalignment mechanism, axion field is not fixed at minimum but oscillates with frequency $\omega$.

$\Rightarrow$ time-dependent neutron EDM proportional to $\sqrt{s_0}$

Local axion density

Absolute magnitude of $s_0$ too small to detect

But oscillations may be observable if frequency $\omega \approx \frac{m_a}{2\pi} \leq 100$ MHz

$\Rightarrow m_a \leq 1$ meV

Very new idea

$\Rightarrow$ first experiment under construction (CASPER)