## 5.2.2 Topological defects

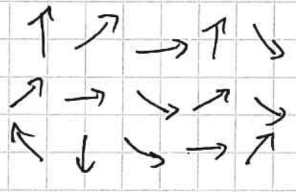
So far: Assumed homogeneous value for axion field in early Universe

↳ Justified if $f_a > \Lambda_I$

scale of inflation

If $f_a < \Lambda_I$, $a$ can take different values in different regions of space

At high T:



where $\rightarrow$ : $\vartheta_0 = 0$

$\uparrow$ : $\vartheta_0 = \frac{\pi}{2}$

etc.

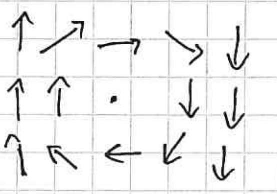
At small T:

Field moves to low-energy configuration (like ferromagnet)

(homogeneous value)

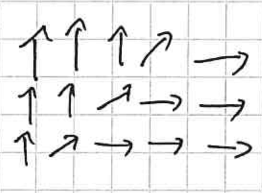
Sometimes this is not possible

E.g.



"Cosmological string"

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



"Domain wall"

$\Rightarrow$ Axion field becomes trapped in high-energy configuration

$\hookrightarrow$ very large contribution to $\Omega_a h^2$

Topological defects are usually unstable & decay to axions

$$\Omega_a \text{ (strings \& walls)} \sim 0.4 \left(\frac{f_a}{10^{11}\,\text{GeV}}\right)^{7/6}$$

## 5.3 Axion phenomenology

$$\mathcal{L} = \frac{1}{32\pi^2} \frac{a}{f_a} G^{a\mu\nu} G^a_{\mu\nu}$$

$a$: spin-0, CP-odd

=> same quantum numbers as $\pi^0$

=> 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: $K_s \to \pi^0 \pi^0$ (BR ~ 30%)

=> Prediction

$$K_s \to \pi^0 \underset{\hookrightarrow \text{ invisible}}{a}$$

=> Used to exclude Weinberg-Wilczek axion

But for $f_a \sim 10^{12}$ GeV : $p \lesssim 10^{-25}$

=> Impossible to produce QCD axions in the lab

Need to rely on cosmological axions!

## 5.3.1 Haloscopes

Most interesting mass range:

$$1\,\mu eV \lessapprox m_a \lessapprox 1\,meV$$

⇒ Corresponds to

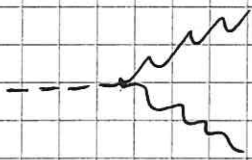
$$\lambda_a = \frac{2\pi}{m_a} \approx 1mm - 1m$$

↳ 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

$$\mathcal{L} \supset -\frac{g_{a\gamma}}{4}\, a\, F^{\mu\nu}\tilde{F}_{\mu\nu}$$



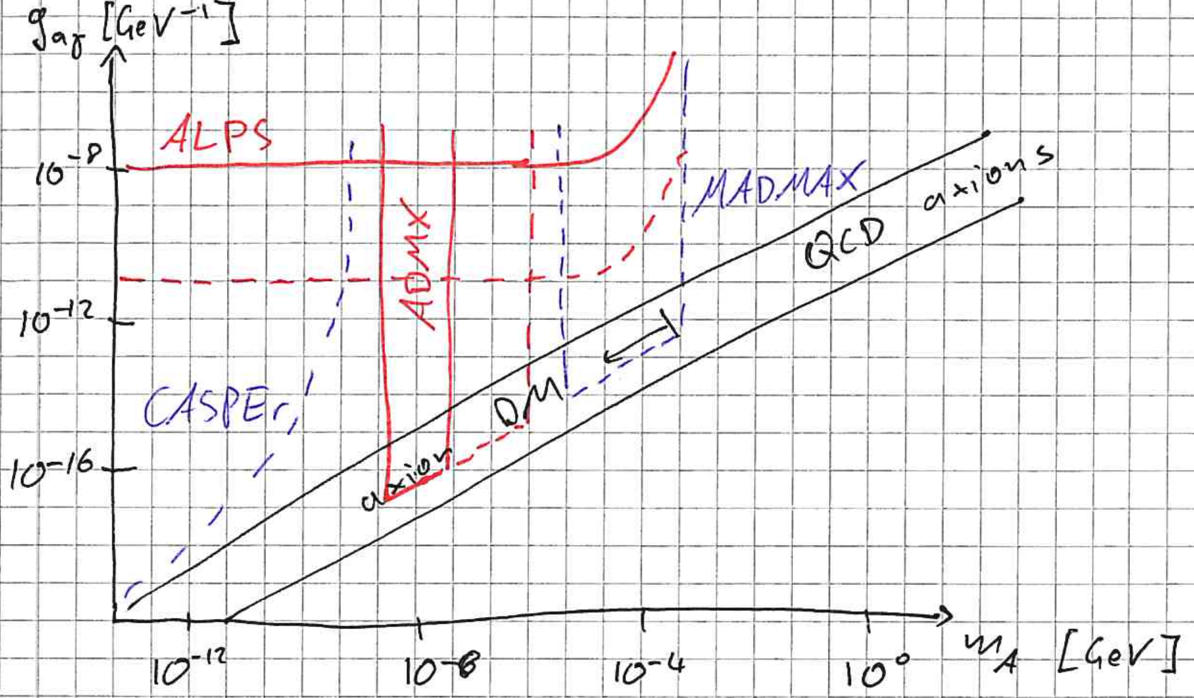
→ ~~Produced~~ Generated via axion-pion mixing and via fermion loops

$$g_\gamma = \frac{\alpha}{2\pi f_A}\Big(\underbrace{-1.95}_{\text{model-independent}} + \underbrace{\frac{E}{N}}_{\text{model-dependent}}\Big)$$

Well-known examples:

DFSZ axions: $\frac{E}{N} = \frac{8}{3}$

KSVZ axions: $\frac{E}{N} = 0$



First consequence: $a \to \gamma\gamma$ decay

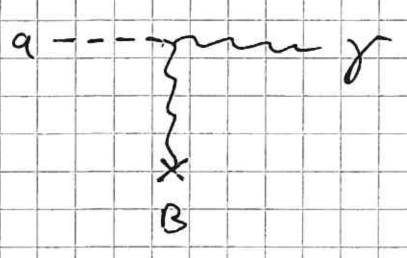
$$\Gamma = \frac{g_{a\gamma}^2 \, m_a^3}{64\pi}$$

$$\Rightarrow \tau \approx 10^{24}\,\mathrm{s} \left(\frac{1\,\mathrm{eV}}{m_A}\right)^5 \gg t_{\text{Universe}}$$

QCD axions are effectively stable if $m_a \lessapprox 20$ eV

More interesting: $F^{\mu\nu}\tilde{F}_{\mu\nu} \simeq -4\,\vec{E}\cdot\vec{B}$

$\Rightarrow$ In a transverse magnetic field axions can convert into photons



$$E_\gamma = m_a \left(+ \frac{1}{2} m_a v^2\right)$$

volume

$$P_{conv} \sim g_{a\gamma}^2 \, B^2 \, V$$

magnetic field

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

Trick: Resonant conversion

→ Set up a resonator tuned to frequency $f_a = \frac{m_a}{2\pi} \Leftrightarrow \lambda_a = \frac{2\pi}{m_a}$

⇒ Conversion probability enhanced by factor Q

quality of resonator (line width)

$Q \sim 10^5$ possible

⇒ Conversion feasible

Problem: We don't know $m_a$

⇒ Need to tune cavity to scan over axion mass

Very slow progress

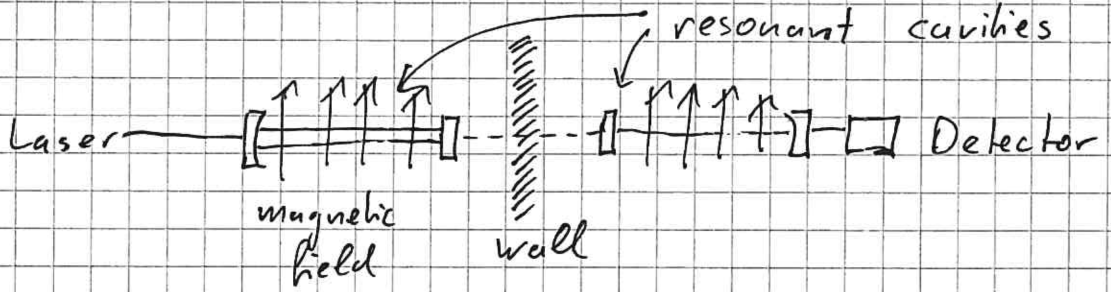
But if we hit right $\lambda_a$, discovery possible within a day!

Strategy stops working for $\lambda_a \lesssim 10\,\mathrm{cm}$

=> Applicable only in narrow $m_a$ range

## 5.3.2 Light Shining Through Walls

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



Cavity stores light injected by laser

=> Power increased by

$$F_p = \frac{\lambda}{l} Q$$

$\lambda$: wavelength
$l$: length of cavity
$Q$: quality factor of cavity

Transverse B-field can convert photons to axions

$$P_{a\gamma} \sim B^2 \ell^2 g_{a\gamma}^2 \, \mathcal{F}(q\cdot\ell)$$

B: magnetic field

q: momentum transfer $\left(q = \frac{m_a^2}{2E_a}\right)$

$$\tilde{\mathcal{F}}(q\cdot\ell) = \frac{2(1-\cos q\ell)}{(q\ell)^2}$$

$\hookrightarrow$ loss of coherence due to finite axion mass

$\mathcal{F}(q\cdot\ell) = 1$ for $q\cdot\ell \ll 1$

$$\Rightarrow \frac{m_a^2 \lambda \ell}{4\pi} \ll 1$$

Typically $\lambda \sim 1\mu m$, $\ell \sim 10m$

$\Rightarrow$ Can search for any axion with $m_a \lesssim 1\,meV$

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

→ Second cavity has same mode & phase

$\Rightarrow$ reconversion probability enhanced by $F_R$

$$P_{\gamma \to a \to \gamma} \approx 10^{-37} F_p F_R \times \left(\frac{g_{a\gamma}}{10^{-10}\,\mathrm{GeV}^{-1}}\right)\left(\frac{B}{1\mathrm{T}}\right)^4\left(\frac{\ell}{10\mathrm{m}}\right)^4$$

ALPS: Current sensitivity: $g_{a\gamma} \sim 10^{-8}\,\mathrm{GeV}^{-1}$

Future plans: $g_{a\gamma} \sim 10^{-11}\,\mathrm{GeV}^{-1}$

$\Rightarrow$ Not enough to reach QCD axions

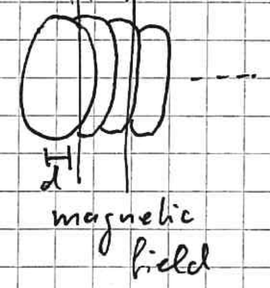
## 5.3.3 Novel ideas

### 5.3.3.1 Dielectric haloscopes

To explore $m_a \gtrsim 10\,\mu\mathrm{eV}$, need to enhance conversion probability for axions with very small $\lambda_a$

Idea: Axion conversion at dielectric interface

$\Rightarrow$ Place large number of dielectric disks in magnetic field



For $d \sim \lambda_a$: 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 $\vartheta_{eff} \to 0$
=> no neutron EDM

But according to misalignment mechanism axion field is not fixed at minimum but oscillates with frequency $m_a$

=> time-dependent neutron EDM proportional to $\sqrt{\rho_a}$
↖ local axion density

Absolute magnitude of $d_n$ too small to detect

But oscillations may be observable if frequency $f \sim \frac{m_a}{2\pi} \lesssim 100\,\mathrm{MHz}$

$\Leftrightarrow m_a \lesssim 1\,\mu\mathrm{eV}$

Very new idea
↳ first experiment under construction (CASPEr