A new way to search for QCD Axion Dark Matter with a Dielectric Haloscope

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The Strong CP-Problem

QCD allows for a term

\[ \mathcal{L} = - \theta \frac{g_s}{32\pi^2} G_{\mu\nu}^a \tilde{G}^{\mu\nu}_a, \quad \theta = -\pi \ldots \pi \]

but experimentally: \(|\theta| < 10^{-10}\) (neutron electric dipole moment)
The Strong CP-Problem

make $\theta$ a dynamic field: $\theta \rightarrow a(t; x)$ (Peccei-Quinn 1977)

$$\mathcal{L} = -a \frac{g_s}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{\mu\nu} + \frac{1}{2} \partial_\mu a \partial^\mu a$$

rolldown to CP conserving limit:

$V(a)$

Symmetry breaking

Coherent oscillation around the minimum
Peccei-Quinn Symmetry Breaking...

before inflation:

- Our Universe
- Cosmic axion string
- $m_A \lesssim \text{meV}$

after inflation:

- Our Universe
- Cosmic axion string
- Random $\theta_i$
- $m_A \sim 100 \mu\text{eV}$
The Axion - Parameterspace

Axion Photon coupling $g_{a \gamma \gamma}$ [GeV$^{-1}$]

Axion mass [µeV]

Dark matter axion predictions:
- KSVZ
- DFSZ

1 m$^2$ mirror 10T 1 week
1 m$^2$ mirror 10T 5 years

MADMAX: MAgnetised Disk-and-Mirror Axion eXperiment
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Axion Electrodynamics

\[ \mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} - j^\mu A_\mu + \frac{1}{2} \partial_\mu a \partial^\mu a - \frac{1}{2} m_a^2 a^2 - \frac{g_{a\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu} \]

Solve EOM under external magnetic field \( B_e \):

\[ \epsilon \nabla \cdot \mathbf{E} = \rho - g_{a\gamma} B_e \cdot \nabla a \]

\[ \nabla \times \mathbf{H} - \dot{\mathbf{E}} = \mathbf{J} + g_{a\gamma} B_e \dot{a} \]

\[ \ddot{a} - \nabla^2 a + m_a^2 a = g_{a\gamma} \mathbf{E} \cdot \mathbf{B}_e \]

Axion induced electric field:

\[ E_a = -\frac{g_{a\gamma} B_e}{\epsilon} a = 1.3 \times 10^{-12} \text{ V m}^{-1} \times \left( \frac{B_e}{10 \text{ T}} \right) \frac{C_{a\gamma} f_{DM}^{1/2}}{\epsilon} \]
Axion - Photon Mixing

\[ E_a = -\frac{g_a \gamma B_e}{\epsilon} a \]

\[ a \propto \cos(m_a t) \]

\[ B_e \]

\[ \sim 10 \text{ m} \]
Axion - Photon Mixing

\[
P_{\text{sig}} = (B^2 Q V C_{nml}) \left( g_{\alpha\gamma\gamma}^2 m_a \rho_a \right)
\]

\(Q:\) Quality Factor, \(C_{nml}:\) mode factor

Axion linewidth
\(\Delta \nu_a \sim 10^{-6} \nu\)

Cavity linewidth
\(\Delta \nu_c\)
Axion - Photon Mixing

\[ E_a = -\frac{g_{a\gamma} B_e}{\epsilon} a \]
**Axion - Photon Mixing**

\[ E_a = -\frac{g_{\alpha\gamma} B_e}{\epsilon} \alpha \]

- **Axions**
- **Detection Idea**
- **Booster Physics**
- **Outlook & Conclusion**

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Axion - Photon Mixing

\[ E_a = -\frac{g_a \gamma B_e}{\epsilon} a \]

\[ E_{||,1} = E_{||,2} \]

\[ \epsilon = 1 \quad \epsilon = 4 \]
Axions - Photon Mixing

\[ E_a = -\frac{g_{a\gamma} B_e}{\epsilon} a \]

\[ P/A = 2.2 \times 10^{-27} \text{ W m}^{-2} \left( \frac{B_e}{10 \text{ T}} \right)^2 C_{a\gamma}^2 \cdot f(\epsilon_1, \epsilon_2) \]
The MADMAX Idea

\[ P/A = 2.2 \times 10^{-27} \text{ W m}^{-2} \left( \frac{B_e}{10 \text{ T}} \right)^2 C_{a\gamma}^2 \cdot 1 \]
The MADMAX Idea

\[ P/A = 2.2 \times 10^{-27} \text{ W m}^{-2} \left( \frac{B_e}{10 \text{ T}} \right)^2 C_{\alpha \gamma}^2 \cdot \beta^2 \]

\[ \beta^2: \text{ power emitted by booster / power emitted by single mirror (} \epsilon = \infty) \]
Power Boost Factor $\beta^2$

adjust disc spacings:

Wide Bandwidth Boost Factor of $10^4 - 10^5$ Possible
Power Boost Factor $\beta^2$

adjus disc spacings:

![Frequency Band Tunable]
The Vision

- ~ 9T magnet
- ~ 80 dielectric disks $\epsilon \approx 24$
- spacing ~cm for 10-100GHz boosts
- ~10K cryogenic environment (?)
- 1.2m spacing ~cm
- metal disc
- focusing mirror
- antenna

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Sensitivity

Dark matter axion predictions:
- KSVZ
- DFSZ

Axion Photon coupling $g_{\text{ax}}$ [GeV$^{-1}$]

Axion mass [µeV]

- 1 m$^2$ mirror 10T 1 week
- 1 m$^2$ mirror 10T 5 years
- ADMX
- Haloscopes
- HAYSTAC
- IAXO projection
- 80 disks 1m$^2$ 5-10$^4$ boost 10T

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Axions
Detection Idea
Booster Physics
Outlook & Conclusion

Sensitivity

The European Physical Journal

Particles and Fields

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well matched to Gaussian beam $w_0 \approx 10 \text{ cm}$
3D Simulations – Beam Shape

\[ \Delta \nu B = 50 \text{MHz at } \nu B = 22 \text{GHz} \]

20 disks, \( \phi = 30 \text{ cm}, \epsilon = 24 \)

well matched to Gaussian beam \( w_0 \approx 10 \text{ cm} \)
3D Simulations – Beam Shape

methods see arXiv:1906.02677

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3D Simulations – Beam Shape

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3D Simulations – Tilts

**MADMAX: MAagnetised Disk-and-Mirror Axion eXperiment**

**t**ilts better than $0.1 \text{ mrad} \approx 30 \mu\text{m}/30 \text{ cm} \text{ required}$
3D Simulations – Tilts

tilts better than $0.1 \text{ mrad} \approx 30 \mu\text{m}/30 \text{ cm}$ required
**3D Simulations – Tilts**

- **total beam power**

  - 20 disks, \( \sigma = 30 \text{ cm}, \varepsilon = 24 \)

- **Max. Tilt:** 0.1 mrad

  - \( \frac{|E|^2}{|E_0|^2} \)

  - Local Normalized Power \( \approx \frac{|E|^2}{|E_0|^2} \)

- **tilts better than 0.1 mrad \( \approx 30 \mu \text{m}/30 \text{ cm} \) required**
3D Simulation – Surface Roughness

10 µm unproblematic
3D Simulation – Surface Roughness

10 µm unproblematic
3D Simulation – Surface Roughness

10 μm unproblematic
3D Simulations – Axion Velocity

each disk: tilted emission with angle $\nu_x$

CDM velocities: **unproblematic**
3D Simulations – Axion Velocity

each disk: tilted emission with angle $v_x$

CDM velocities: unproblematic
3D Simulations – Axion Velocity

each disk: tilted emission with angle $v_x$

CDM velocities: unproblematic
Axions Detection Idea

Booster Physics

Outlook & Conclusion

3D Simulations – Axion Velocity

each disk: tilted emission with angle $v_x$

including antenna $w_0 = 10\,\text{cm}$

20 disks, $\varnothing = 30\,\text{cm} \, , \, \epsilon = 24$

CDM velocities: unproblematic

MADMAX: MAgnitised Disk-and-Mirror Axion eXperiment
Proof of Principle Setup
Proof of Principle Setup

- Precision Motors
- Parabolic Mirror
- K Band Horn Antenna
- Copper Mirror
- Dielectric Disks (sapphire, $\varepsilon \approx 9.4$)
- to VNA

MADMAX: MAgnetised Disk-and-Mirror Axion eXperiment

4 equidistant sapphire discs

predicted electromagnetic response demonstrated
ongoing: comparison with 3D simulation, more discs
Further Challenges...

**9 T Magnet**

- Similar design also by [cea](http://www.cea.fr)
- $B^2 A \sim 100 \, \text{T}^2 \text{m}^2$,
- $\phi \sim 1.5 \, \text{m}$, $\ell \sim 1 \, \text{m}$; NbTi

**Dielectric Discs**

- $\epsilon \approx 24$, $\tan \delta \sim \text{few} \times 10^{-5}$

**Motor R&D** (e.g. Piezo)

- $\sim 30 \, \text{cm}$

U. Hamburg
Roadmap

**ongoing:**

- **magnet design studies:** $B^2A \approx 100 \text{T}^2 \text{m}^2$
  (two independent partners)
- **R&D:** on mechanics, $\text{LaAlO}_3$ dielectric plates, noise contribution of booster, receiver
- **booster studies:** 20 disc seed setup, 3D simulations

**in 1-3 years:**

- **20 disc prototype:** $\varnothing_{\text{disc}} \approx 30 \text{ cm}$, $B = 3 - 4 \text{ T}$
  $\Rightarrow$ first physics results

**afterwards (2025?):**

- full scale experiment
Conclusions

for more information:
MADMAX collaboration white paper,
Bedankt voor uw aandacht

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MADMAX collaboration white paper,

Optimizing the Boost Factor

20 discs, n=5

\[ \Delta \nu_\beta = 200 \text{ MHz} \]

\[ \Delta \nu_\beta = 50 \text{ MHz} \]

Area under Boost Factor curve approximately conserved

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Backup Slides

Receiver System

![Diagram of receiver system]

- **LHe-Bath**: 10GHz - 20GHz, 33 dB, $T_{\text{He}} = 5-8 \text{ K}$
- **Room temperature**: 10 GHz, -10 dB
- **1. Local oscillator**: 2.7 GHz - 12.7 GHz
- **2. Local oscillator**: 5.7245 GHz
- **3. Local oscillator**: 1.5495 GHz
- **-10 dB**
- **-10 dB**
- **-10 dB**
- **50 MHz**

**Signal analyzer**
(4 samplers, 1.4% dead time)

**Front end mixers and amps**

**“Fake Axion”**

LHe bath
$\rightarrow 4K T_{\text{He}} + 5.5K T_{\text{Amp}} \approx 9.5K T_{\text{Sys}}$
Receiver System

**typical one week measurement**

(with higher input signal)

![Graph showing typical one week measurement](image)

with preamp @ 4K:

**signal down to** \( \sim 10^{-23} \text{ W detected} \)
Probing the Boost Factor – Results

Disk Spacings
Repeatability
(Fitting Physical Disk Positions)

Predicted Electromagnetic Response Demonstrated

MADMAX: MAgnitised Disk-and-Mirror Axion eXperiment
Probing the Boost Factor – Results

Boost Factor
Repeatability
(Fitting Model to Measurements)

Predicted Electromagnetic Response Demonstrated
Backup Slides

Boost Factor Repeatability

(errors on boost factor under control)