

Experimental Searches for Dark Matter Axions

Julia K. Vogel July 9, 2024 IDM 2024, L'Aquila, Italy





1. The Axion

- 2. Detection of Axions
 - Haloscopes
 - Light-Shining-Through-Wall Searches
 - Helioscopes
- 3. Conclusions

The Axion

Coupling of axions to photons exploited by many experiments

Relatively "simple" and generic for all axion models



Coupling of axions to photons exploited by many experiments

- Relatively "simple" and generic for all axion models
- Model-dependencies exist however



Traditional benchmark models

- KSVZ: axions couple to BSM quarks only
- DFSZ: axions couple to fermions

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Additional, more recent models e.g.

Sokolov & Ringwald: Photophilic hadronic axion from heavy magnetic monopoles, JHEP 2021, 123 (2021).

C→APA

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Source	Experiments	Model & cosmology dependency
Relic axions	Haloscopes	High (assume axions are all of the DM)
Lab axions	Light-Shining-Through-Wall Experiments	Very low
Solar axions	Helioscopes	Low

Large complementarity between different experimental approaches! Some astrophysical hints favor regions outside typical haloscope range

EXPERIMENTS <u>RELYING</u> ON AXIONS BEING DARK MATTER

HALOSCOPES: Laboratory searches looking for galactic axions

P. Sikivie 1983 PRL 51 1415

Concept:

DM axion converts into photon in microwave cavity placed inside magnetic field

- If axion mass matches resonance frequency of cavity

$$m_a = 2\pi\nu_{\rm res} \sim 4\,\mu{\rm eV}\left(\frac{\nu_{\rm res}}{{\rm GHz}}\right)$$

then power output is $P_{
m out} \sim g_{a\gamma}^2 \, \rho_{
m a} \, B_0^2 \, V \, Q \qquad (Q \sim 10^5)$

Need to tune resonance frequency to scan axion mass range



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- Figure of merit

$$FOM \propto \frac{B^4 V^2 C^2 Q}{T_{SYS}}$$



Haloscopes

Haloscopes

HALOSCOPES: Laboratory searches looking for galactic axions

Microwave cavities

Currently active : ADMX, HAYSTAC, CAPP, GrAHal, ORGAN, QUAX, CAST-CAPP, RADES ADMX

HAYSTAC



Haloscopes

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Microwave cavities

Vacuum Realignment $m_a \sim O(10 \ \mu eV)$ $v \sim O(GHz)$



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For more details see talk by Karl van Bibber (#174), Heather Jackson (#169) & Giovanni Carugno (#267)

Adapted from https://cajohare.github.io/AxionLimits/

C→APA

CAPA

Haloscopes

HALOSCOPES: Laboratory searches looking for galactic axions



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Haloscopes

HALOSCOPES: Laboratory searches looking for galactic axions

How to go to higher masses to search for **post-inflation** axions?

Higher frequencies, (i.e. higher m_a) requires smaller cavities and scans get slower!



Haloscopes

HALOSCOPES: Laboratory searches looking for galactic axions

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Dish Antennas & Plasma Haloscopes!

 $\begin{array}{l} m_a \backsim O(100 \ \mu eV) \\ \nu \ \backsim O(10\text{-}100 \ \text{GHz}) \end{array}$



• HALOSCOPES: DISH ANTENNAS \vec{B}_0 \vec{B}_0 $\vec{E}_{\parallel} = 0$ Outgoing wave \vec{U} \vec

Concept: Axion induced radiation from a magnetized metal slab

- DM axions interact with a static magnetic field

 \rightarrow producing oscillating parallel E-field.

Conducting surface in this field emits plane wave \perp surface with $v \propto m_a$

– Radiated power is low, however, no tuning required!



Horns *et al* JCAP04(2013)016

 $P/A \propto B^2$

Haloscopes



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Haloscopes

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► HALOSCOPES: DISH ANTENNAS

Horns *et al* JCAP04(2013)016 F. Bajjali et al., JCAP 08 (2023), 077



BRASS@ U. Hamburg

- Consists of plane permanently magnetized conversion panel $B = 0.8 \,\mathrm{T}$ $\mathcal{A} = 4.7 \,\mathrm{m}^2$
- Spherical reflector

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HALOSCOPES: DISH ANTENNAS

Horns *et al* JCAP04(2013)016 Liu et al., PRL 128 (2022) 131801



BREAD@ Fermilab

 Cylindric parabolic conversion panel allows use of solenoidal magnetic field

 $B \sim 10 \,\mathrm{T}$

 $\mathcal{A} \sim 10 \,\mathrm{m}^2$

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Haloscopes

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Haloscopes

► HALOSCOPES: DISH ANTENNAS



Enhanced Concept: Boosted dish antenna aka open dielectric resonator concept

- Stack of dielectric plates as booster inside a magnetic field
- Tuned to the radiofrequencies (m_a around 100 μ eV)
- Can enhance measured power by several 10⁴, but tradeoff bandwidth/"boost factor"

For more details see talk by Jacob Egge (#243) on MADMAX

Haloscopes



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Haloscopes

► HALOSCOPES: PLASMA HALOSCOPES



Concept: Oscillating DM axions induce plasmon excitations in magnetized plasma

- Resonant enhancement when plasma frequency matches axion mass
- Can create plasma with tunable plasma frequency in GHz range using wire metamaterial (wire array with variable interwire spacing)
- Tuning then possible via geometry, limited by losses

Haloscopes

► HALOSCOPES: PLASMA HALOSCOPES

ALPHA Pathfinder



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- ALPHA@ORNL

For more details see talk by Andrea Gallo Rosso (#215) on ALPHA

Haloscopes



Haloscopes



Haloscopes

HALOSCOPES: Laboratory searches looking for galactic axions

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Lumped Element Detectors!

 $m_a \sim O(neV)$ $v \sim O(kHz-GHz)$



Haloscopes



Concept: Axion generates oscillating effective current J_{eff} parallel to B_0 in toroidal or solenoidal magnet

- J_{eff} in turn generates oscillating magnetic flux B_a (azimuthal)
- Can use pickup structure to read this
- Couple LC resonator inductively and use SQUID readout scheme

For more details see talk by Alex Droster (#165) on DMRadio

Haloscopes

HALOSCOPES: Laboratory searches looking for galactic axions

Pilot experiments ABRACADABRA ADMX SLIC SHAFT

Next Generation WISPLC DMRadio

- DMRadio-50L
- DMRadio-m³

(improvements in Q, V, B)

– DMRadio-GUT

(ambitious next-next gen)



Haloscopes



EXPERIMENTS NOT RELYING ON AXIONS BEING DARK MATTER

LIGHT-SHINING-THROUGH-WALL EXPERIMENTS: pure laboratory searches



Concept: Axions mixing with photons in external electromagnetic field

- Conversion probability for a photon with energy w converts into axion after having traversed a distance L_B in magnetic field of strength B:

$$P(\gamma \leftrightarrow a) \simeq 4 \frac{\left(g_{a\gamma}\omega B\right)^2}{m_a^4} \sin^2\left(\frac{m_a^2}{4\omega}L_B\right)$$

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- For very light axions, $m_a \ll \left(2\pi\omega/L_B\right)^{1/2} \approx \mathrm{meV}((\omega/\mathrm{eV})(\mathrm{m}/L_B))^{1/2}$:

$$P(\gamma \to a \to \gamma) \simeq \frac{1}{16} \left(g_{a\gamma} B L_B \right)^4$$

Detection of Axions Light-Shining-Through-Wall

LIGHT-SHINING-THROUGH-WALL EXPERIMENTS: pure laboratory searches





- ALPS

Most basic layout of a LSTW experiment

Detection of Axions Light-Shining-Through-Wall

LIGHT-SHINING-THROUGH-WALL EXPERIMENTS: pure laboratory searches





– ALPS-II

AI PS

experiment

- 12 + 12 straightened HERA magnets
- Optical cavities both at production and regeneration sites
- Sensitivity 3000×ALPS

Most basic layout of a LSTW



Light-Shining-Through-Wall



EXPERIMENTS NOT RELYING ON AXIONS BEING DARK MATTER

AXION HELIOSCOPES: laboratory axion searches looking for solar axions



Concept: Axions produced in strong electromagnetic fields of the solar core. and reconversion into x-ray (keV) photons in transverse laboratory B-field

- Use gas to expand axion mass search range
- Helioscope Figure of Merit $\propto B^2 L^2 A$

Helioscopes

AXION HELIOSCOPES: laboratory axion searches looking for solar axions



Solar Axion Searches

Next-gen helioscopes



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Solar Axion Searches

Next-gen helioscopes



Conclusions

- Axions are well motivated DM candidates simultaneously solving strong CP
- Axions/ALPs can be searched for in a variety of laboratory experiments: Haloscopes, Helioscopes and LSTW experiments
- Complementary searches are essential, and there are more than discussed here



The (axion) future is bright! Stay tuned!