First Axion Dark Matter Search with Toroidal Geometry

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Introduction

More than 90% of the content in the Universe are believed to be cold dark matter (CDM) and dark energy according to precision cosmological measurements. One of the most compelling candidates for CDM is the axion provided its mass is about 1 μeV and below 3 meV.

The axion search method proposed by Sikivie, also known as the axion haloscope search, involves a microwave resonant cavity with a static magnetic field that induces axion conversions into microwave photons.

The present state of the axion haloscope employs a cylindrical resonant cavity in a solenoidal field. But we introduced toroidal resonant cavity for axion search instead of cylindrical cavity.

A toroidal geometry offers several advantages, two of which are a large volume for a given space and greatly reduced fringe fields which interfere with our preamps.

In this pioneering search, we exclude the axion-photon coupling $g_{a\gamma\gamma}$ down to about 5 x 10^{-8} GeV^{-1} over the axion mass range from 24.7 to 29.1 μeV at the 90% confidence level.

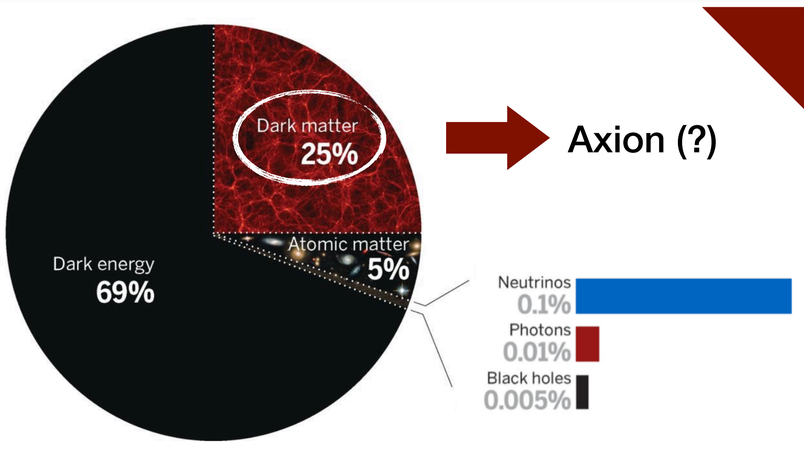
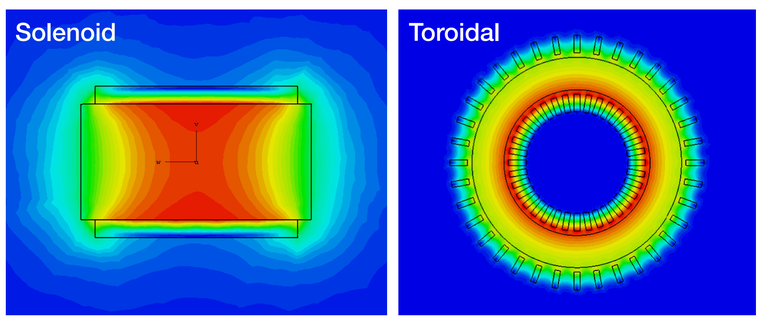


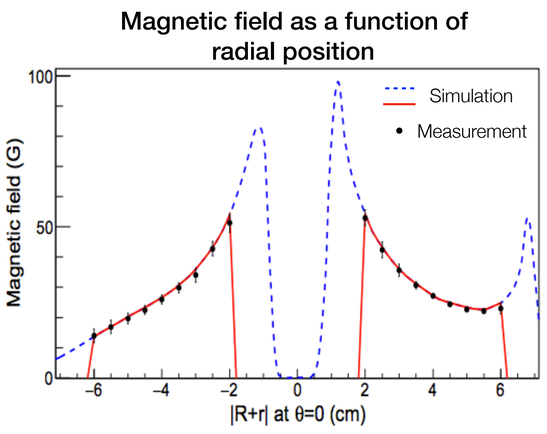
Image from "David N. Spergel, Science 06 Mar 2015: Vol. 347, Issue 6226, pp. 1100-1102"

Cavity Geometry



Characteristics	Cylindrical Geometry	Toroidal Geometry
$\vec{B}_{\text{ext}}$	$\sim B_0 \hat{z}$	$\sim \frac{B_0}{\rho}\hat{\phi}$
$B^2_{\text{avg}}V$	Independent of the cavity location inside a solenoid	Depends on the cavity location inside a toroidal magnet
Cavity Mode	TM_{010}	QTM
Form Factor	$C_E = C_M \propto B^2_{\text{avg}}V$	$C_E = C_M \propto B^2_{\text{avg}}V$
B_{fringe}	Unavoidable	Avoidable with additional coils

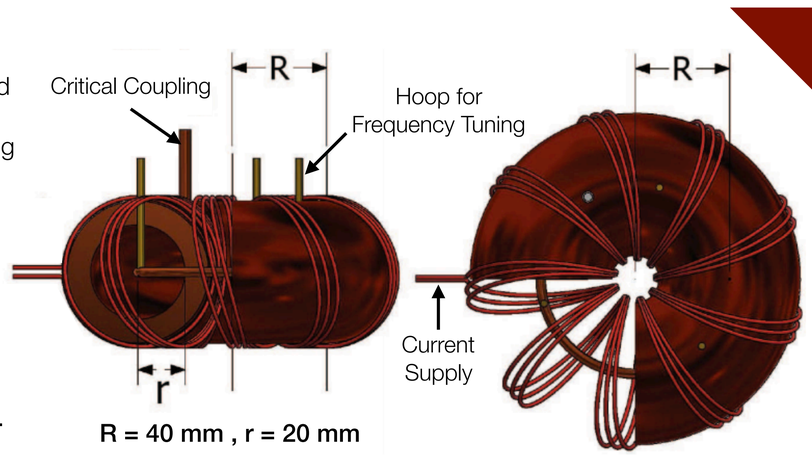
Toroidal Cavity



A static magnetic field was provided by 1.6 mm diameter copper wire ramped up to 20 A with three winding turns as right figure.

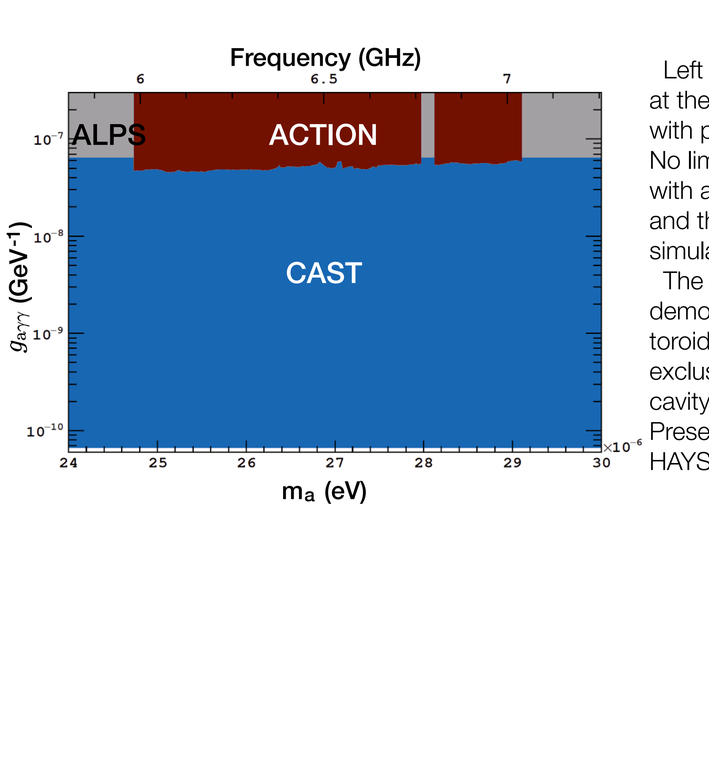
Left figure shows good agreement between measurement with a Hall probe and a simulation.

The tuning hoop can be moved up and down by the piezo actuator. As a result, it provides a resonance frequency range of about 6 ~ 8 GHz.



R = 40 mm , r = 20 mm

Experiment



We refer to this axion dark matter search as **ACTION** for "**A**xion Haloscopes at **C**APP with **T**oro**I**dal res**ON**ators"

Our receiver chain consists of a single data acquisition channel which is analogous to that adopted in ADMX except for the cryogenic parts. Power from the cavity goes through RF components, is then measured by a spectrum analyzer at the end. Cavity associates, ν and Q_L are measured with a network analyzer by toggling microwave switches.

The gain and noise temperature of the chain were measured to be about 35 dB and 400 K taking into account all the attenuation in the chain, for the frequency range from 6 to 7 GHz.

The cavity resonance frequency was controlled through the piezo actuator with 300 kHz steps, the spectrum was obtained after frequency down-conversion of 38 MHz.

Summary

Left figure shows excluded parameter space at the 90 % C.L. by this experiment together with previous results from ALPS and CAST. No limits are set from 6.77 to 6.80 GHz due to with a quasi-TE mode in that frequency region and the TE mode is also confirmed by a simulation.

The goal of this experiment was a demonstration of an axion haloscope with toroidal geometry. Right figure shows expected exclusion limits by the large (single & multiple cavity with cooling) ACTION experiments. Present exclusion limits from RBF, UF, ADMX, HAYSTAC and CAST are also shown.