Search for the Sagittarius tidal stream of axion dark matter around 4.55 μeV

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We report the first search for the Sagittarius tidal stream of axion dark matter around 4.55 μeV using CAPP-12TB haloscope data acquired in March of 2022. Our result excluded the Sagittarius tidal stream of Dine-Fischler-Srednicki-Zhitnitskii and Kim-Shifman-Vainshtein-Zakharov axion dark matter densities of $\rho_a \gtrsim 0.184$ and $\gtrsim 0.025$ GeV/cm^3, respectively, over a mass range from 4.51 to 4.59 μeV at a 90% confidence level.

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1. Introduction

According to the standard model of Big Bang cosmology and precision cosmological measurements [1], matter in our Universe makes up invisible cold dark matter (CDM) approximately of 85%. CDM is unknown to date even though there is strong evidence of the existence of it [2] and cannot be handled by the Standard Model of particle physics (SM).

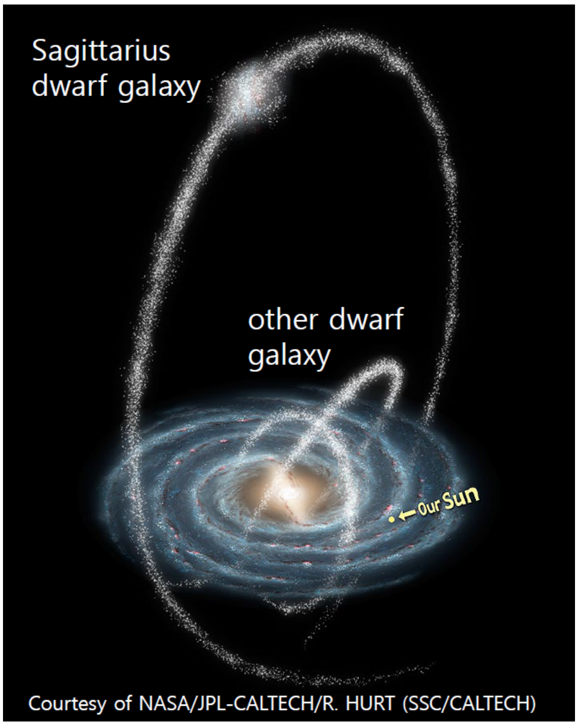

Figure 1: Milky Way and its satellite galaxies.

Dark matter in the halo is believed to dominate the local dark matter density in light of the current galaxy formation and evolution as well as the strong evidence of the dark matter existence. However, there could be additional local dark matter contribution from the Sagittarius dwarf tidal stream according to K. Freese *et al.* [3], where the Sagittarius dwarf galaxy is a satellite galaxy of the Milky Way as shown in Fig. 1. The tidal force from the Milky Way gravitation pulls the dwarf galaxy body so that it can form the streams showering onto the Solar System as also shown in Fig. 1. Since the Sagittarius dwarf galaxy is also believed to contain its own dark matter halo, the dark matter from the dwarf galaxy also makes up the tidal stream and it could contribute at most 23% of the local dark matter density [3]. The standard halo model (SHM) describes the signal shape of dark matter halo in the Milky Way which is indicated by orange lines in Fig. 2 [4]. The dark matter signal shape by the tidal stream model is taken from Ref. [3] and it is

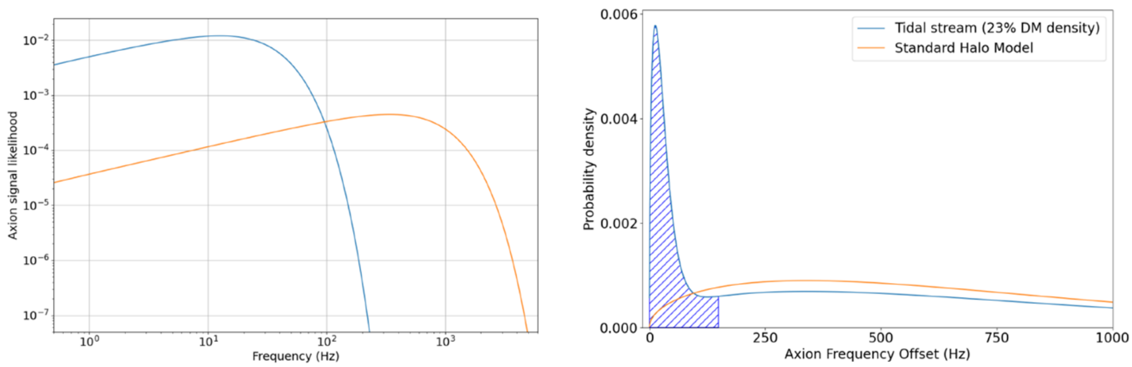

Figure 2: Axion dark matter signal shapes for a corresponding frequency of 1.1 GHz following the SHM (orange lines in the plots) and the tidal stream model (blue line in the left plot). The blue line in the right plot is the dark matter shape for this work assuming axion dark matter constitutes 100% of the local dark matter density, where it contributes 23% from the tidal stream model and 77% from the SHM. Only the blue hatched region in the right plot is considered as the signal region.

the blue line in the left plot of Fig. 2. Blue line in the right plot of Fig. 2 is the expected dark matter signal shape in the presence of the tidal stream contribution of 23% on top of the dark matter halo contribution of 77% and is similar to the model in Ref. [5], but only the blue hatched region in the right plot of Fig. 2 is taken as the signal region in this work.

2. Axion dark matter and axion haloscope

QCD axion or axion [6] was introduced by Peccei and Quinn [7] to solve the strong CP problem in the SM [8] and is predicted to be massive, abundant, and cold and interacts very weakly with the SM [9]. Such axion properties meet the CDM conditions, hence axion is one of the most appreciated CDM candidates nowadays and referred to as axion dark matter. The two most popular benchmark models are the Kim-Shifman-Vainshtein-Zakharov (KSVZ) [10] for QCD axions that couple to beyond the SM heavy quarks, and Dine-Fischler-Srednicki-Zhitnitskii (DFSZ) [11] for those to the SM quarks and leptons, at tree levels.

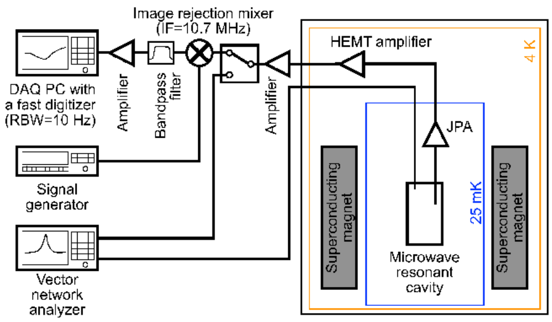

Figure 3: Outline of an axion haloscope, e.g., the CAPP-12TB haloscope.

A direct axion detection by P. Sikivie [12] uses the axion-photon coupling and is known as the axion haloscope. Employing a high-quality microwave cavity makes the axion haloscope the most sensitive axion dark matter searches in the microwave region and Fig. 3 shows a typical outline of the axion haloscope brought by the CAPP-12TB experiment [13].

3. CAPP-12TB experiment

The CAPP-12TB experiment depicted in Fig. 3 constitutes a superconducting solenoid whose central magnetic field is 12 T and bore diameter is 320 mm [14], a 36.85 L frequency tunable copper cylindrical cavity, a heterodyne receiver chain with a Josephson Parametric Amplifier (JPA) [15] as the first amplifier, and the fast data acquisition system [16]. With help from a dilution fridge DRS-1000 [17], the experiment lowered and maintained the physical temperatures of the cavity and the JPA at around 25 mK. CAPP-12TB is the second DFSZ axion dark matter sensitive experiment following the ADMX [18], where both experiments assumed the DFSZ axion dark matter halo makes up 100% of the local dark matter density, i.e., $\rho_a^{\mathrm{DFSZ}} = 0.450$ GeV/cm^3. The overall operation of the experiment and the relevant measurements can be found in Ref. [13].

4. Tidal stream dark matter search

As a complementary dark matter search, this work searched for dark matter of the tidal stream [3] around 4.55 μeV using the same data used for our SHM dark matter search [13], but without a dedicated rescan. Assuming DFSZ axion dark matter makes up 100% of the local dark matter, the aforementioned dark matter model for this work (the blue hatched region in the right plot of Fig. 2) results in $\rho_a^{\rm DFSZ}$ of 0.114 GeV/cm^3. Table 1 summarizes the comparison between our previous SHM dark matter search [13] and this tidal stream dark matter search. Our dark matter model with a signal window of 150 Hz includes contributions from the tidal stream dark matter of 100% and dark matter halo of 2.3%.

	SHM search	this work
dark matter constitution	100% DFSZ axion, 100% SHM contribution	100% DFSZ axion, 23% tidal stream and 77% SHM contributions
signal window	4050 Hz	150 Hz
$\rho_a^{\rm DFSZ}$	0.450 GeV/cm^3	0.114 GeV/cm^3
signal power	higher ($\because$ higher $\rho_a^{\rm DFSZ}$)	lower ($\because$ lower $\rho_a^{\rm DFSZ}$)
background fluctuations	higher ($\because$ wider signal window)	lower ($\because$ narrower signal window)
cut	standard (3.718)	tighter without a rescan

Table 1: Comparison between our previous SHM dark matter search [13] and this tidal stream dark matter search.

5. Results

The results of this work have been recently published [19] and they are summarized in this proceedings. Data processing followed the usual axion haloscope search analysis method [20], but applied tighter conditions to exclude all the excess by a least cut, without a rescan. A cut of 5.4 was applied to exclude all the excess shown in the left plot of Fig. 4. The signal compatibility test was done for the most significant excess shown in the left plot of Fig. 4 by the χ^2 probability. The test statistic and alternative hypothesis are shown in the right plot of Fig. 4

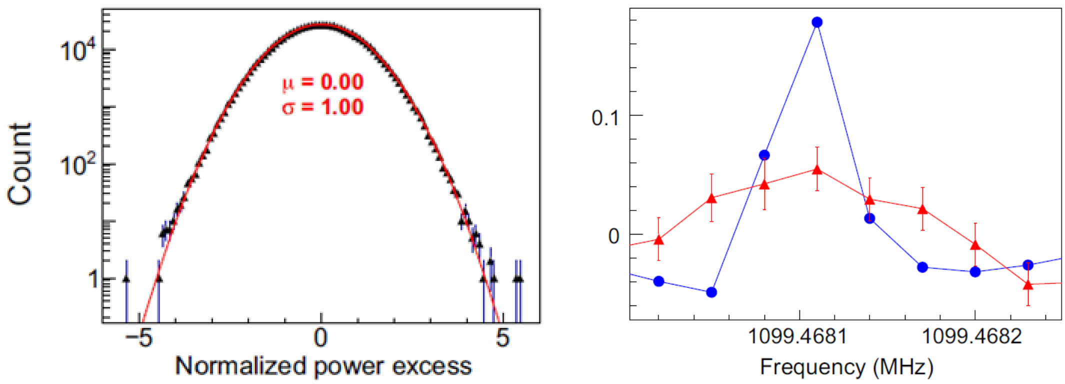

Figure 4: The left shows the normalized power excess distribution of the normalized grand power spectrum and the right shows the test statistic (red solid triangles) and alternative hypothesis (blue solid circles) that were used for the χ^2 probability test. Note that the excesses and errors in the right are dimensionless due to the rescaling in Ref. [19].

and the calculated χ^2 probability of $O(10^{-9})$ implies that they are not compatible with each other. The details of the data processing and the associates also can be found in Ref. [19]. In the absence of the axion dark matter signal, Fig. 5 shows the excluded densities of axion dark matter of the Sagittarius dwarf tidal stream at a 90% confidence level (CL). Dark matter of the tidal streams was ruled out for densities of $\rho_a \gtrsim 0.184$ and $\gtrsim 0.025$ GeV/cm^3 for DFSZ and KSVZ axions, respectively.

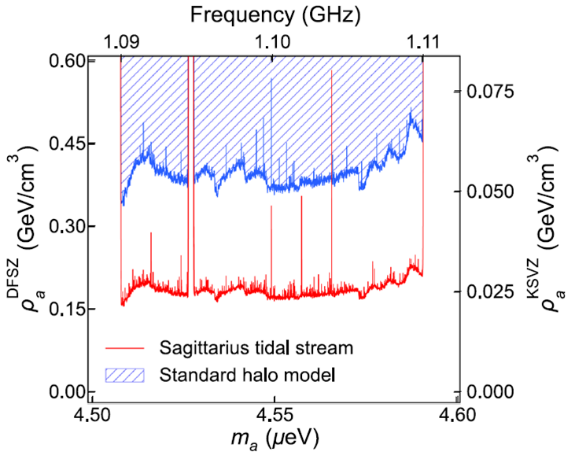

Figure 5: The blue hatched region shows the exclusion limits for the axion dark matter densities from [13] and the red solid line shows those achieved by this work, $\rho_a^{\rm DFSZ}$ in left and $\rho_a^{\rm KSVZ}$ in right. No results are available around an axion mass of 4.527 μeV due to mode crossing. The spikes are less sensitive frequency points with fewer statistics resulting from the filtering procedure [19].

6. Summary

CAPP-12TB is the second axion haloscope sensitive to DFSZ axion dark matter halo. The Sagittarius dwarf tidal stream of axion dark matter was searched for as a complementary to our previous axion dark matter halo search [13]. Although this is a parasitic search without a dedicated rescan, the result is far beyond KSVZ sensitivity for axion dark matter from the tidal stream for the first time. This approach could be extended to the big flow model [21] as done in Ref. [22] in the near future. In summary, we excluded the densities of $\rho_a^{\rm DFSZ} \gtrsim 0.184$ GeV/cm^3 and $\rho_a^{\rm KSZV} \gtrsim 0.025$ GeV/cm^3 over a mass range from 4.51 to 4.59 μeV at a 90% CL.

Acknowledgments

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