Comparison of Different Searching Paradigms for Axion

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Abstract. An “invisible” matter called Dark Matter, which does not interact with the electromagnetic spectrum, is an idea to explain high velocity dispersion in the cluster and observed differences in mass to light ratio. Axion is the hypothetical particle that beyond the standard model, is suggested to resolve the Strong CP violation problem, its light mass enabling it to be a high potential candidate for cold dark matter, meanwhile explaining the violation in matter and antimatter. Therefore, multiple experiments include CAST, ADMX, MADMAX, XENON and ABRA but more than these are searching for different axion models, various axion masses and energy level sources, with theories such as Primakoff conversion. This article illustrates the latest limits for axion model base on ABRA results, with masses between 0.31neV to 8.3 neV, and the upper limit of $g_{a\gamma\gamma} < 3.3\times10^{-9}$ GeV^{-1} and < 1.4×10^{-10} GeV^{-1}, no axion exists. Meanwhile, compared to other results given by CAST, masses range around 0.02 eV and $g_{a\gamma}$ up to 8.8×10^{-11} GeV^{-1} to $g_{a\gamma}$ larger or around 4×10^{-13} GeV^{-1} within the masses from 34.6771 to 34.6738 μeV. These results offer a better understanding of current axion models and research with latest achievements by comparing various detection methods and their observations.

Keywords: Dark matter; CAST; Solar axion; ABRA; QCD axion.

1. Introduction

The term “Dark Matter” is a hypothetical matter, which is a non-baryonic matter that is believed to have formed most of the mass of the universe. The word non-baryonic suggests this kind of matter is not formed by fermion-quarks. Therefore, its properties cannot be constrained by three of the fundamental forces, weak, strong and electromagnetic forces, which are the principal elements supporting the Standard Model of particle physics. As a consequence, DM cannot be observed by any telescope directly as all the telescopes observed via electromagnetic spectrum, based on the Standard Model, to define how the universe runs. In the last 100 years, physicists, astronomists, cosmologists have all tried to define, conclude and construct theories about Dark Matter and it is believed that the discovery of DM will be the next transformation in astronomy and physics. Ideally, this research will be able to further expand human cognition and better define physics in addition to inventing advanced technology [1, 2].

However, Dark Matter is not the first hypothesis towards this “invisible” matter. Around 400 years ago, Galileo’s observations of Jupiter and its four satellites and the composition of the Milky Way already suggested that matter beyond human perception may exist in the universe and the visibility of matter can be highly dependent on observation methods and techniques. This may be the earliest prediction of DM’s existence. Later in 1678, the foundation of modern physics, Philosophic Naturalis Principia Mathematic, was published by Isaac Newtown and the Law of motion and universal gravitation $F = GMm/r^2$ in it demonstrates a very powerful tool to modern scientists, allowing them to link kinetic motion and gravity and mass. Before the hypothesis of DM became popular in the 20th century, the concept of Dark Stars, dark planets and dark nebula had been suggested. John Michell suggested light can be affected by gravity in 1783, thus the Universe could have a “dark star” with such strong gravitational attraction that even light cannot escape from it. Then, in 1793, Pierre Simon Laplace also talked about the hypotheses suggested by John Michell; all the evidence described the existence of dark stars but they could not be observed directly with technology in those days. Based on the effect of gravitational influence, Friederich Bessel, a mathematician, predicted a undiscovered celestial body to explain the abnormal motion of stars Sirius and Procyon in 1844. Since then, astronomers have never stopped observing the motion of stars and planets using gravity; thus

Neptune was discovered in 1846 due to the strange motion of Uranus. On the other hand, the concept of dark clouds was also suggested in 1877 by father Angelo Secchi [3-10].

Furthermore, based on these foundations, later in 1915 Einstein published General Relativity to enhance the illustration of the relationship between gravity, motion and space to the public. It does predict a super massive star (i.e. black hole), with gravity big enough to distort a region of space-time so much that light cannot escape; 104 years later in 2019, scientists published the first image of a black hole. Moreover, General Relativity also suggests the deflection of light in a gravitational field resulting in the phenomenon of gravitational lensing and this has become one of the tools for detecting DM. Back in the 21st century, with all those previous foundations theories, methods and tools, detecting DM is starting to be a clearer process and multiple observations can prove the exist of DM; for instance, using gravitational lensing, galaxy rotation curves, cosmic microwave background radiation (CMBR) and observing the universe at a much large scale [6, 7]. By all those large-scale observations, indirectly calculated DM mass is approximately 85% of the universe mass. Apart from using gradational lensing, galaxy rotation curve and CMBR and so on to determine DM exists on a large scale, there are other models which define DM in servals potentials hypotheses particles on a much smaller scale, on a scale that is beyond Standard Model (SM). Knowing their existence is not satisfying, therefore defining their properties and formations will be a more specific purpose on a smaller scale. A variety of DM candidates are supported by different searching paradigms. For example, one of the candidate WIMPs (Weakly Interacting Massive Particles), is believed such a weak scale hypothesis particle will ideally interact with SM with weak scale cross-section [8]. Thus, there are many experiments searching for it, such as those using the Large Hadron Collider or supersymmetry, therefore it is also one of the highest potential Cold Dark Matter particles. Furthermore, under supersymmetry theories, SUSY neutralino can be the other candidates for DM.

This article will mainly focus on one of the most popular DM candidates, i.e., Axion [11-15], comparing the different detecting methods and models of it. Starting with a brief introduction to define DM in the perspective of different potential hypotheses particle candidate models, the math involved and axion. Then, along with introducing one of the two searching paradigms CAST in three dimensions, the searching theory, detectors and result. After that, second searching paradigm ABRA-10 cm will be introduced with the same structure as the previous one. Then, comparing those two searching paradigms by summarizing their advantages and limits. Eventually, looking in Axion searching paradigms limitation and the improvements.

2. Basic Descriptions of Dark Matter and Axion

Dark Matter means matter that does not interact with the electromagnetic spectrum, thus there are no direct observations with electromagnetic radiation and it becomes dark [2]. Jacobus Kapteyn, a astronomer who pointed out the motion stars can indirectly infer matter that cannot be observed around them 100 years ago (1922) [3]. Therefore, it is believed that this was the earliest comment on DM. After that, many astronomers did try to observe the motion of stars in addition to studying DM. For instance, in 1932 which is 10 years after Jacbus Kapteyn suggested his idea on invisible matter, another astronomer Jan Oort could not find any relevant DM by studying the motion of stars which are close to the solar system [4]. However, one year later in 1933, first indirect evidence of the existence of DM was published by Fritz Zwicky. By using Newton’s law of motion and universal gravitation, he suggested the observed mass in COMA Cluster is far too low thus those masses did not have great enough gravitational pull to balance the high velocity dispersion in each galaxy in the Cluster [5]. Since then, many other astronomers have started to find the disequilibrium in mass, gravity and mass to light ratio in different galaxies and enhanced the hypotheses on DM, meanwhile it coming to a conclusion that suggested DM is not mainly formed by particles in SM, including any fermions or bosons.

DM can be divided in serval sub-fields, such as Cold Dark Matter (CDM) which was firstly suggested in 1982 by James Peebles [6], meanwhile warm Dark Matter was suggested by Richard

Bond, Alex Szalay, and Micheal Turner [7]. The “Cold/Warm/Hot” DM is just a demonstration of the mass of various DM. HDM travels much faster then CDM, close to the speed of light, due to its lower mass. CDM candidates include weakly interacting massive particles (WIMPs) with self-annihilation cross section of:

$$< \sigma v > \cong 3 \times 10^{-26} cm^3 s^{-1} \tag{1}$$

Here, σ is the weak scale cross section and v is the typical velocity.

Among various dark matter candidates, axion is a very light hypothesis form of particle with a mass smaller than WIMPs. Axion was suggested in 1978 independently by Steven Weinberg and Frank Wilczek based on the spontaneously broken in unknown scale fa (axion constant) in Peccei-Quinn theory, which was published by Roberto Peccei and Helen Quinn in 1977 in addition to solve the Strong CP problem in quantum chromodynamics (QCD) and the formula below sums up PQ-theory and axion hypotheses [10, 11]:

$$L_{axion} = -\frac{1}{2}\partial_\mu \varphi\, \partial^\mu \varphi + \frac{g^2}{32\pi^2}\frac{\varphi(x)}{f} G^a_{\mu\nu}\hat{G}^{a\mu\nu} \tag{2}$$

Here, φ(x) is the axion field and f is the axion constant. At $\bar{\theta} = 0$, QCD effective potential $V(\bar{\theta})$ is at its minimum therefore strong CP problem is solved. As the axion is suggested to solve the Strong CP problem in QCD, we also call it QCD axion. Then, axion mass is given by axion constant f as:

$$m \cong 6eV\,\frac{10^6 GeV}{f} \tag{3}$$

Coupling of an axon to two photons is given by:

$$L_{a\gamma\gamma} = -g_\gamma \frac{\alpha}{\pi}\frac{\varphi(x)}{f}\boldsymbol{E}\cdot\boldsymbol{B} \tag{4}$$

Where E and B represents electric and magnetic fields, g_γ is the model-dependent coefficient of order one. Furthermore, the idea of axion existence can not only solve CP violation but it can be one of the best candidates in CDM with its very light mass ranging from 1 $\mu eV/c^2$ to 1 meV/c^2 and existence of Axion does not only define the origin dark matter but also explains why the Strong interaction between quacks is CP symmetry but is not in the weak interaction [8]. Other model Axion BCE is suggested which Bose-Einstein condensate are produced by axion thermalisation, thus allow axion explain the effect of dark matter halos net rotation and arrangement of cosmic microwave anisotropic multipoles that other CDM candidates cannot explain [11]. Moreover, axion can explain the existence of various matter and antimatter and the suggested axion field can explain why more matter than antimatter exists in the universe. Currently, multiple experiments are running to detect various ranges of the mass of axion, from μeV to meV [12]. For instance, ADMX, CAST, MADMAX, ABRA experiments. However, they all share the same properties, axion interaction with the strong electromagnetic magnetic fields thus transferred into observable particles like photons or leptons.

3. Searching Paradigm CAST

3.1. Principle

This section will introuce the solar telescope with the highest detection sensitivity in searching for axion [15], CERN Axion Solar telescope (CAST), which is located in the European Organization for Nuclear Research. The model that the CAST experiment based on for searching axion suggested axion can be produced in the core of the sun due to the Primakoff effect [16], the core of the sun contain a very strong electromagnetic magnetic field meanwhile filled with high energy photons and atom nucleus, thus axion can be produced in such a thermal, strong electromagnetic environment [13]. Using the Primakoff effect, can also detect photons that decay by Solar Axion within the strong electromagnetic field [15] and the formula of the coupling of two-photon is given by below vertex [14]:

$$L_{a\gamma} = -\frac{g_{a\gamma}}{4} F_{\mu\nu} F^{e\mu\nu} a = g_{a\gamma}\, \boldsymbol{E}\cdot\boldsymbol{B} a \tag{5}$$

Where $g_{a\gamma}$ is the coupling constant, F is the Electromagnetic field strength tensor a is the Axion field and this equation is in the natural units. The same coupling constant $g_{a\gamma}$ applies to both production and detection of Axion-Photons. Meanwhile the reaction can be reversed $a \leftrightarrow \gamma$, not only limited on an axion decay in two-photon [13]. The CAST experiment, use dipole magnet in addition to create a 9.5 T strong electromagnetic field and track the sun for 90 minutes individually to sunrise and sunset to detect the solar axion. When the solar axion interacted with strong electromagnetic field and converted back to photons, produced X-ray, it will be observed by the X-ray detector.

3.2. Detectors

A sketch of the detectors is presented in Fig. 1. The helioscope is built by a 9.26 m long LHC prototype magnet which can move ±8 degree up and down, 40 degree left and right, each end with magnet bore diameter 4.3cm is equipped with X-ray detector with high sensitivity towards the photons. With the sunset system at one end of the magnet and sunrise system at the other end allow the helioscope to keep tracking the sun for about 90 minutes during the sunrise and sunset. Meanwhile, the magnet is superconducted by superfluid helium and keeping it at 1.8 K and the B-field of the magnet is where the solar axonometric to the photons. Moreover, the end with the sunrise system also has an X-ray telescope - XRT, in addition to enhance the sensitivity of the X-ray detector of detecting the X-ray as this reduces background noise to the signal and all the signal and background signal are monitored by the two XRT and processed by the same detector to lower other factors impact [17].

CAST started its first run 19 years ago, servals adjustments and detectors applied to CAST during the first 10 years, such as adding He-4 / He-3, increasing the detect masses range, and TPC detector, MICROMEGAS detector, CCD X-ray telescope. The TPC detector is aimed to detect X-ray signal with low intensity and the MICROMEGAS detector is aimed to detect X-ray signal within the range of 1-10KeV and the CCD X-ray telescope is aimed to enhance signal to noise ratio. Later, CAST was equipped with other new detectors to improve its sensitivity and expand its function. For instance, InGrid Based Xray-Detector, GridPix, KWISP, CAST-CAPP and RADES detectors. Enhancing the sensitivity of an energy of X-ray up to 1KeV by InGrid Based Xray-Detector [18] and extending the detection of soft X-ray by GridPix detector [14]. Another detector RADES, which was installed to CAST in 2018 allow it to detect axion above 30 μeV [17]. Moreover, there is also a detector CAST-CAPP, which is searching axion ranging from 21 to 23 μeV.

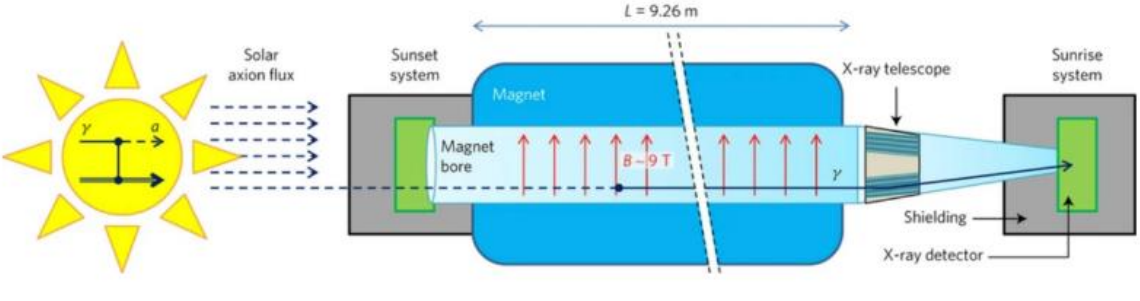

Fig. 1 A sketch of the detectors.

3.3. Searing results

In the past twenty years, CAST has kept searching for Axion. Since 2003, CAST searching axion mass < 0.02 eV, then it was extended to 0.39 eV by adding He-4, after that adding He-3 even extended the mass to 1.15eV. Although there is no direct evidence suggesting axion existence, the different range of axion masses that were searched by the CAST helped to limit the model of axion to a more specific, smaller range of masses meanwhile adjusting the limit of $g_{a\gamma}$. From the suggested initial mass for axion is smaller or around 0.02 eV and $g_{a\gamma}$ up to 8.8×10^{-11} GeV^{-1} to $g_{a\gamma}$ larger or around 4×10^{-13} GeV^{-1} within the masses from 34.6771 to 34.6738 μeV and suggested axion-photon coupling constant (gaγ) is $< 0.66\times10^{-10}$ GeV^{-1} with axion mass lower than 0.02 eV in 2017. Recently, published by CAST in 2021, Detector RADES rose the sensitivity to axion mass to 34.67 μeV and again it helped to limit the axion model [14, 17].

4. Searching Paradigm ABRA-10 CM

4.1. Principle

A Broadband/Resonant Approach to Cosmic Axion Detection with an Amplifying B-field Ring Apparatus, known as the ABRA experiment, is a prototype of directly QCD axion detector with a diameter around 10 cm and is design to test for ultralight axion model [19]. Due to the interaction between axion and eletromagnetism, axion is suggested to interact with neutron stars that have a super strong magnetic field, i.e., magetars and convert themselves into photons. Thus, axion will produce a small magnetic field as the presence of axion causes the strong magnetic field of the magnetar to fluctuate slightly. Meanwhile, the oscillation of the effective current that along the magnetic field lines at axion Compton frequency is produced by the interaction between axion and the static magnetic field. Modified Ampere's law by Axion-photon interaction, one derives

$$\nabla \times \boldsymbol{B} = \frac{\partial \boldsymbol{E}}{\partial t} - g_{a\gamma\gamma}\left(\boldsymbol{E} \times \boldsymbol{\nabla} a - \boldsymbol{B}\frac{\partial a}{\partial t}\right) \tag{6}$$

Based on the modified Ampere's law, applying the Axion field in it:

$$a(t) = a_0 \sin(m_a t) = \frac{\sqrt{2\rho_{DM}}}{m_a \sin(m_a t)} \tag{7}$$

And this give out the Axion effective current:

$$\boldsymbol{J_{eff}} = g_{a\gamma\gamma}\sqrt{2\rho_{DM}}\cos(m_a t)\,\boldsymbol{B_0} \tag{8}$$

Here, $g_{a\gamma\gamma} = g\alpha/(2\pi f a)$, α=1/137, ρ_{DM} is the local Dark matter density which is around 0.3 GeV/cm^{-3}.

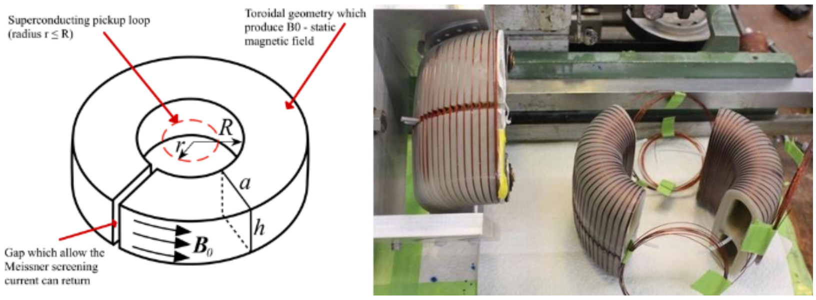

Fig. 2 A sketch of the ABBR.

As shown in the left panel of Fig. 2, Superconducting wire encapsulated the toroidal geometry and the constant current in it will produce the static magnetic field. If axion exists, there will be a oscillating effective current which is parallel to the B0. In addition to converting the axion effective current into real current and readout the data, the pickup loop collects the magnetic flux line and given a real current and the real current is then amplified by SQUID magnetometer.

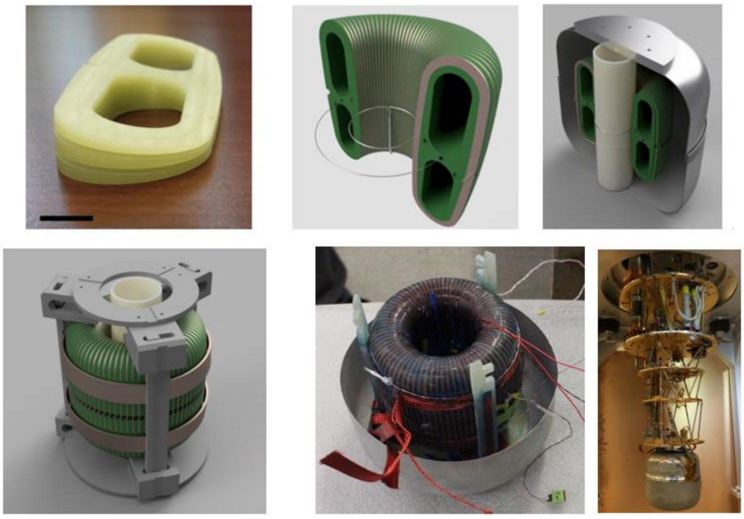

Fig. 3 The skecth of the detectors.

4.2. Detectors

The sketch of the detector is illustrated in Fig. 3. The Toroidal Structure is built by 80 Delrin wedges and its center opened a hole with 1mm diameter in addition to inserting the pickup loop (silver wire with 0.5mm diameter). The green part (Delrin wedges) is the frame with 12 cm height that support 1280 superconducting windings which can produce the strong static magnetic fields (1T). Meanwhile, the white PTFE tube at the center helps to fix the pickup loop. The silver outer shied is the superconducting shield. From the left hand side is the calibration loop, which can detect the effective current oscillation, and it is connected to the pick up loop, which can convert the effective current to real current, and connected by the SQUID sensor to amplify the signal. The structure of the superconducting shield is the refrigerator that cools down the detector to mK which reduces noise.

4.3. Results

Collecting all the data in magnet on and off and the ADC noise help to filter out the background, and when B0 goes to zero, which is the Magnet off, the Axion effective current should be zero as well as they are proportional, thus the spike in orange are all the fake axions signal and both spikes that appear are all fake signals [20, 21]. To convert pickup loop flux power into $g_{a\gamma\gamma}$, an analogy axion signal source (oscillating current) will be run through the ABRA by a wire to observe the response by the detector, thus calibrate the unit. ABRA aim to search for axion mass < 1 μeV and its first result (seen from Fig. 4), the one month observation by ABRA-10CM detect no axion exist in the masses between 0.31neV to 8.3 neV, with the upper litmit of $g_{a\gamma\gamma} < 3.3\times10^{-9}$ GeV^{-1} and $< 1.4\times10^{-10}$ GeV^{-1}.

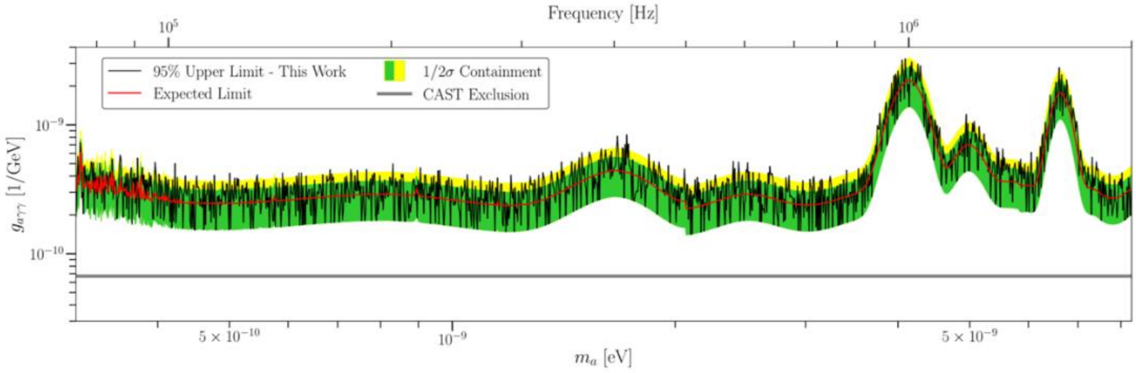

Fig. 4 The limits of $g_{a\gamma\gamma}$ with all the reach data by ABRA with the published data.

5. Comparing CAST and ABRA experiments

5.1. Axion models

CAST aims to detect solar axion and ABRA ideally aims to detect ultralight QCD axion with mass range from 1 μeV to 1 feV. With the latest published research from CAST, it detects for axion mass up to 34.67 μeV and ABRA can detect up to 8.3 neV which is much more sensitive. Meanwhile, the ABRA result is based on their one month data but with the same 95%CL to CAST result, which used data that was collected for a longer period of time. Placing the model of axion in terms of $g_{a\gamma\gamma}$ limit and mass with one month data shows that the ABRA is a very strong detector. Therefore, ABRA is more competitive and sensitive then CAST in searching for light QCD axion.

5.2. Searching theory

The theory that CAST used to detect for solar axion is based on the Primakoff effect, in which the core of the sun produces axion by high energy photons interacting with atom nucleus in a strong electromagnetic field and when solar axion passes through super strong electromagnetic field, they can be converted back to high energy photons. Thus, the produced X-ray can be observed by the X-ray telescope and detected by the X-ray detector. On the other hand, ABRA looks for current that is produced by the oscillated effective current produced by axion interacting with the static magnetic field. This searching paradigm is inspired by a magnetised neutron star that contains a super strong magnetic field. Although the searching theories share the same properties of axion, the interaction is with a strong magnetic field. However due to various observed objects, the detector composition, size and the observation windows are all different.

5.3. Detectors

The size of CAST is huge, as it built with a LHC prototype magnet 9.26 m long. Conversely the size of ABRA is much more smaller, as its diameter is around 10 cm with a 12 cm height. CAST contains a movable platform which allows the horizontal and vertical adjustments of the telescope to track the sun, but it can only track the sun during sunrise and sunset for a total of three hours a day due to the limited movement. Thus, the observation time for CAST is much shorter than ABRA, which does not need to track a specific object and can be turned on all the day for collecting data. Without the movement, the noise produced from it can be reduced, although both of the experiment detectors produce their own noise in their own operation which can affect the data. ABRA records data with magnet turnoff and CAST uses the rest 21 hours to record the backgrounds, thus most of the background noise can be removed in the present data. Overall it shows ABRA-10CM is an ideal model for detecting light axion as it contains high sensitivity compared to the CAST; lighter mass range, less room required and less energy needed and each runs for longer. CAST is more suitable for searching heavier axion or axion-like particles as its mass range is larger than ABRA. The lighter the axion, the longer its wavelength, so the size of the detector depends on the sensitivity of the mass range. Therefore, a bigger ABRA can even have higher sensitivity which may detect even lighter axion.

6. Limitations and future outlook for axion detection

The mass and the axion-photon coupling constant have been modified many times since different experiments searching for a range of axion mass, whether in high energy sources such as sunlight or low energy sources such as our surroundings, heavy or light, strong or weak axion. However, no result shows that axion exist in that range, the limit of the model is getting smaller and smaller. It might be the 9T electromagnetic field produced by the CAST magnet is not large enough to convert solar axion into X-ray, or the X-ray detector is not sensitive enough, or the surrounding temperature is not close enough to absolute zero. Although the sensitivity that CAST contains to axion-photon coupling constant is six times more accurate then the previous axion heliscope and pass $g_{a\gamma}$ limit reached the axion model band, however the result of no axion existing could be due to the sensitivity limitations of above factors.

For ABRA, the sensitivity of the detector with 10 CM diameter is, which placed the new limit of Axion mass and $g_{a\gamma\gamma}$. However, based on the ABRA result and the new limit, axion might be even lighter and weaker then the axion model predicted. The ABRA-10 CM sensitivity is limited by the strength of the static magnetic field, the readout sensor, the background such as radio wave and different radiation. Enhancing the field strength is not enough, due to the effective current needed to be picked up and amplified, the superconducting pickup loop and SQUID sensor are also the important part of the experiment and their sensitivity is the potential limitation to the result.

Regarding all the limitation factors towards the sensitivity and the results for the two experiments above, new generations of the detector have been suggested and are going to be built. They are based on the previous searching theory and detector model but the improvements of different components in the detector will be made to aim for a higher sensitivity. For instance, the International Axion Observatory, i.e., IAXO experiments [22]. The order of magnitude compare to CAST, will be around 4 to 5 times larger, which mean it more sensitive and it aims to detect for $g_{a\gamma}$ in 10^{-12} GeV^{-1} level apply for axion masses below 0.25eV. With the structure that Figure 16 suggested, the telescope will be able to keep a track on the sun for 12 hours per day, given larger observation windows allow more data to be collected. Looking in the range that have not be searched for, store the potential to discover heavy axion. Before DMRadio-M3 construct, DMRadio-50L will act as a prototype although it may not detect any axion signal based on the predicted axion band (yellow-red band), it helps to limit it to give a more specific data for the axion mass. For DMRadio-m3, the geometric of the magnet change from toroid to a solenoid design with a static magnetic field bigger than 4T in addition to detect for higher frequency axion model and mass below 1μeV. Ideally search between the mass range from 20 nano eV to 800 nano eV with frequency between 5Mhz to 200MHz [23].

7. Conclusion

In summary, this paper discusses the state-of-art paradigms and development processing of the axion detectors. Looking through different Axion detection methods, including various Axion models such as QCD and Solar axion, the limit of $g_{a\gamma\gamma}$, $g_{a\gamma}$ and axion masses keep be introduced with the experiments results. The initial Axion model predicts the particle mass is between $1\mu\text{eV}/c^2$ to $1\ \text{meV}/c^2$, however with CAST data, the mass of axion is searching up to 0.02eV with $g_{a\gamma}$ limit (8.8×10^{-11} GeV^{-1}) and 34.67 μeV with $g_{a\gamma}$ up to 4×10^{-13} GeV^{-1} placed the new limit for the interaction between axion and photon. For ABRA data, no axion signal is detected between 0.31 neV to 8.3 neV with the upper limit of $g_{a\gamma\gamma} <3.3\times10^{-9}$ GeV^{-1} and $< 1.4\times10^{-10}$ GeV^{-1}. The sensitivity of the detector which directly affects the result, is limited by the difference in ideal theory data and real-world data with various factors, interruptions such as the field strength or just the little low frequency vibration that is caused by the detector itself. However, with data that is collected, there are always improvements that can be applied to the detectors, scale it, consider various geometry. These results aim to compare the axion detection methods in different searches for various axion models in addition to offering a better understanding for the latest research and detector models.

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