The Proposed Analytical Model and Detection Scenarios for Axion and Wimps

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Abstract. Contemporarily, the detection of dark matter is still an unsolved issue for modern physics. Among all the candidates of the dark matter models, the axion and Weakly interacting massive particles (WIMPs) are the most two appealing cases for realizing detection. On this basis, this paper investigates the analytical model construction of the axion and WIMPs based on the concepts of standard model. Subsequently, the detection mechanisms as well as the state-of-art facilities are demonstrated, respectively. Eventually, guideline for future detection and improvement scheme are proposed in order to find the dark matter mass region. Overall, these results shed light on future dark matter detection and model construction.

Keywords: Dark matter, axion and WIMPs, state-of-art detection facilities.

1. Introduction

Generally, dark matter serves as an import role in acknowledging the modern astrophysics and cosmology, which is an invisible (opacity) substance that theoretically exists in the universe [1, 2]. According to experiment observation as well as analytical model, it might be one of the major components of the matter in the universe, which can be used to explain numerous astronomical observations (e.g., Suspected Newtonian gravity violations). Contemporarily, a large amount of evidence indirectly verifies the presence of dark matter, e.g., gravitational lensing effect, microwave background radiation etc. [3-6]. Based on the so-called Standard Cosmological model (ΛCDM) combining with microwave background anisotropy observations, it can be concluded that dark matter accounts for 85% of the total mass [7-9].

In retrospect, the lasting debates of the reality of dark matter originated from the end of the 19th century, where the stars are observed unevenly distributed in the universe [10]. Subsequently, plenty of dynamic estimation were presented to illuminate the dark matter in Milky way [11-13]. The first attempt of the concept of dark matter can be attributed to Jacobus Kaptey, who indicated the existence of invisible matter among celestial bodies. Additionally, Friederich Bessel wrote in his paper that the appropriate motion of the starts Sirius and Procyon possibly will merely be clarified by the existence of some undetected matter that affects the stars gravitationally in 1844. He is possibly the first who predicted the presence of something like dark matter by inferring from its gravitational impacts.

The investigation of dark matter revolved at first around proving the existence of it. In 1933, Swiss-American astronomer Fritz Zwicky used the virial theorem to calculate the mass of a galaxy cluster. According to his analysis, Zwicky concluded that if his calculations were to be confirmed, dark matter would exist in a much larger amount than visible matter. As more and more evidence suggesting the presence of dark matter appeared, many scholars had turned their way toward figuring out the inherit of dark matter [14]. Afterward, plenty of scholars have developed the models as well as proposed detection approaches [1-3, 15-18]. Among the numerous candidates of dark matter, axion and WIMPs are the two major types that have been explored deeply. To be specific, Axion is a very light neutral particle with a mass on the order of 1μeV [19, 20] while WIMPs correspond to the stable particle whose mass and interaction strength are near the electroweak scale [21-23]. Dark matter doesn't interact with electromagnetic wave (or light), meaning that they neither absorb the light nor reflect it, which is exactly the reason that we can't detect it even with the modern advancements in technologies. Investigating the inherit of the dark matter paves a path to better understand the component of universe. Perhaps at an indeterminate time in the future, human being might be able to properly utilize this kind of matter.

In this paper, we will focus on the two well-known types of dark matter (axion and WIMPs) and demonstrate the model descriptions as well as the state-of-art detection scenarios. The rest of the paper is organized as follow. The Sec. 2 will introduce the theoretical model of axion, searching plans and the corresponding recent experiment progress. The Sec. 3 will present the analysis for WIMPs as well as the detection evolution. Eventually, a brief summary is given in Sec. 4.

2. Axion

Axion is subatomic particles that exist in nature and predict "existence" in particle physics, astrophysics and condensed matter physics. The energy spectra of the axion particles in nature are spatial dimension linear particle equation of one dimension movement quality. It can be any particle generated by collision of super symmetric particles and election-positron pairs. Besides, another perspective treats the axion as the boson level "diffraction+radiation" energy loss escaping the polarization of new particle repulsive particle.

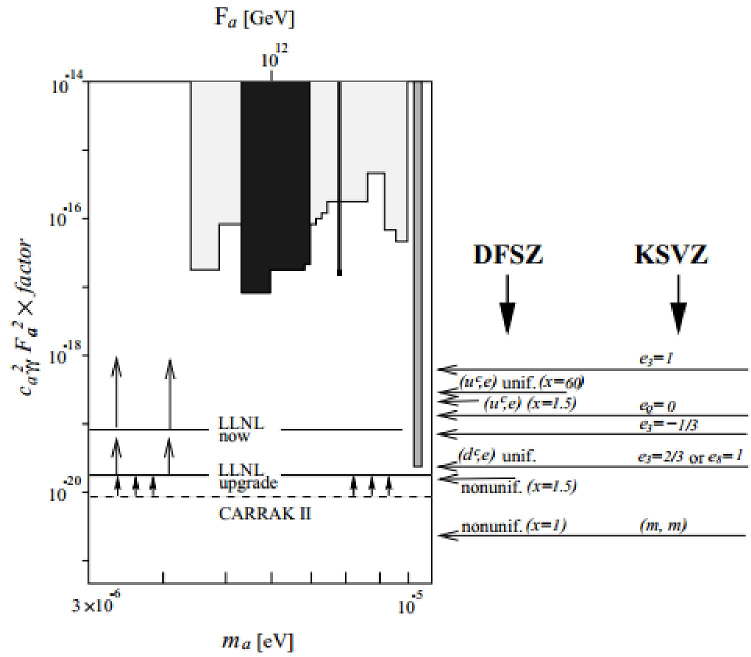

Figure 1. A sketch of axion detection [27]

2.1. Analytical model of Axion

As a matter of fact, the descriptions of axion are strongly related to the Quantum Chromodynamics (QCD), which is still unclear in terms of nonperturbative effects. Based on the non-Abelian gauge theories, the θ-terms must include in QCD which can be described as [19, 20, 24]:

$$L_\theta = \frac{\theta}{16\pi^2} Tr F_{\mu v} F^{\mu v} \tag{1}$$

According to Eq. (1), it violates the CP invariance and restricts the vacuum angle (e.g., $|\theta<10^{-9}|$ [24]), which is also known as Strong CP problem. Among all the solutions, the so-called axion solution is the most appealing one, which is a dynamic process according to Ref. [25, 26]. Based on previous analysis, there is a strong restriction in mass parameter F_a of axion. From approximation and the boundary in terms of astrophysics and cosmology, the 10^9 GeV<F_a<10^{12} GeV [24].

Typically, there are various reaction channels to generate axions, see, e.g., $\gamma + e$ (or Z) $\rightarrow a + e$ (or Z), $n + n \rightarrow n + n + a$, $\gamma + e \rightarrow a + e$, $e^+ + e^- \rightarrow a + \gamma$, etc. In fact, the field envelope of the axion can be described as nonrelativistic particles with the energy contribution [24]:

$$\Omega_a h^2 \sim 0.13 \times 10^{\pm 0.4} \Lambda_{200}^{-0.7} f(\theta_1) \left(\frac{10^{-5} eV}{m_a}\right)^{1.8} N_{DW}^2 \tag{2}$$

Where θ_1 is the θ value at the cosmic temperature T_1. Based on such approach, the axion detection can be carried out in terms of the coupling between axion–electromagnetic as illustrated in Fig. 1.

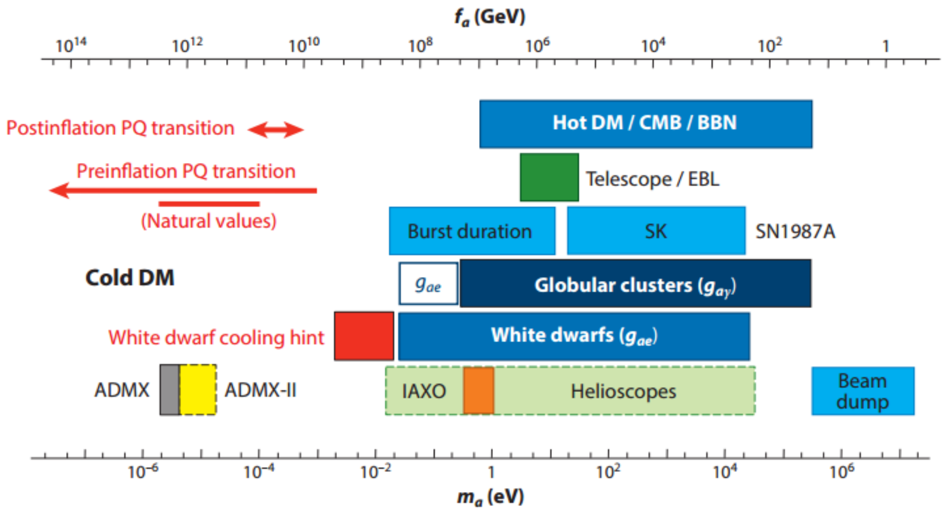

Figure 2. The state-of-art searching limitations on the axion mass [28]

2.2. Detection of Axion

Different from the searching of preliminary particles predicted by standard model, the scanning energy has no boundaries that causes plenty of difficulties. In spite of all the hardships, scholars have shortened the energy spectrum of possible axion to a much smaller range as shown in Fig. 2.

Axion Dark Matter Experiment is used in determined the cavity of microwave within a large super-conducting magnet to figure out the cold dark matter axions. It is closely connected to the researchers from all over the world. Nowadays, the ADMX has searched for dark matter axion by a high-Q mirowave cavity and printed out by their resonant conversions. So far, the obtaining data is range ~1GHz or few micro-eV. With the new technology in Yale University, one is able to start the second stages, i.e., looking for the data around ~10GHz. Fig. 3 illustrate the sensitivity of the two approaches of CASPEr.

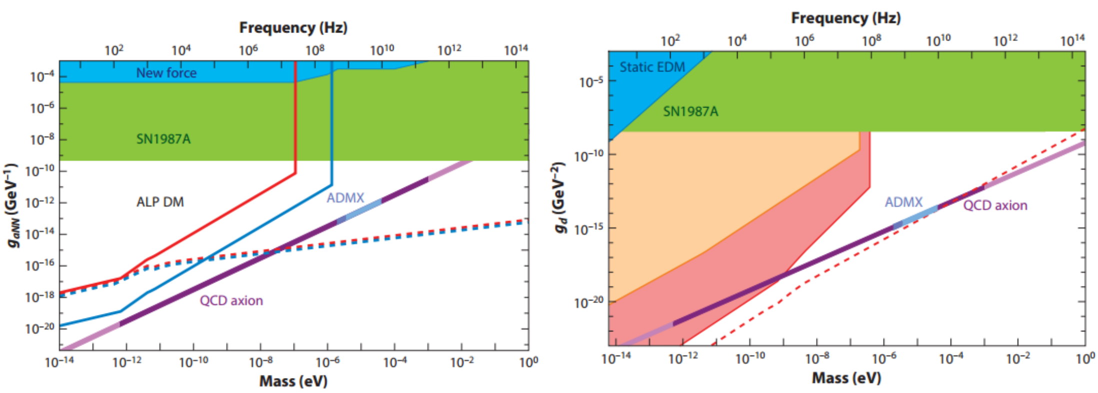

Figure 3. The sensitivity of the two approaches of CASPEr (the left panel for wind proposal while right panel for electric proposal) [29, 30]

3. WIMPS

3.1. Basic Descriptions

WIMPs are theoretical particles that are one of the recommended entrants for dark matter [21-23]. Generally, the clear definition of a WIMP is non-existent. However broadly, a WIMP is a new fundamental particle that interacts through gravity and any other forces potentially not included in the Standard Model itself.

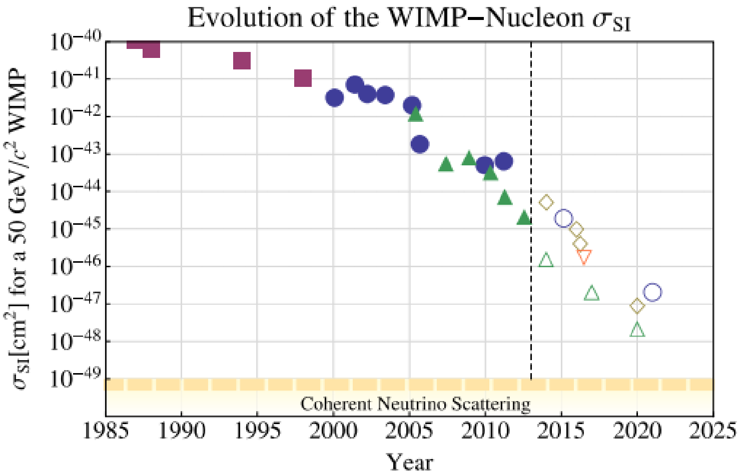

Figure 4. The limit of WIMP detection has been narrowed down greatly, which is predicted to become more smaller [31]

Nevertheless, latest null results from direct-detection experiments with the failure to generate evidence of supersymmetry in the Large Hadron Collider (LHC) experiment has cast doubt on the simplest WIMP hypothesis. So far, the limit of WIMP detection has been narrowed down greatly, which is predicted to become more smaller in the future as depicted in Fig. 4.

Indirect detection attempts concentrate on locations where WIMP dark matter is supposed to accumulate the most. Another type of indirect WIMP signal is likely to originate from the Sun. A technique involving Cryogenic Dark Matter Search detector at the Soudan Mine depends on multiple very cold germanium and silicon crystals. A typical sketch of the facility is exhibited in Fig. 5.

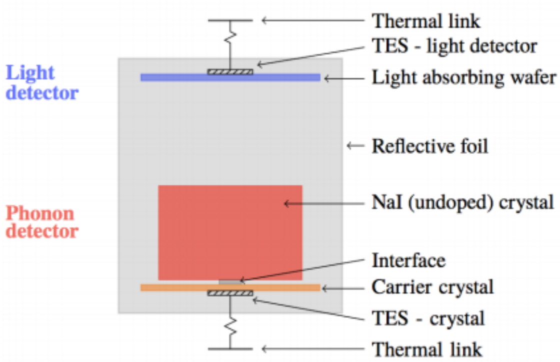

Figure 5. The Sketch of Cryogenic crystal detector [31]

PICASSO demonstrates results (November 2009) for spin-dependent WIMP interactions on 19F, for masses of 24 GeV new stringent limits have been acquired on the spin-dependent cross section of 13.9 pb (90% CL). The resultant limits impede recent interpretations of the DAMA/LIBRA annual modulation effect in terms of spin dependent interactions. PICO is an expansion of the concept planned in 2015.

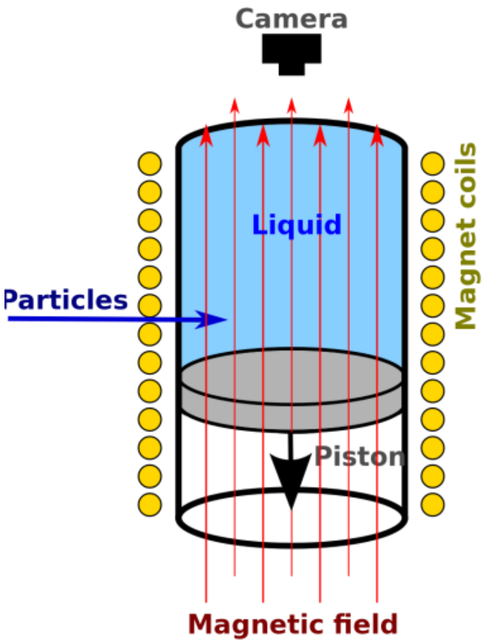

Figure 6. It is normally made by filling a large cylinder with a liquid heated to just below its boiling point [32]

4. Conclusion

In summary, this paper summarizes the recent progress for the axion and WIMPs dark matter searching. Specifically, the analytical models of the two types of dark matter are introduced and derived, respectively. In addition, the current state-of-art detection facilities, observation results and future detection plans are demonstrated accordingly. In the future, higher resolution and larger parameter ranges are required for the detector in order to search wide energy range. Overall, these results offer a guideline for future detection dark matter detection.

References

[1] Petraki K, Volkas R R. Review of asymmetric dark matter [J]. International Journal of Modern Physics A, 2013, 28(19): 1330028.

[2] Arun K, Gudennavar S B, Sivaram C. Dark matter, dark energy, and alternate models: A review [J]. Advances in Space Research, 2017, 60(1): 166-186.

[3] Zaldarriaga M, Seljak U. Gravitational lensing effect on cosmic microwave background polarization [J]. Physical Review D, 1998, 58(2): 023003.

[4] Wambsganss J. Gravitational lensing in astronomy [J]. Living Reviews in Relativity, 1998, 1(1): 1-74.

[5] de Bernardis P, Ade P A R, Bock J J, et al. A flat Universe from high-resolution maps of the cosmic microwave background radiation [J]. Nature, 2000, 404(6781): 955-959.

[6] Schlegel D J, Finkbeiner D P, Davis M. Maps of dust infrared emission for use in estimation of reddening and cosmic microwave background radiation foregrounds [J]. The Astrophysical Journal, 1998, 500(2): 525.

[7] Bertone G, Hooper D. History of dark matter [J]. Reviews of Modern Physics, 2018, 90(4): 045002.

[8] Van den Bergh S. The early history of dark matter [J]. Publications of the Astronomical Society of the Pacific, 1999, 111(760): 657-660.

[9] Springel V, Hernquist L. The history of star formation in a Λ cold dark matter universe [J]. Monthly Notices of the Royal Astronomical Society, 2003, 339(2): 312-334.

[10] British Astronomical Association. Journal of the British Astronomical Association [M]. British Astronomical Association, 1895.

[11] Kelvin L W T. Baltimore lectures on molecular dynamics and the wave theory of light [M]. CUP Archive, 1904.
[12] Poincaré H. The milky way and the theory of gases [J]. Popular Astronomy, 1906, 14: 475-488.
[13] Poincaré H. Sur la dynamique de l'électron [M]. Circolo Matematico di Palermo, 1906.
[14] Kapteyn J C. No. 230. First attempt at a theory of the arrangement and motion of the sideral system [J]. Contributions from the Mount Wilson Observatory/Carnegie Institution of Washington, 1922, 230: 1-27.
[15] Oort J H. The force exerted by the stellar system in the direction perpendicular to the galactic plane and some related problems [J]. Bulletin of the Astronomical Institutes of the Netherlands, 1932, 6: 249.
[16] Zwicky F. Die rotverschiebung von extragalaktischen nebeln [J]. Helvetica physica acta, 1933, 6: 110-127.
[17] Kahn F D, Woltjer L. Intergalactic Matter and the Galaxy [J]. The Astrophysical Journal, 1959, 130: 705.
[18] Roberts M S, Rots A H. Comparison of rotation curves of different galaxy types [J]. Astronomy and Astrophysics, 1973, 26: 483-485.
[19] Pajer E, Peloso M. A review of Axion Inflation in the era of Planck [J]. Classical and Quantum Gravity, 2013, 30(21): 214002.
[20] Graham P W, Irastorza I G, Lamoreaux S K, et al. Experimental searches for the axion and axion-like particles [J]. Annual Review of Nuclear and Particle Science, 2015, 65: 485-514.
[21] Chang S, Edezhath R, Hutchinson J, et al. Effective WIMPs [J]. Physical Review D, 2014, 89(1): 015011.
[22] Armengaud E, Augier C, Benoit A, et al. Search for low-mass WIMPs with EDELWEISS-II heat-and-ionization detectors [J]. Physical Review D, 2012, 86(5): 051701.
[23] Arcadi G, Dutra M, Ghosh P, et al. The waning of the WIMP? A review of models, searches, and constraints [J]. The European Physical Journal C, 2018, 78(3): 1-57.
[24] Kim J E. A theoretical review of axion [J]. Cosmo-99, 2000: 43-53.
[25] Peccei R D, Quinn H R. CP Conservation in the Presence of Instantons [J]. Phys. Rev. Lett, 1977, 38(1440-1443): 328.
[26] Vafa C, Witten E. Parity conservation in quantum chromodynamics [J]. Physical Review Letters, 1984, 53(6): 535.
[27] Kim J E. Constraints on very light axions from cavity experiments [J]. Physical Review D, 1998, 58(5): 055006.
[28] Olive K A, Agashe K, Amsler C, et al. Review of particle physics [J]. Chinese physics C, 2014, 38(9): 090001.
[29] Graham P W, Rajendran S. New observables for direct detection of axion dark matter [J]. Physical Review D, 2013, 88(3): 035023.
[30] Budker D, Graham P W, Ledbetter M, et al. Proposal for a cosmic axion spin precession experiment (CASPEr) [J]. Physical Review X, 2014, 4(2): 021030.
[31] Cushman P, Galbiati C, McKinsey D N, et al. Working group report: WIMP dark matter direct detection [R]. Fermi National Accelerator Lab. (FNAL), Batavia, IL (United States), 2013.
[32] Angloher G, Carniti P, Cassina L, et al. Results from the first cryogenic NaI detector for the COSINUS project [J]. Journal of Instrumentation, 2017, 12(11): P11007.