Demonstration of Models and Detection Scenarios for WIMP And Axion

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Abstract. The dark matter physics is a significant part of high energy physics. The model of the dark matter candidate was proposed in last century. In this paper, the analytical models and detection approaches for the WIMPs and axion will be discussed. As one of the candidates, weakly interacting massive particle was proposed to be a good candidate in the past few decades and its model was well established. Many miracles and coincidence of the WIMP properties make it become the most popular candidate for researchers and a lot of detection method was conducted. Direct detection of WIMP is the corner stone of dark matter detection. However, there is no notable progress for WIMP detection until now and the wave dark matter has become popular for researchers. The axion (one of the candidates of dark matter) can resolve the small-scale problem caused by particle dark matter profile. Besides, wave nature of the axion allows researchers to use the pulsar signal to detect them. This paper will give a picture of WIMPs and axion model and detection, inspiring researchers to improve the detection method. These results shed light on guiding further exploration of dark matter searching.

Keywords: Dark matter candidates; WIMP; axion; direction detection; pulsar timing array.

1. Introduction

Dark Matter (DM) has been a focal point of research for over a century. Although scholars have not detected the DM particles, there is still plenty of evidence for DM. The first research about the existence of the dark matter was done by Oort and Zwicky. Oort and Zwicky successively discovered that luminous mass of the galax is smaller than the dynamic mass of it, and Zwicky attribute this difference in mass to Dunkle Materie (dark matter in German). In the 1960s, Vera Rubin observed that the rotation velocity of the galax did not follow the Kepler's law. The rotation velocity nearly remains constant even in the region far from the luminous area in the galaxy. This evidence shows that there must be plenty of DM pulling the galaxy to let it keep the rotation velocity. For the inconsistency between the observation and theoretical prediction of the galaxy rotation curve, invisible matter must exist in the outskirt of the galaxy [1]. The exploration of the dark matter will lead to the extension of the Standard Model and judge the correctness of the supersymmetry theory.

For the candidates of dark matter, researchers first focused on the neutrinos which are included by the standard model. They are stable and do not engage in strong or electromagnetic interaction, making them viable dark matter candidate [2]. Though standard model neutrinos are proved to be unable to account for the universe large scale structure, they inspired researchers to establish the WIMP (weakly interacting massive particle) model, which is also a main topic of this paper. WIMP is popular because it coincides with the particle that the supersymmetry predicted. Although WIMPs have amounts of miracles that fits the theoretical result. For example, the dark matter self-annihilate cross section is very similar as the weak interaction cross section, but they haven't been detected by LHC. Other researchers focus on ultralight wave dark matter (e.g., axion). Axions are first hypothesis in order to solve the strong CP problem, i.e., there is no theoretical evidence that the CP symmetry should conserve in the strong interaction, which was observed in the experiment. The wave nature of axion dark matter can solve the small-scale problem in particle dark matter model.

This paper will focus on the WIMPs and axion dark matter in order to give a general picture of dark matter candidate and detection, giving raise to the improvement of the theoretical model and experiment method in order to detect the dark matter. The rest part of the paper is organized as follows.

The Sec. 2 will introduce WIMPs dark matter. The Sec. 3 will describe axion dark matter which has the different properties with WIMP. Afterwards, the limitations of current dark matter models and searching scenarios are discussed and prospect are proposed accordingly. Eventually, a brief summary will be given in Sec. 5.

2. WIMP Dark Matter

2.1. Overview of dark matter candidates

A good dark matter candidate is required to be non-relativistic and weakly interacting. The relative matter may escape from the galaxy and it's not fit the observation. The current catalog for dark matter is based on the dark matter mass. Firstly, the primordial black holes are super heavy dark matter candidate. The mass of them is constrained in the range of $10^{-17}eV \sim 50M_{Sun}$ because of the evaporation caused by the Hawking radiation and CMB observation [3]. The next one is WIMP, they have to have the mass over keV which is so called the WDM limit. The fermion dark matter is constrained by the Pauli exclusion principle and by our observation of the galaxy as well as large scale structure, the mass of fermion dark matter candidate must be greater O(keV) [4]. Beyond this, wave dark matter has the ultralight mass and induces some different wave like properties. Then, this paper will discuss the latter two candidates as shown in Fig. 1.

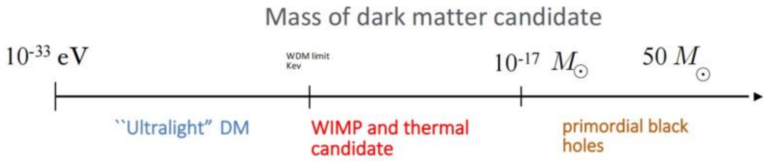

Fig. 1 Mass range of the dark matter candidates. (data from calculation in this paper)

2.2. WIMP dark matter and direct detection

WIMP is one of the thermal dark matter candidates which are in the thermal equilibrium with the standard model thermal bath. It implies there may exists some interaction between the DM particles and standard model particles. For the density to match the calculated thermal relic abundance, the dark matter particle must contain self-annihilating term in the Langrangian and the cross section is $2 \cdot 10^{-26}cm^{-3}/s$. While this number is miraculously similar to the weak interaction cross section. That means that a weak interaction particle interacts with force carrier and annihilates, it would freeze-out with a similar relic abundance with the dark matter. This result is consistent with the model in the scale of the electroweak and put the WIMP to be a promising dark matter [5]. There is a lot of experiment to detect it and this paper will introduce one of them. The direct detection is an important way to search for the WIMP dark matter. The dark matter is move through the milky way and the velocity and velocity dispersion is to the order of 10^{-3}. The direct means that a target particle is set to directly scattered by the dark matter. For the reason that in our solar system the Earth moves around the Sun through the dark matter particles populating the entire galaxy, the annual modulation of the scattering signal is the goal of the detection.

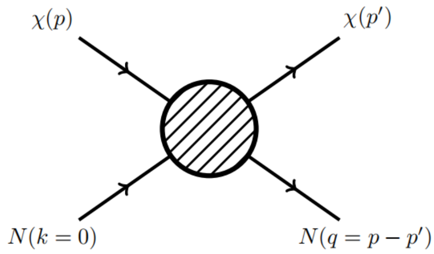

Fig. 2 A DM particle scatters into a nucleon.

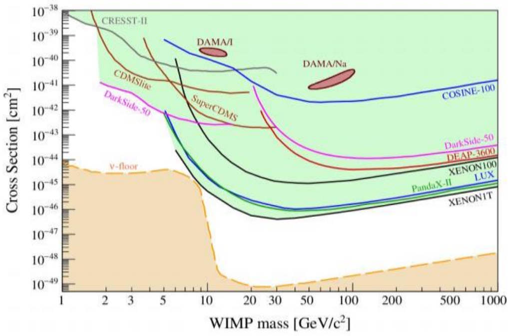

Fig. 3 A Landscape of current constraints on WIMP mass.

The recoil energy of the target particle (for example the nucleus) is required to be maximum because in this case the detector can receive stronger signal which increases the possibility to detect the dark matter as shown in Fig. 2. The recoil energy is written as

$$E_R = \frac{2\mu_{\chi N}^2 v^2}{m_N} \tag{1}$$

where $\mu_{\chi N}$ is the reduced matter of the nucleus N and the dark matter χ. The maximum condition is $m_\chi = m_N$ which constrain the mass range of the direct detection. The mass of the dark matter candidate has to be comparable to the target nucleon in order to make sure the signal intensity highest.

However, scholars haven't got any evidence of the existence of WIMP dark matter from direct detection. Direct detection deal with Sub-GeV scale where the target nucleon is laying, so how to separate the detection signals from the radioactive back ground is the biggest barrier [6]. The final result is illustrated in Fig.3. The shaded area is excluded and the blank part is the parameter space left for us. While there is a contradictory experiment, the DAMA experiment showed different result from others. But the DAMA group have never published their experiment method and nothing related to DAMA can be repeated so for now there is still no convinced direct detection experiment result shown the existence of WIMP [7].

3. Axion

3.1. Axion dark matter

3.1.1 Basic properties of Axion dark matter

The axions are spin 0 particle and it have no charge. They are mostly at a velocity of 10^{-3} which is the speed of the matter in galaxy. The wave nature of the axion dark matter is obvious under the circumstance that the mass range of the axion is approximately 10^{-23}eV~10^{-22}eV [8]. The momentum of the axion is easy to obtain $p = mv$. To show the wave nature of the axion dark matter, the de Broglie wavelength is necessary, which can be written as:

$$\lambda_{dB} = \frac{2\pi}{mv} \approx 4000pc \left(\frac{10^{-23}eV}{m}\right)\left(\frac{10^{-3}}{v}\right) \tag{2}$$

In order to make the thing easier to understand, the occupation number is calculated by

$$n\lambda_{dB}^3 \approx 10^{96} \left(\frac{\rho_{axion}}{0.3GeV/cm^3}\right)\left(\frac{10^{-23}eV}{m}\right) \tag{3}$$

As the result showed, the occupation is so big that the classical field theory is valid. In this case, a set of axion particles can be described as plane waves which stand for the change of axion field. In electromagnetism, a number of photons can be described as the change of electromagnetic field. Besides, such ultralight particle can't be fermion because of the Pauli exclusion principle. Axions are be postulate as spin 0 particles which can be describe by Klein-Gordon equation. As the paper discussed before, a capable cold dark matter candidate is necessary to be non-relativistic so the Klein-

Gordon equation will degenerate to Schrodinger equation. The axion is need to be an ultralight boson so it's normal to think of Goldstone bosons. However, let's first focus on the Lagrangian density [9]:

$$\mathcal{L} = -\frac{1}{2}\left(\partial_\mu \phi^*\right)\partial^\mu \phi - V(\phi) \tag{4}$$

and the equation of motion is written as

$$\ddot{\phi} + 3H\dot{\phi} + \partial_\phi V = 0 \tag{5}$$

This is like the form of damped oscillator; the Hubble constant play a role of friction called Hubble friction. The axion mass has a constrain that the it can't below the value of 10^{-33}eV, otherwise it will be a kind of dark energy rather than dark matter. Start from the property of dark energy. By the Quintessence model, the state parameter is written as

$$\omega = \frac{p}{\rho} = \frac{\frac{1}{2}\dot{\phi}^2 - V(\phi)}{\frac{1}{2}\dot{\phi}^2 + V(\phi)} \tag{6}$$

When $\omega < -1/3$, the axions would have the repulse effect, which means they are a kind of dark energy rather than dark matter. When looking at the extreme situation that the $\omega = -1$, the kinetic energy $\dot{\phi}^2/2$ of the axion is equal to zero. To make it approach to 0, the equation of motion inspires us to consider the overdamp condition. The damped ratio is $\xi = 3H/2m$ and when it greater than 1, the "axion field oscillator" would be overdamped and the state parameter is approaching to -1. Therefore, the mass of the axion must greater than Hubble constant in order to make sure it's dark matter. The Hubble constant today is 10^{-33}eV and that is the story of the mass constrain. Moreover, the result gives us better understanding of the axion field. In the very beginning of universe, the Hubble constant is rather big. The Hubble friction would make the axion field rolling very slow, actually, it stuck at a value called misalignment angle. As the universe evolution, the Hubble constant get small, the axion field start to oscillate. The axions which can be seen as a set of particles red shifting are losing energy to the Hubble friction so the axion can't be relativistic. The interaction intensity of the axions which is rather weak can be inferred from the Lagrangian. These two properties make the axions to be a good candidate of dark matter [10].

3.1.2 The wave dynamics of axion.

In order to discuss the possibility of the axion field to have spatial fluctuation, this study constructs a complex scalar ψ

$$\phi = \frac{1}{\sqrt{2m}}\left(\psi e^{-imt} + \psi^* e^{imt}\right) \tag{7}$$

The Schrodinger equation is valid for axions by the classical field theory

$$i\partial_t \psi = -\frac{\nabla^2}{2m}\psi + V\psi \tag{8}$$

It is assumed that there is only gravitational potential here it can be described by the Poisson function

$$\nabla^2\Phi = 4\pi G\rho, \rho = m|\psi|^2 \tag{9}$$

In the CDM model, the dark matter are regarded as the collision less fluid. According to the fluid dynamics, the wave function $\psi = \sqrt{\rho/m} e^{i\theta}$. And the velocity of the fluid is obtained

$$\vec{v} = \frac{\nabla\theta}{m} = \frac{i}{2m|\psi|^2}(\psi\nabla\psi^* - \psi^*\nabla\psi) \tag{10}$$

Solving the Schrodinger equation, one derives:

$$\partial_t \vec{v} + (\vec{v}\,\nabla)\vec{v} = -\nabla\Phi + \frac{1}{2m^2}\nabla\left(\frac{\nabla^2\sqrt{\rho}}{\sqrt{\rho}}\right) \tag{11}$$

The U(1) symmetry would lead to a mass conservation. The last term of the equation gives us a pressure term so called quantum pressure. If the mass of the dark matter is very big, this term approach to 0 and it's what the particle dark matter behaves [11]. However, the opposite situation is interesting. The wave dark matter has the quantum pressure that can solve the small-scale problems caused by traditional dark matter model such as “too big to fail" problem which is arise from particle dark matter model. Particle dark matter model predict the Galactic halos will have higher central densities than estimate from the satellites of galaxy. By adding the quantum pressure term to dark matter simulations, there won't be divergence of dark matter density in the center of galaxy.

2.2.3 Use pulsar timing array to detect the axion dark matter

As the paper has already displayed a lot advantage for axion as dark matter candidate. A way to detect the axion dark matter is to be introduced. Actually, there are many ways to detect the axion dark matter. This paper will only focus on one of them, which is using the pulsar timing array to detect the axion dark matter. PTA is known as a way to detect the gravitational waves; the gravitational oscillation will slightly change the distance between the pulsar and earth. This will lead to a time residual which can be measured by us. The motivation is that the axion field would also cause a gravitational oscillation similar to gravitational wave [12]. If one can detect the feature time residual for axion field, the axion is proved to be existed. Let’s begin with the energy momentum tensor of the axion field. Axion field a scalar field:

$$T_{\mu\nu} = \partial_\mu \phi \, \partial_\nu \phi - \frac{1}{2} g_{\mu\nu}((\partial\phi)^2 + m^2\phi^2) \tag{12}$$

The pressure is given by the special part of the tensor which is

$$T_{ij} = -\frac{1}{2} m^2 A^2 cos(2mt + 2\alpha)\delta_{ij} \tag{13}$$

Here, $i, j = 1,2,3$. The Einstein field equation induced that the diagonal terms of the energy momentum tensor will lead to a gravitational potential oscillation. The ij component of Einstein field equation is written as

$$\ddot{\Psi} = -\frac{4}{3}\pi G T_{kk} \tag{14}$$

The Ψ is the gravitational potential which may cause the arrival time of pulsar signal to vary by nanoseconds:

$$\Psi = \Psi_0(x) + \frac{G\pi A^2}{2} cos\big(2mt + 2\alpha(x)\big) \tag{15}$$

The first term would be cancelled when calculating the time residual:

$$R = \int_0^t \frac{T_{obs} - T_0}{T_0} dt \tag{16}$$

The integral part is not easy to obtain direction, but it can be calculated by the frequency. The relationship is given by $\frac{T_{obs}-T_0}{T_0} \approx -\frac{\Omega_{obs}-\Omega_0}{\Omega_0}$ when the $\Omega_0 \gg \Omega_{obs} - \Omega_0$. Ω_0 is the frequency of signal emitted at the pulsar, and Ω_{obs} is the frequency measured by the observers:

$$\frac{\Omega_{obs} - \Omega_0}{\Omega_0} = \Psi(0, t') - \Psi(x, t) + 2\int_{t'}^{t} n(\nabla\Psi) dt \tag{17}$$

and the time residual is

$$R = \frac{\Psi_c}{m} sin\big(m(t - t') + \alpha(0) - \alpha(x)\big) \tag{18}$$

The time residual for axions has special feature. It has nothing to do with the angle. However, the time residual of the gravitational wave is written as

$$R_{GW} = \frac{A}{\omega} sin\left(\frac{\omega D(1 - cos\theta)}{2}\right) sin(2\alpha)(1 + cos\theta) \tag{19}$$

where θ is the angle between the pulsar and gravitational wave and the pulsar pulse. Contemporarily, researchers haven't found any of the axion dark matter through the PTA, but the model gives the theoretical prediction [12, 13]. The results are depicted in Fig. 4.

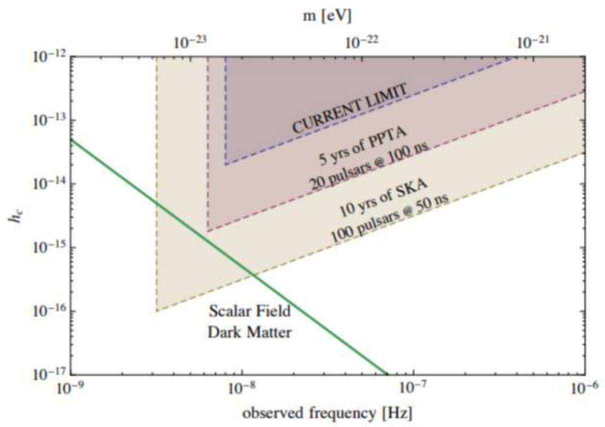

Fig. 4 The current PTA sensitivity (shaded wedges) and the DM signal amplitude (green line) expressed in the parameters for gravitational waves, h and f.

4. Limitations & Prospects

Unfortunately, so far, no dark matter signal was detected by the direct detection or pulsar timing array. In the direct detection, the signal becomes strongest when the dark matter mass is comparable to the nucleon mass. As a result, the mass range of dark matter particles are constrained by nucleon mass. This is possibility that the loss of the signal is caused by the dark matter mass is not fit the mass of nucleon. Alternative methods to directly detect WIMP dark matter is proposed. It is possible that the WIMP dark matter mass is far smaller than the nucleon mass. Therefore, it's reasonable to use the electron recoil. Compared to nucleon recoil, the electron can be accelerated to the velocity that is much faster than dark matter typical velocity. The phonons coupling is also a way to detect the lighter particle dark matter. The momentum transfer for DM-phonon corresponds to the sub-MeV candidates. Besides, phonons have lower excited energy, making more DM deposited on the target, which is easier to detect. Moreover, the photons which can be created by the DM-nucleon interaction is also a way to detect the dark matter [14]. The sun of our solar system emits neutrinos to the space, leading to the neutrino floor in Fig. 3. It's possible that some of the dark matter candidates lay in this parameter space. Researchers may use the probe in the deep space to detect the dark matter candidate.

For the axion, the sensitivity of the pulsar timing array is to be improved. Except for the gravitational potential oscillations, the stellar emission of the axion also may also help researchers detect the axions. Axions can couples to fermions, photons and gluons. Although the interaction strength is weak, in the interior of the star, there would be axion production that can affect the star evolution. This is applicable to Sun and the Supernova 1987 [15], giving another method of detection.

5. Conclusion

In summary, this paper discusses the properties of the WIMPs and axions from the perspective of being good dark matter candidates and the way to detect them. Specifically, the WIMPs have the particle like properties and the axions have the wave like properties. According to the analysis, the heavier particles can use the way of direction to search. Besides, the ultralight particles mass cannot below 10^{-33}eV. In addition, the wave nature of the axion can lead to gravitational oscillation which can be detected by the pulsar timing array. Moreover, the time residual of the axion do not depend on the angle. Nevertheless, there is no signal of dark matter candidate. In the future, the detection device accuracy can be improved. Overall, these results offer a guideline for the future detection of the dark matter.

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