Dark Matter: Astrophysical Evidence and Constraints*

GONG Yan and CHEN Xuelei
National Astronomical Observatories, CAS

1. Introduction

Modern physics and astronomy are now obscured by two "dark clouds," namely, dark matter and dark energy. All the stuff that we are familiar with in our everyday life, such as flowers, rocks, water and air, which are made of molecules or atoms, including electrons and photons, constitutes only 5% of the energy content of the universe. Even the standard model of elementary particles, the most successful ever, is only able to explain such a small fraction of the composition in our universe, leaving the remaining 95% to be perceived solely through gravity. Let us tentatively call them dark energy (about 70%) and dark matter (about 25%), whose nature is actually of complete ignorance.

From a philosophical point of view, dark energy is in fact not "energy" in the ordinary sense, but a special form of matter. It has a peculiar property that can be roughly understood as a universal repulsion, unlike the known matter that is always experiencing gravitational attraction and condensation. Such a fundamental property can be taken as a defining label for dark energy. In the theory of general relativity, the concept of Newton's universal gravitation is replaced with the curvature of the space and time caused by the energy and momentum of matter. Contrary to the ordinary matter, dark energy bends the space and time in the opposite direction, so it seems to possess a kind of negative momentum, leading to an accelerating expansion of the universe. Relatively speaking, dark matter is seemingly much easier to understand, since it gives rise to gravity and attracts each other like the ordinary matter.

Immediately one may think of some lightless stars as the candidates for dark matter, such as brown dwarfs, planets, mini black holes and rubble piles. However, with the help of various astronomical observations, such a possibility has already been excluded. For instance, the standard theory of Big Bang Nucleosynthesis tells us that had a large fraction of dark matter been composed of baryonic matter, the baryon number density in the early universe would have been much higher, resulting in larger rates of nuclear reactions and thus reducing the primordial abundance of deuterium to a level far below the observed value. The observations of primordial abundances of light nuclear elements and cosmic microwave background radiation (CMB) correspond to a fraction of baryonic matter accounting for about 4.7% of the whole energy density in the universe. Therefore, dark matter has to be comprised of some unknown particles, which have no electric charges and cannot emit any light (*i.e.*, electromagnetic waves). That is why such kind of matter is "dark."

So far, we have not yet observed any signals of dark matter in terrestrial laboratories, although many experiments have been carried out to search for them. Hence the main knowledge about dark matter has merely come from the astronomical and cosmological observations. From these observations we can learn something about

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the intrinsic properties of dark matter; Although it is not possible to answer what dark matter is, many possible candidates can be ruled out.

2. Observational Evidence for Dark Matter

Astronomical observations should be given the credit for the discovery of dark matter. Early in the 1930s, Fritz Zwicky, a Swiss astronomer working in the United States, analyzed the observational data of the Coma Cluster of galaxies, which is relatively close to us, and found that the true mass of the Coma Cluster obtained from the peculiar velocities of galaxies (their radial velocities can be determined via the Doppler effects on the spectral lines) should be much larger than the mass inferred from their brightness. In other words, if the mass of any a galaxy in the cluster is attributed solely to the mass of its stars, which are similar to the Sun or other well observed stars, then the derived gravity would be far from enough to bound the galaxy that is flying at an extremely high velocity within the cluster. This indicates that there exists a huge amount of invisible matter, which dominates the mass of the cluster. Zwicky coined this matter as "*dunkle Materie*", which is just "dark matter" in German. Almost at the same time, Dutch astronomer Jan Hendrik Oort investigated the velocities of stars in the galactic plane and discovered that the mass of the Milky Way is larger than the total mass of observed luminous stars.

Later in the 1970s, Vera Rubin and others measured the rotational velocities of stars in some nearby spiral galaxies, including the Milky Way and M31. In the spiral galaxy, the stars and gases are revolving as a whole around the galactic center, the centripetal force for their rotations can be ascribed to the gravity. Thus the measurement of the rotational velocities reveals the distribution of gravity. In this way, we can draw the rotational velocity as a function of the distance to the galactic center in Figure 1. If the mass of the galaxy is mainly contributed by the luminous matter, then at the edge of or in the region beyond the stellar disc the rotational velocity should decrease rapidly as the gravity reduces. However, the observations show that the velocity is not diminishing quickly but even keeps constant, indicating that there exists a spherical or elliptic halo of non-luminous dark matter outside the stellar disc[*2].

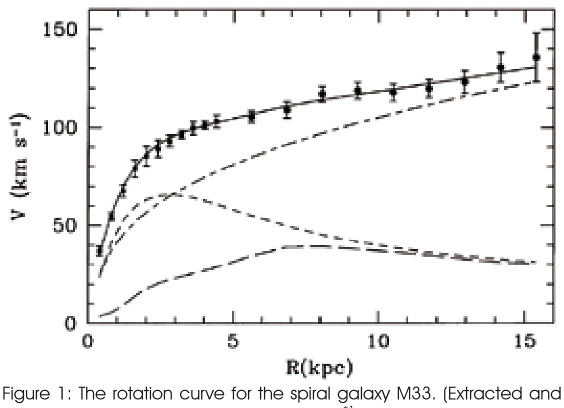

Figure 1: The rotation curve for the spiral galaxy M33. (Extracted and adapted from E. Corbelli and P. Salucci[*1], "The extended rotation curve and the dark matter halo of M33", *Mon. Not. R. Astron. Soc.* 311 (2000) 441)

For elliptical galaxies, it is difficult to find the evidence for dark matter. The stars within the elliptical galaxy are not moving as a whole while each individual star flies distinctively, so only the velocity dispersion can be measured. In addition, neutral hydrogen gas is thin in the area surrounding elliptical galaxies and hence hard to observe. Nevertheless, the present observational data implies that the velocity dispersion in the outer region of an elliptical galaxy does not significantly reduce, suggesting that the galaxy should also be located in a dark matter halo.

Nowadays, evidence for the existence of dark matter has been discovered in various astronomical observations. In galaxy clusters, besides using the rotational velocities of member galaxies to infer the mass (namely, the dynamical mass), just as Zwicky did, it is possible to implement other different approaches. For example, galaxy clusters are filled with high-temperature gases, which emit X-rays. Suppose that these gases stay in a hydrodynamic equilibrium, *i.e.*, the pressure gradient is balanced by the gravity, from this we can also estimate the mass of the cluster.

Another approach is to make use of the gravitational lensing effects. As is well known, the light passing a galaxy or a cluster of galaxies will be bent by the gravity. Therefore, if we observe a galaxy behind a cluster of galaxies, the image of the galaxy will be distorted (in the case of weak gravitational lensing), or even light arcs and multiple images may be produced (in the case of strong gravitational lensing), as shown in Figure 2. Through such gravitational lensing effects, we are able to determine the mass of the galaxy cluster. All these observations clearly

[*1] The plot in Figure 1 is not exactly the same as that in the original article, but both of them are just used to illustrate why the rotation curves provide the evidence for dark matter.

[*2] Beyond the stellar disc, there are very few visible stars and a disc of neutral hydrogen gas. Though it is possible to measure its velocity through the 21 cm spectral line, the total mass of the gaseous disc itself is much smaller than that of the stellar disc and it cannot afford the desired strong gravity.

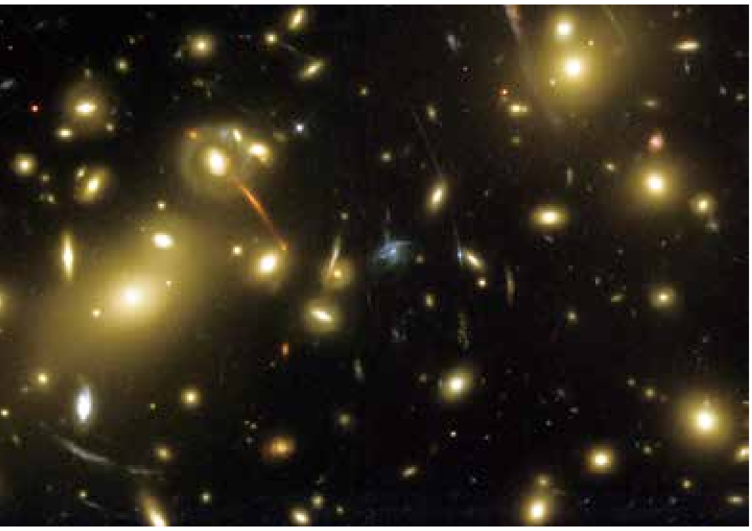

Figure 2: The light arcs induced by the gravitational lensing of the galaxy cluster Abell 2218. (Credit: NASA/ESA)

suggest that dark matter does exist in galaxies.

As for the rotation curve problem, besides dark matter, another solution has been proposed: the universal gravitational law may be invalid at the scale of galaxies, although it has been well tested experimentally in the solar system. Israeli physicist Mordehai Milgrom put forward a theory of Modified Newton Dynamics (MOND), which is also able to fit the rotation curves quite well. However, it is rather difficult to construct a self-consistent and complete theory of gravity along this line. Moreover, MOND cannot provide a good explanation for the dark matter problem in galaxy clusters. MOND is also suffering a severe difficulty in explaining the gravity center of the Bullet cluster of galaxies, where two clusters of galaxies are colliding with each other, as shown in Figure3. Through weak gravitational lensing, we learn that the location where the matter is densest in the Bullet cluster is also where the galaxies are most concentrated. But this density distribution of matter doesn't coincide with the light intensity of X-rays, which reflects the density distribution of gases and normal matter. This observation clearly proves that the center of gravity is not the location of the gases. Without introducing dark matter, it would be extremely difficult for MOND to explain such a phenomenon, whereas the theory of dark matter offers a natural interpretation: since dark matter interacts very weakly with ordinary matter, it can be separated from the gases during the collision of the two galaxy clusters.

3. Dark Matter and Theory of Structure Formation

The standard Big Bang theory of cosmology predicts that the photons originated from the Big Bang will survive today and be red-shifted to the range of microwave frequencies. Since CMB was accidentally discovered in the 1960s, cosmologists have been working within this framework to build a model of the universe. Due to its gravity, dark matter is playing an important role in the formation and evolution of galaxies, and also an indispensable part of proposed cosmological models.

The temperature of CMB from all directions turns out to be almost the same, except for a tiny fluctuation (of a relative size about 1/100,000), implying that the universe was highly homogeneous in the early time and has been evolving under the impact of gravity to the present inhomogeneous state with various galaxies. This sets an important constraint for the nature of dark matter: it cannot

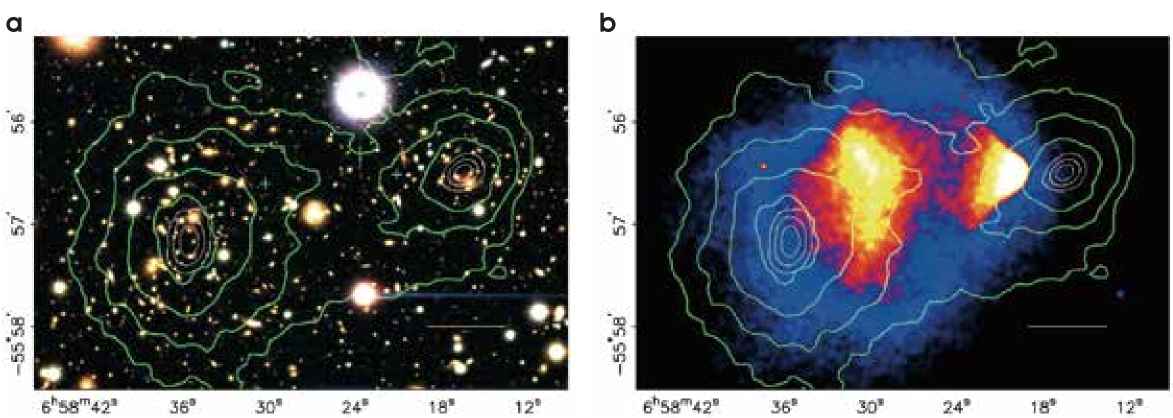

Figure 3: The Bullet Cluster of galaxies 1E0657-56: (a) the optical image and (b) the X-ray image, where the curves denote the projected density distribution. (Extracted from D. Clowe, *et al*., "A Direct Empirical Proof of the Existence of Dark Matter," *Astrophysical Journal*, Vol. 648, No. 2, 2006, p. L109. doi:10.1086/508162)

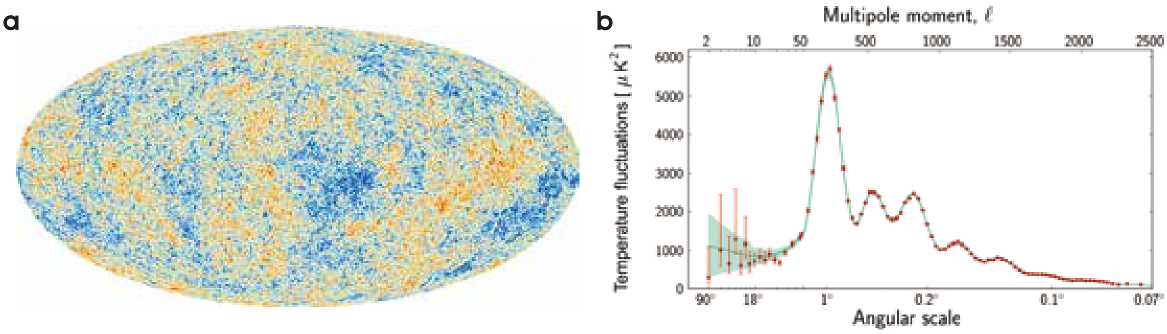

Figure 4: (a) the sky map of the anisotropy in the temperature fluctuations of CMB as measured by the Planck satellite; (b) the temperature fluctuations of CMB at different spatial scales, where the red dots stand for the observed values and green curve denotes the theoretical predictions. (Credit: Planck Team)

be too warm. If dark matter was hot in the early universe, in other words, it was moving nearly at the speed of light, the small-scale structures of the early cosmos would be smoothed out. In this case, to arrive at the present cosmic structure, large-scale structures would have to form in the first place, and then break into small-scale galaxies of today. But it was realized in the 1980s that such a scenario is inconsistent with the observations of galaxies. Consequently, the hot dark matter model has been ruled out, leaving the cold and warm dark matter as two viable scenarios (“warm” means that the velocity of the dark matter is far smaller than the speed of light, but higher than that of cold dark matter, so the density fluctuations below the galaxy scale would be smoothed away). This directly excluded neutrinos, which were once thought the most similar to dark matter in the standard model of elementary particles, as a dark matter candidate. Electrically neutral and feebly interact with ordinary matter, they were once thought to be the best candidate for dark matter; Unfortunately, with tiny masses they would acquire very large velocities in the early universe, therefore would fall into the category of “hot dark matter.”

The early universe was actually filled with a plasma soup made of photons, protons and electrons, which are intimately coupled with each other. Certainly, dark matter did exist initially in the universe, and it would decouple from photons and the plasma because of its very weak interactions with photons and ordinary matter, and cluster together under the gravitational force. Meanwhile, the plasma of photons, protons and electrons fell into the gravitational potential well created by dark matter, then the gravity and the light radiation pressure drove the photons and the plasma to oscillate. The amplitude and pattern of such oscillations depend on the density and temperature of the plasma on the one hand, and on the dark matter density and phase-space distribution on the other. As the plasma gradually recombined into neutral atoms, the universe became transparent and the photons began to be freely streaming. But the imprint of the oscillations was perfectly preserved in photons. After propagating for more than 10 billion years, the initially hot photons cooled down and became today’s CMB (see Figure 4). The oscillations were also recorded in dark matter and ordinary matter. By observing the density fluctuations in the large-scale distribution of galaxies, one can also notice the signatures of oscillations similar to those left in the CMB, which are named Baryon Acoustic Oscillations (BAO). Via the analysis of the CMB power spectrum and BAO, we can deduce the relative proportions of baryonic matter, photons and dark matter in the universe, and even learn some other properties of dark matter.

Introducing dark energy as cosmological constant into the model, Lambda cold dark matter (LCDM) theory can describe the formation and evolution of galaxies very well. However, some of its predictions are inconsistent with observations, particularly when it comes to small-scale structures. For instance, the N-body simulations demonstrate that the dark halos of those galaxies, which are around the same size as our Milky Way, should have hundreds of sub-halos around, but we have thus far seen only dozens of satellite galaxies (*i.e.*, the missing satellite problem) and these satellite galaxies are even smaller than the largest satellite galaxies predicted by the numerical simulations. Moreover, the N-body simulations show that the density profile of the dark halo is steep around the center (namely, the density increases rapidly as the distance to the center decreases). But, via the observations of the dwarf galaxies that are mainly made of dark matter, it has been found that the central density is not rapidly increasing. These inconsistencies can be attributed to either the properties of dark matter (*e.g.*, the warm dark matter, self-interacting dark matter and decaying dark matter have been put forward in order to address this issue) or possible astrophysical effects. After all, it is relatively easier to carry out numerical simulations taking account of gravity only, while it will become much more difficult to give accurate simulations when complicated processes for gases are involved, particularly when taking into account their cooling, and the star formation and feedback effects occurring in them.

4. Weakly Interacting Dark Matter

A candidate for cold dark matter has been proposed as "weakly interacting massive particles (WIMPs)." Hypothetically, they only participate in gravity and weak interactions, rather than electromagnetic and strong interactions; their masses are larger than a few times of proton mass, with a typical value ranging from tens to hundreds of GeV. WIMPs possess all the properties of cold dark matter, and survive most current astronomical and cosmological observations. On the other hand, many theories beyond the standard model of elementary particles, *e.g.*, the supersymmetric theory, naturally predict such kind of particles. Moreover, based on the thermodynamics of the Big Bang cosmology, the estimated relic abundance of WIMPs happens to be close to the observed value, which is called the "WIMP Miracle" by the surprised and pleased physicists. Therefore, WIMPs have been regarded as the most promising candidate for dark matter.

In principle, WIMPs are interacting weakly such that they can be directly probed by high-sensitivity detectors installed in underground laboratories, where the cosmic-ray backgrounds are negligible. On the other hand, they may also decay or annihilate into high-energy photons (*e.g.*, X-rays or gamma rays), or neutrinos and cosmic rays (namely, electrons, protons, helium nuclei and a small number of antiparticles from the cosmos). The annihilation of WIMPs can take place in the dark halo of the Milky Way and perhaps at the center of the Earth or the Sun as the WIMPs can be gravitationally captured and accumulate therein. The signals from these WIMP annihilation events can be detected via the high-energy neutrinos produced. At present, many experiments are searching for dark matter in an indirect way by observing the products of this annihilation. For example, the Fermi-LAT satellite for gamma rays, the PAMELA satellite for cosmic rays, the AMS-02 for antimatter particles, and the Chinese satellite-borne experiment DArk Matter Particle Explorer (DAMPE) or *Wukong**, which has been depicted in Figure 5 (a). As a satellite-borne experiment for dark matter particles, *Wukong* covers the broadest spectrum of particle energies and offers the highest energy resolution. It can probe dark matter via both gamma rays and cosmic rays, just as the Monkey King, the hero in the ancient Chinese novel *Journey to the West*, is able to identify ghosts via his piercing eyes.

These satellites look like boxes that are collecting high-energy particles via the built-in detectors. When the high-energy photons or cosmic rays enter into the boxes, the detectors will discriminate the particle type and record the relevant parameters, such as its energy. Finally, we obtain the energy spectrum, namely, the number of particles in a unit solid angle and energy interval per second per square centimeter. Through the energy spectrum it is possible to judge whether there is a hint for the existence of dark

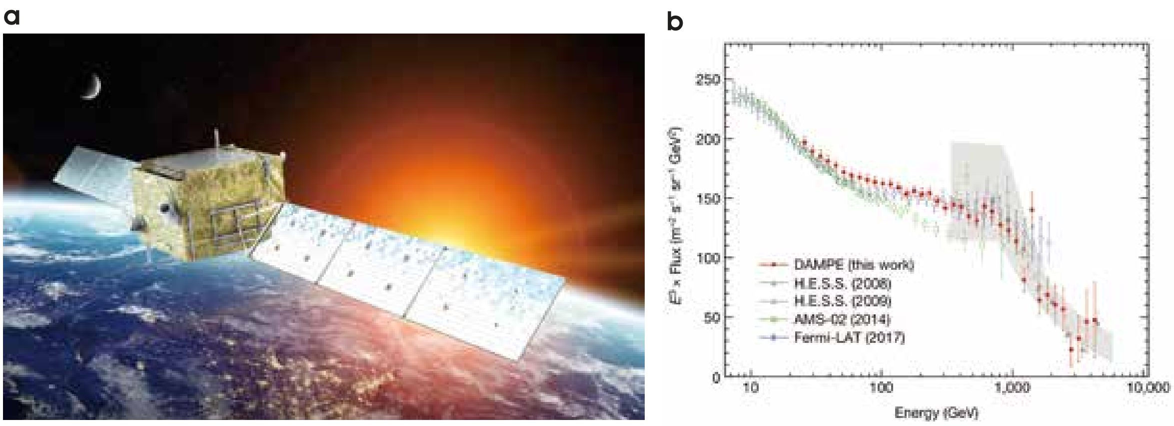

Figure 5: (a) The Chinese satellite-borne experiment DArk Matter Particle Explorer (DAMPE) or *Wukong*; (b) The spectrum of high-energy photons measured by *Wukong*, which offers the broadest energy coverage and highest energy resolution among the same class of satellite-borne experiments. (Credit: DAMPE Collaboration)

* The Monkey King, whose Chinese name is SUN Wukong, is the main character in the 16th century Chinese classical novel *Journey to the West*. The interested readers are referred to a brief introduction to this novel at the website https://en.wikipedia.org/wiki/Sun_Wukong.

matter annihilation or decays.

According to the observations by these satellites, some clues for dark matter have seemingly been found, but no clear evidence for its existence obtained. The PAMELA satellite did see a large excess of positrons from the cosmos, which has been confirmed by the AMS observations; on the other hand, Fermi-LAT has also found that the distribution of gamma rays from the Milky Way is spherically symmetric, and the intensity becomes stronger when approaching the center. This obviously coincides with the prediction by the annihilation or decays of WIMPs. However, such kind of signals can also be produced by rapidly rotating neutron stars (*i.e.*, millisecond pulsars), and we have not yet observed similar signals from dwarf galaxies, where the density of dark matter is supposed to be even higher. Thus, it is unclear whether the signal is really coming from dark matter. In addition, *Wukong* has observed a peak at around 1.4 TeV in the energy spectrum, as indicated by the red dots in Figure 5 (b). This peak could be explained by possible sub-halos of dark matter close to the solar system. Nevertheless, due to the insufficient number of samples, it is not yet possible to determine whether this is a real signal or a statistical fluctuation.

5. Searching for Axions

Apart from WIMPs, other candidates for dark matter have been proposed, among which the light particle "axion" is very promising and has attracted a lot of attention. Just like WIMPs, axion is a hypothetical particle beyond the standard model. In the 1970s, axion was introduced to solve the strong CP problem in Quantum Chromodynamics (QCD). Needless to say, QCD is a very successful theory of strong interaction (*i.e.*, the interaction among quarks and gluons). However, it has been noted that the charge-parity symmetry can in principle be violated in QCD, and consequently the neutron will have a sizable electric-dipole moment, which however has been experimentally demonstrated to be negligibly small. In order to naturally explain this phenomenon, American physicists Roberto Peccei and Helen Quinn figured out a solution via spontaneous breaking of the so-called Peccei-Quinn symmetry, *i.e.*, a global Abelian U(1) symmetry. As a consequence of the symmetry breaking, the light particle "axion" is predicted. Similar to WIMPs, axion is weakly interacting with ordinary matter, but its mass is much smaller than the WIMP mass. Light as their mass is, as the model predicted, axions gained only extremely low momenta when they were produced as a Bose-Einstein condensate, so they can be a candidate for cold dark matter. Generally speaking, leaving the strong CP problem aside, one can also consider a light boson similar to axion, namely, an axion-like particle. Theoretically the mass of axions or axion-like particles is loosely constrained, allowing for a wide range of masses from 10^{-12} eV to 10^{6} eV.

But how can we detect axions? There are two possible scenarios for axions to interact with photons. The first one is the decays of axions into two photons. Namely, the axion has a finite lifetime, and the lifetime is longer for a smaller mass. The other one is that an axion can be converted into a photon of the same energy in a magnetic field, and vice versa. Hence these two ways of interactions can be implemented to detect axions. For QCD axions, due to the tiny mass, their lifetime is extremely long, such that they may have never decayed into photons in the present universe aged more than 13.7 billion years. Therefore, the second scenario with an external magnetic field is usually utilized to probe axions. For the moment, there are several experimental approaches taking advantage of this scenario, such as "wall tunneling." The main idea is to send a beam of photons through the strong magnetic field so that a few photons will be converted into axions, which can go through a wall and then be observed after changing back to photons. Another way is to use an instrument called axion helioscope to look toward the Sun, which is supposed to emit a huge number of axions, and the latter will be converted into photons in magnetic fields. In addition, axion haloscope can also be used to search for axions from the dark halo of the Milky Way, following the same principle. Unfortunately, none of these experiments has yet discovered any clues for axions, and their sensitivities should be further improved.

Though the terrestrial experiments come out with no signals, astronomers may have discovered something in the sky. In 2014, the XMM-Newton space telescope found an emission line of 3.5 keV in the galaxy clusters with low redshifts. Such an X-ray line has also been observed by other satellites, and may exist even in the galaxies, such as the Andromeda Galaxy and the Milky Way (this emission line has not yet been confirmed as there are some claims of null signals). The 3.5 keV line cannot simply be interpreted as the emission line from atoms or plasma ions. If this X-ray line does exist in nature, it is quite possible that it arises from dark matter annihilation or decays. Based on the current observations, this emission line has something to do with the magnetic fields in the galaxies or the galaxy clusters. One possible explanation is that the axions of energies around 3.5 keV have been changed into photons of the same energies in the galactic or intergalactic magnetic fields (see Figure 6). Theoretical calculations show that the axion-photon conversion can indeed explain the 3.5

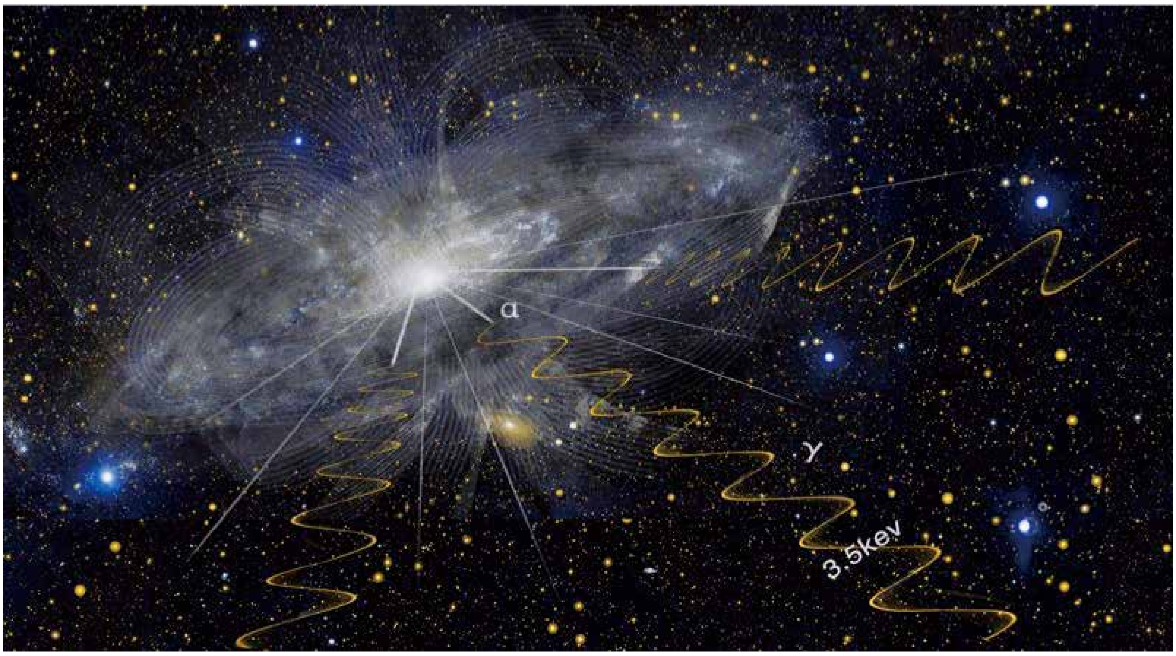

Figure 6: A sketch for conversion of axions in the magnetic field of the spiral galaxy into 3.5 keV photons. Comparing the polarization of the photons with the direction of the magnetic field at the position of the axion-photon conversion, we can verify or disprove whether the 3.5 keV emission line observed is from this conversion. (Credit: NAOC)

keV line in a more natural way. We have been involved in research of this field and proposed that such an explanation can be further tested by comparing the polarization of the 3.5 keV photons with the direction of the magnetic field at the position where the axion-photon conversion occurs. If such a coincidence is found, it will offer a strong support for the correctness of the theory. Otherwise, such a theory can be excluded immediately.

What is dark matter? Is it an unknown particle or a gravitational mirage? There are plenty of puzzles in nature awaiting our answers, which are challenges but also opportunities at the same time. Scientists have to go forward firmly and confidently in order to capture and understand such a "phantom" in our universe.