The particles concepts and physical detection schemes of dark matter

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Abstract. It is still unable to determine the categories of particle that composes the dark matter due to the shortage of detection methods. In this paper, we used the methods of separation of variables, analogy, and dimensional analysis to investigate dark matter detection. The three different models, including the WIMP, axions, and MACHOs, are considered first, which described the properties of dark matter as well. Subsequently, the three currents methods of detecting dark matter, and shortage of those methods are discussed. According to the drawbacks, we have related Gravitational Waves and Cosmic Rays to detecting dark matter, which may contribute to the further detection of dark matter. The milestones achieved these years have also been briefly described, followed by some up-gradations of detectors and further research schemes. These new methods proposed in theory will be upgraded and implemented soon. These results shed light for future dark matter detection.

Keywords: Dark matter, WIMP, Axions, MACHOs, Collider, weak nuclear force, gravitational wave, cosmic ray.

1. Introduction

Dark matter is a sort of matter that scientists imagine due to the existence of phenomena that existing theories cannot explain. Their sizes could be smaller than electrons and photons. They are without charges and do not interfere with electrons. They can travel through electromagnetic and gravitational fields, which is an important part of the universe. The density of dark matter is very small, but its size is incredibly large. As a result, its total mass is big, about 26% of the total mass in the universe. On the other hand, humans can only detect less than 5% of the total cosmic mass (about 4.9%) [1-4]. Even though dark matter cannot be directly observed, it can interfere with the light waves or gravitational force from the stars, and its presence can clearly be observed.

A large number of experiments have shown that dark matter is not made up of heavy particles. In 2014, a major achievement of the Alpha Magnetic Spectrometer (AMS) project cooperated by the Shandong University of China team and Nobel laureate and Chinese-American physicist may have proved that dark matter exists.

Five of the six relevant features demonstrating the existence of dark matter experiments have been confirmed in the completed observations. In 2017, Scientists published a report on the preprint website of Archife's paper on January 29, saying that NASA data from the Chandra X-ray Observatory showed a bulge on the excess X-ray order chart issued at specific energies. It is known that X-rays can reveal the presence of dark matter. Recently, in 2021, scientists at Beijing University find that dark photonic dark matter can be converted into photons in a resonant way in the solar coronal layer.

The first part of the paper is related to dark matter itself and its basic models, its properties, and three kinds of models [1]: The WIMP paradigm [5-8], axions [9, 10], and MACHOs. The second part will introduce methods that are used to detect dark matter. Two main parts are separately concerned with previous methods and three modern methods: Direct detection, indirect detection, and collider detection. The third part is about the proposed methods of dark matter detection and their formulas. Scientists attempt to confirm the existence of dark matter by satellite (DAMPE) capturing cosmic rays produced by dark matter. They attempt to link dark matter to GW, and CR confirms the presence of dark matter by detecting its reactions as well.

2. Basic models of Dark Matter

In the 1930s, the scientist Fritz Zwicky first found out that the mass of galaxies is far from enough to provide enough gravity to hold themselves together when spinning around the centre at speed up to 350 miles per second. He stated that galaxies should be missing about 99 percent of their mass [1,2], while 99 percent is not quite a precise number. His theory about mass absence is correct. This is true because it has been observed by Vera Rubin later that the angular velocities of stars rotating around the galactic center are the same everywhere, both for the inner and outer rings. According to how centrifugal force behaves, the outcome would result in the stars from the outer ring of the galaxies escaping.

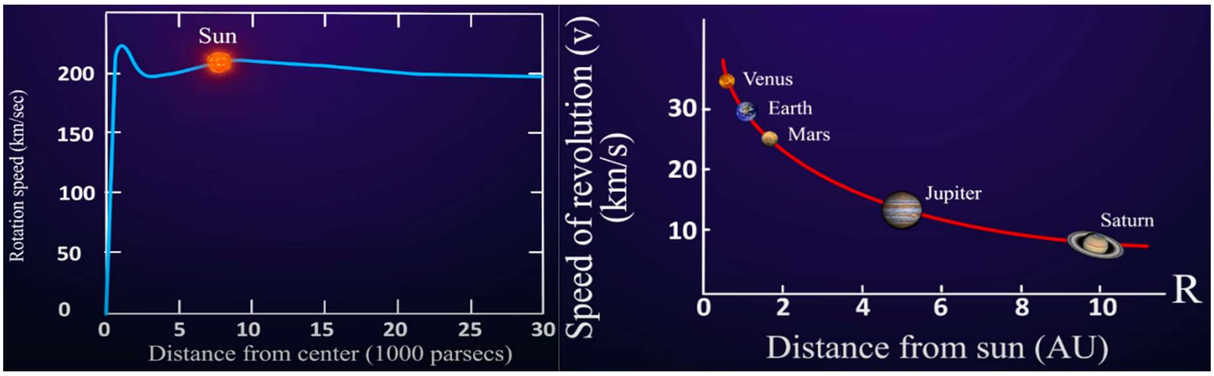

Figure 1. speed of planets rotating the sun as the distance to the sun increases and the speed of stars rotating the galactic centre as the distance to the centre increases. Unlike for planet orbiting the stars, Vera Rubin found that the angular velocity does not change significantly for the stars in the inner ring and outer ring of a galaxy. [1]

Conversely, in reality, galaxies are spinning like usual without constant escaping stars. Therefore, there must be some matters that are currently unable to detect, but interact with gravity somehow, so they can lock the stars in the galaxy and prevent them from escaping. These matters cannot be detected by radiation. Therefore, we call them Dark Matters (DM). If DM really exists (It is not 100% proofed yet) [3], it should have these following properties:

1. It mostly does not interact with electromagnetic radiation.
2. It must not be moving at high speed. (ie., cosmologically stable) [1, 4]
3. It interacts with gravity via some methods.

With these properties settled, several possible models of dark matters have been established, and the following will introduce mainly three of the most popular ones.

2.1. The WIMP paradigm

As their name suggests, weak Interaction Mass particles (WIMP) are a type of particles that interact only with weak nuclear force and gravity [1, 5]. It does not interact with the strong or electromagnetic force, which satisfies the properties of DM. Moreover, what makes it a top reliable candidate for DM particles is the WIMP Miracle.

In the early age of the universe, the environment satisfies thermal and chemical equilibrium [6], WIMP and anti-WIMP particles annihilate each other. When the universe's temperature dropped to some point, the probability of particles finding and annihilating each other became very small, ie., the number of WIMP particles is suddenly stabilized. This is what is called a "freeze out".[7]

After the freeze out, the amount of DM left is what we will be able to observe. One key aspect of learning DM is to know the interaction between strong DM particles and anti DM particles. To quantify the difficulties of observing the interactions Boltzmann equation is utilized:

$$\Omega_{WIMP} \approx \frac{10^{-26} cm^3/s}{(\sigma v)} \tag{1}$$

where(σv) represents two WIMP's annihilation cross section, v represents the relative speed among particles [8]. Ω_{WIMP}, as for DM requires, is approximately equal to 1. The specific calculations and the principle behind them will not be discussed here. But after the calculation, coincidentally, it has been found that the annihilation force is exactly equal to the weak nuclear force [1, 7], which is just what WIMP interacts through. This brought the WIMP model a huge advantage over other DM models.

2.2. Axions

Axions are a kind of particle originally invented by scientists Roberto Peccei and Helen Quinn to solve a problem related to high energy physics, known as the Strong-CP problem [1]. The C and P in the strong-CP problem stand for its charge and parity. In the laws of physic, a reverse in particle's charge or its coordinate in the space should have it maintain the same property [1]. This is what is known as the C-symmetry and the P-symmetry. According to the math calculations of quantum chromodynamics, the strong nuclear force should violate the CP-symmetry (QCD). In contrast, no violations have currently been detected. The differentiation in the formula and the real result is the origin of the strong-CP problem. [9, 10]. The math formula for the calculation is as follows:

$$L = -\frac{1}{4}F_{\mu\nu}\tilde{F}^{\mu\nu} - \frac{n_f g^2 \theta}{32\pi^2}F_{\mu\nu}\tilde{F}^{\mu\nu} + \bar{\varphi}(i\gamma^{\mu}D_{\mu} - me^{i\theta'\gamma_5})\varphi \tag{2}$$

This equation contains many variables which are complicated to define. Still, to solve the strong-CP problem, we only need the θ in the formula to be extremely close to zero, which cancels the entire second term which is related to the strong force to be zero, in this case, the strong force would not have an impact on C-symmetry and P-symmetry. Having this problem in mind, a theory called Peccei–Quinn theory was proposed by Roberto Peccei and Helen Quinn. This theory suggests that the θ is not a constant. It is a type of quantum field that fluctuates in space and time. This way, θ will be fluctuating around zero, which satisfies our requirement. It adds an extra type of particle called the axion, which excites the energy state of the field to cause fluctuations [1, 11].

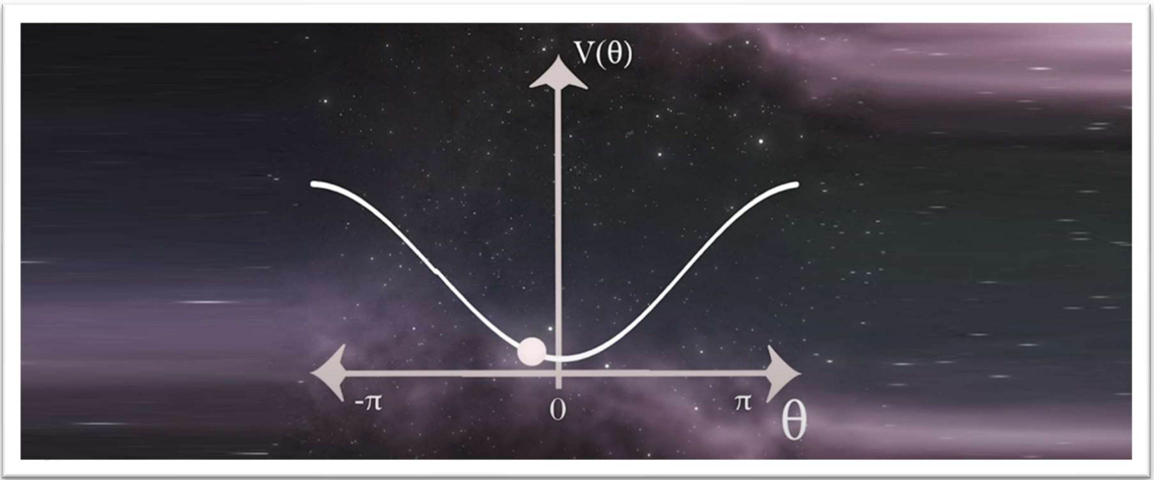

Figure 2. To solve the strong-CP problem, θ had been suggested as a variable that changes both in space and time [12], it oscillates around zero, the slight oscillation of θ is the effect of axion (note: the purpose of the graph is to give a rough view of θ)

Axion is a very light type of particle compared with WIMP, its mass is only about $10^{-4}eV$, but exists in a large quantity thanks to the massive production in the early age of the universe. As a result, it produces a fair amount of gravity. Axions do not interact with normal matters very much. These two properties make axions the perfect candidate for DM particles. If Axions are proved to exist, it will solve both the strong-CP problem and the DM problem all at once.

2.3. MACHOs

MACHOs (Massive Astrophysical Compact Halo Object) has been confirmed to exist unlike the WIMP or axion. More interestingly, they can be black holes, free traveling planets or ultra-dim stars which barely interact with radiations. It is possible to use gravitational microlensing to spot such an object, and current equipment can detect dimmed objects with the mass from $\mathbf{10^{-5}m_{\odot}\sim 10^{2}m_{\odot}}$ (future equipment might be enhanced) [13], It is currently unsure that MACHOs are indeed DM is because an extreme number of MACHOs needs to be found to satisfy the lack of mass in Vera Rubin's original calculation. Moreover, researchers using currently available equipment had found out that the total mass of MACHOs with mass range from $\mathbf{2.5\times 10^{-7}m_{\odot}\sim 8.1\times 10^{-2}m_{\odot}}$ is not enough to fulfill the DM mass requirement, which means confirmation requires more MACHOs out of that range to be detected. [14]

3. Detection of dark matter

3.1. Previous methods

With regard to the methods to prove the presence of dark matter, we can trace it back to the 20th century. Dark matter is actually a hypothetical form of matter that was first proposed in 1922 by Jacobus Kapteyn. He made this theoretical deduction based on the motion of the celestial body.

Soon after that, according to the train of thought of Kapteyn, Fritz Zwicky used spectral redshift to measure the relative speed of galaxies in the Coma cluster to the Coma cluster itself. By means of the virial theorem, he noticed that the velocity dispersion of galaxies in the Coma cluster is excessively high and the gravity of the total mass of visible galaxies produced is insufficient to Coma cluster, so he reckoned that the dark matter is abundant in this cluster of galaxies. Three years later, the result of spectral research of Andromeda Galaxy sustains that opinion as well. etc. [15]

Scientists in the 20th century have gradually confirmed the existence of dark matter in the abstract. As time goes by, increasingly more impressive methods have been developed.

3.2. Modern Direct Methods

If dark matter is made of microscopic particles, then there should be huge amounts of dark matter particles passing through the Earth all the time. Suppose one of the particles hits the nucleus in the detector's matter. In that case, the detector can detect variations in nuclear energy and understand the dark matter properties by analyzing the nature of the impact. However, for weakly interacting mass particles (WIMPs), the probability of being captured with the detector is very low because their interaction with ordinary matters is extremely weak. To maximize the interference of other types of cosmic rays, direct detection experiments of the dark matter tend to occur deep underground. Dozens of experiments of dark matter underground detection are underway around the world. There is no conclusive evidence of direct detection tests for the presence of dark matter particles. The results of these experiments strongly limit the mass and interaction strength of the dark matter particles.

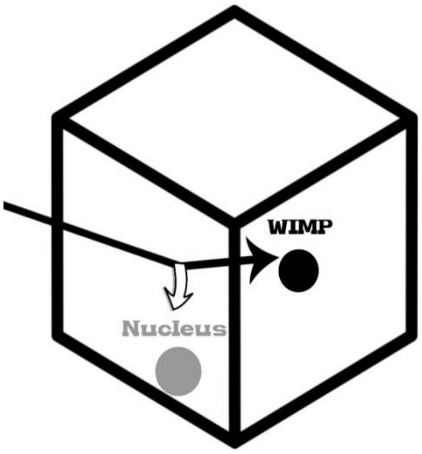

Figure 3. The principle of direct detection of dark matter

For the direct detection of light dark matter under 10 kilovolts, the low threshold point electrode high-pure germanium technology used by the CDEX Cooperation Group led by Tsinghua University and the phonon amplification high-pure germanium technology used by the US CDMSLite Cooperation Group are two representative technical routes. For heavy dark matter detection above 10 kV, there are advantages based on gas-liquid two-phase xenon/argon detectors. The international liquid xenon-based experiments mainly include the American LZ, joint XENON and the Chinese PandaX experiment, and the liquid argon-based experiments have the European DarkSide experiment.[16]

3.3. Modern Indirect Methods

Since there are a large number of dark matter particles in the Milky Way, we should be able to detect the conventional basic particles generated by their annihilation or decay. Indirect detection is to find such annihilation or decay signals in astronomical observations, including high energy gamma rays, positive-negative electrons, positive-antiprotons, neutrons, neutrinos and various cosmic line nucleons. Experiments with indirect detection can be a direct collection of cosmic linear particles using a space detector carried by a satellite or space station, or showers or Cherenkov light effect during terrestrial observation of high-energy cosmic linear particles entering the Earth's atmosphere. By analysing the number and energy spectra of various particles in the cosmic line, information about the decay or annihilation of dark matter in the universe can be extracted. The difficulty of indirect detection of dark matter is that the universe has many high-energy ray sources that are not produced by dark matter. The cosmic line that experiences a complex propagation process from generation to arrival near Earth is a case in point. The current understanding of the cosmic line production and propagation process is not comprehensive, which challenges finding dark matter signals in the cosmic lines. There are many dark matter space detection experiments worldwide in the world. For instance, the US-led ICECube experimental group built giant ice detectors measuring about a cubic kilometer under the Antarctic ice cap to detect dark matter indirectly [17].

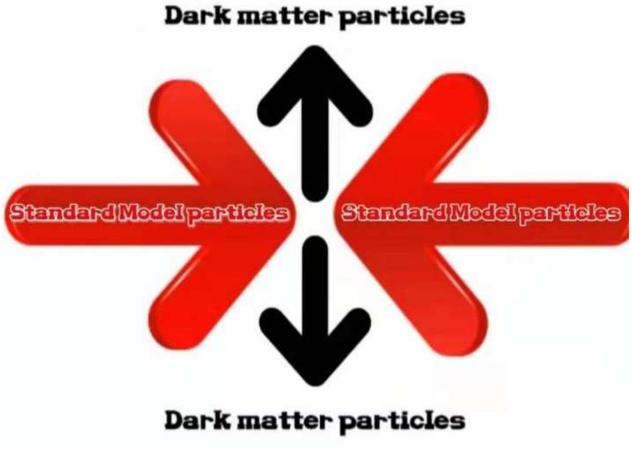

Figure 4. The principle of indirect detection of dark matter

3.4. Collider detection

Another way to find dark matter is to produce dark matter particles in the laboratory. In high-energy particle collision experiments, dark matter particles may be produced. Suppose the collision produces a dark matter particle. In that case, it is not difficult to be directly detected by the detector, resulting in the change of the total energy and the momentum of the collision particle detected by the detector. This is a feature that produces invisible particles. Combining with direct or indirect detection can help determine whether the particles produced at the collider are dark matter or not.

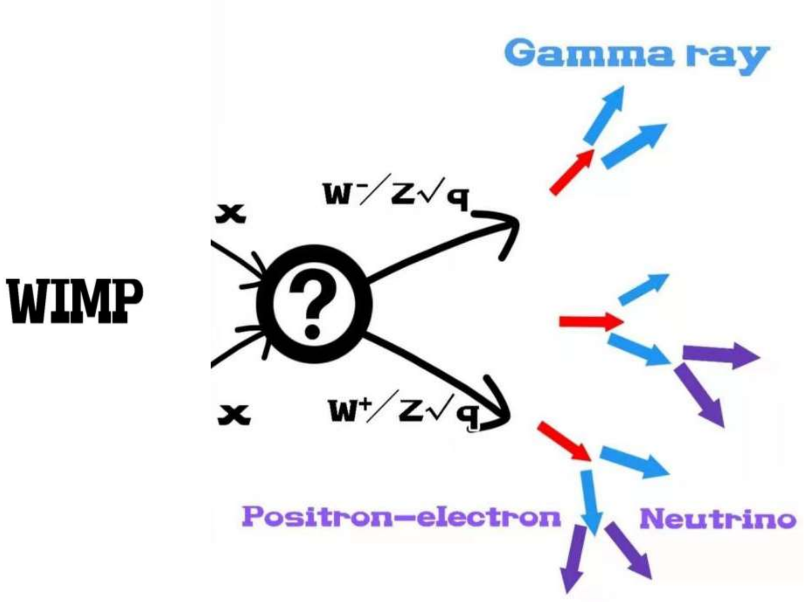

Figure 5. The principle of collider detection of dark matter

A typical Accelerator dark matter experiment requires the accelerator to accelerate standard model particles to higher energies. Currently international scientists are based mainly on the LHC (Large Hardon Collider) at the European Nucleon Centre (CERN), who have not still given possible signals for dark matter yet.[18]

4. Proposed approach for dark matter detection

Dark matter can only participate in the weak nuclear force and gravitational force, the two weakest forces among the four fundamental forces. Dark matter is invisible because of the none interference of dark matter with light (Electromagnetism). China has launched DAMPE to space in an attempt to observe the High-Energy Electron Diffraction (HEED) and High Energy Cosmic Rays with high resolution. The annihilation of the dark matter will produce Cosmic Rays followed by the explosion of a supernova. When DAMPE receives the sign of cosmic rays with a different value calculated, the intensity of cosmic rays will break the standard model, which can observe the existence of dark matter. The expansion and cooling of the universe make the collision between dark matter particles gradually impossible since temperature and density are the main factors of the speed of particles. The measurements of the gravitational force between planets and stars can determine the density of the dark matter because there must be dark matter supporting the formation [19] and collapse of planets and stars.

$$\Omega = \rho_{universe}/\rho_{critical} \tag{3}$$

Dividing matters into two parts, one is luminous and the other is non-luminous. According to the method of microlensing [20] to measure the curvature of the light, we can calculate the mass whether the mass is luminous or non-luminous. Via the measurements of the mass of these two parts, we can determine their density, and the critical density of the universe. Considering $\Omega_{luminous} = 4.4\%$ $\Omega_{luminous} + \Omega_{non-luminou} = 27\%$, substituting

$$M = \rho v = \rho \frac{4}{3} \pi D^3 \tag{4}$$

one derives

$$V_{escape} = HD = \sqrt{2G\rho\, {}^{4}\!/_{3}\, \pi D^2} \tag{5}$$

square both sides $H^2 D^2 = 2G\rho\, {}^{4}\!/_{3}\, \pi D^2$
Substituting data

$$\rho_{critical} = \frac{3H^2}{8\pi G} = \frac{3\times(2.33\times10^{-1}\ )^2}{8\pi\times6.67\times10^{-1}} = 9.7 \times 10^{-27} kg/m^3 \tag{6}$$

where H is the Hubble's constant, G is the gravitational constant, D is the distance. Hence the $\rho_{critical} = 9.7 \times 10^{-27} kg/m^3$, i.e., one obtains $\rho_{non-luminous} = 2.3 \times 10^{-27} kg/m^3$

Dark matter belongs to the category of non-luminous matter, so the density of dark matter is nearly $2.3 \times 10^{-27} kg/m^3$(Assuming the density of dark matter and dark energy is similar, because they have the similar property of electric neutrality, and providing gravitational force, etc.) Gravitational Waves (GW) [21] or the Cosmic Rays (CR) [22] may produce interference with the dark matter, as these do not belong to the category of electromagnetism. The space-time curvature [23] can be used to measure the dark matter when GW or CR passes by the dark matter, where GW will produce gravitational force to the dark matter by their ripples, CR will produce the weak nuclear force by their high-energy reaction.

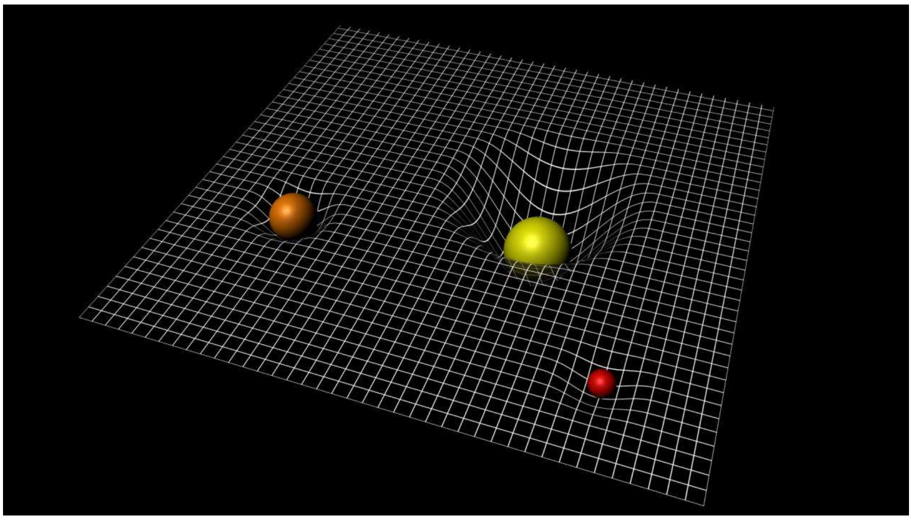

Figure 6. The diagram shows how the mass of planets bend space-time [24]

So far, experiments like the Hadron Collider Experiment [25], the Collision between dark matter and atomic nucleus underground [26] (Reduce the influence of the CR) do not connect the dark matter with GW, and CR. The observations of GW and CR are really rare since the sign of these is so weak that interferometers like LIGO, GEO and Virgo [27] require a really precise measurement ability. LIGO has detected GW produced by the orbiting of two black holes from a billion light years away.

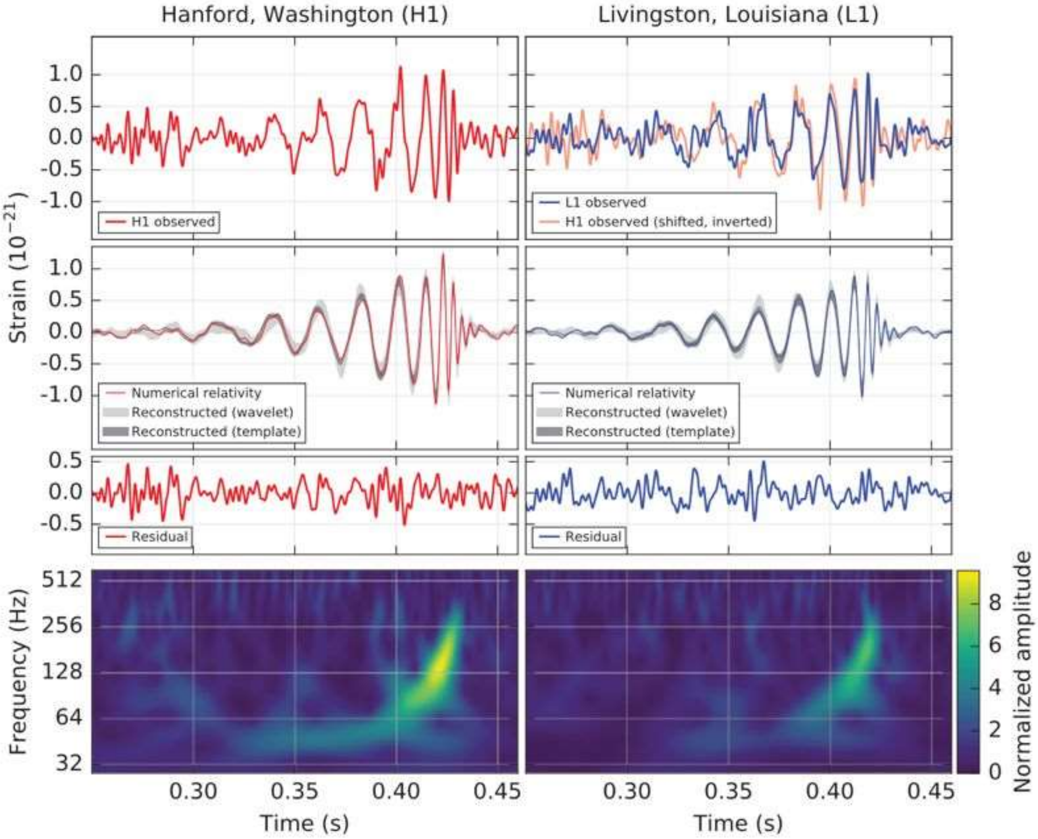

Figure 7. These figures show how the gravitational waves produced by the orbiting of black holes were detected by LIGO in two different areas of America at the same time [24].

The explosion of supernova, the combination of binary stars, and the collision between the comet and planet can produce GW due to the gravitational force change. In contrast, these can also produce CR because of the large high-energy particle collision. In fact, the requirement of the ground laser detector becomes increasingly precise, which is gradually close to the standard quantum limit [28]. Based on this limit, the detection of the gravitational wave will reach the endpoint, so the main purpose for some scientists is to break through the standard quantum limit. With regard to CR, the energy of CR is over 10^{20}eV which is much larger than that of Particle Accelerator on the earth of 10^{12}eV. CR in the future also has a high value for detecting of dark matter because of its high-energy reaction of particles.

5. Conclusion

In summary, we demonstrate the proposed models of DM as well as its progress in detection. Specifically, we introduced some methods currently used to detect DM and some experiments going on. Besides, some new ideas possible of DM detection are also proposed. Vera Rubin spots DM that the exceedingly high velocity of stars on the outer ring of the galaxy needs more mass to generate more gravity to support them. The three most popular models of DM are WIMP, Axion, and MACHOs. Direct DM detection is categorized into under 10 KeV and above 10 KeV leading by a different team using different technologies. Indirect DM detection is mainly based on DM particles and anti DM particles annihilation detection and gravitational microlensing. Trying to produce DM particles in the laboratory is another way. We proposed that it is possible to use gravitational force between planets and stars to calculate the density of DM. Absolutely, this paper may not include the most in-depth detail about all these DM models, but we hope that humanity in the future will find out what DM, the invisible myth, really is. These results offer a guideline for future DM detection.

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