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The Current Development and Theories about Dark Matter

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ABSTRACT

Dark matter has been in the discussion of important theories for long time. As technology developed, more and more particles have been suggested to be the candidate of dark matter. This review will first discuss the observation evidence of the existence of dark matter in the aspect of cosmic microwave background, galaxy rotation curves, velocity dispersions and gravitational lensing. We then focus on some important collider researches, such as HL-LHC and CEPC about dark matter candidates: WIMPs. Finally, we extend the topic considering dark energy and inflation.

1. INTRODUCTION

In 1934, the Swiss astronomer, Fritz Zwicky found that using Virial theorem to calculate total mass of the galaxy is far greater than calculating luminosity mass with photometric observation. The ratio of two values using two different methods can be as high as 160, which means that more than 99% of the substance in the galaxy cannot be found. Therefore, he claims that most of the matter in galaxies is invisible. The problem was then known as the "missing mass" problem. Utilizing modern technology, more accurate observations show that although this ratio is no longer as great as Zwicky's calculation, it is sufficiently proves that most of the matter in galaxies and clusters is indeed invisible, which means they only have strong gravitational forces, but does not radiate any electromagnetic waves. Doppler effect can be used to measure the rotation speed of galaxies. According to the general view, if Newton's law of gravity is correct, then the speed of the galaxy's rotation should decrease as the radius increases (*i.e.*, the Kepler rotation curve). However, in the 1970s, American female astronomer Vera Rubin found that the gas in the galaxy at different distances from the center of the galaxy rotates at almost constant speed around the center of the galaxy. This discovery also supported Zwicky's finding and created a new mystery: the flat rotation curve of the galaxy. Apparently, this high-speed rotation of the galaxy also relies on the strong gravitational pull of the missing mass to maintain its balance. Since the establishment of supersymmetry in the 1970s (the idea that every fermion has a boson of the same mass) and the desire to break through the standard model of particle physics (the unified theory of weak electricity and quantum chromodynamics), the mystery of the “missing mass” in astrophysics has been known as the “dark matter” problem. The characteristic of dark matter includes the absence from electromagnetic interactions, because it does not emit light or any other electromagnetic radiation; thus, it cannot be composed of ordinary baryons such as protons and neutrons [1, 2].

It is invisible to the entire electromagnetic spectrum, making it extremely difficult to detect using usual astronomical equipment. However, there are few methods to detect dark matter which include accelerator generation, that is studying dark matter directly through accelerators; direct detection experiment, that is to determine the existence by detecting the scattering of dark matter particles and experimental target nuclei; indirect detection, that is the detection of particles produced by the annihilation or decay of dark matter. In addition, since the 1920s, when Hubble discovered that the universe was expanding, people have been searching for an invisible form of energy, dark energy, which they believe stretches the fabric of space and causes the universe to expand faster. The observation evidence and collider researches become crucial to solve the mystery of the universe [3].

2. OBSERVATION EVIDENCE OF THE EXISTENCE OF DARK MATTER

2.1. Cosmic Microwave

Although both dark matter and ordinary matter are matter, they do not behave in the same way. In particular, in the early universe, ordinary matter was ionized and interacted strongly with radiation. Dark matter does not interact directly with radiation, but it does affect the CMB by its gravitational potential, and by its effects on the density and velocity of ordinary matter. Ordinary and dark matter perturbations, therefore, evolve differently with time and leave different imprints on the cosmic microwave background (CMB).

The cosmic microwave background is very close to a perfect blackbody but contains very small temperature anisotropies of a few parts in 100,000. A sky map of anisotropies can be decomposed into an angular power spectrum, which is observed to contain a series of acoustic peaks at near-equal spacing but different heights (see in **Figure 1**). The series of peaks can be predicted for any assumed set of cosmological

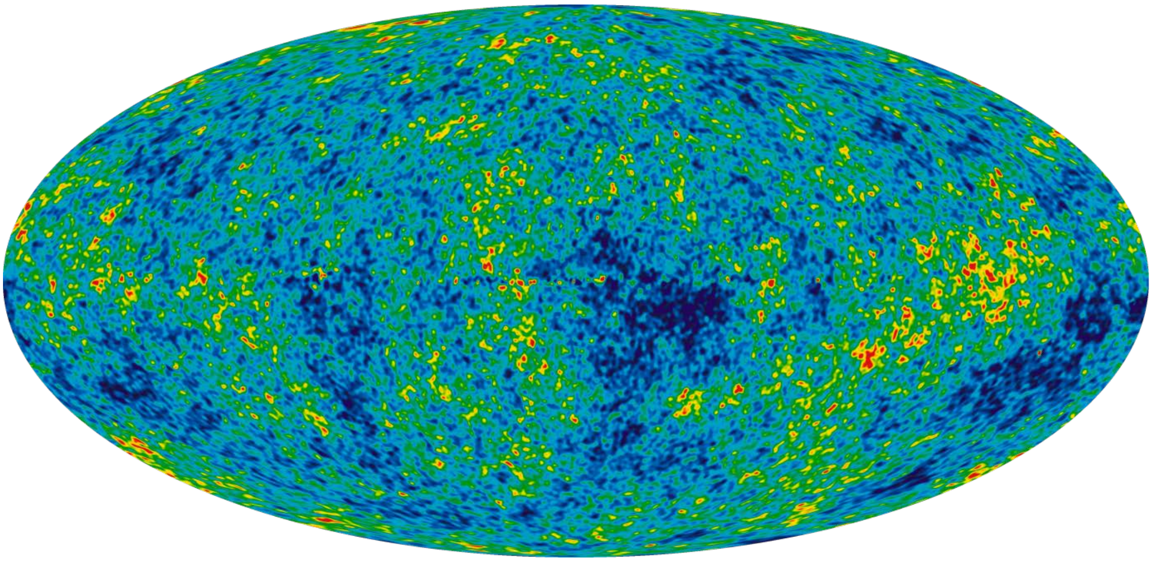

Figure 1. **Nine Year Microwave Sky the detailed, all-sky picture of the infant universe created from nine years of WMAP data. The image reveals 13.77 billion year old temperature fluctuations (shown as color differences) that correspond to the seeds that grew to become the galaxies. The signal from our galaxy was subtracted using the multi-frequency data. This image shows a temperature range of ±200 microKelvin [4].**

parameters by modern computer codes and matching theory to data, therefore, constrains cosmological parameters. The first peak mostly shows the density of baryonic matter, while the third peak relates mostly to the density of dark matter, measuring the density of matter and the density of atoms.

The CMB anisotropy was first discovered by COBE in 1992, though this had too coarse resolution to detect the acoustic peaks. After the discovery of the first acoustic peak by the balloon-borne BOOMERanG experiment in 2000, the power spectrum was precisely observed by WMAP in 2003-2012, and even more precisely by the Planck spacecraft in 2013-2015. The results support the Lambda-CDM model.

The observed CMB angular power spectrum provides powerful evidence in support of dark matter, as its precise structure is well fitted by the Lambda-CDM model, but difficult to reproduce with any competing model such as modified Newtonian dynamics (MOND) [4].

2.2. Galaxy Rotation Curves

The rotation curve of a disc galaxy (see in **Figure 2**) (also called a velocity curve) is a plot of the orbital speeds of visible stars or gas in that galaxy versus their radial distance from that galaxy's centre.

The galaxy rotation problem is the discrepancy between observed galaxy rotation curves and the theoretical prediction, assuming a centrally dominated mass associated with the observed luminous material. When mass profiles of galaxies are calculated from the distribution of stars in spirals and mass-to-light ratios in the stellar disks, they do not match with the masses derived from the observed rotation curves and the law of gravity. A solution to this conundrum is to hypothesize the existence of dark matter and to assume its distribution from the galaxy's center out to its halo.

Observations with ESO's Very Large Telescope suggest that such massive star-forming disc galaxies in the early Universe were less influenced by dark matter (shown in **Figure 3**), as it was less concentrated. As a result the outer parts of distant galaxies rotate more slowly than comparable regions of galaxies in the local Universe [4].

2.3. Velocity Dispersions

Stars in bound systems must obey the virial theorem. The theorem, together with the measured velocity distribution, can be used to measure the mass distribution in a bound system, such as elliptical galaxies

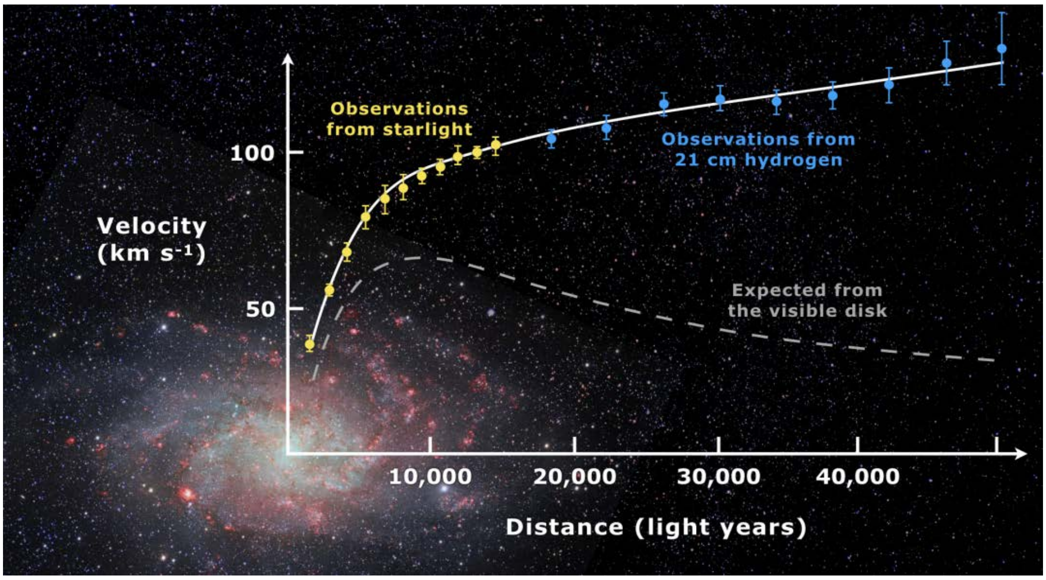

Figure 2. Rotation curve of spiral galaxy Messier 33 (yellow and blue points with error bars), and a predicted one from distribution of the visible matter (gray line). The discrepancy between the two curves can be accounted for by adding a dark matter halo surrounding the galaxy [4].

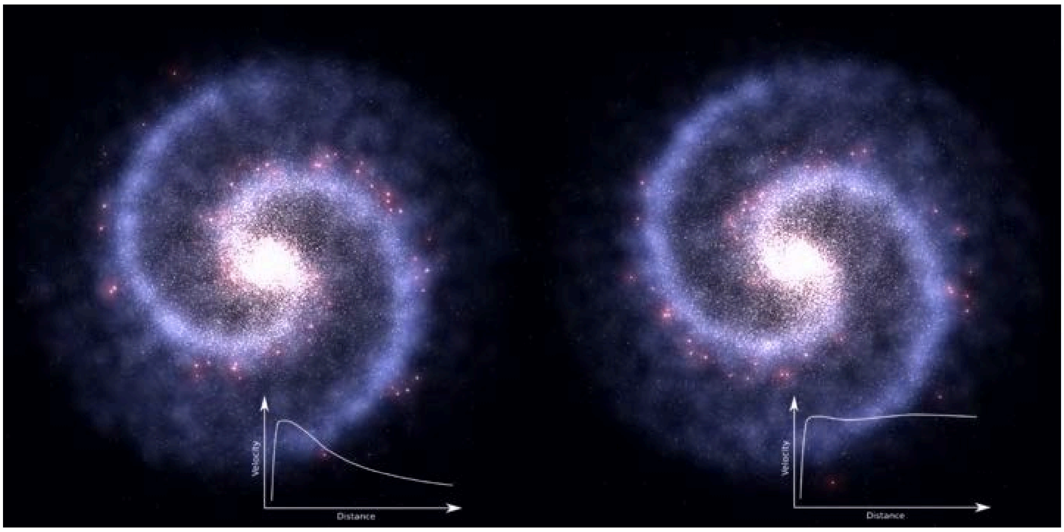

Figure 3. **Left: A simulated galaxy without dark matter. Right: Galaxy with a flat rotation curve that would be expected under the presence of dark matter [4].**

or globular clusters. With some exceptions, velocity dispersion estimates of elliptical galaxies do not match the predicted velocity dispersion from the observed mass distribution, even assuming complicated distributions of stellar orbits.In order to resolve the discrepancy, scientists postulate the existence of non-luminous matter. They speculate that dark matter may be one of the reason for this phenomenon [4].

2.4. Gravitational Lensing

One of the consequences of general relativity is that massive objects (such as a cluster of galaxies) lying between a more distant source (such as a quasar) and an observer should act as a lens to bend the light from this source. The more massive an object, the more lensing is observed.

Strong lensing is the observed distortion of background galaxies into arcs when their light passes through such a gravitational lens. It has been observed around many distant clusters including Abell 1689. By measuring the distortion geometry, the mass of the intervening cluster can be obtained. In the dozens of cases where this has been done, the mass-to-light ratios obtained correspond to the dynamical dark matter measurements of clusters. Lensing can lead to multiple copies of an image. By analyzing the distribution of multiple image copies, scientists have been able to deduce and map the distribution of dark matter around the MACS J0416.1-2403 galaxy cluster.

Weak gravitational lensing investigates minute distortions of galaxies, using statistical analyses from vast galaxy surveys. By examining the apparent shear deformation of the adjacent background galaxies, the mean distribution of dark matter can be characterized (see in **Figure 4**). The mass-to-light ratios correspond to dark matter densities predicted by other large-scale structure measurements. Dark matter does not bend light itself; mass (in this case the mass of the dark matter) bends spacetime. Light follows the curvature of spacetime, resulting in the lensing effect [4].

3. COLLIDER RESEARCH FOR DARK MATTER

3.1. Weakly Interacting Massive Particles

Weakly interacting massive particles (WIMPs) are hypothetical particles that are thought to constitute dark matter. There exists no clear definition of a WIMP, but broadly, a WIMP is a new elementary particle which interacts via gravity and any other force (or forces), potentially not part of the standard model itself, which is as weak as or weaker than the weak nuclear force, but also non-vanishing in its strength. A WIMP must also have been produced thermally in the early Universe, similarly to the particles

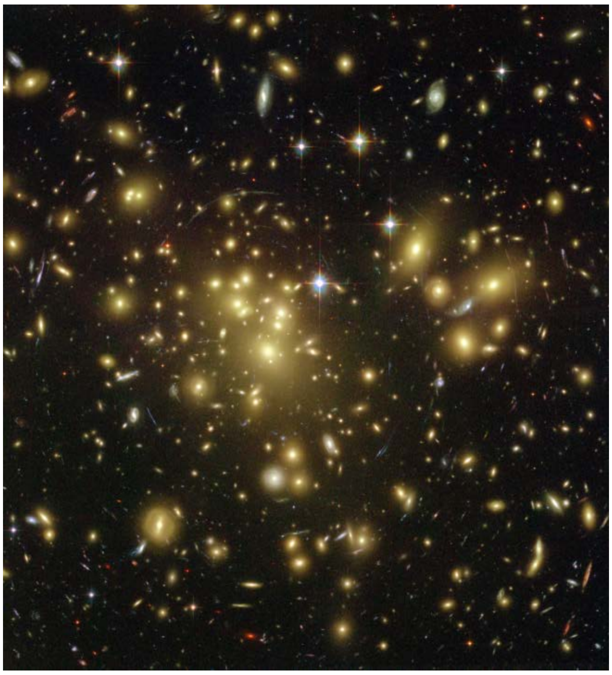

Figure 4. **Strong gravitational lensing as observed by the Hubble Space Telescope in Abell 1689 indicates the presence of dark matter—enlarge the image to see the lensing arcs.**

of the standard model according to Big Bang cosmology, and usually will constitute cold dark matter. Obtaining the correct abundance of dark matter today via thermal production requires a self-annihilation cross section, which is roughly what is expected for a new particle in the 100 GeV mass range that interacts via the electroweak force. Because supersymmetric extensions of the standard model of particle physics readily predict a new particle with these properties, this apparent coincidence is known as the "WIMP miracle", and a stable supersymmetric partner has long been a prime WIMP candidate [5].

3.2. Introduction of Collider Research

An approach to the detection of dark matter particles in nature is to produce them in a laboratory. Experiments with the Large Hadron Collider (LHC) may be able to detect dark matter particles produced in collisions of the LHC proton beams. Because a dark matter particle should have negligible interactions with normal visible matter, it may be detected indirectly as (large amounts of) missing energy and momentum that escape the detectors, provided other (non-negligible) collision products are detected. Constraints on dark matter also exist from the LEP experiment using a similar principle, but probing the interaction of dark matter particles with electrons rather than quarks. It is important to note that any discovery from collider searches must be corroborated by discoveries in the indirect or direct detection sectors to prove that the particle discovered is, in fact, dark matter [6].

3.3. Dark Matter Analysis in HL-LHC

The search and/or characterization of dark matter (DM) in the form of Weakly Interacting Massive Particles (WIMPs) will be one of the top priorities of the HL-LHC. This analysis uses DELPHES simulated signal and background samples and performs a full signal event selection which follows the actual Run-2 analysis as closely as possible.

Constraints on the axial vector (AV) interaction can be translated to limits on spin-dependent DM-nucleon interactions and compared to those from the direct detection experiments. The results of searches for DM at the LHC so far have shown that colliders can place competitive constraints on spin-dependent interactions for this simplified model. For the pseudoscalar mediated model (PS) shown in **Figure 5**, the LHC is uniquely placed to probe this interaction as it leads to velocity suppressed scattering cross sections for the direct detection experiments and is effectively inaccessible to them. Both models thus represent well-motivated benchmarks to study the projections of the HL-LHC.

3.4. Searching for Higgs Boson Decays to Dark Matter Particles in CEPC

Neutrinos interact weakly with the detector and for all practical purposes escape detection without traces. The same is true for the hypothesized dark matter particles. However, their existences can be inferred from detectable ("visible") particles. The total energy and momentum of these "missing" particles, missing energy and momentum as they are usually called, can be calculated from the energies and momenta of visible particles through the energy-momentum conservation. In spite of their elusive nature, neutrinos are as important as visible particles for the CEPC physics program. About 20% of the Z bosons and 30% of the W bosons decay directly into final states with neutrinos. Searching for Higgs boson decays to dark matter particles is a key physics goal of the Higgs factory [6].

The excellent energy and momentum resolutions of the CEPC baseline conceptual detector for visible particles allow for the determinations of missing energy and momentum with good precision. This is demonstrated using e^+e^- —> ZH events which shows the missing mass distributions of events from, respectively, (*Z* —> *qq*, *H* —> *inv*) and (Z —> *vv*, H —> *bb*/*cc*/*gg*) decays (see in **Figure 6**). The missing mass, calculated from the missing energy and momentum, is the invariant mass of the system of undetected particles. The missing mass distribution peaks at the Higgs boson mass for the *H* —> *inv* decay and at the *Z* boson mass for the *Z* — *vv* decay, as expected. Contributions from different jet flavors are shown separately. The Higgs and Z boson masses can be determined from missing masses with good precision, allowing their identification without direct detection (see in **Figure 7**) [5].

4. INFLATION

4.1. Background of Inflation

In physical cosmology, cosmic inflation, cosmological inflation, or just inflation, is a theory of exponential expansion of space in the early universe. The inflationary epoch lasted from 10 - 36 seconds after the conjectured Big Bang singularity to some time between 10 - 33 and 10 - 32 seconds after the singularity. Following the inflationary period, the universe continues to expand, but at a less rapid rate [7].

4.2. Dark Energy and Inflation

After introducing the theory of cosmic inflation, many cosmologists believe that our universe is

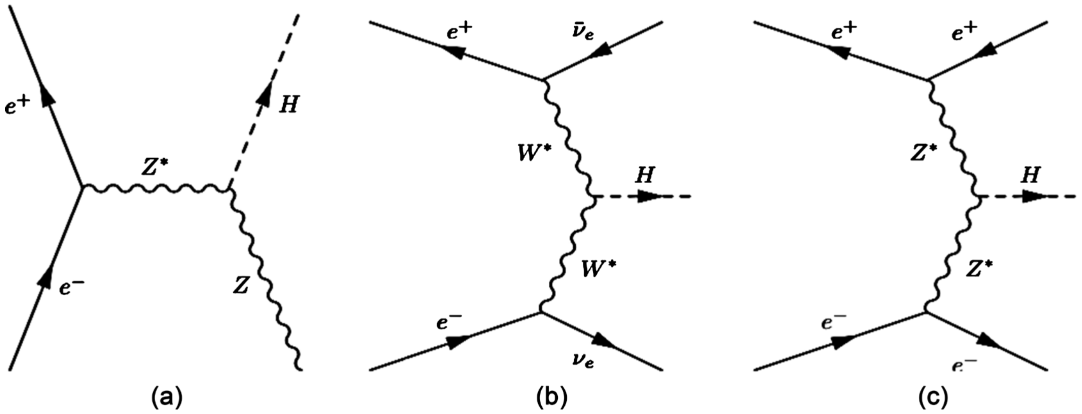

Figure 5. **Feynman diagrams of the Higgs boson production processes at the CPEC: (a) e^+e^- —> ZH, (b) e^+e^- — >ve$\bar{v}$eH, (c) e^+e^- —> e^+e^-H [6].**

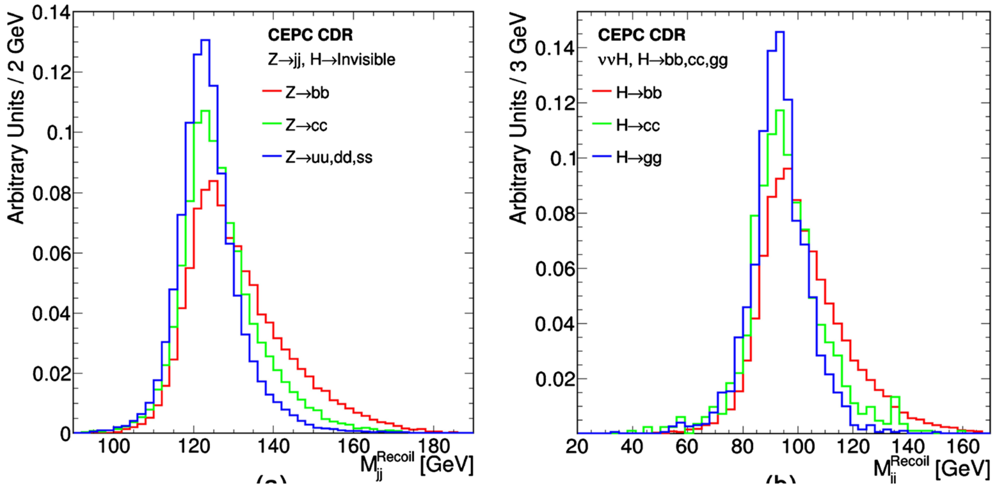

Figure 6. The dijet recoil mass [5].

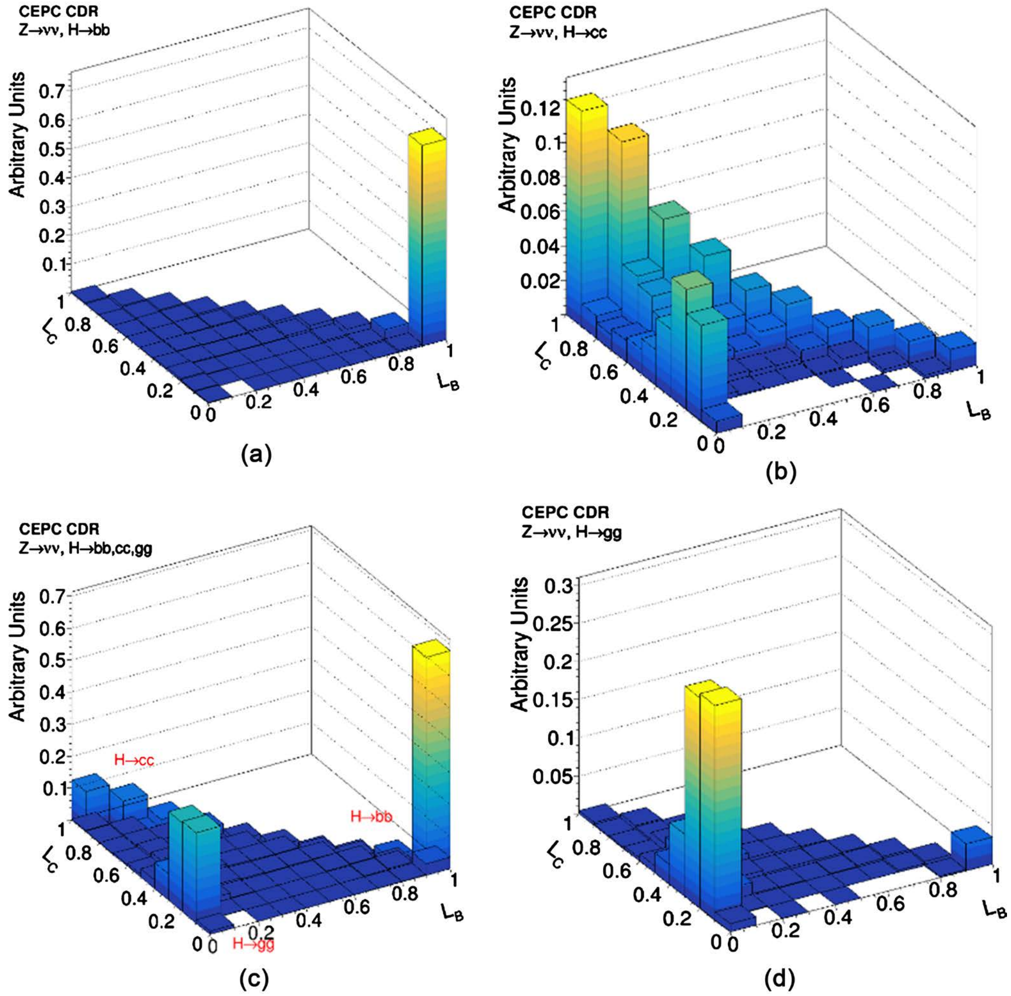

Figure 7. The two-dimensional distributions. The two-dimensional distributions of b-likeliness LB and c-likeliness LC of jets from the H —>bb, H —> cc and H —> gg decays showing separately (a)-(c) and combined (d) [5].

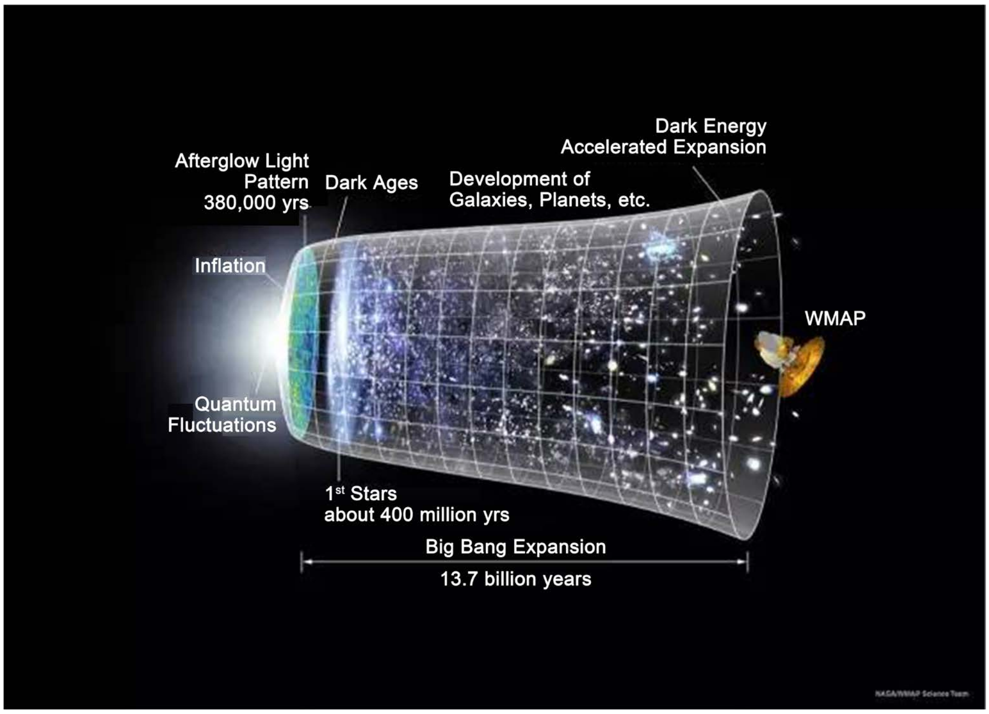

Figure 8. **The development of universe after the big bang [8].**

straight, and that the total energy density of the universe must be equal to the critical value (this threshold is used to distinguish whether the universe is closed or open). At the same time, cosmologists tend to think of a simple universe in which energy density occurs in the form of matter, including 4% of ordinary matter and 96% of cosmic dark matter. But in fact, observations have never been consistent with this. Although there is a large error in the estimation of the total material density, this error is not so large that the total amount of matter reaches a critical value, and the inconsistency between this observation and the theoretical model becomes worse and worse over time.

Dark energy emerges when it is realized that there is not enough material to explain the structure and properties of the universe (see in **Figure 8**). The only thing in common between dark energy and dark matter in the universe is that they neither illuminate nor absorb light. Microscopically, their composition is completely different. More importantly, like ordinary matter, the dark matter of the universe is gravitationally self-attracting, and it forms a group with ordinary matter and forms a galaxy. Dark energy is self-repulsive and is almost evenly distributed in the universe. Therefore, dark energy is lost when counting the energy of a galaxy. Therefore, dark energy can account for 70% - 80% difference between the observed material density and the critical density predicted by the inflation theory. Later, two independent groups of astronomers discovered through the observation of supernova that the universe is accelerating. Thus, the model of dark energy dominating universe becomes a harmonious universe model. Observations made by the Wilkinson Microwave Anisotrope Probe (WMAP) have independently confirmed the existence of dark energy and made it part of the standard model [7].

5. CONCLUSION

Due to the development of modern technology, different approaches have proven the existence of dark matter, which are discussed in the report above. Scientist also did experiments about the possible candidate of dark matter: Higgs boson. Dark energy, which have some characteristics similar to dark matter, not only affects the universe as a whole, but also seems to manipulate its inhabitants, guiding the evolution of stars, galaxies and galaxy clusters, predicting the future of universe, which makes this field of study promising in the future.

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CONFLICTS OF INTEREST

The author declares no conflicts of interest regarding the publication of this paper.

REFERENCES

1. Shen, J.Q. (2018) Review of the Mysteries of Galactic Dark Matter. *Modern Physics*, **8**, Article ID: 25777. https://doi.org/10.12677/MP.2018.84020
2. Liu, J. (2009) Dark Matter Theories. *Physics*, **38**, 865.
3. Zhong, C.X. (2018) Proof of Hubble's Law, the Expansion of the Universe, Dark Matter and Dark Energy. *Scientific and Technological Innovation*, 2096-4390(2019)08-0015-03. https://www.ixueshu.com/document/b6a0a2e89f6b9322534f906ac671eadc318947a18e7f9386.html
4. Dark Matter. https://en.wikipedia.org/wiki/Dark_matter
5. The CEPC Study Group (2018) CEPC Conceptual Design Report Volume II-Physics & Detector (IHEP-CEPC-DR-2018-02). 1-424.
6. ATLAS Collaboration (2012) Letter of Intent for the Phase-II Upgrade of the ATLAS Experiment (CERN-2012-022, LHCC-1-023). 1-136.
7. Inflation. https://en.wikipedia.org/wiki/Inflation_(cosmology)?wprov=srpw10
8. Cosmic Expansion Model. http://image.baidu.com/search/index?ct=201326592&cl=2&st=-1&lm=-1&nc=1&ie=utf-8&tn=baiduimage&ipn=r&rps=1&pv=&fm=rs3&word=宇宙膨胀模型&oriquery=宇宙膨胀&ofr=宇宙膨胀&sensitive=0