Interdisciplinary Frontiers in Dark Matter Research: From Particle Physics to Galactic Dynamics

Jiahe Chen *

Beijing No. 80 Middle School International Department, Beijing, China

* Corresponding Author Email: 17810271067@163.com

Abstract. This article reviews the background and motivation of dark matter research, and points out the current theoretical frameworks and experimental efforts in particle physics and galactic dynamics for studying dark matter, as well as the challenges and limitations faced. This reflects the importance of interdisciplinary research methods. The next step outlines the specific steps for using interdisciplinary methods to study dark matter. It involves cross-validation through particle physics and galactic dynamics to improve the current dark matter model, as well as conducting research on simulating dark matter using machine learning, high-performance computing, and multi-messenger methods, and comparing the results with those from cosmological observations to find commonalities. It calls for the establishment of a unified interdisciplinary platform for collaborative efforts among multiple parties to facilitate future research.

Keywords: Interdisciplinary research, dark matter, cosmology.

1. Introduction

Dark matter is a theoretical substance that may exist in the universe and is invisible. It might be the main component of the universe's matter, but it does not belong to any of the known substances that make up visible celestial bodies. The suspected violations of Newton's law of universal gravitation discovered in a large number of astronomical observations can be reasonably explained under the assumption of the existence of dark matter. Modern astronomy, through observations of celestial bodies' movements, the phenomenon of Newtonian universal gravitation, gravitational lensing effect, the formation of the large-scale structure of the universe, and cosmic microwave background radiation, indicates that dark matter may exist in large quantities in galaxies, star clusters, and the universe, with its mass far exceeding the total mass of all visible celestial bodies in the universe. Dark matter plays a crucial role in cosmological research. It forms the framework that supports the formation of galaxies and galaxy clusters. It also affects the rotation and structural characteristics of galaxies, and determines the statistical properties of large-scale structures, ultimately influencing the interpretation and inference of cosmological observations.

At present, research on dark matter has made some progress, but there has been no major breakthrough. Candidate particles for dark matter have been identified, including weakly interacting massive particles (WIMPs), axions and axion-like particles (ALPs), sub-GeV dark matter and light mediators, fuzzy/super-light dark matter (Fuzzy/ULDM), and so on. The study of dark matter helps explain the formation and evolution of the large-scale structure of the universe, account for the anomalies observed in gravitational lensing and cosmological observations, reveal the boundaries of physical laws, and refine the parameters of cosmology.

To study it, an interdisciplinary approach is required. By comparing the detection signals predicted by the particle model with the observational results from celestial bodies, common constraints can be formed.

To bridge the gaps between particle physics, astrophysics and cosmology, the key lies in establishing a unified language, a common data framework, and a repeatable analysis process, so that the three fields can mutually validate each other and iteratively progress together.

Returning to the subject of dark matter itself, its nature remains unknown. To date, no conclusive discoveries have been made in any detection channels. It is necessary to distinguish the dark matter signal from the complex astrophysical processes, establish a reliable background model, implement

systematic error control, and conduct cross-experiment verification. This remains a very challenging task.

2. Particle Physics and Dark Matter

2.1. Theoretical Framework

Regarding the model description of dark matter, although the standard model has achieved success in many aspects, issues such as hierarchy problems, dark matter, matter-antimatter asymmetry, neutrino mass and coupling unification still suggest the existence of deeper physics. The theories of supersymmetry [1], extra dimensions [2], and beyond-the-standard-model theories may explain these problems. Supersymmetry stabilizes weak-scale physics, provides dark matter candidates, and improves coupling through the symmetry of pairing bosons and fermions; however, there is currently no conclusive experimental evidence. The LHC has set high mass limits under various simplified models, while the Higgs properties and observational results impose constraints on the parameter space. The extra-dimensional theory resolves hierarchy problems through the compactification or curvature of extra dimensions, and affects gravity and particle spectra.

2.2. Experimental Efforts

The method of exploring dark matter through collider search involves directly generating dark matter through high-energy collisions and identifying it through undetected MET (missing transverse energy) signals, as well as the signals produced when dark matter interacts with standard model particles. Currently, the LHC (ATLAS, CMS) has excluded a considerable portion of the coupling-mass space through multiple channels, significantly narrowing the parameter range of the simplified model. However, no definitive signals have been found yet. Future colliders, such as FCC-hh/SPPC, will greatly enhance the detection capabilities for heavy dark matter and intermediate particles under the conditions of ~100 TeV main energy and high luminosity. Meanwhile, linear colliders (such as ILC, CLIC, CEPC) will also strengthen the constraints on the properties of dark matter through their advantages of clean initial states and high-precision measurements.

Experiments for directly detecting dark matter achieve this by observing the extremely tiny scattering of dark matter particles from the Milky Way on the atomic nuclei or electrons of the detection material. The core of these experiments lies in low-background and high-sensitivity detection technologies, which can be used to distinguish background signals such as nuclear recoil and electron recoil. Representative experiments such as LUX-ZEPLIN (LZ) and XENONnT use a dual-phase Time Projection Chamber with liquid Xenon, and achieve three-dimensional positioning and particle identification by combining light signals with charge signals. They have already set upper limits under various coupling-mass models, significantly narrowing the coupling strength and mass range of WIMP.

Indirect detection through cosmic rays or gamma rays, which is the strategy of searching for dark matter signals by observing cosmic rays and gamma rays. Since dark matter particles produce high-energy gamma rays, electron-positron pairs, antiprotons and other products during annihilation or decay, and these products can be directly detected by observatories and detectors such as Fermi-LAT and AMS-02 in space, it is possible to precisely model the gamma-ray spectrum, angular correlation, spatial distribution and cosmic ray background. If an abnormal spectral jump and spatial distribution, or a signal inconsistent with the background is observed, it may point to the products generated by the annihilation/decay of dark matter.

2.3. Challenges and Open Questions

Constraints on mass and interaction cross-section: The current results from direct detection, indirect detection, and cosmological observations provide limits on the mass and interaction cross-section of dark matter particles, but there is still uncertainty. Direct detection is less sensitive to low-mass or weakly coupled dark matter; indirect detection relies on modeling of stellar sources, exposure

time, cosmic background, and the density distribution of galactic dark matter, so the diversity of cross-sections and channels can lead to local detectability differences in the parameter space among different models. In the future, higher-sensitivity detectors, more precise background modeling, and joint analysis across observational data will be needed to further narrow the upper and lower limits of mass and cross-section in the parameter space and distinguish the possibility of different candidate particle classes.

Distinguishing dark matter signals from background noise: In indirect detection, dark matter annihilation/decay signals often manifest in the form of gamma rays, electron-positron pairs, antiprotons, etc. However, these products are usually highly similar to the results of stellar activity, supernova explosions, pulsars, and interstellar medium processes. Therefore, the key challenge lies in accurately modeling the spatial distribution, energy spectrum shape, and fluctuations of the astrophysical background, as well as handling systematic errors, observational selection effects, and background uncertainties. To enhance the discrimination ability, it is necessary to rigorously test the unique predictive features of dark matter signals and develop stronger model selection and exclusion strategies.

3. Astrophysics and galactic dynamics study dark matter

3.1. Observational Evidence of Dark Matter

The observational results show that the outer contour rotation curves of the Milky Way and other galaxies tend to be flat as the radius increases. This indicates that the observable optical matter is insufficient to explain the rotational speed at the end, thereby providing direct evidence for the existence of dark matter halos. This phenomenon is observed in both high-surface-brightness and low-surface-brightness galaxies, and factors such as visible mass, gas distribution, and possible non-circular motion need to be taken into account. The classical work began with Rubin, Ford, Thonnard, laying the foundation, and later Bosma, Sofue & Rubin, systematically organized and compared the rotation curves of various types of galaxies [3-5].

The gravitational lensing effect provides a direct measurement method for large-scale mass distribution, independent of the intensity of light radiation. Weak lensing statistics and strong lensing inversion can reveal the dark matter density and substructure information in galaxy clusters and large-scale structures, making it an important tool for constraining the interactions and particle properties of dark matter. The core work includes the comprehensive analysis of weak lensing results, as well as the quality reconstruction and model comparison of the strong lensing system, such as the important evidence of the Bullet Cluster. Bartelmann & Schneider introduced the theoretical framework and measurement methods of weak gravitational lensing, Clowe et al. studied the Bullet Cluster and found that most of the matter in the galaxy is invisible, and Heymans et al. and Mandelbaum et al. conducted systematic analyses of weak lensing statistics, which also revealed the existence of dark matter [6-9].

The temperature and polarization anisotropy of the cosmic microwave background radiation (CMB) provide highly accurate physical conditions for the early universe. The influence of dark matter on cosmological parameters is reflected in the acoustic peak structure and the shape of the power spectrum. Satellite observations such as Planck and WMAP have established the ΛCDM framework and provided indirect constraints on the nature of cold and hot dark matter, as well as the impact of dark matter on the early density fluctuations, thereby confirming the existence of dark matter.

3.2. Modeling Dark Matter in Galactic Dynamics

In the modeling of galactic dynamics, N-body simulations are the core tool for understanding dark matter halos, substructures, and the formation and evolution of galaxies [10]. By tracking the gravitational interactions of a large number of matter particles, it can reveal the density distribution,

the shape of the halos, and the evolution of substructures under the cold dark matter (CDM) framework, as well as the evolution at different reconstruction resolutions.

Within the framework of galaxy evolution, dark matter halos provide the gravitational background and interface for baryonic accretion, cooling, star formation, and feedback processes. The depth, shape, and angular momentum coupling with the galactic disk of the halo will directly affect the disk structure, the assembly history of the galaxy, and the stability of the spiral arms.

The interaction between baryonic matter and dark matter is also very important. It is not simply a superposition of gravitational forces, but has a significant impact during the formation process, feedback, and redistribution. Processes such as stellar winds, supernova explosions, and AGN feedback can cause redistribution effects on the density profile, core structure, and ring/circular nucleus morphology of the dark matter halo, thereby altering the rotation curve, lensing signal, and local density distribution [11].

3.3. Challenges in Astrophysical Observations

When inferring the mass distribution of dark matter, the observational data need to be combined with theoretical models. However, the limited observables, systematic errors, and the coupling of baryonic processes lead to significant uncertainties in the mass distribution of dark matter halos, contours, and substructures. The main sources of uncertainty in the results include the separation of signal and background, the effects of orientation and projection, the redistribution effect of baryonic feedback on the halo contours, resolution limitations, and the limitations of model assumptions.

Under the ΛCDM framework, numerical simulations usually predict a large number of small-scale substructures and the core density profiles of dark matter halos. However, there are "missing satellites" and cusp-core problems in observations. The number of low-mass satellites around the Milky Way and its surroundings is significantly less than the early predictions; the observed density profiles in low-mass systems tend to be more rounded towards the core, which is inconsistent with the cusp prediction in cold dark matter.

4. Interdisciplinary Approaches

4.1. Synergy Between Particle Physics and Astrophysics

In the collaborative research of modern particle physics and cosmology, by inputting the parameters at the particle level (such as mass, coupling constants, stability, etc.) into the cosmic chemistry and thermal history models, it is possible to predict the energy injection in the early universe and its effects on dark radiation, recombination, and galaxy formation, thereby unifying the results of particle physics experiments and cosmic observation data (such as CMB, BAO, supernovae, weak lensing, etc.) within the same framework for consistency checks. The typical approaches currently include joint parameter estimation and full posterior analysis, using boundary conditions from particle experiments to constrain cosmological parameters, and simultaneously conducting exclusive tests using astronomical observations on the thermal history of new particles, cold/thermal dark matter components, and energy injection into radiation, in order to exclude parameter regions that do not match the observations. The application of this approach covers constraints on the thermal history of dark matter, the influence of additional effective neutrino classes on N_{eff}, and the signals of energy injection (such as decay/annihilation) on CMB and large-scale structure. This demonstrates the crucial role of interdisciplinary collaboration in enhancing the distinguishability of models.

By cross-verifying particle physics models using astrophysical data, in other words, by using astrophysical observations as an independent and non-laboratory-based verification method, to assess the feasibility and consistency of particle physics theories on a macroscopic scale. Map the properties of particle models (mass, decay channels, interaction strength) onto the predictions of astrophysical phenomena, such as the distribution and aggregation of dark matter, the structure of galactic halos, the rotation curves of galaxies, and the thermal history and X-ray/radio signals of galaxy clusters, and conduct cross-domain consistency tests with multi-source and multi-wavelength data. Finally,

through statistical methods such as Bayesian model comparison and information criteria, evaluate the performance of different particle models in astrophysical observations, and thereby be able to eliminate models that do not conform to the data or narrow the parameter space. This cross-validation not only helps solve small-scale structure problems such as the "missing satellite problem" or "core-shell problem", but also can use indirect astrophysical signals (such as gamma rays, cosmic rays, etc.) to provide independent constraints for particle decay/annihilation models. However, the challenge lies in the handling of astrophysical background and systematic errors, as well as how to efficiently integrate multi-source data from CMB, weak lensing, strong lensing, galaxy cluster observations, etc. to enhance the intensity of exclusive tests.

4.2. Computational Advances

In the interdisciplinary research of particle physics and galactic dynamics, machine learning is widely employed to accelerate dark matter simulations, improve sub-grid physics modeling, and enhance the analytical sensitivity of observational data. Specifically, deep learning and surrogate models are utilized to approximate the nonlinear evolution processes in complex high-resolution N-body and fluid dynamics simulations, thereby significantly reducing the overall computational cost while maintaining physical consistency. This facilitates rapid exploration and joint constraint analysis within a large parameter space. Moreover, machine learning is also applied to reconstruct dark matter density fields, identify minute structural features in weak lensing signals, and extract indirect evidence related to particle physics models from multi-wavelength observational data (such as CMB, galaxy cluster X-rays, weak lensing, etc.).

High-performance computing (HPC) also plays a crucial role in large-scale simulations of dark matter and galaxy formation, enabling repeatable experimental exploration at resolutions and time scales approaching the cosmological scale. Through parallelized physical modules such as N-body, magnetohydrodynamics (MHD), and radiative transfer, the HPC platform achieves high-fidelity simulations spanning multiple scales from "macroscopic structure evolution" to "microscopic gamma-ray generation". Modern simulation frameworks often employ hybrid parallel strategies, enabling efficient computation of massive particles and grids on multi-node clusters, while combining adaptive mesh refinement (AMR) and a hybrid of spectral/particle methods to accurately handle density jumps and gravitational field details.

4.3. Multi-Messenger Astronomy

The collaborative utilization of multiple sources of signals is also a way to reveal the properties of dark matter [12]. Gravitational waves provide a direct detection window for extreme celestial events and new physical fields, such as binary collapse events accompanied by neutrinos, the products of black hole mergers, and possible new phenomena related to dark matter. High-energy neutrinos and electromagnetic signals such as gamma rays provide direct observational evidence for the self-interaction, decay or annihilation processes of dark matter, especially in gamma-ray and cosmic-ray spectra in galaxy clusters, galactic halos outside the Milky Way, and the central regions of the Milky Way. The data analysis framework of cross-observational networking unifies the localized information of gravitational wave events, neutrino tracking, and multi-band electromagnetic observations into a unified physical model, enabling strict correlation tests in time and space, thereby narrowing the parameter space of dark matter.

5. Future Directions(Next-Generation Experiments)

Future particle physics and astronomical cosmic observations will be driven by a new batch of detectors, including the Vera Rubin Observatory (VRO), Euclid, and CMB-S4. VRO can conduct large-scale time-domain observations over a period of ten years, repeatedly imaging billions of celestial bodies each night, forming a time-domain star catalog with both depth and time resolution, revealing statistical patterns of dark energy, galactic structures, supernovae, exoplanets, and more;

Euclid is an orbiting probe satellite capable of achieving weak lensing shape measurements and galaxy distance acquisition with large samples, as well as forming multi-probe joint analyses with ground-based telescopes and other satellite data; CMB-S4 can conduct high-sensitivity observations of polarized signals using large multi-band arrays, further probing inflation, neutrino masses, and new physics.

6. Conclusion

At present, the research on dark matter still faces many challenges. In particle physics, there are various candidate models, while direct dark matter detection experiments will continue to lower the upper limit of the cross-section, collider detection and indirect detection are exploring the pathways of production, annihilation/decay. In galactic dynamics, high-resolution simulations and observations have revealed various behaviors of dark matter from small scales to large scales. The contradictions at small scales prompt people to consider SIDM, changes in the distribution of hot/cold dark matter, and in the large-scale structure, the ΛCDM framework still shows good consistency. In this interdisciplinary field, the core challenges include: accurately distinguishing particle physics signals from astrophysical backgrounds and systematic errors in experiments and observations, achieving reliable quantification of uncertainties in a large-scale parameter space and model comparison; establishing consistent multi-messenger constraints between different data sources; and converting microscopic models into testable macroscopic predictions and establishing transparent and reproducible analysis processes.

The significance of interdisciplinary research lies in integrating particle theory, observational astrophysics, cosmology and computational science. This enables model verification, methodology sharing and innovative data analysis, thereby accelerating the progress of dark matter research. The role of computational methods is particularly prominent: machine learning and high-performance computing make it possible to conduct rapid exploration in large parameter spaces and approximate expensive simulations. Through collaborative efforts, breakthroughs are expected in the future in direct detection, cross-messenger indirect signals, and new physical explanations for cosmological contradictions.

To achieve these goals, it is necessary to establish feasible cooperation paths and action strategies. Promote the establishment of cooperation frameworks, such as joint research plans and shared data repositories. Develop and adopt integrated tools and unified standards, such as creating interoperable simulation and data analysis software. Promote the joint strategy of multi-messenger observations, set trigger conditions and joint frameworks, and maximize the discovery potential. Support open science and funding mechanisms, encourage researchers to publish their work openly and transparently.

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