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Origin of Cosmic Structures —From Detailed Characterization of the Milky Way to Statistical Description of the Deep-Field Universe Postprint

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Abstract

In 1609, while people elsewhere in the world were still observing the heavens with naked eyes, on the Apennine Peninsula, an Italian named Galileo—who had long been fascinated by the starry sky—inadvertently pointed a homemade telescope of merely 2.5 centimeters in aperture toward the heavens, observing the lunar surface and Jupiter' s satellites. This act fundamentally transformed humanity' s centuries-long reliance on naked-eye exploration of the cosmos. Over the subsequent 400-plus years, telescope apertures have grown ever larger, while observational methods and techniques have undergone tremendous evolution: expanding from the original optical band to nearly the entire electromagnetic spectrum, extending from electromagnetic means to cosmic particles and even the recent detection of gravitational waves, and transitioning from ground-based to space-based platforms. It is precisely the richness of these observational approaches and the diversity of detection methods that have revolutionized humanity' s understanding of the universe in just a few short centuries, particularly over the past century. Humanity can now traverse the vast river of cosmic evolution, mapping out the history of the universe' s development: from minute quantum fluctuations in the early universe amplified by gravitational instability, forming the diverse structures we see today—from dense black holes to the Milky Way in which we reside (Figure 1), from galaxy clusters to the filamentary large-scale structure of the cosmos. Leveraging observations from the most advanced ground-based and space telescopes along with physical theories, our research in astrophysics has entered the era of precision cosmology. This means we are no longer simply satisfied with discovering new astronomical phenomena, but are more focused on the physical nature of the fundamental material components that govern our universe' s evolution and the numerous physical processes underlying the origin of cosmic structures. And seeking to understand these numerous origin processes and their physical nature is precisely the goal of

cosmic structure formation research—from the detailed characterization of the Milky Way to deep-field cosmology programs.

Full Text

Preamble

In 1609, while people around the world still observed the heavens with naked eyes, a curious Italian named Galileo on the Apennine Peninsula pointed a homemade 2.5-centimeter telescope skyward and glimpsed the lunar surface and Jupiter' s moons. This moment forever transformed humanity' s cosmic exploration, which had previously relied solely on unaided vision. Over the subsequent four centuries, telescopes grew ever larger, while detection methods evolved dramatically—from the original optical band to nearly the entire electromagnetic spectrum, from electromagnetic radiation to cosmic particles and, most recently, gravitational waves, and from ground-based observatories to space-based platforms. This rich diversity of detection techniques and methods has revolutionized our understanding of the universe in just a few short centuries, particularly over the past hundred years. Today, we can traverse the vast expanse of cosmic evolution and map out the history of our magnificent universe: minute quantum fluctuations in the early universe, amplified by gravitational instability, have given rise to the diverse structures we see today—from dense black holes to our own Milky Way galaxy [Figure 1: see original paper].

Galaxies constitute the fundamental building blocks of the cosmos, so studying the origin of cosmic structure necessarily entails understanding how these basic units themselves form and evolve. Chinese astronomy has long pursued a selective, focused investment strategy rather than comprehensive coverage, cultivating new capabilities in large-scale facilities, talent development, and original research. This approach has established China' s astronomical research system and its supporting infrastructure for major instruments. The Strategic Priority Research Program on Cosmic Structure Origin organizes collaborative research efforts on this foundation, aiming to create a high ground for astronomical research and advance the field further.

1. Project Overview

The Strategic Priority Research Program (Category B) of the Chinese Academy of Sciences, titled "Cosmic Structure Origin: From Detailed Characterization of the Milky Way to Statistical Description of the Deep Universe," was launched in 2014. Hosted by the National Astronomical Observatories of the Chinese Academy of Sciences (NAOC), the program involves collaborative participation from the Purple Mountain Observatory, Shanghai Astronomical Observatory, Institute of High Energy Physics, and University of Science and Technology of China. The chief scientist is Professor Mao Shude, and the program comprises 101 key researchers from 17 domestic research institutions and universities.

This program centers on the field of structure origin, targeting currently unresolved major questions. It leverages domestic large-scale scientific facilities and specialized equipment, combined with international sky surveys and high-precision numerical simulations, to conduct cutting-edge research across multiple scales—from the Milky Way and nearby universe to the deep cosmos. The program explores the properties, nature, and structure formation physics of the three fundamental cosmic components: dark matter, dark energy, and baryonic matter. Organized around this central scientific question of structure origin, the program has established four closely related projects. These projects investigate the fundamental physics of dark matter and dark energy, the complex astrophysical processes of structure formation, and examine a particularly uncertain key physical process in structure formation—the impact of black hole accretion and feedback on galaxy formation and evolution—using multi-wavelength observations and diverse research approaches from galactic to extragalactic scales, while simultaneously fostering emerging areas of astronomical research through observational support.

2. Project Progress

Since its inception in 2014, the program has established and improved domestic and international observational platforms, laying the foundation for its smooth progress. By integrating strengths from China' s astronomical community and related fields, with astronomy as the focal point, the program collaborates extensively with particle physics and maintains close partnerships with mathematics and high-tech fields to conduct pioneering scientific and technological research. Through this initiative, we have achieved several internationally visible research outcomes.

2.1. Fundamental Physics of Dark Matter and Dark Energy

Modern astronomical observations have established the existence of dark matter and dark energy, yet their fundamental nature remains unknown—these represent two basic questions in modern physics. Program members have employed multiple research methods to address these questions. Through international collaboration and utilizing the BOSS (Baryon Oscillation Spectroscopic Survey), the world' s largest galaxy survey project, we have precisely measured baryon acoustic oscillation signals at multiple redshifts. These measurements have enabled reconstruction of the time evolution history of the dark energy equation of state. Our research reveals evidence for dynamical evolution of dark energy at 3.5 standard deviations, significantly higher than the early cosmological constant model. Additionally, program members collaborated with the eBOSS (the next-generation upgrade of BOSS) international consortium to complete cosmological feasibility studies for this survey, finding that eBOSS could improve the figure of merit for the dark energy equation of state by approximately threefold. This work first identified dark energy dynamics at higher confidence levels and distinguished between the two degenerate neutrino mass hierarchy patterns

[Figure 2: see original paper].

Dark matter candidates are typically divided into two major categories: cold dark matter and warm dark matter. While both models predict similar large-scale structure formation, warm dark matter models predict significantly less small-scale structure. Program members have conducted in-depth studies of Milky Way-scale galaxy formation in warm dark matter cosmological models using high-resolution hydrodynamic simulations. The research reveals that smooth, dense filamentary structures several megaparsecs in length form around redshift 2, leading to the formation of special extended Lyman-limit systems. From an observational perspective, measurements of the correlation function of extended Lyman-limit systems can be used to test the nature of dark matter. This study provides new observational targets for current and future galaxy surveys investigating dark matter properties.

In redshift survey cosmological analyses, a key assumption is that the velocity bias of dark matter halos equals unity on large scales, meaning the relative velocity between dark matter halos and dark matter particles is zero. However, this assumption has not been verified through numerical simulations and, in fact, contradicts the classic BBKS theory of large-scale structure formation. Understanding dark matter halo bias across different scales can help reduce systematic errors in galaxy survey data analysis, which is crucial for dark energy research. Nevertheless, precisely measuring halo velocity bias is extremely challenging. We have developed a new theoretical method to accurately measure halo velocity bias and validated its accuracy using high-resolution N-body numerical simulations. This marks the first time internationally that numerical simulations have measured halo velocity bias within 2% error margins. The results show that below scales of 300 million light-years, halo velocity bias does not equal unity, inconsistent with previous key assumptions. Consequently, this research holds significant importance for cosmological studies using large-scale galaxy spectroscopic surveys.

2.2. Extreme Astrophysics: Black Holes, Supernova Discovery, and Accretion Physics

Through the Time Allocation for Paying to use foreign telescopes (TAP) program, program members discovered ASASSN-15lh, the brightest supernova observed to date. This extremely luminous supernova' s total radiated energy reaches the upper limit of the magnetar model, the popular energy supply mechanism for SLSN-I (Superluminous Supernovae Type I), providing new clues for unveiling the mechanism behind superluminous supernovae [Figure 3: see original paper]. ASASSN-15lh has generated intense interest among astronomers, prompting immediate follow-up observations by many large telescopes worldwide and NASA' s Swift X-ray space telescope. The discovery was published in *Science* magazine, and researchers around the globe continue to monitor this supernova across radio, optical, X-ray, and other bands to this day.

Program members also utilized the 2.4-meter optical telescope at the Yunnan Astronomical Observatory' s Lijiang station, the 2.16-meter optical telescope at the Xinglong Observatory base of NAOC, and three telescopes in the United States and Australia to discover 72 extremely bright quasars around redshift 5 and three high-redshift quasars above redshift 5.7. Among these, a black hole at redshift 6.3 with a mass of 12 billion solar masses represents the most massive high-redshift ($z > 6$) black hole discovered to date. This achievement was published in the top international journal *Nature*, attracting widespread attention from scholars both domestically and internationally. *Nature* held a special press conference for this discovery and commissioned a commentary article in its "News & Views" section.

Program members selected a sample of AGNs and quasars with high accretion rates (approximately 30 target sources) and conducted long-term spectroscopic monitoring of super-Eddington accreting massive black holes using the Lijiang 2.4-meter telescope. These observations revealed that such sources have quite special properties, providing initial insights into their fundamental characteristics.

Additionally, program members discovered highly blueshifted hydrogen emission lines in the spectrum of the ultraluminous supersoft X-ray source ULS-1 in M81, revealing the presence of relativistic baryonic jets with velocities reaching 0.2 times the speed of light. This marks the first detection of relativistic high-velocity jets from a supersoft X-ray source, breaking previous astronomical understanding and revealing new modes of black hole accretion and jet formation. This result has been published in *Nature*.

2.3. Structure Formation Physics

LAMOST (also known as the Guo Shoujing Telescope, [Figure 4: see original paper]) has now obtained approximately 7 million stellar spectra, forming the world' s largest stellar spectral database. Using this database, program members have performed stellar classification and parameter estimation, achieving notable success in identifying and confirming special stars. For instance, LAMOST has discovered nearly 200 extremely metal-poor stars, accounting for nearly one-quarter of the total discovered internationally. The program has also measured the shape and radial distribution of the Milky Way' s dark matter halo. In studies of the galactic disk, we have reconstructed the radial and tangential velocity component distributions near the Sun, revealing several new substructures. Program members have also independently measured the local dark matter density using LAMOST stellar samples; the current precision is about 30% and can be further improved using additional LAMOST data.

Numerical simulations of cosmic evolution depend on the selection of reasonable initial conditions. Program members have independently developed a method for reconstructing initial conditions of the nearby universe. This method has been successfully applied to SDSS redshift survey galaxy samples to construct the initial density field of the nearby universe and run a set of 3,072^3 particle, 500 Mpc/h simulations of the nearby universe. These simulations accurately reproduce the matter structure of the real universe on both large and small scales (including dark halo substructures and accretion histories). This simulation platform provides an effective foundation for subsequent research into the baryonic physics processes of galaxy formation, ultimately offering powerful constraints on galaxy formation physics.

MaNGA, one of the three major programs in SDSS-IV, will provide the world' s largest dataset of IFU (Integral Field Unit) data for 10,000 galaxies. Program members have used SDSS-IV/MaNGA pilot observation data to study the two-dimensional distribution of star formation histories within galaxies, finding that the cessation of star formation activity in galaxies more massive than the Milky Way proceeds gradually from the galactic center outward, while low-mass galaxies show no significant gradient, indicating that different regions within these galaxies evolve more synchronously. Mass emerges as the dominant parameter. This article was among the first three scientific papers published by SDSS-IV, with follow-up work expected to yield high-visibility results.

2.4. Field Contributions and Talent Cultivation

Over the two years since its launch, the program has cultivated several excellent teams in astronomical observation and high-energy astrophysics, fostering extensive collaboration between CAS institutes and universities while strengthening researcher cohesion. These achievements have established a solid foundation and necessary conditions for future long-term objectives.

Building upon existing resources, the program has established and improved a domestic and international observational network public platform—the Time Allocation for Paying to use foreign telescopes (TAP, [Figure 5: see original paper]). This platform enables Chinese astronomers to access international advanced facilities across multiple wavelengths, expanding domestic capabilities and forming a complementary network with domestic observational equipment. TAP prepares talent for constructing and operating indigenous facilities while providing a foundation and training for competition in international open telescope time. Additionally, the program plays an active role in promoting equipment construction and international cooperation, serving as a precursor for future major international collaborative facilities such as SKA and TMT.

This program represents a major project in cosmic structure formation and evolution within China' s astronomical field, bringing together the strengths of CAS institutes and universities in this research direction. Driven by these major scientific questions, CAS established the CAS Astronomical Big Science Research Center, while the University of Chinese Academy of Sciences founded the School of Astronomy and Space Science integrating education and research. Key members of this program play crucial roles in both the Big Science Center and the School of Astronomy, particularly contributing to teaching, research support, and student cultivation in the School of Astronomy.

3. Summary and Outlook

Since its establishment in 2014, the program has achieved several high-visibility results in fundamental dark matter-dark energy physics, extreme astrophysics, and galaxy formation physics, enhancing international recognition of China's frontier astronomical research. It has formed complementary domestic and international observational platforms, contributing to scientific breakthroughs and cultivating the next generation of observational talent. The completion of FAST in 2016, the successful launch of the DAMPE dark matter satellite, and the upcoming 2017 launch of HXMT provide new momentum for the program to reach new heights in the coming two years. Meanwhile, the massive survey data from LAMOST and SDSS-IV offer Chinese astronomers an international stage to explore cosmic structure evolution.

Although the program is progressing well, it faces certain management challenges due to its relatively large personnel size, involvement of multiple units, and inclusion of approximately 15% university members. The program is strengthening its promotion and public outreach, making minor personnel adjustments, further focusing research topics, and enhancing internal collaboration through small, efficient workshops, striving to form an internationally influential excellent team in this field. (Host institution: National Astronomical Observatories, Chinese Academy of Sciences)

Evaluation by Simon White

Director of the Max Planck Institute for Astrophysics in Germany, Fellow of the Royal Society, Foreign Associate of the US National Academy of Sciences, and recipient of the Gruber Prize in Cosmology, the Royal Astronomical Society Gold Medal, and the American Astronomical Society Helen B. Warner Prize. A pioneer in using numerical simulations to explore cosmic structure formation and one of the founders of the modern standard cosmological model, with nearly 500 published papers and over 80,000 citations, making him one of the most highly cited astronomers in the world.

The origin of the universe is a fundamental question in natural science. For a long time, major astronomical powers worldwide have designated this direction as a strategic priority and invested substantial research resources. The Strategic Priority Research Program on "Cosmic Structure Origin" closely focuses on this direction, targeting currently unresolved major questions. Relying on domestic large-scale scientific facilities and specialized equipment, combined with international sky surveys and high-precision numerical simulations, the program conducts cutting-edge research across multiple scales from the Milky Way to the nearby universe and deep cosmos, exploring the properties and nature of the three fundamental cosmic components—dark matter, dark energy, and baryonic matter. The program has assembled top domestic talent from CAS institutes and universities, achieving numerous important results since its launch, publishing a batch of high-level articles in top international journals, and making significant progress in several directions. The program has also established and developed an observational network based on foreign telescopes (TAP) tailored to the status of domestic astronomical facilities, playing an important role in cultivating observing talent for large telescopes and achieving scientific results.

In its future plans, the program would do best to concentrate on high-quality activities with international participation, while appropriately reducing support for projects that primarily impact the local and national levels.

Evaluation by Li Tiebei

Academician of the Chinese Academy of Sciences, high-energy astrophysicist, researcher at the Institute of High Energy Physics of CAS, and professor at Tsinghua University. He has made important contributions to both high-energy physics and astrophysics and their interdisciplinary fields, with research experience and significant achievements in experimental observation, data analysis, and theoretical modeling. He is the chief scientist of the Hard X-ray Modulation Telescope (HXMT), scheduled for launch in 2017.

The origin of cosmic structure is a fundamental question in natural science. For a long time, major astronomical powers worldwide have designated this direction as a strategic priority and invested substantial research resources. The Strategic Priority Research Program on "Cosmic Structure Origin" closely focuses on this direction, targeting currently unresolved major questions. Relying on domestic large-scale scientific facilities and specialized equipment, combined with international sky surveys and high-precision numerical simulations, the program conducts cutting-edge research across multiple scales from the Milky Way to the nearby universe and deep cosmos, exploring the properties and nature of the three fundamental cosmic components—dark matter, dark energy, and baryonic matter. The program has assembled top domestic talent from CAS institutes and universities, achieving numerous important results since its launch, publishing a batch of high-level articles in top international journals, and making significant progress in several directions. The program has also established and developed an observational network based on foreign telescopes (TAP) tailored to the status of domestic astronomical facilities, playing an important role in cultivating observing talent for large telescopes and achieving scientific results.

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