# Doctoral Dissertation Abstracts Selected for Publication

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## Abstract

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# Cosmological Studies Based on Binary Neutron-Star Merger Events and High-Redshift Galaxies

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Cosmological research has now entered the era of precision measurement. The cold dark matter model with a cosmological constant, ΛCDM, is widely regarded as the standard model of cosmology. However, observational phenomena such as the Hubble constant crisis, the $S_8$ crisis, and the extremely high-redshift, ultra-massive galaxies discovered by the James Webb Space Telescope (JWST) have challenged this model. Against this background, this thesis uses the latest data from gravitational-wave detections and JWST high-redshift observations to conduct related studies centered on crisis issues in cosmology.

Chapter 2, based on the only multi-messenger gravitational-wave event to date, GW170817, compiles its afterglow observations in the optical, radio, and X-ray bands over nearly the past 5 yr, and constructs an afterglow model encompassing forward-shock radiation, a relativistically decelerating jet, and sub-relativistic kilonova afterglow radiation. By further combining the joint constraints on the inclination angle $\iota$ and luminosity distance $d_L$ from its apparent superluminal motion in the radio band, the degeneracy between the two in gravitational-wave data analysis is broken, yielding a Hubble constant of $H_0 = 72.57^{+4.09}_{-4.17}\ \mathrm{km \cdot s^{-1} \cdot Mpc^{-1}}$, which tends to support measurements in the nearby universe.

Chapter 3 forecasts the constraining power of future on-axis multi-messenger gravitational-wave events on the Hubble constant. In this case, the uncertainty in the inclination angle is of the same order as the opening angle of a short gamma-ray burst jet, satisfying $\Delta\iota \leq 0.1$ rad. Using three methods—the Fisher information matrix, error propagation, and gravitational-wave simulations—we find that in the LIGO (Laser Interferometer Gravitational-wave Observatory) O5 phase, if there is a single relatively nearby ($d_L \leq 250$ Mpc) multi-messenger gravitational-wave event, the measurement precision of $H_0$ can be improved to $\Delta H_0/H_0 \sim 3\%$. At this precision, for off-axis multi-messenger events, gravitational-wave data alone can constrain the inclination angle to $\Delta\iota \leq 0.1$ rad, thereby testing or calibrating afterglow models.

Chapter 4 starts from the dark-matter halo mass function and establishes a galaxy ultraviolet luminosity function (UV LF) model that includes the stellar formation efficiency (SFE), stellar initial mass function, and dust extinction. We reselect high-redshift massive-galaxy candidates and take into account the influence of cosmic variance, finding that the SFE over the redshift range 7.5–9.1 remains consistent with observations of the nearby universe. For galaxies at still higher redshift ($z \sim 13$), the excess in their UV LFs can be explained by the absence of extinction effects or by introducing massive Population III stars with low metallicity. Further analysis shows that the SFE varies with dark-matter halo mass and redshift, and may exhibit a trough near $z \sim 9$.

Chapter 5 further constructs a more general UV LF model. Specifically, the SFE that is independent in each redshift interval is rewritten as a redshift-dependent function; through the transformations between density and number, and between absolute magnitude and apparent magnitude, biases arising from coordinate selection are eliminated. Based on the Planck 2018 cosmological framework and UV LF observations at $z = 4 \sim 10$, we analyze the evolution with redshift of the galaxy SFE, stellar-formation-rate density, neutral hydrogen fraction, and Thomson optical depth, and obtain the cosmic structure growth parameter $\sigma_8 = 0.82 \pm 0.03$, consistent with the prediction of the standard cosmological model.

Chapter 6 summarizes the work of the thesis and looks ahead to the future development of gravitational-wave detections and high-redshift galaxy observations, discussing the new opportunities that next-generation observational projects will bring to cosmological research.

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## Cosmological Researches Based on Binary Neutron Stars Coalescing and High-redshift Galaxies

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Modern cosmology has entered the era of precision measurements. The cold dark matter model with a cosmological constant, ΛCDM, is widely regarded as the standard cosmological model. However, the Hubble tension, the $S_8$ tension, and the discovery of extremely high-redshift massive galaxies by the James Webb Space Telescope (JWST) challenge this paradigm. Motivated by these developments, this thesis investigates a series of related cosmological issues using gravitational-wave and JWST high-redshift data.

In Chapter 2, we study the only multi-messenger gravitational-wave event currently available, GW170817, by compiling its afterglow observations over the

past five years in the optical, radio, and X-ray bands. We construct an afterglow model that incorporates forward-shock emission, a relativistic decelerating jet, and a sub-relativistic kilonova afterglow component. By further combining the joint constraint of the inclination angle $\iota$ and the luminosity distance $d_{\mathrm{L}}$ from the apparent superluminal motion observed in the radio band, we break the degeneracy between these two parameters in gravitational-wave data analysis and obtain $H_0 = 72.57^{+4.09}_{-4.17}\ \mathrm{km \cdot s^{-1} \cdot Mpc^{-1}}$, which tends to favor local measurements of the Hubble constant.

In Chapter 3, we forecast the capability of future on-axis multi-messenger gravitational-wave events to constrain the Hubble constant. In this case, the uncertainty of $\iota$ is comparable to the viewing angle of the GRB jet, satisfying $\Delta\iota \leq 0.1$ rad. Using three approaches, including the Fisher information matrix, error propagation analysis, and gravitational-wave simulations, we find that a single nearby multi-messenger event with $d_{\mathrm{L}} \leq 250$ Mpc could improve the precision of the Hubble constant measurement to $\Delta H_0/H_0 \sim 3\%$ during the O5 period. With such precision, the inclination angle can be constrained to $\Delta\iota \leq 0.1$ rad solely using off-axis GW event, which would be sufficient to test or calibrate the afterglow model.

In Chapter 4, based on the dark matter halo mass function, we develop a model for the galaxy ultraviolet luminosity functions (UV LFs) that includes the star formation efficiency (SFE), the stellar initial mass function, and dust extinction. After updating the high-redshift massive galaxy candidates and considering the impact of cosmological variance, we find that the SFE in the redshift range of $7.5 - 9.1$ remains consistent with observations in the local Universe. At $z \sim 13$, bright UV LFs can be well fitted with non-dust attenuation or a top-heavy IMF (Initial Mass Function) for Population III stars. Further analysis suggests that the SFE evolves with dark matter halo mass and redshift, and may exhibit a dip around $z \sim 9$.

In Chapter 5, we construct a more universal UV LF model, modifying the initially redshift-independent SFE to a function related to redshift. In addition, by converting the densities and absolute magnitudes to counts and apparent magnitudes, we remove biases introduced by coordinate framework. Based on the Planck 2018 framework, utilizing the UV LF data within the redshift range of $4 - 10$, we analyze the evolution of galaxy SFE, star formation rate density, neutral hydrogen fraction in the universe, and Thomson optical depth with increasing redshift. We further obtain the cosmic structure growth parameter $\sigma_8 = 0.82 \pm 0.03$, which is consistent with the standard cosmological model.

In Chapter 6, I provide a brief summary of the above work and look into the future, hoping that developments in various observational projects will bring new opportunities for cosmological study.

*Note: Figure translations are in progress. See original paper for figures.*