第 67 卷 第 3 期 天 文 学 报 Vol. 67 No. 3
2026 年 5 月 ACTA ASTRONOMICA SINICA May, 2026

doi: 10.15940/j.cnki.0001-5245.2026.03.013



# 基于双中子星并合事件及高红移星系的宇宙学研究

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当前宇宙学研究已进入精密测量时代, 含宇宙学常数的冷暗物质模型ΛCDM被广泛认为是宇宙学的标准模型. 然而, 哈勃常数危机、$S_8$危机、詹姆斯·韦伯太空望远镜(JWST)发现的极高红移超大质量星系等观测现象挑战了该模型. 基于此, 本文利用引力波探测和JWST高红移观测等最新数据, 围绕宇宙学危机问题开展相关研究.

第2章基于目前唯一一例多信使引力波事件GW170817, 统计了其近5 yr来, 光学、射电、X射线波段的余辉观测, 构建了涵盖正向激波辐射、相对论性减速喷流、亚相对论性千新星余辉辐射的余辉模型. 进一步结合其射电波段视超光速现象对倾角$\iota$和光度距离$d_{\rm L}$的联合约束, 打破了引力波数据分析中二者的简并性, 得到哈勃常数$H_0 = 72.57^{+4.09}_{-4.17}\ {\rm km\cdot s^{-1}\cdot Mpc^{-1}}$, 倾向于支持近邻宇宙的测量结果.

第3章预测了未来正轴多信使引力波事件对哈勃常数的约束能力. 在此情形下, 倾角的不确定度与短伽马暴喷流张角同量级, 满足$\Delta\iota \leqslant 0.1\,{\rm rad}$. 采用Fisher信息矩阵、误差传播和引力波模拟3种方法, 我们发现, 在LIGO (Laser Interferometer Gravitational-wave Observatory) O5阶段, 若有单个距离较近($d_{\rm L} \leqslant 250\,{\rm Mpc}$)的多信使引力波事件, 可将$H_0$的测量精度提升至$\Delta H_0/H_0 \sim 3\%$. 在此精度下, 对偏轴多信使事件, 仅利用引力波数据可约束倾角至$\Delta\iota \leqslant 0.1\,{\rm rad}$, 从而检验或校正余辉模型.

第4章以暗物质晕质量函数为起点, 建立了包含恒星形成效率(SFE)、恒星初始质量函数和尘埃消光的星系紫外光度函数(UV LF)模型. 我们重新筛选高红移大质量星系候选体并考虑宇宙学方差的影响, 发现红移$7.5-9.1$范围的SFE仍与近邻宇宙观测一致. 对于更高红移($z\sim13$)星系, 其UV LFs的超出可用消光效应缺失或引入低金属丰度的大质量星族III恒星解释. 进一步分析表明, SFE随暗物质晕质量和红移变化, 在$z\sim9$附近可能存在低谷.

第5章进一步构建了更普适的UV LF模型, 具体方法是将各红移区间彼此独立的SFE改写为红移相关的函数, 并通过密度与数量、绝对星等与视星等的转换, 消除了坐标选择产生的偏差. 基于Planck 2018宇宙学框架和$z=4\sim10$的UV LF观测, 我们分析了星系SFE、恒星形成率密度、中性氢占比以及Thomson光深随红移的演化, 并得到宇宙结构生长参数$\sigma_8 = 0.82\pm0.03$, 与标准宇宙学模型的预言一致.

第6章总结全文工作, 并展望未来引力波探测和高红移星系观测的发展, 讨论新一代观测项目为宇宙学研究带来的新机遇.

2026-04-22收到原稿, 2026-04-25收到修改稿

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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 extremely high-redshift massive galaxies discovery by the James Webb Space Telescope (JWST), challenge the 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 jointly constraint of the inclination angle $\iota$ and the luminosity distance $d_{\rm L}$ 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 $H_0 = 72.57^{+4.09}_{-4.17}\ \rm km\cdot s^{-1}\cdot Mpc^{-1}$, 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 $\Delta\iota \leqslant 0.1\,\rm rad$. 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 $d_{\rm L} \leqslant 250\,\rm Mpc$ could improve the precision of the Hubble constant measurement to $\Delta H_0/H_0 \sim 3\%$ during O5 period. With such precision, the inclination angle can be constrained to $\Delta\iota \leqslant 0.1\,\rm rad$ 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 galaxies 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 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 redshift increasing. 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 the developments in various observational projects will bring new opportunities for cosmological study.