ISSN 2959-6157

Exploring the Cosmos: Impact and Significance of the James Webb Space Telescope

Junru Niu[1, *]

[1]Abington Friends School, Jenkintown, the United States
*Corresponding author: zongan.chen@sjtu.edu.cn

Abstract:

The James Webb Space Telescope (JWST) marks a pivotal advancement in astronomical research, building upon the legacy of its predecessors by enhancing the observational capabilities and expanding the understanding of the universe. This study explores the transformative impact of JWST, emphasizing its role in studying the formation and evolution of early galaxies, stars, and planetary systems. By utilizing its advanced infrared capabilities, JWST can penetrate cosmic dust and observe celestial phenomena that were previously obscured, thereby providing unprecedented insights into the early universe and the origins of life's building blocks. The findings from JWST are expected to challenge existing theories and assumptions in cosmology and astrophysics, facilitating a paradigm shift in the comprehension of cosmic structures and the fundamental processes governing them. Furthermore, the telescope's ability to analyze exoplanetary atmospheres will contribute significantly to the search for life beyond Earth. Ultimately, the JWST not only represents a technological marvel but also serves as a cornerstone for future astronomical discoveries, shaping the conception of the cosmos for generations to come

Keywords: James Webb Space Telescope, astronomical research, early galaxies, exoplanets, cosmic evolution.

1. Introduction

Throughout most of history, humans could only observe what was visible to the naked eye and measure with tools like astrolabes [1]. The development and widespread use of telescopes expanded astronomers‘ ability to see further and to uncover more detailed information about nearby objects [2]. Brian Odom, the acting NASA Historian, also noted that telescopes have opened a new field of scientific discovery that was once beyond the imagination.

The origins of the telescope can be traced back to the Netherlands. According to Center for History of Physics, in October 1608, an evaluation of a patent registration for a gadget meant to „view distant objects as if they were near [3]. This early telescope, which employed a cylindrical object containing a convex and concave lens combination, provided a magnification of three to four times. Despite the government's decision not to grant a patent due to the device's simplicity and ease of replication, they awarded a modest prize to Jacob Metius and engaged Hans Lipperhey to manufacture several binocular models, for which Lipperhey received substantial compensation.

Over the past decades and even centuries, there are lots of scientific theories that have been proven to be wrong in later times: Before the first to recognize the fact of the planet being a round sphere, people believed that the Earth is flat. It is believed that Earth is the central point of the cosmos and all celestial bodies orbit around it until Copernicus proposed the solar system‘s heliocentric model. Moving to eras that are closer to us, according to Hurley, in the 1950s, the steady state theory was widely accepted [4]. This theory posited that the Universe is boundless, eternal, and uniform in all aspects and throughout every phase, whether historical and contemporary.

The theory recognizes that changes occur on a smaller scale, but in a sufficiently vast area of space almost billion of light years across is a where the average light output is constant over time. A comparion of the two theories is shown in Fig. 1 [5]. It addresses this by proposing that newly formed things is perpetually generated from no substance at a minuscule speed of a single particle of hydrogen in every six cubic km annually. New celestial bodies are ultimately formed by such freshly produced stuff, ensuring that, in a sufficiently vast area of the Universe, the overall density remains unchanged with time. This theory was proved to be wrong by later evidences. For instance, Maarten Schmidt investigated the radio source

3C 273, which was peculiar as its radio waves seemed to originate from a celestial being [6]. He then found which, actually, the peculiar spectrum were bright emission lines from hydrogen gas that had been wavelength-shifted. Based on Hubble‘s Law, anything having such a redshift would be hundreds of millions of light-years distant, and to look as brilliant like a star from such separation, it has to be far more luminous than one million galaxies. A typical collection diagram is presented in Fig. 2 [7].

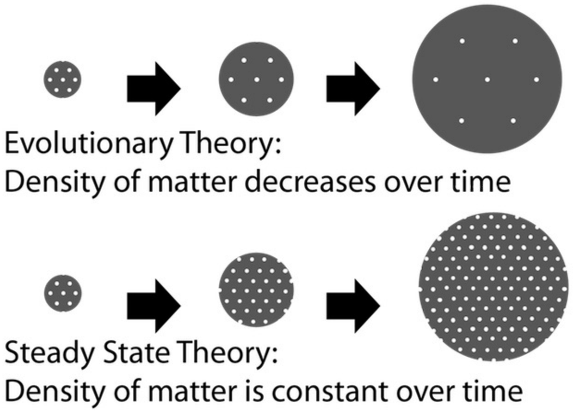

Fig. 1 A comparisons of two theories [5].

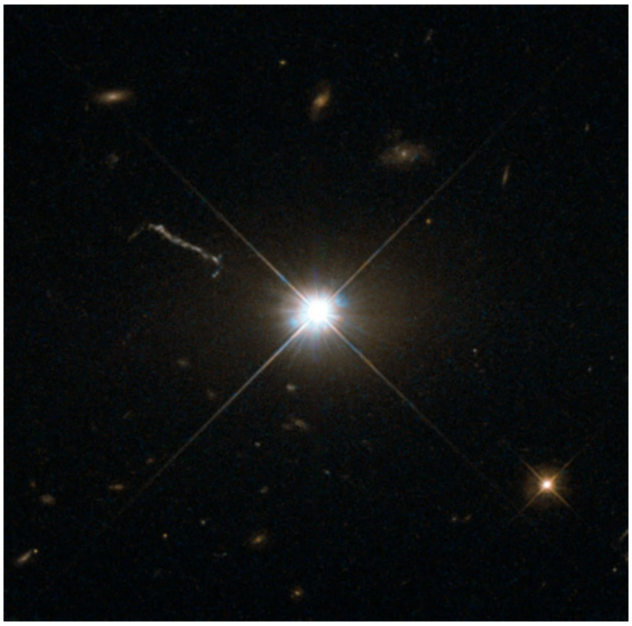

Fig. 2 Image taken by Hubble telescope [7].

Strong proof that the Universe has altered over time is provided by the fact that quasars are only present in the early Universe. Throughout the cases mentioned, it seems to show that the lack of information and observational data could cause invalid assumptions in early times although they seemed to be plausible, and eventually evolve to paradigm shifts within further discoveries. Thus, nowadays, in an era that one seems to have enough abundant information, one may curiosty about whay cause the possibilities of invalid conclusions and theories. As it known to all, in the field of modern physics, simulation is an essential tool in researching because it’s repeatable, low-cost and it’s hard to really create a precise revivification of the universe on Earth. However, a key factor of whether these simulation-based researches are successful is that the conditions used in the simulation should be accurate and current, especially in the case of astrophysics, where the cosmological constants and current theories of the universe are not absolutely sure to be true. Current and accurate data is crucial for simulations to provide reliable predictions, which is essential for making informed decisions in fields like climate science, finance, and engineering. Up-to-date data allows for the validation and calibration of simulation models, ensuring that they accurately reflect real-world conditions and thus improve their credibility and usefulness. Accurate simulations, based on current data, enable policymakers to craft effective strategies and interventions by providing a realistic assessment of potential outcomes and risks. In technology development, precise data ensures that simulations can accurately model new systems and technologies, leading to more effective design and optimization processes. Therefore, having access to directly know things about the universe is quite critical, and here comes to a main object of this research, i.e., the JWST.

2. Descriptions of JWST

Whether human beings are alone, which according to NASA, is a bold scientific project aimed at providing answers to these queries. Webb extends the achievements of earlier telescopes in orbit, advancing the understanding by exploring the beginnings of galaxies as well as the outer reaches of other planets. The principal contractor in charge of building the spacecraft bus while incorporating the telescope with its instruments was Northrop Grumman. This work was carried out at facilities in Redondo Beach, California. Then, Goddard Space Flight Center managed the general program administration, structures engineering, and mission integration. GSFC also developed the Integrated Science Instrument Module (ISIM), which houses JWST‘s scientific instruments. GSFC is located in Greenbelt, Maryland. The European Space Agency (ESA) contributed major components to JWST, including the Ariane 5 launch vehicle and the Near Infrared Spectrograph (NIRSpec). ESA‘s contributions were primarily coordinated through various member states and contractor facilities across Europe [8]. Similar to past NASA objectives, the space telescope named James Webb was conceived out of a query. „What‘s next?“ was initially posed in 1989, even before to the advent of the Hubble Space Telescope.

according to The Next Generation Telescope by the organization of the Webb telescope. NASA and the Space Telescope Science Institute (STScI) co-hosted a workshop to discuss the next step after Hubble. The text also showed that at first, scientists from NASA and STScI recognized the need for a telescope to build on Hubble‘s discoveries. The Next Generation Space Telescope was formally suggested and authorized during the mid-1990s as an infrared telescope with a mirror bigger than four meters (approximately 13 ft).

JWST is too distant from Earth for astronaut repairs, so it must be flawlessly designed and constructed, or it risks falling short of expectations. Therefore, the estimated total cost of the JWST project has been around $10 billion USD. This figure includes all aspects of the project from its inception to its planned operational phase. A significant portion of the budget went into the development and construction of the telescope itself. This includes the design, manufacturing, and testing of its various components such as the primary mirror, sunshield, instruments, and spacecraft bus. Extensive testing and integration phases were crucial to ensure the telescope’s functionality and reliability in the harsh conditions of space. Costs related to the launch vehicle (Ariane 5 rocket), launch services, and deployment operations added to the overall budget. Future costs will also include operations and maintenance of the telescope once it is deployed and begins its scientific mission.

Astronomical instruments James Webb (JWST) & Space Telescope Hubble (HST) are both powerful instruments designed for space observation, but they have significant differences in capabilities. One of the most significant differences is that JWST is designed with IR detection in mind, while HST primarily operates in the visible and ultraviolet wavelengths. This permits JWST to study objects that are too cool or too distant for Hubble to observe effectively. Compared to Hubble, JWST has a significantly bigger main mirror. Hubble‘s diameter is 2.4 meters, whereas JWST‘s mirror is 6.5 meters. A bigger mirror means JWST is able to get greater detail and gather more light for its infrared studies. JWST has a five-layer sunshield that helps to keep its instruments cold. This is crucial because JWST‘s infrared instruments need to operate at very low temperatures (around 40 Kelvin, or about -233 degrees Celsius) to find weak infrared signals coming from far-off objects without interference from its own heat. While both telescopes contribute to a wide range of astronomical research, their specific scientific goals differ due to their different capabilities. Hubble has made significant contributions to understanding the universe across various wavelengths of light, while JWST is expected to focus particularly on studying the first galaxies, stars forming in the galaxy, exoplanet atmospheres, and other infrared-sensitive phenomena [9].

The primary scientific objectives of JWST are as follows. JWST aims to explore a few of the first galaxies that formed after the Big Bang, and the very first stars that ignited in the universe. By detecting light from these ancient celestial objects, JWST will help scientists comprehend the formation and evolution of galaxies and stars over cosmic time. Besides, JWST will investigate the formation and evolution of planets and their systems, such as the Solar System and beyond. It will study the atmospheres of exoplanets, looking for signatures of Methane, carbon dioxide, water, and other chemicals that could suggest availability to live or the presence of life-supporting conditions. In addition, the telescope will peer through dust clouds within the galaxy to observe the creation of planetary systems and the emergence of stars. The infrared capabilities of JWST are essential here, as they can penetrate these dusty regions where visible light is obscured. Moreover, JWST will explore the assembly and galaxy development throughout cosmic time. It will study the interactions between galaxies, supermassive black holes‘ development at their cores, and how dark matter influences how galaxies develop. By observing molecular clouds, JWST will investigate the distribution and abundance of complex organic molecules, i.e., essential building blocks for life. This includes studying the chemistry of regions where stars and planetary systems are forming. JWST will contribute to the understanding of dark matter by observing how its gravitational influence affects the formation and composition of galaxy clusters and galaxies. It will also probe the universe‘s vast spread of matter. Through deep observations of distant galaxies and measuring the properties of supernovae and other cosmic phenomena, JWST will test and refine the models of cosmology. This includes studying the universe‘s pace of expanding and dark energy‘s characteristics.

JWST orbits around 1.5 million kilometers away Earth at the second Lagrange point (L2), whereas Hubble orbits much closer, at around 550 kilometers above Earth‘s surface. Being at L2 gives JWST a steady atmosphere with little disturbance from the Moon and Earth, which is essential for its sensitive infrared instruments. Speaking of which, there are also some other unique aspects of this location:

l Stability. A location in universe known as L2 lies beneath the combined gravitational pulls of the Earth and the Sun create a stable equilibrium for objects to remain relatively stationary with respect to both bodies. This stability allows JWST to maintain its position without expending significant amounts of fuel for station-keeping maneuvers, unlike satellites in low Earth orbit (LEO) that need periodic boosts to counteract atmospheric drag.

l Uninterrupted Observations. JWST‘s position at L2 keeps it continuously oriented to face Earth as it orbits the Sun. This means it can observe the universe without interruptions from Earth‘s shadow, which is crucial for conducting long-duration observations in infrared wavelengths. For instance, Hubble, in low Earth orbit, experiences orbit-related interruptions, limiting its continuous observation capabilities.

l Thermal Environment. L2 provides a thermally stable environment for JWST‘s sensitive instruments. By orbiting at L2, JWST can keep its instruments cold by deploying a large sunshield to keep light and warmth from the Earth, Moon, and Sun out. This shields the telescope‘s infrared detectors from external thermal interference, enabling it to detect faint heat signatures from distant objects in the universe.

l Communication. JWST‘s position at L2 makes it possible for consistent communication with Earth. It is within range of Earth-based communication systems and can transmit data back to Earth effectively. This positioning ensures that scientists can receive data and commands in a timely manner, facilitating real-time monitoring and adjustments.

Overall, the L2 point offers JWST a stable, thermally advantageous, and communication-friendly environment, perfectly suited for its mission to explore the universe in infrared wavelengths with unprecedented sensitivity and clarity.

3. Observation Results

Previously, researchers revealed that in its photographs of the cosmos taken between 500 million and 700 million years after the Big Bang, the James Webb Space Telescope (JWST) identified galaxies as big as the Milky Way [10]. According to current concepts and frameworks, these galaxies are unexpectedly massive, and the presence of mature red stars in them is too advanced for that early period. The work’s writers noted that these findings “pose significant challenges to the understanding of science.” Joel Leja, a co-author and astronomer at Penn State, commented that this discovery “raises serious questions about the established model of early galaxy formation.” The JWST captured three galaxies that are currently forming by drawing in surrounding hydrogen and helium to generate new stars and support their growth. Although these galaxies appear irregular and chaotic hundreds of millions years or less upon the Big Bang, they are expected to eventually develop into more recognizable structures, like the Milky Way’s spiraling form. They have been described as the initial “direct” pictures of a galaxy’s development captured according to Kasper Elm Heintz, the study’s principal author as well as an astrophysicist at the Cosmic Dawn Center. While the JWST has previously indicated early galaxies in more advanced stages of evolution, these images allow us to observe their initial formation and the creation of the universe’s first star systems [11].

Contemporarily, the finding of both the most ancient as well as far away galaxies ever discovered was made public by a global group of scientists., originating from just 300 million years following the Big Bang. This breakthrough, achieved with JWST, represents a significant advancement in the exploration of the early Universe. The JWST Advanced Deep Extragalactic Survey team achieved the findings, the Center for Astrophysics | Harvard University and the Smithsonian Institution (CfA) researcher in charge and leader of the JADES program, spearheaded the effort. Zihao Wu, a Harvard doctorate in candidate at CfA, and Research Scientists Ben Johnson and Phillip Cargile also contributed significantly. Due to the Universe’s expansion, as light travels, it extends to more extended wavelengths from galaxies in the distance. For these two galaxies, this stretching is so pronounced that their ultraviolet light shifts into the infrared spectrum, detectable only by JWST. Since light travels over time, further galaxies are observed like their counterparts in an earlier period. Both newly discovered record-setting galaxies are named JADES-GS-z14-0 and JADES-GS-z14-1, with JADES-GS-z14-0 being the more distanced of the two (seen from Fig. 3) [12]. Not only does JADES-GS-z14-0 set a new distance record, but it is also notable for its size and brightness. The galaxy’s size indicates that its light is largely generated by numerous nascent stellar objects, instead of by matter colliding with a gigantic black hole at its center, which would make it appear much smaller.

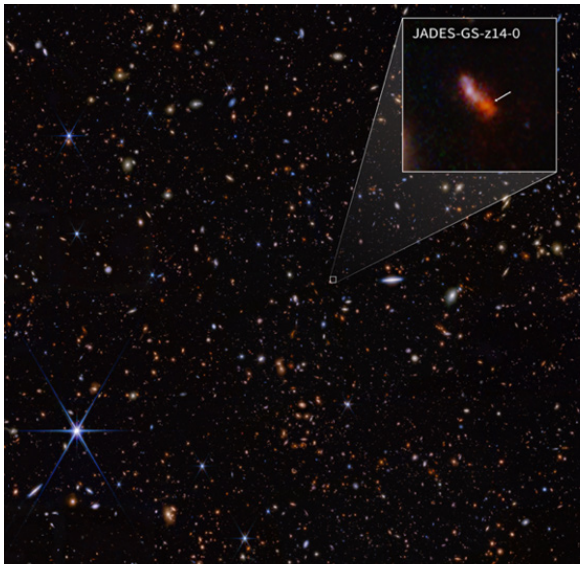

Fig. 3 JADES-GS-z14-0 Pullout (NIRCam) [12].

The extreme luminosity of JADES-GS-z14-0, driven by newly formed stars, offers the strongest evidence so far for the ancient Universe's quick creation of tremendous, enormous galaxies. When astronomers first observed earliest cosmic galaxies with NASA's JWST, they anticipated discovering small, nascent galaxies. Instead, they encountered what seemed like exceptionally large and mature galaxies. Some of these galaxies seemed to have expanded so quickly and yet massively that existing simulations cannot explain their development. This led some researchers to propose that there might be issues with the standard model of cosmology, which describes the universe's composition and evolution since the Big Bang. This finding showed in Science X again highlighted the point that existing scientific paradigms cannot be absolutely true until there's enough data.

A recent study in the Astronomical Journal, led by Katherine Chworowsky, a graduate student at the University of Texas at Austin, reveals that a couple of these ancient galaxies are considerably fewer dense than initially thought. Because of the presence of black holes in these galaxies, they seem to be significantly more luminous and larger than their true size [13]. According to Chworowsky, scholars continue to observe greater numbers of galaxies than anticipated, though not any of them have masses so massive as to 'break' the universe." The Cosmic Evolution Early Release Science Survey supplied the proof from the Webb telescope, directed by Steven Finkelstein, a UT Austin astronomical professor who co-wrote the study [12].

4. Limitations and Challenges

JWST observe ancient and distant galaxies using the fact that light needs time to travel through space, therefore, although JWST excels in observing distant and faint objects, it is still limited by the light‘s limited pace and the universe's age. Observing very early cosmic events is challenging because the light from these events is extremely faint and redshifted. In addition, considered of the features of its design, JWST's ability to study objects with certain wavelengths and its operational environments are also limited since it operates in the infrared spectrum, which means it cannot observe visible light or ultraviolet light and its instruments are very sensitive and need to be kept extremely cold to avoid interference from thermal radiation. Moreover, JWST has a smaller field of view compared to some other telescopes. This means it observes a narrower portion of the sky at any given time, which limits its ability to survey large areas.

Last year, the James Webb Space Telescope (JWST) reportedly found signs of possible life in the atmosphere of one or more distant exoplanets. The powerful space telescope reportedly detected dimethyl sulfide (DMS) in the atmosphere of the super-Earth exoplanet K2-18b, which is about 120 light-years away from Earth, which is significant because on Earth, DMS is produced primarily by marine phytoplankton. However, the new study suggests that this detection was a false positive when the JWST data were re-evaluated, resulting in the disappearance of the DMS signal. The study questions whether JWST can see DMS unless it has a very large volume in this super-Earth‘s atmosphere. The signal strongly overlaps with the methane signal, and one thinks that detecting DMS from methane is beyond the capabilities of the instrument [11]. Fortunately, this limitation might be potentially solved by collaborating the JWST with other telescopes.

JWST's findings can complement data from other observatories, like the upcoming Nancy Grace Roman Space Telescope, they could collaborate by combining their distinct observational capabilities. As mentioned previously, JWST excels in infrared observations, revealing details about the early universe and exoplanets but lack of capability of large-area surveys while the Roman Space Telescope specializes in wide-field surveys in visible and near-infrared light [14]. Together, they could provide a comprehensive view of cosmic phenomena, with JWST offering detailed follow-up observations of targets identified by Roman‘s broad surveys, fostering a more comprehensive view of the cosmos.

JWST could enable deeper exploration of the universe‘s early stages. As mentioned in the abstract of a paper by Mark.V et al, the sources of reionization are still unknown since there is a dearth of high-redshift observational data [15], this problem was solved using the Thesan project, an initiative that uses simulations and observations to study the infancy years of universe‘s genesis and development of the earliest galaxies and cosmological features. In the THESAN project, JWST provided high-resolution infrared observations that help validate and refine simulations of the early universe. This suggests that it has already contributed to the investigation of how stars, black holes, and galaxies initially formed. With the JWST, researchers could gain understanding of the star and galaxy formation processes, revealing the intricate details of cosmic evolution, mapping the distribution of dark matter and dark energy, enhancing the comprehension of the growth and structure of the cosmos. Detailed observations of exoplanet atmospheres might also be provided, potentially identifying signs of habitability or even life.

5. Conclusion

To sum up, this study realized the importance of having premier observatories such as the JWST to adjust and optimize existing simulations based on observational data. This work highlights the transformative impact of the JWST and the historical significance of telescopes in expanding on information of the universe, emphasizes that the invention of telescopes has revolutionized astronomy by enhancing observational capabilities, allowing for the discovery of previously unseen celestial bodies, and shifting the authority of astronomical knowledge from speculation to empirical evidence. The JWST, as a culmination of these advancements, represents a significant leap in the ability to explore the cosmos, particularly in studying the formation of early galaxies and the fundamental questions about the existence in the universe. As one continues to push the boundaries of astronomical research, the insights gained from telescopes like the JWST will undoubtedly form the conception of the cosmos for generations to come. All in all, the JWST could accelerate current cosmological and astrophysical research, while on the other hand, with the update of information and observational data of the early universe, there's great possibility that more and more theories and assumptions might be validated or disproved.

References

[1] Hockey T. How We See the Sky: A Naked-Eye Tour of Day & Night. University of Chicago Press, 2011.

[2] Kitchin C R, Kitchin C R. Telescopes and Techniques. Springer, 2013.

[3] Harrison E. Cosmology: the science of the universe. Cambridge University Press, 2000.

[4] Hoyle F, Bondi H. The steady state theory. Google Books, 1958.

[5] NASA's Cosmic Times. Origin of Everything: Hot Bang or Ageless Universe? Retrieved from: https://imagine.gsfc.nasa.gov/educators/programs/cosmictimes/online_edition/1955/images/steady_state_big_bang_lg.jpg

[6] Greenstein J L, Schmidt M. The quasi-stellar radio sources 3c 48 and 3c 273. A Source Book in Astronomy and Astrophysics, 1900–1975. Harvard University Press, 1979: 811-818.

[7] NASA Hubble Mission Team. NASA's Hubble Gets the Best Image of Bright Quasar 3C 273. Retrieved from: https://science.nasa.gov/wp-content/uploads/2023/04/potw1346a-jpg.webp?w=2560&format=webp

[8] Rigby J, Perrin M, McElwain M, et al. The science performance of JWST as characterized in commissioning. Publications of the Astronomical Society of the Pacific, 2023, 135(1046): 048001.

[9] Clampin M. Recent progress with the JWST Observatory. Space Telescopes and Instrumentation 2014: Optical, Infrared, and Millimeter Wave. SPIE, 2014, 9143: 914302.

[10] Mann A. The James Webb Space Telescope prompts a rethink of how galaxies form. Proceedings of the National Academy of Sciences, 2023, 120(32): e2311963120.

[11] Howell E. NASA's James Webb Space Telescope mission: Live updates, 2020, Retrieved from: https://www.space.com/news/live/james-webb-space-telescope-updates

[12] NASA, ESA, CSA. JADES-GS-z14-0 Pullout (NIRCam). Retrieved from: https://webbtelescope.org/contents/media/images/01HZ083EXXCJNE64ERAH2ER2FM.

[13] Chworowsky K, Finkelstein S L, Boylan-Kolchin M, et al. Evidence for a Shallow Evolution in the Volume Densities of Massive Galaxies at $ z= 4$ to $8 $ from CEERS. arxiv preprint arxiv:2311.14804, 2023.

[14] Meinke B, Milam S. JWST: Launch, Commissioning, and Cycle 1 Science. Proceedings of the International Astronomical Union, 2018, 14(A30): 423-446.

[15] Yeh J Y C, Smith A, Kannan R, et al. The thesan project: ionizing escape fractions of reionization-era galaxies. Monthly Notices of the Royal Astronomical Society, 2023, 520(2): 2757-2780.