# Analysis and Comparison of the State-of-Art Telescopes: Evidence from JWST, EHT and FGST

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Keywords: Telescope, EHT, JWST, FGST.

Abstract: As a matter of fact, the telescope has been a crucial tool in advancing astronomical knowledge since its invention in the early 17th century. From Hans Lippershey's initial patents to Galileo Galilei's improvements, the telescope has undergone a substantial evolution, reaching its current state as a sophisticated and innovative instrument. These developments have facilitated a more profound comprehension of the universe, enabling the observation of galaxies, stars, and planets, and have also propelled the investigation of dark matter and energy. This paper examines the significant contributions and prospects of three advanced telescopes: the James Webb Space Telescope (JWST), the Event Horizon Telescope (EHT), and the Fermi Gamma-ray Space Telescope (FGST). Through a comparative analysis of their research outcomes and technical specifications, this study elucidates their role in contemporary astronomical research. Furthermore, this research discusses the current challenges and the potential for future innovations that will continue to advance the understanding of the universe.

## 1. INTRODUCTION

The telescope has been a seminal instrument in advancing astronomical knowledge since its inception in the early 17th century. In 1608, Hans Lippershey, a Dutch eyeglass maker, submitted a patent to the Dutch Parliament, which, at the time, was the highest authority in the country. Therefore, Lippershey is considered the first to invent the telescope. However, the Dutch Parliament should have regarded as Hans's knowledge of the device. Subsequent reports from that period were disseminated, and in 1609, the Italian scientist Galileo Galilei implemented structural modifications to the telescope based on Hans Lippershey's account. Galileo constructed his initial telescope (subsequently designated the "Galilean telescope") with a convex objective lens and a concave eyepiece. He utilized this instrument to conduct a substantial number of astronomical observations. Such observations included the discovery that Venus revolves around the Sun. This challenged the geocentric model and supported the heliocentric theory proposed by Nicolaus Copernicus. These findings laid the foundation for modern astronomy.

The design and capabilities of telescopes have undergone significant evolutions over the years. These evolutions have encompassed a range of innovations, from the simple refracting telescope used by Galileo to the reflecting telescope invented by Isaac Newton and on to the space telescopes. All these innovations have greatly enriched mankind's understanding of the universe. The successful launches of the HST and the JWST have further advanced the frontiers of astronomical research.

Telescopes are essential in basic astronomical research, helping scientists observe and study galaxies, stars, and planets and making significant contributions to exploring the origin of the universe, dark matter, and dark energy, among other areas. For example, observations from the HST have helped to confirm the accelerated expansion of the universe. At the same time, the JWST has excellent performance in infrared observations and is capable of capturing information about the more distant and earlier universe.

In recent years, significant advancements have been made in the field of telescopes. Notable among

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Hong, Y.
Analysis and Comparison of the State-of-Art Telescopes: Evidence from JWST, EHT and FGST.
DOI: 10.5220/0013075400004601

In *Proceedings of the 1st International Conference on Innovations in Applied Mathematics, Physics and Astronomy (IAMPA 2024)*, pages 300-306
ISBN: 978-989-758-722-1

these are the JWST, the EHT, and the FGST, which may be considered the three most representative advanced telescopes. The JWST was successfully launched in 2021 (Dicken et al., 2024). The JWST's primary strengths lie in infrared astronomy. Due to its considerable dimensions, the JWST is equipped with instruments of exceptional sensitivity and resolution, enabling astronomers to study the initial galaxies and stars in the universe, thereby providing further ideas into the formation and evolution of the universe (Crompvoets et al., 2023). The telescope's achievements extend beyond the observation of the formation of stars and galaxies. Its contributions to the understanding of phenomena, such as the formation of the universe, are also significant. The EHT is a network of multiple radio telescopes worldwide (Akiyama et al., 2021a). It is a global network of radio observatories or radio telescope facilities that enables high-resolution observations using Very-long-baseline Interferometry (VLBI). The underlying principle is to utilize a multitude of radio antennas in a phased array configuration, thereby achieving a larger effective aperture and enhanced angular resolution. In 2019, the EHT achieved the first-ever capture of a black hole event horizon, measuring it at a wavelength of 1.3 millimeters and attaining a theoretical diffraction-limited resolution of 25 microarcseconds. The black hole is situated at the core of Messier 87 and is designated M87* (Patel et al., 2022). This achievement has been celebrated as a significant advancement in astronomical research, significantly enhancing the understanding of black holes and their environment. Moreover, it constituted a test of Einstein's general theory of relativity. FGST, previously designated the Gamma-ray Large Area Space Telescope (GLAST), is a space-based observatory designed to study high-energy gamma rays. The spacecraft was successfully launched in June 2008 and was named in honor of the renowned physicist Enrico Fermi. It is a space observatory whose principal function is the observation of gamma rays in low Earth orbit. The observatory houses two principal instruments: the Large Area Telescope (LAT), which is used to study active galactic nuclei, pulsars, and dark matter, and the Gamma-ray Burst Monitor (GBM), which is employed to examine gamma-ray bursts and solar flares.

As a fundamental instrument in astronomical research, telescope technology's ongoing advancement and implementation plays a pivotal role in propelling scientific progress. The objective of this paper is to examine the significant contributions and prospective avenues of advancement of the three cutting-edge telescopes (JWST, EHT, and FGST) in contemporary astronomical research. This will be achieved through a comparative analysis of their research outcomes and technical specifications. Additionally, the paper will present a comprehensive overview of the telescopes and discuss the constraints inherent to existing telescopes. The rest part is organized as follows. Sec. 2 gives an introduction to the definition, classification, development, and number of telescopes. Sec. 3 focuses on the JWST, focusing on its use, principles, instruments, and recent results. Sec. 4 presents a detailed examination of the EHT, encompassing its applications, underlying principles, instrumentation, and recent outcomes. Sec. 5 presents a detailed examination of the FGST, encompassing its applications, underlying principles, instrumentation, and recent outcomes. Sec. 6 shows an examination of the constraints of contemporary telescopes and proposals for future developments. A brief summary is given in Sec. 7.

## 2 DESCRIPTION OF TELESCOPE

Telescopes are defined as devices that detect distant objects by emitting, absorbing, or reflecting electromagnetic radiation from them. The fundamental concept is to utilize a lens or reflector to collect and focus electromagnetic radiation, thereby creating an enlarged image that enables the human eye or other detectors to observe greater detail. The visible light band does not constrain telescopes, but rather, they encompass the entirety of the electromagnetic spectrum, extending from radio waves to gamma rays. The term "telescope" was first used by the Greek mathematician Giovanni Demisiani in 1611 to describe an instrument that was subsequently provided to Galileo. The word "tele" is derived from the Greek word for "far," while "skopein" means "to see." Thus, the term "teleskopos" can be translated as "to see far."

Telescopes can be classified according to three primary criteria: their working principle, observing bands, and intended use. Refracting telescope employs a lens as an objective lens to refract light, thereby forming an image. This particular telescope design enjoyed considerable popularity during the late 19th century, but is now more commonly employed in other optical devices, including binoculars and telephoto lenses. Reflecting telescope employs a combination of single or multiple curved mirrors to reflect light and form an image. The inaugural reflecting telescope was devised by Isaac Newton in the 17th century; however, it was still imperfect and generated optical aberrations. The HST employs this technique. Catadioptric Telescopes integrates the principles of refraction and reflection with lenses and mirrors that function in conjunction to reduce aberration and chromatic aberration and enhance image quality.

The classifications according to the observation wavelength is as follows. Optical telescope collects and gathers light from the visible part of the electromagnetic spectrum. Three methods are employed to generate images: refraction, reflection, and retroreflection. Radio telescopes are employed to observe radio waves, with large dish antennas typically utilized to collect and focus radio wave signals. These devices possess a single receiver, which can record a single signal. Infrared detectors and cooling systems can be employed to observe the infrared band and reduce thermal noise. All celestial objects have a temperature are observed to emit electromagnetic radiation. Ultraviolet telescopes are used to observe in the ultraviolet band, and they must be operated in space since most of the ultraviolet light is absorbed by the atmosphere. X-ray telescopes are used to observe the X-ray band, employing special mirrors and detectors to focus and detect high-energy X-rays. Gamma-ray telescopes are used to observe the gamma-ray spectrum, and they utilize coded aperture masks to generate images. They are typically mounted in Earth orbit.

According to the usage location, they can be categories as follows. Ground-based telescopes are mounted on the Earth's surface. They typically have large-aperture mirrors and advanced observing techniques, as well as advanced optical systems for data acquisition and analysis. They are less expensive than space-based telescopes and can be easily upgraded and maintained, such as the European Southern Observatory (ESO) in Chile. Challenges include atmospheric interference and limited observations due to weather or seasons. Space-based telescopes are installed outside the Earth's atmosphere, such as the HST and the JWST. The advantages are that there is no Earth's atmosphere to interfere with the instrument's camera, it has a very stable window, and different wavelengths can be detected by different telescopes. The disadvantages are that space telescopes are expensive to launch and build, and have a very short lifetime. Space telescopes are difficult to maintain and upgrade compared to ground-based telescopes.

The technology and applications of telescopes have continued to develop and expand, and since the mid-20th century, advances in electronics and computer technology have greatly increased the power and resolution of telescopes. Computers can help people make simulations and predictions. Modern optical telescopes have evolved to use adaptive optics, astigmatism, and optical interferometry to overcome atmospheric disturbances and greatly improve image resolution. Large ground-based optical telescopes such as the Keck Telescope and the Very Large Telescope are representative. Radio telescope arrays such as the VLA in the United States and the FAST in China are among the telescopes. They have achieved significant results in the search for dark matter and black holes. The JWST is the most advanced infrared space telescope available and will advance the study of the early universe and galaxy formation; the Nancy Grace-Roman Space Telescope, to be launched around 2027, will be in a Sun-Earth $L_2$ orbit.

There are a number of ground-based and space-based telescopes located around the world and in space. Ground-based telescopes are mainly located in areas that are less affected by the Earth's atmosphere and less air pollution, such as Hawaii, the Atacama Desert in Chile, and the Canary Islands. Space telescopes are mainly located in Low Earth orbit or deeper space, such as HST and JWST, which one is in Low Earth orbit and one is in Sun-Earth L2 orbit. According to statistics, there are 29 active space telescopes and over 350 ground-based telescopes.

## 3 JAMES WEBB SPACE TELESCOPE

JWST uses MIRI (Mid Infrared Instrument), NIRCam (Near Infrared Camera), NIRISS (Near Infrared Imager and Slitless Spectrograph) and NIRSpec (Near Infrared Spectrograph) as imaging methods. In wavelength range $0.6\mu m<\lambda<5\mu m$, NIRCam will be responsible for imaging by using modes of parallel or primary. In wavelength range $0.8\mu m <\lambda<5\mu m$, NIRISS will be responsible for imaging by using modes of parallel or primary (Lau et al. 2024). In wavelength range $5.6\mu m<\lambda<25.5\mu m$, NIRISS will be responsible for imaging by using modes of parallel or primary. In wavelength range $0.6\mu m<\lambda<5.3\mu m$, NIRSpec enables to analyze the formation of galaxy and characteristics of stellar populations (Whalen et al., 2012). MIRI's FOV (field of view) covers an area of 112.6" by 73.5", which covers wavelength from 5.6 to 25.5 μm. It has 9 broadband filters: F560W, F770W, F1000W, F1130W, F1280W, F1500W, F1800W, F2100W, F2550W (seen from Table 1).

Table 1: All MIRI broadband filters are broadband (λ/Δλ ~ 5) except F1130W, which isolates the 11.3μm PAH emission feature (λ/Δλ ~ 16) explicitly.

| Filter Name | λ0 (μm) | Feature(s) |
|---|---|---|
| F560W | 5.6 | Broadband Imaging |
| F770W | 7.7 | PAH, broadband imaging |
| F1000W | 10 | Silicate, broadband imaging |
| F1130W | 11.3 | PAH |
| F1280W | 12.8 | Broadband imaging |
| F1500W | 15 | Broadband imaging |
| F1800W | 18 | Silicate, broadband imaging |
| F2100W | 21 | Broadband imaging |
| F2550W | 25.5 | Broadband imaging |

NIRCam's FOV covers a 9.7 arcmin2 with range of $0.6 - 2.3\ \mu m\ (0.031''/pix)$ and $2.4 - 5.0\ \mu m\ (0.063''/pix)$. It is separated into two channels: short wavelength channel and long wavelength channel. In short wavelength, its FOV is 2 × 2.2'× 2.2' with 4" – 5" gaps and imaging pixels can reach 8 × 2040 ×2040 pixels. Its long wavelength channel's FOV is 2 × 2.2'× 2.2' and imaging pixels can reach 2 × 2040 ×2040 pixels. These two channels allow it to peer through dust clouds that obscure visible light, revealing objects and phenomena that are hidden from view. It has 4 observing modes, which cover a wavelength range from 0.8 – 5 μm. Those four observing modes are WFSS, SOSS, AMI, and Imaging. WFSS has wavelength coverage of $0.8 - 2.2\ \mu m$ with pixel scale of 0.066"/ pixel (arcsec/pixel). It has a FOV of 133×133 arcsec. Its resolving power $(R = \lambda / \Delta\lambda)$ is 150 @ 1.4 μm. SOSS has wavelength coverage of $0.6 - 2.8\ \mu m$ with pixel scale of 0.066"/pixel (arcsec/pixel). It uses a R = λ/Δλ = 700 grism to disperse the light from the target object into its constituent wavelengths without the use of a slit. AMI has the highest spatial resolution imaging which employs a mask with 7 small holes or sub-apertures and turns the full aperture of JWST into a interferometric array to analyze to reconstruct high-resolution images. Its FOV is 5.2 × 5.2 arcsec with pixel scale of 0.066" / pixel. Imaging mode allows NIRISS to capture high-resolution images in the near-infrared spectrum from wavelength range of 0.8 – 5 μm. Since NIRISS has 12 filters (except F158M), NIRCam has correspond filter which can help imaging. When NIRISS and NIRCam work at same time for imaging, NIRISS will become the third channel for NIRCam including long wavelength channel and short wavelength channel. It designs to perform spectroscopy in the near-infrared spectrum from $0.6 - 5.3\ \mu m$ within a 3.4 × 3.6 arcmin FOV, using MSA, IFU, and FSs. Each observing mode have different aperture or slit size (arcsec): MSA has aperture of 0.20 × 0.46; IFU has aperture of 3.0 × 3.0; FSs has three size 0.2 × 3.2, 0.4 × 3.65, 1.6 × 1.6; and BOTS has aperture of 1.6 × 1.6. Their wavelength coverage including range can also be separated into five parts: 0.6-5.3 μm (prism), 0.7-1.27 μm (f070lp), 0.97-1.89 μm (f100lp) , 1.66-3.17 μm (f170lp) and 2.87-5.27 μm (f295lp).

The JWST is comprised of three primary components: the spacecraft bus and sun shield, the OTE, and the ISIM. The JWST is divided into two sections: a 300K section facing the Sun and a 40K section facing away from the Sun. The sun shield is employed to safeguard the OTE and ISIM from solar radiation, thus preventing overheating of the equipment. Due to its capacity to permit only 1W of heat transfer, the shield is capable of maintaining the essential components of the telescope at the requisite low temperatures without the use of consumable refrigerants. This is made possible by its distinctive five-layer polyimide film (such as Kapton), with each layer coated with a reflective material to minimize heat transfer. Each layer is approximately 21 meters long and 14 meters wide.

In September 2023, the JWST identified the presence of carbon-based molecules in the atmosphere of the exoplanet K2-18 b, which is hypothesized to possess an ocean. Prior research and observations conducted with the HST have indicated that the planet may be a "Hycean" world, characterized by the presence of liquid water, which is an essential component of life. K2-18 b has a radius that is two to three times that of the Earth and is situated approximately 120 light-years from the solar system. The planet has a mass approximately 8.6 times that of Earth and is situated within the habitable zone of its star, indicating that this region is neither excessively hot nor cold. The most recent findings indicate the presence of carbon dioxide and methane in the atmosphere of K2-18 b, yet no ammonia has been detected. This could be indicative of the existence of a water-rich ocean beneath the hydrogen-dominated atmosphere. This could contribute to the understanding of the atmospheric and environmental conditions of sub-Neptunian and Hycean worlds.

# 4 THE EVENT HORIZON TELESCOPE

The EHT is a globally distributed network of radio telescopes that employs a technique called Very Long Baseline Interferometry (VLBI). This technique enables the network to achieve extremely high angular resolution by combining multiple long-range radio telescopes to form an Earth-sized virtual telescope. VLBI is a technique for observing the same object by synchronizing radio telescopes situated at disparate locations. The resolution of the system is directly proportional to the baseline distance between the telescopes (Zhang et al., 2024). Each telescope collects and records a substantial quantity of radio data (Psaltis, 2019). To guarantee the accuracy of the data, an atomic clock, is utilized to provide an accurate time reference. The data are transmitted to a data center via a high-speed data chain, where the two data sets are compared and multiplied by the speed of light, thereby yielding the geometric distance along the line of sight to the quasar. More precisely, the VLBI can be considered to be a radio interferometer. Two antennas are oriented towards the same location in the sky, with the signal emitted by antenna 1 being at a distance of τg greater than that of antenna 2. The two signals are then multiplied together and averaged into a correlator, which results in a complex number, denoted phase by $2\pi\tau g c/\lambda$. Here, λ is the wavelength of the received radio waves and c is the speed of light. However, the resulting phase would be exceedingly large. To reduce the phase to zero, it is sufficient to introduce a compensating delay τg at the second antenna, thereby enabling the array to alter its orientation with respect to the target source in the sky, despite the Earth's rotation. For HT, the radio antennas are separated by considerable geographic distances. These include the ALMA, APEX, the IRAM 30-meter telescope, the JCMT, and the LMT. These include the SMA, SMT, SPT, the Greenland Telescope, the NOEMA in France, and the Arizona ARO 12-meter Telescope at Kitt Peak. The EHT's VLBI is now capable of observing at a wavelength of 1.3 millimeters, representing the shortest wavelength currently available. At each site, it records radio waves at a rate of 64 gigabits per second.

Image reconstruction is the process of converting processed radio data into a visual representation. As individual telescope observations are frequently incomplete and noisy, image reconstruction necessitates the application of sophisticated algorithms and models to fill data gaps and remove noise. This motivates the use of principal-component interferometric modeling (PRIMO), which is trained on a large number of accretion black hole simulation images (Akiyama et al., 2021a; Akiyama et al., 2021b). This approach employs principal components analysis (PCA) to achieve high-fidelity general relativistic magnetohydrodynamic (GRMHD) results. Subsequently, the data are subjected to analysis employing the Markov Chain Monte Carlo (MCMC) PCA components of the Fourier transform of the linear combination space. A sketch is shown in Fig. 1.

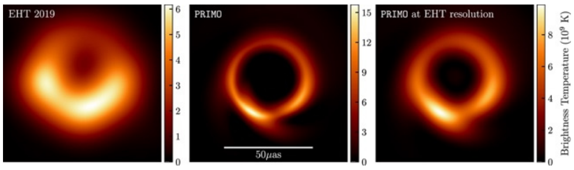

Figure 1: The image on the far left depicts EHT's data from 2017, the image in the middle represents the result of reconstructing the image after PRIMO, and the image on the far right is a combination of the two. It is evident that the resolution has increased significantly, and the diameter and bezel width have decreased (Akiyama et al., 2021a).

Since its inception, the EHT has yielded a number of significant scientific findings, particularly in the domain of supermassive black holes. The initial outcome was the dissemination of the inaugural image of the black hole situated at the nucleus of the M87 galaxy. In April 2019, the EHT team published the first photograph of a black hole, marking a significant milestone in the history of astronomy. The black hole is situated within the galaxy M87, approximately 55 million light-years from Earth. In the image, a bright ring-like structure with a dark central region is evident, which is believed to represent the event horizon of the black hole. This validated Einstein's theory of general relativity and furnished insights into the genesis and dynamics of black hole jets. In 2023, the EHT released a new image of the M87 black hole, created using the PRIMO algorithm. The second result was an image of Sagittarius A*, a black hole at the center of the Milky Way (Medeiros et al., 2023). The image is of markedly greater clarity, and the black hole is observed to exhibit reduced activity, with an accretion rate that is similarly low. The results provide data regarding the event horizon of black holes, the material in their vicinity, and the effects of these phenomena.

## 5 THE FERMI GAMMA-RAY SPACE TELESCOPE

The imaging methodology employed by the Fermi telescope is contingent upon the capabilities of its two principal instruments: the Large Area Telescope (LAT) and the Gamma-ray Burst Monitor (GBM). The Large Area Telescope is responsible for the capture and imaging of gamma rays from the universe. It covers the energy range from about 20 MeV to more than 500 GeV, with a FOV of about 2.4 steradians. The process is comprised of four distinct steps: gamma-ray detection, energy measurement, orientation reconstruction, and image reconstruction. Gamma rays interact with the telescope material, creating electron-positron pairs that are detected by LAT silicon microstrip detectors and trackers (Thompson, 2022). Subsequently, the calorimeter below measures the energy of these particles and records the data. Following the collection and subsequent software analysis of the gamma-ray events, the data is converted into images of the objects in order to facilitate their visualization. The GBM represents the second principal instrument of the FGST for the detection and study of GRBs. The instrument is comprised of 14 scintillation detectors, 12 sodium iodide crystals (NaI), and two bismuth germanate crystals (BGO), which collectively cover the 10 keV - 40 MeV energy range. This also guarantees that the FGST is capable of continuous operation, always monitoring the sky and detecting GRBs in a prompt manner. Moreover, the GBM can measure the energy spectrum of gamma-ray bursts, thereby confirming the energy distribution and process of these bursts.

Although the FGST is still operational, it has exceeded its design lifespan and has yielded significant scientific insights in the field of astrophysics. LAT observations have found thousands of gamma-ray sources, including stars, galaxies, and explosions. Additionally, the GBM has detected a considerable number of gamma-ray bursts, yielding a substantial corpus of data. The FGST has fulfilled its intended purpose. Furthermore, the FGST has detected gamma-ray signals from dark matter and observed high-energy gamma rays. These observations provide a crucial scientific foundation for understanding the most extreme physical processes in the universe.

## 6 LIMITATIONS AND PROSPECTS

A comparative analysis of the various telescopes reveals that each is subject to inherent limitations. For instance, the JWST is constrained by operational temperature, field of view, and maintenance requirements over its lifetime. The JWST relies heavily on its sunshade and passive cooling system to maintain its operation, as extremely low temperatures are required to prevent the infrared (IR) detector from being affected by thermal radiation. Secondly, the JWST has a relatively narrow field of view, which restricts its ability to observe a comprehensive area simultaneously. If observations are to be made over a large area of the sky, it is necessary to undertake multiple observations, which are then spliced together. This approach compromises both efficiency and accuracy. Additionally, the JWST is situated at a considerable distance from Earth, which will render repairs to the telescope a challenging undertaking in comparison to the Hubble telescope. The EHT is constrained by the diameter of the Earth, meteorological conditions, and the intricacy of the data. Although the EHT's VLBI technology is highly sophisticated, its largest span is the diameter of the Earth, which represents the only viable means of observing the target star. This renders observation of certain minute or remote objects unfeasible. Secondly, the EHT necessitates favorable meteorological conditions across multiple regions simultaneously, which is not a reliable or consistent occurrence. In addition, the EHT requires the processing of highly intricate data, which results in the generation and analysis of images that are time-consuming and laborious. Furthermore, the FGST is constrained by limitations in energy range and resolution. Its energy range extends from 20 MeV to 500 GeV, and it cannot observe gamma rays at either lower or higher energies. Secondly, the spatial and temporal resolutions of the FGST and LAT are insufficient for observing subtle variations in phenomena with efficiency.

The future of telescopes will likely involve coordinated observations across multiple wavelength bands and an increased demand for high-resolution and sensitive instruments. By simultaneously observing data in different bands, the telescope will facilitate a more comprehensive understanding of the physical properties of celestial objects and enable the revelation of details that cannot be observed in a single band. The resolution and sensitivity of a telescope are the primary determinants of its observational capability. The forthcoming generation of telescopes, exemplified by the WFIRST, will possess enhanced resolution and sensitivity, thereby facilitating more comprehensive investigations of the early universe and the center of the Milky Way.

## 7 CONCLUSIONS

The telescope has been a vital tool in the advancement of astronomical knowledge since it was invented in the early 17th century. The technology and capabilities of telescopes have changed a lot over time. Modern telescopes, such as the JWST, the EHT, and the FGST, represent the cutting edge of astronomical research today. The main strength of the JWST lies in infrared astronomy, where its high sensitivity and resolution allow it to study the initial galaxies and stars in the universe. The EHT with VLBI has captured an image of the black hole at the center of the Galaxy M87. The FGST studies high-energy gamma rays and other phenomena. The successful launches and observations of these telescopes have really moved the needle in astronomy. They've helped scientists observe and study galaxies, stars, planets, the origins of the Universe, dark matter and dark energy, and more. With further tech development, one will see even more from these telescopes.

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