

Very Large Area Gamma-ray Space Telescope Program

Authors: Fan Yizhong, Chang Jin, Guo Jianhua, Yuan Qiang, Hu Yiming, Li Xiang, Yue Chuan, Huang Guangshun, Liu Shubin, Feng Changqing, Zhang Yunlong, Wei Yifeng, Sun Zhiyu, Yu Yuhong, Kong Jie, Zhao Chengxin, Zang Jingjing, Jiang Wei, Pan Xu, Wei Jiaju, Wang Shen, Duan Kaikai, Shen Zhaoqiang, Xia Ziqing, Xu Zunlei, Feng Lei, Huang Xiaoyuan, Cai Yuelin, Wei Junjie, Zeng Houdun, He Haoning, Li Jian, Yang Ruizhi, Yan Jingzhi, Zhang Yi, Wu Xuefeng, Wei Daming, Yizhong Fan, Chang Jin

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Abstract

High-energy gamma-ray detection represents one of the primary approaches for investigating extreme astrophysical phenomena. Space-based high-energy gamma-ray detection provides exceptional advantages, including wide energy band coverage, excellent temporal continuity, and high energy resolution. Building upon the successful development and operation of China's first astronomical satellite—“Wukong”, the Purple Mountain Observatory, in collaboration with several domestic institutions, has proposed the development of the Very Large Area gamma-ray Space Telescope (VLAST). This telescope will achieve an acceptance as high as $10 \text{ m}^2 \cdot \text{sr}$ in the GeV–TeV energy range and will possess strong detection capabilities in the MeV–GeV band, with its overall performance expected to exceed that of the Fermi Large Area Telescope (Fermi-LAT) by more than an order of magnitude. This paper primarily introduces the main scientific objectives, preliminary detector configuration, and anticipated performance specifications of VLAST.

Full Text

Abstract

High-energy gamma-ray detection is one of the primary approaches for studying extreme astrophysical phenomena. Space-based detection of high-energy gamma rays offers distinct advantages including broad energy coverage, excellent temporal continuity, and high energy resolution. Building upon the successful development and operation of China's first astronomical satellite, the

Dark Matter Particle Explorer (DAMPE), the Purple Mountain Observatory, in collaboration with several domestic institutions, proposes a new satellite mission: the Very Large Area gamma-ray Space Telescope (VLAST). This telescope will achieve an acceptance of approximately $10 \text{ m}^2 \cdot \text{sr}$ in the GeV–TeV energy band while maintaining strong detection capabilities in the MeV–GeV range, representing an overall performance improvement of more than tenfold over the Fermi Large Area Telescope (Fermi-LAT). This paper focuses on introducing VLAST's primary scientific objectives, preliminary detector configuration, and expected performance metrics.

Key words: Instrumentation: detectors, Gamma rays: general, Radiation mechanisms: non-thermal, Astroparticle physics

2.1 Indirect Detection of Dark Matter Particles

Numerous astronomical observations across cosmological to sub-galactic scales have demonstrated the existence of abundant dark matter in the universe. Its total mass is approximately five times greater than that of ordinary matter composing stars and interstellar medium, accounting for roughly one-quarter of the universe's total energy content. The prevailing theoretical framework posits that dark matter consists of one or more new particles beyond the Standard Model, characterized by substantial mass and weak interactions. This theory naturally explains dark matter's production, abundance, and structural distribution. Based on this theoretical model, three detection approaches have been proposed: direct detection of dark matter collisions with ordinary matter, production of dark matter particles in high-energy particle colliders, and indirect detection through observations of cosmic rays, gamma rays, and neutrinos. In addition to these weakly interacting massive particles (WIMPs), diverse alternative dark matter candidates exist theoretically, such as sterile neutrinos, axions, and ultra-light bosonic dark matter. As a next-generation flagship space-based gamma-ray observatory featuring large acceptance and high energy resolution, VLAST holds the potential to achieve major breakthroughs in various forms of dark matter indirect detection.

2.1.1 Dark Matter Line Spectrum Search Dark matter may annihilate or decay into final states such as $\gamma\gamma$ or γZ^0 , producing monochromatic gamma-ray line spectra [39]. Since astrophysical processes typically generate continuous gamma-ray spectra above the GeV range, discovering a spectral line would indicate an unknown process originating from dark matter or new physics. Over the past decade, numerous studies have searched for such line signals in the Galactic Center, galaxy clusters, and dwarf galaxies using Fermi-LAT data, with some tentative line-like features reported [40–41]. However, some of these results were later attributed to systematic uncertainties, while others lacked sufficient statistical significance to confirm their authenticity. To date, no definitive line signal above the GeV band has been conclusively identified [42]. The DAMPE satellite also conducted a blind all-sky search for line signals, yielding null results [22].

The sensitivity of line signal detection depends on two critical factors: energy resolution and statistics. VLAST will significantly surpass previous experiments in both aspects, substantially improving line search sensitivity. This will enable testing of tentative signals present in Fermi-LAT data and potentially lead to the first discovery of monochromatic gamma-ray lines.

2.1.2 Dark Matter Signal Search in the Galactic Center The Galactic Center has long been a prime target for dark matter indirect detection due to its proximity to Earth and the expected high density of dark matter distribution. Since Fermi's launch, multiple research groups analyzing Fermi-LAT data have suggested the presence of an approximately spherically symmetric excess in the GeV band continuous spectrum at the Galactic Center. Its spatial distribution and spectral shape can be explained by dark matter annihilation with masses of tens of GeV, with an annihilation cross-section consistent with standard thermal dark matter model predictions [8–9]. Given that this gamma-ray excess and the subsequent AMS-02 antiproton excess can be described by similar dark matter parameters [14–15], the Galactic Center GeV gamma-ray excess has become a particularly intriguing dark matter candidate signal. However, some studies indicate that this excess can also be explained by numerous millisecond pulsars, which, due to fluxes below Fermi-LAT's sensitivity threshold, may be misidentified as diffuse emission [43–44]. Limited by Fermi-LAT's statistics, a definitive distinction between the dark matter and millisecond pulsar interpretations remains impossible. Further investigation of the spatial and spectral distribution of the Galactic Center GeV excess, along with searches for faint millisecond pulsars near the Galactic Center, will be among VLAST's key scientific objectives, providing crucial evidence for the physical nature of this excess. Dark matter particle annihilation or decay in the Galactic halo will also produce diffuse gamma radiation, particularly if substantial dark matter substructures exist, making the resulting gamma-ray emission potentially significant. VLAST will probe potential dark matter signals in the Galactic halo through precise measurements of diffuse gamma-ray spectra and spatial distributions.

2.1.3 Dark Matter Signal Search in Dwarf Spheroidal Galaxies Dwarf spheroidal galaxies are characterized by sparse stellar and gaseous content, with dark matter dominating their total mass. Existing dynamical measurements indicate that in some dwarf spheroidal galaxies, dark matter mass can be thousands of times greater than the mass of stars and gas. For high-latitude dwarf spheroidal galaxies, the scarcity of black holes and neutron stars means they generally do not produce strong gamma-ray emission. Consequently, any detected gamma-ray radiation would likely originate from dark matter annihilation. Fermi-LAT data have not revealed definitive gamma-ray signals from dwarf spheroidal galaxies [45], although faint excesses observed in individual systems remain ambiguous, potentially representing statistical fluctuations [46–47]. Fermi-LAT observations toward several dwarf spheroidal galaxies have excluded the possibility of dark matter particles annihilating to quark or lepton

pairs with thermally produced cross-sections across broad parameter spaces [48]. However, these constraints depend on the total mass and spatial distribution of dark matter within dwarf spheroidal galaxies, introducing certain uncertainties [49]. VLAST's enhanced sensitivity will enable detection of fainter gamma-ray sources, potentially leading to the first discovery of gamma-ray emission from dwarf spheroidal galaxies and allowing investigation of whether such emission arises from dark matter annihilation or decay.

2.1.4 Axion and Axion-Like Particle Dark Matter Signal Search Axions are hypothetical elementary particles proposed in particle physics to resolve the strong interaction charge-parity problem (the renowned strong CP problem). Research has shown that axions also satisfy the primary characteristics of dark matter, making axions and their generalized axion-like particles (ALPs) compelling dark matter candidates. In electromagnetic fields, axions and ALPs can interconvert with photons. This property enables indirect detection of axions and ALPs by searching for characteristic photon-ALP oscillation signatures in the spectra of gamma-ray sources. Gamma-ray observations offer unique advantages in searching for axion and ALP signals, complementing other detection methods. Compared to ground-based experiments for direct axion/ALP detection, indirect detection using gamma-ray observations has been demonstrated to achieve higher sensitivity in certain mass regions [50]. Specifically, for ALPs in the neV mass range, Fermi-LAT gamma-ray observations of the active galactic nucleus NGC 1275 have provided the strongest current constraints on the photon-ALP coupling constant [51].

Additionally, some tentative photon-ALP oscillation structures have been identified in Fermi-LAT observations of bright Galactic supernova remnants [52] and pulsars [53]. However, the ALP parameter spaces derived from fitting these data conflict with existing solar axion telescope experimental results, suggesting these “oscillation” features may originate from unknown systematic errors. Indirect detection of axions and ALPs represents another key scientific objective for VLAST. The telescope's exceptional energy resolution provides significant advantages in searching for ALP oscillation signatures.

2.2 High-Energy Astrophysical Sources

2.2.1 Active Galactic Nuclei (AGN) Active galactic nuclei constitute the vast majority of extragalactic high-energy gamma-ray sources detected by Fermi-LAT (see the 12-year source catalog 4FGL-DR3 [54]). The non-thermal X-ray emission from AGN is generally believed to originate from synchrotron radiation and/or inverse Compton scattering, while high-energy gamma-ray emission arises from inverse Compton processes, particularly external inverse Compton scattering of optical-UV photons from supermassive black hole accretion disks. However, proton synchrotron models have also been proposed, and some experts suggest a hadronic origin [55]. Since many AGN have redshifts greater than 1, background absorption during propagation becomes significant for the \$100

GeV range where ground-based Cherenkov telescopes are most sensitive. Consequently, space-based MeV–TeV gamma-ray detection plays a crucial role in comprehensively revealing AGN radiation mechanisms, determining the cosmic gamma-ray horizon, and measuring intergalactic magnetic fields (the latter two discussed in Section 2.4), areas where VLAST will make substantial contributions.

2.2.2 Gamma-Ray Bursts (GRBs) The primary progenitors of gamma-ray bursts include the deaths of massive stars and mergers of neutron star binary systems, with a small fraction originating from tidal disruption of stars by massive black holes [56]. The prompt emission of GRBs is typically concentrated in the keV–MeV band. Some GRBs exhibit GeV and even TeV radiation, with durations significantly longer than the prompt emission [57]. The prompt GRB emission is generally believed to arise from electron synchrotron radiation or Comptonized thermal radiation, while GeV–TeV emission originates from inverse Compton processes. Although GRBs are transient sources with short observational windows, their extreme brightness enables GeV radiation to be used for studying the cosmic gamma-ray horizon at high redshifts. Given VLAST’s simultaneous wide-band MeV–TeV observations, it will be possible to continuously characterize the spectral evolution of bright bursts and elucidate their underlying physical processes. While VLAST’s positioning accuracy for MeV radiation itself is limited, its precise GeV–TeV localization will effectively guide follow-up observations with ground-based narrow-field telescopes.

2.2.3 Millisecond Pulsars (MSPs) Millisecond pulsars are typically defined as pulsars with rotation periods shorter than 30 milliseconds. The prevailing view holds that they are old neutron stars that have accreted material from companion stars, gaining angular momentum to achieve rapid rotation. Globular clusters host substantial populations of millisecond pulsars, with their dense stellar environments providing ideal sources for accretion material. Consequently, the discovery of numerous millisecond pulsars in globular clusters has provided observational support for the accretion origin theory. Millisecond pulsars exhibit prominent radio and gamma-ray emission, with 187 sources identified as millisecond pulsars in the Fermi-LAT fourth source catalog [58]. Their spectral peaks commonly occur in the few-GeV range [59], making them an important class of gamma-ray sources in the sky, second only to AGN. Millisecond pulsars possess exceptional stability, enabling high-precision timing applications. Beyond revealing their surrounding environments (such as companion stars), they can be used to explore fundamental physics frontiers including low-frequency gravitational waves. Their relatively complex circumstellar environments have somewhat hindered radio detections. With its larger acceptance compared to Fermi-LAT, VLAST is expected to discover significantly more gamma-ray millisecond pulsars.

2.2.4 X-ray Binaries X-ray binaries are binary systems composed of compact objects (black holes and neutron stars) and companion stars, representing numerous high-energy radiation sources within the Milky Way. Among these, gamma-ray binaries and gamma-ray microquasars in X-ray binary systems exhibit gamma-ray emission [60]. Gamma-ray binaries consist of massive OB stars and compact objects, with eight sources detected to date, three of which have compact objects identified as pulsars. Microquasars are accreting X-ray binaries with steady or transient jets, with a total sample of approximately 15-20 sources. Gamma-ray emission from microquasars originates near the compact object [61] or from interactions between jets and surrounding interstellar medium at greater distances [62-63]. Due to orbital motion, periodic precession, or transient behavior of the jets, gamma-ray fluxes from these binary systems and microquasars show temporal evolution, providing ideal astrophysical laboratories for studying particle acceleration and high-energy radiation mechanisms in binary systems [64]. With current samples of gamma-ray binaries and microquasars being quite small, discovering new sources to investigate the unified origin of their high-energy emission remains a primary concern in this field. Gamma-ray binaries and microquasars are predominantly distributed along the Galactic plane, yet Fermi-LAT's spatial resolution, sensitivity, and complex Galactic plane diffuse background have hindered their detection. Future VLAST observations, with broader energy coverage and improved spatial resolution, will facilitate the discovery of additional gamma-ray binaries and gamma-ray microquasars.

2.2.5 Colliding-Wind Binaries (CWBs) Colliding-wind binaries are binary systems composed of massive OB or Wolf-Rayet stars. Powerful radiation pressure from these stars drives stellar winds at velocities of $1000\text{--}2000\text{ km s}^{-1}$, resulting in mass loss rates of $10^{-8}\text{--}10^{-3}\text{ M} \cdot \text{yr}^{-1}$. Wind collisions create shocks within the binary orbit that accelerate particles and produce multi-wavelength radiation. Synchrotron radiation from colliding-wind binaries has been detected in radio and X-ray bands [65-66], and gamma-ray emission through inverse Compton scattering is also expected [67]. To date, however, only Eta Carinae and WR 11 have been detected as gamma-ray sources [68-69]. Colliding-wind binaries represent an important component in studying gamma-ray emission from binary systems and are crucial for understanding particle acceleration mechanisms in binaries. VLAST's high sensitivity will likely enable the discovery of more colliding-wind binaries in the gamma-ray band, advancing research into their gamma-ray radiation mechanisms.

2.2.6 Transient Phenomena: Novae, Supernovae, Soft Gamma Repeaters, and Tidal Disruption Events Novae are violent thermonuclear explosions caused by hydrogen accreted onto white dwarf surfaces being heated to high temperatures. Fermi-LAT observations have demonstrated that novae are also important gamma-ray sources in the Milky Way, significantly advancing our understanding of nova eruption physics. VLAST is expected to detect radiation from more novae and provide clearer resolution of temporal and spectral

characteristics of high-energy emission from bright novae. Supernova remnants are widely recognized as accelerators of high-energy cosmic rays. It is reasonable to expect that shock waves and particle acceleration processes should also exist during the early stages of supernova explosions, physically similar to nova eruptions. Particularly if dense material clumps exist near supernovae, they may also serve as gamma-ray sources. Analysis of Fermi-LAT data has revealed several gamma-ray transient sources potentially associated with supernovae [70–71], though their specific connections to supernovae, especially their light curve behaviors, require more precise observations for clarification. VLAST will play an important role in identifying gamma-ray supernovae and studying early particle acceleration processes. Soft gamma repeaters (SGRs) are bursts of soft gamma rays produced by highly magnetized neutron stars and may also be sources of high-energy gamma-ray emission [72], though none have been detected to date. VLAST's high sensitivity offers the prospect of detecting high-energy gamma-ray radiation from giant SGR flares. Tidal disruption events (TDEs) generally produce only sub-relativistic jets, but a few cases such as Sw 1644+57 have generated relativistic jets [73], with magnetic energy dissipation producing bright gamma-ray bursts (initially designated GRB 110328A). Such events may be accompanied by GeV radiation, which VLAST's high-sensitivity observations could potentially discover.

2.3 Cosmic Ray Physics

The propagation of cosmic rays through matter fields can produce high-energy gamma rays through several primary radiation mechanisms: decay of neutral pions from inelastic strong interactions, inverse Compton scattering of electrons and positrons with background radiation fields, and bremsstrahlung of electrons and positrons in matter. Gamma-ray observations are crucial for identifying cosmic-ray acceleration sources and studying cosmic-ray propagation and interaction processes. Most importantly, gamma rays propagate in straight lines over long distances, enabling detection of cosmic-ray distribution characteristics at different spatial locations—distinctly different from charged particle measurements. Gamma rays provide comprehensive knowledge about cosmic rays, powerfully advancing our understanding of cosmic-ray related phenomena.

2.3.1 Supernova Remnants Supernova remnants are widely considered the primary cosmic-ray acceleration sources in the Milky Way [74]. The main rationale is that supernova explosions occur several times per century in our galaxy on average, releasing shock kinetic energy of approximately 10^{51} erg per explosion. If the energy conversion efficiency to cosmic rays reaches 10%, the energy produced by supernova remnants would be comparable to that required to maintain the observed cosmic-ray flux. Through diffusive shock acceleration mechanisms, supernova remnant shocks can accelerate particles to relativistic energies. Observed radio, X-ray, and gamma-ray emission from supernova remnants provides compelling evidence for particle acceleration to relativistic energies. In recent years, Fermi-LAT space observations in the gamma-ray band

have become a powerful tool for detecting GeV radiation from supernova remnants, with over 30 remnants already identified [75]. Fermi-LAT observations of supernova remnants IC 443 and W44 have revealed direct evidence of hadronic radiation [76], strongly supporting the hypothesis that supernova remnants are the origin of cosmic-ray acceleration. Currently, numerous uncertainties remain regarding the physical processes of high-energy particle acceleration, radiation, and escape in supernova remnants. VLAST's coverage of a very broad MeV–TeV energy band, combined with its high sensitivity and energy resolution, will enable better measurement of hadronic origin signatures in supernova remnant spectra, determination of spectral break positions [77], and address important questions about time-evolving high-energy particle acceleration and radiation processes.

2.3.2 Pulsar Wind Nebulae Most of a pulsar's rotational energy loss is converted into relativistic pulsar winds. When these winds encounter supernova ejecta or interstellar medium, shocks form, creating pulsar wind nebulae regions filled with electrons and positrons. Pulsar wind nebulae produce multi-wavelength radiation and represent major gamma-ray sources in the Milky Way. Low-energy emission from pulsar wind nebulae is generally believed to arise from synchrotron radiation of electrons and positrons in magnetic fields, while high-energy emission originates from inverse Compton scattering of these particles. Recently, LHAASO has detected 12 ultra-high-energy gamma-ray sources above 100 TeV [78], several of which are positionally coincident with pulsars and may be pulsar wind nebula systems. Additionally, LHAASO has detected PeV photons from the Crab pulsar wind nebula [79], providing new possible support for pulsar wind nebulae as cosmic-ray accelerators [80–81]. VLAST's high sensitivity and broad energy coverage can effectively distinguish between different theoretical models, providing

2.3.3 Young Massive Star Clusters Massive stars continuously inject substantial kinetic energy into interstellar space through their high-velocity winds and significant mass loss, making them potential cosmic-ray acceleration sources [82]. Furthermore, massive stars in the Milky Way are distributed in clustered associations or stellar clusters. Recent gamma-ray observations have revealed significant gamma-ray emission near several massive star clusters [83–84]. Particularly intriguingly, Aharonian et al. [84] found that in a series of young massive star clusters, the spatial distribution of cosmic rays can be universally described by a $1/r$ profile when combining gamma-ray and gas distribution observations, indicating that these cosmic rays are continuously injected by young massive star clusters throughout their million-year lifespans. Notably, since most massive stars are distributed along the Galactic plane, the aforementioned gamma-ray emission regions contain not only young massive star clusters but also potential contributions from pulsar wind nebulae and supernova remnants. Therefore, VLAST observations of these regions with higher energy resolution and greater statistics will be particularly important for understanding the gamma-ray radi-

ation mechanisms and the corresponding cosmic-ray acceleration, injection, and propagation processes. Additionally, thanks to its improved sensitivity, VLAST may also identify more such gamma-ray sources within diffuse gamma-ray emission along the Galactic plane.

2.3.4 Galactic Center The Galactic Center region contains a supermassive black hole, supernova remnants, pulsar wind nebulae, and presumably abundant dark matter, sustaining longstanding research interest and establishing the Galactic Center as one of the most important astrophysical laboratories for astronomers. In 2016, H.E.S.S. observations of diffuse gamma-ray emission near the Galactic Center revealed persistent cosmic-ray acceleration capable of accelerating particles to PeV energies, likely associated with activity from the Galactic Center's supermassive black hole [85]. Recent work using Fermi-LAT data has identified this acceleration source in the low-energy regime and found that central molecular clouds act as a barrier, effectively preventing high-energy particles from the cosmic-ray "sea" from penetrating this region [86]. Future VLAST studies of the Galactic Center will explore the connection between central black hole activity and cosmic-ray acceleration, as well as interactions between cosmic rays and the surrounding environment. These studies will also provide important knowledge for constructing the astrophysical background model for the Galactic Center GeV excess discussed in Section 2.1.2.

2.3.5 Fermi Bubbles The Fermi Bubbles are extended gamma-ray structures discovered by Fermi-LAT toward the Galactic Center [10], spanning thousands of square degrees. They share some spatial distribution similarities with lower-energy WMAP haze structures [87] and eROSITA bubble structures [88]. These structures are all believed to be related to energy injection from the Galactic Center region, but the specific physical mechanisms remain unclear. For instance, do these non-thermal emissions originate from hadronic or leptonic processes? Does the energy driving these structures come from activity of the Galactic Center supermassive black hole or from star formation processes? These fundamental questions urgently require answers. VLAST's high sensitivity will enable deeper observations of the Fermi Bubble region, particularly spectral measurements below GeV and above 100 GeV, resolving potential substructures within the bubbles and obtaining information about their connection to the Galactic Center region. Additionally, thanks to VLAST's high sensitivity, we will also search for similar gamma-ray radiation phenomena in nearby galaxies.

2.3.6 Galactic Diffuse Background Cosmic rays interacting with matter and radiation fields near acceleration sources and in the interstellar medium of the Milky Way produce diffuse gamma-ray emission. Consequently, diffuse gamma-ray radiation serves as a powerful probe of cosmic-ray distribution and propagation processes within the Galaxy. From early missions like OSO-3, COS-B, and EGRET to today's Fermi-LAT, measurements of all-sky diffuse gamma-

ray emission have enabled the development of relatively complete cosmic-ray propagation and interaction models to explain both diffuse gamma-ray and local cosmic-ray observations [89]. However, more detailed studies have revealed that cosmic-ray spatial distributions do not fully match simple propagation model predictions. For example, cosmic-ray density gradients in the outer Galaxy are flatter than model expectations [90], variations in Galactic cosmic-ray flux and spectral index derived from gamma rays differ from model predictions across spatial locations [91], and diffuse gamma-ray excesses above several GeV exist in the Galactic plane region [89]. These results indicate that cosmic-ray propagation models require improvement. Through VLAST's precise measurements of Galactic diffuse gamma rays across a broader energy band, we can better constrain cosmic-ray propagation models.

2.3.7 Nearby and Starburst Galaxies Starburst galaxies are gas-rich galaxies with exceptionally high star formation rates. High star formation rates correspond to high supernova and GRB production rates, both of which can accelerate cosmic rays [92]. Additionally, large-scale terminal shocks in superbubbles or superwinds generated by numerous massive stars can also accelerate cosmic rays [82]. High-energy cosmic rays may escape from starburst galaxies and propagate to Earth for detection. The Pierre Auger Observatory (PAO) group has found, through analyzing spatial correlations between ultra-high-energy cosmic rays and candidate sources, that nearby starburst galaxies contribute approximately 9.7% of ultra-high-energy cosmic rays (with energies above 39 EeV), with four nearby starburst galaxies (NGC 4945, NGC 253, M83, and NGC 1068) accounting for about 90% of the anisotropic flux [93]. Lower-energy cosmic rays may interact with dense gas in galaxies before escaping, producing secondary photons and neutrinos. Currently, Fermi-LAT has detected 100 MeV-100 GeV photons from nearby starburst galaxies including M82, NGC 253, NGC 4945, and NGC 1068 [94], VERITAS has observed photons above TeV energies from M82 [95], and H.E.S.S. has detected photons in the 100 GeV-10 TeV range from NGC 253 [96]. Similar to the Milky Way, supernova remnants and pulsar wind nebulae in normal galaxies can also accelerate cosmic rays and emit gamma rays. Fermi-LAT has detected several nearby galaxies including M31 and the Magellanic Clouds [97-98]. However, most normal galaxies remain undetected due to their low gamma-ray luminosities. Future VLAST observations of more nearby and starburst galaxies will enable studies of cosmic-ray distribution, propagation, and interaction properties in these galaxies and facilitate interesting comparisons with the Milky Way.

2.3.8 Galaxy Clusters Relativistic jets from supermassive black holes at galaxy cluster centers or large-scale shocks at cluster peripheries can accelerate cosmic rays to extremely high energies [99]. Accelerated cosmic rays propagating through galaxy clusters interact with cluster matter and photons, producing high-energy gamma rays and neutrinos. These high-energy photons, spatially co-

incident with galaxy clusters, may be observed by VLAST. Additionally, some cosmic rays can escape from galaxy clusters and propagate through the universe, interacting with extragalactic background light and cosmic microwave background photons during propagation to produce high-energy gamma rays and neutrinos that may contribute to the extragalactic diffuse gamma-ray background [100]. VLAST observations of galaxy clusters will enable studies of particle acceleration processes in clusters, constrain energy loss efficiencies of cosmic-ray propagation within clusters, and observations of the extragalactic diffuse gamma-ray background can also limit galaxy clusters' contributions to ultra-high-energy cosmic rays.

2.4 Cosmology and Intergalactic Medium

2.4.1 Extragalactic Gamma-ray Background Extragalactic gamma-ray radiation primarily originates from active galactic nuclei, star-forming galaxies, and gamma-ray bursts. Currently, the largest single-source sample detected consists of blazars, a class of AGN, with over 3,700 sources [105]. The extragalactic diffuse gamma-ray background refers to the remaining extragalactic gamma-ray emission after subtracting detected point sources and Galactic gamma-ray foreground. This isotropic radiation is generally believed to arise from the cumulative contribution of extragalactic sources too faint to be individually detected, with blazars considered the dominant contributor. However, the exact composition remains unclear; for instance, numerous low-luminosity starburst galaxies could potentially dominate the entire extragalactic diffuse gamma-ray background [106]. A small fraction of the extragalactic gamma-ray background may also originate from dark matter particle annihilation or decay [107]. VLAST's high sensitivity will help reveal extragalactic gamma-ray

2.4.2 Gamma-ray Horizon The gamma-ray horizon refers to an absorption effect where high-energy gamma rays interact with extragalactic background light during propagation, converting into electron-positron pairs. This effect causes a sharp decline in gamma-ray flux above certain energies from sources beyond a specific distance (where the optical depth equals 1). It reflects the universe's opacity to high-energy gamma-ray photons. Extragalactic background light from UV/optical to far-infrared bands depends on galaxy and star formation processes throughout cosmic evolutionary history, making this opacity a function of redshift. For example, the gamma-ray spectrum of source Mkn 501 at redshift 0.034 cuts off near 10 TeV, while at redshift 3, the cutoff energy decreases to approximately 50 GeV. Typically, existing extragalactic background light (EBL) models [108-109] and gamma-ray energy limits from blazars can be used to estimate the gamma-ray horizon. Alternative methods independent of EBL models have also been developed to estimate the cosmic gamma-ray horizon [110]. Furthermore, Fermi-LAT has constrained the EBL spectrum and evolution using average gamma-ray optical depth measurements at various cosmological distances [111]. With higher sensitivity and energy resolution, VLAST can better map the gamma-ray horizon's evolution with redshift and constrain

EBL absorption cutoff energies and redshift evolution.

2.4.3 Cosmological Parameter Measurements As noted in the previous section, optical depth is a function of redshift, with cosmological parameters such as the Hubble constant and cosmological density playing important roles in its calculation. Consequently, optical depth measurements at different redshifts can, in turn, place important constraints on cosmological parameters. Based on certain extragalactic background light (EBL) models [108-109] and optical depth measurements in the redshift range 0-3 [111], the Fermi-LAT collaboration first used gamma-ray absorption effects to constrain the Hubble constant and cosmological density [112]. Some studies have also used the observed redshift distribution of blazars and the extragalactic diffuse gamma-ray background, assuming that the background's cutoff energy originates from EBL absorption, to constrain cosmological parameters [113]. VLAST's high sensitivity and large statistical datasets will significantly advance research in this area.

2.4.4 Intergalactic Magnetic Field The magnitude of intergalactic magnetic fields is extremely difficult to measure. Current studies, including Faraday rotation measurements of quasar radio signals and simulations of ultra-high-energy cosmic ray arrival directions pointing toward Cen A, suggest intergalactic magnetic fields are weaker than 10^{-8} Gauss. As previously discussed, TeV photons emitted by high-energy sources interact with extragalactic background photons during propagation, producing electron-positron pairs. These high-energy pairs subsequently upscatter cosmic microwave background photons to GeV energies through inverse Compton scattering, a process known as secondary or cascade radiation from TeV sources. During cascade radiation, electrons and positrons are deflected by intergalactic magnetic fields, enabling gamma-ray astronomy to provide a novel method for measuring intergalactic magnetic fields through observations of cascade radiation from high-energy point sources [114-117]. Based on this method, some studies have obtained lower limits on intergalactic magnetic fields of approximately 10^{-15} Gauss using GeV flux upper limits from Fermi [117-119], though these values depend on assumed deflection angles. Highly sensitive VLAST observations should provide more stringent lower limits or potentially direct measurements of intergalactic magnetic field values.

2.5 Tests of Fundamental Physics

General relativity and quantum mechanics are the two pillars of modern physics. Numerous quantum gravity theories have been proposed to unify the description of gravity and quantum physics. To celebrate the 125th anniversary of Science magazine, the journal published 125 of the world's most challenging scientific frontier questions, ranking "Can the laws of physics be unified?" as the fifth most important question. Quantum gravity theories predict that fundamental assumptions of relativity (such as Lorentz invariance and the weak equivalence principle) must be violated, potentially producing observable physical effects

including vacuum dispersion and vacuum birefringence [101]. High-energy explosive phenomena at cosmological distances provide optimal experimental platforms for testing these physical effects. Exploring new physics and testing fundamental physics principles and assumptions have become important scientific objectives for international high-energy astronomical facilities.

2.5.1 Lorentz Invariance Test Lorentz invariance is a fundamental postulate of Einstein's special relativity. When theoretical physicists attempt to unify quantum mechanics and general relativity, they find this assumption may need to be violated, leading to so-called Lorentz invariance violation. Lorentz invariance violation induces vacuum dispersion effects, where photon propagation speed in vacuum is no longer constant c but depends on photon energy. Due to their short spectral time delays, high photon energies, and occurrence at cosmological distances, gamma-ray bursts are considered ideal probes for testing Lorentz invariance violation [102]. Thanks to high-energy gamma-ray burst radiation (GeV photons) detected by Fermi, the Fermi team has placed stringent constraints on Lorentz invariance violation [61]. This work received widespread international attention upon publication, representing a successful example of obtaining important original results using new observational windows. Future VLAST observations may enable more detailed characterization of high-energy gamma-ray burst light curves in the GeV-TeV band, allowing more precise measurements of spectral time delays and consequently placing even more stringent constraints on Lorentz invariance violation.

2.5.2 Gravitational Wave Speed Measurement and Equivalence Principle Test The first binary neutron star merger gravitational wave event GW170817 and its successful electromagnetic counterpart detection [103–104] extended humanity's ability to study cosmic objects from electromagnetic waves to gravitational waves, marking astronomy's further entry into the multi-messenger era. Compact object gravitational wave sources and their electromagnetic counterparts provide optimal laboratories for testing fundamental physics laws. Einstein's general relativity predicts that gravitational waves propagate at the speed of light. Therefore, by measuring arrival time differences between gravitational waves and their electromagnetic counterparts, one can constrain gravitational wave propagation speed and test general relativity. Additionally, the weak equivalence principle represents a crucial pillar of Einstein's general relativity and other gravitational theories. Based on the Shapiro time delay effect, the weak equivalence principle can be tested by comparing time delays experienced by different messenger particles (photons, neutrinos, or even gravitational waves) simultaneously emitted from extragalactic transient sources as they traverse the same gravitational field. Future coordinated observations between VLAST and gravitational wave detectors may detect more coincident gravitational wave and gamma-ray burst events. Leveraging these coincident events, we can conduct higher-precision constraints on gravitational wave speed and tests of the weak equivalence principle.

3. Preliminary Detector Configuration

The entire VLAST payload consists of two parts: the detector system and the trigger/data acquisition system. According to the physical design, VLAST's payload composition is shown in Fig. 1. VLAST's detectors from top to bottom include: the Anti-Coincidence Detector (ACD), the Silicon Tracker and Low-Energy gamma-ray Detector (STED), and the High-Energy Imaging Calorimeter (HEIC).

Fig. 1 The schematic plot of the payload of VLAST.

3.1 Anti-Coincidence Detector (ACD)

VLAST requires an anti-coincidence detector to distinguish charged particles from gamma photons, achieving electron-gamma discrimination through high-efficiency detection and track reconstruction of incident charged particles. Additionally, VLAST's anti-coincidence detector will enable identification of light nuclear species through energy loss measurements of charged particles in the detector. As shown in Fig. 1, VLAST's anti-coincidence detector is located at the top and sides. To reduce misidentification caused by secondary recoil particles from gamma rays hitting the anti-coincidence detector and to avoid multiplicity issues from large area coverage, the anti-coincidence detector requires certain position measurement capabilities. VLAST's anti-coincidence detector is designed as a block-stacked configuration. According to physics requirements, the main technical specifications are: a) Detector unit granularity: $< 1000 \text{ cm}^2$; b) Detector unit dynamic range: electrons, ions ($Z = 1-8$); c) Detection efficiency: better than 99.97%; d) Provide trigger hit signals for charged particles with minimum trigger threshold of 0.1 MIPs (minimum ionizing particles); e) Capability to process incident particles at 10 kHz/m^2 with internal scientific data buffering to reduce dead time.

The anti-coincidence detector will employ block-shaped organic plastic scintillator as the sensitive detector material [18, 23–25]. As shown in Fig. 1, the anti-coincidence detector consists of block-shaped sensitive units at the top and four sides, forming an overall “square hat without brim” configuration. The top anti-coincidence detector has an effective detection area of $3.1 \text{ m} \times 3.1 \text{ m}$, while each side panel has an effective detection area of $3.1 \text{ m} \times 0.6 \text{ m}$. To achieve its primary functions, a modular configuration design is adopted, with sensitive unit modules having main dimensions of approximately $0.3 \text{ m} \times 0.3 \text{ m}$. To meet the design requirement of dead-zone-free sensitive area, adjacent unit modules must overlap structurally or incorporate additional sensitive detectors such as plastic scintillating fibers. In our preliminary structural design, the anti-coincidence detector uses carbon fiber reinforced honeycomb panels combined into a square hat-shaped primary support structure. Detector unit modules are arranged in an overlapping configuration on the top and sides of the support structure, pressed onto the support structure through layered carbon fiber strip cover plates, and mechanically integrated with the support structure to form a

complete assembly.

To ensure signal readout amplitude is independent of particle hit position, each plastic scintillator unit in the anti-coincidence detector employs embedded wavelength-shifting fibers for readout. Simultaneously, to achieve high-reliability charged particle/gamma discrimination and measurement of different light nuclear species, a design combining photomultiplier tube (PMT) double-dynode readout with charge-measurement ASIC chips is proposed to meet requirements for large dynamic range coverage, high integration, and high sensitivity. Furthermore, to improve effective space gamma-ray measurements, signal readout channels from all detector units will participate in the overall payload trigger. The complete anti-coincidence detector comprises 209 detector units. With PMT readout using double-dynode configuration and 1:1 signal redundancy, there are 418 PMTs, 418 trigger signal measurement channels, and 836 charge measurement channels. Front-end electronics (FEE) are responsible for detector signal acquisition and processing, generating hit signals required by the trigger decision system (located in the payload data management unit).

3.2 Silicon Tracker and Low-Energy gamma-ray Detector (STED)

High-energy (> 30 MeV and above) gamma photons convert into electron-positron pairs in VLAST, with primary photon direction determined through detection of these pair tracks. The tracker and low-energy gamma-ray detector is located at the second layer of the overall detector payload. Its main functions are: to enable conversion of high-energy gamma rays into electron-positron pairs and achieve high angular resolution observations of gamma photons through track measurement of these pairs; and to enable energy and direction measurements of low-energy photons. Silicon microstrips are the preferred sensitive material for track detection. To accommodate detection of low-energy (< 1 MeV) gamma photons, VLAST incorporates cesium iodide (CsI) detector layers between silicon microstrip layers. CsI readout using wavelength-shifting fibers measures energy and direction of low-energy photons, while CsI crystals also serve as converters for high-energy gamma-ray pair production. In VLAST's design, one CsI detection layer combined with two silicon microstrip detection layers (each large layer consisting of single-sided silicon microstrips in X and Y directions) forms a "superlayer," with multiple such superlayers constituting the "Silicon Tracker and Low-Energy gamma-ray Detector." Evidently, VLAST's "Silicon Tracker and Low-Energy gamma-ray Detector" represents major innovations in both functionality and structure compared to DAMPE's silicon tracker [18, 23, 26]. Its main technical specifications are: a) Number of detector layers: 8 superlayers (each superlayer includes a CsI detection layer and two silicon microstrip detection layers, with one silicon microstrip large layer having two sublayers in X and Y); b) Effective detection area per layer: not less than $2.8\text{ m} \times 2.8\text{ m}$; c) Energy range: 1 MeV-100 MeV (in combination with the high-energy imaging calorimeter); d) Spatial resolution: $< 0.1^\circ$ (@50 GeV); e) Provide hit information to trigger logic for trigger decision; f) Internal scientific data buffering in

the detector, with dead time less than 50 μ s.

The structure of the silicon tracker and low-energy gamma-ray detector is shown in Fig. 1. Considering the sensitive area of $2.8\text{ m} \times 2.8\text{ m}$, the entire detector consists of four identical detection arrays combined in a 2×2 close-packed configuration, with each individual array having a sensitive area of $1.4\text{ m} \times 1.4\text{ m}$. Each detection array comprises eight detection superlayers, with internal detector layers supported by structures formed from carbon fiber and aluminum honeycomb panels. The CsI, silicon microstrips, and various structural materials in the silicon tracker and low-energy gamma-ray detector together enable conversion of high-energy gamma photons into electron-positron pairs, with silicon microstrips responsible for measuring tracks of the converted pairs. For low-energy gamma photons (MeV), Compton scattering occurs in the silicon tracker and low-energy gamma-ray detector, with CsI responsible for measuring energy and direction of the Compton-scattered photons.

CsI wavelength-shifting fibers use multi-anode photomultiplier tubes (MAPMTs) or multi-channel silicon photomultipliers (SiPMs) for photoelectric conversion, followed by transmission to front-end electronics for acquisition. Silicon microstrip detection layers are based on single-sided silicon microstrip technology. Since each silicon microstrip chip has dimensions of $0.1\text{ m} \times 0.1\text{ m}$, the silicon microstrip detection layers employ the following layout to form large-area detection layers: seven silicon microstrip chips are connected (with corresponding microstrips on the chips wire-bonded together) to form a silicon microstrip module (ladder); two modules are bonded head-to-head on a carbon fiber structure to create a $0.1\text{ m} \times 1.4\text{ m}$ detection strip; and 14 such detection strips can be assembled into a $1.4\text{ m} \times 1.4\text{ m}$ detection layer.

Signals from each module of the silicon microstrip detection layer are read out by front-end hybrid boards (FEH). All FEH boards are ultimately managed by front-end readout boards (TRB) distributed on four sides for data acquisition, control, and power supply.

3.3 High-Energy Imaging Calorimeter (HEIC)

Similar to DAMPE, VLAST requires a high-energy-resolution imaging electromagnetic calorimeter to measure photon energy [18, 23, 27–28]. The imaging electromagnetic calorimeter measures particle energy deposition while providing high-granularity imaging of high-energy particle showers. It distinguishes between hadronic and electromagnetic showers based on differences in their lateral and longitudinal development within the calorimeter, enabling particle identification and separation of hadrons from photons (and electrons). The main technical specifications for the high-energy imaging calorimeter are: a) Effective detection area per layer: not less than $2.4\text{ m} \times 2.4\text{ m}$; b) Dynamic range: 0.1 GeV–20 TeV (for electrons and gamma photons); c) Energy resolution: better than 2% (@50 GeV); d) Hadron suppression capability: better than 10^4 (@50 GeV); e) Minimum trigger threshold for detection units: <0.5 MIPs; f) Storage

capability: internal scientific data buffering in the calorimeter with dead time less than 50 μ s.

For the high-energy imaging calorimeter, two technical approaches are planned for development: a long-crystal scheme and a small-crystal scheme, with the optimal solution selected during the engineering phase. The long-crystal scheme is similar to DAMPE' s calorimeter design: using individual long BGO crystals stacked into a cube, with crystal orientations in alternating layers orthogonal to each other to enable shower shape measurement [18]. DAMPE' s crystal dimensions are $600 \times 25 \times 25 \text{ mm}^3$, combined with multi-dynode PMT readout to achieve large dynamic range signal measurement. The VLAST experiment requires a high-energy imaging calorimeter area of $2.4 \text{ m} \times 2.4 \text{ m}$, planning to produce meter-scale ($\sim 1.2 \text{ m}$) crystals and combine four (2×2) calorimeter units to form the 2.4 m dimensions. Currently, collaborating institutions in the project team are attempting to grow meter-scale BGO crystals.

The alternative approach for VLAST' s high-energy imaging calorimeter is the small-crystal scheme. This scheme uses small scintillating crystals as sensitive units, directly coupled to semiconductor photodetectors such as silicon photo-multipliers (SiPMs), avalanche photodiodes (APDs), or photodiodes (PDs) for light collection, with electronic systems integrated directly beneath the photodetectors. This scheme' s advantage lies in achieving smaller granularity and enabling fine 3D imaging capabilities.

4. Expected Detector Performance

According to scientific objectives, the VLAST detector must achieve high-sensitivity, precise measurements of GeV-TeV high-energy gamma rays while maintaining certain MeV gamma-ray detection capabilities. To verify and evaluate VLAST' s detection performance, we have developed a dedicated detector simulation software package based on GEANT4 [120], integrating functions including detector geometry modeling, sensitive unit definition, incident particle source definition, physics model selection, detailed simulation of particle-detector interaction processes, detection unit response signal readout, and simulated data digitization. Based on simulated data, we have preliminarily developed reconstruction algorithms for two different types of gamma photon events: Compton scattering and pair production. These algorithms accurately identify gamma photon events based on VLAST sub-detector signals and effectively reconstruct incident event tracks and energies, enabling preliminary analysis of VLAST' s acceptance (geometric factor), effective area, angular resolution, energy resolution, and other performance metrics.

Fig. 2 Preliminary results of acceptance/geometry factor (left) and normal-incident effective area (right) versus energy. The solid red curve at low energies denotes Compton event reconstruction and the one at energies above 10 MeV represents pair event reconstruction. Dashed gray curve is for Fermi-LAT P8R3_{SOURCE}\{V3\} events

(<https://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/Pass8{usage}.html>).

4.1 Acceptance and Effective Area

Fig. 2 shows VLAST detector acceptance (left) and normal-incident effective area (right) as functions of incident energy. The two curve segments correspond to low-energy Compton scattering events and high-energy pair production events, respectively. VLAST' s effective acceptance reaches a maximum of approximately $12 \text{ m}^2 \cdot \text{sr}$, with a maximum normal-incident effective area of about 4 m^2 . Compared to Fermi-LAT, VLAST' s acceptance and effective area in the GeV and above energy range are approximately five times larger. Additionally, VLAST' s effective area in the MeV energy band reaches about 0.5 m^2 , two to three orders of magnitude higher than the previous COMPTEL telescope [121] ($10\text{--}50 \text{ cm}^2$).

4.2 Angular and Energy Resolution

Fig. 3 shows VLAST detector' s 68% angular resolution (left) and 68% energy resolution (right) for photons as functions of incident energy. The two curve segments correspond to low-energy Compton scattering events and high-energy pair production events, respectively. For Compton scattering photon events, angular deviation is defined as the minimum angular difference between the incident direction and the reconstructed Compton scattering ring direction. For high-energy pair production photon events, VLAST' s angular resolution is comparable to Fermi-LAT, while its energy resolution is significantly superior. Given VLAST' s substantially higher geometric factor compared to Fermi-LAT, VLAST' s detection sensitivity for gamma rays in the GeV and above energy range will far exceed that of Fermi-LAT. For low-energy Compton photon events, VLAST' s angular resolution is approximately $3^\circ\text{--}6^\circ$, and energy resolution is about 8%–20%, enabling effective detection of MeV gamma rays.

Fig. 3 Preliminary results of angular resolution (left) and energy resolution (right) as shown by the 68% containment versus energy. The solid red curve at low energies denotes Compton event reconstruction and the one at energies above 10 MeV represents pair event reconstruction. Dashed gray curve is for Fermi-LAT P8R3_{SOURCE}{V3} events (<https://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/Pass8{usage}.html>).

4.3 Observation Sensitivity

In standard survey observation mode, considering only gamma-ray diffuse backgrounds including Galactic diffuse radiation and extragalactic isotropic radiation, on-orbit simulations can evaluate VLAST' s expected observation sensitivity after 5 years of operation toward the Galactic Center, intermediate Galactic latitudes, and north Galactic pole directions, as shown in Fig. 4 (left). For specific point sources (transient sources) in the sky, VLAST' s detector provides excellent angular resolution (better than 0.1° @ 50 GeV), enabling independent

identification of source direction and extended morphology, thereby enabling precise measurements of their spectra and variability in coordination with other experiments for multi-wavelength and multi-messenger observations.

Dark matter annihilation may produce characteristic gamma-ray line spectra, with different energy resolutions causing varying degrees of line broadening that affect detection sensitivity. VLAST's detector features excellent energy resolution (approximately 2% @ 50 GeV), enabling high-sensitivity detection of potential gamma-ray lines from dark matter annihilation or decay. Liang et al. [41] and Shen et al. [122] conducted systematic studies of Fermi-LAT gamma-ray data from 16 nearby galaxy clusters, finding tentative line-like features at 43 GeV. If these are not due to instrumental systematic errors or statistical fluctuations, VLAST observations over 2 years will reliably detect this signal (simulated expected observation results shown in Fig. 4 (right)).

Fig. 4 Left: expected sensitivities of VLAST observation in different galactic regions in 5 years. Right: expected observation result of the 16 nearby galaxy clusters in 5 years, supposing that the weak tentative line signal found in Shen et al. [122] is intrinsic.

4.4 Possible Detector Optimizations

The configurations described above represent the main detector setup. Future optimizations or additions may be implemented based on the principle of maximizing scientific output. For example, to avoid electronics saturation and consequent significant data loss, particularly at high energies, during bright gamma-ray burst outbursts, we will consider special trigger settings and assign detection of very bright MeV burst phenomena to small auxiliary detectors such as a wide-field gamma-ray burst monitor. Additionally, although our core detection target is gamma rays, VLAST possesses tremendous potential for cosmic-ray detection. If launch capacity permits, we will consider adding a $1.2\text{ m} \times 1.2\text{ m} \times 0.2\text{ m}$ calorimeter detection unit (weighing approximately 1800 kg) centrally beneath the ($2\text{ m} \times 2\text{ m}$ array) high-energy imaging calorimeter. This detection unit, combined with the high-energy imaging calorimeter, forms a special "Alchemy Furnace" configuration that, together with the anti-coincidence detector and silicon tracker/low-energy gamma-ray detector, enables large field-of-view, high angular resolution, and relatively high energy resolution detection of electrons, protons, and other cosmic rays, transforming VLAST into a powerful comprehensive space observatory for both gamma rays and cosmic rays.

5. Conclusion

Since its launch in 2008, Fermi-LAT has been operating for over 13 years. Beginning in 2019, it has been unable to perform pointed observations and currently operates in survey mode. The United States has not yet formally approved a plan for a space-based gamma-ray telescope larger than Fermi-LAT. One medium-scale project under development is the All-sky Medium Energy

Gamma-ray Observatory (AMEGO), with an energy range of 0.2 MeV–10 GeV, but its effective detection area in the GeV band is only about 1000 cm² [123], significantly smaller than Fermi-LAT. Another U.S. balloon experiment concept (Advanced Particle-astrophysics Telescope, APT, planned for deep-space orbit) employs a calorimeter scheme using thin CsI crystals with scintillating fiber readout to detect MeV–TeV radiation [124]. This scheme features a large detector effective area comparable to our proposed VLAST, but APT’s energy and angular resolution capabilities are relatively poor [124]; for example, its energy resolution in the TeV range is only 30%. The Institute of High Energy Physics of the Chinese Academy of Sciences and the University of Perugia in Italy are proposing the High Energy cosmic Radiation Detection (HERD) experiment for the Chinese Space Station [125], planned for operation beginning in 2027. If successfully implemented, HERD’s multi-sided readout approach will significantly expand its acceptance for direct measurements of high-energy cosmic rays, establishing leadership in this field. However, its gamma-ray detection capabilities do not surpass Fermi-LAT, particularly for low Earth orbit, where multi-sided readout provides limited assistance for gamma-ray detection.

Currently, no international plan for a Fermi-LAT successor has been approved. Around 2030, the international community will likely face a gap in high-sensitivity space-based gamma-ray detection in the GeV–TeV range, while ground-based Cherenkov telescope indirect detection has limited capabilities below 100 GeV. Considering the burgeoning needs of gamma-ray time-domain astronomy and the fact that gamma rays represent one of the most direct methods for dark matter indirect detection, we have proposed the Very Large Area gamma-ray Space Telescope (VLAST) mission. In early March 2022, we formally submitted a “Background Model” project proposal to the National Space Science Center of the Chinese Academy of Sciences, with the main content of this paper forming an important component of that proposal. VLAST’s primary scientific objectives include searching for evidence of dark matter candidates such as weakly interacting massive particles and axion-like particles, monitoring gamma-ray emission from gravitational wave, neutrino, black hole tidal disruption, and relativistic shock breakout events, discovering high-redshift (>6) GeV burst events in the universe (the current record is an active galactic nucleus at redshift 4.72 [126]), precisely measuring the cosmic gamma-ray horizon, revealing the origin of extragalactic background radiation, studying first-generation stars, high-precision measurement of Galactic diffuse gamma-ray radiation, obtaining three-dimensional cosmic-ray spatial distribution, revealing the origin of Fermi Bubbles, identifying cosmic-ray sources in the sub-GeV band, long-term monitoring of MeV–TeV radiation from variable sources, observing high-energy burst events such as gamma-ray bursts, and discovering new types of high-energy radiation phenomena.

The VLAST satellite is planned to operate in a 500 km altitude orbit with 20°–30° inclination. Based on existing technological capabilities, if supported, the VLAST satellite could be completed before 2029. Once successfully developed and operational, VLAST will establish China’s leadership in high-energy gamma-

ray space detection and become a key component of the international multi-messenger astronomy observation network, bringing breakthrough advances in dark matter, high-energy astrophysics, cosmic-ray physics, and other research fields.

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ABSTRACT

High-energy gamma-rays carry the fundamental information of the astrophysical sources in extreme conditions. The space detection of gamma-rays is distinguished by the wide energy range, the observation continuity as well as the high energy resolution. With the experience in constructing and running the DArk Matter Particle Explorer (DAMPE), we propose a new satellite mission—Very Large Area gamma-ray Space Telescope (VLAST). VLAST has an acceptance of $10 \text{ m}^2 \cdot \text{sr}$ at GeV energies and $1 \text{ m}^2 \cdot \text{sr}$ at MeV energies. Together with a much better energy resolution, VLAST is expected to increase the sensitivity of Fermi Large Area Telescope by a factor of 10. In this work, the main scientific objectives, the detection principle, the payload and the expected performance of VLAST are introduced.

Key words: Instrumentation: detectors, Gamma rays: general, Radiation mechanisms: non-thermal, Astroparticle physics

FAN Yi-Zhong^{1,2,3}, CHANG Jin^{1,2,3,8}, GUO Jian-Hua^{1,2,3}, YUAN Qiang^{1,2,3}, HU Yi-Ming^{1,2}, LI Xiang^{1,2,3}, YUE Chuan^{1,2}, HUANG Guang-Shun^{4,5}, LIU Shu-Bin^{4,5}, FENG Chang-Qin^{4,5}, ZHANG Yun-Long^{4,5}, WEI Yi-Feng^{4,5}, SUN Zhi-Yu⁶, YU Yu-Hong⁶, KONG Jie⁶, ZHAO Cheng-Xin⁶, ZANG Jing-Jing⁷, JIANG Wei^{1,2}, PAN

Xu^{1,2,3}, WEI Jia-Ju^{1,2}, WANG Shen^{1,2}, DUAN Kai-Kai^{1,2}, SHEN Zhao-Qiang^{1,2}, XIA Zhi-Qing^{1,2}, XU Zun-Lei^{1,2}, FENG Lei^{1,2,3}, HUANG Xiao-Yuan^{1,2,3}, CAI Yue-Lin^{1,2}, HE Hao-Ning^{1,2}, WEI Jun-Jie^{1,3}, ZENG Hou-Dun^{1,2}, YANG Rui-Zhi³, LI Jian³, YAN Jing-Zhi^{1,2,3}, ZHANG Yi^{1,2,3}, WU Xue-Feng^{1,2,3}, WEI Da-Ming^{1,2,3}

(1 Purple Mountain Observatory, Chinese Academy of Sciences, Nanjing, Jiangsu 210023)

(2 Key Laboratory of Dark Matter and Space Astronomy, Chinese Academy of Sciences, Nanjing, Jiangsu 210023)

(3 School of Astronomy and Space Science, University of Science and Technology of China, Hefei, Anhui 230026)

(4 State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei, Anhui 230026)

(5 Department of Modern Physics, University of Science and Technology of China, Hefei, Anhui 230026)

(6 Institute of Modern Physics, Chinese Academy of Sciences, Nanchang Road 509, Lanzhou, Gansu 730000)

(7 School of Physics and Electronic Engineering, Linyi University, Linyi, Shandong 276000)

(8 National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100049)

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