2025 Astrophysics Senior Review Panel Report

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Executive Summary

The Senior Review of Operating Missions (hereafter called “the Senior Review”) serves as a triennial assessment of those missions in the NASA Astrophysics Division (APD) that have completed their prime missions and have submitted proposals for extended operations. The Senior Review Panel (hereafter called “the Panel”) focuses its evaluation on the capabilities of the missions to continue to execute transformational science, the missions’ responsiveness to previous reviews and strategic guidance (e.g., the Decadal Surveys and the NASA Science Mission Directorate [SMD] Science Plan), mission health, and cost effectiveness.

The portfolio of reviewed missions enable science across a large swath of the electromagnetic spectrum, from infrared to gamma ray. This portfolio of missions thus allows the study of nearly every type of astrophysical object at nearly all scales. Each mission executes observations of the cosmos that can only be done from space. Each mission creates and engages a community of astronomers through new observations and via data archives. Each mission team has made notable efforts to bring in new users of their mission, ensuring a long-term future for space astrophysics.

The Panel appreciates the significant budget uncertainties facing NASA, SMD, and APD. The Panel recognizes the particular gravity of this report relative to those reports in the recent past. The Panel nevertheless strongly believes **that each mission under review continues to be capable of producing important, impactful science in a cost-effective manner and would do so if allowed to continue operations into the next extended mission cycle**. This belief remains true if missions had to be extended with reduced capability, reduced community resources, or both. Cuts to community resources or capabilities will reduce the science output of these missions, but the missions remain viable and productive. Furthermore, many of the most insightful science results arise from combining the observations of more than one mission in NASA’s fleet, leveraging complementary capabilities.

The portfolio of operating missions is a shining example of a paradigm that has transformed science for decades: NASA has provided cutting-edge observatories, delivering well-calibrated data in a common format through archives that are accessible to the public. The missions fund General Observer (GO) and General Investigator (GI) programs in order to analyze, publish, and disseminate the science from the data to the rest of the world. The result is a fleet that is in high demand both for new and archived data, with a massive scientific return and a proven history of public engagement and inspiration. The portfolio of missions reviewed here is a testament to this paradigm's continued success. The portfolio's value continues to be far more than the sum of its parts. When considered along with missions like JAXA's X-Ray Imaging and Spectroscopy Mission (XRISM) and the James Webb Space Telescope (JWST) that are now operating in their prime mission phase, the current combined suite of APD missions is the most impactful in the history of the study of astrophysics from space. Some of the missions are in multiple decades of operation. These missions are a testament to what NASA can bring to the table: they are built with operational redundancy and resiliency. The missions have dedicated, resourceful mission teams and user communities. The portfolio serves not only to fuel the next generation of ingenuity in astronomy and for Science, Technology, Engineering and Mathematics (STEM) in general but also serves to be a resounding demonstration of science leadership for the United States and its partners.

The Panel wishes to thank each of the missions for their detailed and thorough proposals and for their responses to questions. Additionally, the Panel thanks the team at NASA Headquarters and beyond who enabled the Panel's work. Although this was a non-consensus Panel, the document broadly represents the view of the Panel members.

The Review

The Panel evaluated eight missions. Each mission proposes to enter an extended mission phase for Fiscal Year 2026 (FY26) through FY28. The Neutron star Interior Composition ExploreR (NICER) mission was excluded from this review due to January 2025 repairs in orbit by astronauts on the International Space Station. NICER will be independently reviewed at a later date when its capabilities following the repairs are better understood. This Senior Review represents the first time the IXPE mission is under review.

The missions considered in this review, in order of launch date, are as follows:

Name	**Full Name**	**Launch date**
HST	Hubble Space Telescope	1990
Chandra	Chandra X-Ray Observatory	1999
XMM	X-Ray Multi-Mirror Mission – Newton (ESA mission)	1999
Swift	Neil Gehrels Swift Observatory	2004
Fermi	Fermi Gamma-Ray Space Telescope	2008
NuSTAR	Nuclear Spectroscopic Telescope Array	2012
TESS	Transiting Exoplanet Survey Satellite	2018
IXPE	Imaging X-Ray Polarimetry Explorer	2021

The Panel was asked to rate these missions according to three criteria:
- Scientific merit
- Relevance and responsiveness to objectives of the Astrophysics Division
- Technical capability and management.

The first criterion (A) was given approximately twice the weight of the second (B) and third (C) criteria in determining an overall rating.

Scientific Merit

The Panel found that **every mission received the highest possible rating for potential of scientific return in the three-year period of FY2026 through FY2028**. The missions already operating in the extended mission phase have shown a remarkable ability to evolve, adding capabilities that increase their scientific reach and expand their user communities. The uniqueness of these missions is more than just a matter of the wavelength band in which they operate. The missions have crucial differences in field-of-view, resolution, precision, ability to measure spectra and polarization, and their respective abilities to dynamically adapt observing schedules to transient events and variable sources on different time scales. The full set of detailed capabilities is what makes each mission both unique and complementary.

Each mission also shows strong alignment with the scientific goals of the community and NASA SMD. Every mission supports at least one of the three 2020 Astrophysics Decadal Survey (Astro2020) science pillars as well as one or more of the SMD Science Plan goals. Increasingly, the missions are synergistic with each other, providing an interconnected approach to science questions that could not be answered by a single mission alone. Multiple missions now provide the capability to offer joint proposals to the community, enabling new science, and eliminating “double jeopardy” to proposers. Of particular recent importance is the synergy between these missions and JWST. JWST’s studies of the distant and early universe, exoplanet atmospheres, and stellar nurseries cannot be made complete without multi-wavelength capabilities. Also on the rise is the focus of each mission to participate in Time Domain And Multi-Messenger (TDAMM) science, whether it is rapid response to transient events, long-term monitoring of faint afterglows of these events, or time-critical observations of temporally-varying sources. Many of the missions were not built with TDAMM science in mind, yet all are modifying their operations models to execute this science.

The success of the NASA APD fleet of missions lies not only in the ability for the community of users to do great science, but for that science to be brought to the nation and to the world. Each of the reviewed missions strive to communicate their science through media and public outreach, with a very high return on investment. Unshared science does not benefit anyone. Scientists must share with other scientists to assess and to build upon results, informing the next wave of science inquiry. In addition, the US taxpayer expects to hear about the discoveries their tax dollars have financed. The Astro2020 report says it well: “*Astronomy research continues to offer significant benefits to the nation beyond astronomical discoveries. These discoveries capture the public’s attention, foster general science literacy and proficiency, promote public perception of the value, legitimacy, and integrity of science, and serve as an inspirational gateway to science, technology, engineering, and mathematics careers*.” [1]

A brief summary of each mission follows. The missions are presented in the order that they were launched.

- Well into its fourth decade of operations, the **Hubble Space Telescope (HST)** remains a key symbol of NASA science. HST’s spatial resolution and sensitivity in the ultraviolet and optical

[1] National Academies of Sciences, Engineering, and Medicine (2023), chapter 3. Pathways to Discovery in Astronomy and Astrophysics for the 2020s. Washington, DC: The National Academies Press. https://doi.org/10.17226/26141.

bands remain unmatched. Thanks to these unique capabilities, HST will continue to deliver groundbreaking discoveries that enhance our understanding of the universe ranging from imaging outer Solar System planets to unraveling the mysteries of supermassive black holes. The synergy between HST and JWST is poised to yield transformational results including characterizing exoplanet atmospheres and charting star and galaxy formation across cosmic time. The HST team is also working to enhance the scientific outcomes of the Nancy Grace Roman Space Telescope and lay the foundation for the future flagship, the Habitable Worlds Observatory. The mission's operational model is both efficient and adaptive, effectively managing budgetary constraints by favoring a reduction in supported modes of operation over lesser support for all modes. With the exceptional outreach efforts of the Space Telescope Science Institute, HST has become a worldwide emblem of ingenuity and a reminder to the public of the value of investing in science. From this investment emerges the next generation of educators, engineers, scientists, and innovators.

- **Chandra** remains the sharpest X-ray eye ever built. Chandra's exquisite angular resolution is unmatched, and this capability will not be rivaled even by next-generation facilities. The proposed "Minimal-Cost Mission" represents a significant cut to staffing and budget, yet this mission will continue to deliver the transformative science expected of a Great Observatory. Chandra is productive and in high demand. Chandra has been a workhorse instrument for studying a wide array of high-energy astrophysical sources such as clusters of galaxies, X-ray binaries, and Active Galactic Nuclei (AGN). Chandra is the only X-ray mission that can pinpoint the supermassive black hole Sgr A* at the center of the Milky Way, the only mission sensitive enough to detect the afterglow from the neutron star merger GW170817 more than five years after the initial merger detection, and the only mission that can confirm the presence of black holes in distant galaxies detected by the JWST. Now is arguably the most compelling time for Chandra to operate, joining the Hubble Space Telescope and JWST to enable sub-arcsecond observations across the electromagnetic spectrum from mid-infrared to X-rays. This set of three flagship observatories is a powerhouse that will provide unparalleled scientific potential that will not be superseded for many years.

- Twenty-five years on, **XMM-Newton** (XMM) remains a cutting-edge flagship X-ray space telescope that is positioned to deliver high impact science for another decade or more. XMM is operated by the ESA with NASA partnership via the United States General Observer Facility. The XMM science program is driven by GOs and spans the breadth of astrophysics, from the Solar System to the edge of the cosmos. XMM has recently increased its role in TDAMM science. It is the only X-ray mission that can perform uninterrupted observations lasting up to 1.5 days, a duration which is key for understanding Tidal Disruption Events (TDEs) and Extreme Mass Ratio Inspirals (EMRIs). To maximize the science return from this capability, XMM now routinely responds to Target of Opportunity (ToO) requests within days. XMM also uniquely characterizes the high-energy emission from late-type stars hosting exoplanets, offering insight into planetary habitability. XMM offers strong synergy with other observatories including the JWST, NuSTAR, XRISM, Swift, and others. Excellent management and updates to XMM's data and software packages are leading to new programs and support for new users. US participation in XMM offers excellent value for the investment: a small NASA budget enables US investigators to make full use of a Great Observatory-class telescope.

- **Swift** is unique among NASA's missions for its combination of spectral coverage and rapid response. These capabilities enable fast transient follow-up, precise transient source localization, and agile multi-wavelength monitoring. After 20 years of operations, Swift has transformed from a mission that was dedicated to study gamma-ray bursts to an observatory that is capable of addressing all areas of astrophysics. These areas range from solar system studies to how heavy elements are synthesized, and how black holes swallow stars. Swift is the only mission capable of reacting within seconds and repositioning its UltraViolet (UV)-optical and X-ray instruments to observe virtually any transient source in the sky. Swift can also raster large sky areas while looking for poorly localized sources like the transients from gravitational wave detectors. These capabilities make Swift a key asset in the forthcoming golden era of TDAMM science. In the next three years, the increased transient discovery rate from powerful new facilities (e.g., the Vera C. Rubin Observatory, the Nancy Grace Roman Space Telescope, and ULTRASAT) provides tremendous opportunities for Swift to make groundbreaking discoveries due to its rapid follow-up capabilities. The mission has achieved excellent operational efficiency with a lean staff while simultaneously making operational enhancements and improving access to Swift data.

- **Fermi** is an integral part of NASA's multi-wavelength observatory portfolio. Fermi covers a unique bandpass as the only mission that spans 8 decades in energy (between 8 keV and 300 GeV) and is a crucial link between space-based hard X-ray/soft gamma-ray observatories and ground-based Cherenkov telescopes. As such, Fermi is an essential observatory for TDAMM science. Fermi does not execute pointed observations. Fermi is instead constantly scanning the gamma-ray sky with an all-sky monitor called the Gamma-ray Burst Monitor (GBM, covering the range from 8 keV to 40 MeV) and with the Large Area Telescope (LAT, covering the range from 20 MeV to 300 GeV). For any given position in the sky, Fermi observes the position every three hours. As the bridge between hard X-ray and TeV gamma-ray astrophysics and constantly monitoring of the sky, Fermi is able to detect objects like short gamma-ray bursts and blazars that are the links to gravitational wave sources and neutrino astrophysics. Fermi therefore plays a crucial role for our understanding of the final stages of stellar evolution and our understanding of the formation and evolution of galactic jets.

- **NuSTAR** is the first focusing hard X-ray telescope, offering an unparalleled view of extreme astrophysical objects like accreting black holes and neutron stars. As the most sensitive X-ray telescope in NASA's fleet above 10 keV, NuSTAR detects light from obscured environments and from explosive transients at the earliest phases that would be missed otherwise. With 90% of the sky accessible at any time, flexible scheduling, and rapid response to triggers, NuSTAR is at the forefront of TDAMM science. Coordinated programs XMM, Chandra, Swift, NICER, and IXPE enable simultaneous observations that capture the panchromatic behavior of astrophysical events, optimizing all of the missions' scientific returns. As the Vera C. Rubin Observatory and the Nancy Grace Roman Space Telescope begin operations, NuSTAR will play a critical role in the discovery of exciting transients that may be invisible to soft X-ray missions.

- Now in its seventh year of operation, **TESS** has been a planet-finding dynamo. TESS has yielded more than 7000/600 candidate/confirmed exoplanets to date. By virtue of having observed 85% of the sky, the TESS data are a treasure trove of discovery. TESS has maintained exquisite photometric precision (nearly photon-limited over a very wide field-of-view), which enables a wide range of additional science. These data drive science topics spanning the solar system to extragalactic topics and include significant contributions to time-domain astrophysics. TESS's large field-of-view, regular and fast cadence, data analysis pipeline, and associated products provide a community resource that is incredibly valuable. This value is proven by the high publication rate of TESS data. More than 600 papers were published with TESS data in 2024 and if trends hold, future years will likely be higher. The GI program is an important resource for TESS planet follow-up, and is critical now given the limited lifetime of JWST, which provides key follow-up for longer-period planets that may be terrestrial and temperate.

- **IXPE** provides a powerful new view of the X-ray universe through the unique ability to measure and map polarization within X-ray images in the 2 keV-to-8 keV energy range. This transformative capability holds the promise of distinguishing between theoretical models in ways that regular imaging and spectroscopic observations cannot. IXPE has already begun to reshape our understanding of the geometry and origin of the X-ray emitting corona near a black hole that is actively accreting material, as well as the geometry and dynamics of relativistic jets. The IXPE mission supports a broad General Observer program that is observing targets of many different types in order to study accretion in active galactic nuclei, time-varying polarization from material flows and X-ray reprocessing in X-ray binaries, generation of relativistic jets near black holes, polarized emission and tests of a predicted vacuum birefringence effect near highly magnetized neutron stars, and X-rays from shocks in pulsar wind nebulae and supernova remnants. Joint observing programs with NICER, NuSTAR, Swift, and the National Radio Astronomy Observatory provide deeper time-domain astrophysics insights by imaging sources with wider spectral coverage and adding precise timing to complement IXPE's polarization measurements. The discoveries to date are only the beginning of what can be learned from IXPE polarimetry.

Relevance to the Scientific Mission of NASA and Astro2020 Goals

The Science Mission Directorate has identified three broad mission objectives under which the main 2020 Astrophysics Decadal Survey science pillars can be collected. These objectives have been previously summarized in the Big Questions: How does the Universe work? How did we get here? Are we alone? The Astro2020 scientific pillars are:

1. *Worlds and Suns in Context* includes a priority of exploring Pathways to Habitable Worlds. Finding and characterizing exoplanets, progressing from the hot Jupiters to the lower mass and colder worlds (e.g., mini-Neptunes, water worlds, super Earths, Earth twins) were listed in a key Astro2020 recommendation entitled "Habitable Worlds.".

2. *New Messengers and New Physics* includes a priority of opening New Windows on the Dynamic Universe. This category includes TDAMM. Astro2020 classified this area as "Extreme Physics," which includes both broad-spectrum, multi-messenger campaigns that require the simultaneous electromagnetic views of the universe with campaigns that sample gravitational waves, neutrinos, and other ultra-high energy cosmic rays. This area requires coordinated, rapid-response capabilities that can respond in real time to powerful but transient explosive events.

3. *Cosmic Ecosystems* includes a priority on Unveiling Drivers of Cosmic Growth. This category includes the study of the evolution of galaxies including their gaseous halos. Context includes the cosmological growth of large-scale structure, the co-evolution of supermassive black holes and their host galaxies, the underlying connections between those systems, the emergence of galaxies and supermassive black holes in the high redshift universe, and the evolution of the cosmic baryons (i.e., chemical enrichment, thermodynamics, energy transport in plasmas, star formation). This endeavor is inherently multiwavelength, requiring NASA facilities from the far-infrared through the X-ray region in order to provide the complete picture of these ecosystems.

The Panel finds that **both individually and as a portfolio, the missions provide strong support of making future progress toward these science pillars.** A brief summary of how the missions address these science pillars is given here.

Pathways to Habitable Worlds

TESS and **HST** promise continuing progress in exoplanet science. This progress is especially timely while **JWST** is still in its prime phase. TESS is crucial in the discovery of new exoplanets around host stars that are sufficiently bright for spectral atmospheric absorption characterization with JWST observations. The recovery of precise orbital parameters and predicted eclipses for known planets narrows the time window for JWST observations. However, the atmospheres of planets sensitively depend on their environment, including irradiation from their host stars. The combined X-ray and UV observations of a planet's host star constrain the amount of elusive but very influential Extreme UltraViolet (EUV) radiation. For this work, **HST** (providing UV), **Swift** (providing simultaneous X-ray and UV stellar photometry of relatively isolated or bright stars), **Chandra** (providing X-ray photometry of even faint stars in complex fields), and **XMM** (providing X-ray spectroscopy of stars) allow stellar astronomers to study a range of stars and stellar environments.

New Windows on the Dynamic Universe

The campaign investigating the neutron star merger discovered in August 2017 in gravitational waves by the Laser Interferometer Gravitational-Wave Observatory (LIGO) and the Virgo detector hosted by the European Gravitational Observatory, is a perfect case study for the capabilities of the 2025 senior review portfolio. A compilation of this multi-messenger campaign is provided in B. P. Abbott et al. (2017), ApJL, 848, L12. Because **Fermi** monitors nearly the entire sky in gamma rays multiple times per day, Fermi detected the first electromagnetic pulse in gamma rays. Precise localization was provided by ground-based optical observations, but **Swift** detected the UV counterpart only 15 hours post-merger. **HST** and **Swift** then provided the extended-time UV light curve. **HST** contributed space-based near-IR (InfraRed) and optical photometry. The IR grism observations were crucial for identifying lanthanide absorption features in the ejecta spectrum. After restrictive X-ray non-detections by Swift, the source brightened in the X-ray region. **Chandra** observations detected the counterpart nine days post-merger. Chandra's resolution allowed the counterpart to be clearly distinguished from the X-ray source at the center of the host galaxy. By early September 2017, the source had moved too close to the Sun in the sky, and **NuSTAR** was the only X-ray telescope that could safely monitor the source through December 2017. **XMM-Newton** picked up the X-ray monitoring as the counterpart re-emerged from the other side of our Sun, confirming that the source had passed its peak X-ray brightness and was by then fading. **Chandra** continued to monitor and detect the source for over five years post-merger. With its large field-of-view, **TESS** (launched in 2018) is currently monitoring potential new binary neutron star mergers. This landmark event, capturing the full spectrum electromagnetic emission from the aftermath of a neutron star merger, confirmed the suspicion that many of the heaviest stable elements in our periodic table may be primarily produced in these rare and extreme mergers. This case study captures the need for a healthy, nimble multi-messenger system of space-based observatories.

Black holes and neutron stars provide laboratories for extreme physics, which is one of the priority areas identified by Astro2020. Measuring the properties of black holes and neutron stars requires simultaneous or near-simultaneous observations by multiple observatories because of the broadband and variable nature of their photon production processes. For example, the Fe K emission line at 6.4 keV is an important and prominent diagnostic of chemical composition and dynamics in otherwise highly ionized plasmas. Relativistic motions and black hole spins can be inferred from line-broadening. Simultaneous spectroscopy by **NuSTAR** and XRISM, **XMM,** or **Chandra** allow tight constraints of the spectrum, including the continuum on both sides of that crucial and potentially highly-broadened emission line for many scientific applications. This joint observational mode is in very high demand from the science community. **IXPE** and **Fermi** provide unique insights about the corona and the base of the jet as the sources of high-energy radiation from accreting black holes.

Unveiling Drivers of Cosmic Growth

In the last decade, our picture of galaxy evolution has almost completely transformed. Supermassive black holes have somehow co-evolved with their galaxy hosts. Our best hypothesis for this trend has been called

``AGN feedback." Determining exactly how AGN regulate their cosmic environments requires learning how AGN are fueled (i.e., accretion disk physics) and how AGN launch energy to cosmic scales via jets and winds. Chemical composition also yields important clues about how galaxies grow. While stars, supernovae, and the mergers of stellar remnants provide nearly all of the chemical evolution in the universe, AGN may play a role in pushing heavy elements away from galaxies, thereby enriching the circumgalactic and intergalactic medium. Careful observations at both the small and large scales are needed for progress. These observations must be combined with the assessment of the chemical, thermodynamic, and kinematic state of plasma in emission and absorption in the gas reservoirs surrounding galaxies and clusters of galaxies. JWST discoveries of galaxies and black holes forming with extremely high efficiencies in the first billion years of the universe provide an important early snapshot of these systems, perhaps with star formation or black hole growth temporarily "unregulated."

A complete picture of this history requires multi-wavelength observations. Stars emit mostly in the near-IR or optical wavelengths. The preponderance of baryons associated with a galaxy emits or absorbs primarily in the rest-frame X-ray or UV. The UV and X-ray spectra are rich with line diagnostics for temperature and abundances.

The portfolio of missions is well-positioned to make progress here while future missions are under development. **Chandra** is unique in its exquisite X-ray angular resolution, giving it a sensitivity to X-ray point sources and sharp features (e.g., revealing otherwise hidden AGN in high redshift galaxies that are identified and pinpointed by **JWST**, resolving the sizes and shapes of AGN bubbles and shocks in hot clusters that allow for a direct measurement of the actual energy deposition by AGN) that cannot be achieved with the optics of other X-ray missions. **XMM-Newton**'s X-ray sensitivity to galaxy and group thermal gas emission at energies below 1.5 keV is now a precious resource; Chandra's sensitivity in that bandpass is largely gone, and XRISM's unfortunately closed gate filter current prevents observations in this energy range. Polarization measurements from **IXPE** will unpack the structures of AGN accretion disks and jets in a much wider variety of AGN classes in a brand new, innovative way. **HST** spectroscopic UV observations are crucially sensitive to the absorption features from gas reservoirs around galaxies at a wide range of redshifts. HST's angular resolution provides close-in views of AGN and their hosts. HST and JWST have demonstrated the power of gravitational lensing not only as a means to map the gravitational matter around galaxies and clusters and galaxies but also as an amplification of the more representative galactic population at redshifts and luminosities that are otherwise unavailable to the unaided telescope.

Cost Efficiency, Data Availability, and Budget Considerations

The mission teams across the portfolio have made significant, sustained efforts to operate efficiently and provide strong science returns to the community. The extended mission paradigm is working: these missions are well operated, impactful, efficient machines. In most cases, the missions have reached equilibrium in operational efficiency. The in-guide budget proposals for most of the missions now represent cuts against that equilibrium, reducing one or a combination of mission capability, mission, staffing, or community funding. These cuts are further exacerbated by the past history and possible future of a lack of adjustment for inflation. Purchasing power for these missions has been reduced annually, making the missions' scientific return even more remarkable.

It is important to highlight the very different scales of the missions under review, either in terms of initial investment, ongoing operations, or user community size. Furthermore, many missions operate in photon-limited environments to yield the science their communities propose, requiring long observation times on many targets. A direct comparison in cost efficiency between the missions is well beyond the ability of any Senior Review given the complex, multi-dimensional space of the issues above, whether that comparison is in terms of publications, citations, or other metrics. The Panel instead chose to review the mission's individual scientific potential in a forward-looking way, including how that mission might complement the fleet.

All of the missions reviewed are meeting the mandate of data accessibility. This accessibility requires significant processing of the raw data, which by itself is not usable. Prompt delivery to archives and curation by those archives is also a strength of the portfolio. Each of the mission teams are doing what they can within their budgets to improve archives. The teams work with their user communities to provide open-source analysis software, robust documentation, and user tutorials. Additionally, mission teams and their user communities go beyond requirements to produce higher-level science products. The net result is better data products that are easier to use by astronomers in the United States and around the world. The Panel notes that many of the in-guide budgets, if adopted, threaten continued development of accessible data products and analysis support services.

The mission teams were asked to identify under-guide budgets that represented capabilities and community funding below which mission termination should be considered. The Panel felt that the proposals did not follow this guidance in general. Instead, the proposals presented under-guide budgets that represented the minimum mission that would still yield high productivity science instead of the minimum possible mission. A mission might survive the temporary emergency reduction of costs unrelated to operating the mission; however, **such drastic reductions would severely compromise the scientific productivity of a mission, through irrevocable loss of observing time from a finite mission lifespan, missed significant rare scientific opportunities (e.g. near-Earth asteroids, supernova explosions, and neutron star mergers), and irreplaceable drains of expertise.** The Panel emphasizes that because full mission termination is an irreversible "solution" to a (sometimes) short-term problem, a temporary emergency reduction beyond the underguide is preferable to cancellation, but cannot be done without significantly and adversely harming the science return from the mission.

In addition to scientific merit and alignment with strategic scientific priorities, each mission was evaluated on the current and future projected health of the spacecraft and instrumentation. The Panel's evaluation focused on a mission team's identification of significant risks and the mission team's plan to mitigate or retire those risks. The Panel did not assign major weaknesses to a mission's proposal simply because a risk existed.

The Panel notes that in the case of Chandra, a proposal identified as the "Minimal Cost Mission" by the Chandra team was substituted for the in-guide budget proposal for review, because the in-guide budget followed the Fiscal Year 2025 President's Budget Request, which represented a closeout budget. In the case of HST, the Panel notes that the budget for the NASA Hubble Fellowship Program (NHFP) was considered as an unchangeable aspect of any budget proposal.

GO/GI and Mission Support

NASA Astrophysics programs lead the world because of investment in both mission development and research productivity. To maximize scientific returns on the substantial costs of mission development, construction, and launch, these programs ensure that a rich period of scientific harvest ensues. This period occurs first during the prime mission and then is sustained by continuing to fund research during an extended mission phase. Meanwhile, the mission's freely-accessible data archives grow and enable new and innovative lines of research beyond those key questions envisioned by the mission's builders.

These scientific returns on investment are why the operating budget of an extended mission provides GO or GI funding in support of additional research. This budget enables:

- Better understanding and more effective analysis of the archived data

- Development of new scientific models motivated by a mission's earlier findings
- Careful testing of the new hypotheses using statistics, simulations, and follow-up observations
- Communication and discussion of newly emerging results with other scientists

… and perhaps most importantly:

- Sharing the most exciting new findings with rest of the world.

To further these ends, NASA Astrophysics makes all of the scientific data its missions have collected available to everyone worldwide through fully public data archives. These archives are enormously valuable data warehouses but are also much more than that. The archives are continually augmented with higher-level scientific products and data-analysis tools that build upon lessons learned. Funding of both new observations and archival data analysis during an extended mission helps to broaden the mission's research footprint. Investment in the mission initiates and expands research programs in nearly all of our country's 50 states (**Figure 1**).

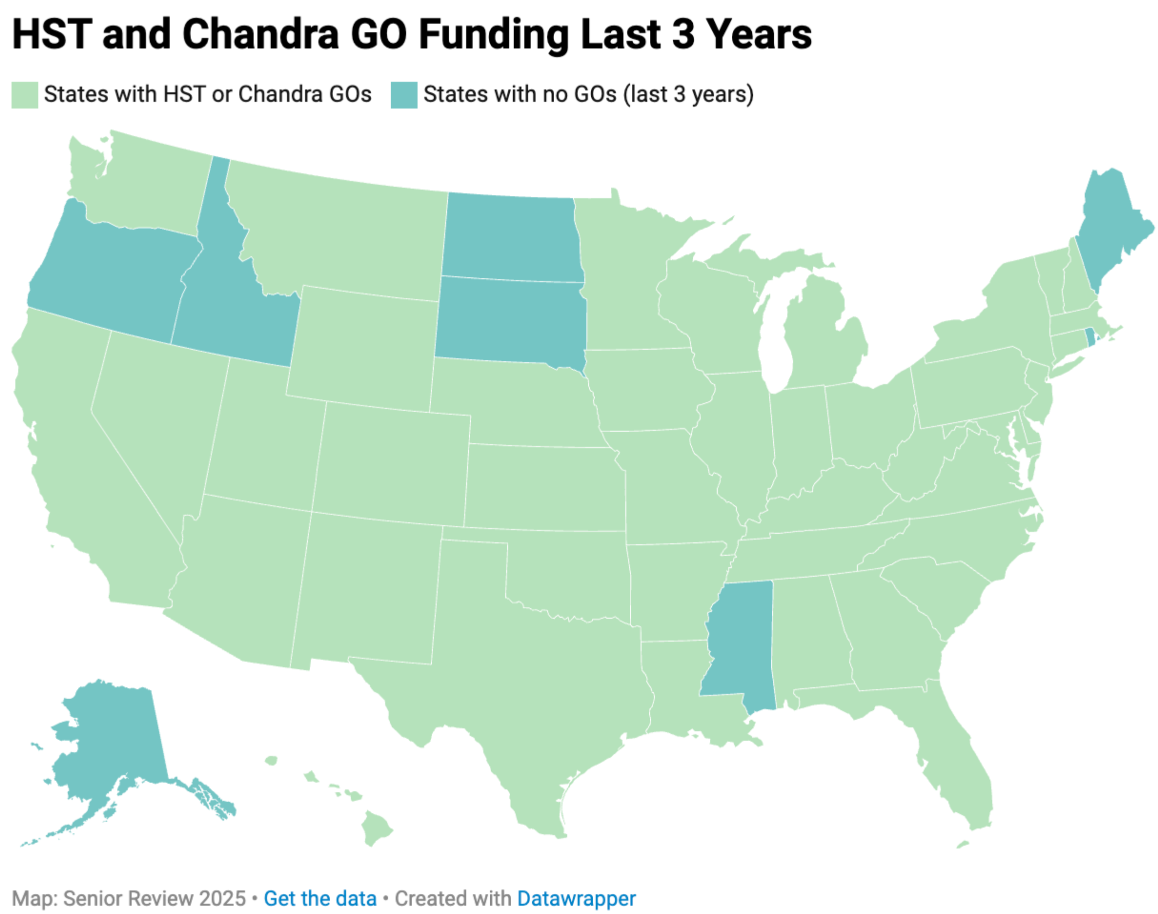

Figure 1: HST and Chandra GO+Archival Research awards over 2021-2024: US Map. A snapshot of three years of competitive awards made to principal investigators by state (light green); no awards in that time period (dark teal).

Mature NASA Astrophysics missions are therefore massively productive science factories. The missions capitalize on the sheer size and innovative prowess of the US astrophysics community and that of the global scientific community using NASA facilities. The creativity and innovation of that community is confirmed by the sheer volume of research proposals received by every one of the missions in the NASA Senior Review portfolio. Opportunities for general observers and general investigators with these missions are typically oversubscribed by factors of more than 6-to-1. Many worthy investigations must be declined simply because there is not enough time and funding to perform them all.

To keep those science factories running, the program budgets reviewed by the Panel have committed a median of about 20% of the total funding to GO programs. This fraction may be an emergent best-practice minimum ratio. Those funds purchase hardware and computing resources, support graduate and undergraduate students in answering cutting-edge astronomical questions with world-class observatories, and enable US researchers from any university to collaborate, contribute, and lead teams of international researchers. An unfunded US researcher is at a clear disadvantage compared to a funded foreign researcher with full access to the public US data archive. There are other ways of supporting science (e.g., group grants to a few institutions), but NASA’s approach has been shown to be broadly successful and efficient.

Extended mission funding also helps to level the playing field. Funding and data-sharing policies developed by NASA’s Astrophysics Division utterly transformed the landscape of astronomical research. Historically, access to high-quality data and research funding was limited to a handful of elite institutions. NASA changed that by establishing open-access data archives, such as those hosted by the Mikulski Archive for Space Telescopes (MAST), the InfraRed Science Archive (IRSA) and the High Energy Astrophysics Science Archive Research Center (HEASARC), which made world-class observational data from missions like Hubble, Chandra, and Spitzer freely available to the global scientific community. In parallel, NASA developed competitive, peer-reviewed data analysis and theory programs, distributing funding to support observing, archival, and theoretical research proposals from institutions across the United States. These programs democratized access to space-based data and enabled cutting-edge astrophysical research to flourish well beyond traditional research centers (Figure 1). World-class astronomical research has become possible no matter where the research is being done.

While it can be argued that an extended mission does not absolutely require a GO budget to continue operations, the Panel finds strong alignment with NASA's past policy and its demonstrated success. A healthy and scientifically viable mission program needs a GO program in order to continue to achieve the mission’s full scientific potential. A healthy GO program fuels dissemination and publication of science results, engages the broad community of minds that both maximizes and optimizes the science scope and programming of the mission, and allows strategic and fundamental preparation of the NASA science workforce of the future. With the full support of the missions’ respective user communities, the mission teams have concluded in nearly every Senior Review proposal that a temporary reduction of GO funding could be tolerated if it helped a program survive in the near term. If cuts were permanent, however, such a choice would result in ever deeper cuts to the scientific productivity of the mission. **Reducing or eliminating GO support to US scientists will profoundly disadvantage the US astronomical community compared to international peers and would erode US stature in the world scientific community.**

Cross-Mission Considerations

In addition to evaluating the missions individually, the Panel also considered a number of cross-mission topics. ”Cross-mission” can either mean explicit relationships and issues between missions or themes that were seen across multiple mission proposals. These topics include the following:

- In an individual and coordinated cross-mission way, missions are increasingly responsive to the needs of the time domain astrophysics communities. Missions are expanding the ability to perform both target of opportunity observations and coordinated time-critical observations on varying sources. These responses are in direct support of the science goals of the 2020 Astrophysics Decadal Survey.

- The Tracking and Data Relay Satellite System (TDRSS) suite of satellites is aging, and there is no current plan for NASA to deploy and operate a replacement that is compatible with currently operating missions. Many of the missions utilize TDRSS for prompt notification to the ground and for rapid-response targeting. This use represents a risk to the future science viability of these missions as TDRSS progressively goes offline.

- Information Technology (IT) Security is becoming a new cost growth driver for missions. With flat or declining budgets, meeting the requirements for enhanced security comes at the expense of other aspects of the mission.

- Many missions viewed the resources needed to respond to anomalies as an additional contingency request to NASA as opposed to including the necessary staffing as part of the missions' in-guide budgets.

- As the landscape of users evolves and as missions age, there is an increasing need for sound management of mission teams. Best practices including succession planning, mentoring, cross-training, and onboarding of mission teams deserve investment and focus.

- Community user groups are innovation engines for missions. Many missions considered changes in science operations as informed by their respective user groups. These groups also identified potential near-term and long-term issues facing the missions and their communities. Such issues include publication policies, strategic observing campaigns, and grant award procedures. Critically, these user groups also served as drivers for growing the missions' community of users and for increasing cross-mission approaches to science.

The Future of the Fleet

The missions considered by the Panel are all delivering transformational science today. Each mission team has presented a compelling future for science in the coming three years. Each mission in the portfolio is nevertheless aging, and some missions face significant challenges. Over the next extended mission period, it is likely that at least one mission in the portfolio will have to cease operations. The missions become more precious with this prospect in mind, particularly in the knowledge that none of the missions under review has a replacement on the way.

Three missions face notable technical and operational challenges. Recent calculations show a significant probability that the Swift orbit will decay, and the spacecraft may reenter the atmosphere during the next extended mission cycle. HST's Science Instrument Command and Data Handling system is currently operating without redundancy capability. An effort to restore that redundancy continues. The observatory is using only a single gyroscope for science operations. Chandra's thermal blanketing is degrading, so the spacecraft must be pointed to control heating. Redundancy in Chandra's High Resolution Camera (HRC) instrument has been lost along with redundancy in Sun fine-sensing capability. While these issues are significant, they are well characterized and understood. Mitigations are in place or planned in order to maintain the maximum possible mission lifetime and reliability.

All of the missions in the portfolio will end at some point. Missions must develop plans to "immortalize" their data, with robust documentation in order to ensure that both the mission data processing pipeline and the science user software of today are usable in the future. Through user groups and other efforts, the community should work with the mission teams now in order to begin identifying final campaigns of key legacy science to execute in the coming years. A development of a standard practice for scientific "last call" planning is warranted, whether for individual capabilities in a mission or for the mission as a whole. HST and Chandra have source catalogs amassed over years of observations but no longer have the resources to add new observations to these catalogs. For these missions, resourcing a final catalog would be a valuable complement to traditional closeout efforts.

Scientifically, the future for APD missions is very bright. JWST and XRISM will be proposing for extended operations at the time of the next Senior Review, and SPHEREx will be on the verge of completing its prime mission. The current portfolio is preparing for the next portfolio, with many missions executing programs in support of future flagships such as the Nancy Grace Roman Space Telescope in the near term and the Habitable Worlds Observatory on the horizon. Missions are also set to provide firm foundations for other future capabilities such as the ESA-led New Athena, the ESA-NASA Laser Interferometer Space Antenna (LISA), and NASA's UltraViolet EXplorer (UVEX). The workforce continues to evolve. More early-career astronomers are doing multi-wavelength multi-mission science than ever before while contributing to open science initiatives in a rapidly expanding way. This evolution is driven by the current portfolio and will be one of its lasting legacies.

Over-guide and Under-guide Budget Considerations

In addition to the in-guide budget proposal, each mission team was asked to identify an under-guide budget below which mission termination should be considered. The Panel recognizes that budget uncertainty may drive the decision to resource the missions at the under-guide budget level but notes that operating any of the missions at the under-guide level is not a sustainable path. This report discusses under-guides in context with mission operations and funding for science support and analysis in the Sections above on Cost Efficiency, Data Availability, and Budget Considerations, and on GO/GI and Mission Support.

For this Senior Review, the in-guide budget for Chandra was set at the level of the Fiscal Year 2025 (FY25) President's Budget Request, which was intended as a close-out budget. The Chandra team was asked to provide a minimum-cost mission, although the cost was expected to exceed the in-guide budget; the Panel was directed to evaluate that minimum-cost mission in place of the in-guide close-out plan.

Mission teams also had the opportunity to provide an over-guide budget. None of the missions' over-guide requests were prioritized by the Panel over any of the missions' in-guide requests, including that of the Chandra "Minimal Cost Mission". However, if the resources are available, the Panel found scientific merit in many of the over-guide requests from the missions. The Panel identified three tiers of possible over-guides in order of decreasing urgency by tier for consideration by APD.

Tier One over-guides are those over-guides that are aimed at mitigating risks to missions and retiring threats to the health and safety of the mission and operations integrity. In this tier, the Panel prioritized a focus on addressing mission-threatening anomalies, followed by cases that can tolerate slower response. The cases are listed as follows:

> **IXPE:** Proposed Over-guide #1 would avoid the cuts to staffing at Marshall Space Flight Center (MSFC) that are outlined in the in-guide mission plan. Specifically, the over-guide would add back staffing in project management, system engineering, science planning, data analysis tools, and software support roles. This over-guide funding would reduce spacecraft risk, enable more reliable science planning, and avoid or resolve issues in science data processing and software.
>
> **HST:** Proposed Over-guide #3 includes augmented support for Flight Operations/Subsystem Engineering, Flight Software Sustaining Engineering, and Ground System Software/ Hardware/ Network. This over-guide restores staffing levels of the Planning and Scheduling team in order to minimize risk associated with future anomalies.

NuSTAR: The first request is associated with the need to replace the Space Force satellite tracking with a commercial entity (i.e., LeoLabs). NuSTAR does not carry a receiver for the Global Positioning System (GPS); commercial tracking would prevent NuSTAR from being lost when the Space Force is unable to track it. The second request is associated with the need to accommodate increasing NASA IT and cybersecurity requirements at the Mission Operations Center (MOC).

Fermi: The LAT data processing transition from the Stanford Linear Accelerator Center (SLAC) to Goddard Space Flight Center (GSFC) was the highest Panel-ranked over-guide for Fermi. This cost is to compensate for personnel costs at SLAC. The request will ensure that the data pipeline move can be maintained by the NASA-funded team. This cost is also linked to mission planning and the idea to restore the ToO capacity. This transfer is related to knowledge and skills rather than a transfer of technology. A possible risk of not granting this request is that the transition will take significantly longer than the anticipated one year remaining in the transition phase.

Chandra: The "Minimal-Cost Mission", which the Panel was charged to consider as both under-guide and in-guide, proposes reductions in rapid return-to-science support following anomalies, minimization of monitoring and trending of instruments, minimization of Verification and Validation work, and minimization of special processing efforts. These proposed reductions may make it difficult for the team to address unanticipated problems in the future.

Swift: Over-guide Request 1 (OG1) reduces risks to the mission due to the lack of redundancy in key operations roles. This over-guide enables more-timely implementation of IT security upgrades that are recommended by NASA. OG1 will mitigate efficiency losses in the event of an anomaly. This over-guide is considered to be highest priority for Swift.

Tier two over-guides are those over-guides that are focused either on instrument restoration or potential enhancements to science yield. These cases are listed in decreasing priority preference:

1. **Chandra HRC Science**. The baseline mission removes HRC from use, and this over-guide would retain HRC. Although the HRC has not been used as much as the ACIS instrument on Chandra, HRC is the only camera that offers full sampling of the Chandra Point Spread Function (PSF) and the only Chandra camera with remaining functional sensitivity to low-energy ($E<1.5$ keV) X-rays. Retention of HRC would allow the 16-microsecond timing capability to be exploited for studying millisecond pulsars. Certain calibration observations are best performed by HRC, including PSF width monitoring and monitoring the relationship between PSF width and grating dispersion.

2. **IXPE GO augmentation:** Over-guide #3 would increase funding for the GO program by approximately 40% relative to the in-guide budget. The proposal makes a strong case for a broad GO program, given the wide range of science investigations that the mission enables. Supporting a wider variety of approved programs from a growing user community is appropriate for the mission at this stage.

3. **TESS development of high-quality light curves for any source in its Full-Frame Images (FFIs):** The TESS mission's proposed over-guide activity #2 is to create high-quality light curves from the 200-second FFIs for any target. This activity would be the most impactful for the community at large and is strongly endorsed by the Panel. The Panel rates this #2 request ahead of the mission over-guide request #1, which adds to the TESS GI program.

4. **All Other Missions:** Augment GO levels to match the missions' respective over-guide requests to best serve community analysis and dissemination of the science.

Tier three over-guides represent the remaining high-priority efforts that the Panel felt would yield enhanced scientific return. These over-guides are, in no particular order:

Chandra: Retaining Community support: The "Chandra for the Future" over-guide restores critical support for the community. Under the baseline mission scenario, there would no longer be workshops on the CIAO/Sherpa data analysis software. HelpDesk support would be minimized. No more Chandra conferences or newsletters would be produced. These changes represent a user environment with little support for new users including students. That scenario would likely have a negative impact on the Chandra user community and its scientific productivity.

Fermi: Community support: This over-guide provides software development/support for three years with FermiPy prioritized over new tools by the Panel.

IXPE: Software support: Over-guide #5 is proposed to develop neural-network processing that potentially enhances polarization sensitivity of future and past observations.

Acronyms

ACIS	Advanced Charge-coupled device Imaging Spectrometer
AGN	Active Galactic Nuclei
APD	Astrophysics Division in NASA's Science Mission Directorate
Astro2020	2020 Astrophysics Decadal Survey
CIAO	Chandra Interactive Analysis of Observations
CXC	Chandra X-ray Center
EMRI	Extreme Mass Ratio Inspiral
ESA	European Space Agency
EUV	Extreme UltraViolet
FFI	Full-Frame Image
GBM	Gamma-ray Burst Monitor
GI	General Investigator
GO	General Observer
GOF	General Observer Facility
GPS	Global Positioning System
GSFC	Goddard Space Flight Center
HEASARC	High Energy Astrophysics Science Archive Research Center
HRC	High Resolution Camera (Chandra instrument)
HST	Hubble Space Telescope
IR	InfraRed
IRSA	InfraRed Science Archive
IT	Information Technology
IXPE	Imaging X-ray Polarimetry Explorer
JWST	James Webb Space Telescope
LAT	Large Area Telescope (Fermi instrument)
LIGO	Laser Interferometer Gravitational-Wave Observatory
LISA	Laser Interferometer Space Antenna
MAST	Mikulski Archive for Space Telescopes
MOC	Mission Operations Center
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
NHFP	NASA Hubble Fellowship Program
NICER	Neutron star Interior Composition ExploreR
OG	Over-guide
PSF	Point Spread Function
SLAC	Stanford Linear Accelerator Center
SMD	NASA's Science Mission Directorate
SPHEREx Explorer	Spectro-Photometer for the History of the Universe, Epoch of Reionization and Ices
STEM	Science, Technology, Engineering, and Mathematics
TDAMM	Time Domain and Multi-Messenger
TDE	Tidal Disruption Event
TDRSS	Tracking and Data Relay Satellite System
ToO	Target of Opportunity
ULTRASAT	Ultraviolet Transient Astronomy Satellite
UV	UltraViolet
UVEX	UltraViolet EXplorer (NASA Explorers mission planned to launch in 2030)
XRISM	X-Ray Imaging and Spectroscopy Mission (JAXA)