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March 14, 2025

Dr. Sethuraman Panchanathan
Director, U.S. National Science Foundation
2415 Eisenhower Avenue, Suite 19000
Alexandria, VA 22314

The Honorable Janet Petro
Acting Administrator
National Aeronautics and Space Administration
NASA Headquarters
Washington, DC 20546-0001

The Honorable Chris Wright
Secretary, U.S. Department of Energy
1000 Independence Avenue
SW Washington, DC 20585

The Honorable Brian Babin
Chairman, Committee on Science, Space and Technology
United States House of Representatives
Washington, DC 20515

The Honorable Ted Cruz
Chairman, Committee on Commerce, Science and Transportation
United States Senate
Washington, DC 20510

The Honorable Bill Cassidy
Chairman, Committee on Health, Education, Labor & Pensions
United States Senate
Washington, DC 20510

Dear Dr. Panchanathan, Acting Administrator Petro, Secretary Wright, Chairman Babin, Chairman Cruz, and Chairman Cassidy:

I am pleased to transmit to you the annual report of the Astronomy and Astrophysics Advisory Committee for 2024-2025.

The Astronomy and Astrophysics Advisory Committee (AAAC) is a Federal Advisory Committee that was established by the U.S. Congress under the National Science Foundation Authorization Act of 2002[1] to provide independent assessments and recommendations regarding the coordination of astronomy and astrophysics programs of the National Science Foundation, the National Aeronautics and Space Administration, and the Department of Energy. As part of its founding charge, the AAAC specifically evaluates the agencies' progress toward the priorities outlined in the National Research Council's decadal surveys in astronomy and astrophysics and transmits its findings and recommendations to the agencies and Congress no later than March 15 of each year.

The attached document is the twenty-first such report, which has been carefully considered and prepared by our committee in full compliance with our congressional charter and requirements of the Federal Advisory Committee Act. We note that our committee regrettably lost the opportunity to hold two scheduled public meetings in January and February 2025 due to administrative disruptions at the agencies, and we hope those can be rescheduled in the coming months. Attached below you will find an executive summary, followed by our report, with findings and recommendations for NSF, NASA, and DOE regarding their support of the nation's astronomy and astrophysics research enterprise, along with detailed recommendations concerning specific projects and programs. The report is also being sent to other Congressional Committees of Jurisdiction.

I would be glad to provide you with a personal briefing if desired.

Sincerely yours, on behalf of the Committee,

Dr. Britt Lundgren
Chair, Astronomy and Astrophysics Advisory Committee

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[1] https://www.govinfo.gov/app/details/PLAW-107publ368/

Cc: The Honorable Zoe Lofgren, Ranking Member, Committee on Science, Space, and Technology, United States House of Representatives

The Honorable Maria Cantwell, Ranking Member, Committee on Commerce, Science, and Transportation, United States Senate

The Honorable Bernie Sanders, Ranking Member, Committee on Health, Education, Labor, and Pensions, United States Senate

The Honorable Jerry Moran, Chair, Subcommittee on Commerce, Justice, Science, and Related Agencies, Committee on Appropriations, United States Senate

The Honorable Chris Van Hollen, Ranking Member, Subcommittee on Commerce, Justice, Science, and Related Agencies, Committee on Appropriations, United States Senate

The Honorable Mike Lee, Chairman, Committee on Energy & Natural Resources, United States Senate

The Honorable Martin Heinrich, Ranking Member, Committee on Energy & Natural Resources, United States Senate

The Honorable Bob Latta, Chairman, Subcommittee on Energy, Committee on Energy and Commerce, United States House of Representatives

The Honorable Kathy Castor, Ranking Member, Subcommittee on Energy, Committee on Energy and Commerce, United States House of Representatives

The Honorable Hal Rogers, Chairman, Subcommittee on Commerce, Justice, Science and Related Agencies, Committee on Appropriations, United States House of Representatives

The Honorable Matt Cartwright, Ranking Member, Subcommittee on Commerce, Justice, Science and Related Agencies, Committee on Appropriations, United States House of Representatives

The Honorable John Kennedy, Chair, Subcommittee on Energy and Water Development, Committee on Appropriations, United States Senate

The Honorable Patty Murray, Ranking Member, Subcommittee on Energy and Water Development, Committee on Appropriations, United States Senate

The Honorable Chuck Fleischmann, Chairman, Subcommittee on Energy and Water Development, Committee on Appropriations, United States House of Representatives

The Honorable Marcy Kaptur, Ranking Member, Subcommittee on Energy and Water Development, and Related Agencies, Committee on Appropriations, United States House of Representatives

Dr. Harriet Kung, Acting Director, Office of Science, U.S. Department of Energy

Dr. Regina Rameika, Associate Director, Office of High Energy Physics, Office of Science, U.S. Department of Energy

Dr. Glen Crawford, Division Director, Research Division, Office of High Energy Physics, Office of Science, U.S. Department of Energy

Dr. Kathleen Turner, Program Manager, Office of High Energy Physics, Office of Science, U.S. Department of Energy

Dr. Bryan Field, Program Manager, Office of High Energy Physics, Office of Science, U.S. Department of Energy

Cc: Dr. Nicola Fox, Associate Administrator, Science Mission Directorate, National Aeronautics and Space Administration

Dr. Mark Clampin, Acting Deputy Associate Administrator, Science Mission Directorate, National Aeronautics and Space Administration

Dr. Shawn Domagal-Goldman, Acting Astrophysics Division Director, National Aeronautics and Space Administration

Dr. Lori Glaze, Acting Associate Administrator, Exploration Systems Development Mission Directorate, National Aeronautics and Space Administration

Dr. R. Chris Smith, Interim Division Director, Division of Astronomical Sciences, U.S. National Science Foundation

Dr. James Neff, Deputy Division Director, Division of Astronomical Sciences, U.S. National Science Foundation

Dr. Daniel Fabrycky, Program Director, Division of Astronomical Sciences, U.S. National Science Foundation

Dr. Karen Marrongelle, Chief Science Officer, Office of the Director, U.S. National Science Foundation

Dr. Linnea Avallone, Chief Officer for Research Facilities, Office of the Director, U.S. National Science Foundation

Dr. David Berkowitz, Assistant Director, Directorate for Mathematical and Physical Sciences, U.S. National Science Foundation

Dr. Tie Luo, Deputy Assistant Director, Directorate for Mathematical and Physical Sciences, U.S. National Science Foundation

Dr. Jean Cottam Allen, Acting Office Director, Office of Polar Programs, U.S. National Science Foundation

Dr. Vladimir Papitashvili, Program Director, Office of Polar Programs, U.S. National Science Foundation

Dr. Saul Gonzalez, Division Director, Division of Physics, U.S. National Science Foundation

Dr. Michael Cavagnero, Acting Deputy Division Director, Division of Physics, U.S. National Science Foundation

Ms. Amanda Greenwell, Head, Office of Legislative and Public Affairs, U.S. National Science Foundation

Mr. Robert Moller, Deputy Office Head, Office of Legislative and Public Affairs, U.S. National Science Foundation

Mr. Chris Hillesheim, Government Affairs Specialist, Office of Legislative and Public Affairs, U.S. National Science Foundation

Astronomy and Astrophysics Advisory Committee Members:

Dr. Darcy Barron (Deputy Chair) - University of New Mexico
Dr. Steven Boggs - University of California San Diego
Dr. Alyson Brooks (Deputy Chair) - Rutgers, the State University of New Jersey
Dr. Katherine Follette - Amherst College
Dr. Sarah Hörst - Johns Hopkins University
Dr. Dana Longcope - Montana State University
Dr. Britt Lundgren (Chair) - University of North Carolina Asheville
Dr. Michael McCarthy - Center for Astrophysics, Harvard University
Dr. Lara Arielle Phillips - University of Notre Dame
Dr. Anja von der Linden - Stony Brook University
Dr. Hee-Jong Seo - Ohio University
Dr. Ann Zabludoff - University of Arizona

Conflict of Interest Disclosure

The AAAC is an independent advisory committee with members who are scientists working in the field of astronomy and astrophysics. The AAAC is committed to ensuring that our annual report is both fair and balanced. For this reason, it is obligatory to identify and disclose any potential conflicts of interest (COIs) that could influence the perspectives and judgments, whether they be personal or institutional. To maintain the integrity of our analysis and the trust of our audience, the content on each major topic in our report was reviewed and approved by one or more members of the AAAC Committee who have no personal or institutional conflict.

Below, we provide a detailed summary of the potential conflicts of interest identified among our members. In alphabetical order: Barron, Boggs, McCarthy, Seo, von der Linden, and Zabludoff:

Barron:
Personal COI: A member of Cosmic Microwave Background Stage 4 (CMB-S4) collaboration.
Institutional COI: Associated with an institution involved in the Next Generation Very Large Array (ngVLA).

Boggs:
Personal COI: None stated with respect to the Decadal recommendations.
Institutional COI: Institutional conflict with the U.S. Extremely Large Telescope (US-ELT) Program (TMT) and the CMB-S4 project.

McCarthy:
Personal COI: None stated with respect to the Decadal recommendations.
Institutional COI: As part of the Center for Astrophysics, involved the US ELT Program (GMT), the CMB-S4 project, the ngVLA, and NASA's Chandra X-ray Observatory.

Seo:
Personal COI: A member of DESI collaboration and a member of NASA Roman survey.
Institutional COI: None.

von der Linden:
Personal COI: A member of the LSST-DESC collaboration.
Institutional COI: None.

Zabludoff:
Personal COI: None explicitly stated with the US-ELT Program.
Institutional COI: Institutional conflict with the US-ELT Program (GMT).

By making this disclosure, we hope to ensure that the insights and conclusions presented in the AAAC report are informed by an objective and comprehensive analysis and not influenced by personal or institutional biases.

Astronomy and Astrophysics Advisory Committee Annual Report for 2024-2025

Background

Astronomy, often described as the "oldest science," seeks answers to some of humanity's most profound questions about our origins and place in the cosmos. For millennia, astronomers have pursued these questions while returning tangible benefits to society. Astronomical observations have played a vital role in timekeeping, navigation, and agriculture since prehistory. In more recent times, astronomers have paved the way for groundbreaking discoveries in modern physics, such as our deepened understanding of the composition and dynamics of the universe, the origin of the elements, and the nature of light, gravity, and space-time.

Thanks to continued investments in astronomy and astrophysics research, humans—despite our relatively short lifespans—can explore the events of the past 13.7 billion years of cosmic history and even predict what lies in the distant future for our solar system and the universe at large. Moreover, many modern technologies used in our everyday lives, such as satellites, GPS systems, digital camera sensors, MRI scanners, and Wi-Fi, owe their existence to basic research in astronomy and physics. Additionally, astronomical observations have provided the primary evidence that new avenues of physics remain to be discovered (i.e., dark matter and dark energy), and understanding this new physics is likely to be transformative. Perhaps still the greatest impact astronomy will have on society will be the one it prevents, as astronomers play a critical role in planetary defense through the detection and monitoring of hazardous asteroids and comets.

Through decades of planning and investment, the United States has built and maintained its status as a world leader in astronomy and astrophysics. Complex, cutting-edge observatories like the James Webb Space Telescope, designed to observe the first stars and study potentially habitable exoplanets, are only possible with federal support. These investments pay dividends in both scientific productivity, with the U.S. leading the world in high-impact research in astronomy, as well as broader societal and economic benefits. Astronomy is a “gateway science,” with majestic images and exotic phenomena that spark broad interest amongst the public and lead students into a wide range of careers in science, technology, engineering, and math. Moreover, the data-intensive nature of the field has driven astronomers to be early adopters and innovators in machine learning and artificial intelligence technologies, further demonstrating astronomy’s position at the forefront of technological innovation.

Unlike many other sciences in which researchers develop individual laboratories, astronomy is advanced by large, transformative projects that create vast, shared datasets for exploration. The scale of these projects means that federal funding drives the majority of modern research in astronomy and astrophysics. Hence, decadal surveys commissioned by the National Research Council play a crucial role in shaping the field’s direction. These decadal surveys provide Congress and federal science agencies with expert, consensus recommendations from across the research community, assessing the current state of the field and setting national funding priorities to ensure the most efficient and effective advancement of American leadership in future discoveries. The seventh decadal survey, *Pathways to Discovery in Astronomy and Astrophysics for the 2020s (Astro2020)*[1], was published in November 2021. Progress toward the goals of the decadal survey is evaluated formally at the five-year mark by the National Research Council, with annual progress reports provided by this committee.

Executive Summary

This year marks 100 years since the American astronomer Edwin Hubble measured the distance to the Andromeda galaxy, thereby confirming the existence of other galaxies beyond our own Milky Way and exponentially expanding the known size of the observable universe. In the century since Hubble's landmark measurement, significant federal investments in facilities, research, and workforce development have positioned the U.S. as a global leader in astronomy and astrophysics research.

We are submitting this 2024-2025 AAAC Report at a time of great uncertainty for federal science agencies and the research communities they support. Our committee reaffirms the critical importance of continuing to cultivate and sustain investments in astronomy and astrophysics. Maintaining U.S. scientific leadership in the decades to come will require:

- sustaining levels of federal science funding that maximize existing investments and promote the advancement of basic research and development activities in U.S. universities and government laboratories;
- retaining a full complement of staff at federal science agencies to ensure the most promising science is selected and funded through the gold standard practice of expert peer review;
- investing in next-generation facilities prioritized by the decadal surveys; and
- supporting educational pathways to science, technology, engineering, and math (STEM) careers that maximize the pool of talent for the next generation of scientific leaders.

The National Science Foundation (NSF), the National Aeronautics and Space Administration (NASA), and the Department of Energy (DOE) provide the primary support for astronomy and astrophysics research in the U.S. Over the past year these agencies have made measurable progress toward the goals of *Astro2020*, while realizing the goals of prior decadal surveys, like the NSF-DOE Vera C. Rubin Observatory, and continuing to maintain critical, legacy investments in facilities, research, and workforce development. The astronomy and astrophysics research enterprise models efficiency through its prioritization of shared public facilities and collaborative projects that split costs and commitments across agencies and leverage their respective strengths. Only a small sample of the immense scientific return from these investments can be effectively captured in this report.

This AAAC report provides a brief assessment of the agencies' support of astronomy and astrophysics priorities over the past year, based on material presented by the agencies in public forums. This report

[1] https://www.nationalacademies.org/our-work/decadal-survey-on-astronomy-and-astrophysics-2020-astro2020

also outlines findings and recommendations related to the following high-priority topics that have been identified by the Committee:

- Progress toward Major Projects Prioritized in *Astro2020*
- Protection of Dark and Quiet Skies
- Community Astronomy
- Workforce Development
- Infrastructure Development for Time Domain and Multi-Messenger (TDAMM) science
- Investments in Machine Learning and Artificial Intelligence (ML/AI)
- Supporting Laboratory Astrophysics

Federal investments in the projects and facilities prioritized by previous decadal surveys continue to drive significant advancements in the field of astronomy and astrophysics. However, recent budget leveling and uncertainties have slowed progress on several of *Astro2020's* forward-looking priorities. Further reductions to science agency funding could risk stalling or even reversing U.S. leadership in astronomy and astrophysics research. In this context, our committee underscores the vital importance of completing a mid-decadal assessment in the coming year to safeguard continued progress and ensure the field's momentum is sustained and strengthened.

I. Agency and Science Highlights

NSF Astronomical Sciences Division

This year marks the 75th anniversary of the National Science Foundation's establishment as a federal agency and the nation's primary engine for basic research. From its inception, the NSF has been at the forefront of developing world-class facilities for astronomy and astrophysics. In its first decade, the NSF established two major national observatories: the National Radio Astronomy Observatory (NRAO) in 1956 and Kitt Peak National Observatory in 1958. The NSF's commitment to advancing "big science" through the construction and support of large, publicly accessible, ground-based astronomy facilities continues today through the ongoing work of NRAO, the National Solar Observatory, and the National Optical-Infrared Astronomy Research Laboratory (NOIRLab), which respectively oversee the national radio, solar, and optical-infrared observatories and data centers across the U.S. and Chile.

Over the past year, NSF has supported an increasingly productive ecosystem of world-class astronomy facilities to meet community demand. Now entering its second decade of operations, the Atacama Large Millimeter/submillimeter Array (ALMA), the world's largest radio telescope, continues to enable research on topics ranging from planet formation to the physical properties of galaxies in the early universe. The last observing cycle produced a record number of quality observations, prompting a new record number of proposals (~1,700) for the cycle now underway. Midlife maintenance of the Green Bank Telescope, the world's largest steerable radio telescope, has been initiated to enable two more decades of operation. NSF has also supported instrument upgrades at NOIRLab's International Gemini Observatory and Cerro Tololo International Observatory in Chile, ensuring that these major investments in ground-based optical and infrared capabilities continue to operate at the cutting edge.

Kitt Peak National Observatory, operated by NSF NOIRLab, hosts two substantial collaborative projects with NASA and the DOE: NN-EXPLORE and DESI. Established in response to the Astro2010 Decadal Survey, the NASA-NSF Exoplanet Exploration Program (NN-EXPLORE) uses the NEID spectrograph on the WIYN Telescope to measure exoplanet radial velocities as slow as the crawling speed of an infant. The technical capabilities resulting from this collaboration have enabled successful searches for previously undetectable low-mass exoplanets around bright, nearby stars. The Dark Energy Spectroscopic Instrument (DESI) survey, with instrumentation and telescope operations funded by the DOE to investigate the role of dark energy in the expansion history of the universe, has been actively taking data for the past three years on the NSF's Mayall Telescope. Major science results from these cooperative projects in the past year are highlighted below.

The NSF has also committed significant resources over the past several years to support the development and implementation for two of *Astro2020's* recommended next-generation ground-based facilities: the U.S. Extremely Large Telescope (US-ELT) Program and the Next Generation Very Large Array (ngVLA).

In addition to funding the construction of the NSF-DOE Vera C. Rubin Observatory, which will begin full operations later this year, the NSF has provided the primary support for workforce development to ensure the science output from this investment is maximized over the coming decade. Funding from the NSF Astronomical Sciences Division, supplemented with donor funds, has supported a growing cohort of world-class early career astronomers working on topics related to Rubin's primary science.

The NSF continues to play a critical role in the development of the nation's scientific workforce. Since its founding, the NSF has supported the education and research careers of 268 Nobel laureates, with 77 in physics, which includes astronomy and astrophysics. NSF's individual investigator grant programs, research experiences, and fellowship opportunities continue to propel the field of astronomy and astrophysics forward by training and supporting the next generation of scientists. Notably, the NSF made significant investments over the past year in advancing astronomy research, development, and workforce training in artificial intelligence (AI). This effort included the establishment of two large collaborative AI institutes, each backed by $5 million in funding from NSF AST, with matching funds from the Simons Foundation. These institutes will serve the broader astronomical community, providing data, models, tools, and programs of education and public outreach.

NASA Astrophysics Division

The portfolio of the NASA Astrophysics Division continues to power innovation in the fields of astronomy and astrophysics, pushing back the frontier of the observable universe. The science productivity of the Hubble Space Telescope (HST) is at an all-time high, with over twenty-one thousand publications since 1991 and strong user demand, second only to the James Webb Space Telescope (JWST). JWST has already produced over 540 publications since 2022 and demand for observing time has exceeded any astronomical observatory in history. The Chandra X-ray Observatory continues to be remarkably productive, playing a crucial role in studies of high-energy astrophysics, and providing invaluable data on black holes, neutron stars, and the hot, energetic universe, complementing discoveries from HST and JWST. Two NASA scientists gained major national and international recognition this year for their contributions to these observatories: Dr. Jane Rigby received the Medal of Freedom for her work as Senior Project Scientist on JWST, and Dr. Marcia Rieke was awarded the Gruber Prize for her work on HST and JWST.

NASA Astrophysics attained major milestones, with the successful launch of the MIDEX Astrophysics Observatory SPHEREx on March 12, 2025, which will produce the first all-sky infrared spectral survey and collect data on over 300 million galaxies and 100 million stars, and four SmallSat/CubeSat missions, including BurstCube, whose "primary goal is to detect, localize, and characterize short Gamma-ray Bursts". A fleet of Pioneer SmallSat missions (Aspera, Pandora, StarBurst, PUEO, TIGERISS) are set to launch in 2025 and 2026. The Optical Telescope Assembly for the Nancy Grace Roman Space telescope was completed and delivered to the world's largest clean room at NASA's Goddard Space Flight Center on November 7, 2024. With this final major delivery, the mission remains on track for launch in 2027. The X-ray Imaging Spectroscopy Mission (XRISM) was successfully launched in September 2023, and the second cycle of Guest Observer proposals has already been announced. The Euclid Consortium – a European Space Agency mission with important contributions from NASA – released the first science results from its Early Release Observation phase. The Chandra X-ray Observatory celebrated the 25th Anniversary of its launch by releasing 25 never-before-seen images, selected from over 25,000 observations. The images showcased Chandra's unique capabilities and complementarity with NASA's other great observatories.

Department of Energy (DOE) Office of Science, Office of High Energy Physics

The DOE is the largest federal funder of fundamental research in the physical sciences and has supported the education and research careers of 118 Nobel Laureates, with 73 in physics. Much of the research is supported and carried out through the ten DOE national research laboratories.

The NSF-DOE Vera C. Rubin Observatory, the top-ranked large ground-based initiative in the 2010 Decadal Survey in Astronomy and Astrophysics, is on track to begin the Legacy Survey of Space and Time (LSST) in late 2025. Rubin Observatory is a partnership between NSF and the flagship project in DOE's Office of High Energy Physics, Cosmic Frontiers portfolio. It promises to revolutionize our understanding of time-variable phenomena in the universe by repeatedly imaging the sky over the next decade. Rubin underwent a successful seven-week commissioning campaign with the Commissioning Camera (ComCam), in preparation for commissioning the much larger LSST Camera (LSSTCam). The campaign achieved control of the Active Optics System (AOS) to deliver excellent image quality (0.65 arcseconds) over the ComCam field of view. Results from the ComCam campaign were presented at the 245th American Astronomical Society meeting in January 2025. The installation of LSSTCam onto NSF's Simonyi Survey Telescope was completed on March 6, and is on track for "First Look" in summer 2025 and the start of the ten-year LSST Survey later in 2025.

The Dark Energy Spectroscopic Instrument (DESI) survey, with instrumentation and telescope operations funded by DOE, successfully completed three years of data taking on the NSF's Mayall Telescope and released cosmology results from its first year of observations. Object catalogs based on the Year 1 data

Fig. 1 – Left: The shipping crate holding the LSST Camera is transported the final 35 kilometers (21.7 miles) up the winding dirt road to Rubin Observatory on the summit of Cerro Pachón. Credit: Travis Lange/SLAC National Accelerator Laboratory.
Right: The LSST Camera, the largest digital camera in the world, is lifted out of its shipping crate on the third level of Rubin Observatory. Credit: Olivier Bonin/SLAC National Accelerator Laboratory

are expected to be released to the public later this year. The Dark Energy Survey (DES), which operates on NSF NOIRLab's Blanco Telescope in Cerro Tololo, Chile, completed its final data release of calibrated object catalogs for cosmology analyses, based on its six-year imaging survey of nearly 5000 square degrees, one quarter of the full sky. DES cosmology results from weak lensing and galaxy clustering are expected to be announced shortly.

Science Highlights from the Agencies

The NSF's Daniel K. Inouye Solar Telescope (DKIST), the world's most powerful solar telescope, achieved a milestone by producing its first detailed maps of the magnetic fields in the Sun's corona using a new, powerful technique for mapping the solar corona (Zeeman imaging). Magnetic fields are the driver of most of the space weather affecting the Earth and its space assets, and their state in the corona is a crucial predictor of these effects. DKIST's first highly detailed map shows promise of being able to understand and forecast such space weather.

The Dark Energy Spectroscopic Instrument (DESI) Survey released its first cosmological results in April 2024, measuring the most precise expansion history to date by detecting baryon acoustic oscillations in the three-dimensional galaxy map of six million galaxies, quasars, and Lyman-α emitters, which trace the evolution of large-scale structure throughout 11 billion years of cosmic history. Among many important cosmological implications, DESI reveals a tantalizing implication on one of the most profound science questions of our time: why the expansion of the Universe is accelerating. When combined with data from other studies, DESI reports a deviation from the prediction of the standard Lambda CDM cosmological model, and therefore a hint for a time-evolving dark energy. The second set of the results in November 2024 provided one of the most stringent tests of gravity and reports a consistency with Einstein's theory of general relativity. DESI is currently preparing for the cosmology result release using its second data release in March 2025.

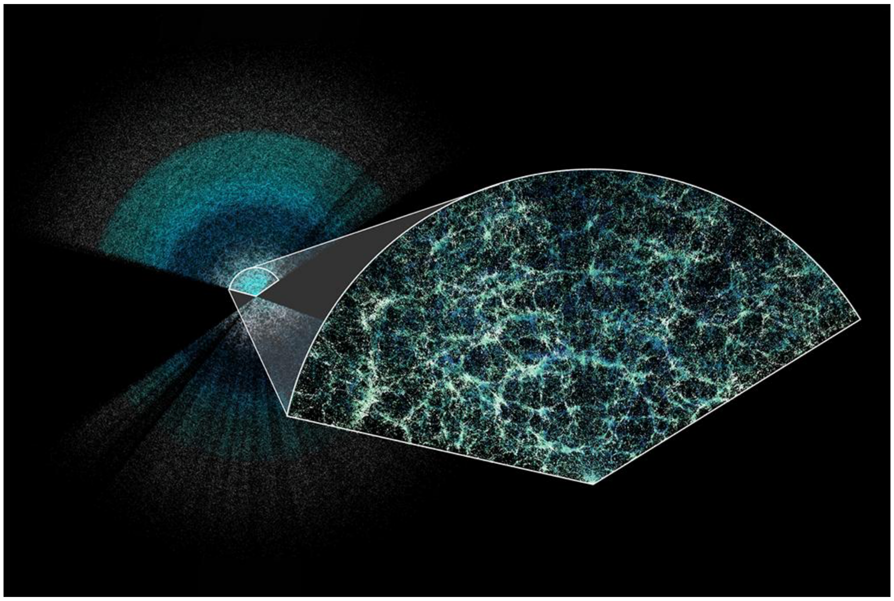

Fig. 2 – DESI has made the largest 3D map of our universe to date. Earth is at the center of this thin slice of the full map. In the magnified section, it is easy to see the underlying structure of matter in our universe. Credit: Claire Lamman/DESI collaboration.

NASA's James Webb Space Telescope (JWST) continues to fulfill its promise of providing a view into the formation of the earliest stars and galaxies. Scientists using data from JWST found the most distant known galaxy in the universe, JADES-GS-z14-0[2] as part of the JWST Advanced Deep Extragalactic Survey (JADES). The galaxy is currently the record holder at a redshift of 14.32 (+0.08/-0.20), seen less than 300 million years after the Big Bang.

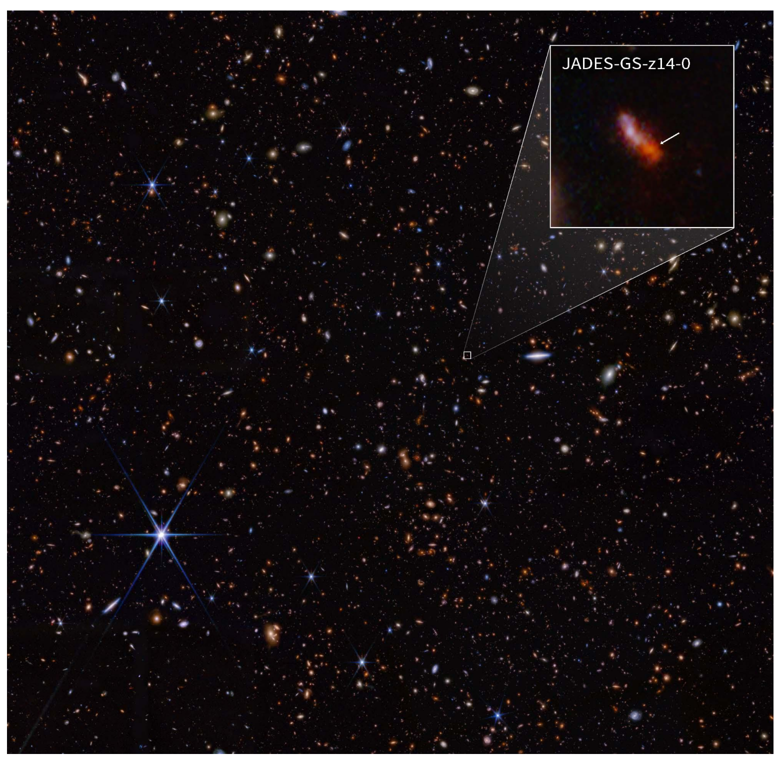

Fig. 3 - JADES-GS-z14-0 (shown in the zoomed in insert) is the current record holder for the most distant galaxy observed by humanity. Credit: NASA, ESA, CSA, STScI, B. Robertson (UC Santa Cruz), B. Johnson (CfA), S. Tacchella (Cambridge), P. Cargile (CfA).

[2] https://webbtelescope.org/contents/early-highlights/nasas-james-webb-space-telescope-finds-most-distant-known-galaxy

Fig. 4 – Left: This illustration shows a red, early-universe dwarf galaxy that hosts a rapidly growing black hole at its center. Using data from NASA's James Webb Space Telescope and Chandra X-ray Observatory, a team of astronomers discovered a low-mass supermassive black hole at the center of a galaxy just 1.5 billion years after the Big Bang. Credit: NOIRLab/NSF/AURA/J. da Silva/M. Zamani; *Right*: This illustration depicts two quasars (actively accreting supermassive black holes) in the process of merging. Astronomers using NSF NOIRLab's International Gemini Observatory discovered the first confirmed pair of merging quasars seen only 900 million years after the Big Bang. Credit: International Gemini Observatory/NOIRLab/NSF/AURA/M. Garlick

Observations spanning the electromagnetic spectrum, using facilities supported by all three agencies, have led to significant progress in the past year in solving a long-standing puzzle of how supermassive black holes form and grow. The DOE-funded DESI Survey has tripled the number of known intermediate-mass black holes[3] – an elusive missing link amongst observable black hole populations, which are overwhelmingly either lightweight (less than 100 times the mass of our Sun) or supermassive (more than one million times the mass of our Sun). Data from NASA's James Webb Space Telescope and Chandra X-ray Observatory revealed a super-Eddington accretion rate in a low-mass supermassive black hole at the center of a dwarf galaxy in the early universe.[4] The combination of multi-wavelength observations from these two space-based observatories were essential to this result, which provides the first observational evidence to test theories that supermassive black holes may form from either the death of the universe's first stars or the direct collapse of gas clouds. Such rapid accretion of mass onto supermassive black holes in the early universe may also explain the widely publicized and puzzling discovery of "little red dots" in early James Webb Space Telescope images.[5] Supermassive black holes are also expected to grow through mergers, but they are rarely caught in the act. Astronomers using NSF NOIRLab's International Gemini Observatory discovered the first confirmed pair of merging supermassive black holes found in the early period of the Universe known as Cosmic Dawn.

Scientists using data from NASA missions have also been leading in the exploration of black holes in our own galaxy. This past year, astronomers using JWST discovered rapid variability from the supermassive black hole at the center of the Milky Way[6], and researchers highlighted the dividends of the long-term

[3] https://kpno.noirlab.edu/news/noirlab2508/
[4] https://www.nasa.gov/missions/chandra/astronomers-find-early-fast-feeding-black-hole-using-nasa-telescopes/
[5] https://science.nasa.gov/missions/webb/newfound-galaxy-class-may-indicate-early-black-hole-growth-webb-finds/
[6] https://webbtelescope.org/contents/news-releases/2025/news-2025-110

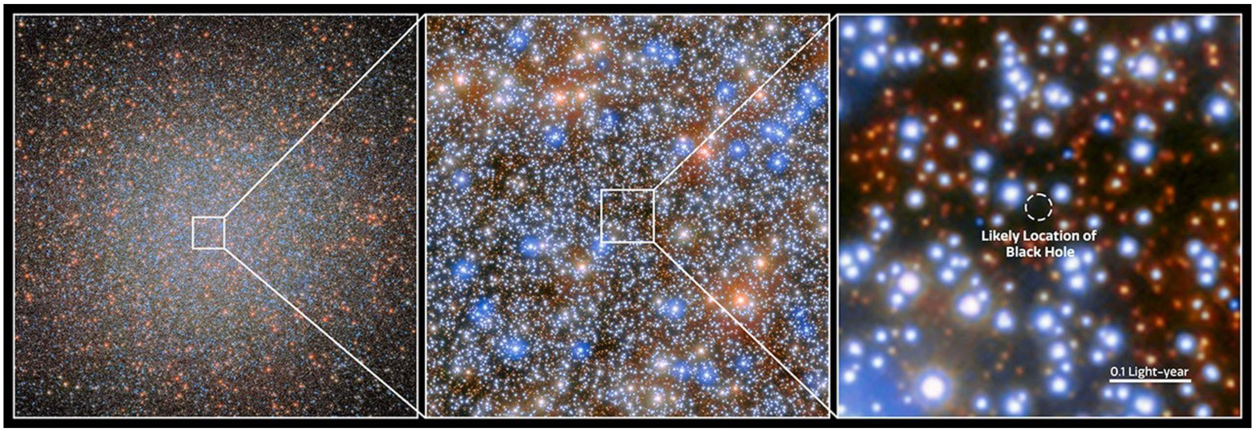

Fig. 5 – A candidate intermediate mass black hole was found in the globular cluster Omega Centauri, a collection of thousands of stars in our Milky Way galaxy, by researchers, using over 500 Hubble Space Telescope images collected over two decades. Credit: ESA/Hubble, NASA, Maximilian Häberle (MPIA).

continuous operation of Hubble Space Telescope by using 500 HST images, spanning two decades, to deliver one of very few intermediate mass black hole candidates in a nearby star cluster.[7]

Exciting advances have been made this year in the study of nearby exoplanets and the search for life's building blocks beyond Earth. The NASA/NSF Exoplanet Exploration Program's (NN-EXPLORE) NEID Earth Twin Survey, with its improved sensitivity in detecting exoplanets, recently led to the discovery of a new "super-Earth."[8] Meanwhile, NASA's JWST continues to revolutionize exoplanet research; in May 2024, it provided evidence of an atmosphere surrounding 55 Cancri e, a hot rocky planet just 41 light-years away.[9] Radio astronomers using the NSF NRAO Green Bank Telescope detected isomers of cyanopyrene, a polycyclic aromatic hydrocarbon (PAH) and a key component of complex organic matter, within a cold interstellar cloud. PAHs are thought to be precursors to life-essential molecules, and this discovery challenges long-standing ideas about their formation. Even closer to home, JWST mapped a surprisingly large water plume jetting from one of Saturn's moons, providing more data on essential ingredients for life elsewhere in our solar system.[10]

II. Progress Towards Major Projects Prioritized in *Astro2020*

A. Ground-Based Initiatives

Astro2020 endorsed the US Extremely Large Telescope (US-ELT) Program as the highest-ranking priority for major facilities projects. The second highest priority puts equal weight toward two other facilities, the Next-Generation Very Large Array (ngVLA) and the Cosmic Microwave Background Stage 4 (CMB-S4), a ground-based cosmic microwave background experiment.

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[7] https://science.nasa.gov/missions/hubble/nasas-hubble-finds-strong-evidence-for-intermediate-mass-black-hole-in-omega-centauri/

[8] https://kpno.noirlab.edu/announcements/ann24034/

[9] https://science.nasa.gov/missions/webb/nasas-webb-hints-at-possible-atmosphere-surrounding-rocky-exoplanet/

[10] https://www.nasa.gov/solar-system/webb-maps-surprisingly-large-plume-jetting-from-saturns-moon-enceladus/

1. US Extremely Large Telescope (ELT) Program

Two consortia are vying for inclusion in the US-ELT Program, the Giant Magellan Telescope (GMT) and the Thirty Meter Telescope (TMT), both of which seek to construct a 30-m class optical telescope in the coming decade. A 39-meter aperture European ELT is already under construction in Chile's Atacama Desert, with first light expected in 2028. Without access to facilities of a similar scale in the near and long term, the U.S. astronomy community will be unable to lead discovery in nearly all the key science priorities of *Astro2020*.

Finding: Congress provided $30M in funding to the NSF in both FY23 and FY24 to support the development of the US ELT Program and other *Astro2020* priorities. In their FY25 funding proposals, both houses of Congress again requested funding in support of the US ELT Program and went so far as to endorse the future construction of two ELTs, one in the southern hemisphere and one in the northern hemisphere. ELT access in both hemispheres would maximize support for discoveries from JWST and future space telescopes, the Rubin Observatory, the Square Kilometer Array (SKA), ngVLA, and other emerging science cases.

Finding: Both the US-ELT Program and the ngVLA represent large initiatives on a scale exceeding historically supported project costs (billion-dollar level with operations and maintenance costs northward of $100M/year). In February 2024, the National Science Board (NSB) recommended that "the US-ELT Total Project Cost to NSF not exceed the $1.6 billion Major Research Equipment and Facilities Construction (MREFC) investment proposed by *Astro2020*."[11] Even with that cap, the NSB expressed concern "that the US ELT alone would require about 80% of the historical MREFC budget."

Finding: An external panel was convened in 2024 to evaluate the readiness of either ELT project to progress to the Final Design Phase. As part of their report, the panel recommended that Congress augment both the MREFC and Research and Related Activities accounts for future projects at this unprecedented scale, noting that operations and maintenance "must be considered for the expected operating lifetime of the telescope(s). Because these funds come from programmatic budgets in AST, failure by Congress to also provide these additional non-MREFC funds would substantially reduce the AST research and education budget for many years to come, potentially requiring a significant reallocation of resources within NSF to make up the difference. Such reallocation would then have a cascading, deleterious impact on several NSF programs, including those of particular national interest (e.g., those within the Technology, Innovation and Partnerships Directorate and for emerging industries such as artificial intelligence, quantum computing and advanced telecommunications)."[12]

Finding: In response to the concerns highlighted above and at the recommendation of the National Science Board (NSB)[13], the NSF created the Facility Operation Transition (FOT) pilot program. The

[11] https://www.nsf.gov/nsb/news/news_summ.jsp?cntn_id=309171
[12] https://nsf-gov-resources.nsf.gov/files/ELT-Evaluation-Panel-Report.pdf
[13] http://www.nsf.gov/pubs/2018/nsb201817/nsb201817.pdf

Senate FY25 report encouraged the continued use of FOT, and asked NSF to begin providing five-year estimates of maintenance and operations costs for projects that have graduated from MREFC.

Recommendation ELT.1: The AAAC recommends that NSF proceed with all due deliberate speed toward a funding decision of the US ELT Program, consistent with internal review policies, and consistent with the recommendations of *Astro2020*.

Recommendation ELT.2: Given the budgetary uncertainty around major facilities, and the impediments encountered in Antarctic science (see CMB-S4 section, below), the AAAC recommends that the mid-decadal review be conducted on schedule starting in 2025. Research supported by AST and to a lesser extent PHY in the MPS Directorate is heavily dependent on the use of large, shared facilities; this model is less so in many other disciplines. For this reason, community input in the form of a decadal survey is central to developing consensus around the highest priority initiatives on a multi-year timescale.

2. Next Generation Very Large Array (ngVLA)

Although it will not be completed until the 2030's, *Astro2020* ranks the ngVLA as the second-highest ground-based priority for this decade (alongside CMB-S4), calling for design and development, NSF assessment of the project readiness, and construction, if viable. The ngVLA will surpass existing radio facilities in sensitivity and spatial resolution by more than an order of magnitude. Current plans are for more than 250 ngVLA antennas to be deployed across roughly ten U.S. states and territories, with accompanying investments in economic infrastructure including transportation, energy, and communications.

Finding: The NSF awarded a $21M grant to advance the ngVLA design in 2024-2026. These developments demonstrate the project's strong scientific and technical promise and NSF's continued commitment to U.S. leadership in radio astronomy.

Finding: In September 2024, the ngVLA project successfully passed its NSF Conceptual Design Review. The ngVLA is now ready to be considered for entry into the Preliminary Design phase.

Finding: Construction and testing of a prototype antenna for the ngVLA is ongoing near the existing VLA site in New Mexico.

Finding: As construction costs are estimated to be of order $2.5B and operation costs in the range of $100M/year, the findings and recommendations related to the financial hurdles for the US ELT program apply to financing the ngVLA as well.

Recommendation ngVLA.1: To maintain momentum, and to maximize investment and U.S. leadership in radio astronomy, the AAAC recommends that the ngVLA proceed to the Preliminary Design phase.

3. Cosmic Microwave Background Stage Four (CMB-S4)

The next-generation ground-based cosmic microwave background experiment, CMB-S4, will make precision measurements that would provide fundamental insights into a broad range of physics and astronomy. Because of these broad capabilities, CMB-S4 has the support of both the astronomy and particle physics communities and requires coordination between and within funding agencies. CMB-S4 was identified as the second-highest priority ground-based facility of *Astro2020* (along with ngVLA), with a recommendation that the NSF and DOE jointly pursue the design and implementation of this project. The 2023 High Energy Physics Advisory Panel's P5 report[14] identified CMB-S4 as the highest priority among new projects and identified observations from both Chile and the US South Pole station as critical for achieving its science goals.

Finding: CMB-S4 has ambitious, theoretically motivated science goals and a design based on demonstrated performance of prior generation instruments. While CMB-S4 has been significantly delayed, CMB science and cutting-edge instruments continue to be supported by NSF, DOE, and NASA, resulting in exciting scientific results and technology demonstrations.

Finding: In May 2024, NSF decided not to move the CMB-S4 project in its current form, with telescopes at the South Pole and in Chile, into the NSF Major Facility Design Stage. This decision was made due to the critical state of infrastructure at NSF's Amundsen-Scott South Pole Station.

Finding: NSF has paused making any plans for scientific construction at NSF's Amundsen-Scott South Pole Station indefinitely while an updated South Pole Master Plan is developed, with a plan to support the station for the next 35-50 years. A draft master plan was published for comment in the Federal Register in June 2024.

Finding: In September 2024, DOE and NSF jointly developed a charge for the CMB-S4 team to develop a revised project concept that would meet the full set of science goals with new project instrumentation only in Chile, while maintaining reasonable costs, schedule, and risk. This charge also requested a broad evaluation of the capabilities of all current and upcoming CMB experiments (including ground instruments in the South Pole and Chile and spaced based instruments) that are expected to take data in the next ten years which may contribute to CMB-S4's science goals.

Recommendation CMB-S4.1: CMB-S4 has been a project requiring significant communication and coordination within and across agencies. With the significant revision of CMB-S4's concept and plan in progress, the DOE and NSF should ensure that all relevant agency stakeholders are involved in this process to determine what is needed from current and next-generation instruments to achieve CMB-S4's science goals.

Recommendation CMB-S4.2: As described in the P5 report, the United States South Pole Station remains critical for studies of the cosmic microwave background and astrophysical neutrinos. Infrastructure upgrades are also critical for the station to survive and support current and future scientific

[14] https://www.usparticlephysics.org/2023-p5-report/

endeavors. NSF’s Office of Polar Programs should work to release the updated South Pole Master Plan in a timely fashion, so that the scientific community can have a clear timeline of anticipated infrastructure work and a timeline for the capacity for the station to support current and future scientific projects.

B. Space-Based Initiatives

1. The Habitable Worlds Observatory

Astro2020’s top priority for flagship space initiatives is a large (~6m) infrared/optical/ultraviolet telescope that is capable of both a range of broad astrophysical observations as well as observing habitable exoplanets. This mission is expected to launch no sooner than the late 2030s, and likely in the early 2040s. The project is now referred to as the Habitable Worlds Observatory (HWO).

Finding: NASA is currently soliciting self-nominations of the HWO Community Science and Instrument Team (CSIT). The CSIT will help define a baseline mission concept and analyze potential science instruments.

Finding: In June 2024, NASA awarded $17.5 million in contracts to three industry proposals aimed at advancing technologies for future large space telescopes, supporting the Habitable Worlds Observatory mission concept.

Comment: The AAAC commends NASA’s advancement of this major project.

2. Great Observatories Maturation Program

Astro2020 recommended an established program to guide flagship missions to maturation, given that the timeline for planning and implementation usually spans multiple decades. This recommendation coincided with NASA’s own Science Mission Directorate undertaking a review and planning exercise for Large Missions.[15]

Finding: NASA has embraced the *Astro2020* recommendations to establish a protocol for maturing large projects, establishing the Great Observatory Mission and Technology Maturation Program (GOMAP). These protocols work to develop a predictable cost and schedule for large projects, while minimizing risks of overruns. Such coordinated activities help to ensure the scope of all future flagship missions are clearly defined and will advance technologies to deliver revolutionary science.

[15] https://science.nasa.gov/wp-content/uploads/2023/04/SMD_LMS_eBook_report2.pdf

3. A Panchromatic Suite

The remainder of medium to large space-based projects endorsed by *Astro2020* revolve around maintaining a suite of programs that allows for discovery across the full electro-magnetic spectrum, from the UV to the X-ray, which is only possible with space-based instruments.

One of the major themes of *Astro2020* is the advancement of Time Domain and Multi-Messenger (TDAMM) science. This largely unexplored frontier of astrophysics requires the integration of observations across different wavelengths and as a function of time. Such studies require the full spectrum to be accessible simultaneously, and *Astro2020* noted that such a program cannot rely on flagship missions, which generally take multiple decades to mature and are thus often planned in serial. TDAMM science requires smaller, faster projects that can be developed in parallel. Hence, *Astro2020* recommended with equal priority two missions, a far-IR spectroscopy and imaging mission, and a high spatial and spectral resolution X-ray mission. The recommended cost cap for each was ~$1.5 billion.

Finding: NASA has implemented the suggestions of *Astro2020*, announcing a new mission class of Probe Explorers within their existing Explorers Program.[16] The first two missions selected for funding, each capped at $1B, are the Advanced X-ray Imaging Satellite and the Probe far-Infrared Mission for Astrophysics.

Finding: NASA's future TDAMM missions, including the two new Probe Explorers (Far-IR and X-ray wavelengths), will consist of the Roman Space Telescope (Near-IR, Mid-IR), the Compton Spectrometer and Imager (COSI; Gamma-ray), UltraViolet Explorer (UVEX; Near- and Far-UV), and Starburst (Gamma-ray).

Finding: The major challenge to implementation of NASA's TDAMM missions is the lack of certainty regarding communication for future telescopes. In April 2022, NASA announced plans to develop commercial near-Earth space communication services that would replace NASA's Tracking and Data Relay Satellite System (TDRSS). Nearly all (99%) of NASA missions in low-Earth orbit make use of TDRSS, but all future missions are prevented from including TDRSS in their mission planning. For future TDAMM mission planning, there is currently a gap in knowledge about how to conduct communications. Likewise, NASA must ensure that the future communication system is TDAMM compatible. TDAMM science requires fast and nimble communications between multiple telescopes. Finally, the new communication system must be backwards compatible for existing TDAMM missions that will still be operating.

Finding: The Lunar Exploration Ground Segment (LEGS) is currently being rolled out. LEGS is a series of communications telescopes that are government owned but commercially operated. LEGS will be used for Near Space Network (NSN) communications (out to L1/L2), relieving the overloaded Deep Space Network.

[16] https://www.nasa.gov/news-release/nasa-establishes-new-class-of-astrophysics-missions-selects-studies/

Finding: NASA commissioned a Science Analysis Group (SAG) to produce a report on TDAMM science requirements for communications in July 2023. The report results are discussed further in Section VI (TDAMM).

III. Protecting Dark and Quiet Skies

Astro2020 highlights the increasing challenge posed by very large satellite constellations to astronomical observations, both in the optical due to reflected sunlight and in the radio due to unintentional radio frequency interference (RFI). The number of Low Earth Orbit (LEO) satellites has reached well over 10,000, with over 50,000 anticipated in the next decade. Not only do these satellites have implications for U.S. investments in optical and radio astronomy, but they also substantially increase the debris risk in LEO.

Finding: The FCC approved Supplemental Coverage from Space[17] (SCS; aka direct-to-cell) satellite service to begin mid-2024. Direct-to-cell satellites generally fly very low and are larger than previous satellite constellations. Hence, they will be very bright in the optical, and their transmissions will reach previously radio quiet observatories.

Finding: The IAU Centre for the Protection of the Dark and Quiet Skies from Satellite Constellation Interference (CPS), which is co-hosted by NSF's NOIRLab and the SKAO, has released a paper entitled *Call to Protect the Dark and Quiet Sky from Harmful Interference by Satellite Constellations*[18] that states its recommendations for the mitigation of satellite constellations' impact on astronomy. The document is the culmination of 18 months of work by a multidisciplinary group of experts, including astronomers, industry representatives and policy advisors. The report offers advice on, e.g., brightness limits as a function of orbital height, or figuring out how to protect radio-quiet zones from space signals.

Finding: The NSF supported work on satellite constellation interference through two rounds of the SWIFT-SAT (Spectrum and Wireless Innovation enabled by Future Technologies - Satellite-Terrestrial Coexistence) solicitation. This included support for NSF's NOIRLab to develop satellite position and brightness forecasting tools, along with measuring impacts to some LSST science goals.

Finding: While some companies have taken steps to reduce the brightness of reflected light from satellites, there are currently no regulations requiring companies or international bodies to mitigate the impact of satellite constellations on astronomical observations.

Finding: Despite extensive work to establish radio-quiet zones around some major radio telescope facilities, these zones do not extend into space. Pollution of the radio frequencies in these areas by satellite constellations adds significant time and cost to radio astronomy surveys.

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[17] https://www.fcc.gov/document/fcc-advances-supplemental-coverage-space-framework-0
[18] https://cps.iau.org/documents/49/techdoc102.pdf

Finding: Two of the most pristine radio quiet environments currently available to astronomers, the South Pole in Antarctica and the Shielded Zone of the Moon (SZM), require complex interagency coordination and cooperation for scientific installations to succeed. These radio-quiet sites also have unique legal statuses that exclude them from more typical regulatory methods.

Recommendation DQS.1: The CPS report described above recommended that, for optical wavelengths, *"Government support is needed to establish a network of test labs that can predict brightness from prototype satellites, as is available for radio frequency testing, and also basic research to assess alternative materials that may reduce brightness."* The AAAC encourages the agencies to use their combined expertise to pursue avenues for accomplishing this recommendation.

Recommendation DQS.2: While RFI limitations have been established, international cooperation is needed to regulate the burden of such limitations. Meanwhile, regulatory limits do not apply to *unintended* RFI, which is unavoidable from any radio transmitter or antennae (mitigation of which increases cost). International agreements regarding compliance standards for spacecraft (such as those that already exist for devices on Earth's surface), are needed. NSF and NASA should coordinate and share expertise on developing recommendations for these compliance standards and support international efforts to come to agreements on standards for spacecraft.

Recommendation DQS.3: Agencies should continue to develop funding opportunities that support vital work by astronomers and partners on monitoring satellites and mitigating their impact on astronomical observations across the electromagnetic spectrum.

Recommendation DQS.4: NASA and NSF should coordinate more closely on efforts to mitigate the impacts from satellite constellations on astronomy and astrophysics research. NASA has concerns about satellite conjunctions and space debris, and it has expertise in maintaining a sustainable ecosystem in LEO. Likewise, NSF has concerns about preserving investments in optical and radio astronomy and experience in coordinating spectrum protections. As NASA increases its collaboration with commercial partners, it may become necessary for these diverse stakeholders to convene in addressing the needs and priorities of all parties.

IV. Community Astronomy

In recognition of the fact that many existing and proposed ground-based astronomy facilities are located on lands that hold deep cultural and spiritual significance for Indigenous communities, *Astro2020* recommended supporting a Community Astronomy model of engagement that "advances scientific research while respecting, empowering, and benefiting local communities."

Finding: The U.S. astronomy community conducts astronomical research on I'oligam Du'ag (Kitt Peak) in Arizona, on Maunakea in Hawai'i, and on Cerro Tololo and Cerro Pachón in Chile. NSF NOIRLab is supporting meaningful research, education, and outreach activities that acknowledge the significant cultural role and reverence of I'oligam Du'ag to the Tohono O'odham Nation, and Maunakea to the Kanaka Maoli (Native Hawaiian) community.

Finding: NSF responded to the 2021 Presidential Memorandum on Tribal Consultation and Strengthening Nation to Nation Relationships[19] by organizing town hall meetings and listening sessions. NSF created the Tribal Consultation and Engagement Working Group, held internal training, and set a new requirement in the Proposal and Award Policies and Procedures Guide: Proposers seeking NSF funding must first obtain the permission (or written documentation that such permission is not needed) from a Tribal Nation if their proposed activities have the potential to impact the interests or resources of the Tribal Nation(s).

Finding: Enhancements to existing platforms on Maunakea and the potential addition of a Thirty Meter Telescope (TMT) aim to revolutionize U.S. ground-based astronomy; however, the continued development of the Maunakea summit has raised objections from many Native Hawaiians and conservationists. The lack of federal recognition and the absence of a Tribal government equivalent for Native Hawaiians has complicated channels for consultation and engagement in line with NSF's updated guidance (referenced above). In response, NSF initiated the Pilina Initiative, which aims to improve trust and build collaborative relations with Native Hawaiian communities.

Finding: The Maunakea Stewardship and Oversight Authority is co-managing Maunakea with the University of Hawai'i until June 21, 2028, when the Authority takes full control. The Authority plans to create a roadmap for stewardship of Maunakea, while prioritizing engagement of the community in its creation and building trust.

Comments: AAAC commends the efforts and initiatives of the NSF to build partnerships with local and Indigenous communities. Although minimizing timeline uncertainties for facilities like TMT is important for the astronomical community, it is essential to allow the necessary time for gradual and meaningful progress in building these partnerships.

Finding: There is a dearth of data that can be used to meaningfully assess the agencies' progress toward the *Astro2020* goal of providing "culturally supported pathways for the inclusion of Indigenous members within the profession."

Recommendation CA.1: NSF should continue to meaningfully broaden and strengthen channels of communication and collaboration with communities local to the major astronomy facility sites to build capacity for respectful and mutually beneficial partnerships. Strategic planning should honor local and Indigenous perspectives about the stewardship of the land and support the inclusion of local traditional knowledge in education and outreach activities.

[19] https://www.federalregister.gov/documents/2021/01/29/2021-02075/tribal-consultation-and-strengthening-nation-to--nation-relationships

V. Workforce Development

Attracting and cultivating the next generation of astronomers is essential to unlocking the full scientific potential of federal investments in advanced facilities and cutting-edge instrumentation. Astronomy holds a uniquely pivotal role in shaping the STEM workforce in the United States, driving progress not only in astronomy and astrophysics research but also fueling growth in the broader tech economy. Graduates from astronomy programs embark on diverse STEM careers, from joining private satellite and data science companies to serving in federal defense and scientific agencies. Many also inspire future scientists and innovators as educators and science communicators, further bolstering pathways into STEM fields.

Finding: The number of bachelor's degrees awarded in astronomy at US institutions continues to reach all-time highs, with an increase of 300% since 2009.[20]

Finding: Our community embraces the role of astronomy as a "gateway" to other STEM disciplines. Data compiled by the American Institute of Physics reveal that annual introductory astronomy course enrollments have long hovered in the range of 200,000 students annually[21]. It is estimated that an additional 100,000 students take introductory astronomy courses every year at community colleges.[22] These enrollments indicate that ~7% of U.S. college students take an introductory astronomy course.

Finding: For decades, there has been strong bipartisan support for broadening participation in STEM fields to enhance the United States' scientific leadership and economic competitiveness. The 2018 five-year Federal STEM Education Strategic Plan[23] laid out a vision for a future where "all Americans will have lifelong access to high-quality STEM education and the United States will be the global leader in STEM literacy, innovation, and employment." This plan broadly aligned with the workforce development goals of *Astro2020*, and until recently, the agencies had made significant progress towards enacting this plan and realizing the full benefits of the Nation's STEM enterprise.

Finding: The DOE FAIR & RENEW[24] grants, applauded in the 2023-2024 AAAC report for their support of individuals and institutions traditionally underrepresented in the DOE Office of Science portfolio, have been abruptly cancelled. The NSF MPS-Ascend[25] program, designed to broaden the participation of groups that are underrepresented in the mathematical and physical sciences, has also been archived.

Finding: One of the highest priorities of the decadal survey was increasing individual investigator grants, given their critical role in advancing scientific discovery. This priority has yet to be fully addressed by federal science funding agencies and has faced additional challenges due to recent restructuring,

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[20] https://ww2.aip.org/statistics/roster-of-astronomy-departments-with-enrollment-and-degree-data-2023
[21] https://aip.brightspotcdn.com/d4/97/6bfc42eabb384389e5617fd5856c/enroll-degree-a-10.pdf
[22] https://eric.ed.gov/?id=EJ853242
[23] https://www.energy.gov/sites/prod/files/2019/05/f62/STEM-Education-Strategic-Plan-2018.pdf
[24] https://eesm.science.energy.gov/news/doe-funding-opportunities-fy2024-fair-and-renew-initiatives
[25] https://www.nsf.gov/funding/opportunities/mps-ascend-mathematical-physical-sciences-ascending-postdoctoral/505879/nsf23-501

modification, and delays of grant programs. For individual investigators who have submitted or are already preparing grant proposals for these programs, these changes have created uncertainty and disruptions, making it more difficult to plan research and advance their scientific work efficiently.

Finding: Program cancellations and delays in federal science funding have had a negative impact on the training and career development of the earliest-career scientists, particularly by limiting summer research internship opportunities. These programs have long been a vital training experience for STEM undergraduates, who have only a brief window of eligibility.

Finding: Admissions to astronomy and astrophysics graduate programs for the 2025-26 academic year have also been curtailed due to uncertainty and delay surrounding federal science funding.

Recommendation WD.1: The agencies should prioritize expanding and sustaining funding initiatives that support and broaden the pool of early-career astronomers, including bridge programs, Research Experiences for Undergraduates (REUs), and postdoctoral fellowships, to foster the next generation of innovative leaders in the field.

VI. Infrastructure Development for Time Domain and Multi-Messenger Science

The field of Time Domain and Multi-Messenger Astrophysics (TDAMM) is one of the top priorities of *Astro2020* but faces challenges due to its inherently multi-messenger, multi-wavelength, and multi-observatory nature, requiring seamless and rapid coordination across both ground- and space-based facilities. The upcoming Vera Rubin Observatory's LSST survey, set to generate upwards of 10 million alerts per night starting in late 2025, highlights the urgent need for scalable data infrastructure and automated follow-up strategies. To maximize the science return, real-time coordination is essential to prevent competing observations and optimize time-domain studies, public access to critical data must be ensured through structured sharing plans, and wide-field, fast-response X-ray and gamma-ray monitors must be developed with arcminute resolution to enhance observational capabilities. Additionally, expanding agreements between observatories for Target of Opportunity observations will be needed to improve efficiency and responsiveness across the TDAMM ecosystem.

Finding: The Time-Domain and MultiMessenger Communications Science Analysis Group (TDAMMCommSAG) released its report in July 2024[26] on whether the current plan for the transition from NASA-operated space and ground relays to commercial services will adequately service NASA astrophysics missions studying the transient and variable Universe. This report found that there are scientific and operational advantages and communications challenges to non-LEO orbits, and this is an area where NASA could focus its development, as there is a much weaker driver for commercial applications of non-LEO communications satellites.

[26] https://pcos.gsfc.nasa.gov/sags/tdammcomm-sag/documents/TDAMM_Comms_SAG_Report_FINAL.pdf

Finding: To preserve capacity for existing users of NASA's Tracking and Data Relay Satellite (TDRS) system, NASA suspended new mission commitments for this service at the end of 2024. NASA is assessing whether TDRS backwards compatible services are required for its commercial replacements, which are expected to be available starting in 2031.

Finding: TDAMM missions have unique and challenging communications requirements, which should drive the requirements of NASA's next-generation space communications system, following the recommendations of the TDAMMCommSAG report. This improved communications infrastructure will benefit all space operations.

Finding: As the transition from current NASA services to commercial communication services spans many years, continuity for existing missions and missions currently in development is essential.

Recommendation TDAMM.1: As a wide range of commercial services are developed to serve NASA mission operational and communication needs, compatibility with science needs from NASA and other agencies for Dark and Quiet Skies should be part of the requirements. This will help protect exciting new opportunities and investments at unique observing sites, like radio astronomy from the shielded zone of the Moon.

Finding: The 3rd TDAMM Workshop[27] titled "*Multidisciplinary Science in the Multimessenger Era*" was held in September 2024 and focused on using astrophysical observations to study extreme physics, including turbulence, magnetic fields, and accretion processes. Key topics included multi-messenger astrophysics, turbulence-driven molecular cloud evolution, and magnetic fields in star and planet formation. The workshop also highlighted advances in numerical modeling, machine learning, and high-performance computing for improving simulations and data analysis, emphasizing interdisciplinary collaboration in modern astrophysics.

Finding: Rubin is expected to produce on order 10 million alerts each night, with most alerts not needing any action or follow-up. Rubin has agreed to send this full alert stream directly to seven community alert brokers, and these independent brokers have mature pipelines to prioritize follow-up observations.

Finding: While numerous satellites and other space objects including debris will appear as transient and variable objects in the Rubin LSST survey, significant progress has been made on identifying and flagging these objects. The alert production pipeline has satellite streak detection capabilities to remove images with clear satellite streaks. More validation is needed with full survey data, and further work is needed to be able to detect astrophysical transients in regions affected by a known satellite streak. Work towards these efforts has been funded through NSF's SWIFT-SAT program, with funding going to members of the International Astronomical Union's Centre for the Protection of the Dark and Quiet Sky from Satellite Constellation Interference (IAU-CPS).

[27] https://sites.google.com/view/3rd-tdamm-workshop/home

Recommendation TDAMM.2: The recommendations in Section III of this report on Protecting Dark and Quiet Skies are also relevant here, as satellites and space debris appear as transients that can create false alerts or obscure real astrophysical phenomena.

VII. Investments in Machine Learning and Artificial Intelligence

Given the nature of the large datasets produced by astronomical surveys, as well as the large simulations developed by theoretical astrophysicists, the astronomy community has a decades-long history of experience with machine learning (ML). More recently, it has embraced advancements in artificial intelligence (AI) to scale its science in unprecedented ways. Due to the timing of its rapid rise in functionality and adoption, AI/ML was not a major topic in *Astro2020*; however, it is now clear that the associated technologies will be major players in advancing the science envisioned in *Astro2020*.

Finding: Astronomers have been exploring ways to advance much of the science prioritized in the decadal survey with AI/ML. The DOE continues to support a large AI/ML effort and considers development of AI/ML and computational technologies as part of its core mission. New initiatives at DOE include the Hardware-Aware AI for HEP funding opportunity. Other new federal initiatives include the NSF-Simons AI institutes and the support of development and use of AI/ML theory, methods, and tools in funded research.

Finding: Existing commercial AI/ML tools are not generally applicable to astronomical data and problems.

Finding: While many departments recognize the need to integrate AI/ML into their teaching, a standard curriculum has yet to emerge that could be used to equip the next generation with the skills to effectively and responsibly apply AI/ML tools to advance domain expertise.

Recommendation AI.1: The upcoming mid-decadal survey and next decadal survey should include focus topics on the use of AI/ML in astronomy and astrophysics and on training the next generation of users.

Recommendation AI.2: Agencies should continue to support and expand the development and application of AI/ML technologies in astronomy and astrophysics research.

Finding: The reliability and interpretability of AI/ML tools continue to pose significant challenges in achieving publication-quality results from their application in astronomy and astrophysics. Rigorous validation is essential to ensure results from these tools meet the high standards of scientific research.

Recommendation AI.3: The agencies should invest in domain experts to improve reliability and interpretability of AI scientific results.

Recommendation AI.4: The agencies should coordinate effort and expertise in determining the anticipated costs and impacts of AI usage for astronomy, including competition with other methods, environmental impacts, gaps created in access among different potential user communities, and the overall impacts on the scientific process and the education and training of the future workforce.

Recommendation AI.5: Agencies should coordinate with each other and with the AAS to develop a consistent set of AI guidelines for creating and evaluating scientific content fairly, ethically, and accurately.

VIII. Continued Investments in Laboratory Astrophysics

Laboratory astrophysics is essential to astronomy and planetary science, encompassing experiments (e.g., spectroscopy, kinetics), theoretical modeling, and studies across the electromagnetic spectrum. It provides crucial data for interpreting astronomical observations, particularly as observatories like ALMA and JWST generate vast amounts of data.

Despite its critical role in astronomy, laboratory astrophysics has not been adequately recognized or prioritized, as highlighted in the 2000, 2010, and 2020 Decadal Surveys, and most recently in the Laboratory Astrophysics Taskforce report[28], *"Enabling Cosmic Discoveries: The Vital Role of Laboratory Astrophysics,"* which was submitted and approved by the AAAC in February 2024.

Continued investment is needed to ensure that laboratory astrophysics keeps pace with the rapid advancements in observational capabilities, enabling accurate interpretation of data from next-generation telescopes and missions. Strengthening this field will allow the U.S. to fully capitalize on transformative discoveries made possible by cutting-edge observatories. Furthermore, sustained support will help train the next generation of researchers, fostering a skilled workforce capable of addressing key scientific challenges and maintaining U.S. leadership in astrophysics and related STEM fields, including planetary science, space exploration, and advanced instrumentation development.

Recommendation LA.1: To maximize the impact of laboratory astrophysics, NSF, NASA, and DOE should explore the feasibility of a coordinated strategy that ensures sustained and synergistic support across agencies. This collaboration might include regular interagency meetings, joint funding initiatives, and shared infrastructure investments to prevent redundancy and optimize resource allocation.

Recommendation LA.2: To increase funding opportunities for laboratory astrophysics, NSF and NASA should broaden the scope of existing funding programs to explicitly include laboratory astrophysics research. Additionally, and to the extent possible, funding agencies should establish dedicated review panels or specific proposal tracks within these programs to ensure laboratory astrophysics proposals are fairly evaluated alongside observational and theoretical astrophysics research.

Finding: To facilitate communication between laboratory astrophysicists, observational astronomers, and mission planners, a workshop has been proposed for the Summer 2025 AAS meeting. The workshop will unite key stakeholders to address challenges, set research priorities, and strengthen collaboration.

[28] https://nsf-gov-resources.nsf.gov/files/latf-report-r.pdf?VersionId=J3fsKoLIehM4C8_jpUASxVhbhAj0B.hH

Featuring talks, discussions, and networking, it will foster connections between laboratory data producers and consumers. A key outcome will be white papers informing the mid-decadal review and funding strategies. This workshop aims to bridge communication gaps, ensuring laboratory astrophysics is integrated into major astronomical missions.