The National Academies of
SCIENCES • ENGINEERING • MEDICINE

Pathways to Discovery in Astronomy and Astrophysics for the 2020s

nationalacademies.org/astro2020

Approach

NASA, NSF, and DOE provided budget guidance, bounded by ambitious and conservative scenarios

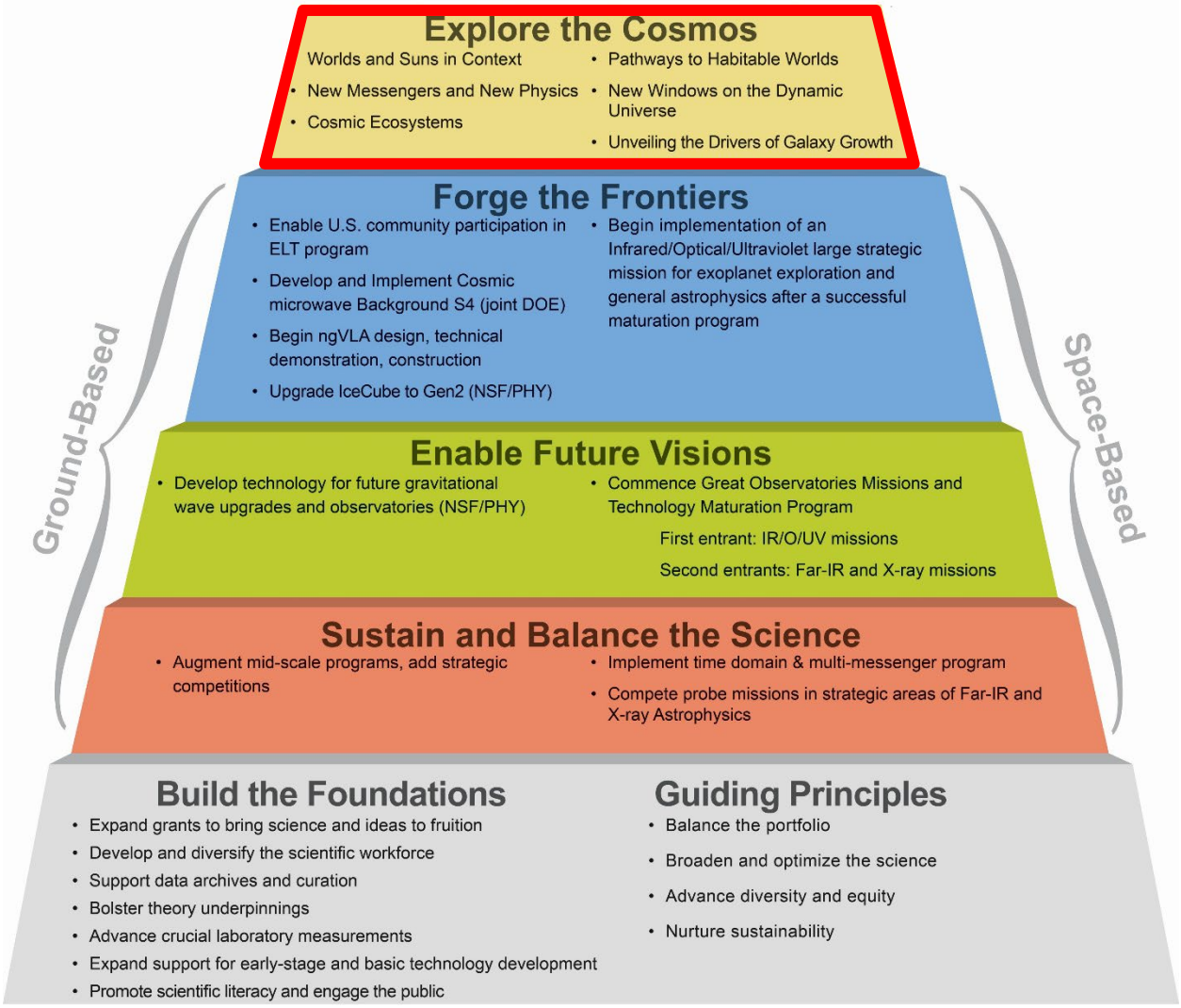
The agencies urged the survey to develop an “ambitious”, “aspirational”, and “inspirational” plan

But a plan also needs to be realistic, responsible, achievable, sustainable

The Survey’s Approach:

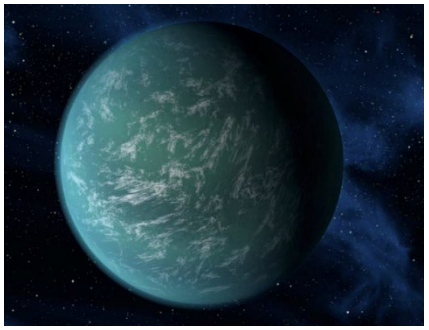
- Propose an ambitious program, but with decision rules, decision points, and contingencies
- Emphasize phased development of many projects to lower risks and provide flexibility to agencies
- Present a strategy, with details of implementation resting with agencies and their advisory committees

Realizing the Astro2020 Program: Pathways From Foundations to Frontiers



Science: A New Cosmic Perspective

573 community science white papers
6 science panel reports (App. B-G)
24 science panel frontier questions
5 science panel discovery areas



3 major science themes

- Worlds and Suns in Context
- New Messengers and New Physics
- Cosmic Ecosystems

3 priority science areas

- Pathways to Habitable Worlds
- New Windows on the Dynamic Universe
- Unveiling the Drivers of Galaxy Growth

TABLE 2.1 Science Panel Questions

Question	Theme(s)
Panel on Compact Objects and Energetic Phenomena	
What are the mass and spin distributions of neutron stars and stellar mass black holes?	New Messengers and New Physics
What powers the diversity of explosive phenomena across the electromagnetic spectrum?	New Messengers and New Physics
What do some compact objects eject material at nearly-light-speed jets, and what is that material made of?	New Messengers and New Physics
What seeds supermassive black holes and how to they grow?	New Messengers and New Physics, Cosmic Ecosystem
Panel on Cosmology	
What set the hot Big Bang in motion?	New Messengers and New Physics
What are the properties of dark matter and the dark sector?	New Messengers and New Physics
What physics drives the cosmic expansion and the large-scale evolution of the universe?	New Messengers and New Physics
How will measurements of gravitational waves reshape our cosmological view?	New Messengers and New Physics
Panel on Galaxies	
How did the intergalactic medium and the first sources of radiation evolve from cosmic dawn through the epoch of reionization?	Cosmic Ecosystem
How do gas, metals, and dust flow into, through, and out of galaxies?	Cosmic Ecosystem
How do supermassive black holes form and how is their growth coupled to the evolution of their host galaxies?	Cosmic Ecosystem, New Messengers and New Physics
How do the histories of galaxies and their dark matter halos shape their observable properties?	Cosmic Ecosystem

Panel on Exoplanets, Astrobiology, and the Solar System	
What is the range of planetary system architectures, and is the configuration of the solar system common?	Worlds and Suns in Context
What are the properties of individual planets, and which processes lead to planetary diversity?	Worlds and Suns in Context
How do habitable environments arise and evolve within the context of their planetary systems?	Worlds and Suns in Context
How can signs of habitable life be identified and interpreted in the context of their planetary environments?	Worlds and Suns in Context
Panel on the Interstellar Medium and Star and Planet Formation	
How to star-forming structures arise from, and interact with, the diffuse ISM?	Cosmic Ecosystem
What regulates the structures and motions within molecular clouds?	Cosmic Ecosystem
How does gas flow from parsec scales down to protostars and disks?	Cosmic Ecosystem
Is planet formation fast or slow?	Worlds and Suns in Context, Cosmic Ecosystem
Panel on Stars, the Sun, and Stellar Populations	
What are the most extreme stars and stellar populations?	Worlds and Suns in Context, Cosmic Ecosystem
How does multiplicity affect the way a star lives and dies?	Worlds and Suns in Context
What would stars look like if we view them like we do the Sun?	Worlds and Suns in Context
How do the Sun and other stars create space weather?	Worlds and Suns in Context

TABLE 2.2 Science Panel Discovery Areas

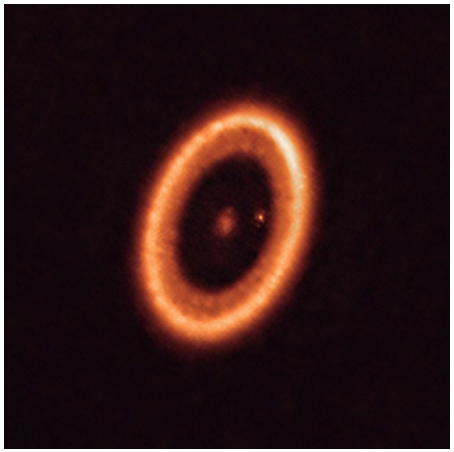
Discovery Area	Theme(s)
Panel on Compact Objects and Energetic Phenomena:	New Messengers and New Physics
Transforming our View of the Universe by Combining New Information from Light, Particles, and Gravitational Waves	
Panel on Cosmology:	New Messengers and New Physics
The Dark Ages as a Cosmological Probe	
Panel on Galaxies:	Cosmic Ecosystem
Mapping the Circumgalactic Medium and Intergalactic Medium in Emission	
Panel on Exoplanets, Astrobiology, and the Solar System:	Worlds and Suns in Context
The Search for Life on Exoplanets	
Panel on the Interstellar Medium and Star and Planet Formation:	Worlds and Suns in Context
Detecting and Characterizing Forming Planets	
Panel on Stars, the Sun, and Stellar Populations:	Worlds and Suns in Context, Cosmic Ecosystem
"Industrial Scale" Spectroscopy	

Science Theme: Worlds and Suns in Context

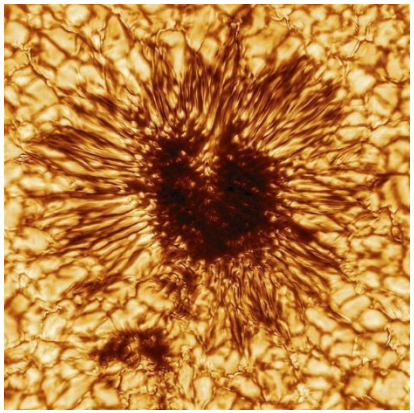
The quest to *understand the interconnected systems of stars and the worlds orbiting them, from the nascent disks of dust and gas from which they form, through the formation and evolution of the vast array of extrasolar planetary systems so wildly different than the one in which Earth resides*

This theme is forefront this decade because of:

- The extraordinary rate of discovery of new exoplanets– understanding the demographics and finding the nearest planets for detailed study
- The promise of JWST to make pioneering observations of exoplanet atmospheres
- The revolution DKIST will bring to understanding the Sun's atmosphere
- The revolution in studying planet formation by imaging protoplanets and their accretion disks using large ground-based telescopes (OIR and ALMA)



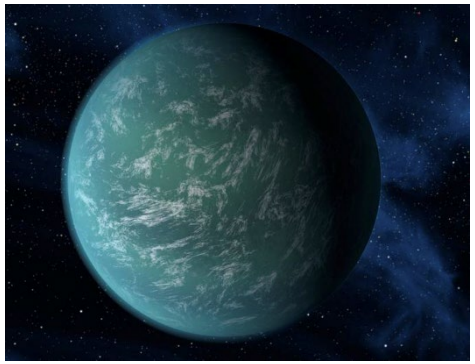
ALMA image of a young planet-forming star



DKIST image of a sunspot

Priority Area: Pathways to Habitable Worlds

We are on a path to exploring worlds resembling Earth and answering the question: "Are we alone?" The task for the next decades will be finding the easiest of such planets to characterize, and then studying them in detail, searching for signatures of life.



The needed capabilities include:

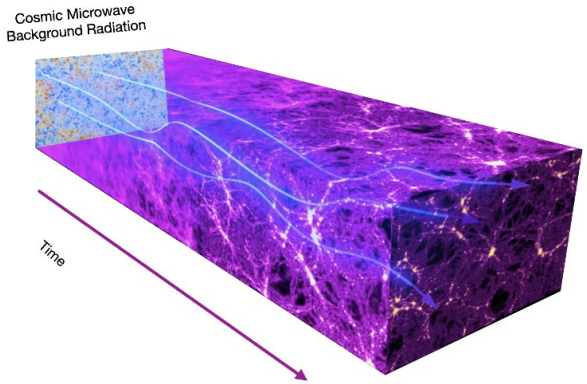
- Ground-based ELTs equipped with high-resolution spectroscopy, high-performance AO, and high-contrast imaging

- A large space-based IR/O/UV telescope with high contrast imaging and spectroscopy capable of observing planets 10 billion times fainter than their host star
- High spatial and spectral resolution X-ray observations to probe stellar activity across the entire range of stellar types

- Laboratory and theoretical studies

Science Theme: New Messengers and New Physics

New Messengers and New Physics captures the scientific questions associated with inquiries ranging from astronomical constraints on the nature of dark matter and dark energy, to the new astrophysics enabled by combined observations with particles, neutrinos, gravitational waves, and light

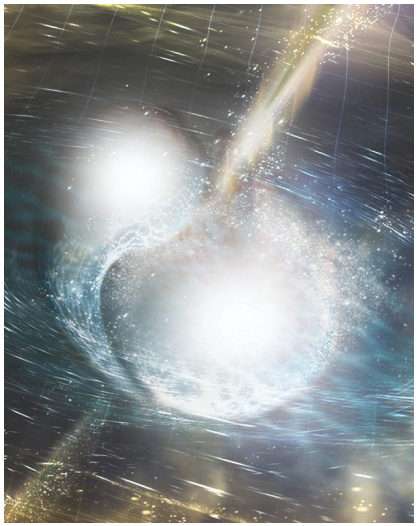


This theme is forefront this decade because of:

- Tremendous progress in observations of the Cosmic Microwave Background
- Time domain surveys that have uncovered an astounding array of transient phenomena
- The discovery of compact object mergers with LIGO, and the detection of electromagnetic counterparts
- Ice Cube's detection of high energy neutrinos of astrophysical origin

Priority Area: New Windows on the Dynamic Universe

The New Windows on the Dynamic Universe priority area involves using light in all its forms, gravitational waves, and neutrinos to study cosmic explosions on all scales and the mergers of compact objects

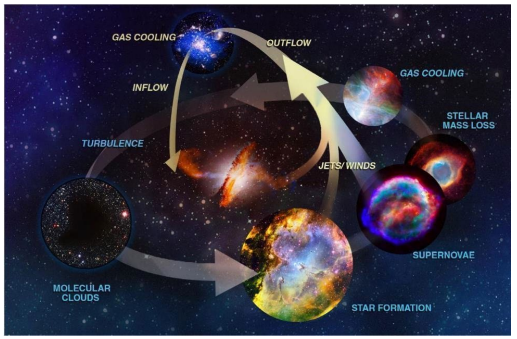


The needed capabilities include:

- Facilities to discover and characterize the brightness and spectra of transient sources as they appear and fade away
- Ground-based ELTs to see light coincident with mergers
- A next-generation radio observatory to detect the relativistic jets produced by neutron stars and black holes
- Next generation CMB telescopes to search for the polarization produced by gravitational waves in the infant universe
- Upgrades to current ground-based gravitational wave detectors, and development of next generation technologies
- Improvements in the sensitivity and angular resolution of high energy neutrino observatories

Science Theme: Cosmic Ecosystems

The universe is characterized by an enormous range of physical scales and hierarchy in structure, from stars and planetary systems to galaxies and a cosmological web of complex filaments connecting them



This theme is forefront because:

- JWST will provide definitive observations of the earliest stages of galaxy formation and evolution
- The Rubin Observatory, Roman, and Euclid will provide imaging and spectral energy information for millions of galaxies, complementing the in-depth observations from JWST
- Progress in numerical simulations is evolving rapidly and is driving our understanding of the observations

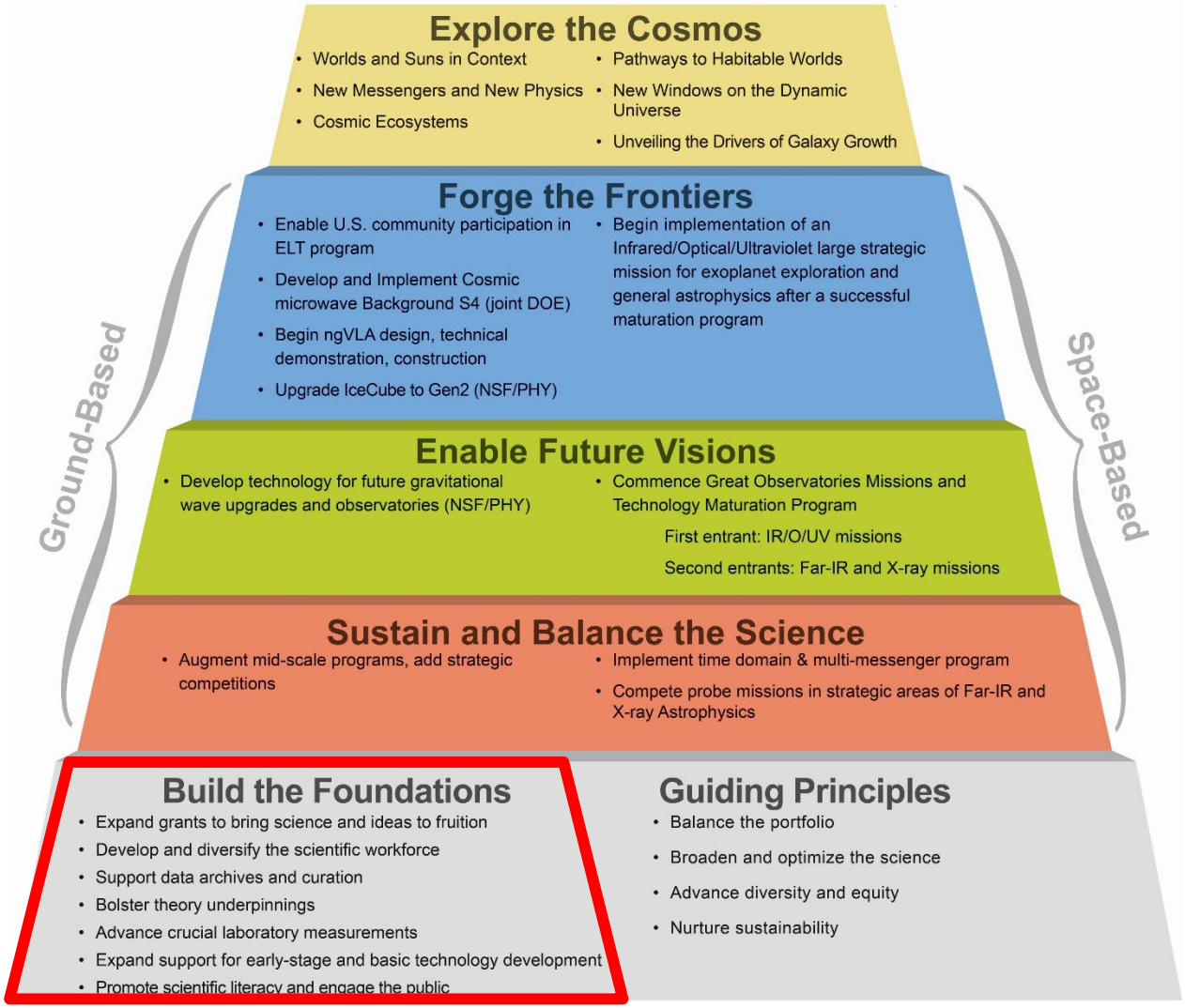
Priority Area: Unveiling the Drivers of Galaxy Growth

The priority area involves unveiling the drivers of galaxy growth, focusing on processes affecting galactic scales

The needed capabilities include:

- ELTs to observe galaxies in the young universe
- A next generation radio telescope to map emission lines of molecular gas, tracing cold gas
- A next generation IR/O/UV space telescope to trace the details of the nearby, evolved universe
- FIR and X-ray missions to peer into the dusty hearts of galaxies to reveal enshrouded black holes, and trace the hottest gas phases
- Investments in theory to realize a new scientific foundation for understanding galaxy evolution

Realizing the Astro2020 Program: Pathways From Foundations to Frontiers



Chapter 3: The Profession and its Societal Impacts: Gateways to Science, Pathways to Divesity, Equity, and Sustainability

Astro2020 was the first decadal survey (in any subject) to fully address this area

Our Charge: *Assess the state of the profession, using information available externally and, if necessary, data gathered by the study itself, including workforce and demographic issues in the field. Identify areas of concern and importance to the community raised by this assessment in service of the future vitality and capability of the astronomy and astrophysics work force. Where possible, provide specific, actionable and practical recommendations to the agencies and community to address these areas. This report shall be made available following the completion of the study.*

The Profession and its Societal Impacts

> *"The pursuit of science, and scientific excellence, is inseparable from the humans who animate it."*
> *-- Panel on the State of the Profession and Societal Impacts*

Guiding principles: diversity, equitable access, benefits to the nation and the world, sustainability and accountability

Astro2020 report includes 10 recommendations in this area

State of the Profession and Societal Impacts panel report addresses subject in more depth (Appendix N)

Key Issues, Recommendations

Assessment of equity in review and awarding of grants and projects is difficult because of disparity of available data on proposers, awards

Recommendation: NASA, NSF, and DOE should implement a cross-agency committee or working group tasked with establishing a consistent format and policy for regularly collecting, evaluating, and publicly reporting demographic data and indicators pertaining at a minimum to outcomes of proposal competitions

Although gender parity overall has improved steadily over the decade, imbalances persist in leadership ranks of missions and projects on all scales. The representation of URMs remains almost non-existent

Recommendation: NASA, DOE, and NSF should consider explicitly including diversity -- of project teams, and participants, and beneficiaries -- in the evaluation of funding awards to individual investigators, project and mission teams, and third-party organizations that manage facilities. Approaches would be agency specific, and appropriate to the scale of the projects

Key Issues, Recommendations

Despite increased awareness of sexual harassment, bullying, and other unprofessional conduct, problems persist, with potentially devastating impacts on victims

Conclusion: The persistence of harassment and discrimination in astronomy and astrophysics is intolerable, and must not be tolerated if the astronomy and astrophysics profession is to retain and successfully draw from the full diversity of talent available, not to mention avoiding the toxic and corrosive effects that such behaviors have on individuals, organizations, and the entire profession

Recommendation: NASA, NSF, DOE, and professional societies should ensure that their scientific integrity policies address harassment and discrimination by individuals as forms of research/scientific misconduct

Training and Workforce Related Actions

Programs aimed at promoting participation and retention of under-represented groups have been highly effective but support for these has decreased in the last decade. It is a high priority to reinstate and augment these

Recommendation: NASA, NSF, and DOE should reinvest in professional workforce diversity programs… Because academic pipeline transitions are loss points, supporting the creation and continued operation of "bridge" type programs across junctures in the higher-education pipeline and into the professional ranks appear especially promising

Recommendation: NSF, DOE and NASA should implement undergraduate and graduate "traineeship" funding, akin to the NIH MARC and NIH "T" training grant programs, to incentivize department/institution-level commitment to professional workforce development, and prioritize interdisciplinary training, diversity, and preparation for a variety of career outcomes

Recommendation: Funding agencies should increase incentives for improving diversity among the college/university astronomy and astrophysics faculty, for example by increasing the number of awards that invest in the development and retention of early-career faculty and other activities for members of under-represented groups

Sustainability and Community Relations

Ground-based astronomy is in significant part pursued on lands and sites with cultural and environmental significance

A sustainable model of engagement with local and Indigenous communities is needed

Recommendation: The astronomy community should, through the American Astronomical Society in partnership with other major professional societies... work with experts from other experienced disciplines (such as archaeology and social sciences) and representatives from local communities to define a Community Astronomy model of engagement that advances scientific research while respecting, empowering and benefiting local communities.

Conclusion: NSF, NASA, DOE, facility managing organizations, project consortia, individual institutions, and other stakeholders can work to build partnerships with Indigenous and local communities that are more functional and sustained through a Community Astronomy approach, and by increasing the modes of engagement and funding for: (i) meaningful, mutually beneficial partnerships with Indigenous and local communities, (ii) culturally supported pathways for the inclusion of Indigenous members within the profession, and (iii) true sustainability, preservation, and restoration of sites.

Dark Sky Protection

The rapid increase in satellite constellations has raised awareness of the urgency of light pollution and radio spectrum protection

Recommendation: The NSF should work with the appropriate federal regulatory agencies to develop and implement a regulatory framework to control the impacts of satellite constellations on astronomy and on the human experience of the night sky. All stakeholders (U.S. astronomers, federal agencies, Congress, satellite manufacturers/ operators, and citizens who care about the night sky) should be involved in this process. This is an international issue; therefore, international coordination is also vital

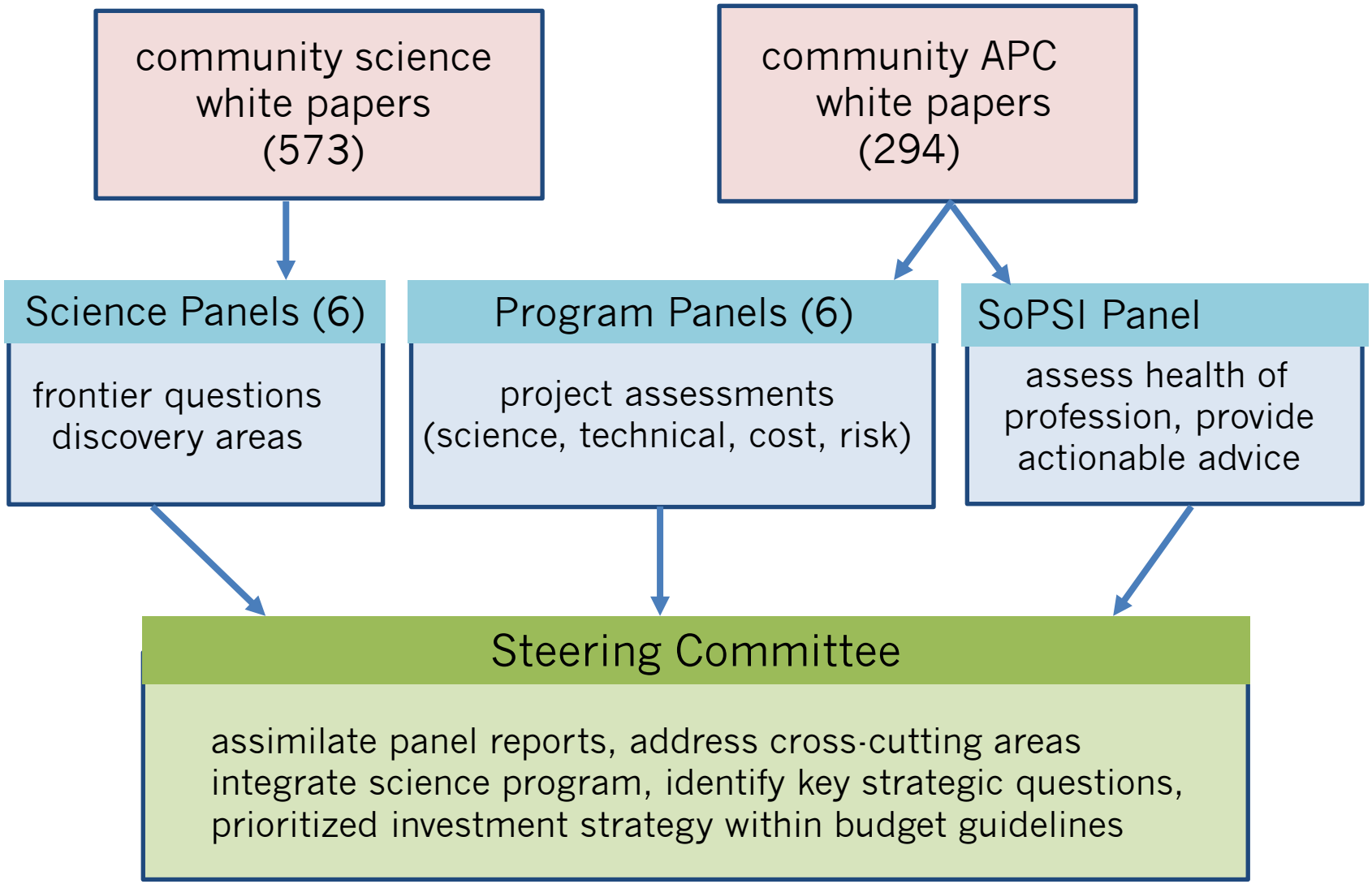
Recommendation: To ensure that the skies remain open to radio astronomy, NSF in partnership with other agencies as appropriate, should support and fund a multi-faceted approach to the avoidance and mitigation of radio-frequency interference. It is critical that the astronomical community formally monitor commercial and federal uses of the spectrum managed by the FCC and the NTIA and actively participate in the spectrum management process by seeking critical primary allocations to radio astronomy in the high frequency bands above 95 GHz, by providing comments to filings for spectrum allocations, and by supporting the efforts of CORF, NRAO, and the ESM division of the NSF. To be most effective, international coordination is required

House Science, Space and Technology Committee Dec 1, 2021

Subcommittee on Space and Aeronautics
Subcommittee on Research and Technology

Backup Slides

Astro2020 Process



Chapter 2: A New Cosmic Perspective

- Foundation: 573 community white papers
- White papers were read, discussed by 6 science panels
  - Compact Objects and Energetic Processes
  - Cosmology
  - Galaxies
  - Exoplanets, Astrobiology, and the Solar System
  - Interstellar Medium, Star and Planet Formation
  - Stars, the Sun, and Stellar Populations
- Panels prepared reports (Appendices B-G), and identified four priority science questions and one discovery area
- Steering Committee distilled panel questions and discovery areas into three overarching science themes and three priority areas