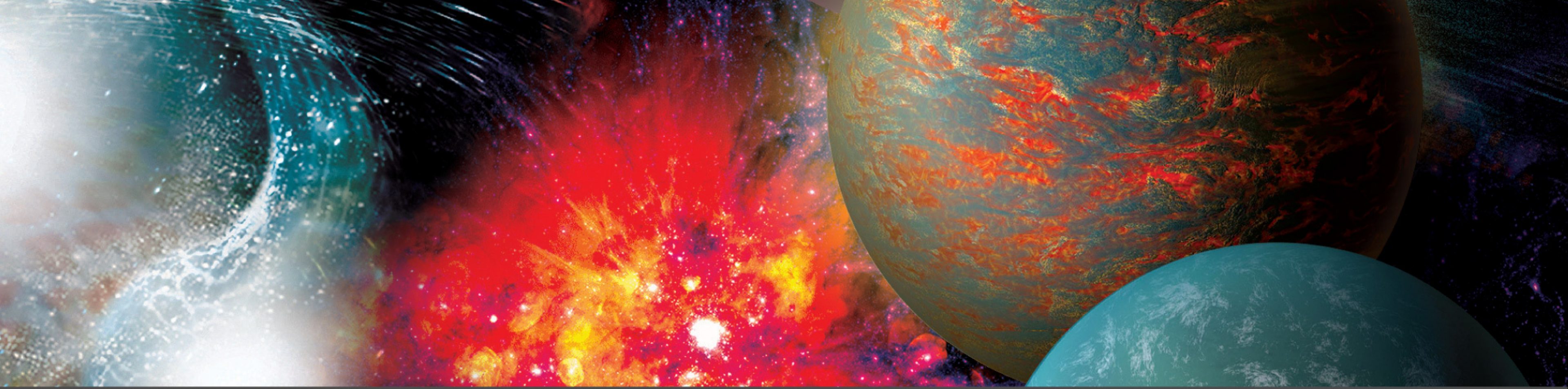


The National Academies of
SCIENCES · ENGINEERING · MEDICINE

Pathways to Discovery in Astronomy and Astrophysics for the 2020s

nap.edu/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

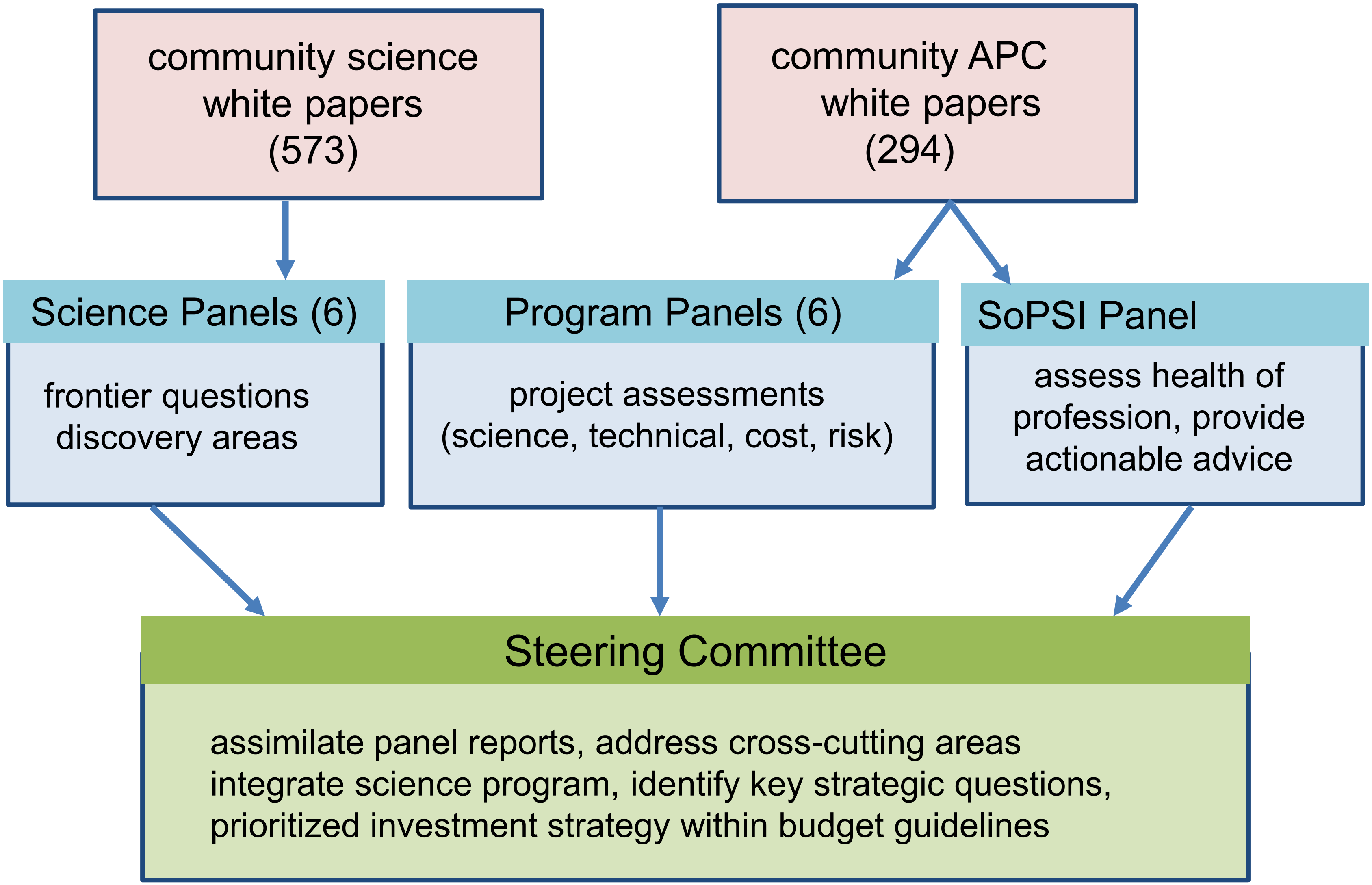
But a plan also needs to be realistic, responsible, achievable, sustainable

The Survey’s Approach:

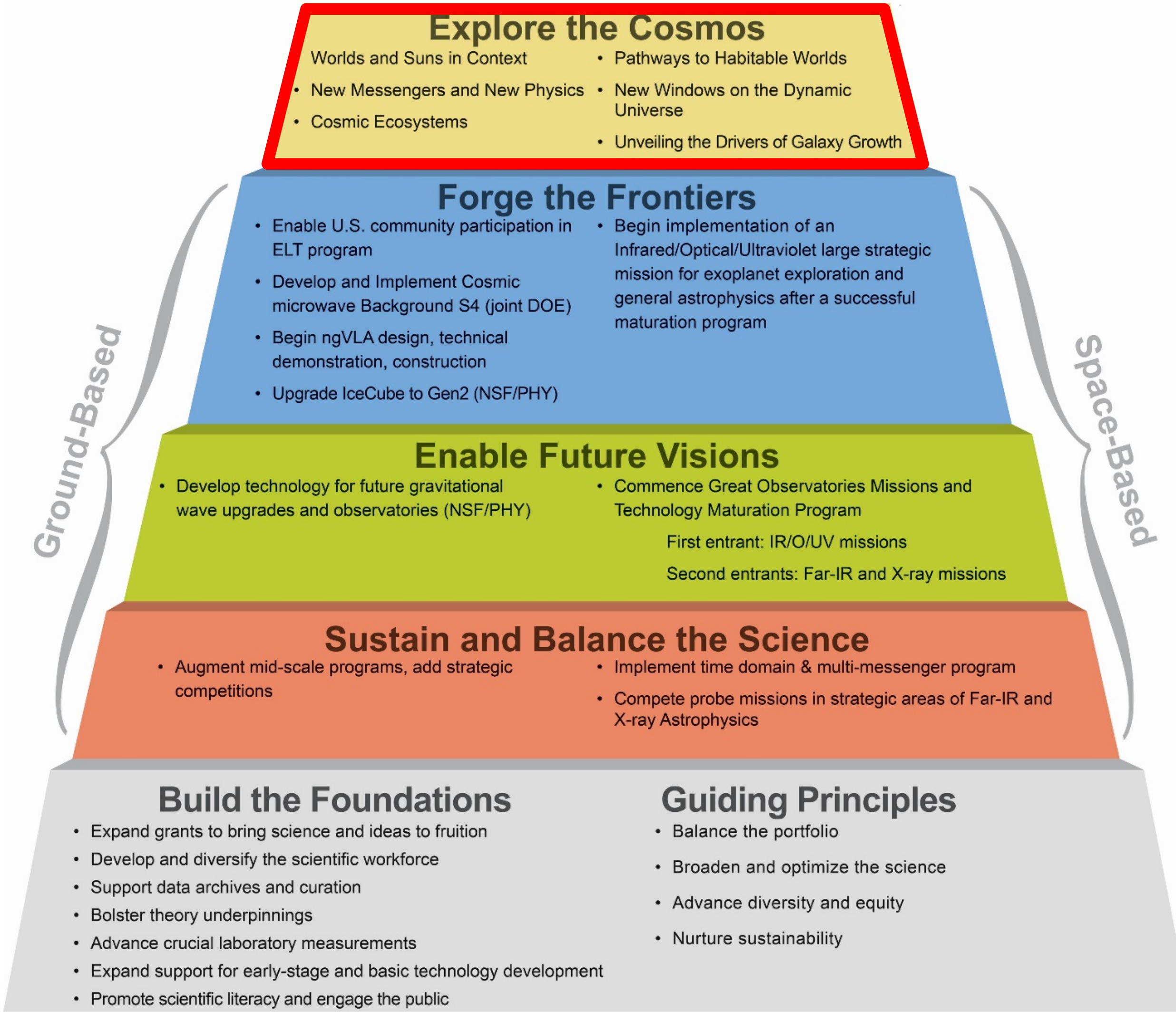
- Propose an ambitious program, but with decision rules, decision points, and contingencies
- Emphasize phased development of many projects to lower risks and provide flexibility to agencies
- Present a strategy, with details of implementation resting with agencies and their advisory committees

Astro2020 steering committee and staff, in their native habitat…

Astro2020 Process



Realizing the Astro2020 Program: Pathways From Foundations to Frontiers



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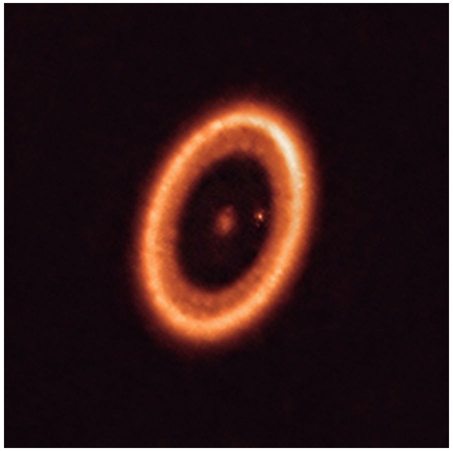
Science Theme: Worlds and Suns in Context

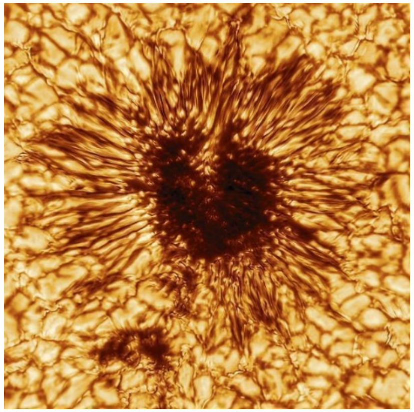
The quest to understand the interconnected systems of stars and the worlds orbiting them, from the nascent disks of dust and gas from which they form, through the formation and evolution of the vast array of extrasolar planetary systems so wildly different than the one in which Earth resides

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)



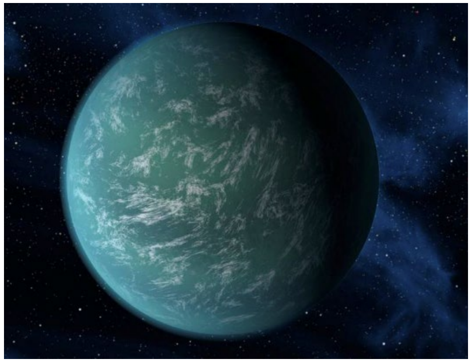
ALMA image of a young planet-forming star



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.

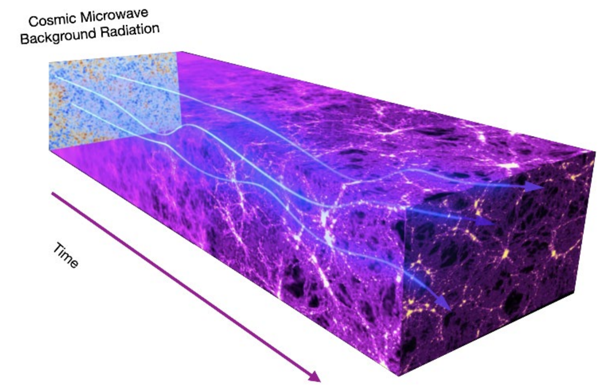


The needed capabilities include:

- 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

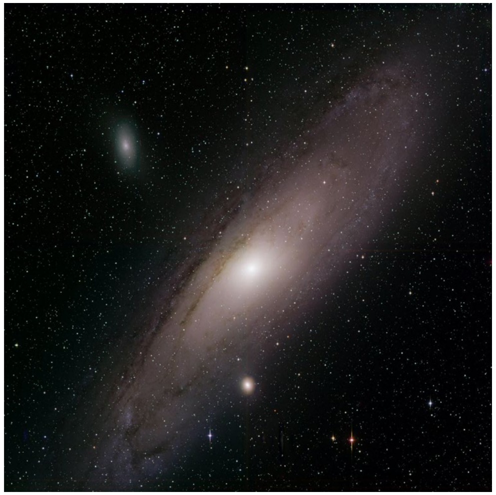
Science Theme: New Messengers and New Physics

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



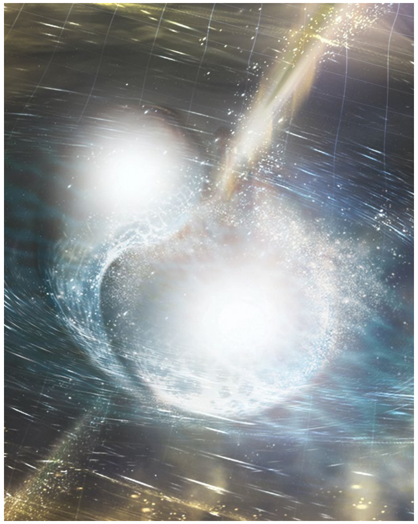
This theme is forefront this decade because of:

- 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

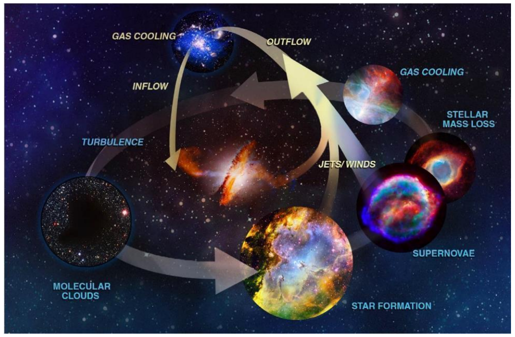


The needed capabilities include:

- 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

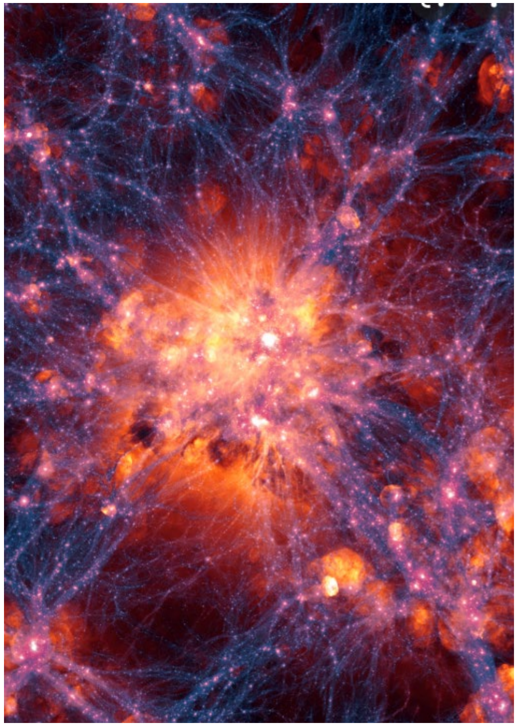


This theme is forefront because:

- 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

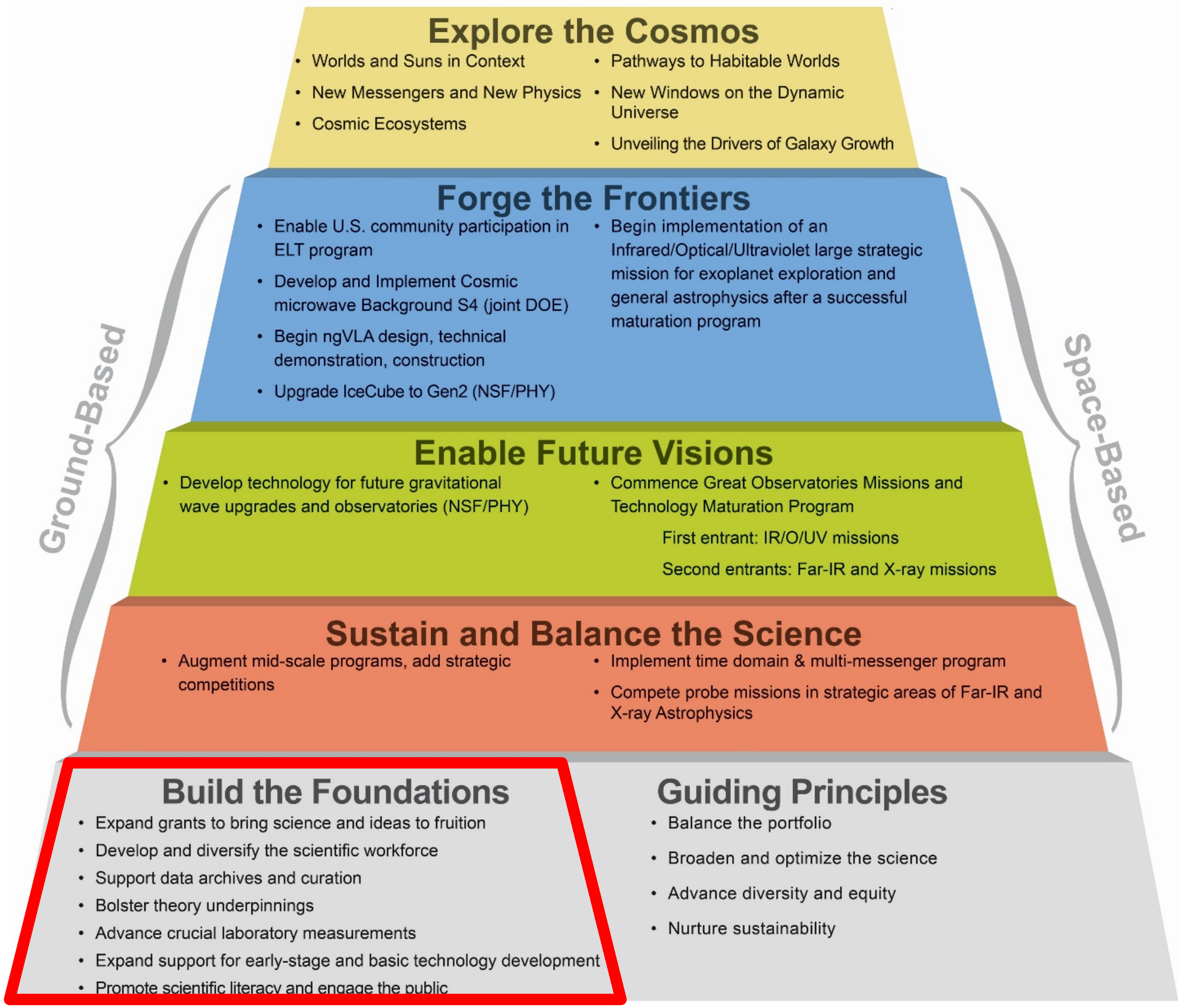
The priority area involves unveiling the drivers of galaxy growth, focusing on processes affecting galactic scales



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



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

Here we provide a brief synopsis: see the full report for additional discussions of education, career paths and pipelines, public outreach and engagement, climate change, and benefits to the nation

The Profession and its Societal Impacts

Areas of key recommendations for the state of the profession

- Collecting demographic data to understand equity in funding
- Diversity of the profession
  - Improving diversity of project and mission teams
  - Investing in and sustaining workforce diversity ”bridge” programs
  - Undergraduate and graduate traineeship programs
- Professional policies related to harassment and discrimination
- Community relations
- Dark skies and protecting the radio frequency spectrum

Optimizing the Research Foundations

A balanced portfolio must support not just big projects, but the activities that support and enable the scientific return

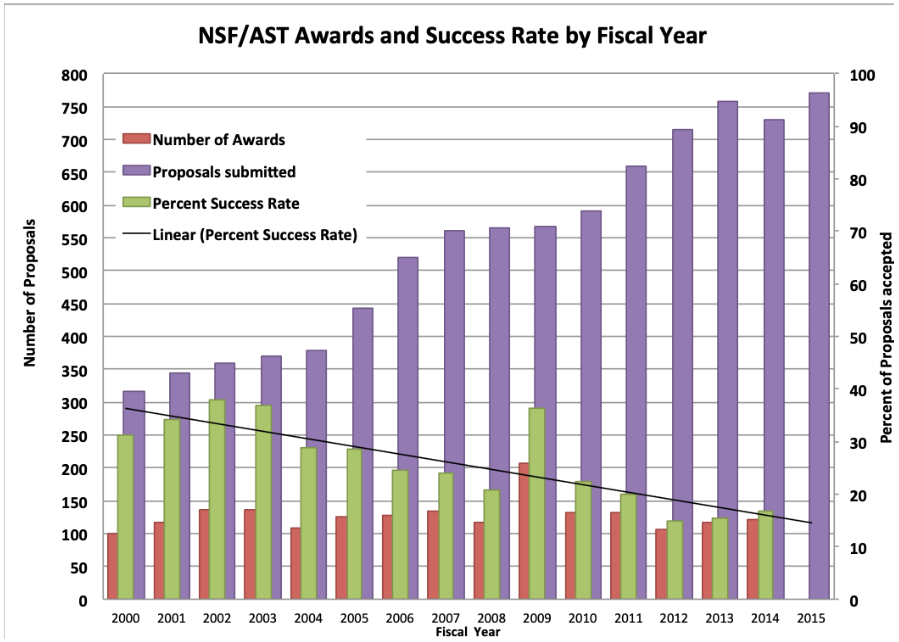
- Ensuring the programs that ensure the research community returns excellent science are adequately supported
- Capitalizing on this era of big data and making sure the community is prepared to meet the upcoming data and computational challenges
- Providing the basic laboratory measurements to interpret the astrophysics data
- Supporting the basic theoretical underpinnings crucial for motivating observations and interpreting the data
- Ensuring that basic, early-stage technology development is adequately supported, as the fuel of future innovation and technological competitiveness

NSF Investigator Grants Programs

The NSF AAG program is a cornerstone of the enabling research foundation

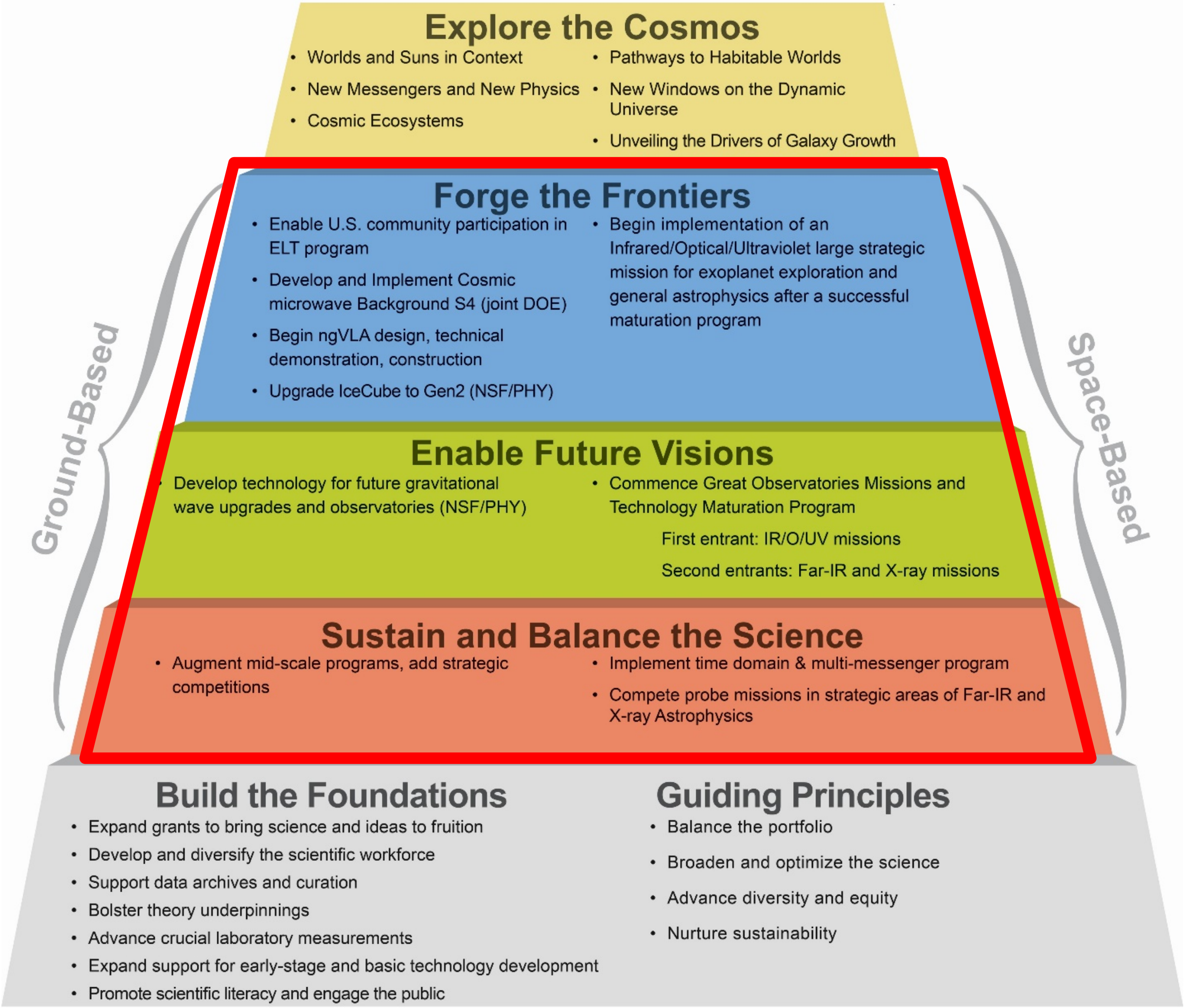
Over the past 20 years success rates have steadily declined from 45% to 25% or lower; much lower for first-time proposers

These grants are crucial for achieving the scientific goals of the decadal survey



Recommendation: NSF should increase funding for the individual investigator Astronomy and Astrophysics Research Grants by 30 percent in real dollars (i.e. above the rate of inflation) over five years from 2023-2028 starting with the FY 2019 budget inflated appropriately. This will have the effect of restoring success rates to a healthy competitive level

Realizing the Astro2020 Program: Pathways From Foundations to Frontiers



The Frontiers: Major New Projects and Sustaining Programs

The compelling programs recommended by past surveys are vital to the scientific vibrancy of the coming decade

Ground

- Midscale Innovations Program
- Daniel K. Inouye Solar Telescope
- Vera Rubin Observatory

Space

- Explorer Program Augmentation
- James Webb Space Telescope
- Roman Space Telescope
- US Contribution to Euclid
- US Contribution to Athena
- US Contribution to LISA

Conclusion: The Survey's recommendations for advancing the new programs or augmentations are predicated on the assumption that the major astrophysics facilities and missions in NASA, NSF, and DOE's current plans are completed and fully supported for baseline operations and science

Space Program Medium/Large Programs Overview

Enabling and Realizing Large Strategic Missions

Great Observatories Mission and Technology Maturation Program

Infrared/optical/UV mission

High resolution X-ray imaging mission

Far-IR imaging and spectroscopy mission

2022

Review

2032

Implement Infrared/optical/UV mission

Sustaining Programs

Time Domain Astrophysics Program

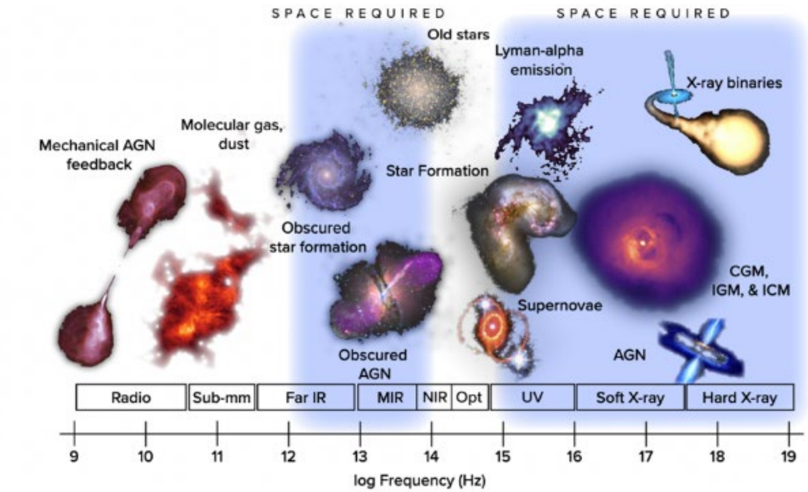
A Competed Line of Probe Missions with areas identified by Decadal Surveys

Large Strategic Missions: Background

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

All priority science areas require multiwavelength observations with highly capable facilities

The richness of 21st century astrophysics requires a panchromatic approach with overlapping lifetimes, as was achieved with NASA's Great Observatories



Large Strategic Missions: Background

NASA's Large Strategic Missions - History

Observatory	Waveband	Launch date	Development (yr)	2020 Cost (B$)
Hubble	UV/O	1990	18	9.4*
Compton GRO	Gamma-ray	1991	14	1.2
Chandra	X-ray	1999	17	3.1
Spitzer	IR	2003	11	1.0
JWST	IR/O	2021 (expected)	21	11
Roman	IR/O	2026 (expected)	16	3.5

*Cost at launch not including servicing

The community's ambitious and visionary ideas as presented to the survey require timelines that are pan-decadal, and even multi-generational

Mission	Waveband	TRACE Cost Est. (FY20, B$)	development time**
LUVOIR-B	UV/O/IR	17	20
HabEx 4-H	UV/O/IR	10.5	18
Lynx	X-ray	9	18.5
Origins	Far-IR	10.6	15.5

**TRACE assessment, minimum, assuming immediate start and optimum budget profile

Great Observatories Mission and Technology Maturation Program

Optimizing the cadence and scale of strategic missions must recognize that evaluating strategic missions is a process that spans multiple decades. This optimization requires that:

- Decadal surveys set the scope for strategic missions presented to them, defining cost targets as deemed appropriate for the scientific return
- For compelling missions, a maturation program is established with significant investment is co-developing the mission science, architecture, and technologies consistent with decadal advice
- Clear gates are established prior to adoption accomplished through decadal surveys, mid-decadal reviews, or other independent reviews

Recommendation: The NASA Astrophysics Division should establish a Great Observatories Mission and Technology Maturation Program, the purpose of which is to co-develop the science, mission architecture, and technologies for NASA large strategic missions identified as high priority by decadal surveys

Recommended Missions for Maturation

Highest Priority:

- *An IR/O/UV Large Telescope Optimized for Observing Habitable Exoplanets and General Astrophysics*

  To the program as soon as possible. Target cost for mission: 11B$ (FY20). Analysis estimates maturation program of ~six years, $800M required before review and transition to mission adoption

Of Co-equal Priority:

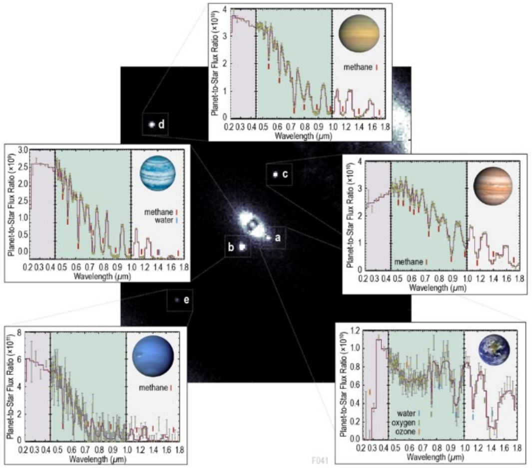
- *A far-IR spectroscopy and/or imaging strategic mission*

  To start mid-decade. Target cost for mission: 3 – 5 B$ (FY20). ~40M$ required for maturation program this decade

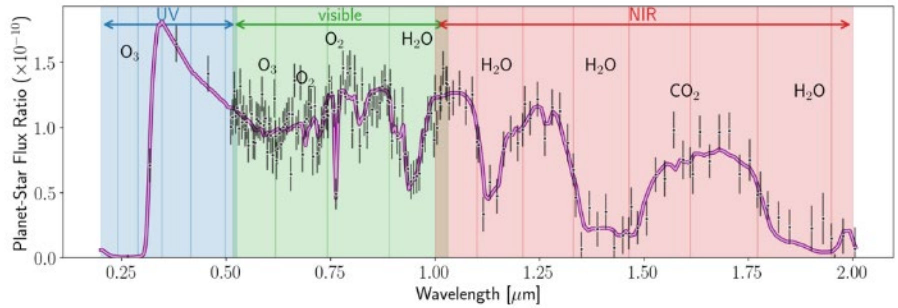
- *A high spatial and spectral resolution X-ray strategic mission*

  To start mid-decade. Target cost for mission: 3 – 5 B$ (FY20). ~40M$ required for maturation program this decade

A Future IR/Optical/UV Telescope Optimized for Observing Habitable Exoplanets and General Astrophysics



Simulated space-telescope image of a complete planetary system including a life-bearing Earth-like planet



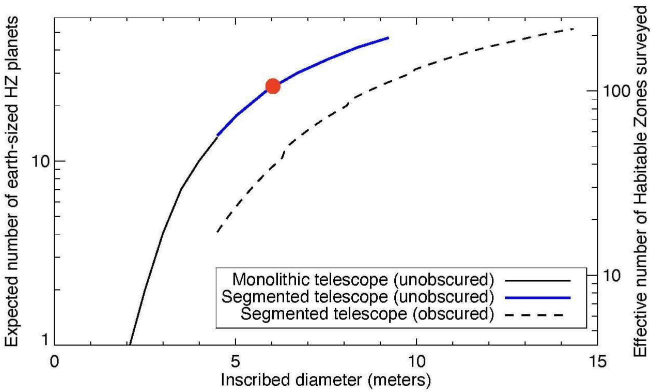
Simulated spectrum of an Earth-twin planet observed from the UV to near-IR by a space coronagraph

Recommendation: After a successful mission and technology maturation program, NASA should embark on a program to realize a mission to search for biosignatures from a robust number of about ~25 habitable zone planets and to be a transformative facility for general astrophysics. If mission and technology maturation are successful, as determined by an independent review, implementation should start in the latter part of the decade, with a target launch in the first half of the 2040’s

A Future IR/Optical/UV Telescope Optimized for Observing Habitable Exoplanets and General Astrophysics

IR/O/UV Telescope Characteristics

- ~6 m off-axis inscribed diameter provides robust sample of ~25 spectra of potentially habitable planets, and would be transformative for general astrophysics
- Estimated cost: 11B$
- Target launch: first half of 2040’s

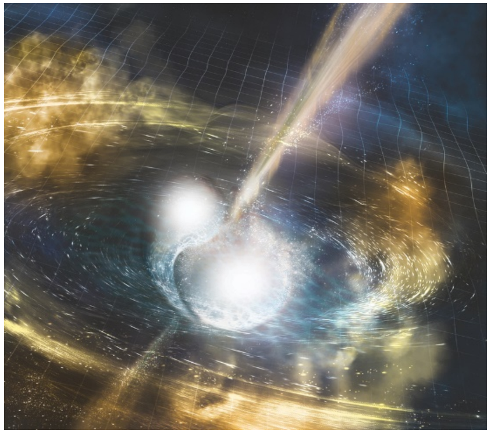


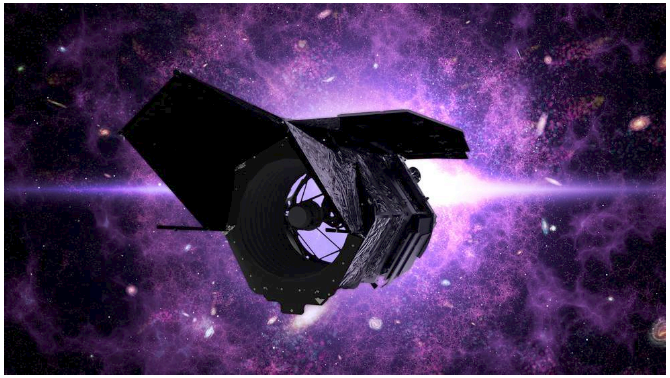
The scientific goals of this mission, when achieved, have the potential to change the way that we as humans view our place in the Universe

With sufficient ambition, we are poised to make this transformational step

This is a quest at the technical forefront, and of an ambitious scale that only NASA can undertake, and where the U.S. is uniquely situated to lead

Sustaining Activities: Time Domain Astrophysics Program





New Windows on the Dynamic Universe is a priority science area where return on major US facilities (LIGO, Rubin, Roman) requires an agile fleet of small to medium scale missions

Recommendation: NASA should establish a time-domain program to realize and sustain the necessary suite of space-based electromagnetic capabilities required to study transient and time-variable phenomena, and to follow-up multi-messenger events. This program should support the targeted development and launch of competed Explorer-scale or somewhat larger missions and missions of opportunity

Sustaining Activities: Probe Mission Line

The large gap in cost and capability between Explorer class missions (300M$) and large strategic missions (3 – 11 B$) is a significant impediment to achieving the broad set of Astro2020 decadal scientific priorities

The addition of a probe line, modeled after the Planetary Sciences New Frontiers program will help ensure the required range of panchromatic observational capabilities

Recommendation: The NASA Astrophysics Division should implement a line of probe missions with a mission cost cap of ~$1.5 billion FY20 and a targeted launch rate of approximately one per decade. These missions should be competed, with solicitations calling for concepts in priority areas identified by decadal surveys

Sustaining Activities: Probe Mission Line

Priority Areas for Probe Missions this decade (co-equal)

A far-IR imaging or spectroscopy probe mission would address scientific objectives central to Astro2020, and would fill an important gap in world-wide capabilities

Because of the unique science that can be addressed by such a mission, *a targeted X-ray probe* that complements ESA's *Athena* mission is another priority areas

Area for strategic technology development for a probe competition next decade

An early universe cosmology and fundamental physics probe to fully exploit studies of the Cosmic Microwave Background

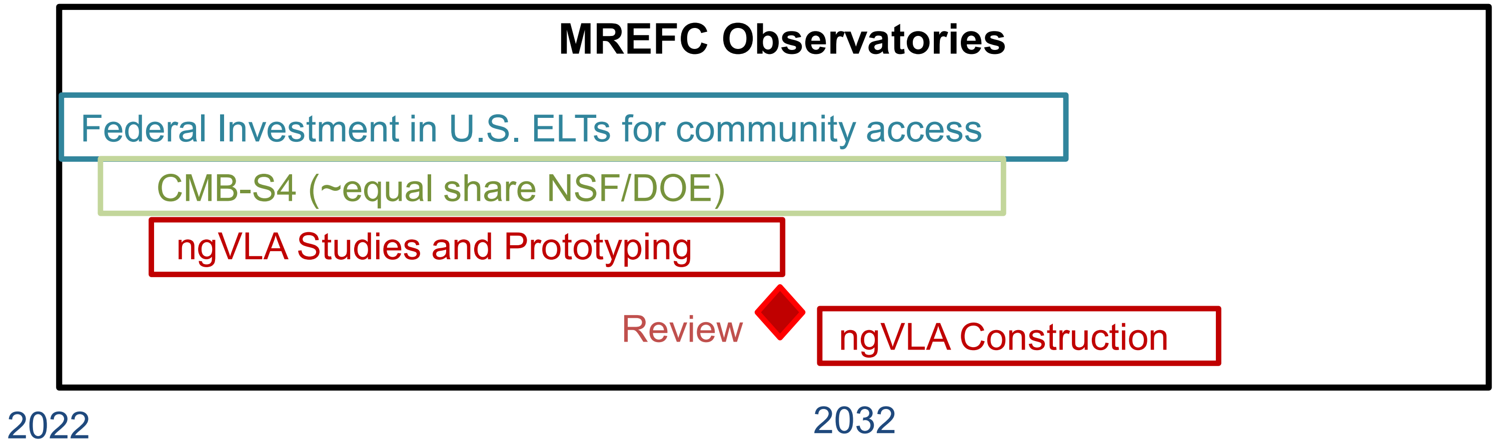
NASA's Program of Record

The Survey provided advice on NASA's program of record

- Roman Space Telescope should reevaluate the fraction of time going to major surveys vs. guest investigator programs
- The US contribution to Athena is on track, and the survey supports NASA's current plans
- NASA must ensure that the full scope of LISA's capabilities, as identified by Astro2010 are achieve - even if it requires increasing NASA's investment, NASA must aggressively support the US science community
- The cost for SOFIA operations is similar to Chandra and HST, however the science return is far from commensurate.   NASA should discontinue SOFIA operations in 2023

Ground Medium/Large Program Overview

Enabling and Realizing Major Observatories



Sustaining Programs

Enhancements to Astronomy Mid-scale Programs

Endorsements for Programs in NSF/PHYS

Technology Development for Future Gravitational Wave Observatories

The IceCube-Generation 2 High Energy Neutrino Observatory

NSF Funding for Major Research Facilities

Astronomy frontiers have been driven by new observatories

Construction costs have been borne by MREFC

Operations costs then transfer to AST

This is not sustainable

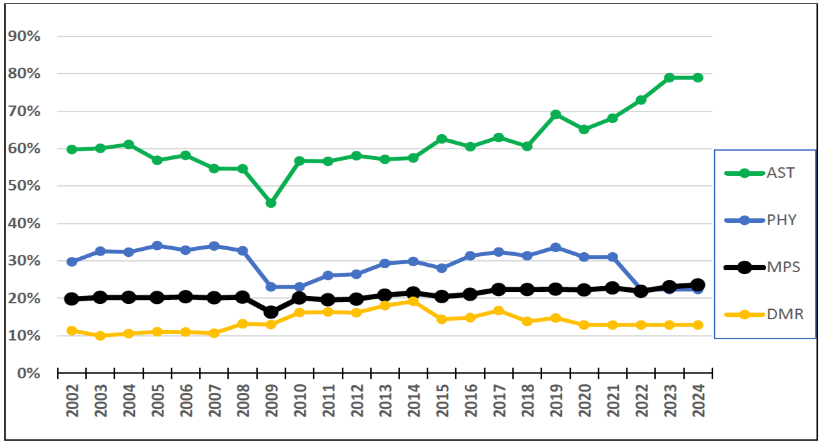
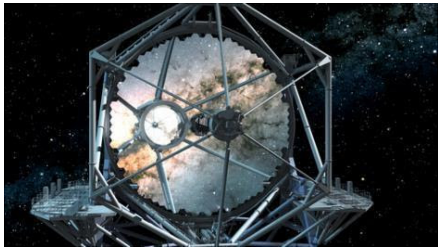


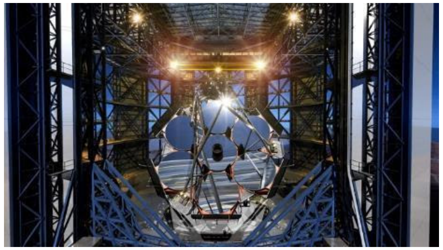
Figure 2, Percentage of Selected MPS Division Budgets to Facilities (O&M) and Overall MPS Share. AST: Division of Astronomical Sciences, PHY: Division of Physics, MPS: Directorate of Mathematical and Physical Sciences, DMR: Division of Materials Research

Recommendation: The NSF should develop a sustainable plan for supporting the operations and maintenance costs of its astronomical facilities, while preserving an appropriate balance with funding essential scientific foundations and the remainder of the NSF AST portfolio. *The addition of new MREFC facilities should be contingent on implementation of this plan*

U.S. Extremely Large Telescope Program



Thirty Meter Telescope



Giant Magellan Telescope

The scientific potential of 20-40m optical-infrared telescopes is vast

- resolution of 0.01-0.02 arcsec with adaptive optics

  1-2 au @ 100 pc, 0.8-1.6 pc @ Virgo cluster, 60-120 pc @ z=2.5 (!)

- 36-81x gain for point sources over 10-m telescopes (scales as D^4)
- immense range of scientific goals
  detection, imaging, spectroscopy of rocky planets, exoplanet atmospheres, protoplanetary disks; high-z supernovae and GRBs, cosmological yardsticks; spectroscopy of faint JWST sources; spectra of CGM/IGM, stellar fossil records of Galaxy, …

The combination of TMT, GMT, and NOIRLab (for community and science support) would provide the U.S. community with essential access to these transformative capabilities

US-ELT Program

Recommendation: The NSF should achieve a federal investment equal to at least 50 percent time for the U.S. community in at least one and ideally both of the two extremely large telescope projects – the Giant Magellan Telescope and the Thirty Meter Telescope, with a target level of at least 25% of the time on each telescope. If both projects are viable, then that time should be distributed across the two proposed telescopes. If only one project proves to be viable, the NSF should aim to achieve a larger fraction of the time, in proportion to its share of the costs and up to a maximum of 50 percent

Participation in both projects is the optimal outcome

- full-sky access
- maximizes public nights available (~180/yr total)
- exploit complementary instrumentation

If circumstances preclude participation of one observatory (financial, site availability) goal should be to obtain as large a share on the other as available

This is the survey's top priority MREFC recommendation due to the timeliness and transformative potential

US-ELT Program: Decision Rules

Prior to major investment by the NSF, a review must determine that:

- The projects have demonstrated financial viability with agreed-upon commitments from partners for all necessary capital and operations funds, pending only NSF investment
- A final site selection has been made in the case of the TMT
- A public share of telescope time (run through the NSF's NOIRLab) roughly equivalent to the NSF's share of total federal investment of construction and operations expenses
- Development of a management plan and governance structure for the joint project, including the relevant observatory corporations and the NSF

Success of both projects at the levels presented to the survey represents an NSF investment of 1.8 B$*, leveraging private and international investments of 3.6 B$, bringing these transformative observatories on-line early in the 2030's

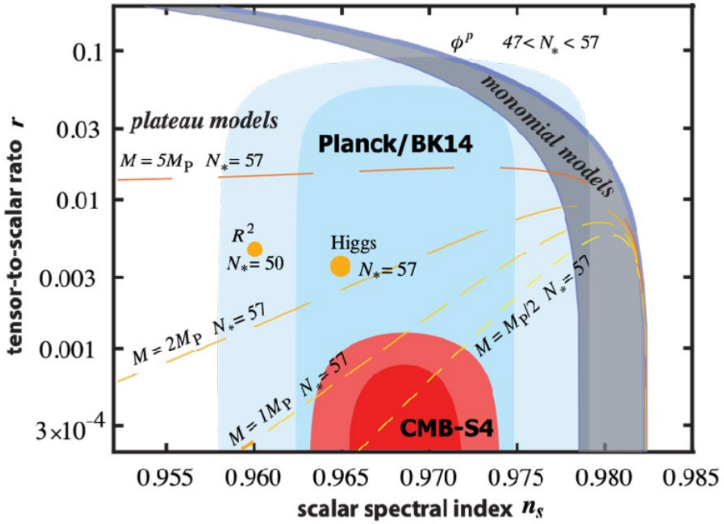
*Based on TRACE evaluation

The Cosmic Microwave Background Stage 4 Observatory

CMB-S4 builds on the foundation of decades of CMB measurements to take a major leap, pushing CMB science to the next level

Scientific goals

- B-mode CMB polarization signatures of primordial gravitational waves and inflation
- Maps 50% sky, every other day from 0.1- 1 cm with unprecedented sensitivity
- Broad science including systematic time domain science



CMB-S4 consists of a systematically planned suite of facilities in Antarctica and Chile designed to sample a wide range of independent frequencies, and probe a combination of large and small angular scales

The Cosmic Microwave Background Stage 4 Observatory

Key Attributes

- Balanced program between DOE (60%) and NSF (40%) for all phases

  Brings wide range of technical and scientific expertise to bear from community and national labs

- Total design, development and construction cost: $660M

- First observations could begin by 2030

Recommendation: The NSF and DOE should jointly pursue the design and implementation of the next generation ground-based cosmic microwave background experiment (CMB-S4).

Because of its great potential to advance general astrophysics and open discovery space, it is essential that CMB-S4 produce transient alerts, as well as calibrated maps in all bands and on all angular scales that are openly usable and accessible on as rapid a cadence as practical

The Next Generation Very Large Array (ngVLA)

The U.S. has led the world in radio astronomy through the premier radio facilities – the JVLA and VLBA. The ngVLA will replace both with a next-generation observatory

The ngVLA provides transformational capabilities: sub-milliarcsecond resolution, <m/s velocity resolution, order-of-magnitude sensitivity gains over the VLA

The ngVLA will address a broad range of science questions including:

- imaging of protoplanetary disks over time, planet formation in action
- radio emission from transient events, gravitational wave sources
- mapping of circumgalactic, intergalactic media, gas flows within galaxies
- surface mapping of stars

The ngVLA is of essential importance to many of the survey's science questions

Conclusion: It is of essential importance to astronomy that the JVLA and VLBA be replaced by an observatory that can achieve roughly an order of magnitude improvement in sensitivity compared to these facilities, with the ability to image radio sources on scales of arcminutes to fractions of a milliarcsecond.

The Next Generation Very Large Array (ngVLA)

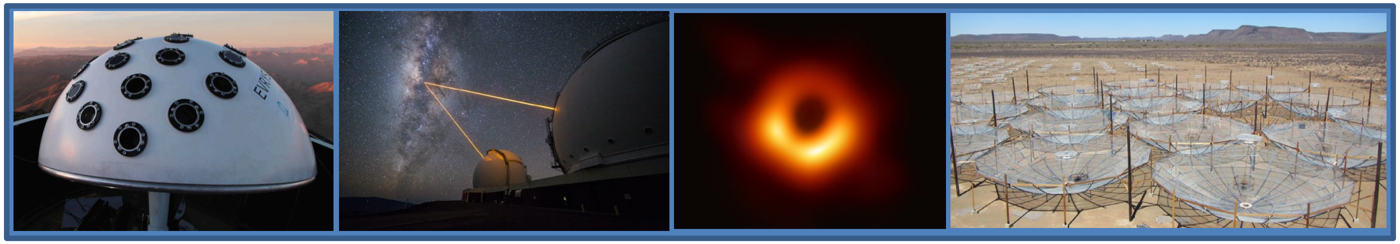
The ngVLA presented to the survey is a very ambitious project

- Estimated cost $3.2B (75% NSF, 25% foreign contribution TBD); operations >$100M/yr
- Up to 224 antennas arrayed across North America; operates from 1.2 - 116 GHz

Astro2020 concluded that the project scope and design need further development before a review determines the scope is appropriate, and before proceeding to construction

Recommendation: The NSF should proceed with a program to support science design, development, cost studies, and antenna prototyping for the Next Generation Very Large Array. After completion of the studies, NSF should convene a review to assess the project's readiness and available budget and proceed with construction if possible.

NSF Mid-Scale Program Background



Mid-scale (4 – 100 M$) competed programs harness the creativity of the community and fuel innovation

A broad, balanced scientific program demands expansion of opportunities at the mid-scale to fulfill strategic needs and harness innovations

Recommendation: The NSF Division of Astronomical Sciences (AST) should create three tracks within the AST Mid-Scale Innovations Program and within (its share of) the NSF-wide Mid-Scale Research Infrastructure Program. The first track should be for *regularly competed, open calls*, the second track should solicit proposals in strategically identified priority areas, and the third should invite ideas for upgrading and developing new instrumentation on existing facilities. All tracks should solicit proposals broadly enough to ensure healthy competition.

NSF Mid-Scale Programs

The survey received many very compelling mid-scale whitepapers, generally at the larger (~$100M) scale

A broad, balanced scientific program demands expansion of opportunities at the mid-scale to fulfill strategic needs and harness innovations

Recommendation: The NSF Division of Astronomical Sciences (AST) should create three tracks within the AST Mid-Scale Innovations Program and within (its share of) the NSF-wide Mid-Scale Research Infrastructure Program. The first track should be for *regularly competed, open calls*, the second track should solicit proposals in strategically identified priority areas, and the third should invite ideas for upgrading and developing new instrumentation on existing facilities. All tracks should solicit proposals broadly enough to ensure healthy competition.

Strategic priority areas for Astro2020:

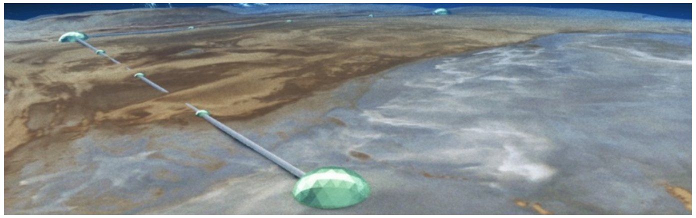
- A time-domain astrophysics program supporting a range of activities
- Radio instrumentation (wide-field radio camera, EoR)
- Highly multiplexed spectroscopy

NSF Mid-Scale Programs

There is very strong scientific motivation to support projects across all scales and across all wavebands, and this will require increased funding

Recommendation: The NSF should increase the funding available in its mid-scale programs that support astronomy and astrophysics with a target of reaching $50 million per year for the combination of the Mid-Scale Innovations Program and the Mid-Scale Research Infrastructure Program

Technology Development for Future Ground-based Gravitational Wave Observatories



Gravitational wave detection is one of the most exciting and expanding scientific frontiers impacting central questions in astronomy

- Directly relevant to two Astro2020 priority areas: New Windows on the Dynamic Universe, Hidden Drivers of Galaxy Formation

More advanced detectors in the current LIGO facility (beyond A+) and planning for future generation facilities such as Cosmic Explorer are essential

Conclusion: … Continuous technology development will be needed this decade for next generation detectors like Cosmic Explorer. These developments will also be of benefit to the astrophysical reach of current facilities.

IceCube-Generation 2 Neutrino Observatory

IceCube at South Pole detects 100 TeV – 10 PeV cosmic neutrinos

Upgrade to Generation-2 observatory will add detector elements and a radio array to increase sensitivity (5x), detection rate (10x), and energy range (to 1000 PeV)

- resolve diffuse (currently) cosmic neutrino background
- localize, identify individual astrophysical sources
- coordinated multi-messenger observations

Conclusion: The IceCube-Generation 2 neutrino observatory would provide significantly enhanced capabilities for detecting high-energy neutrinos, including the ability to resolve the bright, hard-spectrum TeV-PeV neutrino background into discrete sources. Its capabilities are important for achieving key scientific objectives of this survey

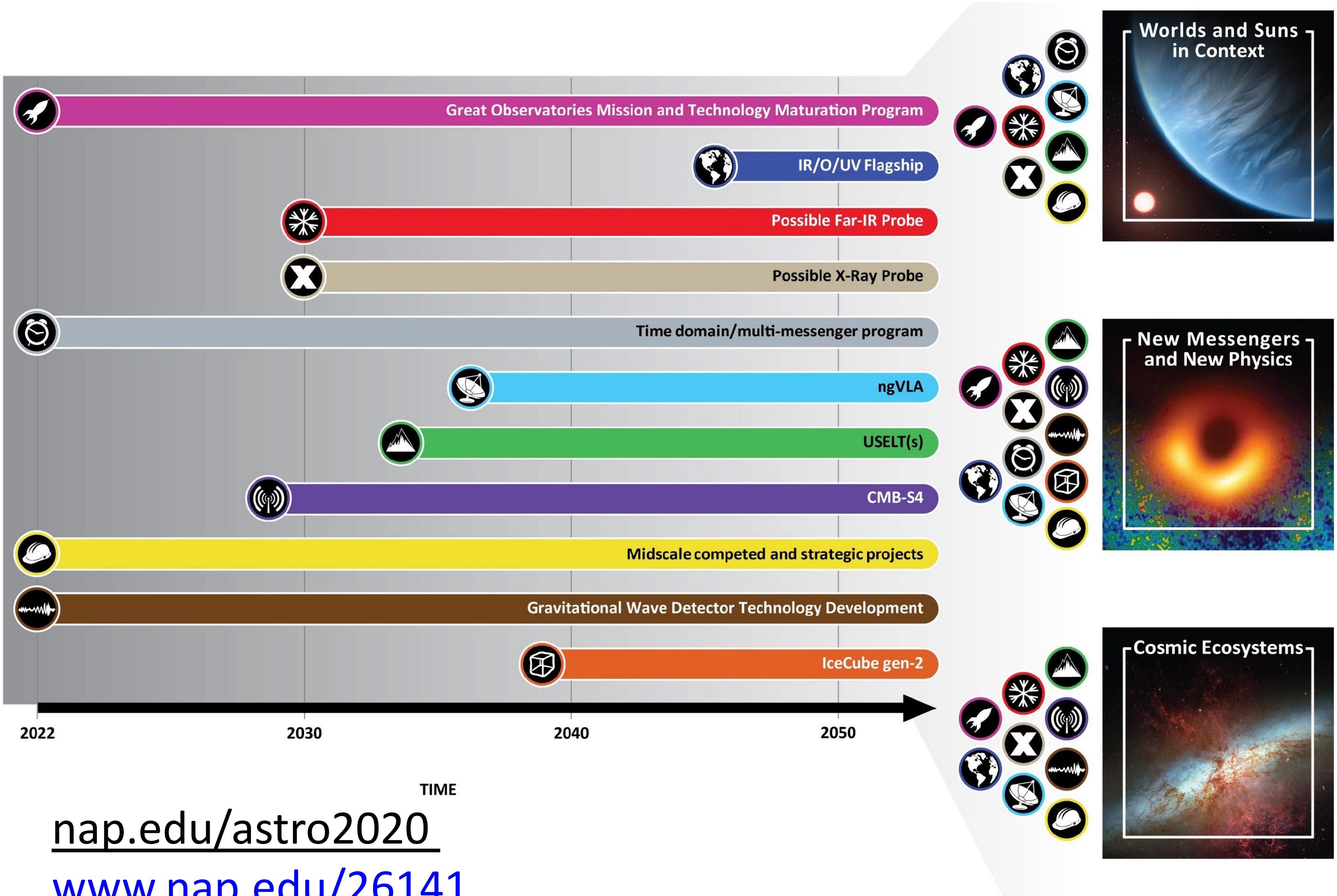
Consistency with Budget Guidance

Agency budgets projected forward are uncertain

We planned our program to be within the optimistic scenarios provided by the agencies (time averaged)

The program we set forth allows for future opportunities

We live in exciting times for astronomy and astrophysics.   Amazing scientific opportunities lie in front of us that strongly motivate increased investment in the future



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