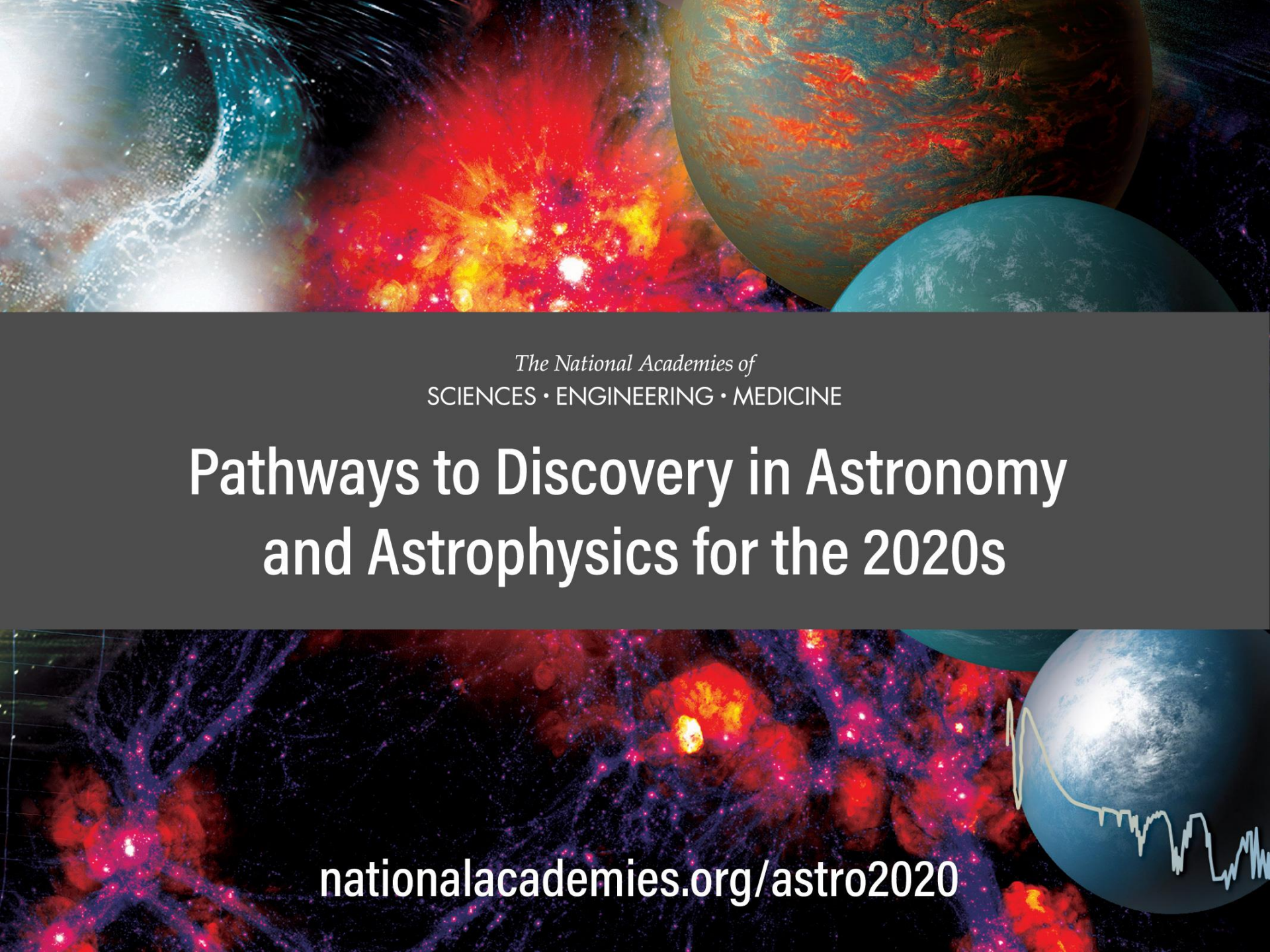


The background of the entire slide is a vibrant cosmic scene. It features a large, bright, orange and red nebula or galaxy core in the upper center. To the left, there's a blue and white structure resembling a spiral galaxy or a comet's tail. In the upper right, a large, textured sphere with orange and red patterns is visible. Below it, a smaller, blue sphere with white clouds is partially shown. The lower half of the slide is a dark grey band containing text. Below the grey band, the background continues with a complex network of red and purple filaments, possibly representing the cosmic web, and a large blue sphere with a white line graph overlaid on its right side.

The National Academies of
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Pathways to Discovery in Astronomy and Astrophysics for the 2020s

nationalacademies.org/astro2020

Major New Projects and Sustaining Programs : Guiding Principles

Precepts and Guiding Principles

- Must **advance bold and broad visions** while ensuring a program that can respond to scientific opportunity – **range of mission scales**
- Portfolio should be scientifically broad and balanced
- Complement and leverage international efforts, and public-private partnerships
- Maximize return on existing and upcoming facilities and bring about entirely new capabilities
- Time from inception to science is an important consideration, and estimates must be based on optimal but realistically achievable budget profiles

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

Competed missions and missions of opportunity to realize and sustain the suite of capabilities required to study transient phenomena and follow-up multi-messenger events

Competed Line of Probe Missions

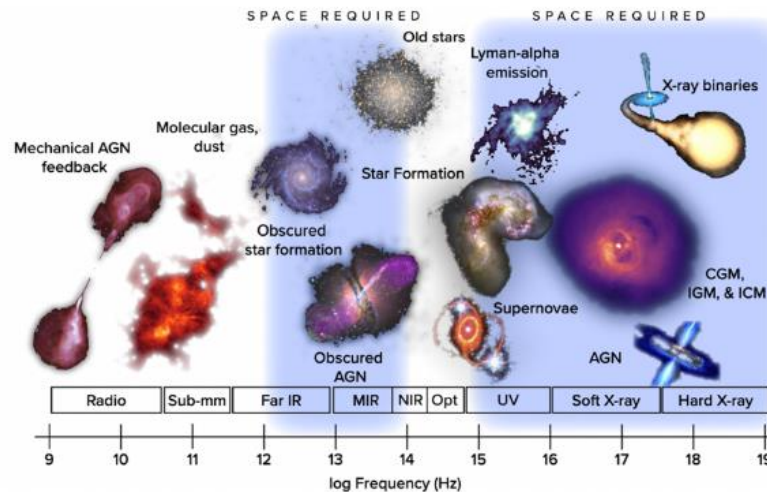
Competed within selected areas, with individual mission cost cap of \$1.5B, launch of 1 per decade

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

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

NASA's successful Great Observatories model propelled major scientific advances on broad fronts over the course of two decades or more

The near-contemporaneous operation of the Great Observatories was key to their scientific success

The Great Observatories spanned a wide range of cost scales and development times, from probe scale (~1.5B) to the ambitious HST
For Chandra and Spitzer, this was the result of rescoping after initial decadal concept

Large Strategic Missions: Background

Mission	Waveband	TRACE Cost Est. (FY20, B\$)	TRACE 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

**Minimum, assuming immediate start and optimum budget profile

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

Conclusion: Establishing a panchromatic suite of observatories over the next thirty years is essential to address key questions in all three of the Survey's priority science themes. The large strategic mission implementations presented to the Survey cannot all be built and launched in an optimal timeframe given the current designs, available budgets, and approaches to mission development

Large Strategic Missions: Lesson

Observation: Four Large Mission Concepts (two of them having multiple instantiations) were put forward to the survey. Astro2020 advanced none of them.

Opinion: There is limited value in developing mission concepts of specific scale and scientific scope without evaluation by a survey, which is balancing many considerations and evaluating science return in a larger context

Finding: *For a decadal survey to confidently recommend implementation of a strategic mission as its highest priority, the mission's technology and architecture need to be developed to a level of maturity that allows a reasonable assessment of budget profile, scientific performance, and technology risk. The mission's cost range and development time scale must be deemed appropriate for the scientific scope.*

Great Observatories Mission and Technology Maturation Program

Accelerating the cadence of strategic missions will require

- limiting their scope through careful selection of capabilities
- a new approach to the phasing of mission and technology maturation, with more significant and coordinated investment prior to a decadal survey recommendation to proceed with mission development

This rephrasing

- better recognizes the multi-decadal timescales required for conceptualizing, maturing and implementing strategic missions
- avoids the negative consequences of commencing missions prior to appropriate maturation
- provides a means for the survey process to more optimally align a mission's cost range and development timescale as it deems appropriate for the scientific return

Great Observatories Mission and Technology Maturation Program

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

Crucial program attributes

- Iterating and defining the science using broad community engagement
- Developing the mission architecture best suited to accommodate programmatic constraints
- Supporting mission-specific subsystem-level demonstrations, and demonstration of production processes of sufficient scale
- Transitioning collaboratively from The Great Observatories Maturation Program Office to detailed design and implementation, **as recommended by a decadal survey or mid-term decadal assessment, or a dedicated review**

Great Observatories Mission and Technology Maturation Program

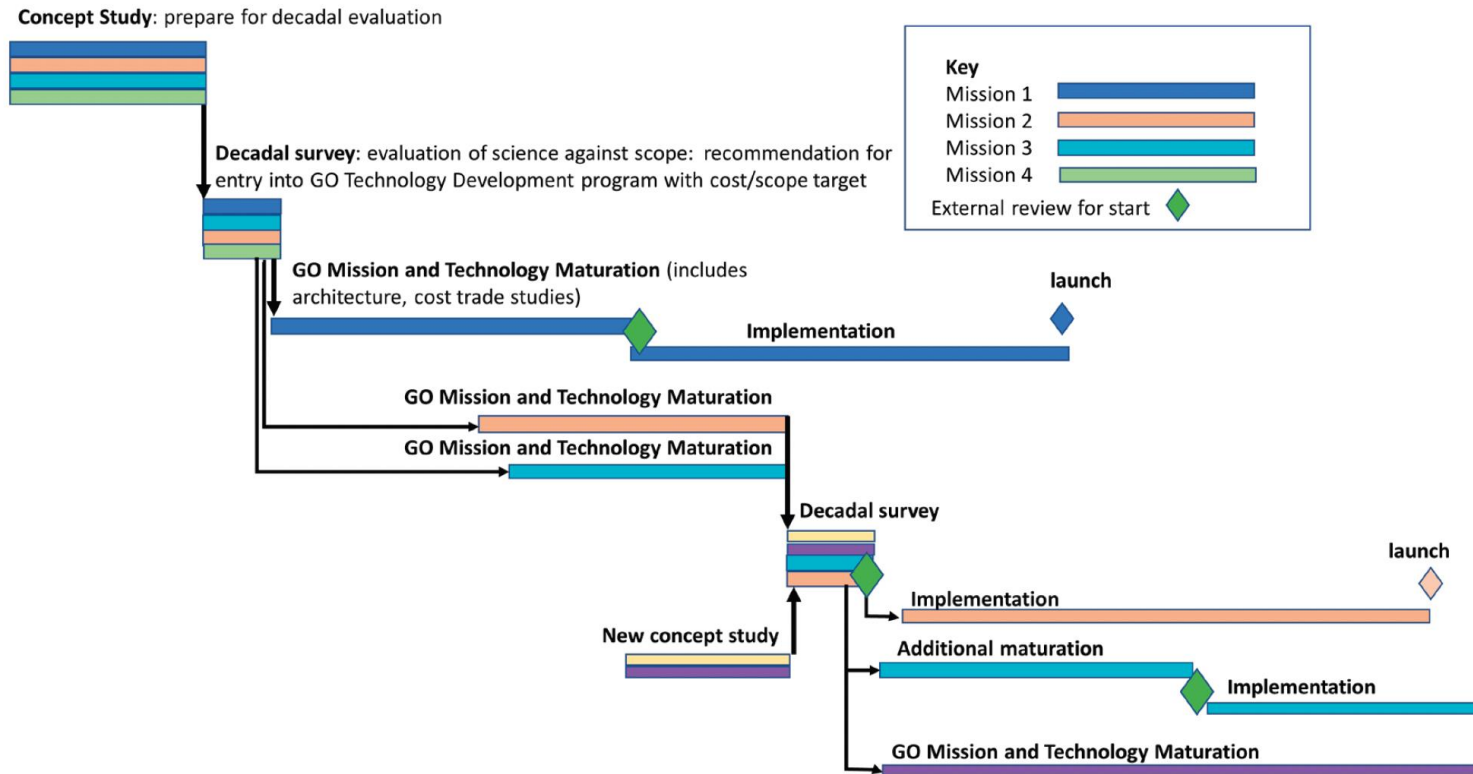


FIGURE 7.2 Flow diagram showing the concept for maturation, recommendation, and implementation of NASA large strategic missions. This does not represent the actual recommendations in this report; instead, it represents how the program would be structured in general. If implemented, this survey would be the first to adopt this process by recommending the first entrant into the Great Observatories (GO) Mission and Technology Maturation Program. SOURCE: Courtesy of Fiona Harrison.

Process

The first stage is an initial mission concept study, similar to those done in preparation for this survey. However, rather than develop a small number of design reference missions, these studies would emphasize identifying key scientific break points, architecture options, and trades, and would provide a description of key technologies and their maturation requirements and risks.

These studies would get submitted to the survey, so that the survey can evaluate whether the recommend advancement, and also what cost and time scale is appropriate to the science reach of the mission.

Recommended Missions for Maturation

Highest Priority:

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

To start as soon as possible. Target cost for mission: 11B\$. 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 imaging strategic mission*

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

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

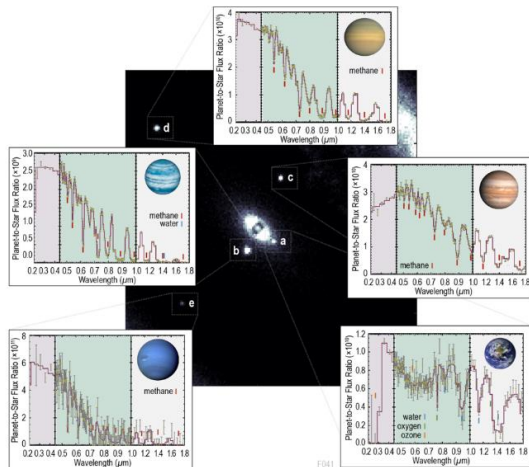
To start mid-decade. Target cost for mission: 3 – 5 B\$. ~40M\$ required for maturation program this decade

Personal Observations

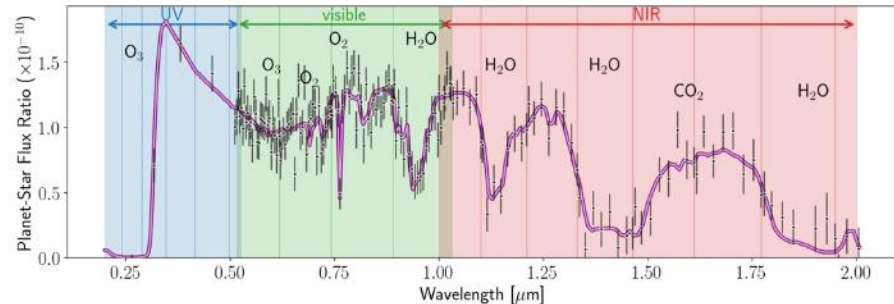
- The actual budgets for the decade so-far are lower than the most pessimistic profile provided to the survey
This requires some adjustment of the sequence as imagined by Astro202
- HWO has not yet reached the External Review milestone that would evaluate it against the cost target and scientific
- Far-IR mission may be advanced in the probe line, scientific gaps would be identified by the mid-decadal or next decadal
- X-ray mission has the advantage of a decadal review setting cost scale, but inputs to next survey required to evaluate science breaks and technology readiness, depending on how much investment can be made this decade
- Other possible concepts should focus on *key scientific break points, architecture options, and trades, and would provide a description of key technologies and their maturation requirements and risks* not on point designs

Backup Slides

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



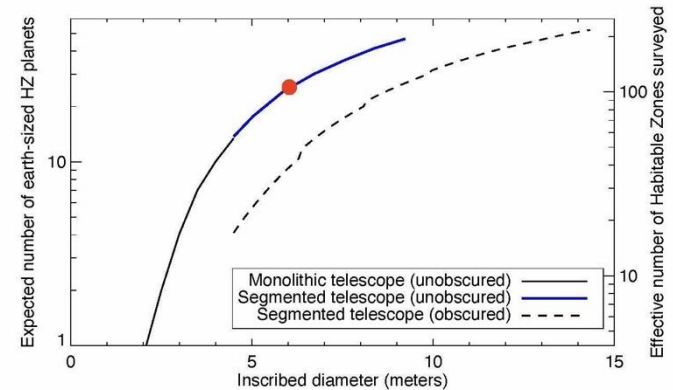
Simulated spectrum of an Earth-twin planet observed from the UV to near-IR by a space coronagraph

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

Large 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

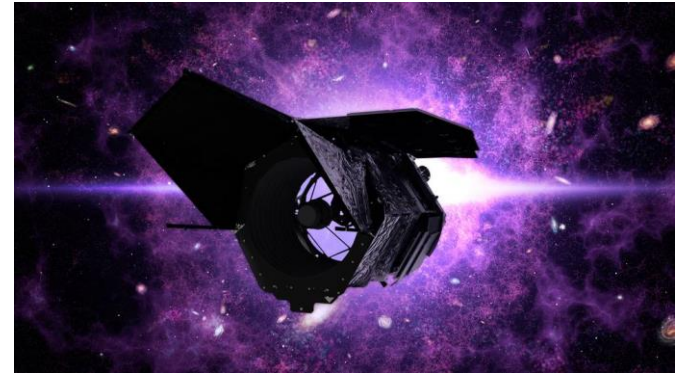
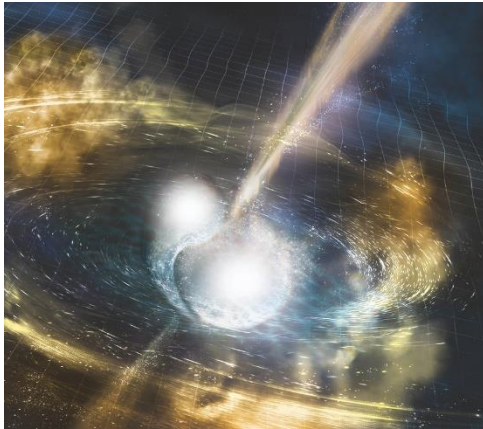


The scientific goals of this mission, when achieved, have the potential to change the way that we as humans view our place in the Universe

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

- LIGO/Virgo/Kagra upgrades, Rubin, Roman, IceCube will offer greatly expanded scientific opportunities and discovery space

Key space-based capabilities must be established and sustained to capitalize on the unique opportunities

- Flexible wide-field imaging and spectroscopic follow-up in the X-ray, UV, IR
- Wide-field monitoring in the hard X-ray/gamma-ray

Sustaining Activities: Time Domain Astrophysics Program

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

A standing planning or advisory structure could provide tactical advice to NASA on pending needs and priority capabilities, evaluated in the international landscape

Estimated total Program cost: \$500 – 800 M added over the decade (above current Explorer program)

Due to the timeliness, this is the highest priority sustaining activity

Sustaining Activities: Probe Mission Line

The large gap in cost and capability between Explorer class missions and large strategic missions is a significant impediment to achieving the broad set of Astro2020 decadal scientific priorities

In concert with the Great Observatories Mission and Technology Development Program, which is intended to decrease development timescales for large strategic missions, the addition of a probe line 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

Advice on the NASA Program of Record

Because they are still in active formulation and development, the Survey offers advice on Roman, Athena, and LISA

Roman Space Telescope

The Roman Space Telescope remains both powerful and necessary for achieving the scientific goals set by *New Worlds*, *New Horizons* (Astro2010)

The scientific landscape and the Roman Space Telescope's capabilities have changed significantly since it was first envisioned by *New Worlds*, *New Horizons*

Recommendation: The NASA Astrophysics Division should hold a non-advocate review of the Roman Space Telescope's science program to set the appropriate mix of survey time devoted to the weak lensing, baryon acoustic oscillations, supernovae, and microlensing programs relative to guest investigator-led observing programs during the primary five-year mission

Advice on the NASA Program of Record

US Contribution to Athena

The scope of the U.S. investment in the European Space Agency's Athena mission is appropriate both for the hardware contribution as well as for the U.S. Guest Observer and science center

US Contribution to LISA

ESA's LISA mission remains a very high priority for the U.S. community, and NASA contributions of hardware and data analysis tools are essential to ensuring the full scientific capability of the mission is achieved, as envisioned by *New Worlds*, *New Horizons* and the subsequent mid-decadal assessment

Recommendation: NASA should work with the European Space Agency to ensure the Laser Interferometer Space Antenna (LISA) achieves the full scientific capability envisioned by *New Worlds*, *New Horizons*. NASA should continue calls for LISA Preparatory Science with a known cadence during the decade. After a jointly developed plan for LISA data analysis and management are clear, and a few years prior to launch, NASA should establish funding for LISA science at a level that ensures U.S. scientists can fully participate in LISA analysis, interpretation, and theory

SOFIA

The Survey has significant concerns about SOFIA

- NASA's portion of SOFIA's operating budget is \$86 million a year, comparable to Hubble and Chandra
- SOFIA's scientific productivity has been very low: 178 total papers after 6 years (from May 2014 to May 2020). The science impact is also low – with only 1242 total citations

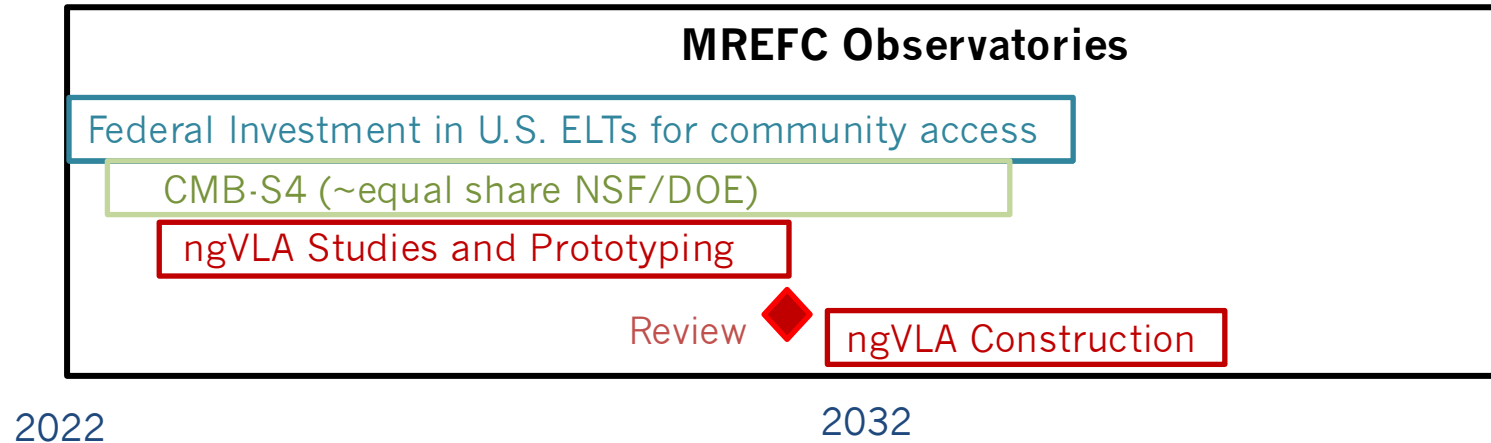
Conclusion: The cost of SOFIA's yearly budget is comparable to NASA's Hubble and Chandra flagship missions, yet the scientific productivity is significantly lower. There is no evidence that SOFIA could transition to a significantly more productive scientific future.

Recommendation: NASA should end SOFIA operations by 2023, consistent with its current plan.

The survey views the path forward for SOFIA science to lie with a far-IR probe mission or, on a longer timescale, a strategic mission, both of which would revolutionize capabilities to meet the needs of Astro2020 science objectives

Ground Medium/Large Program Overview

Enabling and Realizing Major Observatories



Sustaining Programs

Enhancements to Astronomy Mid-scale Programs

Increased investment in midscale programs across the range 4M\$ - 120M\$

Addition of targeted solicitations designed to advance decadal priorities

Addition of calls targeted at sustaining and advancing instrumentation on existing telescopes

Ground Medium/Large Program Overview

Endorsements for Programs in NSF/PHYS

Technology Development for Future Gravitational Wave Observatories

Upgrades to LIGO and preparation for future generation facilities

The IceCube-Generation 2 High Energy Neutrino Observatory

Upgrades to IceCube Antarctic neutrino observatory

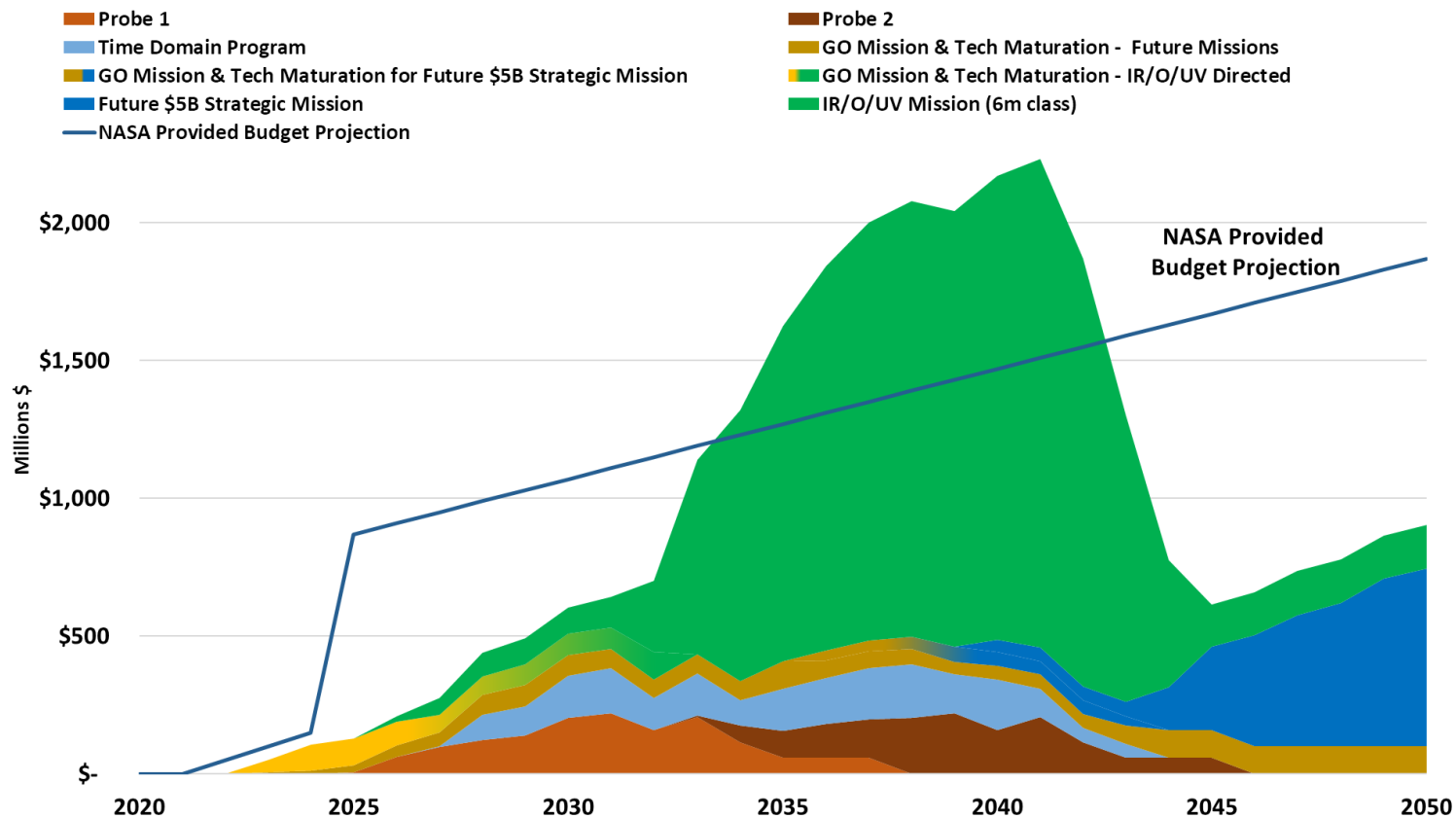
Budget Analyses

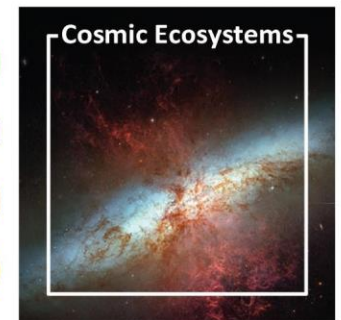
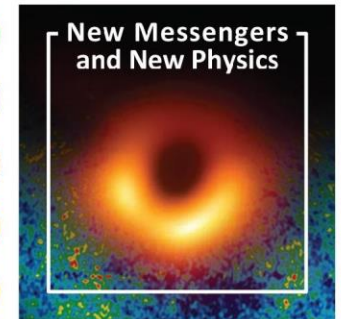
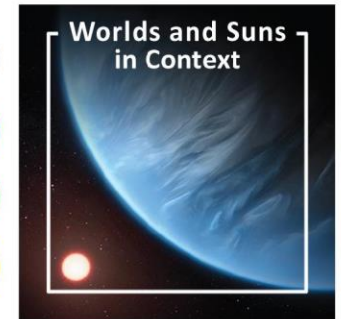
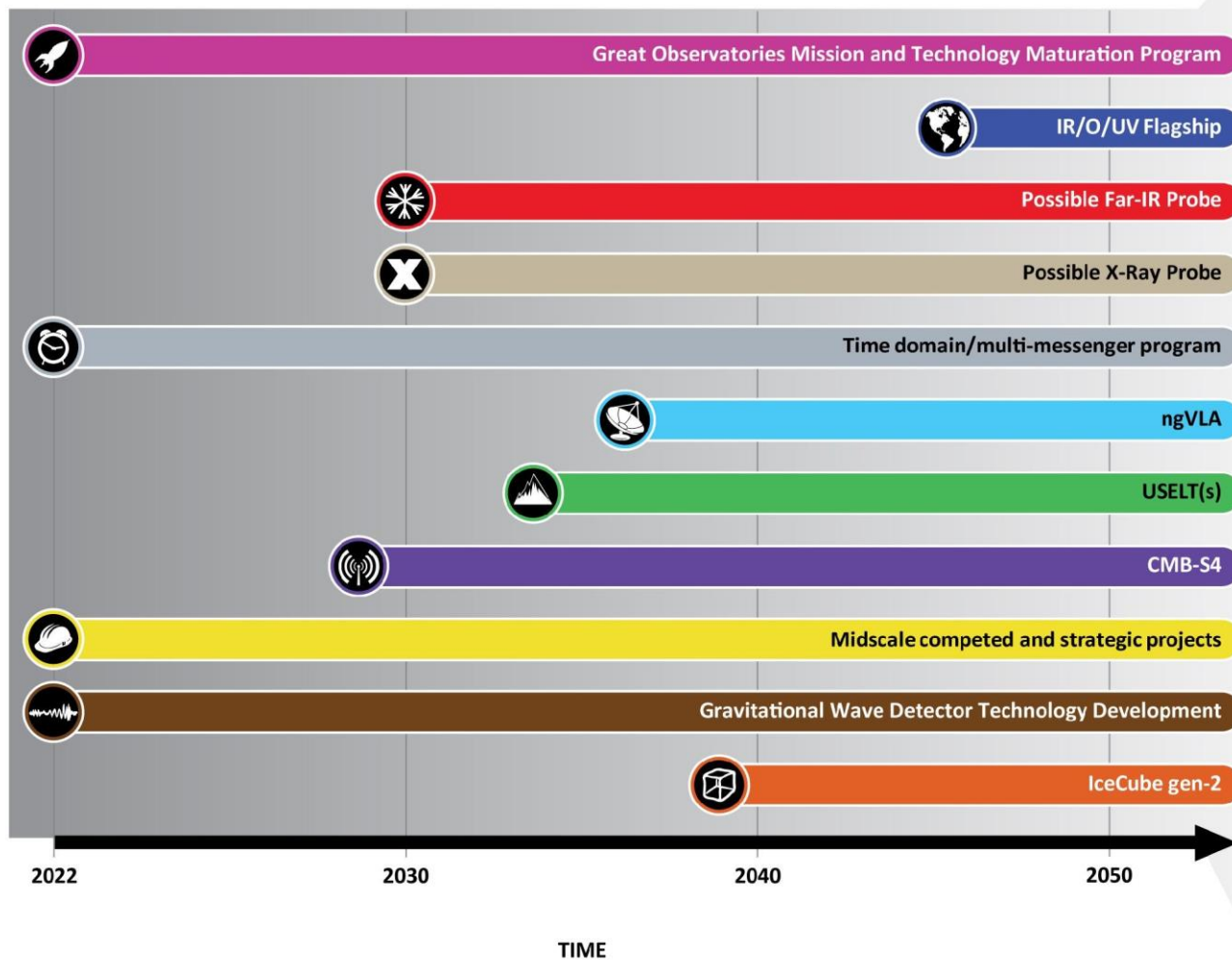
Budget analysis compares Agency guidance to program requirements

Assumptions:

- Adopted TRACE cost and schedule profiles (assumes agencies can provide optimal profiles) with only minor adjustments
- Inflation is built in at 2.7%
- Where costs are shared or have international/private contributions only the relevant agency cost is included

NASA Budget Requirements





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

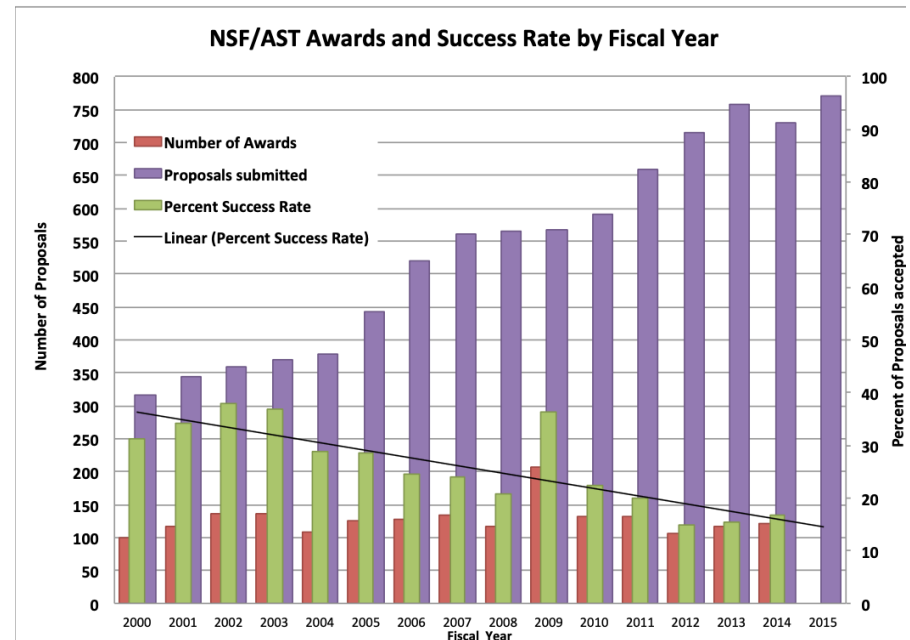
Recommendation: To ensure that the skies remain open to radio astronomy, NSF in partnership with other agencies as appropriate, should **support and fund a multi-faceted approach to the avoidance and mitigation of radio-frequency interference.** It is critical that the astronomical community formally 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

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

Technology Foundations

Strong support for early-stage technology development is essential for driving innovation, and training the next generation of instrumentalists

Technology Foundations at NSF

- NSF's ATI program supports the development of innovative, potentially transformative technologies (even at high technical risk)
- Astro2010 recommended increases to ATI, however in the last decade the program has been cut further

Recommendation: NSF should restore the Advanced Technologies and Instrumentation Program to \$14 million a year (FY20)—the same level of support it had in 2010—and further increase it to a target level of \$20 million a year (FY20) by 2028.

NSF Funding for Major Research Facilities

Astronomy frontiers have been driven by new observatories

Construction costs have been borne by MREFC

Operations costs transfer to AST - an increasing fraction of AST funding (reaching 80%) will soon go to operations rather than science

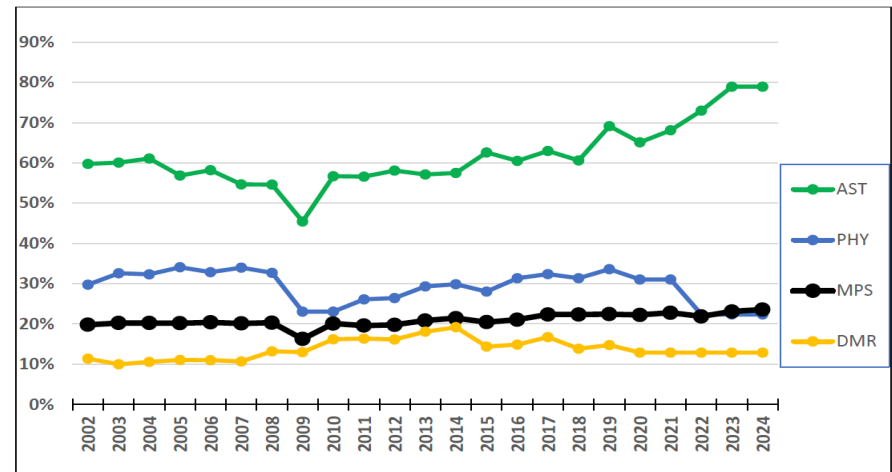
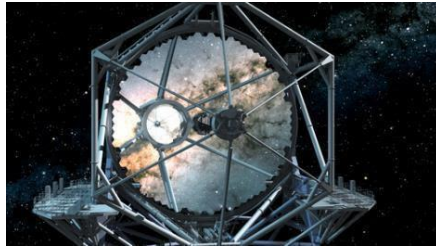


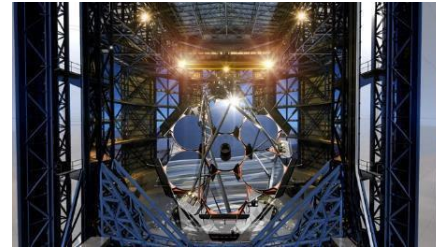
Figure 2, Percentage of Selected MPS Division Budgets to Facilities (O&M) and Overall MPS Share. AST: Division of Astronomical Sciences, PHY: Division of Physics, MPS: Directorate of Mathematical and Physical Sciences, DMR: Division of Materials Research

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 1.6 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



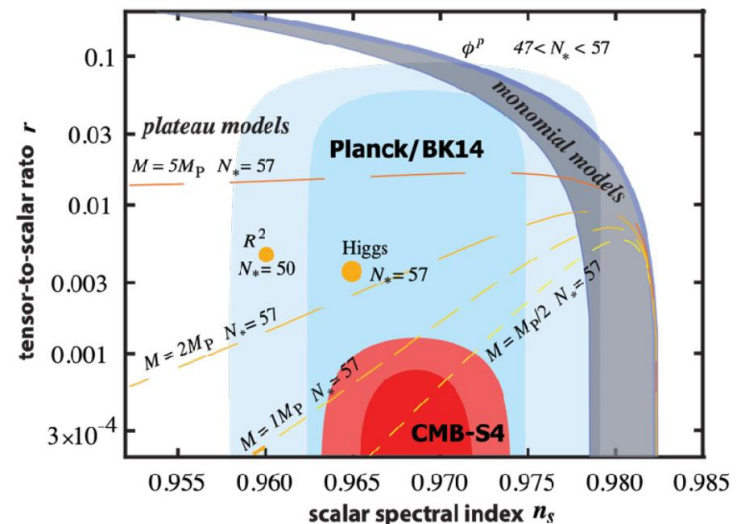
CMB-S4 builds on the foundation of decades of CMB measurements to take a major leap, pushing CMB science to the next level

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, $< \text{m/s}$ 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



Astro2010 envisioned the competed Mid-Scale Innovations Program (MSIP) to support projects across the \$4-120M scale, with the program reaching an investment of \$40M/yr

MSIP led to exciting, high-impact projects with broad science reach, engaging the creativity of the community in cutting edge projects.

- AST MSIP supported projects from few - <\$20M
- Funding levels have fallen far short of those envisioned

Recently NSF established an agency-wide mid-scale research initiative (MSRI), which can support larger projects through two tracks

- To-date two astronomy projects have been supported in the smaller (MSRI1) track (\$6 – 20 M)

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

Conclusion: Current budget levels for AST mid-scale projects are not sufficient to advance the full range of astronomy and astrophysics priorities

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

The Arecibo Observatory

The collapse of the storied Arecibo radio telescope ended a remarkably productive 55-year service to the astronomical, planetary, ionospheric, defense, and space-science communities

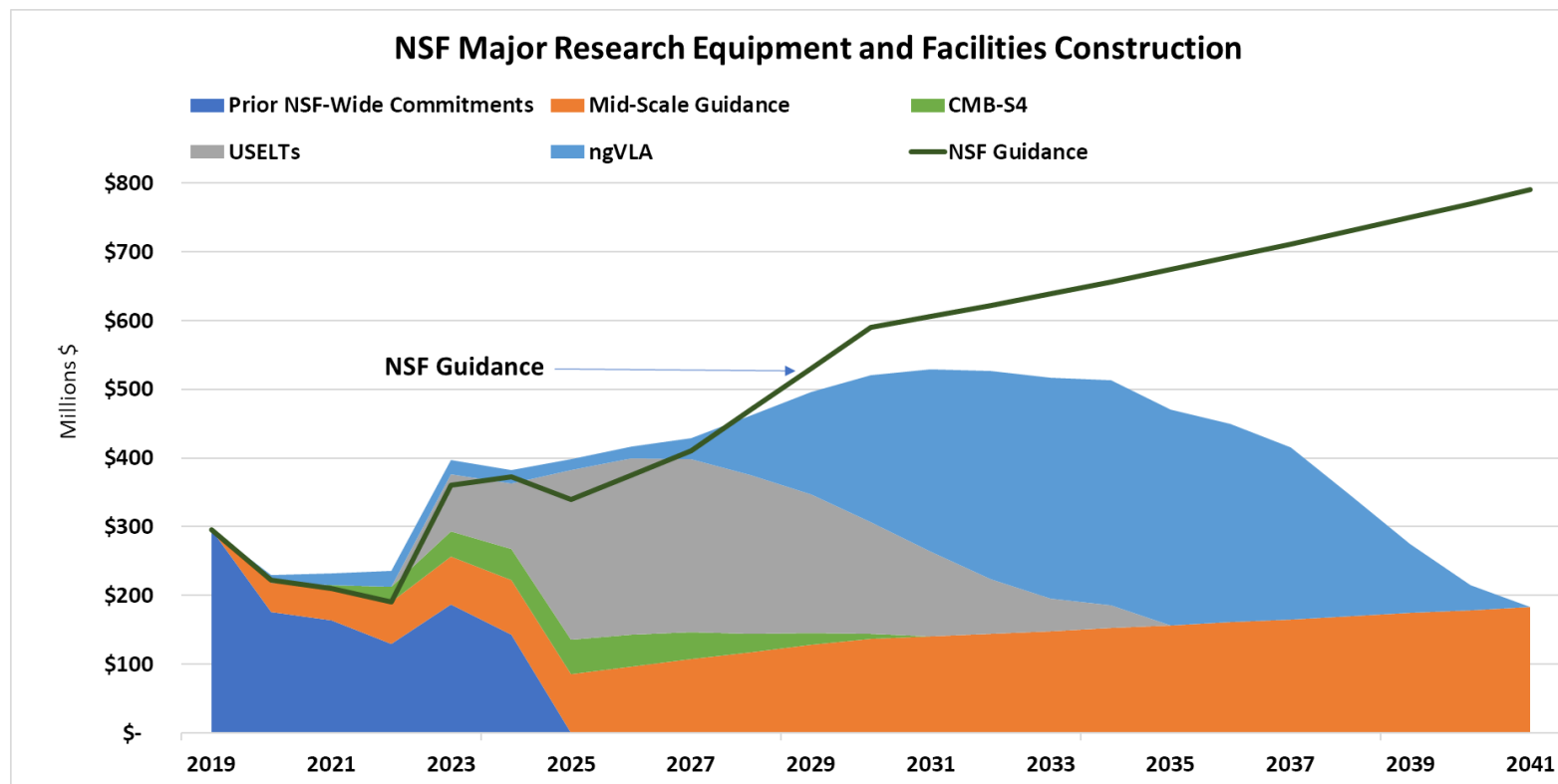
Astro2020 considered the demise of Arecibo in the context of its effect on the survey's scientific goals

- The most significant impact is Arecibo's contribution to searching for and timing pulsars that can collectively be used to detect and analyze gravitational waves
- The discovery of new pulsars is being undertaken by the Chinese FAST, and international collaborations can utilize these discoveries
- Pulsar timing needs can be accomplished by increased investment in the GBT and the JVLA

For new scientific advances beyond the reach of current facilities relevant to Astro2020 mid-scale programs and the ngVLA pave an exciting path forward

Conclusion: Much of the science relevant to the Astro2020 goals lost with Arecibo can be recovered through additional investment in existing facilities, and through international partnerships, while the new facilities recommended by this survey are realized

NSF MREFC Budget Requirements



NSF AST Budget Requirements

