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

**Science Panels (6)**
- frontier questions
- discovery areas

**Program Panels (6)**
- project assessments
  - (science, technical, cost, risk)

**SoPSI Panel**
- assess health of profession, provide actionable advice

**Steering Committee**
- assimilate panel reports, address cross-cutting areas
- integrate science program, identify key strategic questions, prioritized investment strategy within budget guidelines
Realizing the Astro2020 Program: Pathways From Foundations to Frontiers

Explore the Cosmos
- Worlds and Suns in Context
  - New Messengers and New Physics
  - Cosmic Ecosystems
- Pathways to Habitable Worlds
  - New Windows on the Dynamic Universe
  - Unveiling the Drivers of Galaxy Growth

Forge the Frontiers
- Enable U.S. community participation in ELT program
- Develop and Implement Cosmic microwave Background S4 (joint DOE)
- Begin ngVLA design, technical demonstration, construction
- Upgrade IceCube to Gen2 (NSF/PHY)
- Begin implementation of an Infrared/Optical/Ultraviolet large strategic mission for exoplanet exploration and general astrophysics after a successful maturation program

Enable Future Visions
- Develop technology for future gravitational wave upgrades and observatories (NSF/PHY)
- Commence Great Observatories Missions and Technology Maturation Program
  First entrant: IR/O/UV missions
  Second entrants: Far-IR and X-ray missions

Sustain and Balance the Science
- Augment mid-scale programs, add strategic competitions
- Implement time domain & multi-messenger program
- Compete probe missions in strategic areas of Far-IR and X-ray Astrophysics

Build the Foundations
- Expand grants to bring science and ideas to fruition
- Develop and diversify the scientific workforce
- Support data archives and curation
- Bolster theory underpinnings
- Advance crucial laboratory measurements
- Expand support for early-stage and basic technology development
- Promote scientific literacy and engage the public

Guiding Principles
- Balance the portfolio
- Broaden and optimize the science
- Advance diversity and equity
- Nurture sustainability

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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)
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
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
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.
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

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**Guiding Principles**
- Balance the portfolio
- Broaden and optimize the science
- Advance diversity and equity
- Nurture sustainability

*The National Academies of Sciences • Engineering • Medicine*
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 pursuit of science, and scientific excellence, is inseparable from the humans who animate it.”
-- Panel on the State of the Profession and Societal Impacts
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
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
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

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The National Academies of
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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

<table>
<thead>
<tr>
<th>Ground</th>
<th>Space</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Midscale Innovations Program</td>
<td>• Explorer Program Augmentation</td>
</tr>
<tr>
<td>• Daniel K. Inouye Solar Telescope</td>
<td>• James Webb Space Telescope</td>
</tr>
<tr>
<td>• Vera Rubin Observatory</td>
<td>• Roman Space Telescope</td>
</tr>
<tr>
<td></td>
<td>• US Contribution to Euclid</td>
</tr>
<tr>
<td></td>
<td>• US Contribution to Athena</td>
</tr>
<tr>
<td></td>
<td>• US Contribution to LISA</td>
</tr>
</tbody>
</table>

**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

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

- 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

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

*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.

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

**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 in 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.
**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.
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.
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 worldwide 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 area.

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.
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 achieved - 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

MREFC Observatories

- Federal Investment in U.S. ELTs for community access
- CMB-S4 (~equal share NSF/DOE)
- ngVLA Studies and Prototyping
- Review
- ngVLA Construction

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

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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

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

- resolution of 0.01-0.02 arcsec with adaptive optics
  
  \[1-2 \text{ au } @ 100 \text{ pc, } 0.8-1.6 \text{ pc } @ \text{ Virgo cluster, } 60-120 \text{ 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
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.
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
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.
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.

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

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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
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 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.
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