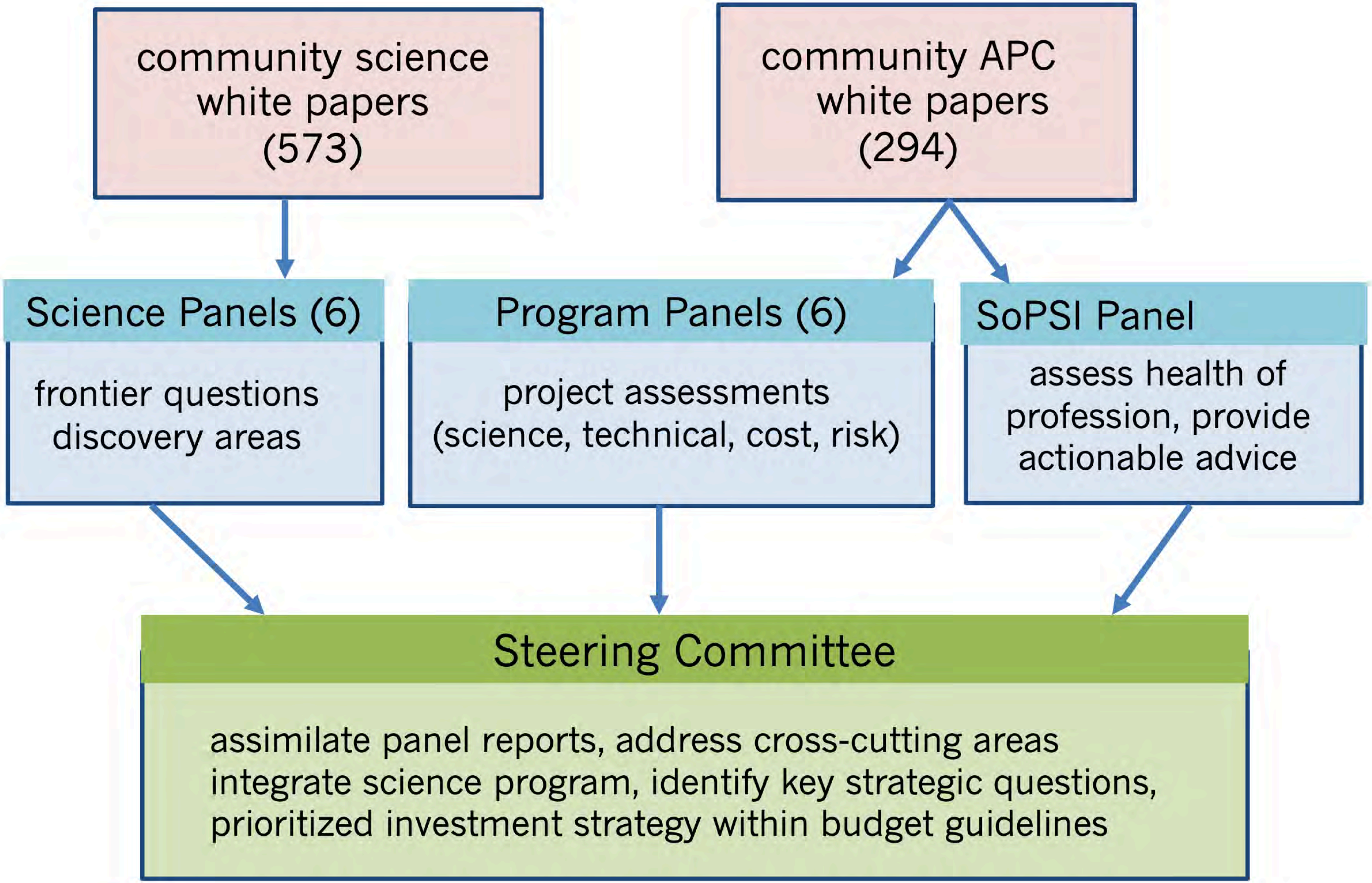
The National Academies of

SCIENCES · ENGINEERING · MEDICINE

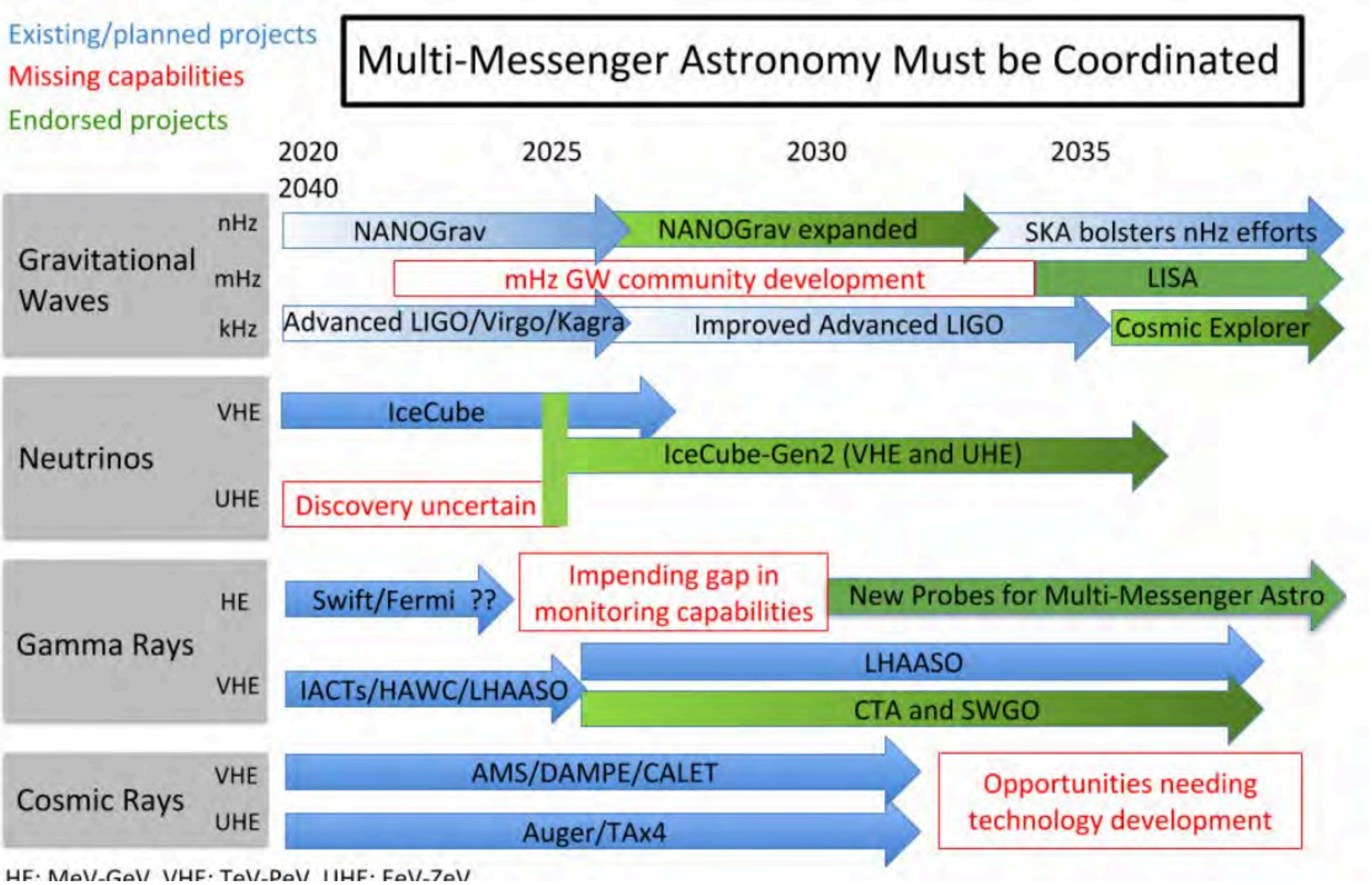
Pathways to Discovery in Astronomy and Astrophysics for the 2020s


community science white papers (573)
community APC white papers (294)
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

Bottom Line for PA

- Main Report
  - IceCube Gen 2 - endorsed but not explicitly recommended because it’s NSF Physics not Astro
  - CMB S-4 recommended
  - Tech development for next Gen Gravitational Wave Detectors
  - Recommended enhancement of Mid-scale funding
- PAG panel report
  - SWGO recommended (~$20M)
  - US participation in CTA recommended (~$40M)
  - Continued support for current generation detectors (HAWC, IceCube, LIGO (A+), Fermi)

PAG Report


Existing/planned projects
Missing capabilities
Endorsed projects
Multi-Messenger Astronomy Must be Coordinated
2020
2025
2030
2035
2040
Gravitational Waves
nHz
mHz
kHz
NANOGrav
NANOGrav expanded
SKA bolsters nHz efforts
mHz GW community development
LISA
Advanced LIGO/Virgo/Kagra
Improved Advanced LIGO
Cosmic Explorer
Neutrinos
VHE
UHE
IceCube
IceCube-Gen2 (VHE and UHE)
Discovery uncertain
Gamma Rays
HE
VHE
Swift/Fermi ??
Impending gap in monitoring capabilities
New Probes for Multi-Messenger Astro
LHAASO
IACTs/HAWC/LHAASO
CTA and SWGO
Cosmic Rays
VHE
UHE
AMS/DAMPE/CALET
Auger/TAx4
Opportunities needing technology development
HE: MeV-GeV, VHE: TeV-PeV, UHE: EeV-ZeV

PAG Report

BOX L.2 Multi-messenger Program for the 2020s Endorsed by the PAG Panel

- **Large-scale:** IceCube-Gen2 Neutrino Observatory (NSF MREFC program), $345 million.
- **Medium-scale, Gravitational Wave Program:** Investment in three gravitational-wave bands, with support for technology developments towards Cosmic Explorer (NSF), $66 million; increased sensitivity for NANOGrav (NSF), $118 million; and increased U.S. participation in LISA data analysis and science (NASA), $100 million.
- **Medium-scale, Gamma-Ray Program:** Investment in a gamma-ray program both in space, with a new NASA Probe-scale mission, in the range $0.5 to 1.5 billion; and on the ground, with NSF support for participation in the international CTA and SWGO efforts (NSF), $70M and $20M, respectively.
- **Small-scale:** Technology development, plus theory and computation, to enable breakthroughs in future capabilities.

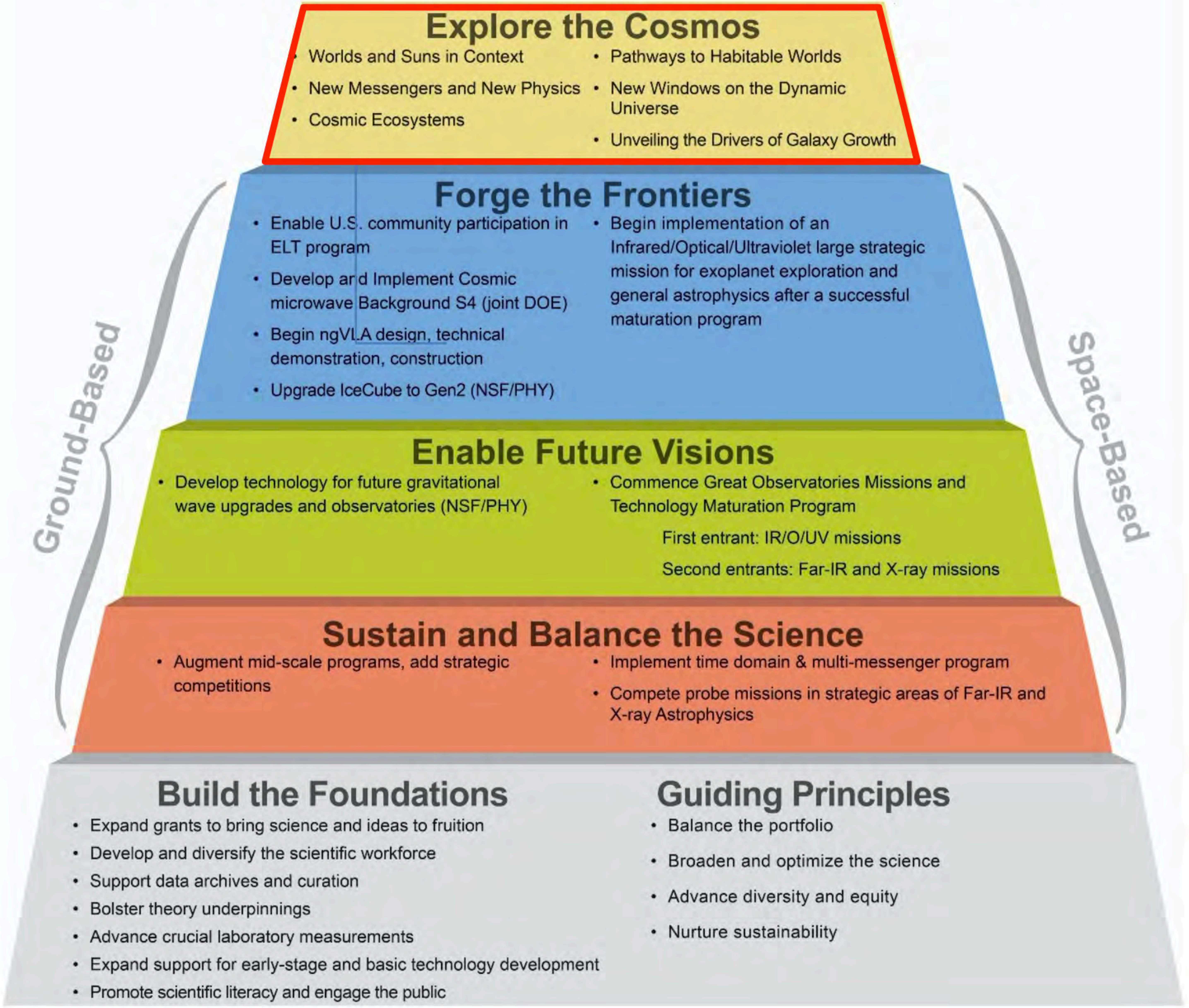
PAG Report

- IceCube-Gen2 (Page L-9) -
  - TRACE - found that the programmatic risk (science and costs) and schedule risk of IceCube-Gen2 are both medium-to-low. The TRACE cost estimate is 20 percent higher than the project-estimated cost
  - Radio should be a part of the project vs other radio projects
- Cosmic Explorer (40Km LIGO) (Page L-13)
  - Design study, at the level of $65.7 million in FYs 2020 to 2025: $33 million for two engineering studies, $20 million for a prototype CE chamber, and the remainder for other upgrades
- Probe-Scale Mission for Multi-Messenger Sources (Page L-16)
  - A Probe-scale mission dedicated to the study of multi-messenger sources would provide wide-field multiwavelength observations, at keV-MeV-GeV energies, at the sensitivities needed to achieve multi-messenger discoveries..

PAG Report

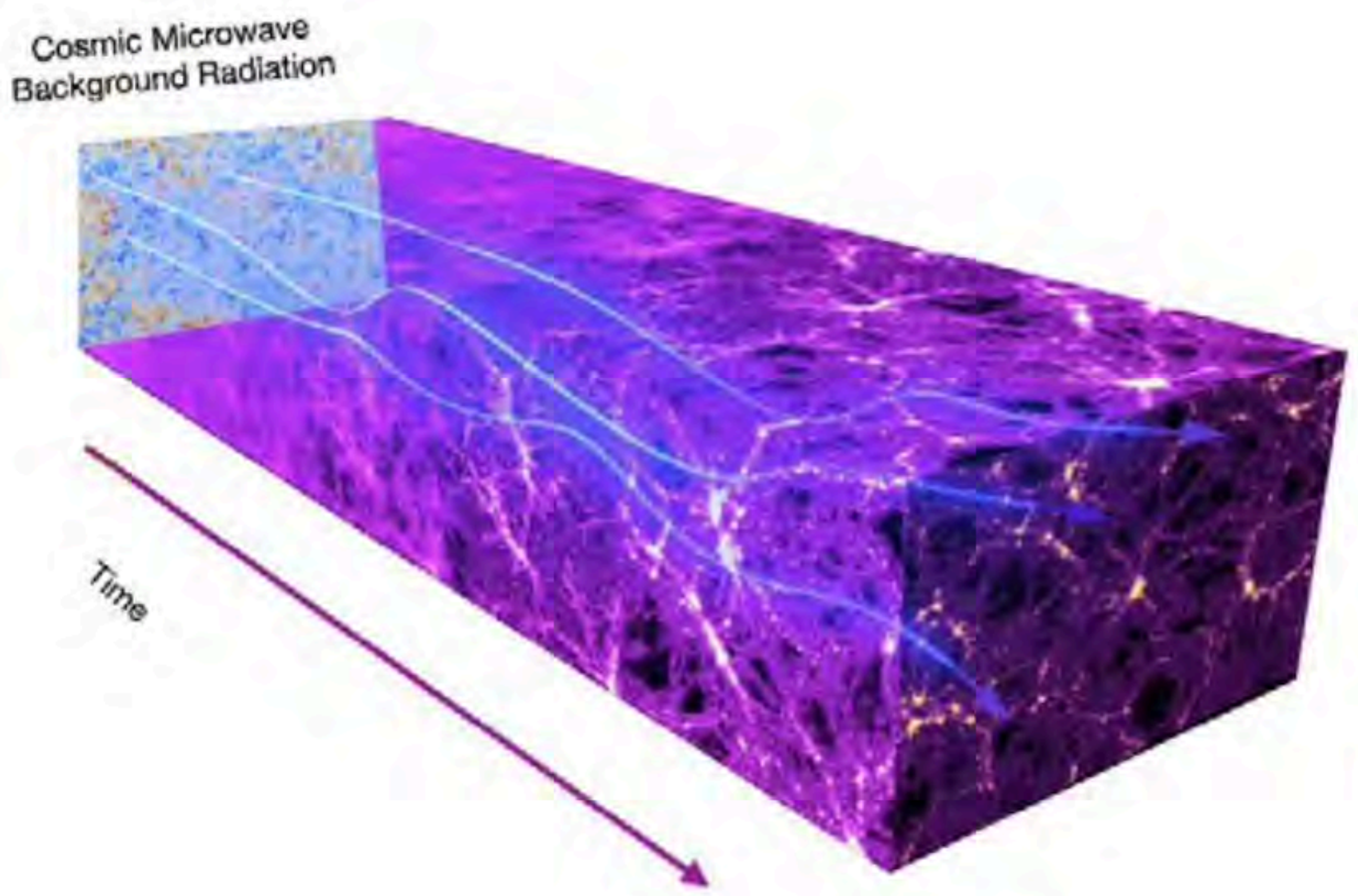
- U.S. Participation in the Cherenkov Telescope Array (CTA) and the Southern Wide- field Gamma-ray Observatory (SWGO) (Page L-17)
  - The combination of CTA and LHAASO/SWGO provides an integrated observational capability that maximizes the scientific opportunities for all-sky multi-messenger astronomy. The success of the broad U.S. program in multi-messenger astrophysics would be greatly enhanced by access to these world-leading facilities. The development of these facilities depends critically on decades of U.S. investment that cannot be capitalized upon without continued U.S. involvement.

Realizing the Astro2020 Program: Pathways From Foundations to Frontiers



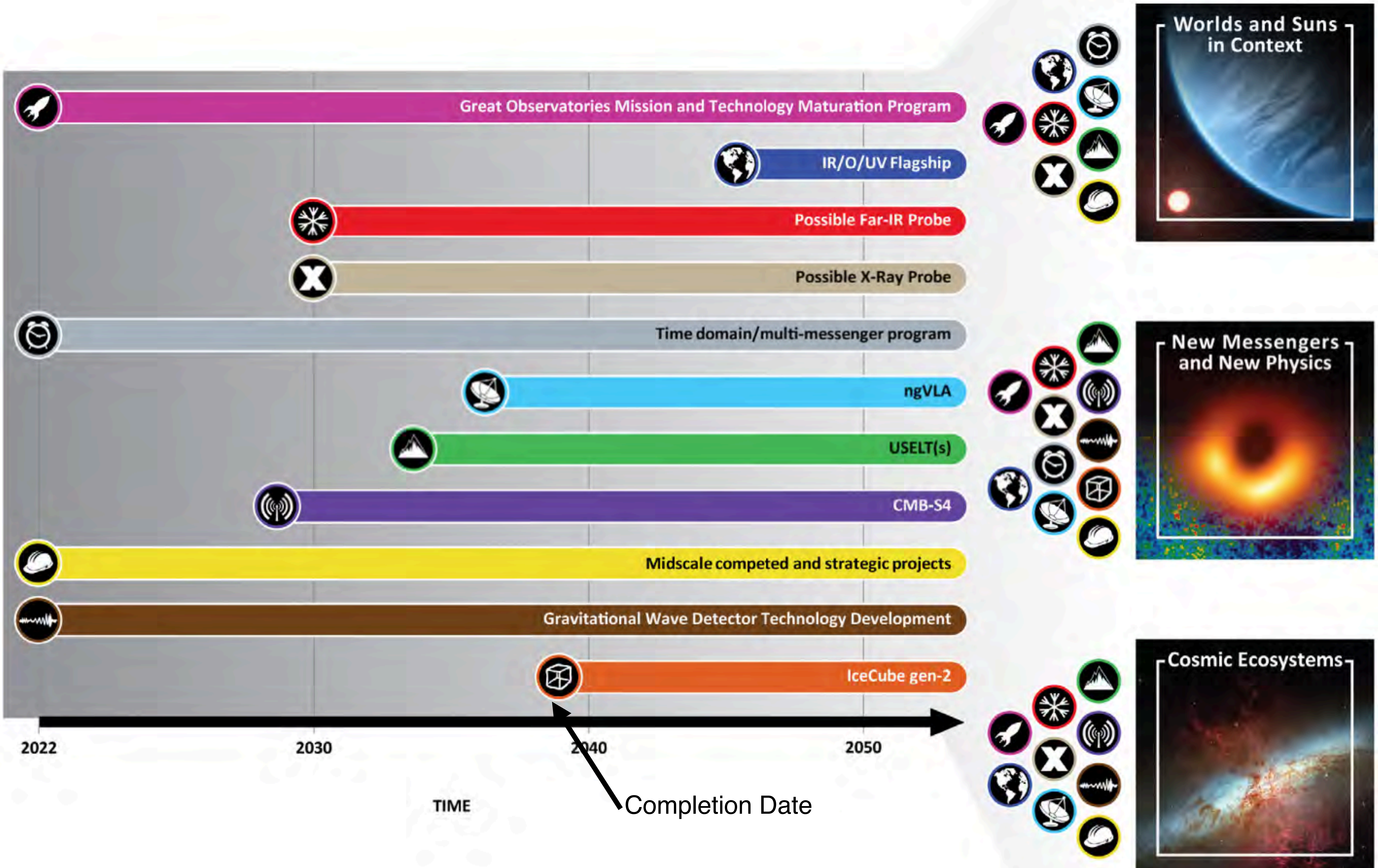
Science Theme: New Messengers and New Physics

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:

- The tremendous progress in observations of the Cosmic Microwave Background
- Time domain surveys in optical and radio that have uncovered an astounding array of transient phenomena
- The discovery of black hole-black hole mergers and neutron star – neutron star mergers with LIGO, and the detection of electromagnetic counterparts
- Ice Cube's detection of high energy neutrinos of astrophysical origin


Great Observatories Mission and Technology Maturation Program
IR/O/UV Flagship
Possible Far-IR Probe
Possible X-Ray Probe
Time domain/multi-messenger program
ngVLA
USELT(s)
CMB-S4
Midscale competed and strategic projects
Gravitational Wave Detector Technology Development
IceCube gen-2
2022
2030
2040
2050
TIME
Completion Date
Worlds and Suns in Context
New Messengers and New Physics
Cosmic Ecosystems

IceCube Gen 2

- Observations of high-energy neutrinos enable astrophysical advances in the study of some of the most energetic phenomena in the universe. In particular, the most extreme accelerators in the universe produce huge luminosities of charged particles and accompanying gamma rays and neutrinos, with per-particle energies ranging up to the TeV-PeV range, and sometimes higher. The IceCube observations of the diffuse neutrino flux suggest a dominant population of sources that are gamma-ray obscured, showing that neutrino observations are essential for understanding and studying such energetic phenomena.
-

IceCube Gen 2

- A large-scale MREFC investment by NSF in IceCube-Gen2 would greatly enhance this observatory's capabilities. "IceCube-Gen2 will increase the annual rate of observed cosmic neutrinos by a factor of ten compared to IceCube, and will be able to detect sources five times fainter than its predecessor. Furthermore, through the addition of a radio array, IceCube-Gen2 will extend the energy range by several orders of magnitude compared to IceCube."15 The primary scientific objectives for this upgrade are to resolve the bright, hard-spectrum TeV-PeV diffuse neutrino background into discrete sources, make the first detections at higher neutrino energies, and identify neutrino emission with specific astrophysical sources in order to gain insight into sites of extreme particle acceleration. The PAG panel, supported by a TRACE study of the observatory upgrade, finds that the project is well-understood, uses mature technology, and with a cost of $345 million in FY2020 is feasible to implement this decade. This survey was not charged to make project recommendations to NSF PHY; however, we endorse the observatory as important to key astrophysics scientific objectives of this survey.

IceCube Gen 2

- Observations of high-energy neutrinos enable astrophysical advances in the study of some of the most energetic phenomena in the universe. The IceCube-Gen2 would greatly enhance the capabilities relative to IceCube, would be able to resolve the bright, hard-spectrum TeV-PeV diffuse neutrino background into discrete sources, and would make the first detections at higher neutrino energies. Multi-messenger astrophysics is a major theme of this report, and the survey endorses the IceCube-Gen2 observatory as important to many key survey scientific objectives. Because it is funded by NSF Physics, it is beyond the survey’s charge to recommend this investment
- 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.

TABLE 7.2 New Medium and Large Projects, Activities and Augmentations (2023–2033)

<table>
<tr><th colspan="2">The Frontiers: Major New Projects (Space)</th></tr>
<tr><td colspan="2">IR/O/UV Large Strategic Mission</td></tr>
<tr><td colspan="2">IR/O/UV telescope for exoplanet characterization and general astronomy. Mission-specific funding to begin mid-late decade after mission and technology maturation program</td></tr>
<tr><td colspan="2"></td></tr>
<tr><td colspan="2">Total implementation and operations cost (5 years) estimated at $11 billion[a]</td></tr>
<tr><td colspan="2"></td></tr>
<tr><td colspan="2">Enabling Programs (Space)</td></tr>
<tr><td colspan="2">Great Observatories Mission and Technology Maturation Program</td></tr>
<tr><td colspan="2">Program to co-mature large strategic missions and technologies. First entrant: IR/O/UV observatory, Far-IR and high resolution X-ray observatories recommended to enter in second half of the decade</td></tr>
<tr><td colspan="2"></td></tr>
<tr><td colspan="2">Sustaining Programs (Space)</td></tr>
<tr><td>Time-Domain Program (highest priority)</td><td>Probe Line</td></tr>
<tr><td>A program of 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.</td><td>Competed line of cost-capped probe missions to bridge the gap between Explorers and strategic missions; focused on gaps in science and wavelength capabilities– this decade Far-IR and an X-ray complement to Athena</td></tr>
<tr><td>Notional cost: $500 million–$800 million over the decade</td><td>$1.5 billion/mission, cadence of approx. one/decade</td></tr>
</table>

The Frontiers: Major New Projects (Ground)		
Extremely Large Telescope (ELT) Program (highest priority)	*CMB-S4*	*The ngVLA*
Federal investment in the U.S.-ELT program for the U.S. community	Stage 4 Cosmic Microwave Background Observatory	Design, cost trade studies and prototyping to prepare for construction, which could begin by the end of the decade
$1.7 billion NSF share of $5.1 billion project	NSF share $273 million, DOE share $387 million	$2.5 billion NSF share of $3.2 billion project

Sustaining Projects (Ground)
Mid-scale Augmentation: Open, Strategic and Sustaining Instrumentation Calls
Augmentation to mid-scale programs; inclusion of *open calls* that tap into the creativity of the entire community, *strategic* calls that maintain scientific breadth and foundational instrumentation capacity, and *sustaining instrumentation calls* to optimize the return on the investment in existing facilities. Strategic calls for the coming decade are in time domain astrophysics (highest priority), radio instrumentation, and highly-multiplexed optical spectroscopy.

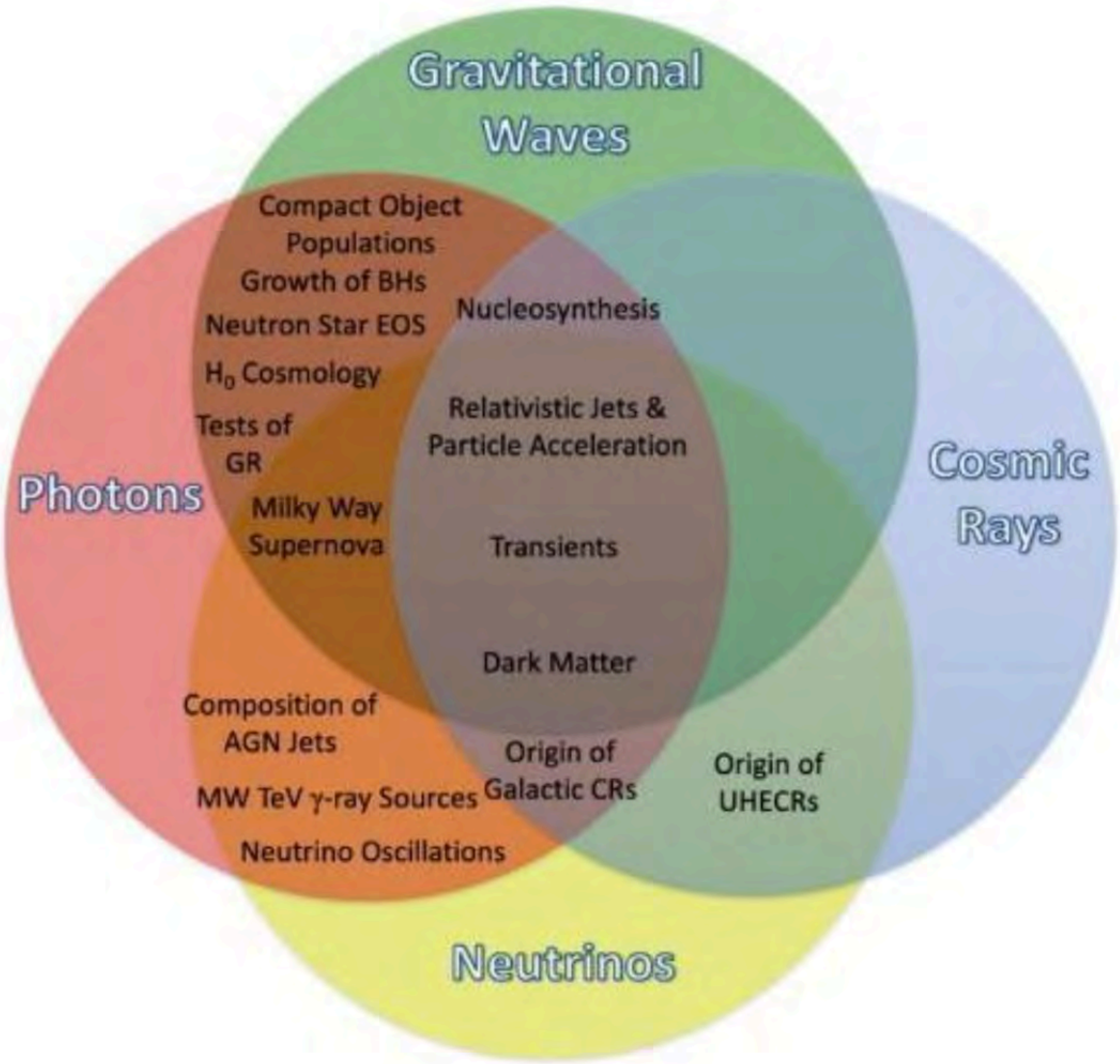
Programs and Facilities Funded through NSF Physics	
Technology Development for Future Gravitational Wave Detectors	*IceCube-Gen2 Neutrino Detector*
Technology development for LIGO upgrades, such as Voyager, and for next generation observatories such as Cosmic Explorer.	Upgrades to the IceCube high-energy neutrino detector

[a] Project costs are in FY20$

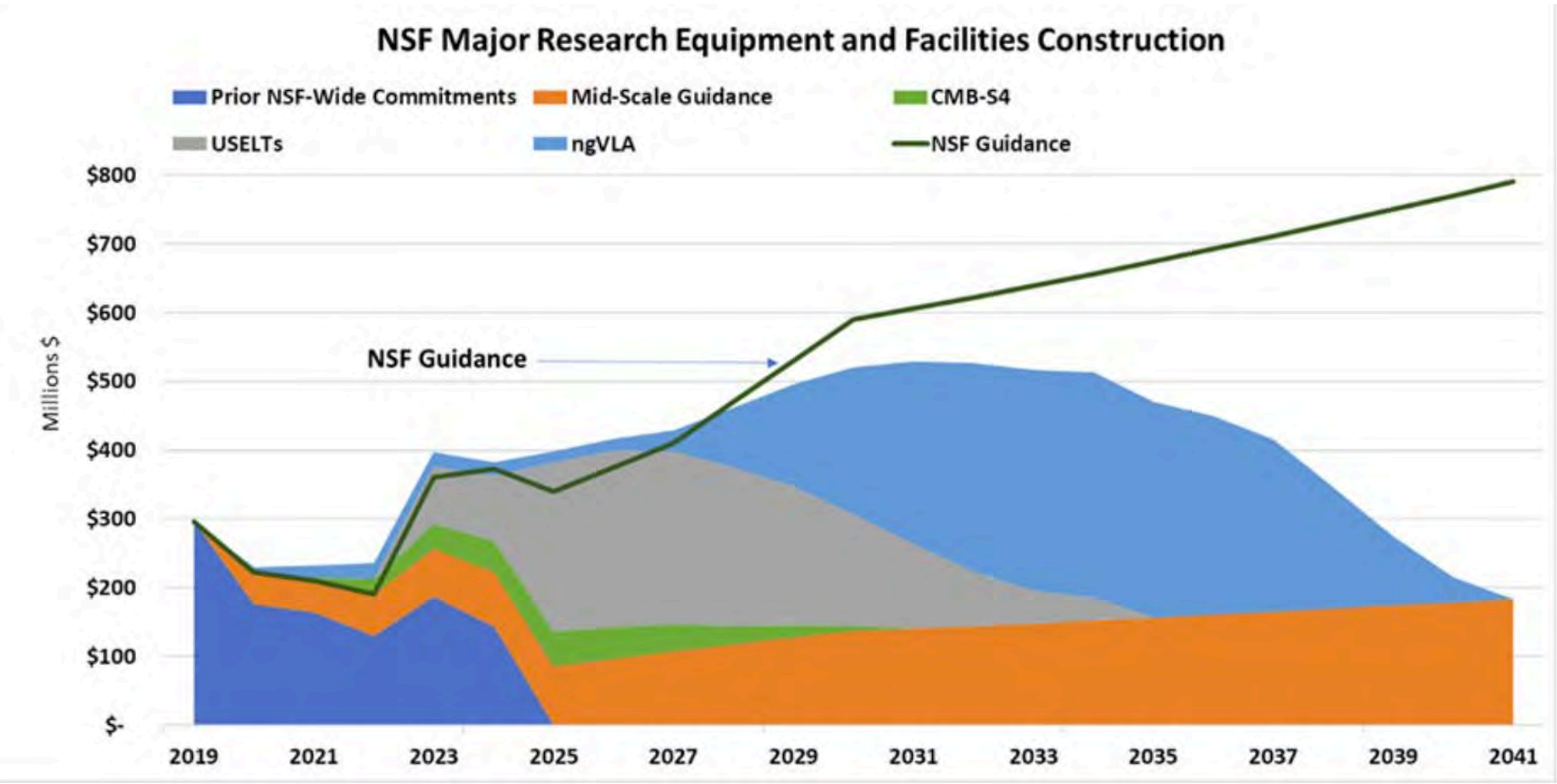
Mid-Scale

- Mid-scale programs across the entire range of scales (~$4 million–$120 million) are vital to the enabling foundation of astronomy research, and for capitalizing and amplifying return on our investment in major facilities.
- The survey received a large number of APC white papers for midscale projects, concentrated at the higher end of the cost range (~$100 million) that were evaluated by the OIR, Panel on Particle Astrophysics and Gravitation, and RMS program panels. All three panels provided multiple superb examples of compelling mid-scale ideas in this cost range. The panels all emphasize the high science value, cost effectiveness, and agility of mid-scale programs at all cost levels to address new science opportunities throughout the decade. Across the range of project scales, mid-scale programs are essential both for achieving the broad range of science prioritized by the survey, for addressing targeted strategic goals, and for ensuring that existing facilities have modern instrumentation to maximize their scientific productivity and community access

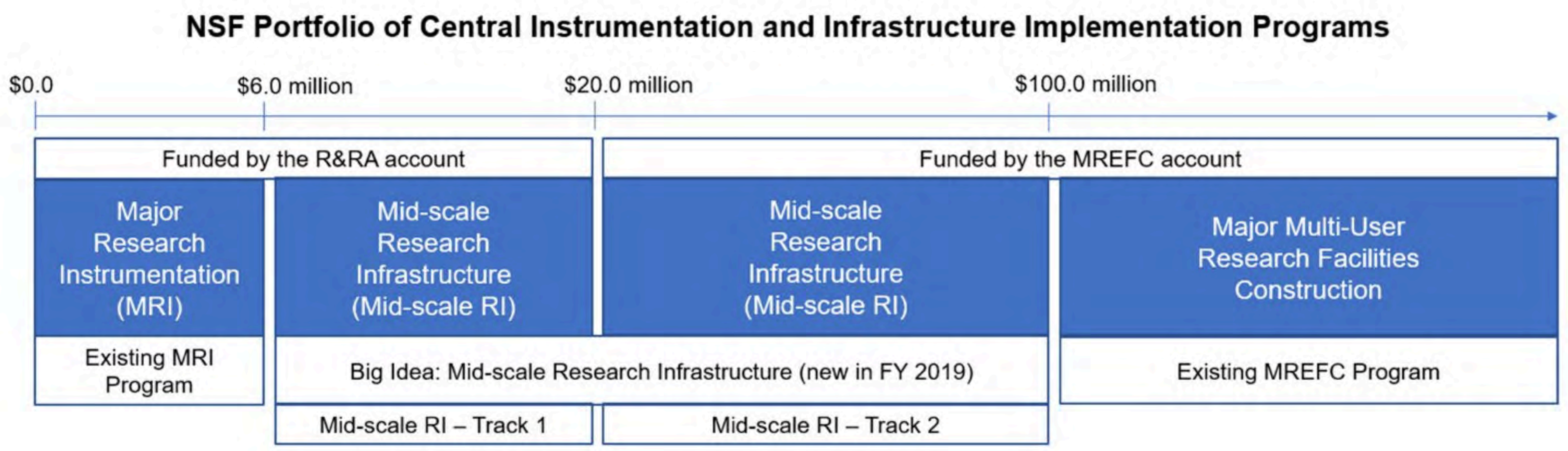
Multi-Messenger Astronomy



Major Instrumentation (Astro 2020)



NSF Budget


NSF Portfolio of Central Instrumentation and Infrastructure Implementation Programs
$0.0
$6.0 million
$20.0 million
$100.0 million
Funded by the R&RA account
Funded by the MREFC account
Major Research Instrumentation (MRI)
Mid-scale Research Infrastructure (Mid-scale RI)
Mid-scale Research Infrastructure (Mid-scale RI)
Major Multi-User Research Facilities Construction
Existing MRI Program
Big Idea: Mid-scale Research Infrastructure (new in FY 2019)
Existing MREFC Program
Mid-scale RI – Track 1
Mid-scale RI – Track 2

NSF Budget

MREFC Account Funding, by Project

(Dollars in Millions)

	FY 2020 Actual	FY 2021 Estimate[1]	FY 2022 Request	FY 2023 Estimate	FY 2024 Estimate	FY 2025 Estimate	FY 2026 Estimate	FY 2027 Estimate
Antarctic Infrastructure Recapitalization	$48.78	$90.00	$90.00	$60.00	$60.00	TBD	TBD	TBD
DKIST	-	-	-	-	-	-	-	-
HL-LHC Upgrade	33.00	33.00	36.00	33.00	18.00	-	-	-
Mid-scale Research Infrastructure[2]	-	76.25	76.25	76.25	76.25	76.25	76.25	76.25
NEON	0.74	-	-	-	-	-	-	-
RCRV	25.00	-	5.00	15.00	-	-	-	-
Vera C. Rubin Observatory	46.35	40.75	40.75	15.00	-	-	-	-
Dedicated Construction Oversight	0.97	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Total	**$154.84**	**$241.00**	**$249.00**	**$200.25**	**$155.25**	**$77.25**	**$77.25**	**$77.25**

[1] A total of $129.35 million was carried forward from FY 2020 into FY 2021: $29.71 million for AIMS, $9.40 million for DKIST, $65.0 million for Mid-scale RI, $10.97 million for RCRV, $10.07 million for the Rubin Observatory, and $780,000 for Dedicated Construction Oversight.

Space

Large Strategic Missions: Background

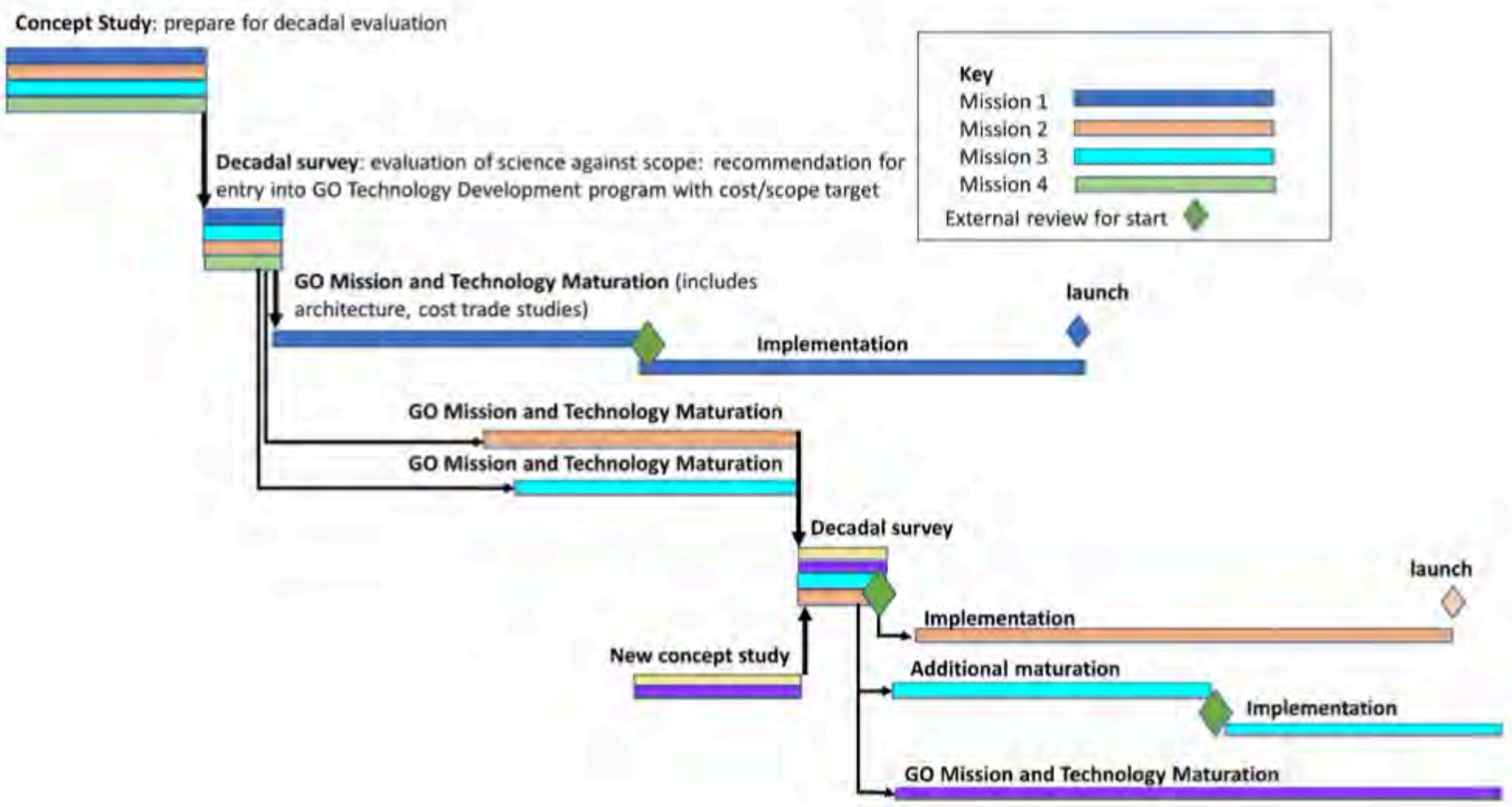
Mission	Waveband	TRACE Cost Est. (FY20, B$)	TRACE development time**
LUVOIR-B	UV/O/IR	17	20
HabEx 4-H	UV/O/IR	10.5	18
Lynx	X-ray	9	18.5
Origins	Far-IR	10.6	15.5

**Minimum, assuming immediate start and optimum budget profile

Space

- Great Observatories Mission and Technology Maturation Program
  - Accelerating the cadence of strategic missions will require
  - limiting their scope through careful selection of capabilities
  - significant and coordinated investment prior to a decadal survey recommendation to proceed with mission development
  - This rephasing 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
  -

Space



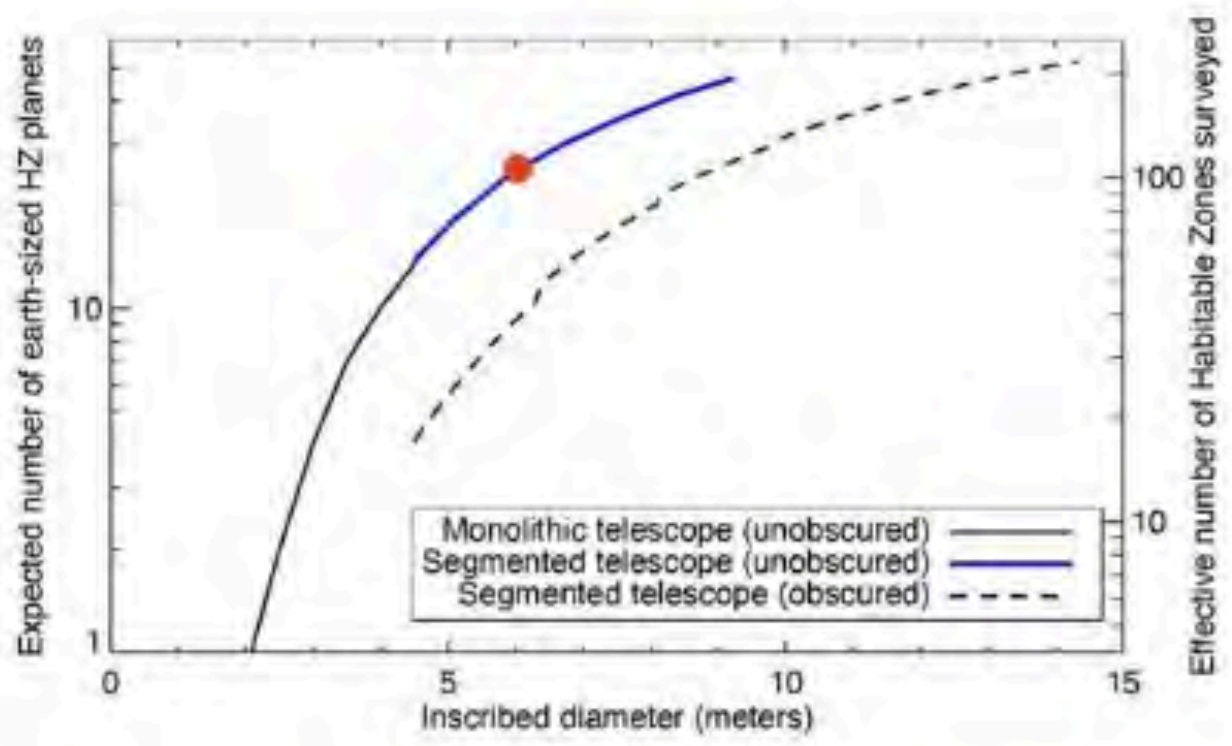
Concept Study: prepare for decadal evaluation
Key
Mission 1
Mission 2
Mission 3
Mission 4
External review for start
Decadal survey: evaluation of science against scope: recommendation for entry into GO Technology Development program with cost/scope target
GO Mission and Technology Maturation (includes architecture, cost trade studies)
launch
Implementation
GO Mission and Technology Maturation
GO Mission and Technology Maturation
Decadal survey
launch
Implementation
New concept study
Additional maturation
Implementation
GO Mission and Technology Maturation

Space

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

Space

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

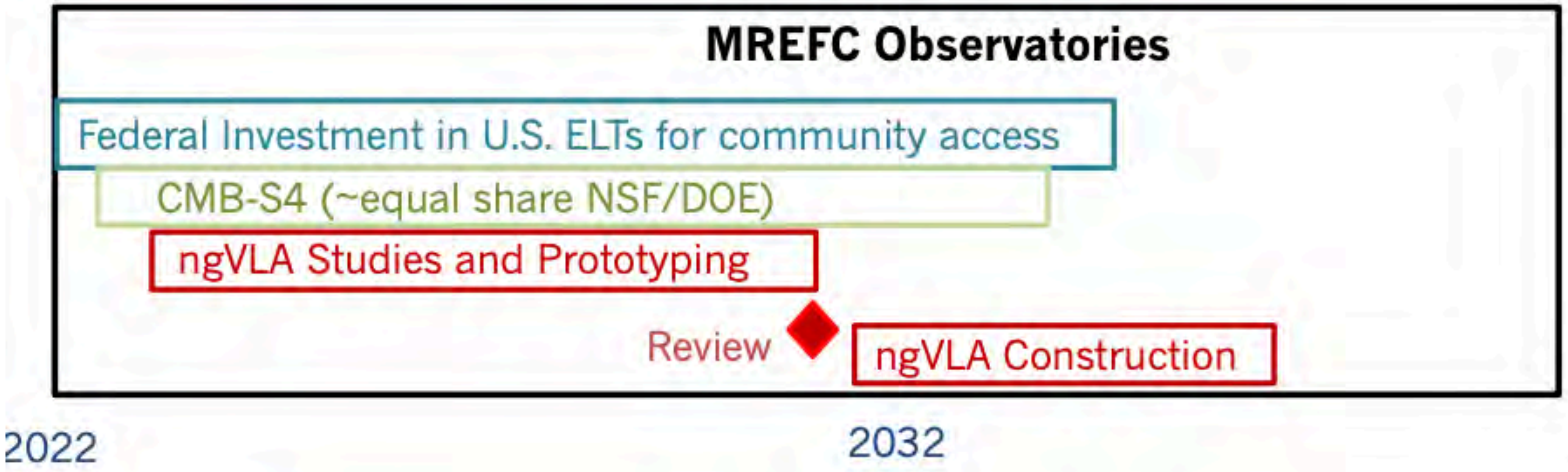
Estimated total Program cost: $500 – 800 M added over the decade (above current Explorer program)

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

Ground

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

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

Ground

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

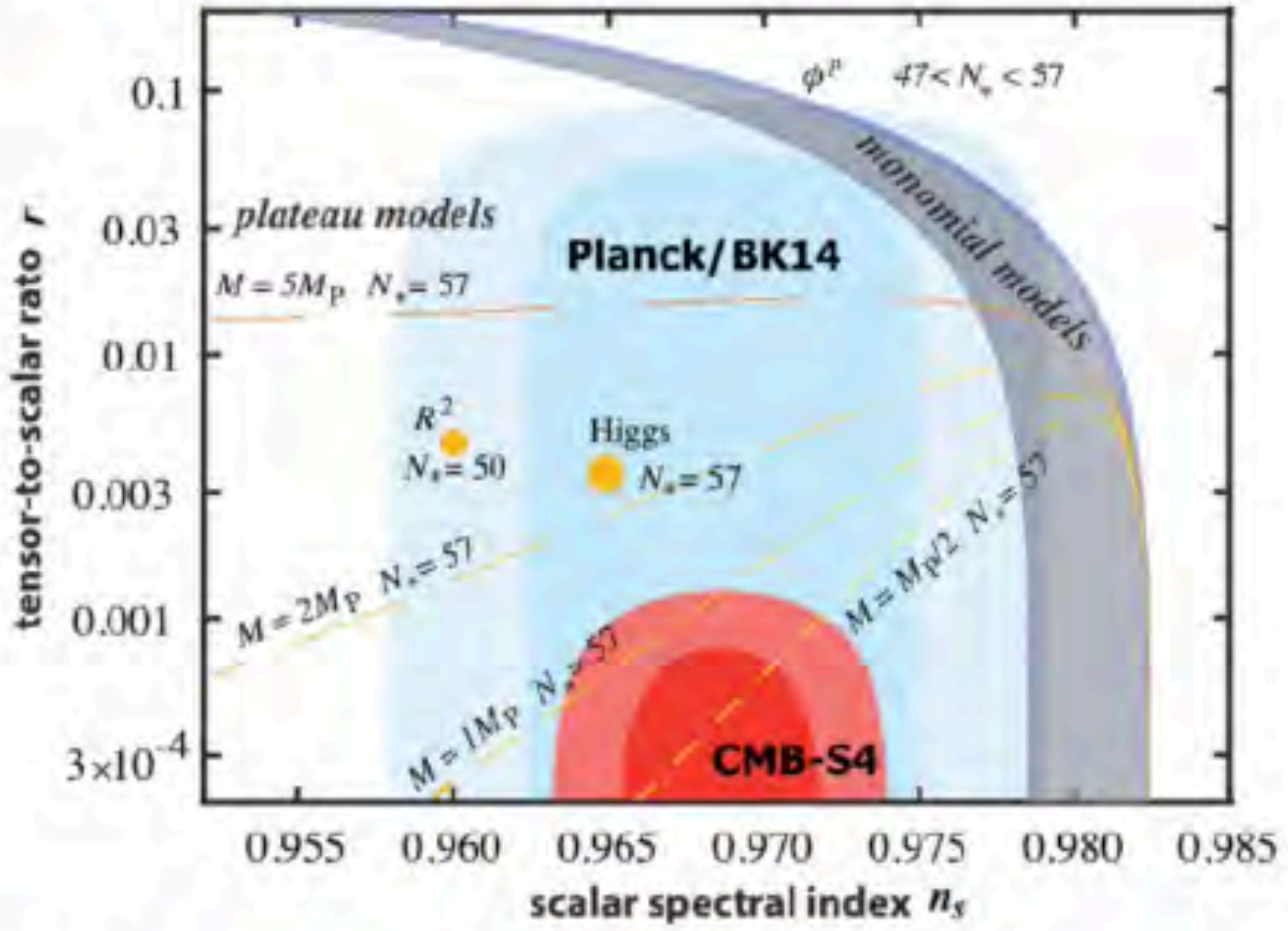
Ground

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

Ground

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

Ground

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.