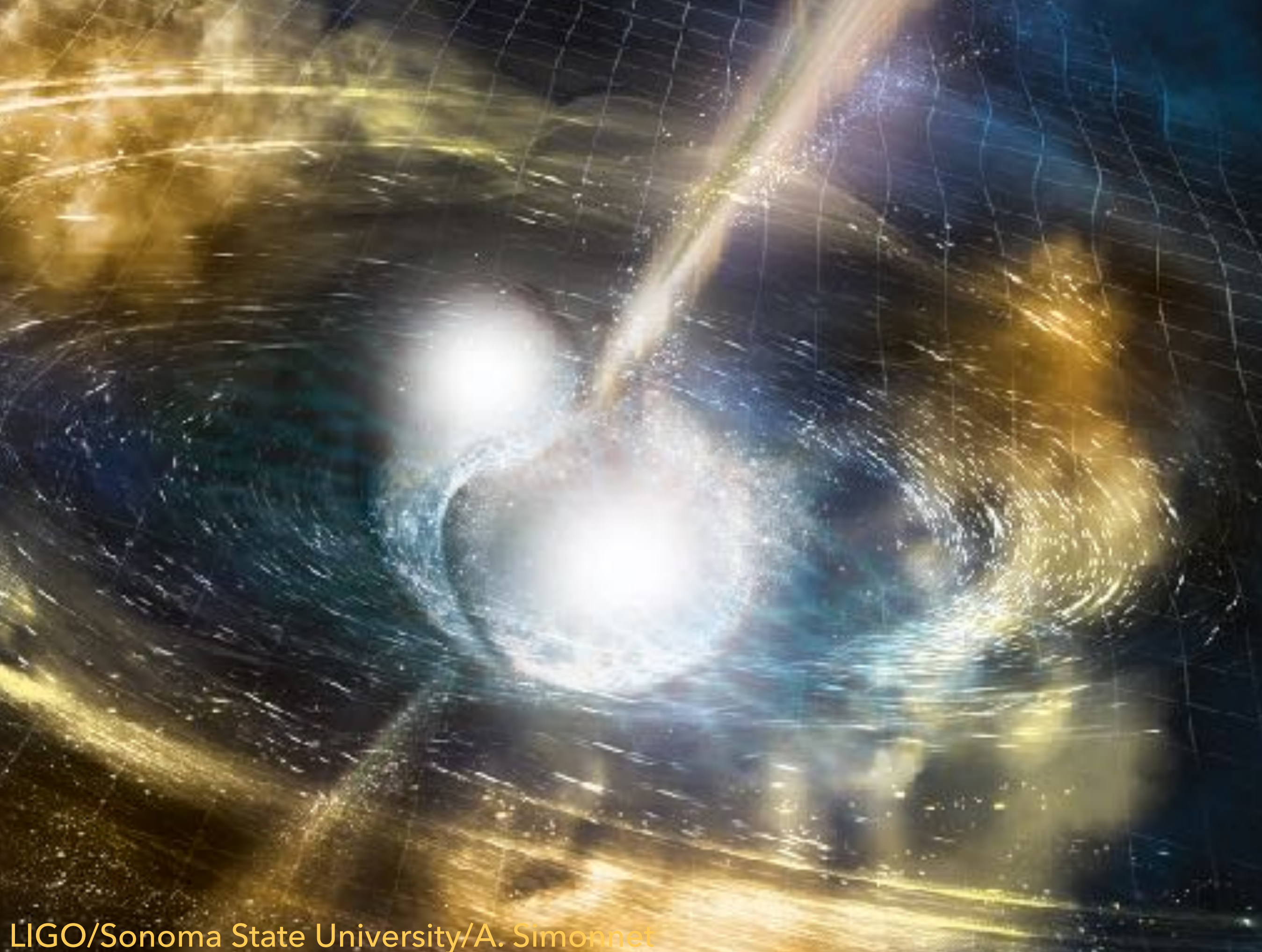
Astro2020


LIGO/Sonoma State University/A. Simonnet


LIGO

NATIONAL ACADEMY
OF SCIENCES

Daniel Holz
University of Chicago

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

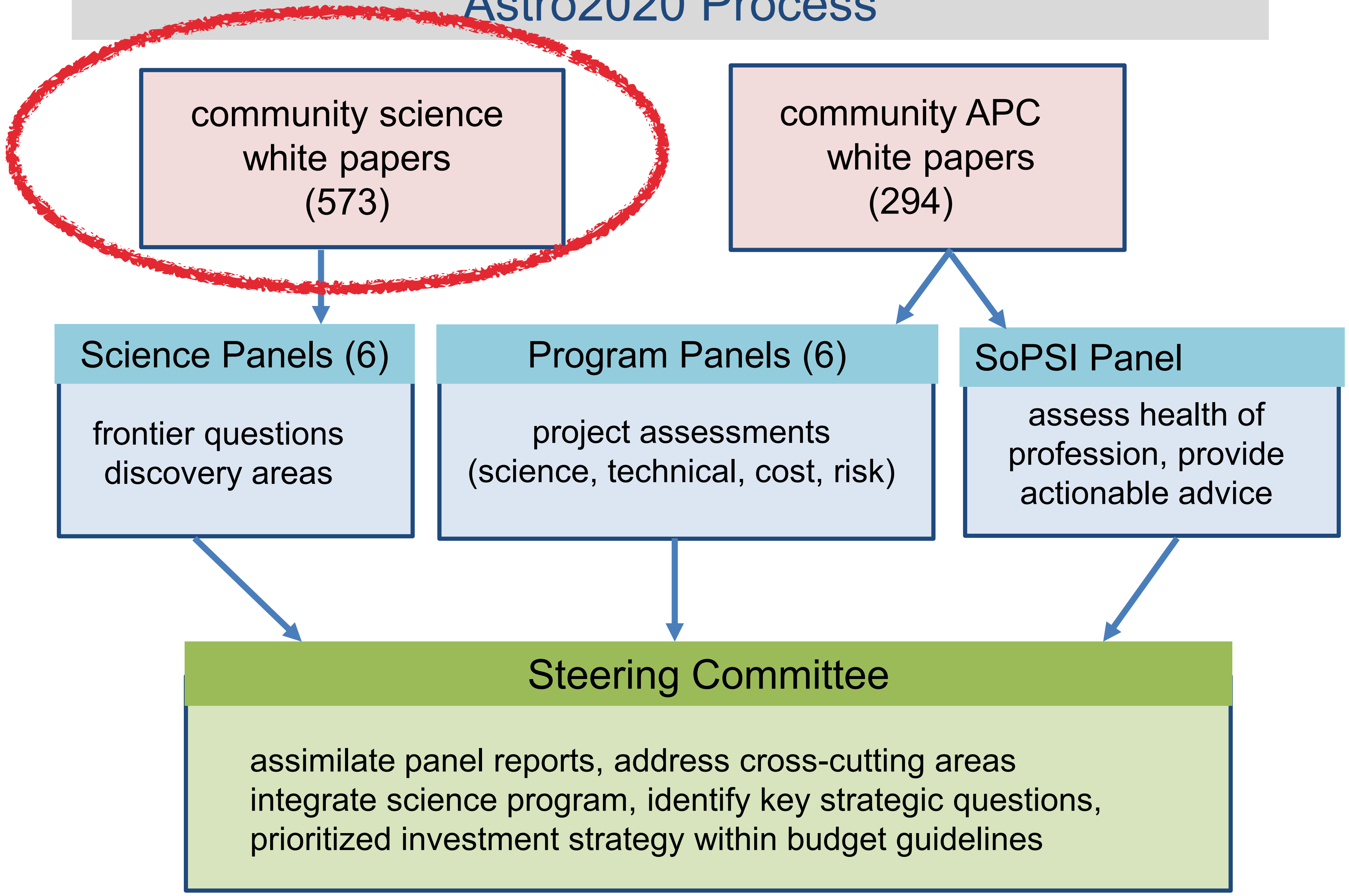
But a plan also needs to be realistic, responsible, achievable, sustainable

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

Astro2020 Process



White papers

- 572 science papers on all subjects
- 294 papers on Activities, Projects, and State of the Profession Considerations (APC)
  - Available at nationalacademies.org and ADS, etc.
- 47 science papers including “gravitational wave” in abstract

1 2019astro2020T.570Y 2019/05
Exploring Dark Energy and Gravity in Space Laboratories
Yu, Nan; Chiow, Sheng-wey; Cutler, Curt J. and 13 more

2 2019astro2020T.318B 2019/05 cited: 2
Detecting Offset Active Galactic Nuclei
Blecha, Laura; Brisken, Walter; Burke-Spolaor, Sarah and 5 more

3 2019BAAS...51c.553V 2019/05
Multi-messenger and transient astrophysics with very-high-energy gamma rays
Vandenbroucke, Justin; Santander, Marcos

4 2019BAAS...51c.490K 2019/05 cited: 7
Multi-Messenger Astrophysics With Pulsar Timing Arrays
Kelley, Luke; Charisi, M.; Burke-Spolaor, S. and 29 more

5 2019BAAS...51c.461L 2019/05
The Virtues of Time and Cadence for Pulsars and Fast Transients
Lynch, Ryan; Brook, Paul; Chatterjee, Shami and 7 more

6 2019BAAS...51c.455M 2019/05
The state of gravitational-wave astrophysics in 2020
McWilliams, Sean; Caldwell, Robert; Holley-Bockelmann, Kelly and 2 more

7 2019BAAS...51c.453H 2019/05
Gravitational Waves in the Mid-band with Atom Interferometry
Hogan, Jason; Berti, Emanuele; Chattopadhyay, Swapan and 16 more

8 2019BAAS...51c.452S 2019/05
Gravitational wave astronomy with LIGO and similar detectors in the next decade
Shoemaker, David; LIGO Scientific Collaboration

9 2019BAAS...51c.447C 2019/05 cited: 2
Gravitational Waves, Extreme Astrophysics, and Fundamental Physics with Precision Pulsar Timing
Cordes, James; McLaughlin, Maura A.; Nanograv Collaboration

10 2019BAAS...51c.437S 2019/05
Physics Beyond the Standard Model With Pulsar Timing Arrays
Siemens, Xavier; Hazboun, Jeffrey; Baker, Paul T. and 5 more

11 2019BAAS...51c.432C 2019/05
The Gravitational View of Massive Black Hole Mergers
Colpi, Monica; Holley-Bockelmann, K.; Bogdanović, T. and 16 more

12 2019BAAS...51c.382M 2019/05
Mid-Frequency-Band Space Gravitational Wave Observations for the 2020 Decade
Michelson, Peter; Byer, Robert L.; Buchman, Saps (Sasha) and 3 more

13 2019BAAS...51c.361C 2019/05
Joint Gravitational Wave and Electromagnetic Astronomy with LIGO and LSST in the 2020's
Cowperthwaite, Philip; Chen, Hsin-Yu; Margalit, Ben and 4 more

14 2019BAAS...51c.338S 2019/05 cited: 16
Probing the origin of our Universe through cosmic microwave background constraints on gravitational waves
Shandera, Sarah; Adshead, Peter; Amin, Mustafa and 16 more

15 2019BAAS...51c.336T 2019/05 cited: 4
Supermassive Black-hole Demographics &Environments With Pulsar Timing Arrays
Taylor, Stephen; Burke-Spolaor, Sarah; Baker, Paul T. and 7 more

16 2019BAAS...51c.331H 2019/05
Tracking the time-variable Millimeter-wave sky with CMB experiments
Holder, Gilbert; Berger, Edo; Bleem, Lindsey and 3 more

17 2019BAAS...51c.310P 2019/05 cited: 12
Gravitational wave cosmology and astrophysics with large spectroscopic galaxy surveys
Palmese, Antonella; Graur, Or; Annis, James T. and 12 more

18 2019BAAS...51c.304Z 2019/05
X-ray binaries: laboratories for understanding the evolution of compact objects from their birth to their mergers
Zezas, Andreas; Andrews, Jeffrey; Antoniou, Vallia and 9 more

19 2019BAAS...51c.295F 2019/05 cited: 3
Gravity and Light: Combining Gravitational Wave and Electromagnetic Observations in the 2020s
Foley, Ryan; Alexander, K. D.; Andreoni, I. and 110 more

20 2019BAAS...51c.276S 2019/05 cited: 15
Multimessenger universe with gravitational waves from binary systems
Sathyaprakash, Bangalore; Bailes, Matthew; Kasliwal, Mansi M. and 9 more

21 2019BAAS...51c.261L 2019/05 cited: 5
Radio Pulsar Populations
Lorimer, Duncan; Pol, Nihan; Rajwade, Kaustubh and 9 more

22 2019BAAS...51c.260B 2019/05 cited: 2
Gamma Rays and Gravitational Waves
Burns, Eric; Zhu, S.; Hui, C. M. and 28 more

23 2019BAAS...51c.251S 2019/05 cited: 42
Extreme gravity and fundamental physics
Sathyaprakash, Bangalore; Buonanno, Alessandra; Lehner, Luis and 26 more

24 2019BAAS...51c.248S 2019/05 cited: 15
Cosmology and the early universe
Sathyaprakash, Bangalore; Belgacem, Enis; Bertacca, Daniele and 14 more

25 2019BAAS...51c.247F 2019/05 cited: 2
AGN (and other) astrophysics with Gravitational Wave Events
Ford, K. E. Saavik; Bartos, Imre; McKernan, Barry and 14 more

26 2019BAAS...51c.242K 2019/05 cited: 12
Deeper, Wider, Sharper: Next-Generation Ground-based Gravitational-Wave Observations of Binary Black Holes
Kalogera, Vicky; Berry, Christopher P. L.; Colpi, Monica and 10 more

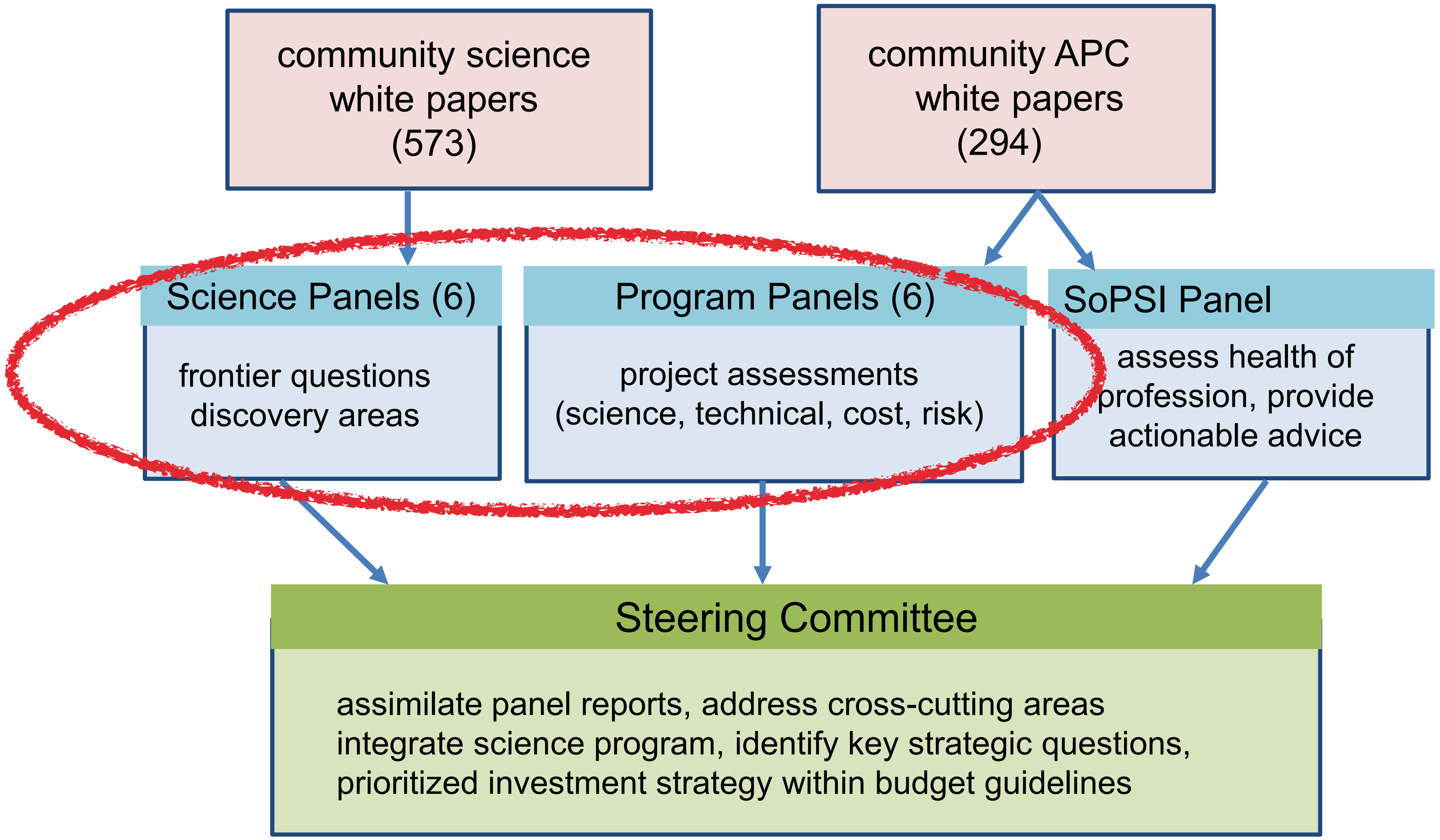
27 2019BAAS...51c.239K 2019/05 cited: 9
The Yet-unobserved Multi-Messenger Gravitational-Wave Universe
Kalogera, Vassiliki; Bizouard, Marie-Anne; Burrows, Adam and 9 more

28 2019BAAS...51c.237C 2019/05 cited: 3
Multi-Messenger Astronomy with Extremely Large Telescopes
Chornock, Ryan; Cowperthwaite, Philip S.; Margutti, Raffaella and 52 more

29 2019BAAS...51c.232S 2019/05
Gravitational-Wave Astronomy in the 2020s and Beyond: A view across the gravitational wave spectrum
Shoemaker, David; McLaughlin, Maura; Thorpe, James Ira and 1 more

30 2019BAAS...51c.209C 2019/05
Radio Counterparts of Compact Object Mergers in the Era of Gravitational-Wave

Astro2020 Process



Science Panels

- Astro2020: Panel on Compact Objects and Energetic Phenomena
- Astro2020: Panel on Cosmology
- Astro2020: Panel on Galaxies
- Astro2020: Panel on Exoplanets, Astrobiology, and the Solar System
- Astro2020: Panel on the Interstellar Medium and Star and Planet Formation
- Astro2020: Panel on Stars, the Sun, and Stellar Populations

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Program Panels

- Astro2020: Panel on An Enabling Foundation for Research
- Astro2020: Panel on Electromagnetic Observations from Space 1
- Astro2020: Panel on Electromagnetic Observations from Space 2
- Astro2020: Panel on Optical and Infrared Observations from the Ground
- Astro2020: Panel on Particle Astrophysics and Gravitation
- Astro2020: Panel on Radio, Millimeter and Submillimeter Observations from the Ground

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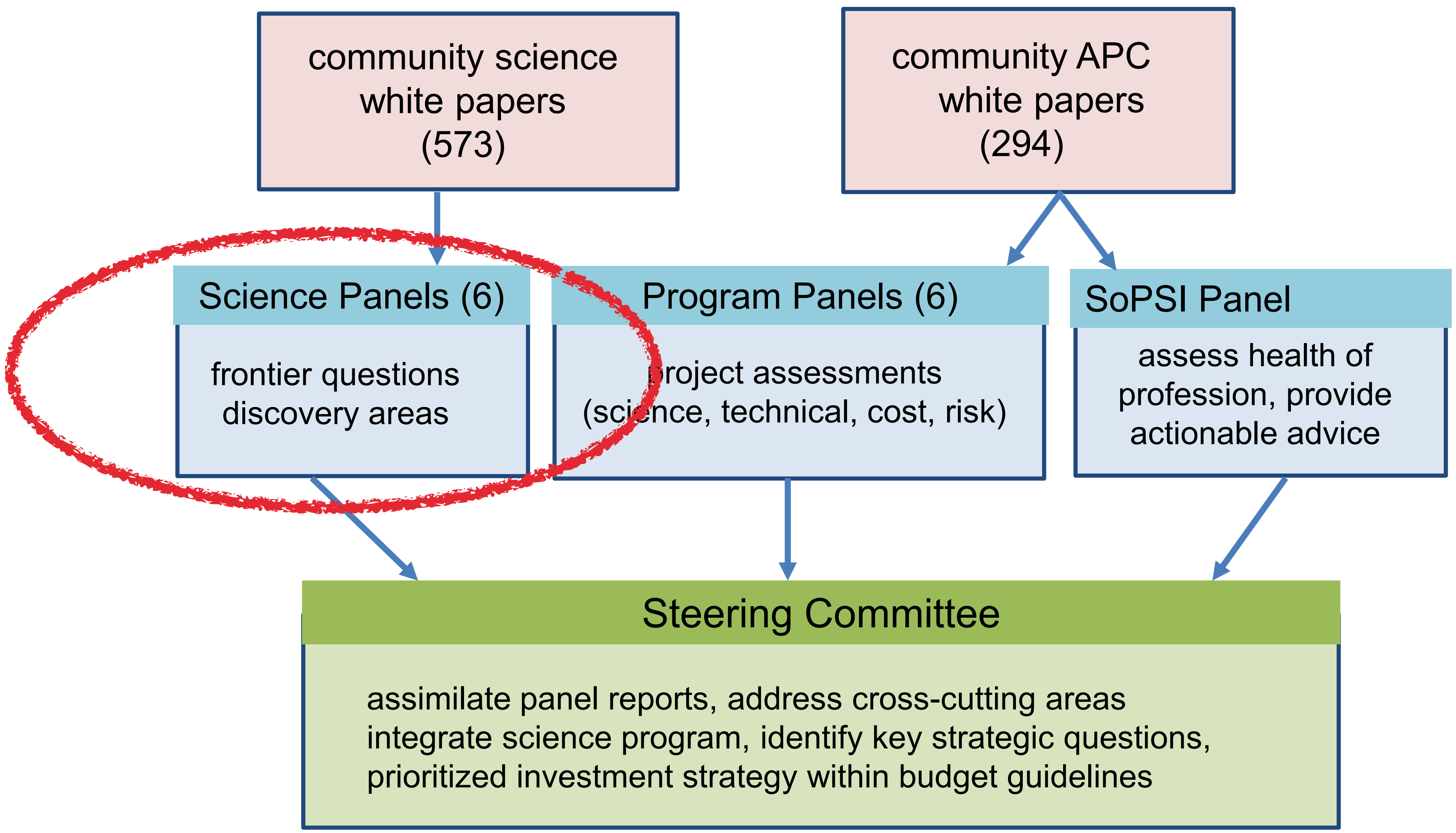
State of the Profession

- Astro2020: Panel on State of the Profession and Societal Impacts

Astro2020 Process



Panel on Compact Objects and Energetic Phenomena

Committee

CHAIR
Deepto Chakrabarty

MEMBER
Laura B. Chomiuk

MEMBER
Daniel Holz

MEMBER
Raffaella Margutti

MEMBER
Julie McEnery

MEMBER
Peter Istvan Meszaros

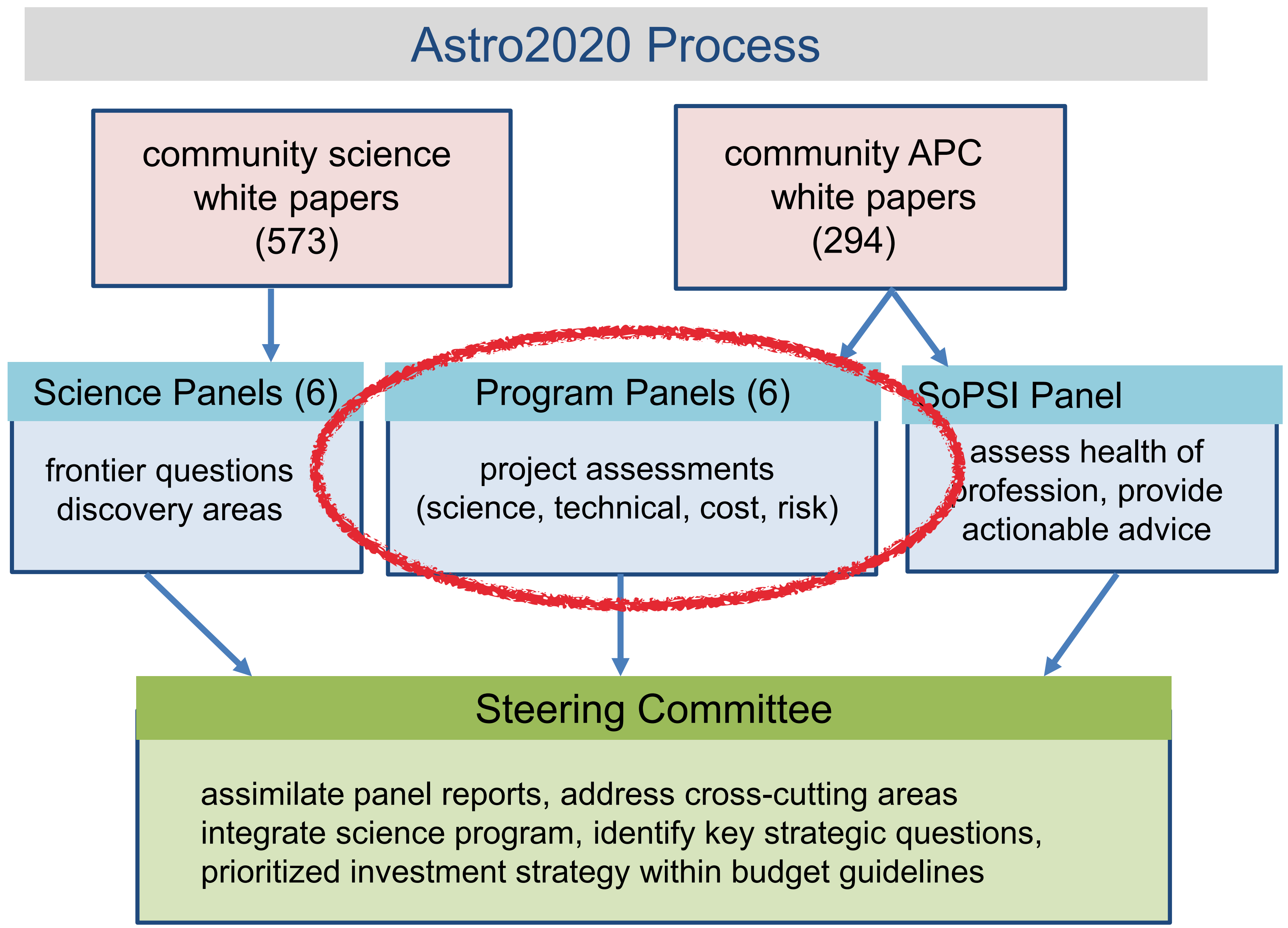
MEMBER
Ramesh Narayan

MEMBER
Eliot Quataert

MEMBER
Scott M. Ransom

MEMBER
Todd A. Thompson

Panel on Compact Objects and Energetic Phenomena


Astro2020 Process
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

Panel on Particle Astrophysics and Gravitation

Committee

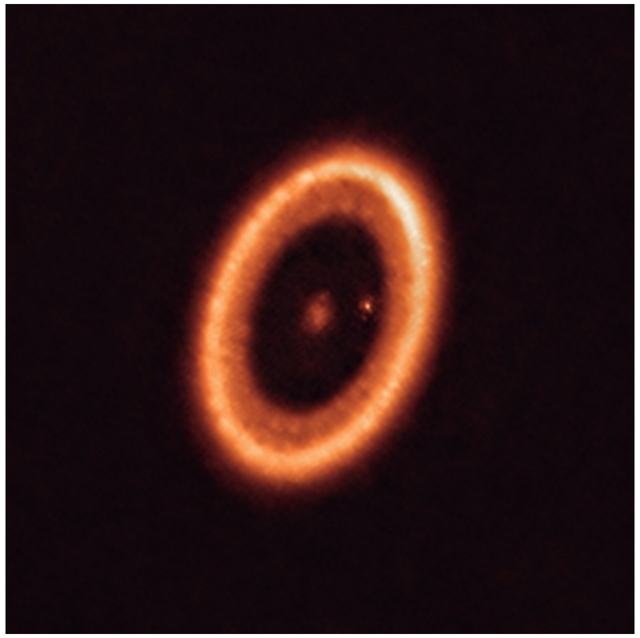
CHAIR **John F. Beacom**	CO-CHAIR **Laura Cadonati**	MEMBER **David Besson**	MEMBER **Gabriela Gonzalez**
MEMBER **Jordan A. Goodman**	MEMBER **Elizabeth Hays**	MEMBER **N. J. Kasdin**	MEMBER **David Kieda**
MEMBER **Andrea Lommen**	MEMBER **Brian Metzger**	MEMBER **James Yeck**	MEMBER **Nicolas Yunes**

Science Theme: Worlds and Suns in Context

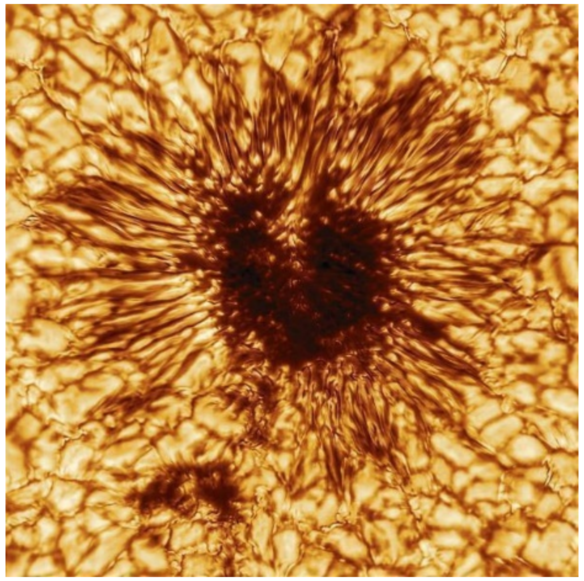
The quest to understand the interconnected systems of stars and the worlds orbiting them, from the nascent disks of dust and gas from which they form, through the formation and evolution of the vast array of extrasolar planetary systems so wildly different than the one in which Earth resides

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)



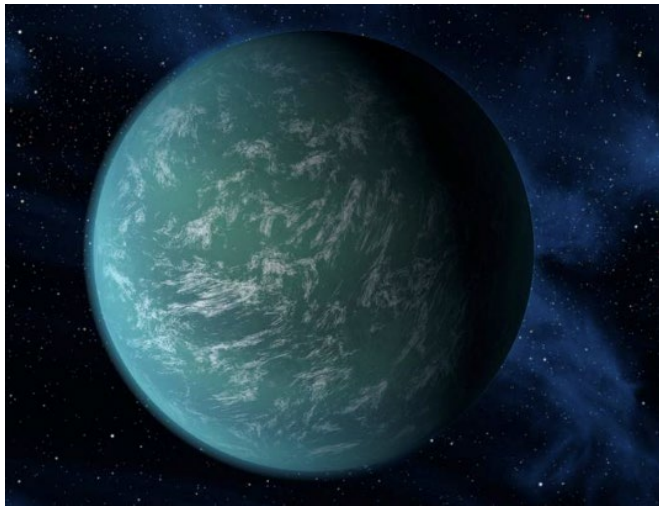
ALMA image of a young planet-forming star



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.

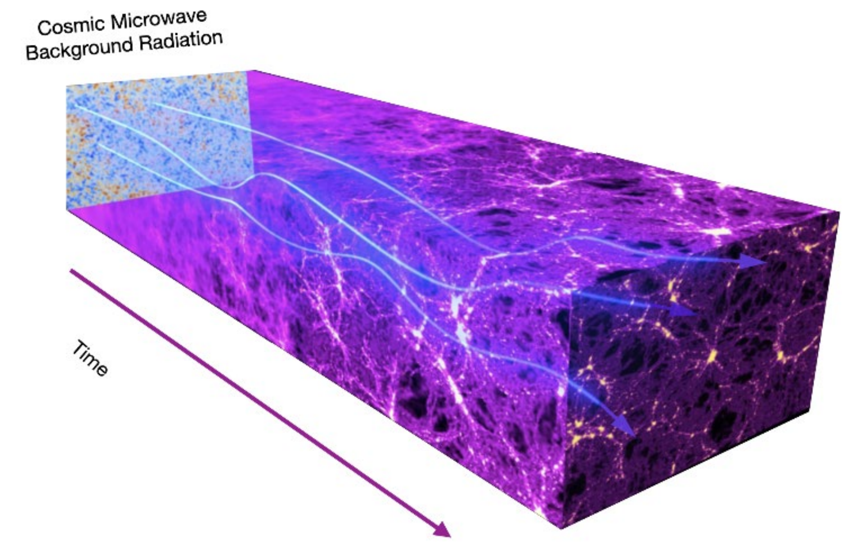


The needed capabilities include:

- 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

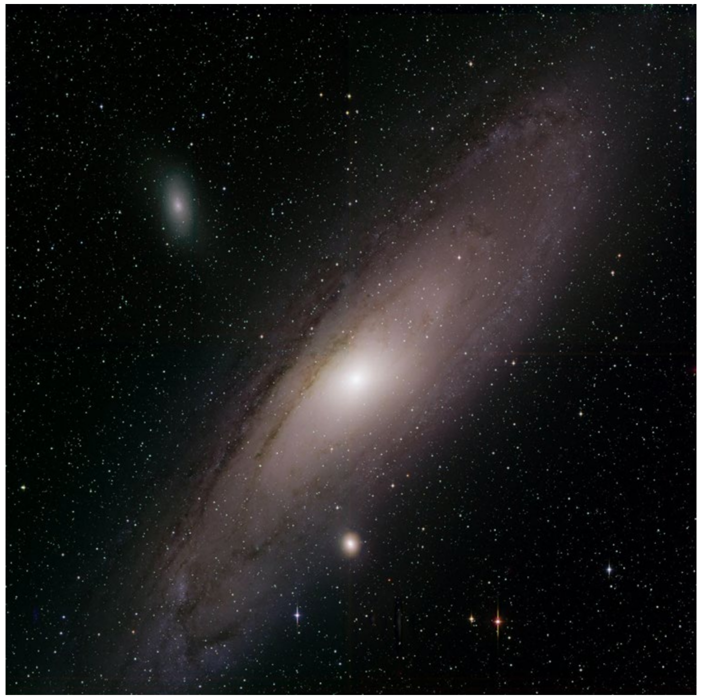
Science Theme: New Messengers and New Physics

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



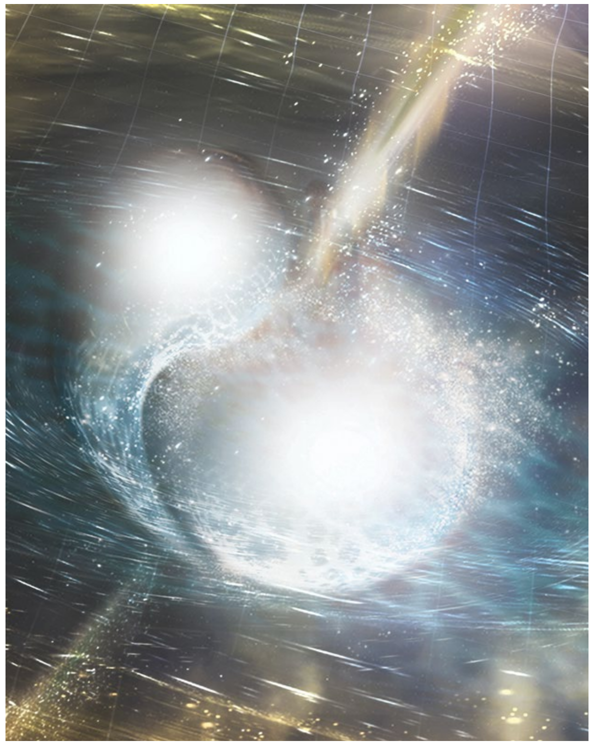
This theme is forefront this decade because of:

- 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

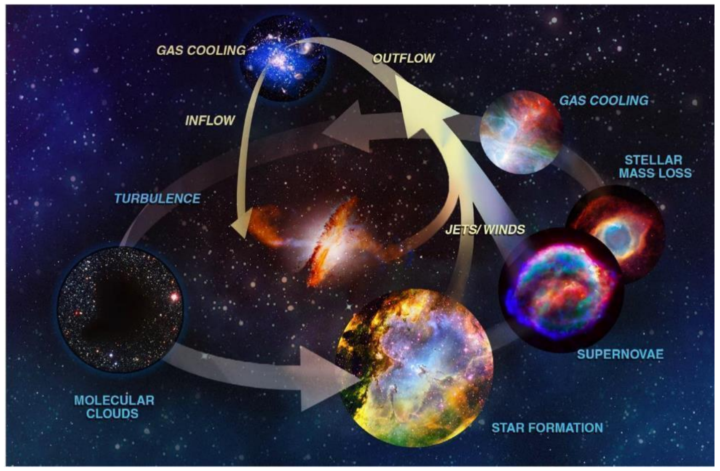


The needed capabilities include:

- 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:

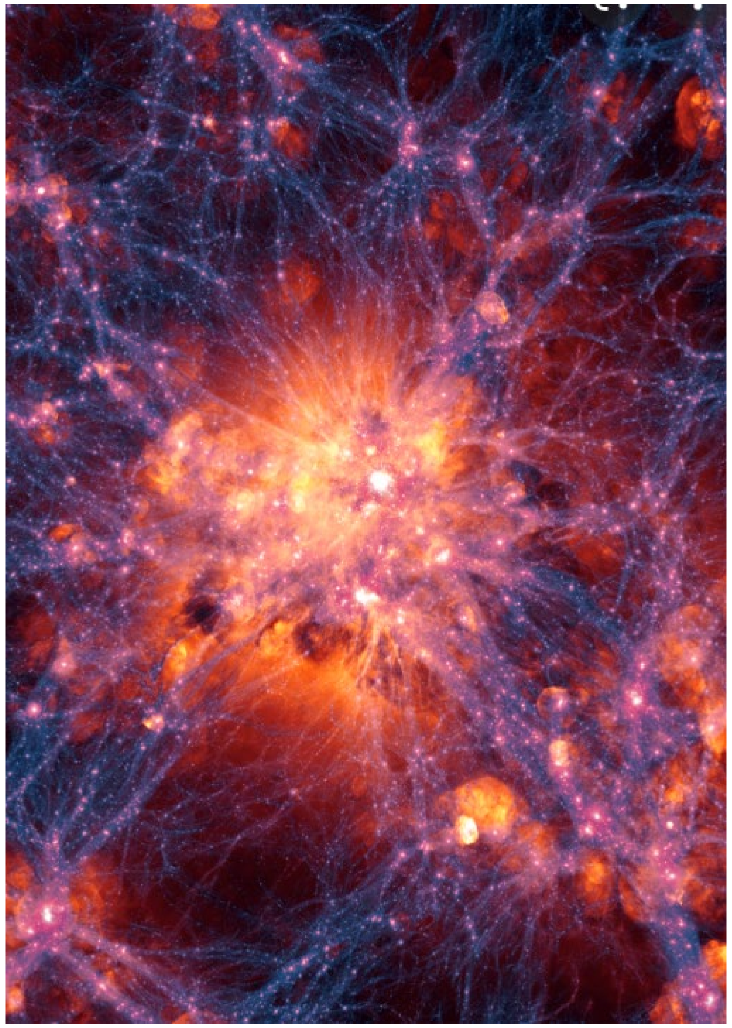
- JWST will provide definitive observations of the earliest stages of galaxy formation and evolution
- The Rubin Observatory, Roman, and Euclid will provide imaging and spectral energy information for millions of galaxies, complementing the in-depth observations from JWST
- Progress in numerical simulations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



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

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

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:

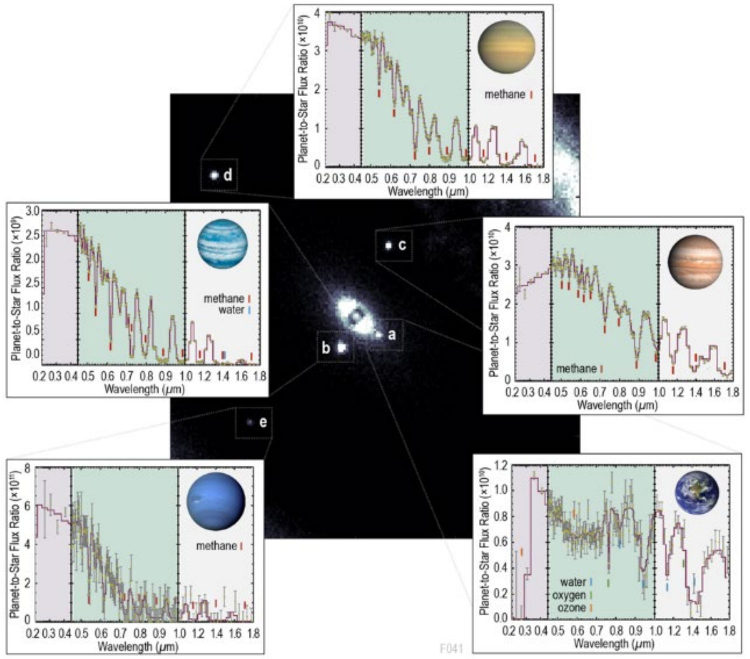
- *A far-IR spectroscopy and/or imaging strategic mission*

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

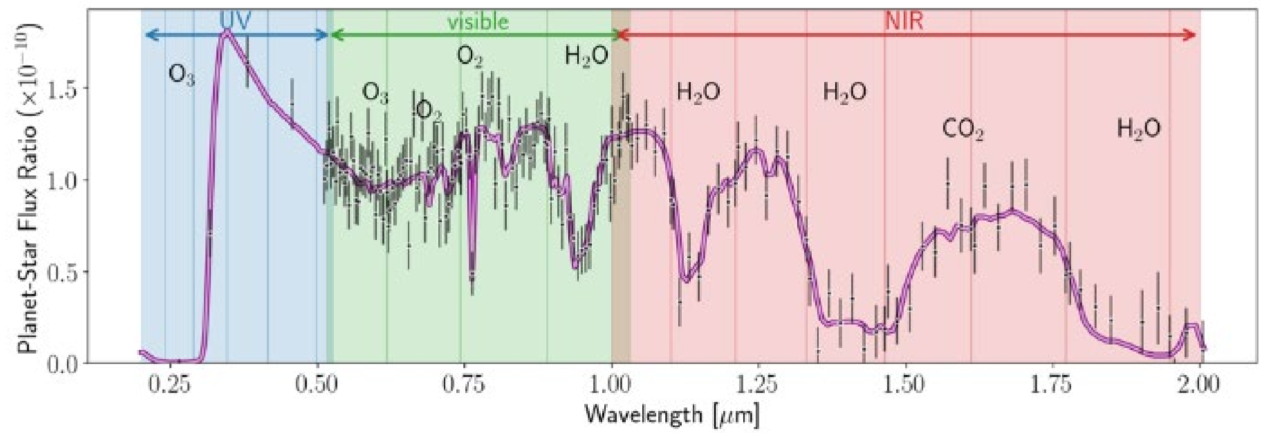
- *A high spatial and spectral resolution X-ray strategic mission*

  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



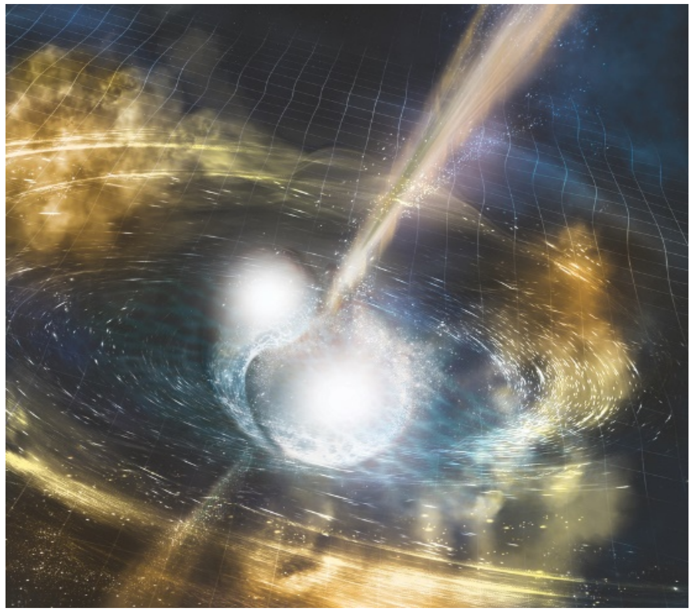
Simulated space-telescope image of a complete planetary system including a life-bearing Earth-like planet

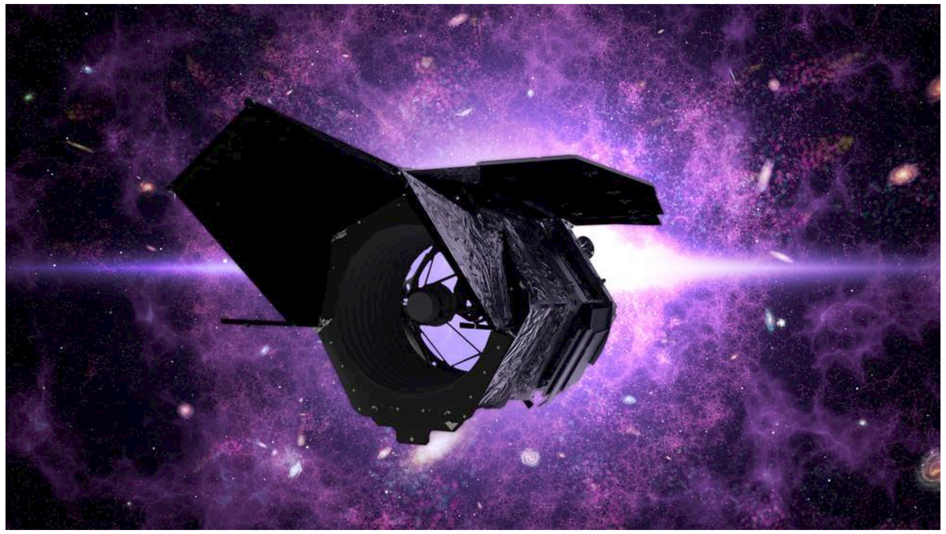


Simulated spectrum of an Earth-twin planet observed from the UV to near-IR by a space coronagraph

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

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

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

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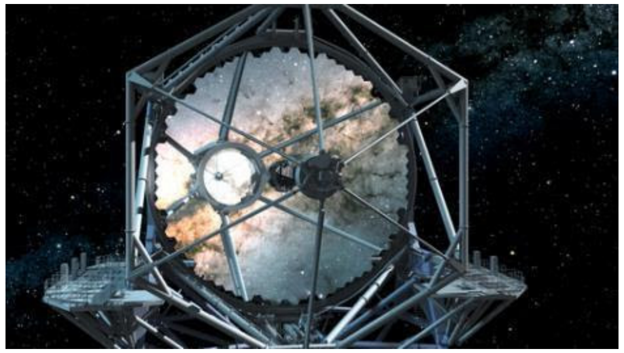
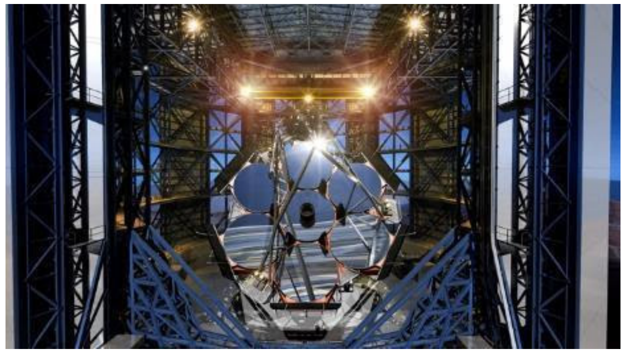
U.S. Extremely Large Telescope Program



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

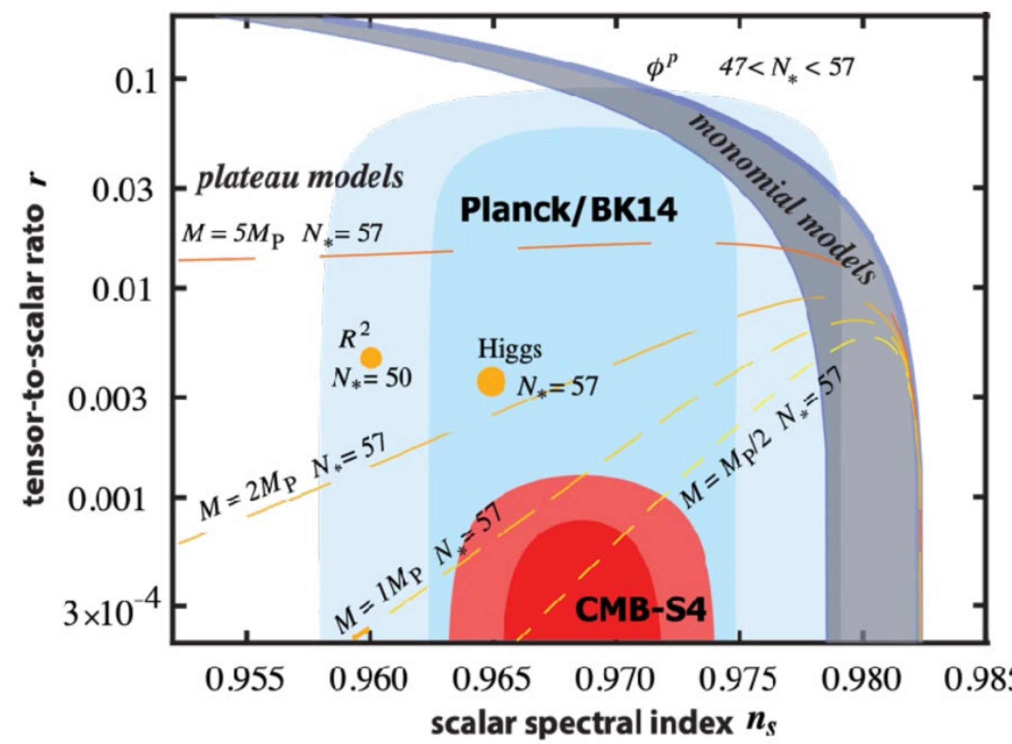
This is the survey's top priority MREFC recommendation due to the timeliness and transformative potential

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 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

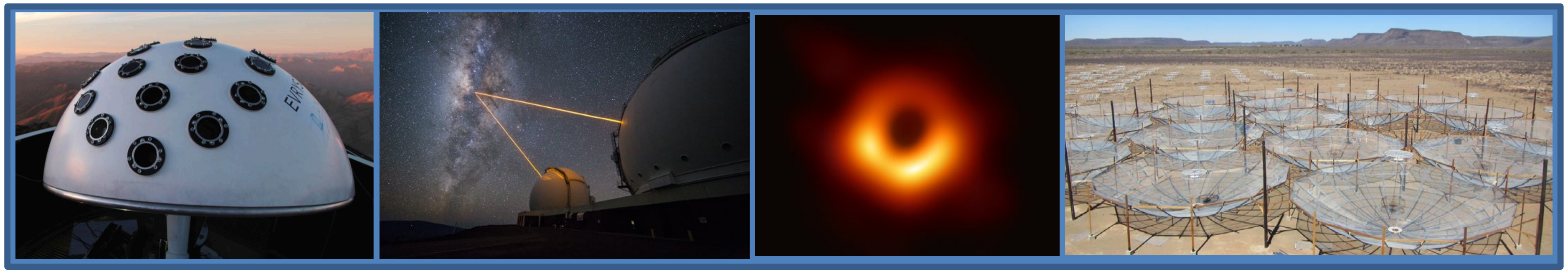
The ngVLA will address a broad range of science questions including:

- 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.

NSF Mid-Scale Program Background

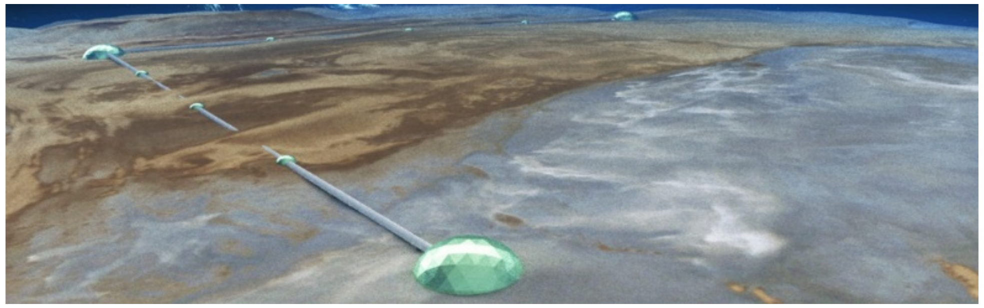


Mid-scale (4 – 100 M$) competed programs harness the creativity of the community and fuel innovation

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.

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.

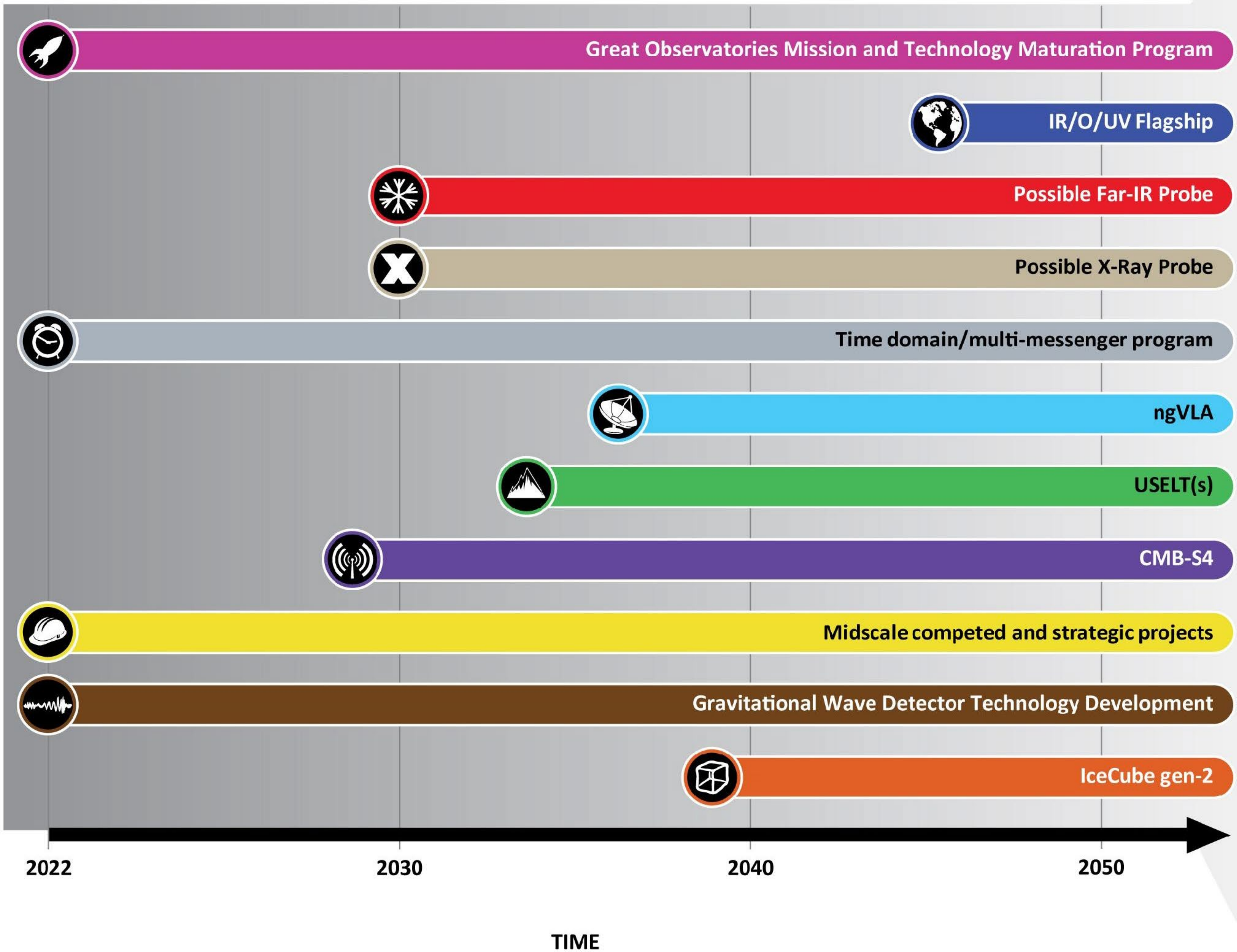
IceCube-Generation 2 Neutrino Observatory

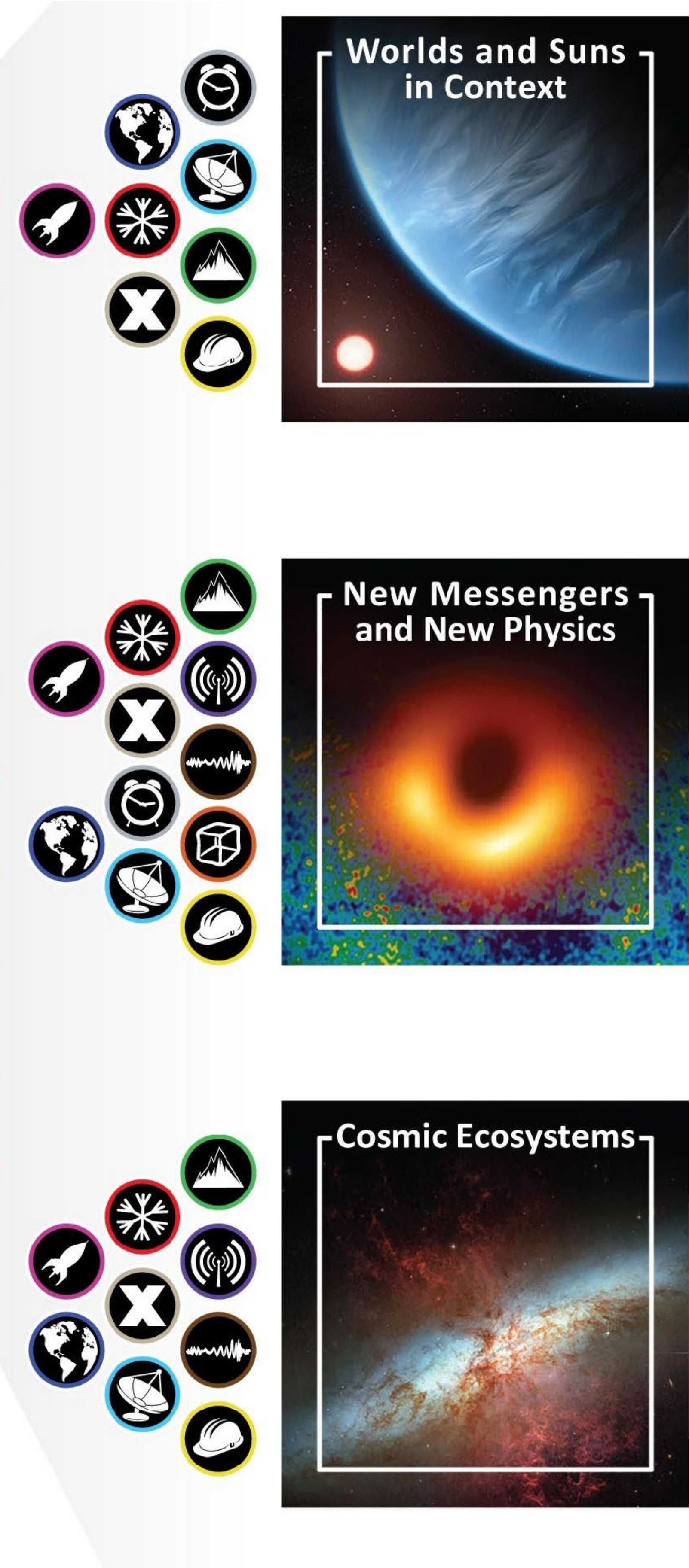
IceCube at South Pole detects 100 TeV – 10 PeV cosmic neutrinos

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





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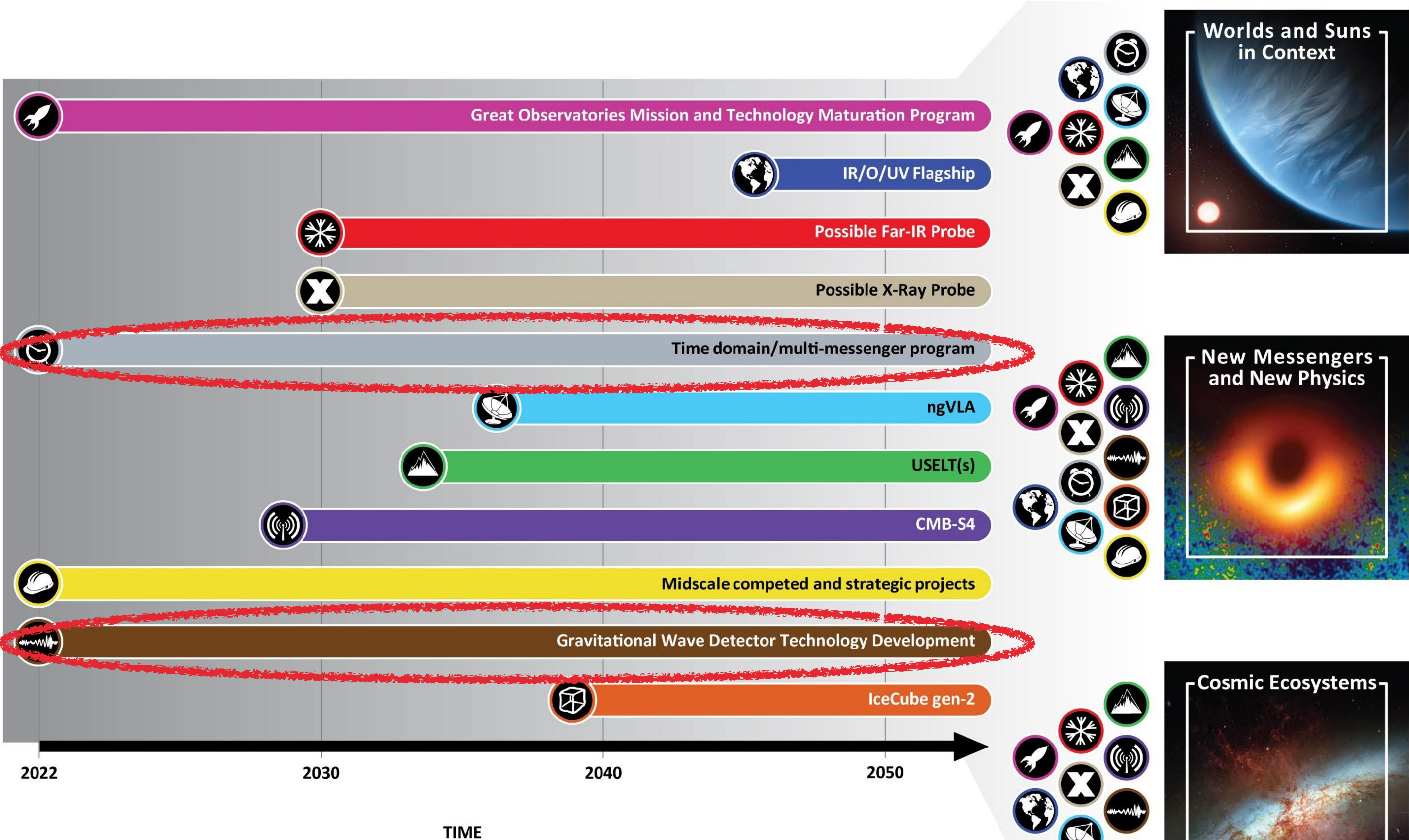

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