NATIONAL ACADEMIES *Sciences Engineering Medicine*

Thriving in Space - Ensuring the Future of Biological and Physical Sciences Research

A Decadal Survey for 2023-2032

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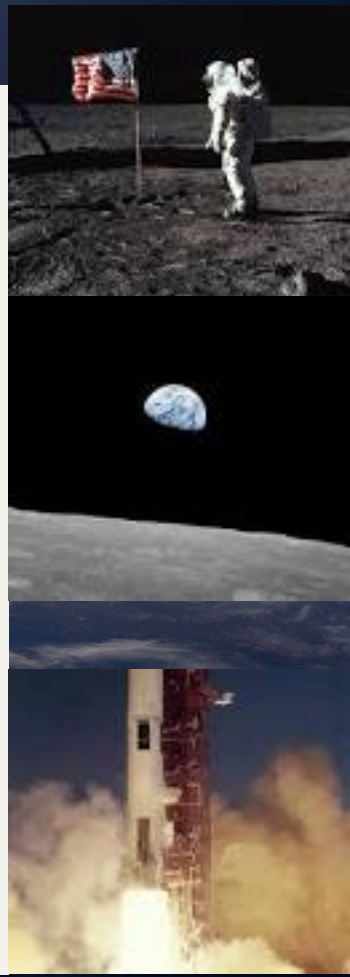
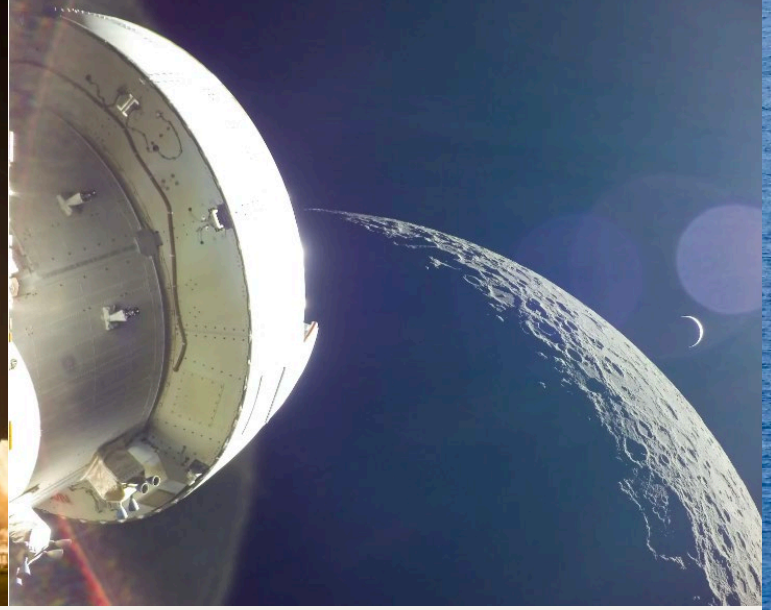
nationalacademies.org/bps-decadal

REPORT BRIEFING:NASEM CBPSS

Not since Apollo missions have so many looked toward space for inspiration and new solutions.

The next decade heralds exciting new advances as we move to explore the Moon and Mars.





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The space ecosystem is expanding rapidly

The next decade will involve:

- More people
- More destinations, including the Moon and Mars
- Longer duration missions
- More activity types
- More commercialization

Thriving in Space – we live in a different world

This last decade in space science research was one of:

- Rebuilding researcher engagement
- Adapting to change
- Struggling for priority
- And *still* making amazing new discoveries and grappling with new challenges for space exploration and space-enabled breakthroughs in science.

The next decade of biological + physical space science (BPS) research is critical to US leadership of **sustainable path from Moon to Mars**.

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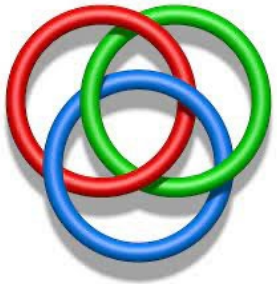
Steering Committee, Expert Panels, & Community Input



Biological Sciences
Physical Sciences
Engineering and Science Interface

Steering Committee: 18 experts from across the US and the BPS disciplines

Panels: 50+ experts, organized in working groups that mixed BPS disciplinary expertise on the current state of the field, future science priorities, and feasibility

Community Input: 250+ topical concept papers; 60+ research campaign concept papers; 2+ years of public meetings with government + industry experts

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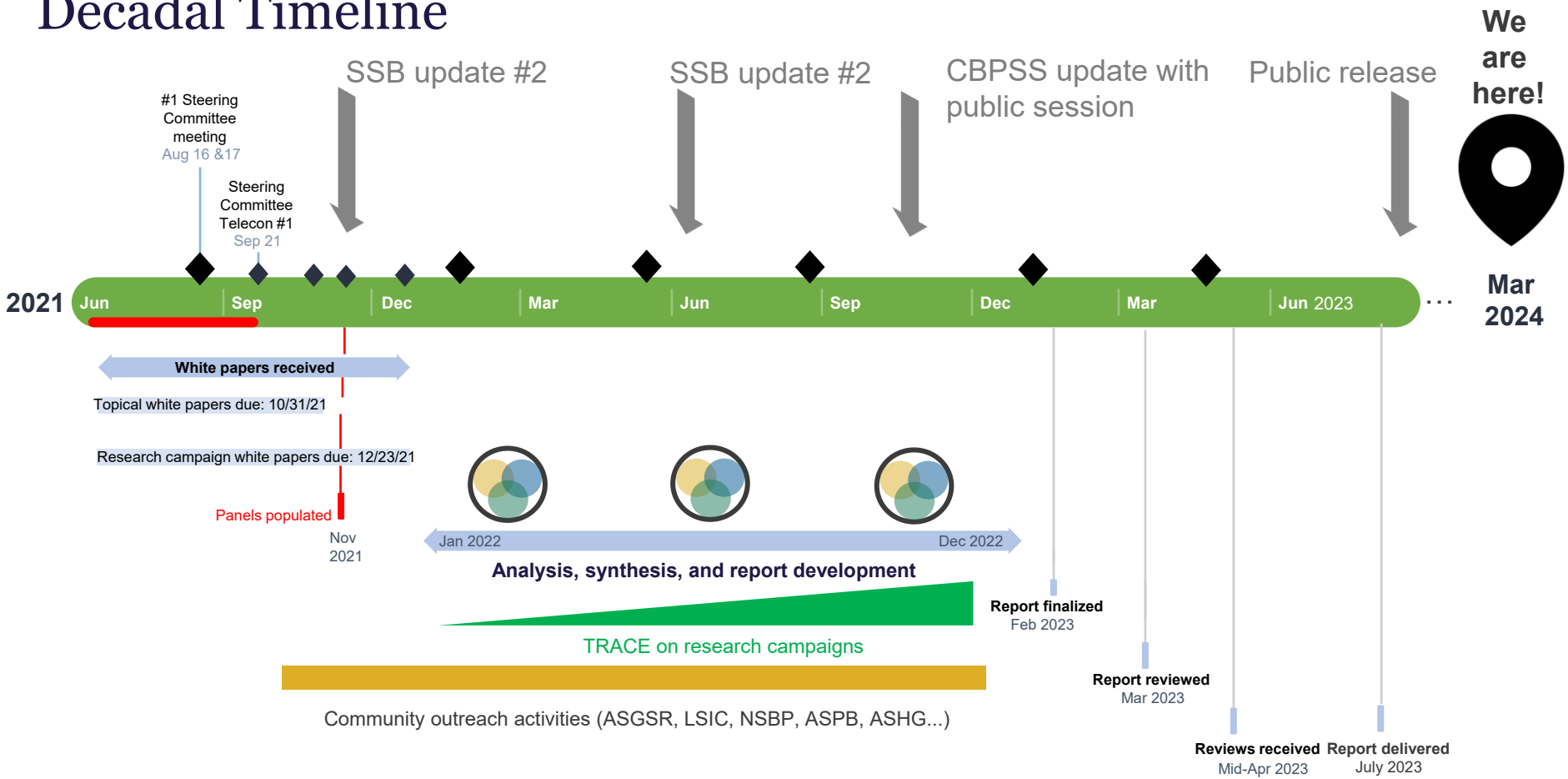
Decadal Timeline



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Report Snapshot

nationalacademies.org/bps-decadal

- Summary
- 1: Introduction
- 2: Current State of Knowledge in BPS
- 3: Key Science Themes and Questions
- 4: Science to Enable Space Exploration
- 5: Science Enabled by the Space Environment
- 6: Research Campaigns
- 7: Infrastructure, Access, and Community

3	11	2	25
Science Themes	Science Questions	Research Campaigns	Recs

4500 downloads as of today

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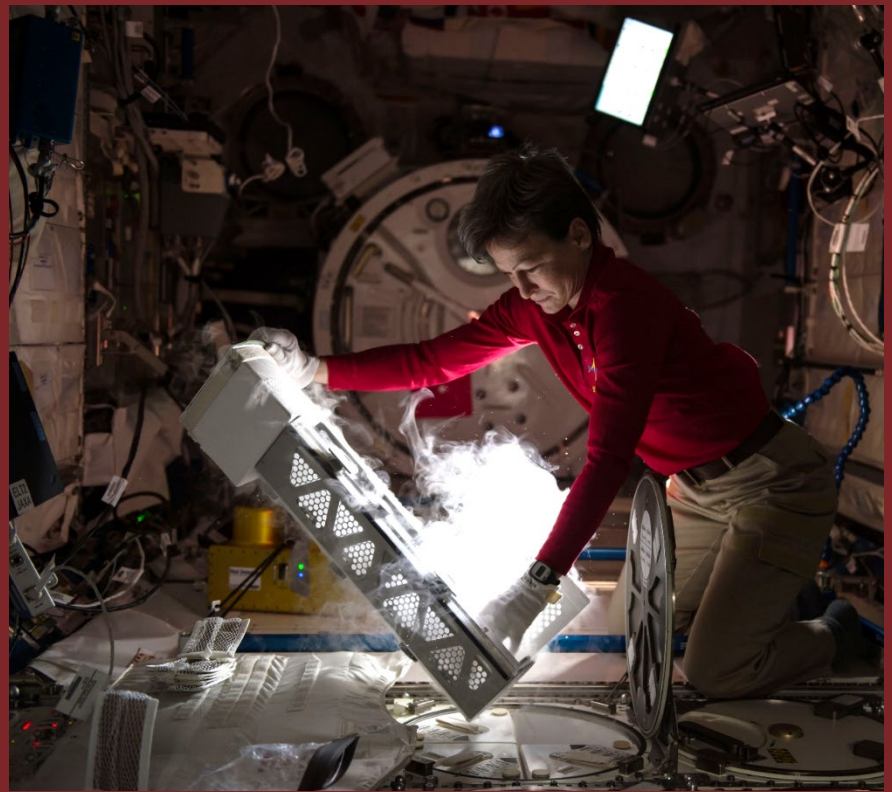
US *Thriving in Space* includes

1. **Increasing BPS research resources tenfold.** Exploration goals demand it and national research excellence demands it, with clear ROI to the rest of us on Earth during the ISS sunsetting phase.
2. **Focusing on 11 Key Scientific Questions.** The answers to these hard questions frame three themes that help us thrive as a nation and as a community of researchers. The coordination within and among public-private sectors can rally around this compelling set of questions and their anticipated impact on society.
3. **Adopting at least two research campaigns.** Mission-focused with audacious goals that will help us lead and make best use of missions to the Moon and Mars.
4. **Broadening the workforce.** Thriving in the next decade is meant for all of us, and the BPS research community is early in its broadened representation of all kinds of thinkers and doers.
5. **Planning for the unexpected.** Decision rules that help the US respond nimbly to opportunity and downturns will help us thrive in the long run, even as we know we do not see the future opportunities of space-based research collaborations & competition fully.

BPS Decadal Survey Outreach

Event	Day/Time (ET)
Embargoed Prepub to NASA	Sep 5, 2023
Embargoed Prepub to Hill & OSTP-OMB	Sep 5, 2023
Embargoed Briefing to NASA	Sep 8, 2023
Embargoed Briefing to House	Sep 8, 2023
Embargoed Briefing to Senate	Sep 8, 2023
Public Release Event (Washington, DC)	**Sep 12, 2023**
Briefing to DEPSCom	Sep 12, 2023
Briefing to Joint CBPSS/ASEB (CA)	Oct 17, 2023
Briefing to Space Science Board (CA)	Nov 14, 2023
ASGSR	Nov 16, 2023
Briefing to OSTP/OMB	Jan 4, 2024
House Science Committee Discussion on the current landscape for ISS, Commercial LEO Destinations (CLDs), and the future transition in LEO	Feb 2, 2024
The Committee on Science, Space, and Technology of the U.S. House of Representatives Hearing titled, "ISS and Beyond: The Present and Future of American Low-Earth Orbit Activities"	**Feb 14, 2024**
Future In-Space Operations (FISO)	Feb 21, 2024
Follow-up Briefing to CBPSS	**Mar 20, 2024**
Briefing to BPAC	April 26, 2024
Briefing to BPA	May 8, 2024
Briefing to NASA Deputy Administrator	To be rescheduled

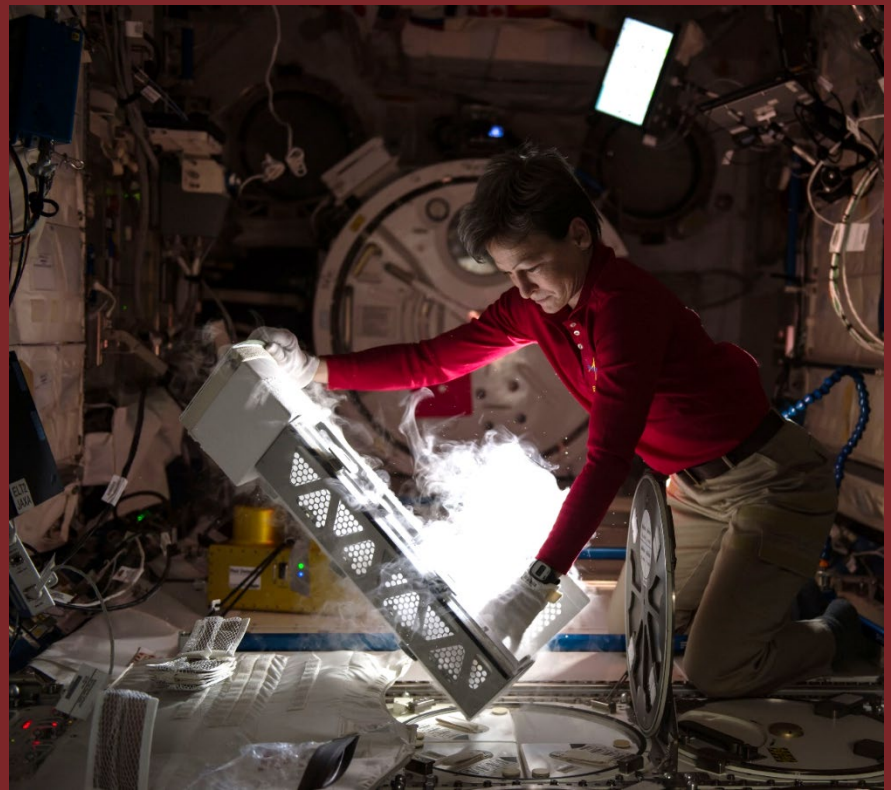
Increase national investment and engagement



Increasing Investment in BPS Research

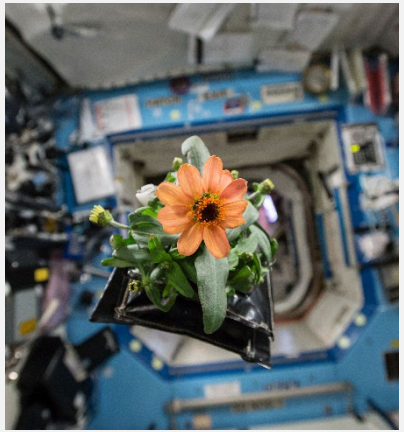
RECOMMENDATION: To retire many of the key scientific questions by the end of the decade, NASA should establish support for the Biological and Physical Sciences program to levels that reflect the current national need and to build the science community in size, diversity of technical expertise and lived experience, and capability to reach the science goals of the nation, toward levels that are an **order of magnitude above the current funding and well before the end of the decade**.

Focus on Key Scientific Questions



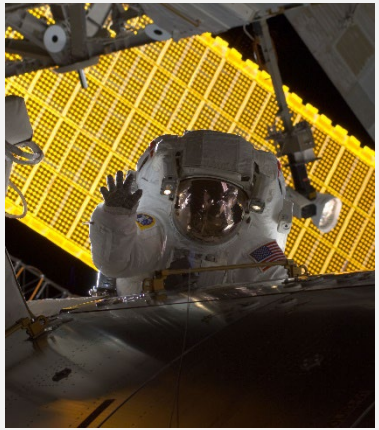
Key Science Themes

ADAPTING TO SPACE



What fundamental processes change when away from Earth?

LIVING AND TRAVELING IN SPACE



What does it take to occupy space environment over the long haul?

PROBING PHENOMENA HIDDEN BY EARTH

What principles are hidden by gravity or revealed only by being in space?

Key Scientific Questions: *Why these 11?*

KSQs prioritized in terms of those questions that are best posed in the coming decade to:

- answer grand science challenges and usher transformational change.
- require access to the space environment to achieve pivotal discoveries.
- reduce uncertainty about both benefits and risks of space exploration.
- solve terrestrial problems or yield societal benefit.
- reduce the costs of space exploration.
- lead to entirely new options for exploration missions, to bring revolutionary change to space exploration.

Key Scientific Questions: *Why these 11?*

"These KSQs were, by design and where possible, intended to be biologically motivated yet physics aware or physics motivated yet biologically aware, but recognizing that there could be subquestions framed as purely biological or physical.

Importantly, and as a result of the maturity and increasing interdisciplinarity of space science research over the past decade, many KSQs are broader than any one scientific discipline—spanning multiple biological species, material classes, or physical principles. These concepts of interdisciplinarity and comprehensiveness informed all of the recommendations."

Summary, p. 5

Adapting to Space
Key Scientific Questions

- How does the space environment influence biological mechanisms required for organisms to survive the transitions to and from space, and thrive while off Earth?
- How do genetic diversity and life history influence adaptation to the space environment?
- How does the space environment alter interactions between organisms?

Living and Traveling in Space

Key Scientific Questions

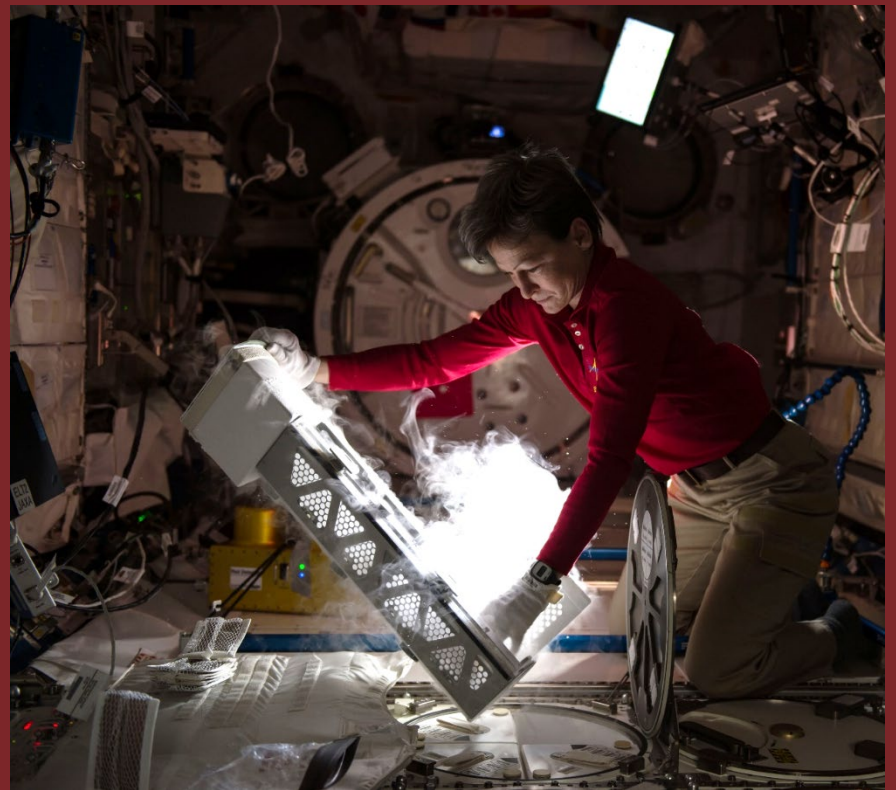
- What are the important multi-generational effects of the space environment on growth, development, and reproduction?
- What principles guide the integration of biological and abiotic systems to create sustainable and functional extraterrestrial habitats?
- What principles enable identification, extraction, processing, and use of materials found in extraterrestrial environments to enable long-term, sustained human and robotic space exploration?
- What are the relevant chemical and physical properties and phenomena that govern the behavior of fluids in space environments?

Probing Phenomena Hidden by Gravity or Terrestrial Limitations

Key Scientific Questions

- What are the mechanisms by which organisms sense and respond to physical properties of surroundings, and to applied mechanical forces including gravitational force?
- What are the fundamental principles that organize the structure and functionality of materials, including but not limited to soft and active matter?
- What are the fundamental laws that govern the behavior of systems that are far from equilibrium?
- What new physics, including particle physics, general relativity, and quantum mechanics, can be discovered with experiments that can only be carried out in space?

Connect to societal impact with Research Campaigns



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New **Research Campaigns** with audacious goals will help drive solutions to the key science questions within the decade and make best use of missions to the Moon and Mars.

Research Campaigns

BLiSS

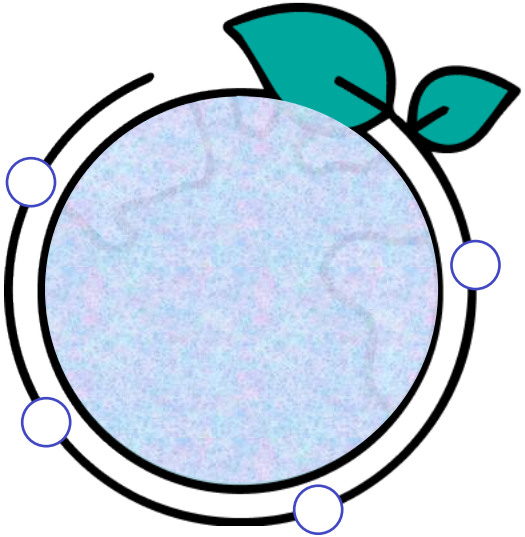
Bioregenerative **Li**fe **S**upport **S**ystems

MATRICES

Manufacturing m**ATeR**ials and Process**Es** for **S**ustainability in Space

Research Campaigns

BLiSS Goals



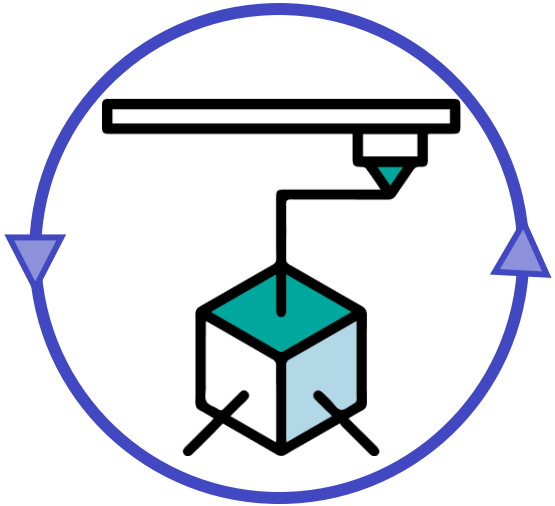
1. Self-sustainable system to produce food, clean water, renew air, process waste, and create critical materials to meet the challenges of long-duration space missions.

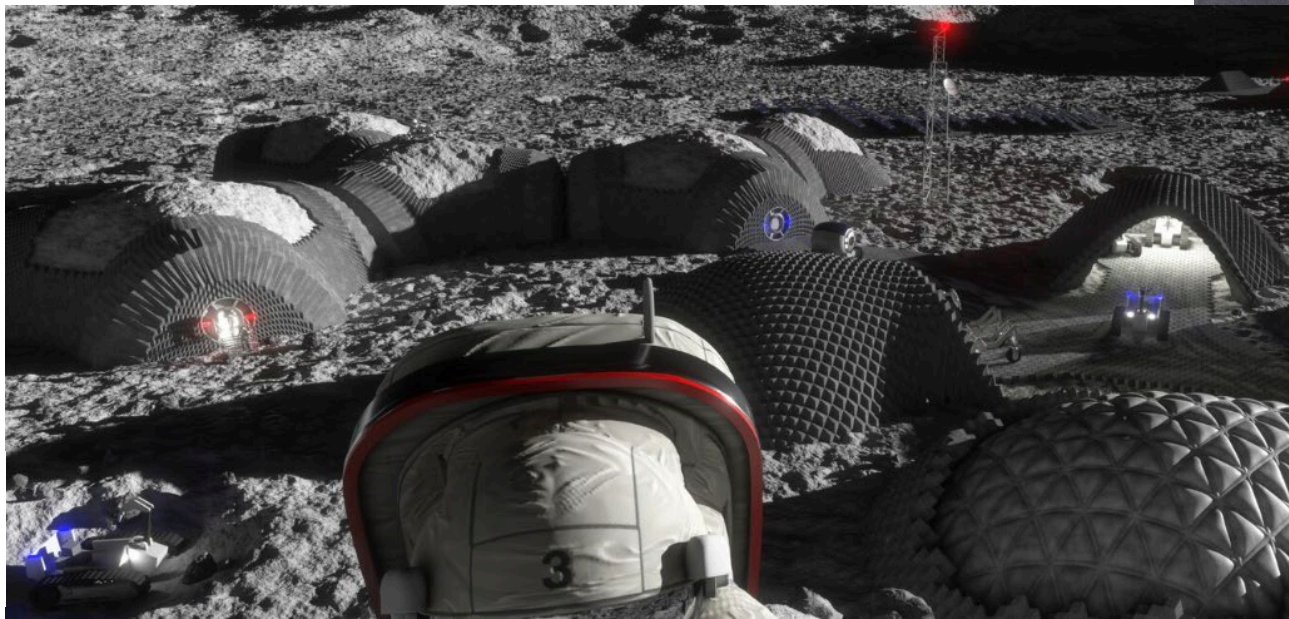
In the context of global competition for LEO research with Earth benefits

Research Campaigns

MATRICES Goals

1. Learn how materials and energy interact in non-terrestrial environments, and use that knowledge to design infrastructure for responsible space exploration.

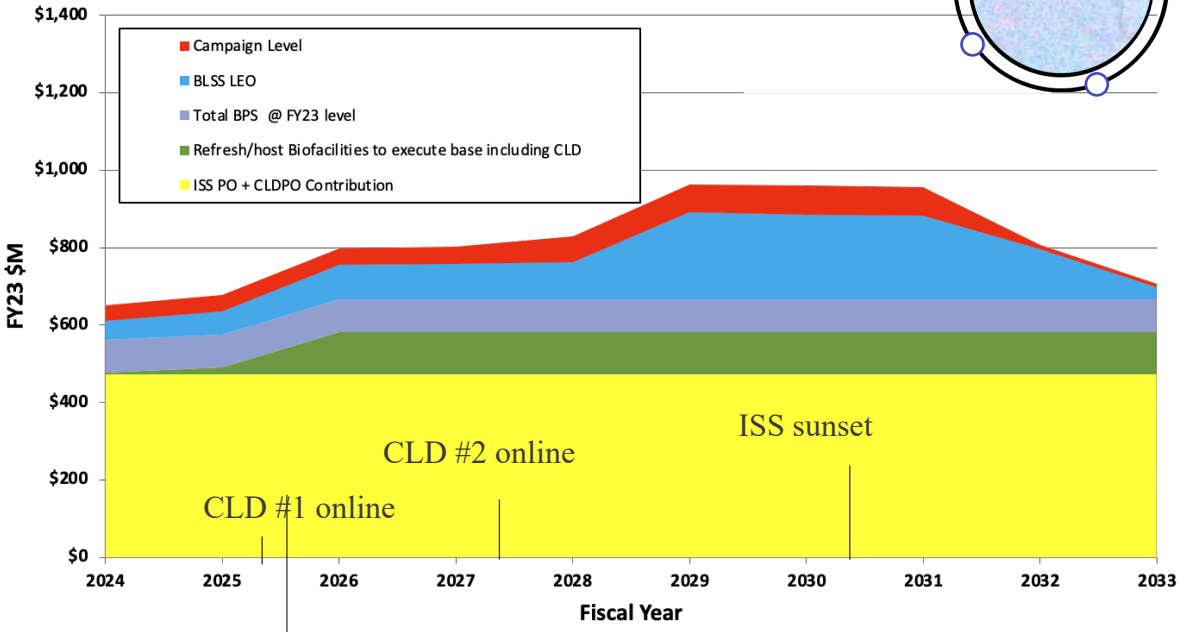




In the context of global competition for resource use & manufacturing expertise off-Earth

Research Campaign Assumptions

- At least 2 commercial lunar destinations (CLDs) *for scientific research u*se this decade. Otherwise, US severely disadvantaged on prep for Moon to Mars.
- Launch costs excluded from *BPS research program* cost estimates, consistent with current practice
- Coordination services provided by US Program Office, for LEO and other research destinations

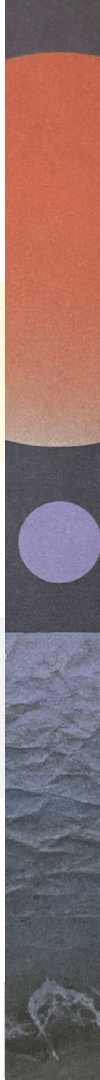


ISS+CLD PO CLD Contribution: ROM estimate of the allocation of launch and return vehicle services, crew time and integration and operations services provided for the total BPS program

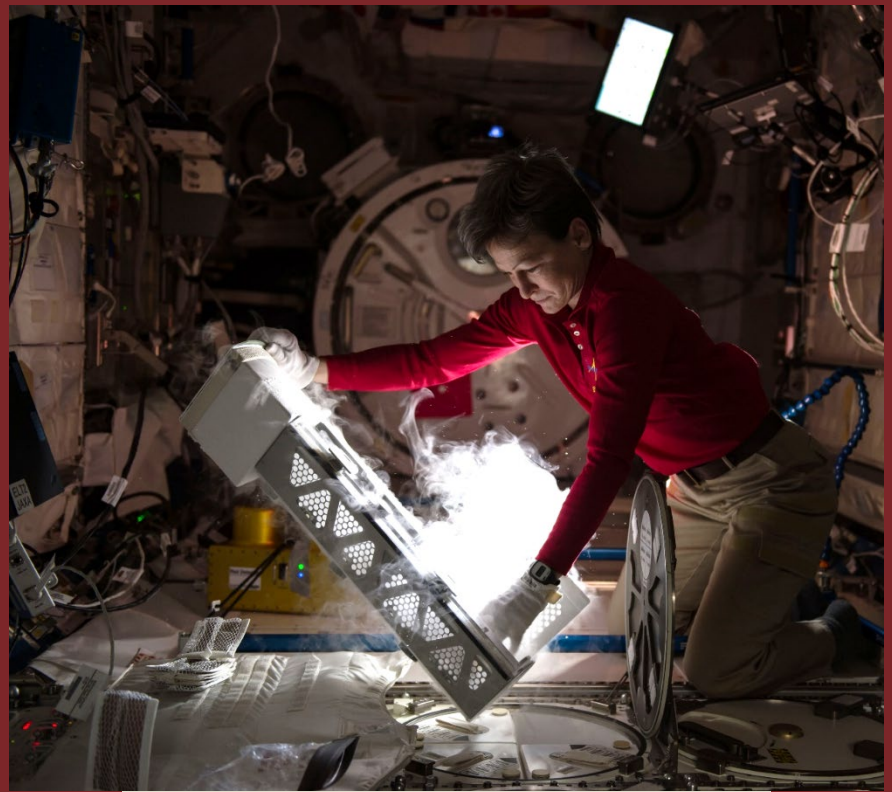
Beyond NASA-anchored Campaigns

PFaST: Probing the Fabric of Space-Time
Multiagency Opportunity

PROMO: Polar Radiation of Model Organisms
Notional Concept



Broaden the BPS Research Talent Spectrum



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Bolstering U.S. space science research excellence

FINDING: A robust and resilient BPS program requires:

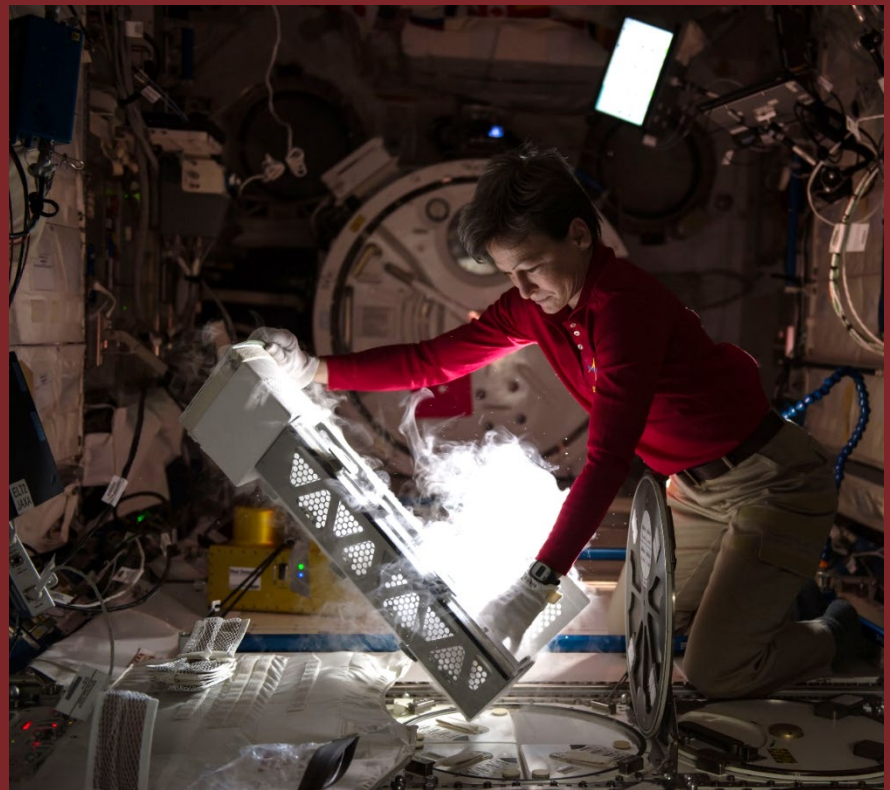
- a **healthy and regular cadence of proposal calls and grant dollar awards** that are consistent with sustaining a diverse and productive BPS community over the course of the next decade, including the necessity of training a diverse scientific workforce of sufficient size and caliber to maintain the BPS community over a generational timescale;
- **broadened and more inclusive participation in the U.S. BPS community**, including diversity of both scientific expertise and by lived socioeconomic experience, recognizing the slow progress in attracting and retaining women and persons of color into graduate and post-graduate research roles;
- a **total science budget sufficient to meet current national needs** and international competitor/collaborator challenges;
- **interactions with other U.S. government and non-U.S. space agencies** necessary for optimal BPS community productivity in science and technology development; and
- significant awareness and **collaboration with the emerging commercial space science, platforms and activities**, as appropriate for BPS program goals.

Space Science Researchers propel us forward

In a highly competitive global science and engineering environment, the **U.S. must stay on the leading edge** of the practice of science & engineering,
improving the research environment and setting the standard for ethics and values.

—Dr. Ellen Ochoa

Plan for the Unexpected



Plan for the Unexpected.

1. NASA is appropriated *more* or *less* federal funding for the BPS Division.
2. NASA-sponsored researchers are granted *more* or *less* access to the International Space Station (ISS)
3. BPS researchers have *more* or *less* access to commercial LEO destinations (CLDs) or payload service providers
4. NASA gains *more* or *less* U.S. interagency cooperation and co-funding of BPS research
5. The United States enjoys *more* or *less* international cooperation with launch, crew time for research, or infrastructure and mission co-development

Plan for the Unexpected.

2. NASA-sponsored researchers are granted *more* or *less* access to the ISS:

If researchers are granted *more* crew time or upmass on the ISS, experiments that serve as development or validation of commercial low Earth orbit (LEO) destination-planned experiments are prioritized.

If researchers are granted *less* crew time or upmass on ISS, technical/biological replicate experiments are prioritized.

3. BPS researchers have *more* or *less* access to commercial LEO destinations (CLDs) or payload service providers:

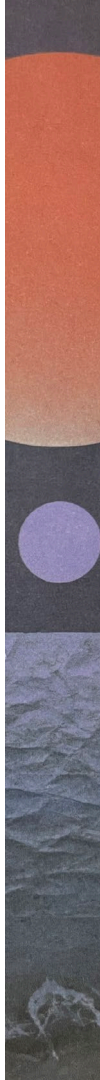
If researchers have *more* access to CLDs, projects focused on KSQs representing all three themes and research campaign elements are prioritized.

If researchers have *less* access to CLDs, projects focused on KSQs representing at least the adapting to space theme and probing hidden phenomena theme are prioritized until answered.

Thriving in Space:
Ensuring the Future of Biological and Physical Sciences Research

By the end of the decade, the ISS will be a relic of past partnerships, and several missions will take research questions well beyond the hostile environment of LEO.

The U.S. BPS community has an amazing decade of discovery, transformation, and translation ahead—**if we seize it**.



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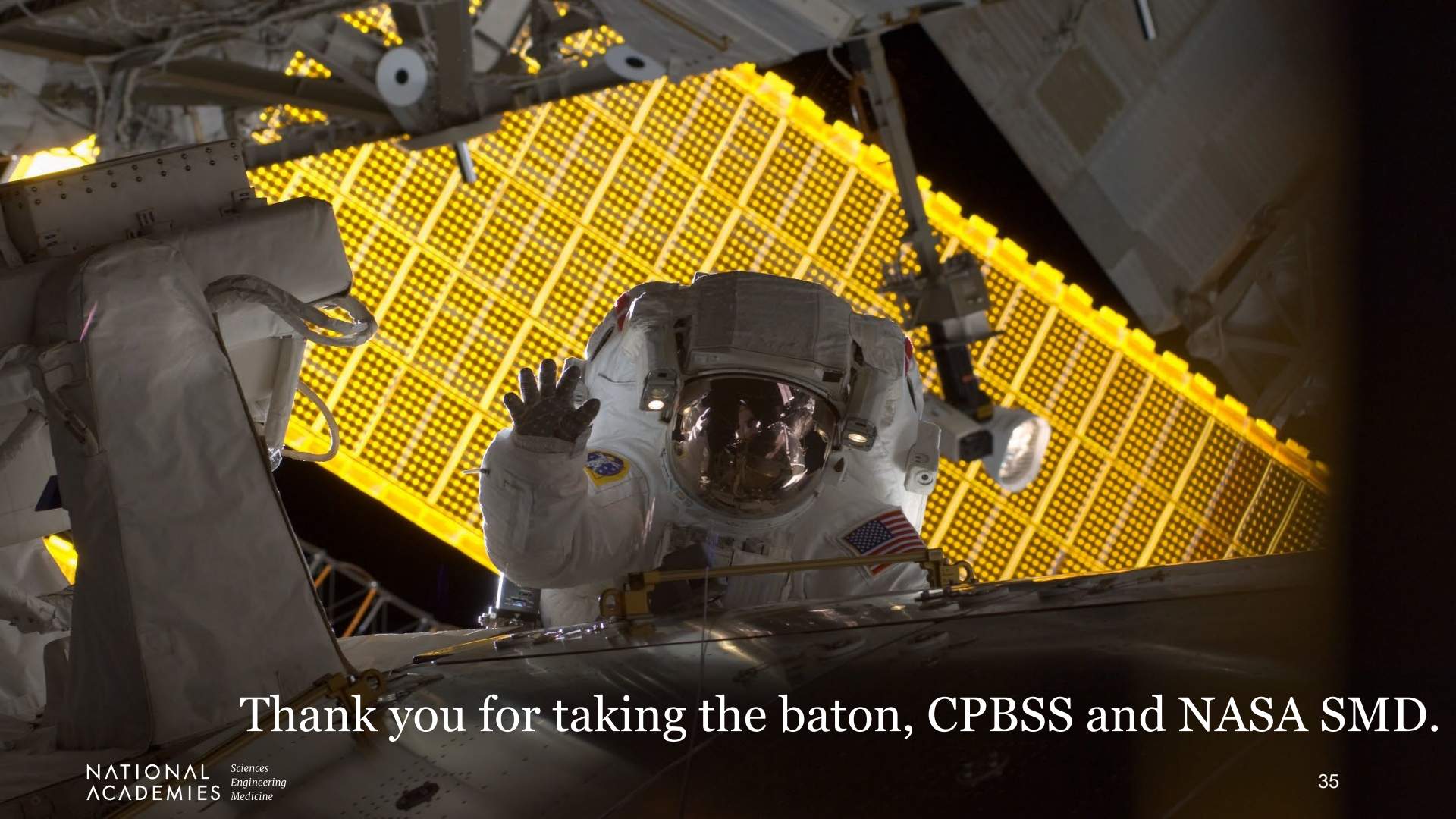

Thank you for taking the baton, CPBSS and NASA SMD.

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