National Aeronautics and Space Administration

1


# *Emerging Technologies for Astrophysics Missions*

Mario R. Perez
Astrophysics Chief Technologist
Astrophysics Division
NASA Headquarters
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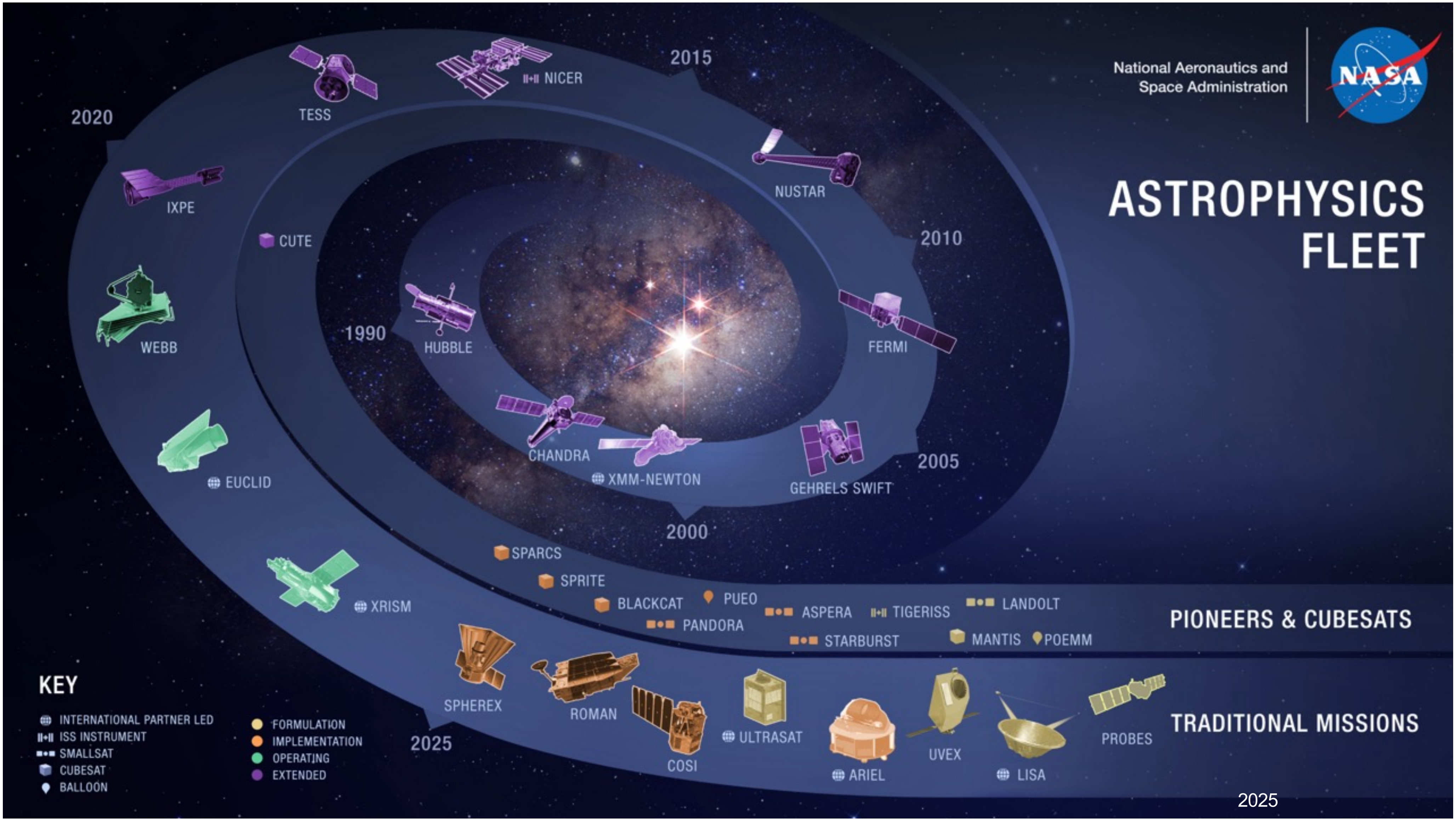
Why Astrophysics?
How did our universe begin and evolve?
How did galaxies, stars, and planets come to be?
Are we alone?
Enduring National Strategic Drivers
1972
1982
1991
2001
2010
2021
Astrophysics is humankind's scientific endeavor to understand the universe and our place in it.


National Aeronautics and Space Administration
NASA
ASTROPHYSICS FLEET
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CHANDRA
XMM-NEWTON
GEHRELS SWIFT
EUCLID
XRISM
SPARCS
SPRITE
BLACKCAT
PUEO
PANDORA
ASPERA
TIGERISS
LANDOLT
STARBURST
MANTIS
POEMM
PIONEERS & CUBESATS
SPHEREX
ROMAN
COSI
ULTRASAT
ARIEL
UVEX
LISA
PROBES
TRADITIONAL MISSIONS
KEY
INTERNATIONAL PARTNER LED
ISS INSTRUMENT
SMALLSAT
CUBESAT
BALLOON
FORMULATION
IMPLEMENTATION
OPERATING
EXTENDED
2025

Astrophysics Program Offices

# Technology Development

Addressing the fundamental questions:

"How does the universe work?"

"How did we get here?"

"Are we alone?"


## 2024 Astrophysics Technology Update (ATU)

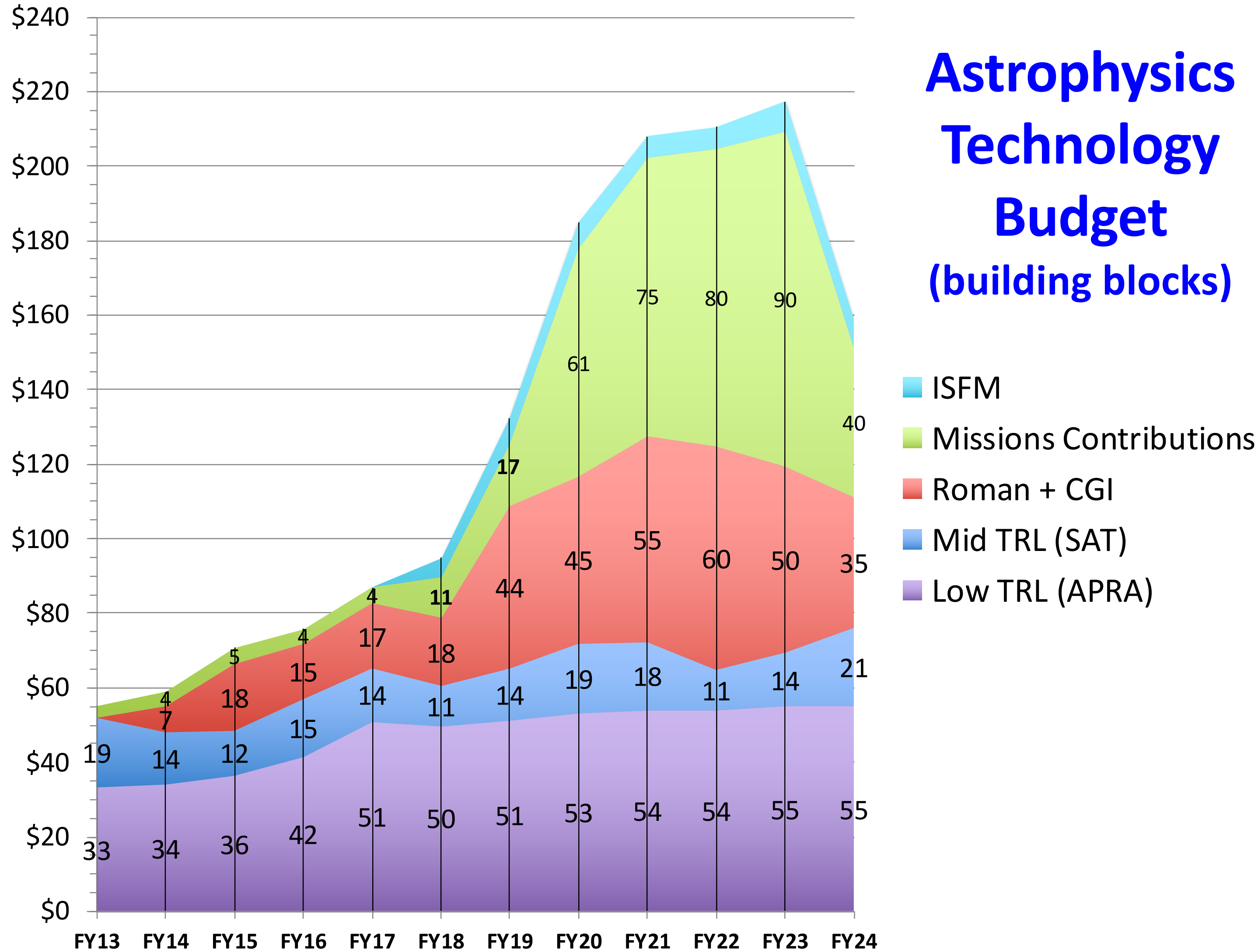
This first Astrophysics Technology Update (ATU) highlights 12 examples of developments in technology maturation projects, from early 2022 to date, funded by NASA's Astrophysics Division.


## 2024 Astrophysics Biennial Technology Report (ABTR)

This is the third ABTR, presenting joint technology reporting from the three Astrophysics science-theme-focused Program Offices -- Physics of the Cosmos (PhysCOS), Cosmic Origins (COR), and Exoplanet Exploration Program (ExEP).

Astrophysics Archives: https://www.astrostrategictech.us/
TechPort: https://techport.nasa.gov/dashboards

# Astrophysics Technology Budget
## (building blocks)

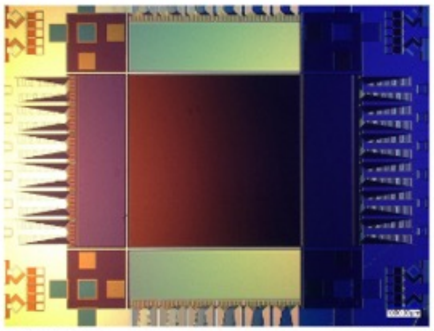


# In FY24, 54 ongoing technology maturation programs o



## Quantum Detection: Superconducting Nanowire Single-Photon Detectors

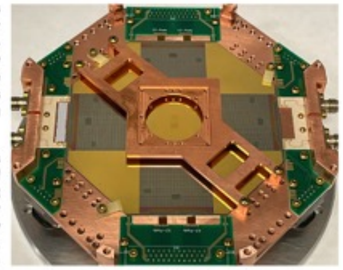
When imaging faint objects such as distant stars or exoplanets orbiting them, cameras must capture every single photon with extremely low noise. Superconducting cameras excel in both criteria but have historically not been widely applicable because they rarely exceeded a few thousand pixels, limiting their ability to capture high-resolution images. A team of researchers recently shattered that barrier with a 400,000-pixel superconducting camera that could detect faint astronomical signals from the ultraviolet (UV) to the infrared (IR). For every billion photons captured by these superconducting cameras, fewer than ten may be due to noise. Because these detectors are so sensitive, it's hard to pack them densely without causing interference between pixels. In addition, since these detectors need to be kept cold, only a handful of wires can be used to carry signals from the camera to its warm readout electronics.



*A 400,000-pixel superconducting camera based on SNSPDs. Image credit: Adam McCaughan*

## New X-ray Detectors to View the High-Energy Universe

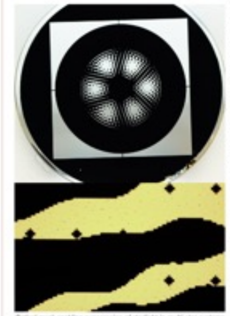
High-energy-resolution imaging X-ray spectrometers are crucial for studying galactic cores, needed for understanding galaxy formation. Large, high-angular-resolution imaging X-ray spectrometers help study the essential drivers of galaxy evolution, which leave imprints in the warm-to-hot plasma that cosmologists believe exists in the spaces between galaxies, making up to half of the universe's "normal matter."



*Prototype 100,000-pixel MMC array developed via collaboration between GSFC and MIT/LL. Image credit: Wonsik Yook*

Microcalorimeters are a class of X-ray spectrometers operating at very low temperatures, a few percent of a degree Kelvin above absolute zero. Over the past five years, groups at Goddard Space Flight Center (GSFC), Massachusetts Institute of Technology Lincoln Laboratory (MIT/LL), and NIST in Boulder, Colorado have been developing an ambitious new X-ray camera with unprecedented imaging and spectroscopic capabilities. This camera is based on a new type of X-ray detector, magnetic microcalorimeters (MMCs), which significantly extends the technology's capabilities. For example, the Japan Aerospace Exploration Agency/NASA's XRISM has a 36-pixel microcalorimeter array. The European Space Agency's flagship ATHENA mission, planned to launch in 2035, will fly a 2000-pixel microcalorimeter array. The NASA/MIT/NIST effort is working on a 100,000-pixel array, targeting angular scales and array sizes normally associated with CCD cameras, but with an energy resolution two orders of magnitude better.

## Detecting Exo-Earths in Multi-Star Systems



*Optical mask enabling suppression of starlight in multi-star systems, revealing planets in such systems (top). Microscopic detail showing mild periodic grating ("v" shapes) that enables MSWC (bottom). This mask is planned to fly as a contributed mode on the Roman Space Telescope coronagraphic instrument. Image credit: Eduardo Bendek*

Imaging exoplanets in single-star systems requires a ten-orders-of-magnitude starlight suppression to avoid losing the dim reflected light from the exoplanet in the star's glare. This challenge is even greater in the many nearby star systems, such as Alpha Centauri, that are home to multiple stars. To image exo-Earths in such systems and search them for signs of life, we need a multi-star wavefront-control (MSWC) technology to suppress the light from all the stars in that system.

MSWC, invented at NASA's Ames Research Center (ARC) in 2014, relies on two innovations. The first is a way to control a DM to suppress light from two stars independently using two different sets of shapes (spatial frequency modes) on the DM for different stars. The second technique, "super-Nyquist wavefront control," allows DMs to suppress starlight beyond their normal limits by using a special "mild grating" (image).

Normally, a DM can only suppress starlight in a small region around a star – a DM control region. This poses a problem when imaging binary stars because a typical DM can only suppress starlight from both stars if those stars' control regions overlap. However, binary stars tend to be far apart, so there's no overlap. The mild grating solves this problem by creating a grid of faint copies of the second star ("diffraction orders"), extending the DM's reach to a much larger region around each star. Merging the two techniques, a coronagraph can overcome cross-contamination and increase starlight contrast to image exoplanets in binary star systems.

Because DMs will be present in all future coronagraphic


Detecting Exo-Earths in Multi-Star Systems

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## Deformable Mirrors in Space: Enabling Direct Imaging of Exo-Earths

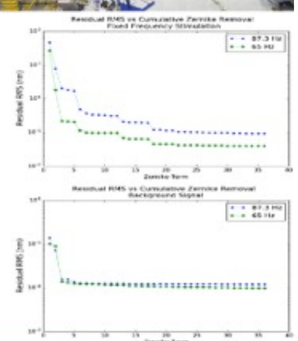
*A Boston Micromachines Corporation (BMC) 2k DM with 2040 actuators on a 400-μm pitch. Image credit: Eduardo Bendek*

Finding and studying Earth-like planets orbiting nearby stars is critical to understanding if we are alone in the universe. To study such planets and assess if they can sustain life, they must be directly imaged. However, glare from the host star is ten billion times brighter than the light reflected by the planet, overwhelming the signal. A coronagraph can remove that glare. Deformable mirrors (DMs) are essential components of coronagraphs, as they can correct the tiniest of imperfections in the telescope, down to under half a billionth of an inch, 10 picometers (pm) – a fraction of the size of a hydrogen atom – removing any remaining starlight contamination.

DMs adjust the optical path of incoming light by changing the shape of a reflective mirror using precisely controlled piston-like actuators. These adjustments "correct" the wavefront that's perturbated by optical aberrations upstream and downstream of the DM, such as defects and/or optical misalignments internal to the telescope that may be driven by changing thermal gradients as the telescope and detectors are heated or cooled.

## Ultra-Stable Testbed: Enabling Development of the Habitable Worlds Observatory

HWO, recommended by Astro2020, will directly image 25 exo-Earths in search of biosignatures. This requires high contrast, $10^{-10}$, and even more demanding contrast stability, $10^{-11}$. Contrast stability requires maintaining a stable telescope prescription, defined by the shape and position of all optical elements, affected by environmental effects such as mechanism vibrations and slow thermal drift of the metering structure and optical elements. To achieve such remarkable contrast stability, the primary mirror must be stable to 10 pm, a fraction of a hydrogen atom size, over a seconds-to-minutes telescope control cycle.



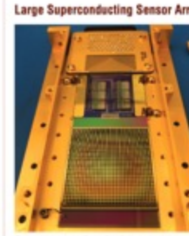


Designing such a telescope requires a new spatial metrology system and new environmental controls to measure component and system stability to a corresponding level. A GSFC Strategic Astrophysics Technology (SAT) team, led by Babak Saif and Lee Feinberg, with representatives from the Space Telescope Science Institute and the Smithsonian Astrophysical Observatory, is developing the Ultra-stable Structures Laboratory to enable the design and development of large ultra-stable telescopes.

The lab can measure pm dimensional stability of both dynamic and temporal disturbances for diffuse and specular surfaces at rates up to 5.9 kHz and temperature control <±1 mK – very challenging precision. By comparison, jet engine components are controlled to tens of μm, 10[illegible]× less stringent, and the James Webb Space Telescope's (JWST)

*The first version of the High-Speed Interferometer was used to measure*

## Large Superconducting Sensor Arrays Enabling Far-IR Observatories



*The interface between a "Double Stack" detector (bottom component) and cryogenic readout SQUID multiplexers (above the detector). Image credit: Felipe A. Colazo Petit*

Astro2020 recommended a series of flagships and Probe-class missions, including far-IR imaging or spectroscopy ones, requiring cryogenic telescopes with unprecedented sensitivities and mapping speeds. Such missions could measure the masses of protoplanetary disks; track the role of water, ice, and volatiles in planet formation; investigate the interplay between the interstellar medium and star formation across the Milky Way; and diagnose the state of gas and its radiation environment in nearby galaxies, including outer galaxy disks and extra-planar material associated with feedback and gas accretion. These advanced telescopes could also study the evolution of galaxies and the matter they're made of throughout the history of the universe, from the formation of the first dust clouds to star-forming galaxies at the cosmic noon (when significantly more stars were formed per time unit than today) and perform detailed investigations of the matter making up the Milky Way. Far-IR observatories can see through layers of matter that block visible light. They can observe the super-massive black holes embedded in the dense central regions of many galaxies, allowing astronomers to determine how black-hole creation proceeded throughout the universe's history.

# SBIR Astrophysics Technology Highlight

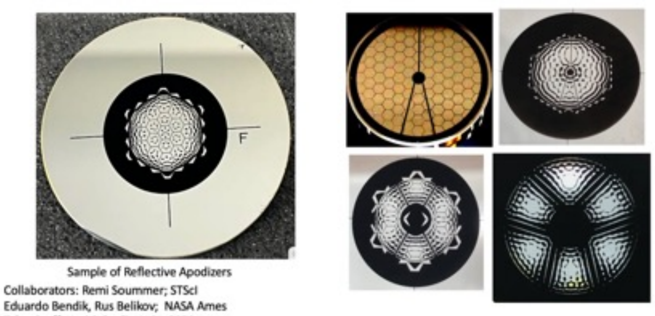
## September 3, 2024

## Carbon Nanotubes and the Search for Life on Other Planets

A NASA-developed material made of carbon nanotubes will enable our search for exoplanets — some of which might be capable of supporting life. Originally developed in 2007 by a team of researchers led by Innovators of the Year John Hagopian and Stephanie Getty at NASA's Goddard Space Flight Center, this carbon nanotube technology is being refined for potential use on NASA's upcoming Habitable Worlds Observatory (HWO) — the first telescope designed specifically to search for signs of life on planets orbiting other stars.

As shown in the figure below, carbon nanotubes look like graphene (a single layer of carbon atoms arranged in a hexagonal lattice) that is rolled into a tube. The super-dark material consists of multiwalled carbon nanotubes (i.e., nested nanotubes) that grow vertically into a "forest." The carbon nanotubes are 99% empty space so the light entering the material doesn't get reflected. Instead, the light enters the nanotube forest and jiggles electrons in the hexagonal lattice of carbon atoms, converting the light to heat. The ability of the carbon nanotubes to eliminate almost all light is enabling for NASA's scientific instruments because stray light limits how sensitive the observations can be. When applied to instrument structures, this material can eliminate much of the stray light and enable new and better observations.

Reflective Apodizers delivered to NASA Ames, GSFC and STScI



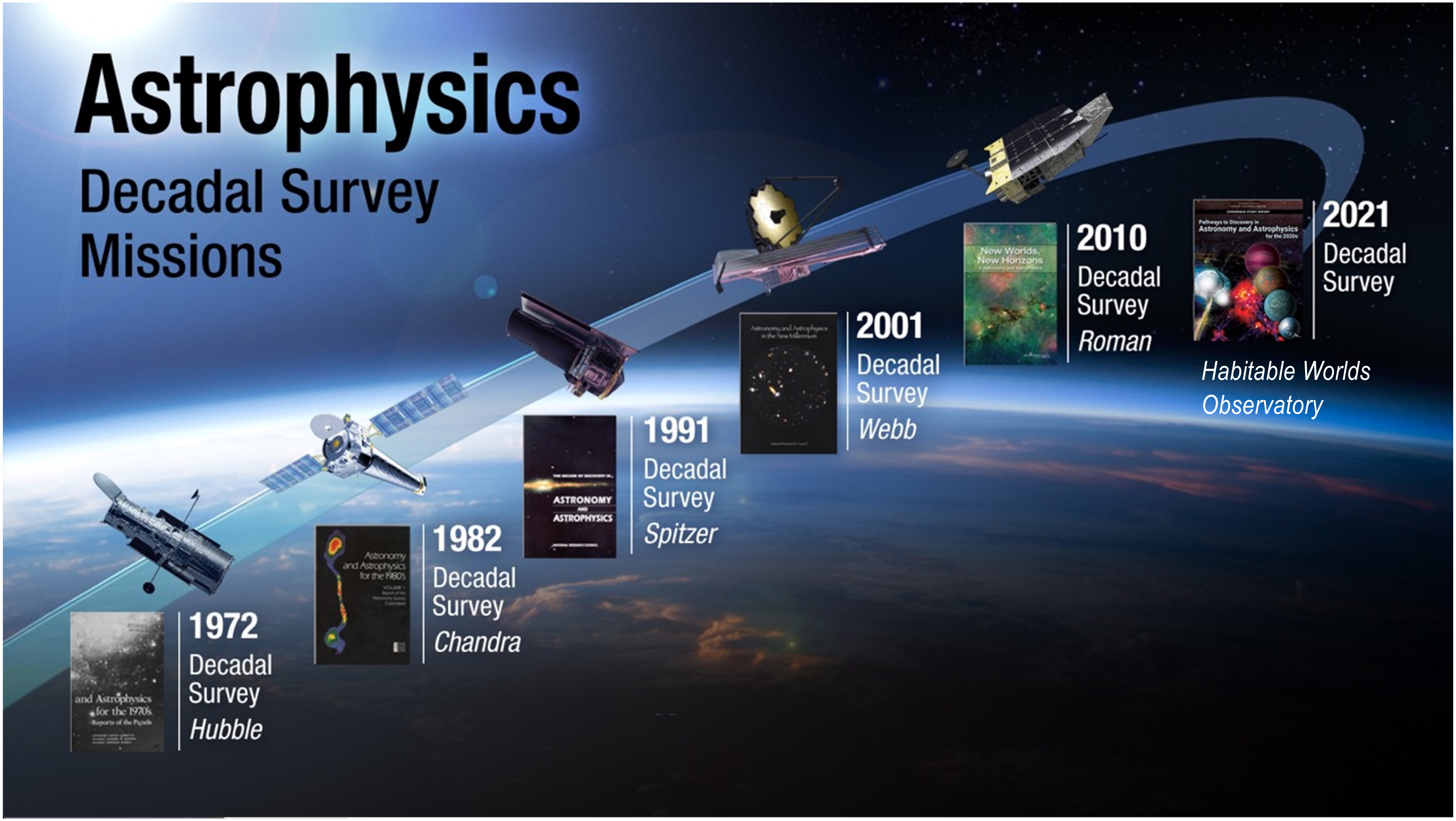

Sample of Reflective Apodizers

Collaborators: Remi Soummer; STScI
Eduardo Bendik, Rus Belikov; NASA Ames
Tyler Groff, Hari Subedi; NASA GSFC

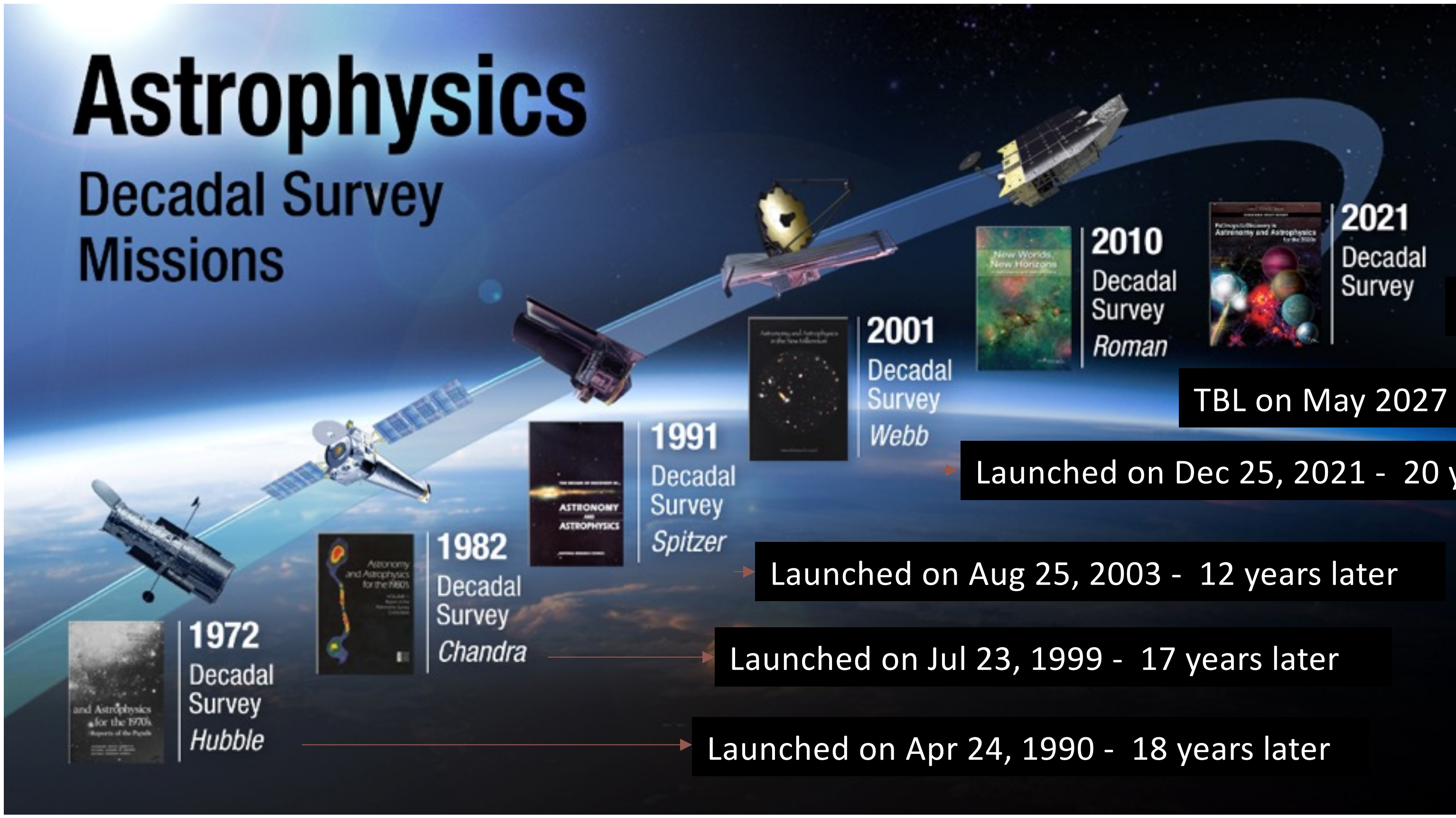
Tyler Groff (left) and John Hagopian (right) display a carbon nanotube patterned apodizer mirror used in the NASA Goddard Space Flight Center coronagraph test bed.

Credit: Advanced Nanophotonics/John Hagopian, LLC

# Why Do We Need This Workshop?


Astrophysics
Decadal Survey
Missions
1972
Decadal
Survey
Hubble
1982
Decadal
Survey
Chandra
1991
Decadal
Survey
Spitzer
2001
Decadal
Survey
Webb
2010
Decadal
Survey
Roman
2021
Decadal
Survey
Habitable Worlds
Observatory

# (1) Schedule: Long Life Cycle of Development and Implementation




TBL on 2040 - 20 years later

TBL on May 2027 - 17 years later

Launched on Dec 25, 2021 - 20 years later

Launched on Aug 25, 2003 - 12 years later

Launched on Jul 23, 1999 - 17 years later

Launched on Apr 24, 1990 - 18 years later

~17 years for Flagships

~20-30 years for components (e.g., detectors, optical elements)

# (2) Large Cost of Astrophysics Missions

- *“I’m not interested in estimating the precision of the cost of future Astrophysics missions and instrumentation; I’m only interested in lowering their costs”*
  - Paul Hertz, Past NASA HQ Astrophysics Director, circa 2013 (NAC Astrophysics Subcommittee meeting)
- *“Why Astrophysics flagship missions are so expensive?”*
  - Thomas Zurbuchen, Former NASA Associate Administrator for Science Mission Directorate, circa 2018.

# (3) Exquisite Performance: Astrophysics Technology Requirements

Demanding Requirements:

- S/C and/or Payload Ultrastability
- High Contrast Imaging
- Optics and Detectors:
  - Large Format
  - Spectral Resolution
  - High Dynamical Range
  - Zero Persistence
  - Negligible Noise
  - Fast Readouts
- Thermal Demands
- Zero Contamination

TECHNOLOGY GAPS

**Tier-1 Technology Gaps**

Coronagraph Contrast and Efficiency in the Near IR
Coronagraph Contrast and Efficiency in the Near UV
Coronagraph Stability
Cryogenic Readouts for Large-Format Far-IR Detectors
Fast, Low-Noise, Megapixel X-ray Imaging Arrays with Moderate Spectral Resolution
High-Bandwidth Cryogenic Readout Technologies for Compact and Large-Format Calorimeter Arrays
High-Efficiency, Low-Scatter, High- and Low-Ruling-Density, High- and Low-Blazed-Angle UV Gratings
High-Efficiency X-ray Grating Arrays for High-Resolution Spectroscopy
High-Performance Sub-Kelvin Coolers
High-Reflectivity Broadband Far-UV-to-Near-IR Mirror Coatings
High-Resolution, Lightweight X-ray Optics
High-Throughput, Large-Format Object-Selection Technologies for Multi-Object and Integral-Field Spectroscopy
Integrated Modeling for HWO: Multi-Physics Systems Modeling, Uncertainty Quantification, and Model Validation
Large-Format, High-Resolution Far-UV (100-200 nm) Detectors
Large-Format, High-Resolution Near-UV (200-400 nm) Detectors
Low-Stress, Low-Roughness, High-Stability X-ray Reflective Coatings
Mirror Technologies for High Angular Resolution (UV/Visible/Near IR)
Optical Blocking Filters for X-ray Instruments
Scaling and Metrology for Advanced Broadband Mirror Coatings for HWO
Segmented-Pupil Coronagraph Contrast and Efficiency in the Visible Band
UV Multi-Object Spectrograph Calibration Technologies
UV Single-Photon Detection Sensitivity
Visible/Near-IR Single-Photon Detection Sensitivity

**Tier-2 Technology Gaps**

Advanced Cryocoolers
Broadband X-ray Detectors
Compact, Integrated Spectrometers for 100 to 1000 μm
Cryogenic Far-IR to mm-Wave Focal-Plane Detectors
Far-IR Imaging Interferometer for High-Resolution Spectroscopy
Far-IR Spatio-Spectral Interferometry
Heterodyne Far-IR Detector Systems
High-Performance Computing for Event Reconstruction
High-Resolution, Direct-Detection Spectrometers for Far-IR Wavelengths
High-Throughput Focusing Optics for 0.1-1 MeV Photons
High-Throughput UV Bandpass Standalone and Detector-Integrated Filters and Bandpass Selection
Improving the Calibration of Far-IR Heterodyne Measurements
Large-Format, High-Spectral-Resolution, Small-Pixel X-ray Focal-Plane Arrays
Large-Format, Low-Noise and Ultralow-Noise, Far-IR Direct Detectors
Low-Power Readout and Multiplexing for CMB Detectors
Millimeter-Wave Focal-Plane Arrays for CMB Polarimetry
Optical Elements for a CMB Space Mission
Starshade Deployment and Shape Stability
Starshade Starlight Suppression and Model Validation
Stellar Reflex Motion Sensitivity: Astrometry
Stellar Reflex Motion Sensitivity: Extreme Precision Radial Velocity
Warm Readout Electronics for Large-Format Far-IR Detectors

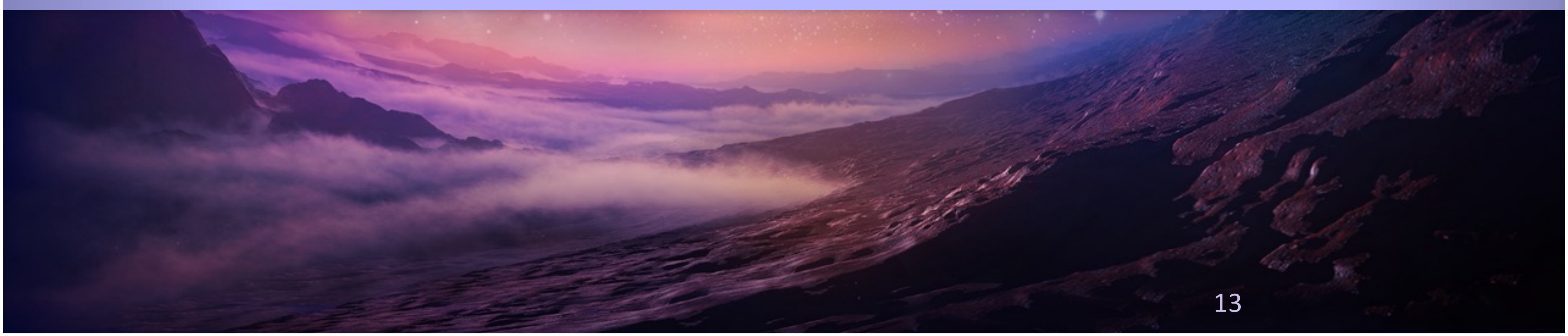
**Tier-3 Technology Gaps**

Broadband X-ray Polarimeter
Charged-Particle-Discriminating X-ray/Gamma-Ray Detectors
Dynamic Switching for Ultra-Low-Power, High-Resolution Charge Readout
High-Energy-Resolution Gamma-Ray Detectors
Large-Aperture Deployable Antennas for Far-IR/THz/sub-mm Astronomy for Frequencies Above 100 GHz
Large Cryogenic Optics for the Mid IR to Far IR
Large Field-of-View and Effective-Area Gamma-Ray Detectors
Low-Power, Low-Cost Semiconductor Detectors
Low-Power Readout for Silicon Photomultipliers
Photometric and Spectro-Photometric Precision of Time-Domain and Time-Series Measurements
Precision Timing Measurement Technology
Radiation-Tolerant, Photon-Counting Light Detectors
Sensitive Spectrometer for CMB Spectrum Measurement
UV/Optical/Near-IR Tunable Narrowband Imaging Capability

**Non-Strategic**

Advancement of X-ray Polarimeter Sensitivity
Detection Stability in Mid-IR

# Astrophysics’ Uniqueness

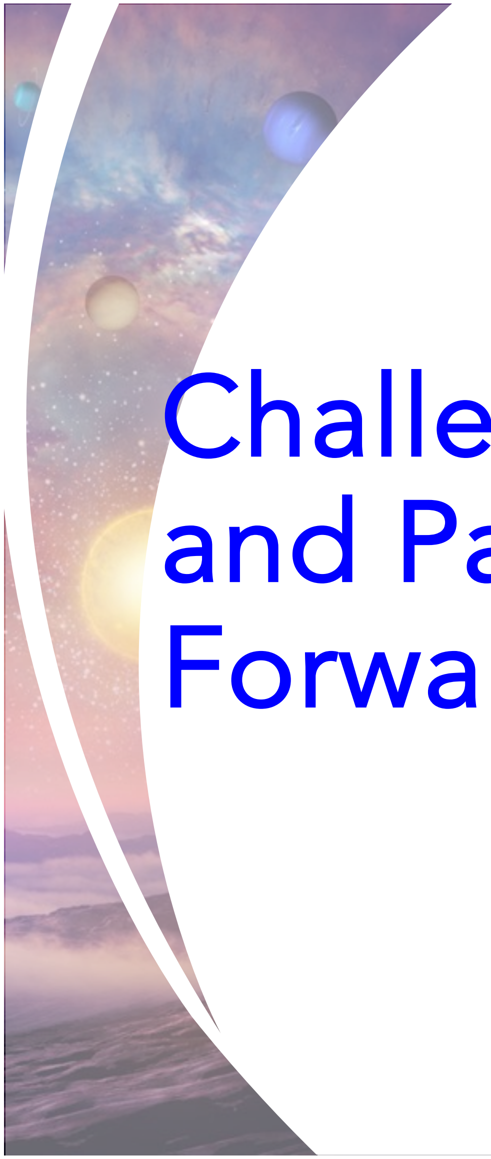


# The Uniqueness and Exceptionalism of Space-Based Observational Astrophysics

NASA Astrophysics addresses the most difficult and profound questions about the nature and origin of the Universe and is seeking life outside our Solar System.

Astrophysics is a photon-starved discipline, demanding exquisite performance from all systems and subsystems utilized in on-sky observation and detection.

Current astrophysical science and technology requirements are exquisite and highly demanding (e.g., search for life, dark matter, dark energy) that makes them enabling for astrophysical research but enhancing for the rest of other sciences and applications.



# Challenge and Path Forward

*"None of the obstacles to reach the next level of detection in observational astrophysics are astrophysical in nature; they are technological in nature."*

# Connection of Observational Astrophysics and Technology

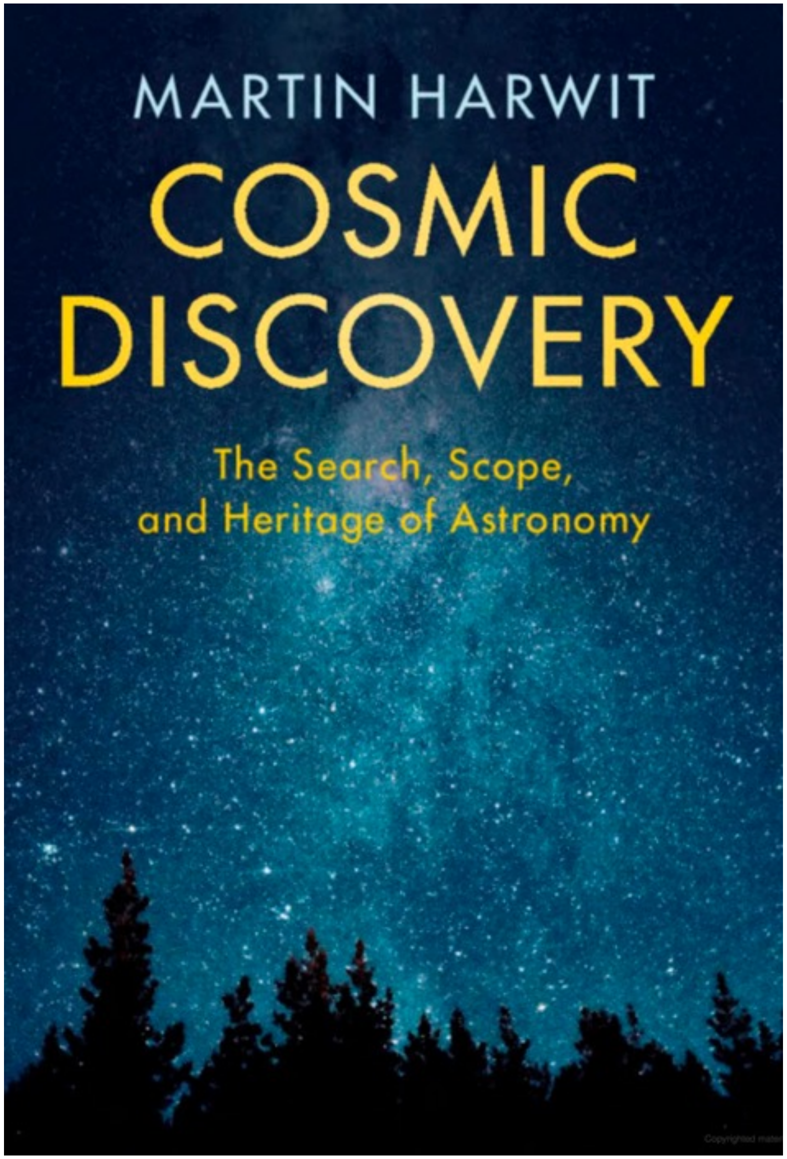
*"Groundbreaking discoveries in astrophysics are directly related to advancements in technology."*

Corollary: *Lack of investments on technologies will impact negatively science achievements.*

# The Urgent Need of Innovation and Better Practices

- In the efforts of lowering the cost of space missions, *innovation is not an option; it is required to break the current paradigm of practices and status-quo.*
- Innovation initiatives should be a unified and focused effort by academia, industry and government laboratories.
- *"For a great many (space) missions, we should be able to reduce cost by a factor of 5 to 10, while maintaining high reliability and reducing fragility and vulnerability. If, instead, we continue with business as usual, we simply don't have enough money to do the things that we need to do and want to do in space."*

https://smad.com/wp-content/uploads/2018/09/Cost-Reduction-paper.pdf

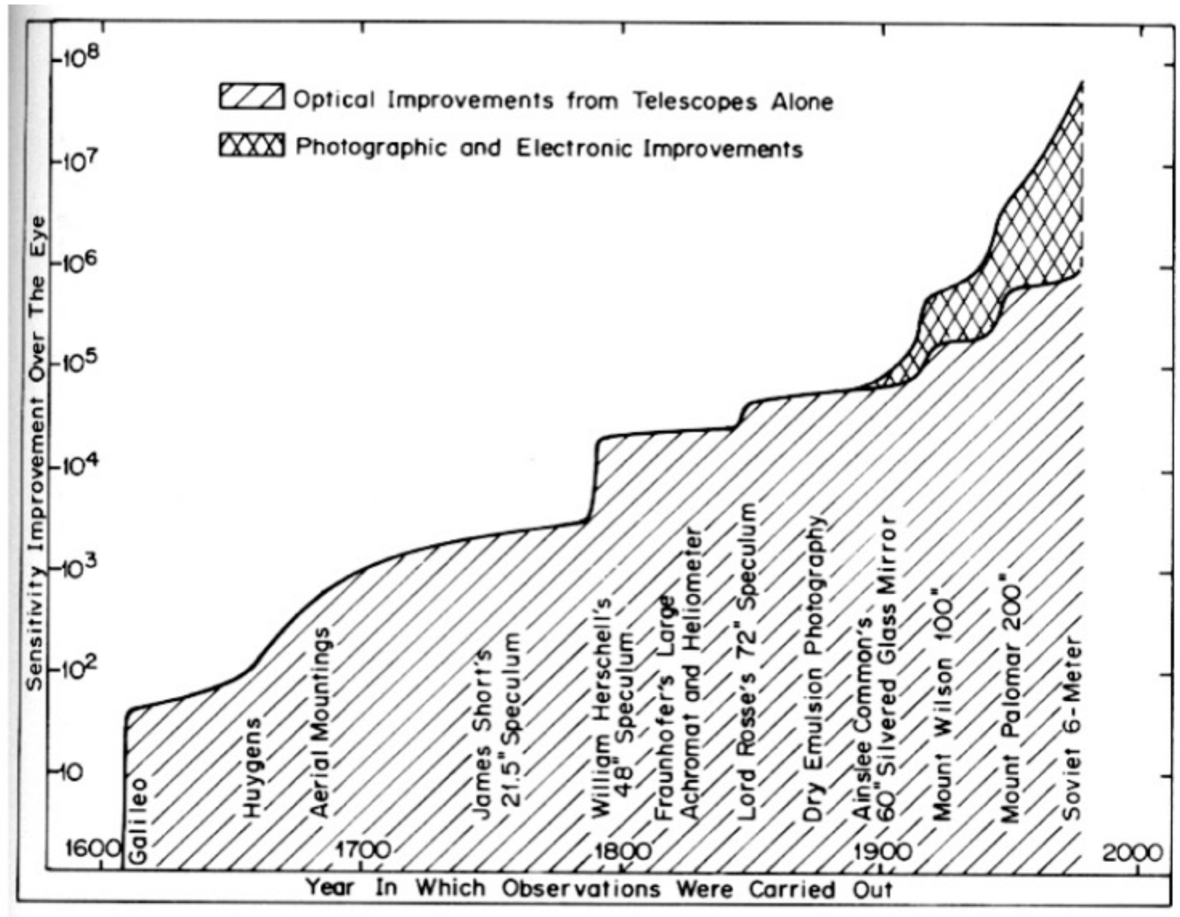



# Cosmic Discovery
## by Martin Harwit (1981)

*"When I wrote Cosmic Discovery, I wanted to dispel two mystiques. The first was that advances in astrophysics came about as a result of theoretical insight; the second was that further advances would require the building of ever-larger optical telescopes. The only way I could show that neither was relevant was to document the [often] surprising discoveries brought about by small radio, infrared, x-ray, and gamma-ray telescopes. Neither theory nor large optical telescopes had delivered anything like these novel technologies."*

*- Physics Today, Q&A with Martin Harwit, 10 October 2014*

Cosmic Discovery (1981)
by Martin Harwit



*“Progress in astronomy is largely driven by advances in technology. Yet, only a tiny fraction of the worldwide investment in technology directly targets the needs of astronomy, so astronomers must seek to leverage and harness technology advancements made for other purposes.”*

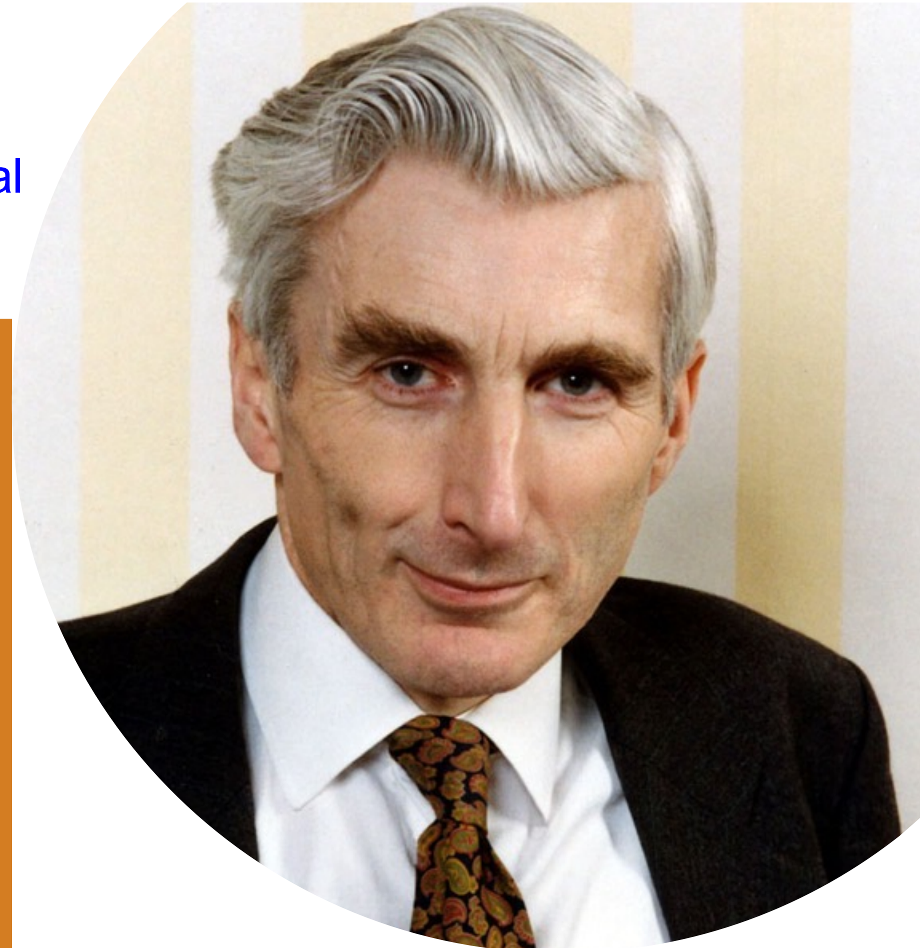
- *Jonas Zmuidzinas (2020), Caltech Professor*

# A Royal Opinion

## Sir Martin Rees, UK Astronomer Royal

*"But it is important to emphasize that progress will continue to depend, as it has up till now, **ninety-five percent on advancing instruments and technology**—less than five percent on armchair theory, but that theory will be augmented by artificial intelligence and the ability to make simulations."*

*(Taken from "Towards a New Enlightenment? A Transcendent Decade" by Martin Rees, 2019)*



# Astrophysics Innovations

# Innovation

*"The electric light bulb did not come from continuous improvement of candles"*

# WORKSHOP

# Emerging Technologies for Astrophysics Missions

*(invitation only)*

## March 25-27, 2025

## NASA Ames Conference Center
## Mountain View, CA

# Emerging Technologies for Astrophysics Missions

**Astrophotonics**

(as applied to spectroscopy and imaging)

**Artificial Intelligence and Machine Learning Algorithms**

(for technology development)

**Advanced Materials**

(meta-materials, nanofabrication, additive manufacturing, composites)

**Quantum Technologies**

(sensing, imaging, calibration)

Article

# A superconducting nanowire single-photon camera with 400,000 pixels

https://doi.org/10.1038/s41586-023-06550-2

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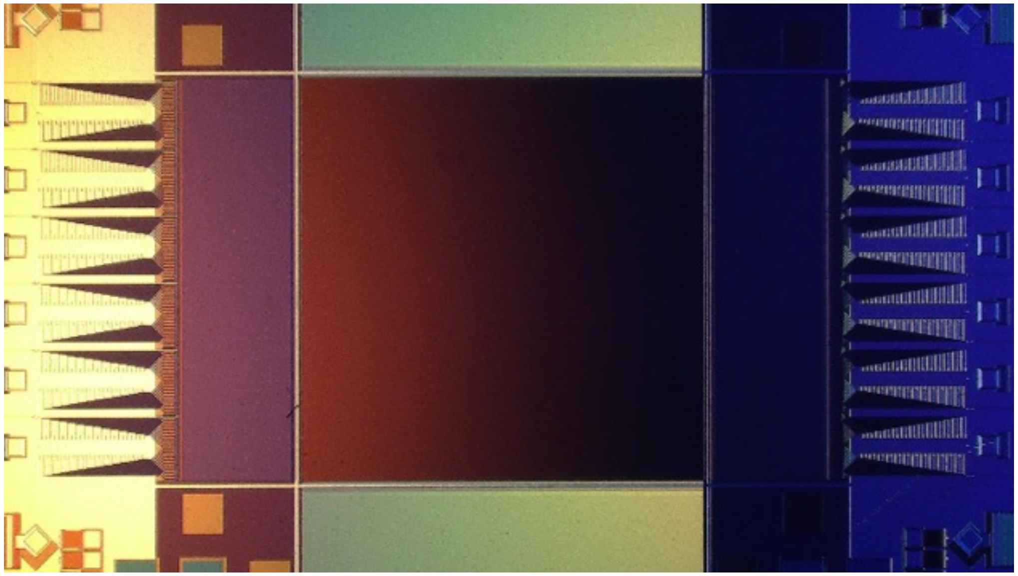
Check for updates

B. G. Oripov[1,2✉], D. S. Rampini[1,2], J. Allmaras[3], M. D. Shaw[3], S. W. Nam[1], B. Korzh[3] & A. N. McCaughan[1]

For the past 50 years, superconducting detectors have offered exceptional sensitivity and speed for detecting faint electromagnetic signals in a wide range of applications. These detectors operate at very low temperatures and generate a minimum of excess noise, making them ideal for testing the non-local nature of reality[1,2], investigating dark matter[3,4], mapping the early universe[5–7] and performing quantum computation[8–10] and communication[11–14]. Despite their appealing properties, however, there are at present no large-scale superconducting cameras—even the largest demonstrations have never exceeded 20,000 pixels[15]. This is especially true for superconducting nanowire single-photon detectors (SNSPDs)[16–18]. These detectors have been demonstrated with system detection efficiencies of 98.0% (ref. 19), sub-3-ps timing jitter[20], sensitivity from the ultraviolet[21] to the mid-infrared[22] and microhertz dark-count rates[3], but have never achieved an array size larger than a kilopixel[23,24]. Here we report on the development of a 400,000-pixel SNSPD camera, a factor of 400 improvement over the state of the art. The array spanned an area of 4 × 2.5 mm with 5 × 5-μm resolution, reached unity quantum efficiency at wavelengths of 370 nm and 635 nm, counted at a rate of $1.1 \times 10^5$ counts per second (cps) and had a dark-count rate of $1.0 \times 10^{-4}$ cps per detector (corresponding to 0.13 cps over the whole array). The imaging area contains no ancillary circuitry and the architecture is scalable well beyond the present demonstration, paving the way for large-format superconducting cameras with near-unity detection efficiencies across a wide range of the electromagnetic spectrum.



- **Quantum Sensing**

*“In the search for life, we are going to need nearly perfect detectors. Superconducting detectors are not perfect, but they are closer in their noise performance than semiconductor detectors.”*

- ***Bernard Rauscher, NASA GSFC Scientist and Technologist (2024)***

# 2025 – International Year of Quantum Science and Technology (IYQ)

- The United Nations has declared 2025 to be the International Year of Quantum Science and Technology (IYQ) to celebrate 100 years of quantum mechanics.

INTERNATIONAL YEAR OF
Quantum Science
and Technology

ASTROPHYSICS DIVISION

January 2025


# Others Areas of Innovation for Astrophysics (not included in this workshop)

- Solid State Refrigeration
- Electric Propulsion-Microthrusters
- Optical Communications
- Space Assembly and Manufacturing
- Advanced Cryogenics

# Future Opportunities and Challenges

JPhys Photonics

**ACCEPTED MANUSCRIPT · OPEN ACCESS**

## 2023 Astrophotonics Roadmap: pathways to realizing multi-integrated astrophotonic instruments

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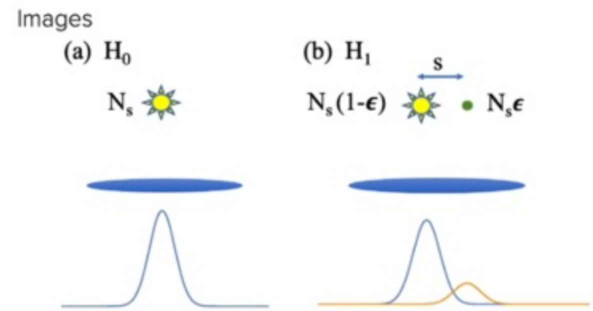
## Quantum Hypothesis Testing for Exoplanet Detection

Zixin Huang and Cosmo Lupo
Phys. Rev. Lett. **127**, 130502 – Published 23 September 2021




$\epsilon$ depends on:

1. angular separation between the star and the planet,
2. the brightness ratio of the two objects, and
3. the number of photos collected by the telescope.

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optica

## Deterministic phase measurements exhibiting super-sensitivity and super-resolution

Clemens Schäfermeier,[1,2,*] Miroslav Ježek,[3] Lars S. Madsen,[1,4] Tobias Gehring,[1] and Ulrik L. Andersen[1,5]

[1]Technical University of Denmark, Department of Physics, Fysikvej 309, 2800 Kongens Lyngby, Denmark
[2]Kavli Institute of Nanoscience, Delft University of Technology, 2628 CJ Delft, The Netherlands
[3]Department of Optics, Faculty of Science, Palacky University, 17. listopadu 1192/12, 77146 Olomouc, Czech Republic
[4]Currently at Centre for Engineered Quantum Systems, School of Mathematics and Physics, University of Queensland, St. Lucia, QLD 4072, Australia
[5]e-mail: ulrik.andersen@fysik.dtu.dk
*Corresponding author: clemens@fh-muenster.de

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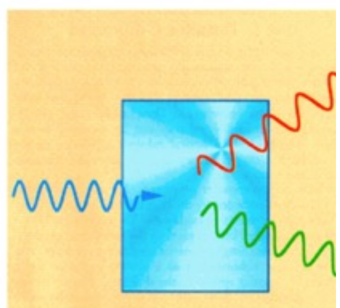
Phase super-sensitivity is obtained when the sensitivity in a phase measurement goes beyond the quantum shot noise limit, whereas super-resolution is obtained when the interference fringes in an interferometer are narrower than half the input wavelength. Here we show experimentally that these two features can be simultaneously achieved using a relatively simple setup based on Gaussian states and homodyne measurement. Using 430 photons shared between a coherent and a squeezed vacuum state, we demonstrate a 22-fold improvement in the phase resolution, while we observe a 1.7-fold improvement in the sensitivity. In contrast to previous demonstrations of super-resolution and super-sensitivity, this approach is fully deterministic. 

**OCIS codes:** (270.0270) Quantum optics; (270.6570) Squeezed states; (120.5050) Phase measurement.

https://doi.org/10.1364/OPTICA.5.000060

## Correlated-Ph Photo-Detector



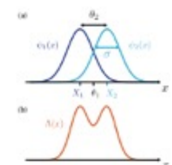
Physics Today, January 1999, 41
Twin-photon techniques for photo-detector calibration, G. Brida et al. 2006, Laser Physics Letters, 3, 115
Absolute calibration of a charge-coupled device camera with twin beams, A. Meda, et al. 2014, Appl. Phys. Lett. 105, 10113

Jet Propulsion Laboratory
California Institute of Technology
National Aeronautics and Space Administration

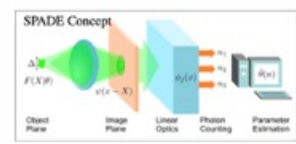
## Super-resolution Detection

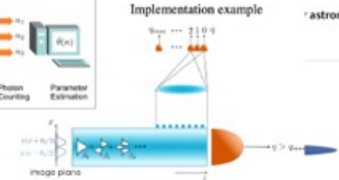
**Spatial- mode demultiplexing (SPADE) or pre-detection mode sorting for sub-Rayleigh resolution**
(From Quantum Information Theory)

PHYS. REV. X 6, 031033 (2016)
Optica, Vol.6(5), pp.534-541; 2019-05-20;

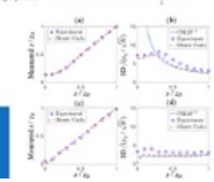


Wave diffraction limited resolution
Rayleigh criteria




Physical explanation: Multiple modes are used for centroid discrimination, which has the exquisite sensitivity of the mode-coupling efficiencies to the offset of the wave functions from the centroid.



**Challenges:**
- High efficiency linear mode transformation optics
- Number of modes for full imaging

SYNOPSIS

n

astronomers to

20


From innovation to application
From innovation to application

# From Innovation to Infusion

**159 infusions** and **68 potential infusions** (definitions below) resulting from **APD funding** to technology-maturation PIs (from Jan 2009 to Dec 2024; includes SAT/ISFM funding and APRA funding of SAT/ISFM PIs)

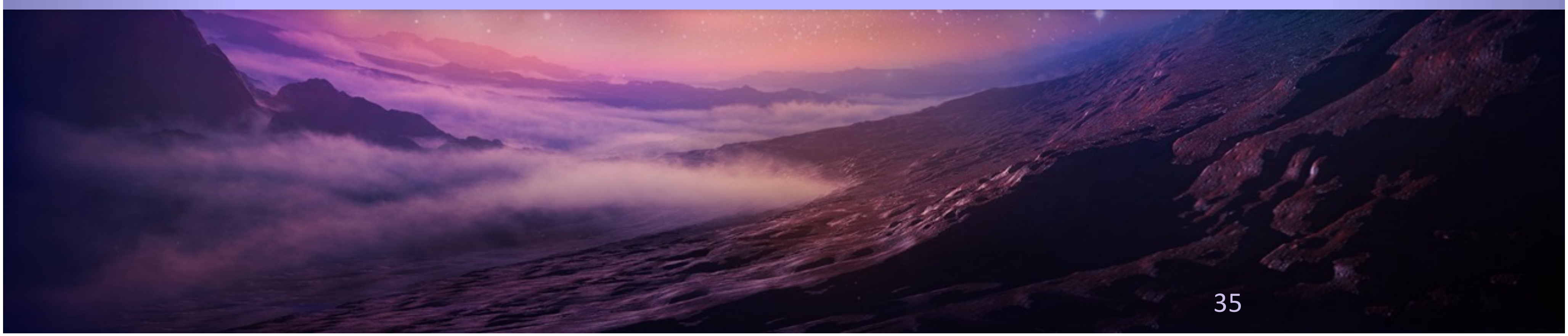
| | | Space | Rocket | Balloon | Airborne | Ground | Total |
|---|---|---|---|---|---|---|---|
| Infused | Implemented[1] | 20 | 29 | 13 | 3 | 43 | **108** |
| | Upcoming[2] | 30 | 9 | 5 | 1 | 6 | **51** |
| **Infused Subtotal** | | **50** | **38** | **18** | **4** | **49** | **159** |

1. **Implemented** in a past or current flight mission or ground-based project (e.g., Hitomi, XRISM, ICON, Solar Orbiter).
2. **Upcoming** flight mission or ground project (e.g., RST, LISA, ATHENA, Sprite CubeSat) baselined the tech.

| | | Space | Rocket | Balloon | Airborne | Ground | Total |
|---|---|---|---|---|---|---|---|
| Potential | Concepts[3] | 66 | - | - | - | - | **66** |
| | Ready[4] | 2 | - | - | - | - | **2** |
| **Potential Subtotal** | | **68** | **-** | **-** | **-** | **-** | **68** |
| **Infused/Infusable Total** | | **118** | **38** | **18** | **4** | **49** | **227** |

3. **Concept** or reference design of APD-funded large-mission study (LUVOIR, HabEx, Lynx, Origins); Probe (e.g., PICO, AXIS, GEP, CETUS, AXIS, PRIMA); or Phase-1 Explorer or Mission of Opportunity study/proposal (e.g., STAR-X) baselined the tech.
4. **Infusion-ready** at TRL 5 but not yet included in any of the above categories, likely due to lack of opportunity.

# Astrophysics Technology Lessons



# Astrophysics Technologies Uniqueness Lessons Identified

1. Innovation to Infusion – long cycles of more than 20 years for technology infusion
2. Management of Technology Grants – needs active management and contacts
3. “Failure is an Option” – technology programs should be experimental with some risks
4. NASA Internal versus External Technology Scope – constant tension, no final answer
5. Experimental Astrophysicists are Closer to the Science – unique feature in astrophysics
6. Critical Role of Innovation in Astrophysics – A way to reduce cost, schedule and increase performance
7. Broad Scope of Astrophysics Technology Gaps – Exquisite requirements make astrophysics unique
8. Importance of System Engineering – Crucial in the design and implementation of new missions
9. The Duty of Broadcasting and Promoting Technology Gaps – There is merit in informing the community

# Deliverables & Path Forward

# What this Workshop is and is NOT

- Not to create more R&D activities
- Not to blame anyone or anything for our challenges
- Not to solve concrete problems, but to **identify applications**
- Not to find or create reasons why these technologies are impossible
- Not to give up on trying new and innovate solutions for future astrophysics missions

- Yes, to move disruptive ideas to a higher technology readiness level (TRL)
- Yes, to push innovative solutions on their path to mission infusion
- Yes, to experimentation and prototyping solutions
- Yes, to testbeds tinkering
- Yes, to true technological breakthroughs

# DELIVERABLES

- REPORT TO ASTROPHYSICS DIVISION (April-May)

ASTROPHYSICS
NASA Science Mission Directorate

- Path Forward:
  - Add to current solicitations
  - Create new solicitations for Emerging Technologies

- Broadcast Results
- Share within NASA
- Partner with OGAs & Industry

# The End