National Aeronautics and Space Administration

NASA

PCOS COR

Physics of the Cosmos Cosmic Origins

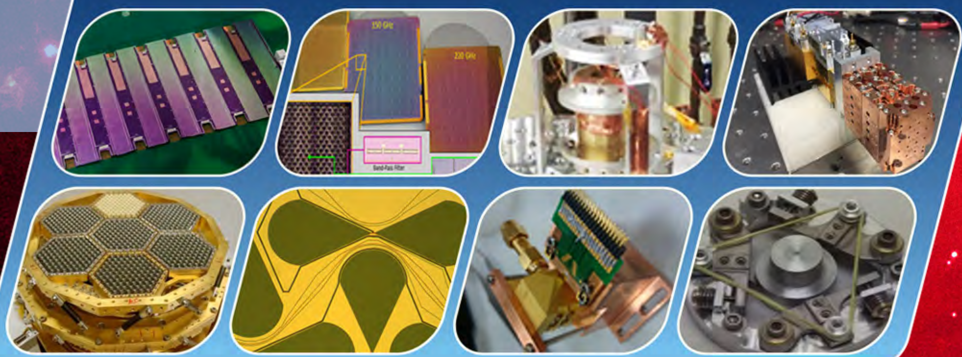
Astrophysics Program Office

Technology Development Highlights 2018

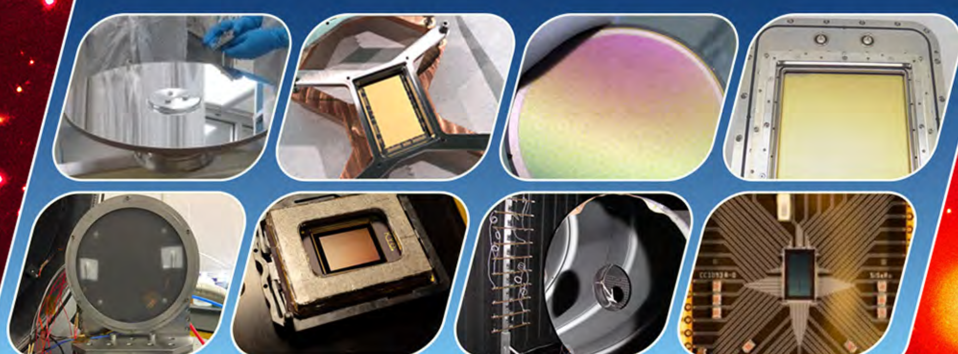
NASA Astrophysics Science Programs

NASA's Astrophysics Division set up three science Programs, Physics of the Cosmos (PCOS), Cosmic Origins (COR), and Exoplanet Exploration Program (ExEP), to address three fundamental questions: "**How does the universe work**?" (PCOS) "**How did we get here?**" (COR) and "**Are we alone?**" (ExEP).

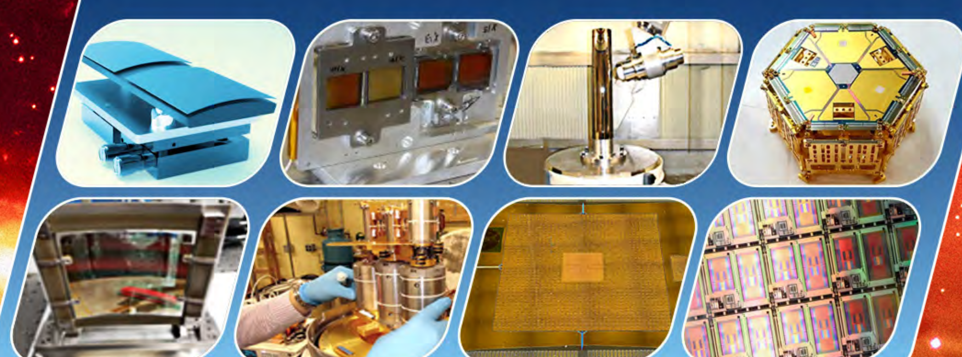
Far-IR/Sub-mm-Related Technologies



UVOIR-Related Technologies



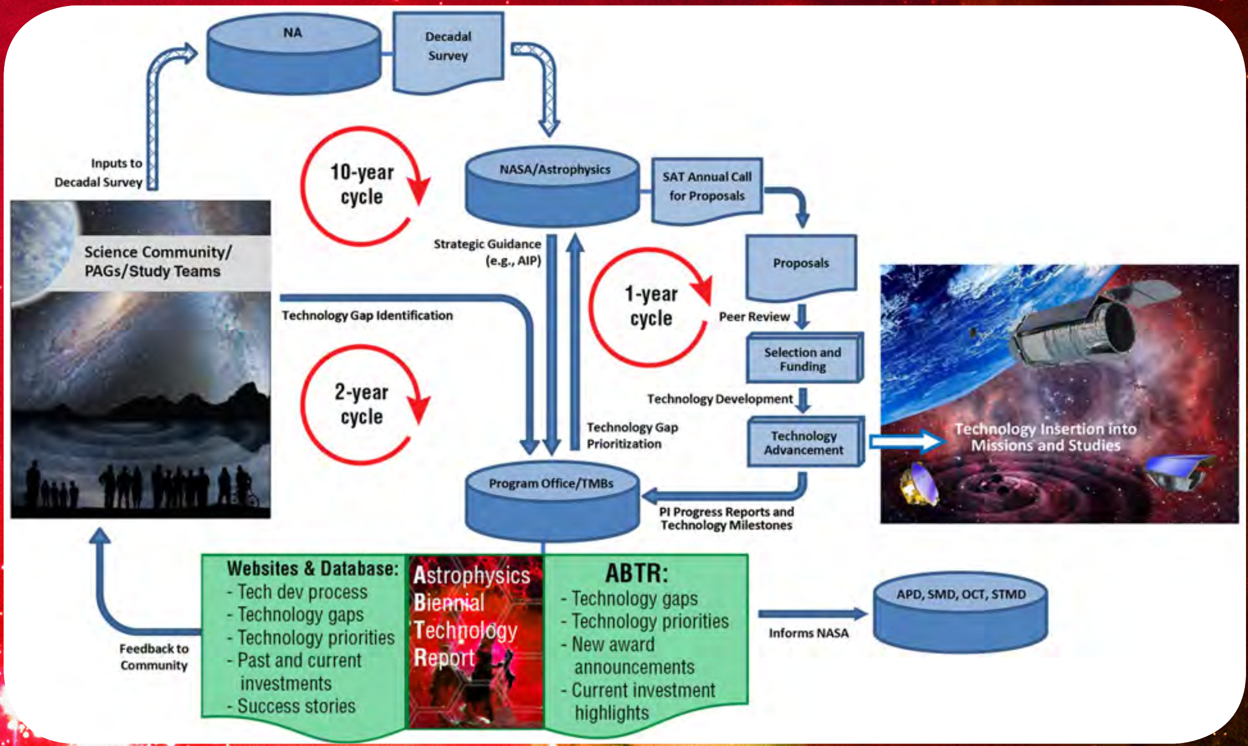
X-Ray-Related Technologies



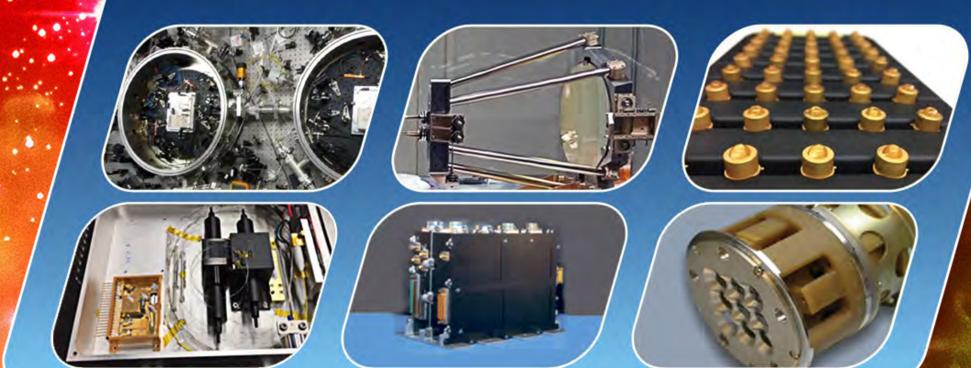
PCOS and COR Program Office Technology Development

The PCOS and COR Program Office serves the critical function of developing concepts and technologies for strategic missions and facilitating science investigations derived from them [1], specifically:

- Assess and prioritize technologies, collecting inputs from the community and study teams [2], informing headquarters decisions on technology, solicitations, and investments.
- Manage projects that mature technologies for strategic missions from initial Technology Readiness Levels (TRLs) of 3, 4, or 5; including both competed Strategic Astrophysics Technology (SAT) and direct-funded projects.
- Promote infusion and leveraging of technologies into astrophysics missions and projects.
- Conduct mission studies and develop mission concepts to enable future scientific discoveries.
- Communicate progress to and coordinate with the scientific community.
- Inform the general public about progress achieved by the Programs.



Gravitational-Wave-Related Technologies



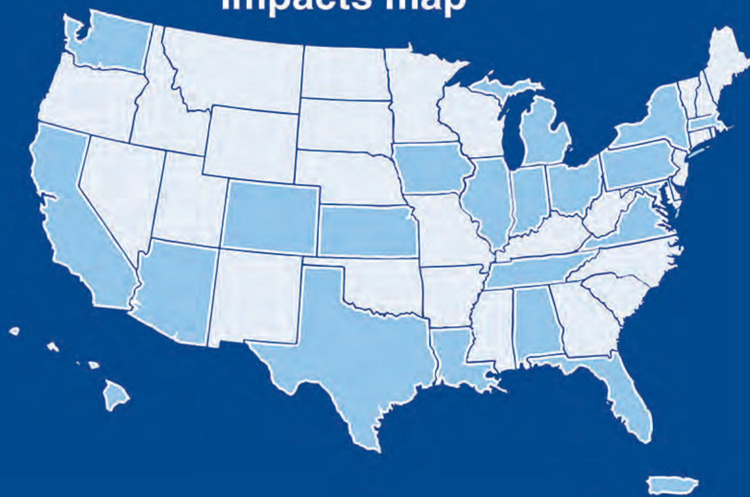
By the Numbers

Astrophysics Program Office Technology Development

88 Projects to date

56 Distinct technologies developed

Impacts map



43 projects active in 2018

5 Students and postdocs per project

29% Proposal win rate

30% advanced TRL

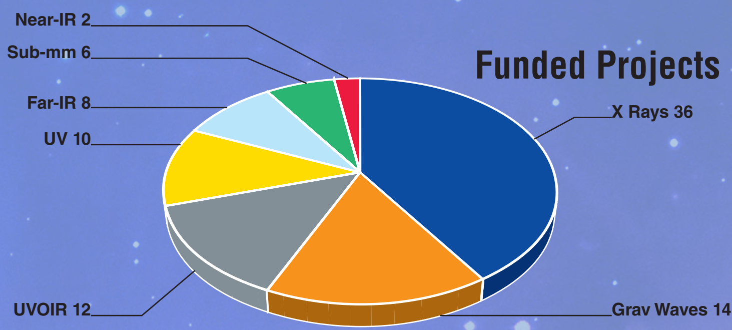
17 PI institutions

19 | 5 | 6 | 2 | 4

36 Technology infusions

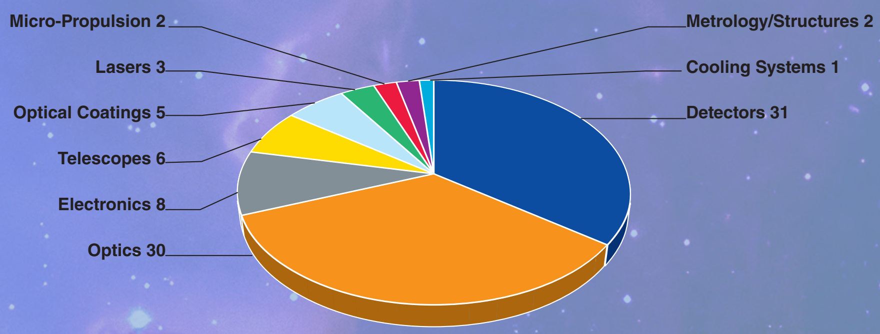
- 88 PCOS/COR technology projects funded to date at 17 PI institutions.
- 58 SAT projects competitively awarded from 2009 program inception to date.
- 29% SAT proposal win rate to date.
- Work spread across 22 states.
- 30% of technologies advanced TRL at least one level to date [3].
- 36 technology infusions (19 flown or baselined for space, 13 suborbital, 4 in ground-based observatories).
- Nearly 75% of projects hired an average of ~5 students and/or postdocs each, training our future astrophysics technology workforce for decades to come.

Signal types addressed include X rays, gravitational waves, UV/Optical/IR (UVOIR), UV, far-IR, sub-mm, and near-IR. Technology areas include detectors, optics, electronics, telescopes, optical coatings, lasers, and others, with approximately 70% of projects invested in detectors and optics.



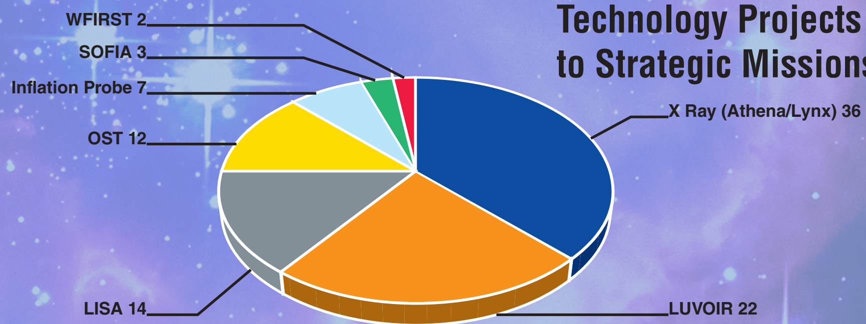
Funded Projects by Signal Type

Funded Projects by Technology Type



Each of the 88 projects supported (or still supports) at least one strategic mission*, and some supported more than one.

Technology Projects Applicable to Strategic Missions

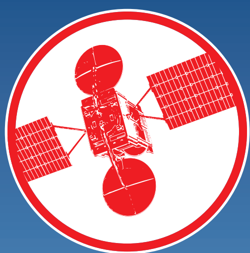


* Strategic astrophysics missions are medium- to large-class non-competed missions that the Astrophysics Division is developing, participating in, or interested in, to respond to high-priority science questions or mandates.

Technology Infusion Timeline

Infused* Technologies — 2010s

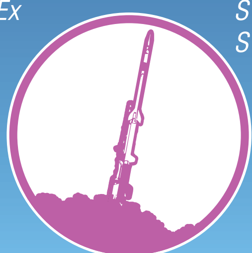
4.7 THz Local Oscillator
Advanced CCD Detectors
Antenna-Coupled TES Bolometers
Digital Micro-mirror Device (DMD)
Directly Deposited Optical Blocking Filters
Feedhorn-Coupled TES Detectors
Heterodyne Detectors
HIRMES
Phasemeter
TES Bolometers
TiN Kinetic Inductance Detectors (KIDs)
UV Coatings
X-ray Reflection Gratings



GOLD
GRACE-FO
ICON
OSIRIS-REx

BLAST-TNG
FIREBall
Spider
STO
STO-2

BICEP2
BICEP3/Keck
CLASS
SOAR



WRXR

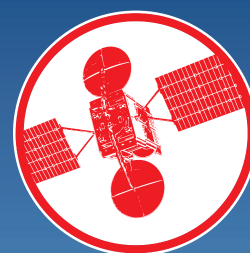
SOFIA (2 technologies)

Missions/Projects

- 4.7 THz local oscillator flew on STO-2
- Advanced CCD detectors flew on FIREBall
- Antenna-coupled detectors were deployed on BICEP2, BICEP3/Keck, and flew on Spider
- Directly deposited optical blocking filters flying on OSIRIS-REx
- DMDs were deployed on the 4.1-m SOAR telescope
- Feedhorn-coupled detectors will be deployed on CLASS
- Heterodyne detectors flew on STO
- HIRMES is planned to fly on SOFIA
- Phasemeter flying on GRACE Follow-On
- TES Bolometers for the HAWC+ flew on SOFIA
- TiN KIDs were integrated into BLAST-TNG balloon mission
- UV coatings flying on GOLD and will fly on ICON
- X-ray reflection grating flew on WRXR

Planned Technology Infusions

4.7 THz Local Oscillator
CMB Detectors
H4RG IR Detectors
Micro-Channel Plate (MCP) Detectors
Micro-Calorimeters
X-ray Reflection Gratings



Athena
LiteBIRD
SPRITE CubeSat
WFIRST

Missions/Projects

- 4.7 THz local oscillators are baselined for GUSTO
- CMB detectors are planned for LiteBIRD
- H4RG IR detectors are baselined for WFIRST
- MCP detectors to fly on SPRITE, INFUSE, and SIST
- Micro-calorimeters are baselined for Athena
- X-ray reflection gratings to be flown on OGRE and T

* Infusion here means that a technology was implem
by a mission, or incorporated into a strategic missi

As can be
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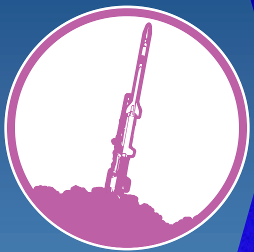
2020s

GUSTO

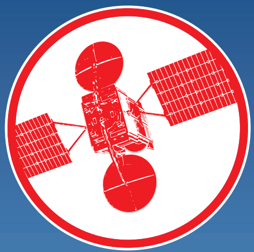


INFUSE
OGRE
SISTINE
TREXS

Planned Technology Infusions

2030s +

- Continuous ADR
- Directly Deposited Optical Blocking Filters
- MCP Detectors
- Micro-Newton Thrusters
- Predictive Thermal Control (PTC)
- Single-Crystal Silicon X-Ray Mirrors
- X-Ray Gratings
- Zerodur Mirror Thermal Test Data



HabEx (4 technologies)
Lynx (4 technologies)
LUVOIR
Origins
PICO

Missions/Projects

INE

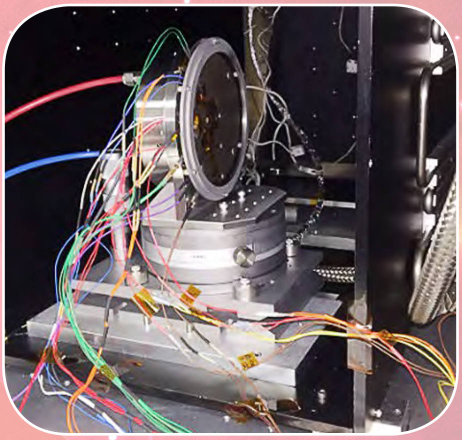
TREXS

- Continuous ADR is baselined for Lynx as are single-crystal silicon X-ray mirrors and X-ray gratings
- Continuous ADR is also baselined for Origins and PICO
- Directly deposited optical blocking filters baselined for Lynx
- MCP detectors are baselined for HabEx and LUVOIR
- Micro-newton thrusters are baselined for HabEx fine pointing and jitter suppression
- PTC is expected to serve as a pathfinder for zonal thermal control in HabEx
- Zerodur® mirror thermal test data from PTC provided basis for HabEx thermal stability error budget

nented in a mission/project, baselined on concept's reference design

e seen from the above list, technologies developed for strategic astrophysics missions often find applications beyond strategic missions, including , Explorers, sub-orbital rockets, balloon missions, and ground-based projects. Further, applications aren't limited to astrophysics, with technologies used into cross-cutting applications in Earth Science (GRACE-FO and GOLD), Planetary Science (OSIRIS-REx), and Heliophysics (ICON). Finally, since d projects prefer to use state-of-the-art technologies available without investing in maturing low-TRL technologies, we expect strategic technologies eloped now to be infused into more and more competed missions as time goes by.

Ultra-Stable Structures: Development and Characterization Using Spatial Dynamic Metrology



Coronagraphic observations in direct imaging and characterization of habitable planets require actively and passively correcting wave-front errors of telescopes up to 15 meters in diameter (larger than a volleyball court), and keeping them stable to 10 pm (1/5 the radius of a hydrogen atom) for the duration of the science observation. **The picometer-level metrology test-bed developed by this project enables the characterization of thermal and dynamic behavior of optical systems, crucial for missions such as the Large UV/Optical/IR (LUVOIR) Surveyor and Habitable Exoplanet Observatory (HabEx).**

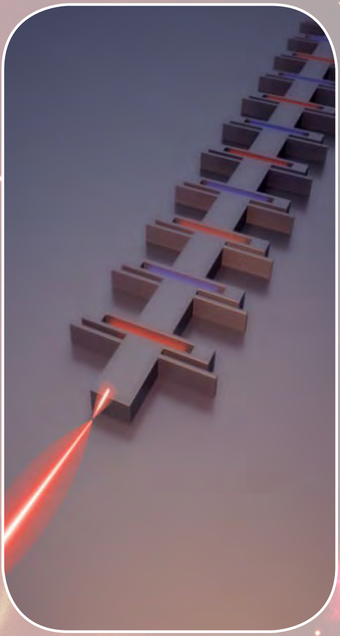
Next-Generation X-ray Optics: High Angular Resolution, High Throughput, and Low Cost

Accurately imaging astrophysical X-ray sources is crucial to studying the high-energy processes in the universe. X rays can only be reflected at very shallow angles, so X-ray telescopes use grazing-incidence reflections to focus X rays on detectors several meters away. **The project develops a process that carves out thin curved slices from commercial blocks of single-crystal silicon, then etches, polishes, trims, and coats them to make 0.5-mm-thin 10×10 cm² segments that are among the highest-quality mirrors in the world.** Once the project reaches its performance target, it will enable many future X-ray astronomical missions, including the Lynx mission which requires nearly 40,000 segments assembled into a 3-m-diameter barrel, with 30× larger collection area than Chandra, at a cost that fits within a flagship-mission-level budget.

Advanced Packaging for Critical-Angle-X-ray Transmission Gratings

Critical-angle transmission (CAT) gratings, used in combination with grazing-incidence X-ray mirrors and CCD detectors, promise an order-of-magnitude improvement in efficiency and another order-of-magnitude improvement in resolving power over existing spectrographs, enabling absorption- and emission-line spectroscopy needed to study the large-scale structure of the universe, cosmic feedback, and the interstellar and intergalactic media. **After previously developing nano-fabrication techniques for making CAT gratings demonstrating single-grating resolution of >10,000 at TRL 4, the project now successfully fabricated larger (32×32 mm²) gratings, frame-mounted and aligned them to each other, and tested them in an X-ray beam line.**

Raising the Technology Readiness Level of 4.7-THz Local Oscillators



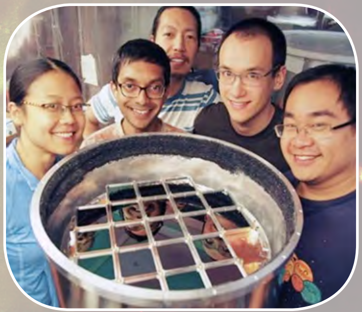
The 63-µm (4.744 THz) [OI] fine-structure line is the dominant cooling line of warm, dense, neutral atomic gas, crucial for astrophysics observations. Spectrally resolved observations of this line with a heterodyne receiver array will let users study the energy balance, physical conditions, morphology, and dynamics of these complex extended regions, providing new and unique insights into the interrelationship of stars and gas in a wide range of galactic and extragalactic environments. **The project designed, fabricated, and tested antenna-coupled 3rd-order Distributed-Feedback structures; and developed a novel scheme of electrically tuning the frequency by ~10 GHz. The lasing frequency and >1 mW power level already meet the project's final goal. The maximum operating temperature, at ~30 K, is close to actual observatories' 40-K requirement.** Several devices were shipped to SRON collaborators to test their beam splitters and hot-electron-bolometer mixers for the recently initiated Gal/Xgal/U/LDB Spectroscopic/Stratospheric THz Observatory (GUSTO) project.

Advanced FUVUV/Visible Photon-Counting and Ultralow-Noise Detectors

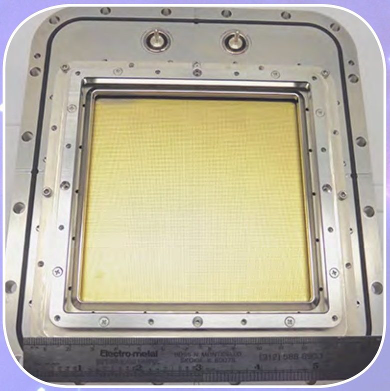
This project develops high-performance UV and visible detectors and coating technologies essential for LUVOIR and HabEx, two large-mission concepts studied by NASA as potential astrophysics flagship missions. To address the need for far-UV science, the team uses super-lattice doping and ALD thin-film coatings to modify large-format, commercial electron-multiplying CCDs and silicon CMOS active-pixel sensors, creating photon-counting, ultra-low-noise, solar-blind detectors with significantly enhanced UV response. **Beyond enabling large missions, the dramatic increases in detector efficiency enable flagship-class science with the smaller apertures possible for Probe- and Explorer-class missions.**

Superconducting Antenna-Coupled Detectors for CMB Polarimetry with the Inflation Probe

The Cosmic Microwave Background (CMB) is a background glow from the early universe. Finding a so-called B-mode polarization signature in the CMB would support the concept that the universe expanded exponentially in a tiny fraction of a second in an episode cosmologists call "Inflation." Unfortunately, polarized foreground emission from our galaxy makes measuring CMB B-mode polarization challenging. The project developed antenna-coupled detectors with the sensitivity, 30-300 GHz coverage, and systematic-error control needed for space-based CMB-polarization experiments. Deployed in the ground-based BICEP2, BICEP3, and Keck experiments, **these detectors were used to create the deepest CMB maps ever made, in a small section of the sky. Deployed on a future space-based Inflation Probe (IP), this capability would expand to map the entire sky.**



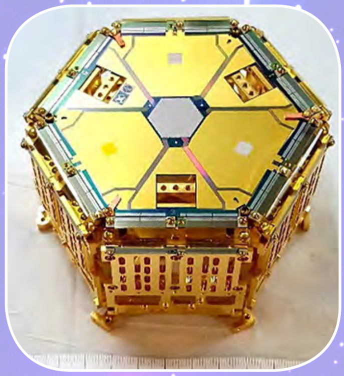
High-Performance Cross-Strip (XS) Photon-Counting Sensors for UV-Vis Astrophysics Instruments



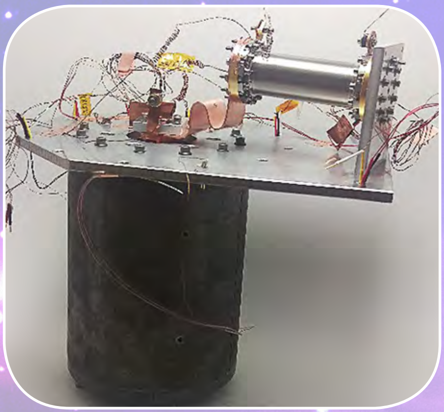
Microchannel-plate (MCP) detectors have been the detector of choice for many UV astronomy missions and instruments over the last two decades. MCPs combine high spatial resolution and noiseless imaging in a robust, radiation-hard package, scalable to large formats (>10×10 cm^2 and > 5k×5k pixels), and even curved focal planes. **The project has developed and begun testing such large-format detectors, with readout electronics designed to support their noiseless operation.** Demonstrating that XS detectors with ALD MCPs can be implemented as robust, high-performance detectors addresses the needs of LUVOIR and HabEx, and should do the same for many future NASA missions.

Providing Enabling and Enhancing Technologies for a Demonstration Model of the Athena X-IFU

The Athena X-ray Integral Field Unit (X-IFU) will enable high-resolution spectroscopy of X rays emitted from the hot and energetic universe, with high spatial resolution over a wide field of view. This will allow scientists to study the formation of large structures in the universe, the evolution of black holes, and many other astrophysical targets of interest. To achieve this unprecedented capability, X-IFU will use transition-edge-sensor micro-calorimeter pixels developed by NASA, NIST, and Stanford University. **The detectors developed by this collaboration demonstrate improved reproducibility and uniformity of flight-scale (4096-pixel) detector arrays. The team also developed alternate multiplexing techniques that improve performance compared to traditional ones, providing Athena with viable options to trade.**



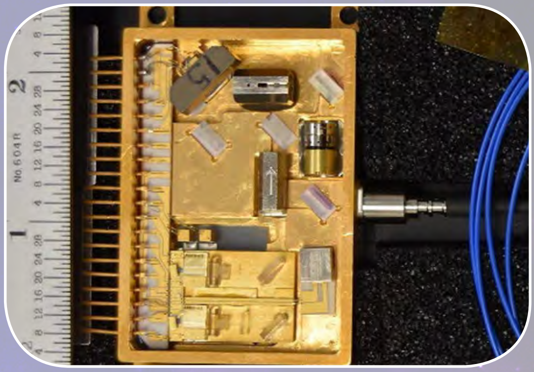
High-Efficiency Continuous Cooling for Cryogenic Instruments and Sub-Kelvin Detectors



Future major astrophysics missions such as OST, Lynx, and IP include large superconductor-based focal planes cooled to near absolute zero (below -459°F!). These missions require greater cooling power at lower operating temperatures than any previous mission. Achieving this without liquid helium (which runs out, ending the mission) and without jitter that disturbs sensitive measurements is extremely challenging. **The project was able to fabricate and assemble a flight-like 10-to-4-K of a six-stage 10-to-0.5-K Continuous Adiabatic Demagnetization Refrigerator (CADR), and test it through a complete cooling cycle.** The above three mission concepts have all baselined this technology into their reference designs, and are considering the 10-to-4-K part as well.

Space-based Gravitational Wave Laser Technology Development Project for the LISA Mission

The recent first-ever detection of gravitational waves opened a new window to observe some of the most extreme phenomena in the universe, such as mergers of supermassive black holes that occur when galaxies collide. LISA, planned to launch in the 2030s, will be the largest experiment ever constructed by humanity, with three spacecraft flying in a triangular formation over 1.5 million miles on a side. **The project recently demonstrated a breadboard prototype of the extremely stable, low-noise mNPRO laser, a first step needed to achieve the goal of measuring a change as small as 10 pm (for comparison, a hydrogen atom's size is about 50 pm) in the immense distance between spacecraft.**



Looking to the Future

The PCOS and COR Program Office currently supports teams established by the Astrophysics Division to study and develop concepts for large and medium strategic missions, in preparation for the 2020 Astronomy and Astrophysics Decadal Survey.

Analysis of the technology gaps identified by these study teams will inform future Astrophysics Division technology development investment strategies. The PCOS and COR Program Office will actively pursue development and infusion of these technologies into future strategic missions prioritized by the 2020 Decadal Survey.

References

[1] M.R. Perez, B.T. Pham, and P.R. Lawson, "*Technology Maturation Process: the NASA Strategic Astrophysics Technology (SAT) Program*," Proc. SPIE 9143, Space Telescopes and Instrumentation 2014: Optical, Infrared, and Millimeter Wave, 914313 (2 August 2014); doi: 10.1117/12.2057961

[2] B.T. Pham, O. Ganel, and H.A. Thronson, "*NASA's Physics of the Cosmos and Cosmic Origins Programs Manage Strategic Astrophysics Technology Development in Preparation for the Next Decadal Survey*," Proc. SPIE 10698, Space Telescopes and Instrumentation 2018: Optical, Infrared, and Millimeter Wave, 106986J (6 July 2018); doi: 10.1117/12.2314832

[3] A. Valinia, B.T. Pham, and O. Ganel, "*A Summary and Analysis of NASA's Strategic Astrophysics Technology PCOS/COR Investments Since Program Inception*," Proc. SPIE 10706, Advances in Optical and Mechanical Technologies for Telescopes and Instrumentation III, 107060A (10 July 2018); doi: 10.1117/12.2311672

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