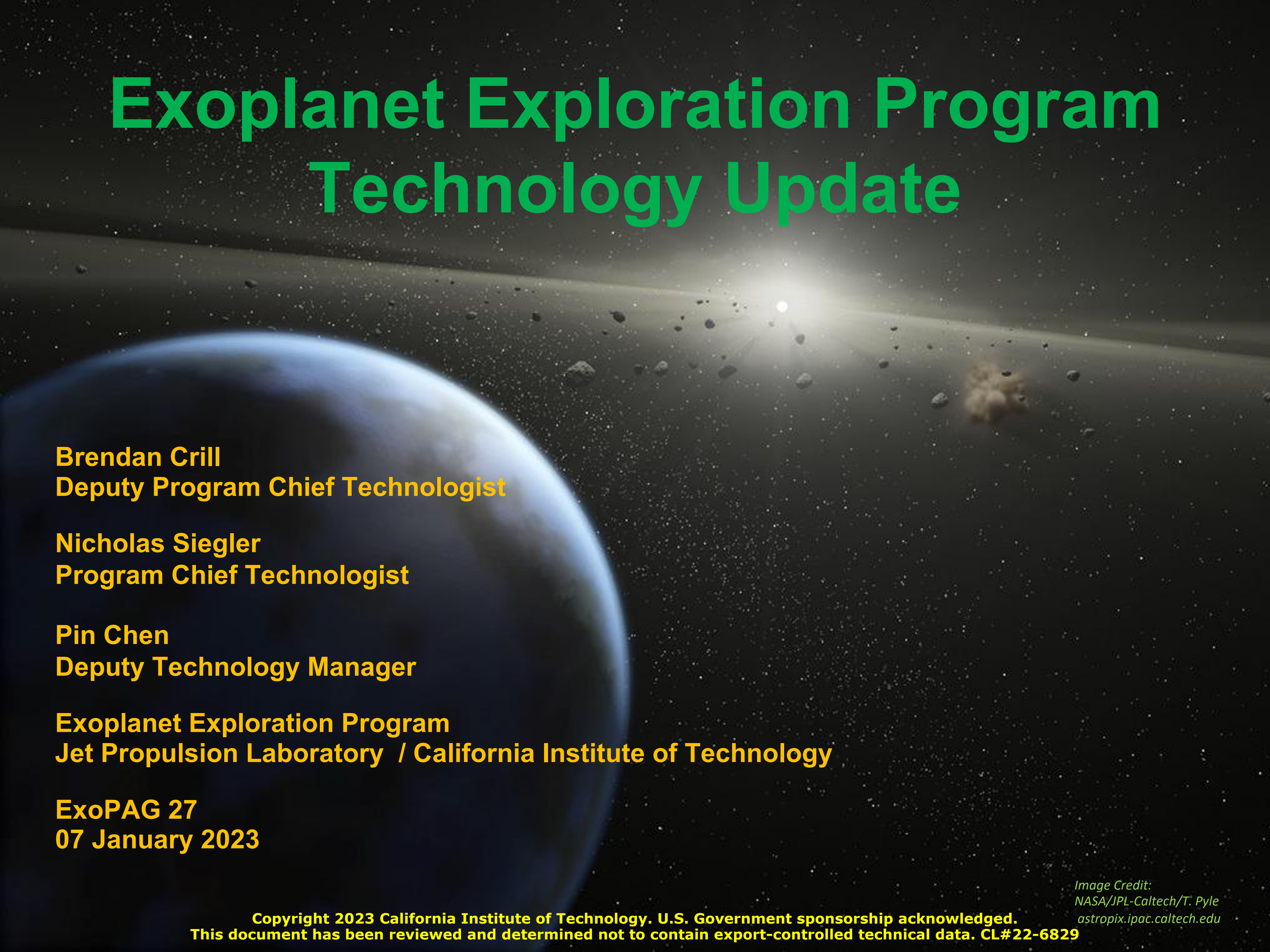
Exoplanet Exploration Program Technology Update



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Exoplanet Exploration Program
Jet Propulsion Laboratory / California Institute of Technology

ExoPAG 27
07 January 2023

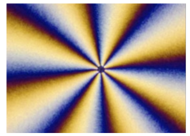
Image Credit:
NASA/JPL-Caltech/T. Pyle
astropix.ipac.caltech.edu

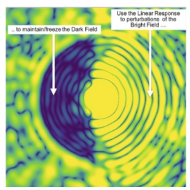
ExEP develops technology for future exoplanet missions

Ongoing Technology Activities

Technology Gaps

Strategic Astrophysics Technology (SAT) Grants



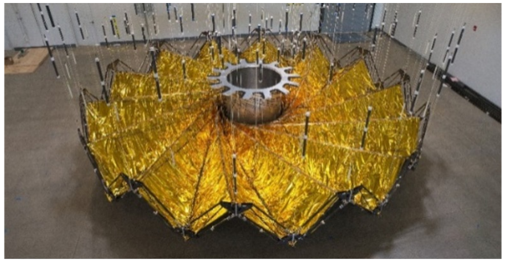


- *Coronagraph architectures: modeling and demonstrations*
- *Wavefront control*
- *Extreme Precision Radial Velocity*
- *Detectors*

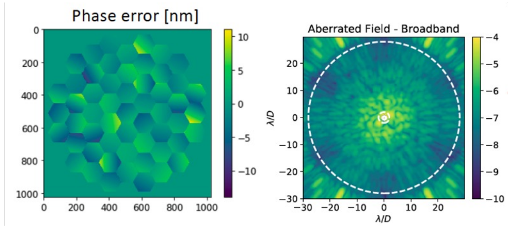
Ultra-Stable Coronagraph Testbeds

Technosignatures Gap List Study

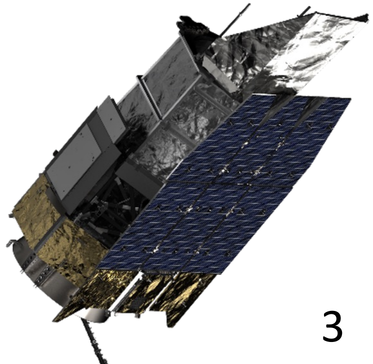
Starshade Technology Development



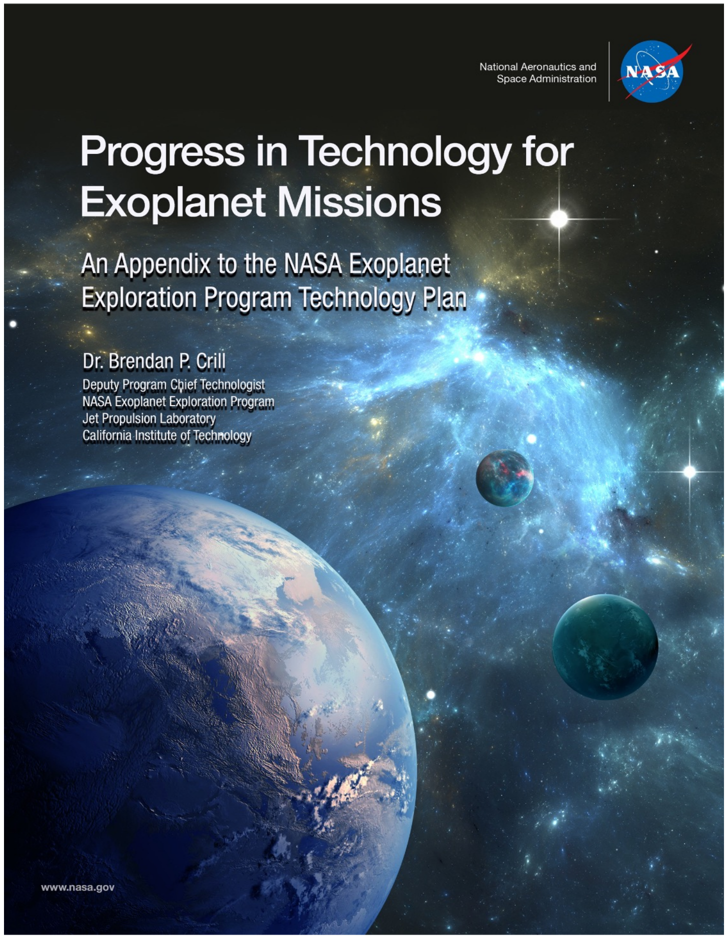
Segmented Coronagraph Design & Analysis Study



Roman Coronagraph



Progress in Technology for Exoplanet Missions



- **NASA Astrophysics Division maintains a prioritized Technology Gap List** **https://apd440.gsfc.nasa.gov/tech_gap_priorities.html**

- **ExEP published a document called *Progress in Technology for Exoplanet Missions***
  - A review of ExEP's technology gaps and the state-of-the-art technologies to close the gaps
  - Available on ExEP technology website https://exoplanets.nasa.gov/exep/technology/technology-overview/

Strategic Astrophysics Technology (SAT) Awards for Exoplanet Technology

Coronagraph masks/architectures

- Vortex Coronagraph (Serabyn/NASA-JPL)
- Phase Induced Amplitude Apodization Complex Mask Coronagraph (Belikov/NASA-ARC)
- Super-Lyot Coronagraph (Trauger/NASA-JPL)
- Apodized Pupil Lyot Coronagraph (Soummer/STScI)
- Dual Purpose Coronagraph Masks (Wallace/JPL)

Extreme Precision Radial Velocity

- Micro-resonator optical etalon for radial velocity measurements (Vasisht/NASA-JPL)

Wavefront-control techniques

- Single mode fiber and optimization for spectroscopy (Mawet/Caltech)
- Linear Dark Field Control (Guyon/Arizona)
- Multi-star Wavefront Control (Belikov/NASA-ARC)
- Adaptive Wavefront Control Algorithms (Cahoy/MIT)

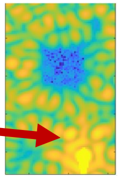
Ultra-low Noise Detectors

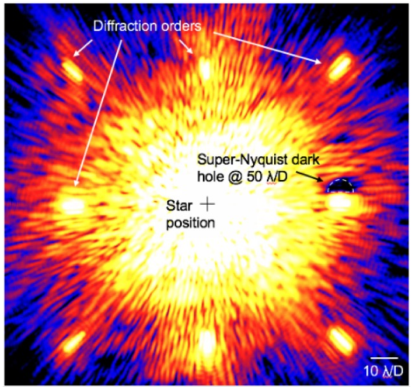
- Vis-band rad-hard photon-counting detectors (Rauscher/NASA-GSFC)
- Ultra-stable mid-IR detector array (Staguhn/JHU)

Recent results from Strategic Astrophysics Technology (SAT)

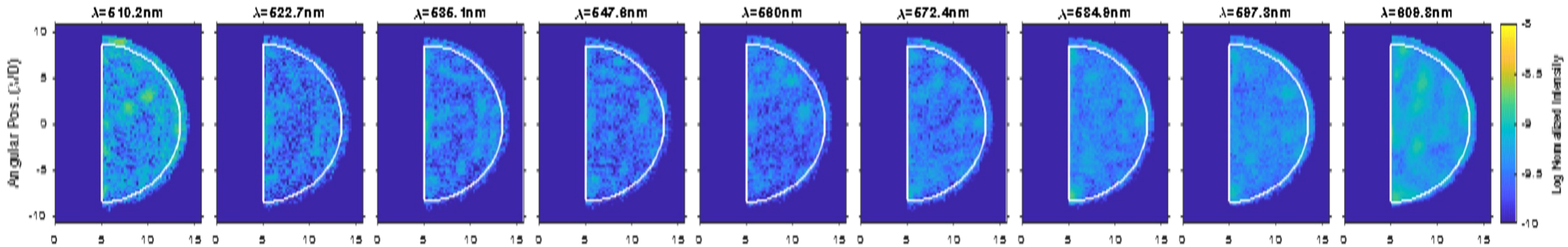
- **Multistar Wavefront Control (PI Rus Belikov)**
  - Aims to enable direct imaging in multistar systems
  - Achieved first demonstrations of starlight suppression using higher order diffraction spots

3rd diffraction spot



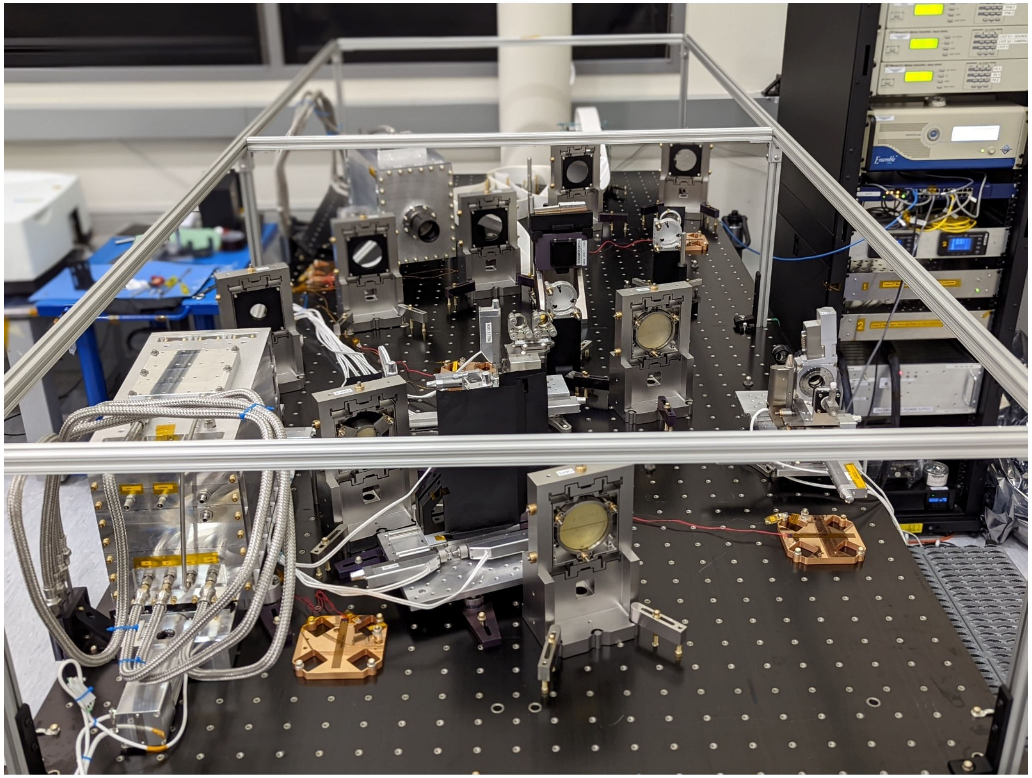


- **High-bandwidth coronagraphy for optimizing spectroscopy (PI Dimitri Mawet)**
  - Aims to suppress starlight over a wide band for faster spectroscopy
  - Record contrast (4×10^{-10}) achieved at 20% bandwidth



Coronagraph Testbed Infrastructure

- **Decadal Survey Testbed 2 available**
  - New ultrastable coronagraph testbed bench
  - additional capacity for Strategic Astrophysics Technology (SAT) demonstrations and anticipated directed work for Habitable Worlds Observatory

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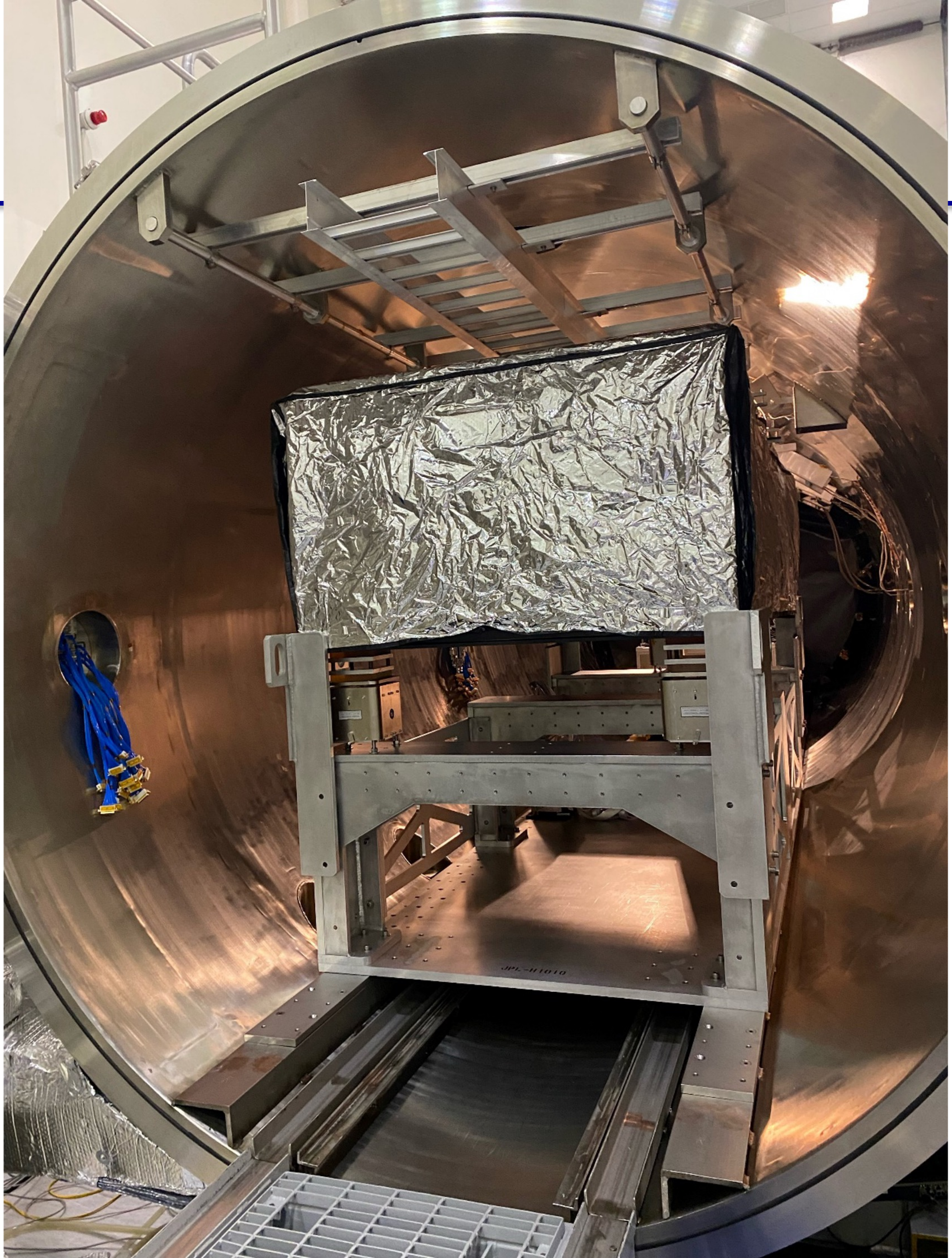
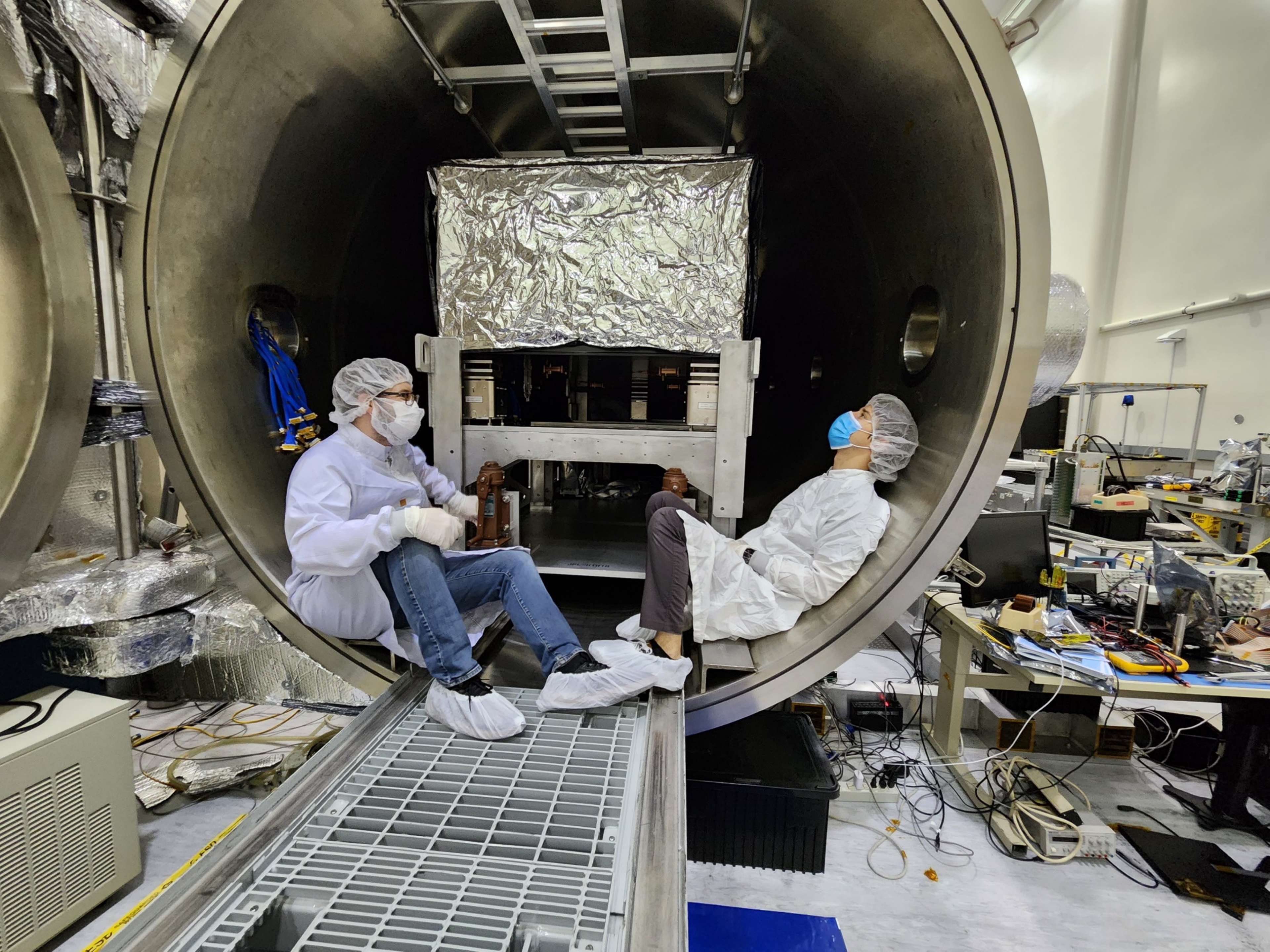
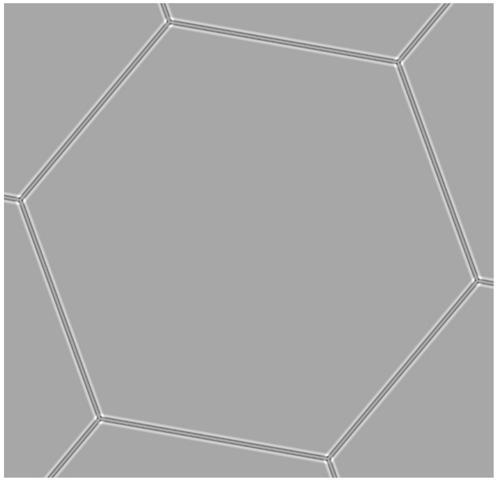




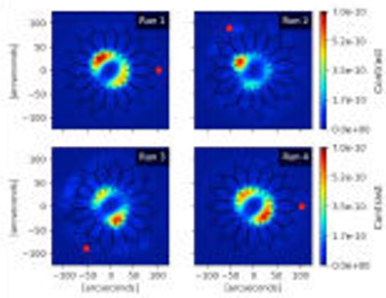
Segmented Coronagraph Design & Analysis Study (SCDA)

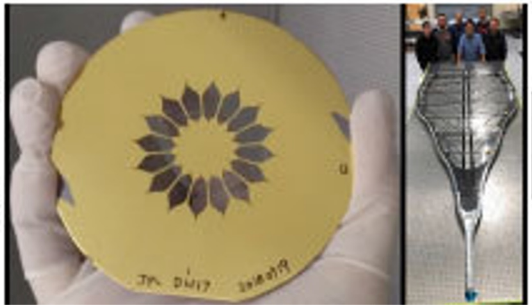
- Can a coronagraph and a segmented telescope work together as a system to directly image Earth-like exoplanets?
- SCDA is a multi-institutional study of segmented telescope/ coronagraph systems
  - end-to-end modeling: including telescope dynamics, wavefront control, coronagraph, and estimating science yield
- Recently completed:
  - Wavefront control studies with realistic telescope models: two papers in JATIS: Potier et al (2022) and Juanola-Parramon et al (2022)
- Currently underway:
  - Polarization aberration study
  - Segment edge roll-off study
  - More telescope dynamics…

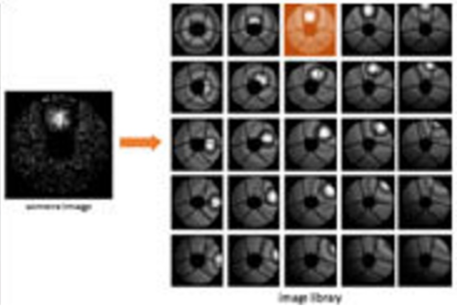


Starshade Technology Development

- Since 2016, ExEP's Starshade Technology Activity (also known as S5) has overseen starshade technology development
  - https://exoplanets.nasa.gov/exep/technology/starshade/





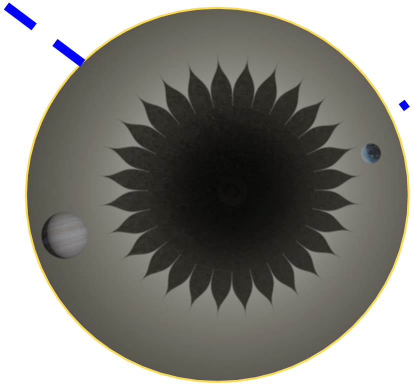


- Starshade technology development is transitioning from directed funding to competed funding
  - starshade technology investigations are now eligible for Strategic Astrophysics Technology (SAT) grants

Starshade Technology Activity (S5)'s work towards closing Starshade Technology Gaps

Starlight Suppression

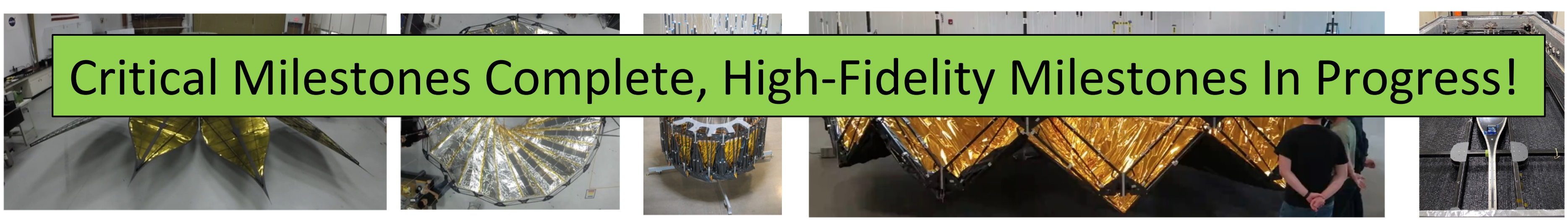
All Milestones Complete!



Formation Sensing and Control

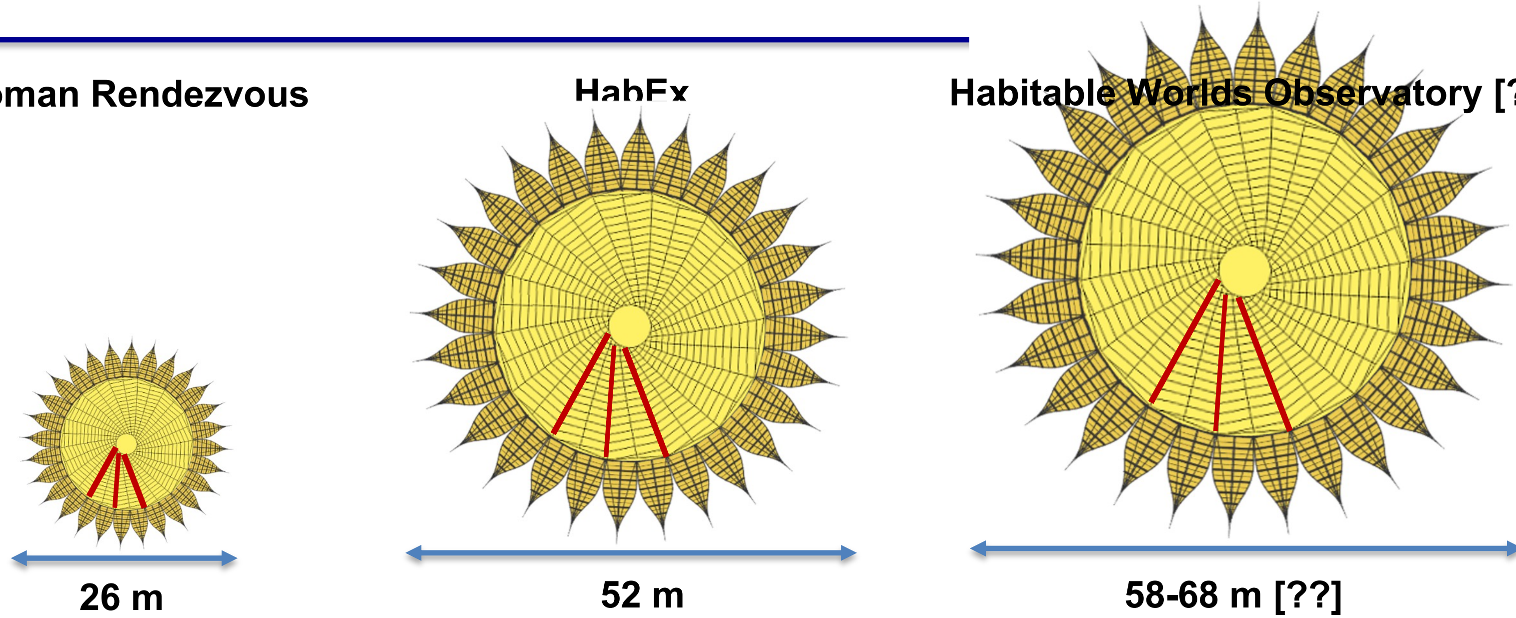
All Milestones Complete!

Deployment Accuracy and Shape Stability



Critical Milestones Complete, High-Fidelity Milestones In Progress!

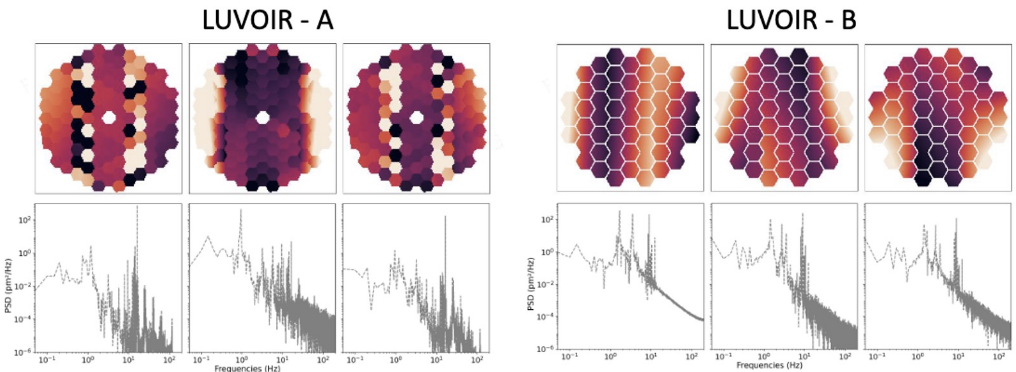
But have the goalposts moved?

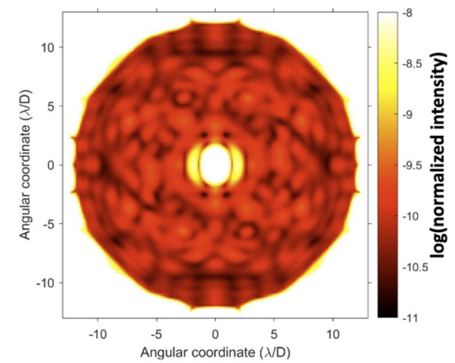


- Maturity of technology directly depends on requirements
- Do the achievements of Starshade Technology Activity (S5) translate to a mission with a 6m-primary mirror telescope?
- Starshade Technology Activity (S5) to assess this question in 2023-24 as they complete their remaining milestones

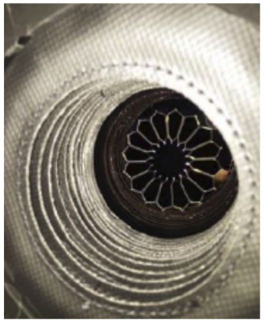
Exoplanet Exploration Technology Colloquium Series

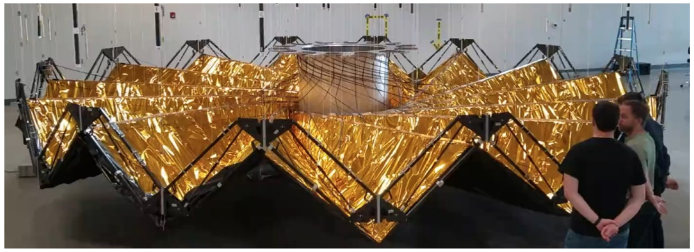
- ***Wavefront Control for Coronagraphs on Segmented Space Telescopes***
  Laurent Pueyo (STScI), Axel Potier (JPL)

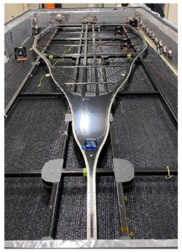




- ***Updates on Starshade: Prospects for a Great Observatory***
  Case Bradford (JPL)







- **Recordings and slides available:**
  - https://exoplanets.nasa.gov/exep/technology/tech_colloquium/

New 2023 ExEP Technology Initiatives

- **Four activities in 2023-2024 to inform the GOMAP once it commences**

- **Deformable Mirror Roadmapping Activity**
  - Leads: Tyler Groff (GSFC), Eduardo Bendek (JPL)
  - How will the community mature deformable mirror technology to the point where it can infuse into the Habitable Worlds Observatory mission with low risk (TRL 5)?

- **Coronagraph Architecture Survey**
  - Leads: Rus Belikov (ARC), Chris Stark (GSFC)
  - Which coronagraph architectures offer the highest likelihood of success? Which merit investment and demonstration opportunities?

- **Coronagraph Roadmapping Activity**
  - Leads: Laurent Puyeo (STScI), Pin Chen (ExEP/JPL)
  - How will the community mature coronagraph technology to the point where it can infuse into the Habitable Worlds Observatory mission with low risk (TRL 5)?

- **Segmented Optical Telescope Assembly Study**
  - Leads: TBD
  - How can we best simulate the light from a segmented telescope to understand coronagraph performance?

Announcing: Starlight Suppression Workshop

- **Workshop objectives**:
  - A primer on how coronagraphs and starshades work
  - Present their state-of the-art
  - Discuss performance levels needed for Habitable Worlds Observatory to establish ”gaps”
  - Communicate potential plans, concerns, challenges, and risks moving forward

- A three-day hybrid workshop, in-person location at JPL: tentative dates Aug 8-10, 2023.

- Stay tuned for further announcements.

How you can be involved

- **Propose to NASA programs to help develop technology:**
  - Strategic Astrophysics Technology (SAT)
  - Astrophysics Research and Analysis (APRA)
  - Nancy Grace Roman Technology Fellowships
- **Tune in to the ExEP Technology Colloquium Series**
  - or propose a talk!
- **Participate in the ExEP Technology Initiatives**
- **Join us at the AAS splinter session on Starlight Suppression Technology Tuesday 9-11am**

BACKUP

2022 Astrophysics Technology Gaps

Tier 1 Technology Gaps

- Advanced Cryocoolers
- Coronagraph Contrast and Efficiency
- Coronagraph Stability
- Cryogenic Readouts for Large-Format Far-IR Detectors
- Heterodyne Far-IR Detector Systems
- High-Performance, Sub-Kelvin Coolers
- High-Reflectivity Broadband Far-UV-to-Near-IR Mirror Coatings
- High-Resolution, Large-Area, Lightweight X-ray Optics
- High-Throughput Bandpass Selection for UV/VIS
- High-Throughput, Large-Format Object Selection Technologies for Multi-Object and Integral Field Spectroscopy
- Large Cryogenic Optics for the Mid IR to Far IR
- Large-Format, High-Resolution Focal Plane Arrays
- Large-Format, Low-Darkrate, High-Efficiency, Photon-Counting, Solar-blind, Far- and Near-UV Detectors
- Large-Format, Low-Noise and Ultralow-Noise Far-IR Direct Detectors
- Long-Wavelength-Blocking Filters for X-ray Micro-Calorimeters
- Low-Stress, High-Stability, X-ray Reflective Coatings
- Mirror Technologies for High Angular Resolution (UV/Vis/Near IR)
- Stellar Reflex Motion Sensitivity – Astrometry
- Stellar Reflex Motion Sensitivity – Extreme Precision Radial Velocity
- Vis/Near-IR Detection Sensitivity

Tier 2 Technology Gaps

- Broadband X-ray Detectors
- Compact, Integrated Spectrometers for 100 to 1000 µm
- Far-IR Imaging Interferometer for High-Resolution Spectroscopy
- Far-IR Spatio-Spectral Interferometry
- Fast, Low-Noise, Megapixel X-ray Imaging Arrays with Moderate Spectral Resolution
- High-Efficiency X-ray Grating Arrays for High-Resolution Spectroscopy
- High-Resolution, Direct-Detection Spectrometers for Far-IR Wavelengths
- Improving the Calibration of Far-IR Heterodyne Measurements
- Large-Aperture Deployable Antennas for Far-IR/THz/sub-mm Astronomy for Frequencies over 100 GHz
- Large-Format, High-Spectral-Resolution, Small-Pixel X-ray Focal-Plane Arrays
- Polarization-Preserving Millimeter-Wave Optical Elements
- Precision Timing for Space-Based Astrophysics
- Rapid Readout Electronics for X-ray Detectors
- Starshade Deployment and Shape Stability
- Starshade Starlight Suppression and Model Validation
- UV Detection Sensitivity

Tier 3 Technology Gaps

- Advancement of X-ray Polarimeter Sensitivity
- Detection Stability in Mid-IR
- Far-UV Imaging Bandpass Filters
- High-Efficiency Far-UV Mirror
- High-Efficiency, Low-Scatter, High- and Low-Ruling-Density, High- and Low-Blazed-Angle UV Gratings
- High-Quantum-Efficiency, Solar-Blind, Broadband Near-UV Detector
- Photon-Counting, Large-Format UV Detectors
- Short-Wave UV Coatings
- Warm Readout Electronics for Large-Format Far-IR Detectors

Tier 4 Technology Gaps

- Advanced Millimeter-Wave Focal-Plane Arrays for CMB Polarimetry
- Improving the Photometric and Spectro-Photometric Precision of Time-Domain and Time-Series Measurements
- UV/Opt/Near-IR Tunable Narrow-Band Imaging Capability
- Very-Wide-Field Focusing Instrument for Time-Domain X-ray Astronomy

Tier 5 Technology Gaps

- Complex Ultra-Stable Structures for Future Gravitational-Wave Missions
- Disturbance Reduction for Gravitational-Wave Missions
- Gravitational Reference Sensor
- High-Performance Spectral Dispersion Component/Device
- High-Power, High-Stability Laser for Gravitational-Wave Missions
- Laser Phase Measurement Chain for a Decihertz Gravitational-Wave Mission
- Micro-Newton Thrusters for Gravitational Wave-Missions
- Stable Telescopes for Gravitational Wave-Missions

The 10 ExEP Technology Gaps

Where to find the Gap List

ExEP NASA EXOPLANET EXPLORATION PROGRAM

https://apd440.gsfc.nasa.gov/tech_gap_priorities.html

ASTROPHYSICS TECHNOLOGY DEVELOPMENT

Overview | Technology | Outreach

Astrophysics Program Offices

2022 Astrophysics Strategic Technology Gaps

TECHNOLOGY GAPS: OVERVIEW / TECH GAP PRIORITIES / PRIORITIZATION PROCESS / TECH GAP DESCRIPTIONS

Gap Name	Description	Current SOA	TRL	Performance Goals and Objectives	Scientific, Engineering and/or Programmatic Benefits	Applications and Potential Relevant Missions	Urgency
Coronagraph Stability	The capability to maintain the deep starlight suppression provided by a coronagraph for a time period long enough to detect light from an exo-Earth.	RST CGI demonstrated ~10^{-8} contrast in a simulated dynamic environment using LOWFS (which obtained 12 pm focus sensitivity) SIM and non-NASA work has demonstrated nm accuracy and stability with laser metrology Capacitive gap sensors demonstrated at 10 pm 80 dB vibration isolation demonstrated Gaia cold gas microthrusters and LISA pathfinder colloidal microthrusters can reduce vibrations	3	Contrast stability on time scales needed for spectral measurements (possibly as long as days). Achieving this stability requires an integrated approach to the coronagraph and telescope, possibly including wavefront sense/control, metrology and correction of mirror segment phasing, vibration isolation/reduction This stability is likely to require wavefront error stability at the level of 10-100 pm per control step (of order 10 minutes). Sub-gaps that could partially or fully close this gap: - Ultra-stable Telescope - Integrated Modeling of Telescope/Coronagraph system - Disturbance Reduction and	This gap is likely to be closed by a combination of many factors in a coronagraph/observatory system, including active wavefront control at the coronagraph level, thermal control, active and passive ultra-stable structures, and disturbance isolation/ reduction. Integrated modeling for tracability to flight environments is likely to be a key capability to close this gap.	IR/O/UV Great Observatory; or any other coronagraph-based exoplanet direct-imaging mission.	Demonstration of feability and as much risk reduction as possible prior to mission formulation. TRL 6 in the mid-to-late 2020's.

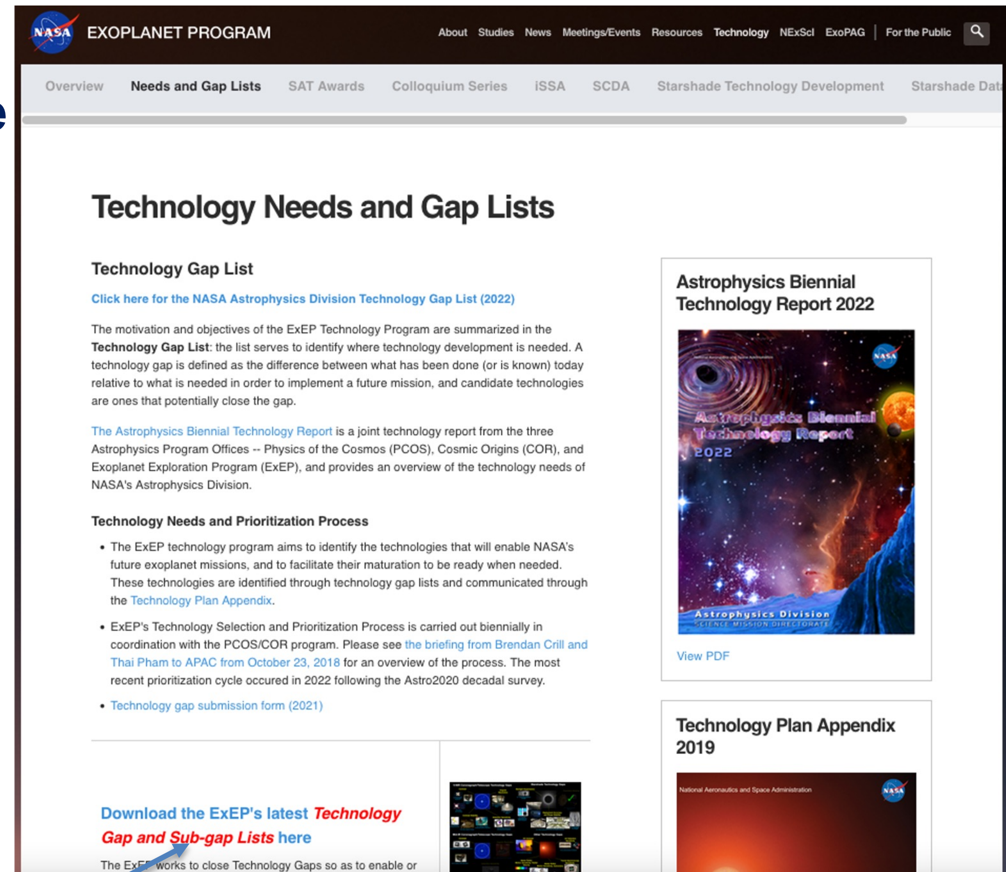
Click on the tiers for details

Exoplanet Technology Gaps and Subgaps

https://exoplanets.nasa.gov/exep/technology/gap-lists/

- **10 Technology Gaps related to NASA's exoplanet science goals**

- **Some ExEP gaps include *subgaps***
  - Subgaps are missing capabilities that if achieved, will partly or fully close the full gap
  - Each subgap is associated with a higher level gap, and includes additional details.



Click here for a PDF with all exoplanet technology gaps and subgaps

Next-Generation Deformable Mirror Drive Electronics

- Next generation, and much smaller, readout electronics delivered for use in the HCIT facility
- A significant error term at 10^{-10} contrast level from the bit resolution of DM driver electronics (historically 16 bit)
- New electronics are 18-bit native, 20-bit with dithering