Exoplanet Exploration Program Technology

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ExoPAG 25
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NASA/Ames/JPL-Caltech/T. Pyle
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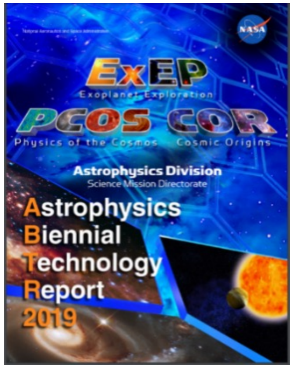
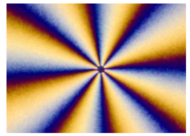
Recent Technology Activities

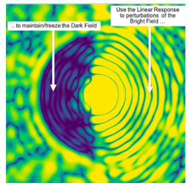
ExEP NASA EXOPLANET EXPLORATION PROGRAM

Technology Gaps



Strategic Astrophysics Technology (SAT) Grants

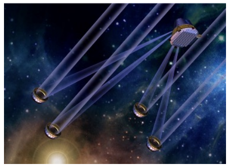




- *Coronagraph architectures: modeling and demonstrations*
- *Wavefront control*
- *Extreme Precision Radial Velocity*
- *Detectors*

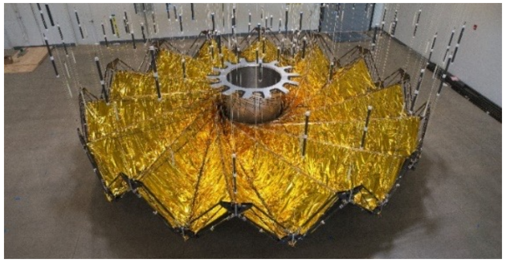
Ultra-Stable Coronagraph Testbeds

Nulling Interferometry Study

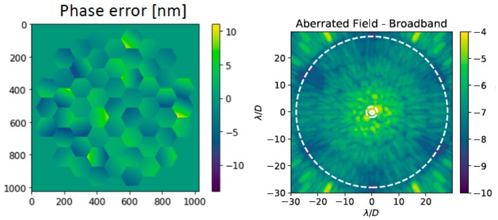


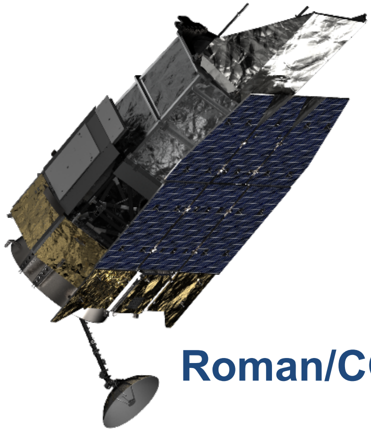
Technosignatures Gap List Study

Starshade Technology Development



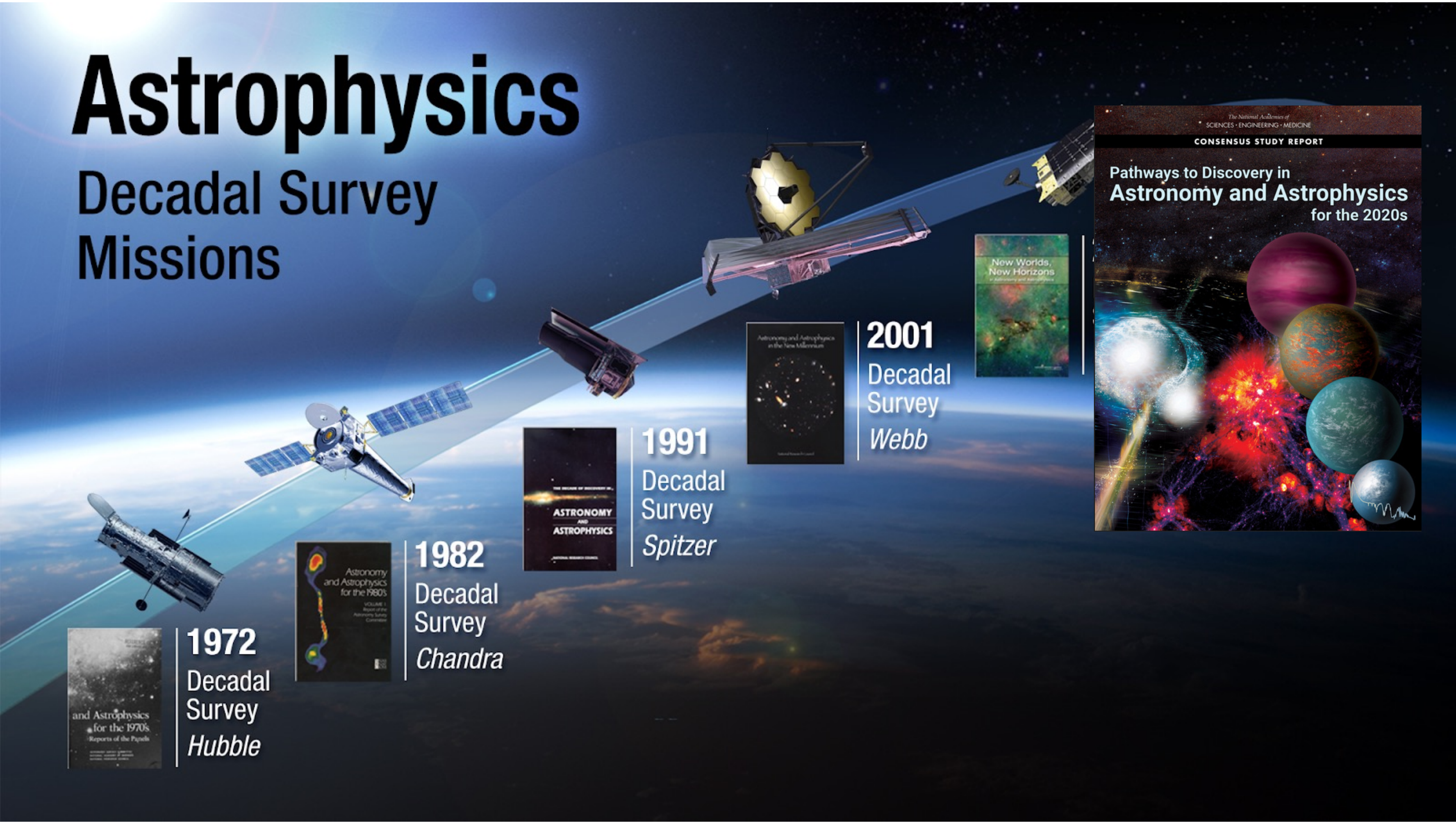
Segmented Coronagraph Design & Analysis Study





Roman/CGI

The Future is Here!



Key Exoplanet Decadal Recommendations

Introducing the Maturation Program:

***Recommendation*: The NASA Astrophysics Division should establish a Great Observatories Mission and Technology Maturation Program, the purpose of which is to co-develop the science, mission architecture, and technologies for NASA large strategic missions identified as high priority by decadal surveys.**

An IR/O/UV Great Observatory focused on exoplanet science is first:

***Recommendation:* After a successful mission and technology maturation program, NASA should embark on a program to realize a mission to search for biosignatures from a robust number of about ~ 25 habitable zone planets and to be a transformative facility for general astrophysics. If mission and technology maturation are successful, as determined by an independent review, implementation should start in the latter part of the decade, with a target launch in the first half of the 2040s.**

NASA's response to the Decadal

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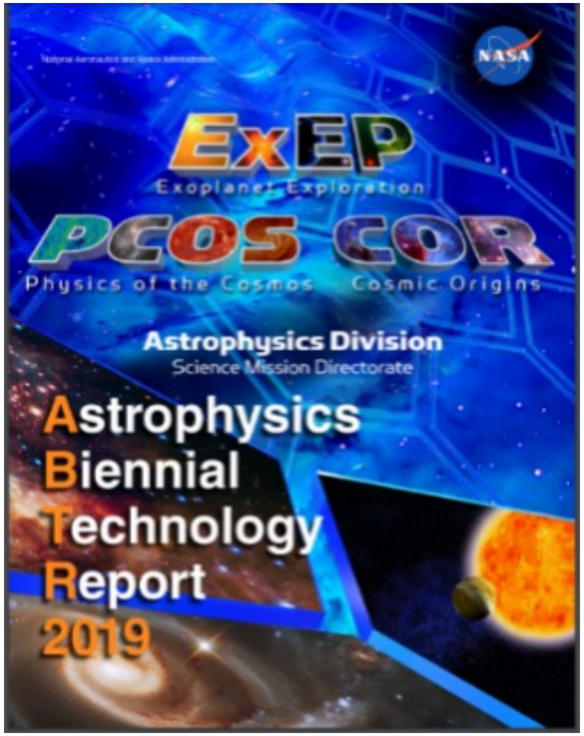
See Paul Hertz town hall from Jan 11, 2022

- **Future Great Observatory preparation in pre-Phase A stages:**
  - Stage 1 is now; includes precursor science and technology work
  - Stage 2 starts in a few years; begins the Maturation Program and will add an Analysis of Alternatives and science / technology / architecture trades
  - Stage 3 includes the decision to start and a transition to the classic pre-Phase-A
- **APD is defining what technology development means under the Maturation Program**
  - How to best use SATs and other funding mechanisms to advance technology
  - How to engage industry
  - Understanding the future of large launch vehicles
  - Considering servicing of future large missions
  - Exploring international collaborations

Astrophysics Technology Gaps

- **A technology gap is the difference between a capability needed to enable a future mission and the current state-of-the-art**
- **The Astrophysics Division maintains a prioritized Technology Gap List**
- **Program Office technologists carry out a biennial Technology Selection and Prioritization Process:**
  - **Identify Technology Gaps** applicable to Astrophysics strategic objectives
  - **Rank Technology Gaps** to prioritize them for investment
  - **Inform the community** of NASA's technology needs
- **The last update was in 2019**



2019 Astrophysics Technology Gaps

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Tier 1 Technology Gaps
Angular Resolution (UV/Vis/NIR)
Coronagraph Contrast
Coronagraph Contrast Stability
Cryogenic Readouts for Large-Format Far-IR Detectors
Fast, Low-Noise, Megapixel X-Ray Imaging Arrays with Moderate Spectral Resolution
High-Efficiency X-Ray Grating Arrays for High-Resolution Spectroscopy
High-Resolution, Large-Area, Lightweight X-Ray Optics
Large-Format, High-Resolution, UV/Vis Focal Plane Arrays
Large-Format, High-Spectral-Resolution, Small-Pixel X-Ray Focal-Plane Arrays
Large-Format, Low-Noise and Ultralow-Noise Far-IR Direct Detectors
Large-Format, Low-Noise, High-QE Far-UV Detectors
Next-Generation, Large-Format, Object Selection Technology for Multi-Object Spectrometers for LUVOIR
Vis/NIR Detection Sensitivity

Tier 2 Technology Gaps
Advanced Millimeter-Wave Focal-Plane Arrays for CMB Polarimetry
Detection Stability in Mid-IR
Heterodyne FIR Detector Arrays and Related Technologies
High-Efficiency Object Selection Technology for UV Multi-Object Spectrometers
High-Performance Spectral Dispersion Component/Device
High-Reflectivity Broadband FUV-to-NIR Mirror Coatings
High-Throughput Bandpass Selection for UV/Vis
Large-Format Object Selection Technology for Multi-Object Spectrometers for HabEx
Starshade Deployment and Shape Stability
Starshade Starlight Suppression and Model Validation
Stellar Reflex Motion Sensitivity – Astrometry
Stellar Reflex Motion Sensitivity – Extreme Precision Radial Velocity

Tier 3 Technology Gaps
Advanced Cryocoolers
High-Performance, Sub-Kelvin Coolers
Large Cryogenic Optics for the Mid-IR to Far-IR
Long-Wavelength-Blocking Filters for X-Ray Micro-Calorimeters
Low-Noise, High-QE UV Detectors
Low-Stress, Highly Stable X-Ray Reflective Coatings
Photon-Counting, Large-Format UV Detectors
Polarization-Preserving Millimeter-Wave Optical Elements
UV Coatings
UV Detection Sensitivity
UV/Vis/NIR Tunable Narrow-Band Imaging Capability
Warm Readout Electronics for Large-Format Far-IR Detectors

Tier 4 Technology Gaps
Compact, Integrated Spectrometers for 100 to 1000 μm
Optical-Blocking Filters
Rapid Readout Electronics for X-Ray Detectors
Short-Wave UV Coatings

Tier 5 Technology Gaps
Advancement of X-Ray Polarimeter Sensitivity
Far-IR Spatio-Spectral Interferometry
High-Precision Low-Frequency Radio Spectrometers and Interferometers
Mid-IR Coronagraph Contrast
Ultra-High-Resolution Focusing X-Ray Observatory Telescope
Very-Wide-Field Focusing Instrument for Time-Domain X-Ray Astronomy
Wide-Bandwidth, High-Spectral-Dynamic-Range Receiving System for Low-Radio-Frequency Observations on the Lunar Far Side

ExEP Technology Gaps

Astrophysics Technology Gaps

- **Inputs from the community were due Jan 3, 2022**
- **96 gap submissions received**
  - 48 gaps currently on the gap list
- **Next Steps:**
  - Each gap assigned to one of the 3 program offices: PCOS,COR, ExEP
  - Disposition, review and consolidate gaps
  - Prioritize gaps
  - Work reviewed by ExoTAC
- **Delivery of Gap List to community in April 2022**

10 Currently Active Strategic Astrophysics Technology (SAT) Awards

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)

Detectors

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

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)

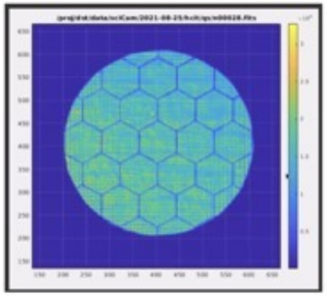
Extreme Precision Radial Velocity

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

SAT coronagraph demonstrations in the High-Contrast Imaging Testbed

- **PIAACMC (PI Belikov)**
  - PIAACMC technology promises excellent inner working angle
  - Achieved 1.5×10^{-8} contrast with a segmented pupil, target was 10^{-9}
  - Error budgeting for Final Report coming soon

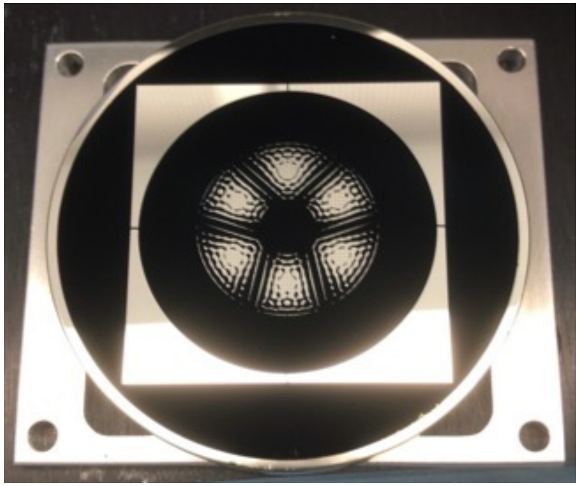
- **Vortex coronagraph (PI Serabyn)**
  - Vortex coronagraph was LUVOIR-B and HabEx baseline
  - New record contrast achieved 2×10^{-9} over 10% band for working angles 3-10 λ/D
  - Record for 20% band: 6×10^{-9} contrast over 3-10 λ/D
  - Earlier in the summer: 5×10^{-9} contrast over 10% band achieved with a static segmented pupil



- **Super Lyot ExoEarth Coronagraph (PI Trauger)**
  - Hybrid Lyot coronagraph has demonstrated the deepest contrast to-date
  - Installed in testbed and next in queue; results coming soon.

Other Recent SAT Highlights

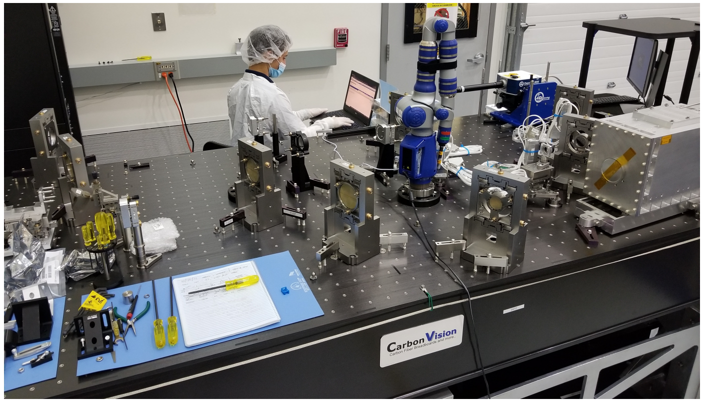
- **Multi-star wavefront control (PI Belikov)**
  - Enables coronagraph to observe planets in multi-star systems
  - Installed in vacuum testbed; demonstrations commencing soon
  - Contributed mask for Roman CGI fabricated (Eduardo Bendek; technical lead)



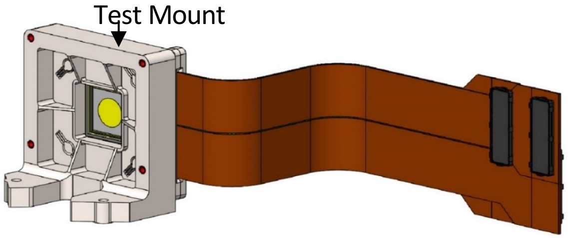
- **Linear Dark Field Control (PI Guyon)**
  - Uses residual starlight outside coronagraph dark hole to stabilize the dark hole, potentially leading to looser telescope stability requirements
  - Milestone report published on ExEP website
  - Spatial dark field control technique demonstrated a factor 30 improvement in coronagraph contrast at 10^{-6} on an in-air testbed
  - Future milestones include tests in vacuum at higher contrast and using spectral information

Testbed Infrastructure

- **Decadal Survey Testbed 2**
  - New ultrastable coronagraph testbed bench with additional pupil plane
  - Achieved first light in November 2021
  - Will be available to future investigators starting with SAT-2021



- **MEMS 2K DM environmental tests**
  - The Boston Micromachines 2k MEMS deformable mirrors (DMs) were subjected to 3-axes random vibe with Roman Space Telescope launch loads.
  - Passed both functional and coronagraph performance testing and achieved better than 10^{-8} contrast in the HCIT's In-Air Coronagraph Testbed.
  - A final report has been completed.



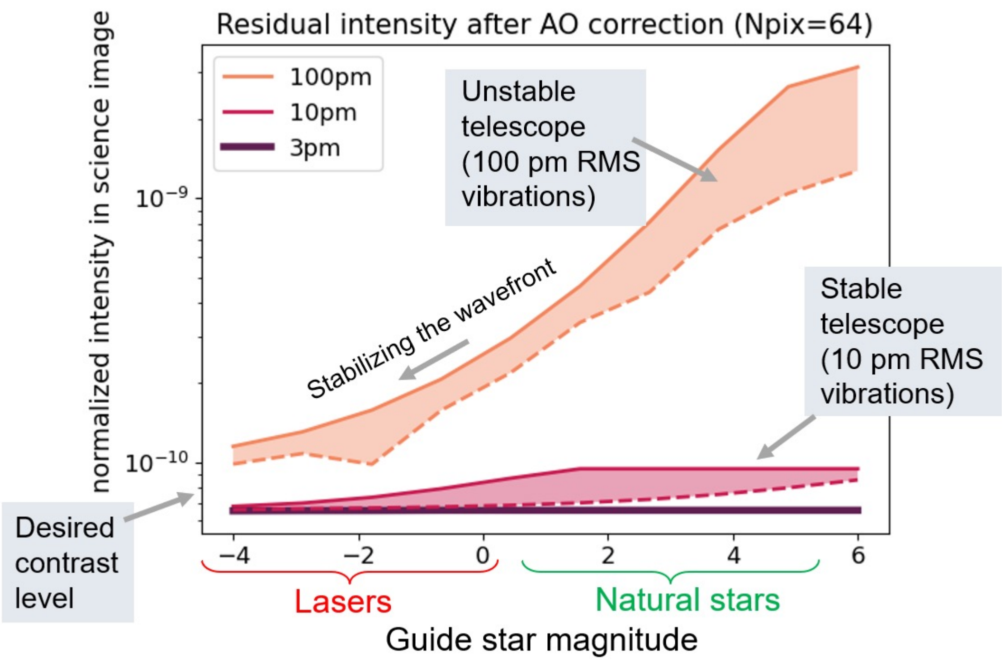
- **A new DM electronics controller under development by Teilsch**
  - 18 bit control, more compact design

Segmented Coronagraph Design & Analysis Study

- **Purpose:**
  - Coronagraph feasibility with segmented-mirror telescope ✓
  - Coronagraph/segmented telescope system feasibility
- **Multi-institutional study of end-to-end modeling of telescope dynamics, wavefront control, and coronagraph -> science yield**
- **In collaboration with Ball, Lockheed Martin telescope modeling and in coordination with STScI wavefront-control modeling (for LUVOIR-A)**
  - Reconfirmed requirement for ~10 pm WFE stability, per LUVOIR report

Possible Next Steps:

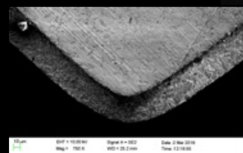
- Study ~ 6-meter-class telescope yield sensitivities
- Telescope model to incorporate active metrology
- Enhance model integration, fidelity, and access



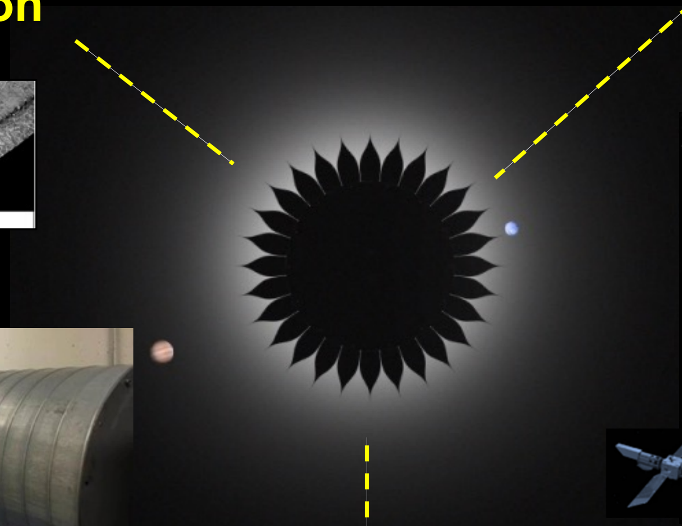
S5: Closing Starshade Technology Gaps

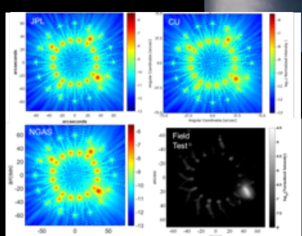
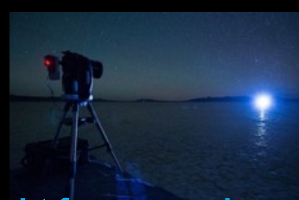
https://exoplanets.nasa.gov/exep/technology/starshade/

(1) Starlight Suppression

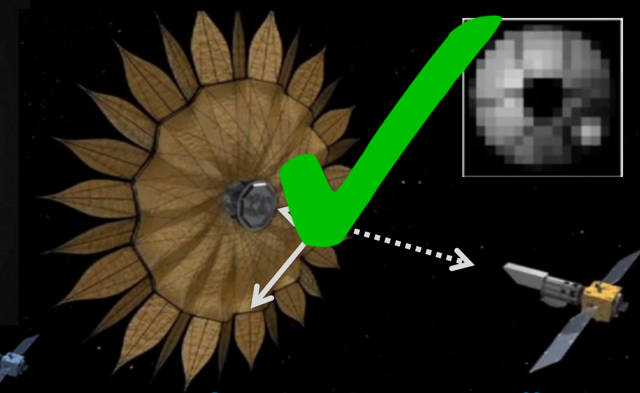
Suppressing scatted light off petal edges from off-axis Sunlight (S-1)



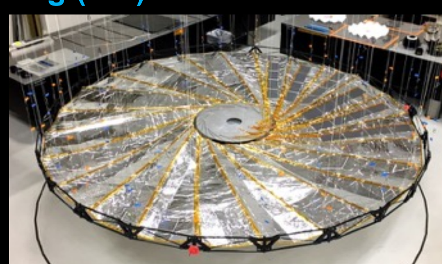
Suppressing diffracted light from on-axis starlight and optical modeling (S-2)

(2) Formation Sensing

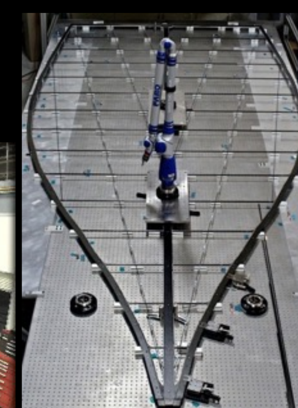


Sensing the lateral offset between the spacecraft (S-3)

(3) Deployment Accuracy and Shape Stability



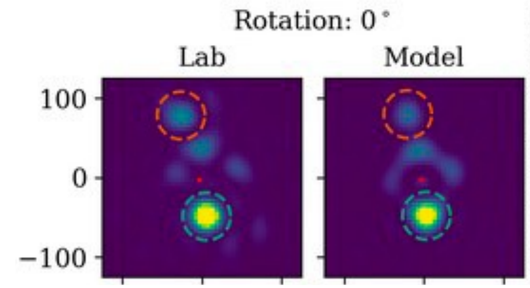

Positioning the petals to high accuracy, blocking on-axis starlight, maintaining overall shape on a highly stable structure (S-5)



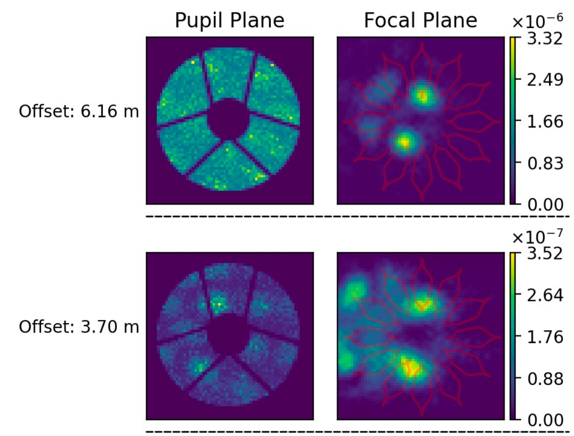
Fabricating the petals to high accuracy (S-4)

Starshade Updates

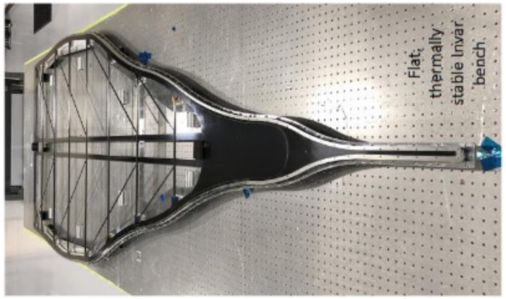
- **Model validation**
  - Traces subscale demo performance to full-scale starshade
  - Including vector diffraction still in progress; agreement not quite at the 25% level.



- **Formation Flying:**
  - Starshade needs sensing of line of sight position relative to telescope to within centimeters with separations of ~10,000 km
  - Princeton subscale testbed demonstration of high contrast with simultaneous position sensing in the loop (PI Kasdin)
  - Final Report on this technique passed review by ExoTAC, is posted on ExEP website



- **Petal Shape Stability**
  - Starshade must maintain shape in operational thermal environment
  - Milestone final report on thermal deformation of petals completed and posted on website



Technosignatures Gap List Study

- The ExEP commenced a fact-finding study to understand where it can make a positive impact towards the search for technological life.

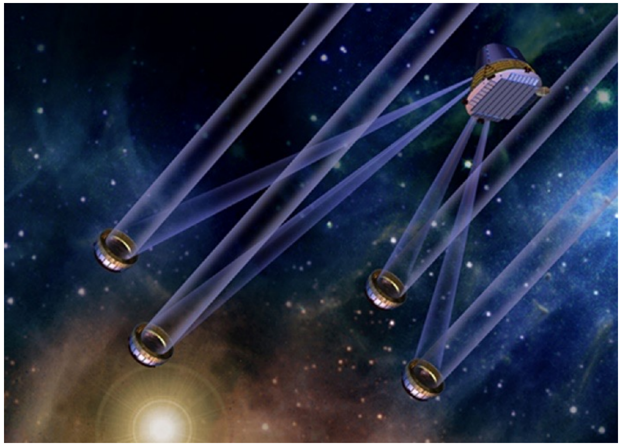
- The Study will help the ExEP better understand the landscape and needs of the field if investments are ever considered again (Congress, donors).

- Key fields within the database will include:
  - ❖ Technosignature search approaches
  - ❖ Technology needs and gaps
  - ❖ Other needs to advance the searches (access to existing facilities, future facilities, AI/ML, $'s, data archiving)

- Study is planned to conclude summer of CY22
  - ❖ First milestone completed in December 2021 (data fields to be collected)
  - ❖ Reviewed by an external Technosignatures Assessment Committee

Completed Nulling Interferometry Study

- **In 2021, ExEP completed a study to update technology gaps related to nulling interferometry**
- **JPL-GSFC Team:** B. Mennesson (PI), G. Serabyn, S. Martin, W. Danchi, C. Stark, P. Chen
  - Revisited TPF-I science goals
  - Summarized lessons learned since TPF-I
  - Preliminarily investigated application of high spectral resolution
  - Identified technology gaps
- **2021 Decadal Survey did not prioritize this capability**



The Gap List

#	Gap Name	#	Gap Name
Gap #1	Cryogenic single mode spatial filters	Gap #6	Cryogenic four-beam nulling
Gap #2	Cryogenic deformable mirrors	Gap #7	Cooling
Gap #3	Cryogenic delay lines	Gap #8	Detector technology
Gap #4	Laser metrology systems	Gap #9	Mirror technology
Gap #5	Cryogenic broadband nulling at N-band	Gap #10	Formation flying technology

Exoplanet Exploration Technology Colloquium Series

- **A Worldwide Survey of Deformable Mirrors**
  Eduardo Bendek (JPL)

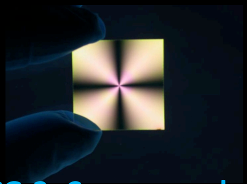
- **Recordings and slides available:**
  – https://exoplanets.nasa.gov/exep/technology/tech_colloquium/


Exoplanet
Missions
Roman
JWST2
TESS
ARIEL7 (CASE8)
PLATO
Kepler
CHEOPS 4
NASA
Missions
Spitzer
Gaia
Hubble1
CoRoT3
ESA Partner
Missions
The path towards the
Future Great Observatories
is under development
W. M. Keck Observatory
1 NASA/ESA Partnership
2 NASA/ESA/CSA Partnership
3 CNES/ESA
4 ESA/Swiss Space Office
7 ESA
8 NASA
Join us!

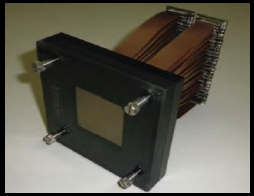
BACKUP

V-NIR Coronagraph/Telescope Technology Gaps

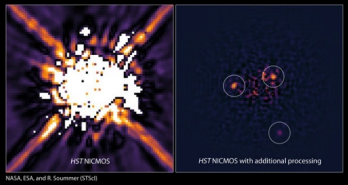
Contrast



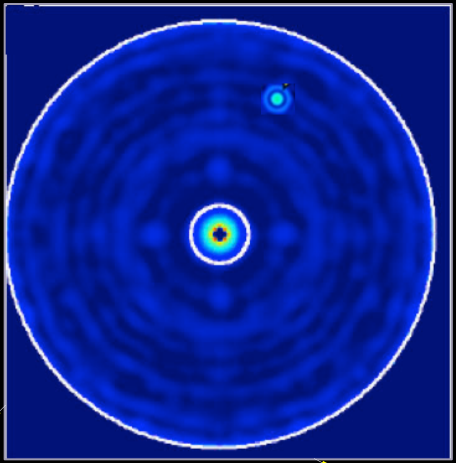
CG-2: Coronagraph Architecture



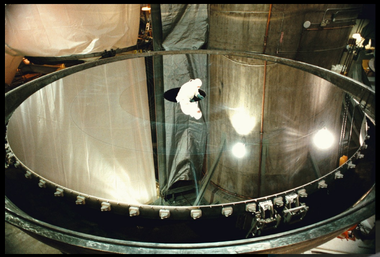
CG-3: Deformable Mirrors



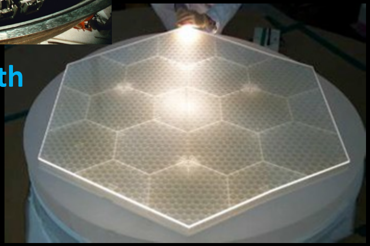
CG-4: Data Post-Processing



Angular Resolution

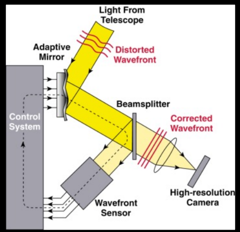


CG-1: Large Monolith Mirrors



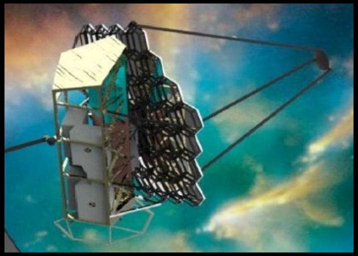
CG-1: Segmented Mirrors

Contrast Stability



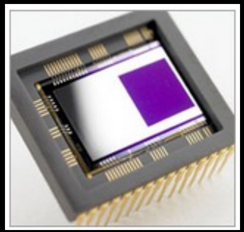
CG-5: Wavefront Sensing and Control

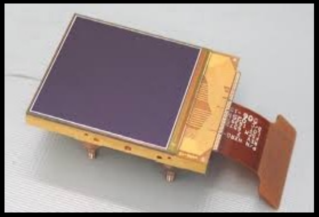
CG-6: Mirror Segment Phasing



CG-7: Telescope Vibration Sensing and Control or Reduction

Detection Sensitivity

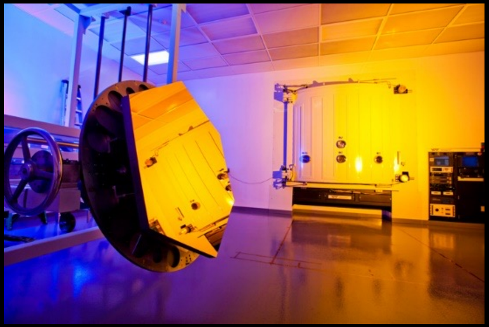




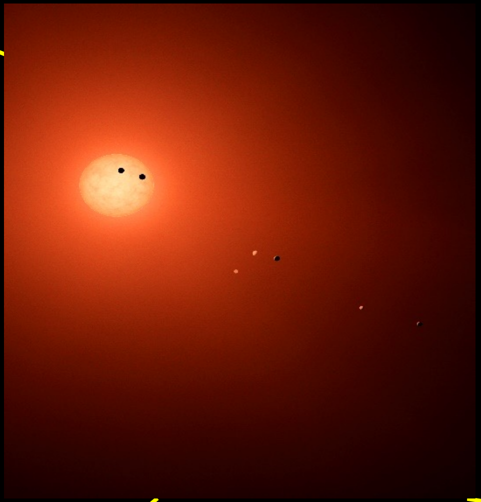
Ultra-low Noise Visible (CG-8) and Infrared (CG-9) Detectors

Other Technology Gaps

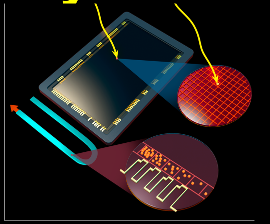
UV Contrast



CG-10 UV/V/NIR Mirror Coatings

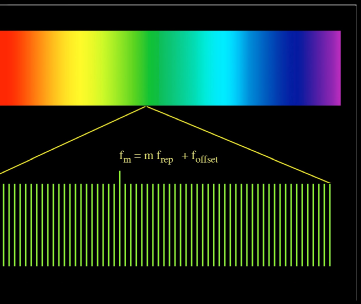


UV Detection Sensitivity

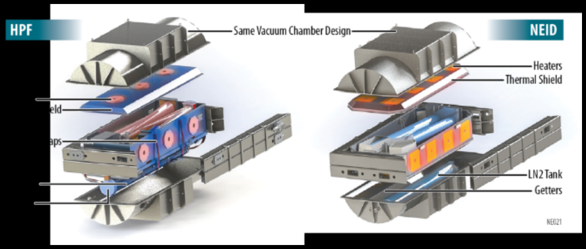


CG-12: Ultra-low Noise UV Detectors

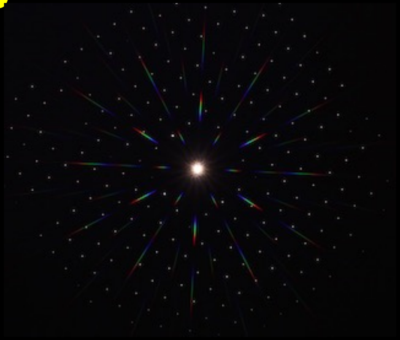
Stellar Reflex Motion Sensitivity



M-2: Laser Frequency Combs for Space-based EPRV

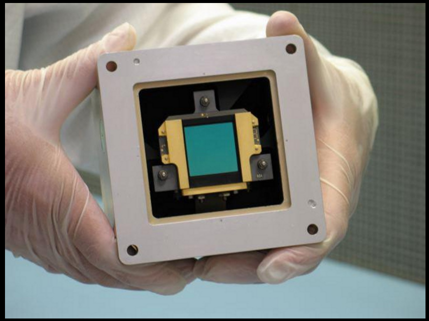


M-1: Ground-based Ultra-high Precision Radial Velocity



M-3: Astrometry

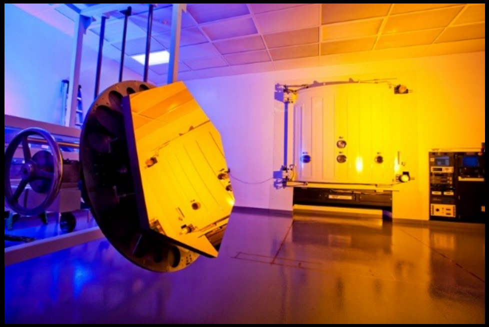
Transit Spectroscopy Sensitivity



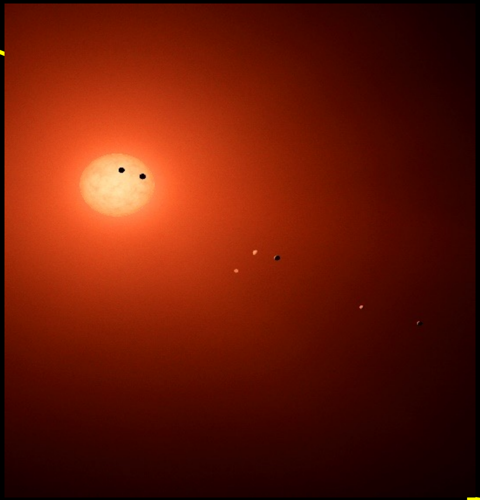
M-4: Ultra-stable Mid-IR Detectors for Transit Spectroscopy

Mid-IR Technology Gaps

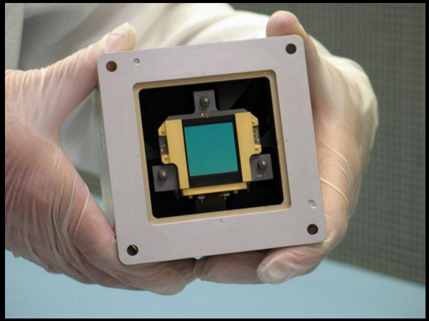
Mid-IR Coronagraph Contrast



CG-10 UV/V/NIR Mirror Coatings



Transit Spectroscopy Sensitivity



M-4: Ultra-stable Mid-IR Detectors for Transit Spectroscopy