Jet Propulsion Laboratory
California Institute of Technology

Technology Needs to Discover Earth 2.0

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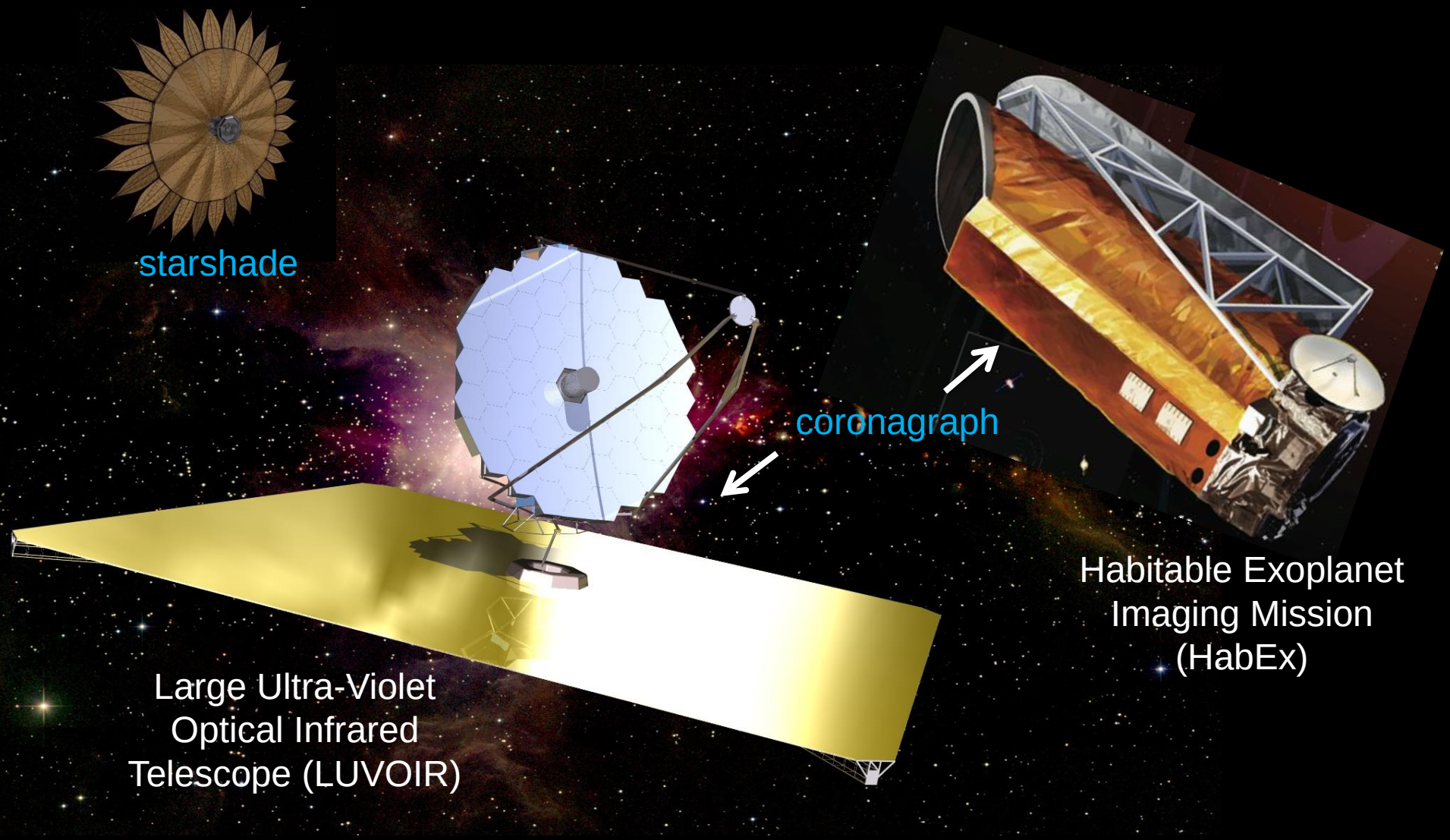
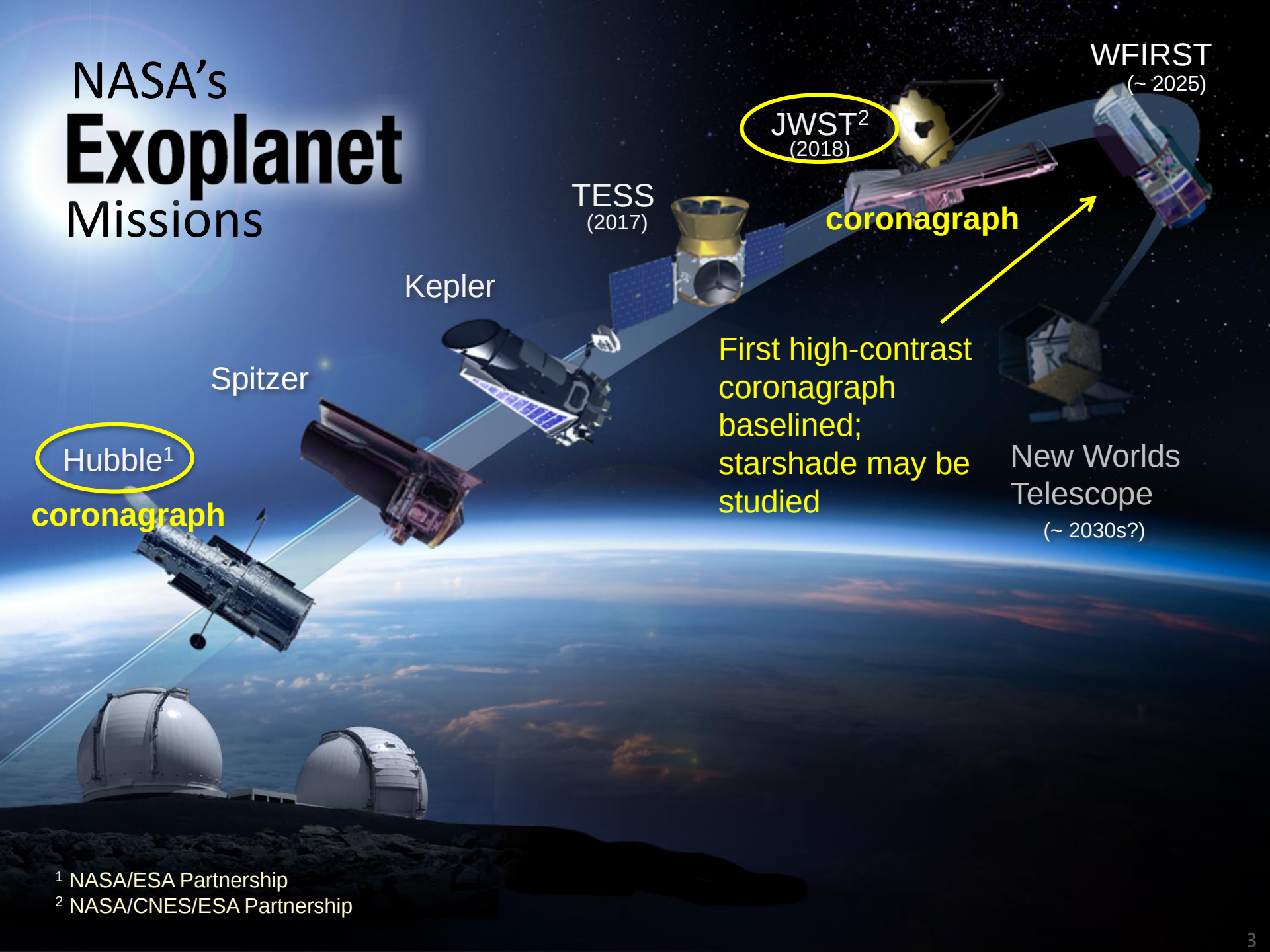
Program Chief Technologist
Jet Propulsion Laboratory / Caltech

September 15, 2016
NASA Exoplanet Exploration Program Updates and Technology Challenges
AIAA Space 2016, SPSC-03, Long Beach CA

Possible New Worlds Exoplanet Telescopes
(mid-2030s)

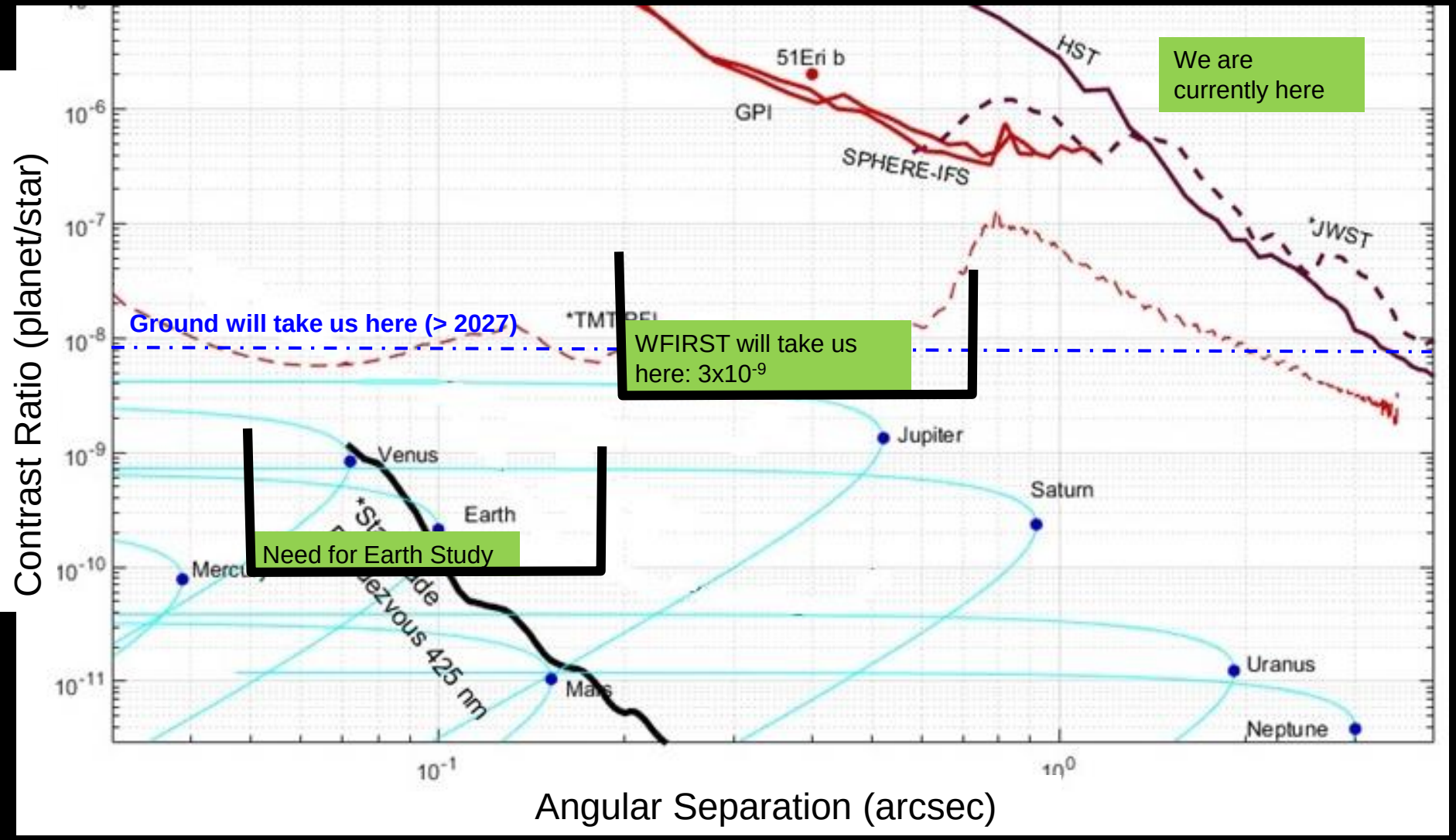


NASA's Exoplanet Missions



[1] NASA/ESA Partnership
[2] NASA/CNES/ESA Partnership

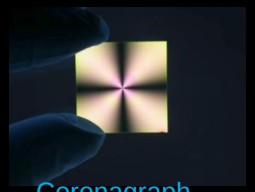
Towards the Detection of Exo-Earths



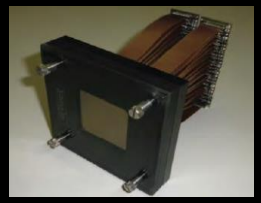
How a Coronagraph Works

Coronagraph/Telescope Technology Needs

Contrast



Coronagraph architectures



Deformable mirrors

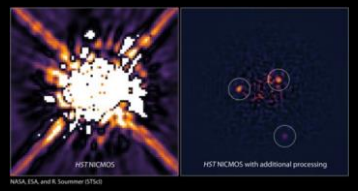
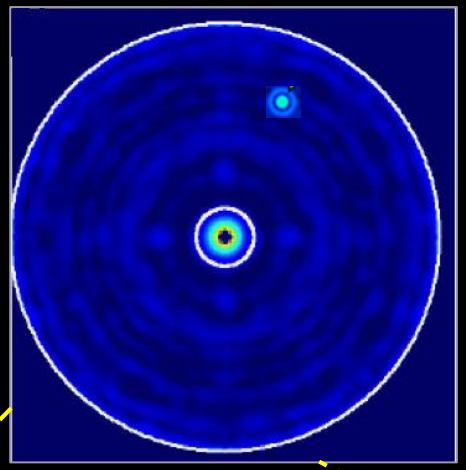
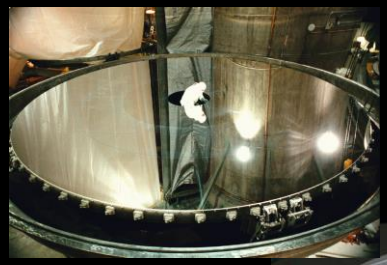


Image post-processing



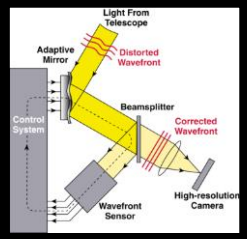
Angular Resolution



Large monolith

Segmented

Contrast Stability

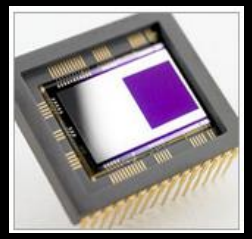


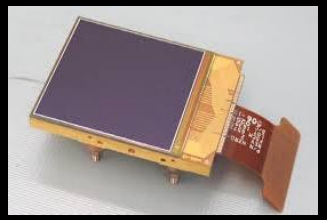
Wavefront sensing and control

Segment phasing and rigid body sensing and control

Telescope vibration sensing and control

Detection Sensitivity



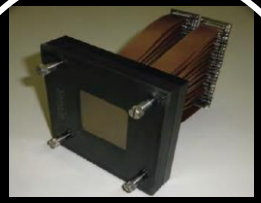


Ultra-low noise visible and infrared detectors

Technology Advancement by the WFIRST Coronagraph

Contrast

Coronagraph architectures



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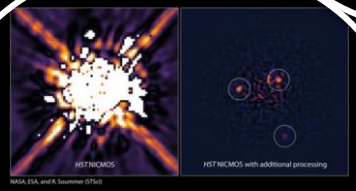
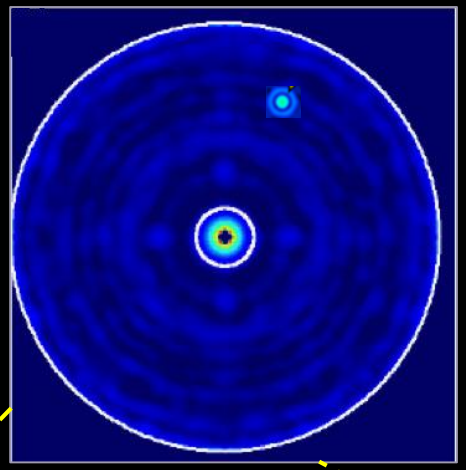
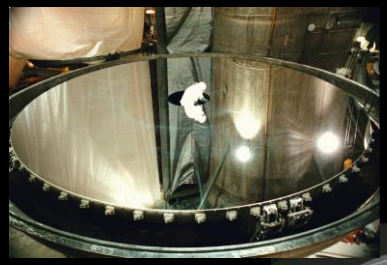


Image post-processing



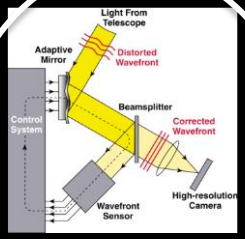
Angular Resolution



Large monolith

Segmented

Contrast Stability



Wavefront sensing and control

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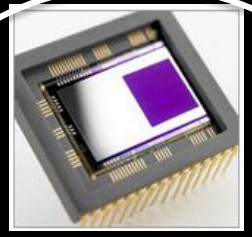
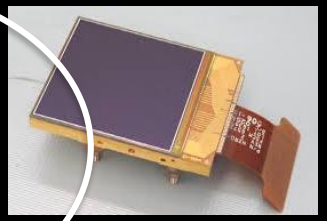
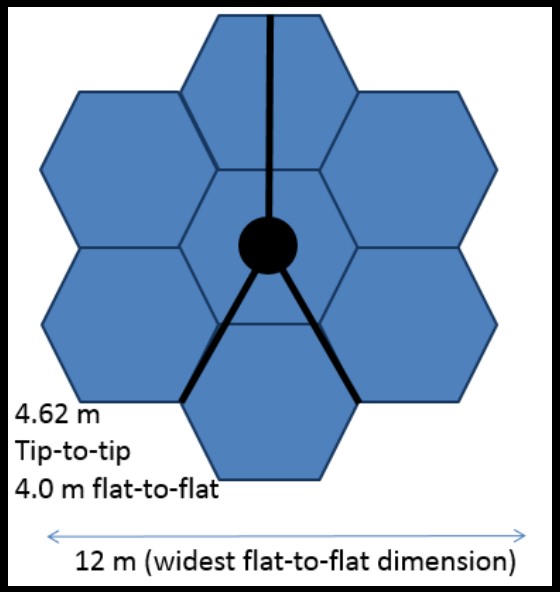
Detection Sensitivity

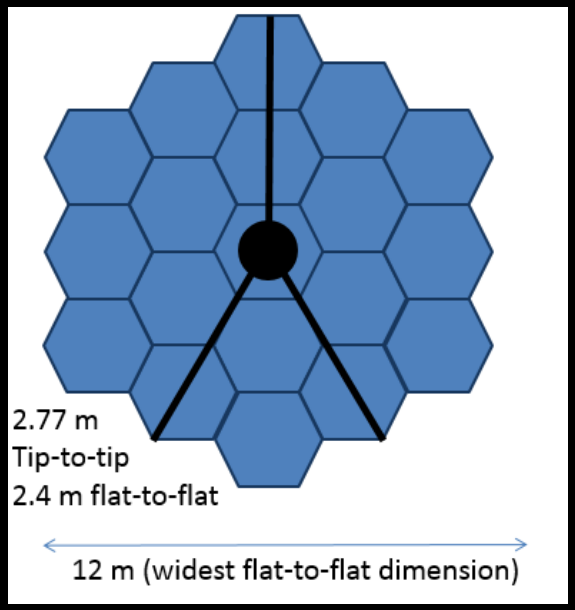


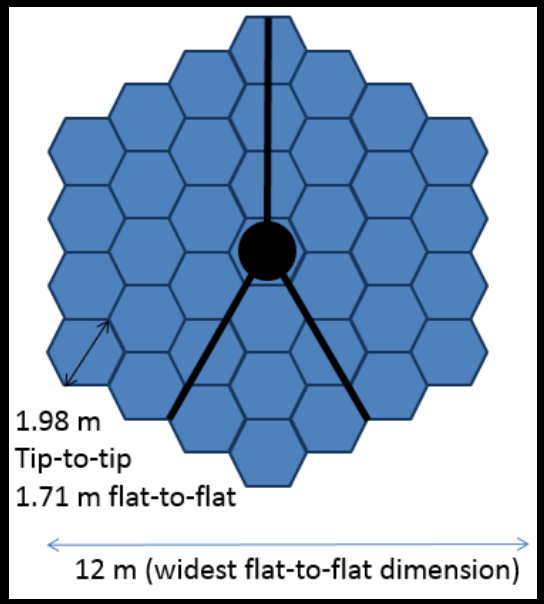


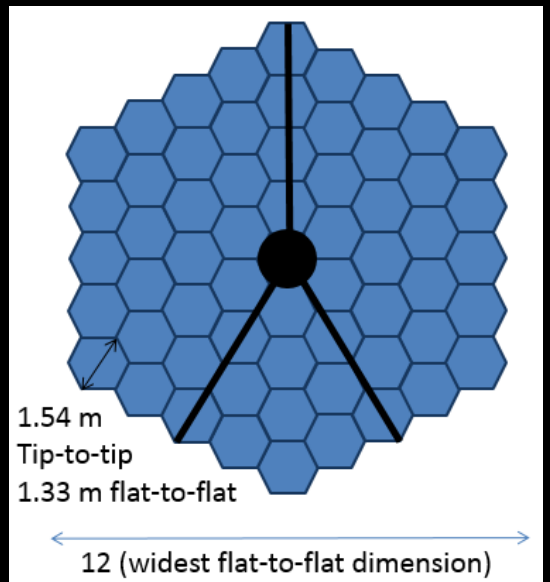
Ultra-low noise visible and infrared detectors

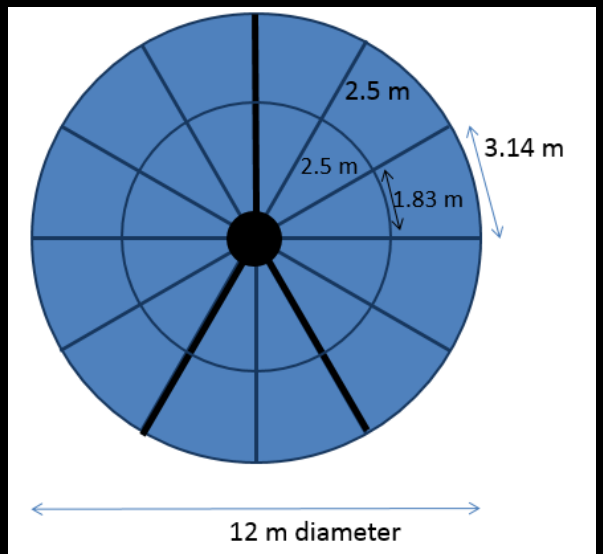
Segmented Coronagraph Design Analysis

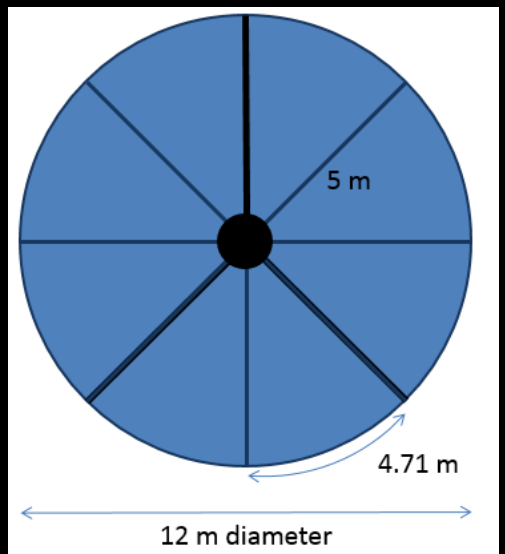




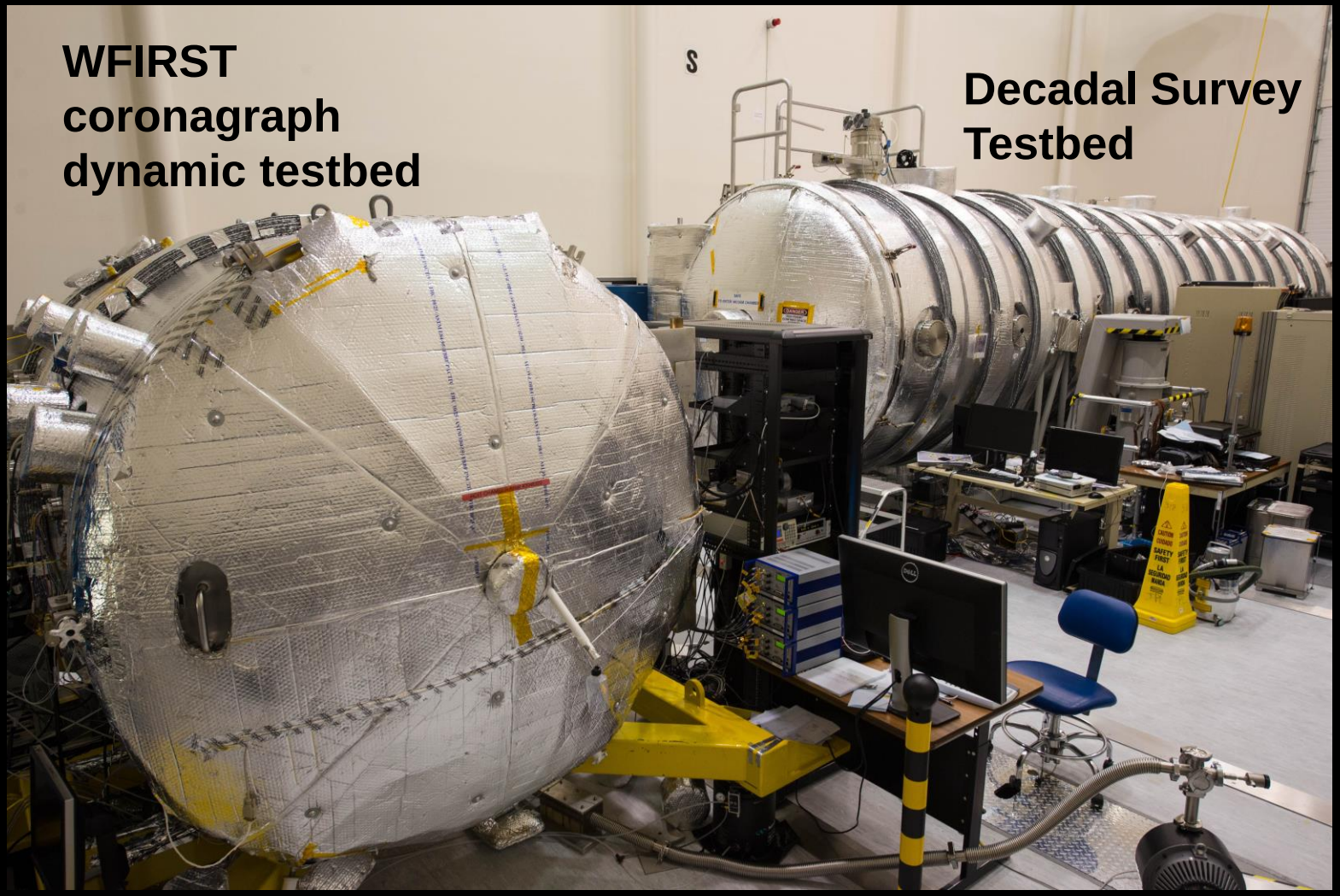




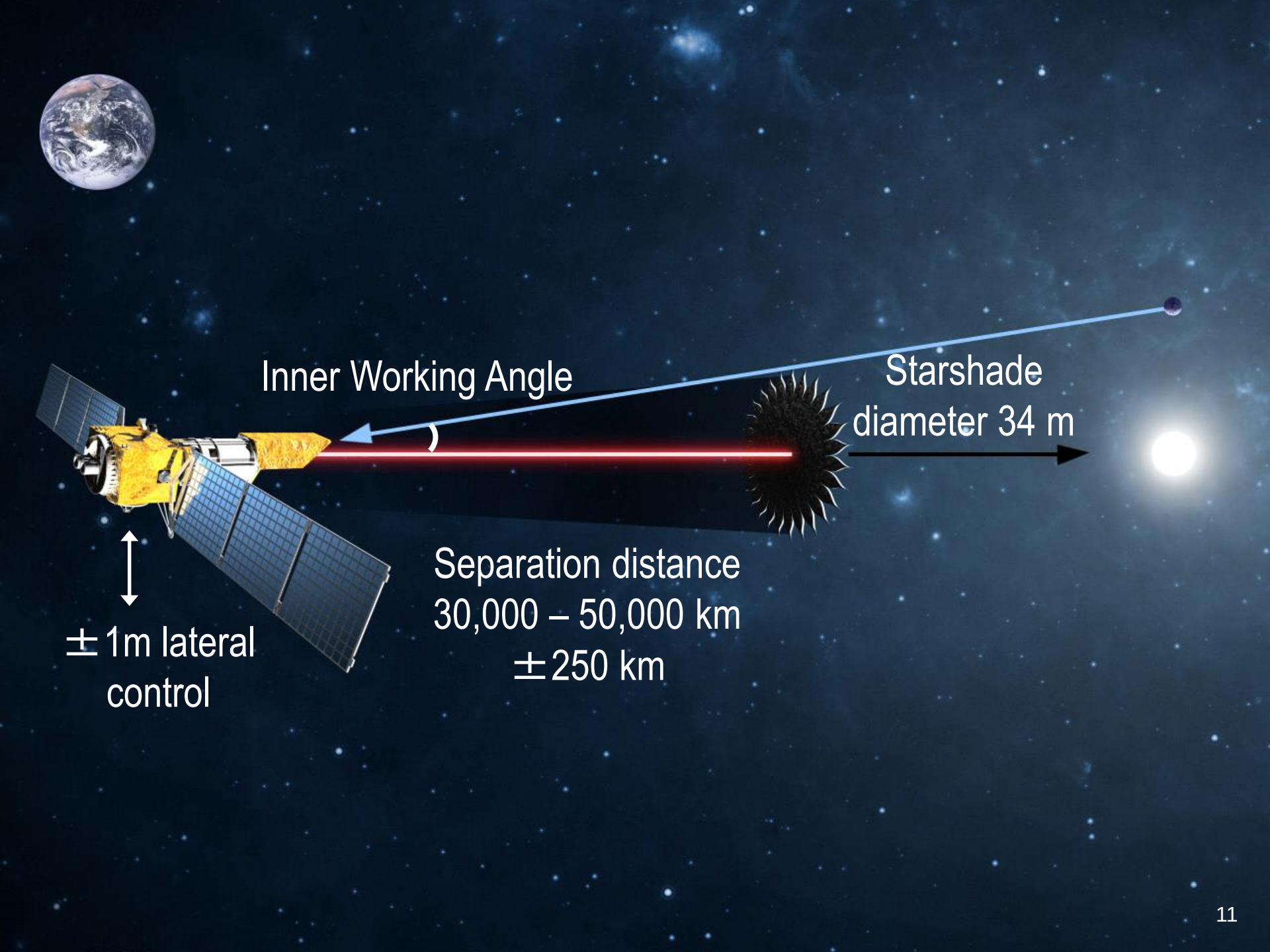




NASA's High Contrast Imaging Testbeds (JPL)



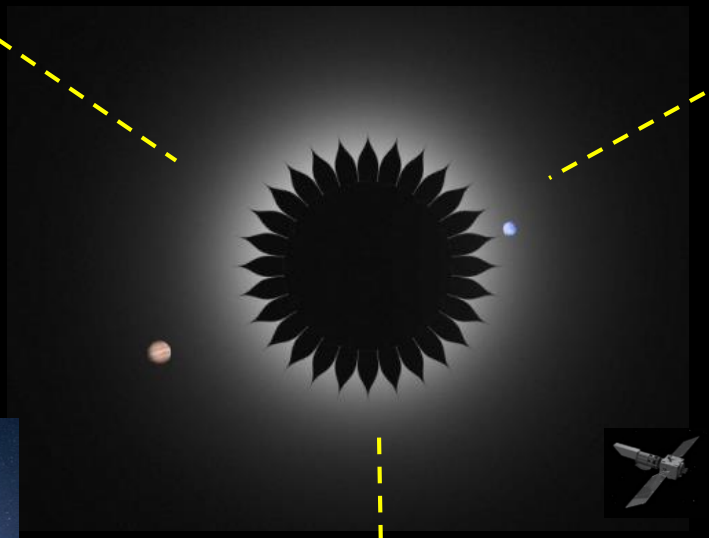
Starshade Concept


Inner Working Angle
Starshade
diameter 34 m
Separation distance
30,000 – 50,000 km
±250 km
±1m lateral
control

Starshade Technology Needs

(1) Light Suppression

(3) Formation Sensing and Control



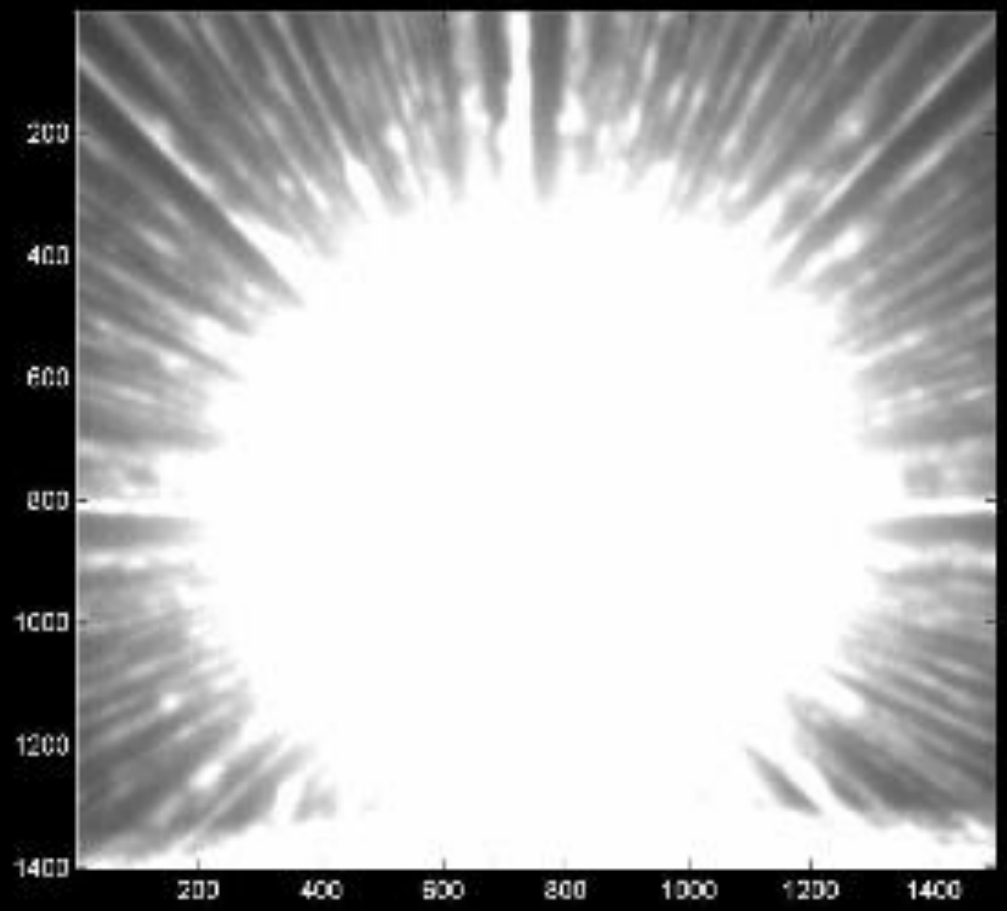
Suppressing diffracted light
from on-axis starlight

(2) Deployment Accuracy and Shape Stability

Desert Testing of the Starshade

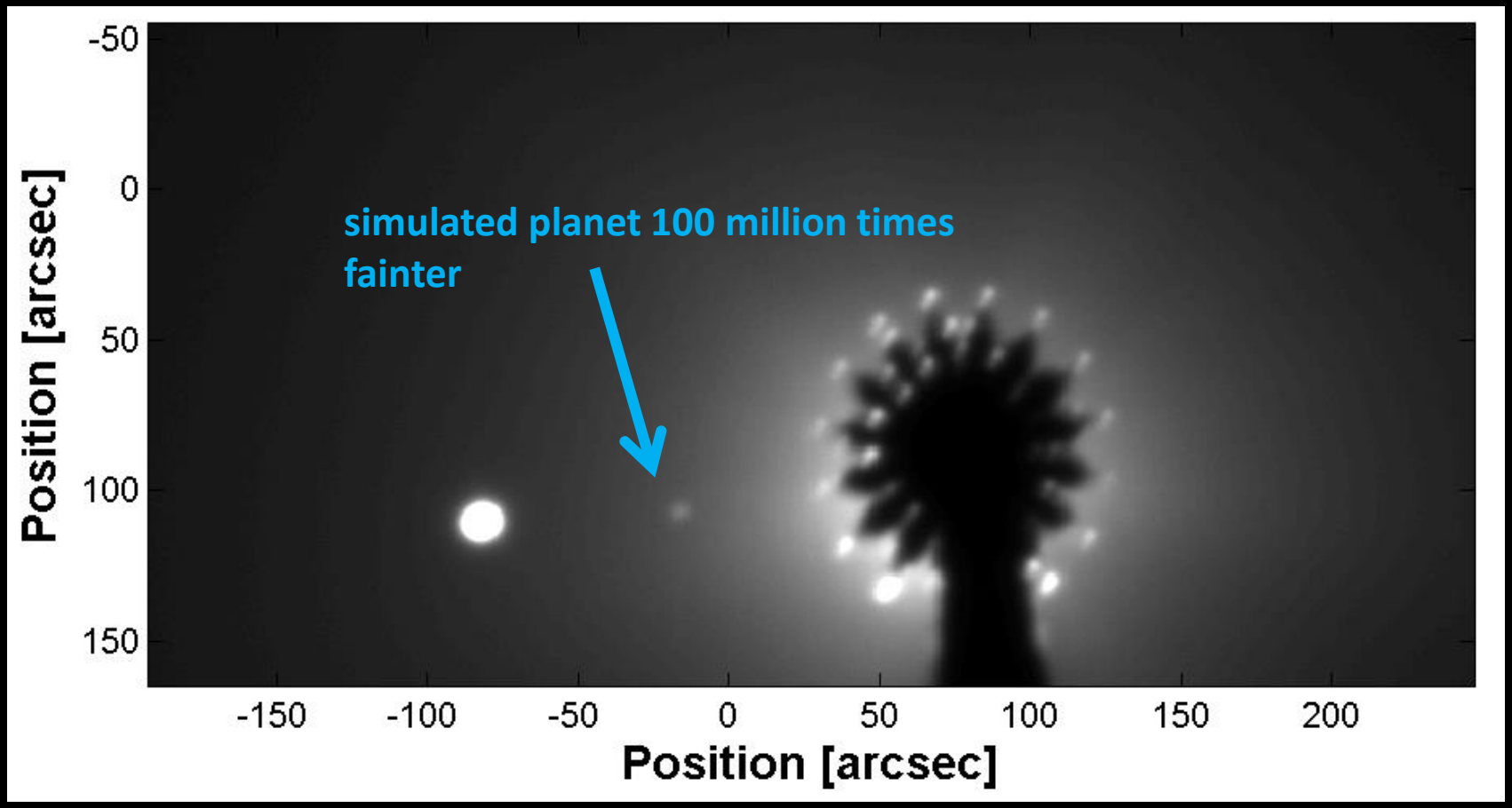
Credit: Northrop Grumman Aerospace Systems

Desert Testing of the Starshade



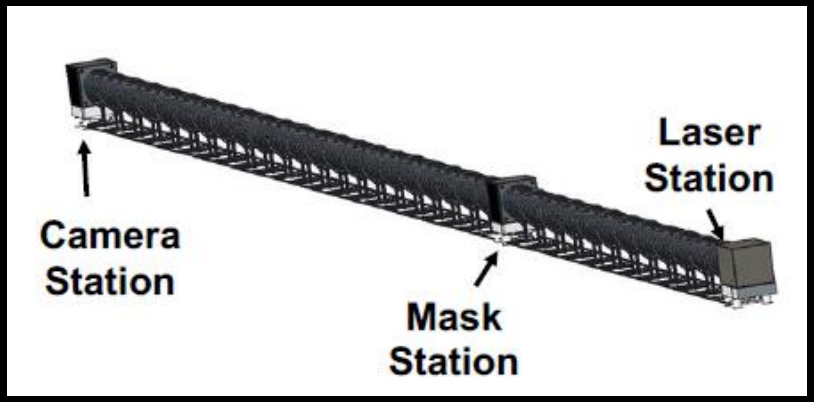
Credit: Northrop Grumman Aerospace Systems

Desert Testing of the Starshade



Credit: Northrop Grumman Aerospace Systems

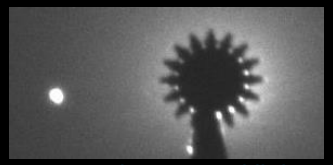
Optical Demonstrations at Princeton University



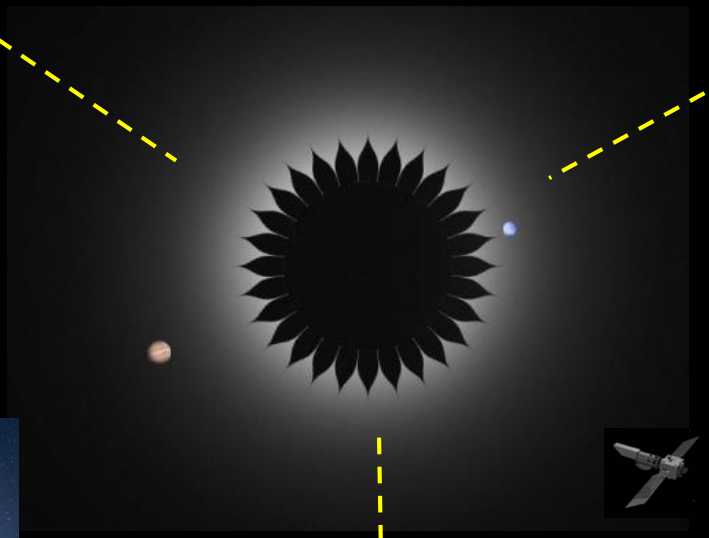
Jeremy Kasdin (Princeton)

Starshade Technology Needs

(1) Light Suppression



Suppressing scatted light off petal edges from off-axis Sunlight

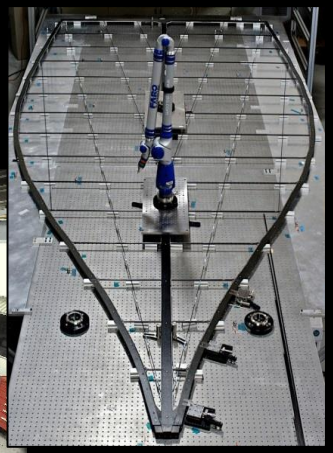


(3) Formation Sensing and Control

Suppressing diffracted light from on-axis starlight

(2) Deployment Accuracy and Shape Stability

Positioning the petals to high precision, blocking on-axis starlight, maintaining overall shape on a highly stable structure



Fabricating the petal to high precision

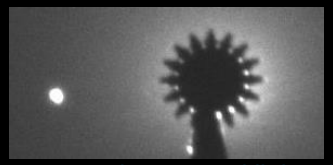
Inner Disk Prototype Deployment Trial at JPL

2 m Optical Shield Prototype Deployment Trial at JPL

5 m Origami Optical Shield Deployment Trial at JPL

Starshade Technology Needs

(1) Starlight Suppression



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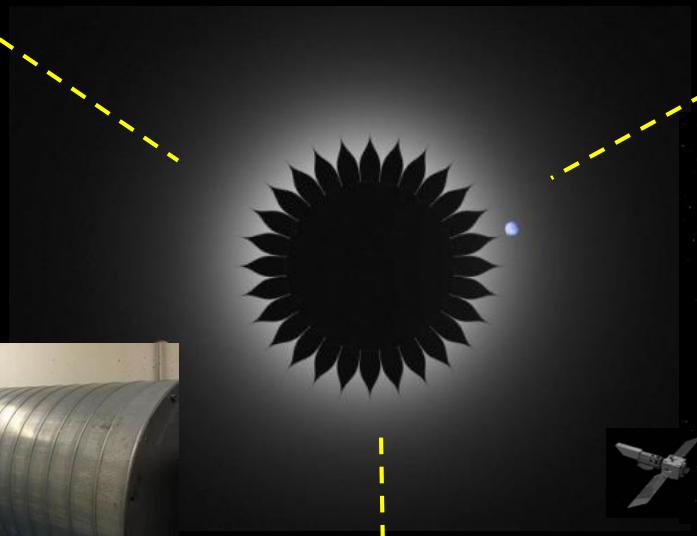
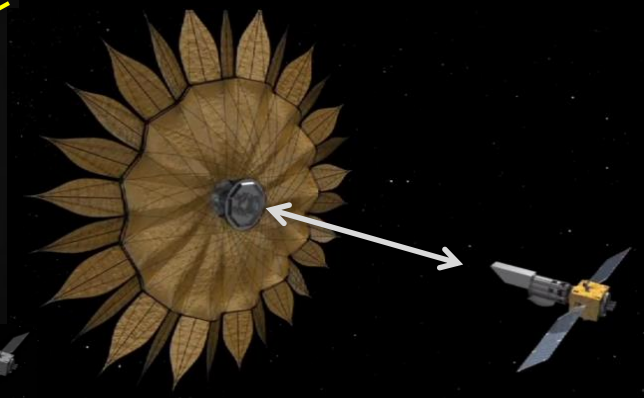


(3) Formation Sensing and Control



Maintaining lateral offset requirement between the spacecrafts

Suppressing diffracted light from on-axis starlight

(2) Deployment Accuracy and Shape Stability

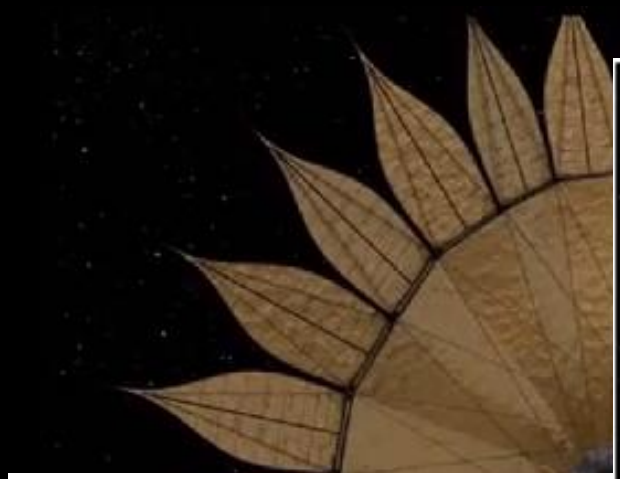
Fabricating the petal to high precision

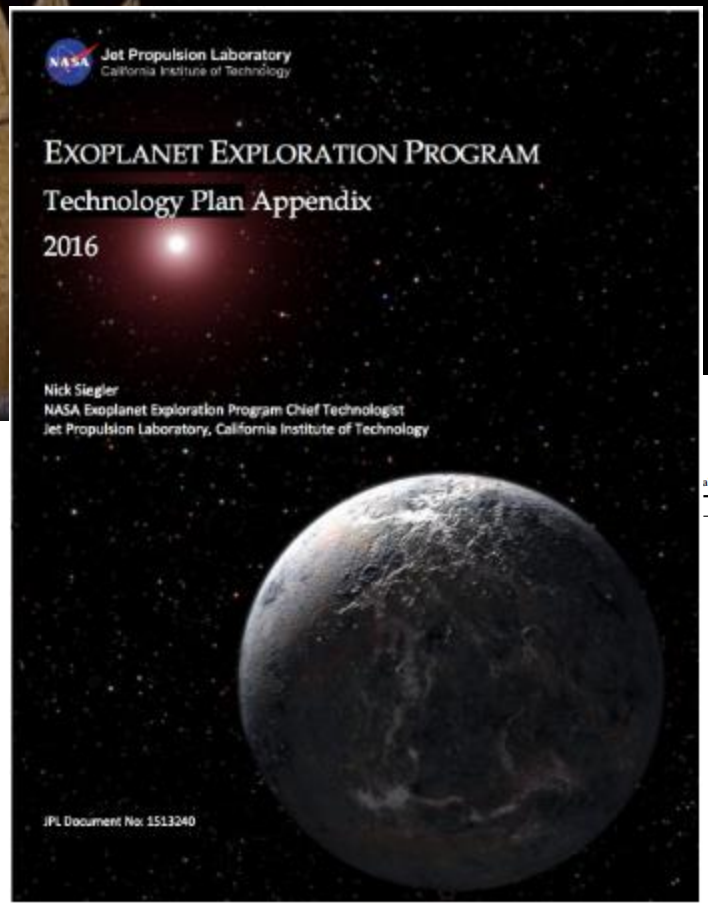
Positioning the petals to high precision, blocking on-axis starlight, maintaining overall shape on a highly stable structure

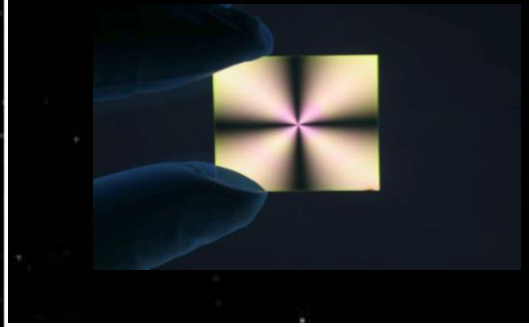
Recent Starshade Technology News

- NASA-chartered starshade technology activity in March
  - *Starshade Technology Project advances technology to TRL-5*
- Starshade Readiness Working Group commenced in January to identify the recommended path to flight for a starshade mission.
  - *Multi-institutional working group and participation*
  - *Report out to NASA HQ by end of month*
- WFIRST is assessing the impact of accommodating a future starshade mission
  - *Final decision will be made no later than summer of 2017.*

ExEP Technology Gap Lists







Starshade Technology Gap List

Table A.4 Starshade Technology Gap List

ID	Title	Description	Current	Required
S-1	Control Edge-Scattered Sunlight	Limit edge-scattered sunlight with optical petal edges that also handle stowed bending strain.	Graphite edges meet all specs except sharpness, with edge radius ≥10 μm.	Optical petal edges manufactured of high flexural strength material with edge radius ≤ 1 μm and reflectivity ≤ 10%.
S-2	Contrast Performance Demonstration and Optical Model Validation	Experimentally validate the equations that predict the contrasts achievable with a starshade.	Experiments have validated optical diffraction models at Fresnel number of ~500 to contrasts of 3×10^{-10} at 632 nm.	Experimentally validate models of starlight suppression to $\leq 3\times10^{-11}$ at Fresnel numbers ≤ 50 over 510-825 nm bandpass.
S-3	Lateral Formation Flying Sensing Accuracy	Demonstrate lateral formation flying sensing accuracy consistent with keeping telescope in starshade's dark shadow.	Centroid accuracy ≥ 1% is common. Simulations have shown that sensing and GN&C is tractable, though sensing demonstration of lateral control has not yet been performed.	Demonstrate sensing lateral errors ≤ 0.20m at scaled flight separations and estimated centroid positions ≤ 0.3% of optical resolution. Control algorithms demonstrated with lateral control errors ≤ 1m.
S-4	Flight-Like Petal Fabrication and Deployment	Demonstrate a high-fidelity, flight-like starshade petal and its unfurling mechanism.	Prototype petal that meets optical edge position tolerances has been demonstrated.	Demonstrate a fully integrated petal, including blankets, edges, and deployment control interfaces. Demonstrate a flight-like unfurling mechanism.
S-5	Inner Disk Deployment	Demonstrate that a starshade can be autonomously deployed to within the budgeted tolerances.	Demonstrated deployment tolerances with 12m heritage Astromesh antenna with four petals, no blankets, no outrigger struts, and no launch restraint.	Demonstrate deployment tolerances with flight-like, minimum half-scale inner disk, with simulated petals, blankets, and interfaces to launch restraint.

Coronagraph/Telescope Technology Gap List

able A.3 Coronagraph Technology Gap List.

ID	Title	Description	Current	Required
C-1	Specialized Coronagraph Optics	Masks, apodizers, or beam-shaping optics to provide starlight suppression and planet detection capability.	A linear mask design has yielded 3.2×10^{-10} mean raw contrast from 3–16 λ/D with 10% bandwidth using an unobscured pupil in a static lab demonstration.	Circularly symmetric masks achieving $\leq 1\times10^{-10}$ contrast with IWA ≤ 3λ/D and ≥ 10% bandwidth on obscured or segmented pupils.
C-2*	Low-Order Wavefront Sensing & Control	Beam jitter and slowly varying large-scale (low-order) optical aberrations may obscure the detection of an exoplanet.	Tip/tilt errors have been sensed and corrected in a stable vacuum environment with a stability of 10^{-3} λ rms at sub-Hz frequencies.	Tip/tilt, focus, astigmatism, and coma sensed and corrected simultaneously to 10^{-4} λ (~10^{-1}'s of pm) rms to maintain raw contrasts of $\leq 1\times10^{-10}$ in a simulated dynamic testing environment.
C-3*	Large-Format Ultra-Low Noise Visible Detectors	Low-noise visible detectors for faint exoplanet characterization with an Integral Field Spectrograph.	Read noise of < 1 e^-/pixel has been demonstrated with EMCCDs in a 1k × 1k format with standard read-out electronics	Read noise < 0.1e^-/pixel in a ≥ 4k × 4k format validated for a space radiation environment and flight-accepted electronics.
C-4*	Large-Format Deformable Mirrors	Maturation of deformable mirror technology toward flight readiness.	Electrostrictive 64x64 DMs have been demonstrated to meet ≤ 10^{-9} contrasts in a vacuum environment and 10% bandwidth.	≥ 64x64 DMs with flight-like electronics capable of wavefront correction to ≤ 10^{-10} contrasts. Full environmental testing validation.
C-5	Efficient Contrast Convergence	Rate at which wavefront control methods achieve 10^{-10} contrast.	Model and measurement uncertainties limit wavefront control convergence and require many tens to hundreds of iterations to get to 10^{-10} contrast from an arbitrary initial wavefront.	Wavefront control methods that enable convergence to 10^{-10} contrast ratios in fewer iterations (10-20).
C-6*	Post-Data Processing	Techniques are needed to characterize exoplanet spectra from residual speckle noise for typical targets.	Few 100x speckle suppression has been achieved by HST and by ground-based AO telescopes in the NIR and in contrast regimes of 10^{-5} to 10^{-4}, dominated by phase errors.	A 10-fold improvement over the raw contrast of ~10^{-4} in the visible where amplitude errors are expected to no longer be negligible with respect to phase errors.

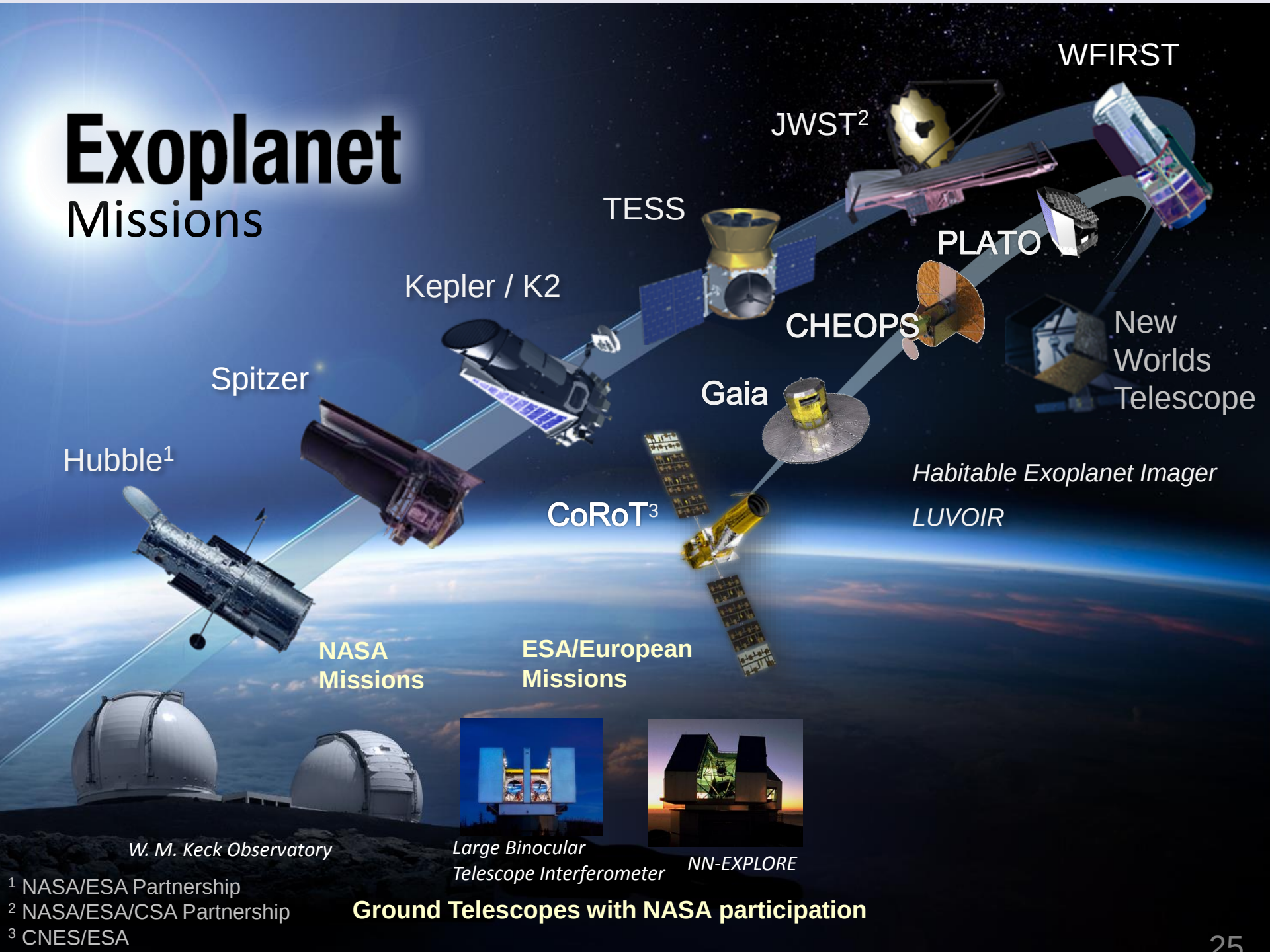
*Topic being addressed by directed-technology development for the WFIRST/AFTA coronagraph. Consequently, coronagraph technologies that will be substantially advanced under the WFIRST/AFTA technology development are not eligible for TDEMs.

https://exoplanets.nasa.gov/exep/technology/technology-overview/

Opportunities to Participate

- Propose for a NASA Strategic Astrophysics Technology (SAT)
  - for TRL 3-5 (http://nspires.nasaprs.com/external/)
- Propose for an NASA Astrophysics Research and Analysis (APRA) grant
  - TRL 1-2 (http://nspires.nasaprs.com/external/)
- Propose for a NASA Small Business Innovation Research (SBIR) grant
  - All ExEP technology gaps are mapped to the 2015 NASA Technology Roadmaps
    - http://www.nasa.gov/offices/oct/home/roadmaps/index.html
- Competed work solicited by the Starshade Technology Project
  - Workshop date to be announced (to be scheduled before end of CY16)
- Visit the Exoplanet Exploration Program (ExEP) technology website
  - https://exoplanets.nasa.gov/exep/technology/technology-overview/

Exoplanet Missions



Ground Telescopes with NASA participation

[1] NASA/ESA Partnership
[2] NASA/ESA/CSA Partnership
[3] CNES/ESA

Acknowledgements

This work was conducted at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration

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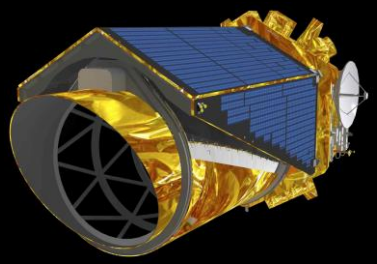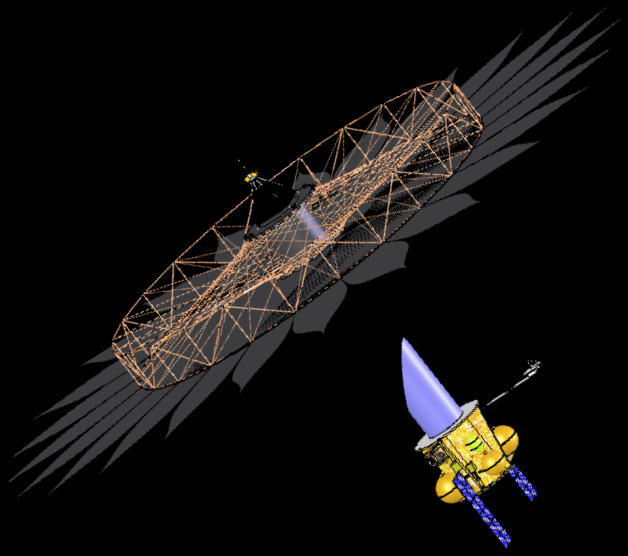
Government sponsorship acknowledged