Jet Propulsion Laboratory
California Institute of Technology

Technology Needs to Discover Earth 2.0

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Jet Propulsion Laboratory / Caltech

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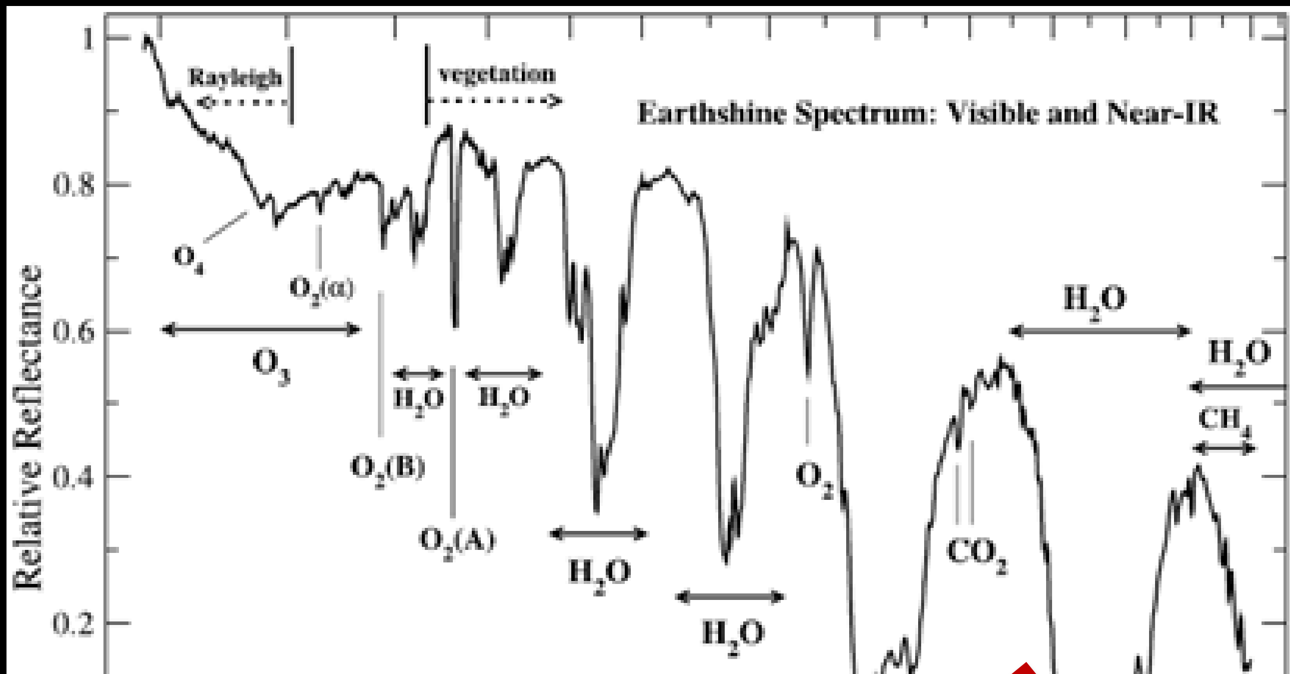
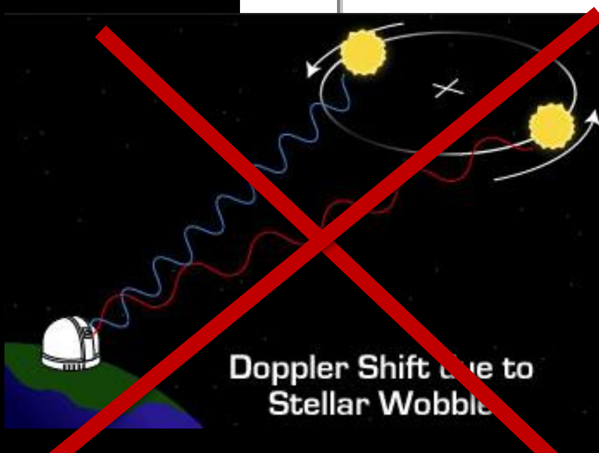
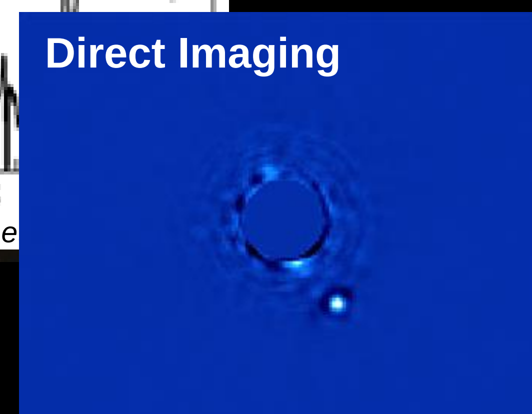
Irvine, CA

CL#16-4258

Starlight Suppression is the Key Technology in the Search for Life on Earth-Size Exoplanets

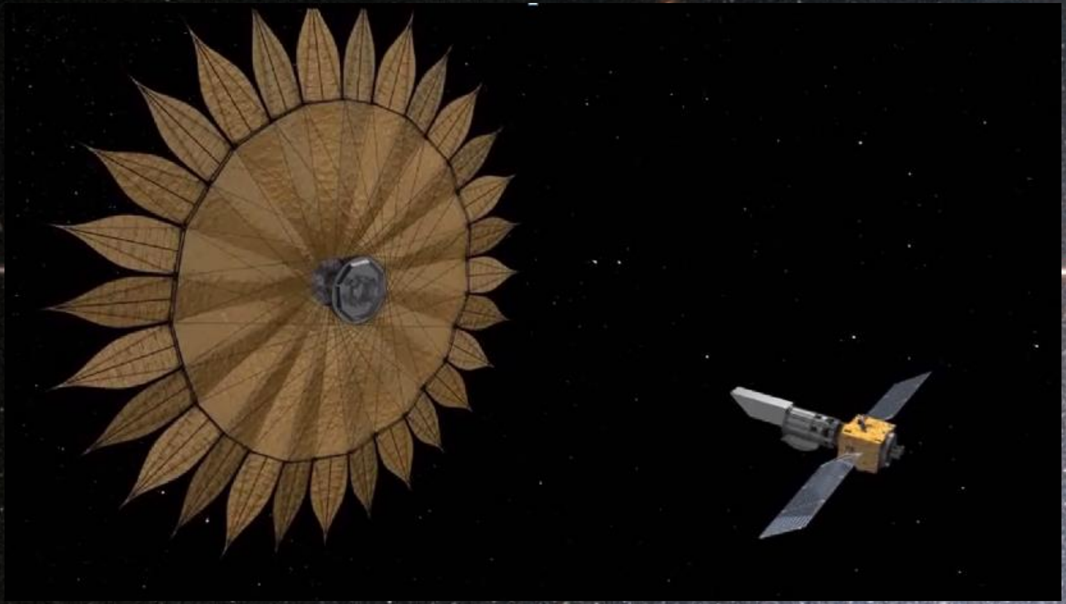


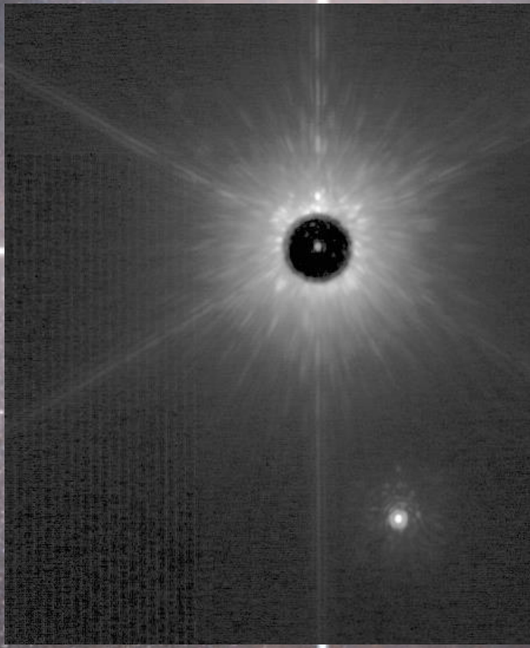




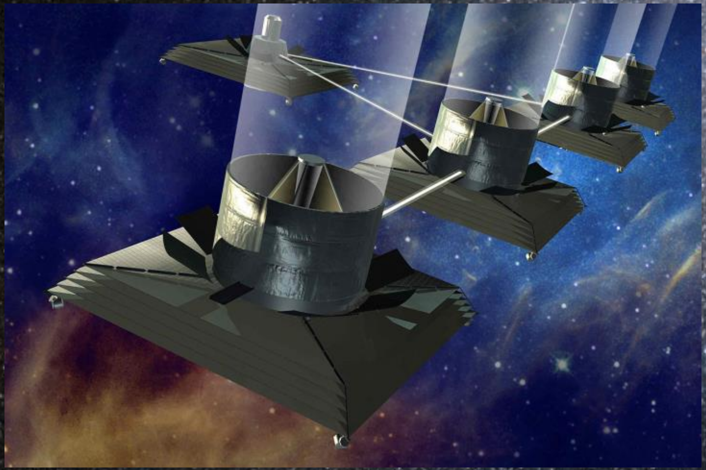
Macintosh et al. 2015

External Occulters (Starshades)

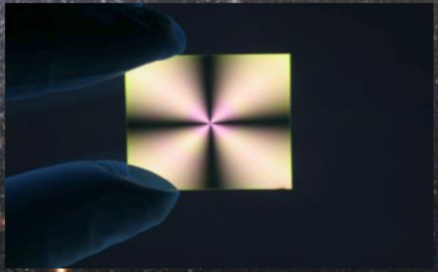


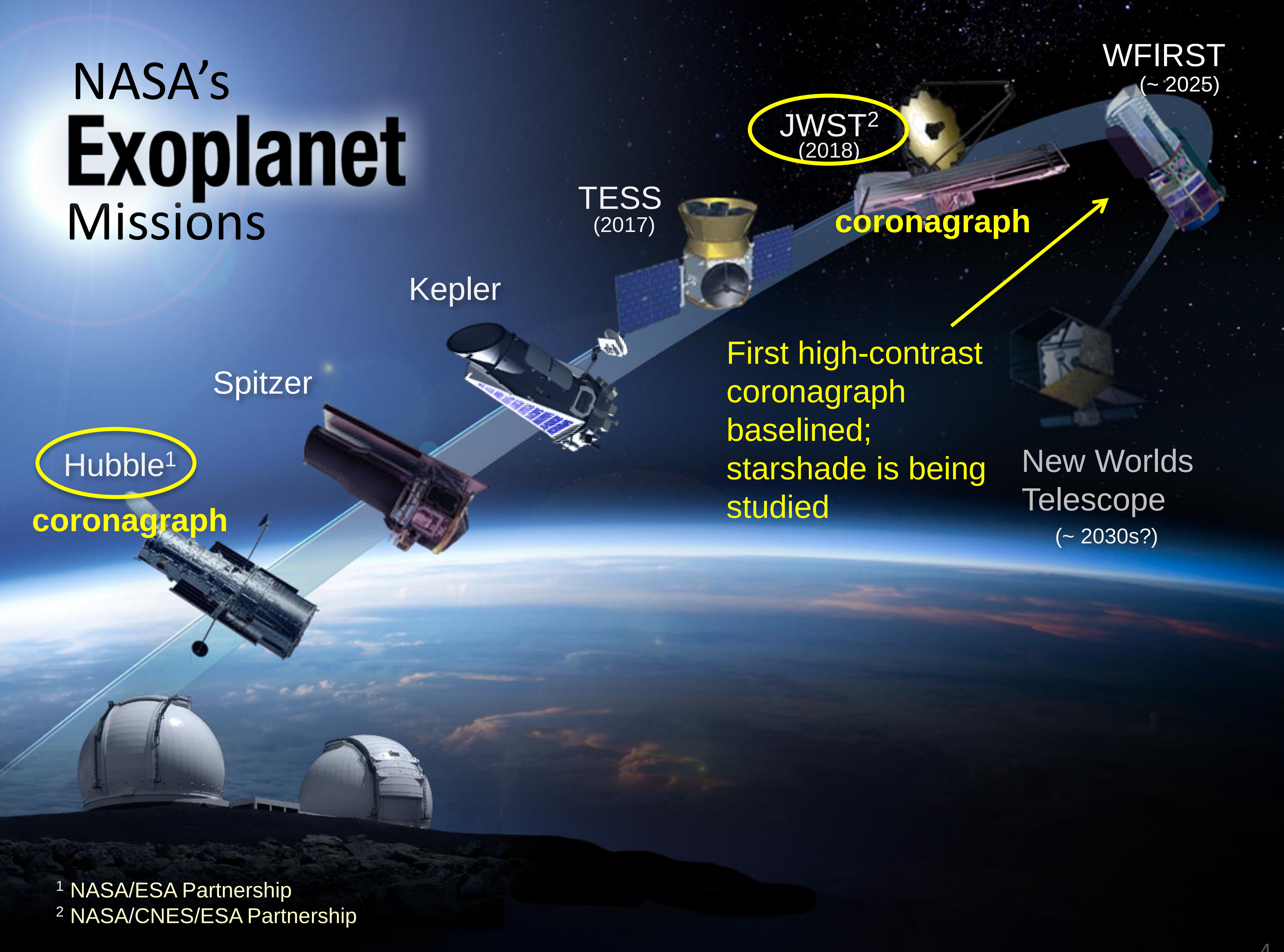


Nulling Interferometry



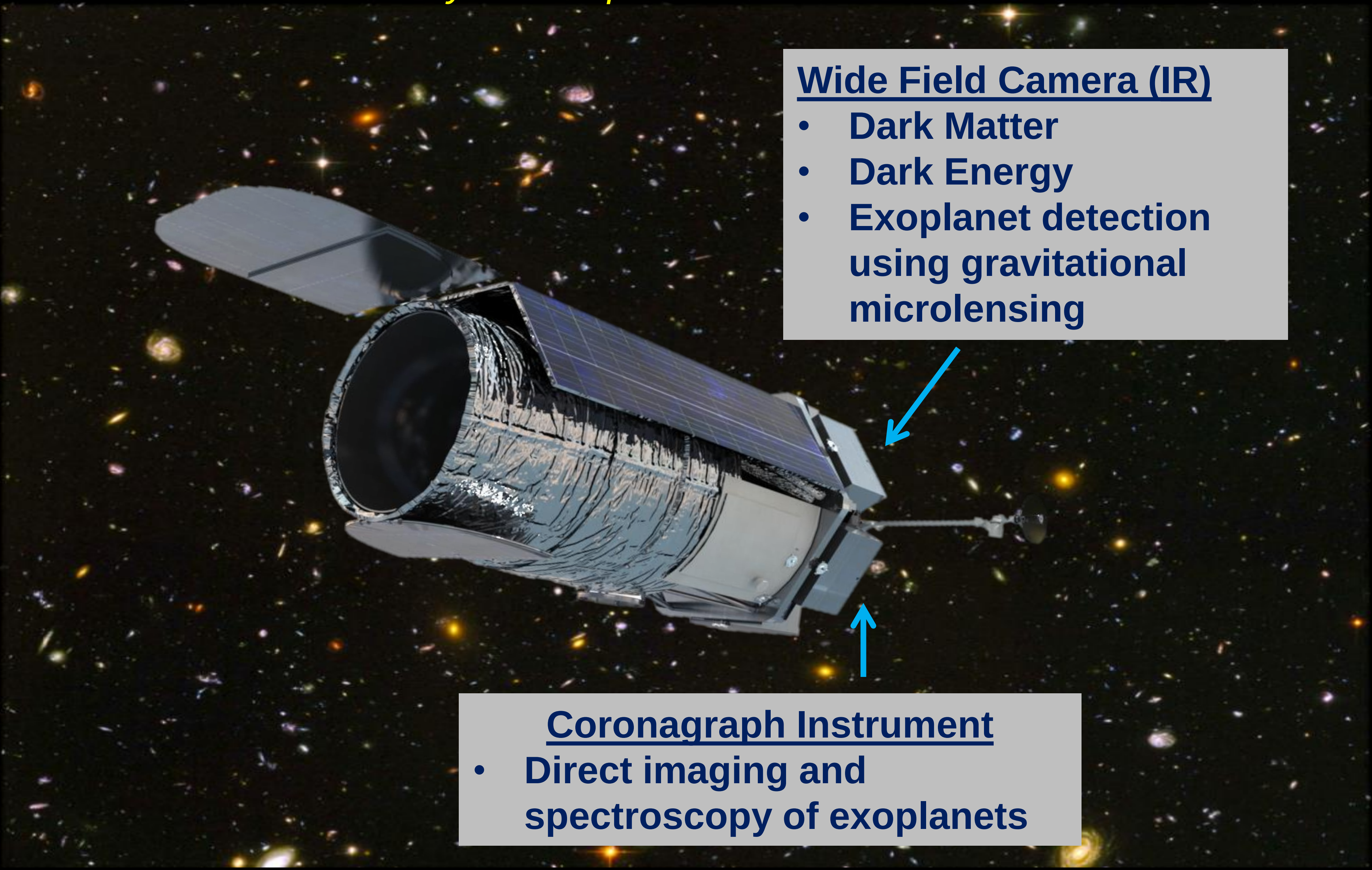
Internal Occulters (Coronagraphs)




NASA's
Exoplanet
Missions
WFIRST
(~ 2025)
JWST[2]
(2018)
coronagraph
TESS
(2017)
Kepler
First high-contrast coronagraph baselined; starshade is being studied
Spitzer
Hubble[1]
coronagraph
New Worlds Telescope
(~ 2030s?)
[1] NASA/ESA Partnership
[2] NASA/CNES/ESA Partnership

WFIRST

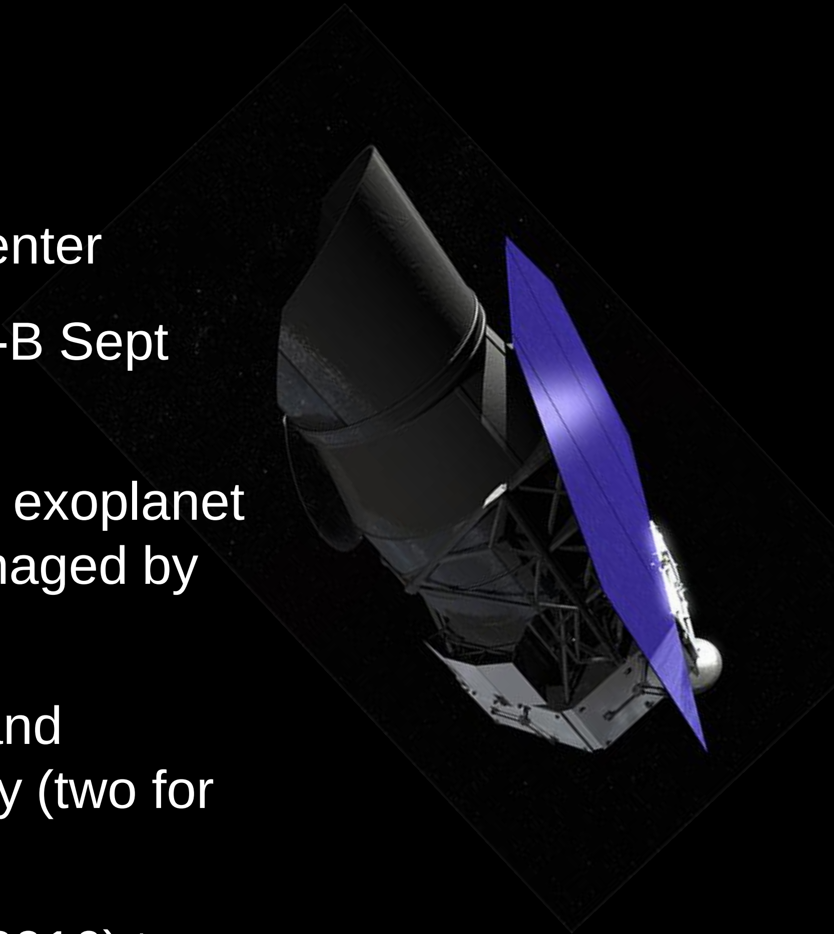
Wide-Field Infrared Survey Telescope



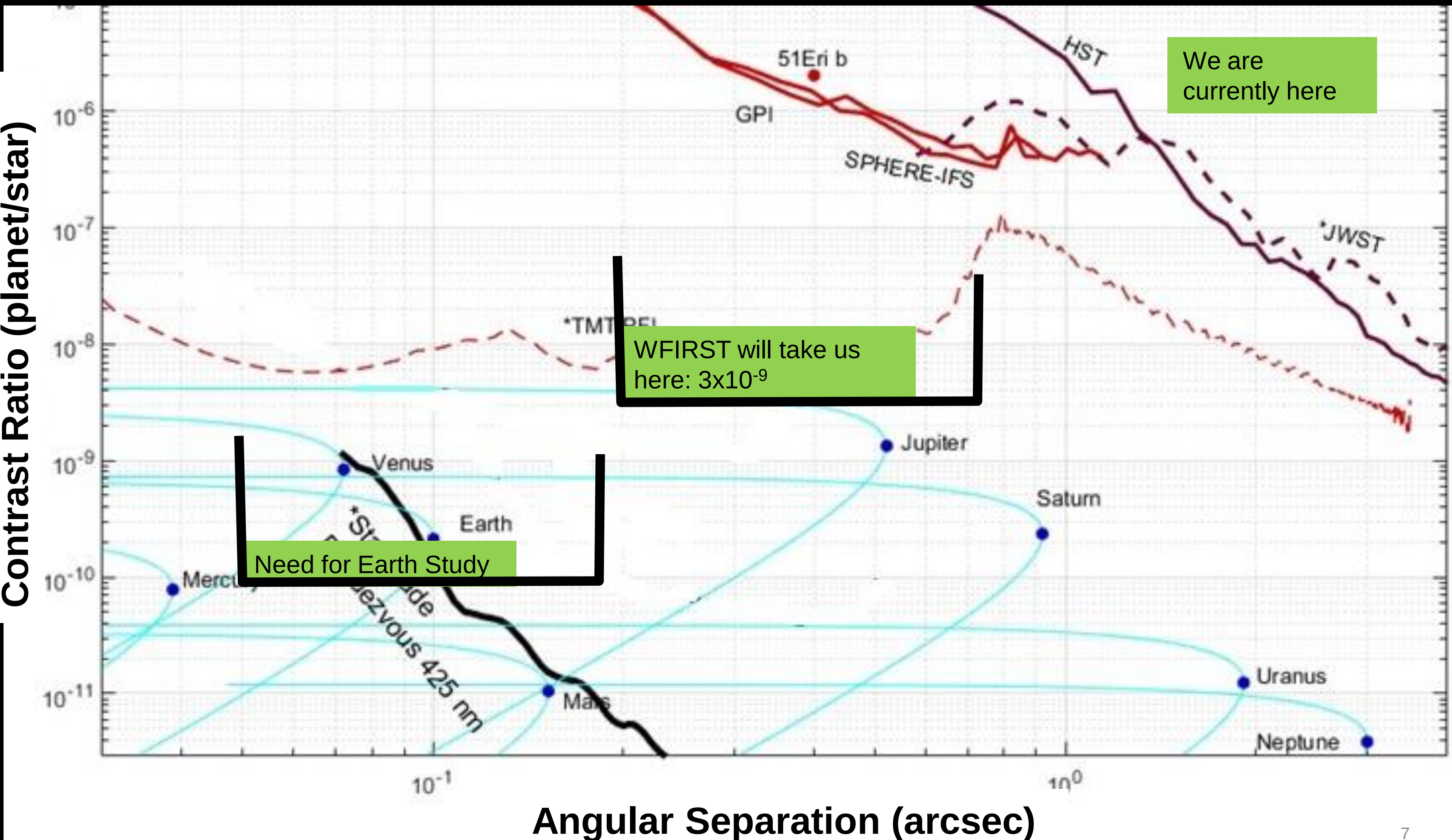
WFIRST

Dark Energy, Alien Worlds

- WFIRST in Formulation Phase
- Managed by Goddard Space Flight Center
- Next NASA Key Decision Point (KDP)-B Sept 2017
- Coronagraph Instrument baselined for exoplanet direct imaging and spectroscopy. Managed by JPL
- Formulation Science Working Group and Science Investigation Teams underway (two for coronagraph: Macintosh, Turnbull)
- Project received APD direction (June 2016) to incorporate starshade compatibility into Phase A DRM – for SMD decision following SRR/MDR



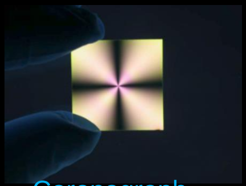
Towards the Detection of Exo-Earths



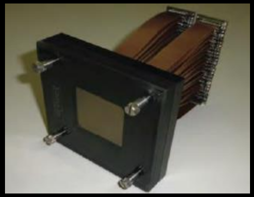
How a Coronagraph Works

Coronagraph/Telescope Technology Needs

Contrast



Coronagraph architectures



Deformable mirrors

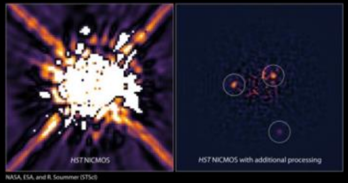
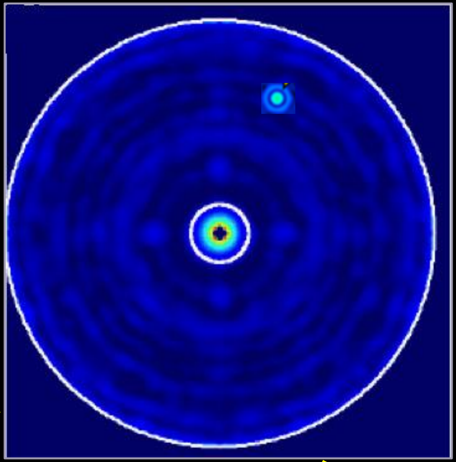
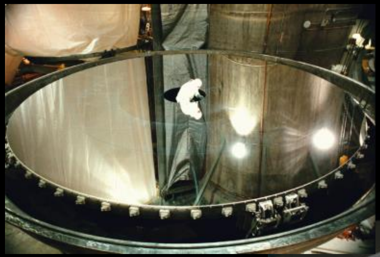


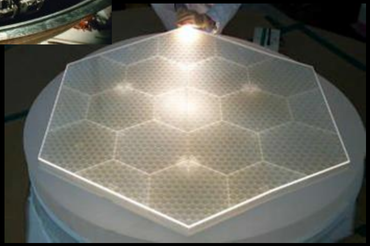
Image post-processing



Angular Resolution

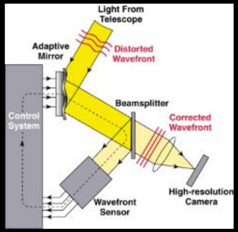


Large monolith

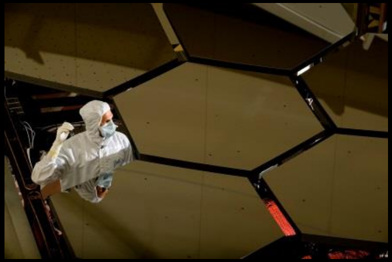


Segmented

Contrast Stability



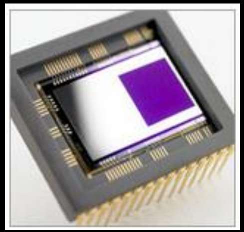
Wavefront sensing and control

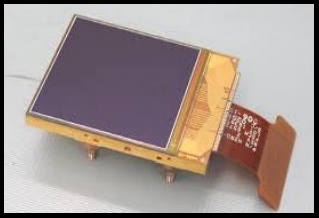


Segment phasing and rigid body sensing and control

Telescope vibration sensing and control

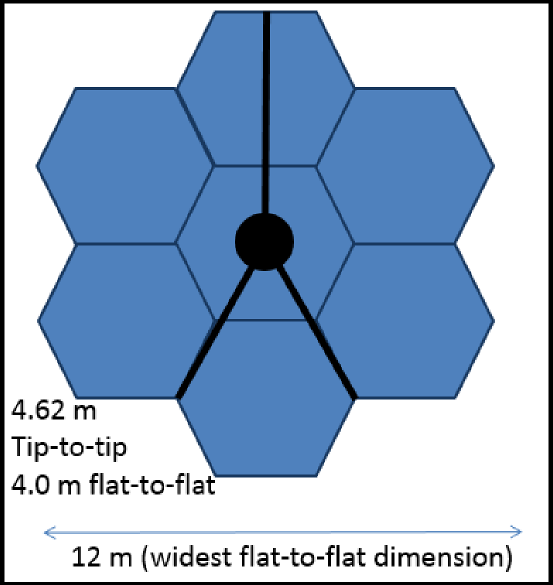
Detection Sensitivity

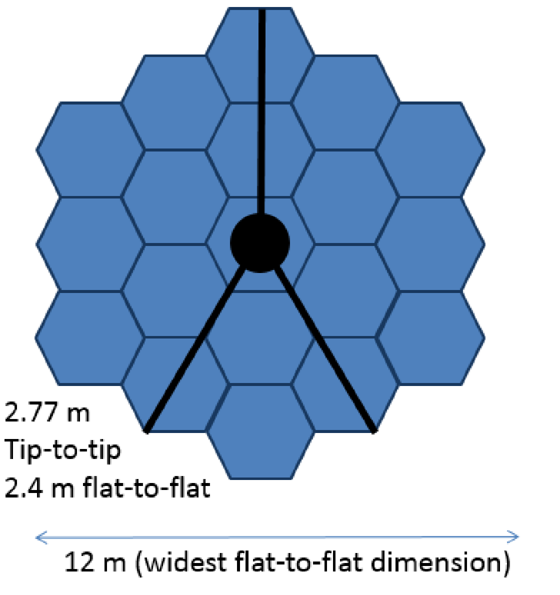


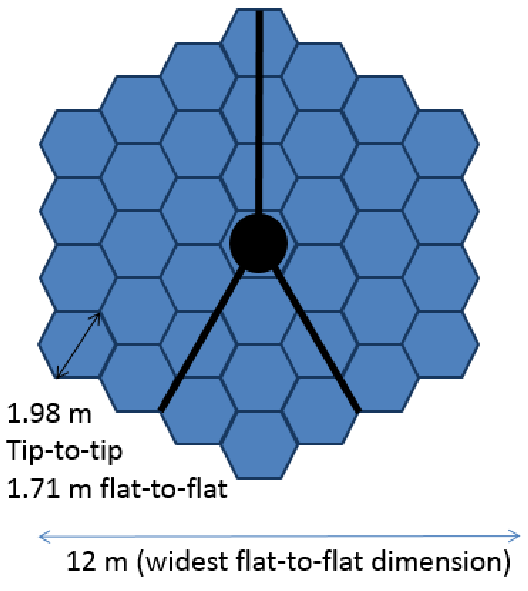


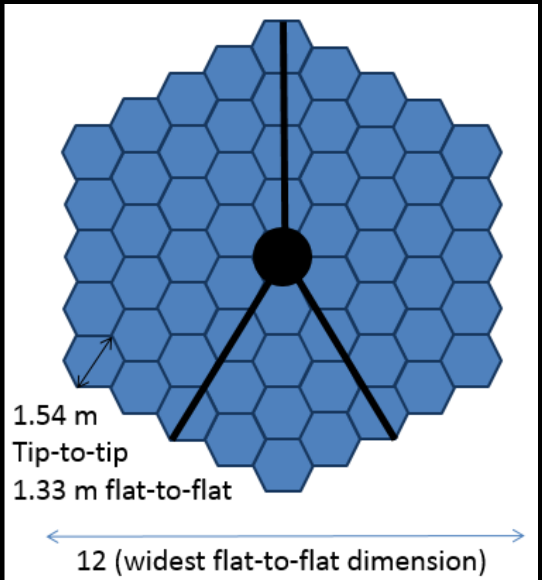
Ultra-low noise visible and infrared detectors

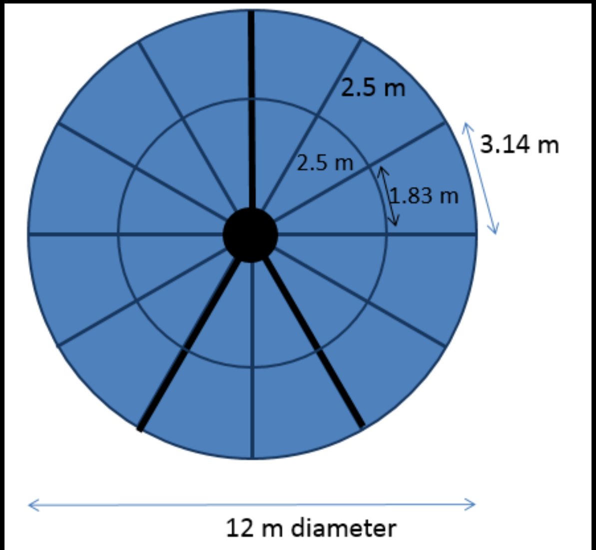
Segmented Coronagraph Design Analysis

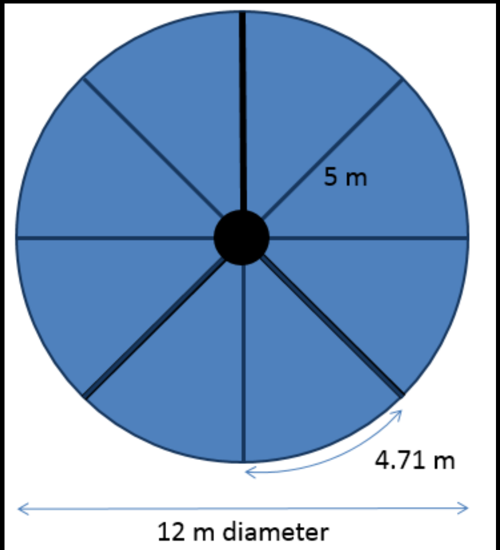




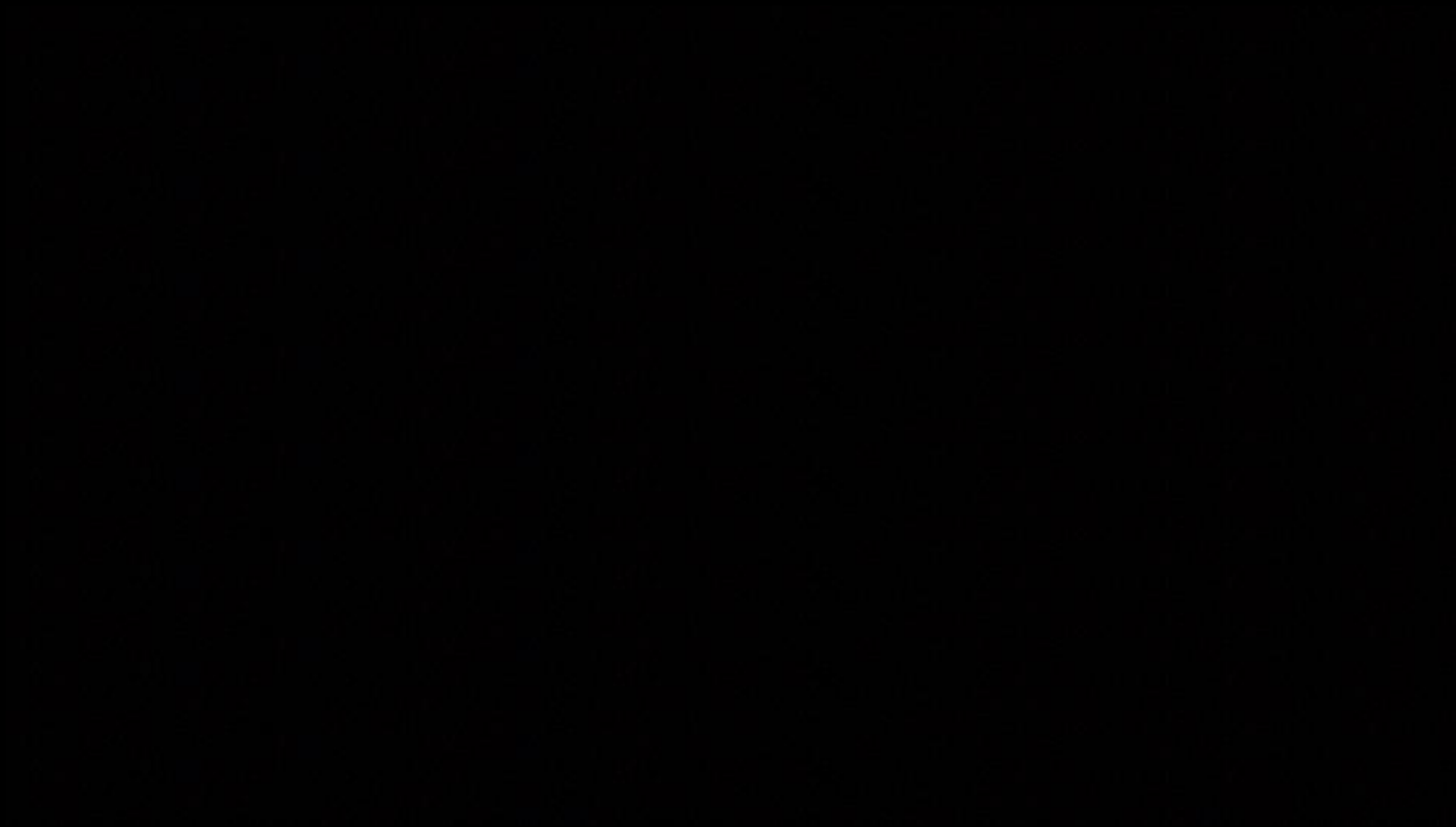


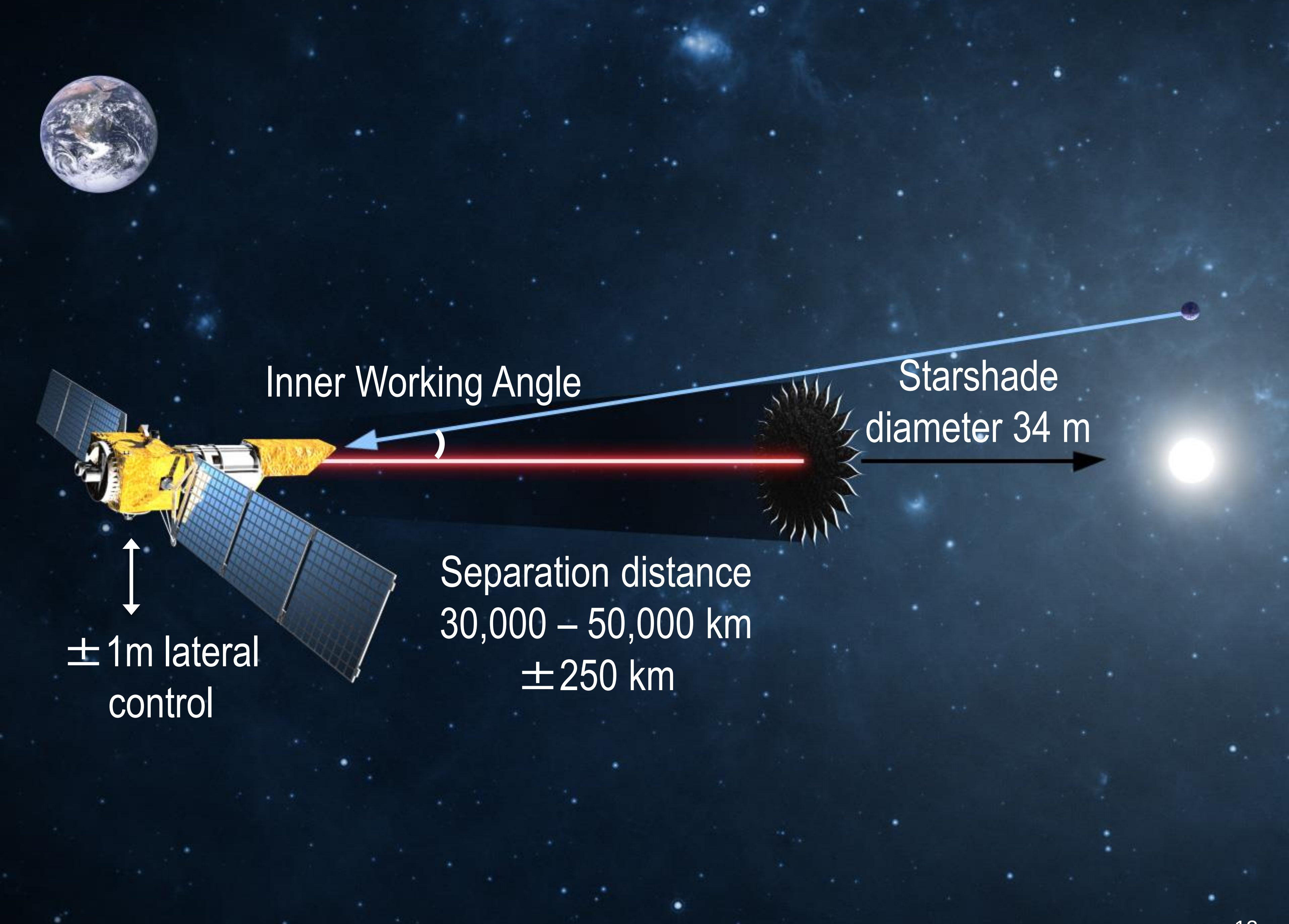






Starshade Concept

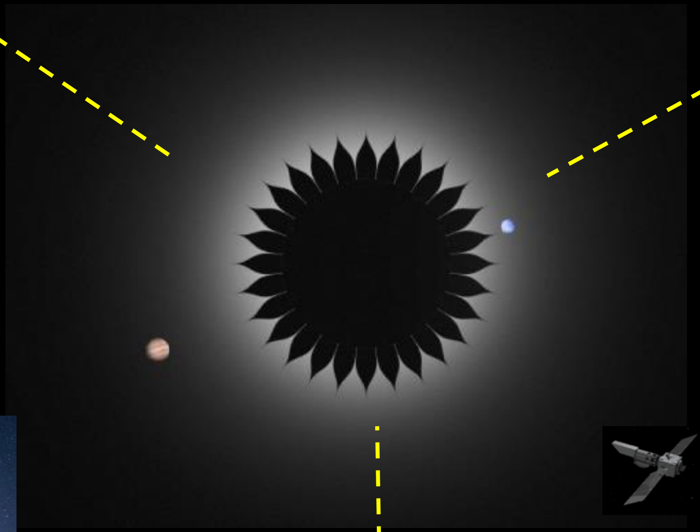



Inner Working Angle
Starshade
diameter 34 m
Separation distance
30,000 – 50,000 km
±250 km
±1m lateral
control

Starshade Technology Needs

Light Suppression

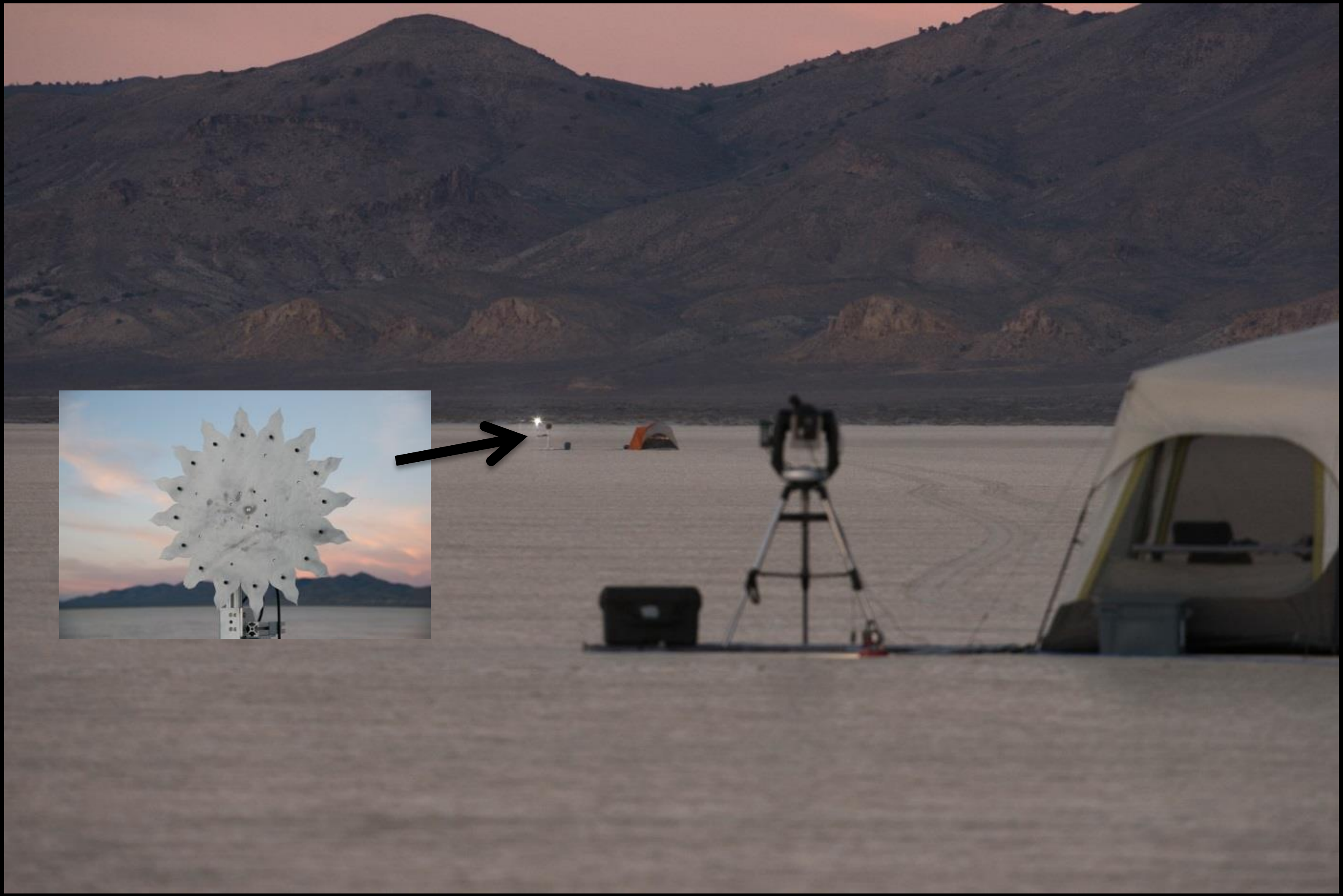
Formation Sensing and Control



Deployment Accuracy and Shape Stability

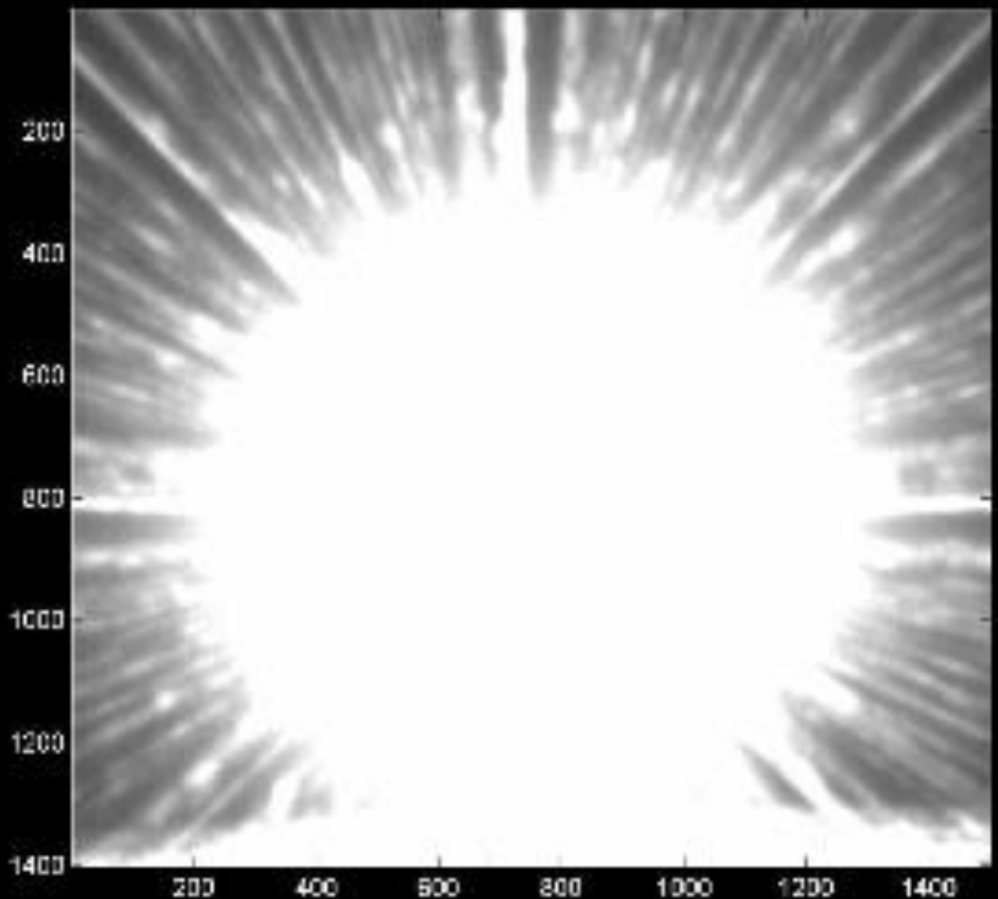
Suppressing diffracted light
from on-axis starlight

Desert Testing of the Starshade



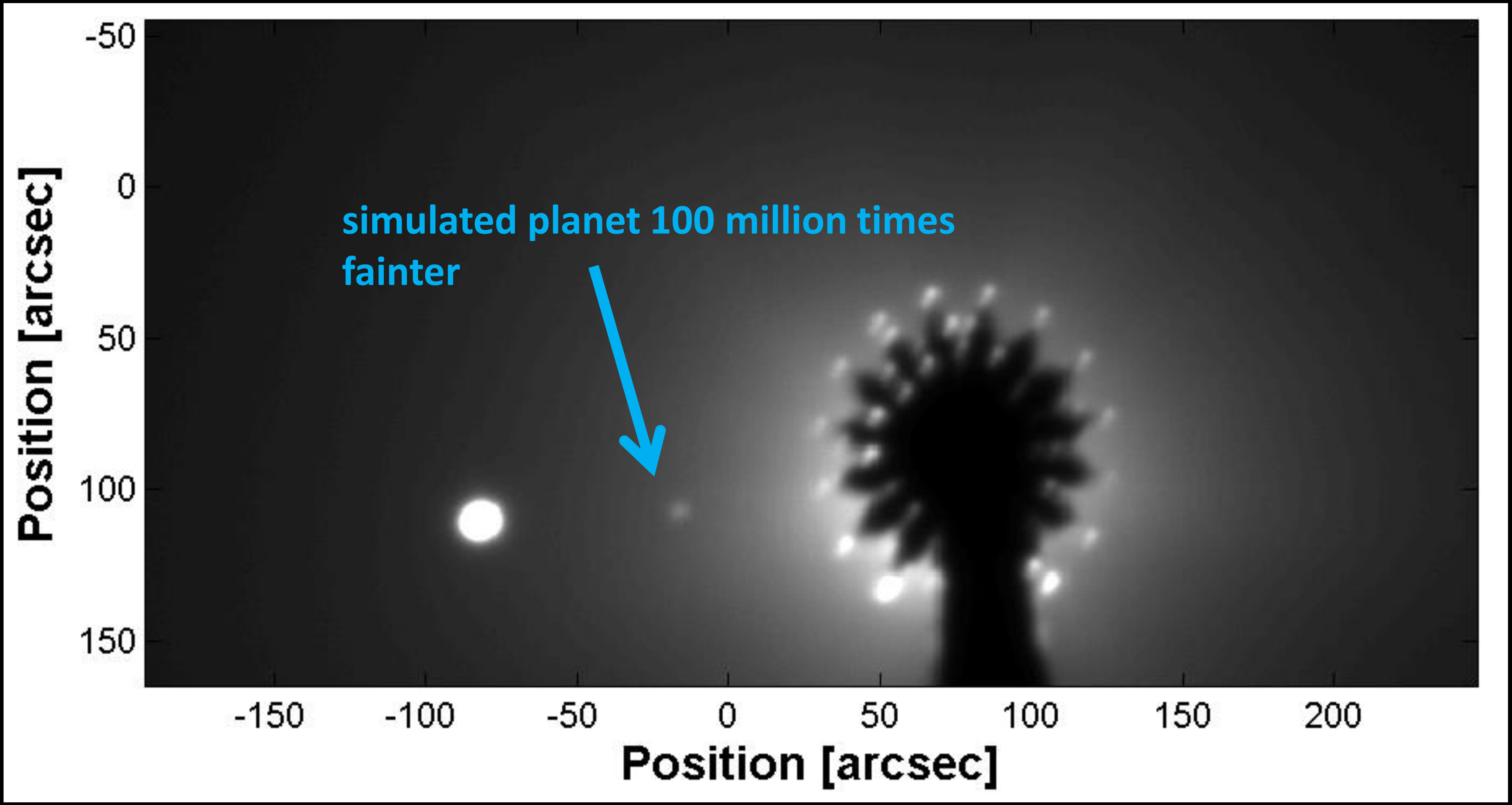
Northrop Grumman Aerospace Systems

Desert Testing of the Starshade



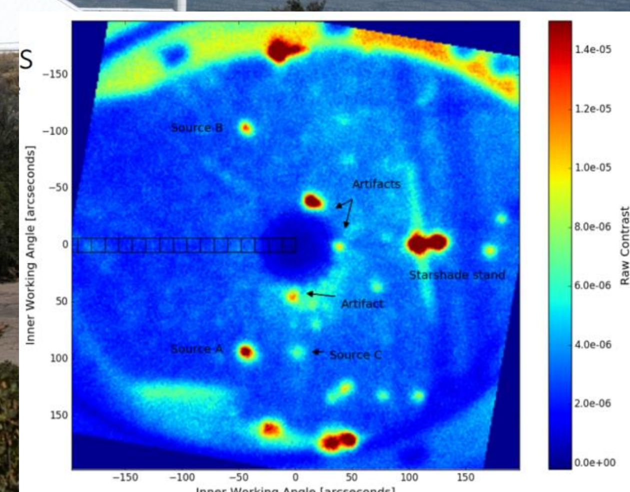
Northrop Grumman Aerospace Systems

Desert Testing of the Starshade



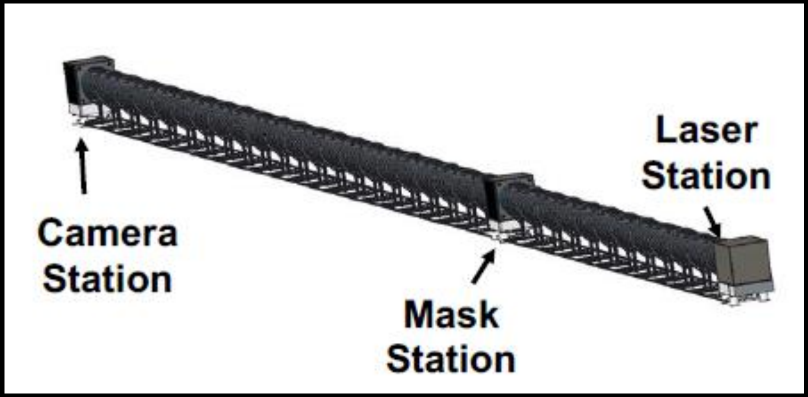
Northrop Grumman Aerospace Systems

Optical Testing at the McMath Solar Telescope



credit: Steve Warwick (NGAS), Web Cash/Anthony Harness (UC-Boulder)

Optical Demonstrations at Princeton University

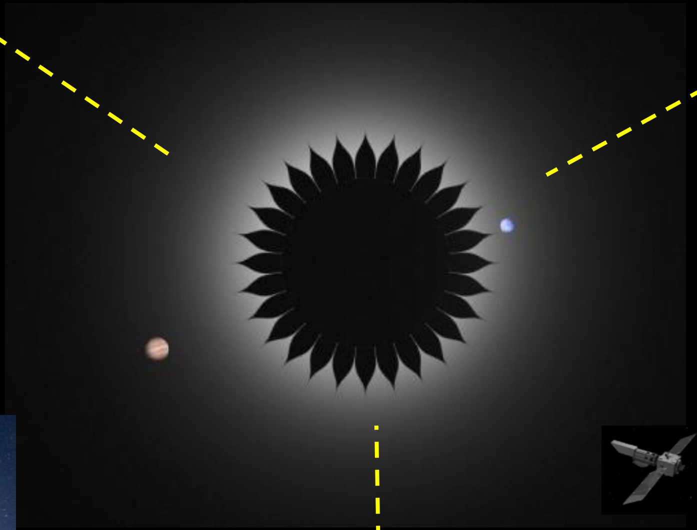


Jeremy Kasdin (Princeton)

Starshade Technology Needs

Light Suppression

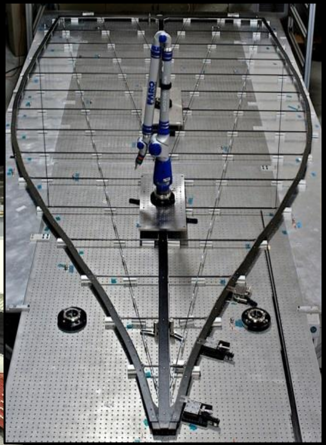
Suppressing scatted light off petal edges from off-axis Sunlight



Formation Sensing and Control

Suppressing diffracted light from on-axis starlight

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

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

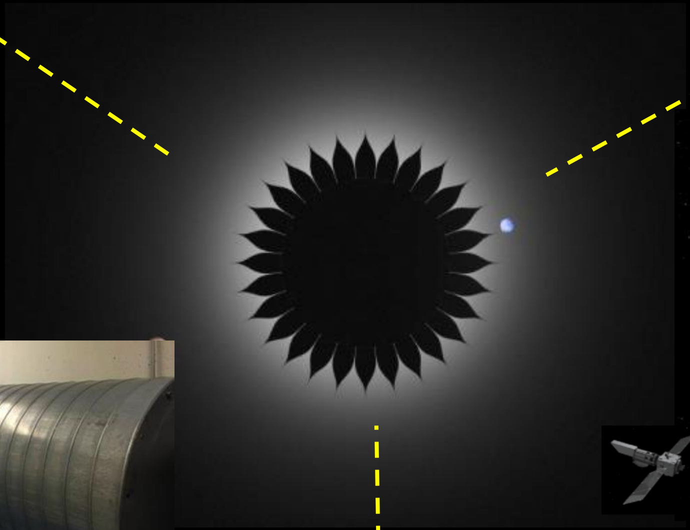
5 m Origami Optical Shield Deployment Trial

(approaching flight-like materials)

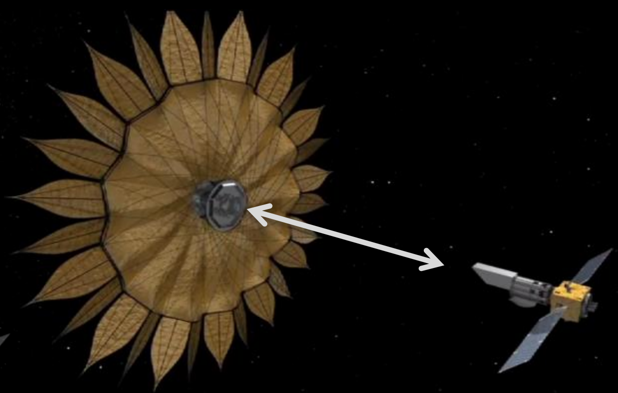
Starshade Technology Needs

Starlight Suppression

Suppressing scatted light off petal edges from off-axis Sunlight



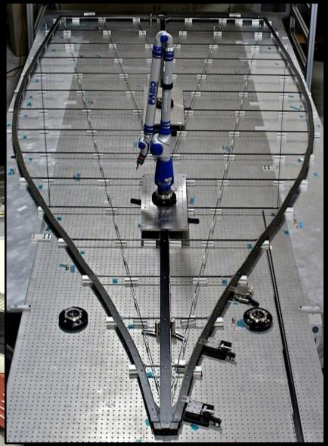
Formation Sensing and Control



Maintaining lateral offset requirement between the spacecrafts

Suppressing diffracted light from on-axis starlight

Deployment Accuracy and Shape Stability

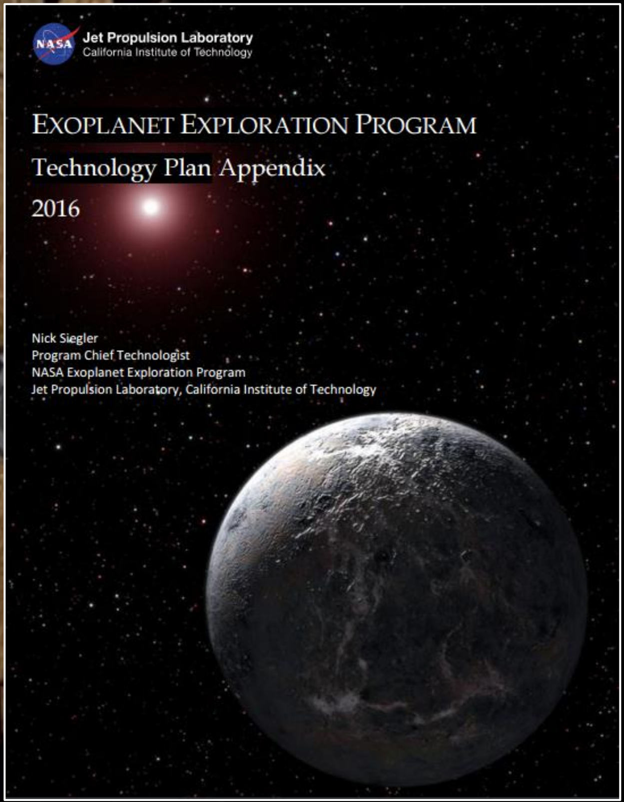


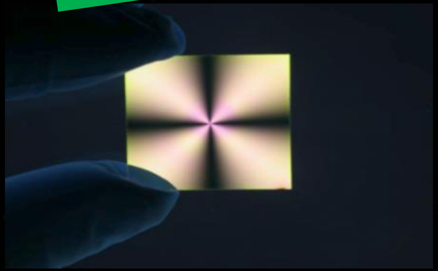
Fabricating the petal to high precision

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

2017 ExEP Technology Plan Appendix

To be updated and posted by end of month





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 ar 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 ≤ 3×10^{-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.

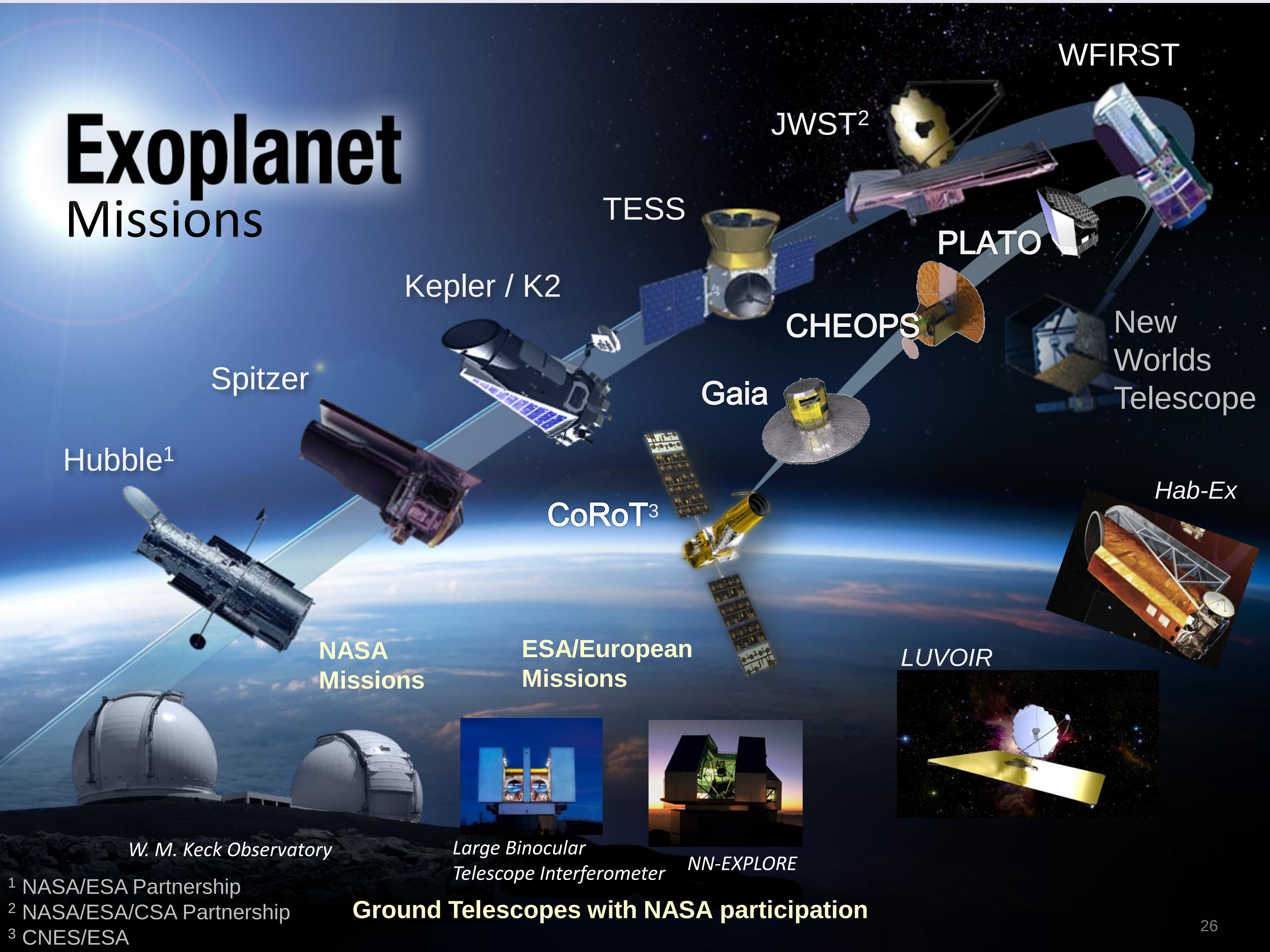
Coronagraph/Telescope Technology Gap List

Table 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 ≤ 1×10^{-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's of pm) rms to maintain raw contrasts of ≤ 1×10^{-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^{-6}, dominated by phase errors.	A 10-fold improvement over the raw contrast of ~10^{-9} 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.

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


Exoplanet
Missions
WFIRST
JWST[2]
TESS
PLATO
Kepler / K2
CHEOPS
New
Worlds
Telescope
Spitzer
Gaia
Hubble[1]
CoRoT[3]
Hab-Ex
NASA
Missions
ESA/European
Missions
LUVOIR
W. M. Keck Observatory
Large Binocular
Telescope Interferometer
NN-EXPLORE
[1] NASA/ESA Partnership
[2] NASA/ESA/CSA Partnership
[3] CNES/ESA
Ground Telescopes with NASA participation

Acknowledgements

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