Jet Propulsion Laboratory
California Institute of Technology

Technology Needs to Discover Earth 2.0

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Jet Propulsion Laboratory / Caltech

October 10, 2016
Origins Seminar
University of Arizona

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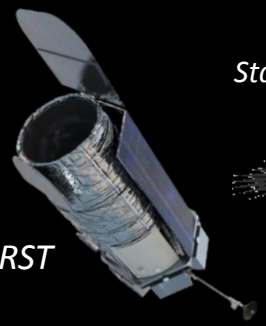
The NASA Exoplanet Exploration Program

Space Missions and Mission Studies

Kepler, K2



WFIRST

Probe-Scale:

Starshade

Coronagraph

Public Engagement

Supporting Research & Technology

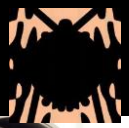
Key Sustaining Research

Large Binocular Telescope Interferometer

Keck Single Aperture Imaging and RV

Extreme Precision Doppler Spectrometer

Technology Development

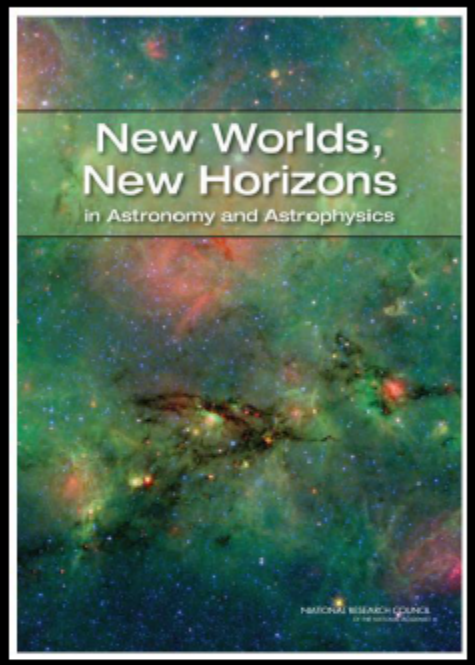


Coronagraphs

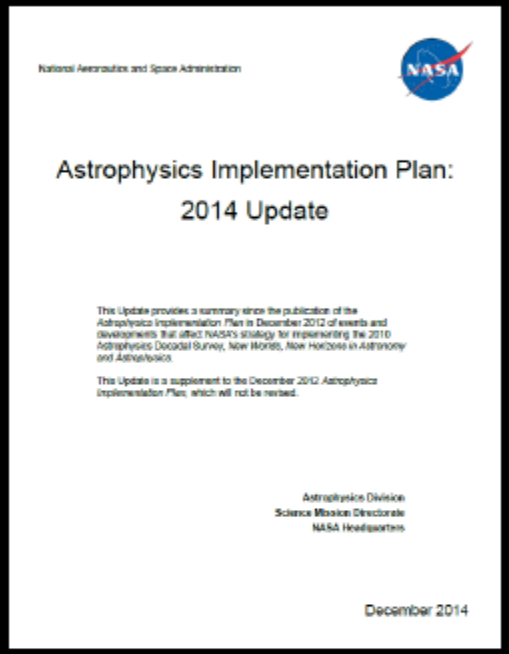
Starshades

NASA Exoplanet Science Institute

Driving Documents Driving the Technology



- #1 large-scale recommendation: WFIRST
- #1 medium-scale recommendation: Preparation for a planet imaging mission (HabEx)


National Aeronautics and Space Administration

Astrophysics Implementation Plan:
2014 Update

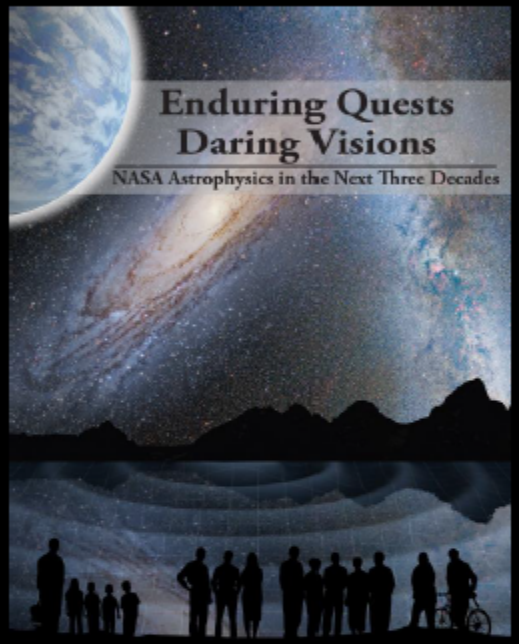
This Update provides a summary since the publication of the Astrophysics Implementation Plan in December 2012 of events and developments that affect NASA's strategy for implementing the 2010 Astrophysics Decadal Survey, *New Worlds, New Horizons in Astronomy and Astrophysics*.

This Update is a supplement to the December 2012 Astrophysics Implementation Plan, which will not be revised.

Astrophysics Division
Science Mission Directorate
NASA Headquarters

December 2014

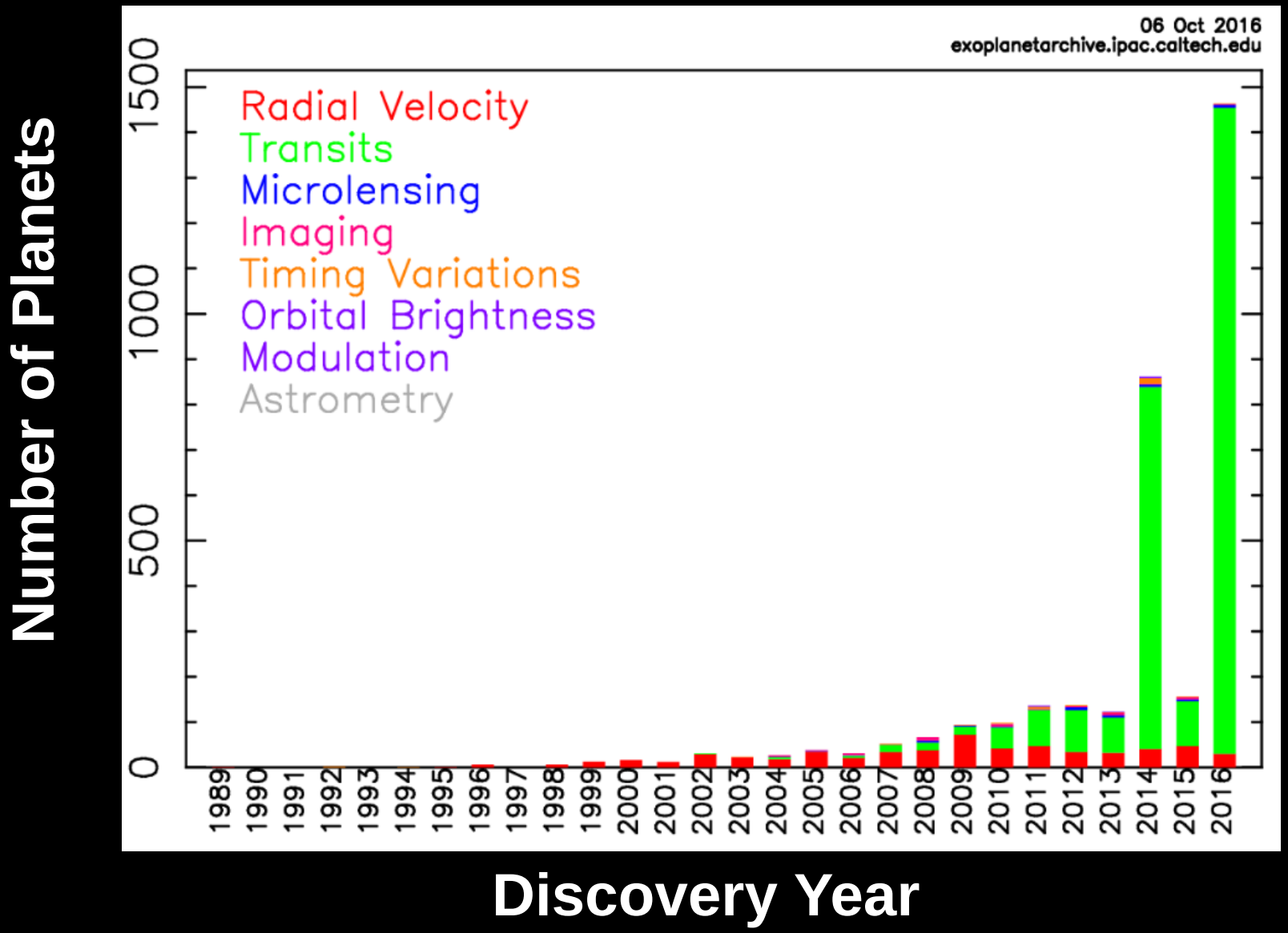
- Confirms WFIRST as #1 Division priority after JWST
- Commissions Exo-C and Exo-S probe-class studies



- LUVOIR Surveyor
- Far-IR Surveyor
- X-Ray Surveyor
- Earth Mapper (interferometer)

3,396 Confirmed Exoplanets

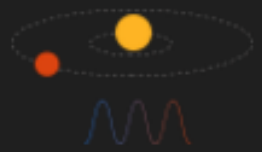
(as of 10/8/16)



:http://exoplanetarchive.ipac.caltech.edu/exoplanetplots/

By Method

78.9% Transit



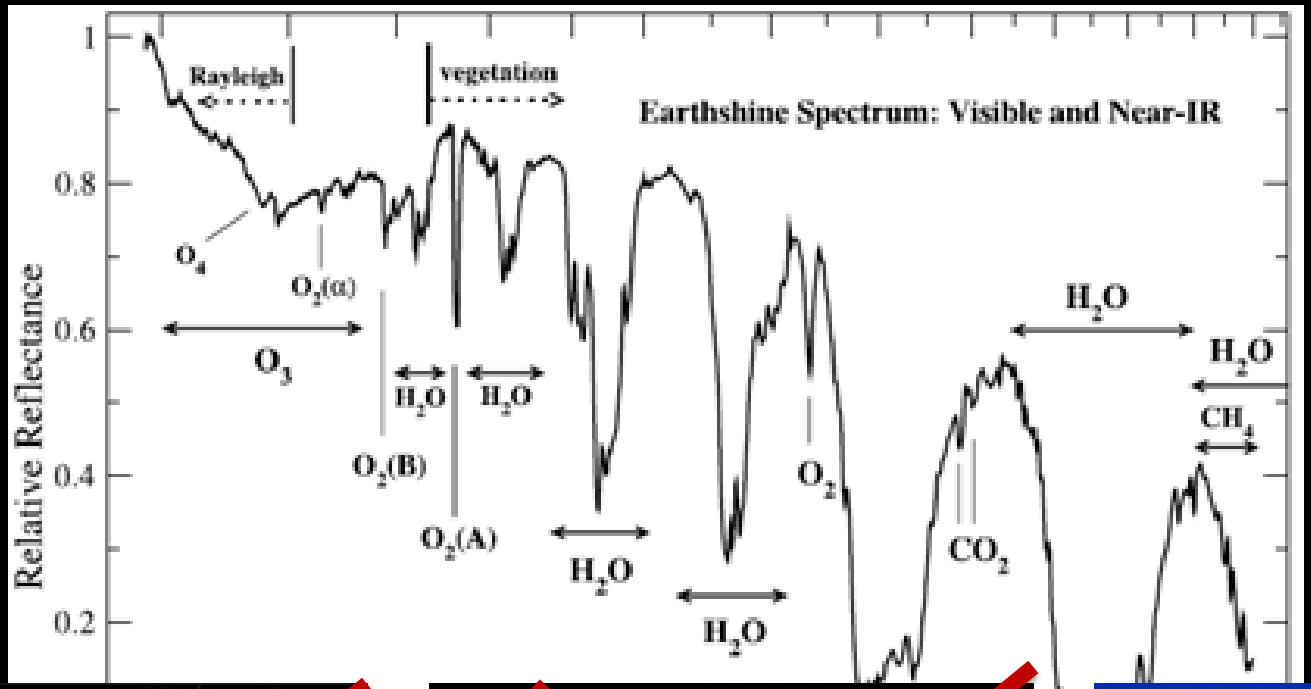
17.6% Radial Velocity

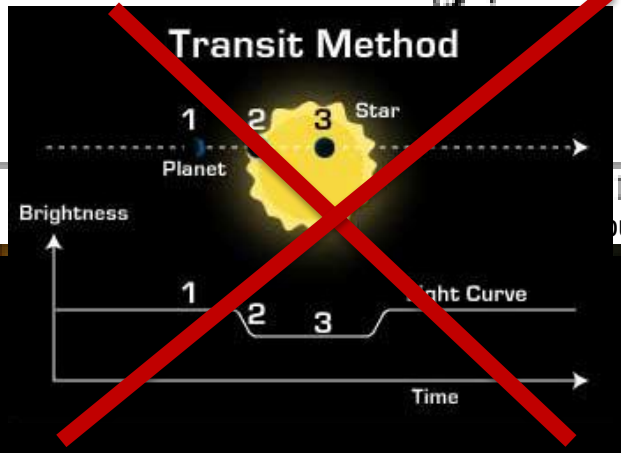
1.3% Imaging

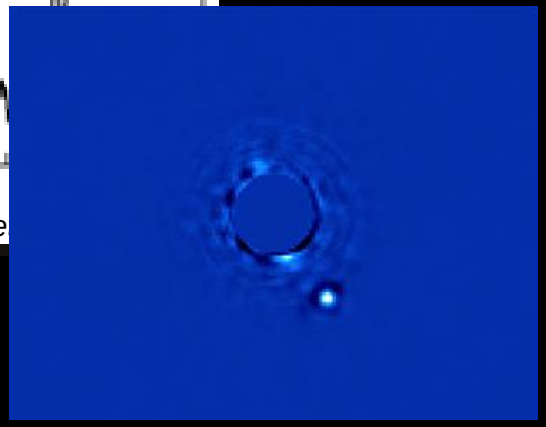
1.2% Microlensing

0.44% Transit Timing Variations, 0.24% Eclipse Timing Variations, 0.18% Orbital Brightness Modulation, 0.15% Pulsar Timing, 0.06% Pulsation Timing Variations, 0.03% Astrometry

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

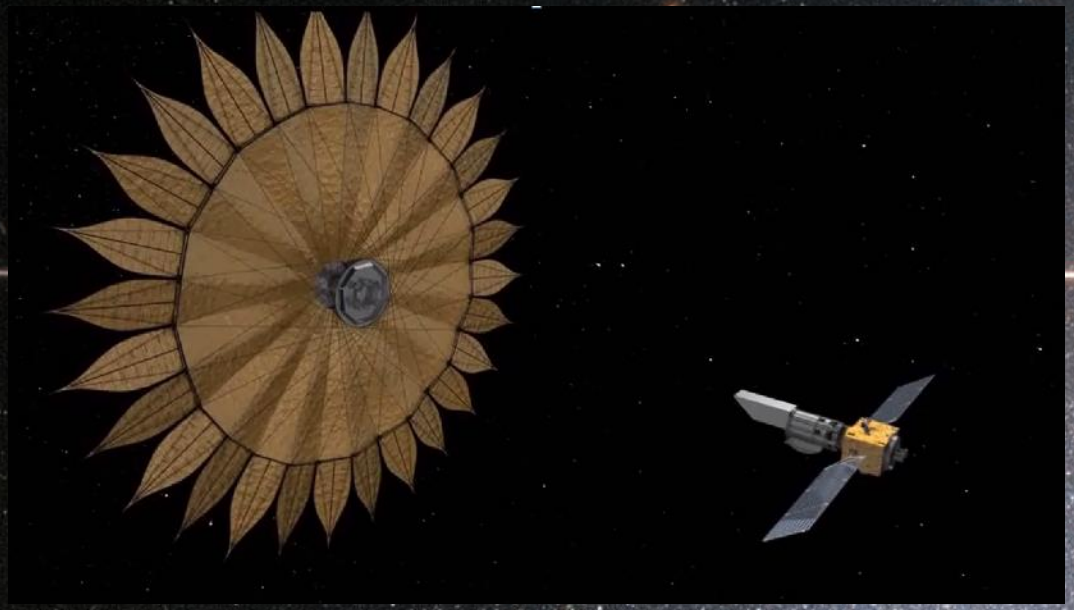


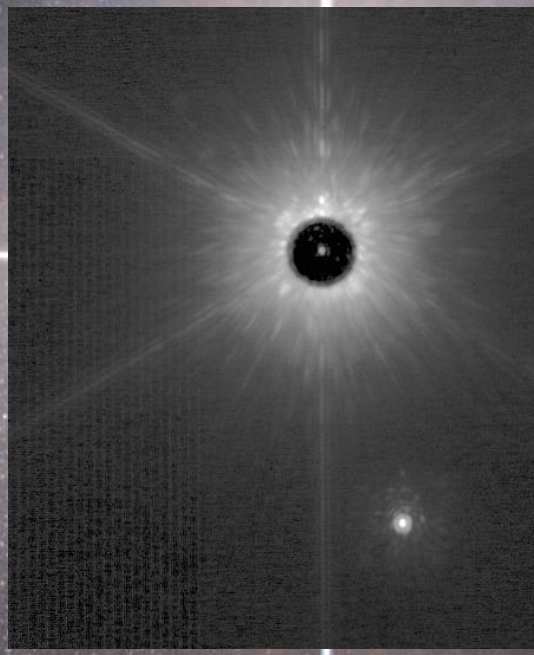




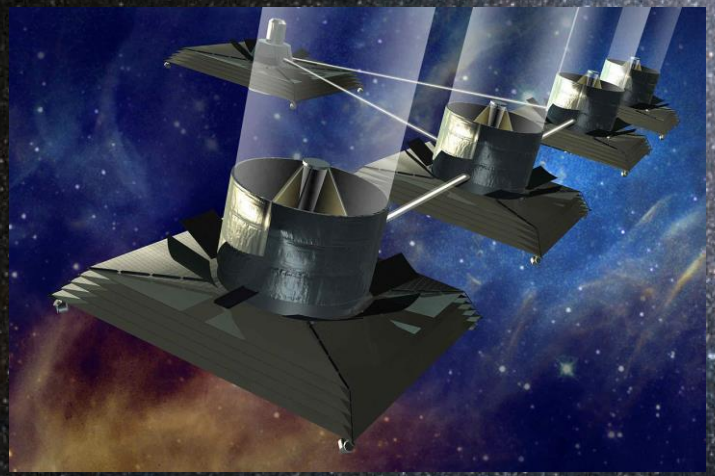
Macintosh et al. 2015

External Occulters (Starshades)

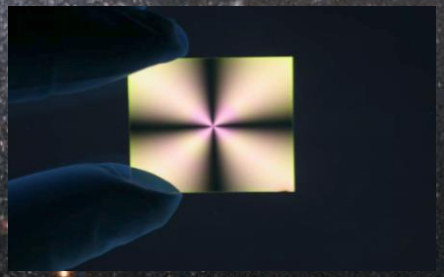




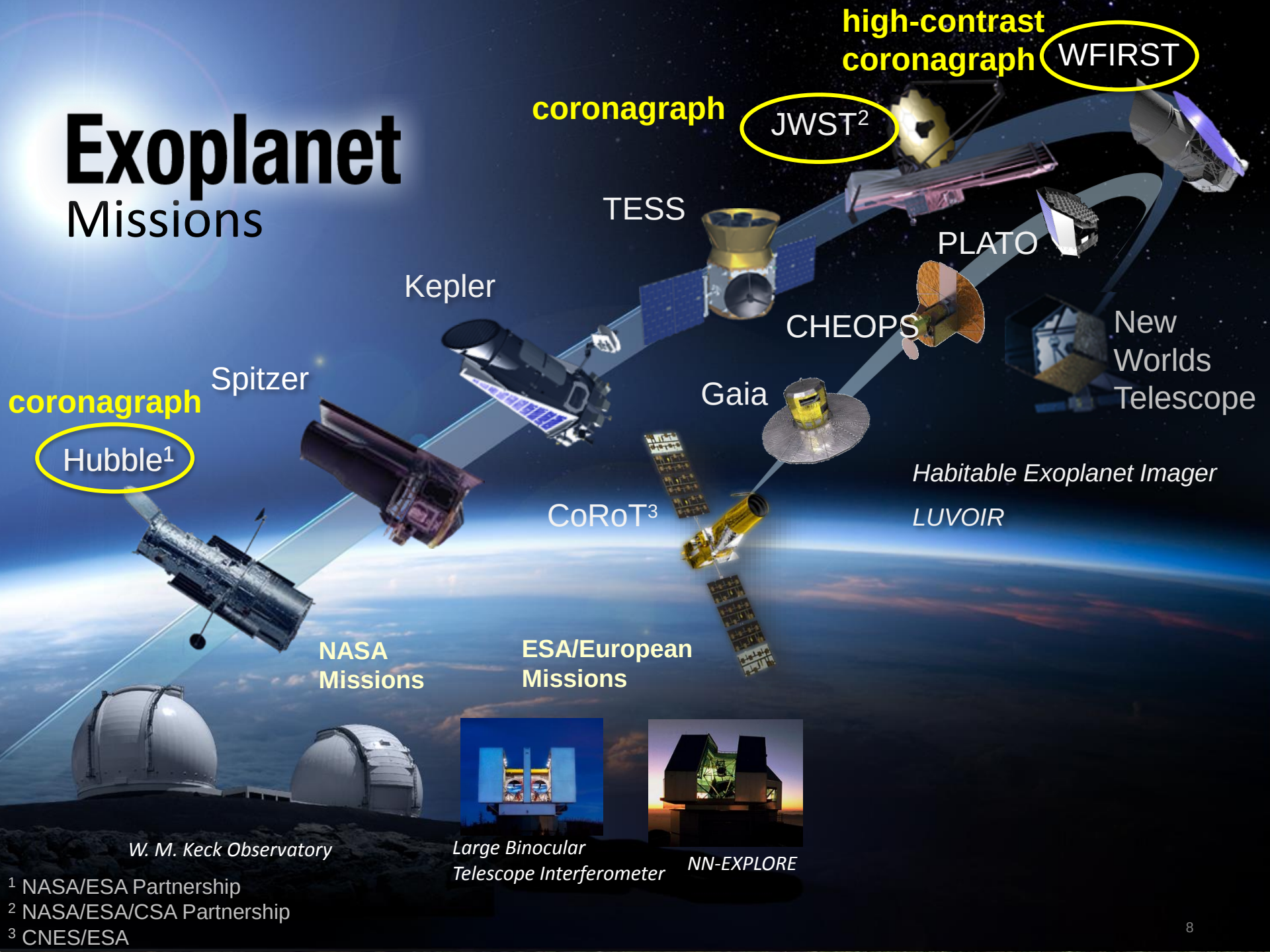
Nulling Interferometry



Internal Occulters (Coronagraphs)

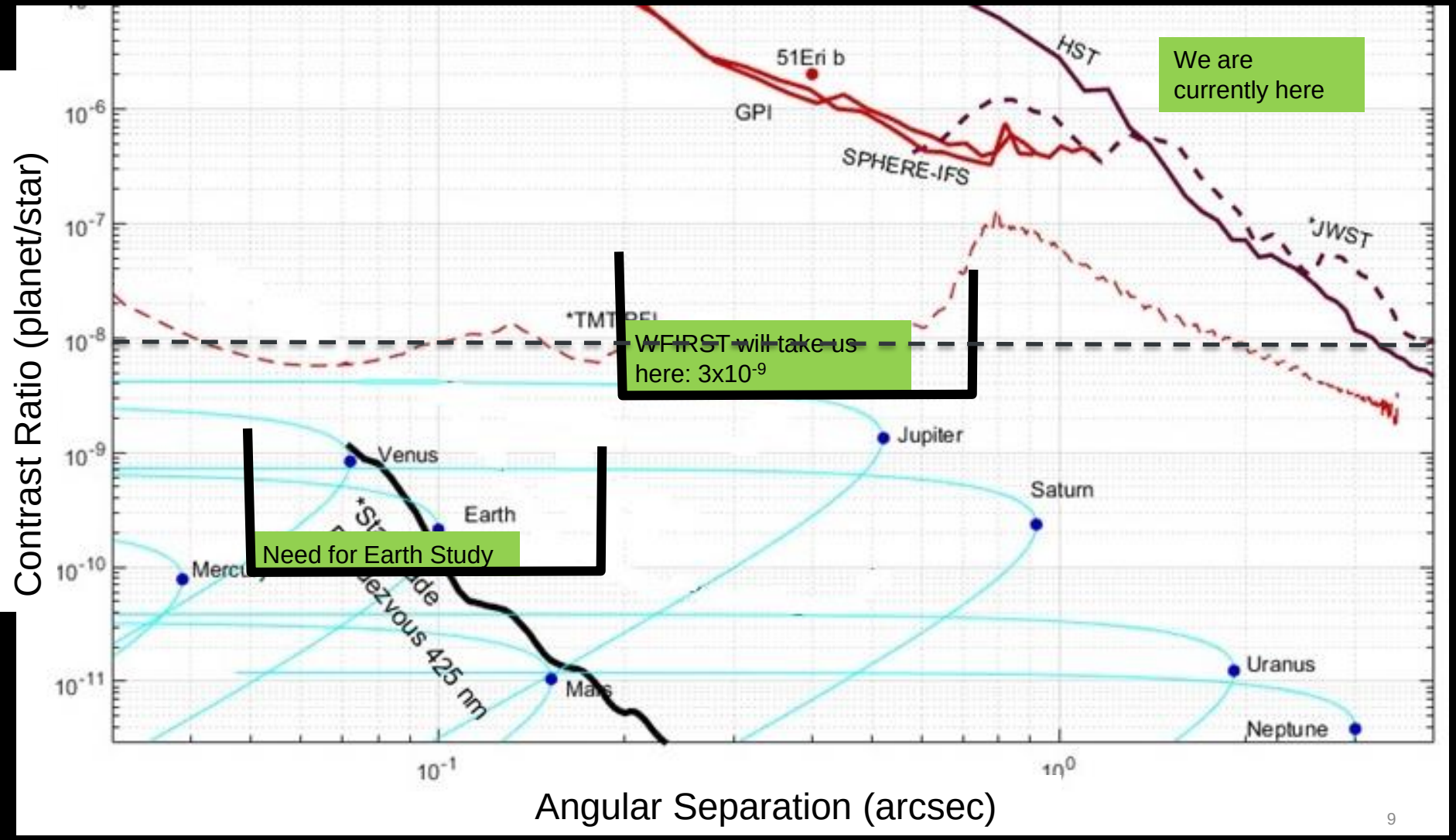


Exoplanet Missions



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

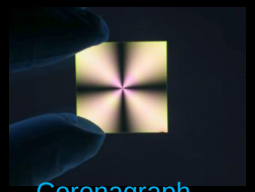
Towards the Detection of Exo-Earths



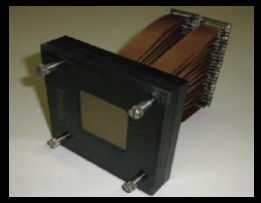
How a Coronagraph Works

Coronagraph/Telescope Technology Needs

Contrast



Coronagraph architectures



Deformable mirrors

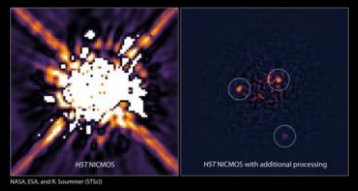
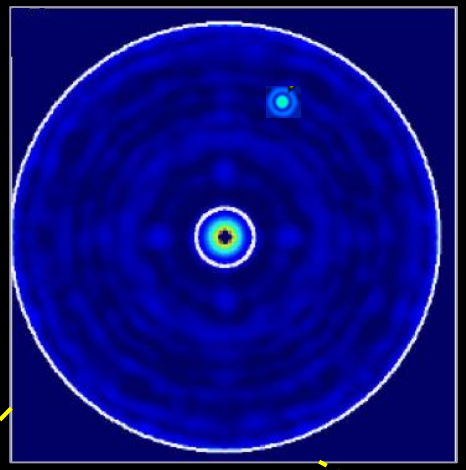
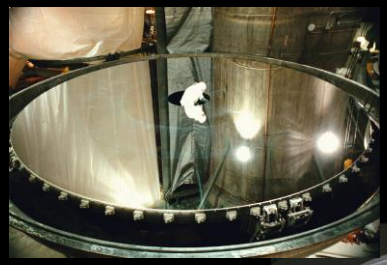


Image post-processing



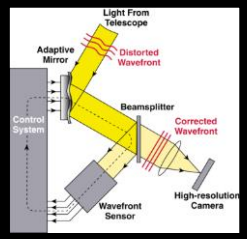
Angular Resolution



Large monolith

Segmented

Contrast Stability

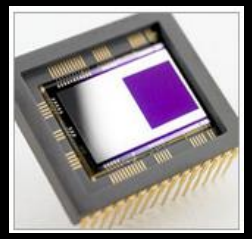


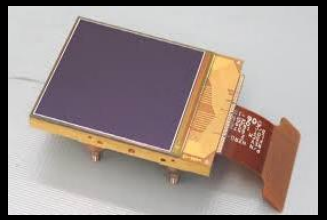
Wavefront sensing and control

Segment phasing and rigid body sensing and control

Telescope vibration sensing and control

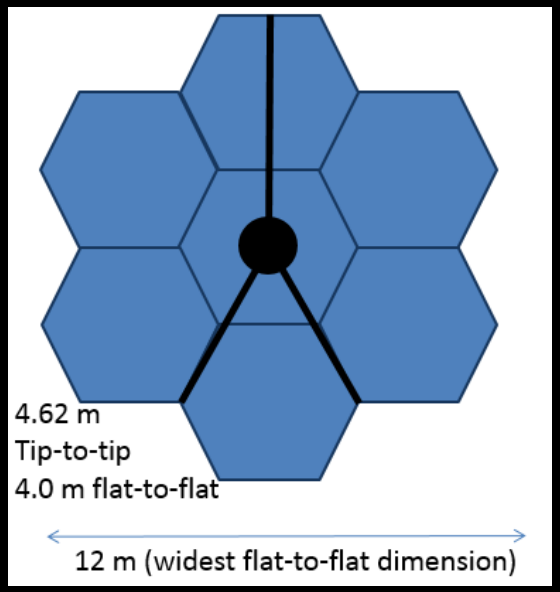
Detection Sensitivity

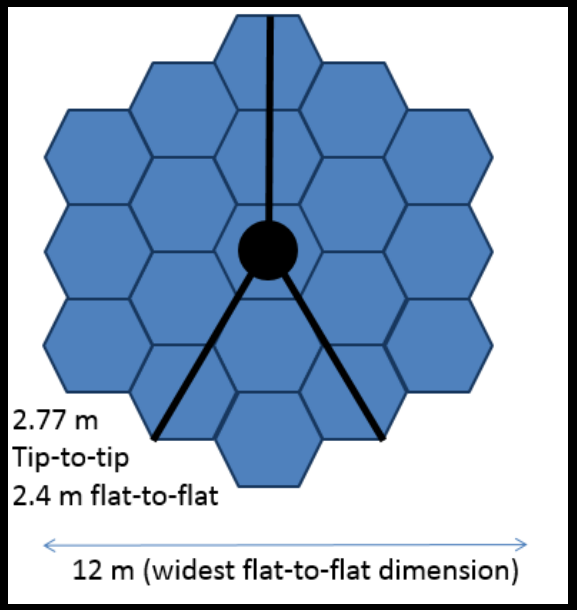


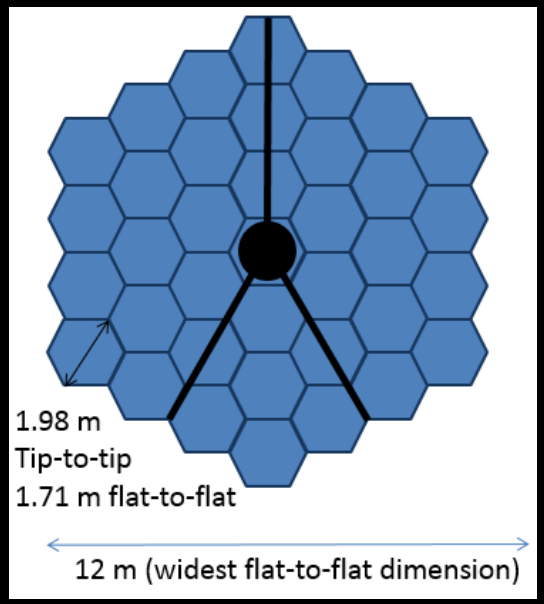


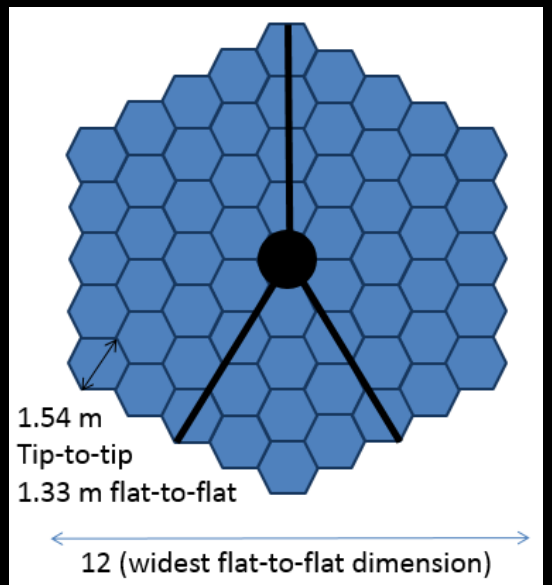
Ultra-low noise visible and infrared detectors

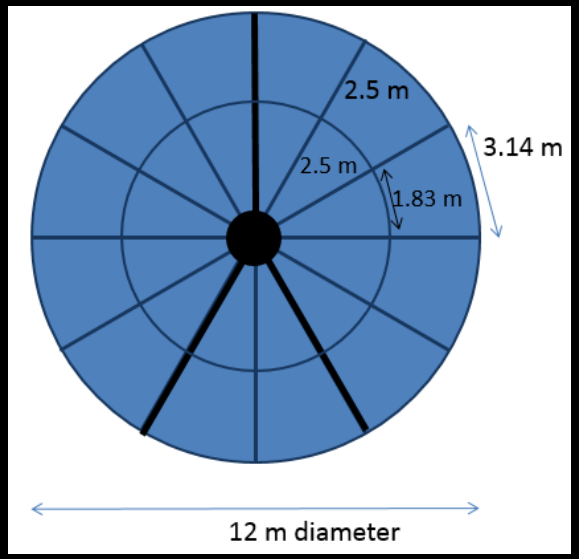
Segmented Coronagraph Design Analysis

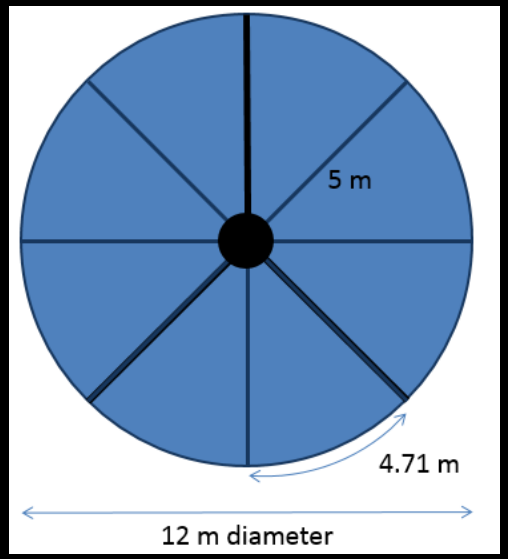




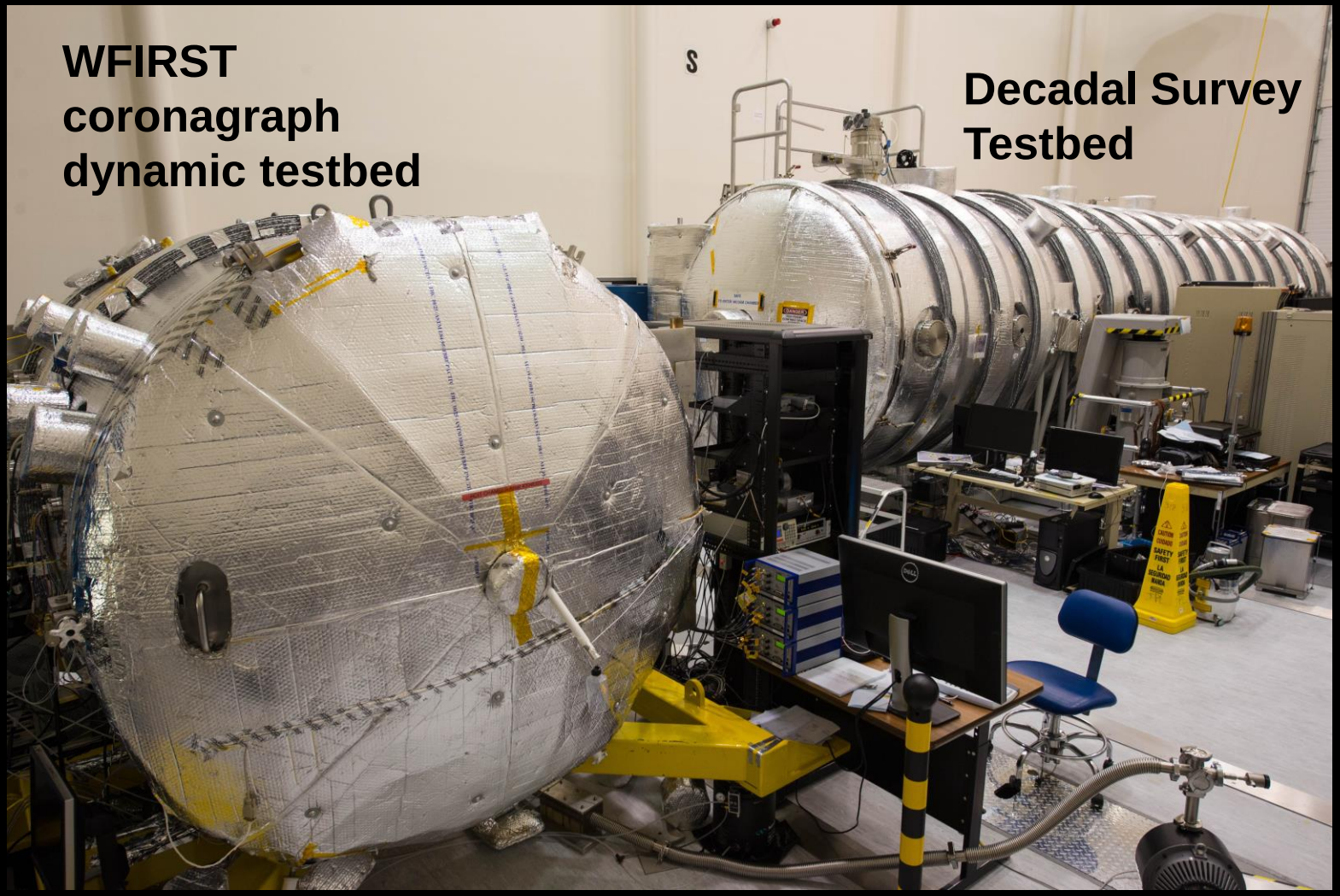




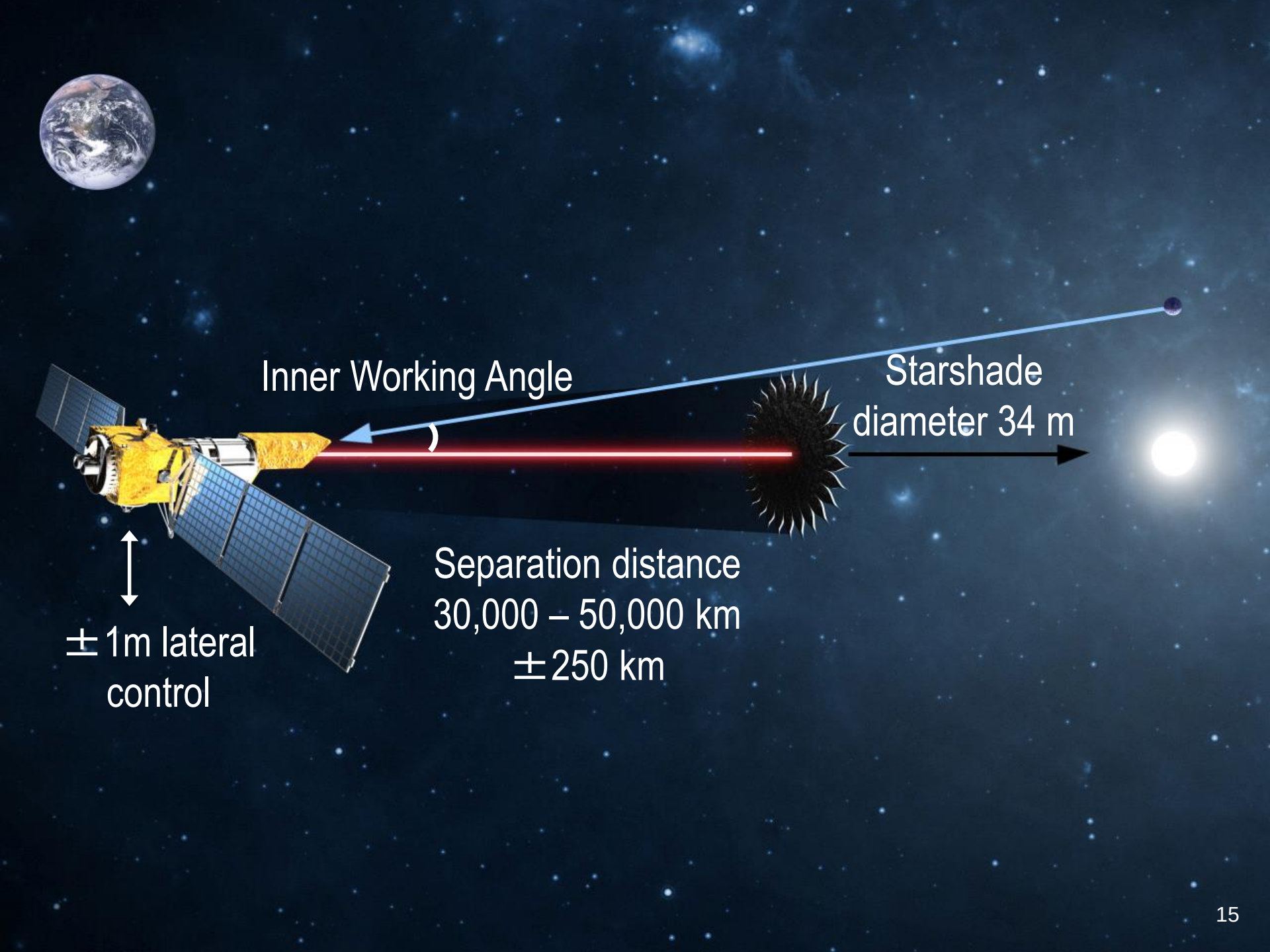




NASA's High Contrast Imaging Testbeds (JPL)



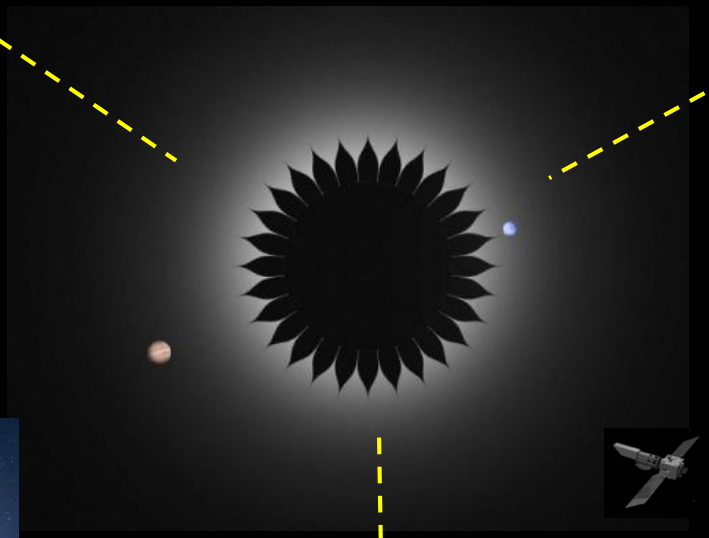
Starshade Concept


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

Starshade Technology Needs

Light Suppression

Formation Sensing and Control



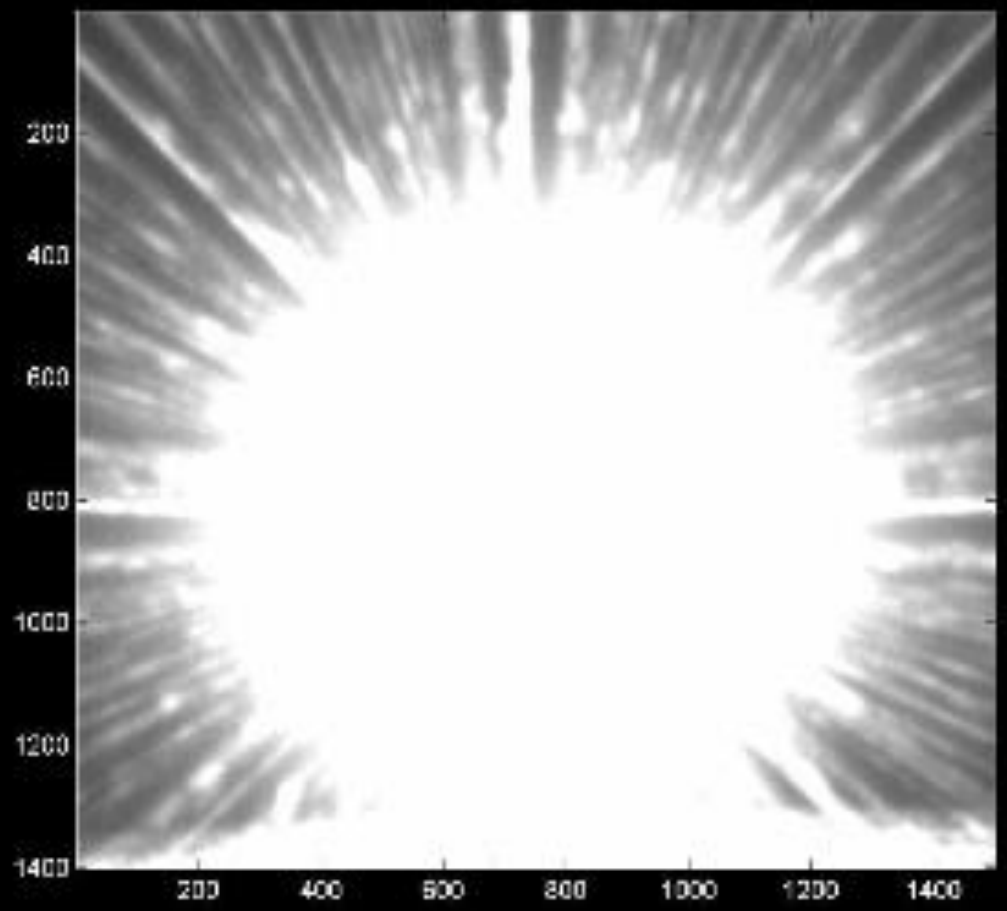
Deployment Accuracy and Shape Stability

Suppressing diffracted light from on-axis starlight

Desert Testing of the Starshade

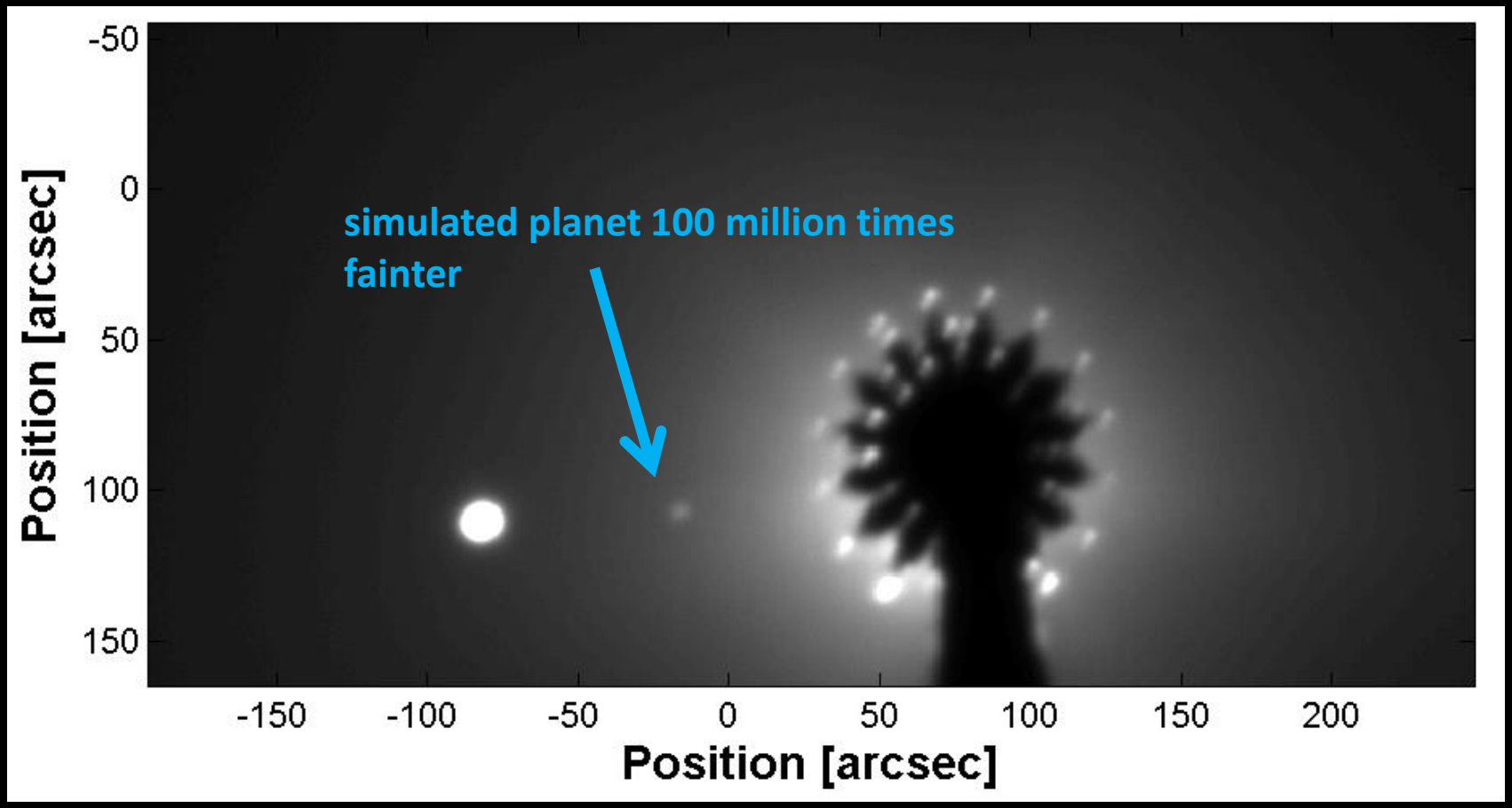
Northrop Grumman Aerospace Systems

Desert Testing of the Starshade



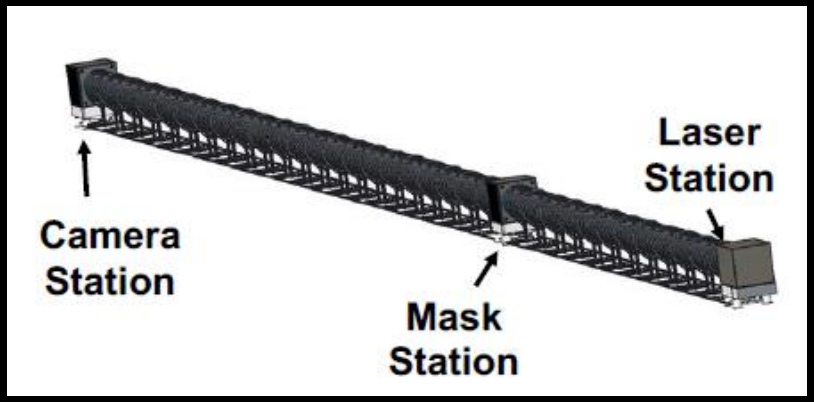
Northrop Grumman Aerospace Systems

Desert Testing of the Starshade



Northrop Grumman Aerospace Systems

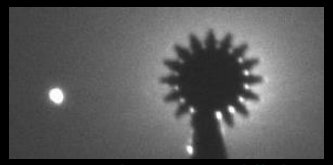
Optical Demonstrations at Princeton University



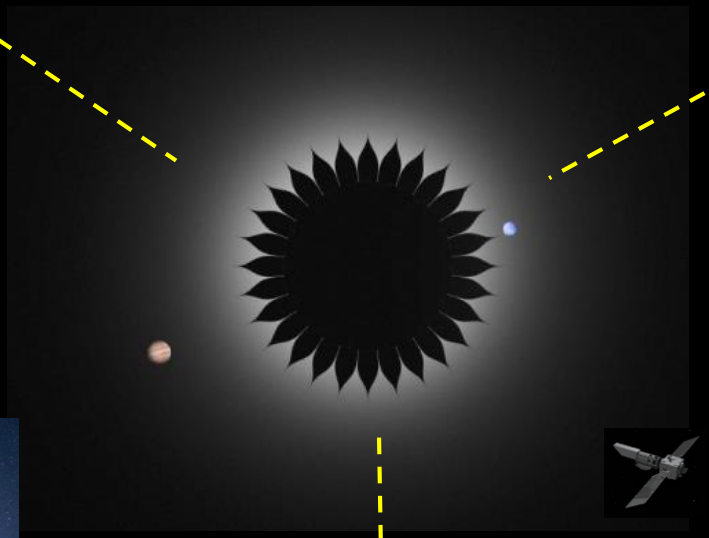
Jeremy Kasdin (Princeton)

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

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

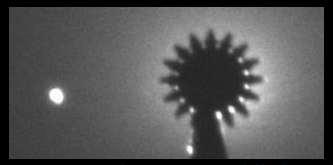
2 m Optical Shield Prototype Deployment Trial at JPL

5 m Origami Optical Shield Deployment Trial at JPL

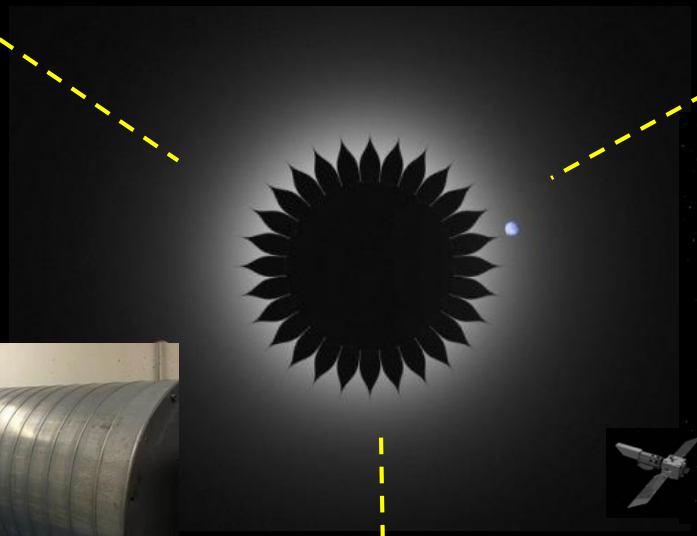
5 m Optical Shield Prototype
(with more flight-like material)

Starshade Technology Needs

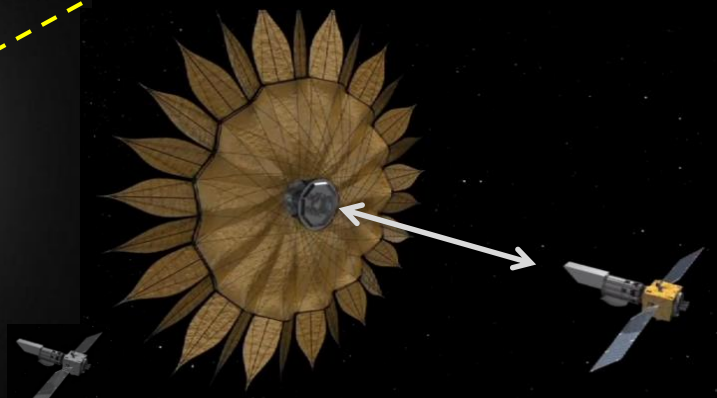
Starlight Suppression



Suppressing scatted light off petal edges from off-axis Sunlight



Formation Sensing and Control



Maintaining lateral offset requirement between the spacecrafts

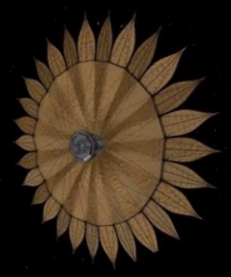
Suppressing diffracted light from on-axis starlight

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

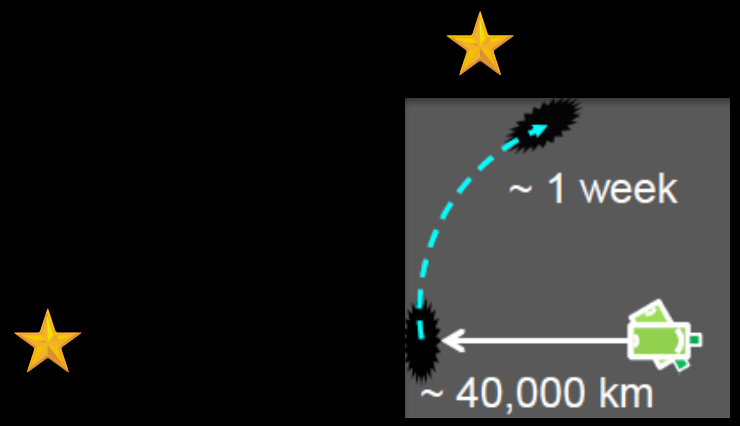
Key Benefits of the Starshade



- A starshade does not care what the telescope looks like.
  - Conventional on-axis and segmented telescopes are fine
    - *Diffraction by the segment gaps is a non-factor, the Starshade does all the starlight suppression*
- Telescope stability requirements significantly relaxed
- Wavefront sensing and correction is unnecessary
- The starshade not the telescope defines the inner working angle
  - Unlike coronagraphs
  - Although it is still wavelength dependent
- High throughput
  - Several times higher than coronagraphs

Key Disadvantages of the Starshade

- Relatively long times between observations
  - Need to slew the starshade between targets



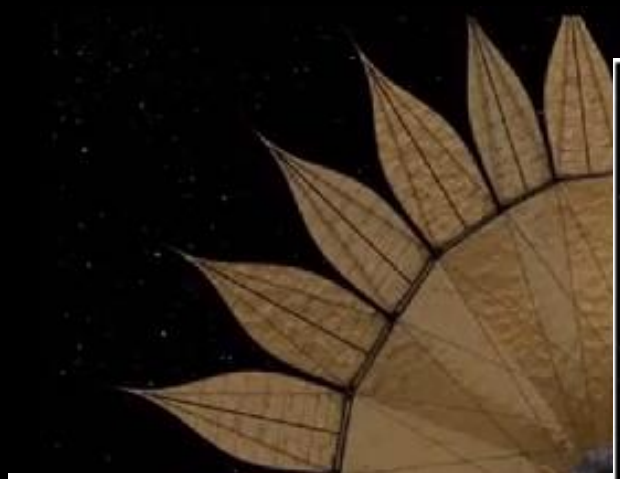
- Limited number of Starshade movements
  - Before you run out of propellant

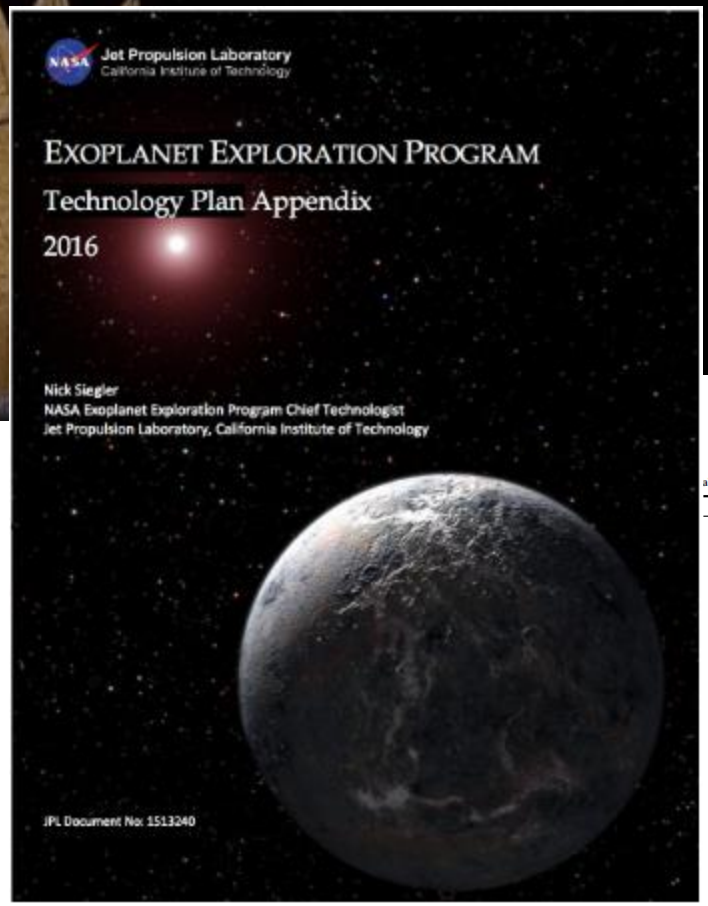
- Full-scale end-to-end system optical testing on the ground not possible
  - Must rely on sub-scale lab and field optical tests as well as high-fidelity, validated models

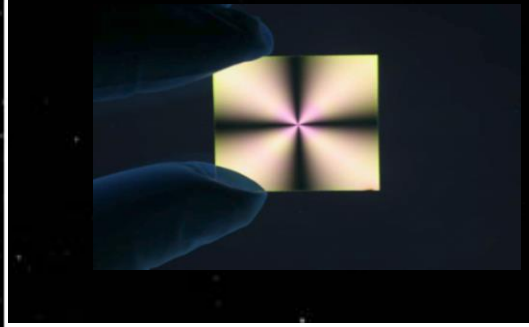
Recent Starshade Technology News

- 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 October 2016*
- WFIRST is assessing the impact of accommodating a potential 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 ≤ 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

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 ≤ 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^{-1}'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^{-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/gap-lists/

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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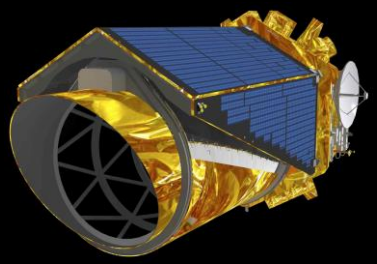
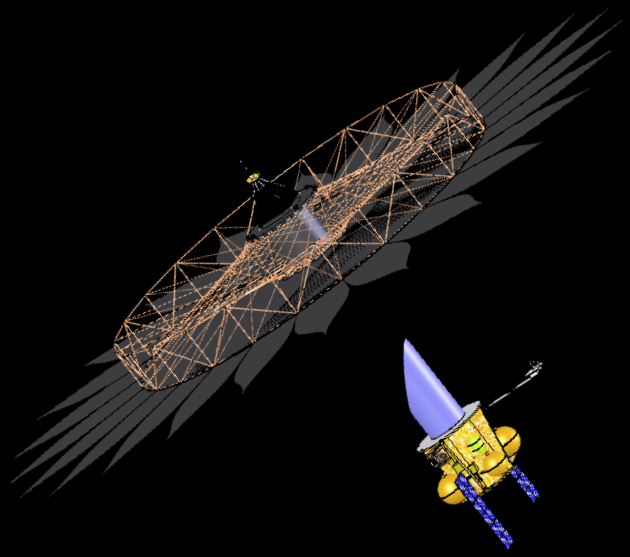
Government sponsorship acknowledged





Additional Slides

The TRL-6 Success Criteria that the SSWG Options Need to Meet

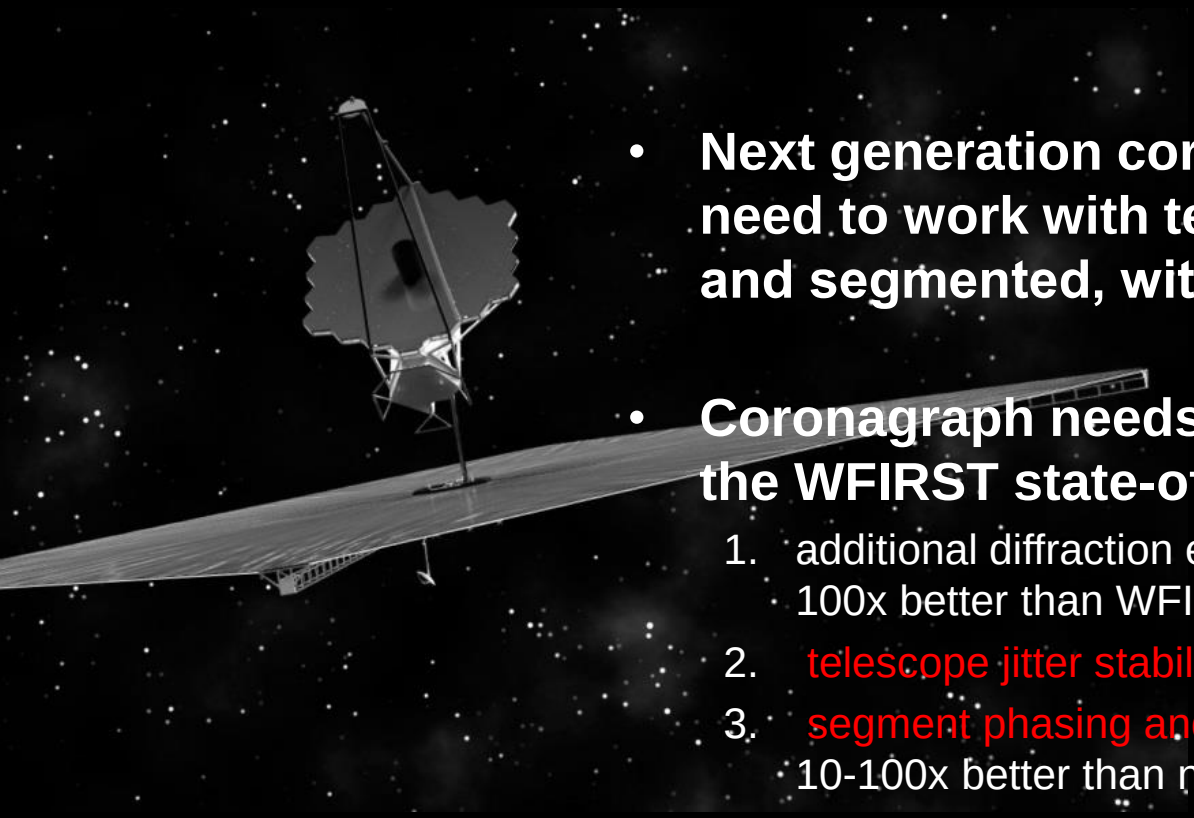
Technology Area	Key Performance Tolerances (3σ)	TRL-6 End-State Fidelity (Prototype)			Tested in Relevant Environment; Life Testing	Performance Verification	Model Validation
		Fit	Form	Function			
Deployment Accuracy and Shape Stability	**Petal Shape and Stability**						
	In-plane envelope: ± 100 µm	High fidelity with scaling issues understood	High-fidelity prototype	Required performance demonstrated with critical interfaces	Deploy and thermal cycles	Measure shape after deployment and thermal cycles; long-term stowed bending strain	CTE, CME, creep
					Temperature and humidity	Measure shape with optical shield at temp; moisture absorption and loss (de-gassing)	Shape vs. applied loads
					Stowed strain	Test on-orbit petal shape with all errors	Shape vs. temperature
	Deployed Petal Position						
	In-plane envelope: ± 1 mm	High fidelity with scaling issues understood	High-fidelity prototype	Required performance demonstrated with critical interfaces	0-gravity and vacuum	Measure position after deployment cycles in air with negligible air drag and imperfect gravity comp.	CTE, CME, creep
					Temperature and humidity	Measure position with optical shield at temp.	Shape vs. applied loads
					Stowed strain	Test on-orbit petal shape with all errors	Shape vs. temperature
Formation Sensing and Control	**Bearing Angle Sensing and Control**						
	Sensing: ± 1 mas Control (modeling): ± 1 m	High fidelity with scaling issues understood	High-fidelity prototype	Required performance demonstrated with critical interfaces	Large separation distance	Measure angular offsets with brassboard guide camera (coronagraph instrument) that simulates PSFs and fluxes from beacon and star	PSFs bearing angle vs. signal
Light Suppression	**Sunlight Suppression**						
	Edge radius x reflectivity: ≤ 10 µm-%	High fidelity with scaling issues understood	High-fidelity prototype	Required performance demonstrated with critical interfaces	Same as for petal shape and stability	Measure petal level scatter after environment tests at discrete angles	Scatter vs. sun angle Scatter vs. dust
					Sun angle	Measure coupon level scatter after environment tests at all sun angles	
					Dust in launch fairing	Test effect for on-orbit solar glint	
	Starlight Suppression						
	Supression (test): $\leq 1\text{x}10^{-9}$ Contrast (modeling): $\leq 1\text{x}10^{-10}$ (validted model)	High fidelity with scaling issues understood (including Fresnel #)	High-fidelity prototype	Required performance demonstrated with critical interfaces	Space	Measure image plane suppression between 500-850 nm	Optical performance, sensitivity to perturbations

All critical scaling and interface issues addressed

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 October 2016*
- WFIRST is assessing the impact of accommodating a potential future starshade mission
  - *Final decision will be made no later than summer of 2017.*

Detecting Rocky Earth-Size Planets



- **Next generation coronagraphs may likely need to work with telescopes that are on-axis and segmented, with apertures ≥ 8m.**

- **Coronagraph needs are expected to exceed the WFIRST state-of-art:**
  1. additional diffraction effects to reach 10^{-10} contrast – 10-100x better than WFIRST
  2. telescope jitter stability – 3-10x better than WFIRST
  3. segment phasing and rigid body sensing and control to 10-100x better than non-NASA
  4. wavefront sensing and control – 3-10x better than WFIRST