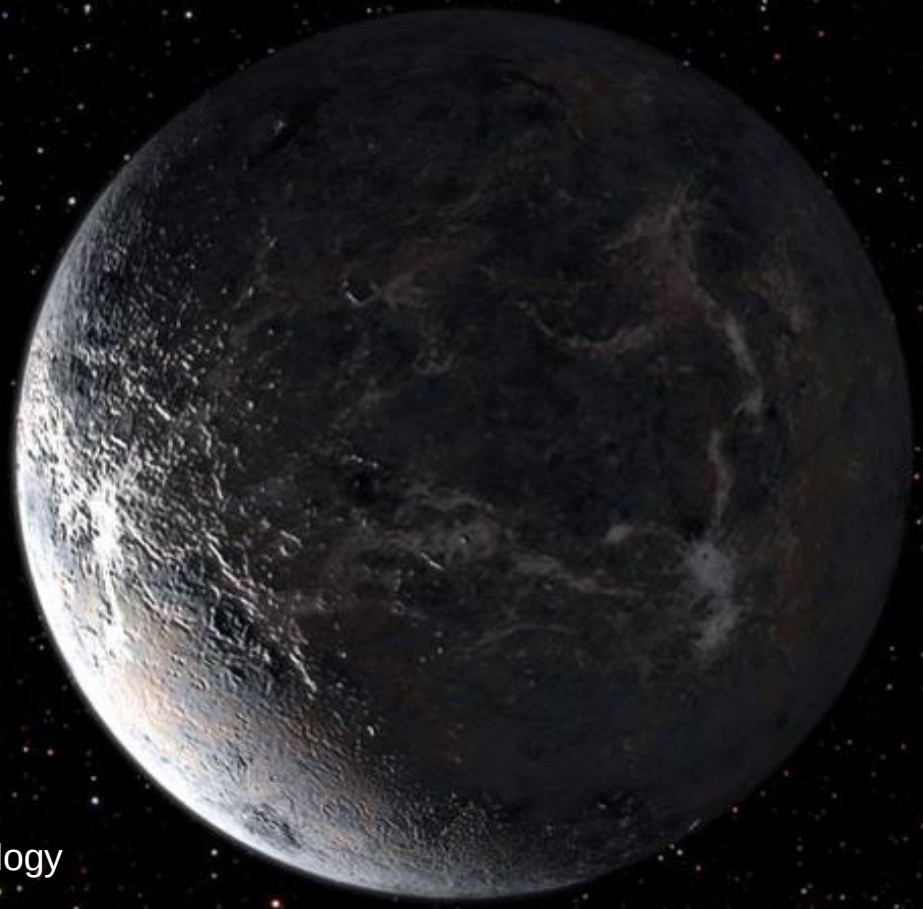
Jet Propulsion Laboratory
California Institute of Technology

Mirror Technology Days Workshop
Greenbelt, MD, November 2016

Technology Needs for the Exoplanet Exploration Program

Dr. Nick Siegler
Program Chief Technologist
NASA Exoplanet Exploration Program
Jet Propulsion Laboratory, California Institute of Technology



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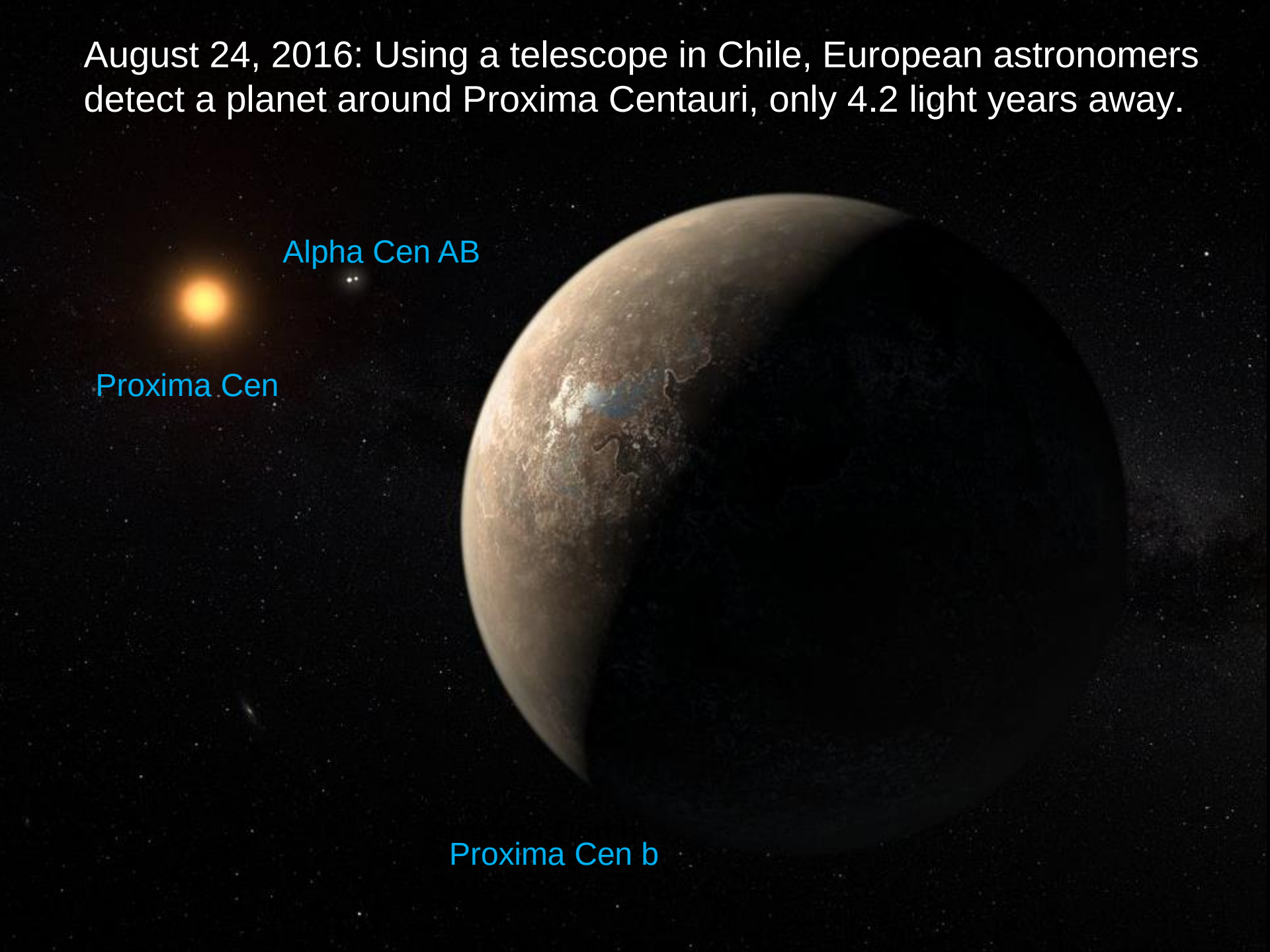
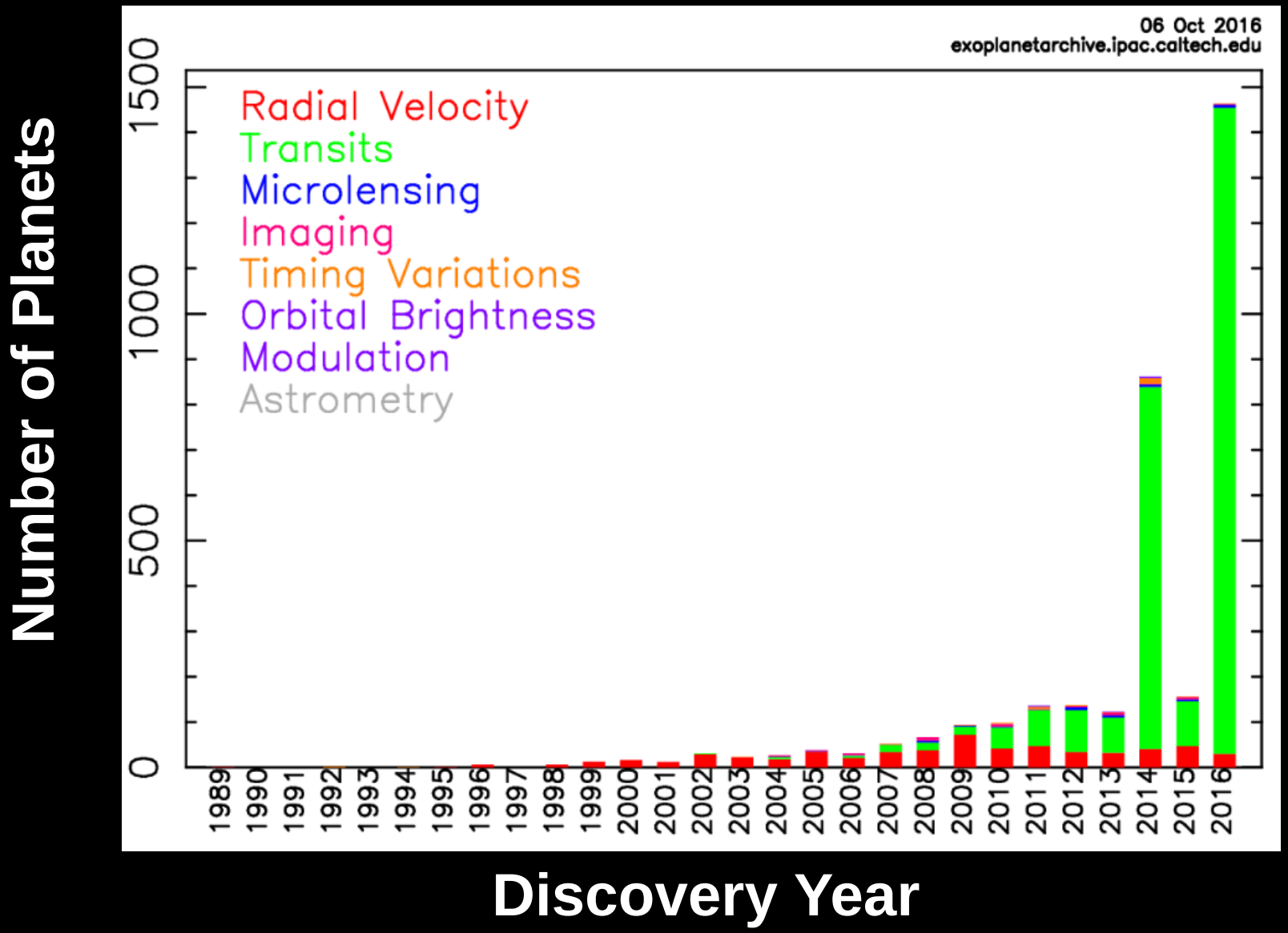
August 24, 2016: Using a telescope in Chile, European astronomers detect a planet around Proxima Centauri, only 4.2 light years away.



3,396 Confirmed Exoplanets

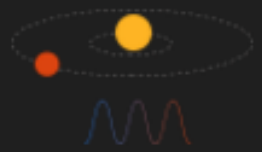
(as of 10/8/16)



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

By Method

78.9% Transit



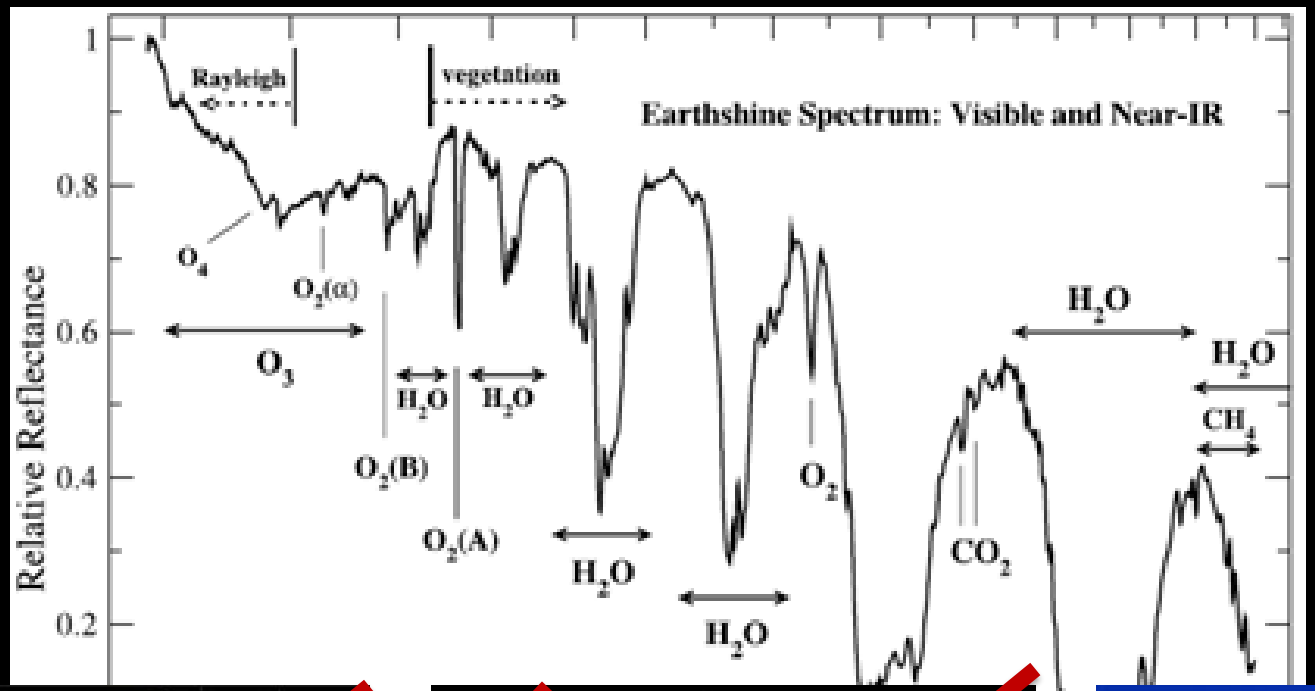
17.6% Radial Velocity

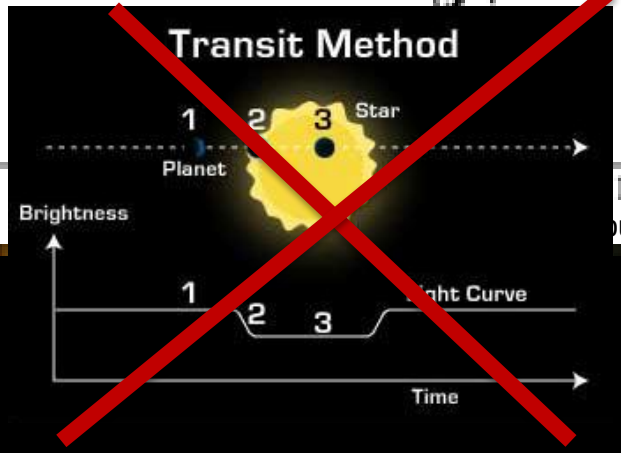
1.3% Imaging

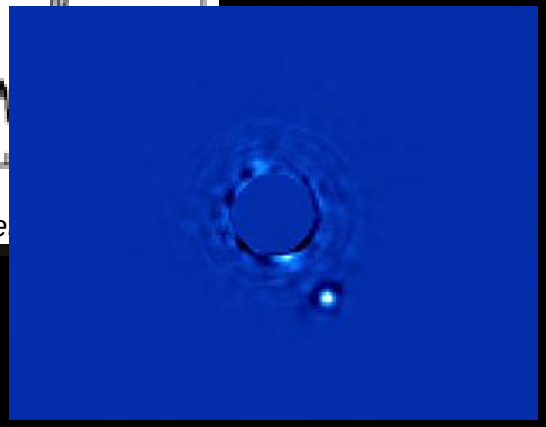
1.2% Microlensing

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 <u>the</u> Key Technology in the Search for Life on Earth-Size Exoplanets



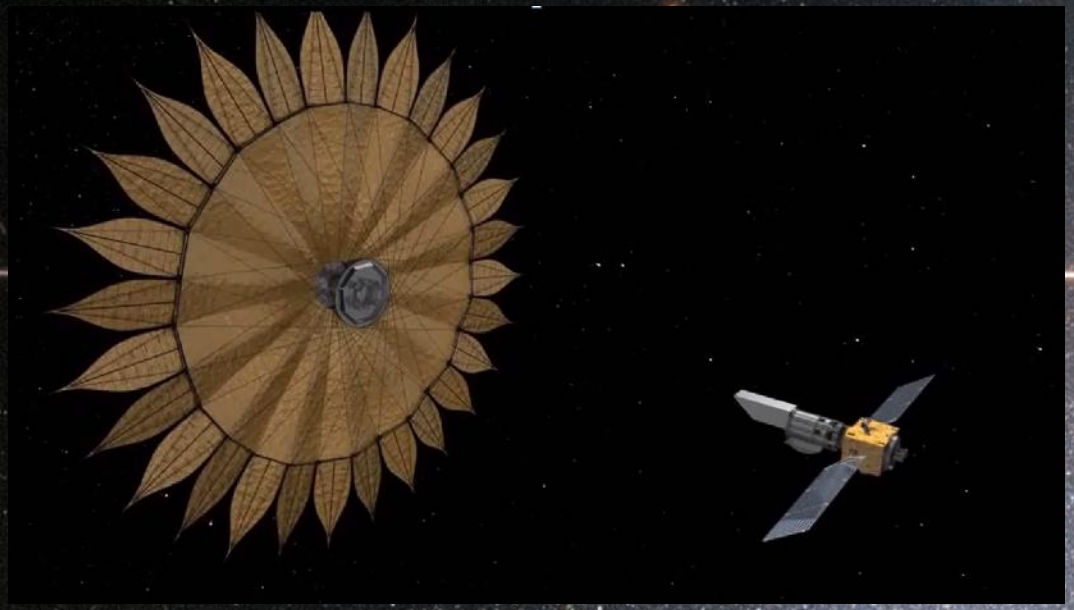


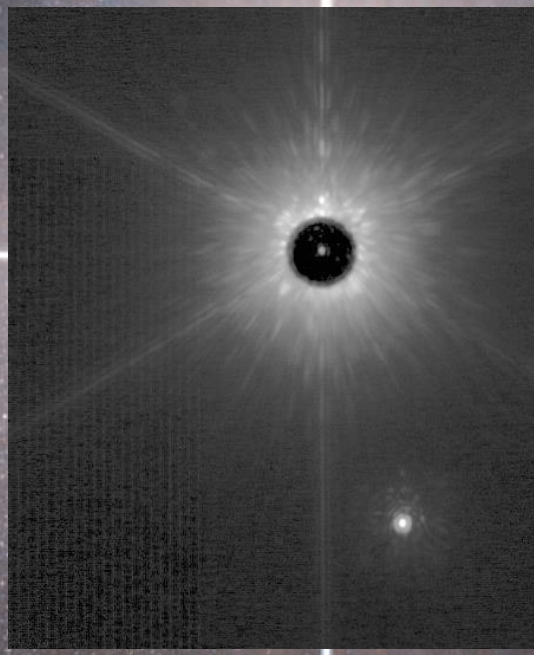


Macintosh et al. 2015

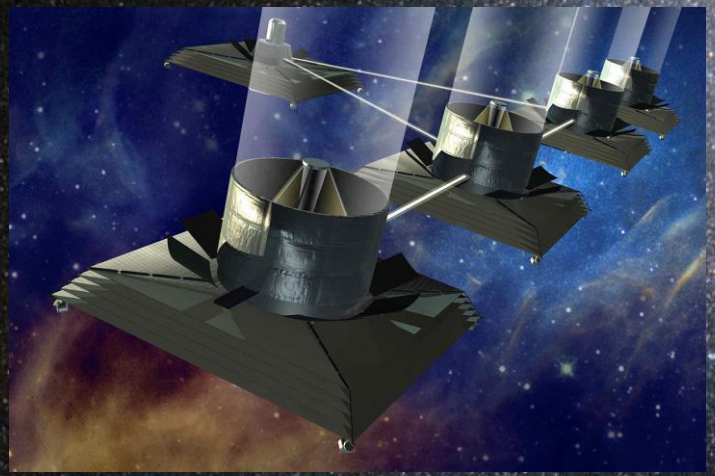
Enabling Starlight Suppression Technologies

External Occulters (Starshades)



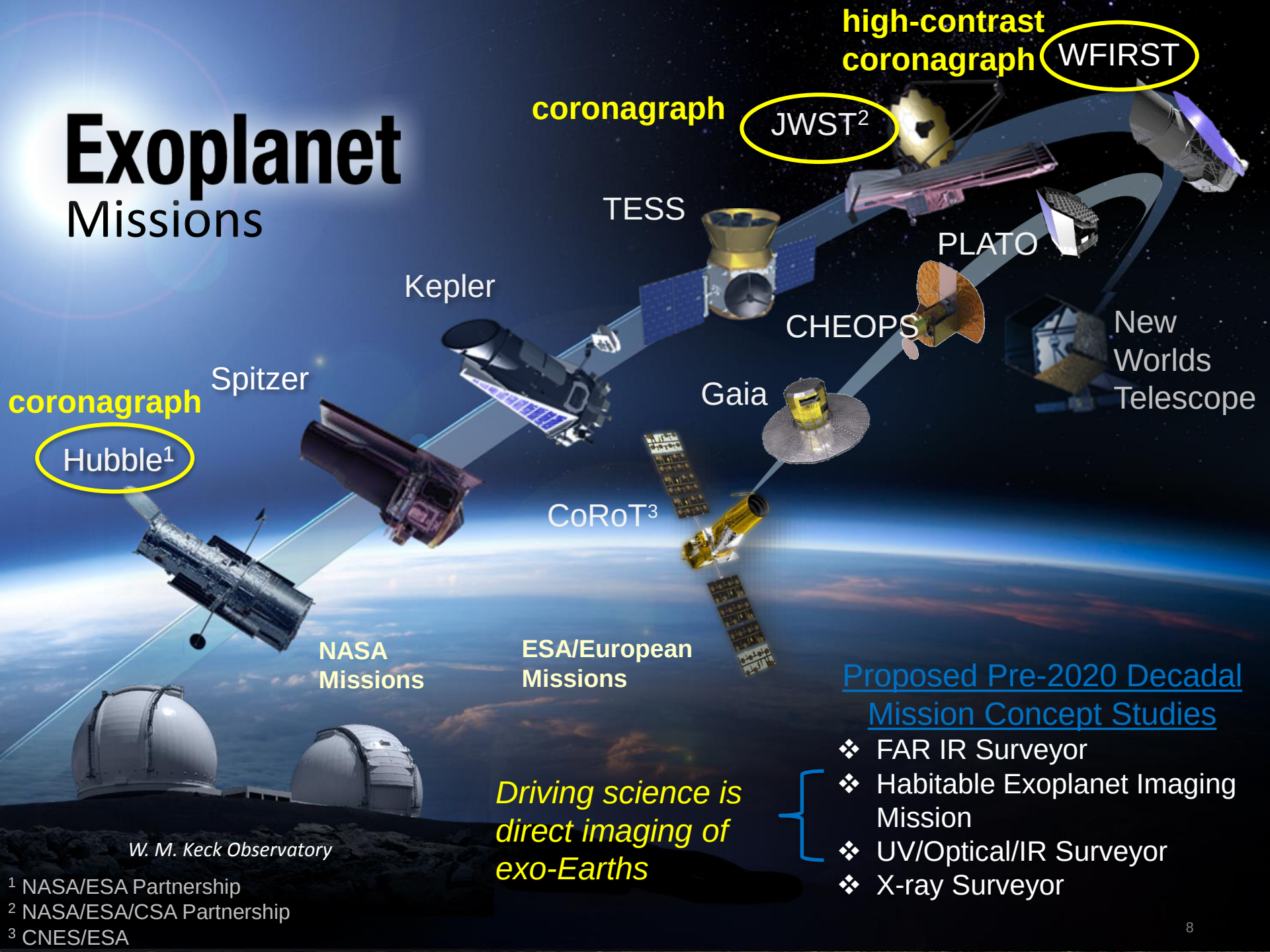


Nulling Interferometry



Internal Occulters (Coronagraphs)

Exoplanet Missions



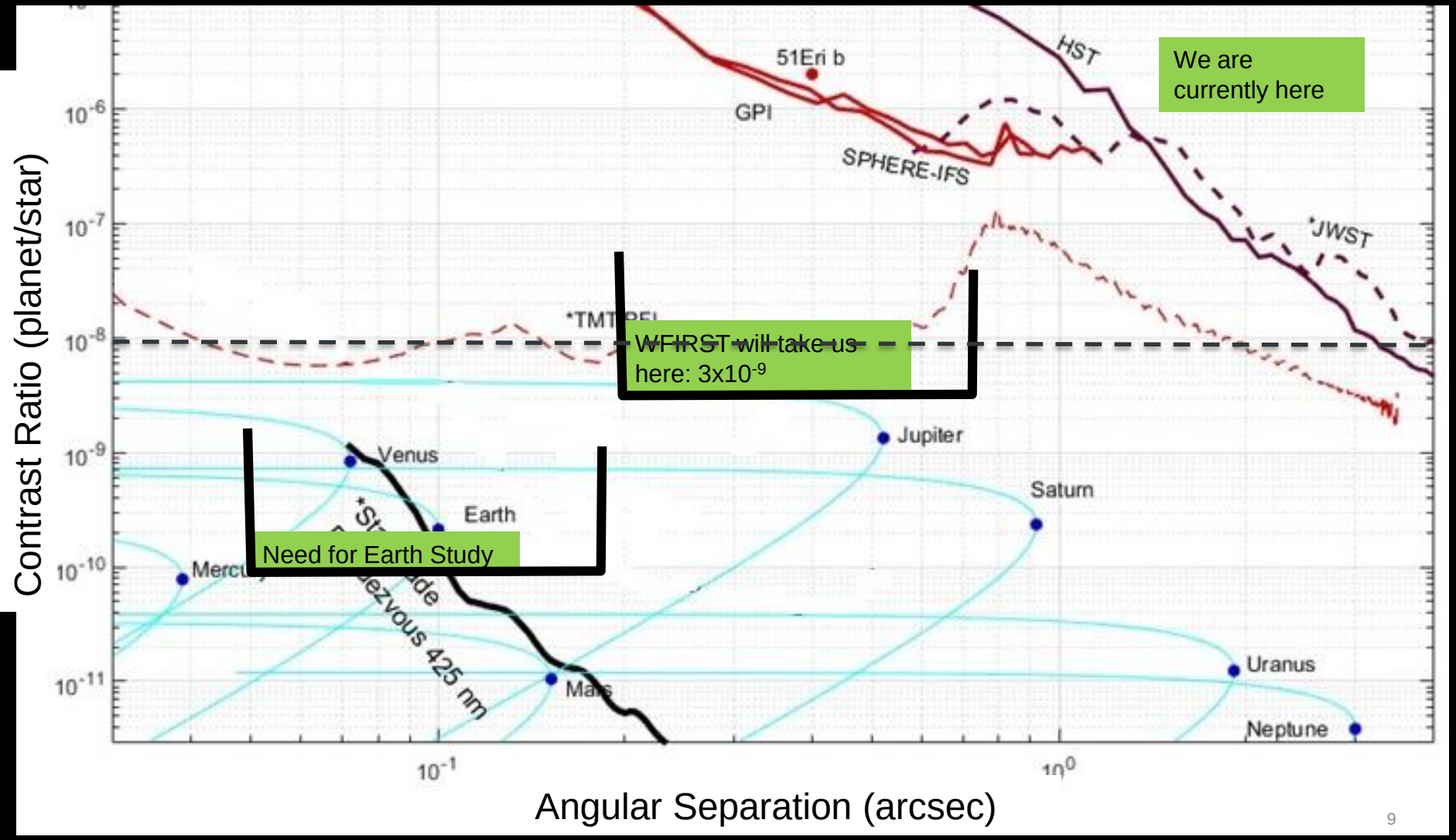
Driving science is direct imaging of exo-Earths

Proposed Pre-2020 Decadal Mission Concept Studies

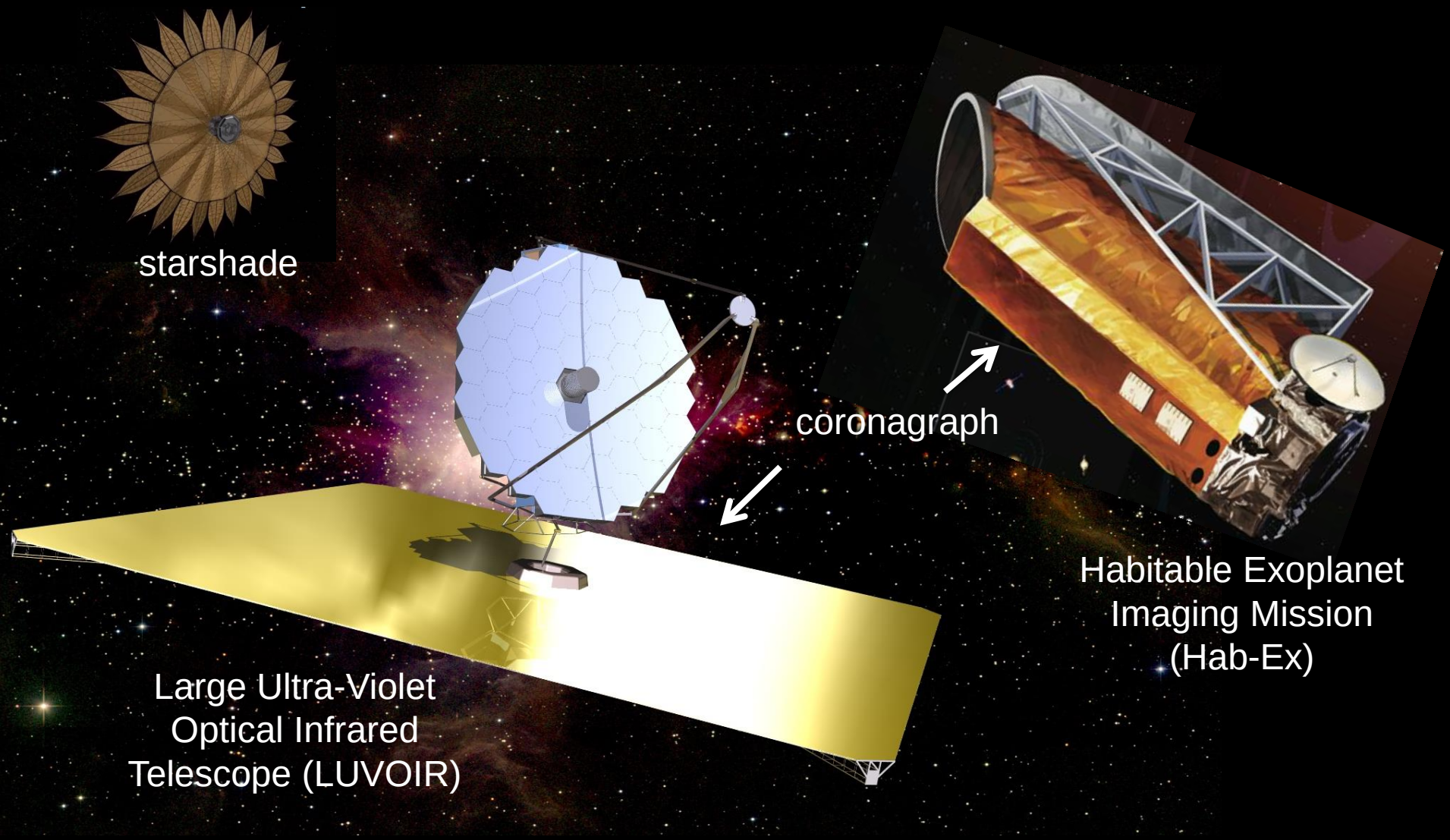
- FAR IR Surveyor
- Habitable Exoplanet Imaging Mission
- UV/Optical/IR Surveyor
- X-ray Surveyor

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

Towards the Detection of Exo-Earths



Possible New Worlds Exoplanet Telescopes
(mid-2030s)



Two direct imaging mission concept studies: HabEx and LUVOIR

- Both have goal of studying Earthlike planets in reflected light; they differ in levels of ambition
  - HabEx to “search for” signs of habitability and biosignatures
  - LUVOIR to “constrain the frequency of” habitability and biosignatures = larger statistical survey of exoEarths, larger aperture
- HabEx to focus on exoplanets, “best effort” only on general astrophysics. Perhaps only 2 instruments, like WFIRST. Aperture < ~8 m. Study led by NASA JPL.
- LUVOIR gives equal priority to exoplanets and general astrophysics. Would be HST- and JWST-like, expansive vision. Aperture 8-12 m. Study led by NASA Goddard.
- They are likely to differ in cost and technical readiness
- Interim reports late 2017; final reports early 2019

NASA Exoplanet Exploration Program

One of three programs within the NASA Astrophysics Division, Science Mission Directorate

Purpose described in 2014 NASA Science Plan

1. Discover planets around other stars
2. Characterize their properties
3. Identify candidates that could harbor life

ExEP serves the science community and NASA by implementing NASA's space science vision for exoplanets

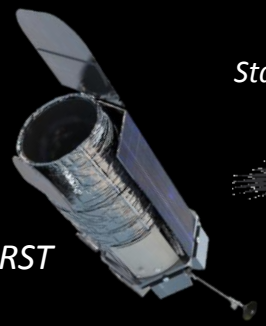
http://exoplanets.nasa.gov/exep

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

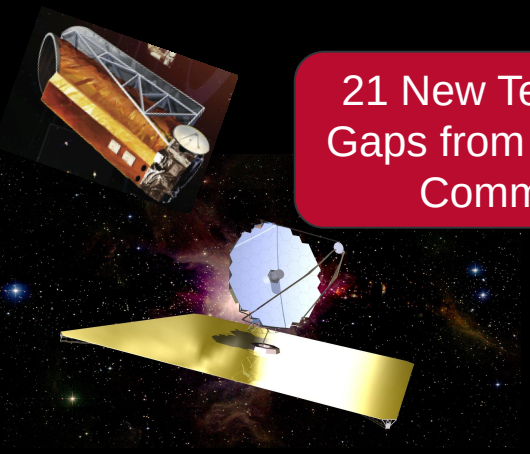
Technology Development

Coronagraphs

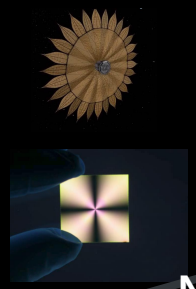
Starshades

NASA Exoplanet Science Institute

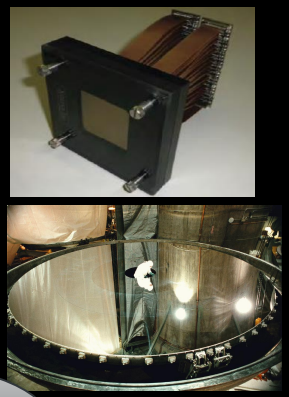
ExEP Technology Selection and Prioritization Process



21 New Technology Gaps from Exoplanet Community



14 Technology gaps carried over from 2016



Selection: enables or enhances direct detection and characterization of exoplanets?

Neither enhancing nor enabling

not accepted

No, but could benefit exoplanet science

List of technologies that benefit exoplanet science, aka "Watch List"

Yes

Prioritize technologies according to criteria (Impact, Urgency, and Trend)

Selection and Prioritization Criteria:

- Peer reviewed
- Exo-TAC reviewed

ExEP Technology Gap List

Reviewed by Exo-TAC

2017 ExEP Technology Gap List

Prioritized List

Gap ID	Gap Title	Impact	Urgency	Trend	Total
S-2	Optical Performance Demonstration and Optical Modeling	4	4	2	90
CG-1	Large Aperture Mirrors	4	3	3	85
CG-2	Coronagraph Architecture	4	3	3	85
CG-6	Mirror Figure (Segment Phasing) Sense & Control	4	3	3	85
CG-7	Telescope Vibration Control	4	3	3	85
CG-9	NIR Ultra-Low Noise Detector	4	3	3	85
S-1	Control Edge-Scattered Sunlight	4	4	1	85
S-3	Lateral Formation Flying Sensing	4	4	1	85
S-4	Petal Shape	4	4	1	85
S-5	Inner Disk Deployment	4	4	1	85
S-6	Petal Deployment	4	4	1	85
CG-3	Low-Order Wavefront Sensing and Control	4	3	2	80
CG-5	Deformable Mirrors	4	3	2	80
CG-8	Visible Ultra-Low Noise Detector	4	3	2	80
M-1	Extreme Precision Radial Velocity	3	3	3	75
CG-4	Post-Data Processing	4	2	2	70
CG-9	UV/NIR/Vis mirror coatings	3	3	2	70
CG-10	Mid-IR Spectral Coronagraph	2	3	3	65
CG-11	UV Ultra-low noise detector	2	3	2	60

Enabling Gap
Enhancing Gap
Watch List

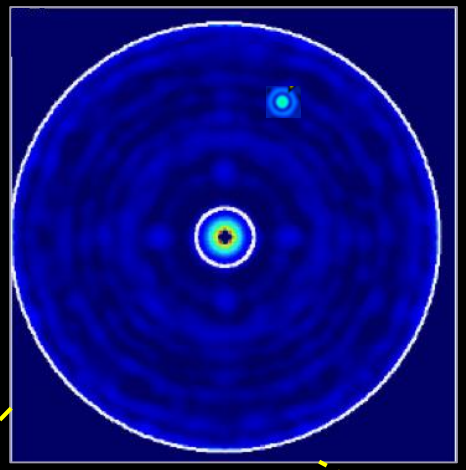
Watch List

Sub-Kelvin Coolers
Advanced Cryocooler
Mid-IR Ultra-low Noise Detector
Astrometry

Coronagraph/Telescope Technology Needs

Starlight Suppression

Angular Resolution

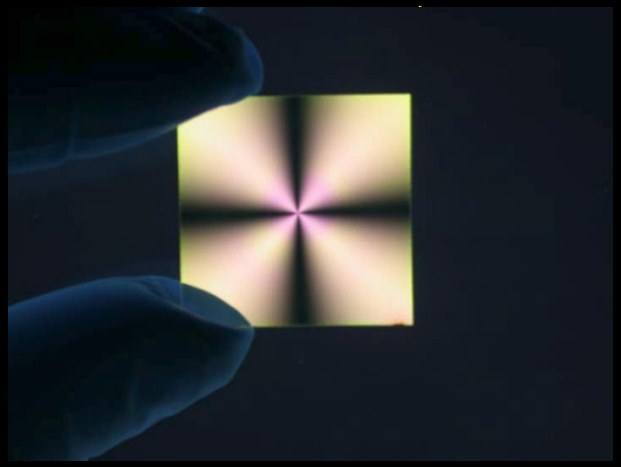


Contrast Stability

Detection Sensitivity

Coronagraph Technology Needs

Starlight Suppression



Coronagraphy optics

Future Needs:

- Raw contrast < 10^{-9} (obscured and segmented)
- IWA ≤ 3 λ/D
- Bandwidth ≥ 10%

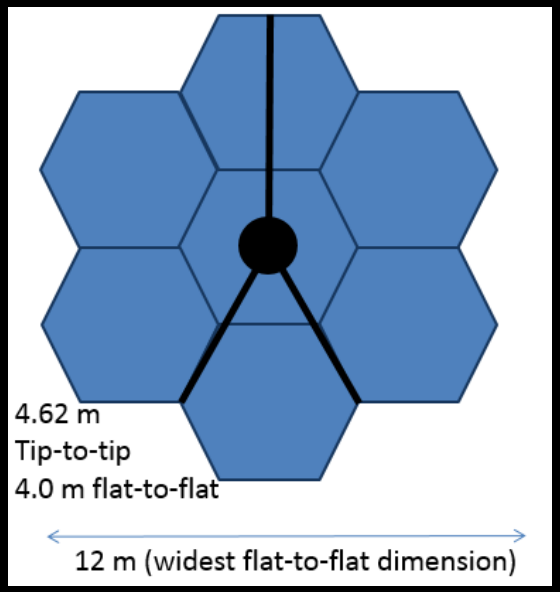
SOA:

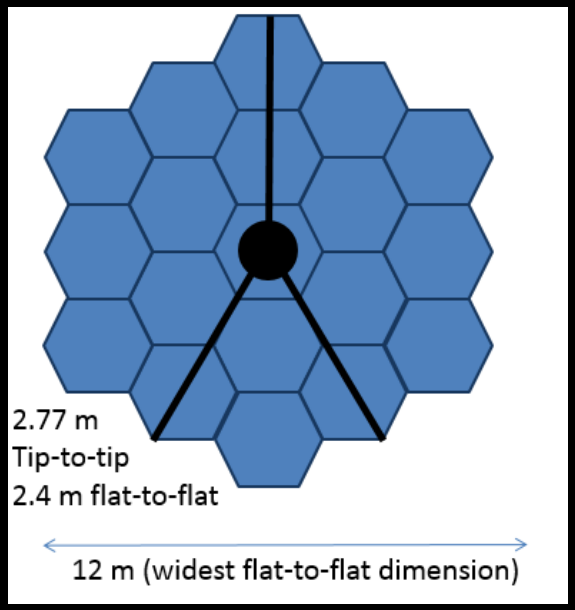
- WFIRST: Raw contrast: few x 10^{-9} (obscured); $3x10^{-10}$ (unobscured; Hybrid Lyot)
- IWA ~ 3 λ/D
- Bandwidth 10%

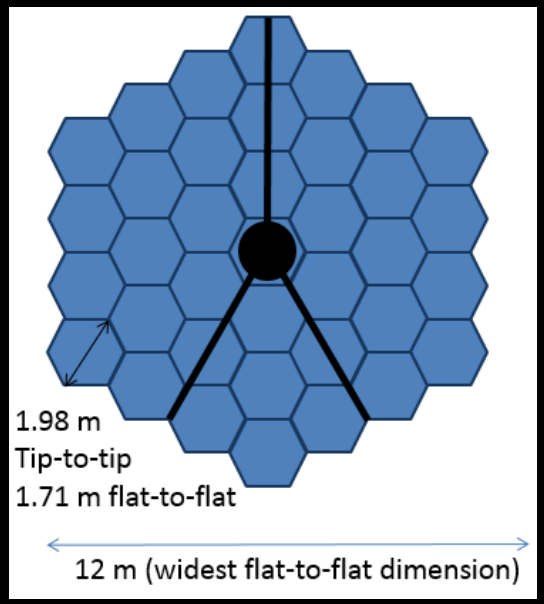
Current Activities:

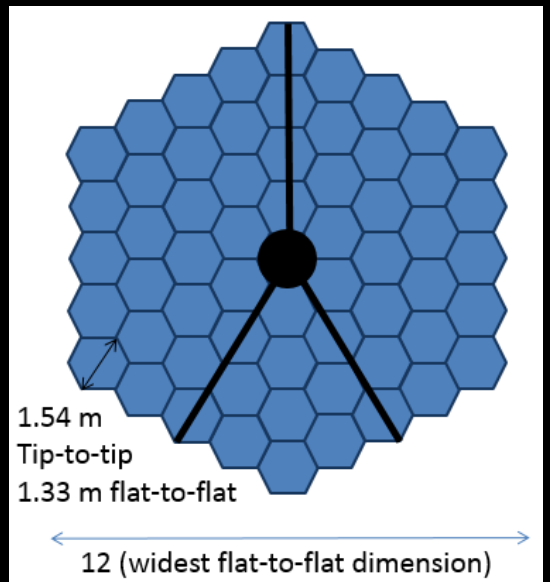
- WFIRST coronagraphs planned to achieve TRL 5 by end FY16
- Additional demonstrations ongoing at STScI (APLC) and GSFC (VNC)
- ExEP planning FY16 design study to identify coronagraph architectures that can reach < 10^{-9} on large segmented apertures (FY16)
- Pre-Decadal mission concepts in FY16-18

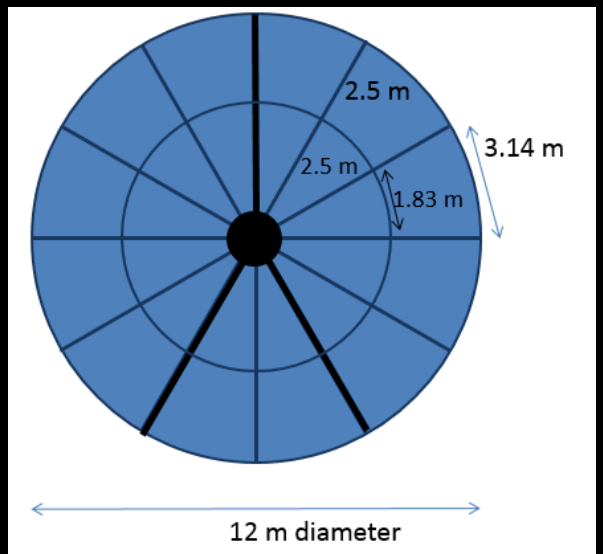
Segmented Coronagraph Design Analysis
(funded by the ExEP)

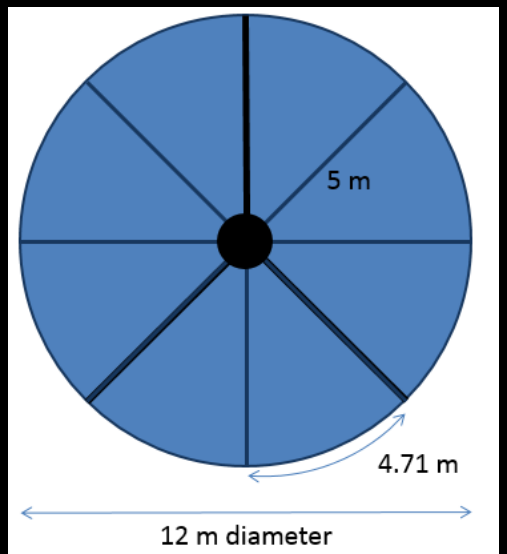






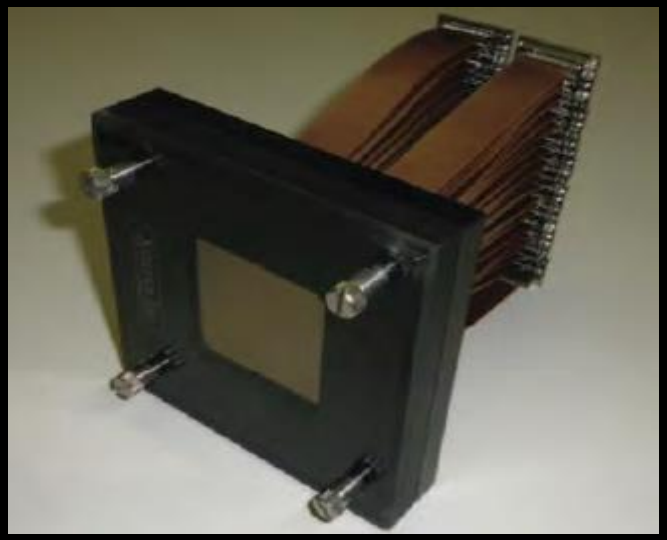






Coronagraph Technology Needs

Starlight Suppression



Deformable mirrors
(Xinetics 48x48)

Need:

- ≥ 96x96 actuators
- radiation and env't qualified
- flight electronics and connectors
- pitch sizes ≤ 1 mm
- stroke ≥ 500 um

SOA:

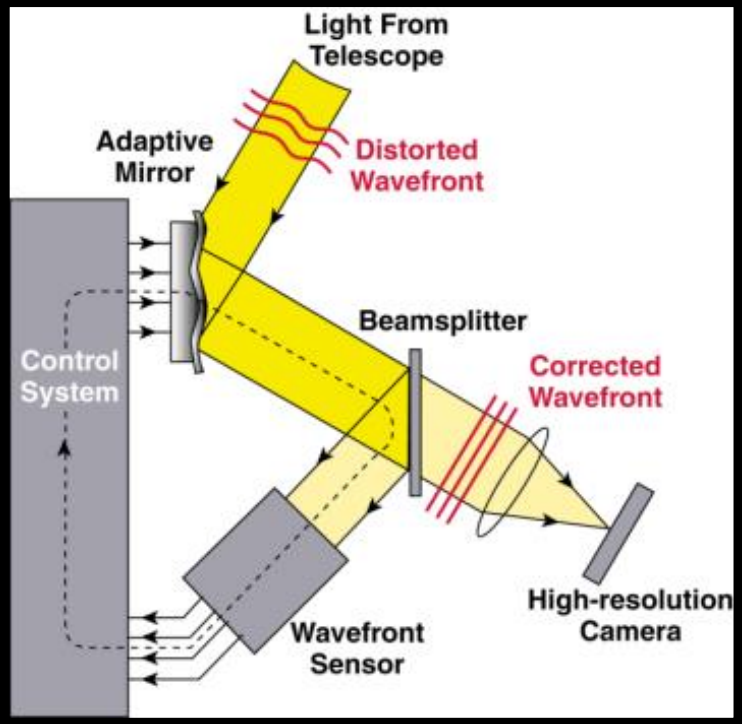
- 64x64 electrostrictive actuators by Xinetics (WFIRST baselined 48x48)
  - pitch size = 1 mm
  - stroke = 500 um
- $3x10^{-10}$ contrast achieved with 32x32

Current Activities:

- 48x48 Xinetics DMs are being flight qualified, connector study, flight electronics design (WFIRST; FY16-17)
- MEMS DMs (BMC and Iris AO) env't testing (FY16-17)
- Pre-Decadal mission concepts in FY16-18

Coronagraph Technology Needs

Wavefront Stability



Low-order wavefront sensing and control

Needs:

- Low-order WFE terms sensed and corrected to maintain 10^{-11} contrast stability
- < 10 pm rms uncorrected WFE

SOA:

- Zernike wavefront sensor baselined on WFIRST
  - 14 mas simulated jitter input (tip/tilt only) corrected to ≤ 0.5 mas rms residual

Current Activities:

- WFIRST LOWFS sensing and controll of first few modes to be demonstrated with a telescope and env't simulator with a coronagraph (FY16)
- Pre-Decadal mission concepts in FY16-18

Coronagraph Technology Needs

Wavefront Stability

Segment phasing and rigid body control

Telescope vibration control

Needs:

- Segment phasing control to < 10 pm rms WFE
- Disturbance: 140 dB at > 40 Hz

Relative to SOA:

- WF stability 2-3 OOM better than HST
- 1-2 OOM segment phasing and rigid body control (non-NASA); 3 OOM JWST
- 1 OOM in vibration control (WFIRST)
- Disturbance: 80 dB at > 40 Hz (JWST; passive)

Current Activities

- Pre-Decadal mission concepts in FY16-18 to conduct key systems trade studies
  - segmented vs monolith primaries
  - active control vs passive vs hybrid for thermal, vibration, SFE

Note: can be relaxed to SOA for starshade

Coronagraph Technology Needs

Needs (Visible):

- 0.4 – 1 um ultra-low noise detectors
- Read noise: << 0.1 e'/pix
- Dark current: < 0.0001 e'/pix/s
- Format: > 2kx2k
- Radiation hard

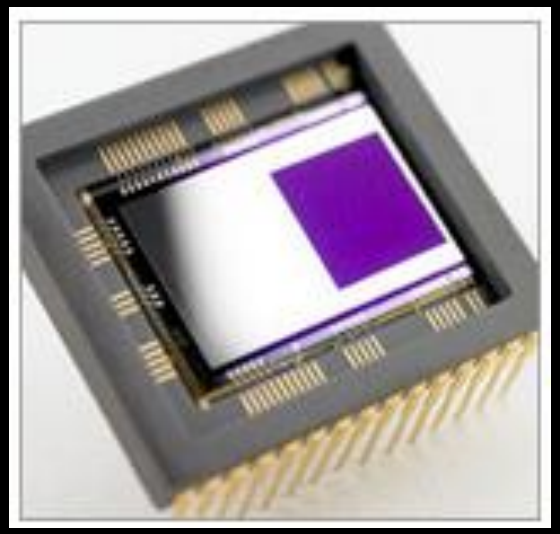
Relative to SOA:

- 1kx1k EMCCD baselined for WFIRST
- OOM in RN and DC
- Not environmentally tested

Current Activities:

- Radiation testing (WFIRST; FY15-16)
- Flight R/O electronics design (WFIRST; FY16-18)
- Env't testing (WFIRST)

Detection Sensitivity



e2V EMCCD 1kx1k

Coronagraph Technology Needs

Needs (IR):

- 1-5 um
- Read noise: < 1 e'/pix
- Dark current: < 0.001 e'/pix/s
- Format: arrays of ≥ 2kx2k
- Radiation hard
- Zero-vibration cooling

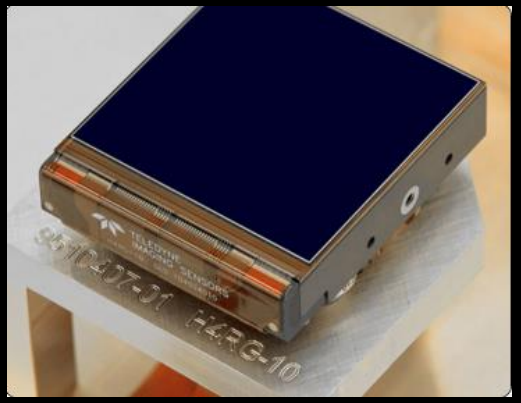
Relative to SOA:

- HgCdTe APD Hybrid
- Read noise: << 1 e'/pix
- Dark current: 10-20 e'/pix/s
- Format: arrays of < 1kx1k

Current Activities:

- HgCdTe (WFIRST) and APD noise reduction efforts
- MKIDS and TES are low-TRL cryo solutions
- Pre-Decadal mission concepts to determine long λ cutoff (FY16)

Detection Sensitivity



Teledyne H4RG-10 IR detector

Technology	Visible 350 — 950 nm	Near-IR 950 nm — 5 μm	Mid-IR 5 μm — 8 μm
CCD	Rad. hardness		
CMOS			
EMCCD	Rad. hardness		
p-channel CCD			
Si PIN Hybrid			
HgCdTe Hybrid			
HgCdTe APD Hybrid	Reduce dark current	Reduce dark current	
MKID array	TRL < 5	TRL < 5	TRL < 5
TES array	TRL < 5	TRL < 5	TRL < 5
SNSPD	Reduce dark current	Reduce dark current	Reduce dark current
Si:As Hybrid			

Baselined by WFIRST → EMCCD

Being evaluated now → HgCdTe APD Hybrid

Cryogenic detectors → MKID array, TES array, SNSPD

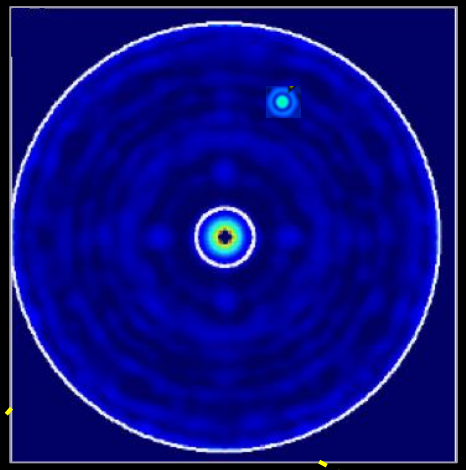
	TRL ≥ 6; Sufficiently mature for pre Phase-A
	Promising technology, more work needed in specific area
	Promising technology
	Cryogenic cooling required
	May be worth looking into with additional optimization

Rauscher et al 2015 (SPIE)

Coronagraph Technology Needs

Starlight Suppression

Angular Resolution



+ increased sensitivity
+ higher throughput
+ shorter integration time
+ greater planet yield

Detection Sensitivity

Wavefront Stability

Coronagraph Technology Needs

Needs:

- ≥ 4m monoliths and ≥ 8m segmented mirrors
- SFE < 10 nm RMS
- Active thermal control; likely figure control for segments

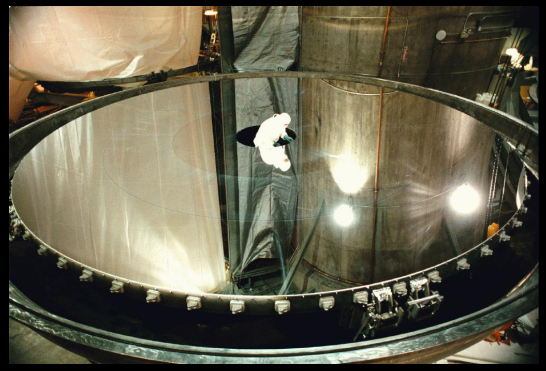
SOA:

- Monolith: HST's 2.4m (~ 10 rms SFE)
- Segmented: JWST's 6.5m (18 segments, 1.3m)
- SFE: < 30 nm RMS

Current Activities:

- Non-NASA investments
- Pre-Decadal mission concepts will study monolith vs segments, materials, active figure control

Angular Resolution



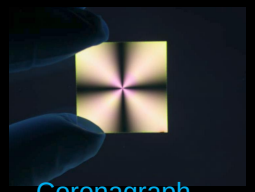
Large monolith
(Gemini 8.1m ULE)

Segmented
(AMSD lightweighted ULE Segment; ITT)

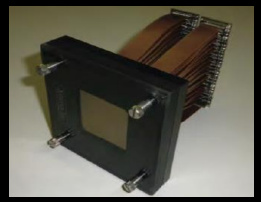
Segmented
AHM SiC-based Segment, Xinetics

Coronagraph/Telescope Technology Needs

Contrast



Coronagraph architectures



Deformable mirrors

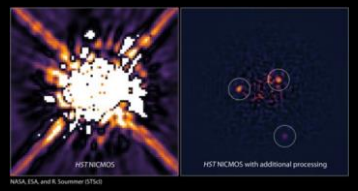
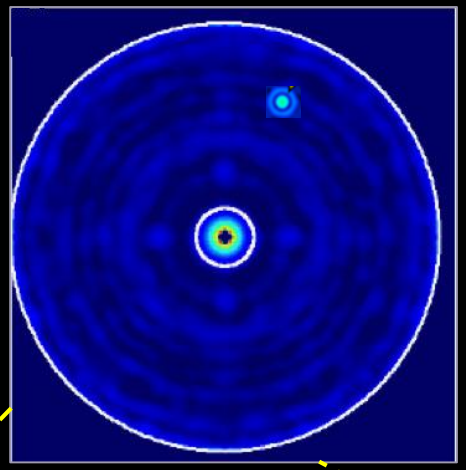
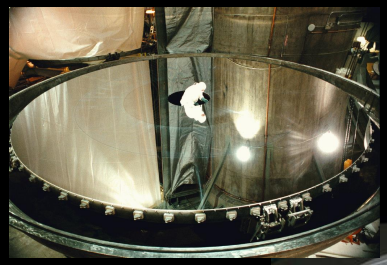


Image post-processing



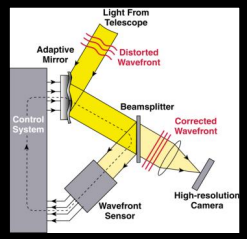
Angular Resolution



Large monolith

Segmented

Contrast Stability

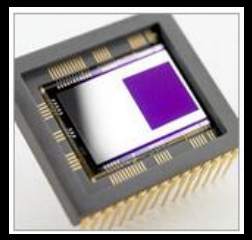


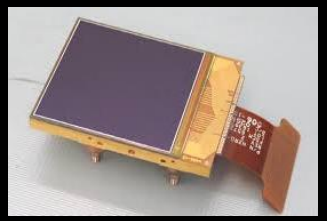
Wavefront sensing and control

Segment phasing and rigid body sensing and control

Telescope vibration sensing and control

Detection Sensitivity

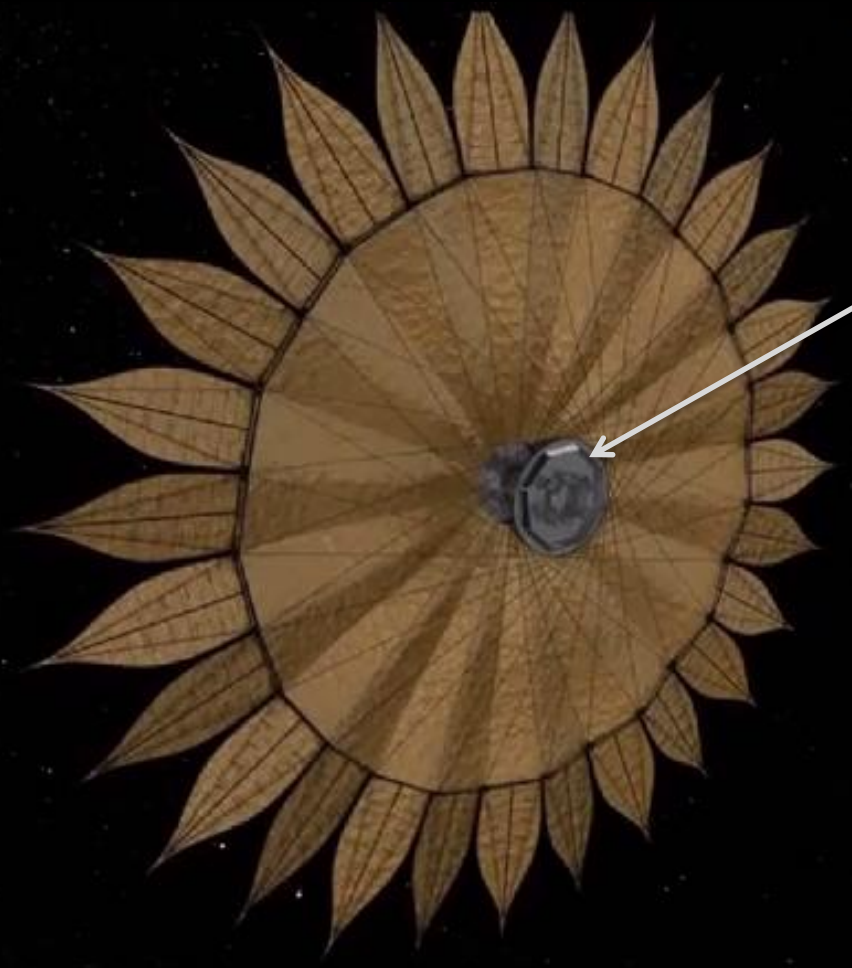




Ultra-low noise visible and infrared detectors

Starshade Technology Needs

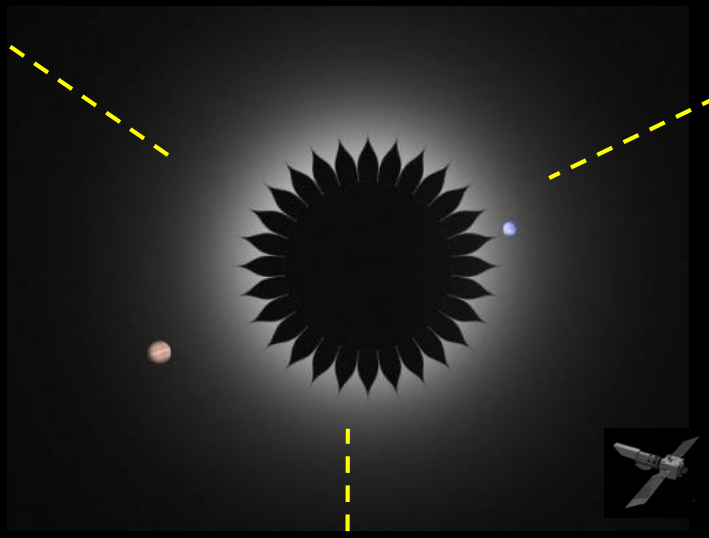
What's not hard…



Starshade Technology Needs

Diffraction and Scattered Light Control

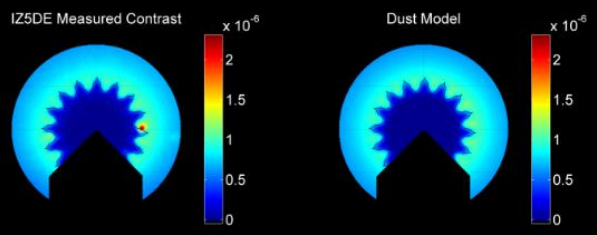
Lateral Formation Flying Sensing



Large Deployed Structures

Starshade Technology Needs

Diffraction and Scattered Light Control



Needs:

- Contrast ≤ 10^{-10} demonstrated near the petal edges at a flight Fresnel number
- Optical model validation
- Optical edge material identified and integrated to a full-scale petal

Current Activities:

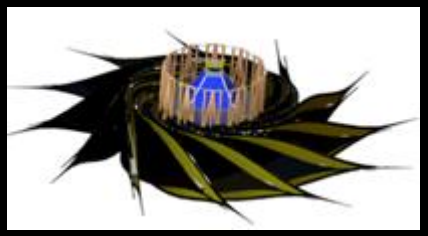
- Optical performance and modeling studies (Princeton/JPL, NGAS, Colorado/JPL) – FY16-18
- Optical edge studies (NGAS, JPL) – FY16-17

Starshade Technology Needs

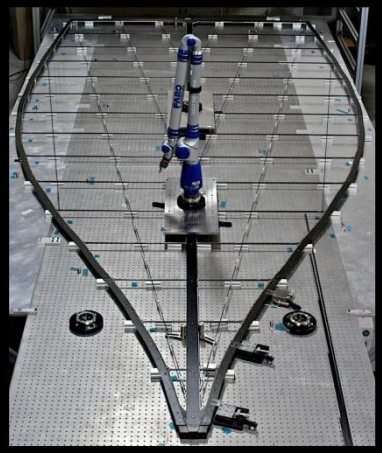
Large Deployable Structures

Half-scale inner disk testbed (JPL)

1/10-scale opaque membrane testbed (JPL)



Petal unfurling concept (Roccor)



6m petal (Princeton/JPL)

Needs:

- Full-scale (~ 7m) petal with flight-like materials that meet manufacturing tolerances (< 70 um).
  - ➢ FY16-17 (Princeton/JPL)
- Half-scale (10m) inner disk prototype with flight-like components and opaque membrane that meets deployment tolerances (< 0.45 mm).
  - ➢ FY16-17 (JPL)
- Full-scale petal latching and unfurling mechanism verifying no edge contact during launch and petal unfurling
  - ➢ FY16-18 (Roccor/JPL)
- 80m-class starshades designs? (TBD)

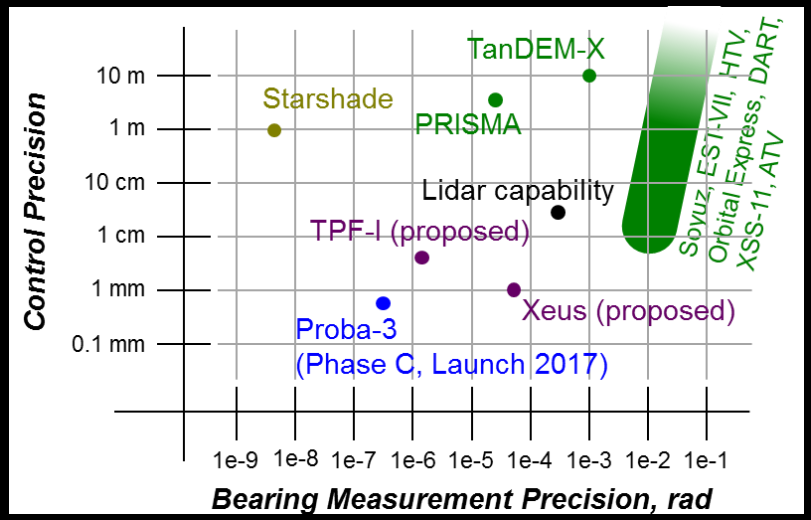
Starshade Technology Needs

Needs:

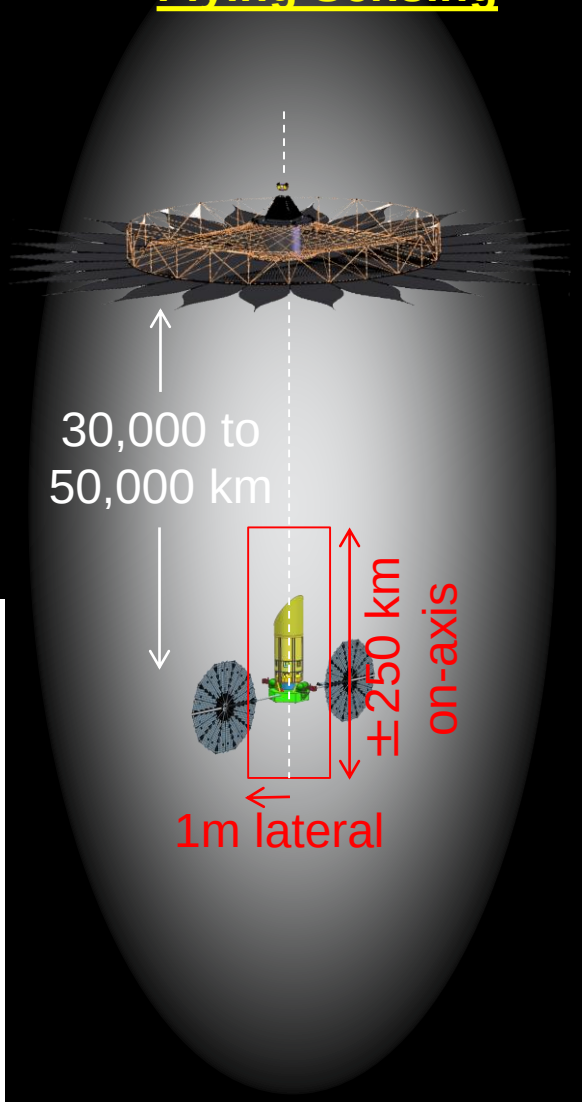
- Sense relative lateral offsets between telescope and starshade to within ± 20 cm at 50,000 km distance
  - Measure bearing angle to within ± 1.25 mas

Current Activities:

- Demonstrating mas bearing sensitivity with feedback control in scaled testbeds
  - ➢ Princeton/JPL, Colorado (FY16-17)

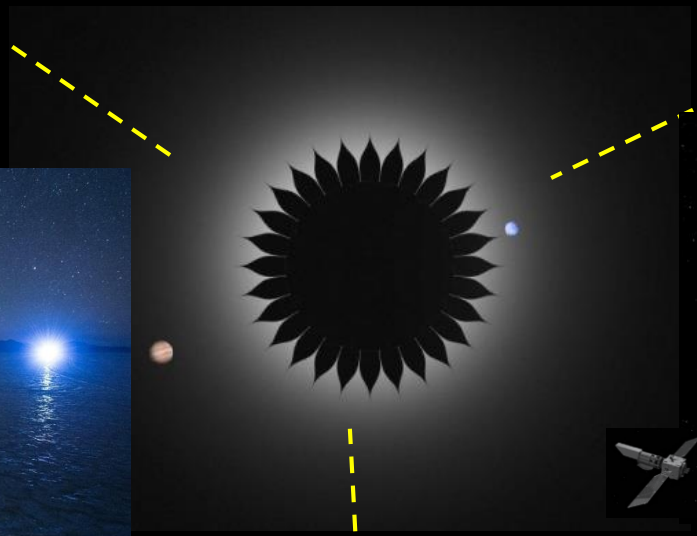


Lateral Formation Flying Sensing

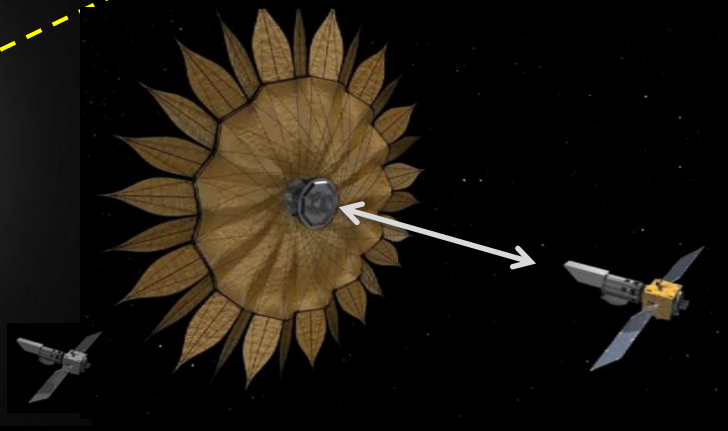


Starshade Technology Needs

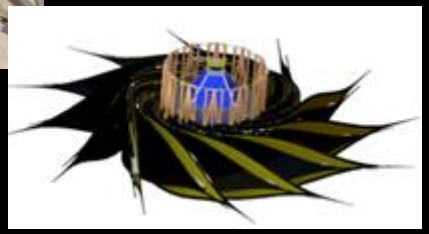
Diffraction and Scattered Light Control

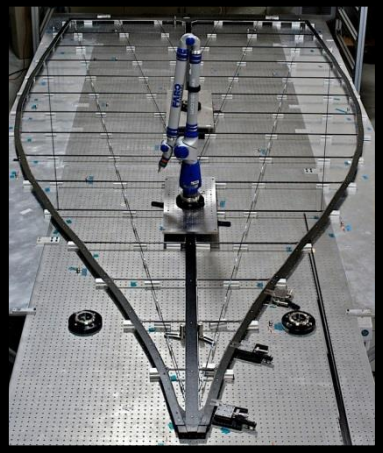


Lateral Formation Flying Sensing



Large Deployable Structures





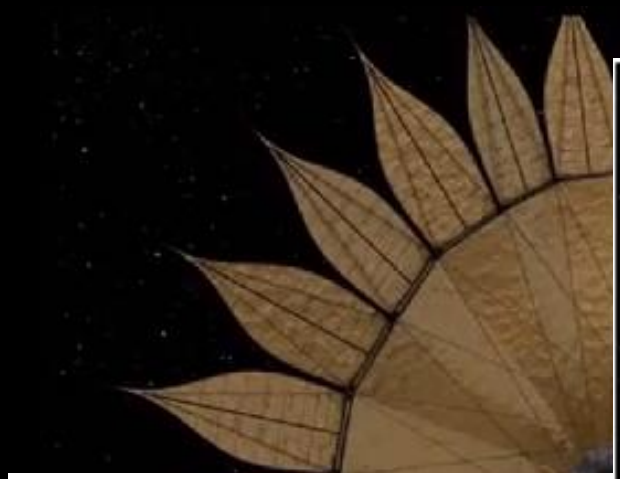
Recent Starshade Technology News

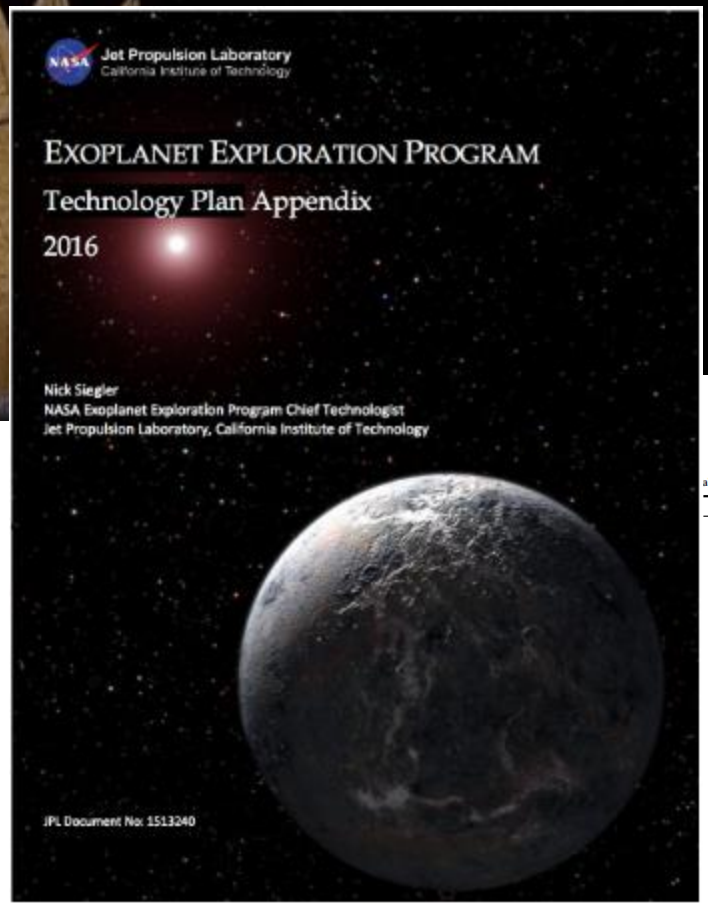
- NASA-chartered starshade technology activity in March
  - *Starshade Technology Project advances technology to TRL-5*
  - *Starshade Technology Community Meeting on December 1*

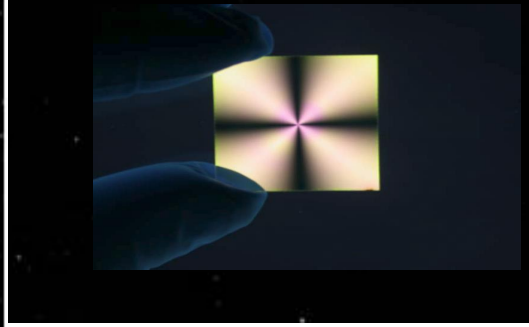
- Starshade Readiness Working Group commenced in January to identify the recommended path to flight for a starshade mission.
  - *Multi-institutional working group and participation*
  - *Report out to NASA HQ in November 2016*

- 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/

Opportunities to Participate

- Engage with the ExoPAG (Program Analysis Group) – the exoplanet community group (http://exep.jpl.nasa.gov/exopag/)
- Propose for a 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
- Propose for a Technology Development for Exoplanet Missions (TDEM)
  - TRL 3-5 (http://nspires.nasaprs.com/external/)
- Propose for an Astrophysics Research and Analysis (APRA) grant
  - TRL 1-2 (http://nspires.nasaprs.com/external/)
- Visit the Exoplanet Exploration Program (ExEP) website
  - http://exep.jpl.nasa.gov/
- Contact me directly: nsiegler@jpl.nasa.gov

Acknowledgements

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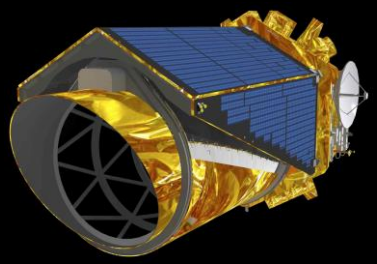
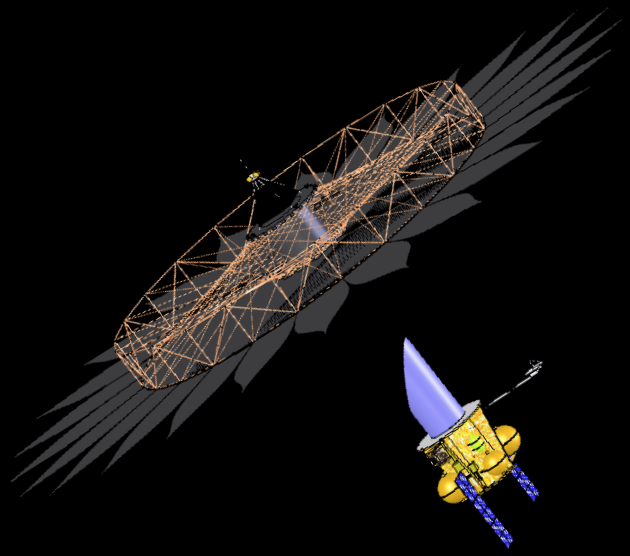
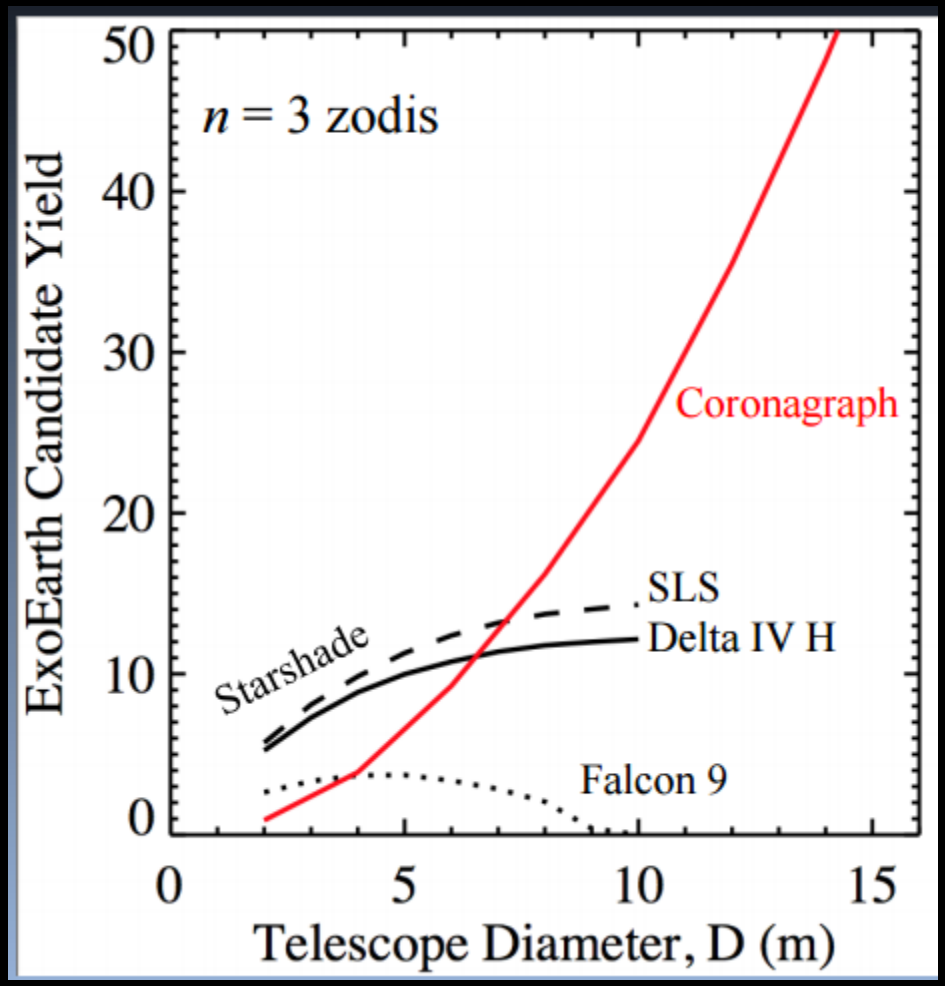
Government sponsorship acknowledged





Coronagraphs versus Starshades



Stark et al. 2016