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
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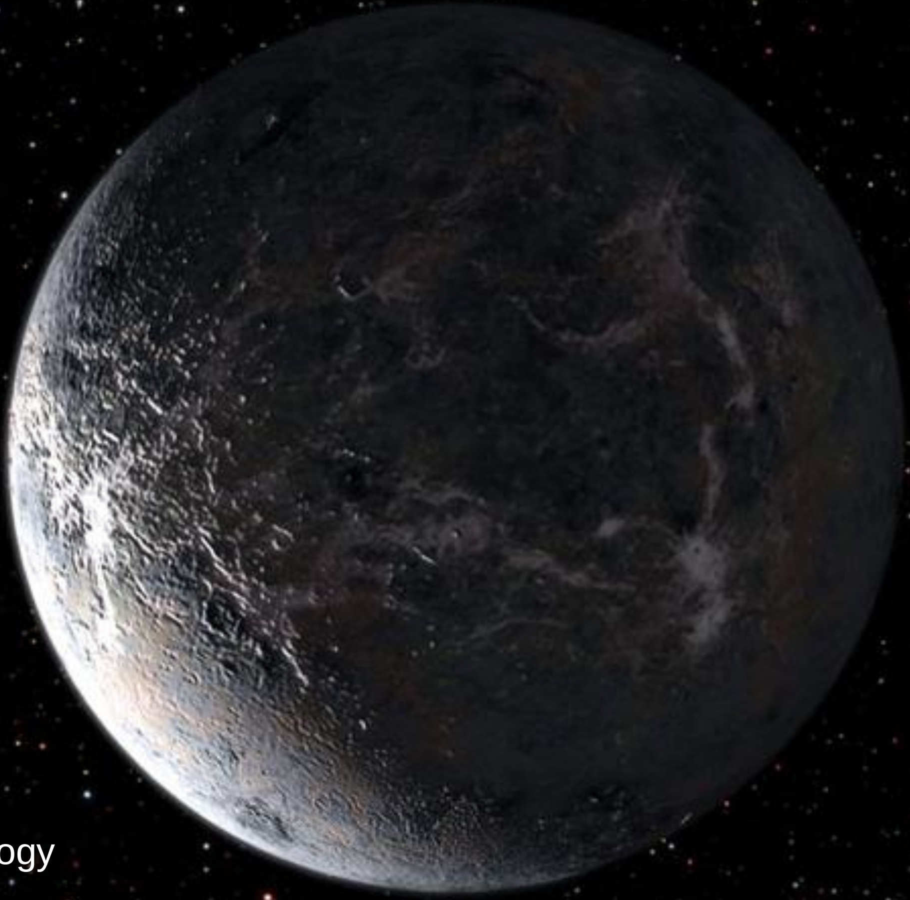
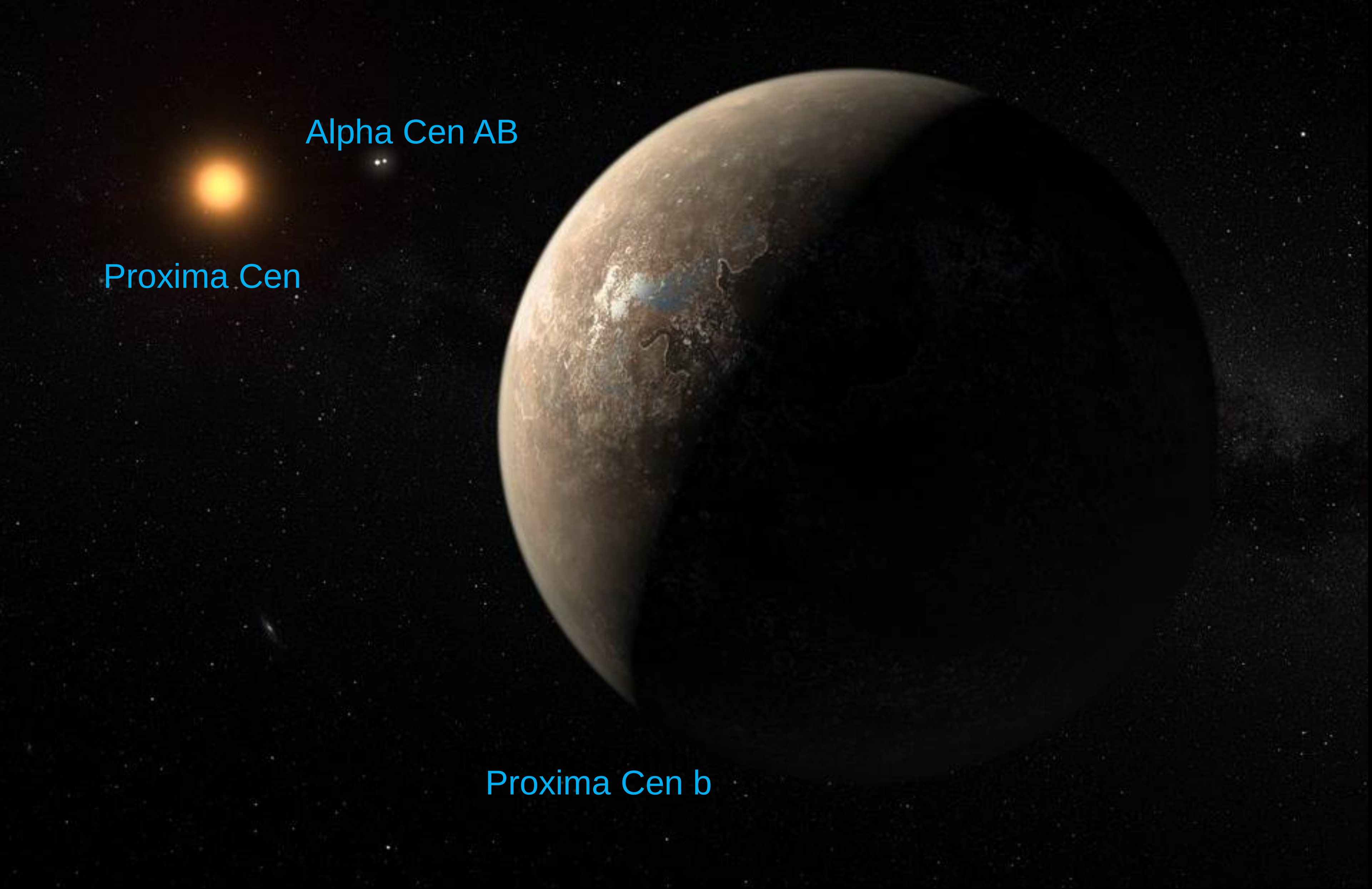
Jet Propulsion Laboratory, California Institute of Technology



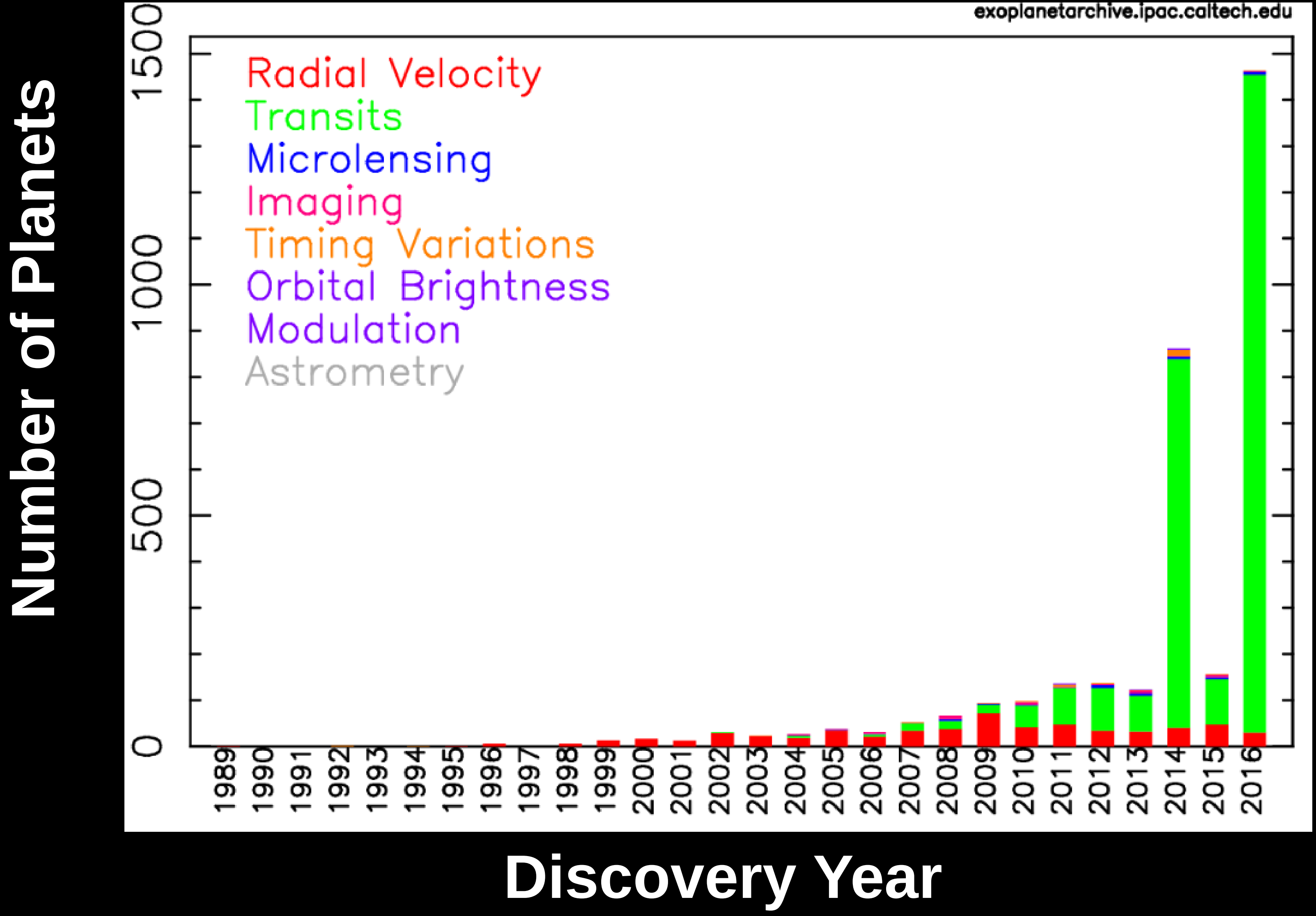
CL#16-5264

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

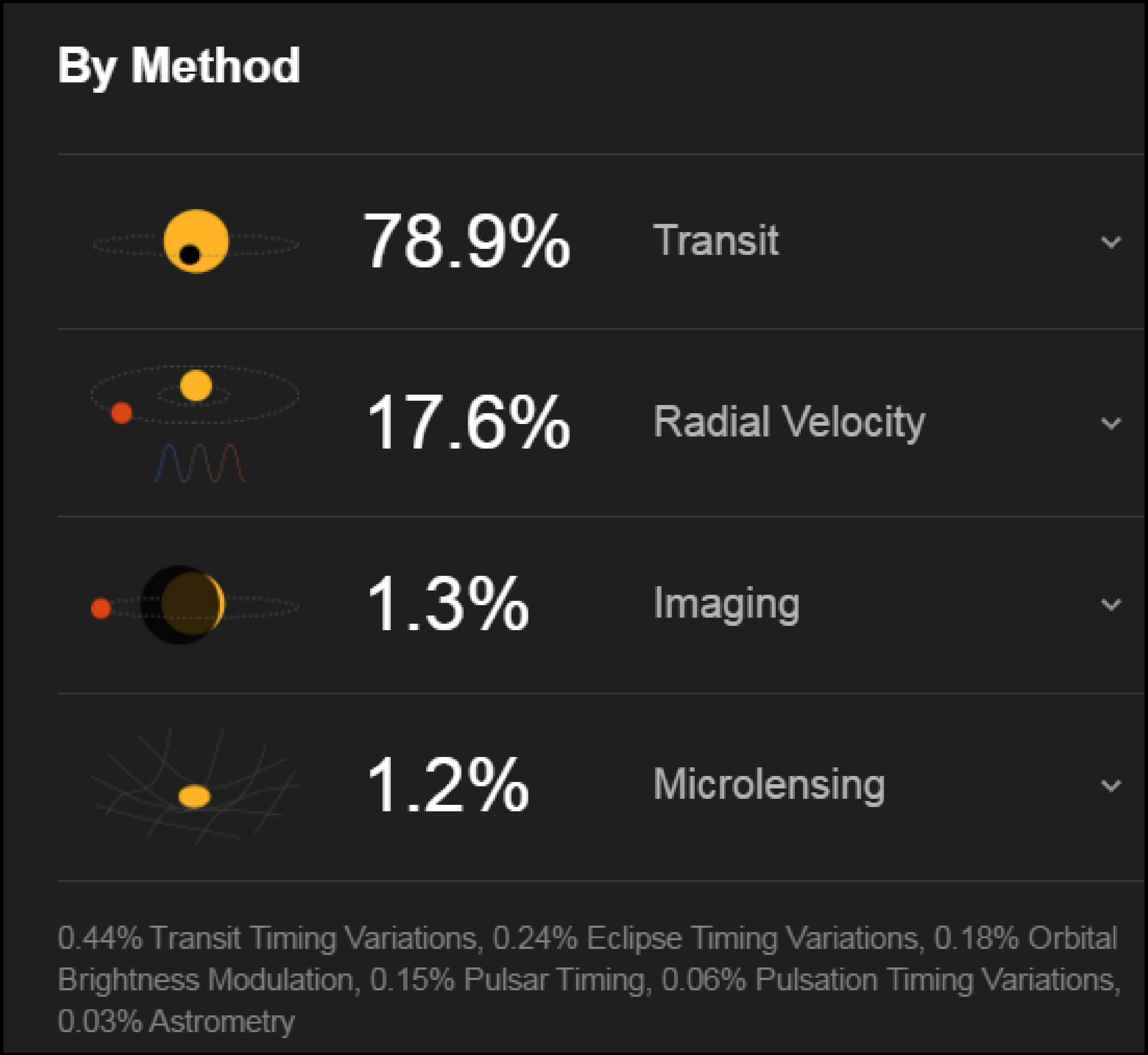


3,402 Confirmed Exoplanets

(as of 10/31/16)



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

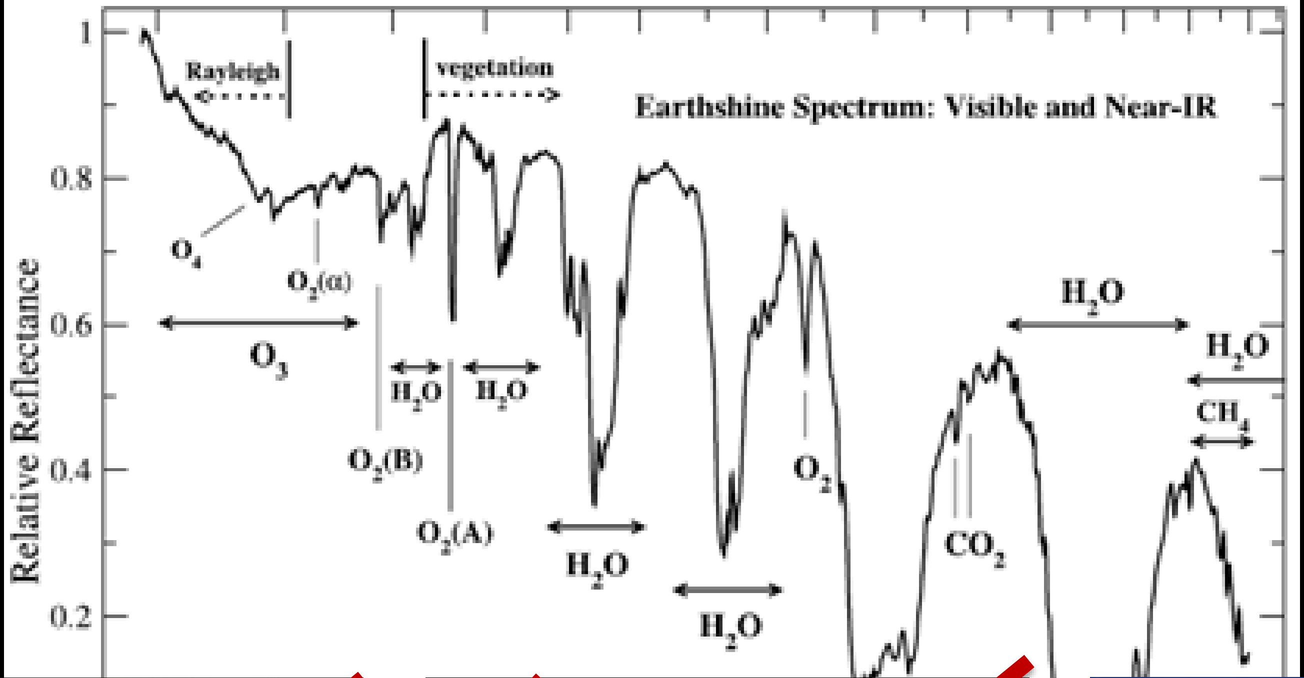


By Method

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



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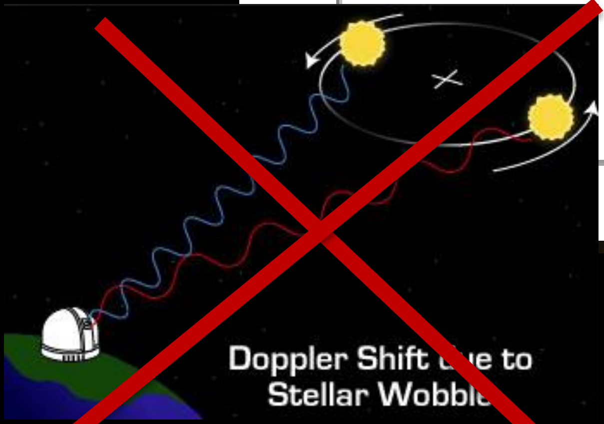
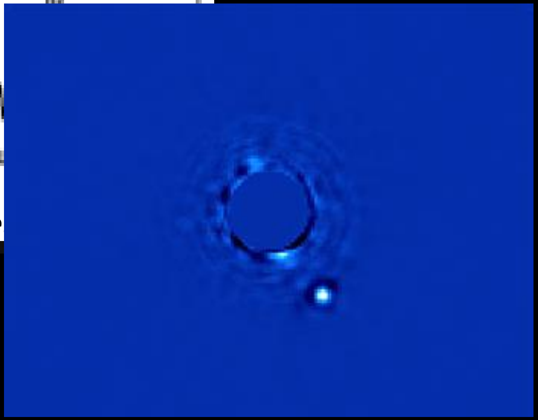
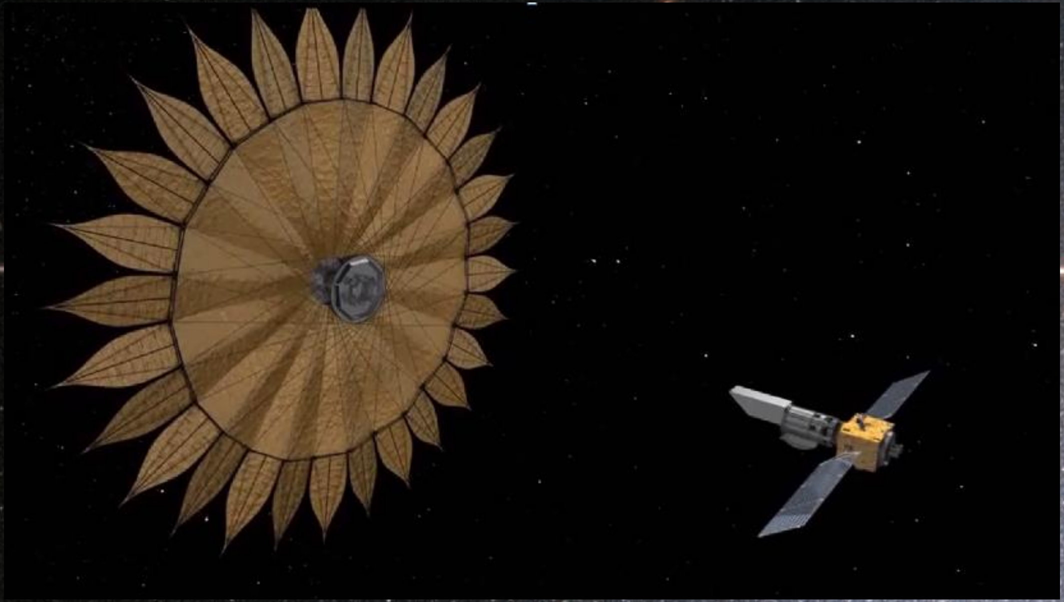


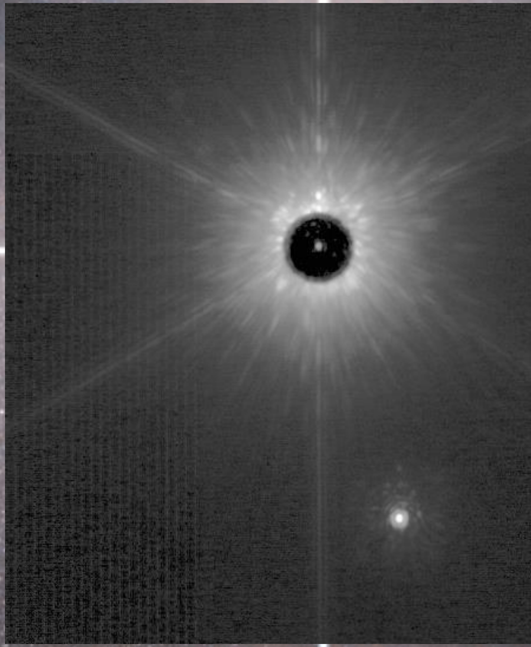


Macintosh et al. 2015

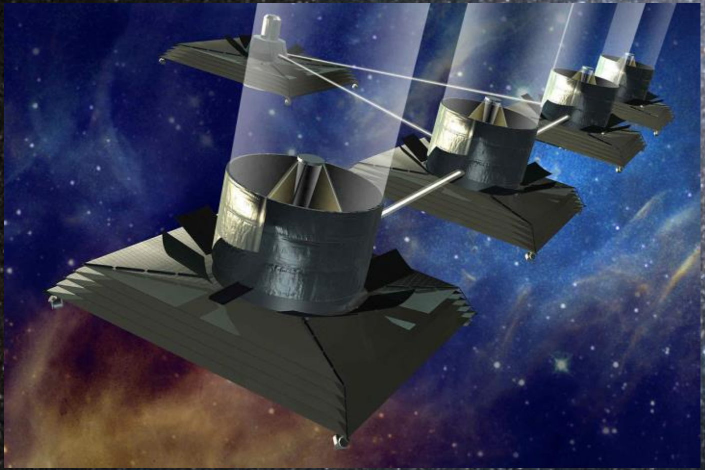
Starlight Suppression Technologies

External Occulters (Starshades)



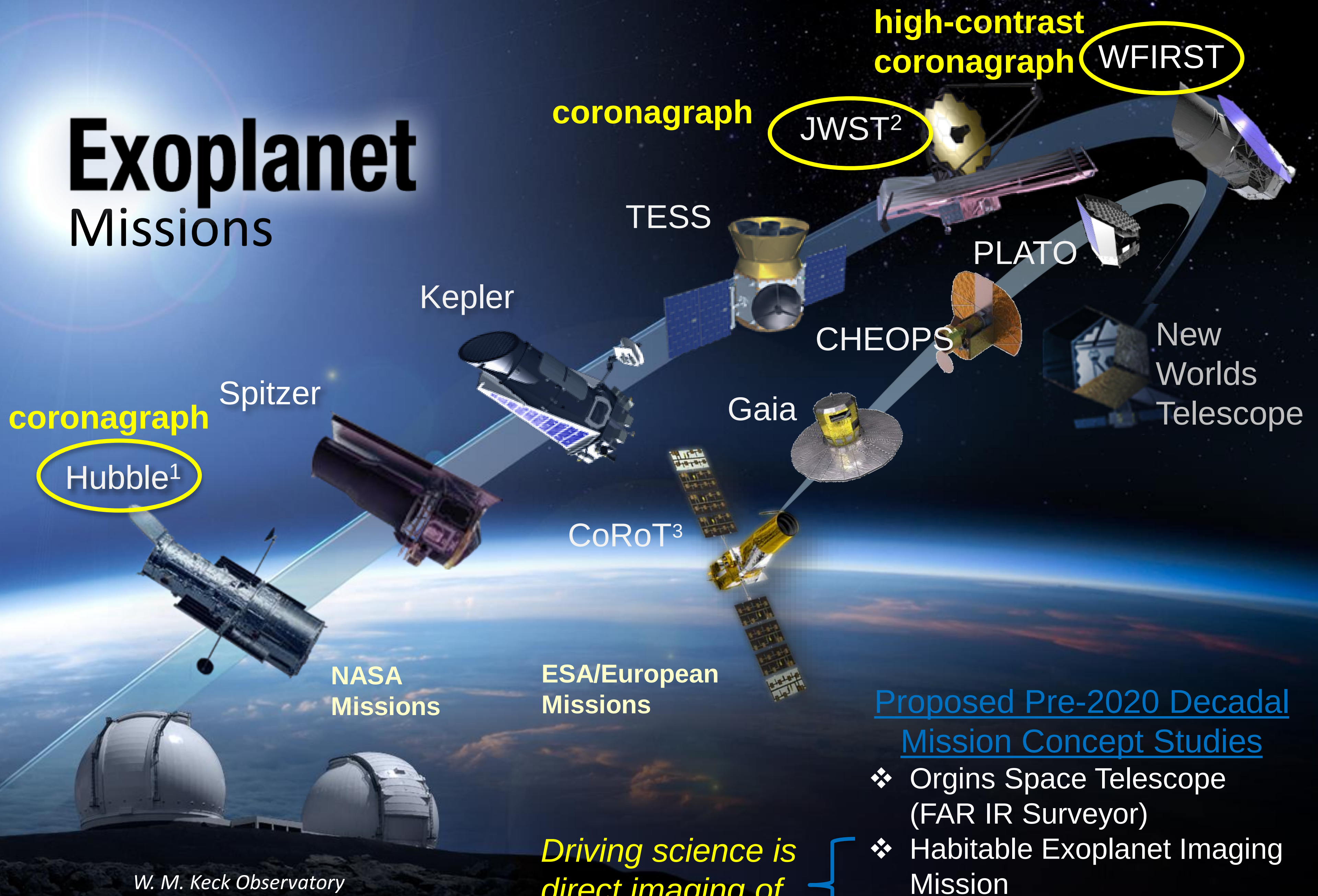


Nulling Interferometry



Internal Occulters (Coronagraphs)

Exoplanet Missions



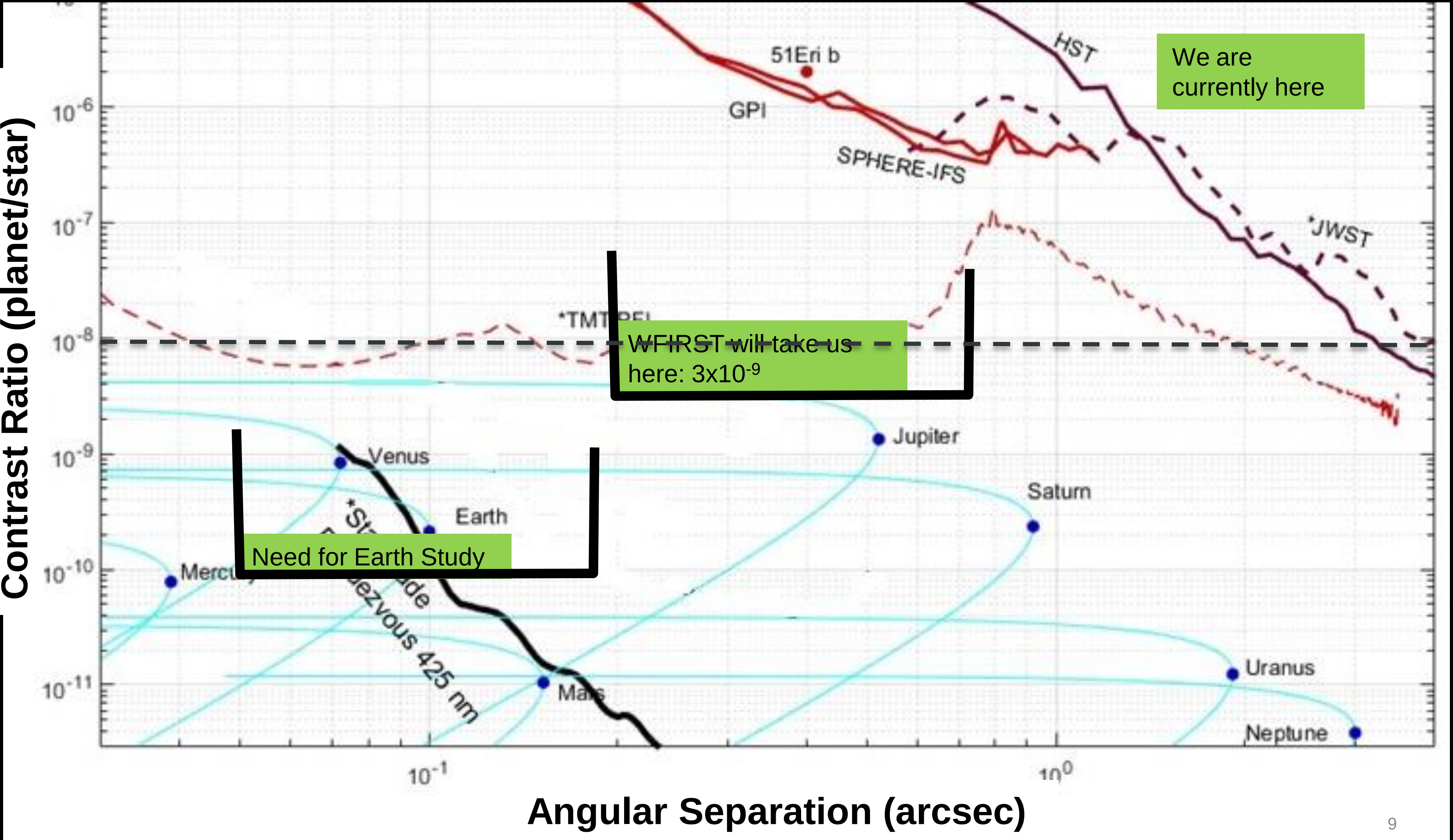
Driving science is direct imaging of exo-Earths

Proposed Pre-2020 Decadal Mission Concept Studies

- ❖ Orgins Space Telescope (FAR IR Surveyor)
- ❖ Habitable Exoplanet Imaging Mission
- ❖ Large 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



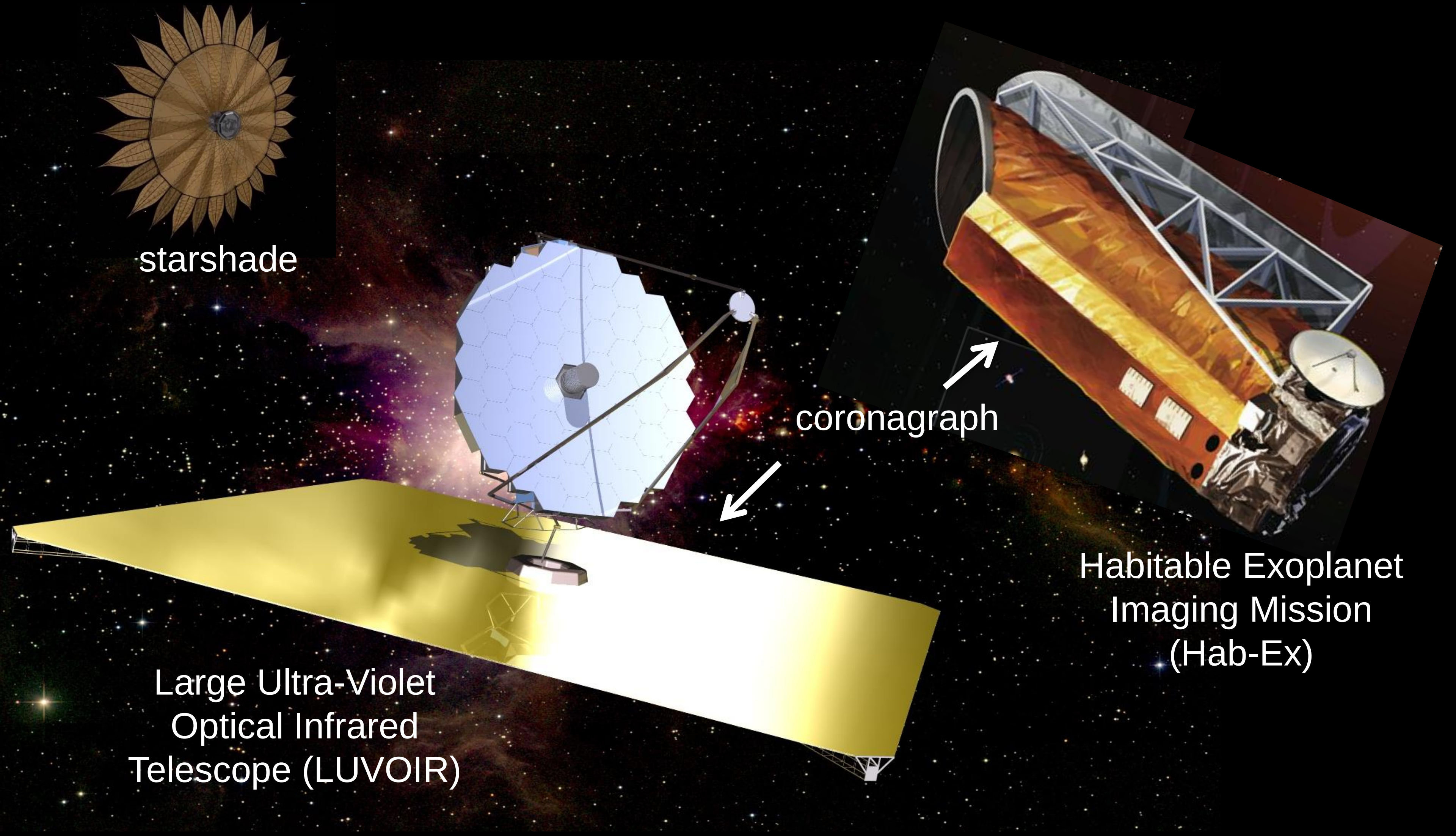
We are currently here

WFIRST will take us here: $3x10^{-9}$

Need for Earth Study

Possible New Worlds Exoplanet Telescopes

(mid-2030s)



starshade

coronagraph

Habitable Exoplanet
Imaging Mission
(Hab-Ex)

Large Ultra-Violet
Optical Infrared
Telescope (LUVOIR)

Two direct imaging mission concept studies:
HabEx and LUVOIR

- **Both have goal of studying Earth-like 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 exo-Earths, larger aperture*

- **Different priorities**
  - *HabEx to focus on exoplanets; "best effort" only on general astrophysics. Aperture < 8 m. Study led by NASA JPL.*
  - *LUVOIR gives equal priority to exoplanets and general astrophysics. Aperture 8-16 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

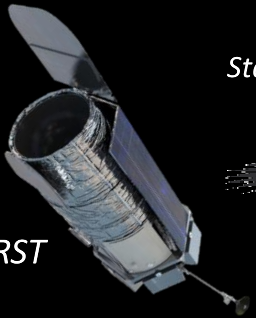
1. Discover planets around other stars
2. Characterize their properties
3. Identify candidates that could harbor life

http://exoplanets.nasa.gov/exep

The NASA Exoplanet Exploration Program

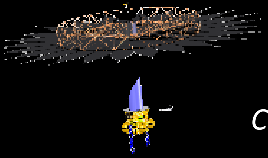
Space Missions and Mission Studies

Kepler, K2



WFIRST

Probe-Scale:



Starshade

Coronagraph

Public Engagement

Supporting Research & Technology

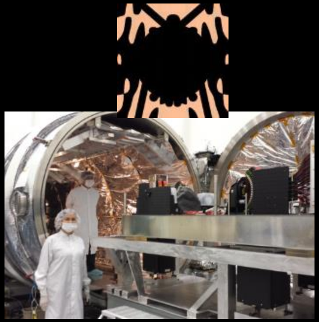
Key Sustaining Research

Large Binocular Telescope Interferometer

Keck Single Aperture Imaging and RV

Extreme Precision Doppler Spectrometer

Technology Development

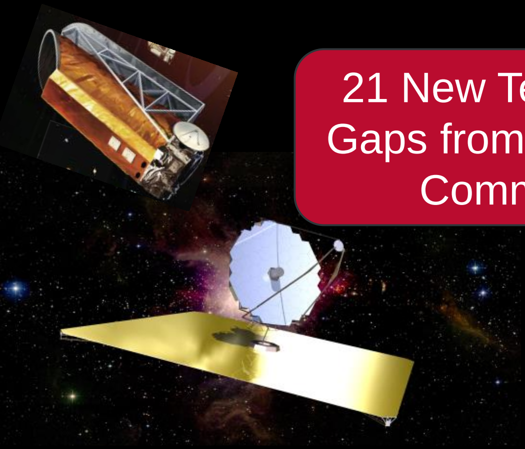


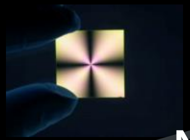
Coronagraphs

Starshades

NASA Exoplanet Science Institute

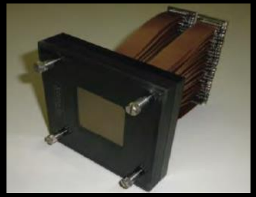
Technology Selection and Prioritization Process





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

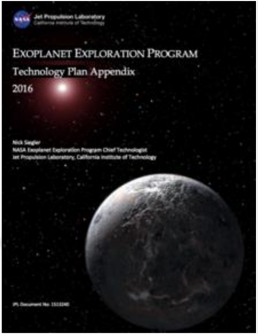
List of technologies that benefit exoplanet science, aka "Watch List"

Yes

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

ExEP Technology Gap List

Reviewed by Exo-TAC



Jet Propulsion Laboratory
California Institute of Technology

EXOPLANET EXPLORATION PROGRAM
Technology Plan Appendix
2016

Nick Siegler
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Jet Propulsion Laboratory, California Institute of Technology

2017 ExEP Technology Gap 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

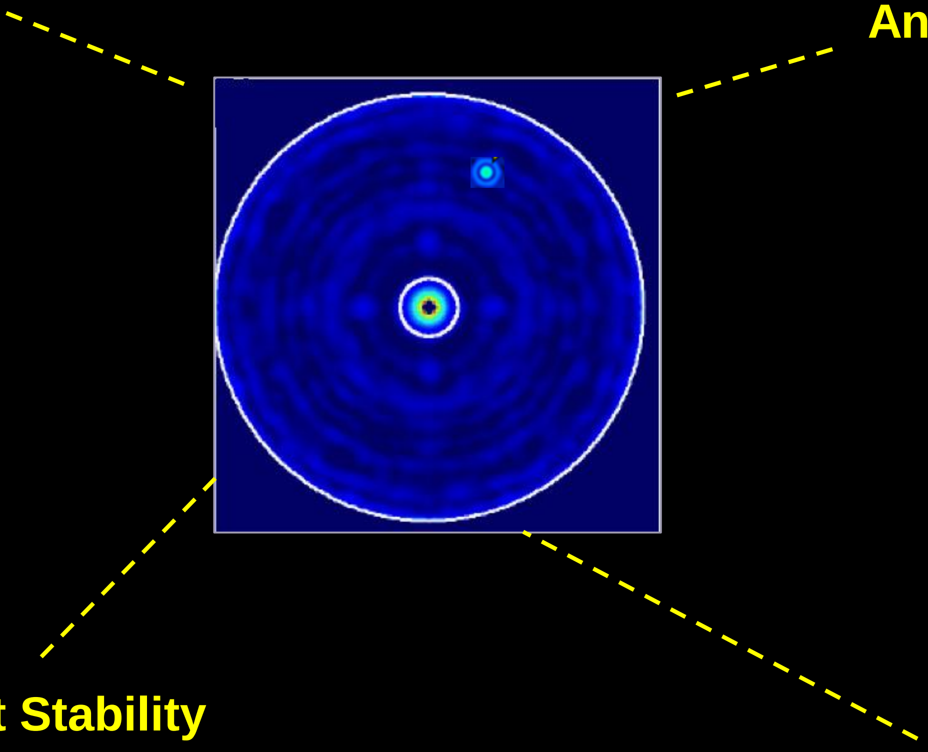
Enabling Gap
Enhancing Gap
Watch List

Watch List

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

Will be posted to website later this month

Coronagraph/Telescope Technology Needs



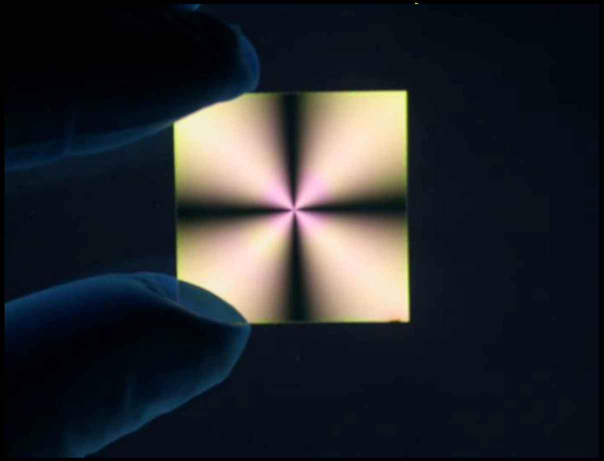
Starlight Suppression (Contrast)

Angular Resolution

Contrast Stability

Detection Sensitivity

Coronagraphy Optics and Architectures



Future Needs:

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

SOA:

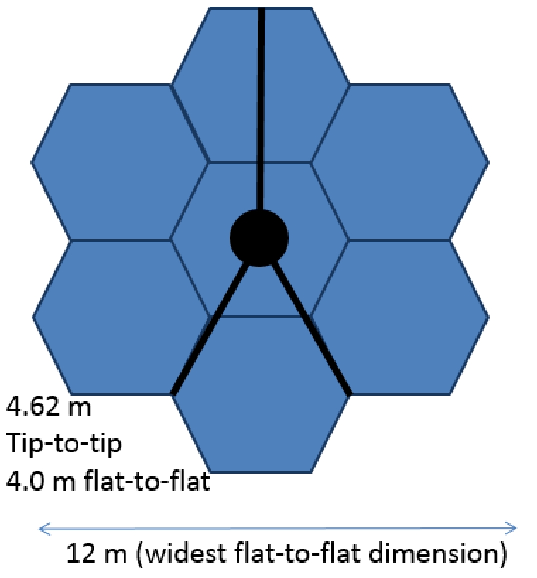
- WFIRST: few x 10^{-9} (obscured; raw contrast)
- Lab: 6x10^{-10} (unobscured; Hybrid Lyot)
- IWA ~ 3 λ/D
- Bandwidth 10%

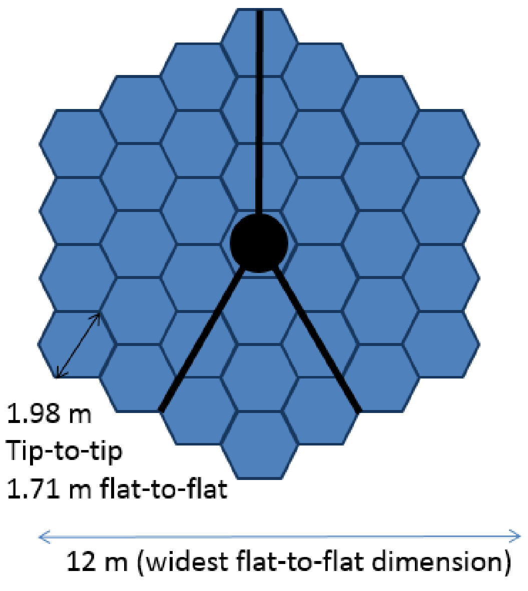
Current Activities:

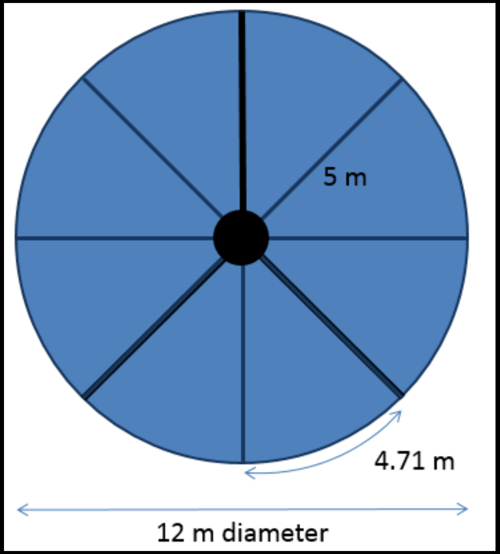
- WFIRST coronagraphs planned to achieve TRL 5 by end FY16; NASA review on 11/8/16
- Additional demonstrations ongoing at STScI (APLC), Vortex (Caltech), and GSFC (VNC)
- ExEP design study to identify coronagraph architectures that can reach < 10^{-9} on large segmented apertures (FY16-17)
- HCIT prepping for a 1e-10 contrast testbed
- Polarization assessments of HabEx/LUVOIR (FY17)

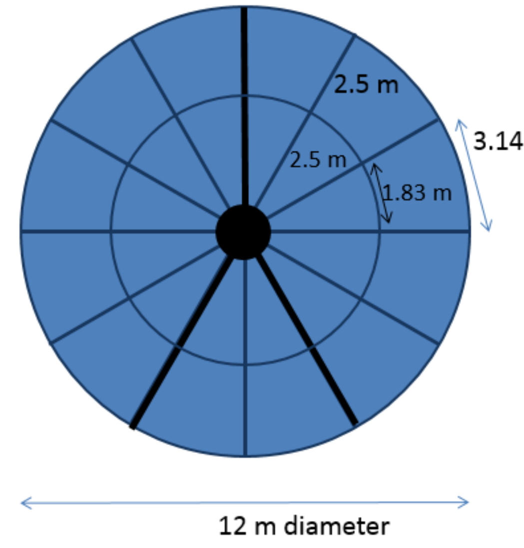
Segmented Coronagraph Design and Analysis

(funded by the ExEP; led by S. Shaklan/JPL)





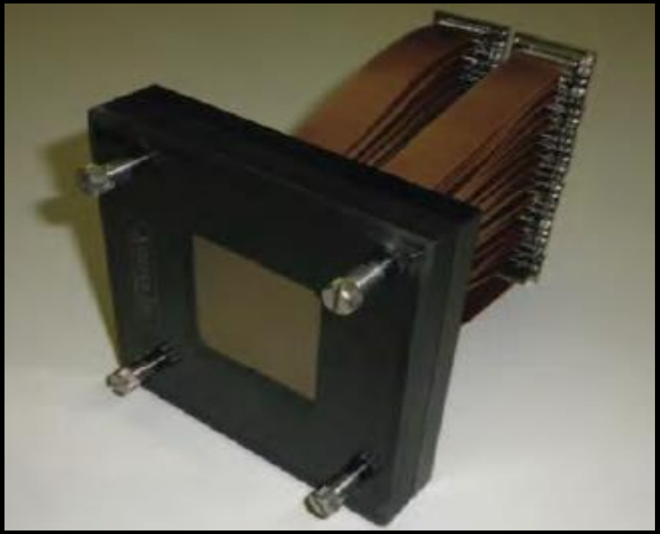




Coronagraph Designs

1. Apodized Pupil Lyot Coronagraph (STScI)
2. Vortex Coronagraph (Caltech)
3. Phase Induced Amplitude Apodization Complex Mask Coronagraph (U of Arizona)
4. Hybrid Lyot (Caltech)
5. Visible Nulling Coronagraph (GSFC)

Deformable Mirrors



Deformable mirrors
(Xinetics 48x48)

Need:

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

SOA:

- 64x64 electrostrictive actuators by Xinetics (WFIRST baselined 48x48)
  - pitch size = 1 mm
  - stroke = 500 um
- 6x10^{-10} contrast achieved with 32x32

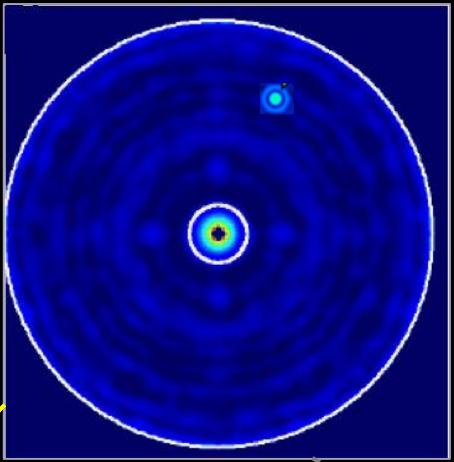
Current Activities:

- 48x48 Xinetics DMs are being flight qualified, connector study, flight electronics design (WFIRST; FY17-18)
- MEMS DMs (BMC and Iris AO) env’t testing (FY18)
- Decadal mission concepts in FY17-18

Coronagraph/Telescope Technology Needs

Starlight Suppression

Angular Resolution

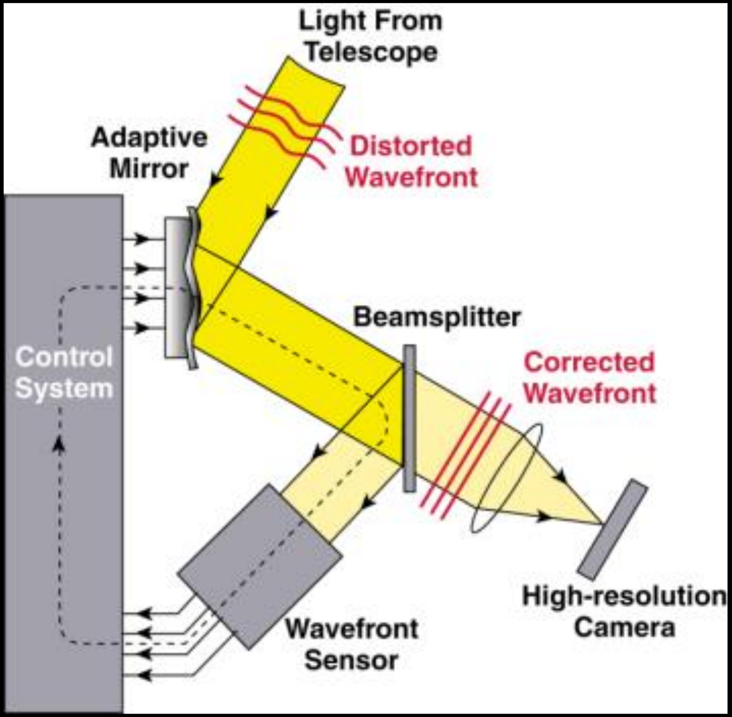


Contrast Stability

Detection Sensitivity

- *10 pm rms uncorrected WFE over ~ 10 min*
  - ❖ *few pm sensitivity*
  - ❖ *> 2 OOM greater than WFIRST*
- 10^{-11} contrast stability
- Systems-level challenge

Wavefront Sensing and Control



Needs:

- Few pm rms WFE sensitivity
- Several (Z ≥ 8) WFE terms sensed and corrected

SOA:

- Zernike wavefront sensor baselined on WFIRST
  - 14 mas simulated jitter input (tip/tilt only) corrected to < 0.5 mas rms residual
  - LoS tilt sensitivity to 0.2 mas and low order modes to the level of 12 pm rms

Current Activities:

- WFIRST LOWFS sensing and control of first few modes demonstrated with a telescope and env’t simulator with a coronagraph (FY16); TAC review on Nov 8

Additional Wavefront Stability Technologies

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 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

- Decadal mission concepts in FY17-18 to conduct key systems trade studies
  - segmented vs monolith primaries
  - Glass vs SiC segments
  - active control vs passive vs hybrid for thermal, vibration

Note: can be relaxed to SOA for starshade

Detection Sensitivity (Visible)

Needs (Visible):

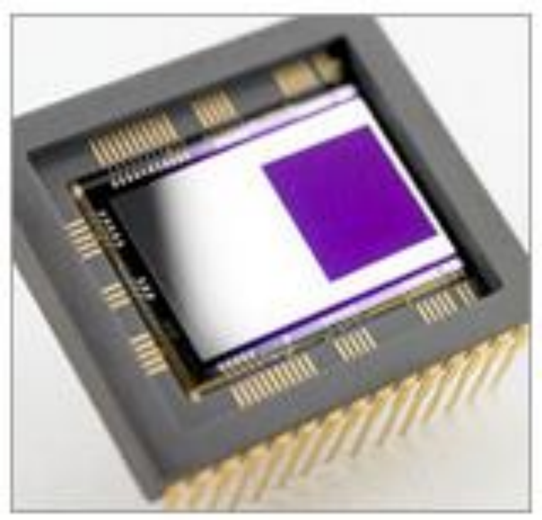
- 0.4 – 1 um ultra-low noise detectors
- Read noise: < 0.1 e'/pix
- Dark current: < 0.0001 e'/pix/s
- Format: > 2kx2k
- Radiation hard

Relative to SOA:

- 1kx1k EMCCD baselined for WFIRST
  - Read noise: ok for WFIRST, need better than factor of 2 for HabEx/LUVOIR
  - Dark current: ok for WFIRST, need better than factor of 5 for HabEx/LUVOIR
- Recently environmentally tested (WFIRST)

Current Activities:

- Flight R/O electronics design (WFIRST; FY17-18)
- e2V 4kx4k EMCCD being tested at University of Montreal



e2V EMCCD 1kx1k

Detection Sensitivity (NIR)

Needs (IR):

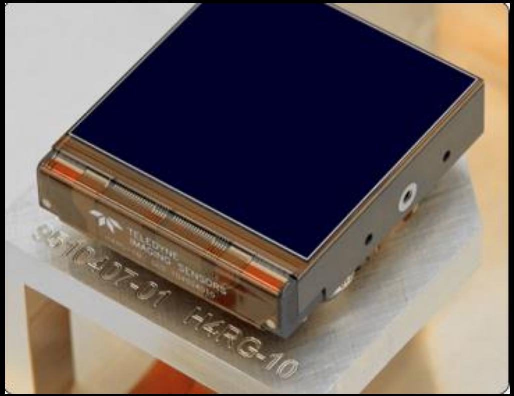
- 1-2.5 um
- Read noise: < 1 e'/pix
- Dark current: < 0.001 e'/pix/s
- Format: arrays of ≥ 2kx2k
- Radiation hard
- Zero-vibration cooling

Relative to SOA:

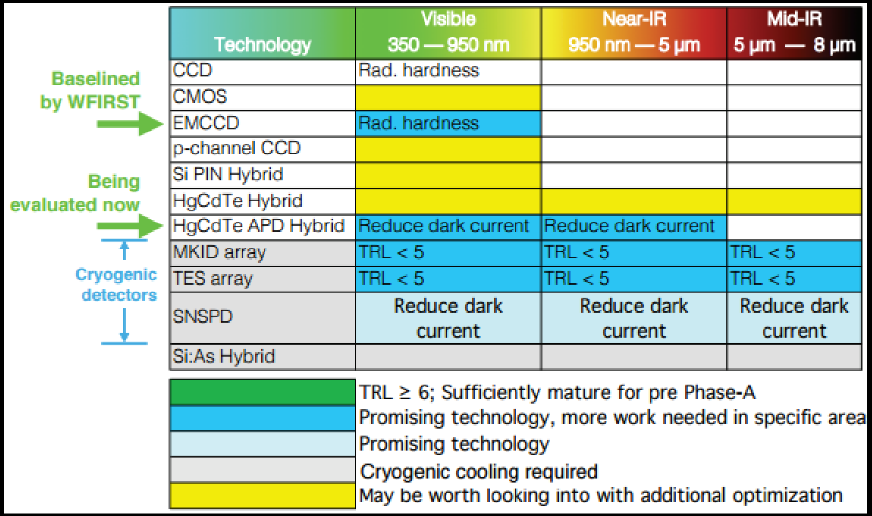
- HgCdTe APD Hybrid
- Read noise: << 1 e'/pix
- Dark current: 10-20 e'/pix/s
- Format: arrays of < 1kx1k
- MKIDS and TES are low-TRL cryo solutions

Current Activities:

- MKIDS high-altitude balloon demo
- HgCdTe (WFIRST) and HgCdTe APD noise reduction efforts?
- Decadal mission concepts to determine long λ cutoff (FY17)



Teledyne H4RG-10 IR detector

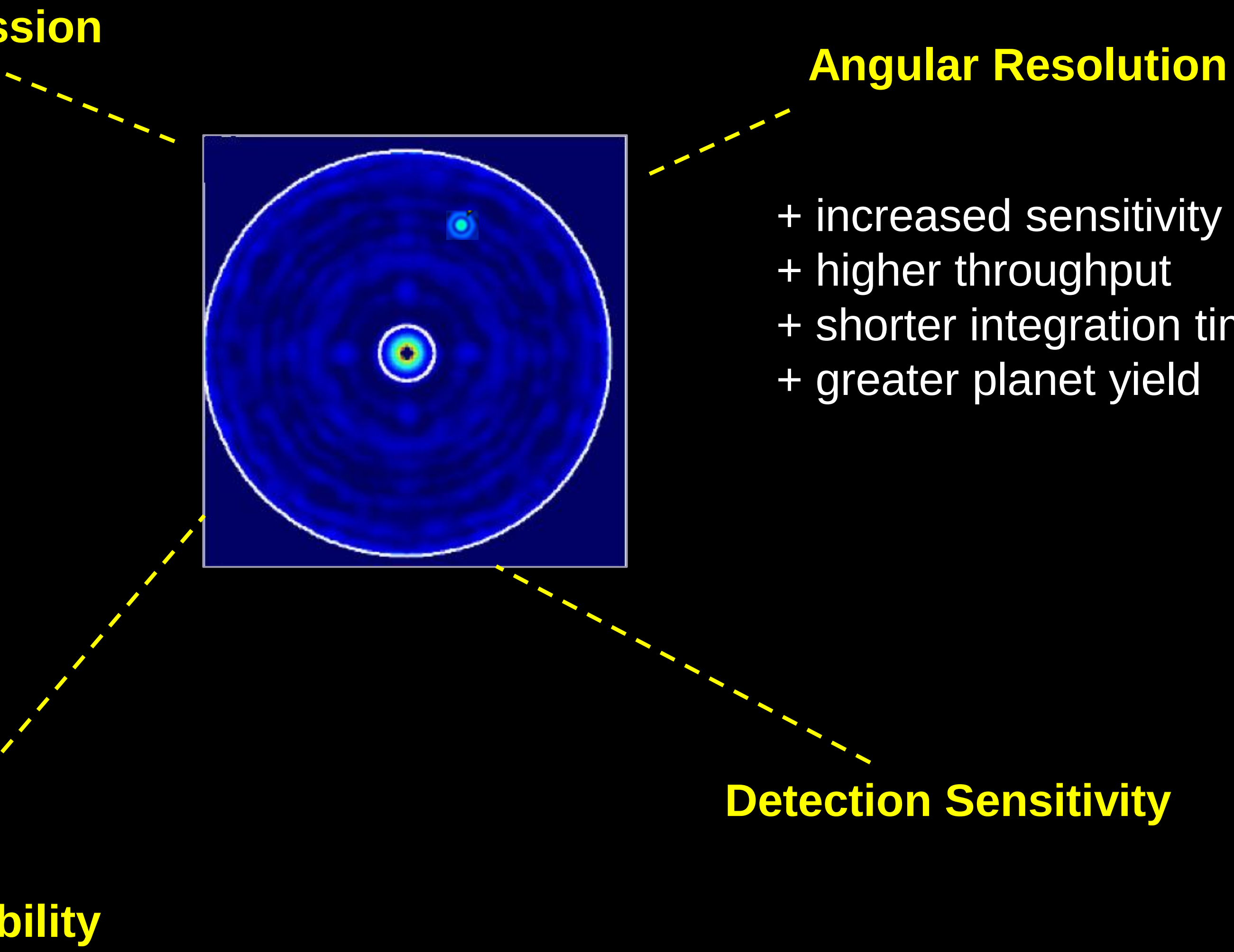


Technology	Visible 350 — 950 nm	Near-IR 950 nm — 5 µm	Mid-IR 5 µm — 8 µm
CCD	Rad. hardness		
CMOS	🟨		
EMCCD	Rad. hardness		
p-channel CCD	🟨		
Si PIN Hybrid	🟨		
HgCdTe Hybrid	🟨	🟨	🟨
HgCdTe APD Hybrid	Reduce dark current	Reduce dark current	
MKID array	TRL < 5	TRL < 5	TRL < 5
TES array	TRL < 5	TRL < 5	TRL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

🟩	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



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

Large Primary Mirrors

Needs:

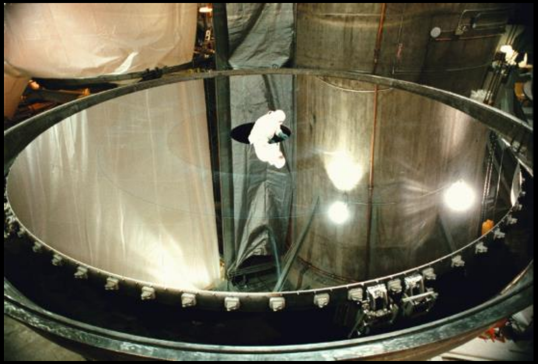
- ≥ 4 m monoliths and 8-16 m segmented mirrors
- SFE < 10 nm RMS
- Active thermal and figure control for segments

SOA:

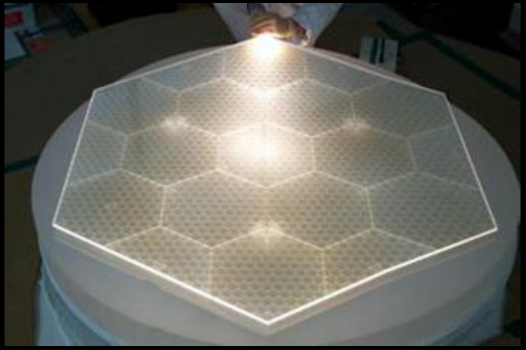
- Monolith: Hershel’s 3.5 m (SiC); HST’s 2.4m (ULE, ~ 10 rms SFE)
- Segmented: JWST’s 6.5 m (1.3 m, Be; SFE: < 30 nm rms)

Current Activities:

- Non-NASA investments
- Advance Mirror Technology Development (Stahl/MSFC)
  - Validate optical/thermal/mechanical integrated models on a 1.5 m ULE and 1.2 m Zerodur mirrors (FY17)
- Decadal mission concepts will study monolith vs segments, materials, active figure control



Large monolith
(Gemini 8.1m ULE)



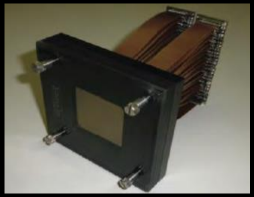
Segmented
(AMSD light-weighted ULE segment; Harris)

Segmented
AHM SiC-based segment, Xinetics

Coronagraph/Telescope Technology Needs

Starlight Suppression (Contrast)

Coronagraph architectures



Deformable mirrors

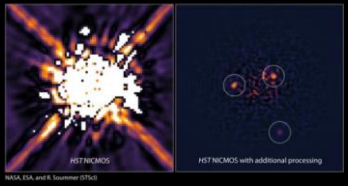
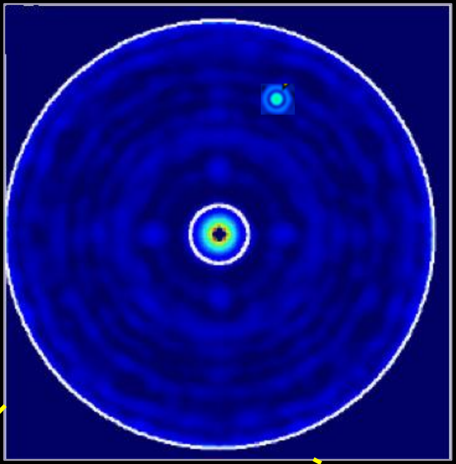
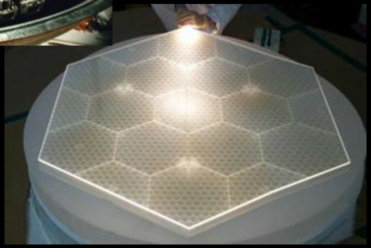


Image post-processing



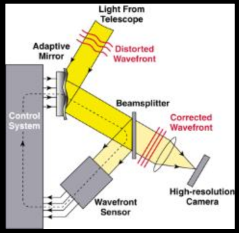
Angular Resolution

Large monolith



Segmented

Contrast Stability

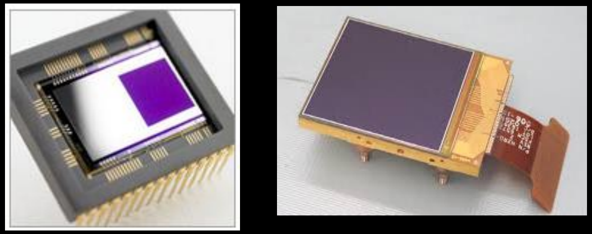


Wavefront sensing and control

Segment phasing and rigid body sensing and control

Telescope vibration sensing and control

Detection Sensitivity



Ultra-low noise visible and infrared detectors

Recent Starshade Technology News

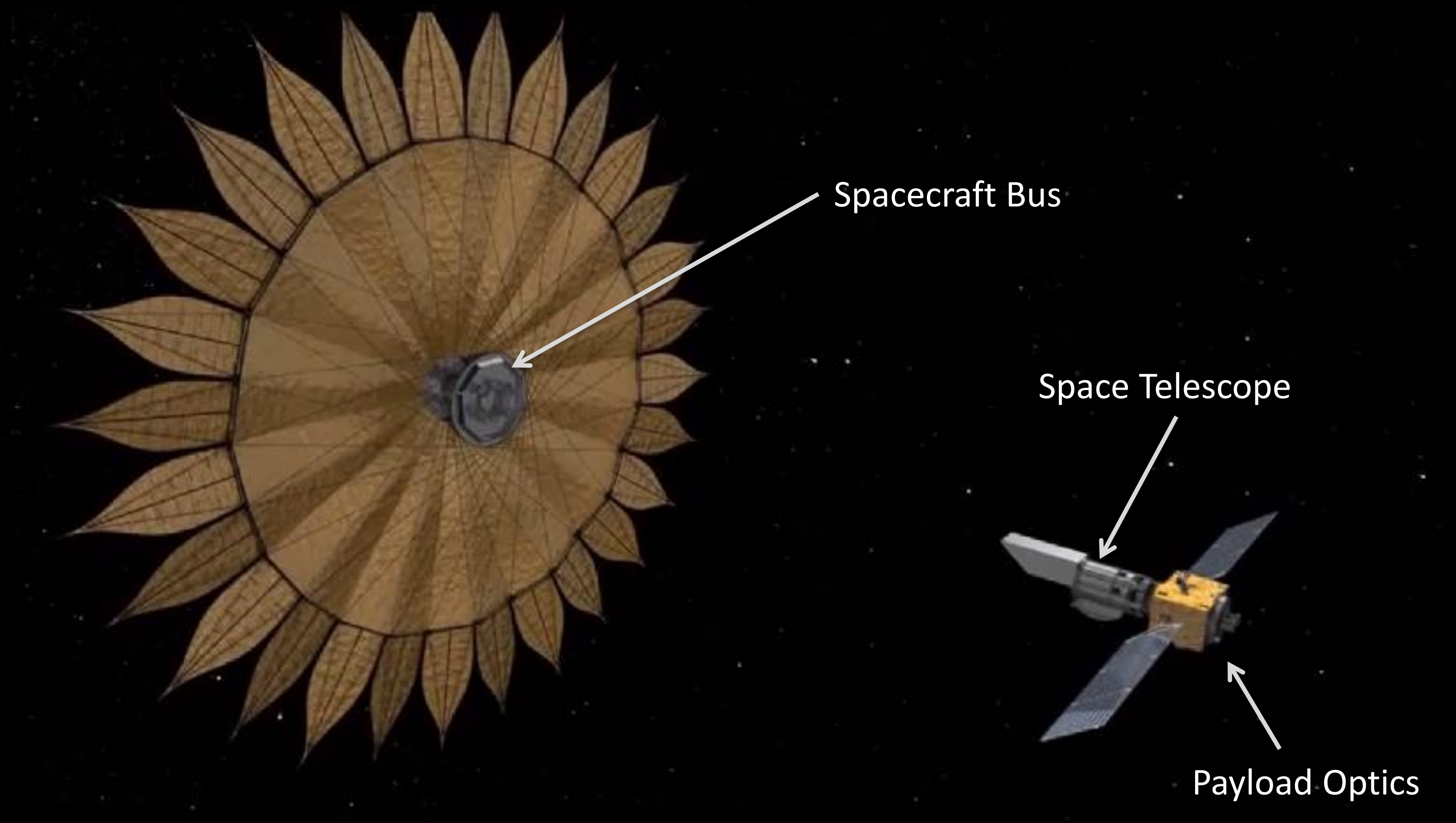
- NASA-chartered starshade technology activity in March
  - *Starshade Technology Project advances technology to TRL-5*
  - *Starshade Technology Community Meeting on December 1*

- 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 on November 9, 2016*

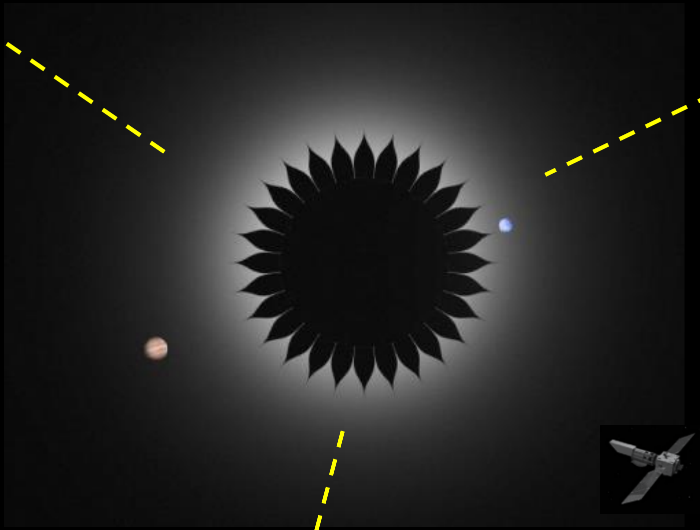
- WFIRST is assessing the impact of accommodating a potential future starshade mission
  - *Final decision will be made no later than summer of 2017.*

Starshade Technology Needs

What's not hard…



Starshade Technology Needs



Starlight Suppression

Formation
Sensing and Control

Deployment Accuracy
and Shape Stability

Starlight Suppression

- **Diffraction from starlight**
- **Reflection from Sun light**


NGAS


NGAS


Princeton

Needs:
- Contrast ≤ 10^{-10} demonstrated near the petal edges at a flight Fresnel number and over different size starshades, wavelengths, and intentional imperfections
- Validated optical models
- Optical edge material identified and integrated to a full-scale petal

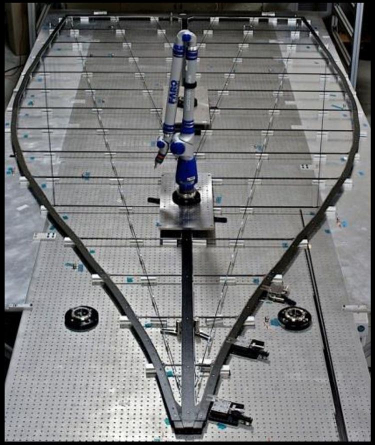
Current Activities:
- Optical demonstrations underway at Princeton in a 78 m testbed
- Optical performance and modeling studies (Princeton, JPL, NGAS, Colorado) – FY17
- Optical edge manufactured and testing (STP; FY17-18); amorphous metal
- Trade study (STP; FY178)

Deployment Accuracy and Shape Stability

Half-scale inner disk testbed (JPL)

1/10-scale opaque membrane testbed (JPL)

Petal unfurling concept
(Roccor)



6m petal (Princeton/JPL)

Needs:

- Large-scale fully-integrated petal with flight-like materials that meet optical shape tolerances (~ 70 um rms) and edge scatter performance

- Large-scale fully-integrated inner disk prototype with flight-like components and opaque membrane that meets deployment tolerances and petal position rqmts (~ 450 um rms)

- Full-scale petal latching and unfolding mechanism verifying controlled petal deployment with no edge contact during and after launch

Current Activities:

- Deployment trade study (STP in CY17)
- SBIR Roccor developing petal unfurling mechanism

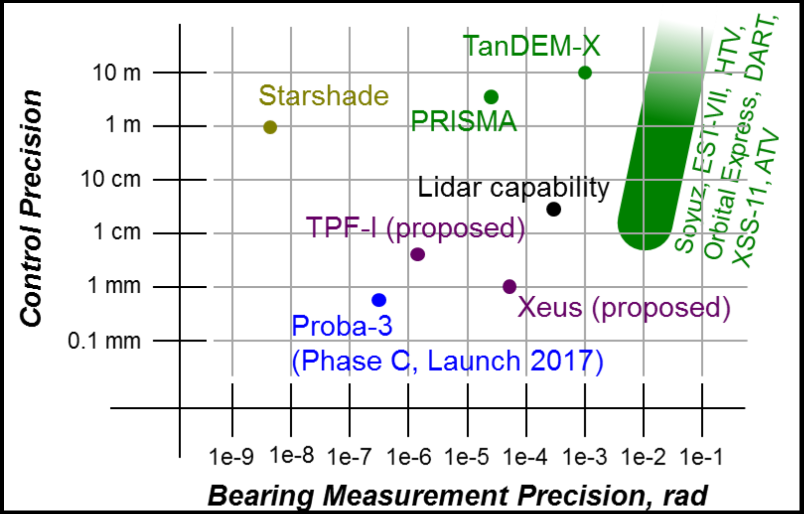
Formation Sensing and Control

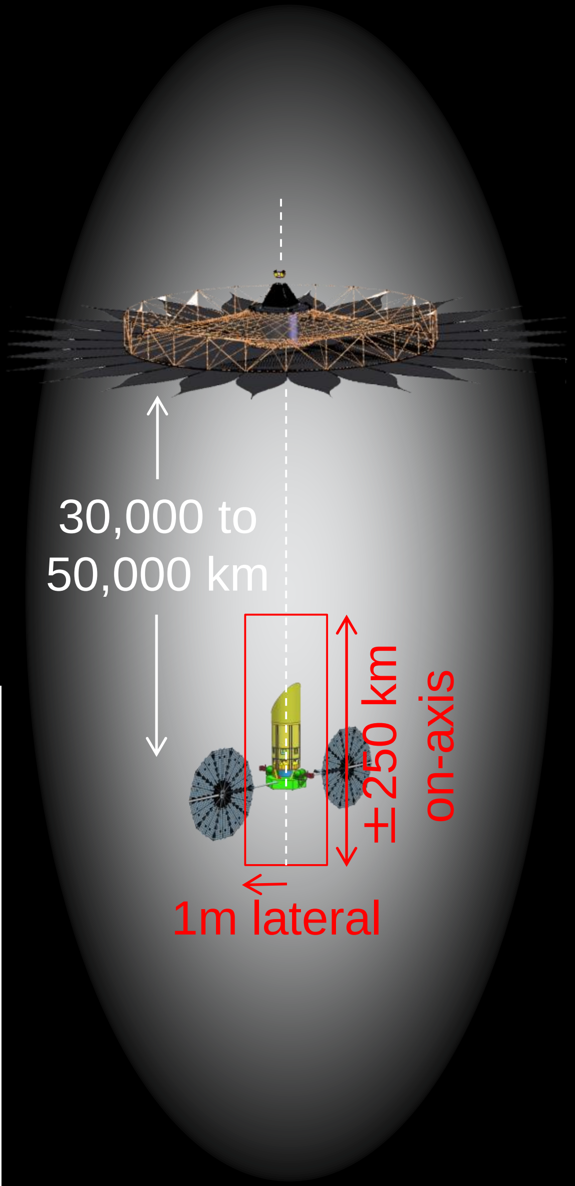
Needs:

- 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; FY17-18)
- Trade study (STP; FY17)

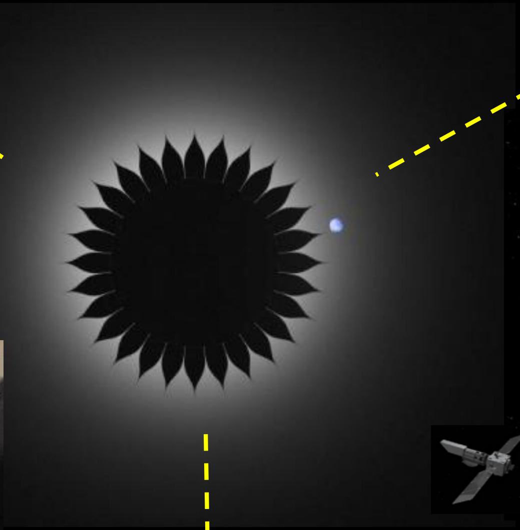




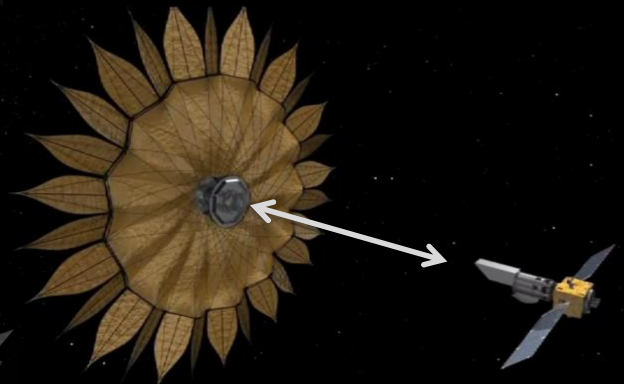
Starshade Technology Needs

Starlight Suppression

Suppressing scatted light off petal edges from off-axis Sunlight



Formation Sensing and Control

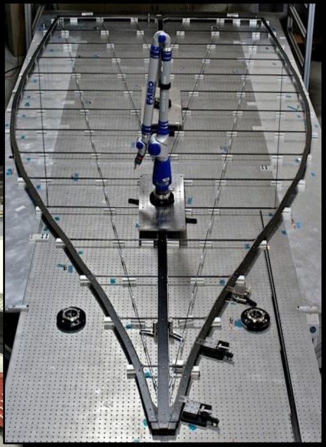


Maintaining lateral offset requirement between the spacecrafts

Suppressing diffracted light from on-axis starlight

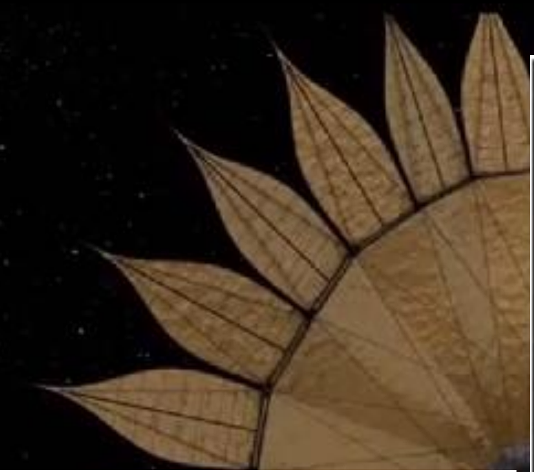
Deployment Accuracy and Shape Stability

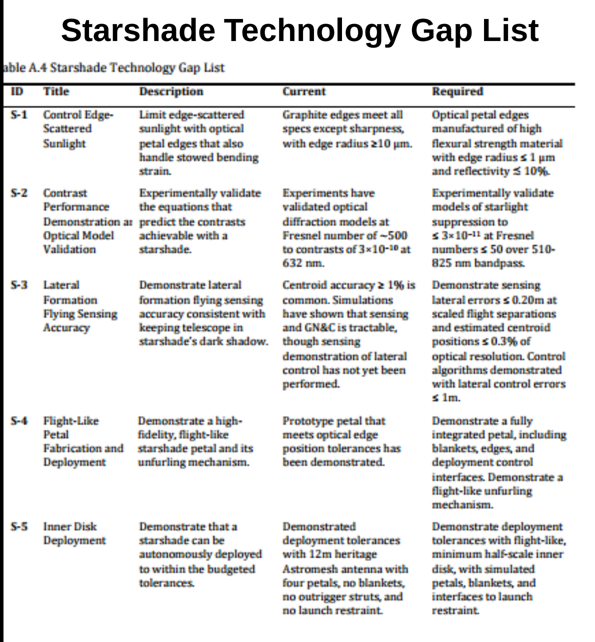
Positioning the petals to high precision, blocking on-axis starlight, maintaining overall shape on a highly stable structure



Fabricating the petal to high precision

ExEP Technology Gap Lists

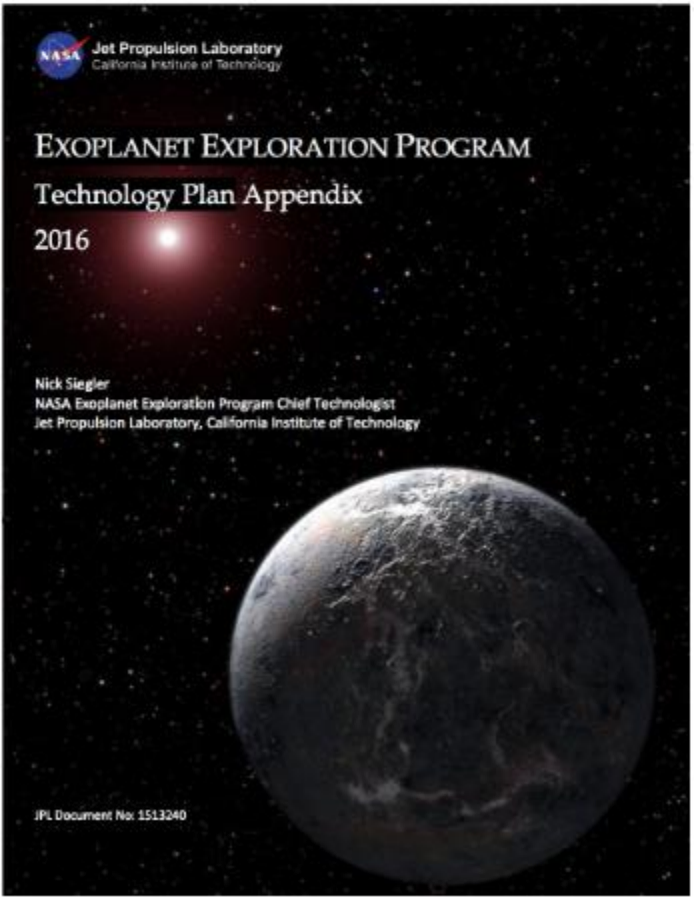




Starshade Technology Gap List

able 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 $\leq 3\times10^{-11}$ 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.



Jet Propulsion Laboratory
California Institute of Technology

EXOPLANET EXPLORATION PROGRAM
Technology Plan Appendix
2016

Nick Siegler
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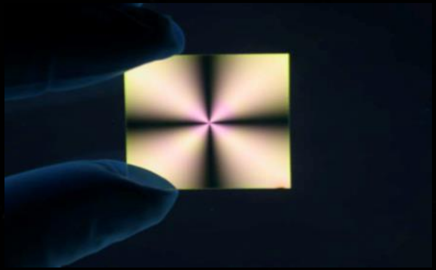
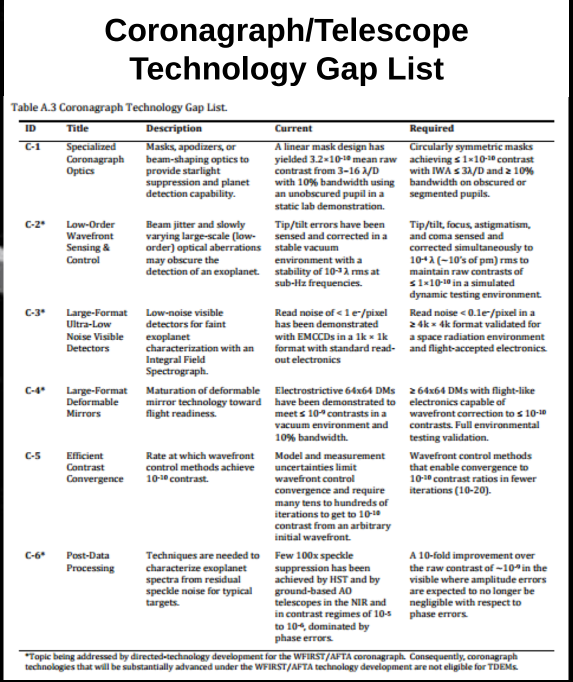
Jet Propulsion Laboratory, California Institute of Technology

JPL Document No: 1513240





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 $\leq 1\times10^{-10}$ 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'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 $\leq 10^{-9}$ contrasts in a vacuum environment and 10% bandwidth.	≥ 64x64 DMs with flight-like electronics capable of wavefront correction to $\leq 10^{-10}$ 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.

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 Strategic Astrophysics Technology (SAT) - 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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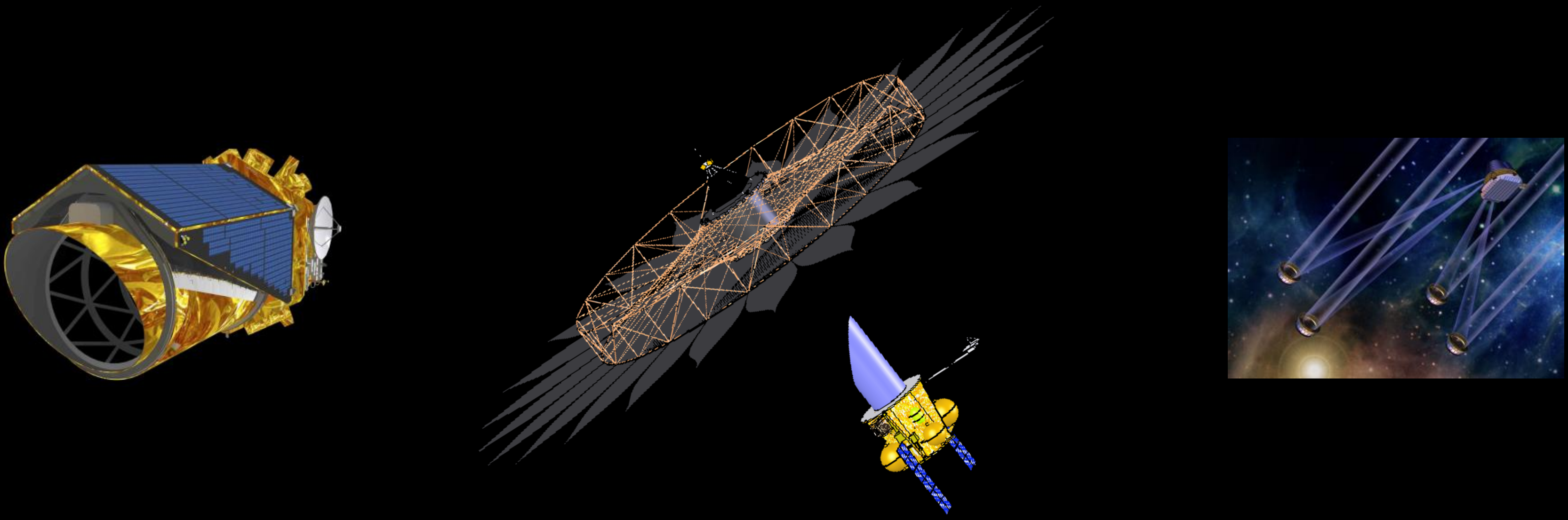
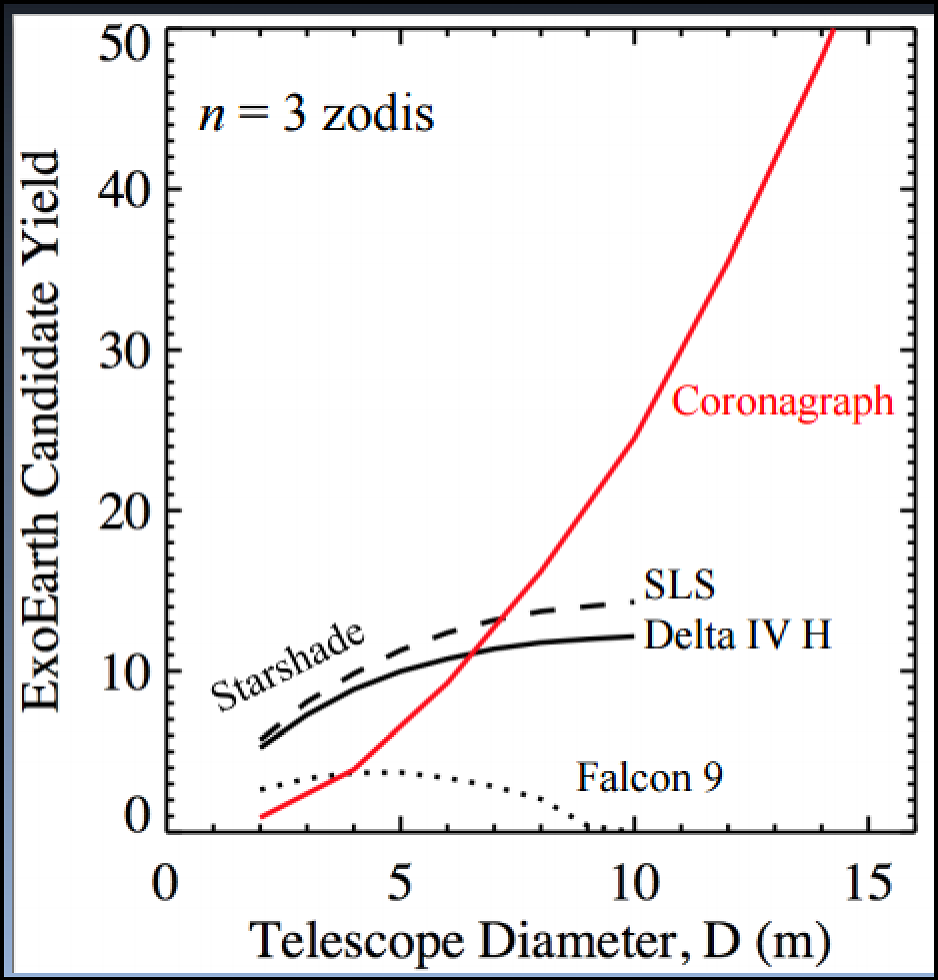


Additional Slides

Coronagraphs versus Starshades



Stark et al. 2016

Key Starshade Requirements

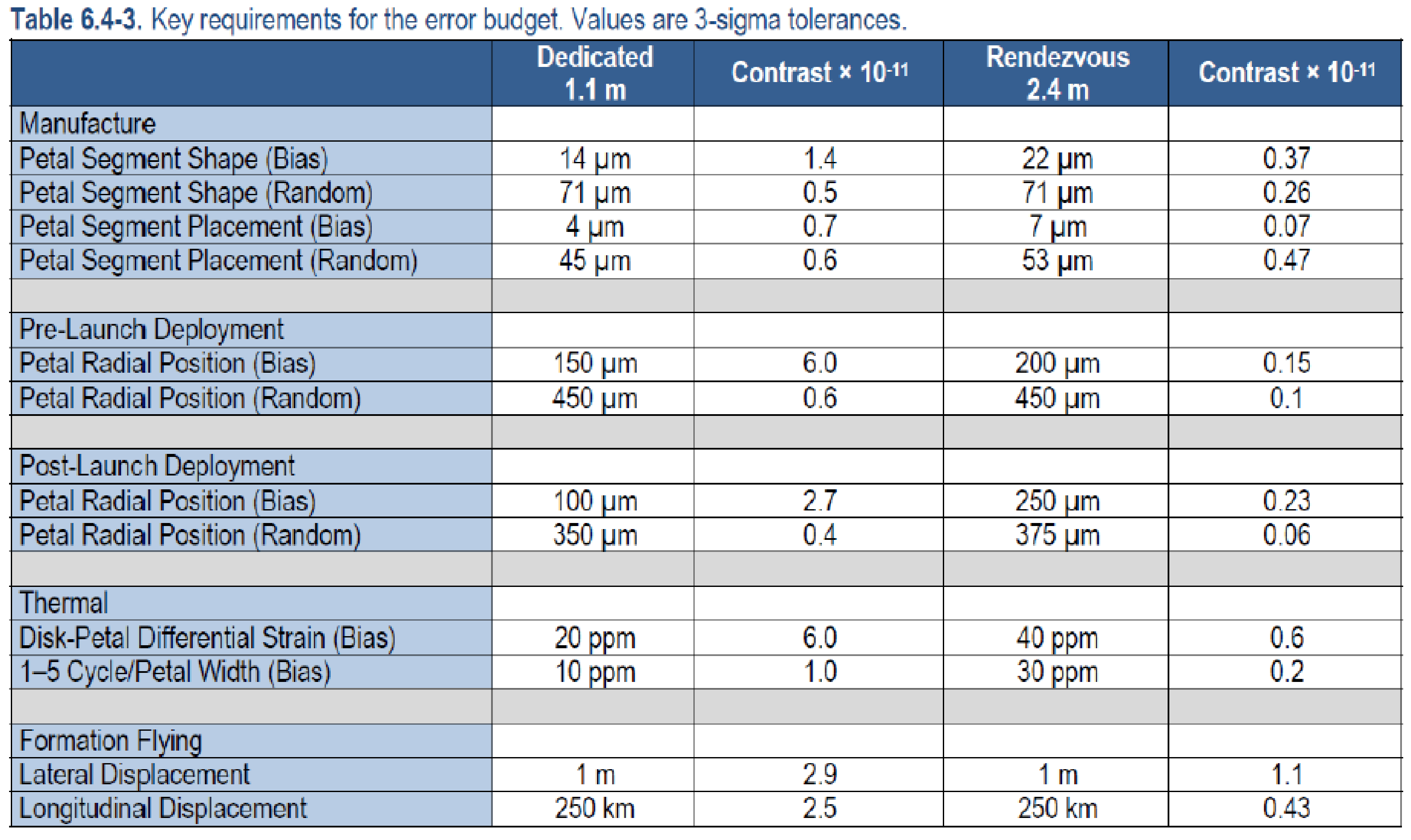


Table 6.4-3. Key requirements for the error budget. Values are 3-sigma tolerances.

	Dedicated 1.1 m	Contrast × 10^{-11}	Rendezvous 2.4 m	Contrast × 10^{-11}
Manufacture				
Petal Segment Shape (Bias)	14 µm	1.4	22 µm	0.37
Petal Segment Shape (Random)	71 µm	0.5	71 µm	0.26
Petal Segment Placement (Bias)	4 µm	0.7	7 µm	0.07
Petal Segment Placement (Random)	45 µm	0.6	53 µm	0.47
Pre-Launch Deployment				
Petal Radial Position (Bias)	150 µm	6.0	200 µm	0.15
Petal Radial Position (Random)	450 µm	0.6	450 µm	0.1
Post-Launch Deployment				
Petal Radial Position (Bias)	100 µm	2.7	250 µm	0.23
Petal Radial Position (Random)	350 µm	0.4	375 µm	0.06
Thermal				
Disk-Petal Differential Strain (Bias)	20 ppm	6.0	40 ppm	0.6
1–5 Cycle/Petal Width (Bias)	10 ppm	1.0	30 ppm	0.2
Formation Flying				
Lateral Displacement	1 m	2.9	1 m	1.1
Longitudinal Displacement	250 km	2.5	250 km	0.43