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The maturing of high contrast imaging and starlight suppression techniques for future NASA exoplanet characterization mssions

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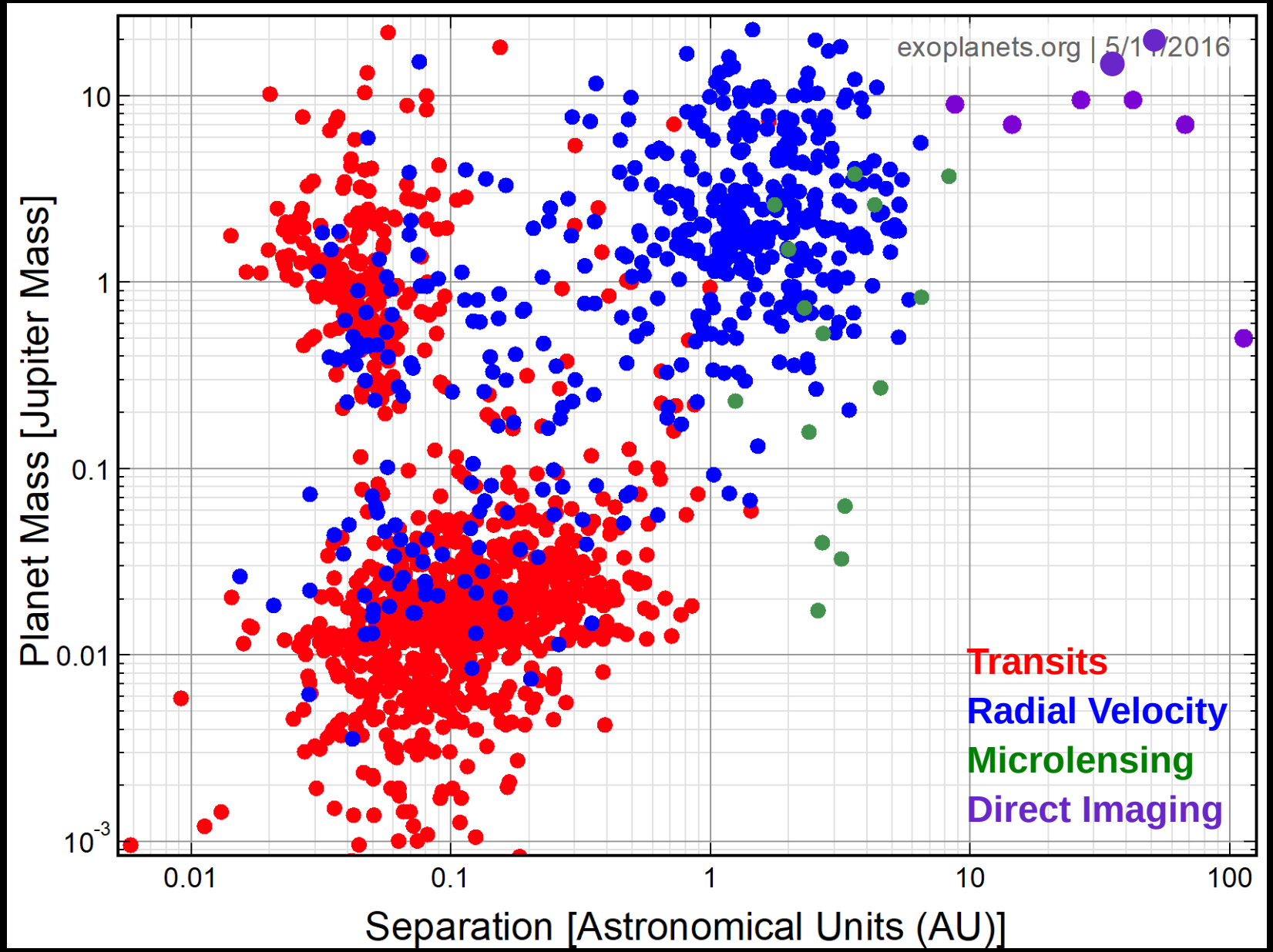
Why are there so few directly imaged planets?



Direct Imaging & Characterization Why do we care?

- 2010 Decadal Survey in Astronomy and Astrophysics, *New Worlds, New Horizons*, ranks exoplanet direct imaging technology demonstration as No. 1 priority in mid-size astrophysics missions

- Current space-based (HST, JWST) and ground-based (GPI) coronagraphs are 3-4 orders of magnitude worse than required for cold exoplanet direct imaging and characterization

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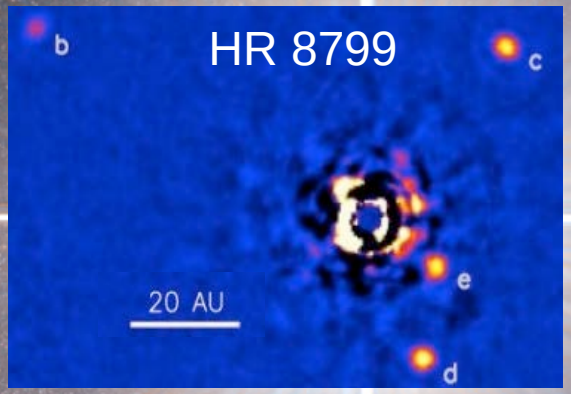
Direct Imaging & Characterization
The Challenges

Contrast

An Earth-like planet in the habitable zone of a Sun-like star is very faint- 10 billion times fainter!



Resolution

A planet in a 1AU orbit around a star at 40pc like HR 8799 has an angular separation of 25 milli-arcsec or 7 millionths of a degree

Marois et al. 2010

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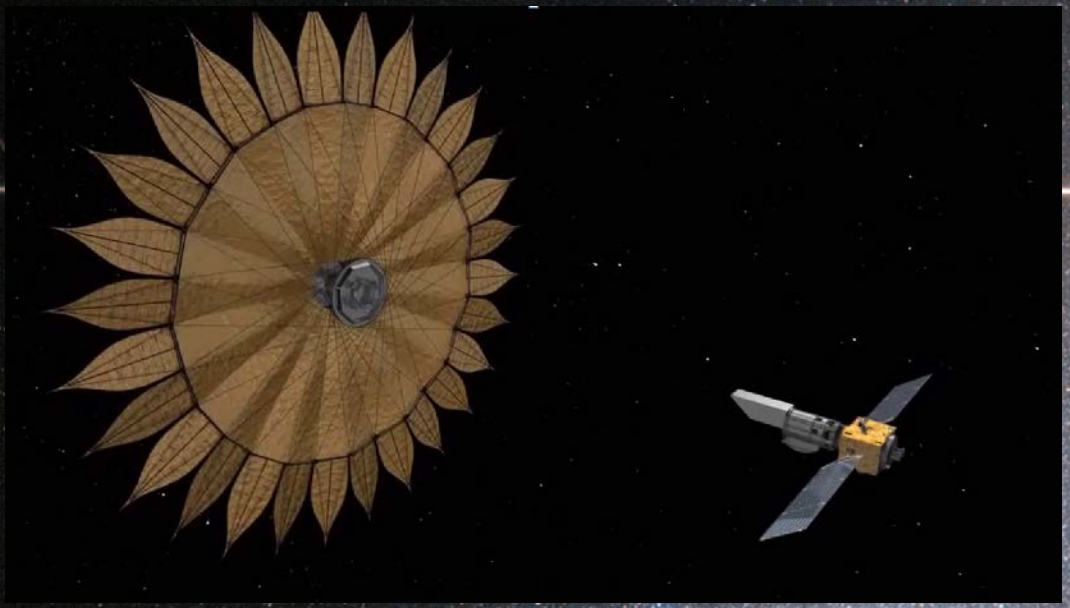
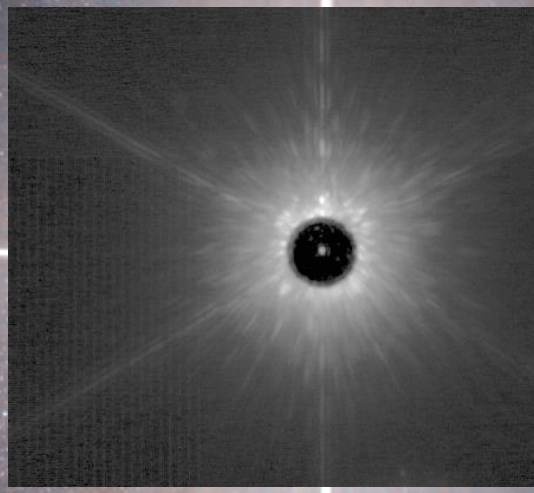
Direct Imaging & Characterization Two Techniques

Starshade





Coronagraph

Coronagraph Animation

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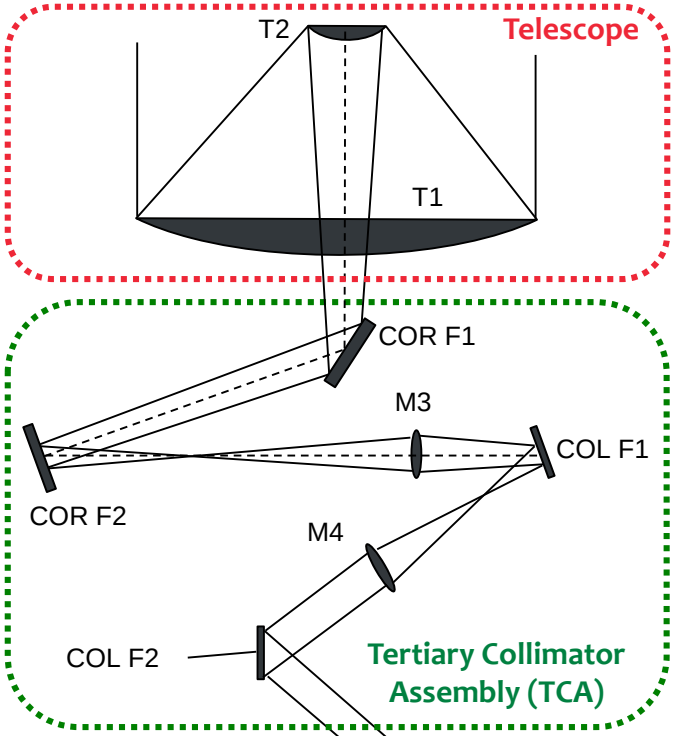
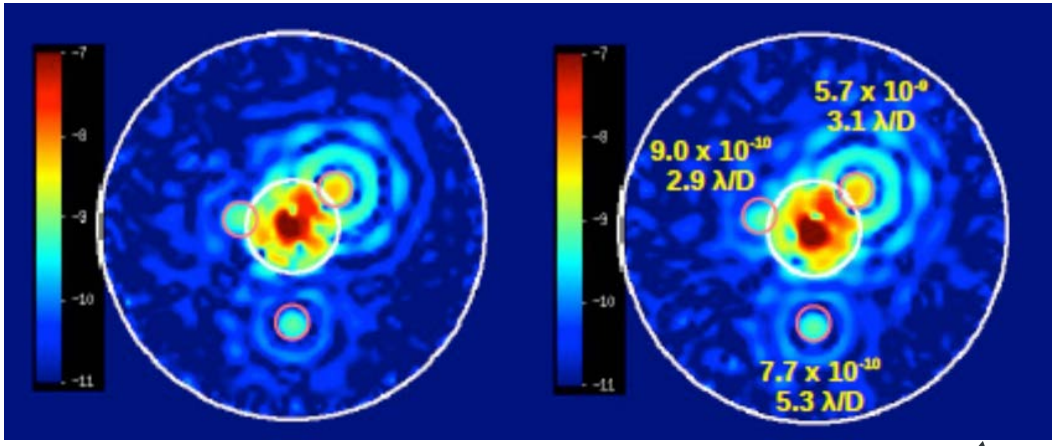
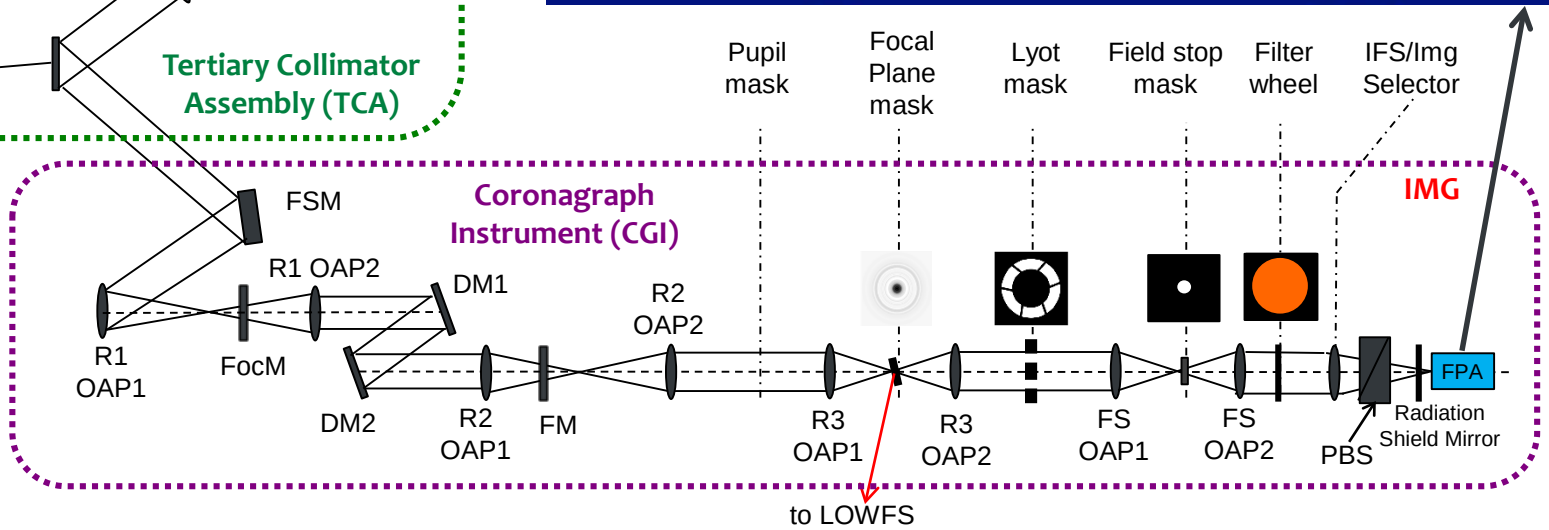
WFIRST Coronagraph Instrument Hybrid Lyot Imaging Mode



Imaging in 2 simultaneous polarizations, simulated planets are circled in red





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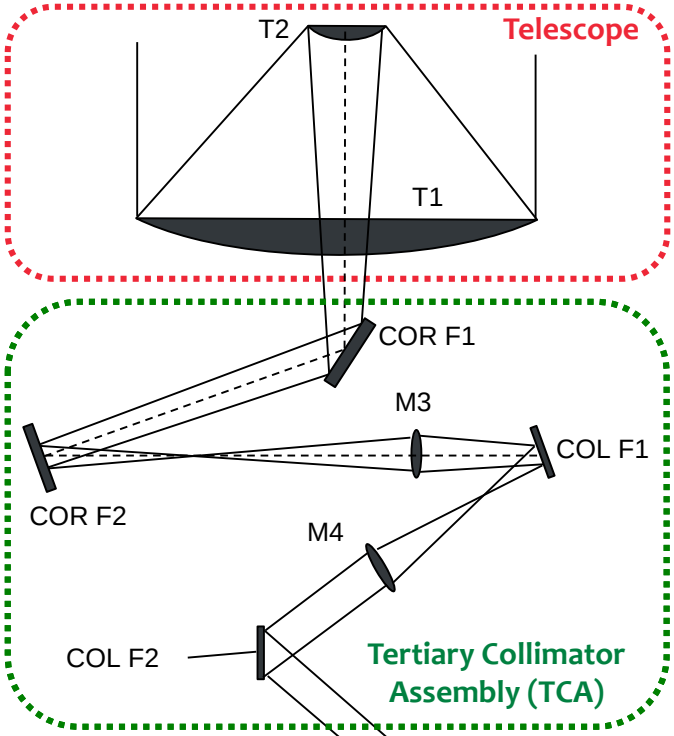
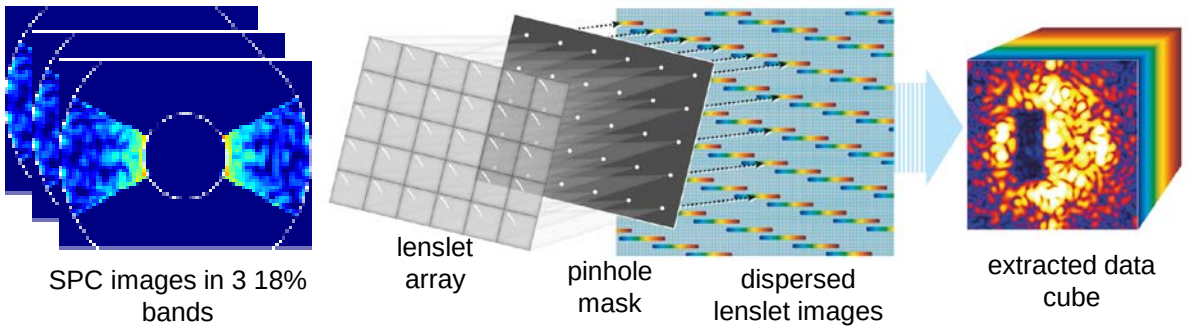
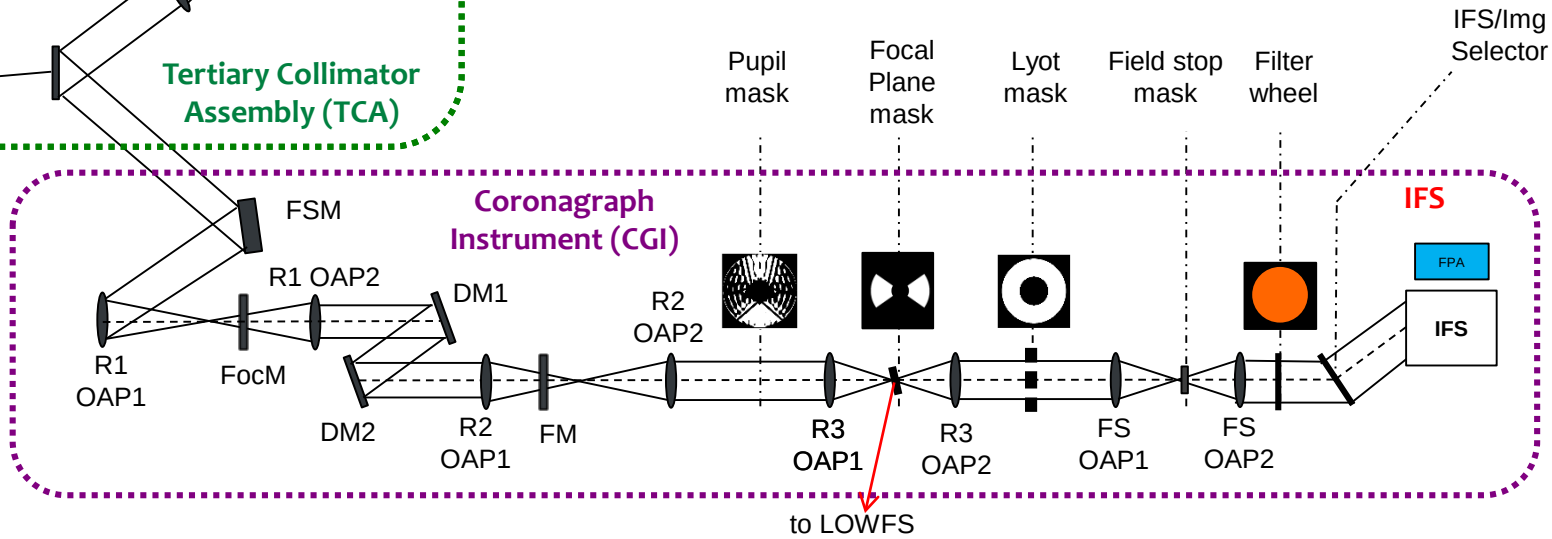
WFIRST Coronagraph Instrument Shaped Pupil Spectroscopy Mode



The IFS uses 3 18% bands to produce an R=70 spectra from 600 to 970 nm





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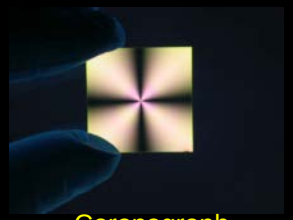
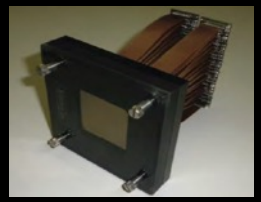
Coronagraph Technology

Contrast



Coronagraph architectures



Deformable mirrors

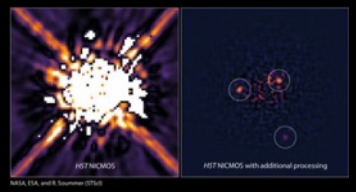
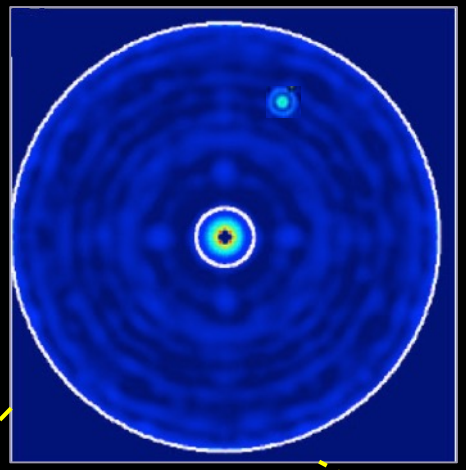
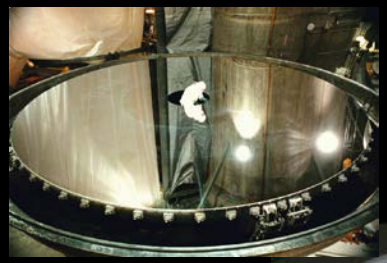


Image post-processing



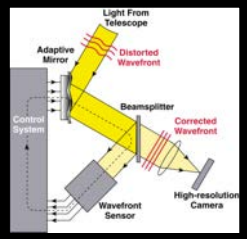
Angular Resolution



Large monolith

Segmented

Contrast Stability

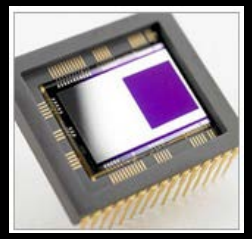


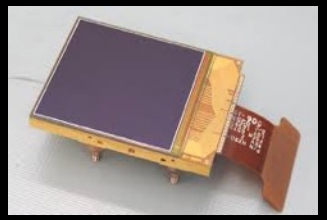
Low-order wavefront sensing and control

Segment phasing and rigid body sensing and control

Telescope vibration sensing and control

Detection Sensitivity





Ultra-low noise visible and infrared detectors

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WFIRST Coronagraph Technology Development Sequence

12/2013
Coronagraph designs that work with AFTA telescope developed, validated by modeling

12/2014
Fabrication of novel coronagraph components: masks and apodizers demonstrated

2/2015
Narrowband coronagraph contrast demonstration in the testbeds

9/2015
Broadband coronagraph contrast demonstration in the testbeds

Broadband coronagraph contrast demonstration in the testbed with representative optical wavefront disturbances

Each milestone is a necessary precondition for the following ones

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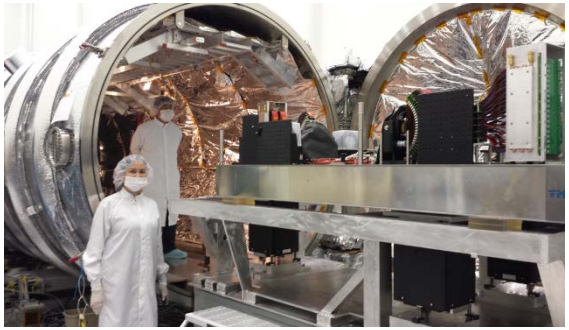
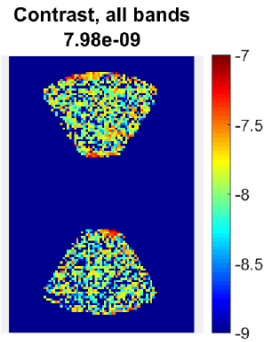
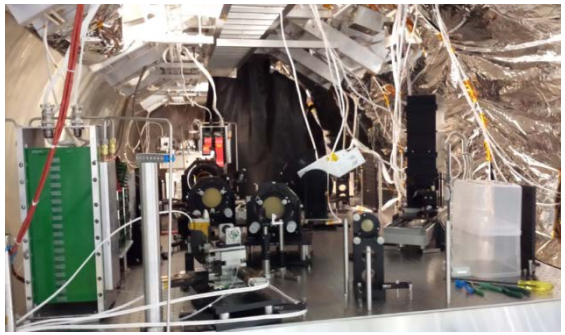
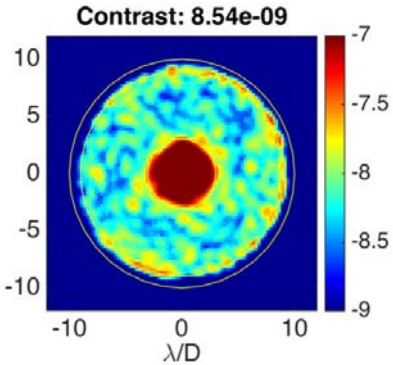
Coronagraph Results in the Laboratory

- **Demonstrated "broadband" (10% at 550nm) high *raw* contrast (<10^{-8}) in a static environment for both**
  - **HLC (Hybrid Lyot Coronagraph)**
  - **SPC (Shaped-Pupil Coronagraph) with WFIRST telescope pupil**

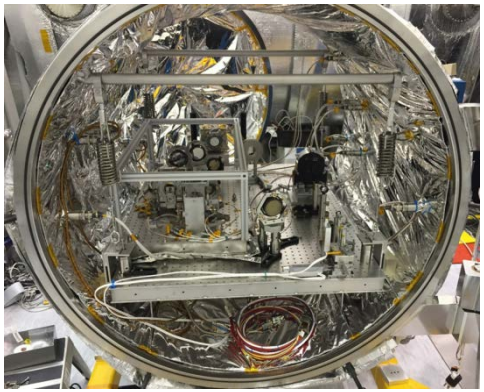


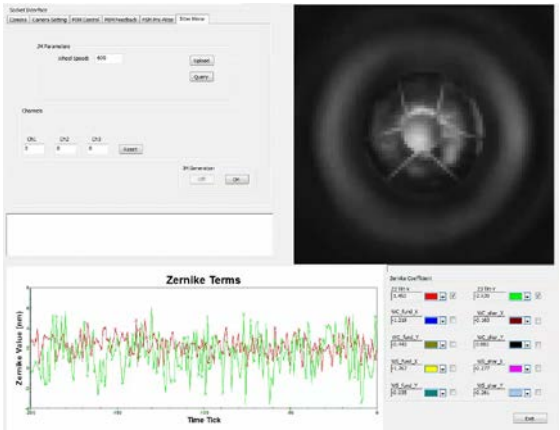






- **Demonstrated low-order wavefront error sensing and close-loop tip/tilt correction**





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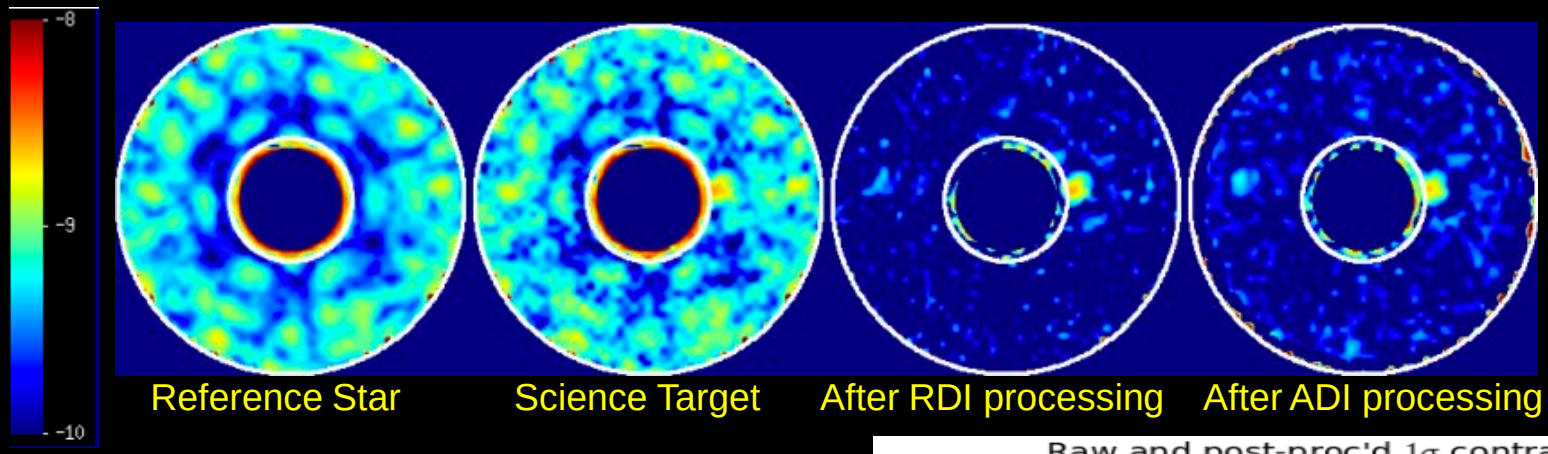
Coronagraph Post Processing

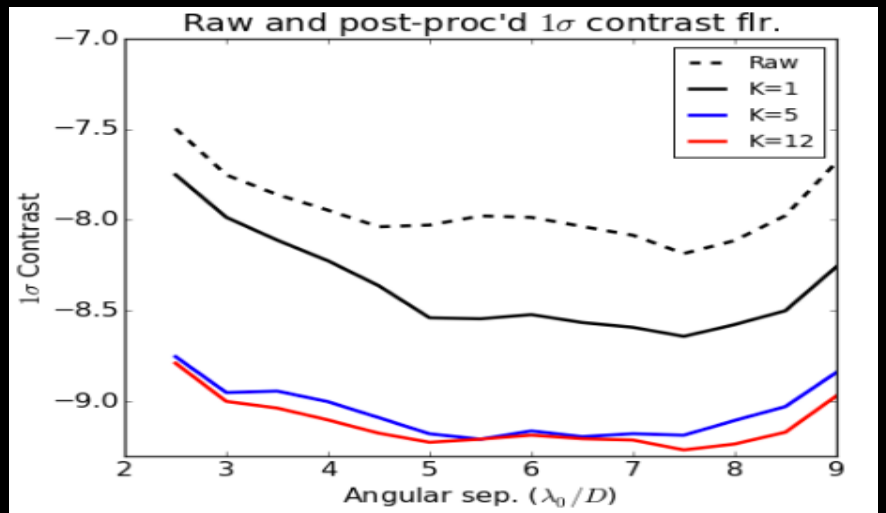
- Exoplanet yield is a strong function of pointing jitter and final contrast in coronagraphic dark hole
- Expected *raw* contrast is ~10^{-8} at 50-100 mas inner working angle for SPC/HLC coronagraphs
- ***Question is: what further gain in contrast can be provided by using reference stars and telescope rolls, together with state of the art post-processing techniques?***
- End-to-end thermal/mechanical/optical simulations of representative observing sequences currently show that close-in planets can be detected at the 10^{-9} level after post-processing:



RDI= Reference Differential Imaging

ADI= Angular Differential Imaging

- Contrast gains of the order of 10 or more are also found when post-processing HCIT data taken hours apart (e.g. SPC 10% bandwidth, "static" conditions)
- Further post-processing efforts are required to analyze IFS spectroscopic data, both from simulations and from HCIT dynamic testbed



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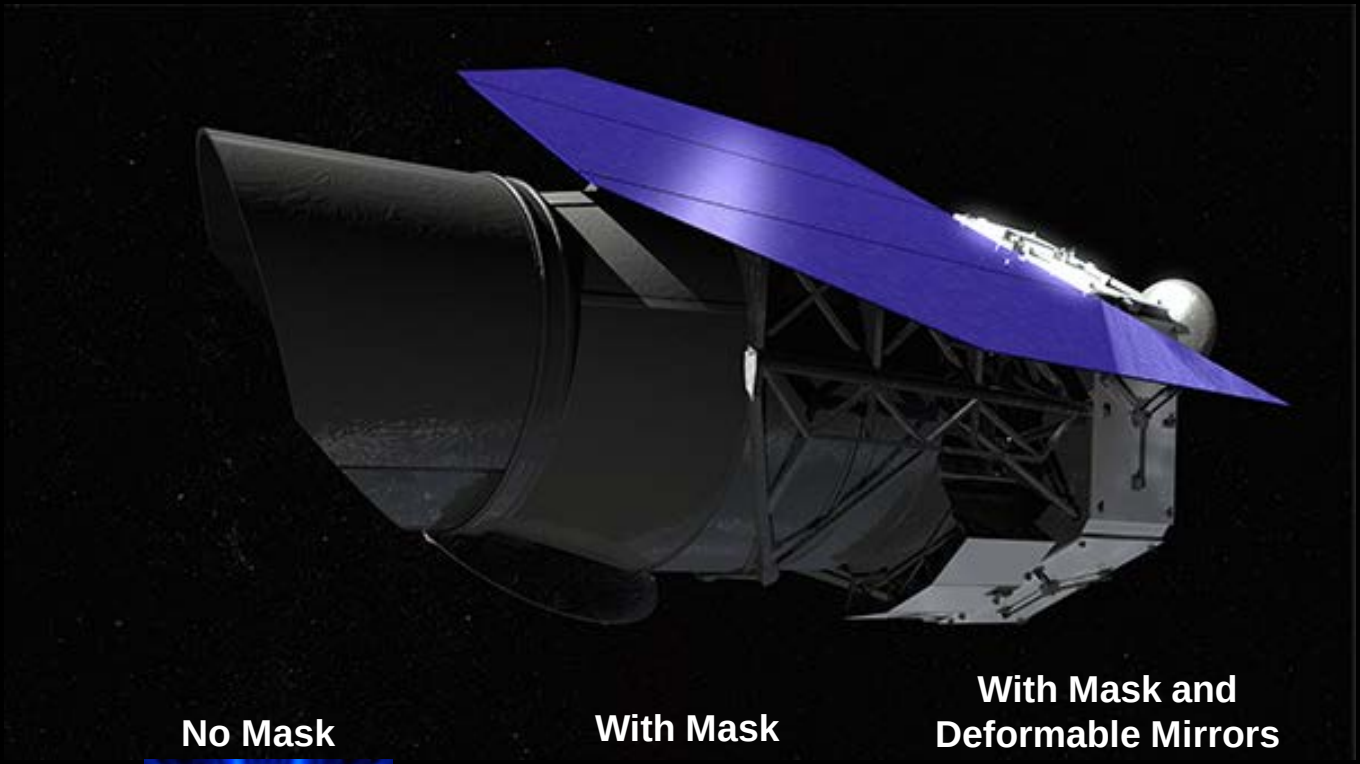
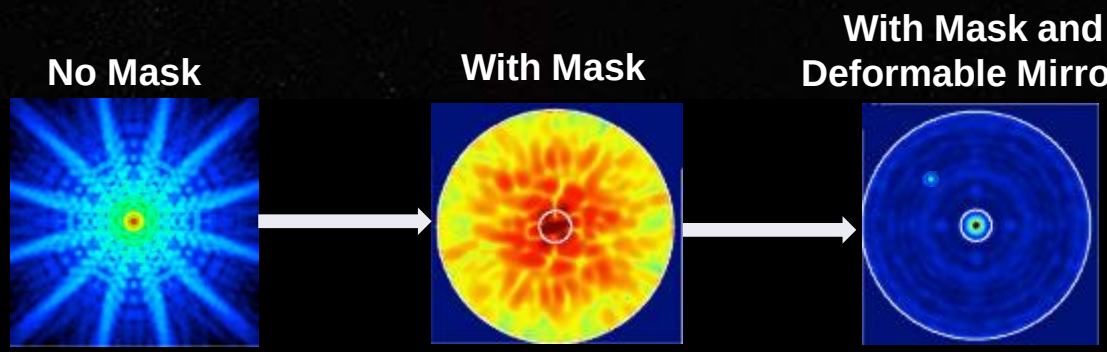
WFIRST Coronagraph (~2024)

Direct Imaging of our Nearest Neighbors





Technology Demonstration for exoEarth-Characterization Missions

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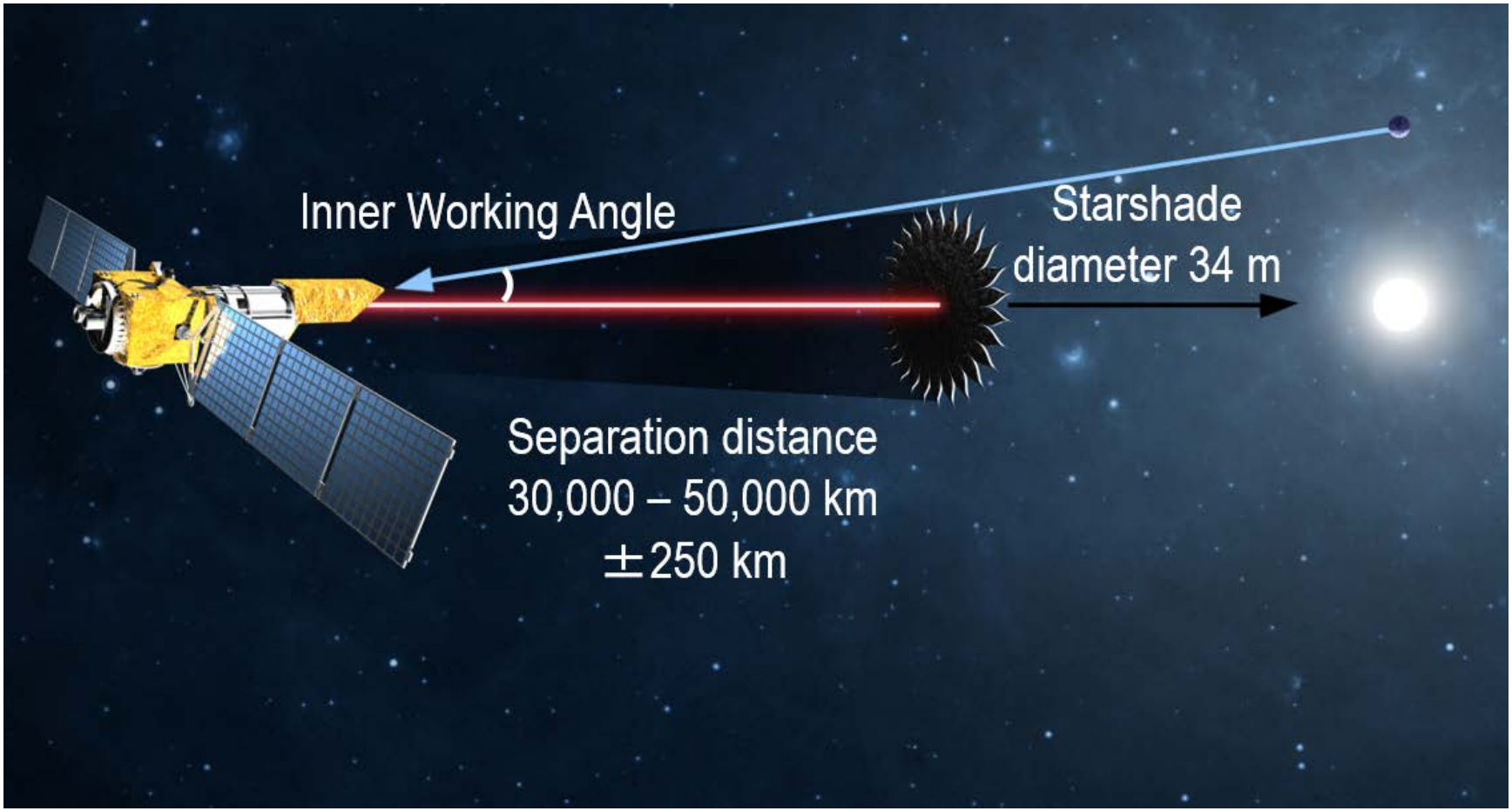
Starshade Concept



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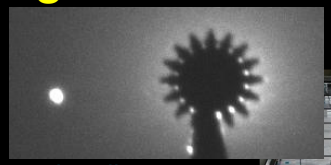
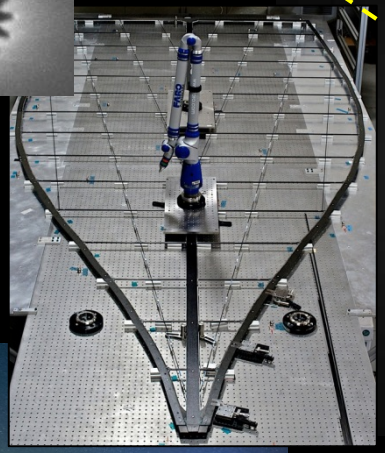
Starshade Technology

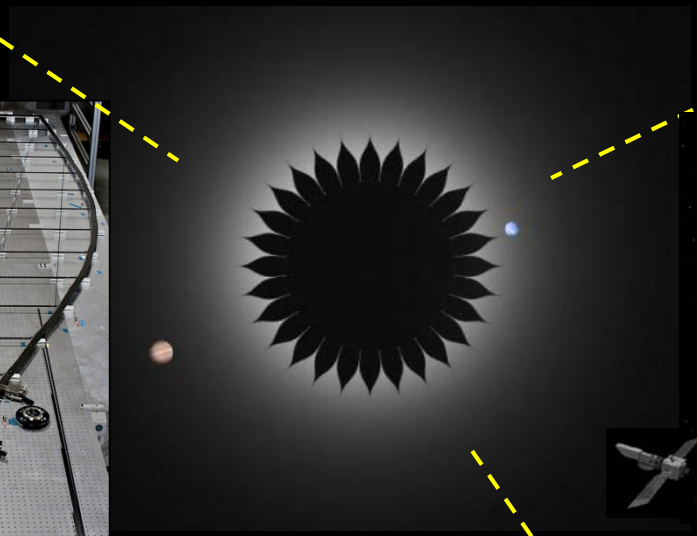
Diffraction and Scattered Light Control



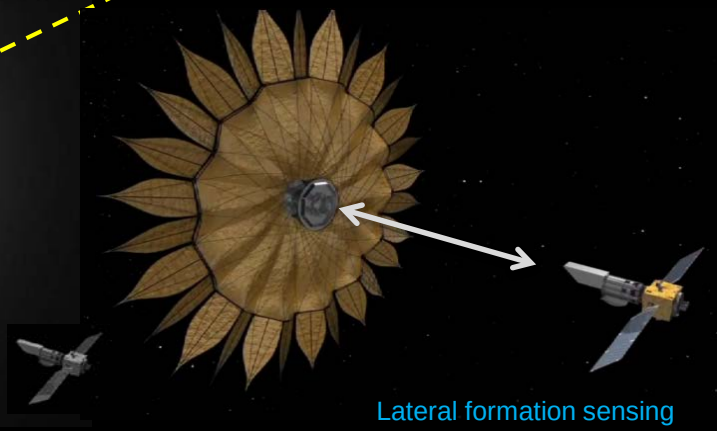
Solar glint



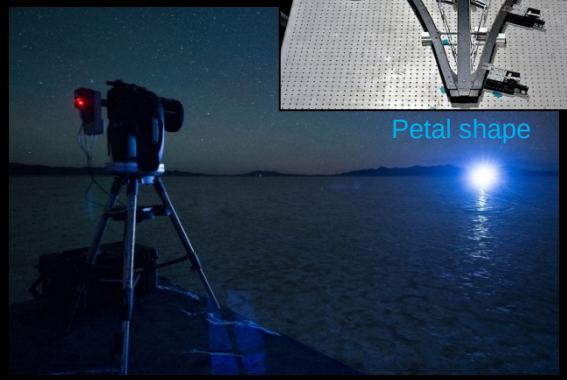
Petal shape



Lateral Formation Flying Sensing



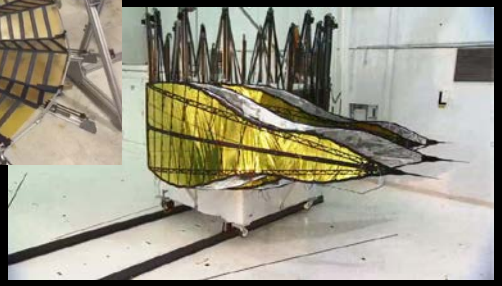
Lateral formation sensing



Optical demonstration and model validation

Precision Deployable Structures

Inner disk deployment



Petal deployment

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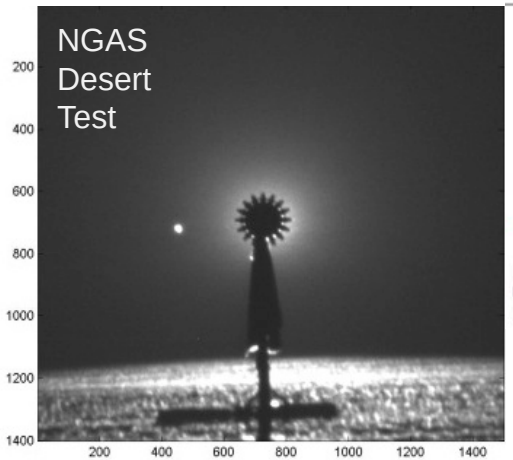
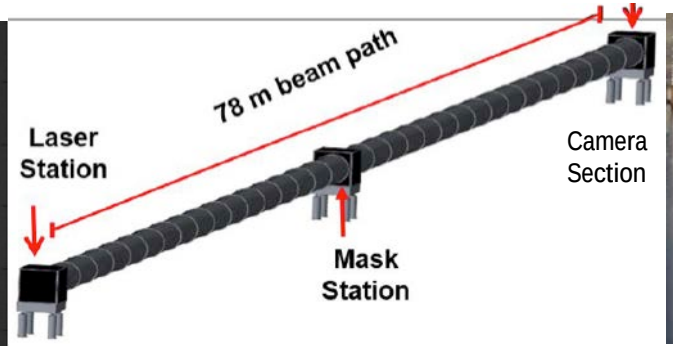
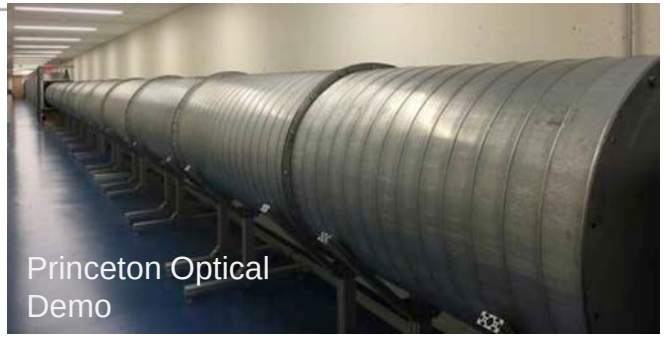
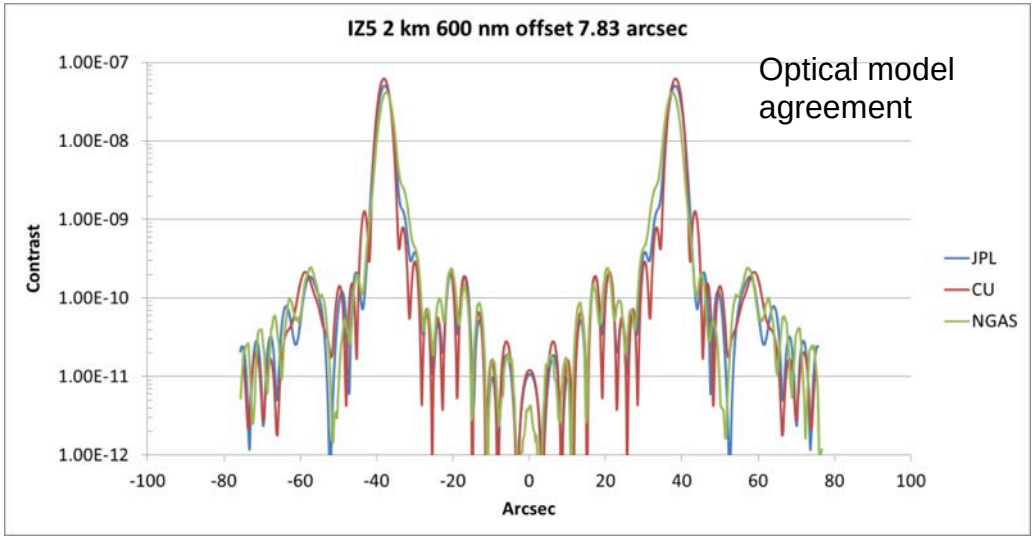
Starshade Optical Model Validation

- Model validation is critical because the distances make ground based verification impractical
  - **TRL-5 plan is to demonstrate 10^{-9} suppression at flight-like Fresnel # in the Princeton testbed**
  - **Validate models of perturbation sensitivities at the 10^{-7} level in the presence of 10^{-9} scatter**
  - **This sensitivity is scaled down to the 10^{-11} level**
- Early NGAS tests in the desert and Kitt Peak demonstrate 10^{-6} suppression and independent models by JPL, NGAS and U. Colorado predict the same sensitivities









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Starlight Suppression State of the Art

Current Situation:

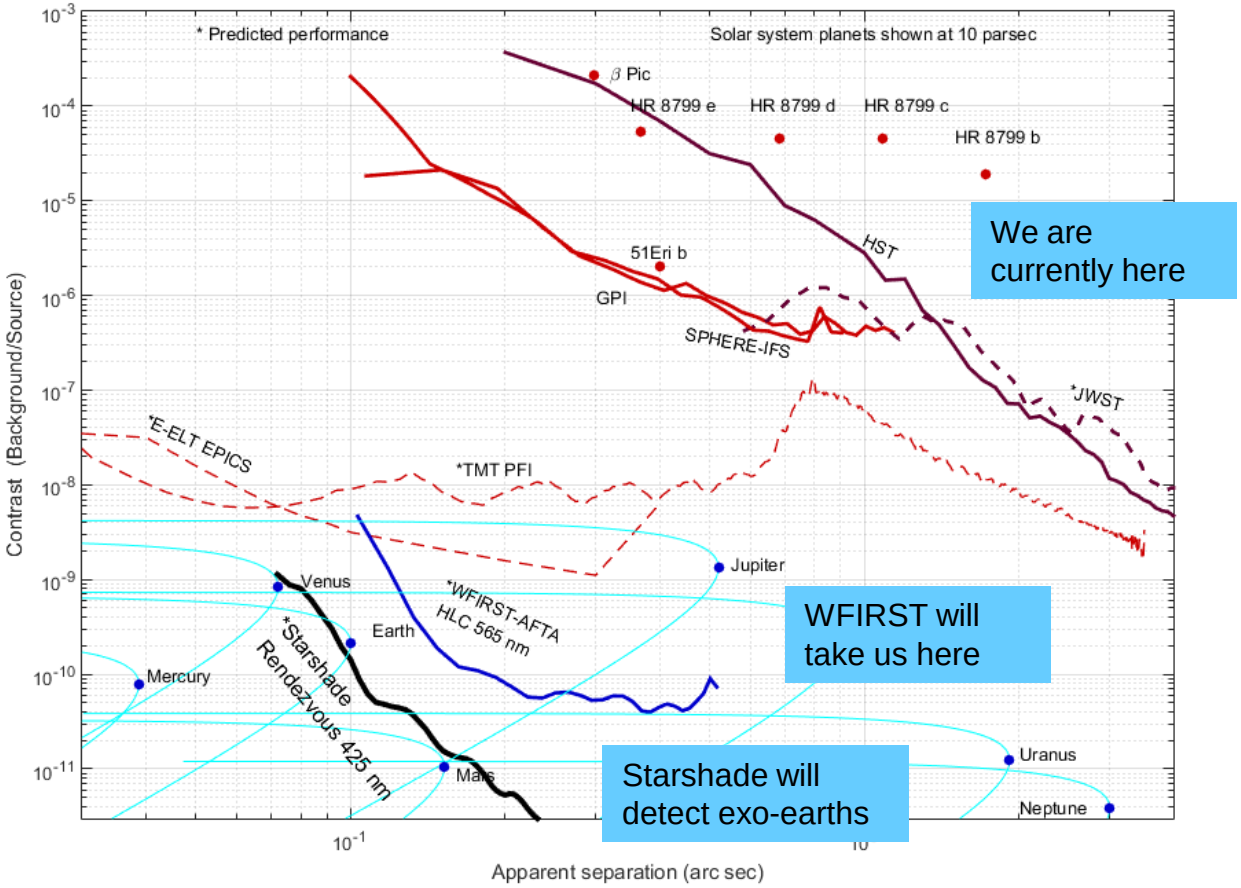
- Ground-based telescopes, SOA contrast are in the NIR:
  - **$2x10^{-5}$ at ~ 110 mas IWA (GPI)**
  - **$8x10^{-7}$ at 500 mas IWA (SPHERE)**
- For space-based telescopes, SOA is HST (IR):
  - **$3x10^{-4}$ at ~ 200 mas IWA**
  - **$3x10^{-5}$ at ~ 500 mas IWA**

In 2025:

- For ground-based telescopes, contrast performance will be limited to ~**10^{-8}** due to uncorrected atmospheric aberrations.
- For space-based telescopes, SOA will be the WFIRST coronagraph (visible):
  - **$5x10^{-9}$ at ~ 110-140 mas IWA (TBD)**
  - **$1x10^{-10}$ at ~ 500 mas IWA (TBD)**

Flight Starshade

- Expected to improve WFIRST performance by > 10x in contrast over its coronagraph and probe over smaller IWA's (visible; see figure).
  - **$1x10^{-9}$ at ~ 75 mas IWA (TBD)**
  - **$2x10^{-10}$ at ~ 100 mas IWA (TBD)**



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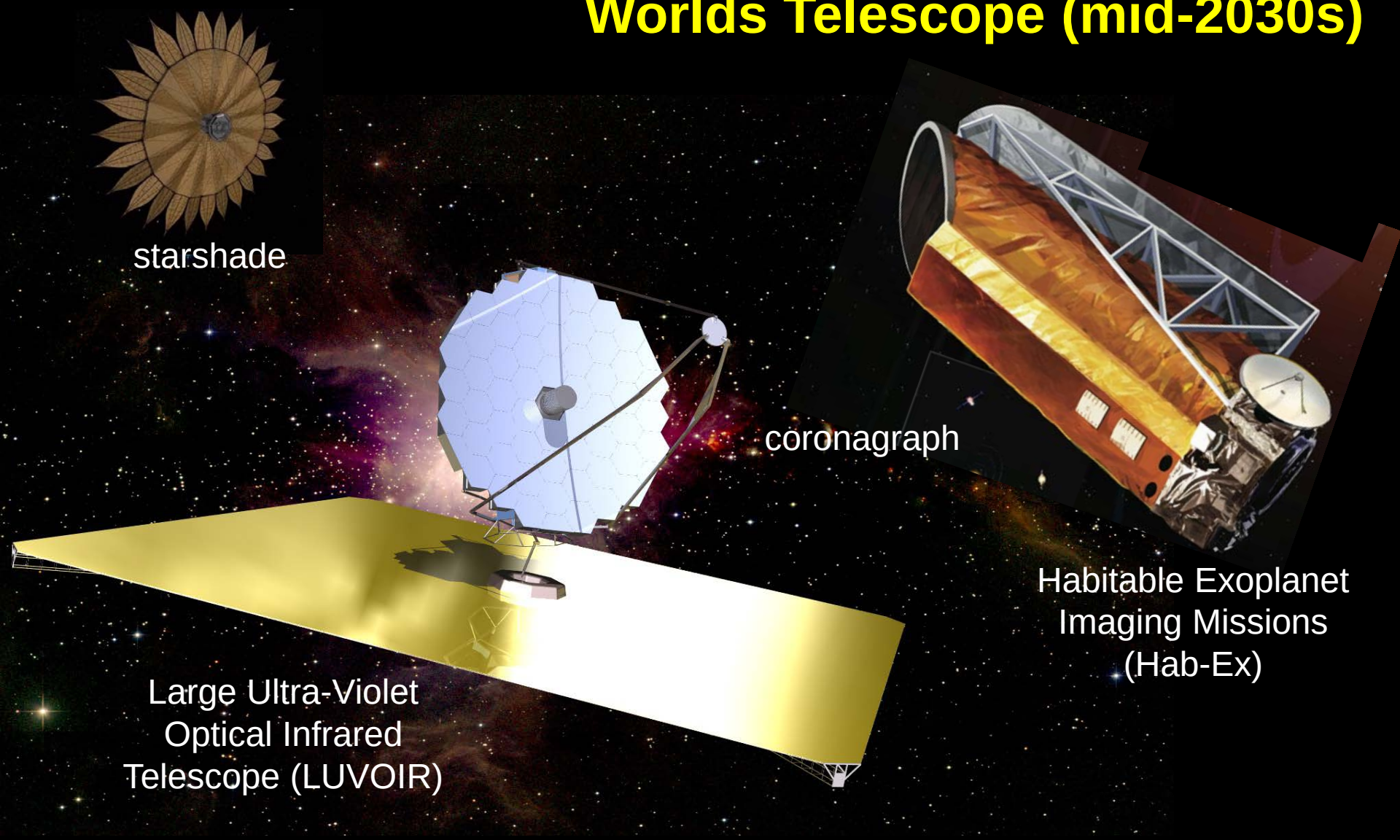
Possibilities for the New Worlds Telescope (mid-2030s)