WFIRST Coronagraph: Status and Performance Expectations

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Exoplanets I – Davos, July 8, 2016

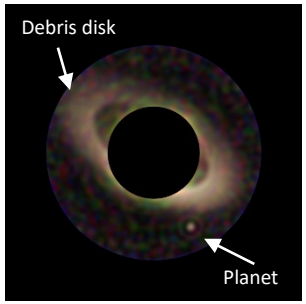
WFIRST Mission Objectives

WFIRST = **W**ide-**F**ield **I**nfrared **S**urvey **T**elescope

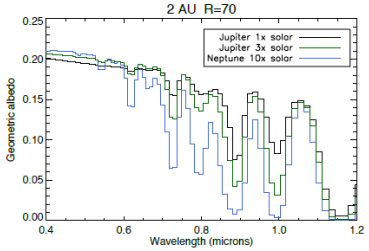
Science Objectives:

Precursor science for Exoplanet Missions

- Characterize the history of cosmic acceleration and structure growth
- Understand how planetary systems form and evolve and determine the prevalence of planets in the colder outer regions
- Demonstrate technology for characterization of atmospheres down to Jupiters around nearby stars
- Characterize debris disks around nearby stars



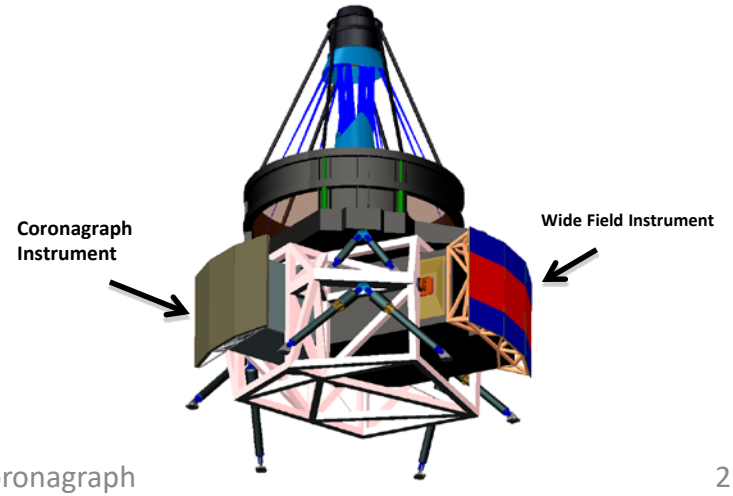
Exo-planet
Direct imaging



Exo-planet
Spectroscopy

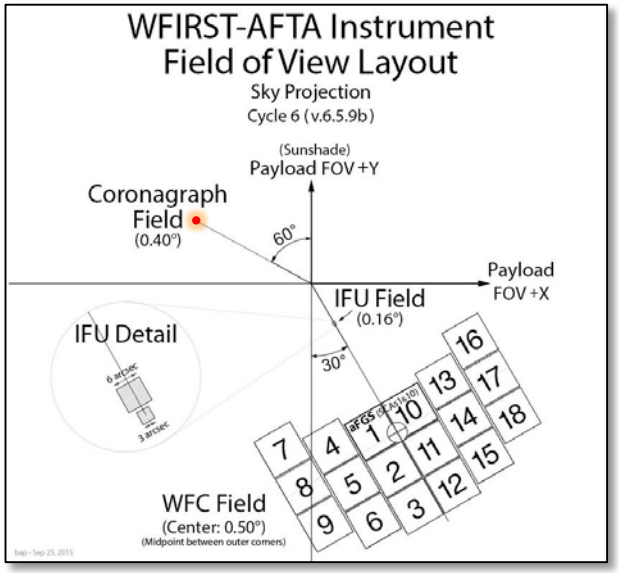
The Instrument

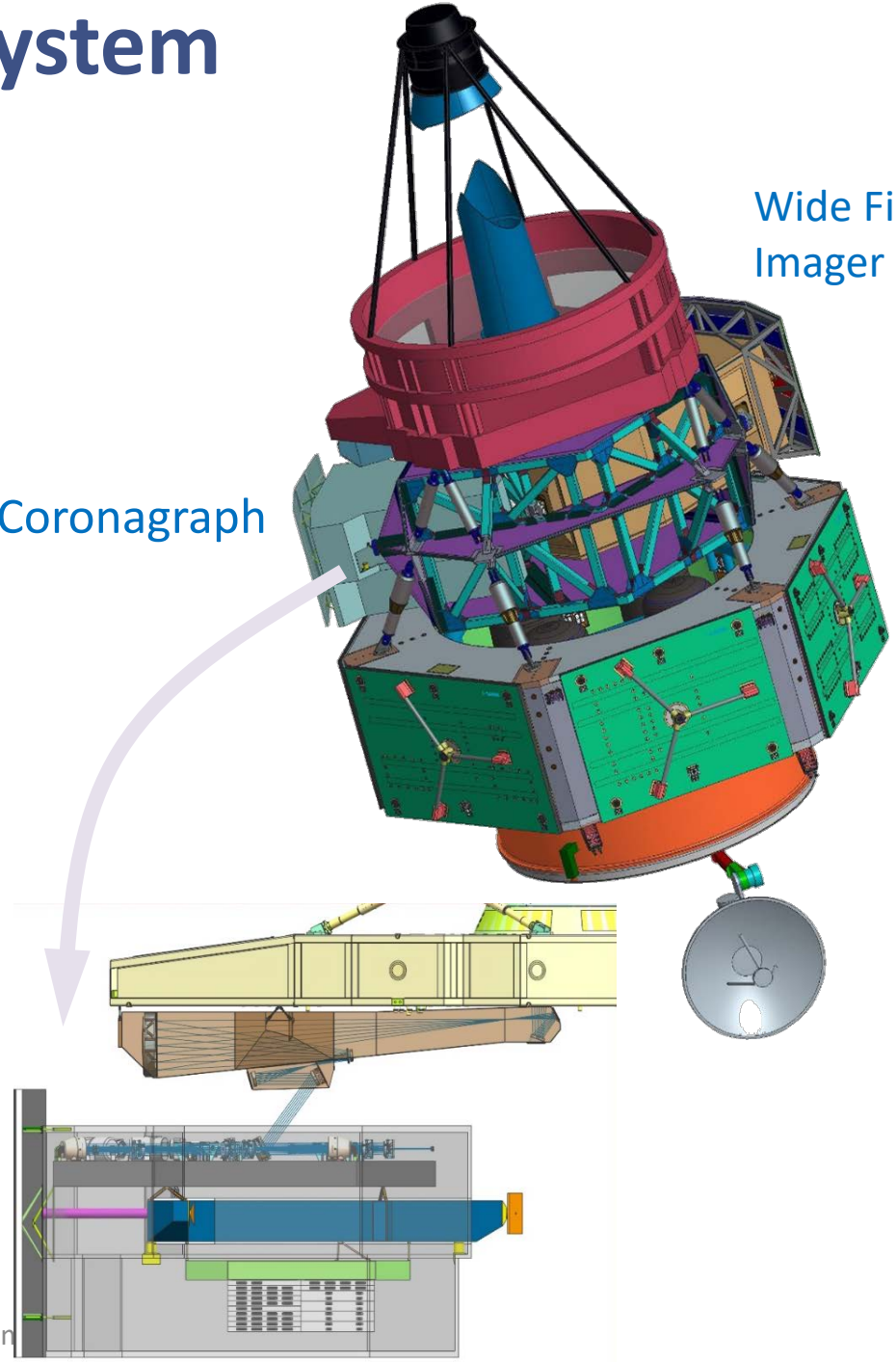
- CGI advances a number of new technologies:
  - Novel coronagraph masks (shaped pupil coronagraph and hybrid Lyot coronagraph)
  - Precision wavefront sensing and control with 2 deformable mirrors (Xinetics)
  - Ultra-low noise detector



WFIRST Flight System

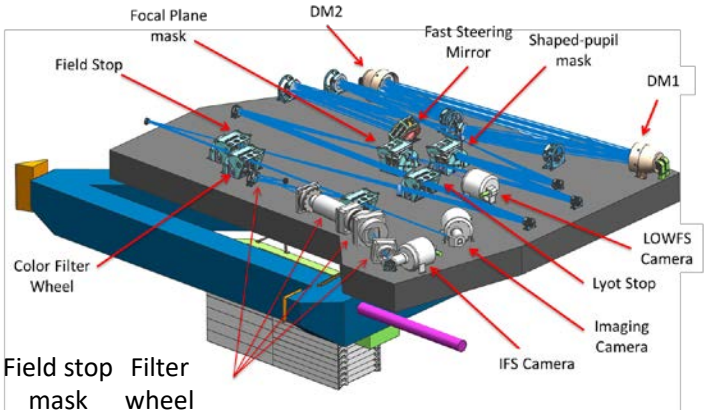
- 2.4 m telescope
  - Already built and flight tested
- Two instruments:
  - Coronagraph
  - Wide field imager
- Orbit:
  - Sun-Earth L2 Orbit
  - 6 yrs. Nominal Mission
- Launch:
  - 2024 on Delta IV heavy or Falcon heavy

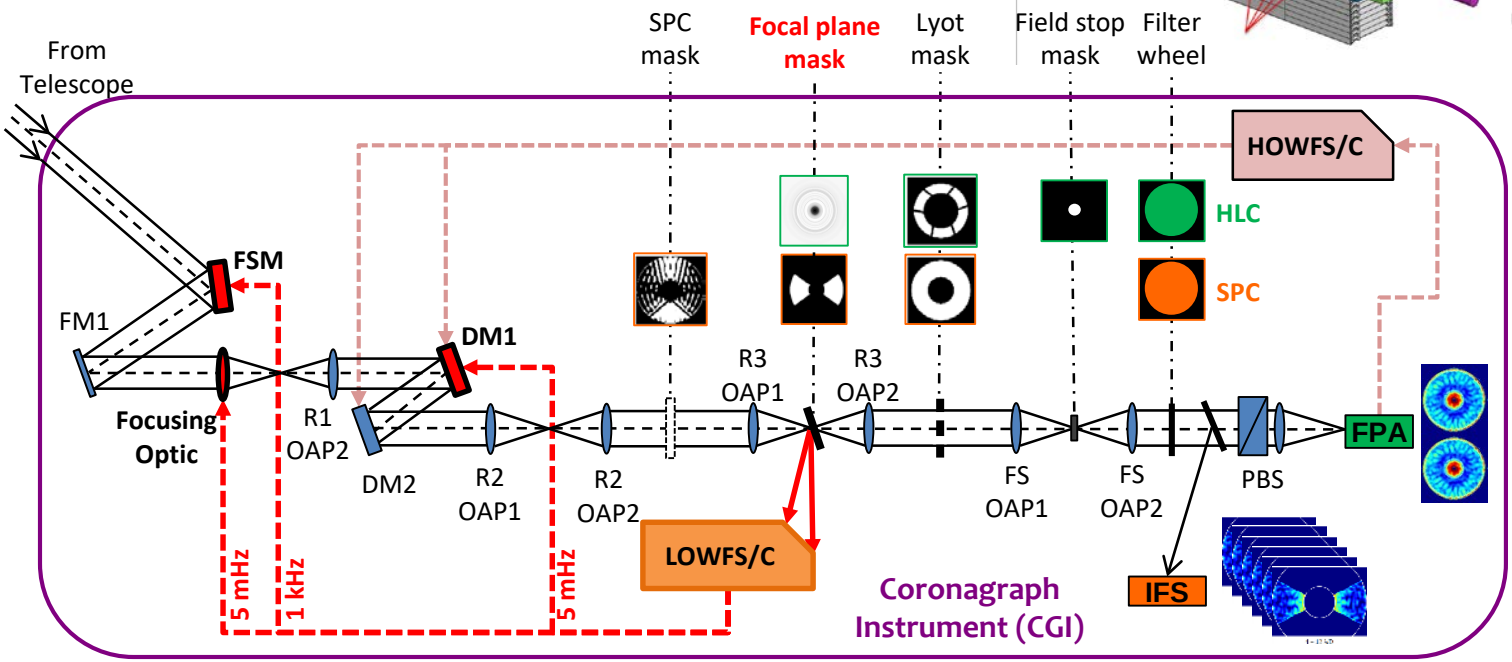




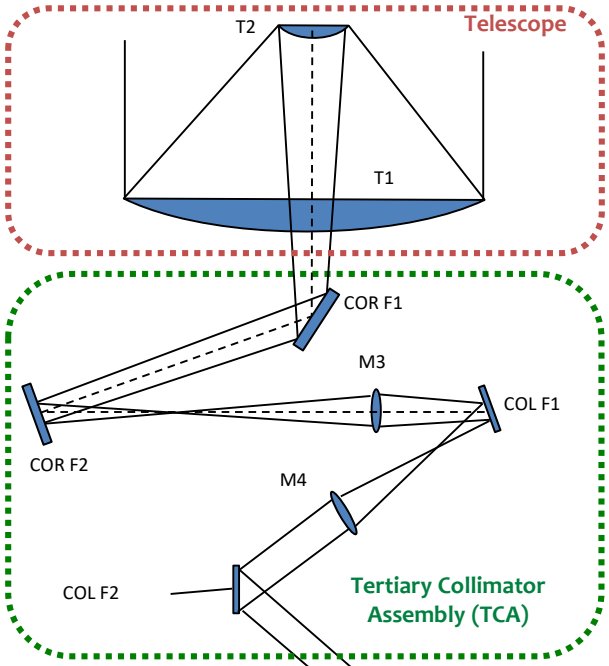
Two Coronagraphs in One

- Primary coronagraph architecture:
  Occulting Mask Coronagraph = Shaped Pupil + Hybrid Lyot
  - SP and HL share same optical layout
  - Operate with different apodizing and occulting masks



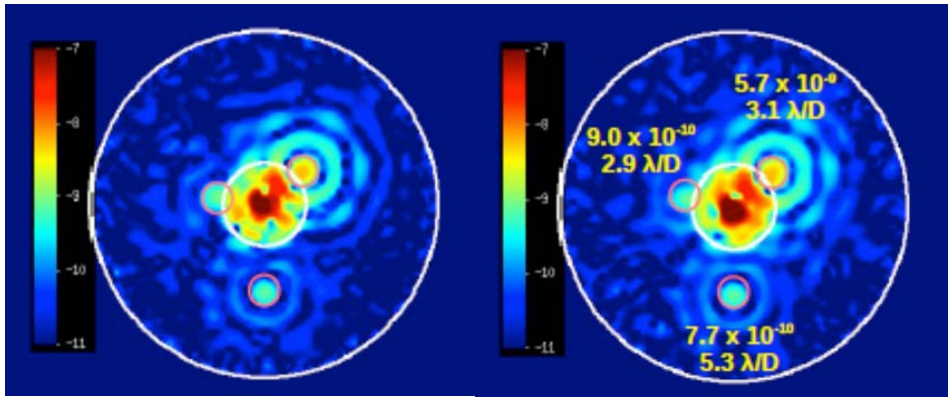


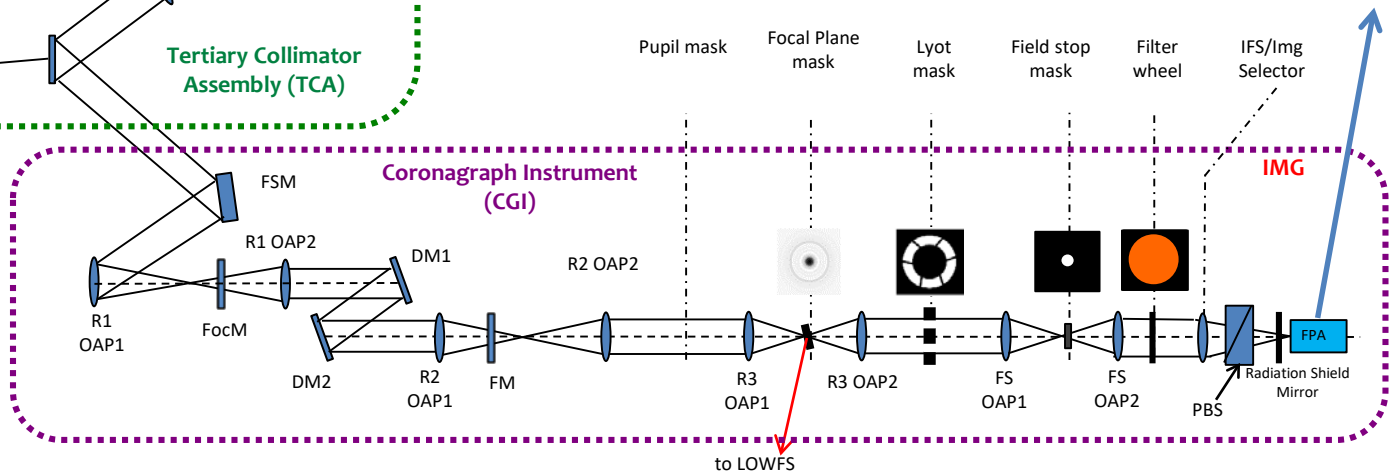
CGI Operational Modes



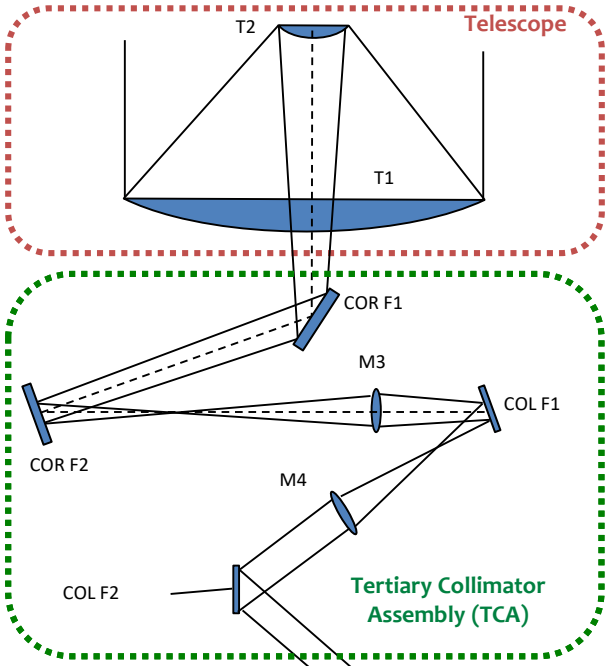
Hybrid Lyot Mode

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



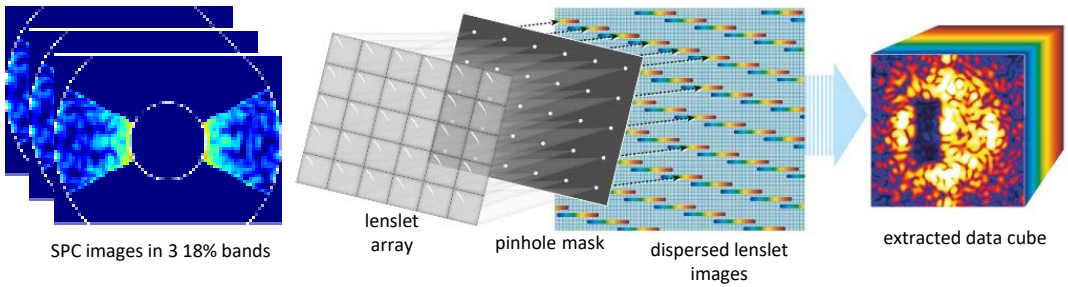


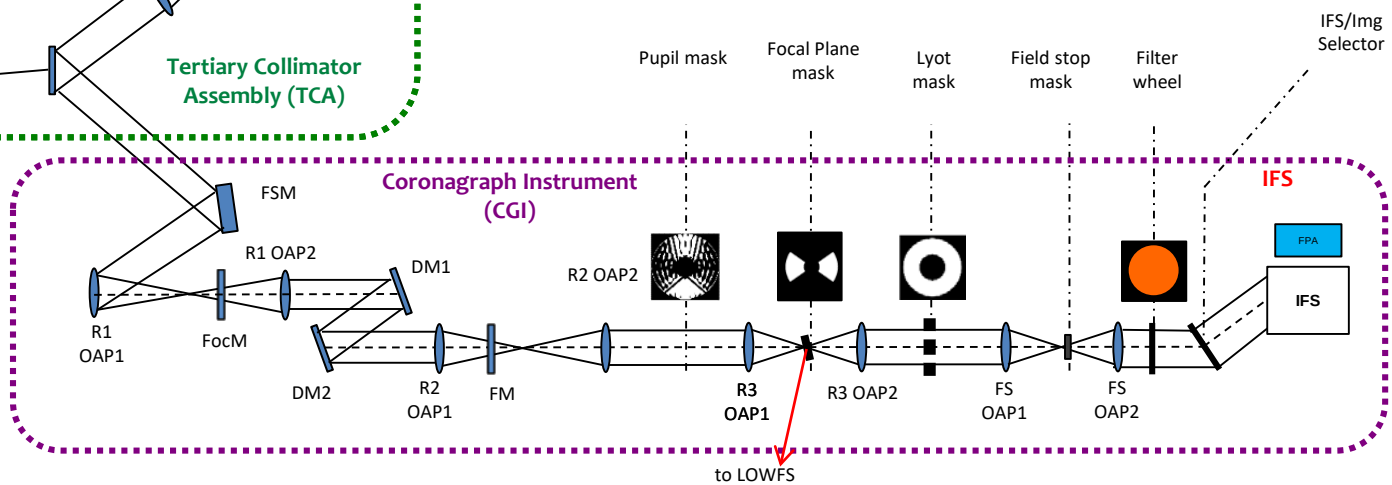
CGI Operational Modes



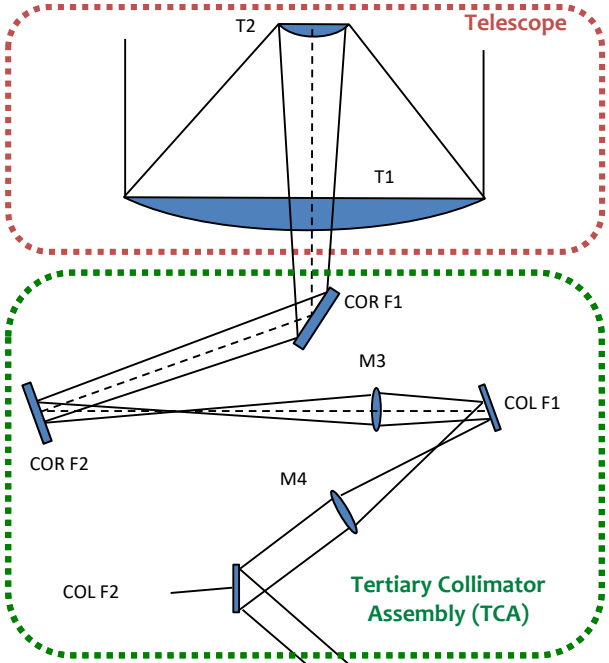
Shaped Pupil Spectroscopy Mode

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





CGI Operational Modes



Shaped Pupil Disk Imaging Mode

Disk Imaging at wavelengths 465 and 890 nm, in 2 simultaneous polarizations

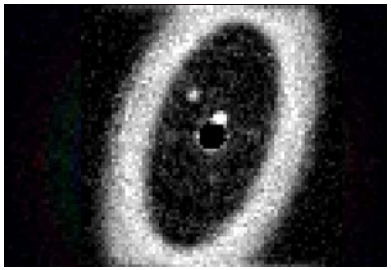
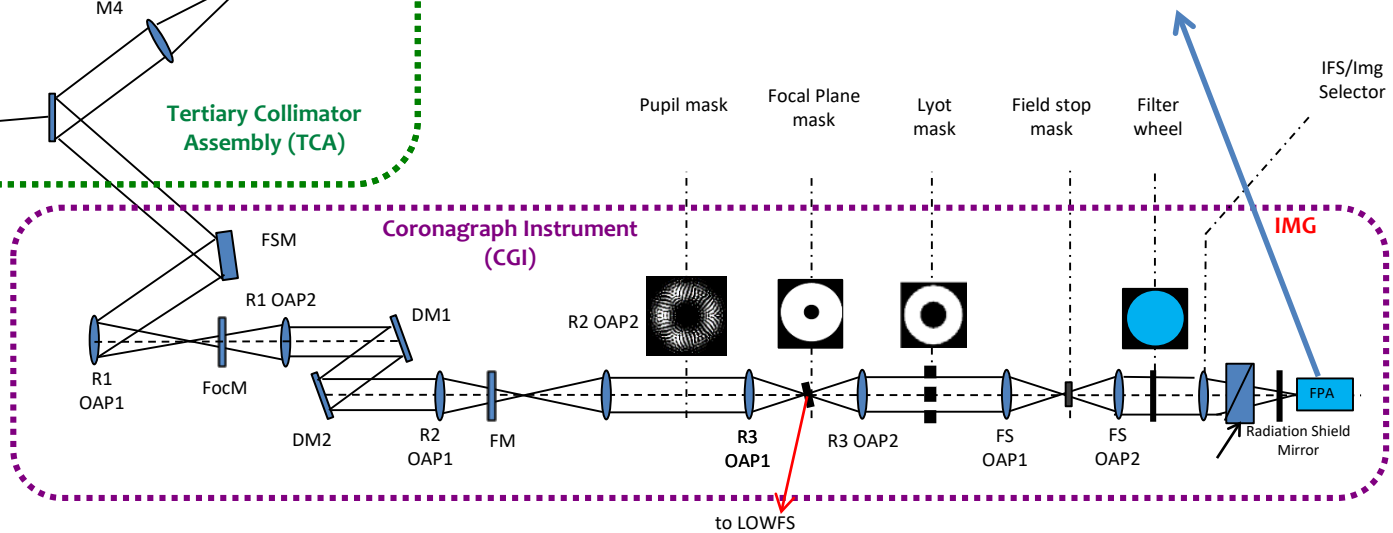


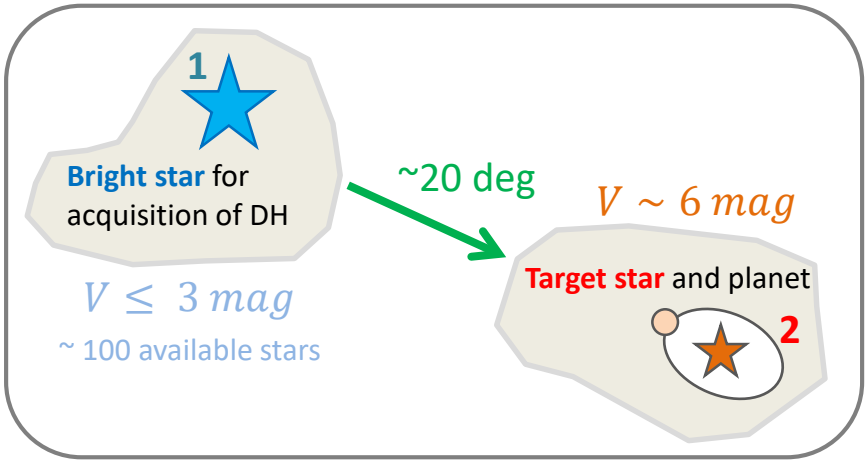
Image from 2015 Exo-C STDT Final Report

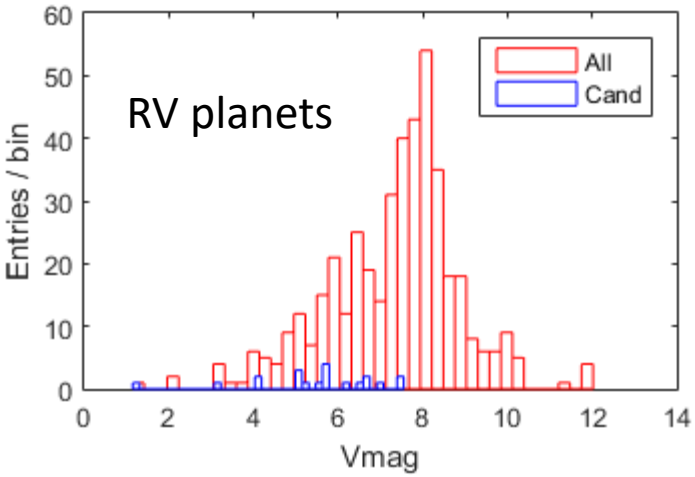


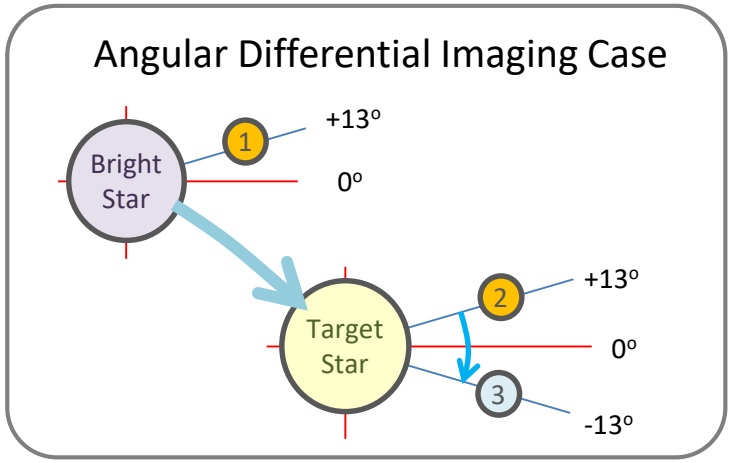
Typical Observing Sequence

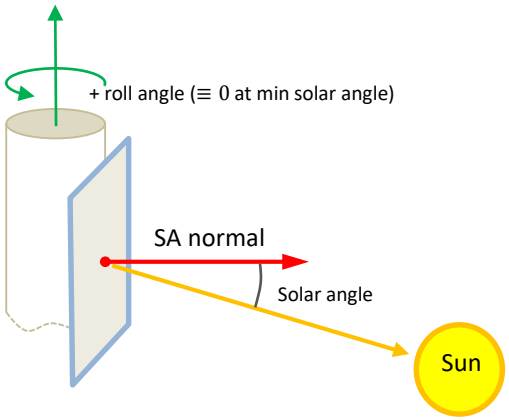
- The typical scenario involves two stars:
  1. A nearby **bright star** for getting a dark hole (~ 3 Hrs)*
  2. The planet host **target star** (~10 Hrs)*

* numbers notional

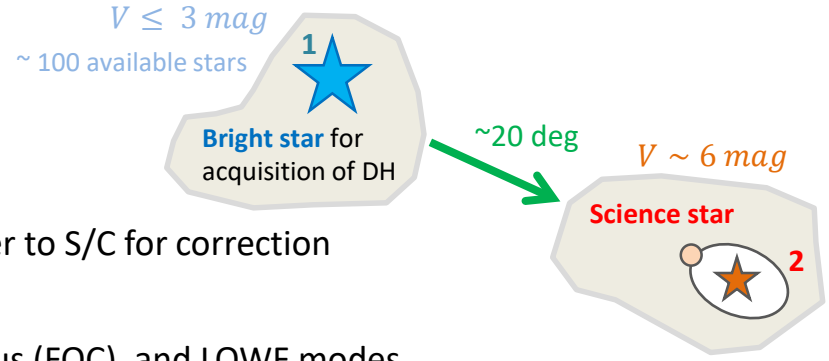






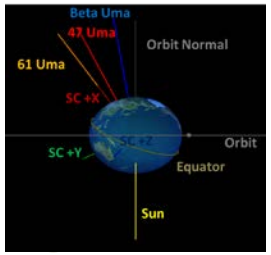


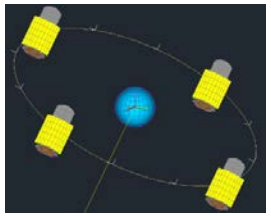
Observing Steps

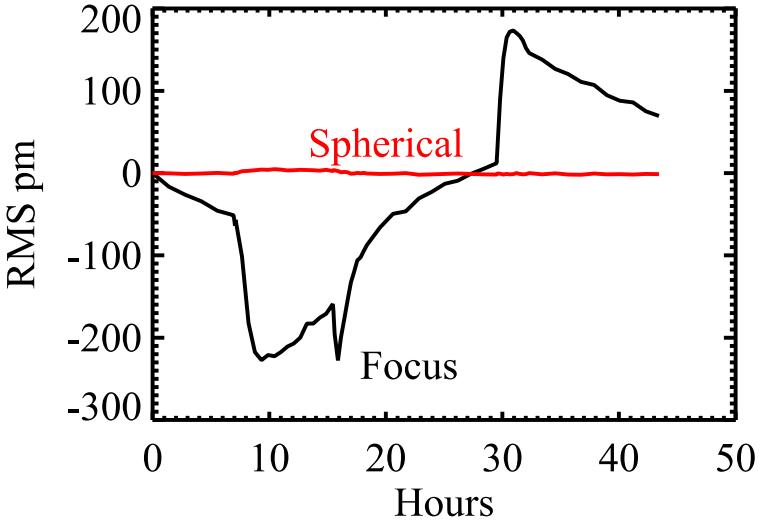


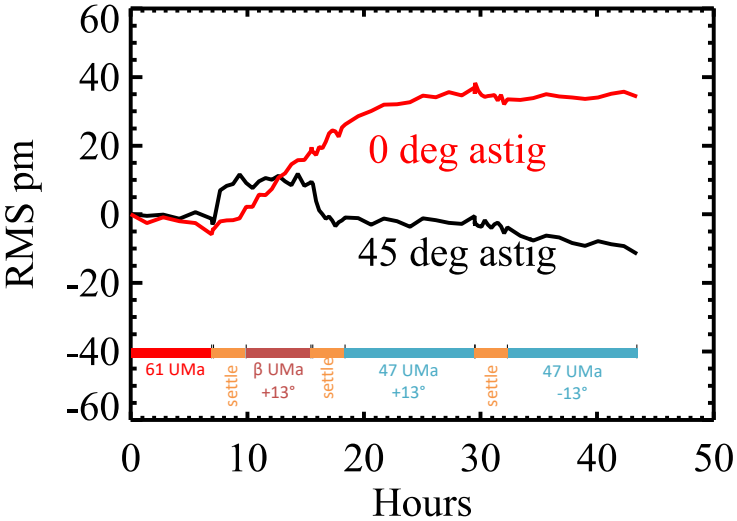
1. **Coarse Acquire Bright Star ($V \leq 3$)**
   1. ACS places the star within the imager FOV
   2. CGI sends pointing error as sensed by imager to S/C for correction
2. **Preconfigure for Dark Hole**
   1. The LOWFS determines the tip tilt (T/T), focus (FOC), and LOWF modes
   2. LOWFC actuates the FSM to zero out the measured T/T
   3. LOWFC initially zeros out focus and LOWF using FocM and DM1
   4. CGI configures masks and filters, and presets DM1 and DM2
3. **Generate Dark Hole**
   1. DM1 and DM2 generate probe fields for dark hole (DH) generation
   2. The system computer iteratively updates DM1,2, re-probes, and makes the DH deeper until delta Contrast is low enough
   3. CGI sets target FOC, LOWF for LOWFS/C based on current state; T/T setting is stored (≡TTDH)
4. **Slew to Science Star**
   1. ACS used to slew S/C to science star: FocM, DM1, DM2 frozen, TTDH saved
5. **Acquire Science Star**
   1. Similar to Bright Star Acquisition, then:
   2. LOWFC actuates the FSM targeting T/T → TTDH from best dark hole
6. **Set Dark Hole and Integrate**
   1. LOWFSC maintains T/T FOC, LOWF at targeted values
   2. DM1, DM2 are only modified to maintain LOWF

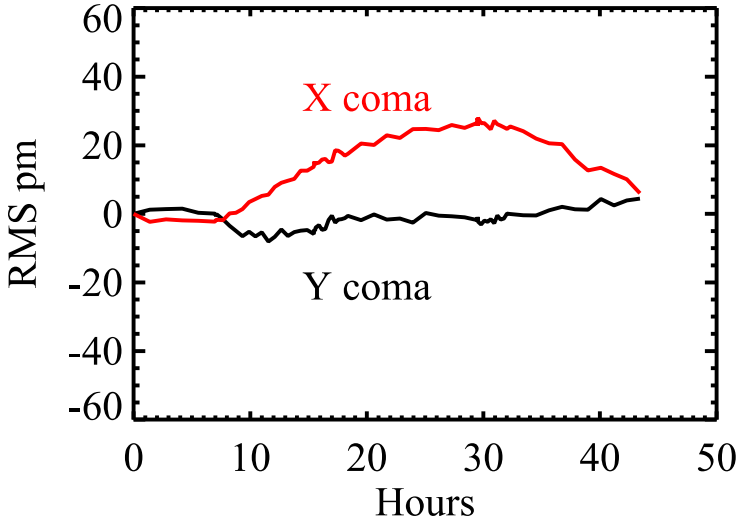
GSFC OS5 (Final) Result

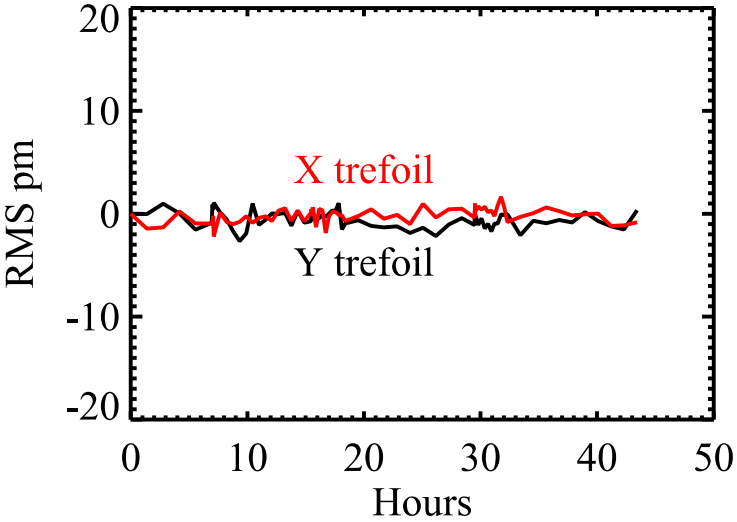




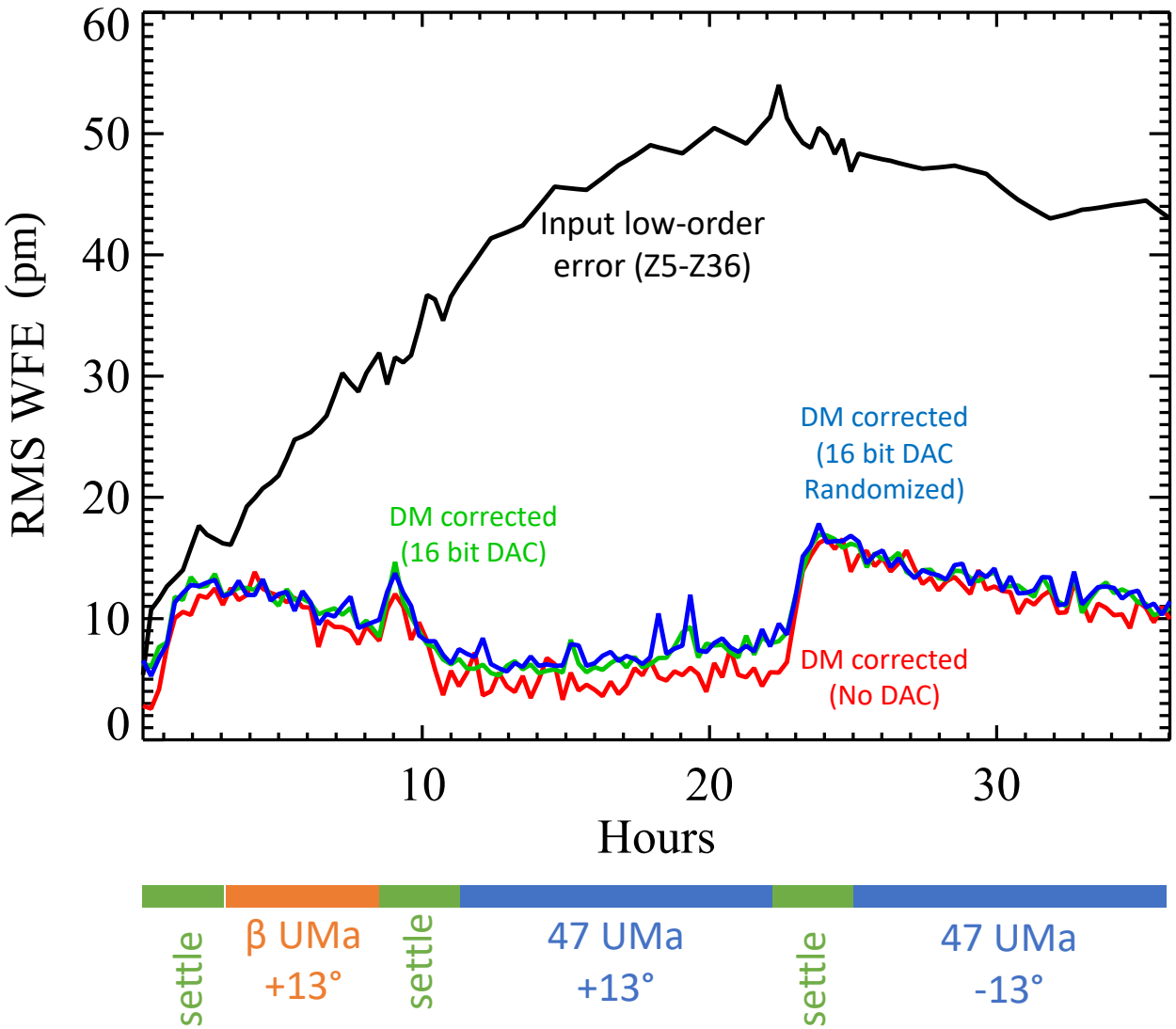








OS5 Wavefront Error: Pre- and Post-Correction



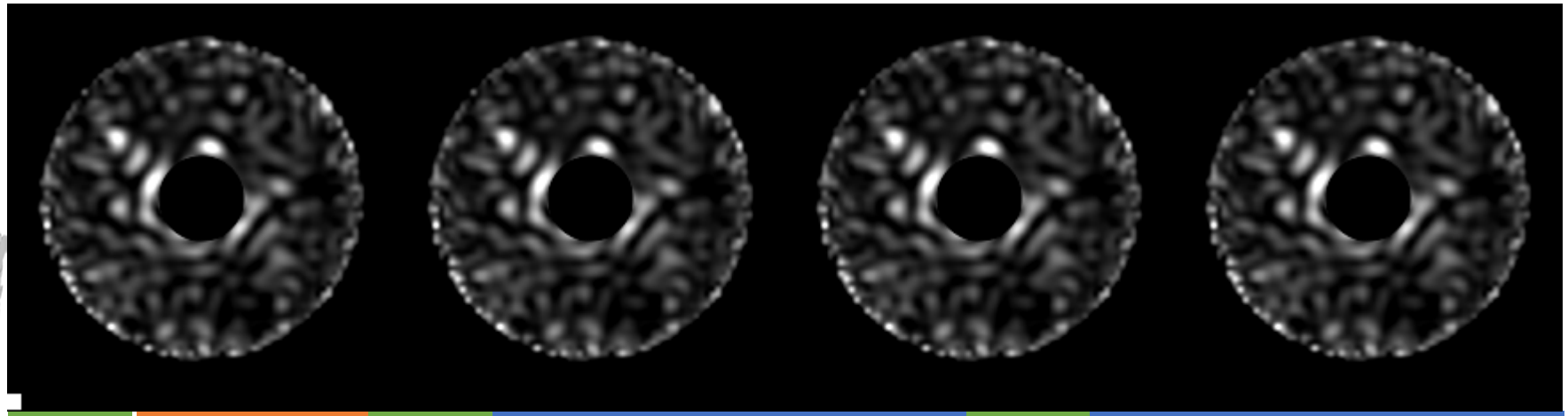
OS5 Speckle Movie

No DM LOWFC

DM LOWFC
No DAC

DM LOWFC
16 bit DAC

DM LOWFC
16 bit DAC
Randomized



settle

β UMa
+13°

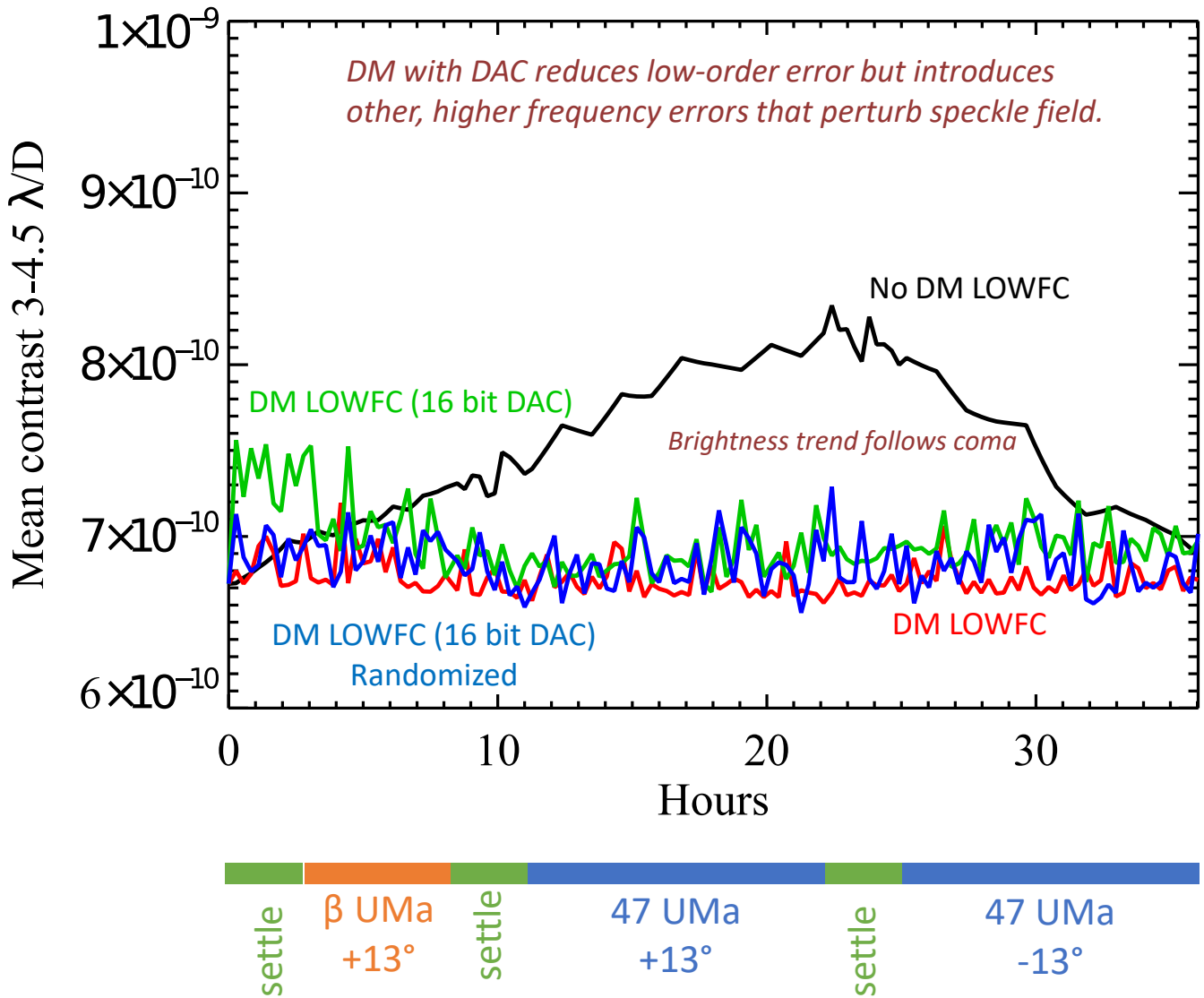
settle

47 UMa
+13°

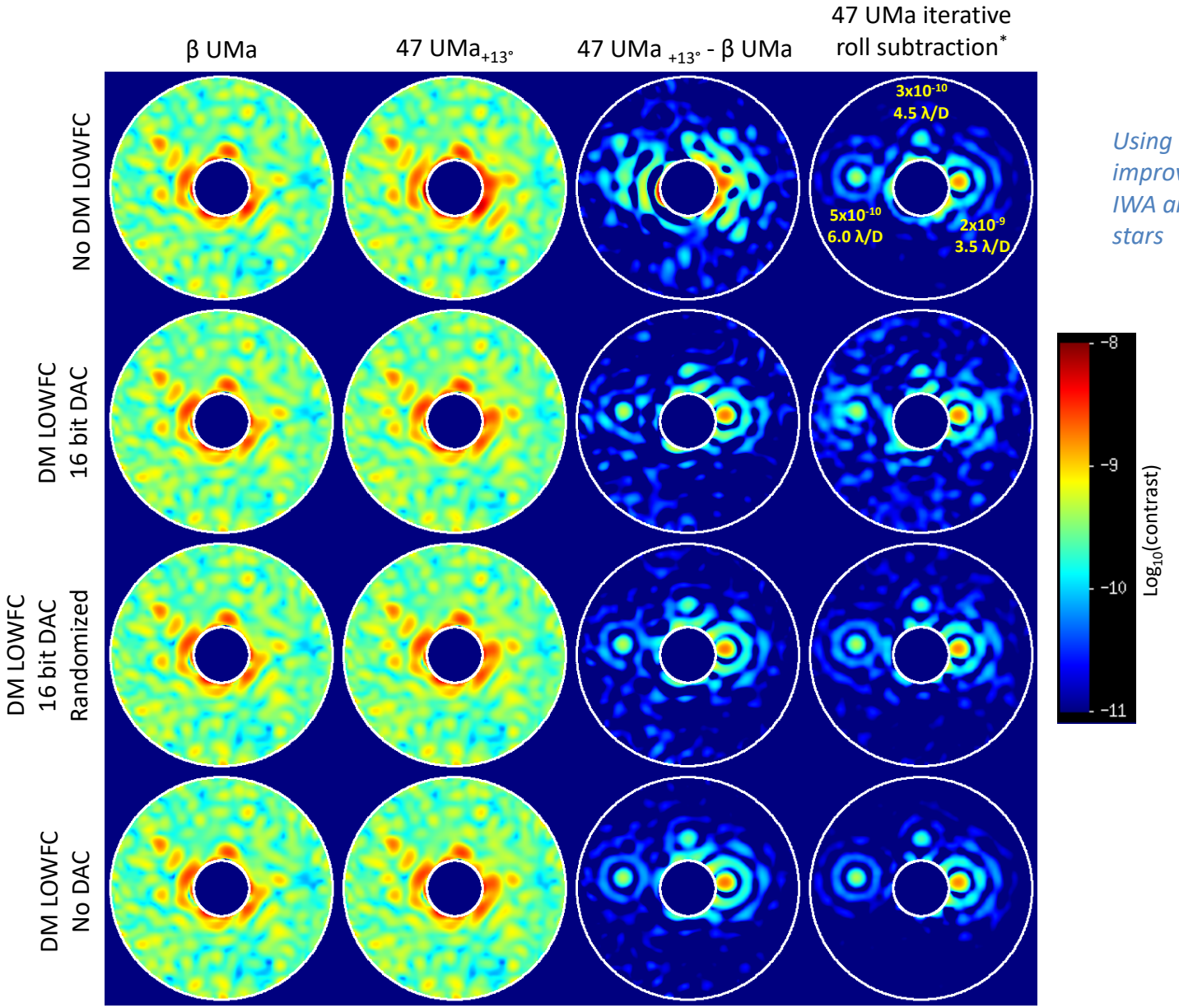
settle

47 UMa
-13°

Mean Contrast 3 – 4.5 λ/D



Reference and angular differential imaging (noiseless): coadded images



Using DM LOWFC improves stability at IWA and between stars

*Described in Krist et al., "HST and Spitzer Observations of the HD 207129 Debris Ring", Astron. J., 140, 1051 (2010).

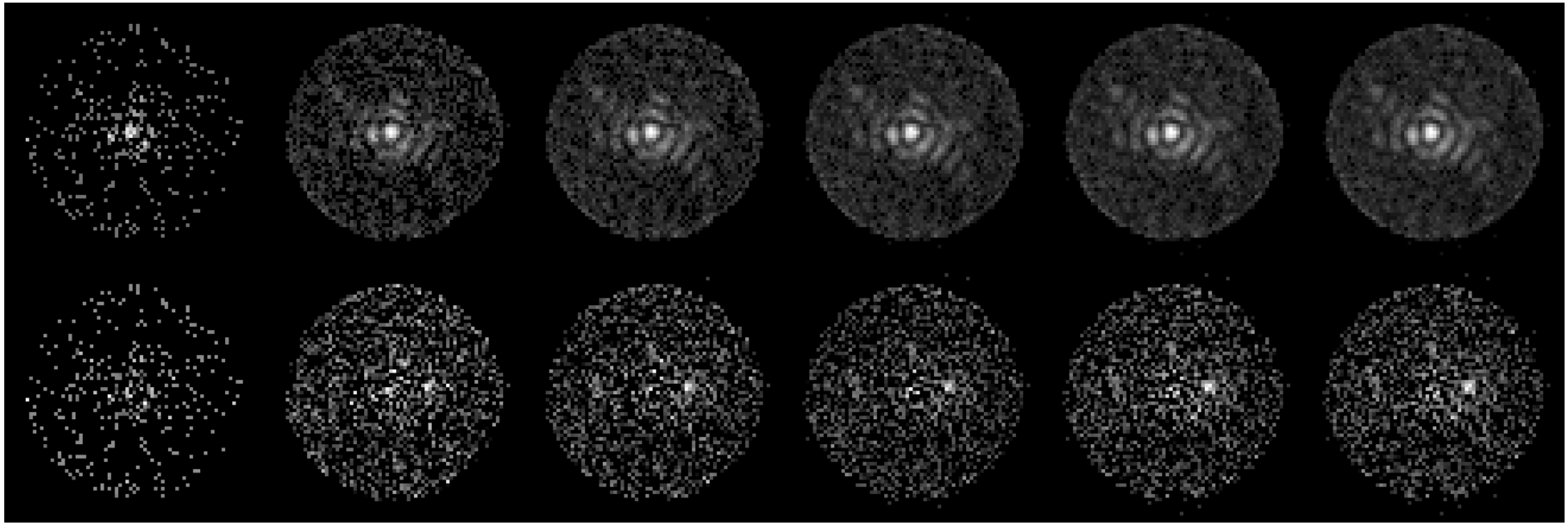
47 UMa$_{+13°}$ with Shot Noise only

Includes V=5.0 signal, losses from coronagraph, reflections, filter, polarizer, CCD
All images shown as sqrt(intensity)

1000 sec | 10000 sec | 20000 sec | 30000 sec | 40000 sec | 50000 sec

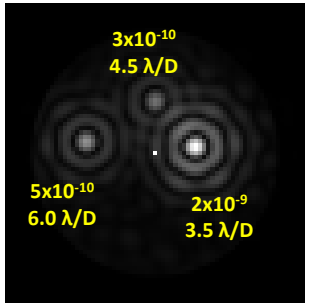
Raw

- noiseless*



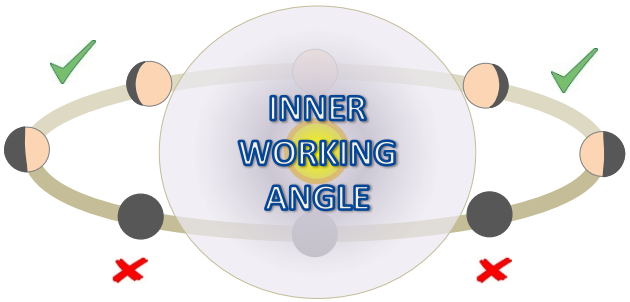
*Noisy image with planets subtracted by noiseless image without planets, revealing the planet + planet shot noise + speckle shot noise

Noiseless planets

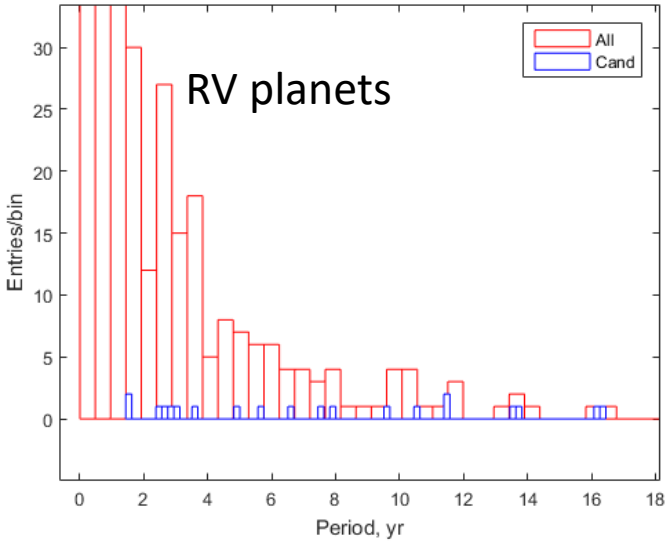


Planet Orbital Phase

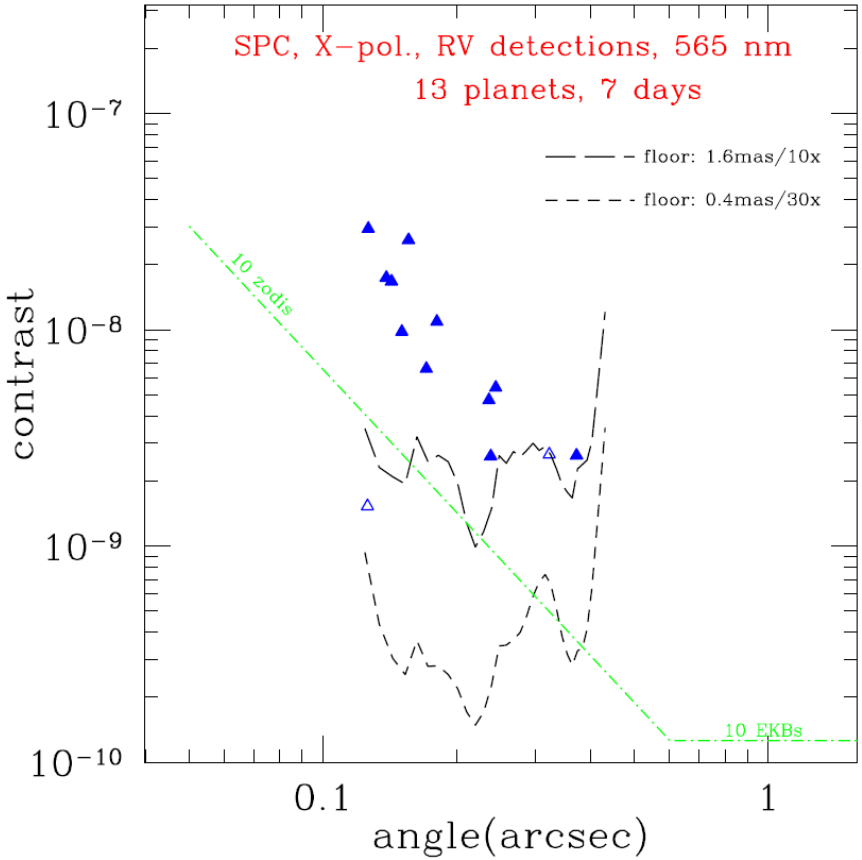
- Planet orbital phase affects the planet contrast.
- In general the planet is only viewable about 1/3 of the time
- The typical RV candidate will have an 8 year orbital period.
- We will want to optimize observation times to 'catch the planet' near a favorable phase.
- Our selected systems will be ones with orbital phase and inclination information available
- One consequence is that planet observations will necessarily be interspersed throughout the mission lifetime.
  - Early ones will see a new detector
  - Last ones will see a detector with traps

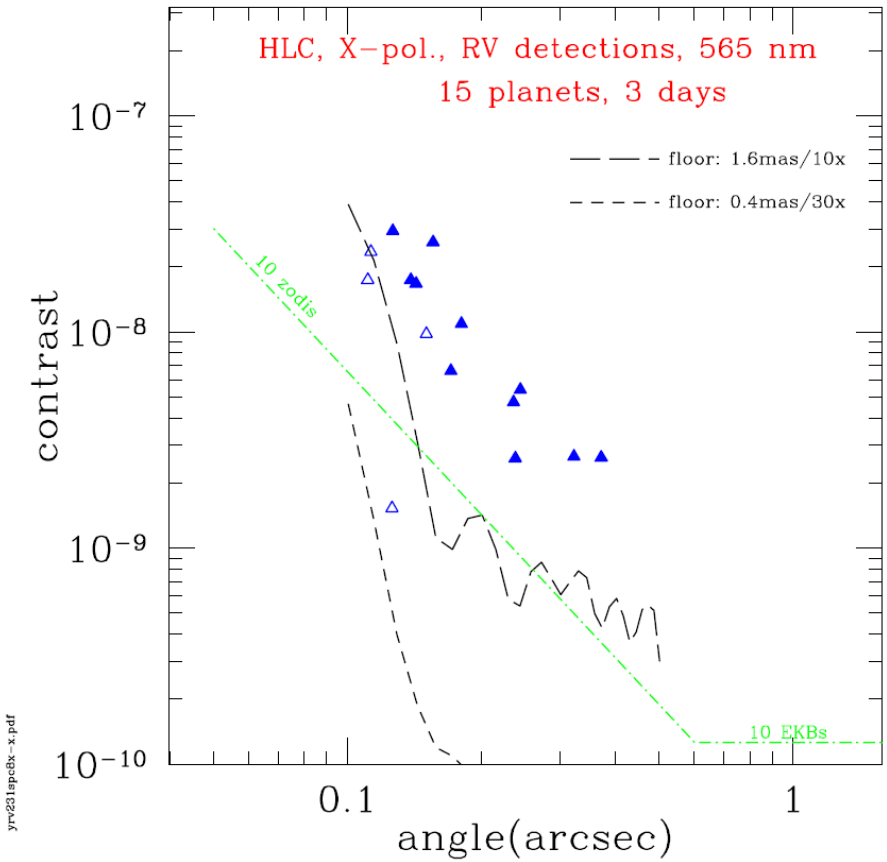


the planet will be observable only ~ 1/3 of the time

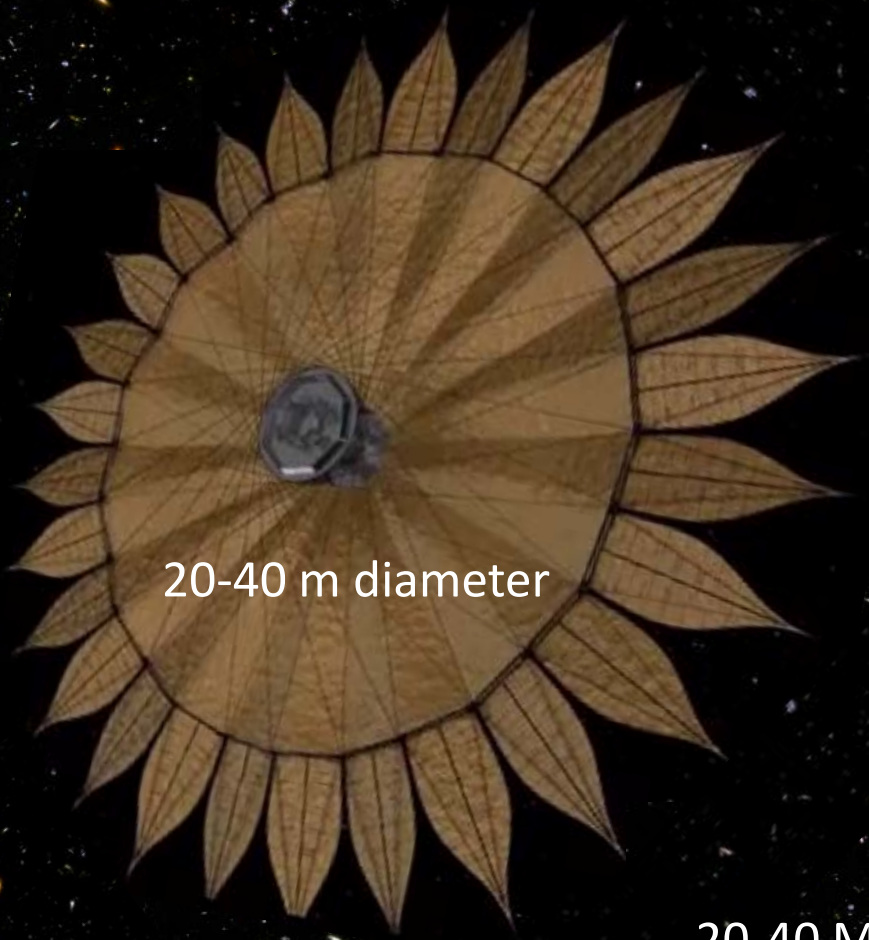


Planet Yield – RV detections





Starshade for WFIRST Rendezvous



Earth-Sun L2 Orbit

2.4 m telescope

20-40 Mm separation

What is a Starshade?

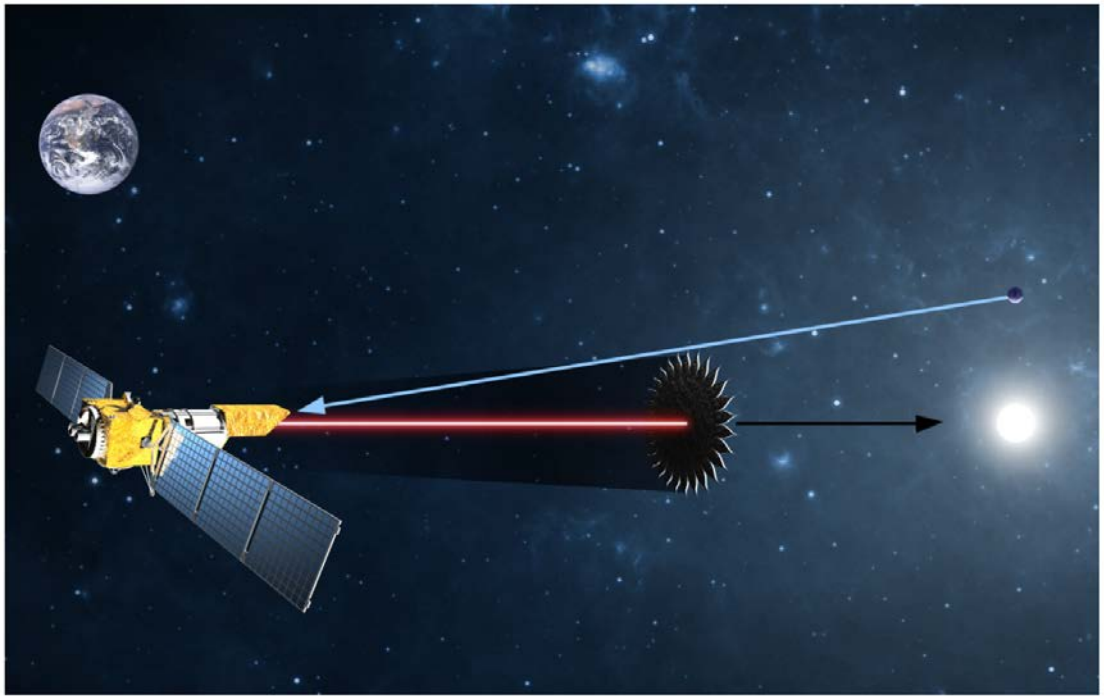


Figure ES-2. A starshade, also called an external occulter, is a precisely shaped screen that flies in formation with a telescope. The starshade blocks starlight to create a high-contrast shadow so that only planet light enters the telescope.

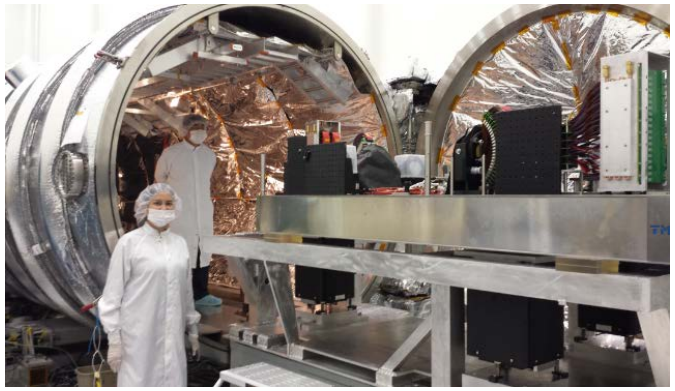
By blocking the light before it gets to the telescope, high-contrast imaging is achieved without imposing any stringent requirements on the telescope optics. Diffraction-limited imaging and few-milli-arcsecond pointing are sufficient.

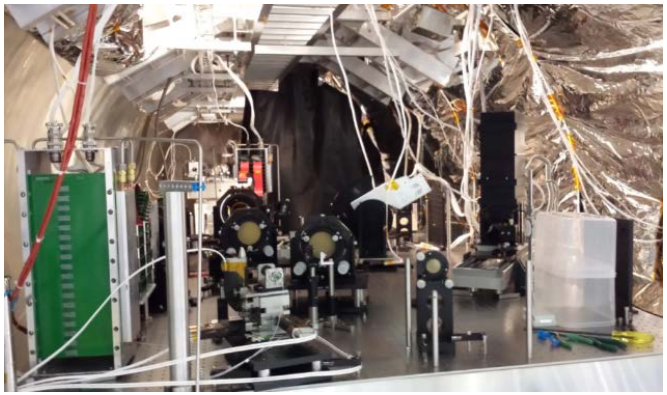
Starshade Take Aways

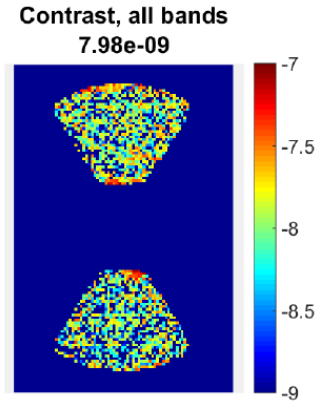
- Rendezvous Starshade will be 20-40 m in diameter, depending on science/technology goals and budget.
- It will be sensitive enough to detect Exo-Earths in the habitable zone.
- We are marching toward TRL-5.
- It will not drive any optical requirements on the telescope or wide-field instrument.

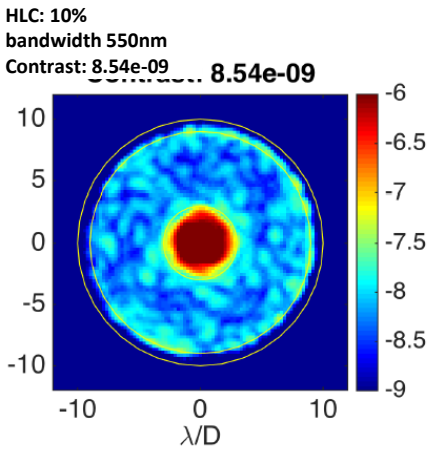
Technology: High Contrast Imaging

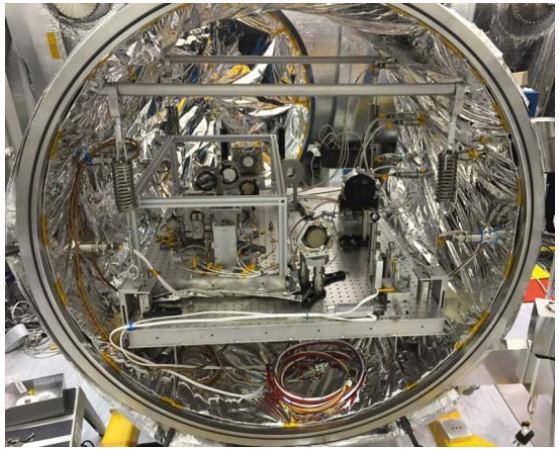
- Demonstrated broadband (10% at 550nm) high raw contrast (<1e-8) in a static environment for both
  - HLC (Hybrid Lyot Coronagraph)
  - SPC (Shaped-Pupil Coronagraph) with WFIRST telescope pupil

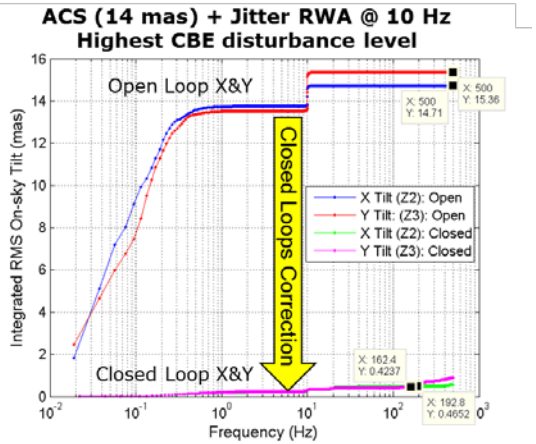








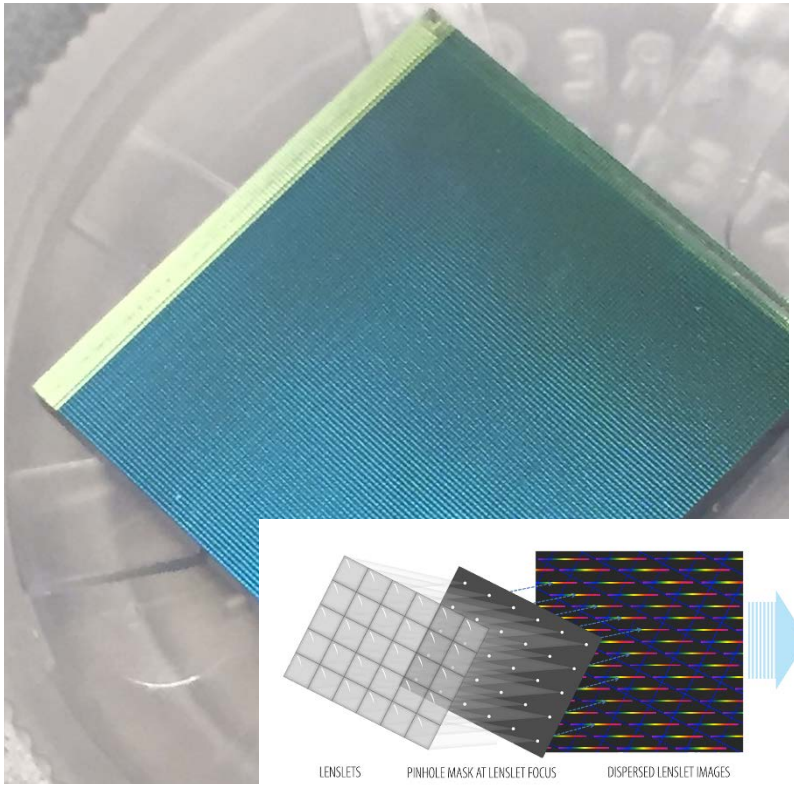


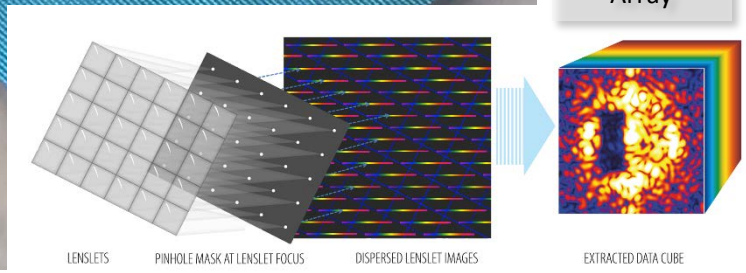


Technology – Integral Field Spectrograph

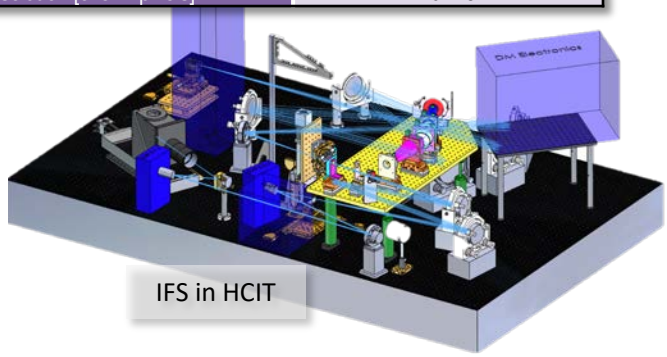
- Demonstrate key performance
  - Ability to preserve high contrast within the IFS
  - Maintain spectrophotometric precision to characterize exoplanetary atmospheres

IFS Specifications			
Band center wavelength (nm)	660	770	890
λmin (nm)	600	700	810
λmax (nm)	720	840	970
# of dispersed pixels	25.2		
Instantaneous bandpass	18%		
f/#	870		
Lenslet pitch (μm)	174		
Lenslet sampling at λ_c [# lenslets/(λ_c /D)]	3.3	3.9	4.6
FoV (# of λ_c/D*) [radius]	14.5	12.4	10.7
FoV (arcsec) [radius]	0.82×0.82		
Pinhole diameter [microns]	25 – 30		
Lenslet array format	76x76		
Magnification from lenslet to detector	1:1		
Spectral resolution [over 2 pixels]	70 ± 5		





Lenslet Array

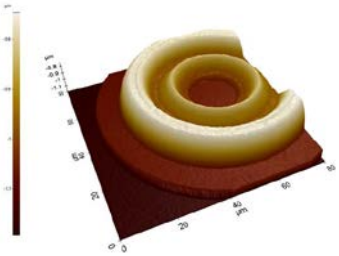


IFS in HCIT

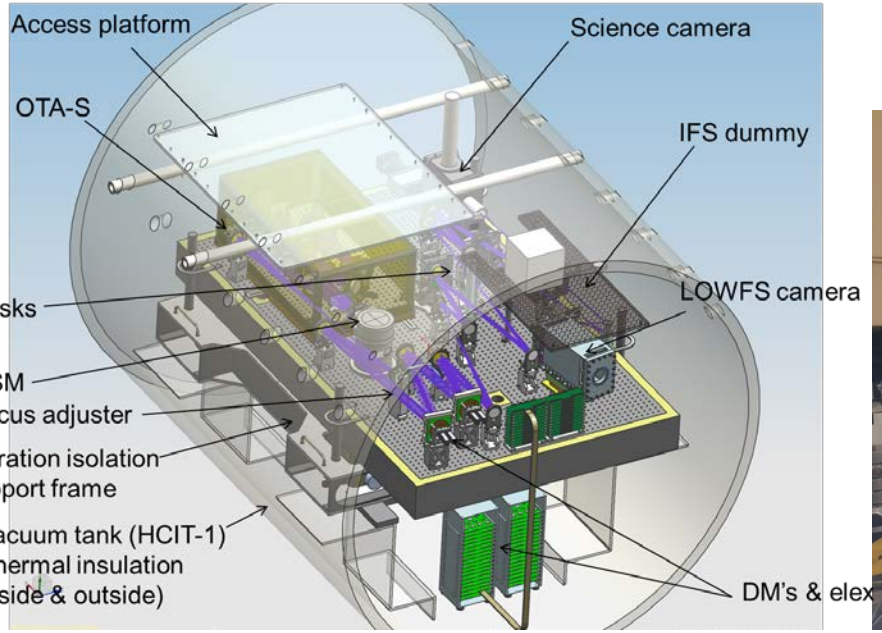
Technology Milestone #9 – TRL 5 Testbed Demonstration

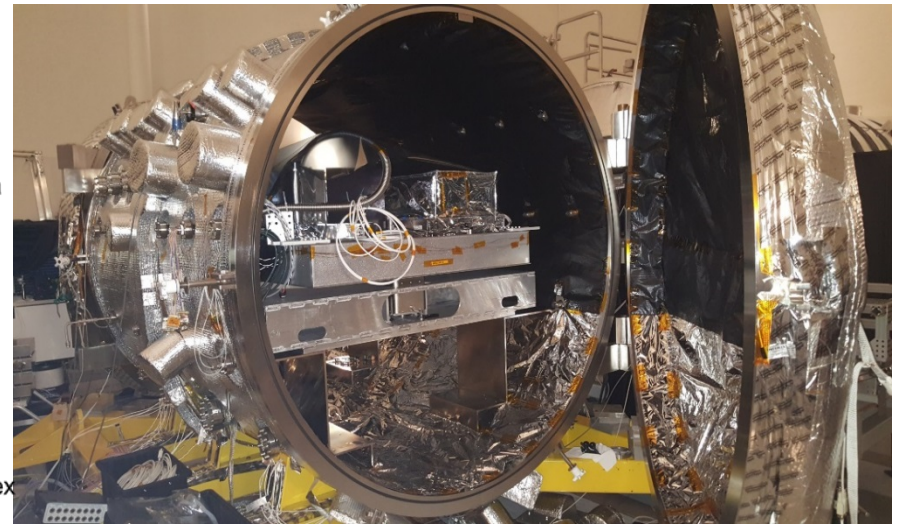
- The Next major technology milestone for the coronagraph is to demonstrate contrast at < 1e-8 with a flight-traceable design and in the presence of flight like perturbations
- Both Coronagraph settings will be tested:
  - Hybrid Lyot Coronagraph (HLC) mode
  - Shaped-pupil Coronagraph (SPC) mode
- On track for 9/30/2016 testbed demonstration (dynamic environment)

SPC mask



HLC mask





Project Status

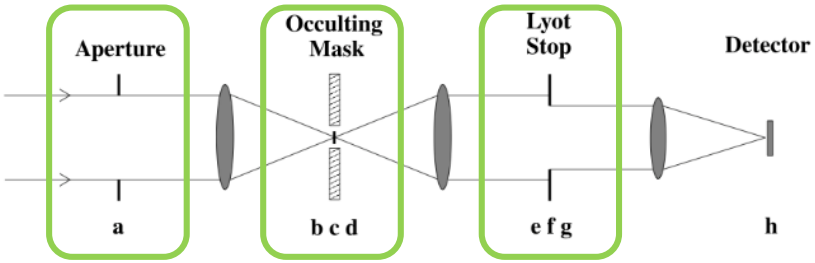
- WFIRST Coronagraph is now in Phase A and making rapid progress
- All the technology milestones so far have been successfully passed
- By October 2017 We Expect:
  - Technology flight readiness at TRL=6
  - Commence the Implementation Phase (NASA Phase B)

BACKUP

Coronagraph Background

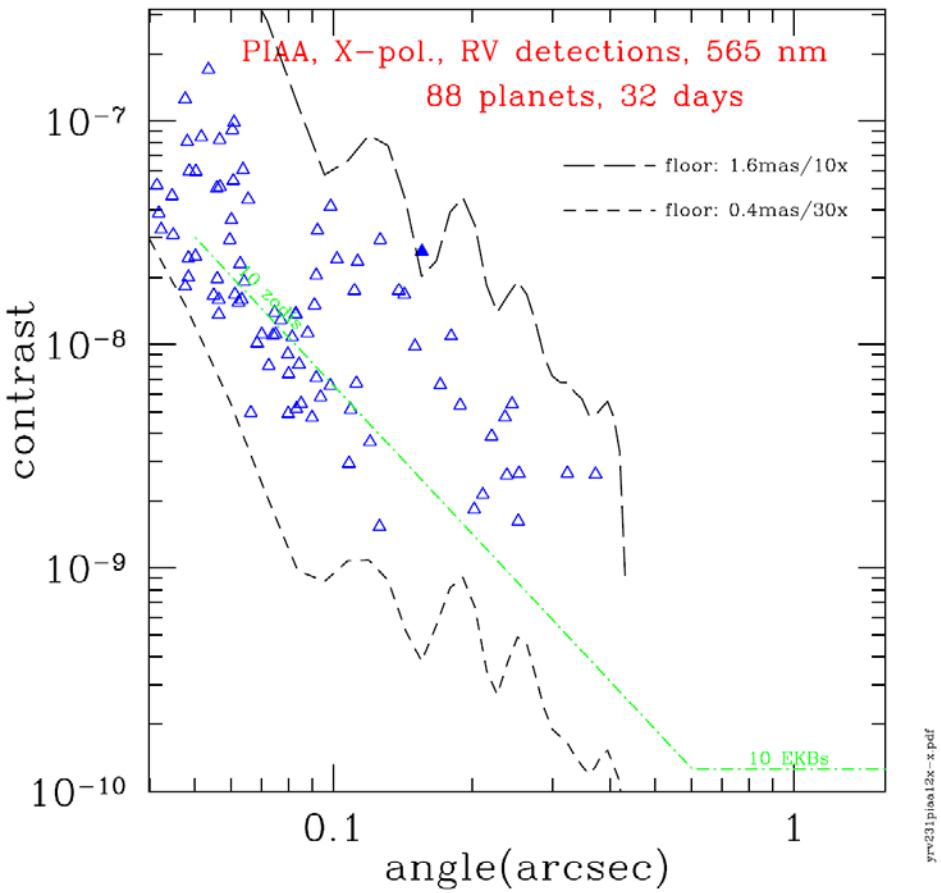
- Classic Coronagraph Description:
  - Opaque disk blocking the sun's glare, so we can see faint objects around the sun, such as corona
  - A coronagraph produces an artificial solar eclipse
    - Occulter + Lyot Stop
- Key parameters:
  - Contrast: residual light intensity outside the disk. Lower is better, allowing observing of faint objects such as exoplanets
  - Inner working angle (IWA): outer edge of the blocking disk. Smaller is better, allowing observing objects closer to the sun (star)
  - Outer working angle (OWA): outer most edge of the dark field

- High Contrast Imaging of Exoplanets
  - Contrast: $<10^{-8}$
  - IWA: ~100 – 250 mas



Need a space coronagraph with precision wave-front control.

PIAA


PIAA, X−pol., RV detections, 565 nm
88 planets, 32 days
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floor: 0.4mas/30x
10 EKBs
contrast
10^{-7}
10^{-8}
10^{-9}
10^{-10}
0.1
1
angle(arcsec)
yrv231piaa12x−x.pdf