NOTE TO THE REVIEWERS:

MOST OF THE FOLLOWING SLIDES WERE PREVIOUSLY CLEARED UNDER URS-259072

NEW SLIDES ARE MARKED WITH A NEW

Jet Propulsion Laboratory
California Institute of Technology

WFIRST Coronagraph: Status and Performance Expectations

Bijan Nemati

WFIRST Coronagraph Modeling Lead

Jet Propulsion Laboratory,

California Institute of Technology

UAH CAO – February 6, 2017

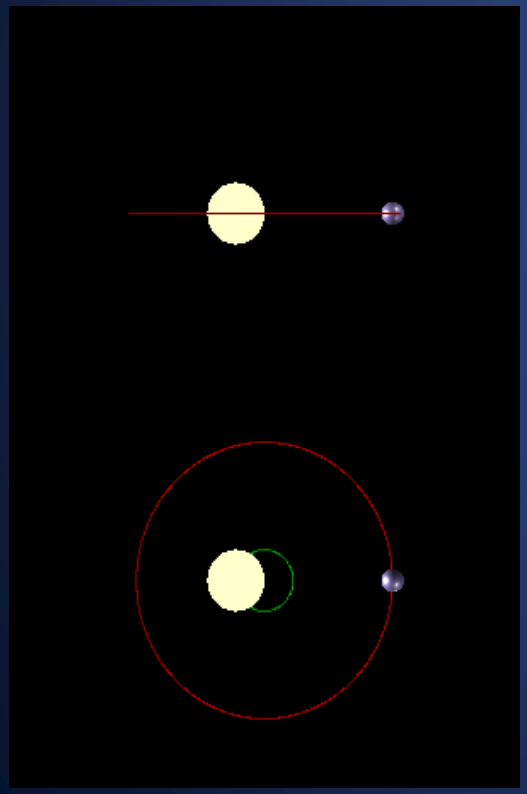
+ possibly more in the future! …

Jet Propulsion Laboratory
California Institute of Technology

Searching for Exo-planets

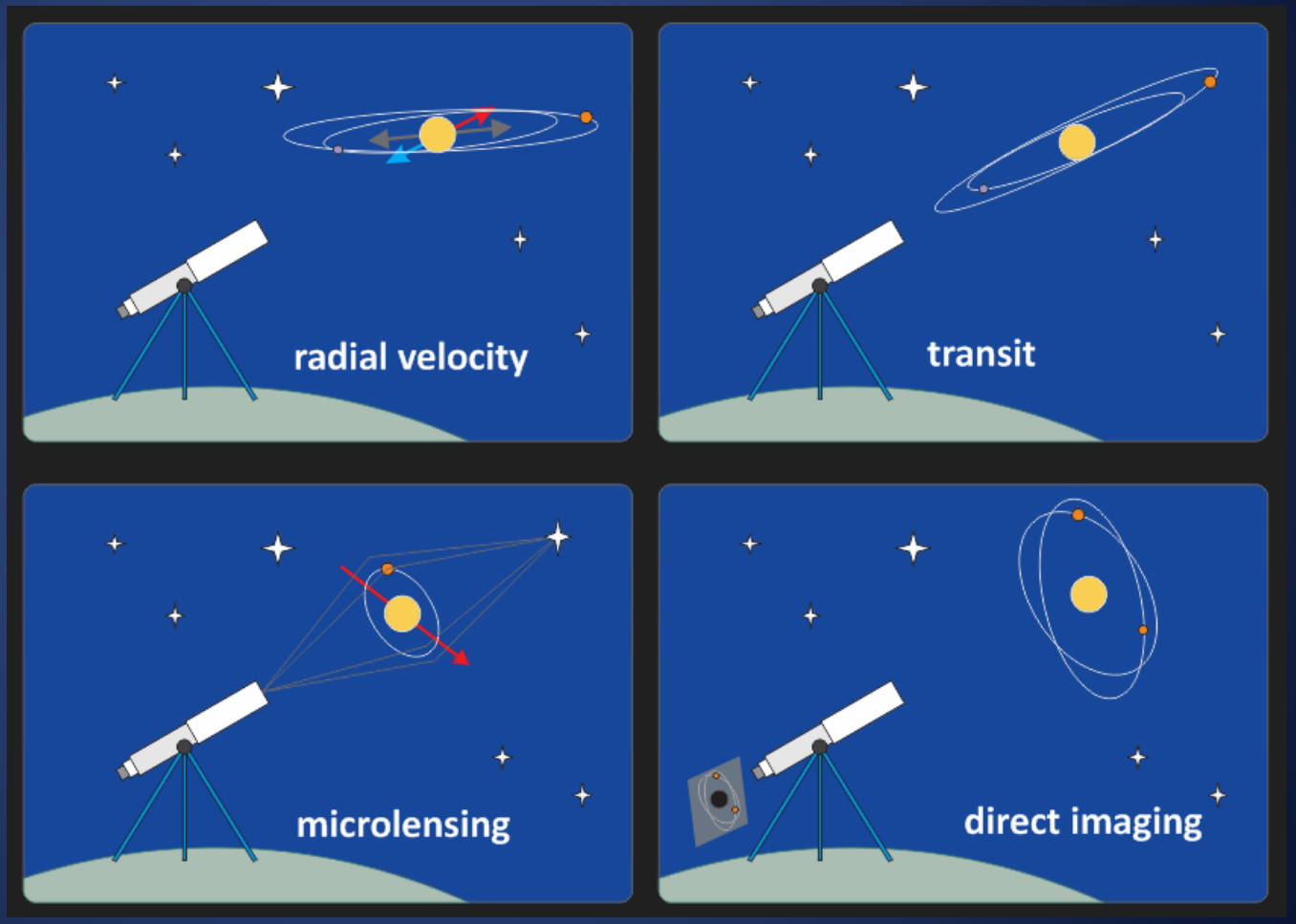
NEW

Exo-planet searches over past 20 years have yielded thousands of planets around other stars.



Measure the star's motion back and forth towards us (red shifts and blue shifts)

Look for a dip in the brightness of the star as the planet moves in front of it

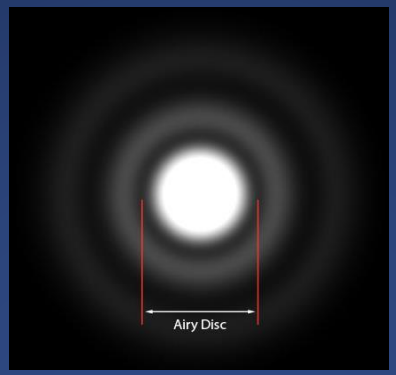


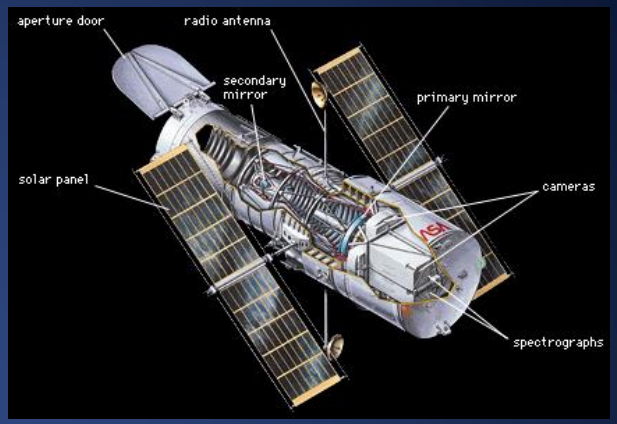
Measure the light from a "source" star while the lensing star and planet move in front of it

Blot out the star light (with a coronagraph) and take a picture of everything around it

How Hard is it to Image Exoplanets?

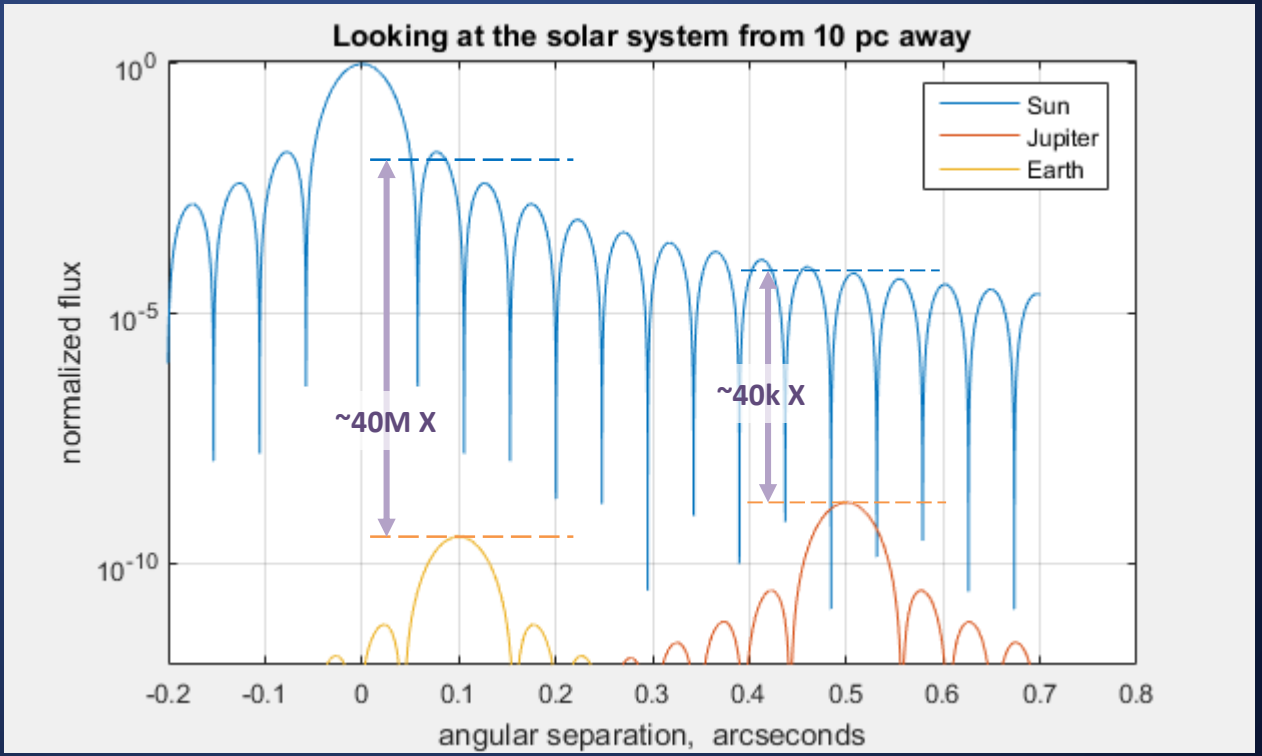
- Diffraction of the star's light **buries** the planet light





- Signal to noise ratio is very small!

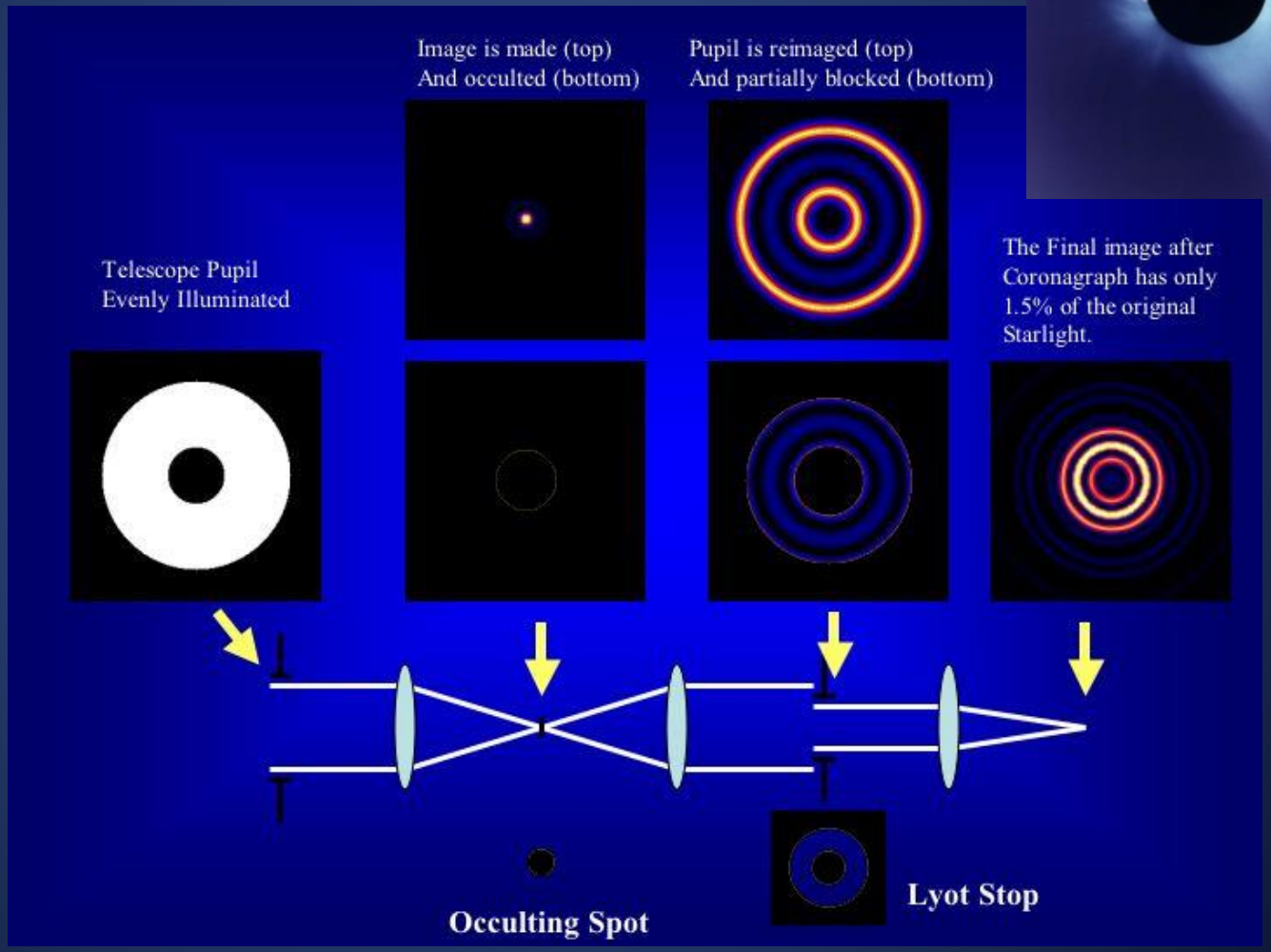
NEW



The Coronagraph

NEW

Bernard Lyot, 1939
French Astronomer
Inventor of the Coronagraph



http://lyot.org/background/coronagraphy.html

WFIRST Coronagraph

What is WFIRST?

Wide-**F**ield **I**nfrared **S**urvey **T**elescope

Originally recommended by the 2010 U.S. Decadal Committee

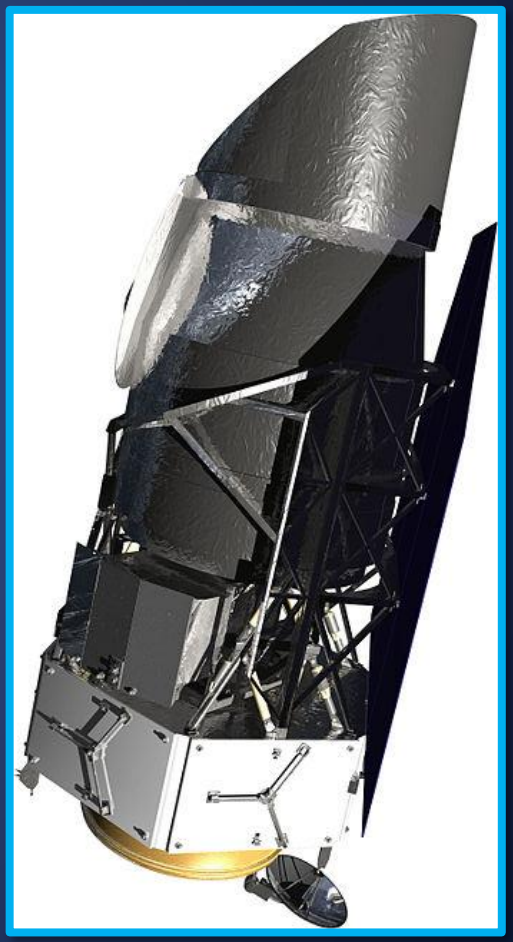
- Characterize the history of cosmic acceleration and structure growth
- Explore Exoplanet Statistics via Planetary Microlensing

The Coronagraph was later added on:

- The first high contrast, active coronagraph in space, to demonstrate:
  - Exoplanet direct imaging
  - Planet Atmosphere Characterization
  - Characterization of debris disks

Precursor for future exo-Earth missions

Existing, Flight Qualified 2.4 m obscured telescope



How It Works

NEW

Video is from https://exoplanets.nasa.gov/exep/coronagraphvideo/

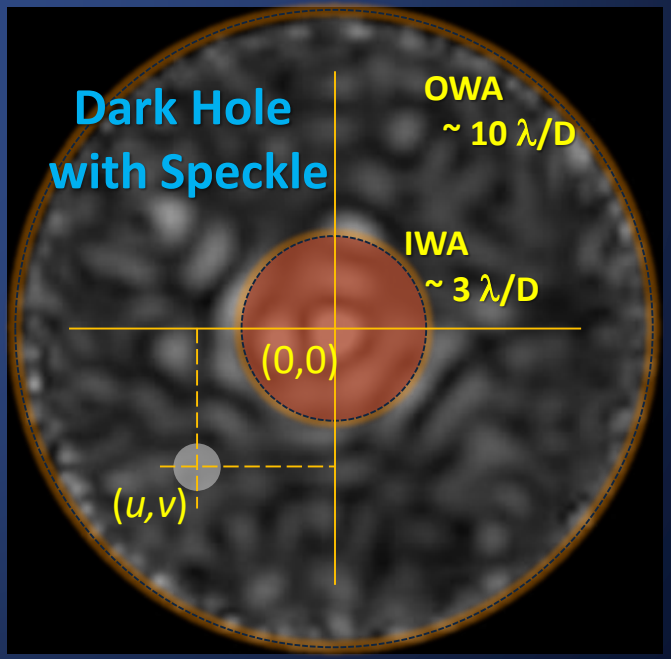
Coronagraph Jargon

- The Coronagraph is designed to suppress the starlight in a given region called a dark hole (DH)
- It does so by controlling phase and amplitude of the incoming wavefront
- The dark hole limits:
  - Inner Working Angle (IWA) : set by coronagraph optics
  - Outer Working Angle (OWA) : set by the number of deformable mirror actuators
- Speckles (or halo) are the residual light after dark hole is created
- The most oft-quoted instrument attribute is the coronagraph contrast:

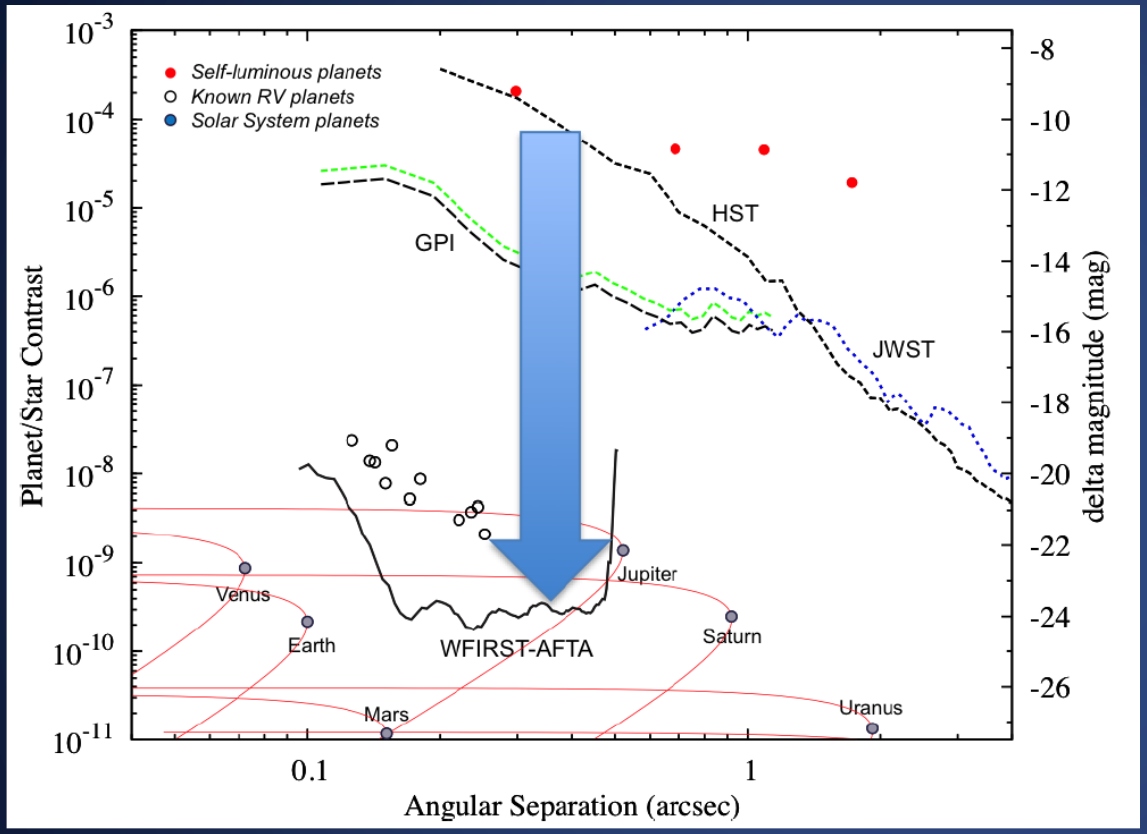
evaluation location | source location

$$C_{CG}(u,v) \equiv \frac{I_{star}(u,v;0,0)}{I_{star}(u,v;u,v)}$$

- Planet Contrast is simply the ratio of planet flux to stellar flux entering the telescope



WFIRST Coronagraph Exploration Space



Design	Value	Comments
Bandpass	430 - 980 nm	Measured sequentially in 10% and 18% bands
Inner Working Angle	150 mas	at 550nm, 3λ/D driven by telescope pupil obscurations
	270 mas	at 1μm
Outer Working Angle	0.5 as	at 550nm, 10λ/D, for highest contrast
	0.9 as	at 1μm, 10λ/D
	0.95 as	at 550, 20λ/D, lower contrast
	1.7 as	At 1μm, 20λ/D, lower contrast

https://wfirst.ipac.caltech.edu/

http://wfirst.gsfc.nasa.gov/science/WFIRST_FactSheet_final.pdf
FS-2014-5-153-GSFC

WFIRST Flight System

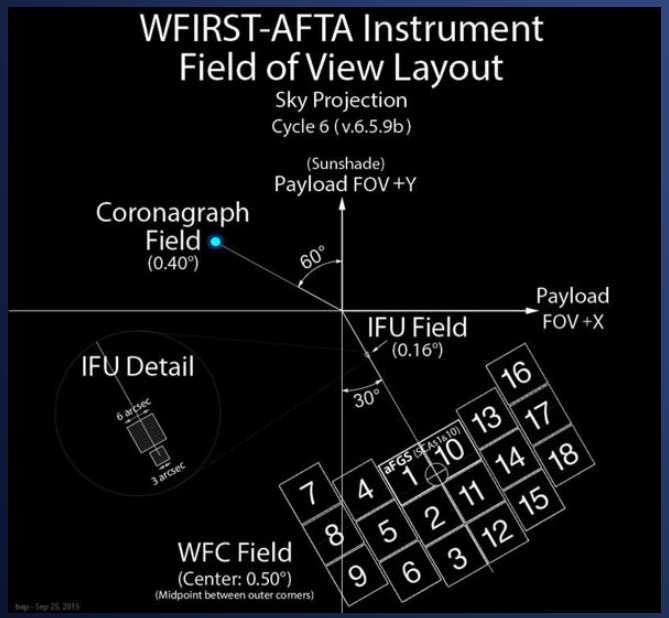
Two instruments:

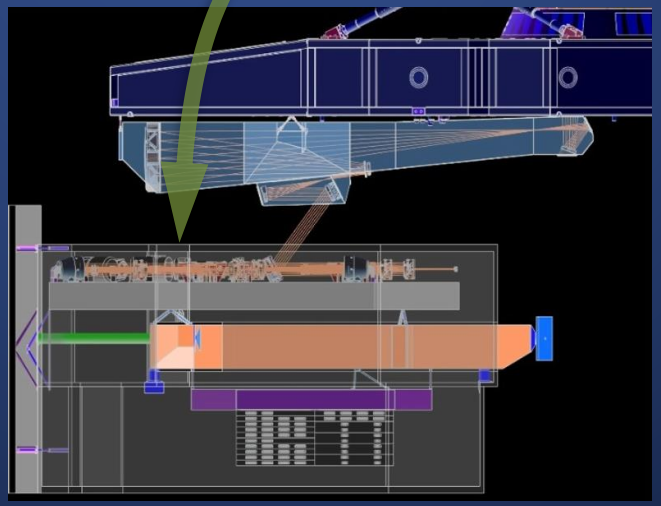
1. Wide field imager
2. Coronagraph

Orbit: Sun-Earth L2 Orbit

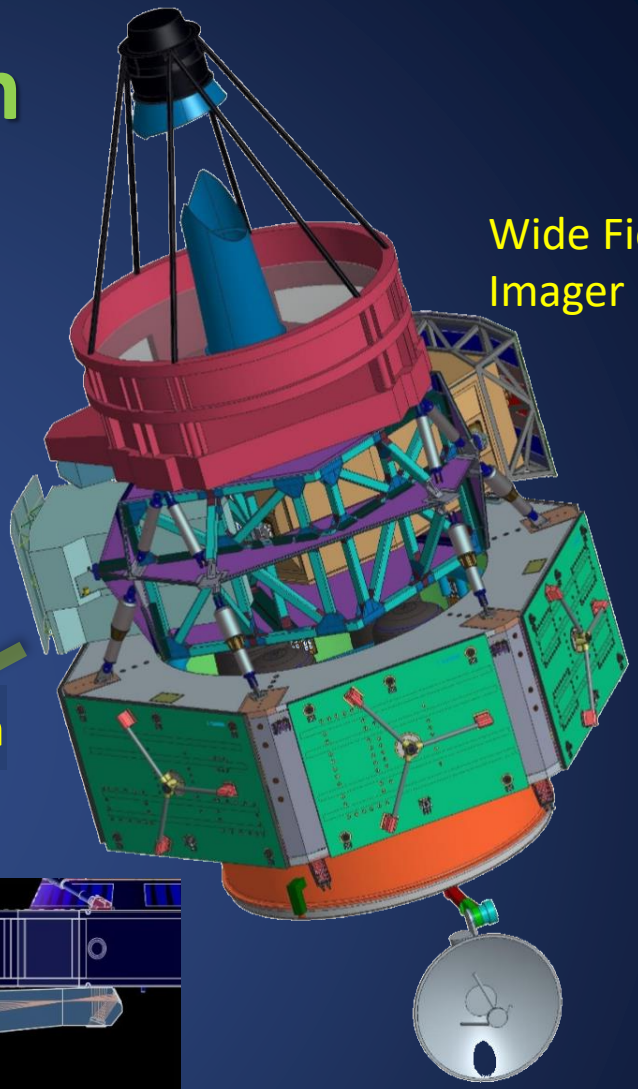
Launch: 2024 on Delta IV or Falcon heavy

Mission Duration: 6 yrs. Nominal





Coronagraph



Wide Field Imager

Coronagraph is allotted 1 year of the mission

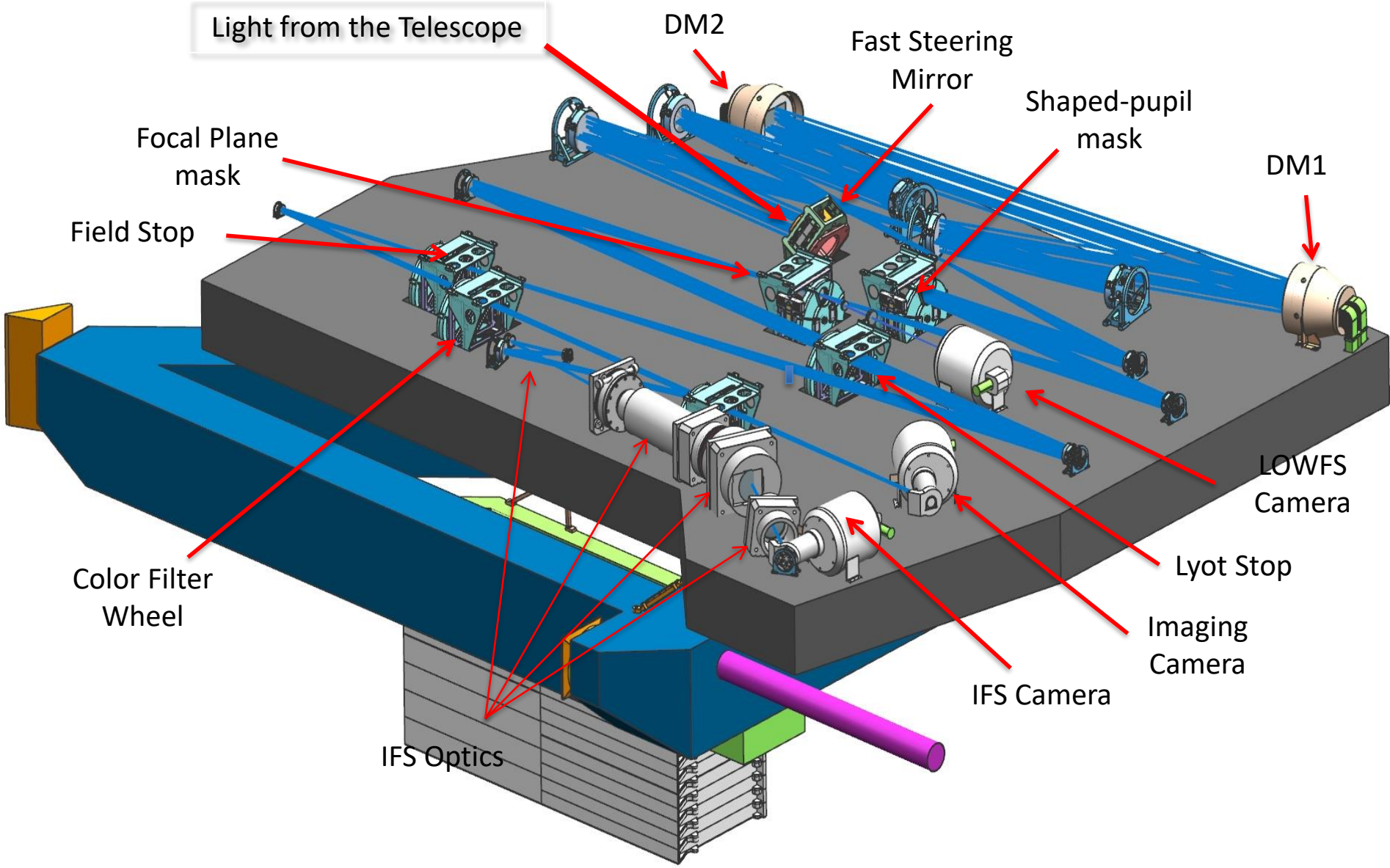
WFIRST Primary Mirror Assembly

NEW

Primary Mirror Assembly , Harris Corporation / TJT Photography

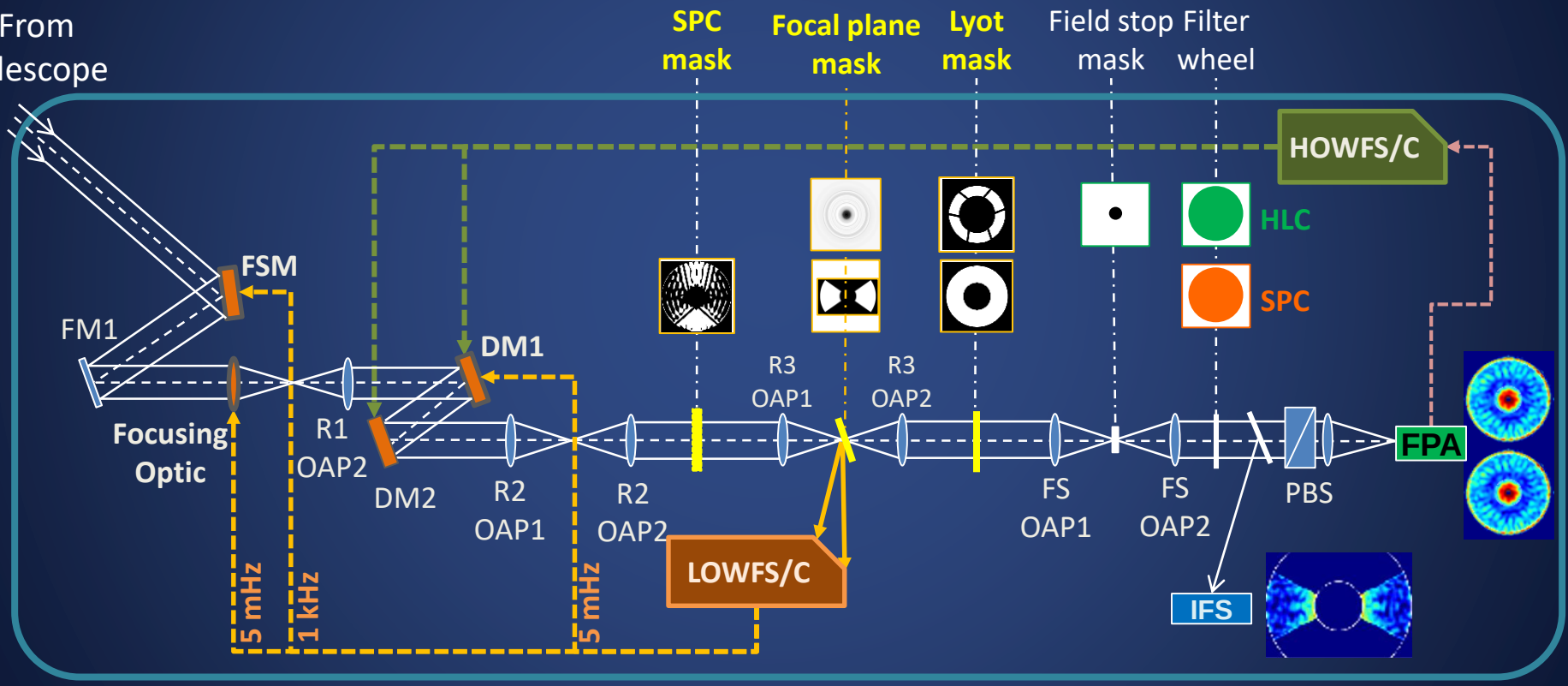
https://wfirst.gsfc.nasa.gov/gallery-photos.html

Coronagraph Optical Design



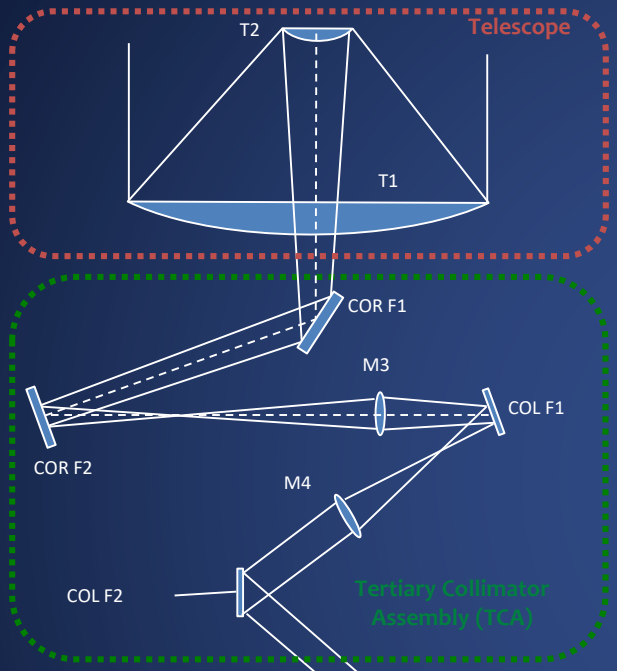
Coronagraph Optical Layout

Three Coronagraph configurations for a variety of science applications



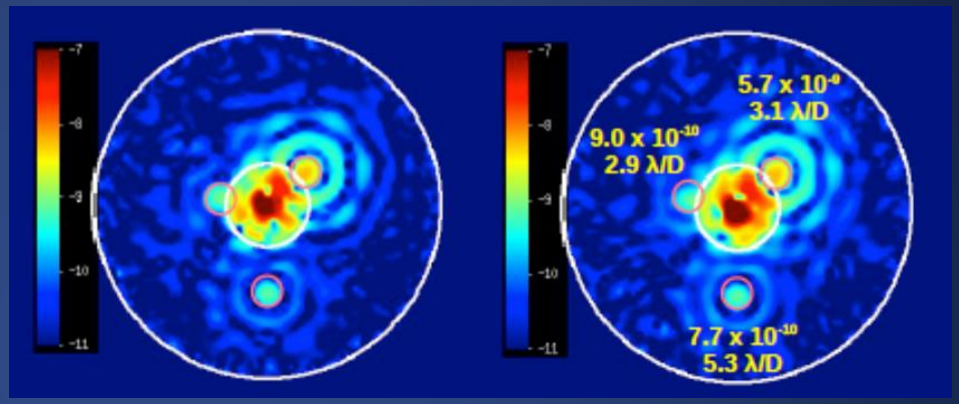
Coronagraph Instrument

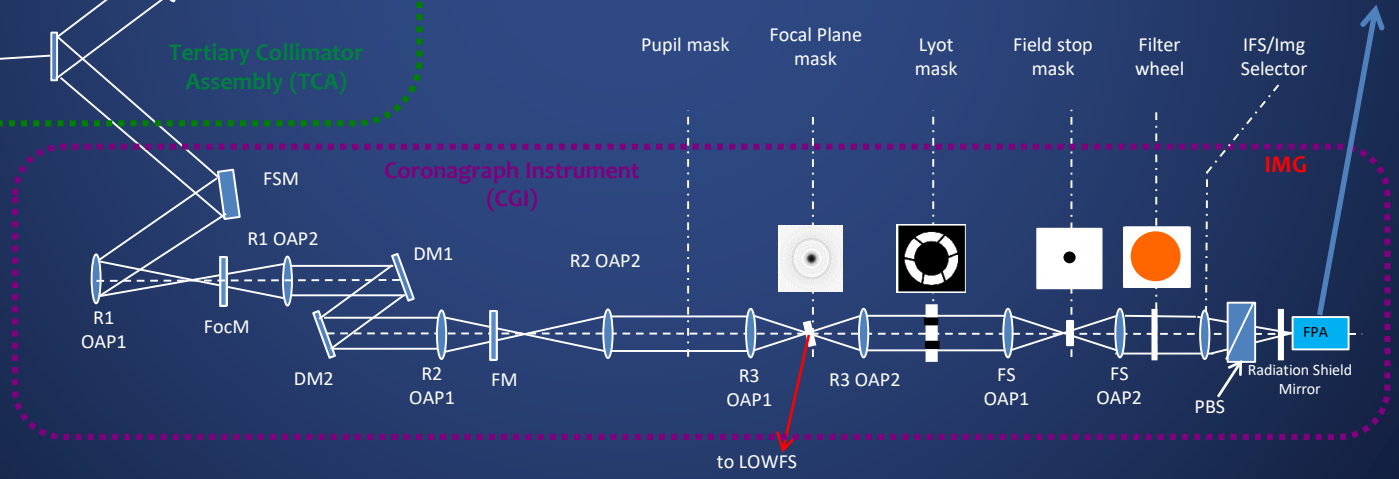
Hybrid Lyot Configuration



Hybrid Lyot Mode

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

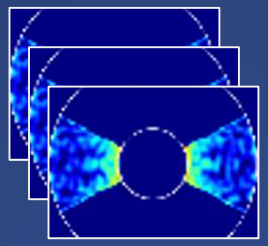




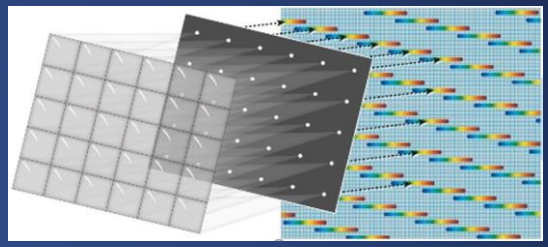
Shaped Pupil – Spectral Characterization

Shaped Pupil Spectroscopy Mode

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

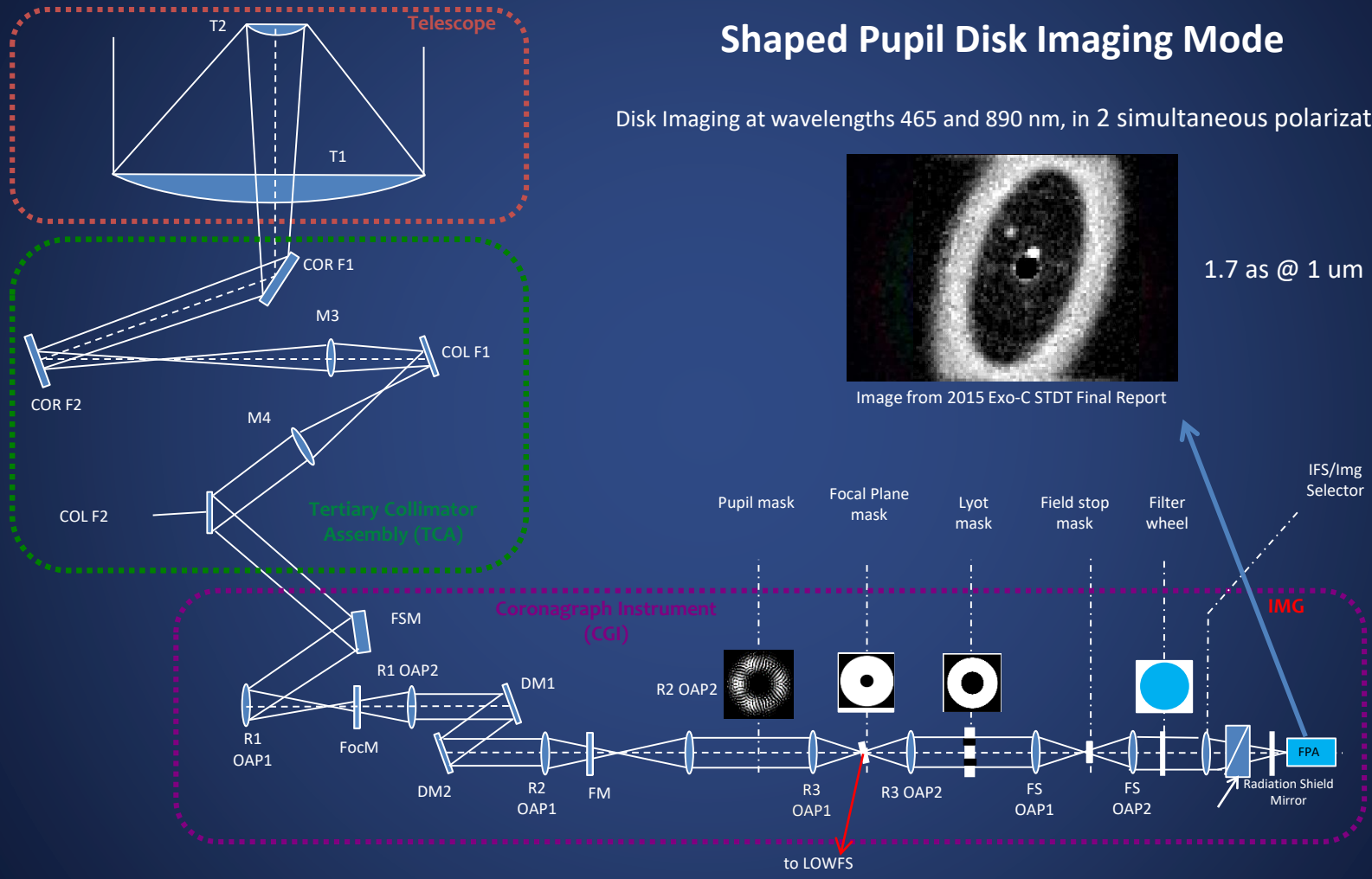


SPC images in 3 18% bands



lenslet array | pinhole mask | dispersed lenslet images

Shaped Pupil – Disk Imaging



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

1.7 as @ 1 um

Planet Orbital Phase

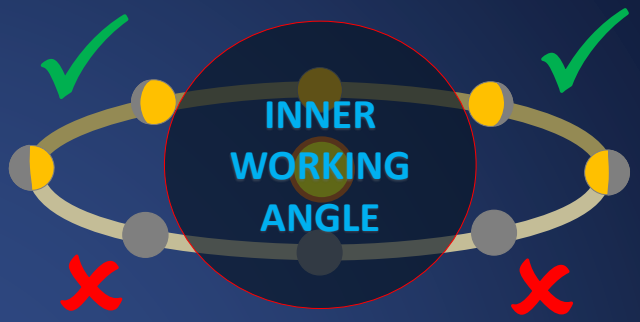
Planet orbital phase affects the planet contrast.

In general the planet is only viewable about 1/3 of the time

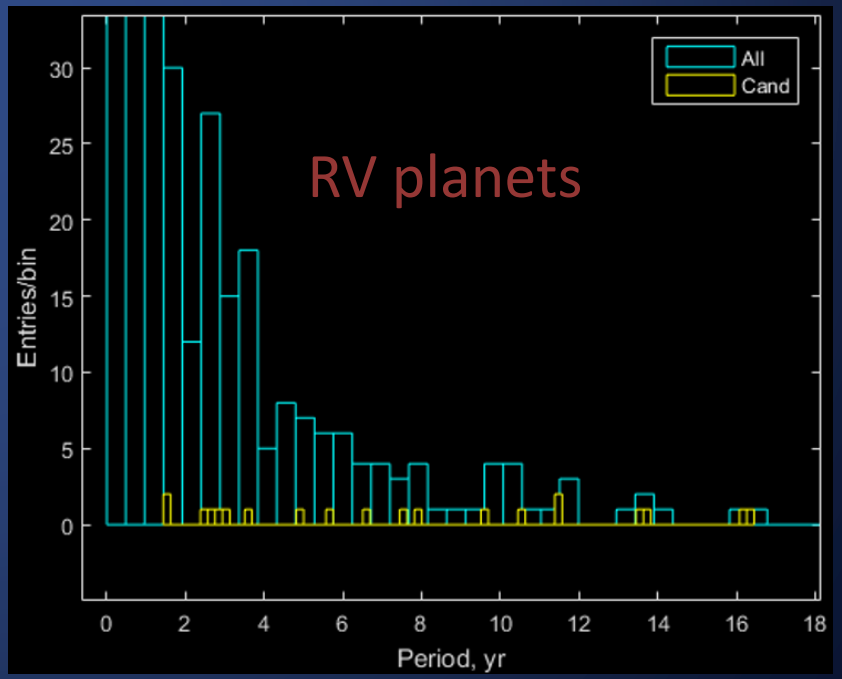
The typical RV candidate will have an 8 year orbital period.

Will optimize observation times to 'catch the planet' near a favorable phase, using improved orbital phase and inclination data.

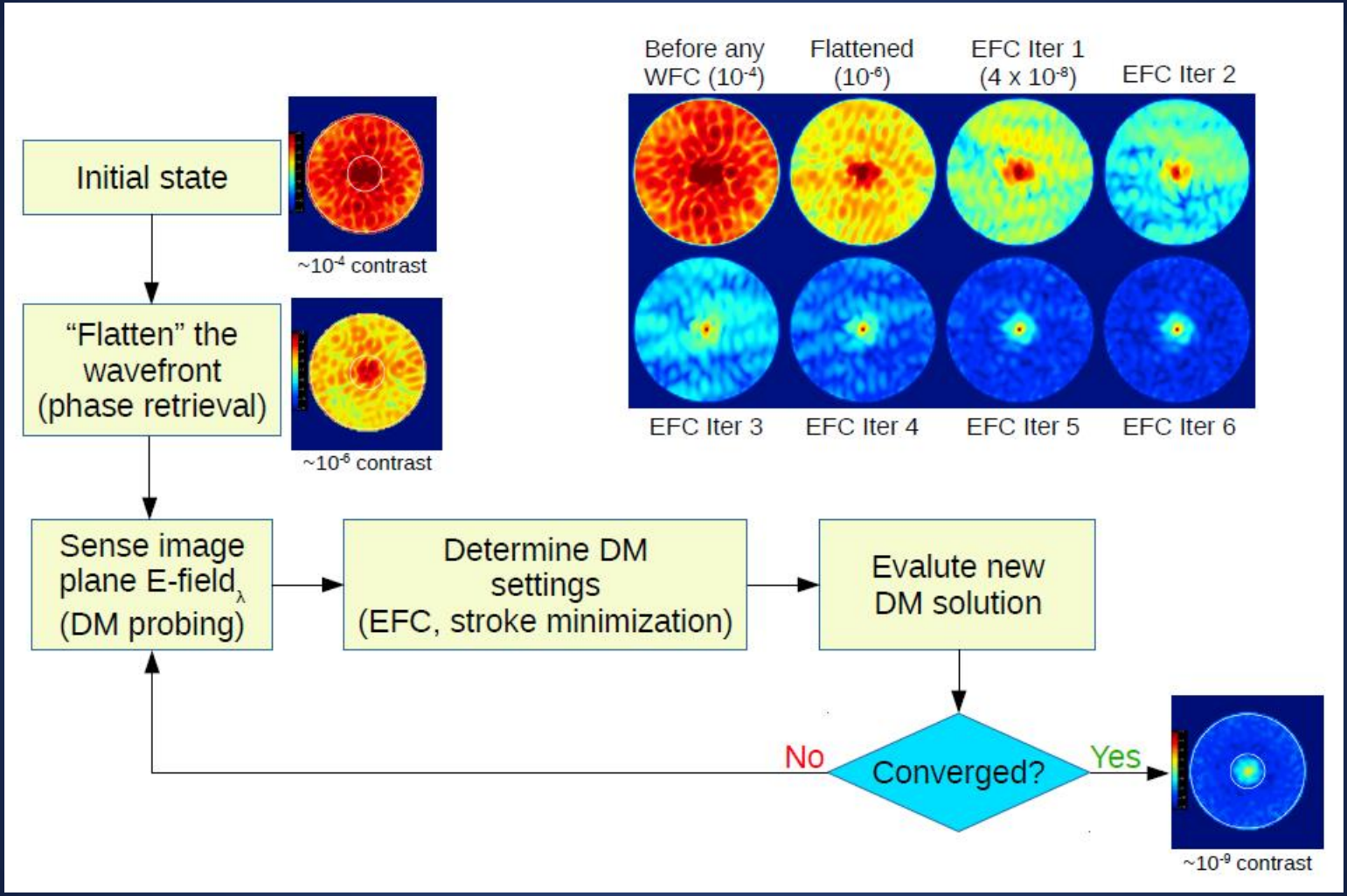
Planet observations will necessarily be interspersed throughout the mission lifetime.



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

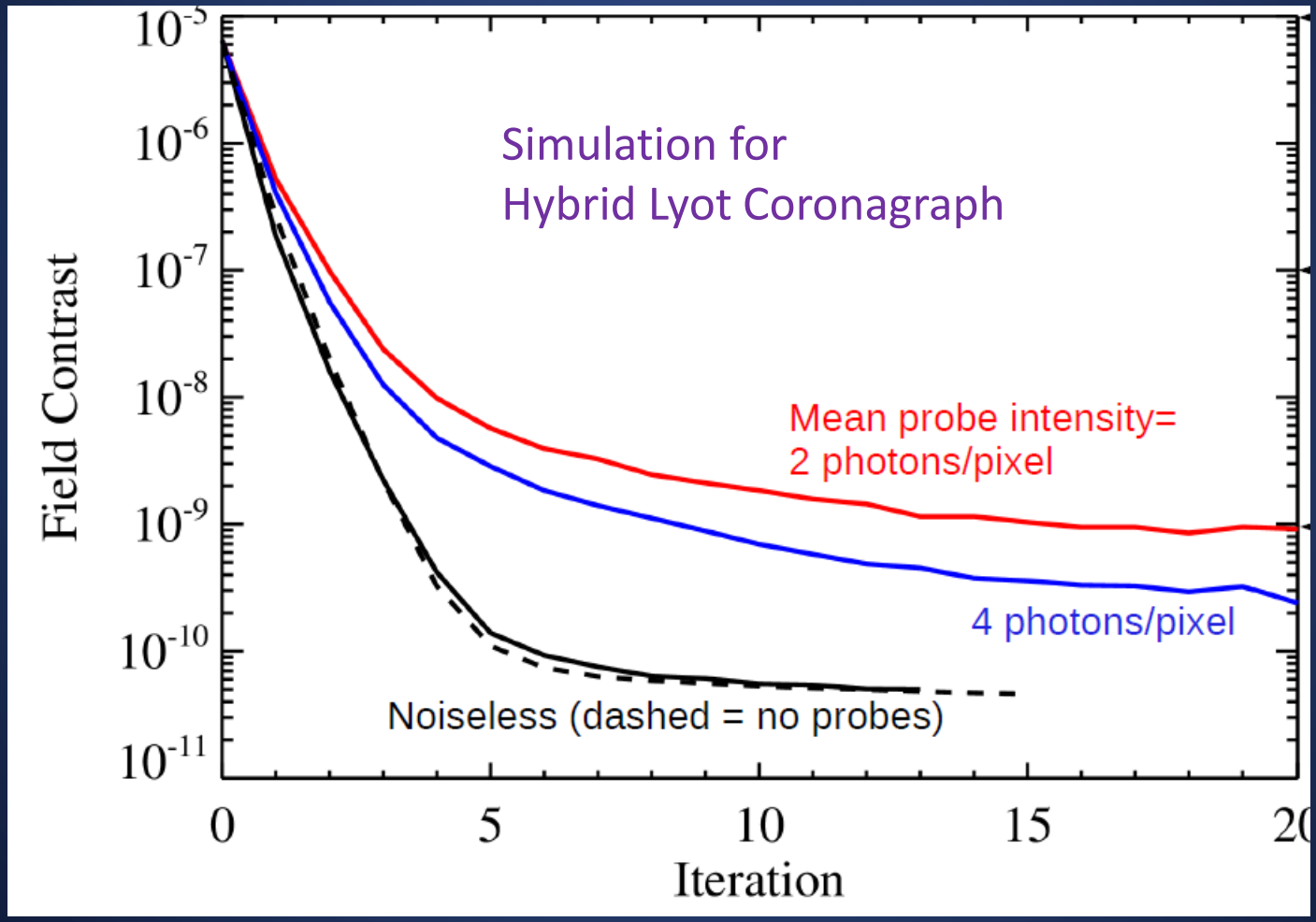


Dark Hole Generation Process



Digging A Dark Hole: Contrast vs. Iteration

WFIRST requirement is C < 1e-8 before post-processing

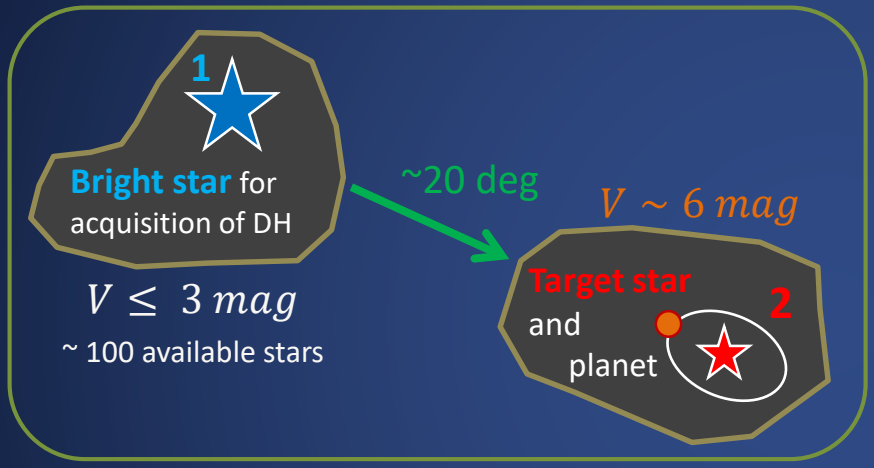


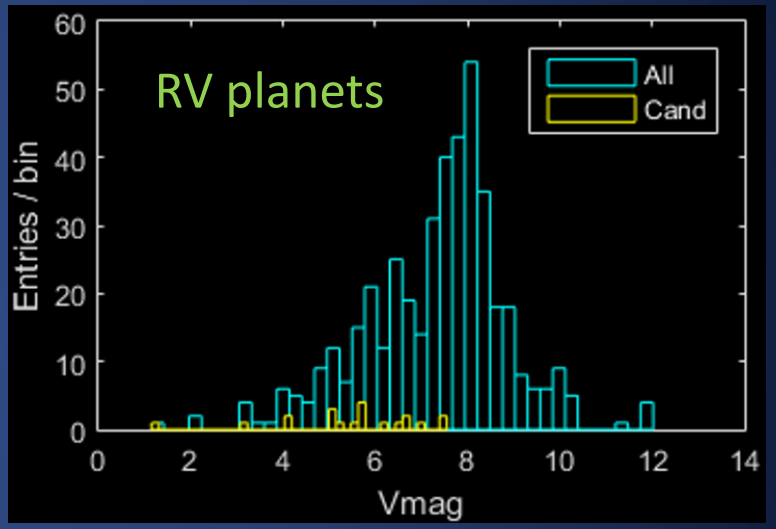
Coronagraph Observing Concept

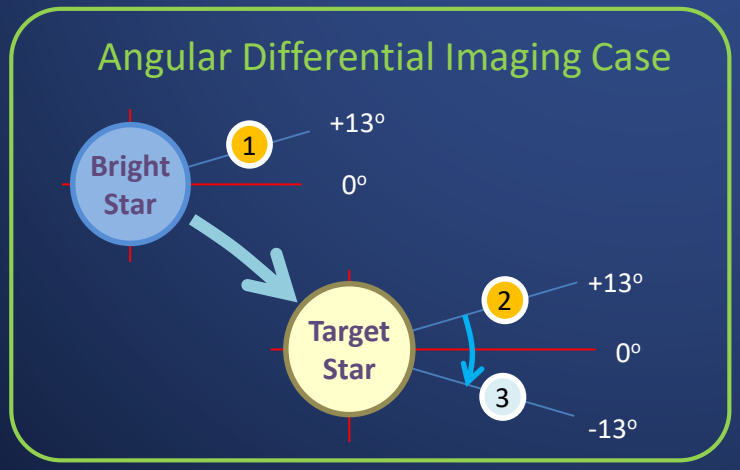
The typical scenario involves two stars:

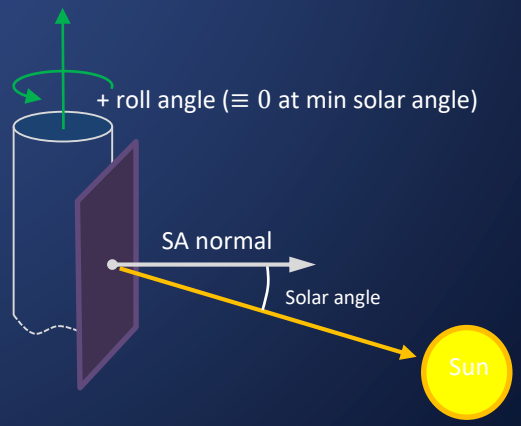
1. A nearby **bright star** for getting a dark hole (~ 3 Hrs)*
2. The planet host **target star** (~10 Hrs)*

* numbers notional



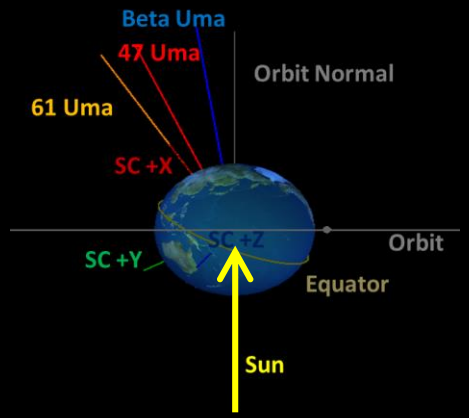


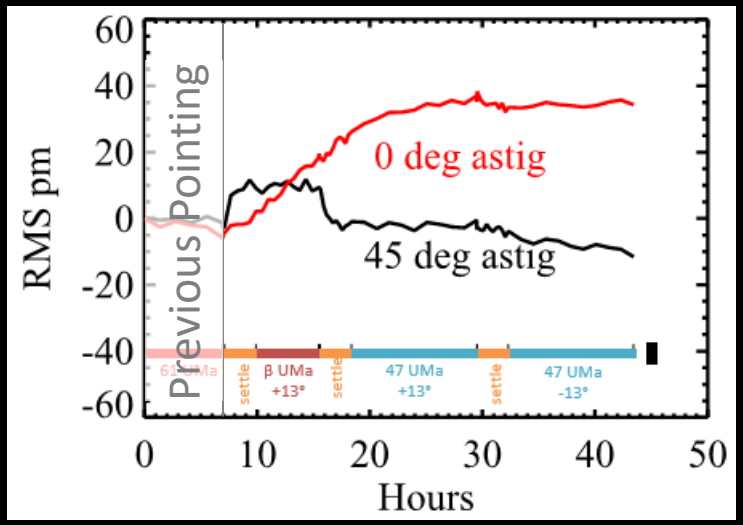




Observing Scenario Speckle Movie

Simulate the entire observing sequence for a 'typical' target, and assess speckle stability





Speckle Instability

settle | β UMa +13° | settle | 47 UMa +13° | settle | 47 UMa -13°

Reference and Angular Differential Imaging

Are the Speckles Stable Enough to Allow Differential Imaging?

RDI

ADI

β UMa

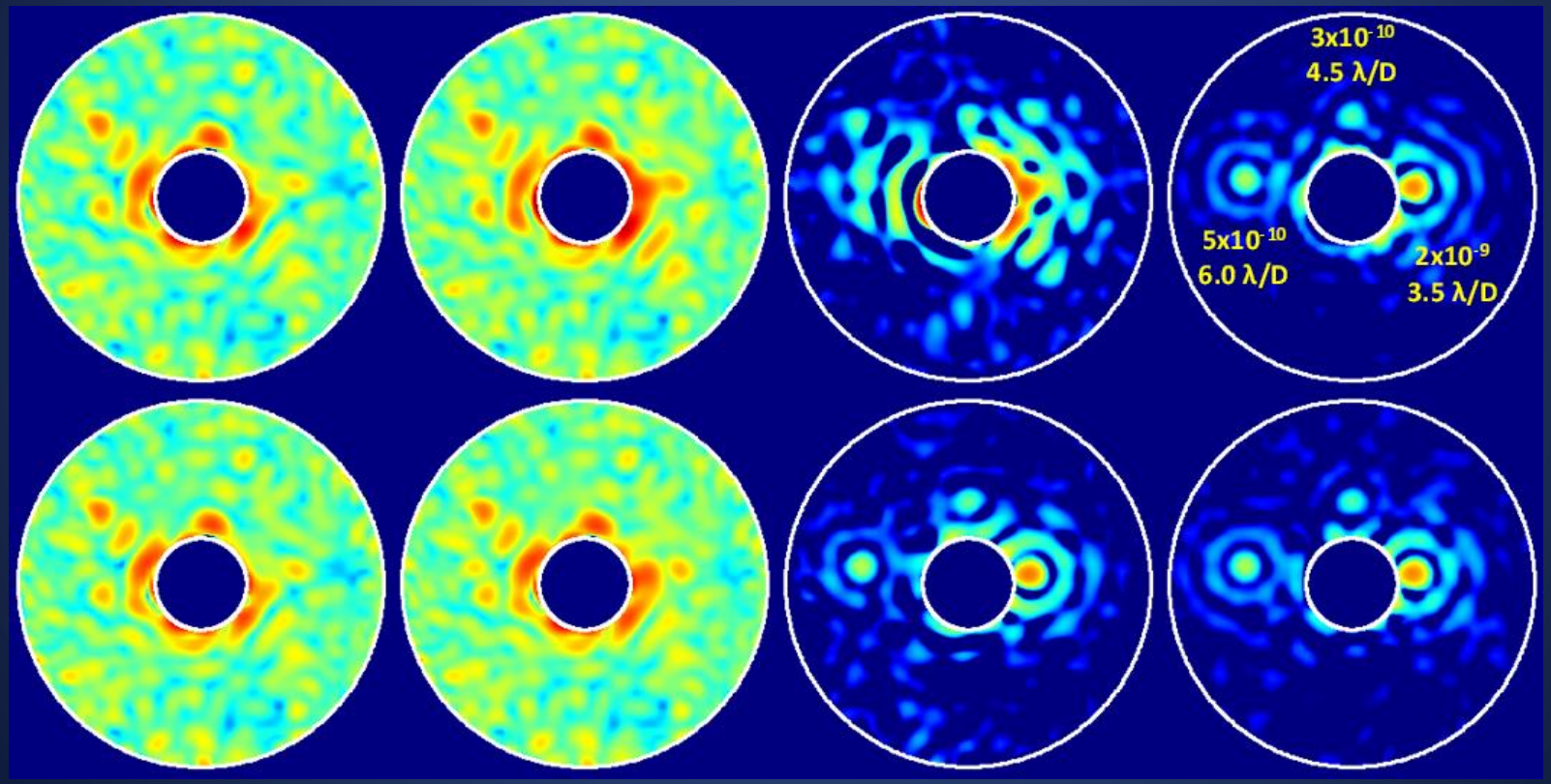
47 UMa$_{+13°}$

47 UMa $_{+13°}$ - β UMa

47 UMa iterative roll subtraction*

Control Off

Low Order Control



Using 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).

Starshade for WFIRST Rendezvous

2016: NASA has directed the WFIRST mission to explore the cost and schedule impact of accommodating a starshade that would rendezvous with WFIRST.

This external occulter would add an instrument sensitive enough to detect Exo-Earths in the habitable zone.

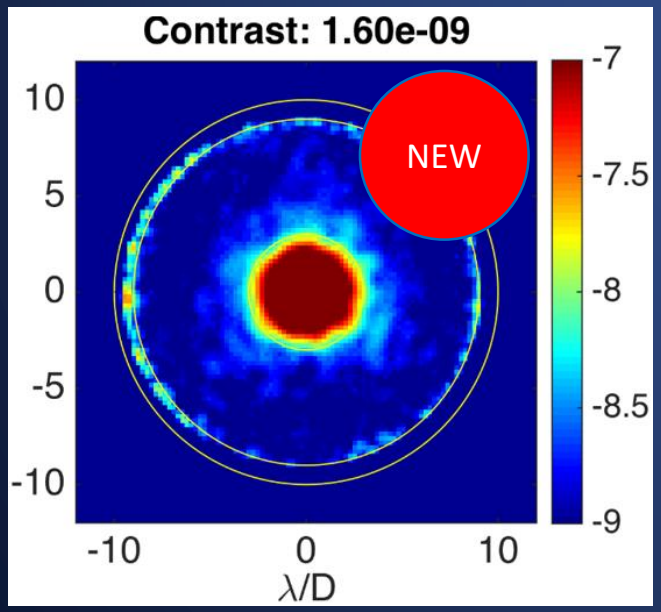
Hear more during
Karl Stapelfeldt's talk!

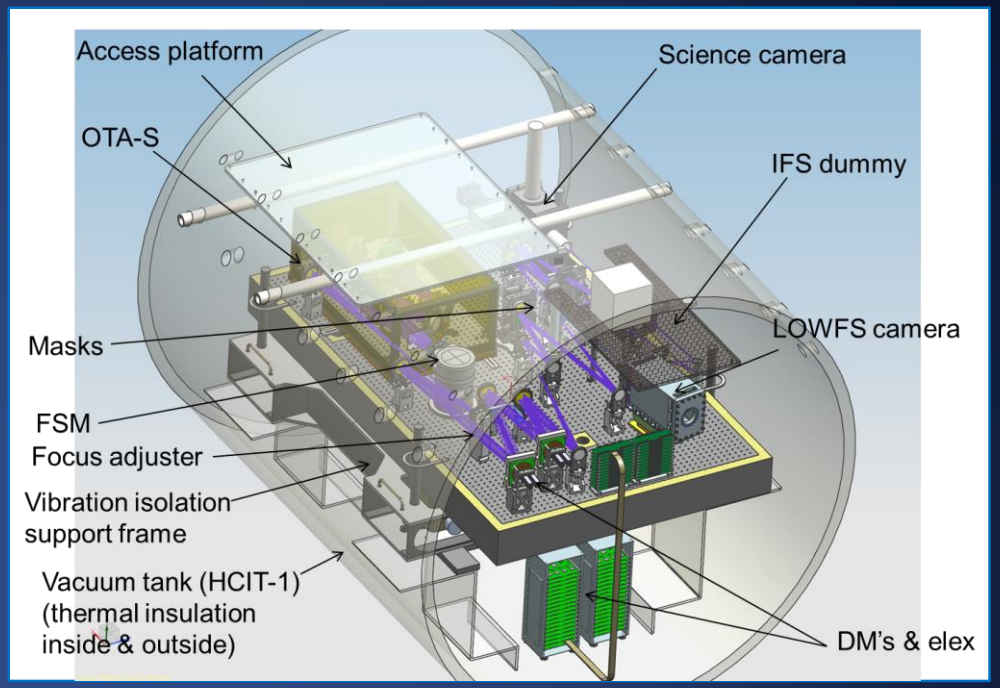
By blocking the light before it gets to the telescope, high-contrast imaging is achieved without imposing any stringent requirements on the telescope optics. Diffraction-limited imaging and few-milli-arcsecond pointing are sufficient.

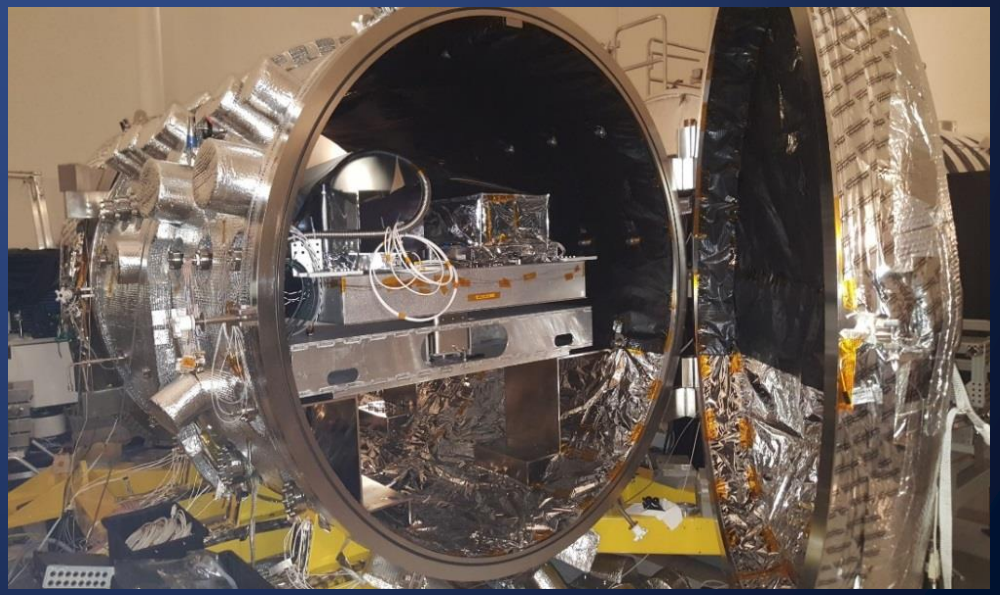
Demonstration of C < 1e-8 with Disturbances

Recent milestone:

- Demonstrated contrast at < 2e-9 with a flight-traceable design
- Operate in the presence of flight like perturbations

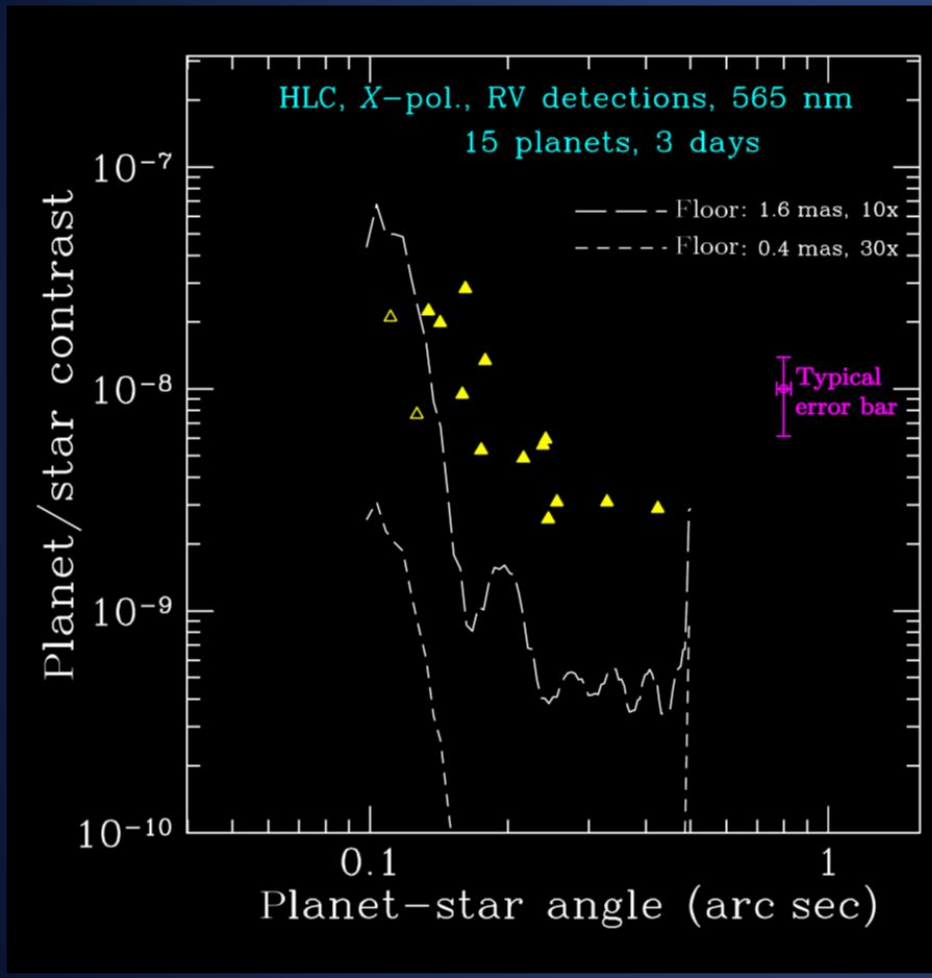




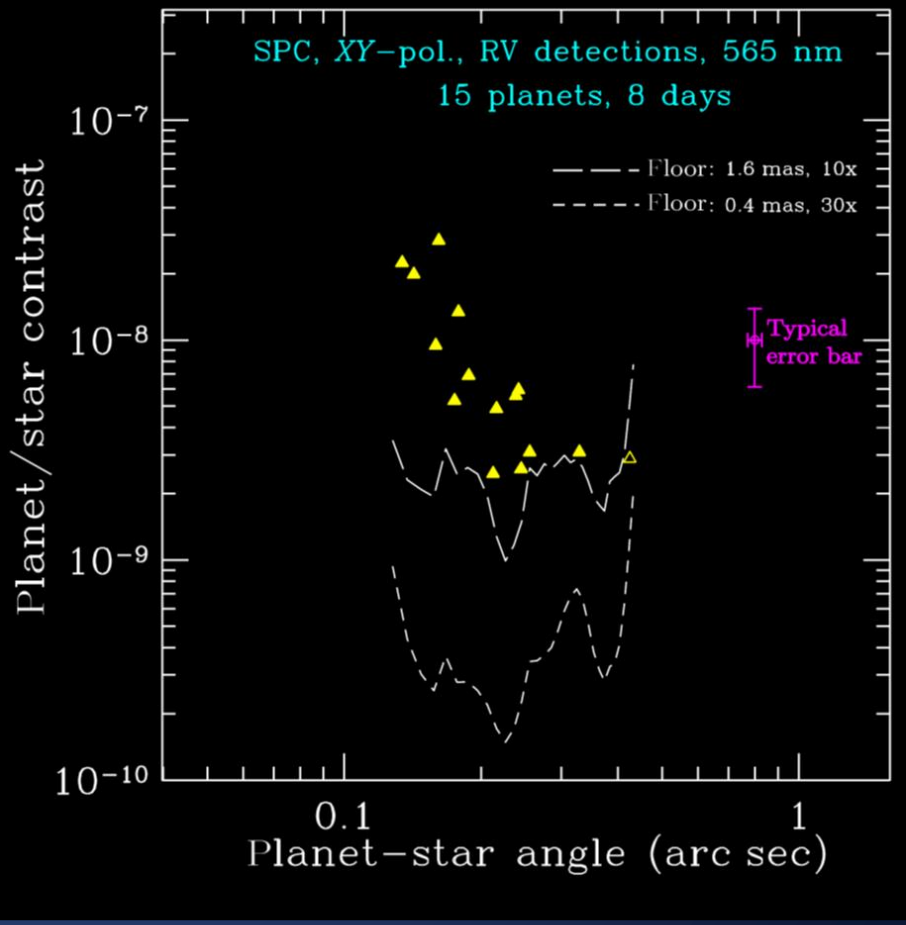


HLC and SPC Estimated RV Planet Images

Hybrid Lyot Coronagraph



Shaped Pupil Coronagraph



Traub, et al. , JATIS, 2016

Project Status

NEW

- The technology milestones are complete
- Currently In NASA Phase A
- System Requirements Review is scheduled for this Summer
- Launch is expected in the mid 2020's