The WFIRST CGI

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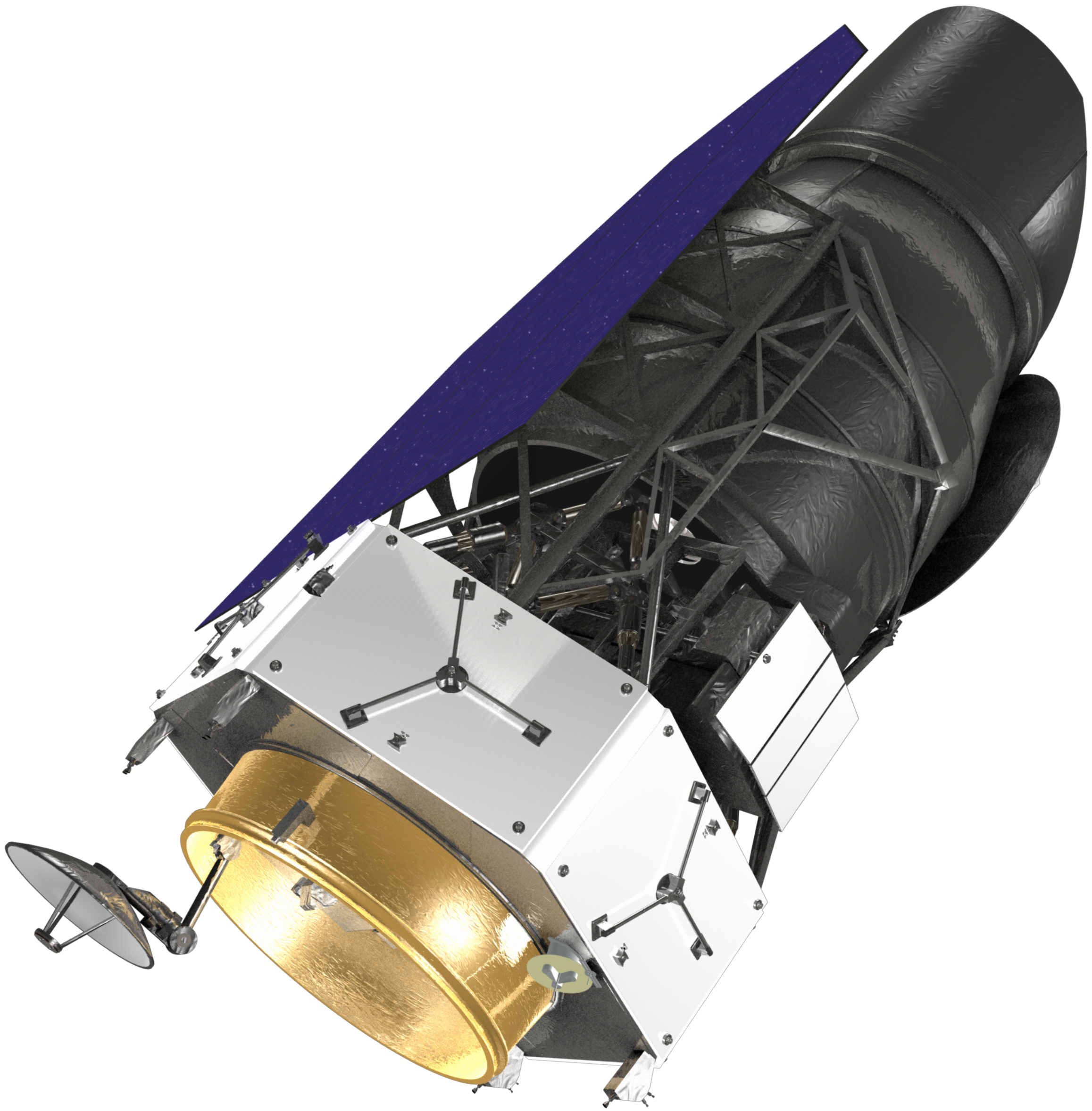
Princeton University

HabEx Face-to-Face
May 17, 2016



Coronagraph Design Goal:

Find a coronagraph architecture that:

Results in the most contrast . . .

Over the largest area of the image . . .

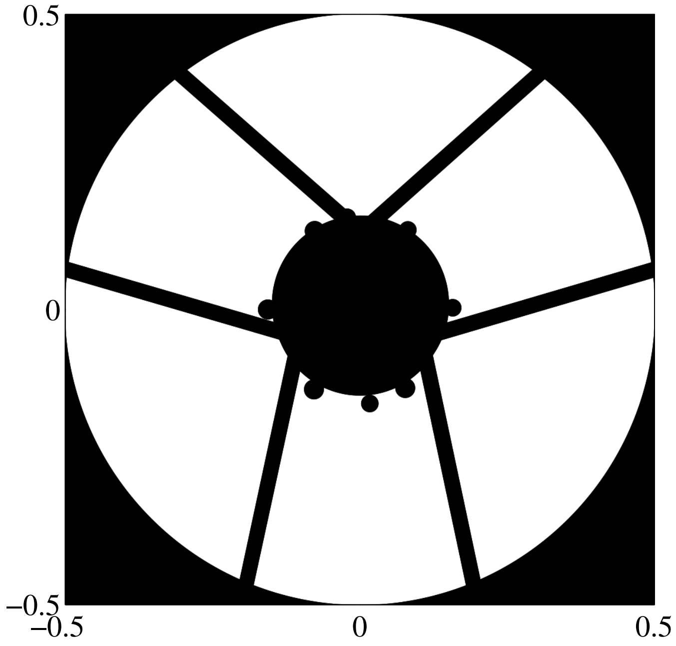
At the smallest possible inner working angle . . .

With the most throughput . . .

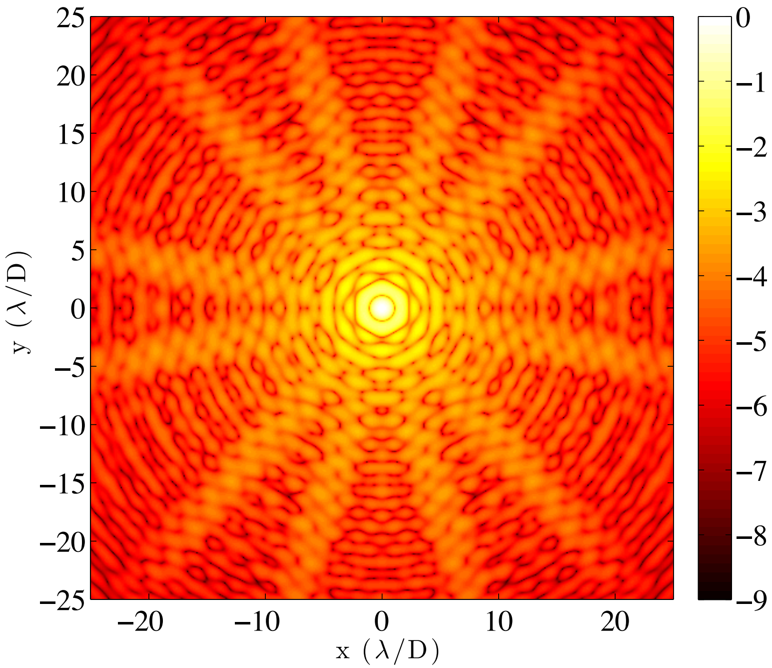
With no changes to the telescope . . .

By December 2014.

The Challenge



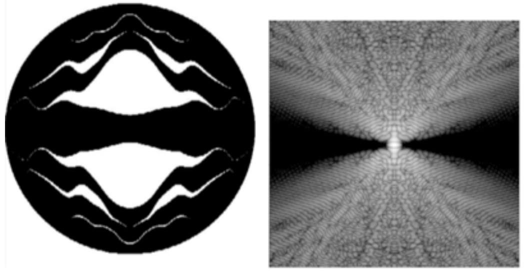
The AFTA Pupil



The AFTA PSF

Coronagraph selection based on maturity, robustness, flexibility

SPC



Pupil Masking (Kasdin, Princeton University)

HLC

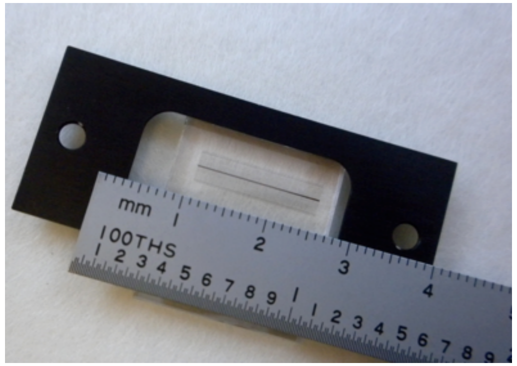
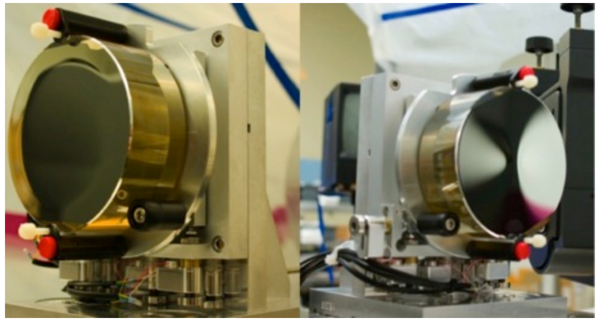


Image Plane Amplitude & Phase Mask (Trauger, JPL)

PIAACMC



Pupil Mapping (Guyon, Univ. Arizona)

VVC

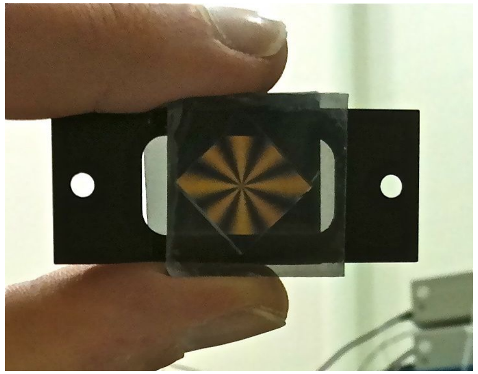
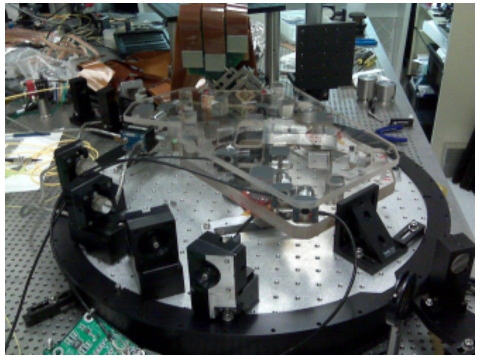


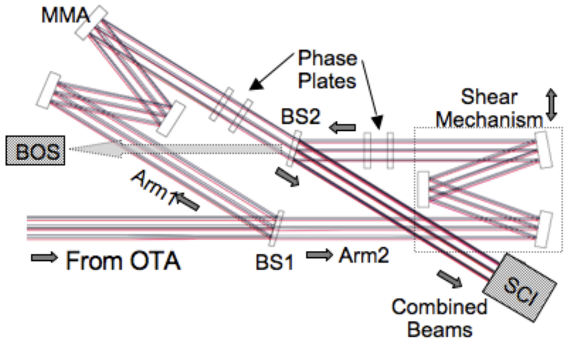
Image Plane
Phase Mask (Serabyn, JPL)

VNC - DAVINCI



Visible Nulller - DAVINCI (Shao, JPL)

VNC-PO



Visible Nuller – Phase Occulting (Clampin, NASA GSFC)

Approach to Recommendation

- **Objective:** Recommend a primary and backup coronagraph architecture to focus design and technology development leading to potential new mission start in F17
- Recommendation by ExEPO and ASO based on inputs from
  - **SDT:** Sets the science requirements
  - **ACWG:** Delivers technical FOMs and technology plans
    > *Aim for the positive: a consensus product*
    > SDT delivers science FOMs
  - **TAC:** Analysis of technical FOM, TRL readiness plans, and risks
- **ExEPO and ASO** recommendation to **APD Director** based on:
  - Technical and Programmatic
  - Musts (Requirements), Wants (Goals), and Risks
  - Distinguish description from evaluation
- **APD Director** will make the decision

ACWG = representatives of ExEPO, ASO, SDT, Community

TAC:
Alan Boss (Carnegie Mellon)
Joe Pitman (EXSCI)
Steve Ridgway (NOAO)
Lisa Poyneer (LLNL)
Ben Oppenheimer (AMNH)

How do we define a successful outcome?

FOM = Figure of Merit

Recommendation Criteria: Defining a Successful Outcome

MUSTS (Requirements): ***Go/No_Go***

1. Science: Does the proposed architecture meet the baseline science drivers?
2. Interfaces: For the baseline science, does the architecture meet telescope and spacecraft requirements of the observatory as specified by the AFTA project (DCIL[1])
3. Technology Readiness Level (TRL) Gates: For baseline science, is there a credible plan to be at TRL5 at the start of FY17 and at TRL6 at the start of FY19 within available resources?
4. Is the option ready in time for this selection process?

WANTS (Goals): ***Relative to each other, for those that pass the Musts:***

1. Science: Relative strength of science beyond the baseline
2. Technical: Relative technical criteria
   - See details
3. Programmatic: Relative cost of plan to meet TRL Gates

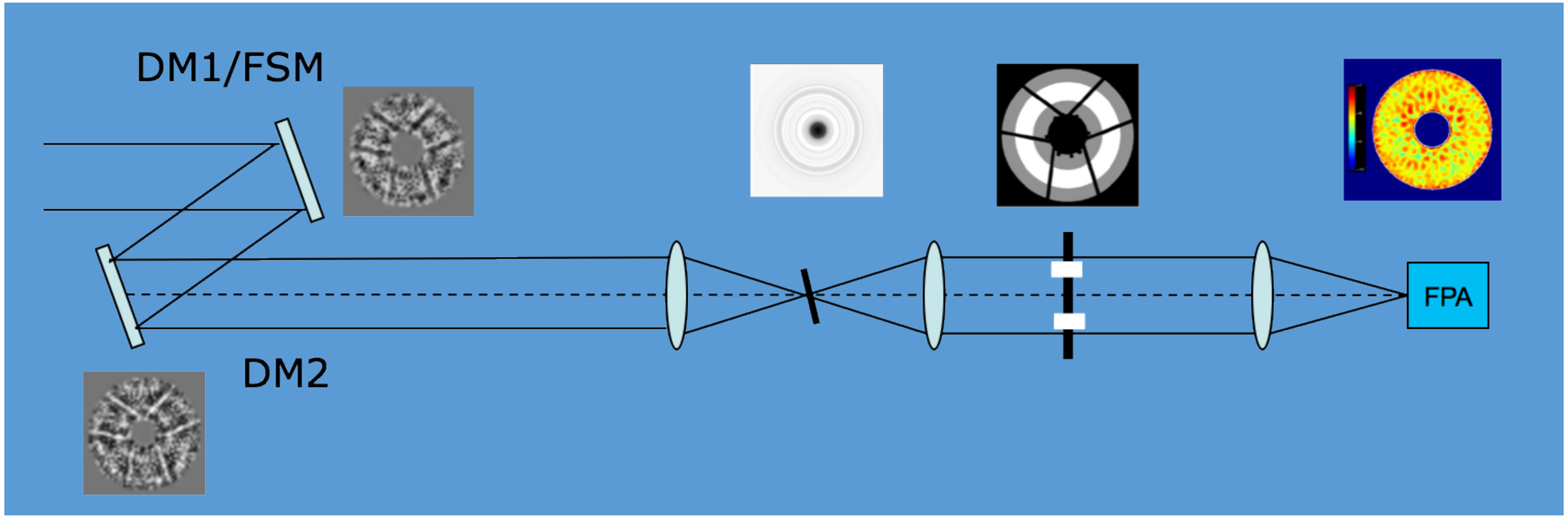
RISKS and OPPORTUNITIES

- See details

[1]DCL = Dave Content Interface List

Hybrid Lyot Coronagraph

Transmission = 48%

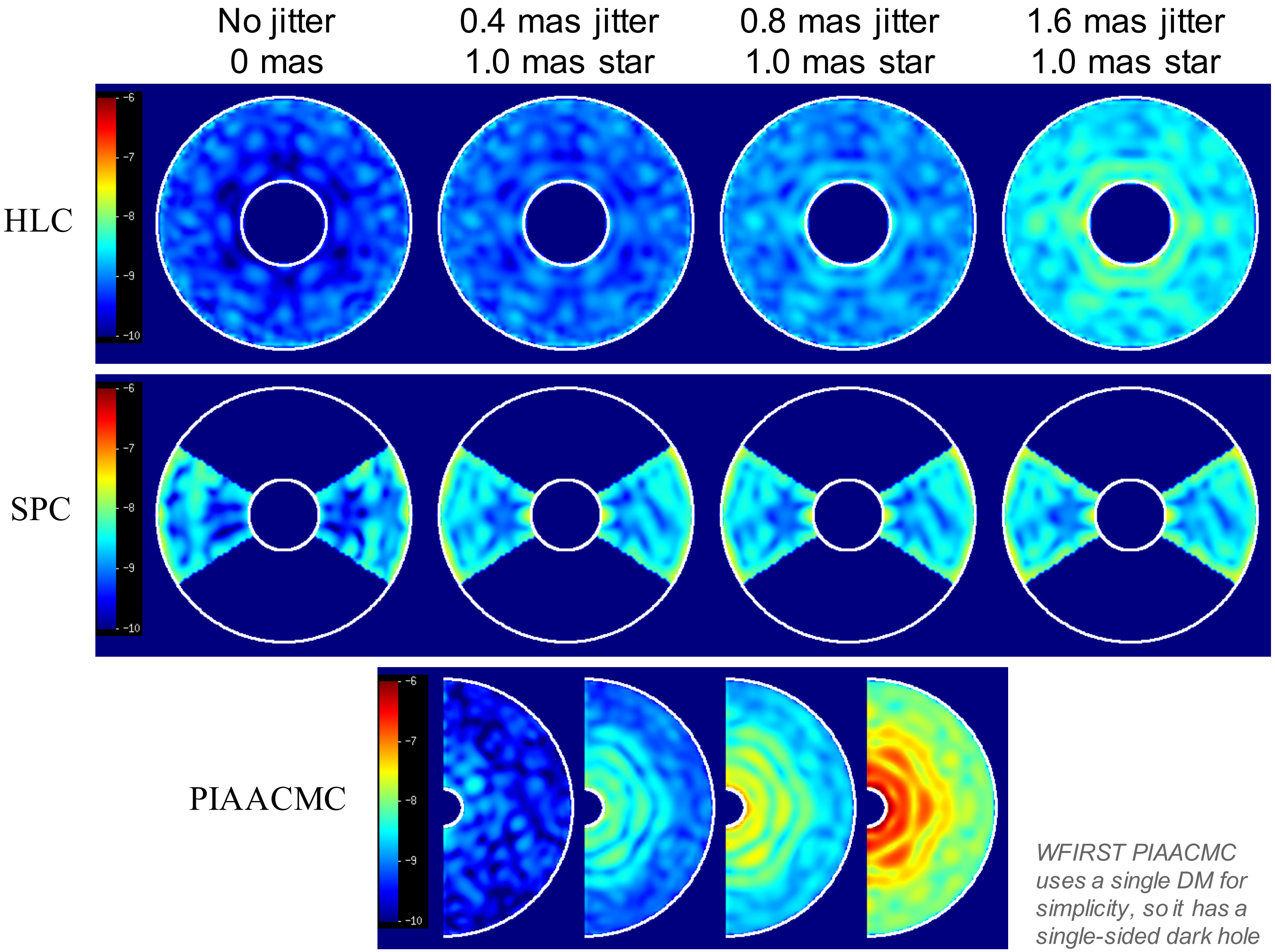


Baseline design for WFIRST/AFTA

Total PSF core throughput = 4.5%

From John Trauger, JPL

WFIRST Dark Holes with Pointing Jitter & Finite Star

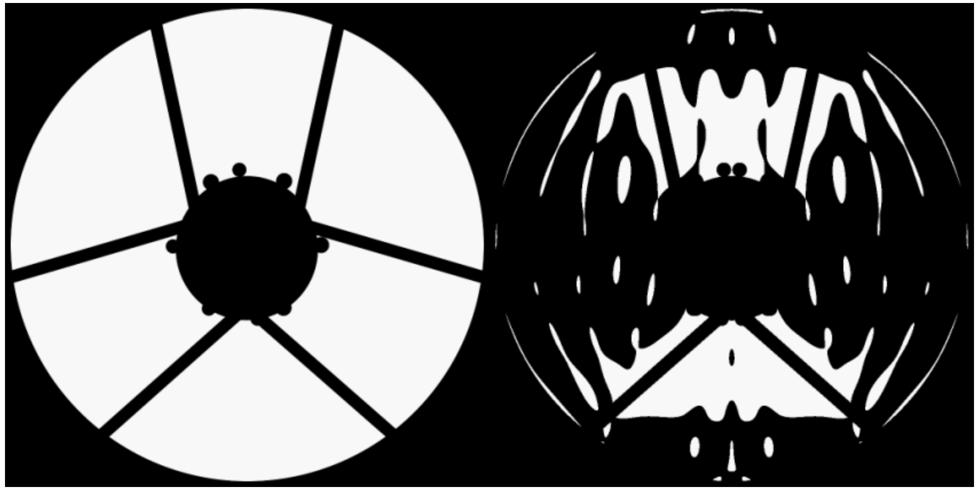


WFIRST PIAACMC uses a single DM for simplicity, so it has a single-sided dark hole

Coronagraph simulations use validated wave-optics code

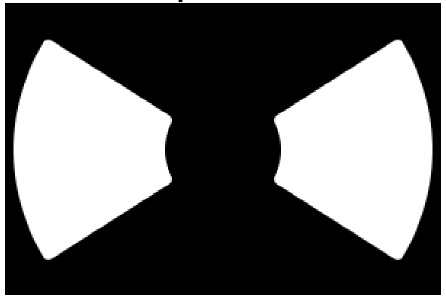
AFTA Pupil

Shaped Pupil

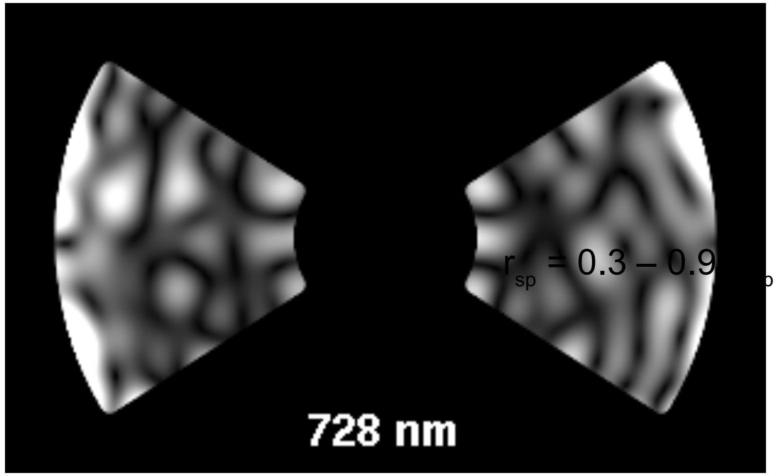


27% mask transmission

Focal plane mask

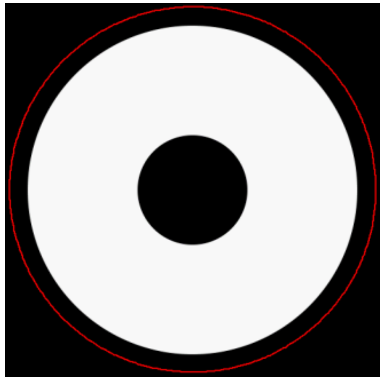


r = 2.5 – 9 λ_c/D
65° opening angle



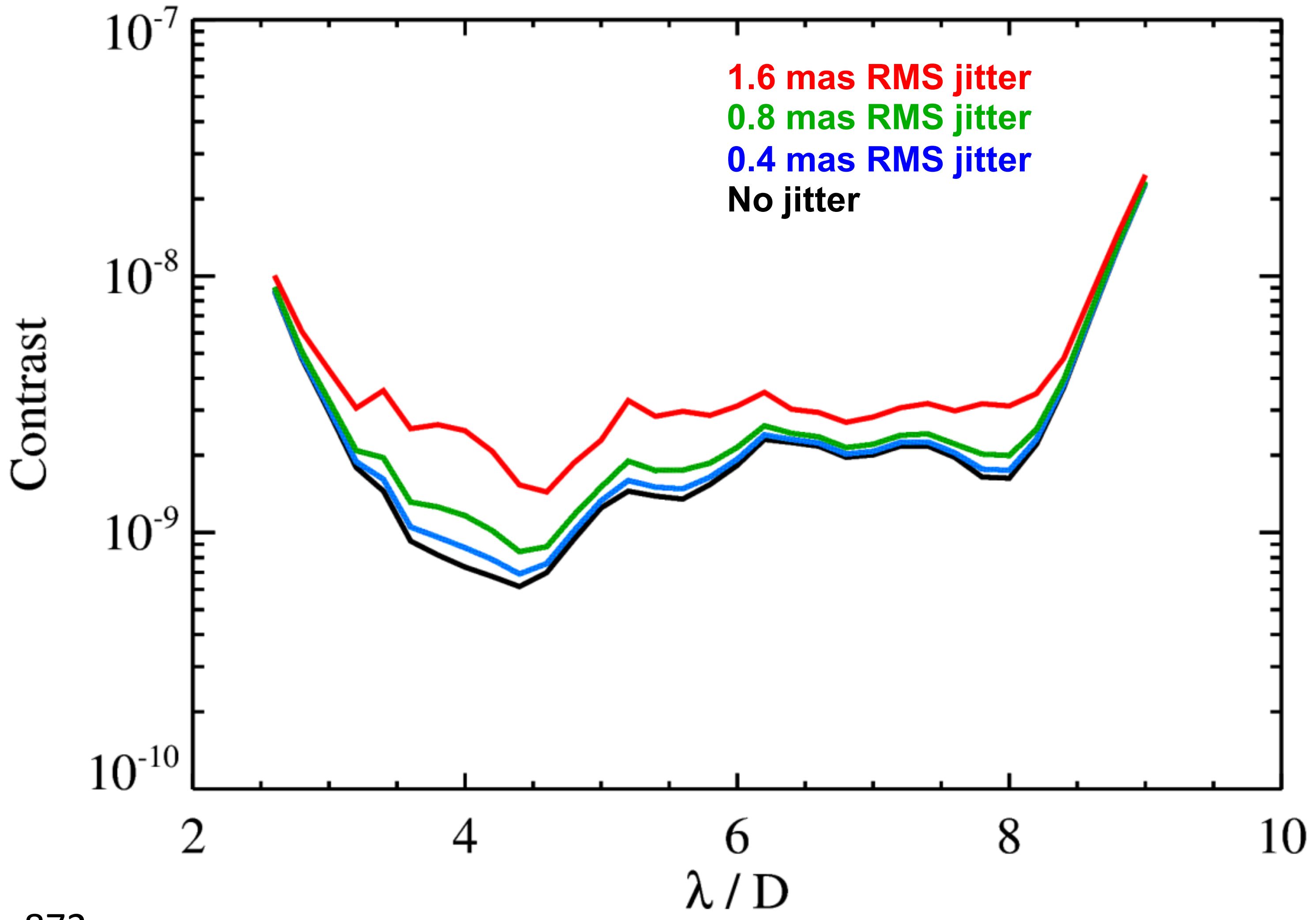
r_{sp} = 0.3 – 0.9

Lyot stop



Total PSF core throughput = 3.7%

Simulations show e.g. robust performance against jitter



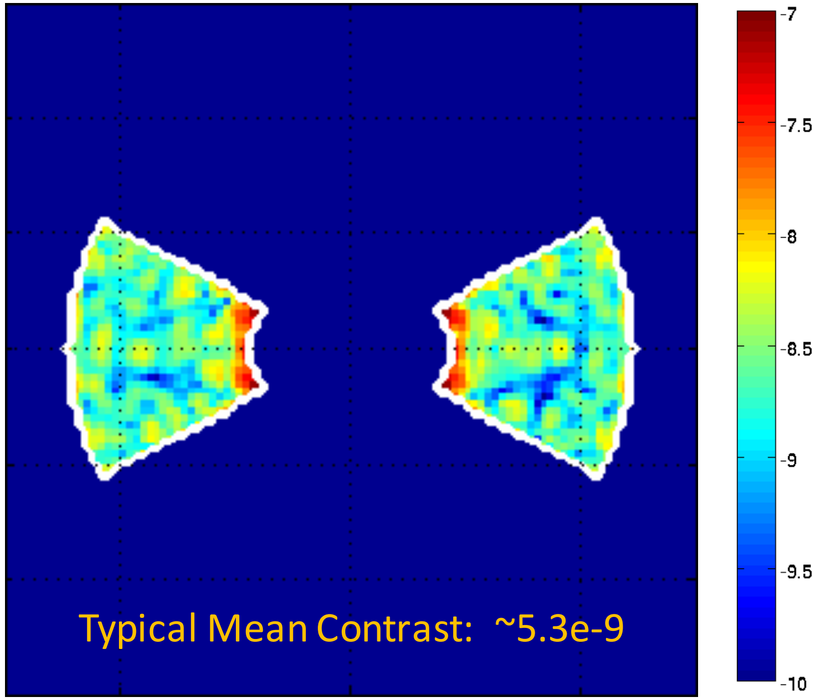
728 – 872 nm

Jitter levels shown here are after coronagraph fast tip/tilt

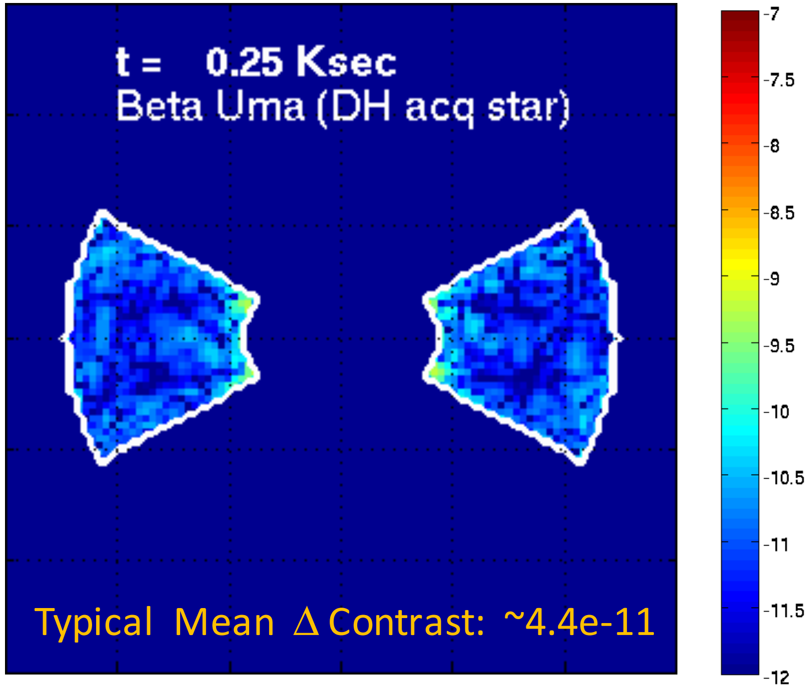
Simulations show stable high contrast with AFTA in thermal scenarios

- Proper EFC correction for telescope nominal wavefront (initial DM setting)
  - Gen 1 SPC design , 10% bandwidth, l = 550 nm, 3.9 ~12.3 l /D WA, 56 deg opening angle
  - Realistic AFTA surface aberration (amplitude +phase), and
  - Piston/tip/tilt/focus correction computed only once initially
  - The system configuration is held constant throughout the observations

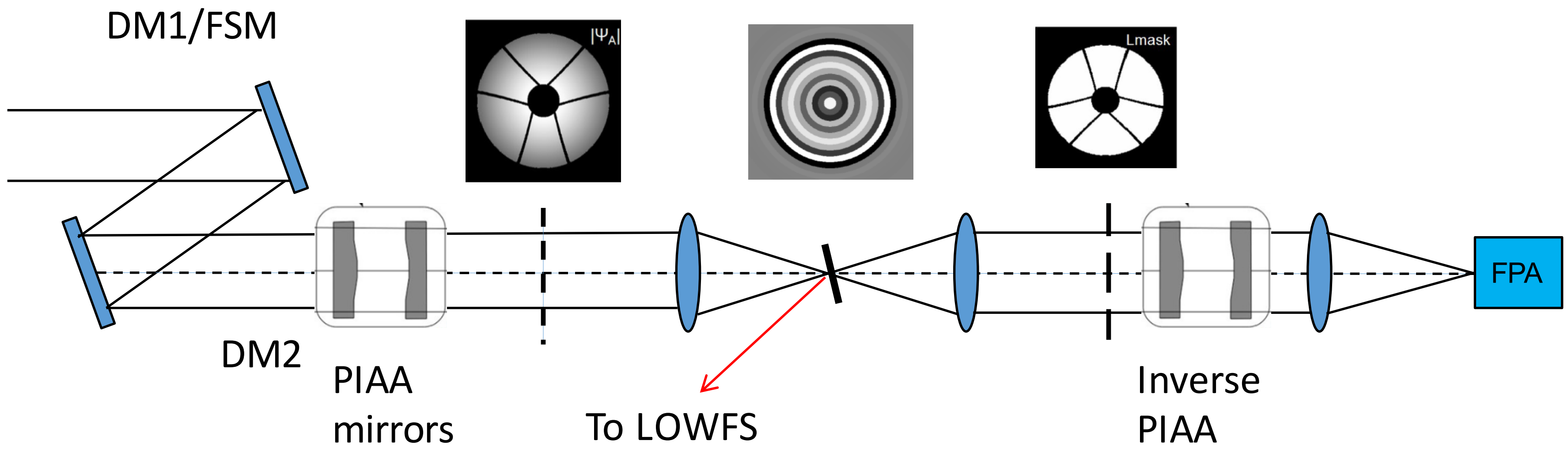
Raw speckle, S(t)



ΔSpeckle (rel. to nominal): S(t) – S(0)



PIAA - CMC



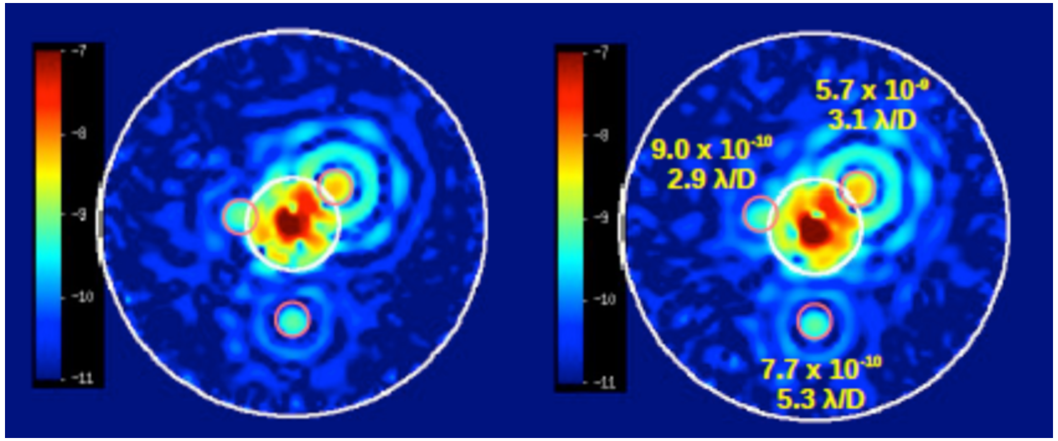
Final design deadline extended to 11/4/2013

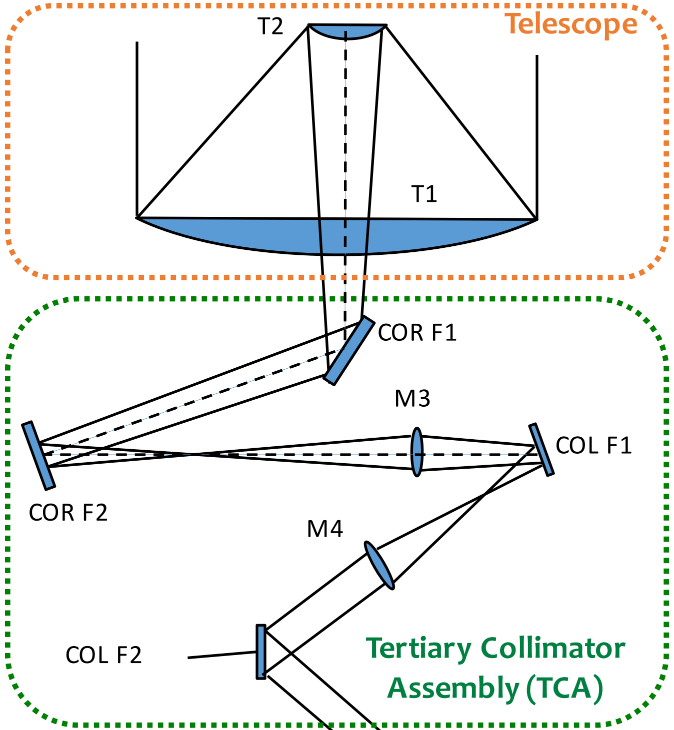
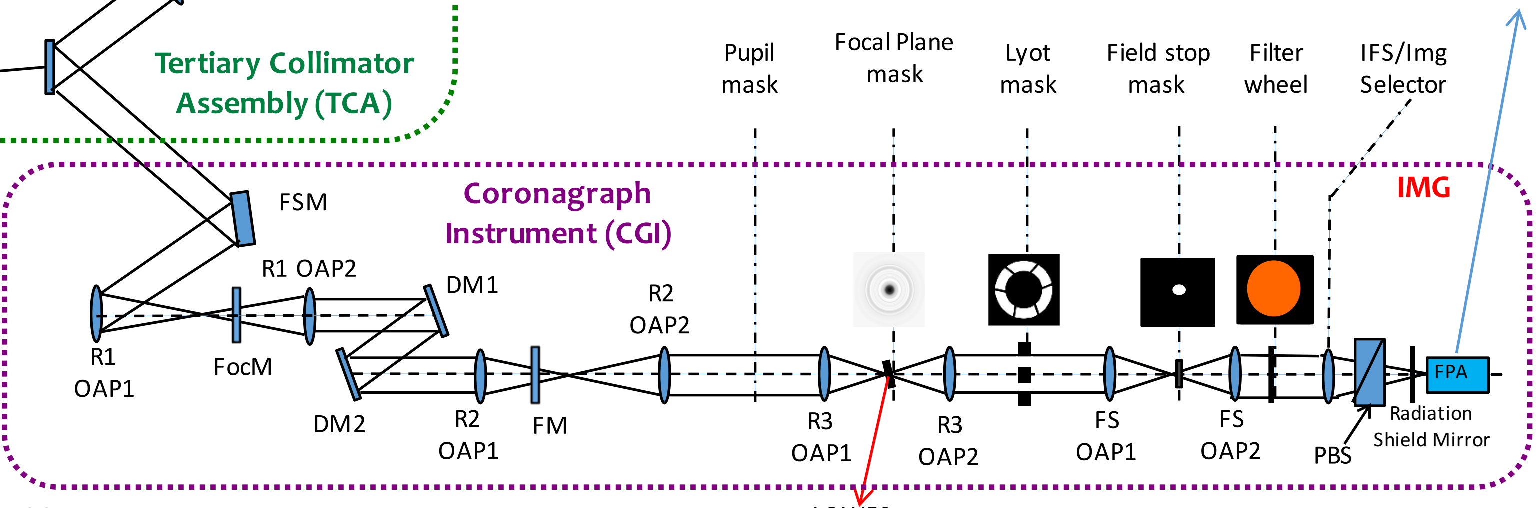
DM1, DM2	Pupil mapping	Apodizer mask	Occulting mask	Lyot stop	Inverse pupil mapping
Medium ACAD on both DMs	PIAA mirrors	Gray scale, filer wheels?	Phase transmission, on filter wheel	Transmission, binary, fixed?	Inverse PIAA mirrors

CGI Operational Modes

Hybrid Lyot Mode

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

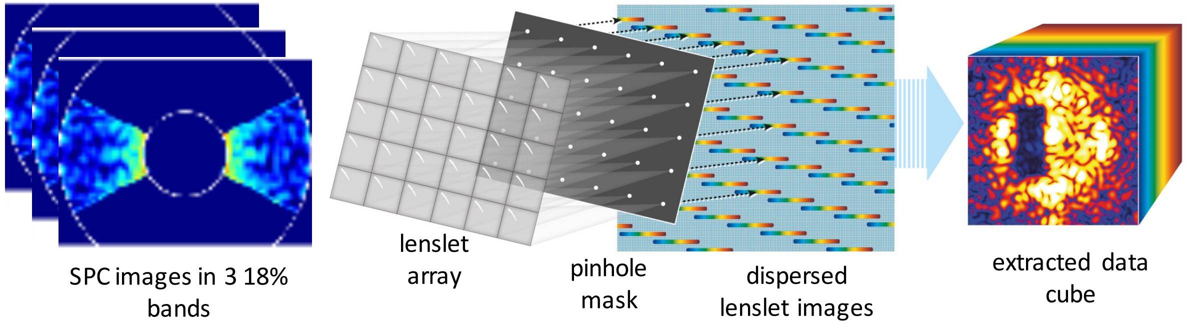


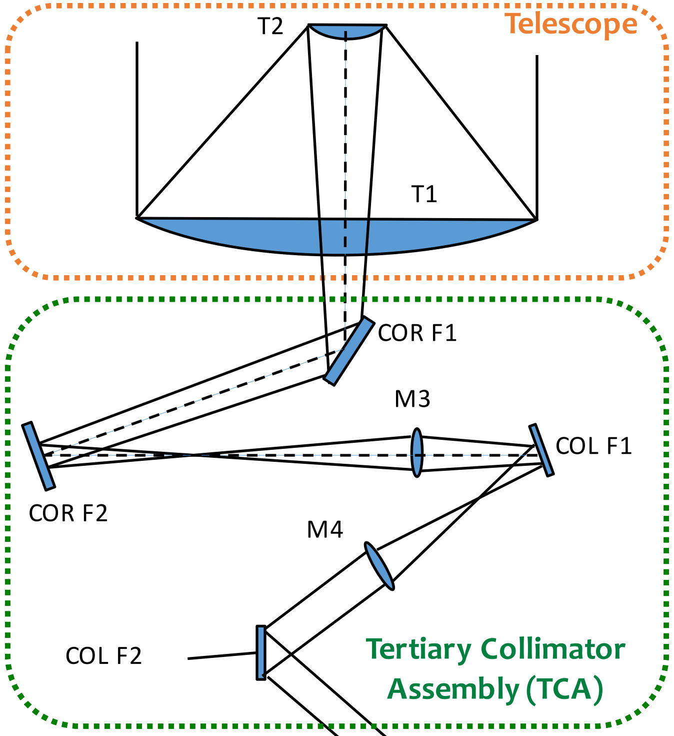



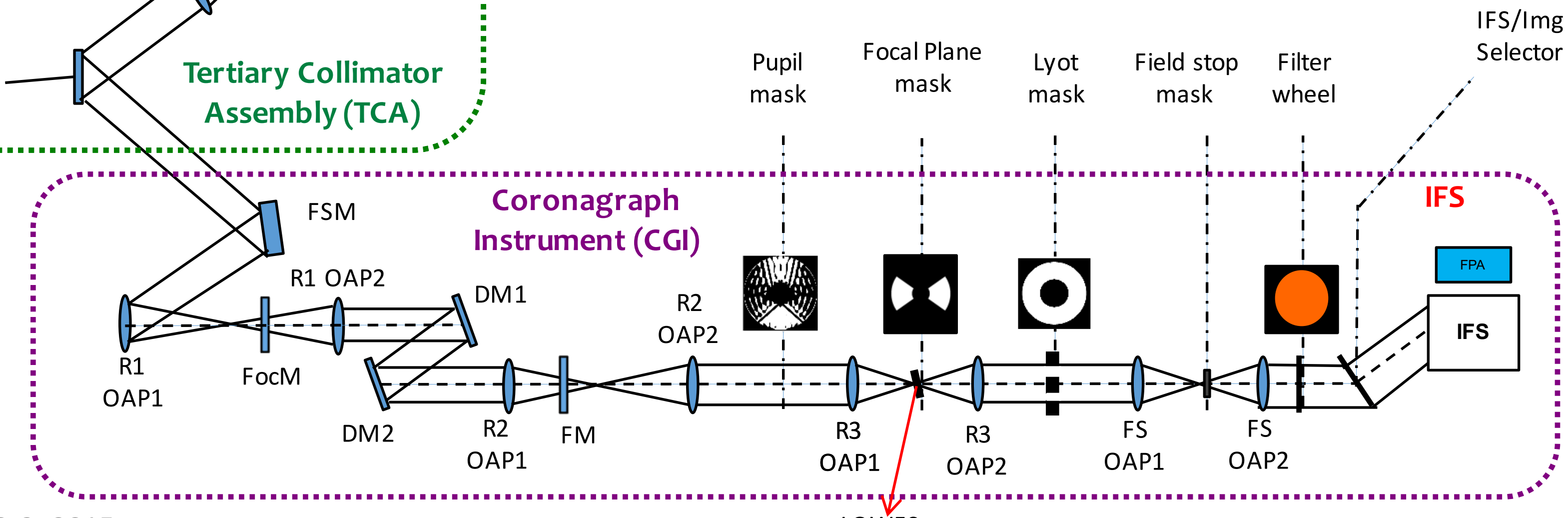
CGI Operational Modes

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

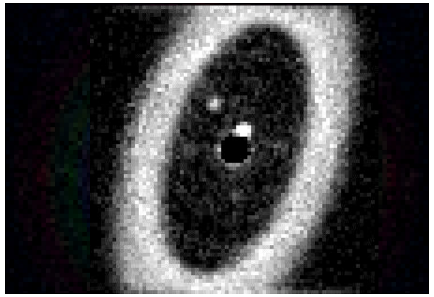
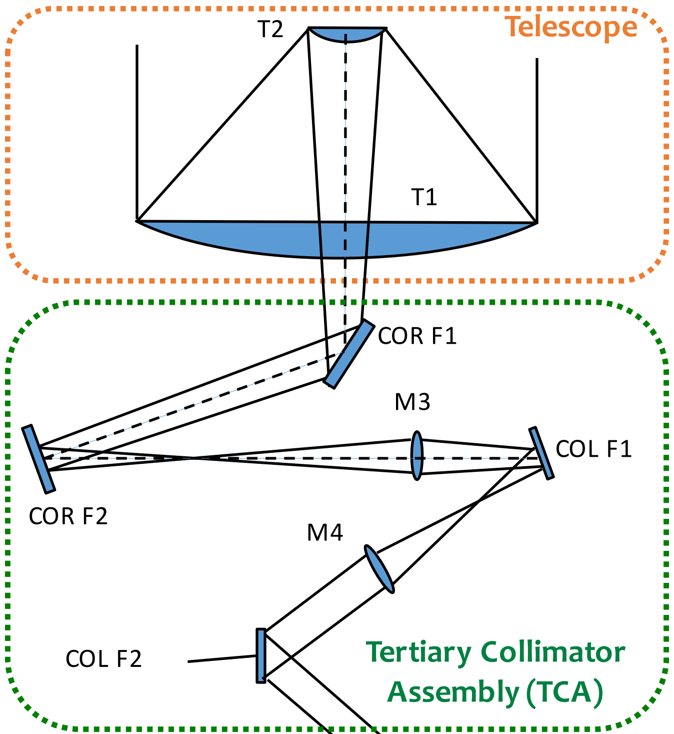
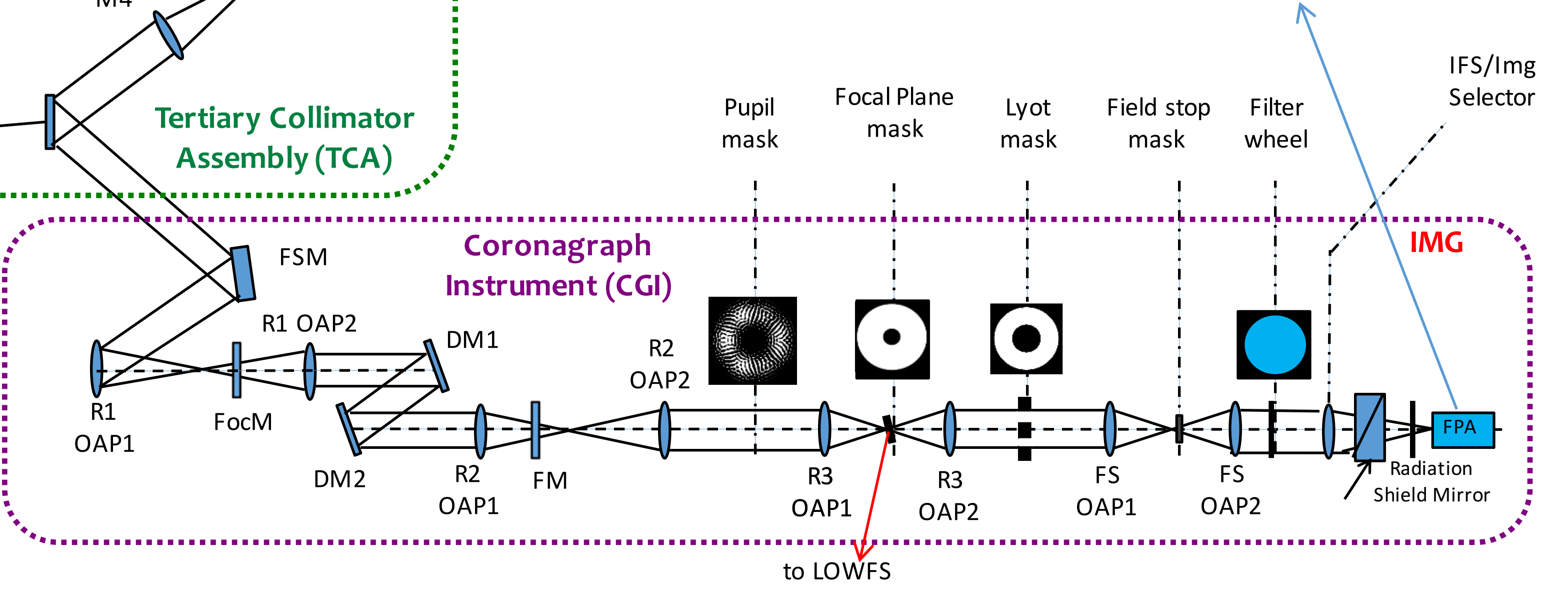
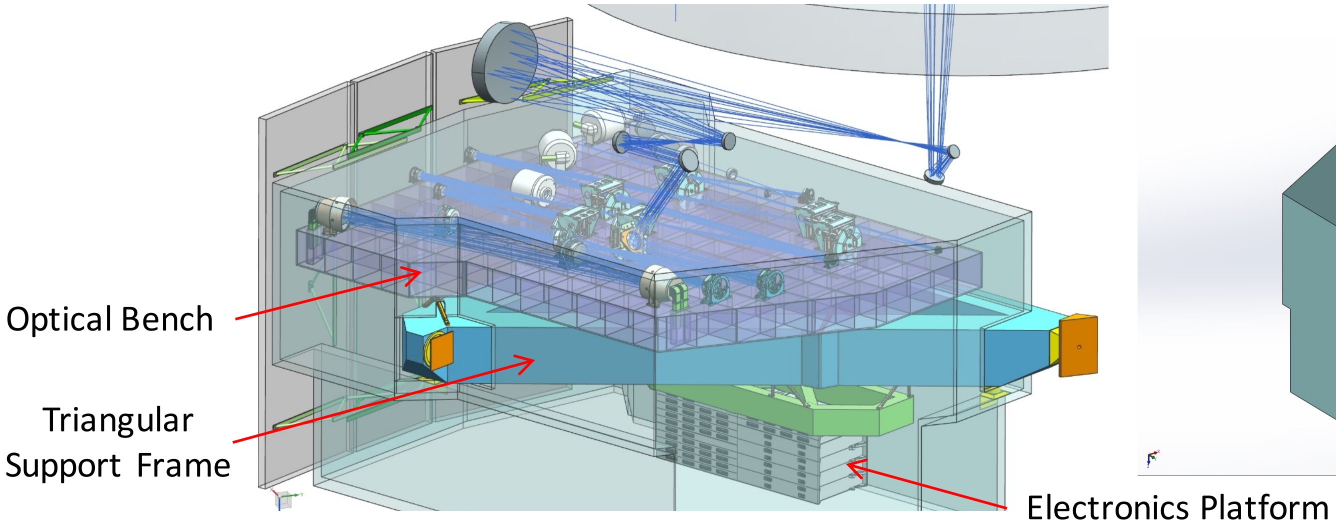


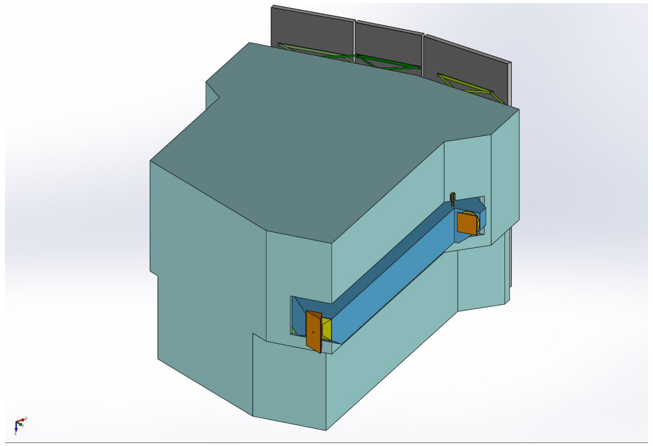
Image from 2015 Exo-C STDT Final Report





The Coronagraph Instrument





Imaging Camera

1k x 1k EMCCD detector

5 arcsec imaging FOV from 430 to 970 nm

4 filters for color photometry

Contrast better than 10^{-8} (raw)

Dark hole from 0.2 to 1 arcsec

Dual polarizations

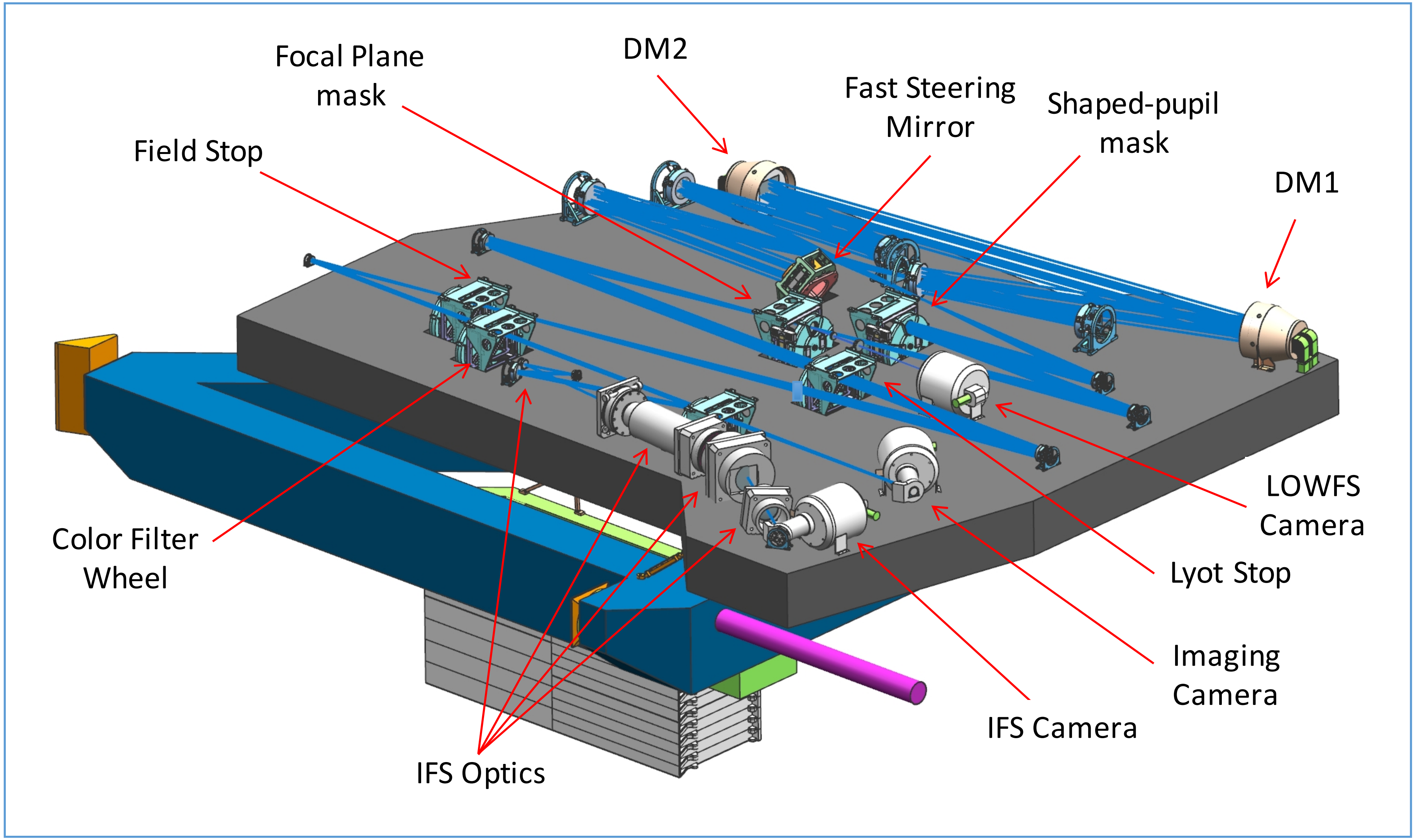
Integral Field Spectrograph

R70 Spectra in IFS 600 to 970 nm

0.5 arcsec FOV

Better than Nyquist sampled PSF

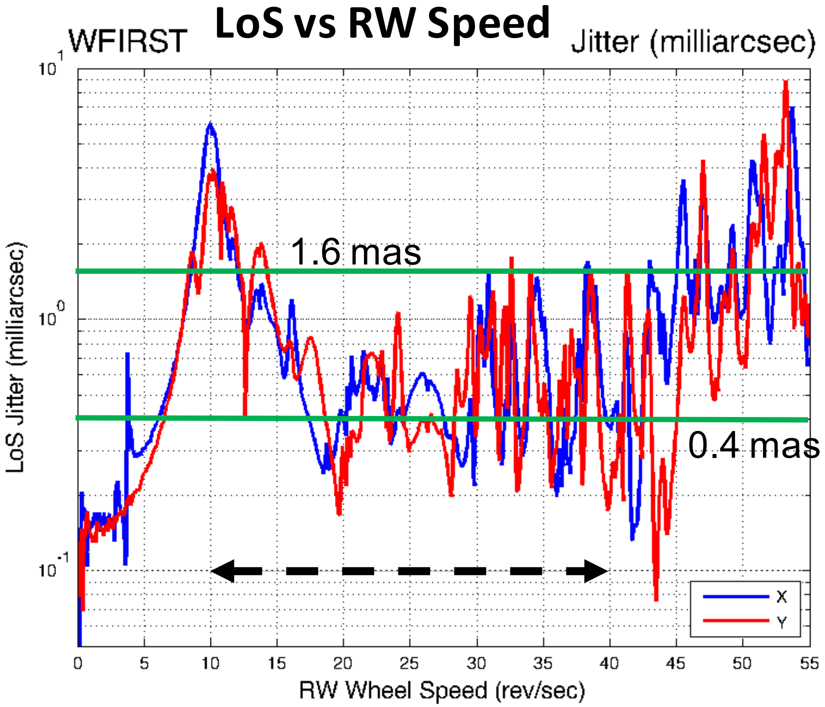
CGI Optical Layout

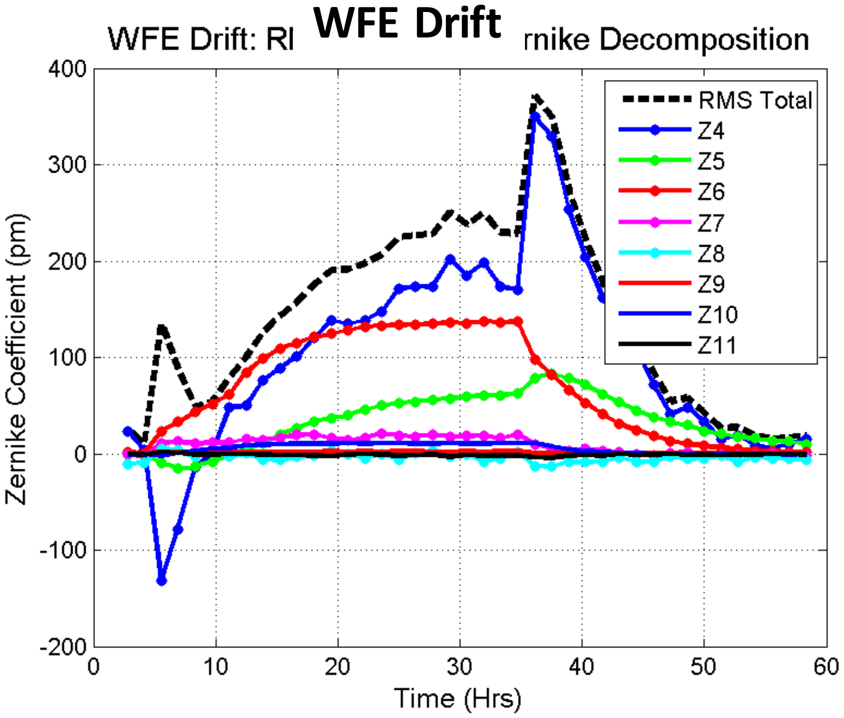


WFIRST Telescope LoS Jitter and WFE Drift

- **Line-of-sight drift and jitter (Cycle 5 model)**
  - Drift (<2Hz): ~14 milli-arcsec ACS pointing.
  - Jitter (>2Hz): < 10 milli-arcsec. Most around 10 Hz with multiple harmonics at each RW speed.
- **RW induced WFE Jitter (Cycle 5 model)**
  - High frequency WFE. Dominant WFE are: astig (Z5, Z6), coma (Z7, Z8), trefoil (Z9, Z10).
  - Impact to coronagraph contrast is small.

- **WFE drift (Cycle 5 model)**
  - Mostly thermal induced rigid body motion of the telescope optics.
  - Slow varying, typically <10 pm/hour.
  - Dominant WFE are: focus (Z4), Astigmatism (Z5, Z6) and coma (Z7, Z8).
  - Severely depredate the coronagraph contrast if left un-corrected.

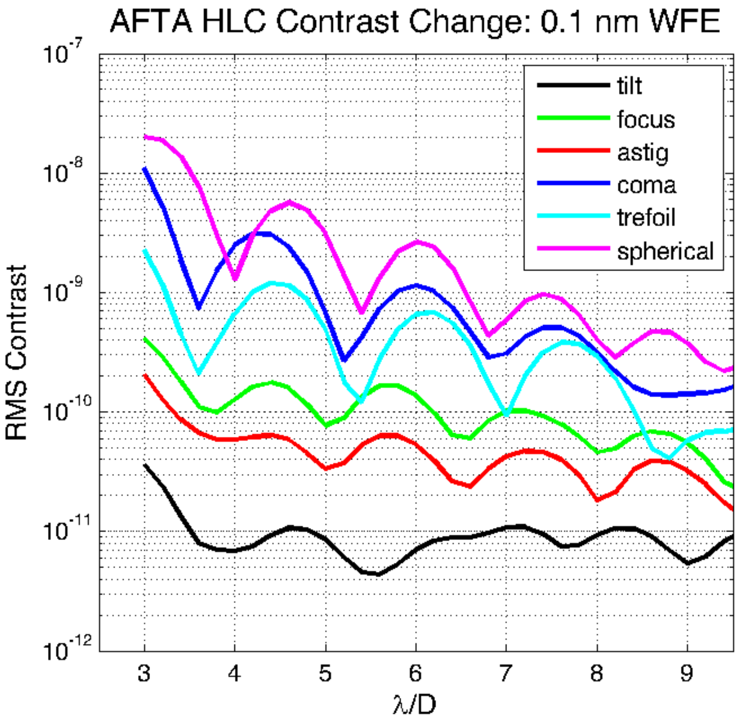


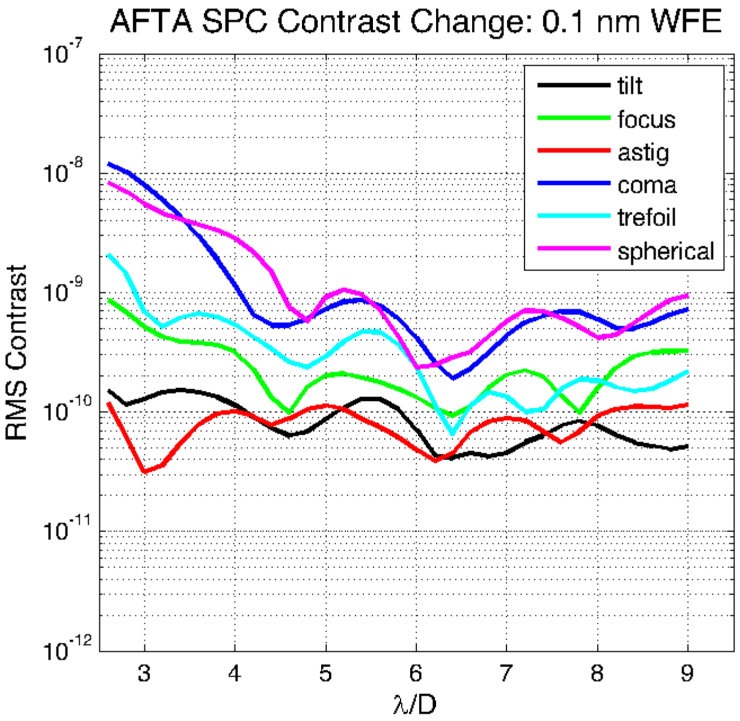


OMC Aberration Sensitivities

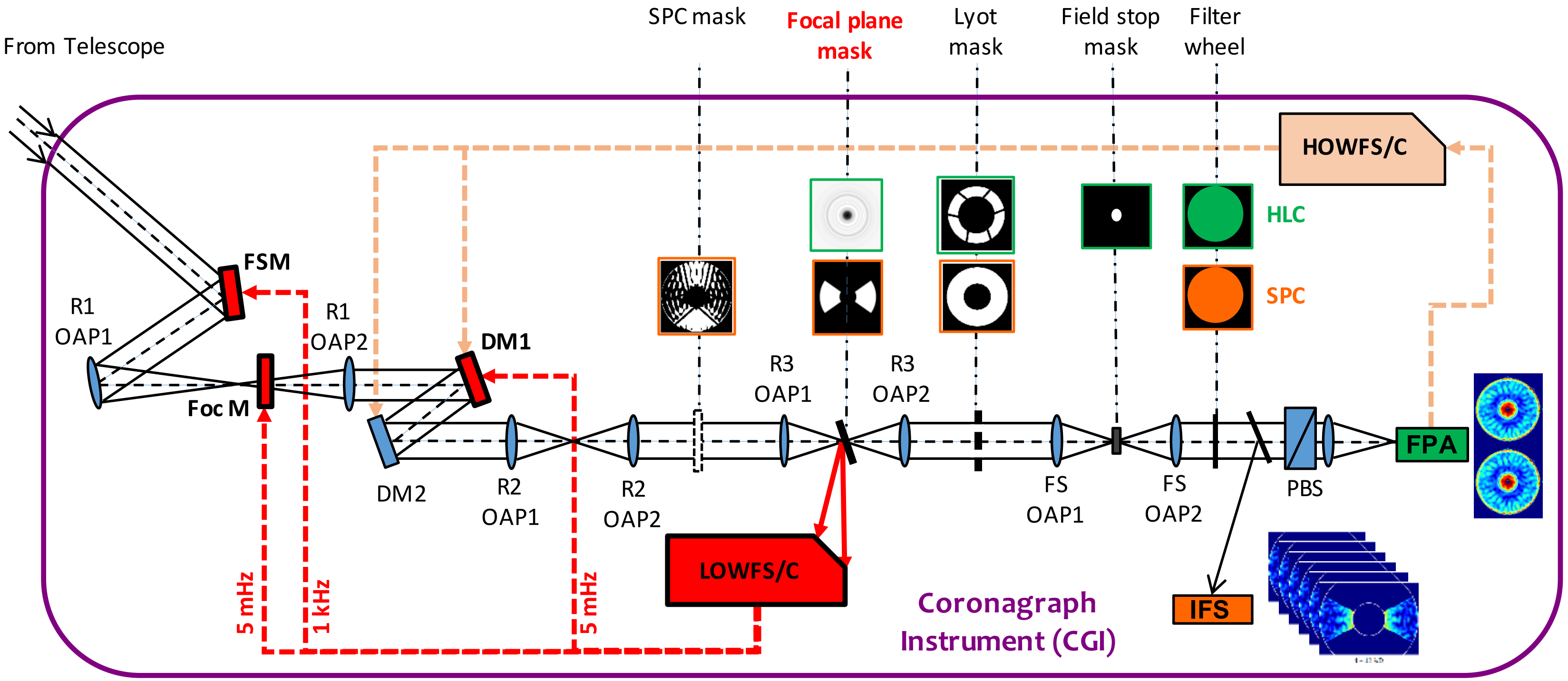
HLC and SPC WFE sensitivities modeled by J. Krist

- Compared to 2013 ACWG down select, HLC sensitivities are lower, SPC sensitivities higher (performance trade-off with the addition of Lyot stop)
- Sensitivity highest to spherical and coma



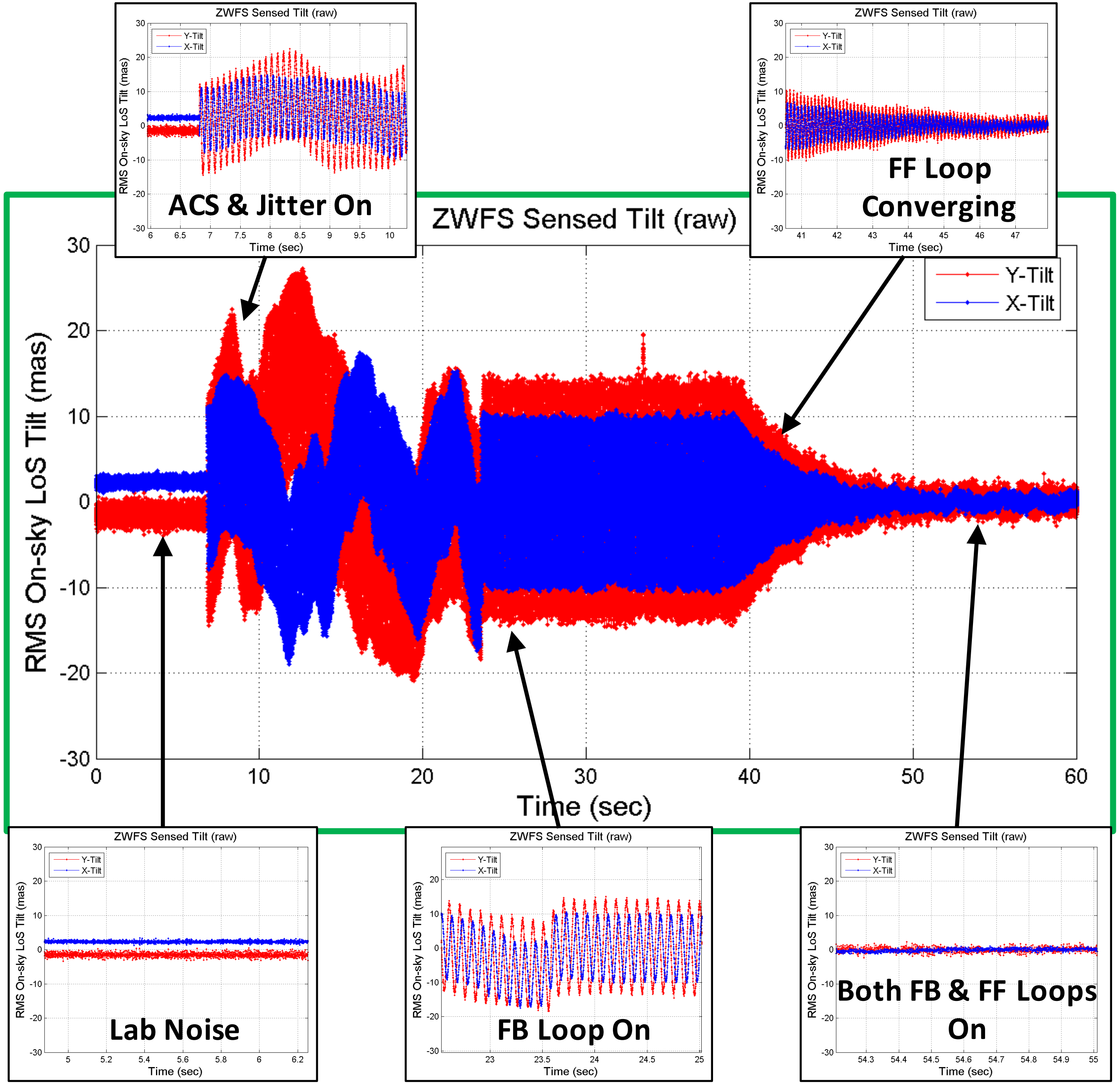


Low Order Wavefront Sensing and Control (LOWFS/C)



- WFIRST LOWFS/C subsystem measures and controls line-of-sight (LoS) jitter and drift as well as the thermally induced low order wavefront drift
- Differential sensor referenced to coronagraph wavefront control: maintains wavefront established for high contrast (HOWFS/C)
- Using rejected starlight from occulter which reduces non-common path error
- LOWFS/C telemetry can be used for coronagraph data post-processing

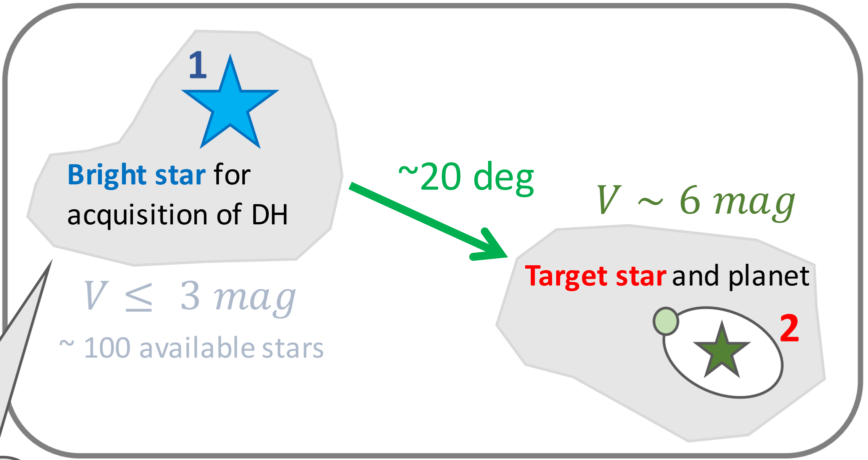
- Disturbance: WFIRST Cycle 5 CBE
- ACS LoS drift
- LoS jitter @ RW of 10 rev/sec (worst case)
- Small plot shows the zoomed in region



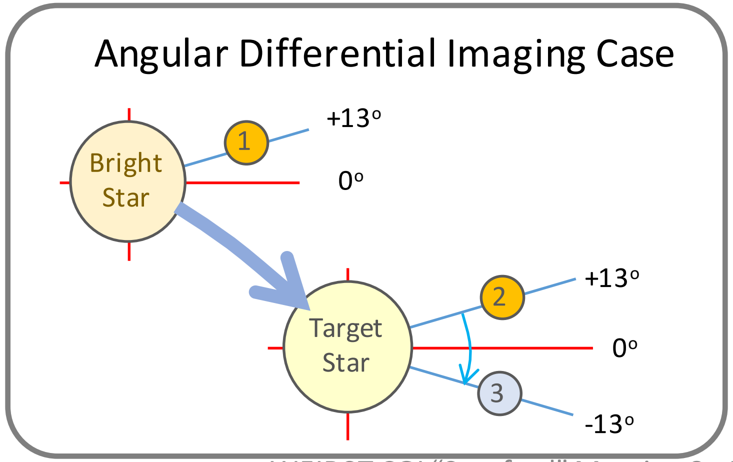
Typical Observing Sequence

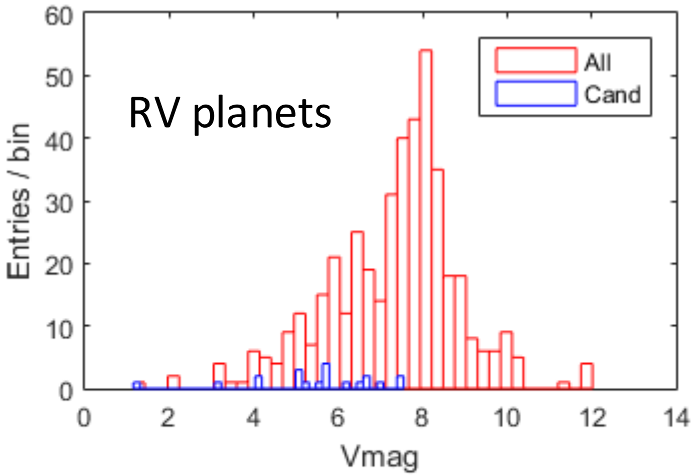
- The typical scenario involves two stars:
  1. A nearby **bright star** for getting a dark hole (~ 3 Hrs)*
  2. The planet host **target star** (~20 Hrs)*

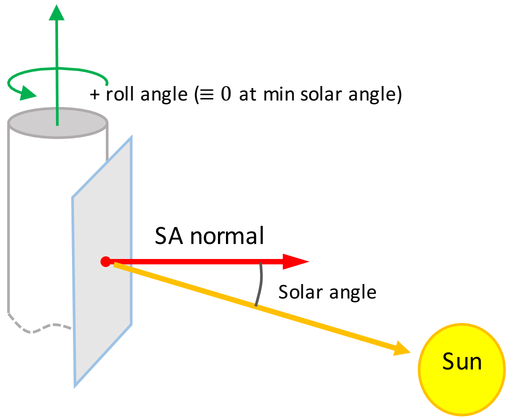
* numbers notional



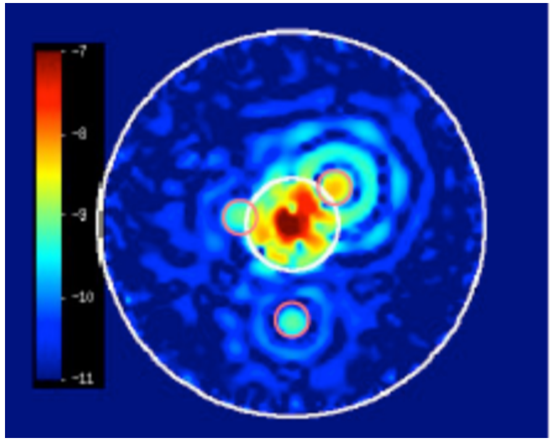
The SIT's can help select the right bright stars!

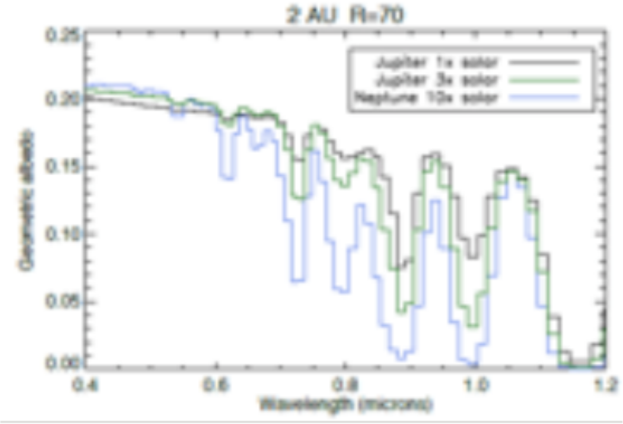


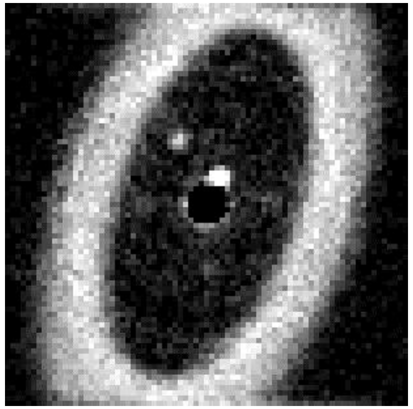




High-Contrast Science with WFIRST







- Characterize Roughly a Dozen Known RV Planets
- Photometrically Discover New Planets Down to Mini-Neptunes
- Image Debris Disks and Exo-Zodi in Two Polarizations
- GO High-Contrast and Narrow Field Science
- Demonstrate technology for future Earth imager

Exoplanet Imaging Survey

- Encompasses 1 year of mission time
- Image previously discovered radial velocity planets in WFIRST CGI range
- Perform searches for new planets in range from Super-Earths to Jupiters
- Search for debris disks and characterize down to a few zodi levels
- Opportunities for general observer science using imager or IFS with our without the coronagraph

Current WFIRST Preparatory Science project and SITs will develop detailed DRM simulations to optimize distribution of mission time and observations.

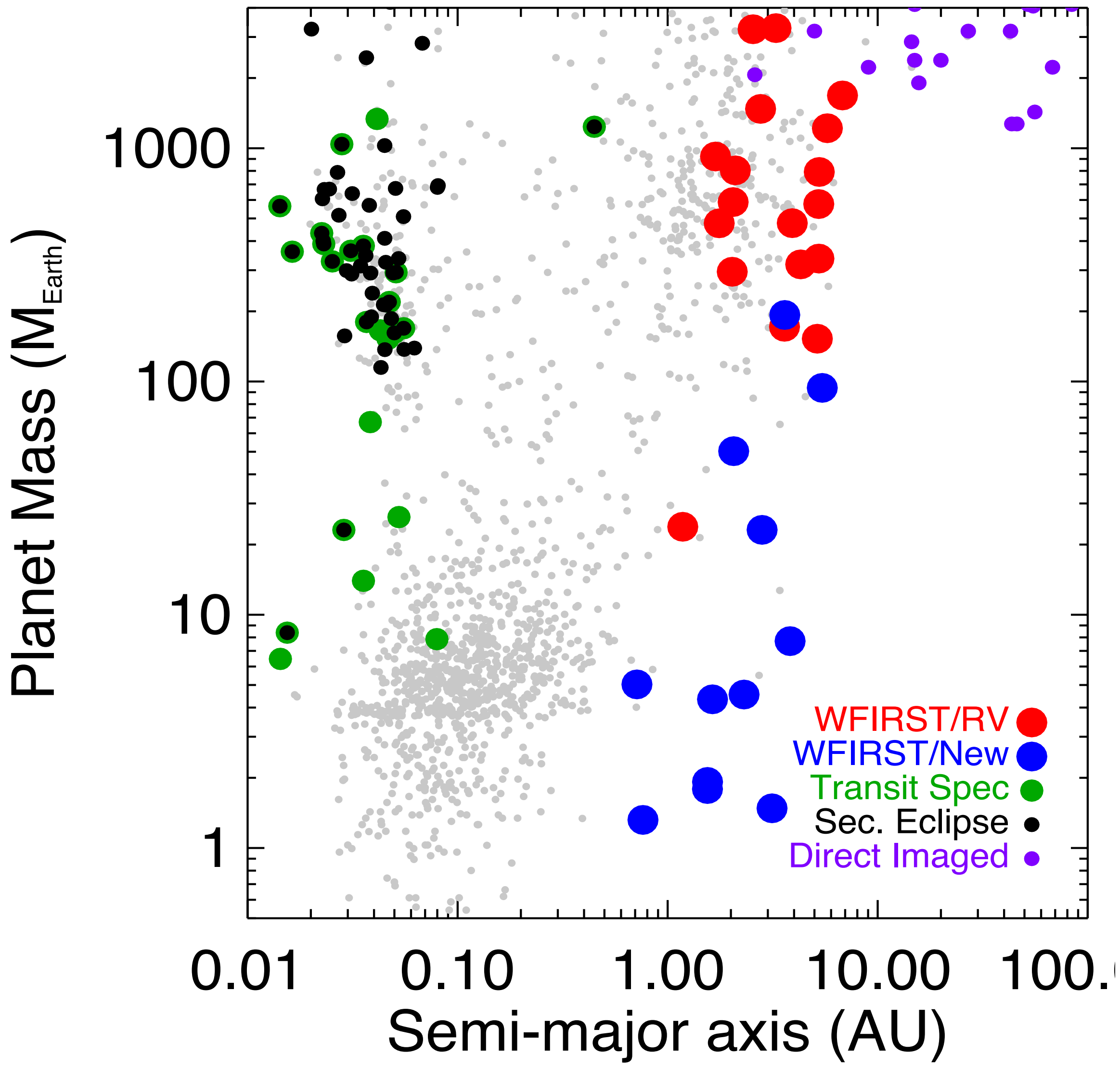
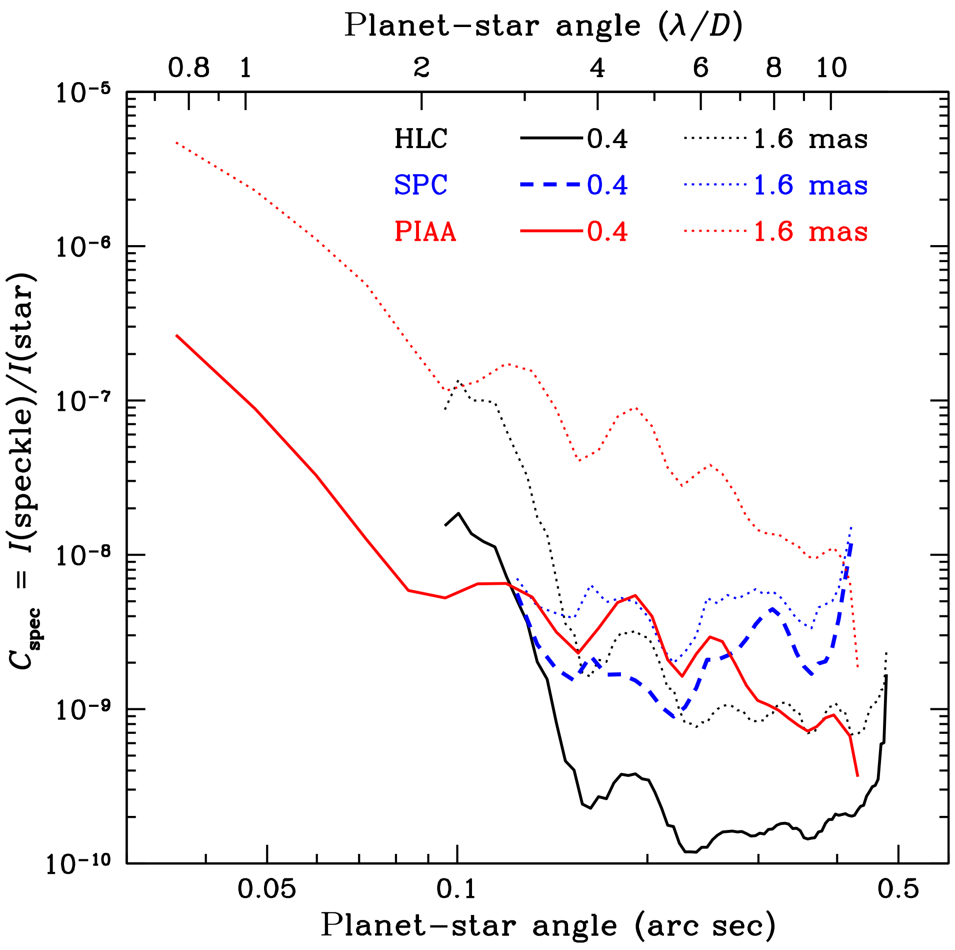
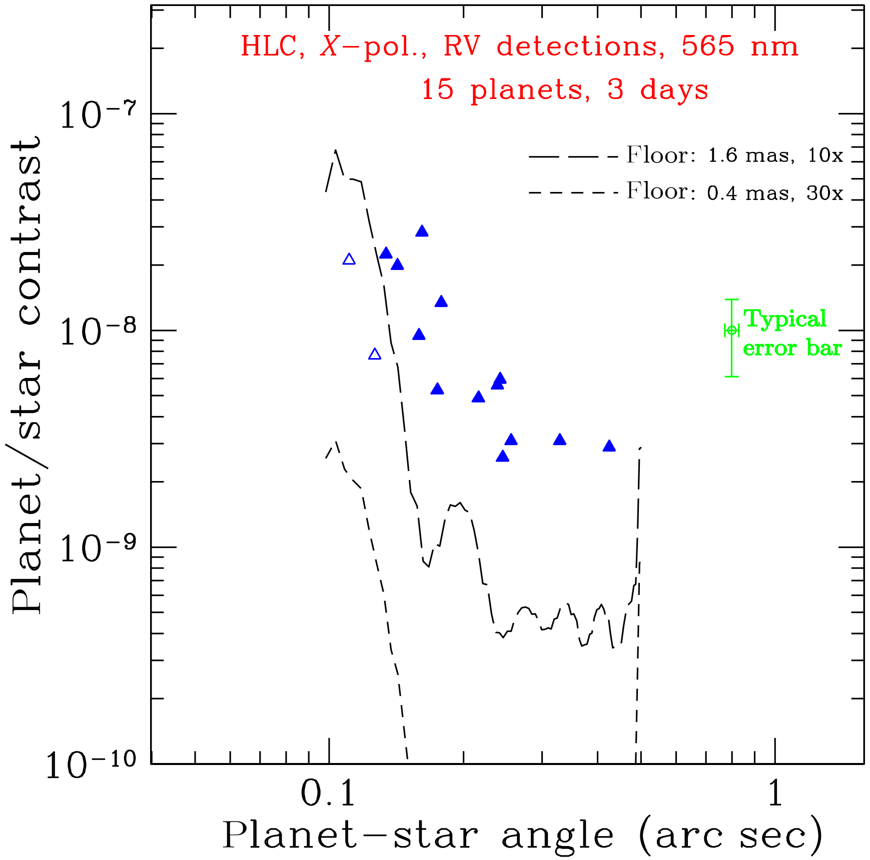


Figure credit Eric Nielsen



Contrast of speckles in the dark hole for each coronagraph, for a small residual jitter (0.4 mas RMS) and a large residual jitter (1.6 mas RMS), at the design wavelength of 550 nm. For other wavelengths, the planet–star angle is replaced by one that is wavelength scaled, as suggested by the λ/D axis at the top.



Science imaging yield of known RV planets with HLC. Solid symbols are RV planets detectable with HLC in a 15% band centered at 565 nm, in less than a day each, in a single polarization, with a signal strength greater than the worst-case floor (long-dash line, 1.6 mas RMS pointing jitter, and a postprocessing factor of 1/10). The open symbols are for the additional detections possible with the best-case floor (0.4 mas jitter, 1/30 factor).

Traub, et al., JATIS, 2016

Key Coronagraph Technology

Coronagraph Design, Masks and Hardware (varies by type)

– Shaped Pupil (SP), SPLC, Hybrid Lyot, APLC, Vector Vortex, PIAA, PIAA/CMC, 4QPM

– Large central obstruction, spiders, segmented mirrors

Wavefront Estimation and Control (common to all)

Probes and Field estimation, Control Algorithms (EFC & Stroke Minimization), Deformable Mirrors, Broadband control (with and without IFS), Low-Order Wavefront Sensing and Control (LOWFSC)

Data Analysis and Planet Identification

PFS Subtraction (LOCI, ADI, KLIP), IFS data cube, Spectral Characterization

Mission Modeling and DRMs

Engineering and Instrumentation

Optical design, polarization, IFS, calibration and test, operations

Error Analysis

Polarization, finite stellar size, stability, thermal bending (low-order aberrations)

CGI as a Technology Demonstrator

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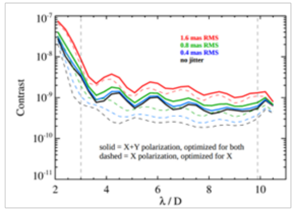
Starshade Rendezvous

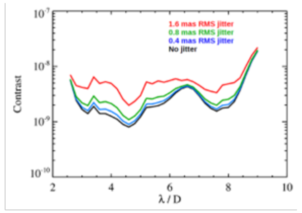
A study is underway to identify needed modifications to make WFIRST “starshade ready”.

Exo-S study provided example of starshade architecture that could fly with WFIRST, expanding the scope of technology demonstration and opening the opportunity for imaging of Earth-size planets.

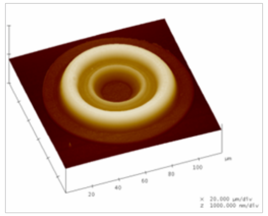
Technology Development

Coronagraph Designs Work with AFTA Telescope “as is” (Computer Model)

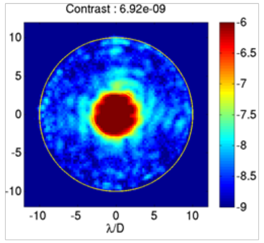


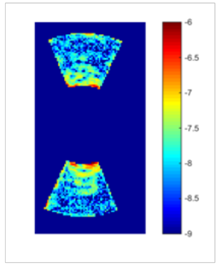


Demonstrate Fabrication of Key Starlight Suppression Components



Demonstrate Starlight Suppression in Narrowband Light

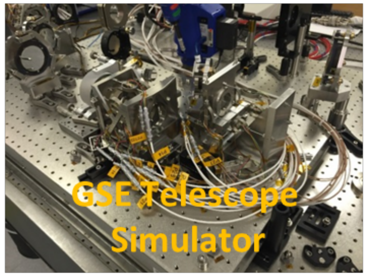




in progress

Demonstrate Starlight Suppression in Broadband Light

Demonstrate Starlight Suppression in Broadband Light, with Simulated Jitter and Drift from “as-is” Telescope



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