The AFTA-WFIRST Coronagraph and Mission Impact

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New Worlds, New Horizons

The most profound discovery in the coming decade may be the detection of potentially habitable Earth-like planets orbiting other stars. To find evidence that life exists beyond our Earth is a longstanding dream of humanity, and it is now coming within our reach. . . . Thus, the plan for the coming decade is to perform the necessary target reconnaissance surveys to inform next-generation mission designs while simultaneously completing the technology development to bring the goals within reach. This decade of dedicated preparatory work is needed so that, one day, parents and children can gaze at the sky and know that a place somewhat like home exists around "THAT" star, where life might be gaining a toehold somewhere along the long and precarious evolutionary process that led, on Earth, to humankind. And perhaps it is staring back at us! (pgs. 37-39)

New Worlds, New Horizons, Recommendations

New Worlds Technology Development Program
– #1 Medium Priority

To prepare for this endeavor, the committee recommends a program to lay the technical and scientific foundations for a future space imaging and spectroscopy mission. . . . In the first part of the decade NASA should support competed technology development to advance multiple possible technologies for a next-decade planet imager, and should accelerate measurements of exozodiacal light levels that will determine the size and complexity of such missions. . . . (pg. 20)

If the scientific groundwork has been laid and the design requirements for an imaging mission have become clear by the second half of this decade, a technology down-select should be made. (pg. 216)

Together with the TDEM program for other technologies, the coronagraph on AFTA advances key technologies to TRL 9 through a competitive process while simultaneously accomplishing profound scientific goals.

EOS Panel Report, NWNH

The panel did evaluate, and found appealing, several "probe-class" concepts employing ~1.5-m primary mirrors and internal starlight suppression systems, often coronagraphs with advanced wavefront control. . . . Such a mission could image about a dozen known (radial velocity) giant planets and search hundreds of other nearby stars for giant planets. Importantly, it could also measure the distribution and amount of exozodiacal disk emission to levels below that in our own solar system (1 zodi) and detect super-Earth planets in the habitable zones of up to two dozen nearby stars. These would be extremely important steps, both technically and scientifically, toward a mission that could find and characterize an Earth-twin. (pgs. 293-294)

Coronagraph for AFTA accomplishes these scientific goals at much lower cost than a probe and with minimal impact on WFIRST.

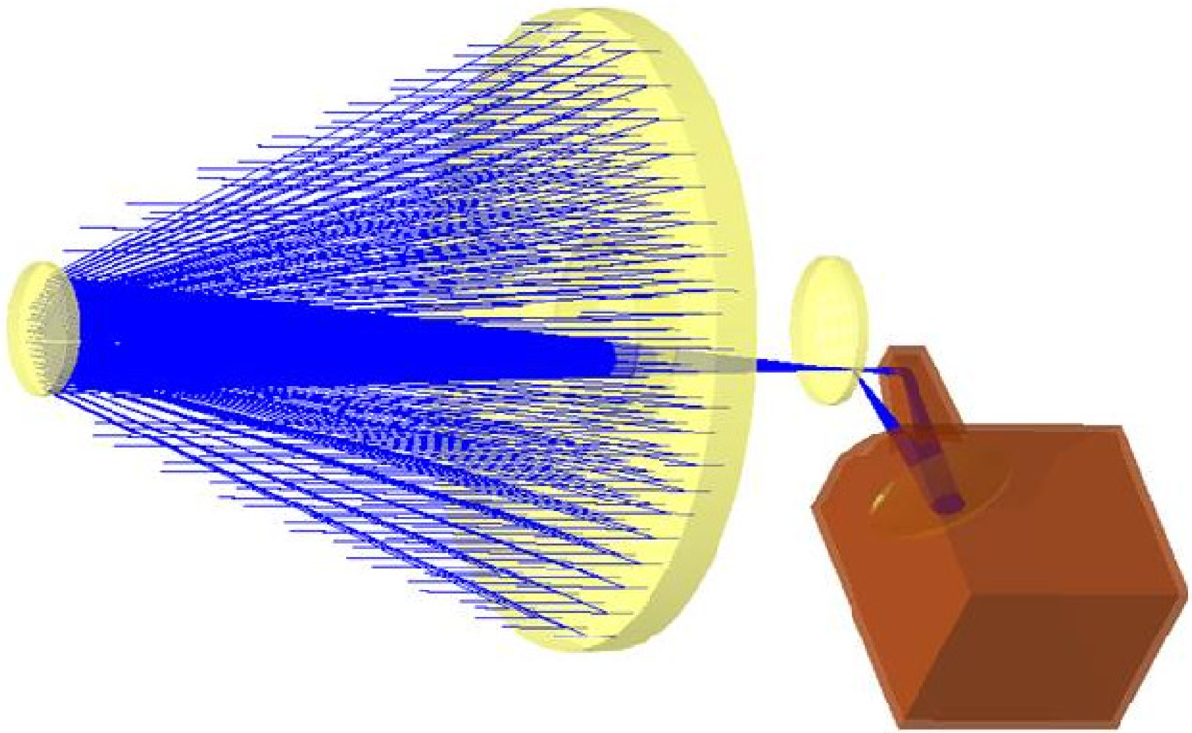
AFTA Coronagraph

AFTA Coronagraph Responds to NWNH goals by:

- Characterizing the spectra of over a dozen radial velocity planets.
- Discovering and characterizing up to a dozen more ice and gas giants.
- Providing crucial information on the physics of planetary atmospheres.
- Measuring the exozodiacal disk level about nearby stars.
- Imaging circumstellar disks for signposts of planet interactions and advancing understanding of planetary system formation.
- Maturing critical coronagraph technologies (common to many types), informing a future technology downselect for a later terrestrial planet imaging mission.

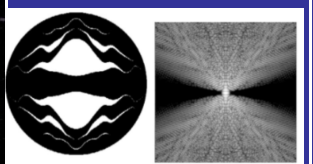
While minimizing new requirements on observatory that could impact risk, cost, or schedule (“use as-is”).

Coronagraph Instrument

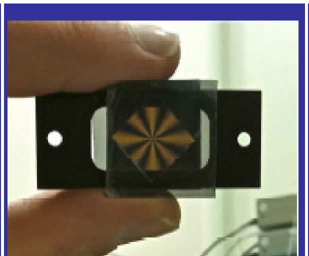


Star light suppression -- Technical Approach

Six different concepts

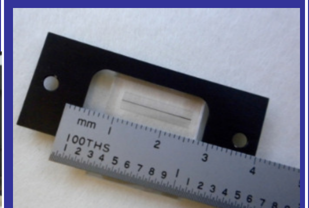


Shaped Pupil Mask Pupil Masking (Vanderbei & Kasdin, Princeton Univ.)

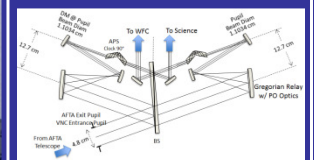


Vector Vortex Mask Image Plane (Serabyn, JPL)

Phase Induced Amplitude Apodization (PIAA) Pupil Re-Mapping (Guyon, Univ. Arizona)



Hybrid / Band-Limited Lyot Mask Image Plane Amplitude & Phase (Trauger, JPL)

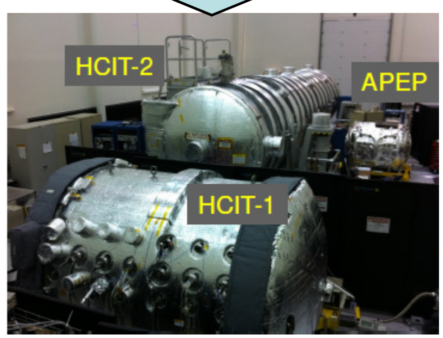


Visible Nuller Coronagraph: Phase-Occulting (Lyon, GSFC)

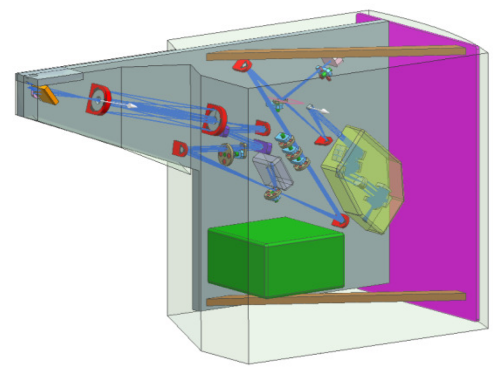
Visible Nuller Coronagraph: DaVinci (Shao, JPL)

Down select 12/15/2013
http://wfirst.gsfc.nasa.gov/

Primary Architecture (OMC)	Back-up Architecture (PIAACMC)



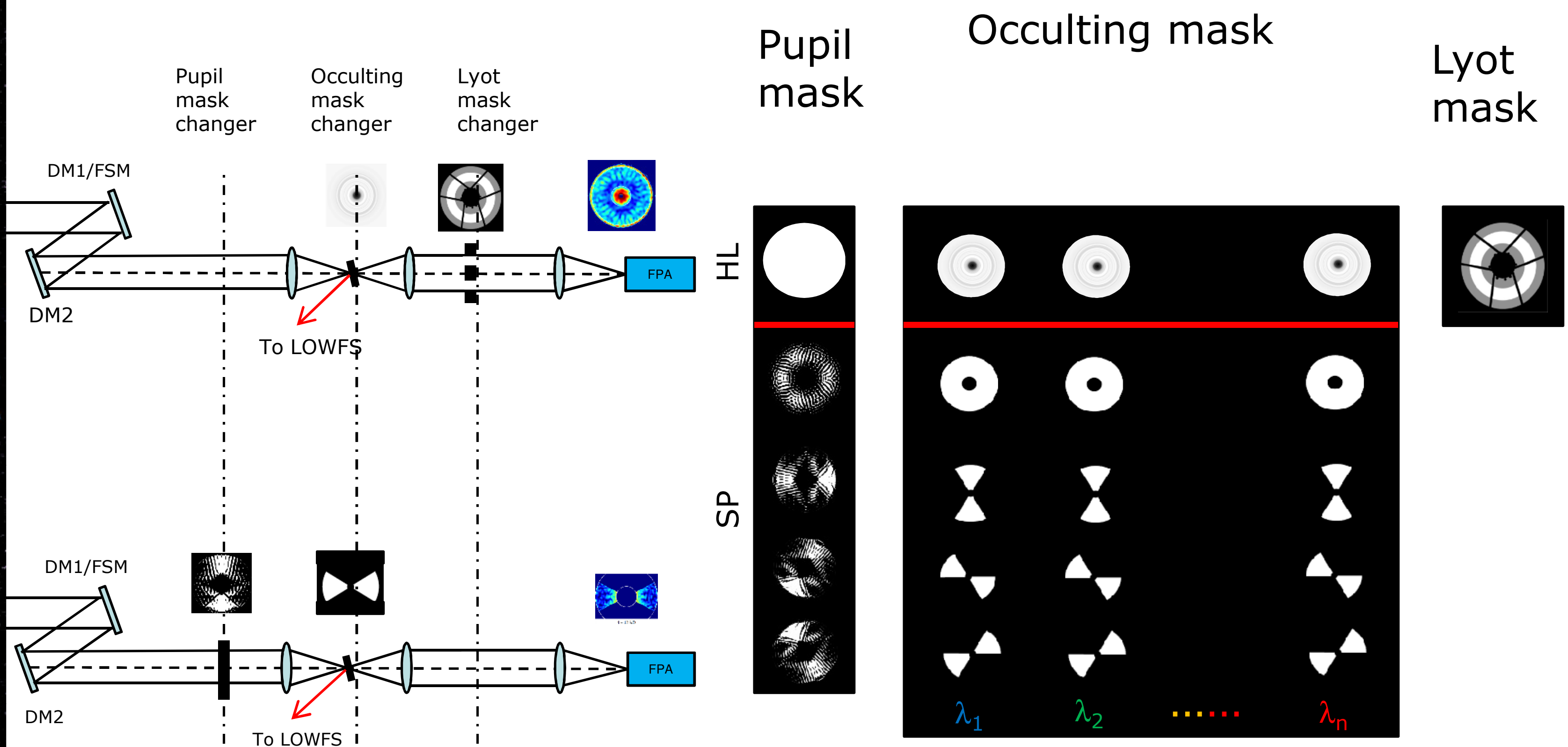
TRL-5 @ start of Phase A (10/2016)



TRL-6 @ PDR (10/2018)

Primary Architecture:
Occulting Mask Coronagraph = Shaped Pupil + Hybrid Lyot

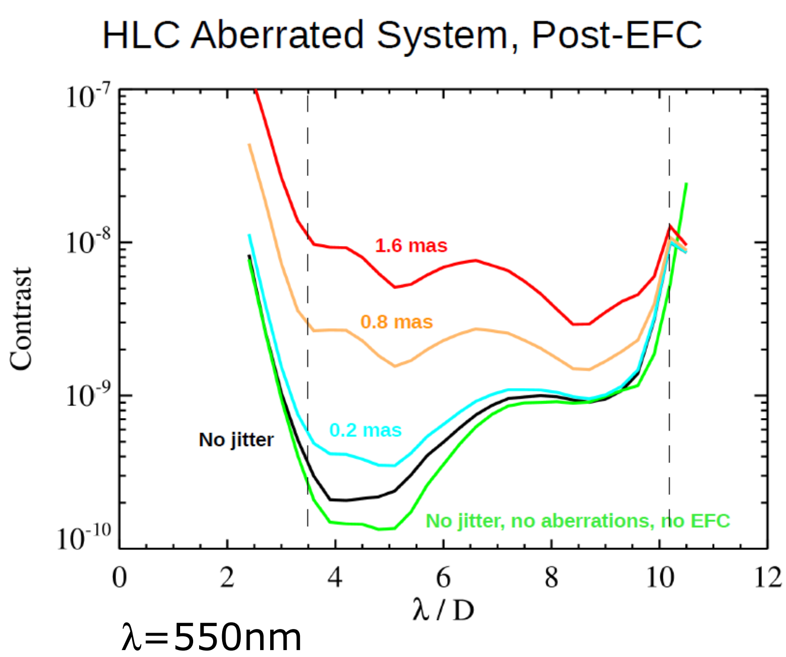
- SP and HL masks share very similar optical layouts
- Small increase in over all complexity compared with single mask implementation

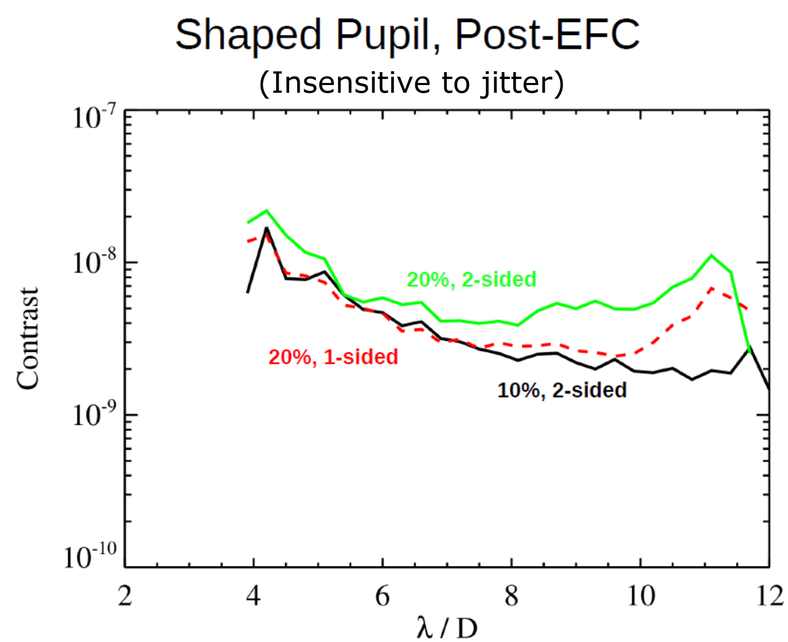


A backup architecture using a higher performing Phase Induced Amplitude Apodization (PIAA) coronagraph is also being studied.

Contrast simulations with AFTA pupil, aberrations and expected range of telescope pointing jitter

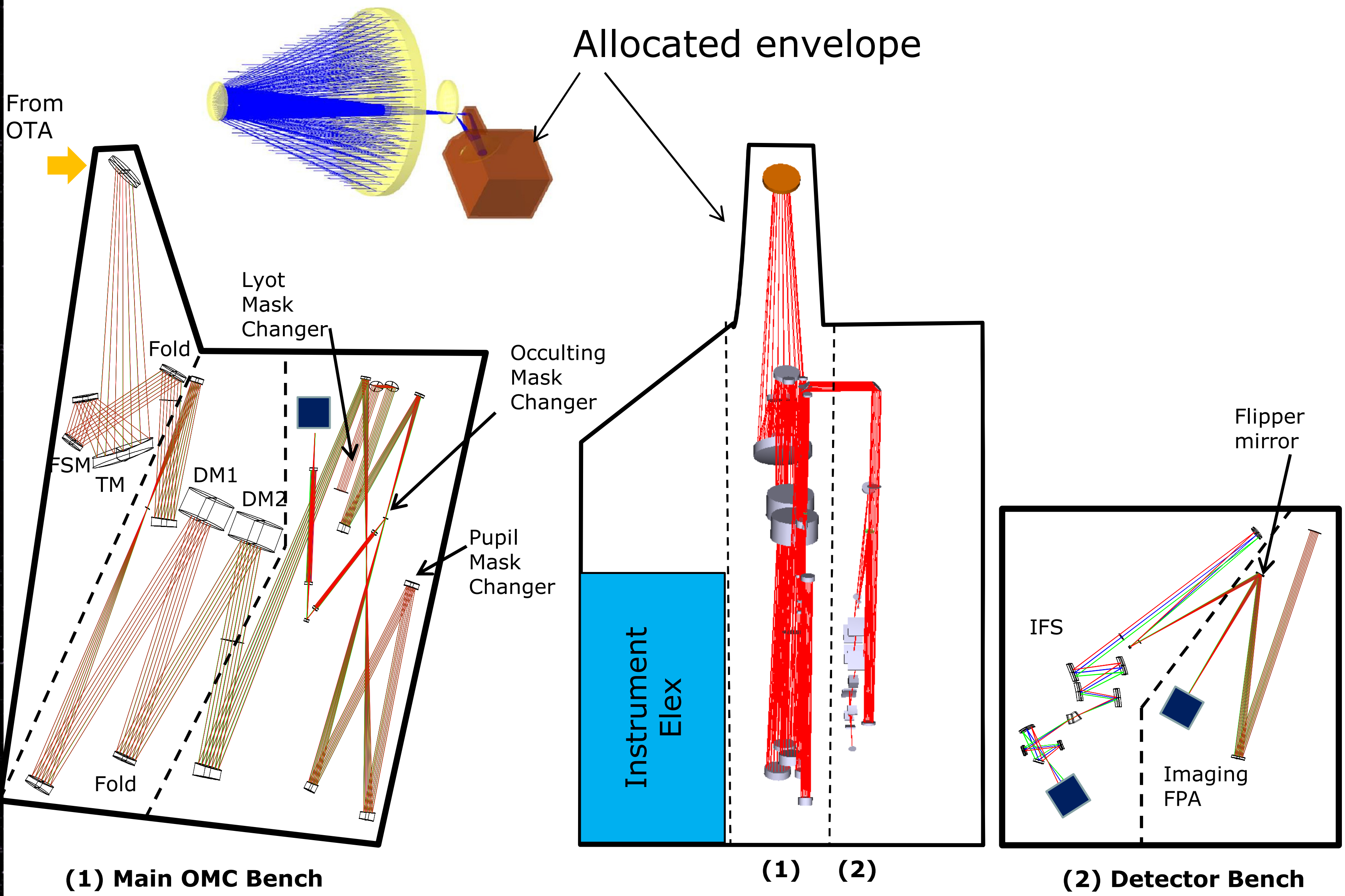
- OMC in its “SP mode” provides the simplest design, lowest risk, easiest technology maturation, most benign set of requirements on the spacecraft and “use-as-is” telescope. This translates to low cost/schedule risk and a design that has a high probability to pass thru the CATE process.
- In its “HL mode”, the OMC affords the potential for greater science, taking advantage of good thermal stability in GEO and low telescope jitter for most of the RAW speed





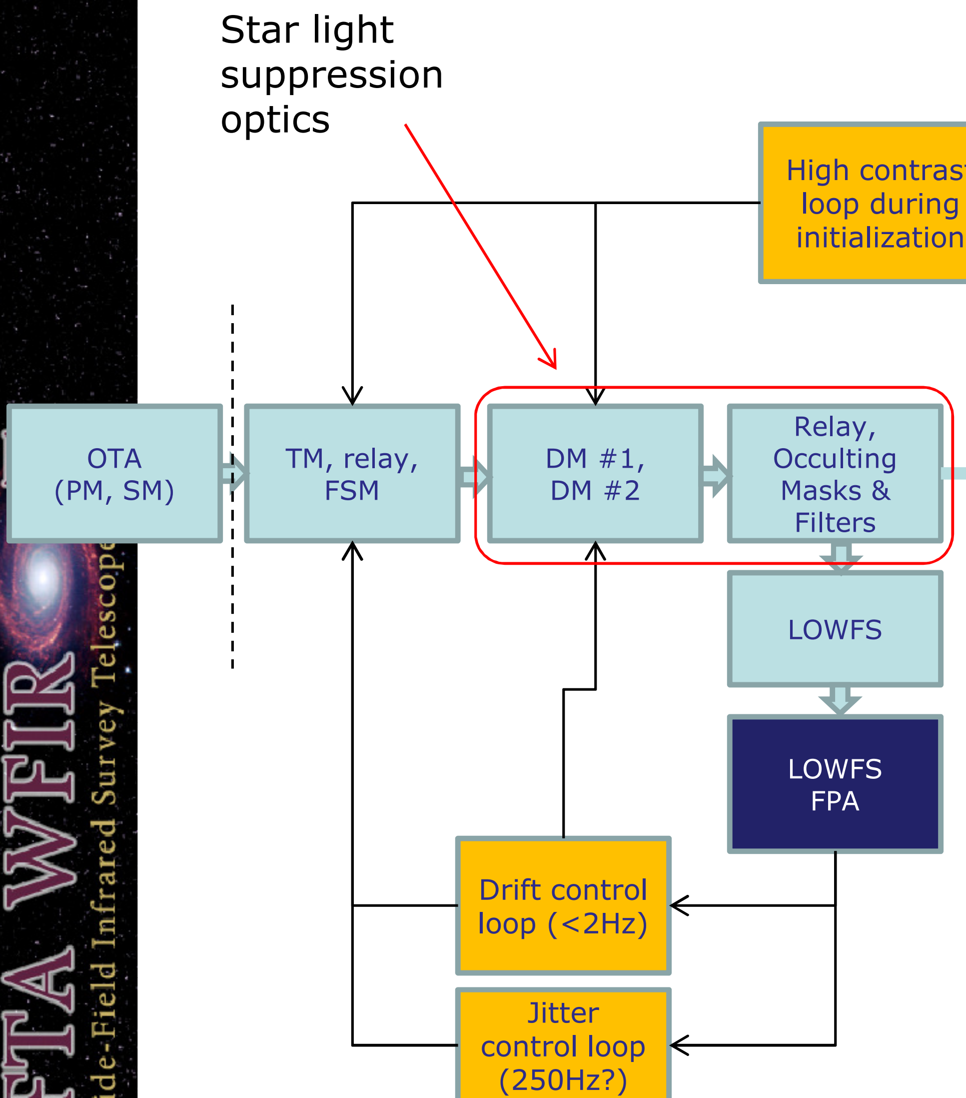
Good balance of science yield and engineering risk

AFTA Coronagraph Instrument



Functional Block Diagram

AFTA WFIRST
Wide-Field Infrared Survey Telescope



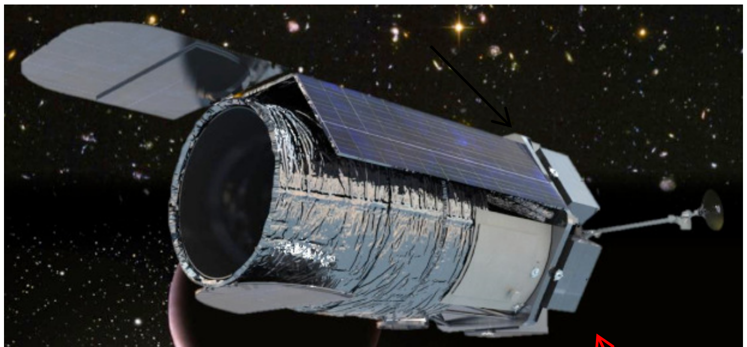
TRL 9 Technology Demonstration:

- Deformable Mirrors
- Low Order Wavefront Sensing & Control
- High-order wavefront control
- Multiple Coronagraph technology
- Visible light, high-contrast IFS
- Fast jitter control loop
- Data processing techniques

Legend:

- Optics
- Control
- Detector
- Post processing on ground

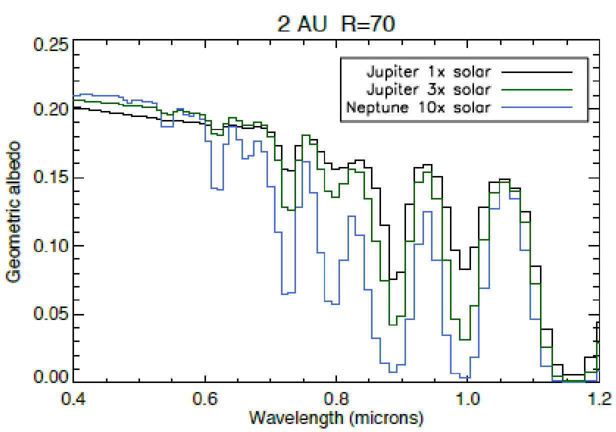
AFTA Coronagraph Instrument



Coronagraph Architecture:

Primary: OMC
Backup: PIAA

Coronagraph Instrument



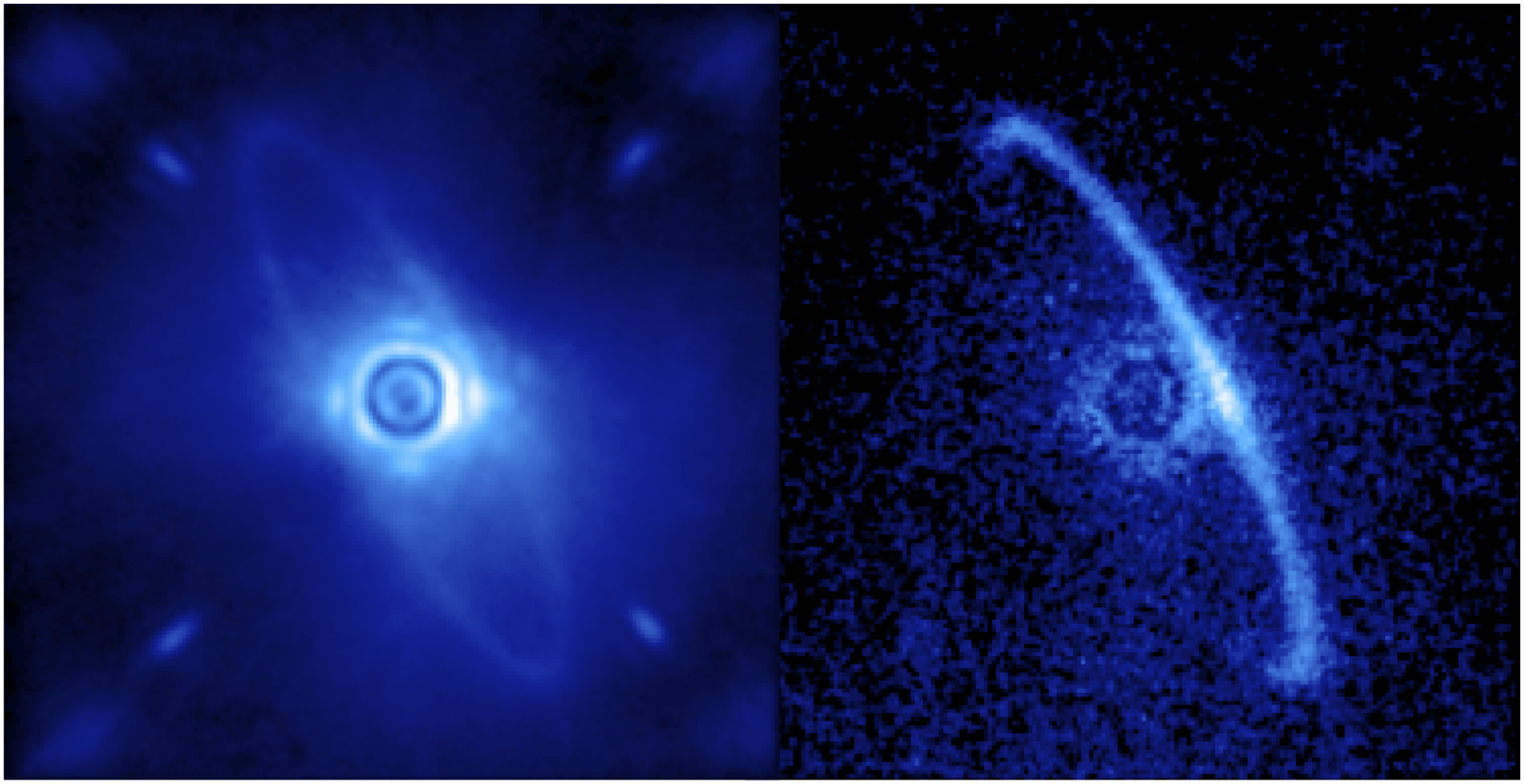
Exo-planet
[Spectroscopy

Bandpass	430 – 980nm	Measured sequentially in five ~10% bands
Inner working angle	100 – 250 mas	~3λ/D, driven by science
Outer working angle	0.75 – 1.8 arcsec	By 48X48 DM
Detection Limit	Contrast ≤ 10^{-9} After post processing)	Cold Jupiters, Neptunes, down to ~2 RE
Spectral Res.	~70	With IFS, R~70 across 600 – 980 nm
IFS Spatial Sampling	17mas	Nyqust for λ~430nm

Coronagraph technology development

- Finalize designs for testing
- Manufacture masks and stops Winter/Spring 2014
- Begin HCIT vacuum facility testing Spring/Summer 2014
- Perform static wavefront control tests followed by dynamic tests with jitter through Summer 2016.
- Goal of TRL 5 by October, 2016.

AFTA High-Contrast Science

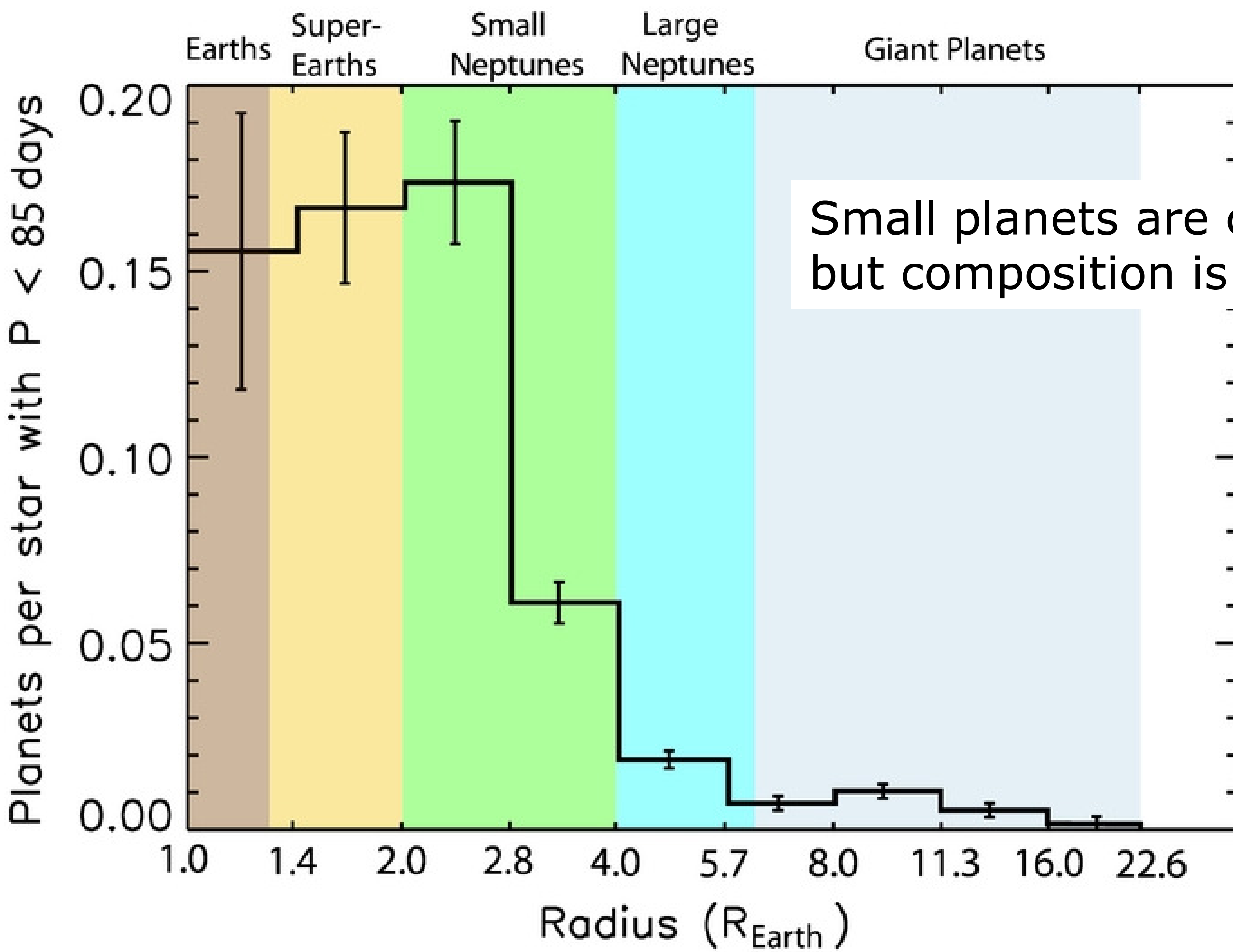


GPI first light image of the HR 4796A circumstellar dusk ring in unpolarized and polarized 2 micron light.

AFTA Exoplanet Science Objectives

1) Survey 200 nearby stars including both those with known extrasolar planets and those for which no constraints will exist (e.g. A stars) spanning the range of spectral types
2) Characterize a significant sample (10-20) of giant planets in broadband reflected-light photometry with an accuracy of 0.03 in albedo, spanning a ~5 bands that are sensitive from Rayleigh scattering to methane absorption
3) Spectroscopicallycharacterize a subset (6-10) of giant planets spanning a range of irradiances and determine the depth of methane, water, and other features
   - Detect a sample (~2-4) of planets of less than 3 RE in broadband photometry of at least 3 bands with an accuracy of 0.05 in albedo
4) Characterize the orbital semi-major-axis (within 20%) and eccentricity (within 0.2) of these planets, in conjunction with Doppler or astrometric measurements

Kepler radius distribution

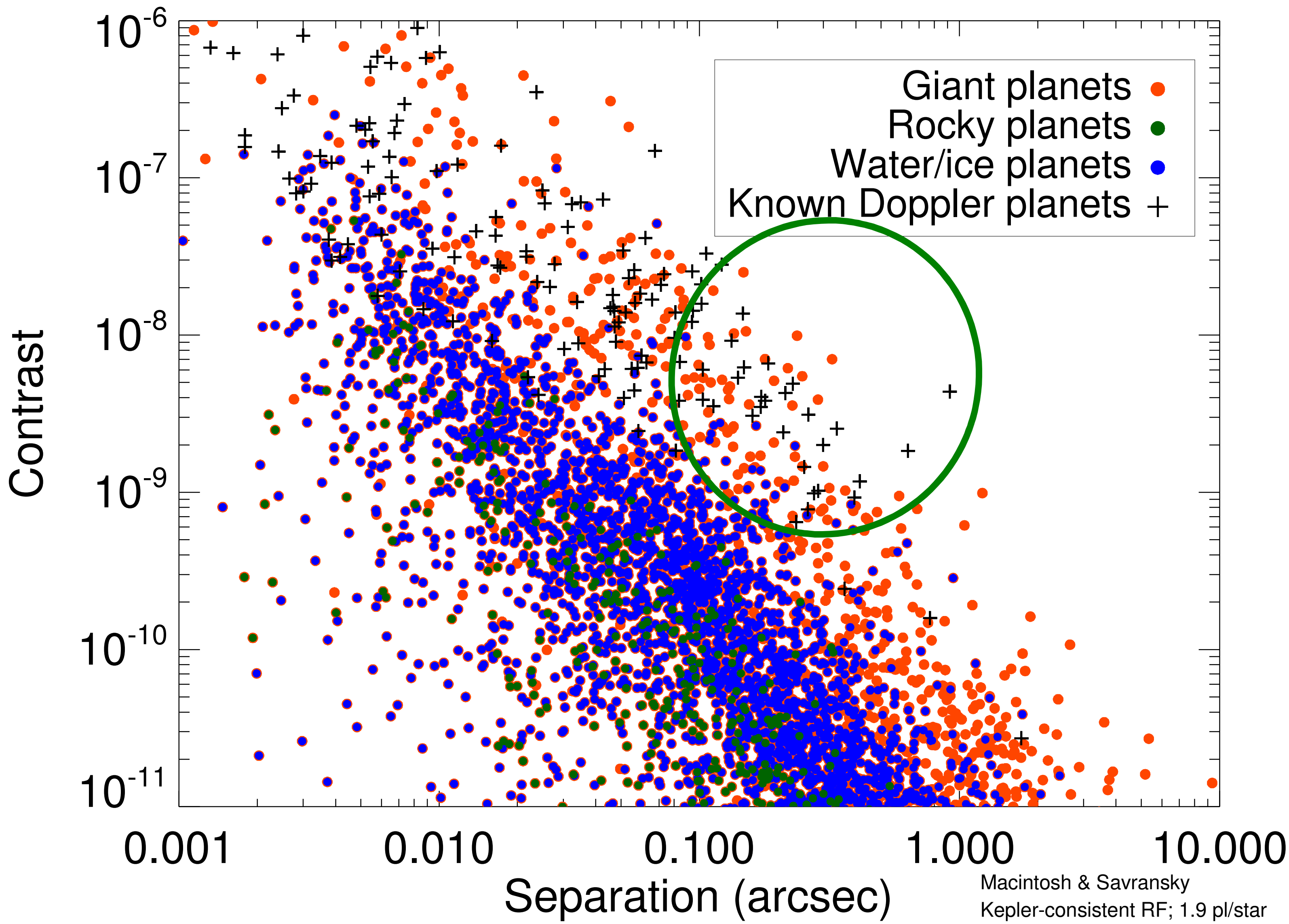


Small planets are common, but composition is unknown.

Fressin et al 2013; Kepler FGKM stars P<85 days

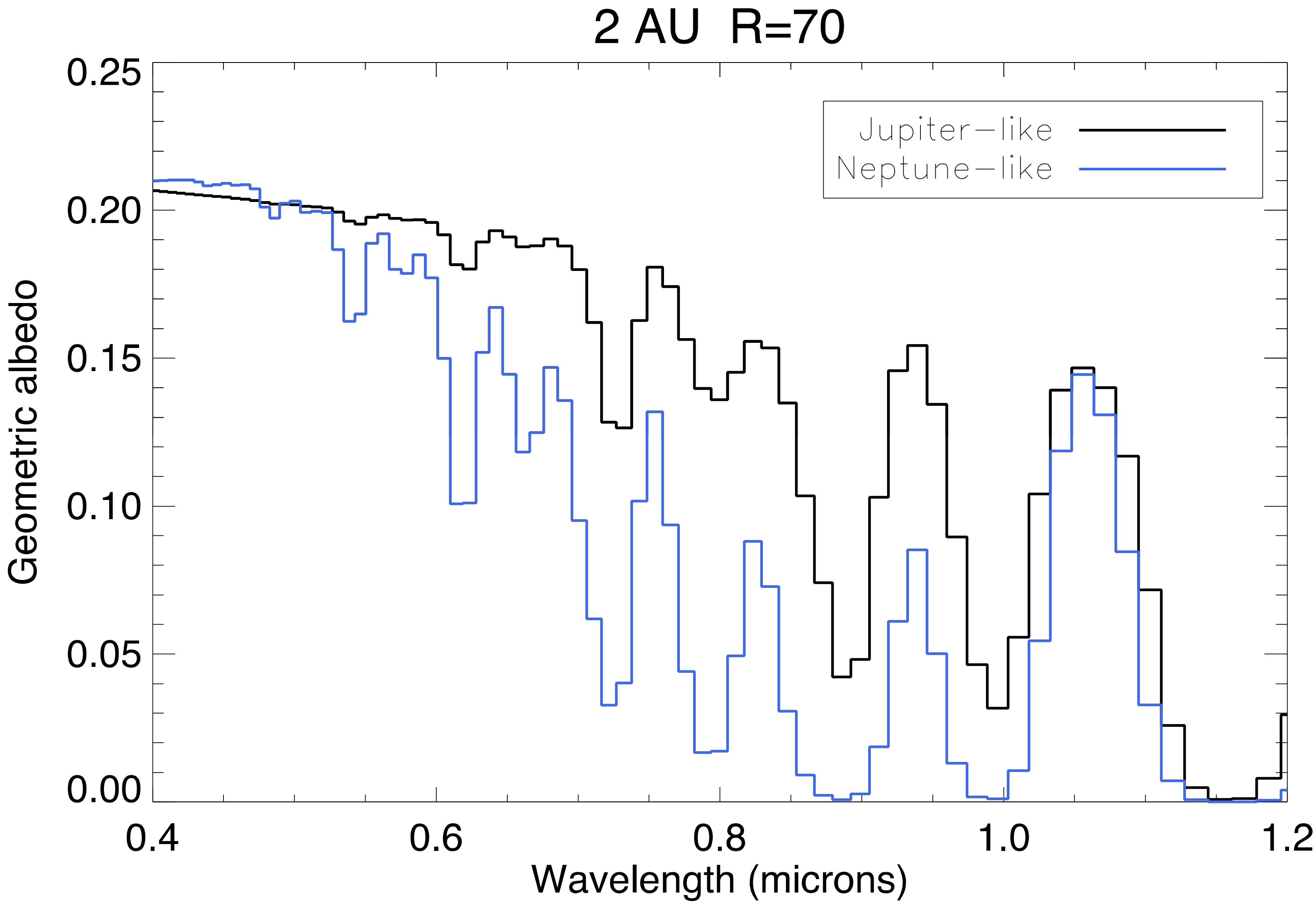
AFTA WFIRST
Wide-Field Infrared Survey Telescope

Simulated Planets within 30 pc consistent with Kepler



Macintosh & Savransky
Kepler-consistent RF; 1.9 pl/star
Main sequence non binary stars

R~70 spectra can determine planet properties



AFTA Circumstellar Disk Science

7) Search for low surface density circumstellar disks around a sample of several dozen nearby stars.

8) Measure the location, surface density and extents of dust particles around nearby stars from habitable zones to beyond ice lines to understand delivery of materials to inner solar systems

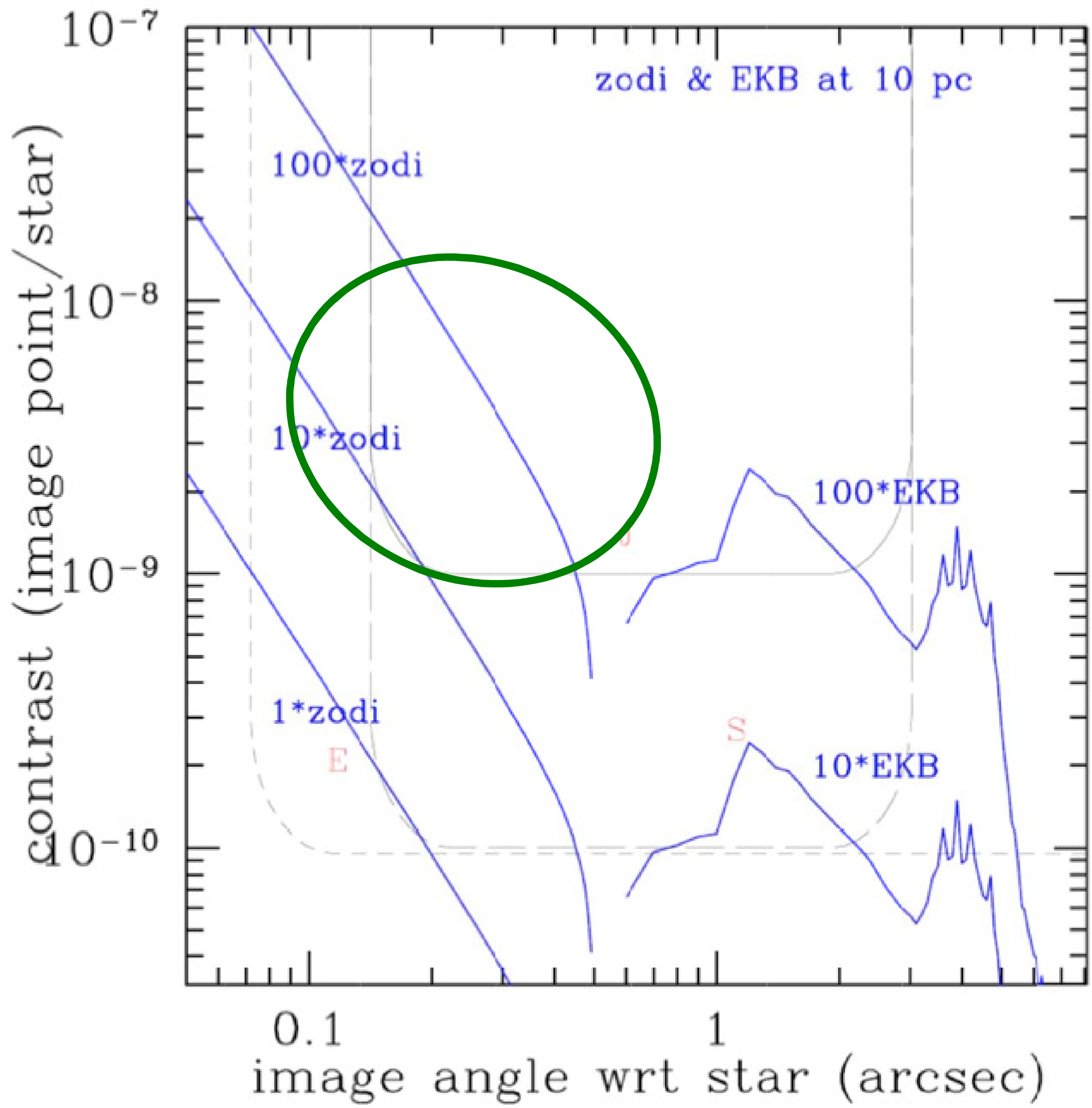
9) Constrain dust grain compositions and sizes

10) Detect and measure substructures within dusty debris that can be used to understand the locations of parent bodies (asteroids, comets) and influences of seen and unseen planets

11) Identify what nearby stars have zodiacal dust levels indicating they may be poor candidates for future terrestrial planet imaging

12) Understand the time evolution of circumstellar disk properties around a broad star sample

Disk densities of 10-100 Zodi should be detectable in inner system



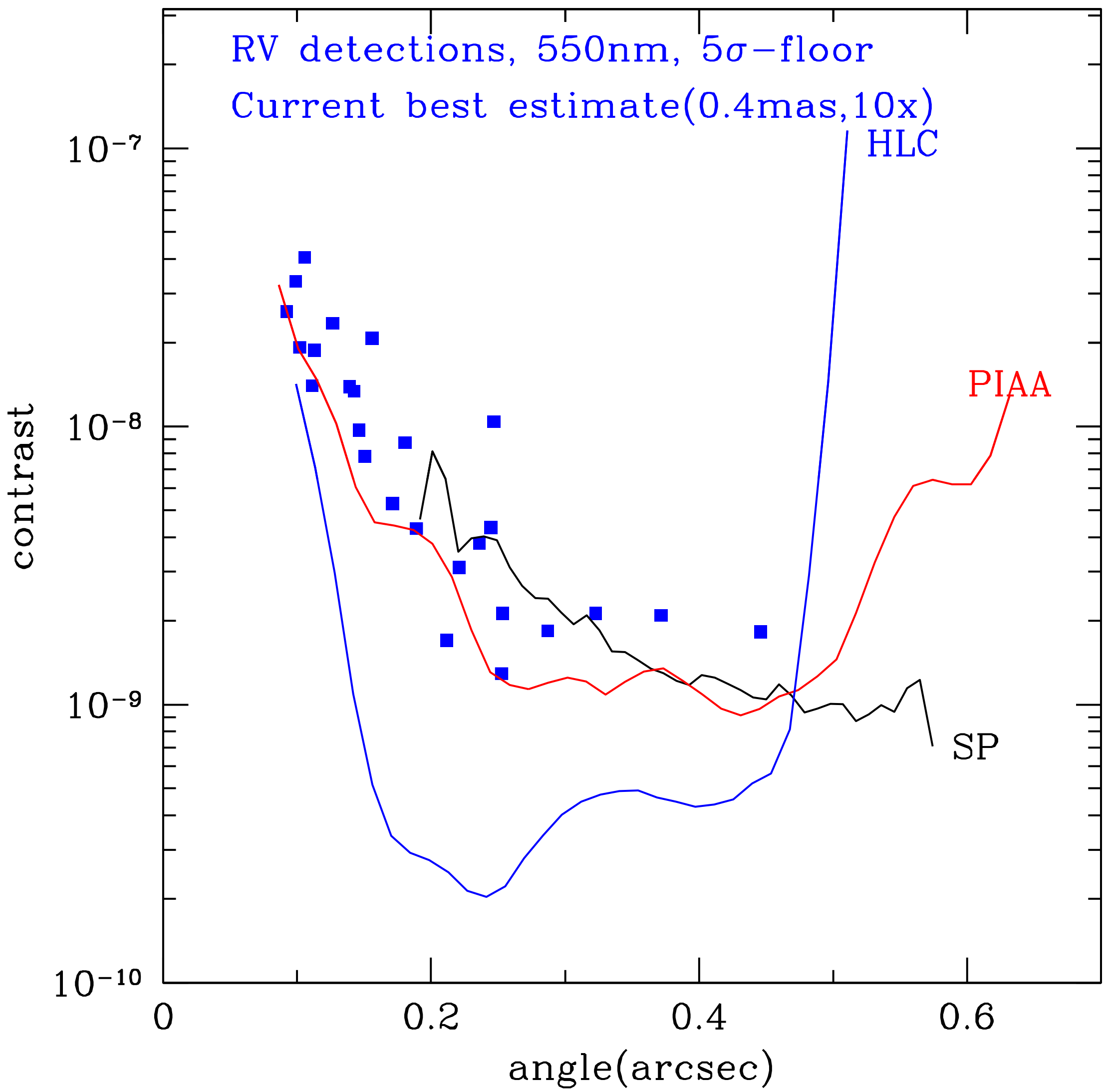
Science Modeling (Wes Traub)

- Science yield modeling focusing on ability to study Doppler planets
- Contrast curves generated from John Krist PROPER models
  - Very dependent on telescope jitter assumptions
  - Recent SPOT modeling shows jitter < 0.4 marcsecrms
- Model residual speckle noise, photon noise from halo, photon noise from foreground and background zodiacal light, detector noise sources
- Significant uncertainty in removal of speckles through post-processing and PSF subtraction

Not all designs have been optimized for latest jitter value so some improvements are possible.

Contrast vs Angle from Star

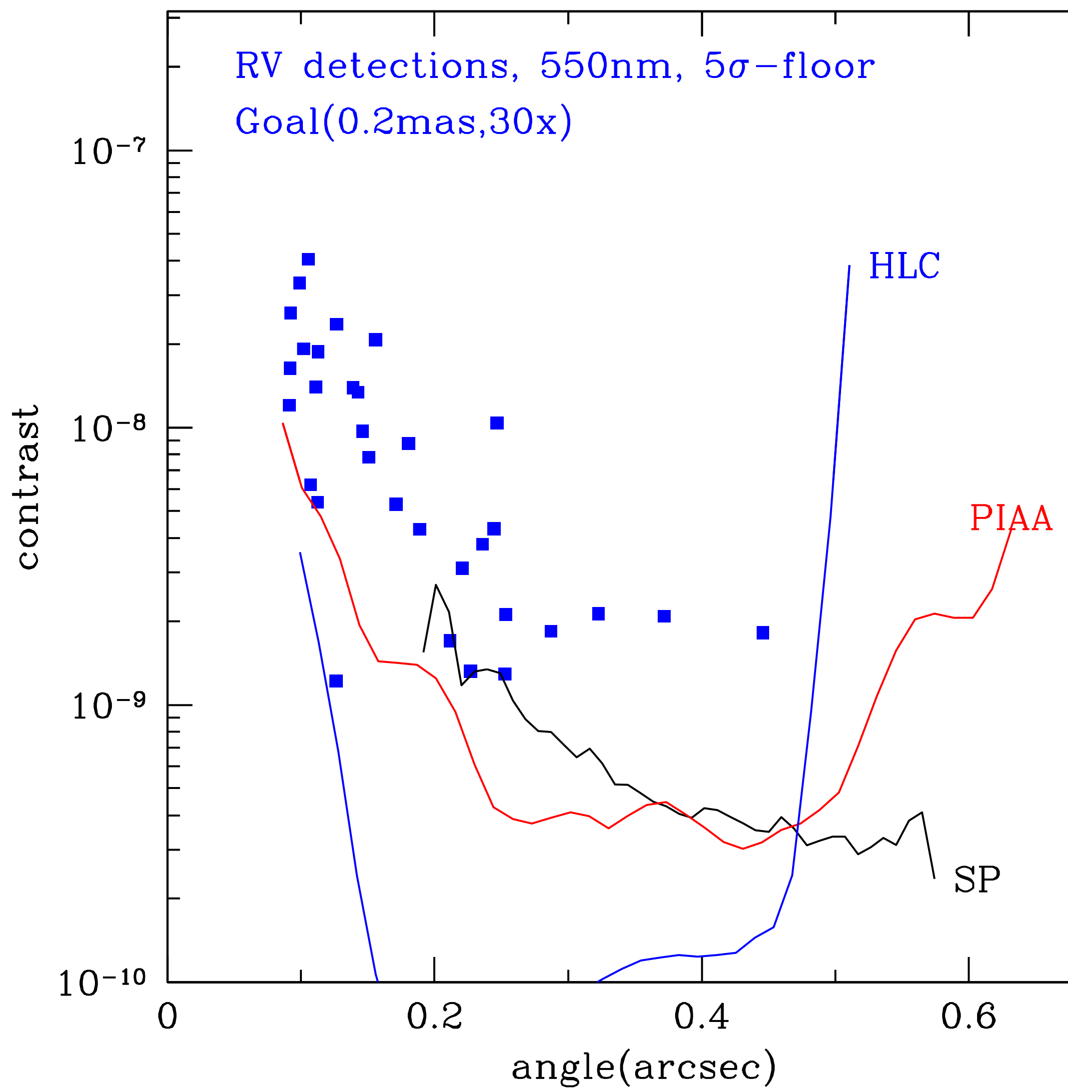
Current best estimate jitter & post-processing factor



Contrast floors here are upper limit for long exposure/very bright star

Contrast vs Angle from Star

Goal jitter & post-processing factor



Contrast floors here are upper limit for long exposure/very bright star

AFTA RV Exoplanet Detection Estimates

- RV exoplanet detections are estimated based on imaging of radial velocity planets from the current RV catalog

Configuration	Design	Inner working angle	# RV planets, 550nm band, 6-month campaign	# spectral bands per target, 6-month campaign
Prime (OMC: Occulting Mask Coron.)	**SP**	0.19	4 7	4.3 4.9
	HL	0.10	18 19	4.3 4.2
Backup	**PIAA**	0.09	23 30	3.2 4.3

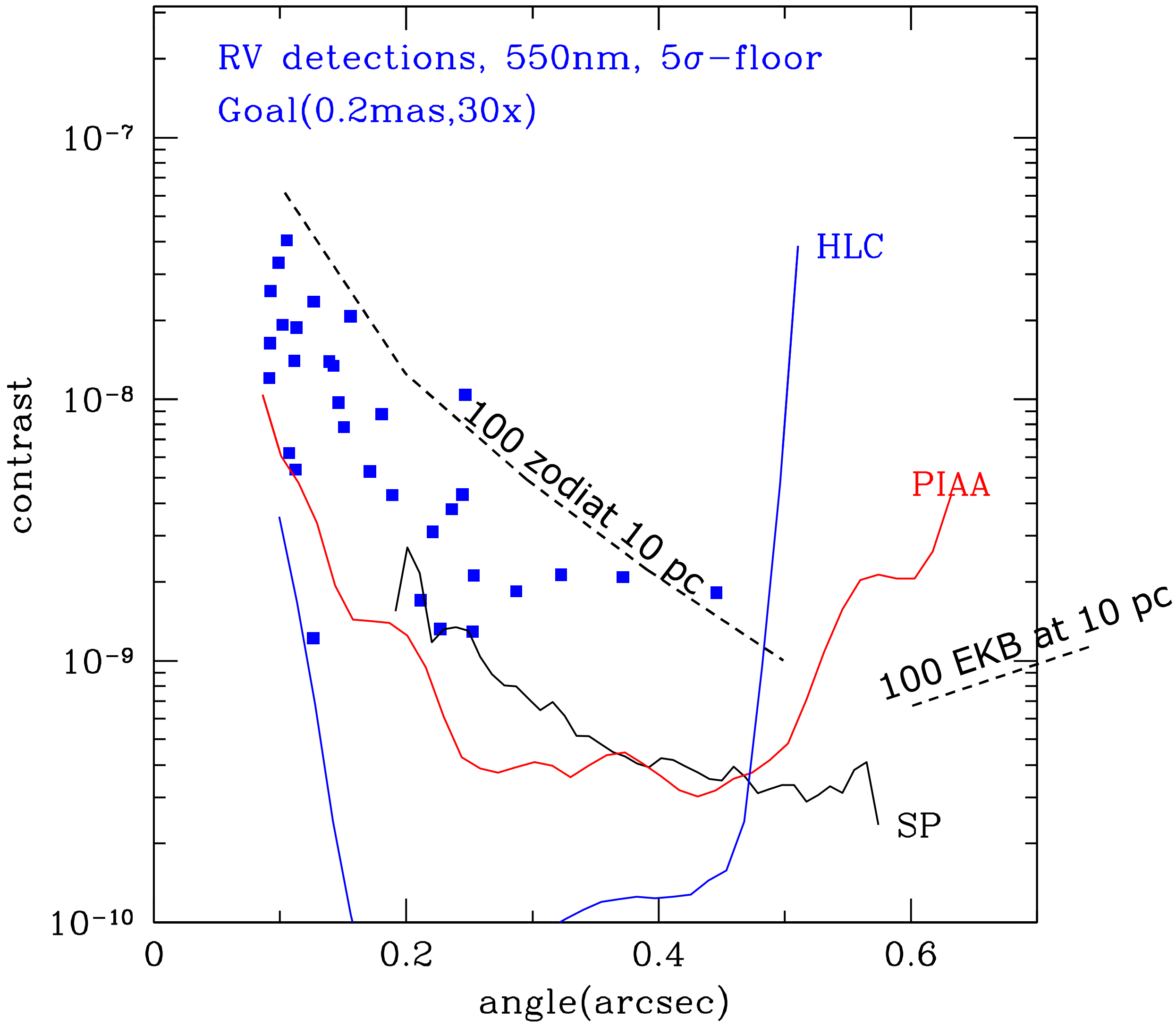
Note 1. Two rows for contrast and # RV images columns are for cases of

- Current Best Estimate: 0.4 mas RMS jitter & 1 mas star, 10x post-processing factor (slide 4)
- Goal: 0.2 mas RMS jitter & 1 mas star, 30x post-processing factor (slide 5)

Note 2. Spectral bands are 10% wide, centered at 450, 550, 650, 800, 950 nm

Contrast vs Angle from Star

Goal jitter & post-processing factor



Future Science Tasks

- Evaluate spectroscopic capabilities of new designs
  - Requires coronagraph modeling at 800 nm
- Evaluate capabilities for 1-4 RE planets
- Assess Doppler completeness of likely target sample
- Additional integrated modeling of coronagraph
- Assess likely disk imaging science using refined coronagraphic capabilities and integrated simulations
- Evaluate speckle removal requirements and capabilities
- Develop mission scenarios

NRC Panel Request

Provide a summary of how mission parameters are affected by the inclusion of coronagraphy. Specifically, these parameters are as follows:

- Pointing accuracy and pointing stability
- Detector+readout performance including sensitivity, stability, and dynamic range
- Payload mass
- Straylight and baffling
- Optical quality (eg. PSF)

Pointing Accuracy and Pointing Stability

- Some coronagraph approaches very sensitive to image motion and jitter.
- Wavefront control system sensitive to slow changes in wavefront error.
- Observatory integrated modeling at early stages.
- Current requirements set at conservative values.
- Coronagraph does NOT set observatory requirements.
- Preliminary analyses show, however, low jitter and wavefront error.

> Coronagraph instrument is designed to be robust to pointing error and jitter through inclusion of fast steering loop and multiple coronagraph designs.

Observatory Pointing& Jitter Requirements

Observatory Jitter Requirements

The Observatory Pointing Spec is 20 masrms/axis, rss'd to:

- **Jitter = 14.0 masecrms/axis (≥2 Hz, uncontrolled by Observatory)**
- Pointing Error = 14.3 masecrms/axis (<2Hz, controlled by Observatory)

The Coronagraph uses LOWFS/C to reduce the pointing error and jitter to ≤1.6 masrms/axis, with a goal in the ≤0.8 masrms/axis range with a tip/tilt fast steering mirror.

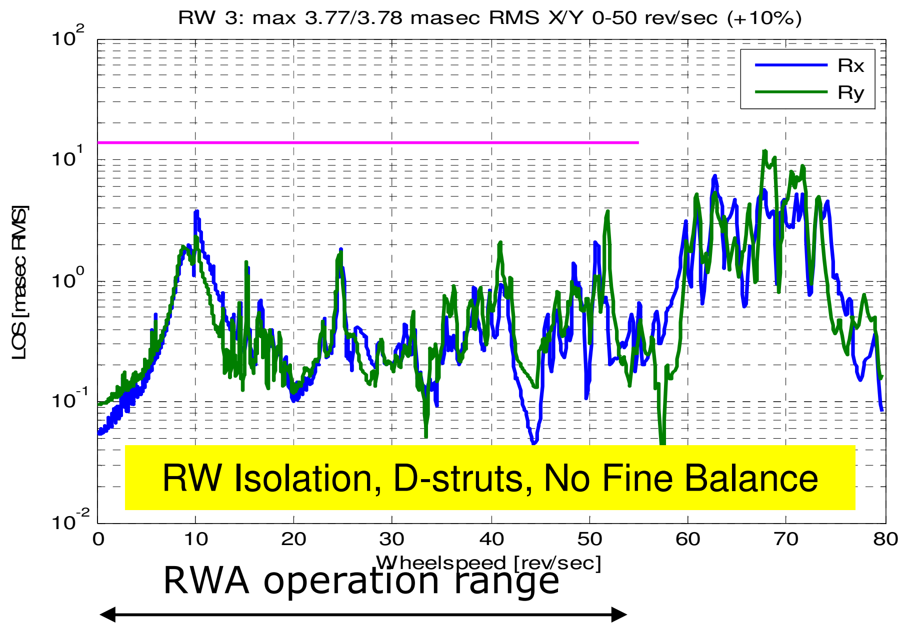
Current Integrated Modeling analysis predicts jitter to be < 4 masrms/axis with internal coronagraph control < 0.4 masrms/axis.

Coronagraph design includes both higher performing masks for low jitter and shaped pupil, which is insensitive to jitter, if at high 1.6 masec (or higher) level.

Observatory Pointing Jitter Estimate

No new requirements, coronagraph selection and predictions based on current best estimates.

- The results indicate telescope LOS jitter less than 4 mas over a wide range of wheel speeds, before LOWFS tip/tilt correction.
  - Except at wheel speed ~10 and 26 rps
- Numerous opportunities exist for further jitter optimization:
  - structural optimization,
  - operational constraints,
  - momentum management strategies,
  - LOWFS design optimization

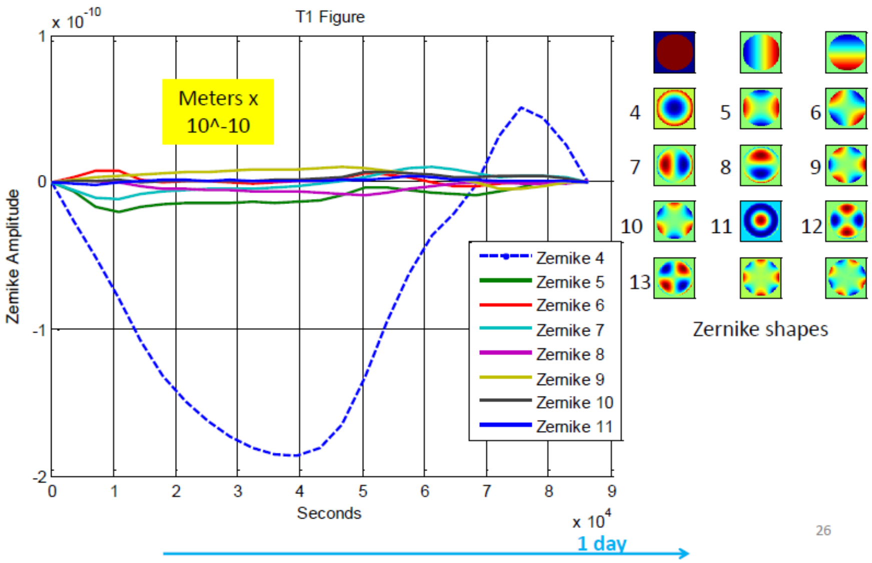


"Model uncertainty factor (MUF)" consistent with pre-Phase A model predictions (MUF=2.5 for f<20Hz, and MUF=6 for f>40Hz, linear in between)

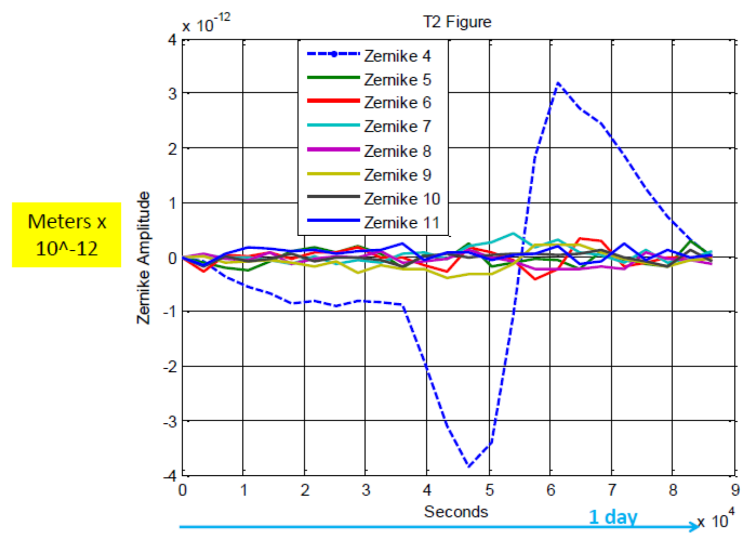
Telescope Thermal Stability Estimate

- Recent STOP model results indicate very stable telescope wavefront during operation
  - Dominant term is focus, ~0.2nm over 24 hrs
  - Other low-order WFE <20pm over 24 hrs

T1 Zernike Amplitudes over 24 Hours



T2 Zernike Amplitudes over 24 Hours



Low Order Errors corrected by LOWFS and Control.

Detector + Readout Performance

Coronagraph Instrument has separate CCD detectors from Wide Field Instrument.

- Baseline for Imager and IFS is an EMCCD detector. Boosts signal for same read noise.
- Analyses in process to assess impact on integration time and overall science yield.
- Requirements under development for both coronagraph architectures.
- Science yield estimates include effect of read noise.

Payload Mass and Power

Item	Qty	Unit CBE Mass (kg)	Cont.	Unit Mass +Cont (kg)	Total CBE Mass (kg)	Total Mass +Cont (kg)
AFTA Coronagraph Instrument	**1**	**111.2**	35%	**150.1**	111.2	150.1
Structure	1	50.0	35%	67.5	50.0	67.5
Optical Elements	1	2.3	35%	3.2	2.3	3.2
Detectors	1	3.0	35%	4.1	3.0	4.1
Optical Mounts	1	4.7	35%	6.3	4.7	6.3
Mechanisms	1	12.2	35%	16.4	12.2	16.4
Thermal Hardware	1	12.0	35%	16.2	12.0	16.2
Electronics	1	27.0	35%	36.5	27.0	36.5

Coronagraph Instrument Mass Breakdown

Observatory Impacts

- Preliminary estimate of coronagraph mass at the time of the April report was 150 kg, including contingency.
  - Additional solid rocket strap on required for the launch vehicle to accommodate the additional mass. This is accounted for in the Project cost estimate which includes the coronagraph.
  - See next slide for mass summary.
- Preliminary estimate of coronagraph power was 80 W.
  - This requires the some additional solar cells to provide the required power with margin; however, the size of the solar array/sunshield easily accommodates the additional cells.

Mass Comparison

	Wide Field Only			Wide Field + Coronagraph		
	CBE Mass (kg)	Cont. (%)	CBE + Contin g (kg)	CBE Mass (kg)	Cont. (%)	CBE + Contin g (kg)
Wide Field Inst.	421	30	547	421	30	547
Coronagraph	-	-	-	111	35	150
Instrument Carrier	208	30	270	208	30	270
Telescope	1595	11	1773	1595	11	1773
Spacecraft	1528	30	1987	1528	30	1987
Observatory (dry)	3752	22	4577	3863	22	4727
Propellant	2544		3095	2618		3196
Observatory (wet)	6296		7672	6481		7923

Lift Capacity to GTO: Atlas V 541: 7915 kg Atlas V 551: 8530 kg

Falcon 9 heavy under consideration.

Straylight and Baffling

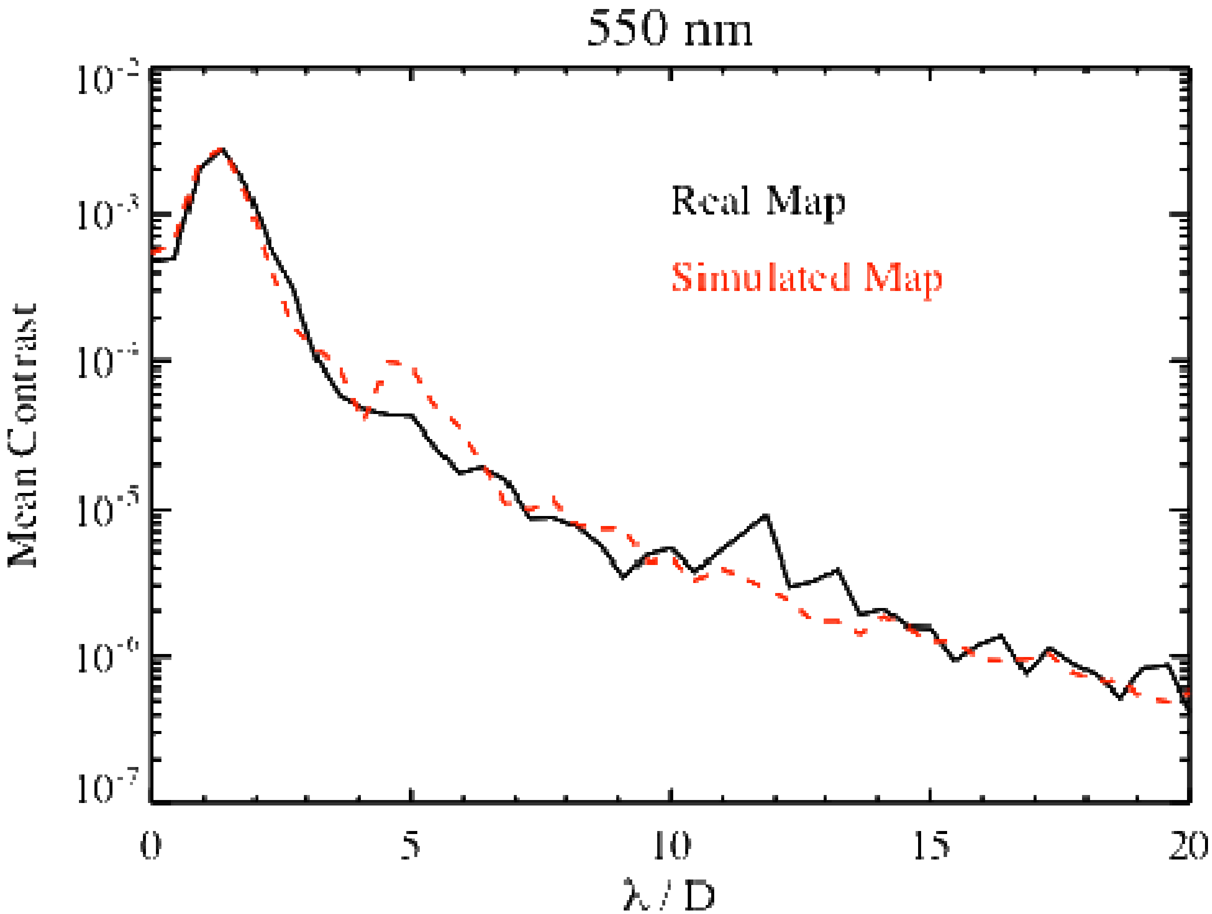
•Straylight requirements and baffling design set by Wide Field Instrument.

•WFI requirements much more stringent than coronagraph.

•Coronagraph requirements driven by speckle and zodi background.

Optical Quality

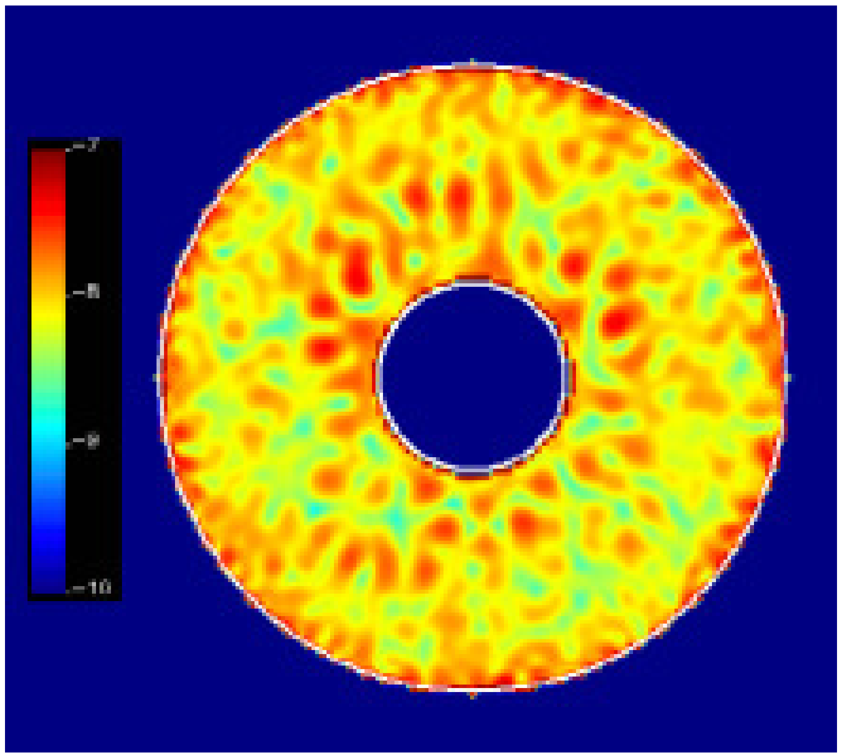
Coronagraph modeling and predictions done with simulation of real optical surface map of primary and secondary.



Uncorrected coronagraph contrast for real and simulated wavefront.

Optical Quality

Wavefront control simulations on all coronagraph architectures show existing errors correctable within DM stroke.



Example:
Corrected dark hole with HLC Coronagraph

Current surface requirements sufficient for coronagraphy.

Conclusion

Baseline coronagraph design has minimal impact on WFIRST-AFTA observatory. There are no driving requirements and it remains off the critical path.

Conclusion

AFTA-WFIRST with a coronagraph will be the first high-contrast, small-inner-working-angle instrument in space with wavefront correction capability. It is an important first step to a future large mission capable of detecting and characterizing Earth-size rocky planets in the habitable zone of nearby stars.