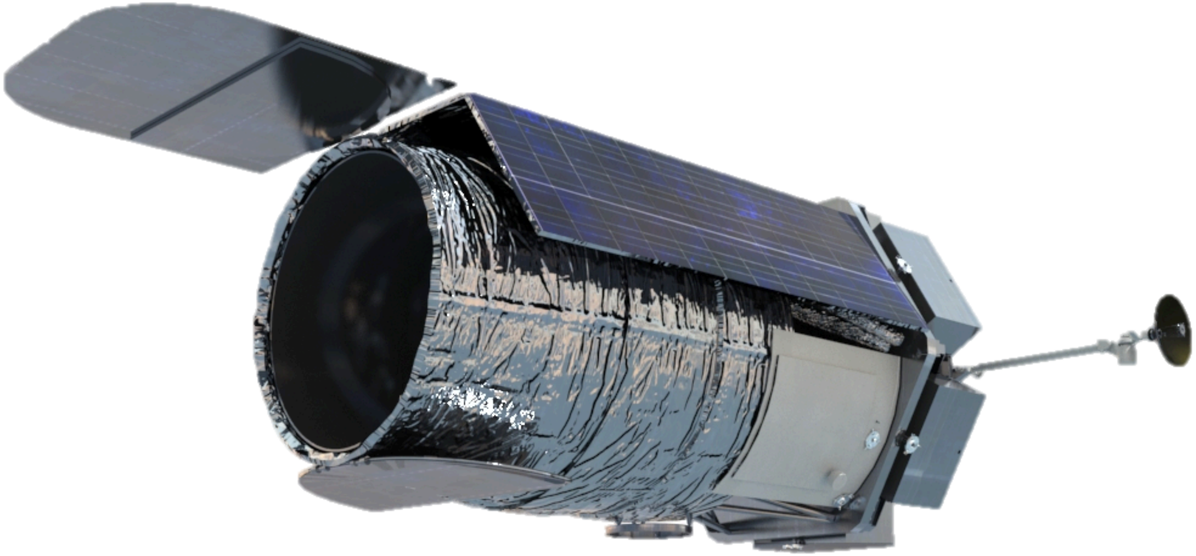
The Future: WFIRST-AFTA Coronagraph

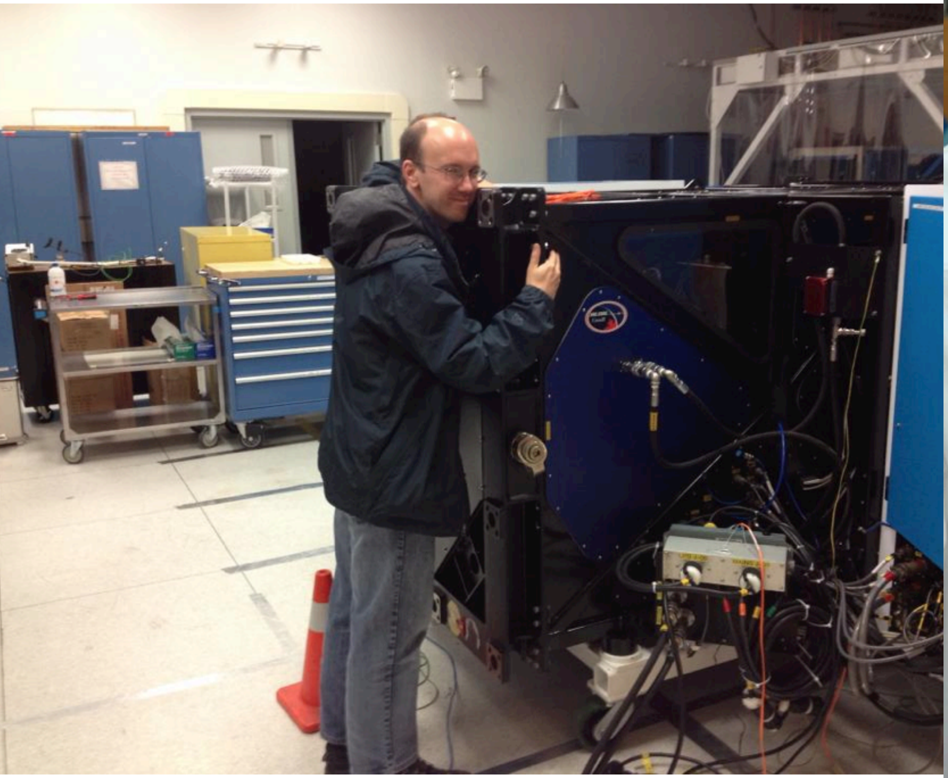


Bruce Macintosh

Based on work by WFIRST SDT (Wes Traub, Tom Greene, Jeremy Kasdin, Olivier Guyon, w. Mark Marley and Dmitry Savranrky) and JPL coronagraph team (Feng Zhao, John Krist, John Trauger, et al.)

http://wfirst.gsfc.nasa.gov

7/25/2014



WFIRST-AFTA SDT

Co-Chairs

- David Spergel, Princeton University
- Neil Gehrels, NASA GSFC

Members

- Charles Baltay, Yale University
- Dave Bennett, University of Notre Dame
- James Breckinridge, California Institute of Technology
- Megan Donahue, Michigan State University
- Alan Dressler, Carnegie Institution for Science
- Scott Gaudi, Ohio State University
- Tom Greene, NASA ARC
- Olivier Guyon, Steward Observatory
- Chris Hirata, Ohio State University
- Jason Kalirai, Space Telescope Science Institute
- Jeremy Kasdin Princeton University
- Bruce MacIntosh, Stanford University
- Warren Moos, Johns Hopkins University
- Saul Perlmutter, University of California Berkeley
- Marc Postman, Space Telescope Science Institute
- Bernie Rauscher, NASA GSFC
- Jason Rhodes, NASA JPL
- David Weinberg, Ohio State University
- Yun Wang, University of Oklahoma

Ex Officio

- Dominic Benford, NASA HQ
- Mike Hudson, Canadian Space Agency
- Yannick Mellier, European Space Agency
- Wes Traub, NASA JPL
- Toru Yamada, Japan Aerospace Exploration Agency

Consultants

- Matthew Penny, Ohio State University
- Dmitry Savransky, Cornell University
- Daniel Stern, NASA JPL

Backstory

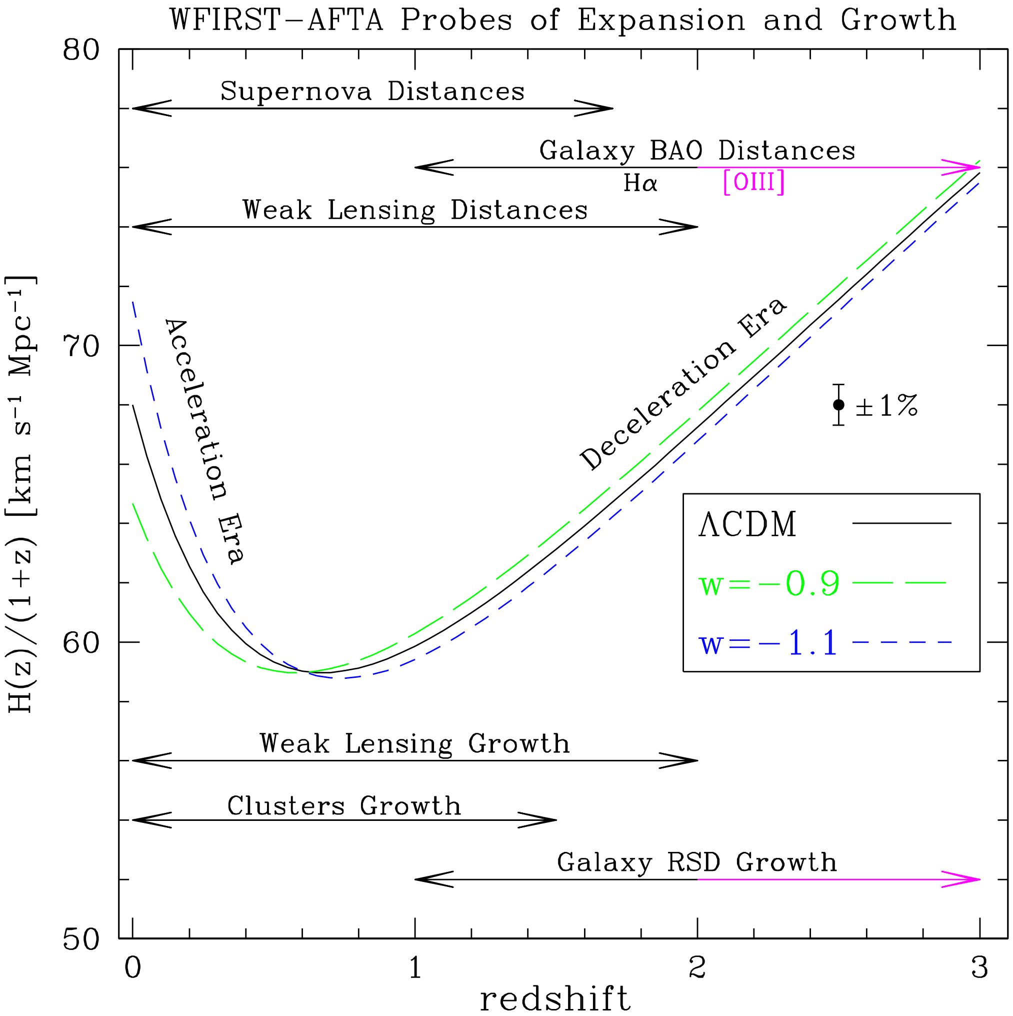
- Astro2010 decadal survey ("New Worlds, New Horizons")
- Recommended a portfolio of future scientific capabilities
- Highest priority ground O/IR: LSST
- Highest priority space: Wide-field IR Space Telescope: WFIRST
  - Combined existing dark energy missions (JDEM) with microlensing and general wide-field survey

New Worlds, New Horizons
in Astronomy and Astrophysics

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

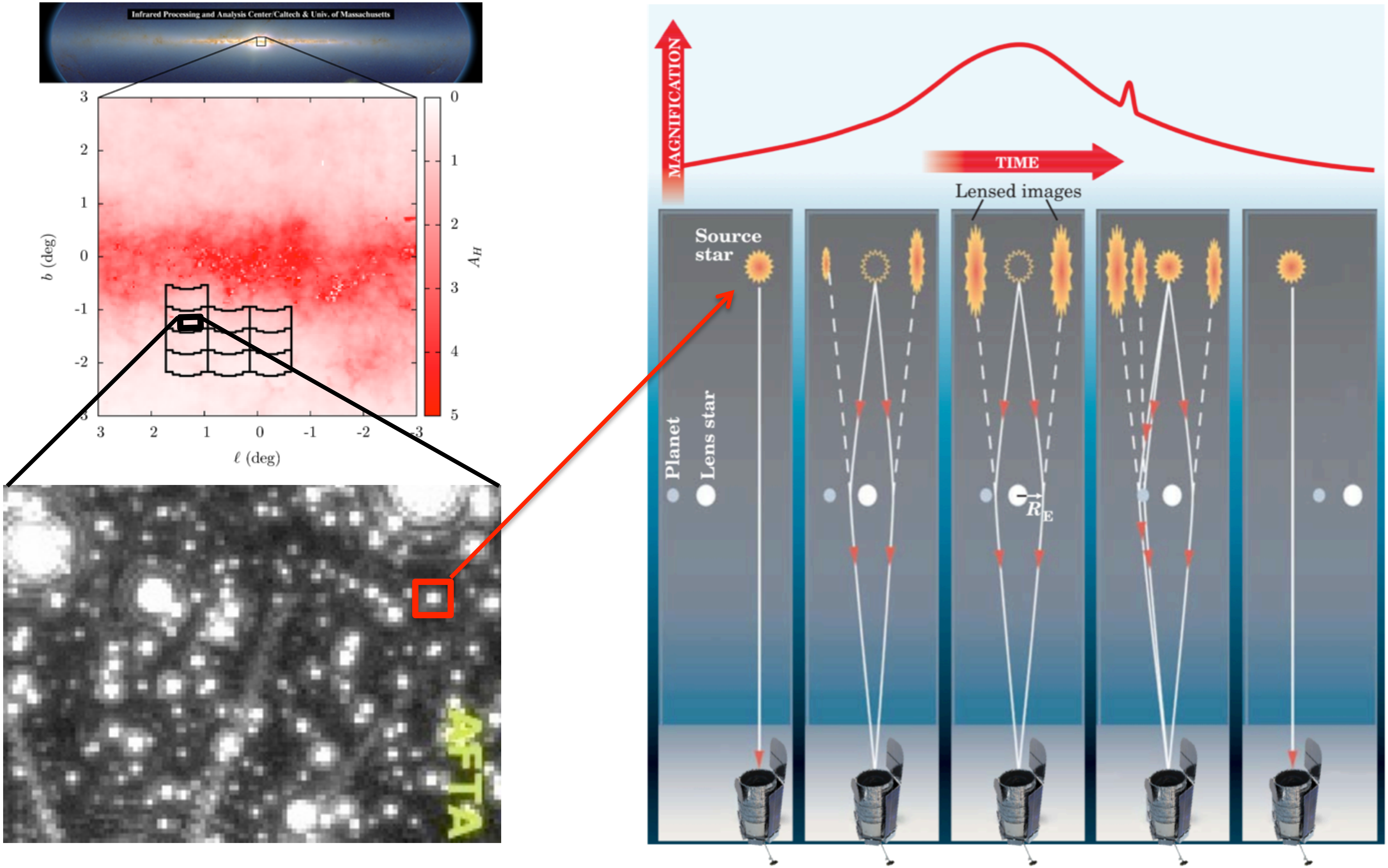
WFIRST-AFTA Dark Energy

- The WFIRST-AFTA Dark Energy program probes the expansion history of the Universe and the growth of cosmic structure with multiple methods in overlapping redshift ranges.
- Tightly constrains the properties of dark energy, the consistency of General Relativity, and the curvature of space.
- The High Latitude Survey is designed with sub-percent control of systematics as a paramount consideration.

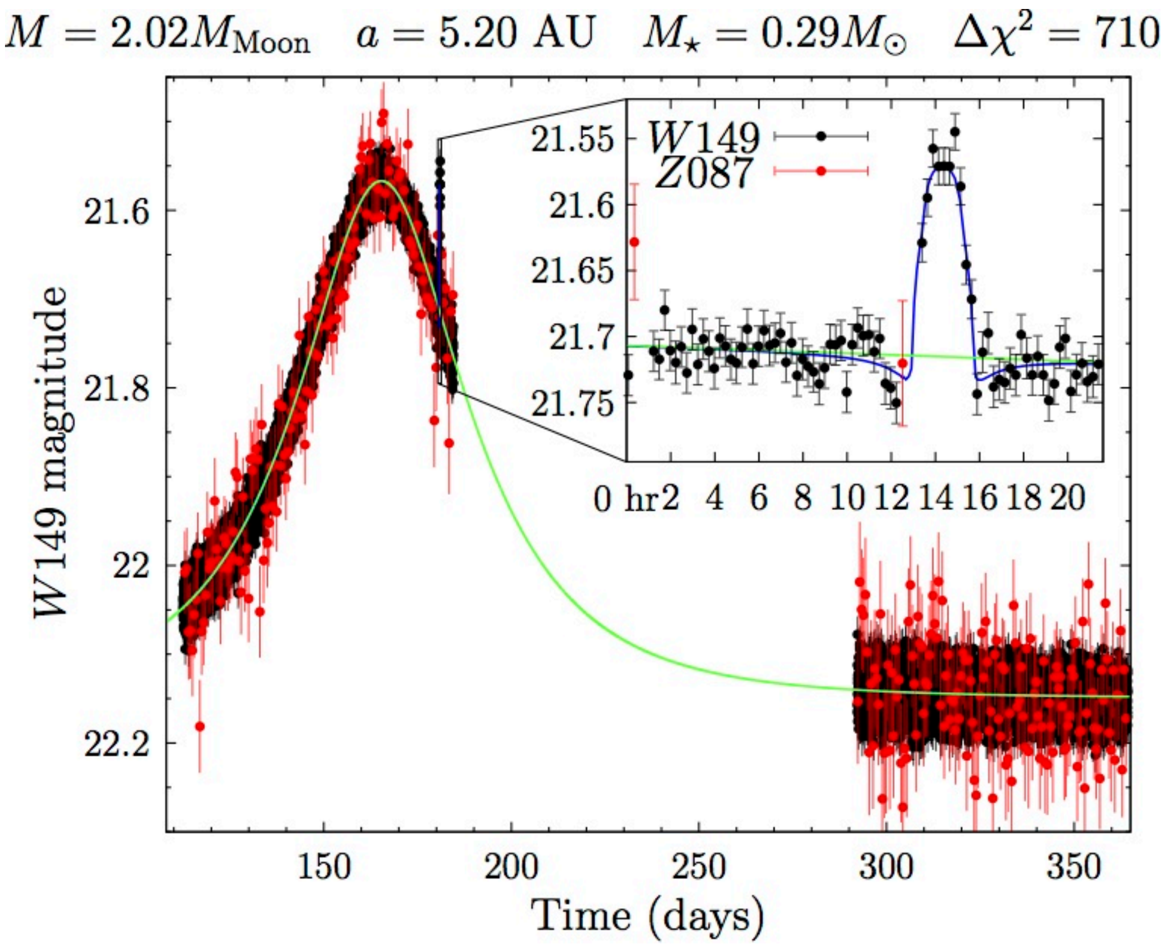


"For each of the cosmological (dark energy) probes in NWNH, WFIRST/AFTA exceeds the goals set out in NWNH" NRC - *Evaluation of the Implementation of WFIRST/AFTA in the Context of New Worlds, New Horizons in Astronomy and Astrophysics*

Detecting Planets with a Microlensing Survey



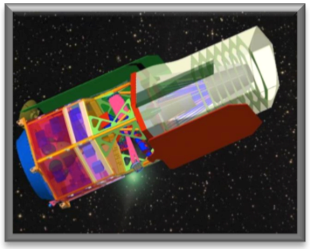
Microlensing Sensitivity to Cold, Very Low-Mass Planets



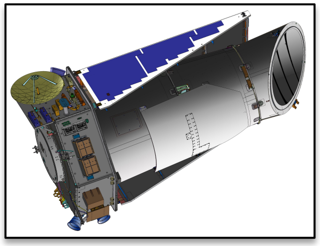
Simulation of a 2 × Mass of the Moon Planet @ 5.2 AU (~27 sigma)

- Embryos with the mass of Mars or less are the building blocks of planets.
- WFIRST-AFTA can detect planets down to a few times the mass of the moon.
- Sensitive to Earth-like moons.
- Detected with high significance.

Microlensing: statistical capabilities

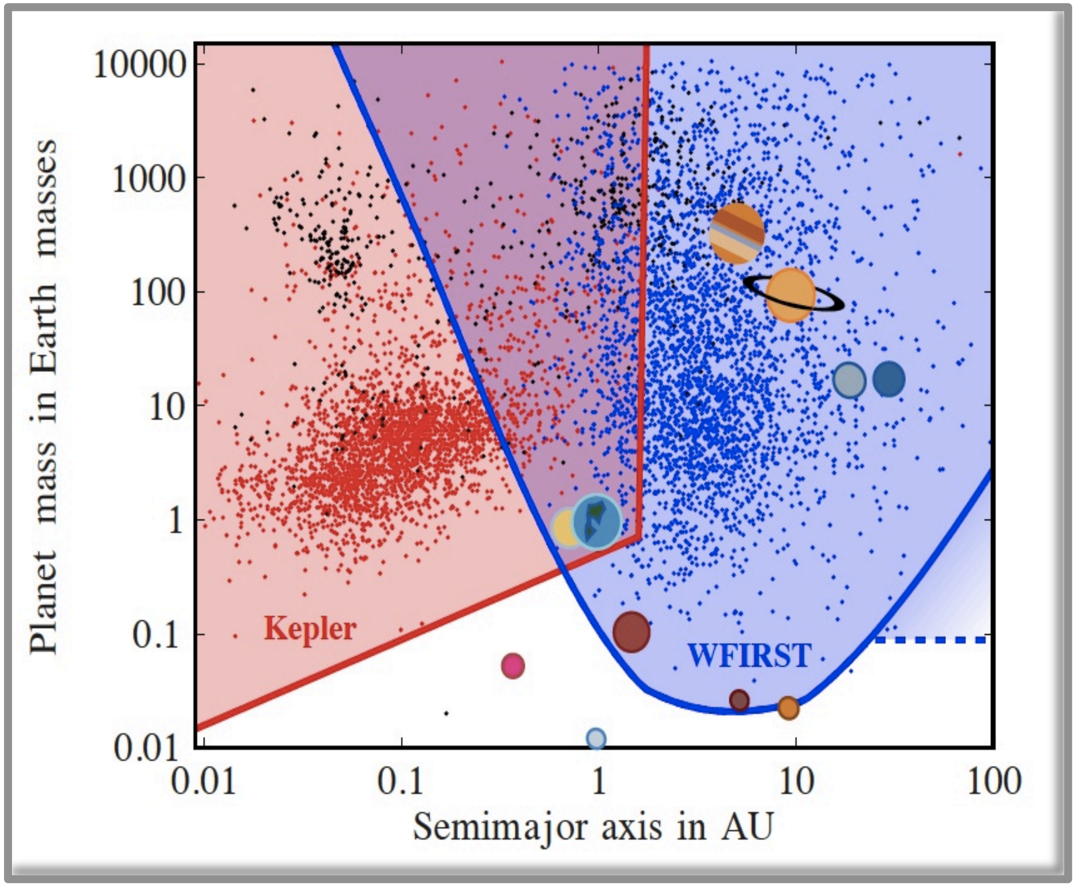


Together, Kepler and WFIRST complete the statistical census of planetary systems in the Galaxy.

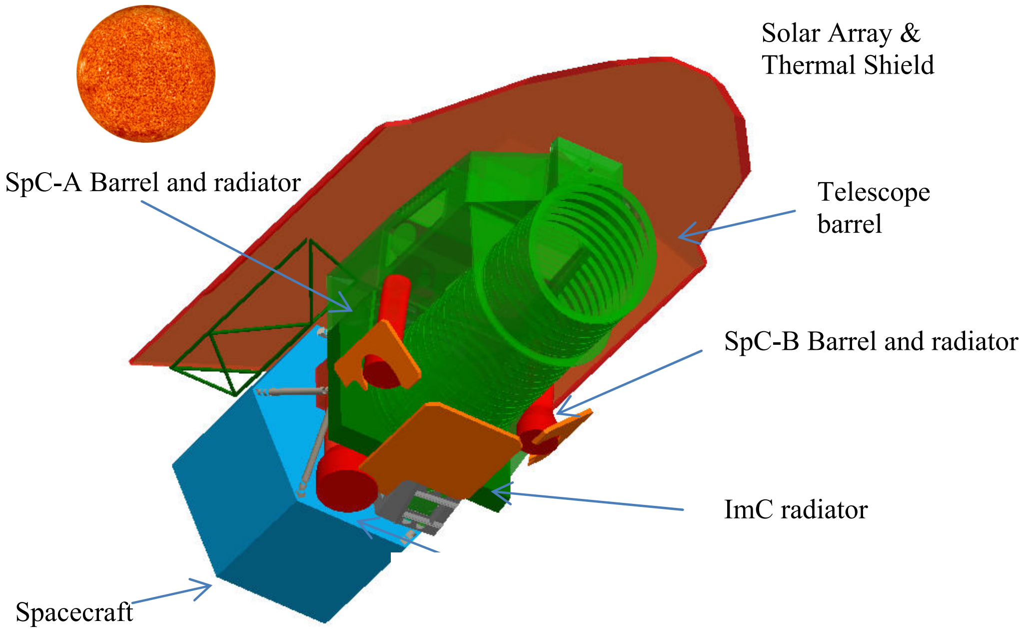


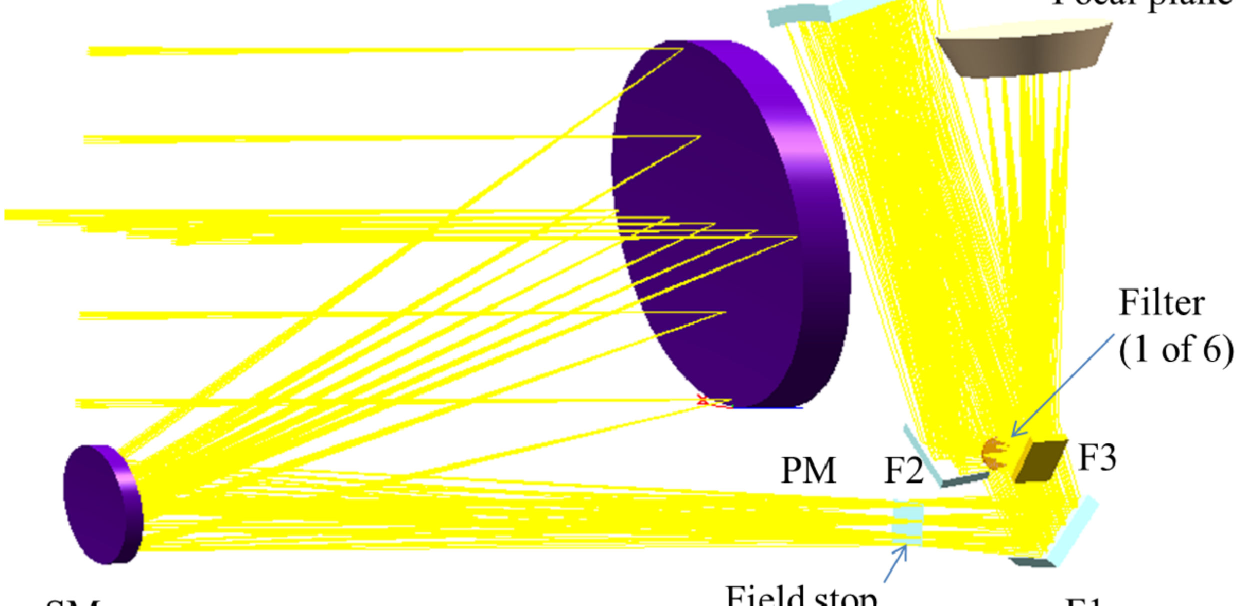
WFIRST will:

- Detect 2800 planets, with orbits from the habitable zone outward, and masses down to a few times the mass of the Moon.
- Have some sensitivity to "outer" habitable zone planets (Mars-like orbits).
- Be sensitive to analogs of all the solar systems planets except Mercury.
- Measure the abundance of free-floating planets in the Galaxy with masses down to the mass of Mars
- Characterize the majority of host systems.

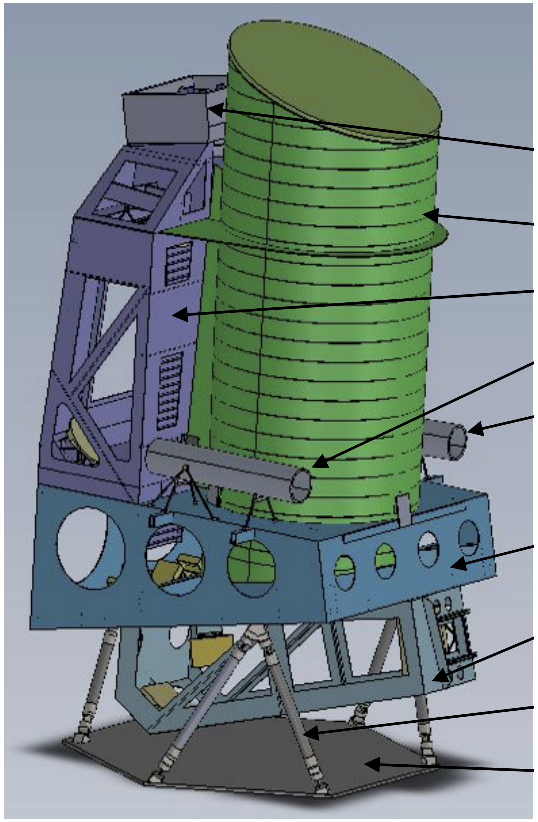


WFIRST Design Reference Mission: 1.4m off-axis wide-field telescope





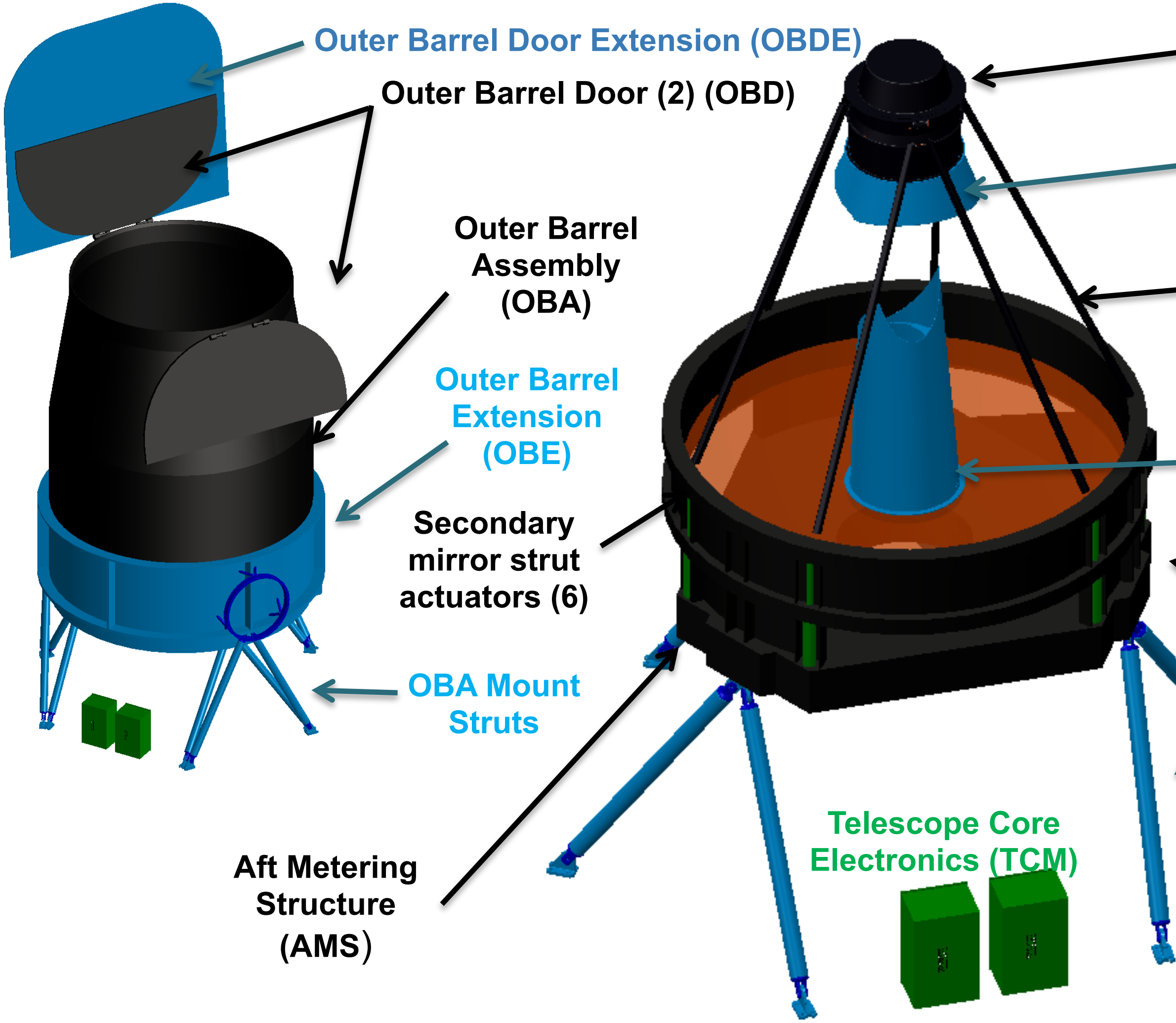
Surprise present for NASA



1.3-m WFIRST DRM

2.4-m telescope assembly

Astrophysics Focused Telescope Assets: AFTA

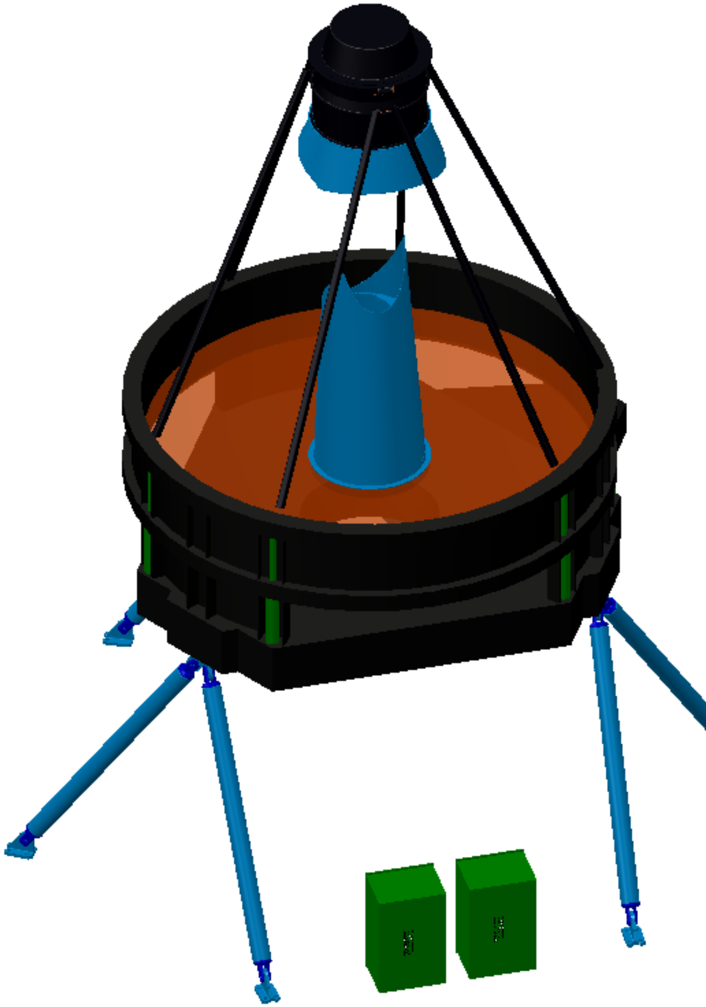


Existing H/W, reuse	1188 kg
Existing design, remake	153 kg
New design	254 kg
TOTAL:	1595 kg

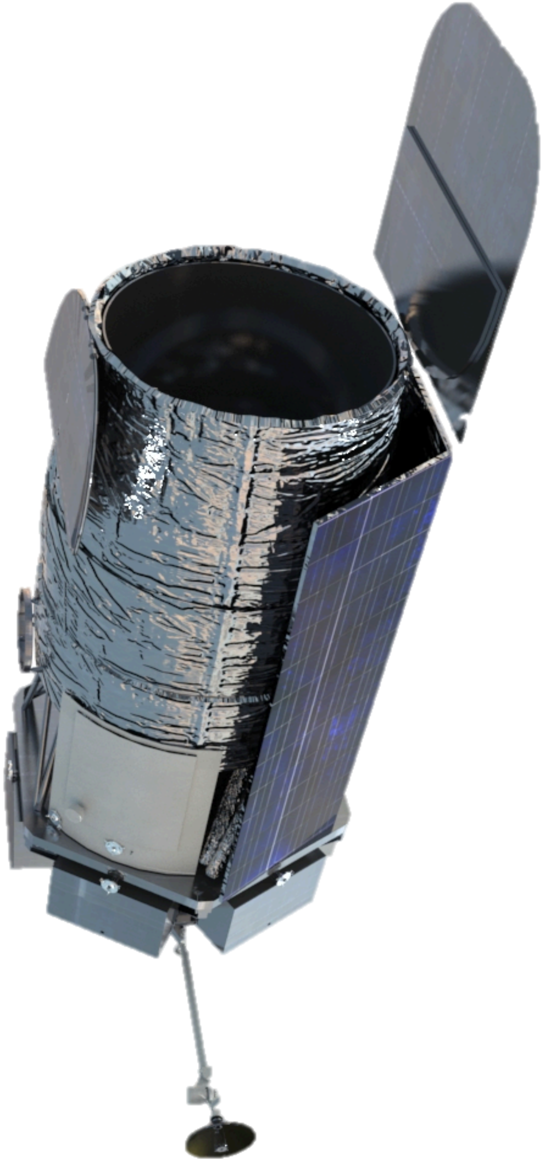
100% of the existing telescope hardware is being re-used. Electronics and baffles not available and must be replaced.

WFIRST AFTA Coronagraph

- 1.1 – 1.4 m WFIRST coronagraphic capability would be very limited
    - Small IWA, limited amount of telescope time
    - No room for coronagraph
- 2.4m telescope is significantly more powerful
    - IF secondary mirror and other pupil geometry does not degrade capability
- Coronagraph authorized as long as
    - Does not impose requirements on spacecraft
    - Does not increase schedule risk



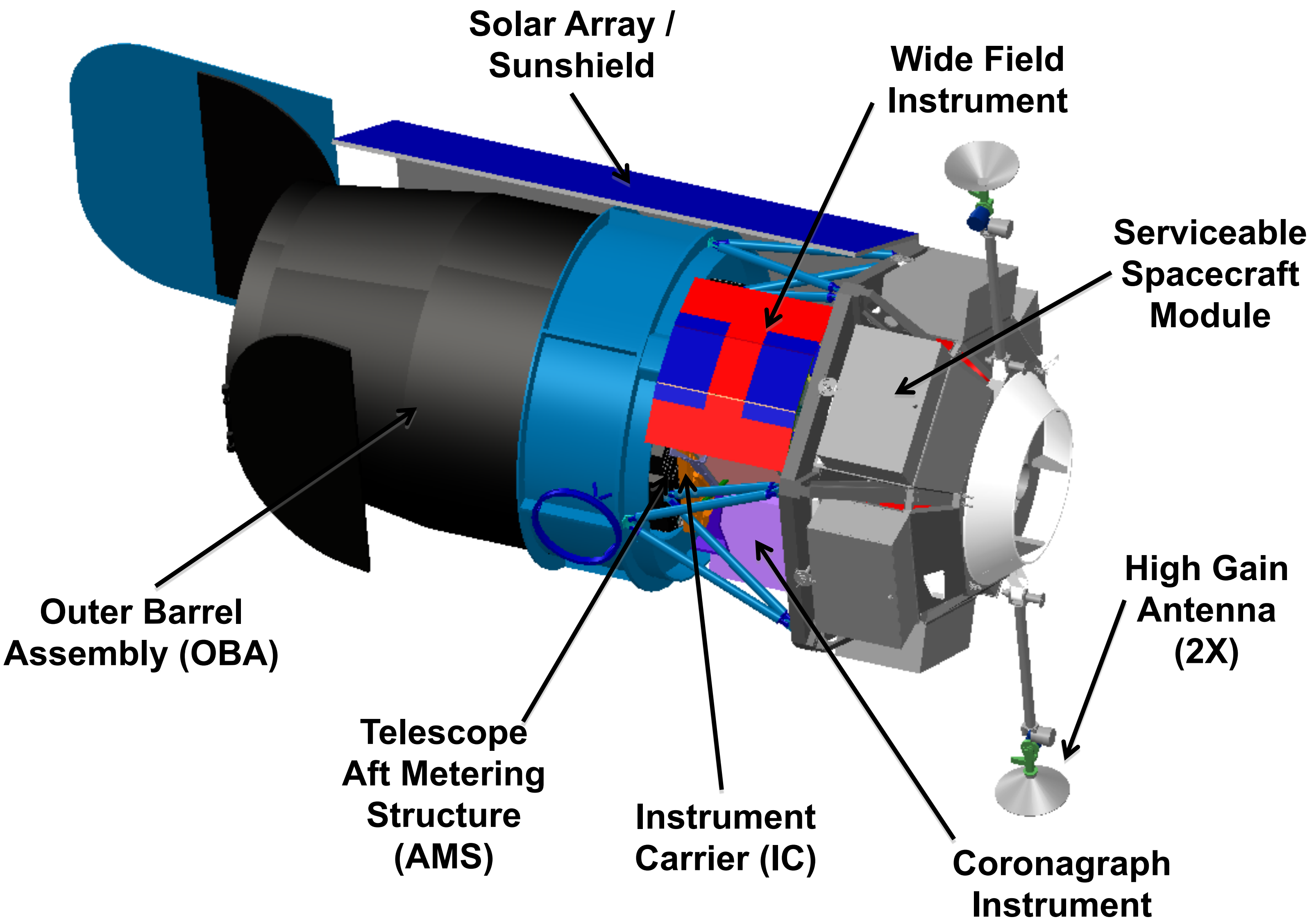
WFIRST-AFTA Observatory Concept



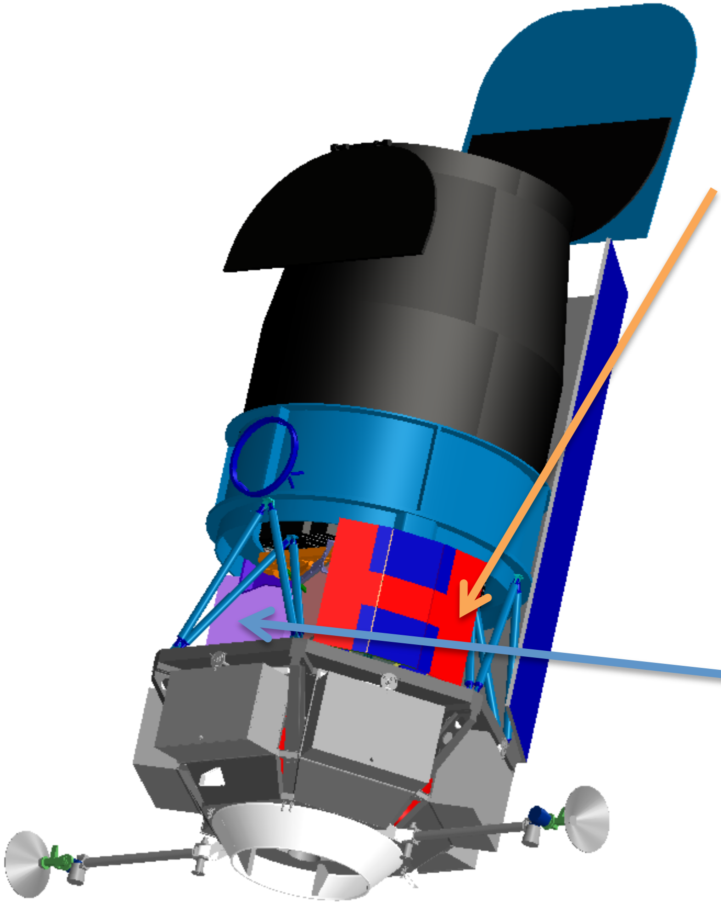
Key Features

- **Telescope** – 2.4m aperture primary
- **Instruments**
  - Single channel wide field instrument, 18 4k x 4k HgCdTe detectors; integral field unit spectrometer incorporated in wide field for SNe observing
  - Internal coronagraph with integral field spectrometer
- **Overall Mass** – ~6500 kg (CBE) with components assembled in modules; ~2600 kg propellant; ~3900 kg (CBE dry mass)
- **Primary Structure** – Graphite Epoxy
- **Downlink Rate** – Continuous 150 Mbps Ka-band to Ground Station
- **Thermal** – passive radiator
- **Power** – 2100 W
- **GN&C** – reaction wheels & thruster unloading
- **Propulsion** – bipropellant
- **GEO orbit**
- **Launch Vehicle** – Atlas V 551

WFIRST-AFTA Observatory Layout



WFIRST-AFTA Instruments



Wide-Field Instrument

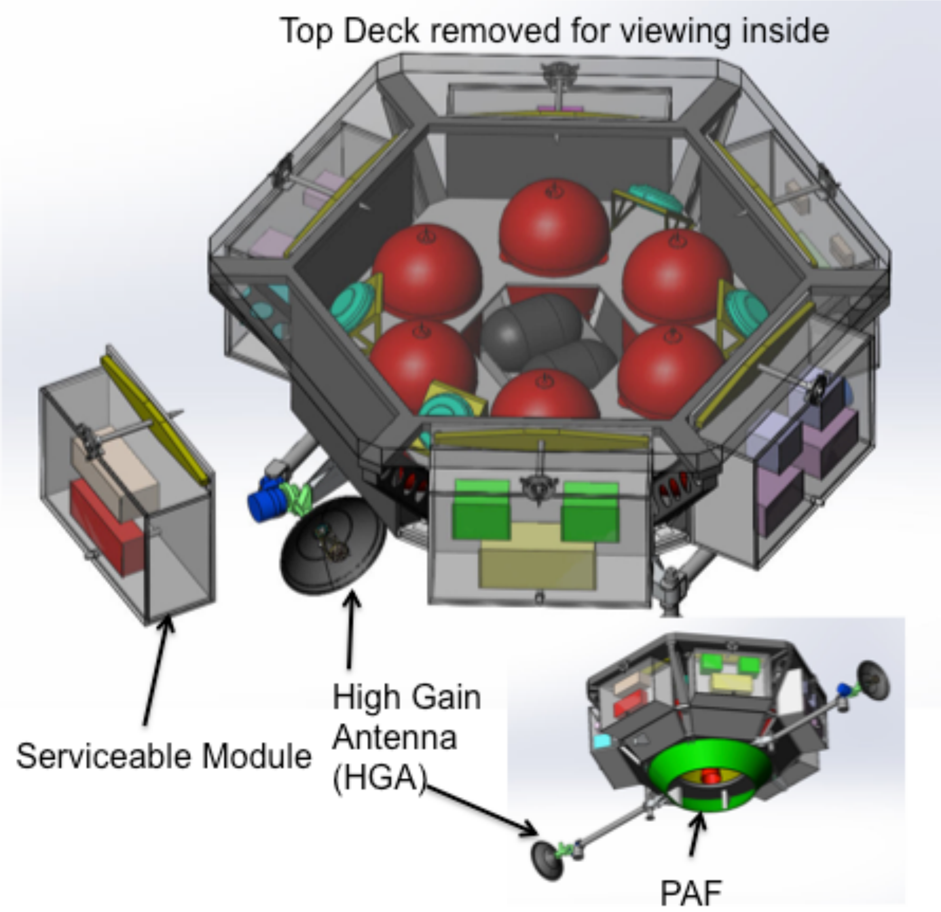
- *Imaging & spectroscopy over 1000s of sq. deg.*
- *Monitoring of SN and microlensing fields*
- 0.7 – 2.0 micron bandpass
- 0.28 deg^2 FoV (100x JWST FoV)
- 18 H4RG detectors (288 Mpixels)
- 6 filter imaging, grism + IFU spectroscopy

Coronagraph

- *Imaging of ice & gas giant exoplanets*
- *Imaging of debris disks*
- 400 – 1000 nm bandpass
- $\leq 10^{-9}$ contrast (after post-processing)
- 100 milliarcsec inner working angle at 400 nm

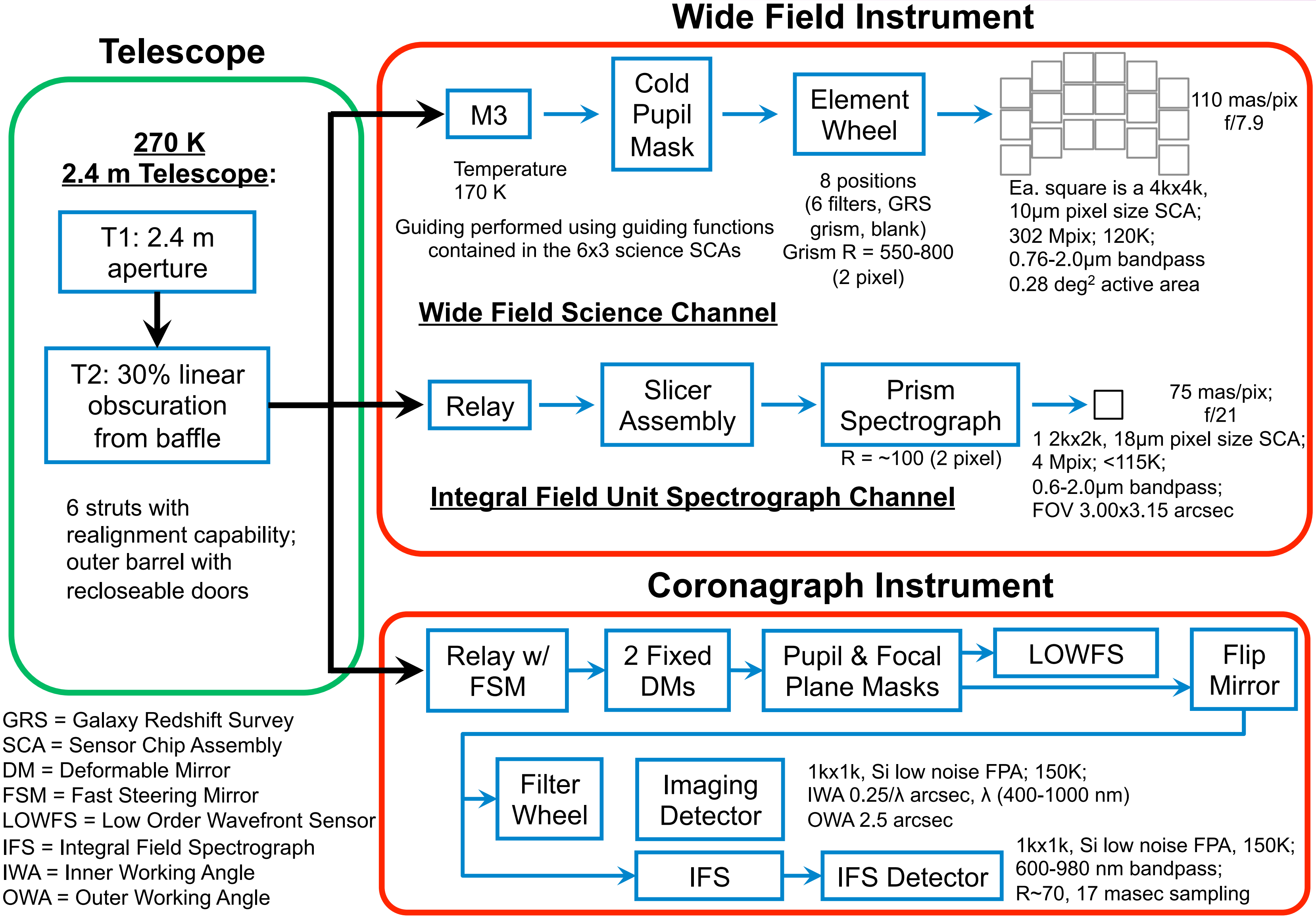
Spacecraft Concept

- Design relies on recent GSFC in-house spacecraft electronics designs, primarily SDO and GPM
- Uses robotically serviceable/ removable modules. The design is reused from the Multimission Modular Spacecraft (MMS).
- 2 deployable high gain antennae provide continuous downlink to the ground
- 6 bi-propellant tanks store fuel to circularize from geosynchronous transfer orbit to 28.5 deg inclined geosynchronous orbit and for stationkeeping



AFTA serviceable bus concept

AFTA will incorporate a real, active-DM high-performance coronagraph



Telescope

270 K
2.4 m Telescope:

T1: 2.4 m aperture

T2: 30% linear obscuration from baffle

6 struts with realignment capability; outer barrel with recloseable doors

Wide Field Instrument

M3 → Cold Pupil Mask → Element Wheel →

Temperature 170 K

Guiding performed using guiding functions contained in the 6x3 science SCAs

8 positions (6 filters, GRS grism, blank)
Grism R = 550-800 (2 pixel)

110 mas/pix
f/7.9

Ea. square is a 4kx4k, 10μm pixel size SCA;
302 Mpix; 120K;
0.76-2.0μm bandpass
0.28 deg^2 active area

Wide Field Science Channel

Relay → Slicer Assembly → Prism Spectrograph →

R = ~100 (2 pixel)

75 mas/pix;
f/21

1 2kx2k, 18μm pixel size SCA;
4 Mpix; <115K;
0.6-2.0μm bandpass;
FOV 3.00x3.15 arcsec

Integral Field Unit Spectrograph Channel

Coronagraph Instrument

Relay w/ FSM → 2 Fixed DMs → Pupil & Focal Plane Masks → LOWFS → Flip Mirror

Filter Wheel

Imaging Detector

1kx1k, Si low noise FPA; 150K;
IWA 0.25/λ arcsec, λ (400-1000 nm)
OWA 2.5 arcsec

IFS → IFS Detector

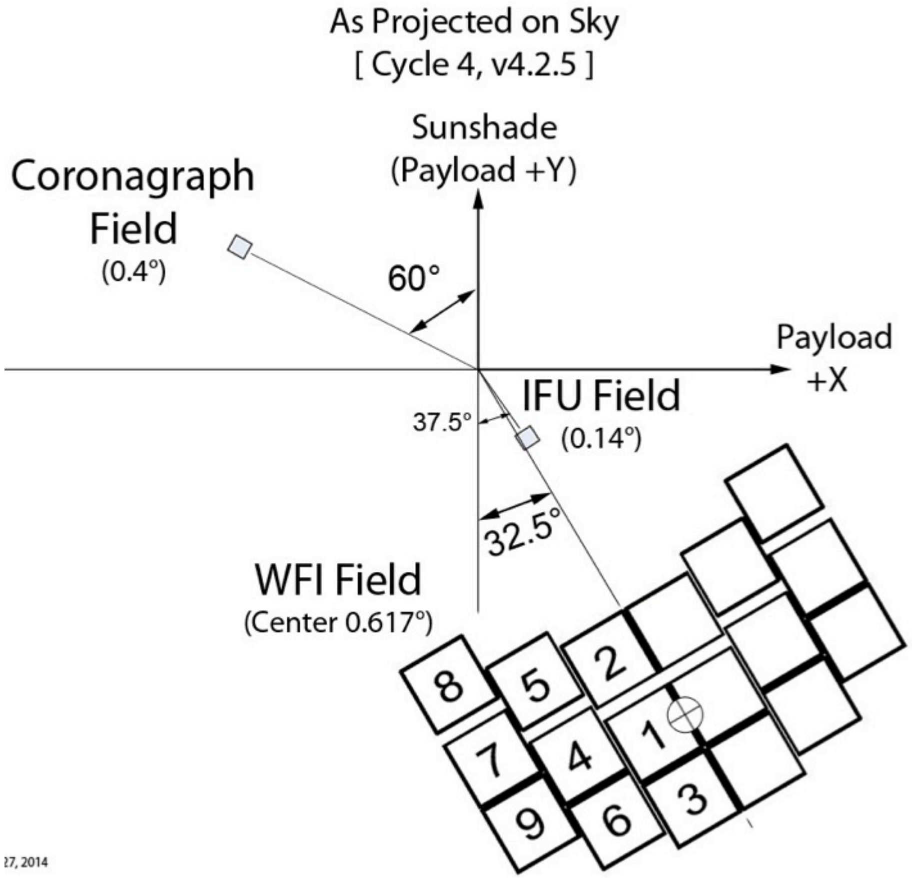
1kx1k, Si low noise FPA, 150K;
600-980 nm bandpass;
R~70, 17 masec sampling

GRS = Galaxy Redshift Survey
SCA = Sensor Chip Assembly
DM = Deformable Mirror
FSM = Fast Steering Mirror
LOWFS = Low Order Wavefront Sensor
IFS = Integral Field Spectrograph
IWA = Inner Working Angle
OWA = Outer Working Angle

Optical Field Layout

- The Wide Field Instrument has two optical channels
  - The wide field channel uses the telescope along with 2 fold mirrors and a conic tertiary mirror in the instrument, to complete a folded three mirror anastigmat optical system.
  - The wide field instrument includes an integral field unit, used for supernova spectroscopy and GO spectroscopy
- The coronagraph is a small field system in a separate field of view

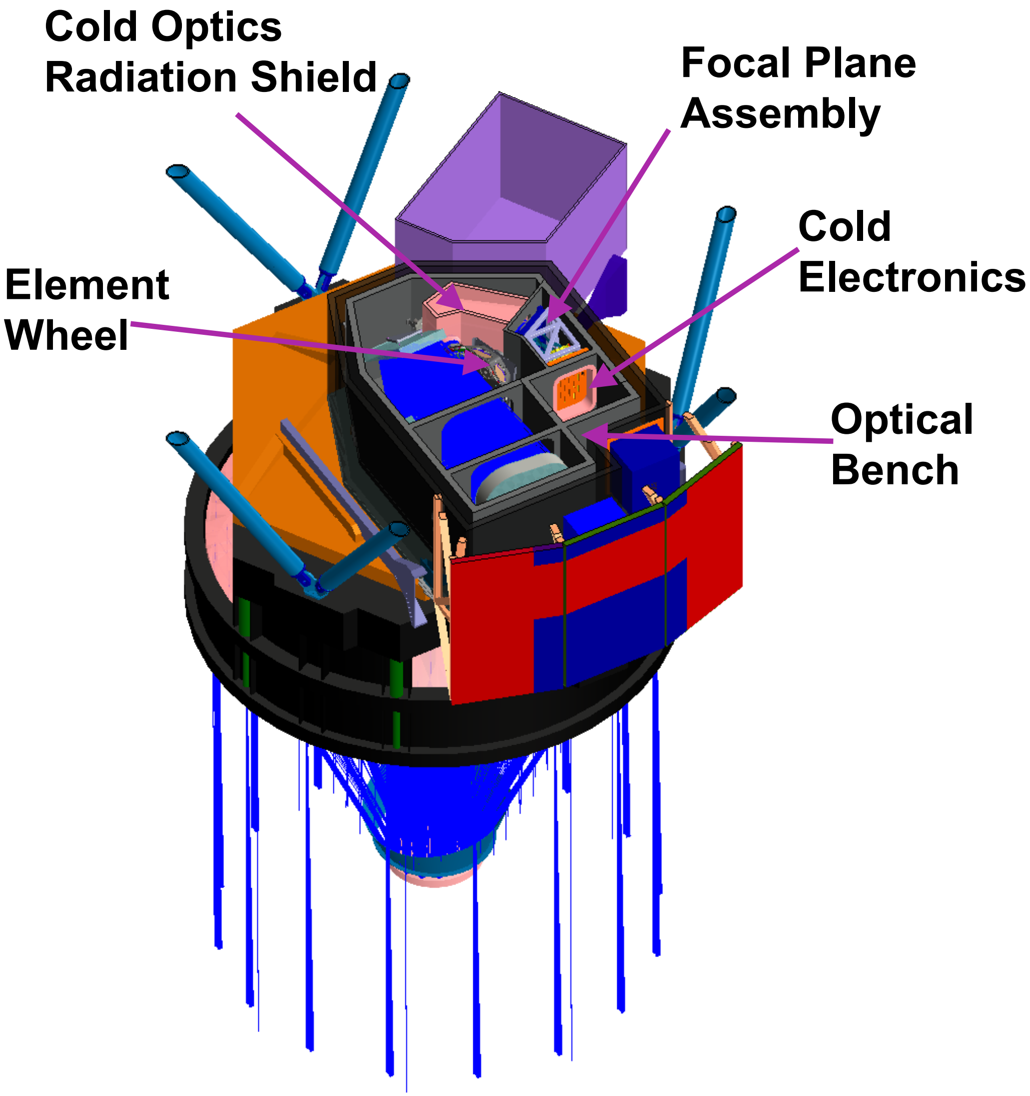
Channel Field Layout for WFIRST-AFTA Instruments



Wide Field Instrument Overview

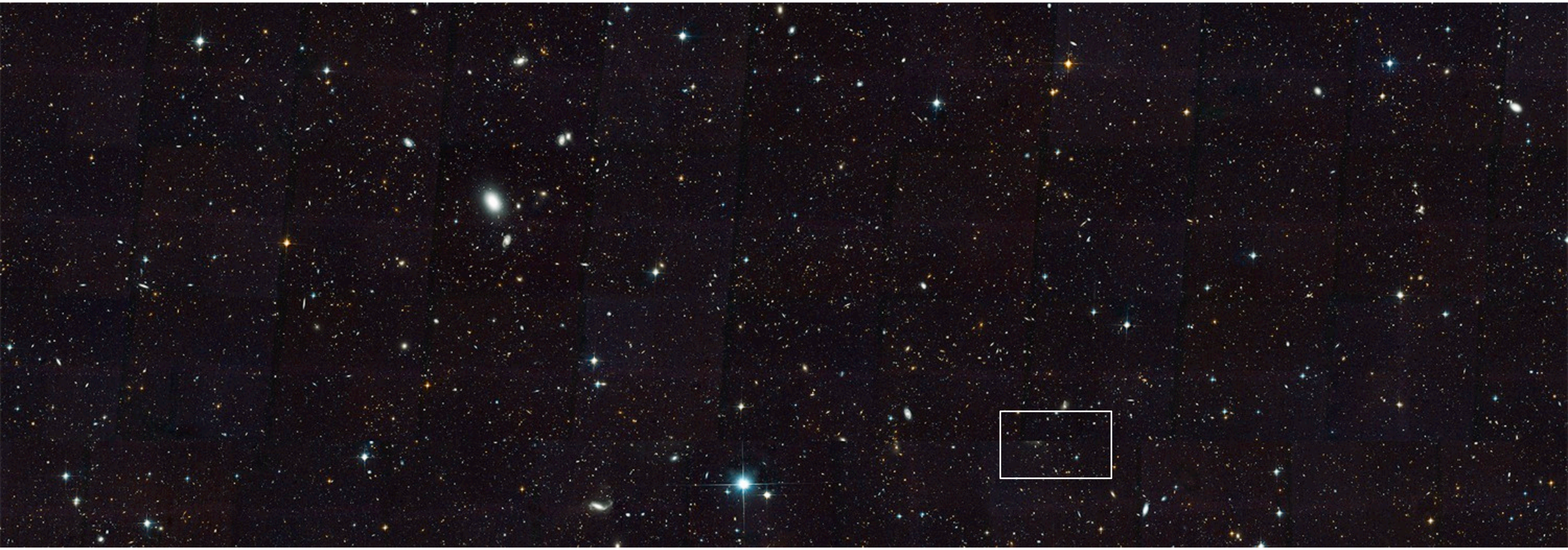
Key Features

- Single wide field channel instrument for both imaging and spectroscopy
    - 3 mirrors, 1 powered
    - 18 4K x 4K HgCdTe detectors cover 0.76 - 2.0 μm
    - 0.11 arc-sec plate scale
    - Grism used for GRS survey covers 1.35 – 1.95 μm with R between 645 - 900
- IFU channel for SNe spectra, single HgCdTe detector covers 0.6 – 2.0 μm with R~75
- Single element wheel for filters and grism



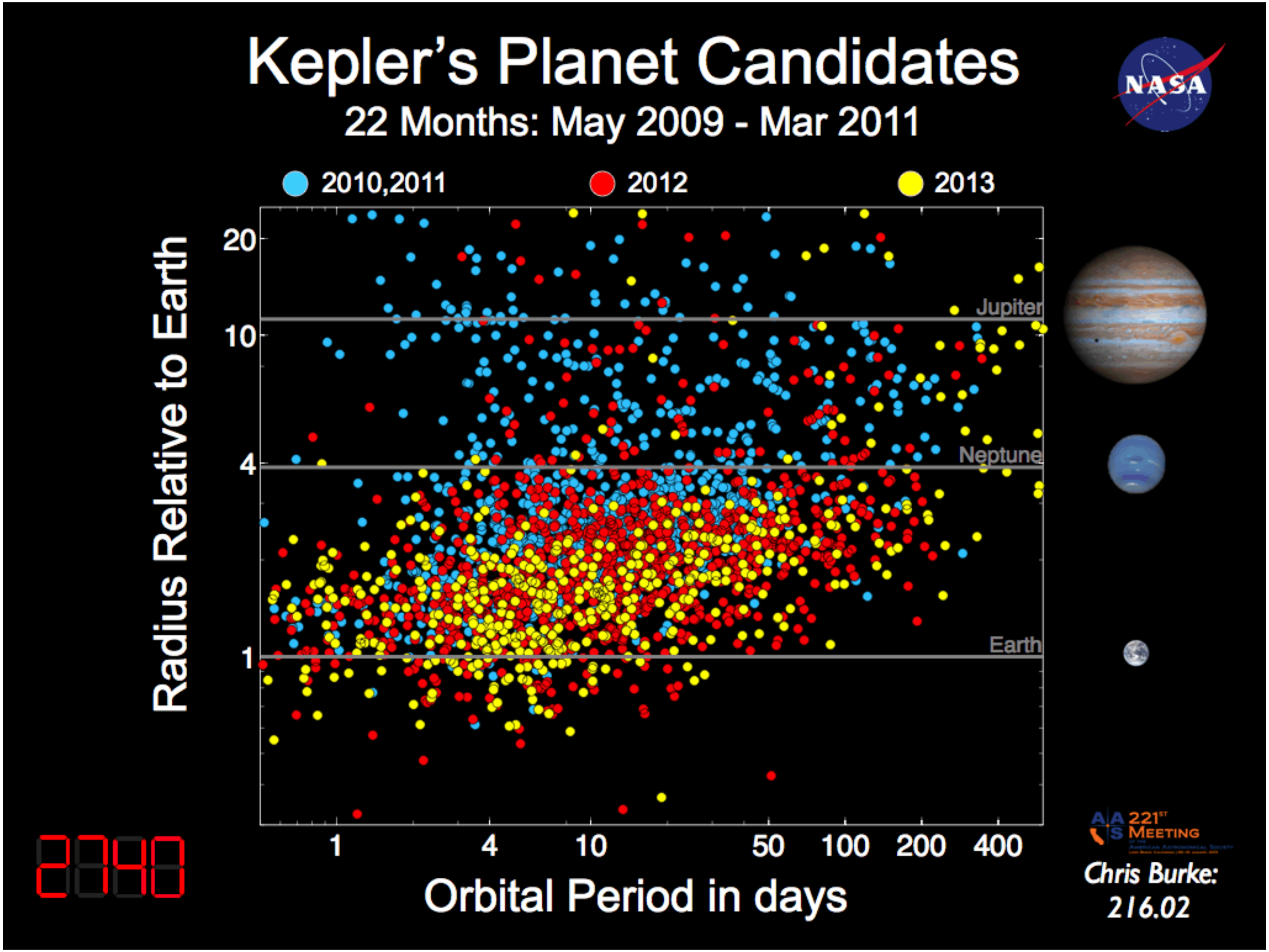
WFIRST-AFTA vs Hubble

Hubble Ultra Deep Field - IR
~5,000 galaxies in one image



WFIRST-AFTA Deep Field
>1,000,000 galaxies in each image

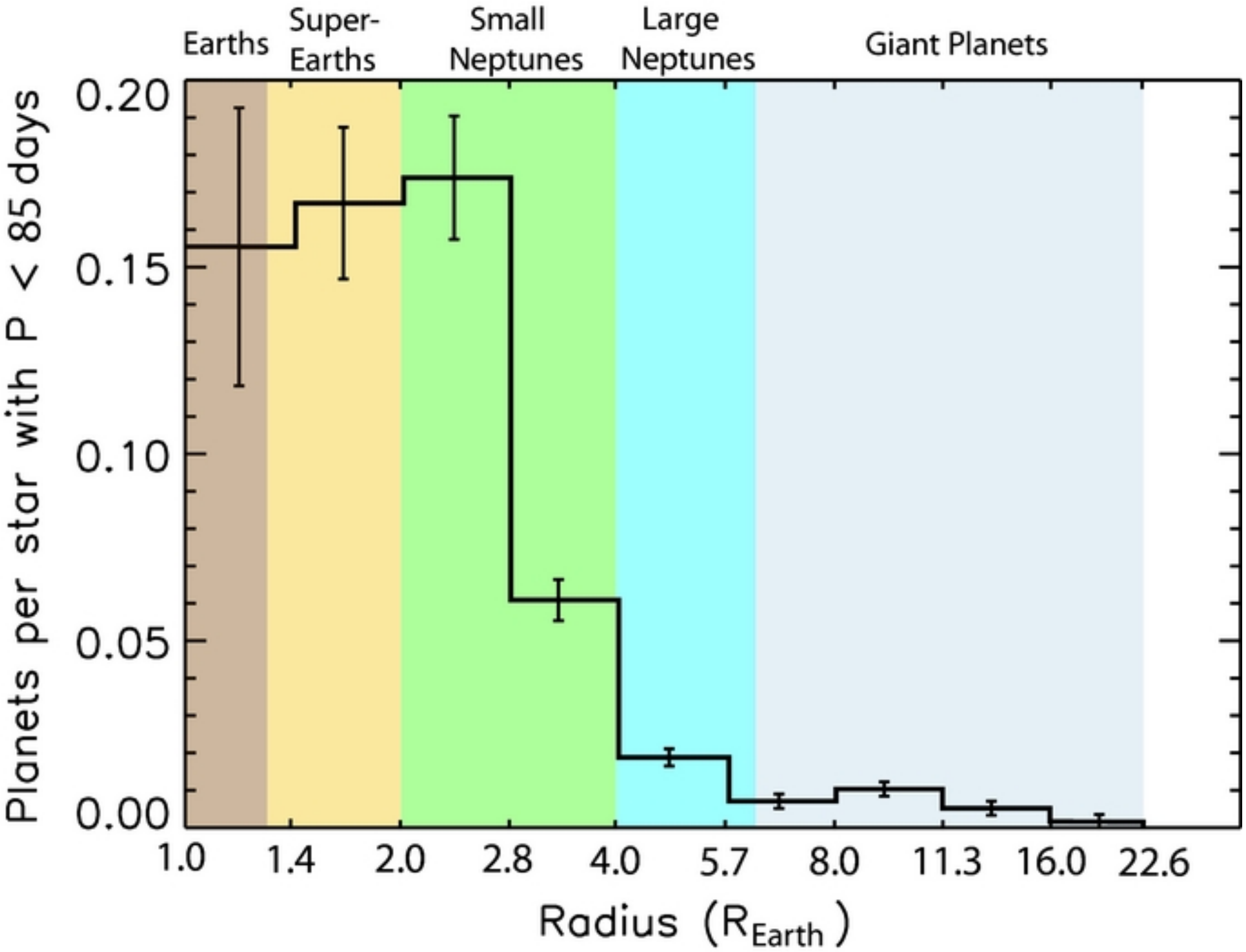
Coronagraph: why we need it



AFTA coronagraph goals

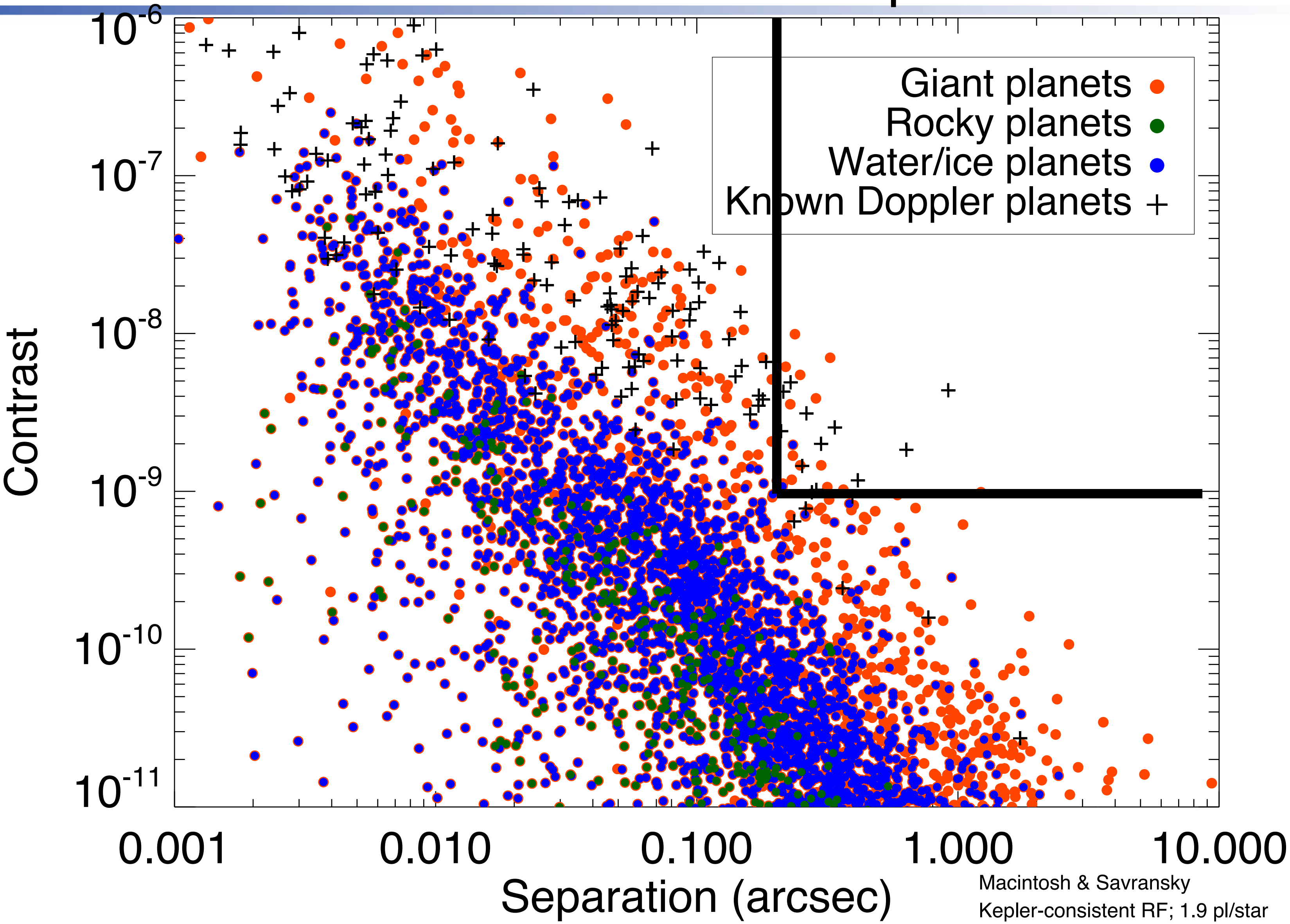
1) Measure and understand the composition and nature of a diverse sample of extrasolar planets orbiting nearby stars
2) Illuminate the process through which planetary systems form
3) Determine which stars have dusty remnant or debris disks, measure their disk properties, and observe how their disks and planets interact
4) Determine which systems (statistically or individually) in the solar neighborhood are suitable targets for future terrestrial-planet characterization
5) Demonstrate and validate coronagraph technology useable for a future habitable-planet-detecting mission

Kepler radius distribution



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

Planets within 30 pc



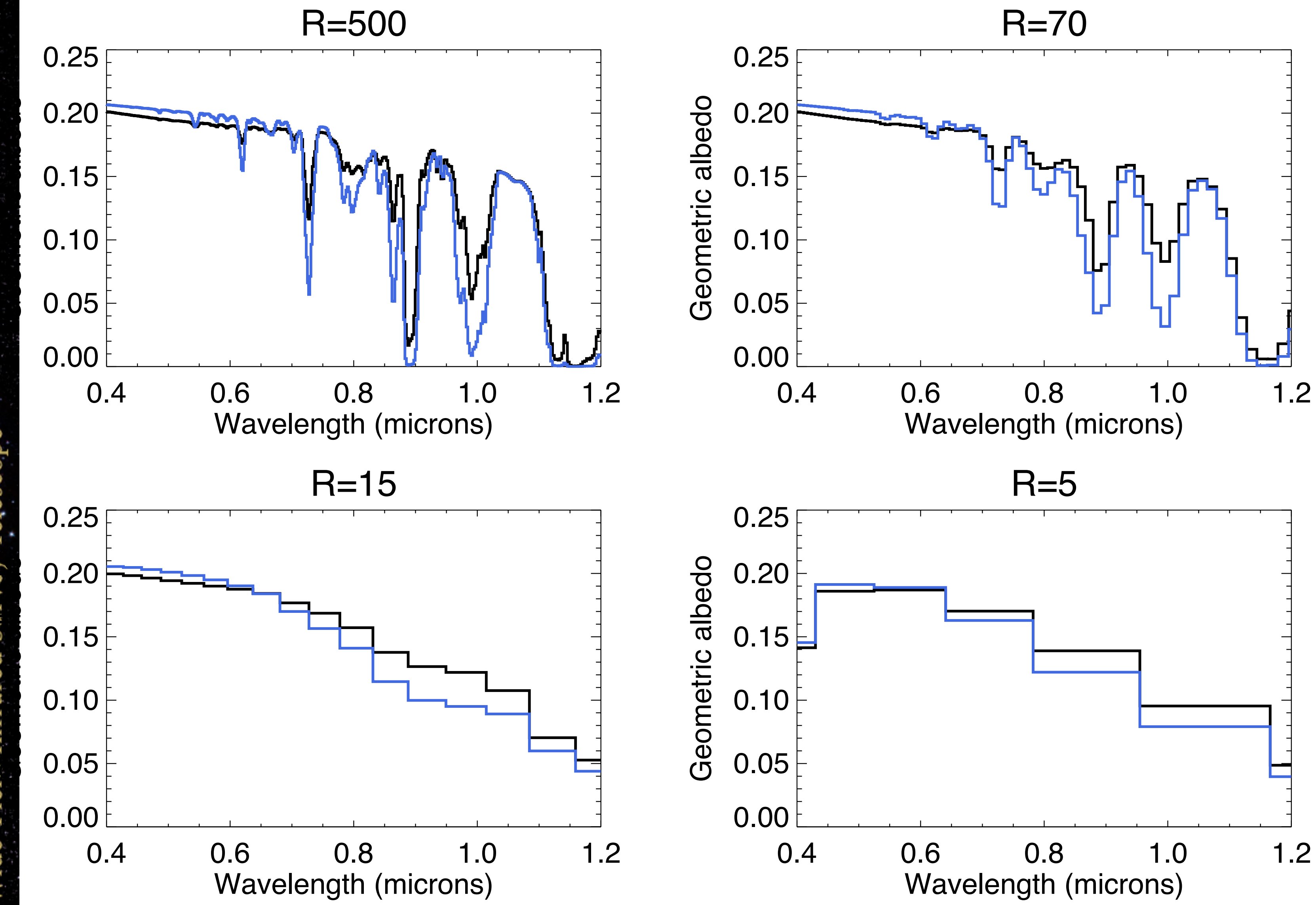
Macintosh & Savransky
Kepler-consistent RF; 1.9 pl/star
Main sequence non binary stars

AFTA WFIRST
Wide-Field Infrared Survey Telescope

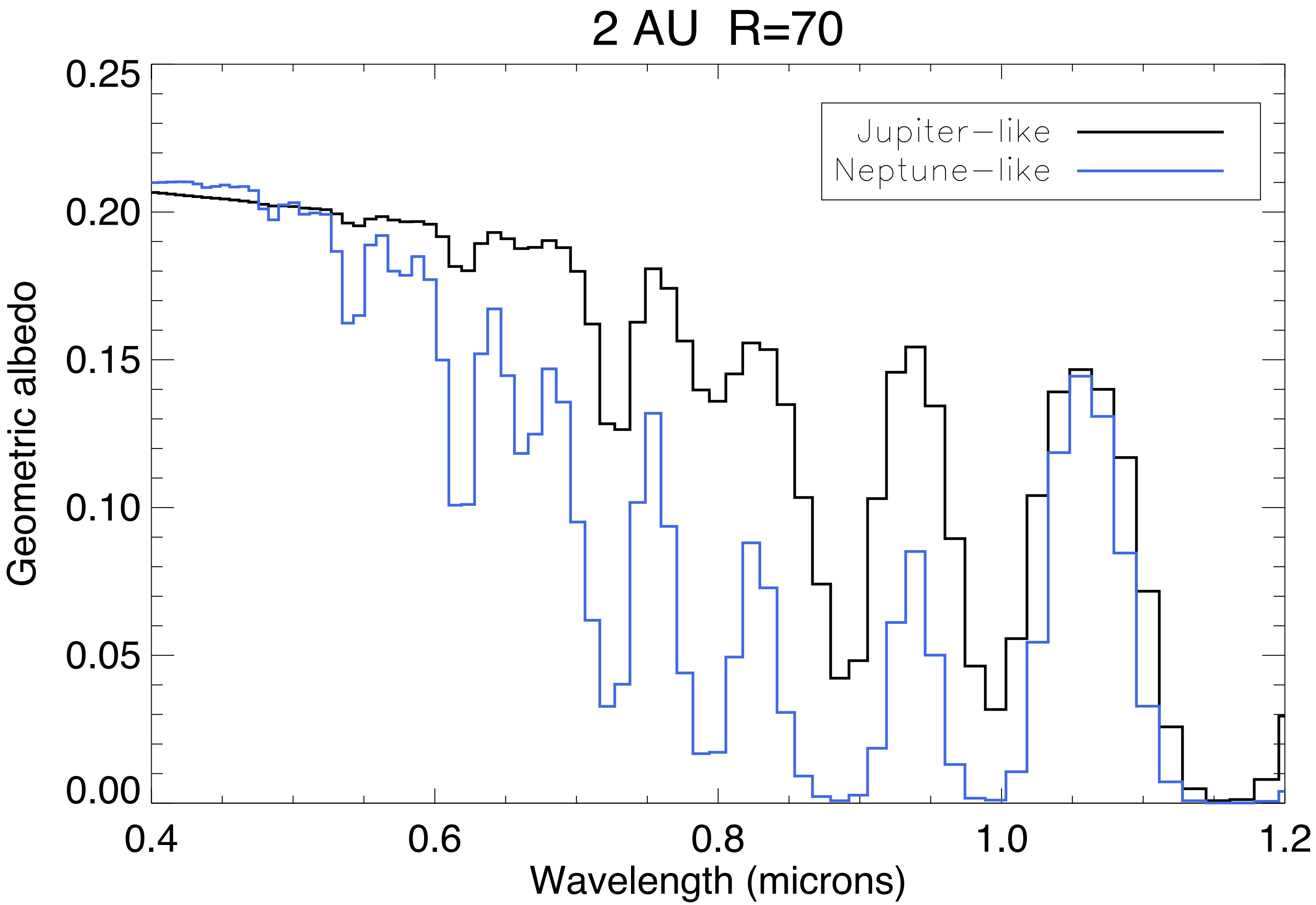
AFTA exoplanet science objectives

1) 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
2) Spectroscopically characterize 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) of planets of less than 3 RE in broadband photometry of at least 3 bands with an accuracy of 0.05 in albedo
3) Characterize the orbital semi-major-axis (within 20%) and eccentricity (within 0.2) of these planets, in conjunction with Doppler or astrometric measurements

2 AU 1x and 5x metallicity (Cahoy et al)



R~70 spectra can determine planet properties



AFTA WFIRST
Wide-Field Infrared Survey Telescope

AFTA disk science objectivs

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

5) 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

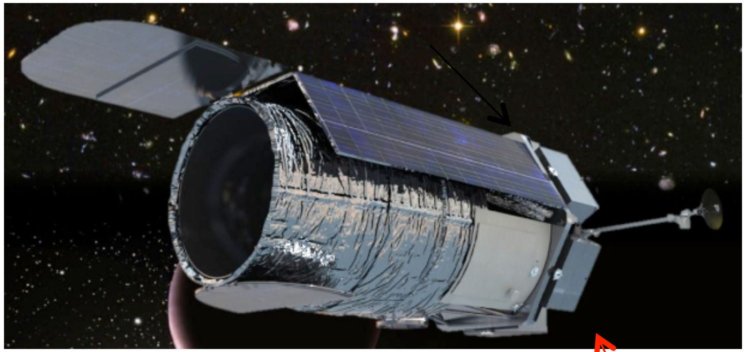
6) Constrain dust grain compositions and sizes

7) 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

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

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

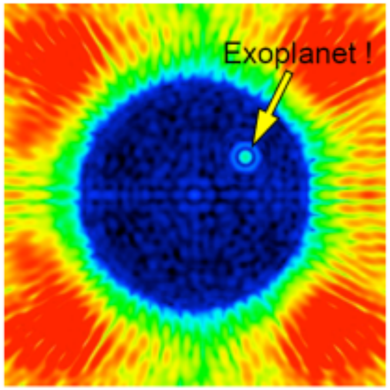
AFTA Coronagraph Instrument



Coronagraph Instrument

Coronagraph Architecture:

Primary: OMC
Backup: PIAA

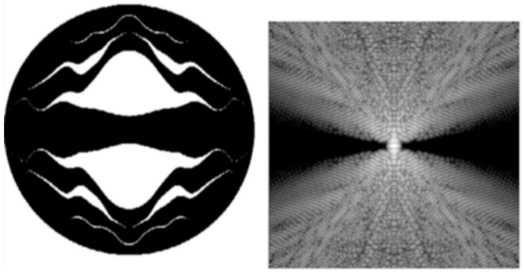


Exo-planet Direct imaging

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 Downselect

SPC



Pupil Masking (Kasdin, Princeton University)

HLC

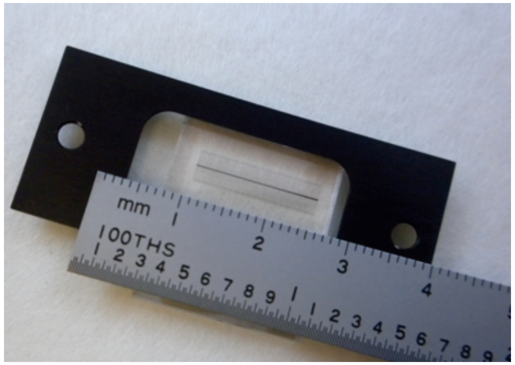
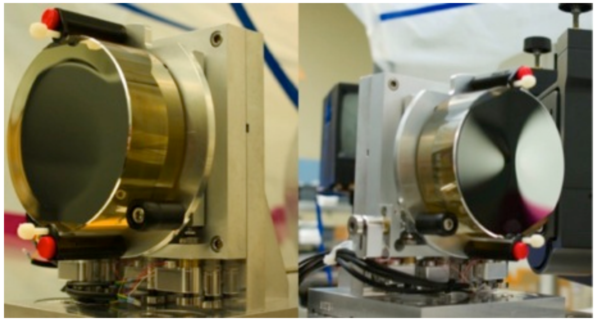


Image Plane Amplitude & Phase Mask (Trauger, JPL)

PIAACMC



Pupil Mapping (Guyon, Univ. Arizona)

VVC

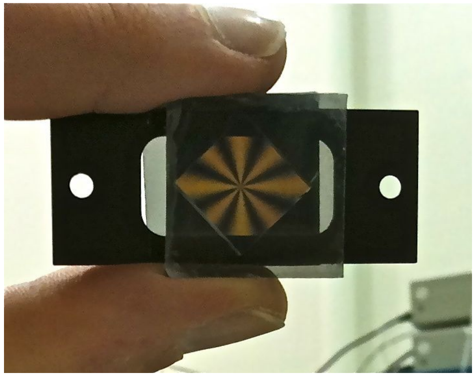
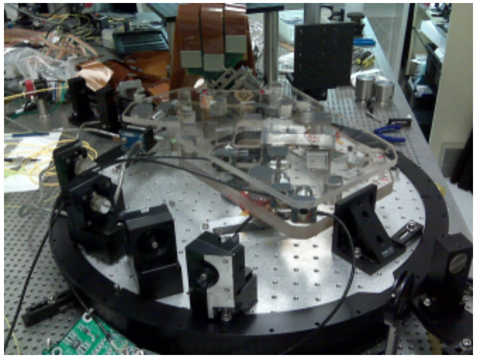


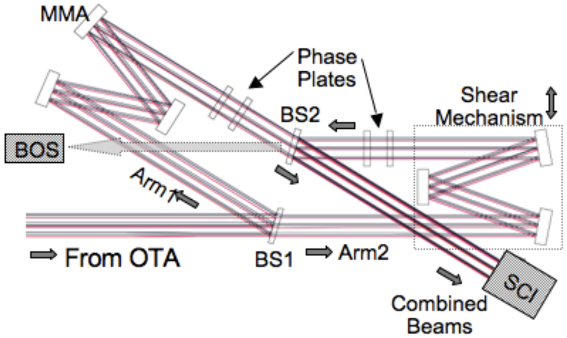
Image Plane Phase Mask (Serabyn, JPL)

VNC - DAVINCI



Visible Nuller - DAVINCI (Shao, JPL)

VNC-PO

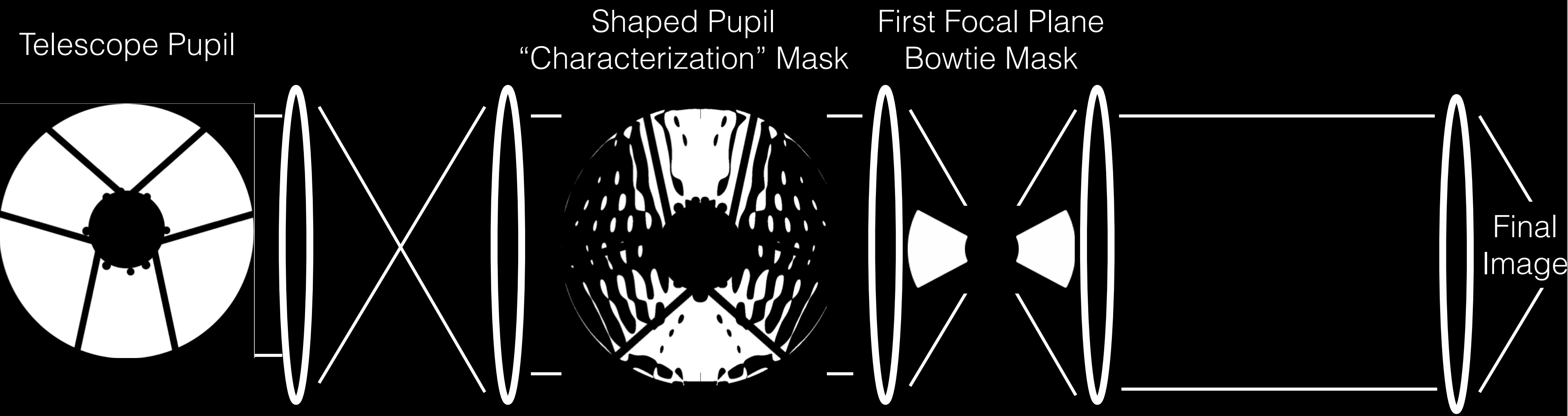


Visible Nuller – Phase Occulting (Clampin, NASA GSFC)

Kasdin (Monday)

Shaped Pupil Coronagraph for WFIRST-AFTA

Riggs et al. (2014)

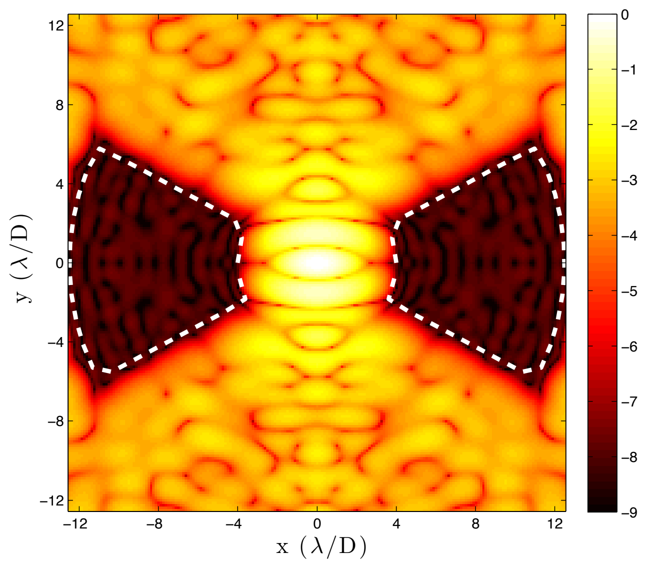

Telescope Pupil

Shaped Pupil "Characterization" Mask

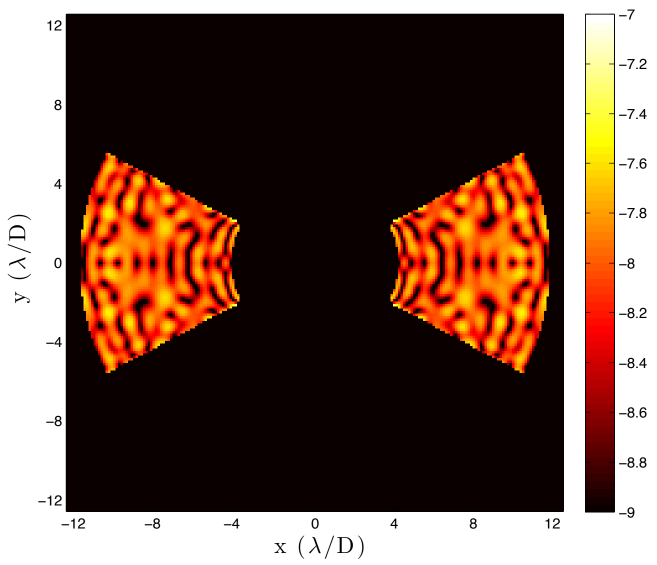
First Focal Plane Bowtie Mask

Final Image

Intensity in First Focal Plane

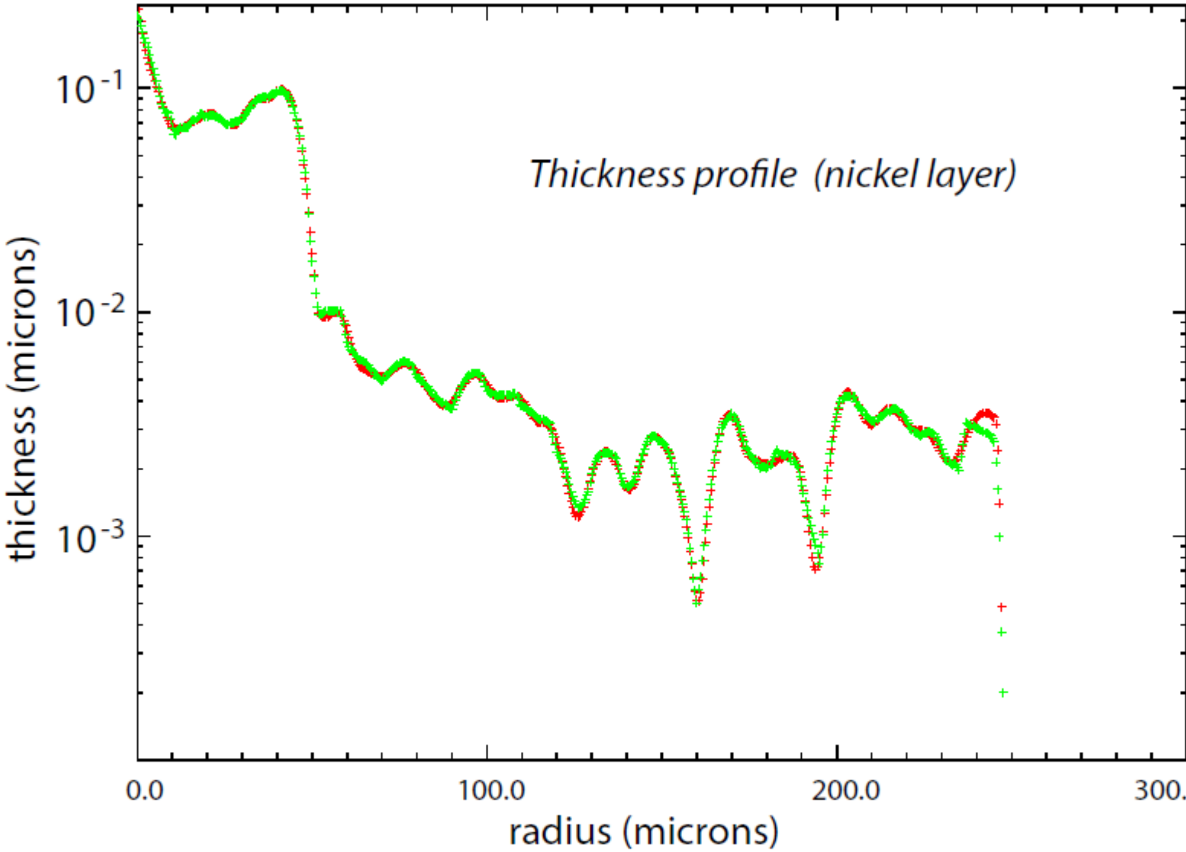


Contrast in Final Image (10^{-8})



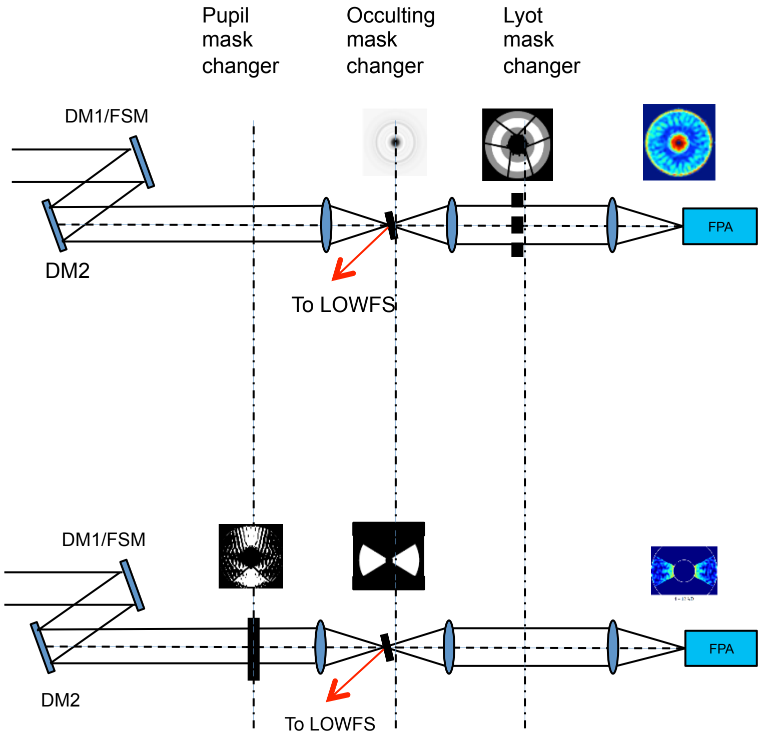
Hybrid Lyot coronagraph

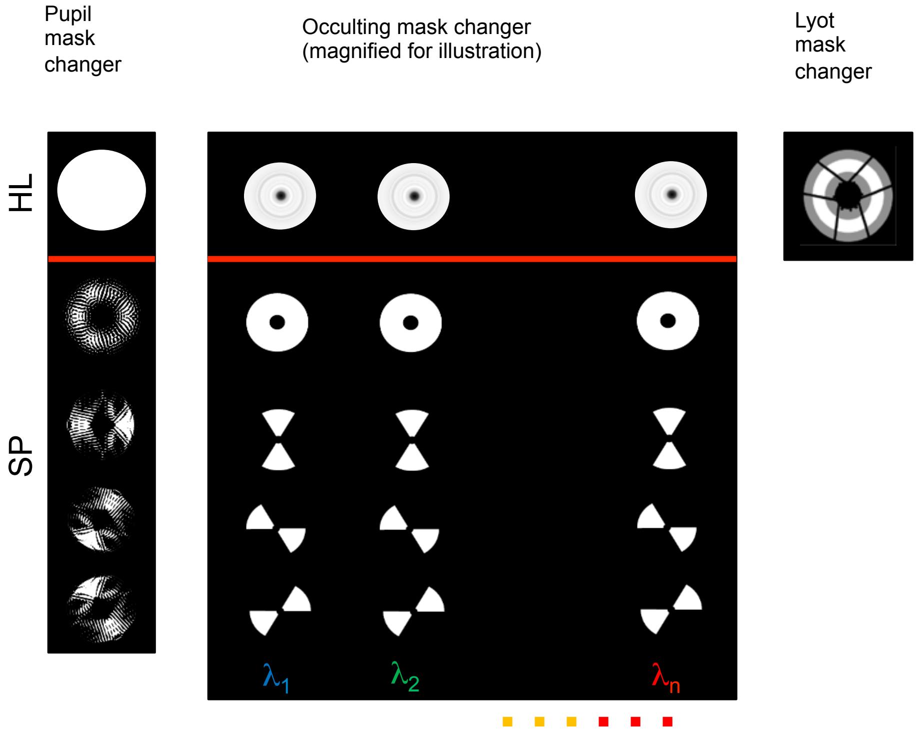
- Tailored focal plane masks provide phase shift and amplitude attenutation in focal plane
- Spider artifacts blocked by Lyot stop and also by DM control (similar to Pueyo & Norman 2013)



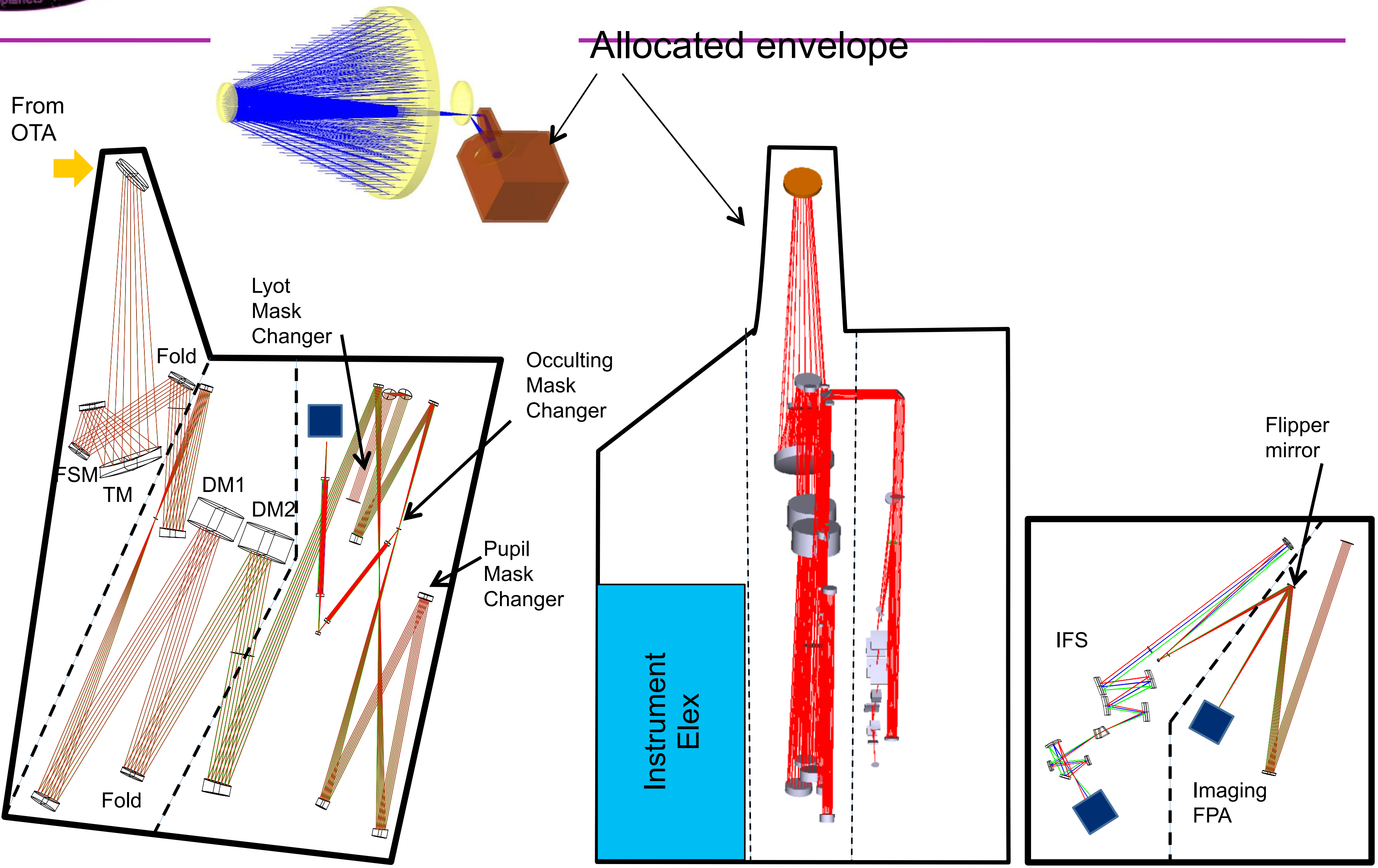
Primary Architecture: Occulting Mask Coronagraph = Shaped Pupil + Hybrid Lyot

- Both are relatively robust against obscured apertures
- Both share similar components
- Risk reduction provided by pursuing two designs





Instrument Layout within the Allocated Envelope

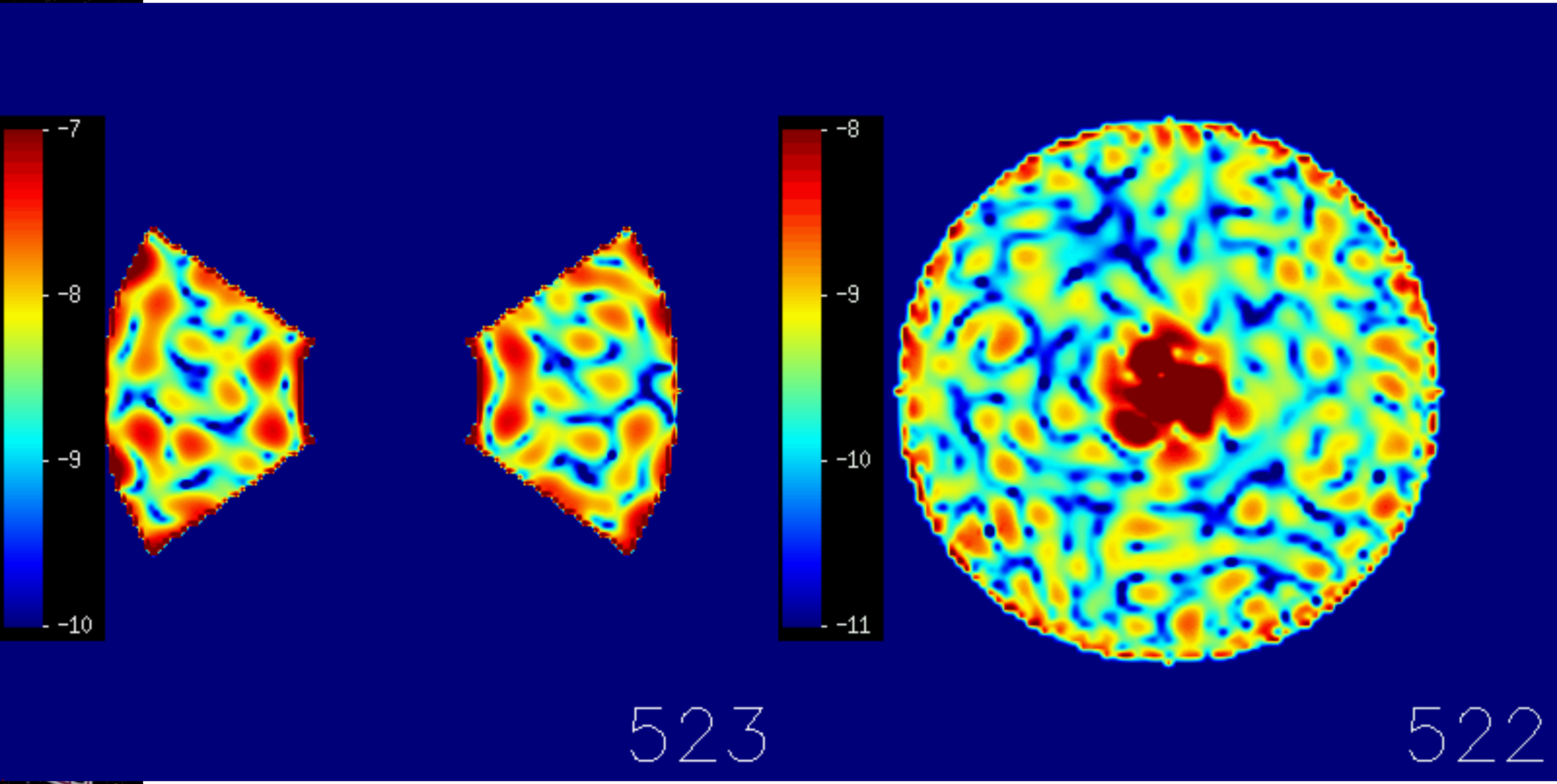


(1) Main OMC Bench

(1) (2)

(2) Detector Bench

PSF simulations



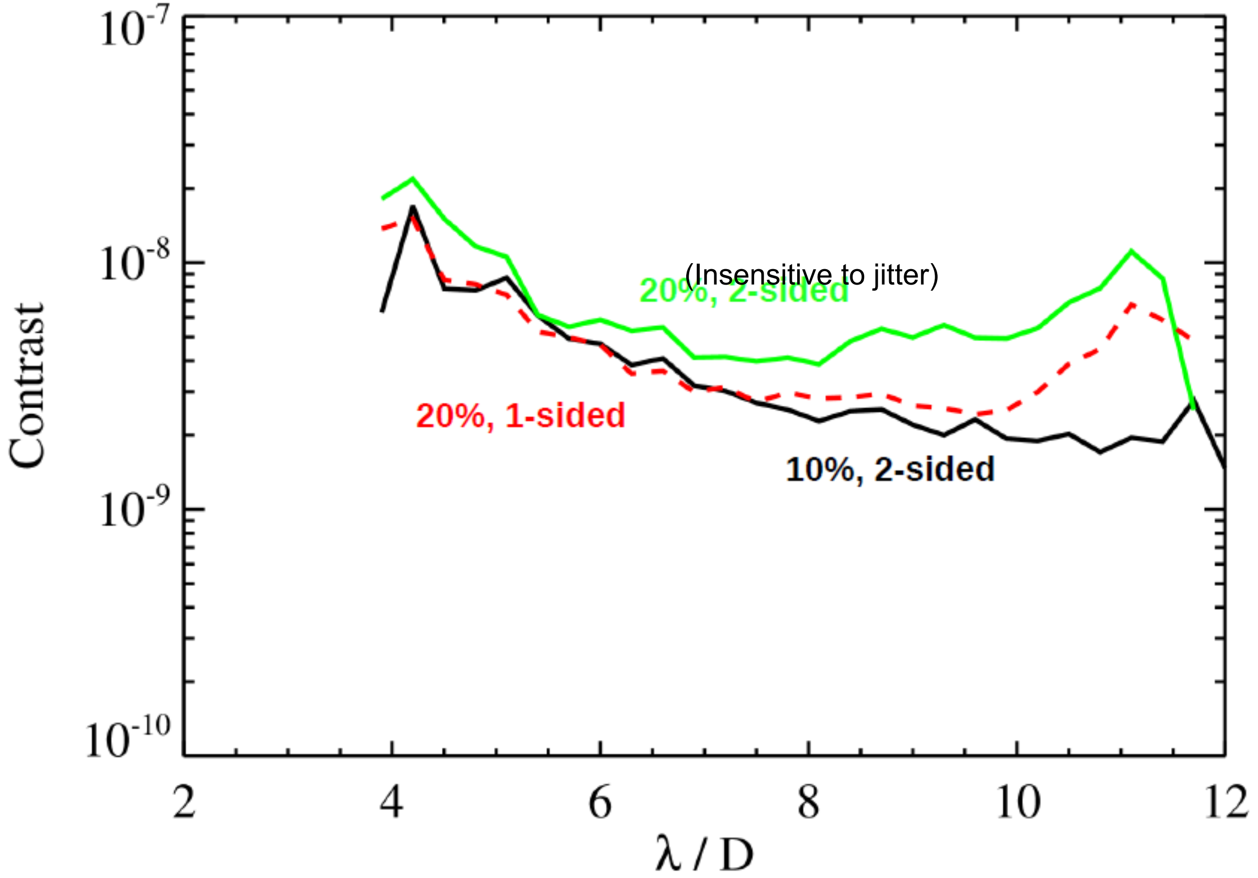
Shaped pupil PSF

HLC PSF

Simulations by John Krist

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

- HLC: high performance but jitter sensitive
- Shaped pupil: very robust
- PIAA: Still in development



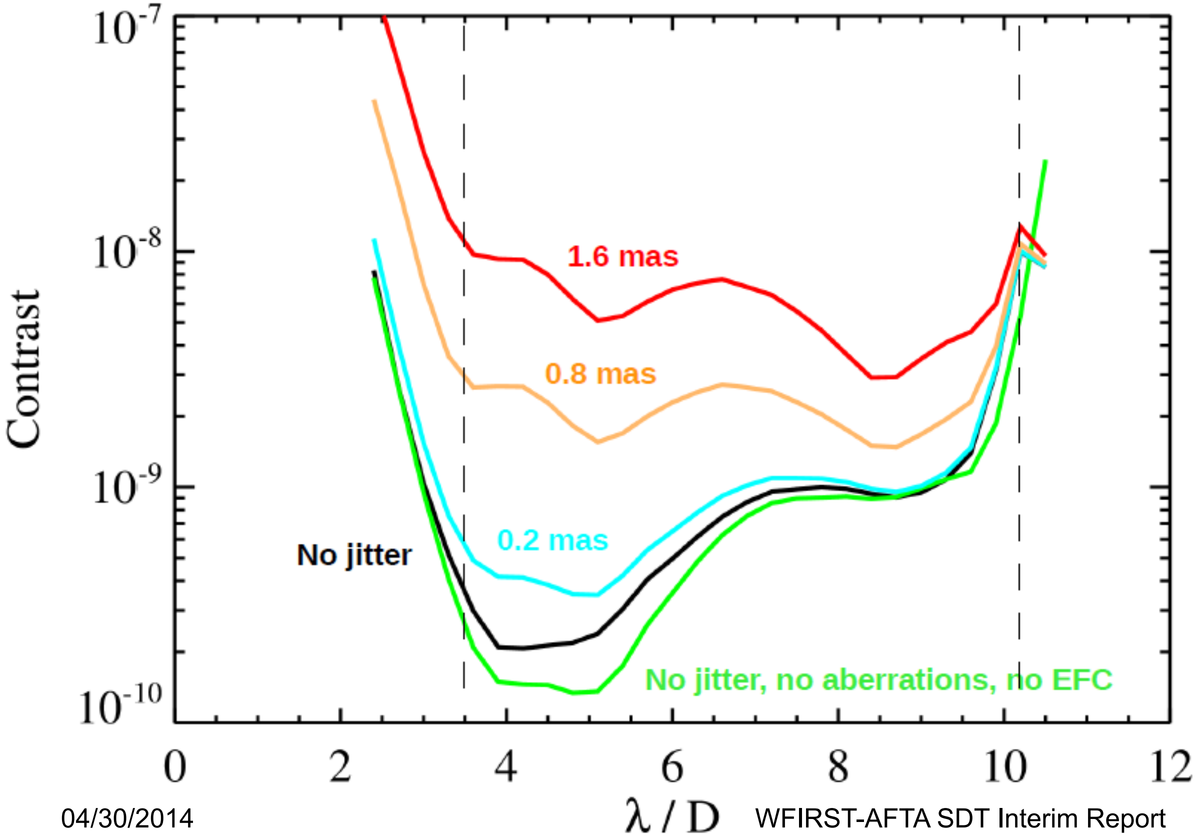
Shaped Pupil, Post-EFC

(Insensitive to jitter)

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

- HLC: high performance but jitter sensitive
- Shaped pupil: very robust (but lower efficiency)
- PIAA: Still in development

HLC Aberrated System, Post-EFC

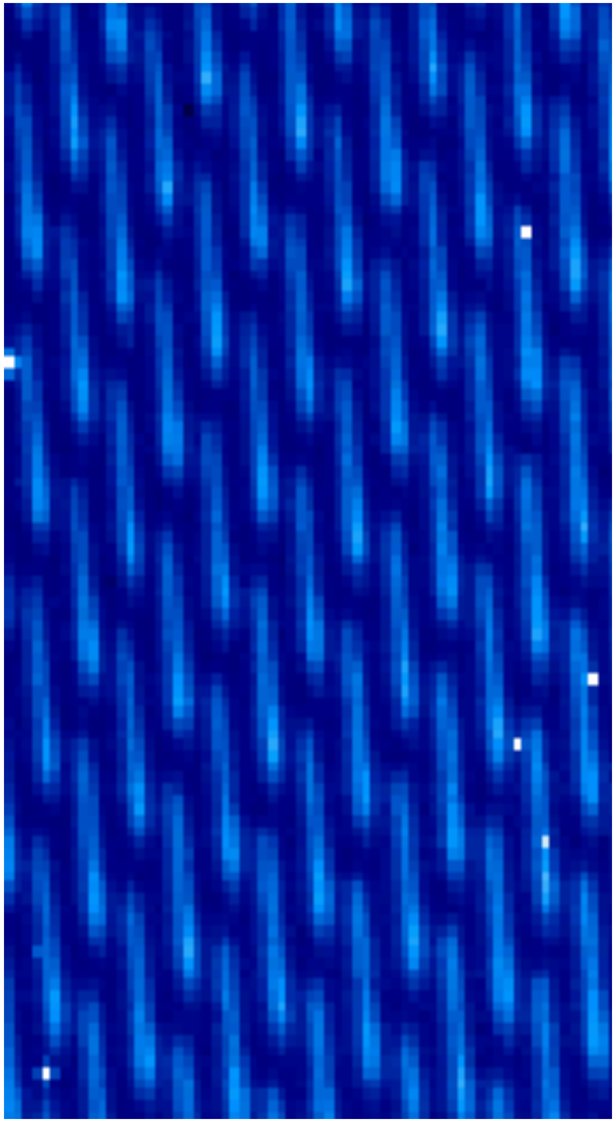


Integral Field Spectrograph

Follows design principles of ground-based IFS instruments, e.g. CHARIS (Princeton), GPI, SPHERE. OSIRIS

140 x 140 lenslet array. Designed to disperse 20% band over 24 detector pixels (SR ~70).

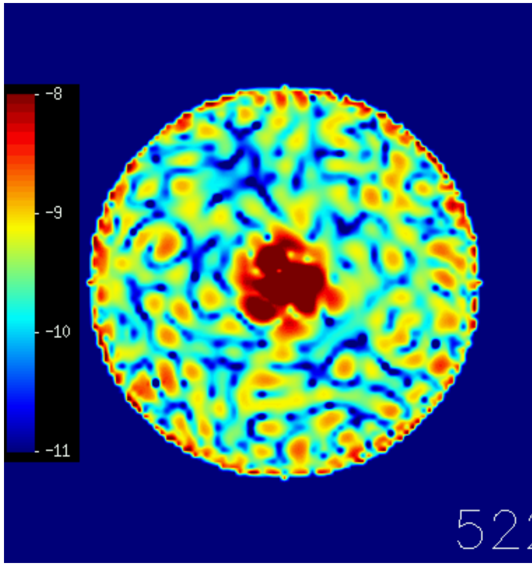
- Accommodates 0.5 – 1 um range using 4 bandpass filters (one at a time)
- 17 mas ‘spaxel’ pitch.



GPI IFS microspectra

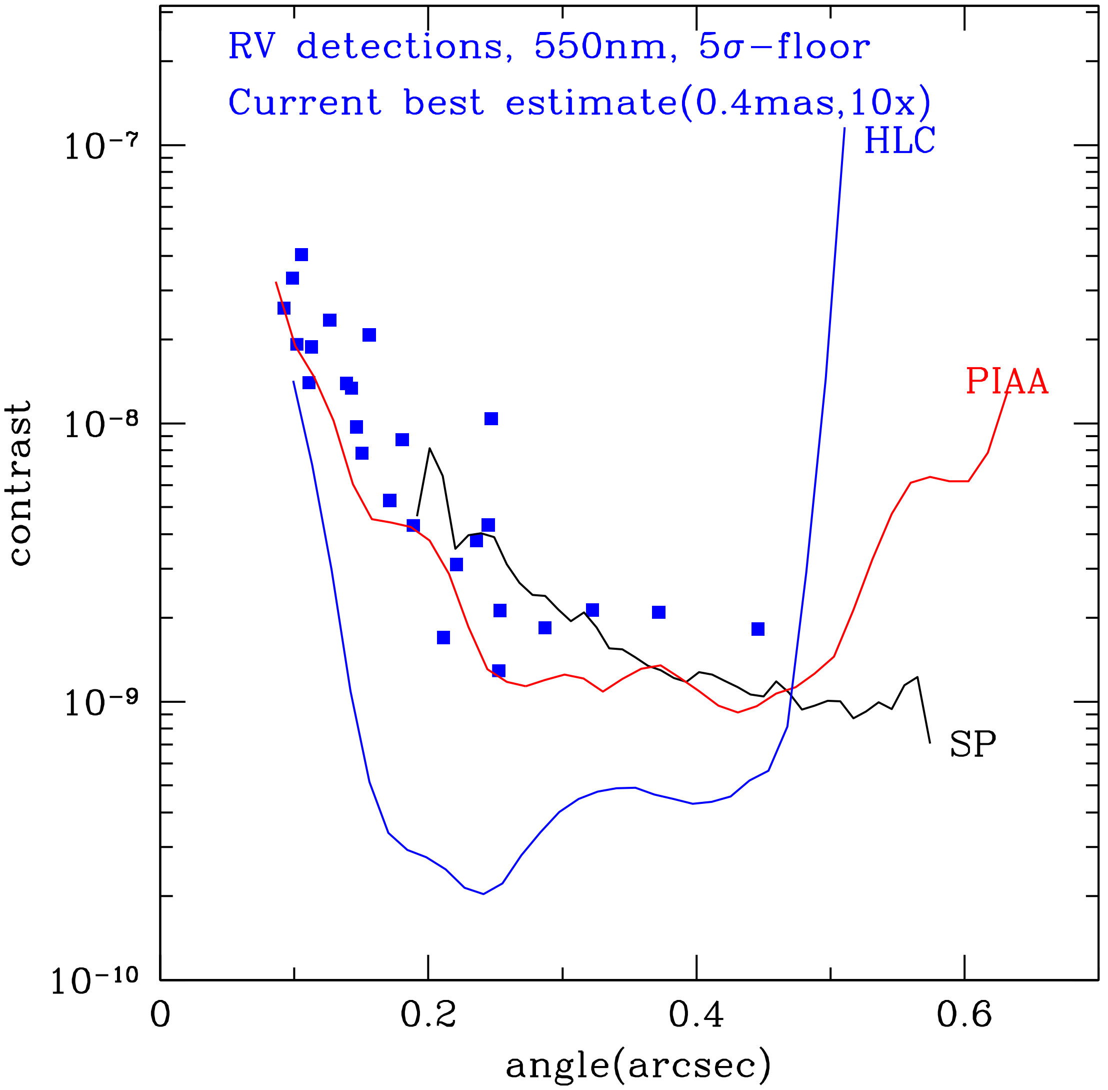
Science modeling

- Science yield modeling focusing on ability to study Doppler planets
- Contrast curves generated from John Krist PROPER models
- 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



Contrast vs Angle from Star

Conservative jitter/post-processing

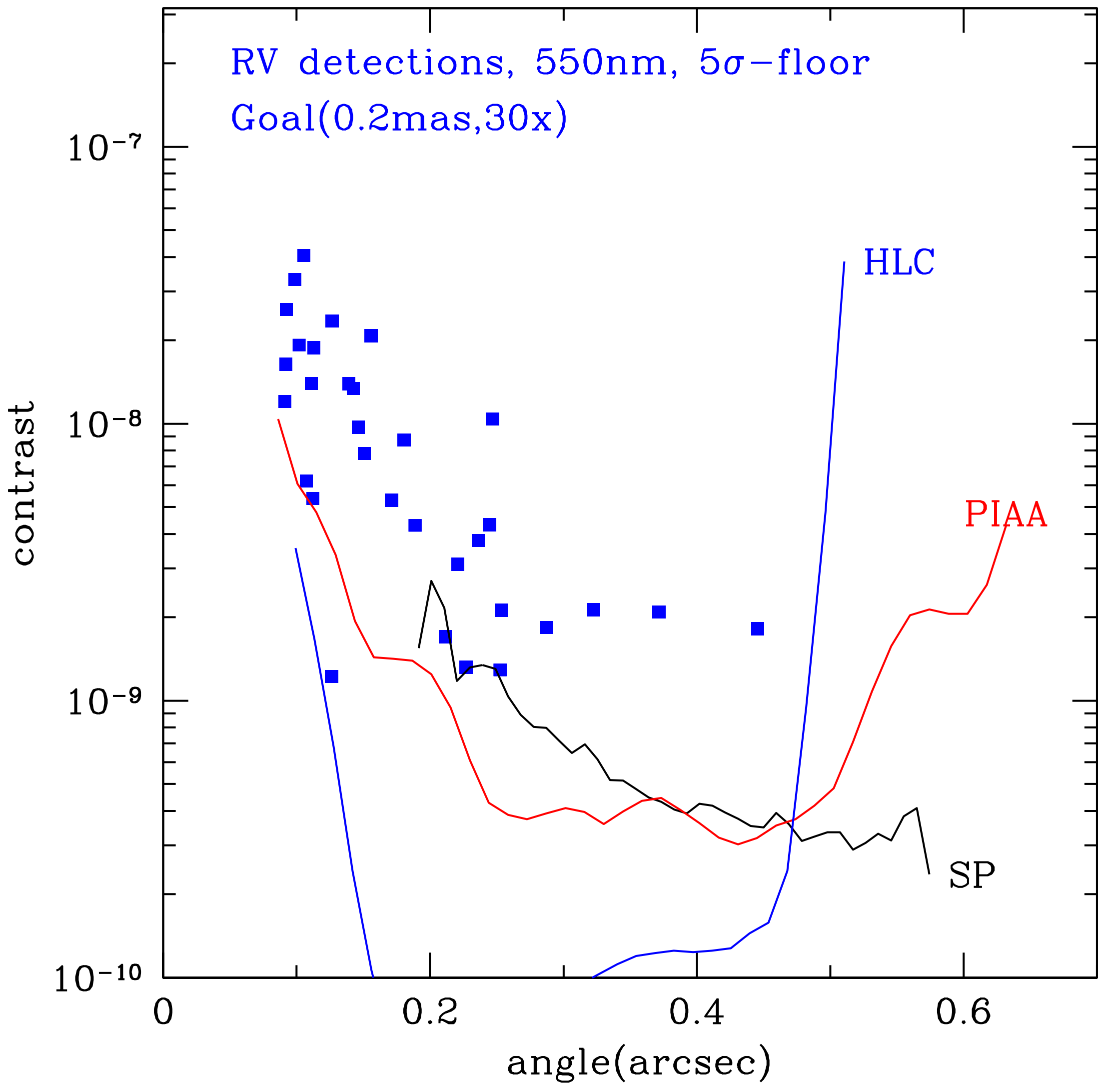


Contrast floors here are upper limit for long exposure/very bright star

PIAA graph obsolete

Contrast vs Angle from Star

Optimistic jitter & post-processing factor



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

AFTA RV Exoplanet Photometric Detection Estimates

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

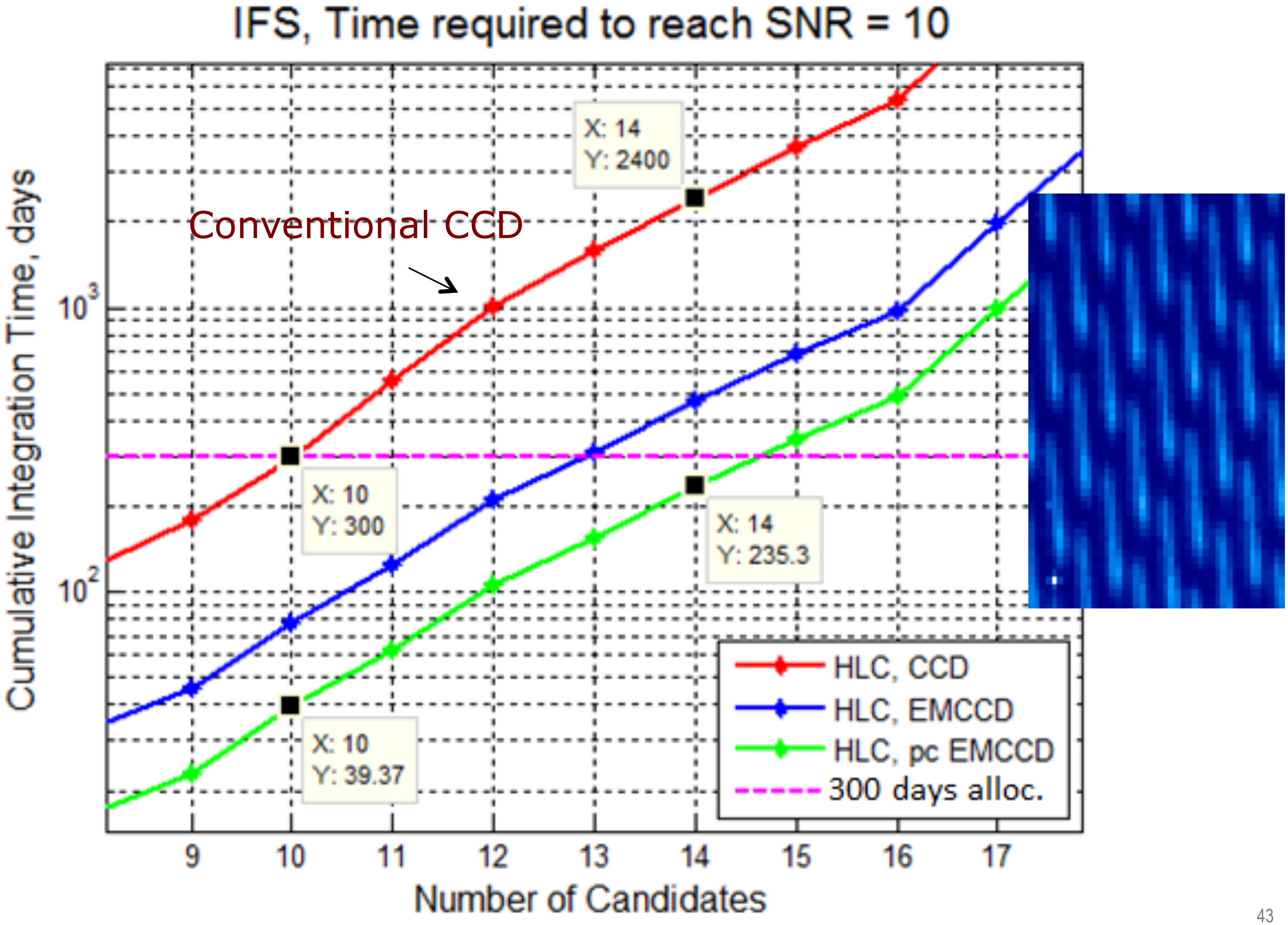
Configuration	Design	Inner working angle	# RV planets, 550nm band, 6-month campaign	# spectral bands per target, 6-month campaign
Prime (OMC: Occulting Mask Coron.)	**SP**	0.19	4 7	4.3 4.9
	HL	0.10	18 19	4.3 4.2
Backup	**PIAA**	0.09	23 30	3.2 4.3

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

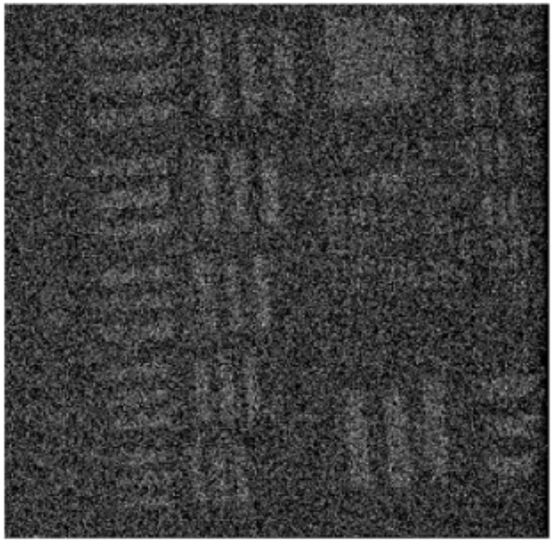
Integration time needed to reach given number of planets with spectroscopic detections



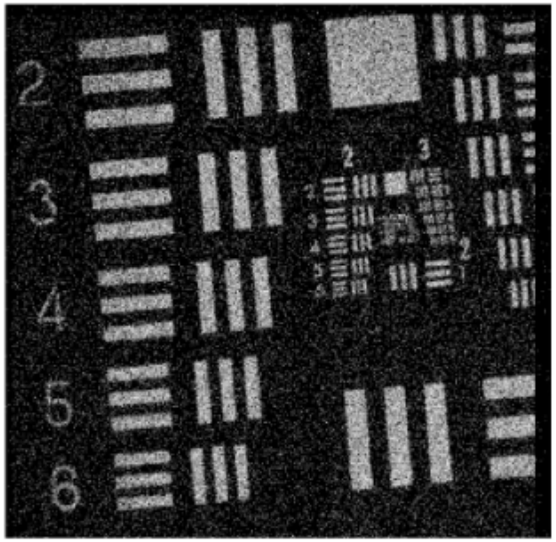
Conventional CCD

EMCCD: Photon Counting

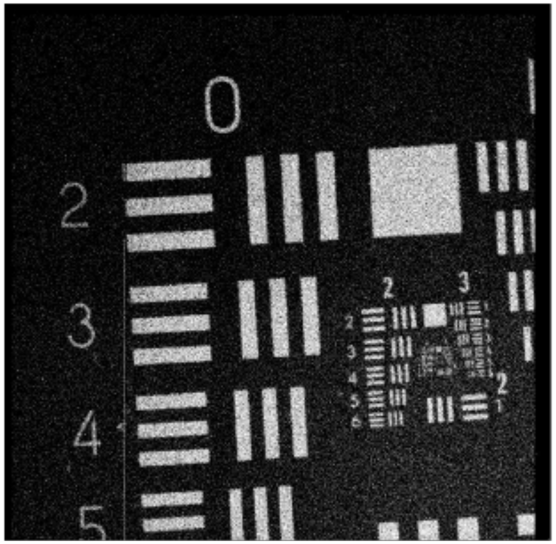
- If the frame rate is faster than the mean photon arrival time, then one can use an EMCCD to count individual photons



Conventional CCD



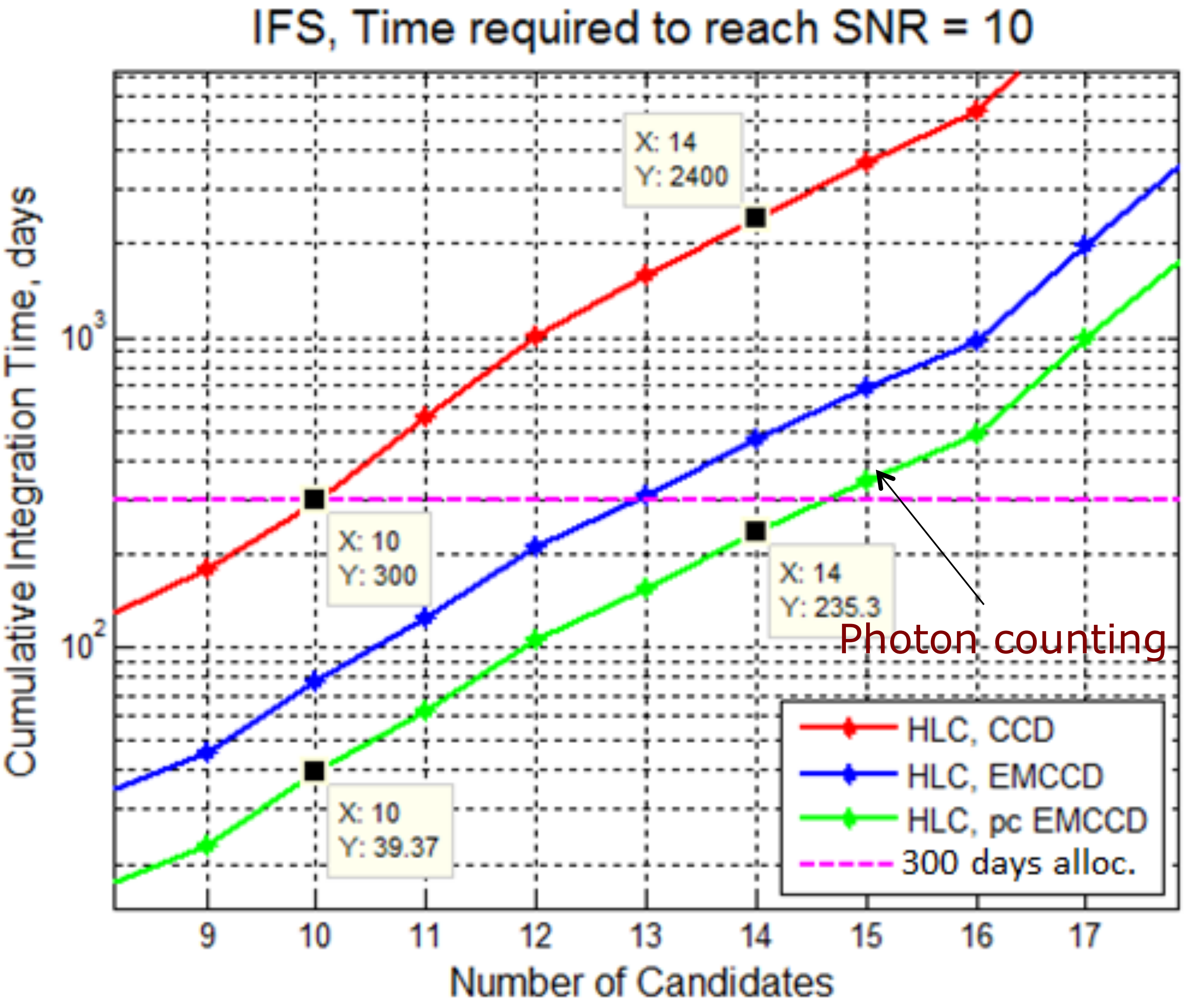
Intensified mode



Photon counting mode

* From Wen, Y., Rauscher, B. J., Baker, R. G., et al. 2006, Proc SPIE, 6276, 44.

Photon counting detector increases spectral yield by 50%



Photon counting

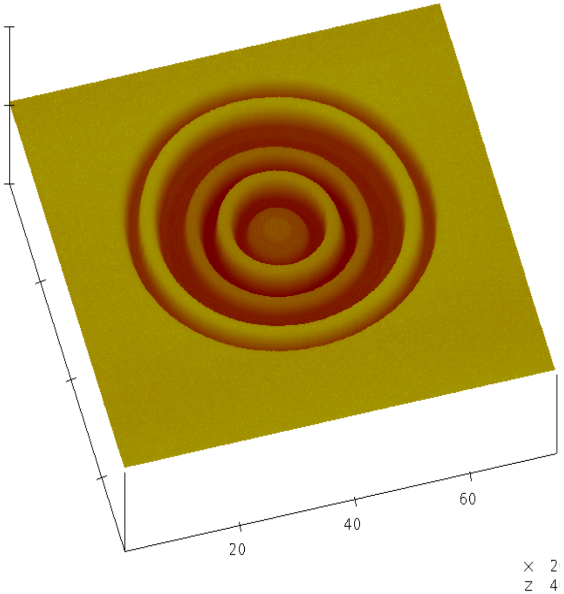
PIAACMC gen2, 20% bandpass, 1.3 λ/D IWA, 67% throughput

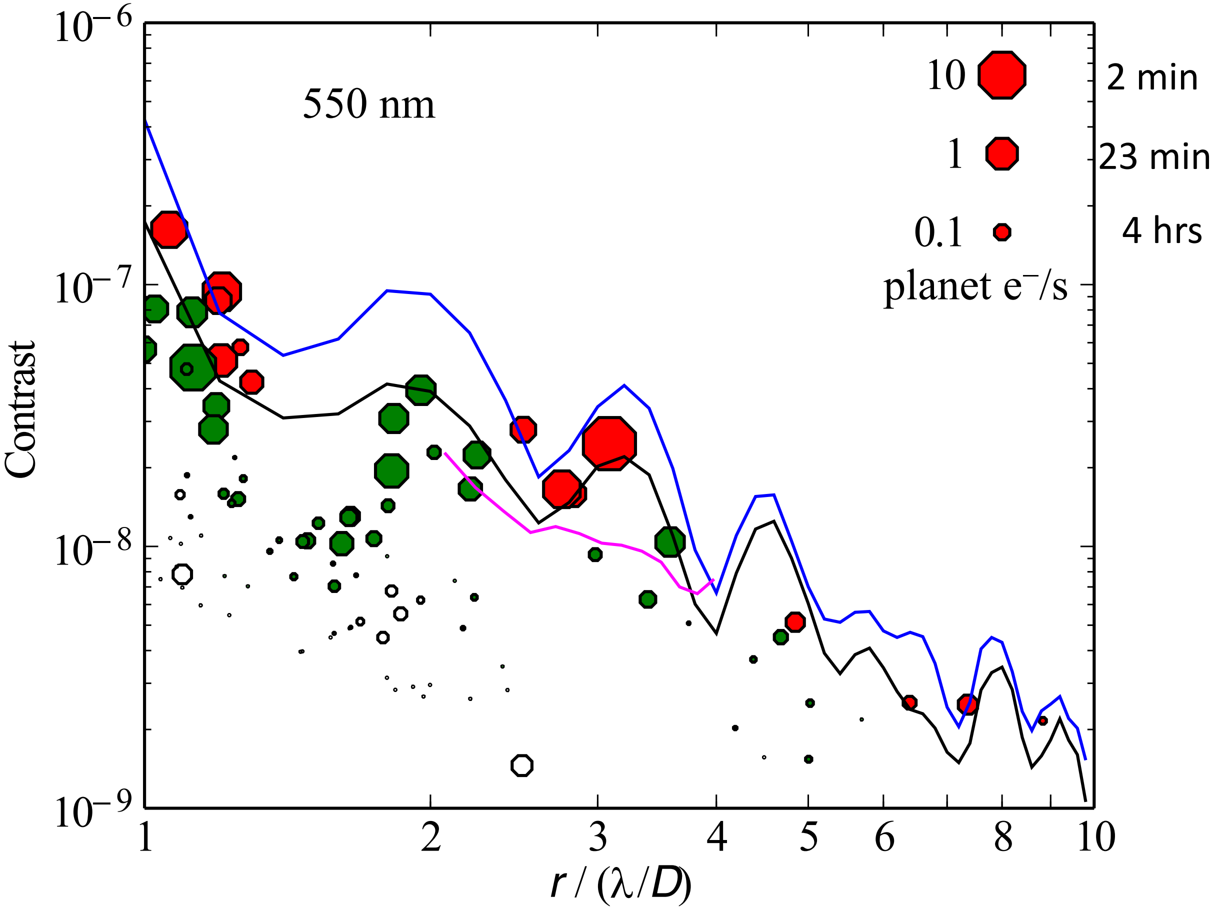
0.33 mas rms per axis 0.2 mas rms per axis

10x postprocessing 30x postprocessing

HCIT 10% bandpass

- Two sim cases (conservative and optimistic)
- 15-50 spectrally characterizable planets

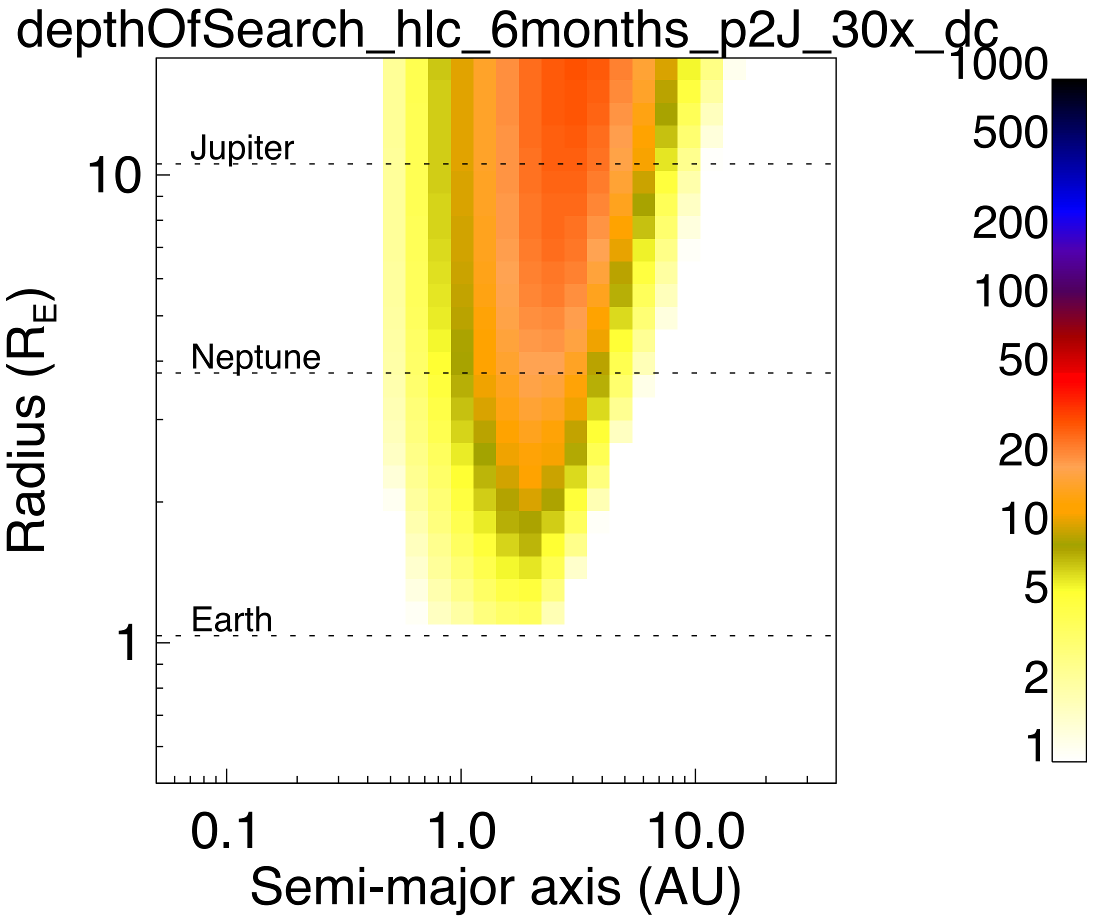




Brian Kern, Olivier Guyon, Rus Belikov, et al.

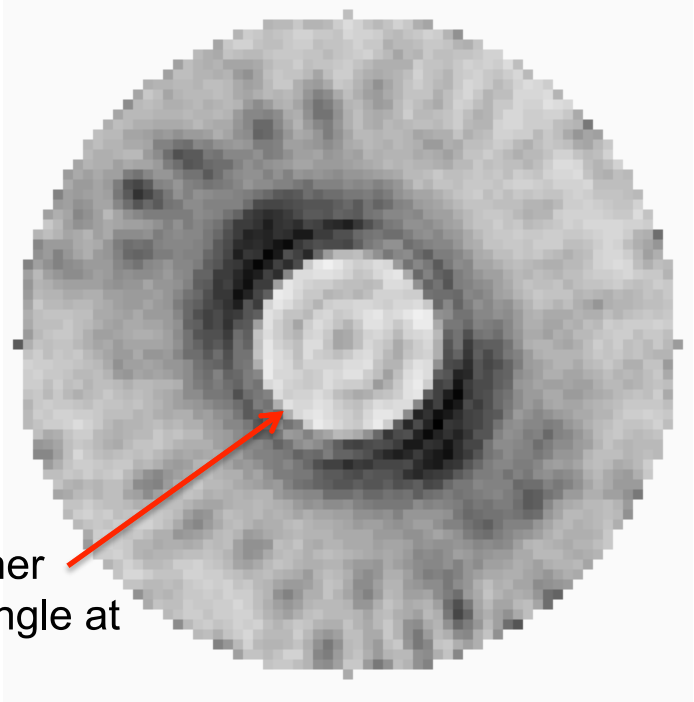
Total survey completeness and blind searches

- Blind search models show that 3 month surveys discovers 3-6 planets of <4 RE
- Blind search discovery late much lower than Doppler
- Strong advantage to Doppler pre-survey



Imaging Nearby Circumstellar Disks

- Circumstellar disks reveal the locations of planets and trace the history of collisions
- Few disks below 100x the solar system dust level (100 zodi) have been detected, and none have resolved images
- WFIRST-AFTA will detect disks down to 10 zodi around nearby stars;
  - Important for planetary systems and for future Earth imaging missions
- WFIRST-AFTA + LBT-I are needed: LBT-I gives total dust amounts; WFIRST-AFTA then gives reflectance; both together give debris properties



1.1 AU inner working angle at d= 8 pc

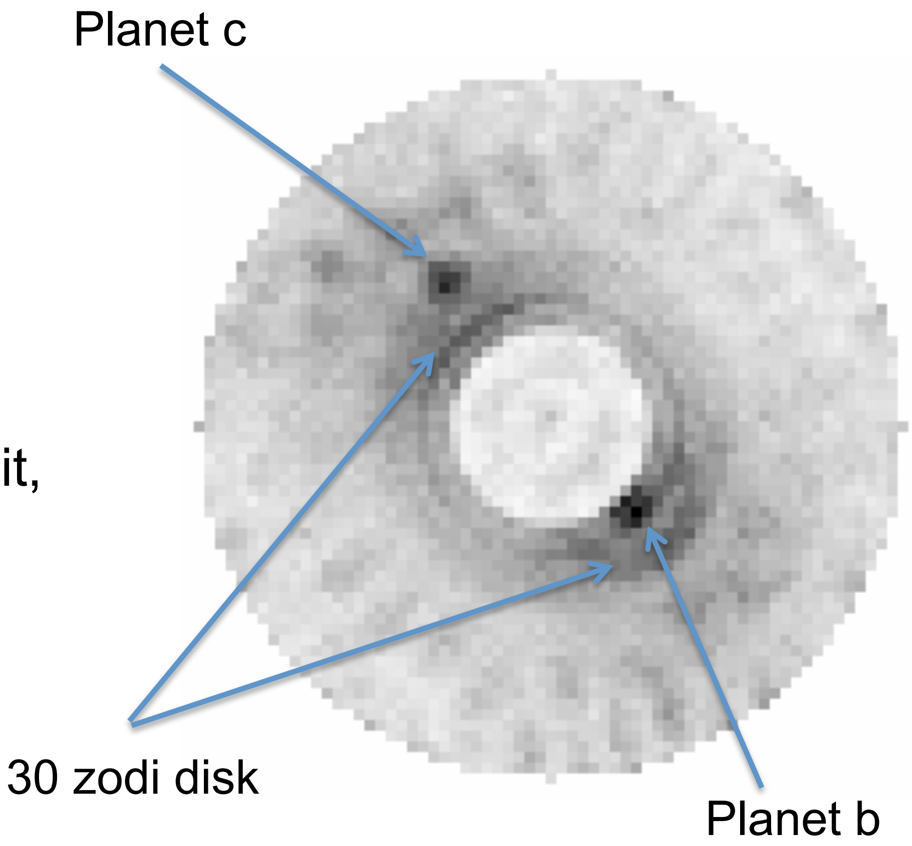
Simulation of 20 zodi disk WFIRST-AFTA image (24 h at 8 pc)

Tom Greene

Imaging Nearby Planetary Systems

- The WFIRST-AFTA coronagraph will give us the first reflected light visible images of the planetary systems of nearby stars

- 47 UMa System with known RV planets (~Jupiter masses)
- G1V star at 14 pc
- Planet b has SMA = 2.1 AU, planet c has SMA = 3.6 AU
- Assume 30 zodi dust dust (628 zodi measured 3 sigma upper limit, Millan-Gabet et al. 2011)
- Assume incl 60 d, PA 45 d, pl. albedo 0.4, pl. orbit -90 d & 70 d

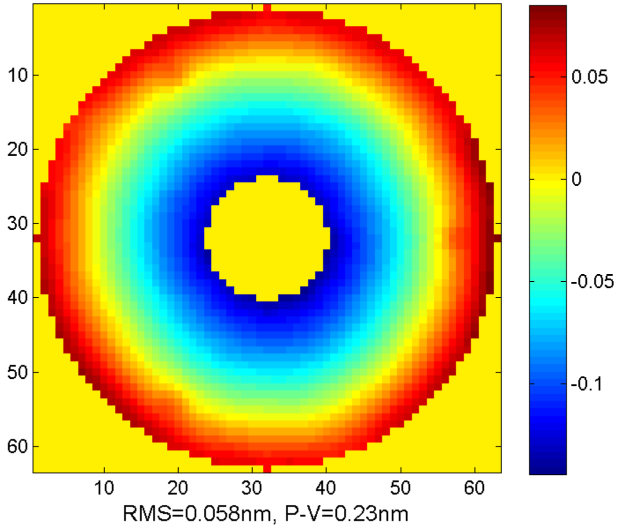


Simulation of a 10 hour exposure with HL coronagraph (0.4 mas jitter / 10 x speckle suppression, 550 nm 10% BW)

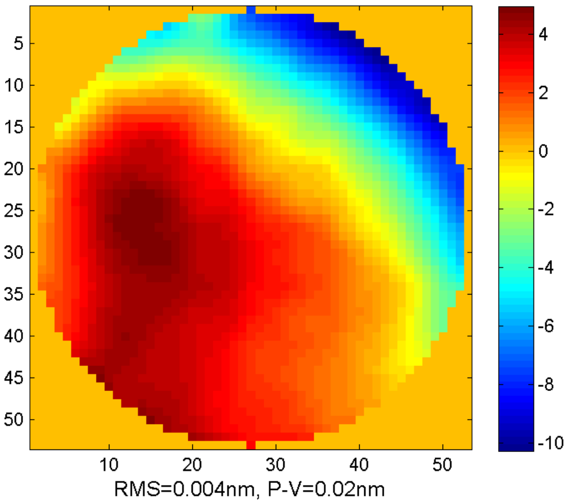
Tom Greene

Simulation efforts – thermal modeling

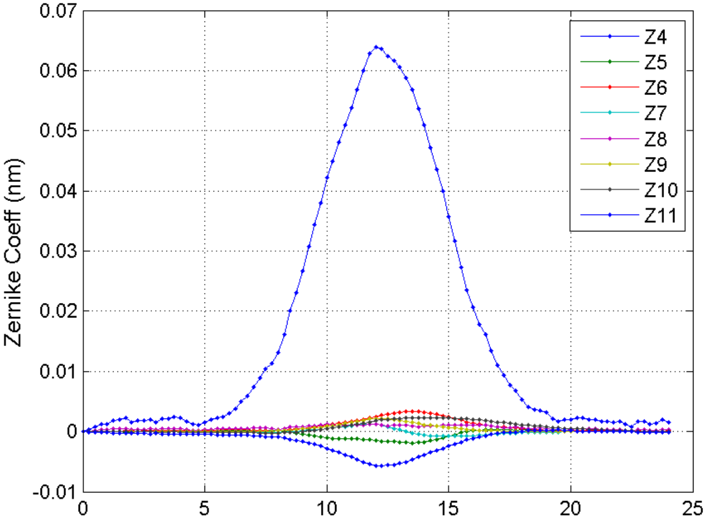
PM WFE: Case 5 at Noon



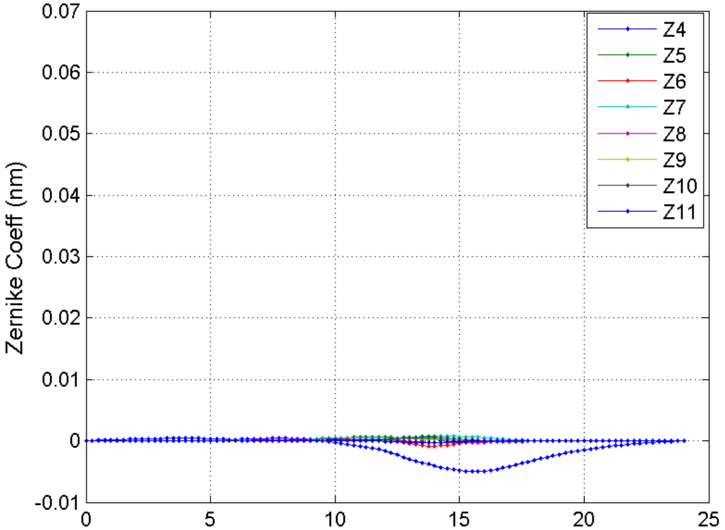
SM WFE: Case 5 at Noon



PM WFE Zernike Coeff: Case #5

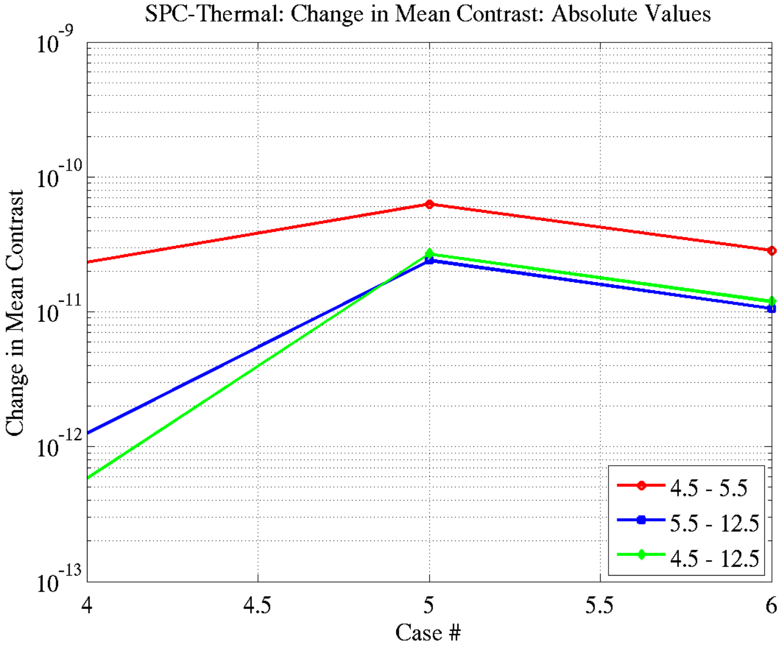


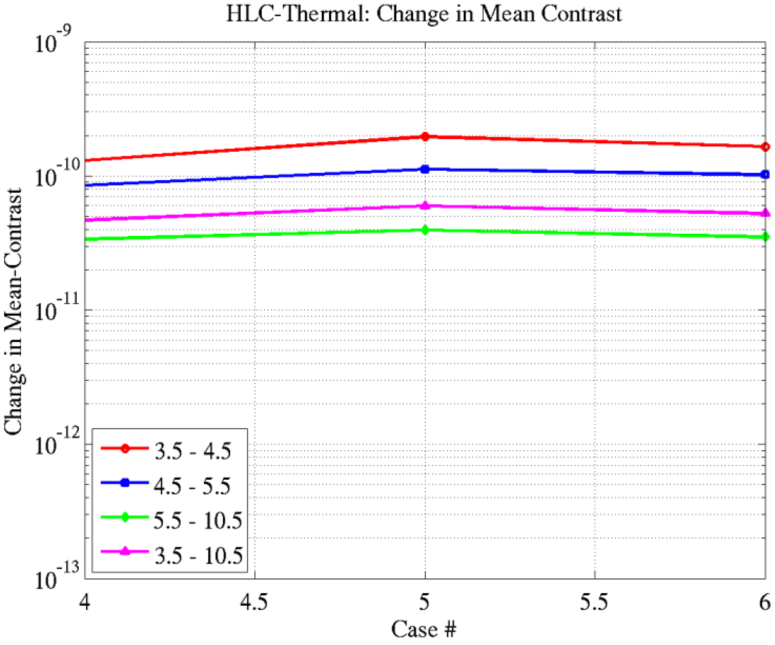
SM WFE Zernike Coeff: Case #5



Effects of telescope drift on final contrast

- The change of contrast from WFE evaluated using J. Krist's PROPER model (low jitter HLC design) end-to-end contrast change analysis is shown below
- Mean contrast **changes** (Δ contrast) are calculated over dark hole regions of 3.5 – 4.5, 4.5 – 5.5, 5.5 – 10.5 and 3.5 – 10.5 λ/D

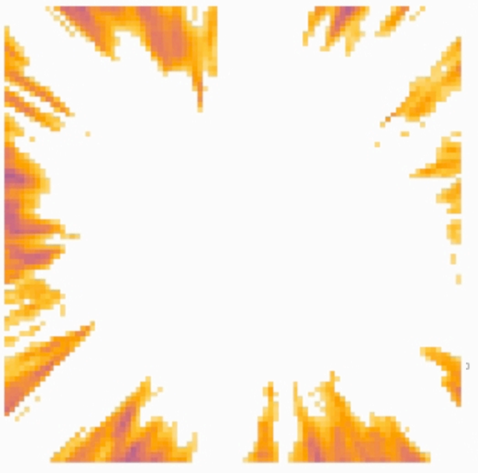

SPC-Thermal: Change in Mean Contrast: Absolute Values

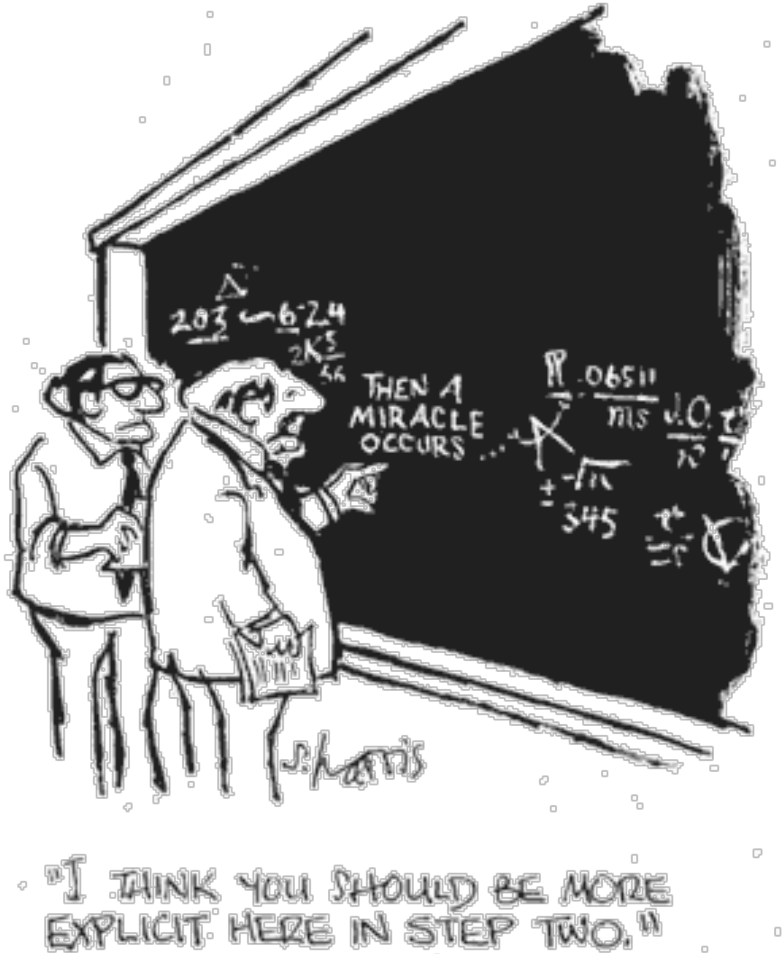

HLC-Thermal: Change in Mean Contrast

- **Impact to contrast from thermal low-order wavefront changes is < 10^{-10} (same for RB effects)**

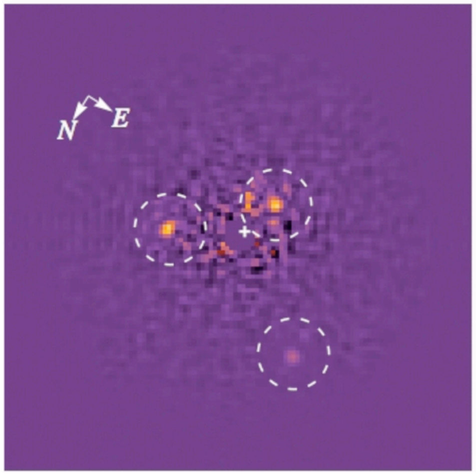
PSF subtraction modeling

Raw instrument contrast
Relatively easy to model

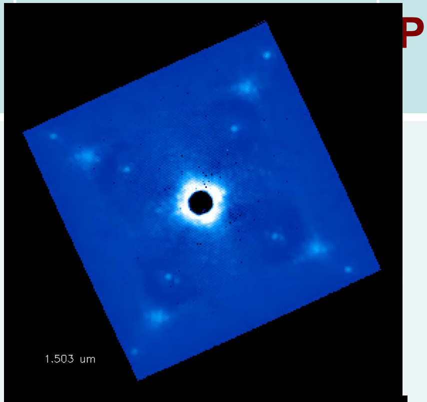
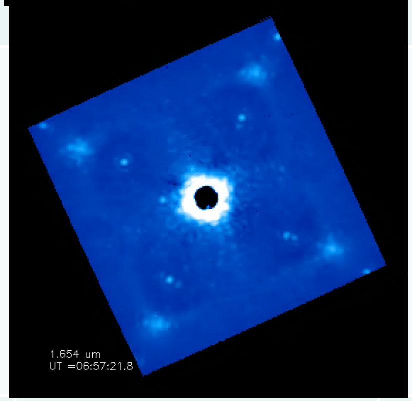




Final post-processed contrast
Easy to define as a scientific figure of merit



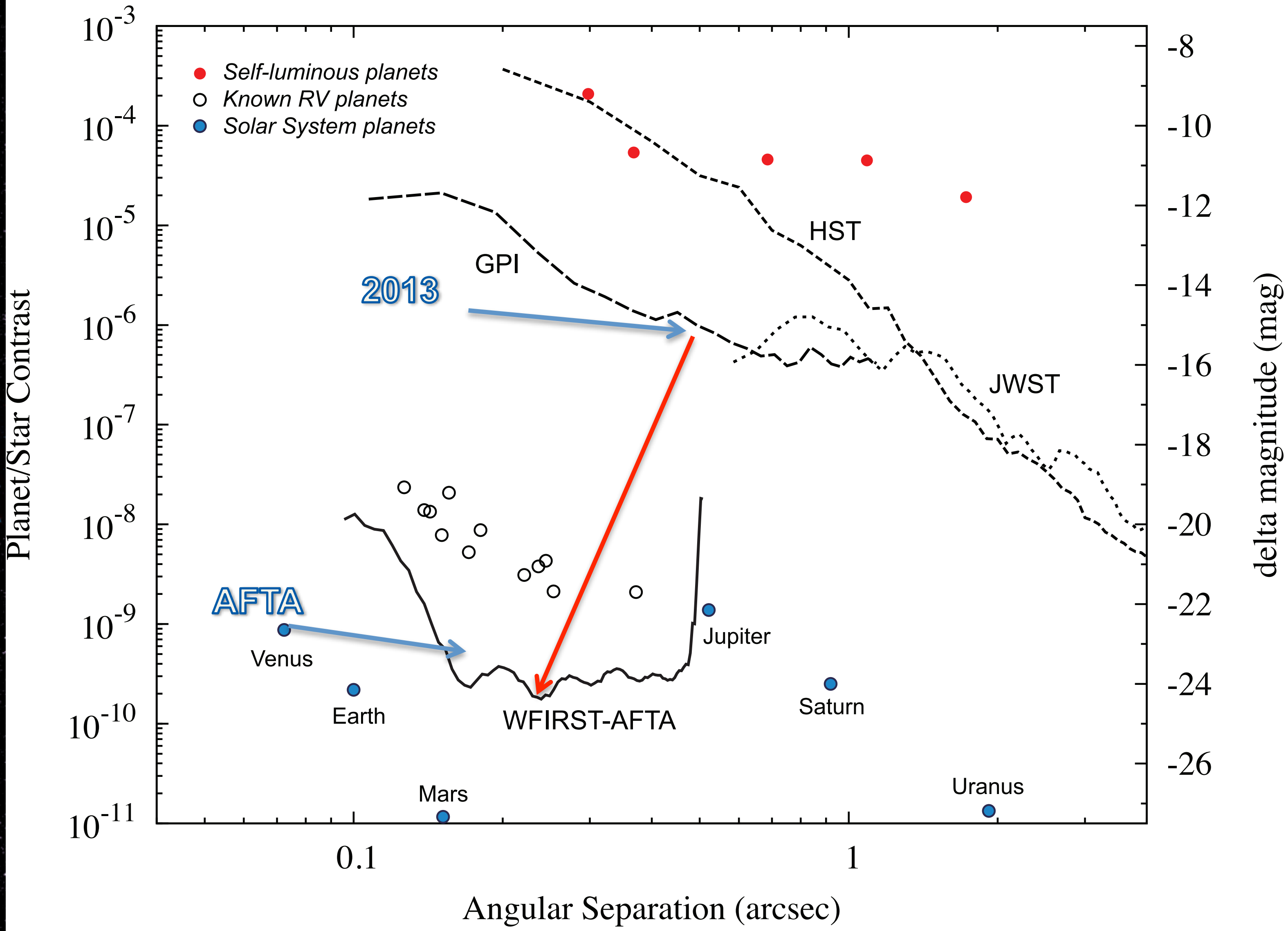
NICMOS images of HR8799 from Soummer et al

		PSF. sub	Least-squares (LOCI)	PCA (KLIP, etc…)	issues
Wavelength diversity (SDI)					PSFs are chromatic
Rotational diversity (ADI)					Can't roll spacecraft
PSF diversity (ref stars) Deliberate choice stars or library?					Baseline? How much do images differ? Stellar size / estimate those terms?
Coherence diversity (CDI)					Continuous DM dithering?

Other uncertainties

- Wavefront acquisition, stability, and control scenarios
- PSF subtraction approach and factor
  - Modeling effort led by STScI but complex integrated modeling
- Polarization modeling in progress, may require operation in single polarization channels
- Coronagraph designs and models at longer wavelengths not yet complete
  - IWA will expand, number of accessible stars in critical methane bands may drop
- Optimal strategies for hybrid Doppler/imaging surveys

Coronagraph Development



Timeline and conclusions

- New telescope provides considerable political momentum
- $66M in FY13, FY14
  - Used to advance design, progress tech development (including coronagraph)
- Coronagraph tech development shows flight-like performance in 2016
- FY 17 new start – fits into "JWST wedge" in following years
- 2023 or 2024 launch
- Probe-class missions also under study
- AFTA will provide a revolutionary coronagraph capability (but needs to be thought of as part of a system)
  - Giant planet spectra, disk images, super-Earth photometry
  - With limited telescope time, prep observations are crucial
- Not TPF, but a huge step towards Earths