



# **WFIRST-AFTA Science Definition Team Interim Report**

April 30, 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

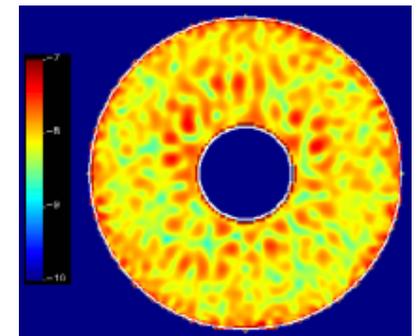
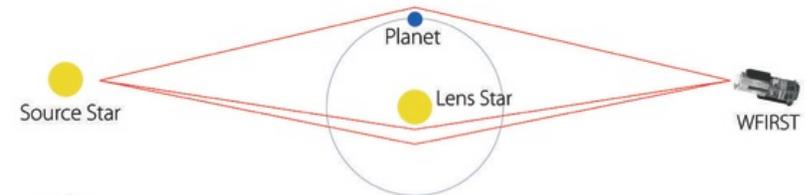
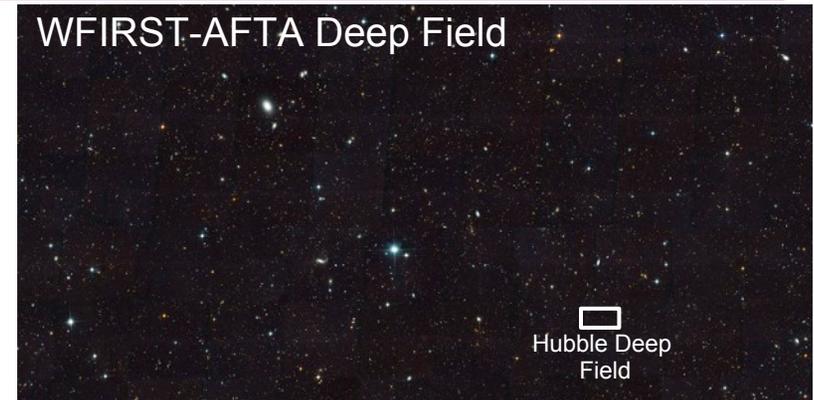
- Matthew Penny, Ohio State University
- Dmitry Savransky, Cornell University
- Daniel Stern, NASA JPL



# WFIRST-AFTA Summary



- WFIRST is the highest ranked NWNH large space mission.
  - Determine the nature of the dark energy that is driving the current accelerating expansion of the universe
  - Perform statistical census of planetary systems through microlensing survey
  - Survey the NIR sky
  - Provide the community with a wide field telescope for pointed wide observations
- Coronagraph characterizes planets and disks, broadens science program and brings humanity closer to imaging Earths.
- WFIRST-AFTA will perform Hubble-quality and -depth imaging over thousands of square degrees
- The WFIRST-AFTA Design Reference Mission has
  - 2.4 m telescope (already exists)
  - NIR instrument with 18 H4RG HgCdTe detectors
  - Baseline exoplanet coronagraph
  - 5 year lifetime, 10 year goal





# Executive Summary

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- “HST quality” NIR imaging over 1000's of square degrees
- 2.5x deeper and 1.6x better resolution than IDRM\*
- More complementary to Euclid & LSST. More synergistic with JWST.
- Enables coronagraphy of giant planets and debris disks to address "new worlds" science of NWNH
- Fine angular resolution and high sensitivity open new discovery areas to the community. More GO science time (25%) than for IDRM.
- WFIRST-AFTA addresses changes in landscape since NWNH: Euclid selection & Kepler discovery that 1-4 Earth radii planets are common.
- Aerospace CATE cost is 8% larger than IDRM (w/o launcher, w/ risks). Coronagraph adds 16% (including 1 extra year of operations), but addresses the top medium scale priority of NWNH.
- Use of donated telescope and addition of coronagraph have increased the interest in WFIRST in government, scientific community and the public.

\* IDRM = 2011 WFIRST mission designed to match NWNH



# WFIRST-AFTA Status

- Significant WFIRST-AFTA funding added to the NASA budget by Congress for FY13 and FY14 totaling \$66M. Supported in President's FY15 budget.
- Funding is being used for pre-Phase A work to prepare for a rapid start and allow a shortened development time
  - Detector array development with H4RGs
  - Coronagraph technology development
  - Science simulations and modeling
  - Requirements flowdown development
  - Observatory design work
- NASA HQ charge for telescope is "use as is as much as possible" and for coronagraph is "not drive requirements". Project / SDT driving toward fastest, cheapest implementation of mission
- Community engagement: PAGs, conferences and outreach
  - Special sessions held at January and June AAS conferences
  - Next conference planned for November 17-22, 2014 in Pasadena  
<http://conference.ipac.caltech.edu/wfirs2014/>



# NRC Review



- Performed in January-February 2014 to determine if WFIRST-AFTA meets the WFIRST requirement in NWNH
- NRC recognized the larger telescope extends scientific reach and capabilities
- Highlights both rewards and risks of coronagraph program

**Finding 2-6: Introducing a technology development program onto a flagship mission creates significant mission risks resulting from the schedule uncertainties inherent in advancing low technical readiness level (TRL) hardware to flight readiness.**

**Finding 1-7: The WFIRST/AFTA coronagraph satisfies some aspects of the broader exoplanet technology program recommended by NWNH by developing and demonstrating advanced coronagraph starlight suppression techniques in space.**

**Recommendation 2-1: NASA should move aggressively to mature the coronagraph design and develop a credible cost, schedule, performance, and observing program so that its impact on the WFIRST mission can be determined. Upon completion ... an independent review**

- Investments in pre-phase A technology development and studies will **reduce these risks**
- Will evaluate descope options in parallel with the development of the baseline design



# WFIRST-AFTA Science



*complements  
Euclid*

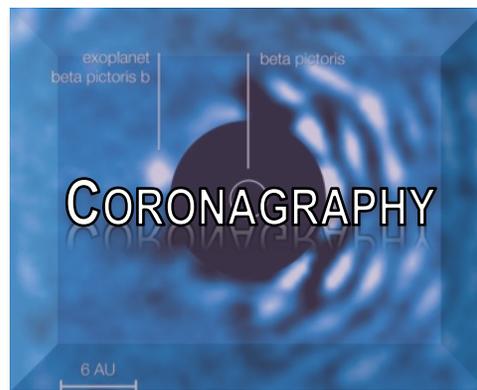
BARYON ACOUSTIC  
OSCILLATIONS

GRAVITATIONAL  
LENSING

LEGACY SCIENCE  
WITH SURVEYS

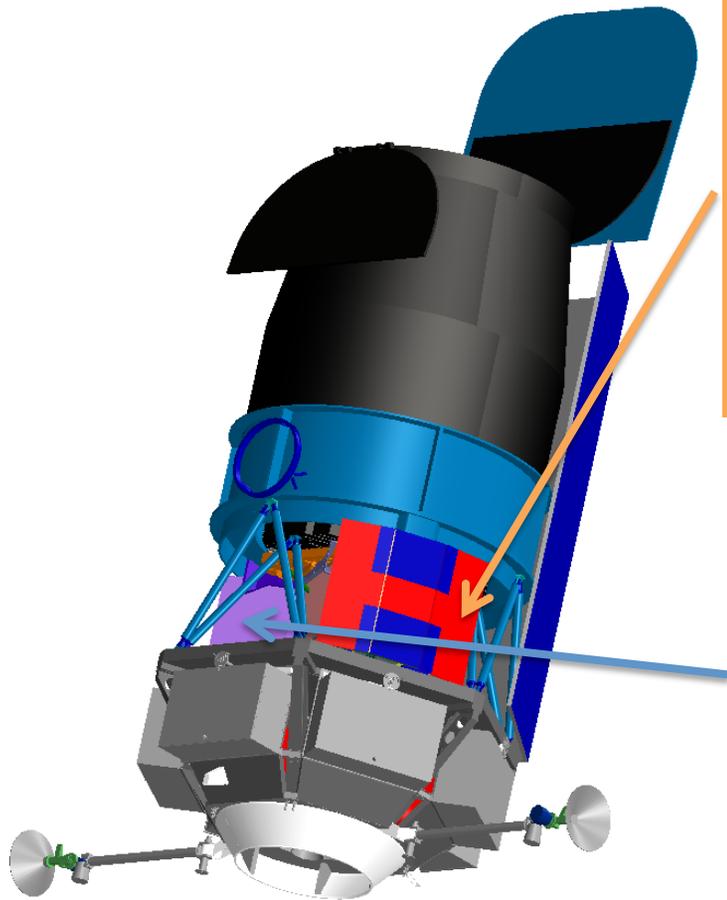
*complements  
LSST*

SUPERNOVAE



*continues  
Great  
Observatory  
legacy*





## 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<sup>2</sup> 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



# The Coronagraph is Cost Effective



- Coronagraph takes full advantage of WFIRST-AFTA 2.4 m telescope to enable revolutionary exoplanet science.
- Extra cost of coronagraph is \$270M including accommodations & extra year of operations
- Coronagraph science fits in WFIRST tripod: dark energy, exoplanets, community surveys
- Addresses NWNH recommendation for investment in direct imaging technology
- Coronagraph addresses NWNH science questions through detection and characterization of exoplanets unreachable from the ground.
- ExoPAG endorsed WFIRST-AFTA coronagraph



# AFTA Addresses 17 of 20 Key Science Questions Ripe for Answering Identified by NWNH



## Frontiers of Knowledge

- *Why is the universe accelerating?*
- *What is the dark matter?*
- *What are the properties of neutrinos?*
- *What controls the mass, radius and spin of compact stellar remnants?*

## Understanding our Origins

- *How did the universe begin?*
- *What were the first objects to light up the universe, and when did they do it?*
- *How do cosmic structures form and evolve?*
- *What are the connections between dark and luminous matter?*
- *What is the fossil record of galaxy assembly from the first stars to the present?*
- *How do stars form?*
- *How do circumstellar disks evolve and form planetary systems?*

## Cosmic Order: Exoplanets

- *How diverse are planetary systems?*
- *Do habitable worlds exist around other stars, and can we identify the telltale signs of life on an exoplanet?*

## Cosmic Order: Stars, Galaxies, Black Holes

- *What controls the mass-energy-chemical cycles within galaxies?*
- *How do the lives of massive stars end?*
- *What are the progenitors of Type Ia supernovae and how do they explode?*
- *How do baryons cycle in and out of galaxies, and what do they do while they are there?*
- *How do rotation and magnetic fields affect stars?*
- *What are the flows of matter and energy in the circumgalactic medium?*
- *How do black holes grow, radiate, and influence their surroundings?*



# Community Members that Submitted 1-page Descriptions of Potential GO Science Programs in the 2013 SDT Report





# WFIRST-AFTA vs Hubble



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



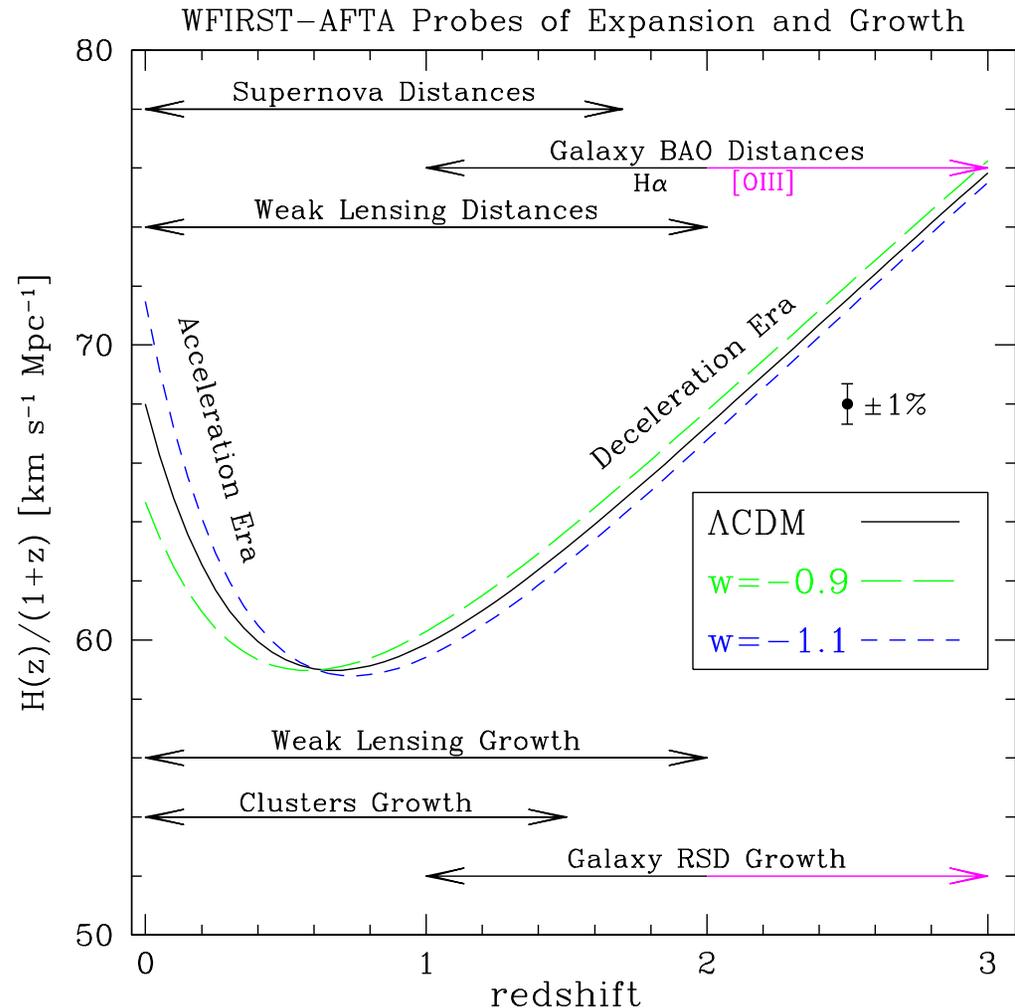
WFIRST-AFTA Deep Field  
>1,000,000 galaxies in each image



# 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**



# WFIRST-AFTA & Euclid Complementary for Dark Energy



## WFIRST-AFTA

**Deep Infrared Survey** (2400 deg<sup>2</sup>)

Lensing

- High Resolution (2.5x the Euclid number density of galaxies)
- Galaxy shapes in IR
- 5 lensing power spectra

Supernovae:

- High quality IFU spectra of >2000 SN

Redshift survey

- High number density of galaxies
- Redshift range extends to  $z = 3$

## Euclid

**Wide Optical and Shallow Infrared Survey** (15000 deg<sup>2</sup>)

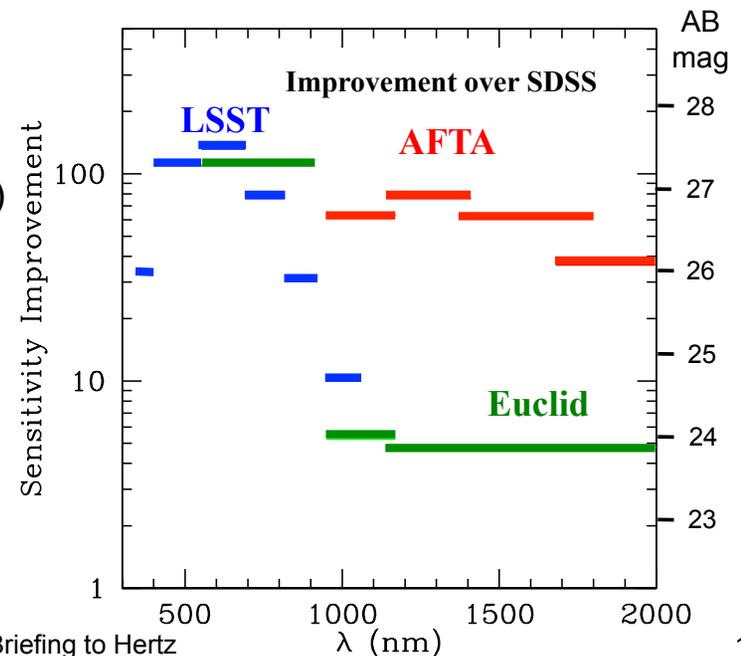
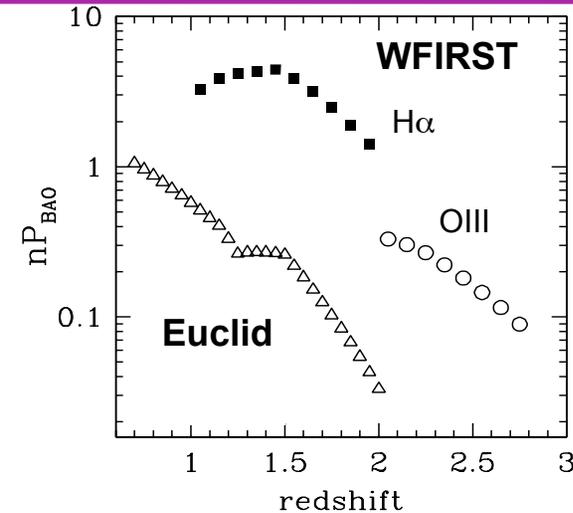
Lensing:

- Lower Resolution
- Galaxy shapes in optical
- 1 lensing power spectrum

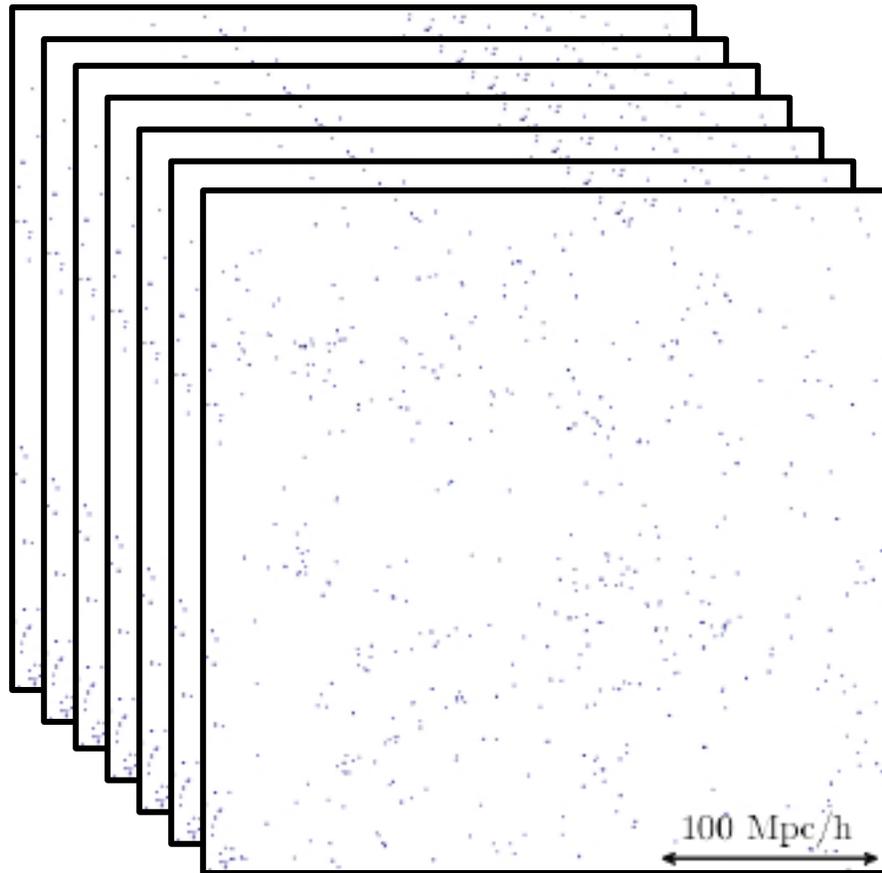
No supernova program

Redshift survey:

- Low number density of galaxies
- Redshift range  $z = 0.7 - 2$



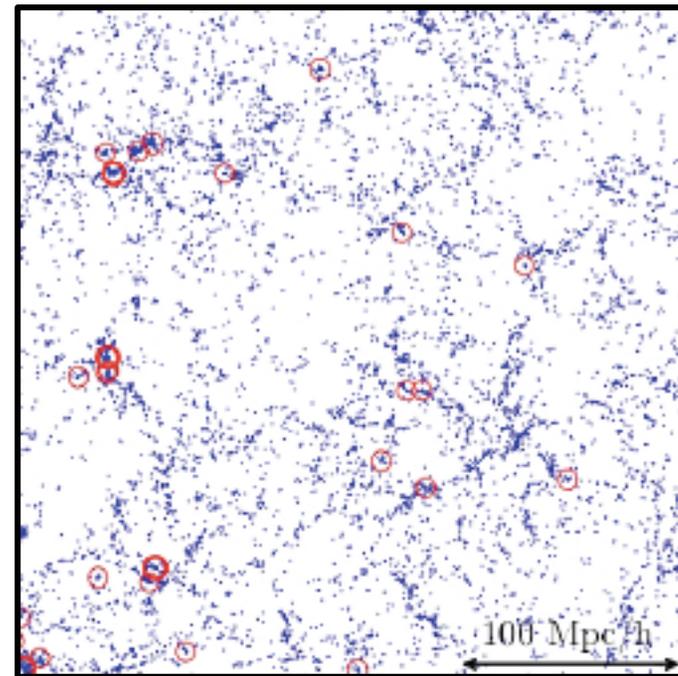
# Detailed 3D Map of Large Scale Structure at $z = 1-2$



**Euclid**

**15,000 deg<sup>2</sup> @ 1700 gal/deg<sup>2</sup>**

Large scale structure simulation showing 0.1% of the total WFIRST-AFTA Galaxy Redshift Survey Volume



**WFIRST**

**2,400 deg<sup>2</sup> @ 12,600 gal/deg<sup>2</sup>**

*Large scale structure simulations from 2013 SDT Report – courtesy of Ying Zu*

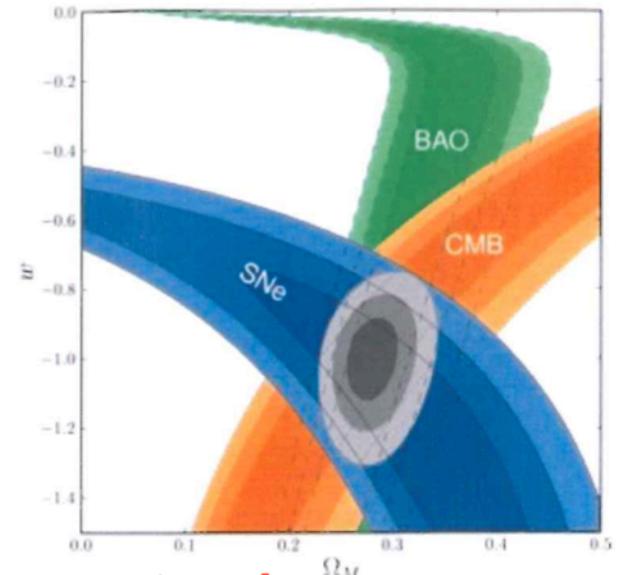
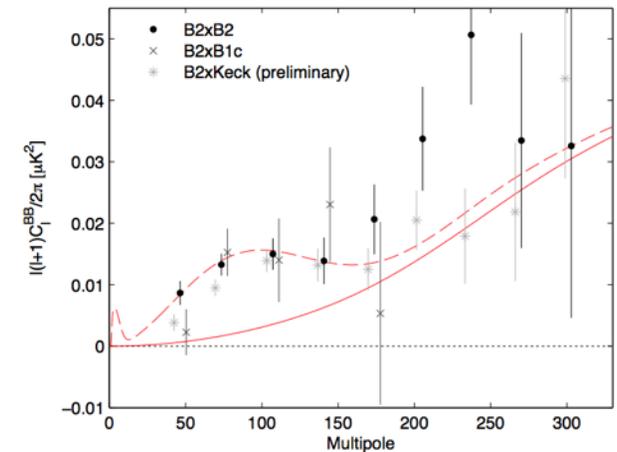
*Thin and thick red circles mark clusters with masses exceeding  $5 \times 10^{13} M_{Sun}$  and  $10^{14} M_{Sun}$ , respectively*



# Lessons from BICEP2 for the WFIRST-AFTA Dark Energy Program



- Nature is full of surprises!
  - No strong theory guidance on value of  $r$ . Factors of 10 improvement matter. Analogous to dark energy.
- Systematics matter
- Importance of multiple independent observations
- Curvature scale could be just “beyond the horizon”
  - High gravity wave signal + large scale CMB anisotropies hint at action near horizon scale. Precise curvature measurements important.
- Design of a dark energy program:
  - Multiple analysis methodologies and statistics used in each probe
  - Multiple probes of DE (SN, WL, GRS)
  - Synergistic with other elements of DE program (LSST, Euclid)
  - Combining data sets is key to systematics reduction.
  - Supernovae & BAO measure expansion history
  - Weak Lensing & RSD measure growth of structure.
  - Comparing the two provides a check on GR

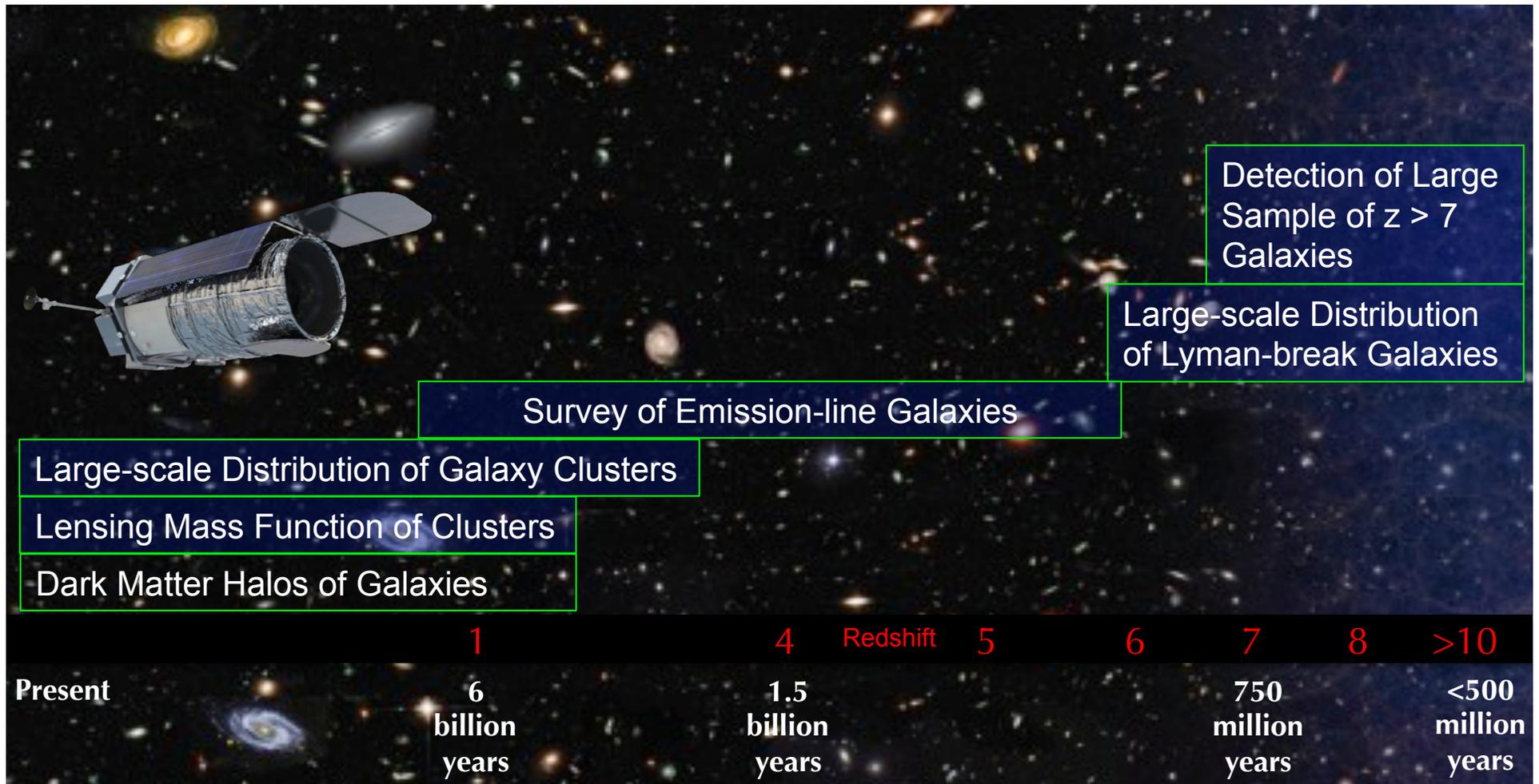




# WFIRST-AFTA: A Unique Probe of Cosmic Structure Formation History



Using Observations from the High Latitude Survey and GO Programs

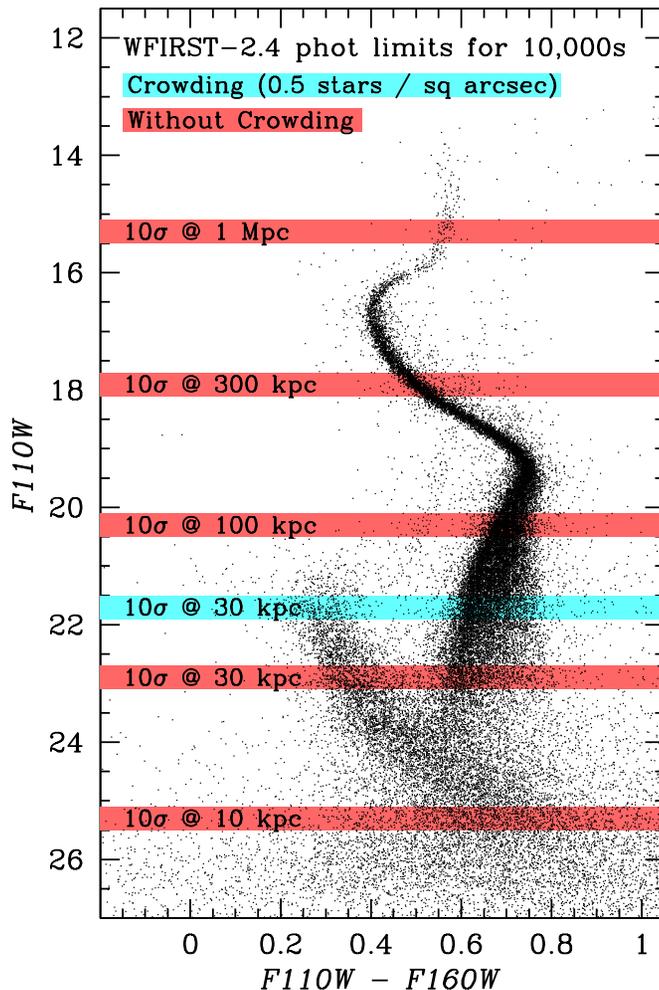




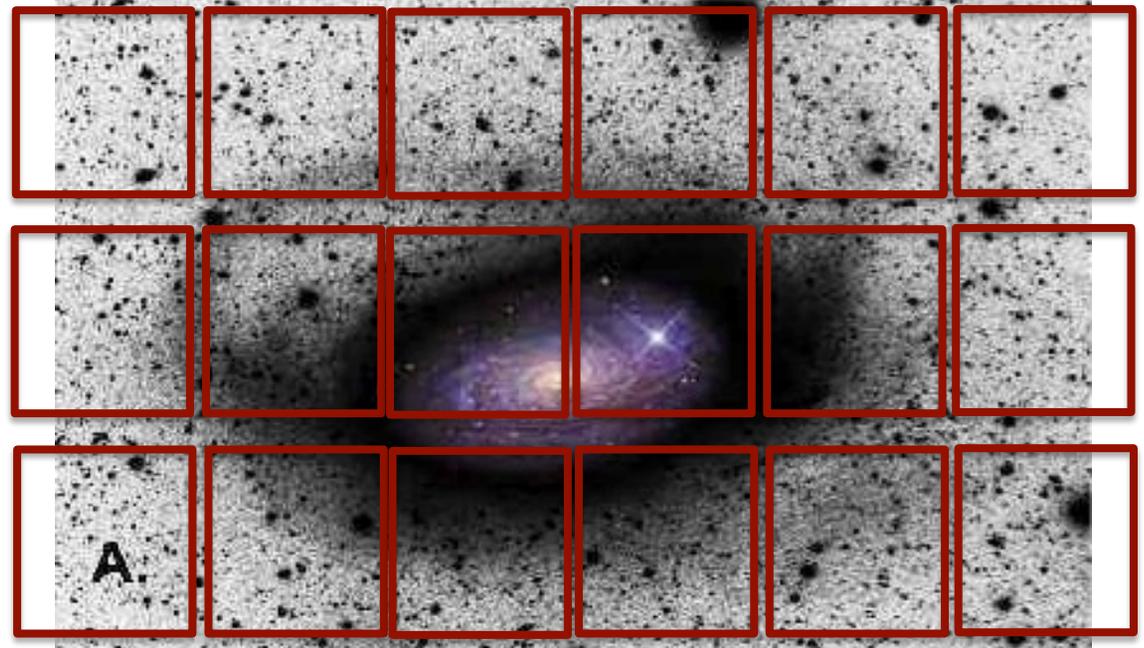
# WFIRST-AFTA – A Unique Probe of Stellar Populations and Nearby Galaxies



Resolve and characterize stellar pops out to large distances (47 Tuc and SMC - Kalirai et al. 2012)



Ultra-deep imaging of galaxy halos (M63 - Martinez-Delgado et al. 2010)





# WFIRST-AFTA Exoplanet Science



The combination of microlensing and direct imaging will dramatically expand our knowledge of other solar systems and will provide a first glimpse at the planetary families of our nearest neighbors.

## Microlensing Survey

Monitor 200 million Galactic bulge stars every 15 minutes for 1.2 years

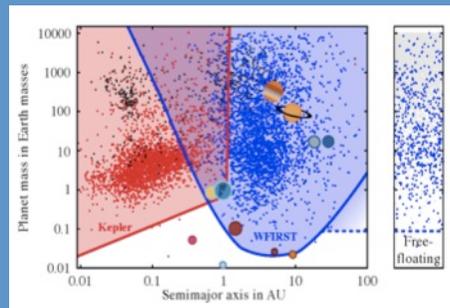
3000 cold exoplanets  
300 Earth-mass planets  
40 Mars-mass or smaller planets  
40 free-floating Earth-mass planets

## High Contrast Imaging

Survey up to 200 nearby stars for planets and debris disks at contrast levels of  $10^{-9}$  on angular scales  $> 0.1''$   
R=70 spectra and polarization between 400-1000 nm

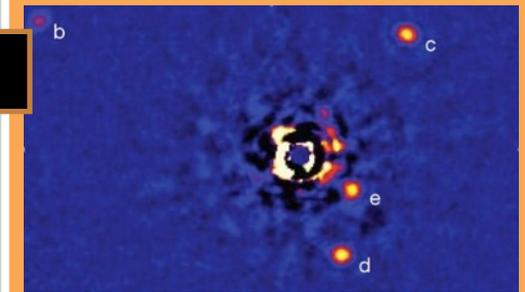
Detailed characterization of up to a dozen giant planets.  
Discovery and characterization of several Neptunes  
Detection of massive debris disks.

## Complete the Exoplanet Census



- How do planetary systems form and evolve?
- What are the constituents and dominant physical processes in planetary atmospheres?
- What kinds of unexpected systems inhabit the outer regions of planetary systems?
- What are the masses, compositions, and structure of nearby circumstellar disks?
- Do small planets in the habitable zone have heavy hydrogen/helium atmospheres?

## Discover and Characterize Nearby Worlds



# Toward the “Pale Blue Dot”

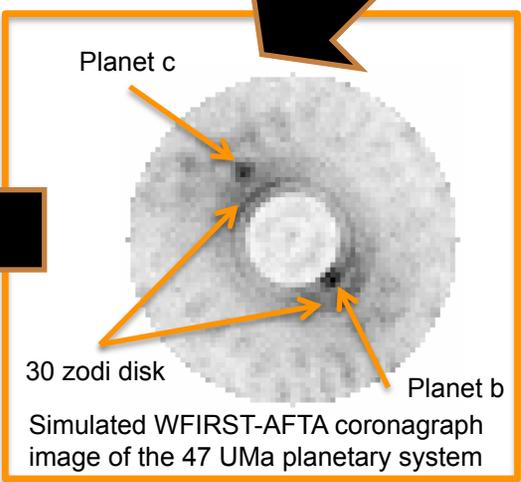
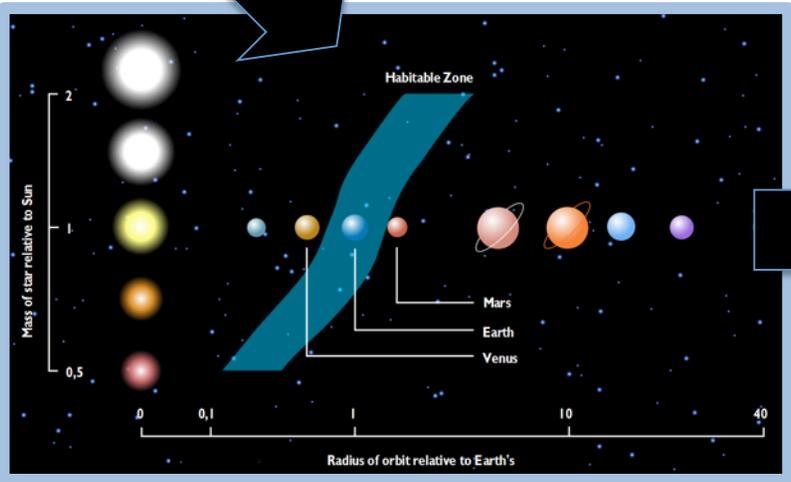
WFIRST will lay the foundation for a future flagship direct imaging mission capable of detection and characterization of Earth-like planets.

## Microlensing Survey

- Inventory the outer parts of planetary systems, potentially the source of the water for habitable planets.
- Quantify the frequency of solar systems like our own.
- Confirm and improve Kepler’s estimate of the frequency of potentially habitable planets.
- When combined with Kepler, provide statistical constraints on the densities and heavy atmospheres of potentially habitable planets.

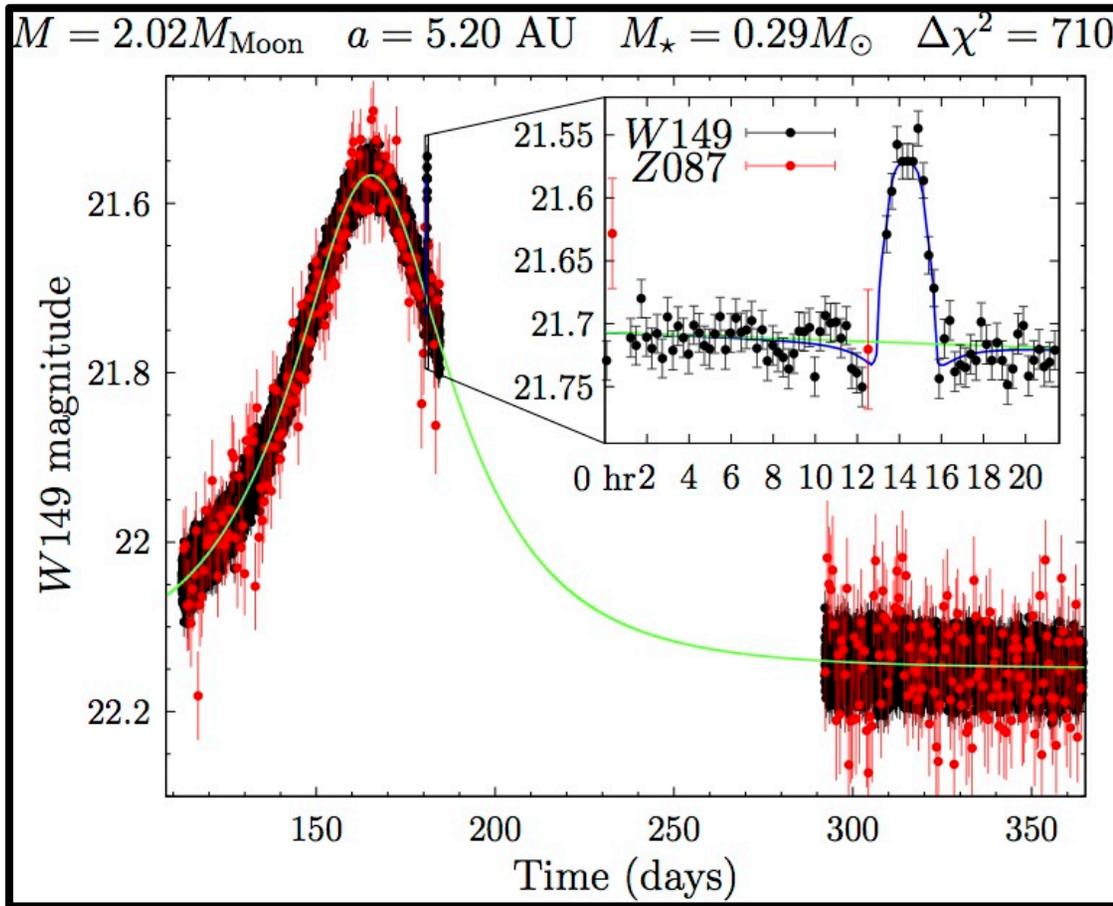
## High Contrast Imaging

- Provide the first direct images of planets around our nearest neighbors similar to our own giant planets.
- Provide important insights about the physics of planetary atmospheres through comparative planetology.
- Assay the population of massive debris disks that will serve as sources of noise and confusion for a flagship mission.
- Develop crucial technologies for a future mission, and provide practical demonstration of these technologies *in flight*.

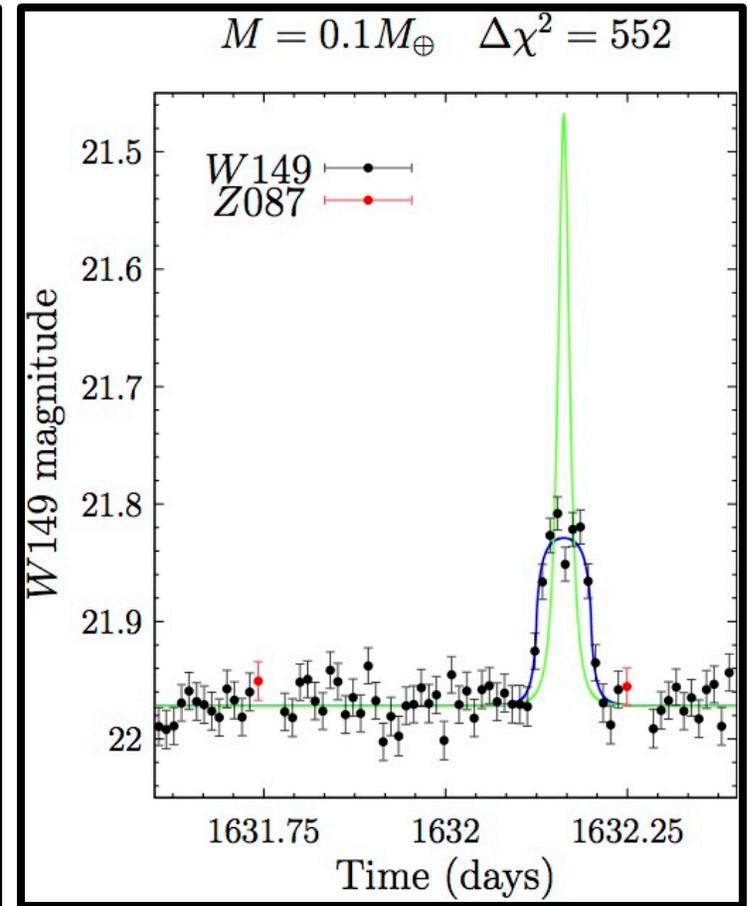




# Exquisite Sensitivity to Cold, Low Mass, and Free Floating Planets



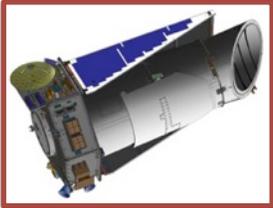
2 × Mass of the Moon @ 5.2 AU  
(~27 sigma)



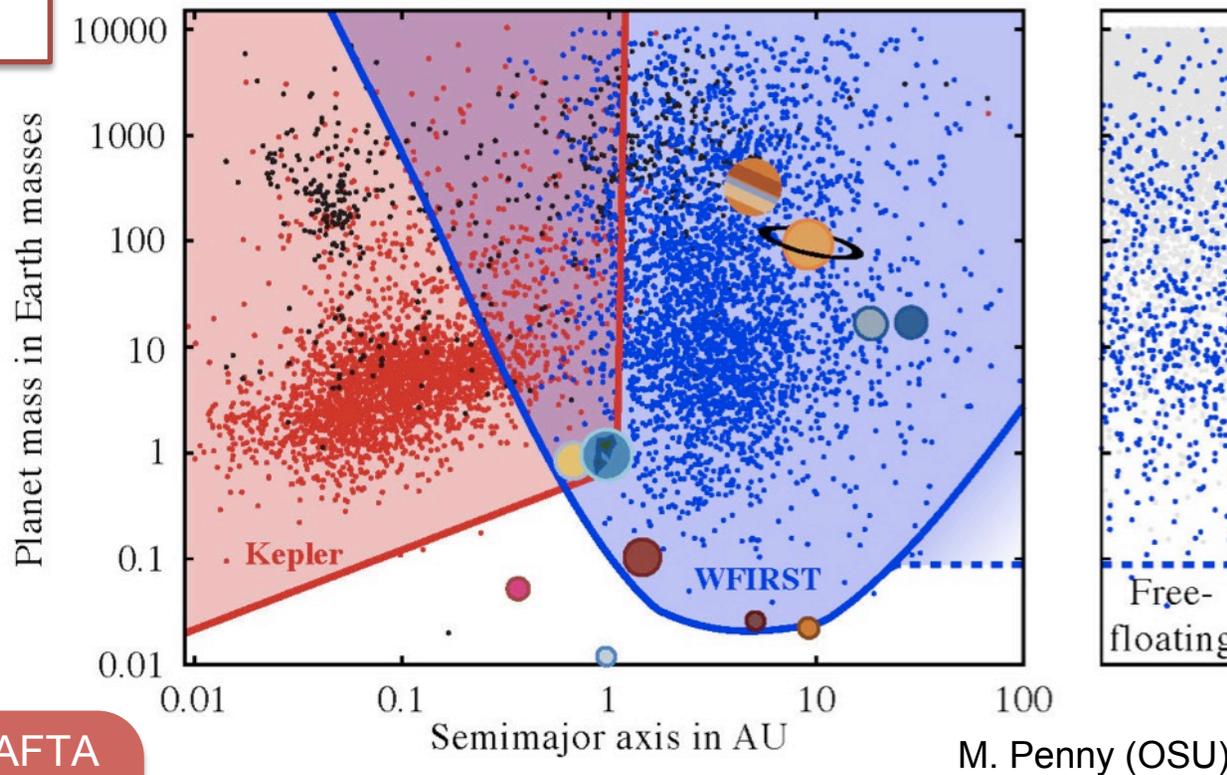
Free floating Mars  
(~23 sigma)



# Completing the Statistical Census of Exoplanets



Combined with space-based transit surveys, WFIRST-AFTA completes the statistical census of planetary systems in the Galaxy.



WFIRST-AFTA perfectly complements Kepler, TESS, and PLATO.

- ~3000 planet detections.
- 300 with Earth mass and below.
- Hundreds of free-floating planets.

WFIRST-AFTA is more capable than the IDRM design

- 1.6 times larger planet yields
- Factor of two better sensitivity to Earth-mass planets.
- Improved ability to measure masses and distances to the microlensing host stars.



## Coronagraph Responds to NWNH Goals



- **Observes and characterizes** a dozen radial velocity planets.
- **Discovers and characterizes** ice and gas giants.
- Provides crucial information on the **physics of planetary atmospheres**.
- Measures the **exozodiacal dust** level about nearby stars.
- Images **circumstellar disks** for signposts of planet interactions and indications of planetary system formation.
- **Matures many critical coronagraph technologies** that will be needed for a future terrestrial planet imaging mission.

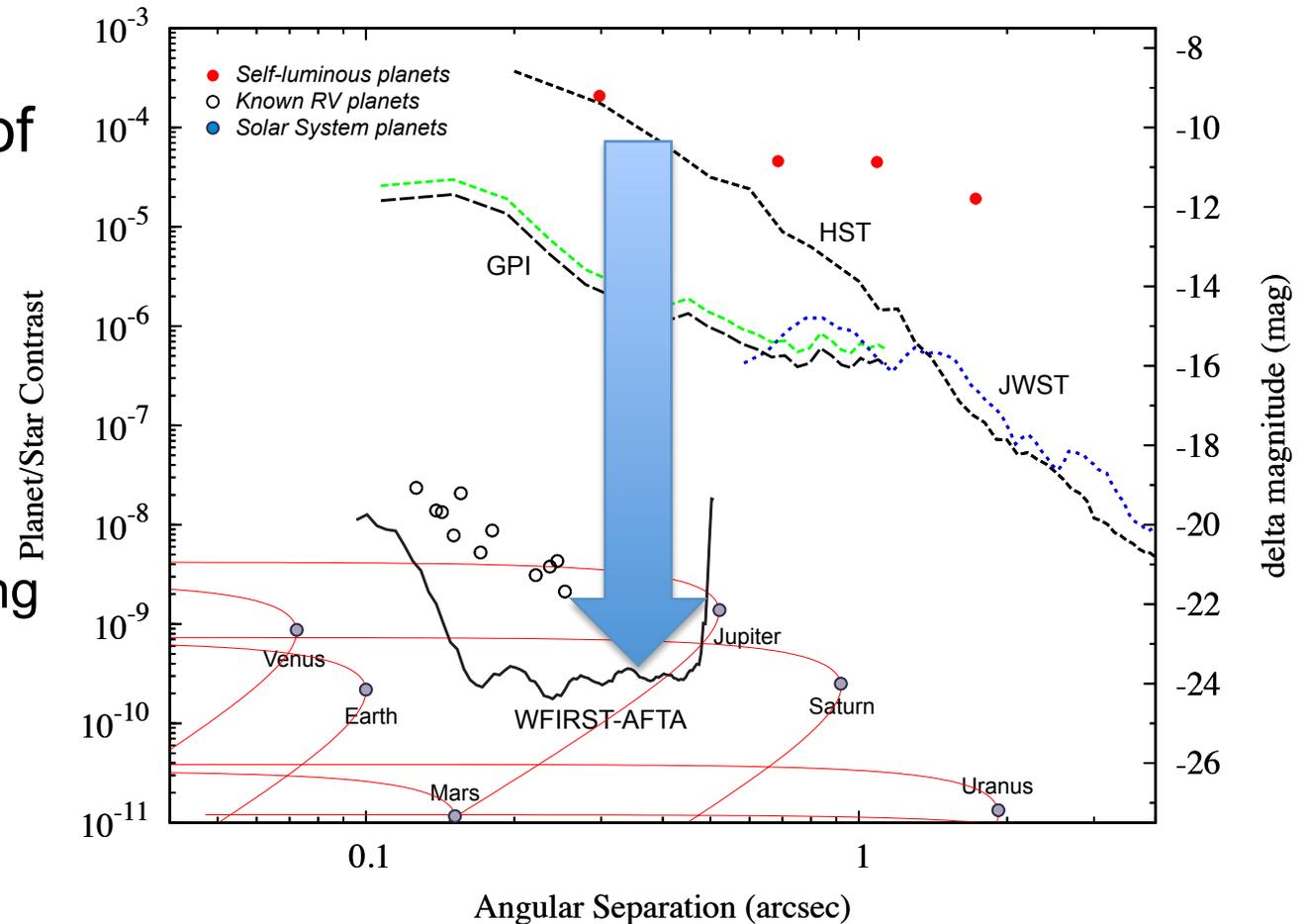
Without new requirements on observatory that could impact risk, cost, or schedule (“use as-is”).



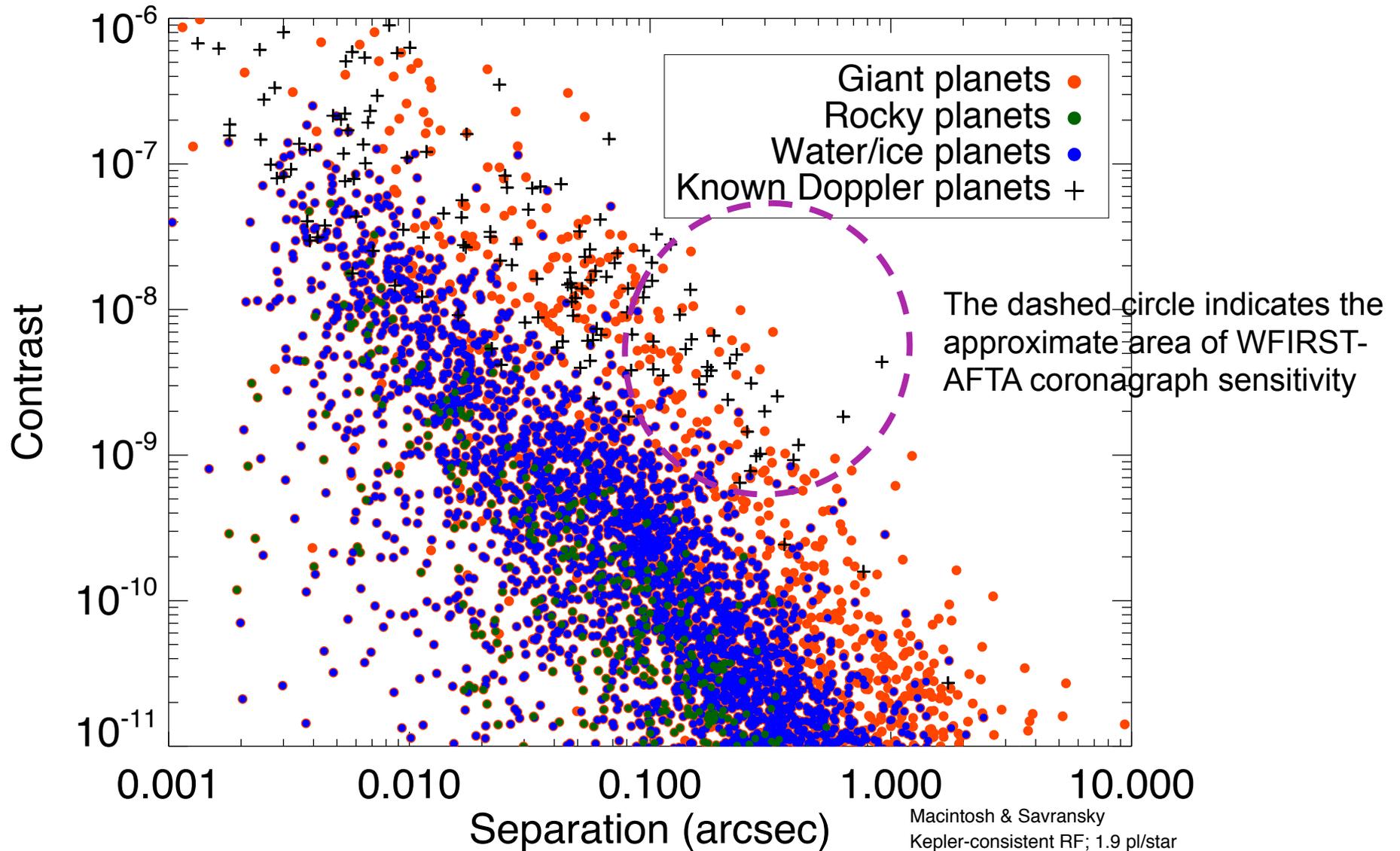
# WFIRST-AFTA Brings Humanity Closer to Characterizing Earths



- WFIRST-AFTA advances many of the key elements needed for a coronagraph to image Earth
  - ✓ Coronagraph
  - ✓ Wavefront sensing & control
  - ✓ Detectors
  - ✓ Algorithms



# Simulated Planets within 30 pc





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# Science Team Selection Process



# Background



- NASA will have an NRA or AO for participation in WFIRST-AFTA at the start of Phase A (~ 2016 or 17)
- Coronagraph and/or wide-field IR imager may be selected competitively or may be provided by NASA. If competitive, those teams would also include scientific investigations.
- Other scientific investigations selected will be selected competitively
  - Large teams with PI, Co-I's and collaborators
  - Interdisciplinary Scientists
  - EPO Scientist
- Paul Hertz has asked the SDT for suggestions on the make-up of the scientific investigations



# Mission Science Team



Typically 15-20 members

- Project Science team (from NASA Centers)
  - Project, Instrument, Telescope, and Detector Scientists
- Science center leads
- PIs of selected investigations / instruments
- Interdisciplinary scientists (IDSs)
- EPO scientist
- Program Scientist (from HQ, ex-officio)
- Foreign representatives



# WFIRST-AFTA Options

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- If instruments are provided by NASA, scientific investigations and interdisciplinary scientists would be selected
- Assume 8 investigations and 3 IDSs
- Option A:
  - 4 investigations for IR survey
  - 4 investigations for exoplanets
- Option B:
  - 1 investigation **each** for WL, BAO, SNe
  - 1 investigation for non-DE survey science
  - 1 or 2 investigations for microlensing
  - 1 or 2 investigations for exoplanet coronagraph
  - 1 or 2 investigations for debris disks



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# Data Rights Considerations



# Background



- 
- Rules for data rights will be determined by NASA HQ prior to science team selections
  - Important for observatory builders, science teams and GIs
  - Different missions have different rules, dependent on field of view, era, and advocacy of particular groups when the mission was formulated
  - Trend is strongly toward "open data" policies



# WFIRST-AFTA Considerations



- Standard of 1 year proprietary time for all data is probably no longer acceptable to NASA or the community
- WFIRST-AFTA wide field imager has wide FoV that makes proprietary data difficult
- Different science areas for WFIRST-AFTA have different data needs, making any proprietary rules complex and likely unworkable.
- An open data policy such as that of LSST and Fermi LAT may be the natural fit for most or all of the WFIRST-AFTA data
- Rapid public access to broad-use survey data has been demonstrated to maximize scientific output.



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# Observatory Overview



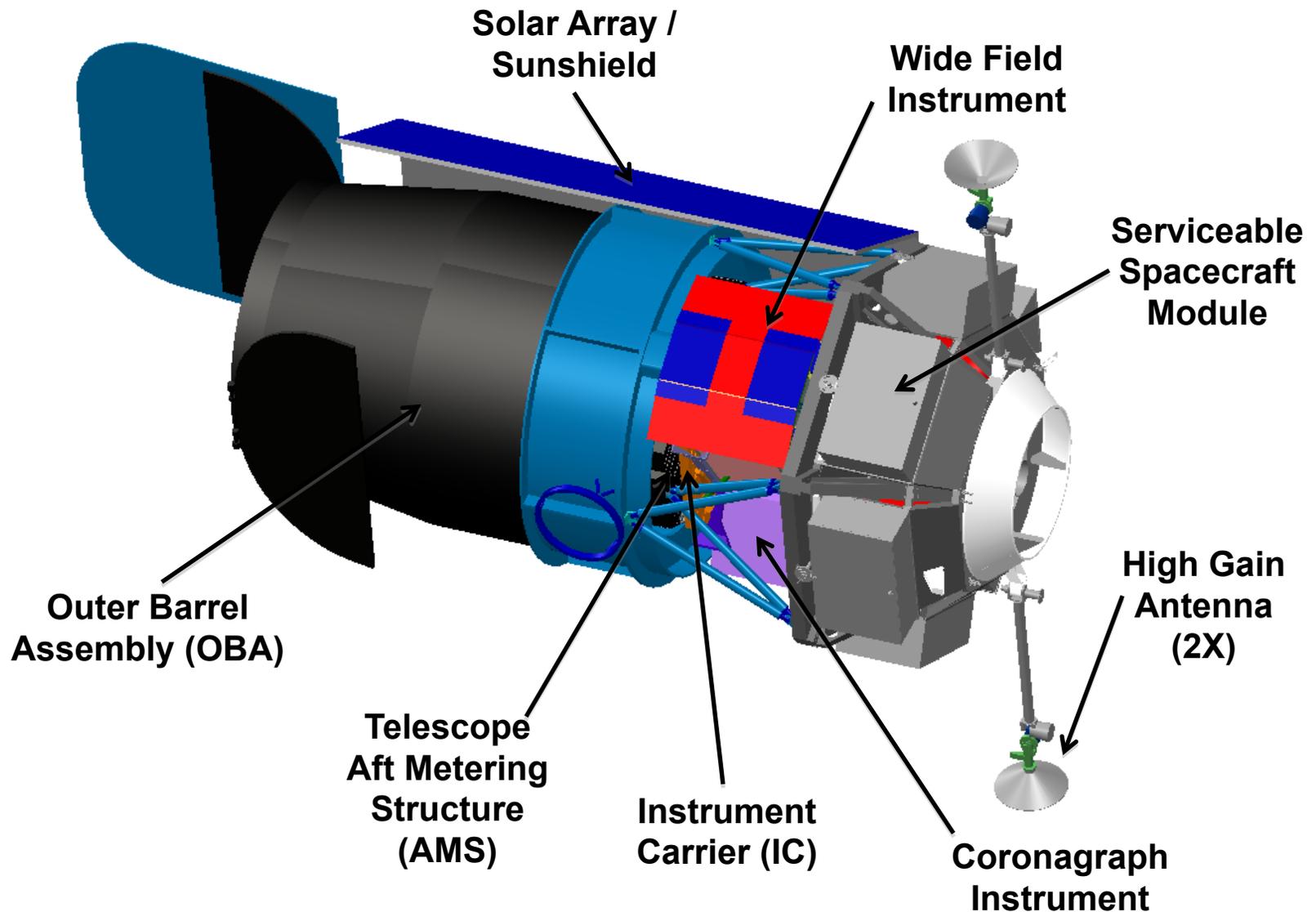
# WFIRST-AFTA Observatory Concept



## Key Features

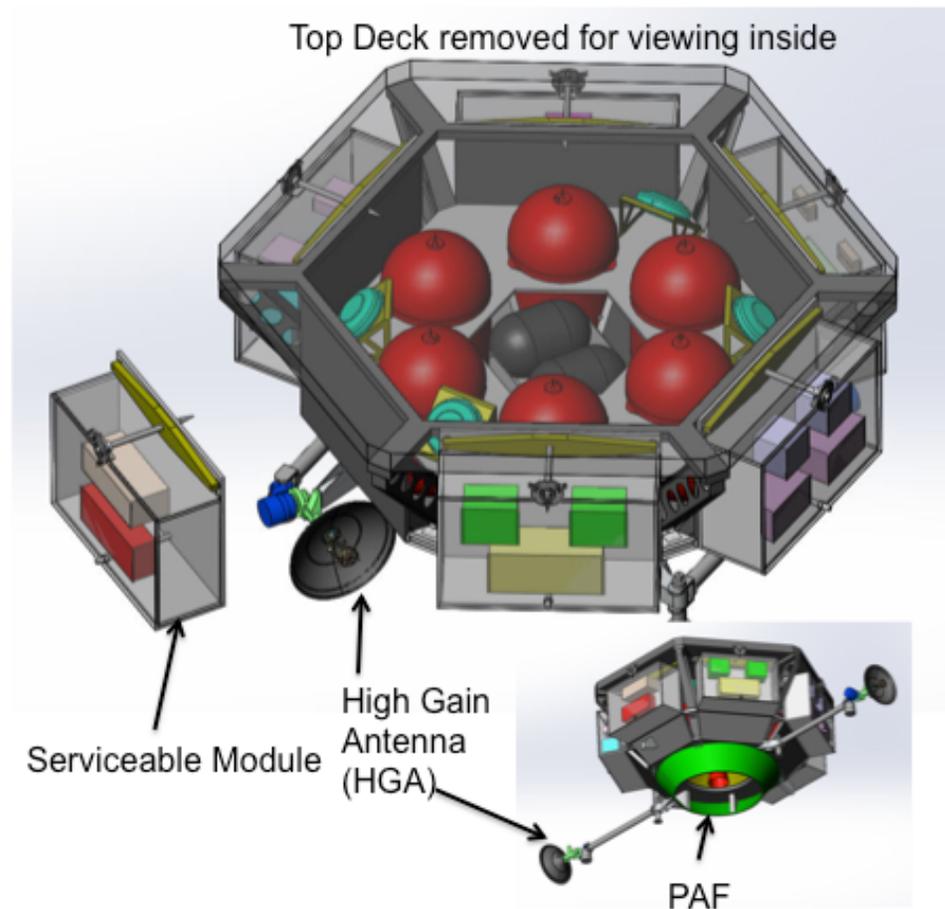
- **Telescope** – 2.4m aperture primary
- **Instruments**
  - Single channel wide field instrument, 18 4k x 4k HgCdTe detectors; integral field unit spectrometer incorporated in wide field for SNe observing
  - Internal coronagraph with integral field spectrometer
- **Overall Mass** – ~6500 kg (CBE) 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



# 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



WFIRST-AFTA serviceable bus concept



# Mass Summary



	CBE Mass (kg)	Cont. (%)	CBE + Cont. (kg)
Wide Field Instrument	421	30	547
Coronagraph Instrument	111	35	150
Instrument Carrier	208	30	270
Telescope	1595	11	1773
Spacecraft	1528	30	1987
Observatory (dry)	3863	22	4727
Propellant	2618		3196
Observatory (wet)	6481		7923
Atlas V 551 Lift Capacity			8530

Mass are in process for the current design cycle



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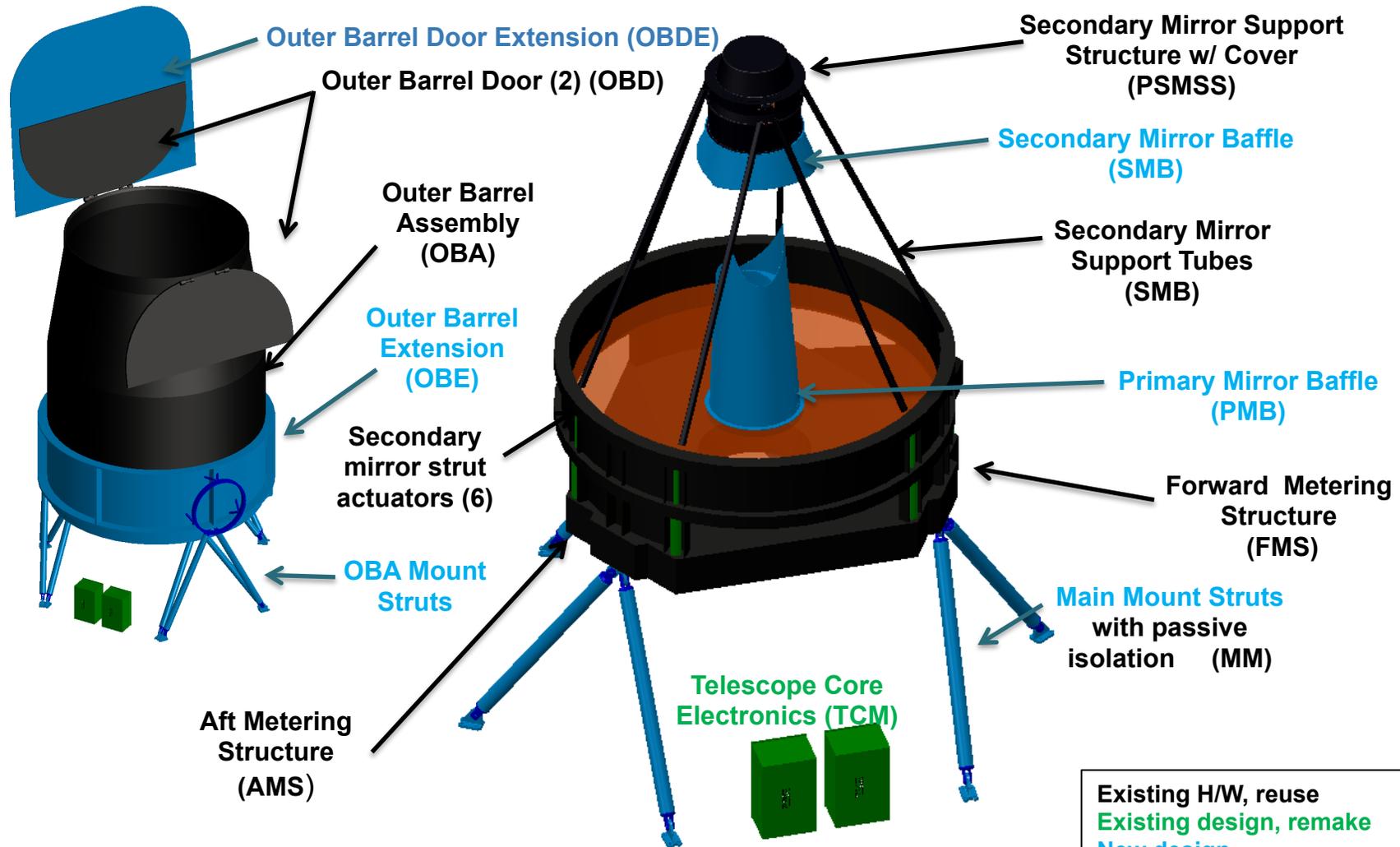
# Telescope



# Telescope Overview

- Two, 2.4 m, two-mirror telescopes provided to NASA. Built by ITT/Exelis
  - Ultra Low Expansion (ULE®) glass mirrors
  - All composite structure
  - Secondary mirror actuators provide 6 degree of freedom control
  - Additional secondary mirror fine focus actuator
  - Active thermal control of structure
  - Designed for operation at room temperature (293 K) with survival temperature of 277 K
  - Outer barrel includes recloseable door
  - Passive damping at the spacecraft interface
- Some telescope modifications are required, but focus is on minimizing telescope cost/risk

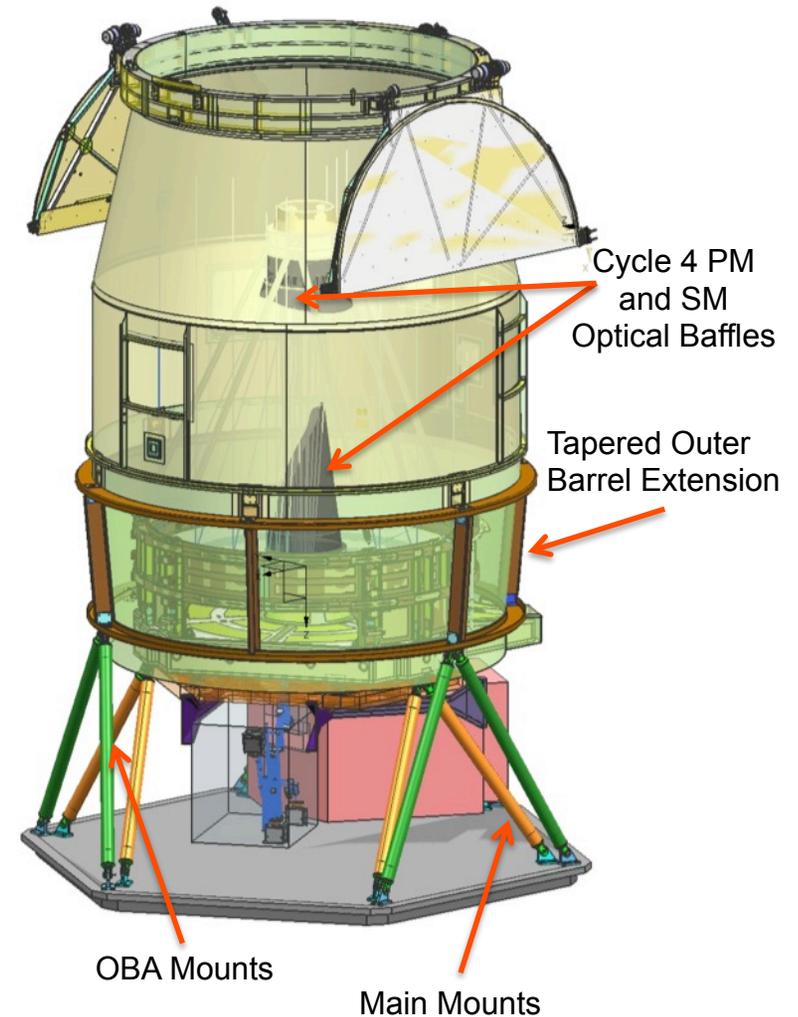
# Telescope Reuse



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

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

- Some additions/modifications required for WFIRST:
  - Small prescription change
    - Refigure and recoat primary mirror
    - Regrind and recoat secondary mirror
  - WFIRST specific PM and SM baffles
  - Outer Barrel Extension for stray light
  - Main Mounts (slightly longer than original)
  - OBA Mounts
  - Telescope electronics not available, will replace with Exelis existing product line
  - Telescope operating temperature lowered to 270K. Plan is in process to validate operation at this temperature.





# Evaluation of Telescope for Operation at Colder Temperatures



- Original telescope qualification temperature was just above the current baseline operating temperature of 270K
- Additionally, the SDT charter requires an assessment of extending the long wavelength cutoff of the wide field instrument to 2.4  $\mu\text{m}$ .
- **The NRC stated that WFIRST-AFTA fully achieves the Decadal science goals at 2.0  $\mu\text{m}$ .**
  - SDT and Project concur that 2.0  $\mu\text{m}$  will be the baseline for the final report.
- The Study Office is currently implementing a plan to evaluate the feasibility of operating the telescope at temperatures between 270 to 250 K.
- Plan activities completed to date
  - CTE measurements of existing composite laminate coupons at room temperature is complete. This verifies no change from original measurements.
  - CTE measurements of existing composite laminate coupons from room temperature down to 235K is complete. This provides properties for improved thermoelastic models.
- Ongoing and future activities
  - Mechanical properties testing of laminates, at room temperature, after thermal cycling to cold temp, is in progress.
  - Mechanical properties testing of laminates at cold temp, after thermal cycling, is in progress.
  - Adhesives characterization at cold temp temperature is planned for FY14.
  - Bond joint testing of laminates-to-laminates and laminates-to-metal joints is planned for FY14-15.



# Results of CTE testing

- ***As reported by ITT-Exelis:***
- “Representative samples for each of the 8 unique laminate types on the FOA were tested to determine room temperature CTE and CTE at the expected mission temperature. All samples were tested at room temperature to form a baseline to compare against historical measurements.”
- “The measured CTE for all laminates was the same as the measured CTE when originally fabricated within the test uncertainty.”
- “Strain was measured over the entire temperature range from room temperature to the expected nominal mission temperature so CTEs can be determined at any temperature within this range if desired. The CTE acceptance criteria range for each laminate is used as a basis for Monte Carlo analyses used to verify FOA optical performance.”
- “For 50 of 51 coupons, the measured CTE of the FOA laminates at the new mission temperature\* fell within this the original acceptance criteria range for the laminates as designed. This data along with the temperature dependent mechanical properties for the other materials in the FOA (metal, glass, adhesives) will allow the FOA performance predictions to be updated.”
- “The coupon that exceeded the design acceptance range was within 2%.”

*\* New mission temperature refers to the coldest temperature under consideration in the long wavelength extension study.*

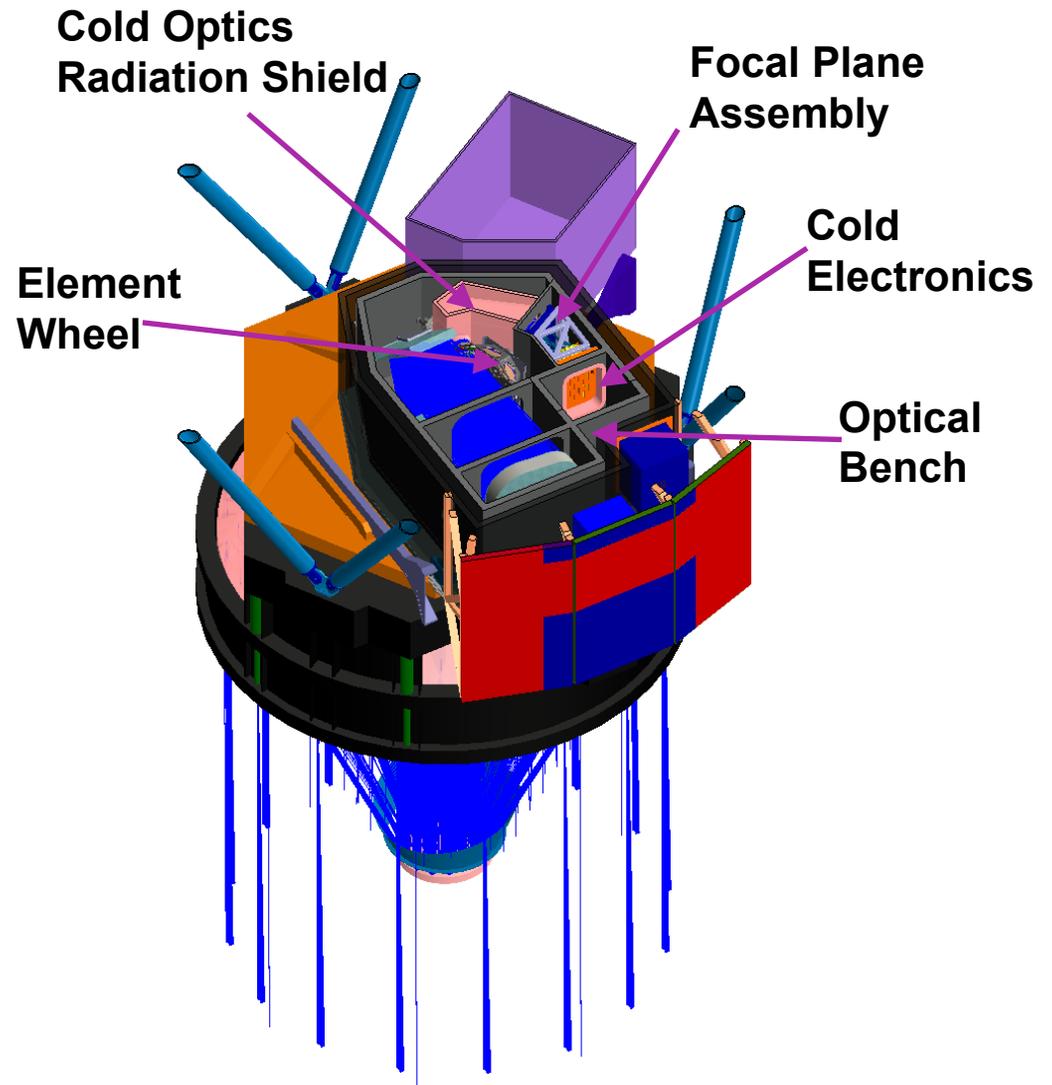


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# Wide-Field Instrument

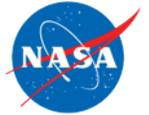
## Key Features

- 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  $\mu\text{m}$
  - 0.11 arc-sec plate scale
  - Grism used for GRS survey covers 1.35 – 1.95  $\mu\text{m}$  with R between 645 - 900
- IFU channel for SNe spectra, single HgCdTe detector covers 0.6 – 2.0  $\mu\text{m}$  with R~75
- Single element wheel for filters and grism



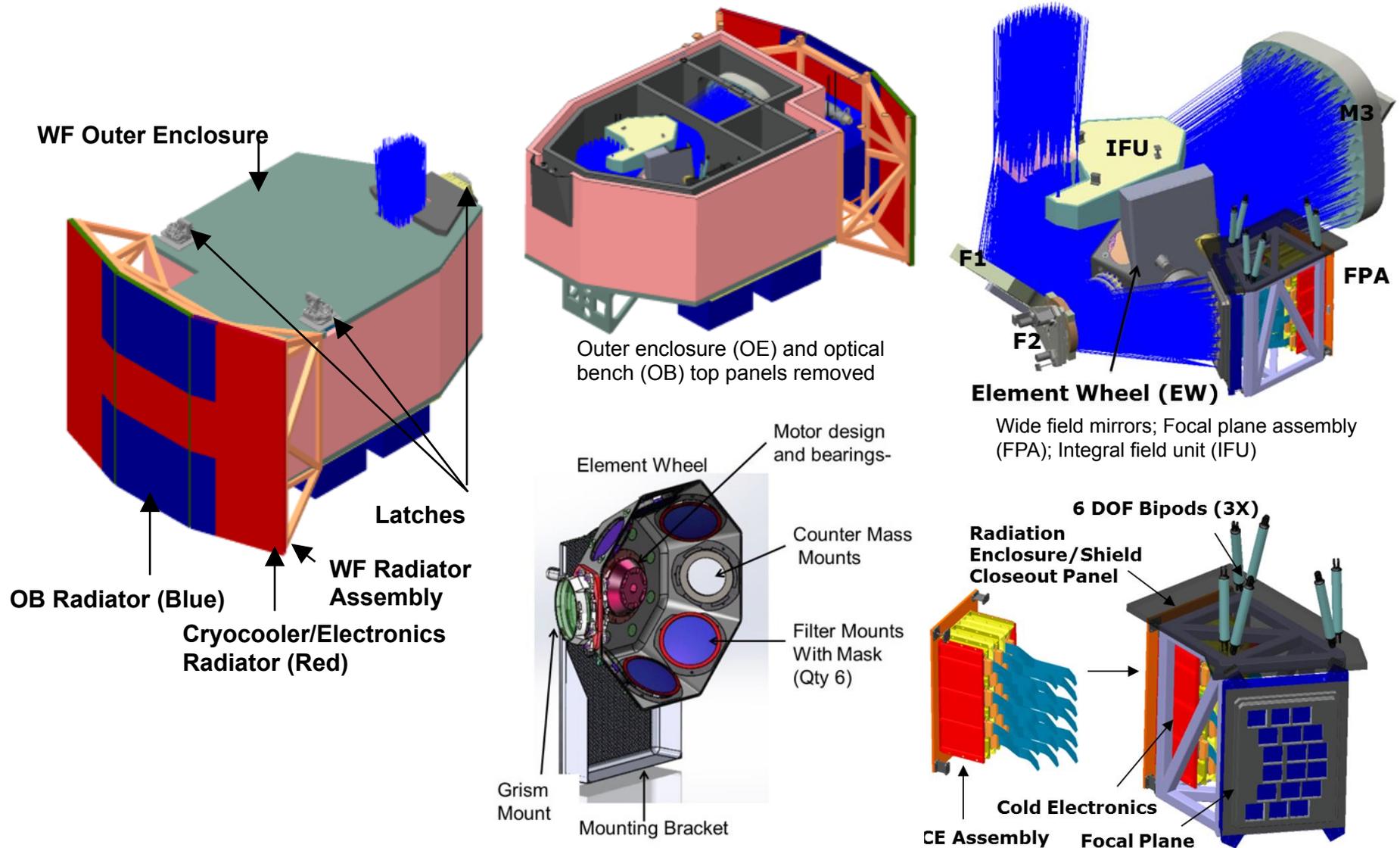


# Updates to Wide Field Instrument Design Since 2013 Report



- Telescope & wide field channel optical design is coaxial
  - Reduced fabrication and alignment risk by simplifying optics in instrument (tertiary mirror is a conic instead of anamorphic)
  - Field of view is arced rather than a rectangular array of 6x3 H4RG-10s; enables favorable optical interface to coronagraph
- IFU is repackaged, similar elements in a much smaller overall volume
  - Simplifies integration by enabling parallel build and integration with wide field channel
  - Relay closer to slicer and spectrograph, shorter relay path
- Grism assembly simplified; all fused silica, 3 elements, with simpler surfaces; 2 instead of previous 1 diffractive surface
- Electronics boxes are integrated with mechanical structure of instrument rather than remote on the spacecraft
  - Reduced wire count across serviceable interface

# Wide Field Instrument Layout and Major Subassemblies





# Engineering Development Activities



- Increased funding in FY14 is being used to reduce risk across the wide field instrument
- Focal plane: see Recent Developments section
- Grism: An engineering development unit of the grism is underway
  - Ultimate goal is to re-validate cold performance testing in NIR at flight temperature, after qualification vibration test
  - Initial progress includes
    - Demonstrating high (>90%) 1<sup>st</sup> order diffraction efficiency of visible-equivalent subscale (25mm square) diffractive structures
    - Demonstrating fabrication of glass surfaces in each of the three components (1 of 3 complete as of 4/28/14)
    - Athermalization of component mount designs over 300K fabrication to 170K operation range
- Tertiary mirror: Mount athermalization and architecture trade study in progress
- Element (filter and grism) wheel; Eight 12.5 cm elements, 170K
  - Planning has begun for an engineering development unit; goal is re-verifying cold operation after qualification vibration test





# IR Detector Development



- Currently building H4RG detectors with several variations in growth and processing to optimize the potential flight recipes.
  - Initial results indicate most variations meeting or are very close to performance targets for QE, dark current, noise, persistence, and intrapixel capacitance.
  - These devices have demonstrated that the technology is capable of producing the required levels of performance.
- Will downselect to one or two recipes this year and build lots of each to demonstrate scaling the selected design to full detectors and achieving these performance levels with reasonable yields (and thus costs).
- Current trend indicates that flight detectors could be fabricated well in front of need date.

**Initial results of recent testing in backup slides**

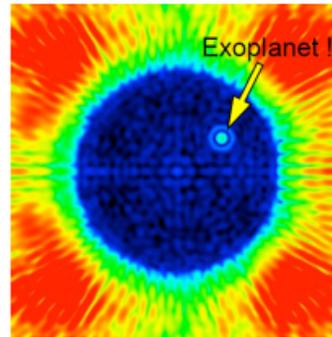


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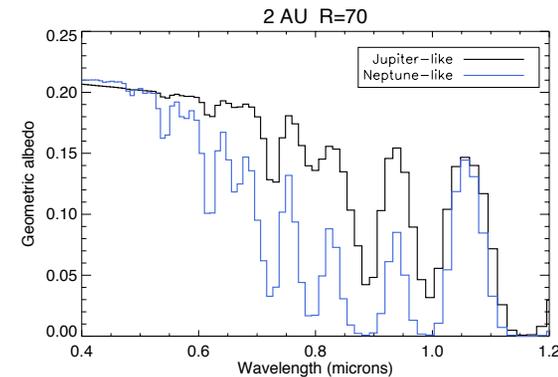
# Coronagraph Instrument



Coronagraph Architecture:  
 Primary: Occulting Mask (OMC)  
 Backup: Phase Induced Amplitude Apodization (PIAA)



Exoplanet Direct Imaging

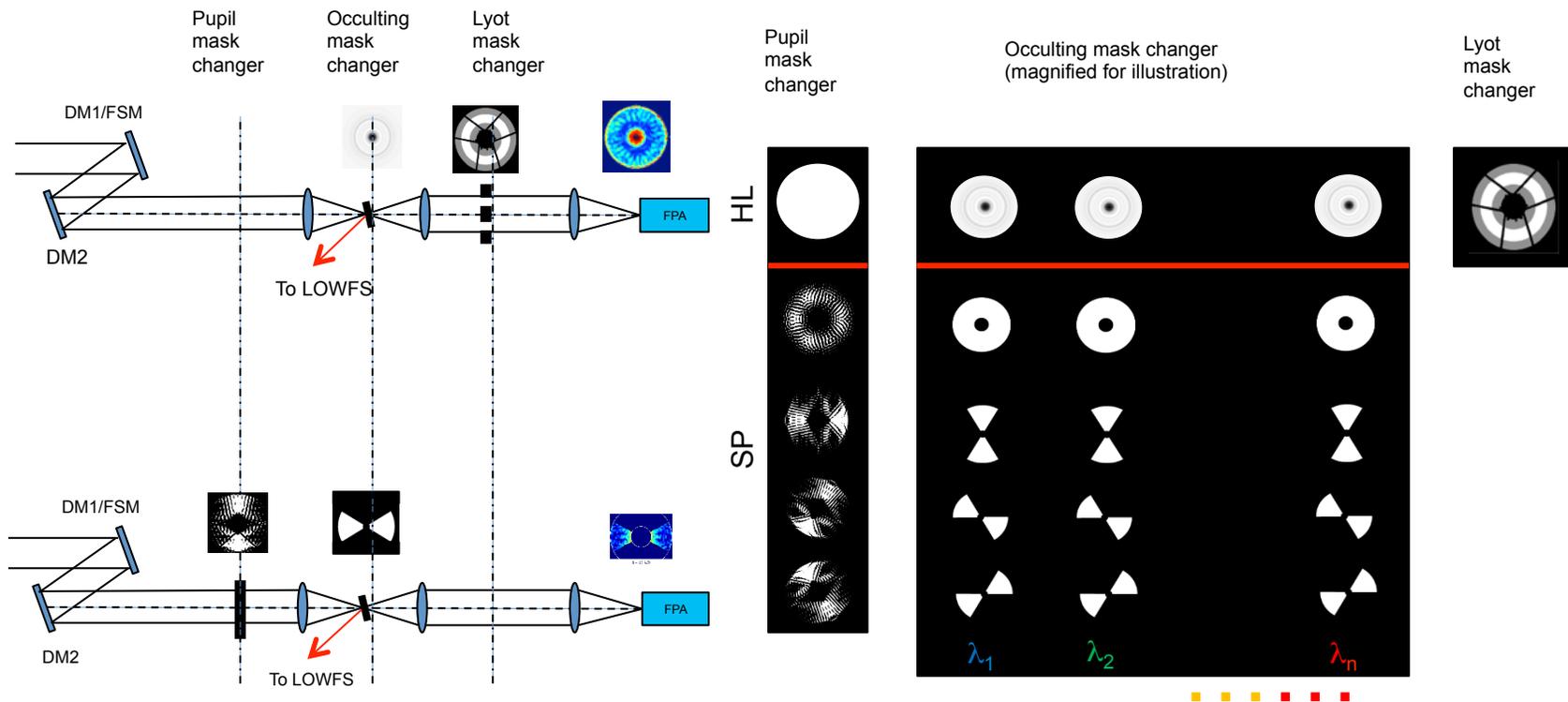


Exoplanet Spectroscopy

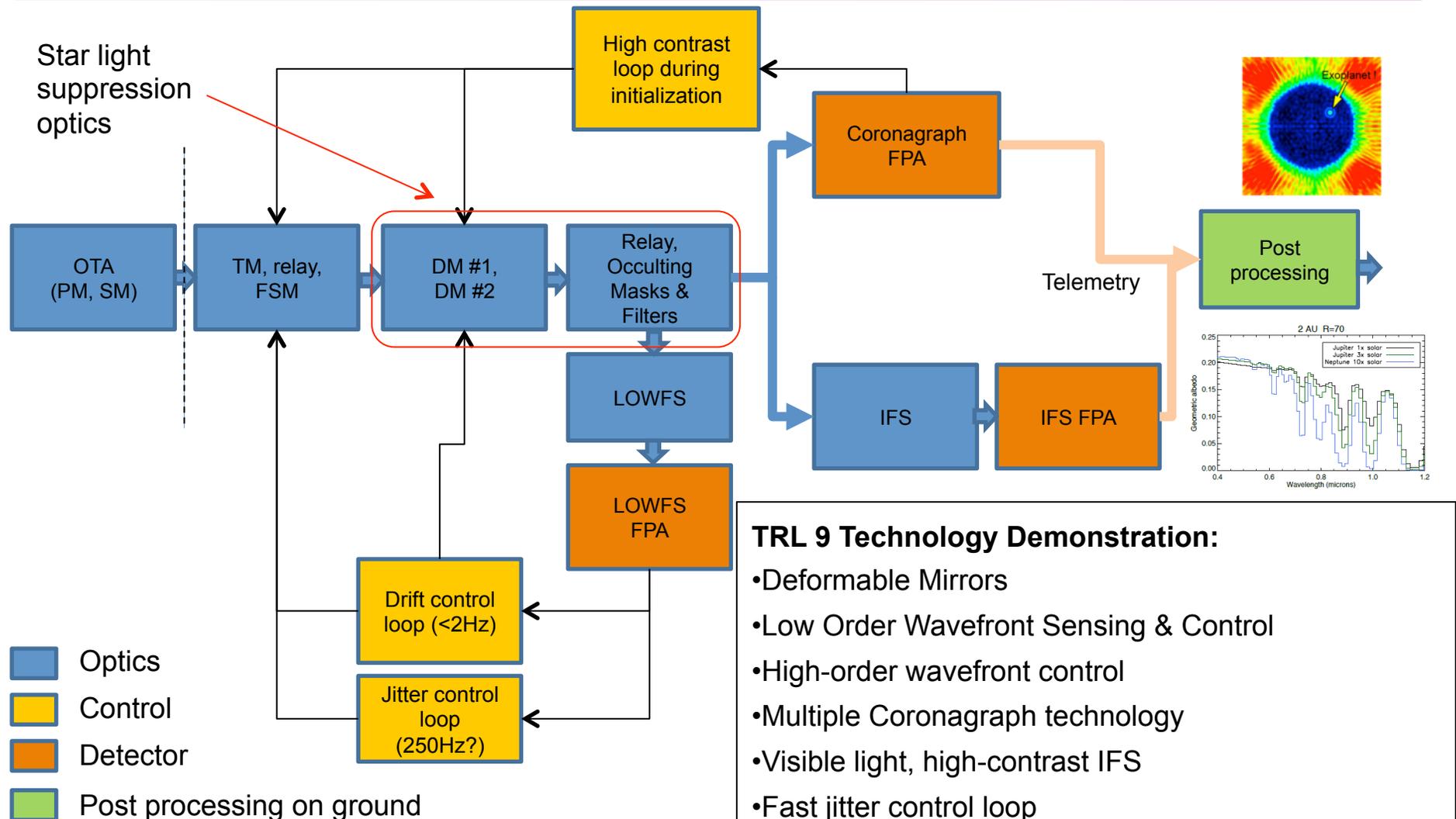
Bandpass	400 – 1000 nm	Measured sequentially in five ~10% bands
Inner working angle	100 – 250 mas	$\sim 3\lambda/D$
Outer working angle	0.75 – 1.8 arcsec	By 48x48 DM
Detection Limit	Contrast $\leq 10^{-9}$ (after post processing)	Cold Jupiters, Neptunes, and icy planets down to $\sim 2$ RE
Spectral Resolution	$\sim 70$	With IFS, $R \sim 70$ across 600 – 980 nm
Spatial Sampling	17 mas	Nyquist for $\lambda \sim 430$ nm

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

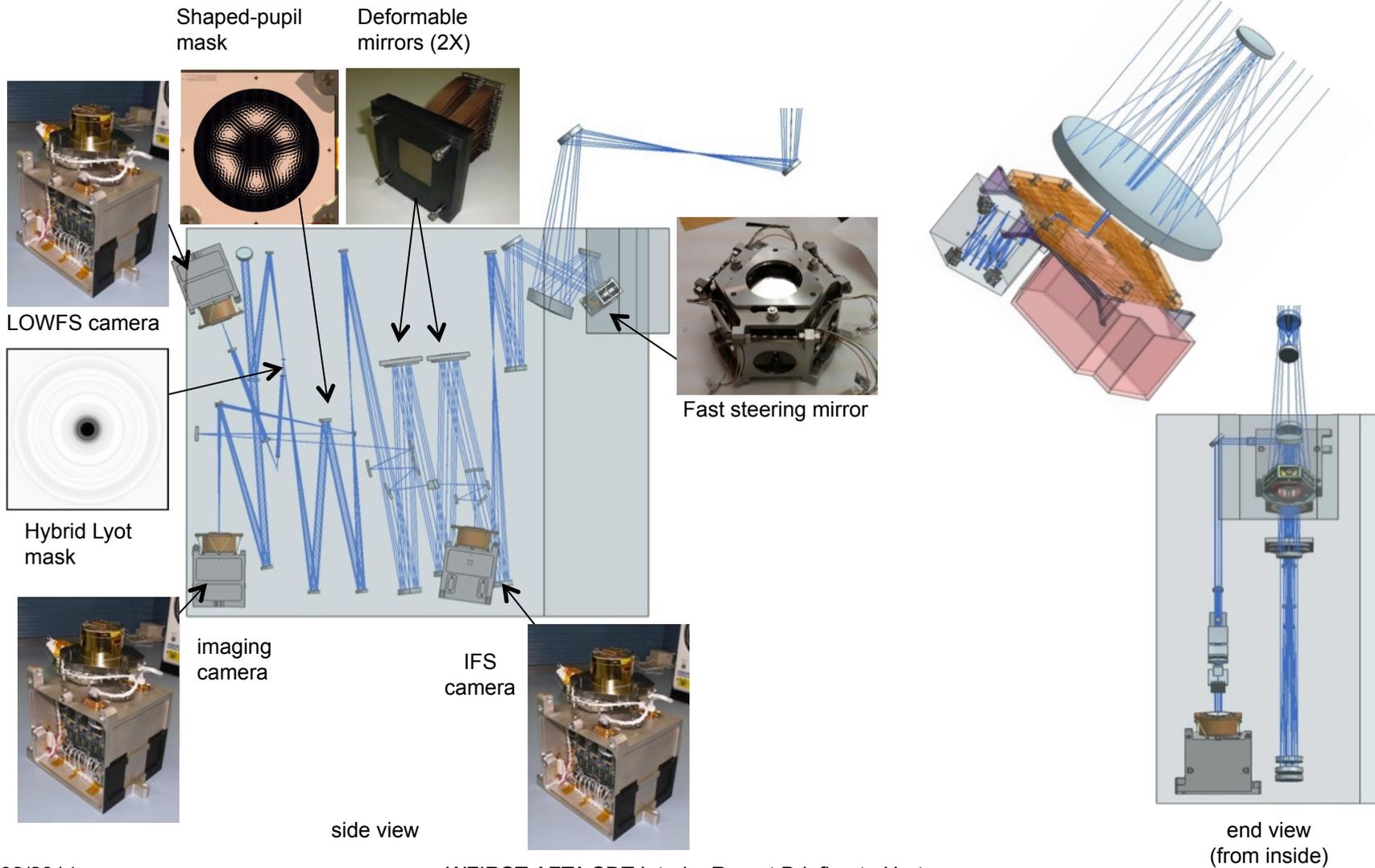
- SP and HL masks share very similar optical layouts
- Small increase in overall complexity compared with single mask implementation



# Functional Block Diagram

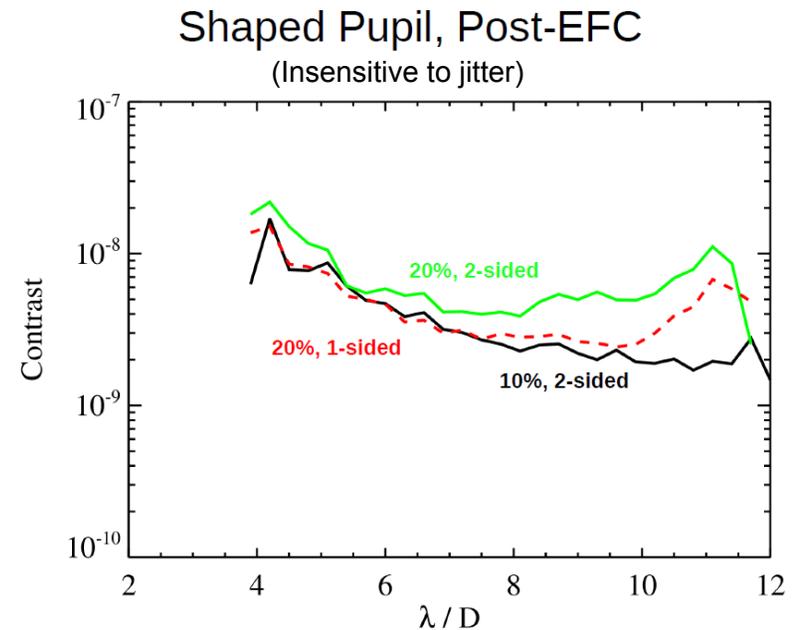
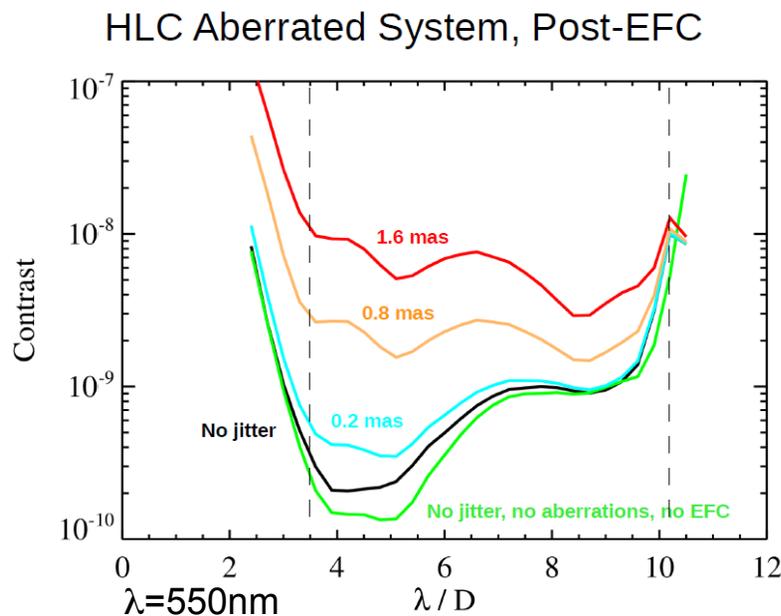


# Coronagraph Instrument



## 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 which is critical for the independent 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



# Coronagraph Technology Plan Funded with STMD Support



- Based on the TAC report, P. Hertz's down-select announcement, ASO and HQ guidance, a plan has been developed for maturing coronagraph technology and retiring major engineering risks by 9/2016
- The plan is currently being revised due to a recent FY14 funding increase that allows acceleration of several aspects of technology development
- 9 key milestones are called out in this plan, representing major technical and engineering accomplishments
  - However, work not explicitly covered by these milestones is also an integral part of the plan
- This plan was reviewed and accepted with TAC and HQ

**Have developed a plan to mature technologies to TRL-5 by 9/2016,  
details in backup slides**



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# Systems



# Science Requirements Status



- Currently iterating with NASA HQ, Project Scientist and SDT members to develop Science Objectives and Requirements held by NASA HQ.
- Beginning work on the flowdown from science objectives to observatory performance requirements.
- For each science program, there will be:
  - Scientific objectives and requirements
  - Observation requirements
  - Operations concept
  - Instrument requirements
  - Archive dataset requirements
  - Requirements will be enumerated; traceability matrix links each to parent requirement



# Integrated Modeling

- The Study Office performed Integrated Modeling on the April 2013 WFIRST-AFTA Report design reference mission to assess Point Spread Function (PSF) Ellipticity, Wave Front Error (WFE), and Line of Sight (LOS) stability margins.
- Structural/Optical/Thermal (STOP) models of the payload were developed, and subjected to orbital thermal and reaction wheel vibration (Jitter) disturbances to assess the optical responses.
- Excellent margins for this preliminary analysis
  - Wide Field Instrument STOP margins (after applying x3 modeling uncertainty factors) were x9 (WFE) and x108 (PSF ellipticity), excellent margins for the critical WL galaxy shape measurements.
  - Telescope Jitter margins (after applying x3 to x6 uncertainty factors) were x3.6 (LOS) and x6.2 (WFE), which along with sub-micron motions and sub-nanometer deformations of the Primary and Secondary Mirrors, were well-received by the Coronagraph team.
- Next steps are to incorporate a detailed coronagraph model as well as wide field grism and IFU models in future iterations.

**Additional details in backup slides**



## Recent Spacecraft Study

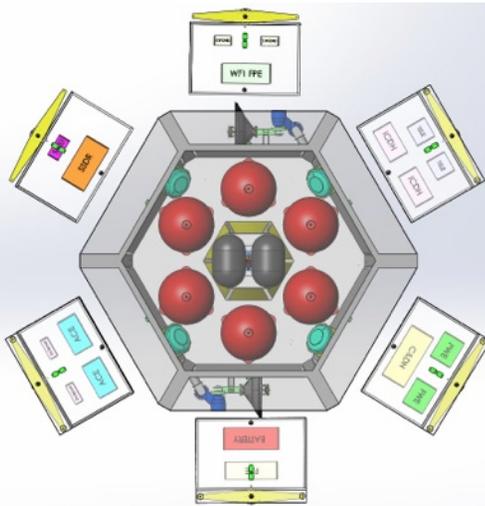
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- The Study Office has been developing an alternate spacecraft configuration over the last couple of months
- The alternate configuration significantly simplifies the spacecraft
  - Eliminates the large bi-prop system and replaces with a smaller, less complex mono-prop system
  - Reduces spacecraft structure mass
  - Reduces overall observatory mass
- However, this simpler spacecraft now requires the launch vehicle to circularize the orbit at GEO
  - Additional cost for larger LV will be partially offset by the spacecraft simplifications
- The LV market is very dynamic and the Study Office continues to track these opportunities with KSC.

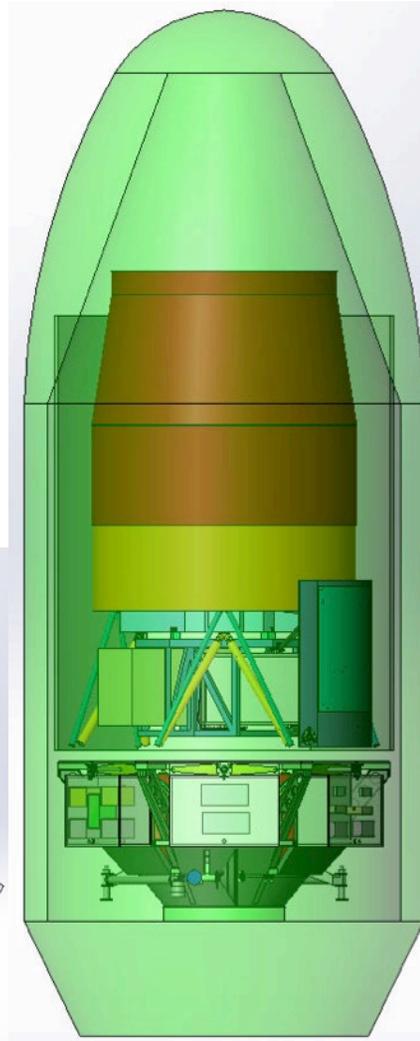
# Spacecraft Configurations

## Baseline Configuration

- 6 prop tanks carry >3000 kg of bi-prop to circularize orbit from GTO and for station keeping
- Taller S/C to accommodate tanks pushes higher into fairing
- Atlas V 551

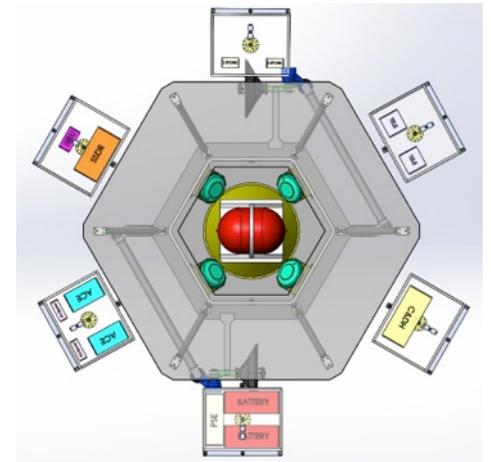


Top View and View in Fairing of Baseline Configuration



## Alternate Configuration

- 1 prop tank carries <100 kg of mono prop for station keeping
- Shorter S/C is lower in fairing
- Falcon Heavy (or Delta IV Heavy)



Top View and View in Fairing of Alternate Configuration



# Path Forward to January Report



- Requirements development/flowdown and science simulations to support this effort
- Continue to mature payload and spacecraft design
  - Iteration of overall payload design is necessary to allow coronagraph instrument to reach comparable maturity level of the wide field instrument.
  - Refine instrument designs and define preliminary payload interfaces
  - Refine spacecraft design to accommodate payload as the payload design matures
  - Develop cost estimates for full observatory
  - Develop potential descope options to reduce cost and/or schedule risk
  - Perform full observatory STOP and jitter analysis
    - Includes coronagraph as well as modeling the wide field grism and IFU
- Telescope
  - Develop detailed schedule based on historical build schedules of the two previous units
  - Complete characterization of laminate and adhesives over potential cold temperature range
  - Update models and perform telescope level STOP analysis to assess performance at operating temperatures
- Wide Field Instrument
  - Near term focus is on detailing the wide field optical error budget to include all fabrication, thermal, and launch effects
  - Complete H4RG process optimization lot and begin full array lot based after downselect
  - Lower maturity items to be moved into EDU development
    - Focal plane; grism; element wheel; tertiary mirror
- Coronagraph Instrument
  - Complete initial OMC mask fabrication and begin verification of performance in narrow band light in HCIT
  - Continue design/development on engineering risk reduction activities
    - Deformable mirrors, EMCCDs, IFS



# BACKUP SLIDES



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# IR Detector Development



# H4RG-10 Detector Development Summary



- The current WFIRST-AFTA Wide-Field Imager configuration is based on a mosaic of 4K x 4K near-infrared detectors.
- The Project initiated pilot lot of 4K x 4K, 10  $\mu\text{m}$  pixel pitch, detectors; characterized during FY12.
  - The results were very encouraging and pointed to the need for some minor process improvements.
- A series of small process development experiments were completed to address the issues identified during the Pilot Run.
- In FY13, the Project started a Process Optimization Lot to optimize the potential flight recipes.
  - The growth and processing of the detector material is varied (among different devices).
  - “Banded” arrays with spatially dependent recipe for efficiently spanning parameters.
  - These devices are currently being delivered, with the final device characterized by the end of FY14.



# H4RG-10 Development Upcoming Work



- Towards the end of FY14, a Full Array Lot will be started to focus on producing full arrays of the selected recipe.
  - Downselected to one or potentially two possible variants.
  - Will confirm that the selected recipe(s) scale to the entire array and provide better full array uniformity and yield information.
  - Analysis will be complete by mid-FY15.
- The final pre-flight lot will be the Yield Demonstration Lot.
  - Anticipated start at the end of FY15.
  - A single flight candidate recipe will be used.
  - These detectors are expected to be of fairly high quality, and will be using during instrument development as engineering devices, for qualification testing, and for detailed performance characterization. Thus, detectors for flight instrument build-up will be available quite early.
  - Completion of the Yield Demonstration Lot is planned to be in FY16, after which the flight build can be started.



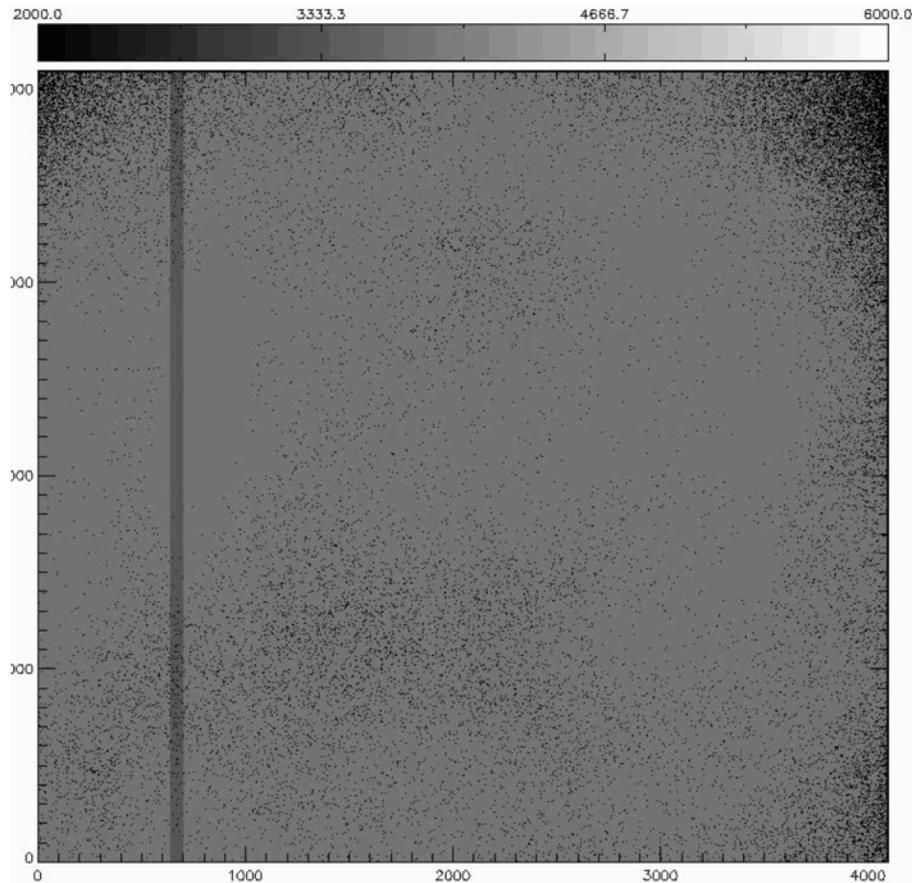
# Current Results



- Results are preliminary, based on testing a small sample of variants and the parallel development/debugging of test procedures
- Main points:
  - Previously discovered interconnect issue is resolved, further improvement anticipated.
  - Previously discovered high CDS noise is resolved.
  - Two very high quality “science grade” devices have been produced to date.
    - Basic parameters QE, dark current, noise, persistence, and intrapixel capacitance are consistent with notional requirements.
    - This is very good performance.



# Interconnect Issues Resolved

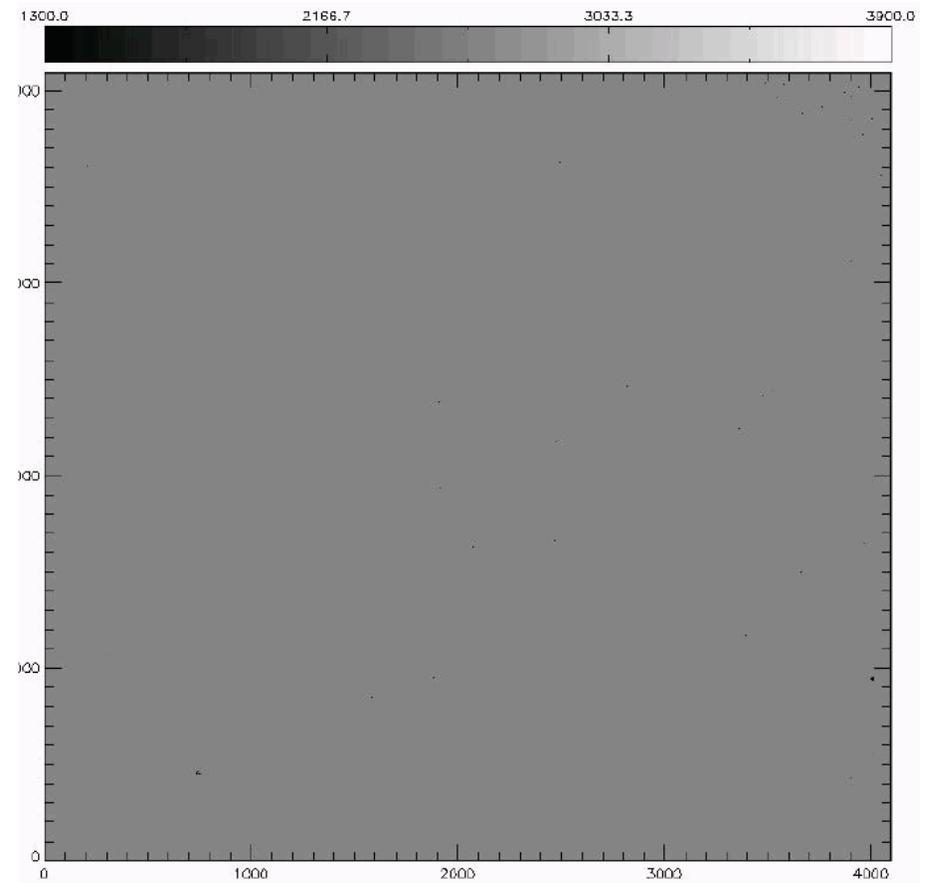


SCA 16361

Previous Pilot Run Lot

Black dots indicate interconnect failures, ~5%.

Takes up the entire notional operability specification.



SCA 17429

Current Process Optimization Lot

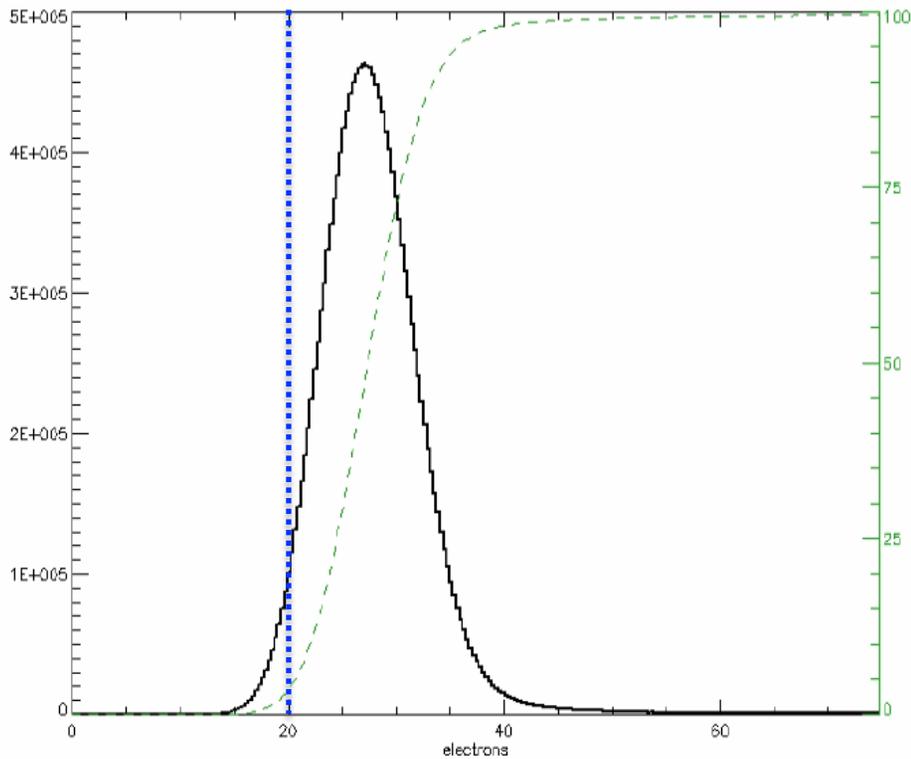
< 0.5% interconnect failures



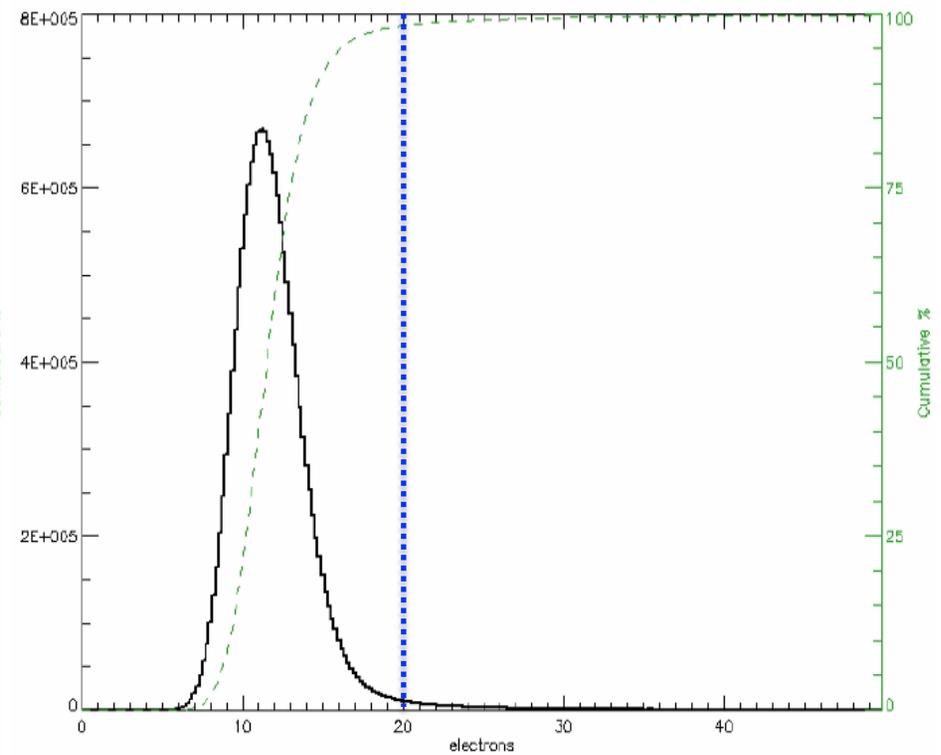
# CDS Noise Is Much Improved



Blue line shows CDS noise target.



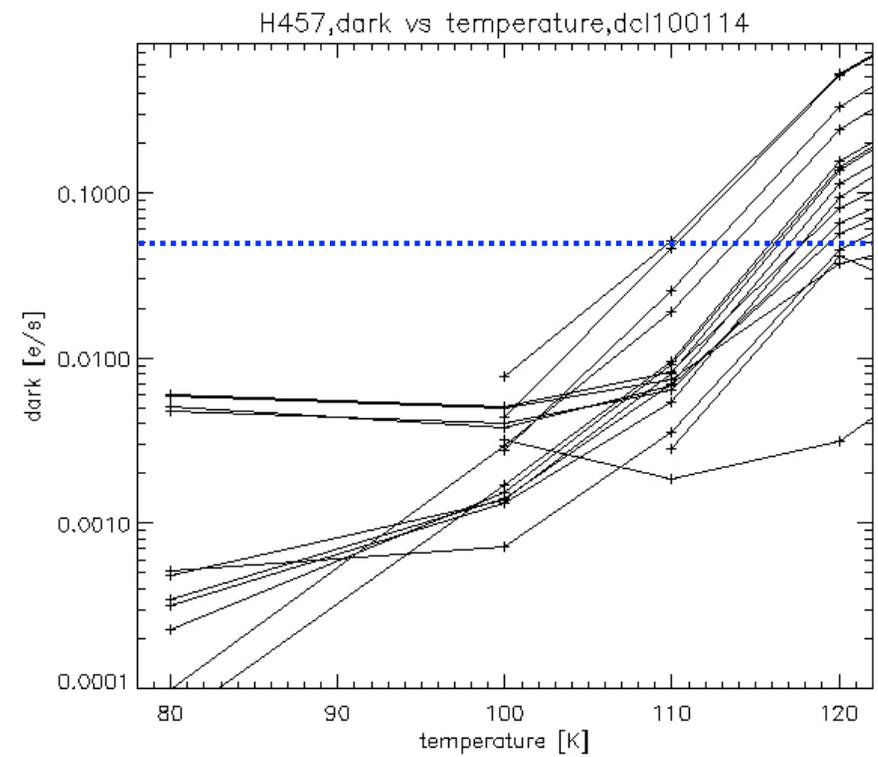
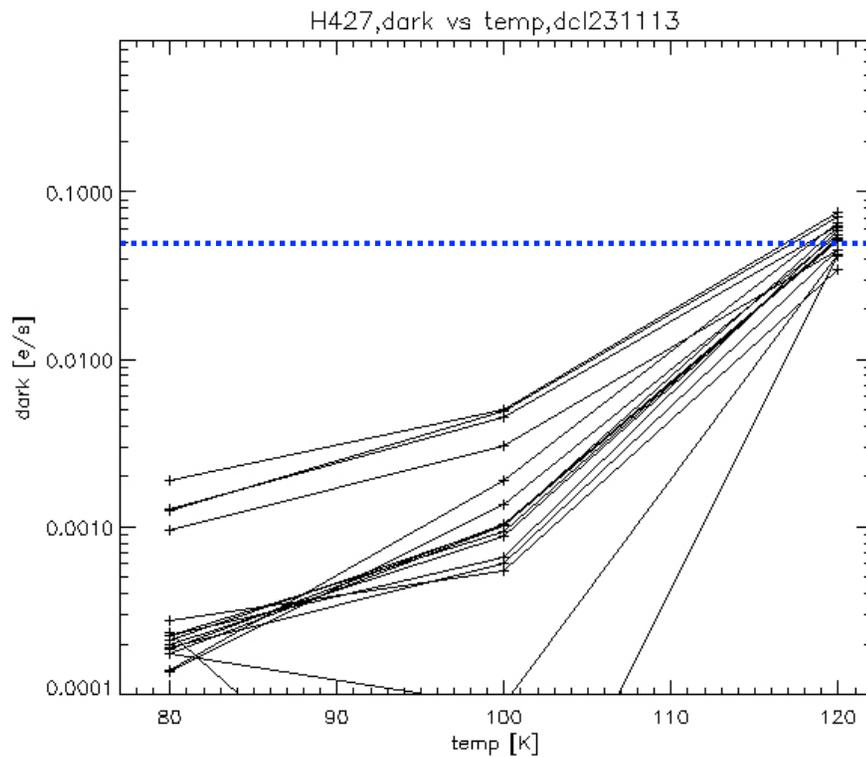
SCA 16360  
(Previous Pilot Run Lot)



SCA 17427  
(Current Process Optimization Lot)

# Example Dark Current

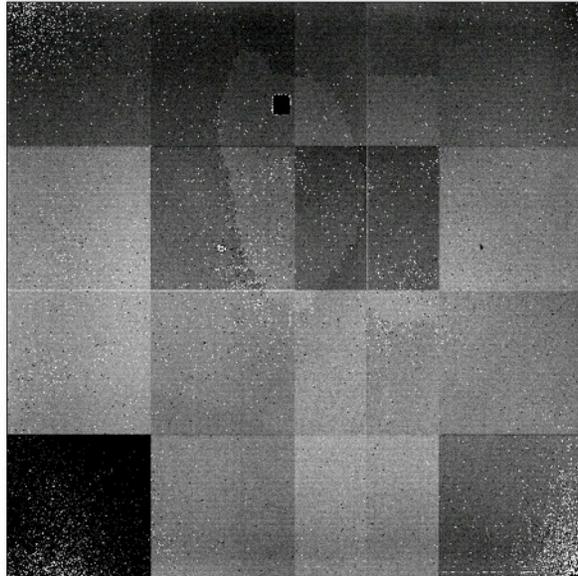
Blue line shows dark current target.  
 Cycle 4 baseline FPA temperature of 90K provides margin.



The lines are the different “bands.”  
 Results below 100K are limited by the data set (need longer integrations to detect smaller dark currents).

# Example Flat Field Response

SCA 17427



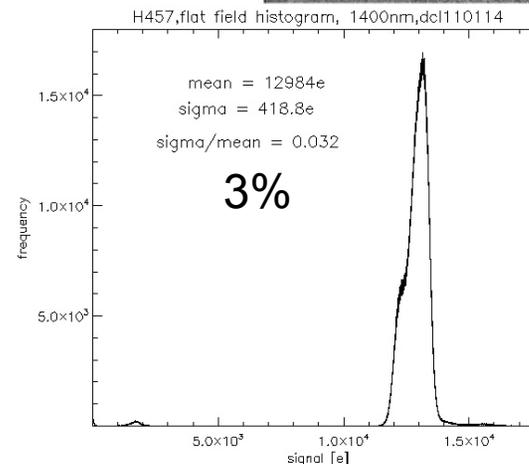
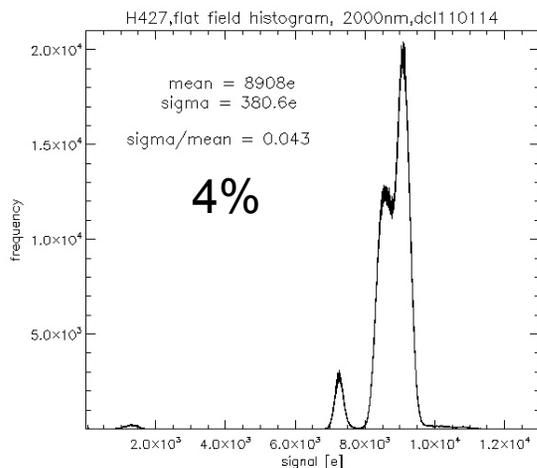
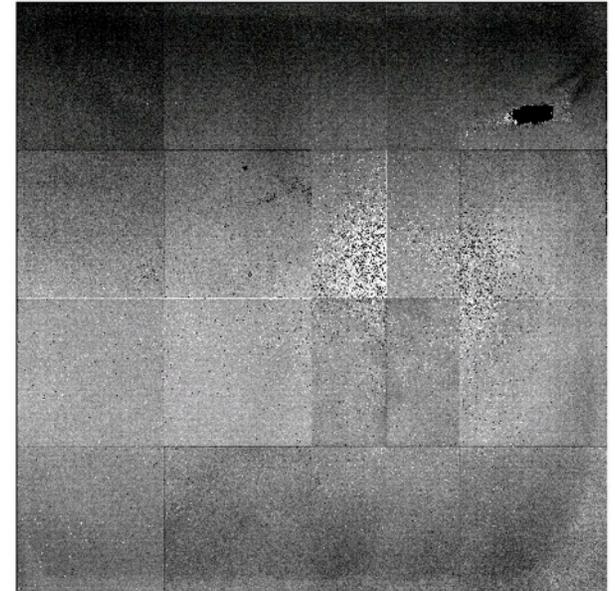
2000 nm exposures.

Scale is +/-10% of mean.

Sigma/mean is very good, especially since the arrays are banded and the non-uniformity of the Lambertian source is not corrected.

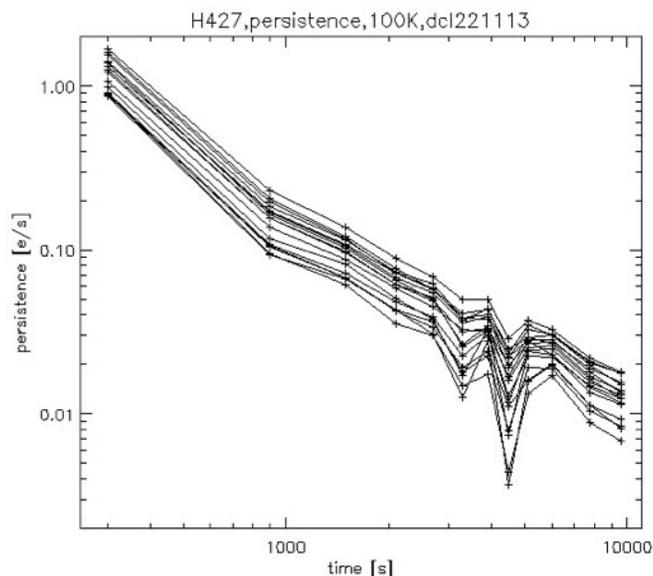
3-4% is comparable to the best HgCdTe devices made to date.

SCA 17457



# Example Persistence

## SCA 17427

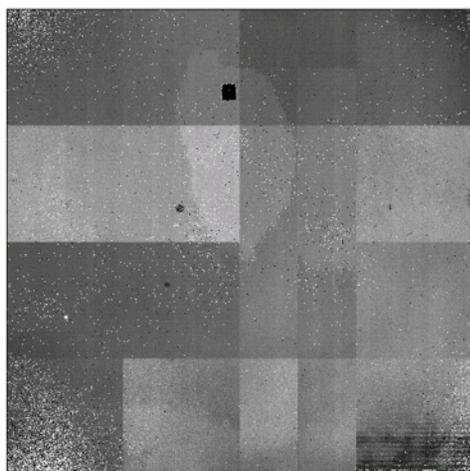


Measurements at 100 K with  
~80000 e- illumination at t=0

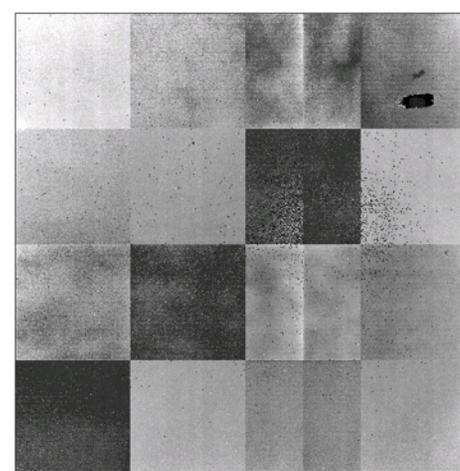
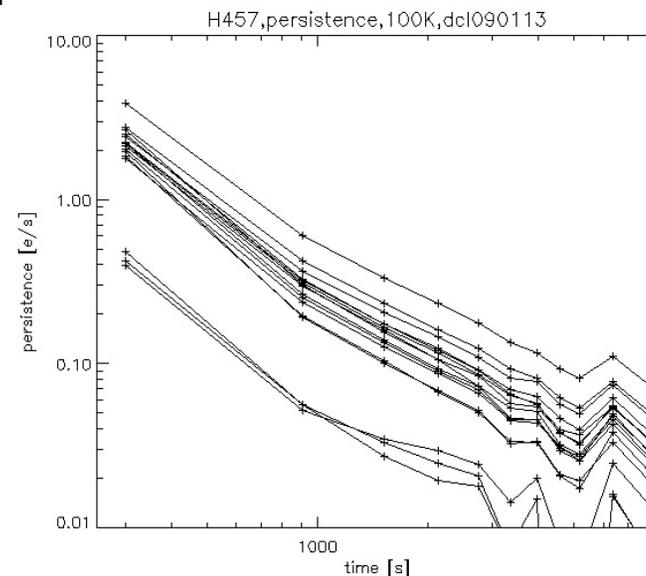
Low persistence at 100 K  
and below, increasing with  
temperature.

Equivalent to JWST  
performance.

Images show effective dark  
current after 600 sec.



## SCA 17457





# Detector Development Summary



- The lot of H4RG detectors currently in process looks very promising.
- Initial results indicate most bands meeting or are very close to performance targets.
- These devices have demonstrated that the technology is capable of producing the required levels of performance.
- The remaining work will demonstrate scaling the selected band design to full arrays and achieving these performance levels with reasonable yields (and thus costs).
- Current trend indicates that flight detectors could be fabricated well in front of need date.



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# AFTA Coronagraph Technology Plan and Progress

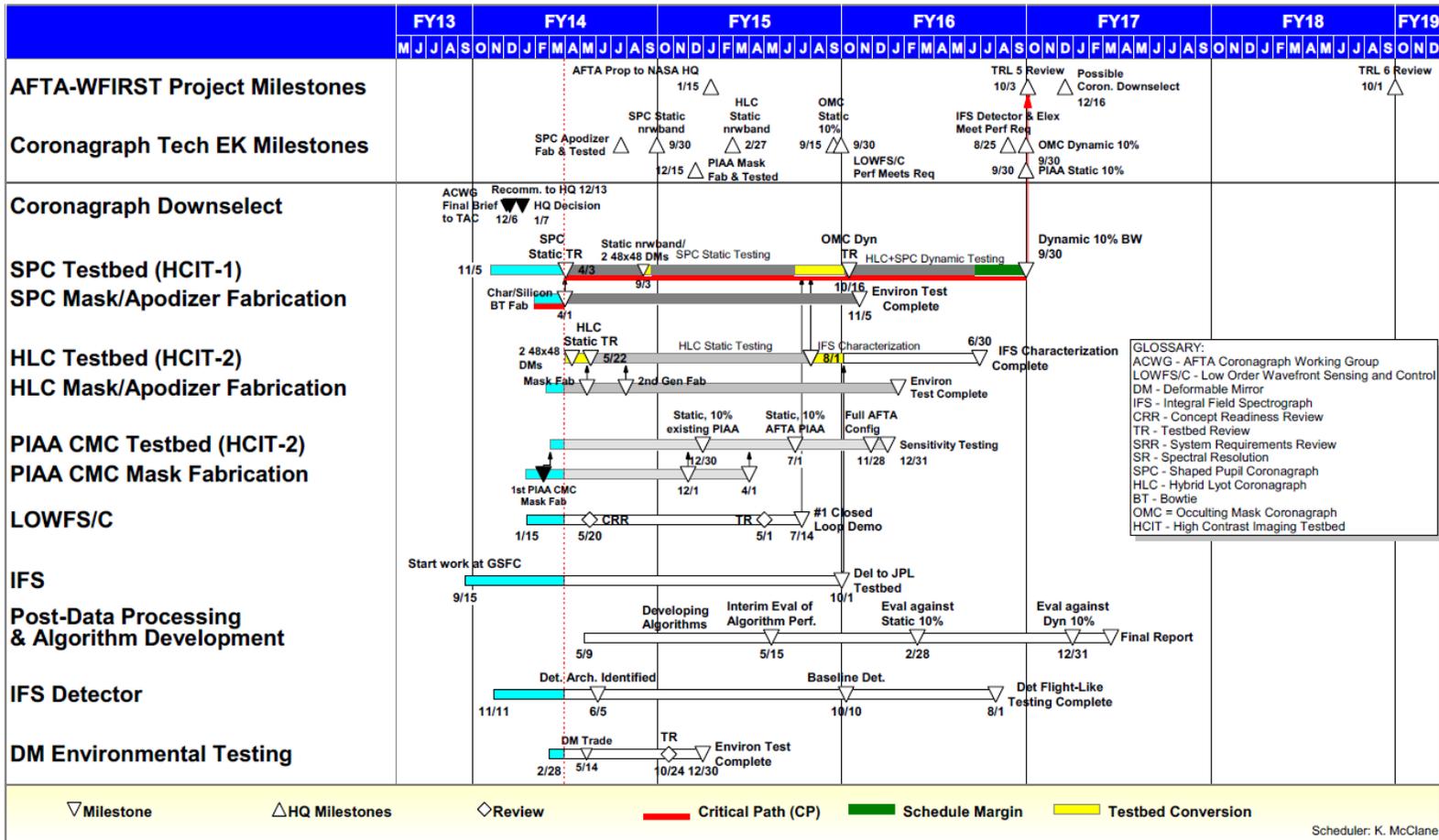


# Coronagraph Technology Development Plan Schedule



## AFTA-WFIRST Coronagraph Technology Development Top Level Schedule

Rev. 4/9/2014



- New funding in FY14 allows acceleration in the following key areas:
  - IFS, post-processing, DM environmental test, detector
- PIAA-CMC accelerated development

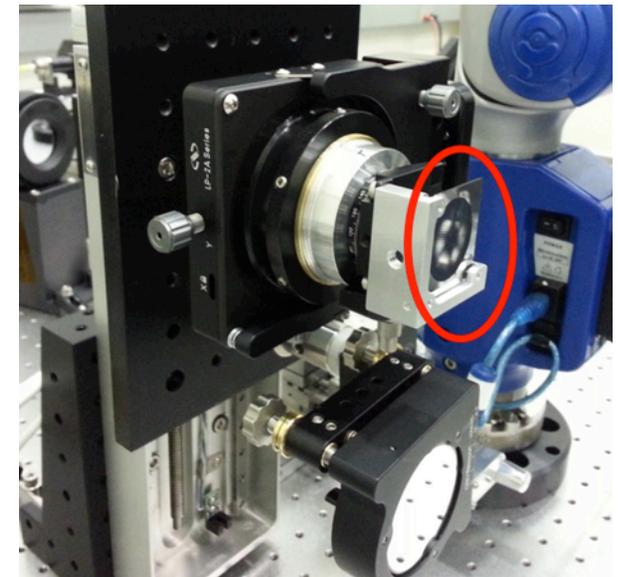
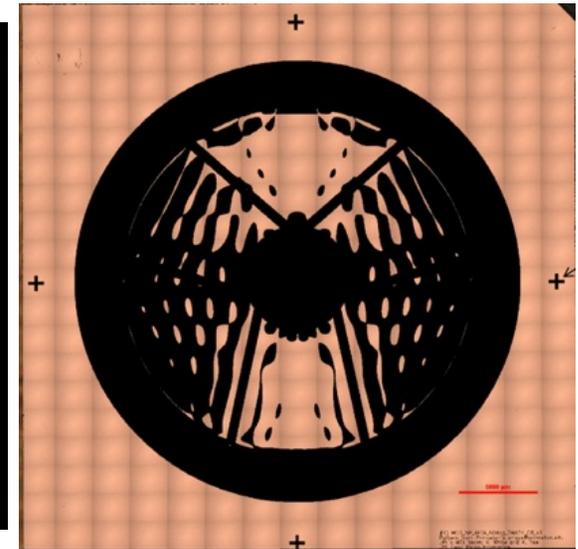
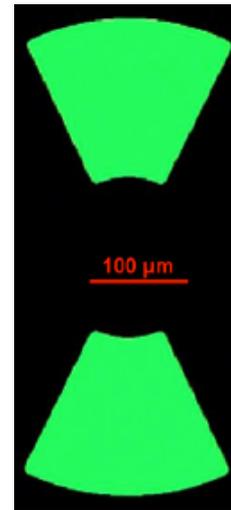


# Coronagraph Key Milestones



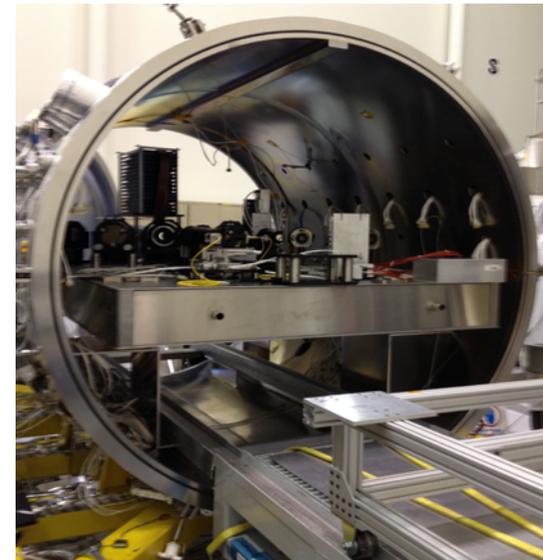
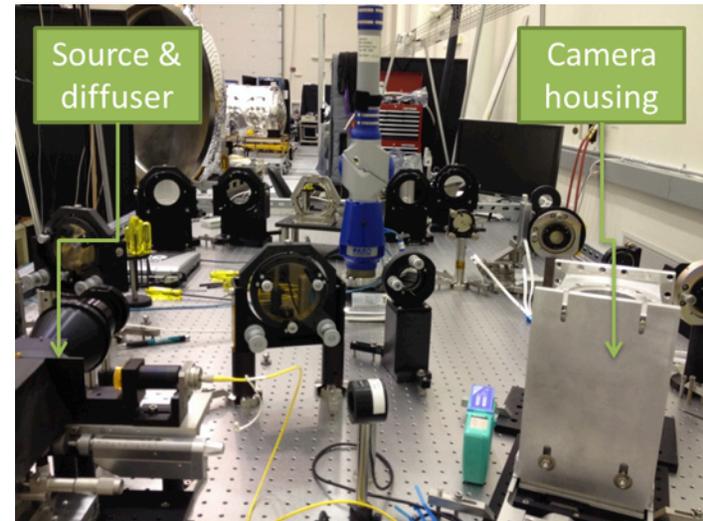
MS #	Milestone	Date
1	First-generation reflective Shaped Pupil apodizing mask has been fabricated with black silicon specular reflectivity of less than $10^{-3}$ and 20 $\mu\text{m}$ pixel size.	7/21/14
2	Shaped Pupil Coronagraph in the High Contrast Imaging Testbed demonstrates $10^{-8}$ raw contrast with narrowband light at 550 nm in a static environment.	9/30/14
3	First-generation PIAACMC focal plane phase mask with at least 12 concentric rings has been fabricated and characterized; results are consistent with model predictions of $10^{-8}$ raw contrast with 10% broadband light centered at 550 nm.	12/15/14
4	Hybrid Lyot Coronagraph in the High Contrast Imaging Testbed demonstrates $10^{-8}$ raw contrast with narrowband light at 550 nm in a static environment.	2/28/15
5	Occulting Mask Coronagraph in the High Contrast Imaging Testbed demonstrates $10^{-8}$ raw contrast with 10% broadband light centered at 550 nm in a static environment.	9/15/15
6	Low Order Wavefront Sensing and Control subsystem provides pointing jitter sensing better than 0.4 mas and meets pointing and low order wavefront drift control requirements.	9/30/15
7	Spectrograph detector and read-out electronics are demonstrated to have dark current less than 0.001 e/pix/s and read noise less than 1 e/pix/frame.	8/25/16
8	PIAACMC coronagraph in the High Contrast Imaging Testbed demonstrates $10^{-8}$ raw contrast with 10% broadband light centered at 550 nm in a static environment; contrast sensitivity to pointing and focus is characterized.	9/30/16
9	Occulting Mask Coronagraph in the High Contrast Imaging Testbed demonstrates $10^{-8}$ raw contrast with 10% broadband light centered at 550 nm in a simulated dynamic environment.	9/30/16

- Mask design delivered from Princeton and translated into machine language
- Successfully fabricated first sets of SP masks (March 2014). Four iterations of reflective shaped pupil masks fabricated at JPL and Caltech
  - Reduced defects from earlier to later iterations due to process improvements
- Measured Si wafer wavefront error, identified acceptable 4" wafers
- Developed mounting approach, built reflective shaped pupil mount, measured WFE stability
- Measured Black Si specular reflectivity ( $\ll 10^{-4}$ )
- Fabricated transmissive field stops
- Modeling the effects of imperfections in the fabricated mask on coronagraph contrast after wavefront control
- **Shaped Pupil mask for coronagraph testbed was delivered to testbed on schedule (April 3, 2014)**

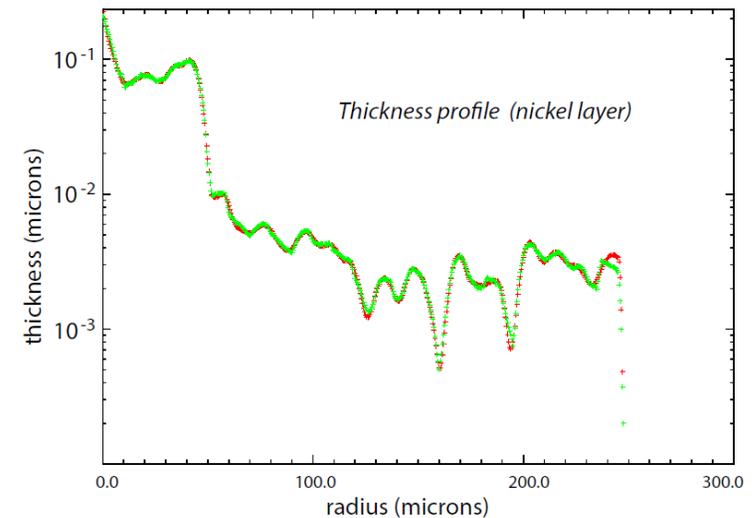


# SPC Progress: Testbed

- Testbed optics have been installed and aligned
- Camera stage and housing installed and functional
- All 2" stages & motors are in place (pinhole, bow-tie, diffuser & source) and functional
- Shaped Pupil masks installed
- Testbed was moved into the vacuum tank and fully connectorized
- **Test Review was held on 4/3/14**
- **Shaped Pupil Testbed is in the process of being commissioned**

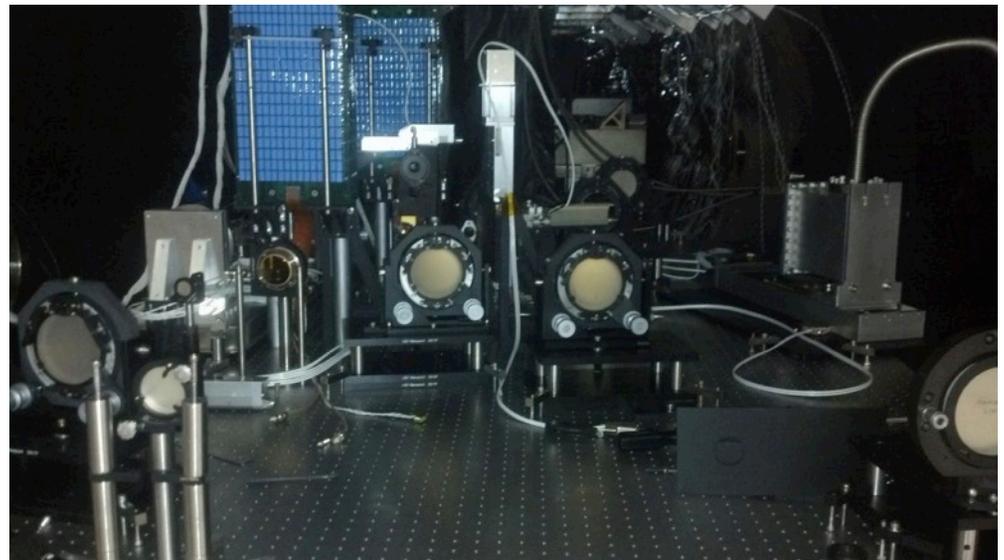
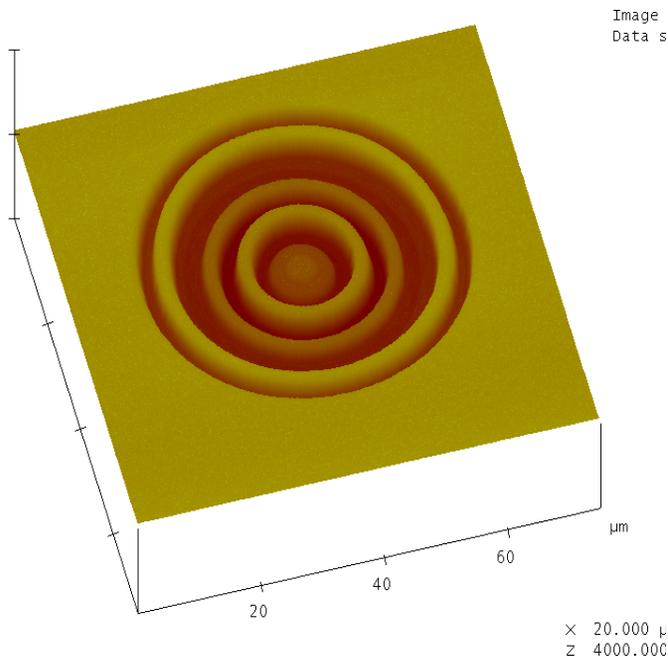


- Deposition fixture fabricated and installed into the chamber
- Fused Si substrates, microstencil plate and alignment reticle fabricated
- Simulations predict good agreement between the desired and actual thickness profiles for the selected set of microstencils
- Targeting first mask delivery for May 2014



# PIAA-CMC Progress

- First set of PIAA-CMC narrowband phase-only focal plane masks have been made using e-beam lithography at JPL's MDL
- Mask characterization results look promising
- Mask installed in the aligned PIAA testbed (with stopped-down old PIAA mirrors)
- Testbed is under vacuum in HCIT2 tank at JPL
- Accelerated PIAA-CMC plan – a collaboration of UofA, JPL, and ARC – has been reviewed by the team





# LOWFS/C Progress



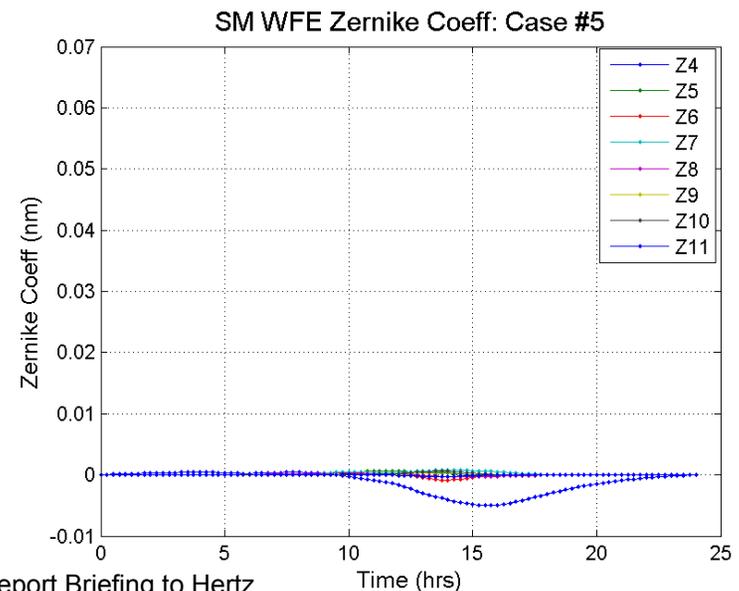
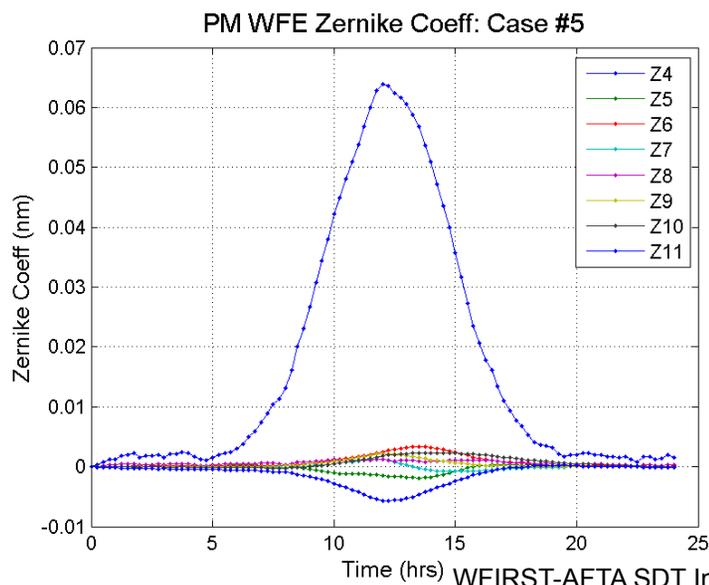
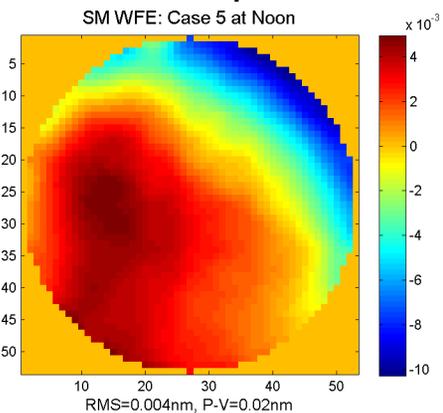
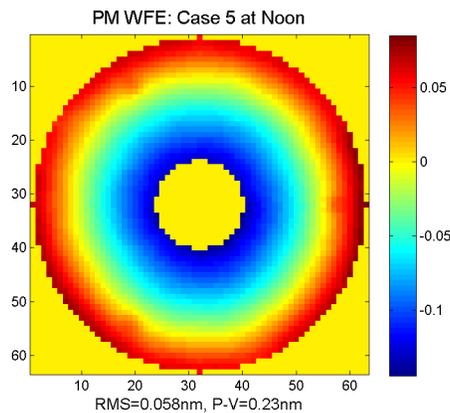
- Low Order Wavefront Sensing & Control (LOWFS/C) uses the rejected star light from the coronagraph for wavefront sensing
  - Star light picked from occulter (HLC) or field stop (SPC)
  - Sense wavefront jitter and suppress lower temporal frequencies
  - Sense (and when necessary correct) slow-varying low order wavefront error such as focus, astigmatism and coma caused by telescope thermal drift
  - Recorded wavefront can be used for data post processing
- LOWFS/C uses the fast steering mirror (FSM) for LOS jitter correction
- Low order WFE corrector must not corrupt coronagraph's high order wavefront control
  - DM calibration
- Currently modeling and evaluating two LOWFS/C sensor concepts; will implement one for HCIT dynamic test
  - Direct imaging of rejected star PSF with a knife edge like mask (O. Guyon)
  - Zernike WFS (K. Wallace)
- **Trade will be completed and produce LOWFS/C architecture selection in May 2014**



# LOWFS/C: Impact of Telescope Drift on Coronagraph Performance



- WFIRST-AFTA PM & SM thermal surface figure drift induced WFE is used to evaluate their impact on coronagraph contrast (**Cases # 5-6 are typical**)
- For each thermal drift case the maximum WFE over the 24 hour period is used

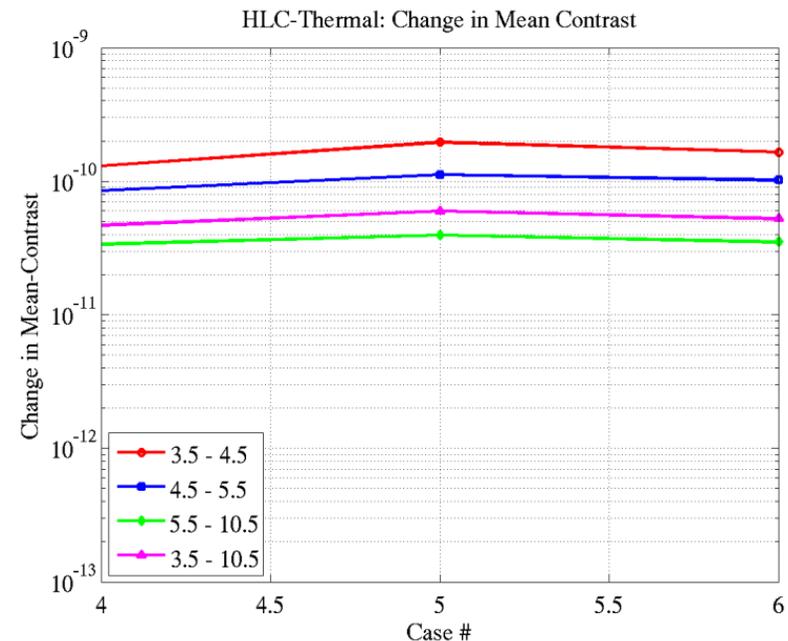
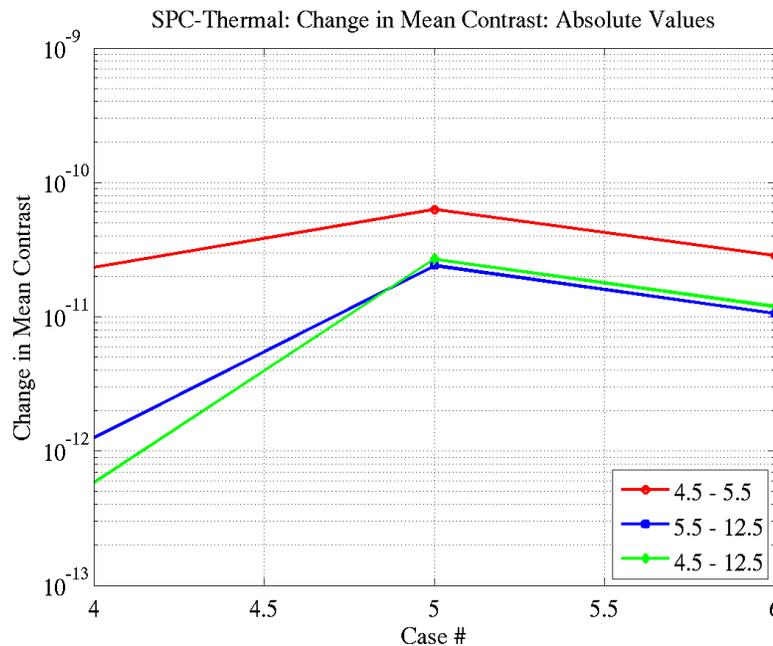




# LOWFS/C: Impact of Telescope Drift on Coronagraph Performance

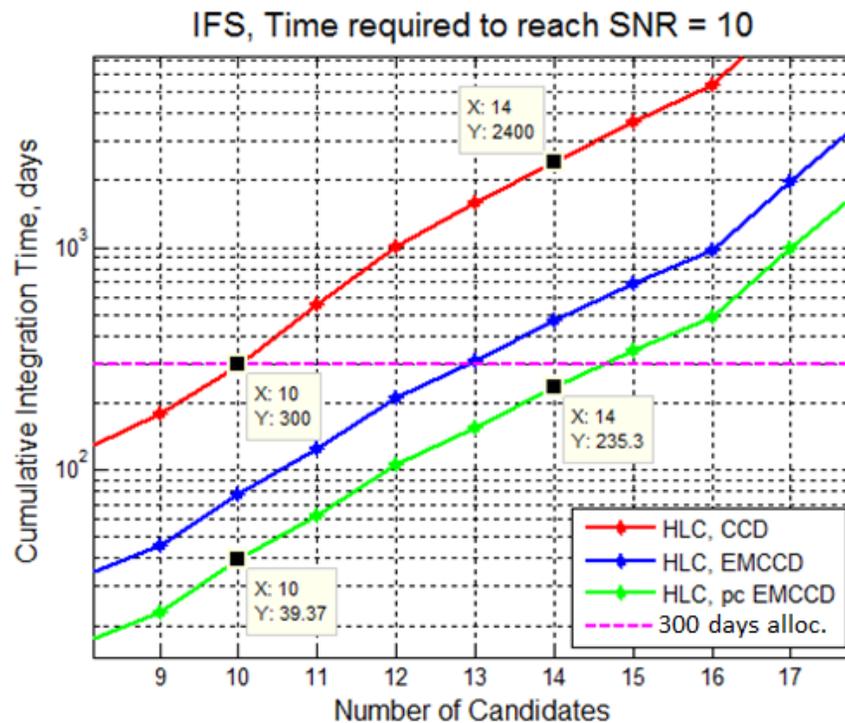


- The change of contrast from WFE evaluated using J. Krist's PROPER model (low jitter HLC design) end-to-end contrast change analysis is shown below
- Mean contrast **changes** ( $\Delta$  contrast) are calculated over dark hole regions of 3.5 – 4.5, 4.5 – 5.5, 5.5 – 10.5 and 3.5 – 10.5  $\lambda/D$



- Impact to contrast from thermal low-order wavefront changes is  $< 10^{-10}$  (same for RB effects)
- Hence LOWFS/C performance beyond tip/tilt is not as critical as previously assumed
- Tip/tilt sensing and control still necessary for HLC and PIAA-CMC

- Preliminary modeling has been done of the effect of the detector characteristics on the planet yield for the coronagraph
- Models show that a workable mission with a conventional CCD, the use of an EMCCD will create 90% savings in integration time, lowering risk of target (null) acquisition and allowing time for more science



Assume:

- dark =  $3e-4$  e/pix/s,
- CIC =  $1e-3$  e/pix/fr,
- jitter = 0.4 mas,
- HLC coronagraph

Option	CCD	EMCCD	PC EMCCD
Read Noise (e-)	3	8	8
EM Gain	1	40	200
ENF	1	1.41	1
Frame Rate (fps)	0.0005	0.0005	0.002

Focal Plane	Area (pix)	Width	Height	shape	SNR Target	SNR pixels	Light fract.
IFS	28	14	2	streak	9	4.0	0.143
Imaging	4.91	2.5	2.5	circle	5	4.91	1.0

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

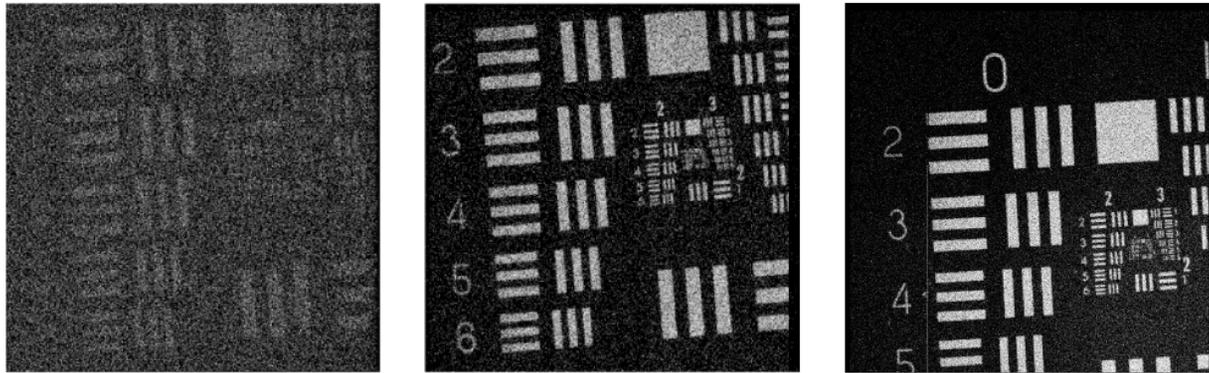


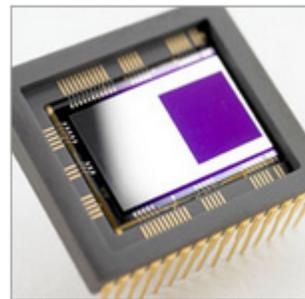
Fig. 4. Imaging an Air Force test pattern illuminated by an Offner relay. Images are as follows; (left) classical CCD mode using EM output, (middle) intensified imaging mode, and (3) photon counting. The illumination level was about the same in all three cases. Because the purpose of this figure is to demonstrate correct function, no special care was taken to ensure matching of gray levels, etc. The apparent signal-to-noise ratio increases are, however, real.

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

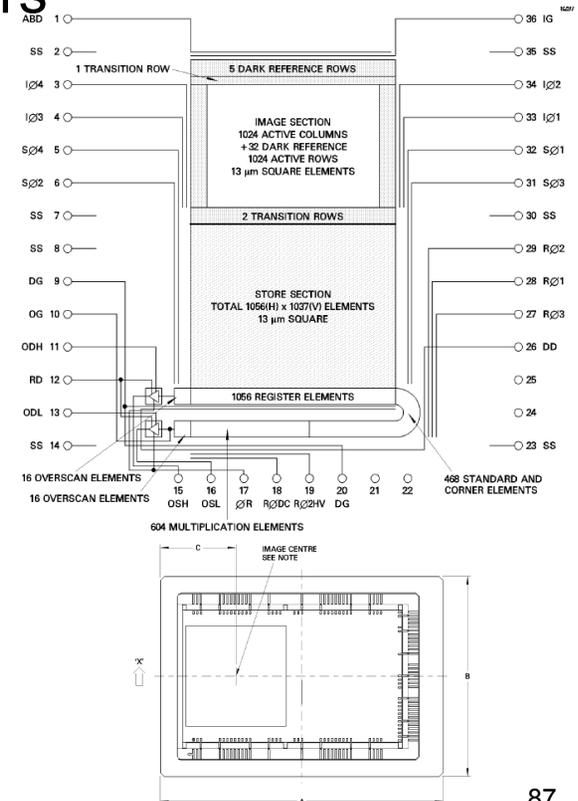
- Working with industry partners (Canada, UK, France) in risk reduction activities
- The test lab is being moved from Caltech to JPL and testing activity is being accelerated
- Putting together a development plan consistent with the rough lead time estimates received from the vendors



Test setup Control Electronics  
(with flight possibility)  
(NuVu Cameras, Canada)



CCD201 - EMCCD  
(a candidate 1k x 1k CCD)  
(e2v, UK)





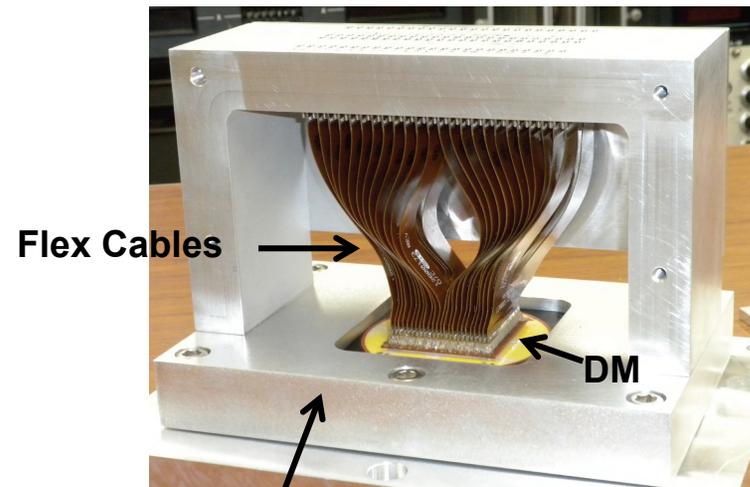
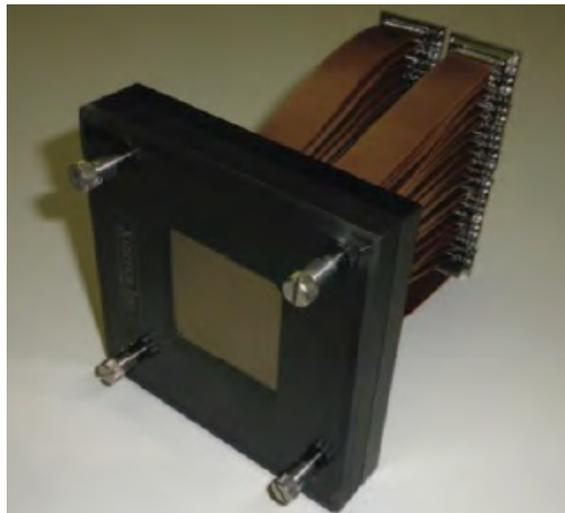
# Proposed Engineering Risk Reduction Activities



- Several key coronagraph subsystems require maturation and testing to reduce instrument engineering risk
  - IFS detector and detector electronics (addressed as Key Milestone 7)
  - Deformable mirror
  - Masks and associated mechanisms
  - IFS demonstration, particularly intra-scene contrast
- Propose performing these maturation and testing activities as early as possible for budget and programmatic reasons in order to retire key coronagraph instrument engineering risks

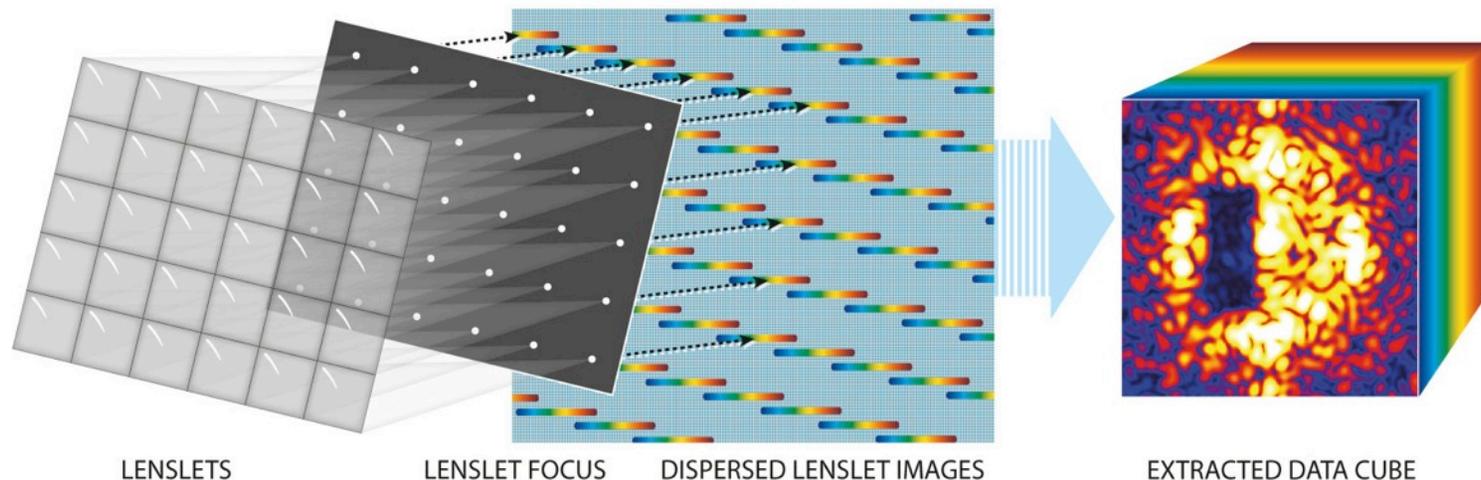
# DM Flight Qualification

- AOX electrostrictive PMN Deformable Mirrors used in HCIT since 2004
  - Produced better than  $10^{-9}$  raw contrast demonstrations
- Two 48x48 AOX DMs baselined for coronagraph instrument, testbeds
  - DMs for HLC testbed with electronics just completed full functionality testing
- Reliable component with excellent surface figure control and stability
- AOX DM was put through and passed a generic protoflight vibration test in 2012
  - 10.6 Grms, 3-axes, 0-2000 Hz
- Pyroshock and thermal cycling tests were recently accelerated to Fall 2014
  - Test article: AOX 48x48 PMN deformable mirror (Delivery: Sept, 2014)



**Vibration Test Fixture**

- Lenslet-based IFS is the baseline spectrograph for WFIRST-AFTA coronagraph
- Mike McElwain (GSFC) was funded by Roman Fellowship to build a facility IFS for HCIT (PISCES)
- Currently working to adapt IFS requirements and interfaces to WFIRST-AFTA needs
- Key engineering challenge is achieving  $10^{-4}$  intra-scene contrast (cross-talk)
- Exploring acceleration options relative to the baseline schedule
  - Aim is to put IFS on WFIRST-AFTA testbed in early FY 16
- Accelerating IFS delivery and integration will also allow its earlier use for
  - Broadband wavefront control
  - Data post-processing





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# Integrated Modeling



# Integrated Modeling (IM) Update



- The IM focus since the April 2013 WFIRST-AFTA report has been on assessing Point Spread Function (PSF) Ellipticity, Wave Front Error (WFE), and Line of Sight (LOS) stability margins
- Structural/Optical/Thermal (STOP) models of the Payload Cycle-3 design were developed, and subjected to orbital thermal and reaction wheel assembly vibrational (for Jitter) disturbances to assess the optical response
- Wide Field Instrument performance was assessed at the focus of the wide field channel (imaging mode only)
- LOS/WFE performance was also assessed at the Telescope Intermediate Focus (TIF) for Jitter, along with Telescope Primary (PM) and Secondary (SM) motions and deformations for STOP, to inform on-going Coronagraph design trades
- All results are preliminary, with no design optimizations



# STOP Predictions/Margins for Fixed Attitude and Worst-Slew Cases



- Stabilities of WFI Imager PSF ellipticity and WFE have significant margins even for a STOP WFI Worst-Case Slew:
  - **x9 margin** on WFE drift ( $\text{rqt} \leq 0.707 \text{ nm drift}/184\text{s}$  at WFI Focus)
    - x25 better than HST WFE variations, which can be  $\pm 30 \text{ nm}$  over an orbit
  - **x108 margin** on PSF ellipticity (total  $\text{rqt} \leq 4.7 \text{ e-}4/184\text{s}$  at WFI Focus)
- PM/SM Position/Shape Stabilities for STOP Fixed-Attitude case were viewed positively by the Coronagraph Team:
  - **Zernike instabilities were dominated by easily corrected focus errors** at a fraction of a nanometer to a few picometers over 12 hours
  - **Rigid body motions were sub-micron** over 24 hours
- **MUF (Model Uncertainty Factor) of x3 is applied to all results, prior to any margin assessment.**



# Predictions/Margins of Jitter Due to Reaction Wheel Assemblies (RWAs)



- Peak LOS Jitter at TIF:  $\leq 4$  msec rms/axis (at 10 Hz wheel speed)
  - **x3.6 margin** on  $\leq 14$  msec rms/axis LOS jitter requirement
- Peak WFE Jitter at TIF:  $\leq 0.114$  nm (at 26 Hz wheel speed)
  - **x6.2 margin** on  $\leq 0.707$  nm WFE Jitter requirement
- Above values for spec RWA, w/ D-strut Forward Optics Assy isolation
  - D-strut performance was critical to establishing margins
  - Values above are at worst wheel speed for worst wheel
  - Off-peak margins for this wheel  $\sim$ double over 0-50 Hz range
  - Total vibration will need to consider the contribution from all 4 wheels, though multiple resonances are unlikely at any given time.
- **MUF (Model Uncertainty Factor) of x2.48(<20Hz) to x5.86 (>40 Hz) is applied to all results, prior to any margin assessment**



# Cryocooler Jitter Estimate Preview



- The Wide Field Instrument is evaluating a reverse Brayton-cycle cryocooler in the current design cycle as part of the trade study of extending the long wavelength cutoff to 2.4 $\mu$ m
  - Uses ~75% of power of **similar HST/NICMOS cooler**
  - Broadband operational forces at/below detectable threshold; NICMOS cooler was not detected in HST ops
  - Enables 80-100 K wide field instrument focal plane operating temperatures
- Results below include a jitter analysis MUF of x10.85 <20 Hz, x13.26 >40Hz, with a linear ramp between 20 and 40 Hz
- Margins on WFE/LOS for both TIF and wide field instrument are substantial.

FREQ	CBE/AXIS	with MUF	PSD with MUF	WFI LOS msec	WFI WFE nm	TIF LOS msec	TIF WFE nm
0-500 Hz	0.1 mN rms	1 mN rms	2x10 <sup>-09</sup> N <sup>2</sup> /Hz	0.21 x66 margin	0.0069 x102 margin	0.13 x109 margin	0.0037 x193 margin
4 kHz	1 N	1 N	1 N <sup>2</sup> /Hz*	Negligible	Negligible	Negligible	Negligible
7 kHz	2 N	2 N	4 N <sup>2</sup> /Hz*	Negligible	Negligible	Negligible	Negligible
			*1 Hz bandwidth				



# ACRONYM LIST



# Acronym List

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$\Lambda$ DCM	Lambda Cold Dark Matter
AAS	American Astronomical Society
ACWG	AFTA Coronagraph Working Group
AFTA	Astrophysics Focused Telescope Assessment
AGN	Active Galactic Nuclei
ALMA	Atacama Large Millimeter/submillimeter Array
AMS	Aft Metering Structure
AO	Announcement of Opportunity
AOX	Adaptive Optics Associates Xinetics
APD	Astrophysics Division
ARC	Ames Research Center
ASO	AFTA Study Office
AU	Astronomical Unit
BAO	Baryon Acoustic Oscillations
BICEP	Background Imaging of Cosmic Extragalactic Polarization
CATE	Cost Appraisal and Technical Evaluation
CBE	Current Best Estimate
CDS	Correlated Double Sample
CLASH	Cluster Lensing and Supernova survey with Hubble
CMB	Cosmic Microwave Background
Co-I	Co-Investigator
DDT	Director's Discretionary Time
DE	Dark Energy
DESI	Dark Energy Spectroscopic Instrument
DM	Deformable Mirror
dSphs	Dwarf Spheroidals



# Acronym List



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DRM1	Design Reference Mission 1
EFC	Electric Field Conjugation
ELG	Emission Line Galaxy
EMCCD	Electron Multiplying Charge Coupled Device
EPO	Education and Public Outreach
ESA	European Space Agency
ExEPO	Exoplanet Exploration Program Office
ExoPAG	Exoplanet Program Analysis Group
FoM	Figure of Merit
FoV	Field of View
FPA	Focal Plane Assembly
FSM	Fast Steering Mirror
FTE	Full Time Equivalent
FY	Fiscal Year
GBM	GLAST Burst Monitor
GEO	Geosynchronous Orbit
GI	Guest Investigator
GO	Guest Observer
GPM	Global Precipitation Measurement
GR	General Relativity
GRS	Galaxy Redshift Survey
GSFC	Goddard Space Flight Center
GTO	Guaranteed Time Observers
HCIT	High-Contrast Imaging Testbed
HgCdTe	Mercury Cadmium Telluride
HL	Hybrid Lyot



# Acronym List



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HLC	Hybrid Lyot Coronagraph
HLS	High Latitude Survey
HQ	Headquarters
HST	Hubble Space Telescope
HUDF	Hubble Ultra Deep Field
Hz	Hertz
IDRM	WFIRST Interim Design Reference Mission
IDS	Interdisciplinary Scientist
IDT	Instrument Development Team
IC	Instrument Carrier
IFS	Integral Field Spectrograph
IFU	Integral Field Unit
IMF	Initial Mass Function
IR	Infrared
ISIM	Integrated Science Instrument Module
ISO	Infrared Space Observatory
IWA	Inner Working Angle
JPL	Jet Propulsion Laboratory
JWST	James Webb Space Telescope
KBO	Kuiper Belt Object
km	Kilometer
LAT	Large Area Telescope
LBT-I	Large Binocular Telescope Interferometer
LOS	Line of Sight
LOWFS	Low Order Wavefront Sensor
LOWFS/C	Low Order Wavefront Sensor & Control



# Acronym List

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LRG	Luminous Red Galaxy
LSST	Large Synoptic Survey Telescope
MACHO	MASSive Compact Halo Object
mas	milli-arcsecond
Mbps	Megabits per second
MDL	Microdevices Laboratory
MIRI	Mid-Infrared Instrument
MMS	Multimission Modular Spacecraft
MUF	Model Uncertainty Factor
MW	Milky Way
NASA	National Aeronautics and Space Administration
NGST	Next Generation Space Telescope
NICMOS	Near Infrared Camera and Multi-Object Spectrometer
NIR	Near Infrared
NIRCam	Near Infrared Camera
NIRSpec	Near Infrared Spectrograph
nm	Nanometer
NRA	NASA Research Announcement
NRC	National Research Council
NWNH	New Worlds New Horizons (2010 Astronomy and Astrophysics Decadal Survey)
OBA	Outer Barrel Assembly
OGLE	Optical Gravitational Lensing Experiment
OMC	Occulting Mask Coronagraph
OWA	Outer Working Angle
PAG	Program Analysis Group
PC	Parsec



# Acronym List

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PHAT	Panchromatic Hubble Andromeda Treasury
PI	Principal Investigator
PIAA	Phase Induced Amplitude Apodization
PIAA-CMC	Phase Induced Amplitude Apodization-Complex Mask Coronagraph
PISCES	Prototype Imaging Spectrograph for Coronagraphic Exoplanet Studies
PLATO	Planetary Transits and Oscillations of stars
PM	Primary Mirror
PMN	Lead Magnesium Niobate
PSF	Point Spread Function
QE	Quantum Efficiency
RA	Right Ascension
RAAN	Right Ascension of the Ascending Node
RMS	Root Mean Square
ROIC	Readout Integrated Circuit
RSD	Redshift Space Distortion
RV	Radial Velocity
RWA	Reaction Wheel Assembly
SB	Surface Brightness
SCA	Sensor Chip Assembly
SDSS	Sloan Digital Sky Survey
SDO	Solar Dynamics Observatory
SDT	Science Definition Team
SFH	Star Formation History
Si	Silicon
SIM	Space Interferometry Mission
SM	Secondary Mirror



# Acronym List

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SMA	Semi-Major Axis
S/N	Signal to Noise
SN	Supernova
SNAP	SuperNova Acceleration Probe
SNe	Supernovae
SNR	Signal to Noise Ratio
SP	Shaped Pupil
SPC	Shaped Pupil Coronagraph
STOP	Structural Thermal Optical
SWG	Science Working Group
TAC	Technology Analysis Committee
TESS	Transiting Exoplanet Survey Satellite
TIF	Telescope Intermediate Focus
TOO	Target of Opportunity
TPF	Terrestrial Planet Finder
UofA	University of Arizona
VIS	Visible
VNC-DAViNCI	Visible Nulling Coronagraph Dilute Aperture Visible Nulling Coronagraph Imager
VNC-PO	Visible Nulling Coronagraph Phase Occulting
VVC	Vector Vortex Coronagraph
WFC3	Wide Field Camera 3
WFE	Wavefront Error
WFI	Wide Field Instrument
WFIRST	Wide Field Infrared Survey Telescope
WFS	Wavefront Sensor
WISE	Wide-field Infrared Survey Explorer
WL	Weak Lensing