WFIRST-AFTA Presentation to the Committee on Astronomy & Astrophysics

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Bruce Macintosh (Coronagraph Scientist, Stanford)

November 3, 2014

WFIRST-AFTA SDT

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previous SDT chairs: J. Green, P. Schechter

Executive Summary

- Project and SDT addressing those areas of concern from the NRC-WFIRST committee
- Good progress on all NRC findings/recommendations
- Coronagraph on track, technology development ahead of schedule
- Wide Field detector technology development on schedule
- Telescope being used within previous structural and thermal limits.
- External Technology Assessment Committee review process set up to provide independent review of technology development
- More formal risk management process instituted with increased funding; integral in allocating resources

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 reduce risk and shorten development time
  - Detector array development with H4RGs
  - Coronagraph technology development
  - Telescope utilization assessment
  - Science simulations and modeling
  - Requirements flowdown development
  - Observatory design work
- NASA objective for telescope is minimize cost/risk. NASA direction for coronagraph is to not drive requirements. Project / SDT driving to minimize cost while achieving NWNH science.
- 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
- Upcoming events
  - SDT report due in January 2015
  - Aerospace CATE completion in February 2015

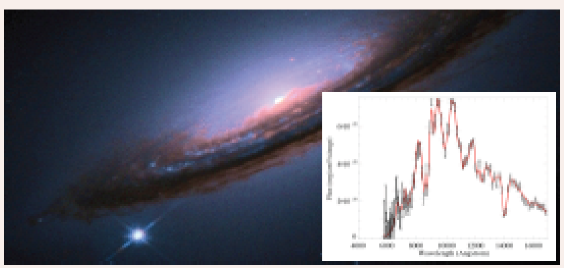
WFIRST-AFT Dark Energy Roadmap

Supernova Survey

wide, medium, & deep imaging
+
IFU spectroscopy

2700 type Ia supernovae
z = 0.1–1.7

standard candle distances
z < 1 to 0.20% and z > 1 to 0.34%



High Latitude Survey

spectroscopic: galaxy redshifts

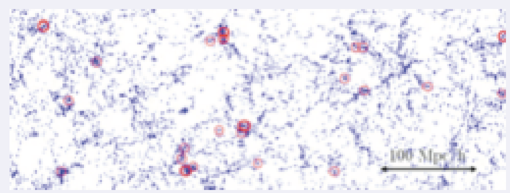
20 million Hα galaxies, z = 1–2
2 million [OIII] galaxies, z = 2–3

imaging: weak lensing shapes

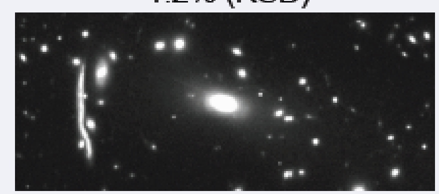
500 million lensed galaxies
40,000 massive clusters

standard ruler

distances	expansion rate
z = 1–2 to 0.4%	z = 1–2 to 0.72%
z = 2–3 to 1.3%	z = 2–3 to 1.8%

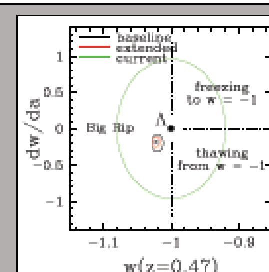


dark matter clustering
z < 1 to 0.16% (WL); 0.14% (CL)
z > 1 to 0.54% (WL); 0.28% (CL)
1.2% (RSD)

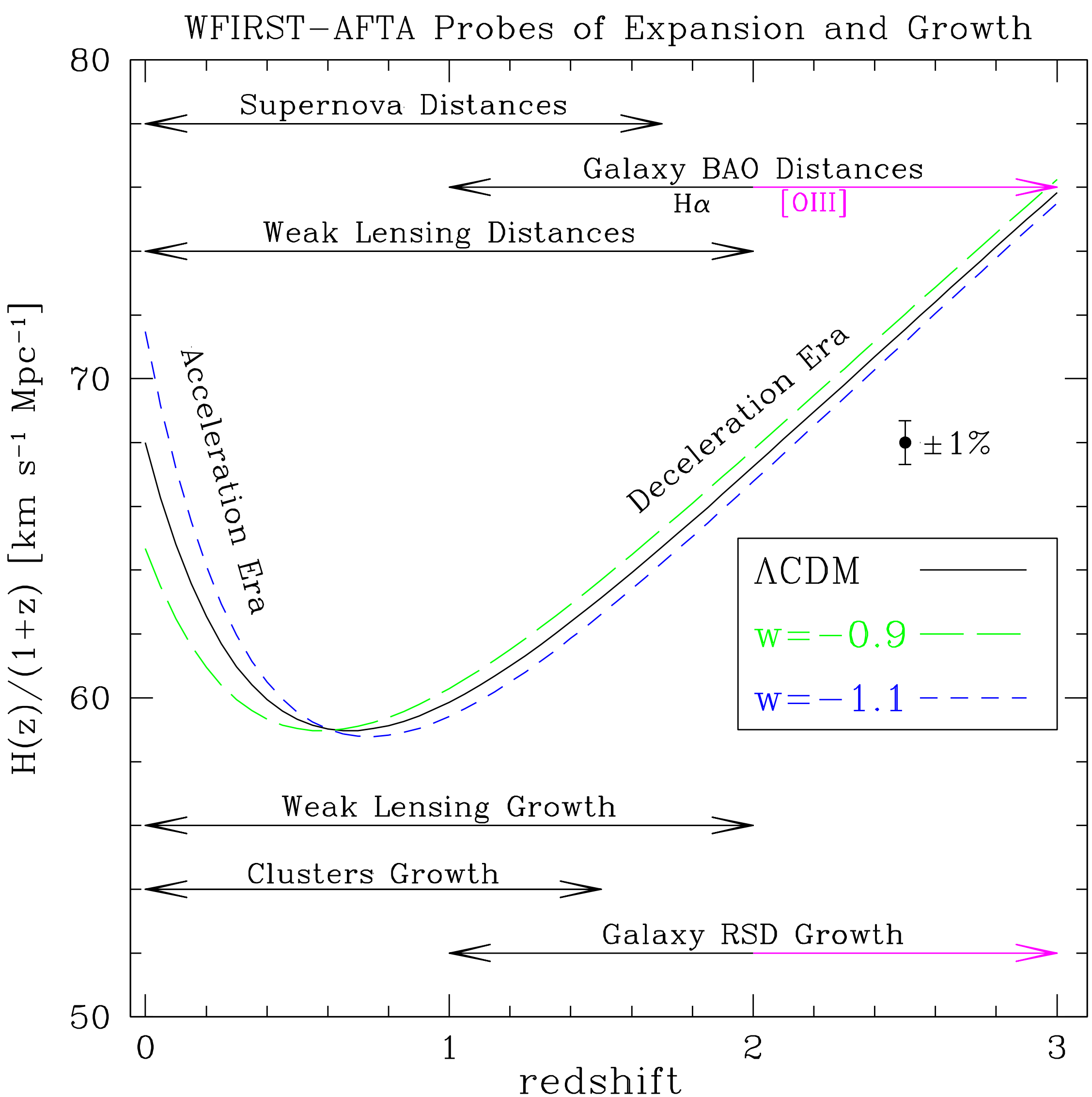


history of dark energy
+
deviations from GR

$w(z)$, $\Delta G(z)$, Φ_{REL}/Φ_{NREL}



WFIRST Dark Energy Program



WFIRST-AFTA & Euclid Complementary for Dark Energy

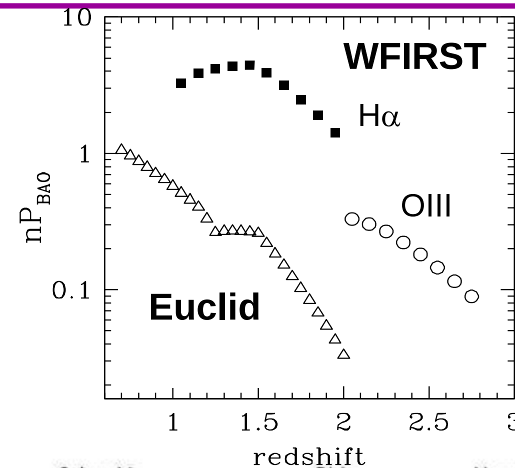
WFIRST-AFTA

Deep Infrared Survey (2,400 deg^2)

Lensing
- High Resolution (68 gal/arcmin^2)
- Galaxy shapes in IR
- 5 lensing power spectra

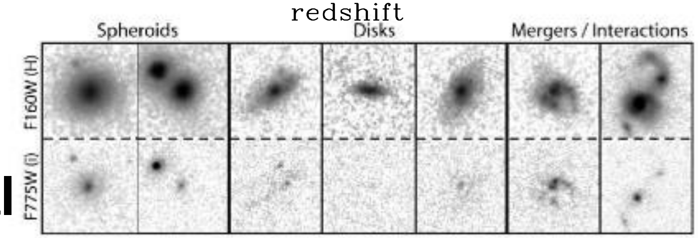
Supernovae:
- High quality IFU spectra of >2000 SN

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



IR

Optical



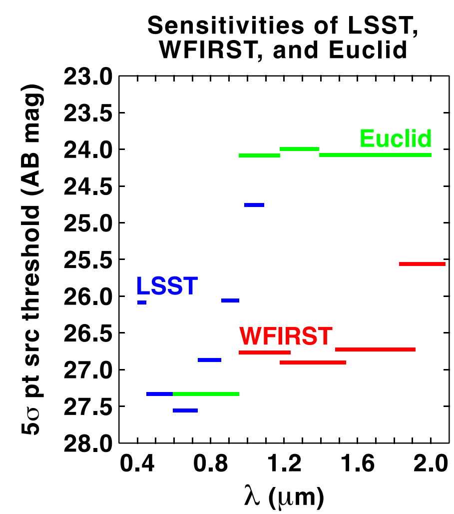
Euclid

Wide Optical and Shallow Infrared Survey (15,000 deg^2)

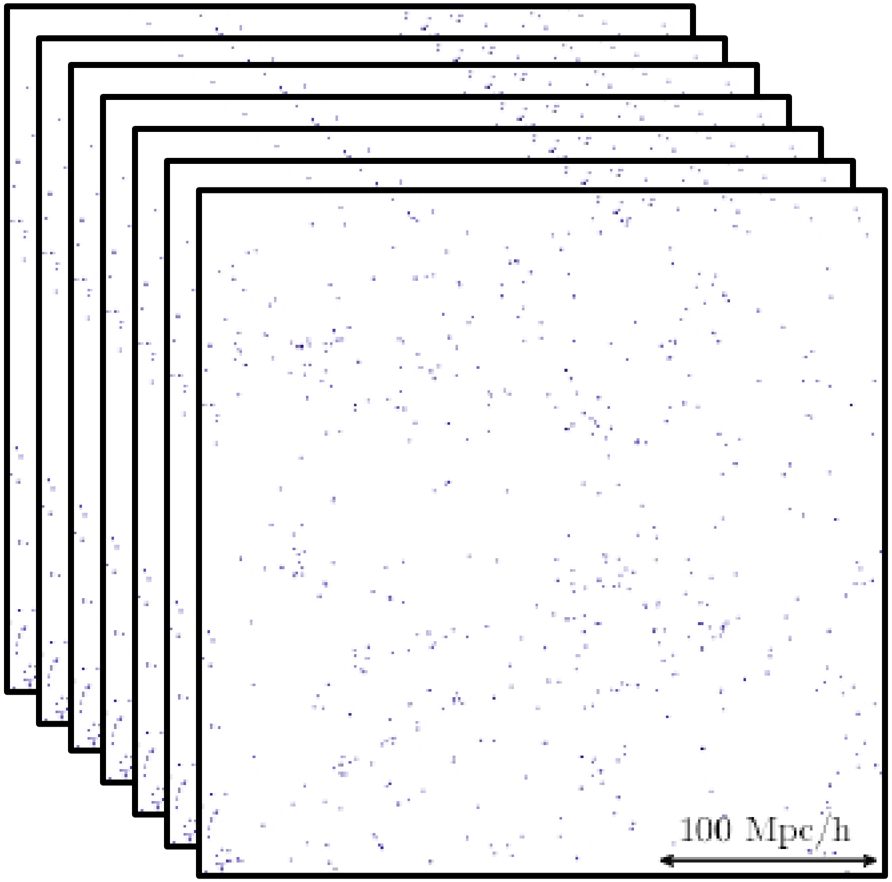
Lensing:
- Lower Resolution (30 gal/arcmin^2)
- Galaxy shapes in optical
- 1 lensing power spectrum

No supernova program

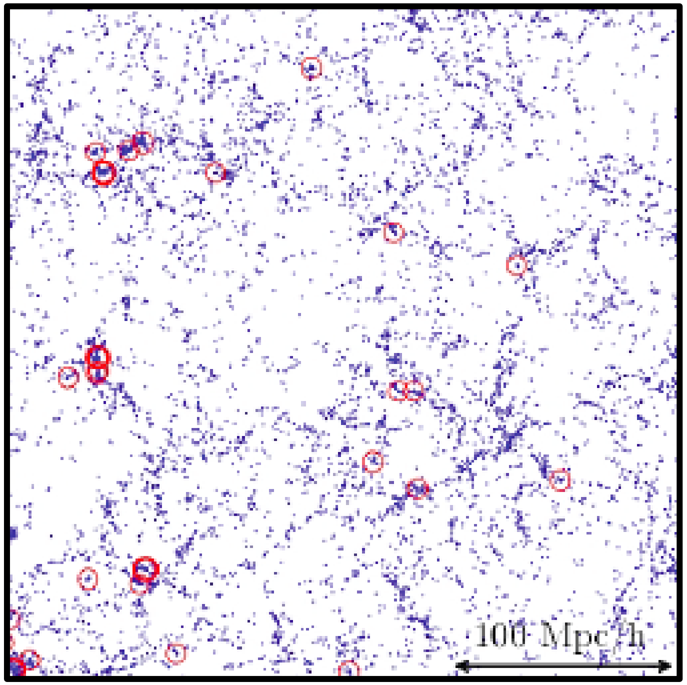
Redshift survey:
- Low number density of galaxies
- Significant number of low redshift galaxies



Redshift Surveys



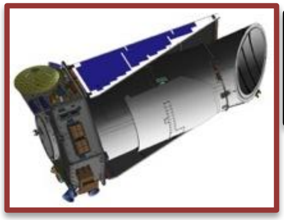
Euclid
15,000 deg^2 @ 1700 gal/deg^2



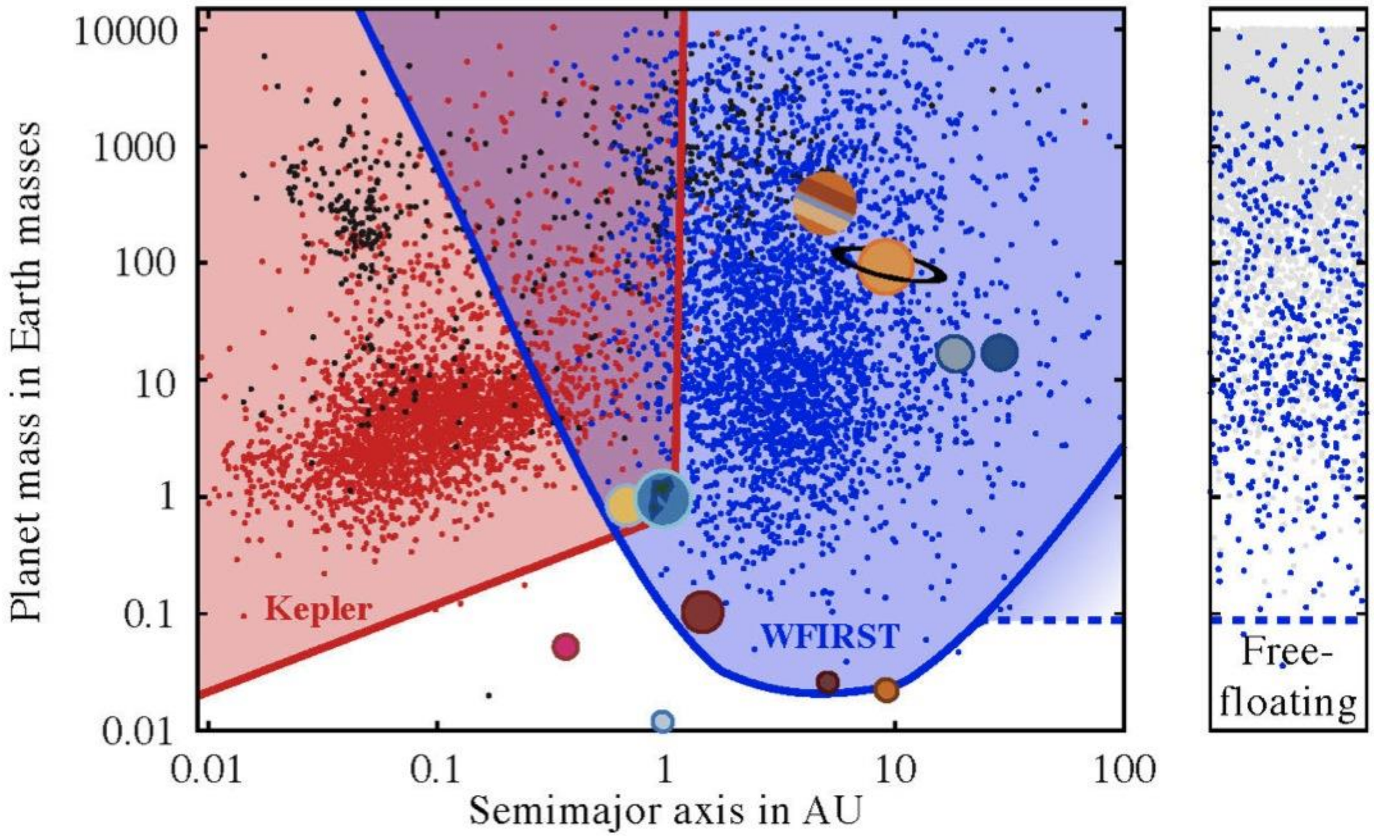
WFIRST
2,050 deg^2 @ 12,600 gal/deg^2

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

Completing the Statistical Census of Exoplanets

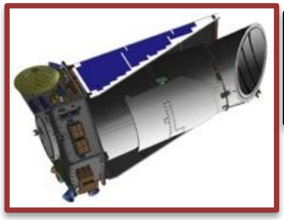


Combined with space-based transit surveys, WFIRST-AFTA completes the statistical census of planetary systems in the Galaxy.



M. Penny (OSU)

Completing the Statistical Census of Exoplanets



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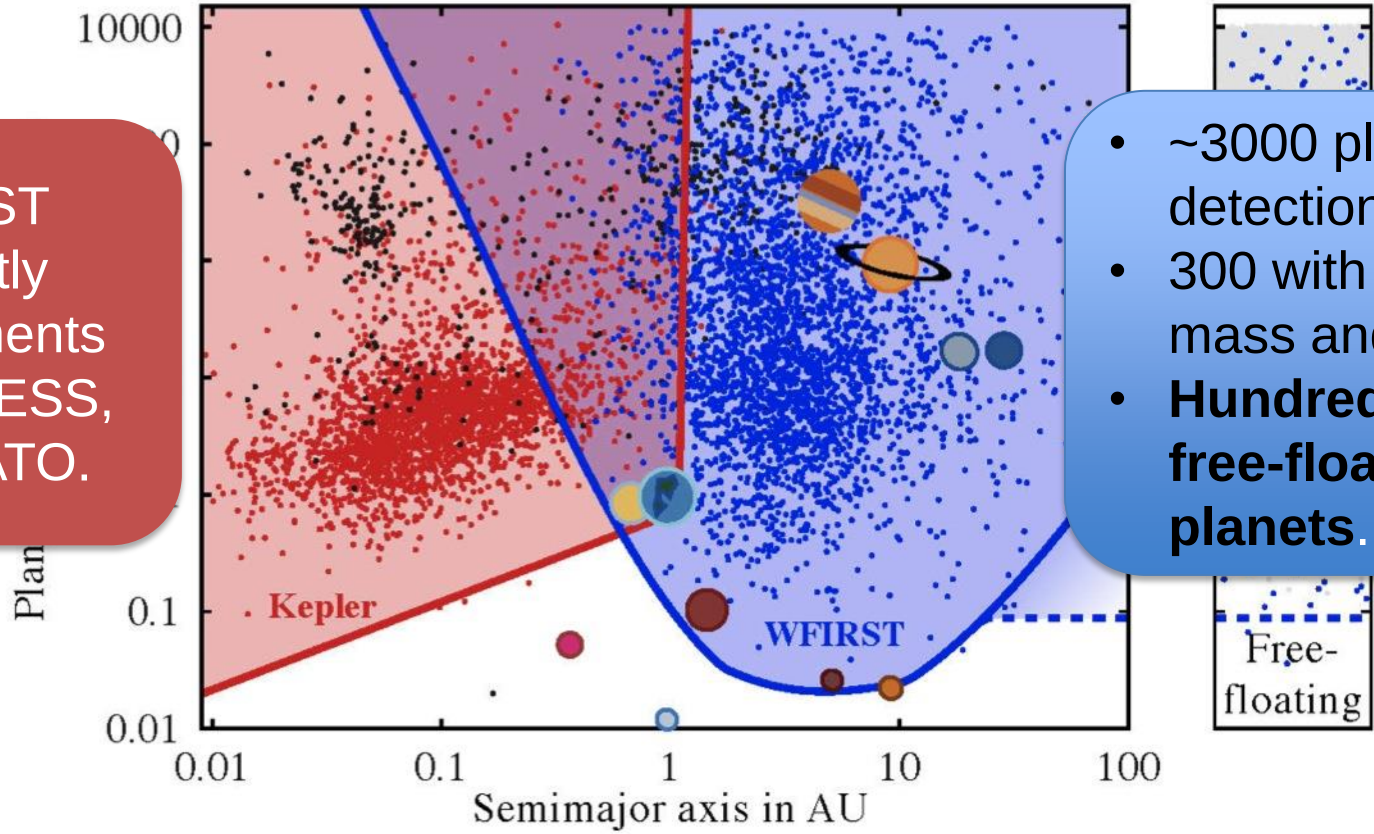
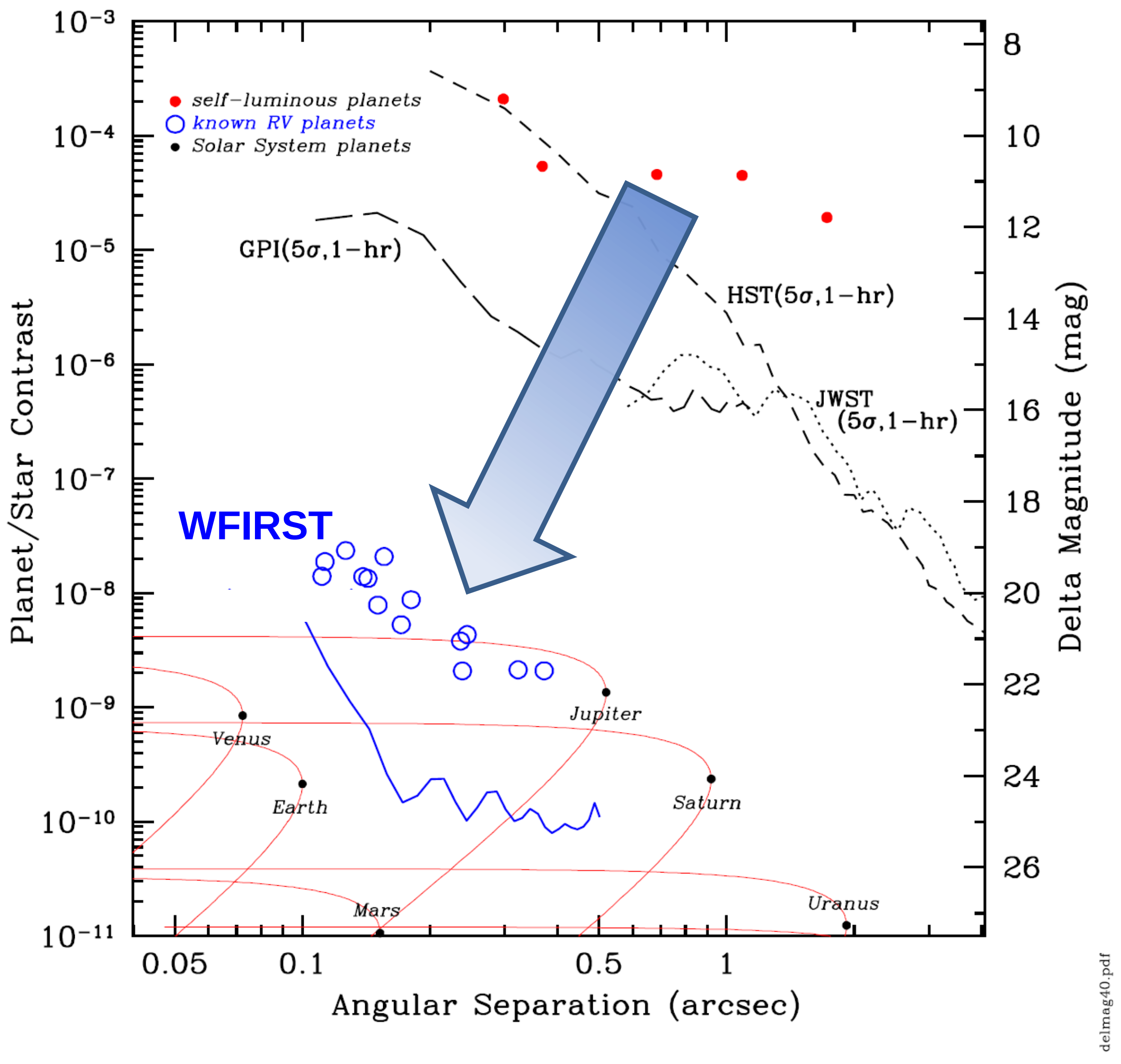


WFIRST perfectly complements Kepler, TESS, and PLATO.

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

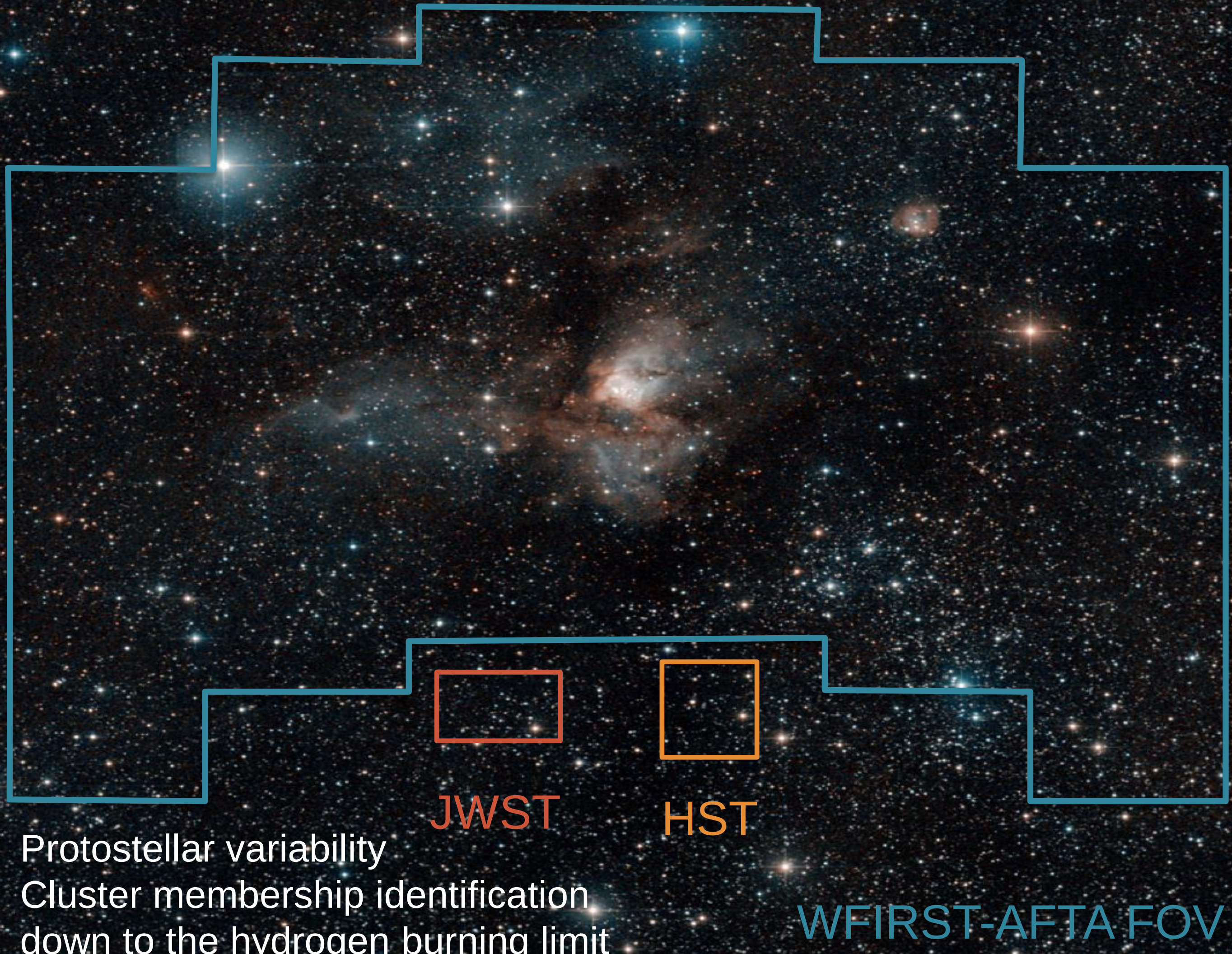
M. Penny (OSU)

Coronagraph Sensitivity



AFTA Provides the First Wide-Field High Resolution Map of the Milky Way

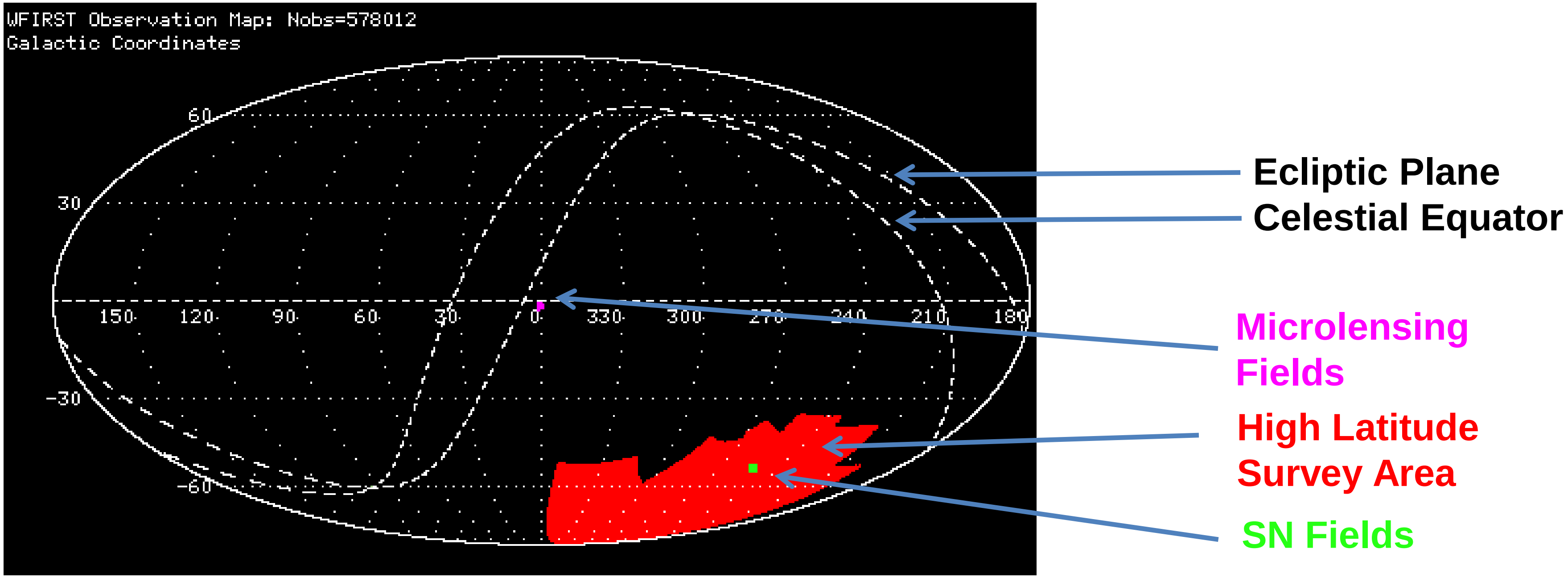
In RCW 38 (2MASS J & H shown) WFIRST-AFTA will reach 1000x deeper with 20x better angular resolution



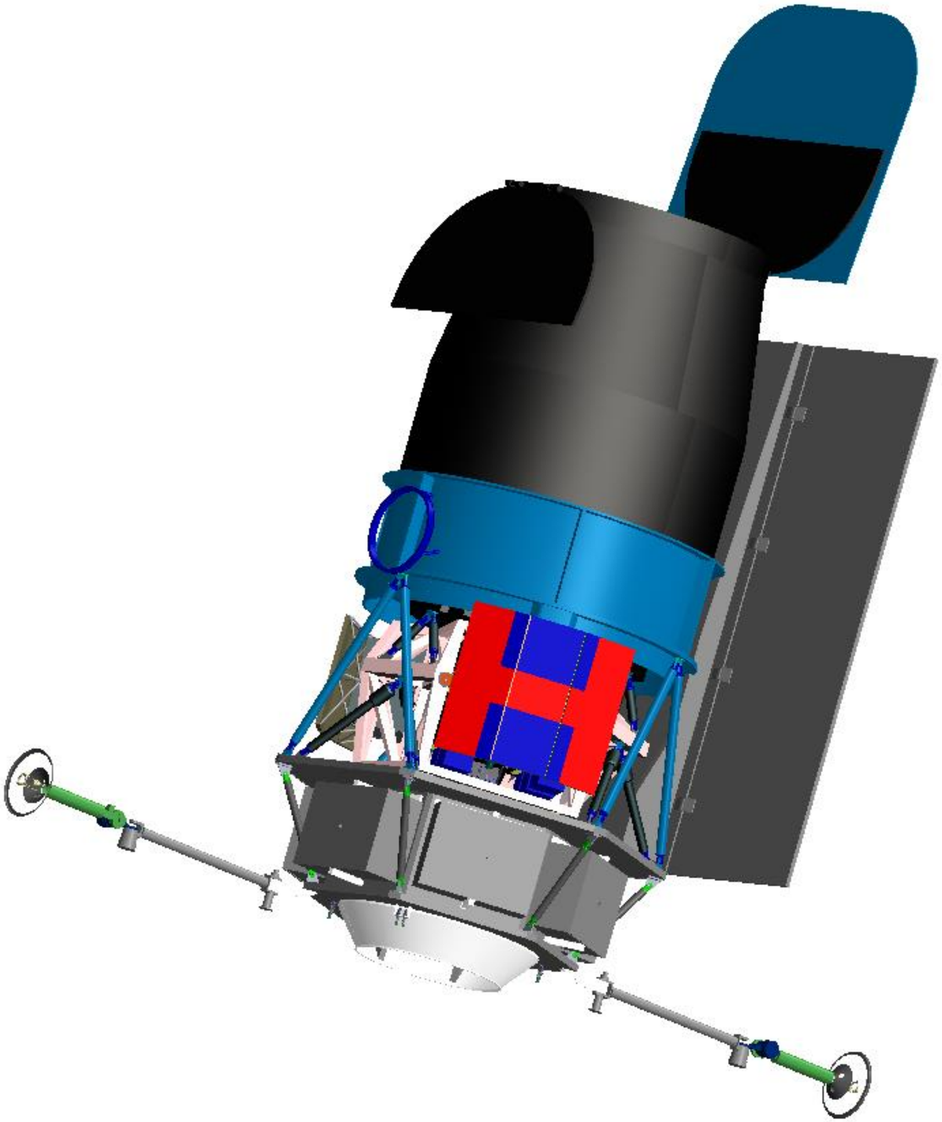
- Protostellar variability
- Cluster membership identification down to the hydrogen burning limit
- Dust extinction mapping

Example Observing Schedule

- High latitude survey (HLS: imaging + spectroscopy): 1.96 years
  - **2400 deg^2** @ ≥3 exposures in all filters (2440 deg^2 bounding box)
- 6 microlensing seasons (0.98 years, after lunar cutouts)
- SN survey in 0.62 years, field embedded in HLS footprint
- 1 year for the coronagraph, interspersed throughout the mission
- GO program is **25%** of the mission



WFIRST-AFTA Observatory Concept

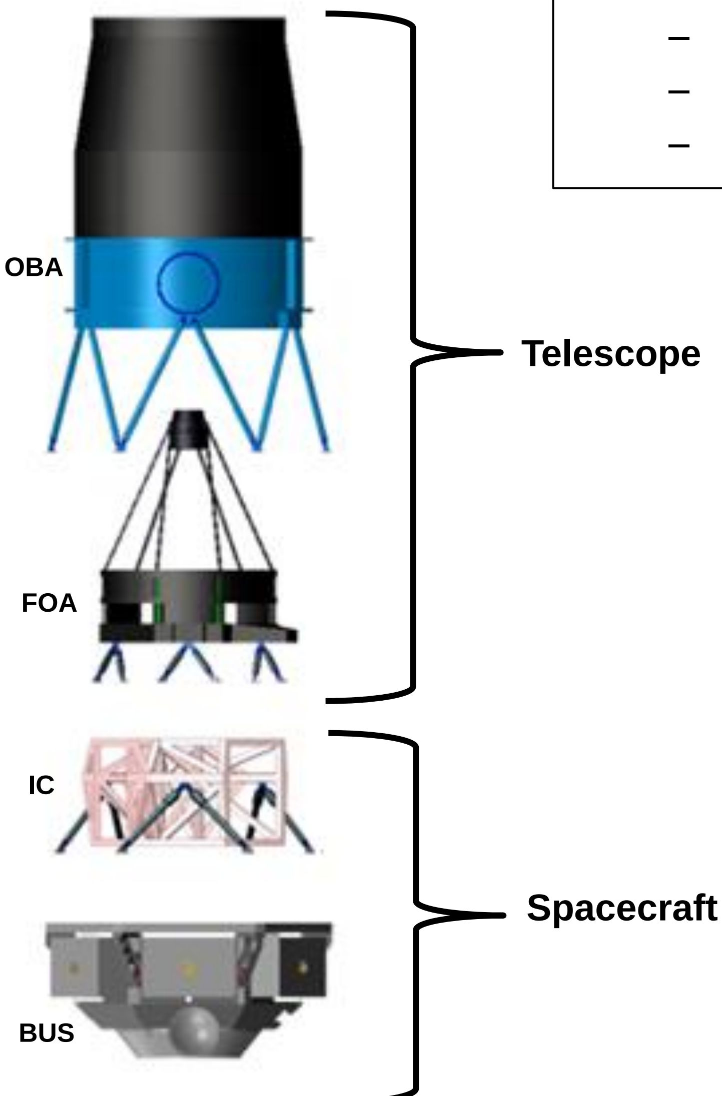


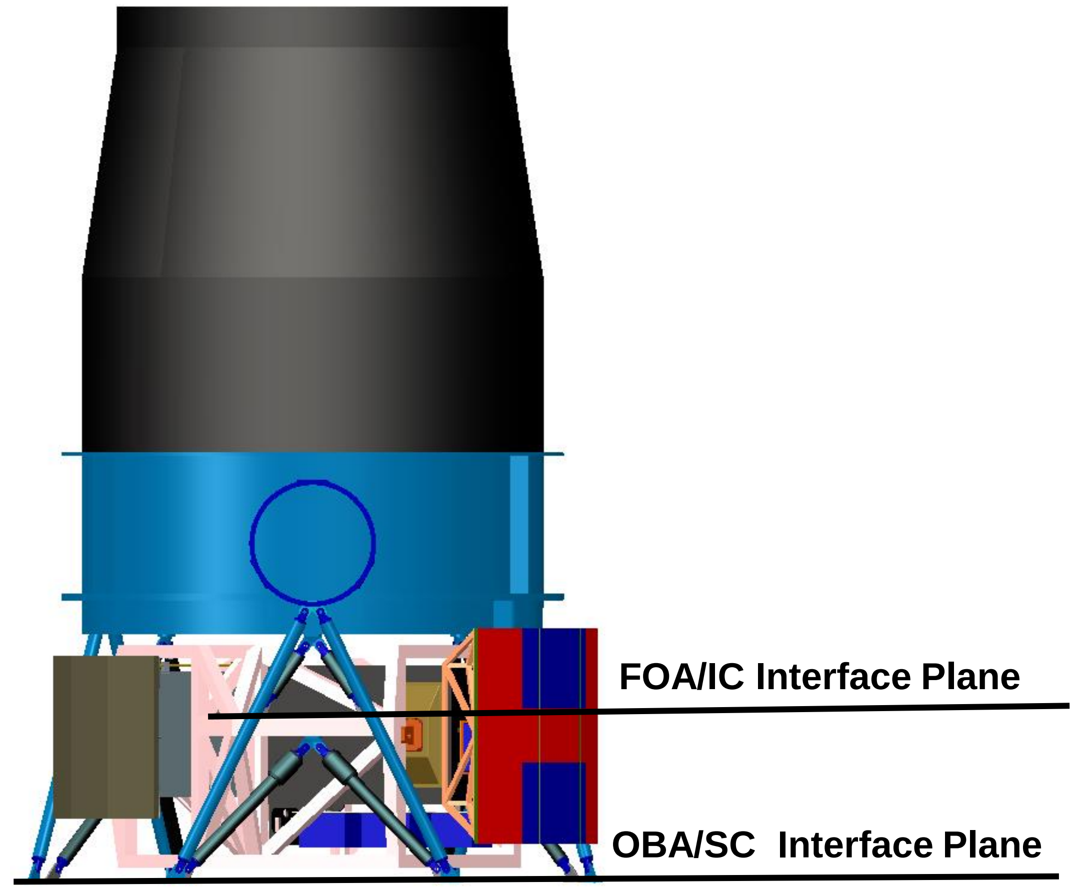
Key Features

- **Telescope**: 2.4m aperture primary
- **Instruments**
  - Wide Field Imager/Spectrometer & Integral Field Unit
  - Internal Coronagraph with Integral Field Spectrometer
- **Overall Mass**: ~4200 kg (CBE)
- **Structure**: high stiffness composites; modular packaging for avionics
- **GN&C/Propulsion**: inertial pointing, 3-axis stabilized, mono-prop system for stationkeeping & momentum unloading
- **Data Downlink Rate**: Continuous ~600 Mbps Ka-band to dedicated ground station
- **C&DH**: low rate bus for housekeeping and spacecraft control, high speed bus for science data
- **Power**: ~2500 W average power (CBE)
- **GEO orbit**
- **Launch Vehicle**: Delta IV Heavy
- **GSFC**: leads mission, wide field instrument, spacecraft
- **JPL**: leads telescope, coronagraph

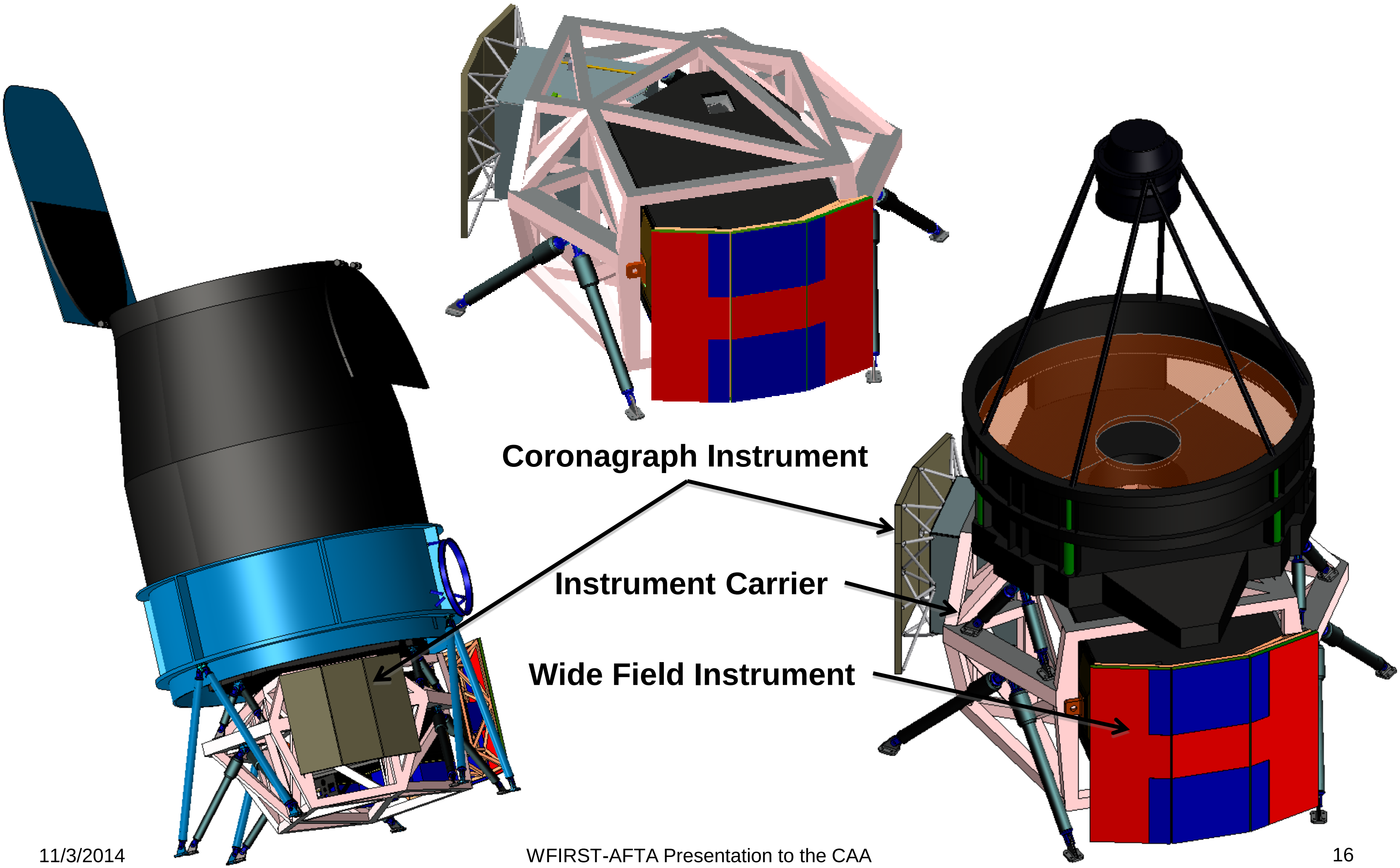
Observatory Interfaces

- **Interface Definition**
  - FOA Struts & OBA Struts are part of Telescope
  - IC & IC D-Struts are part of Spacecraft
  - BUS is part of Spacecraft

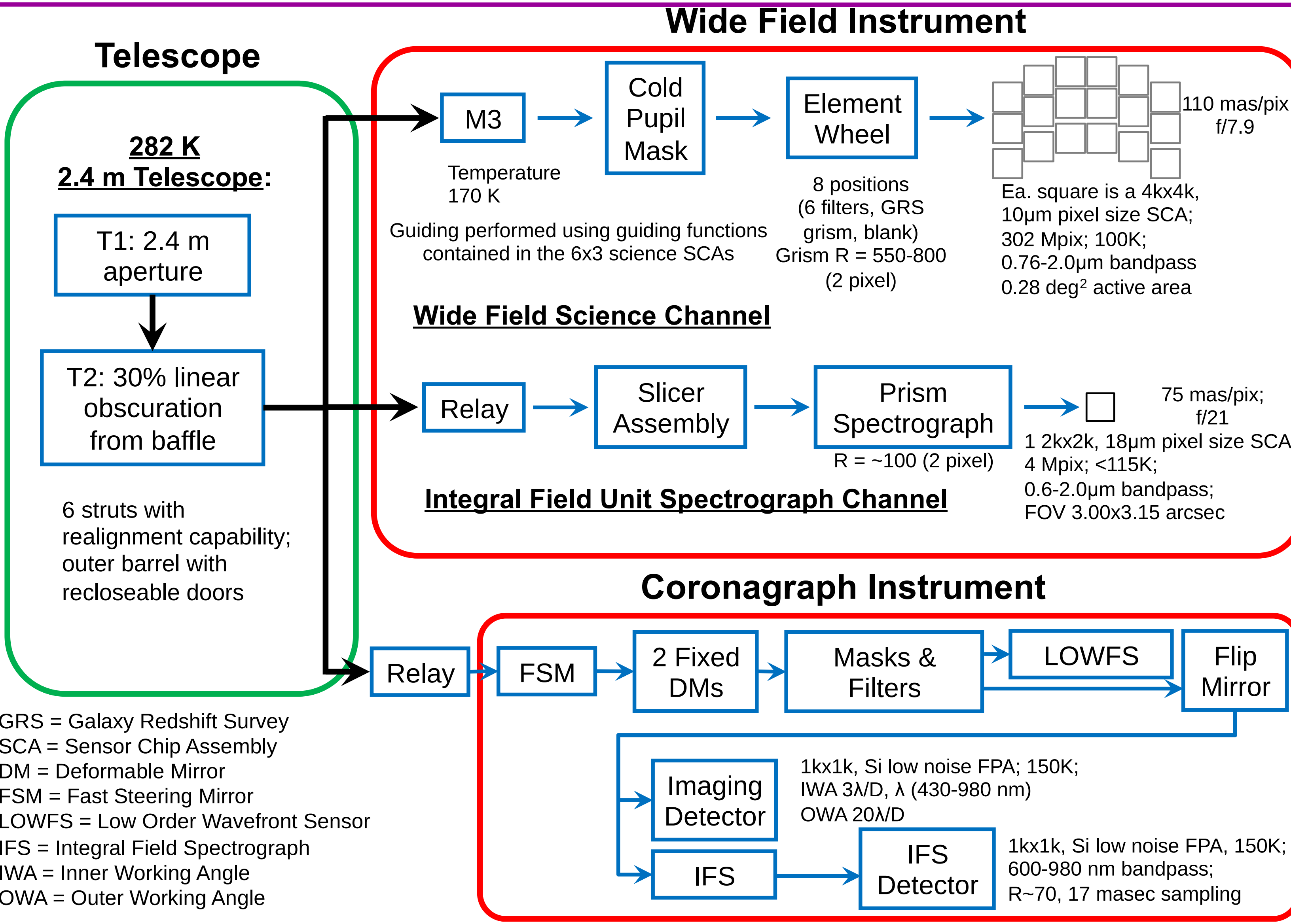




WFIRST-AFTA Payload Layout



WFIRST-AFTA Payload Optical Block Diagram

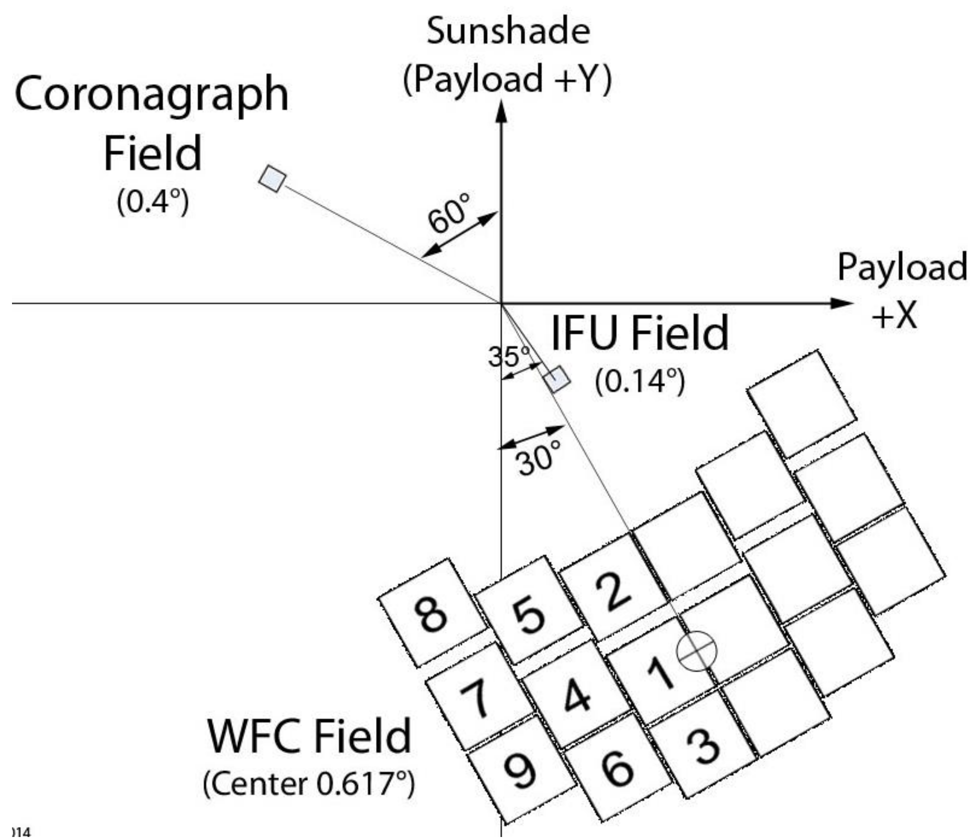


GRS = Galaxy Redshift Survey
SCA = Sensor Chip Assembly
DM = Deformable Mirror
FSM = Fast Steering Mirror
LOWFS = Low Order Wavefront Sensor
IFS = Integral Field Spectrograph
IWA = Inner Working Angle
OWA = Outer Working Angle

Optical Field Layout

- The Wide Field Instrument has two optical channels
  - A wide field imager and grism spectrometer
  - An integral field unit, used for supernova spectroscopy
- The coronagraph is a small field system in a separate field of view
  - Contains an imager and a integral field spectrometer viewing the same field

Channel Field Layout for WFIRST-AFTA Instruments



Telescope Overview

- 2.4 m, two-mirror telescope provided to NASA. Built by 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
  - FOA designed for operation at room temperature (293 K) with lower limit temperature of 277 K, OBA lower limit temperature of 216 K.
  - Outer barrel includes recloseable doors
  - Passive damping via D-struts
  - Primary mirror to be ion-figured and recoated (no grinding required)

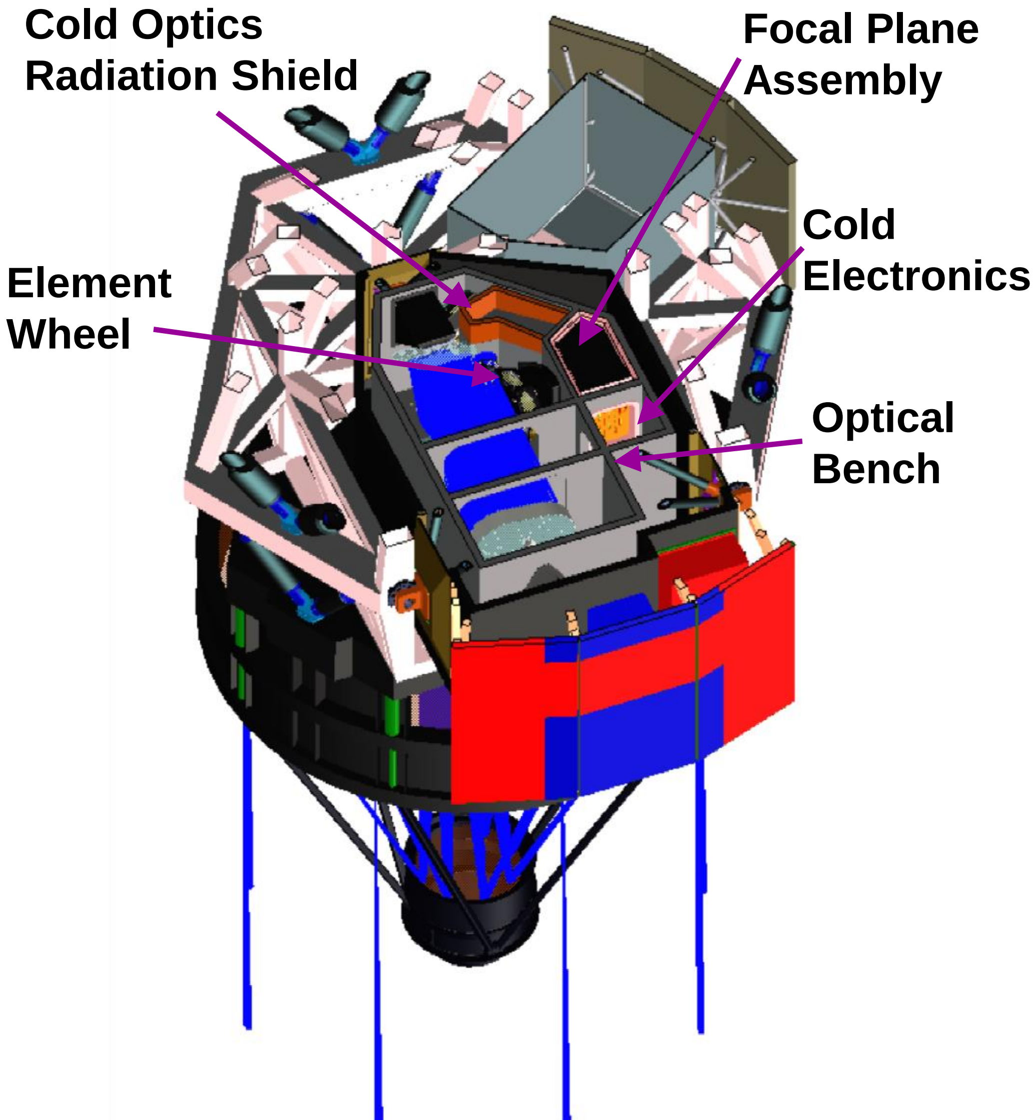
Telescope Design to Minimize Risk

- Exelis/JPL/Project have worked closely together to understand the structural capability of the telescope aft metering structure.
- Current design with the instrument carrier as the interface between the spacecraft and the payload provides substantial margin at the qualified telescope interfaces.
  - Instrument carrier is the prime optical metering structure for the payload, telescope and both instruments are attached to it.
- Telescope operating temperature baseline is 282 K and is within the limits of the heritage program.
- Electronics and actuators that are not available will use the latest designs from the Exelis product lines.

Wide Field Instrument Overview

Key Features

- Wide field channel instrument for both imaging and spectroscopy
  - 3 mirrors, 1 optically powered
  - 18 4K x 4K HgCdTe detectors cover 0.76 - 2.0 μm
  - 0.11 arc-sec plate scale
  - Single element wheel for filters and grism
  - Grism used for GRS survey covers 1.35 – 1.90 μm with R between 645 - 900
- IFU channel for SNe spectra, single HgCdTe detector covers 0.6 – 2.0 μm with R between 80-120



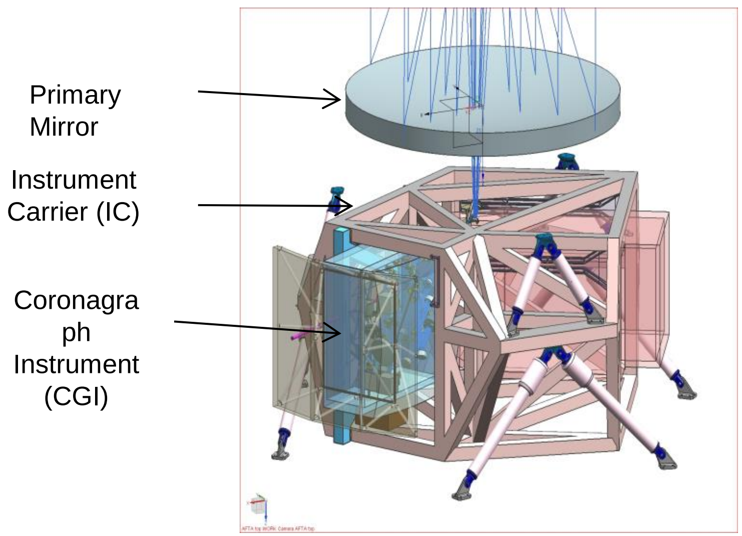
Detector Technology Maturation

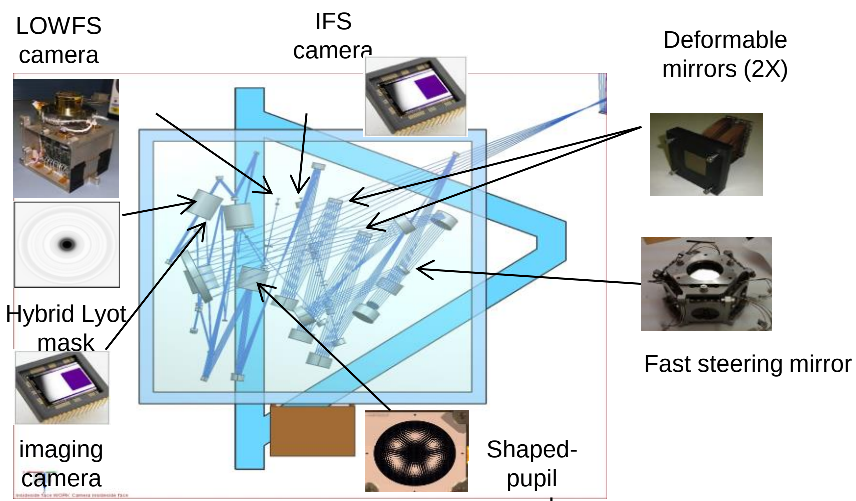
- Detector Technology Development Plan released with 5 key milestones identified to mature the HgCdTe detectors by the end of CY16.
- 5 detector technology milestones negotiated with NASA HQ with independent confirmation of milestone completion by the WFIRST Technology Assessment Committee.
  - Milestones cover process optimization lots, full array lots, the yield lot. and environmental testing with performance targets for key detector requirements.
  - Approved overall plan in April 2014.
  - First milestone review passed in August 2014.
  - Second milestone review to be held by December 2014.
  - TAC Members: Alan Boss, Judy Pipher, Erick Young

Detector Progress Since Last Update

- The wide field detector maturation plan was presented to the CAA in March 2014.
- The "banded array" devices are now all completed and characterized.
- Selected a recipe to move forward with for a lot of "full array" devices
  - Selected recipe meets draft requirements over the selected band.
  - First devices are expected in May 2015.
  - A second lot of another recipe to be started as a backup option
- It is still the plan to build a final development lot, the "yield demonstration" lot, after the best recipe has been selected from the Full Array lots.

Coronagraph Instrument Overview





Temperature	20C for instrument
Temperature	~163k for cameras
Data volume	~30 Gbits/day
Imaging	0.4 – 1.0 microns, 4.8" FoV 0.009" pixel scale, 1K×1K EMCCD
Integral field spectrograph	0.6 – 1.0 microns R~70

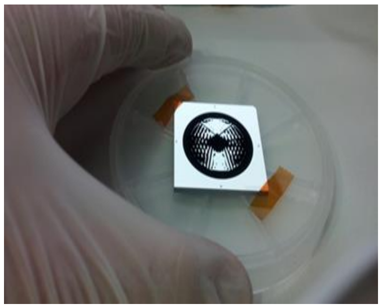
Coronagraph Technology Maturation Progress

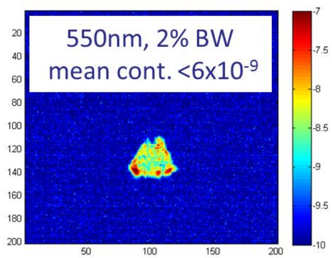
- Coronagraph Technology Development Plan released with 9 key milestones identified to mature the coronagraph technologies by the end of FY16.
- 9 coronagraph technology milestones negotiated with NASA HQ with independent confirmation of milestone completion by the WFIRST Technology Assessment Committee.
  - Milestones cover mask development, contrast demonstration in narrow and broadband light in static and dynamic environments and detector performance.
  - Milestone 1 completed: Demonstrated manufacturability of reflective Shaped Pupil (SP) masks within specifications.
  - Milestone 2 completed: Demonstrated 10^{-8} raw contrast in narrowband light for SP
  - Milestone 5: Demonstrated 10^{-8} raw contrast in broadband light for SP over 1 year early.
  - Currently testing Hybrid Lyot mask, two different manufacturing methods in development for this mask
  - TAC Members: Alan Boss, Rebecca Oppenheimer, Joe Pitman, Lisa Poyneer, Stephen Ridgway

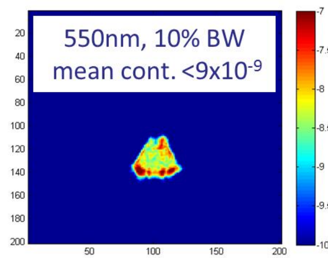
Coronagraph Technology Development Highlights

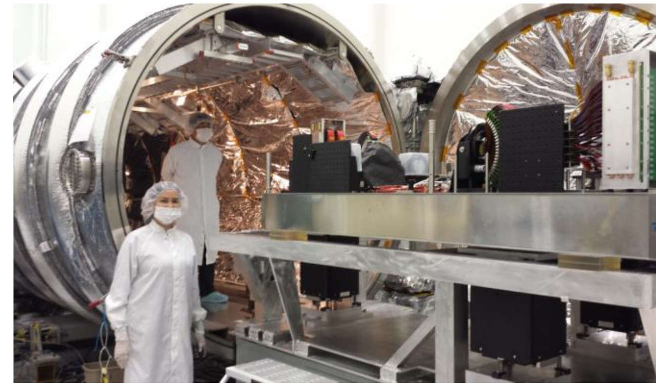
Reflective shaped pupil mask

- Black Si on Al mirror coating demonstrated at JPL/MDL and Caltech/KNI
- High contrast demonstrated at HCIT



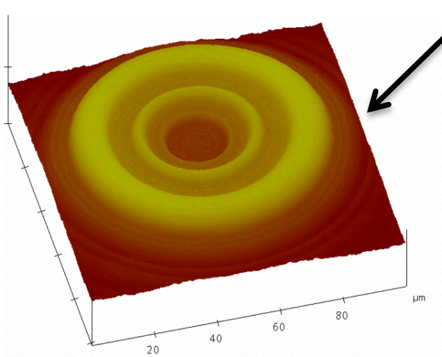


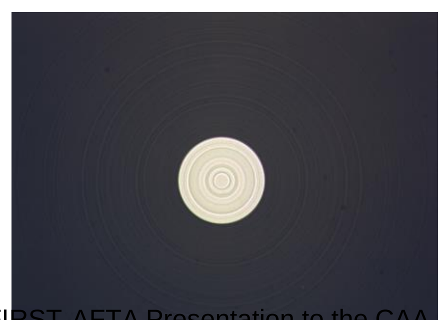


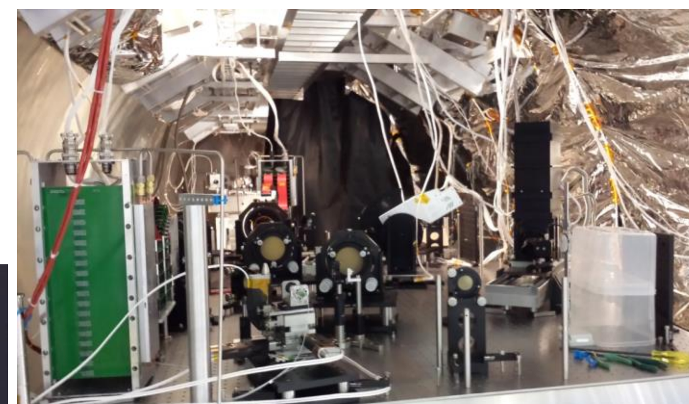


Transmissive hybrid Lyot mask

- Circular mask fabricated and measured
- Testbed commissioned on 8/15/2014

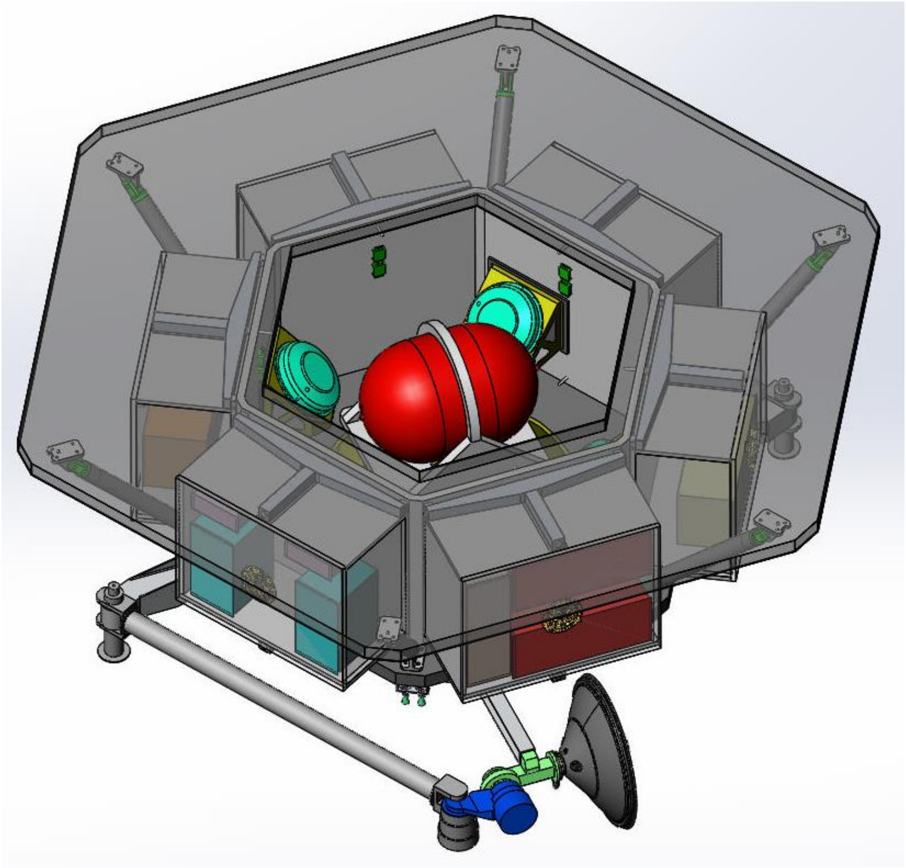






Spacecraft Overview

- Design relies on recent GSFC in-house spacecraft electronics designs
- Spacecraft module design enables serviceability and leverages designs from the Multimission Modular Spacecraft (MMS).
- Uses a distributed avionics architecture to facilitate modular approach



WFIRST-AFTA bus concept

NRC Review Charge

- An ad hoc committee will assess whether AFTA is responsive to the overall strategy to pursue the science objectives of NWNH WFIRST.
- In its assessment, the committee will:

  1. **Compare the NWNH WFIRST to AFTA**, with and without the coronagraph, on the basis of their science objectives, technical complexity, and programmatic rationale, including projected cost.

  2. Based on the above comparison and taking into account any relevant **scientific, technical, and programmatic changes** that have occurred since the release of NWNH:

     a) Assess responsiveness of AFTA, with and without the coronagraph, to the **overall strategy to pursue the science objectives of NWNH WFIRST**

     b) Assess responsiveness of AFTA with the coronagraph to the science & technology objectives of the **NWNH technology development program**

NRC Report – Endorsement of Strength of Science Program

- **Finding 1-5:** The observing program envisioned for WFIRST/AFTA is consistent with the science program described for WFIRST in NWNH.
- **Finding 1-3:** The importance of exploring the diversity of planetary systems in the parameter space probed by the WFIRST microlensing survey is as vital as it was in NWNH. No other current mission or technique can address this issue. Both WFIRST/IDRM and WFIRST/AFTA can carry out the envisioned survey.
- **Finding 1-4:** The WFIRST/AFTA telescope's large number of pixels and better point spread function (PSF) sampling will allow astrometry derived from drift scanning to break degeneracies inherent in interpreting the microlensing data.
- **Finding 1-6:** Budget constraints will slip the start of an Earth-like planet imaging mission beyond the horizon envisioned by NWNH; however, developing the technologies for such a mission and addressing the key uncertainties, such as the levels of exozodiacal light and identifying targets, remains high priority.
- **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.

NRC Theme #1 - Astrophysics Program Balance Response (1 of 3)

- **Finding 3-3:** If implementing WFIRST/AFTA compromises the program balance, then it is inconsistent with the rationale that led to the high-priority ranking.
- **Finding 2-1:** If the funding wedge provided for WFIRST/AFTA is not sufficient to accommodate the mission cost and provide contingency appropriate to the mission risk, it could be very damaging to the program recommended by NWNH.
- **Finding 2-8:** Without corresponding augmentation to other NASA programs accompanying funding to include the coronagraph on WFIRST, the inclusion of the coronagraph is not consistent with stated priorities in NWNH. In a time of reduced budgets, the first priority in NWNH is "to develop, launch, and operate WFIRST, and to implement the Explorer program and core research program recommended augmentations." Implementing the coronagraph would address some aspects of the exoplanet technology development; the exoplanet technology development program was considered a lower priority by NWNH.

RESPONSE:

- The Astrophysics outyear budget funds both WFIRST and a robust Explorer Program (on-going 2014 call and planned 2016 call)

NRC Theme #1 - Astrophysics Program Balance Response (2 of 3)

RESPONSE (cont.):

- The APD has funded multiple independent cost estimates of WFIRST (& JDEM) during pre-formulation, and these numbers have been consistently in close agreement with the Project's estimates (10-20%). This is attributable to the low-medium risk nature of the mission.
- The Project, the JPL telescope team, and Exelis believe the cost of re-assembling the 2.4m telescope is less than the cost of developing a 1.3m off-axis telescope, that has neither been designed nor flown. The telescope costs being used in the upcoming Project estimate are higher fidelity, developed using the build records from the original 2.4 m telescope fabrication.
- Extensive mechanical trades over the past year have led to the selection of a payload structural design that uses the telescope within its original qualification design space, eliminating threats associated with the re-design or re-qualification of the telescope.

NRC Theme #1 - Astrophysics Program Balance Response (3 of 3)

RESPONSE (cont.):

- At HQ's request, the upcoming Project LCC and CATE will isolate the launch vehicle costs to provide clarity in the basic mission cost/risk assessment.
- The cost increase of the mission incorporating the existing 2.4m aperture will not only improve the WFIRST science envisioned by NWNH, but enables a robust **GO program** with better than Hubble-quality and 100x the FoV and an opportunity to perform **high contrast exoplanet imaging and spectroscopy** a decade earlier than current budgets might allow.

> ✓ ***Utilizing the 2.4m telescope on WFIRST creates a highly leveraged science opportunity (high contrast exoplanet imaging) on top of an enhanced WFIRST science mission (surveys & GO).***
>
> ✓ ***Program balance should be examined, with the recognition that a major science program not envisioned by NWNH is added to the mission.***

NRC Theme #2 - Cost Risk with 2.4m WFIRST (1 of 5)

- The committee's evaluation notes that there are risks as well as benefits of utilizing inherited hardware designed for another purpose. Informed by this and the Aerospace cost and technical evaluation (CATE), the committee offers the following finding:

- **Finding 2-4:** The risk of cost growth is significantly higher for WFIRST/AFTA without the coronagraph than for WFIRST/IDRM.
- **Finding 2-2**: The use of inherited hardware designed for another purpose results in design complexity, low thermal and mass margins, and limited descope options that add to the mission risk. These factors will make managing cost growth challenging.

RESPONSE:

- The Project has focused on five key areas over the last year to address the risk of cost growth. These areas are 1) continued maturation of the design with a focus on mass margin, 2) end-to-end optical testing, 3) STOP analysis, 4) understanding the existing telescope hardware, and 5) using the telescope within the existing qualification limits

NRC Theme #2 - Cost Risk with 2.4m WFIRST (2 of 5)

1) Maturation of the design with a focus on mass margin
   - The engineering teams at GSFC, JPL and Exelis have continued to mature the observatory design over the last year to provide greater fidelity to the concepts with a focus on minimizing mass growth during this maturation process.
   - With the addition of the coronagraph and the desire to simplify the spacecraft, the Project moved to a heavy lift launch vehicle to provide direct ascent into the geosynchronous orbit, eliminating the large bi-prop system and >3,000 kg of fuel. The modest cost increase for the larger rocket is offset by savings in structure, prop system/fuel, flight dynamics/operations for the GTO.
2) End-to-end optical testing: the Project has begun defining the end-to-end optical tests to verify performance of the system.
   - Identified tests and associated GSE at the element level (telescope, wide field, coronagraph) as well as at the payload/observatory level
   - Early simulations show that an end-to-end double pass test through the wide field and telescope against a cold autocollimation flat can verify optical performance in flight configuration after subsystem tests such as telescope gravity sag correlation and instrument level testing are completed
   - Incorporated into the overall schedule and cost estimate

NRC Theme #2 - Cost Risk with 2.4m WFIRST (3 of 5)

3) STOP analysis for wide field and coronagraph

- Wide Field structural/thermal/optical performance (STOP) stability specs met with margin
  - Coronagraph STOP stability in line with Wide Field requirements
  - Coronagraph not driving thermal stability requirements
- Wide Field Jitter stability specs met with significant margins for all disturbance sources
  - Coronagraph jitter stability in line with Wide Field
  - Coronagraph not driving jitter stability requirements
    - Sources include all anticipated noise sources during Wide Field science integrations: reaction wheels, high gain antenna, and cryocooler

NRC Theme #2 - Cost Risk with 2.4m WFIRST (4 of 5)

4) Understanding the existing telescope hardware: the focus of overall telescope effort over the last year has been on understanding the capabilities of the existing hardware and what it takes to complete the telescope
   - Multiple technical interchange meetings between JPL/Exelis/GSFC targeting specific topics (e.g. state of the hardware, structural capabilities, integration and test)
   - Exelis established telescope development schedule based on the durations of historic builds for the original two units along with other recent telescope builds. Results in low risk of cost/schedule growth.

5) Using the telescope hardware within existing limits: significant mechanical design efforts by the JPL/Exelis/GSFC Team have resulted in the selection of a payload mechanical design that allows the telescope to be flown on WFIRST within its original structural design specifications.
   - The instrument carrier now supports the telescope and is the optical metering structure for the entire payload.
   - This structure supports the telescope instead of the telescope supporting it. The telescope is only supporting it’s own mass.
   - A mass increase in the instruments ***will not*** require a telescope redesign and the telescope will fly in a more benign loading environment than the original application.

NRC Theme #2 - Cost Risk with 2.4m WFIRST (5 of 5)

5) Using the telescope hardware within existing limits (cont'd)

- The Project and SDT have agreed to baseline an operating temperature of 282K, 5 K above the previous minimum telescope temperature. No additional thermal testing is required to qualify the hardware. Thermal testing will be performed across the operating temperature range as is typical for NASA missions.
  - The science impact of changing the telescope temperature is addressed in NRC Theme #3.

✓ ***DRM has continued to focus on minimizing cost growth while providing additional mass margin through a larger launch vehicle***

✓ ***Early attention to integration and test to identify key cost and schedule drivers***

✓ ***Structural/Thermal/Optical analysis shows both instruments performing within spec***

✓ ***Telescope hardware used within original mechanical and thermal design limits minimizes risk***

NRC Theme #3 – Compromises to Science to Control Risk

- **Finding 2-3**: The mission may have to compromise some science performance to ensure issues associated with the low thermal margins do not lead to significant cost growth and schedule delay.

RESPONSE:

- The Project concurs with the report finding that science performance should be traded against cost and schedule risk.
- Evaluation of the telescope operating temperature is an example of one such trade. A temperature of 282K was selected as the baseline to minimize telescope development risk.
- The WFIRST-AFTA Science Definition Team assessed the impact of raising the telescope temperature from the previous baseline of 270K and determined the impact on the baseline science program is minor.
  - Weak lensing: lose 0.3mag depth in F184 band, 0.08mag in H. Reduction in galaxy number density is only 5% in H, none in Y, J.
  - GRS: shift λ cutoff from 1.95μ to 1.90μ (Hα redshift cutoff shifts from 1.97->1.89). Net reduction in galaxy yield is 11%.
  - SNIa, microlensing: no significant impact
  - Still outperforms NWNH performance goals

✓ ***The Project and SDT agreed to raise the operating temperature to 282K to balance science return with engineering risk.***

✓ ***Very minor impact to the science, still outperforms NWNH***

NRC Theme #4 - Technology Accommodation (1 of 4)

- Because of the immature design and because there has been very limited study of the coronagraph's accommodation on the mission, the committee could not quantitatively assess the cost and risk impact to the WFIRST/AFTA program. However, the committee found the following:
- in addition to the obvious progression of the coronagraph technology
- **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 2-7**: WFIRST's moderate cost, low technical risk, and mature design were important to its ranking as the top priority for a large space mission in NWNH. The inclusion of the coronagraph compromises this rationale.

RESPONSE:

- To understand the level of risk that the coronagraph introduces into an otherwise low-medium risk WFIRST mission, it is necessary to examine:
  - A. coronagraph accommodation requirements on the observatory
  - B. the maturation of the coronagraph technology *(will be addressed in Theme #5)*
  - C. coronagraph schedule dependencies and relationship to the mission critical path, including the coronagraph verification approach
- We'll address each of these potential drivers.

NRC Theme #4 - Technology Accommodation (2 of 4)

- The coronagraph is a tech demo and HQ has directed that the coronagraph will not impose driving requirements onto the mission design.
- During the coronagraph selection process (ACWG) last year, selecting occulting techniques which would not impose driving requirements on the WFIRST payload and observatory was a key criteria.
  - Resulted in Shaped Pupil and Hybrid Lyot being selected.

A. Coronagraph accommodations requirements – The coronagraph imposes modest interface and resource requirements on the WFIRST observatory
  - Mass: The coronagraph mass represents a 3% increase to the observatory mass (116kg/4200kg).
  - Power: The coronagraph increases average power 7% (168W/2500W).
  - Data: The coronagraph increases average data rate 0.05% (0.3Mbps/600Mbps)
  - Pointing jitter: Both SP and HL operational modes achieve performance with baseline wide field jitter requirement (14 mas rms/axis). No driving requirement.
  - Coronagraph designs are being optimized to reduce jitter/low-order WFE sensitivity
  - Low frequency thermal deformation: Wavefront errors induced due to orbital rate movement or observatory retargeting are small (1.2 nm/hr), deterministic, and well within the bandwidth of the coronagraph's LOWFS.

NRC Theme #4 - Technology Accommodation (3 of 4)

B. Coronagraph technology progress – See Theme #5

C. Coronagraph schedule considerations –

- The coronagraph has a separate front-end optic collimator sub-bench which will be delivered to the telescope forward optic assembly during telescope I&T. This establishes the end-to-end telescope alignment and verification (coronagraph optical path) early during the I&T phase.
- Performance testing of the flight coronagraph is accomplished at instrument level, with the dynamic telescope simulator (pupil, jitter, drift, polarization, etc.).
- This eliminates the potential for the coronagraph to drive the payload I&T flow.
- In addition, the coronagraph has inherent descope opportunities if schedule problems arise, as either SP or HL could perform the coronagraph science mission.
- With the coronagraph verification strategy uncoupled from serial payload flow, and the inherent redundancy in operational modes, the coronagraph should not impact the WFIRST critical path.

Other coronagraph descope considerations

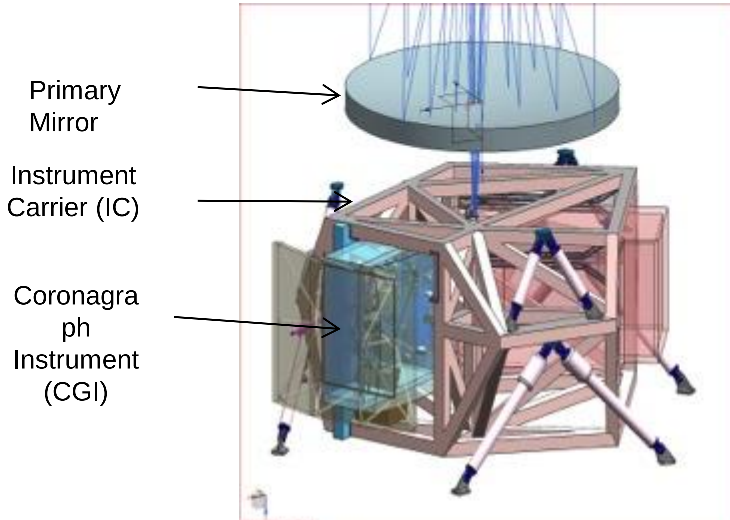
- The improvement between what the WFIRST coronagraph will do, and every previous space mission, is so enormous that even if performance degrades by a factor of ten, the coronagraph will still be a transformational advance both technically and scientifically.

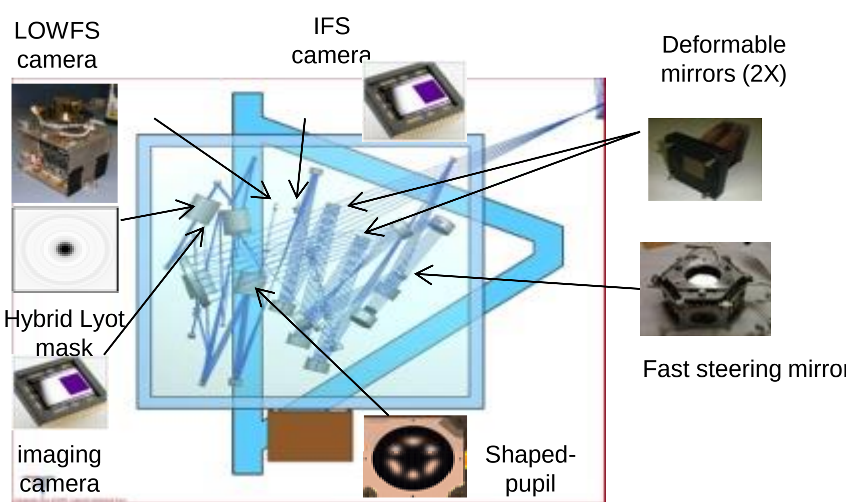
NRC Theme #4 - Technology Accommodation (4 of 4)

- Other coronagraph descope considerations (cont.)
  - As the mission and design matures, if performance shortfalls are predicted, the experience on GPI indicates that major instrument redesigns are not likely, but rather changes such as algorithm modifications or mask modifications could be necessary.
  - The nature of this technology demonstration is that science yield will not fail catastrophically with performance shortfalls. The need for the flight experiment, including the extraction of science, is that the physics is not fully understood.

> ✓ ***The selected coronagraph architectures perform well within the existing Observatory requirements***
>
> ✓ ***The coronagraph imposes only modest interface and resource requirements on the WFIRST observatory***
>
> ✓ ***Coronagraph performance is verified at the instrument level, allowing flexibility in delivery of the coronagraph to Observatory I&T***

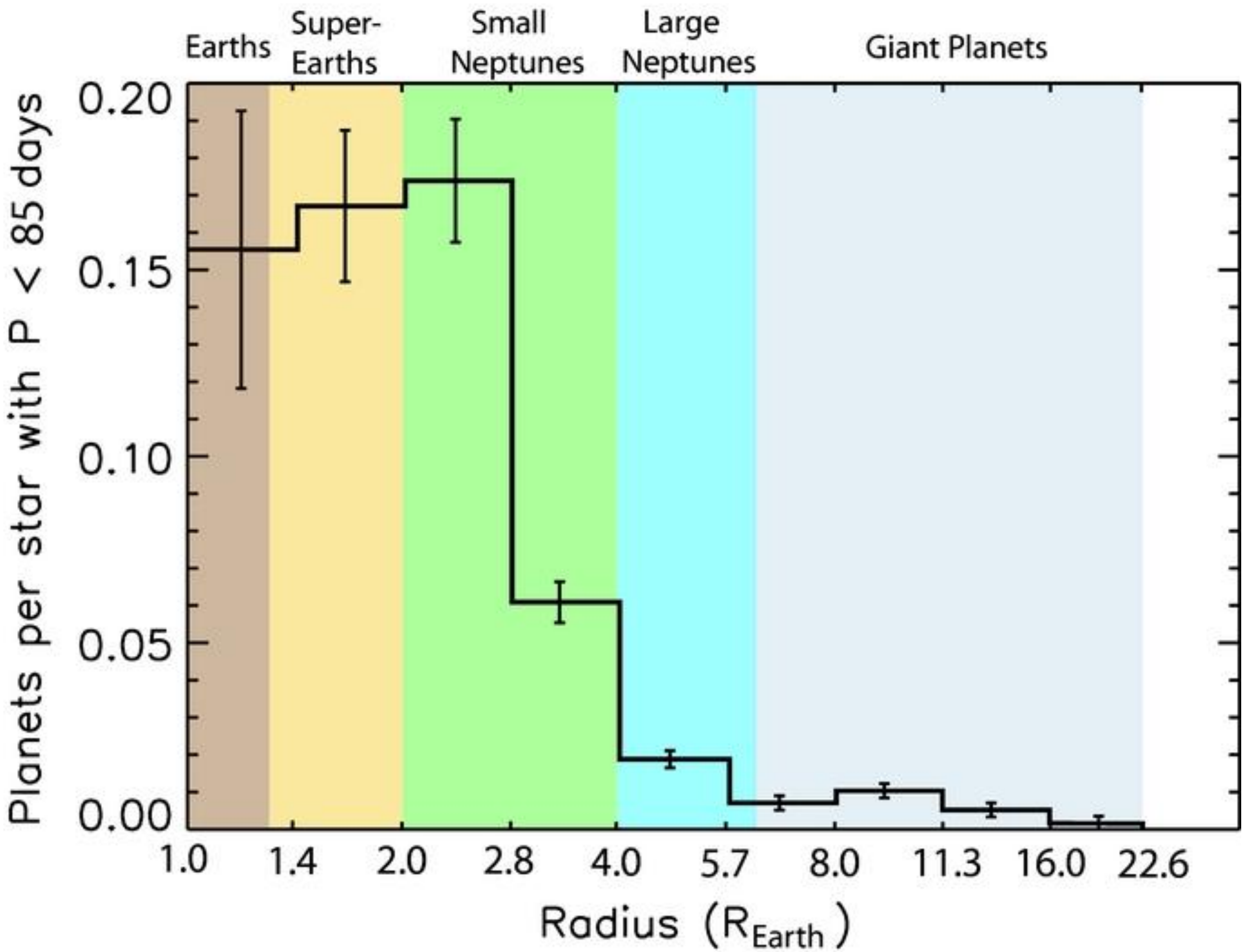
Coronagraph Instrument Overview





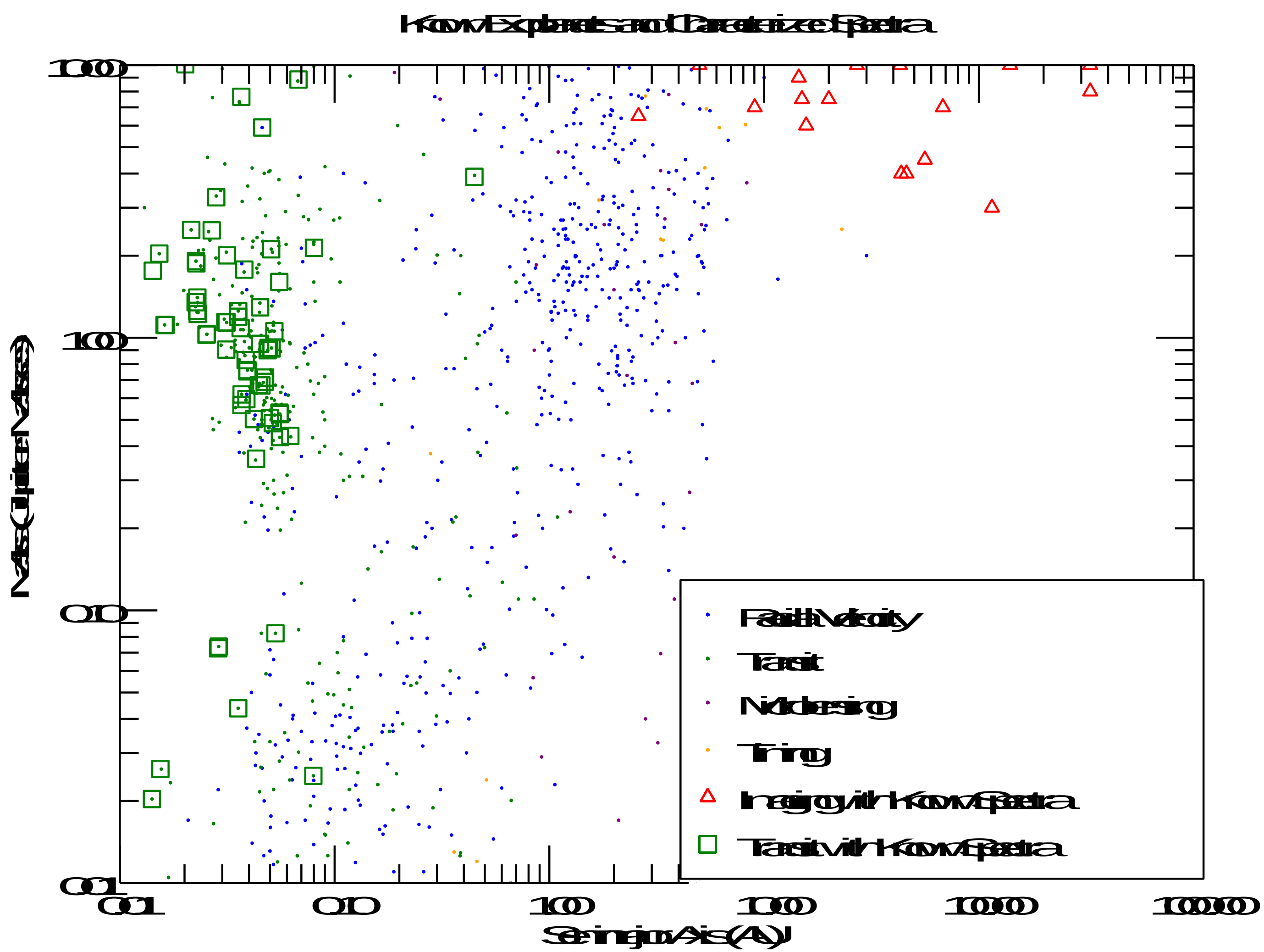
Temperature	20C for instrument
Temperature	~163k for cameras
Data volume	~30 Gbits/day
Imaging	0.4 – 1.0 microns, 4.8" FoV 0.009" pixel scale, 1K×1K EMCCD
Integral field spectrograph	0.6 – 1.0 microns R~70

The most common planets have no equivalent in our solar system

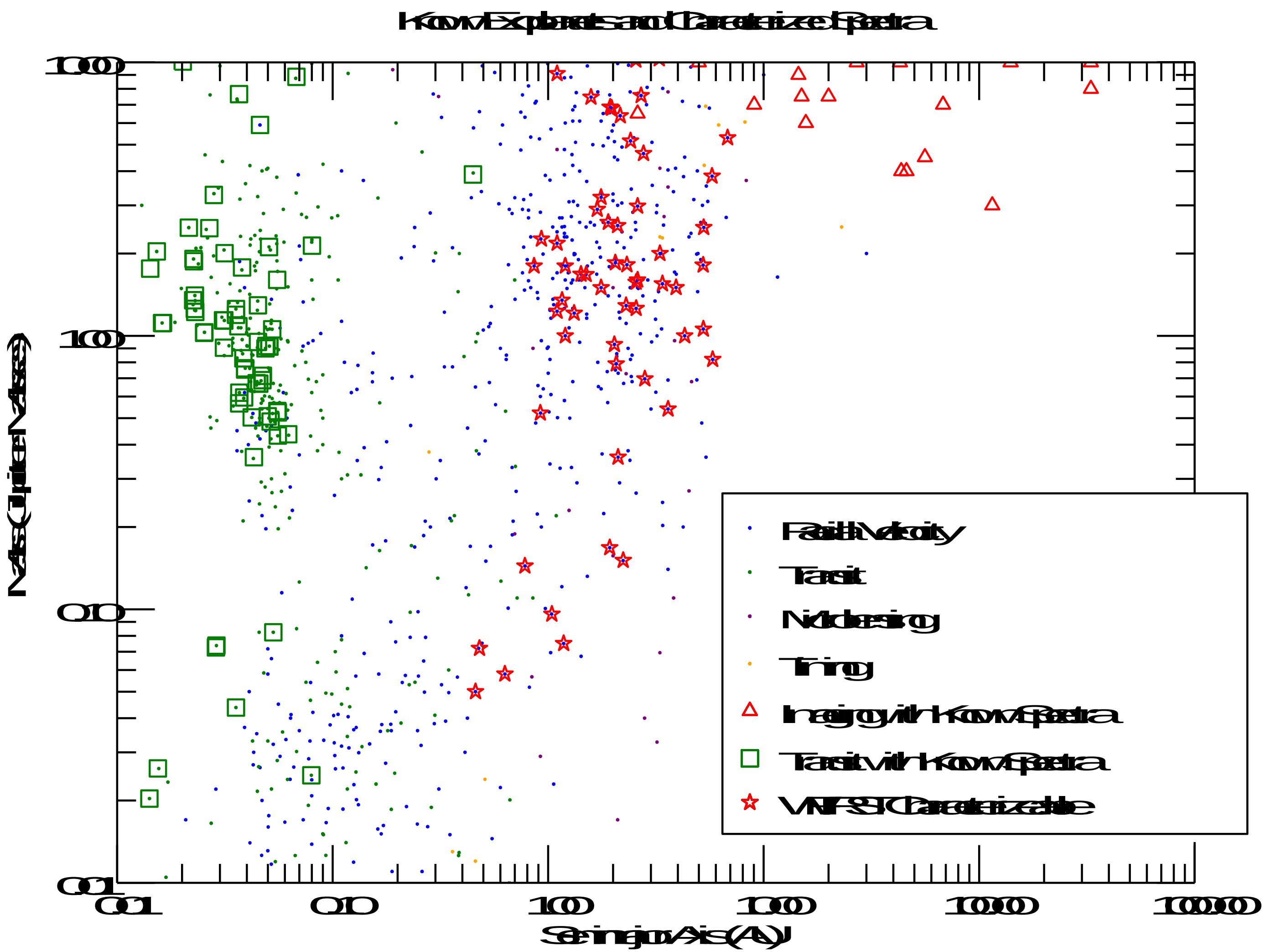


Kepler exoplanet distribution from Fressen et al 2013

Many planets are known, few have been characterized



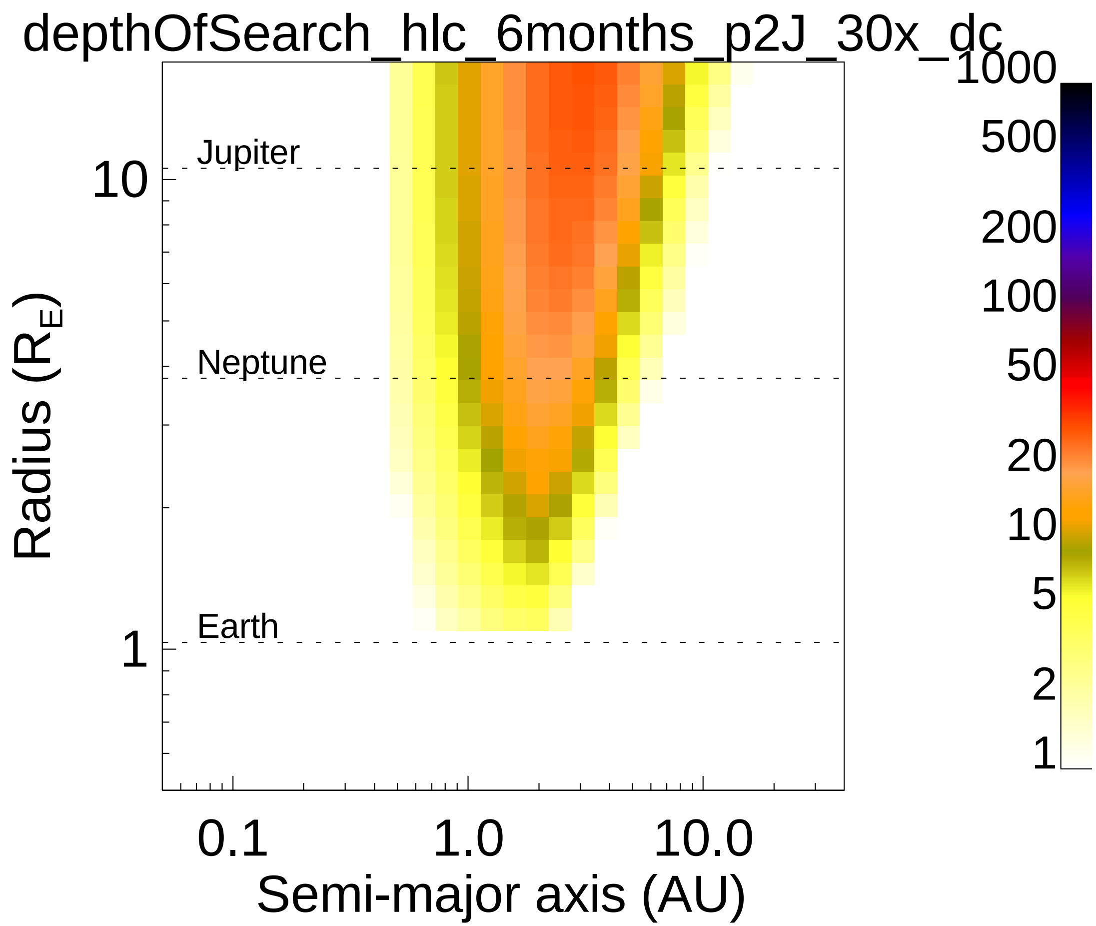
AFTA will characterize planets in completely new regime



WFIRST Characterizable Doppler planets (PIAACMC case)

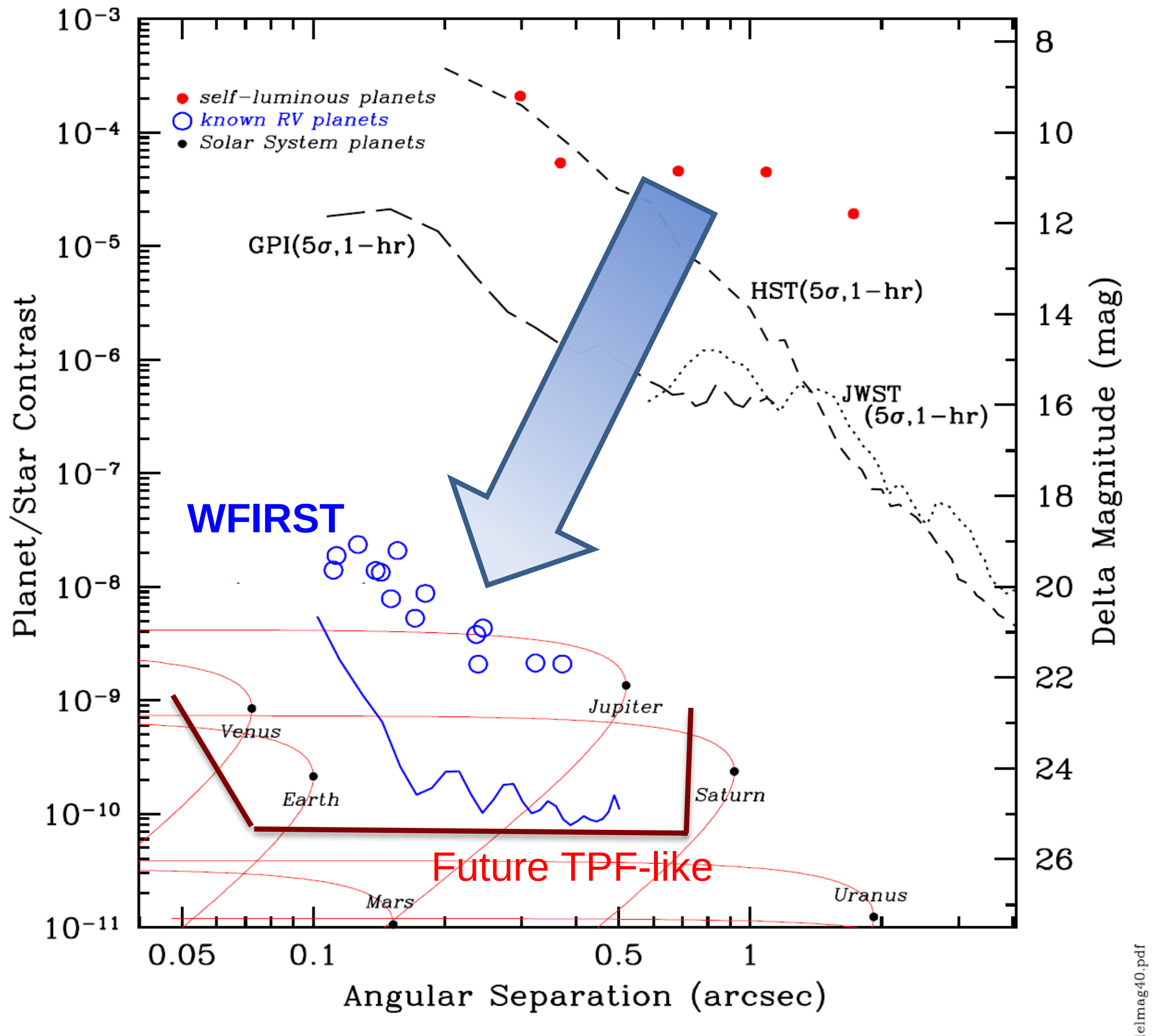
AFTA is sensitive into Super-Earth regime

- Blind search models show that surveys discovers 3-6 planets of <4 RE
- Blind search discovery rate enhanced by Doppler pre-survey



Summed completeness for 3-month AFTA ~100 star survey

Coronagraph Sensitivity

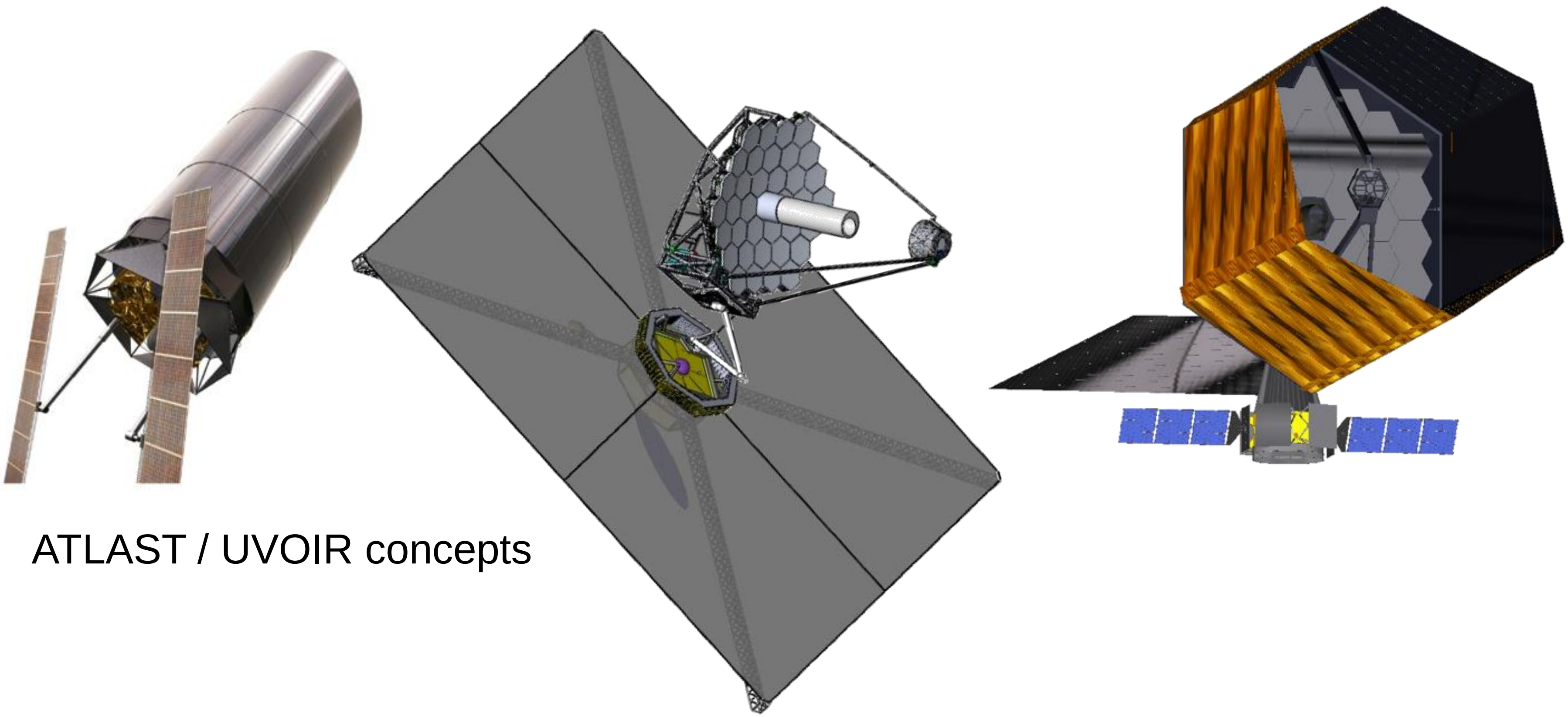


Future space coronagraphs will likely be multipurpose missions

8-meter

9.2-meter

16.8-meter

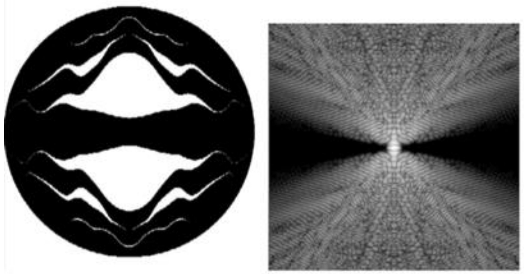


ATLAST / UVOIR concepts

AFTA coronagraph teaches us how to do coronagraphy

Coronagraph selection based on maturity, robustness, flexibility

SPC



Pupil Masking (Kasdin, Princeton University)

HLC

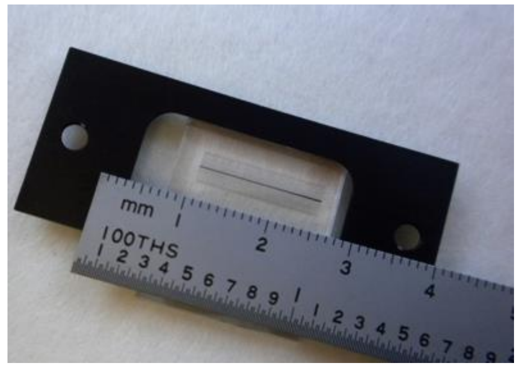
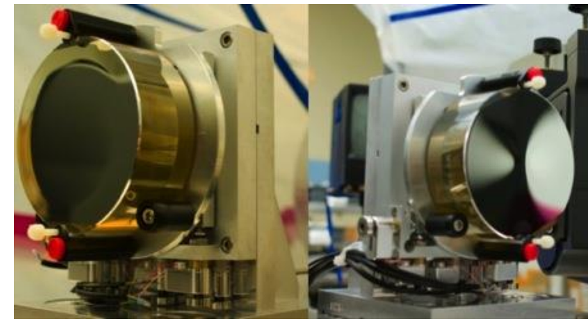


Image Plane Amplitude & Phase Mask (Trauger, JPL)

PIAACMC



Pupil Mapping (Guyon, Univ. Arizona)

VVC

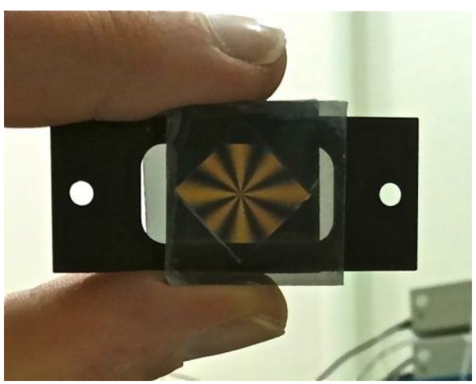
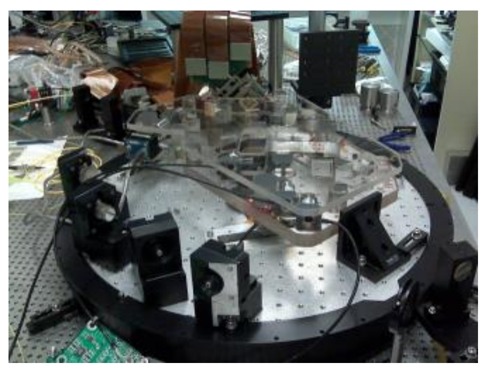


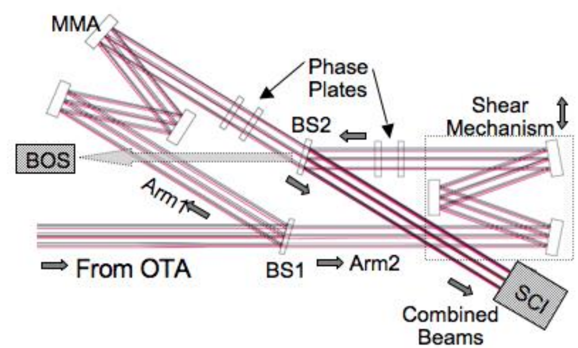
Image Plane
Phase Mask (Serabyn, JPL)

VNC - DAVINCI



Visible Nulller - DAVINCI (Shao, JPL)

VNC-PO

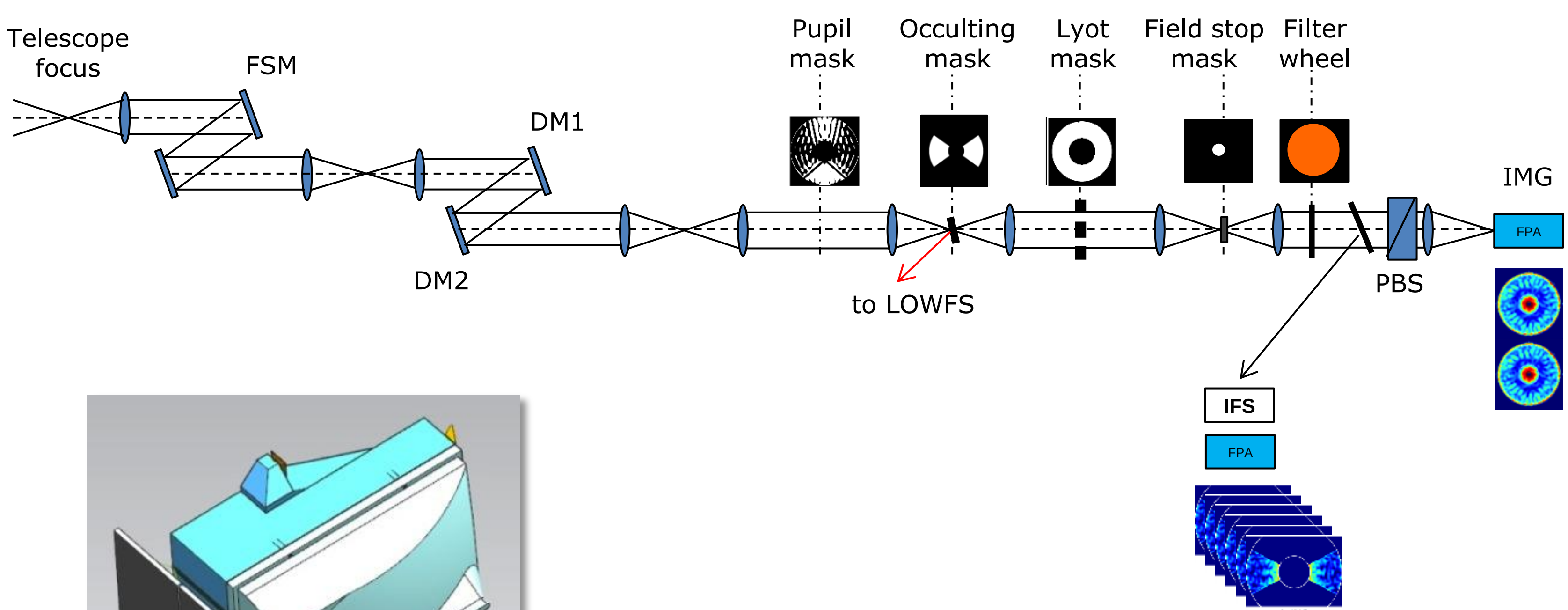


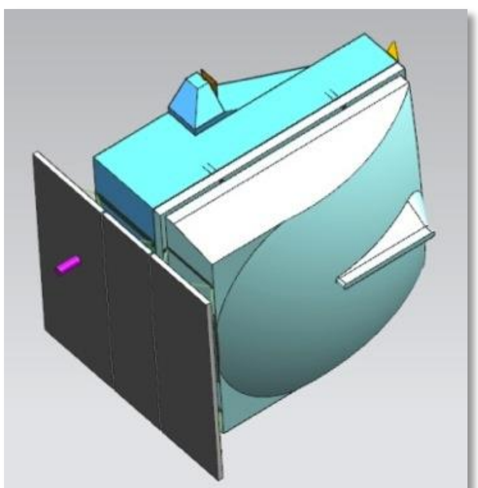
Visible Nuller – Phase Occulting (Clampin, NASA GSFC)

Coronagraph architecture

Baseline coronagraph architecture is flexible combination of hybrid Lyot coronagraph and shaped-pupil apodizer

Hybrid Lyot mode
Shaped Pupil mode





NRC Focus #5 - Driving Coronagraph Requirements

- Because of the immature design and because there has been very limited study of the coronagraph's accommodation on the mission, the committee could not quantitatively assess the cost and risk impact to the WFIRST/AFTA program. However, the committee found the following:

- **Finding 2-5:** The coronagraph design is immature, it involves immature technologies, and there has been limited study of accommodating the instrument on the mission. It is, therefore, not possible to quantitatively assess the cost and risk impact to the WFIRST/AFTA program.

RESPONSE:

- Coronagraph design has been brought to higher maturity level
- Technology development program maturing and testing key components
- Rigorous simulations of coronagraph performance in AFTA environment show that with this telescope, unmodified, a coronagraph can achieve performance goals
- If telescope performance drops, coronagraph degradation is gradual and can be mitigated

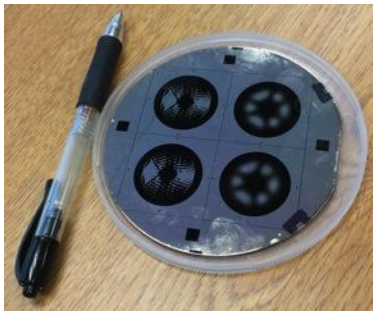
WFIRST-AFTA Coronagraph Key Milestones

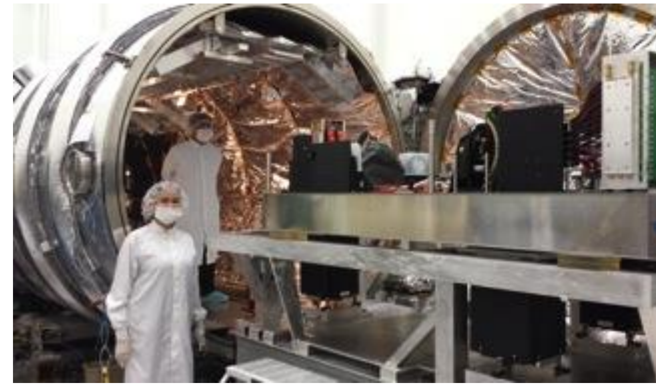
MS #	Milestone	Date
1	First-generation reflective Shaped Pupil apodizing mask has been fabricated with black silicon specular reflectivity of less than 10^{-4} and 20 μm pixel size.	7/21/14
2	Shaped Pupil Coronagraph in the High Contrast Imaging Testbed demonstrates 10^{-8} raw contrast with narrowband 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

Coronagraph Technology Development Highlights

Reflective shaped pupil mask

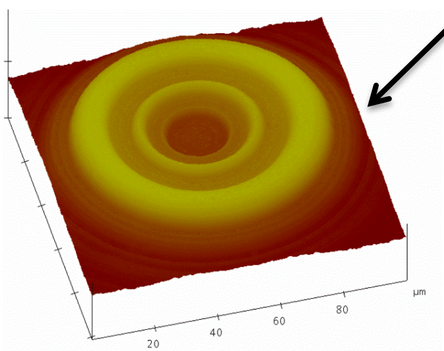
- Black Si on Al mirror coating demonstrated at JPL/MDL and Caltech/KNI
- High contrast demonstrated at HCIT



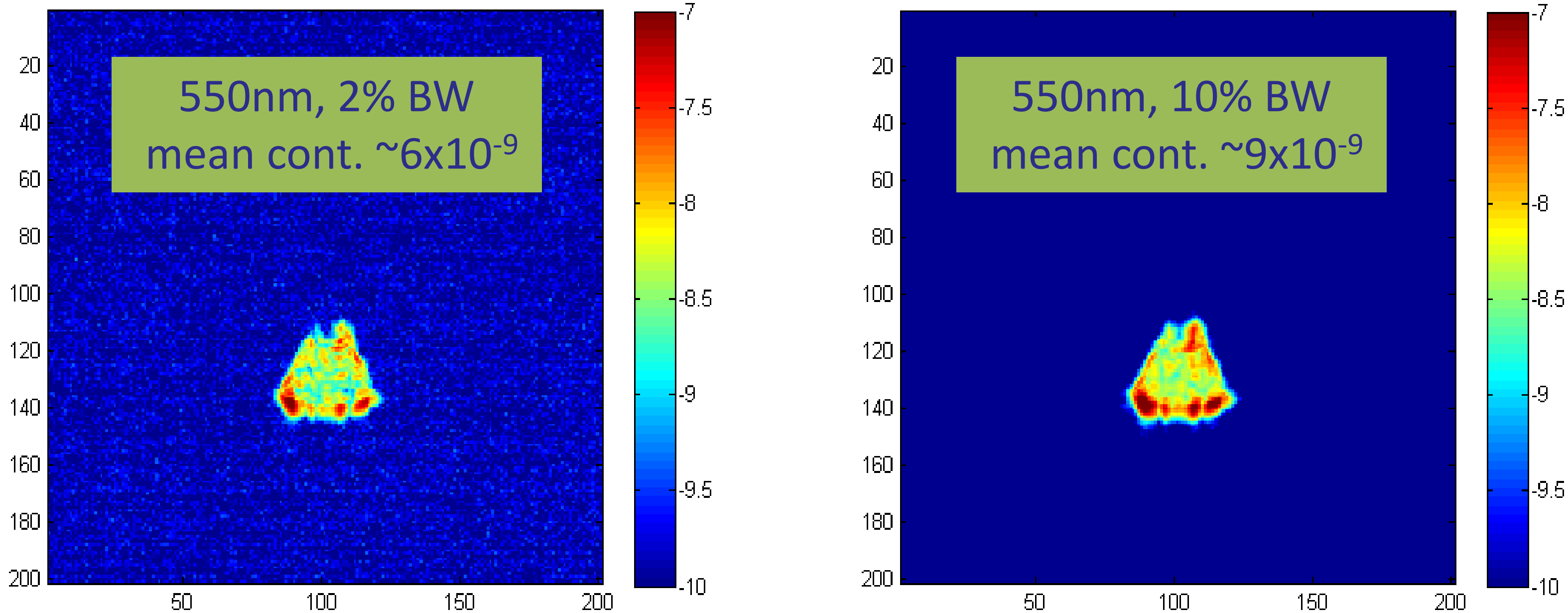


Transmissive hybrid Lyot mask

- Circular mask fabricated and measured
- Testbed commissioned on 8/15/2014



Shaped Pupil Coronagraph Testbed Demonstration



- Narrowband results and early broadband results were submitted to TAC on 9/17/2014
- Milestone 2 approved during review with TAC on 10/8/2014
- Early broadband result meets Milestone 5 success criterion (for shaped pupil)
- **Retired our biggest risk, proving that high contrast is achievable with AFTA telescope pupil**

AFTA-C Detector

Evaluate slightly customized version of OTS e2v EMCCD (m/n CCD 201)
- Modify implant to enable 4-phase clocking
- Mitigation for radiation induced performance degradation

CCD201-20
Back Illuminated 2-Phase IMO Series Electron Multiplying CCD Sensor

GENERAL DATA

Active image area .... 13.3 x 13.3 mm
Image section active pixels ....1024 (H) x 1024 (V)
Image pixel size .... 13 x 13 µm
Number of output amplifiers 2
Fill factor 100%
Additional dark reference columns 32
Additional overscan rows 8

PACKAGE DETAILS (see Fig. 15)

Ceramic Package

Overall dimensions .... 37.4 x 26.5 mm
Number of pins..36
Inter-pin spacing ....2.54 mm
Mounting position ....any

The pin 1 marker is shown in Fig. 15.

STORAGE AND OPERATION TEMPERATURE EXTREMES

	MIN	MAX
Storage temperature (°C)	-200	+100
Operating temperature (°C)	-120	+75
Temperature ramping (°C/min)	-	5

Note: Operation or storage in humid conditions may give rise to moisture on the sensor surface on cooling, causing irreversible damage.

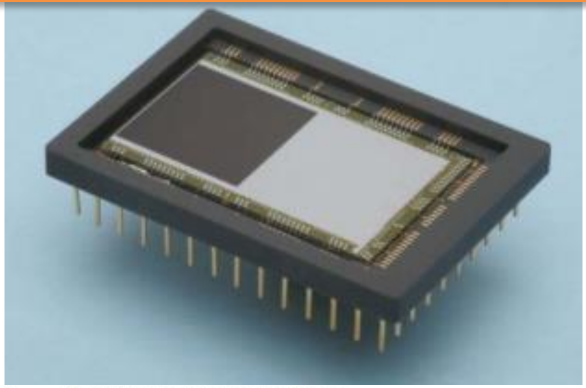
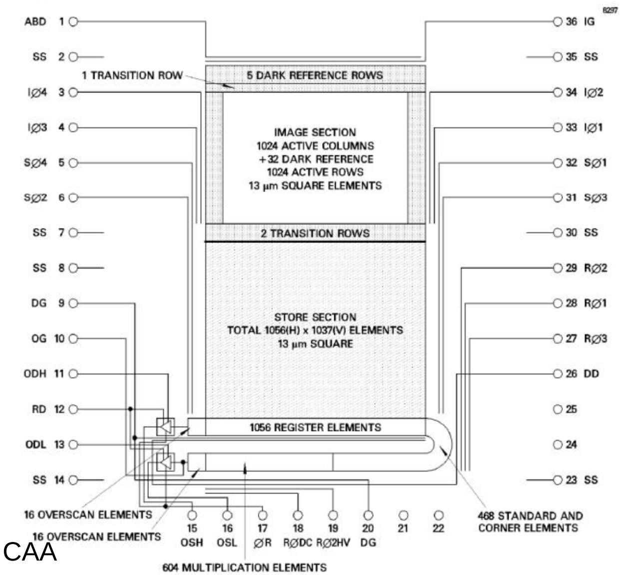
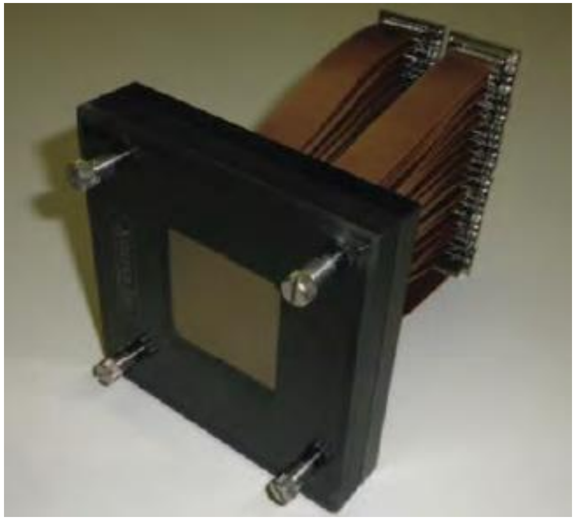


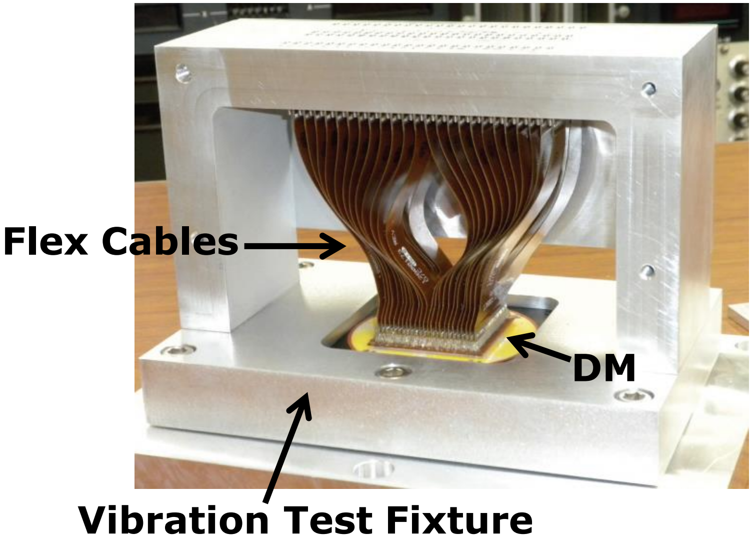
Figure 13: SCHEMATIC CHIP DIAGRAM



Deformable Mirrors

- Northrop Grumman Xinetics (AOX) electrostrictive PMN Deformable Mirrors used in HCIT since 2003
- Produced better than 10^{-9} raw contrast demonstrations
- Two 48x48 actuator AOX DMs baselined for coronagraph instrument, tesbeds
  - 1 mm actuator spacing, 500 nm actuator stroke
- 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





Detailed full-physics simulations to validate coronagraph with AFTA

Parameters:

03 Jan 2023 00:00 ET; Altitude = 35786 km; Period = 86164 sec;

Inclination = 28.5 deg; RA of Ascending Node = 236 deg

Arg. Of Periapsis = 270 deg; Solar = 0.001354 W/mm^2 ;

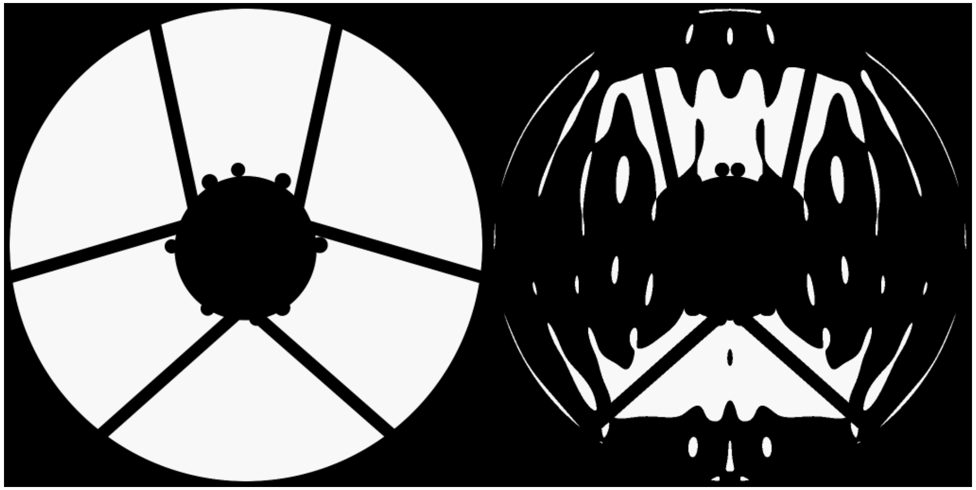
Beta Angle = 41.6 deg; IR = 0.0002215 W/mm^2; Albedo = 0.35

State	Operation	Duration (sec)	Start Time (sec)	RZ	RY	ΔFlux (% abs.)
Prior Star 61 Uma	Stare	infinity	-infinity	-53.7°	26.9°	--
DH Star: Beta Uma	Slew & Settle	700	0	-79.4°	34.1°	+6.4%
	Stare	22000				
Target Star: 47 Uma	Slew & Settle	700	22700	-60.0°	35.7°	+1.6%
	Stare	80300				
Cal Star: 61 Uma	Slew & Settle	700	103700	-53.7°	26.9°	-8.0%
	Stare	80300				

Scenario Defined → Thermal Loads → Structural Deformations → Ray Trace (Sig-Fit + Code V) → Exit Pupil WFE → DM Control (EFC) → Coronagraph (PROPER) → Images / Spectra

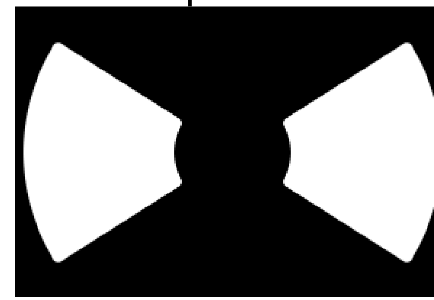
Coronagraph simulations use validated wave-optics code

AFTA Pupil Shaped Pupil



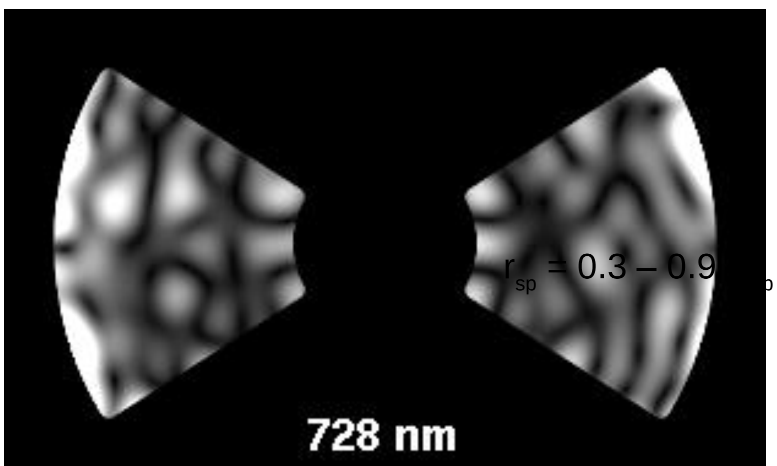
27% mask transmission

Focal plane mask



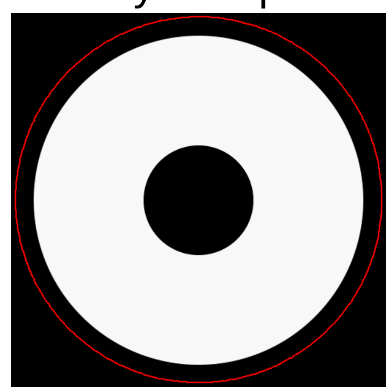
$r = 2.5 – 9\ \lambda_c/D$

65° opening angle

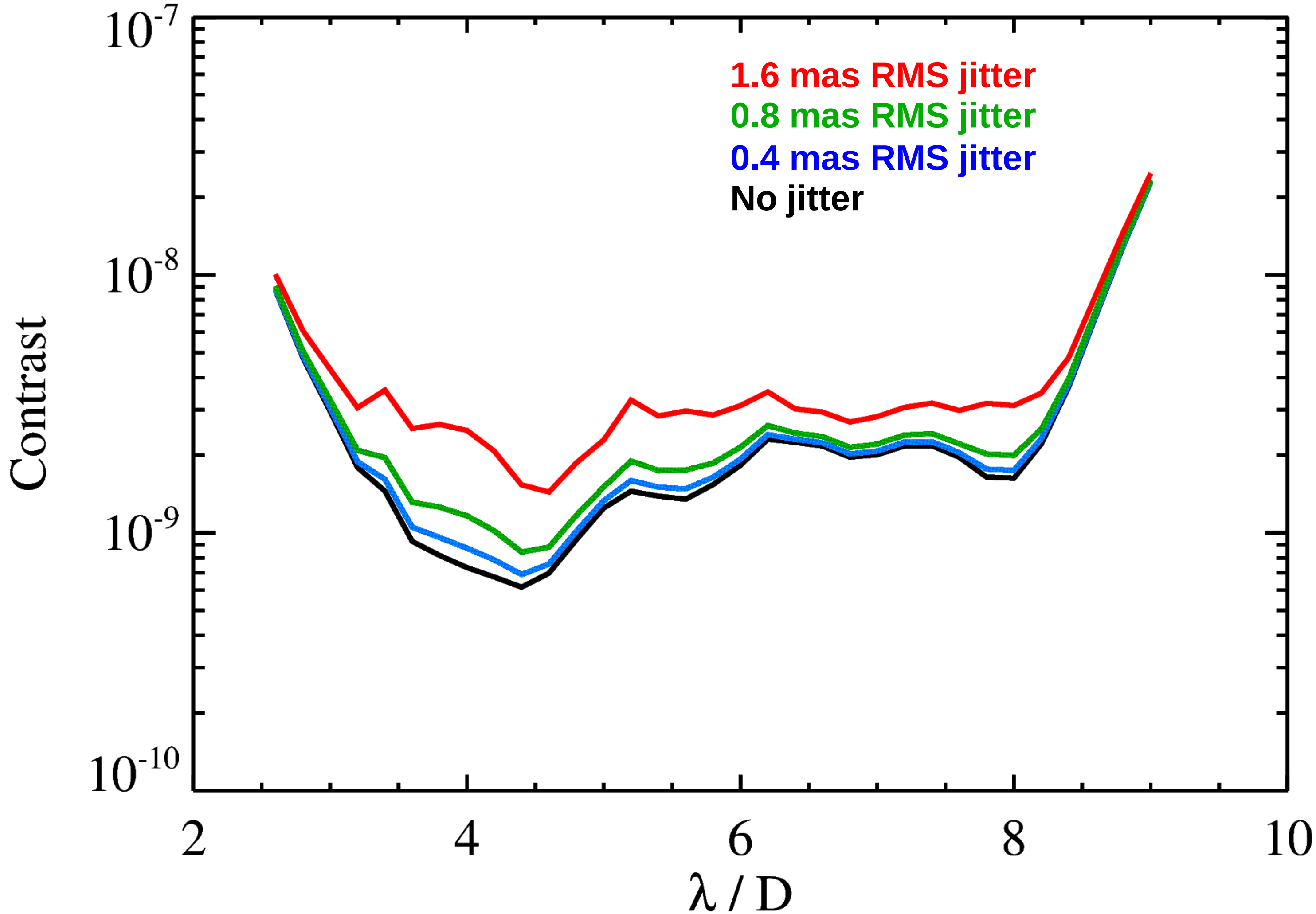


r_{sp} = 0.3 – 0.9

Lyot stop



Simulations show e.g. robust performance against jitter



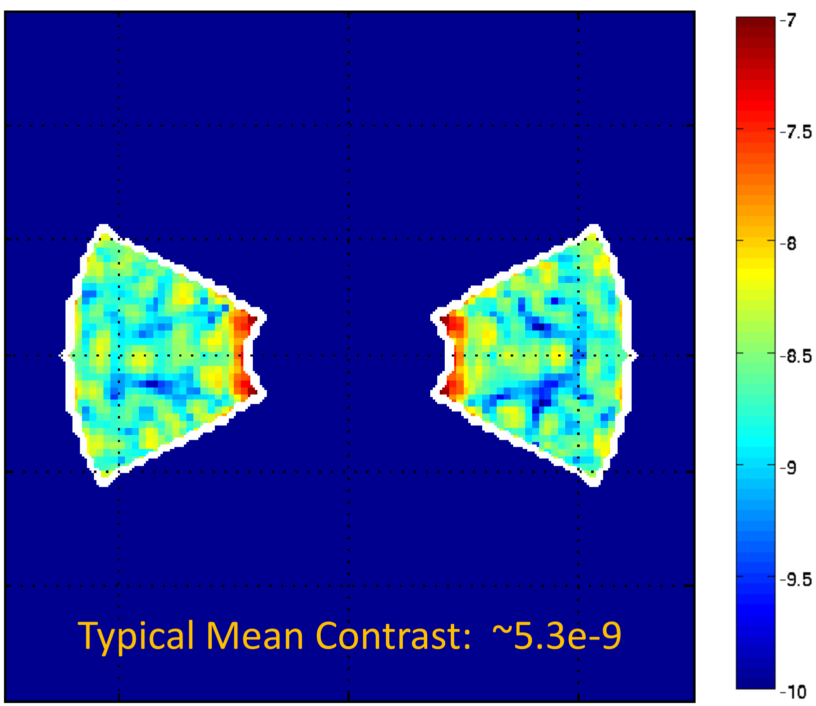
728 – 872 nm

Jitter levels shown here are after coronagraph fast tip/tilt

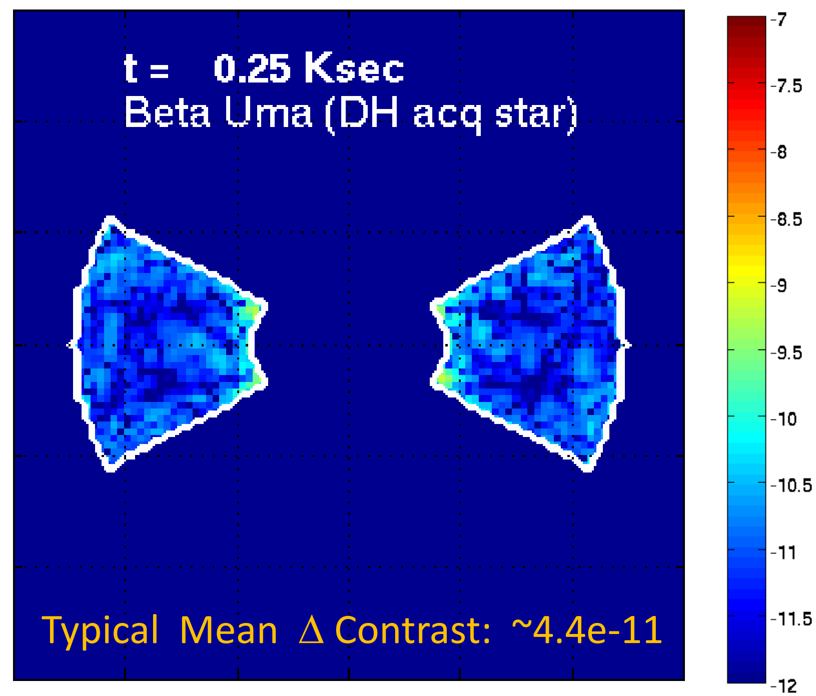
Simulations show stable high contrast with AFTA in thermal scenarios

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

Raw speckle, S(t)



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



Coronagraph Technology Progress Summary

- Excellent results achieved in the past 9 months.
- ***High contrast (<10^{-8}) demonstrated in testbed this summer with WFIRST 2.4m telescope pupil!***
- Broadband shaped pupil high contrast (<10^{-8}) also demonstrated, one year ahead of planned date!
- Repeatable, high-yield and flight traceable mask fabrication at JPL’s Micro Devices Laboratory (multiple masks per wafer, with 2-3 wks per fab run)
- Hybrid Lyot circular mask recently fabricated in JPL MDL. Tolerances consistent with <10^{-8} contrast.
- Hybrid Lyot high contrast testbed will make a high contrast run in the next couple weeks.
- Dynamic WFIRST telescope simulator designed and in fabrication – to be used with both high contrast testbeds and with the flight coronagraph.
- LOWFS uses a classical concept (Zernike phase contrast microscopy), high TRL detector (e2v CCD39) and fast steering mirror (TRL-6 under SIM)
- Deformable mirrors have been used in past TDEM high contrast demonstrations (<10^{-10}), and PMN actuators have rich flight heritage (e.g., HST WFPC2 actuated pick-off mirror)
- Detectors are off-the-shelf (e2v CCD201-20, 1k X 1k) with noise performance demonstrated in the lab

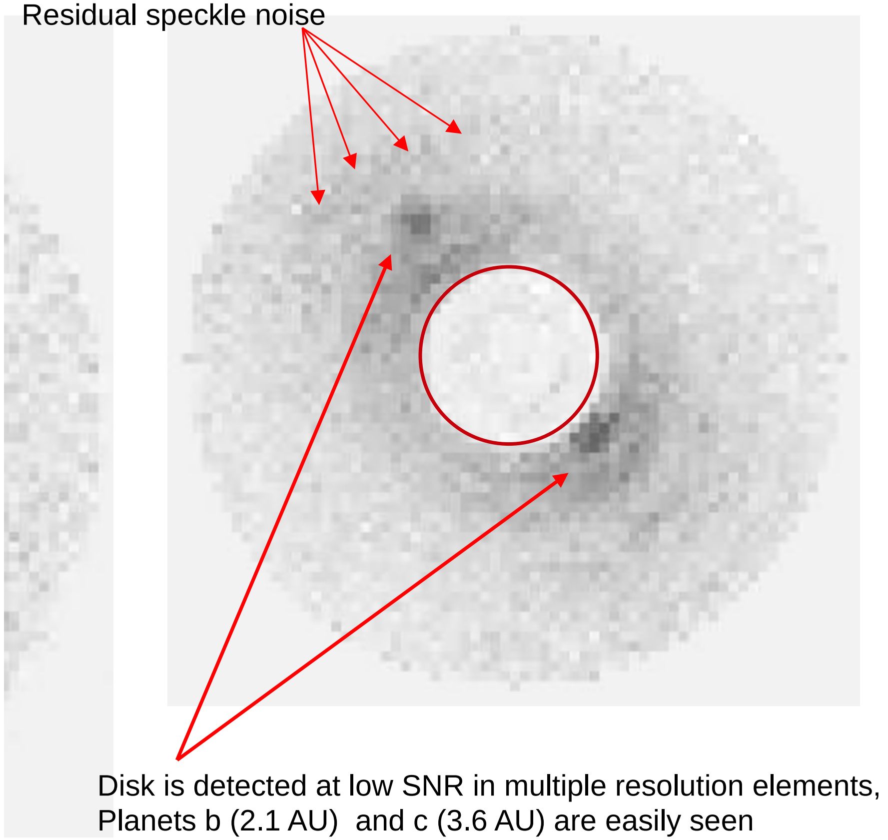
NRC Focus #6 – Establishing Exozodiacal Light Levels

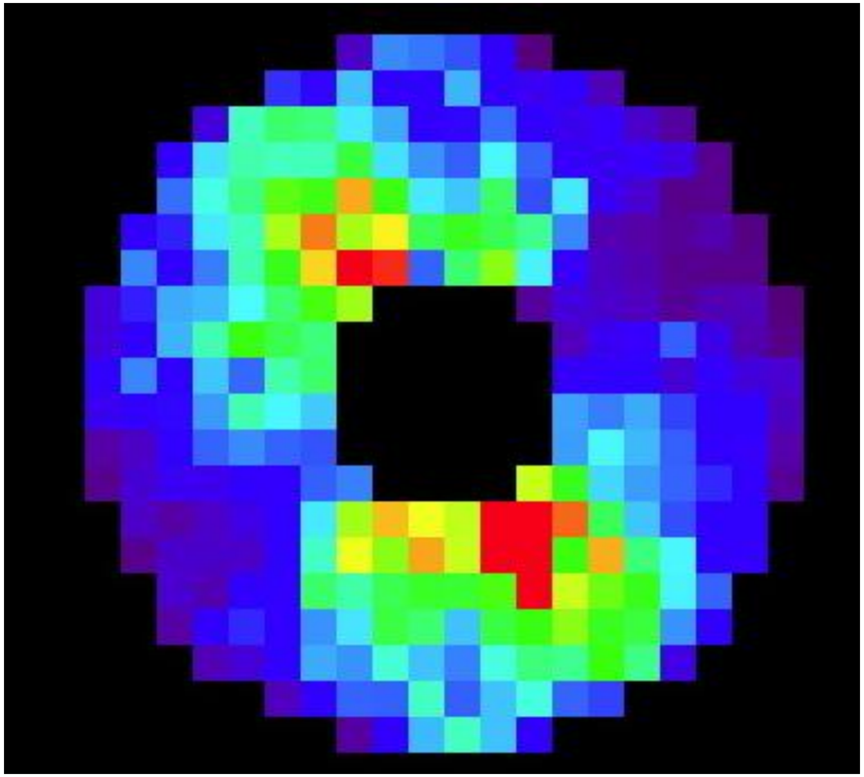
- **Finding 1-8**: Whether the WFIRST/AFTA coronagraph satisfies the NWNH goal to establish exozodiacal light levels at a precision required to plan an Earth-like exoplanet imaging mission is uncertain due to the immaturity of the coronagraph design and uncertainty in the ultimate performance.

RESPONSE:

- Simulations show sensitivity down to ~10x solar-system levels at 1-5 AU separations, consistent with requirements for future Earth finders
- AFTA complements LBTI, measuring visible light, polarization, and structure

47 UMa + 30 Zodi disk





Binned SNR map of disk (peak SNR=15)

PSF-subtracted image

Simulations by Tom Greene and Glenn Schneider using 1st-gen HLC

Coronagraph Summary

- AFTA coronagraph addresses key NWNH and post-NWNH science goals
  - As Kepler and microlensing complete exoplanet census, we move into the era of characterization
- AFTA coronagraph brings wavefront-controlled coronagraphy to flight levels on the path to future Earth-finding missions
  - Not just hardware, but algorithms and science
- Well-developed technology program to achieve appropriate TRL by Phase A
- System design is advanced and detailed
- Rigorous simulation program shows coronagraph performs well with the real telescope and will impose no new requirements

NRC Theme #7 - Recommendation: Mature Coronagraph Technologies

- **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 of this activity, and a cost and technical evaluation of WFIRST/AFTA with the coronagraph, an independent review focused on the coronagraph should be convened to determine whether the impact on WFIRST and on the NASA astrophysics program is acceptable or if the coronagraph should be removed from the mission.

RESPONSE:

- We agree with the recommendation to 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.
- Theme #5 showed the excellent progress that has been made this year in maturing both the coronagraph design and the technology.
- A Technology Assessment Committee has been chartered by HQ to review the progress of the coronagraph technology maturation.
- The Coronagraph Technology Development Plan has these key milestones completed by the end of FY16.
- An initial independent cost estimate (CATE) of WFIRST-AFTA with the coronagraph will be completed in February 2015.

NRC Theme #8 - Recommendation: Conduct External Reviews

- After a decision has been made on the mission implementation, in order to ensure that budget plans and contingencies are adequate to ensure WFIRST's implementation is consistent within the context of all of the NWNH priority recommendations, the committee makes the following recommendation:
- **Recommendation 3-1**: NASA should sponsor an external technical and cost review of the WFIRST/AFTA mission that NASA plans to propose as a new start. This review should be independent of NASA's internal process. The objective of the review should be to ensure that the proposed mission cost and technical risk are consistent with available resources and do not significantly compromise the astrophysics balance defined in the 2010 National Research Council report New Worlds, New Horizons in Astronomy and Astrophysics. This review should occur early enough to influence the exercising of a rescoping of the mission if required.

RESPONSE:

- NASA agrees with the finding to have both external technical and cost reviews of the WFIRST-AFTA mission.
- Dr. Grunsfeld's letter to the NRC provides NASA's plan to address the recommendations in the Harrison report
  - The CATE evaluation in February 2015 will be an independent technical and cost review that occurs early enough to guide a year of pre-formulation activities to ensure a robust mission concept with mitigated risk to cost growth.
  - Regarding program balance, NASA believes the mid-Decadal review serves as the means to re-certify that the new start of WFIRST-AFTA does not significantly compromise the balance of the astrophysics portfolio.
- Additionally, NASA has chartered a Technology Assessment Committee to review the technology maturation process of the wide field detectors and the coronagraph instrument.

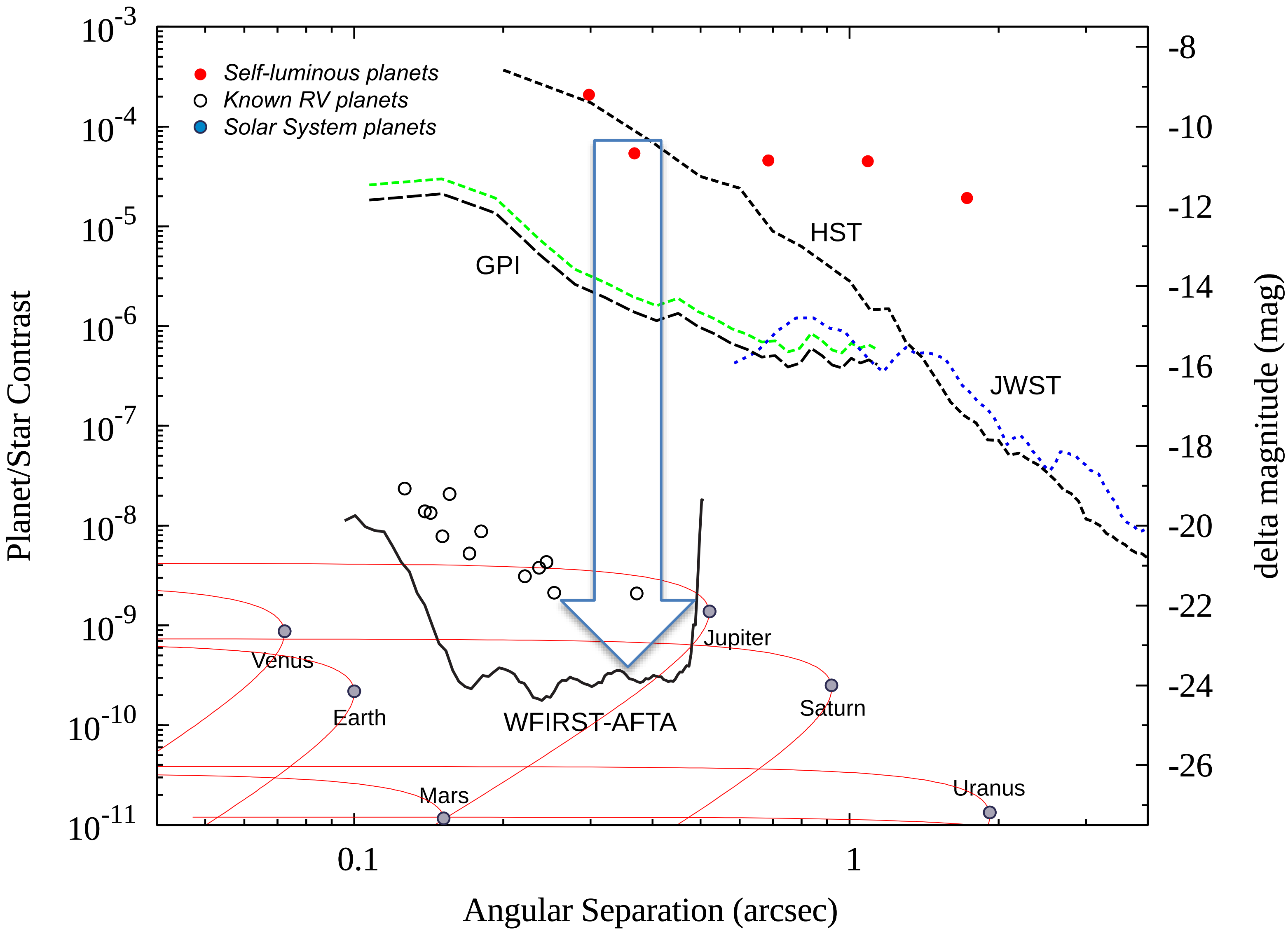
Summary

- The availability of the 2.4m aperture telescope enables not only the #1 Large-Scale NWNH Priority but also the #1 Medium-Scale NWNH Priority (New Worlds Technology Development)
- WFIRST-AFTA concept has continued to mature over the last year with a focus on addressing the findings in the NRC-Harrison report.
- Working hard to minimize risk of development phase cost/schedule growth
  - Using telescope within existing structural and thermal limits
  - Early funding supports detector maturation and risk reduction activities on the wide field and technology maturation on the coronagraph.

f Hirata – 11-1-14

- Neil,
- Thanks for sending this. I think this is exactly the kind of presentation we need to give, and it reads very well.
- I had just a couple comments on telescope temperature impacts (p. 38).
- The impact on WL galaxies in H band is -5% (the -2.6% number was from an earlier version of the calculation -- we should use numbers from v3 of my document).
- Some points related to my document if you get asked: [a] yes there are margins in that calculation; and [b] the degradation to the HLS in going to 282 K is less than textbook scaling laws because there are other sources of noise. I don't think these warrant changes to the slides.
- Chris

Coronagraph Sensitivity



AFTA bridges the gap to future Earth-finding missions