# WFIRST-AFTA
# Presentation to the NRC Mid-Decadal Panel


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**Kevin Grady (NASA-GSFC)**
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**Feng Zhao (JPL/Caltech)**


October 9, 2015

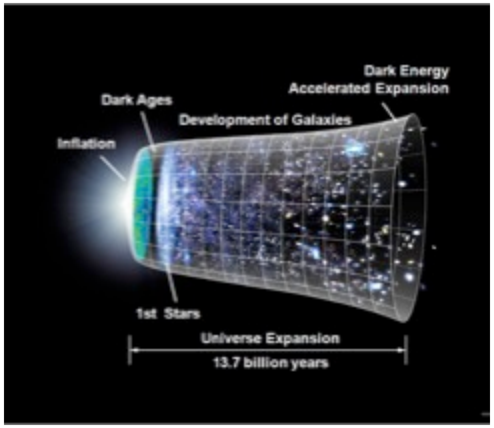
# NRC Questions

1) Please describe the status of your project and agency support in the context of the recommendations of NWNH.
   - This presentation addresses the project status and Paul Hertz's presentation yesterday addresses the agency support.
2) What is the current cost and schedule estimate for WFIRST/AFTA and how was it determined?
   - Paul Hertz's presentation yesterday addressed cost and schedule and this presentation addresses it on pages 43-45
3) The recent NAS report on WFIRST/AFTA concluded that the use of inherited hardware comes at increased risk. What is the plan to manage this risk?
   - This question is addressed on slide 25.

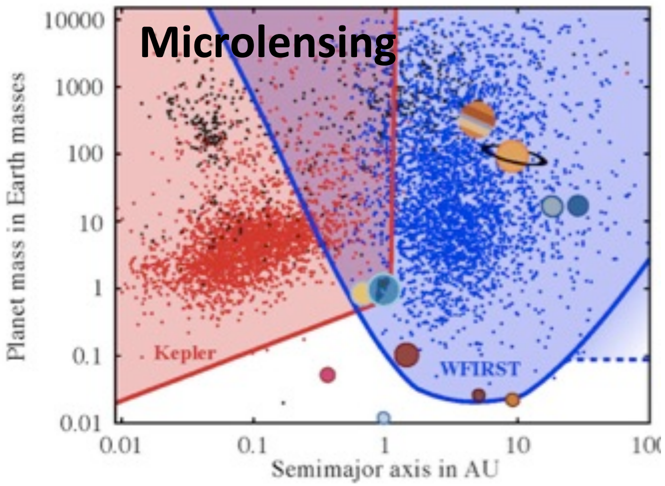
# Discovery Science

- WFIRST was highest ranked large space mission in 2010 Decadal Survey
- Use of 2.4m telescope enables
  - Hubble quality imaging over 100x more sky
  - Imaging of exoplanets with $10^{-9}$ contrast with coronagraph

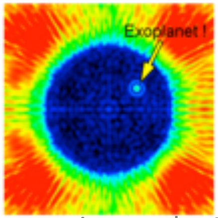
## Dark Energy



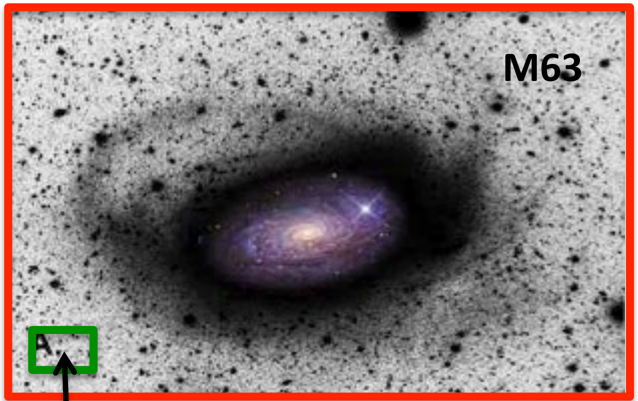

## Exoplanets




**Coronagraph**



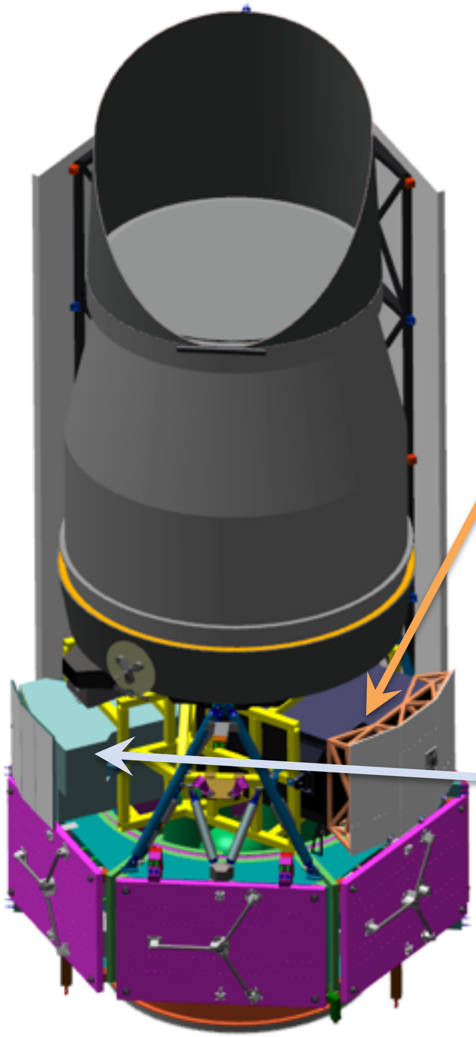

## Astrophysics




**HST**

**WFIRST**

# WFIRST Instruments



## Wide-Field Instrument

- *Imaging & spectroscopy over 1000s of sq. deg.*
- *Monitoring of SN and microlensing fields*
- 0.7-2.0 $\mu$m (imaging), 1.35-1.89 $\mu$m (spec.), 0.6-2.0 $\mu$m (IFU)
- 0.28 deg$^2$ FoV (100x JWST FoV), 9 asec$^2$ & 36 asec$^2$ (IFU)
- 18 H4RG detectors (288 Mpixels), 2 H1RG detectors (IFU)
- 6 filter imaging, grism + IFU spectroscopy

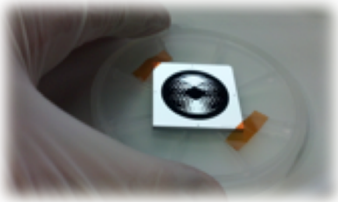
## Coronagraph

- *Image and spectra of exoplanets from super-Earths to giants*
- *Images of debris disks*
- 430 – 970 nm (imaging) & 600 – 970 nm (spec.)
- Final contrast of $10^{-9}$ or better
- Exoplanet images from 0.1 to 0.9 arcsec

# Executive Summary

- Huge progress on WFIRST over the past two years
- SDT studies & NRC Harrison committee report confirm that WFIRST-AFTA exceeds NWNH requirements in all areas.
- $107M in FY14 & 15 has enabled major steps forward and NRC-Harrison committee recommendations have been addressed (H4RGs, coronagraph, mission design). Planning against $56M in FY16, exact amount depends on appropriations.
- Coronagraph on track, technology development on schedule. Wide Field detector technology development on schedule
- MCR scheduled for Dec 8-9.  Prepared for start of formulation (KDP-A) as early as January 2016.
- SDT 2014 & 15 studies completed
- Preparatory Science teams selected
- Pasadena conferences held
- Special session at AAS's & IAU
- Science team NRA released
- Industry study RFIs received
- Significant international interest (Canada, ESA, Japan, Korea)

WFIRST H4RG-10



Shaped-Pupil Coronagraph Mask

# Scientific Objectives

1) Produce NIR sky images and spectra over 1000's of sq deg (J = 27AB imaging, F_line = $10^{-16}$ erg $cm^{-2}$ $sec^{-1}$)

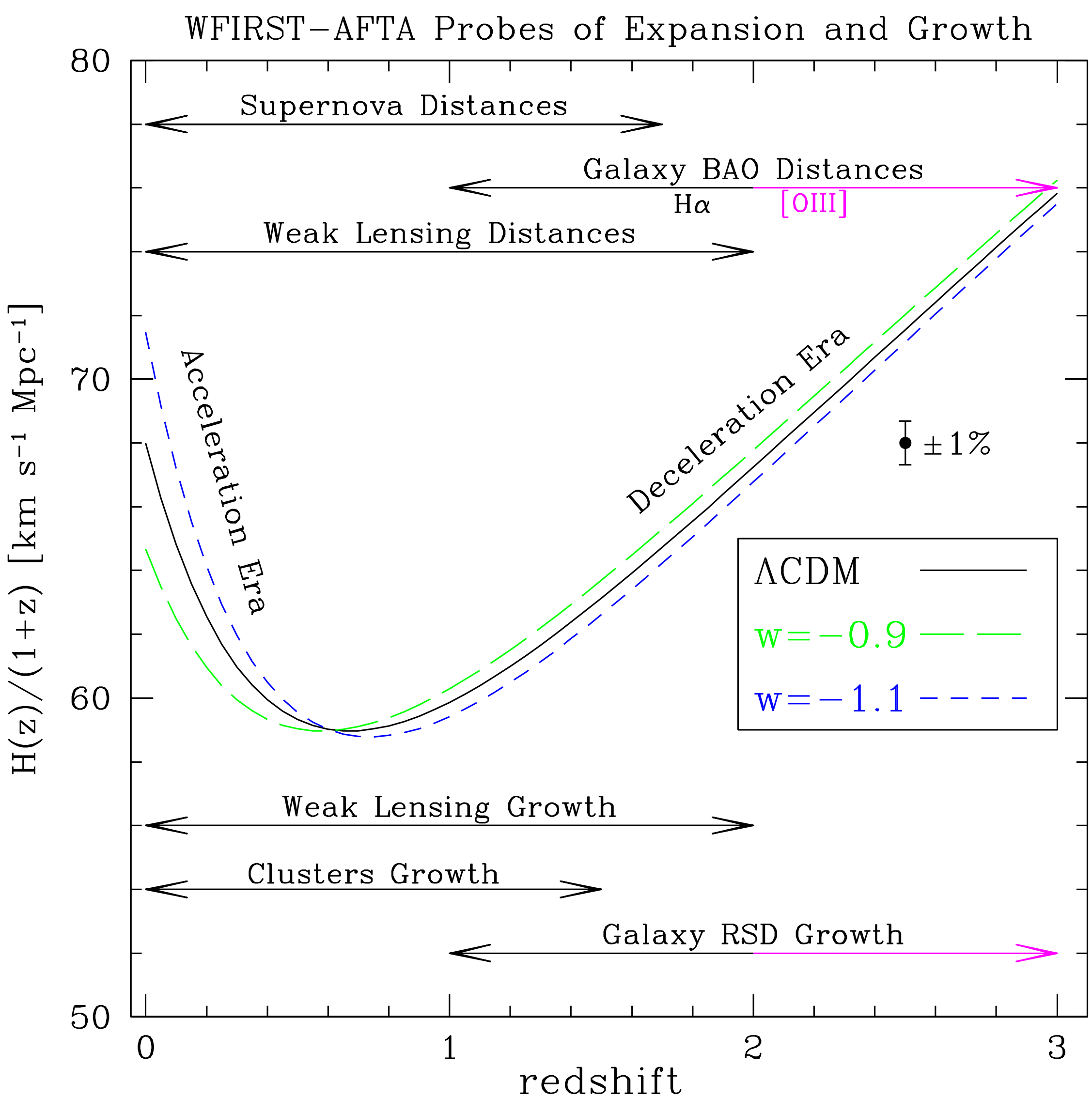
2) Determine the expansion history of the Universe and the growth history of its largest structures in order to test possible explanations of its apparent accelerating expansion including Dark Energy and modifications to Einstein's gravity.

3) Complete the statistical census of planetary systems in the Galaxy, from the outer habitable zone to free floating planets

4) Directly image giant planets and debris disks from habitable zones to beyond the ice lines and characterize their physical properties.

5) Provide a robust guest observer program utilizing a minimum of 25% of the time over the 6 year baseline mission and 100% in following years.

# WFIRST Dark Energy Program



# WFIRST & Euclid Complementary for Dark Energy

**WFIRST**

**Deep Infrared Survey** (2,200 deg$^2$)

Lensing

- High Resolution (50 gal/arcmin$^2$)
- Galaxy shapes in IR
- 5 lensing power spectra

Supernovae:

- High quality IFU spectra of ~2700 SNe

Redshift survey

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

**Euclid**

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

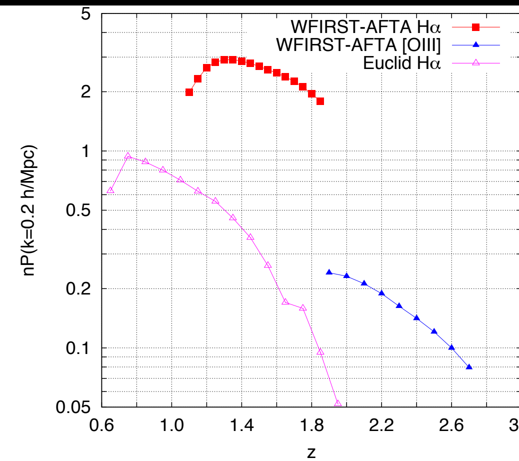
Lensing:

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

No supernova program

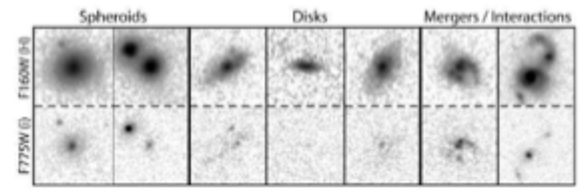
Redshift survey:

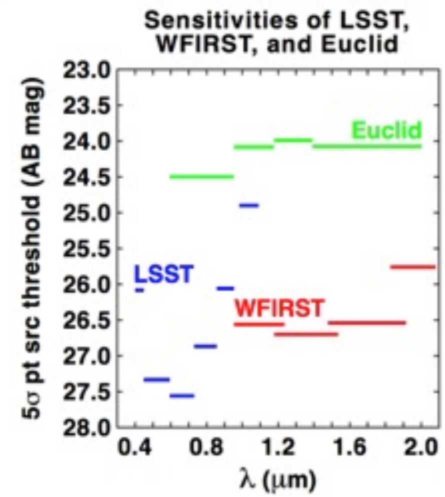
- Low number density of galaxies
- Significant number of low redshift galaxies
- Redshift range extends to z~2




IR

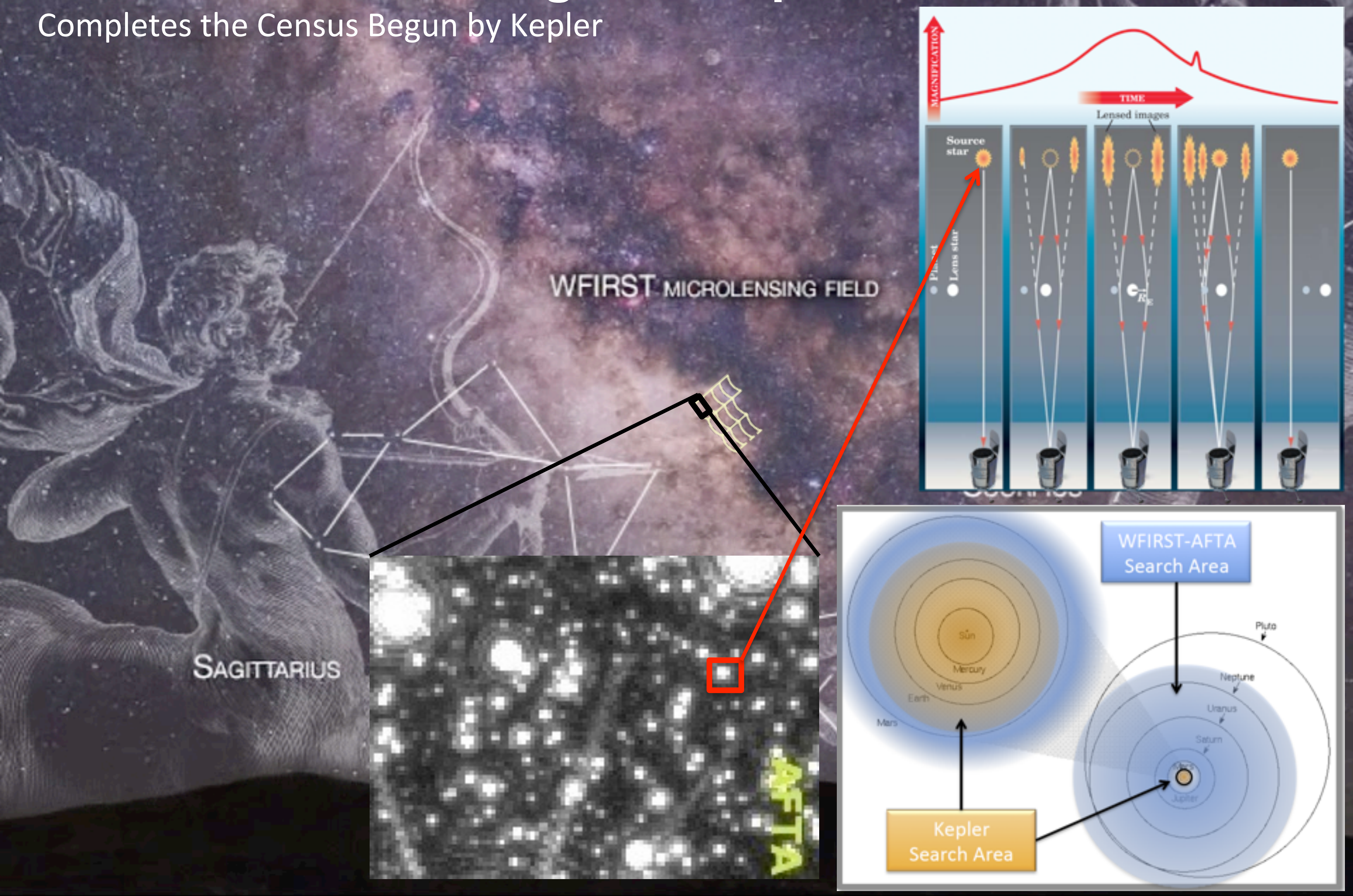
Optical



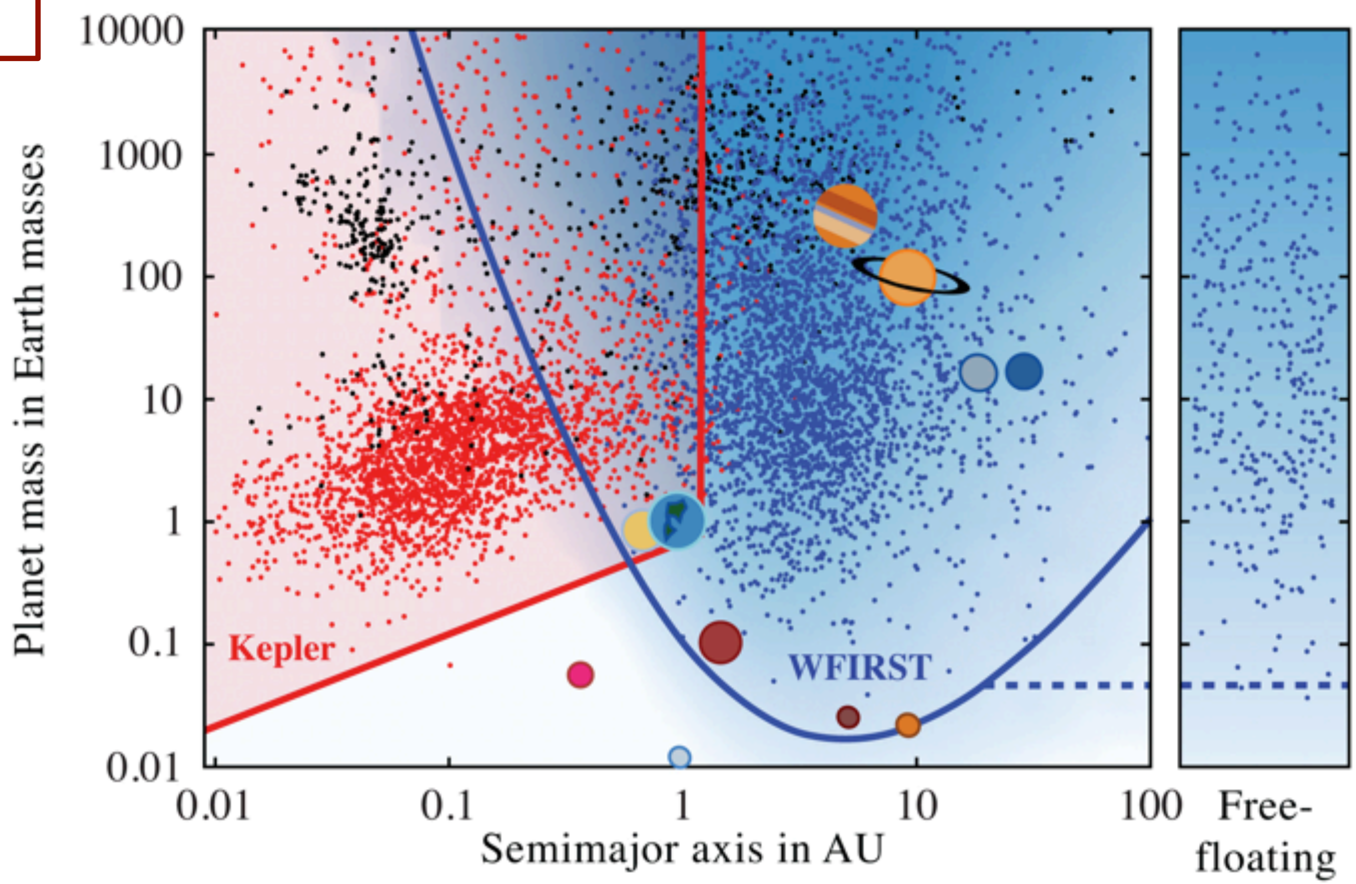
# WFIRST Microlensing for Exoplanets

Completes the Census Begun by Kepler



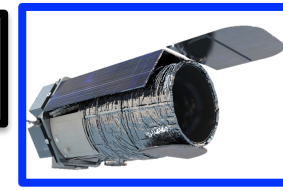
# Completing the Statistical Census of Exoplanets

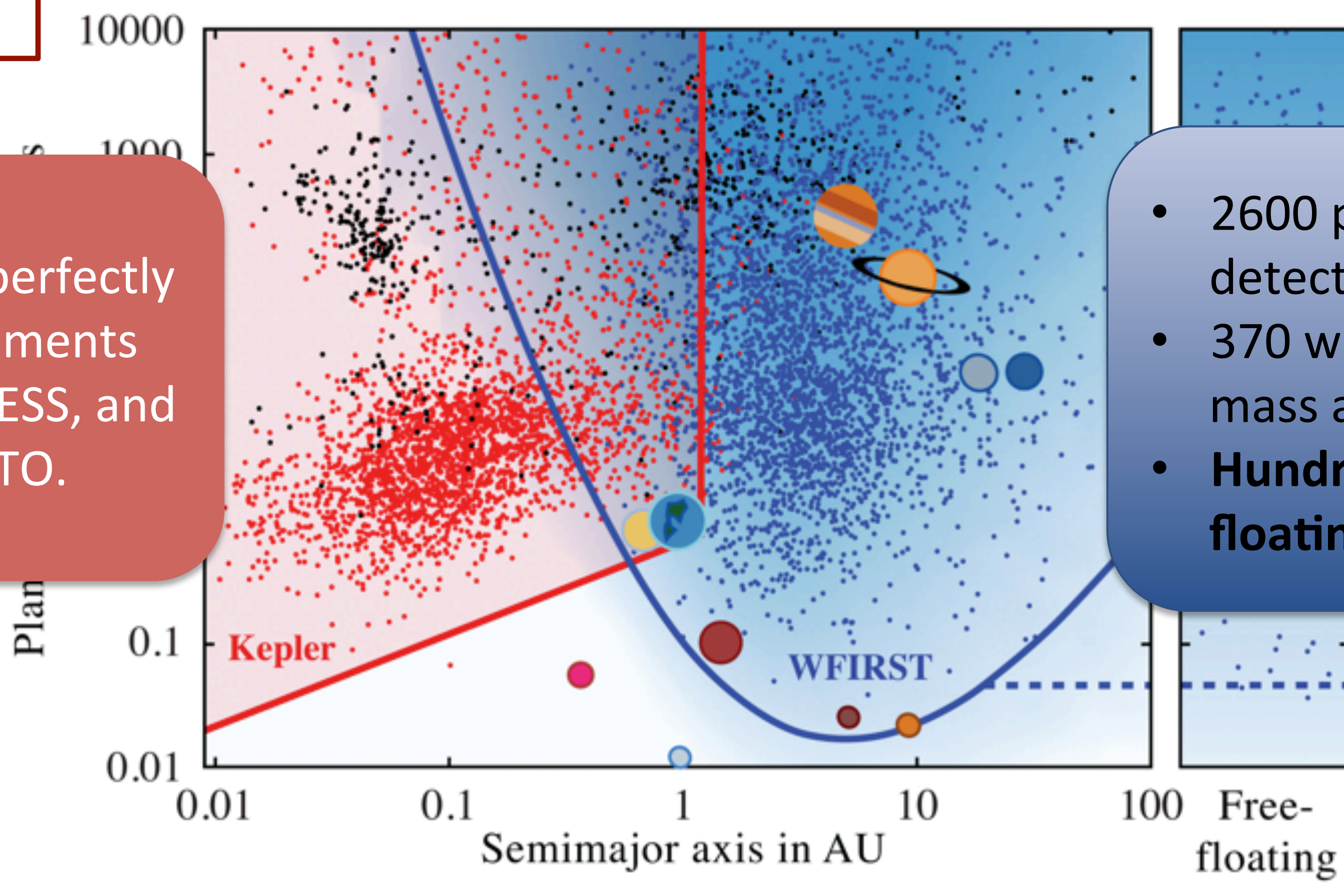
Combined with space-based transit surveys, WFIRST-AFTA completes the statistical census of planetary systems in the Galaxy.



# Completing the Statistical Census of Exoplanets

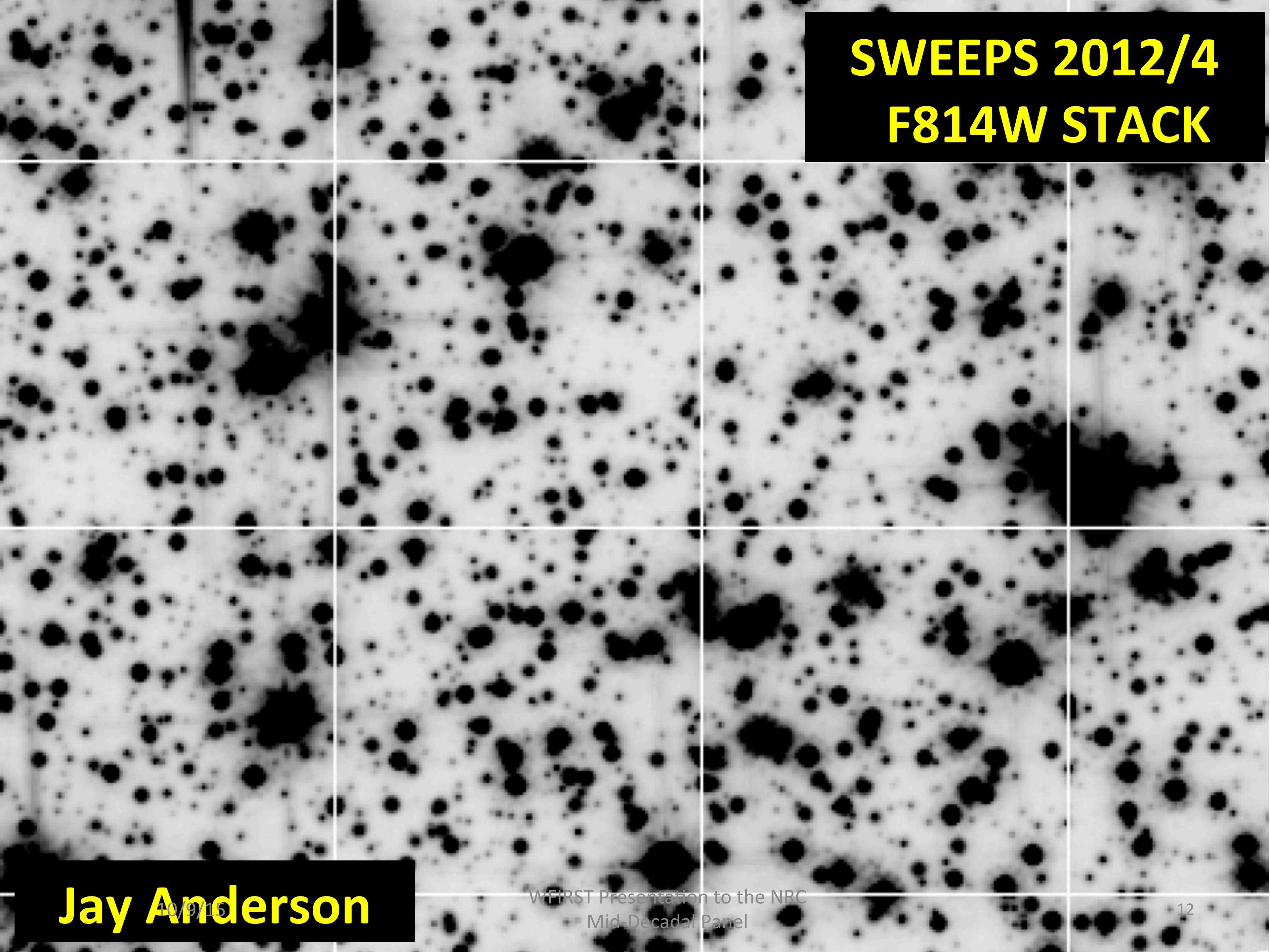
Combined with space-based transit surveys, WFIRST-AFTA completes the statistical census of planetary systems in the Galaxy.

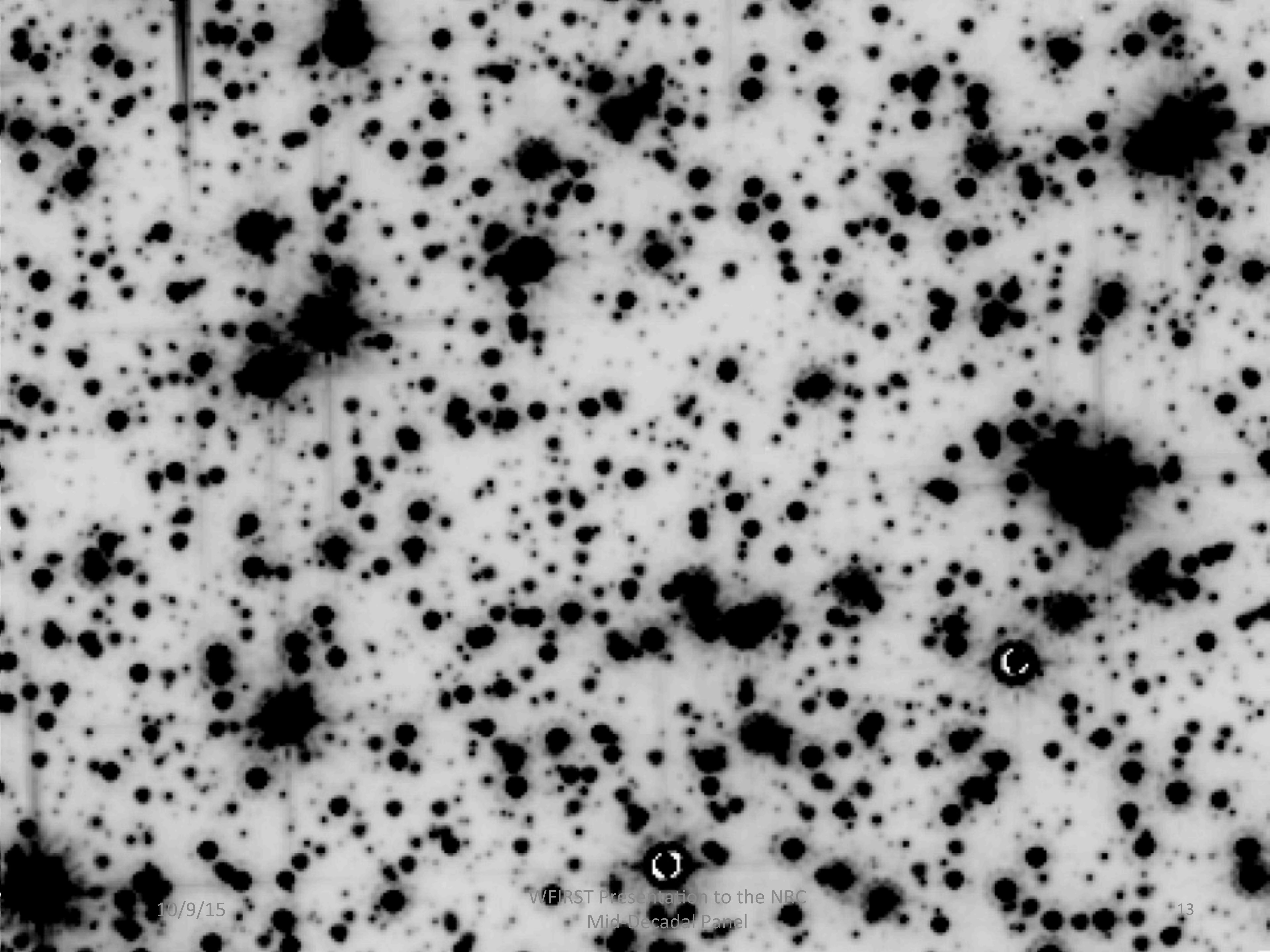





WFIRST perfectly complements Kepler, TESS, and PLATO.

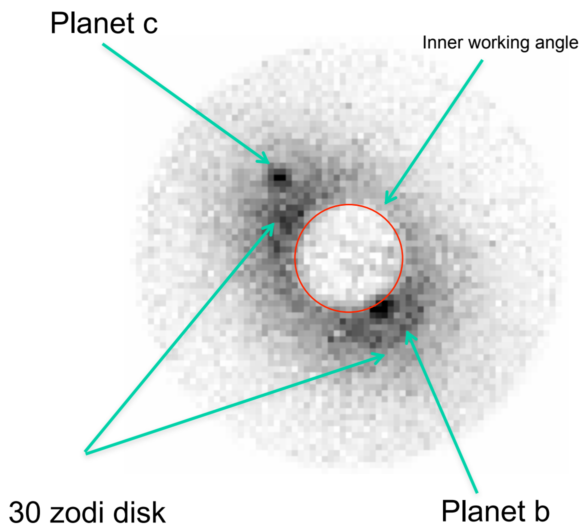
- 2600 planet detections.
- 370 with Earth mass and below.
- **Hundreds of free-floating planets.**


SWEEPS 2012/4
F814W STACK
Jay Anderson

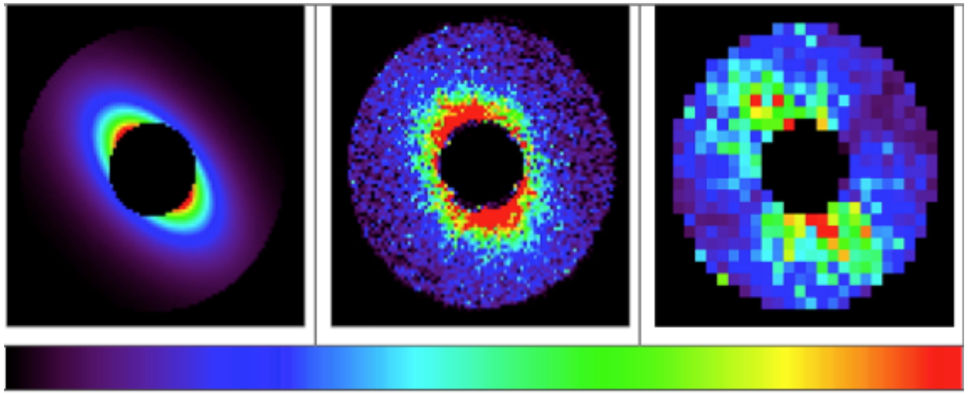


Coronagraphy

- Multi-band imaging at high contrast provides for direct detection and preliminary characterization of exoplanets



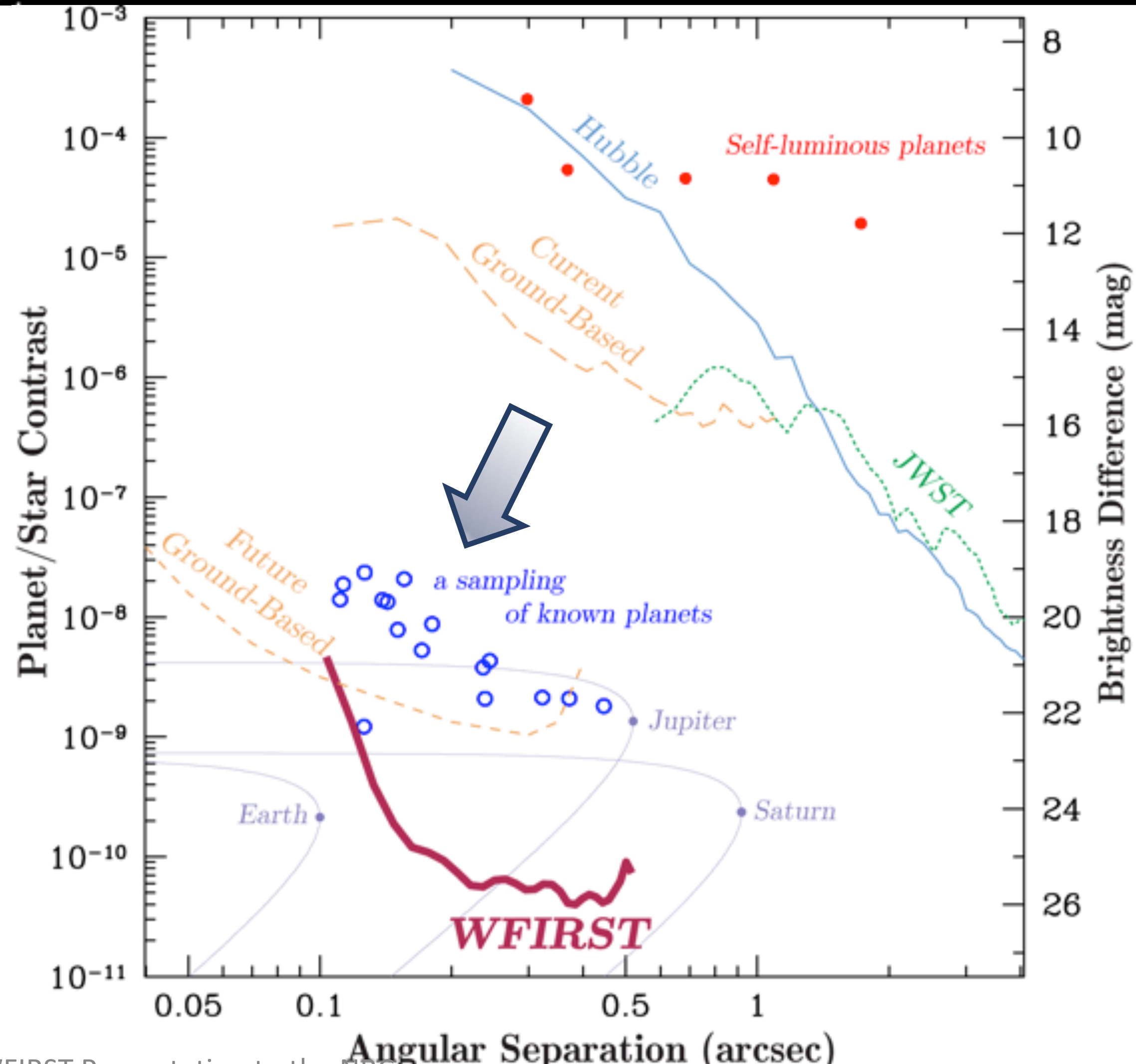

**Simulated WFIRST-AFTA coronagraph image of the star 47 Ursa Majoris, showing two directly detected planets.**



**Simulated WFIRST-AFTA CGI images of a 30 zodi disk around 47 UMa.**

# WFIRST Brings Humanity Closer to Characterizing exo-Earths

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



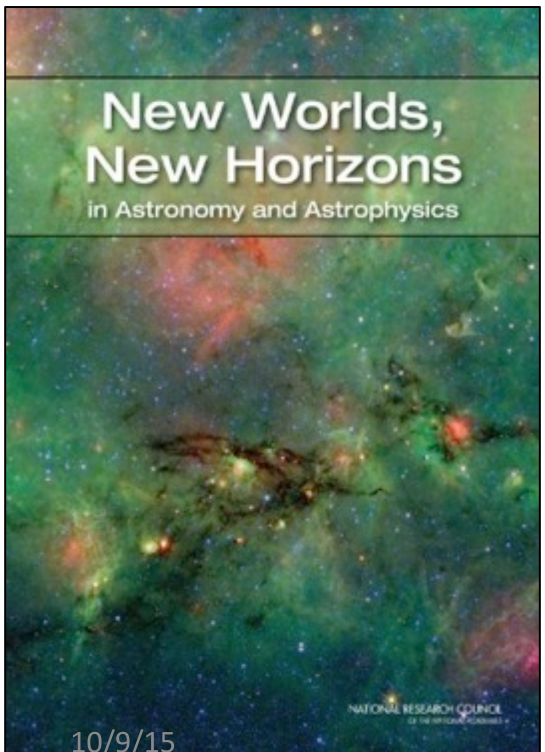
# 25% of WFIRST is GO Time

## Frequently discussed

#1 Large-Scale Priority - Dark Energy, Exoplanets

#1 Medium-Scale Priority - New Worlds Tech. Development (prepare for 2020s planet imaging mission)

## WFIRST covers many other NWNH science goals




### 5 Discovery Science Areas

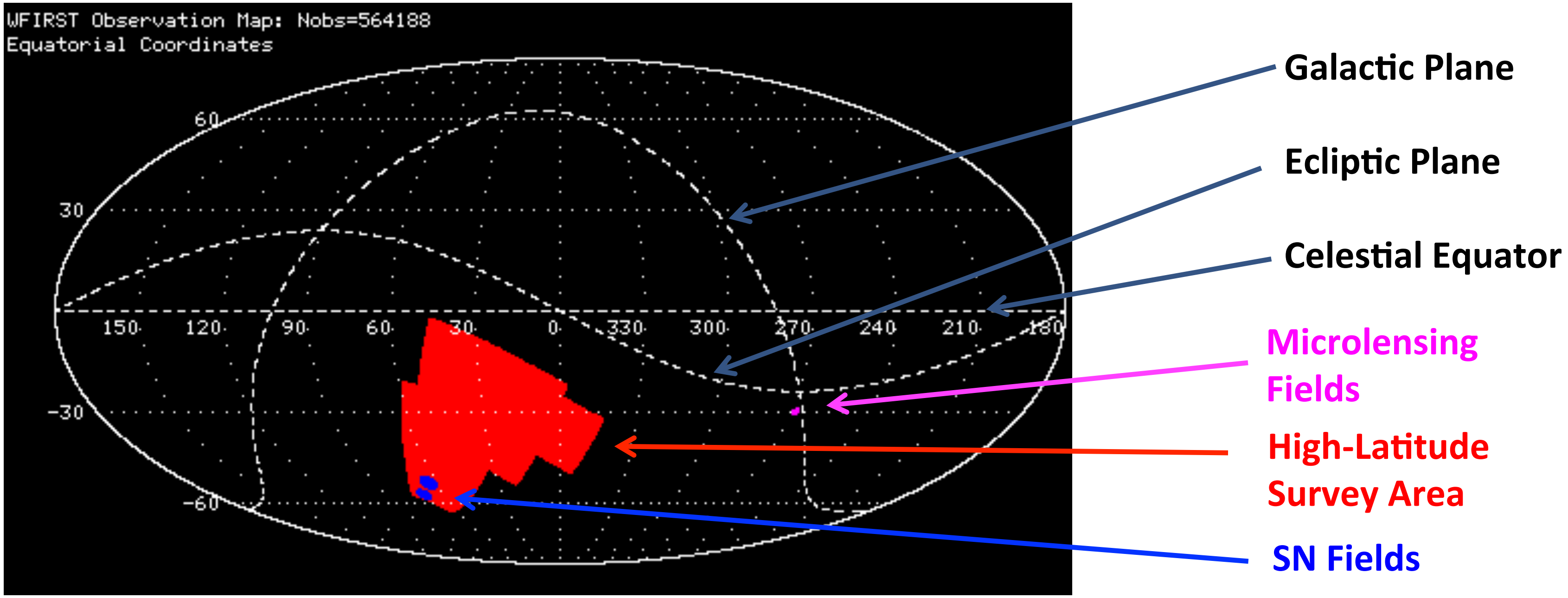
- ID & Characterize Nearby Habitable Exoplanets ✔
- Time-Domain Astronomy ✔
- Astrometry ✔
- Epoch of Reionization ✔
- Gravitational Wave Astrometry

### 20 Key Science Questions

- Origins **(7/7 key areas)**
- Understanding the Cosmic Order **(6/10 key areas)**
- Frontiers of Knowledge **(3/4 key areas)**

# Example Observing Schedule

- High-latitude survey (HLS: imaging + spectroscopy): 2.0 years
  - 2227 deg$^2$ @ ≥3 exposures in all filters (2279 deg$^2$ bounding box)
- 6 microlensing seasons (1.15 years)
- SN survey in 0.6 years, field embedded in HLS footprint
- 0.75 years for the coronagraph, interspersed throughout the mission
- GO program 1.5 years (1.25 years + 0.25 years coronagraph GO)

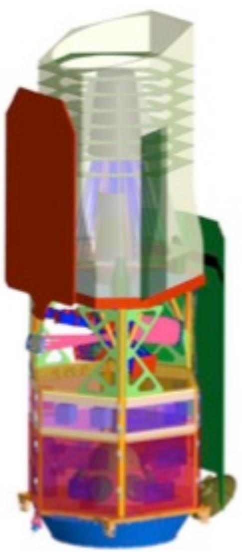


# Comparison to IDRM

- WFIRST-AFTA gives HST imaging over 1000's of sq deg in the NIR
- 2.5x deeper and 1.6x better PSF than IDRM*
- More complementary to Euclid & LSST than IDRM. 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 IDRM.
- WFIRST-AFTA addresses changes in landscape since NWNH: Euclid selection & Kepler discovery that 1-4 Earth radii planets are common.
- Use of 2.4-m telescope and addition of coronagraph have greatly increased the interest in WFIRST in government, scientific community and the public.

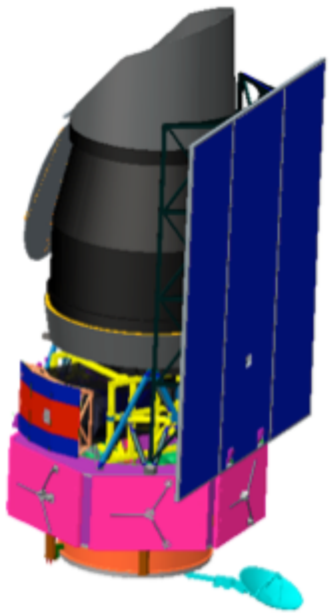
* IDRM = 2011 WFIRST mission design to match NWNH

# Comparison of JDEM-Omega to WFIRST-AFTA



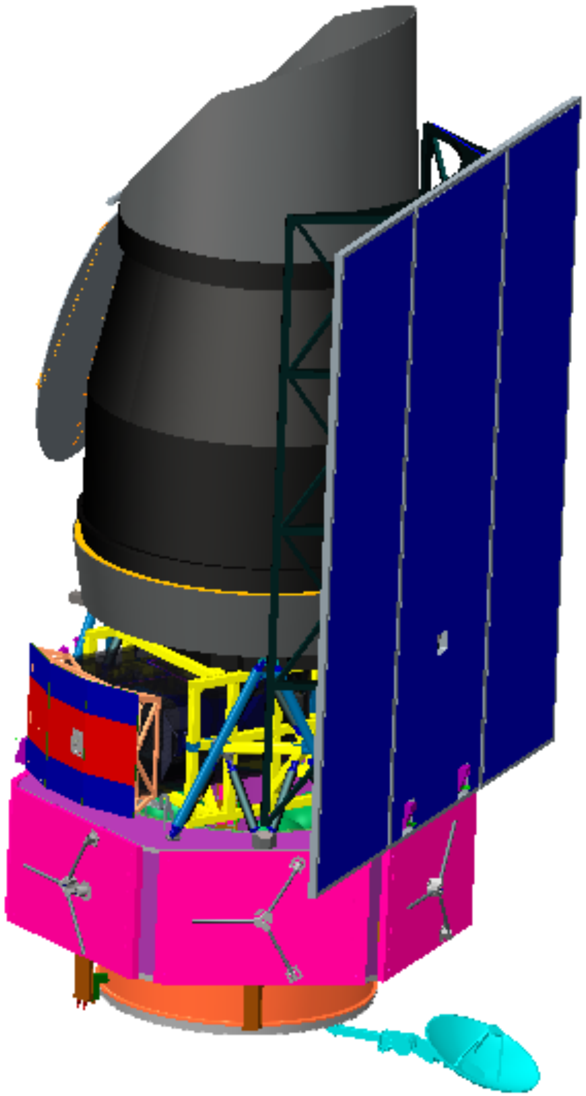
JDEM-Omega
Astro 2010 WFIRST

| Parameter | JDEM-Omega | WFIRST-AFTA |
|---|---|---|
| Imaging bandpass | TBD-2.0μ | 0.76-2.0μ |
| Depth in reddest filter (AB) | 25.5 | 25.8 |
| BAO Spectral bandpass | 1.1-2.0μ | 1.35-1.89 |
| BAO Spectral FoV (sq deg) | 0.264 x 2 | 0.281 |
| GRS line sensitivity 7σ | $1.6 \times 10^{-16}$ erg/cm$^2$/s | $1.2 \times 10^{-16}$ erg/cm$^2$/s |
| SN redshift | 0.2-1.3 | 0.2-1.7 |
| SN bandpass | 0.4-2.0μ | 0.6-2.0μ |
| Telescope temperature | 243K | 282K |
| Imaging FoV (sq deg) | 0.25 | 0.281 |
| Imaging Plate Scale | 0.18” | 0.11” |
| Primary Mirror Diameter (m) | 1.5 | 2.4 |
| # of Science Detectors | 36 H2RG-18 | 18 H4RG-10<br>2 H1RG-18 |



WFIRST-AFTA

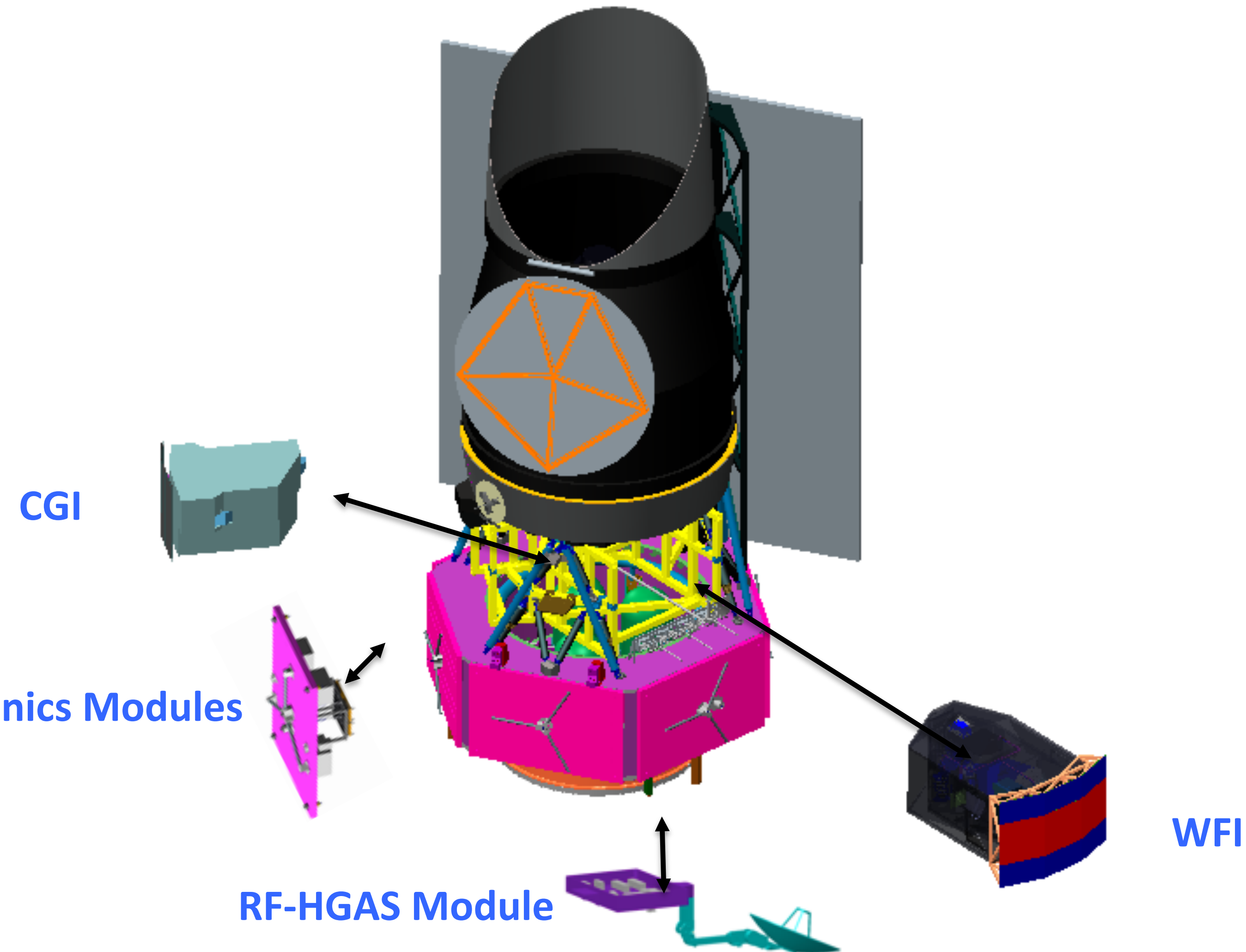
# WFIRST-AFTA Observatory Concept



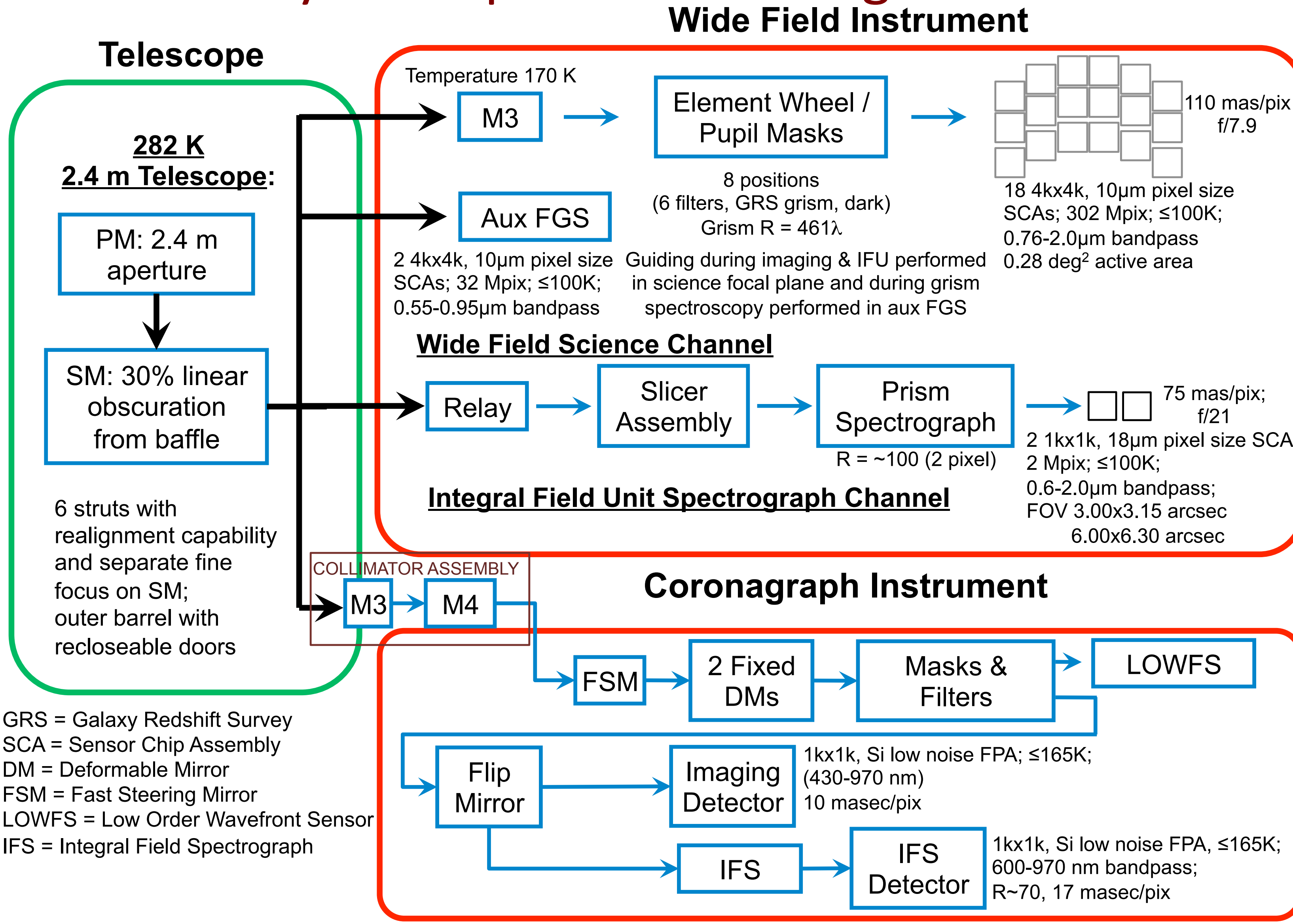
**Key Features**

- **Telescope**: 2.4m aperture primary
- **Instruments**
  - Wide Field Imager/Spectrometer & Integral Field Unit
  - Internal Coronagraph with Integral Field Spectrometer
- **Max Data Downlink Rate**: 275 Mbps downlink
- **Data Volume**: 11 Tb/day
- **Orbit**: Sun-Earth L2
- **Launch Vehicle**: Delta IV Heavy
- **Serviceability**: Observatory designed to be robotically serviceable
- **GSFC**: leads mission and I&T, wide field instrument, spacecraft
- **JPL**: leads telescope, coronagraph

# WFIRST Serviceability



# WFIRST-AFTA
# Payload Optical Block Diagram



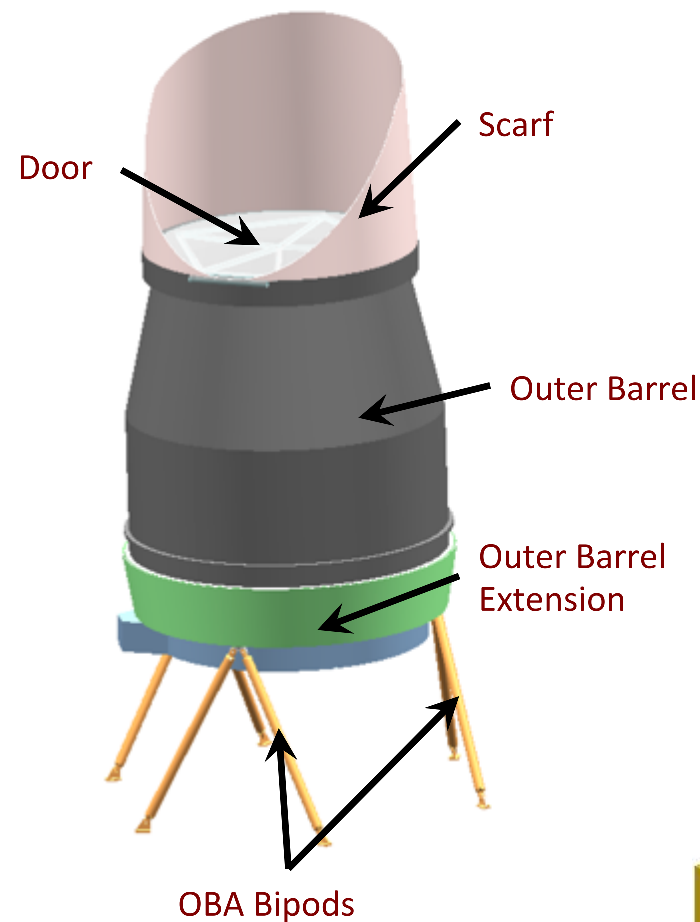

GRS = Galaxy Redshift Survey
SCA = Sensor Chip Assembly
DM = Deformable Mirror
FSM = Fast Steering Mirror
LOWFS = Low Order Wavefront Sensor
IFS = Integral Field Spectrograph

# Telescope Overview

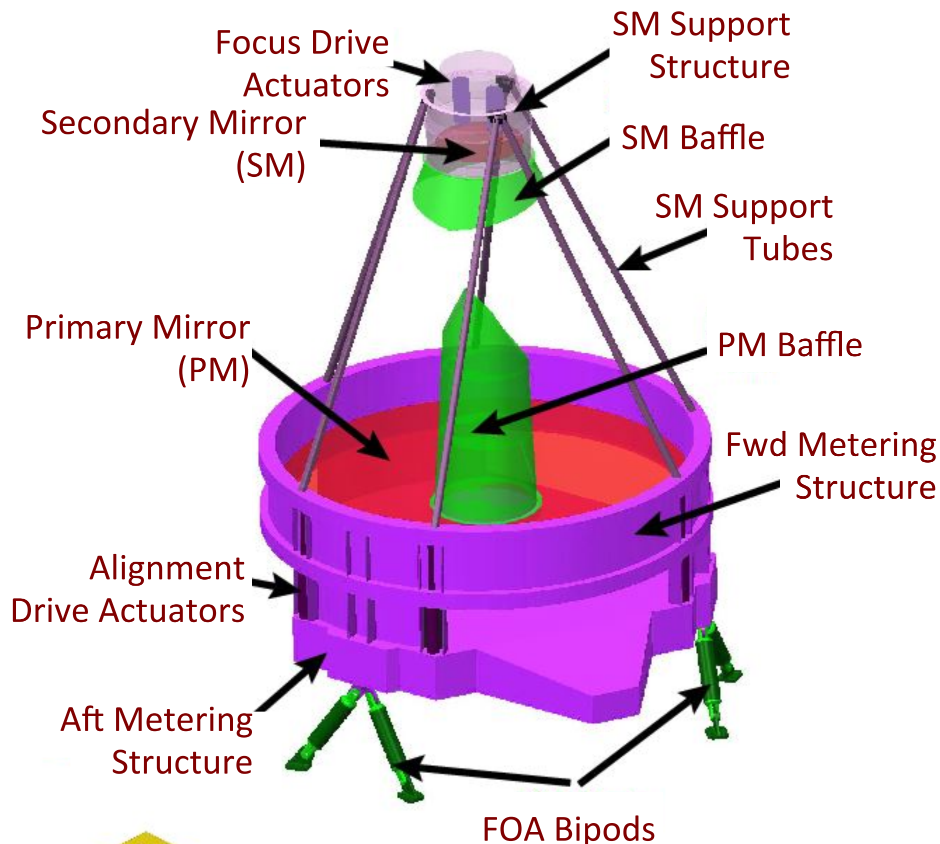
- 2.4 m, two-mirror telescope provided to NASA. Built by Harris (Kodak/ITT/Exelis).
  - Ultra Low Expansion (ULE®) glass mirrors
  - All composite structure
  - Secondary mirror actuators provide 6 degree of freedom control
  - Additional secondary mirror fine focus actuator
  - Active thermal control of structure
  - Designed for operation at room temperature (293 K) with design minimum temperature of 277 K, OBA design minimum temperature of 216 K
  - Outer barrel includes recloseable doors
  - Passive damping via D-struts at the spacecraft interface

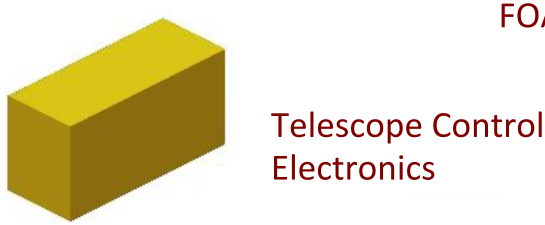
# Telescope Assembly

## Outer Barrel Assembly (OBA)




## Forward Optics Assembly (FOA)



# Telescope Reuse Approach

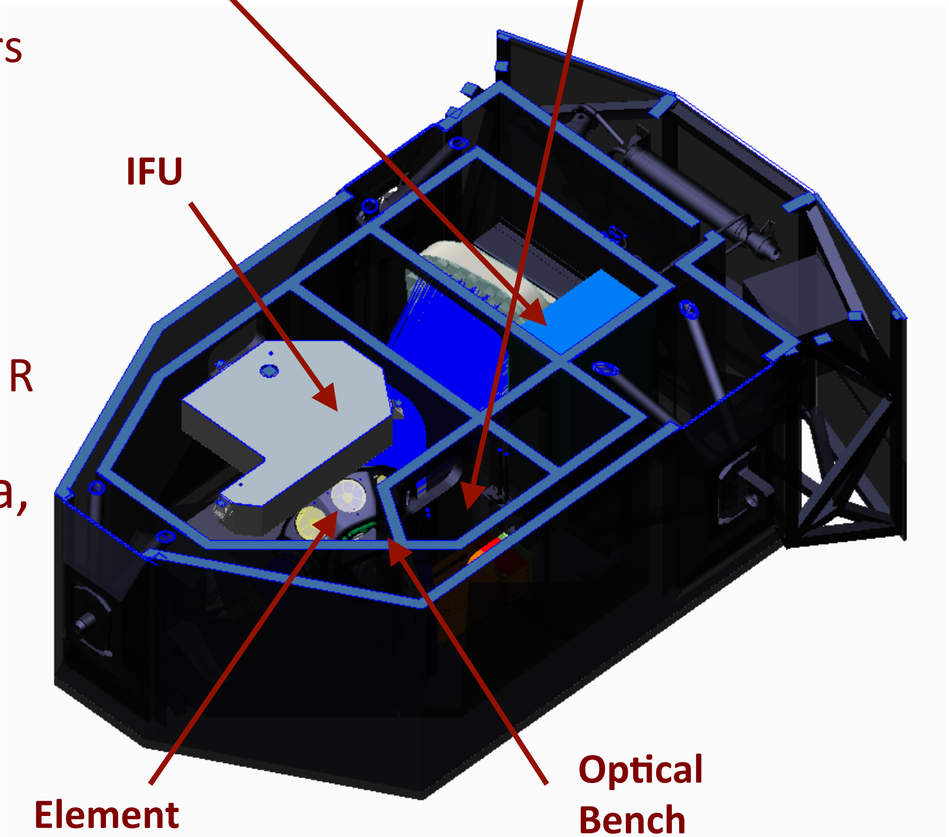
#3

- JPL and the Study Office have worked closely with Harris to understand the telescope hardware.
  - The Observatory design provides an instrument carrier as the prime optical bench for the payload, supporting both the telescope and the instruments, providing substantial structural margin.
  - Set operating temperature at 282K, within heritage hardware design specifications.
    - Continuing to evaluate the feasibility of taking the telescope slightly colder to optimize system design (minimize heater power & improve science performance/margin).
  - Instituted a thorough inheritance audit process to ensure hardware is consistent with the WFIRST application.
    - Includes reviews of original hardware build books and analyses along with new assessments for aging and WFIRST environments.
    - No major issues with planned reuse have emerged to date
  - Detailed build plan, schedule, and cost estimate prepared and reviewed as part of Aerospace CATE.

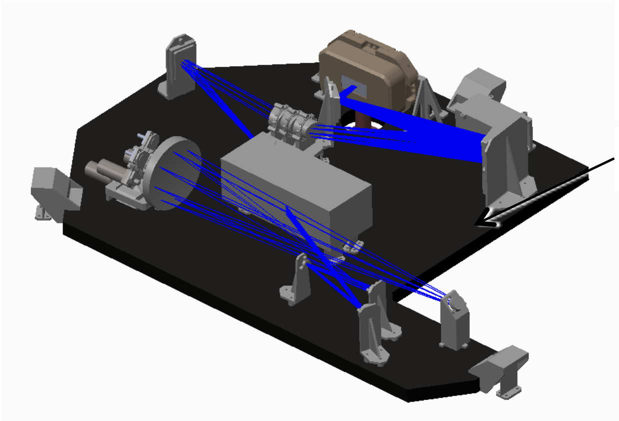
# Wide Field Instrument

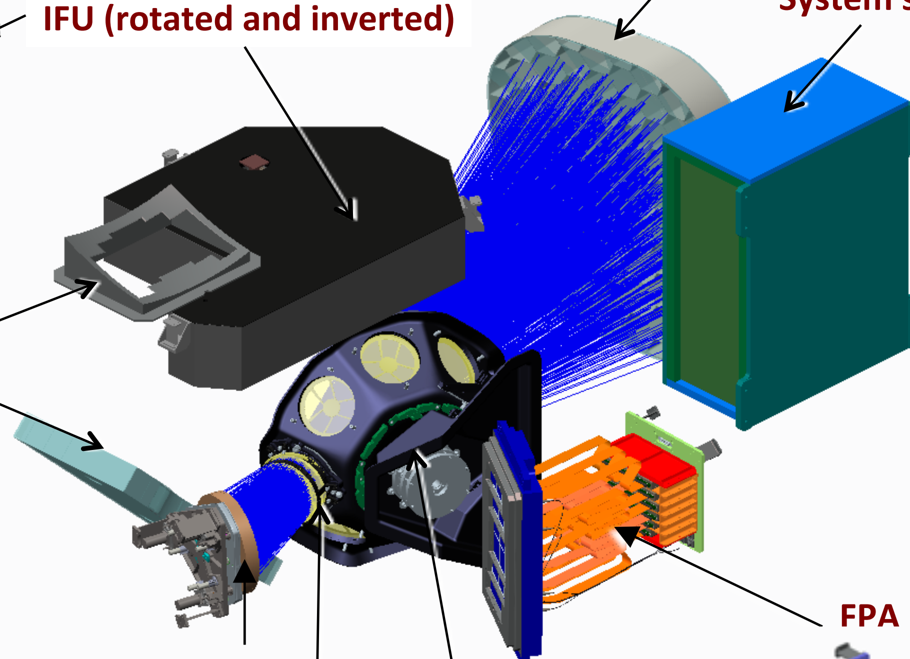
## Key Features

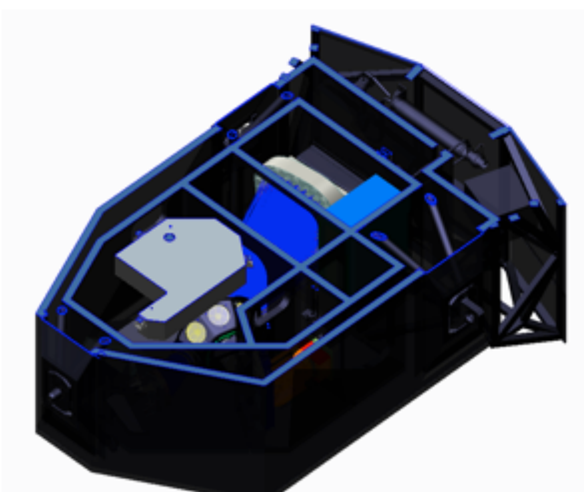
- Wide field channel for both imaging and spectroscopy
  - 3 mirrors, 1 powered
  - 18 4k x 4k HgCdTe detectors cover 0.76 - 2.0 μm
  - 0.11 arc-sec plate scale
  - Single element wheel for filters and grism
  - Grism used for GRS survey covers 1.35 – 1.89 μm with R = 461λ (~620 – 870)
- IFU channel for SNe spectra, single HgCdTe detector covers 0.6 – 2.0 μm with R between 80-120
- Auxiliary guider for guiding during grism spectroscopy mode

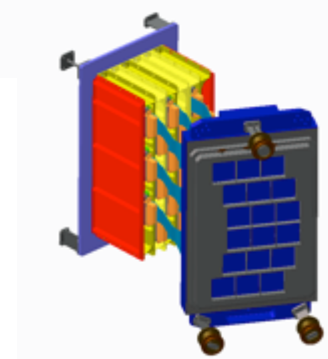


# Wide Field Instrument Layout and Major Subassemblies







# Detector Progress Has Been Steady Since 2014

| MS# | Short Milestone | Date | Status |
|---|---|---|---|
| 1 | Banded Array Performance, PV2 | 7/31/2014 | passed 8/7/14 |
| 2 | Banded Array Performance, PV3 | 12/30/2014 | passed 12/1/14 |
| 3 | Full Array Performance | 9/15/2015 | review 10/28/15 |
| 4 | Yield & Persistence | 9/15/2016 | Yield lot started recently |
| 5 | Environmental test to TRL6 | 12/1/2016 | Test plan in hand |

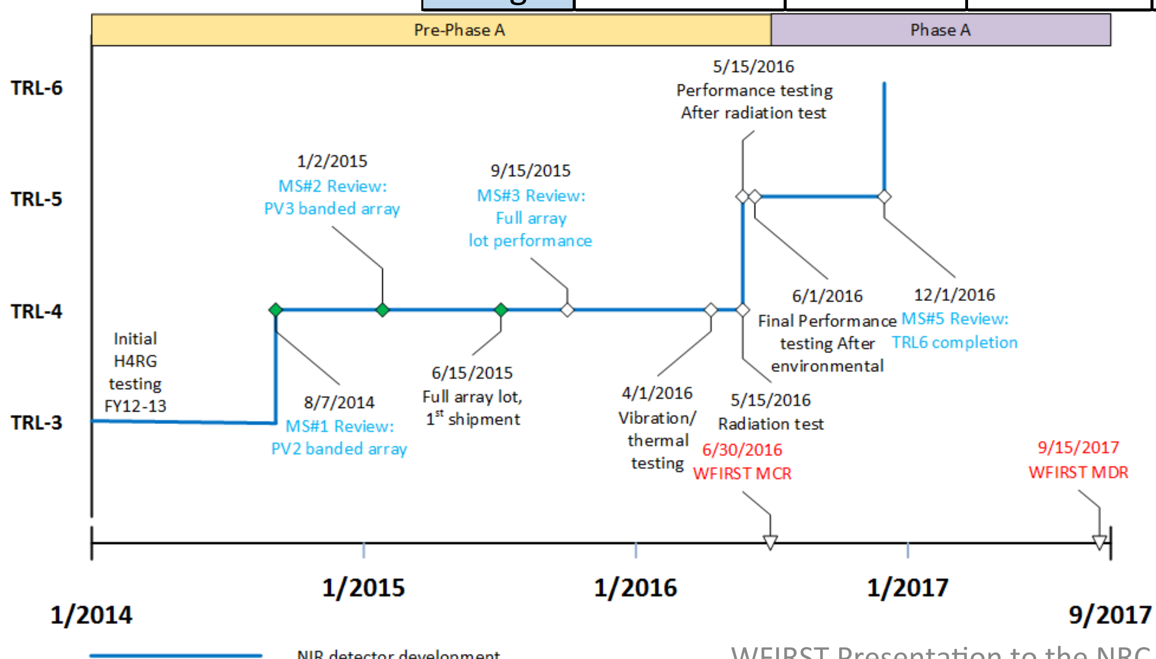
Performance testing of Full Array lot for MS#3 is in progress, with full data on 4 detectors, and partial data on several more.

- FY2014 - Completed pixel design trade, using detectors with 1M pixel banded arrays
- FY2015 - Scaled up to full arrays (MS 9/15/15, review 10/28/2015)
- FY2015 - Increased staffing and test facilities to allow for detailed characterization phase
- FY2016 - Full arrays in process now will be used for environmental qualification in CY16
- Yield lot recently started for MS#4
- Early persistence testing on full array lot in progress (MS#4)

# WFIRST Detector Technology Milestone Progress

Table below shows range of results for the first 4 full arrays; all are within MS#3 specifications.

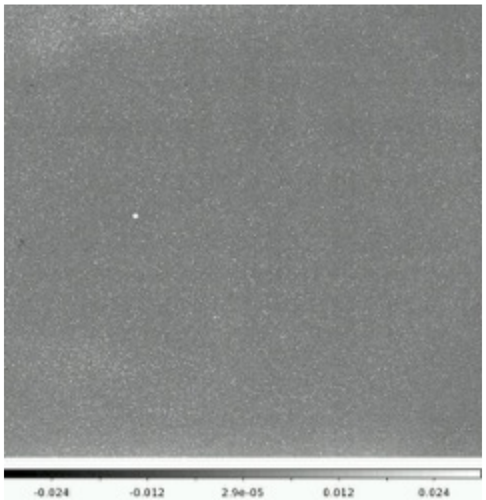
| Detector | Median Dark Current (e/s) | CDS Noise (electrons) | QE (%) (av. 800-2350nm) | Crosstalk (%) (nearest neighbor) | Pixels with Nominal Photo Response |
|---|---|---|---|---|---|
| MS3 req't | <0.1 | <20 | >60 | <3.0 | >95 |
| Range | 0.001-0.007 | 14.5-16.6 | 89-94 | 1.8%-2% | 96-99% |

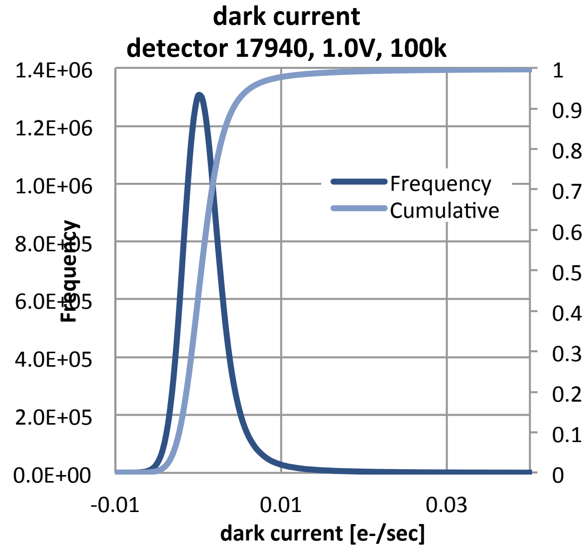


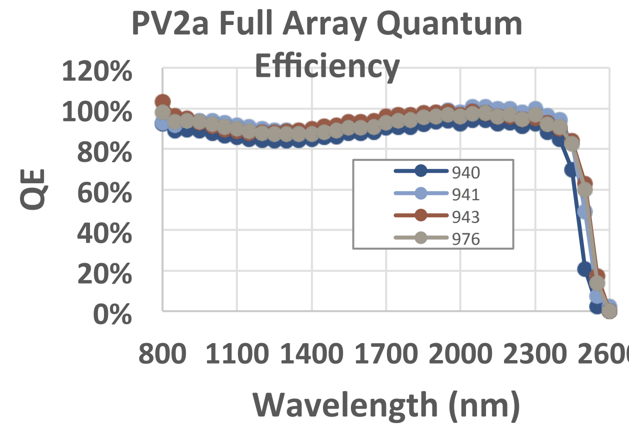

Test timeline uses full arrays to allow early environmental testing for TRL-6 over 2 years before mission PDR.

# Performance is Successfully Scaling to Full Arrays

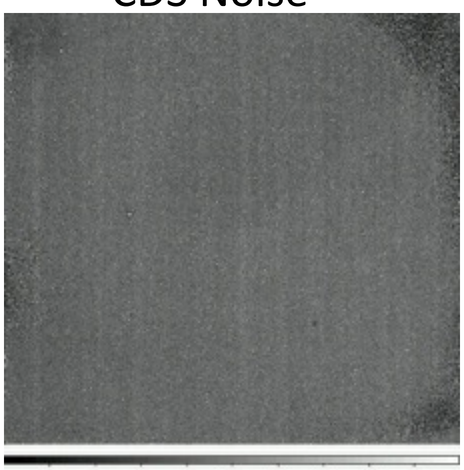
## Dark Current

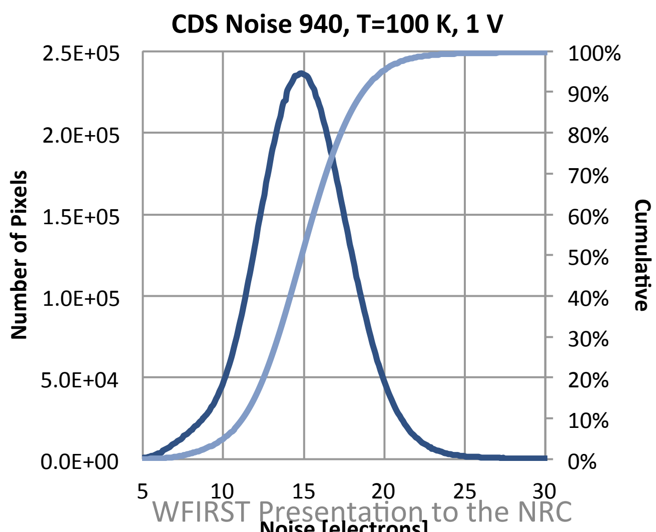



## CDS Noise

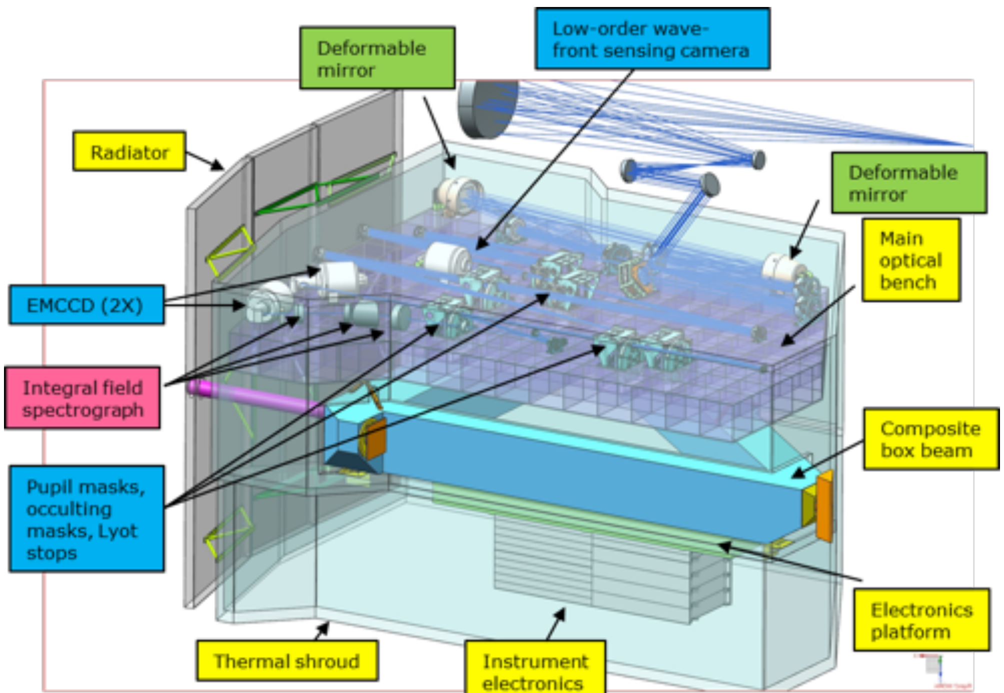





Left column shows image; Middle column shows (log) histogram; QE for 1st several detectors in the full array lot is shown at upper right.

# Coronagraph Instrument

- Completed design for 2015 SDT Report
  - Coronagraph met all WFIRST interface constraints
  - Initial end-end simulations indicate that the coronagraph is likely to achieve all performance goals with the current, unmodified telescope
- Coronagraph cost estimate within expectations
  - NICMs
  - CATE by Aerospace
- Currently working on refining design
  - Improved I&T flow
  - Improved optical throughput (less fold mirrors)




| | | |
|---|---|---|
| **Bandpass** | 430 – 970 nm | Measured sequentially in 10% and 18% bands |
| **Inner Working Angle [radial]** | 100 mas | at 550nm, 2λ/D driven by WFIRST-AFTA pupil obscurations |
| | 270 mas | at 1µm |
| **Outer Working Angle [radial]** | 0.5 as | at 550nm, 10λ/D, driven by 48×48 format DM |
| | 0.9 as | at 1µm (imaging camera) |
| **Detection Limit (Contrast)** | $10^{-9}$ | Cold Jupiters; deeper contrast unlikely due to pupil shape & extreme stability requirements. |
| **Spectral Resolution** | 70 | R = λ/δλ (IFS) |
| **IFS Spatial Sampling** | 17 mas | 3 lenslets per λ/D, better than Nyquist |

# Coronagraph Development Summary

- Team is making good progress on coronagraph technology program to achieve appropriate TRL by Phase A/B
- Coronagraph design is advanced and detailed, not driving mission complexity
- WFIRST coronagraph addresses key 2010 NWNH technology and science goals
  - WFIRST coronagraph brings wavefront-controlled coronagraphy to flight levels on the path to future Earth finding missions, not just hardware, but algorithms
  - As Kepler and microlensing complete the exoplanet census, the WFIRST coronagraph moves into the era of characterization

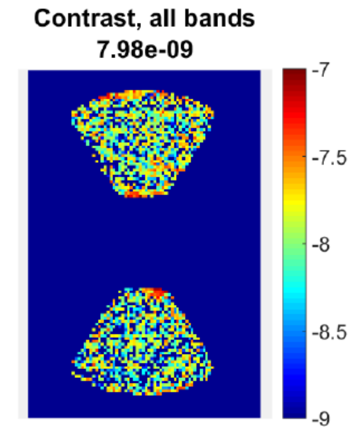
# Coronagraph Technology Milestones

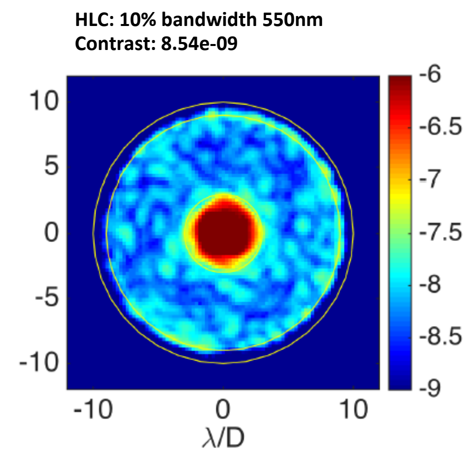
| MS # | Milestone | Date |
|---|---|---|
| 1 ✔ | First-generation reflective Shaped-Pupil apodizing mask has been fabricated with black silicon specular reflectivity of less than $10^{-4}$ and 20 µm pixel size. | 7/21/14 |
| 2 ✔ | Shaped Pupil Coronagraph in the High Contrast Imaging Testbed demonstrates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

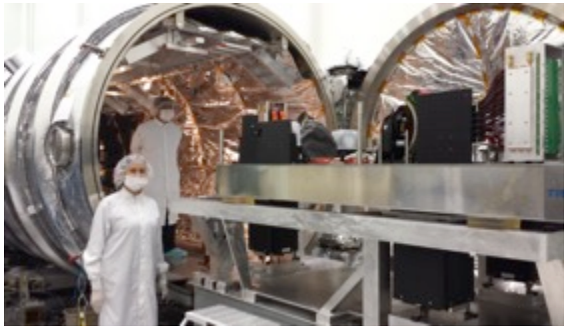
Excellent progress on technology development

# WFIRST Coronagraph Technology Systems Testbed

- Primary coronagraph architecture (Occulting Mask Coronagraph – OMC) consists of two occulting techniques.
  - HLC (Hybrid-Lyot Coronagraph)
  - SPC (Shaped-Pupil coronagraph)
- Demonstrated broadband (10% at 550nm) high contrast (<1x10$^{-8}$) for both designs
- Milestone #5 passed TAC (Technology Assessment Committee) review on 9/29/2015



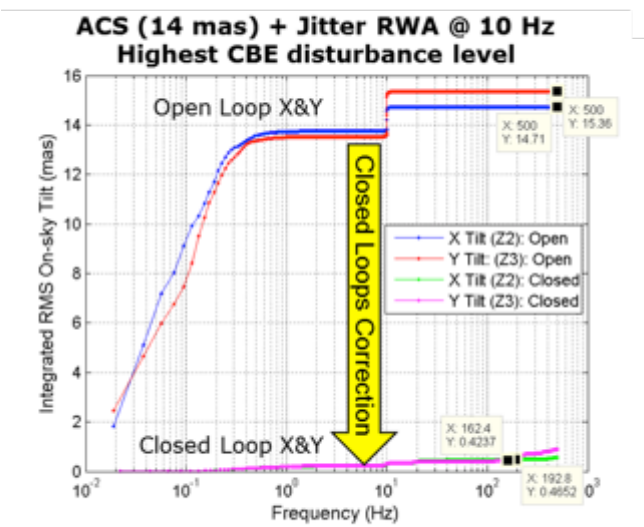



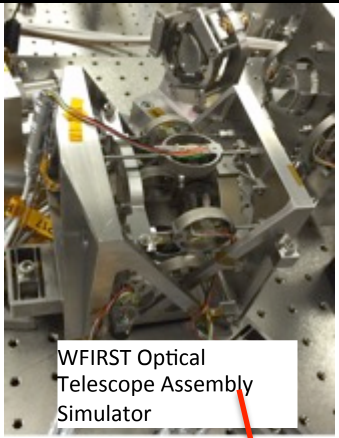



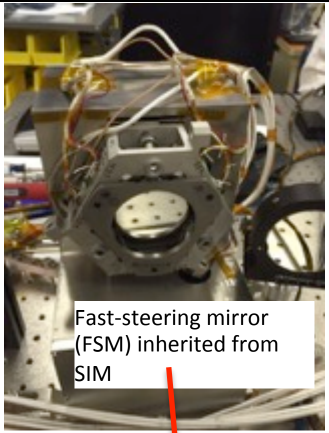
High contrast & broadband demonstration with WFIRST-AFTA pupil!

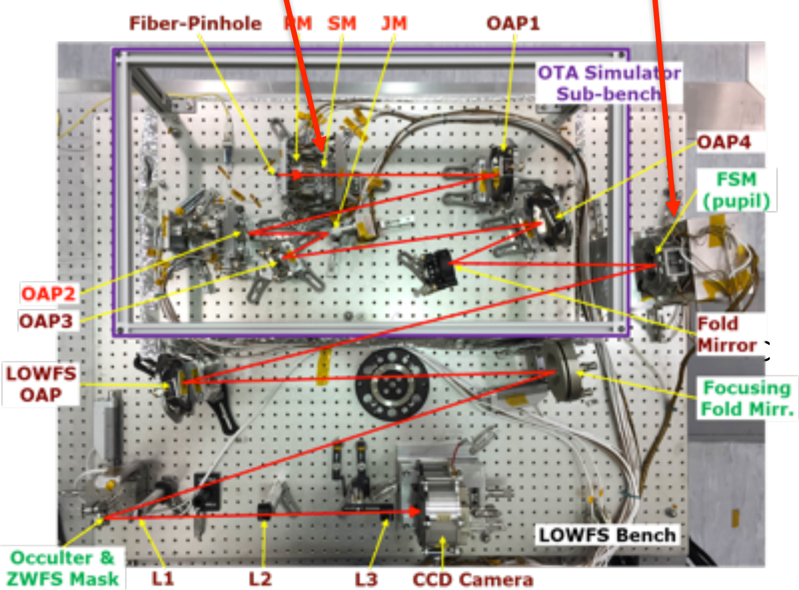
# WFIRST Coronagraph Technology
# Low-Order Wavefront Sensing and Control (LOWFS/C)

- A key enabling technology for coronagraph working with as-built telescope
- Based on Zernike phase contrast microscope
  - Uses rejected star-light and measure observatory pointing jitter and telescope thermal drift.
  - Close-loop with a fast-steering mirror (pointing) and a deformable mirror (telescope thermal drift)
- Milestone #6 passed TAC (Technology Assessment Committee) review on 9/29/2015
  - Low order wavefront error sensing
  - Closed loop tip/tilt correction



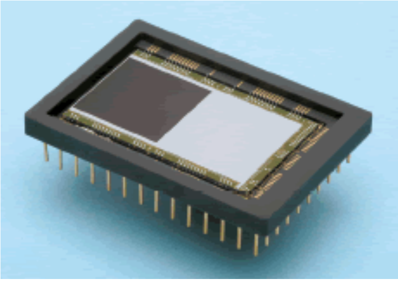




**Closed loop residual LoS error ~0.3 mas rms per axis (good case), ~0.5 mas rms per axis (worst case)**

# Low Noise Detector (EMCCD)

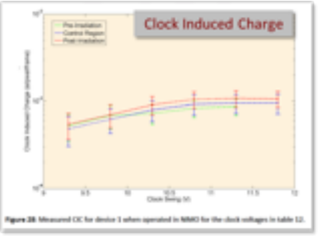
- Electron Multiplying (EM) CCD by e2v (model CCD201-20)
- Laboratory tests show Beginning of Life (BOL) performance requirements are met

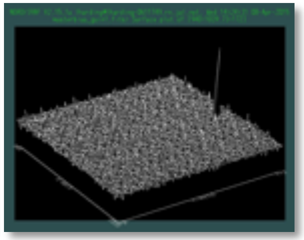
| AFTA-C Detector Performance Requirements | | | | | | |
|---|---|---|---|---|---|---|
| Specification | Goal | Requirement | Measurement | Unit | Notes | Requirement met? |
| Active pixels | N/A | 1024×1024 | 1024x1024 | --- | --- | ✓ |
| Pixel pitch | N/A | 13×13 | 13x13 | microns | Effective area: 177.2mm$^2$ | ✓ |
| Effective read noise w/gain | 0.2 | 0.2 | <0.2 | $e^-$ | EM amp w/EM gain | ✓ |
| Dark current | $1\times10^{-4}$ | $5\times10^{-4}$ | $1.01\times10^{-4}$* | $e^-$/pix/sec | *Measured at Temp 188K, IMO | ✓ |
| Clock induced charge (CIC) @ 5σ threshold | 0.0010 | 0.0018 | 0.0017 | $e^-$/pix/fr | Measured using 10 MHz horiz. Rate, gain x1000 | ✓ |



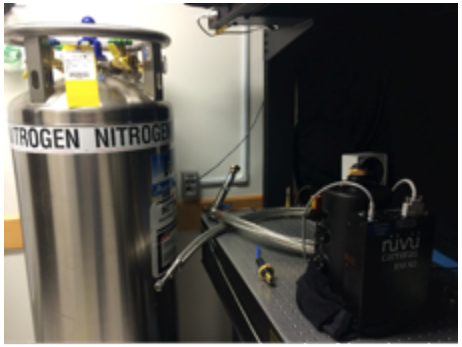
e2v CCD201-20
Electron Multiplying CCD
(1K×1K format)

- Radiation tests on going:
  - Centre of Electronic Imaging at Open University, London
  - Radiation Test #1 at ambient temperature completed on 2015-04-08
  - Radiation Test #2 at low temperatures in 2015-06, data reduction under way



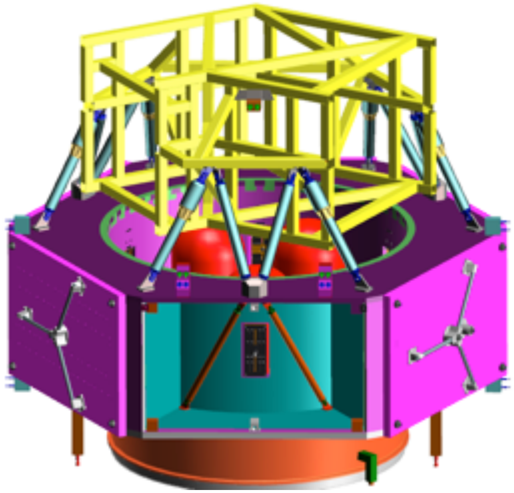
- **Initial results indicate detector performs well after 6 years equivalent radiation in L2**
- **Negligible change in CIC**
- **Post-irradiation Dark Current meets WFIRST requirement**
- **Effect on CTE is being assessed → will be integrated into WFIRST-Coronagraph detector model**



JPL EMCCD LAB

# 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
- Structures/Mechanisms
  - Spacecraft bus structure is aluminum honeycomb with composite facesheets, instrument carrier is a composite truss structure, qualified as an assembly
  - High Gain Antenna (HGA) system contains 2-axis gimbal
- Thermal
  - Passive cooling with coatings, MLI, heatpipes, and heater control
- Power (SDO & GPM heritage)
  - Internally redundant PSE, supplies power, controls array, battery
  - Fixed, body mounted arrays
  - Li-ion batteries for off-pointing during burns to L2

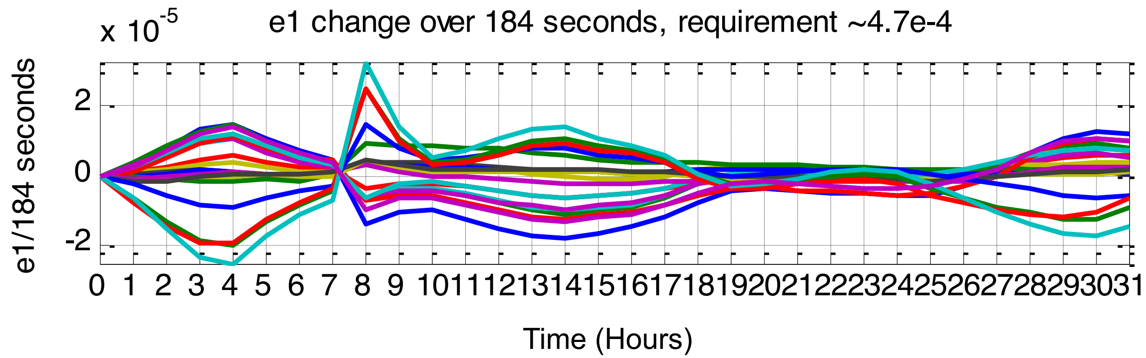


# Spacecraft Overview

- C&DH (SDO & GPM heritage)
  - Platform for FSW: gathers TLM, sends commands, FDC
  - Low rate bus for housekeeping and spacecraft control
  - High speed science data interface between instruments and Ka downlink
    - End-to-end high speed test bed demonstration by end of 2015.
- Comm
  - S-band omni antennas for uplink and housekeeping data downlink
  - Ka-band for science data rate up to 275 Mbps (trading between DSN and dedicated ground stations)
    - GSFC developed transmitter (update of SDO design) with a capability of 1.2 Gbps (prototype on schedule for completion in early 2015)
- Attitude Control/Prop
  - 3-axis stabilized using 4 reaction wheels with thruster unloading
  - 14 mas drift & 14 mas jitter, RMS/axis
  - FGS uses guide window data from Wide Field Instrument
  - Mono-prop system for mid-course correction, station-keeping, momentum unloading and end of life disposal

# Observatory Integrated Modeling

- A key focus of pre-Phase A Observatory analysis has been on integrated modeling (STOP and Jitter).
- Model fidelity is high for this phase of the mission.
  - Benefit of using the existing telescope
  - Required to optimize coronagraph mask designs
  - Critical for assessing PSF ellipticity for WL
- Analysis is on-going now for current configuration. Results below are from the configuration as documented in the 2015 report.
- WFI STOP stability specs met with margin (10x) even for an extreme WFI Worst Slew Case w/MUFs applied
- WFI Jitter stability specs met with margin (1.3x) for all disturbance sources even with MUFs applied
  - Modeled 4 RWAs, cryocooler and HGA jitter disturbances




**Plot of delta ellipticity over a weak lensing observation with time steps of 3600 seconds after a slew at hour 7. $\Delta e1 \leq 3.3 \times 10^{-5}$ / 184 sec provides 14.2x margin on $4.7 \times 10^{-4}$ and $\Delta e2 \leq 4.1 \times 10^{-5}$ / 184 sec provides 11.5x margin on $4.7 \times 10^{-4}$ (not shown). The lines represent the center field point of each of the 18 detectors and a point for the FoV center.**

# Coronagraph STOP Results from 2015 SDT Report Configuration

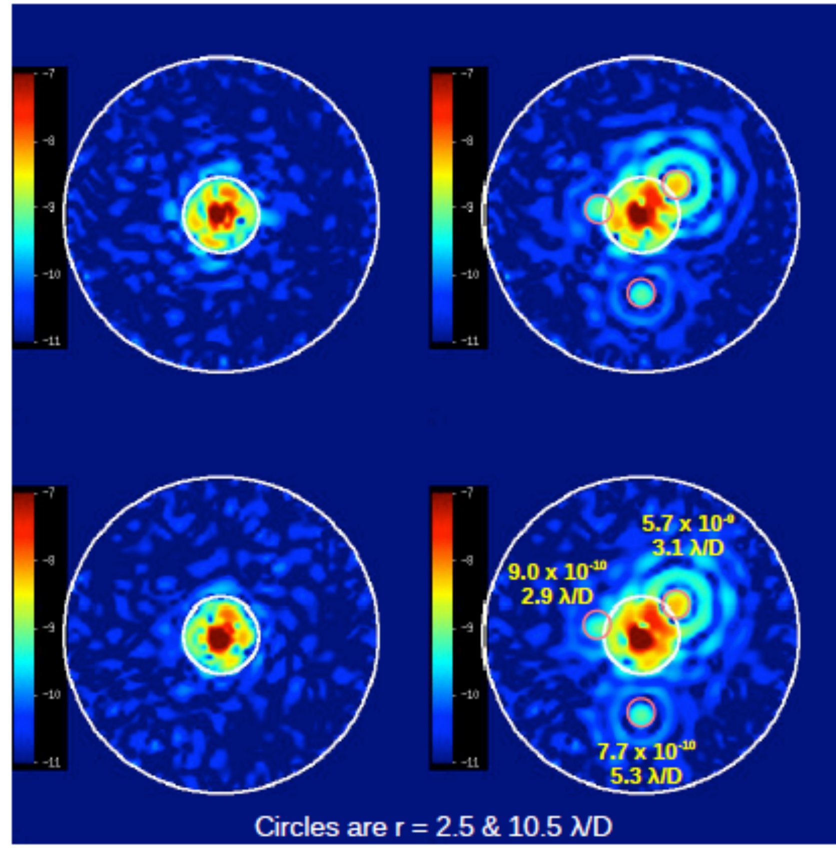
Initial simulations of Coronagraph performance in WFIRST-AFTA environment indicate that the Coronagraph is likely to achieve all performance goals with the current, unmodified telescope.

As part of the recent design refinement process, the Coronagraph collimator was moved from inside the instrument to the telescope aft metering structure. This change makes the Coronagraph >1000x less contrast sensitive to Coronagraph misalignments to the telescope.

No planets | With planets (circled)

|47 Uma - β Uma|

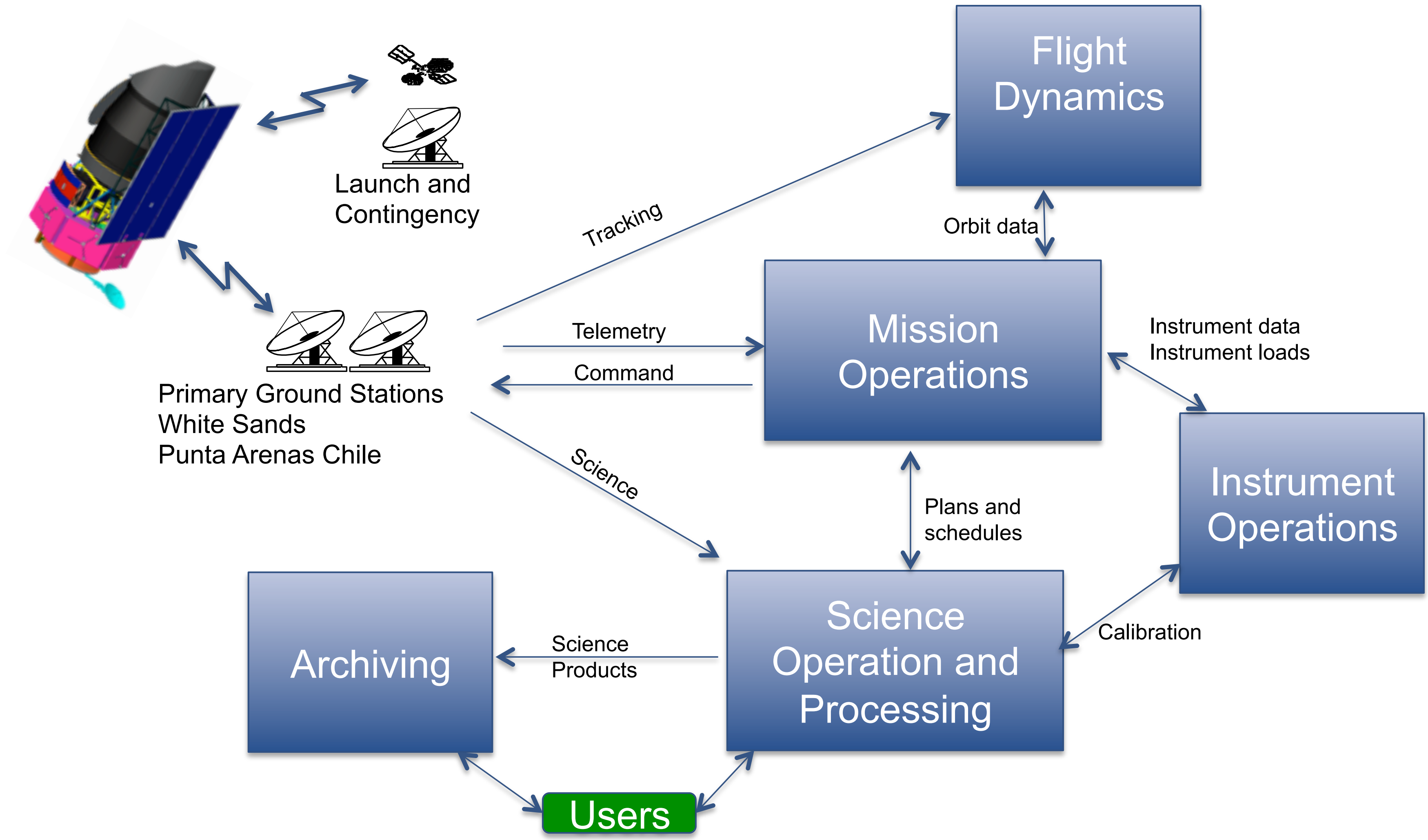
|47 Uma - 61 Uma|



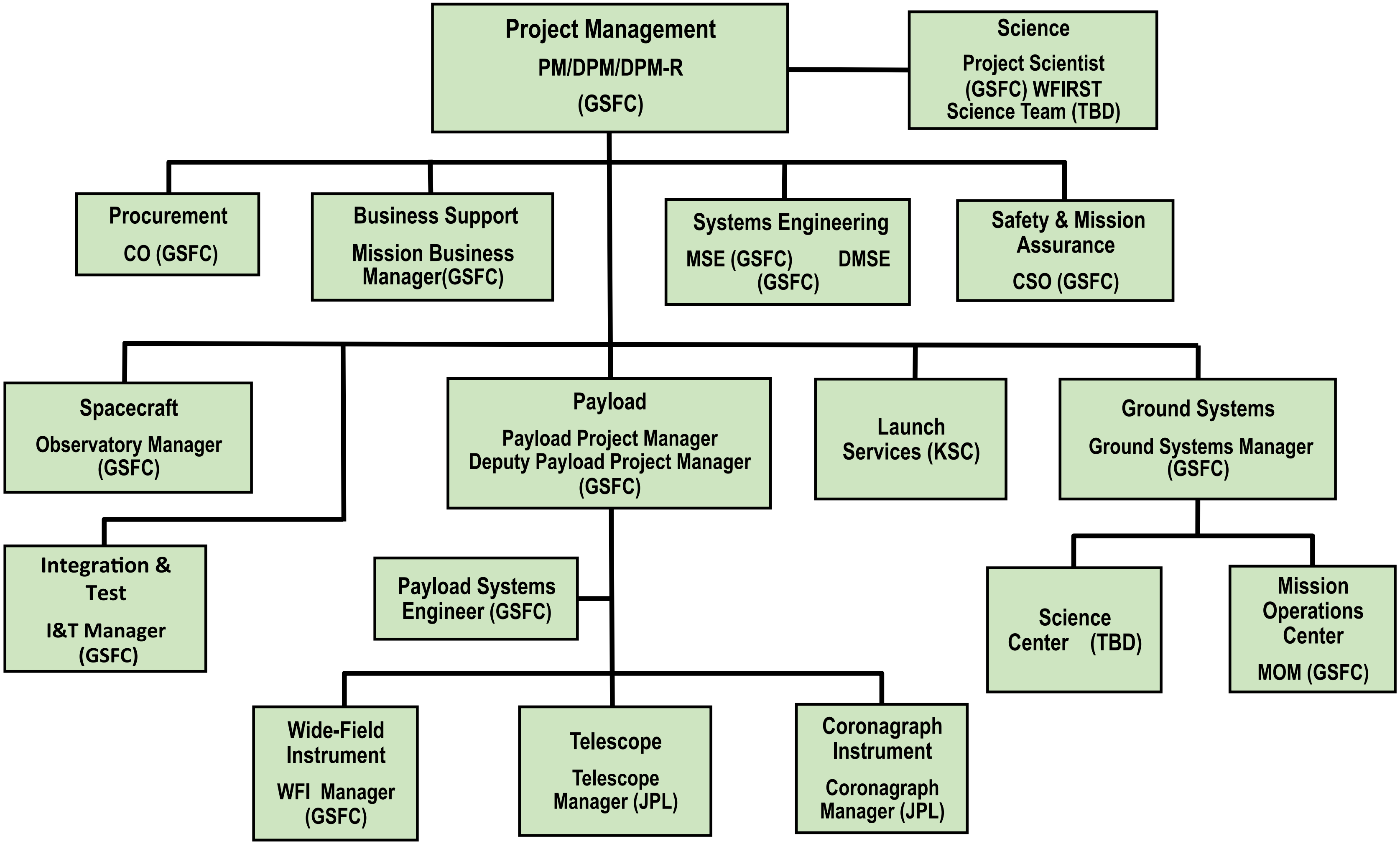

*Color differences between these stars are not important in 10% bandpass.*

Absolute differences of the mean images with DM LOWFC
(1000 sec LOWFS integrations)

# Baseline Ground System Architecture



# WFIRST Project Organization



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#2

# Recent Activities

- Completed design report with SDT – March '15.
- Developed life cycle mission cost (combination of parametric, grassroots, and analogy)
- Validated by independent cost assessment (Aerospace CATE).
- MCR design cycle progressing to completion in December.
- Milestones for Coronagraph and IR detectors continue to make excellent progress.
  - Technology Assessment Committee provides for external review of technology milestones.
- Risk management process being actively utilized.
- Industry RFI for potential participation in WFIRST development recently conducted; study solicitation this fall.
- Solicitation for WFIRST science team released July 17th.

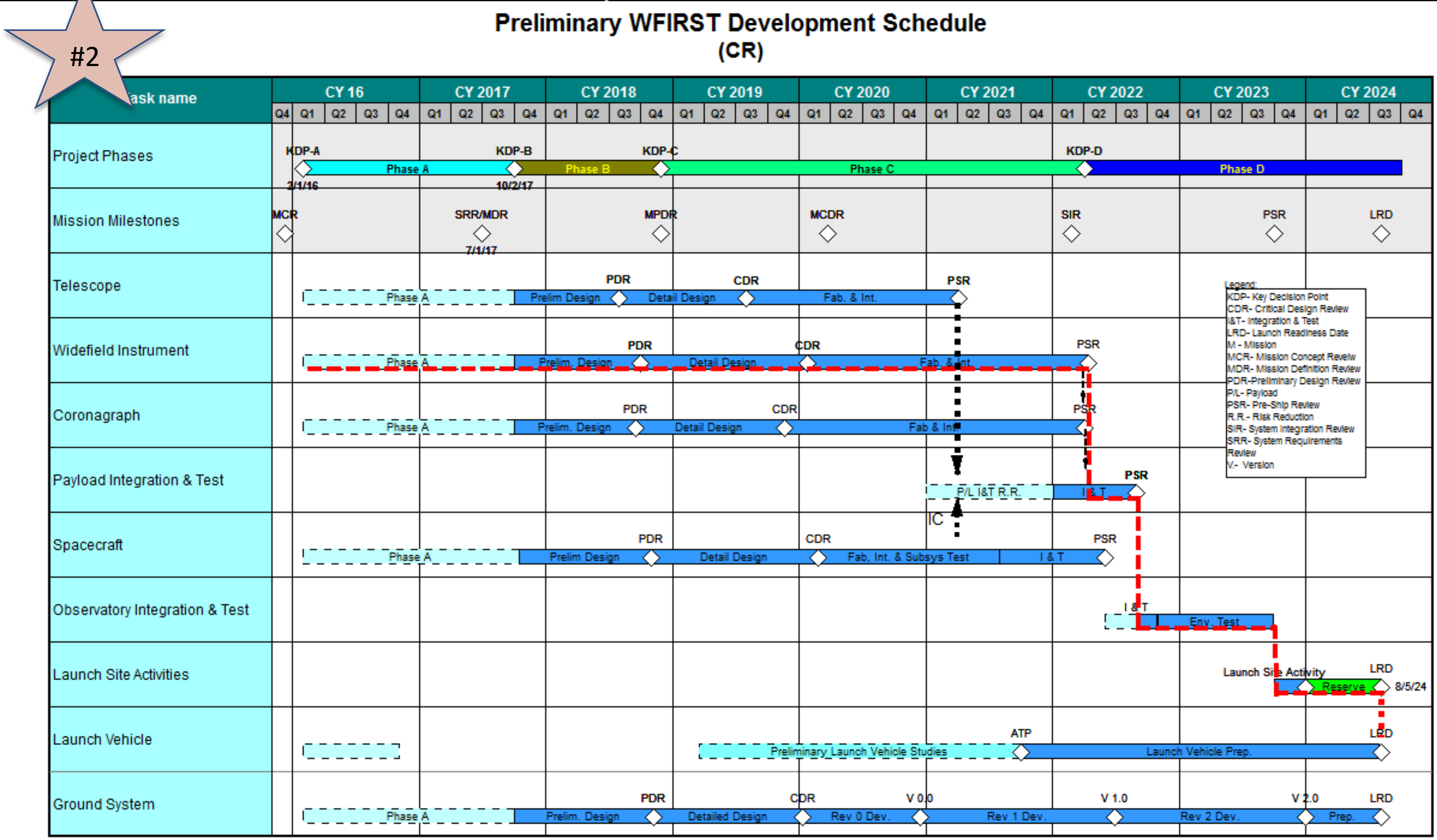
| NASA Cost Estimate | FY10$B | FY15$B | RY$B |
|---|---|---|---|
| Mission Cost w/coronagraph | 1.8-2.1 | 2.0-2.3 | 2.5-2.8 |
| Cost of adding coronagraph | 0.32 | 0.35 | - |
| NWNH Mission Estimate* | 1.6 | 1.8 | - |

* NWNH cost estimate did not include the GI/GO program

# Path Forward

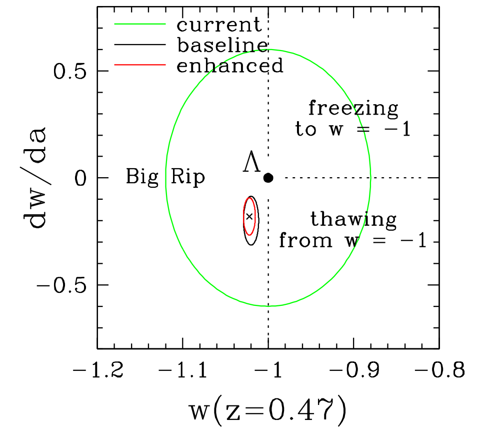
- Mission Concept Review schedule for Dec 8-9.
- Industry study solicitation to be released.
- Developing KDP-A documentation and products per NPR 7120.5E (control plans, descope plan, design reference, Formulation Agreement, etc.)
- Proposals for WFIRST Science Team due October 15; selection around Dec 1.
- Science Investigation Team kick-off planned for the first week of February.
- Award of industry studies in early 2016.
- Prepared for the start of formulation (KDP-A) as early as January 2016.
- Acquisition Strategy Meeting (ASM) in spring; finalizes acquisition approach.
- Systems Requirements Review/Mission Design Review (SRR/MDR) to be held prior to end of Formulation Phase.
- At the conclusion of the Formulation Phase, KDP-B and transition to development.

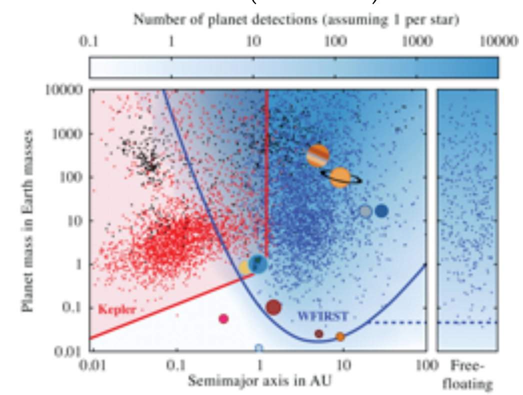
# Preliminary Development Schedule

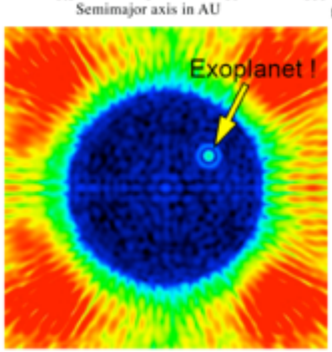


# Summary

- Over the past two years, increased funding has enabled significant progress in technology maturation as well as additional fidelity in the design reference mission.
- WFIRST with the 2.4-m telescope and coronagraph provides an exciting science program, superior to that recommended by NWNH and also advances exoplanet imaging technology (the highest ranked medium-class NWNH recommendation).
- Great opportunity for astronomy and astrophysics discoveries. Broad community support for WFIRST.
- Key development areas are anchored in a decade of investments in JPL's HCIT and GSFC's DCL.
- Great progress made in pre-formulation, ready for KDP-A and launch in mid-2020s.

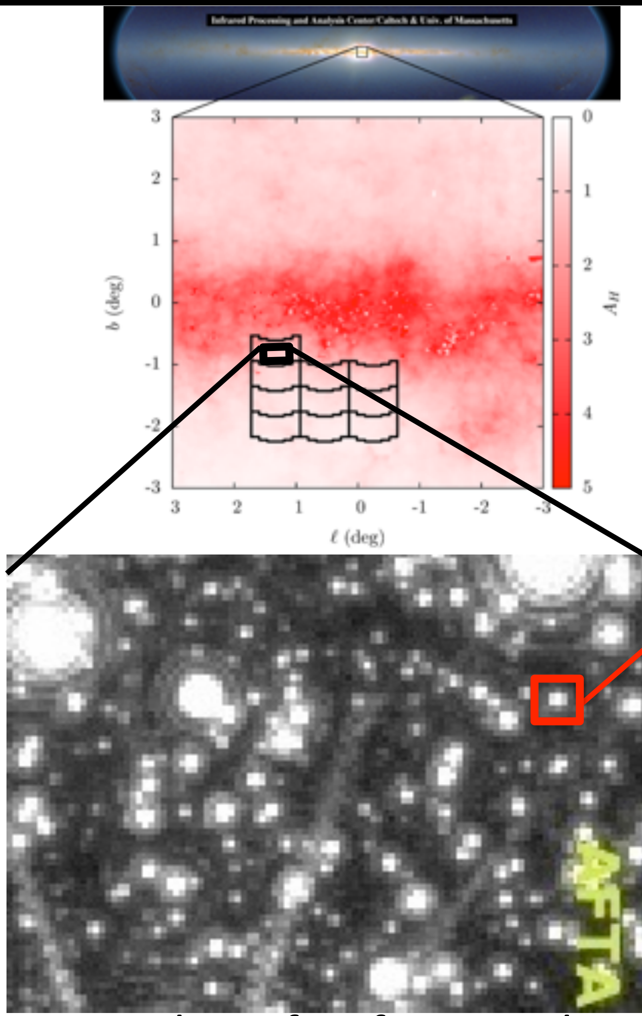


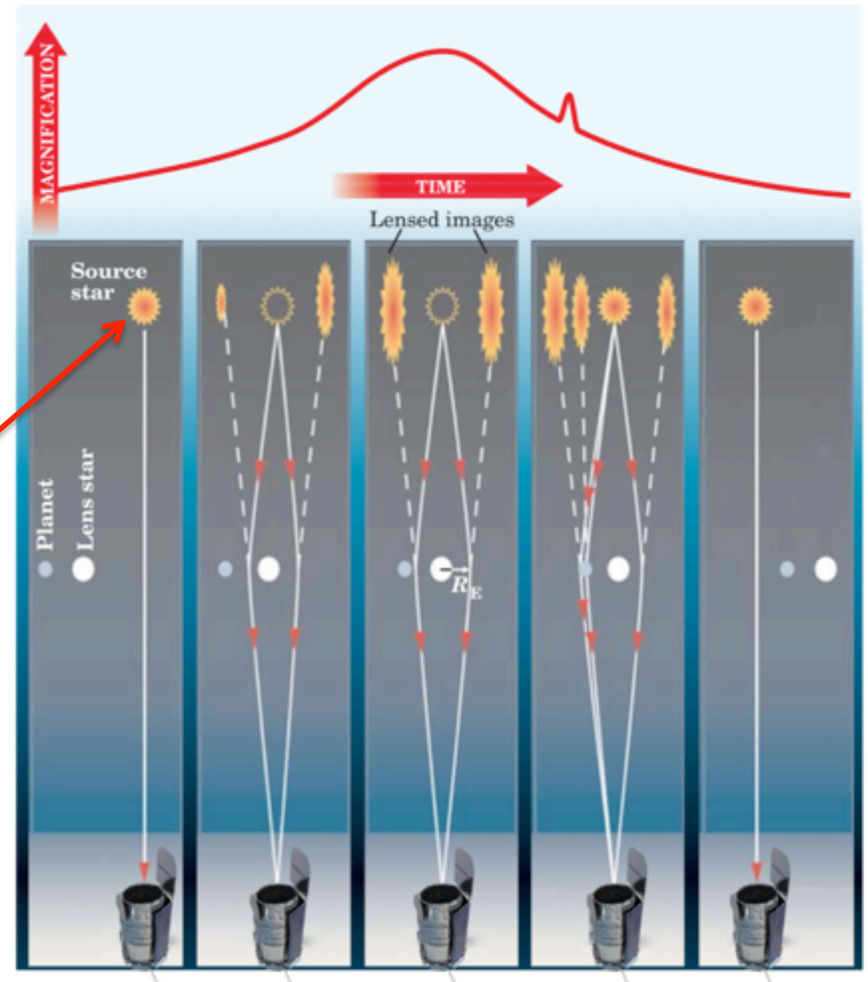



# BACKUP SLIDES

# Microlensing Technique



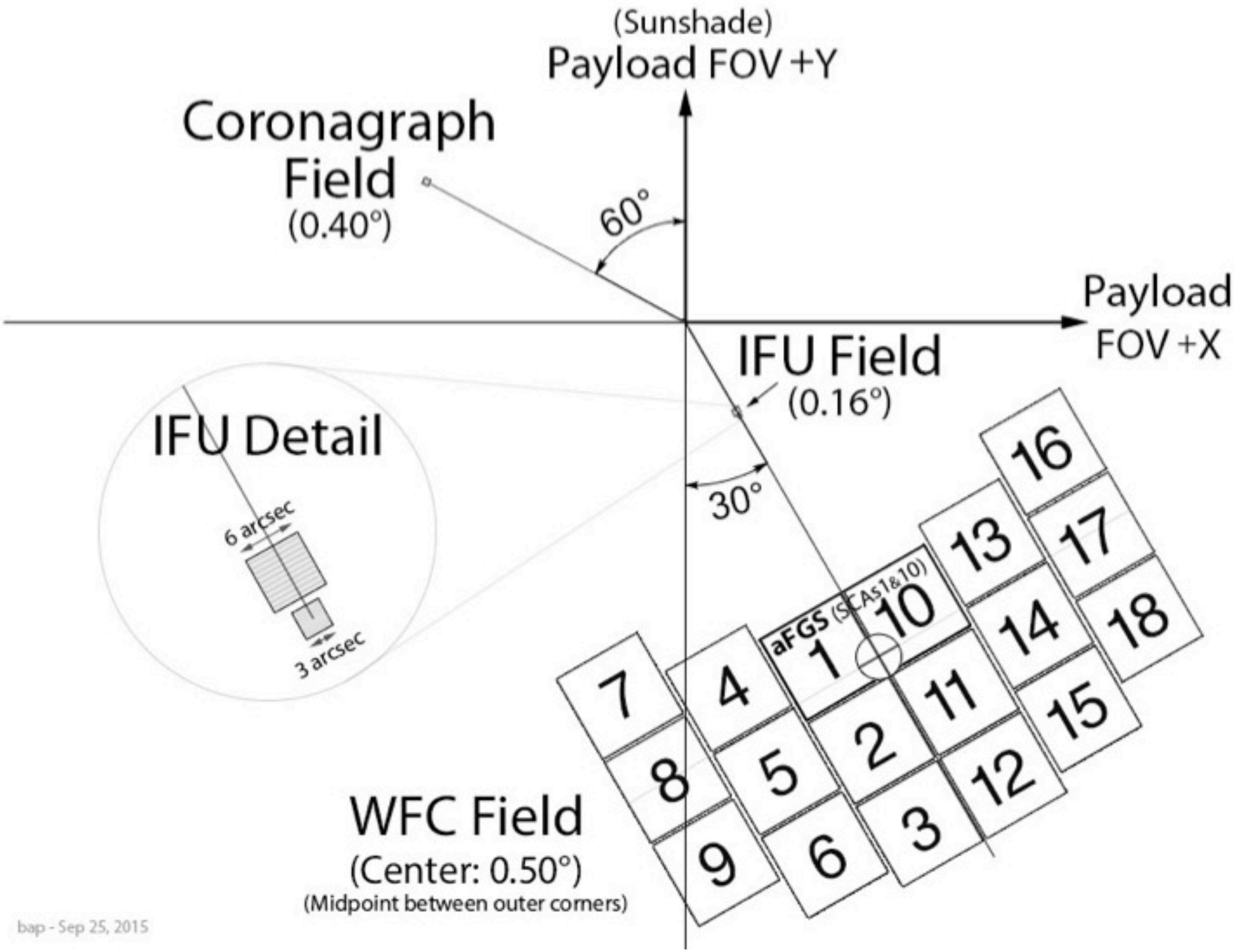

Great benefit of space observations in the crowded galactic bulge field

# Telescope Temperature

- The telescope operating temperature was changed from 270K to 282K for the 2015 report to maintain the heritage hardware within its minimum design temperature with margin.
- Impact of change from 270K to 282K
  - HLIS:
    - F184: loss of 0.28 mag in depth, resulting in 18% reduction in galaxy density for WL
  - GRS:
    - bandpass reduced from 1.95μ to 1.89μ
      - Hα redshift range reduced from z=1.97 to 1.87
    - 11% reduction in Hα galaxies/sq deg at all redshifts
  - SNIa:
    - IFU sensitivity reduced 2X beyond ~1.85μ
  - Microlensing:
    - No significant impact

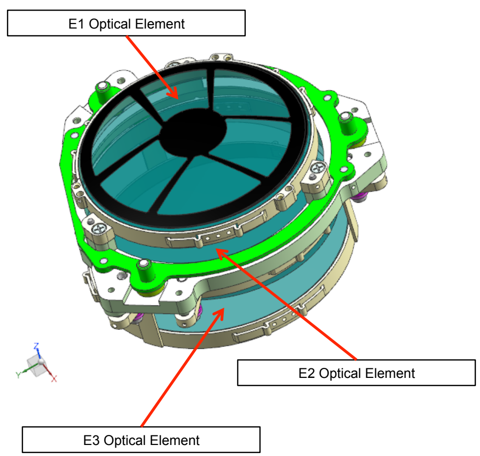
*See SDT report App. A for details (arXiv:1503.03757)*

# Field of View Layout

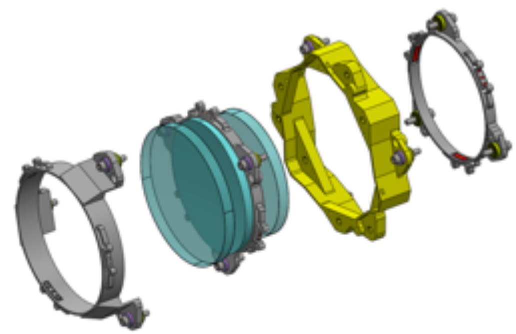


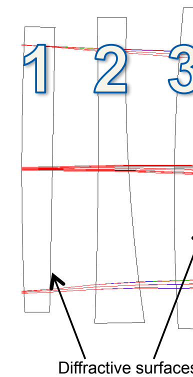
# Early Wide Field Development Activities

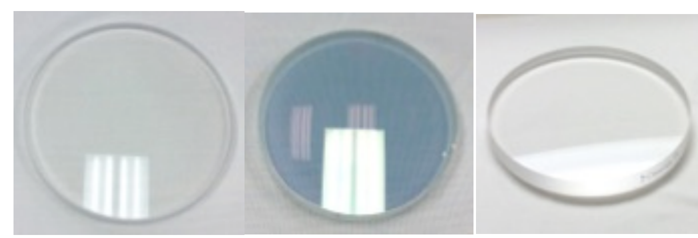
- With the availability of additional resources in FY14 and FY15, the Study Office began some early prototyping activities on the Wide Field grism to assess design and manufacturability of the grism with its wide field of view, large dispersion, broad spectral range, relatively small F/#, and high efficiency diffractive surfaces.



Grism mechanical design







Grism procured substrates


Grism mount


Grism grating samples

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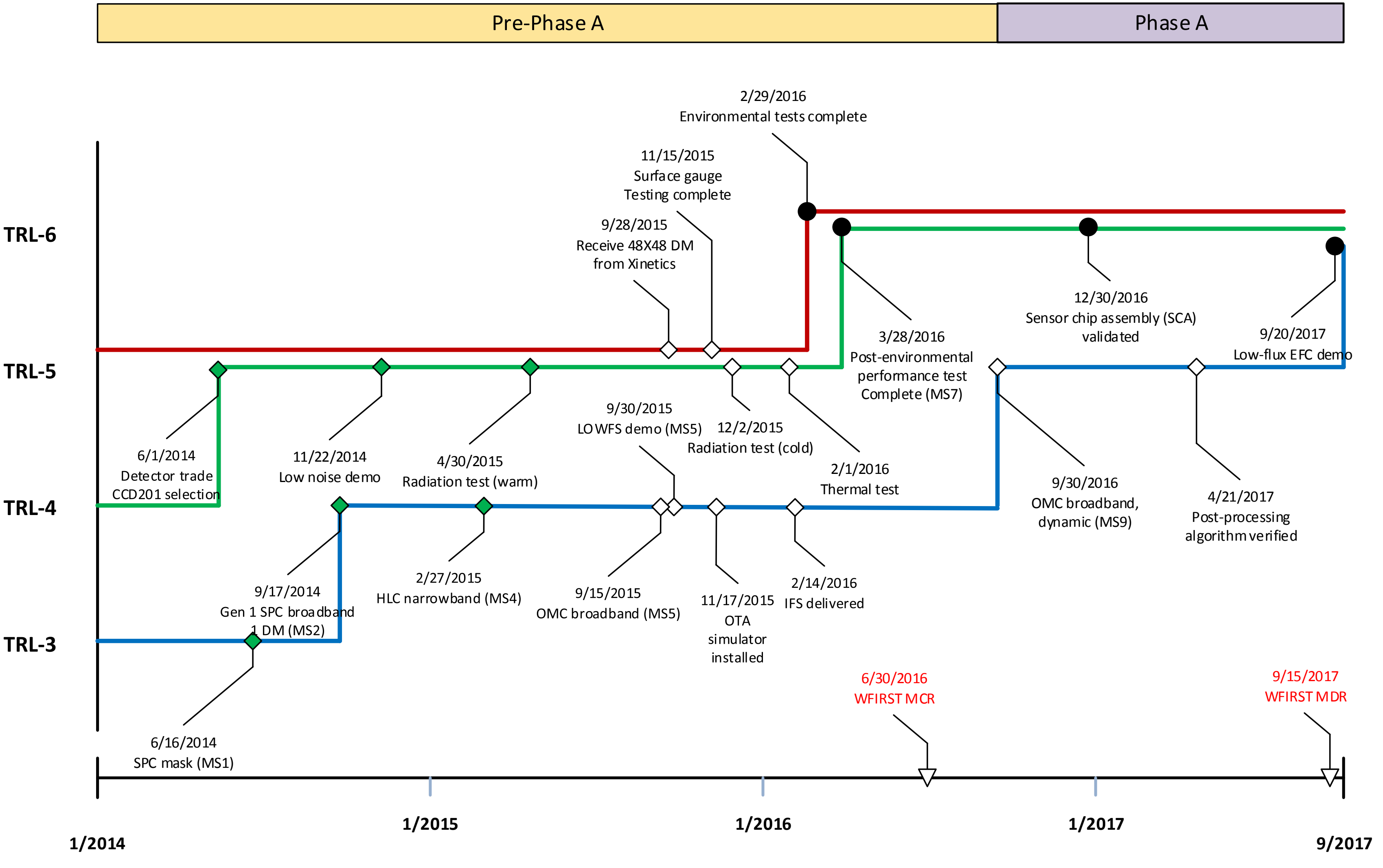
# Coronagraph Technology Path to TRL-6



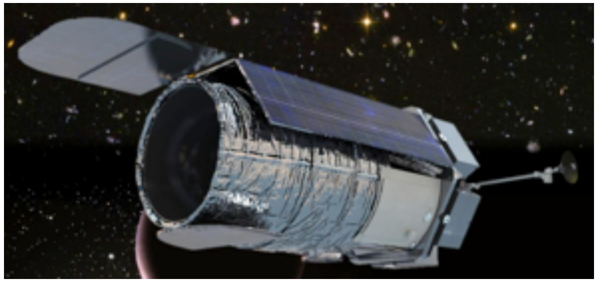

Occulting Mask Coronagraph (OMC) system

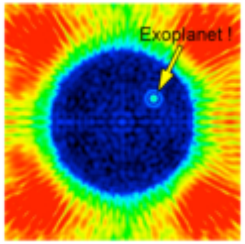
Deformable Mirror (DM)

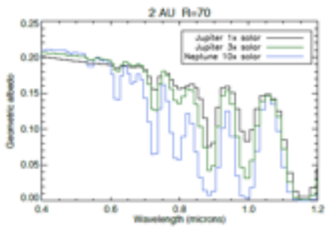
Low noise detector (EMCCD)

# Coronagraph Instrument Summary

- Occulting Mask Coronagraph (OMC):
  - Shaped-Pupil and Hybrid-Lyot coronagraph masks
  - High contrast imaging using precision wavefront sensing and control
  - 2 Deformable mirrors (Xinetics)
  - 2nd instrument on WFIRST-AFTA
    - Exoplanet direct imaging technology demonstration
    - Pre-cursor science for future exo-earth missions
- Team:
  - JPL led technology team, with participations from many US institutions:
  - Princeton University
  - University of Arizona
  - GSFC
  - ARC
  - Caltech/IPAC
  - STScI
  - Northrop-Grumman Xinetics
- Near-term Key Deliverables:
  - ✓ SDT final report 1/2015
  - ✓ CATE 2/1015
  - Mission Concept Review (MCR) 12/2015
  - Technology demonstration by 10/2016:
    - TRL-5 at system level

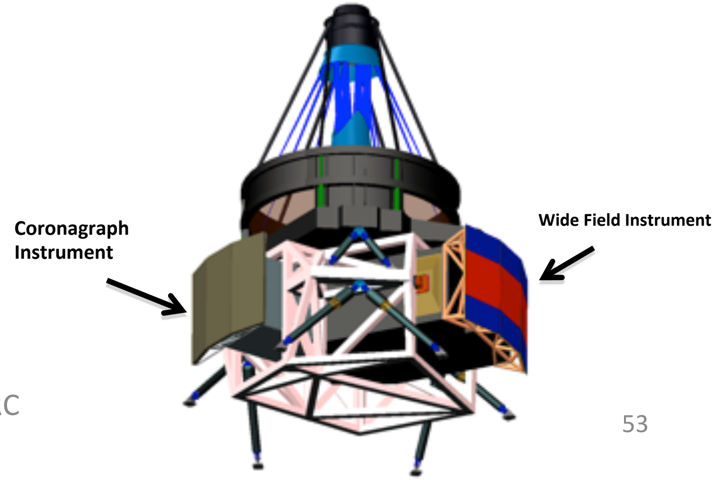




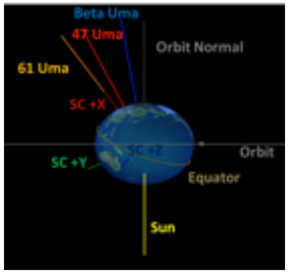



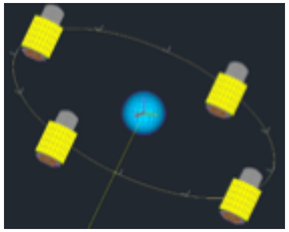
Exoplanet Direct imaging

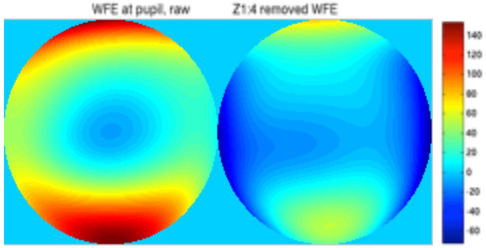
Exoplanet Spectroscopy

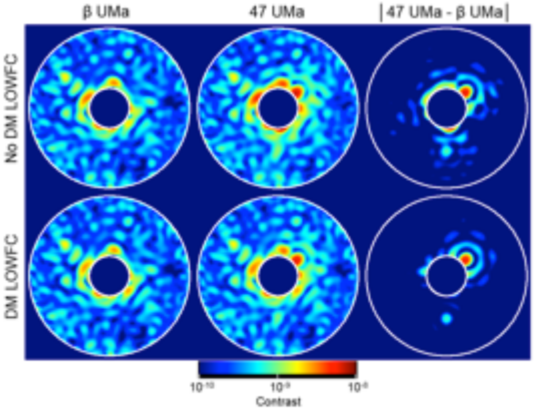


# Detailed Full-Physics Simulations to Validate Coronagraph with WFIRST

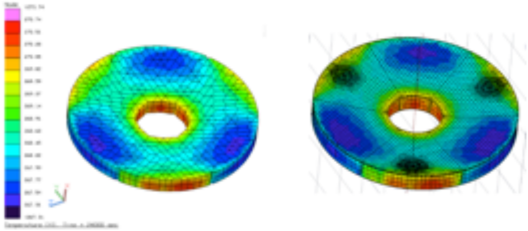


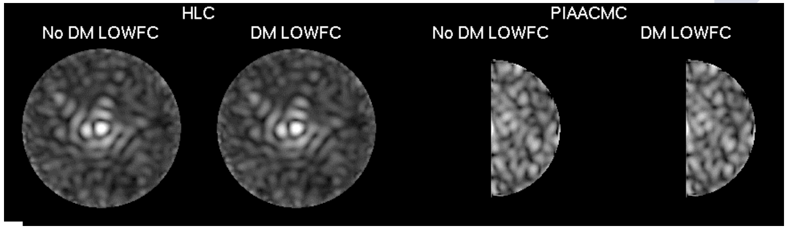






Scenario Defined → Thermal Loads → Structural Deformations → Ray Trace (Sig-Fit + Code V) → Exit Pupil WFE → DM Control (EFC) → Coronagraph (PROPER) → Images/Spectra



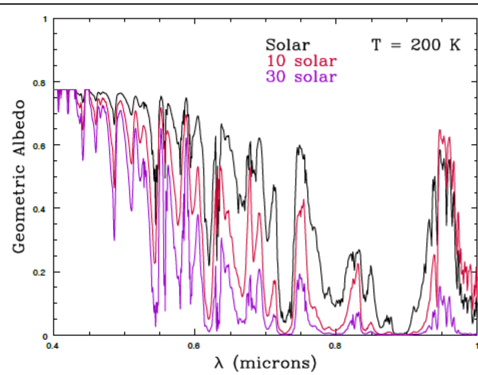


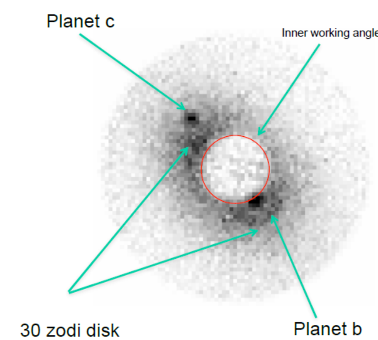

Initial simulations indicate that the coronagraph is likely to achieve all performance goals with the current, unmodified telescope.

# Coronagraph Performance

| Output channel | Coron. name | Spectral resolution | Polarization | Primary science | Wavelength (nm) | Number of RV planets detectable | Requirement |
|---|---|---|---|---|---|---|---|
| imager | HLC | R = 10 | X & Y pol., seperately | RV exoplanets & disks | blue: 465 | **18** | >12 |
| | | | | | green: 565 | **19** | |
| | | | | | red: 835 | **10** | |
| spectrometer (IFS) | SPC | R = 70 | unpolarized | RV exoplanets | near-red: 670 | **10** | >6 |
| | | | | | mid-red: 770 | **8** | |
| | | | | | far-red: 890 | **5** | |

1. Detections assume a best case of small pointing jitter (0.4 mas) and excellent post-processing speckle reduction factor (30x).
2. We expect that the actual case will be close to the best case, by using (a) feedback to control jitter, (b) advanced processing to reduce speckles, and (c) continued RV observations (WIYN) to discover more RV planets.
3. Most planets can be imaged in much less than 1 day; spectra will often take a few days. The totals are for a month-long campaign for imaging, and another month for spectroscopy.
4. **The coronagraph is expected to exceed its requirements, with margin.**



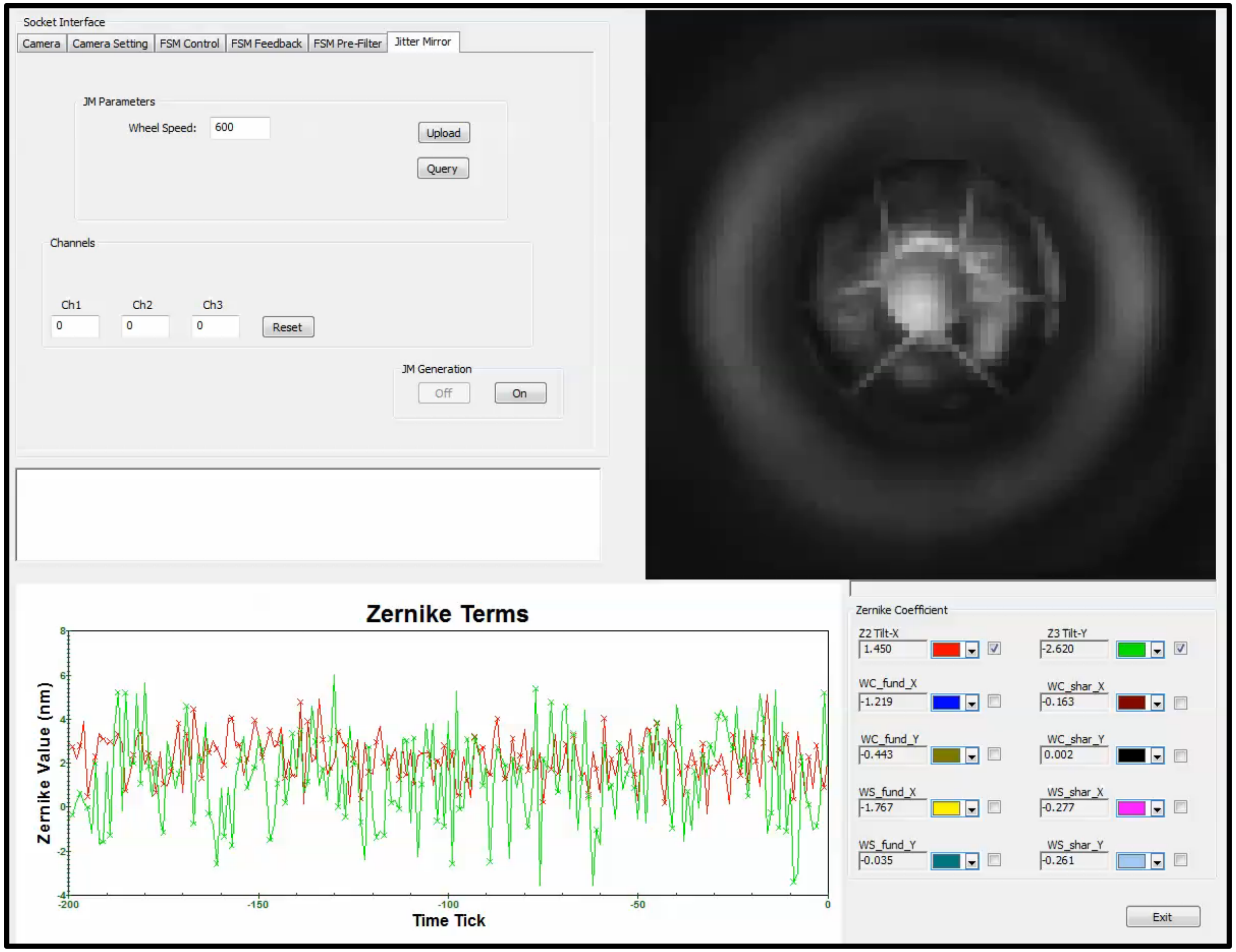




Compelling science from WFIRST coronagraph

# LoS Control Loops Demo Video

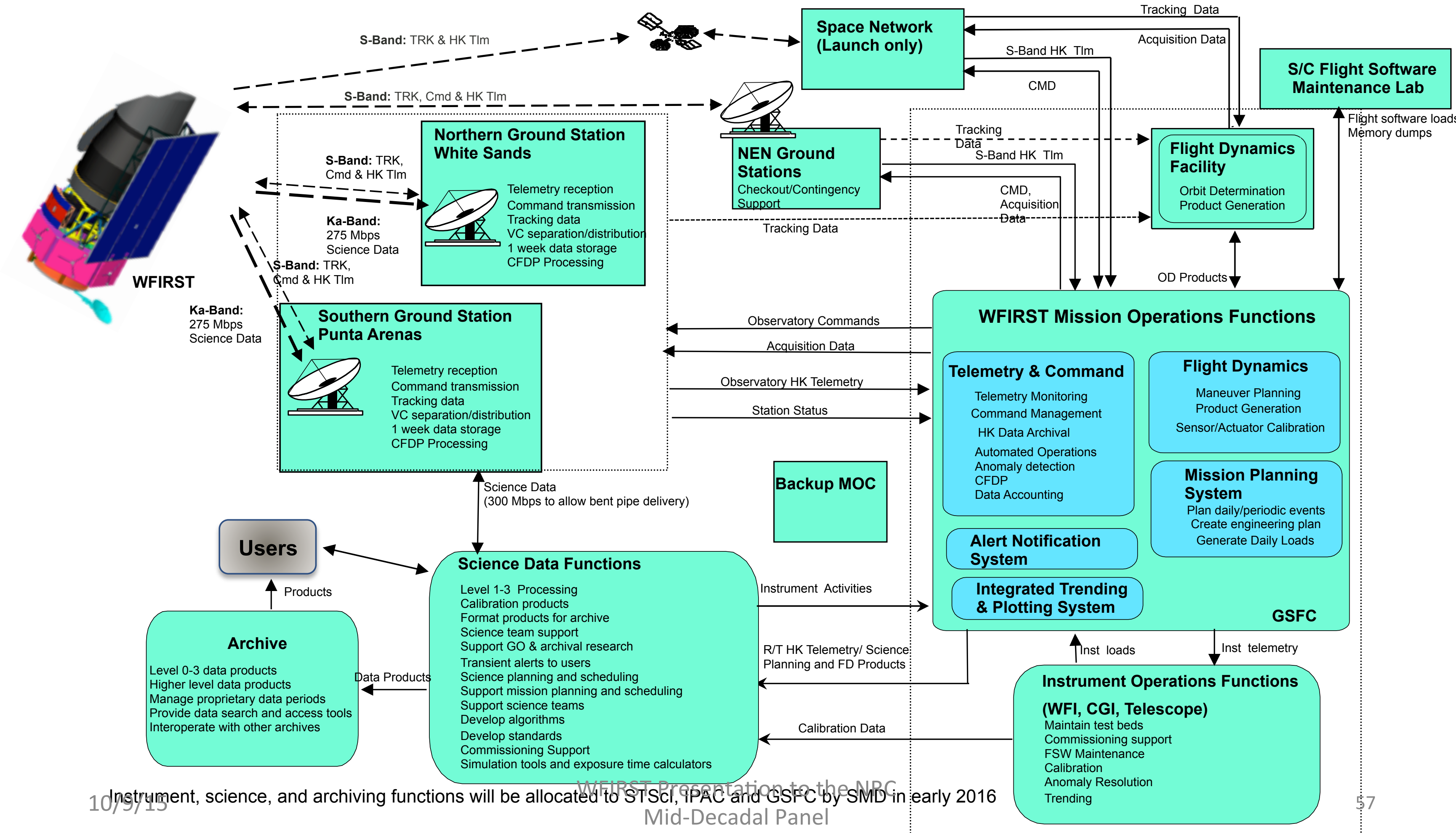
Start: Lab ambient, ACS on (0:10), Jitter on (0:29), FB on (0:50), FF on (1:09)

ZWFS measured X and Y tilt



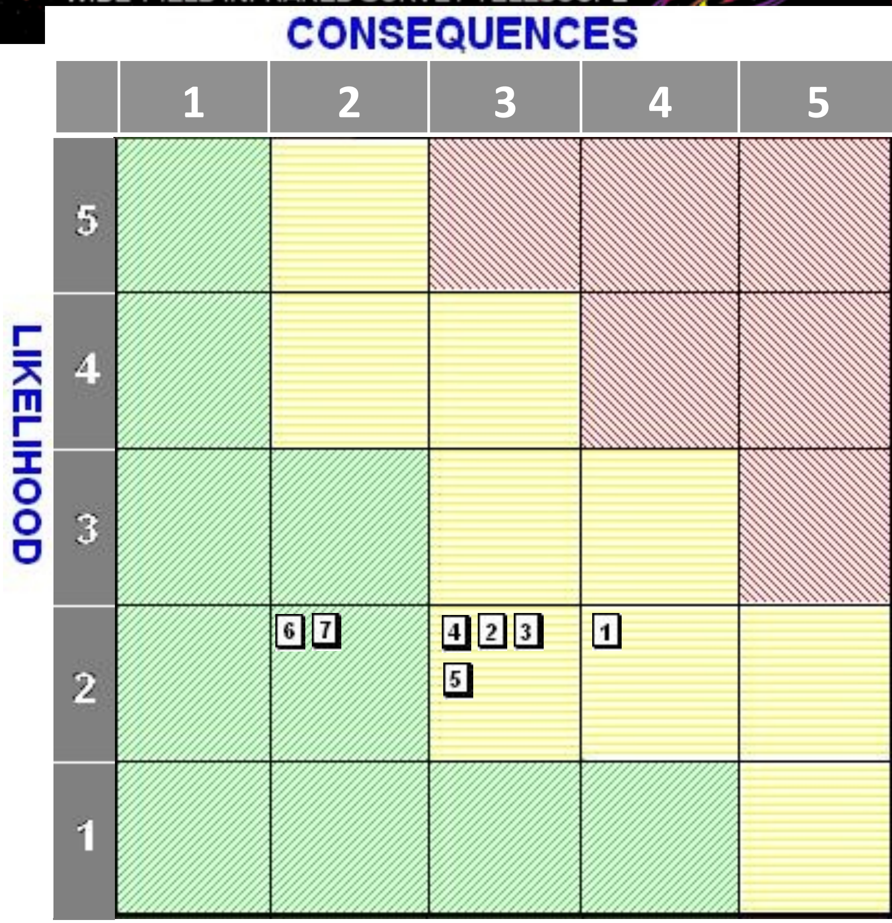

**Closed loop residual LoS error ~0.3 mas rms per axis (good case), ~0.5 mas rms per axis (worst case)**

# Baseline Ground System Architecture




Instrument, science, and archiving functions will be allocated to STScI, IPAC and GSFC by SMD in early 2016

# WFIRST Risk Summary




| Criticality | L x C Trend | Approach |
|---|---|---|
| HIGH | Decreasing (Improving) | M-Mitigate |
| MED | Increasing (Worsening) | W-Watch |
| LOW | Unchanged | A-Accept |
| | NEW New since last month | Ar-Archive |

| Rank/ Trend | ID | TITLE | APPROACH |
|---|---|---|---|
| 1 | WFIRST-RISK-WFI-0001 | Detector Performance | Mitigate |
| 2 | WFIRST-RISK-WFI-0003 | Detector Yield | Mitigate |
| 3 | WFIRST-RISK-WFI-0043 | Focal Plan System Performance | Mitigate |
| 4 | WFIRST-RISK-WFI-0002 | Detector Mfg Issues | Mitigate |
| 5 | WFIRST-RISK-TELE-0027 | Telescope Pedigree & Capability | Mitigate |
| 6 | WFIRST-RISK-WFI-0015 | Grism Optomechanical Performance | Research |
| 7 | WFIRST-RISK-CG-0044 | Deformable Mirror Performance Risk | Mitigate |

# Top Risks

| Risk Summary | Proposed Mitigations | Status |
|---|---|---|
| **Detector Performance**<br>Given that initial detector fabrication met some but not all performance requirements there is a possibility that future devices may also incur similar performance issues resulting in impacts to mission performance | a) Establish by modeling that the limitations experienced are the result of tunable manufacturing parameters and not due to fundamental device physics.<br>b) Run early test lots to demonstrate detector performance<br>c) Demonstrate detector performance on full 4kx4k detectors | - Received 14 of 15 SCAs<br>- Completed testing of 8 full array parts in support of DTAC#3. Performance meets DTAC requirements. |
| **Detector Yield**<br>Given HgCdTe devices using the H4RG-10 format have limited production experience there is the possibility that the device manufacturing yield will be low resulting in increased cost and schedule in order to produce the required number of devices | a) Perform preliminary assessment of yield during Process Optimization and Full Array Lots<br>b) After proposed flight process is determined, run a yield demonstration lot to establish expected yields before committing to flight production. | - 1st Yield demo lot started 9/2/2015<br>- On plan for yield demo lot milestone (12/2016) |
| **Focal Plane System Performance**<br>Given that focal plane assembly (FPA) performance reqs are likely to be challenging there is a possibility that system level FPA issues may be discovered resulting in not meeting FPA system performance requirements | a) Develop a high fidelity engineering model FPA for early assessment of any system level performance issues<br>b) Obtain equipment needed for testing a full-scale focal plane<br>c) Perform early assessment of detector module crosstalk and noise performance | - On Plan for Phase A/B<br>- Plan includes Round Mosaic Plate Performance and Environmental Testing<br>- Cold metrology gantry near complete; automation software in progress. DCL team conducted preliminary testing at GLS week of Aug 25th |

# Top Risks (cont')

| Risk Summary | Proposed Mitigations | Status |
|---|---|---|
| **Detector Manufacturing**<br>Given that some initial test lot devices experienced channel cracking there is a possibility that some flight devices may incur similar reliability concerns resulting in detectors unusable for flight application | a) Examine alternate base material (CE6) that reduces stress on detector material, reducing potential for cracking.<br>b) Perform environmental and performance testing on test devices with candidate base materials (SiC/CE6) to evaluate performance and select flight base material | - SiC testing completed; CE6 testing continues- no cracking.<br>- SiC/CE6 trade will be presented to WFIRST technical team on 10/14/2015 for review |
| **Telescope Pedigree & Capability**<br>Given that the telescope was designed for a different application with different standards there is the possibility that the as-built telescope may have design/pedigree issues resulting in unplanned rework and/or additional verification steps | a) Systematically review Telescope build and verification records and compare to NASA and JPL standards.<br>b) Identify any gaps between Telescope status and WFIRST reqs<br>c) Determine what actions needed to resolve any gaps (e.g. additional verification, refurbishment, replacement, waiver) | - Telescope assessment Audit #1 completed by JPL, GSFC, and Harris technical teams<br>- Audit #1 report delivered and in review. No major issues with planned reuse have emerged to date |
| **Grism Optomechanical Performance**<br>Given that the grism is a complex multi-element optical design there is a possibility that optical shifts, distortions, or misalignments may occur resulting in poor wavefront or throughput performance with degraded science return | a) Conduct a fabrication & alignment feasibility assessment, alignment analysis<br>b) Develop an early EDU to confirm design performance | - Error budget established and being validated by integrated modeling<br>- Grism EDU parts procured/received and unmounted cold testing has started |

# Top Risks (cont')

| Risk Summary | Proposed Mitigations | Status |
|---|---|---|
| **<u>Deformable Mirror Performance Risk</u>**<br>Given that the deformable mirror (DM) is the key component to control coronagraph wavefront errors there is a possibility that 1)DM correction in low-order causes mid to high-order wavefront errors and 2) insufficient stroke available to correct all wavefront errors under required derating, resulting in coronagraph contrast performance degradation. | 1) Decrease coronagraph thermal sensitivity, placing less demand on DM requirement for LOWFS<br>2) Demonstrate coronagraph DM performance capability at system level testbed<br>3) Examine system level parameters to manage DM stroke margins | - Collimator bench location trade leads to a down-selection of AMS mounting, improving wavefront thermal stability<br>- Completed draft DM stroke error budget<br>- Demonstrated a new DM solution with 30% less DM stroke needed at the HLC testbed. HLC DM solution is the largest contributor to DM stroke error budget. |

# Descope List Development

- Study Office has begun identifying potential items for the Descope List.
- This is the initial draft for more detailed evaluation in Phase A, especially as we define the minimum mission success criteria with NASA HQ

# Draft Descope List

| Draft Descope | Impact |
|---|---|
| **Wide Field Instrument** | |
| Accept reduced grism performance. | Protect schedule, reduction in BAO/RSD survey science. |
| Delete GRS grism. | Eliminate BAO/RSD survey capability. |
| Eliminate auxiliary guiding channel. | Degraded pointing in BAO/RSD survey, reduction in BAO/RSD survey science. |
| Delete IFU. | Reduction in SNe science. Assess SNe capability using existing filters and GRS grism. |
| Delete wide filter for microlensing. | Reduction in microlensing survey science. |
| Accept degraded performance detectors. | Protects schedule, assess detector specifications vs. science impacts. |
| Reduce size of wide field focal plane by eliminating detectors and/or increase plate scale. | Saves resources and/or protects schedule, reduces wide field survey science. |
| Eliminate the relative calibration system. | Assess impact of only using astronomical sources. |

# Draft Descope List (cont'd)

| Draft Descope | Impact |
|---|---|
| **Coronagraph Instrument** | |
| Reduce or terminate PIAA-CMC technology investments. | Eliminates backup architecture path. |
| Reduce or eliminate Hybrid-Lyot coronagraph capability. | Single coronagraph capability. Loss of imaging science without redesign. |
| Reduce or eliminate Shaped-Pupil coronagraph capability. | Single coronagraph capability. Loss of spectroscopic science without redesign. |
| Delete IFS. | Eliminate spectroscopic science and only perform photometric science. |
| Accept degraded performance deformable mirrors. | Protect schedule, reduction in coronagraph science. |
| Accept degraded performance EMCCD. | Protect schedule, reduction in coronagraph IFS science. |
| Reduce LOWFS to local feedback only. | Simplifies interfaces to S/C and testing, reduces jitter performance. |
| Eliminate coronagraph. | Protects cost & schedule, no on-orbit demonstration of coronagraph technology. |

# Draft Descope List (cont'd)

| Draft Descope | Impact |
|---|---|
| **Telescope** | |
| Eliminate effort to study colder telescope operating temperature. | Warm temperature consumes larger portion of noise budget, large heater power requirement. |
| Accept existing telescope heater redundancy scheme. | No single fault tolerance in the survival heater string. |
| Eliminate recloseable door. | No protection against contaminates during servicing, no protection available if loss of attitude control. |
| **Spacecraft** | |
| Reduce downlink data rate. | Assess impact to science of fewer samples per exposure. |
| Eliminate reaction wheel isolators. | Assess impact of higher jitter on science. |
| Reduce thruster count. | Maintain propellant sizing, assess impact mission lifetime. |
| Replace composite bus structure with aluminum structure. | Assess impact of lower pointing stability on science. |

# Draft Descope List (cont'd)

| Draft Descope | Impact |
|---|---|
| **Ground System** | |
| Delete second ground station. | Assess impact of lower data volume and impact to orbit determination. |
| Perform all Science Center functions at a consolidated Science Center. | Assess loss of science expertise from the distributed Science Center. |
| **Mission** | |
| Assess emerging launch vehicle opportunities and orbit options. | New launch vehicle at potentially lower cost. |
| Accept degraded pointing performance due to breakpoints in hardware/software | Assess impact of higher jitter on science. |
| Eliminate serviceability. | Eliminates option to extend mission life. |
| Limit components which are serviceable. | Eliminates option to extend mission life. |
| Eliminate "10-year goal" for consummables (propellant). | Eliminates option to extend mission life. |