WFIRST-AFTA Science Definition Team Final Report Presentation to the Astrophysics Subcommittee

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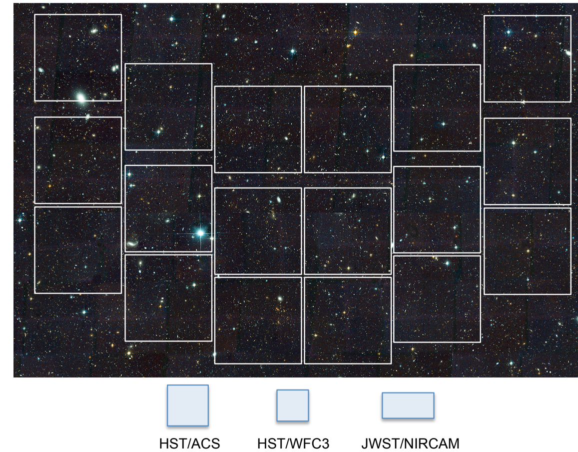
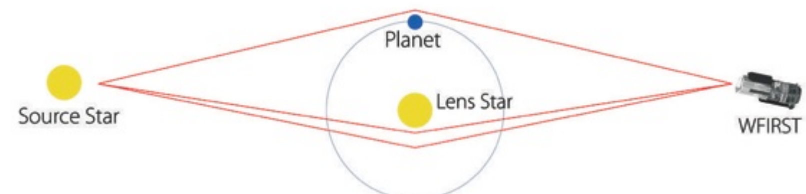
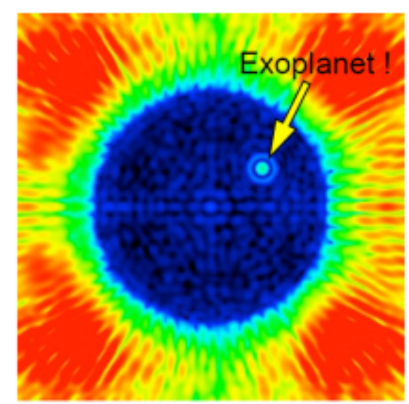
WFIRST-AFTA Summary

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







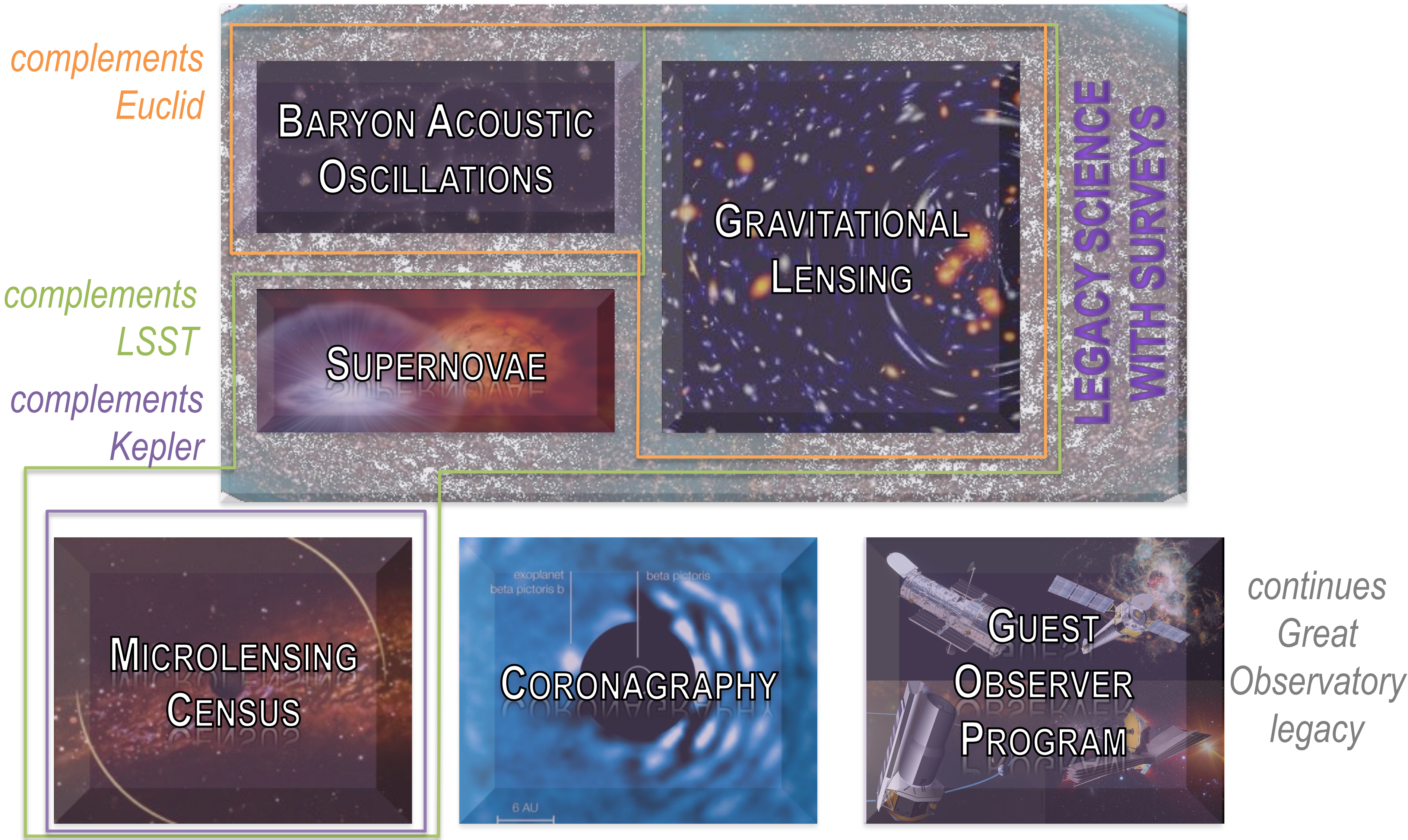
Executive Summary

- “HST quality” NIR imaging over 1000's of square degrees.
- 2.5x deeper and 1.6x better resolution than NWNH requirements
- More complementary to Euclid & LSST. More synergistic with JWST.
- Enables coronagraphy of giant planets and debris disks to address "new worlds" science and technology development in NWNH.
- Fine angular resolution and high sensitivity open new discovery areas to the community. More GO science time (25%) than for IDRM.
- WFIRST-AFTA addresses changes in landscape since NWNH: Euclid selection & Kepler discovery that 1-4 Earth radii planets are common.
- Use of existing 2.4-m telescope and addition of coronagraph have increased the interest in WFIRST in government, scientific community and the public. Funding interest in Congress and STMD have advanced the mission.
- WFIRST-AFTA design has significantly matured over the past two years.

WFIRST-AFTA Status

- Significant WFIRST-AFTA funding added to the NASA budget by Congress for FY14 and FY15 for a total of $106.5M.
- Funding is being used for pre-Phase A work to prepare for a rapid start and allow a shortened development time
  - Detector array development with H4RGs
  - Coronagraph technology development
  - Science simulations and modeling
  - Observatory design work
- NRC Harrison report endorsed strength of WFIRST science and ability to address NWNH requirements. Concerns about risk introduced by coronagraph immaturity and larger telescope are being addressed in pre-Phase A work.
- ROSES "Preparatory Science Opportunity" proposals selected. Seventeen proposals funded at ~$150k each.
- NASA HQ charge for telescope is "use as is as much as possible" and for coronagraph is "not drive requirements". Study Office / SDT driving toward the fastest, cheapest implementation of the mission
- Community engagement: PAGs, conferences and outreach
  - Special sessions held at January & June 2014 and January 2015 AAS conferences
  - Wide-Field Infrared Surveys conference held in November 17-22, 2014 in Pasadena

WFIRST-AFTA Science



Capabilities

WFI:

Imager	**0.76-2.0 microns** 0.28° FoV, 0.11" pixel scale
Filters:	z (0.76 - 0.98), Y (0.93-1.19), J (1.13-1.45), H(1.38-1.77), F184 (1.68-2.0), W149 (0.93-2.00)
Grism:	**1.35-1.89 microns** 0.28° FoV, R=461λ, 0.11" pixel scale
IFU:	**0.6-2.0 microns** 3" & 6" FoV, R~100, 0.075" pixel scale

Coronagraph:

Imager:	**0.43-0.97 microns** 1.63" FoV (radius), 0.01" pixel scale, 1k x 1k EMCCD, 10^{-9} final contrast, 100-200 mas inner working angle
IFS:	**0.60-0.97 microns** 0.82" FoV (radius), R~70

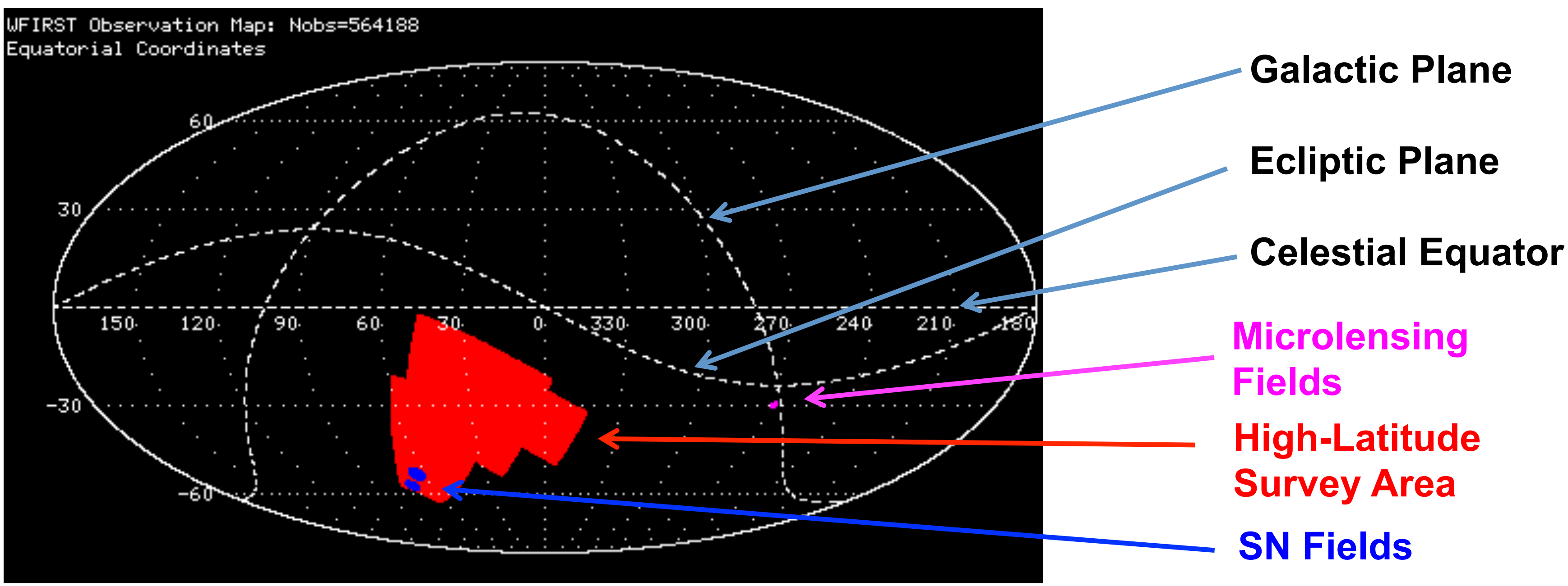
Field of Regard: 54° - 126° 60% of sky

DRM Yields

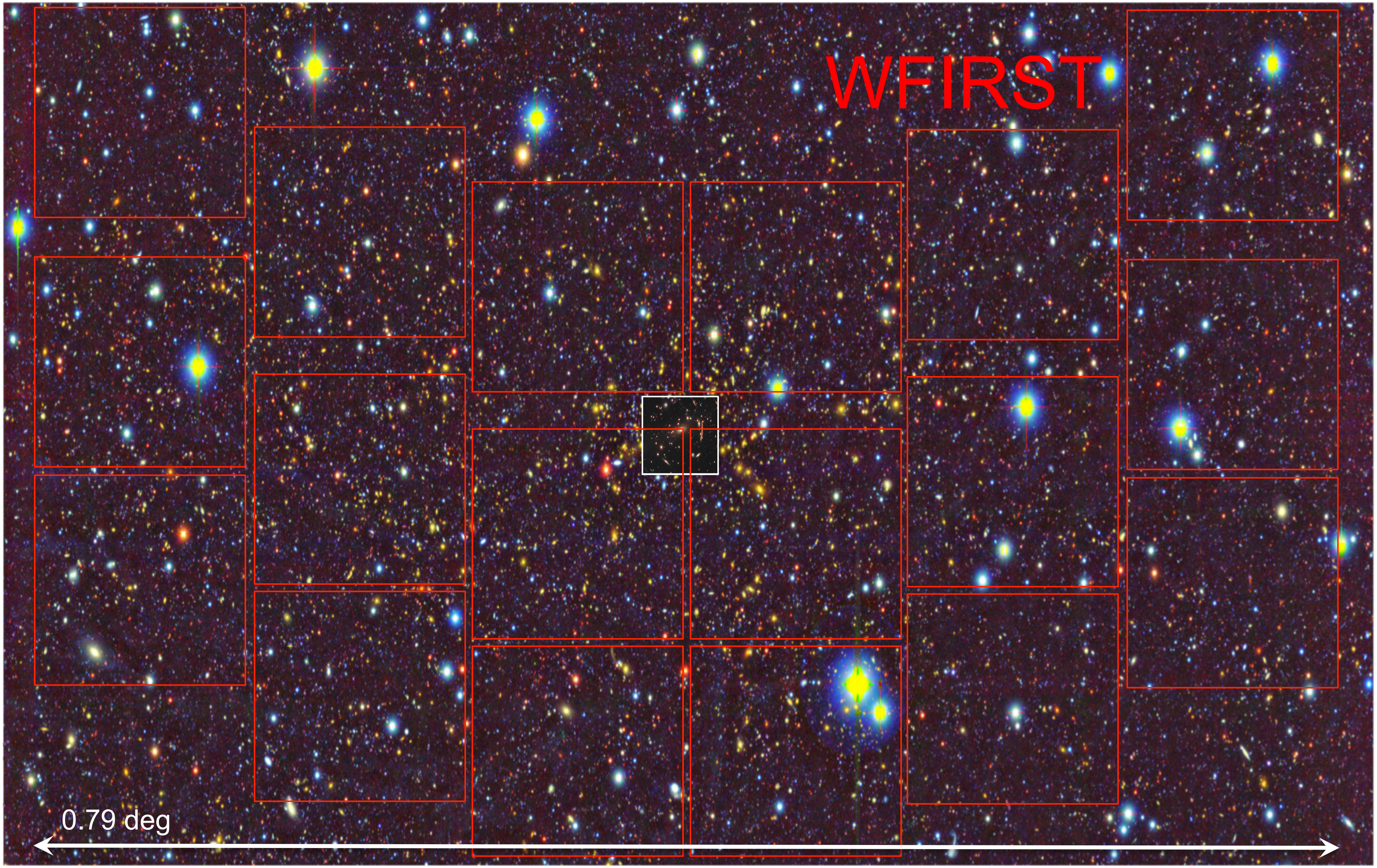
Attributes	WFIRST-AFTA Yields
Imaging survey	J ~ 27 AB over 2200 sq deg
	J ~ 29 AB over 3 sq deg deep fields
Slitless spectroscopy	R~461λ over 2200 sq deg
Number of SN Ia SNe	2700 to z~1.7
Number galaxies with spectra	2×10^7
Number galaxies with shapes	4×10^8
Number of galaxies detected	few x 10^9
Number of massive clusters	4×10^4
Number of microlens exoplanets	2600
Number of imaged exoplanets	10s

Example Observing Schedule

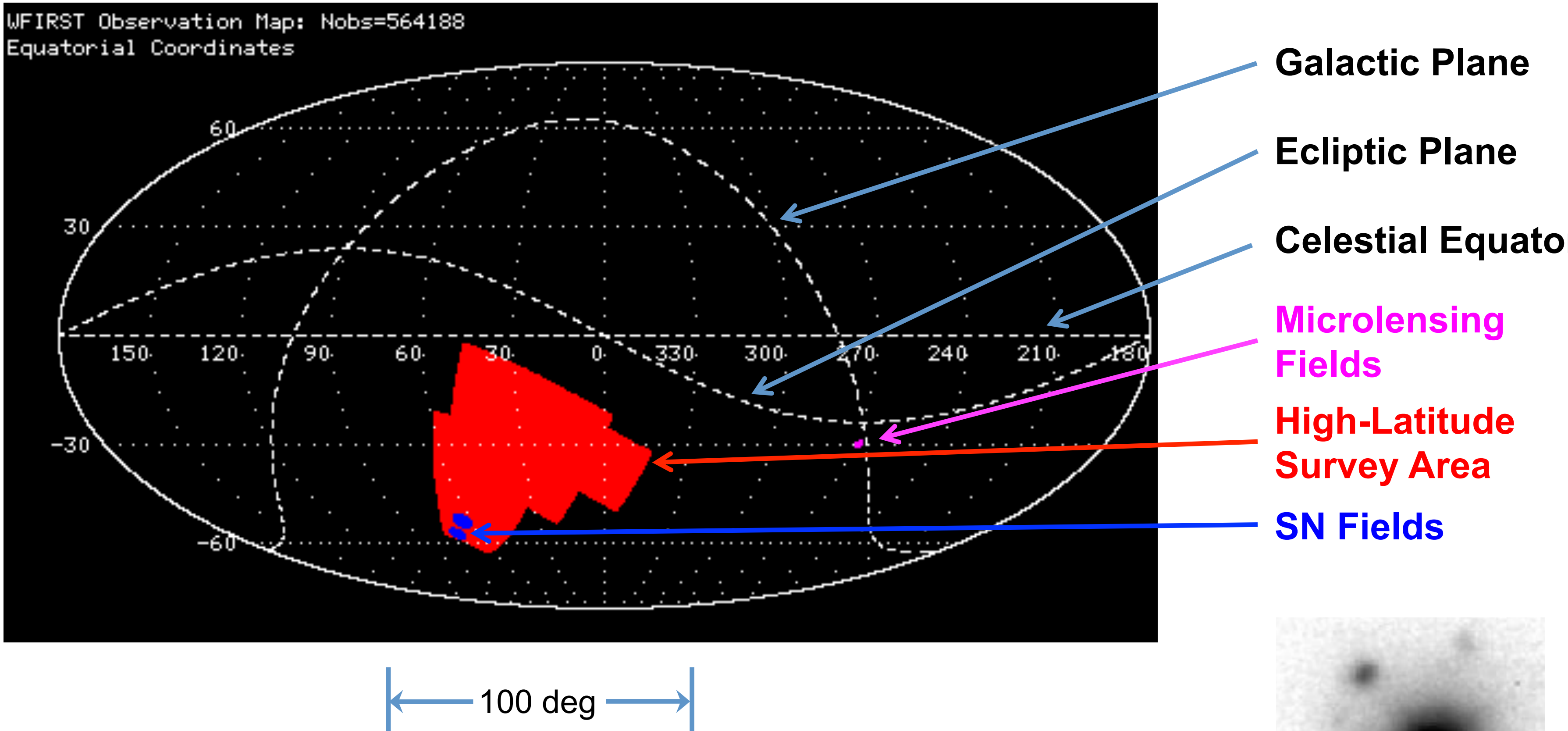
- High-latitude survey (HLS: imaging + spectroscopy): 2.01 years
  - 2227 deg^2 @ ≥3 exposures in all filters (2279 deg^2 bounding box)
- 6 microlensing seasons (0.98 years, after lunar cutouts)
- SN survey in 0.63 years, field embedded in HLS footprint
- 1 year for the coronagraph, interspersed throughout the mission
- Unallocated time is 1.33 years (includes GO program)



Gravitational Lensing

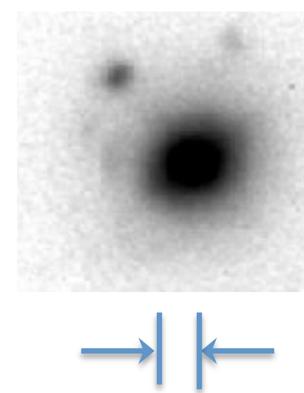


Huge Dynamic Range

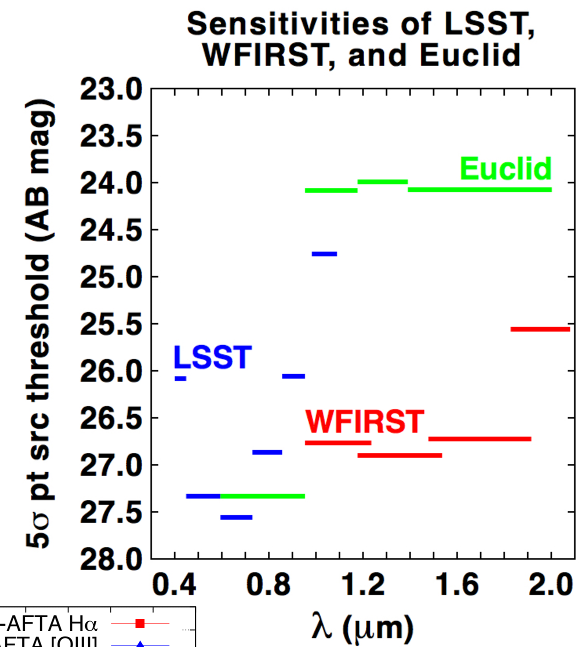


~10^6 dynamic range in size

~2×10^{12} resolution elements in HLS



WFIRST-AFTA Dark Energy



Weak Lensing (2200 deg^2)

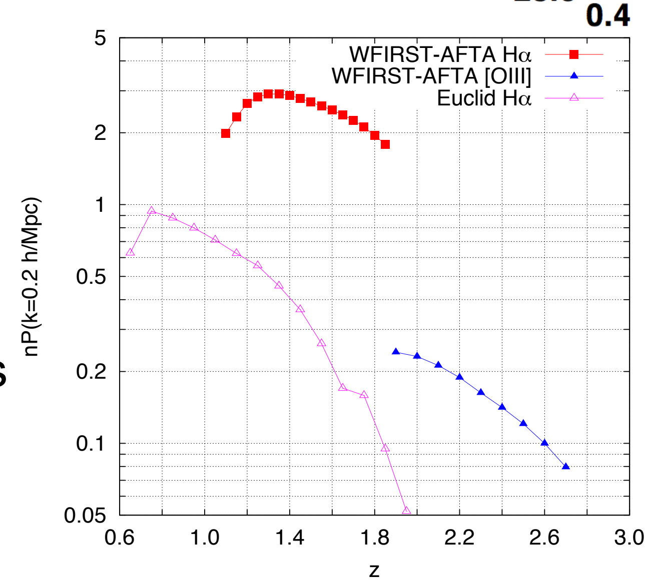
- High angular resolution
- Galaxy shapes in IR
- 380 million galaxies
- Photo-z redshifts
- 4 imaging filters

Supernovae

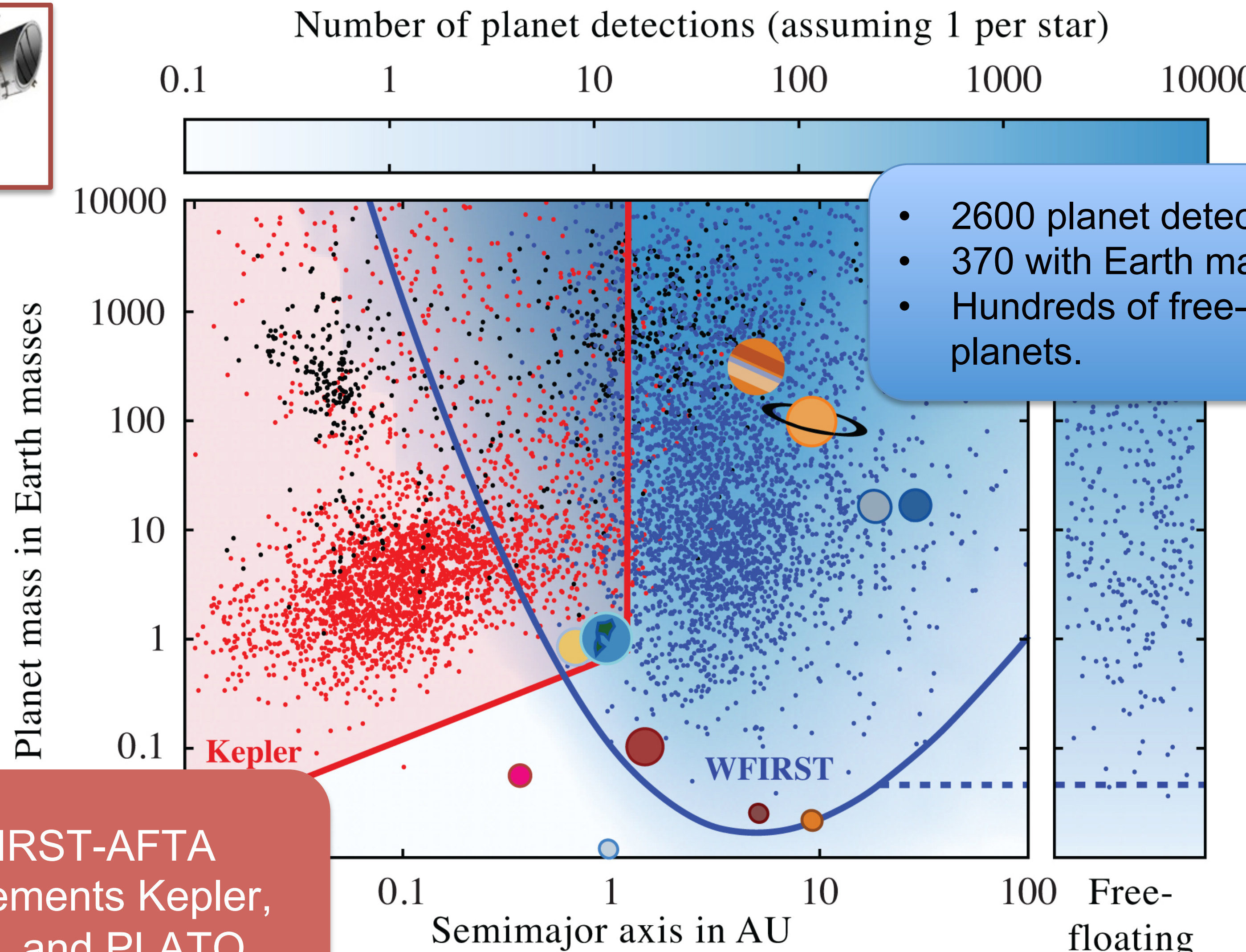
- High quality IFU spectra
- 5 day sampling of light curves
- 2700 SNe

Redshift survey (2200 deg^2)

- BAO & Redshift Space Distortions
- High number density of galaxies
- 16 million galaxies



Exoplanet Surveys
Kepler & WFIRST

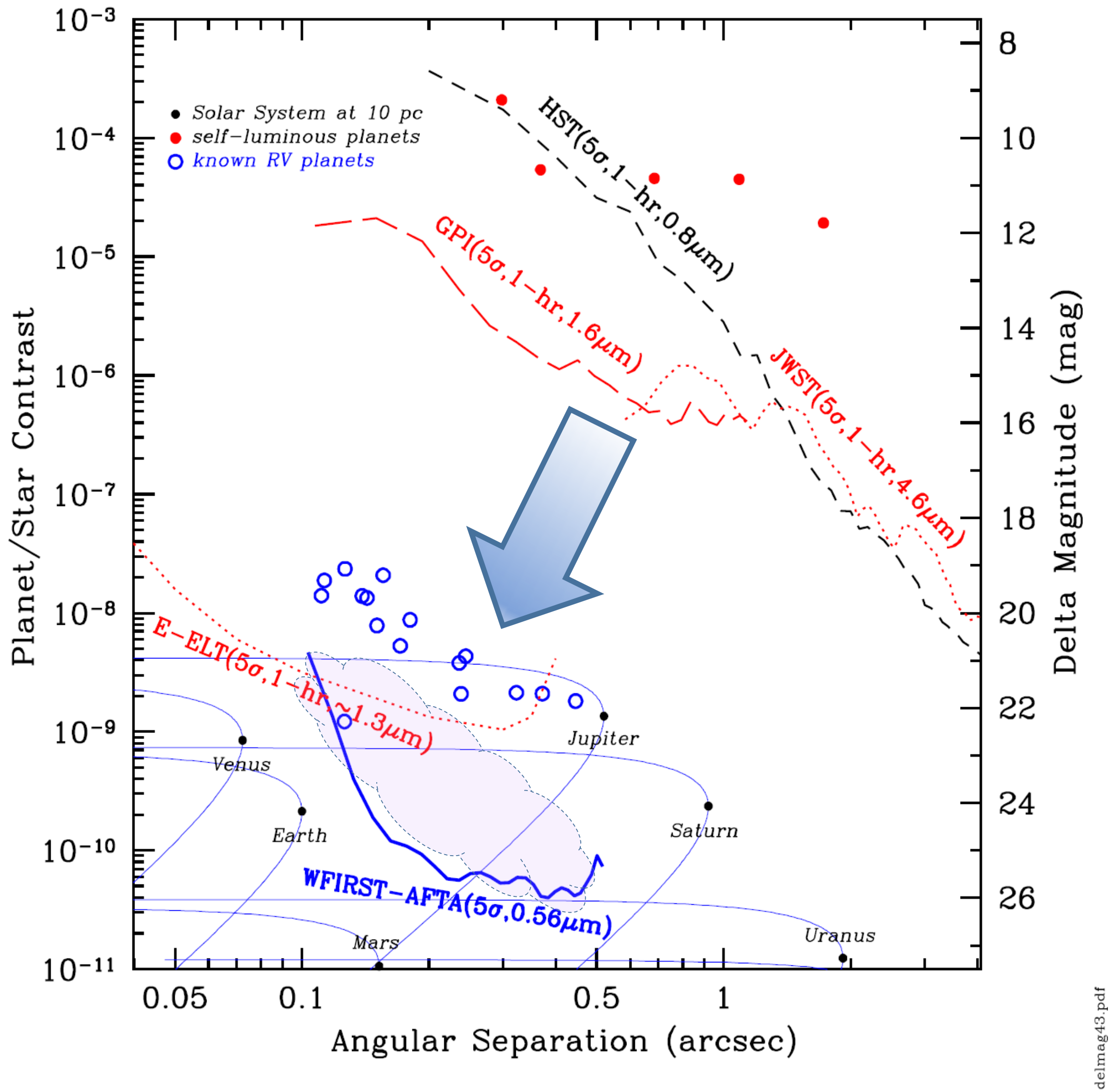


- 2600 planet detections.
- 370 with Earth mass and below.
- Hundreds of free-floating planets.

WFIRST-AFTA complements Kepler, TESS, and PLATO.

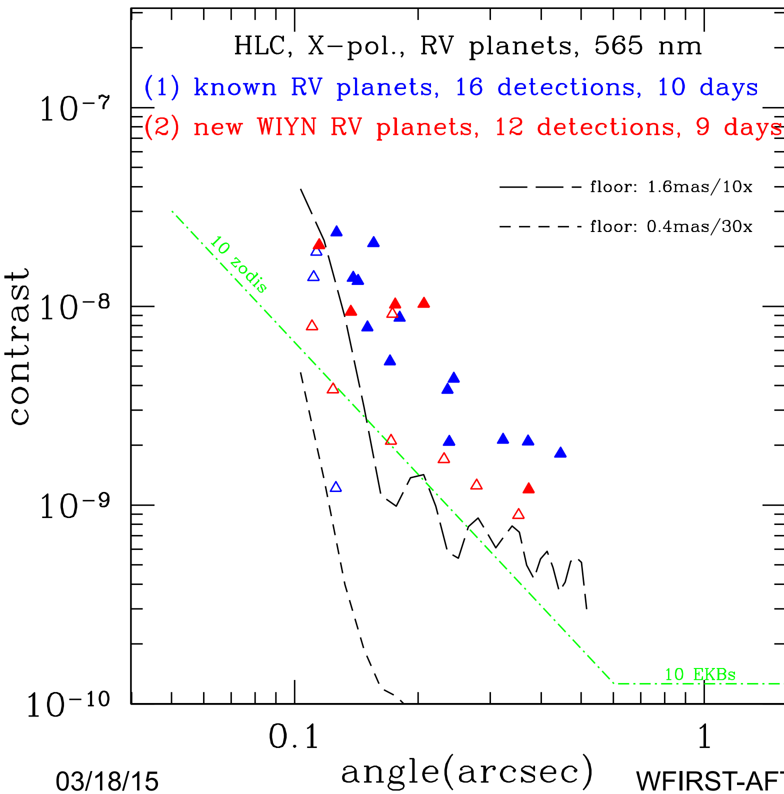
WFIRST-AFTA Brings Humanity Closer to Characterizing exo-Earths

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



Exoplanet Yield Estimates

	Giants (4-15 R_E)	Sub-Neptunes (2-4 R_E)	Super-Earths (1-2 R_E)	Total
Known RV Studies*	16	0	0	16
180-day Blind Search	2	6	4	12
Total**	18	6	4	28



* RV yield will be augmented by the WIYN program for future RV observations

** Yield assumes 0.4 jitter and 30x speckle attenuation

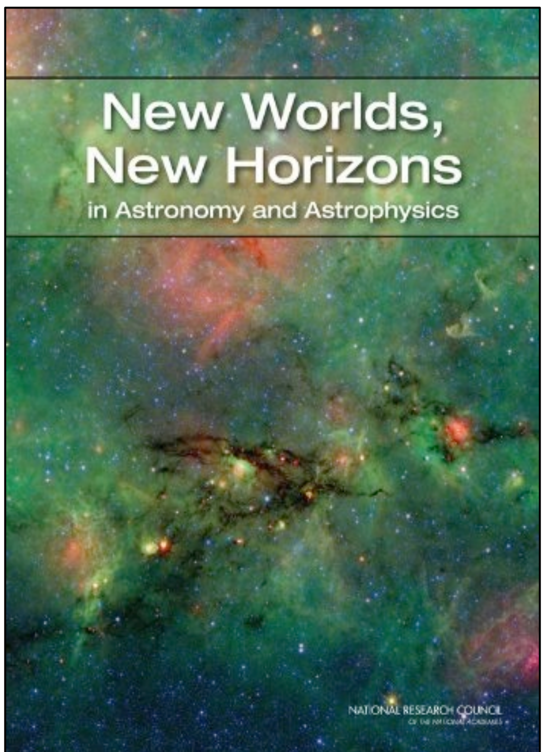
New detections of (1) known RV exoplanets & (2) new exoplanets to be found with the aid of WIYN RV observations

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)**

Science Team Selection Process and Data Rights

Future Science Working Group

Typically 15-20 members

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

Options for SWG Selection

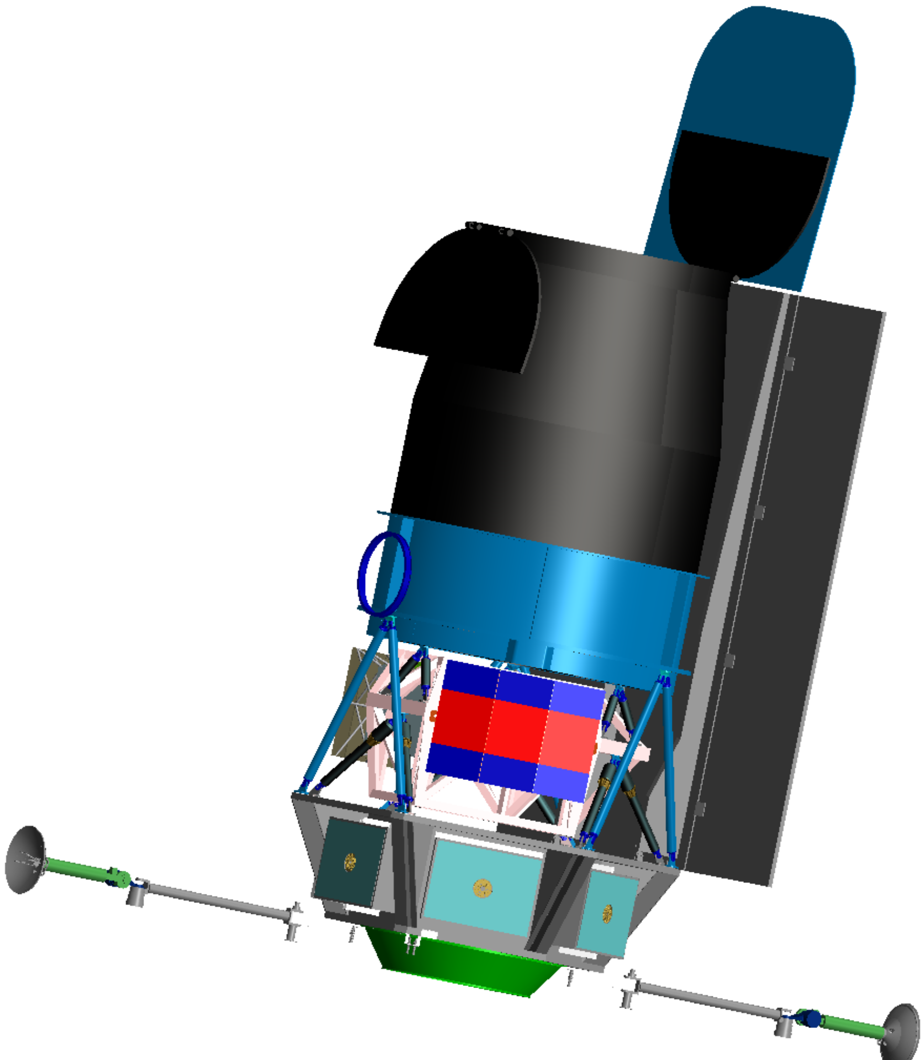
- If instruments are provided by NASA, scientific investigations and interdisciplinary scientists would be selected
- Assume 8 investigations and 3 IDSs
- Option A:
  - 4 investigations for IR survey
  - 4 investigations for exoplanets
- Option B:
  - 1 investigation **each** for WL, BAO, SNe
  - 1 investigation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

Data Rights Considerations

- Standard of 1 year proprietary time for all data is probably no longer acceptable to NASA or the community
- WFIRST-AFTA wide field imager has wide FoV that makes proprietary data difficult
- Different science areas for WFIRST-AFTA have different data needs and processing requirements.
- An open data policy such as that of LSST and Fermi LAT may be the natural fit for most or all of the WFIRST-AFTA data
- Rapid public access to broad-use survey data has been demonstrated to maximize scientific output.
- Will the 1 year of coronagraph science be determined by a selected science team or by GOs or by a combination?

Observatory Overview

WFIRST-AFTA Observatory Concept



Key Features

- **Telescope:** 2.4 m aperture primary mirror
- **Instruments**
  - Wide Field Imager/Spectrometer & Integral Field Unit
  - Internal Coronagraph with Integral Field Spectrometer
- **Overall Dry Mass:** 4059 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:** ~2400 W average power (CBE)
- **GEO orbit**
- **Launch Vehicle:** Delta IV Heavy
- **GSFC:** leads mission, wide field instrument, spacecraft
- **JPL:** leads telescope, coronagraph

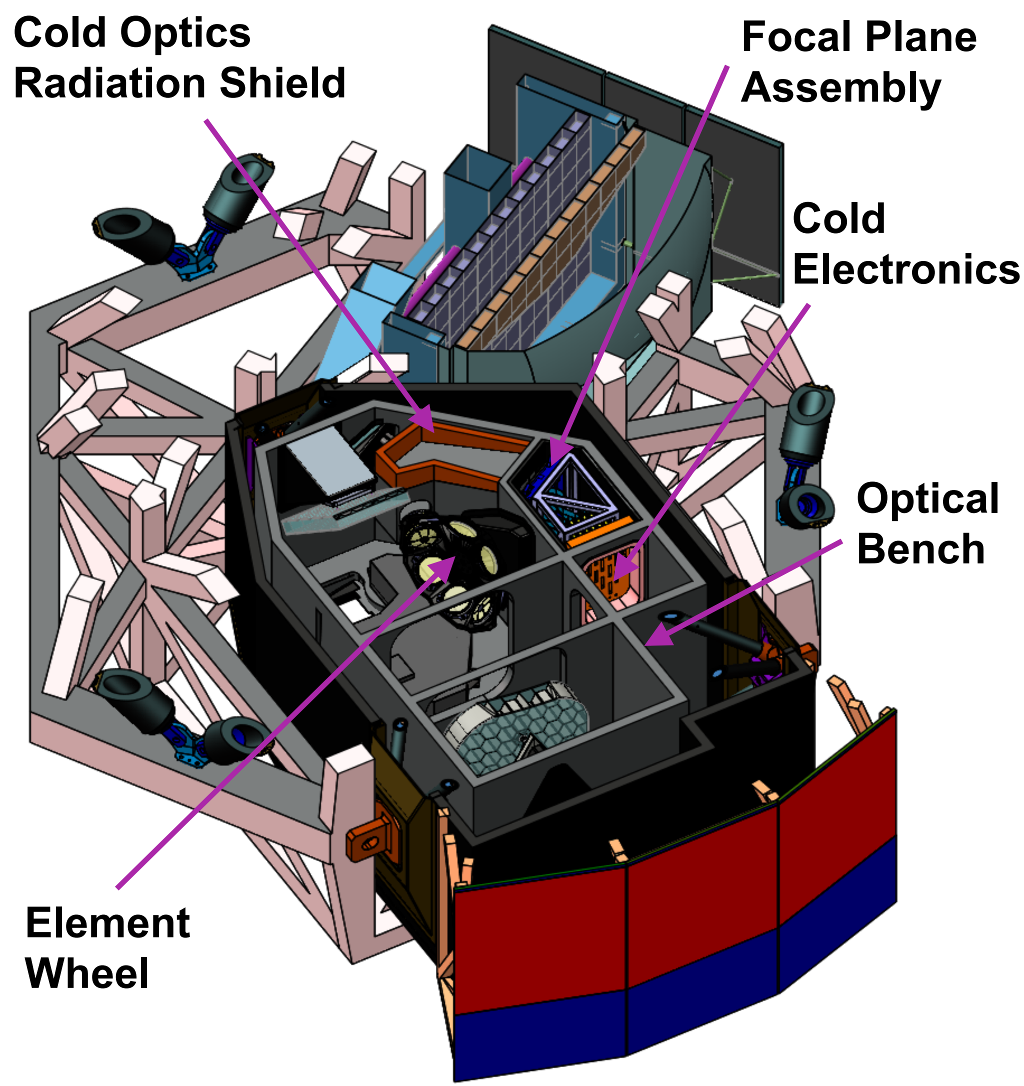
Payload Design to Minimize Telescope Risk

- Exelis/JPL/Study Office have worked closely 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 bench for the payload, telescope and both instruments are attached to it.
- Telescope operating temperature baseline is 282 K and is within the qualification 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

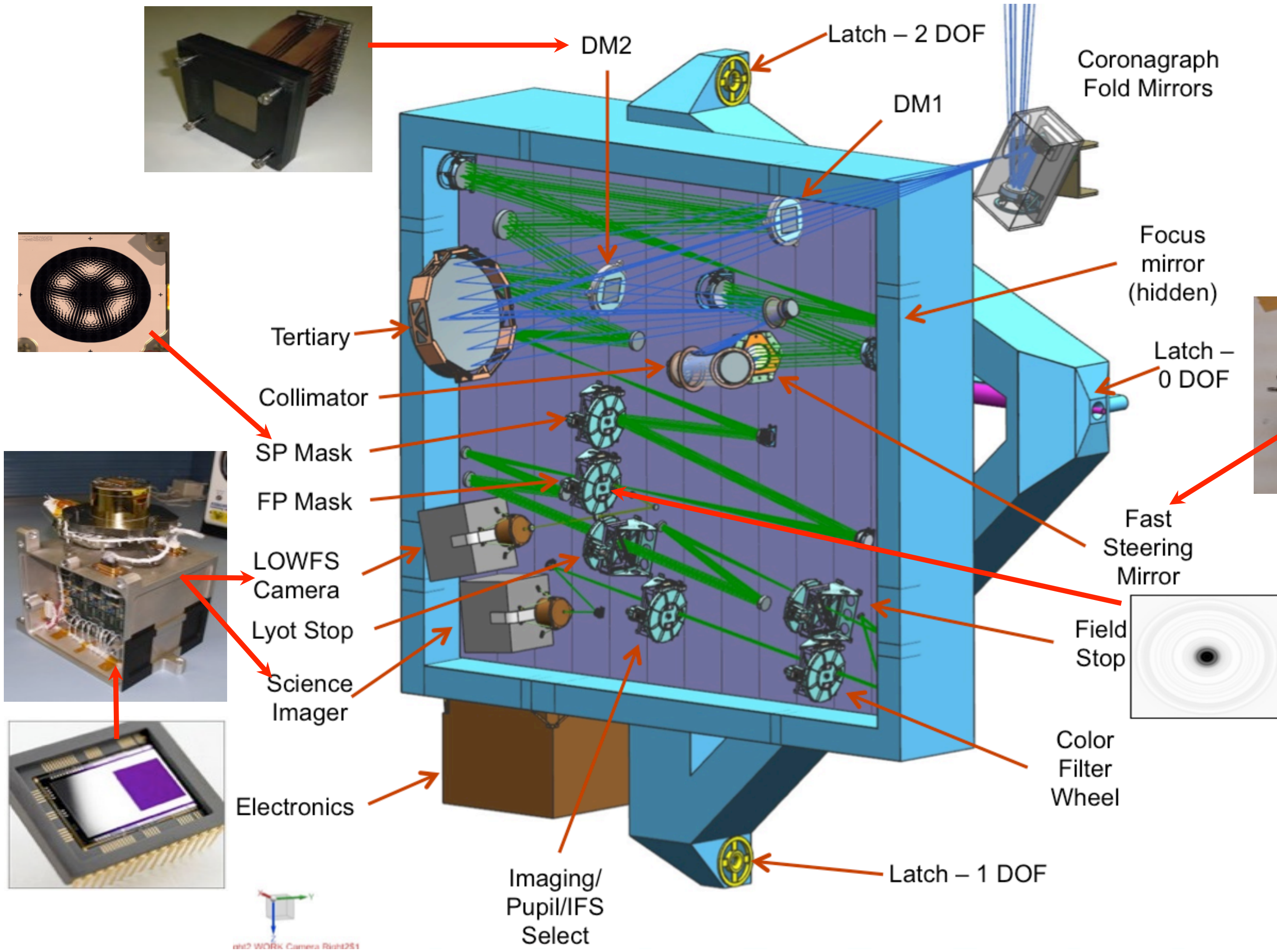
- Wide field channel instrument for both imaging and spectroscopy
  - 3 mirrors, 1 powered
  - 18 4k x 4k HgCdTe detectors cover 0.76 - 2.0 μm
  - 0.11 arc-sec plate scale
  - Single element wheel for filters and grism
  - Grism used for GRS survey covers 1.35 – 1.89 μm with R = 461λ (~620 – 870)
- IFU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

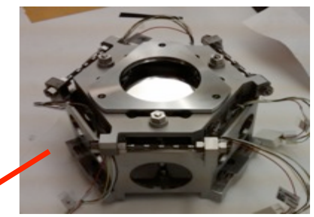


Wide Field Detector Technology Maturation Progress

- Detector Technology Development Plan released with 5 key milestones identified to mature the HgCdTe detectors by the end of CY16.
  - First two milestones successfully completed.
- The Teledyne/GSFC Detector Team has completed a series of experiments (banded arrays) to determine the optimum detector composition for WFIRST. Full array flight composition detectors deliver this summer and will be characterized in the GSFC Detector Characterization Lab.
- The detector Read Out Integrated Circuit (ROIC) design has been optimized for WFIRST performance.
- Developed test hardware to eliminate hybridizing marginal ROICs to good detectors.
- Infrastructure – numerous investments have been made in the GSFC Detector Characterization Lab (DCL) to characterize/ qualify individual detectors and test the entire focal plane

Coronagraph Instrument Overview

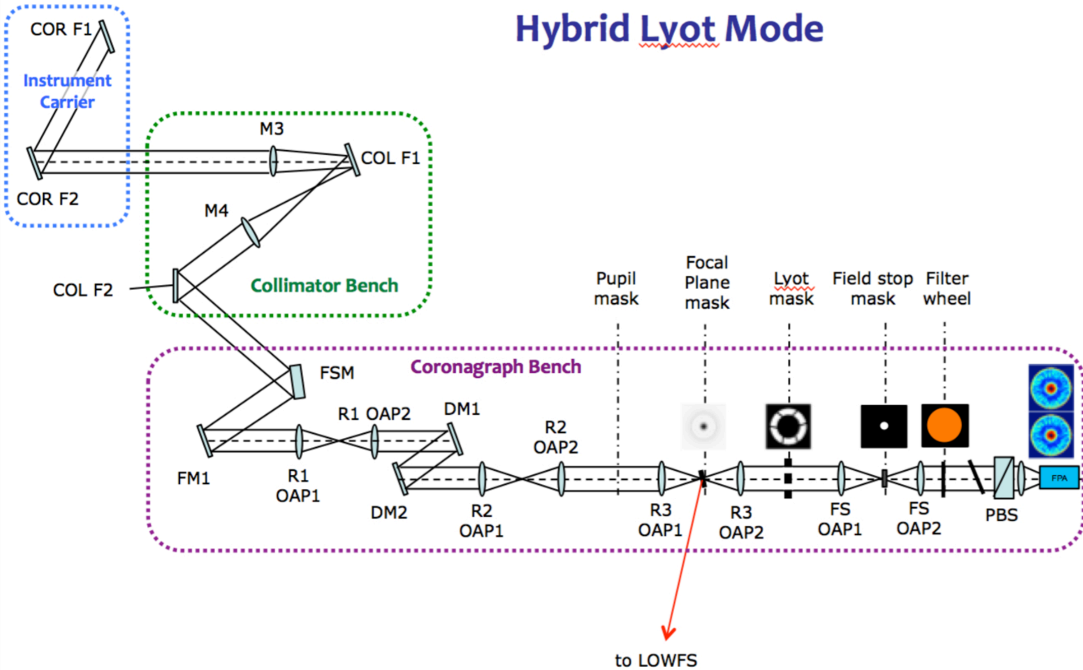


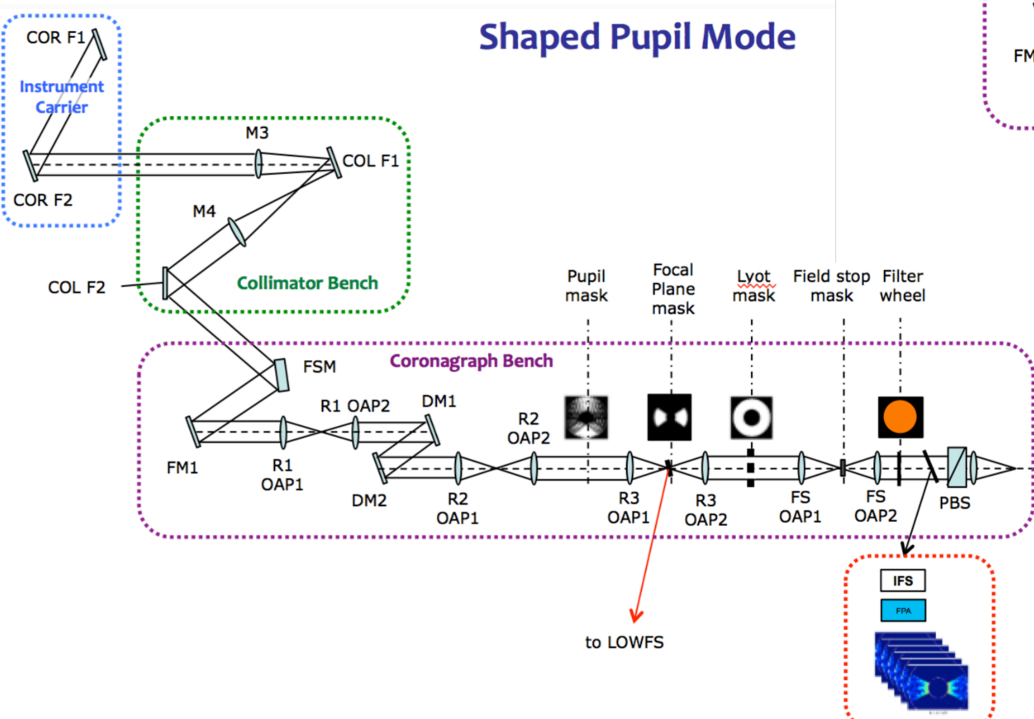


Temperature	293 K for instrument ~165 K for cameras
Data Volume	~30 Gbits/day
Imaging	0.43 – 0.97 microns, 1.63" FoV (radius), 0.01" pixel scale, 1K×1K EMCCD
Integral Field Spectrograph	0.60 – 0.97 microns R~70

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

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



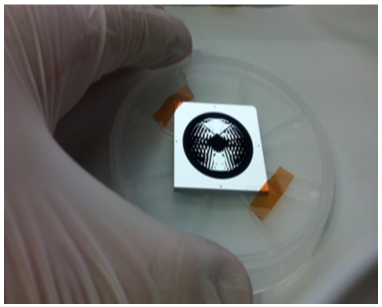


- In “SP mode” provides the simplest design, lowest risk, easiest technology maturation, most benign set of requirements on the spacecraft and “use-as-is” telescope. This translates to low cost/schedule risk which is critical for the independent CATE process.
- In “HL mode”, affords the potential for greater science, taking advantage of good thermal stability in GEO and low telescope jitter for more planet detections in a shorter time

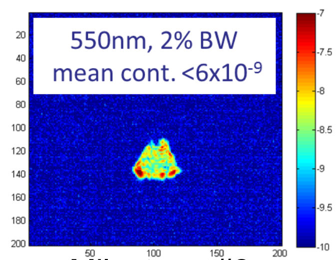
Coronagraph Technology Development Highlights

Reflective shaped pupil mask

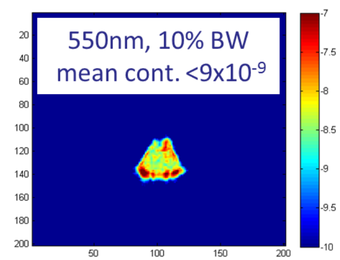
- Black Si on Al mirror coating demonstrated at JPL/MDL and Caltech/KNI
- High contrast demonstrated at HCIT



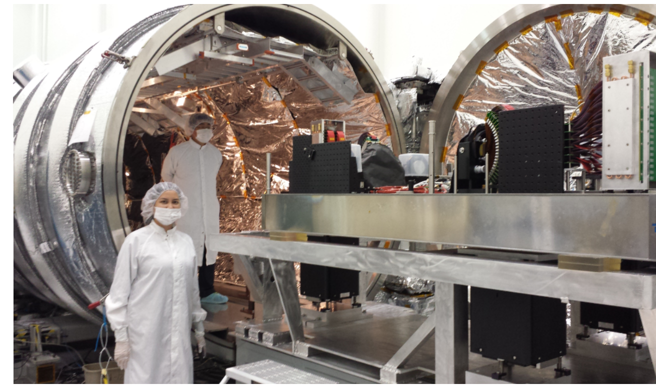
Milestone #1



Milestone #2

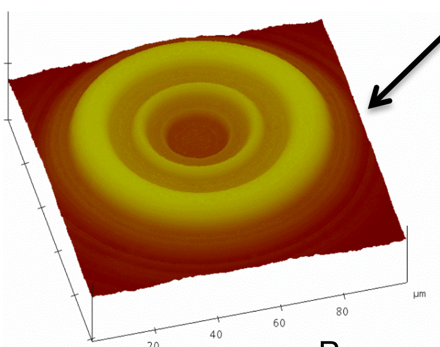


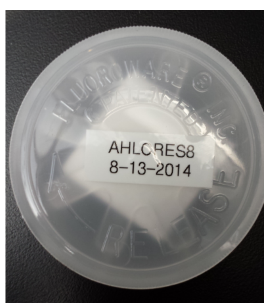
Preview of Milestone #5

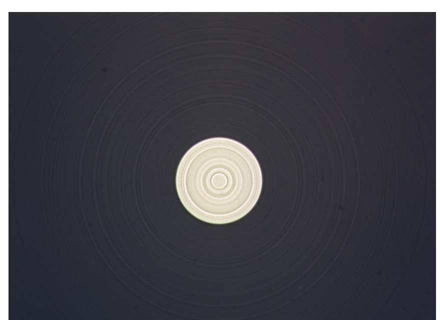


Transmissive hybrid Lyot mask

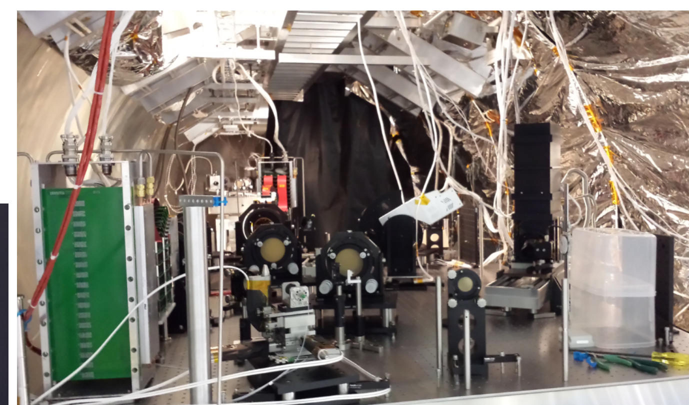
- Circular mask fabricated and measured
- Testbed commissioned on 8/15/2014







Progress for Milestone #4 to be completed this month



Coronagraph Technology Maturation Progress

- High contrast testbed results have demonstrated that better than 10^{-8} raw contrast is achievable with the WFIRST 2.4-m telescope.
- On track to demonstrate dynamic, broadband high contrast testbed performance during formulation.
- Significant investments in deformable mirrors, detectors, low order wavefront control, mechanisms and post-processing algorithms essential for high contrast coronagraphy.
- Developing an Integral Field Spectrograph (IFS) testbed at GSFC for delivery to JPL high contrast testbed this year.

Observatory Integrated Modeling

- Recent focus of Observatory analysis has been on integrated modeling (STOP and Jitter).
- Model fidelity is extremely high
  - Benefit of using the existing telescope
  - Required to optimize coronagraph mask designs
  - Critical for assessing PSF ellipticity for WL
- WFI STOP stability specs met with margin (10x) even for an extreme WFI Worst Slew Case w/MUFs applied
  - WFI spectroscopy and IFU modes and CGI STOP stability analysis in progress
- 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
  - WFI spectroscopy and IFU modes and CGI Jitter stability analysis in progress

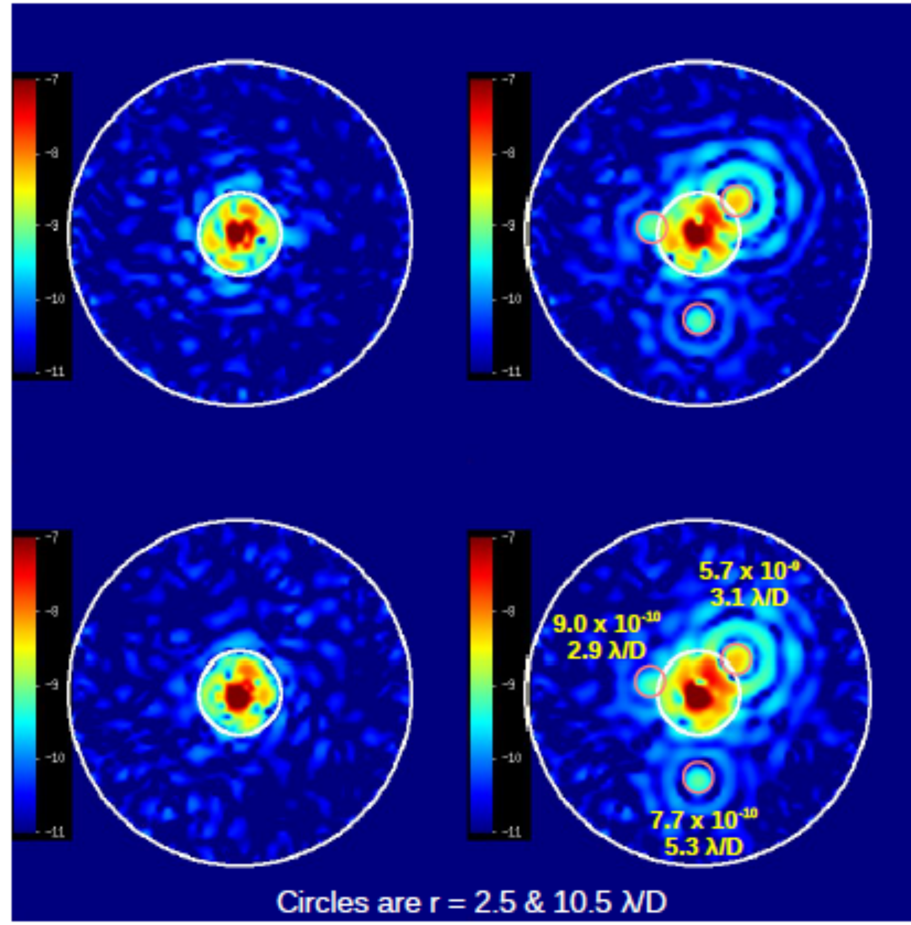
Preliminary Coronagraph STOP Results

"Hot Off the Presses"

No planets | With planets (circled)

|47 Uma - β Uma|

|47 Uma - 61 Uma|



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.

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

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

Path Forward

- Optimization of the Reference Design
  - Study L2 mission concept and perform science/cost trade vs. GEO configuration
  - Study non-exoplanet uses for the coronagraph
  - Perform analysis to improve microlensing event rate predictions
  - Refine wide field IFU design to optimize wavelength range and resolution, and slice scale and sampling of the slices
- Systematic Error Control
  - Develop a calibration strategy
  - Characterize astrometric performance of the WFI
- Synergies with Other Observatories
  - Survey the need for precursor observations for microlensing, low z SNe and RV studies of coronagraph targets
  - Study opportunities for joint observations and requirements for joint analyses with Euclid, LSST and other ground telescopes
- Coronagraph
  - Develop more detailed coronagraph DRM
  - Perform deeper investigation of effects of coronagraph polarization and PSF subtraction
  - Assist with development of wavefront control technology
- Policy Issues
  - Consider possibilities for foreign involvement
- Observatory
  - Further refine servicing architecture and ops concept

Summary

- Recent infusion of additional funding has allowed significant progress in technology maturation as well as additional fidelity in the design reference mission.
- WFIRST-AFTA with the 2.4-m telescope and coronagraph provides 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.
- Opportunity to enhance the scientific return from JWST and WFIRST if missions overlap