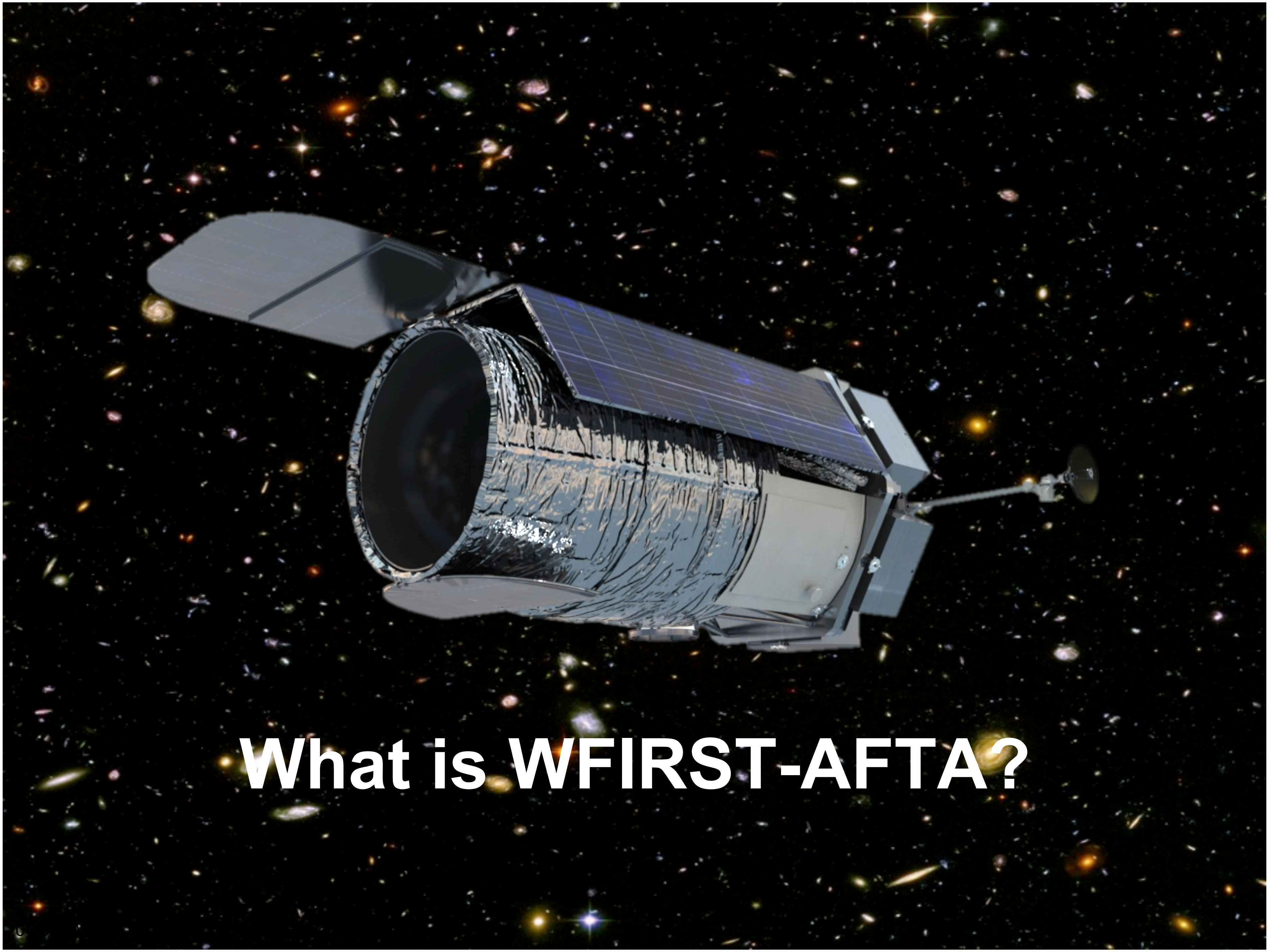
What is WFIRST-AFTA?



Outline

- What is it?   Telescope and Instruments
- What will it do?   Science Program
- Will it happen? Programmatics and Budget
- How can you help make it succeed?

WFIRST-AFTA SDT

Co-Chairs

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

Members

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

Ex Officio

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

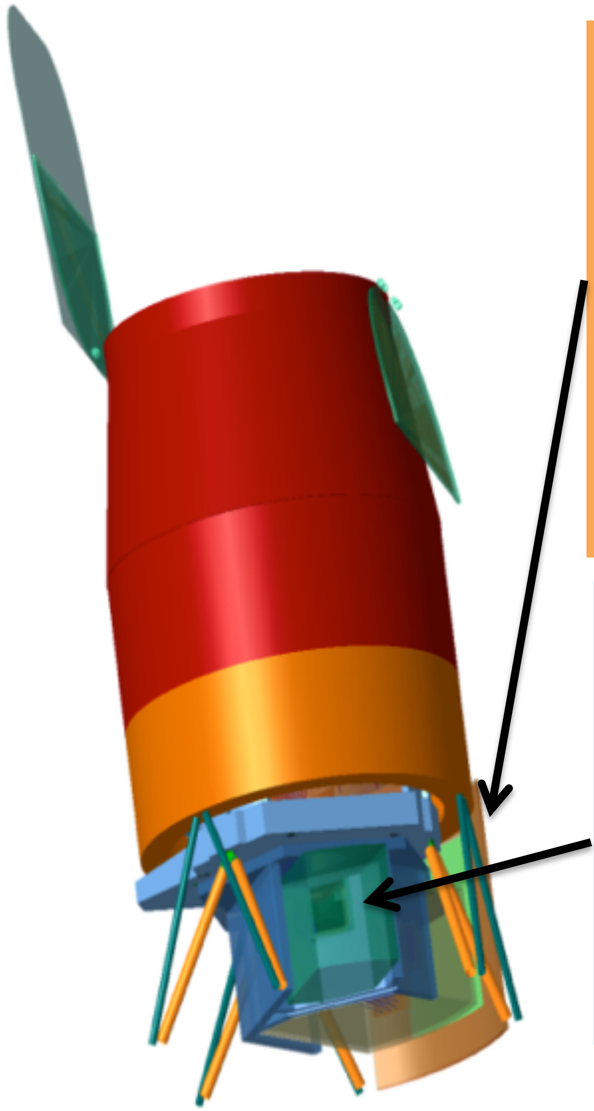
Consultants

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

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)

WFIRST-AFTA Instruments



Wide-Field Instrument

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

Coronagraph

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

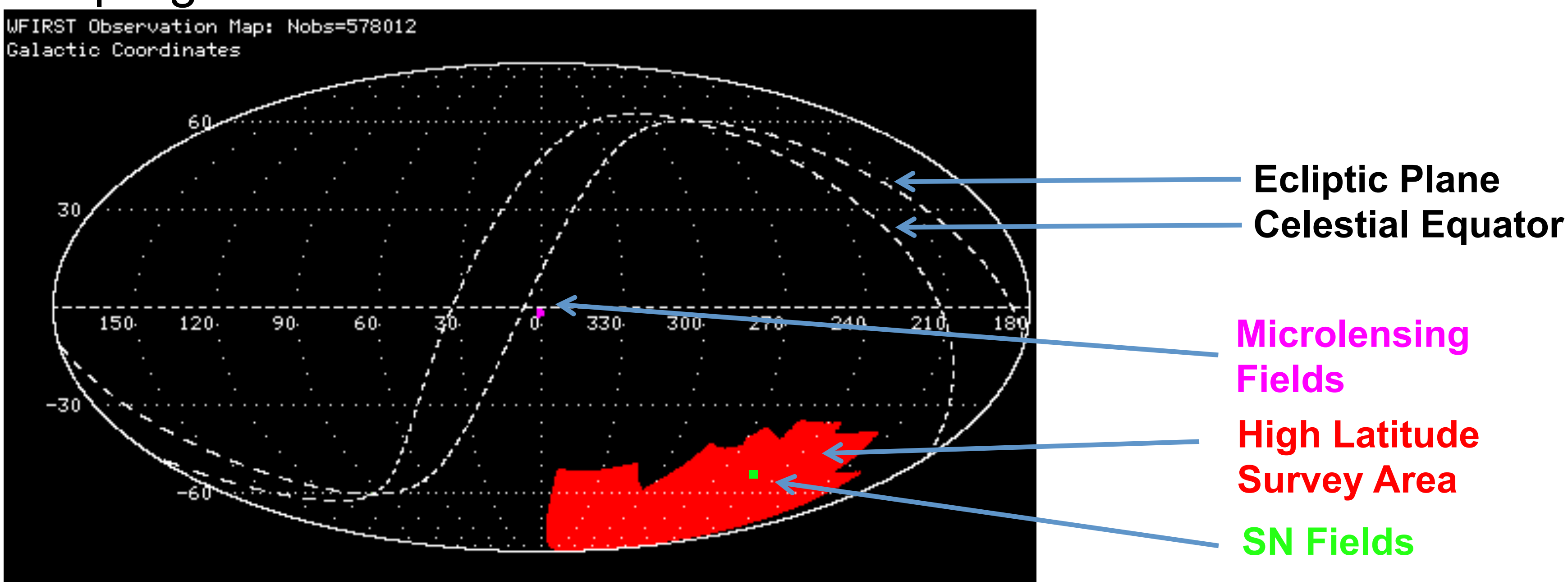
Multi-use Facility

- High Latitude Survey
- Microlensing Survey
- Coronagraph
- General Observing (GO)

WFIRST-2.4 Design Reference Mission Capabilities						
Imaging Capability	0.281 deg^2		0.11 arcsec/pix		0.6 – 2.0 μm	
Filters	Z087	Y106	J129	H158	F184	W149
Wavelength (μm)	0.760-0.977	0.927-1.192	1.131-1.454	1.380-1.774	1.683-2.000	0.927-2.000
PSF EE50 (arcsec)	0.11	0.12	0.12	0.14	0.14	0.13
Spectroscopic Capability	Grism (0.281 deg^2)				IFU (3.00 x 3.15 arcsec)	
	1.35 – 1.95 μm, R = 550-800				0.6 – 2.0 μm, R = ~100	

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



HLS Observing Strategy

	Band (μm)	Exp Time (sec)	Time Required (Days/1000 deg^2)	Point Source Depth	Extended Source Depth	PSF EE50 (arcsec)	Weak Lensing n_{eff} (galaxies/arcmin^2)
Y	0.927-1.192	5 x 184	50	26.8	25.6	0.12	n/a
J	1.131-1.454	6 x 184	59	26.9	25.7	0.12	54
H	1.380-1.774	5 x 184	50	26.8	25.7	0.14	61
F184	1.683-2.000	5 x 184	50	26.2	25.2	0.14	44
Grism	1.350-1.950	6 x 362	118	4.6×10^{-17}	1.0×10^{-16}	0.18	n/a

- Considering shifting bands bluer (and wider)
- Fields chosen to overlap with LSST
- During survey, IFU will be put on a sample of galaxy to provide spectroscopic training set

WFIRST-AFTA & Euclid Complementary for Dark Energy

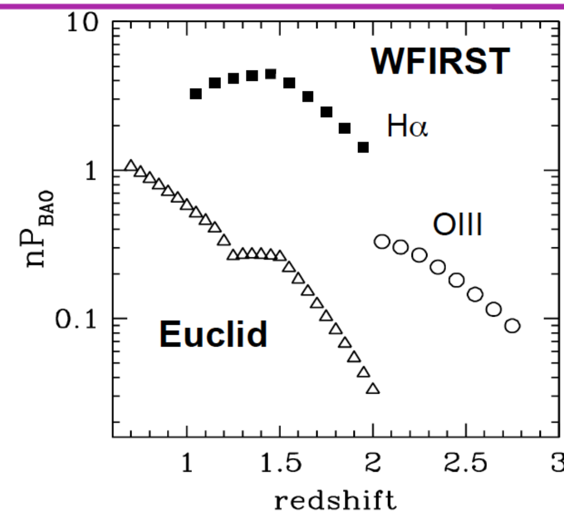
WFIRST-AFTA

Deep Infrared Survey (2400 deg^2)

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

Supernovae:
- High quality IFU spectra of >2000 SN

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



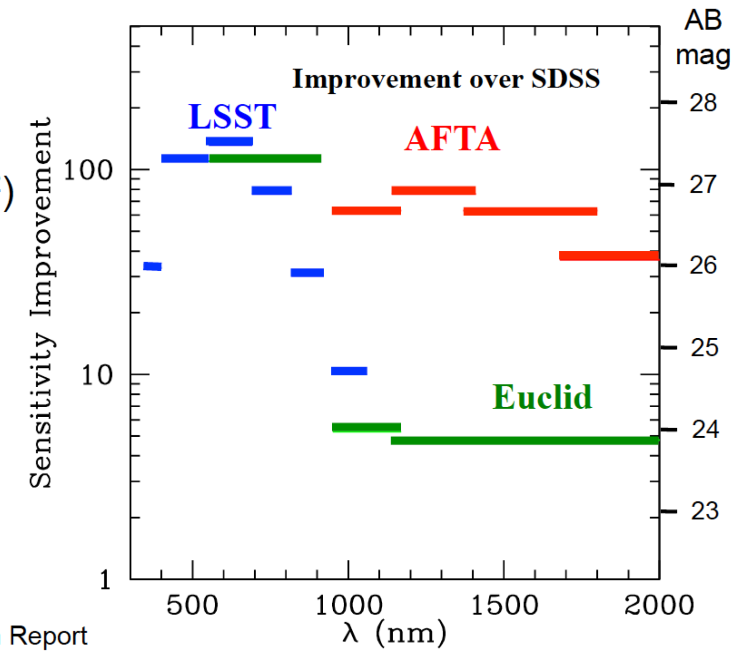
Euclid

Wide Optical and Shallow Infrared Survey (15000 deg^2)

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

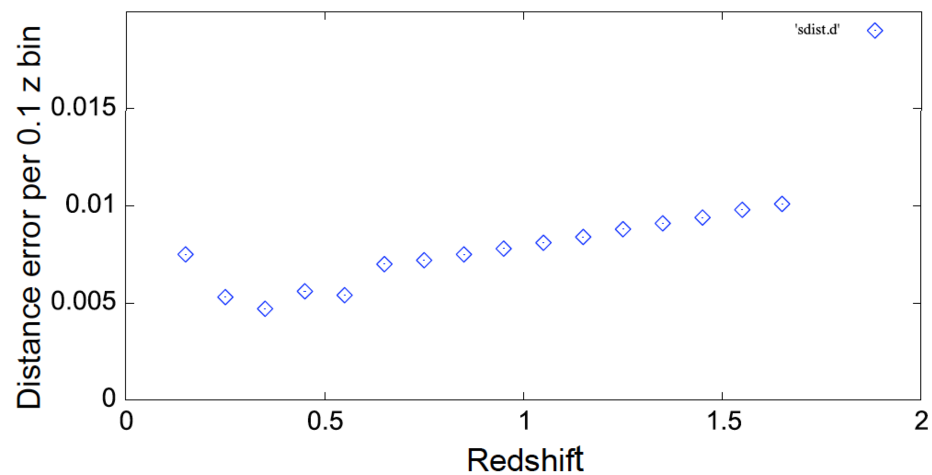
No supernova program

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



The Supernova Survey

- Three tiered survey for low, medium, and high redshift Type Ia supernovae out to redshift of 1.7
- Use the Wide Field Instrument for supernova discovery with a 5 day cadence, the Integral Field Spectrometer (IFU) for lightcurves from spectrophotometry, no need for K corrections
- 2700 supernovae, distance errors 0.5 % to 1.0 % per 0.1 redshift bin including best estimate of systematic errors
- Low infrared background in space allows unique high redshift survey not possible from the ground
- High S/N spectra with the IFU allow reduced systematic errors to match high precision achievable with 2.4 m



Weak Lensing with WFIRST

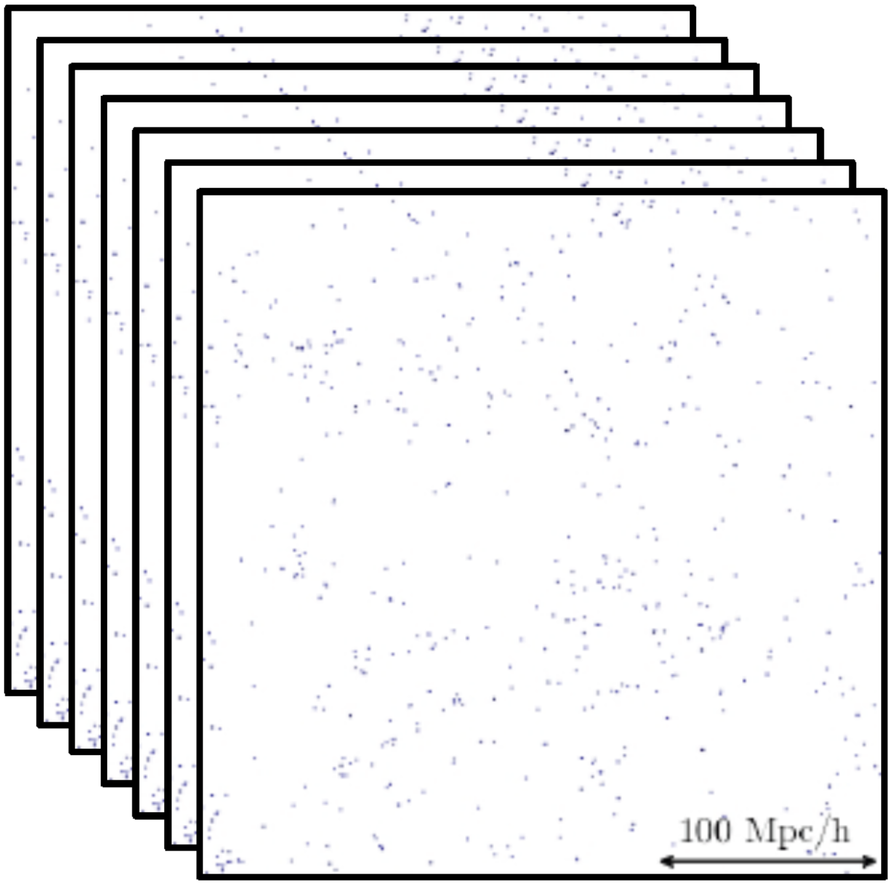
- Powerful probe of matter distribution in the Universe
  - Shapes for >400 million galaxies (50/arcmin^2 over 2400 deg^2).
  - Precision of 0.12% on amplitude of matter clustering from cosmic shear; comparable power from cluster-galaxy and galaxy-galaxy lensing.
  - High number density enables high-resolution mass maps
- Systematic error control
  - Shapes measured in 3 filters, with total of 6 passes over the sky: rich opportunity for null tests, auto- and cross-correlations, and internal calibration. *Crucial* for believing high-precision measurements.
  - Small and stable PSF with 2.4 m space telescope reduces systematic errors in the PSF model and their impact on galaxy ellipticity measurement
  - Dither pattern recovers full sampling, even rejecting cosmic rays at GEO rate

WFIRST-AFTA Galaxy Redshift Survey

- Wide and Deep Galaxy Redshift Survey:
  - ~20 million Hα galaxies ($1<z<2$)
  - ~2 million [OIII] emission line galaxies ($2<z<3$)
  - Baseline survey area 2,400 deg^2
- High Precision Measurement of Cosmic Expansion History and Growth History:
  - Model-independent measurement of cosmic expansion rate $H(z)$ & cosmic structure growth rate $f_g(z)\sigma_8(z)$ at a few % level with $dz=0.1$
  - Cumulative precision of $H(z)$ and $f_g(z)\sigma_8(z)$ at sub percent levels
- High Galaxy Number Density Allows Tight Control of Systematic Effects:
  - Good sampling of cosmic large scale structure
  - Enables subdividing data into subsets for crosschecks
  - Enables higher order statistics
  - More robust to Hα luminosity function uncertainties

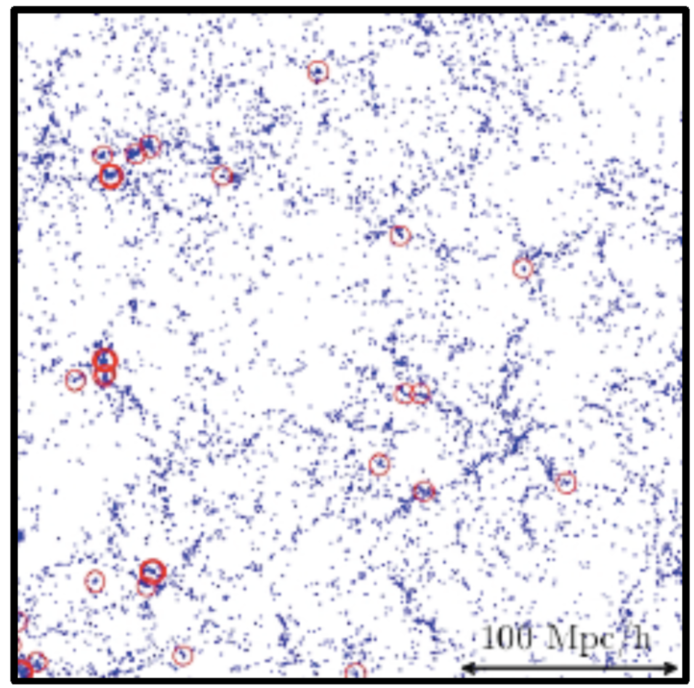
Detailed 3D Map of Large Scale Structure at z = 1-2

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



Euclid

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



WFIRST

2,400 deg^2 @ 12,600 gal/deg^2

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

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

WFIRST and General Astrophysics

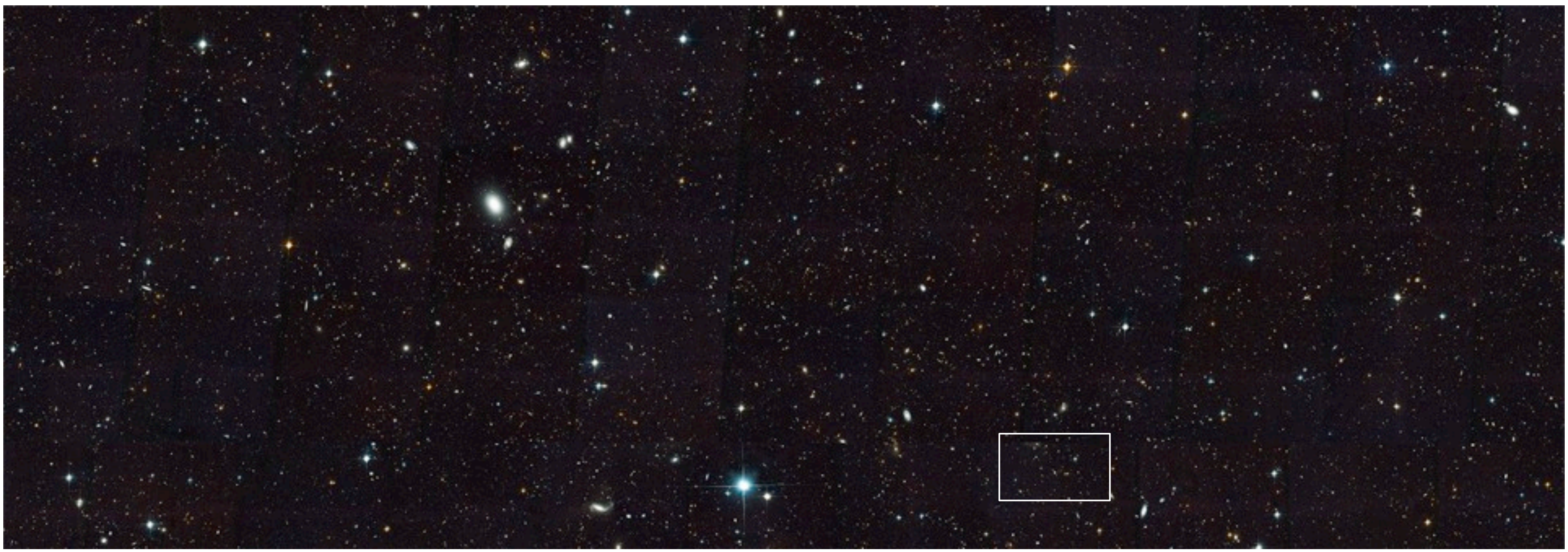
[redacted]

Guest Observer Capabilities						
1.4 years of the 5 year prime mission						
	Z087	Y106	J129	H158	F184	W149
Imaging depth in 1000 seconds (m_{AB})	27.15	27.13	27.14	27.12	26.15	27.67
t_{exp} for $\sigma_{read} = \sigma_{sky}$ (secs)	200	190	180	180	240	90
Grism depth in 1000 sec	S/N=10 per R=~600 element at AB=20.4 (1.45 μm) or 20.5 (1.75 μm) t_{exp} for $\sigma_{read} = \sigma_{sky}$: 170 secs					
IFU depth in 1000 sec	S/N=10 per R~100 element at AB=24.2 (1.5 μm)					
Slew and settle time	chip gap step: 13 sec, full field step: 61 sec, 10 deg step: 178 sec					

Wealth of exciting ideas!

AFTA vs Hubble

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



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

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

Frontiers of Knowledge	•*Why is the universe accelerating?* •*What is the dark matter?* •*What are the properties of neutrinos?* •*What controls the mass, radius and spin of compact stellar remnants?*
Understanding our Origins	•*How did the universe begin?* •*What were the first objects to light up the universe, and when did they do it?* •*How do cosmic structures form and evolve?* •*What are the connections between dark and luminous matter?* •*What is the fossil record of galaxy assembly from the first stars to the present?* •*How do stars form?* •*How do circumstellar disks evolve and form planetary systems?*
Cosmic Order: Exoplanets	•*How diverse are planetary systems?* •*Do habitable worlds exist around other stars, and can we identify the telltale signs of life on an exoplanet?*
Cosmic Order: Stars, Galaxies, Black Holes	•*What controls the mass-energy-chemical cycles within galaxies?* •*How do the lives of massive stars end?* •*What are the progenitors of Type Ia supernovae and how do they explode?* •*How do baryons cycle in and out of galaxies, and what do they do while they are there?* •*How do rotation and magnetic fields affect stars?* •*What are the flows of matter and energy in the circumgalactic medium?* •*How do black holes grow, radiate, and influence their surroundings?*

Galactic Science Examples
Luminous and Dark Matter

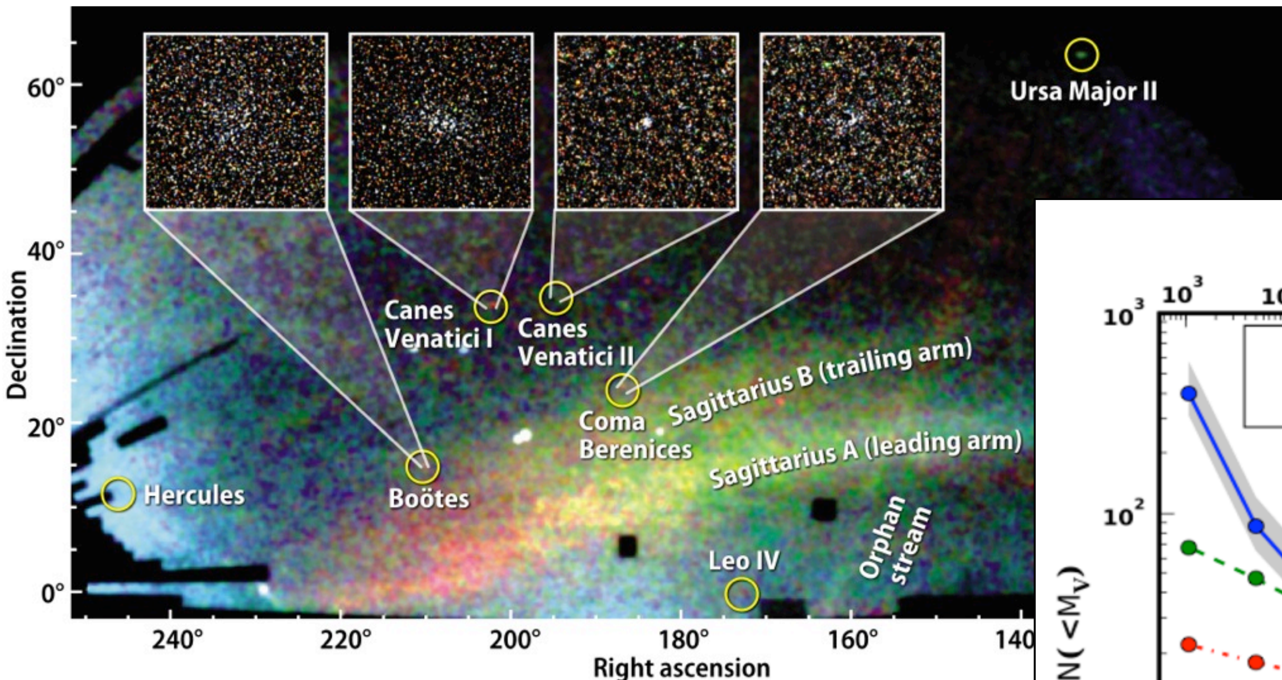
- Masses of the Faintest Milky Way Satellites
  - 80 micro-arcsec/year gives individual star internal velocities
    - provides estimates of dark matter mass and density
    - <2 km/s for 50 stars @ 100 kpc, in 3 years
- The Mass of the Milky Way
  - Tangential velocities of distant tracers in the Milky Way halo
    - <40 km/s error in v_{TAN} at 100 kpc, less than the expected velocity dispersion
    - Breaks the mass-anisotropy degeneracy in the distant halo
- Cold vs Warm Dark Matter
  - Distinguish central density profiles
  - Extrapolate dark matter mass profiles
  - Current v_{RAD} lead to degeneracy b/w the central slope of DM profile and velocity anisotropy.

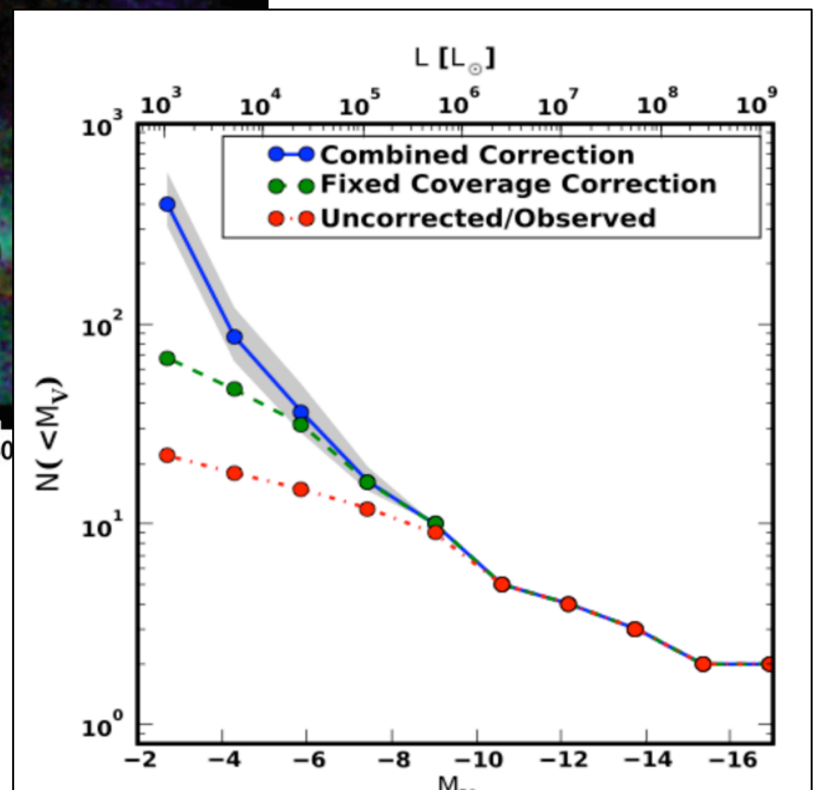
Full science case descriptions are in SDT Report

Galactic Science Example

Dark Matter Properties through Luminous Tracers

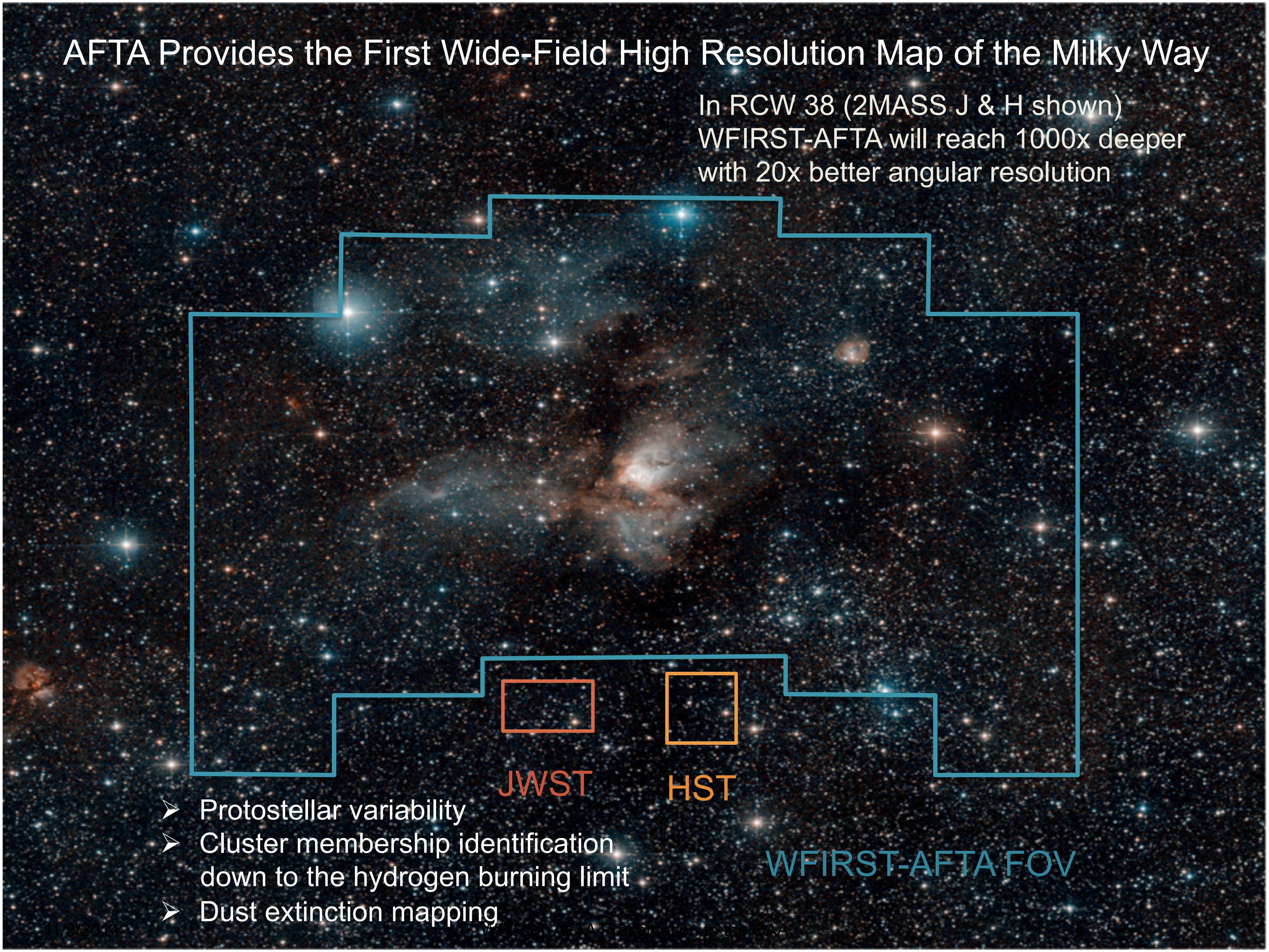
AFTA will survey 2000 sq deg of MW Halo at Hubble's power and IR image quality





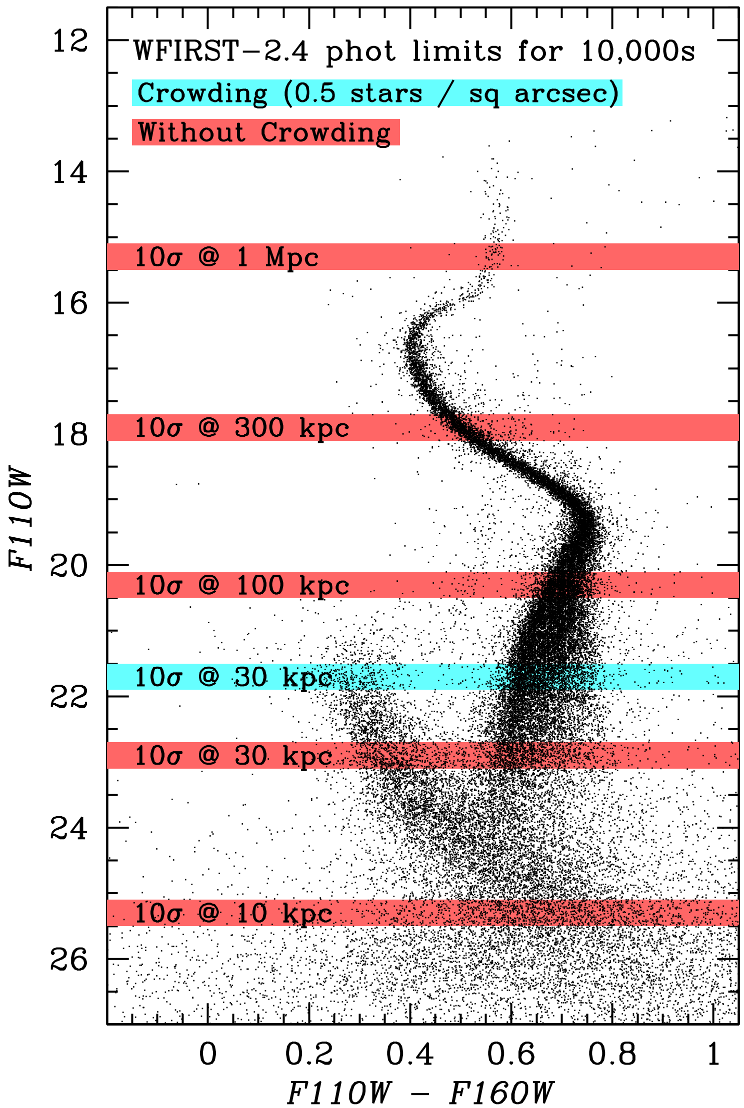
Current census of Milky Way DM-dominated streams and dSphs is heavily incomplete.

WFIRST will be very efficient at finding missing dSphs


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
JWST
HST
WFIRST-AFTA FOV
➢ Protostellar variability
➢ Cluster membership identification down to the hydrogen burning limit
➢ Dust extinction mapping

Galactic Science Example

Stellar Pops and IMF



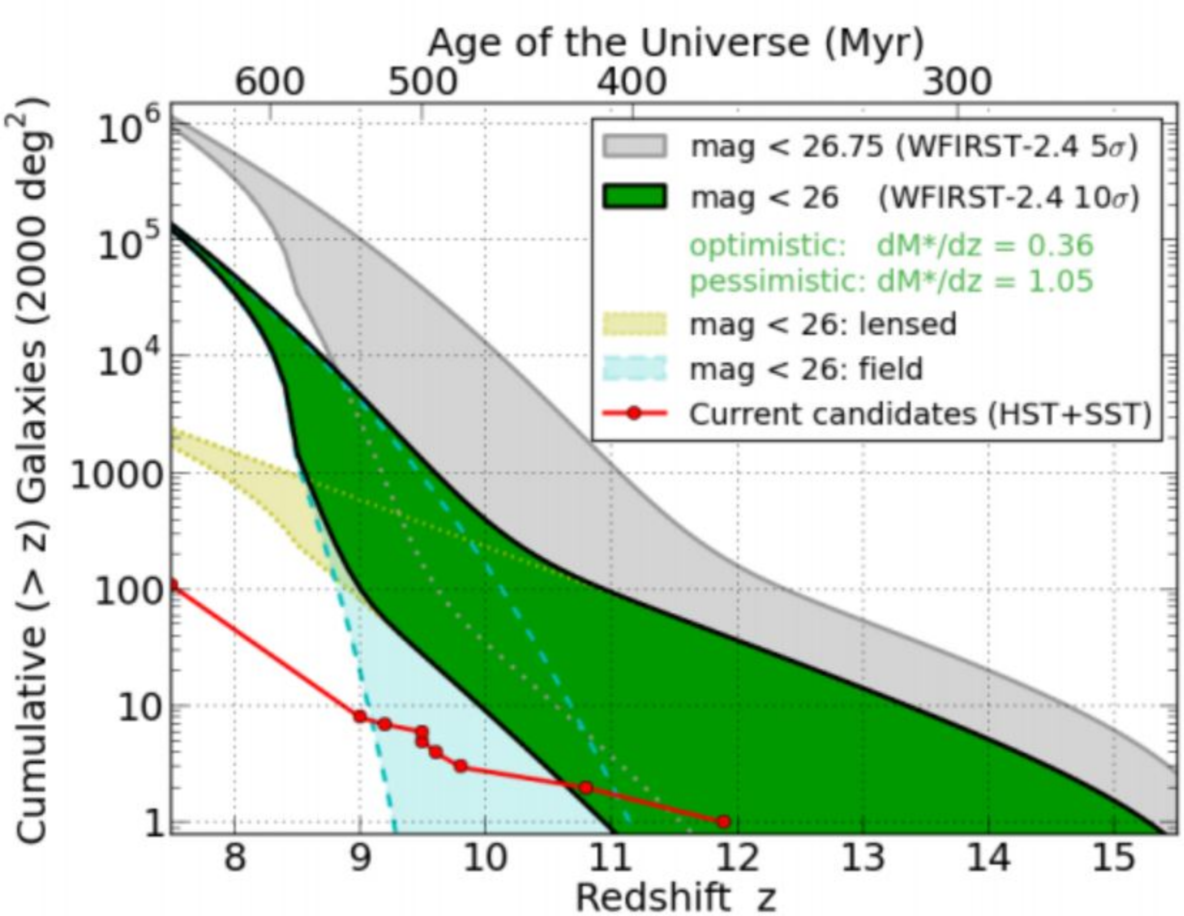
- M dwarfs out to the edge of the Galaxy
- Exquisite star/galaxy separation
  - High-precision photometry
  - Takes advantage of rising stellar luminosity function
    - Discovery of dozens of low SB systems
    - IMFs, SFHs, SB profiles, and structure

A stellar population (47 Tuc + SMC) in the IR (Kalirai et al. 2012)

Extragalactic Science Example

High Redshift Galaxy Luminosity Function

WFIRST's High Latitude Survey will yield up to 2 orders of magnitude more high redshift galaxies than currently known



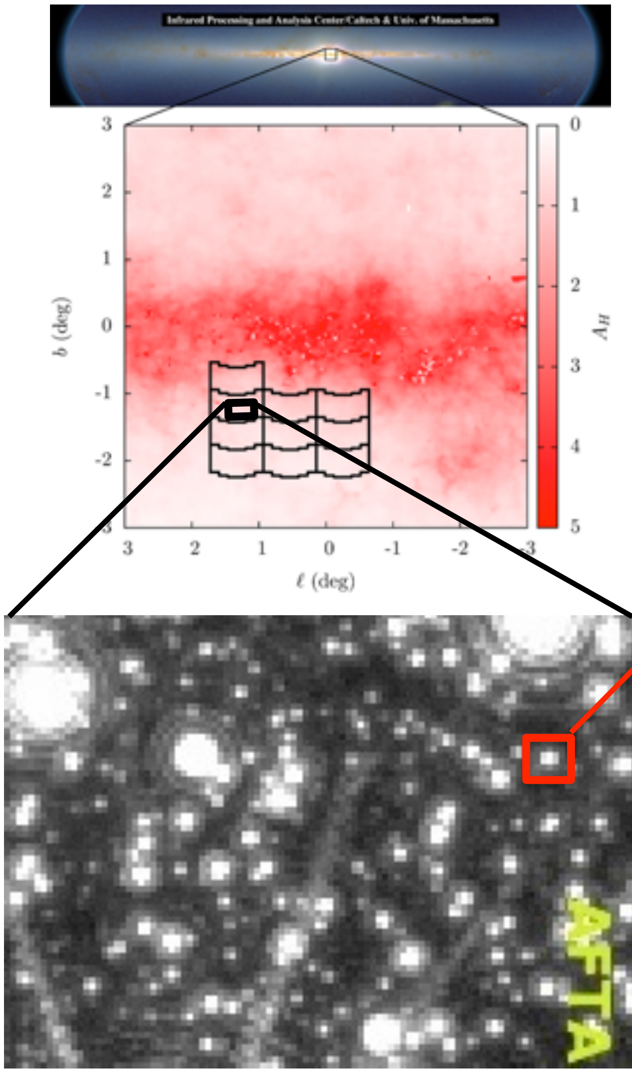
WFIRST-AFTA Microlensing Survey Parameters

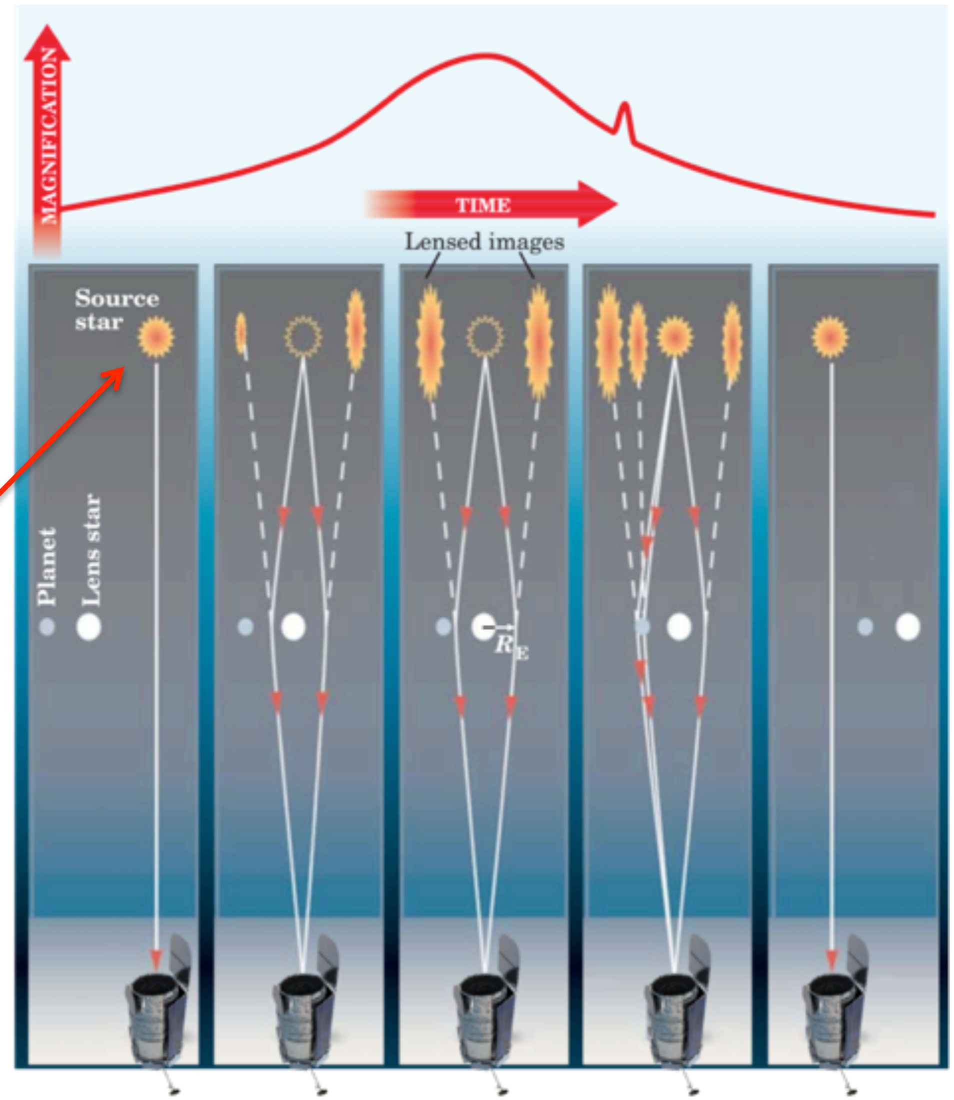
- Properties
  - 10 fields, total of 2.81 deg^2
  - 6 seasons of 72 days each, for a total of 432 days.
  - 52 second exposures in W149, with a cadence of 15 minutes
  - 290 second exposures in Z087, with a cadence of 710 minutes
  - ~80% of the area will have 2 million seconds of integration time in W149
  - ~75 million stars down to $H_{AB}<22$, with ~40,000 measurements per star (~10% in bluer filter).
  - SNR ~ 100 per exposure for a $H_{AB}\sim 21$ source

Completing the Statistical Census of Exoplanets

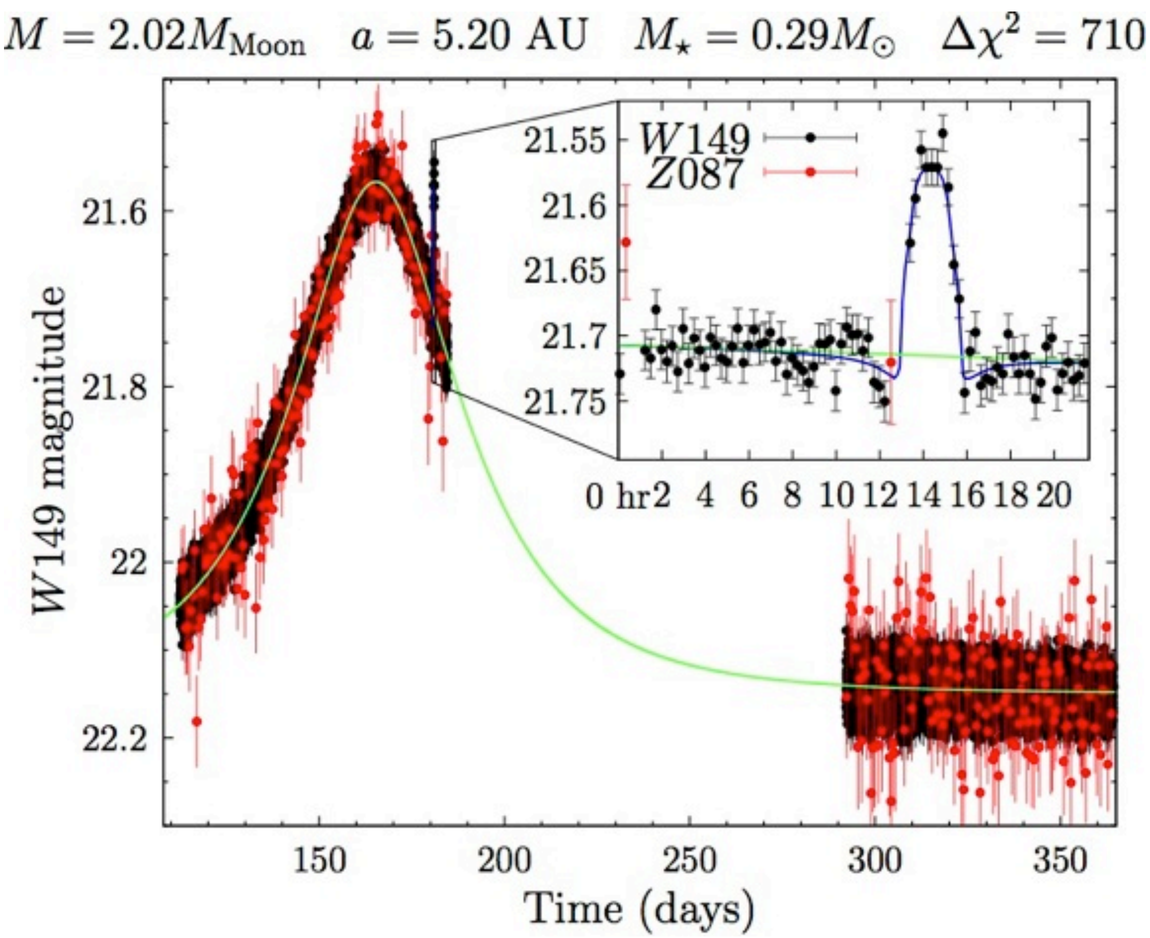
- Golden era of exoplanet science
  - Thousands of planets detected using a bewildering variety of different methods, telescopes, and instruments
  - *Kepler* has revolutionized our understanding of “hot” and “warm” planets
- But, current surveys, including *Kepler*, are mainly sensitive to planets very unlike those in our solar system
- Therefore, many questions remain:
  - How common are solar systems like our own?
  - How do planets form and migrate?
  - What kinds of planets exist in the cold, outer regions of planetary systems?
  - What determines the habitability of Earth-like worlds?
- WFIRST-AFTA will address these questions by completing the census of exoplanets begun by Kepler.
  - Detect ~3000 planets, with orbits from the habitable zone outward, and masses down to a few times the mass of the Moon
  - Sensitive to analogs of all the solar system’s planets except Mercury
  - Measure the abundance of free-floating planets in the Galaxy with masses down to the mass of Mars
  - Measure the masses and distances to the planets and host stars

Detecting Planets with a Microlensing Survey





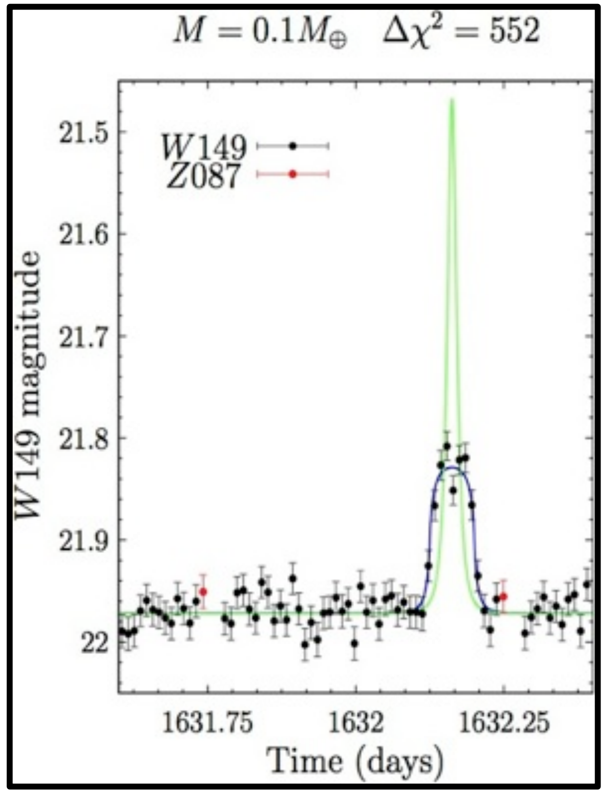
Exquisite Sensitivity to Cold, Very Low-Mass Planets



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

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

Free-Floating Planets

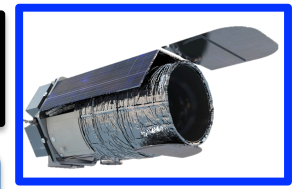


Free floating Mars
(~23 sigma)

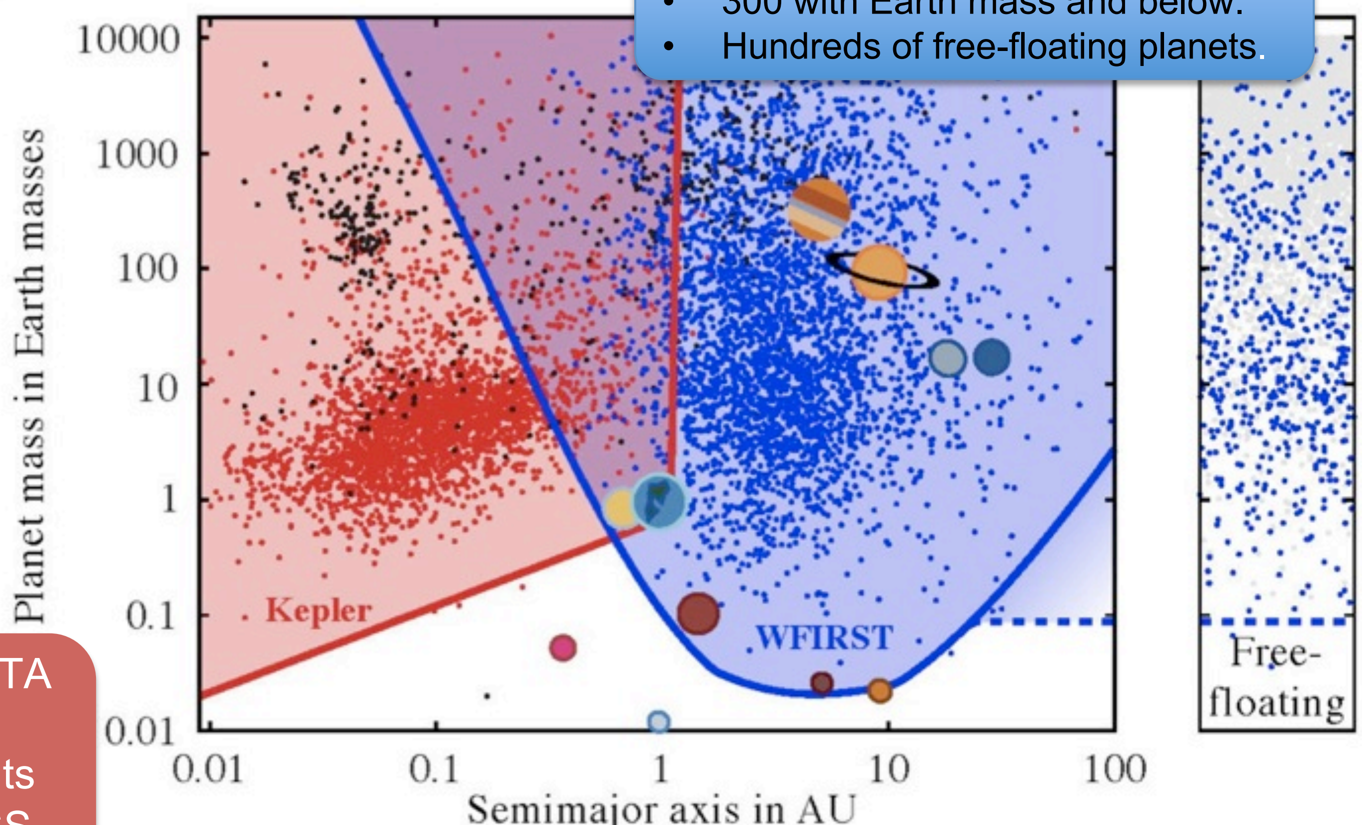
- Free-floating planets may be more common than stars in the Galaxy.
- WFIRST-AFTA can detect free-floating planets down to the mass of Mars.
- Expect to detect hundreds of free-floating planets.
- Sensitive to moons of free-floating planets.

Completing the Statistical Census of Exoplanets

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



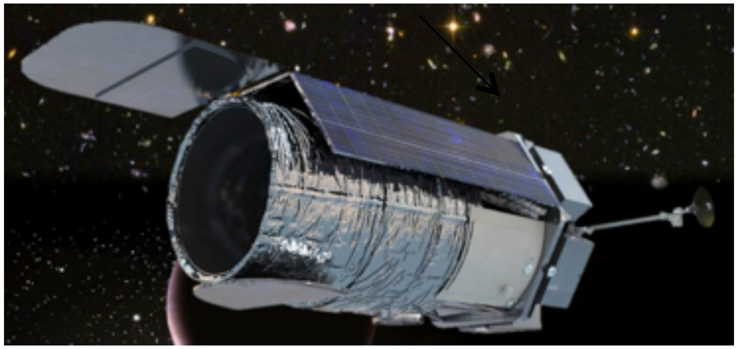
- ~3000 planet detections.
- 300 with Earth mass and below.
- Hundreds of free-floating planets.

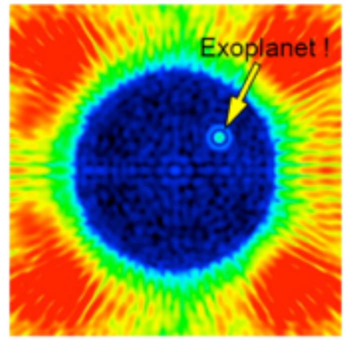


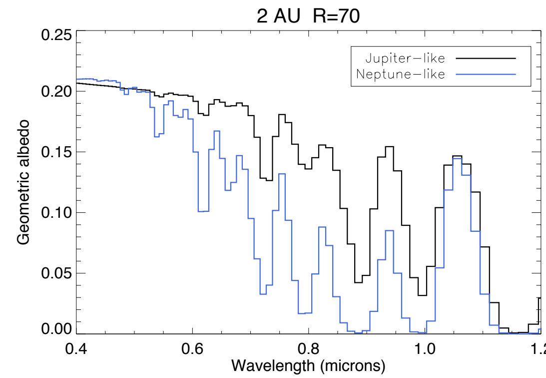
M. Penny (OSU)

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

WFIRST-AFTA Coronagraph Capability







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

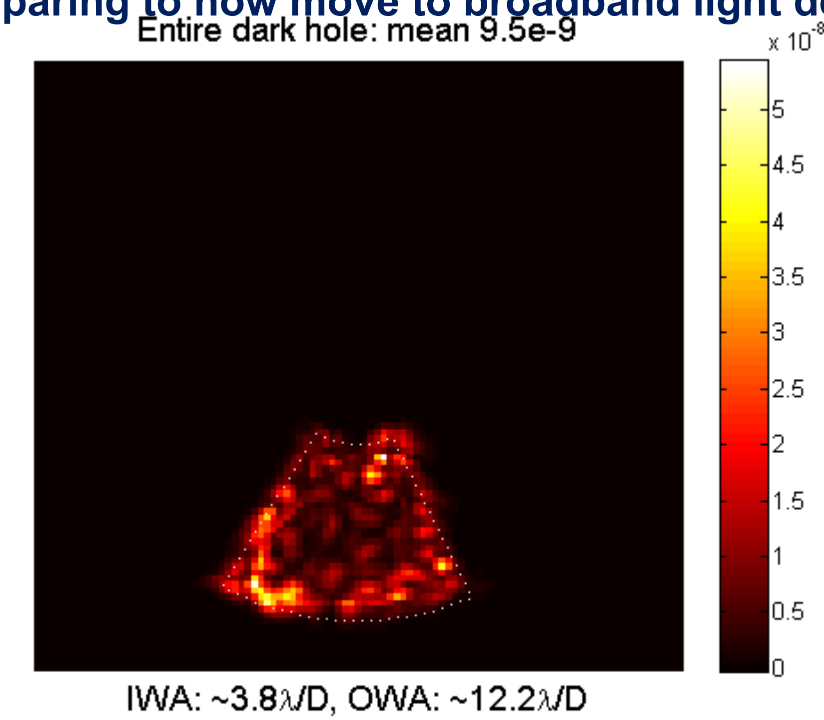
Exoplanet Direct imaging

Exoplanet Spectroscopy

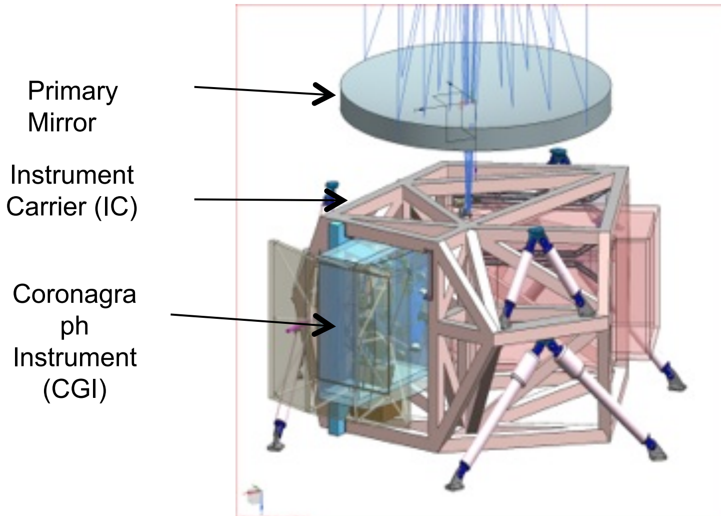
Bandpass	400 – 1000 nm	Measured sequentially in five ~10% bands
Inner working angle	100 – 250 mas	~3λ/D, driven by science
Outer working angle	0.75 – 1.8 arcsec	By 48x48 DM
Detection Limit	Contrast ≤ 10^{-9} (after post processing)	Cold Jupiters, Neptunes, and icy planets down to ~2 RE
Spectral Res.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

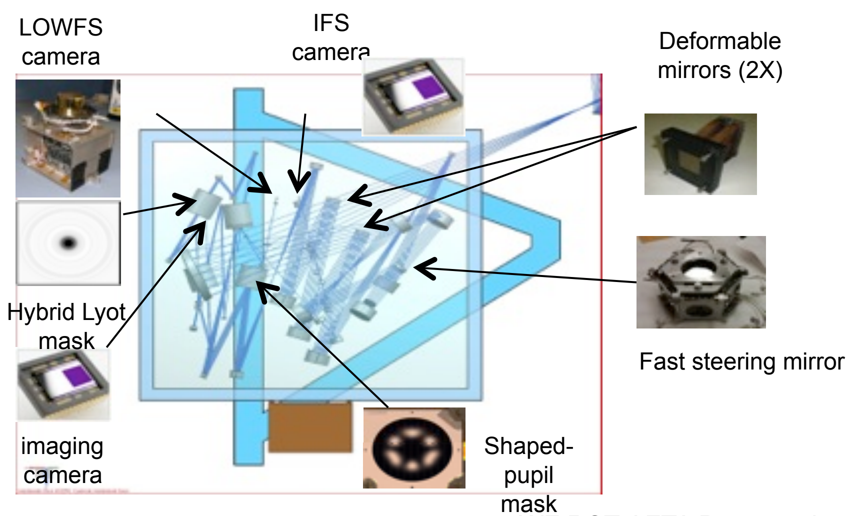
Initial Shaped-Pupil Mask Coronagraph Result

- The AFTA coronagraph using a newly fabricated reflective Shaped-Pupil Mask met its milestone performance of < 1e-8 raw contrast ratio with monochromatic light in the High Contrast Imaging Testbed at JPL (see below) .
  - This mask was designed to accompany the AFTA obscured pupil
  - Work is continuing to push to even greater contrast and smaller inner working angles as a second deformable mirror will be added in August
  - The team is preparing to now move to broadband light demonstrations



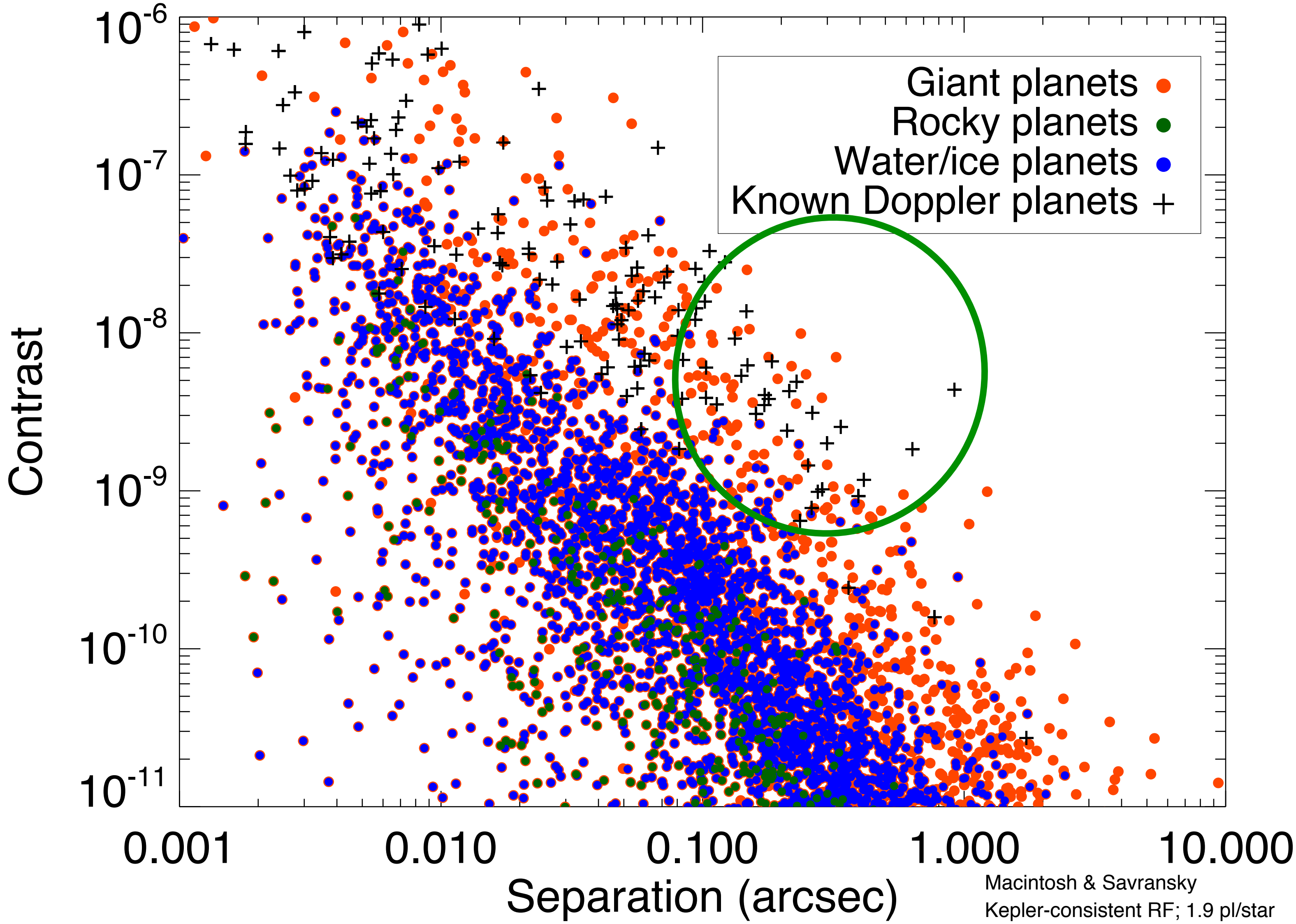
Coronagraph Instrument Overview





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

Simulated Planets within 30 pc

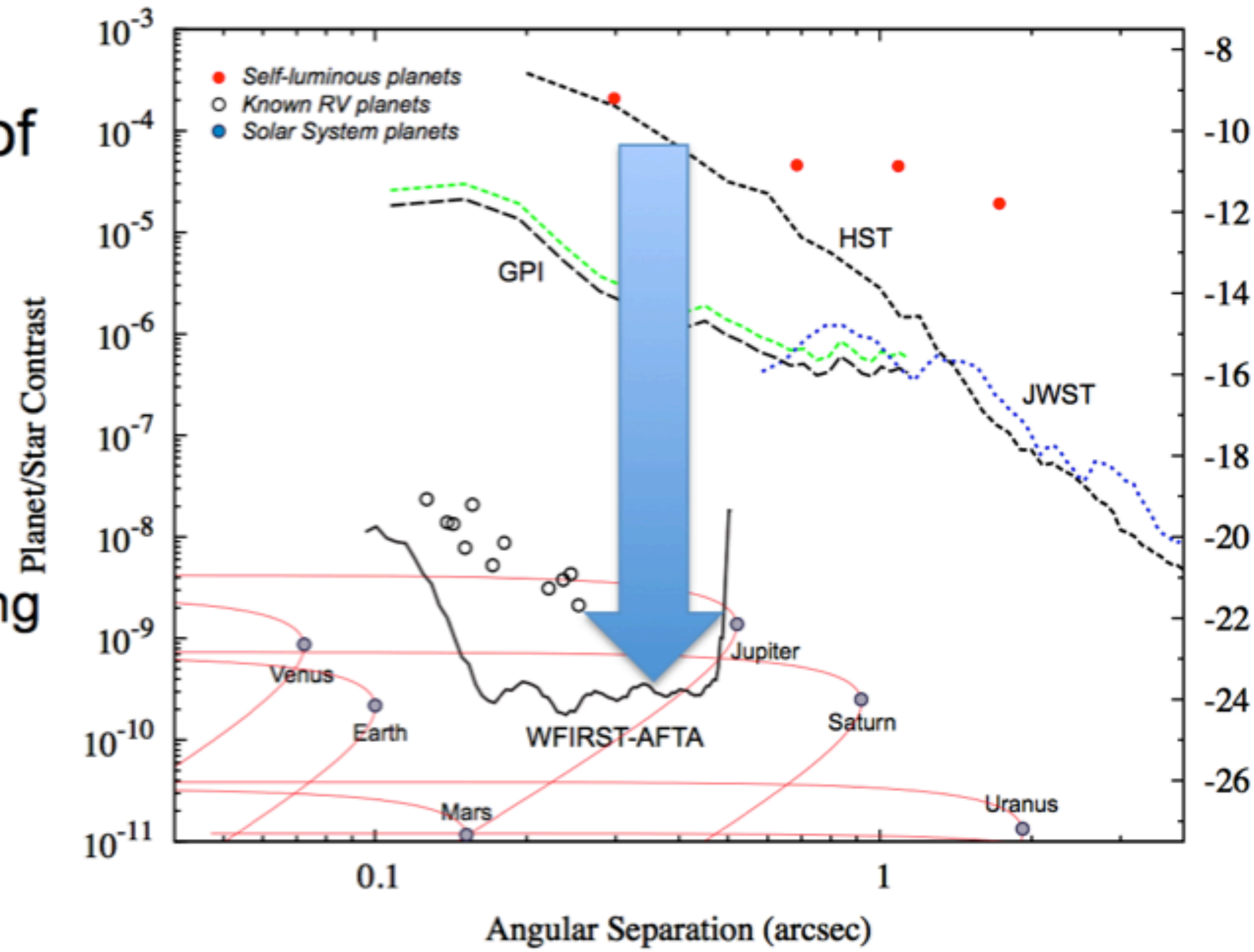


Macintosh & Savransky
Kepler-consistent RF; 1.9 pl/star
Main sequence non binary stars

AFTA Brings Humanity Closer to Characterizing Earths

WFIRST-AFTA advances many of the key elements needed for a coronagraph to image Earth

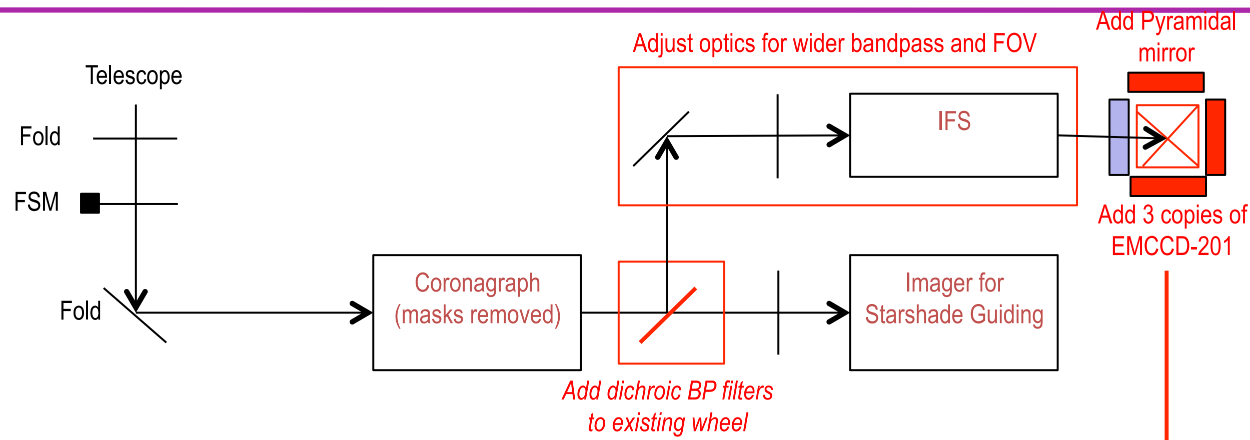
- ✓ Coronagraph
- ✓ Wavefront sensing & control
- ✓ Detectors
- ✓ Algorithms



WFIRST + Starshade?

- Exo-S study has emphasized the potential significant science return from flying a starshade with WFIRST:
  - imaging and characterizing Earth-like planet
- Studying what would it take to make WFIRST/AFTA star-shade compatible
  - Use coronagraph as star-shade camera in open mode
  - Communication with starshade

Option 2: Modified Coronagraph IFS

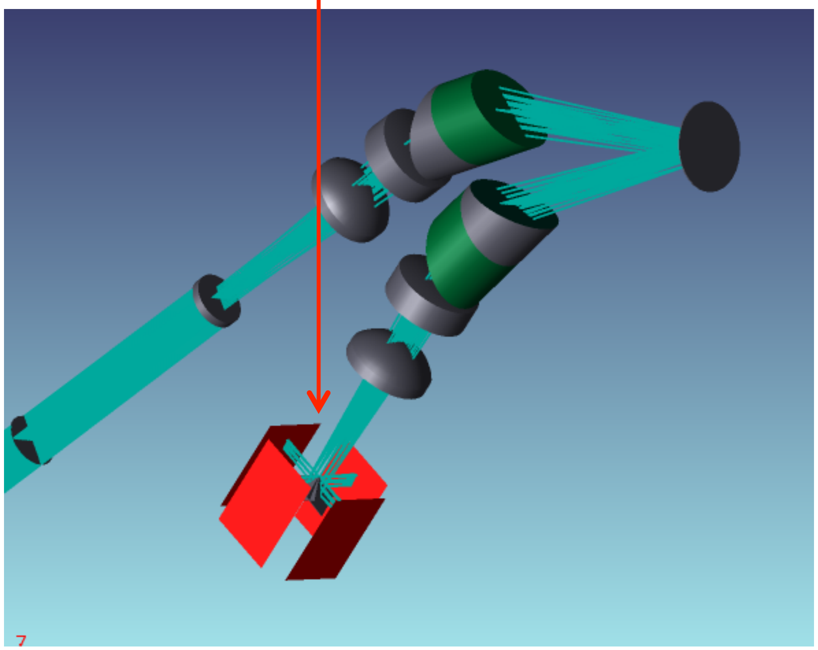


Performance
25% throughput
34% bandpass
1.3 arc-sec FOV

- Increasing FOV while retaining spectrum spacing and pixel scale requires adding detector area
- Baseline detector (low noise, electron mulitplying, photon counting) is only available in 1K x 1K format

- Approach adopted here is to distribute spectrums across 4 different CCDs, all copies of the baseline detector
- Alternative, only if it becomes space qualified, is to use a single 4K x 4K version (EMCCD-282)

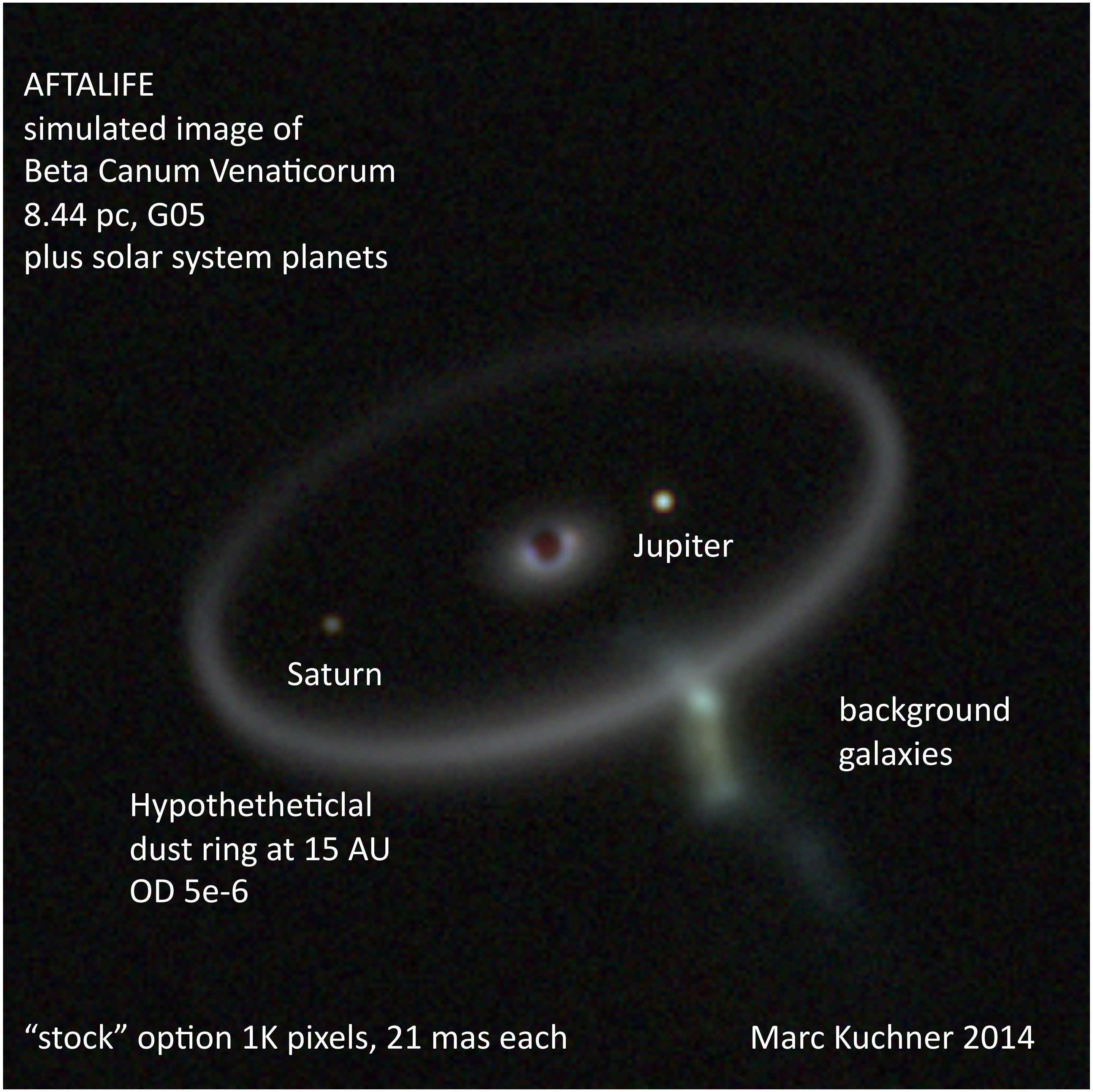
- Also increases FOV for coronagraph, to take full advantage of DM capability



Coronagraph Responds to NWNH Goals

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

> While not driving requirements on observatory that could impact risk, cost, or schedule ("use as-is").

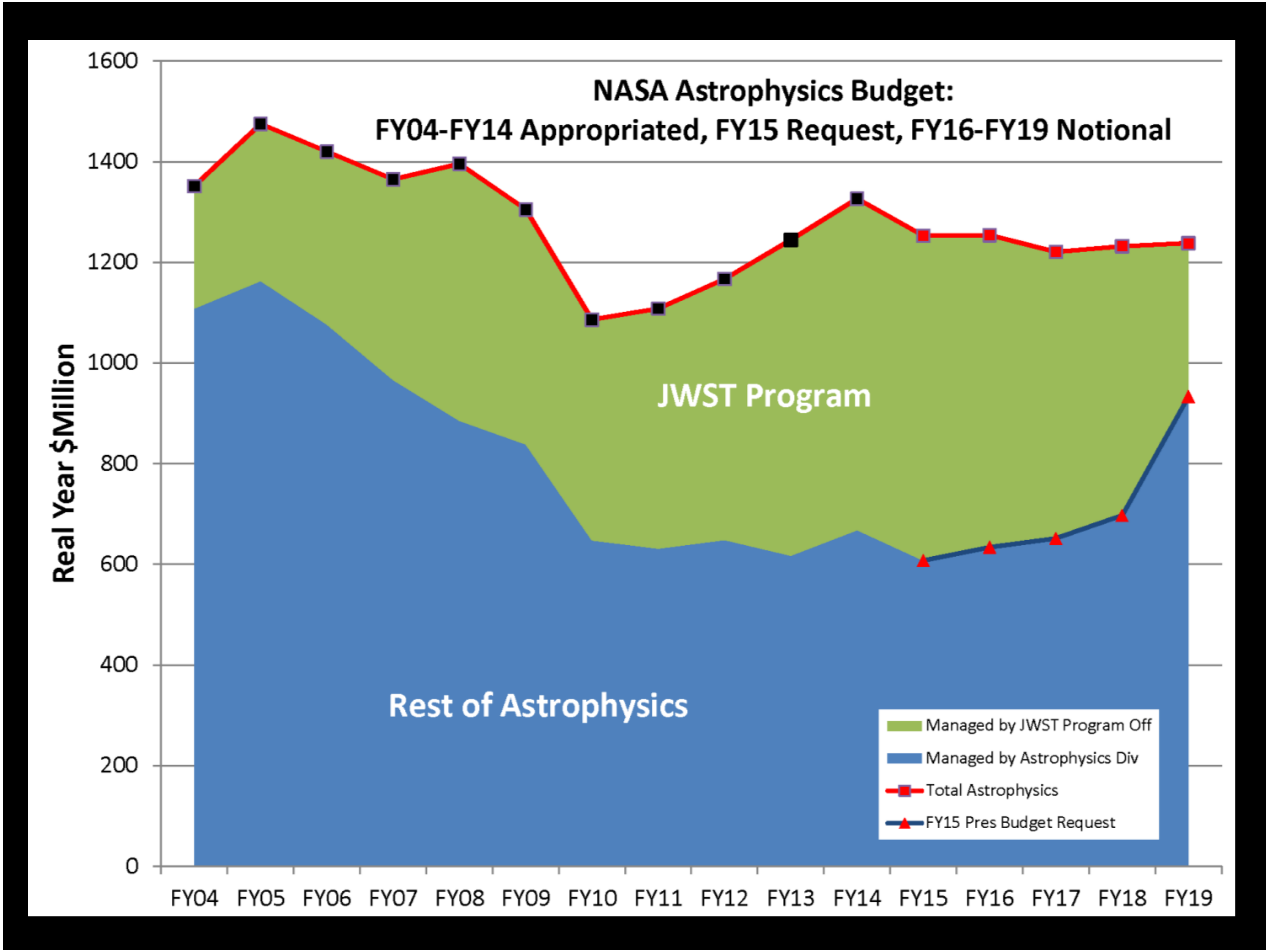

AFTALIFE
simulated image of
Beta Canum Venaticorum
8.44 pc, G05
plus solar system planets
Jupiter
Saturn
background
galaxies
Hypothetheticlal
dust ring at 15 AU
OD 5e-6
“stock” option 1K pixels, 21 mas each
Marc Kuchner 2014

WFIRST-AFTA Status

- Significant WFIRST-AFTA funding added to the NASA budget by Congress for FY13 and FY14 totaling $66M. Supported in President's FY15 budget
- Funding is being used for pre-Phase A work to prepare for a rapid start and allow a shortened development time
  - Detector array development with H4RGs
  - Coronagraph technology development
  - 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
- Upcoming events
  - SDT report due in January 2015
  - Aerospace CATE completion in February 2015

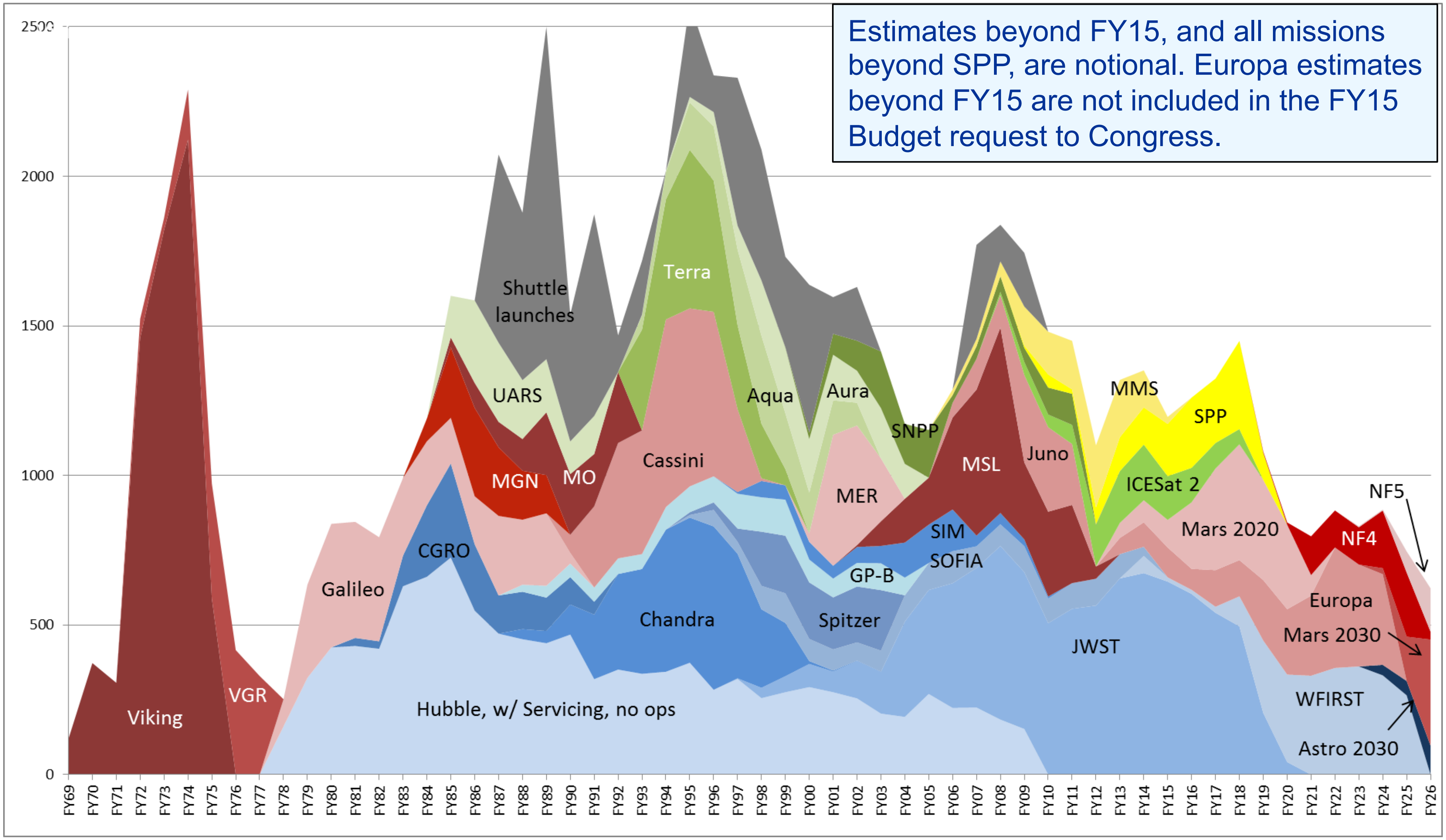
NRC Review

- Performed in January-February 2014 to determine if WFIRST-AFTA meets the WFIRST requirement in NWNH
- Recognized the larger telescope extends the scientific reach and capabilities
  - "The opportunity to increase the telescope aperture and resolution by employing the 2.4-m AFTA mirror will significantly enhance the scientific power of the mission, primarily for cosmology and general survey science, and will also positively impact the exoplanet microlensing survey. WFIRST/AFTA's planned observing program is responsive to all the scientific goals described in NWNH."
  - "WFIRST/AFTA observations will provide a very strong complement to the Euclid and LSST datasets. "
  - "For each of the cosmological probes described in NWNH, WFIRST/AFTA exceeds the goals set out in NWNH. These are the goals that led to the specifications of the WFIRST/IDRM (with 2.0 μm cut-off). "
- Concern that potential cost growth will threaten balance within astrophysics program
  - "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"
  - **Investments in pre-phase A technology development and studies will reduce these risks**
- Highlight both rewards and risks of coronagraph program
  - "Introducing a technology development program onto a flagship mission creates significant mission risks resulting from the schedule uncertainties inherent in advancing low TRL hardware to flight readiness"
  - "Will demonstrate techniques that are more advanced than what have been used to date in space and that are very likely to be applicable to any future planet imaging mission that employs a coronagraph."
- Recommends **"NASA should move aggressively to mature the coronagraph"**


NASA Astrophysics Budget:
FY04-FY14 Appropriated, FY15 Request, FY16-FY19 Notional
Real Year $Million
1600
1400
1200
1000
800
600
400
200
0
FY04
FY05
FY06
FY07
FY08
FY09
FY10
FY11
FY12
FY13
FY14
FY15
FY16
FY17
FY18
FY19
JWST Program
Rest of Astrophysics
Managed by JWST Program Off
Managed by Astrophysics Div
Total Astrophysics
FY15 Pres Budget Request

National Aeronautics and Space Administration

Large Science Mission Budgets
(Phase A-D costs >$1B FY15 dollars)



Making WFIRST/AFTA a Success!

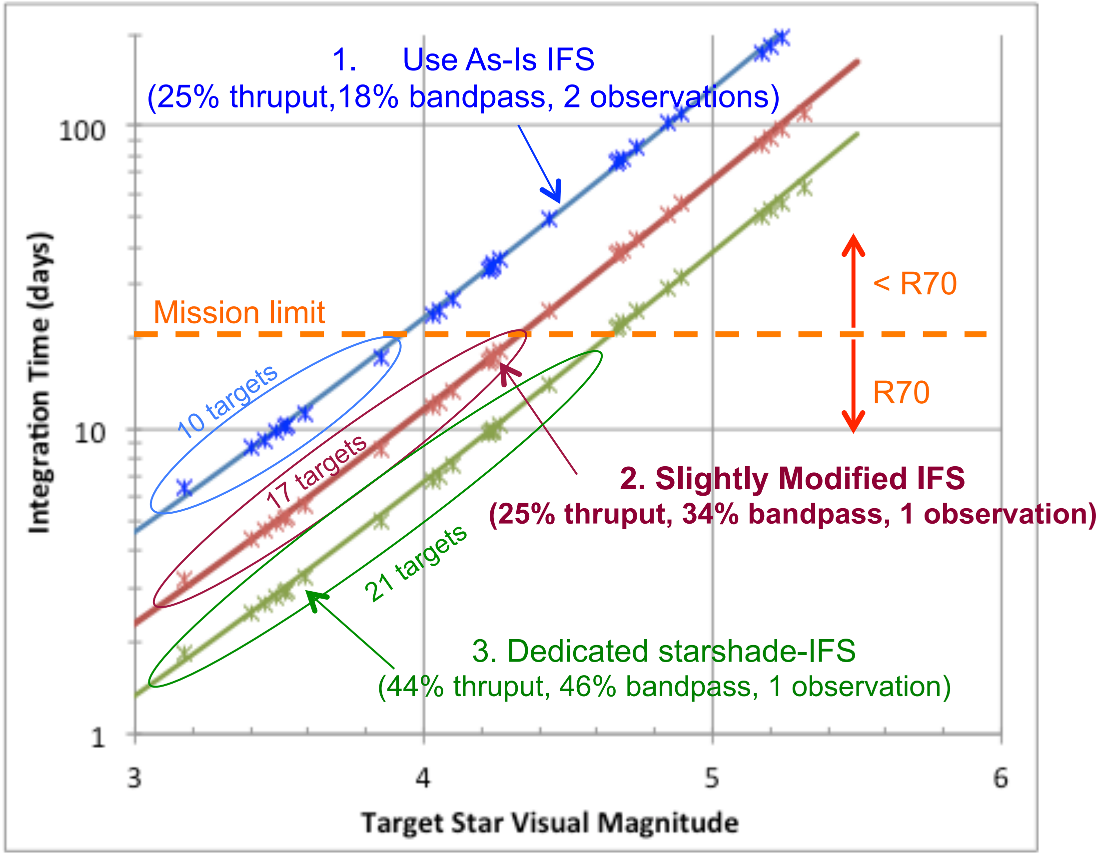
- Broad involvement by the astronomy community will ensure that we do the best possible science with this instrument

WFIRST-AFTA Science Book

- **Describes the science cases that drive the WFIRST mission and its design. Being developed by the WFIRST-AFTA Science Office in collaboration with IPAC and STScI.**
- **Goal: Foster broader community understanding and engagement in the WFIRST-AFTA mission.**
- **Key reference is the May 2013 WFIRST-AFTA SDT report and Jan 2015 update**
- **Other Sources: 1-page science programs, white papers, WFIRS2014 presentations, and YOU!**
- **Schedule:**
  - Solicit contributors at WFIRS2014 meeting
  - mid Dec 2014: draft outline
  - Jan 2015: AAS splinter session and solicitation of white papers
  - April 2015: first drafts of sections due
  - Summer 2015: 1st draft
- **We need volunteers to lead the key science sections – Dark Energy, Deep/Wide Surveys, Exoplanets, GO Science, Observational capabilities/design.**
- **Please contact Lee Armus (lee@ipac.caltech.edu) to participate**

Earth-twin Performance Sensitivity

Integration times for: R70 spectral resolution, SNR=6, ∆mag=25



Low optical throughput & bandpass limits #targets with Earth-twin characterization capability