WFIRST-AFTA Presentation to the Committee on Astronomy & Astrophysics

Neil Gehrels (Study Scientist)
Kevin Grady (Project Manager)
NASA-GSFC

March 4, 2014

WFIRST-AFTA Science Definition Team

David Spergel, Princeton, Co-Chair
Neil Gehrels, NASA GSFC, Co-Chair
Charles Baltay, Yale
Dave Bennett, Notre Dame
James Breckinridge, Caltech
Megan Donahue, Michigan State Univ.
Alan Dressler, Carnegie Observatories
Chris Hirata, Caltech
Scott Gaudi, Ohio State Univ.
Thomas Greene, Ames
Olivier Guyon, Univ. Arizona
Jason Kalirai, STScI
Jeremy Kasdin, Princeton
Bruce Macintosh, Stanford
Warren Moos, Johns Hopkins

Saul Perlmutter, UC Berkeley / LBNL
Marc Postman, STScI
Bernard Rauscher, GSFC
Jason Rhodes, JPL
Yun Wang, Univ. Oklahoma
David Weinberg, Ohio State U.

Michael Hudson, U. Waterloo,
Ex-Officio Canada
Yannick Mellier, IAP France,
Ex-Officio ESA
Toru Yamada, Tokyo U.
Ex-Officio Japan

Dominic Benford, NASA HQ Ex-Officio
Wes Traub, JPL Ex-Officio

previous SDT chairs: J. Green, P. Schechter

Executive Summary

- WFIRST-AFTA gives HST imaging over 1000's of square degrees in NIR
- 2.5x deeper and 1.6x better imaging than IDRM*
- More complementary to Euclid & LSST. More synergistic with JWST.
- Enables coronagraphy of giant planets and debris disks to address "new worlds" science of NWNH
- Fine angular resolution and high sensitivity open new discovery areas to the community. More GO science time (25%) than for IDRM.
- WFIRST-AFTA addresses changes in landscape since NWNH: Euclid selection & Kepler discovery that 1-4 Earth radii planets are common.
- Aerospace CATE cost is 8% larger than IDRM (w/o launcher, w/ risks). Coronagraph adds16%, but addresses another NWNH recommendation.
- Use of NRO telescope and addition of coronagraph have increased the interest in WFIRST in government, scientific community and the public.

* IDRM = 2011 WFIRST mission design to match NWNH

WFIRST-AFTA Status

- Significant WFIRST-AFTA funding added to the NASA budget by Congress for FY13 and FY14 totaling $66M
- Funding is being used for pre-Phase A work to prepare for a rapid start and allow a shortened development time
  - Detector array development with H4RGs
  - Coronagraph technology development
  - Science simulations and modeling
  - Requirements flowdown development
  - Observatory design work
- NASA HQ charge for telescope is "use as is" and for coronagraph is "not drive requirements". Project / SDT driving toward fastest, cheapest implementation of mission
- Community engagement: PAGs, conferences and outreach
  - Special sessions held at January and June AAS conferences
  - Next conference planned for November 17-22, 2014 in Pasadena
- Upcoming events
  - NRC review report due in 1-2 weeks
  - SDT interim report due in April

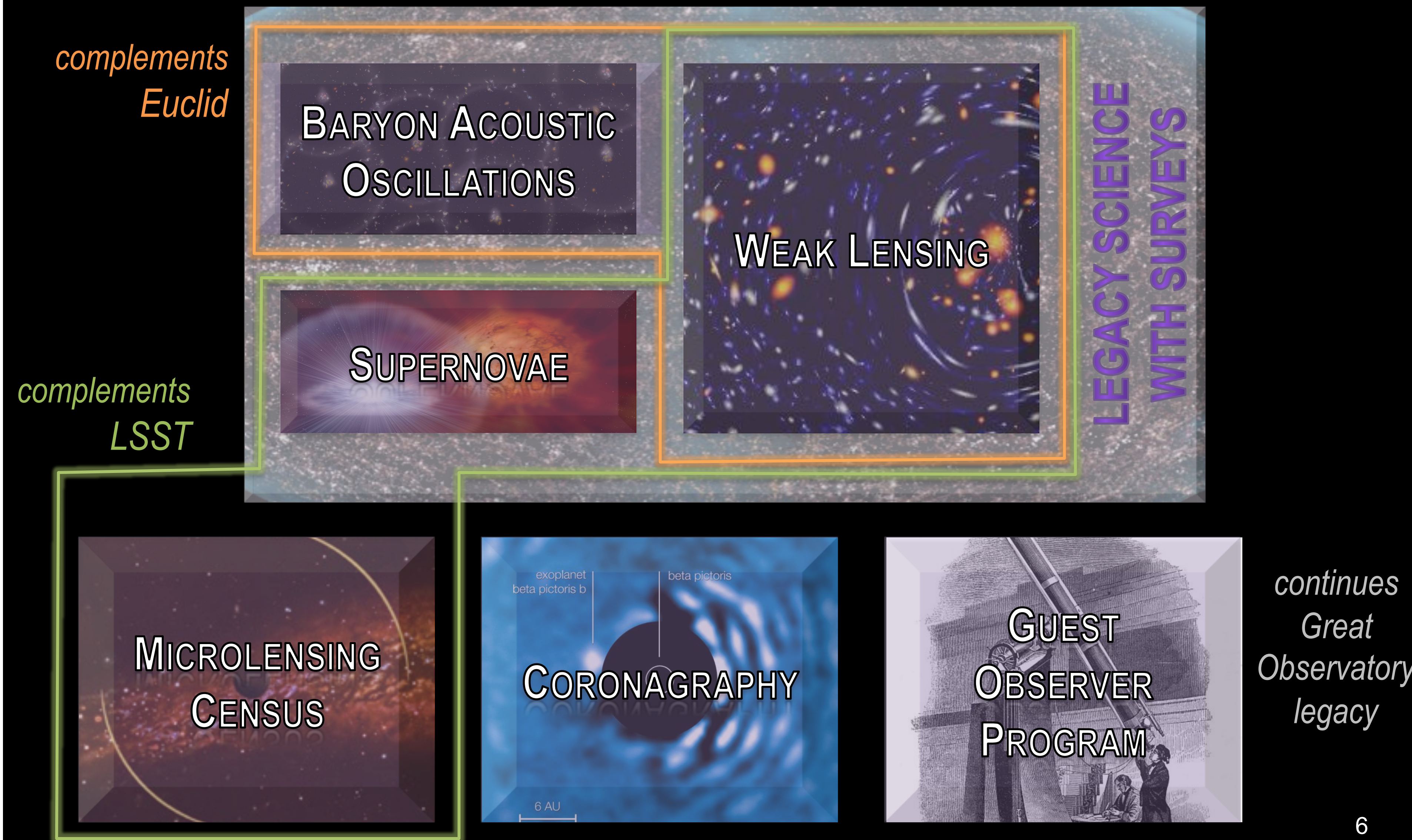
NRC Review Charge

- An ad hoc committee will assess whether AFTA is responsive to the overall strategy to pursue the science objectives of NWNH WFIRST.
- In its assessment, the committee will:
  - 1. **Compare the NWNH WFIRST to AFTA**, with and without the coronagraph, on the basis of their science objectives, technical complexity, and programmatic rationale, including projected cost.
  - 2. Based on the above comparison and taking into account any relevant **scientific, technical, and programmatic changes** that have occurred since the release of NWNH:

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

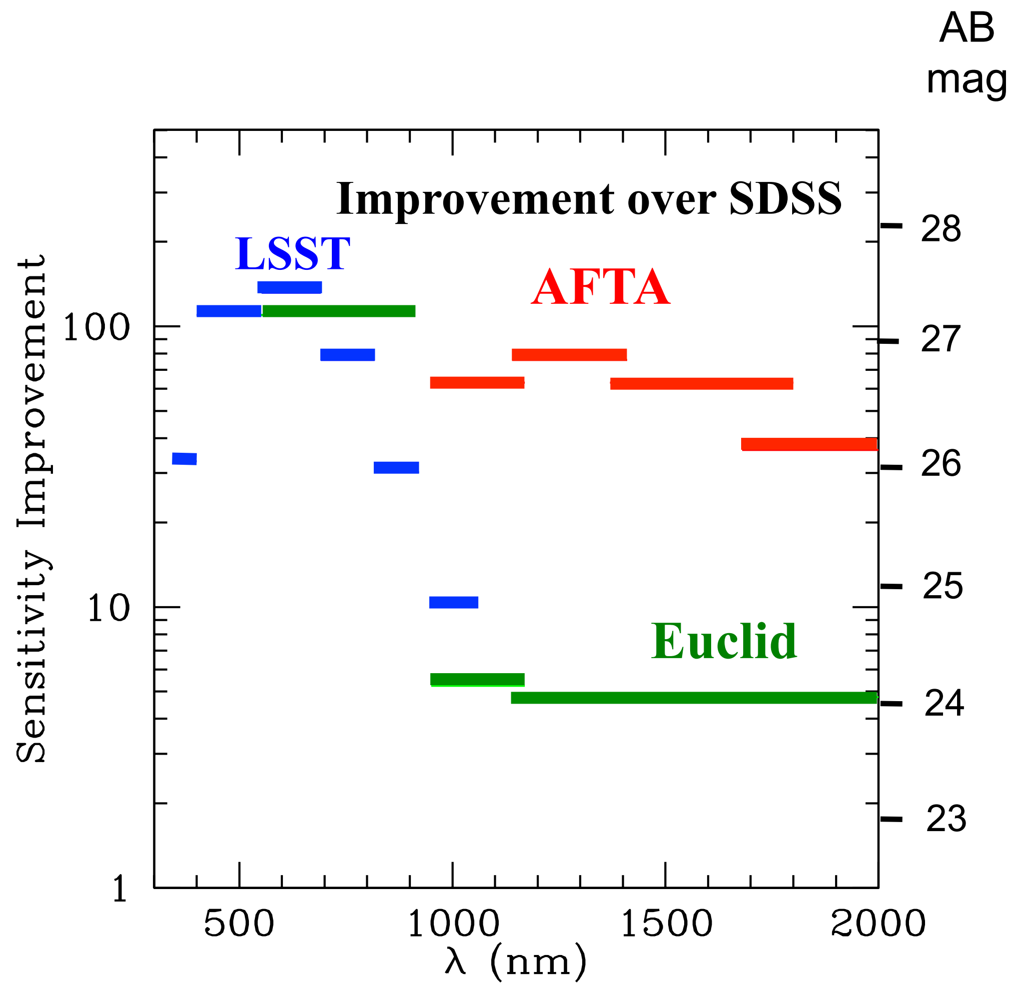
    b) Assess responsiveness of AFTA with the coronagraph to the science & technology objectives of the **NWNH technology development program**

WFIRST Science



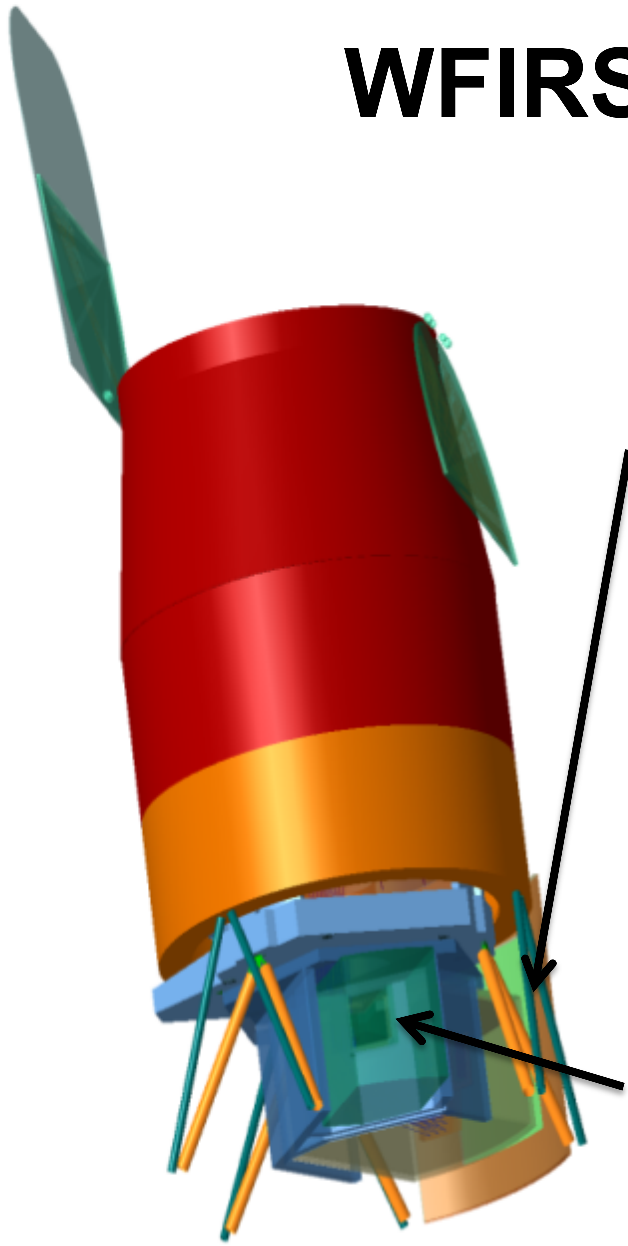
WFIRST-AFTA Surveys

- Multiple surveys:
  - High Latitude Survey
    - Imaging, spectroscopy, supernova monitoring
  - Repeated Observations of Bulge Fields for microlensing
  - 25% Guest Observer Program
  - Coronagraph Observations
- Flexibility to choose optimal approach



High Latitude Survey is 2.5x fainter and 1.6x sharper than IDRM

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
- 100 milliarcsec inner working angle at 400 nm

Why AFTA Coronagraph is Good Deal

- AFTA 2.4m telescope enables high sensitivity, high contrast, high resolution coronagraphy
- Extra cost of coronagraph is $270M including accommodations & extra year of ops
- Coronagraph science fits in WFIRST tripod: DE, exoplanets, community surveys
- Addresses NWNH recommendation for investment in direct imaging technology
- Coronagraph performance modeling is yielding exciting predictions
- ExoPAG endorsed WFIRST-AFTA coronagraph

NWNH Identified 20 Key Science Questions Ripe for Answering

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?*

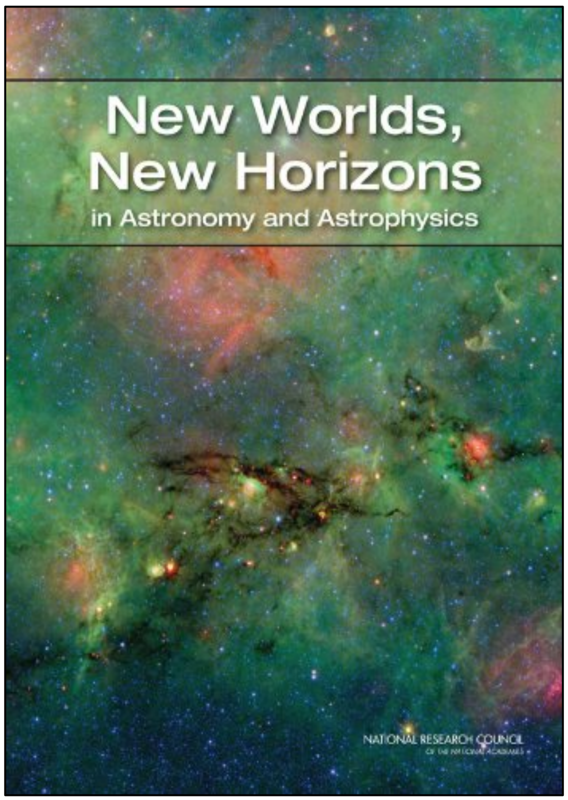
WFIRST-AFTA Addresses These Questions

Frequently discussed

#1 Large-Scale Priority - Dark Energy, Exoplanets

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

But, WFIRST-AFTA provides addresses key questions many other areas….



5 Discovery Science Areas

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

20 Key Science Questions

- Origins **(7/7 key areas)**
- Understanding the Cosmic Order **(7/9 key areas)**
- Frontiers of Knowledge **(3/4 key areas)**

See Table in the AFTA SDT report (p 8 -10) for specific gains over DRM1

AFTA has a robust GO program

Peer-Reviewed and Competed Guest Observer Program

Establishes broad community engagement

Tackles diverse set of astrophysical questions in changing paradigms

Maximizes synergies with JWST and other future telescopes

Open competition inspires creativity

Ensures long-term scientific discovery potential

25% of AFTA is a Guest Observer Program

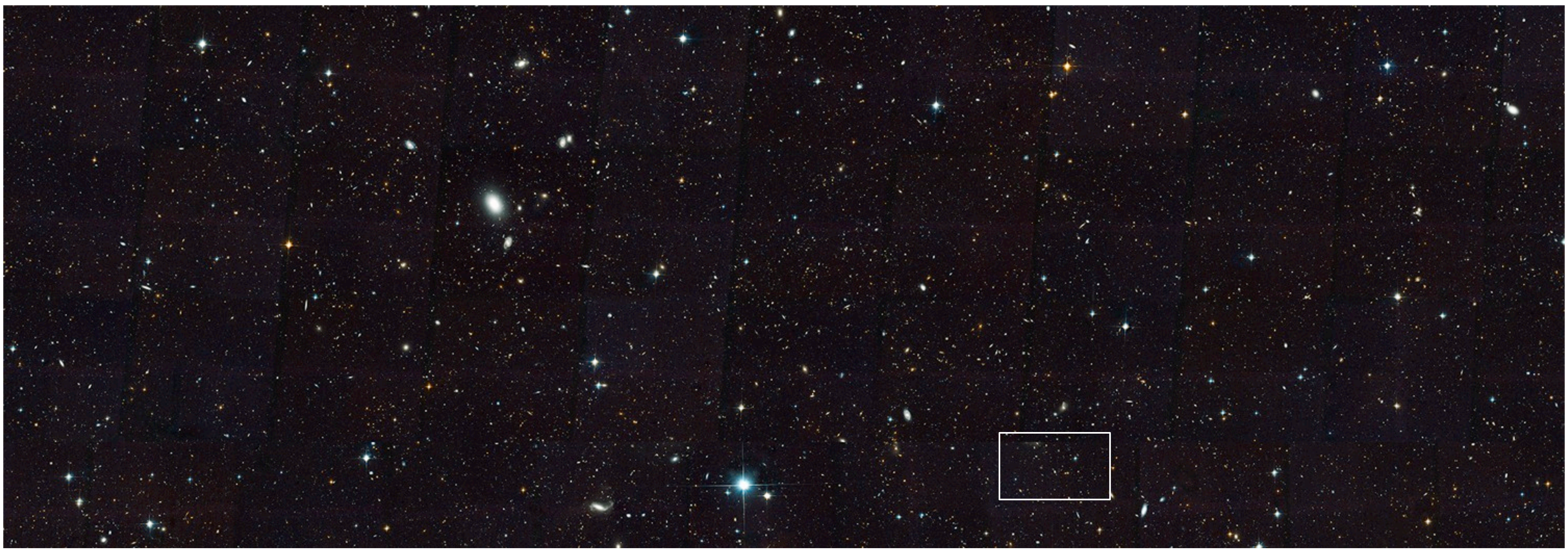
Jason Kalirai

Alan Dressler

Broad Community Engagement

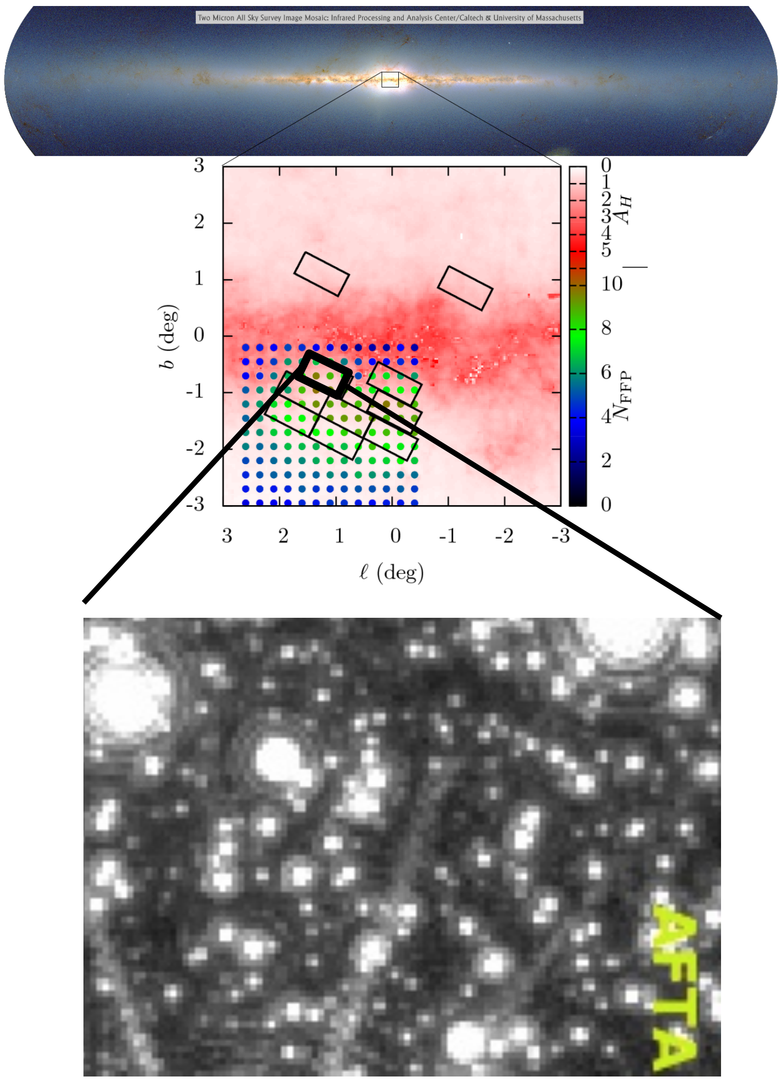
WFIRST-AFTA vs Hubble

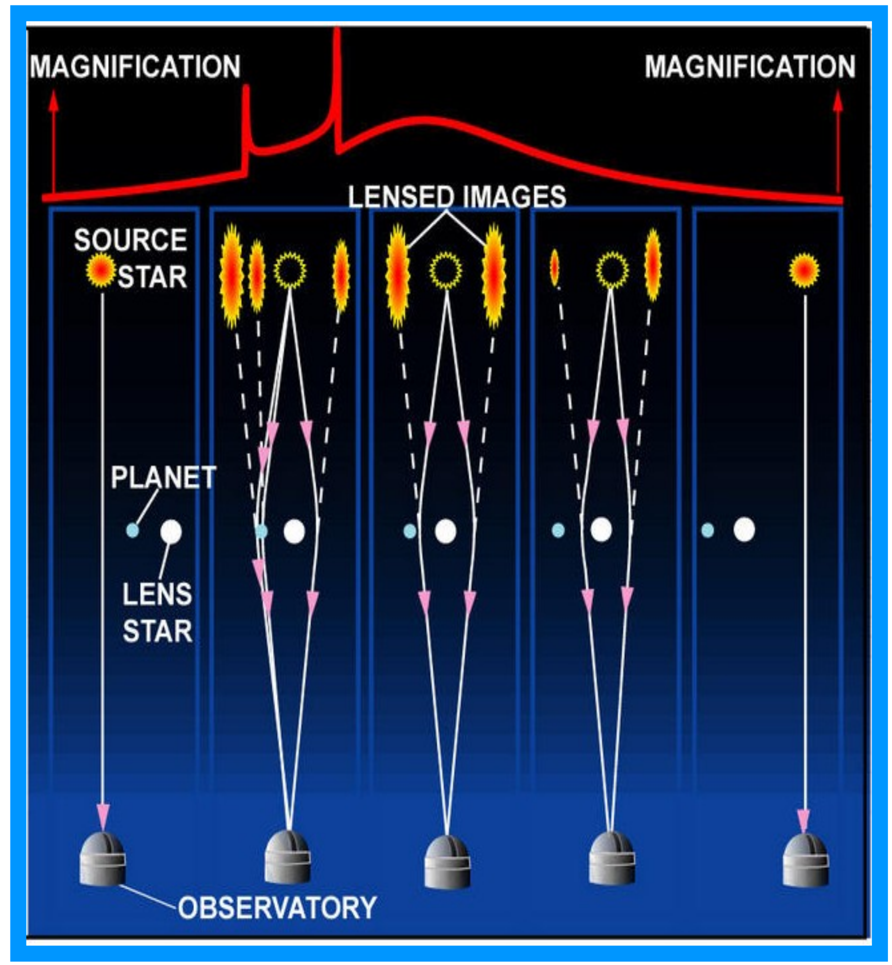
Hubble Ultra Deep Field - IR
~5,000 galaxies in one image



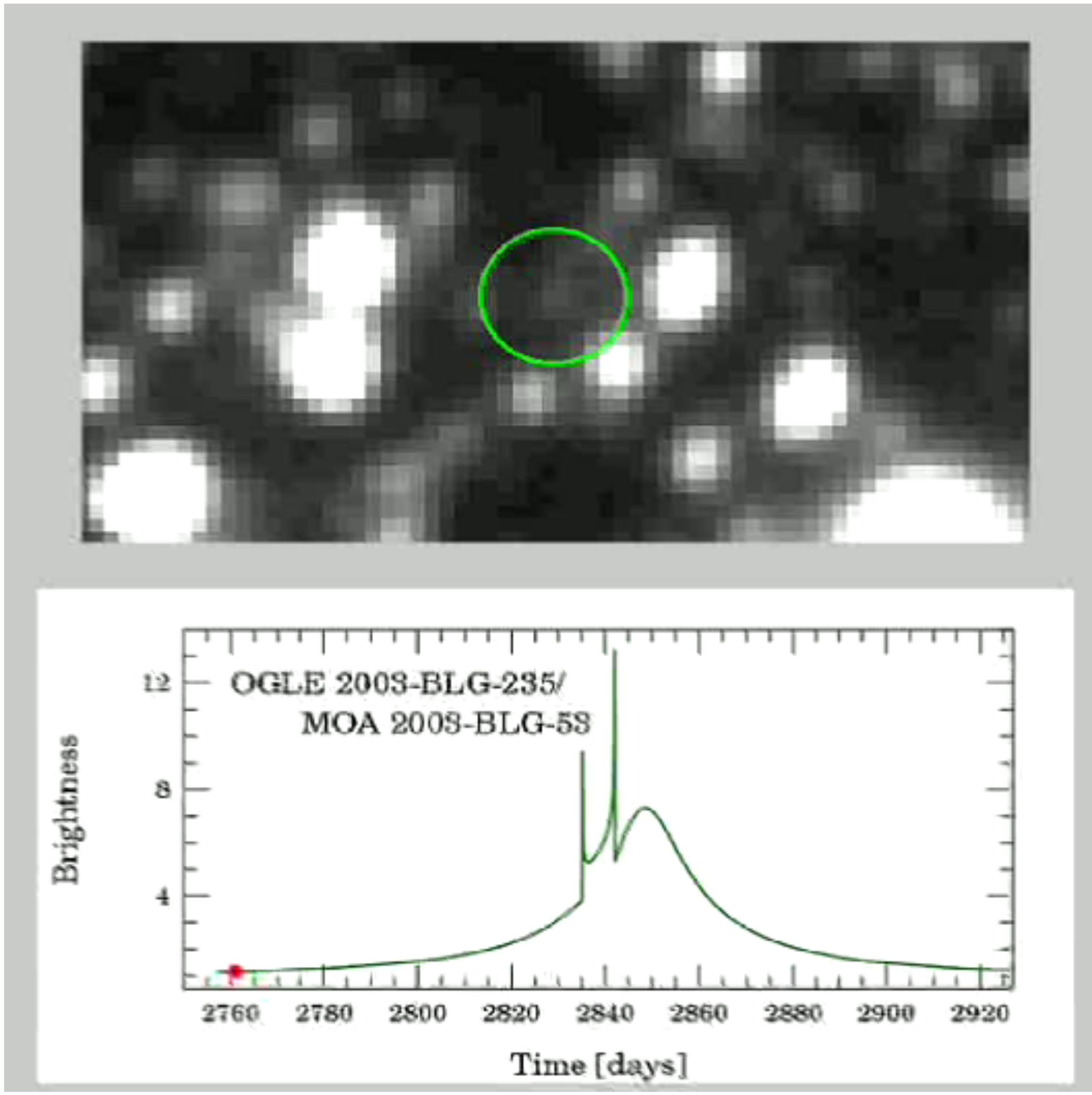
WFIRST-AFTA Deep Field
>1,000,000 galaxies in each image

Detecting Planets with Microlensing



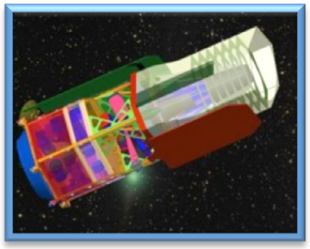


Microlensing Magnification

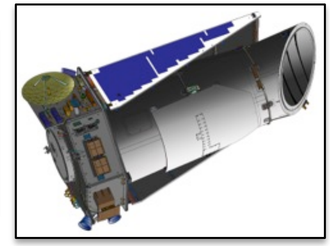


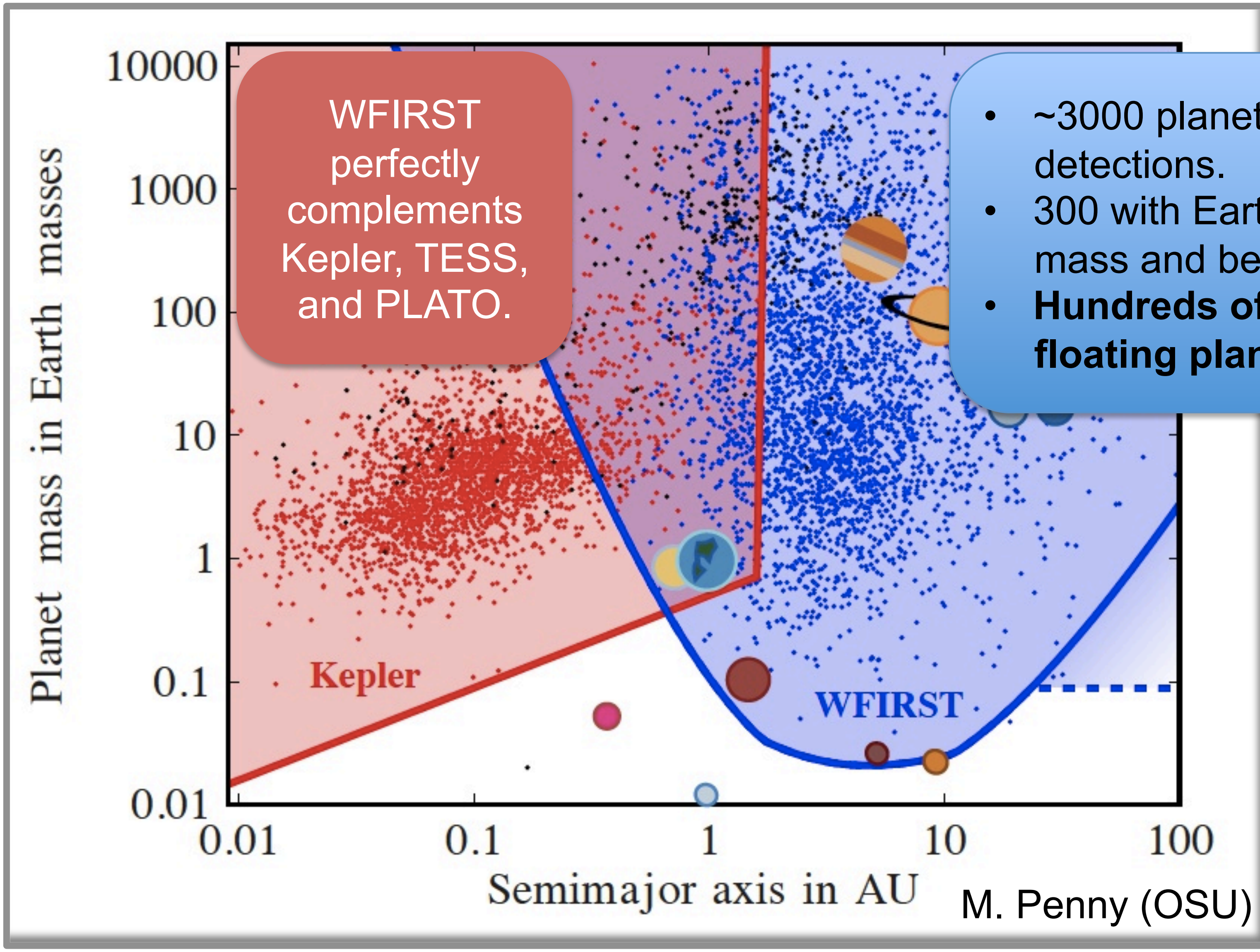
Microlensing Survey: IDRM vs. WFIRST-AFTA

- Per unit observing time, WFIRST-AFTA* is more capable than the IDRM design.
- The primary advantages are:
  - The exoplanet **yields of WFIRST-AFTA are ~1.6 times larger** than IDRM for a fixed observing time.
  - Significantly improved (factor of two) sensitivity to planets with **mass less than that of the Earth.**
  - WFIRST-AFTA will have an improved ability to measure masses and distances to the microlensing **host stars.**



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



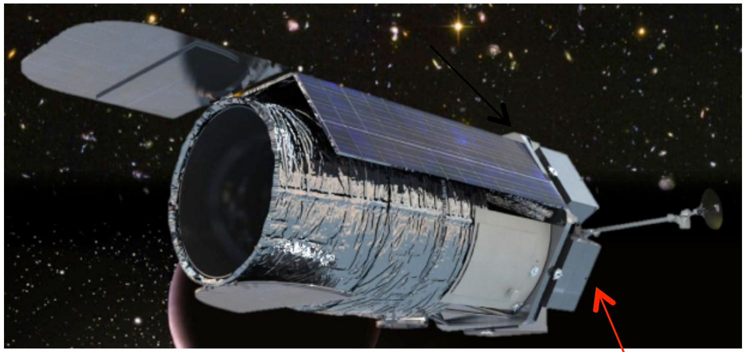


WFIRST perfectly complements Kepler, TESS, and PLATO.

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

M. Penny (OSU)

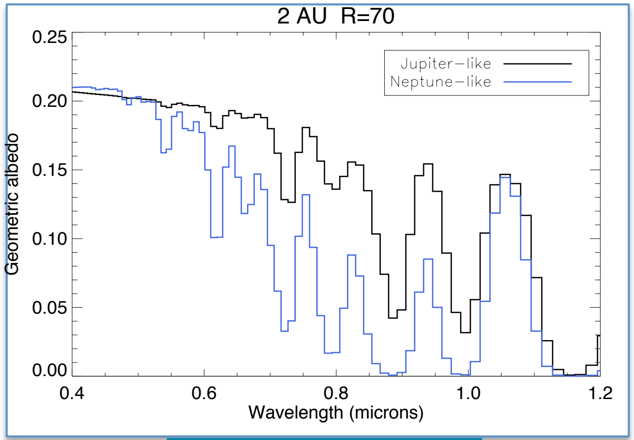
AFTA Coronagraph Capability



Coronagraph Architecture:

Coronagraph Instrument

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



Exo-planet Spectroscopy

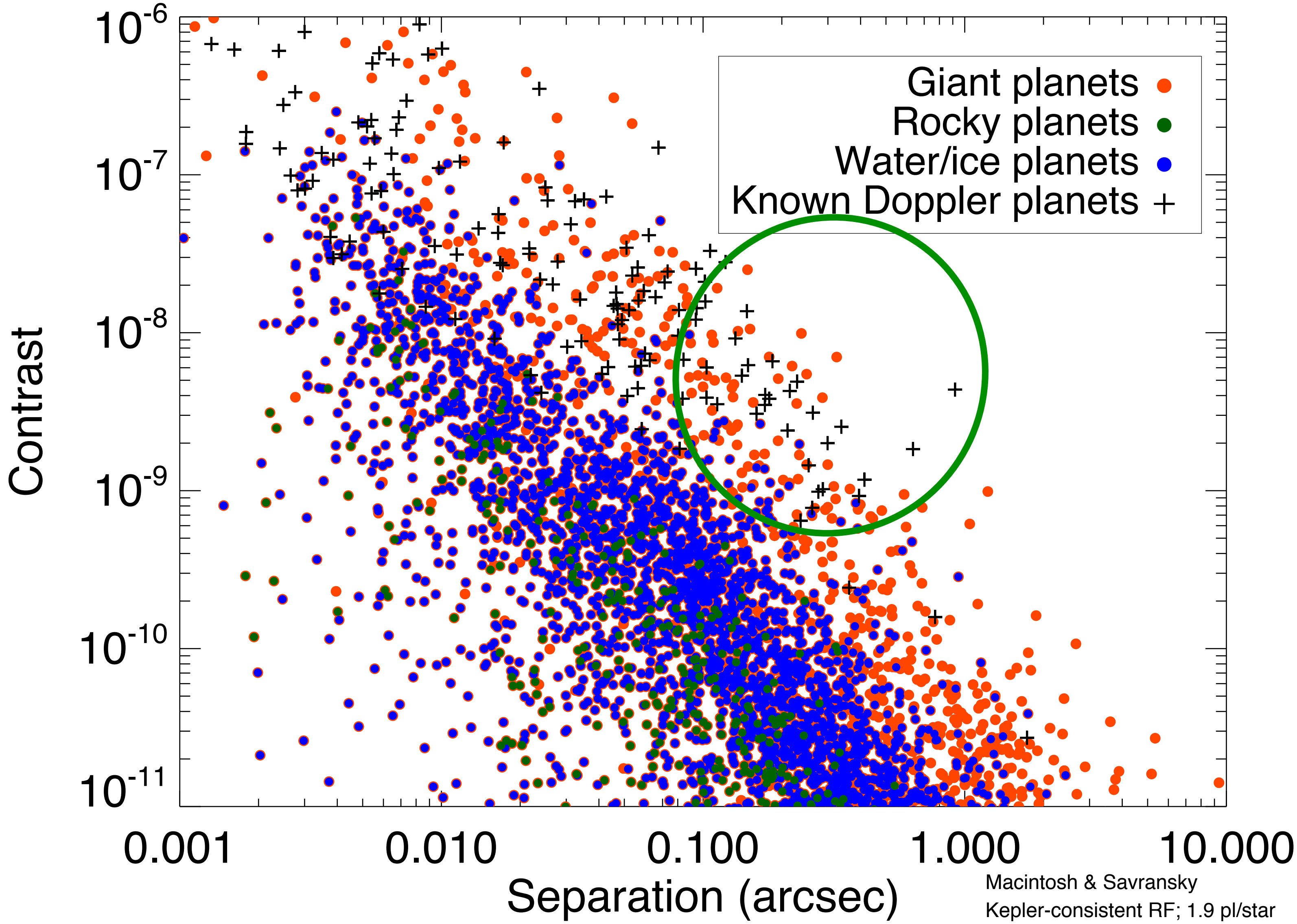
Bandpass	400 – 1000 nm	Measured sequentially in five ~10% bands
Inner working angle	100 – 250 mas	~3λ/D, driven by science
Outer working angle	0.75 – 1.8 arcsec	By 48X48 DM
Detection Limit	Contrast ≤ 10^{-9} (after post processing)	Cold Jupiters, Neptunes, and icy planets down to ~2 RE
Spectral Res.	~70	With IFS, R~70 across 600 – 980 nm
Spatial Sampling	17mas	Nyquist for λ~430nm

Coronagraph Responds to NWNH Goals

- Observe and characterize a dozen radial velocity planets.
- Discovers and characterizes 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 critical coronagraph technologies (common to many types), informing a future technology downselect for a later terrestrial planet imaging mission.

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

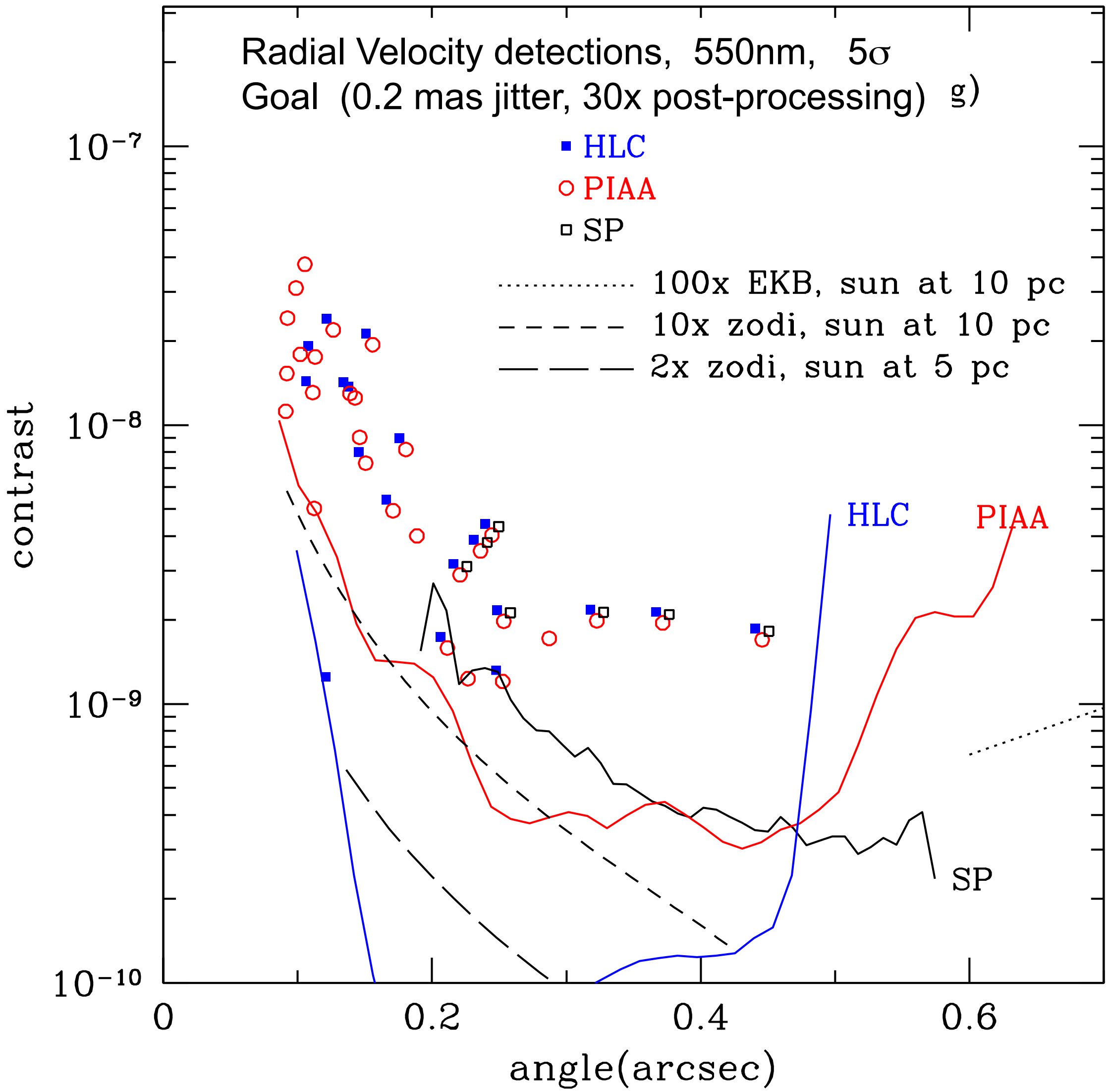
Simulated Planets within 30 pc



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

Predicted Radial Velocity Planet Detection and Spectroscopy

Best Estimates based on Low Jitter and Post-Processing



Contrast (planet/star brightness ratio) of detectable known RV planets vs angular separation from star

Solid lines: 5-σ detection limits

Points: detectable RV planets Up to 20 for HLC.

Dashed lines: zodiacal disk & Edgeworth-Kuiper belt (EKB) brightness around sun, at 5 & 10 pc, scaled to denser values than in solar system

HLC: Hybrid Lyot Coronagraph
SP: Shaped Pupil Coronagraph
PIAA: Phase Induced Amplitude Apodization Coronagraph

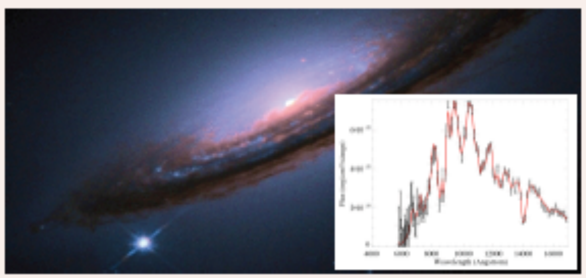
WFIRST-AFT Dark Energy Roadmap

Supernova Survey

wide, medium, & deep imaging
+
IFU spectroscopy

2700 type Ia supernovae
$z = 0.1–1.7$

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



High Latitude Survey

spectroscopic: galaxy redshifts

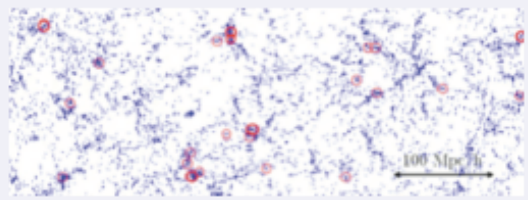
20 million Hα galaxies, $z = 1–2$
2 million [OIII] galaxies, $z = 2–3$

imaging: weak lensing shapes

500 million lensed galaxies
40,000 massive clusters

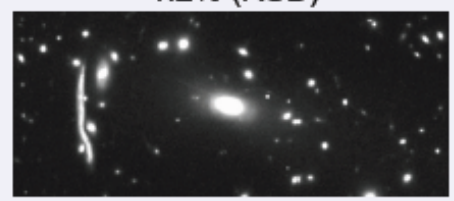
standard ruler

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



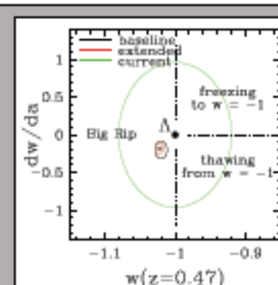
dark matter clustering

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



history of dark energy
+
deviations from GR

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



WFIRST-AFTA & Euclid Complementary for DE

WFIRST-AFTA

Deep Infrared Survey (2000 sq deg)

Lensing

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

Supernovae:

- High quality IFU spectra of >2000 SN

Redshift survey

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

Euclid

Wide optical Survey (15000 sq. deg)

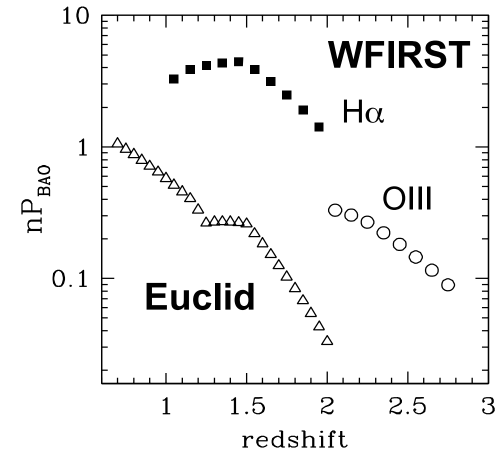
Lensing:

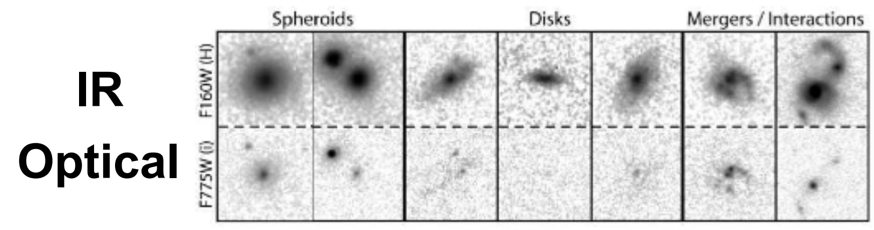
- Lower Resolution (30 gal/arcmin^2)
- Galaxy shapes in optical
- 1 lensing power spectrum

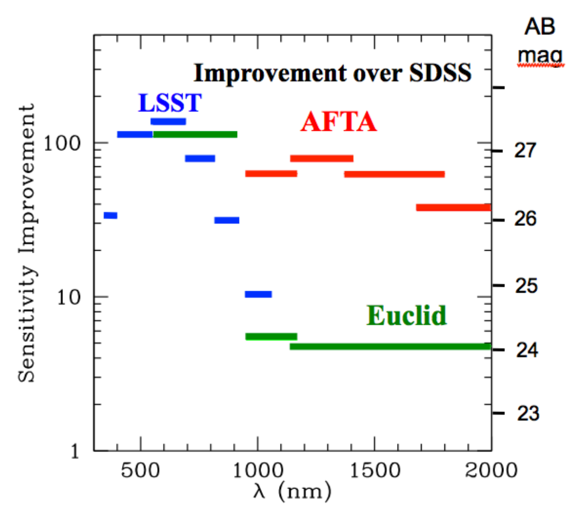
No supernovae program

Redshift survey:

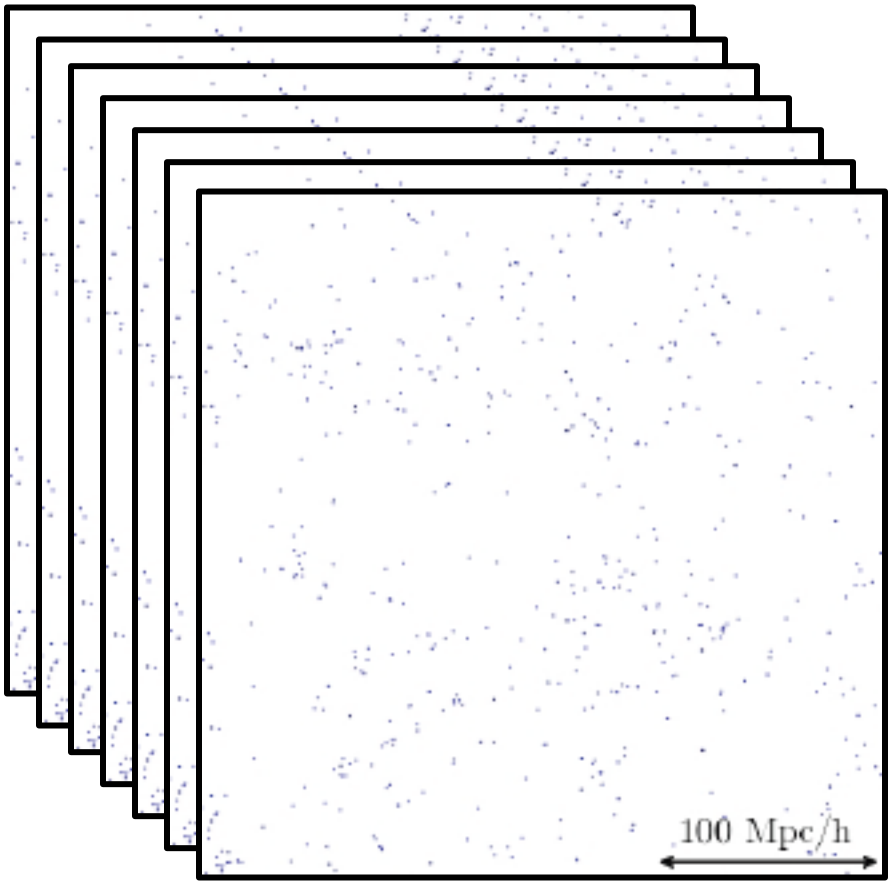
- Low number density of galaxies
- Significant number of low redshift galaxies





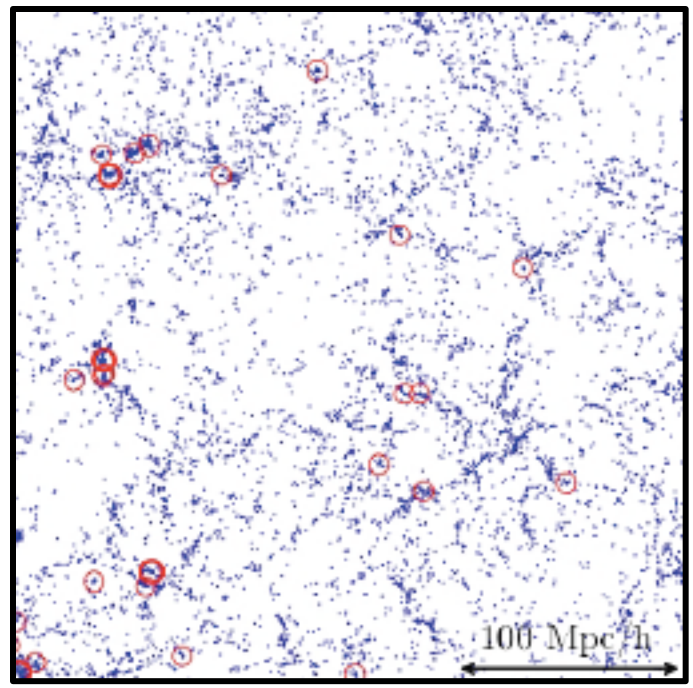


Redshift Surveys



Euclid

15,000 deg2 @ 1700 gal/deg^2



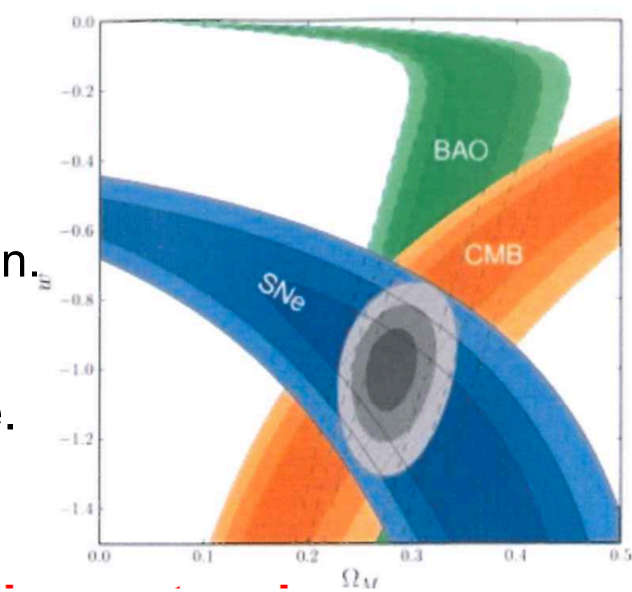
WFIRST

2,050 deg2 @ 12,600 gal/deg^2

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

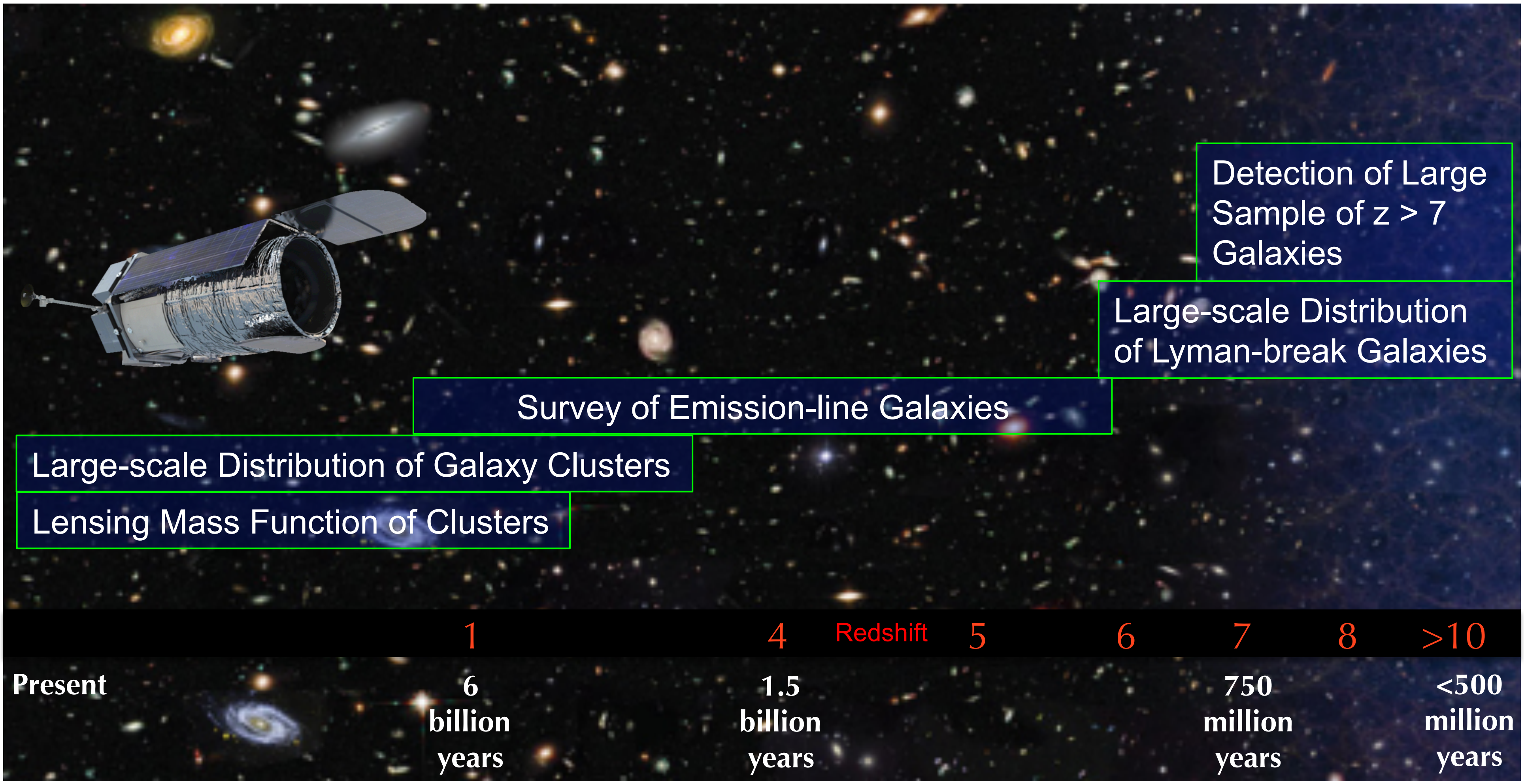
Context of WFIRST-AFTA DE Program

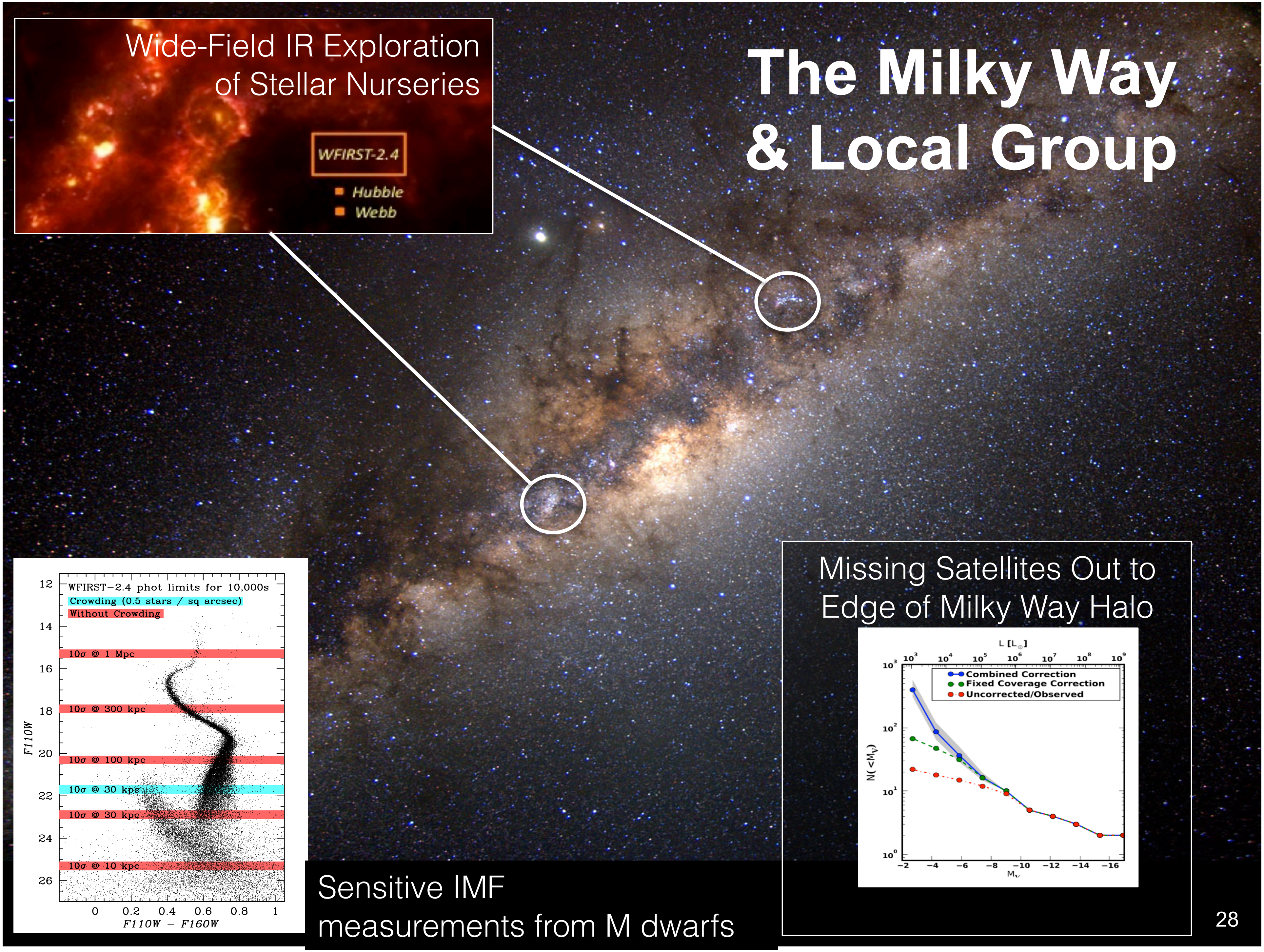
- How do discoveries occur in precision cosmology?
  - First there are hints, then the evidence mounts in terms of statistics (# sigmas), systematics (repeatable, robust to experiment design & analysis), and alternative explanations (consistency of different observables).
  - Robustness is key – not just getting the next 1000 deg^2 in the same "mode".
- Design of a dark energy program:
  - Multiple analysis methodologies and statistics used in each probe
  - Multiple probes of DE (SN, WL, GRS)
- Synergistic with other elements of DE program (LSST, Euclid)
  - Combining data sets is key to systematics reduction.
- Supernovae & BAO measure evolution of space
  Weak Lensing & RSD measure growth of structure.
- Comparing the two provides a check on GR



AFTA: A Unique Probe of Cosmic Structure Formation History

Using Observations from the High-Latitude Survey and GO Programs




The Milky Way
& Local Group
Wide-Field IR Exploration
of Stellar Nurseries
WFIRST-2.4
Hubble
Webb
Missing Satellites Out to
Edge of Milky Way Halo
Combined Correction
Fixed Coverage Correction
Uncorrected/Observed
$N(<M_V)$
M_V
$L\ [L_\odot]$
WFIRST−2.4 phot limits for 10,000s
Crowding (0.5 stars / sq arcsec)
Without Crowding
10σ @ 1 Mpc
10σ @ 300 kpc
10σ @ 100 kpc
10σ @ 30 kpc
10σ @ 30 kpc
10σ @ 10 kpc
F110W
F110W − F160W
Sensitive IMF
measurements from M dwarfs

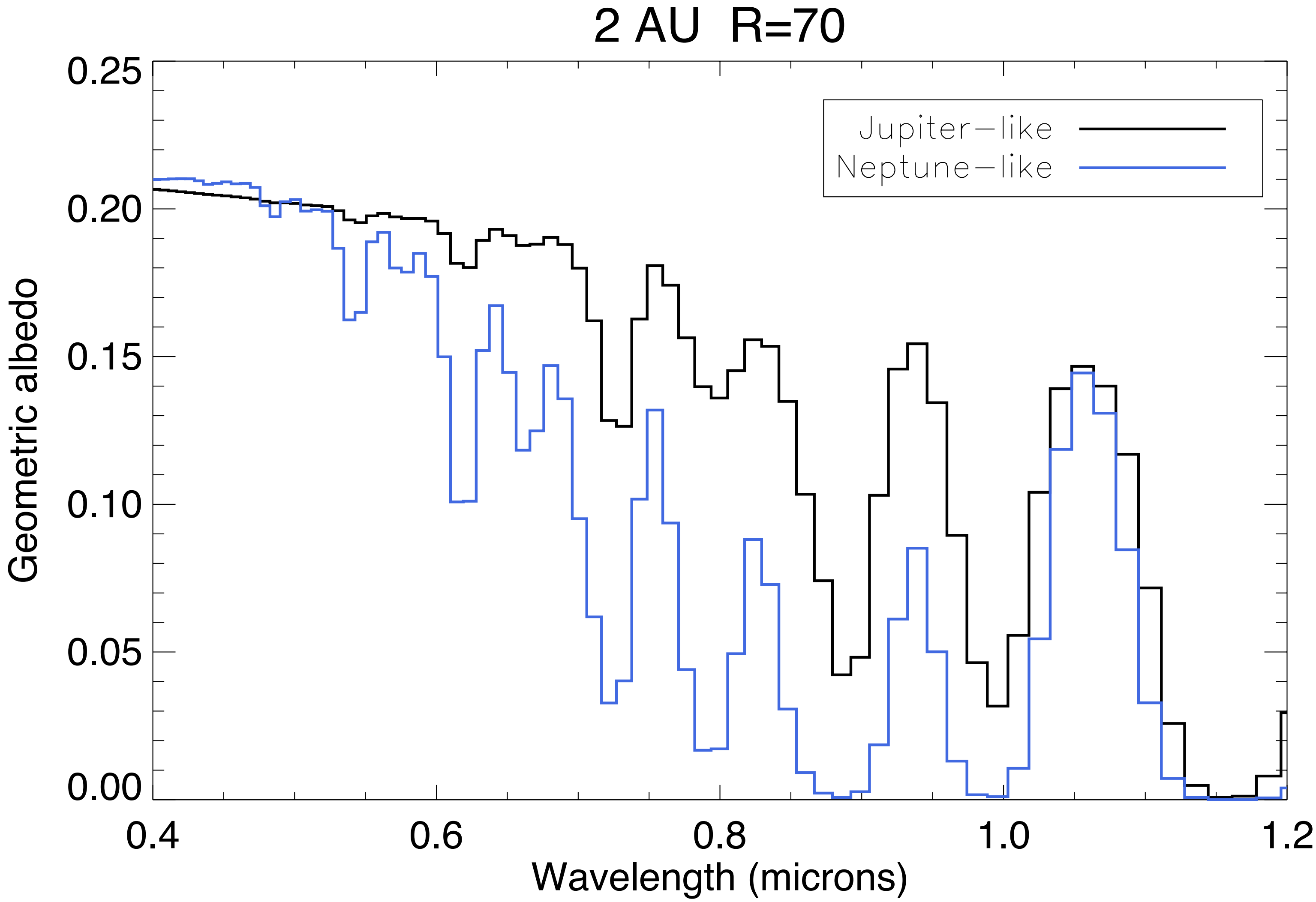
Executive Summary

- WFIRST-AFTA gives HST imaging over 1000's of square degrees in NIR
- 2.5x deeper and 1.6x better imaging than IDRM*
- More complementary to Euclid & LSST. More synergistic with JWST.
- Enables coronagraphy of giant planets and debris disks to address "new worlds" science of NWNH
- Fine angular resolution and high sensitivity open new discovery areas to the community. More GO science time (25%) than for IDRM.
- WFIRST-AFTA addresses changes in landscape since NWNH: Euclid selection & Kepler discovery that 1-4 Earth radii planets are common.
- Aerospace CATE cost is 8% larger than IDRM (w/o launcher, w/ risks). Coronagraph adds16%, but addresses another NWNH recommendation.
- Use of NRO telescope and addition of coronagraph have increased the interest in WFIRST in government, scientific community and the public.

* IDRM = 2011 WFIRST mission design to match NWNH

Backup

R~70 spectra can determine planet properties



AFTA RV Exoplanet Detection Estimates

- RV exoplanet detections are estimated based on imaging of radial velocity planets from the current RV catalog

Configuration	Design	Inner working angle	# RV planets, 550nm band, 6-month campaign	# spectral bands per target, 6-month campaign
Prime (OMC: Occulting Mask Coron.)	**SP**	0.19	4 7	4.3 4.9
	HL	0.10	18 19	4.3 4.2
Backup	**PIAA**	0.09	23 30	3.2 4.3

Note 1. Two rows for contrast and # RV images columns are for cases of

- Current Best Estimate: 0.4 mas RMS jitter & 1 mas star, 10x post-processing factor (slide 4)
- Goal: 0.2 mas RMS jitter & 1 mas star, 30x post-processing factor (slide 5)

Note 2. Spectral bands are 10% wide, centered at 450, 550, 650, 800, 950 nm

Detection and spectroscopy of up to 20 known RV planets is predicted based on simulations of current baseline coronagraph designs. Designs are still being optimized and performance is likely to change.

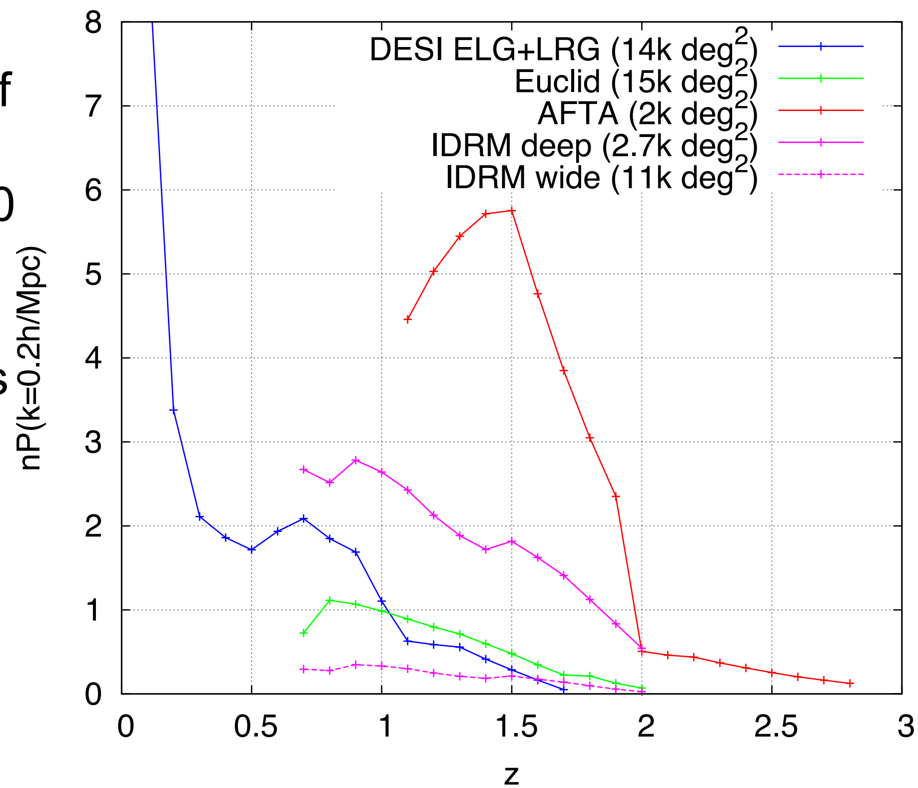
Redshift Survey/BAO Comparison

Comparison to IDRM

- Hα redshift range z = 1-2 (2.7) instead of z=0.7-2
- Smaller survey area (2000 deg^2 vs. 2700 deg^2) but much higher galaxy space density
- FOM ratio = 0.99 for full sample. AFTA is a 1.6x improvements for z> 1
- [OIII] emitters provide sparsely sampled tracers for BAO and RSD at z=2-3

Comparison to Euclid

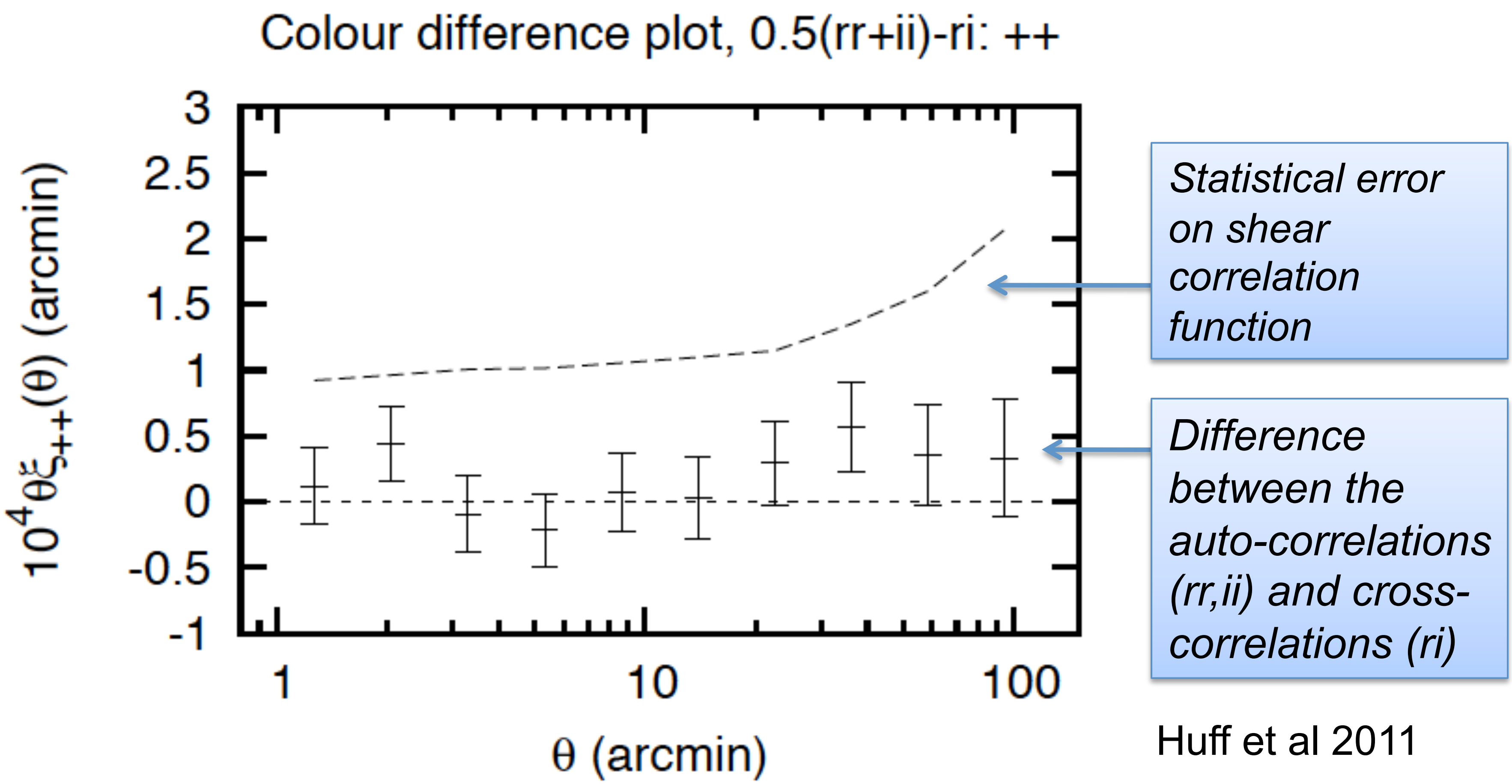
- Euclid has larger area but 10x lower space density.
- DESI numbers (from DESI white paper)



Forecast aggregate precision: 0.40% in D_A, 0.72% in H, at z=1-2
1.3% in D_A, 1.8% in H, at z=2-3 ([OIII] emitters)
1.2% in $\sigma_m(z)f(z)$ at z=1-2 (from RSD)

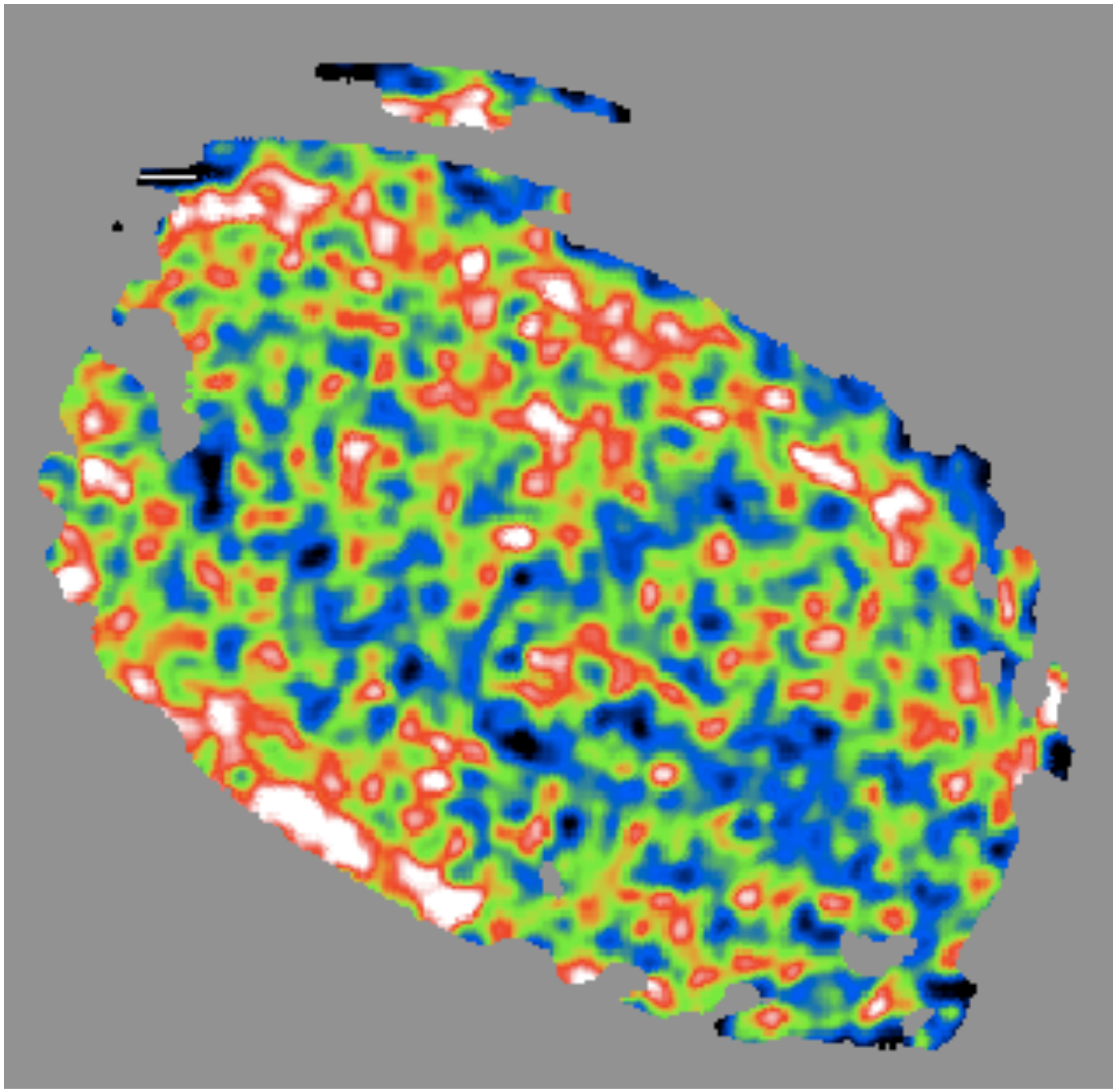
Null Tests in A Real Optical WL Survey

- What tests convince you that you did the measurement correctly?
- The need for redundant measurements – long appreciated in other precision measurements (e.g. CMB) – also applies to weak lensing.



Huff et al 2011

Systematic Effects in Large Scale Surveys



Map of SDSS photometric quasars
(Pullen & Hirata 2013)

Striping clearly visible even though this is one of the best-calibrated surveys in the history of optical astronomy.

Multiple revisits with carefully planned strategies to break degeneracies are the key to separating these effects from real signal, and are an indispensible ingredient for next-generation surveys such as WFIRST and LSST.

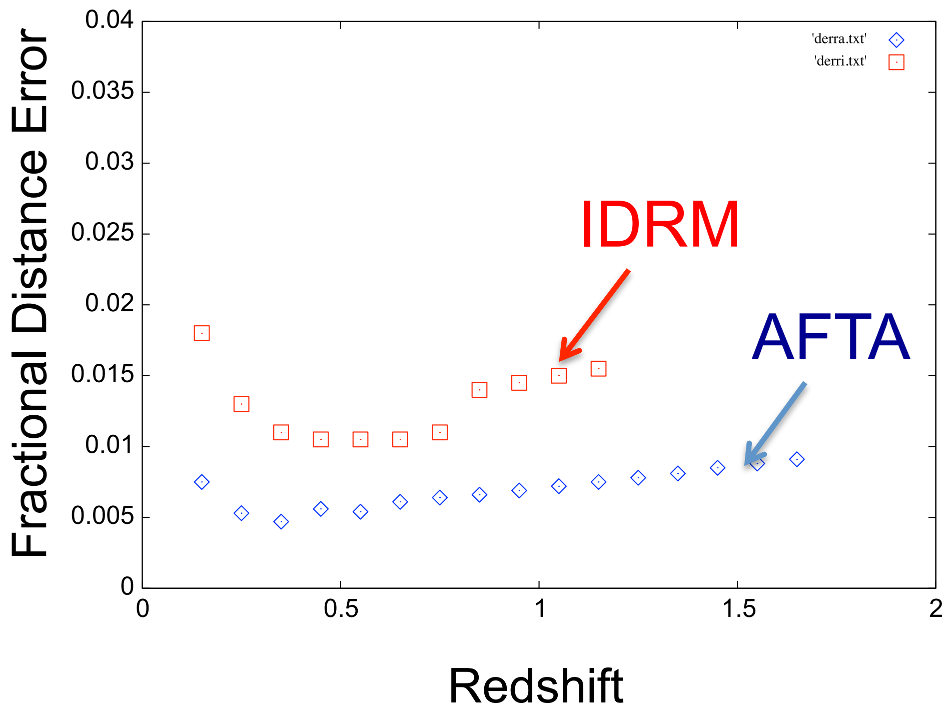
Supernova Comparison

Larger aperture and IFU allow *major* improvements over DRM1 and IDRM:

- More SNe (2750 vs. 1500)
- More even redshift distribution
- *Lower systematics*: Better photometry and calibration, no K-corrections, spectral diagnostics to compare similar high- and low-z SNe

Observing strategy can be tailored to match statistical and systematic uncertainties in each redshift bin.

Euclid has no planned SN program



From SDT Report – April 30, 2013

DISCOVERY SCIENCE

	Key Observation	Improvement over DRM1	Section
Identification and characterization of nearby habitable exoplanets	Characterize tens of Jupiter-like planets around nearby stars. Potential to detect Earth-like planets around nearest stars	**Coronagraph**	2.5.2 A-6, A-8
Gravitational wave astronomy	Detect optical counterparts	*Ability to detect fainter sources*	A-52
Time-domain astronomy	Repeated observations	*3x more sensitive, well matched to LSST*	A-48
Astrometry	Measure star positions and motions	*Achieve same level of accuracy 9x faster*	2.3.3 A-6, A-17, A-18 A-19, A-22, A-23 A-24, A-25, A-26
The epoch of reionization	Detect early galaxies for follow-up by JWST, ALMA, and next generation ground-based telescopes	***~10x increase in JWST targets***	**2.3.1** A-40, A-44, A-45 A-46, B-4

ORIGINS

	Key Observation	Improvement over DRM1	Section
What were the first objects to light up the universe, and when did they do it?	Detect early galaxies and quasars for follow-up by JWST, ALMA, and next generation ground-based telescopes	***~10x increase in high z JWST target galaxies*** ***Very high-z supernova***	**2.3.1** A-43, A-45, A-46 **B-5**
How do cosmic structures form and evolve?	Trace evolution of galaxy properties	*1.9x sharper galaxy images*	A-31, A-32, A-39 A-47, **B-13**
What are the connections between dark and luminous matter?	High resolution 2000 sq. deg map of dark matter distribution and still higher resolution maps in selected fields Dark Matter distribution in dwarfs to rich clusters	*Double the number density of lensed galaxies per unit area.* *Capable of observing 200-300 lensed galaxies/arcmin^2* *Astrometry of stars in nearby dwarfs*	A-25, A-26, A-33 A-35, A-36, A-37 A-38, A-50
What is the fossil record of galaxy assembly from the first stars to the present?	Map the motions and properties of stars in the Milky Way + its neighbors Find faint dwarfs	*3x increase in photometric sensitivity + 9x increase in astrometric speed* *JWST follow-up*	A-21, A-22, A-25 A-26, A-27, A-28 A-29, A-30, **B-19**
How do stars form?	Survey stellar populations across wide range of luminosities, ages and environments	**IFU spectroscopy** *3x more sensitive + 1.9x sharper galaxy images*	A-11, A-12, A-13 A-14, A-15, A-16 A-47, **B-8, B-11**
How do circumstellar disks evolve and form planetary systems?	Image debris disks	**Coronagraph**	2.5.2

ORIGINS cont.

How did the universe begin?	Measure the shape of the galaxy power spectrum at high precision; test for signatures of non-Gaussianity and stochastic bias	*Higher space density of galaxy tracers; higher space density of lensed galaxies*	2.2

UNDERSTANDING THE COSMIC ORDER

	Key Observation	Improvement over DRM1	Section
How do baryons cycle in and out of galaxies, and what do they do while they are there?	Discover the most extreme star forming galaxies and quasars		2.3.4
What are the flows of matter and energy in the circum-galactic medium?			
What controls the mass-energy-chemical cycles within galaxies?	Study effects of black holes on environment	**IFU Spectroscopy**	A-34
How do black holes grow, radiate, and influence their surroundings?	Identify and characterize quasars and AGNs, black hole hosts Use strong lensing to probe black hole disk structure	*Excellent match to LSST sensitivity* *1.9x sharper images*	A-41, A-43, A-48
How do rotation and magnetic fields affect stars?			

UNDERSTANDING THE COSMIC ORDER cont.

How do the lives of massive stars end?	Microlensing census of black holes in the Milky Way		A-18
What are the progenitors of Type Ia supernovae and how do they explode?	Study supernova Ia across cosmic time Detect SN progenitors in near-by galaxies	**IFU Spectroscopy**	**B-7**
How diverse are planetary systems?	Detect 3000 cold exoplanets and complete the census of ex-oplanetary systems throughout the Galaxy.	*60% increase in the number of Earth size and smaller planets detected by microlensing, im-proved characterization of the planetary systems*	2.5.1, 2.5.2.3 A-6, A-7, A-8 **B-15, B-17**
	Detects free-floating planets **Joint lensing studies with JWST** Images of exozodiacal disks around nearby stars	 **IFU** **Coronagraph**	
Do habitable worlds exist around other stars, and can we identify the telltale signs of life on an exoplanet?	Develop precursor coronagraph for TPF Characterize number of planets beyond snow line to understand origins of water	**Coronagraph** *60% increase in the number of Earth size and smaller planets detected by microlensing*	**2.5.2** 2.5.1

FRONTIERS OF KNOWLEDGE

Why is the universe accelerating?	Use SN as standard candles Use BAO to measure distance as a function of redshift Use lensing to trace the evolution of dark matter Use rich clusters to measure the growth rate of structure	*~2x improvement in SN distance measurements and significantly improved control of systematics* *60% higher density of galaxies for the redshift survey* *~2x increase in source density* *Capable of observing 200-300 lensed galaxies/arcmin^2*	2.2
What is dark matter?	Characterize dark matter subhalos around the Milky Way Characterize dark matter in clusters Strong lenses	*~9x increase in astrometry speed* *~1.9x sharper galaxy images* ***~JWST follow-up of strong lenses***	A-22, A-24, A-25 2.3.2, A-38 **B-5**
What are the properties of neutrinos?	Measure neutrino effects on growth rate of structure and shape of galaxy power spectrum	*~2-3x increase in lensed galaxies per unit area* *~2x increase in number density of spectroscopic galaxies*	
What controls the mass, radius, and spin of compact stellar remnants?			