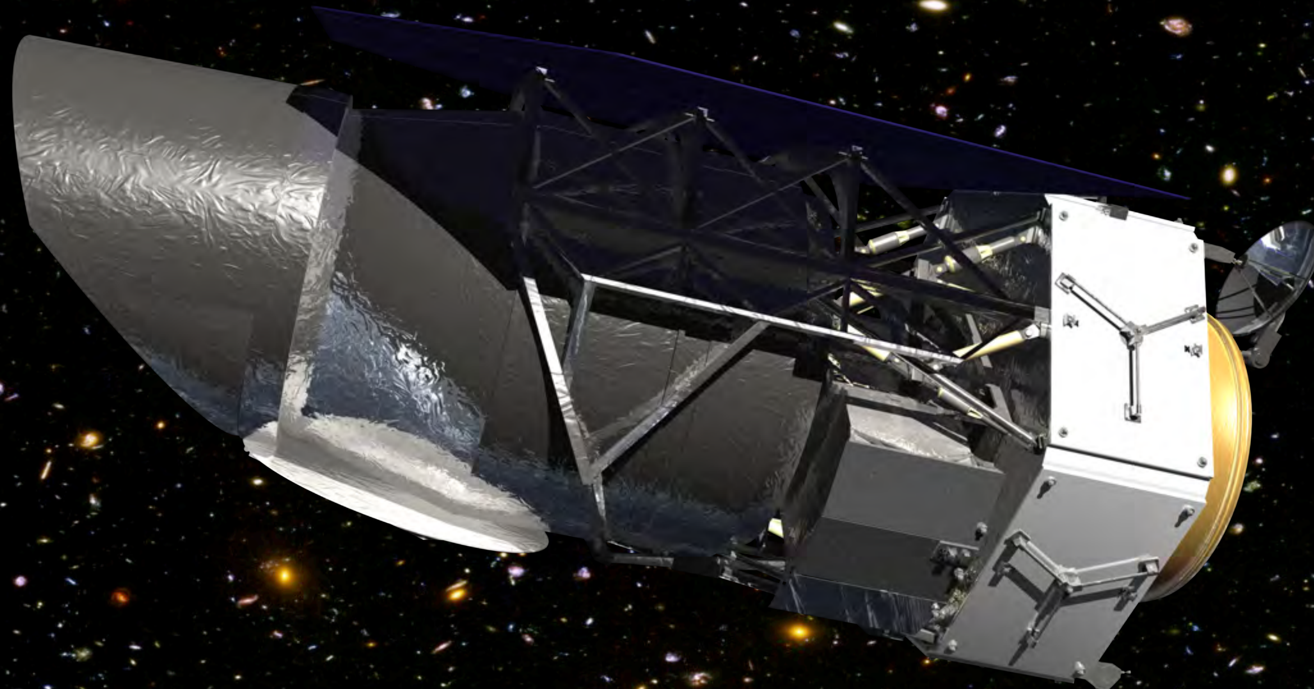
Wide-Field InfraRed Survey Telescope



Jeffrey Kruk (NASA-GSFC)

Outline

- Mission Overview
  - Historical background
  - Observatory
  - Science Program
    - Weak-lensing, galaxy redshift survey
    - Supernova Ia surveys
    - Microlensing
    - Coronagraphy
- Project Status
- Q&A

Historical Context - 1

- 1995 First exoplanet discovered by radial velocity
- 1998,1999: first papers find expansion of universe is accelerating (Type Ia supernovae)
- 2002 First exoplanet discovered by transit
- 2003 **National Research Council recommends NASA/DOE Dark Energy Mission** *(Connecting Quarks to the Cosmos)*
- 2003 NASA Beyond Einstein probe roadmap
- 2004 First exoplanet discovered by microlensing
- 2004 First NASA/DOE Joint Dark Energy Mission SDT
- 2005 JDEM mission concept studies begin
- 2006 Microlensing Planet Finder proposal
- 2006 TPF-C Science & Technology Definition Team report

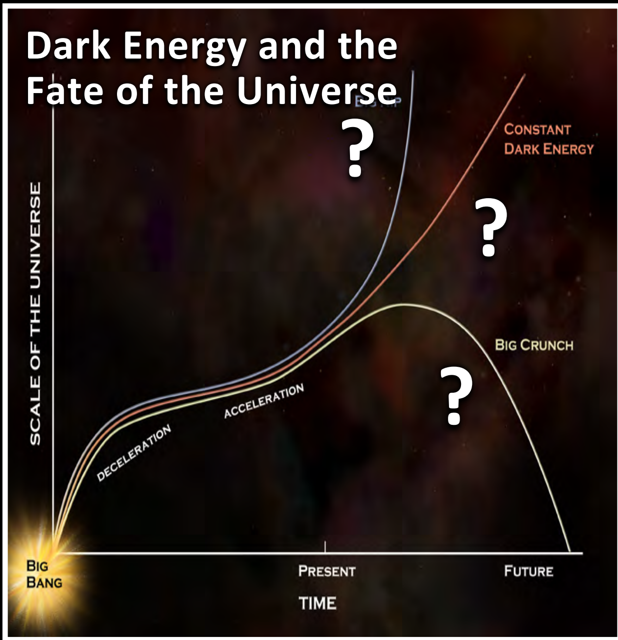
Historical Context - 2

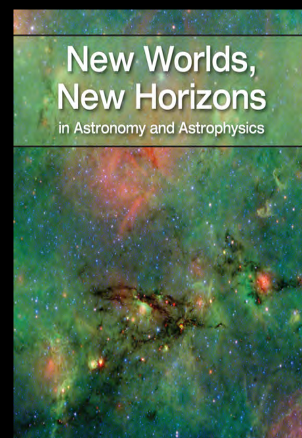
- 2007 **NRC recommends JDEM 2009 start**
- 2009 Kepler launch
  - 2335 confirmed planet detections, 4496 candidates
- 2009 Astro-2010 white paper submissions
  - Mission concepts:
    - JDEM-Omega
    - Microlensing Planet Finder
    - Near InfraRed Sky Surveyor
- **2010 NRC recommends WFIRST**
  - Merger of above 3 science programs (& many non-mission-specific white papers), using JDEM-Omega observatory concept

WFIRST Science Program is guided by NWNH

National Academy of Sciences
Astronomy & Astrophysics Decadal Survey
(2010)

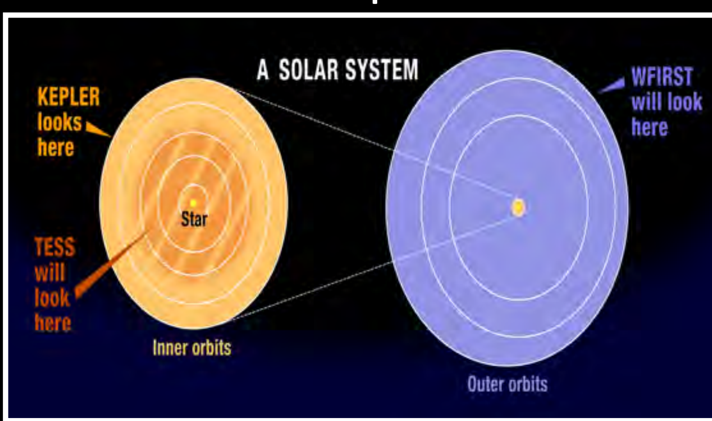
Our Guiding Principle





National Academy of Sciences
Astronomy & Astrophysics
Decadal Survey (2010)

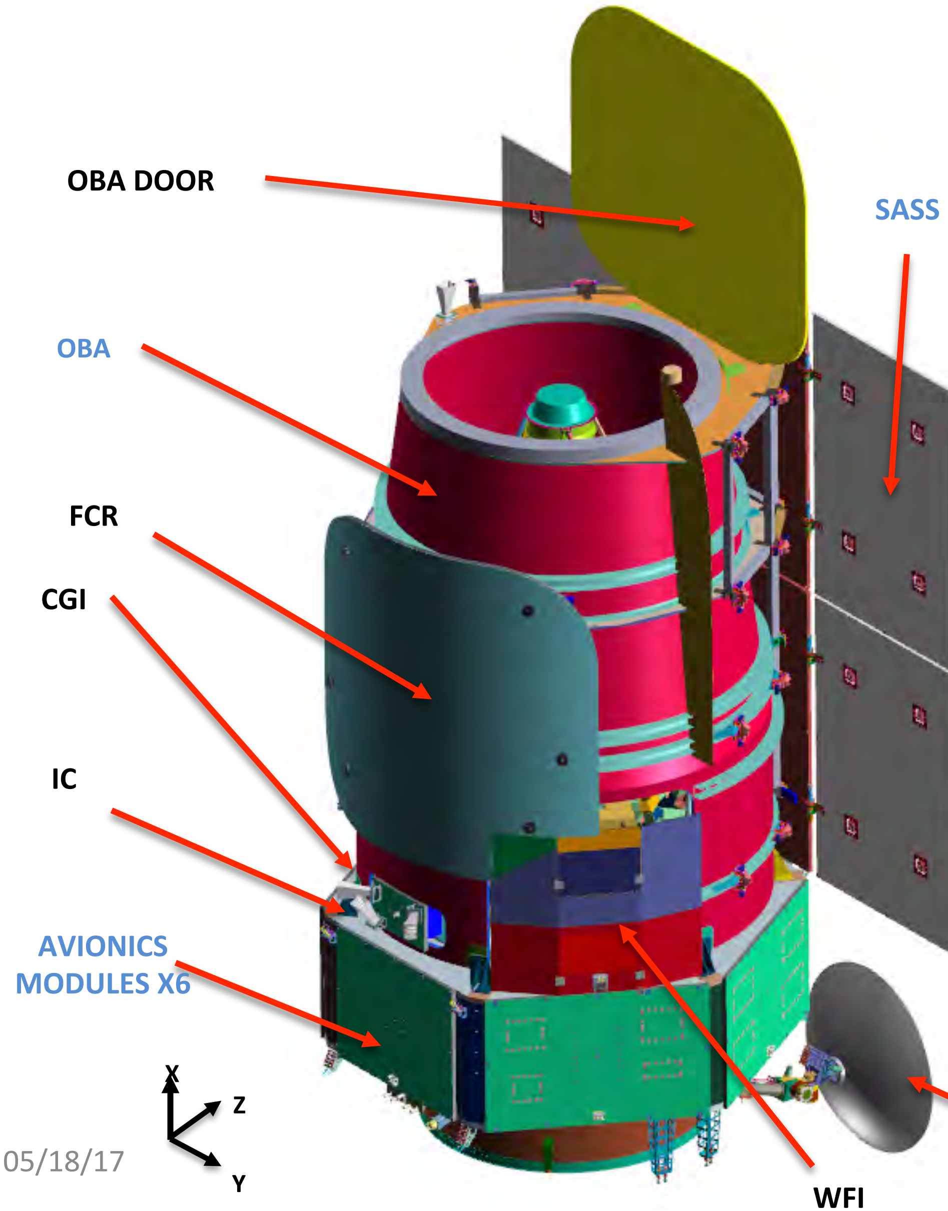
The full distribution of planets around stars



WFIRST pre-Formulation

- 2010 WFIRST SDT#1 convened
- 2012 **NASA acquisition of 2 NRO telescopes**
- 2012 WFIRST SDT#2 convened
  - Final Report: http://arxiv.org/abs/1503.03757
- 2014 **NRC declares AFTA consistent w/NWNH**
  - http://www.nap.edu/catalog/18712/evaluation-of-the-implementation-of-wfirstafta-in-the-context-of-new-worlds-new-horizons-in-astronomy-and-astrophysics
- **2016 Begin Phase A**
  - Appoint Formulation Science Working Group
  - Begin detailed requirements analysis & engineering design

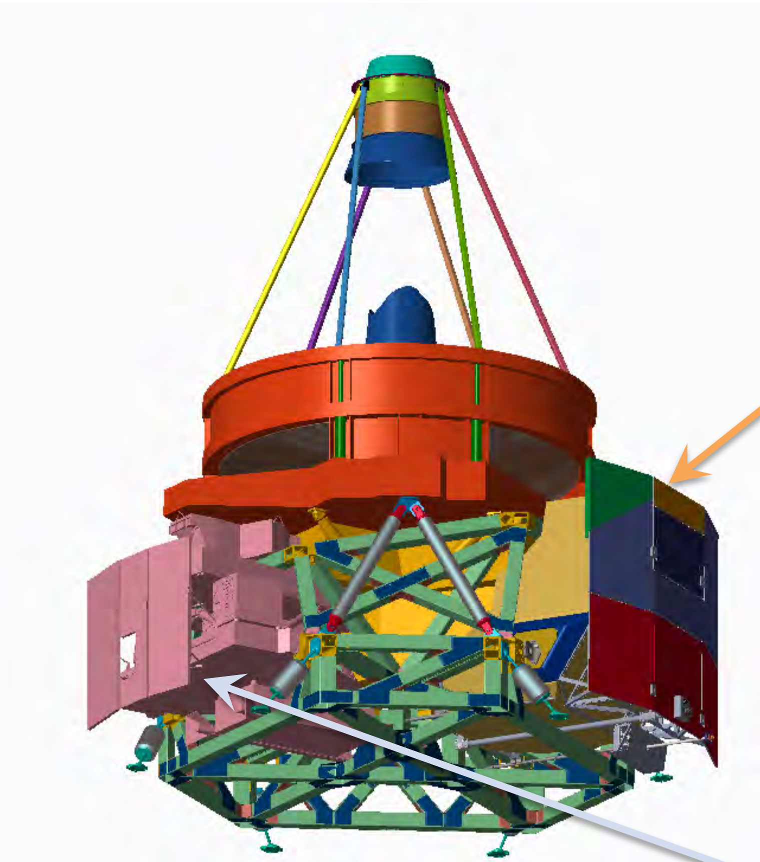
WFIRST Observatory Concept



ey Features

- **Telescope**: 2.4m aperture primary
- **Instruments**
  - Wide Field Imager/Spectrometer & Integral Field Unit
  - Internal Coronagraph with Integral Field Spectrometer
- **Data Downlink Rate**: 275 Mbps downlink
- **Data Volume**: 11 Tb/day
- **Orbit**: Sun-Earth L2
- **Launch Vehicle**: Delta IV Heavy
- **Mission Duration**: 6 yr, 10yr goal
- **Serviceability**: Observatory designed to be robotically serviceable
- **GSFC**: leads mission and I&T, wide field instrument, spacecraft
- **JPL**: leads telescope, coronagraph

WFIRST Instruments



Wide-Field Instrument

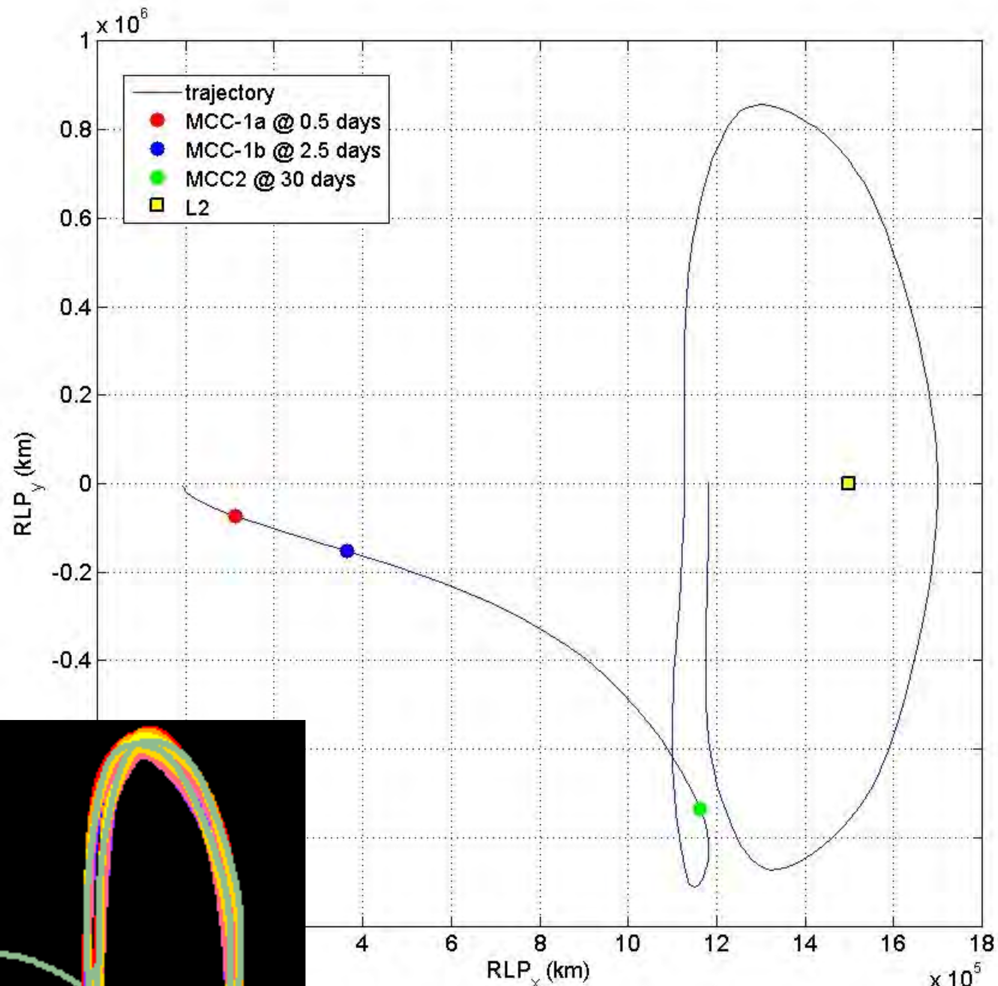
- *Imaging & spectroscopy over 1000s of sq. deg.*
- *Monitoring of SN and microlensing fields*
- 0.7 – 2.0 μm (imaging) & 1.0-1.89 μm (spec.)
- 0.28 deg^2 FoV (100x JWST FoV)
- 18 H4RG detectors (288 Mpixels)
- 7 filter imaging, grism + IFU spectroscopy

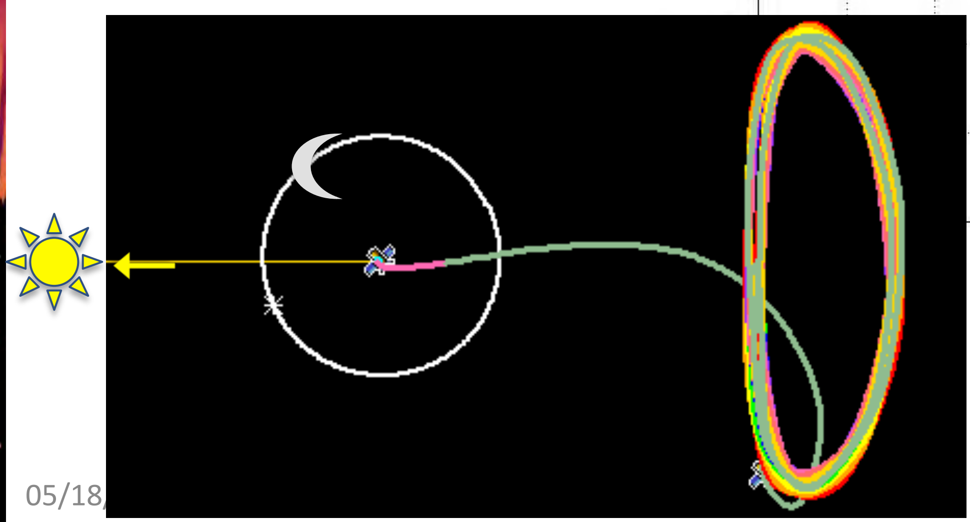
Coronagraph

- *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 1.0 arcsec

Planned Sun-Earth L2 halo orbit

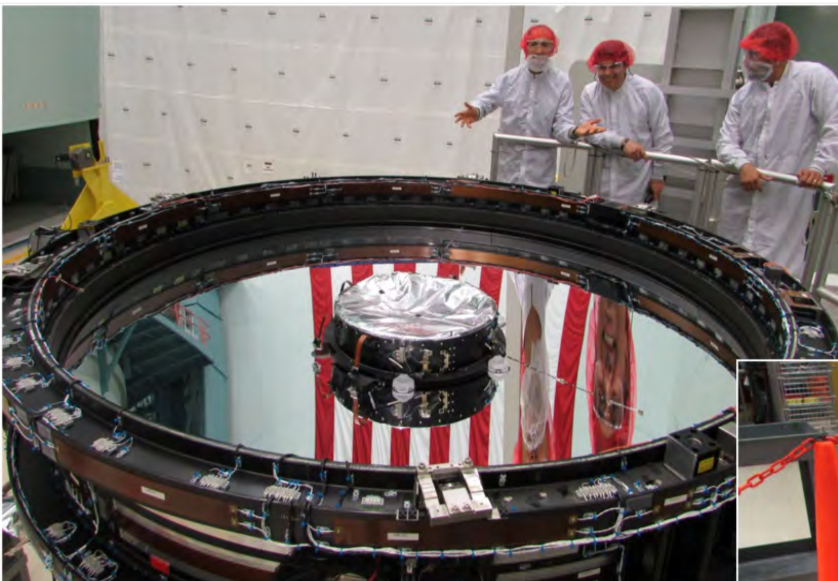
Diameter of planned halo orbit is comparable to Earth-L2 distance

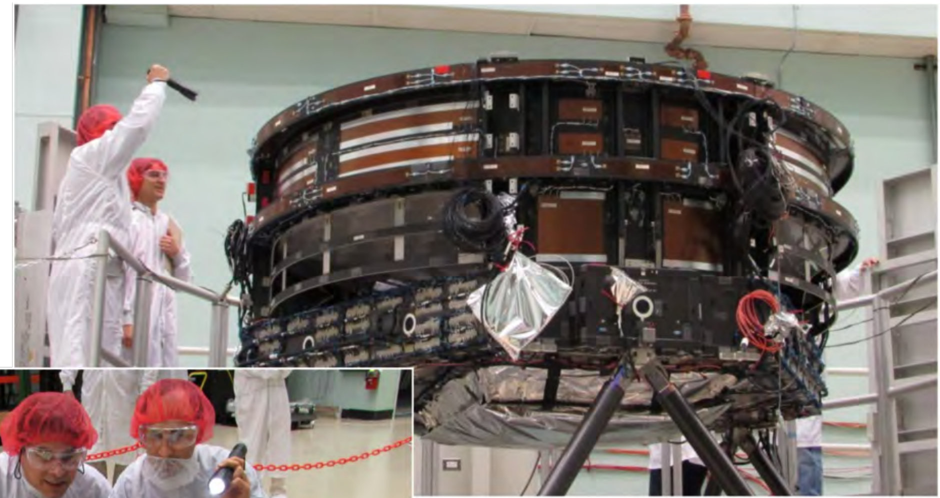




Telescope

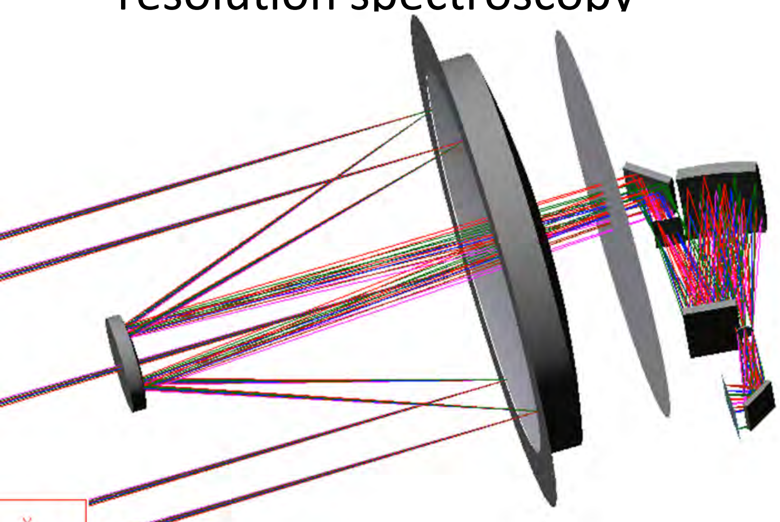
Telescope

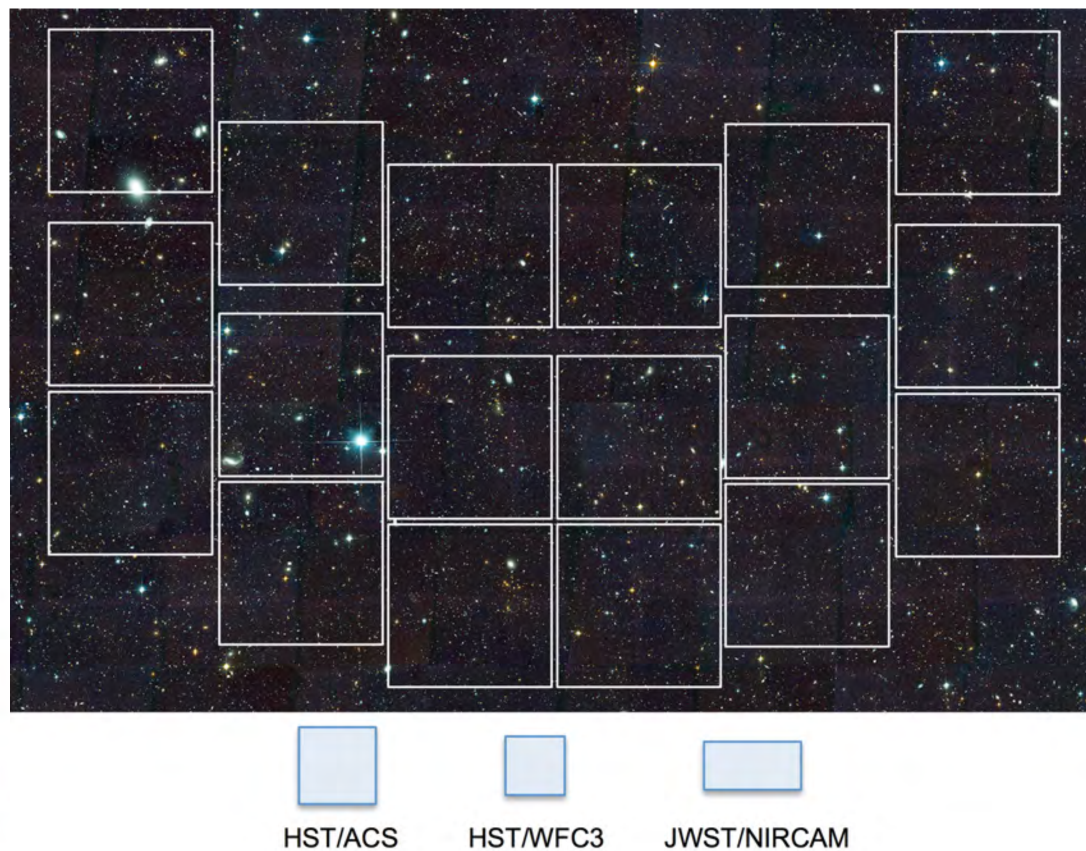




Wide Field Channel

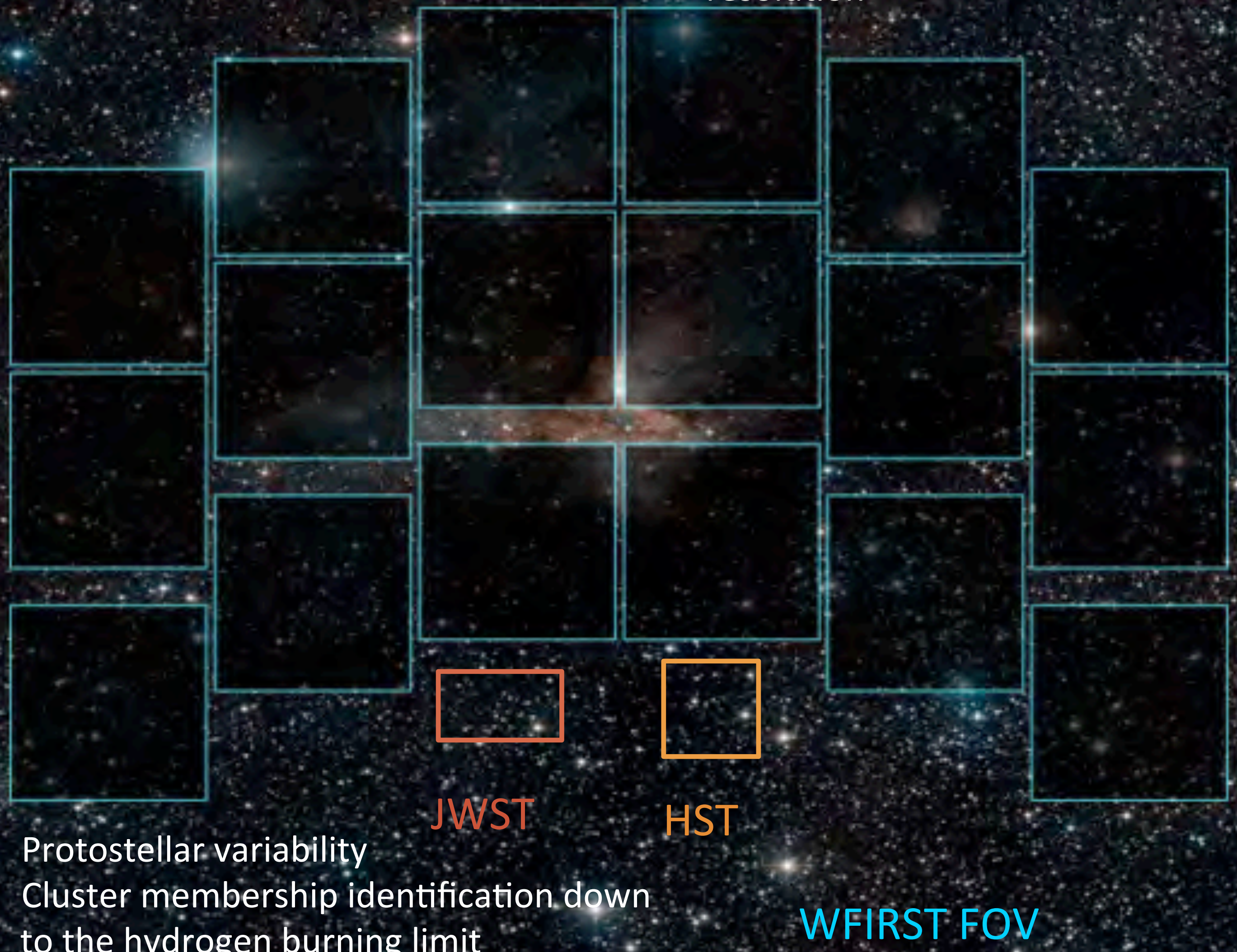
- Very large imaging field of view (FOV) (0.8° x 0.4°)
- High spatial resolution (0.11 arcsec/pixel)
- Stable image quality (1.0 nm RMS wave front error variation in 180 sec)
- 7 imaging filters spanning visible & NIR: 0.76 to 2.0μm
- grism for multi-object, low-resolution spectroscopy



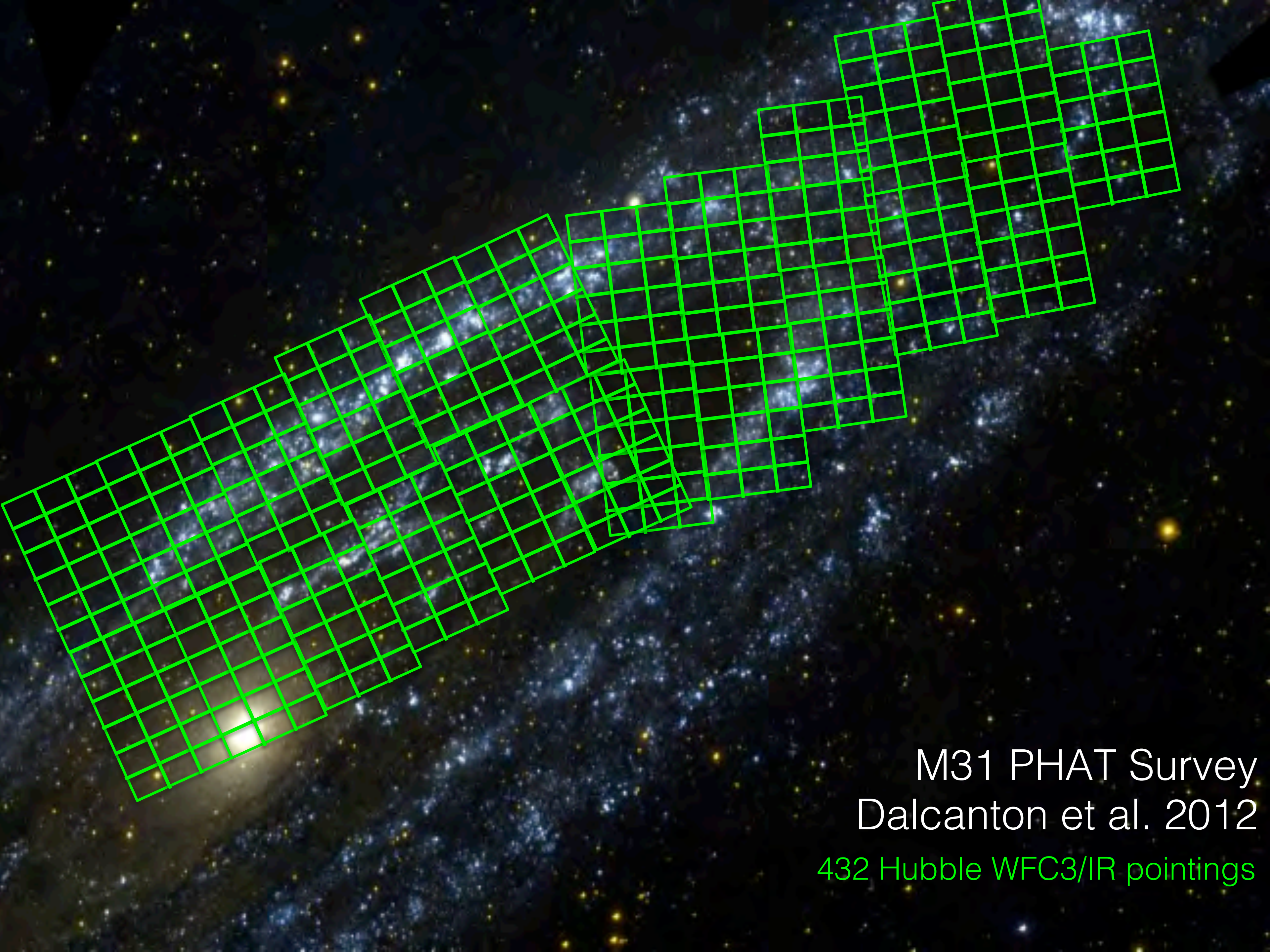


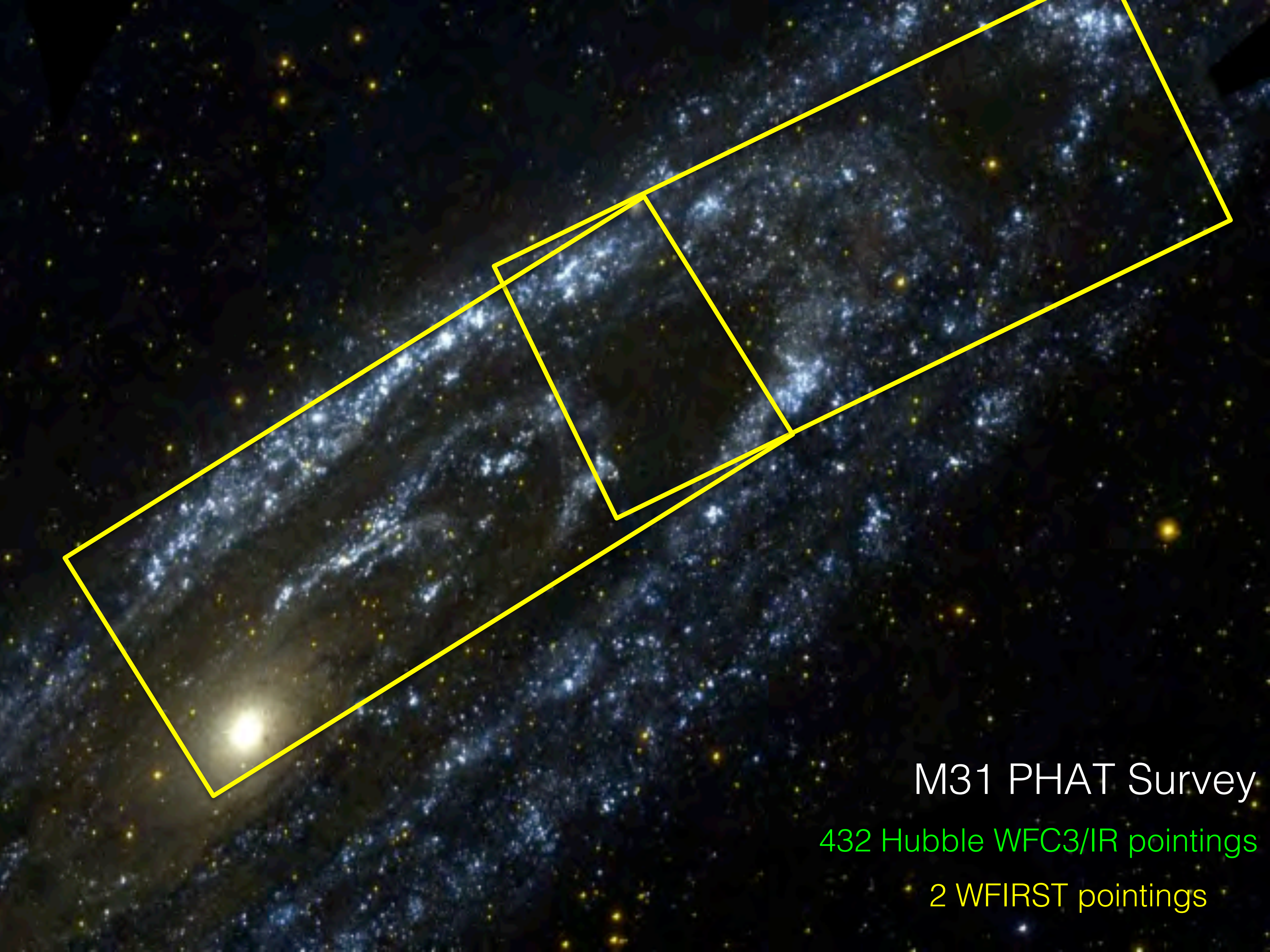
WFIRST Provides the First Wide-Field High Resolution Map of the Milky Way

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



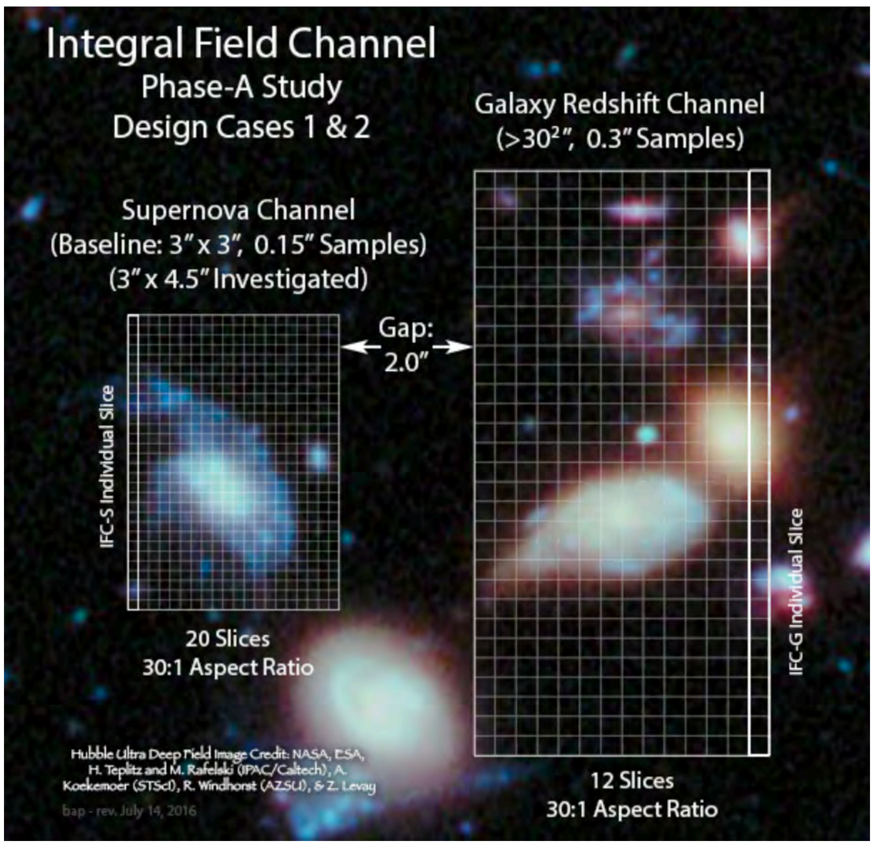
- Protostellar variability
- Cluster membership identification down to the hydrogen burning limit
- Dust extinction mapping

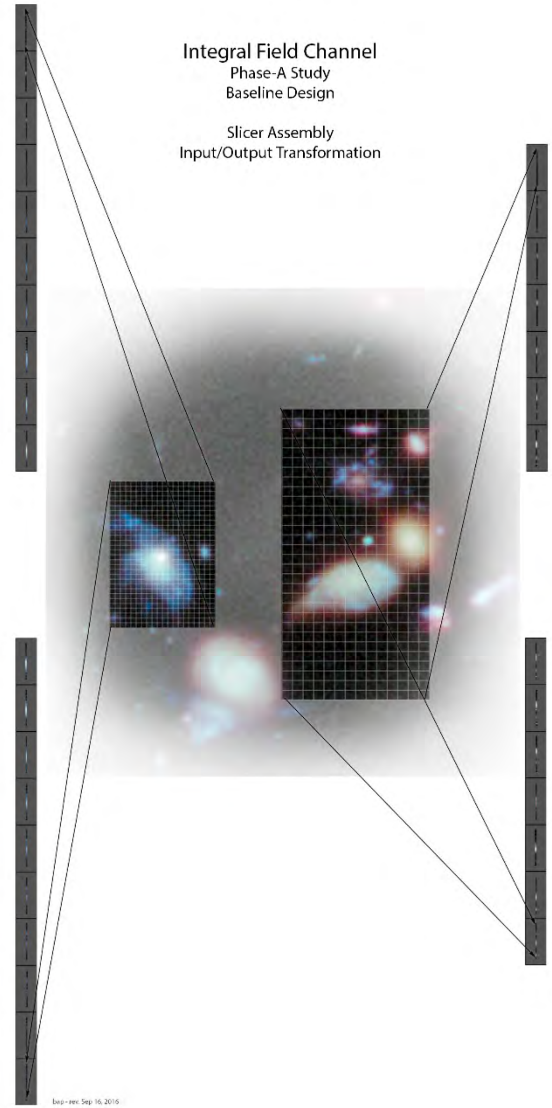

M31 PHAT Survey
Dalcanton et al. 2012
432 Hubble WFC3/IR pointings


M31 PHAT Survey
432 Hubble WFC3/IR pointings
2 WFIRST pointings

Integral Field Spectrograph

- Supernova FOV: 3 x 3 arcsec, 0.075 arcsec/pixel resolution
- Photometric Redshift Calibration FOV 6 x 6 arcsec, 0.15”/pixel
- Very high sensitivity, NIR pass band (0.45-2.0μm)
- Low spectral resolving power (70-140 λ/Δλ)



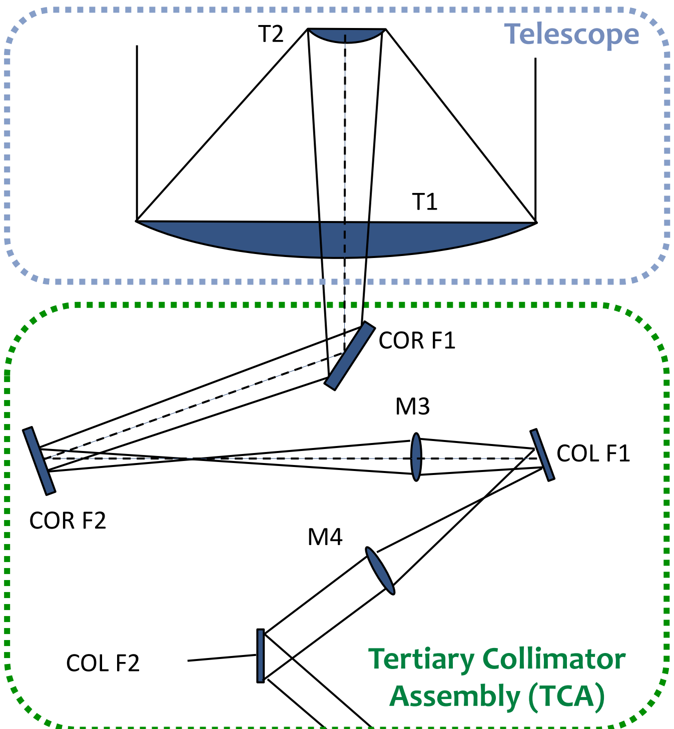


Coronagraph

- Technology Demonstration Instrument
- Two modes:
  - hybrid Lyot
  - shaped pupil

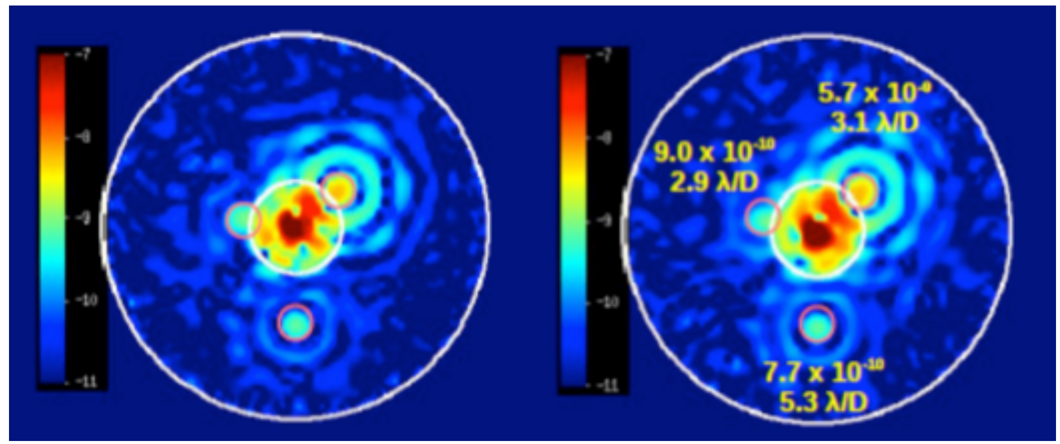
Design Implementation	Value	Comments
Bandpass	430 - 980 nm	Measured sequentially in 10% and 18% bands
Inner Working Angle [radial]	150 mas	at 550nm, 3λ/D driven by telescope pupil obscurations
Inner Working Angle [radial]	270 mas	at 1µm
Outer Working Angle [radial]	0.5 as	at 550nm, 10λ/D, for highest contrast
Outer Working Angle [radial]	0.9 as	at 1µm, 10λ/D
Outer Working Angle [radial]	0.95 as	at 550, 20λ/D, lower contrast
Outer Working Angle [radial]	1.7 as	At 1µm, 20λ/D, lower contrast
Detection Limit (Contrast after post-processing)	3×10^{-9}	Cold Jupiters; deeper contrast unlikely due to pupil shape & extreme stability requirements.
Imaging DL FOV [radius] w/o masks	2.9 as	Without masks in place
Imaging pixel plate scale	0.01 as	
Spectral Resolution	70	R = λ/δλ (IFS)
IFS Spatial Sampling	17 mas	3 lenslets per λ/D, better than Nyquist

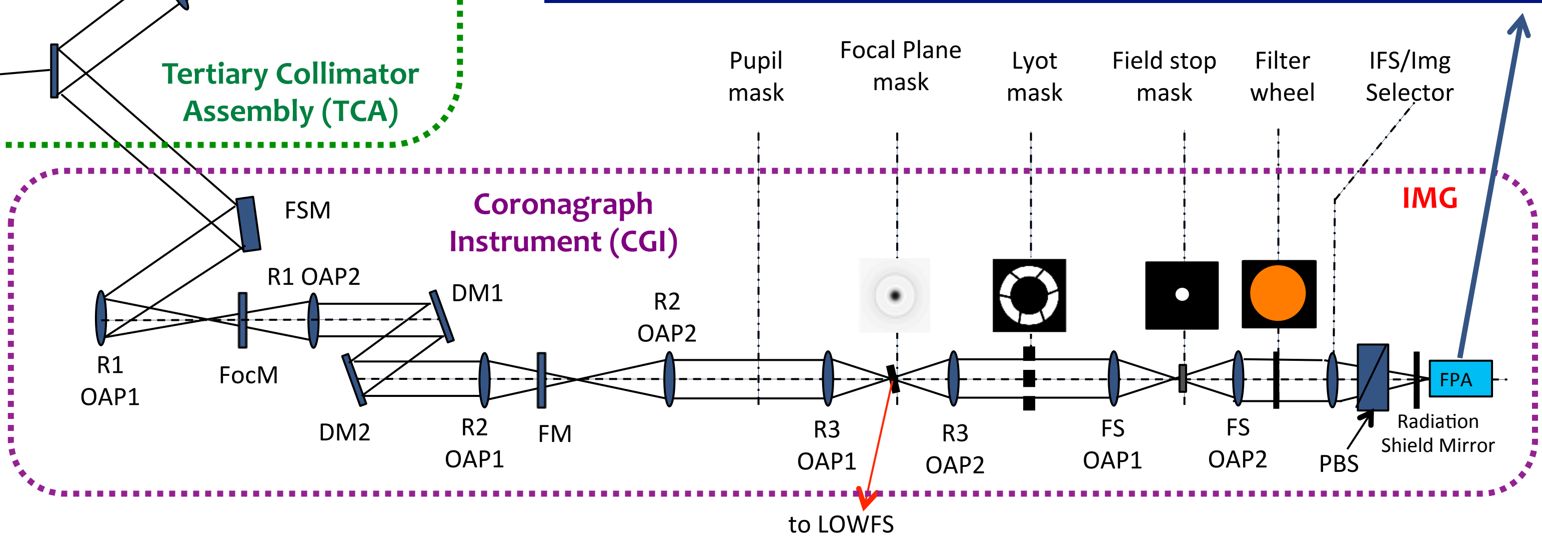
CGI Operational Modes



Hybrid Lyot Mode

Imaging in 2 simultaneous polarizations, simulated planets are circled in red

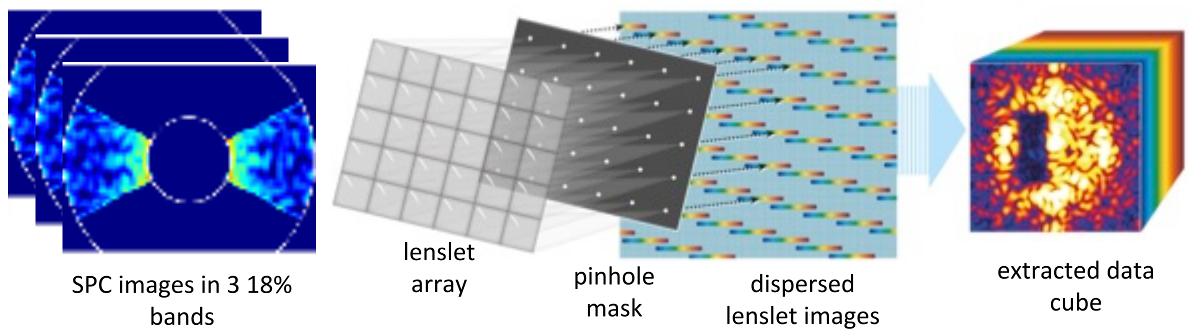


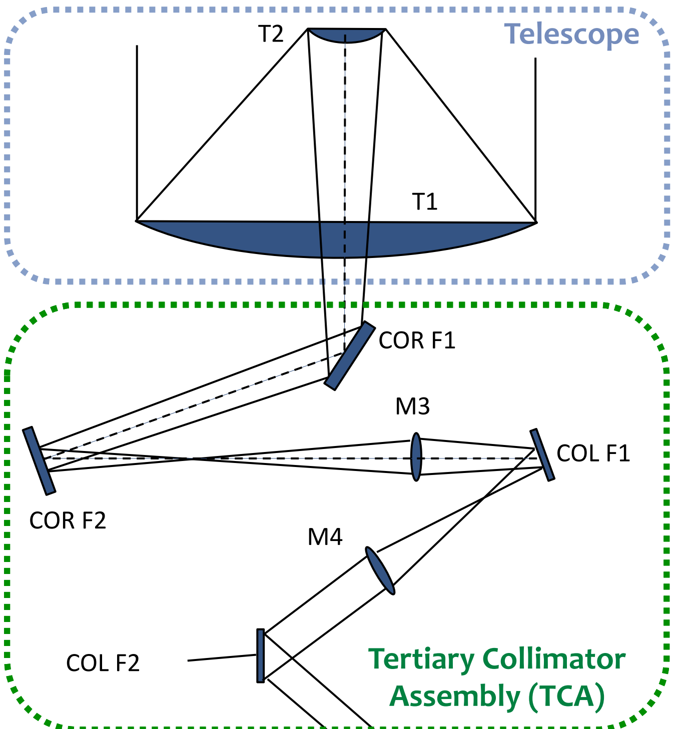


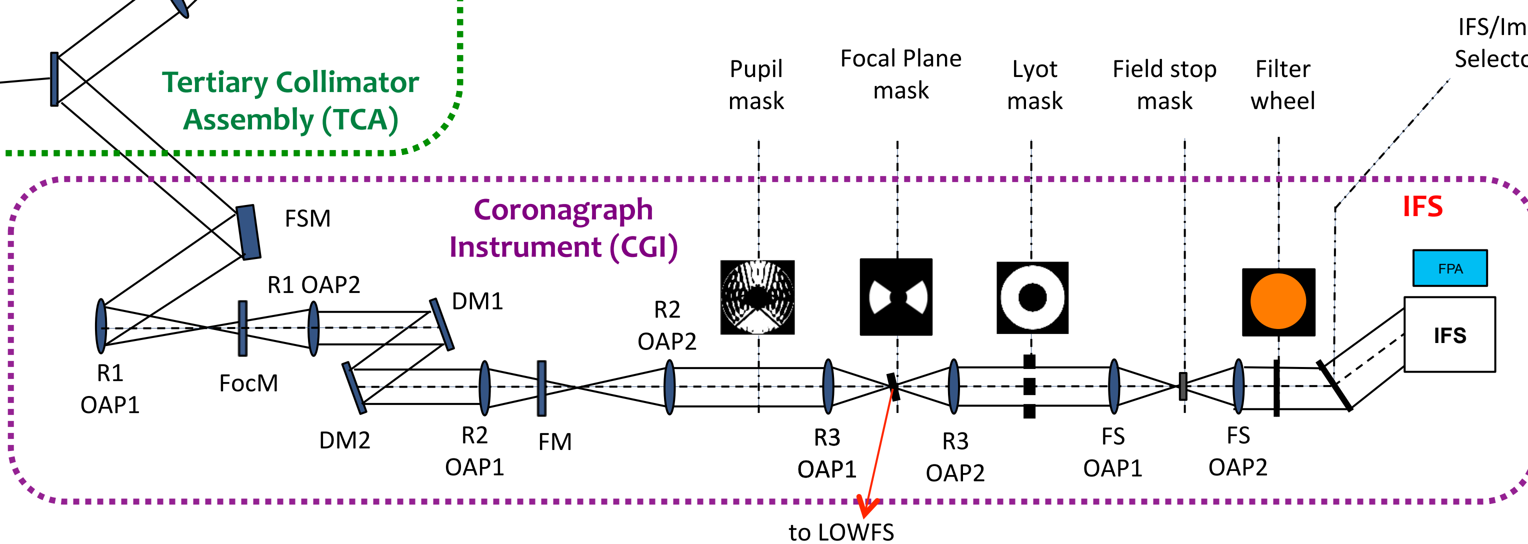
CGI Operational Modes

Shaped Pupil Spectroscopy Mode

The IFS uses 3 18% bands to produce an R=70 spectra from 600 to 970 nm







CGI Operational Modes

Shaped Pupil Disk Imaging Mode

Disk Imaging at wavelengths 465 and 890 nm, in 2 simultaneous polarizations

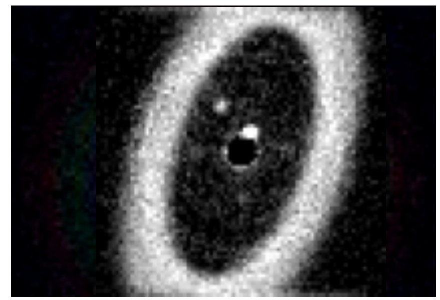
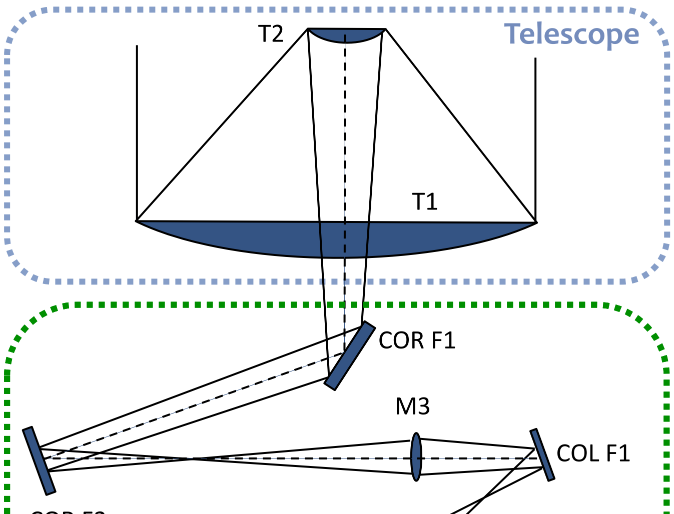
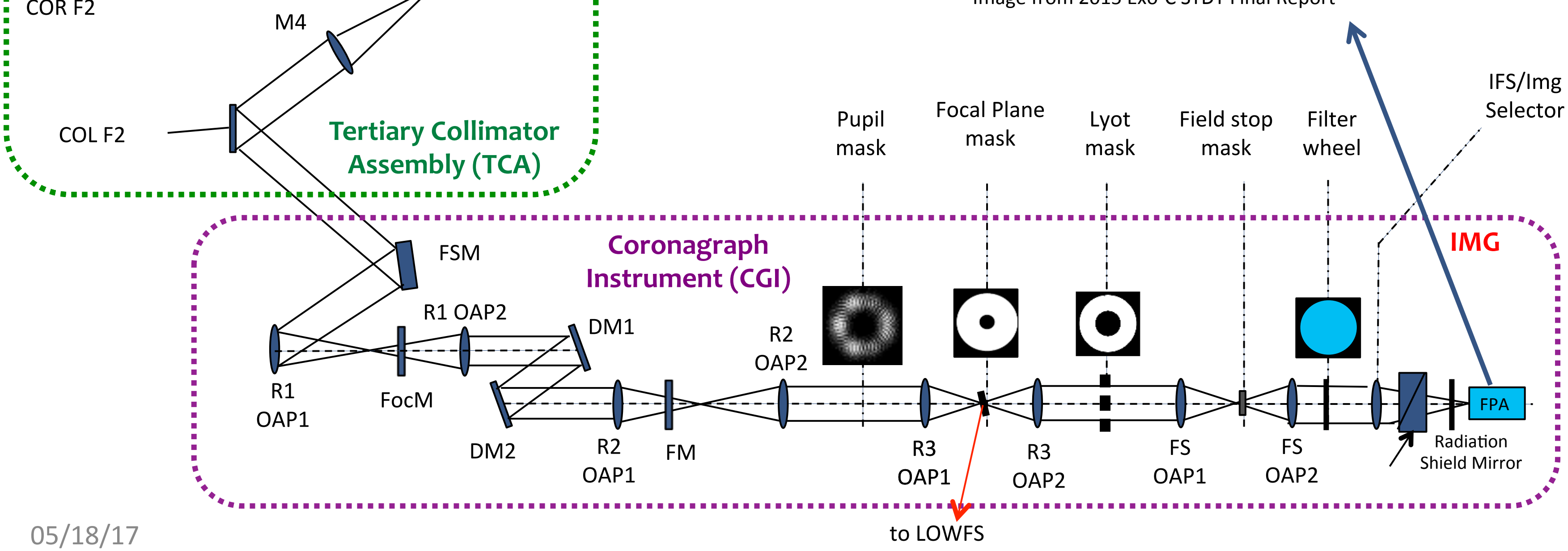


Image from 2015 Exo-C STDT Final Report





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})

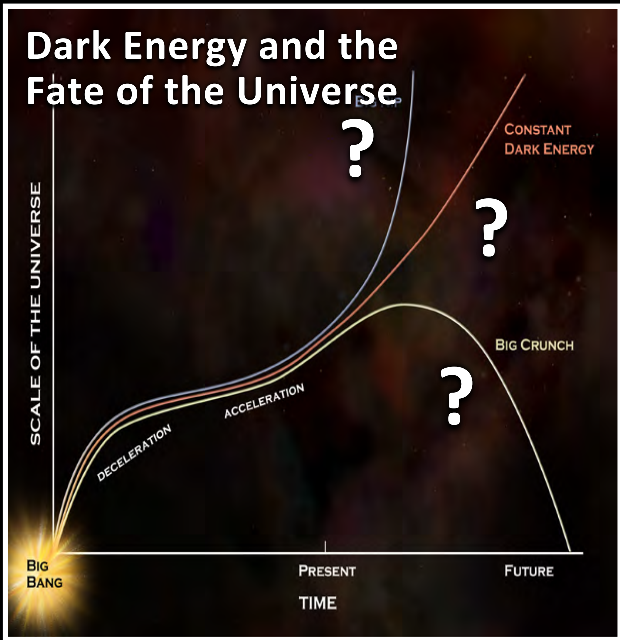
2) Determine the expansion history of the Universe and the growth history of its largest structures in order to test possible explanations of its apparent accelerating expansion including Dark Energy and modifications to Einstein's gravity.

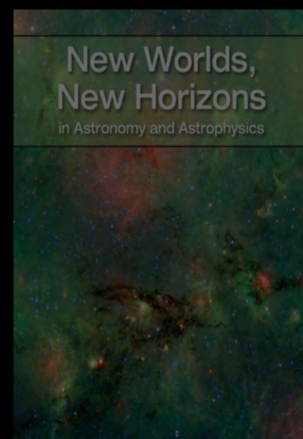
3) Complete the statistical census of planetary systems in the Galaxy, from the outer habitable zone to free floating planets

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.

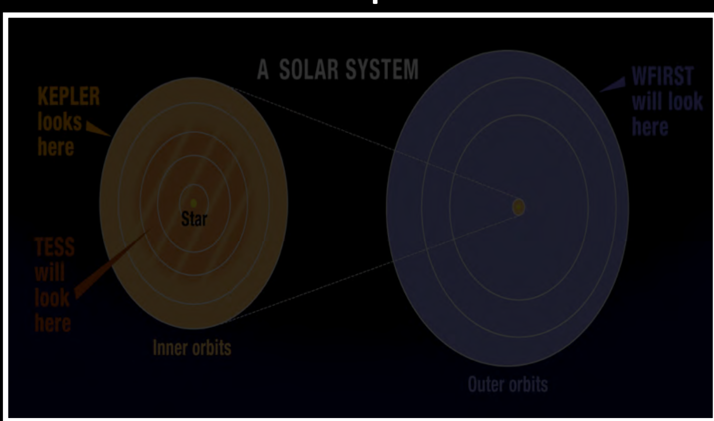
Our Guiding Principle





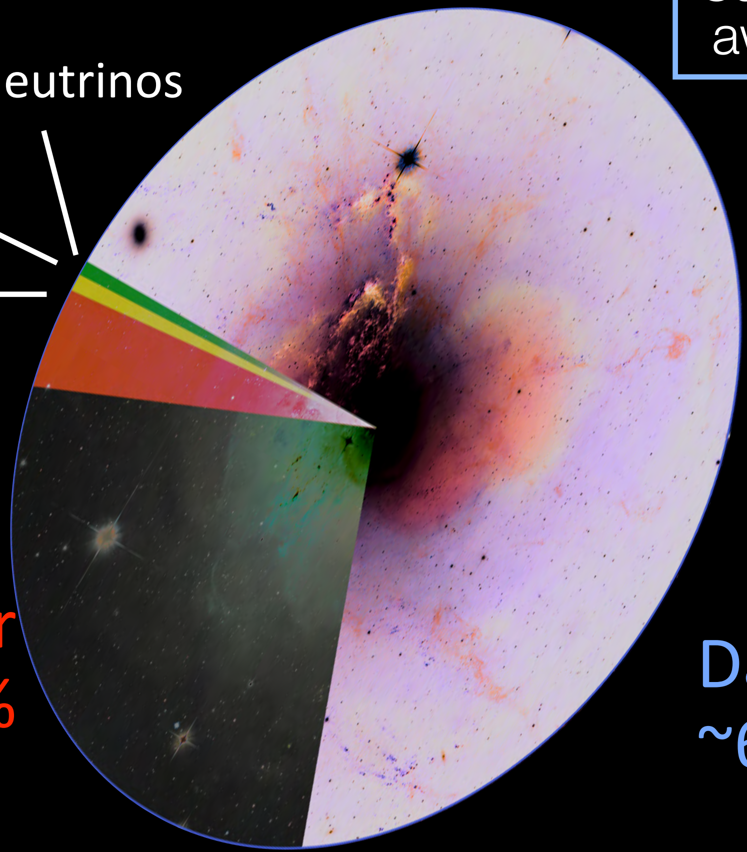
<u>National Academy of Sciences</u>
Astronomy & Astrophysics
Decadal Survey (2010)

The full distribution of planets around stars



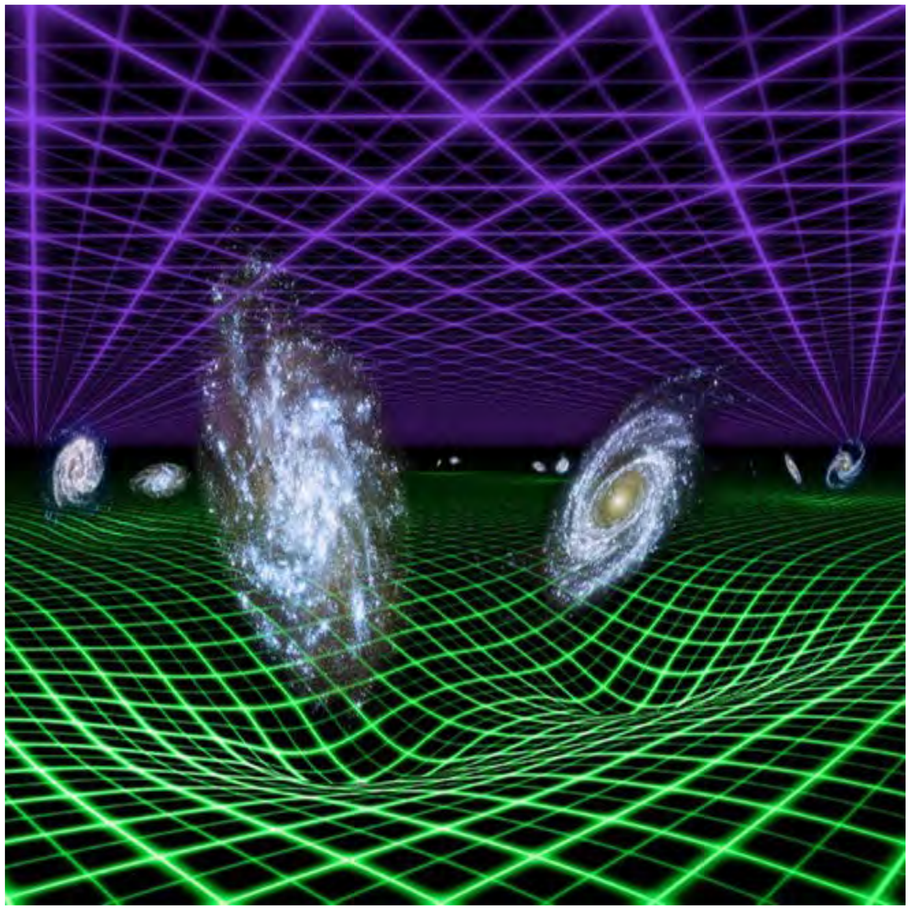
The Universe as a Pie Chart

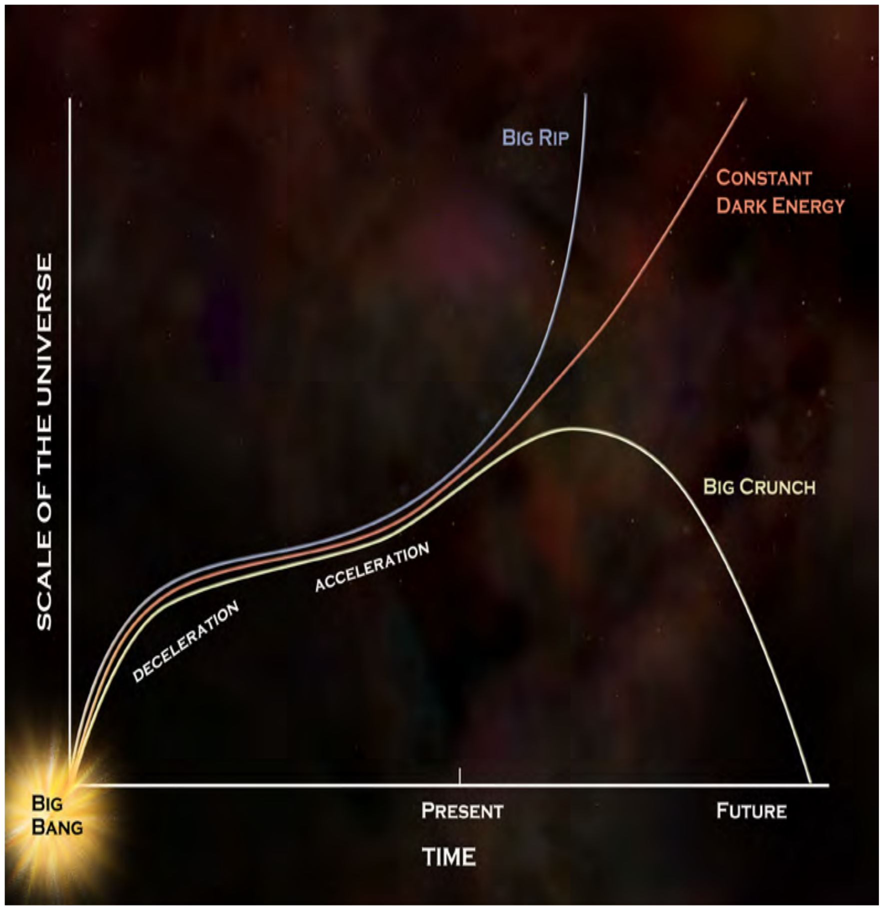
Dark Energy
Is a repulsive force
Affects the speed at which the Universe expands
Causes everything to move away from everything else



Dark Matter
Affected by the attractive force of gravity
Affects how "clustered" objects are
Causes objects to want to move towards one another

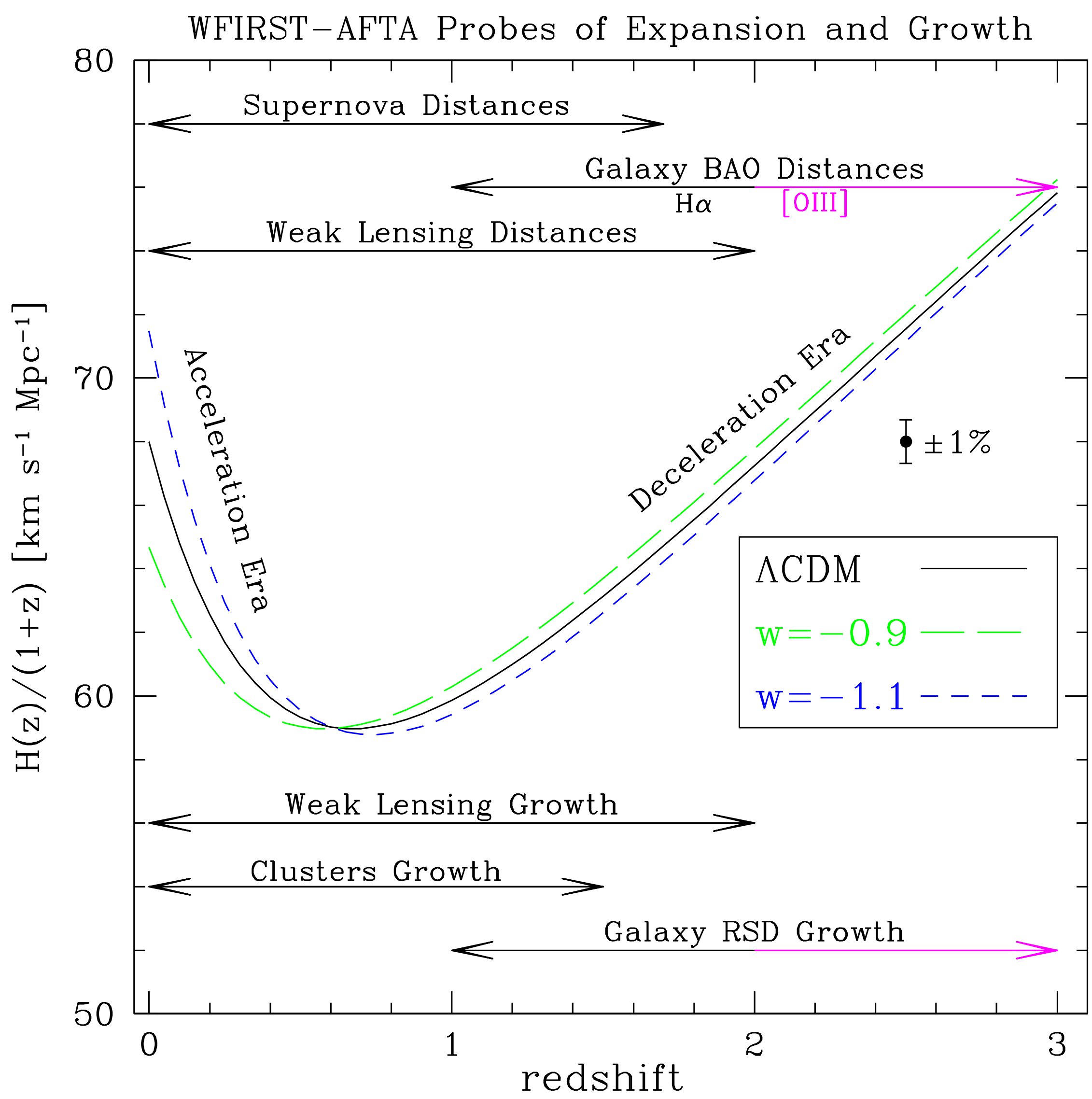
Push-Pull: Dark Energy vs Dark Matter





To understand the Universe's end fate, we must measure both dark matter and dark energy

WFIRST Dark Energy Program



WFIRST Dark Energy Roadmap

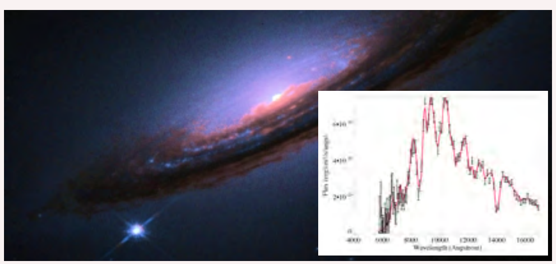
Supernova Survey

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

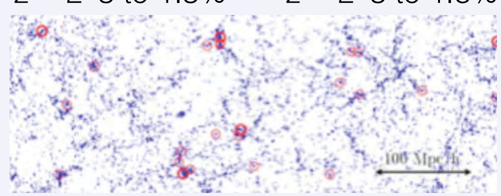
imaging: weak lensing shapes

400 million lensed galaxies
40,000 massive clusters

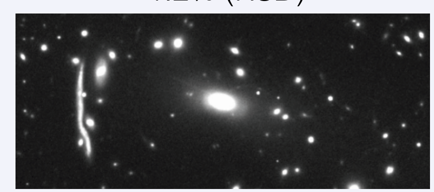
↓

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)



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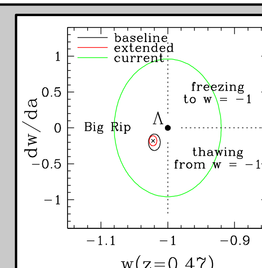
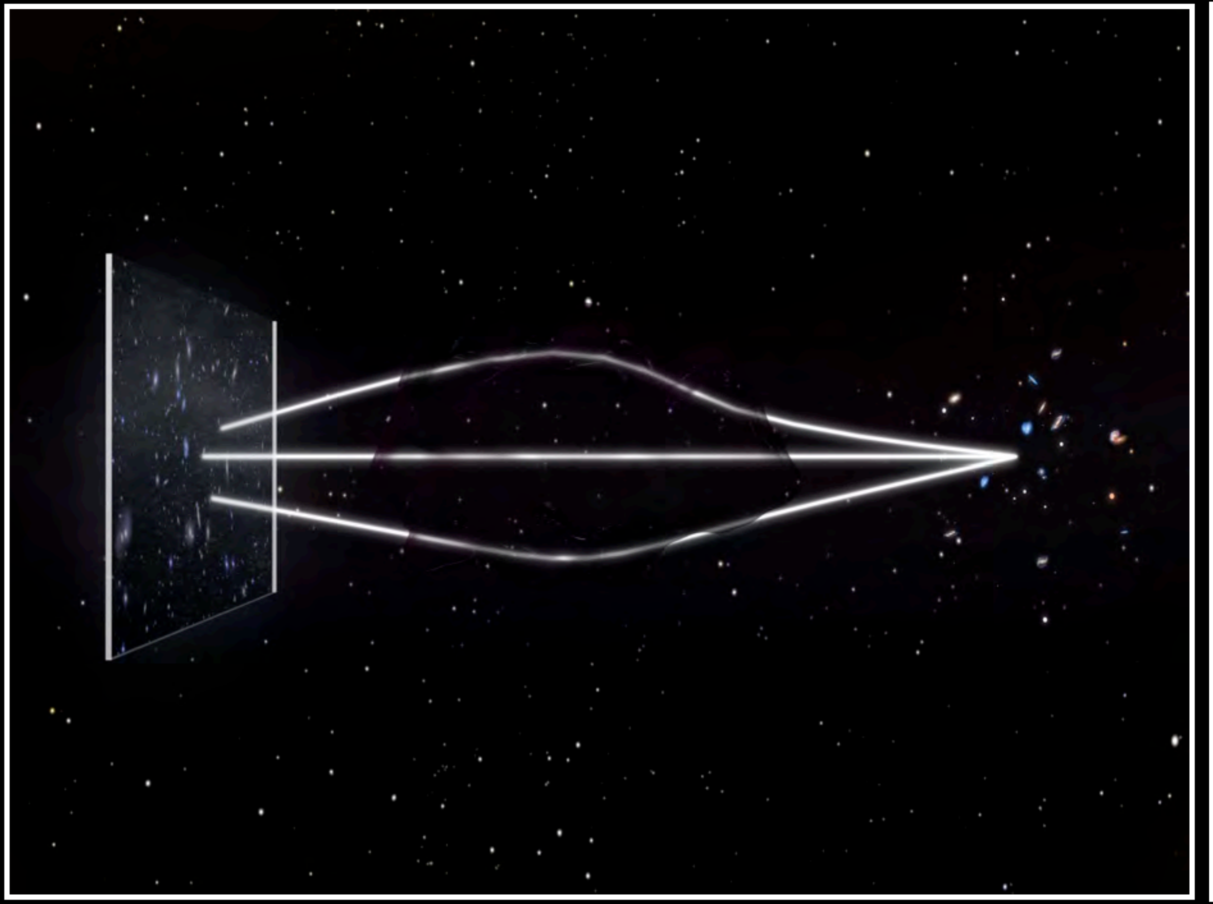
history of dark energy
+
deviations from GR

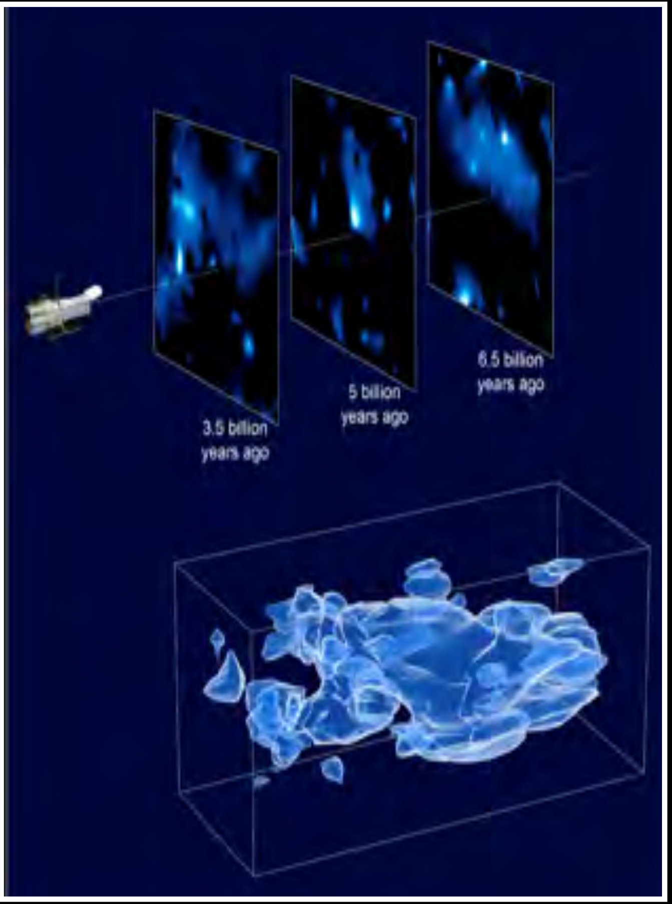
w(z), ΔG(z), Φ_{REL}/Φ_{NREL}



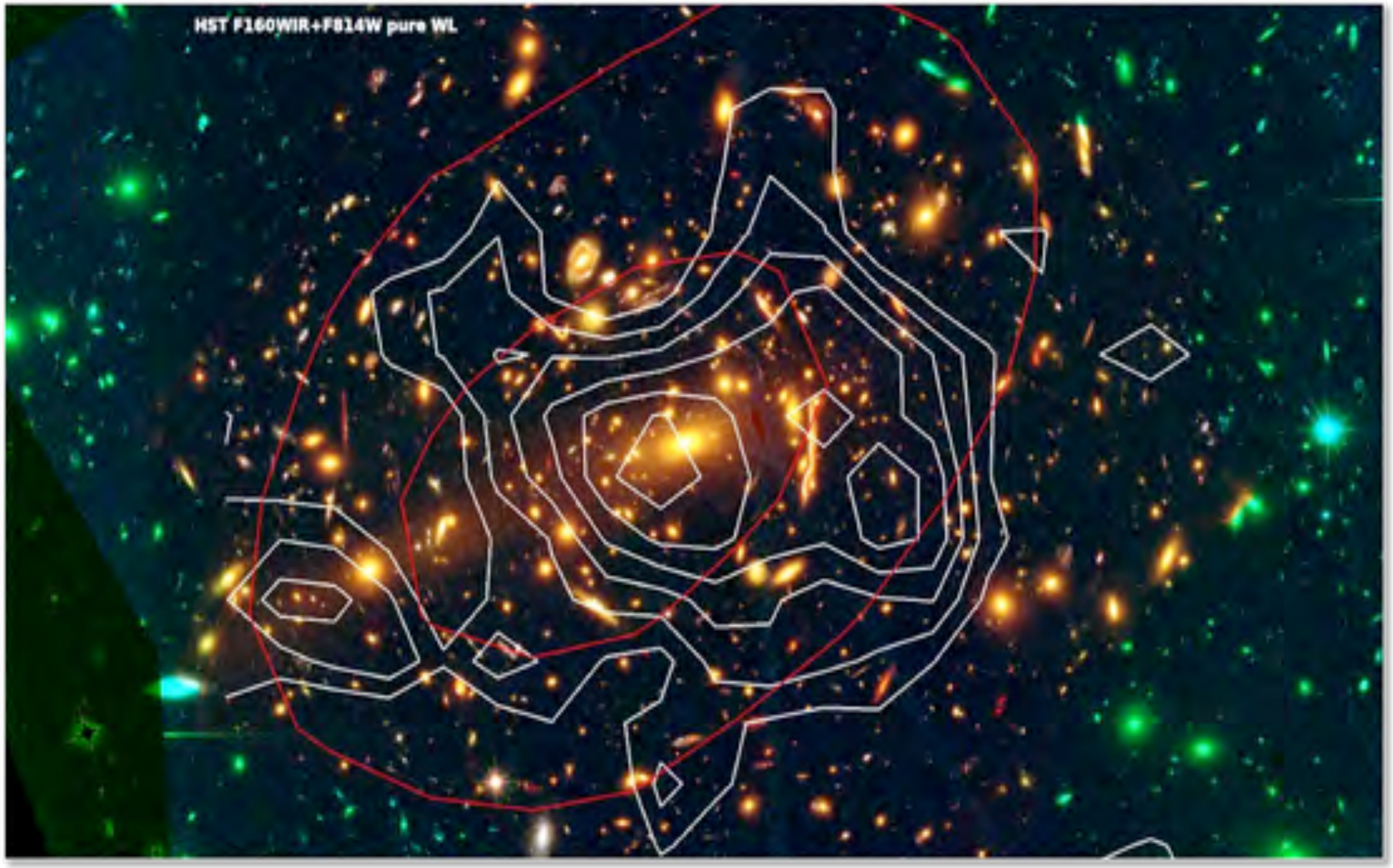
WFIRST will

measure galaxy shapes to map dark matter and measure the growth of galaxies over the Universe's life



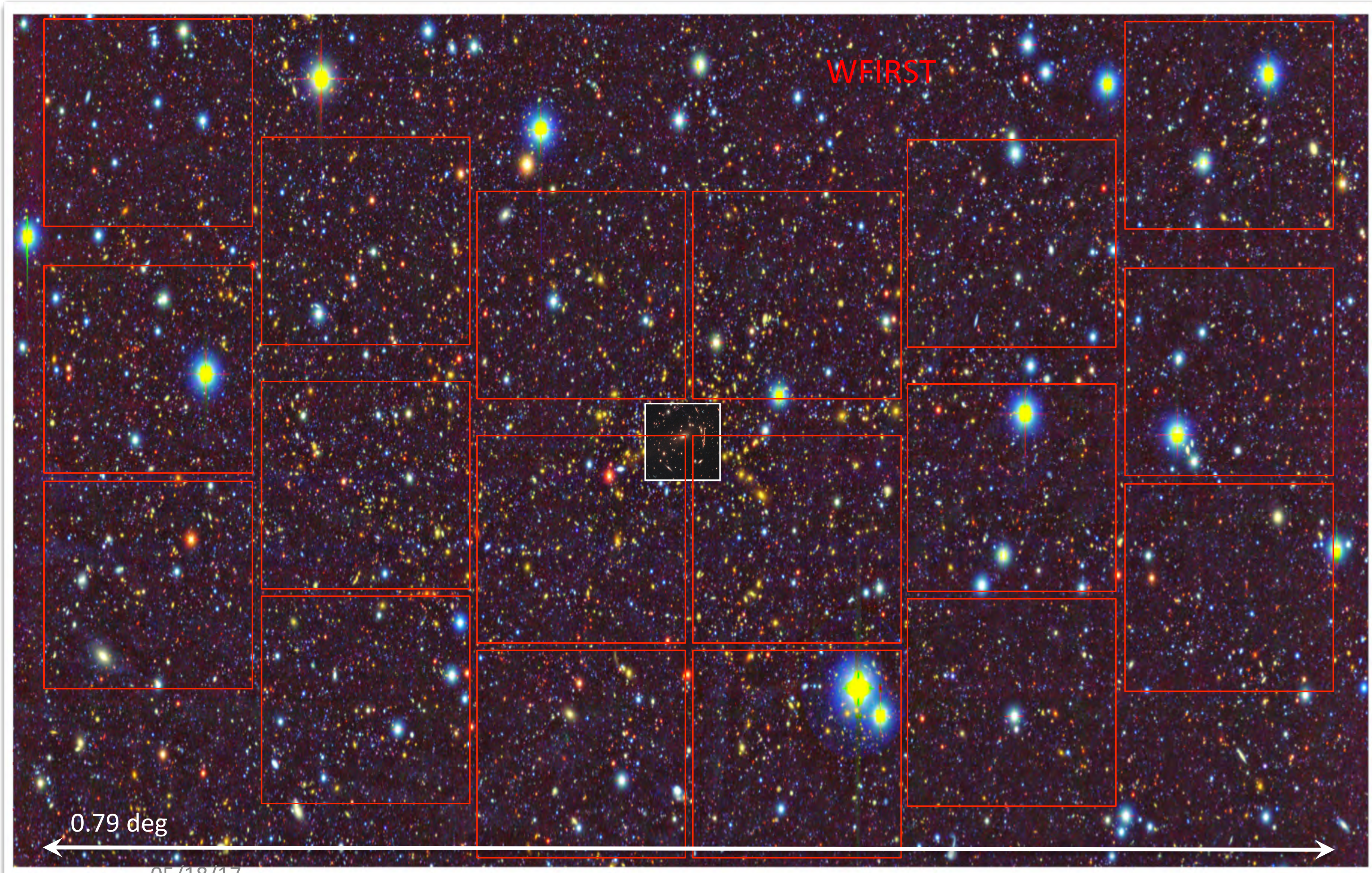


MACS J1206.2-0848 dark matter map



Mass density contours around the cluster MACS J1206.2-0848 derived from a ground-based weak lensing survey with Subaru (red) vs. a weak lensing study with HST/ACS+WFC3 (white). The 10x higher surface density of lensed galaxies achieved from space yields ~3x higher spatial resolution maps. The HST data shown here is representative of the WFIRST-AFTA HLS. WFIRST-AFTA will make a map of this quality over 2,000 square degrees as part of its high latitude survey, a thousand-fold increase over the HST COSMOS mass map.

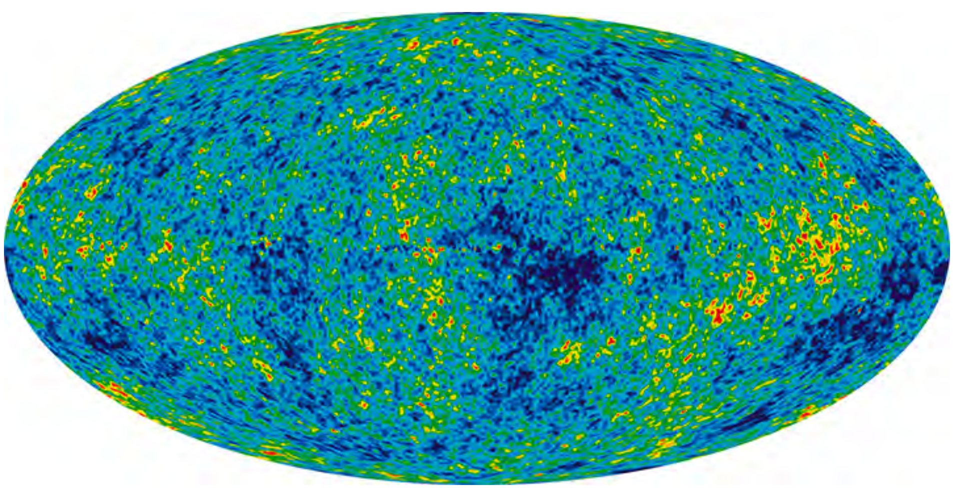
Gravitational Lensing

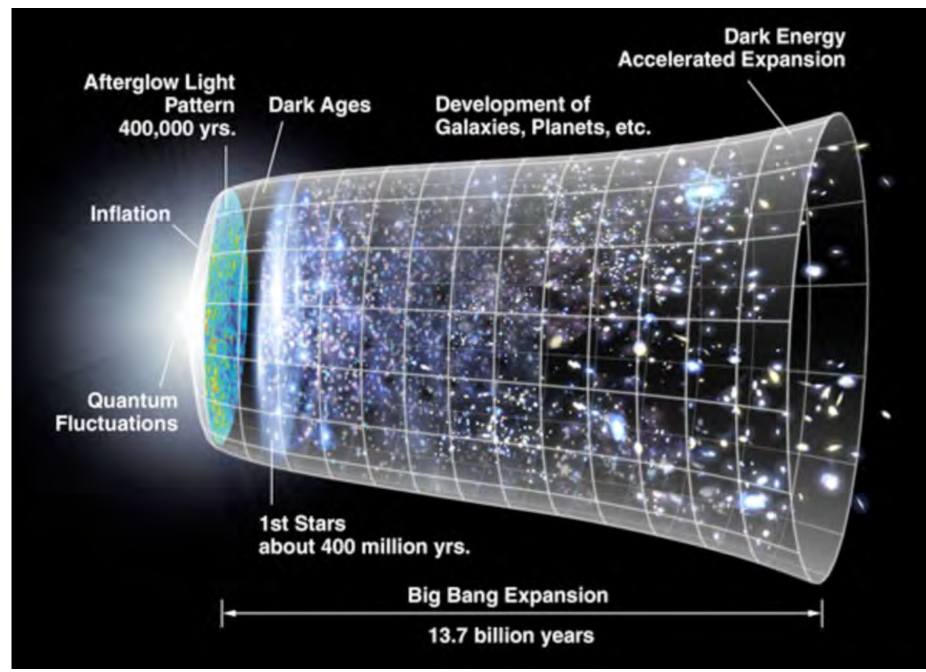


Galaxy Redshift Survey

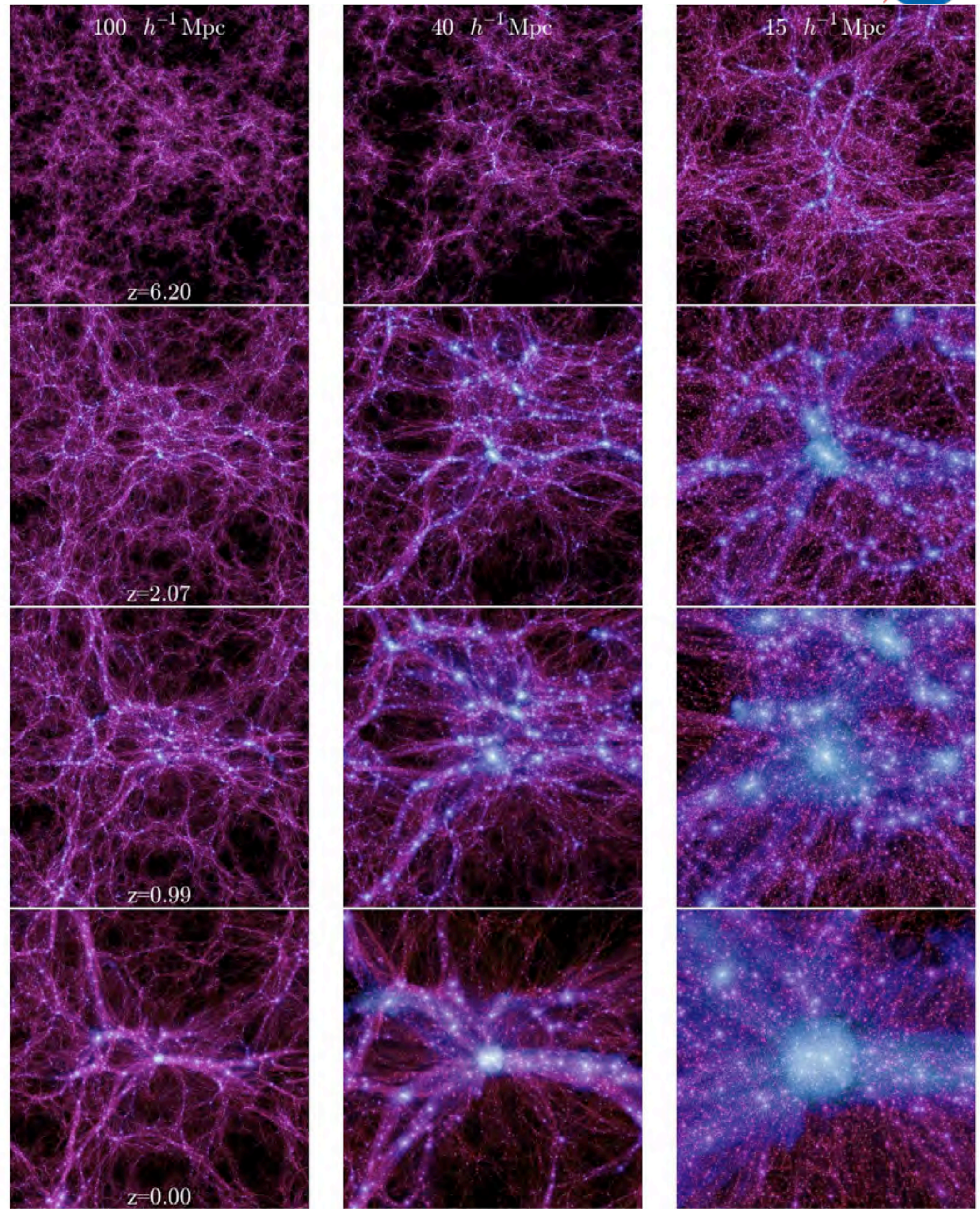
The early Universe imprints clumping on a characteristic length scale, set by the size of the Universe when matter became neutral, and is known from the intrinsic non-uniformity in the Cosmic Background Radiation.

These baryon acoustic oscillations provide a standard ruler in 3 dimensions for measuring cosmic expansion.

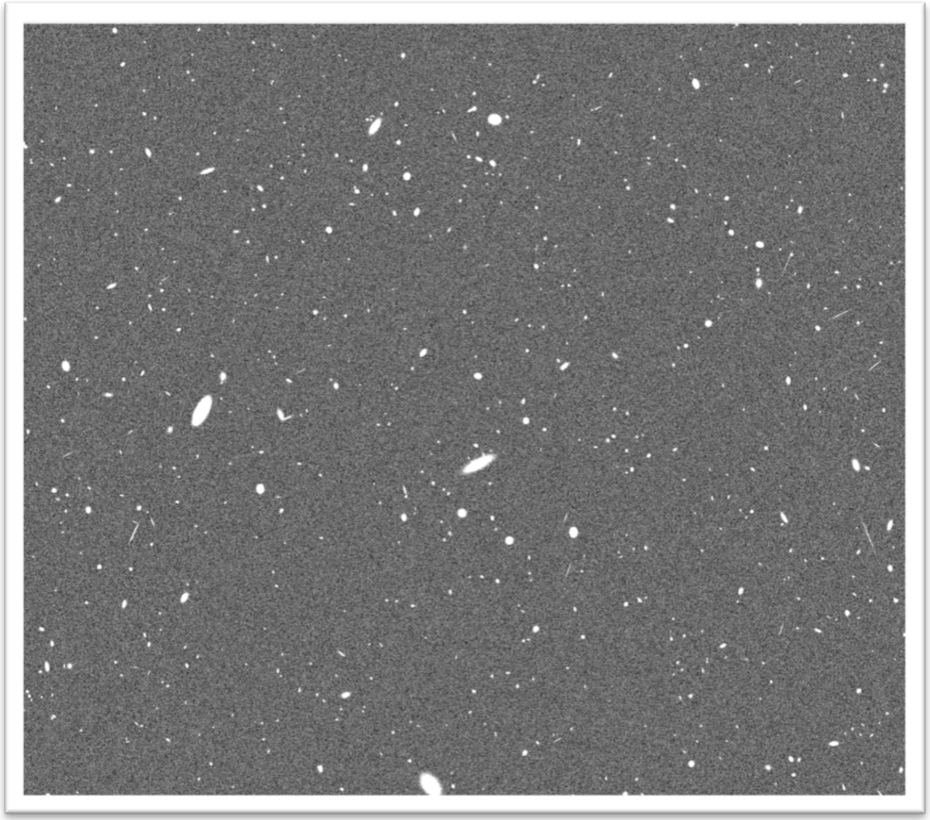


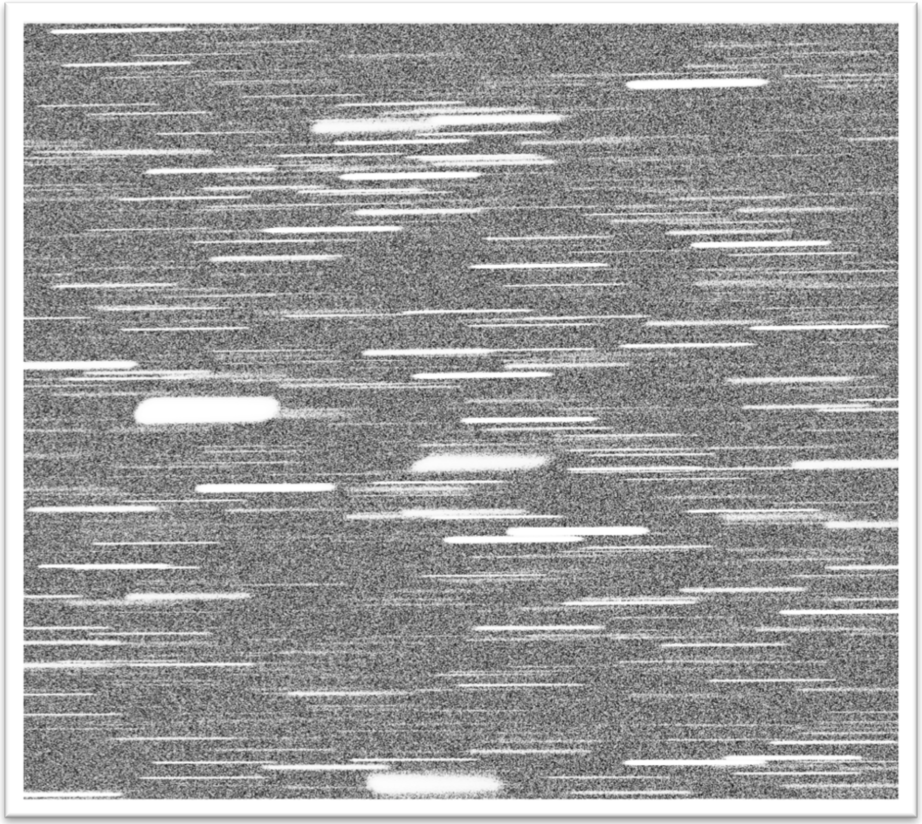


- Cold dark matter distribution from Millennium-II Simulation (Boylan-Kolchin et al. 2009).
    - Zoom varies left to right
    - Time passes top to bottom
- Galaxies form at dense regions.
- Spacing governed by imprint of BAO: standard ruler gives evolution of distance scales as function of redshift.

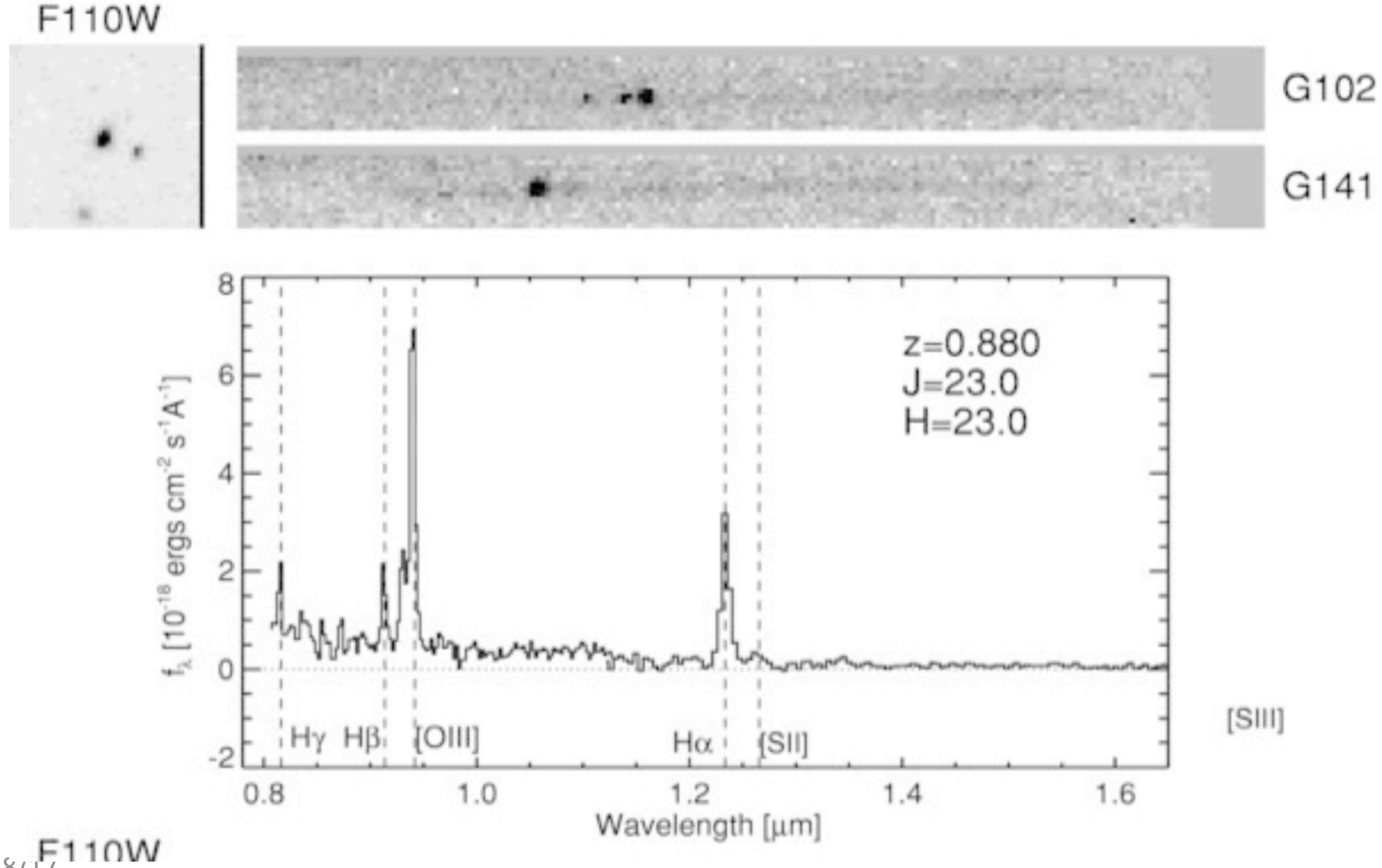


Use imaging & slitless spectroscopy to measure 3-D galaxy distribution



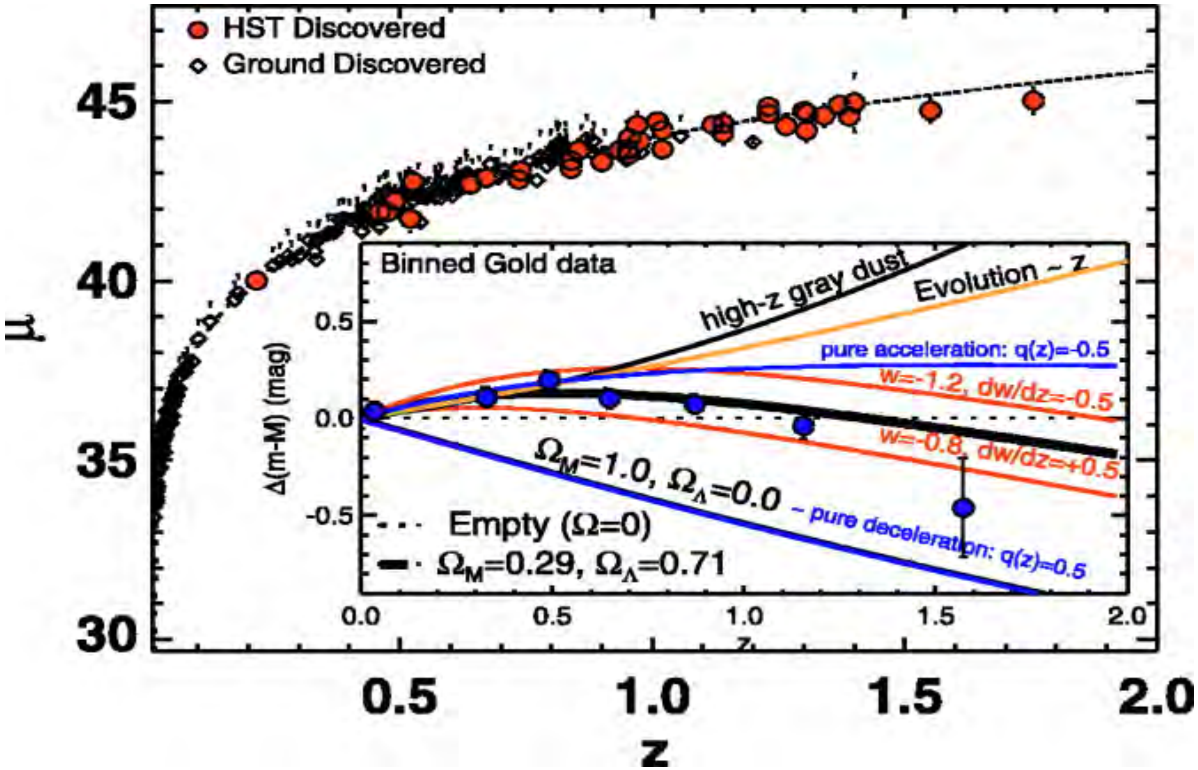


Sample HST WFC3-IR grism spectrum (Atek et al 2010)



Type Ia supernovae

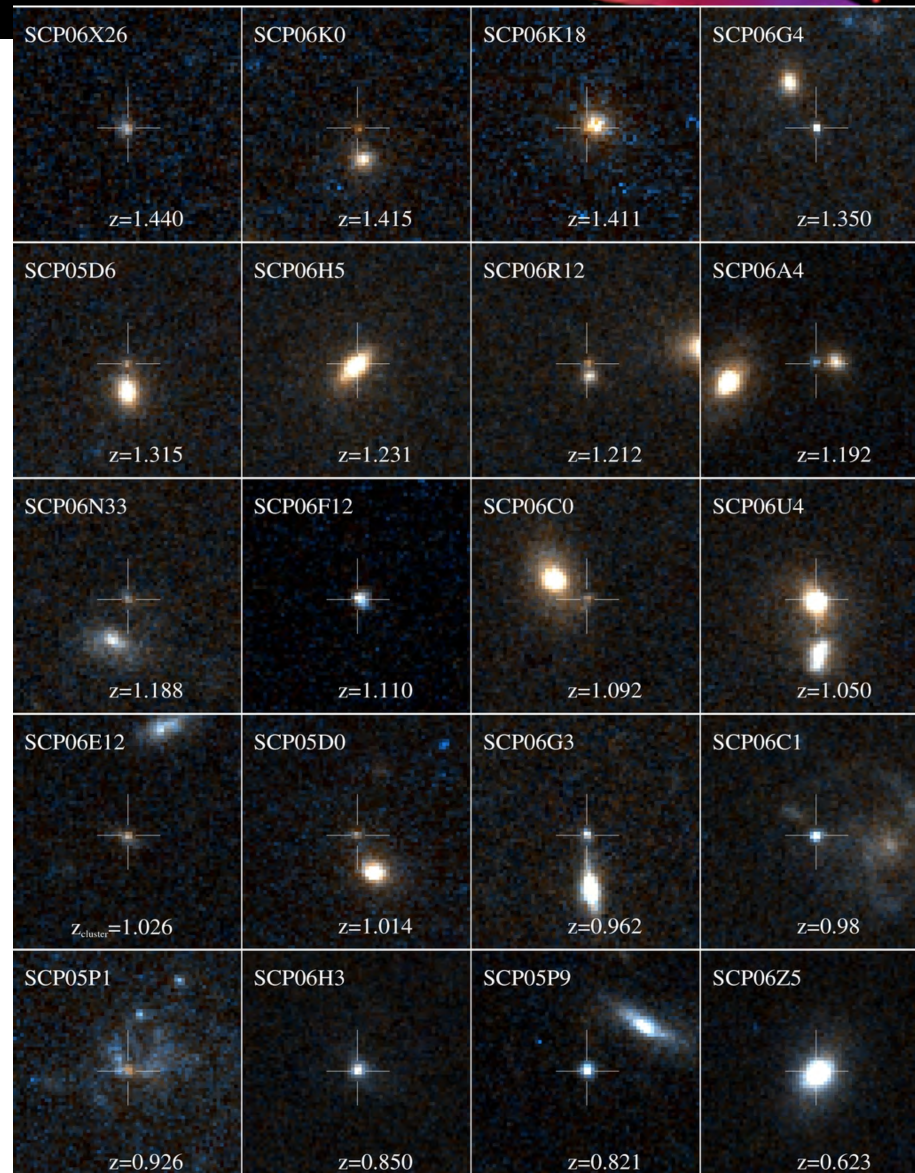
- Type Ia supernovae have “known” peak intensity.
- Number of received photons tells us distance ($1/r^2$).
- Obtain ~100 Ia SNe per $\Delta z=0.1$, for $0.2<z<1.7$



Observing Supernovae

Sometimes SNe are well-separated from their host galaxy, and sometimes they're not!

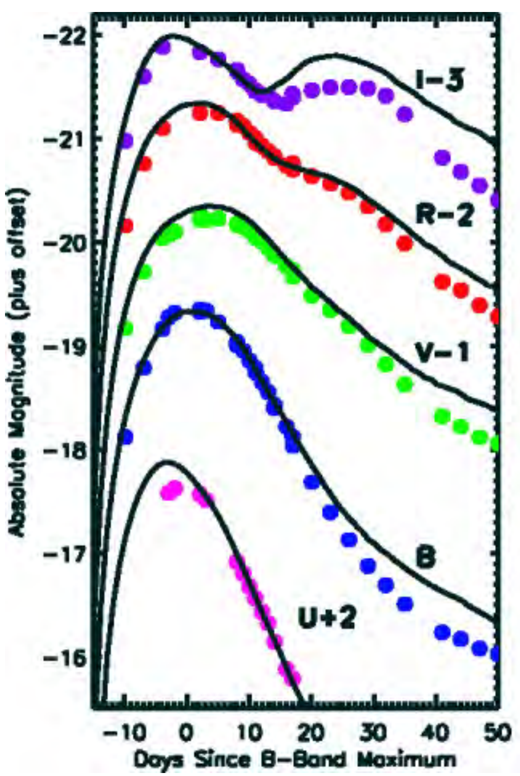
Have to accurately subtract the light of the host galaxy.



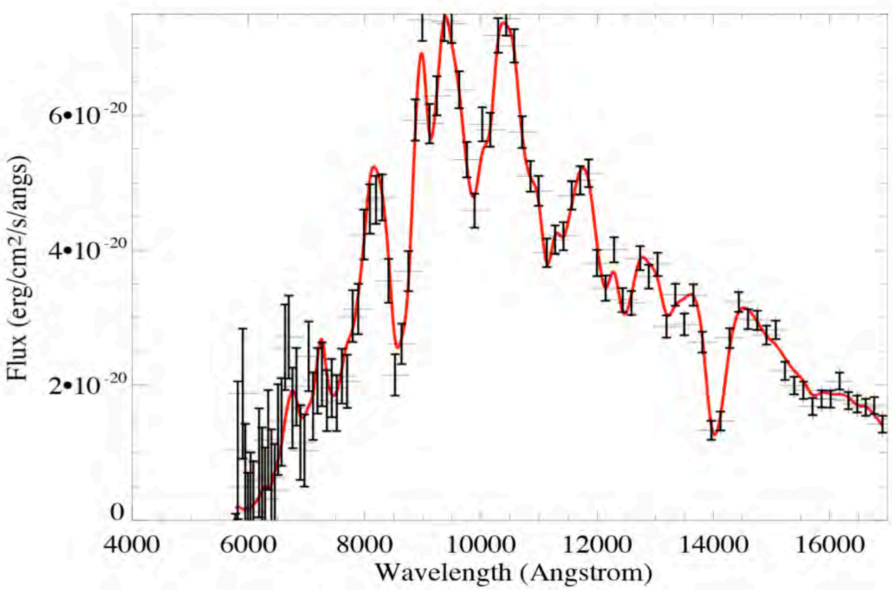
N. Suzuki et al. 2012 ApJ 746 85 doi: 10.1088/0004-637X/746/1/85

WFIRST SN Ia

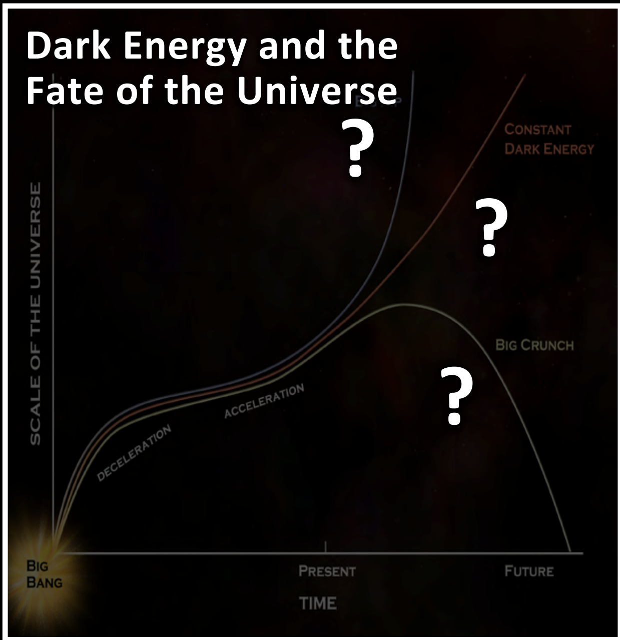
- SN discovery via imaging
- IFU Spectrophotometry for follow-up

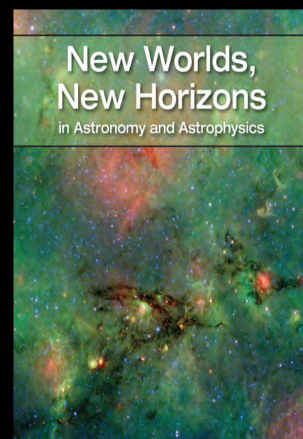


- Need spectrum to measure redshift & confirm type
- Need rest-frame spectral energy distribution to obtain luminosity at fiducial wavelengths and to correct for dust extinction
  - Obtain spectra or multi-band imaging light-curves



Our Guiding Principle





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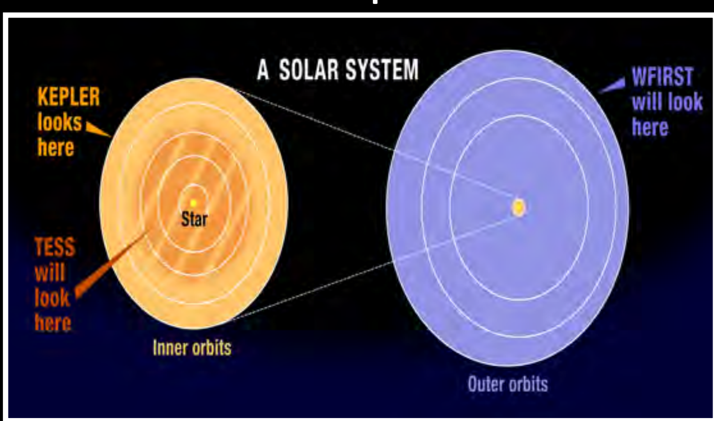
Astronomy & Astrophysics
Decadal Survey (2010)

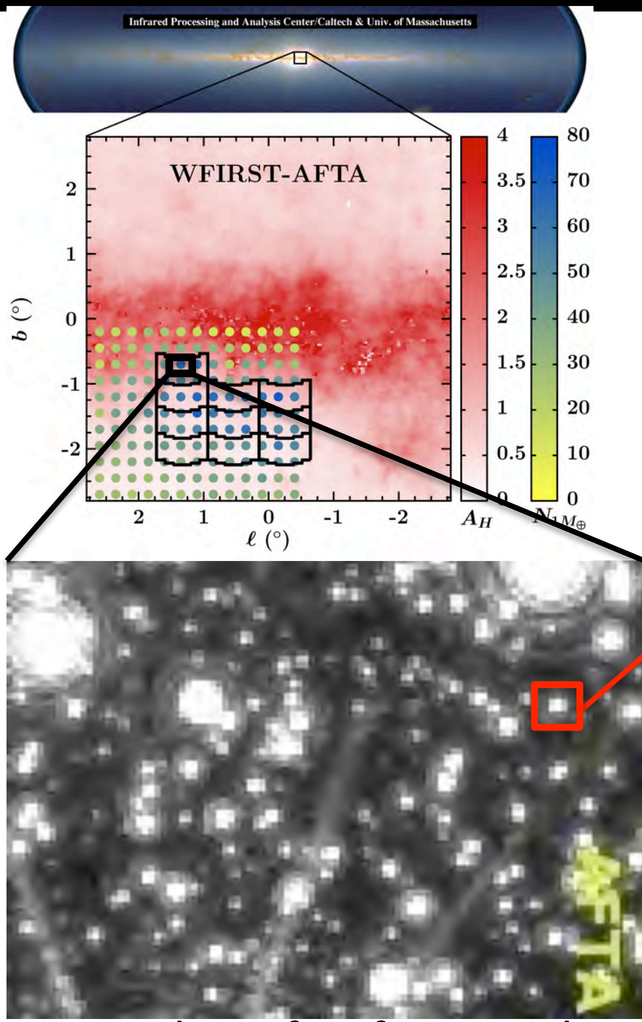
The full distribution of planets around stars

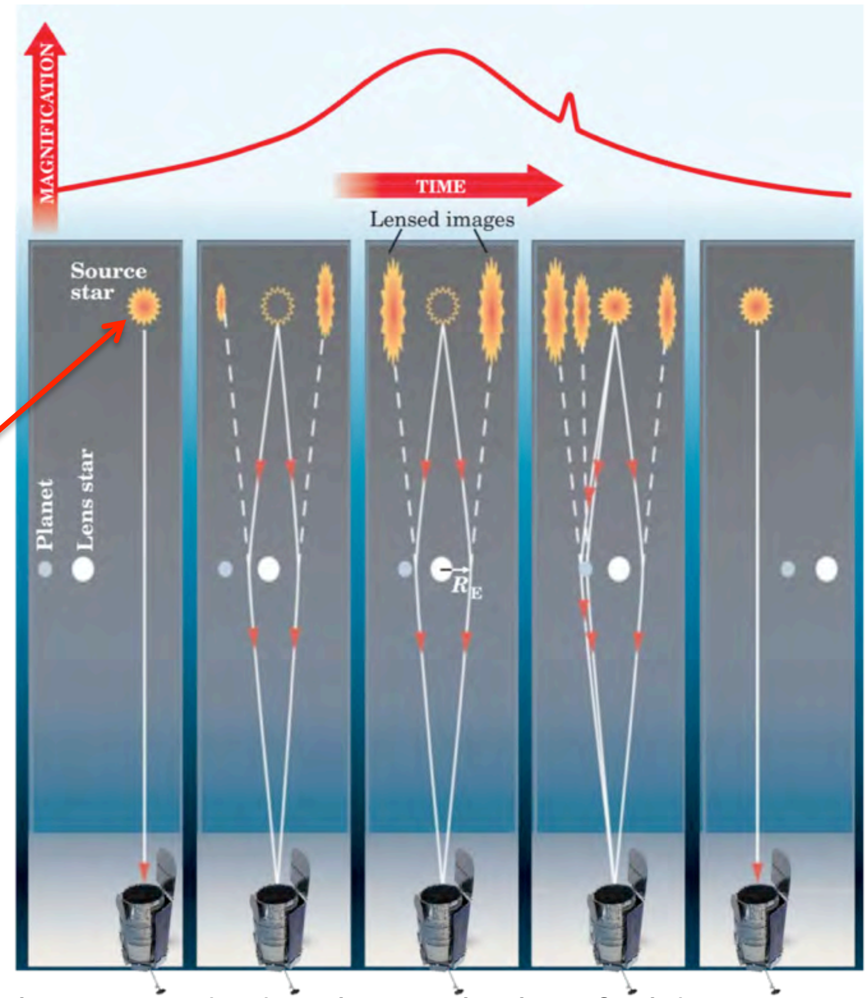


Planetary Microlensing

- Observe gravitational lensing by planets along the line of sight to distant stars
  - Monitor 3 sq deg in Galactic Bulge at 15 minute cadence
- Obtain a census of planet masses and orbit radii at the habitable zone and beyond
- Anticipate discovery of ~2600 bound planets of Mars mass and above, and hundreds of free-floating planets.

Microlensing Technique



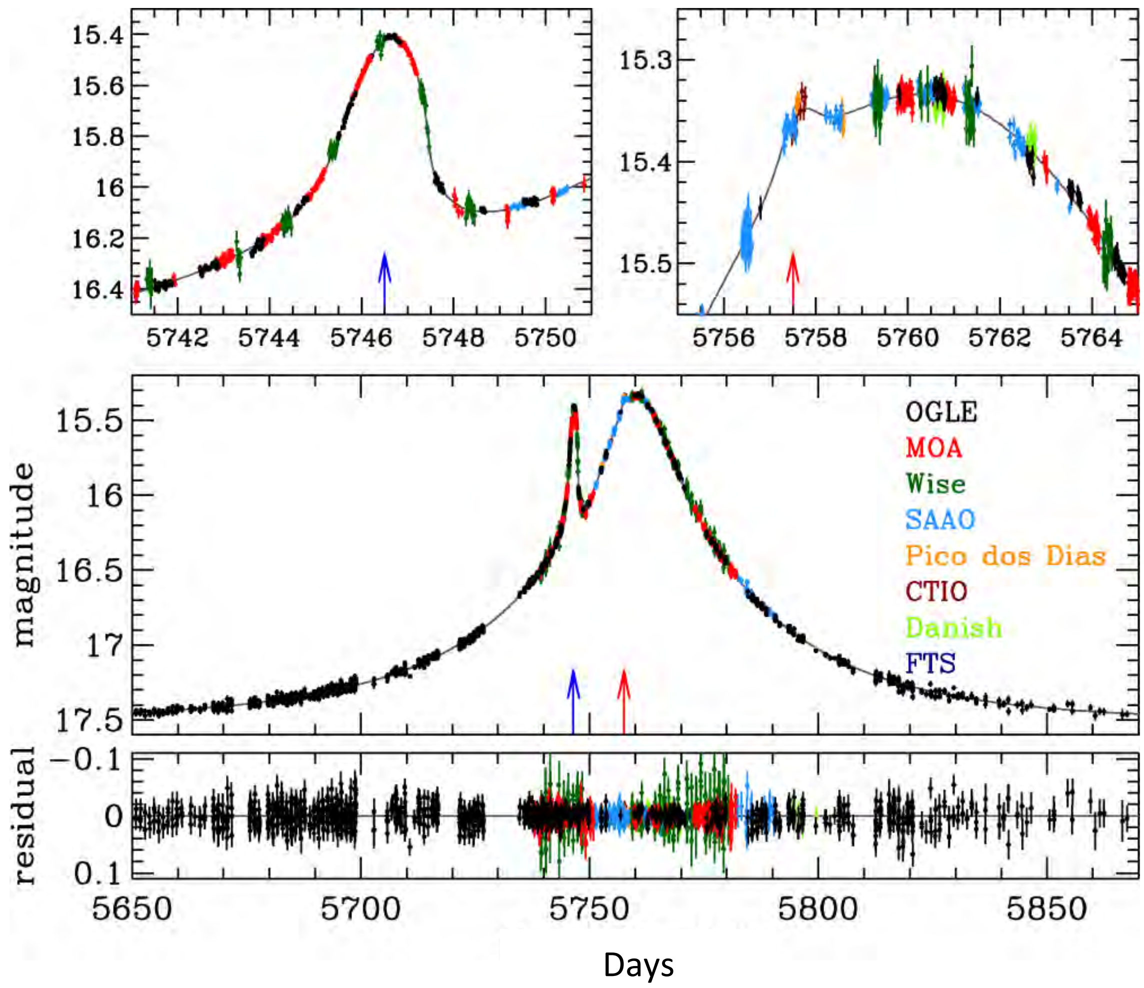


Great benefit of space observations in the crowded galactic bulge field

Microlensing example

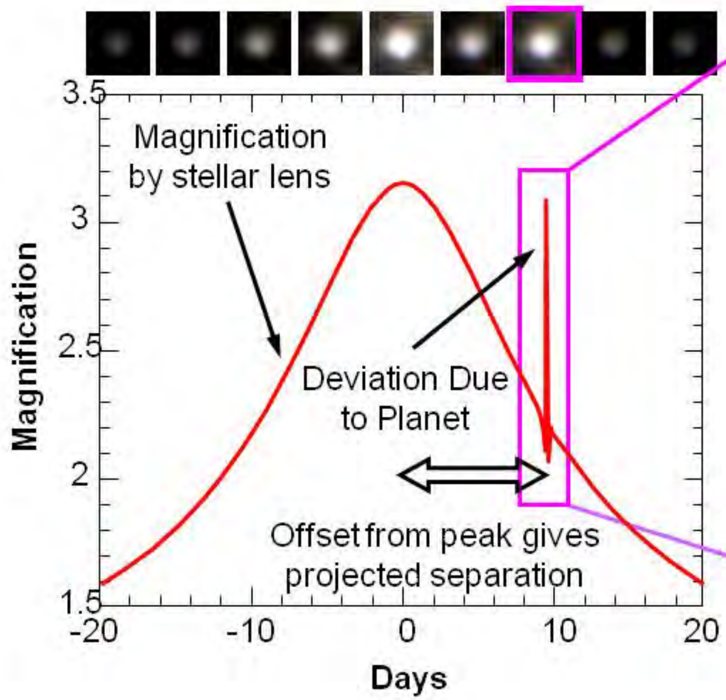
Microlensing event from Jupiter-mass planet around an M-dwarf

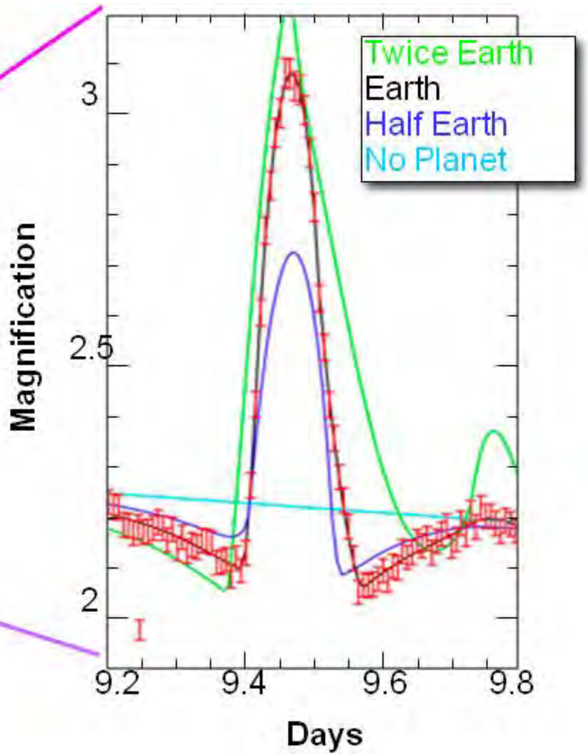
(Skowron et al 2015):



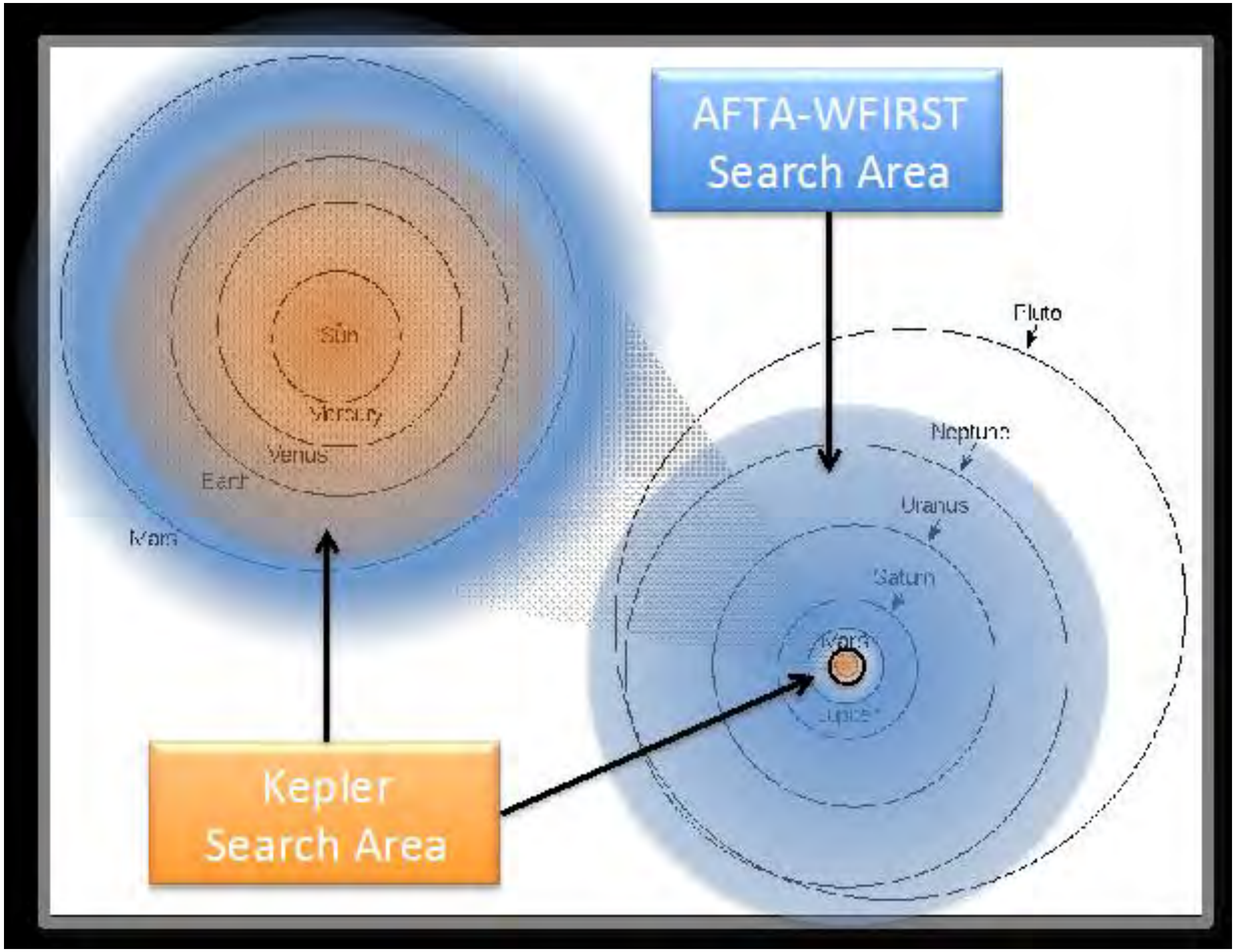
Microlensing simulation

- Simulated WFIRST microlensing event by Earth-mass planet.
  - Magnification by planet is similar to event on previous slide, but duration is ~10X shorter.

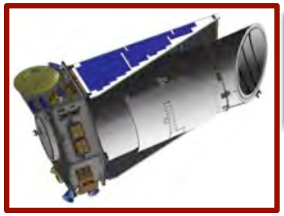




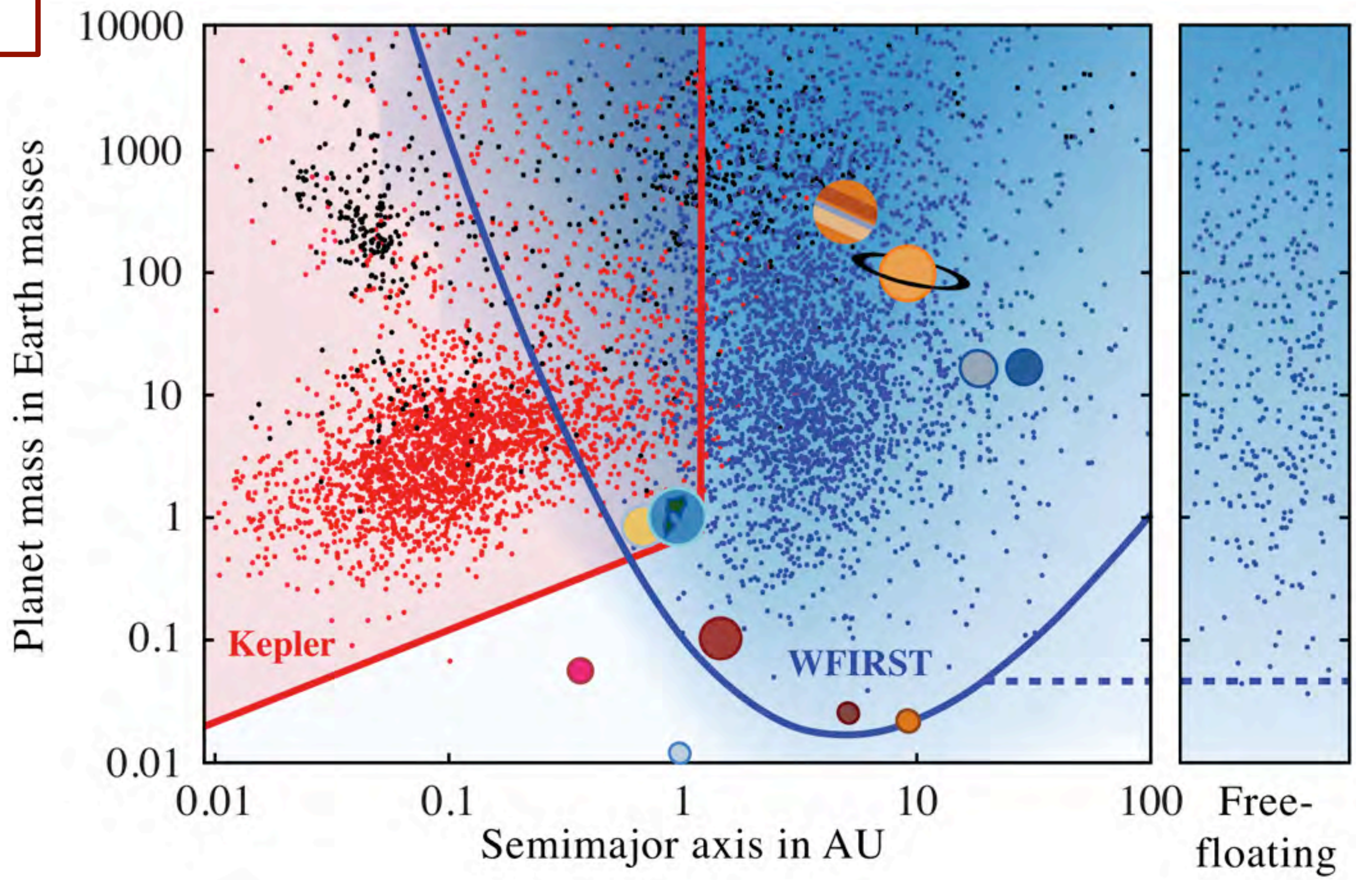
WFIRST Complements Kepler



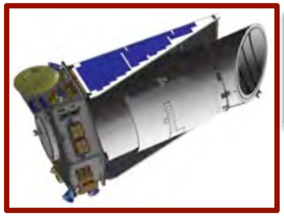
Completing the Statistical Census of Exoplanets



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



Completing the Statistical Census of Exoplanets



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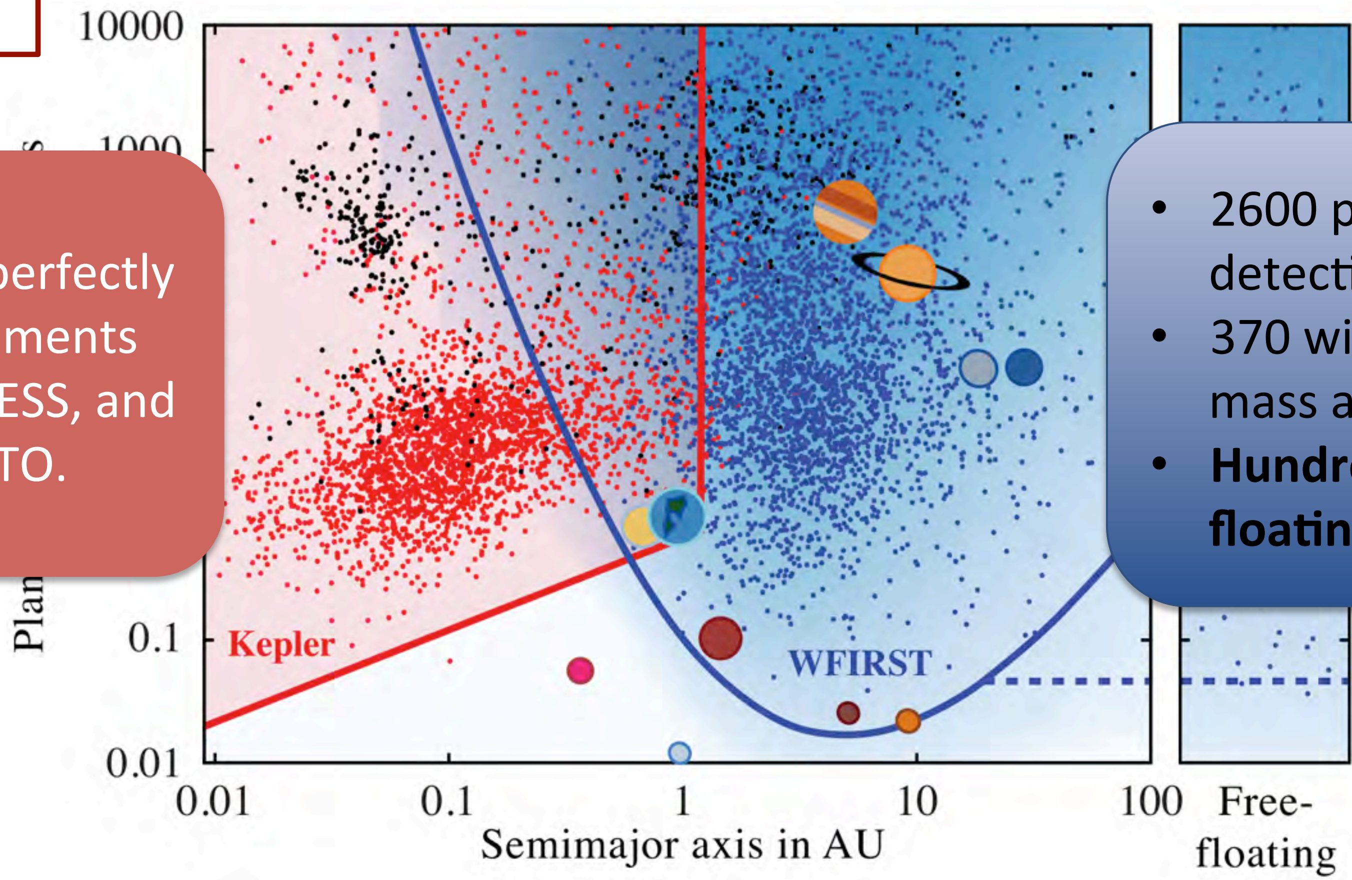
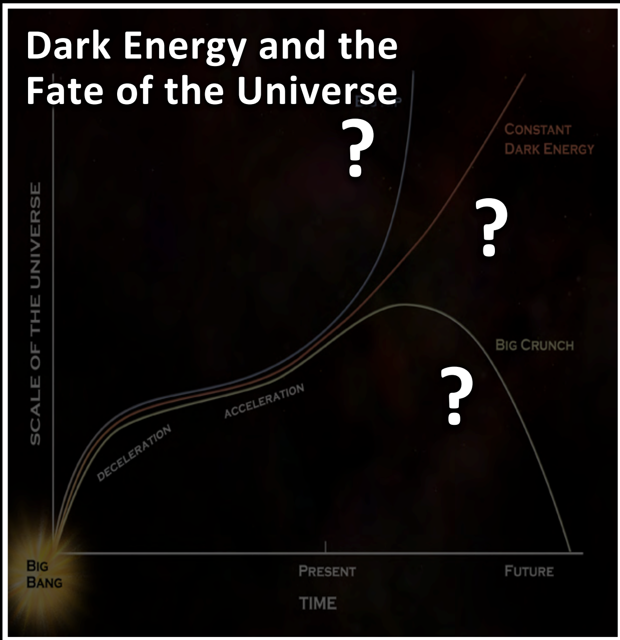
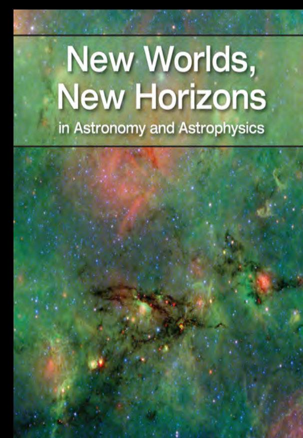


WFIRST perfectly complements Kepler, TESS, and PLATO.

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

Our Guiding Principle





National Academy of Sciences
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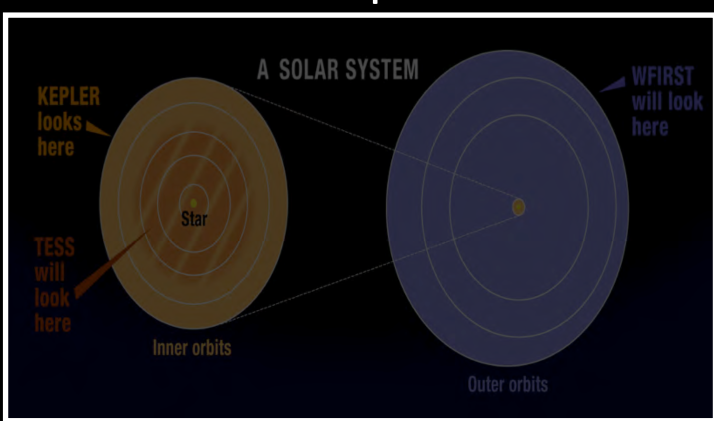

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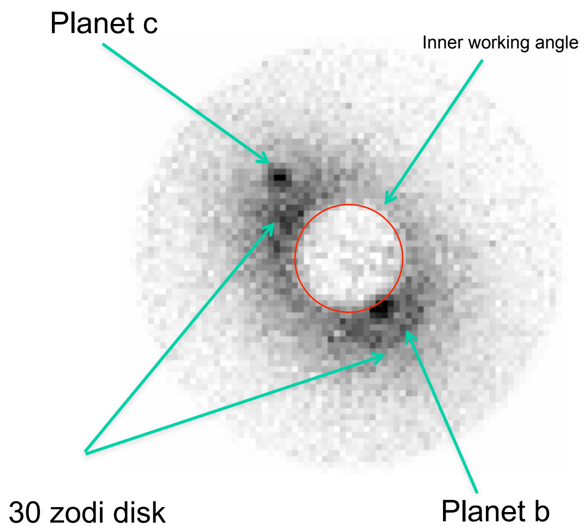
WFIRST Coronagraphy

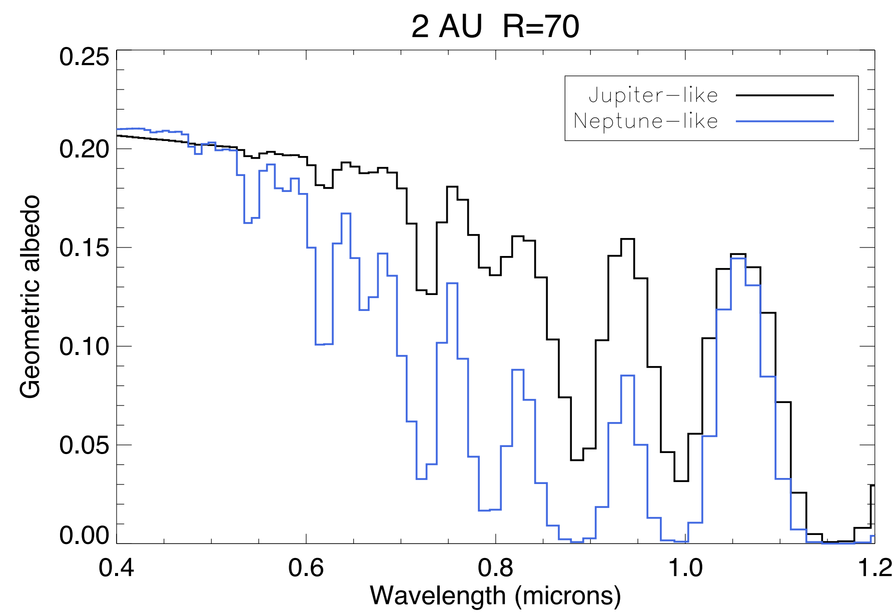
- Science program defined to drive technology, inform instrument design parameter decisions
  - Determine characteristics of exo-zodiacal dust disks
  - Survey ~200 nearby stars, spanning a range of spectral types, with and without known exoplanets
  - Characterize 10-20 planets at $>4R_E$ in reflected light
    - 5 bands, 10% relative photometry
  - Spectroscopic characterization of 6-10 planets
    - Determine depth of H_2O, methane, absorption to 15%
  - Detect sample at $<4R_E$ in reflected light
  - Determine semi-major axis, eccentricity, of each planet

Coronagraphy

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



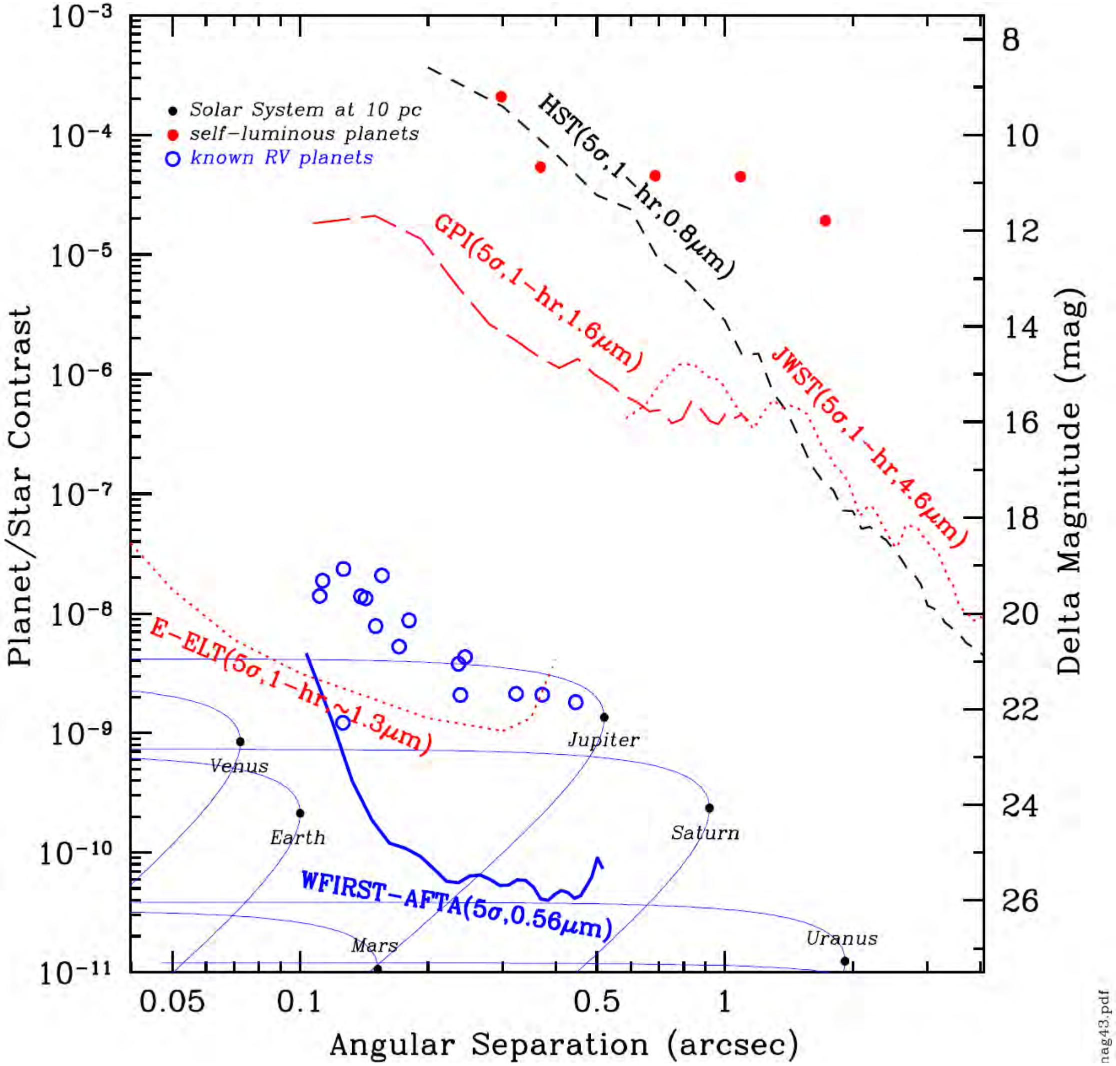
Simulated WFIRST coronagraph image of the star 47 Ursa Majoris, showing two directly detected planets.



Each coronagraph pointing will yield day-long WFI deep-fields (0.28 sq deg).

WFIRST Brings Us Closer to Characterizing exo-Earths

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



WFIRST High-Contrast Imaging

- ✓ WFIRST significantly expands the population of characterized planets
  - Figure at right shows known exoplanets (mostly Kepler detections), those characterized by transit spectroscopy, & representative parameter space of planets that we can expect to explore with WFIRST.

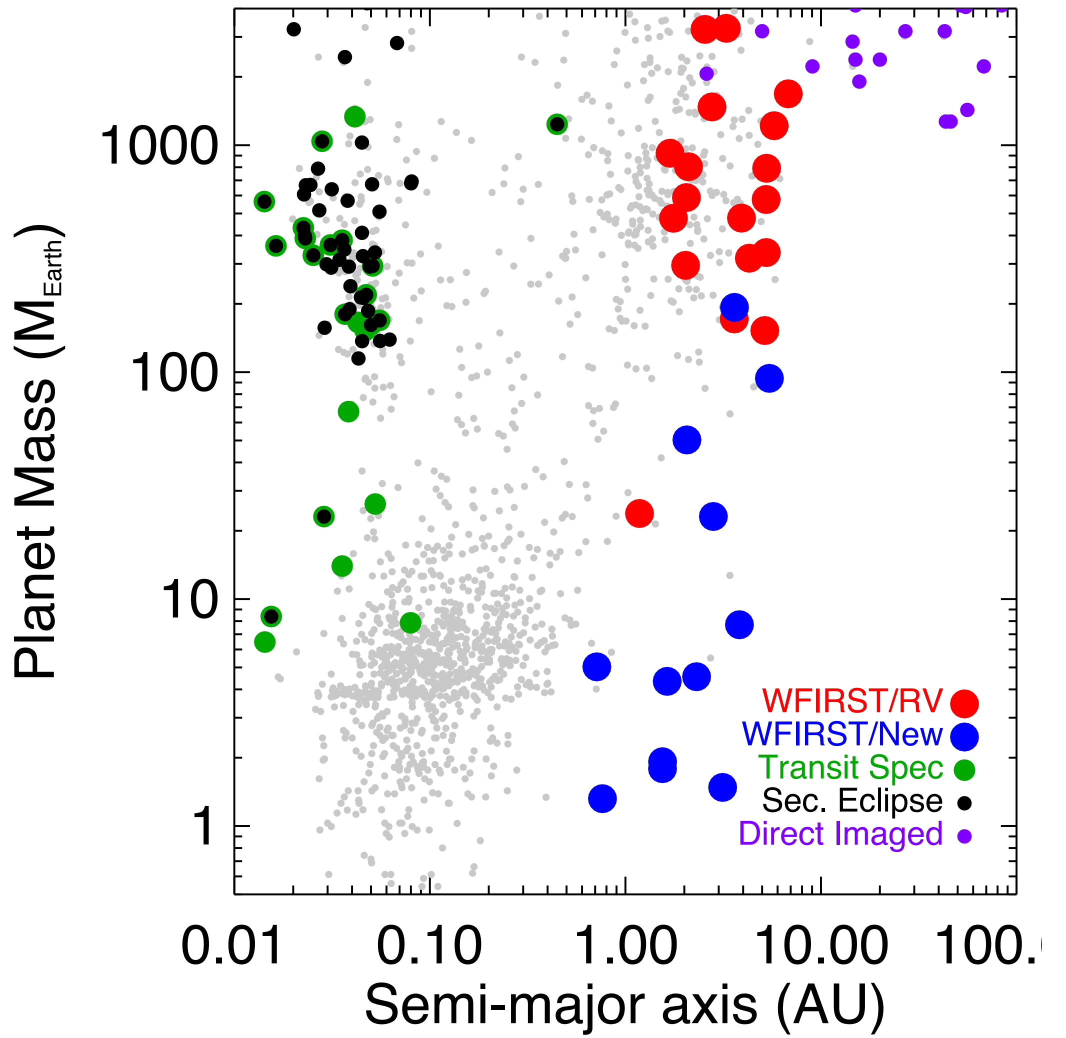
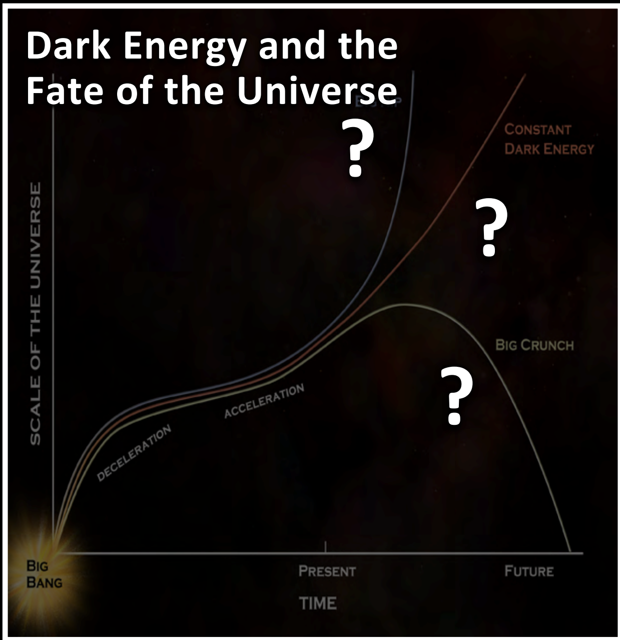
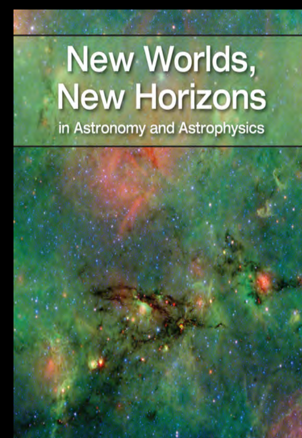


Figure from Eric Neilsen

Our Guiding Principle





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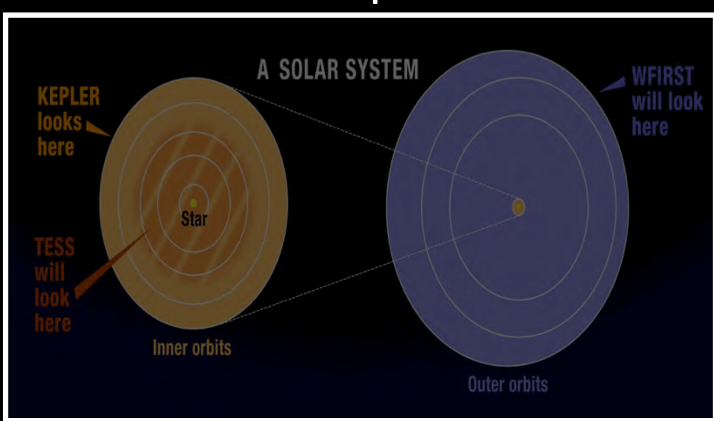
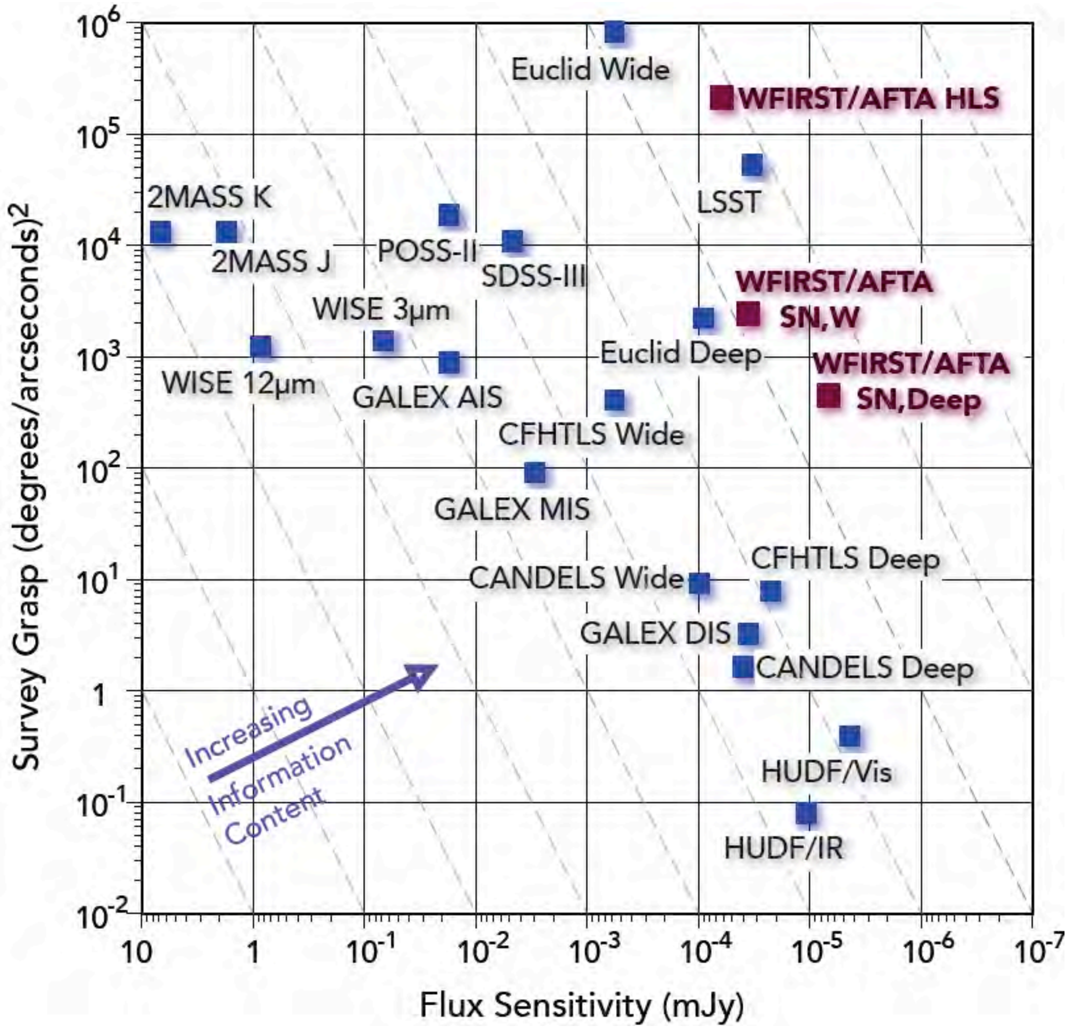
The full distribution of planets around stars



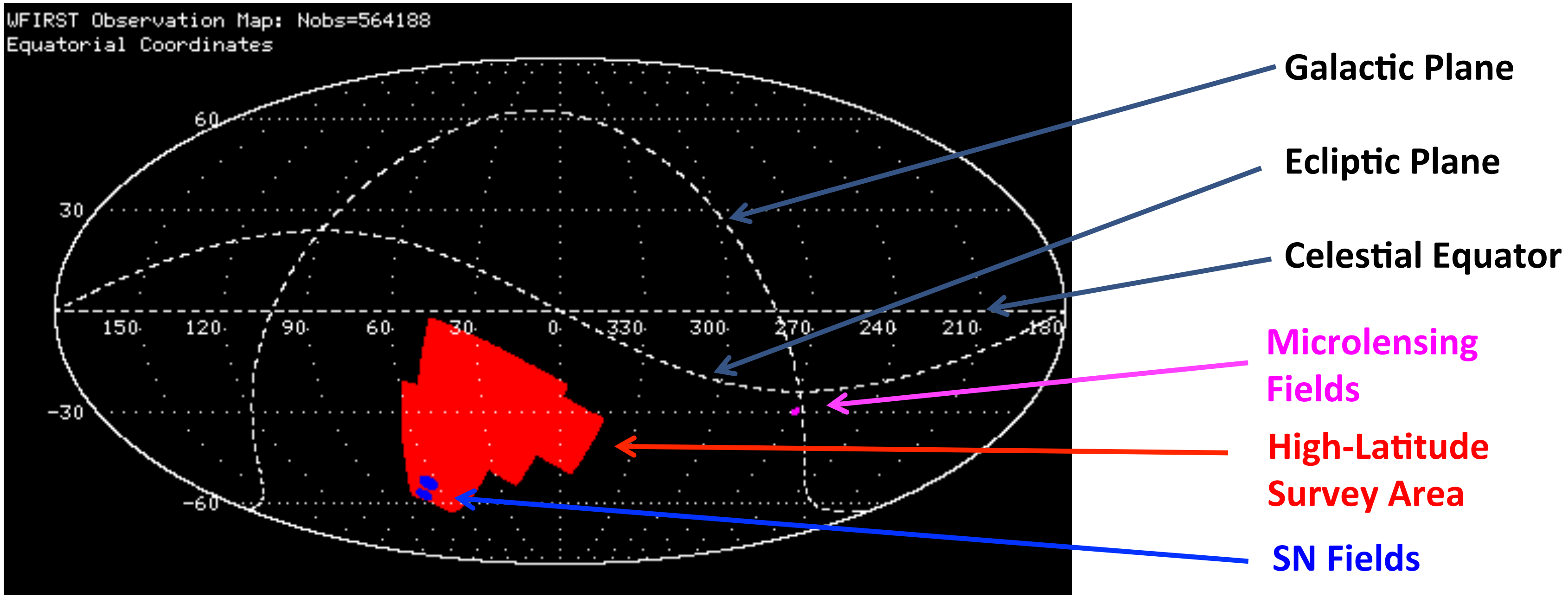
WFIRST Surveys

- 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



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 (GO program)



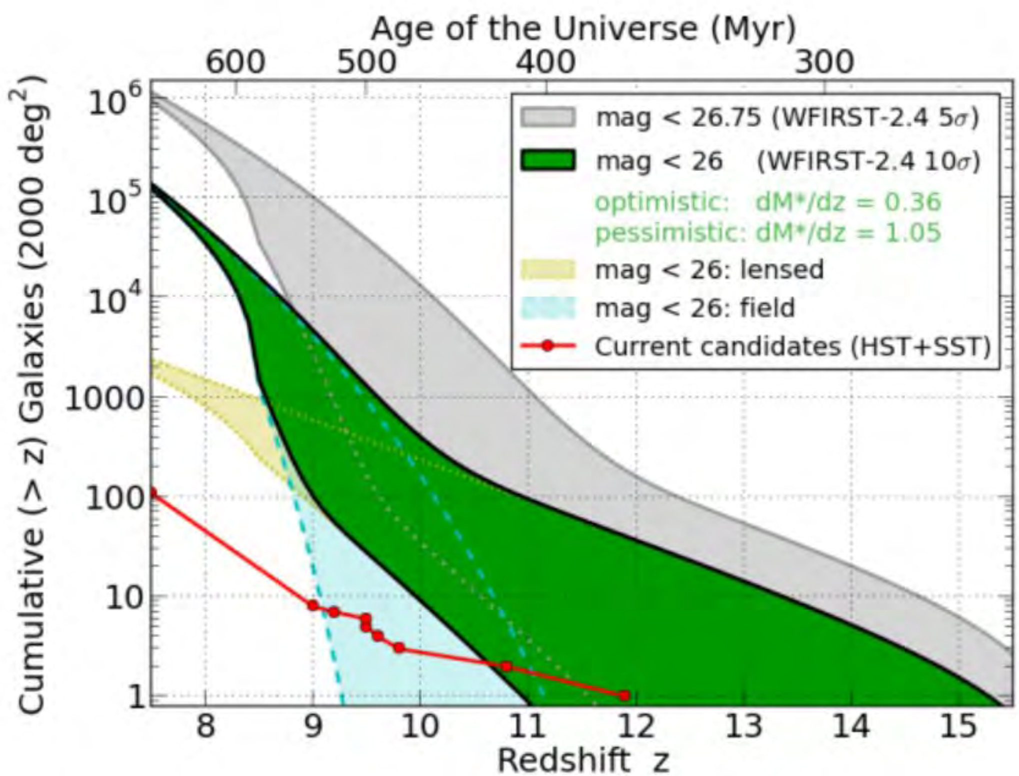
Astrometry with WFIRST

- GAIA stars provide reference frame
  - WFIRST should achieve 500 μas or better on each observation of a GAIA star
  - High Latitude survey
  - ~20 observations per star over ~5 years
    - ~100μas/yr proper motions down to AB~23
- Galactic bulge survey
  - ~40,000 observations per star
  - Sub-μas astrometry?

Finding the Most Distant Galaxies

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

- WFIRST will find interesting distant galaxies for JWST and future narrow-field telescopes to observe



Estimates from Dan Coe & Larry Bradley

Program Status

- Substantial technical progress on WFIRST over the past two years:
  - NIR detector maturation – now at TRL-6
    - Ready to begin flight procurement later this year
  - Coronagraph technology demonstrations
  - Observatory integrated modeling

Program Status

- Mission Concept Review completed Dec 8-9.
- Formulation Science team selected Dec 23
- Begin Phase A February 17, 2016!
- Begin Phase B early 2018
- Significant international interest (Canada, ESA, Japan, Korea)
- Launch: mid - 2025
  - Depends on budget appropriations

Science Investigation Teams

David Spergel	WFI Adjutant Scientist
Jeremy Kasdin	CGI Adjutant Scientist
Olivier Doré	Weak lensing and galaxy redshift survey
Saul Perlmutter	Supernovae
Ryan Foley	Supernovae
Scott Gaudi	Microlensing
Bruce Macintosh	Coronagraphy
Margaret Turnbull	Coronagraphy
Jason Kalirai	GO science, milky way
James Rhoads	GO science, cosmic dawn
Brant Robertson	GO science, galaxy formation & evolution
Benjamin Williams	GO science, nearby galaxies
Alexander Szalay	GI science, archival research

QUESTIONS?

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WFIRST Mandate

- 2010 **NRC (NWNH) recommends WFIRST:**
  - **"Why is the expansion rate of the universe accelerating? And are there other solar systems like ours, with worlds like Earth?"**
  - **"To measure the properties of dark energy, WFIRST will employ three different techniques:**
    - **carry out a detailed study of weak lensing that will provide distance and rate-of-growth information;**
    - **monitor distances and expansion rate using baryon acoustic oscillations**
    - **detect about 2,000 distant supernova explosions, which can be used to measure distances."**

WFIRST Mandate (but wait – there's more!)

- 2010 **NRC (NWNH) recommends WFIRST:**
  - **"WFIRST will carry out a powerful extrasolar planet search by monitoring a large sample of stars in the central bulge of the Milky Way for small deviations in brightness due to microlensing by intervening solar systems. This census, combined with that made by the Kepler mission, will determine how common Earth-like planets are over a wide range of orbital parameters."**
  - **"WFIRST will also offer a guest investigator program"**

Planned Wide-area Surveys

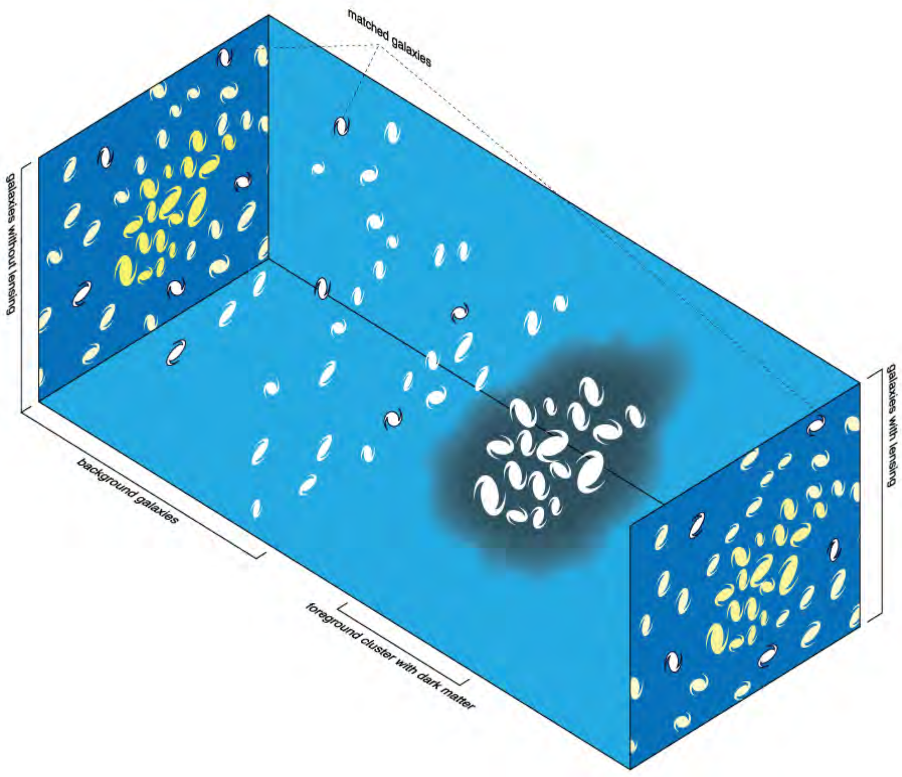
- Based on 2015 Science Definition Team Report
- This is an example of how the mission may be planned, but final surveys may differ
  - Much flexibility in choice of DE surveys
  - May well choose to go wider, shallower

Weak Gravitational Lensing

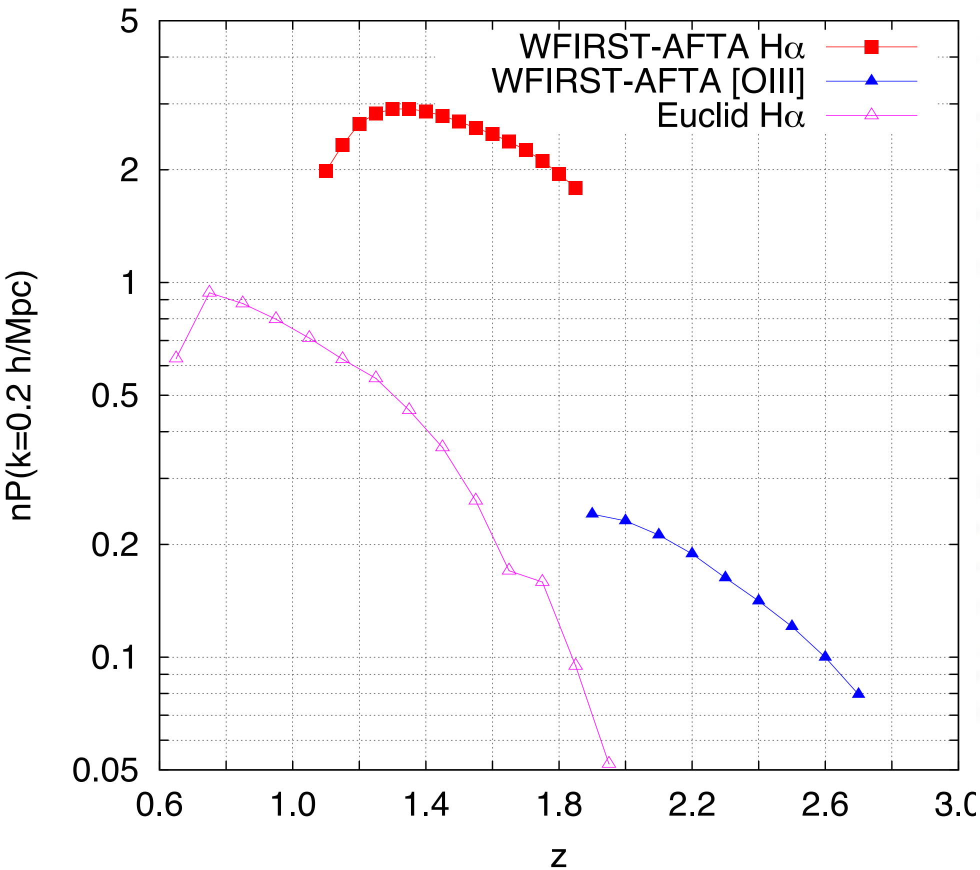
Foreground matter distribution induces correlated distortions in shapes of background galaxies

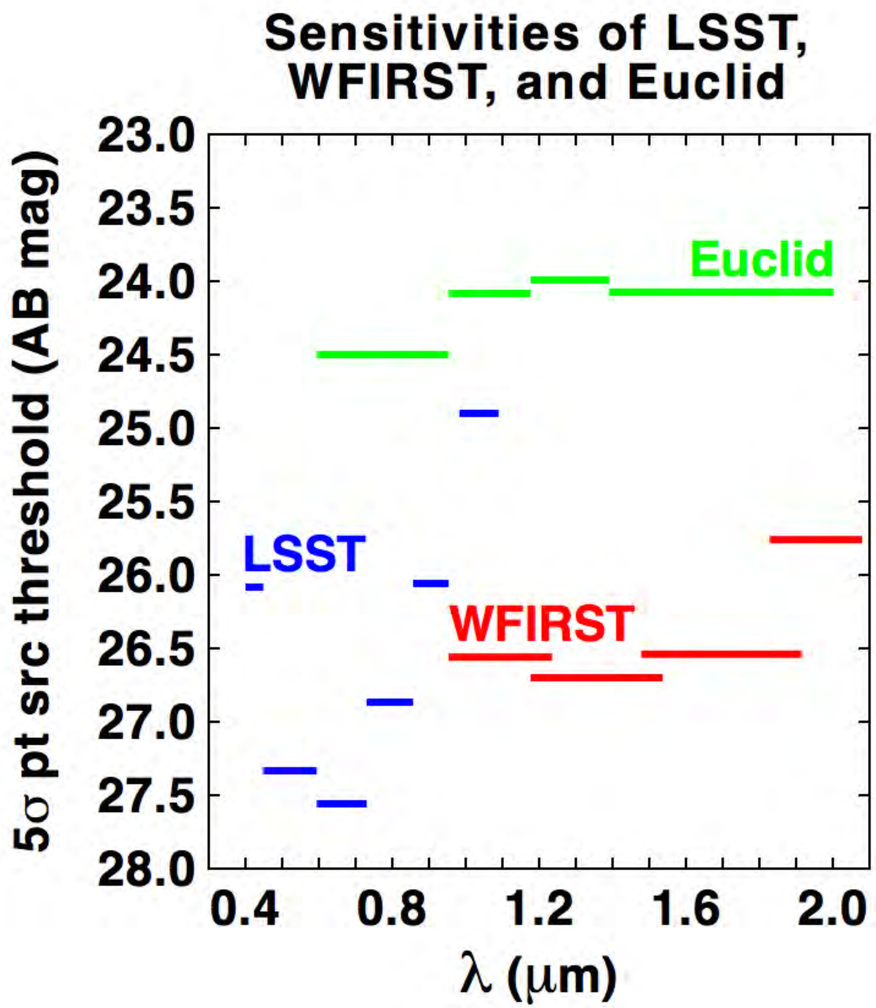
Use weak gravitational lensing to sample matter distribution to z~2

- Obtain deep NIR imaging in multiple bands
- Measure *shapes* of background galaxies to z~3 at sampling density of ≥45/square arcminute
- Derive photometric redshifts by fitting spectral templates to multi-band images



WFIRST High-Latitude Survey





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DE Survey specifics

Weak Lensing Imaging Survey				
Parameter	Y	J	H	F184
λ_{min}(μm)	0.927	1.131	1.380	1.683
λ_{max}(μm)	1.192	1.454	1.774	2.000
PSF (R_{EE50})	0.12”	0.13”	0.13”	0.14”
Exp time	5x174	6x174	5x174	5x174
5σ pt src depth	26.56	26.70	26.54	25.76
WL N_{eff}/sq amin	N/A	32.8	35.2	19.0

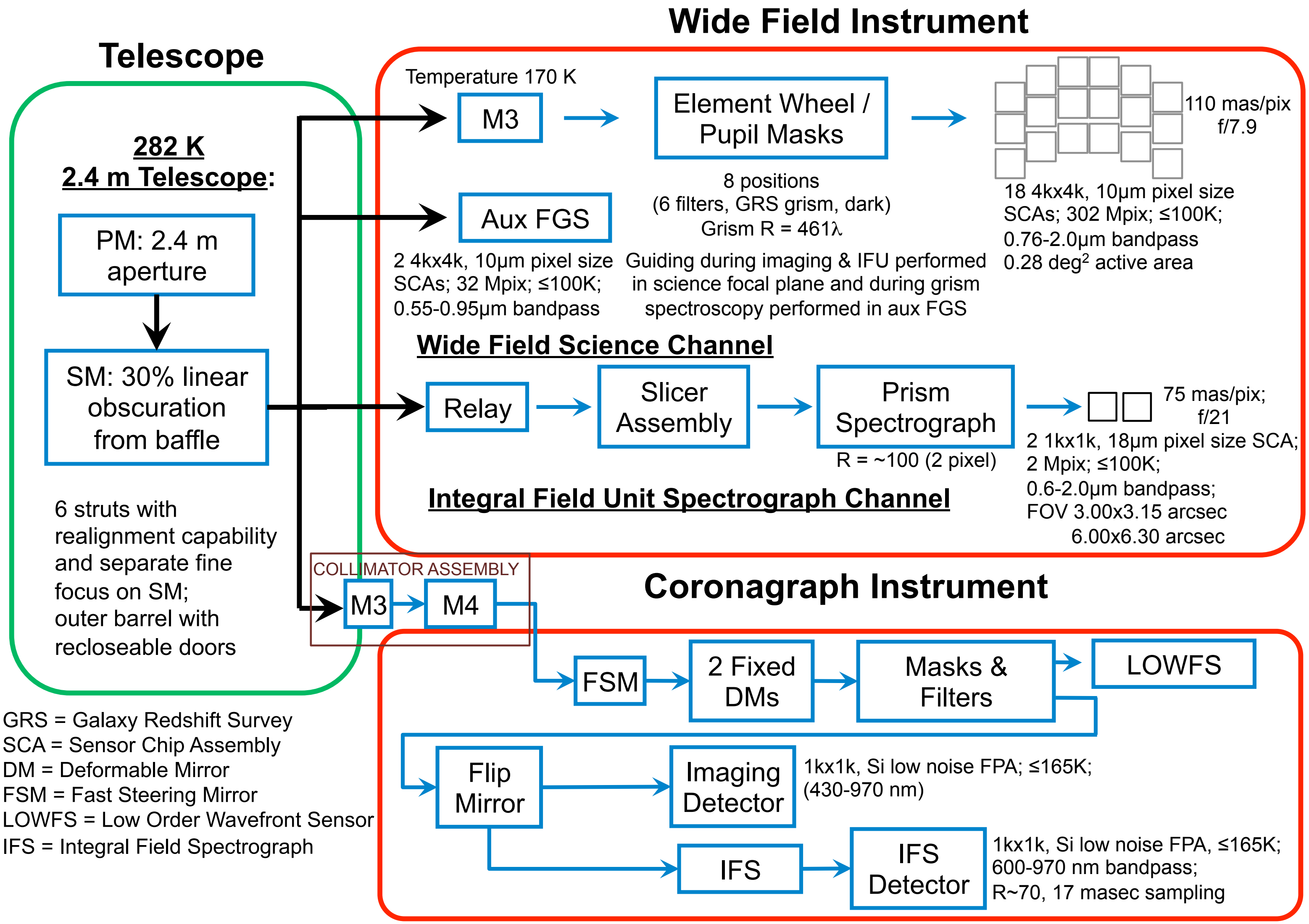
Survey area: 2227 sq deg
Galaxy depth ~1 mag shallower ($r_{1/2}$ ~0.3”)
PSF ~ HST/WFC3-IR, with slightly smaller pixels

SNIa Discovery Imaging				
Redshift Tier	Area Sq deg	Y	J	H
<0.4	27.4	27.5	27.5	
<0.8	9		28.3	28.3
<1.7	5		29.2	29.1

Always observe in WFI & IFU

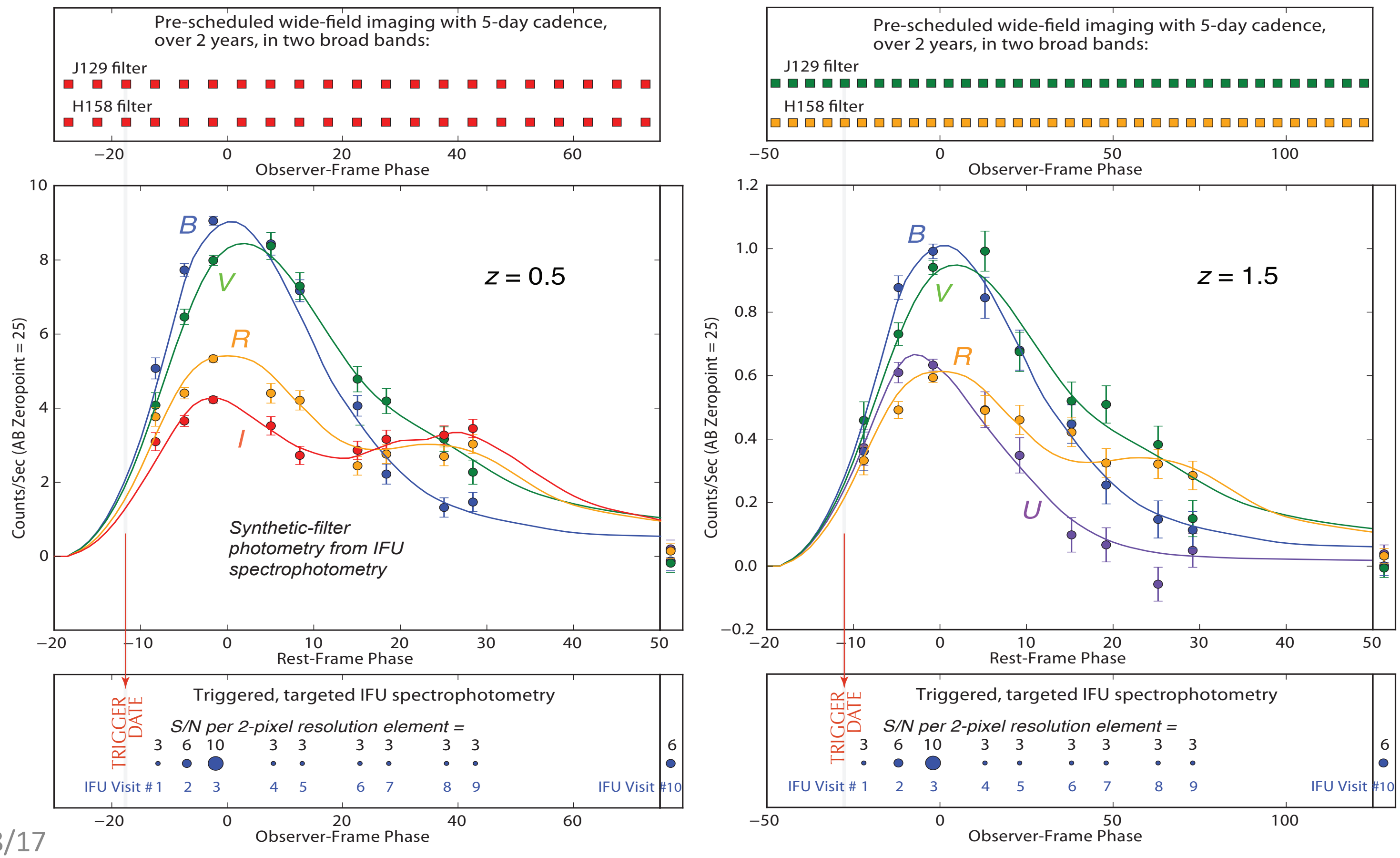
WFI parallel observing with coronagraph will give many dozens of deep fields (AB~30?)

WFIRST
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

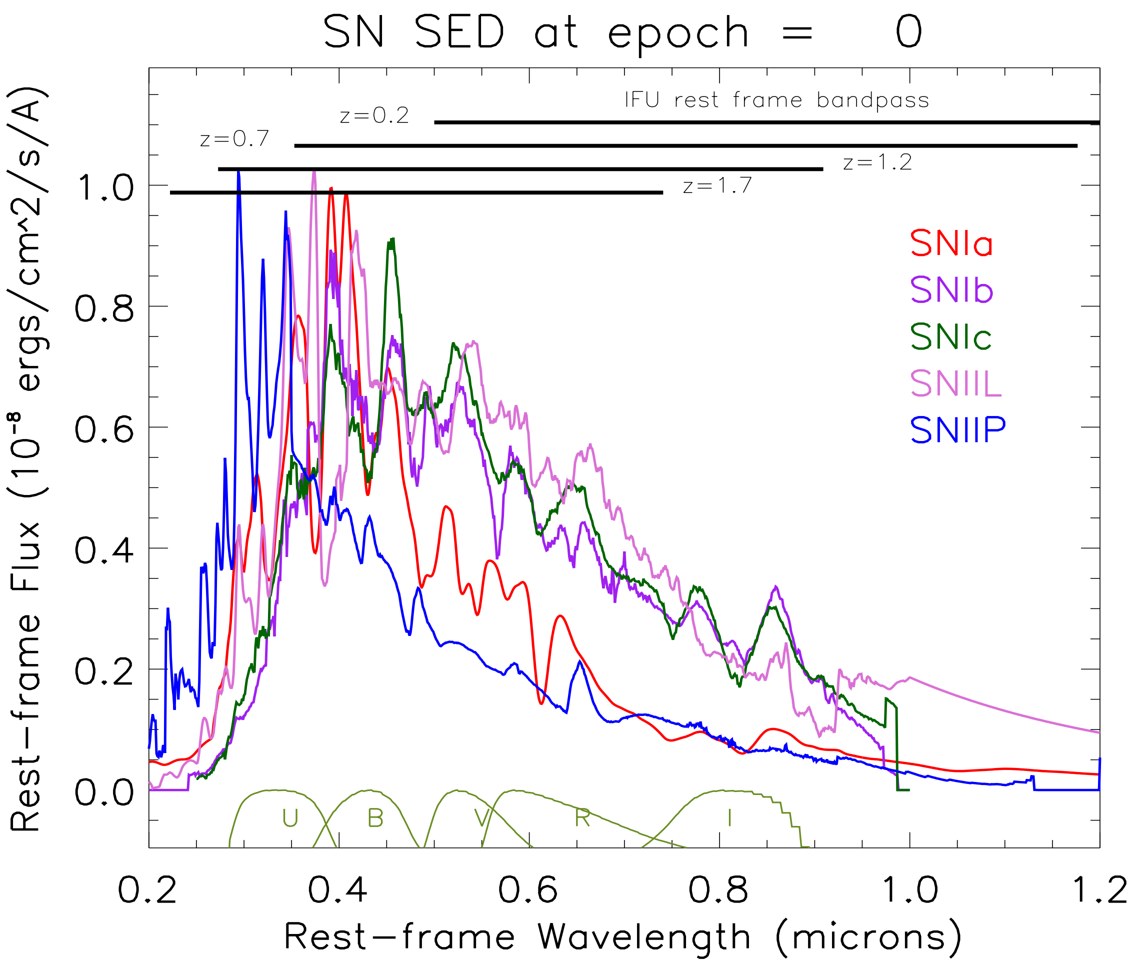
➢IFU Spectrophotometry for light curves



Supernova Spectra - types

Spectral energy distributions of various SN types are shown, at peak flux. This illustrates how spectral features are used to identify the SN types, and that the features are strong enough to use for redshift measurement.

The black bars at the top indicate the portions of the spectrum that will be observed by the IFU for various redshifts. The green curves at the bottom show the traditional filter bandpasses used to characterize SNe



Sample Tiling