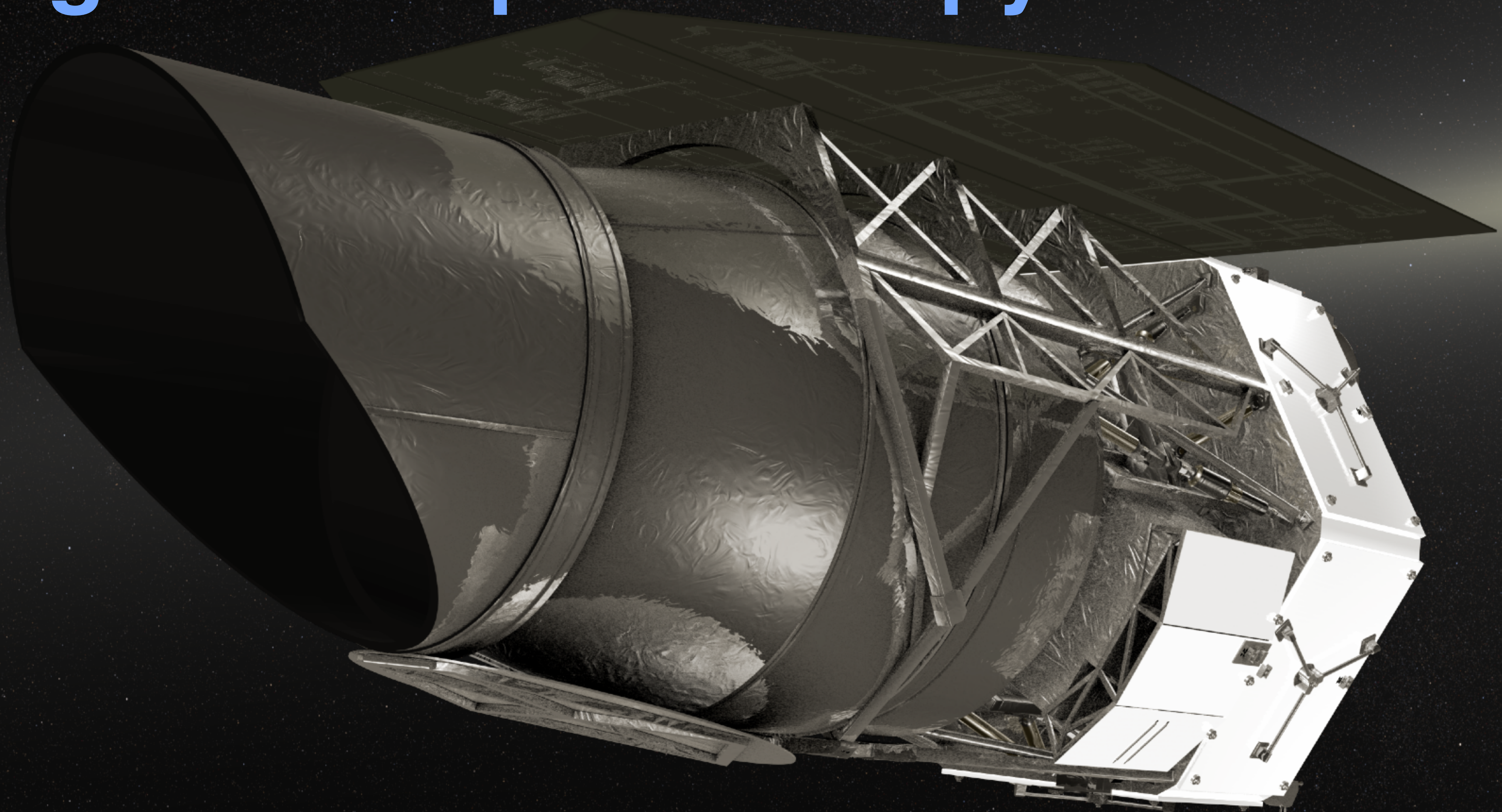
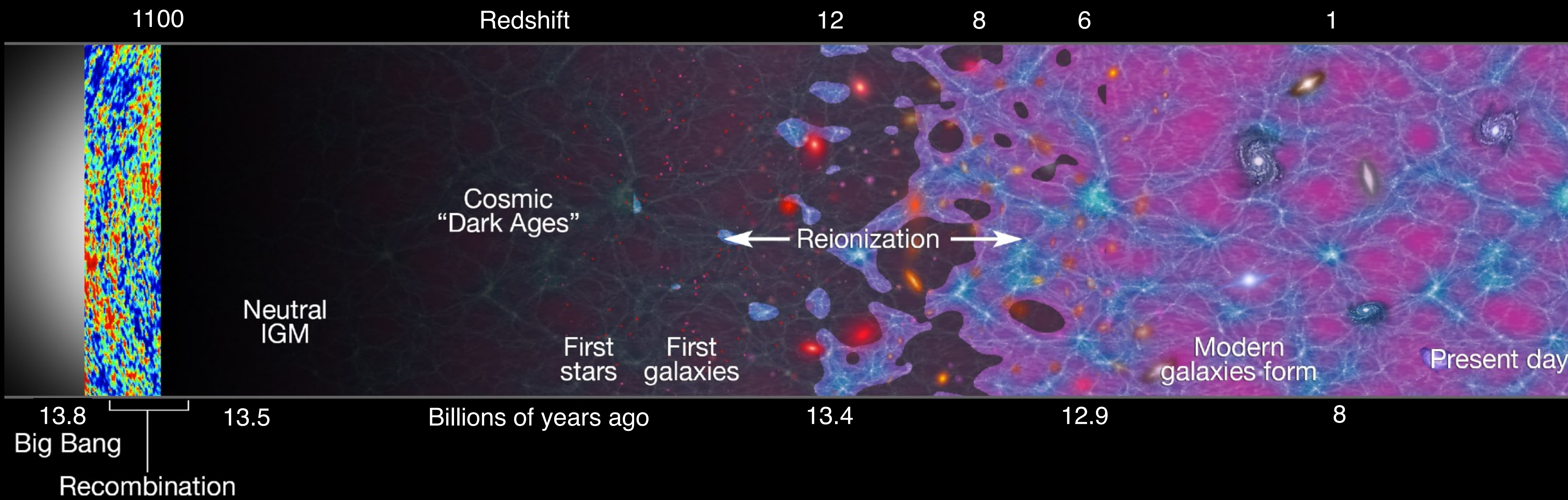
Looking Forward to Looking Backward: Extragalactic Spectroscopy with *WFIRST*



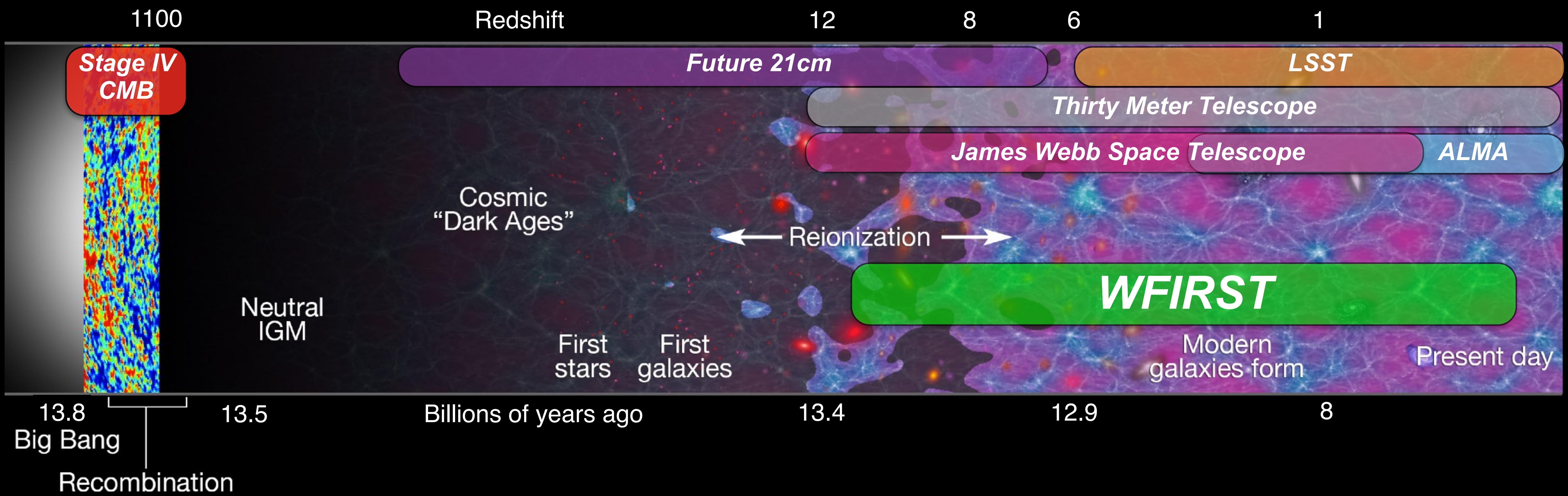
Brant Robertson
UC Santa Cruz (brant@ucsc.edu)
PI, WFIRST Extragalactic Potential Observations (WFIRST-EXPO)
Science Investigation Team

History of Galaxy Evolution



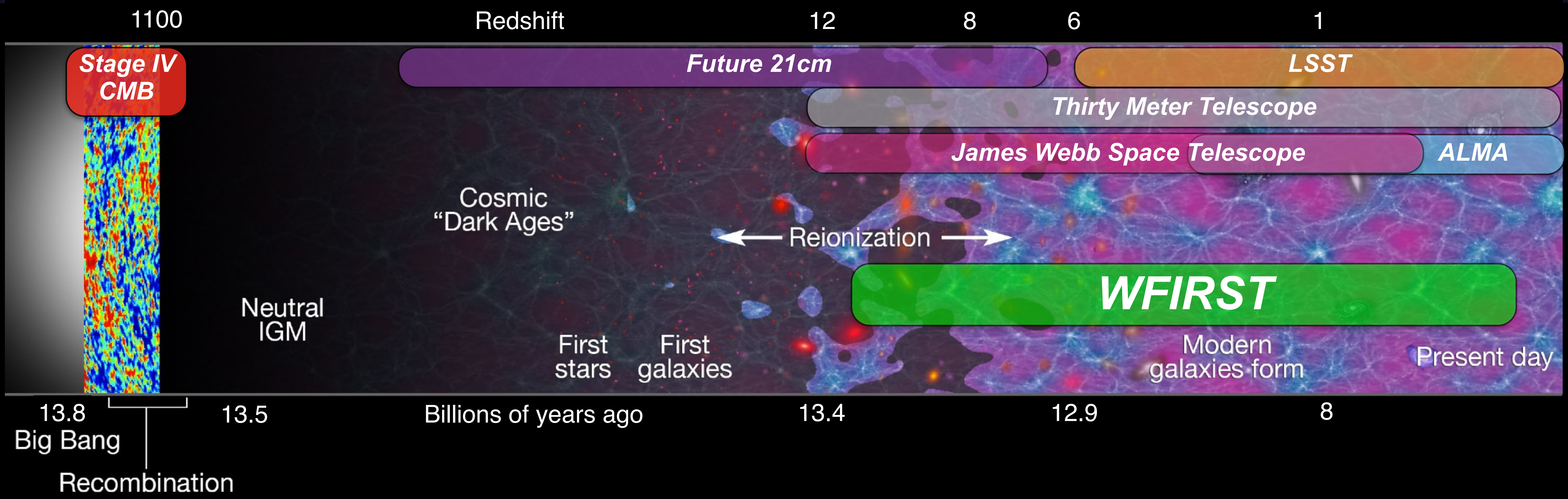
Adapted from Robertson et al. *Nature*, **468,** 49 (2010).

Astronomical Facilities



Observations with ***WFIRST***, JWST, TMT/GMT/E-ELT, LSST, ALMA, and 21-cm experiments will drive astronomical discoveries over the next decade.

Adapted from Robertson et al. *Nature*, **468**, 49 (2010).



Important Questions for *WFIRST*

1.) How do cosmic environments influence galaxy evolution?

WFIRST will provide enormous samples of galaxies that probe all relevant ranges of cosmic density.

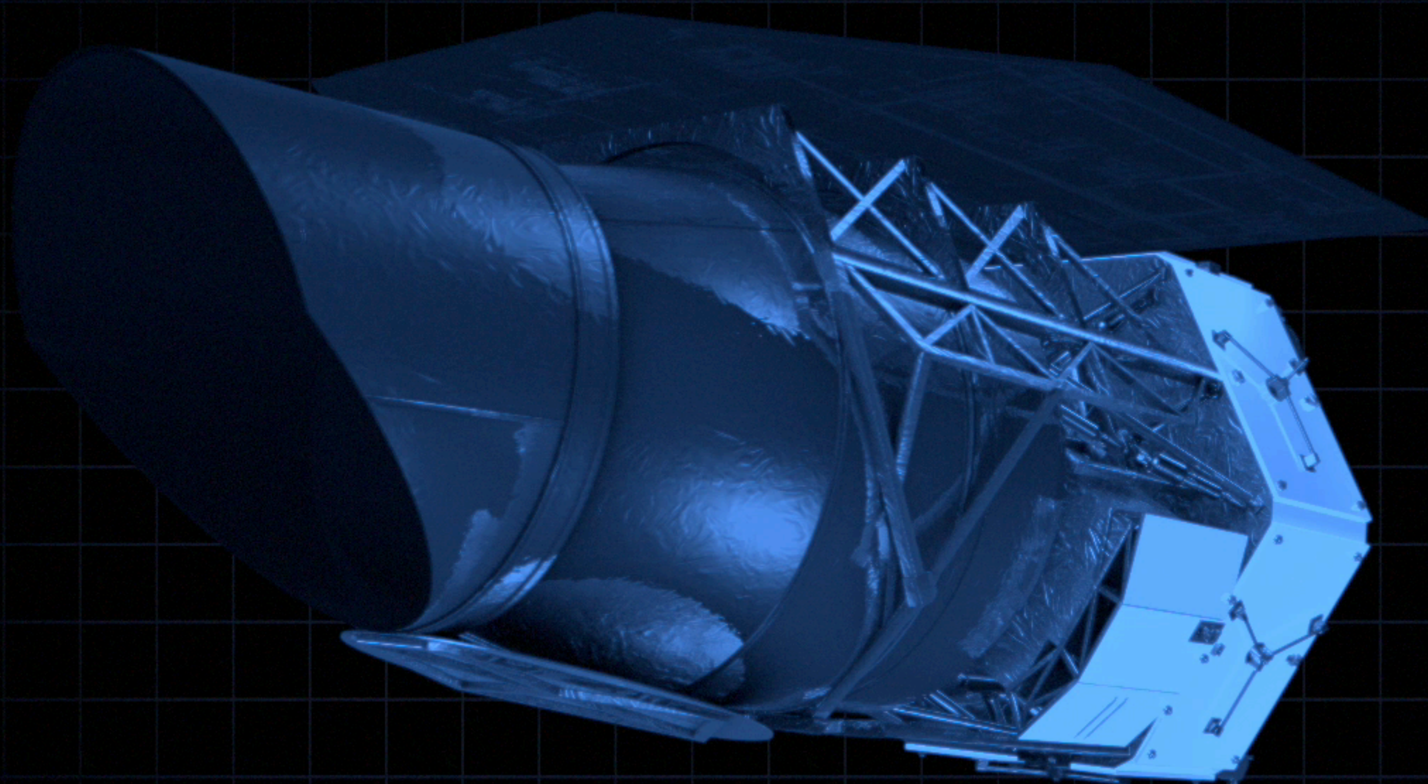
2.) What can rare objects tells us about galaxy formation?

WFIRST can discover the most luminous galaxies and the most massive black holes back to the first 500 million years of cosmic history.

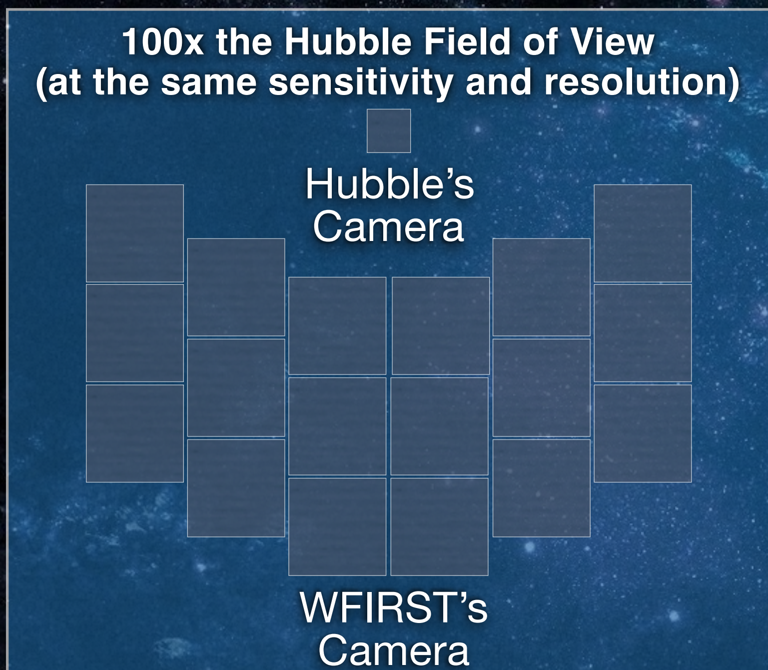
3.) How do galaxies and quasars contribute to cosmic reionization?

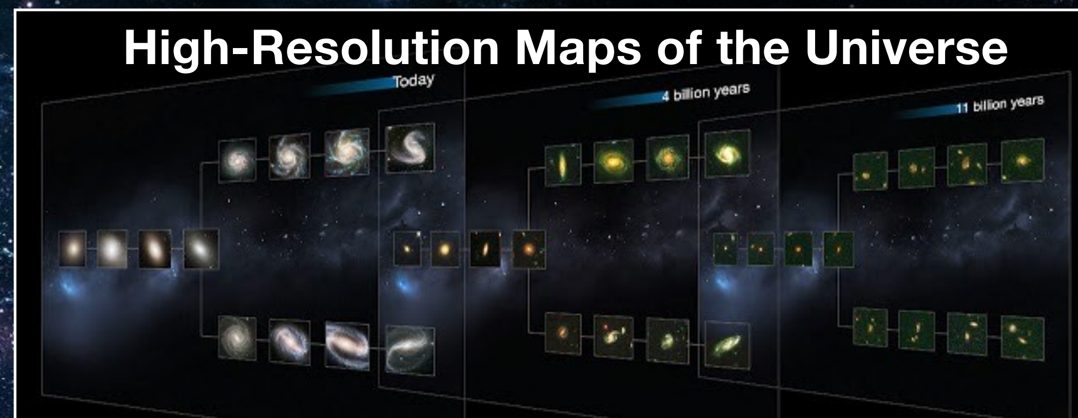
WFIRST can identify representative samples of galaxies and quasars during the reionization epoch, and quantify their relative importance for ionizing the intergalactic medium.

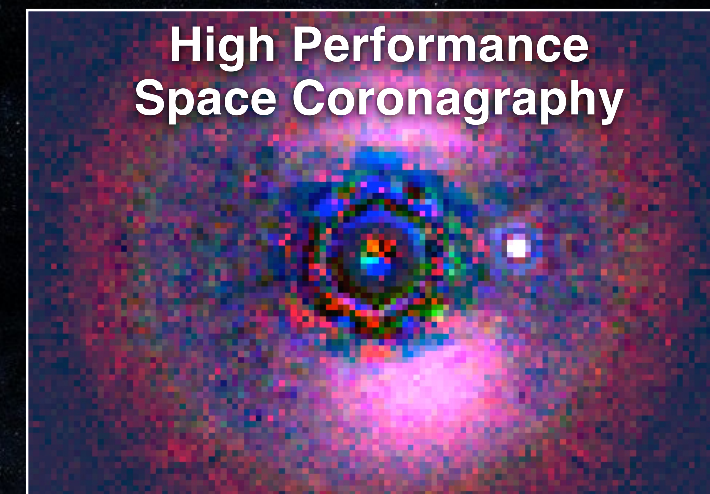
WFIRST

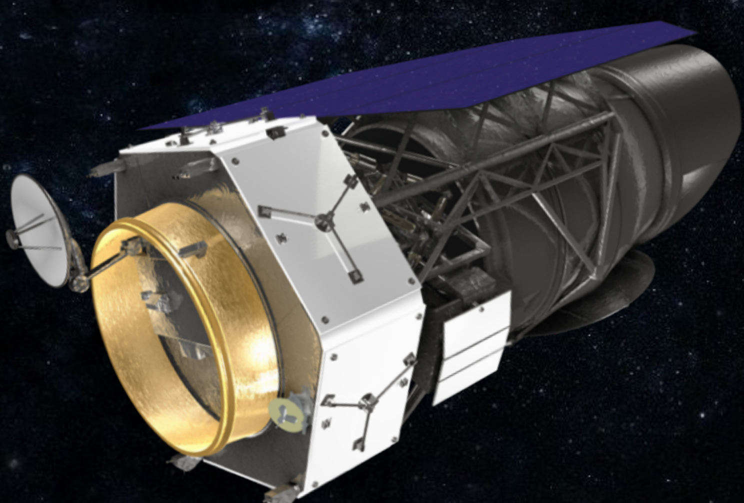


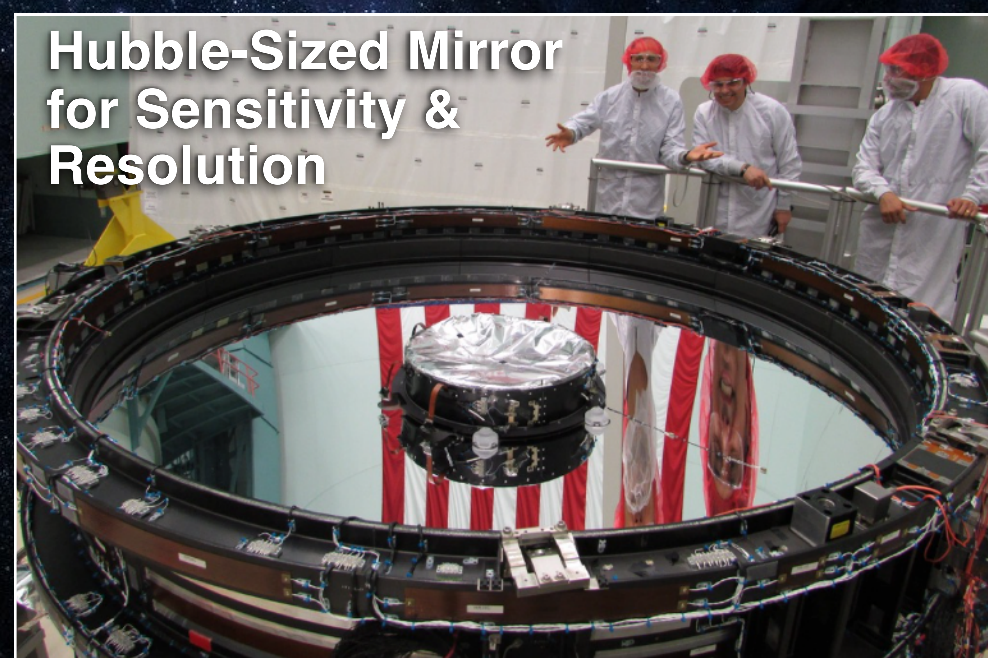
A Mission of Superlatives









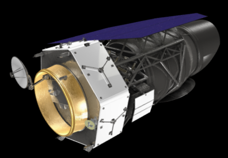


Breakthroughs with WFIRST

High-resolution Mapping of the Universe

Over its amazing 26-year history, Hubble's imaging cameras have surveyed just 1% of the Universe

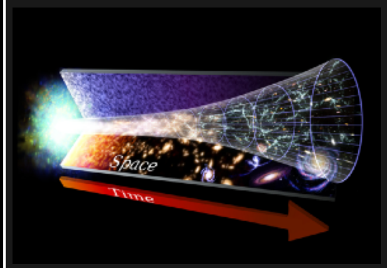
↓



WFIRST will survey Hubble's Universe in 10 weeks, at the same sensitivity and resolution

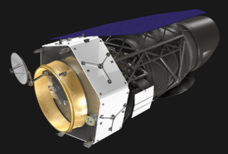
Factor of 100

Expansion of the Universe



Present Figure of Merit: ~30 Supernovae & BAO, plus CMB

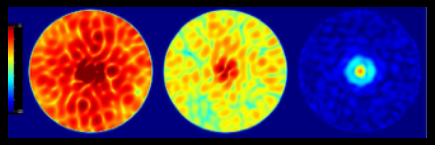
↓



WFIRST will measure dark energy in the universe with a FoM~1000

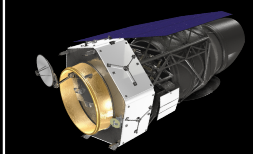
Factor of 30

Directly Imaging Other Worlds



Current state-of-the-art ground and space light-suppression techniques achieve contrast ratios of ~1,000,000:1

↓



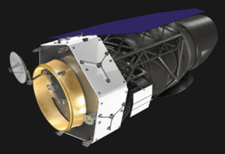
WFIRST's high-performance coronagraph will achieve light-suppression of up to 1,000,000,000:1

Factor of 1000

Structure of Dark Matter

The Dark Energy Survey will measure dark matter via weak lensing using 200M galaxies ~ 0.9" resolution

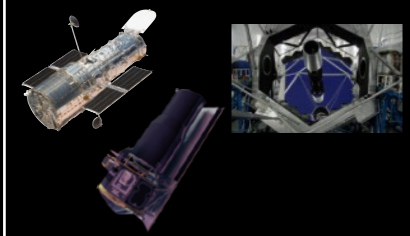
↓



WFIRST will survey dark matter 380M galaxies at 0.12" resolution

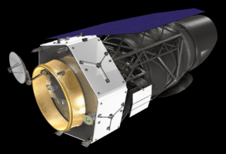
Factor of 100

First Galaxies and Early Universe



Hubble, Spitzer, ground telescopes have discovered ~100 galaxies at z > 8, and only a few at z > 10

↓



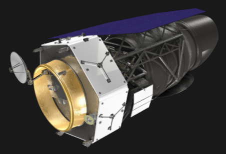
WFIRST's High Latitude Survey will discovery >50,000 z > 8 galaxies, and several 100 z > 10 galaxies

Factor of 500

Census of Exoplanets

Number of Earth/ Super-Earths at 1AU and beyond: 1 known

↓

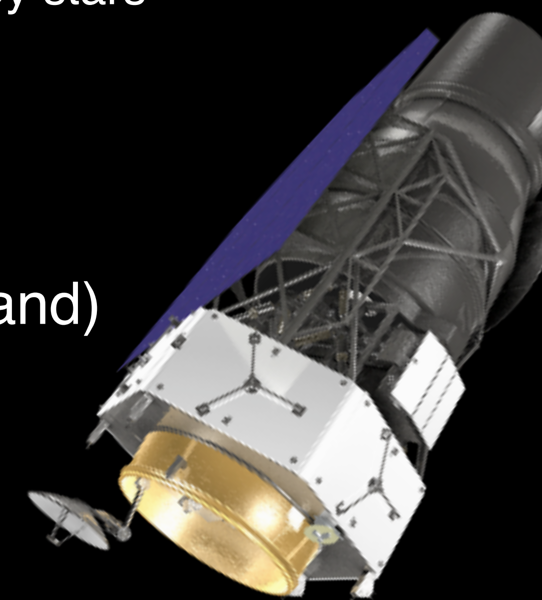


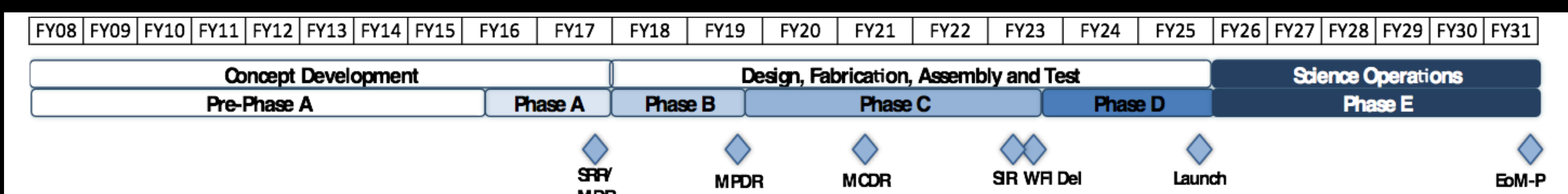
WFIRST will discover 300+ Earth-mass planets beyond 1AU

Factor of 300

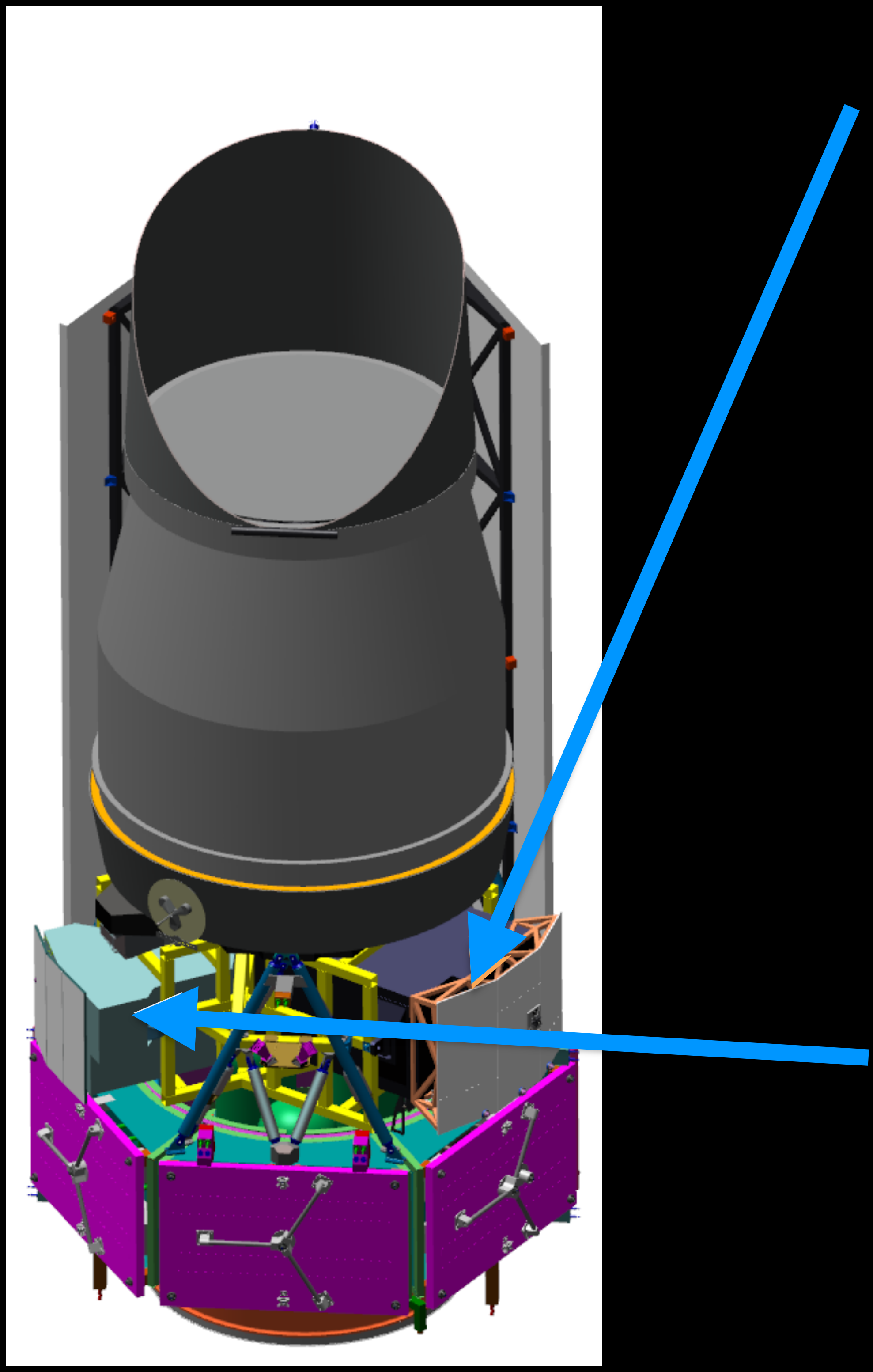
WFIRST Basic Facts

- **Objectives:**
  - Characterize the history of cosmic acceleration and structure growth
  - Understand how planetary systems form and evolve and determine the prevalence of planets in the colder outer regions
  - Understand the compositions and atmospheric constituents of a variety of planets around nearby stars and to determine the properties of debris disks around nearby stars
  - A peer-reviewed Guest Observer program allocated 25% of mission time.
- **Mission Duration:** 6 ¼ years
- **Orbit:** Sun-Earth L2
- **Ground Stations:** Near Earth Network (Ka-band, S-band)
- **Space Network:** S-band for launch
- **Ground System:** MOC/Science Center/IOC
- **Launch Vehicle:** Delta IV Heavy or Falcon Heavy
- **Launch Site:** Eastern Range





WFIRST Instruments



Wide-Field Instrument

- Imaging & spectroscopy over 1000s of sq. deg.
- Monitoring of SN and microlensing fields
- 0.7-2.0um (Imaging), ~1-1.9um (spec.), 0.45-2.0um (IFU)
- 18 H4RG detectors (288 Mpixels), 2 H1RG detectors (IFU)
- 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. arcsec

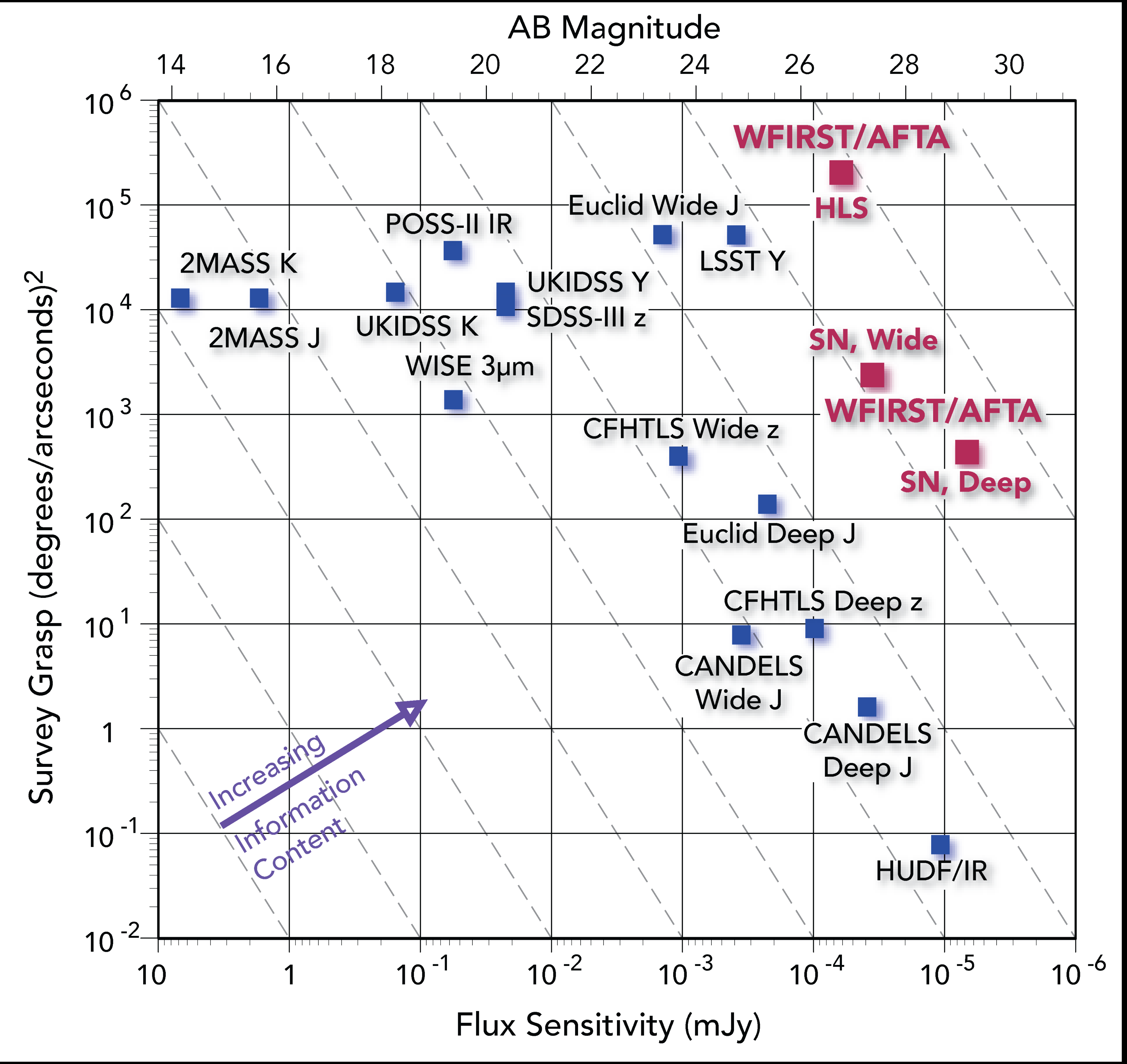
WFIRST Mission Surveys

High Latitude Survey
- BAO, RSD, WL
- ~2000 deg^2
- Y,J,H,F184 to ~26.7AB
- Grism to ~10^{-16} erg/s/cm^2
- ~1.33 years

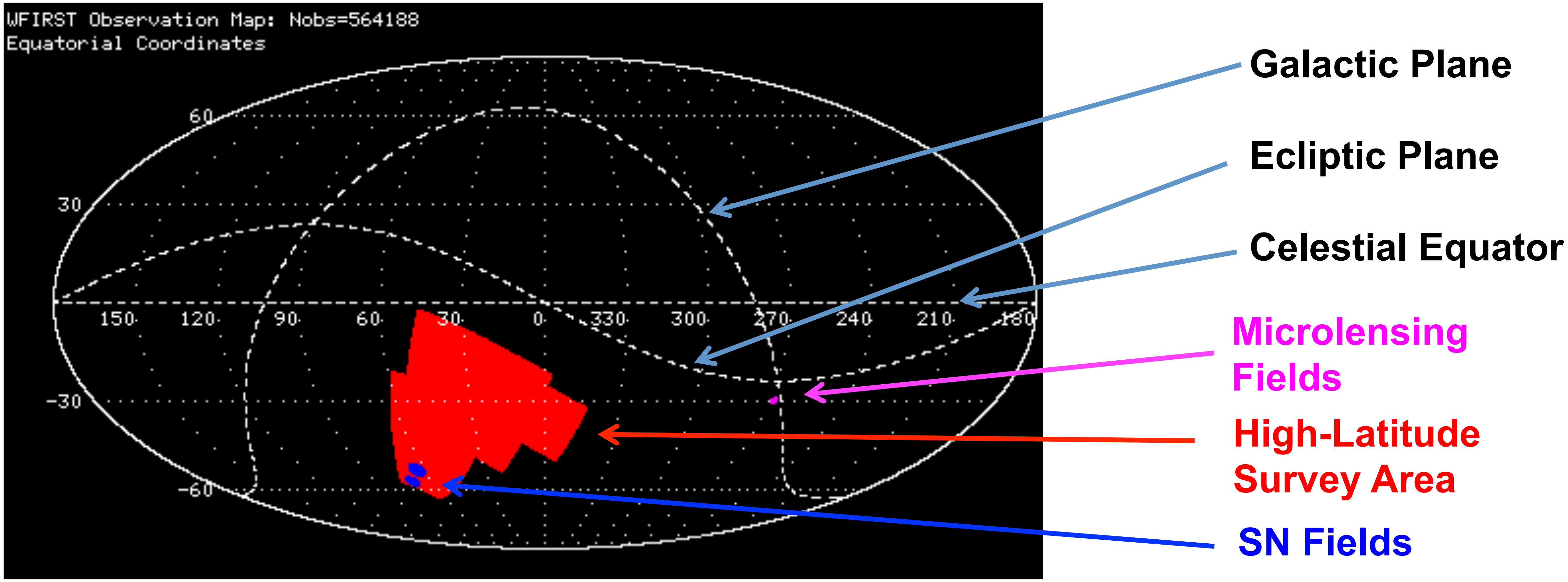
Supernovae Survey
- High-cadence imaging
- ~20 deg^2
- Y,Z,J,H,F184 to ~28.5AB
- IFU follow-up of SN
- ~0.5 years

Microlensing Survey
- ~1.2 years

Coronagraph Observations
- ~0.6 years



WFIRST High Latitude Survey



Hirata & SDT 2015

Example location and footprint — not final

Grism Designs Considered for WFIRST

	a	h	b	i	c	g1 & g2		k1 & k2	
$\Delta\lambda(\mu m)$	1.35–1.89	1.0–1.85	1.0-2.0	0.95–1.9	0.9–1.8	0.9–1.39	1.33–2.05	0.9–1.39	1.33–2.05
D	10.8	10.8	10.8	10.8	10.8	15	10.8	10.8	10.8
Sky (e^-/s)	$0.52^\dagger$	0.88	1.05	0.99	0.97	0.59	0.75	0.59	0.75
$z(H\alpha)$	1.05–1.88	0.52–1.82	0.52–2.05	0.45-1.90	0.37–1.74	0.37–2.12		0.37–2.12	
z(OIII)	1.70–2.77	1.00–2.69	1.00–2.99	0.90–2.79	0.80–2.59	0.80–3.09		0.80–3.09	
$z(H\alpha+OIII)$	1.7–1.88	1.0–1.82	1.0–2.05	0.9–1.9	0.8–1.74	0.80–2.12		0.80–2.12	
$z(\text{Lyman-}\alpha)$	> 10.1	> 7.2	> 7.2	> 6.8	> 6.4	> 6.4		> 6.4	
$10^3\Delta z/(1+z)$ @ $7\sigma^\ddagger$	0.60	0.60	0.60	0.60	0.60	0.83	0.60	0.60	0.60
$10^3\Delta z/(1+z)$ @ 10^{-16}cgs‡	$0.60^\dagger$	0.79	0.86	0.84	0.83	0.90	0.74	0.65	0.74
J_{AB} of 80% overlap	26.6	25.7	25.4	25.5	25.6	27.4	26.0	26.7	26.0
BAO/RSD (cosmology)	λ_b, λ_r	λ_r?		λ_r		D			
Cosmic Dawn (CD)	λ_b	λ_b, overlap	λ_b, overlap	overlap	overlap				
Cosmic Dawn (Expo)	λ_b		λ_b, overlap						
Galaxy props (CD)	$\Delta\lambda$		(T=260)						
Galaxy props (Expo)	$\Delta\lambda$					D			

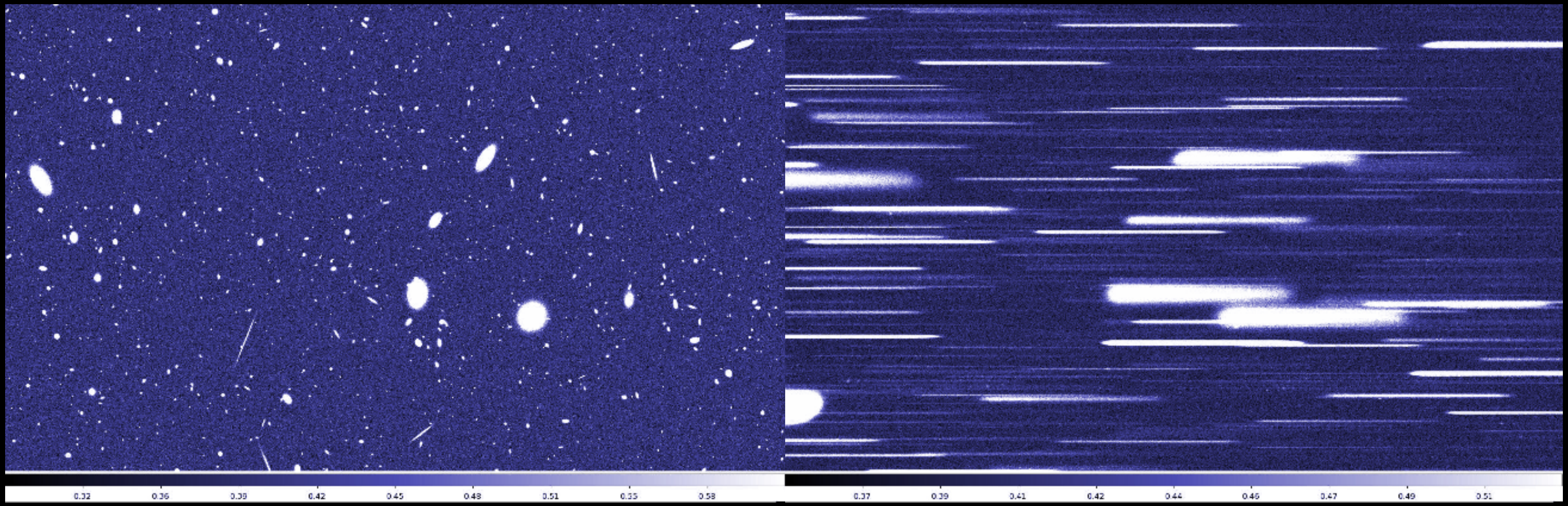
Grism Designs Considered for WFIRST

	a	h	b	i	c	g1 & g2		k1 & k2	
$\Delta\lambda(\mu m)$	1.35–1.89	1.0–1.85	1.0-2.0	0.95–1.9	0.9–1.8	0.9–1.39	1.33–2.05	0.9–1.39	1.33–2.05
D	10.8	10.8	10.8	10.8	10.8	15	10.8	10.8	10.8
Sky (e^-/s)	$0.52^{\dagger}$	0.88	1.05	0.99	0.97	0.59	0.75	0.59	0.75
$z(H\alpha)$	1.05–1.88	0.52–1.82	0.52–2.05	0.45-1.90	0.37–1.74	0.37–2.12		0.37–2.12	
z(OIII)	1.70–2.77	1.00–2.69	1.00–2.99	0.90–2.79	0.80–2.59	0.80–3.09		0.80–3.09	
$z(H\alpha$+OIII)	1.7–1.88	1.0–1.82	1.0–2.05	0.9–1.9	0.8–1.74	0.80–2.12		0.80–2.12	
$z(\text{Lyman-}\alpha)$	> 10.1	> 7.2	> 7.2	> 6.8	> 6.4	> 6.4		> 6.4	
$10^3\Delta z/(1+z)$ @ $7\sigma^{\ddagger}$	0.60	0.60	0.60	0.60	0.60	0.83	0.60	0.60	0.60
$10^3\Delta z/(1+z)$ @ 10^{-16}cgs‡	$0.60^{\dagger}$	0.79	0.86	0.84	0.83	0.90	0.74	0.65	0.74
J_{AB} of 80% overlap	26.6	25.7	25.4	25.5	25.6	27.4	26.0	26.7	26.0
BAO/RSD (cosmology)	λ_b, λ_r	λ_r?		λ_r		D			
Cosmic Dawn (CD)	λ_b	λ_b, overlap	λ_b, overlap	overlap	overlap				
Cosmic Dawn (Expo)	λ_b		λ_b, overlap						
Galaxy props (CD)	$\Delta\lambda$		(T=260)						
Galaxy props (Expo)	$\Delta\lambda$					*D*			

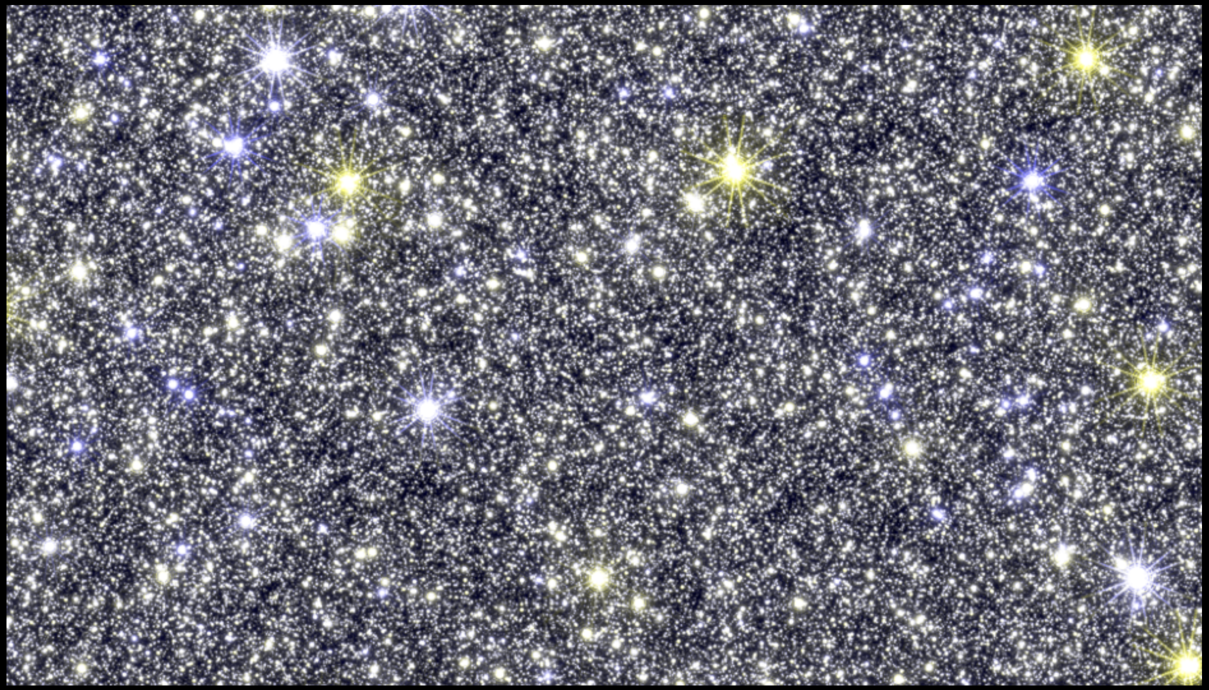
*likely options for the WFIRST grism design

WFIRST Simulations Status

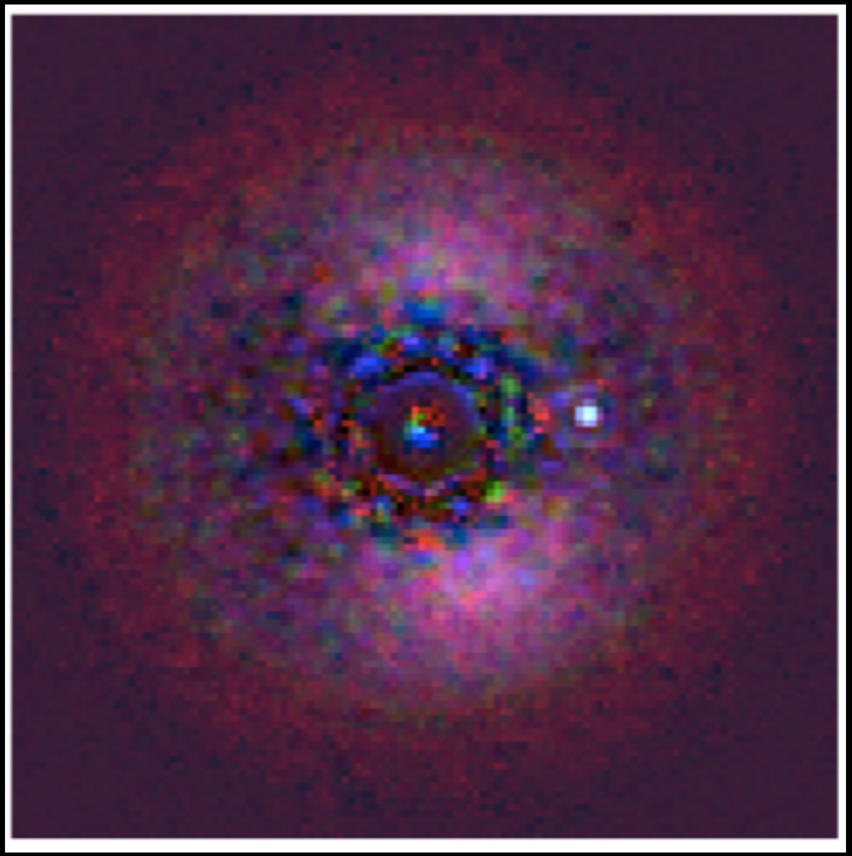
WFIRST Simulations for all science now operational,
working on detailed assessments supporting design efforts



Grism survey simulations



Microlensing survey simulation



Warm Jupiter at 2 AU from G2 star at 3 pc + 10 zodi dust structure .Coronagraph in Shaped pupil “disk mode” (6 - 20 λ/D)

WFIRST Formulation Science Working Group

Project Scientist
Jeffery Kruk (Goddard)

Program Scientist
Dominic Benford (NASA HQ)

WFI Adjutant Scientist
David Spergel
(CCA/Princeton)

CGI Adjutant Scientist
Jeremy Kasdin
(Princeton)

Deputy Project Scientist
Jason Rhodes
(JPL)

Science Investigation Team Leads

Olivier Dore (JPL)
Ryan Foley (UCSC)
Saul Perlmutter (LBL)
Scott Gaudi (OSU)
Bruce Macintosh (Stanford)
Margaret Turnbull (SETI)
Jason Kalirai (STScI)
James Rhoads (Goddard)
Brant Robertson (UCSC)
Alexander Szalay (JHU)
Benjamin Williams (UW)

IPAC Science Center Lead
Roc Cutri

STScI Science Center Leads
Roeland van der Marel
Karrie Gilbert

WFIRST Extragalactic Potential Observations (EXPO) Science Investigation Team

Mark Dickinson
(NOAO)

Harry Ferguson
(STScI)

Steve Furlanetto
(UCLA)

Jenny Greene
(Princeton)

Piero Madau
(UCSC)

Dan Marrone
(Arizona)

*At this meeting

Brant Robertson
(UCSC)

Alice Shapley
(UCLA)

Dan Stark
(Arizona)

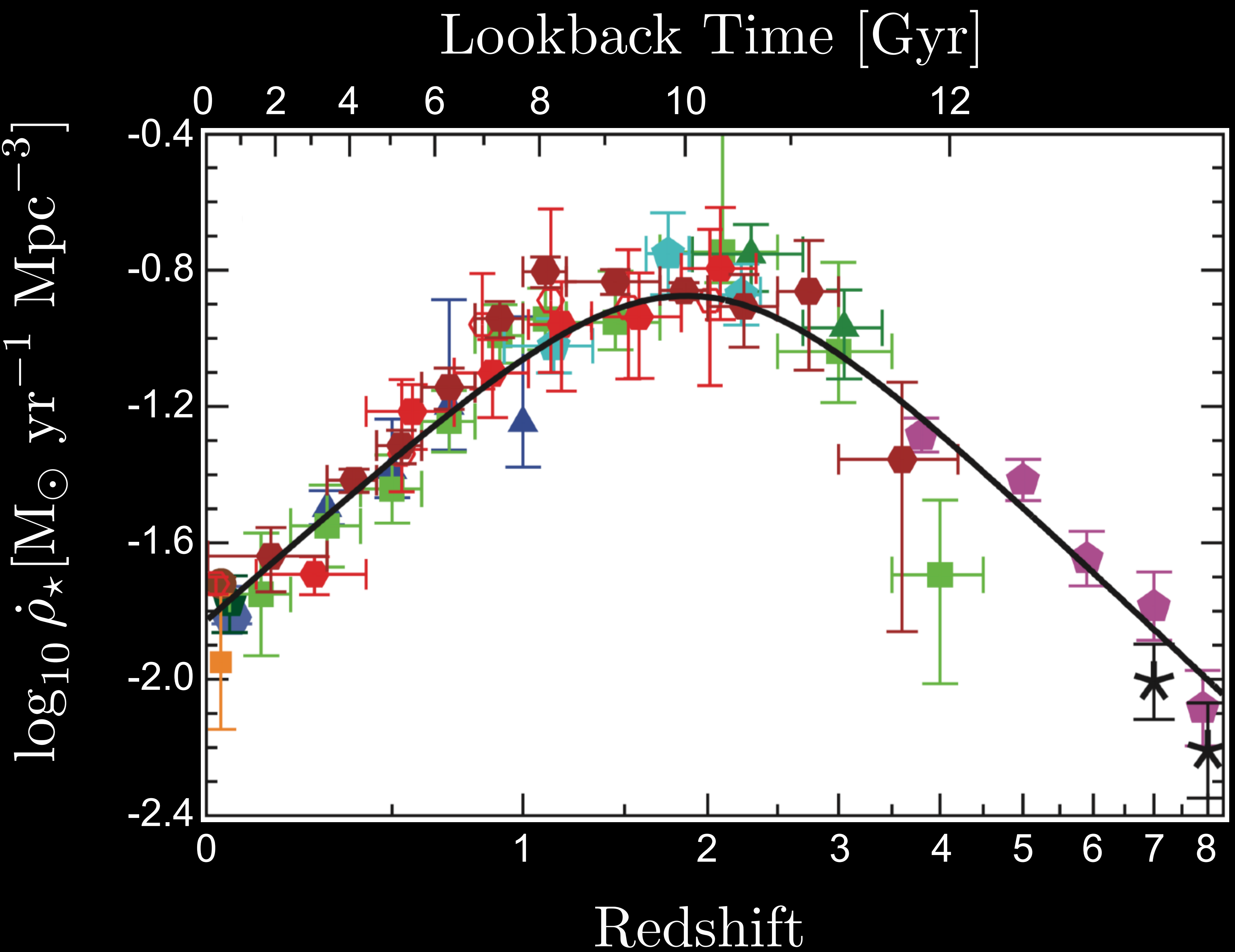
Risa Wechsler
(Stanford)

Stan Woosley
(UCSC)

WFIRST-EXPO: *Science Questions*

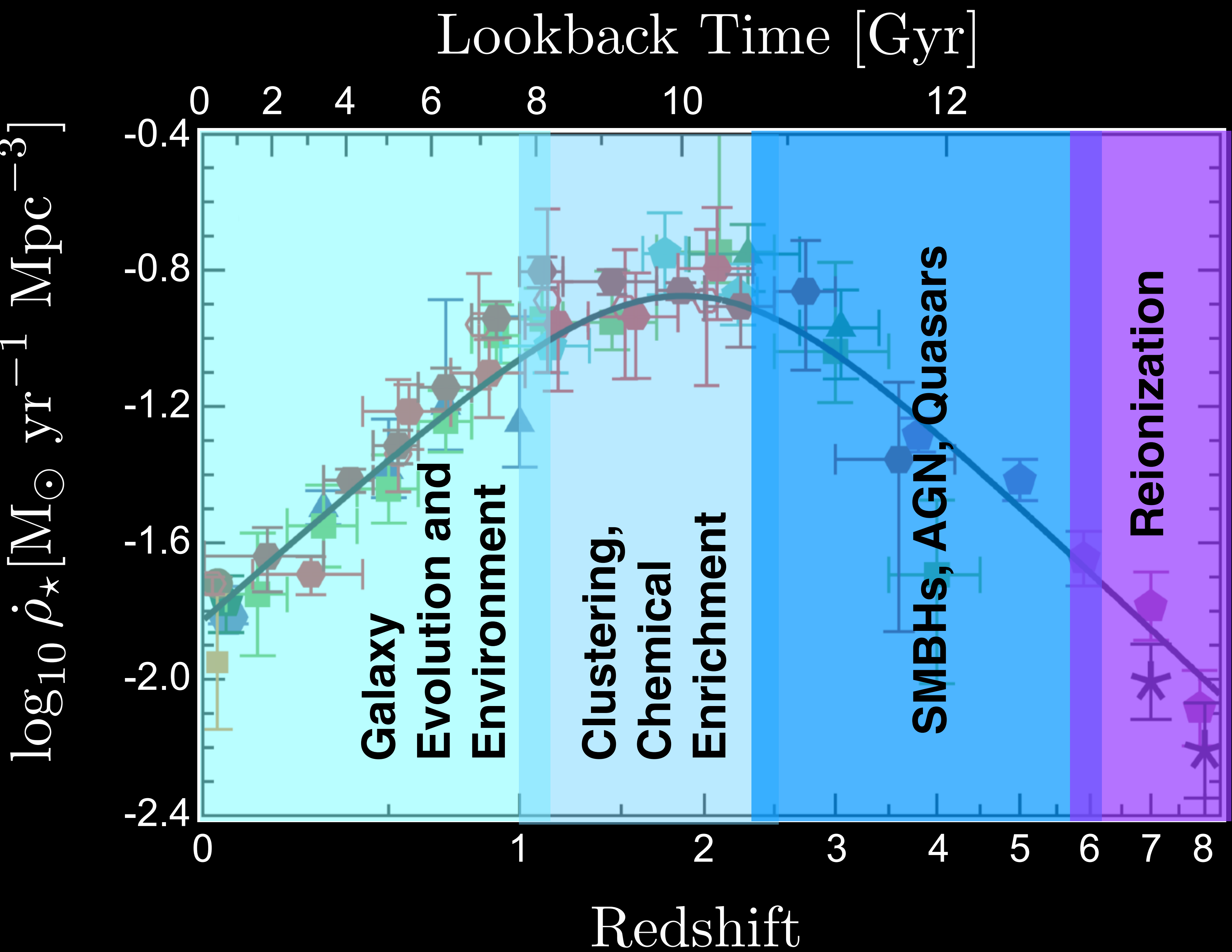
- How will WFIRST help us understand galaxy properties in the context of their environments over cosmic time?
- What will WFIRST spectroscopy teach us about galaxy properties and evolution during the peak era of cosmic star formation?
- How can we leverage WFIRST to discover and characterize rare AGN and quasars?
- Will the massive sample of gravitational lenses discovered by WFIRST inform us about the properties of dark matter?
- Can we quantify the importance of galaxies and quasars for reionization through the statistical samples finally delivered by WFIRST?
- Will WFIRST discover enough exotic, distant supernovae to tell us about the fates of early stellar populations?

Cosmic Star Formation History



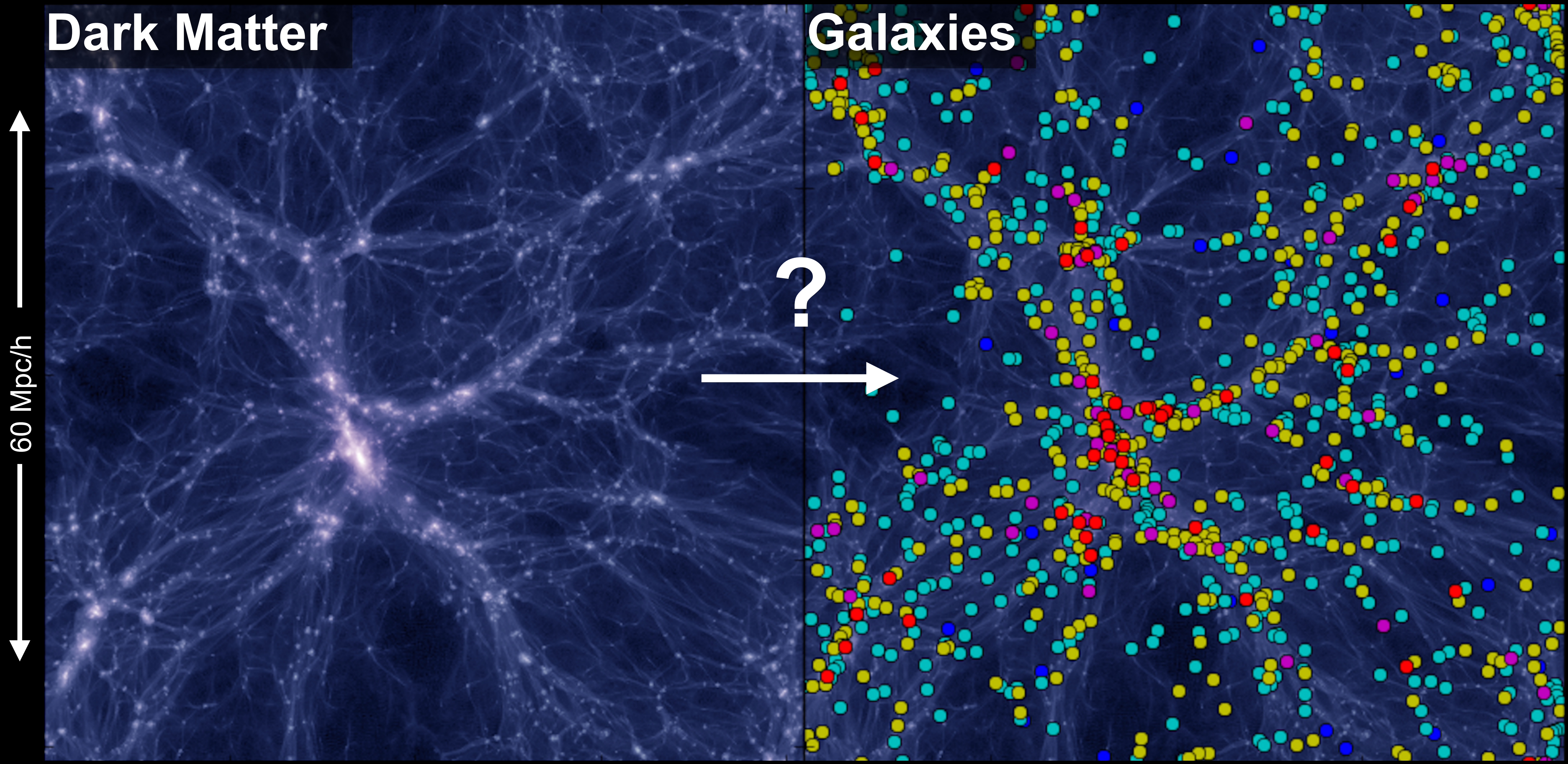
Adapted from Madau & Dickinson, ARAA, **52,** 412 (2014)

WFIRST Science over Cosmic History

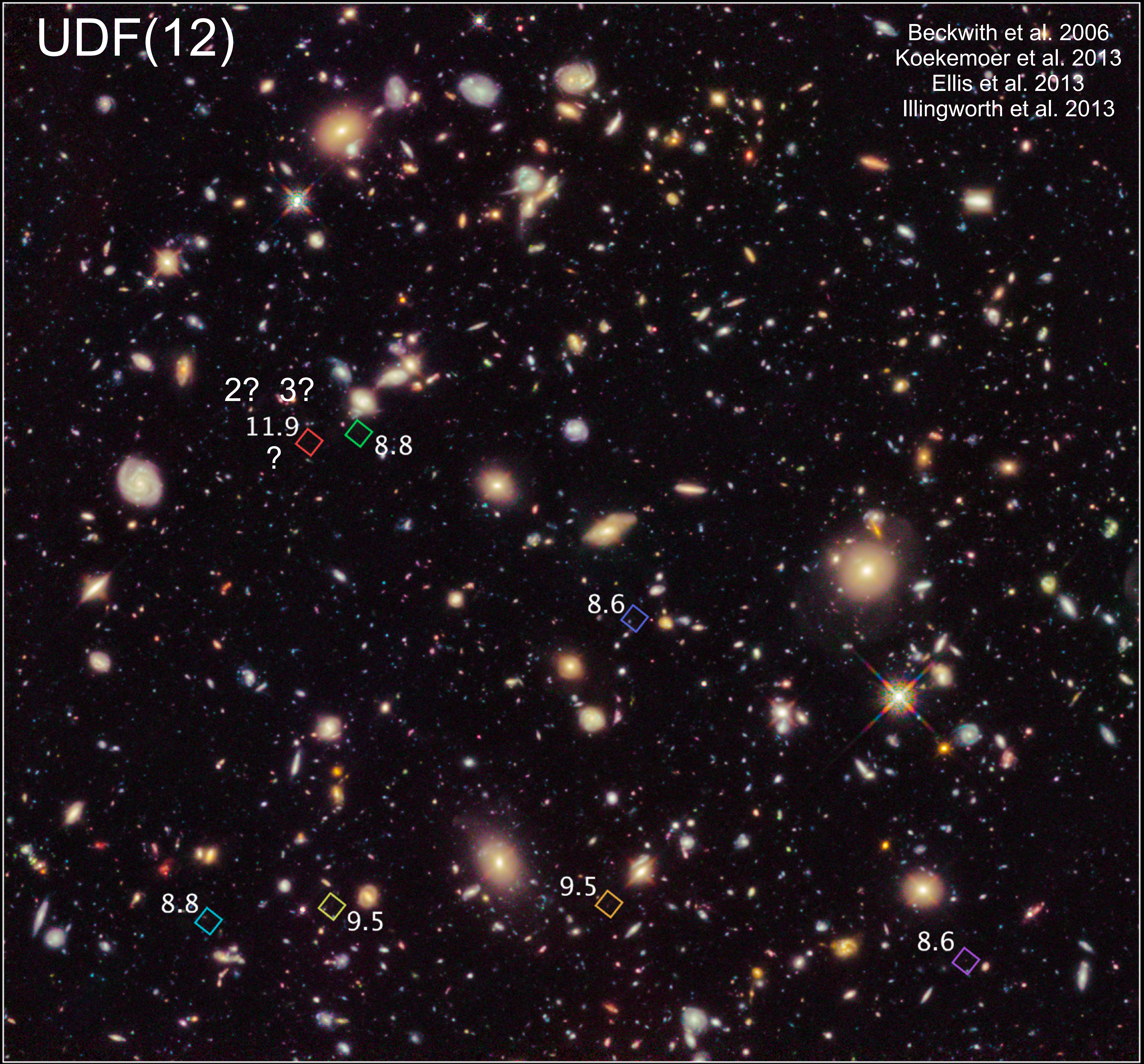


Adapted from Madau & Dickinson, ARAA, **52,** 412 (2014)

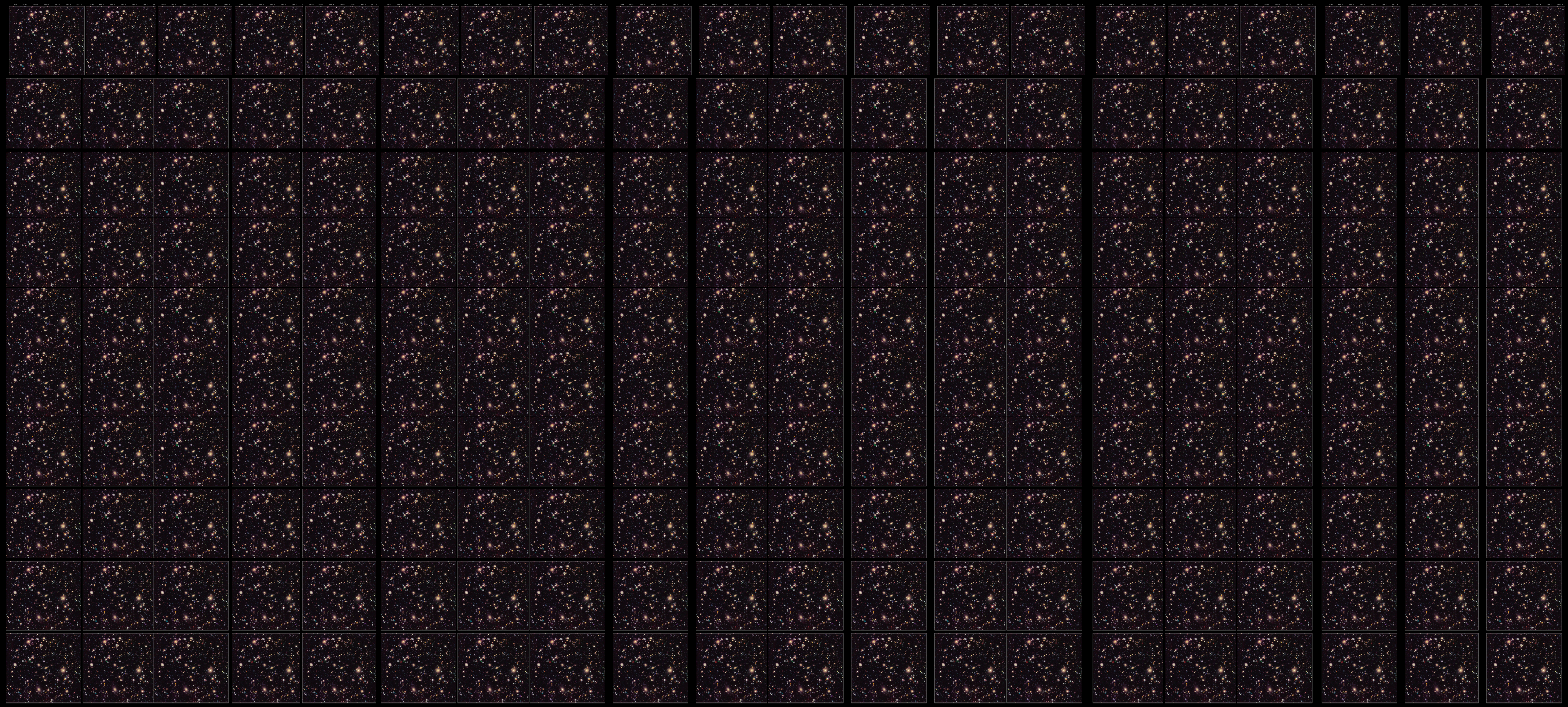
WFIRST Provides a Cosmic Context



How do galaxy properties map onto dark matter structures?
How does cosmic environments affect galaxy evolution?


UDF(12)
Beckwith et al. 2006
Koekemoer et al. 2013
Ellis et al. 2013
Illingworth et al. 2013
2? 3?
11.9
?
8.8
8.6
8.8
9.5
9.5
8.6

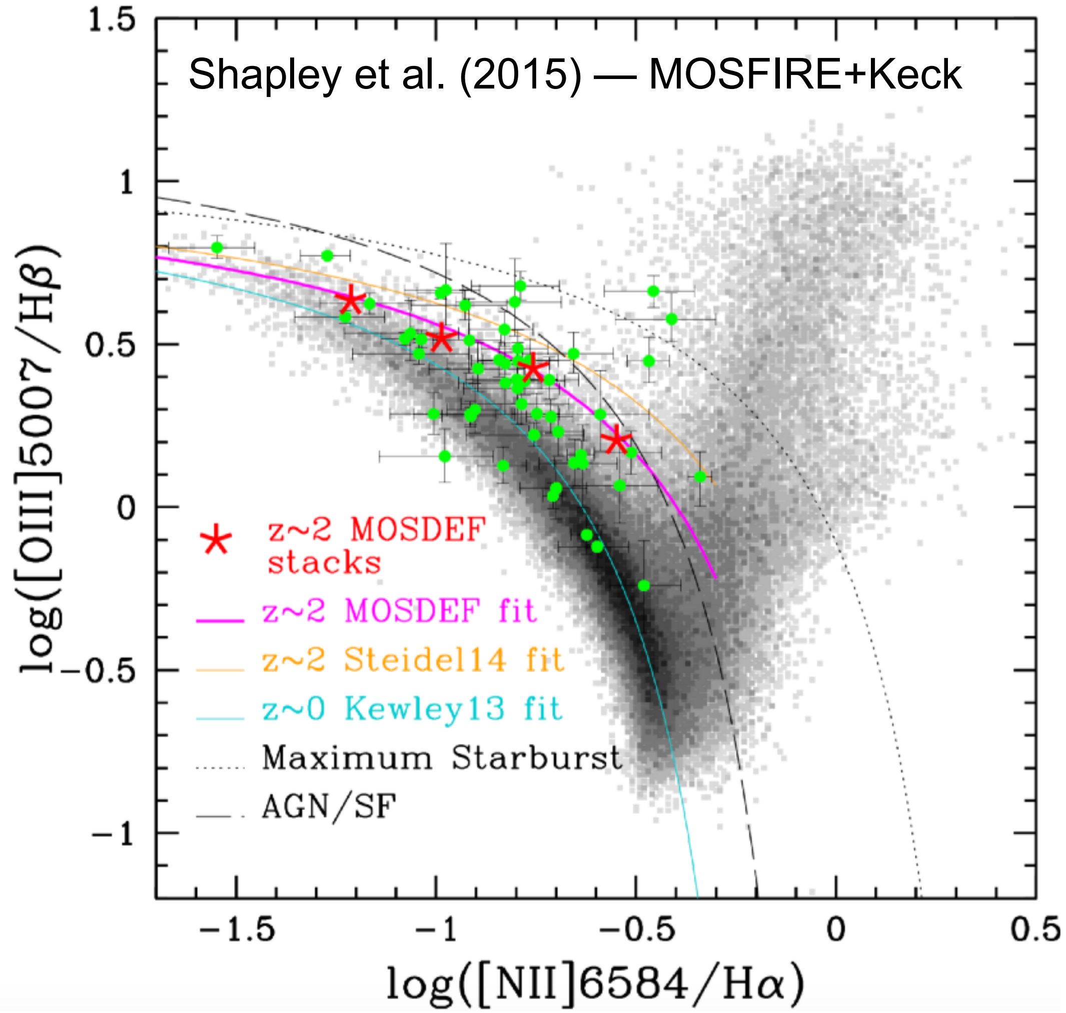
WFIRST Surveys Enormous Areas

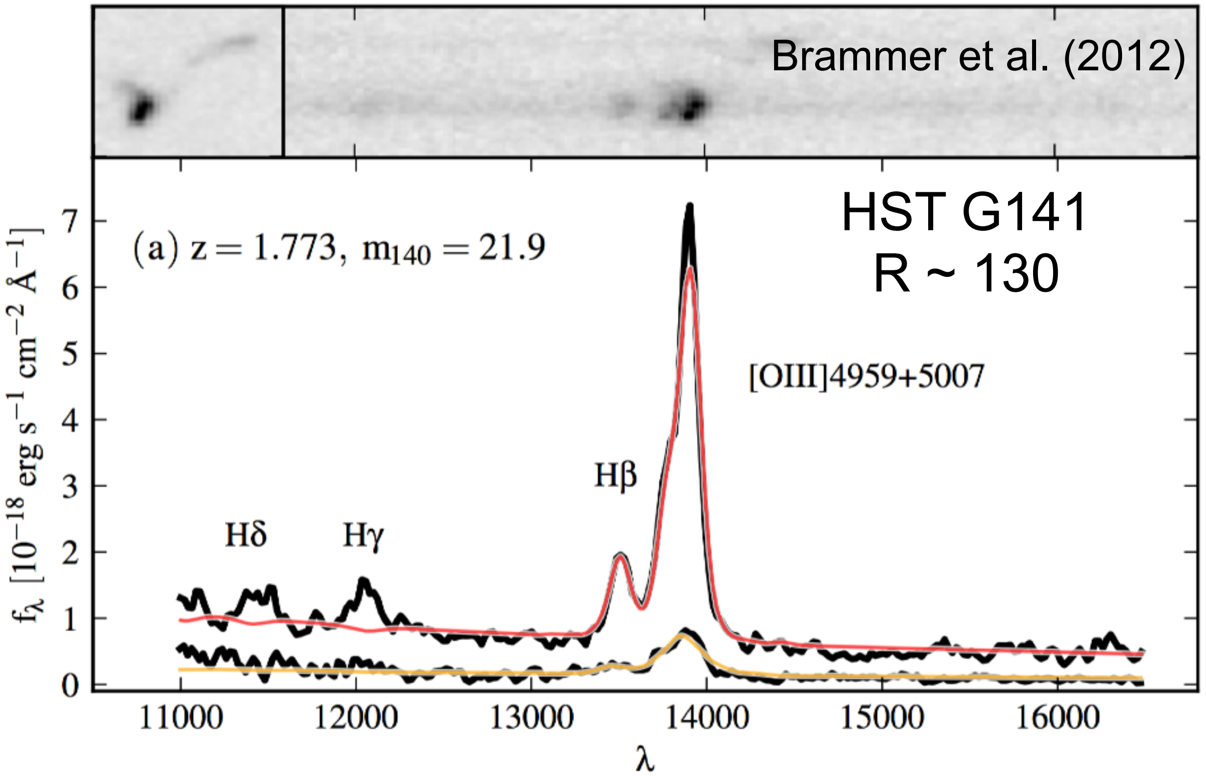


WFIRST field of view is ~100x *HST* WFC3, with similar sensitivity.
Multi-band IR capability is essential for selection, systematics.

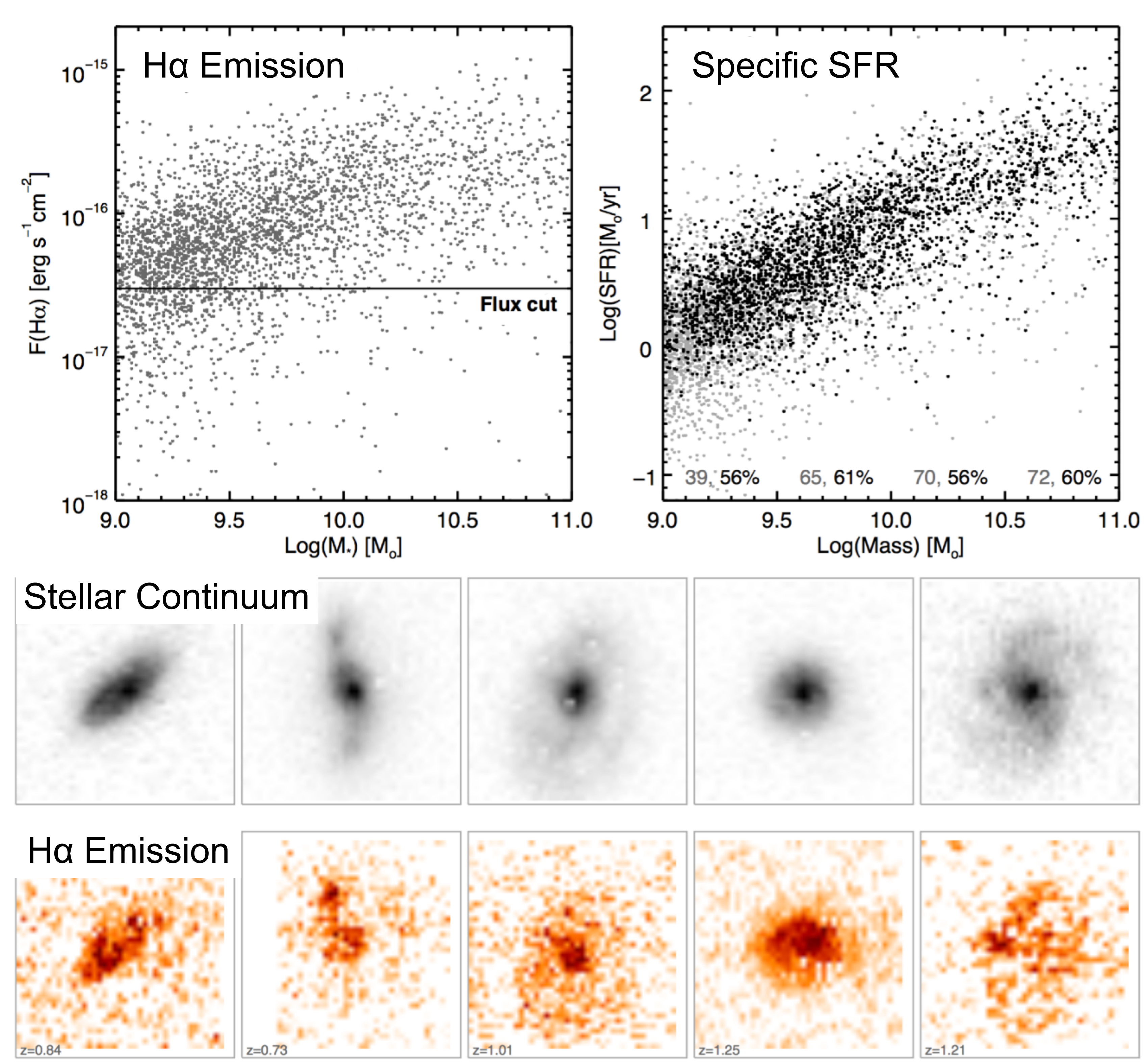
WFIRST Grism Can Revolutionize z~1-2 Galaxy Spectroscopy

- Current design calls for slitless spectroscopy with resolution 550<R<800, and a wavelength coverage ~1µm < λ < ~1.9µm.
- Resolution requirements set to 300km/s redshift accuracy, will resolve [OIII] doublet but blend NII+Hα (on purpose!).
- Significant improvement over HST WFC3 G141 grism, with R~130.





WFIRST Grism Can Revolutionize z~1-2 Galaxy Spectroscopy



Nelson et al. (2015)

- 3DHST Survey (Brammer et al. 2012) has provided WFC3 G141 spectra for ~100,000 galaxies (Momcheva et al. 2015).
- Of these, only ~3% are star forming galaxies with sufficient fluxes to measure both stellar morphologies and resolved Hα emission.
- Enables measures of the SFR vs. stellar mass in z~2 galaxies, and SFR maps (usually stacked).
- WFIRST will increase these numbers by 100x, enable environmental studies.

Notional *WFIRST* Surveys

- WFIRST High Latitude Survey

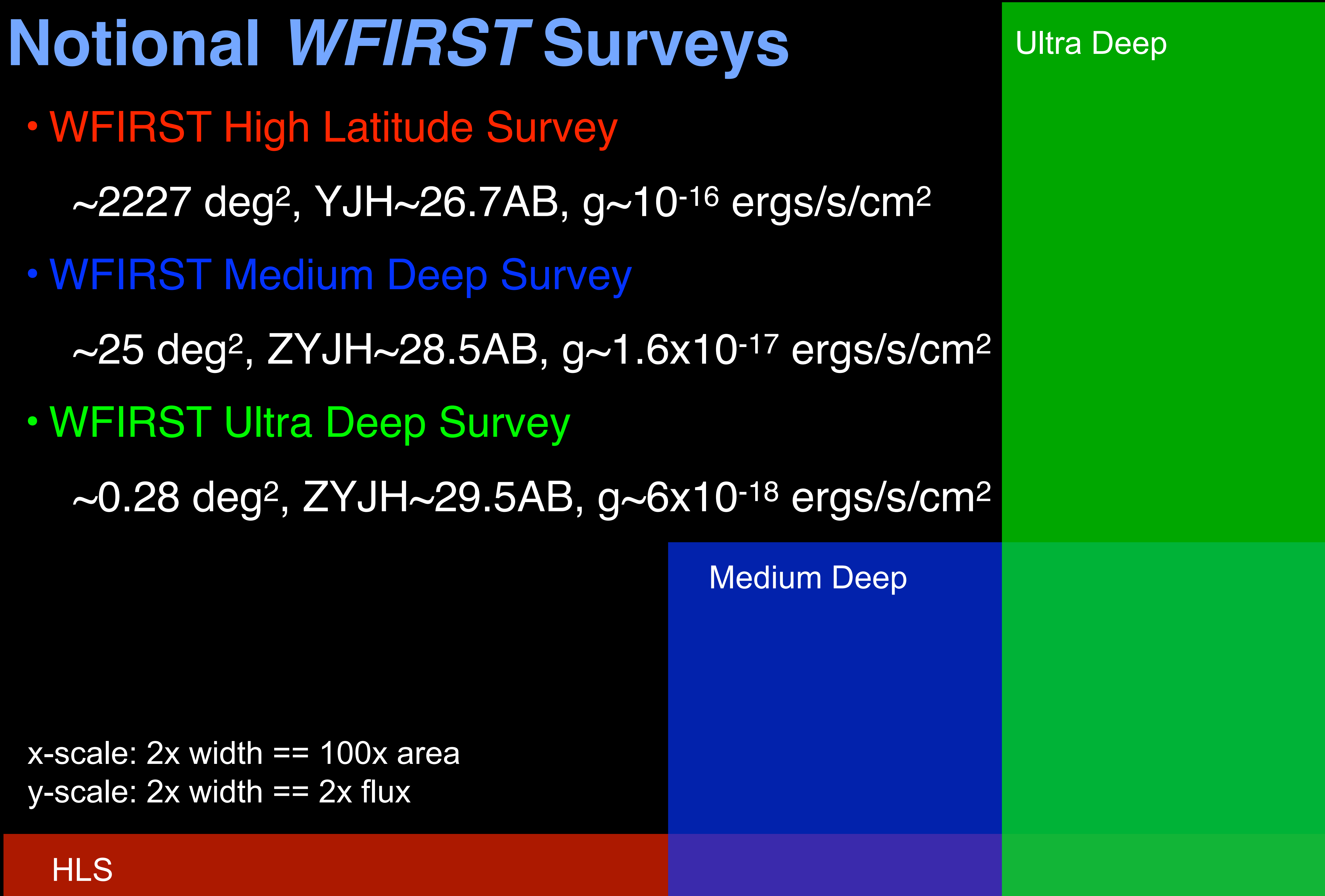
  ~2227 deg^2, YJH~26.7AB, g~10^{-16} ergs/s/cm^2

- WFIRST Medium Deep Survey

  ~25 deg^2, ZYJH~28.5AB, g~1.6×10^{-17} ergs/s/cm^2

- WFIRST Ultra Deep Survey

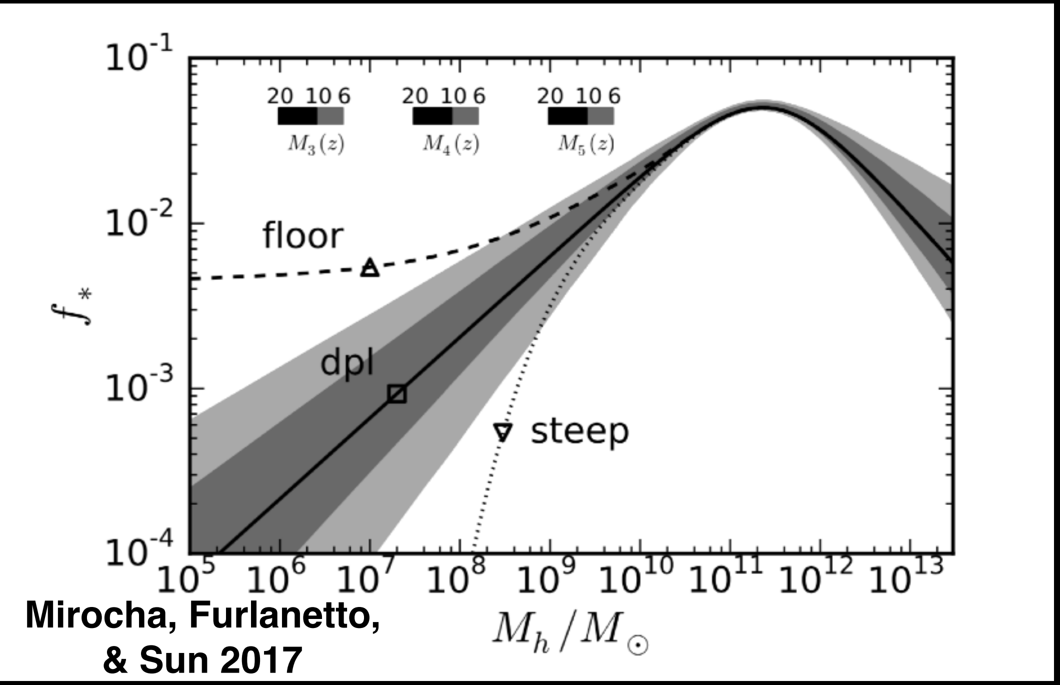
  ~0.28 deg^2, ZYJH~29.5AB, g~6×10^{-18} ergs/s/cm^2



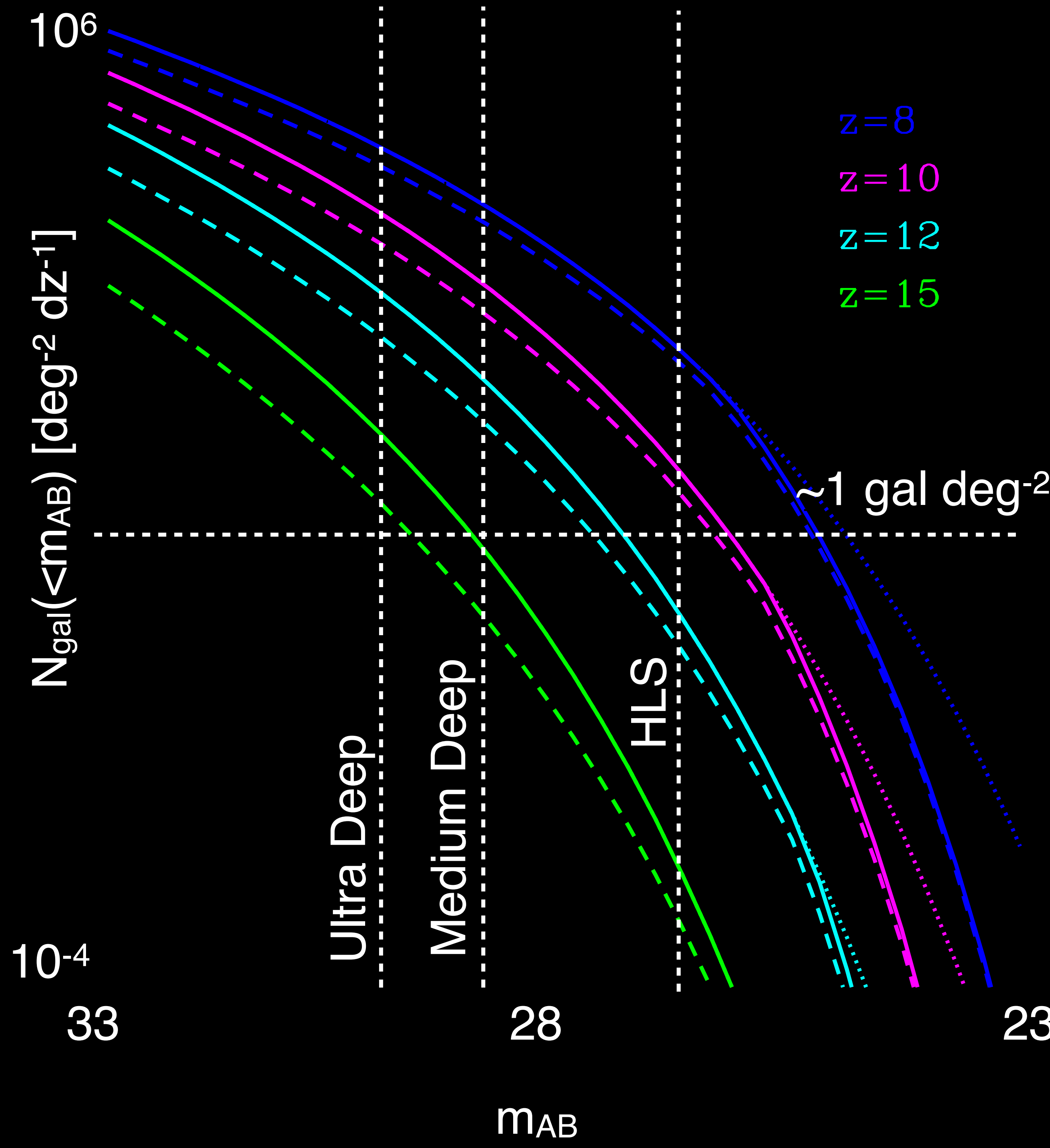
x-scale: 2x width == 100x area
y-scale: 2x width == 2x flux

Predictions for WFIRST High-z Populations

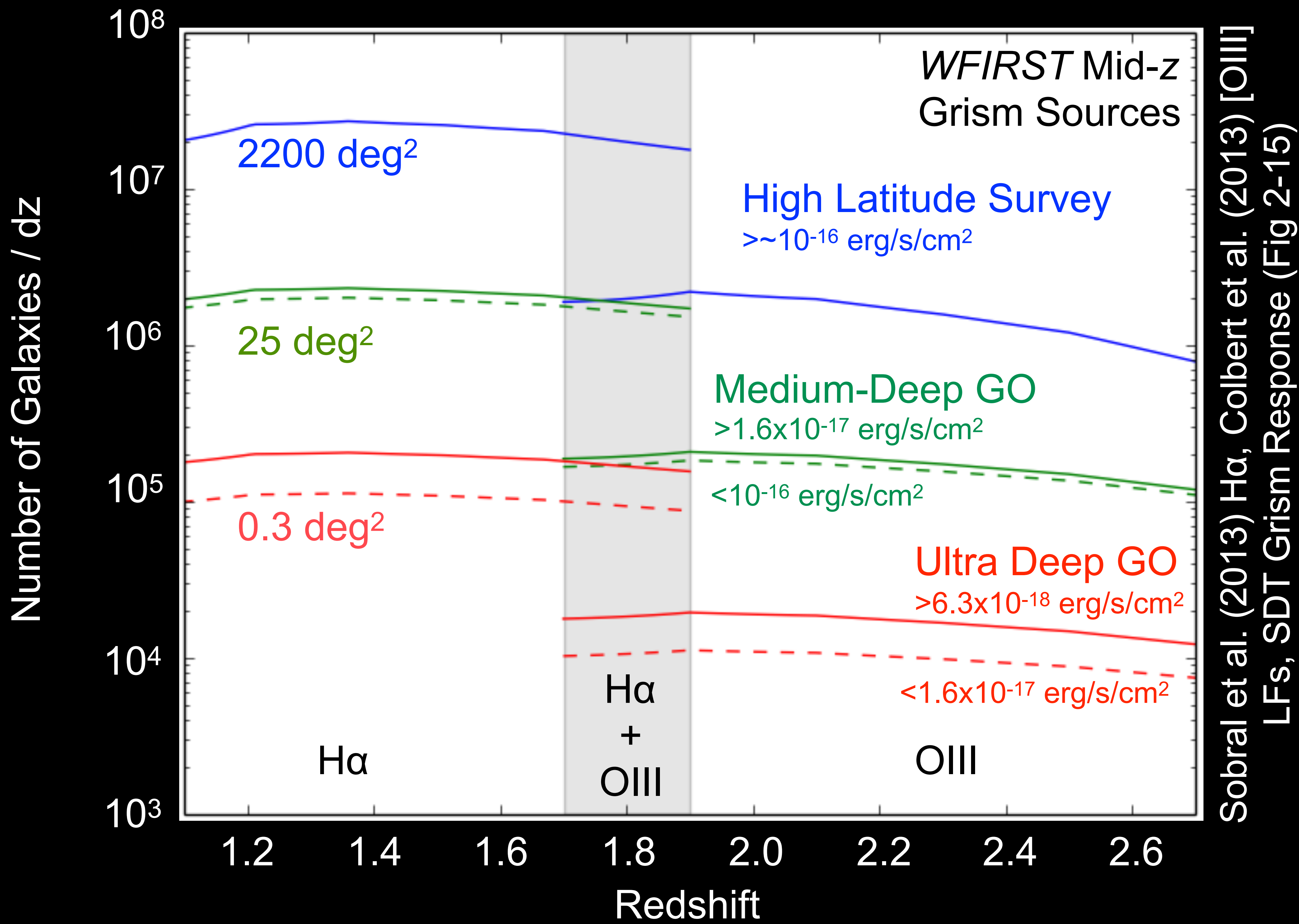
- EXPO team members developed galaxy formation models calibrated to z>6 HST observations, provides baseline predictions for WFIRST surveys
- Lower plot: Empirically determined star formation efficiencies for high-z galaxies, with three different extrapolations to very faint systems
- Right plot: Curves show depth and number densities; solid/dashed/dotted curves are different star formation models



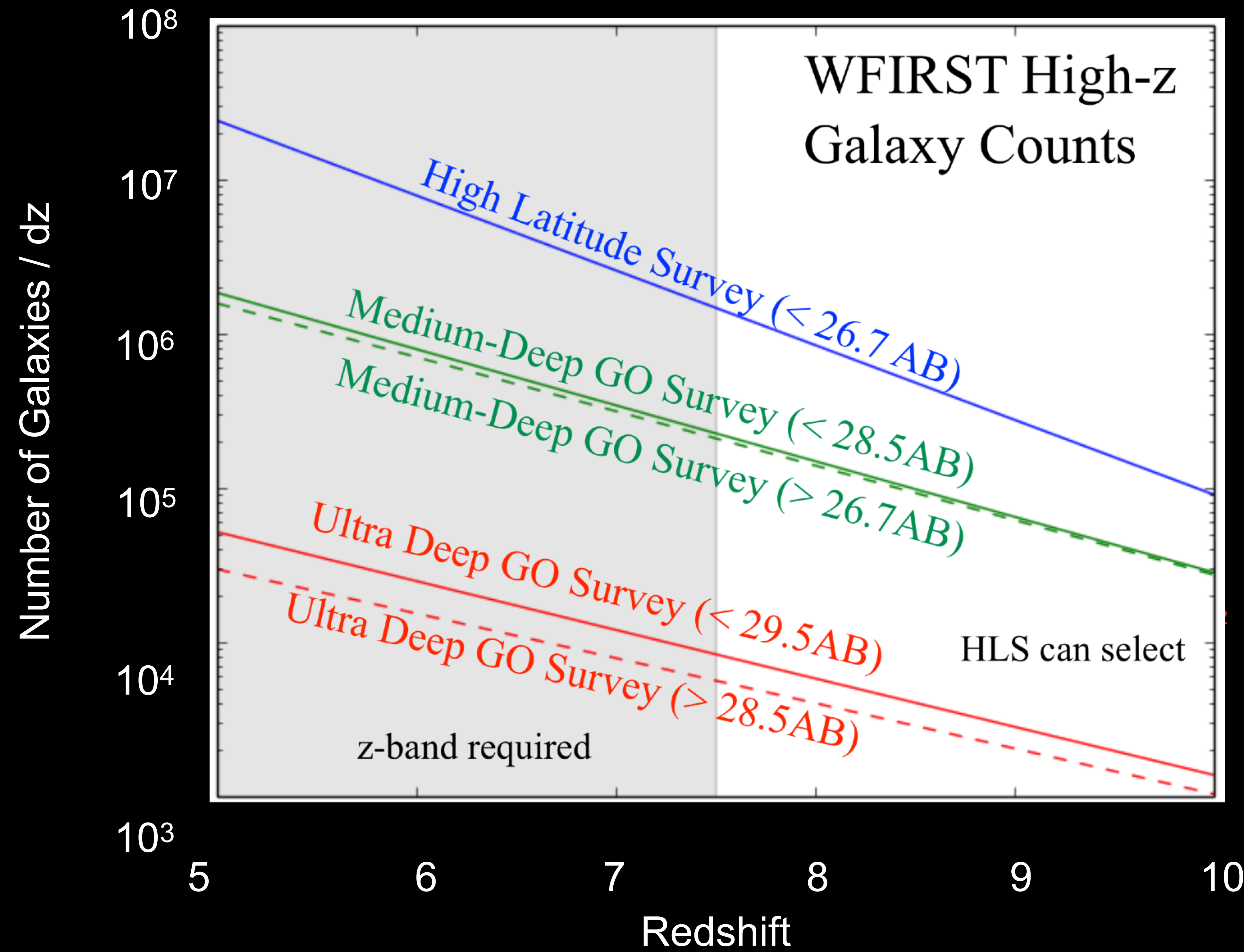
Mirocha, Furlanetto, & Sun 2017



WFIRST Spectroscopy at the

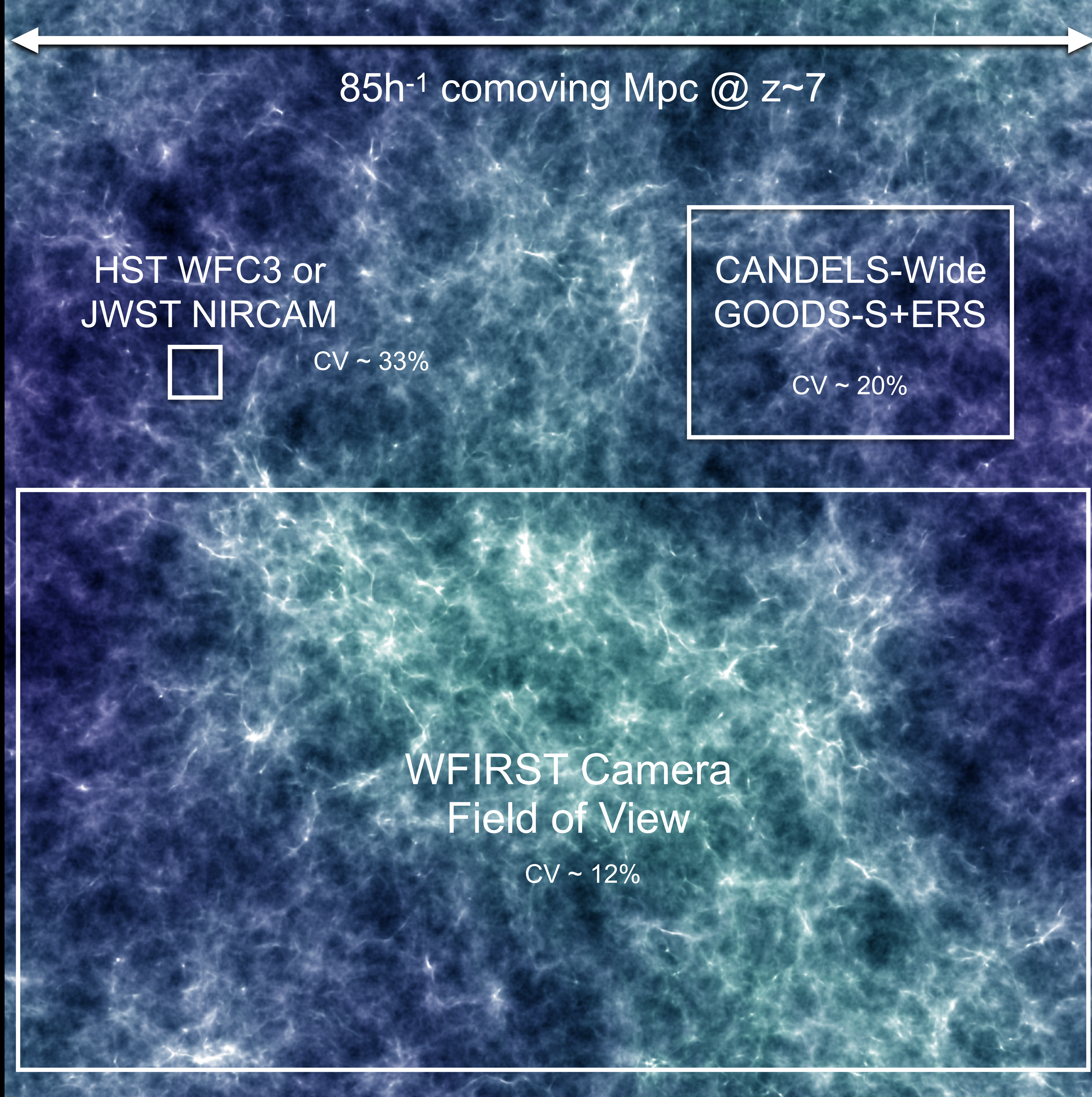


WFIRST High Redshift Galaxy Counts



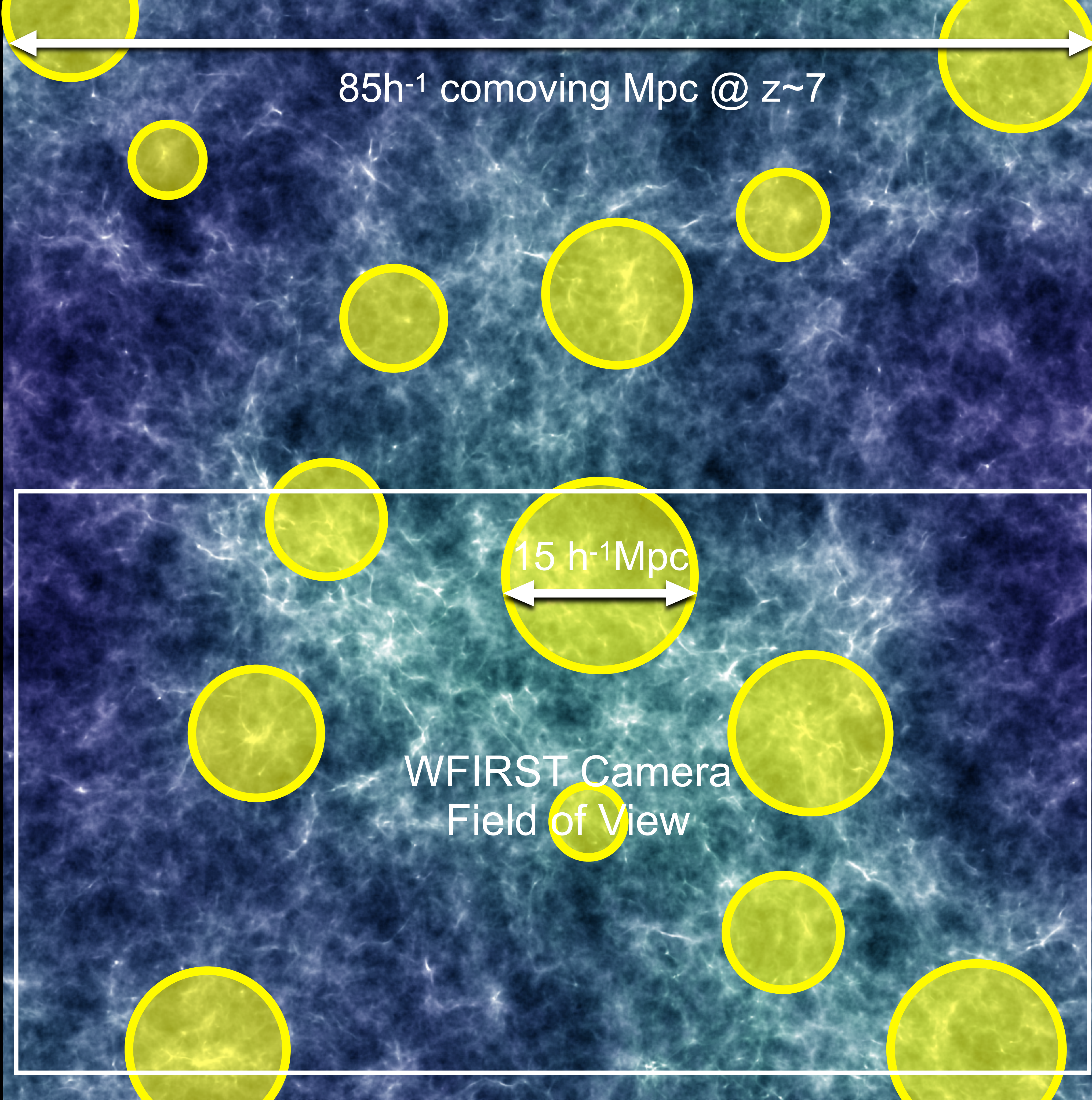
HLS can select the first statistical samples of EoR galaxies.

Cosmic Variance

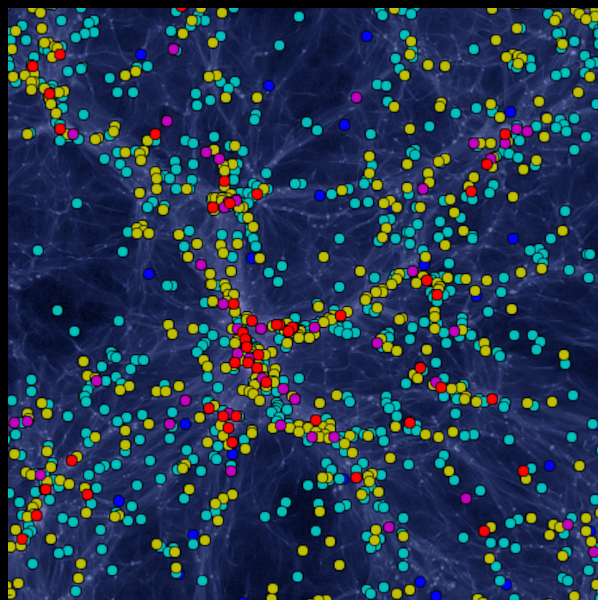


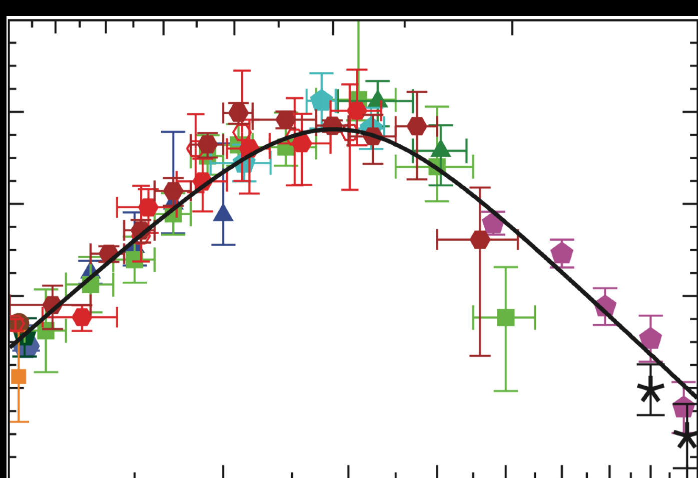
Adapted from Robertson, ApJ, 713, 1266 (2010)

Reionized Bubbles



Summary





- *WFIRST* will be transformative for studies of galaxy evolution and formation.
- *WFIRST* can teach us about the connection between galaxy evolution and cosmic environment.
- *WFIRST* will provide unprecedented spectroscopic samples during the peak of galaxy formation.
- *WFIRST* will provide the first statistical samples for studying early galaxy and quasar populations that cause cosmic reionization.
- The *WFIRST* EXPO team will investigate how to leverage *WFIRST* for galaxy evolution science.