Galaxy Formation and Evolution with *WFIRST*

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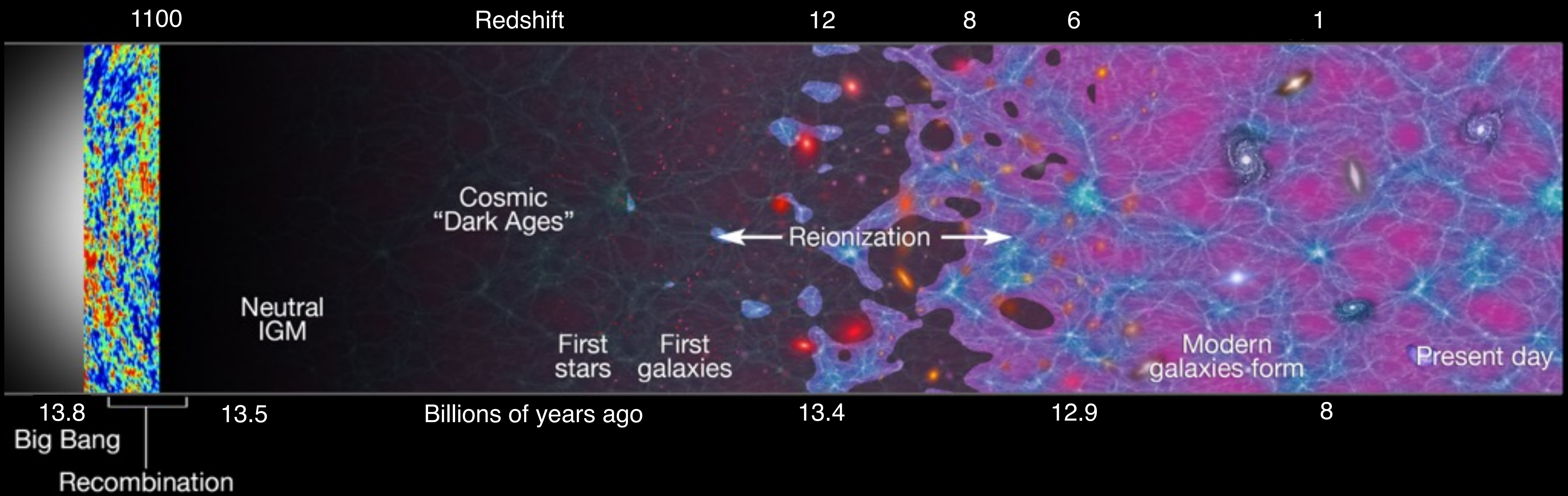
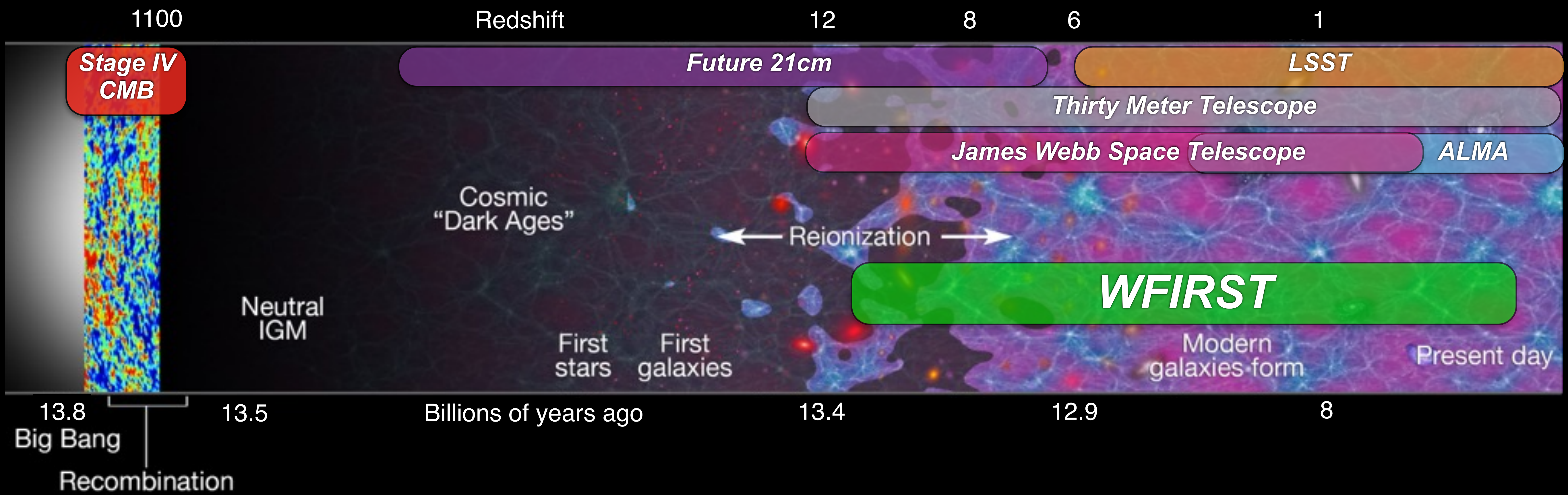
History of Galaxy Evolution over Cosmic Time



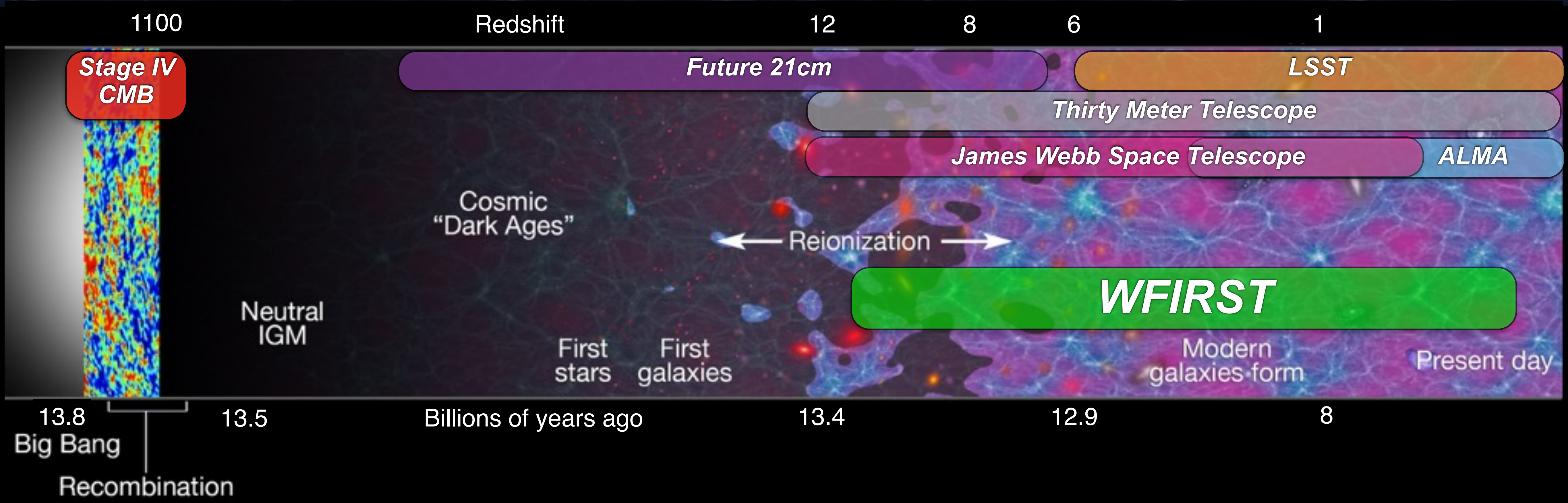
Adapted from Robertson et al. *Nature*, **468,** 49 (2010).

Astronomical Facilities in the Next Decade



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 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)

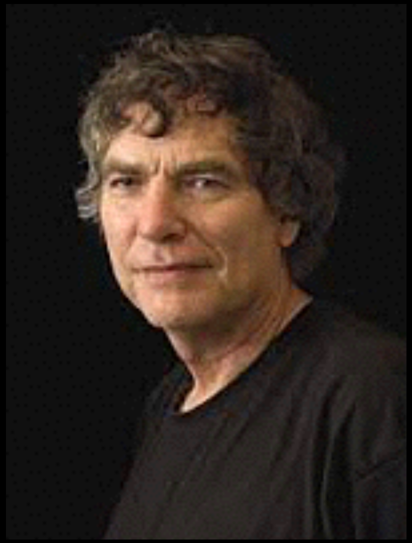
*At this meeting

Brant Robertson
(UCSC; PI)

Alice Shapley
(UCLA)

Dan Stark
(Arizona)

Risa Wechsler
(Stanford)

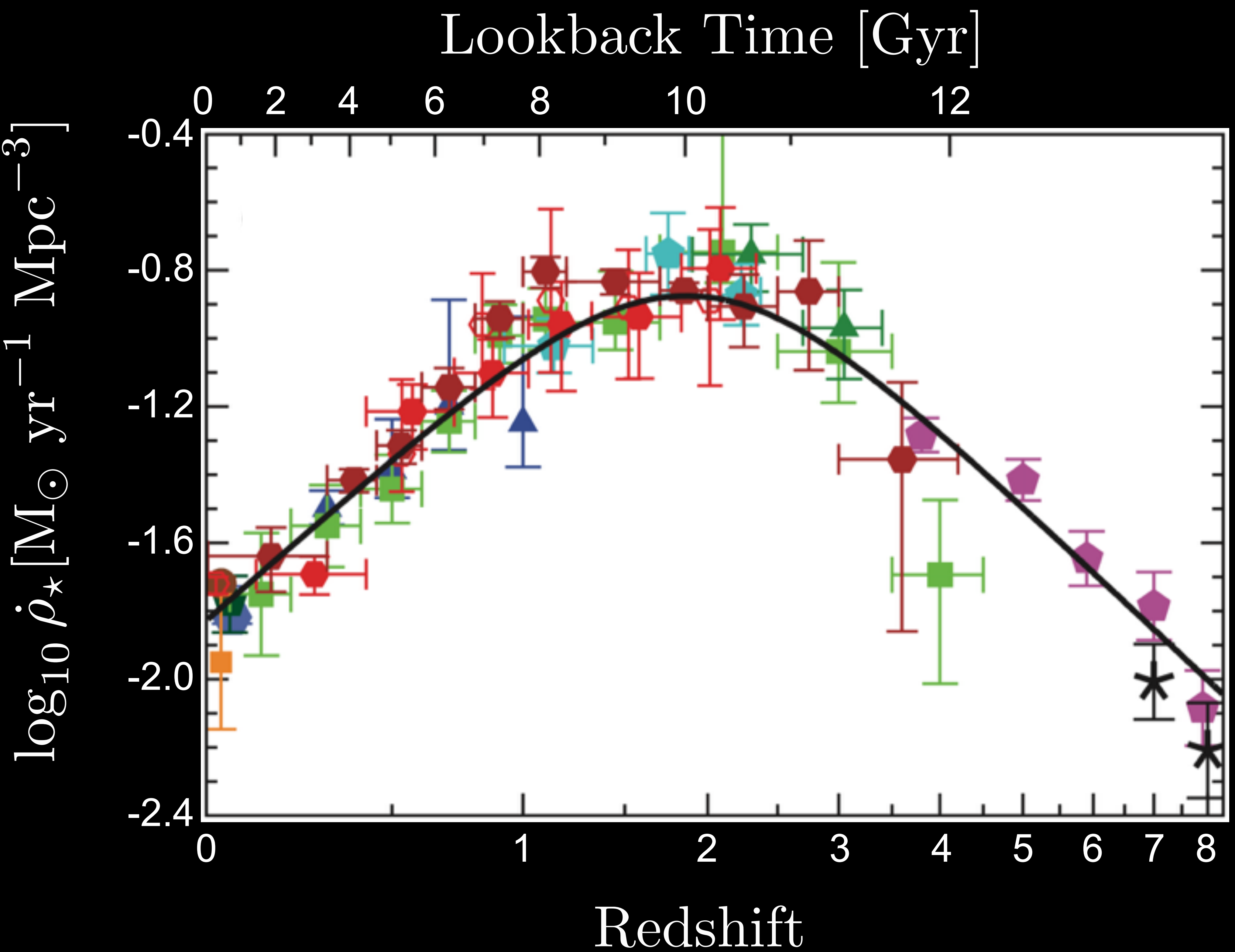


Stan Woosley
(UCSC)

WFIRST-EXPO: *Science Questions*

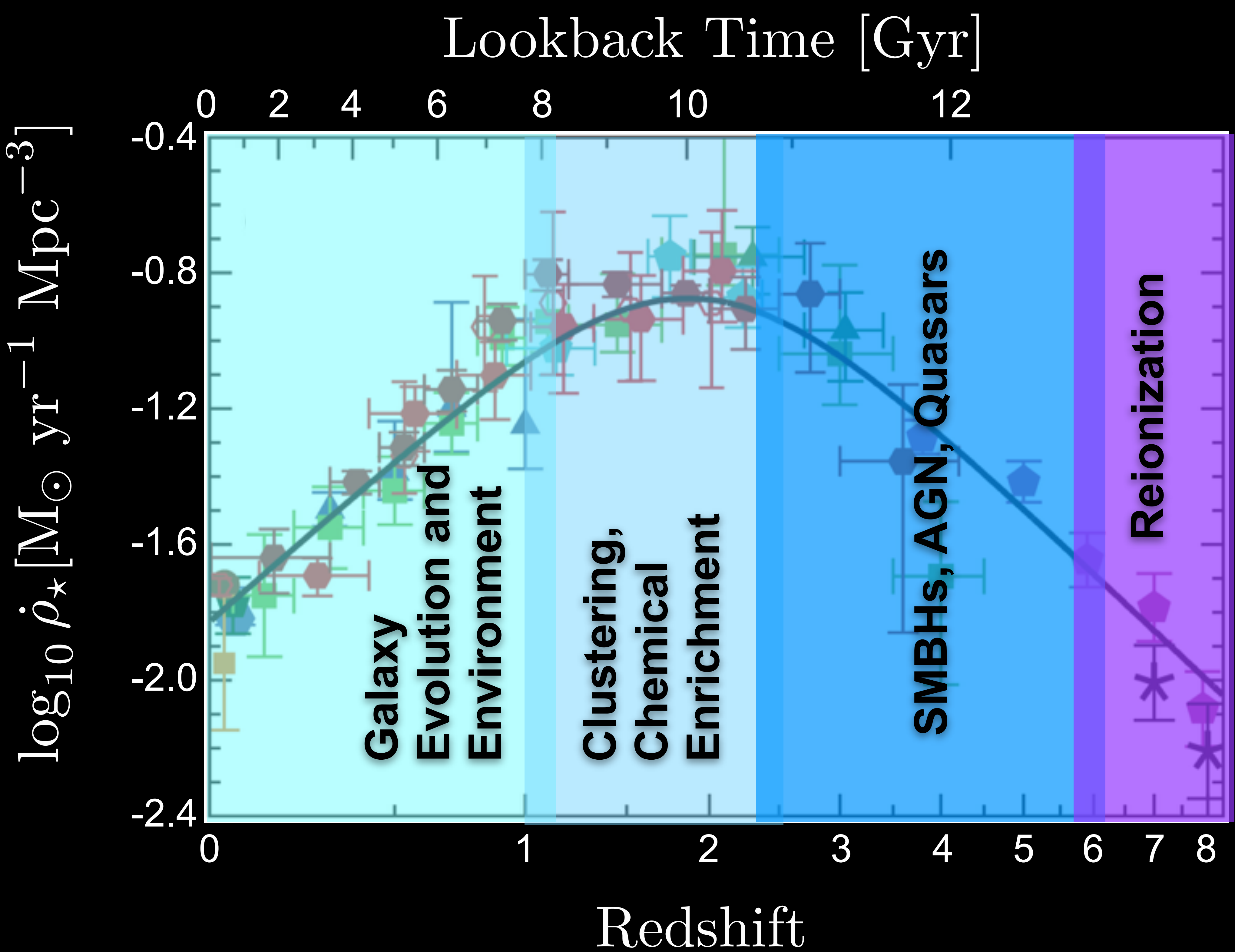
- How will WFIRST help us understand galaxy properties in the context of their environments over cosmic time?
- What will WFIRST spectroscopy teach us about galaxy properties and evolution during the peak era of cosmic star formation?
- How can we leverage WFIRST to discover and characterize rare AGN 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



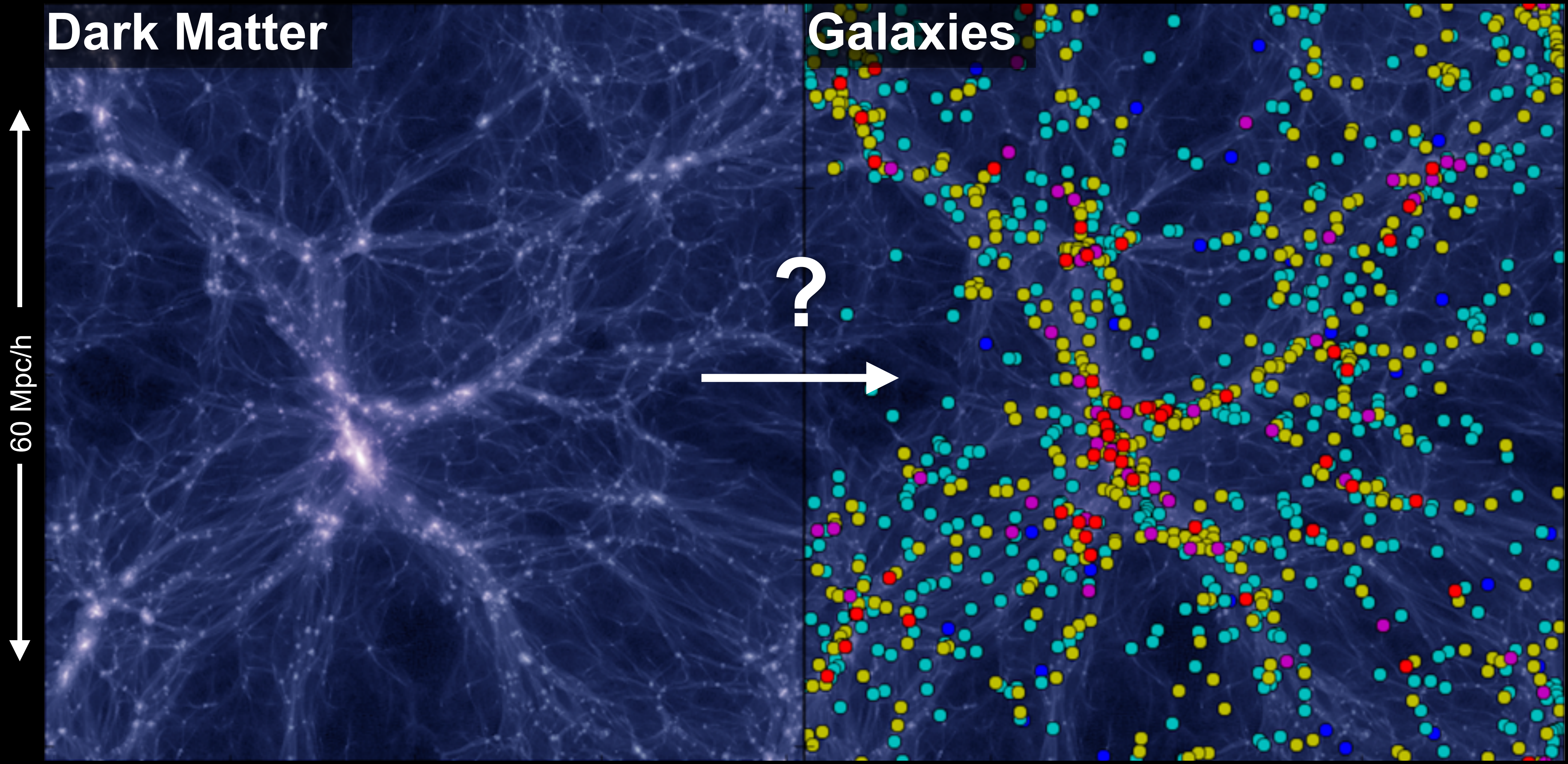
Adapted from Madau & Dickinson, ARAA, **52,** 412 (2014)

WFIRST Science over Cosmic History

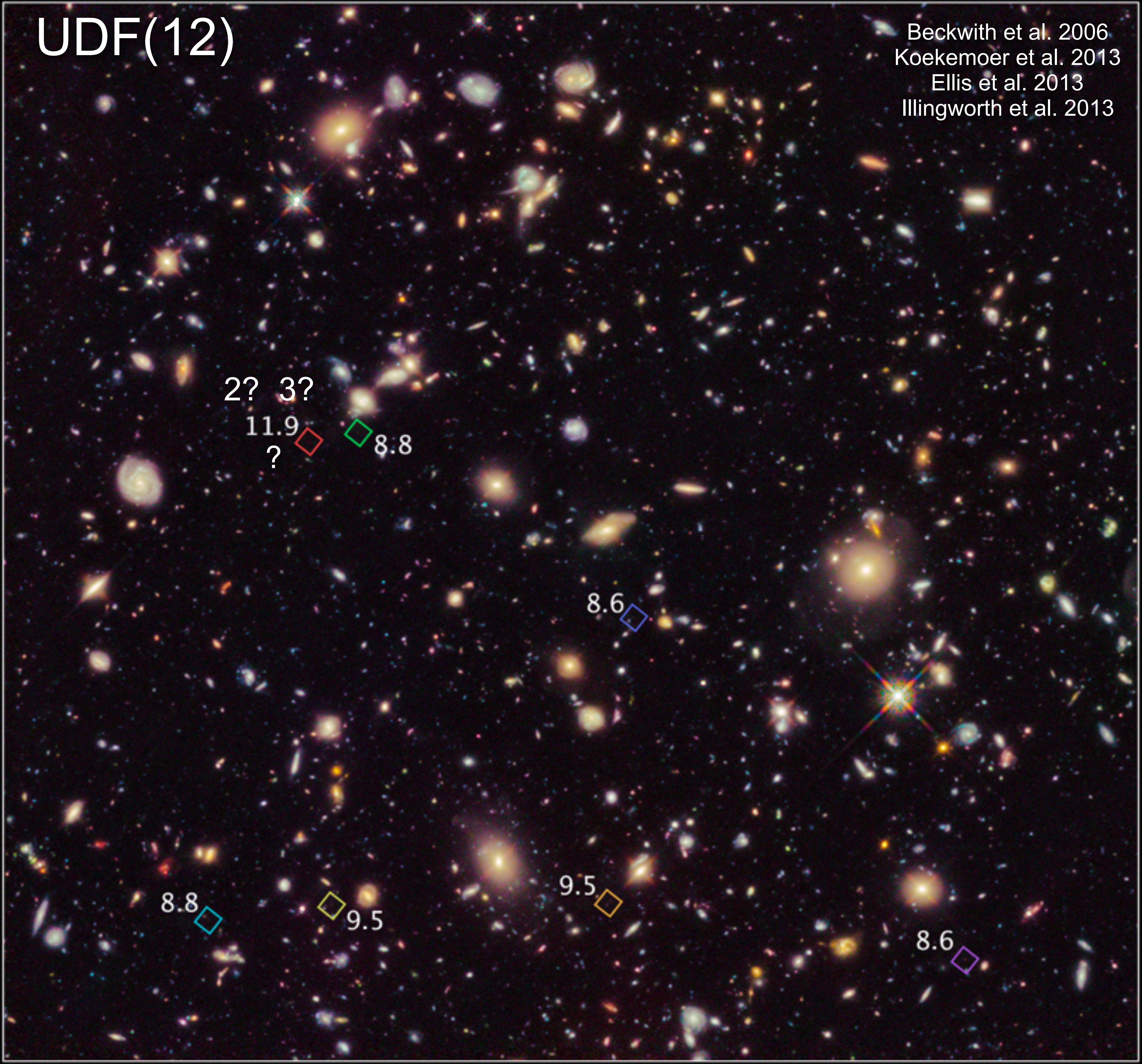


Adapted from Madau & Dickinson, ARAA, **52,** 412 (2014)

WFIRST Provides a Cosmic Context

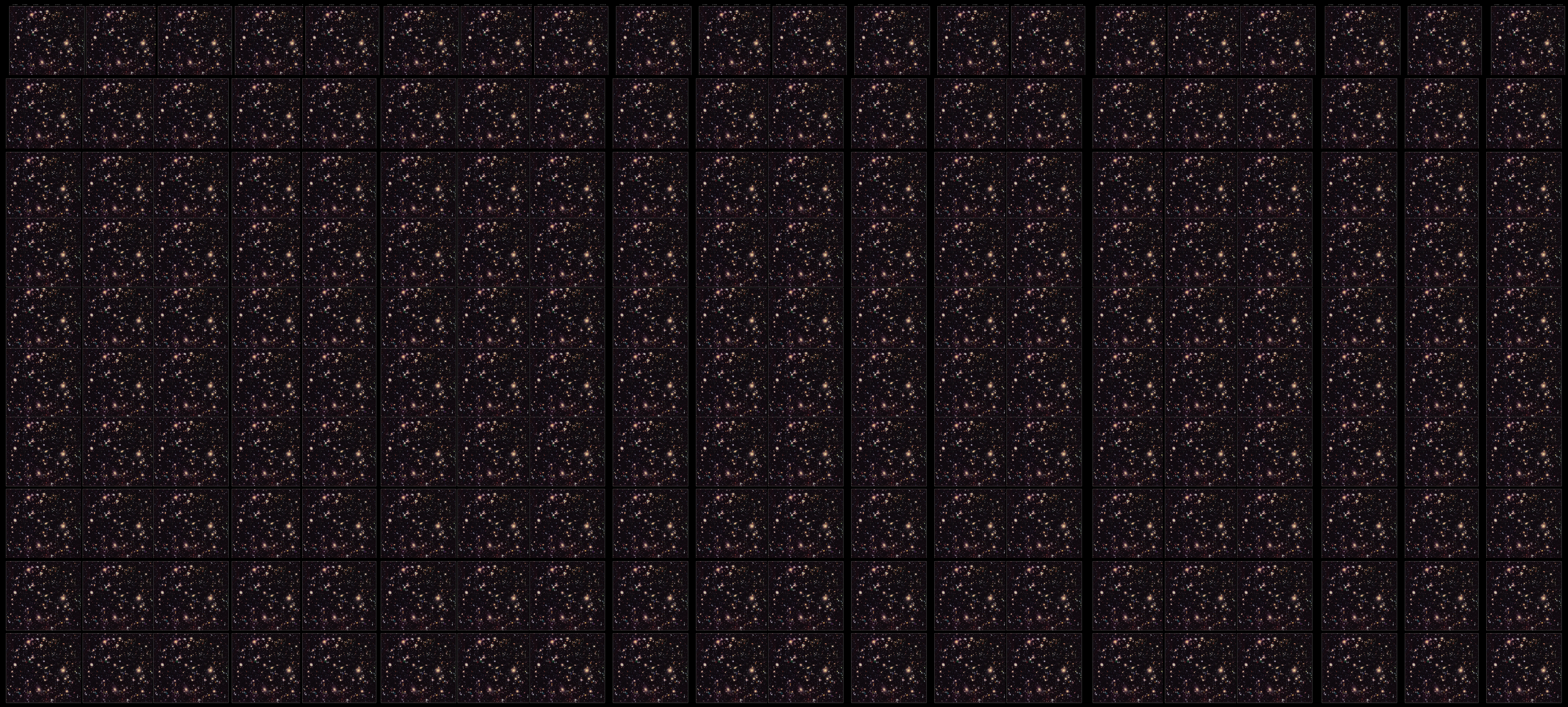


How do galaxy properties map onto dark matter structures?
How does cosmic environments affect galaxy evolution?



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.

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~$1.6x10^{-17}$ $ergs/s/cm^2$

- WFIRST Ultra Deep Survey

  ~0.28 deg^2, ZYJH~29.5AB, g~$6x10^{-18}$ $ergs/s/cm^2$

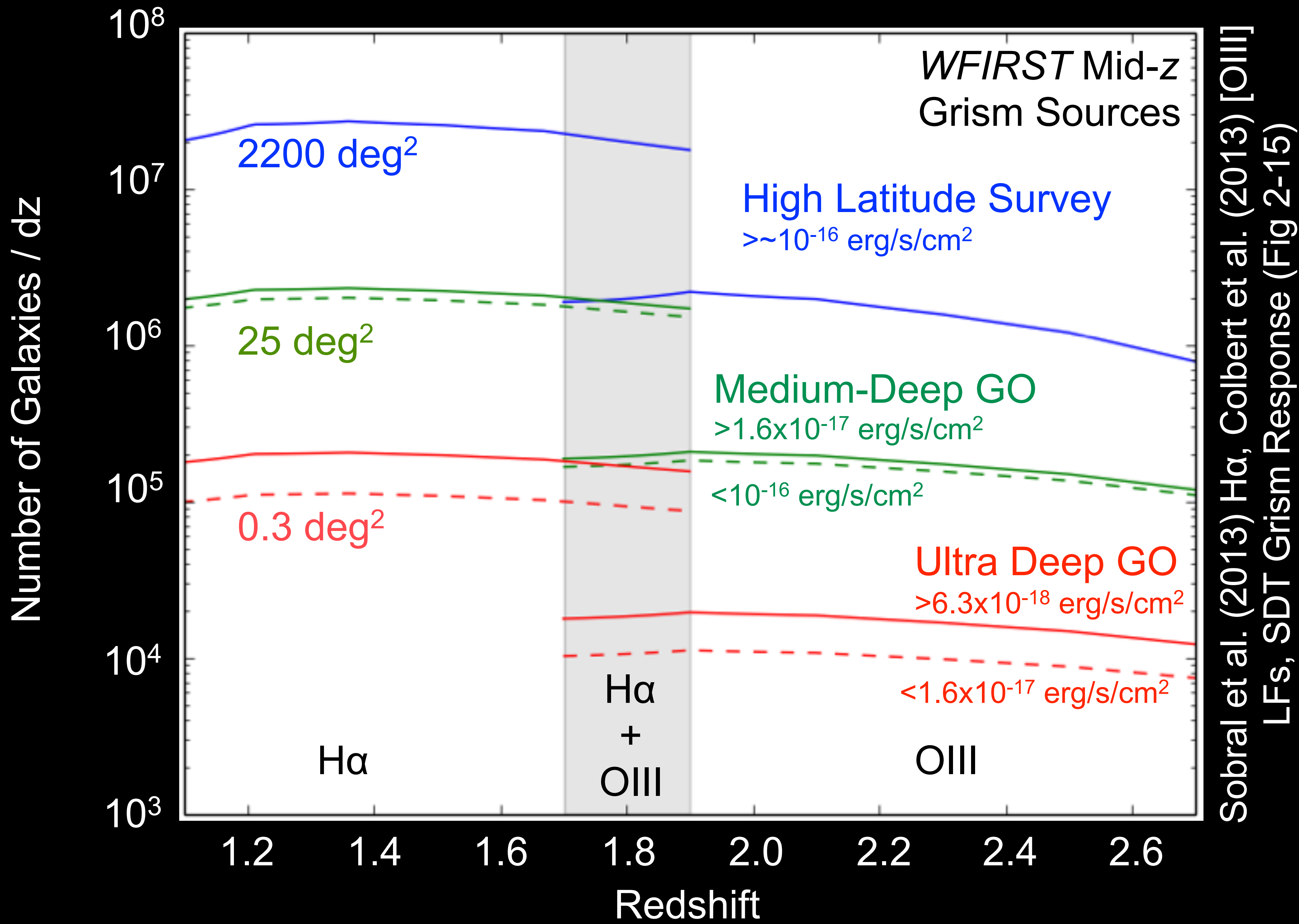
Ultra Deep

Medium Deep

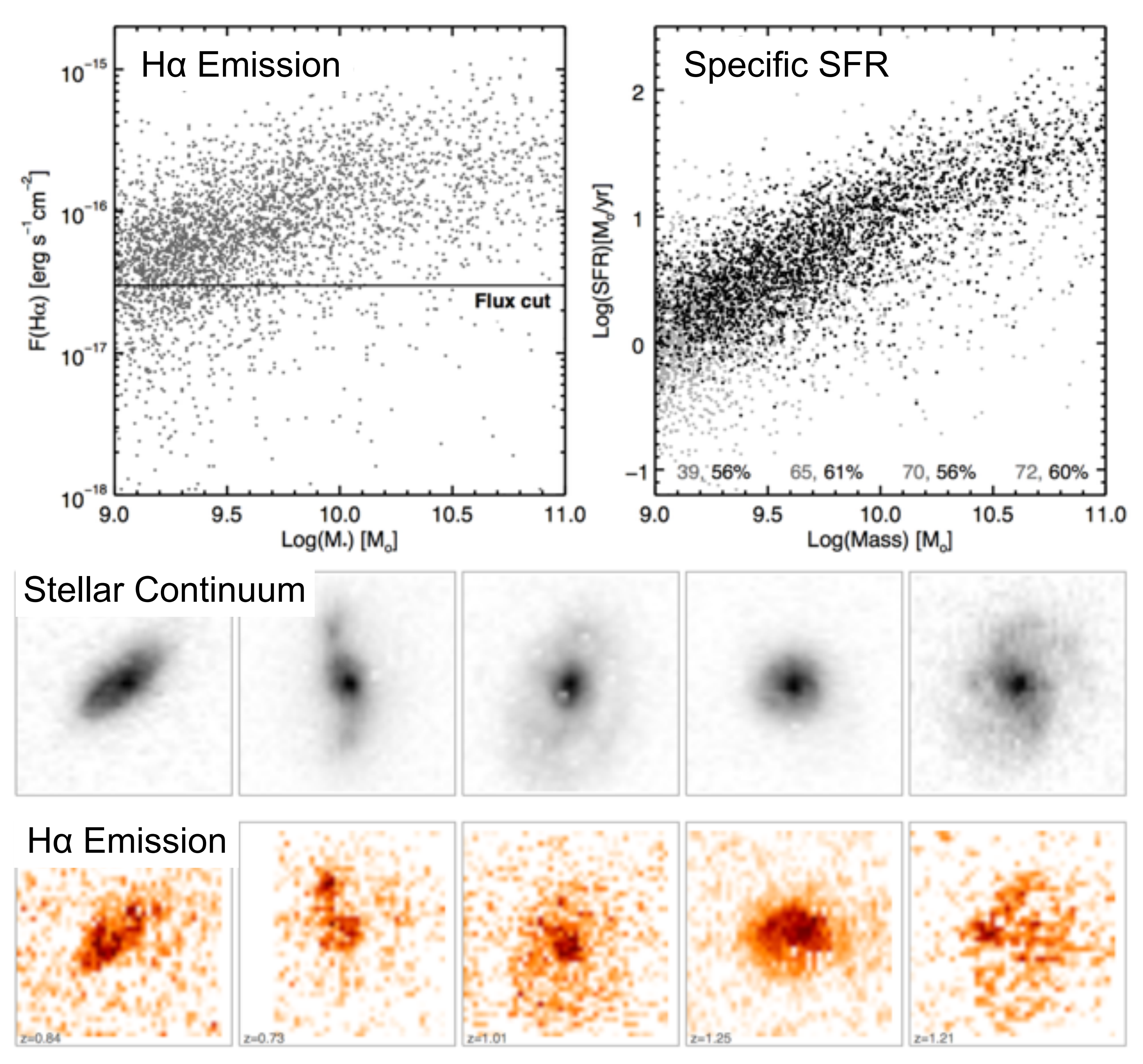
HLS

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

WFIRST Spectroscopy at the Peak of Cosmic Star Formation



WFIRST Grism Can Revolutionize z~1-2 Galaxy Spectroscopy

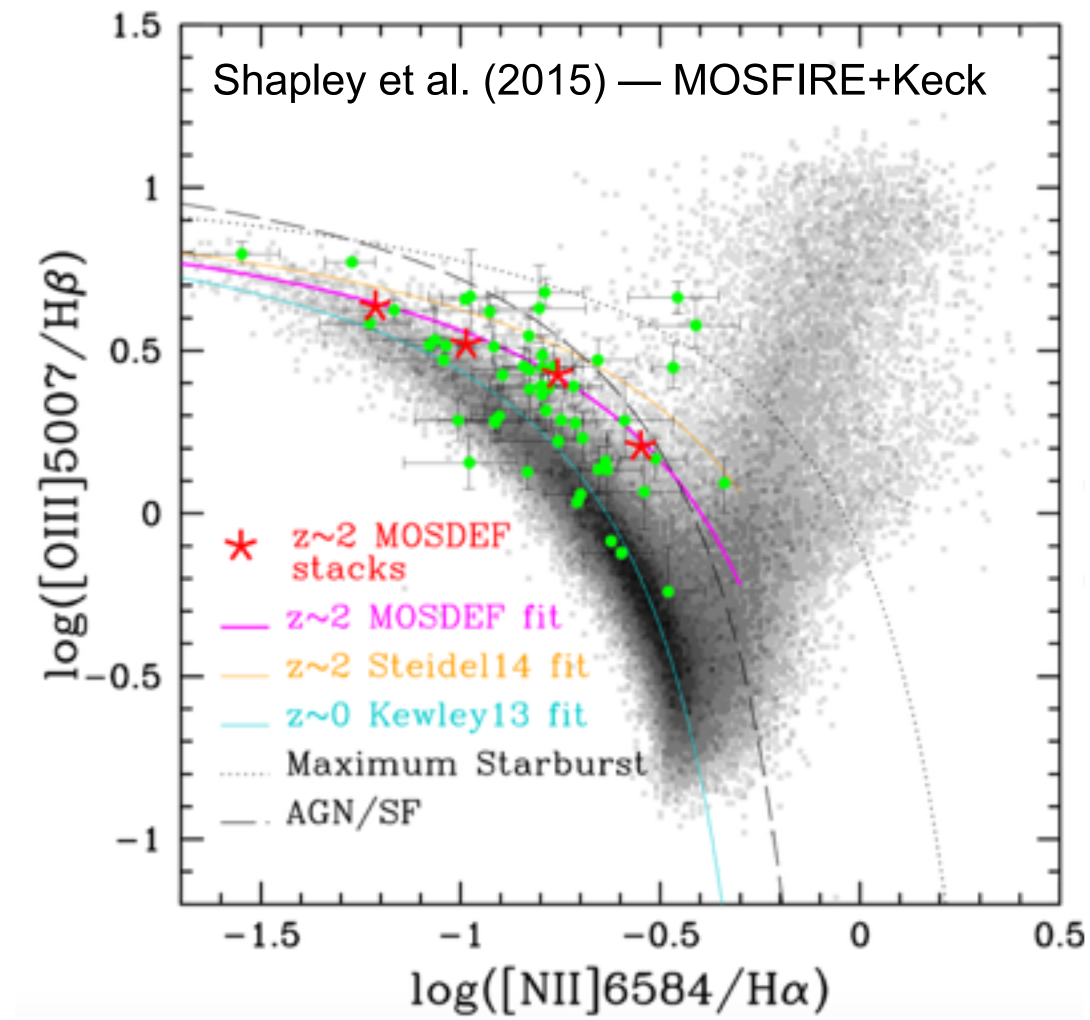


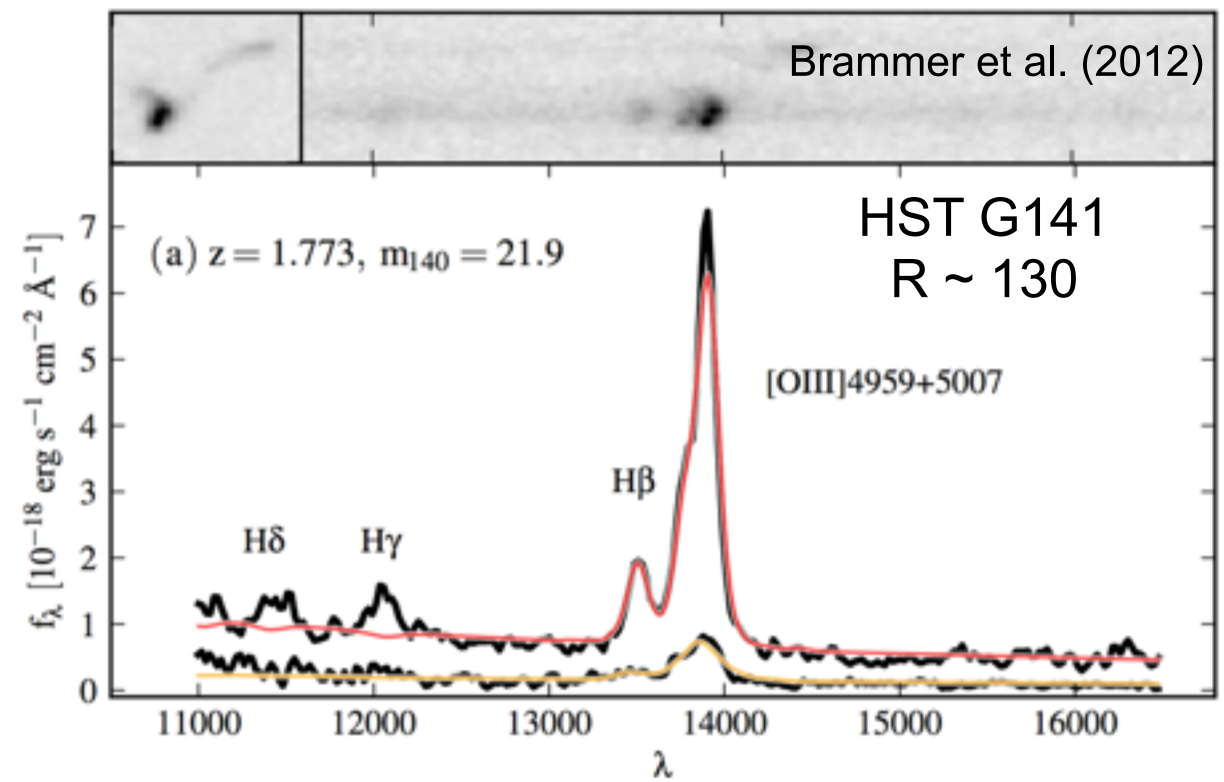
Nelson et al. (2015)

- 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.

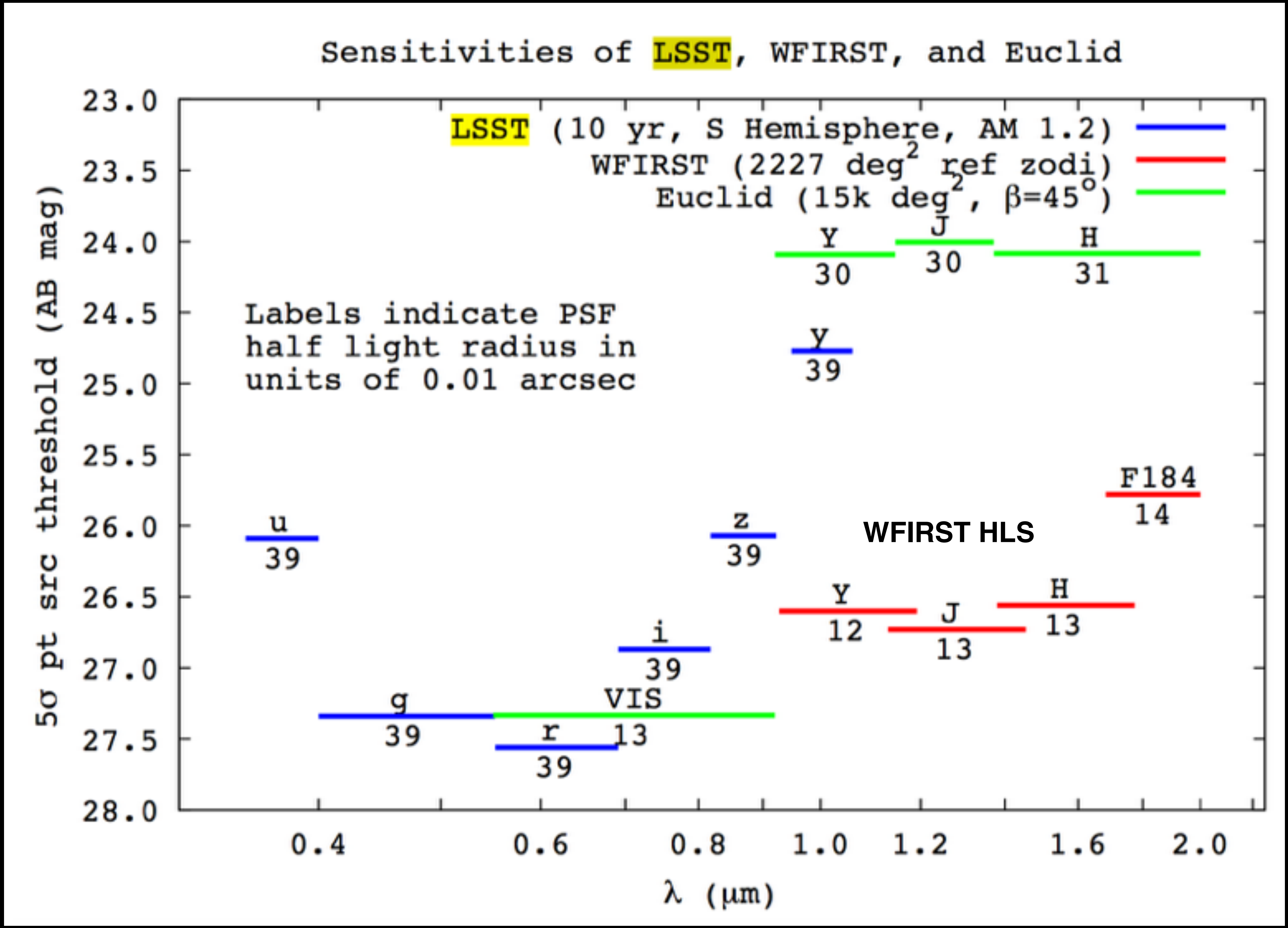
WFIRST Grism Can Revolutionize z~1-2 Galaxy Spectroscopy

- Current design calls for slitless spectroscopy with resolution 550<R<800 (HLSS 7, p39), and a wavelength coverage 1.35μm < λ < 1.85μm (HLSS 10, p39).
- 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.
- A high resolution WFIRST grism could measure the BPT diagram for z~2 galaxies, providing critical information about how excitation correlates with galaxy properties and environment. But req'd R -> from Hβ to NII may not fit in one grism.



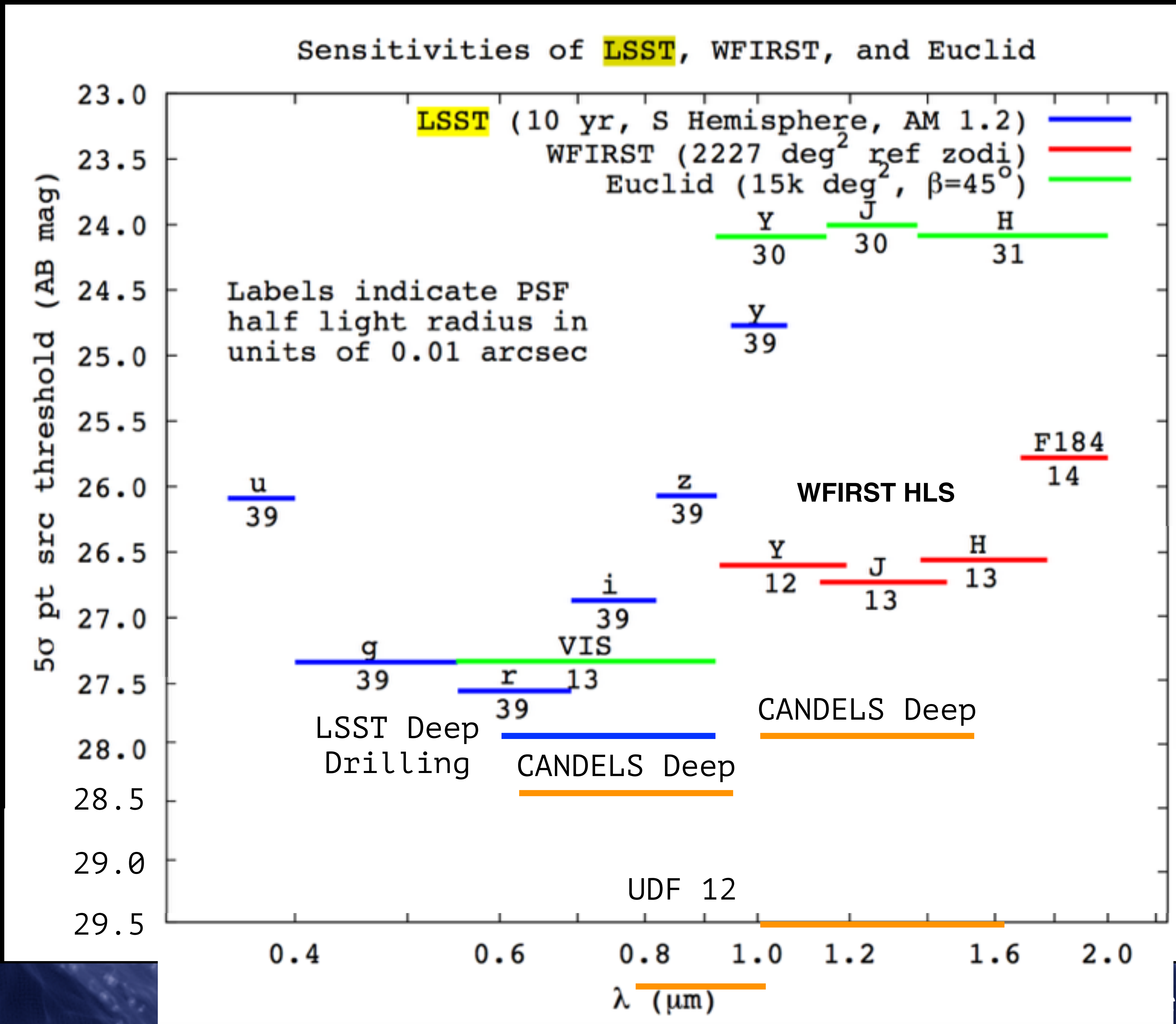


Photometric Depths: WFIRST & LSST



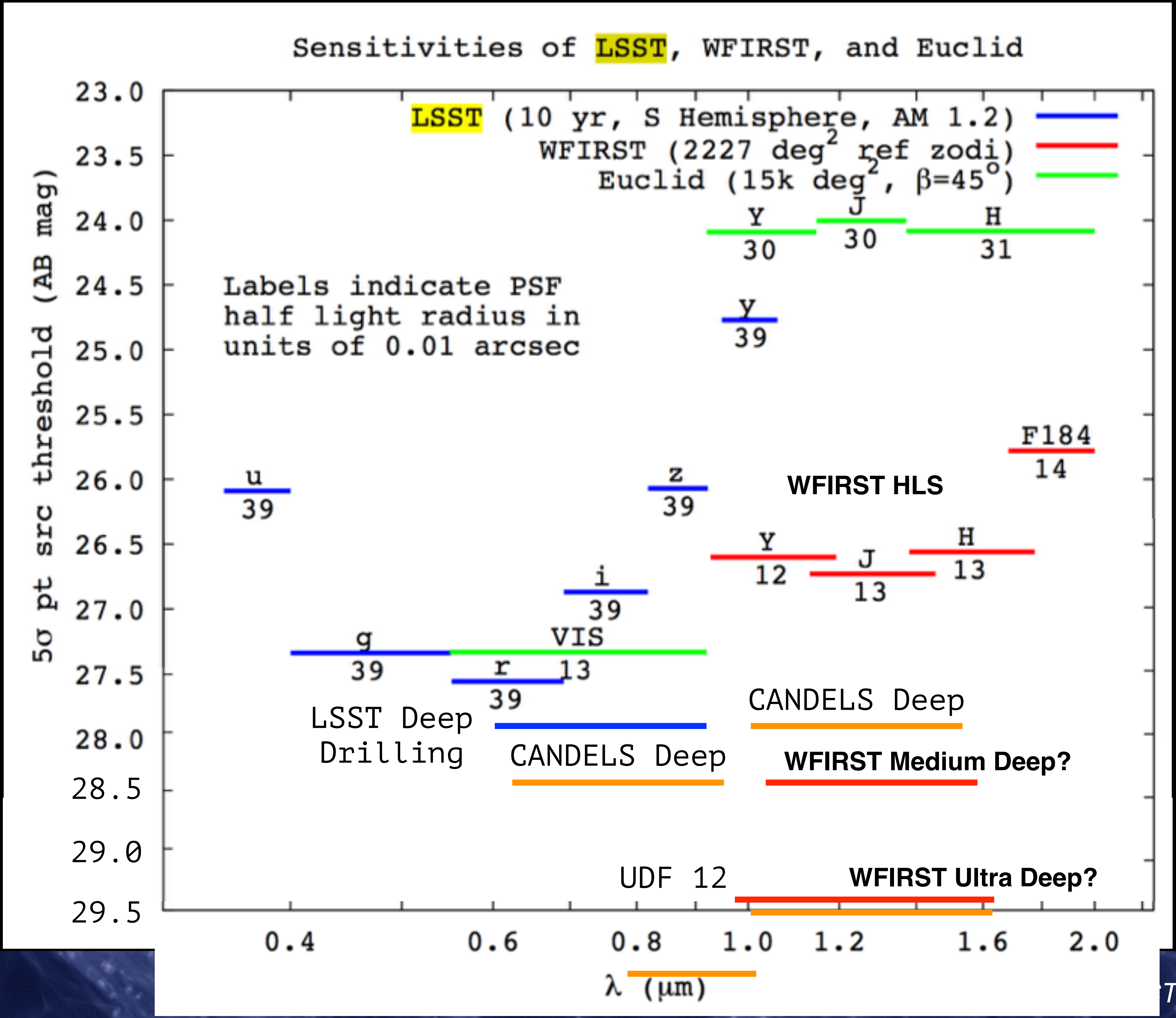
Spergel et al. (2015)

Photometric Depths: WFIRST & LSST



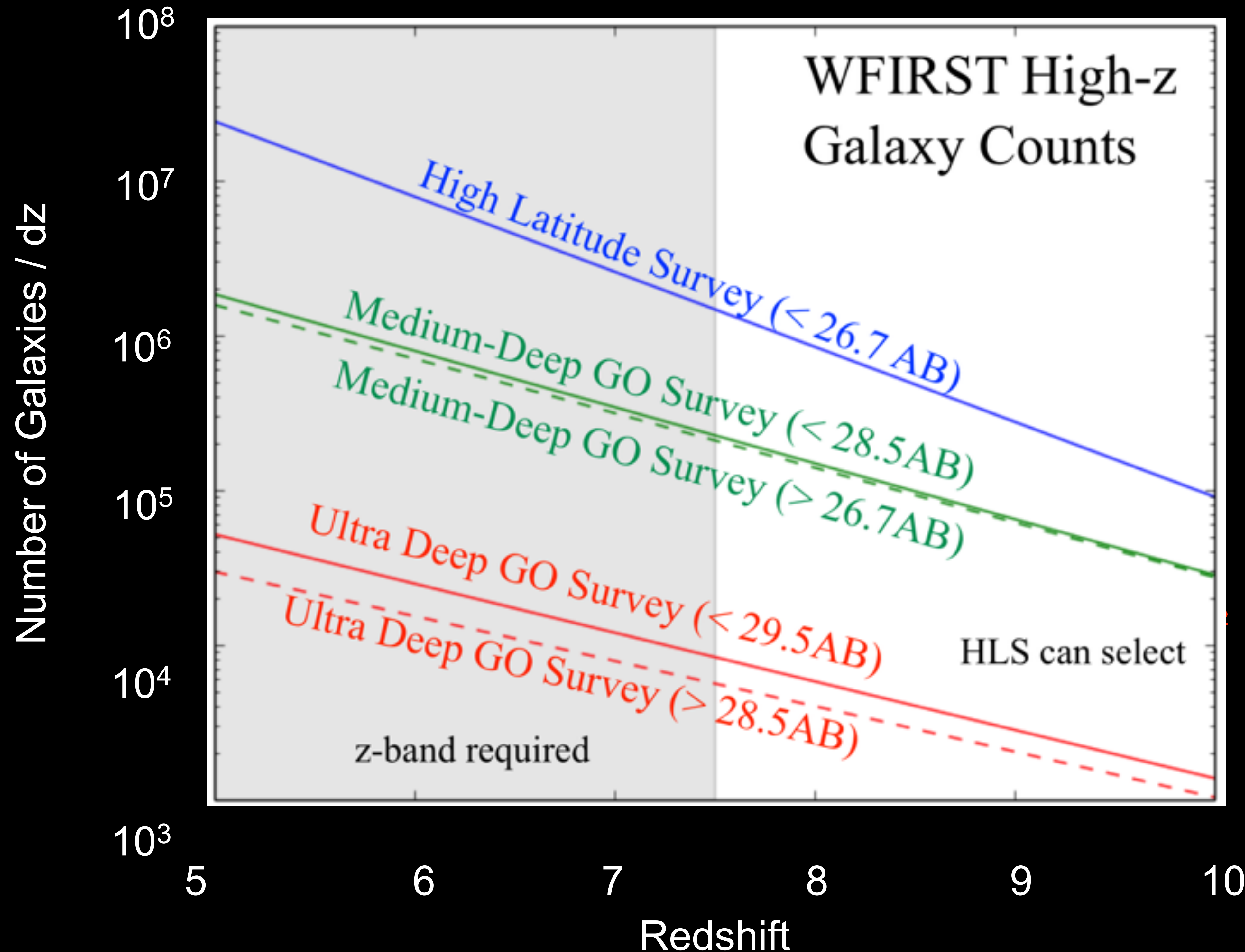
Spergel et al. (2015)

Photometric Depths: WFIRST & LSST



Spergel et al. (2015)

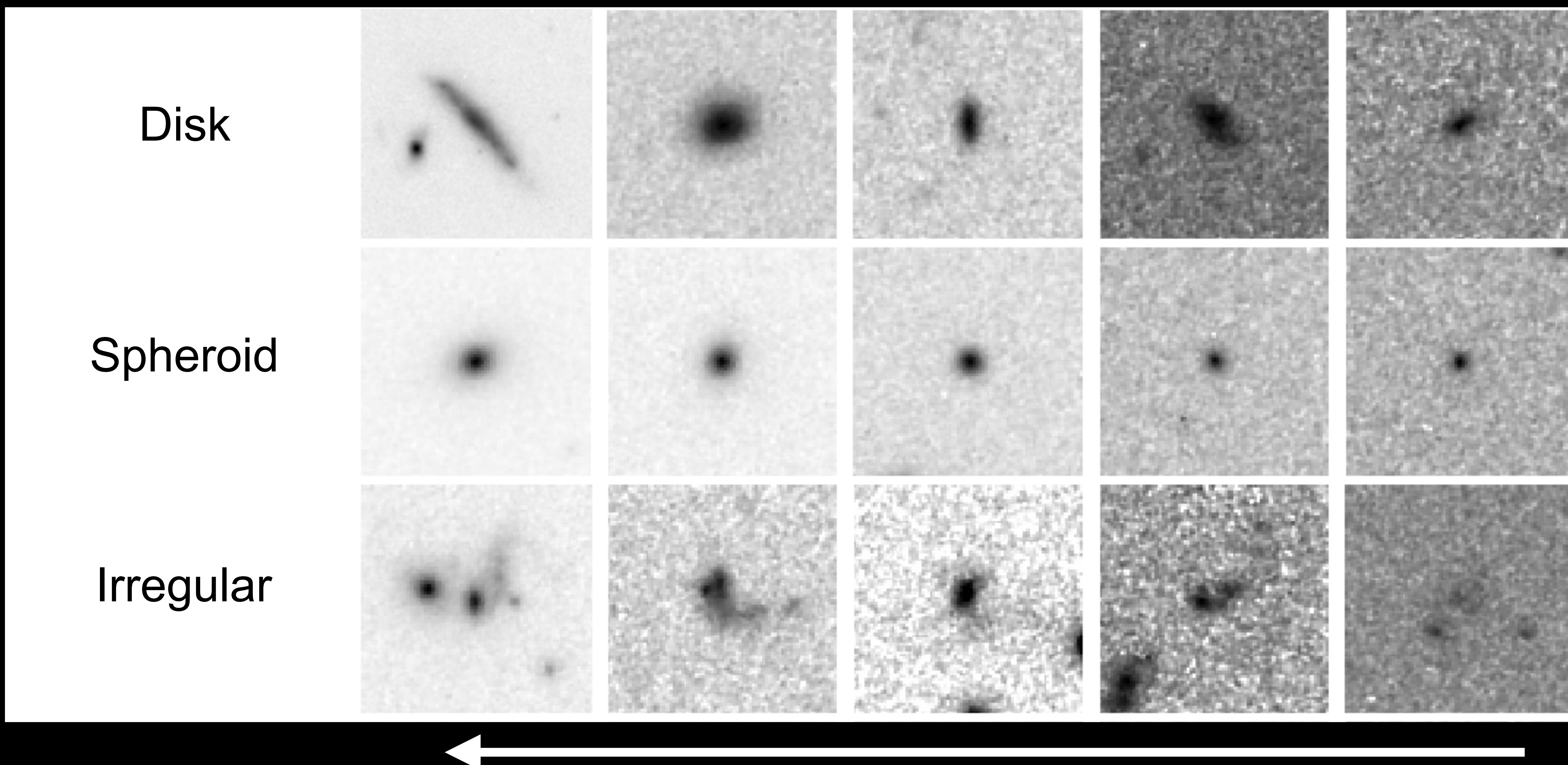
WFIRST High Redshift Galaxy Counts



HLS can select the first statistical samples of EoR galaxies.

Galaxy Morphology with WFIRST

CANDELS HST WFC3



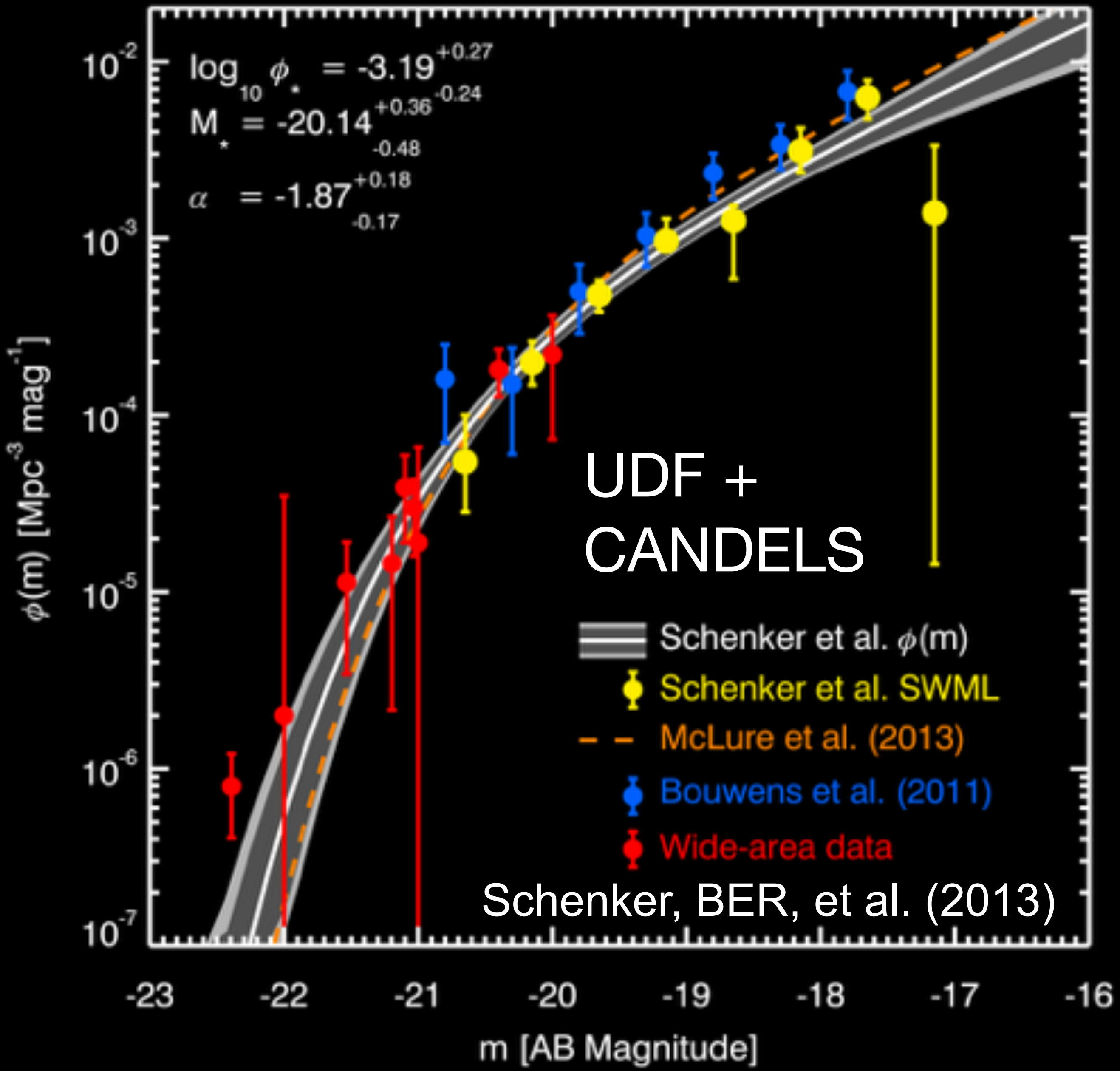
Kartaltepe et al., ApJS, 221, 1 (2015)

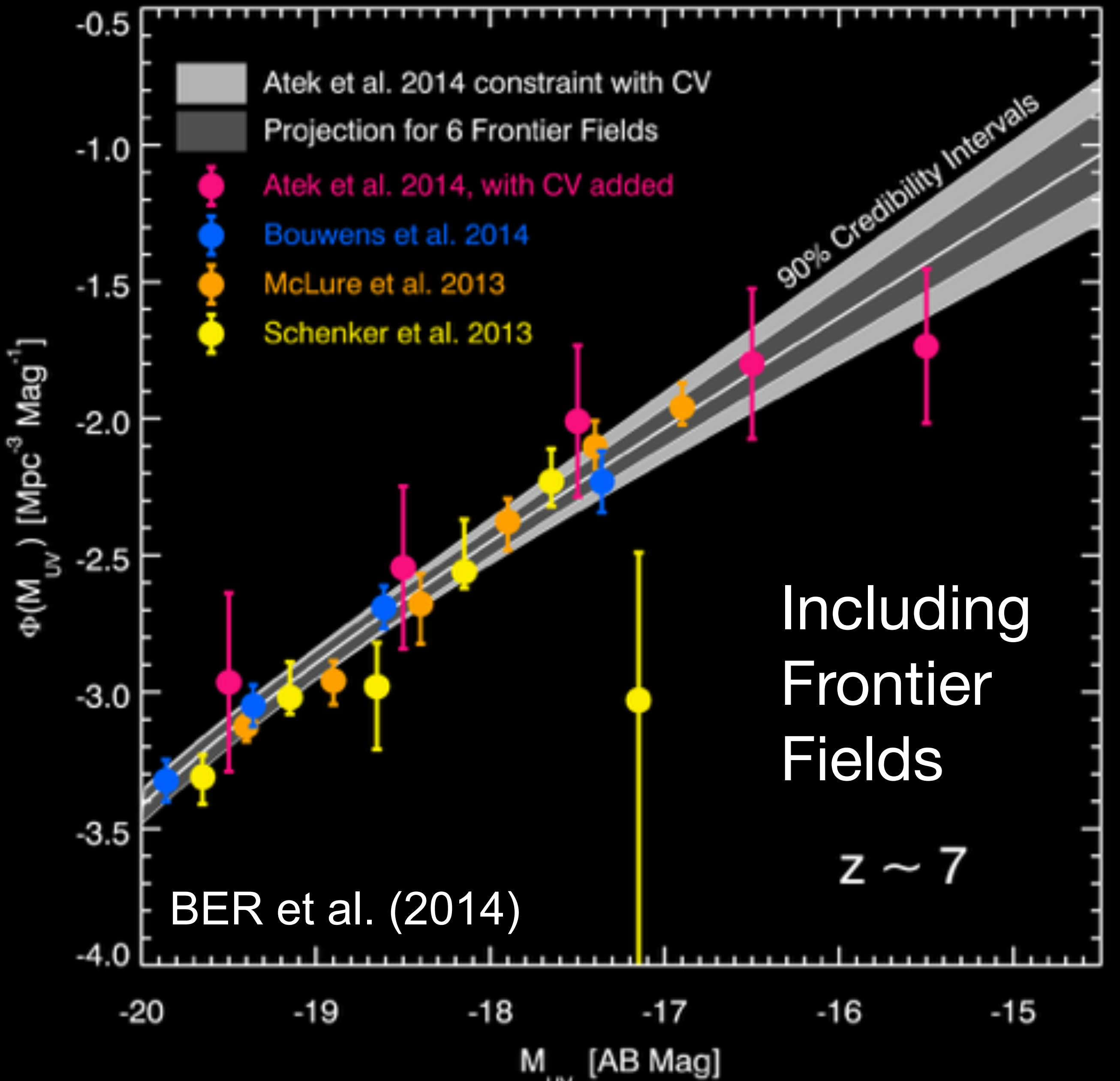
Increasing H-band Luminosity

VISUAL CLASSIFICATIONS: 7634 CANDELS Wide, 2534 CANDELS Deep

WFIRST: Automate classification via, e.g., Deep Learning, Bayesian analysis of parameterized models, connection with environment

UV Luminosity Function @ z~7





The z~7 luminosity function of galaxies has a steep faint-end slope ~-2, meaning most of the light and ionizing radiation are contributed by faint galaxies. Uncertainties dominated by limited volume / cosmic variance. Requires z-band for selection.

Distant, Star-Forming Galaxies

First 7 star-forming galaxies discovered in UDF12 at 8.5<z<12(?)

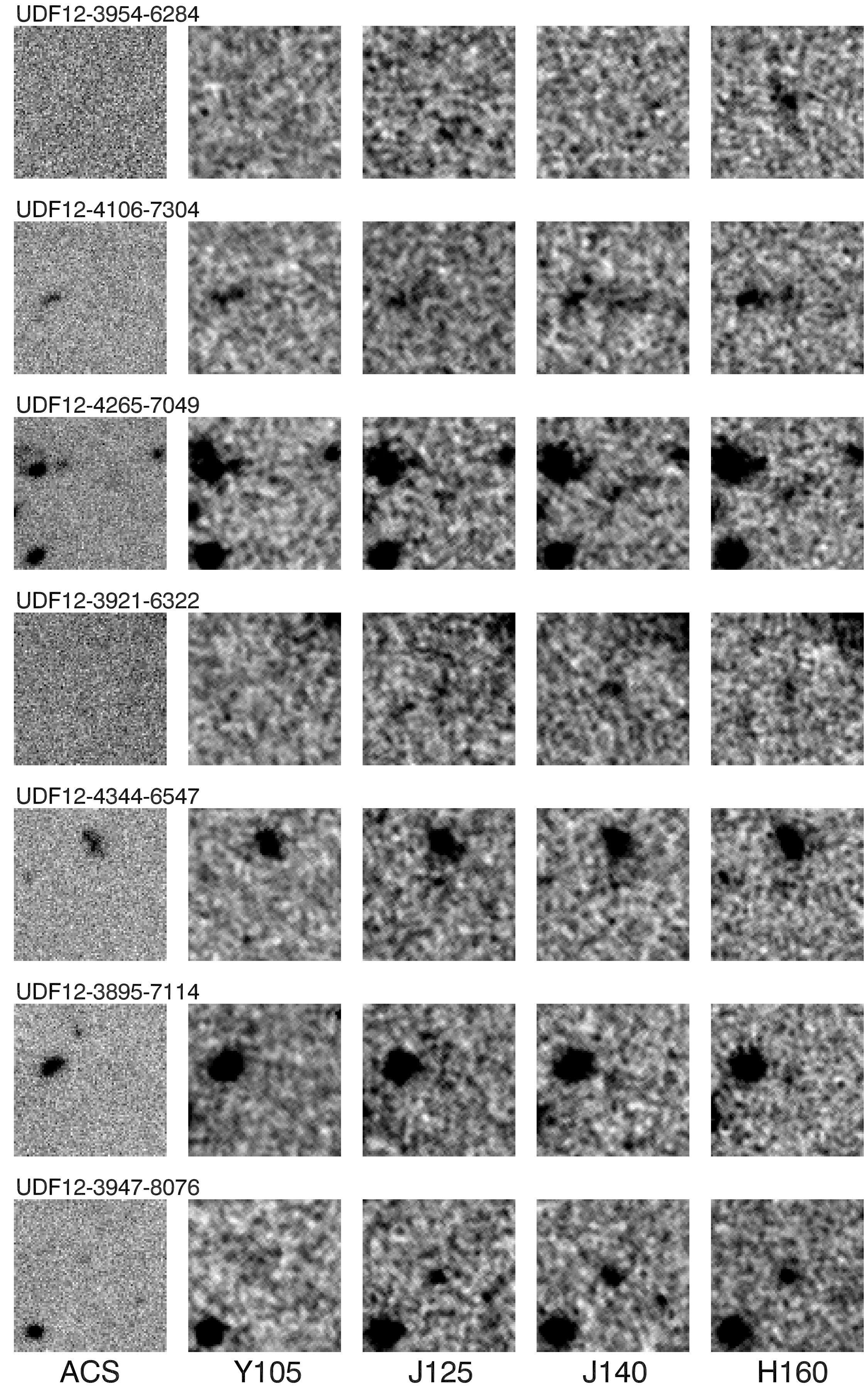
5σ detections in (160W +140W+125W) stack ($m_{AB} < 30.1$)

Requirement: 2σ rejection in ultradeep F105W ($m_{AB} > 31.0$)

Requirement:

2σ rejection in ACS BViz ($m_{AB} > 31.3$)

WFIRST will find 100s-1000s of z>8 galaxies.



Ellis +BER et al, ApJL, 763, L7 (2013)

z=2 or 3 or 12

z=9.5 520 Myr

z=9.5 520 Myr

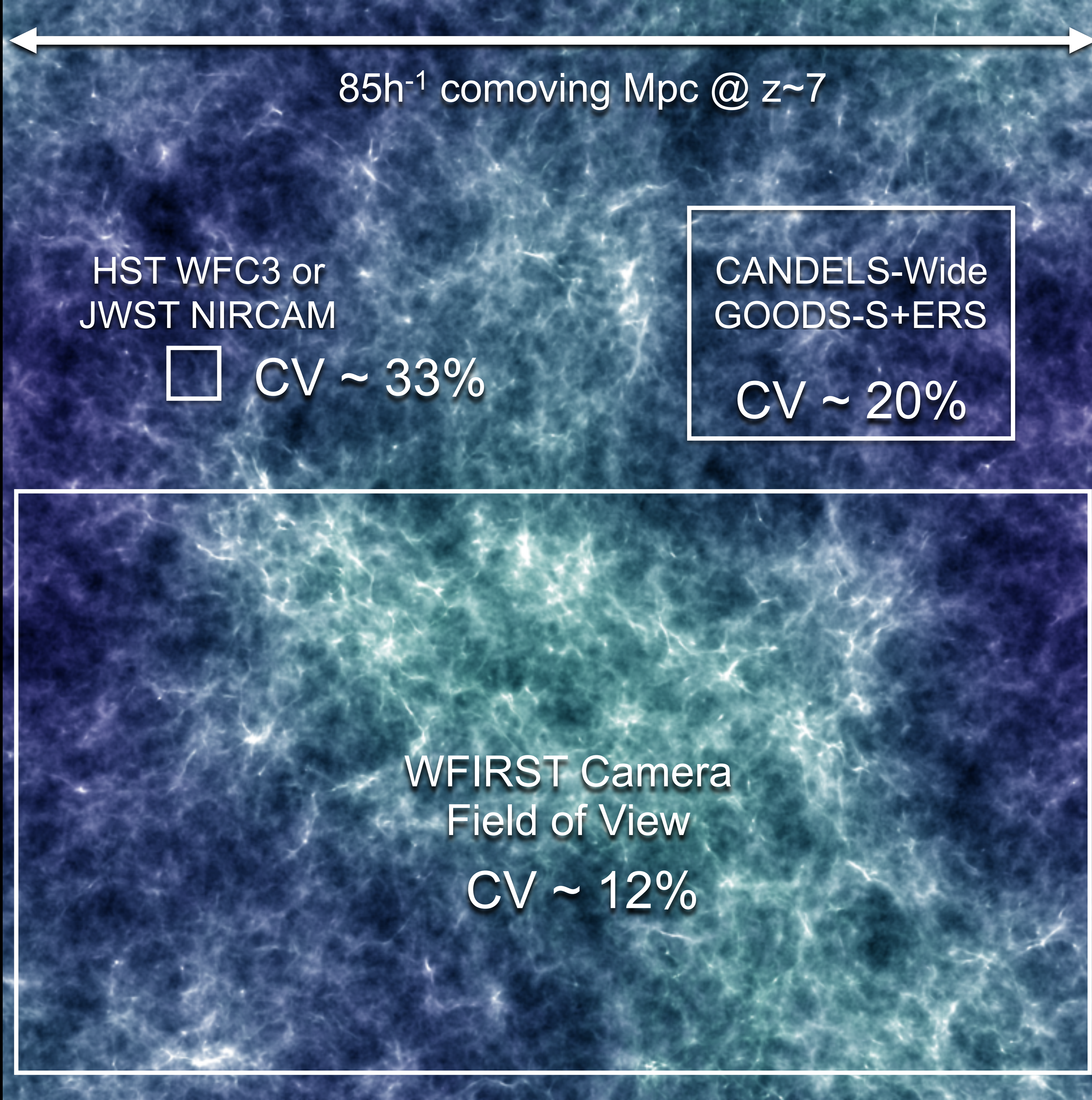
z=8.8 570 Myr

z=8.8 570 Myr

z=8.6 590 Myr

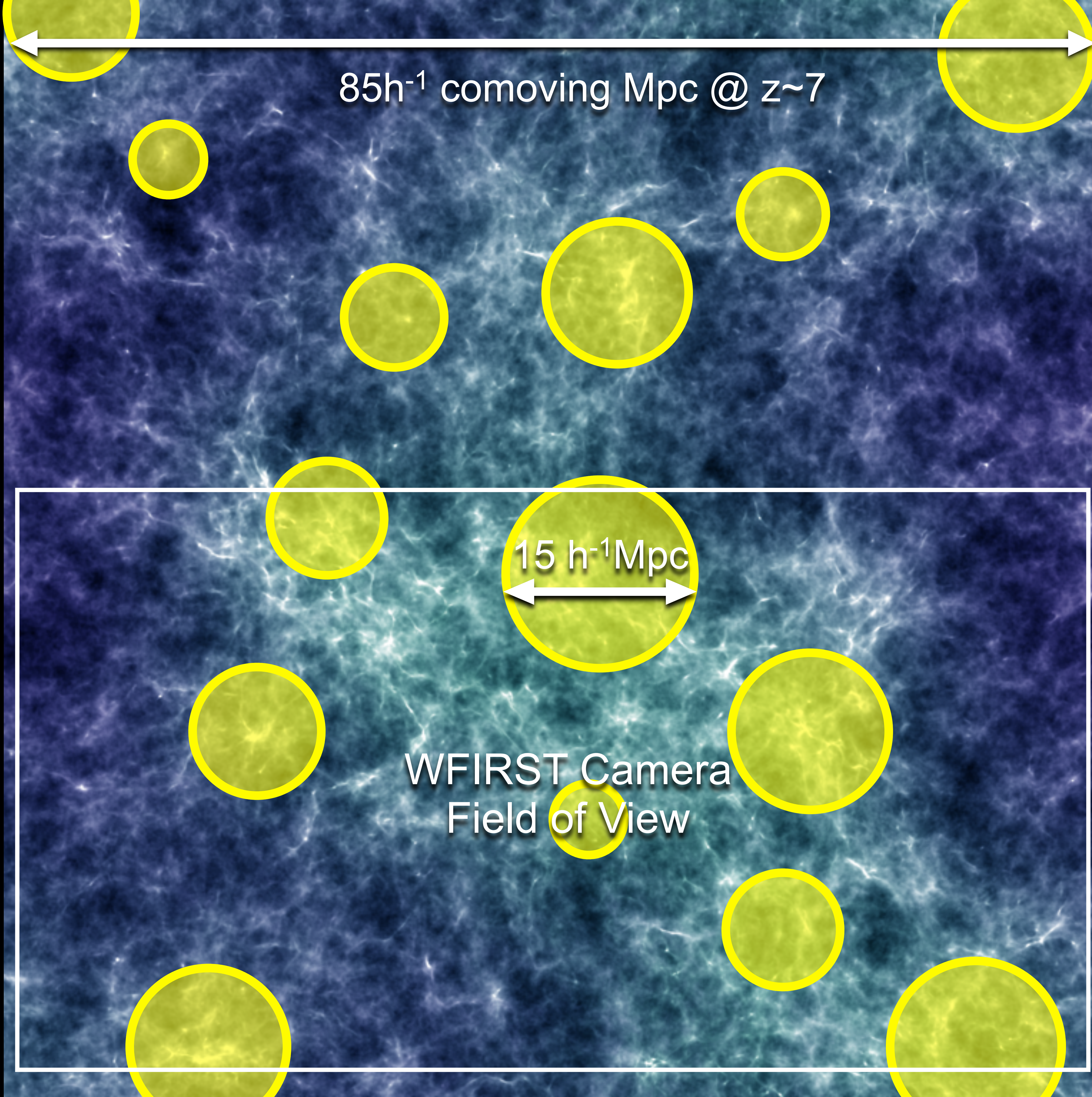
z=8.6 590 Myr

Cosmic Variance



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

Reionized Bubbles



WFIRST-EXPO: *Planned Activities (tentative)*

- Make tools to generate mock catalogs for planning extragalactic astrophysics investigations with the 2200 deg^2 High Latitude Survey and Guest Observer (GO) community programs.
- Simulate images and grism spectra for modeling extragalactic GO programs.
- Produce example GO and Guest Investigator (GI) programs, workflows, and metrics for evaluating the WFIRST extragalactic science return.
- Study possible medium- and ultra-deep imaging and spectroscopic GO/GI programs.
- Evaluate WFIRST design choices that influence extragalactic science return.
- Serve as liaisons to JWST, LSST, TMT/GMT/E-ELT, Subaru/PFS, ALMA, and 21cm experiments for coordinating synergistic WFIRST surveys for extragalactic astrophysics.

WFIRST-EXPO Science Tasks (tentative)

GO/GI Program Evaluation

GO Work Flow
GI Work Flow
WFIRST / Pop III SNeI
WFIRST / Pulsation-Pair SN
WFIRST / Pair-Instability SN
Galaxy-Galaxy Lens Identification in HLIS
Deep Grism Trade Study
HLSS as a Lyα Survey
Galaxy Galaxy Lens Detection Algorithms
Design AGN WFIRST AGN Selections
CANDELS Morphologies as Sim Input
GO Programs as GI Resources
WFIRST Photo-z's
WFIRST Luminosity Functions
WFIRST Stellar Mass Functions
Survey Design Formulation
GO/GI Database Development
Database Schema for GO/GI
GO/GI Clustering Strategies
Medium-Wide Survey Study
Depth Requirements for Morphology

Mocks & Simulated Images

WFIRST Simulated Deep Field Images
Faint-Source Detection
Deep Learning / Morphological Classification
Adapt 21cmFAST to Mock Surveys
Nonlinear Clustering in 21cmFAST
Combine 21cmFAST and ARES
Add AGN to Mock Catalogs
Mock AGN IFU Simulations
Photometry and Source Detection
Source Deblending
WFIRST Image Simulation Support
Mock Catalog Formulation
Catalog Tool Development
Requirements for HLS Mocks
HLS Mock Generation
HLS Mock Validation
ADDGALS WFIRST Implementation
Galaxy Property Modeling for Mocks
CALCLENS WFIRST Modeling
CALCLENS Mock Generation
CALCLENS Mock Validation

Clustering & Environment

Grism Clustering Measurements
Clustering and Galaxy Properties
Clustering vs. Stellar Mass in HLS Data
Hα SFR vs. Environment
Galaxy-Galaxy Lensing
DM Substructure
WFIRST Grism and Lensing
DM Substructure Modeling
Morphology vs. Environment
SF Main Sequence vs. Environment
Clustering & Galaxy Structure
Refine Structure vs. Clustering

Reionization

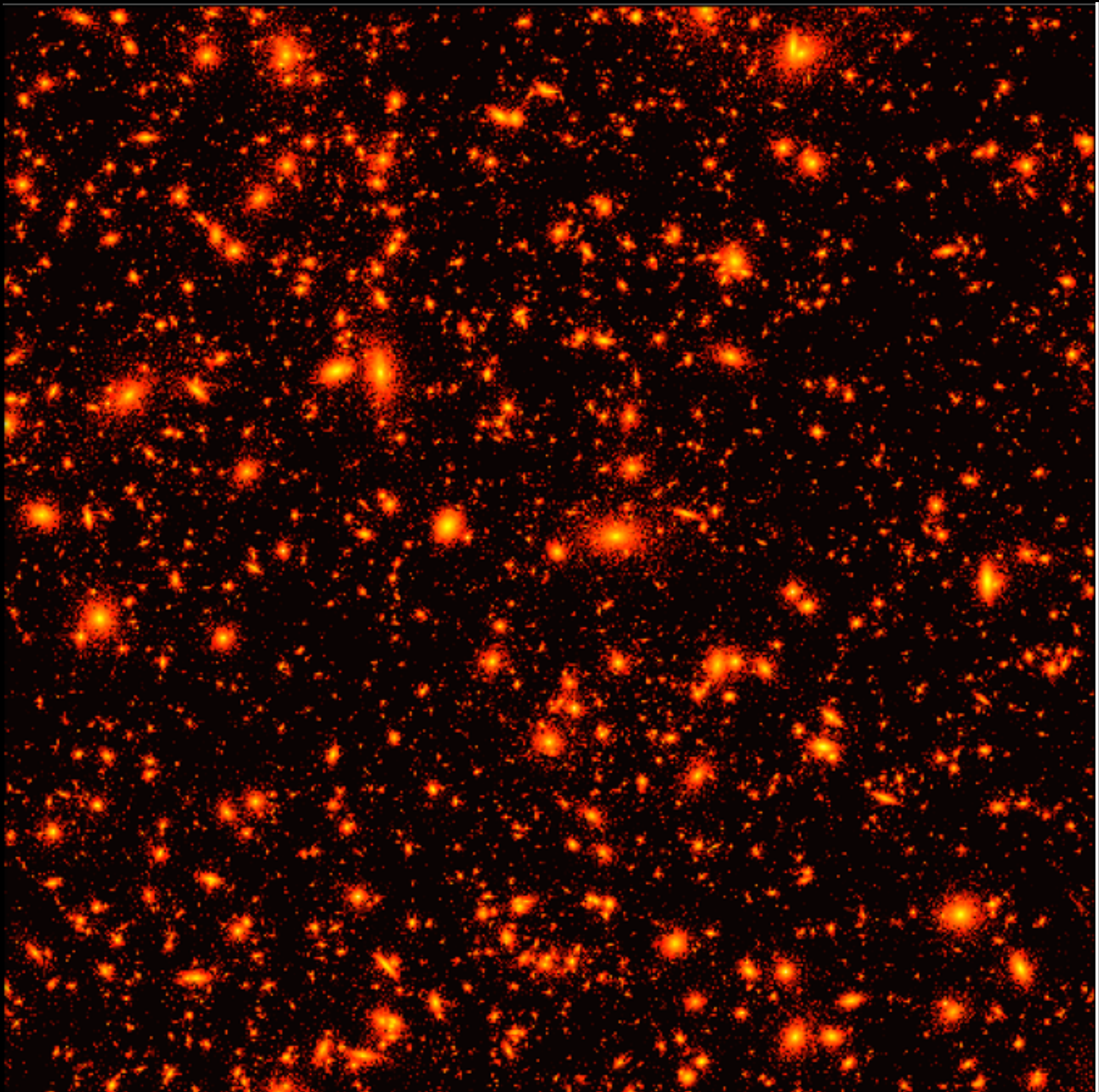
Topology of Reionization
Reionization by WFIRST AGN
UV Luminosity Density Fluctuations
21cmFAST Galaxy Model
Intensity Mapping
Optimize ARES model for 21cm
Cross- Correlations
Nebular Line Clustering with WFIRST

Spectroscopic Studies

Grism Efficacy for Rest-Optical Lines
Line Separation in WFIRST Grism
Grism Continuum Detections
WFIRST and SFR measures at z~2
High-z Rest-frame UV Spectra
Rest-UV Lines in Galaxy-Galaxy Lenses
UV Metal Lines with WFIRST Grism

Synergy with Other Facilities

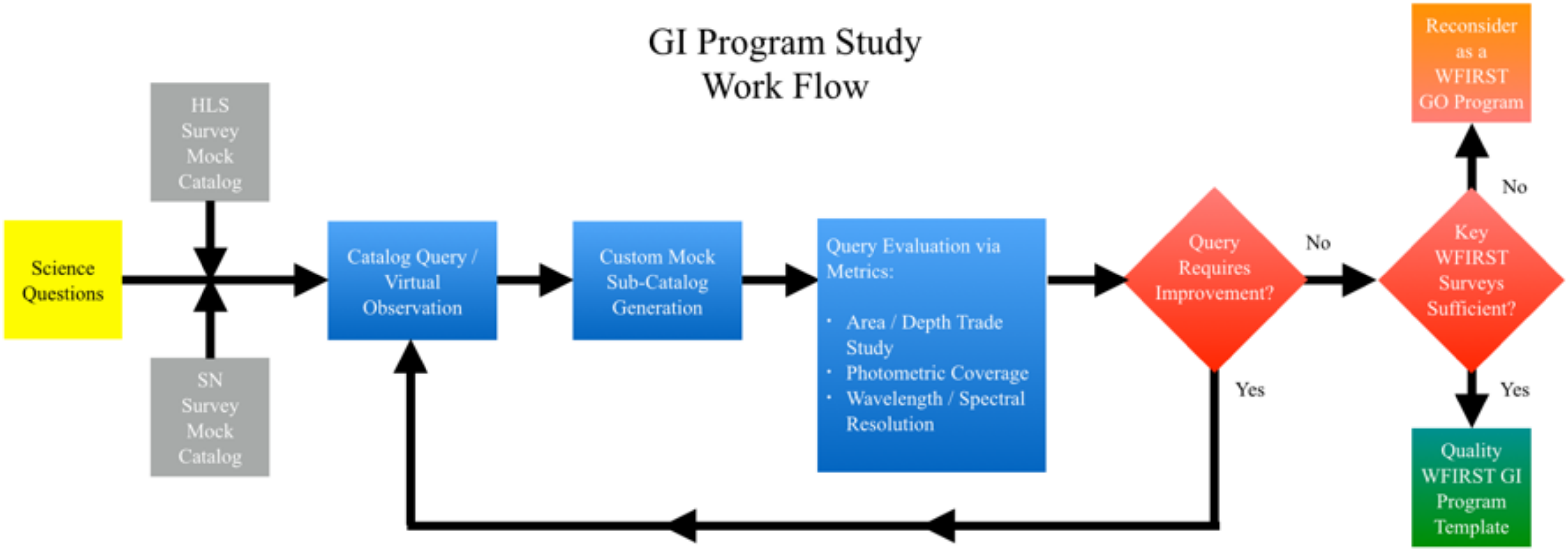
WFIRST/LSST Synergy
Integrate JWST Results / Synergy
Follow-up Opportunities for Rare SN
Revise Model Based on JWST Data
Integrate JWST Spectroscopy
Synergy with ALMA Follow-up
PFS Data for Photo-z Calibration
Using PFS Data for WFIRST Grism Mocks
PFS Data for WFIRST Photo-z Calibration
PFS Morphologies for WFIRST
TMT/GMT/E-ELT/WFIRST Synergy

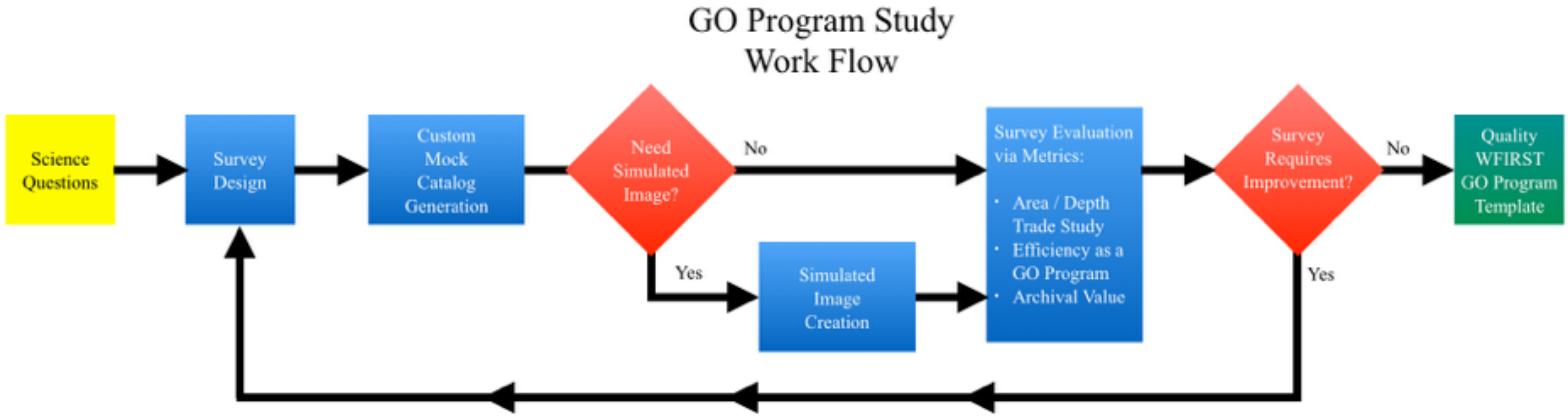


WFIRST-EXPO: *Mock Images For Evaluating GO/GI Programs*

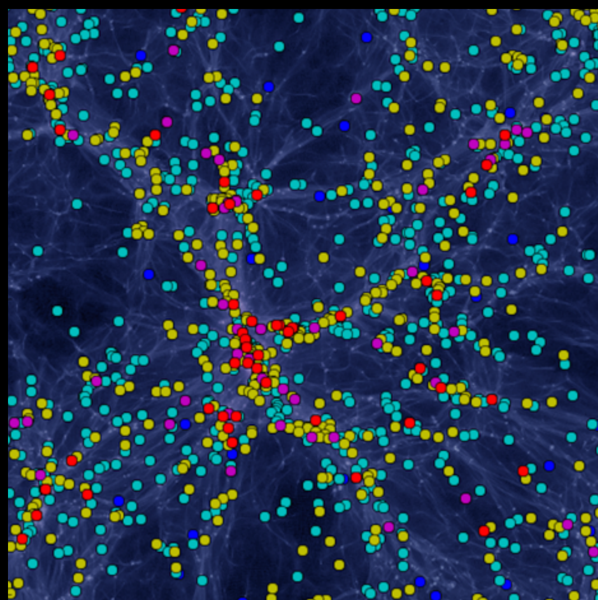
- Mock *H*-band 0.1x0.1 deg^2 image using LSST Phosim software.
- Model calibrated to reproduce GOODS-S CANDELS galaxy population.
- Extend to ~0.3 deg^2, with input from ADDGALS and an extension of 21cmFAST models.
- Method currently assumes Nyqvist sampling of PSF, needs to be extended.

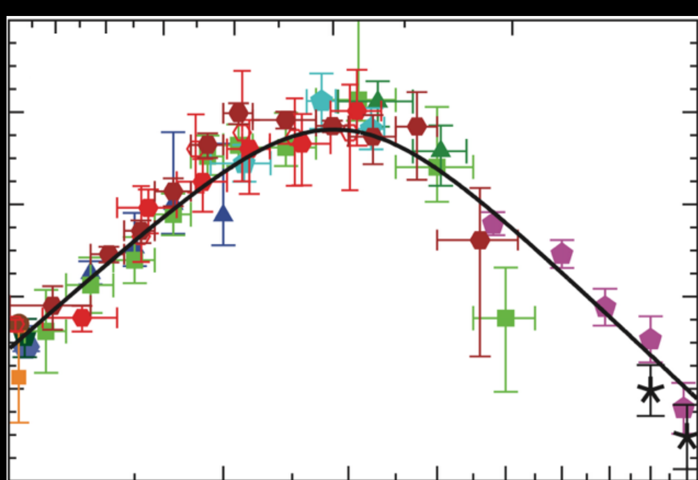
Work Flows for Evaluating *WFIRST* GO/GI Programs





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.