New Constraints on Cosmic Reionization

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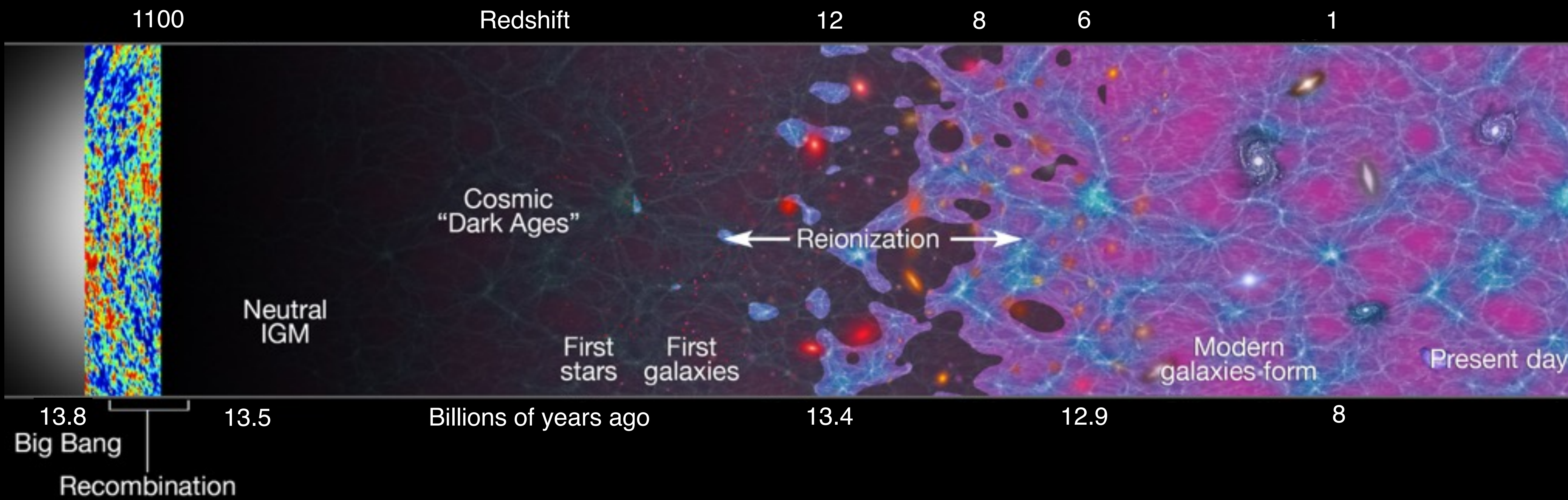
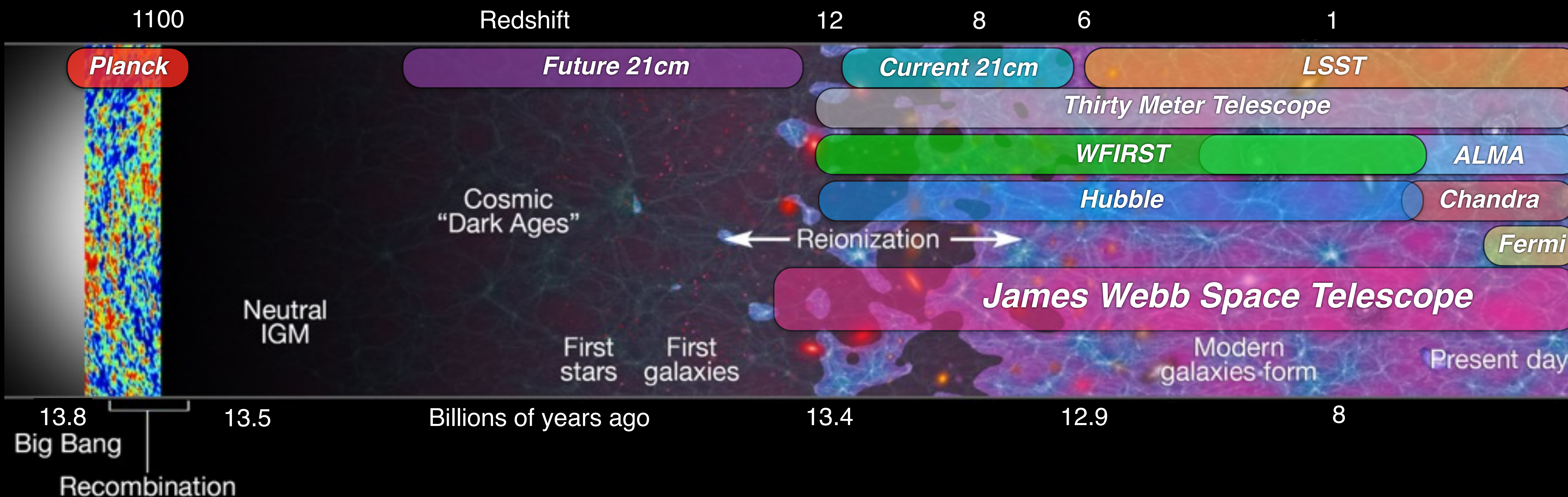
Exploring the Universe with JWST
ESA / ESTEC, The Netherlands
October 12, 2015

Brief History of the Observable Universe



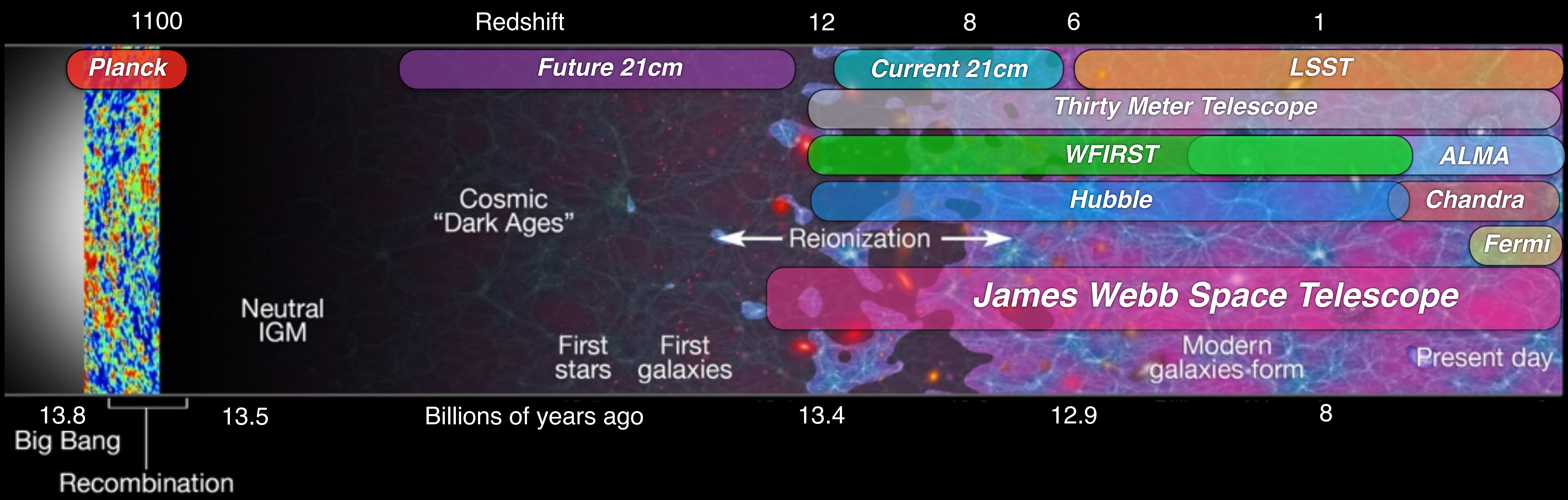
Adapted from Robertson et al. *Nature*, **468,** 49 (2010).

Observational Facilities Over the Next Decade



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

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



1. What can we learn about Cosmic Dawn?

Was it a dramatic event in a narrow period of time or did the birth of galaxies happen gradually?

2. Can we be sure light from early galaxies caused cosmic reionization?

We have some guide on when reionization occurred from studying the thermal glow of the Big Bang (microwave background), but what were the sources of ionizing photons?

3. How can we leverage multiple future facilities to maximize science return?

There is potentially enormous synergy between **JWST**, 21-cm, rest-UV, rest-Optical, CMB, and mm/sub-mm observations of the reionization era, but how can we insure efficacy?

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

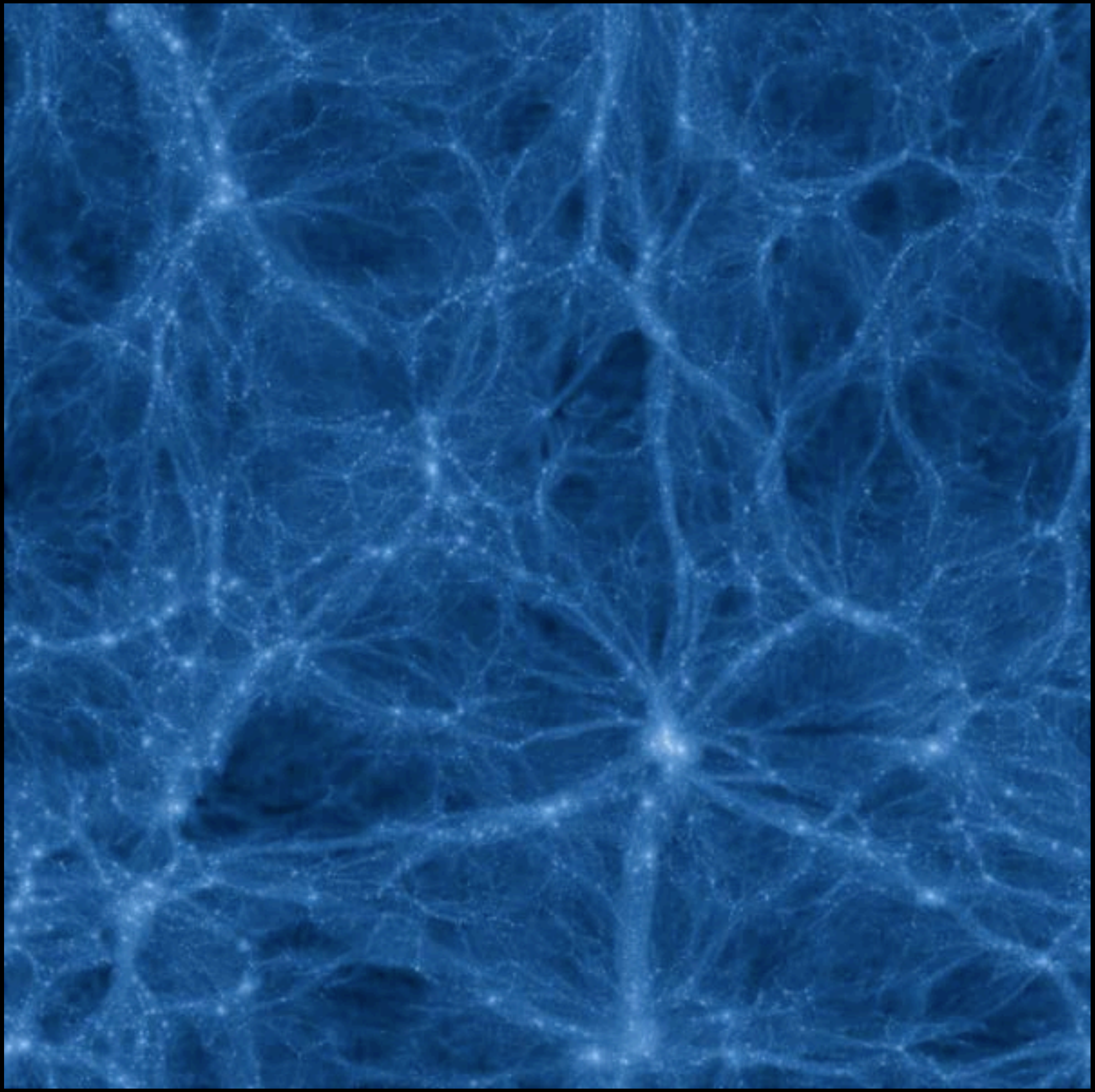
Today
z~0

t<1Gyr
z~7

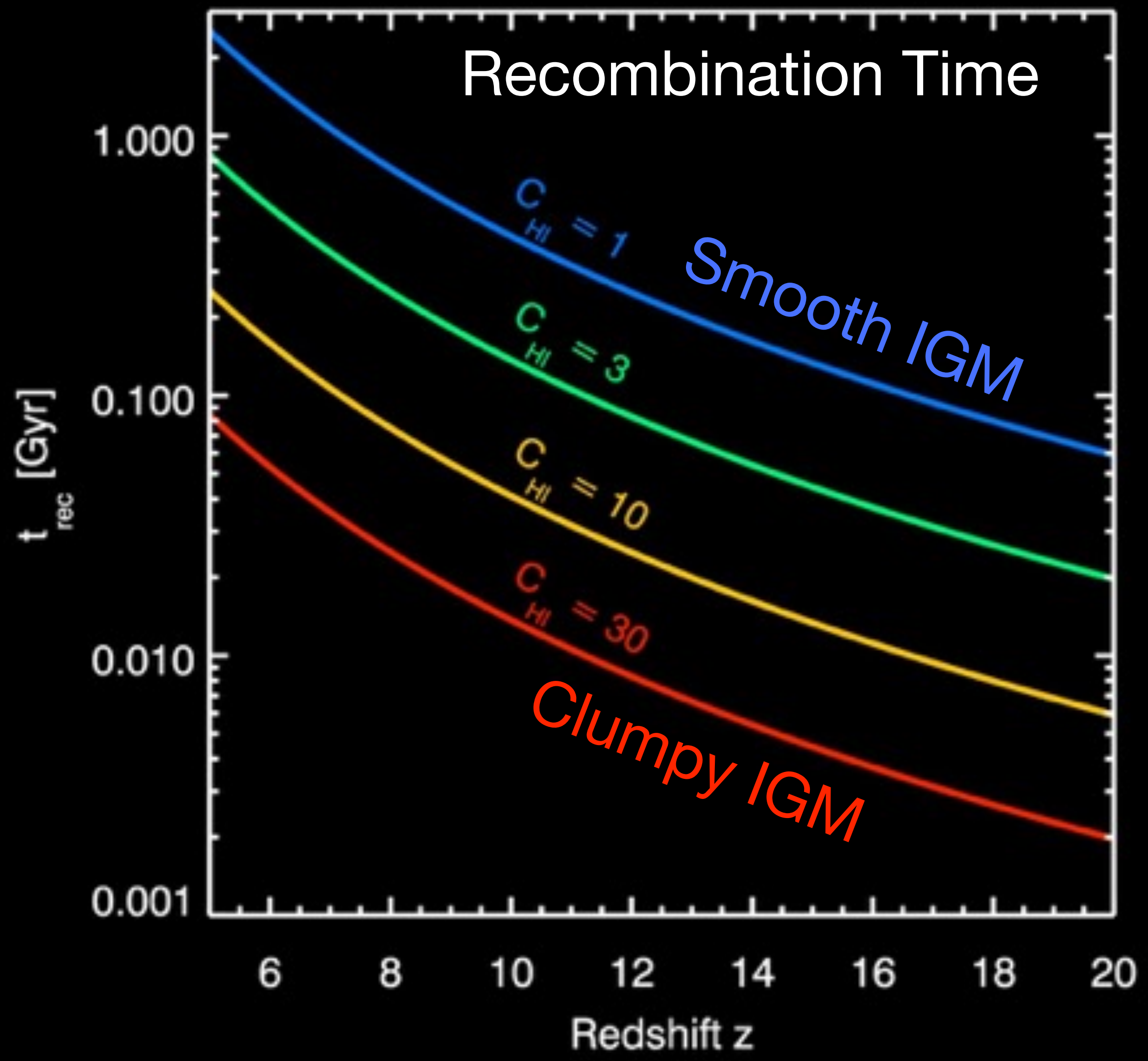
How Does Cosmic Reionization Occur?

As the first galaxies formed, their hot, young stars produced hydrogen-ionizing photons. Some fraction of these photons emerged from galaxies to reionize bubbles of intergalactic hydrogen (blue).

Once star-forming galaxies became abundant and luminous enough to allow ionized bubbles to overlap, the mean free path of ionizing photons dramatically increased. Hydrogen in the IGM then became almost completely ionized (yellow). We call this process “**reionization**”.



How Does Cosmic Reionization Occur?



Ionization Fraction Evolution

Ionizing photon production rate (density)

$$\dot{Q}_{\mathrm{HII}} = \frac{\dot{n}_{\mathrm{ion}}}{\langle n_{\mathrm{H}} \rangle} - \frac{Q_{\mathrm{HII}}}{t_{\mathrm{rec}}}$$

Comoving H density

Recombination time

Ionizing Photon Density

$$\dot{n}_{\mathrm{ion}} = f_{\mathrm{esc}} \xi_{\mathrm{ion}} \rho_{\mathrm{UV}}$$

Escape fraction

Ionizing photons per UV luminosity

Comoving UV luminosity (SFR) density

Recombination Time

$$t_{\mathrm{rec}} = \left[C_{\mathrm{HII}} \alpha_{\mathrm{B}}(T)(1 + Y_{\mathrm{p}}/4X_{\mathrm{p}})\langle n_{\mathrm{H}} \rangle (1+z)^3\right]^{-1}$$

Clumping factor

Case B recomb. coeff.

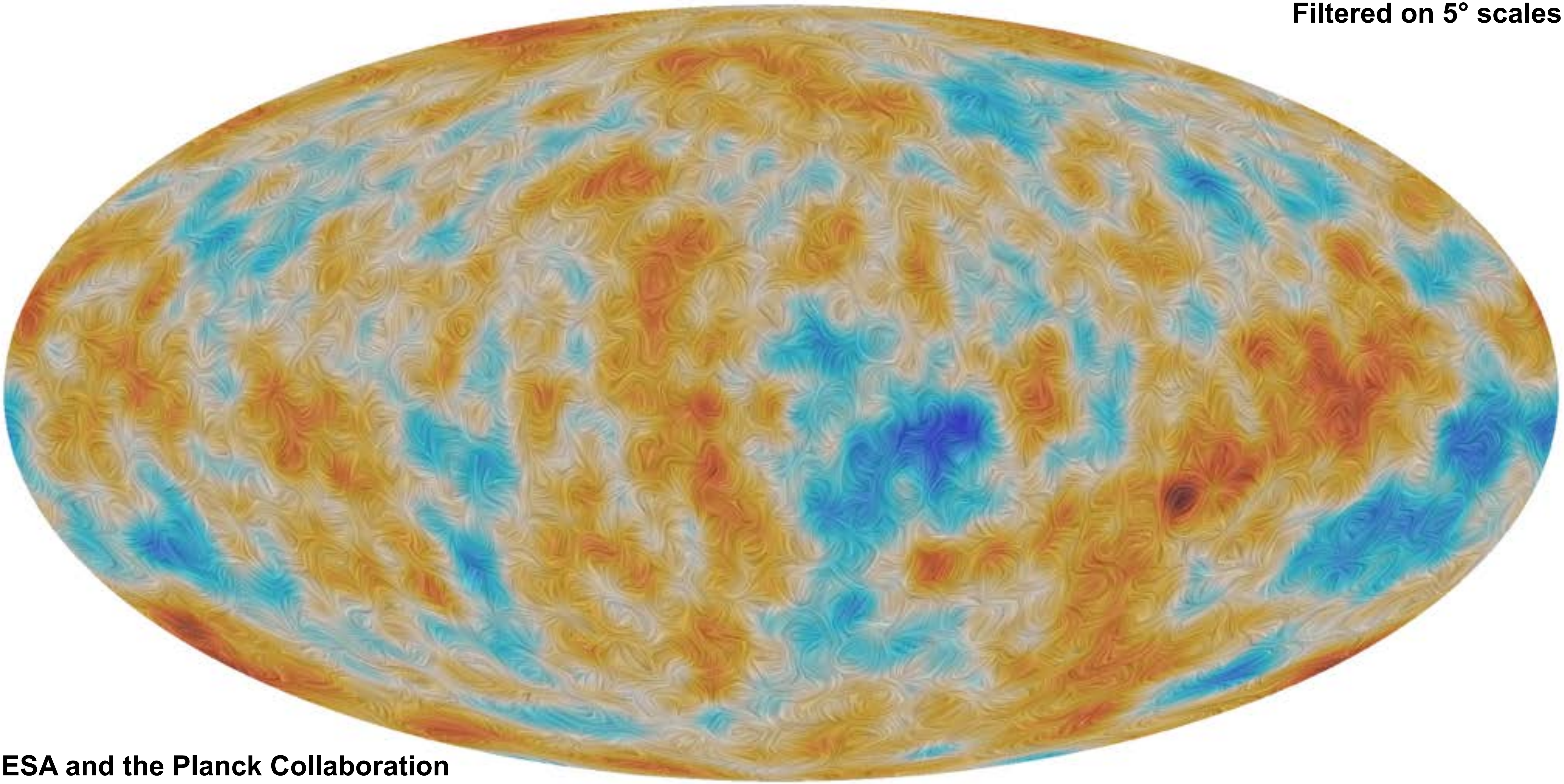
Helium fraction

Clumping Factor

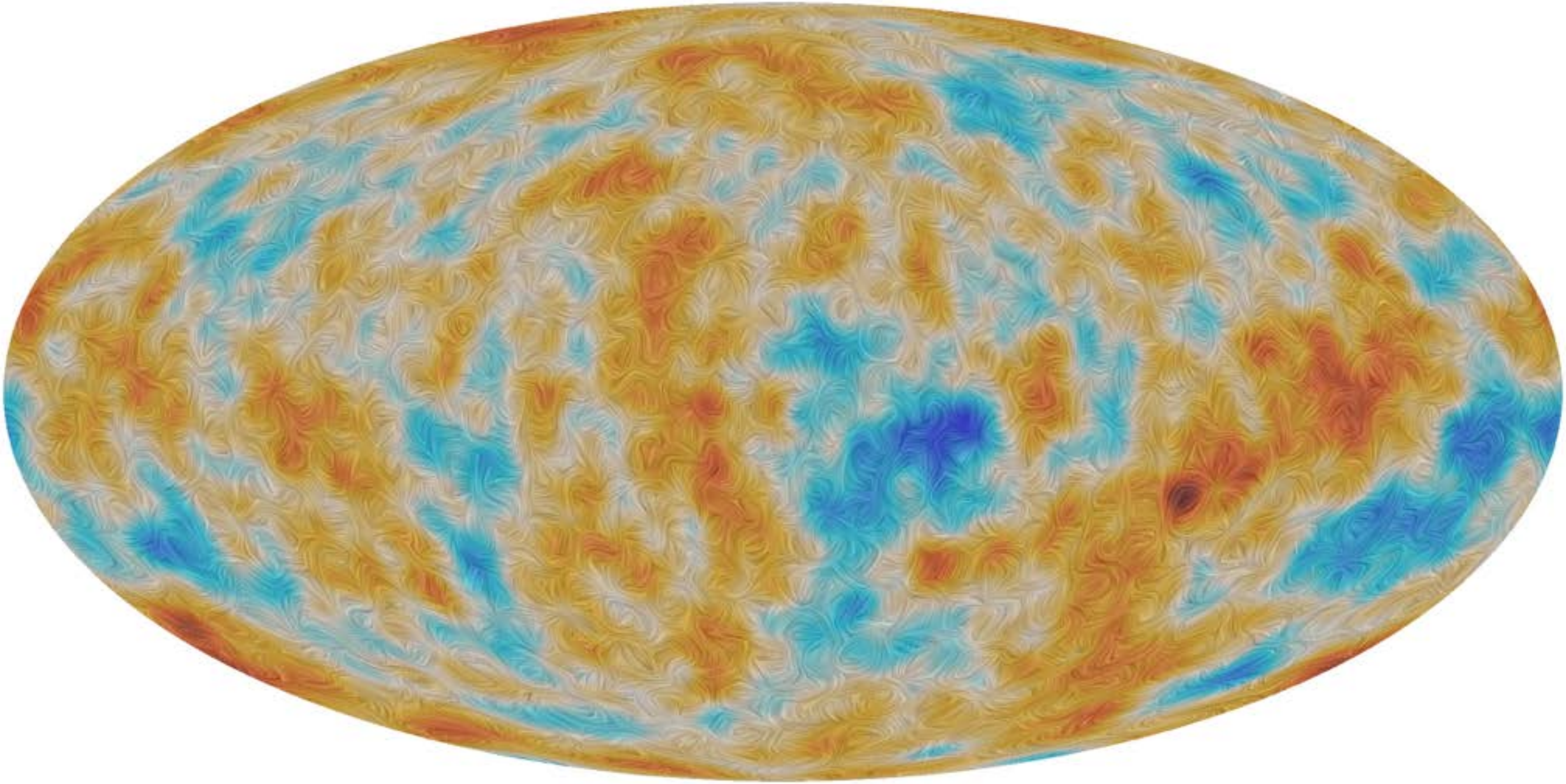
$$C_{\mathrm{HII}} \equiv \frac{\langle n_{\mathrm{HII}}^2 \rangle}{\langle n_{\mathrm{HII}} \rangle^2}$$

~1-6 (Pawlik et al. 2009)

Large-Scale Planck CMB Polarization Maps Constrain Cosmic Reionization



The Planck E-mode polarization maps (contours on top of temperature map) enable a measurement of the Thomson optical depth from electron scattering along the path from the epoch of recombination to the present day.



Thomson Optical Depth

Optical depth to electron scattering

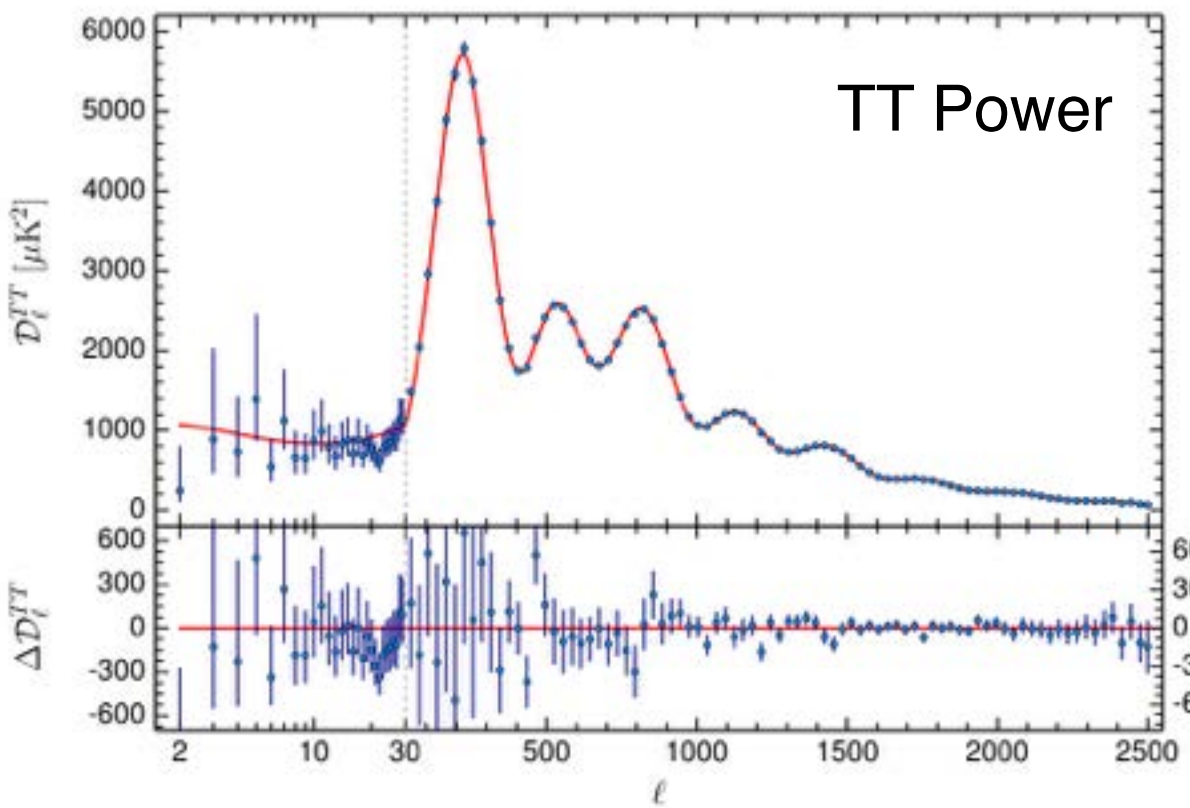
$$\tau(z) = \int_0^z c\langle n_{\rm H}\rangle \sigma_T f_{\rm e} Q_{\rm HII}(z') H^{-1}(z')(1+z')^2 dz'$$

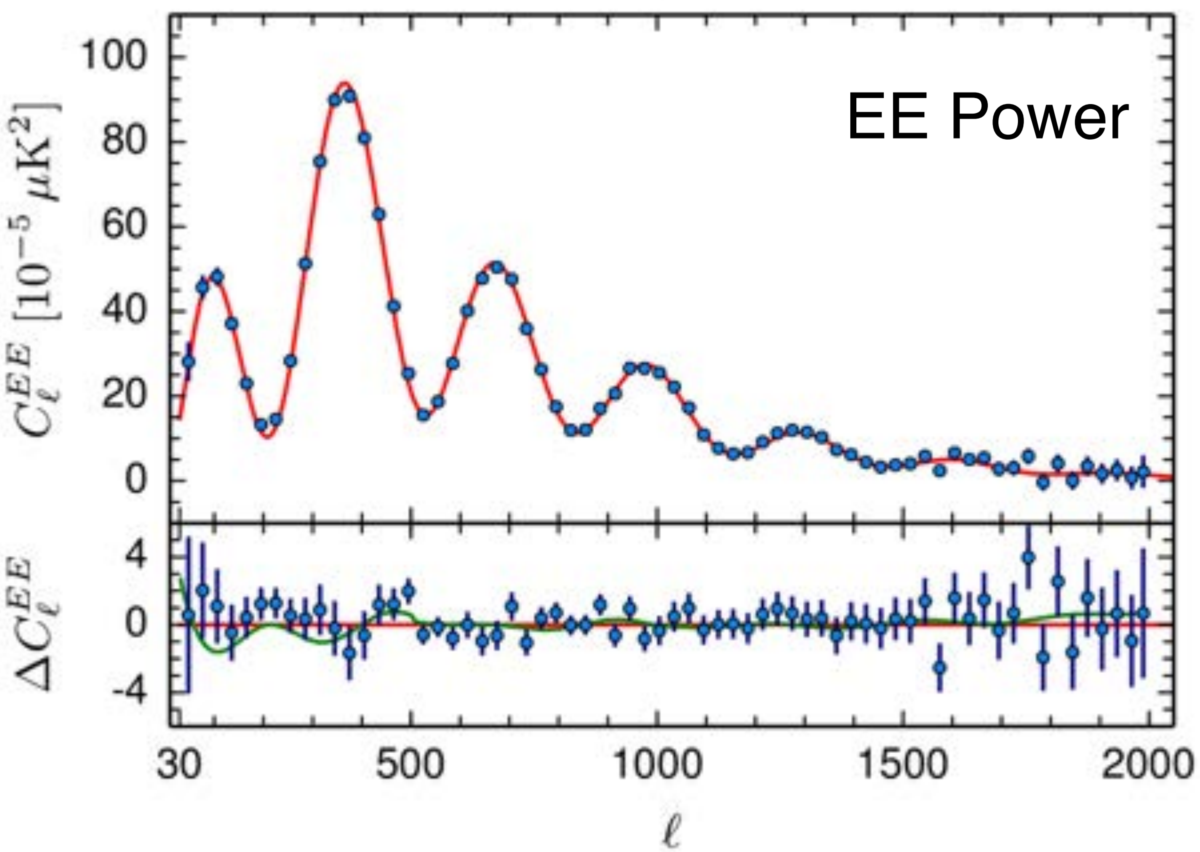
Thomson cross section

Free electrons per ionized hydrogen nucleus

New Planck Constraints on the Thomson Scattering Optical Depth

arXiv:1502.01589



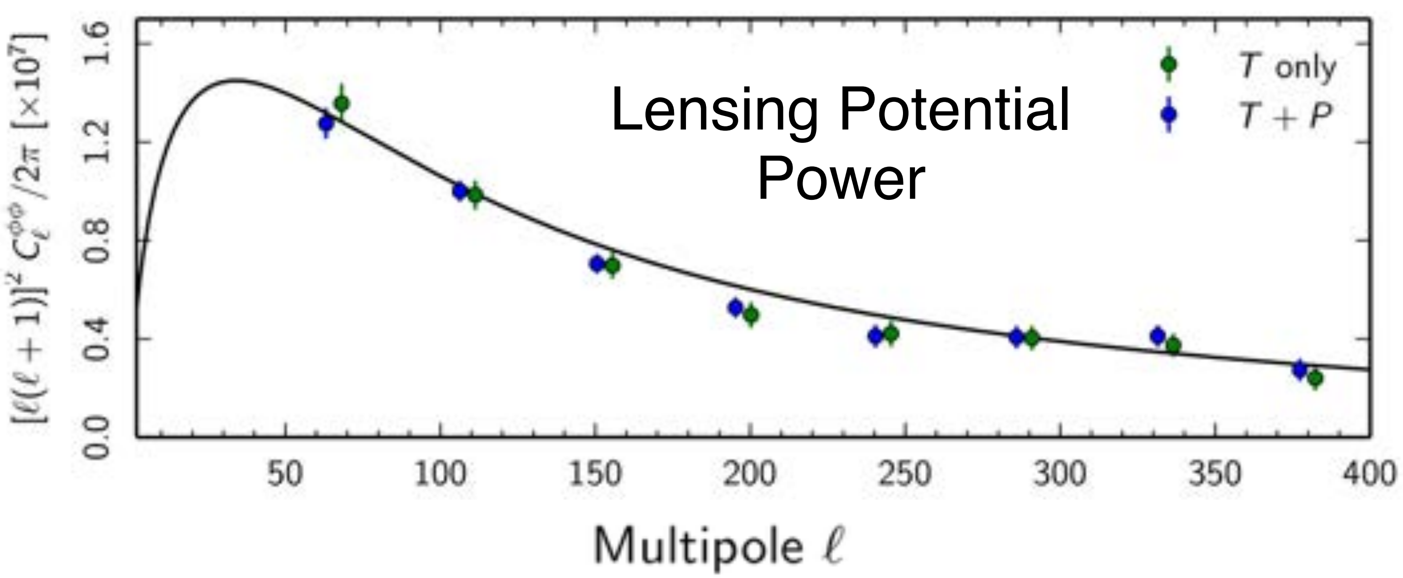


Thomson optical depth constraints informed by Planck Low-Resolution 70GHz Polarization Maps, foreground cleaned with Planck 30GHz LFI and 353 HFI maps.

Combining TT, EE, and lensing power spectrum alleviates degeneracy between amplitude of the power spectrum and the Thomson optical depth.

Planck result: Thomson optical depth is τ ~ 0.065, corresponding to an instantaneous reionization redshift of *z ~ 8.8*.

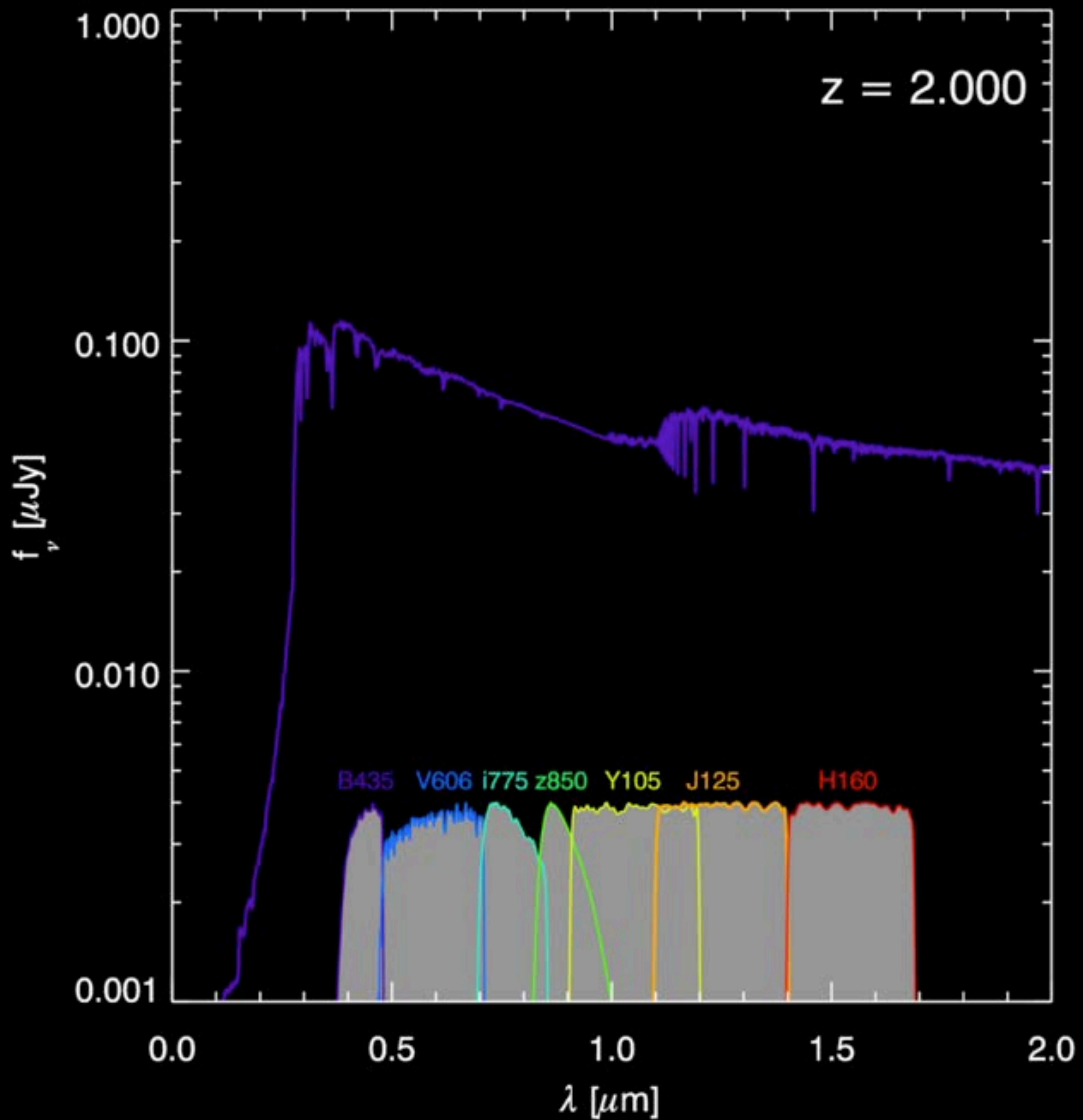
c.f. WMAP result: Thomson optical depth was previously inferred to be τ ~ 0.089, with an instantaneous reionization redshift of *z~10.5*.



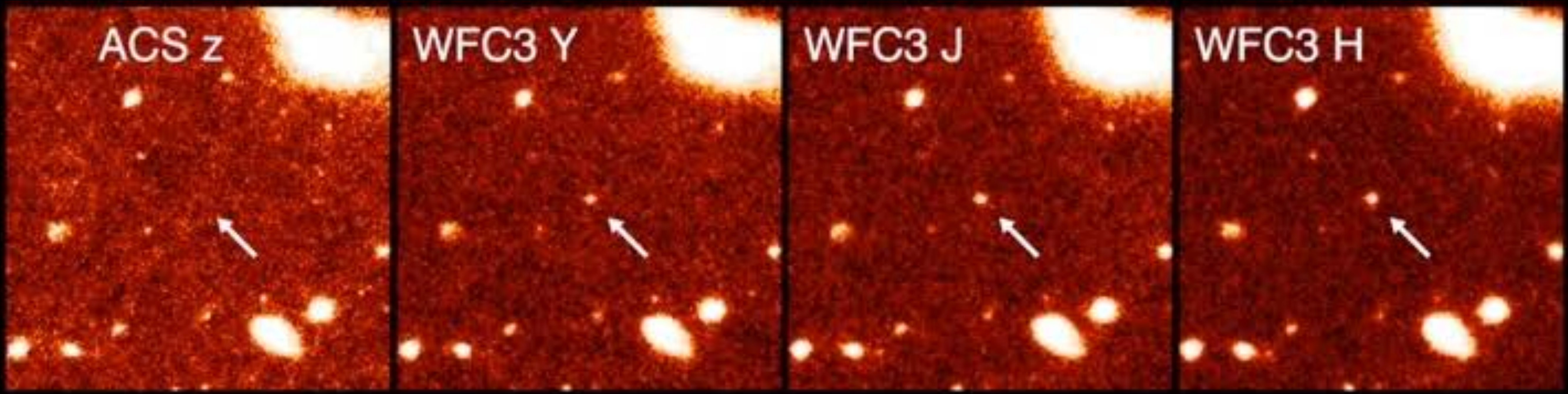
How Do We Identify High-z Galaxies?

This animation shows how the light observed from a galaxy depends on its redshift.

The suppression “break” on the left (blue) side of the spectrum is caused by neutral hydrogen absorption.



How Do We Identify High-Redshift Galaxies?

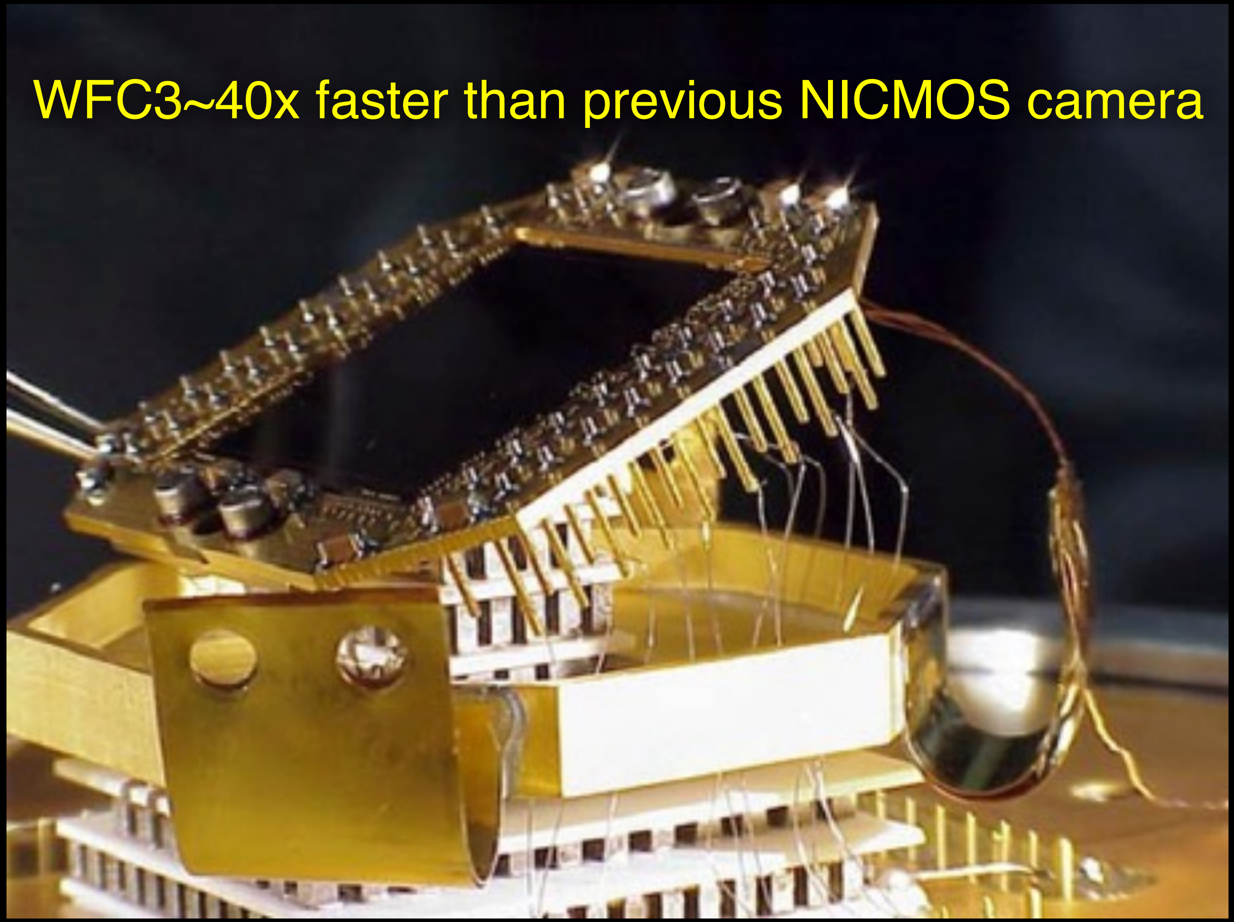


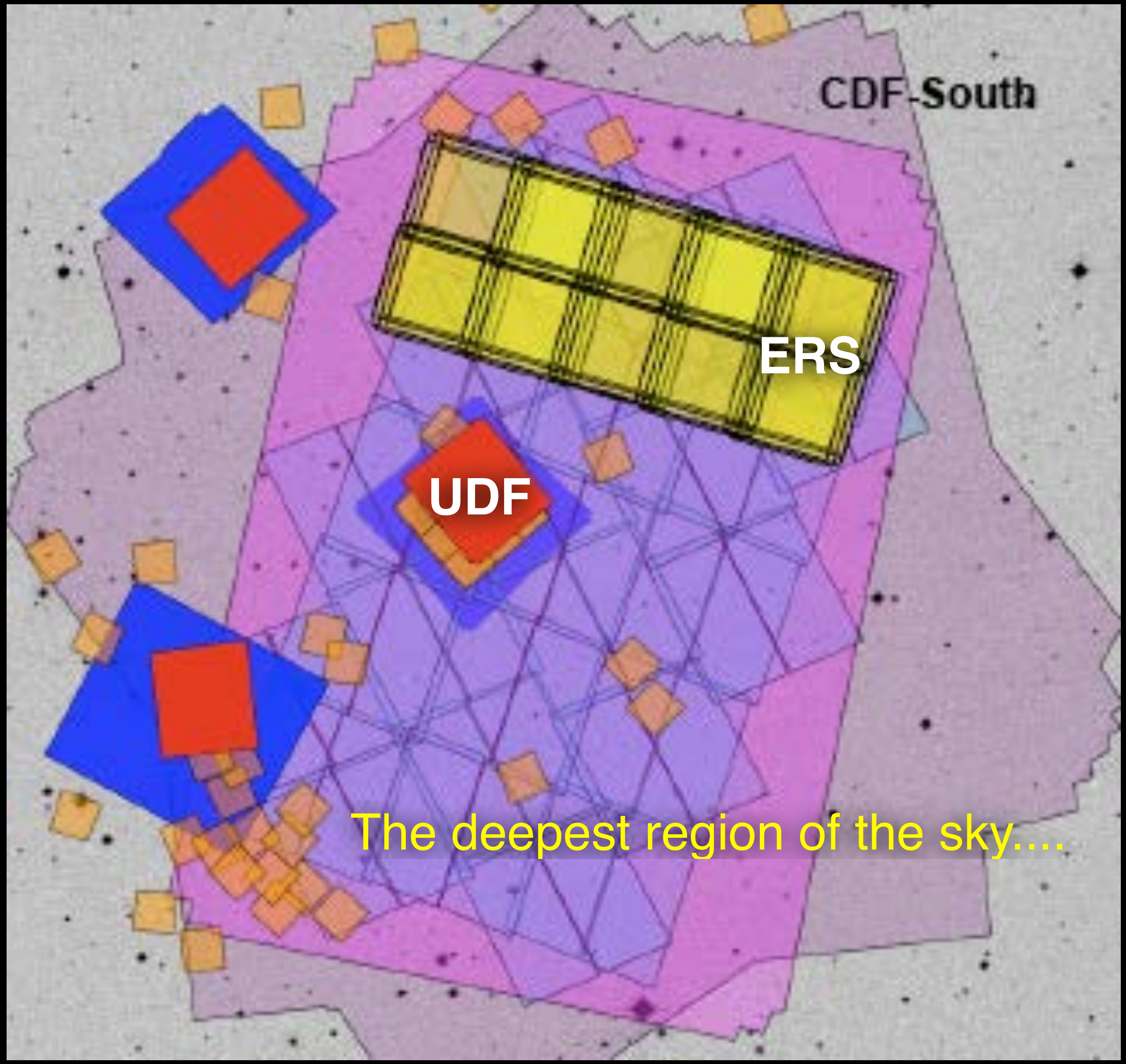
0.9 µm 1.05 µm 1.25 µm 1.6 µm

By taking images in multiple filters, we can identify high-redshift galaxies that "drop-out" of blue images owing to hydrogen absorption.

We can use the wavelength of the drop-out filter to estimate the galaxy redshift from images alone.

Finding the Sources of Reionization with *HST*





1k x 1k HgCdTe Detector, ~80% QE@λ >1μm
126”x132” field of view, YJH wide-band filters

Hubble Ultra Deep Field - 224 orbits (~300h) exposure time in single pointing for 4 bands.

Early Release Science Field - 60 orbits (~45h) in 10 contiguous pointings for 3 bands.

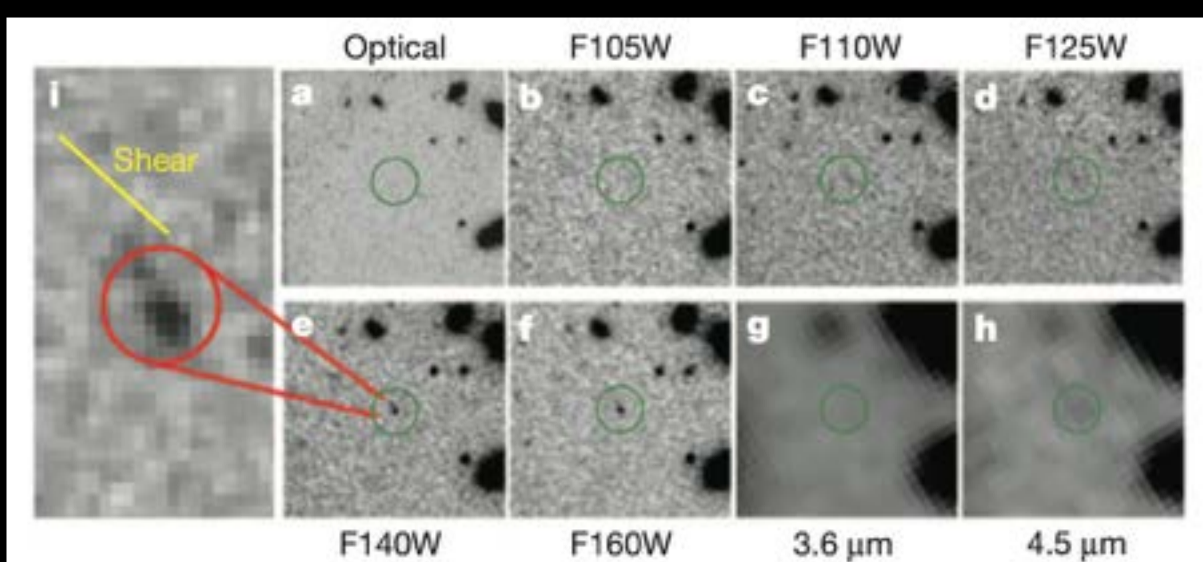
“CANDELS” Multi-Cycle Treasury Program ~ 900 orbits (~1200h) in ~150 pointings.

Multi-Cycle Treasury Programs

CANDELS: Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey

Grogin et al., ApJS, 197, 35 (2011)
Koekemoer et al., ApJS, 197, 36 (2011)

CLASH: The Cluster Lensing and Supernova Survey with Hubble
Postman et al., ApJS, 199, 25 (2012)



z~9 Candidate; Zheng et al., Nature, 489, 406 (2012)

FRONTIER FIELDS

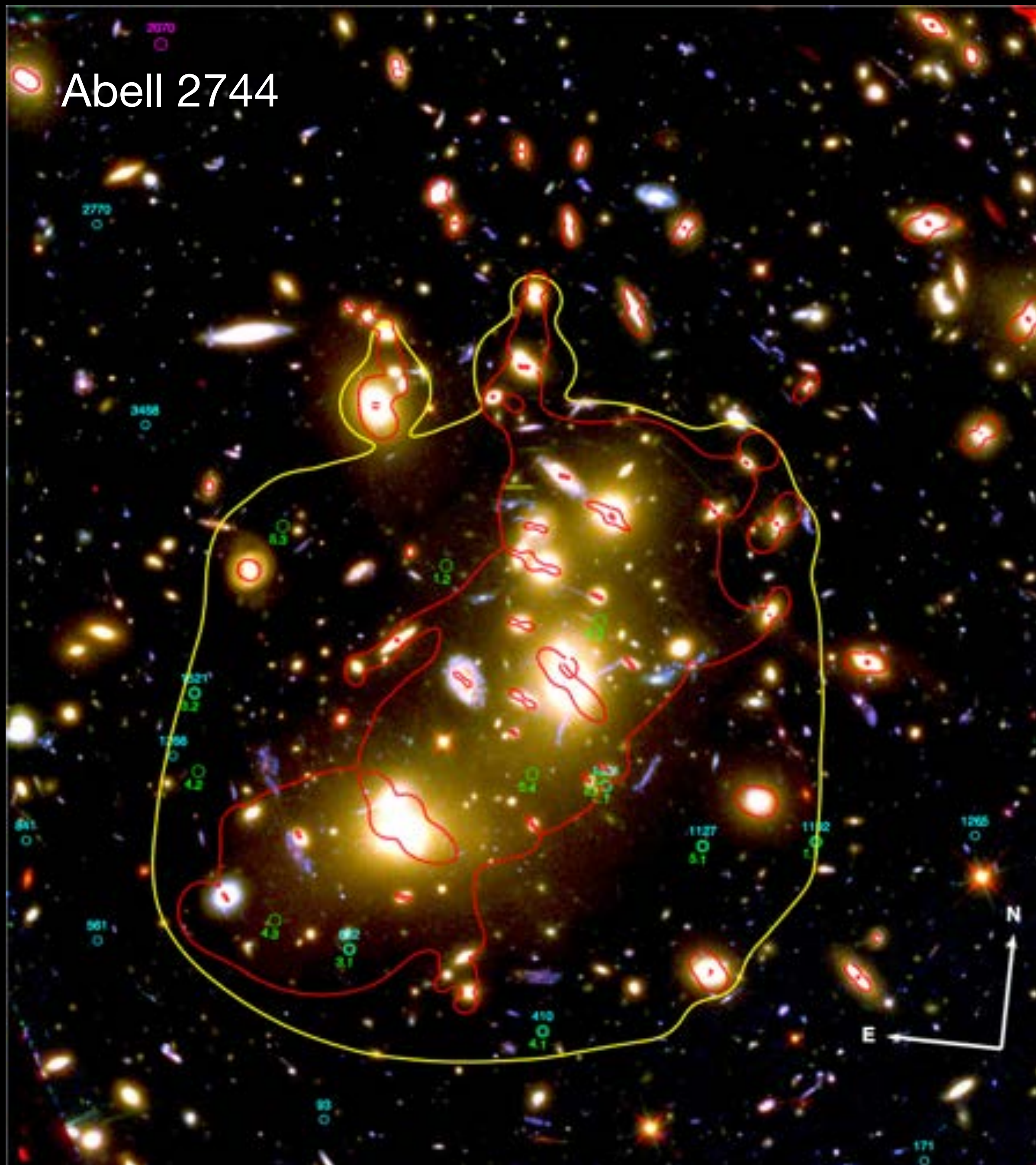
- 6 Lensing clusters with ACS F435W, F606W, F814W and WFC3 F105W, F125W, F140W, and F160W (~28.8AB)
- Total of 840 orbits fully implemented
- Community funded to produce publicly-released gravitational lensing magnification maps.
- Observations compete for two clusters (Abell 2744, MACS J0416-2403)

Hubble Frontier Field Abell 2744
Hubble Space Telescope • ACS • WFC3

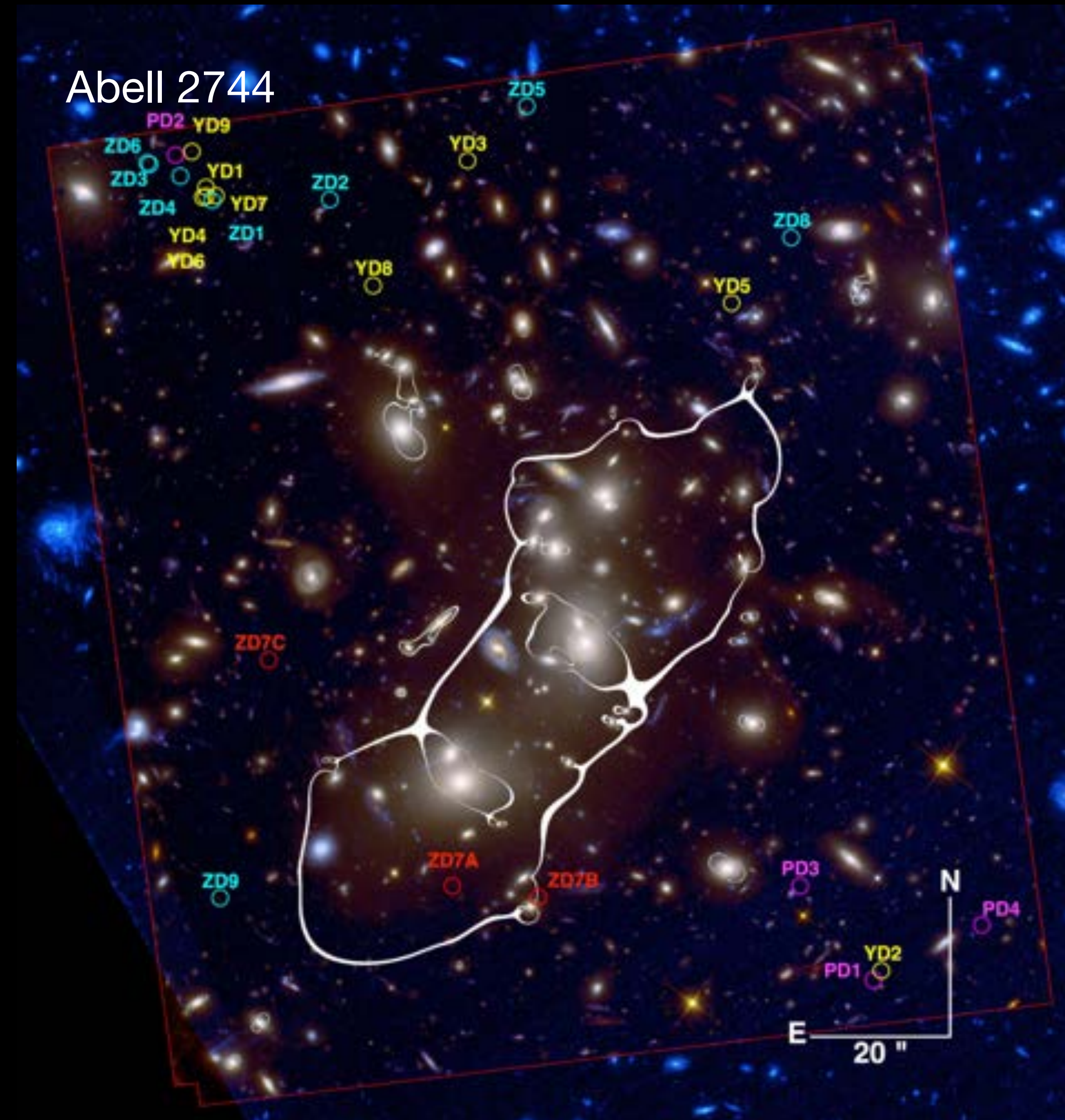
NASA and ESA

STScI-PRC14-01a

High-z Galaxy Searches with the HST Frontier Fields



Atek et al., ApJ, 786, 60 (2014)



Zheng et al. ApJ, 795, 93 (2014)

- DDT Hubble program to observe deeply gravitational lensing galaxy clusters.
- 70 ACS and 70 WFC3 orbits per cluster, sufficient for finding high-z galaxies.
- 16-18 z>6.5 galaxies claimed in Abell 2744, more to come.

The Hubble Ultra Deep Field 2012 Team

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Tokyo

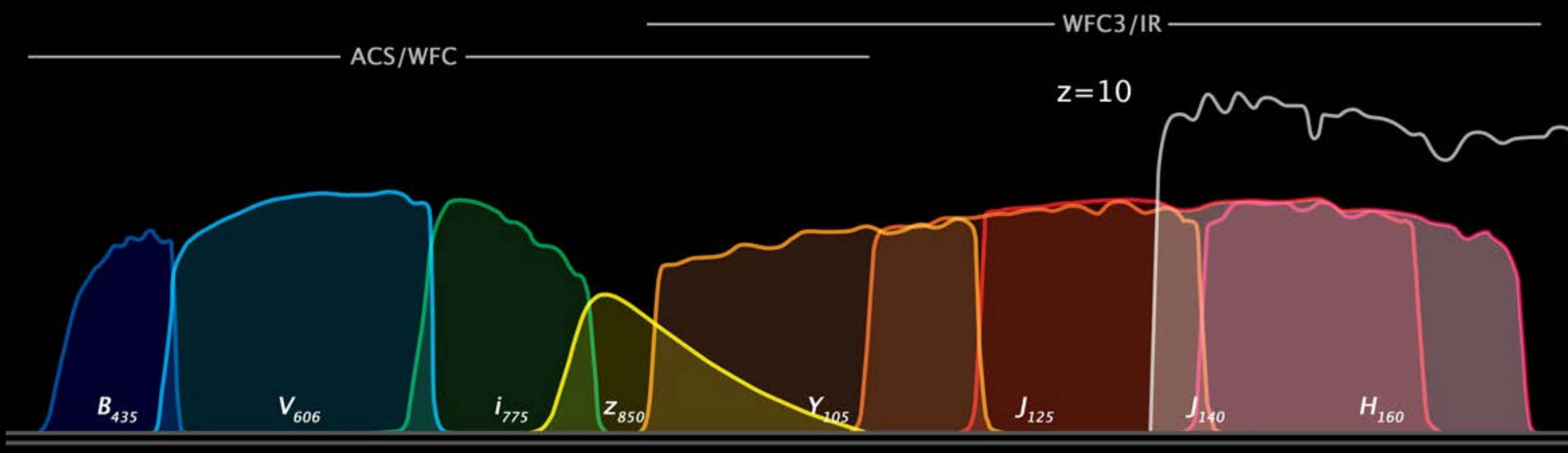
Masami Ouchi
Tokyo

Evan Schneider
Arizona

Stephane Charlot
IAP

Dan Stark
Arizona

The Hubble Ultra Deep Field 2012

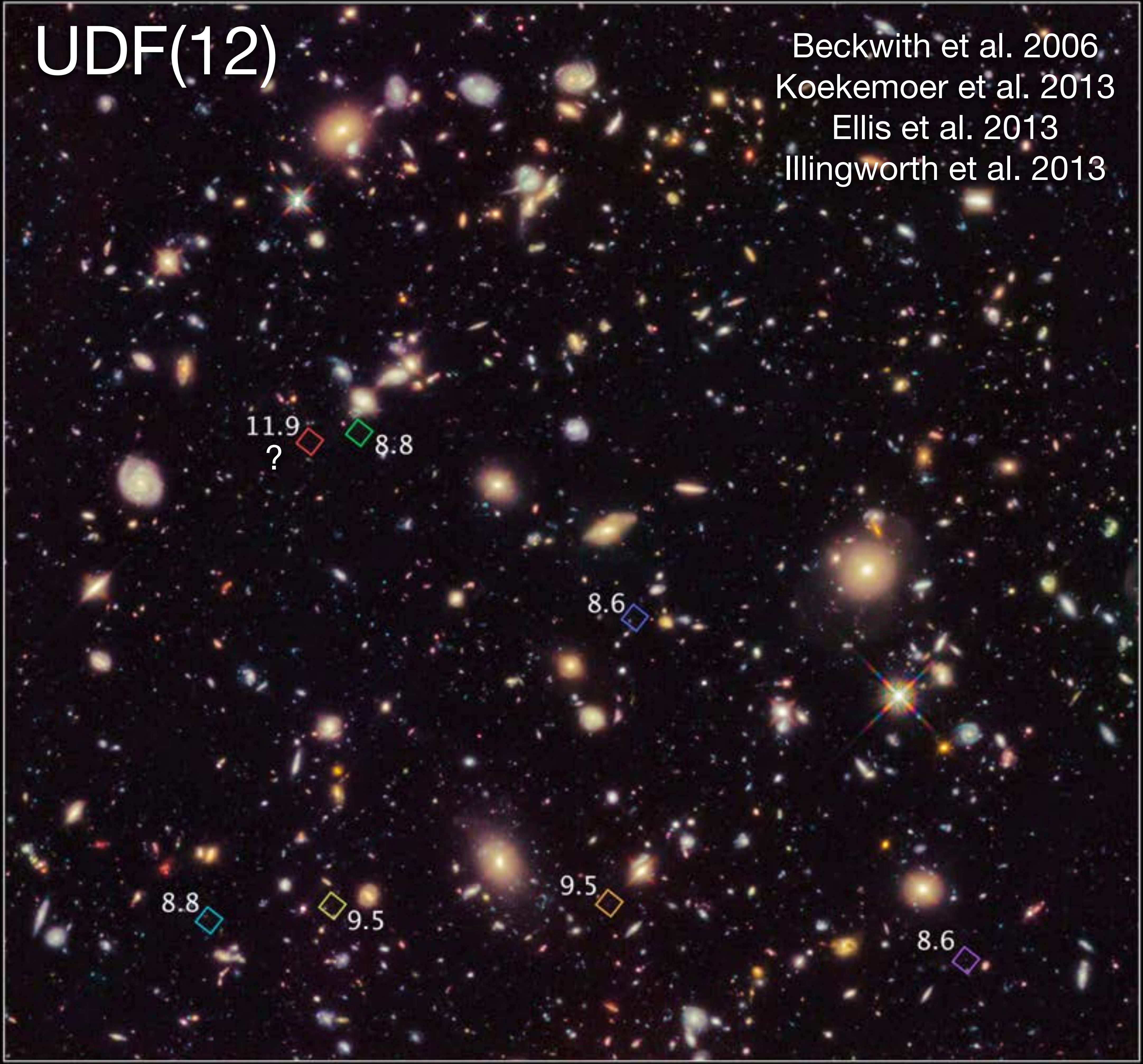


During August and September 2012, Hubble studied the Ultra Deep Field for over 100 hours with its powerful infrared camera WFC3. With earlier data, this provides the deepest Hubble images so far.

A new observing strategy was designed to:

- search for galaxies 350-600 Myrs after the Big Bang when reionization was fully underway
- better characterize the stellar populations in early galaxies
- determine the range of luminosities
- all essential for understanding the reionization process

Deeper data, more filters and much better precision



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

A Census of Star-Forming Galaxies at z>8.5 in the UDF

6 star-forming galaxies likely located $8.5<z<9.5$

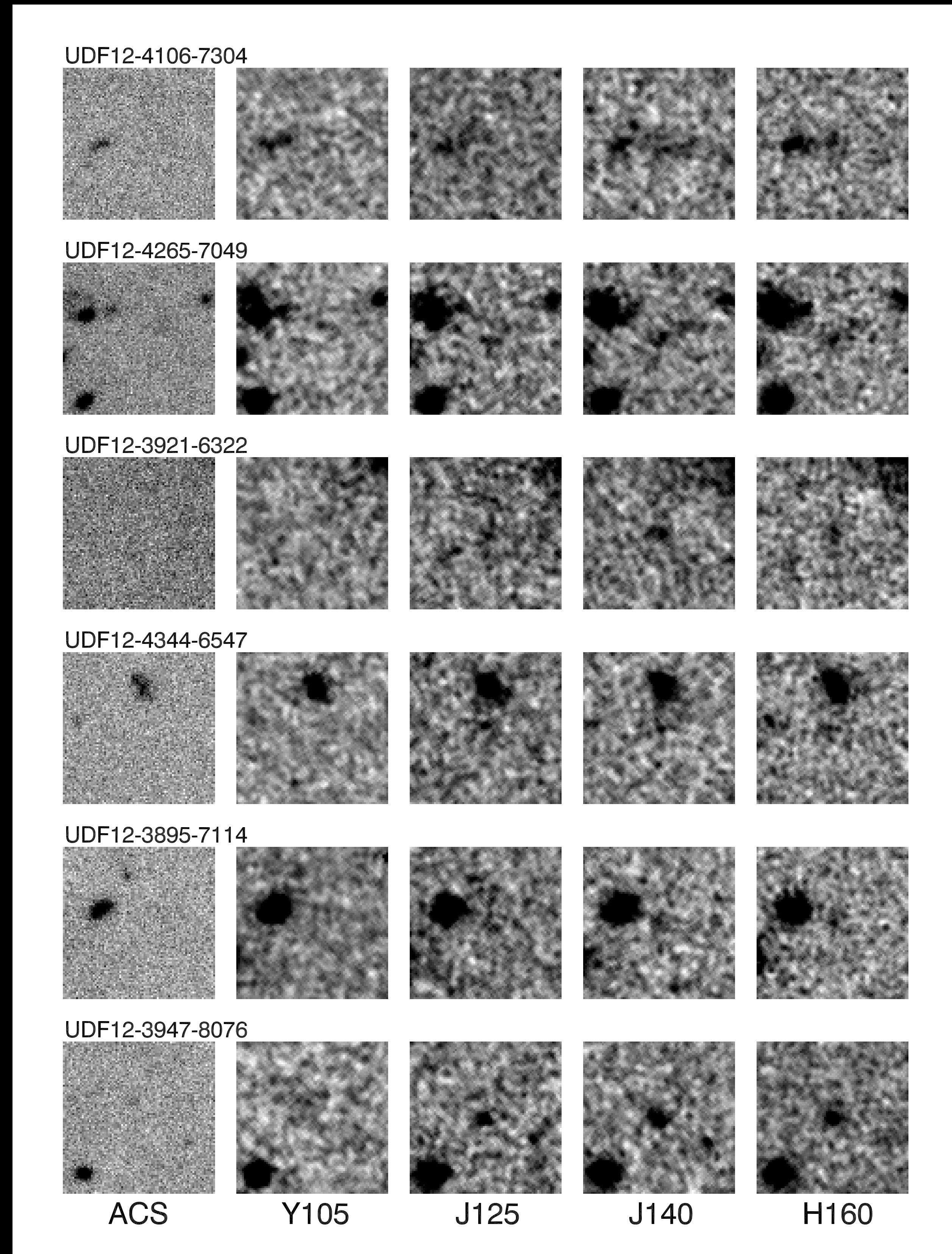
5σ detections in (160W +140W+125W) stack ($m_{AB} < 30.1$)

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

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

z~12 candidate likely at low-z, needs confirmation.

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



z=9.5
520 Myr

z=9.5
520 Myr

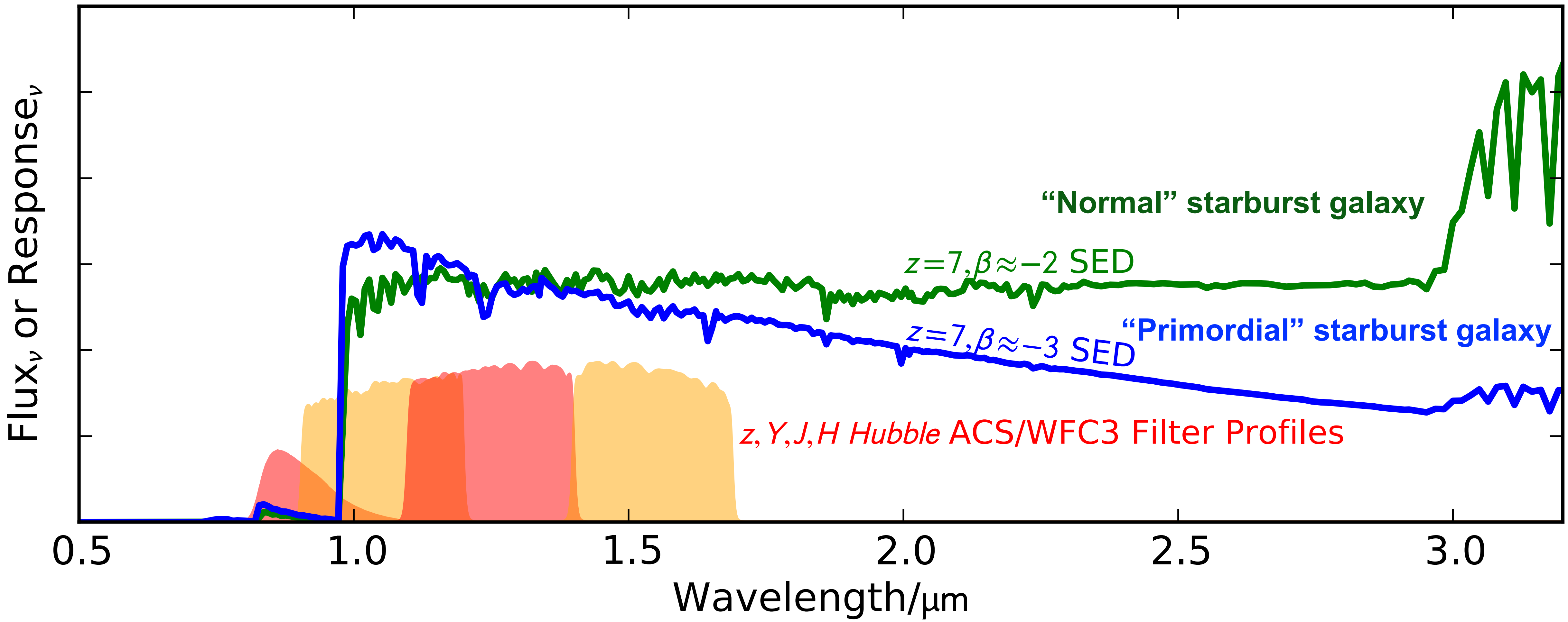
z=8.8
570 Myr

z=8.8
570 Myr

z=8.6
590 Myr

z=8.6
590 Myr

Constraining the Stellar Populations of High Redshift Galaxies



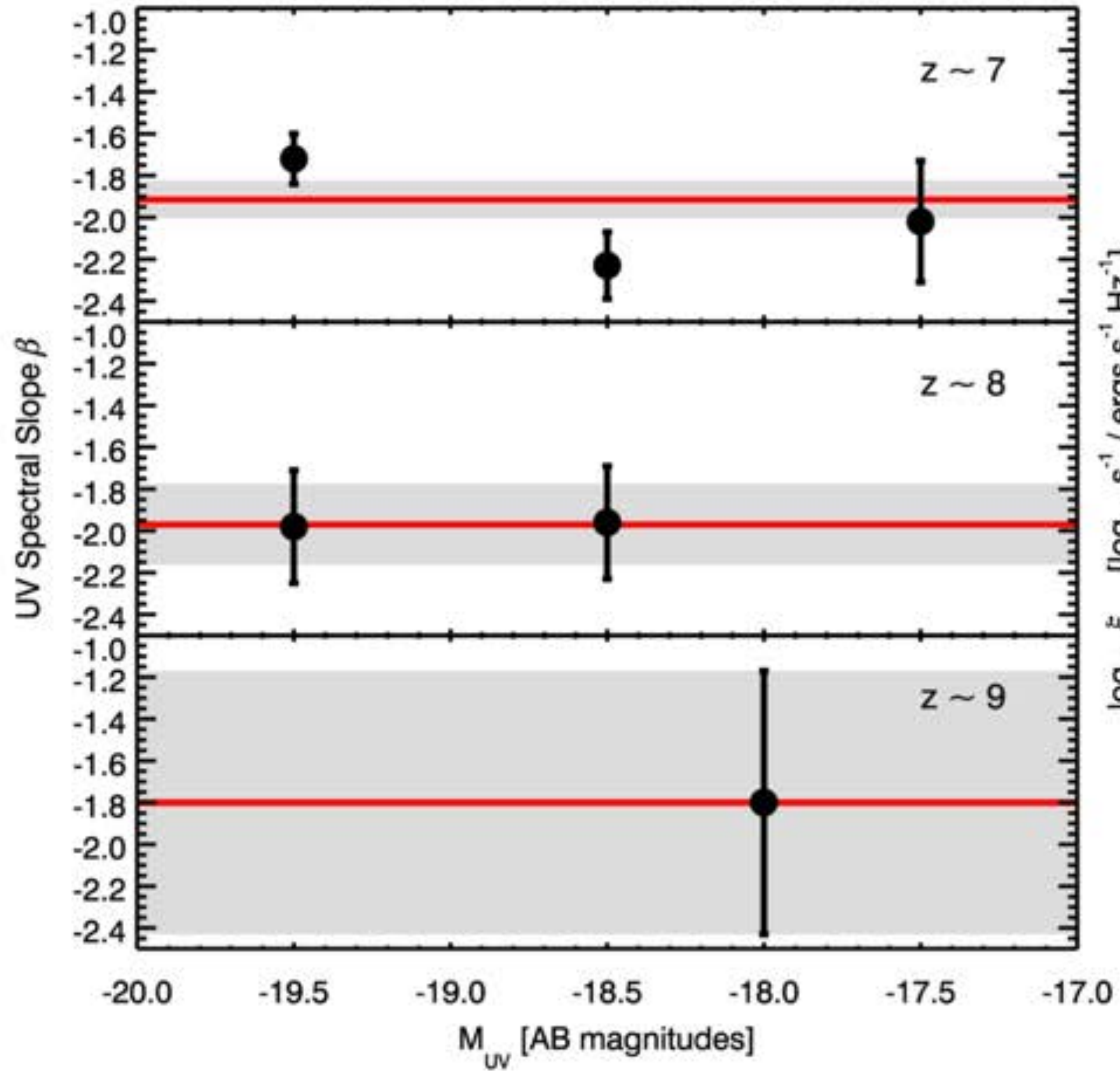
Graphic from Sandy Rogers.

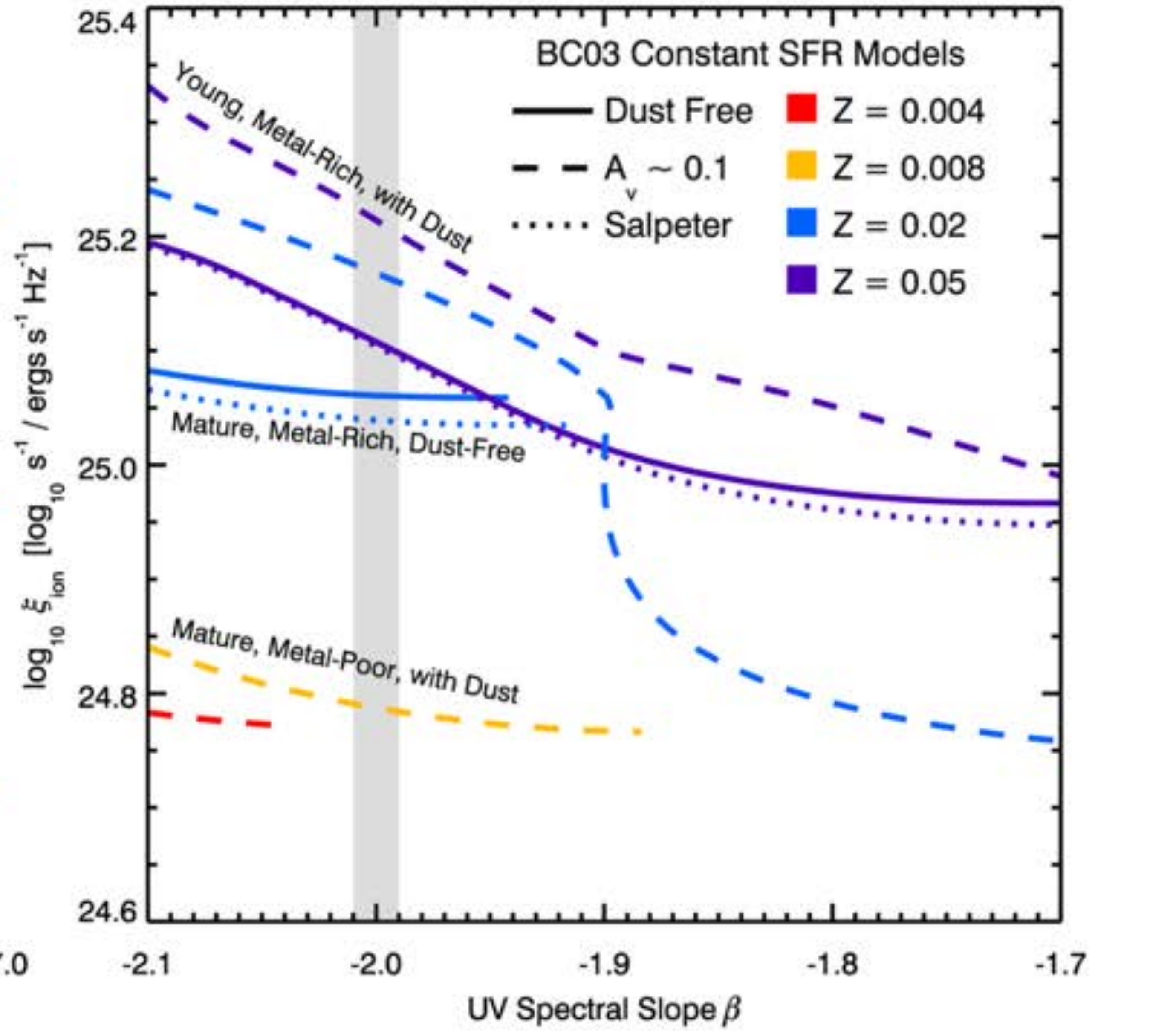
In the early Universe, when galaxies first started to build stars, extremely metal-poor and young stars are expected to be the norm for only a very short time.

Formed of "pristine" gas, galaxies harboring these stellar populations would have very blue colors, corresponding to a steep spectral shape.

High-Redshift Galaxy Stellar Population Constraints from UDF12

Robertson et al., ApJ, 768, 71 (2013)





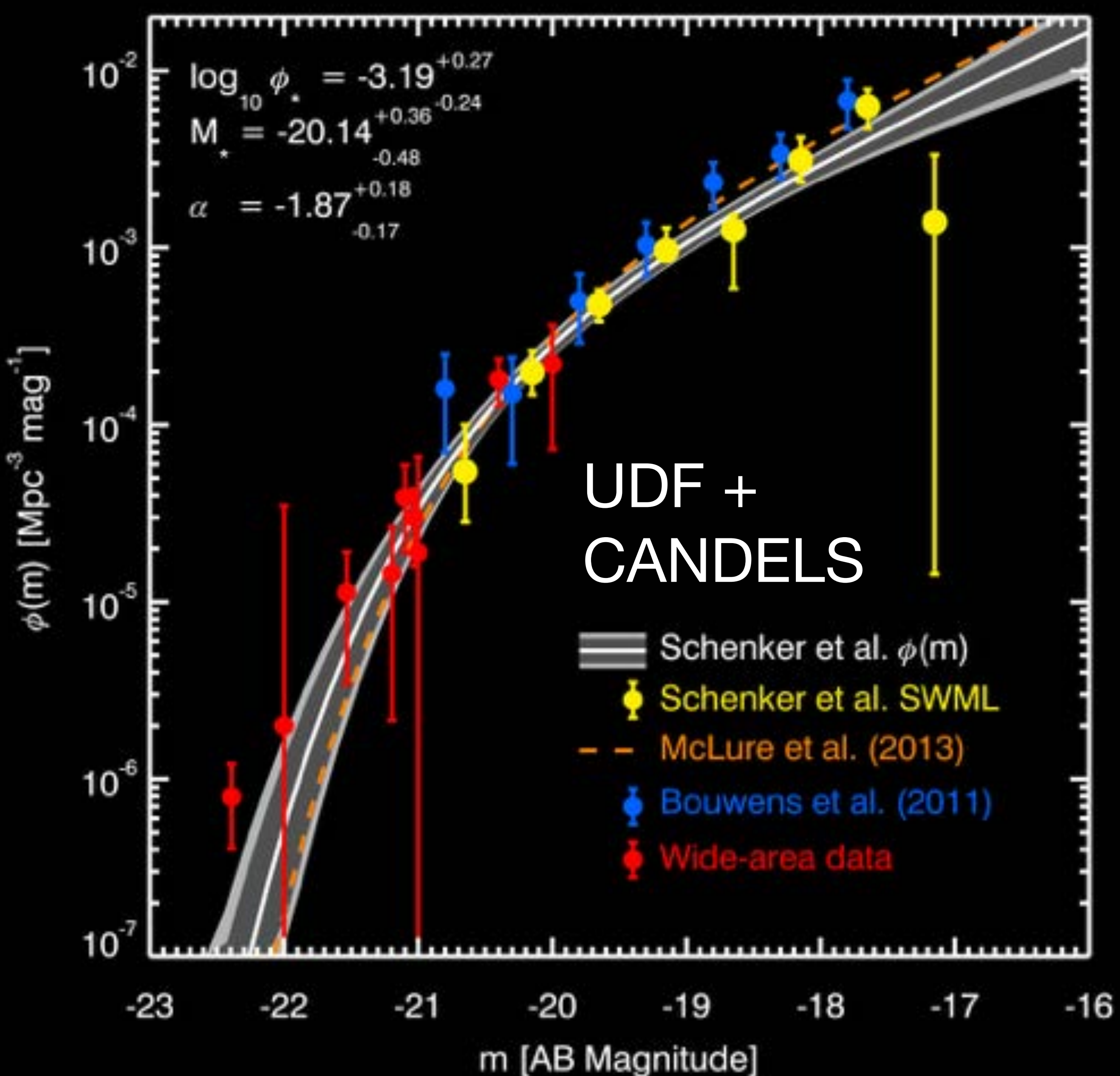
Data from Dunlop et al. (incl. BER), MNRAS, 432, 3520 (2013)

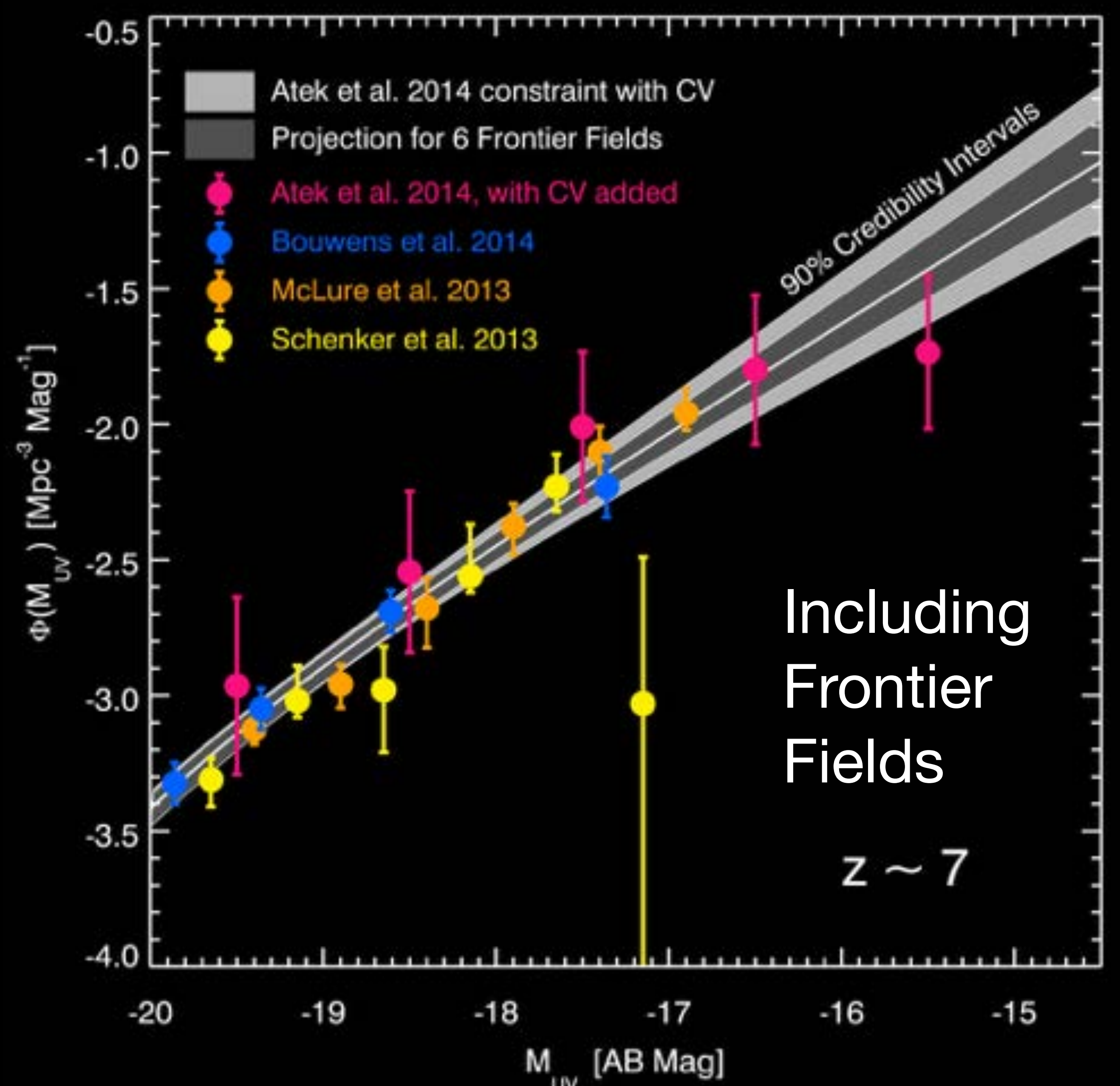
UV continuum slope measurements from UDF12 constrain high-redshift (z~7-9) galaxies to have β~-2, roughly constant with redshift and luminosity.

Translating these constraints into Lyman continuum photon production via Bruzual and Charlot (2003) models, high-redshift galaxies have modest ionizing photon luminosities per unit L_{UV}.

See also Finkelstein et al., ApJ, 756, 164 (2012), Bouwens et al. (2013)

UV Luminosity Function @ z~7

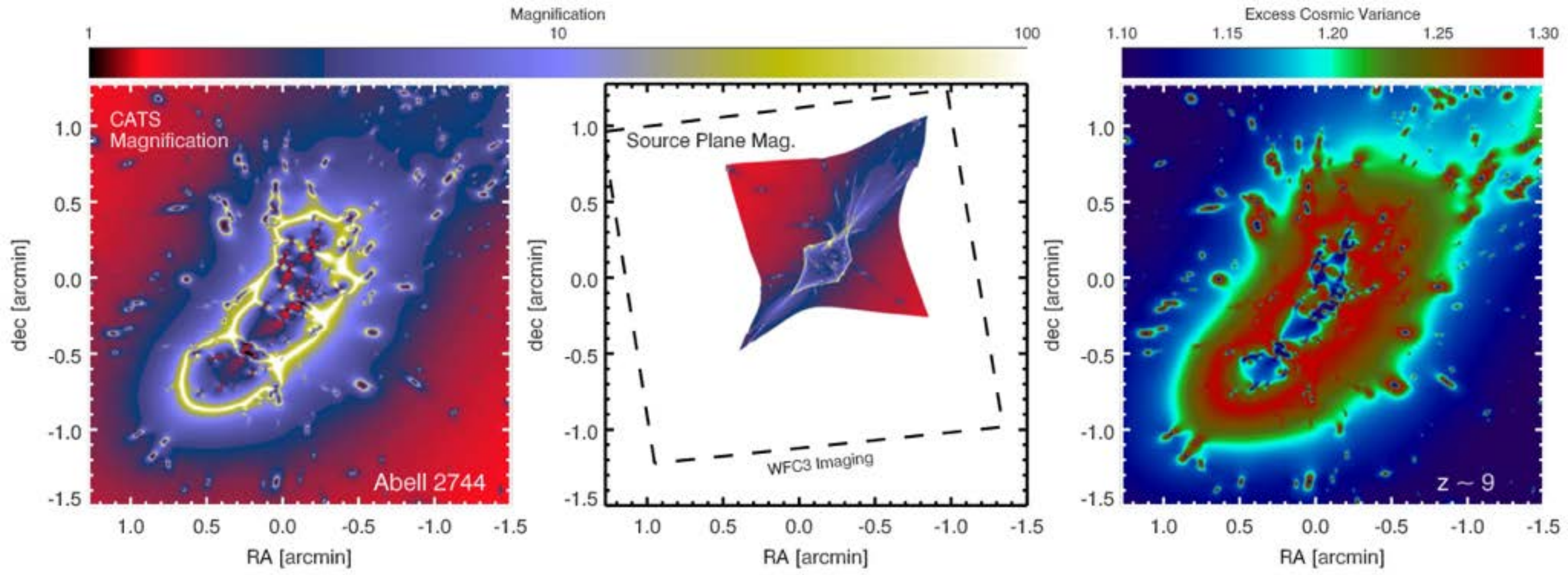




Schenker, BER, et al., ApJ, 768, 196 (2013)

BER et al., ApJL, 796, 27 (2014)

Lensed Clusters Have Increased Cosmic Variance Uncertainty



BER et al., ApJL, 796, 27 (2014)

Magnified regions behind lensing clusters have correspondingly smaller volumes, exacerbating the cosmic variance issues in deep pencil beam surveys.

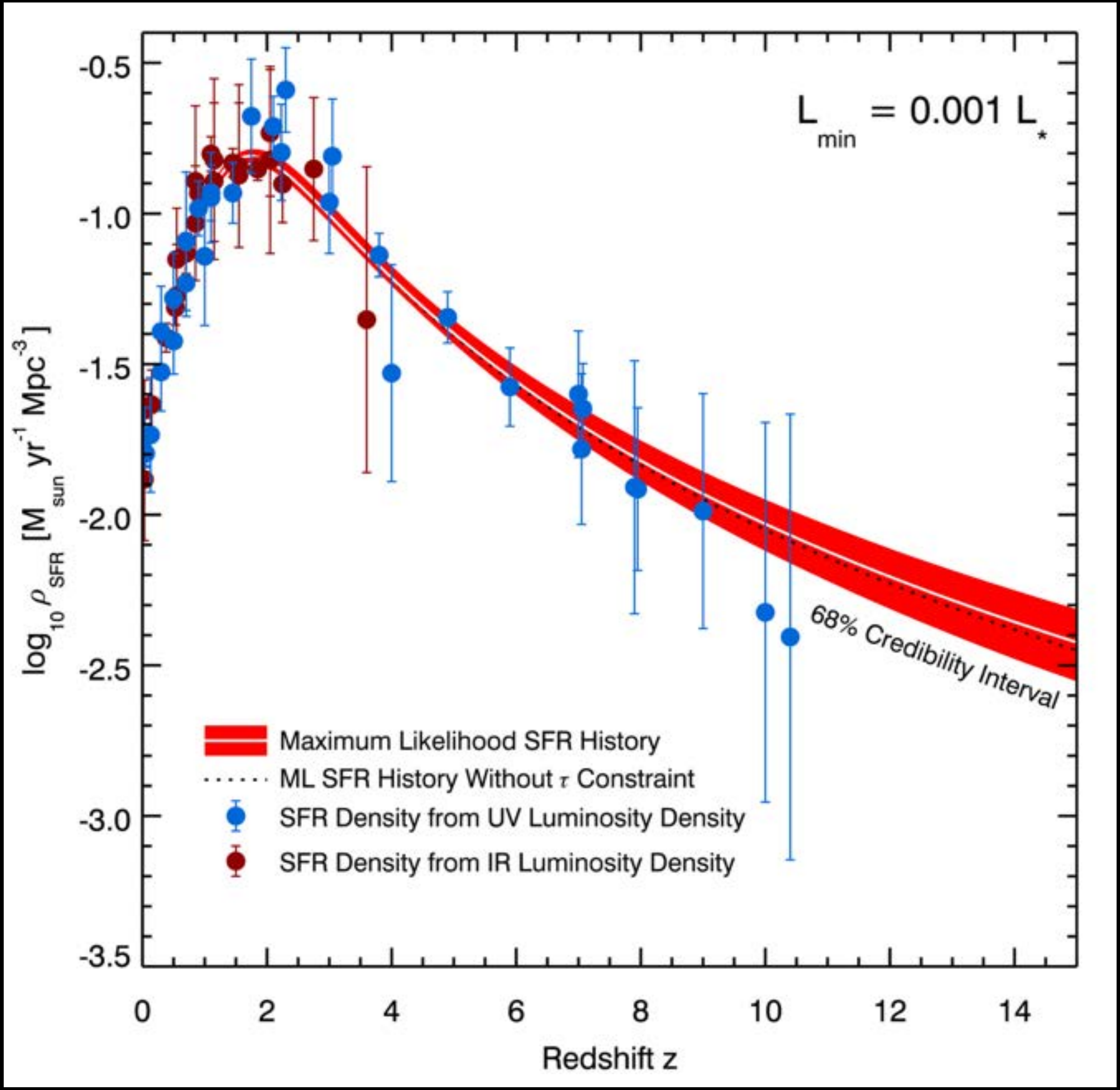
Researchers leveraging the Frontier Fields or planning future surveys should account for this additional uncertainty. See, e.g., McLeod et al. (2015).

Star Formation History of the Universe

Star formation history from UV (blue) and IR (red) observations, adopted from Madau & Dickinson (2014).

We can use this star formation history of the universe to compute the reionization history of the IGM.

BER et al., ApJL, 802, 19 (2015)

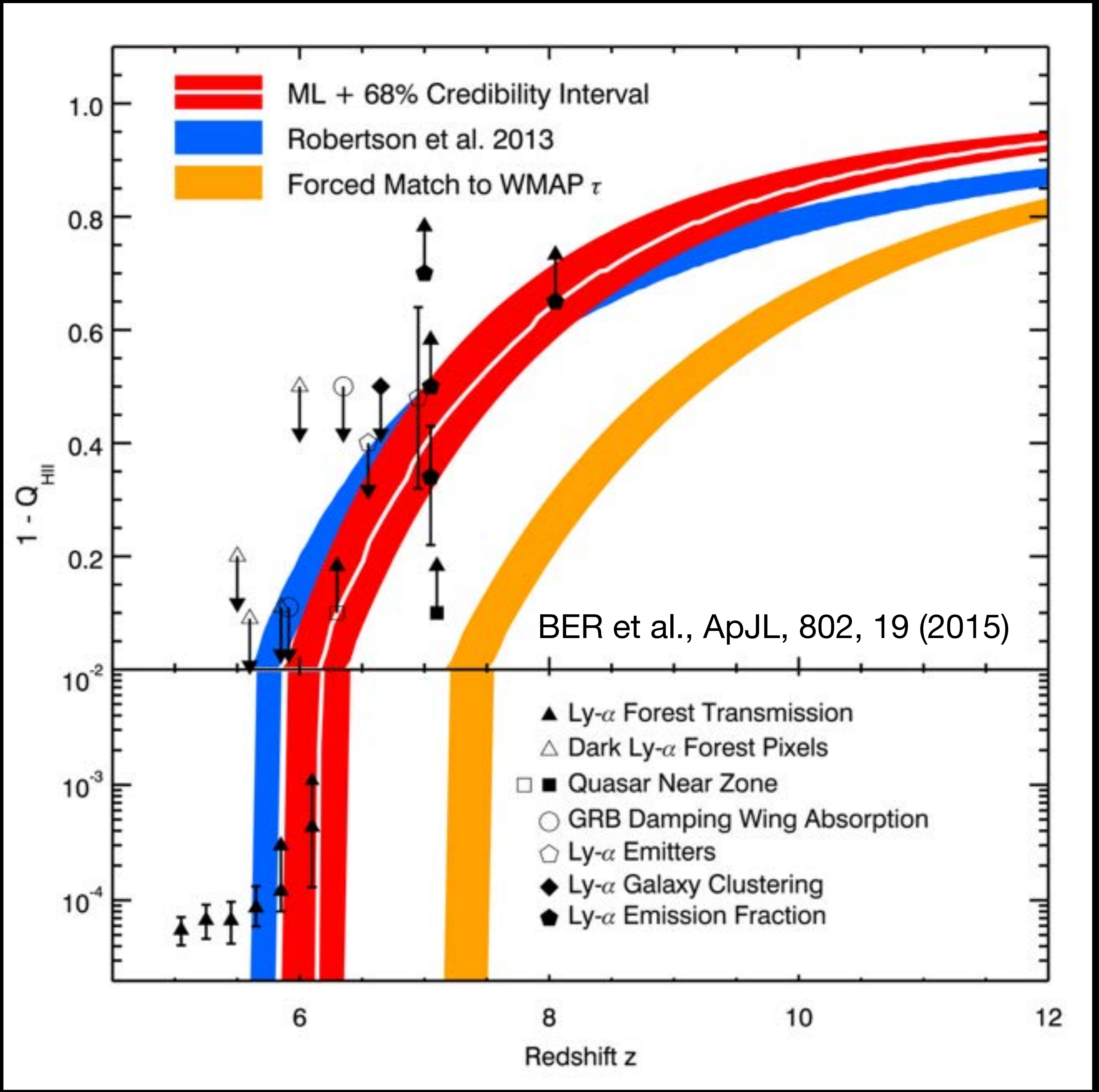


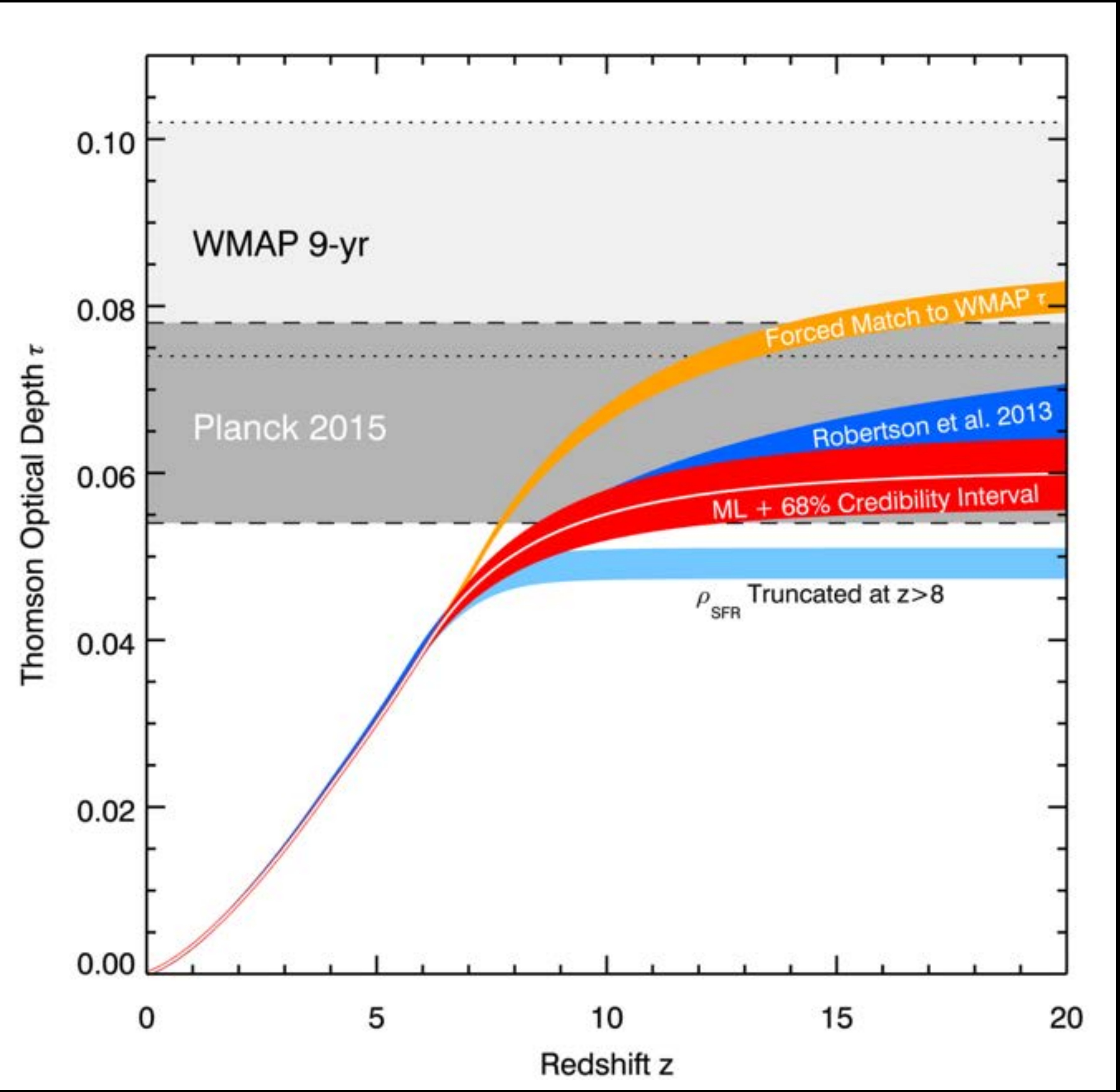
Reionization History Implied by High-z Star Formation

IGM Neutral Fraction, shown with constraints from a variety of independent probes.

Galaxies with L_{UV}>0.001L* are sufficient to reionize the Universe by z~6 (red band). (red band), consistent with other IGM neutrality probes.

Forced match to WMAP Thomson optical depth constraints (orange) requires earlier reionization with same assumptions, not consistent with IGM neutrality constraints.





Thomson Optical Depth to Electron Scattering

Recent Planck results suggest the Thomson optical depth to the CMB is tau ~ 0.065, substantially less than found by WMAP.

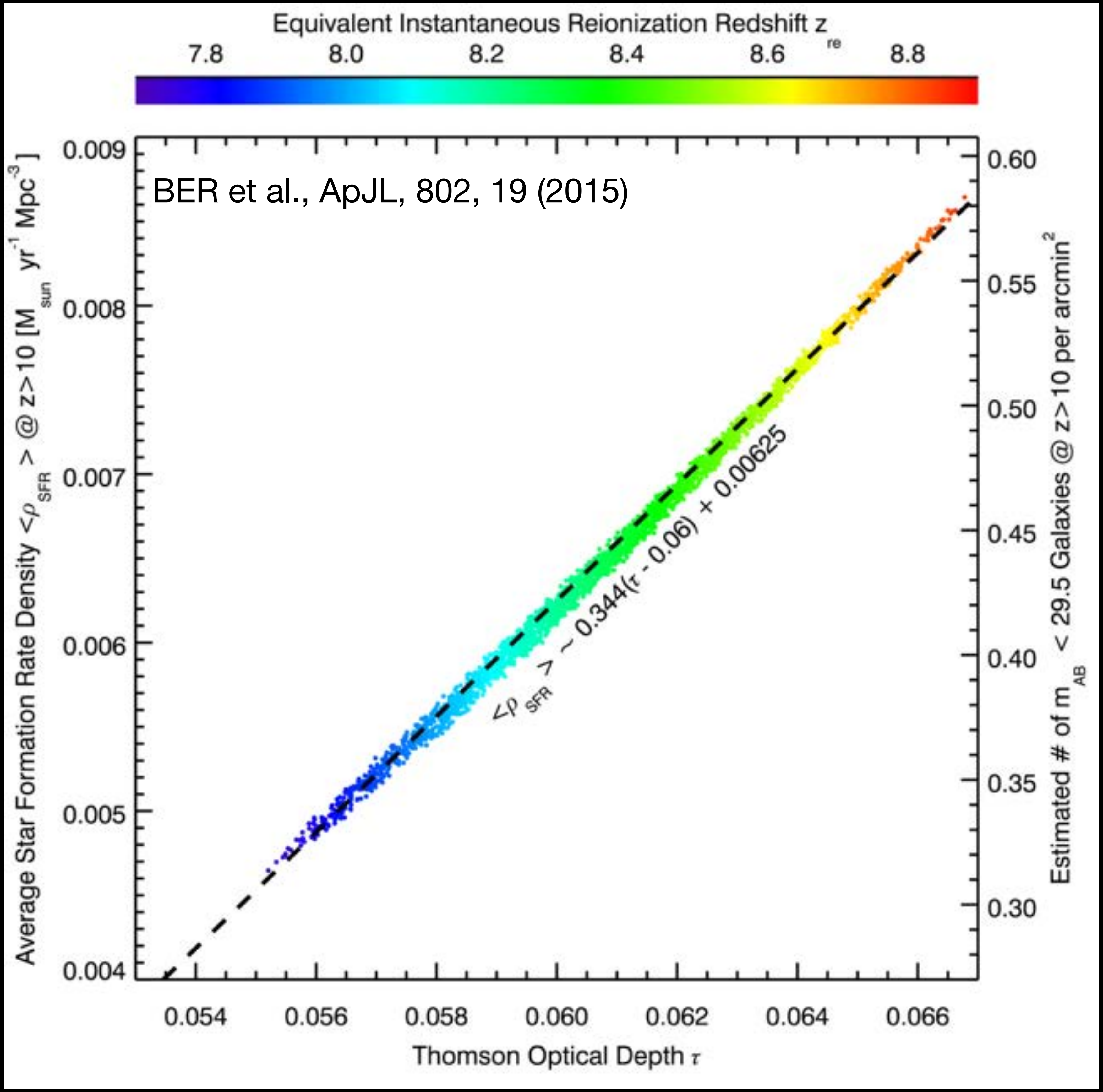
The Thomson optical depth provided by the high-z IGM ionized by star forming galaxies is now fully consistent with the CMB constraints (Robertson et al. 2015).

BER et al., ApJL, 802, 19 (2015)

Implications for High-Redshift Galaxy Observations with James Webb Space Telescope

The Thomson scattering signal in the CMB suggests the presence of high-redshift galaxies.

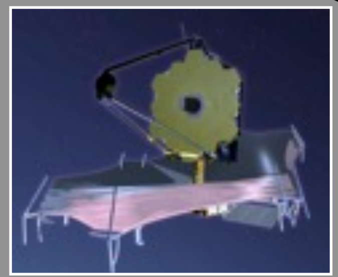
We expect ~0.4-0.5 z>10 galaxies per square arcminute, detectable with JWST in the first deep exposures — ***we should find 5-10 z>10 galaxies in the first year of JWST operations.***



Facilities for Studying High-Redshift Galaxies Over the Next Decade

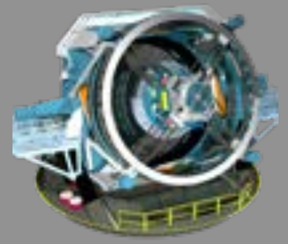
JWST

hi res, NIR, spectroscopy space-based



- 6.4m mirror in 18 segments
- 0.6-5μm NIRCam (30AB)
- 5-28.5μm MIRI
- R~100, 1000, 2700 @ 1-5μm

LSST



wide area, optical, ground-based

- 8.4m with embedded tertiary
- 3.2 Gpixel camera; 60PB raw
- 18,000 deg^2 *ugrizy AB=26.7*
- 4x 9.6 deg^2 *ugrizy* AB>28

ALMA

hi res, (sub)mm, spectroscopy ground-based

- 66 x 12m antennae
- 0.3-9.6mm observations
- 15-18km baselines
- up to 0.005 arcsec resolution

WFIRST

wide area, NIR, R~600, space-based

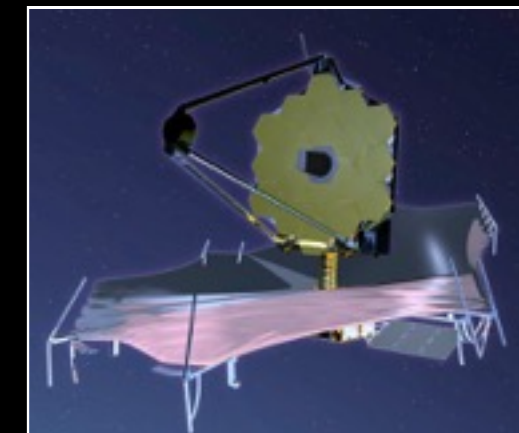
- 2.4m AFTA design from SDO
- 0.28 deg^2 *ZYJHF* detector
- 2,227 deg^2 *YJHF* AB=26.7
- 5-27.44 deg^2 2b AB=27-29

TMT

hi res, NIR, spectroscopy, ground-based

- 30m segmented primary
- 15 arcmin FOV, 0.3-28μm
- NIR diffraction limited
- AO fed spectroscopy

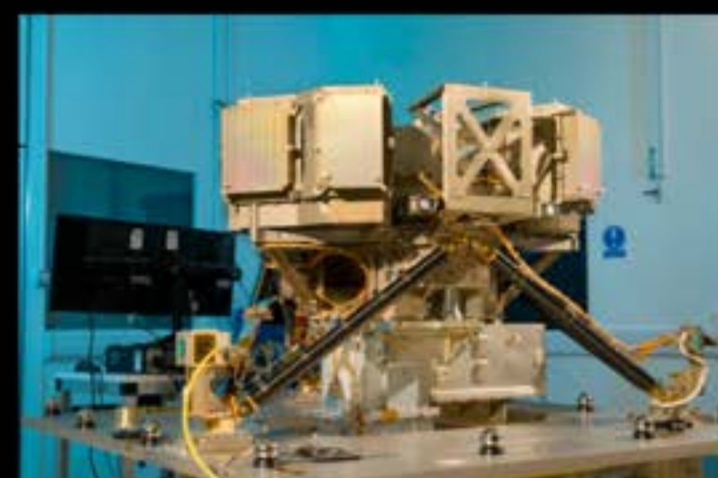
Observations of Distant Galaxies with James Webb Space Telescope



The amazing array of capable instruments on JWST will enable truly synergistic surveys of the high-redshift universe!

NIRCam

NIRISS



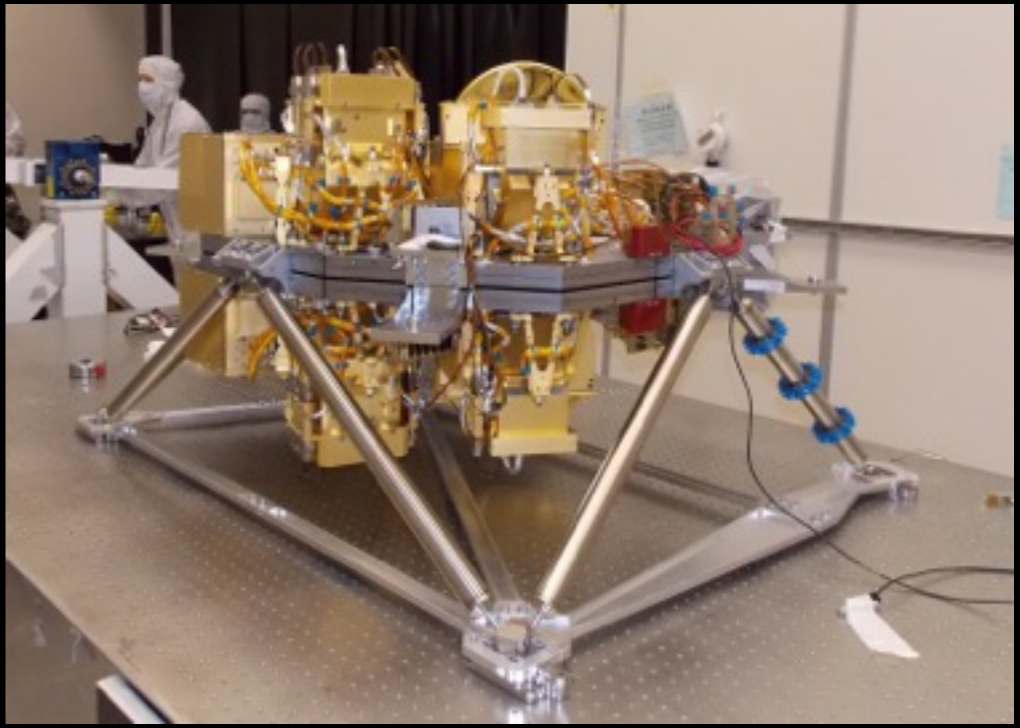
MIRI

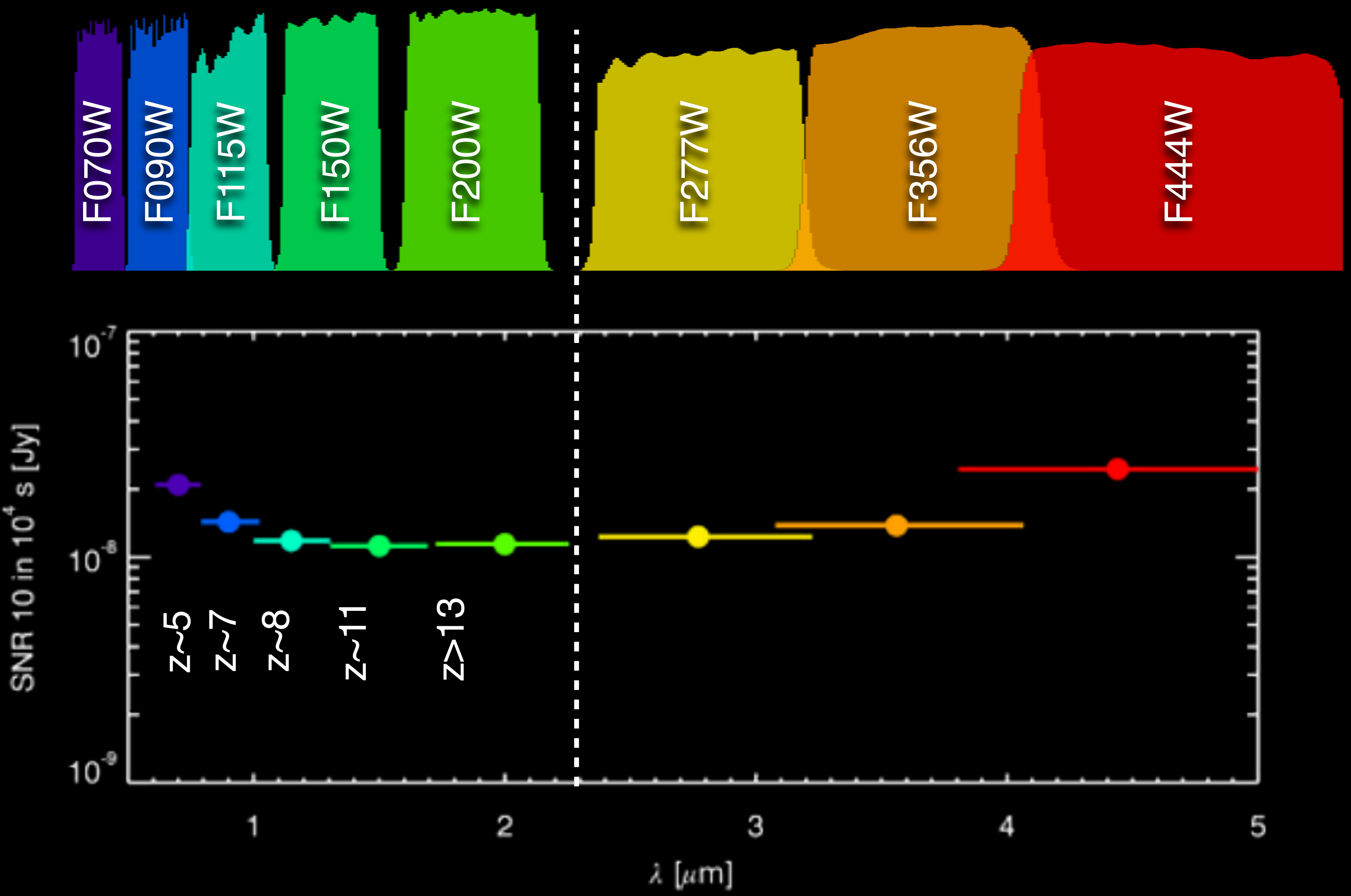
NIRSpec

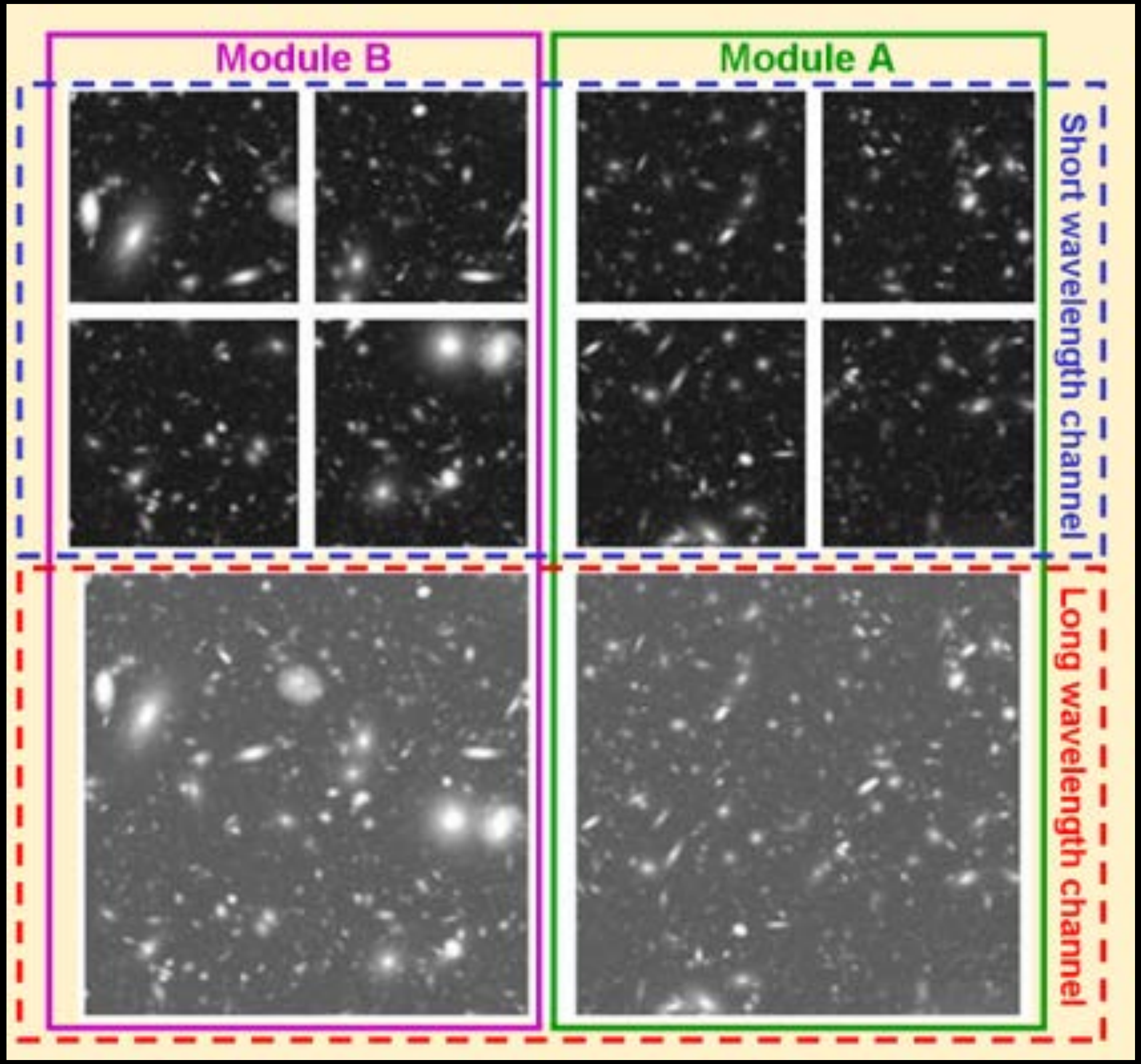
- Spectroscopic confirmation of high-redshift galaxies with NIRSpec, MIRI, NIRISS, NIRCAM
- Spectral signatures of star formation rates and metallicity for high-redshift galaxies
- Clustering of high-redshift galaxies
- Multi-tier depth/area designs for distant galaxy surveys

JWST NIRCam

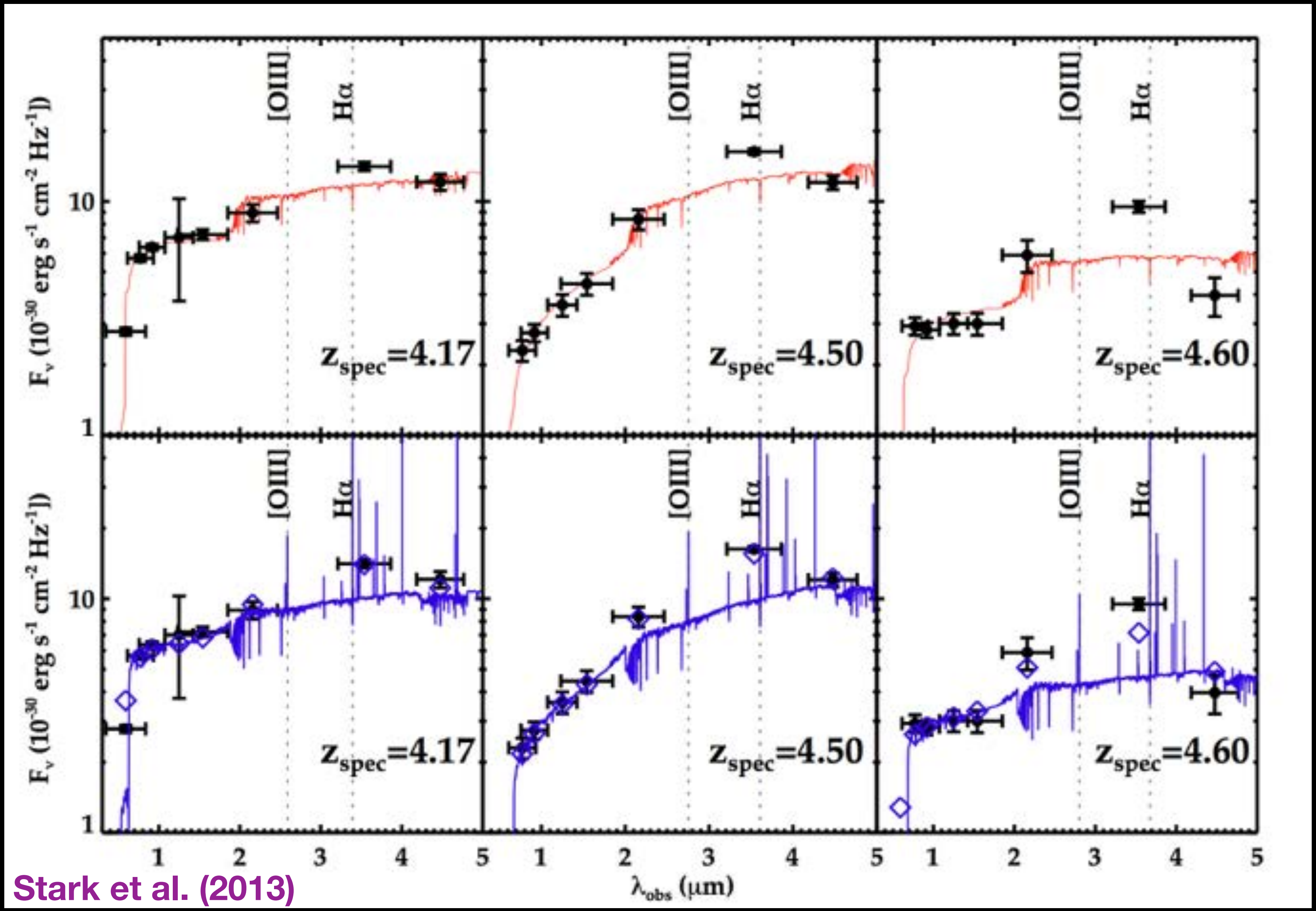
- Simultaneous imaging in “red” (LW) and “blue” (SW) filters in two detector modules.
- Sensitivity is ~29AB in 10^4s @ 2μm
- Pixel scale in SW and LW arms give Nyquist sampling of PSF @ 2μm & 4μm







Nebular Emission in High-z Galaxies



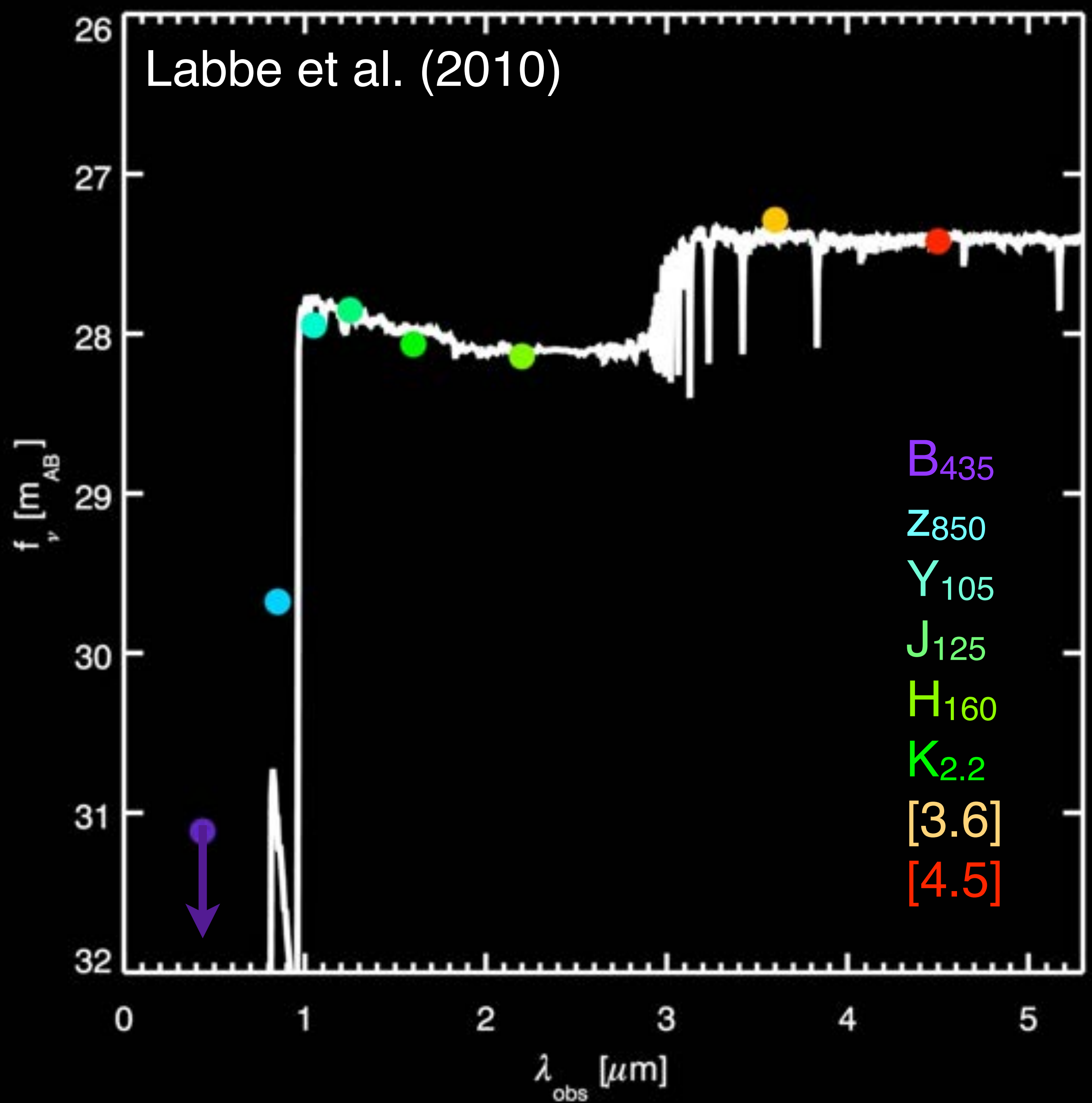
The rest-frame UV photometric data from HST and rest-frame optical data from *Spitzer* enable a fit of stellar population synthesis models to determine stellar masses.

Galaxies in certain redshift windows will have their rest-frame optical photometry affected by nebular line emission.

Nebular continuum emission can also affect rest-frame UV-optical photometry.

See, e.g., Schaerer & de Barros (2009, 2010); Ono et al. (2010); Robertson et al. (2010); Shim et al. (2011); de Barros et al. (2012); Stark et al. (2013), Labbe et al. (2013); de Barros, Schaerer, & Stark (2014); Smit et al. (2014, 2015)

Standard SED Modeling of High-z Galaxies

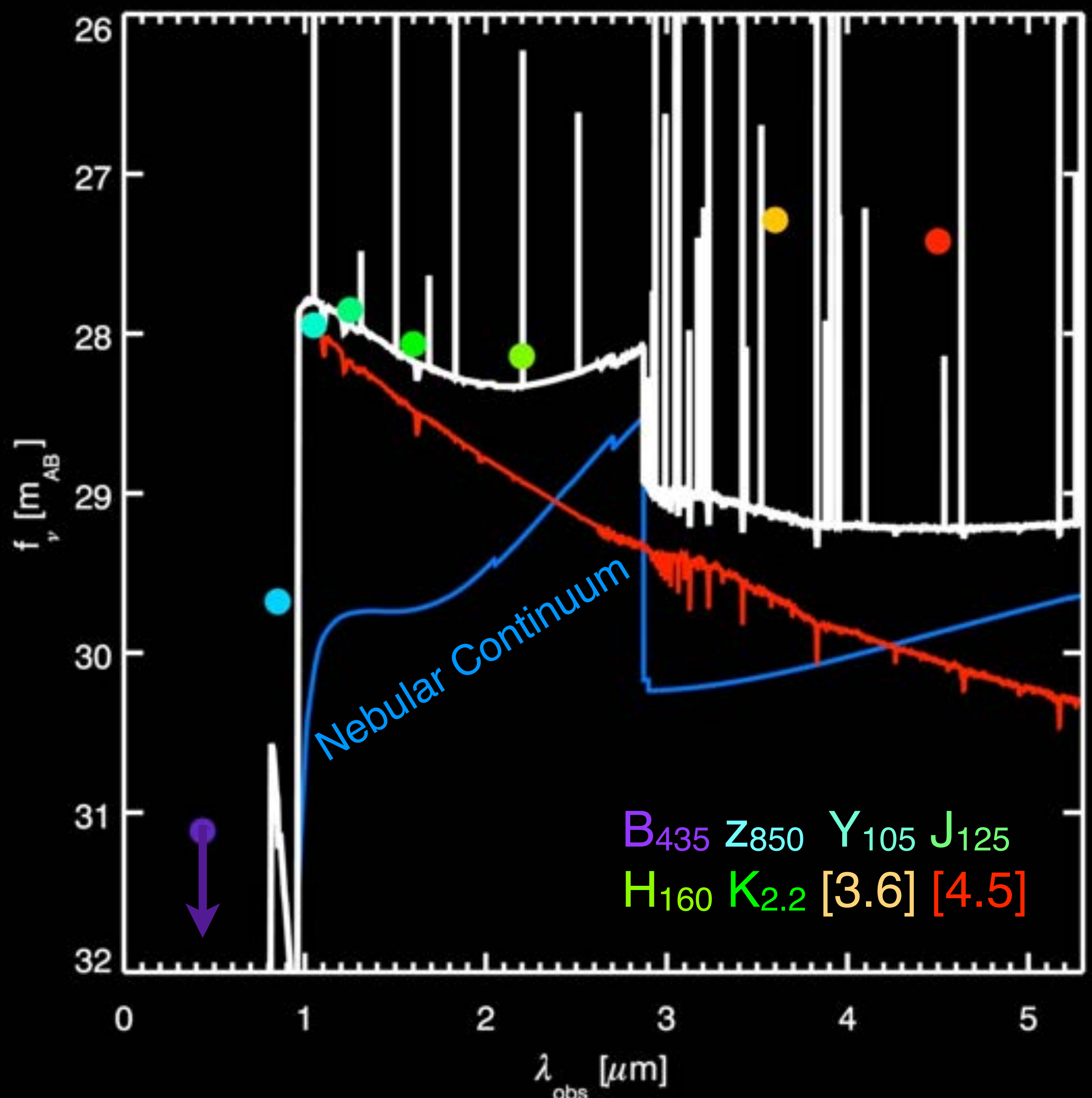


The rest-frame UV photometric data from HST and rest-frame optical data from *Spitzer* enable a fit of stellar population synthesis models.

Best-fit Bruzual & Charlot 2003 model for stacked data:

Age = 4 x 10^8 yrs
SFR = 2 M_{sun} / yr
$M_\star$ = 1.25 x 10^9 M_{sun}

SED Modeling of High-z Galaxies Including Nebular Emission



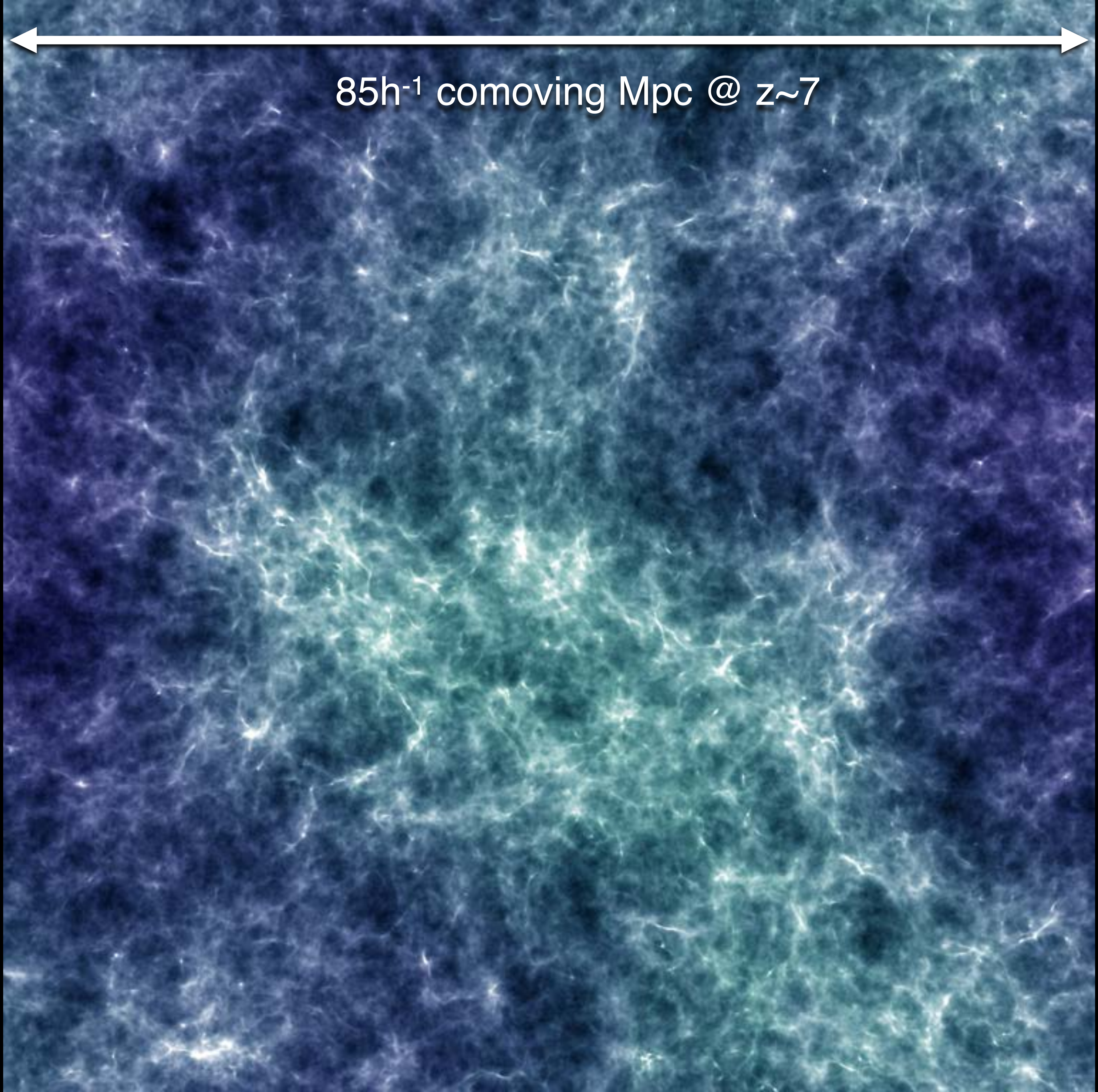
Nebular emission models can fit the photometry equally well, or better than stellar only models. Even seemingly ridiculous ones.

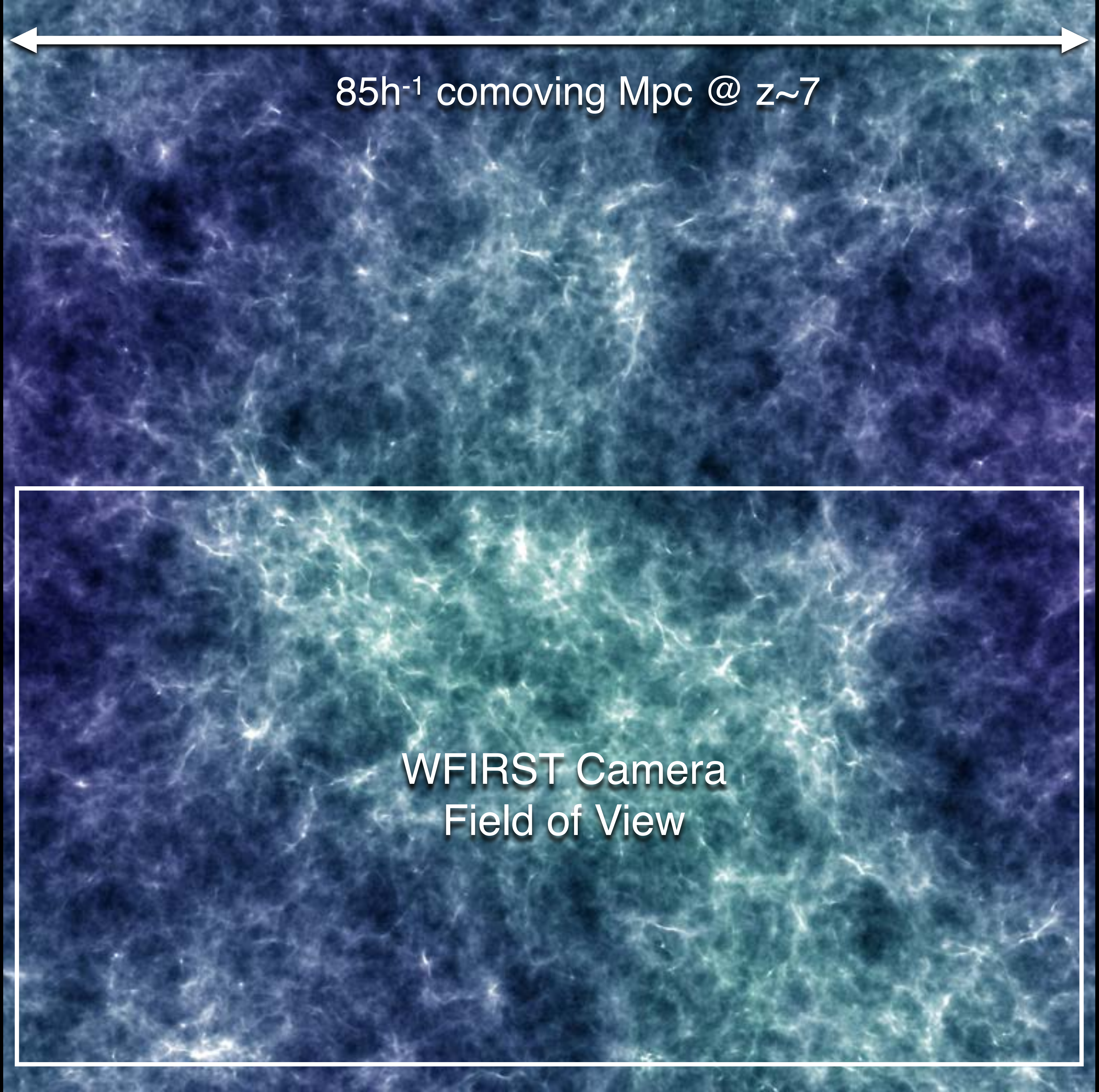
Best-fit Bruzual & Charlot 2003 model + neb. emission (f_{esc}=0) for stacked data:

Age = 1.45 x 10^6 yrs
SFR = 36 M_{sun} / yr
$M_\star$ = 5.25 x 10^7 M_{sun}

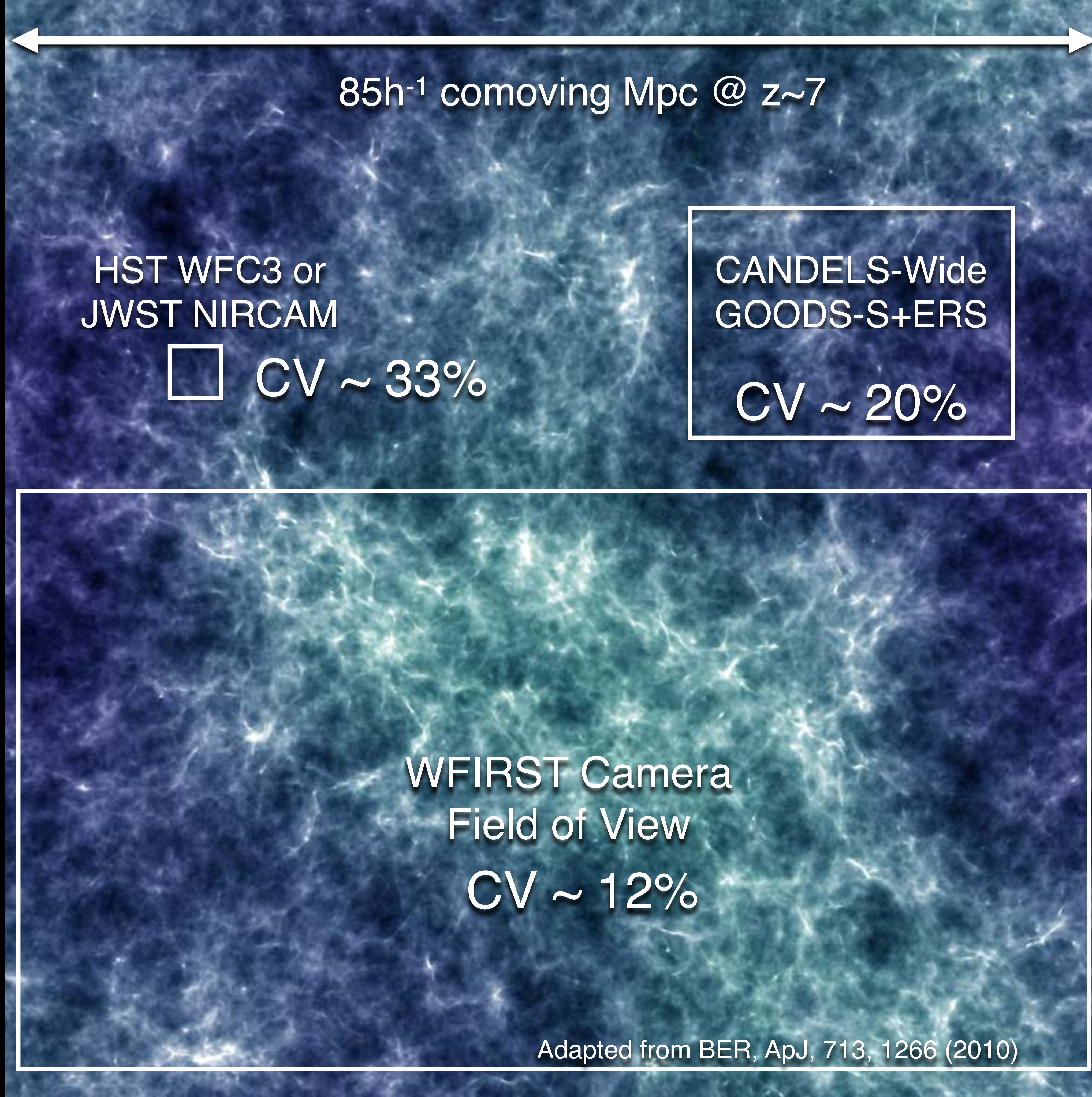
Constraints on the nebular emission are going to be necessary to constrain tightly stellar mass at high-z.

James Webb Space Telescope Synergy with the Wide-Field InfraRed Survey Telescope

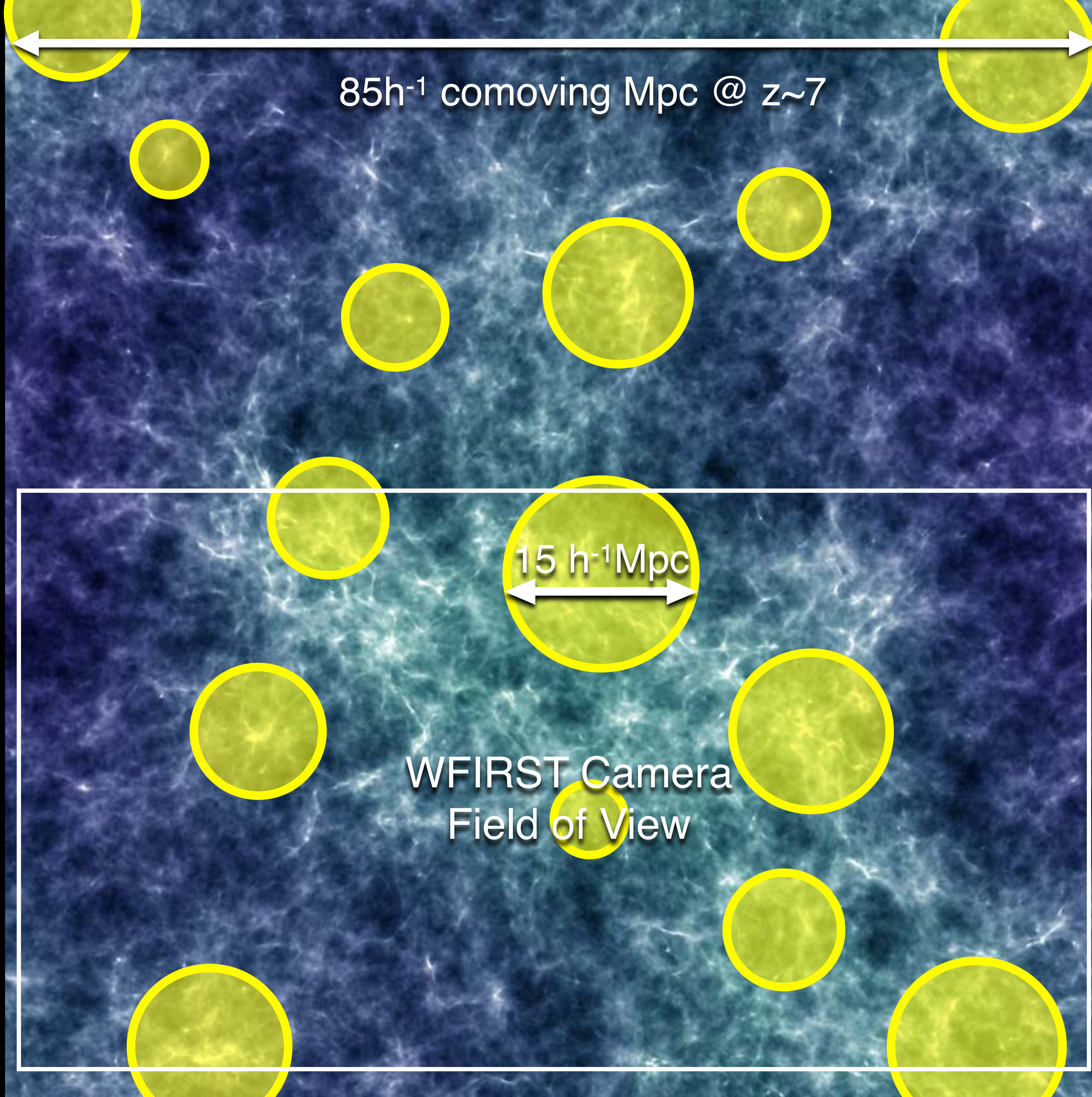

85h-1 comoving Mpc @ z~7


85h-1 comoving Mpc @ z~7
WFIRST Camera
Field of View

Cosmic Variance



Reionized Bubbles



SUMMARY: New Constraints on Cosmic Reionization

UDF12 Team / NASA / ESA / STScI

Constraints on galaxy abundance and spectral character from HST surveys suggest that galaxies with luminosities $L_{UV}>0.001L_{\star}$ are sufficient to both reionize the universe by z~6 and reproduce Planck CMB constraints on the Thomson optical depth.

These results imply that JWST should find evidence of galaxies at z~10-15 in its first year of operations.

So many interesting future opportunities with JWST!!!

For more info, see:

Robertson et al. *Nature*, 468, 49 (2010).
Robertson et al., ApJ, 768, 71 (2013)
Robertson et al., ApJL, 802, 19 (2015)