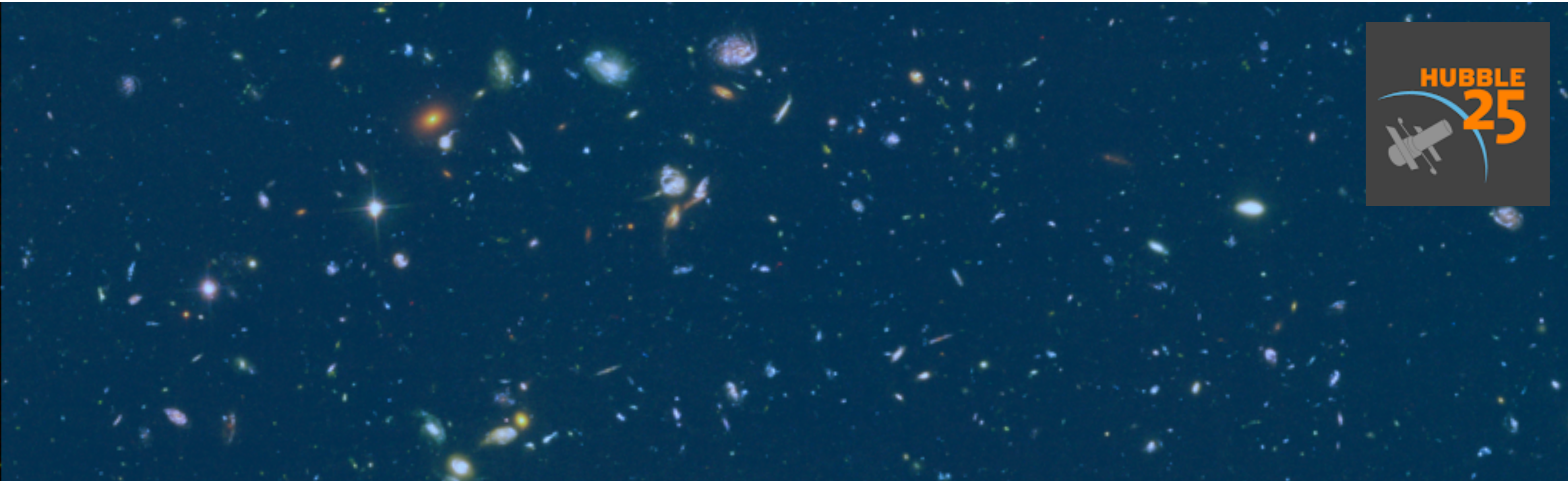
Yale Center for
Astronomy and Astrophysics

Galaxy Build-up at Cosmic Dawn:
Lessons from Ultra-Deep HST and Spitzer/IRAC Observations

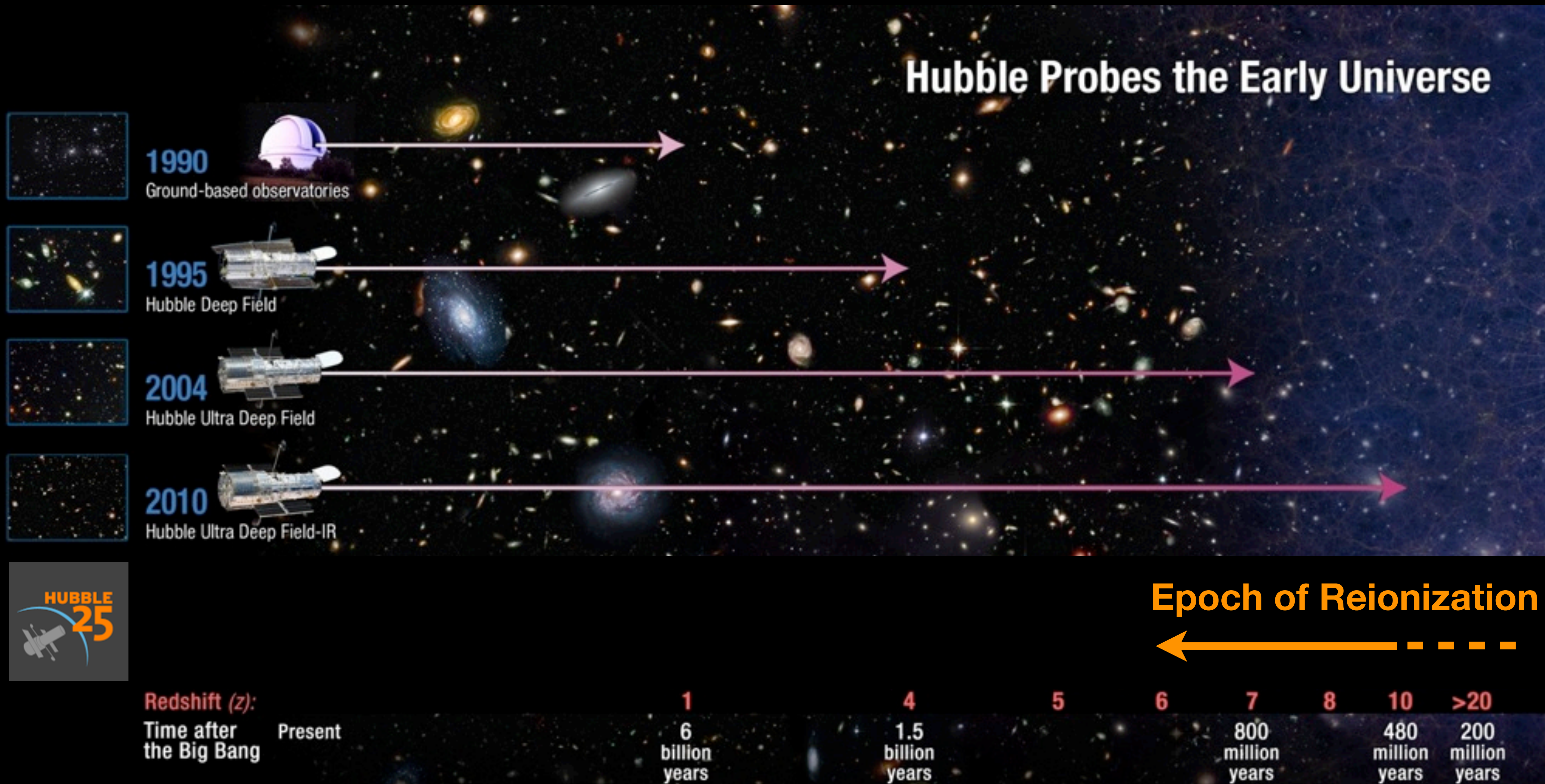
ATLAST/LUVOIR Seminar GSFC

Pascal Oesch
Yale University

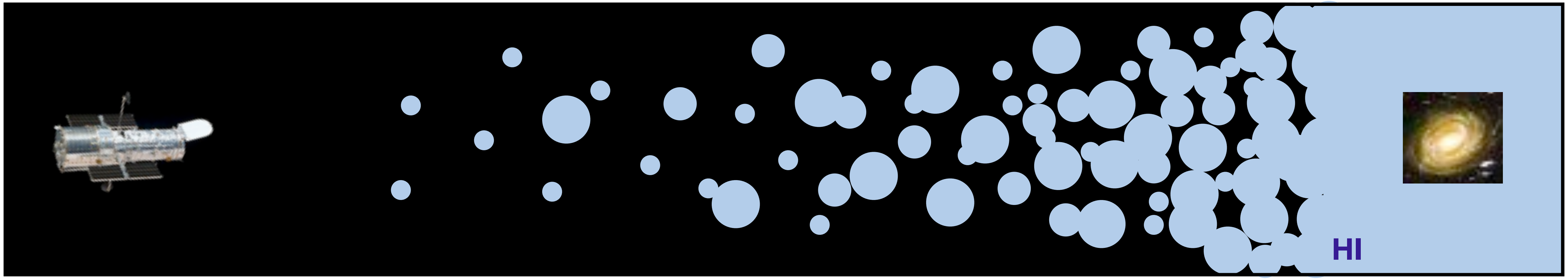


with **XDF Team+**: G. Illingworth, R. Bouwens, I. Labbé, V. Gonzalez, M. Franx, P. van Dokkum, D. Magee, M. Trenti, C.M. Carollo, M. Stiavelli, R. Smit + L. Spitler, G. Fazio, M. Ashby, S. Willner, J-S Huang +
BORG Team: L. Bradley, V. Calvi, K. Borello Schmidt, T. Treu, D. Coe, B. Holwerda, J. MacKenty, C. Mason, T. Puzia, M. Shull

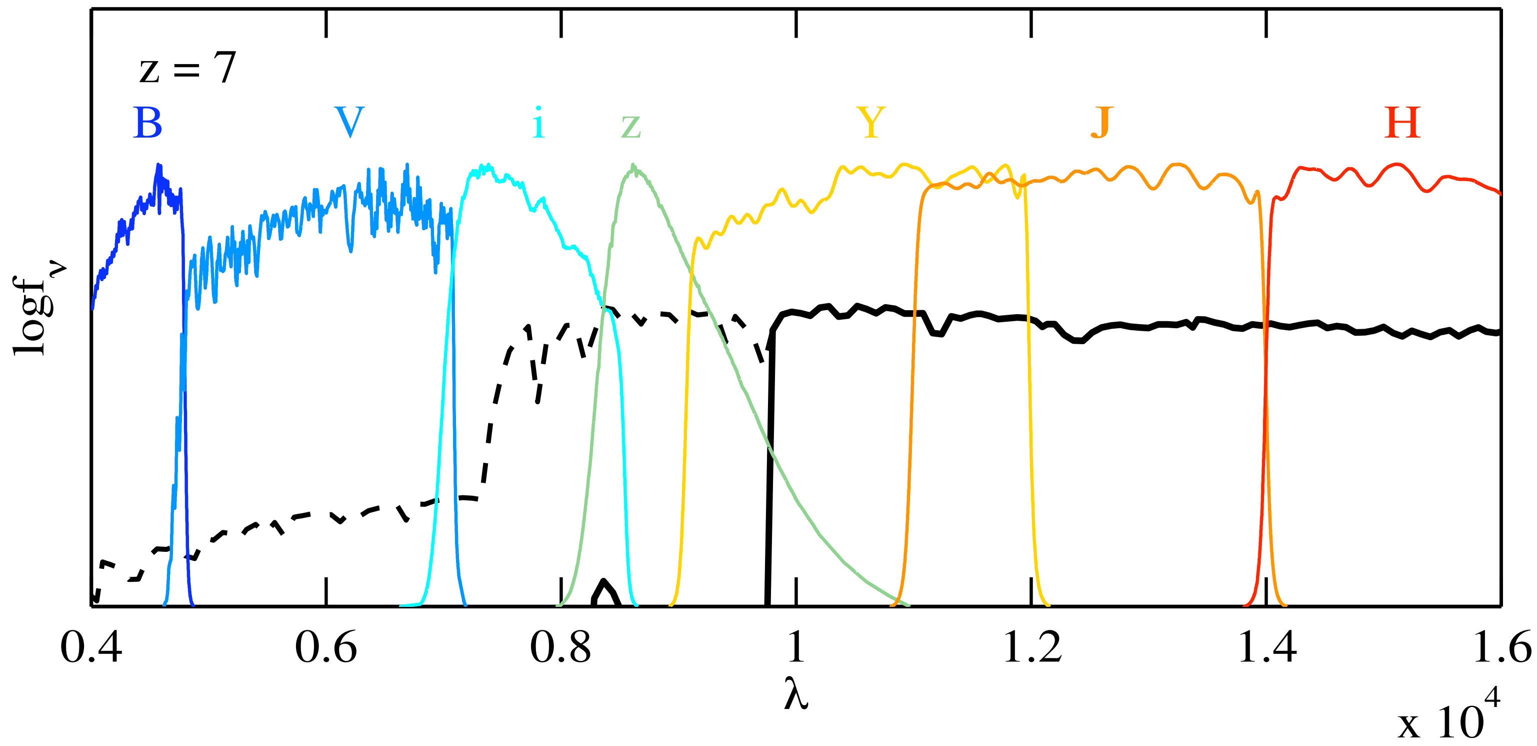

The history of astronomy is a history of receding horizons.
E. P. Hubble



The Lyman Break Technique

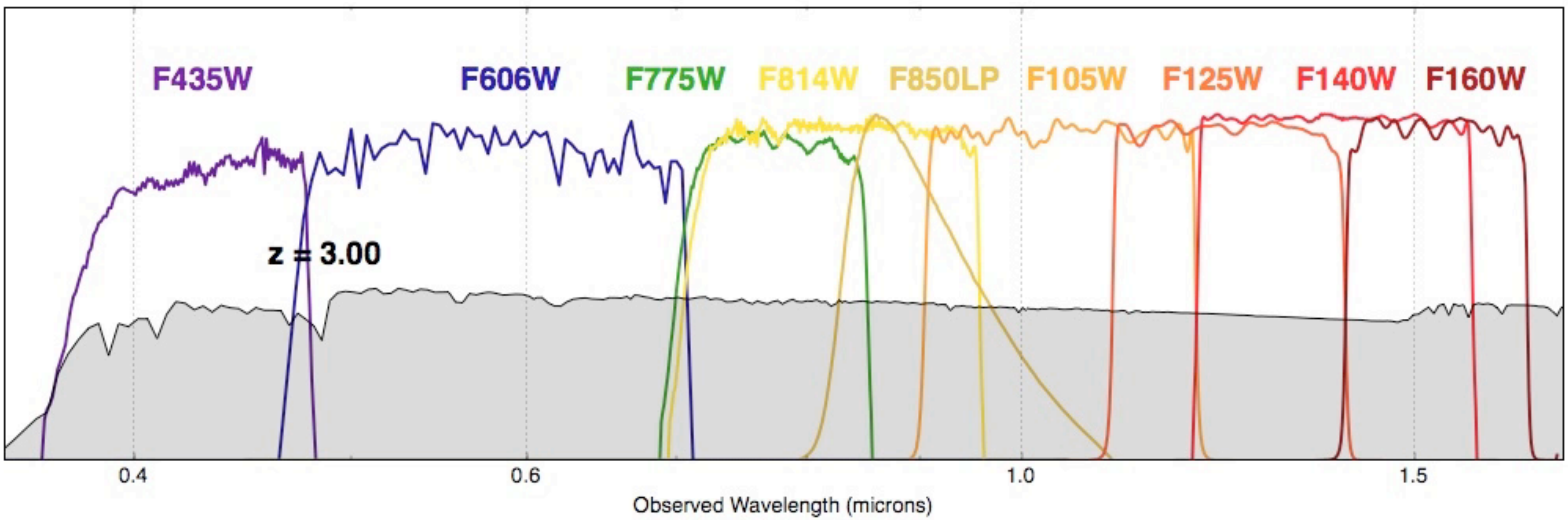


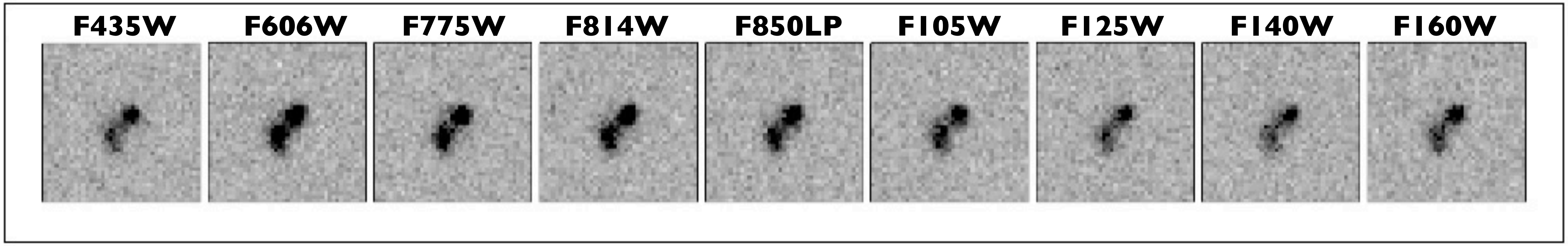
Lyman Break Galaxy Selection: based on IGM absorption



z>=7 galaxies can only be seen at NIR wavelengths

What is the limit we can reach with HST?





optical ACS

near-IR WFC3/IR

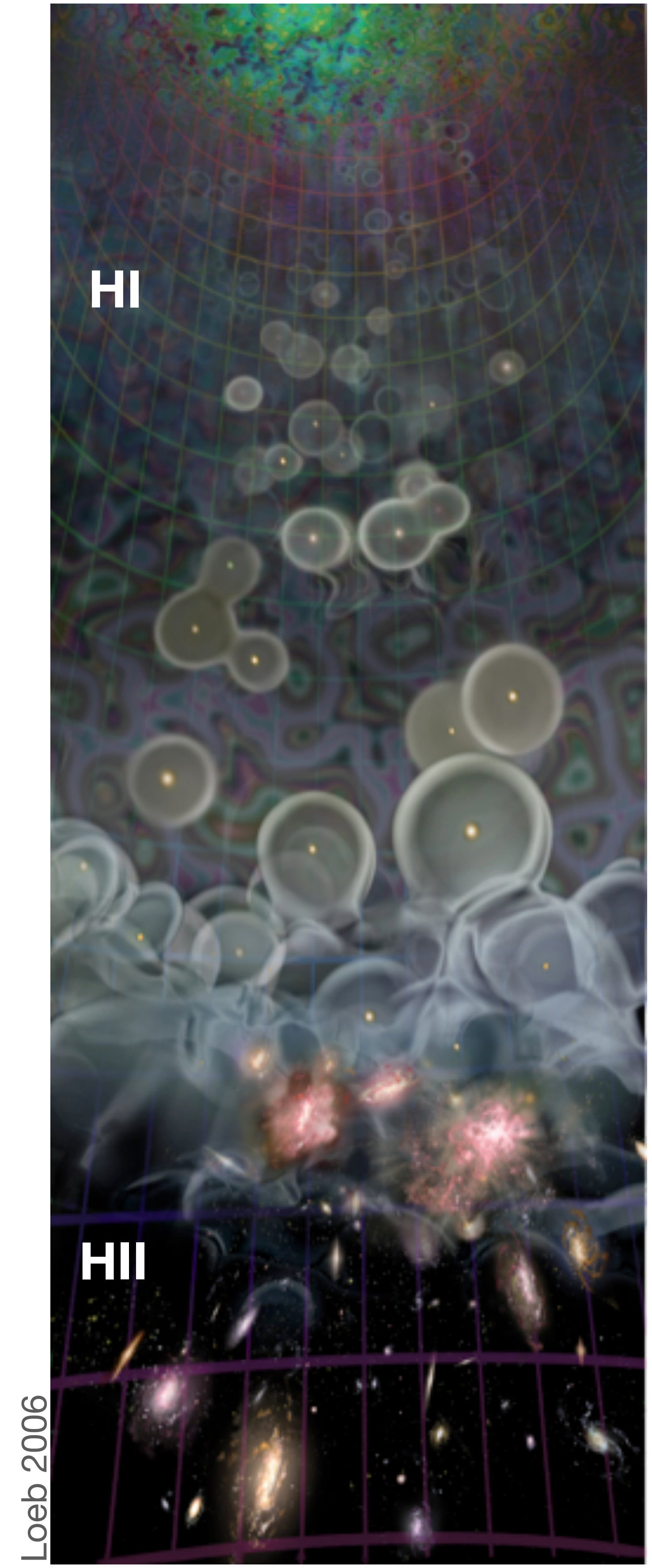
The First 1Gyr

The epoch when the first light was emitted

The epoch when the first metals form

The epoch when the first galaxies form

The epoch when the universe was reionized



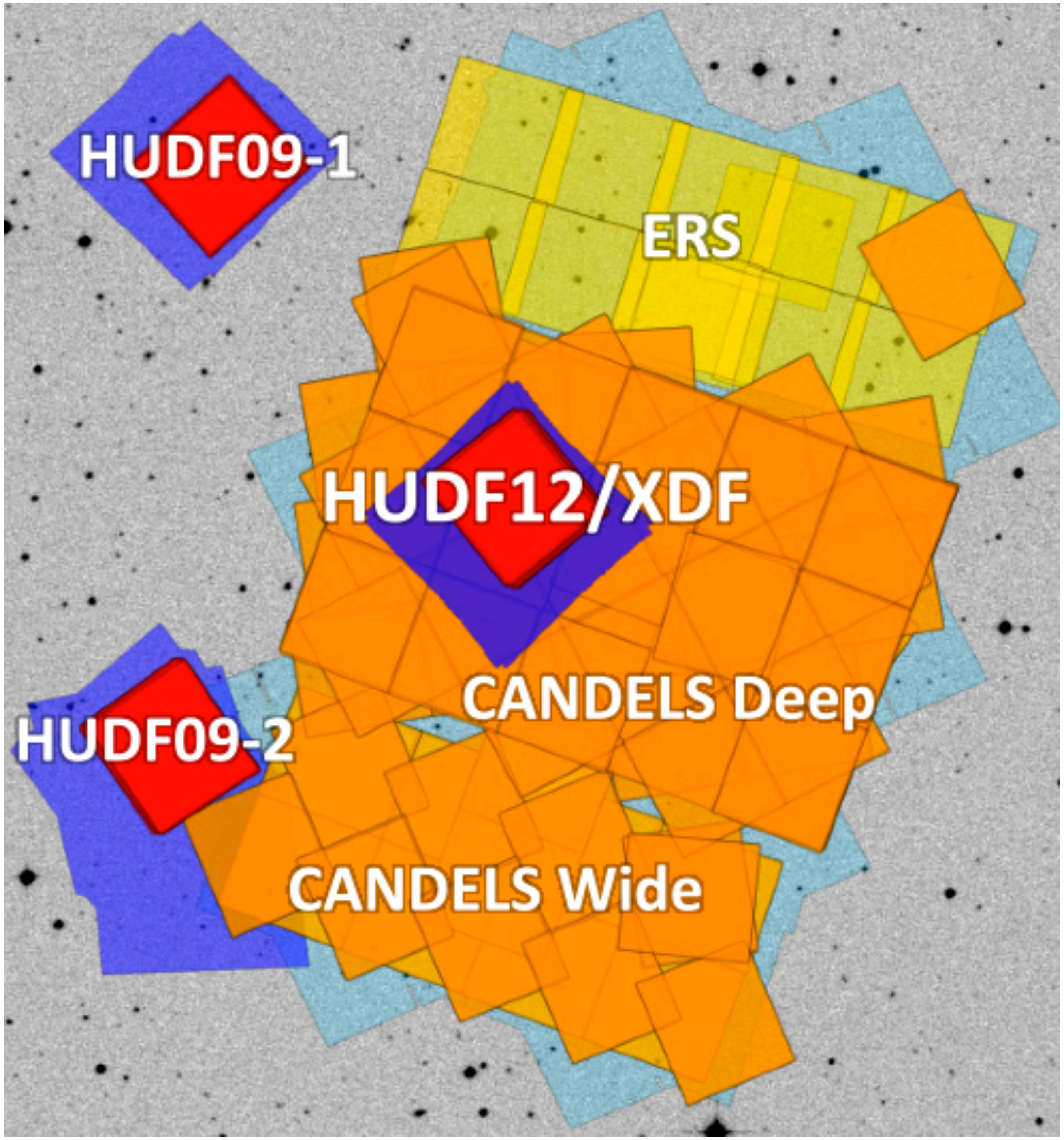
z~1100: CMB
(0.4 Myr)

z~20-30: First Stars
(100-200 Myr)

z~12-6: Reionization
(0.3 - 1 Gyr)

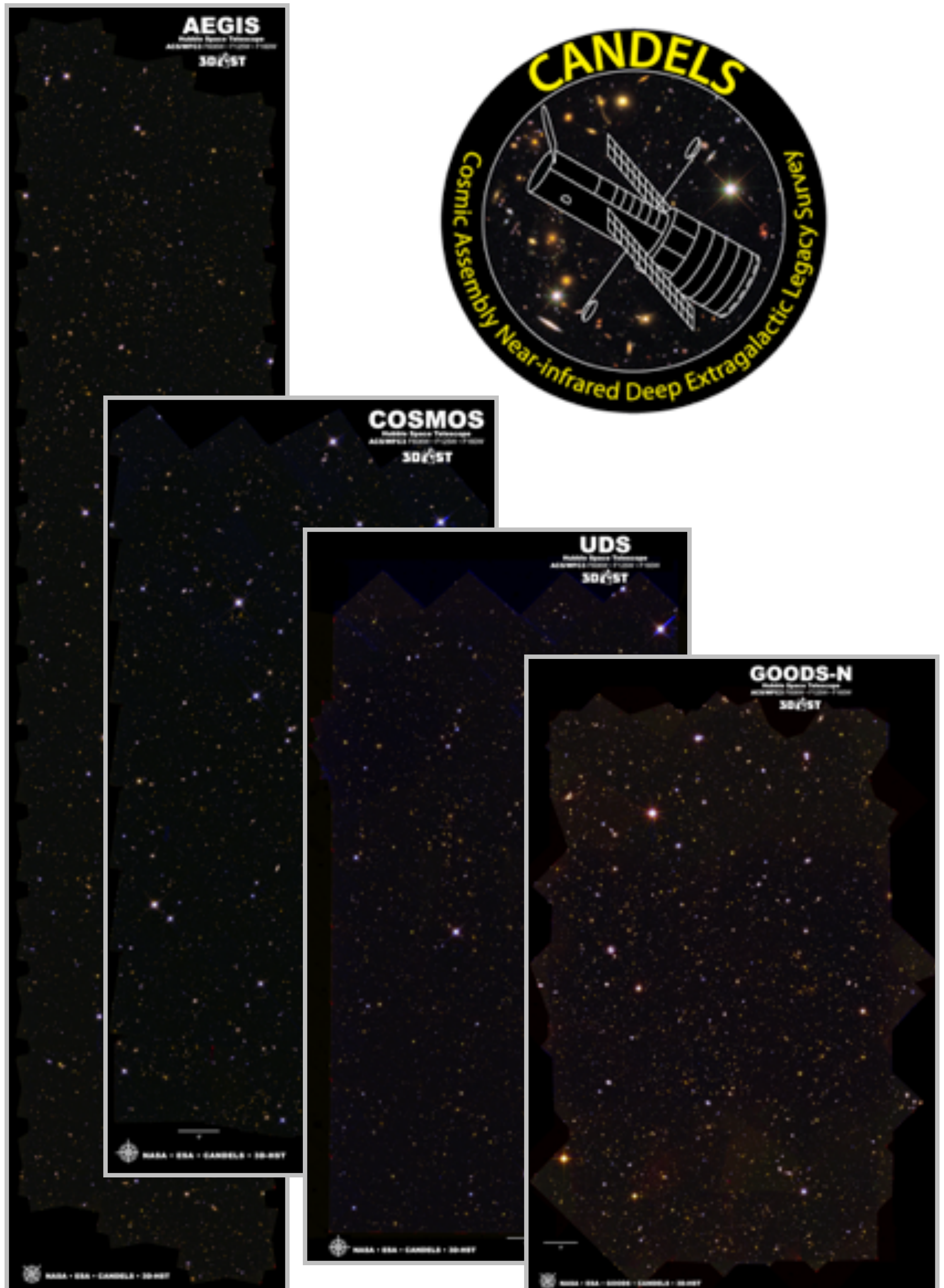
z<6: Build-up of today's galaxies

WFC3/IR Data around GOODS-South



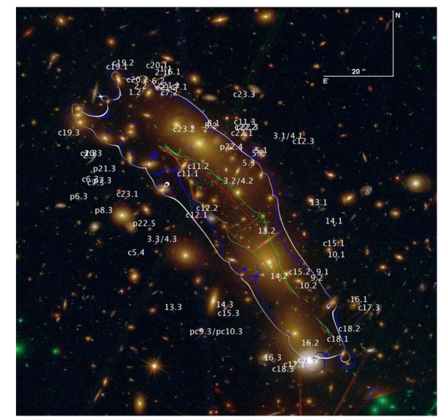
- CDFS provides perfect dataset for z>7 galaxy search
- Large amount of public optical (ACS) and NIR (WFC3) data
  - *HUDF12 & XDF*
  - *UDF05/HUDF09*
  - *ERS*
  - *CANDELS* (Deep & Wide)
- Total of ~160 $arcmin^2$
- Reach to 27.5 - 29.8 AB mag

Multi-Tiered Dataset for High-z Studies



CANDELS
Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey

CLASH

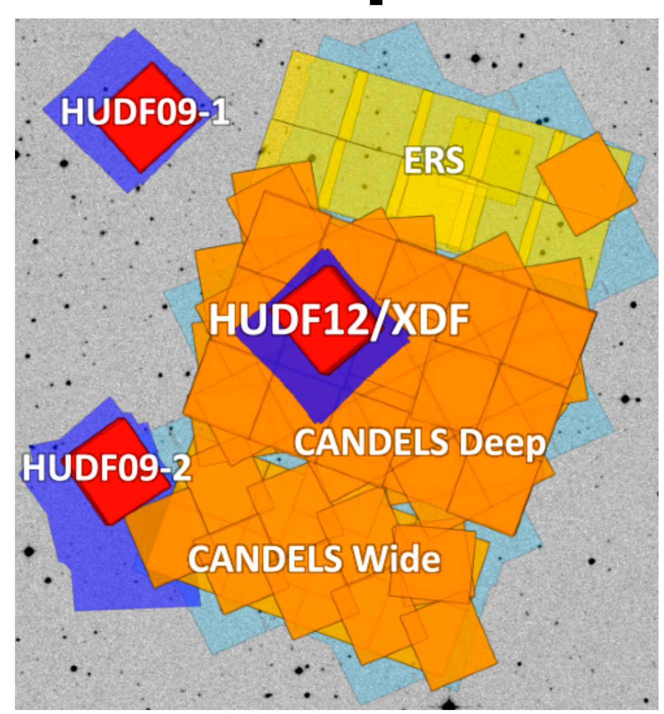


x25

WFC3 BoRG SURVEY

Pure Parallel

Ultra-Deep Fields

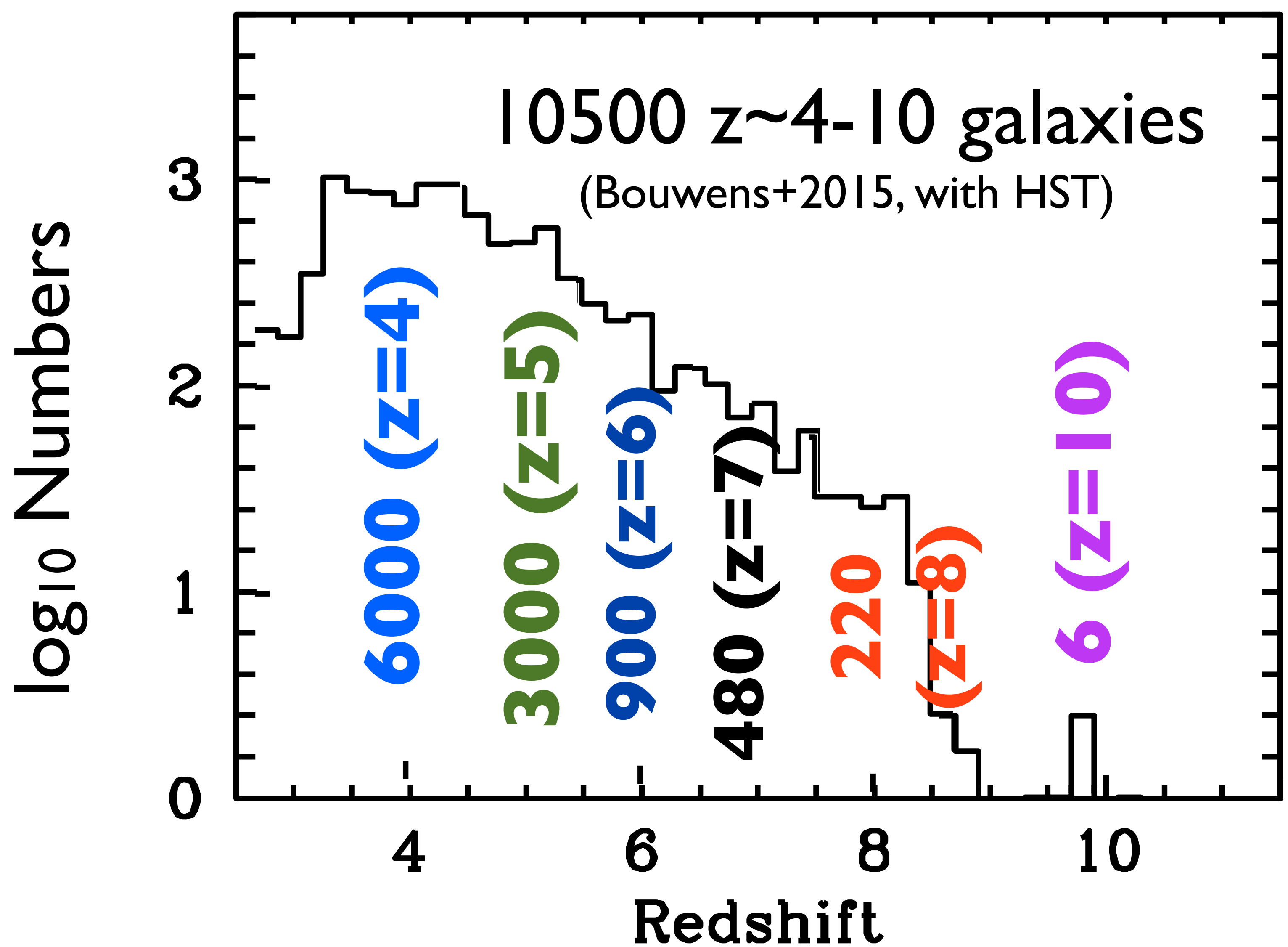


FRONTIER FIELDS

x12

Unprecedented Galaxy Samples at z>=4

(from HST's blank fields only)

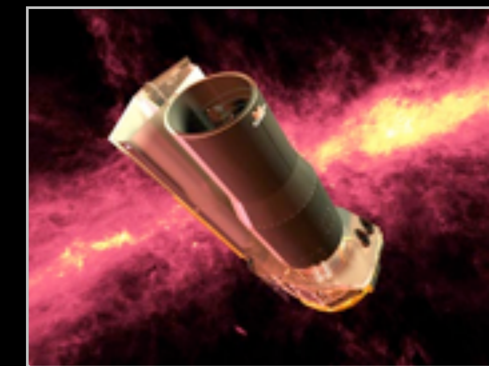


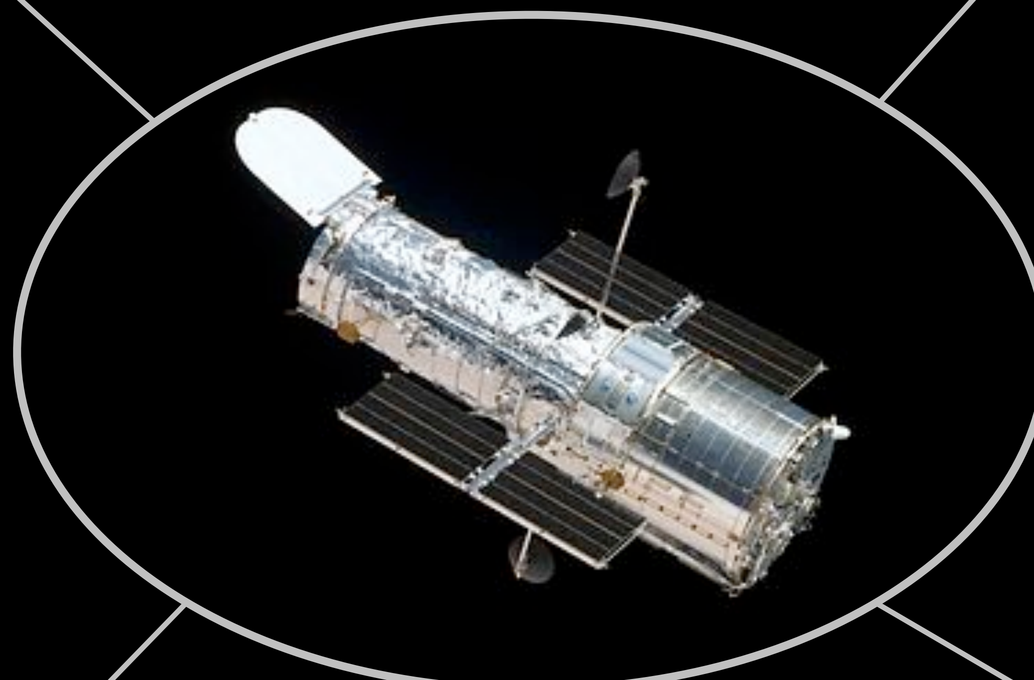
Almost 1000 galaxies in the epoch of reionization at z>6

Current frontier: z~9-10

ISM Properties
Dust Reemission

Rest-frame Optical
Stellar Masses



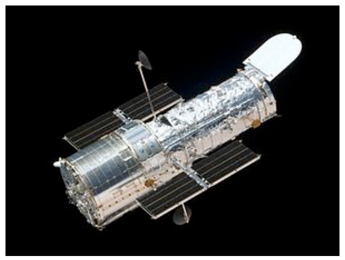


Source identification
UV Light / SFRs

Spectroscopic Confirmation

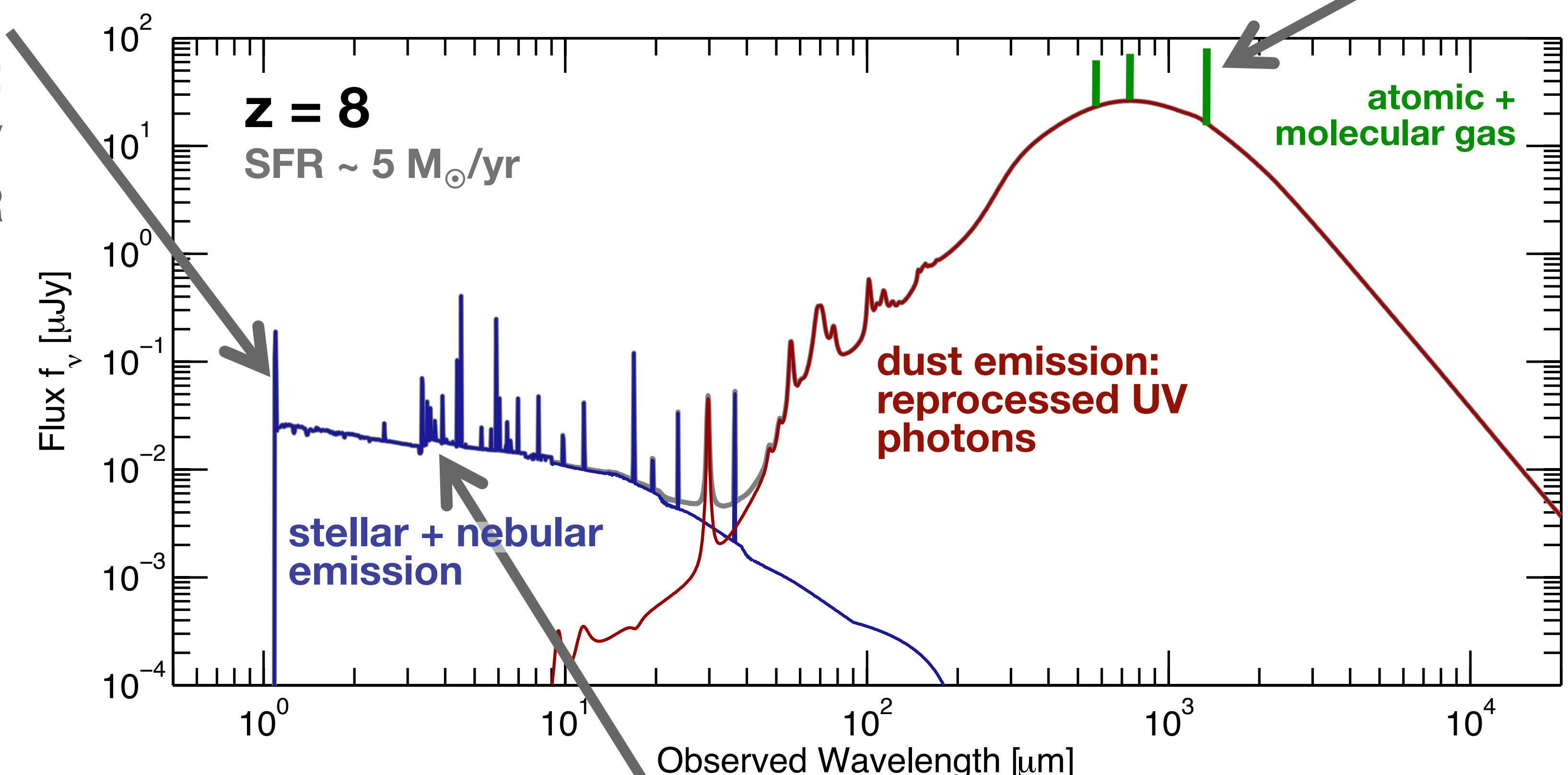
AGN?

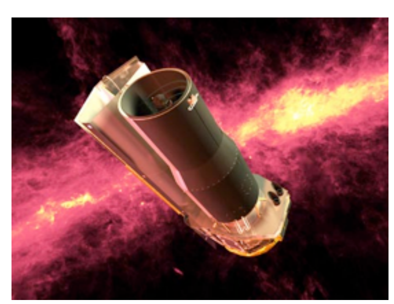
Our Multi-Wavelength Census of Early Galaxies



HST:
rest-frame UV
un-obscured SFR

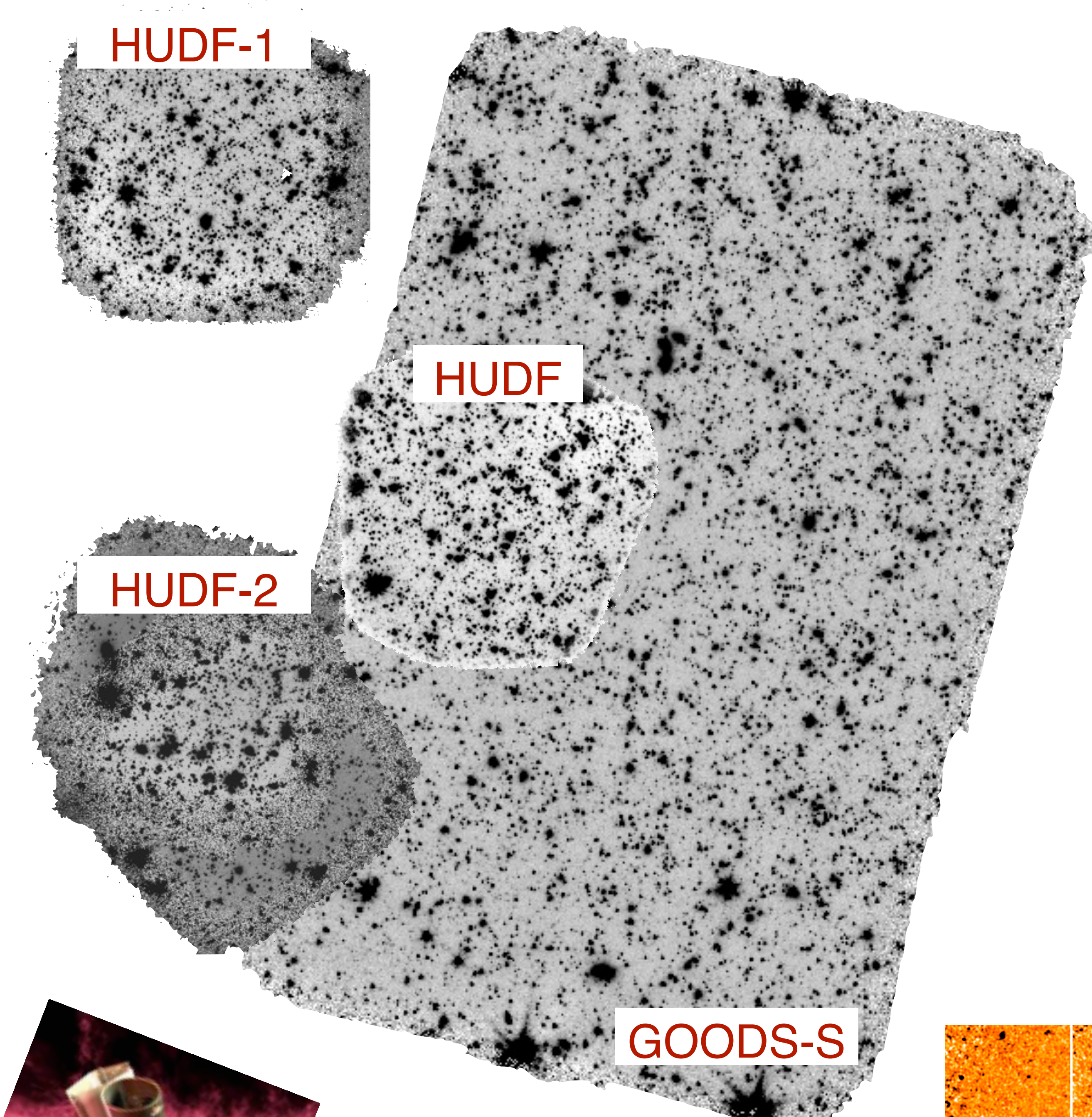
ALMA/PdBI:
cold gas
dust re-emission
closes energy balance



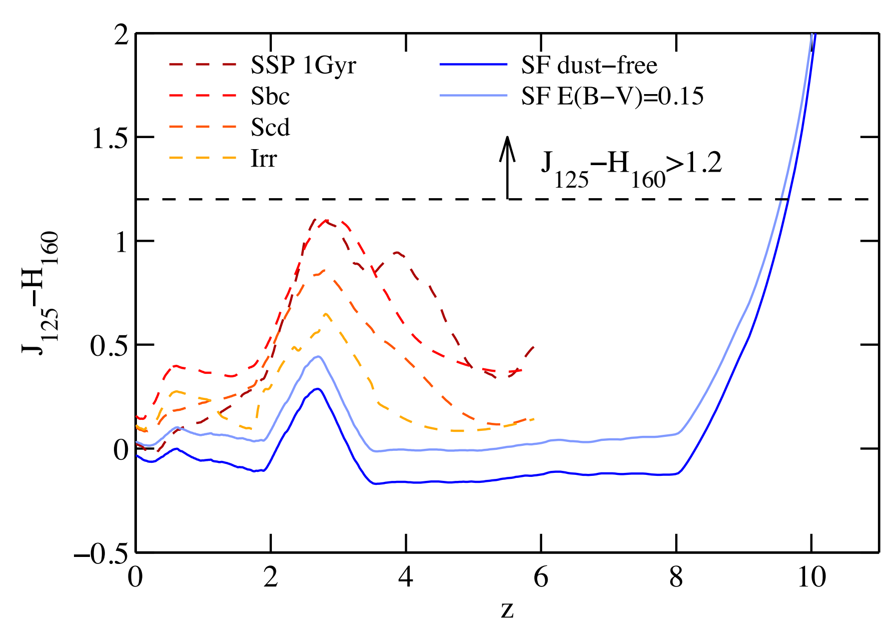


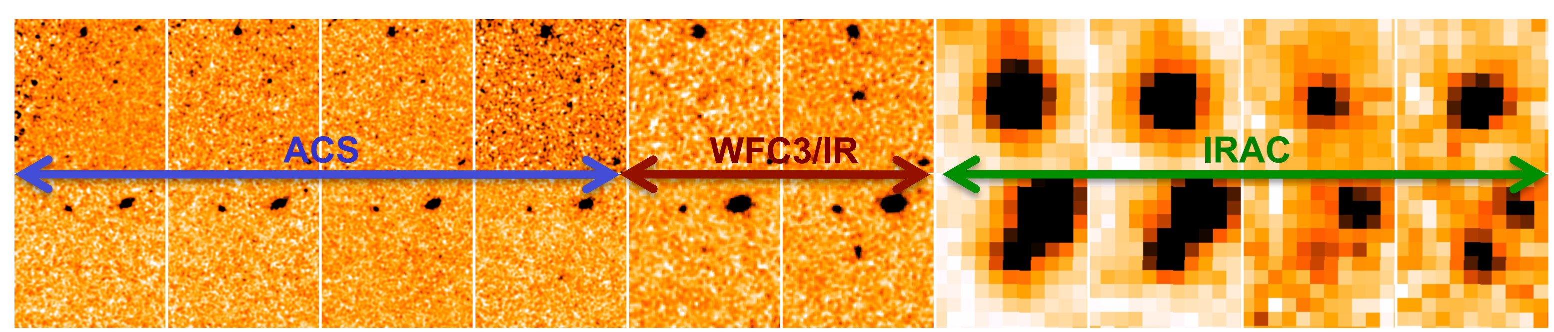
Spitzer:
rest-frame optical imaging
stellar masses
(rest-frame optical emission lines!)

Matched Ultra-deep Rest-frame Optical Data



- Deep Spitzer/IRAC complements prime HST datasets (S-CANDELS+SEDS)
- Deepest data available over HUDF09/ GOODS-S (GREATS program ongoing!)
- IRAC crucial for
  - stellar mass estimates
  - excluding contaminants

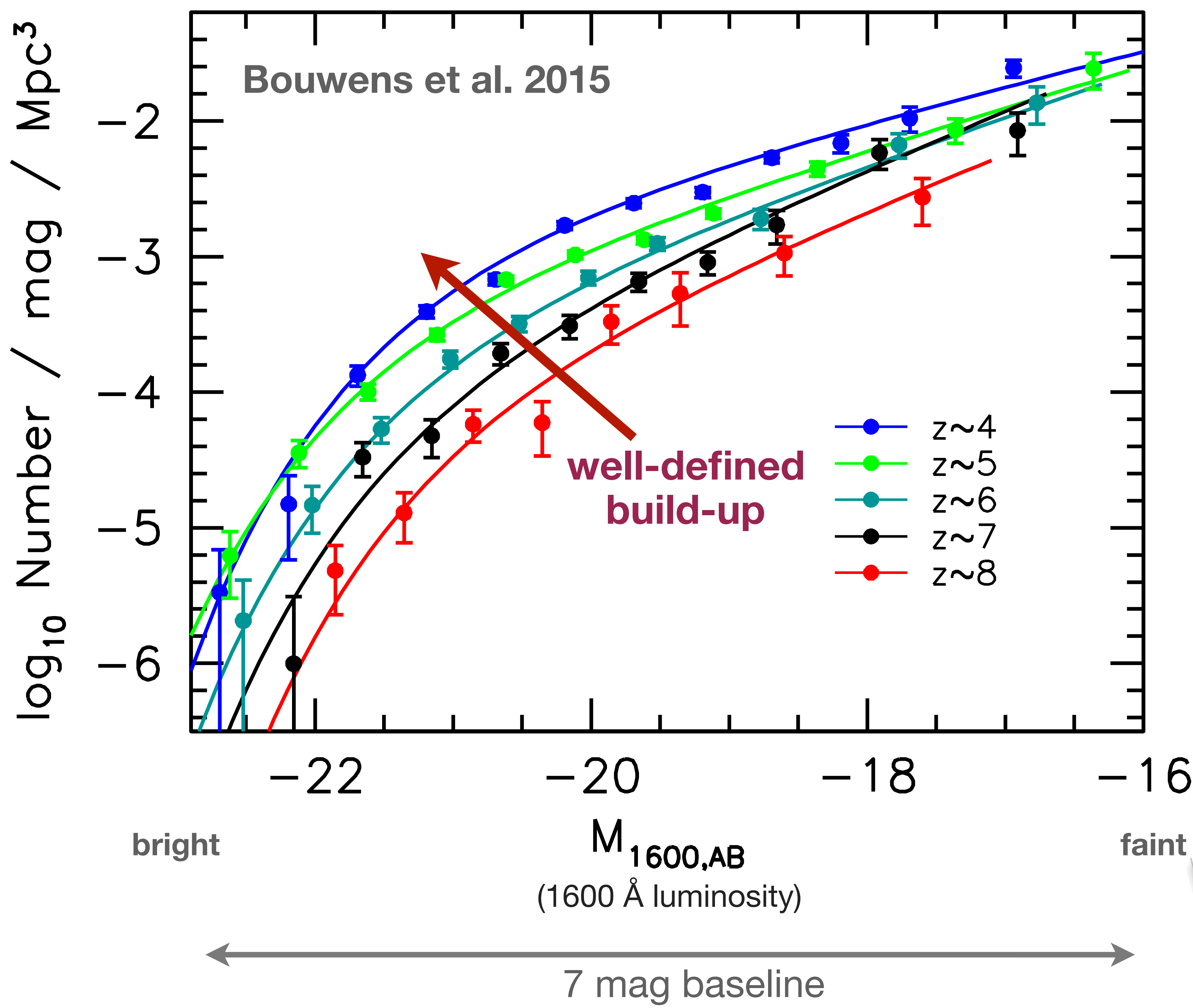




What did we learn about these early galaxy populations?

➔ Science Highlights

The Evolution of the UV Luminosity Function to z~8

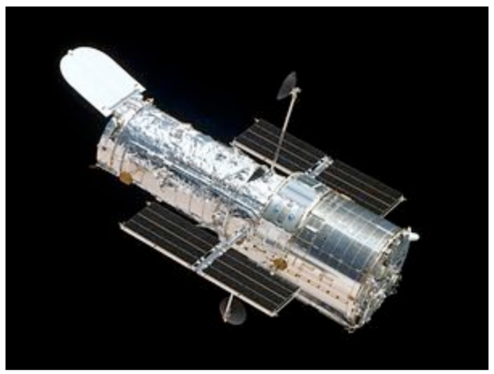


See Steve Finkelstein's talk

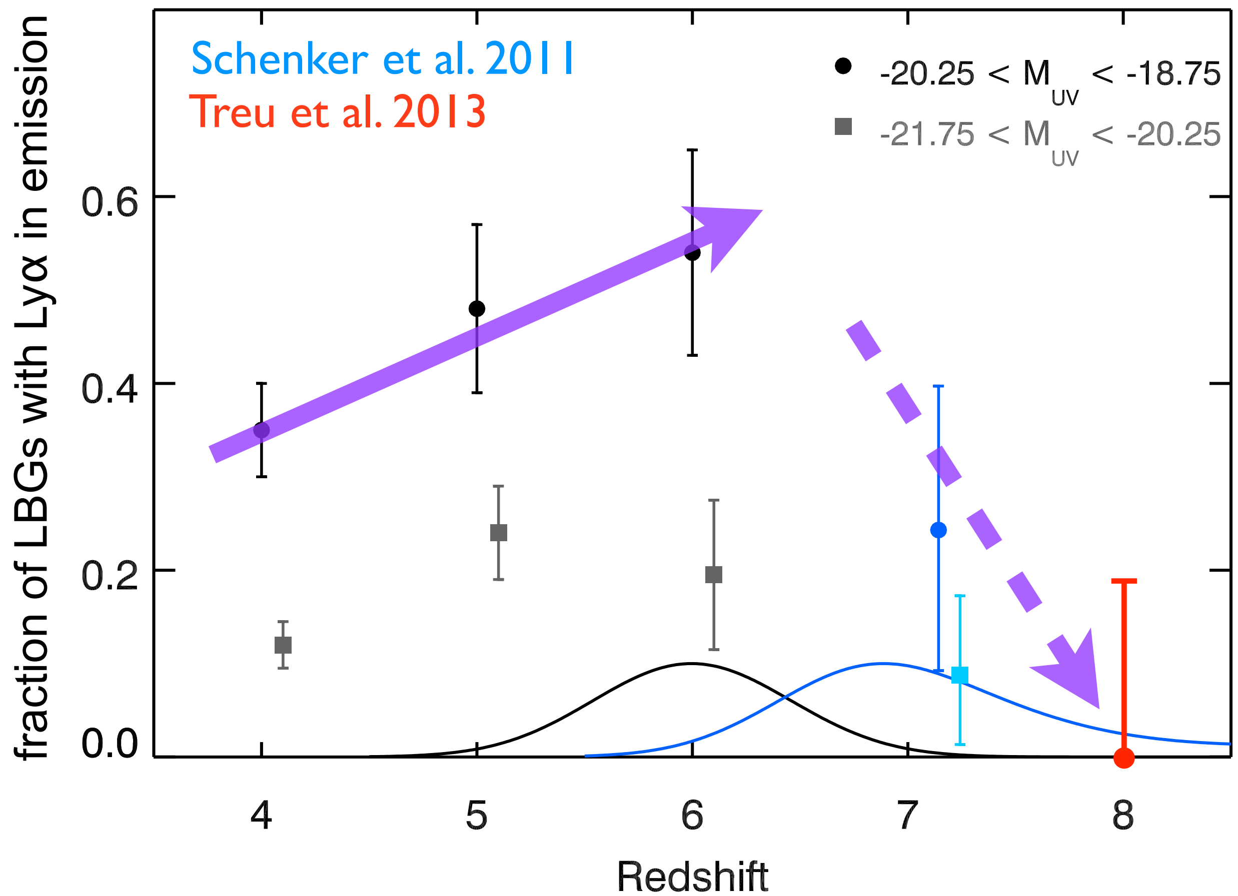
See also: e.g. Oesch+10a/12, Bouwens+10a,11,12; Bunker+10, Finkelstein+10/14, Wilkins+10/11, McLure+10/13, Yan+12, Bradley+12, ...

Lyman Alpha in the Reionization Epoch

Spectra show: LBG selection very reliable at z~4-6 (<15% contamination)



+

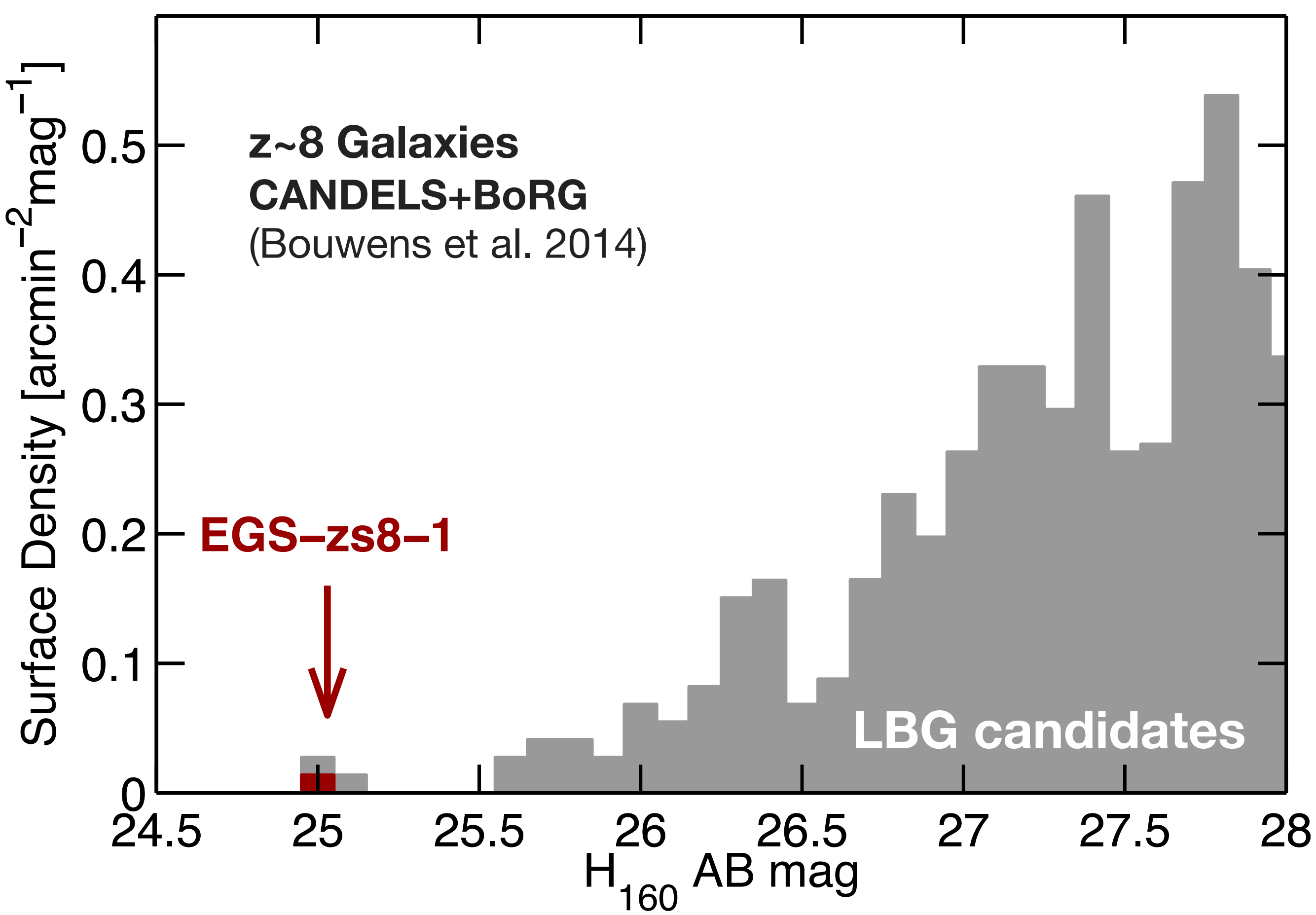


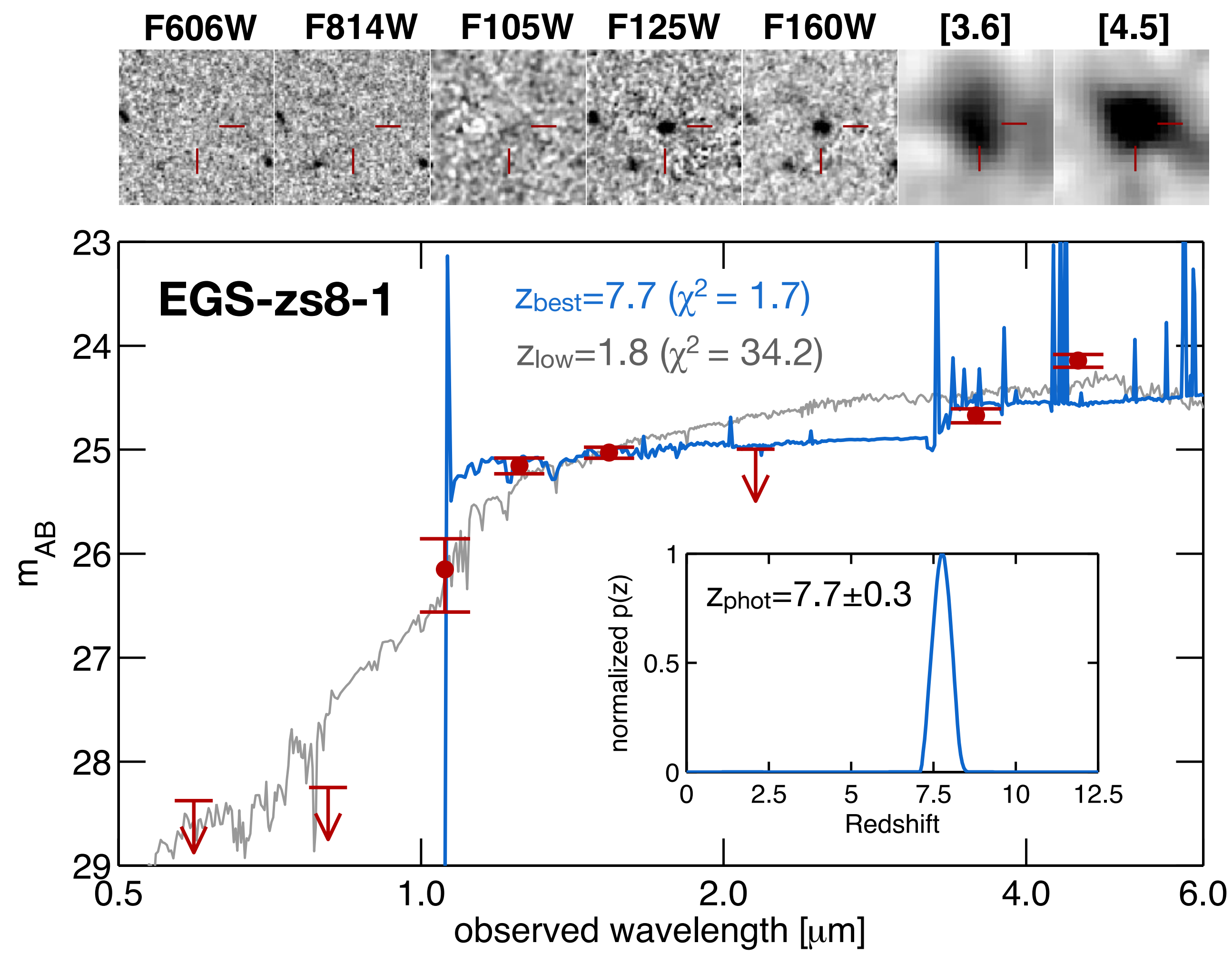
Spectroscopic confirmation of sources in the reionization epoch has proven very difficult, even with new efficient NIR spectrographs.

Fraction of Lyα line emitters drops across z=6.5 to z=7:
imprint of cosmic reionization?

Spectroscopic Follow-up of Bright Galaxies: z~8

Search over CANDELS-WIDE for z~8 galaxy candidates revealed three remarkably bright sources with H = 25 mag



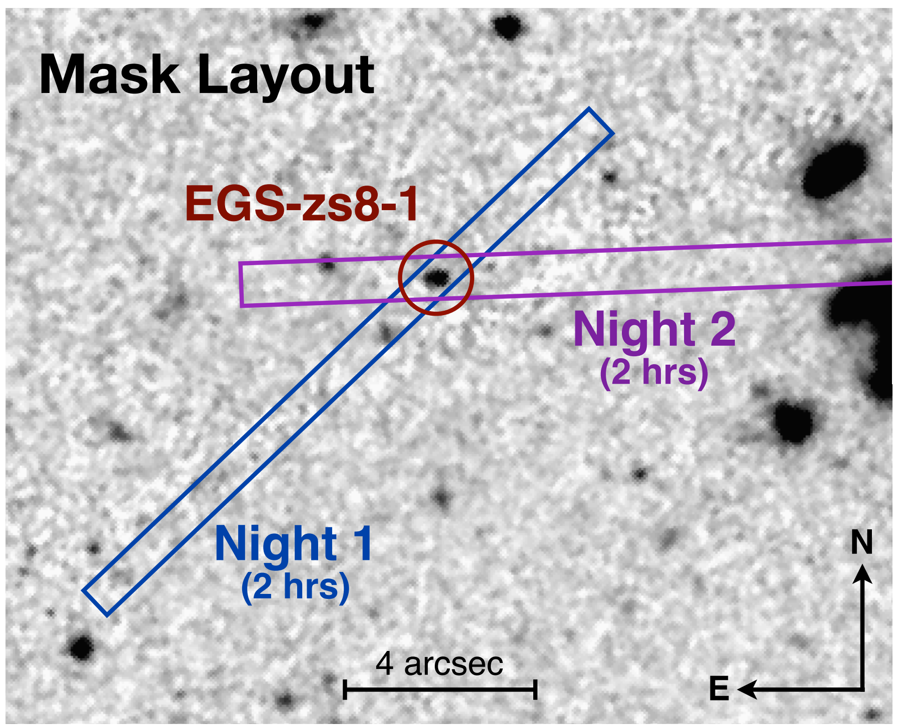


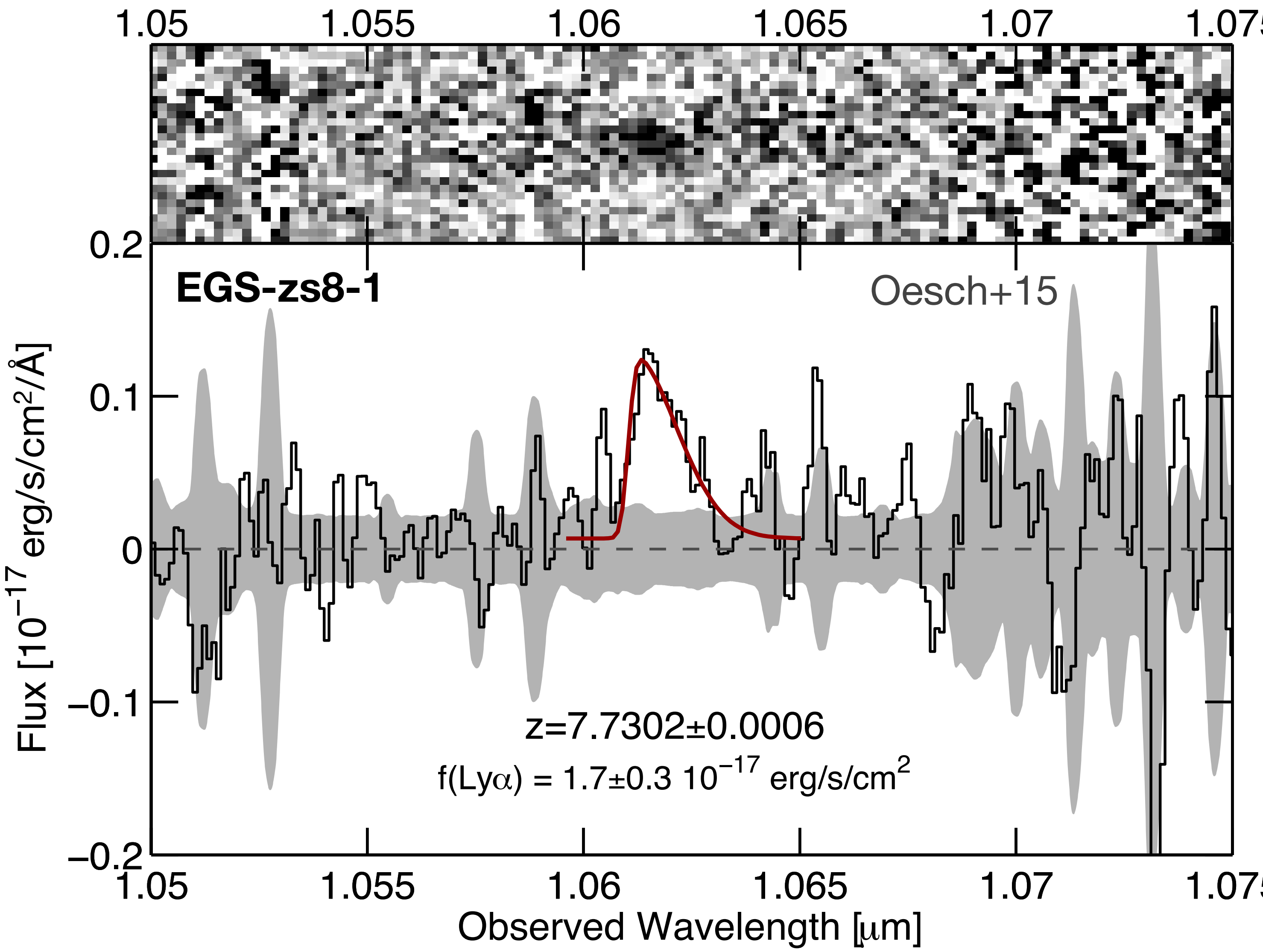
All of these show extremely red IRAC colors, indicating strong rest-frame optical emission lines dominating the IRAC flux at 4.5 μm

The (Until Recently) Most Distant Confirmed Source

MOSFIRE

Multi-Object Spectrometer for Infra-Red Exploration



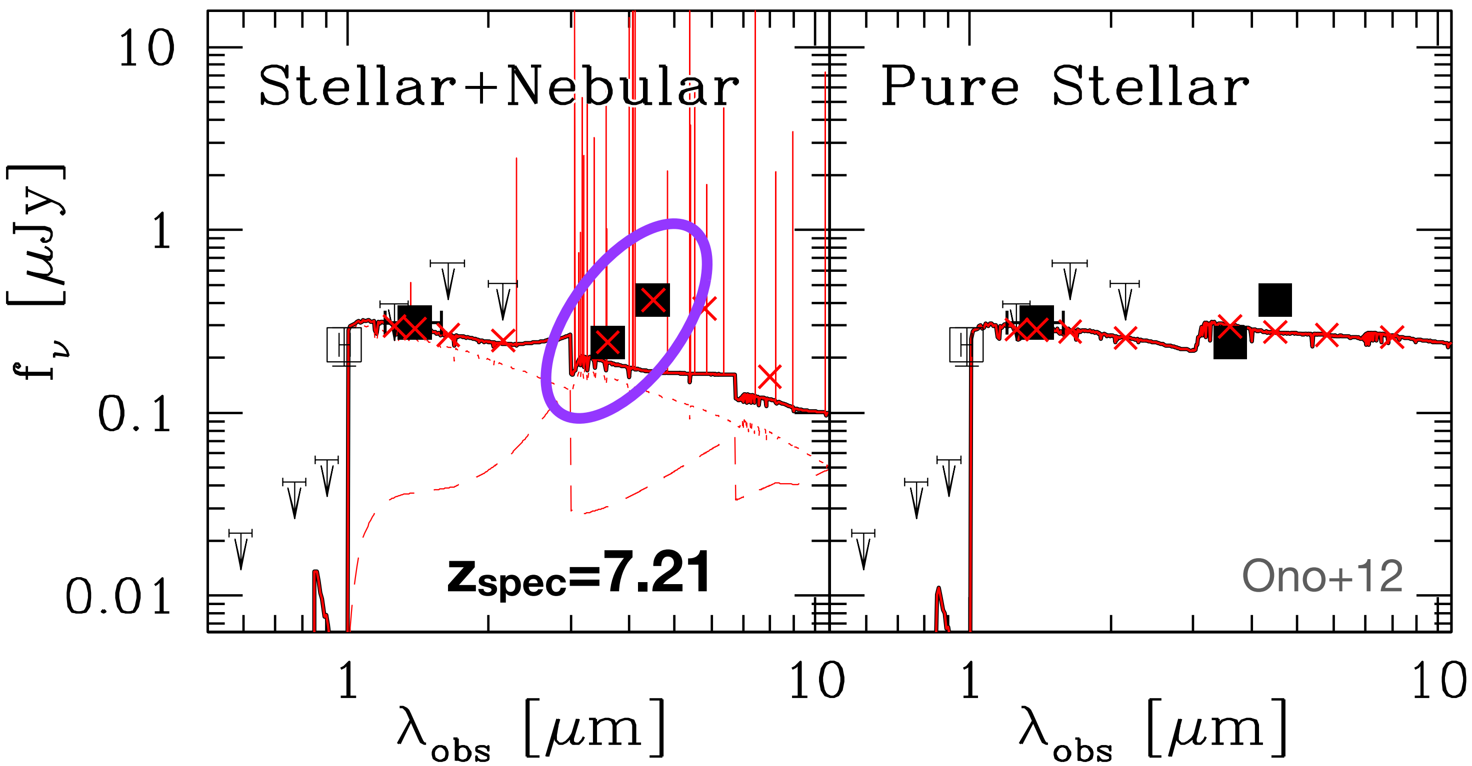


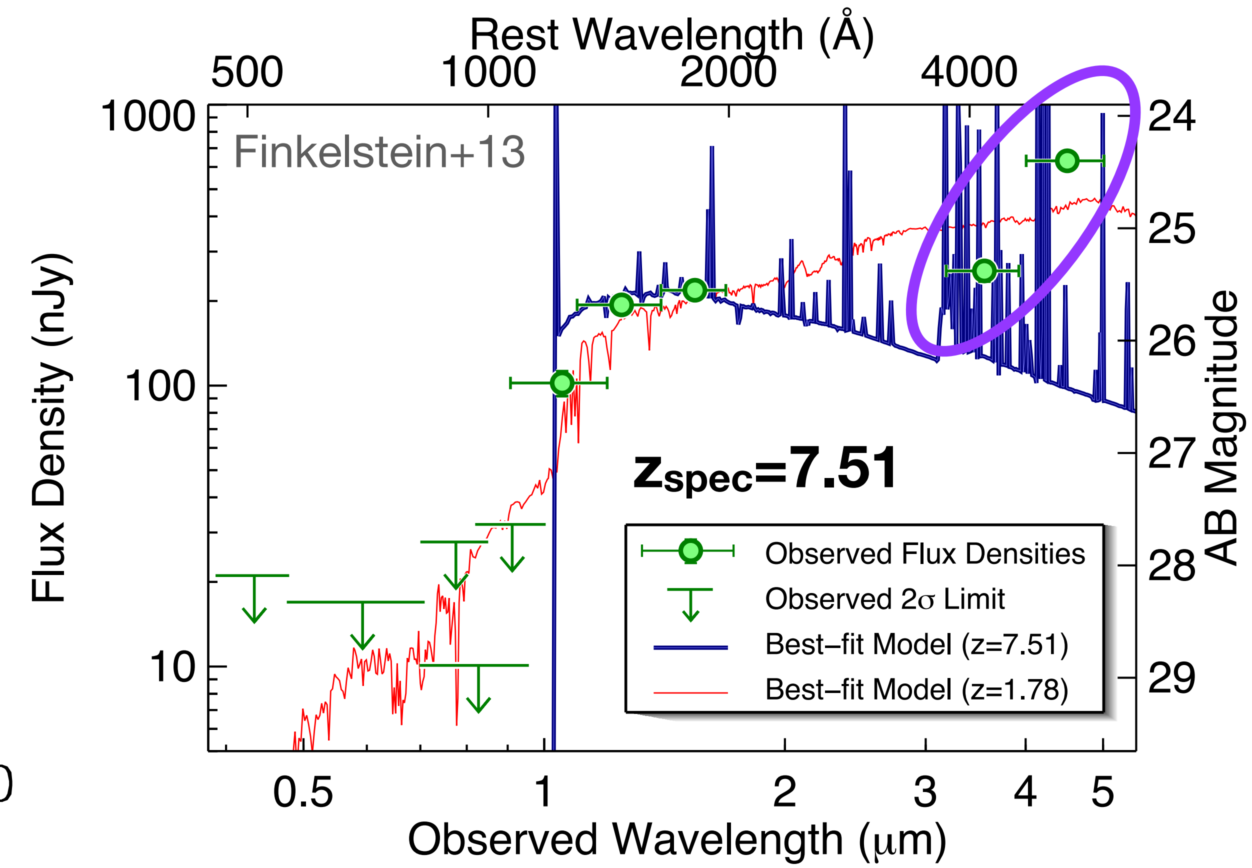
A 2x2hr MOSFIRE exposure in two masks revealed a significant emission line in both. Combined line shows asymmetric profile as expected for Lyα at high redshift.

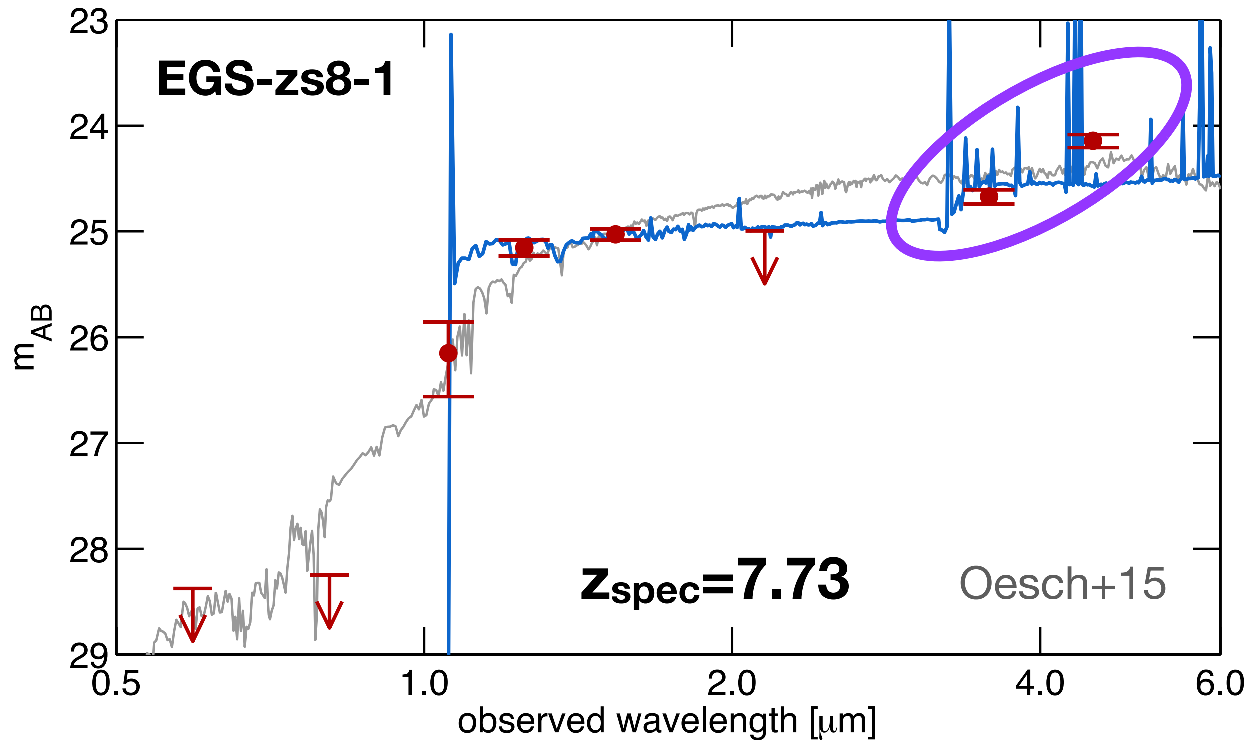
A handful of confirmed redshifts exist now at z>7.0

(e.g. Ono et al. 2012, Finkelstein et al. 2013, Oesch et al. 2015, Watson et al. 2015)

The SEDs of Redshift Record Holders





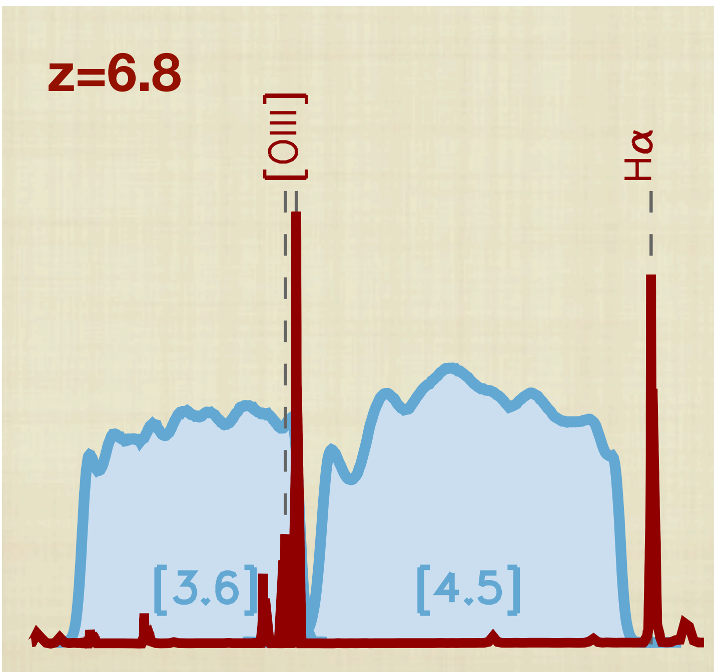


All sources with spectroscopic redshift at z>7.2 show extremely red IRAC colors.

Galaxies at very high redshift show extremely strong rest-frame optical emission lines

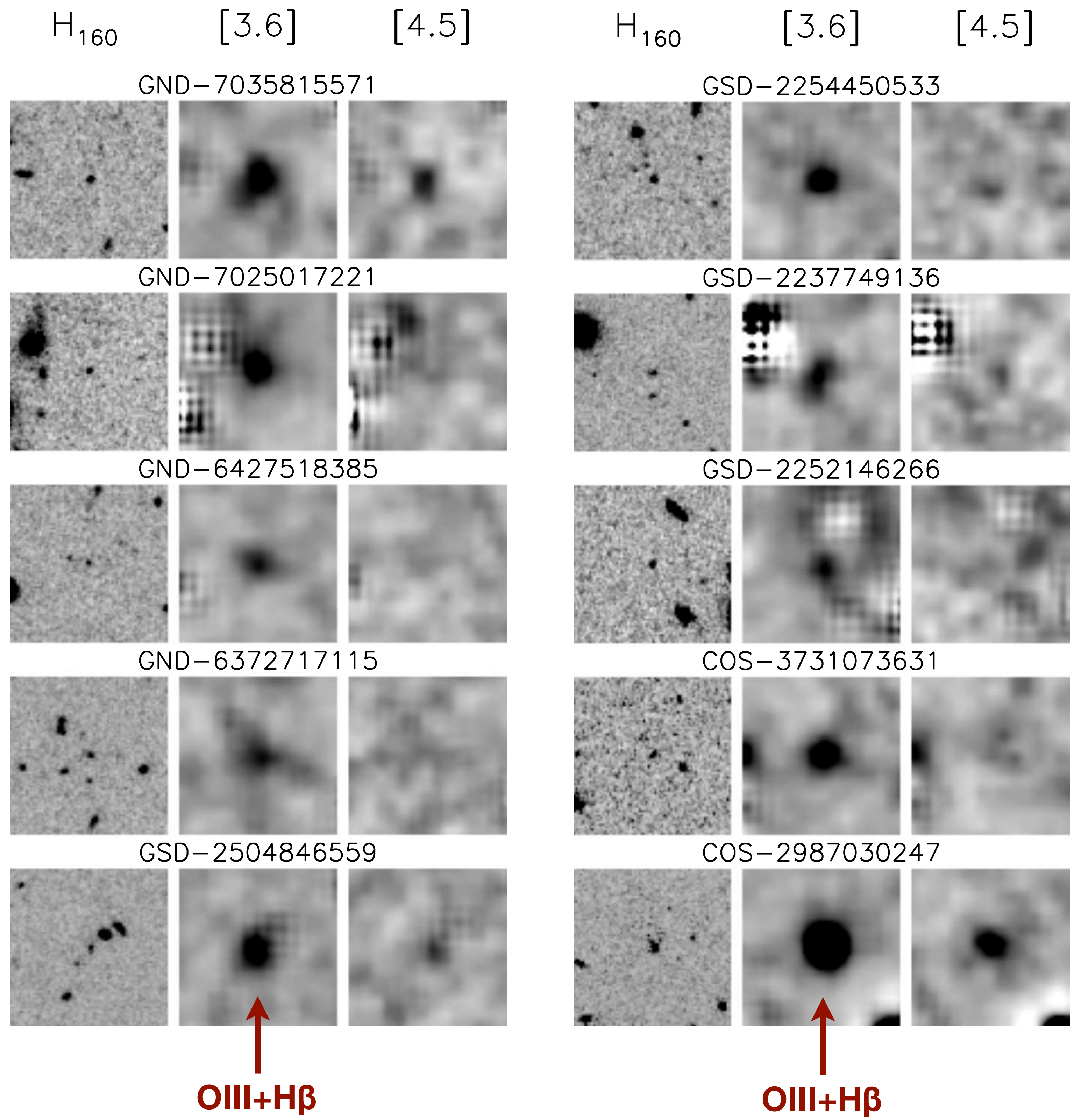
Extremely Strong Lines are Ubiquitous at z>6

Smit et al. 2014, 2015



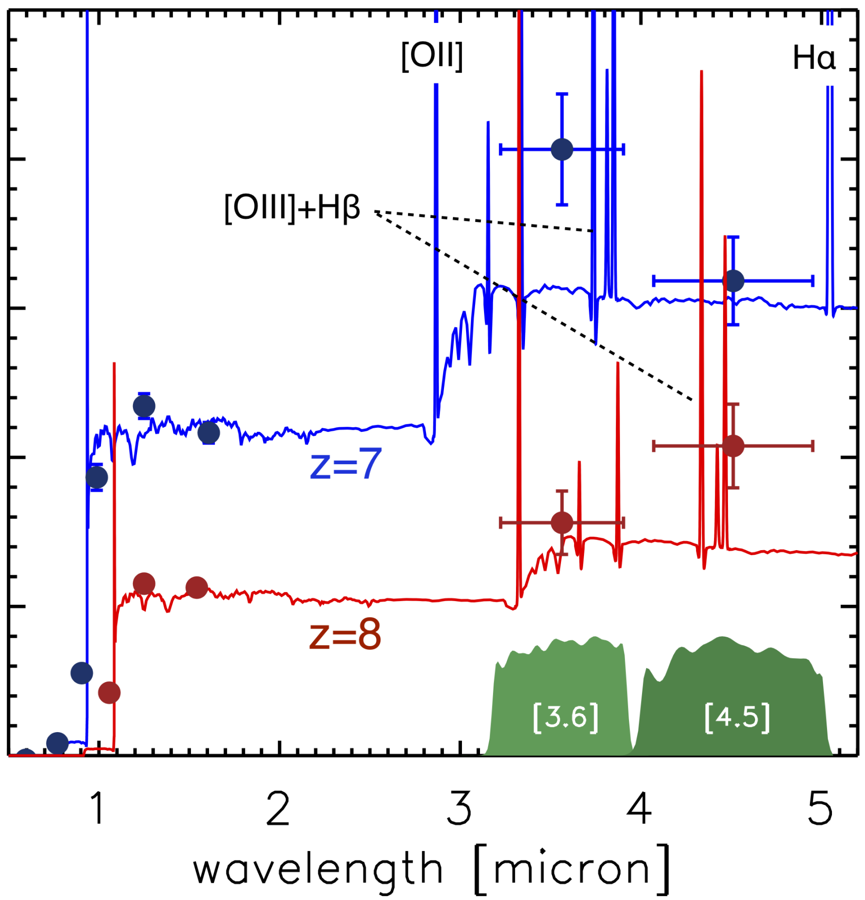
At z~6.8 Spitzer/IRAC [3.6] provides a clean probe of OIII+Hβ lines.

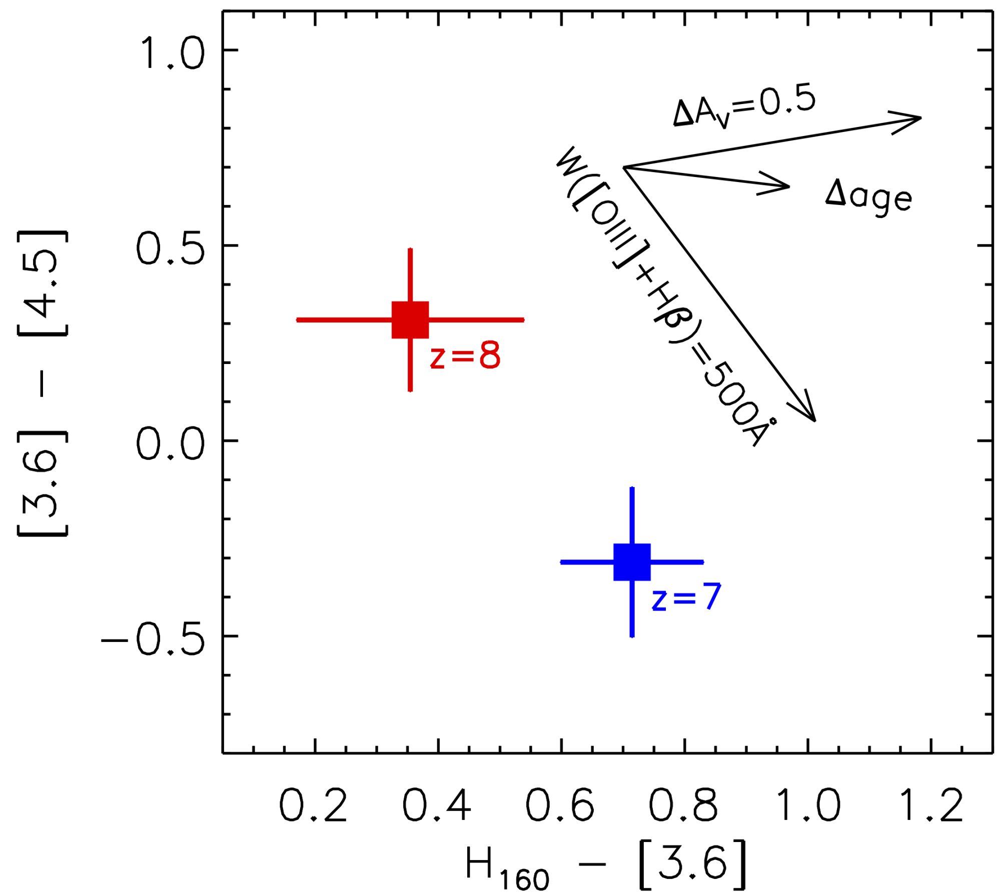
Extremely strong rest-frame EWs reaching over 1000 Å are common at these redshifts!



Extreme Rest-Frame Optical Emission Lines

Labbe, Oesch et al. 2013





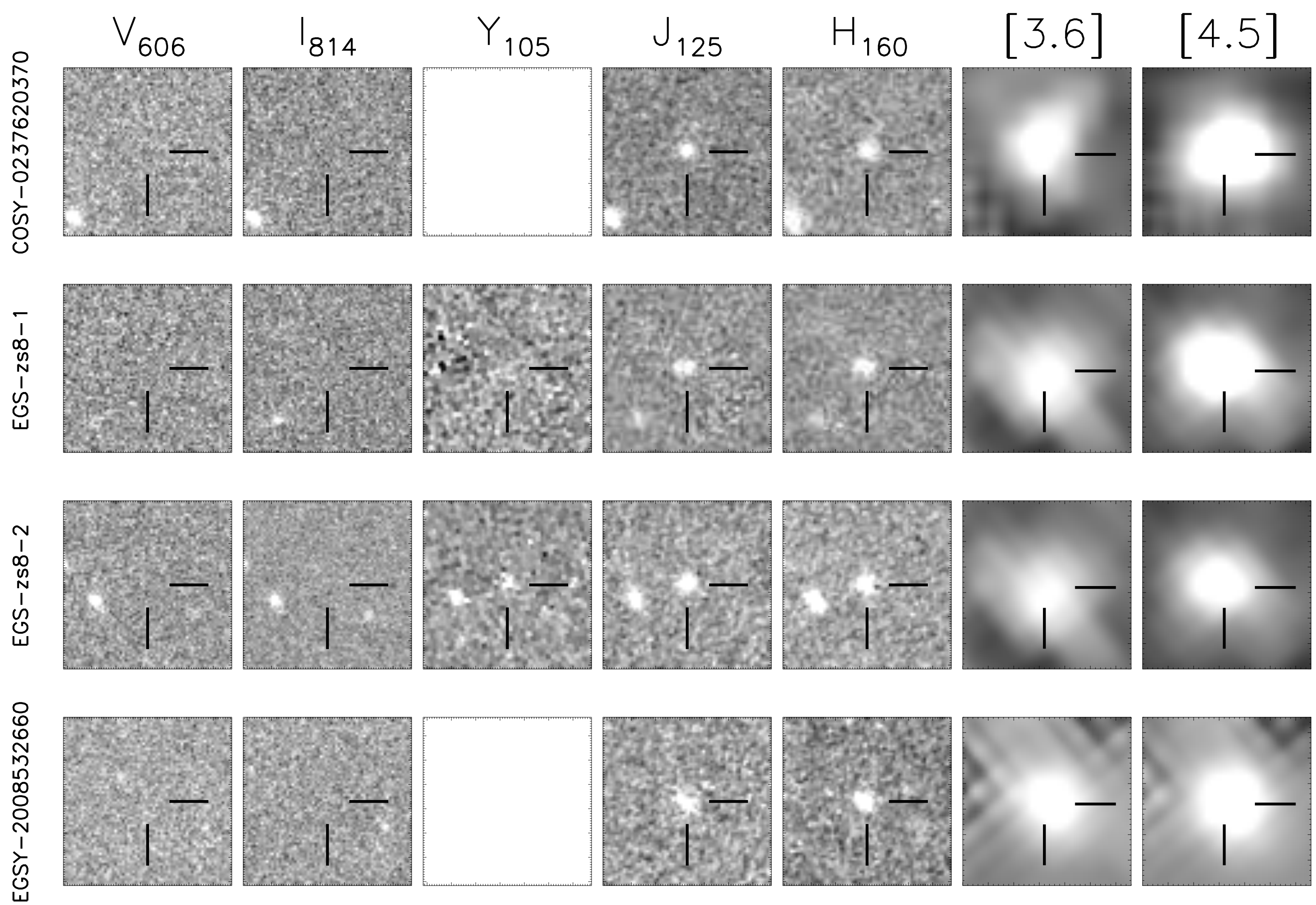
Spitzer/IRAC revealed: z~7-8 galaxies have extreme OIII+Hβ line emission

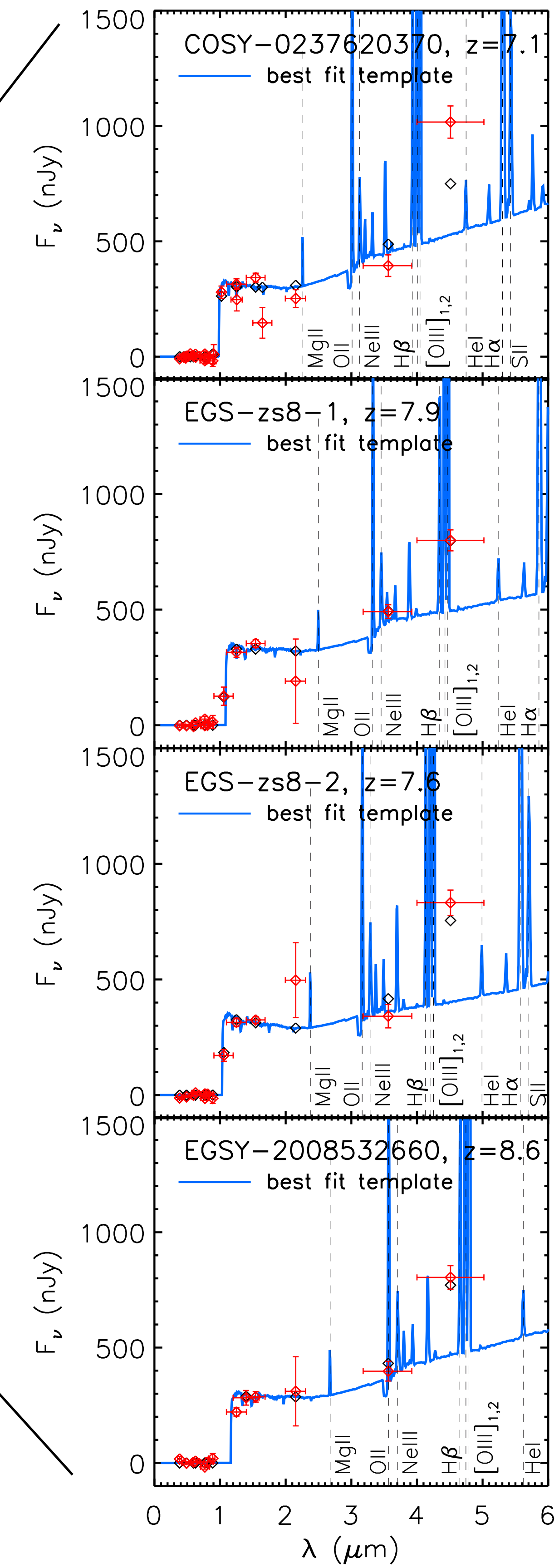
Rest-frame equivalent widths on **average** are 500 Å!

(<0.1% of local galaxies show such strong lines)

Select z>7 Sources with IRAC Excess

Roberts-Borsani+15

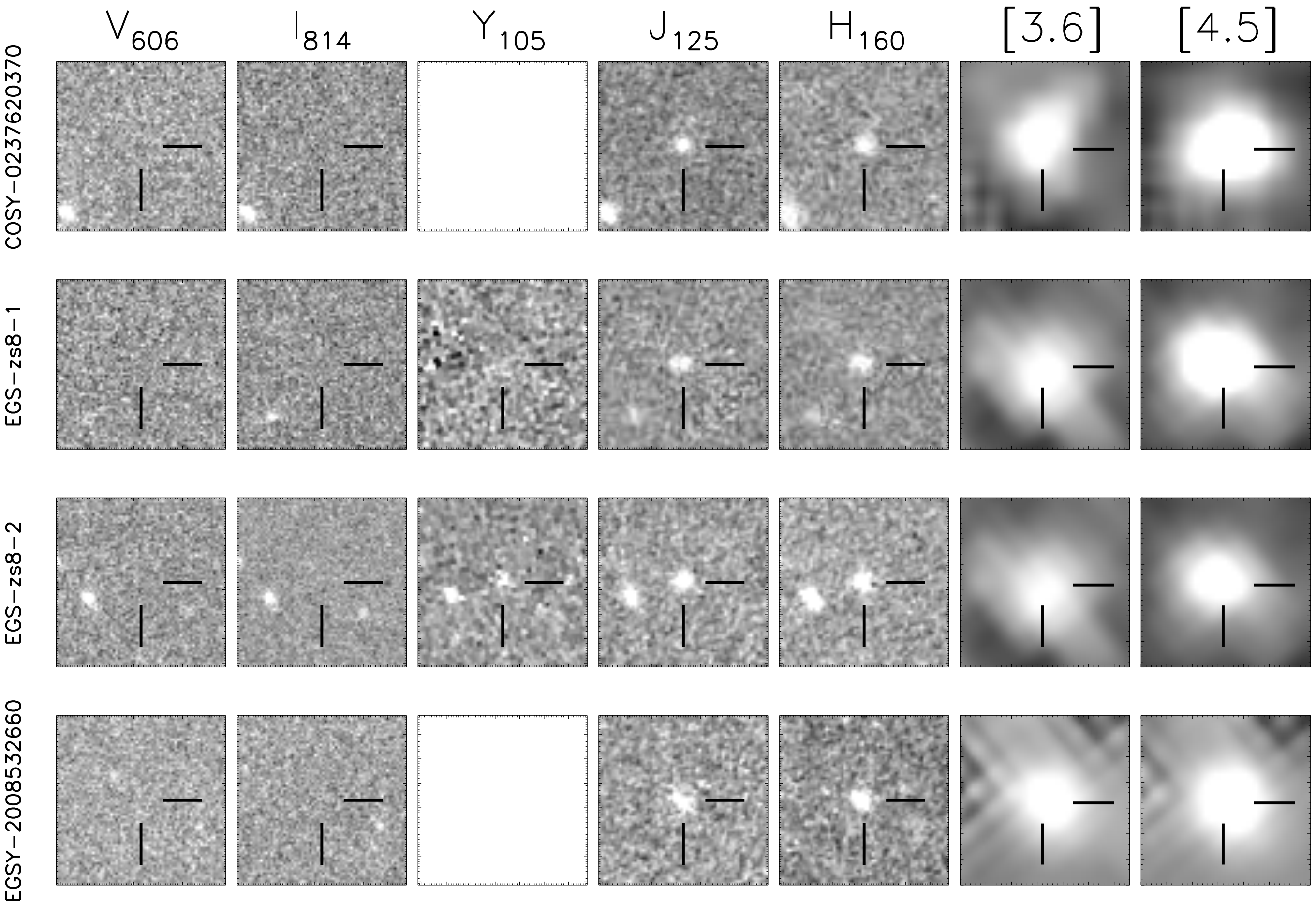




Can use IRAC [4.5] excess as prior to identify high-confidence, very bright z>7 galaxy candidates

z>7 Sources with IRAC Excess

Roberts-Borsani+15

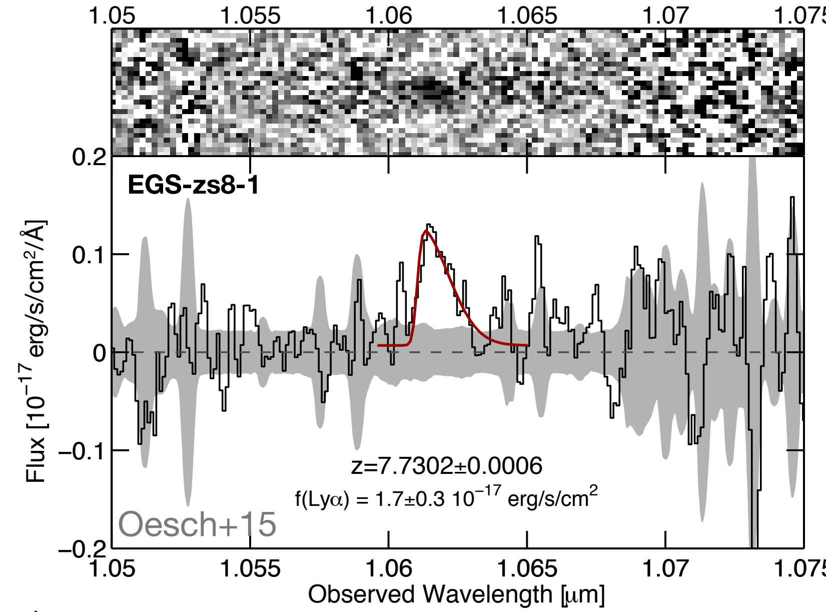


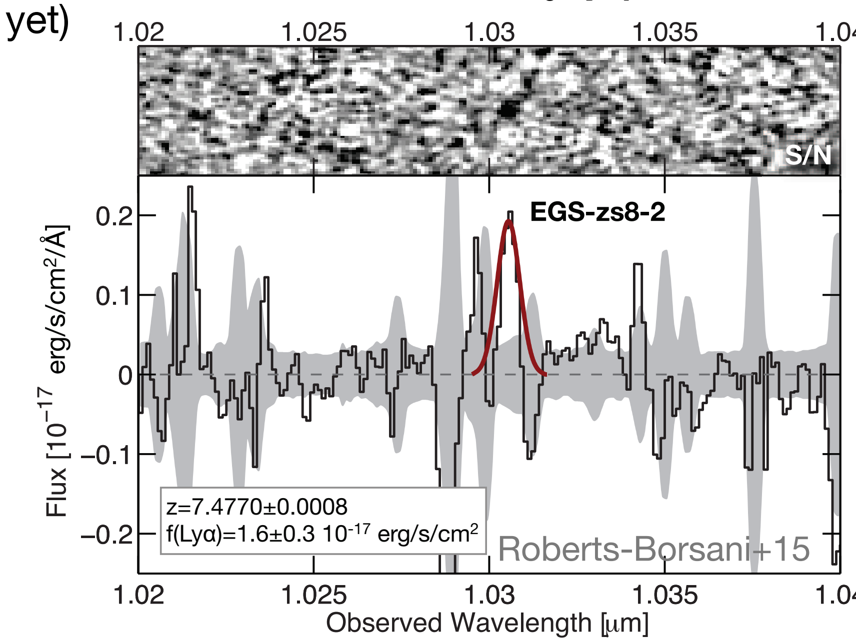
? (not observed yet)

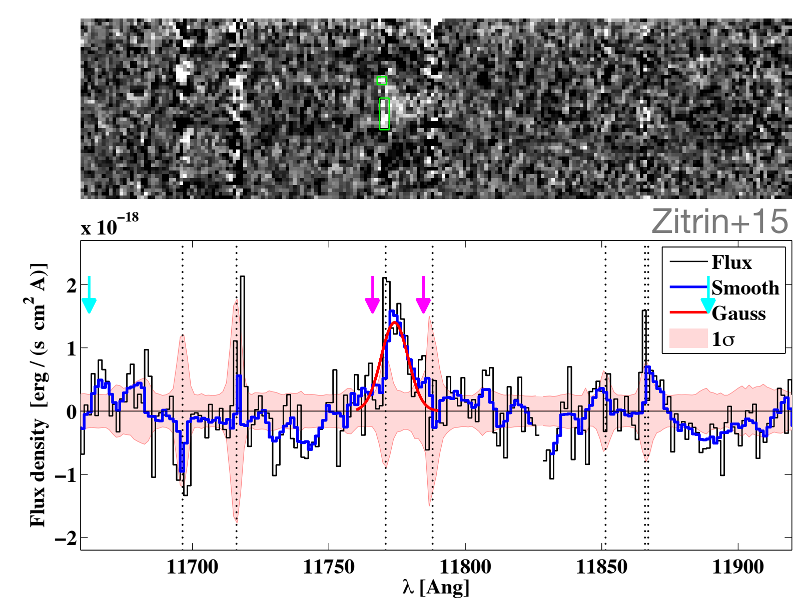
✔ z_{spec}=7.73

✔ z_{spec}=7.48

✔ z_{spec}=8.68



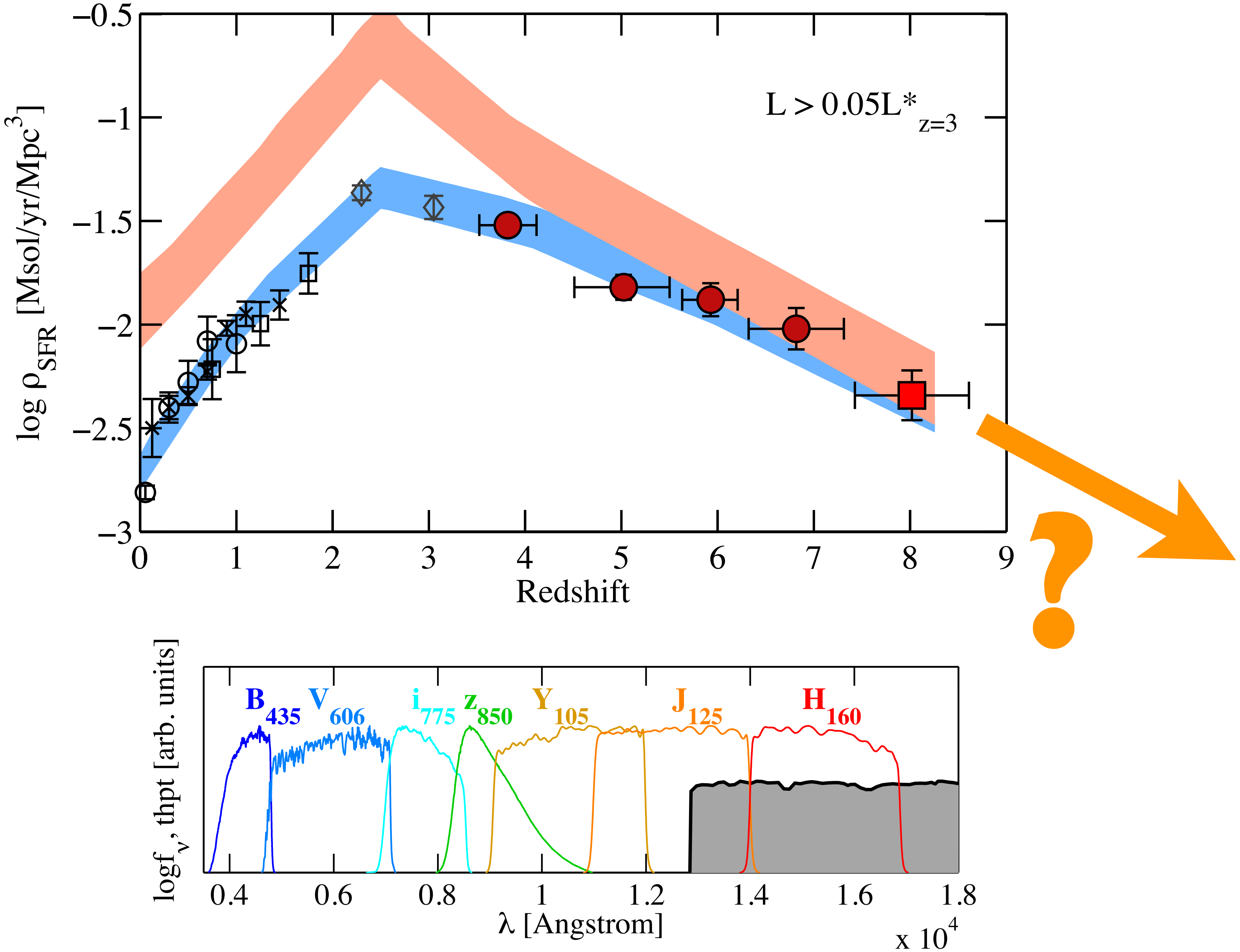




So far, this selection method resulted in 100% success rate, and includes the two most distant confirmed redshifts.

Probing the Frontier of Galaxies

HST can detect galaxies out to z~10-12



Sample of Bright z~10 Candidates in XDF+GOODS

XDF

H=29.8

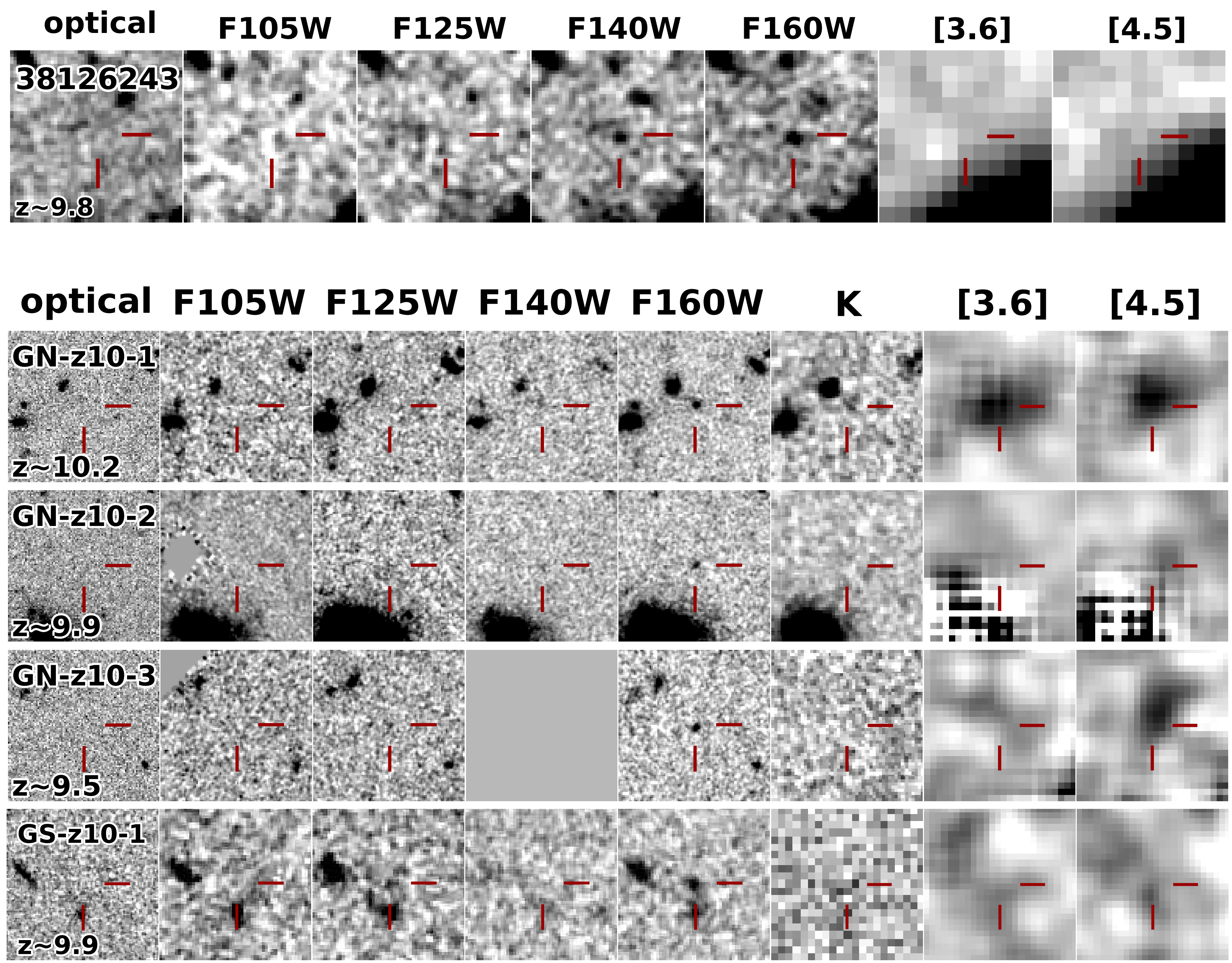
GOODS

H=26.0

H=26.8

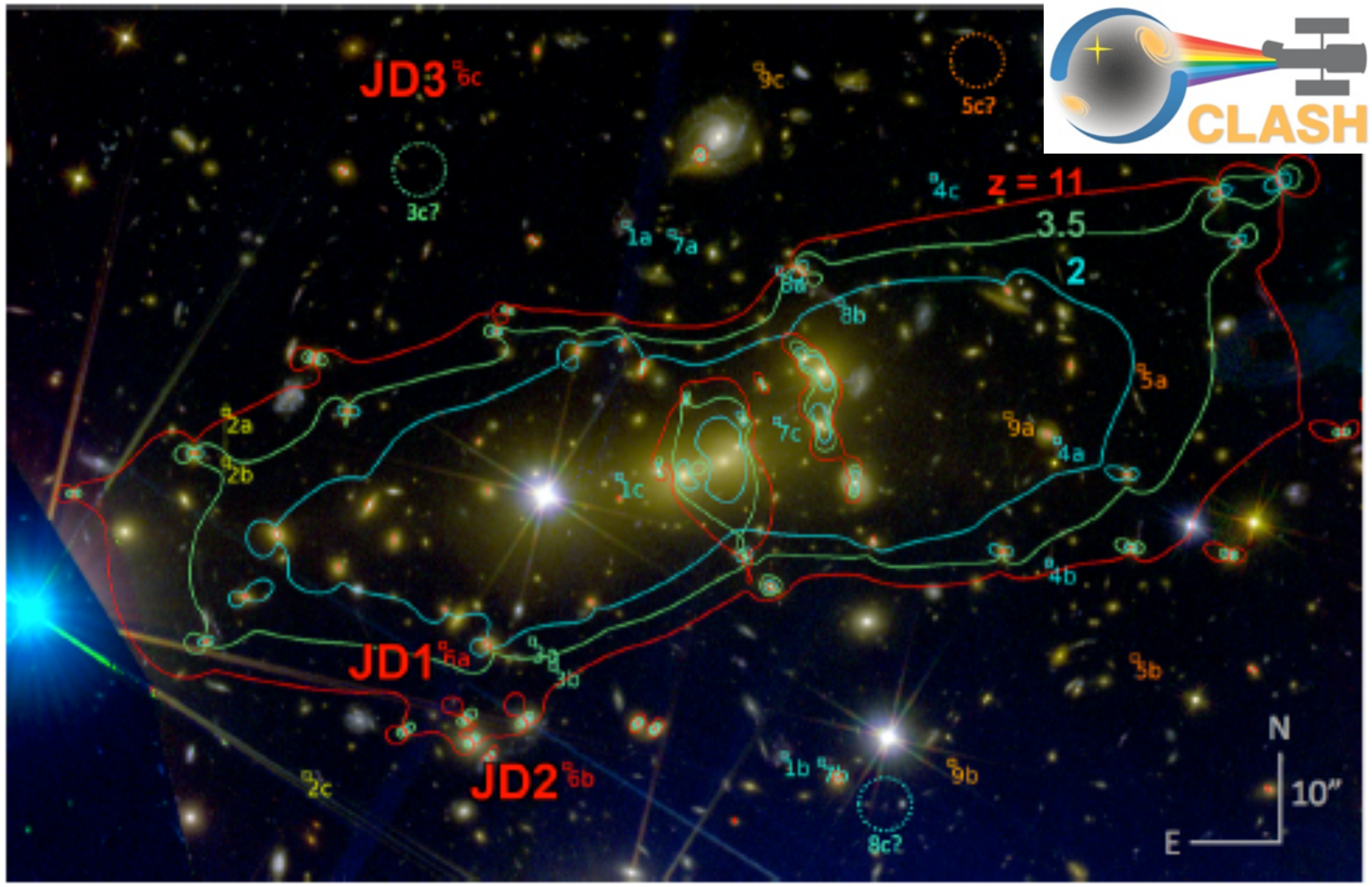
H=26.8

H=26.9

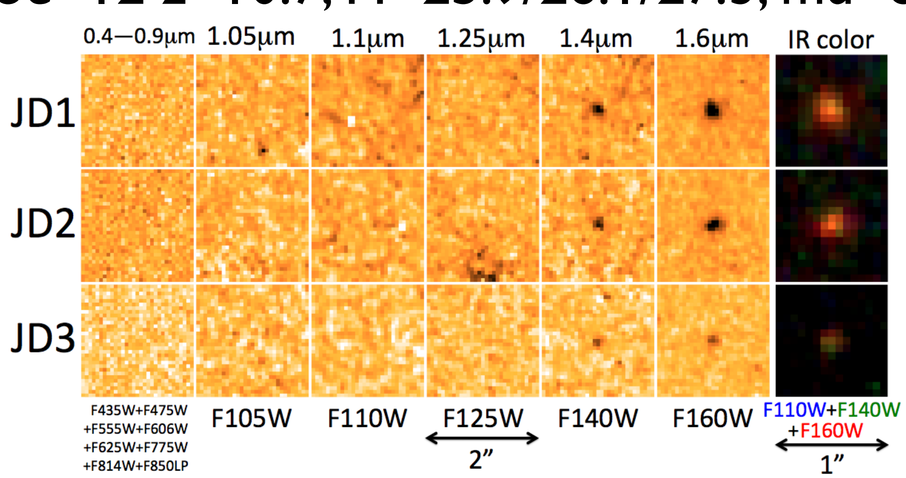


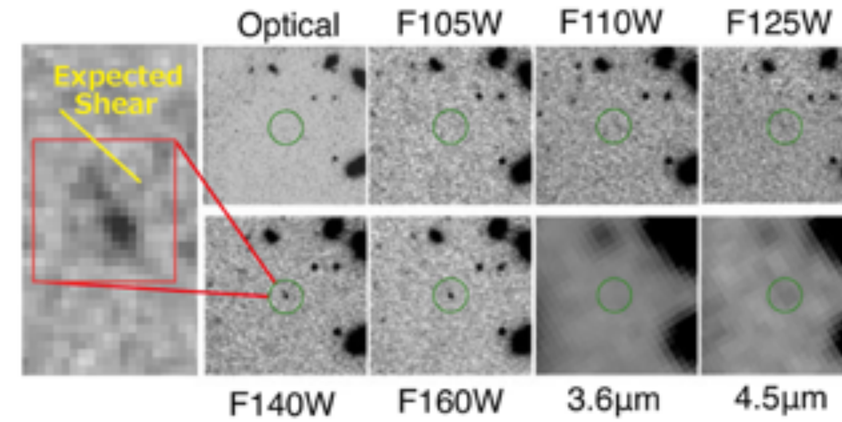
Note: No z~10 galaxy candidates found in the two UDF09 parallel fields

Two z~10 Candidates from CLASH

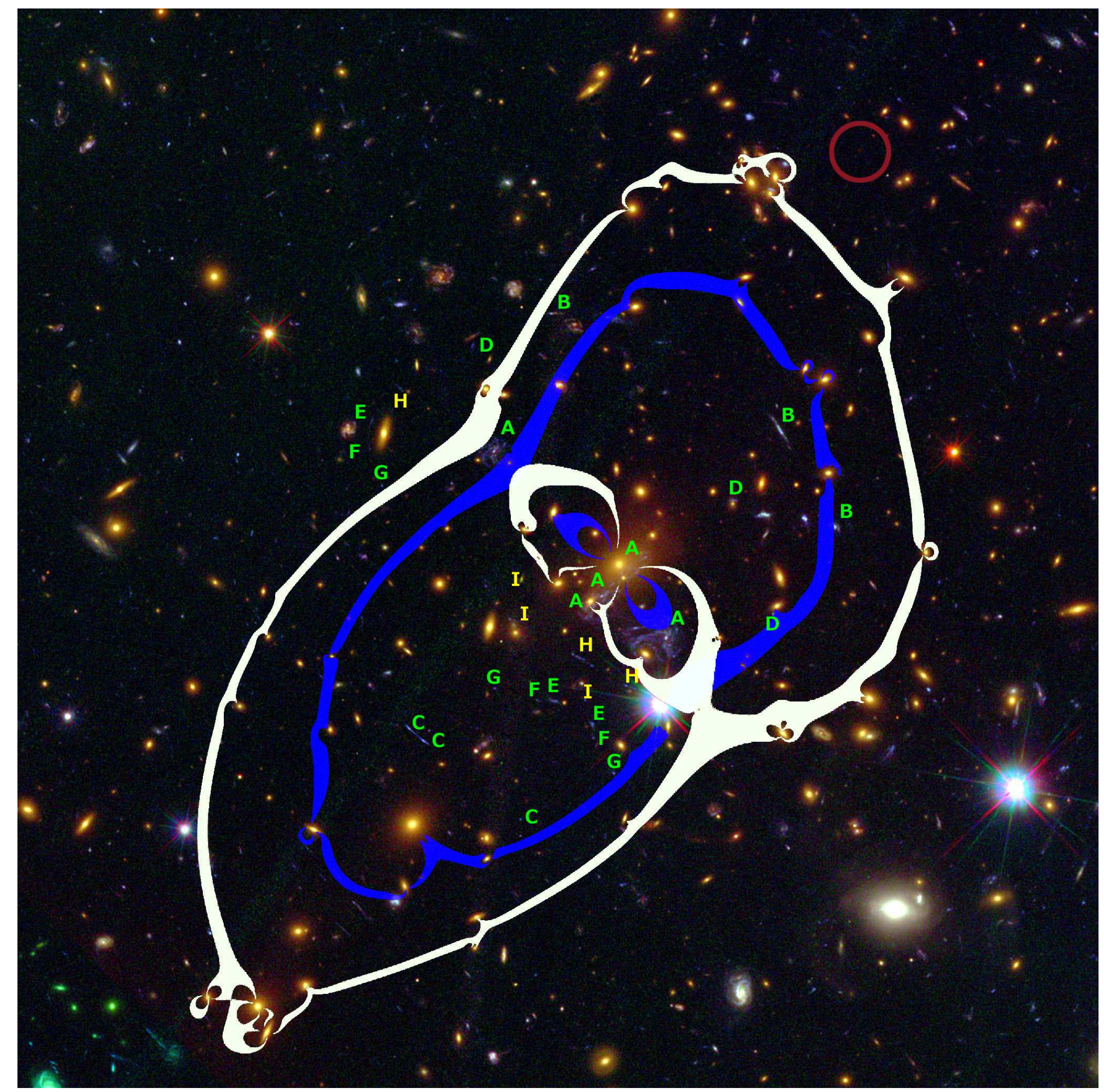


Coe+12 z=10.7, H=25.9/26.1/27.3, mu~8/7/2



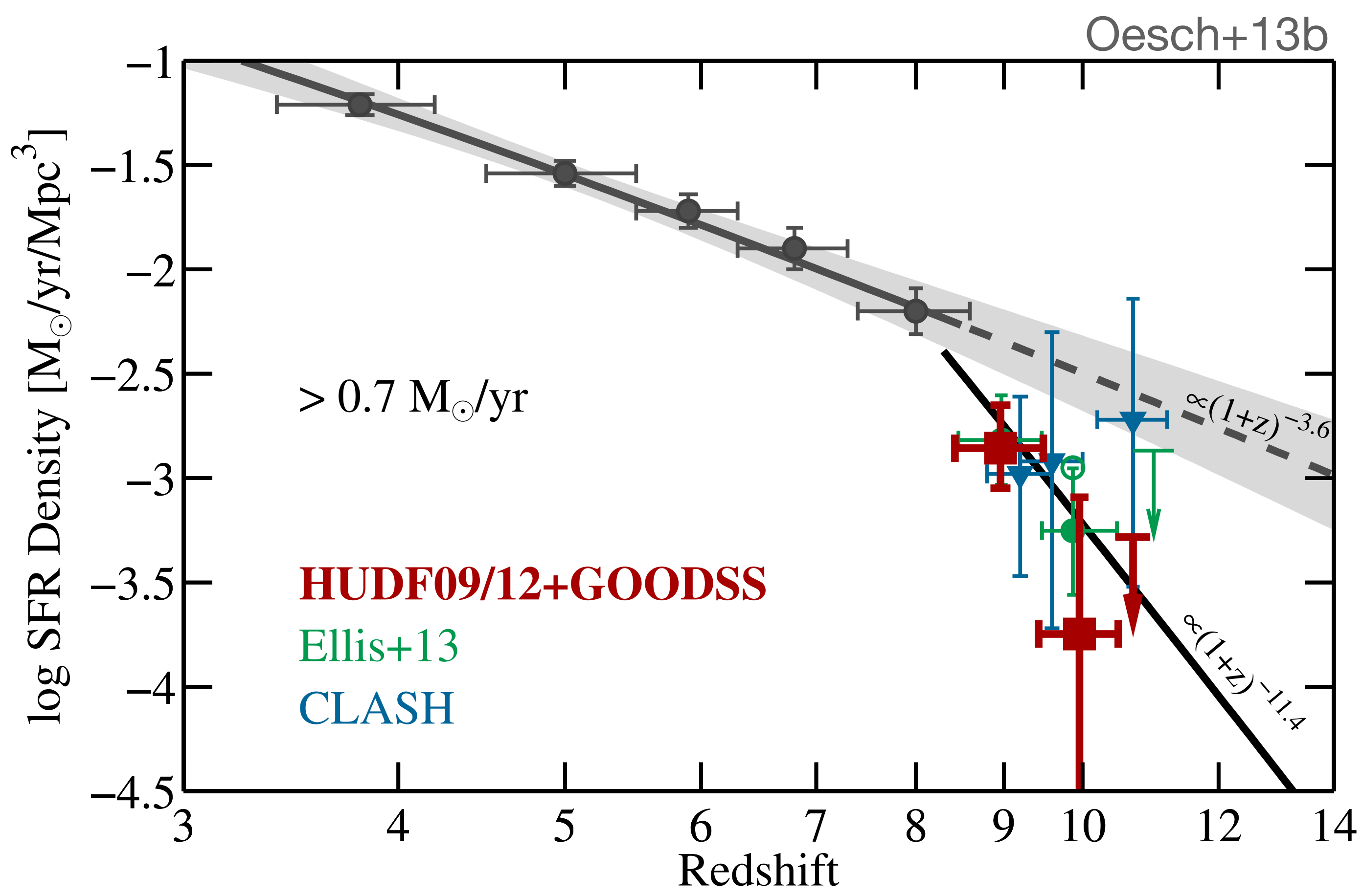


Zheng+12 z=9.6, H=25.7, mu=14-26

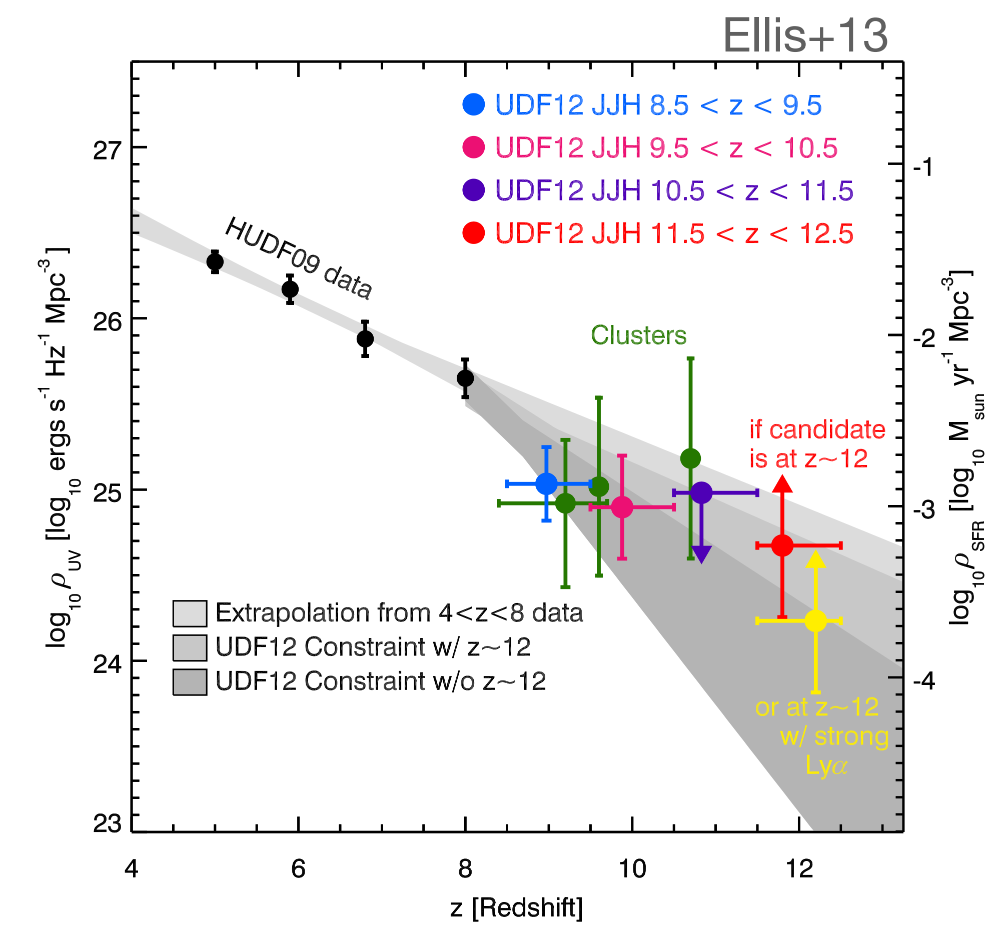


One of the Biggest Open Questions

Cosmic SFRD beyond z~8: accelerated evolution or not?

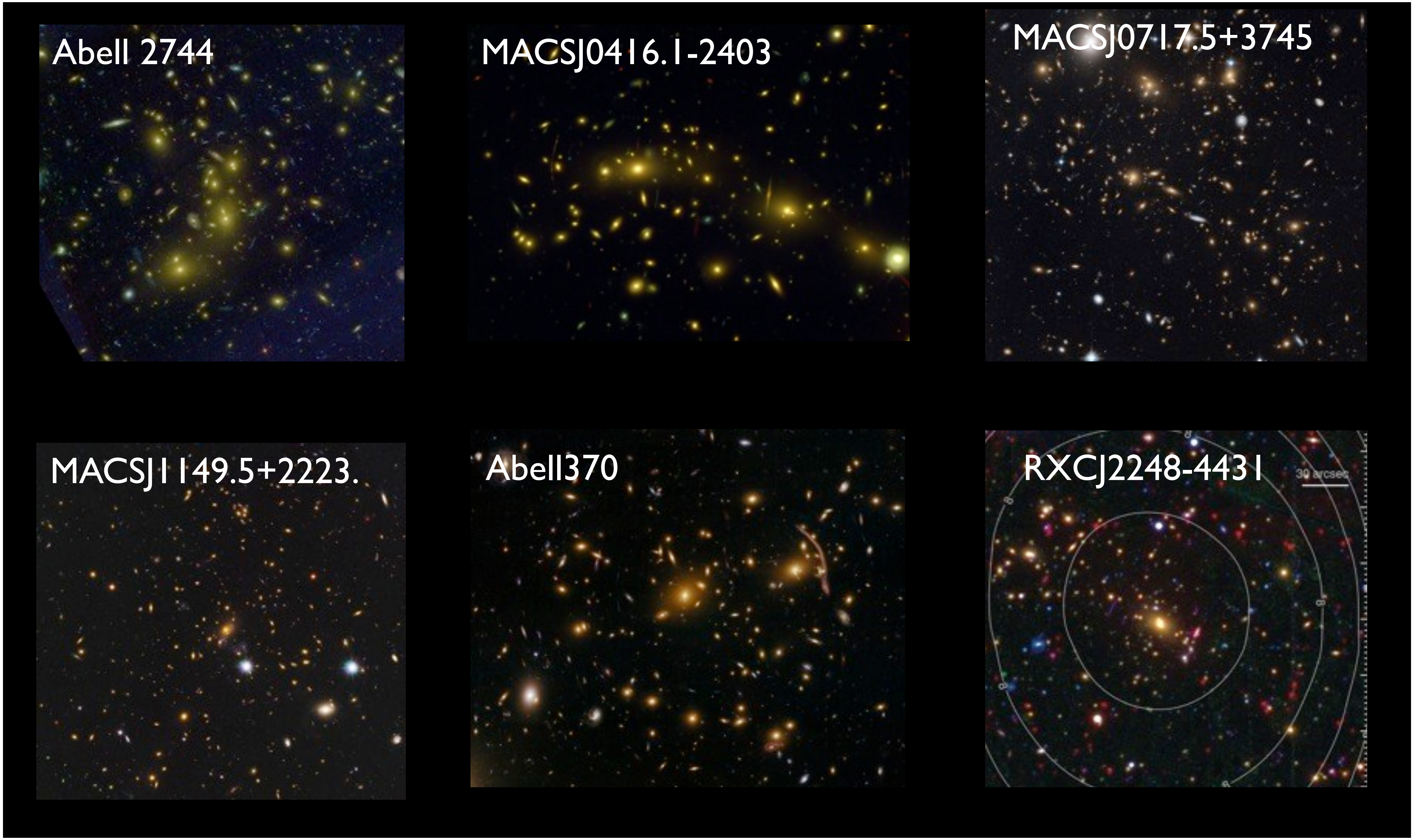


vs.



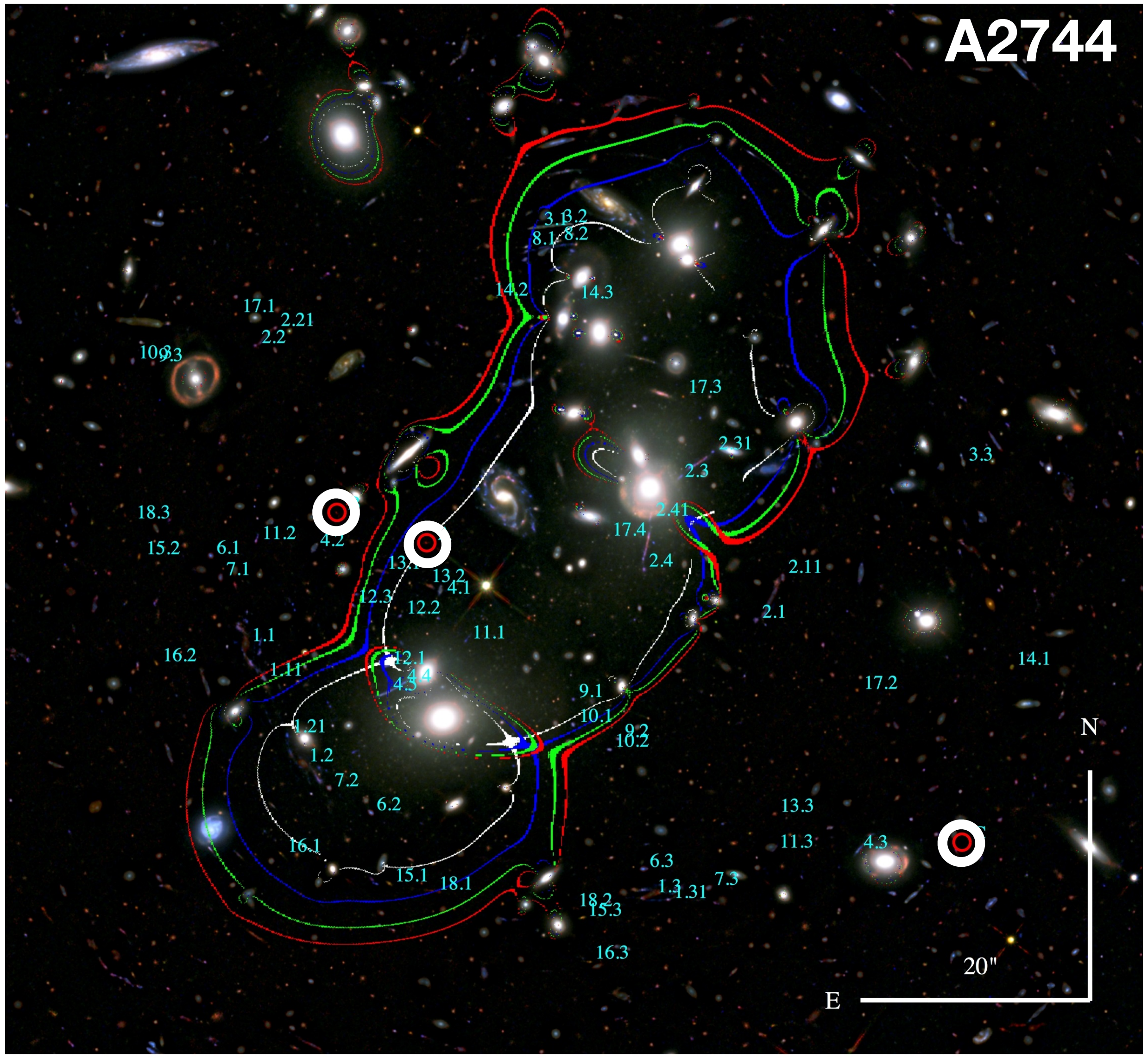
Frontier Field dataset perfectly suited to resolve this question!

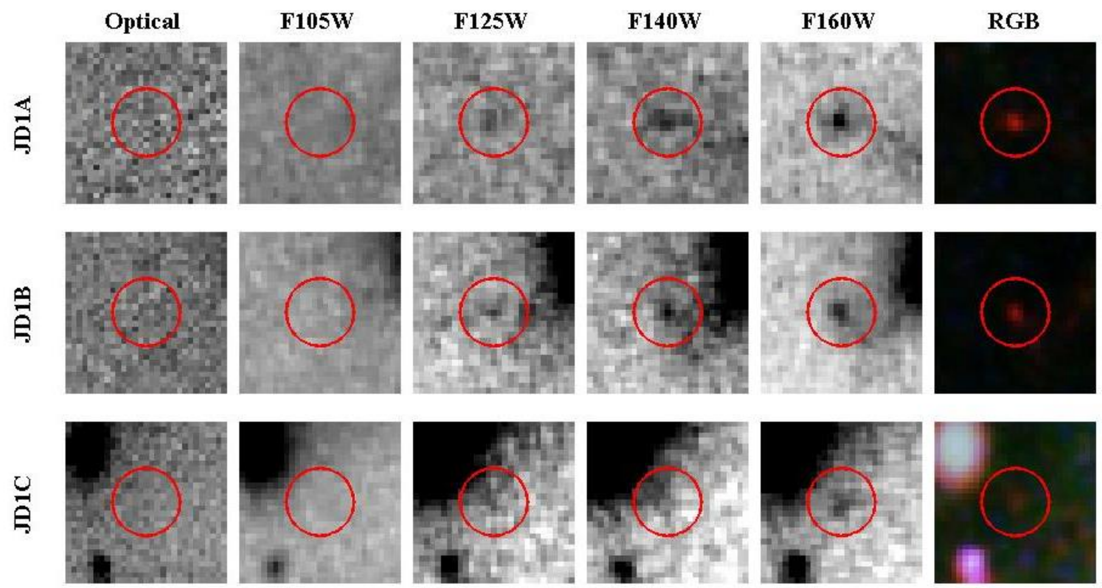
Hubble Frontier Fields

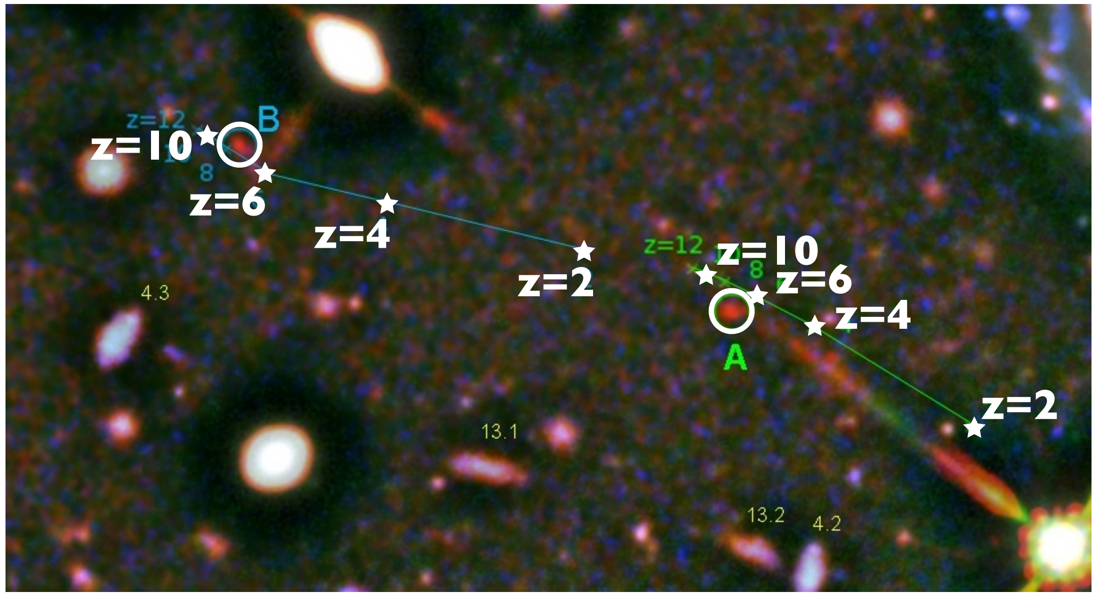


Triply Imaged z~10 Candidate in First FF Cluster

Zitrin+14 (see also Oesch et al. 2015)







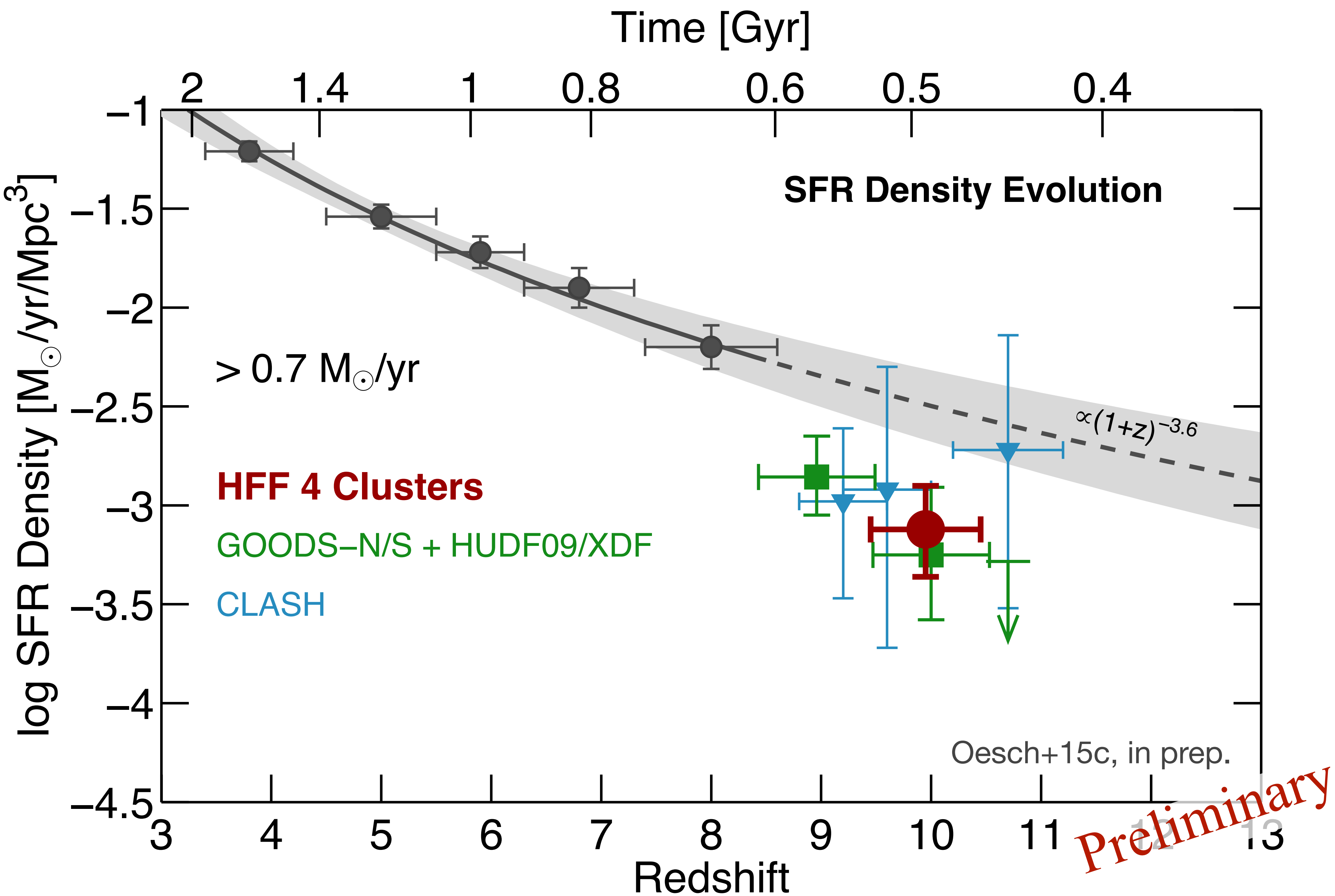
H = 29.9 mag (de-magnified)
zphot = 9.8±0.4

magnification: 10-11x

strong geometric support of high redshift solution of photo-z

FRONTIER FIELDS

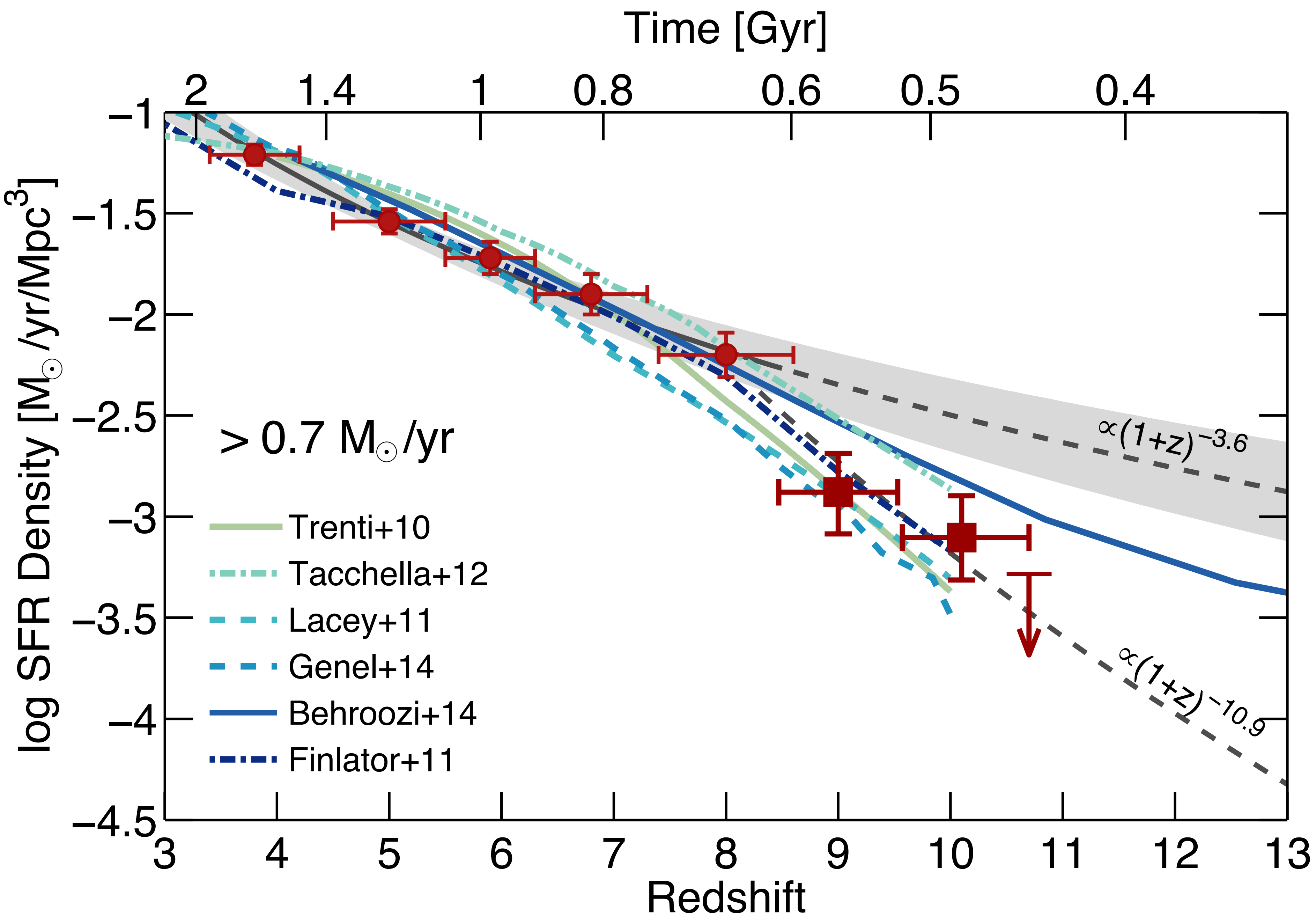
SFRD Evolution at z>8



Full analysis of first 4 HFFs confirms: SFRD evolves rapidly beyond z~8!

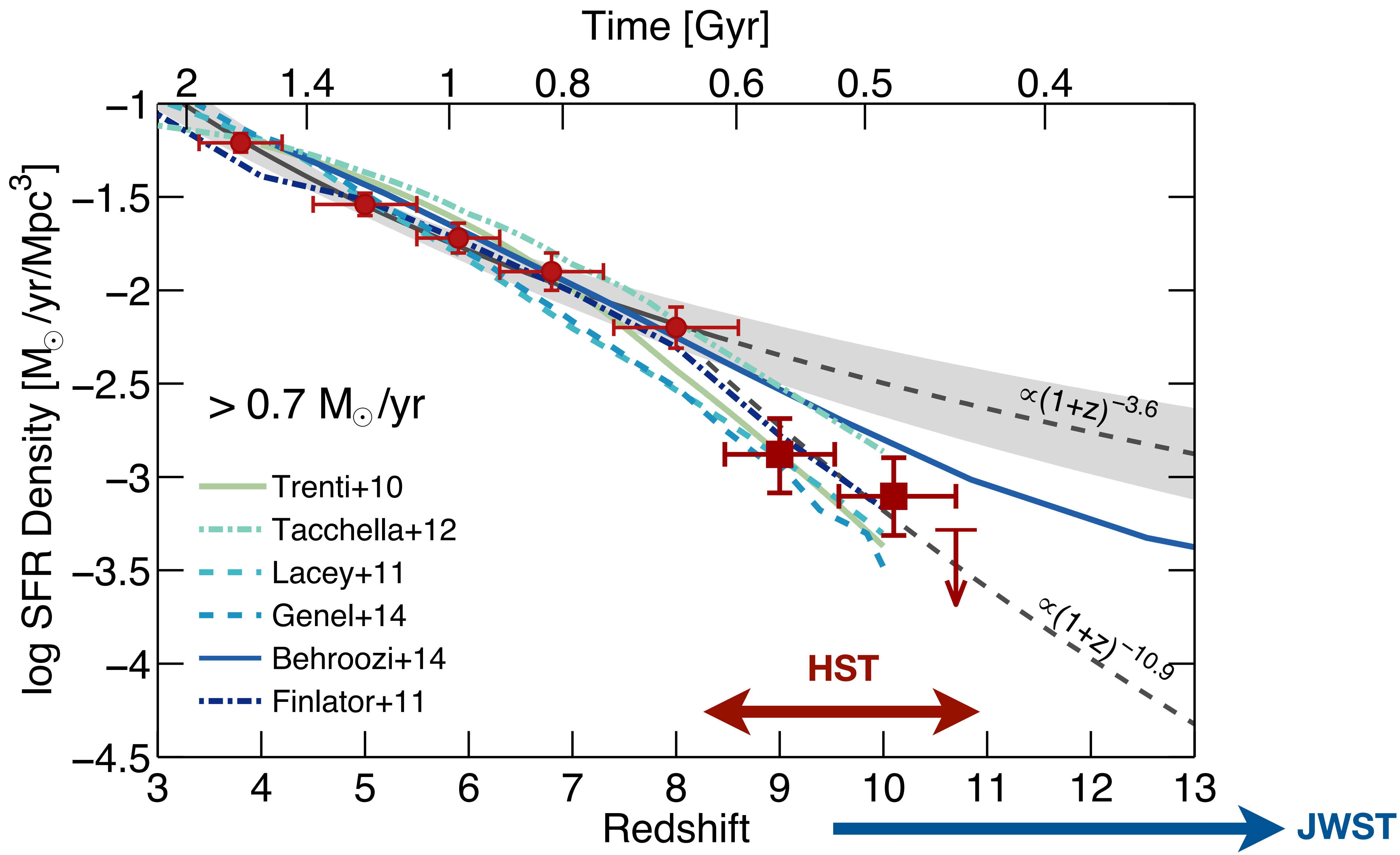
see also: Zheng+12, Coe+13, Bouwens+13/14, Ellis+13, McLure+13, Ishigaki+14

SFRD Evolution at z>8



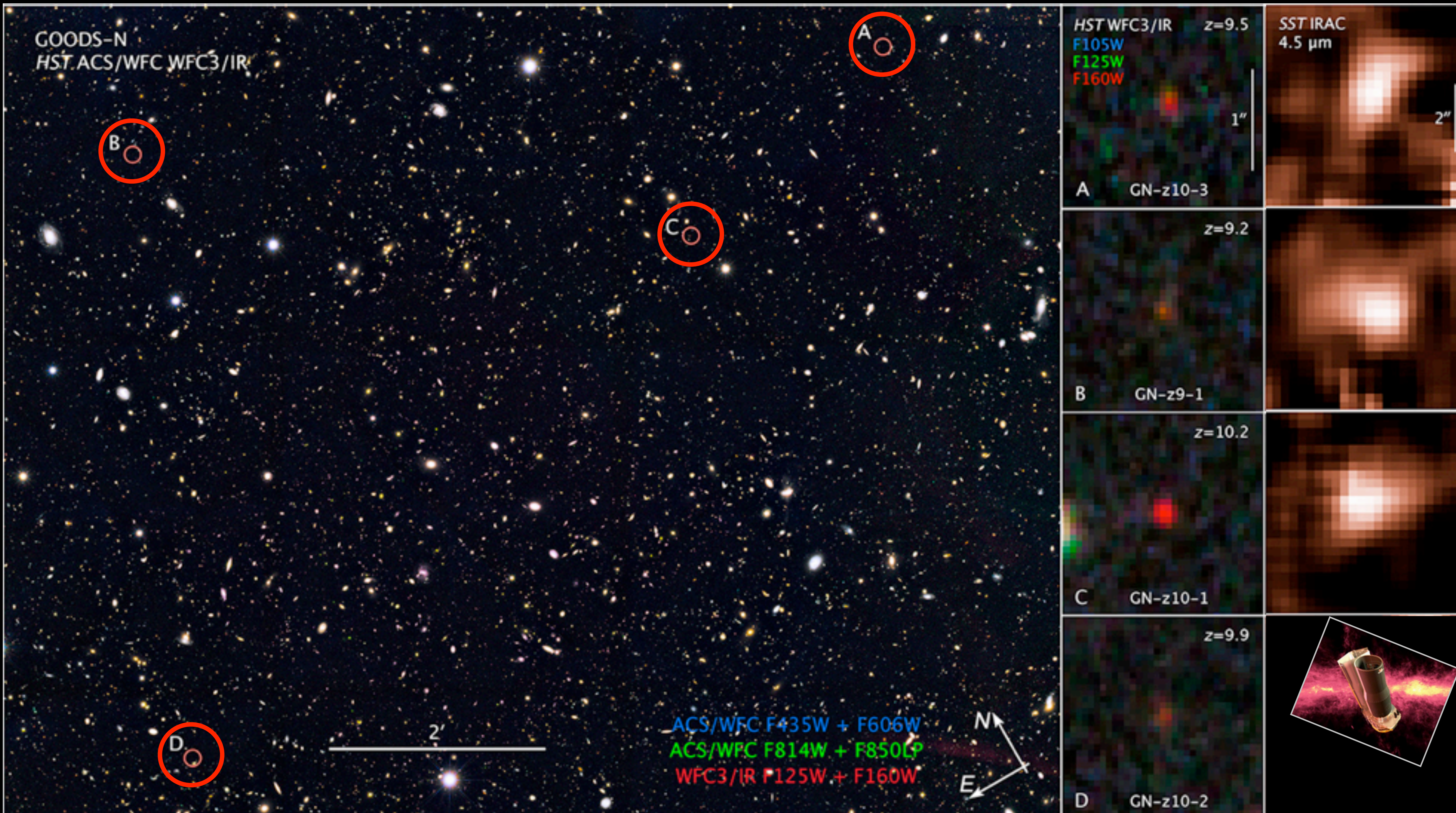
Rapid decline in the cosmic SFRD is consistent with most models, but there is a considerable range in predicted evolutions at z>8.

SFRD Evolution at z>8



Final HFF data will further improve current measurement
and JWST will extend it to z>10

Sample of 4 Bright z~9-10 Galaxy Candidates



NASA and ESA

STScI-PRC14-05a

Powerful combination of HST and Spitzer to explore most distant galaxies

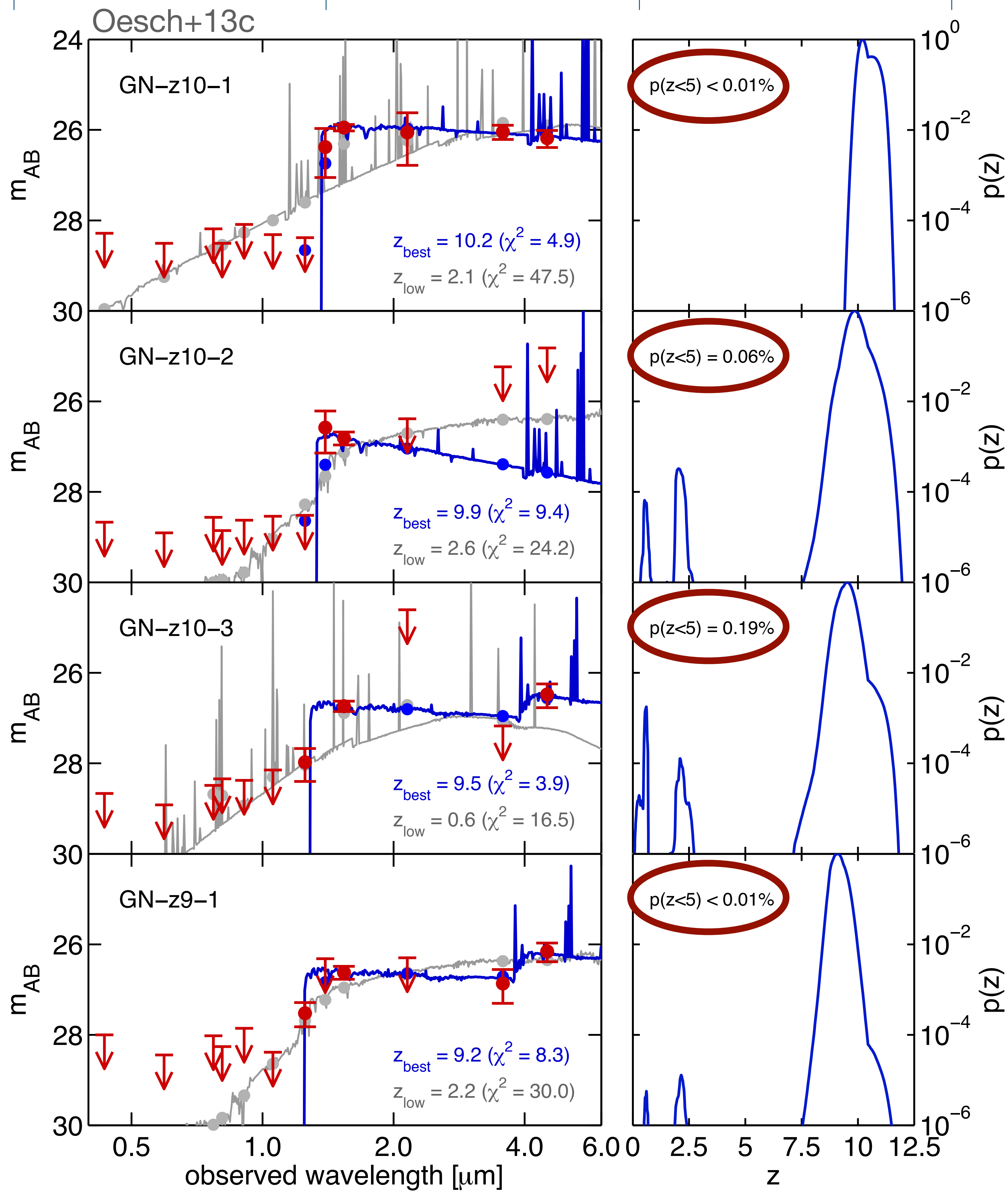
Accurate Sampling of Spectral Energy Distribution

Photometry from rest-frame UV to optical, thanks to IRAC detections

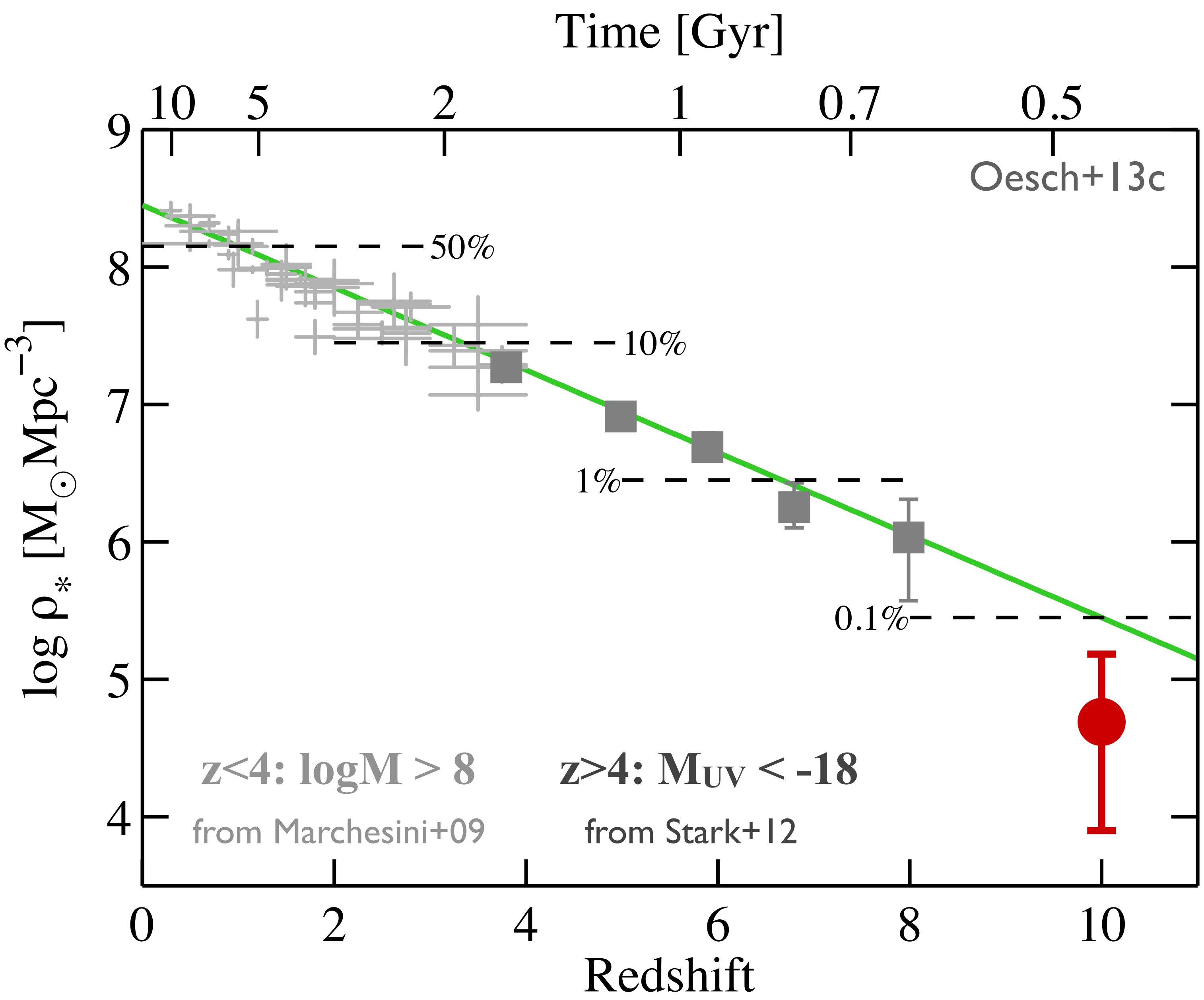
Due to brightness: extremely low probability of lower redshift contamination!

IRAC Detections result in constraints on Masses: **~10^9 M$_\odot$**

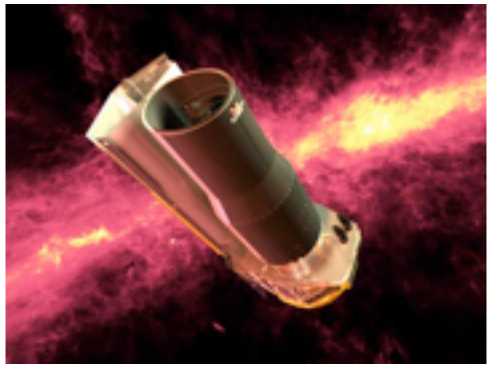
and Ages: **100-300 Myr**



Stellar Mass Density Evolution to z~10

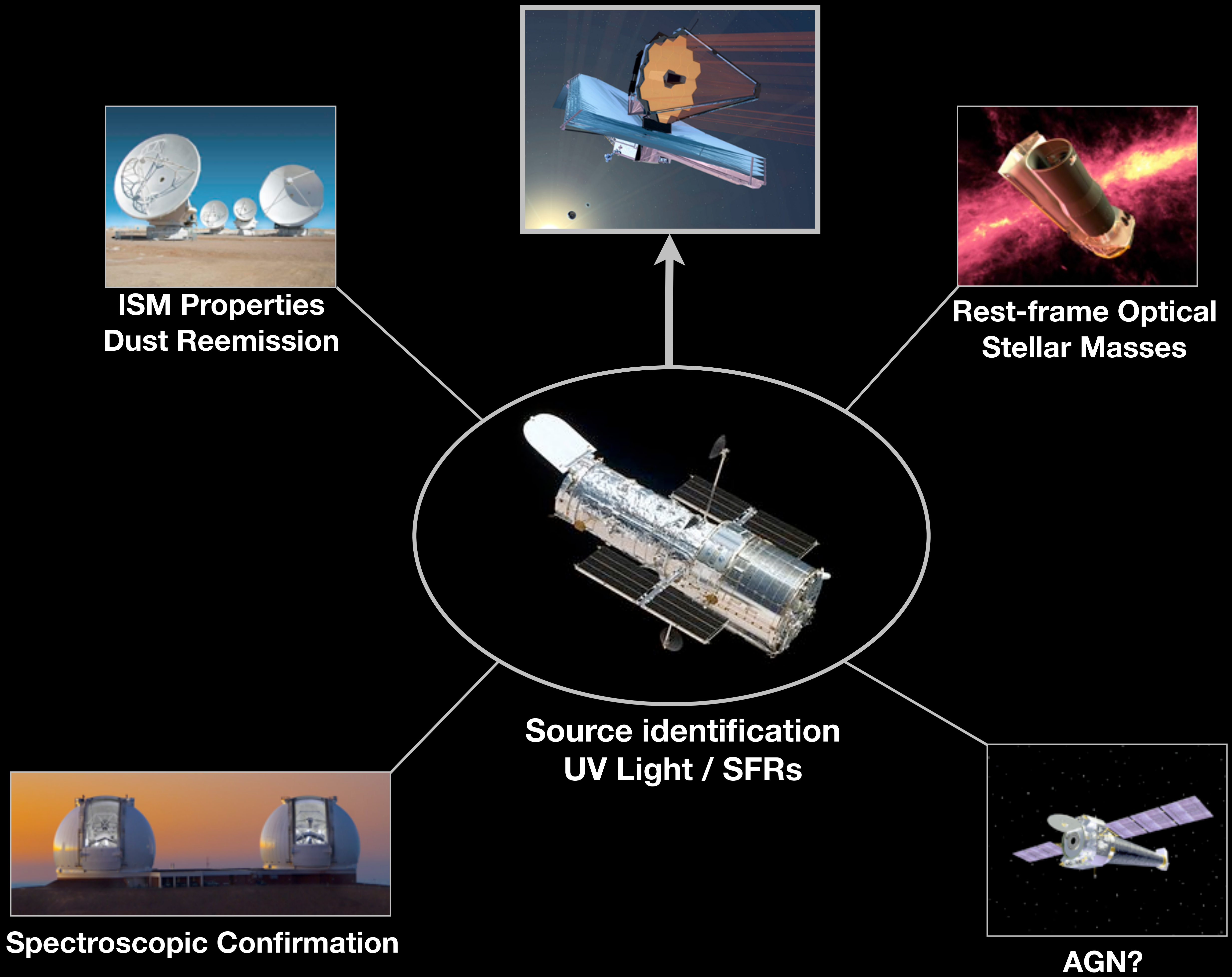


+

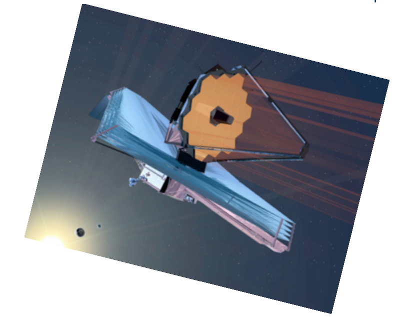


Luminosity limited SMD estimates at z>4 nicely match up with mass limited studies at z<4.

Are witnessing the assembly of the first 0.1% of local stellar mass density!

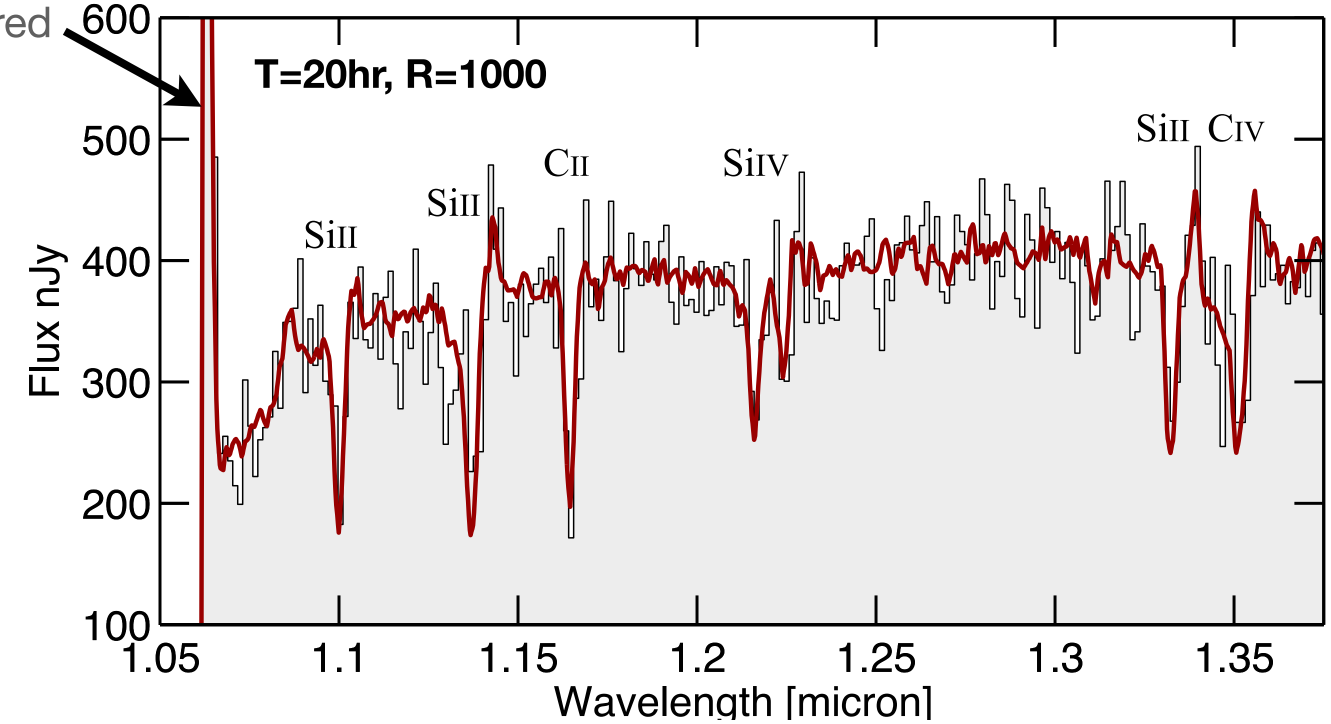

ISM Properties
Dust Reemission
Rest-frame Optical
Stellar Masses
Source identification
UV Light / SFRs
Spectroscopic Confirmation
AGN?

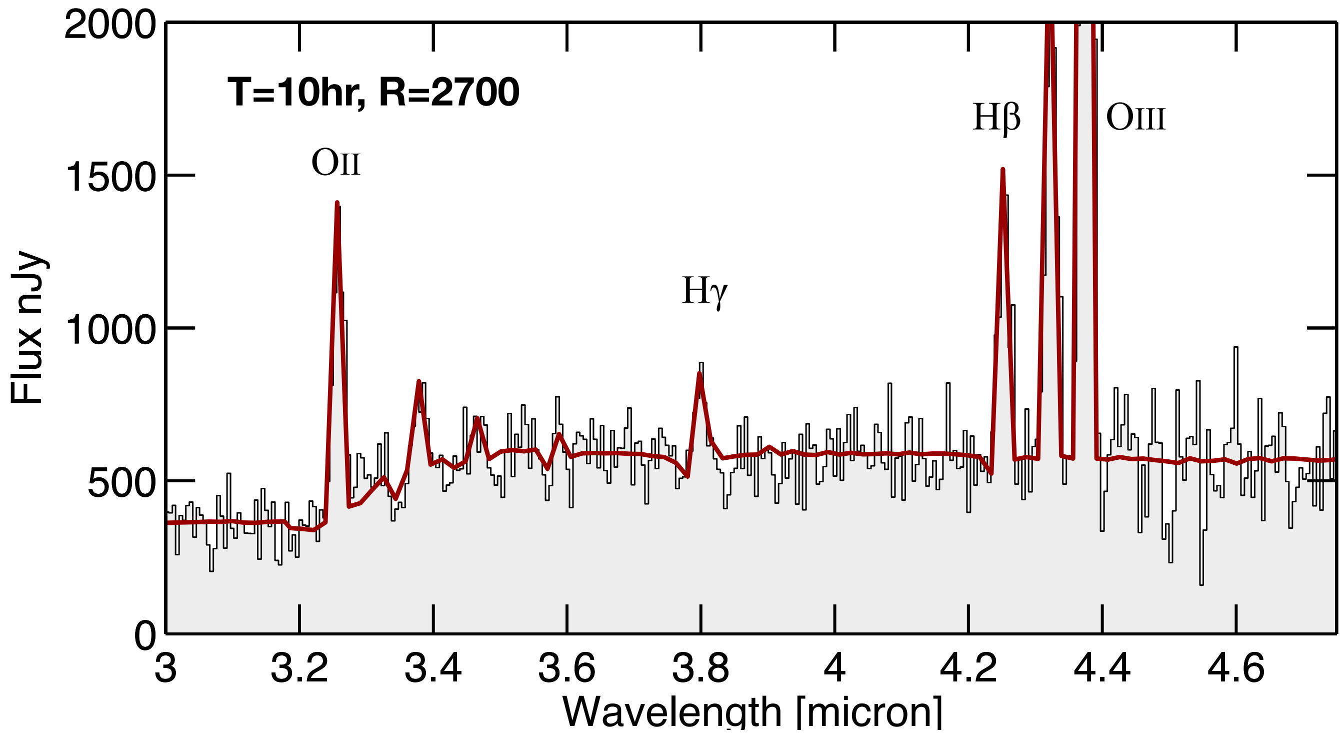
JWST/NIRSpec: Unprecedented Spectra



only line currently measured

Simulation based on z=7.73 source from Oesch+15





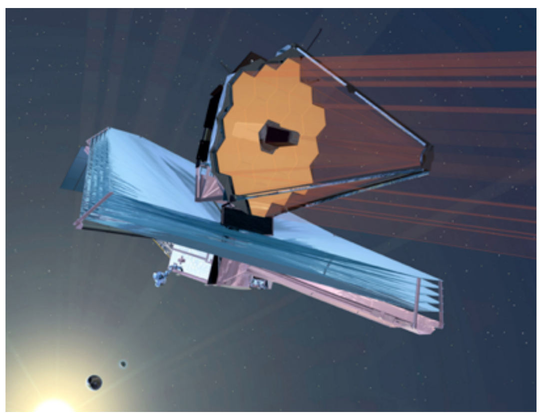
- JWST will be extremely efficient in spectroscopic characterization of z>7 galaxies
- For brightest targets, like the recently confirmed target EGS-zs8-1 at z=7.73, we will even be able to measure absorption lines

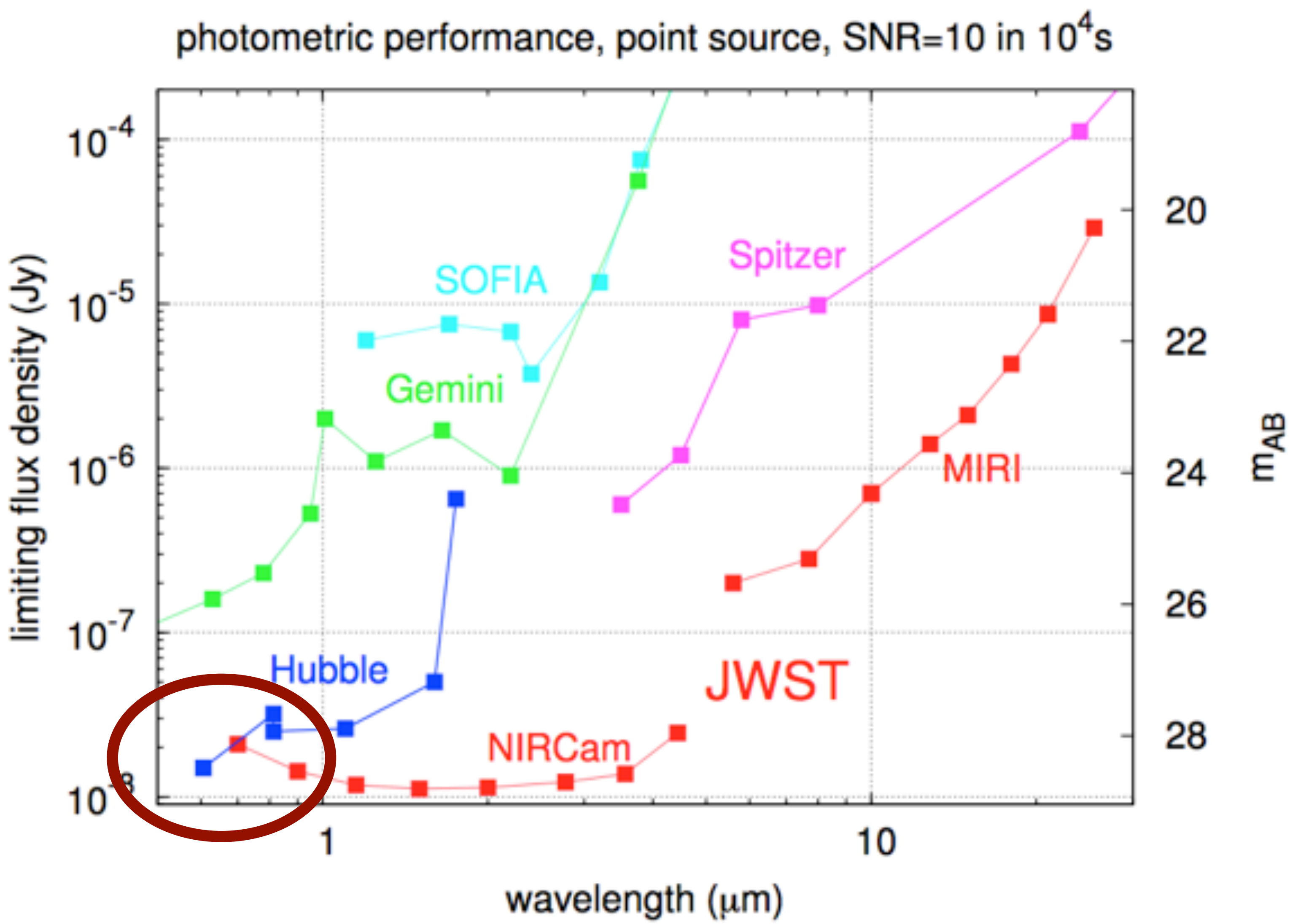
What is the ionization state of gas in early galaxies?

What is their dynamical state?

Need to find bright targets for JWST!

JWST's (Lack) of Efficiency in the Blue



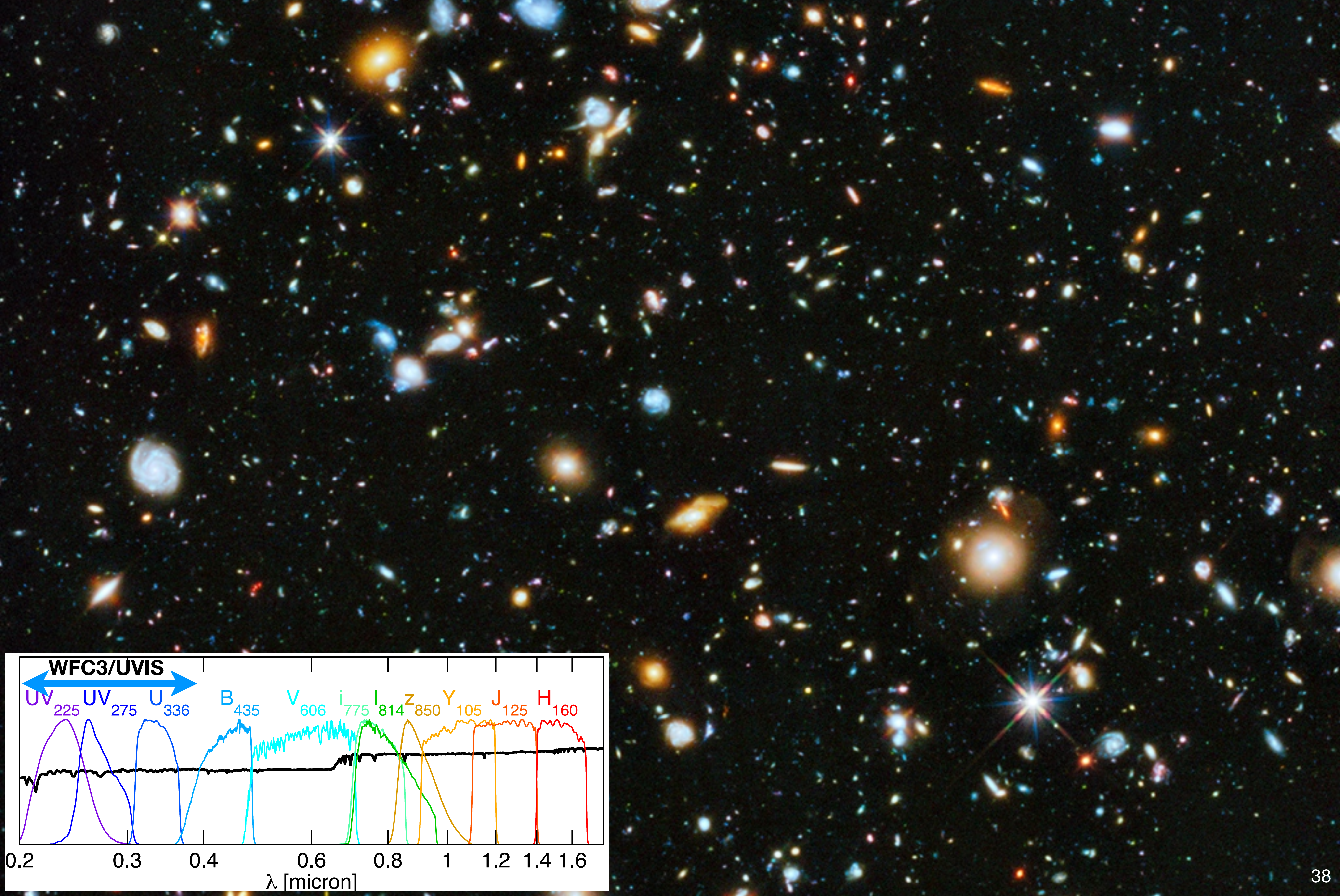


HST is the only way to obtain deep data at <~7000 Å for now!

- ➔ Most extragalactic surveys now take B-band parallel imaging to build up HST's "blue" legacy
- ➔ HST's UV initiative

Latest Image of HUDF/XDF

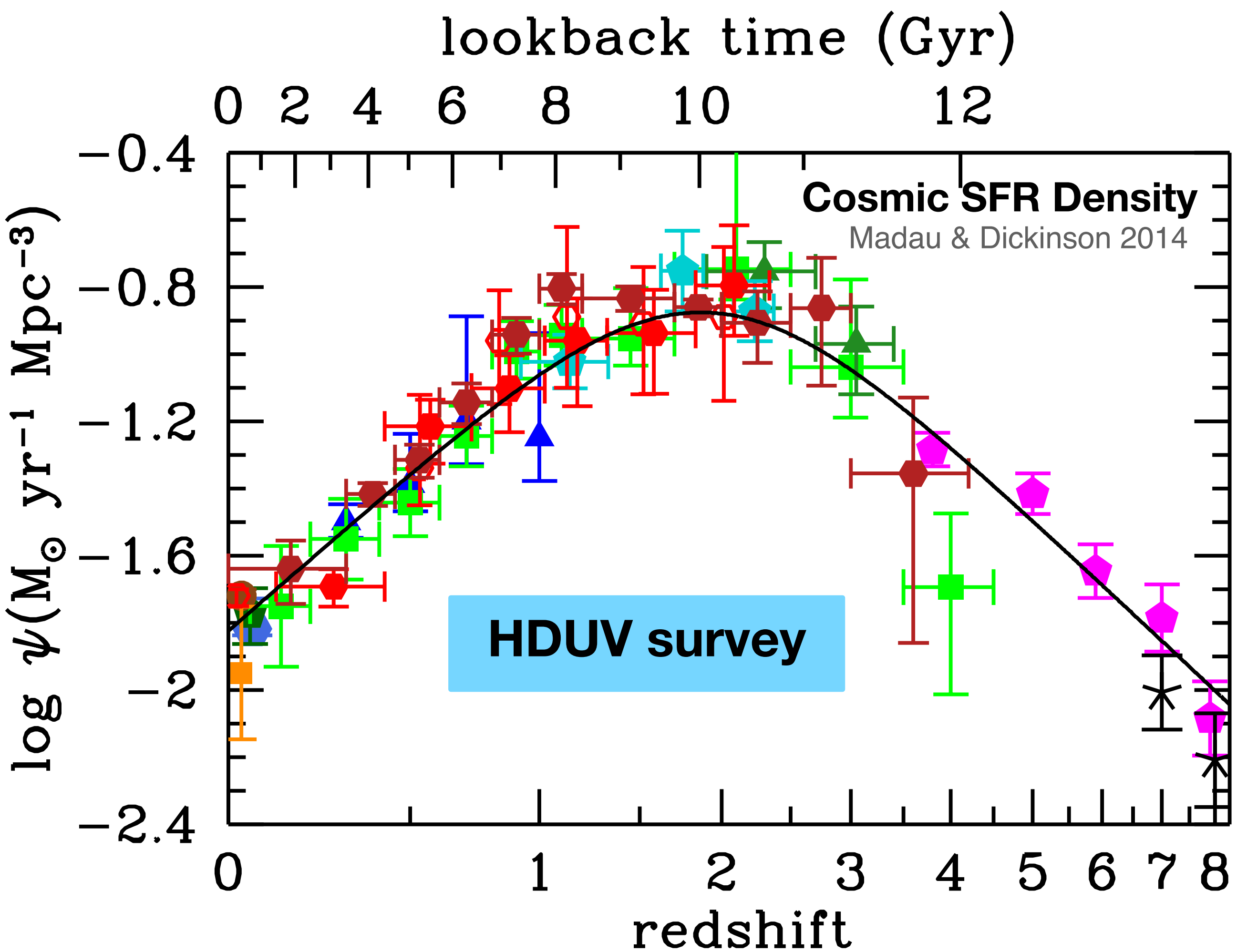
Teplitz et al. (2013)

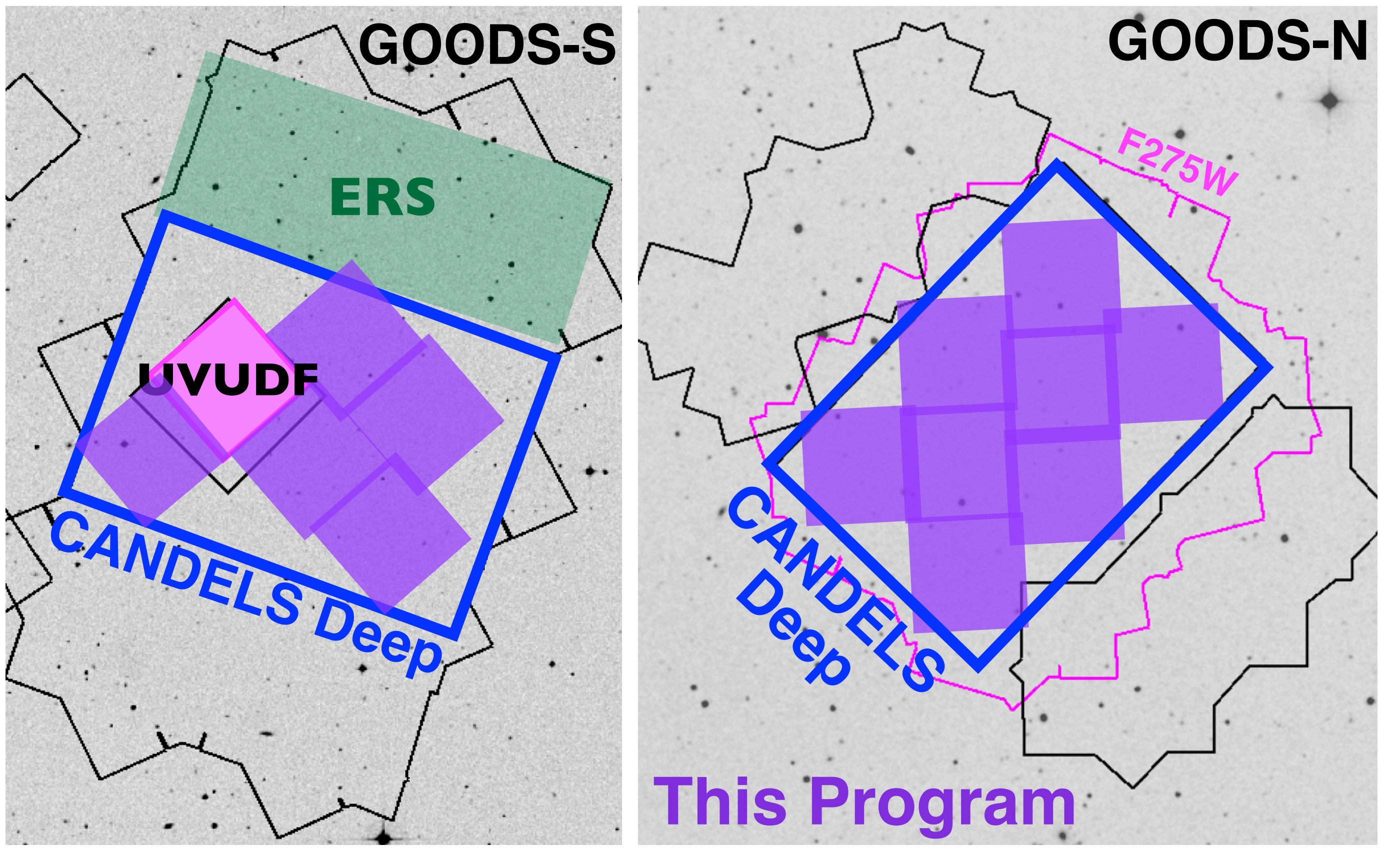


Hubble Deep UV Legacy Survey

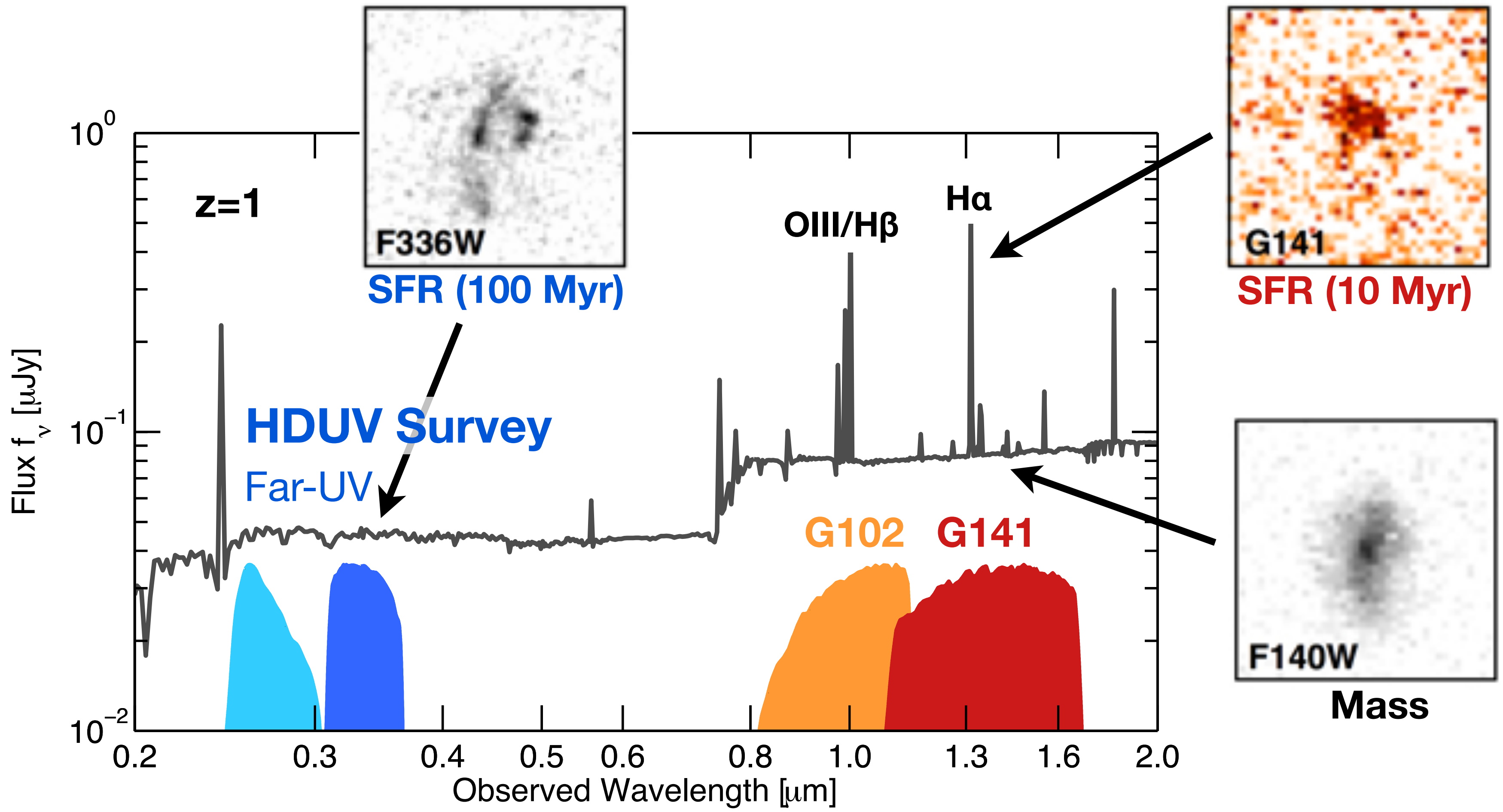
PI: Oesch

132 orbits with WFC3/UVIS
2 filters: F275W and F336W, down to 27.5-28.0
CANDELS Deep areas in GOODS-S/N (100 arcmin^2)
www.astro.yale.edu/hduv



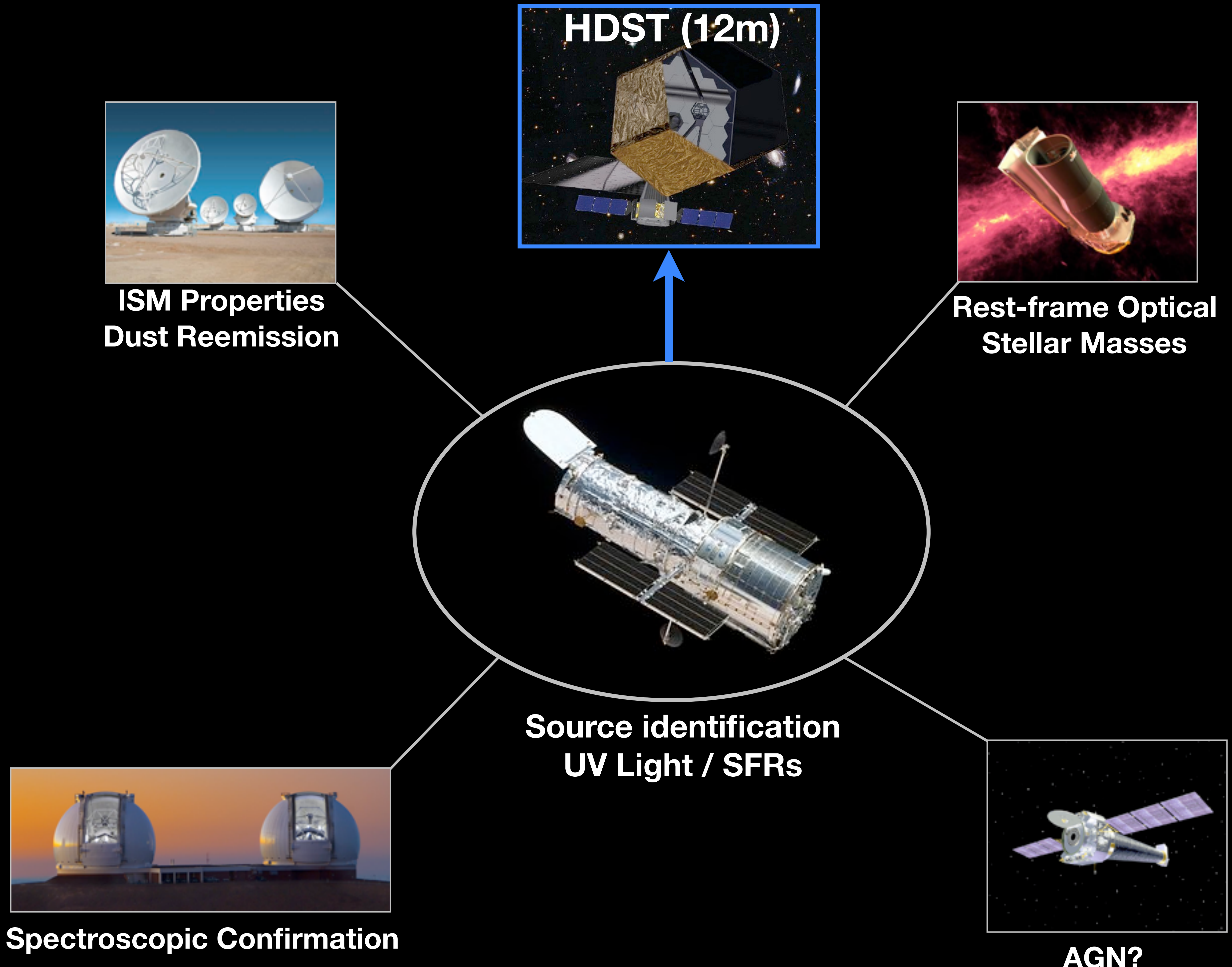


A Unique Panchromatic View of z~0.5-2 Galaxies

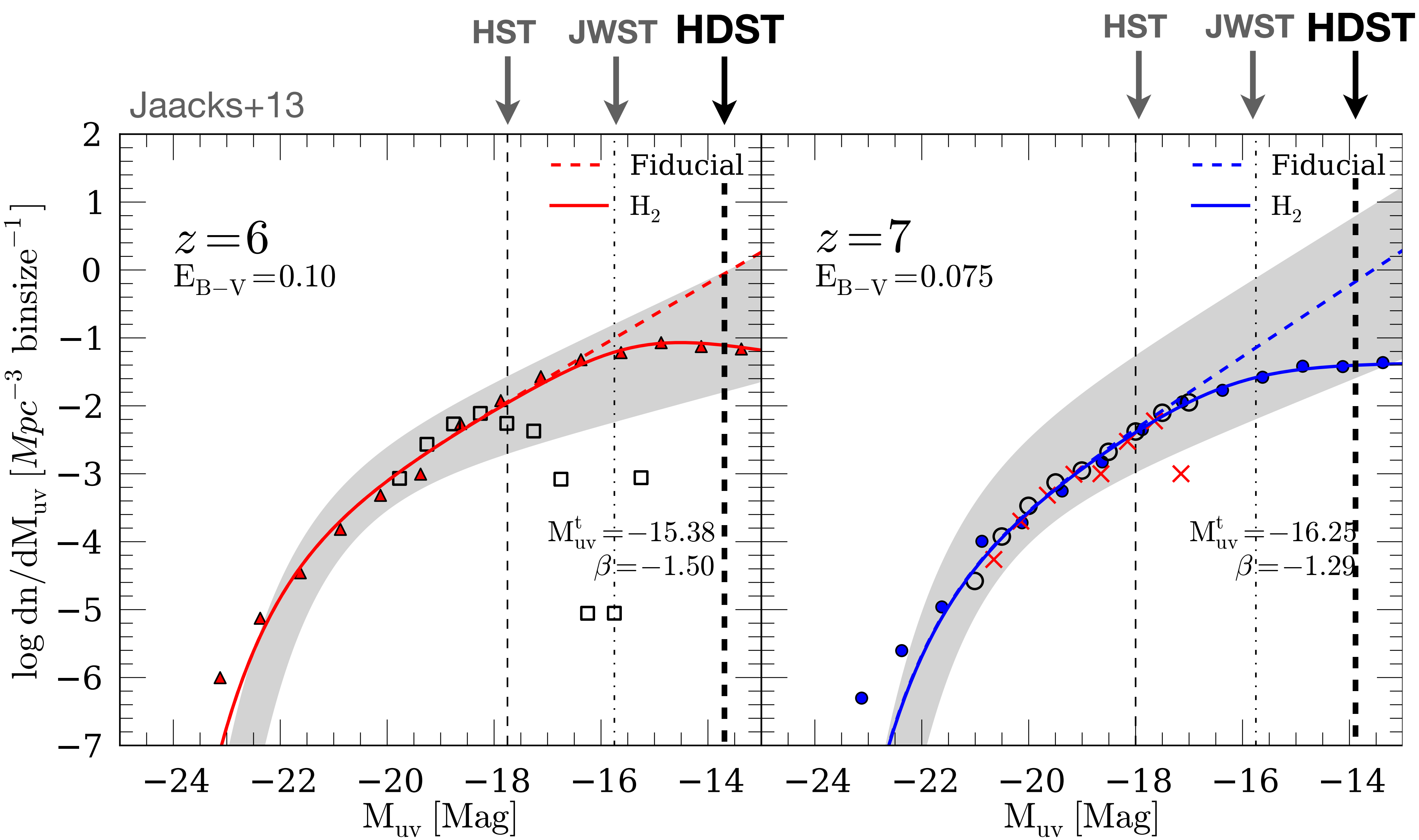


With HDUV we have:

- resolved far-UV imaging, unobscured SF on 100 Myr timescales (600 pc resolution)
- rest-frame UV-optical HST imaging: morphologies and physical properties
- grisms: emission line maps at HST resolution
- GOODS fields: environment
- higher resolution NIR spectra: emission line profiles, kinematics, winds


HDST (12m)
ISM Properties
Dust Reemission
Rest-frame Optical
Stellar Masses
Source identification
UV Light / SFRs
Spectroscopic Confirmation
AGN?

Galaxies During Cosmic Reionization with 12m

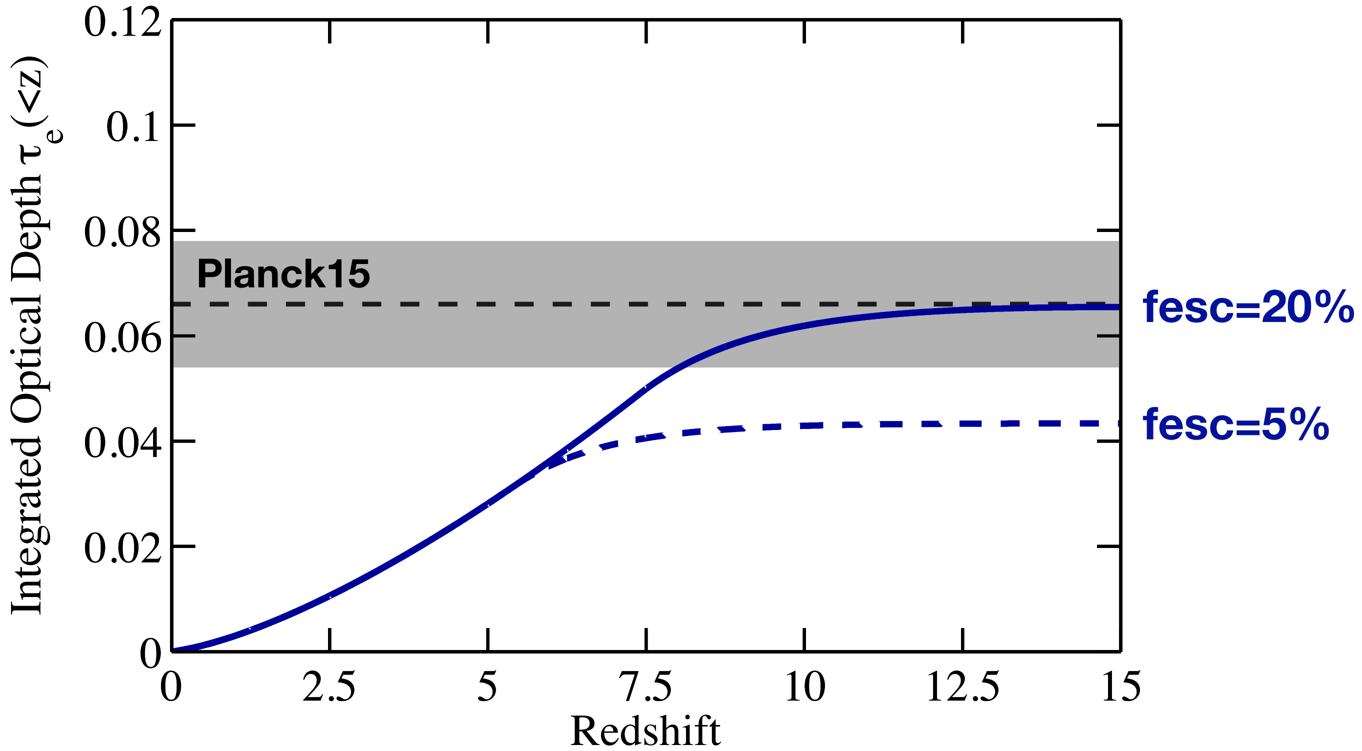


With larger aperture of a ~12m UVOIR space telescope, we can push into a theoretically interesting regime of dwarf galaxies at z>6 and probe the physics of early star-formation.

+ probe the bulk of the ionizing flux density

See Steve Finkelstein's talk

UV Sensitivity: Unique Probe of Ionizing Escape Fraction



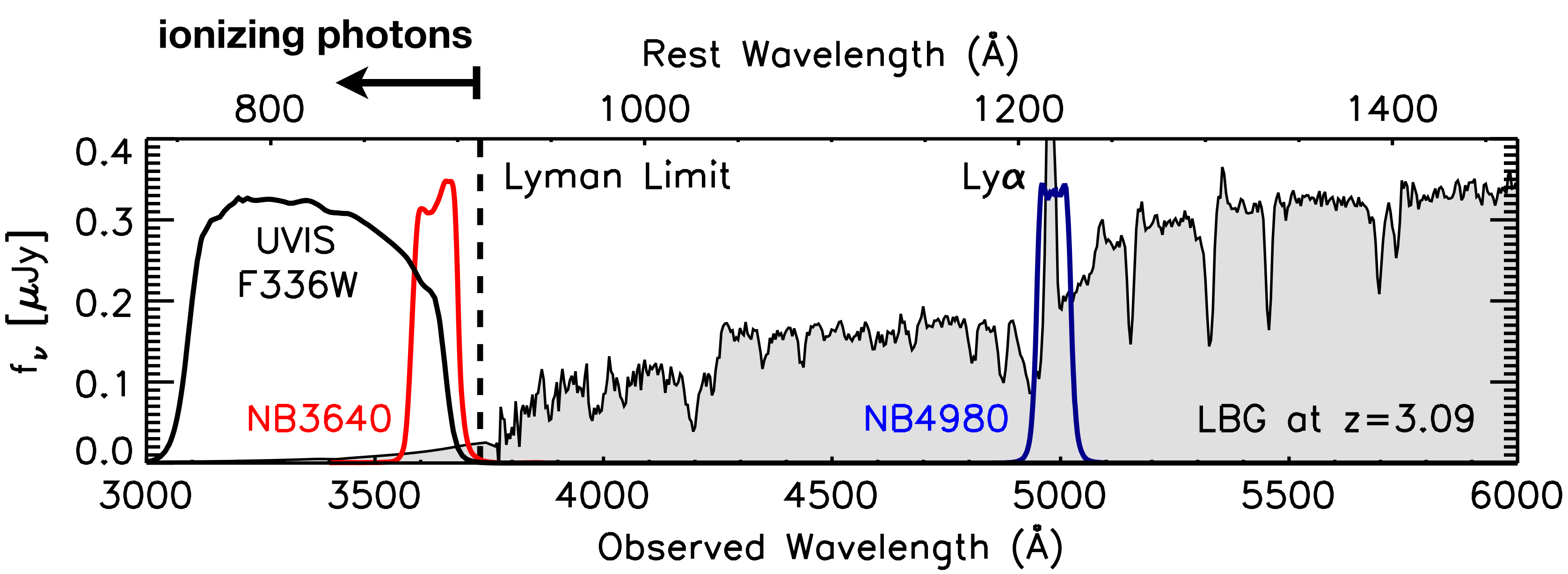
Even if we can probe the bulk of the ionizing photon flux density, there is a **big unknown** whether galaxies can reionize the universe:

the escape fraction of ionizing photons!

Its value and redshift evolution is highly debated and uncertain.

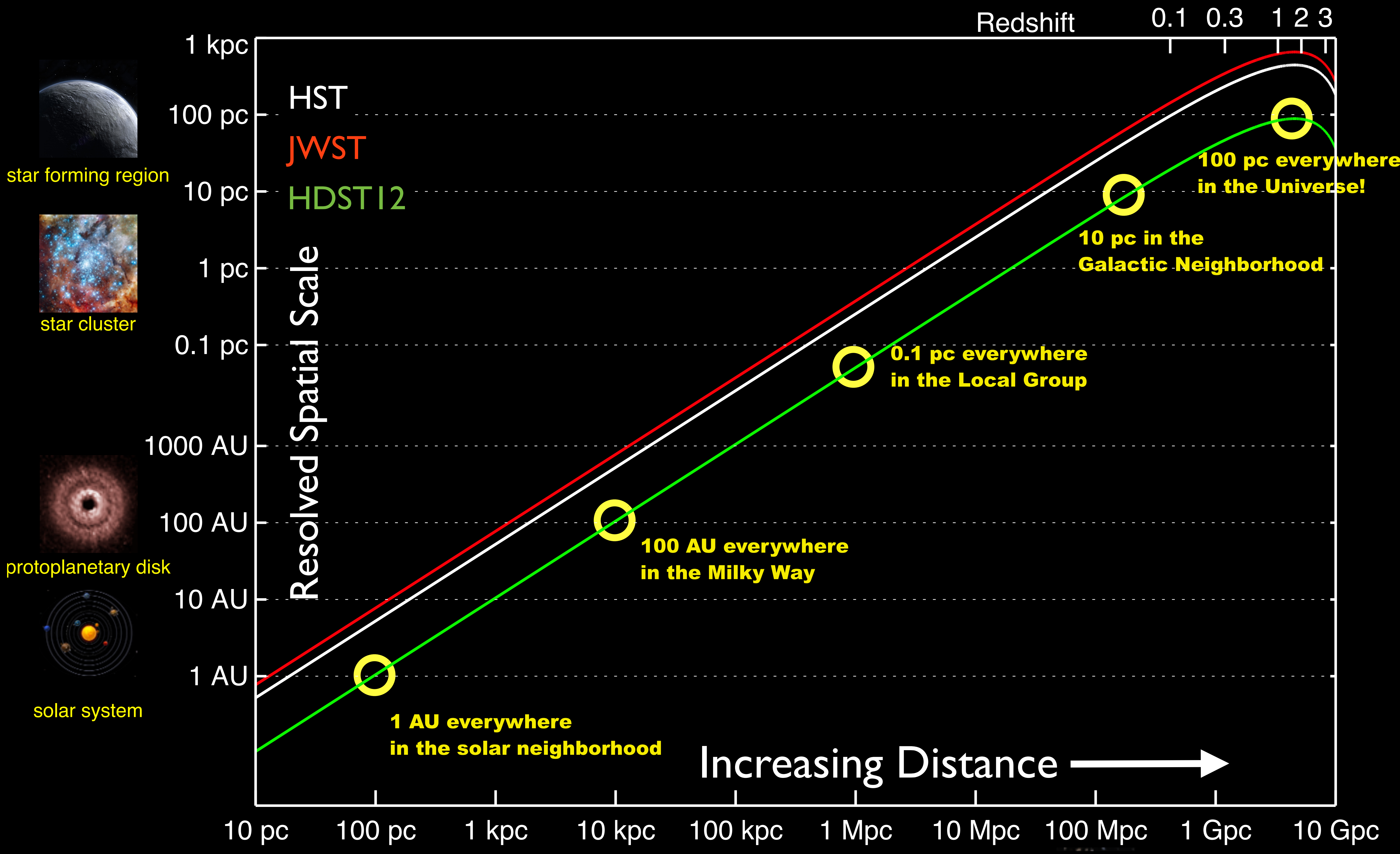
Due to thick IGM in early universe, we can only probe fesc out to z~3

need UV sensitivity at < 3500 Å



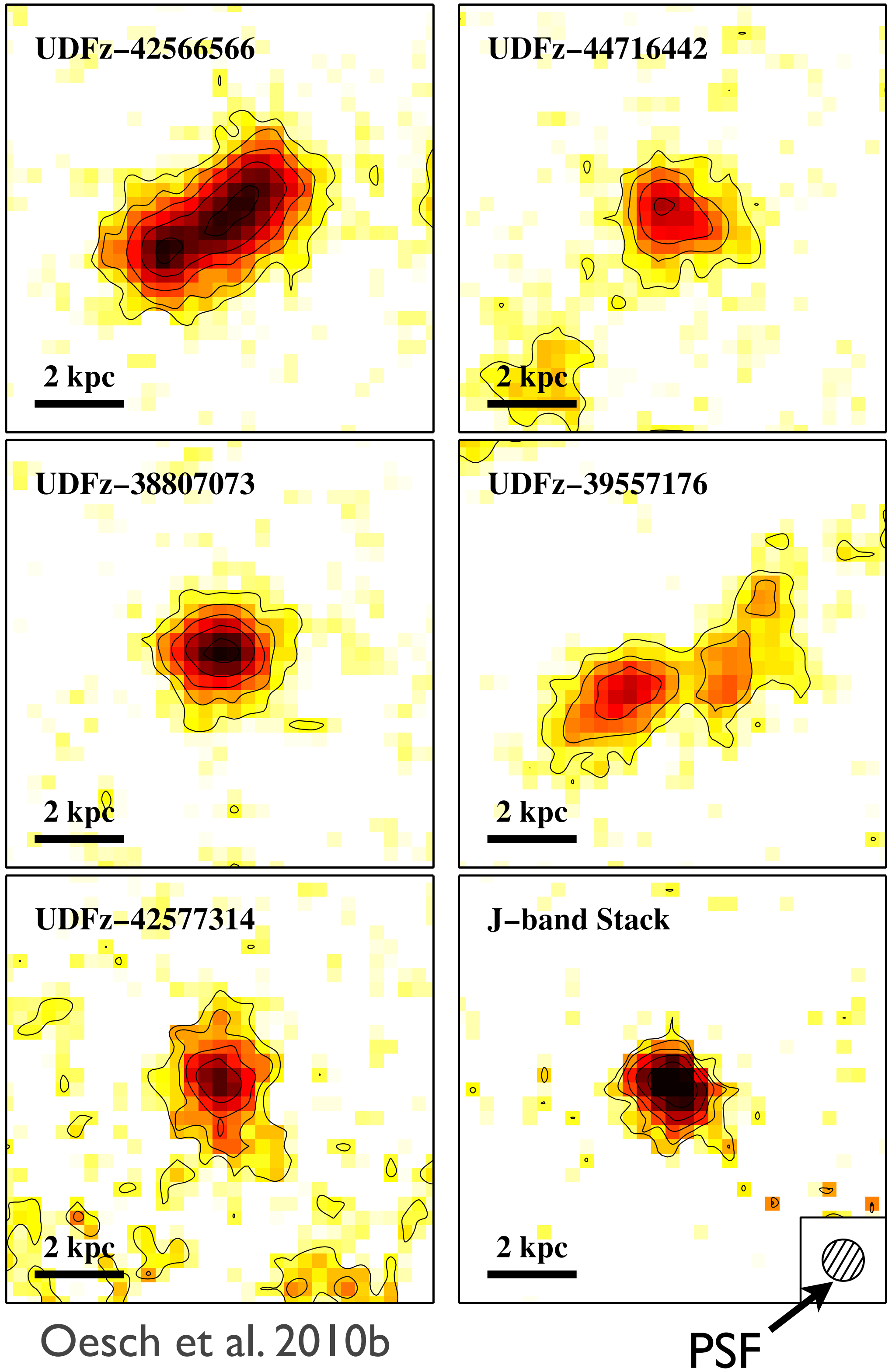
Example of Siana+15 to probe ionizing flux with imaging at z~3

HDST: Breaking Resolution Barriers in the UV/Optical

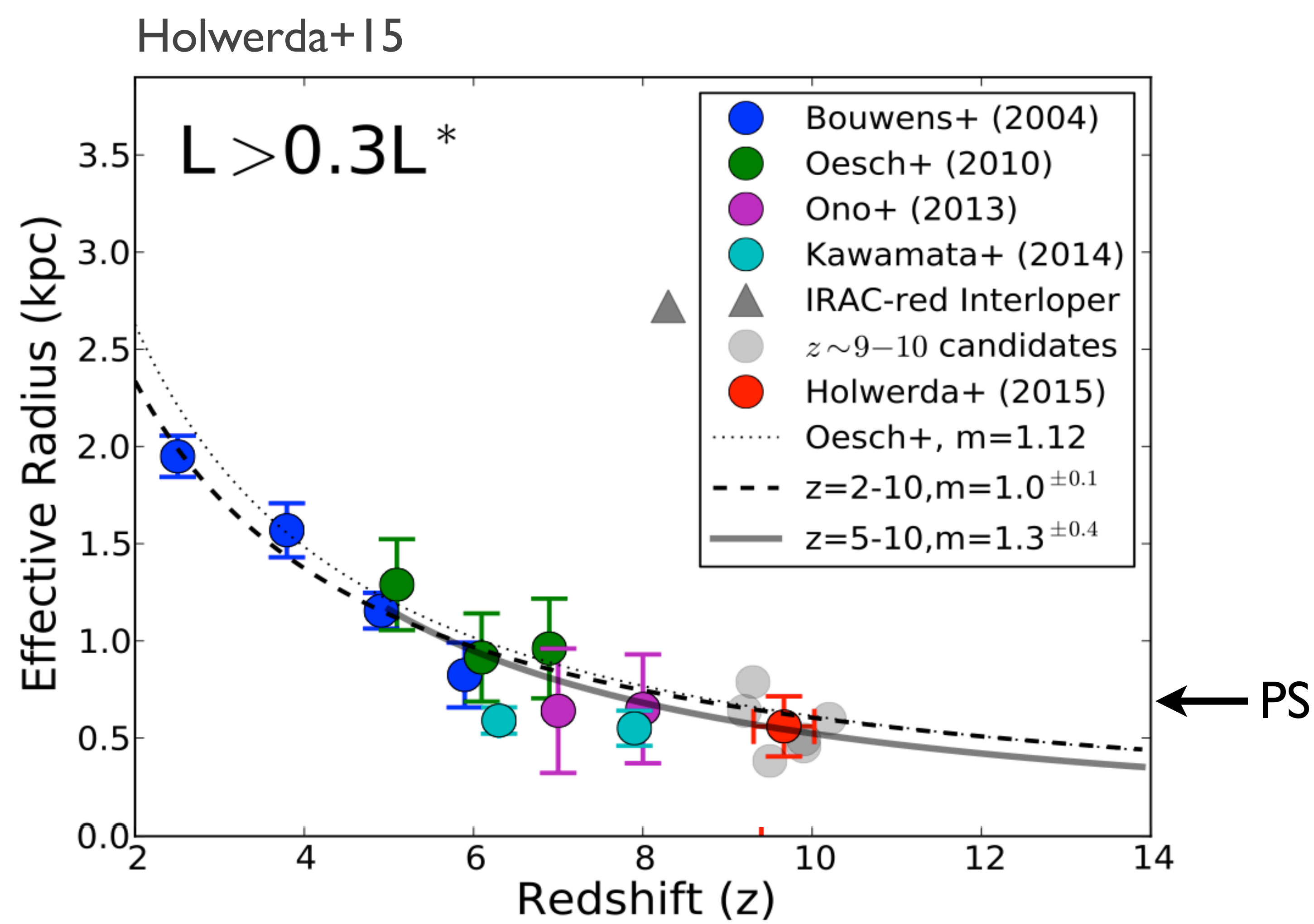


Slide Credit: Marc Postman (HDST Team)

Early Galaxies at HST Resolution



Oesch et al. 2010b

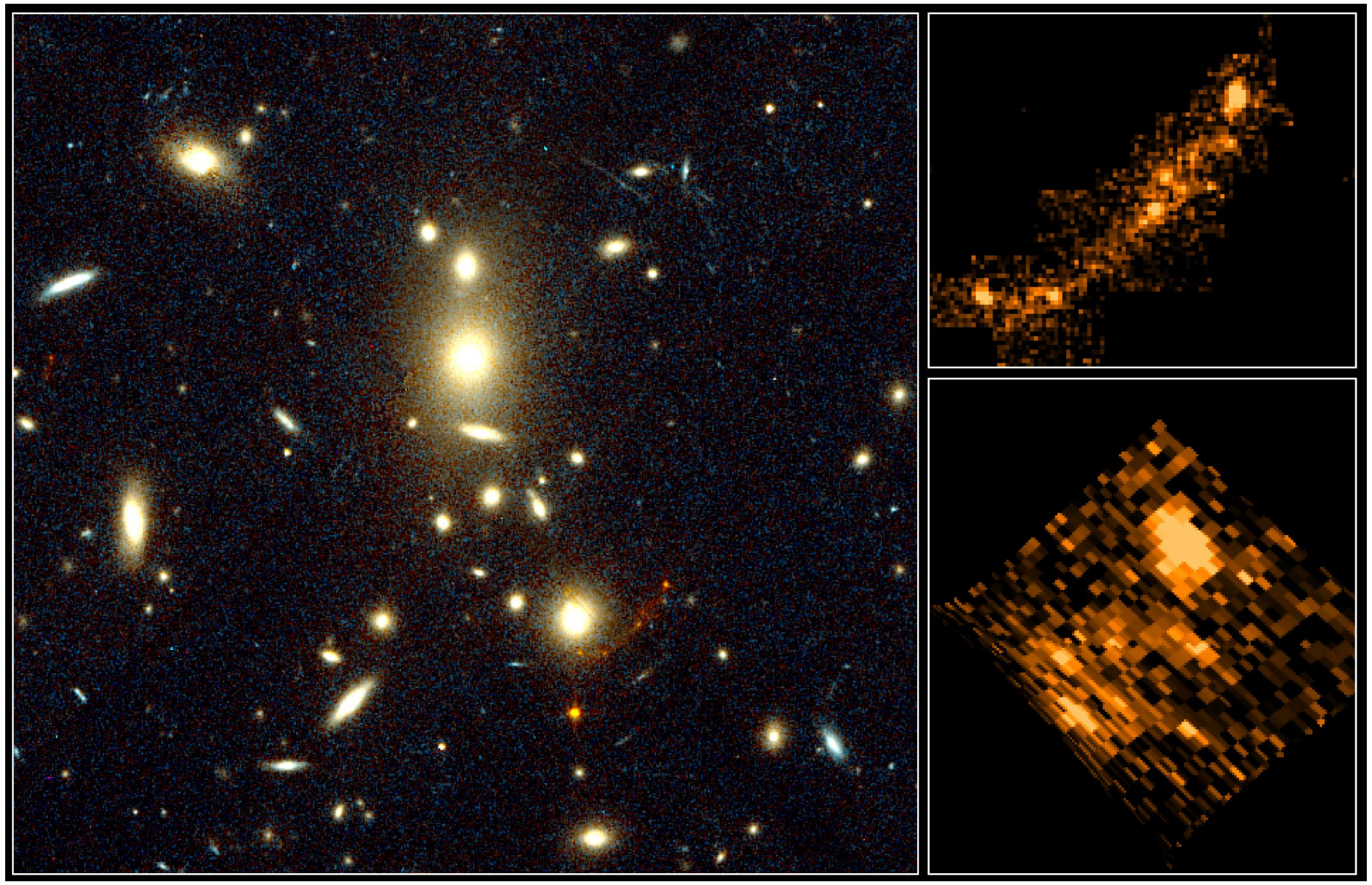


With current resolution, can only marginally resolve early galaxies, get limited information on morphologies.

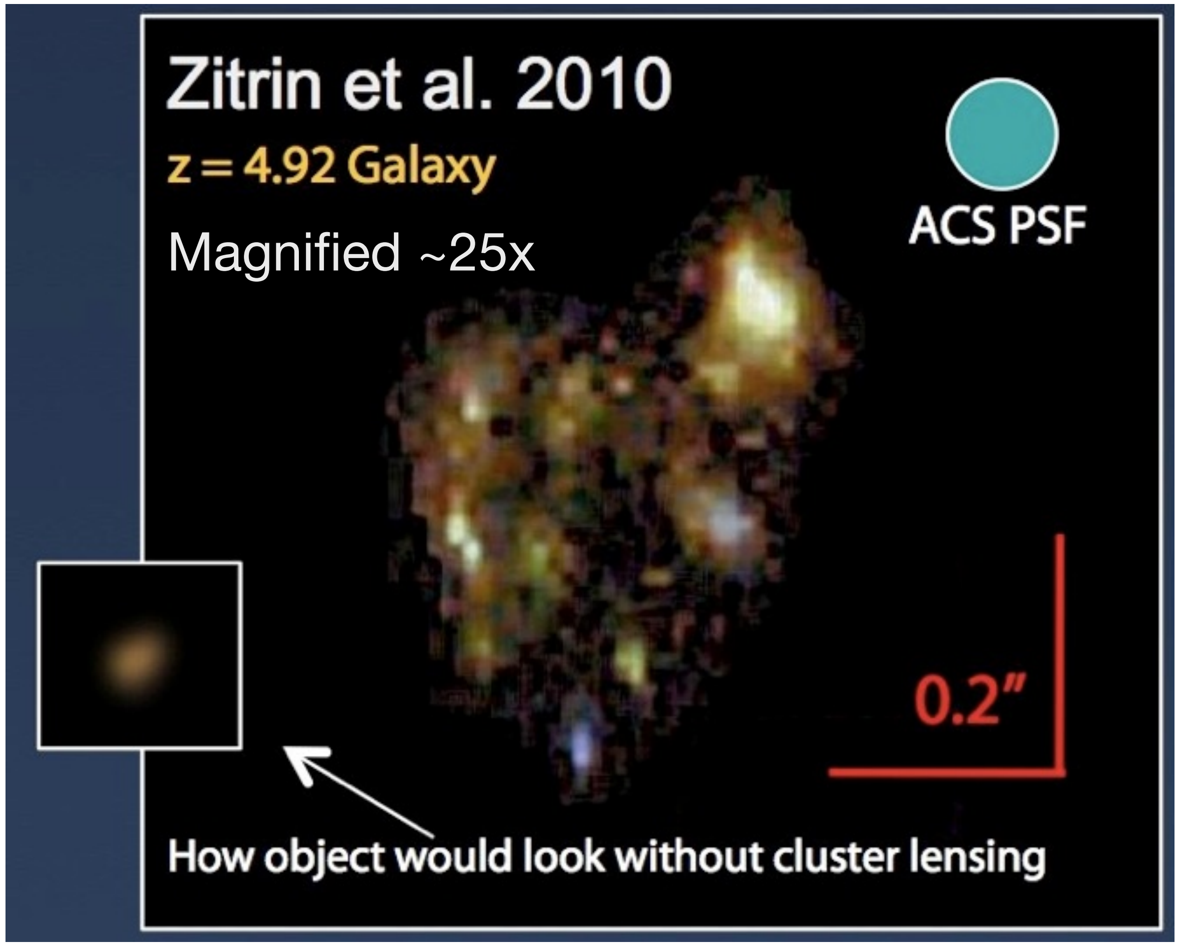
see also: Ferguson+04, Huang+13, Kawamata+15, Curtis-Lake+15

Insight from (very few!) Highly Magnified Galaxies

Lensing by massive foreground clusters enables highly magnified view of early galaxies: but only few known at z>4



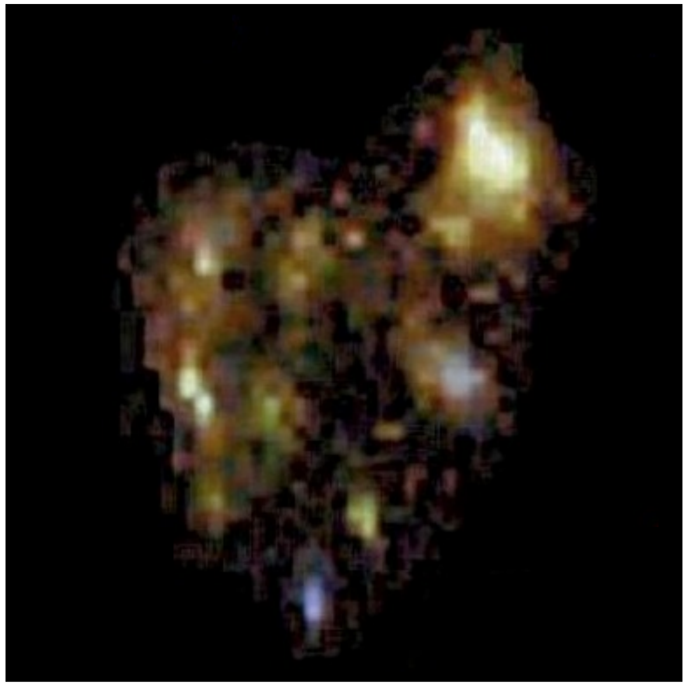
Franx+97



Early galaxies appear to be extremely clumpy, not nicely rotating disks.
UV flux is dominated by individual star-forming regions of just a few 100 parsec in size.

A 12m space telescope would likely reveal a completely new picture of early galaxies!

HDST: Extremely Sensitive Resolved Spectroscopy?



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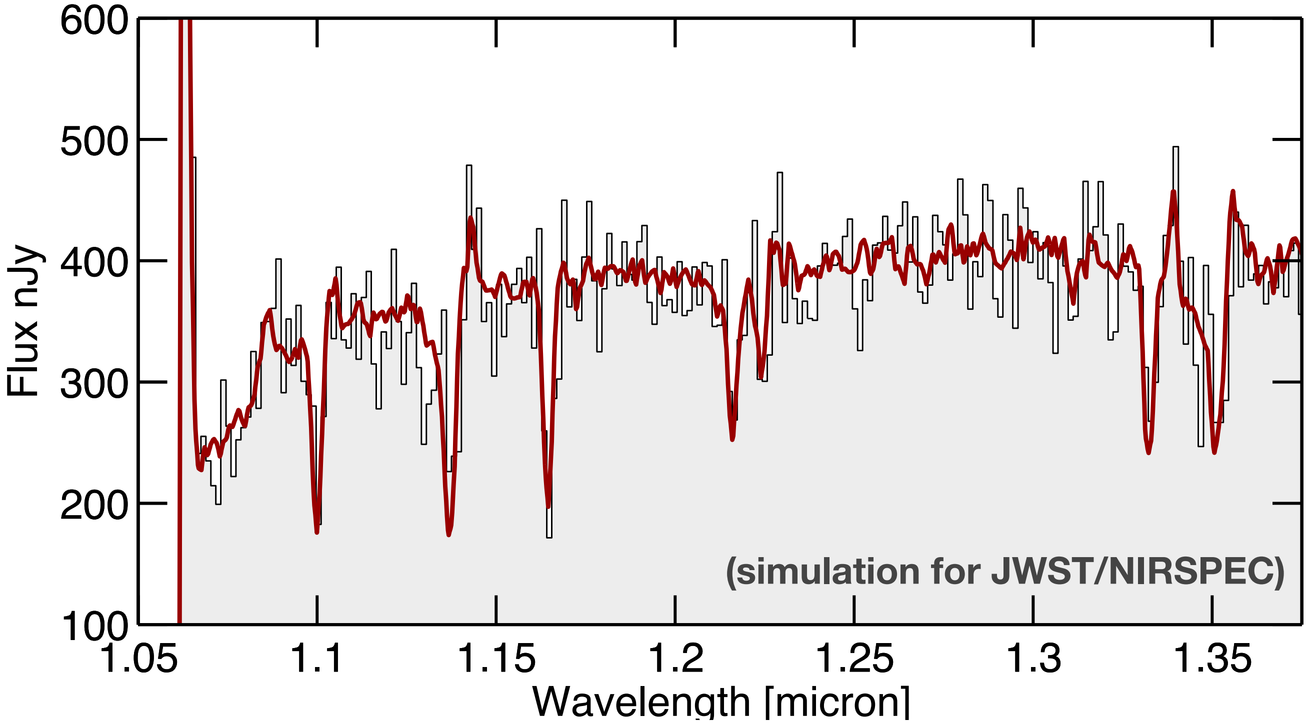

High spatial resolution coupled with much more sensitive spectroscopy:

revolutionary insight into the dynamical states, chemical enrichment, and ISM properties even at the earliest redshifts.

This is completely unexplored territory and could only be achieved by a large aperture space telescope.

Some Questions we Could Address with an HDST

- Did galaxies reionize the universe? (probe bulk of UV and SFR density at z>6 + constrain evolution of ionizing escape fraction out to z~3)
- What physics determine the star-formation efficiencies in very low mass galaxies during the epoch of reionization? (test cutoff in UV LFs)
- How large are early galaxies and what are their morphologies, i.e. how clumpy are they? (probe the assembly of SF regions at ~100 pc resolution)
- What are the dynamical states and resolved ISM properties of early galaxies? (resolved spectroscopy)

Summary

- Over the last 25 years, the HST has **pushed back** our observational **horizon** of galaxies to only **~500 Myr** after the Big Bang
- **HST** is the centerpiece in the exploration of **galaxy build-up at the cosmic dawn:** current horizon at z~9-10
- **Combination of HST and Spitzer/IRAC is extremely powerful** to probe the stellar **mass build-up** out **to z~10** and even rest-frame optical **emission lines**
- **HST** resolution **UV** imaging data are **only now being taken** over large areas: probe star-formation on 100 Myr timescale + escape fraction of ionizing photons
- A **12m space telescope** would completely **revolutionize** our understanding of early galaxies, and probe physics which are currenly competely out of reach