(One Science Case for Extensive)
Spectroscopic Follow-up of Euclid

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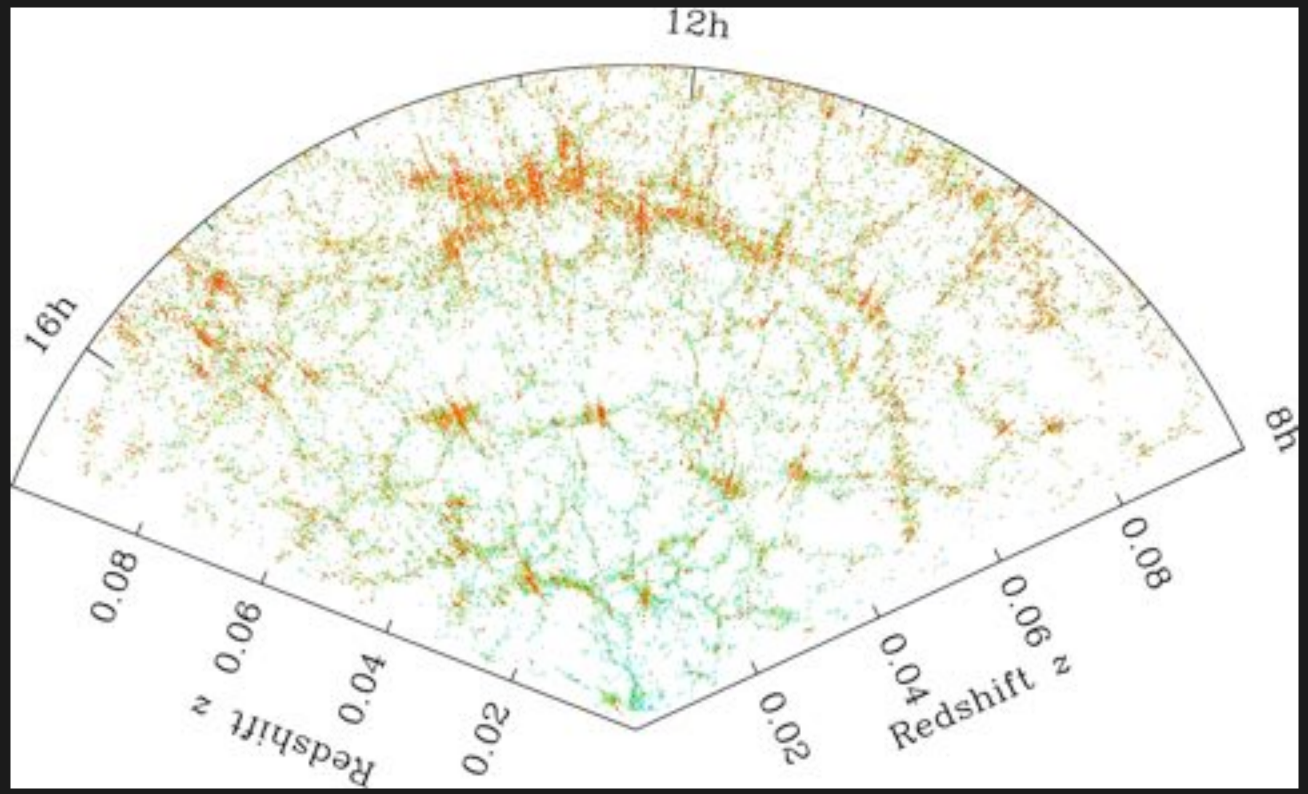
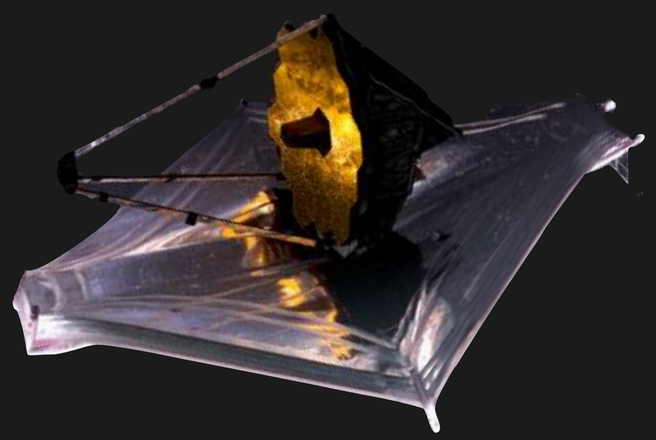
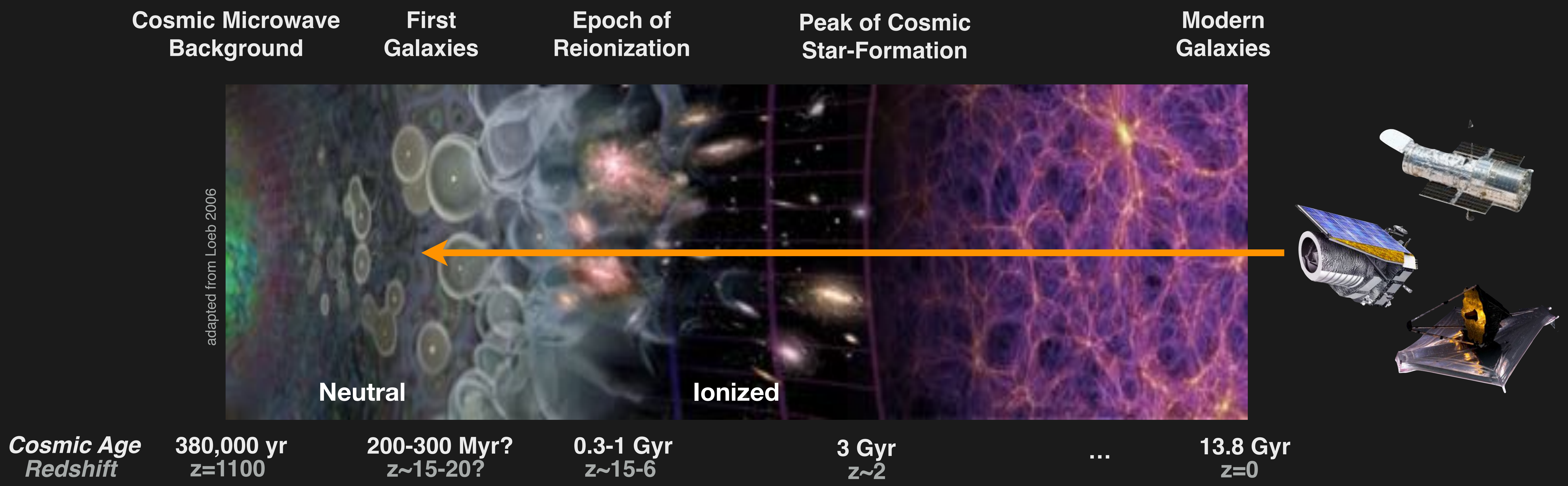
ESA/ESO Workshop Madrid, Oct 2022

The Synergy Between Imaging and Spectroscopy





Cosmic Dawn: The First 1 Gyr of Cosmic History



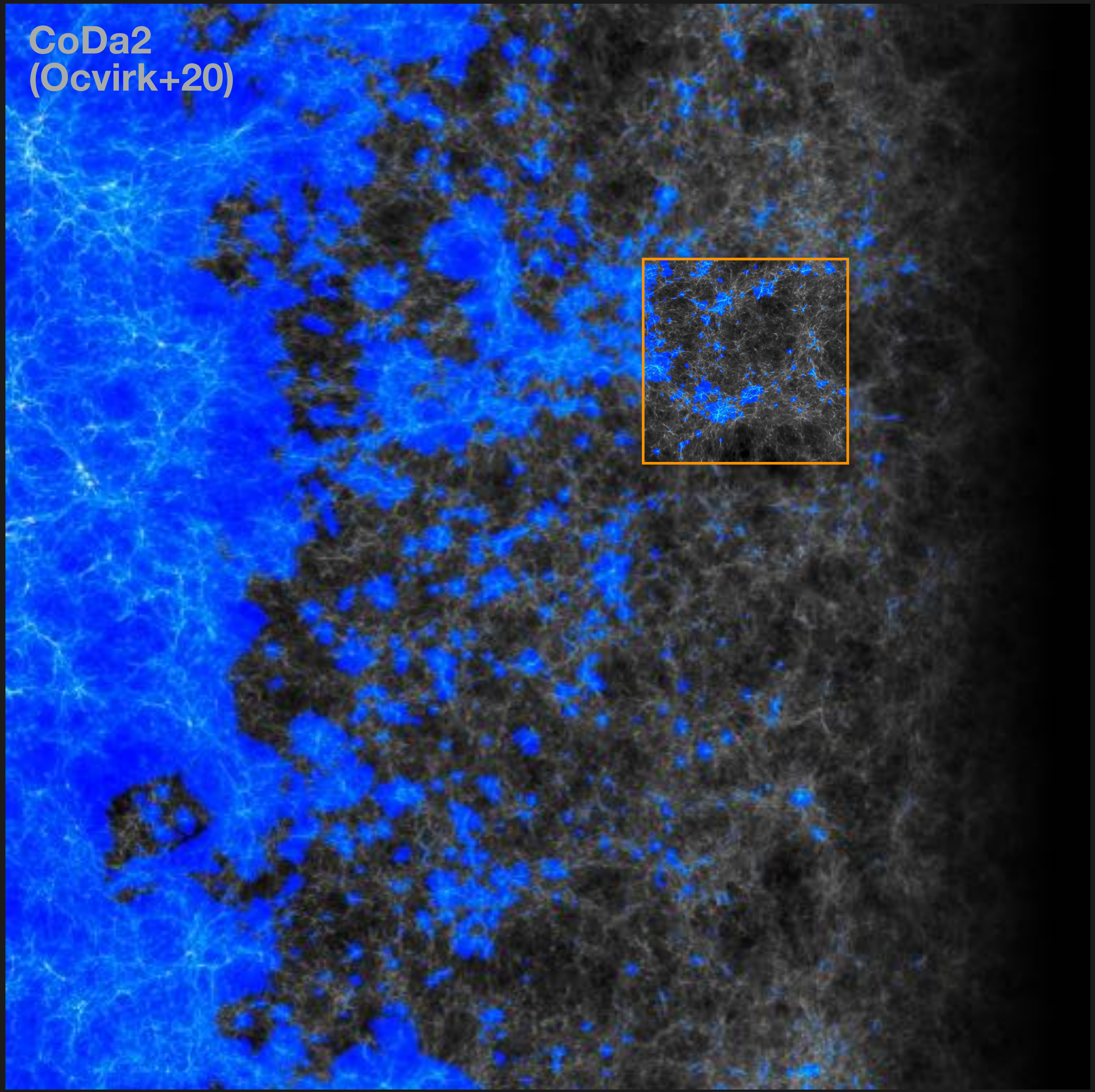
When and how did the first galaxies form?

How did they contribute to cosmic reionization?

How is this connected to the underlying DM skeleton?

Large Scale Structure - First Galaxies - Reionization

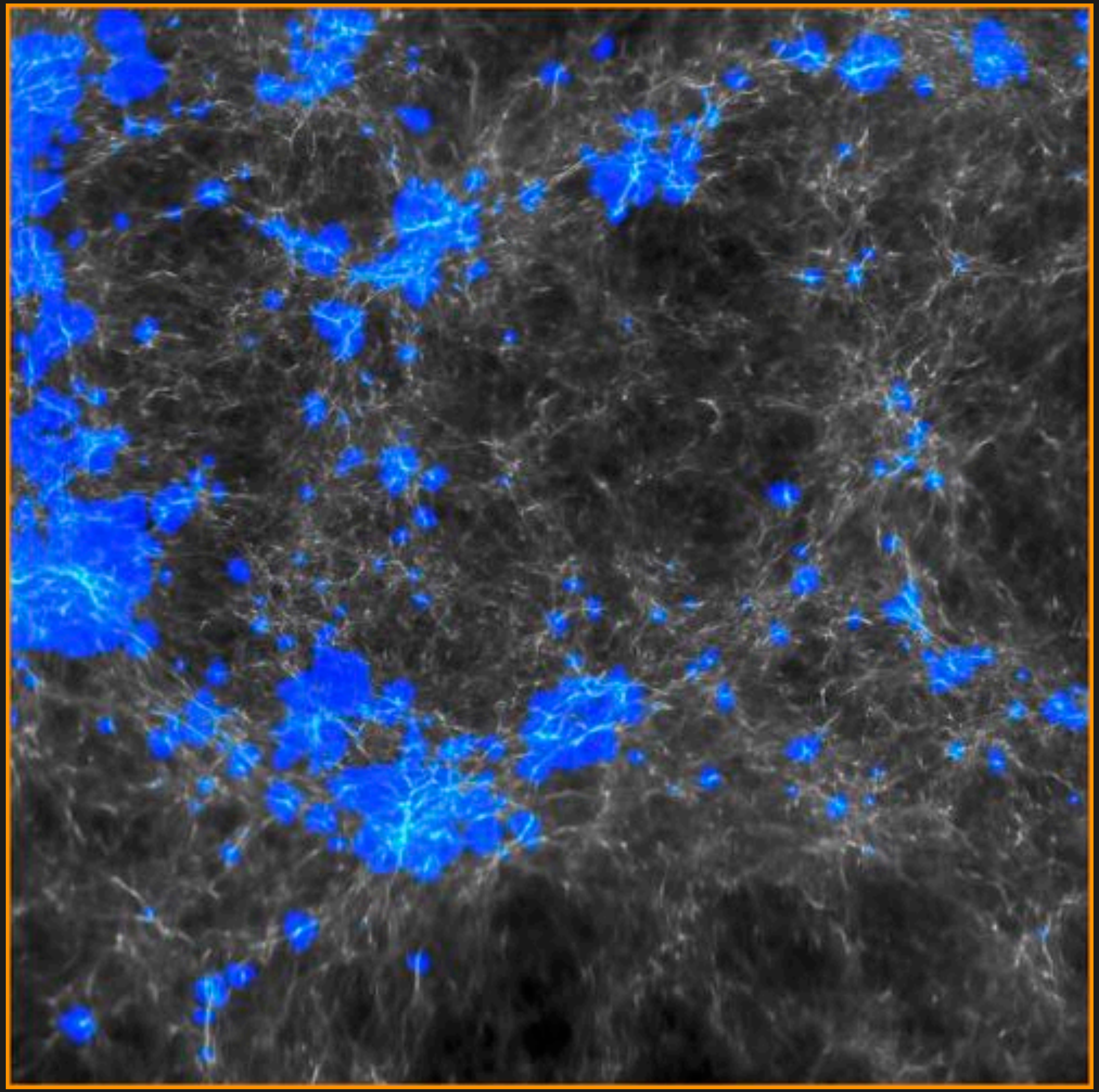
gray: DM density
blue: photo-ionized

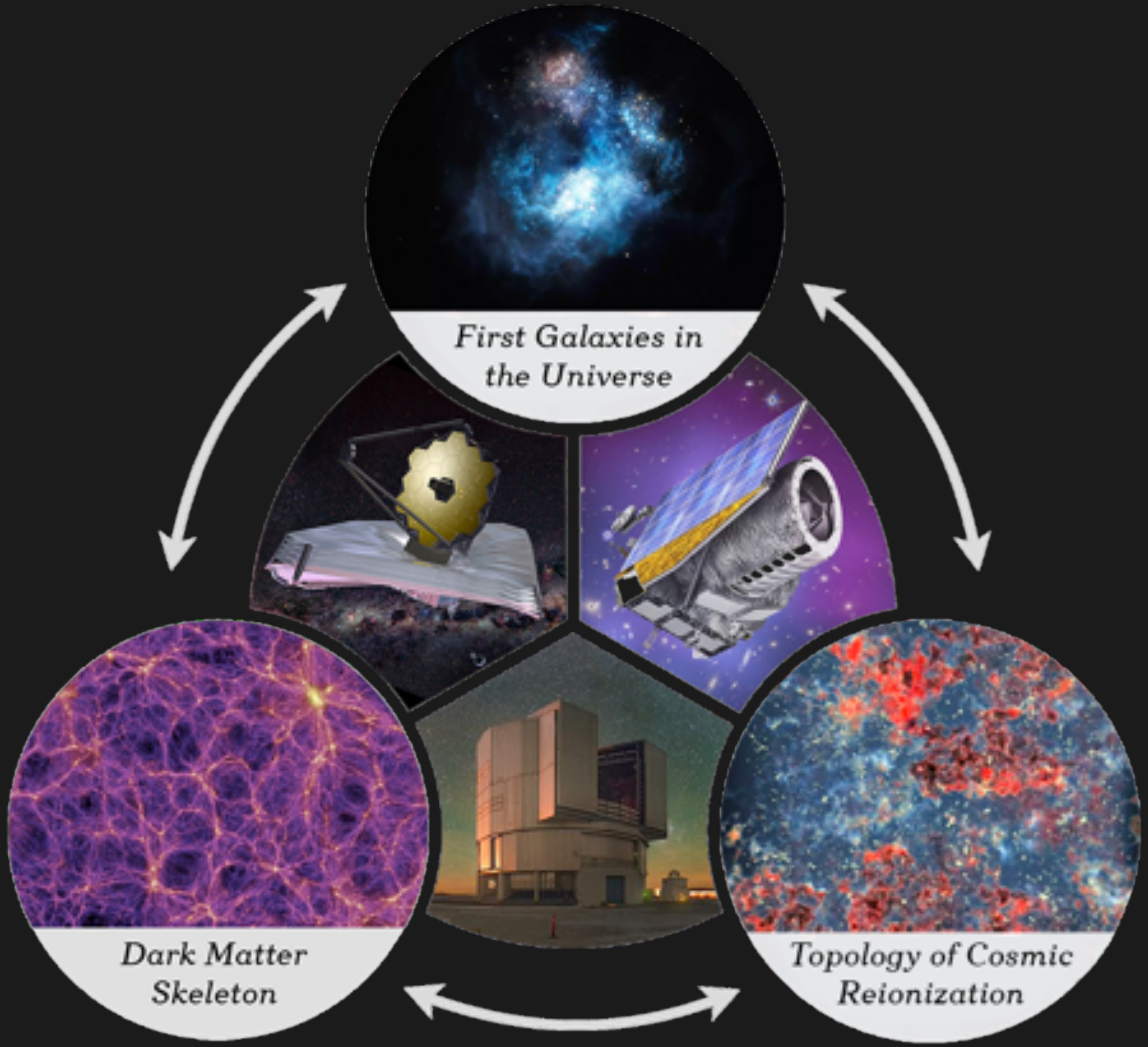


94 cMpc
=
0.6 deg @ z=8

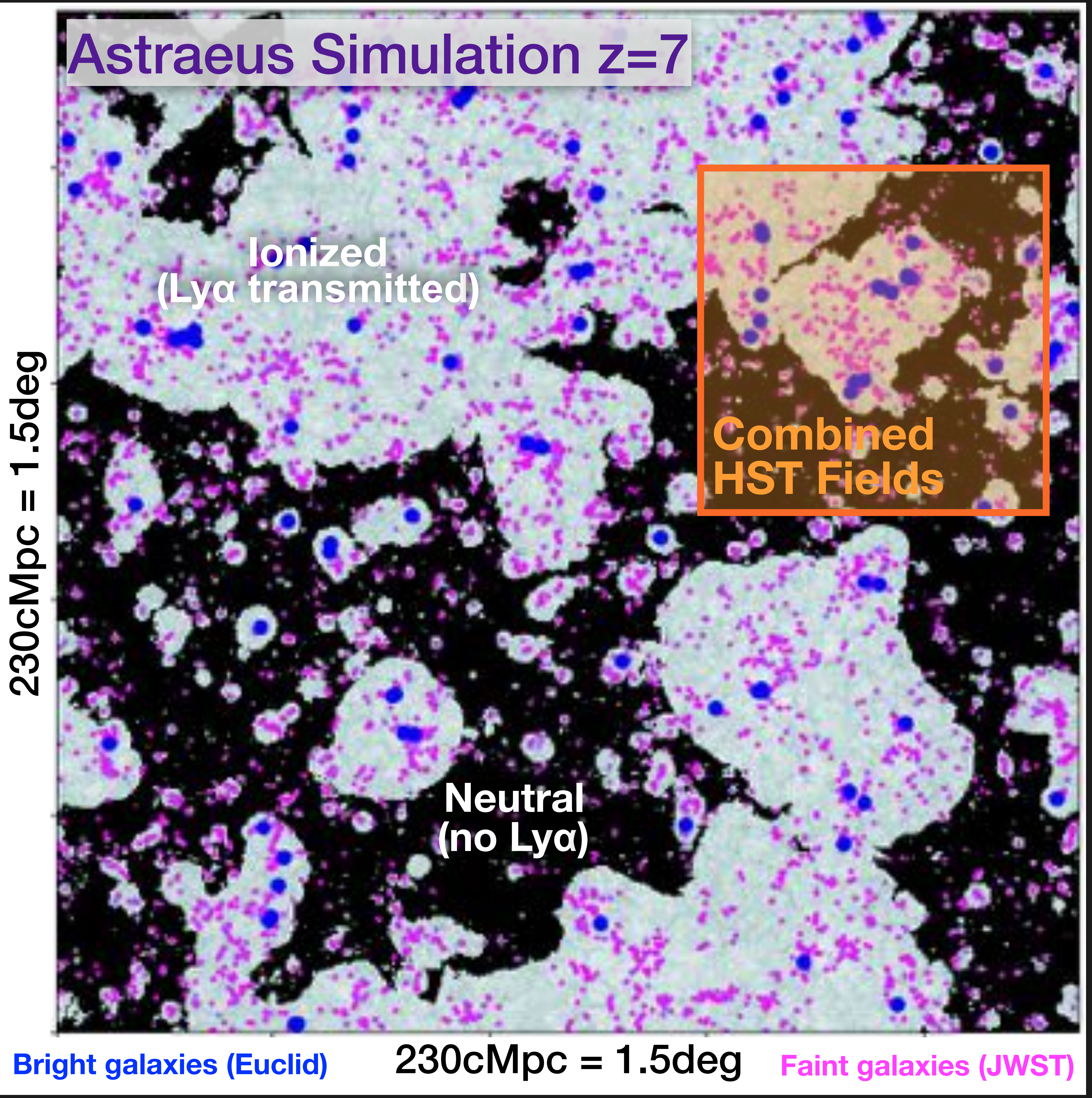
z=5.8 ⟵ Time z=150

Large Scale Structure - First Galaxies - Reionization





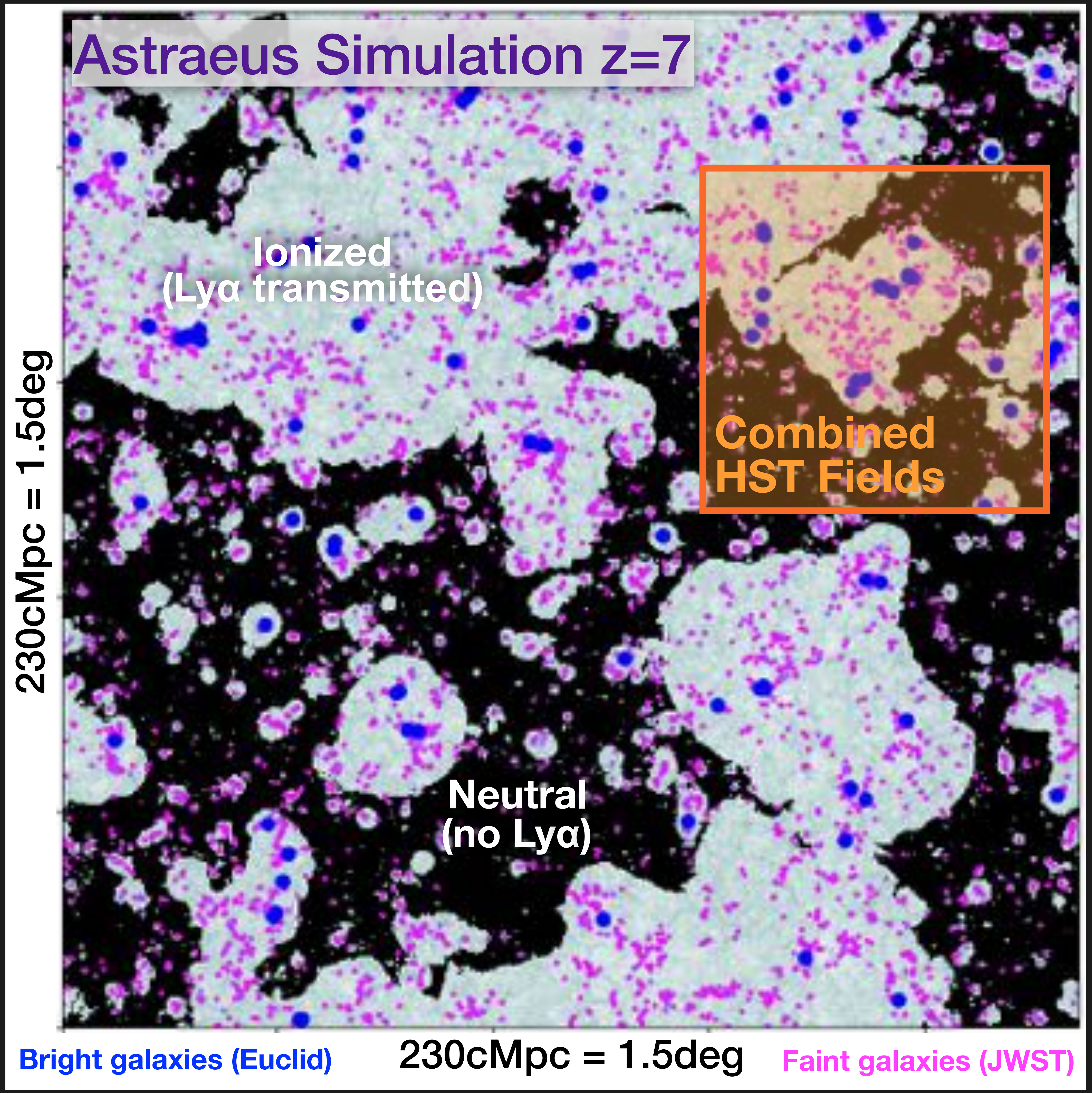
Reionization: a complex multi-scale problem



See, e.g., Hutter+20

- Simulations show: Reionization is inhomogeneous, starts first in overdense regions
- Brightest galaxies expected to be the **signposts of early reionization bubbles**
- Survey area of several **deg²** required, otherwise might miss the sites of the most massive halos, where reionization and galaxy build-up started
- Euclid/Deep Fields!

Reionization: a complex multi-scale problem



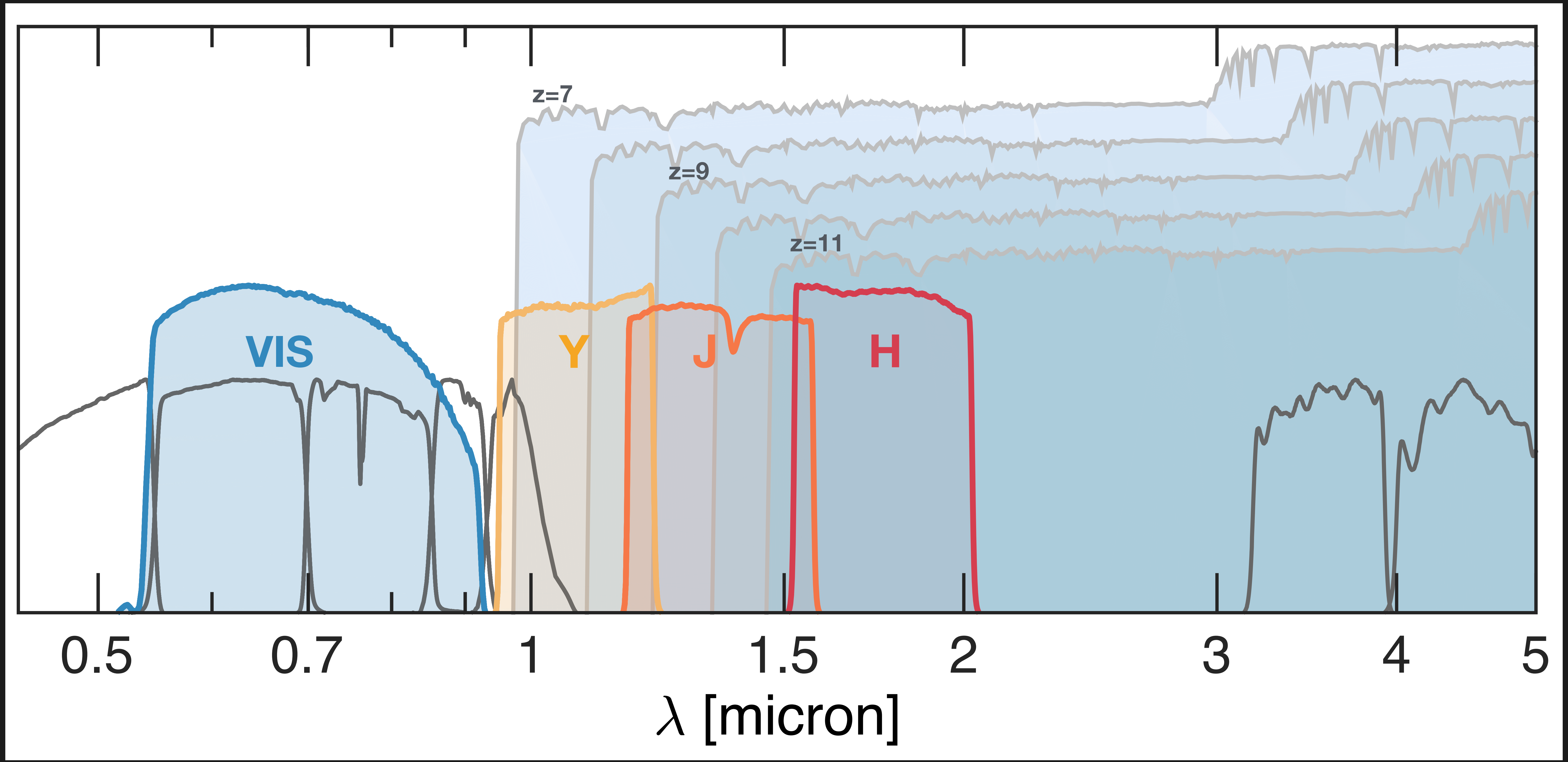
See, e.g., Hutter+20

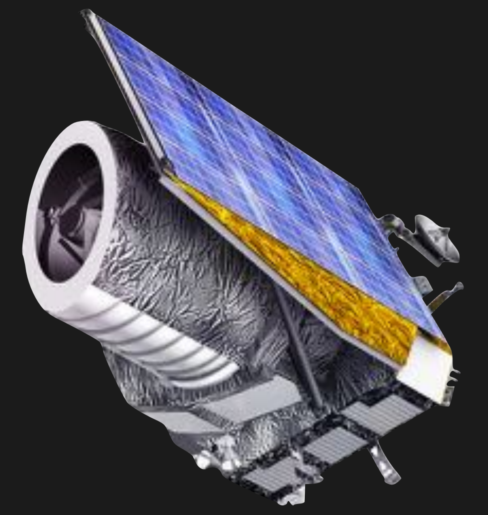
Euclid/Deep Fields:
50deg² YJH imaging to 26 mag
to find rare overdensities

VLT/MOONS:
Multi-Object Spectroscopy 0.6-1.8 μm
to confirm ionized regions through Lyα

JWST:
NIR imaging & spectroscopy
of the drivers of reionization

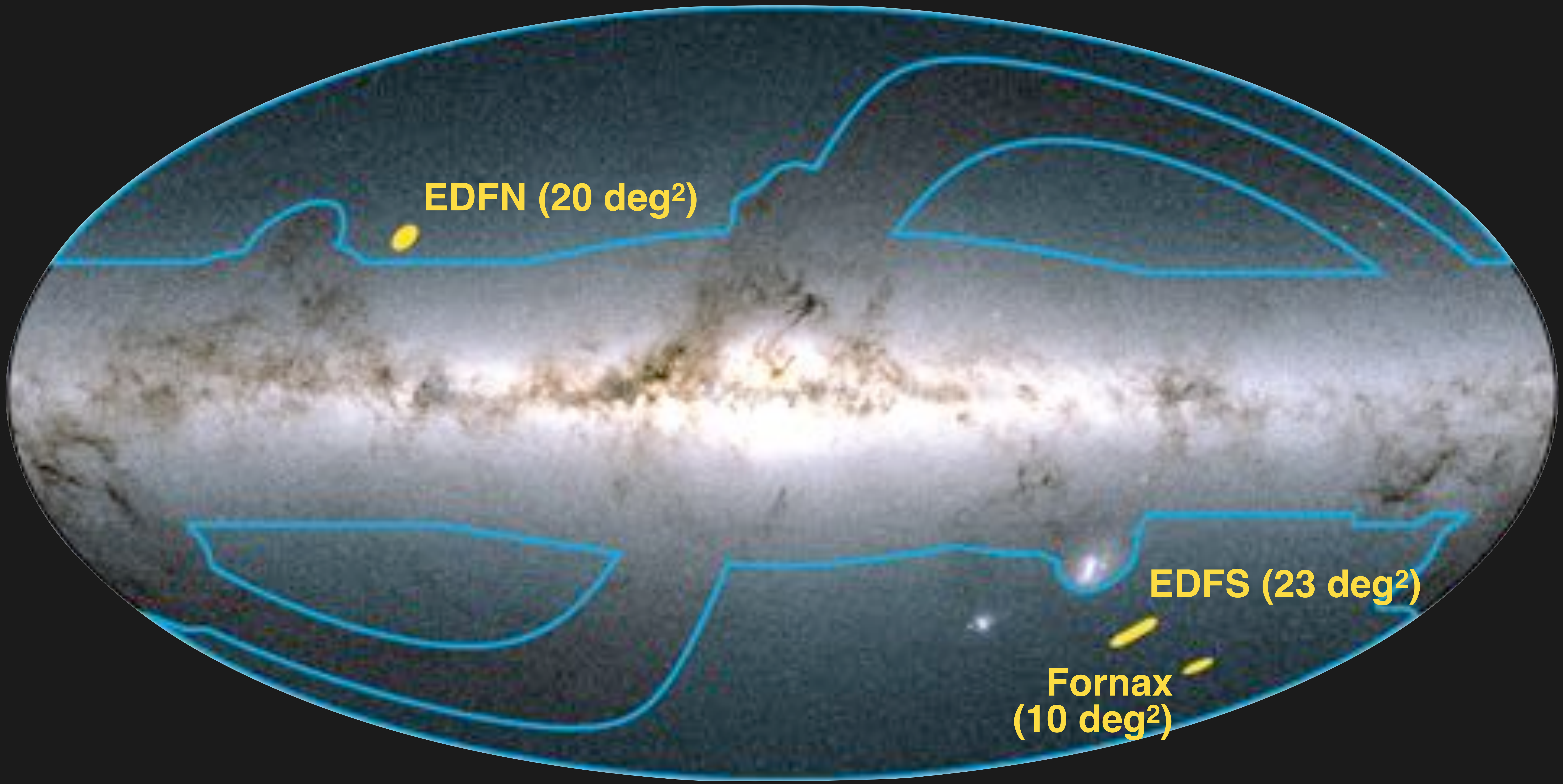
Euclid's Power to Identify Very Early Galaxies

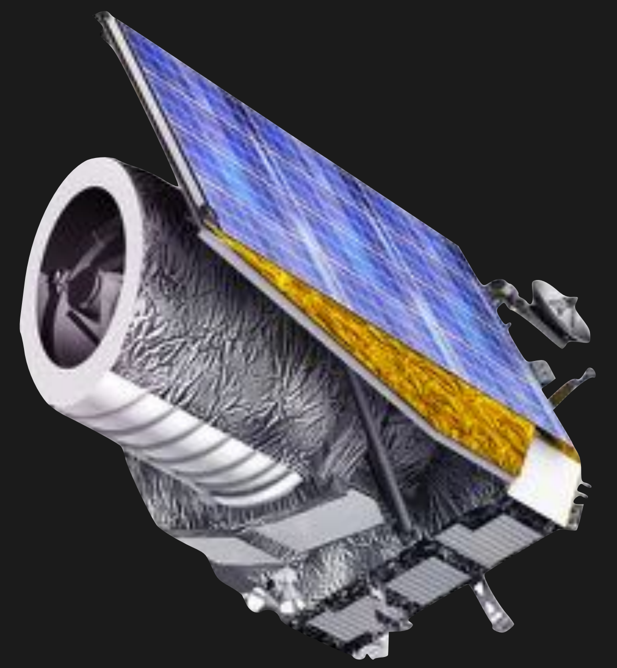




Galaxies during the Epoch of Reionization:
Invisible in the optical due to absorption of rest-UV photons by neutral hydrogen
NIR imaging needed for detections

Euclid's Deep + Calibration Fields

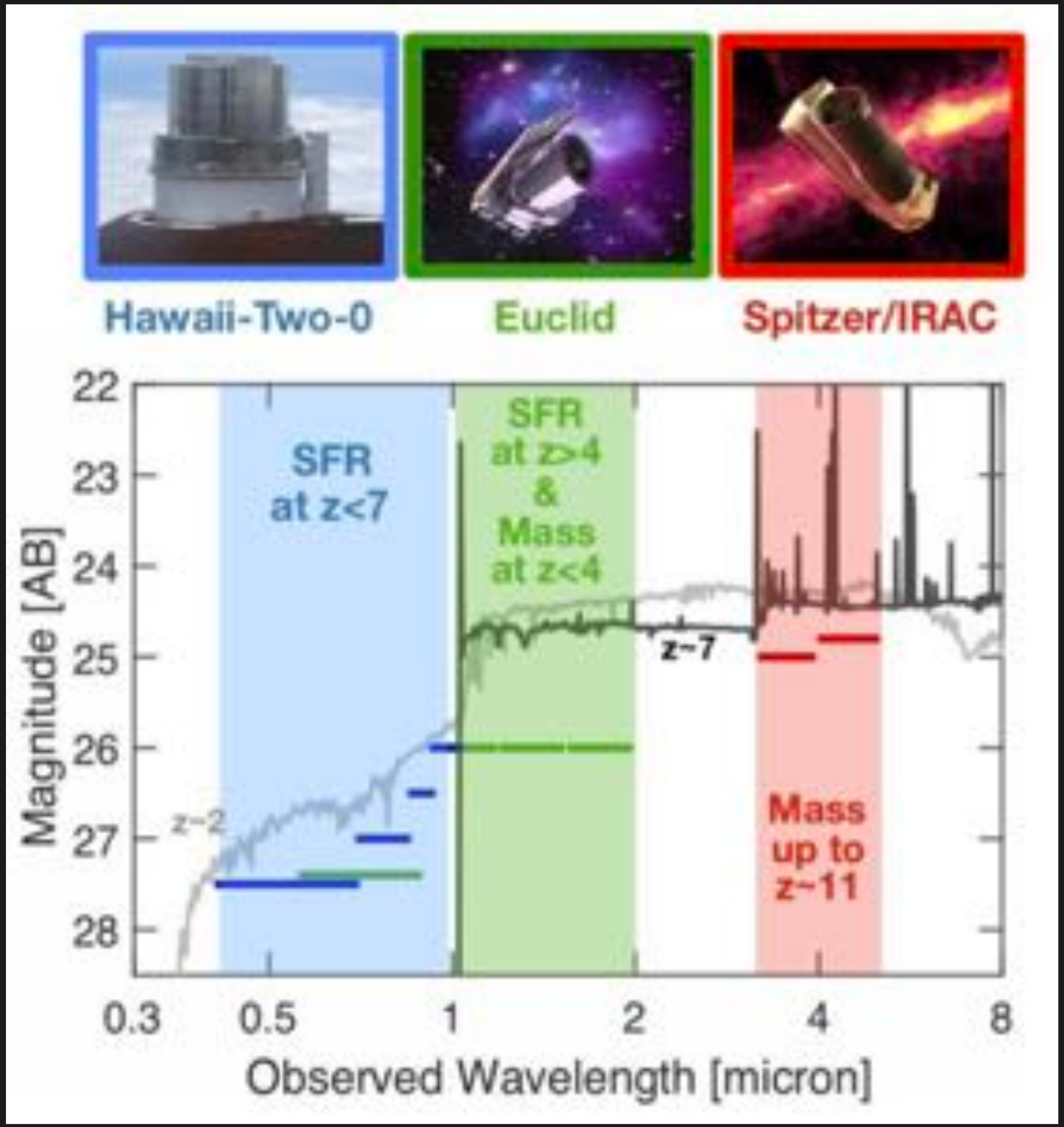


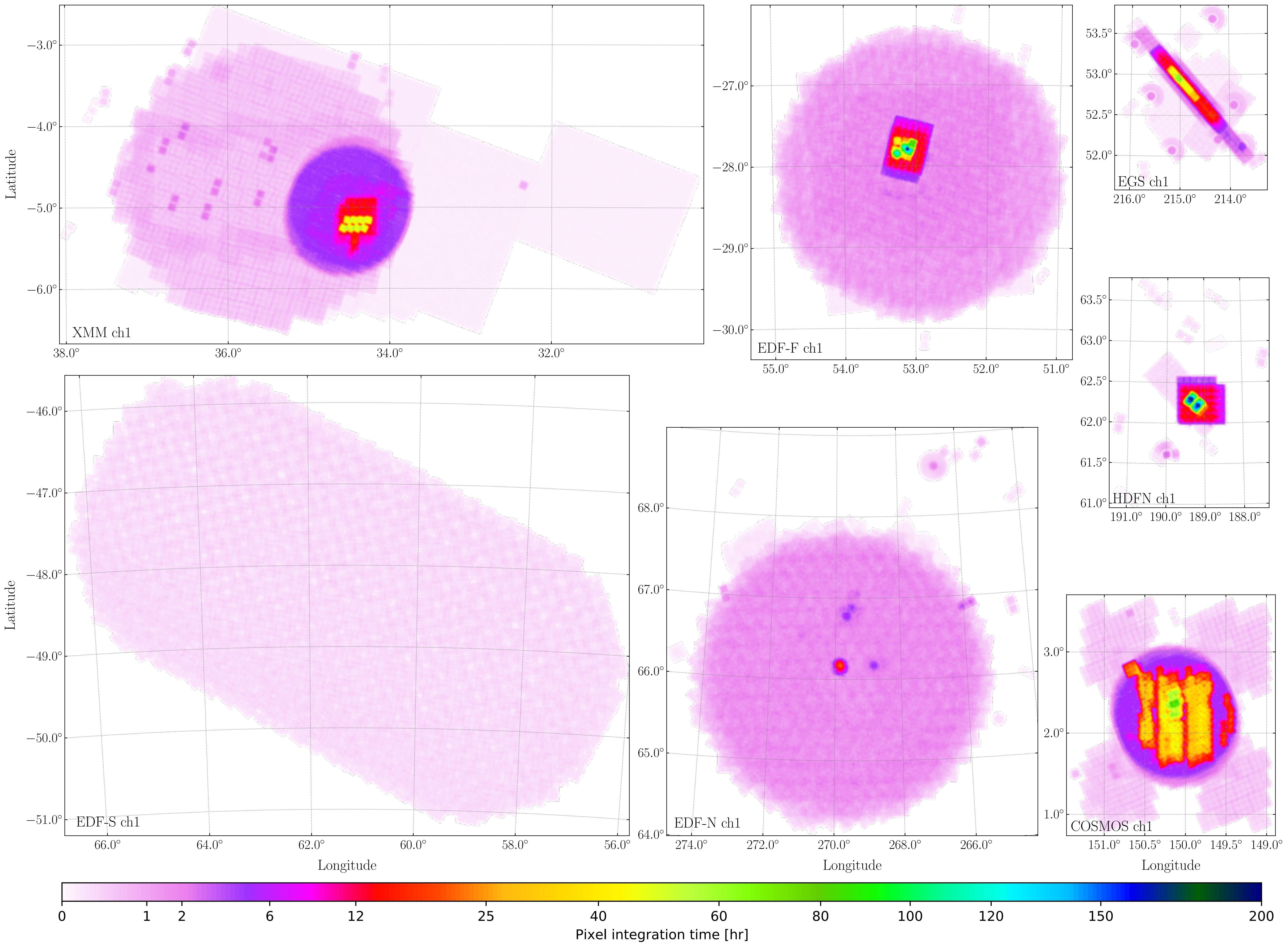


Focus on:

- **53 deg²** DEEP Fields (VIS=27mag, NIR=26mag)
- **6.8 deg²** Photo-z Calibration Fields (5 previous extragalactic fields)
- **1-4 deg²** Self-Calibration Field (NEP)

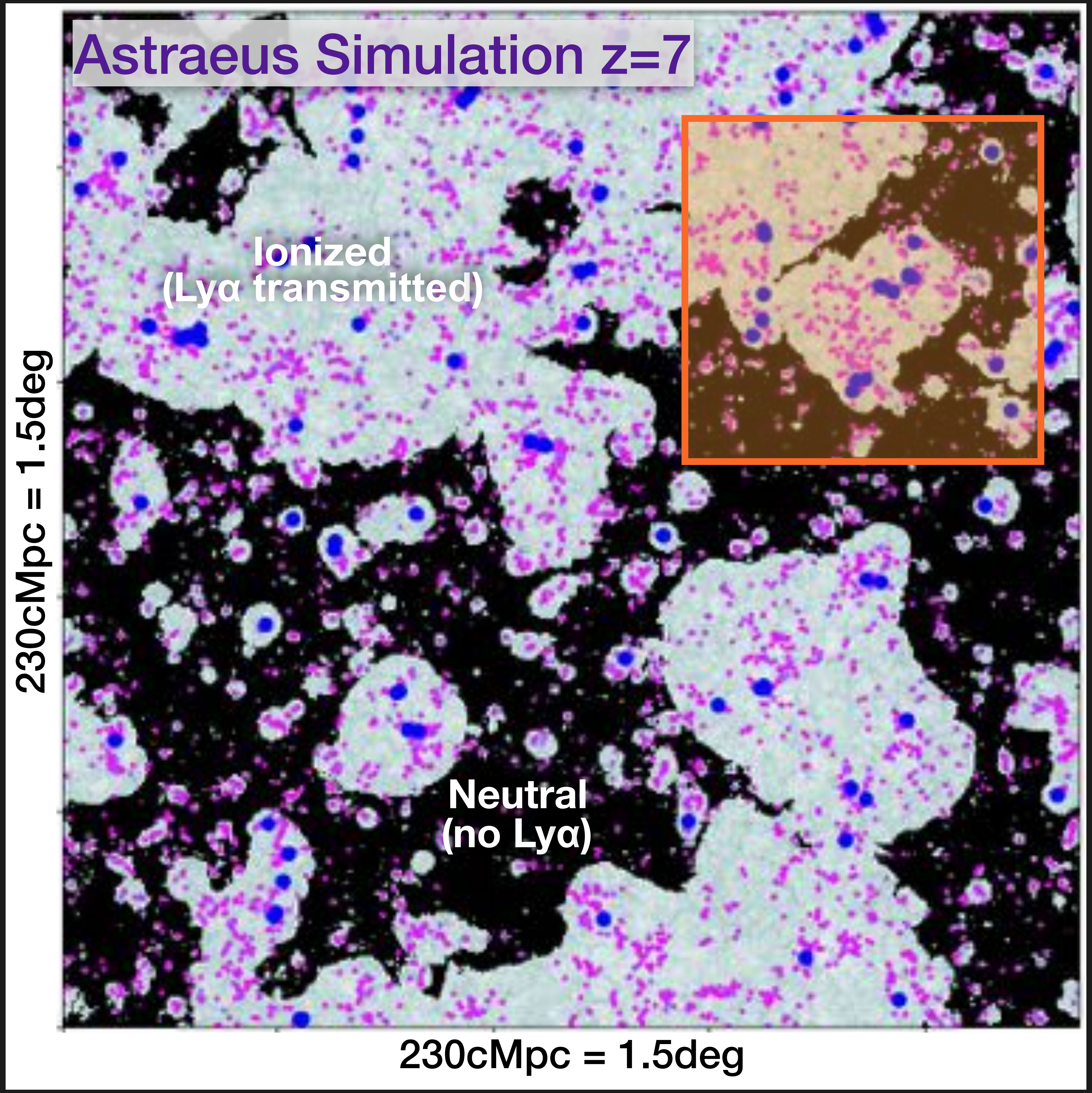
Spitzer Coverage in the Euclid Deep + Calibration Fields



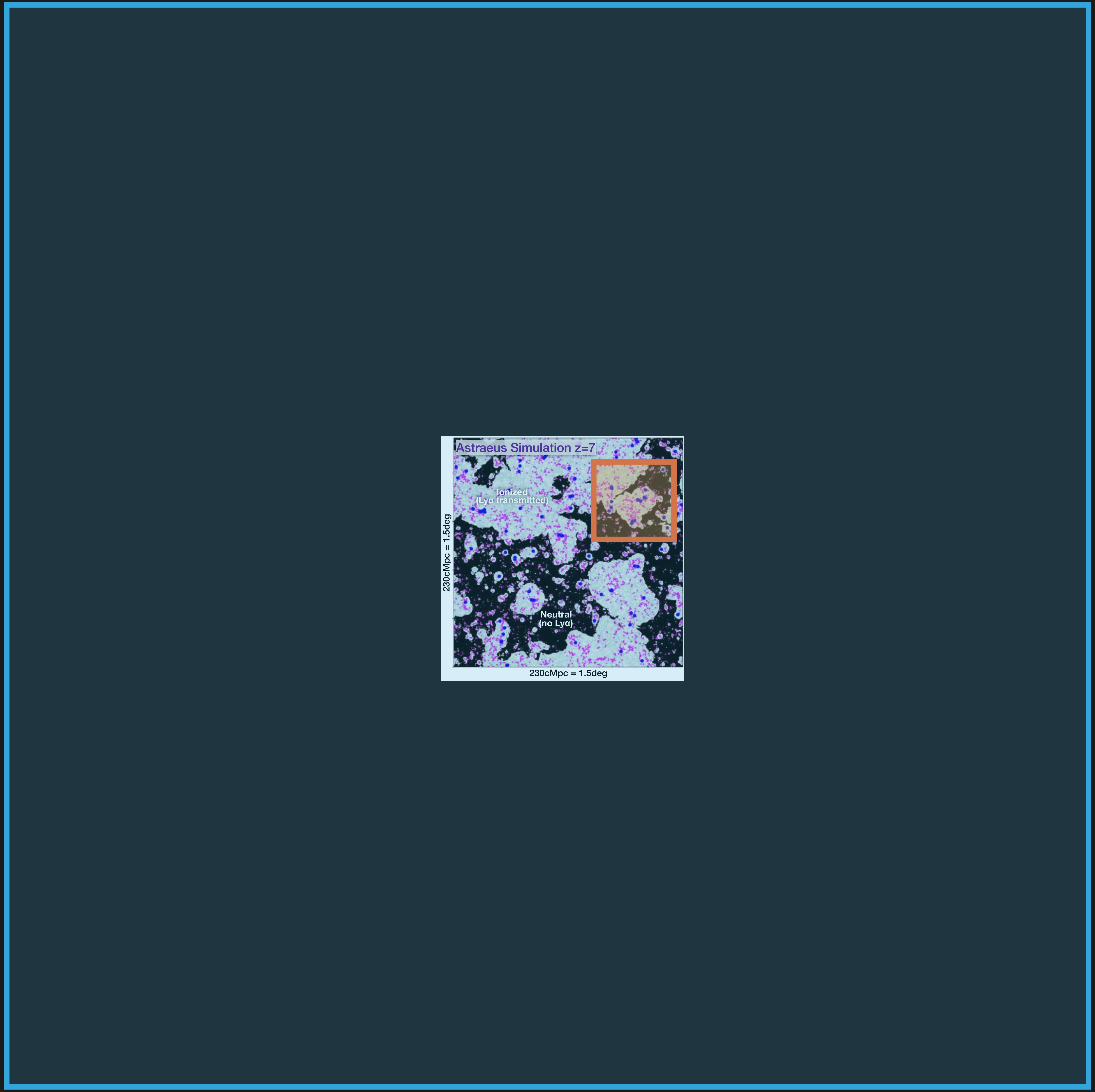


Moneti+22

Euclid Deep


Astraeus Simulation z=7
Ionized
(Lyα transmitted)
Neutral
(no Lyα)
230cMpc = 1.5deg
230cMpc = 1.5deg

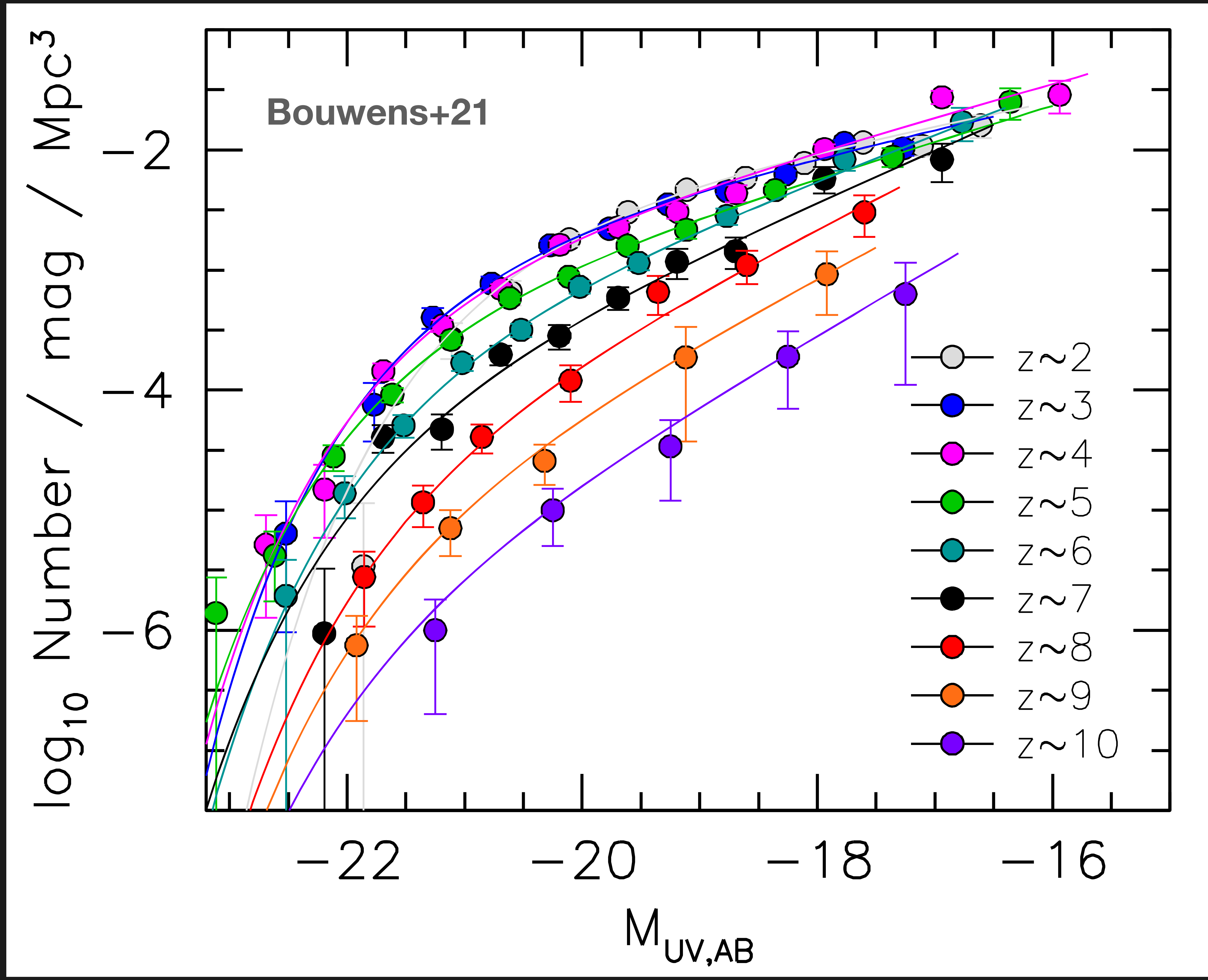
Euclid Deep

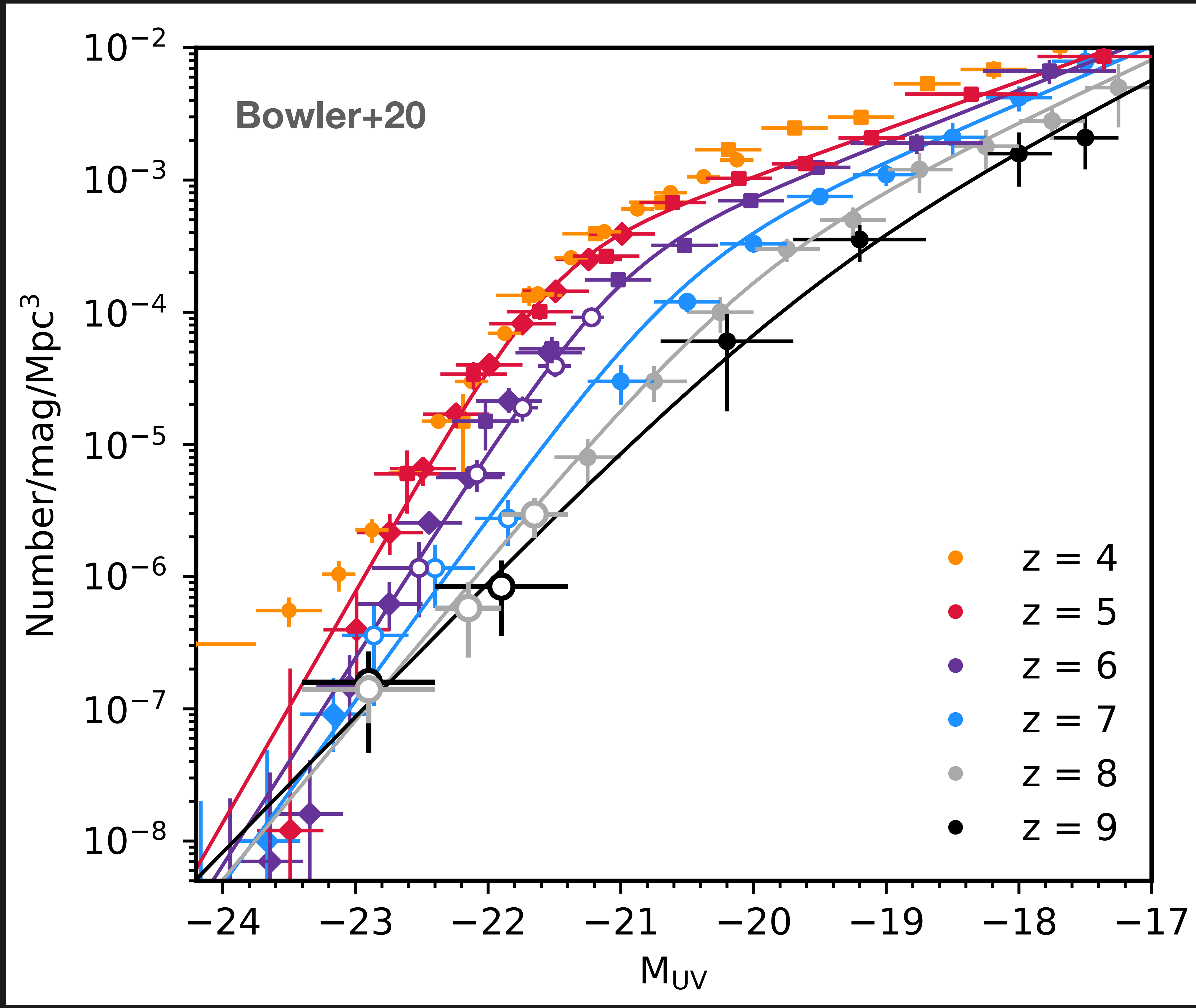


Astraeus Simulation z=7
Ionized
(Lyα transmitted)
Neutral
(no Lyα)
230cMpc = 1.5deg
230cMpc = 1.5deg

How Many Galaxies will Euclid Detect at z>6?

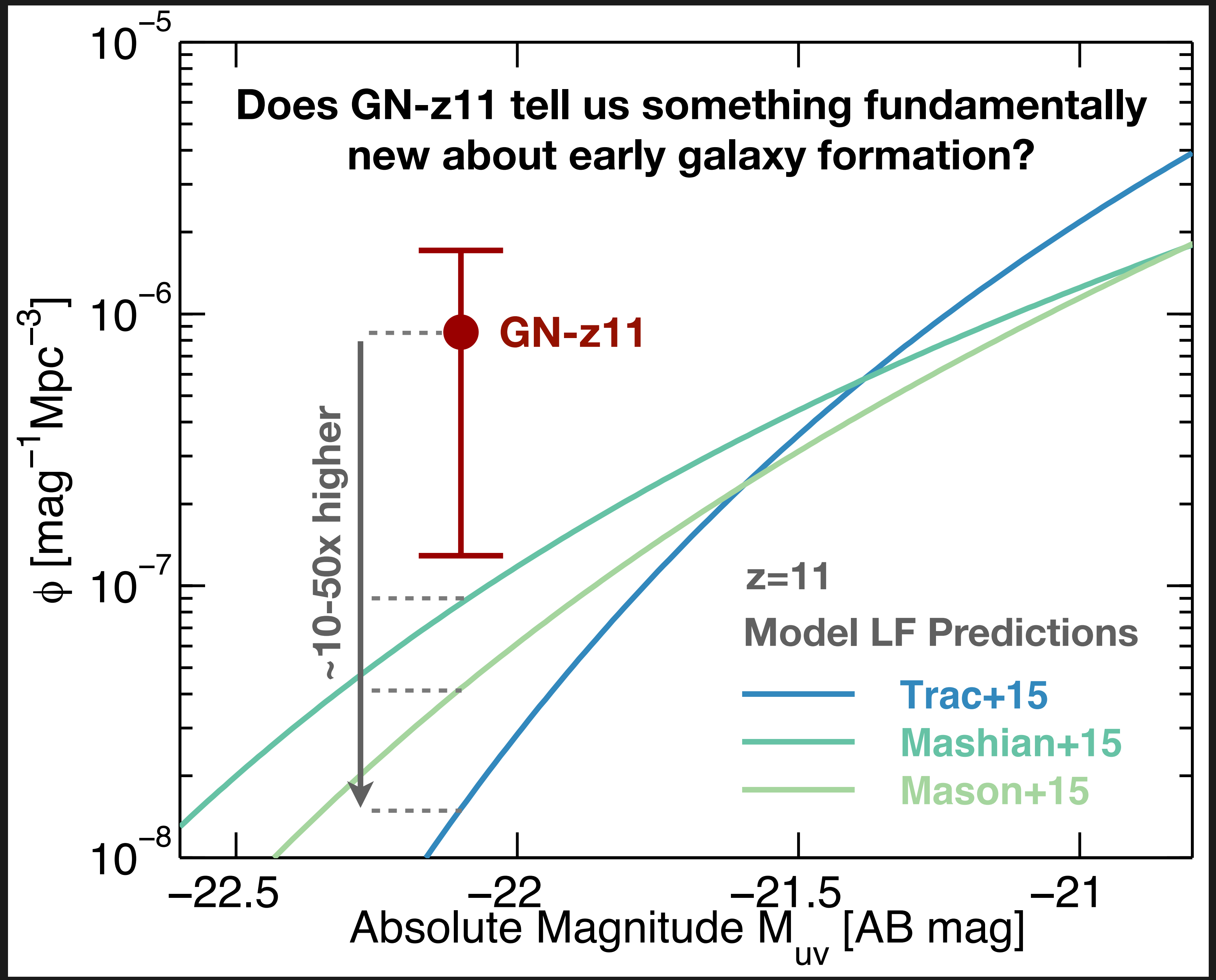
Schechter vs Double-Power Law LF

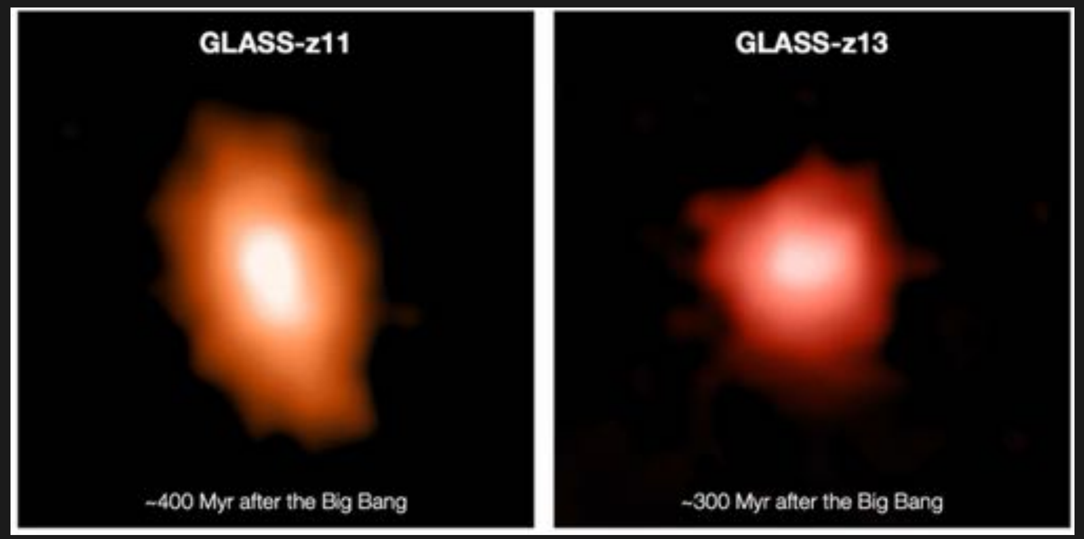


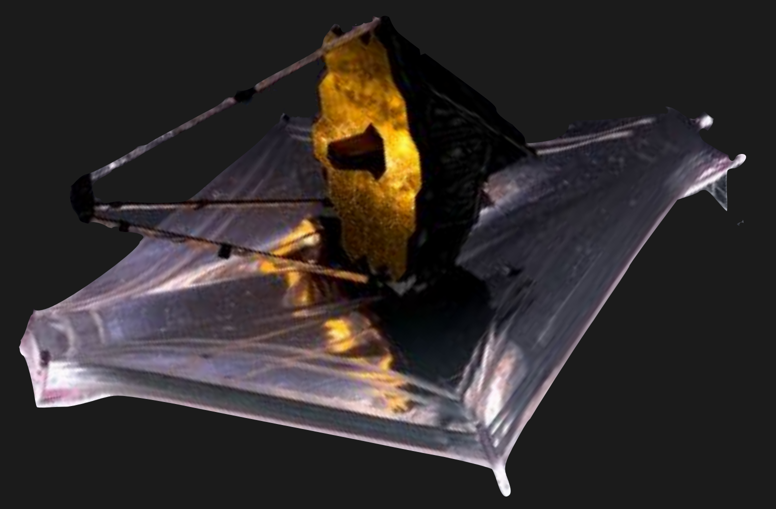


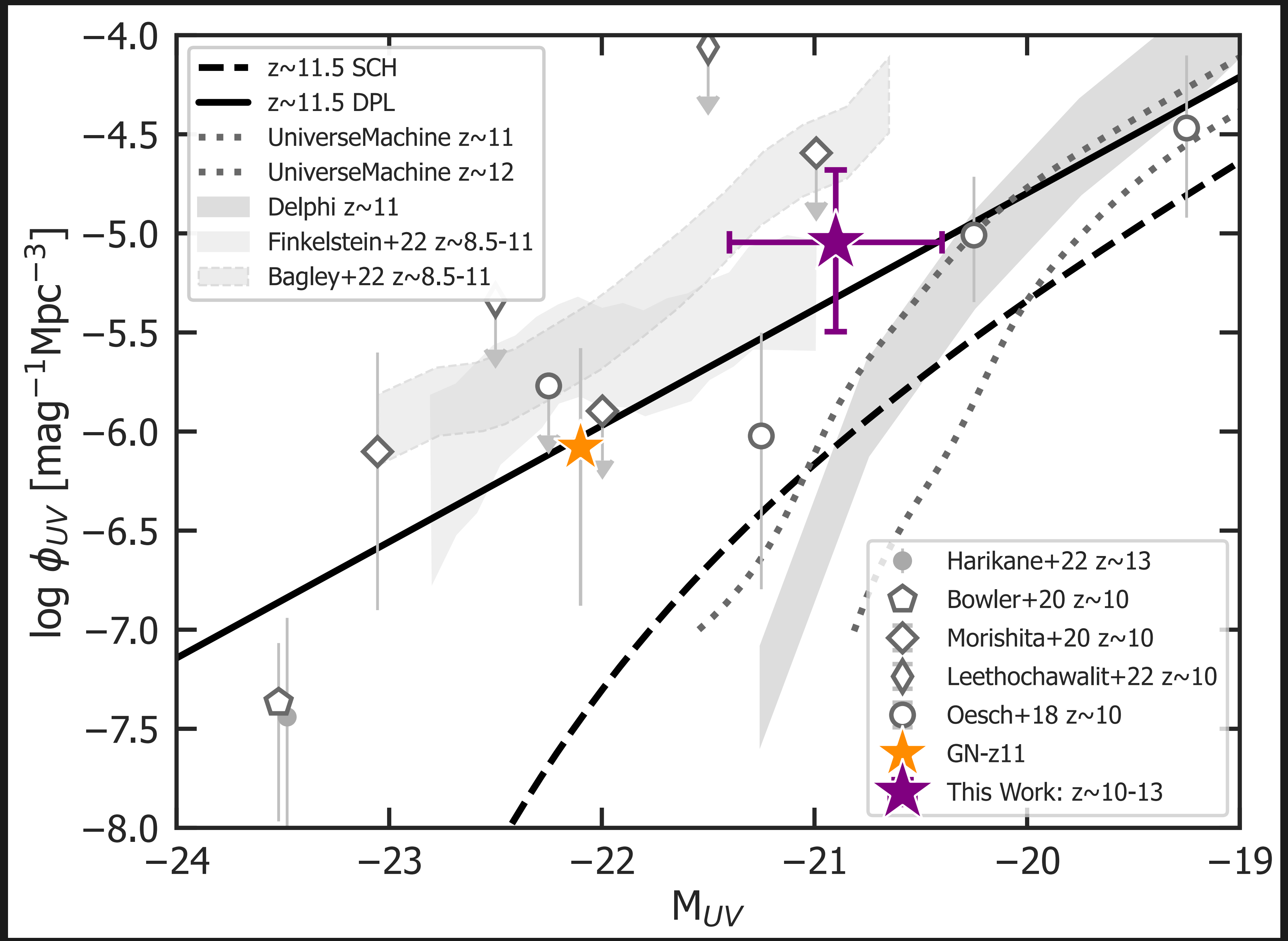
Euclid/Deep
z~8 -> ~3000-4000 galaxies
z~10 -> 80 vs 500 galaxies

A high abundance of luminous sources at z>9?







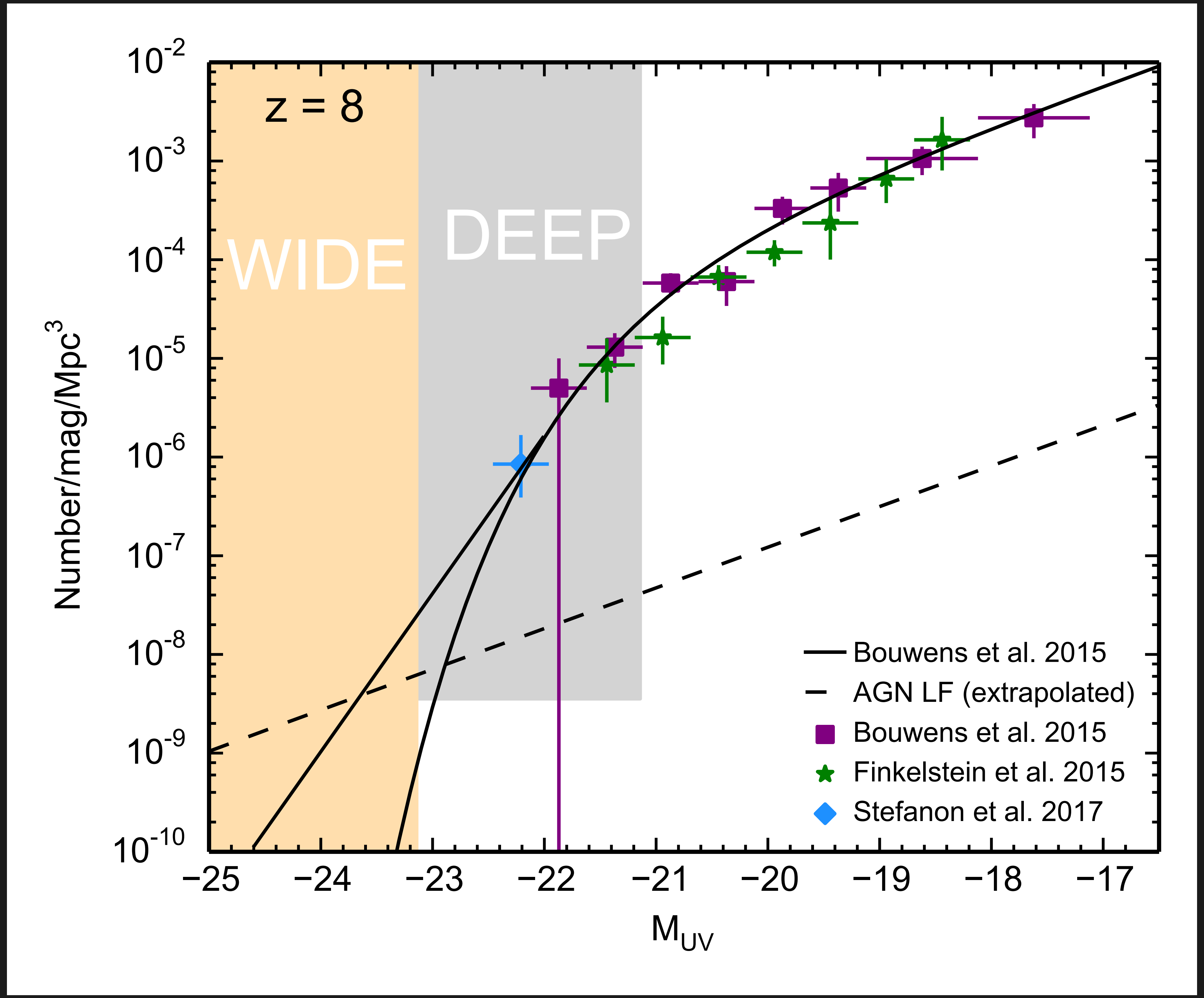


Naidu+22

GNz11 in 0.25 deg^2

➔ >100 such galaxies in 40 deg^2?

Expected High-z Number Counts in Euclid/Deep



Credit: R. Bowler

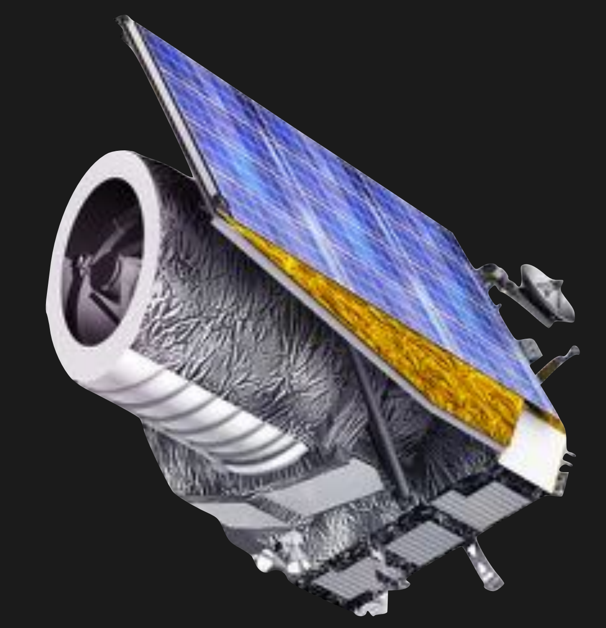
Redshift	LBG (Schechter LF)	LBG (DPL LF)	AGN
6	46000	57000	200
7	14000	14000	48
8	2300	1900	12
9	410	630	3
10	80	220	1
11	0-100??		

To be revised with early JWST data

At highest redshifts, z>8.5

- **up to 1000 uniquely luminous galaxies**
- **plus (very) few AGN**

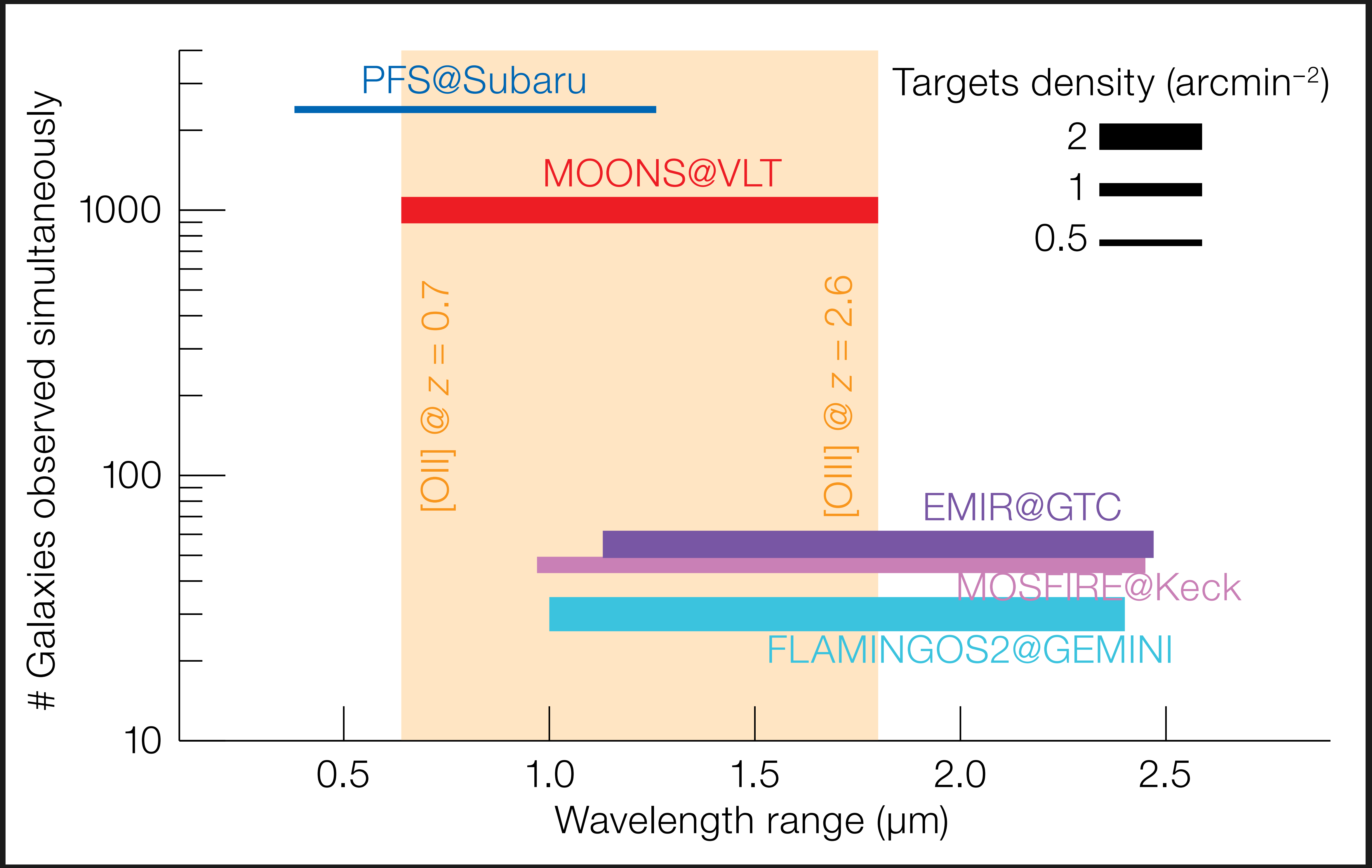
Most valuable targets for spectroscopic followup!

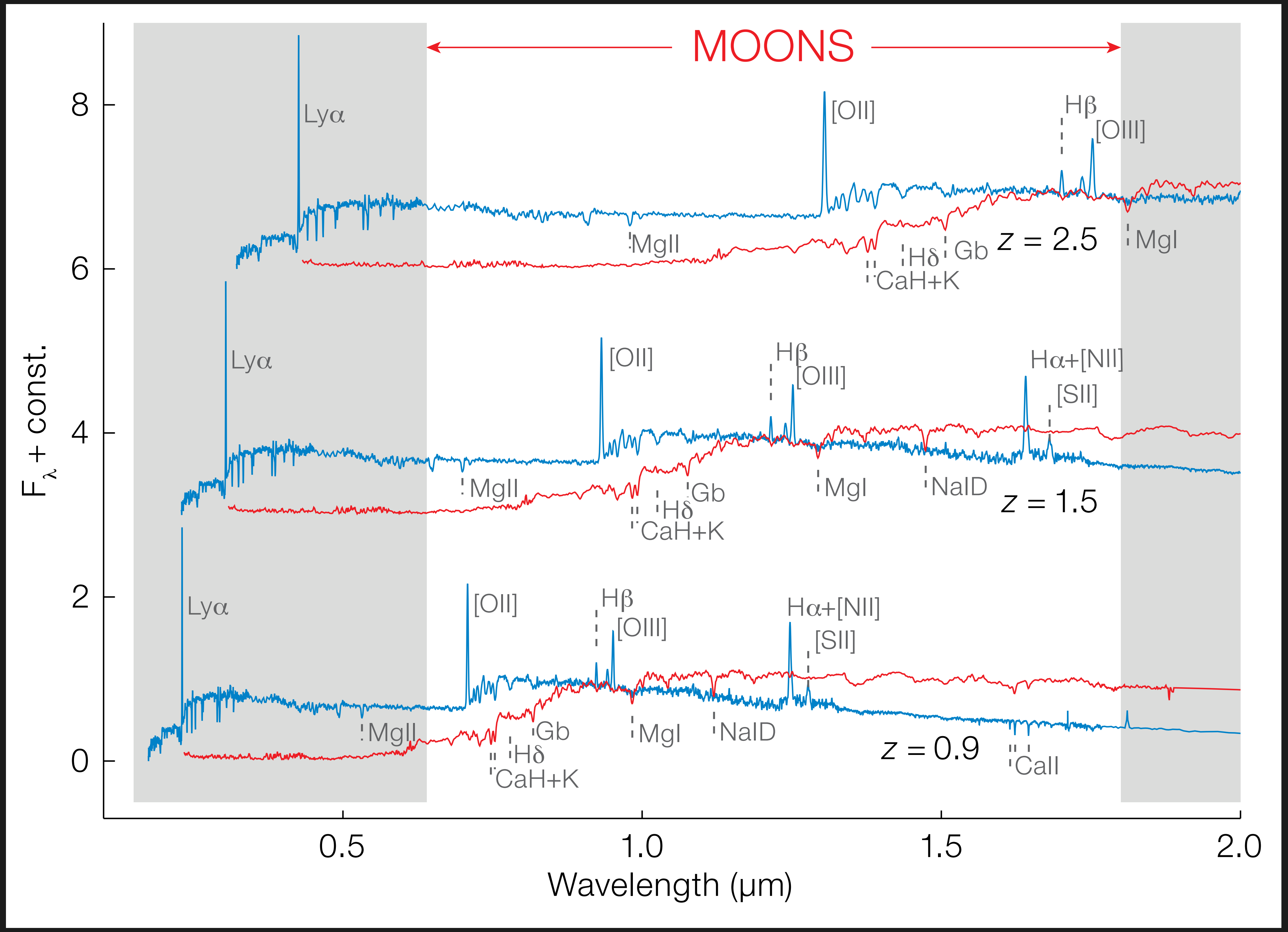


The ESO/MOONS Spectrograph

Start: Q1 2024

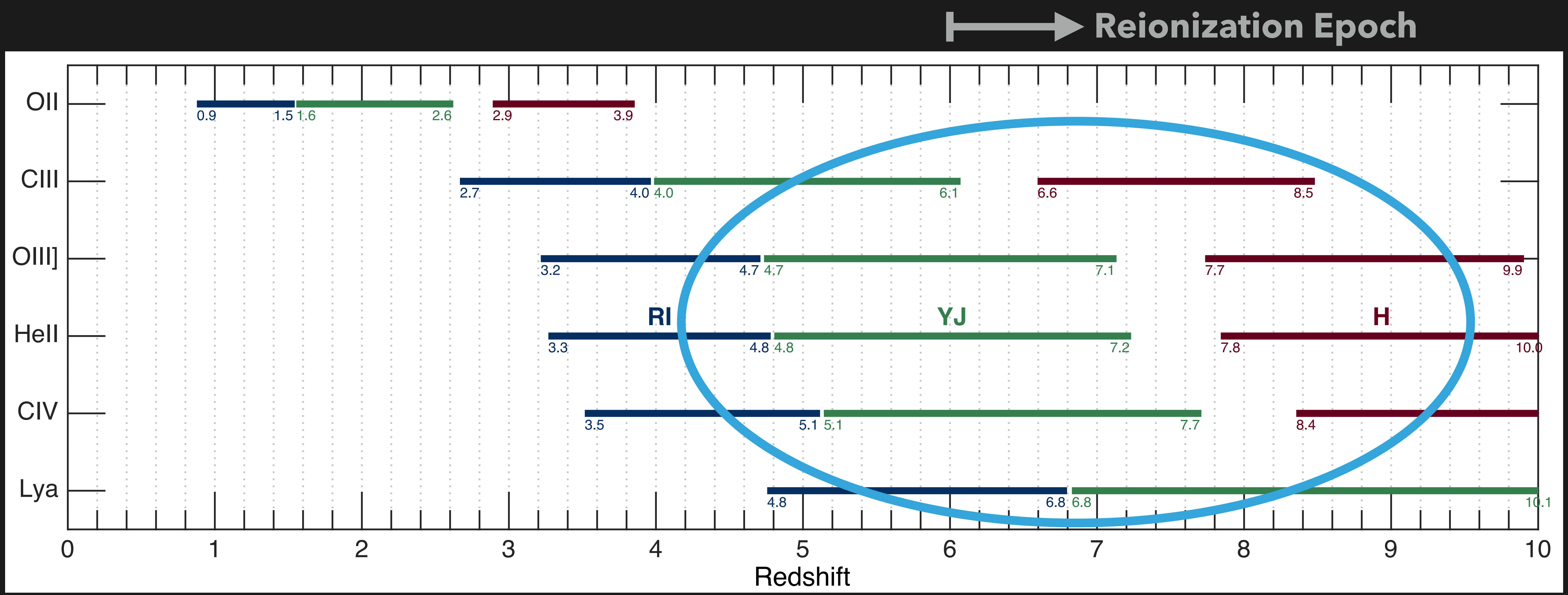
Next generation multi-object spectrograph for the VLT
500 arcmin², 1000 fibres, 0.65-1.8micron, R~4000-6000





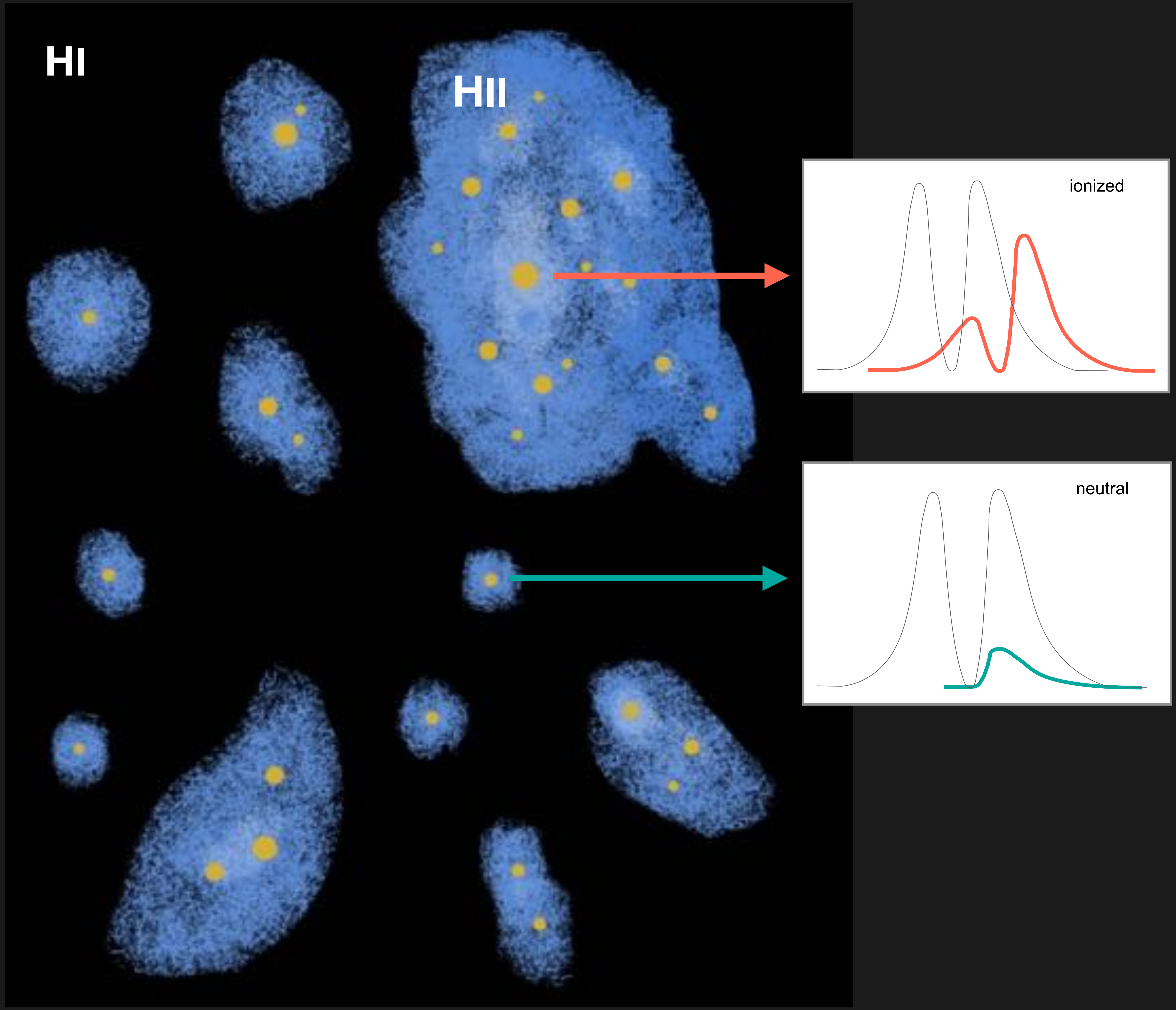
Cirasuolo+ ESO Messenger

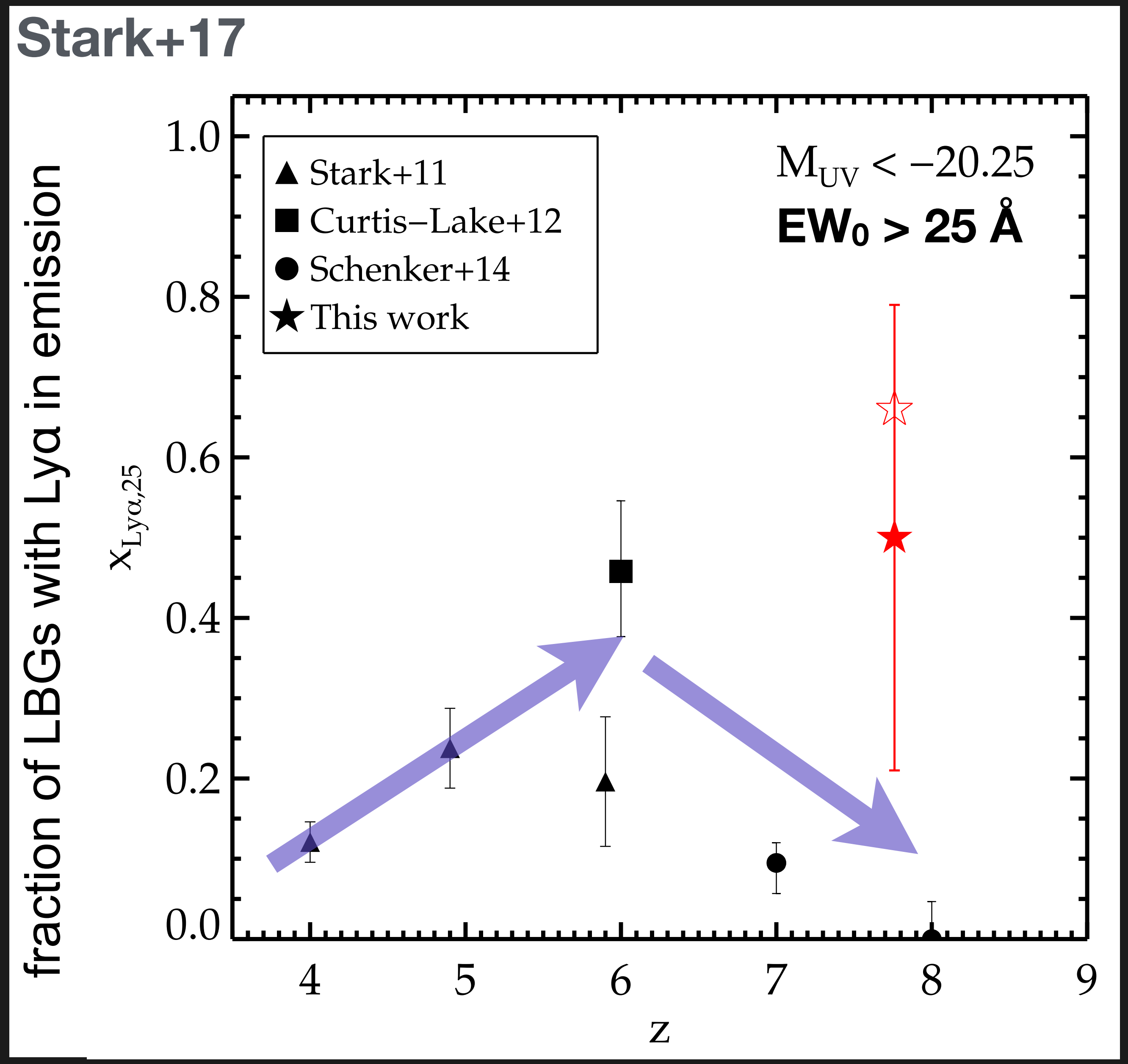
MOONS Line Coverage at High-z

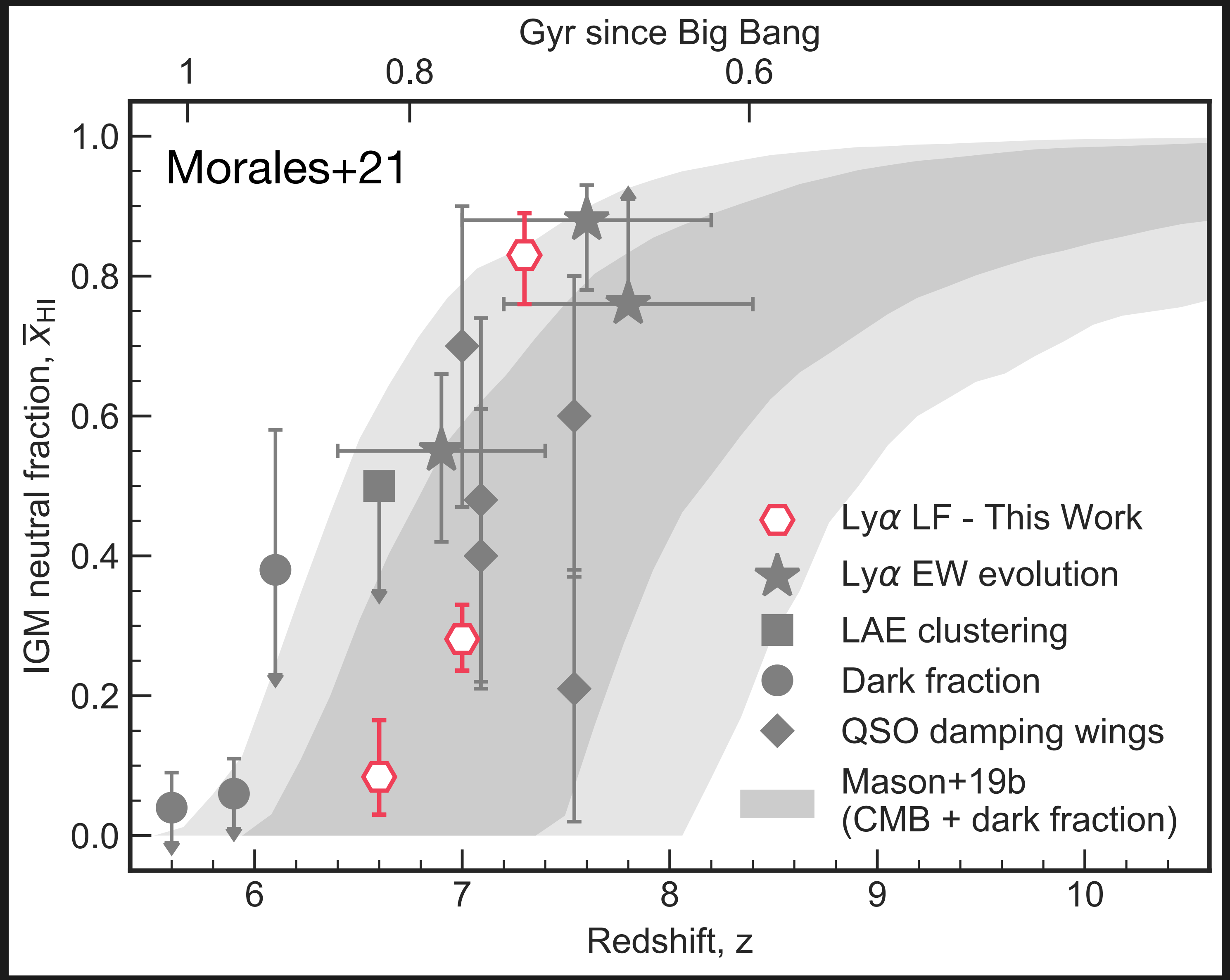


- The NIR window of MOONS finally opens up the spectroscopic characterization of high-z galaxies, based on a large number of rest-UV lines, apart from Lyα
- In particular, the z>=5 window would be ideal, where MOONS has access to both Lya and UV lines. Can study changes of galaxy properties across EoR boundary.

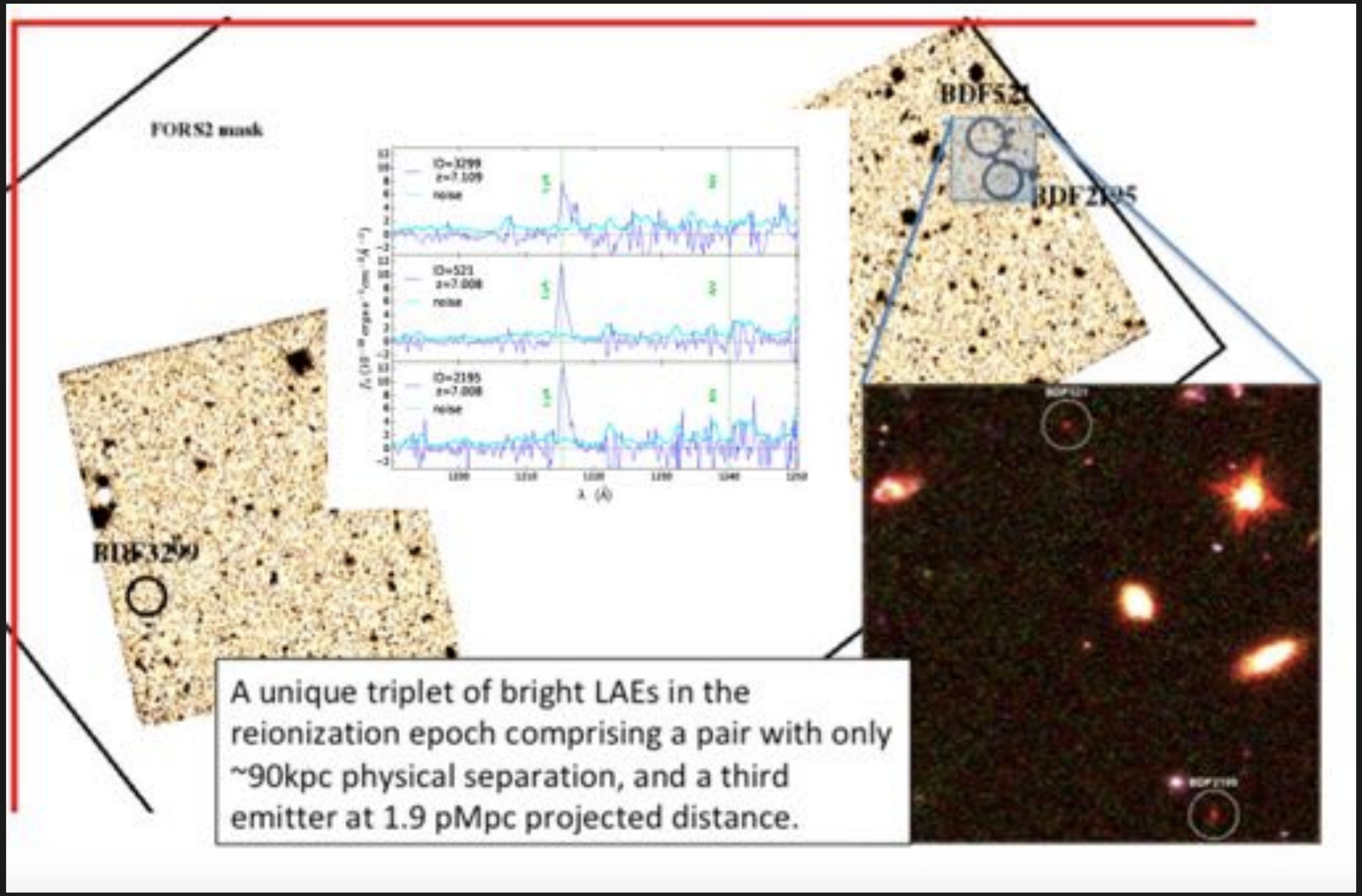
Using LAEs to constrain reionization



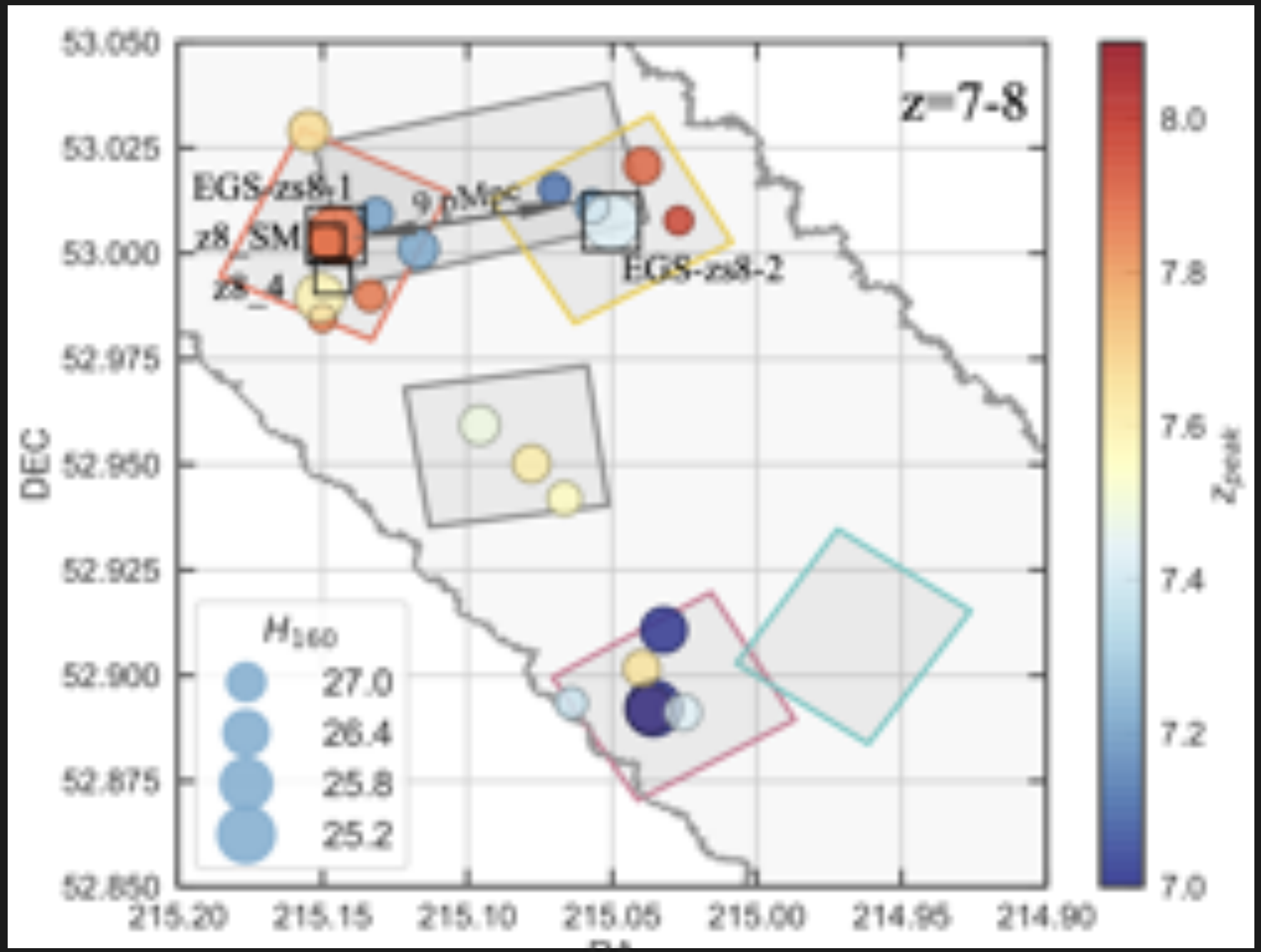


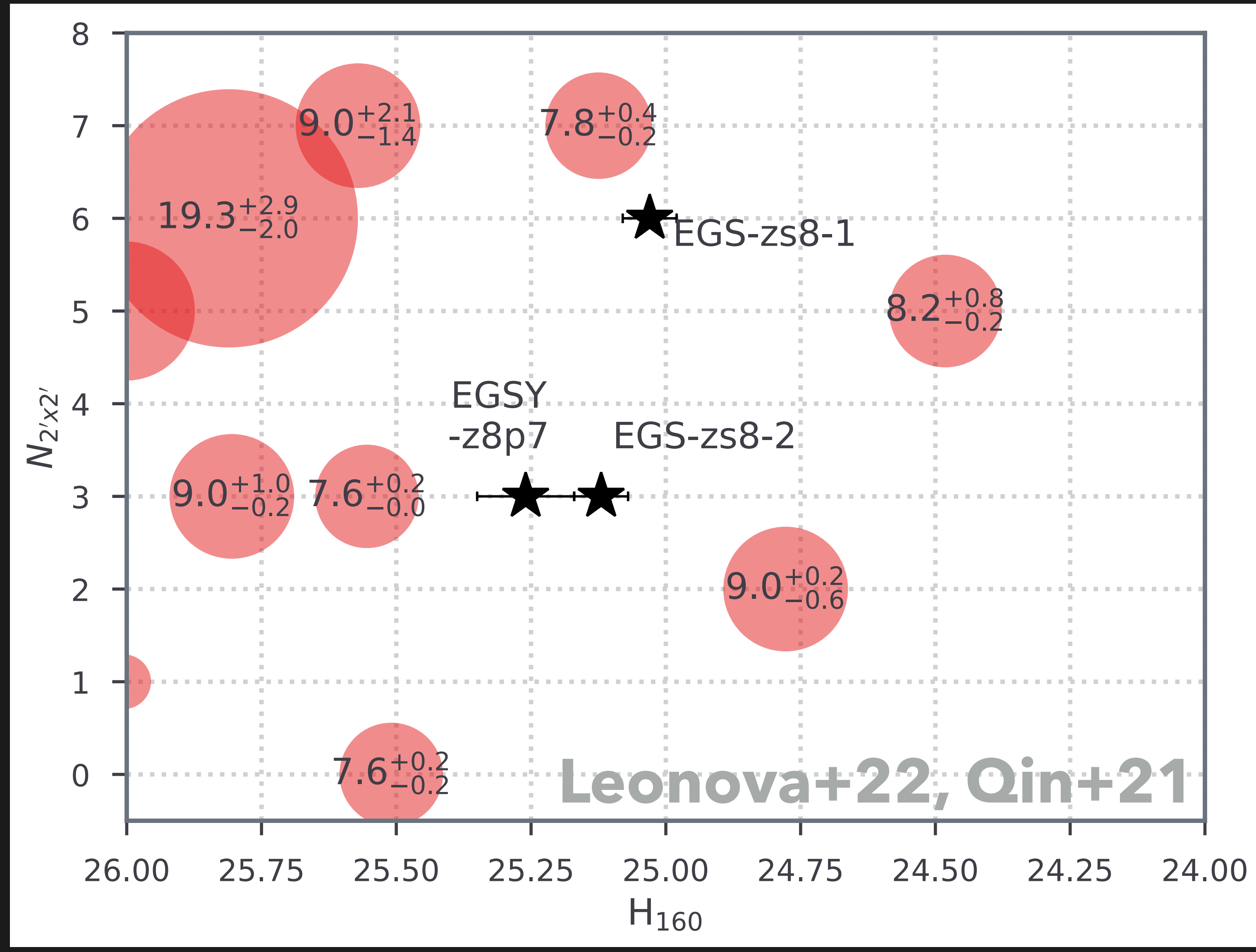


Overdensities of LAEs - Ionized Bubbles



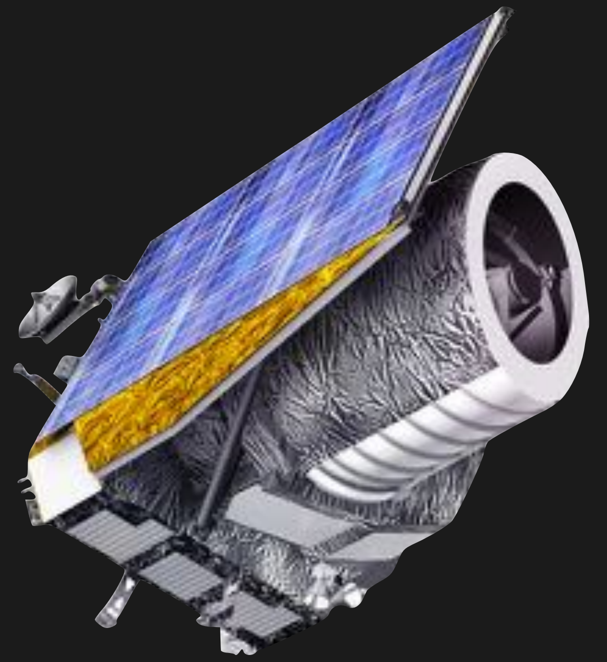
Castellano+16,18, 22





See also: Mason+18, Tilvi+20,Endsley+21

The Euclid - MOONS Synergy



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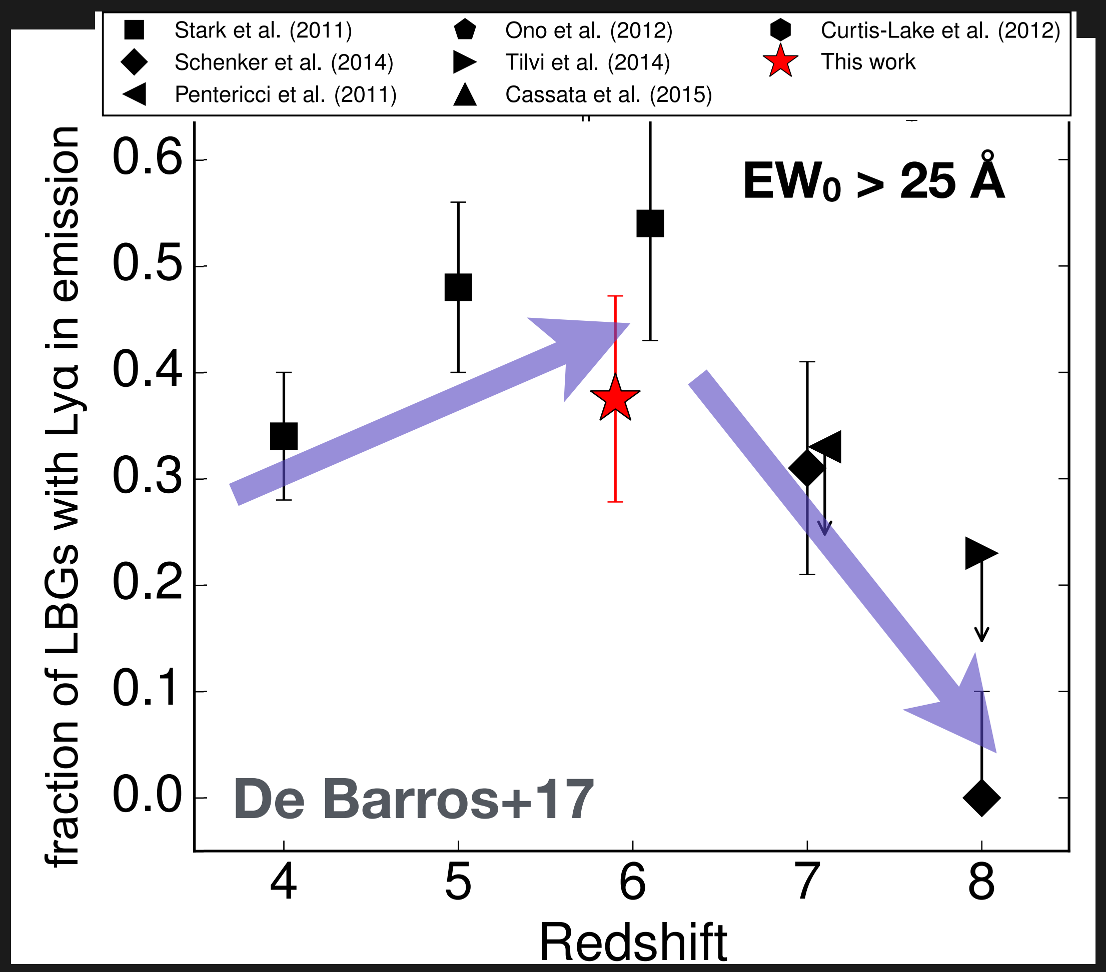
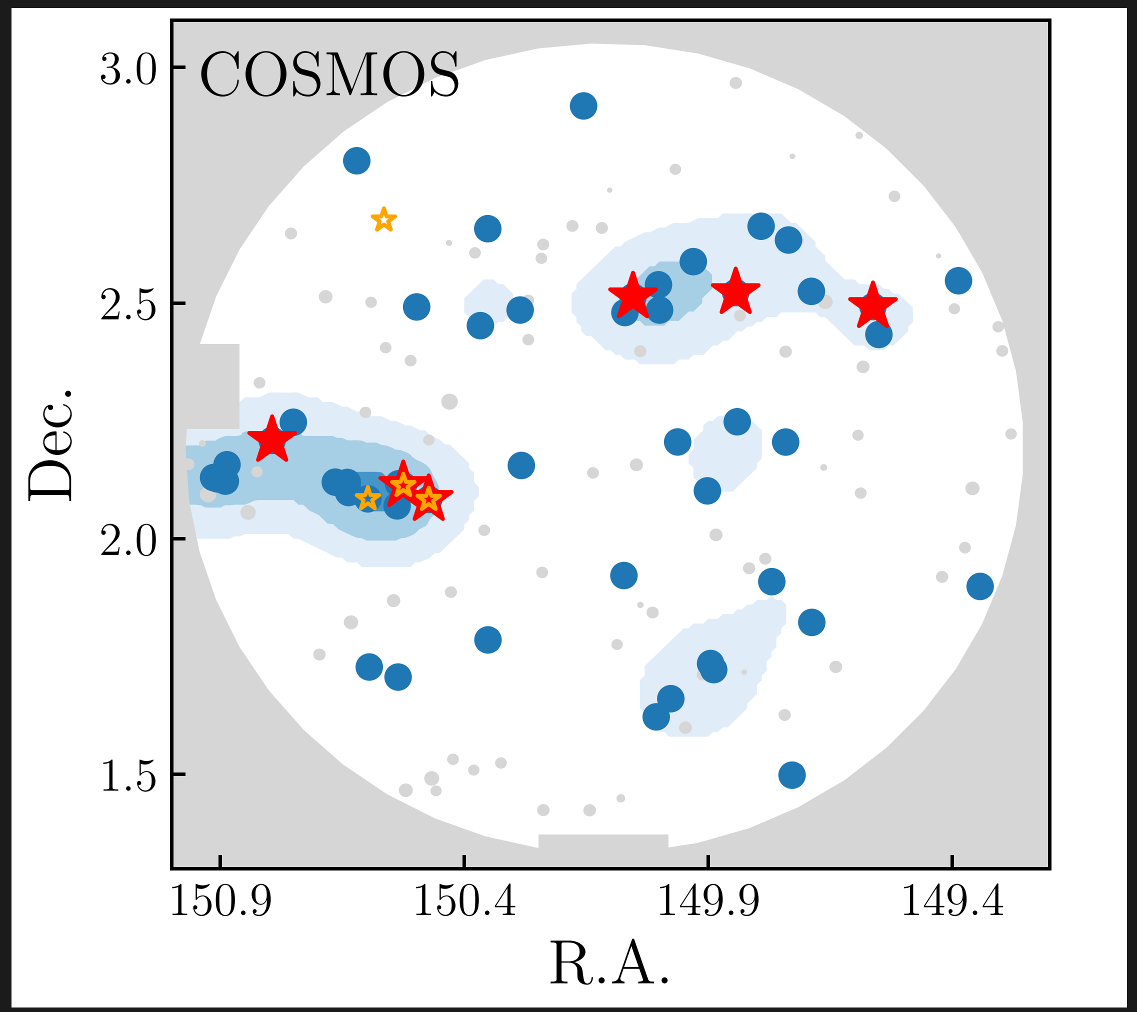
Reionization & the sources responsible for it

Neutral Fraction through Lyα Statistics

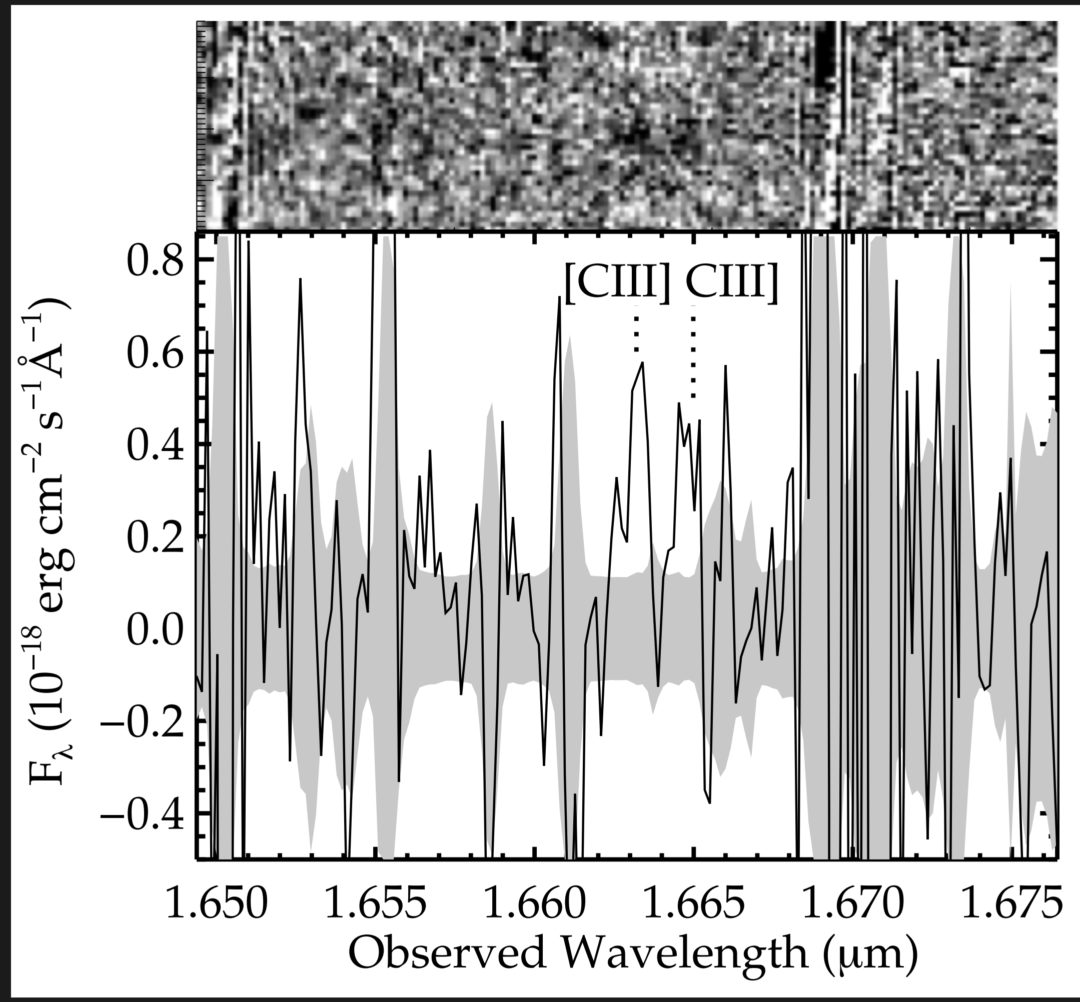


Topology of Reionization through 3D Clustering



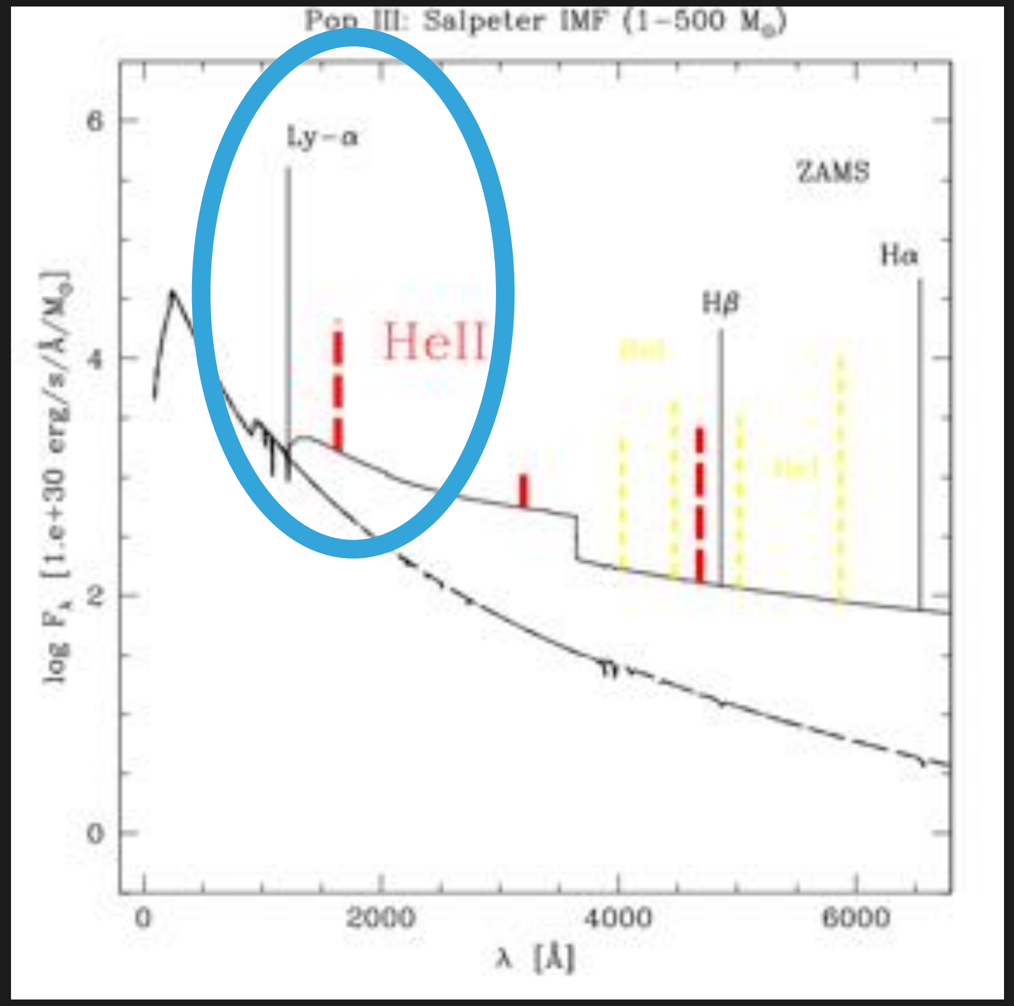
Hu+19: LAGER z~7 LAEs

Ionization State through Rest-UV Lines, AGN fraction



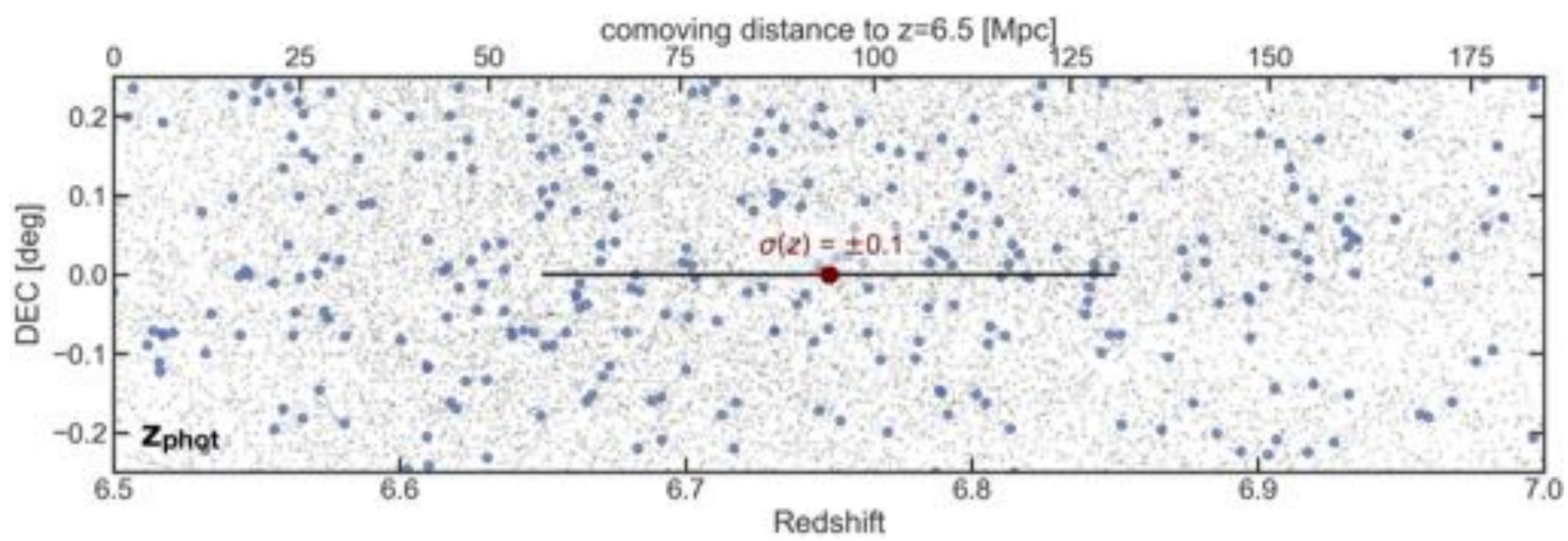
Stark+16

Search for rare PopIII sources w strong HeII



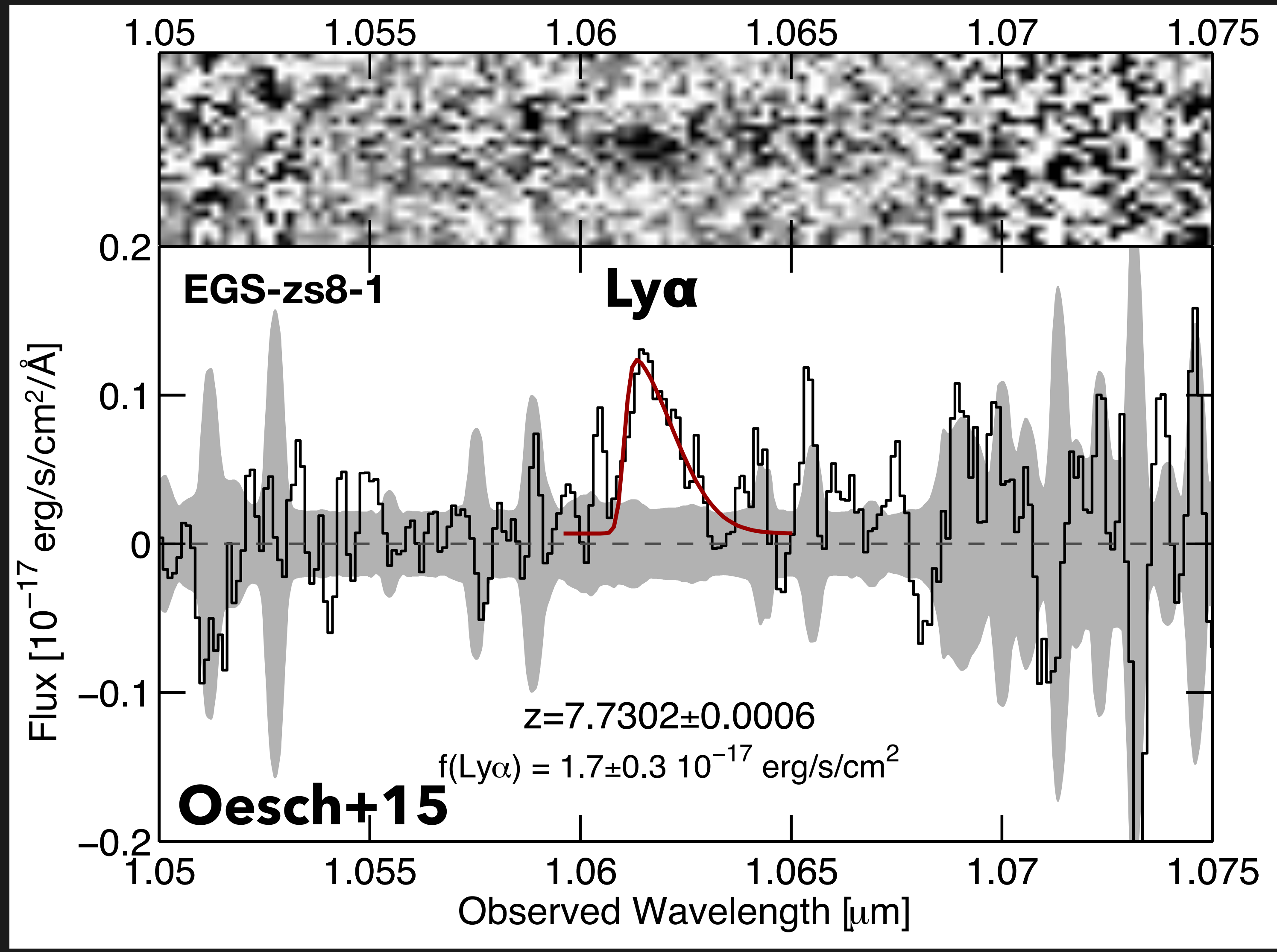
Schaerer+02

The Need for Accurate Spectroscopic Redshifts

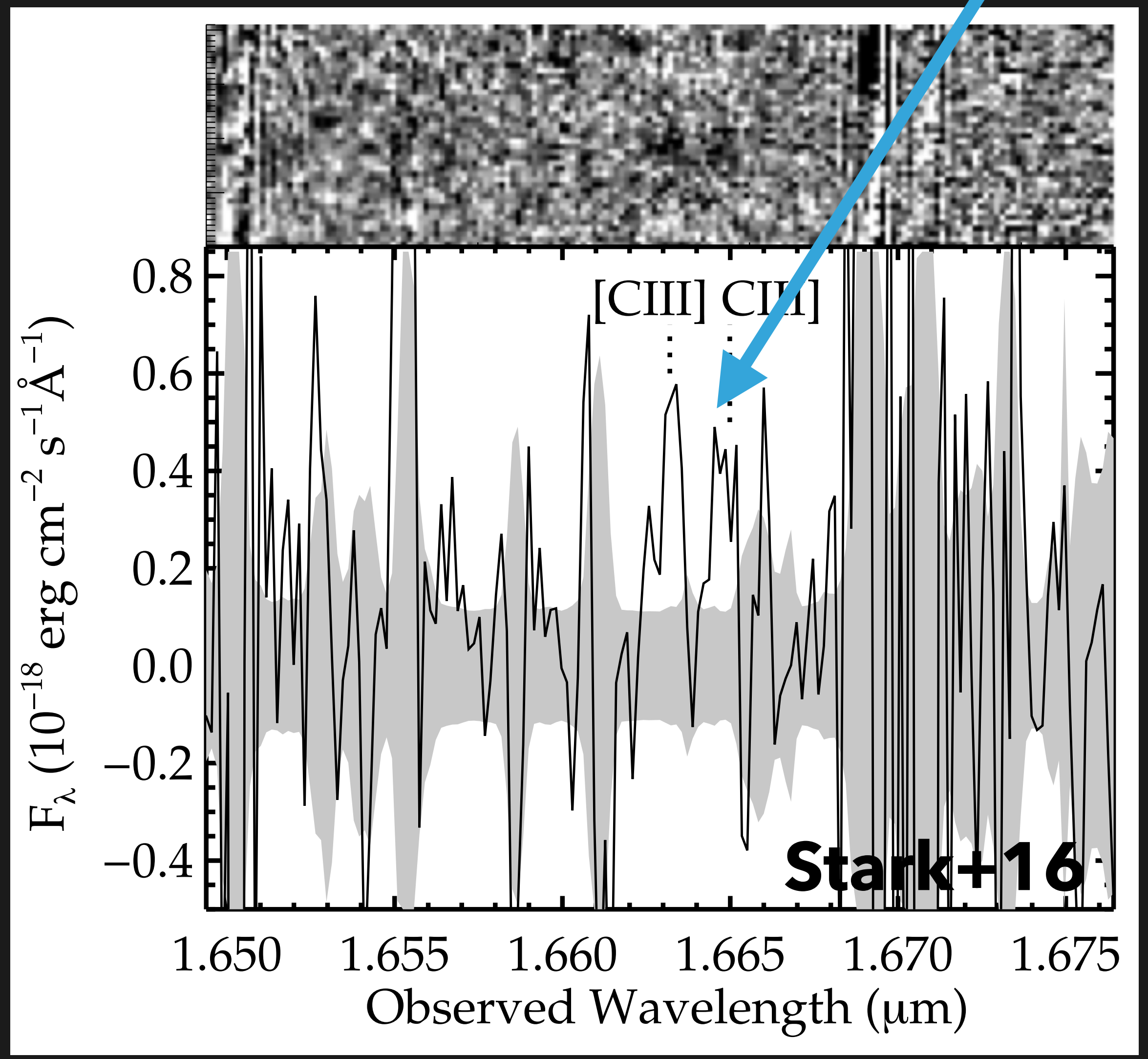


Spectroscopic Characterisation Pushes Telescopes to their Limits

Only a handful of galaxies at z>6 have UV line detections apart from Lya.
Here: EGS-zs8-1 at z=7.73



4.5e-18cgs & 3.6e-18cgs



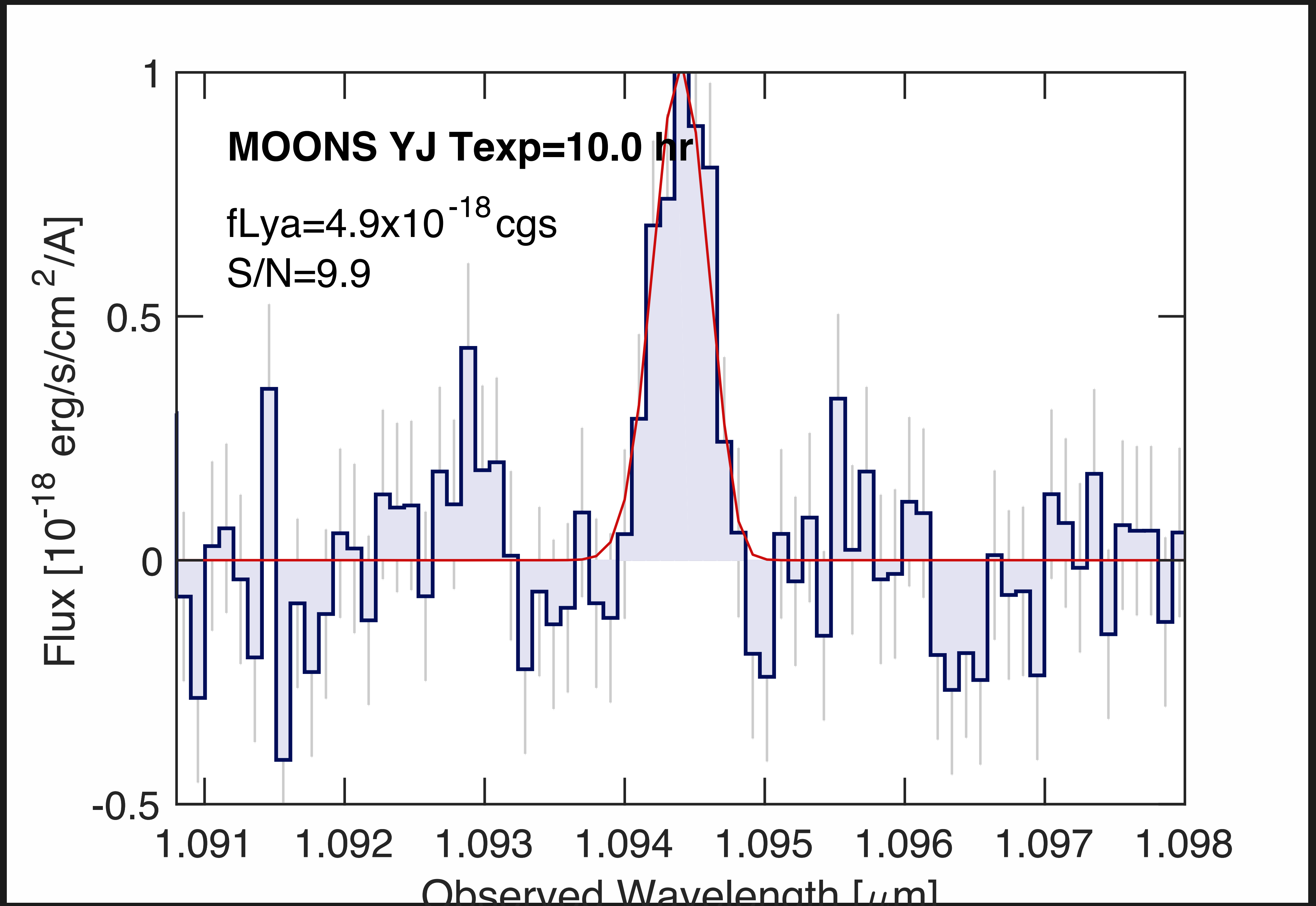
Surprising: very high EW CIII] emission (W_0=22+-2 Å)

Mainali+18: 5 of 13 known Lyα emitters at z>7 have been shown to have intense UV line emission (CIII], CIV, HeII), suggesting that very strong radiation fields could be commonplace among the Lyα population.

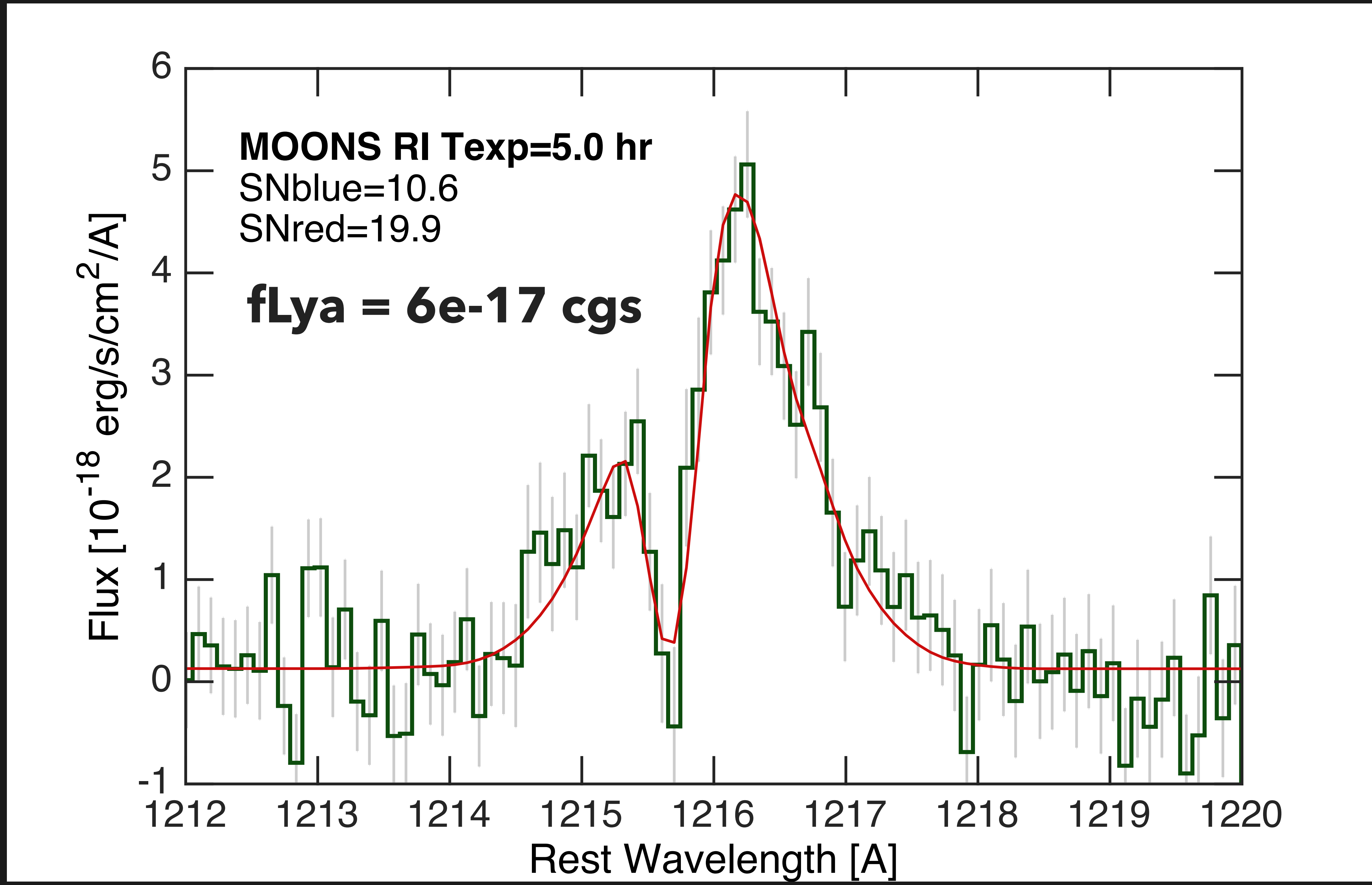
Nevertheless, line fluxes are hard to detect ~4e-18 erg/s/cm2

Faint Lines Require Long Integration Times

Simulation of faint LAE at z=8



Simulation of COLA1 z=6.59 (Matthee+18)



Exposure times of 8hrs: ~5e-18 erg/s/cm2 at S/N>6-9 <-> EW_0~10Å for H~26 mag galaxy

For rest-UV lines (e.g. HeII, [CIII]) with 2e-18 erg/s/cm2 exposure times up to 40hrs would be needed

The ‘Ideal’ EoR Survey of Euclid+MOONS

- A survey over >10 deg^2 is needed to sample build statistical samples including the rarest, highest-density regions, and for a comprehensive probe of reionisation topology
- 10 deg^2: ~100x larger area than existing surveys with the required sensitivity

- To cover this with MOONS: **72 pointings**
- To reach faint Lyα lines: need **8hr exposure times**

- Requires more than can reasonably done with ESO Large Program
- Important: cannot completely fill the available fibres! Can be combined with other survey

ESO/ESA Community Surveys?

- Euclid has a unique opportunity for high impact legacy science
- Follow-up surveys will require lots of nights
- Currently, there is no obvious proposal category for extensive Euclid spectroscopic follow-up at ESO
- Some possibilities:
  - Dedicated Large Community Surveys
  - Euclid SWG-driven, shared proposal
  - Multiple, individual programs

Summary

- Euclid imaging and ground-based spectrographs: extraordinary synergies
- One possible science case: probing reionization through the combination of Euclid + MOONS
- To make an impact: need extensive time required
  - **ESO Public Legacy Surveys**
  - **Euclid community needs to get organized**