9 February 2023 APEC seminar @ Kavli IPMU

First results from the EIGER survey on galaxies, IGM, and SMBH in the Epoch of Reionization

Daichi KASHINO
Nagoya University

On behalf of the EIGER team

Contents

- The EIGER project
  - Strategy and major science goals
  - Observations, analysis, line detections
- Science results at z~6 in the first observation of J0100
  - Spectroscopic sample of [OIII]-emitters and their properties
  - Reionization proved by the IGM vs. galaxies correlation
  - On the earliest SMBHs
- Summary

EIGER

strategy and goals

The EIGER project

JWST GTO 1243 PI Simon Lilly

***E**mission-line galaxies and **I**ntergalactic **G**as in the **E**poch of **R**eionization*

Large spectroscopic galaxy surveys using 110 hours of JWST

Eiger is a famous beautiful mountain in Switzerland.

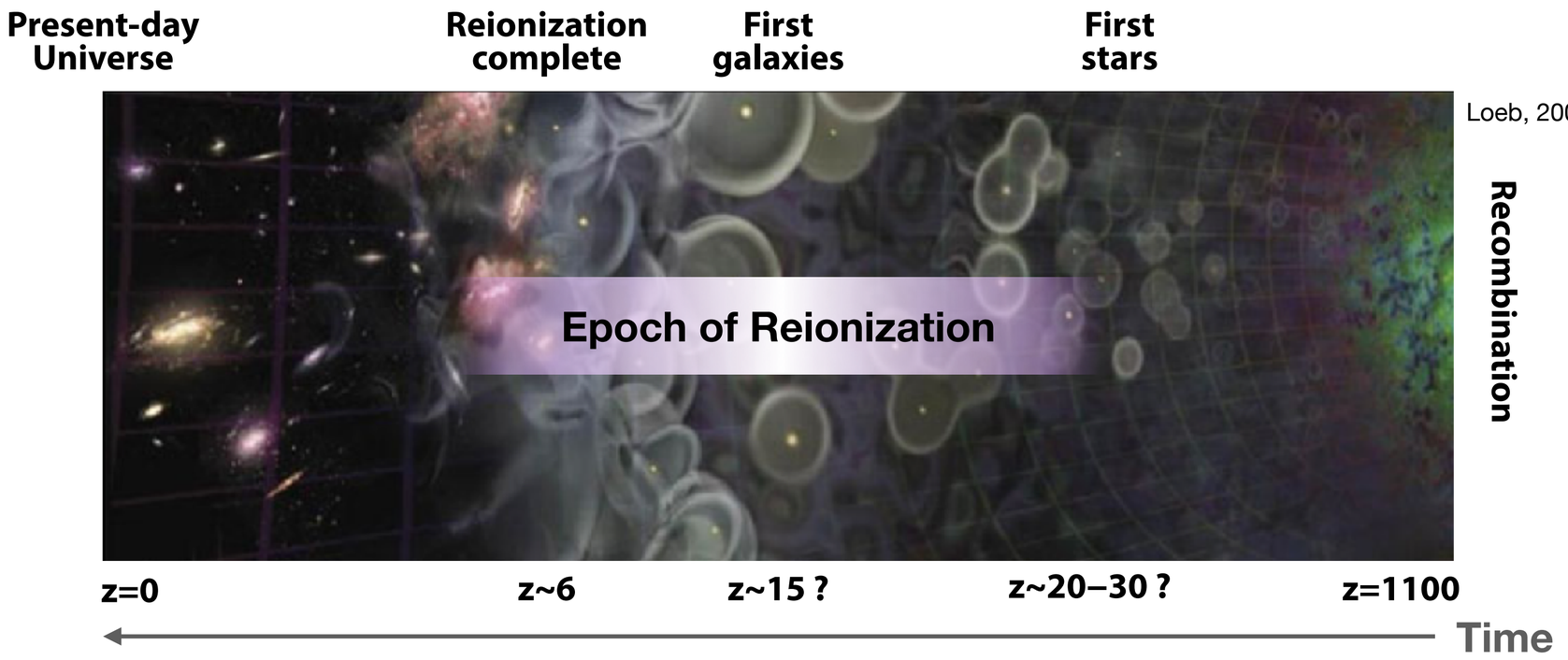
Core team members

S. J. Lilly, J. Matthee
R. Mackenzie

D. Kashino

R. Simcoe, R. Bordoloi
A-C. Eilers

Exploring the tail end of reionization



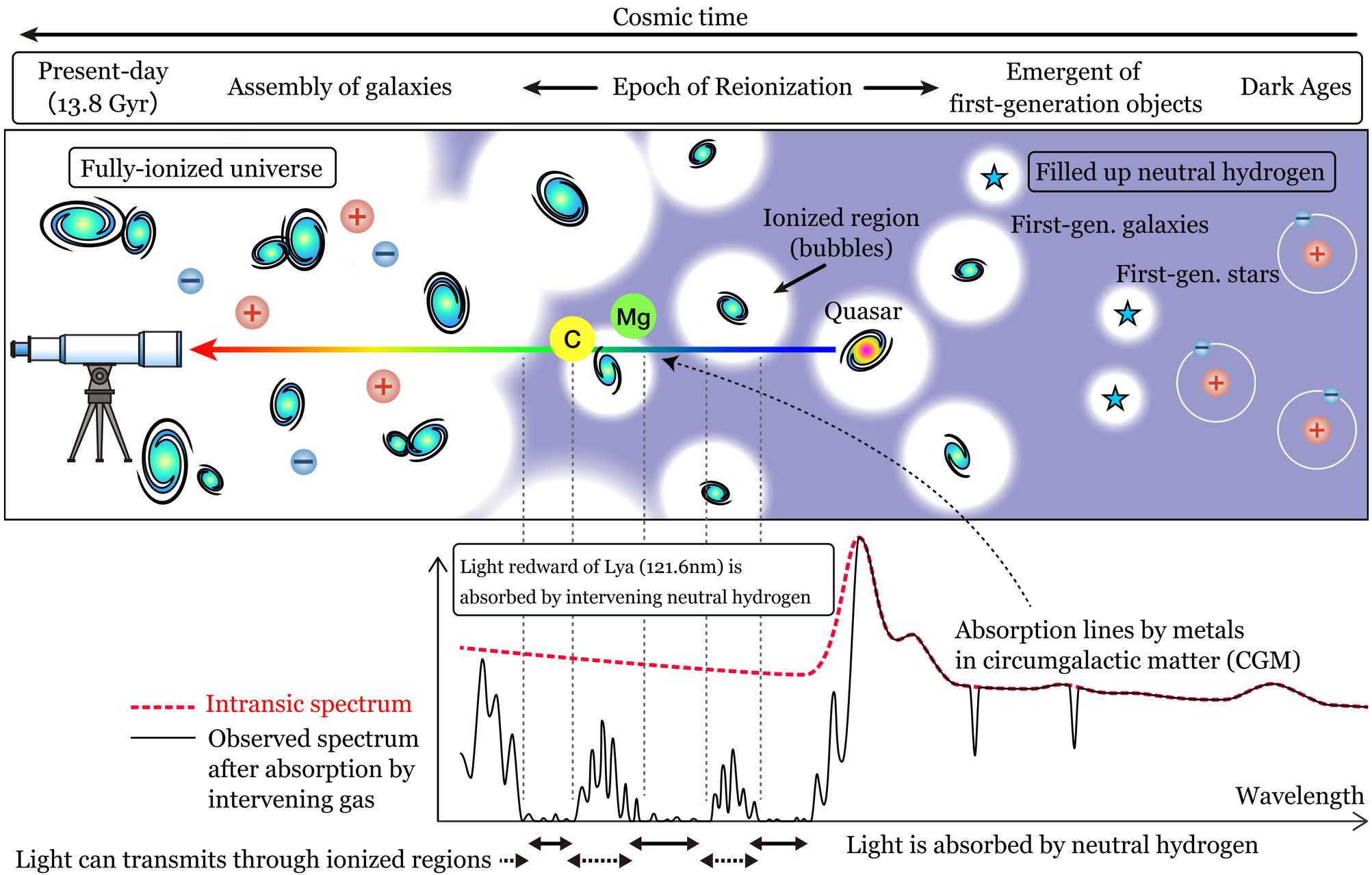
Loeb, 2006, Scientific American

The hydrogen gas filling the intergalactic space was reionized by high-energy (>UV) photons emitted by astronomical objects forming in the first billion years – "**reionization"**

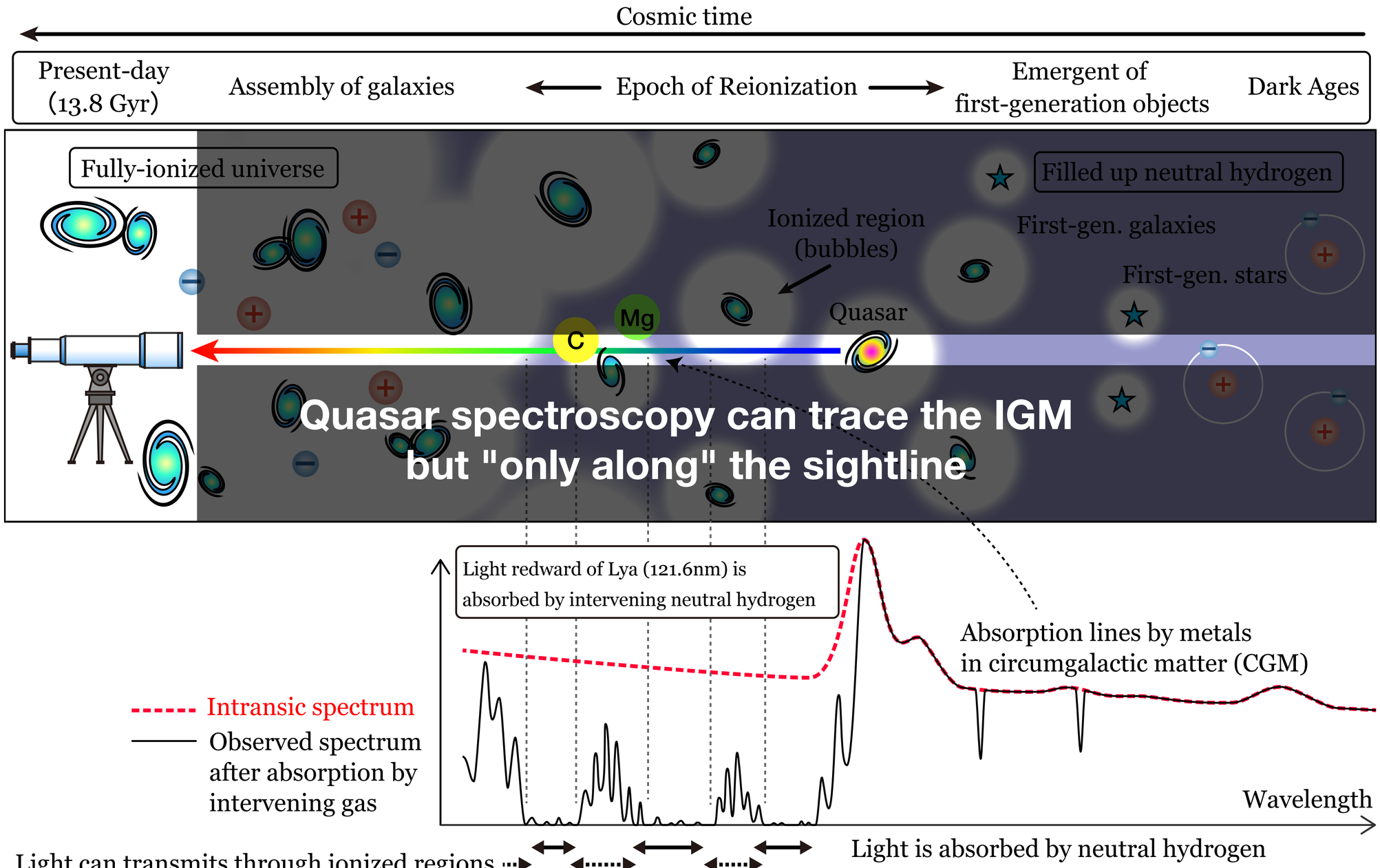
Reionization is the last major event happened across the entire universe, attributed to interactions between galaxies and the intergalactic gas.

Questions may be aggregated into
What caused? When happened? How proceeded?

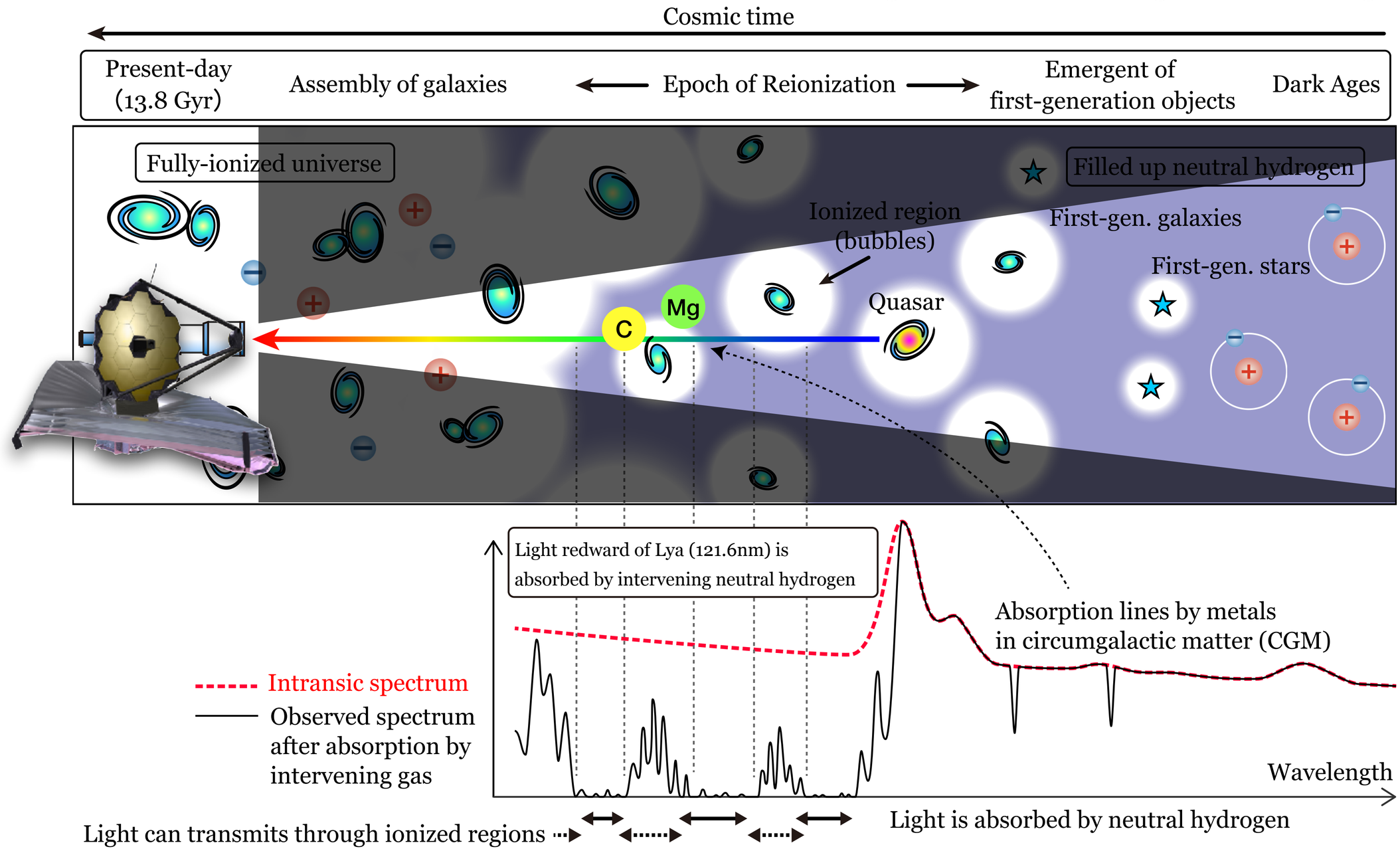
Probing the IGM using quasars



Probing the IGM using quasars



EIGER = Quasar spectroscopy x Galaxy surveys

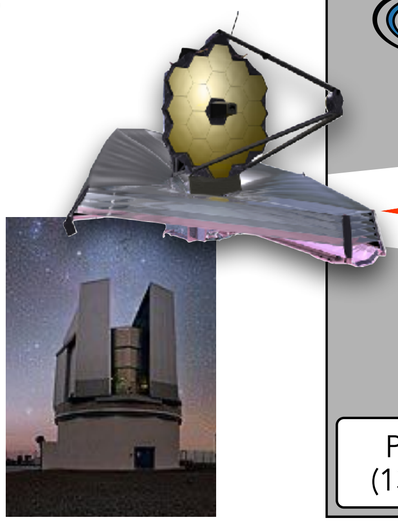


EIGER's major goals

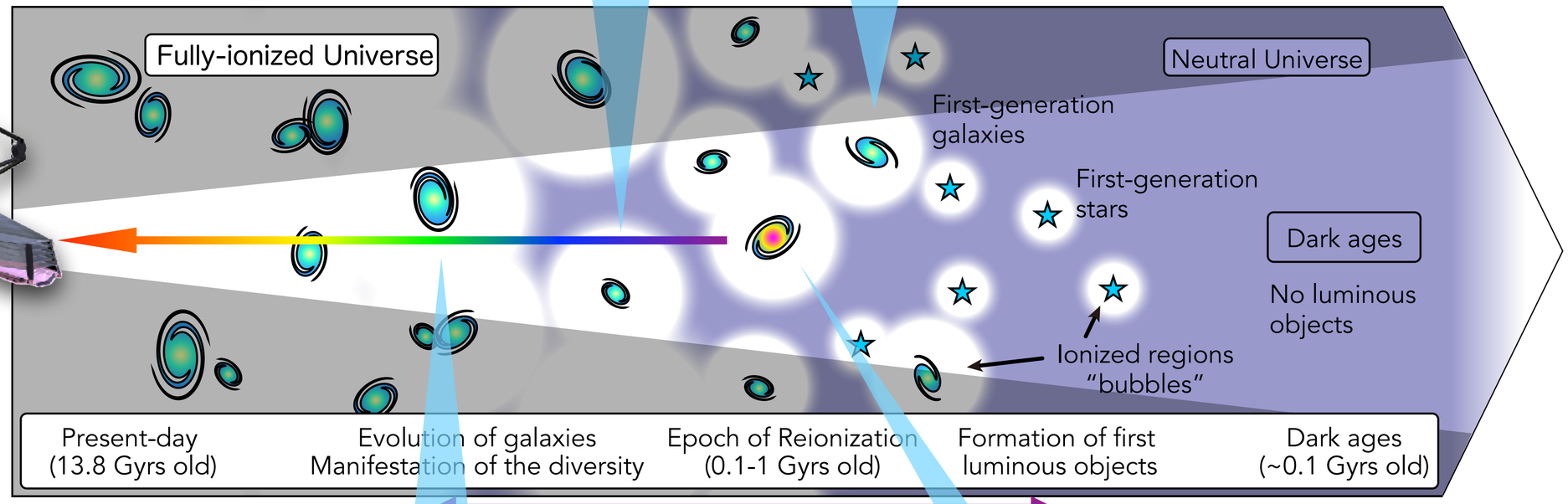
Processes of **cosmic reionization** and the role of galaxies

Galaxy formation and evolution in the EoR

Galaxy survey with JWST



Deep spectroscopy of the quasars with ground-based telescopes



Interplay between galaxies and **the circumgalactic media (CGM)**

Formation of the earliest **supermassive black holes**

Observations and analysis

NIRCam Wide-field slitless spectroscopy (WFSS)

WFSS in F356W + SW imaging

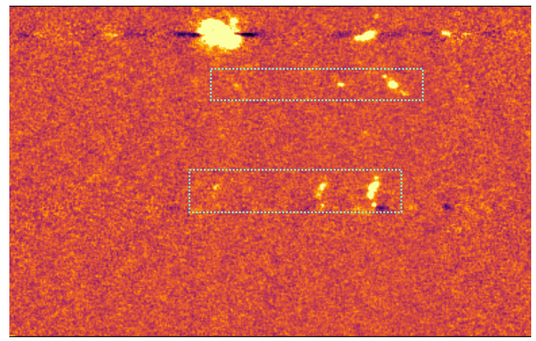
- [OIII] doublet (5007, 4960) + Hβ: 5.3<z<7.0

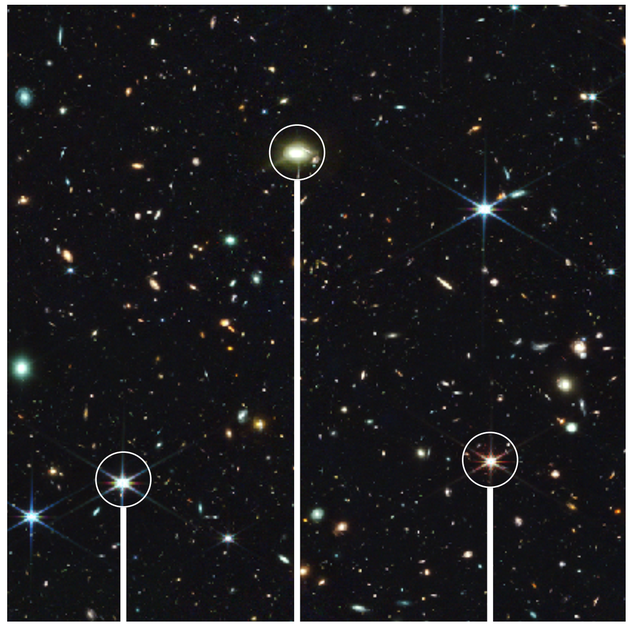
+ two bluer filters: rest FUV + NUV for z~6

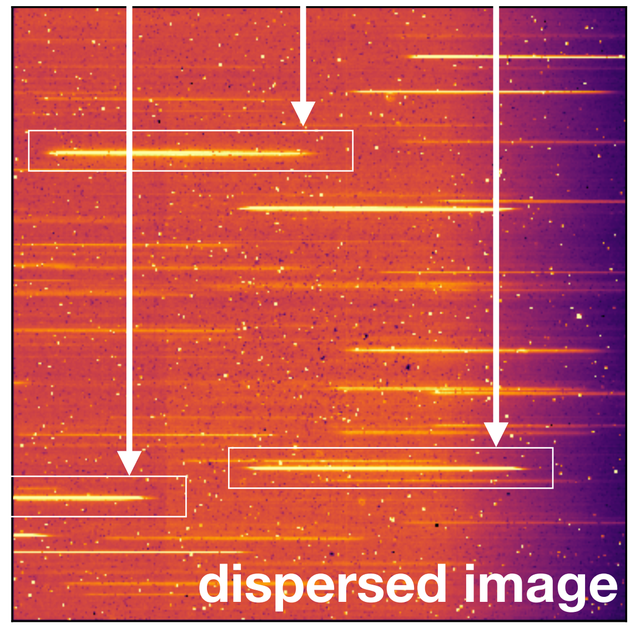
Very powerful way to search for emission-line galaxies.

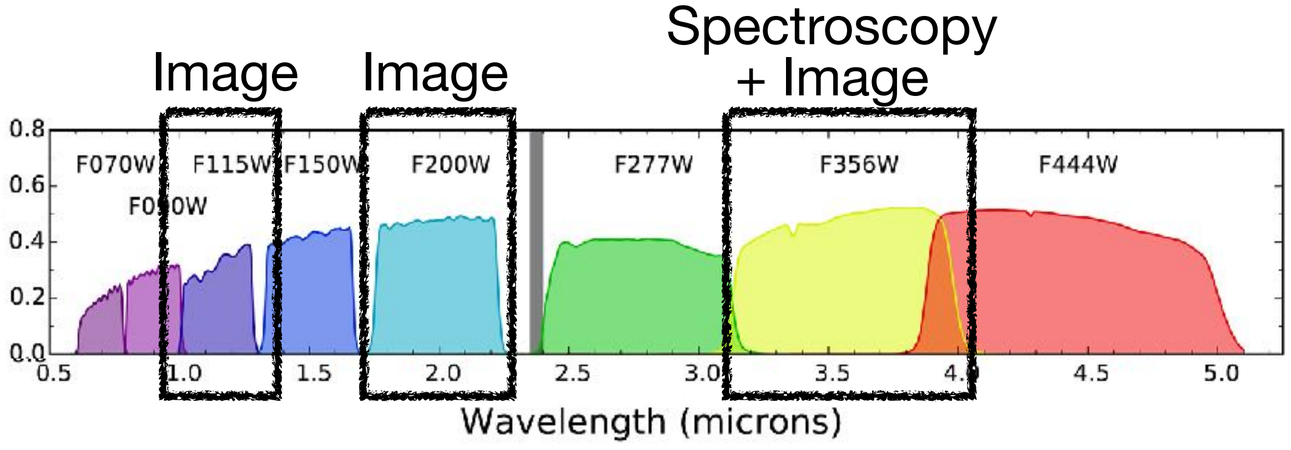
- No pre-selection of targets are needed.
- The [OIII] doublet (+Hβ) enables unambiguous identifications of the lines and the sources that are responsible for the lines.

Zoom-in continuum-subtracted image









Mosaic

FoV: two 2.2' x 2.2'

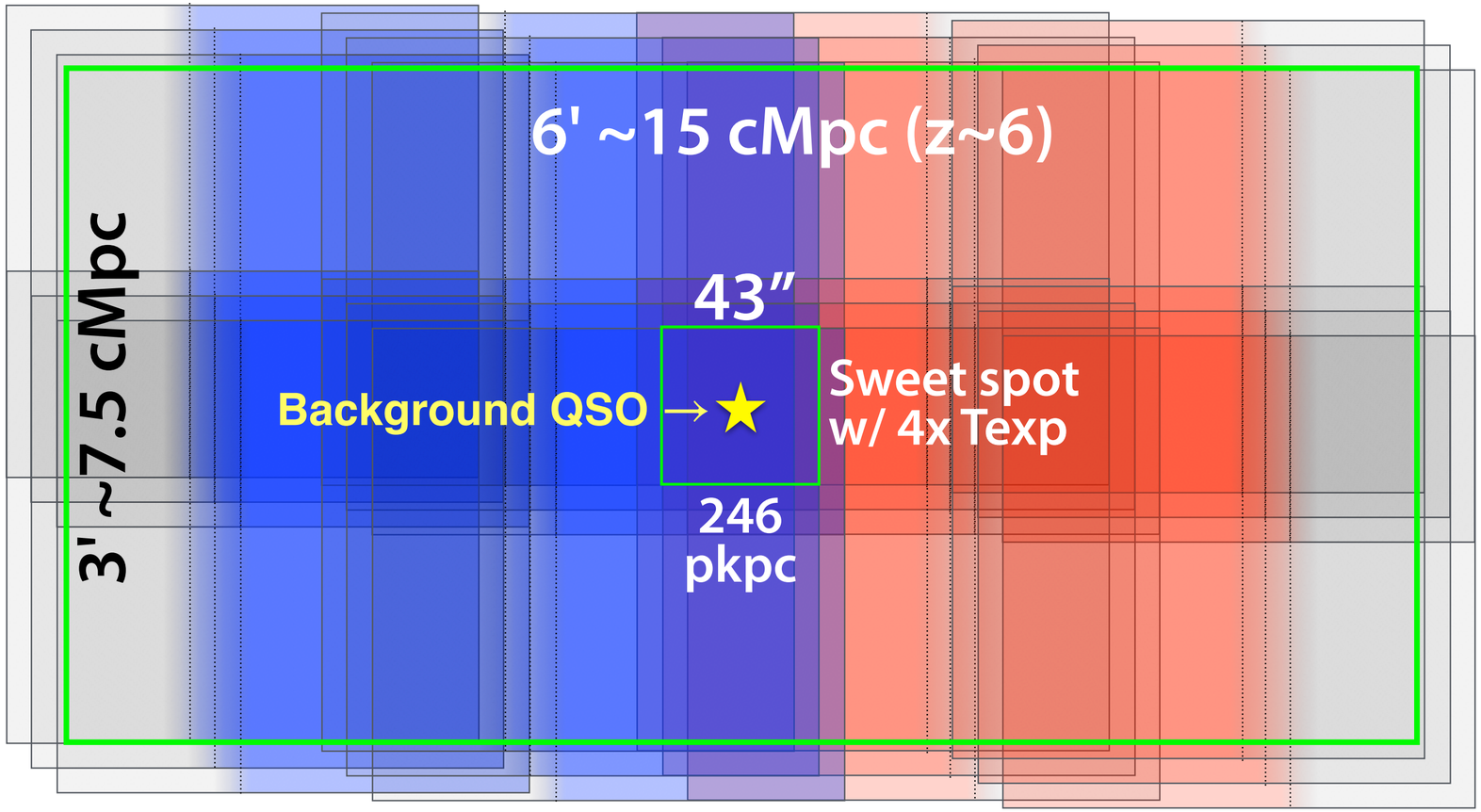
Mosaic of 2x2 separate pointings

Module A

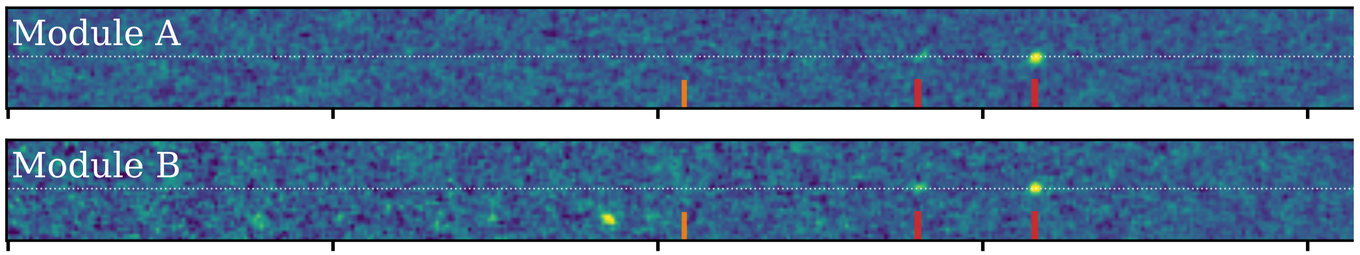
λ → **Grism R**

Module B

← λ **Grism R**

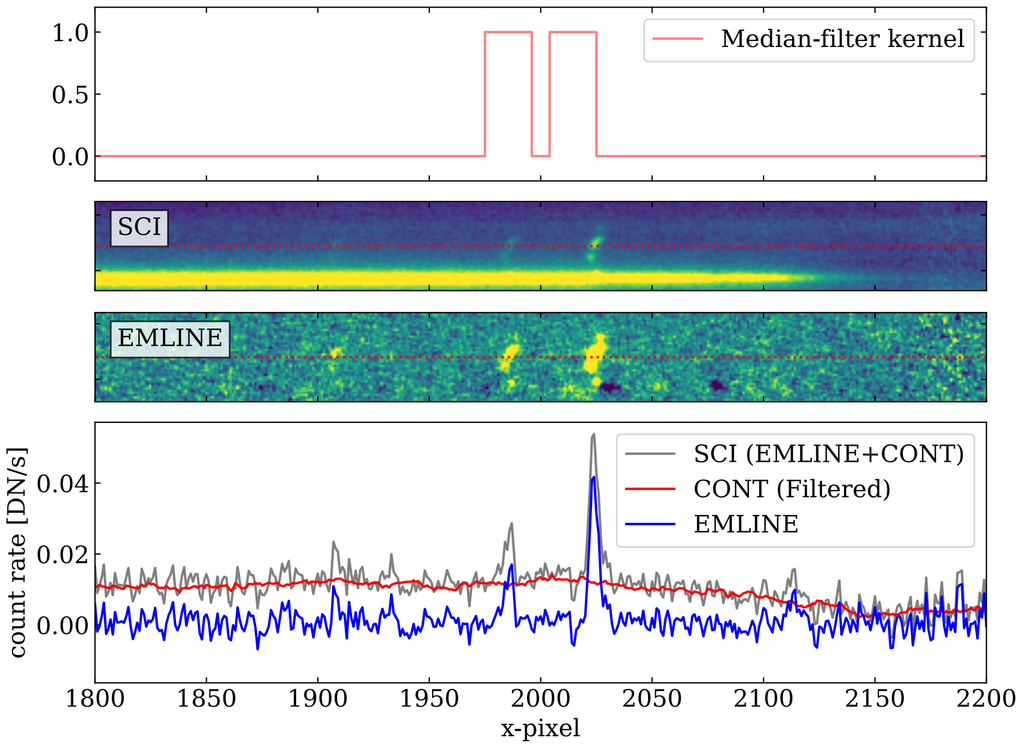


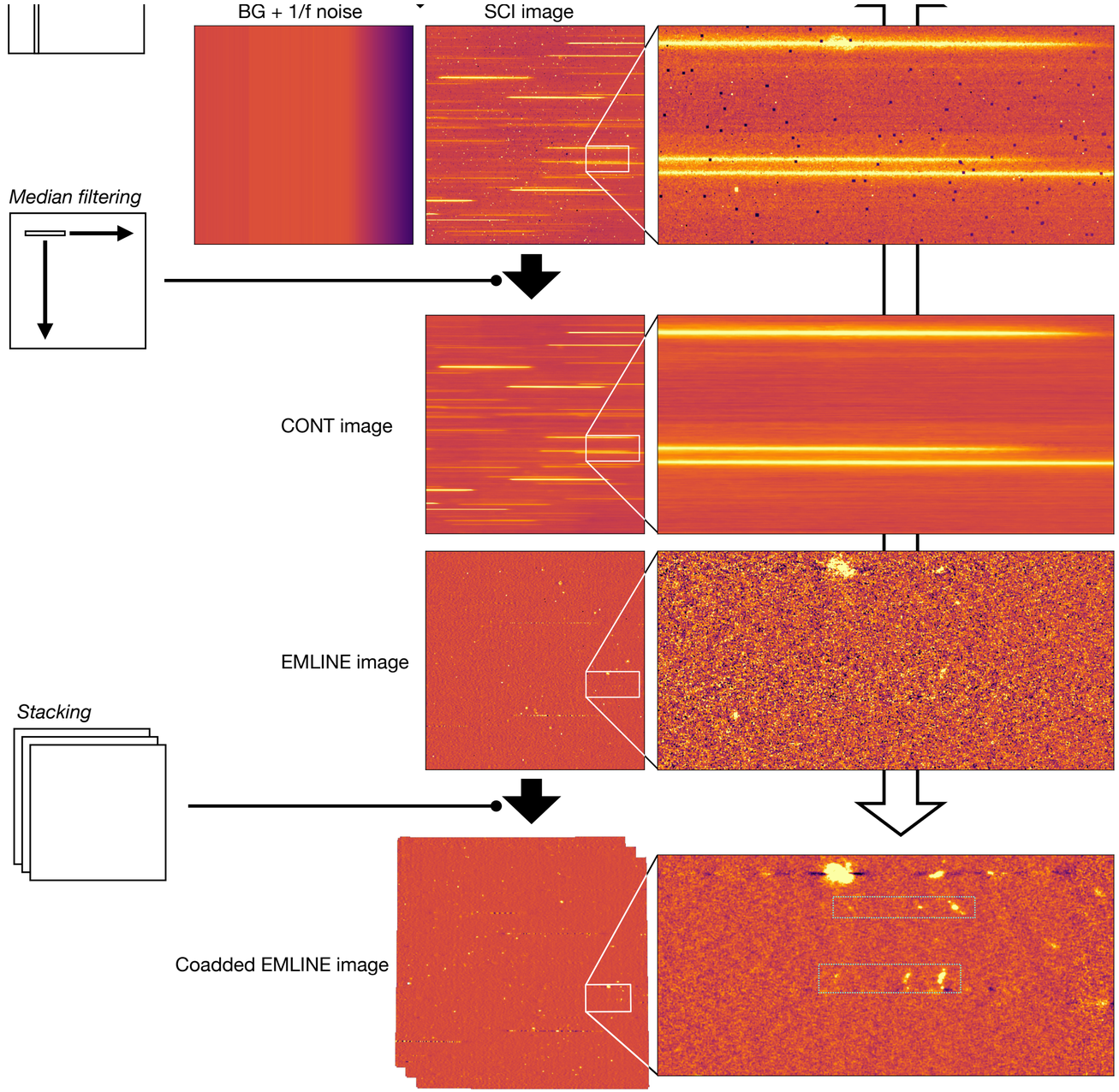
Reversed dispersions around the quasar enables for unambiguous line–source identifications.



Emission-line identification

Simple median-filtering works quite well to isolate emission lines from continua thanks to its high-resolution (R~1000)





Target quasar fields

Name	z	Features	Schedule
J0100+2802	6.3258	Ultraluminous. Many metal absorption systems (incl. 3 OI)	Aug, 2022
J0148+0600	5.98	Extremely long Lyα trough	Dec, 2022 – Jan, 2023
J1120+0641	7.084	Highest-z quasar as of the proposal submission. Some absorption systems.	
J1148+5251	6.4189	Many metal absorption systems (incl. 4 OI)	
J1030+0524	6.308	Well studied. Many metal absorption systems.	Apr – Jun, 2023
J159-02	6.35	Strong MgII at z~6	

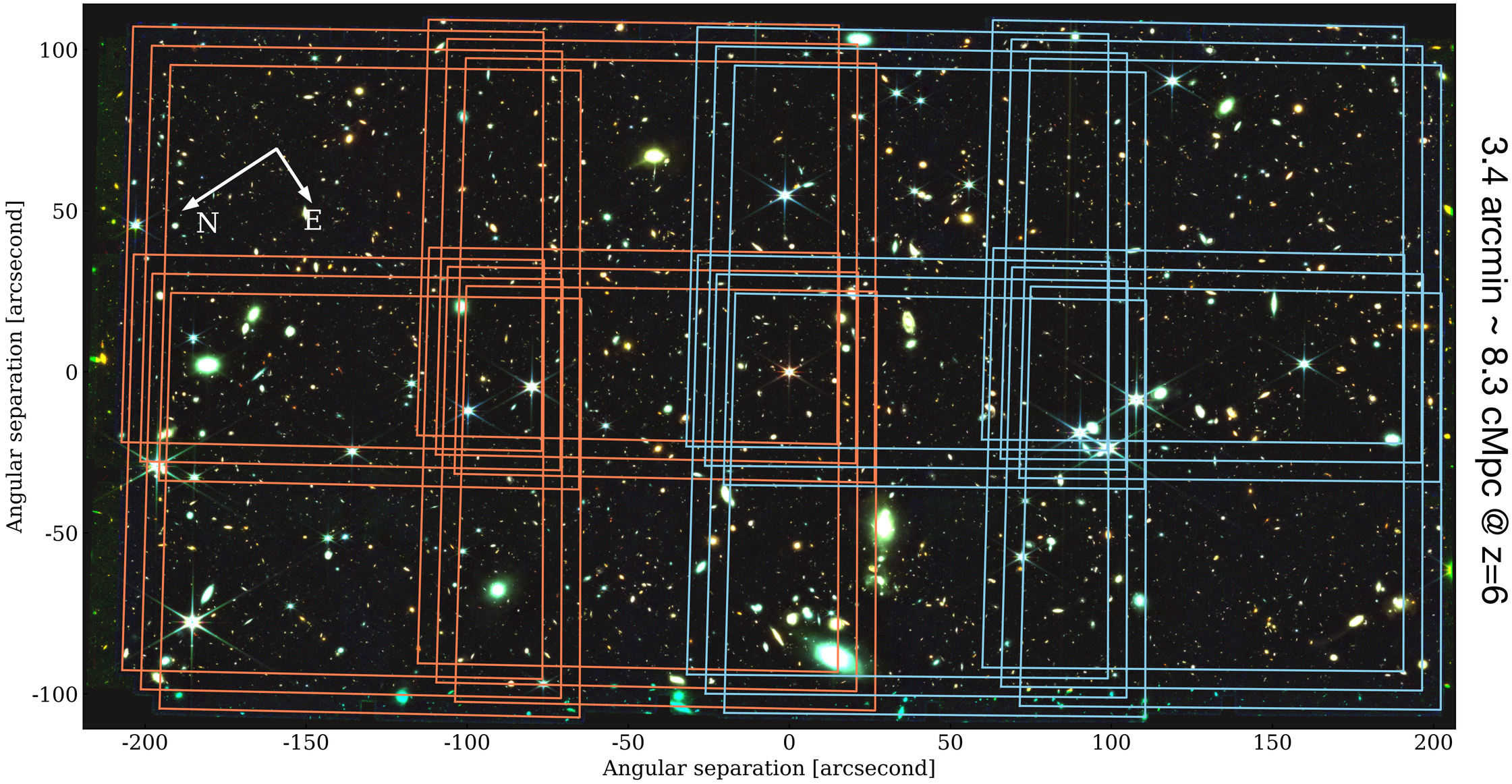
First observation in the ultraluminous quasar J0100+2802

2211.08254 Paper I **Kashino**+: survey design, analysis, and correlation with the IGM transmission

2211.08255 Paper II **Matthee**+:characterization of the [OIII]-selected galaxies

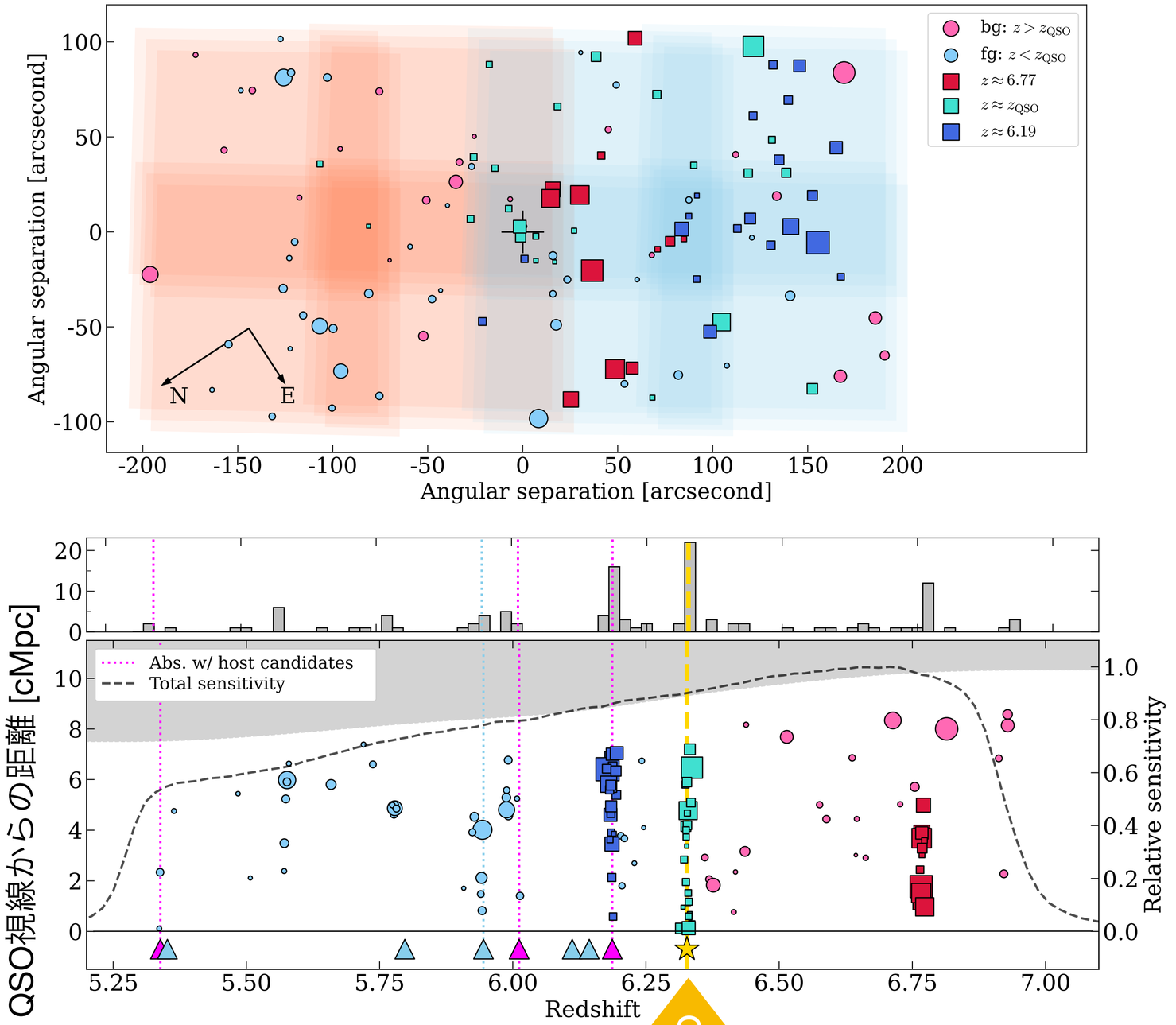
2211.16261 Paper III **Eilers**+: SMBH measurement of QSO J0100+2802 from Hβ

3.5 um image of the field QSO J0100+2802



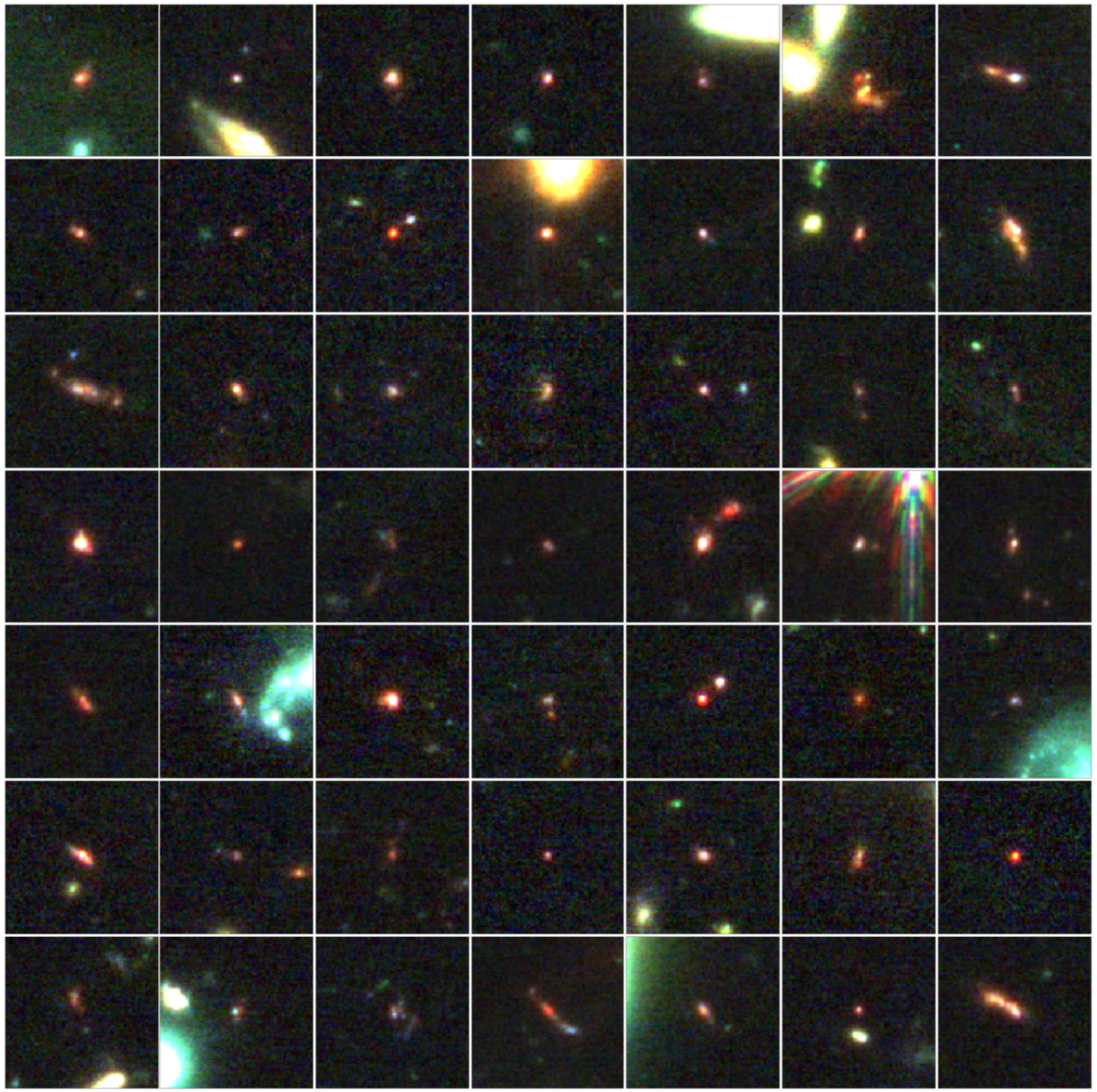
[OIII] emitters at z=5.3–6.9

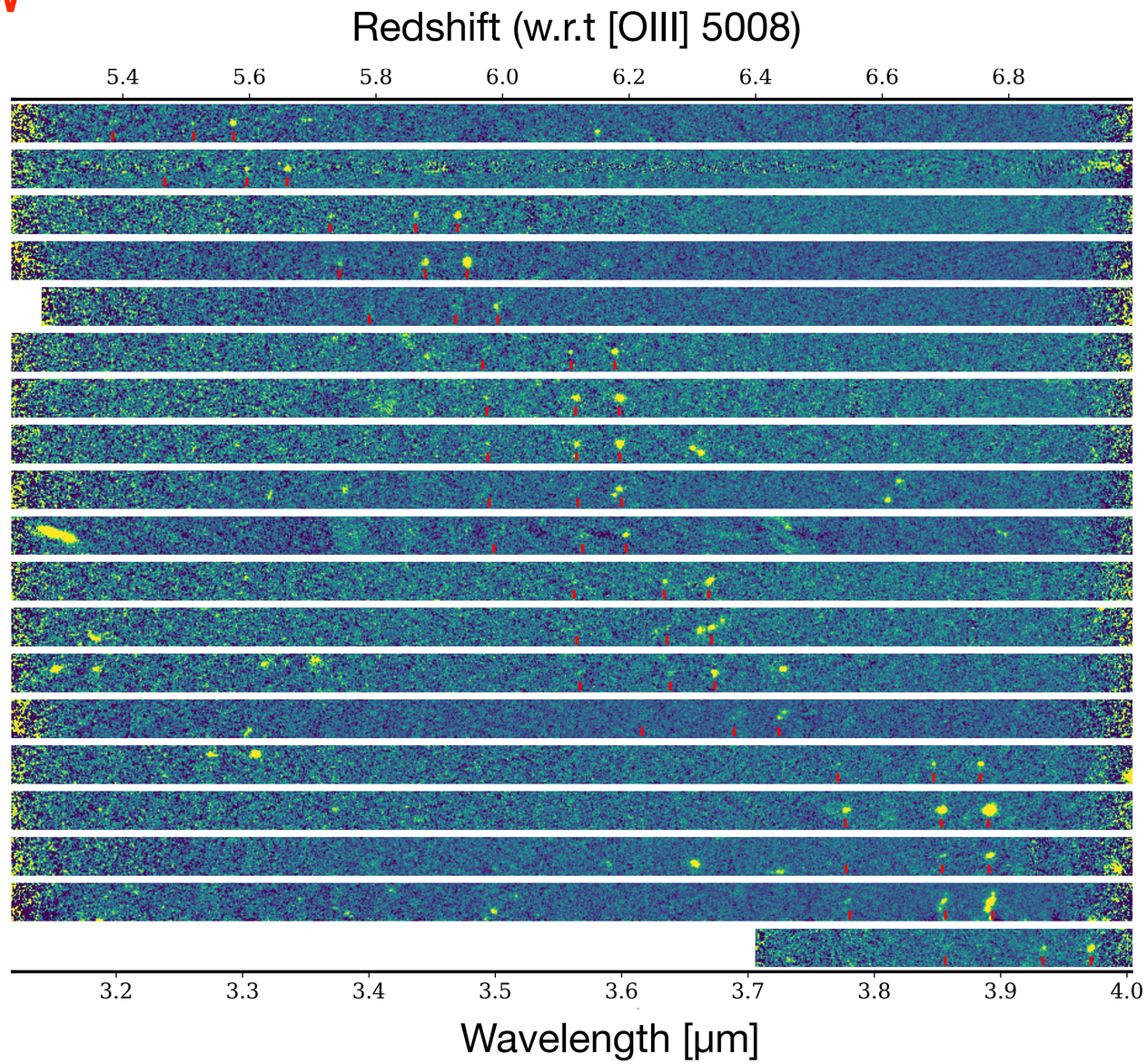
- 117 [OIII]-selected galaxies were identified across z=5.3–6.9
- Strongly clustered in the redshift space
- Three overdensities:
  - z=6.19 (N=20)
  - **z=6.33 (N=24) at the quasar redshift!**
  - z=6.78 (N=12)
- >=1 galaxies were found within 300 pkpc of four metal absorption systems.



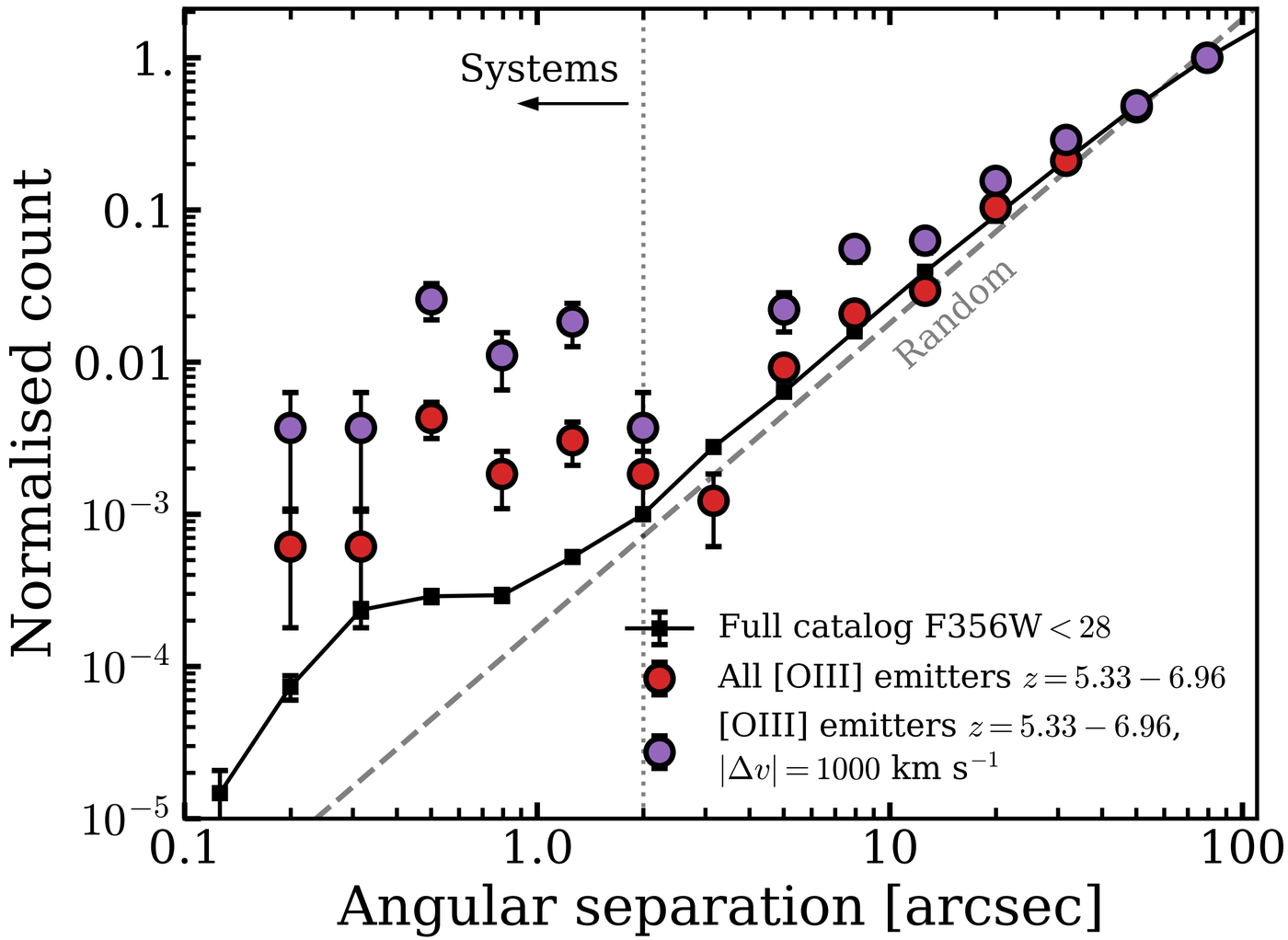
[OIII] emitters at z=5.3–6.9

1.1 um + 2.0 um + 3.5 um They are red for [OIII] in F356W





Auto spatial correlation of [OIII]-emitting clumps

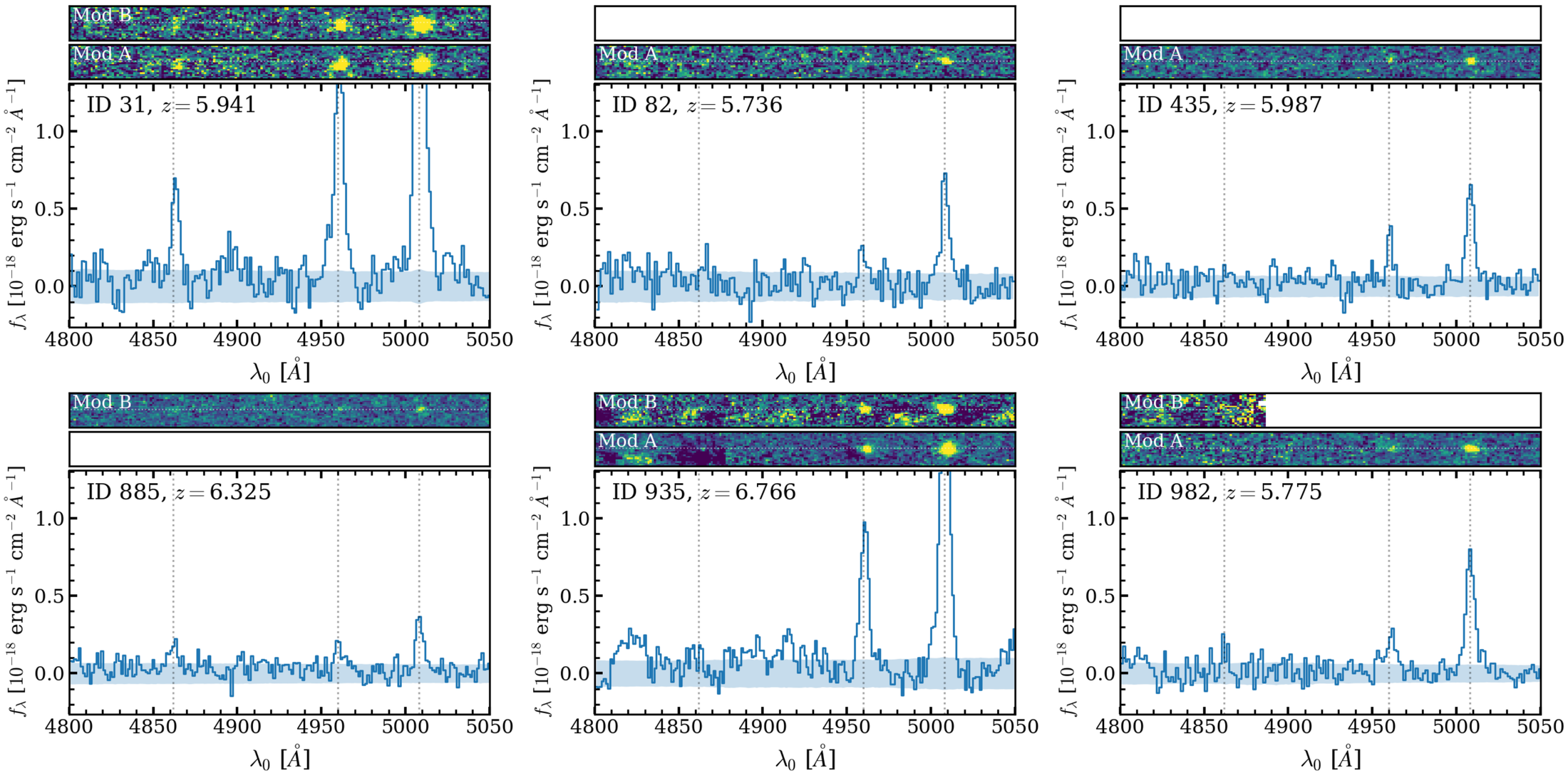


Paper II (Matthee+)

Clumps connected within 2" are regarded as a single "system".

The morphological properties of the sample will be studied in more details in future papers.

Example spectra



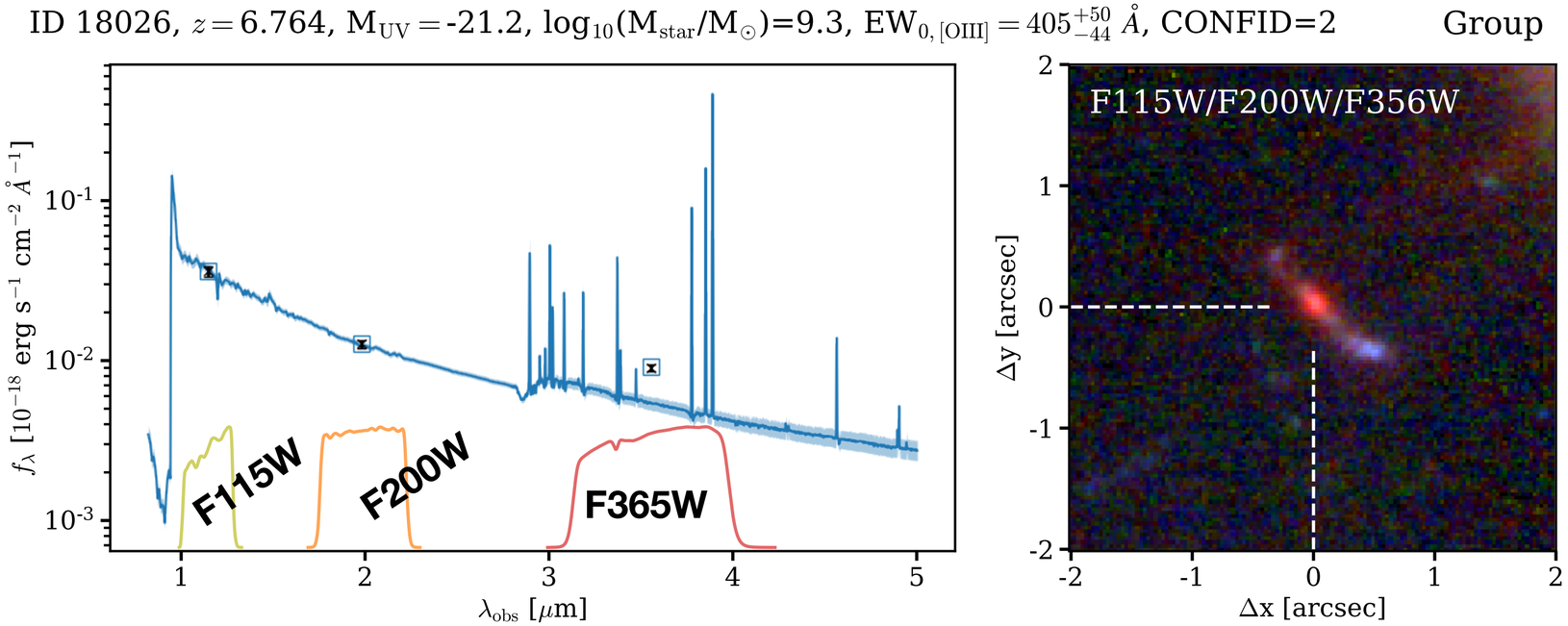
Paper II (Matthee+)

Physical properties

- EW_0 ([OIII]4960,5008) ~ 850 (200–3000) Å
- Stellar mass logMstar/Msun ~ 7–10
- Ages ~30–300 Myr
- Metallicity ~ 0.1 solar

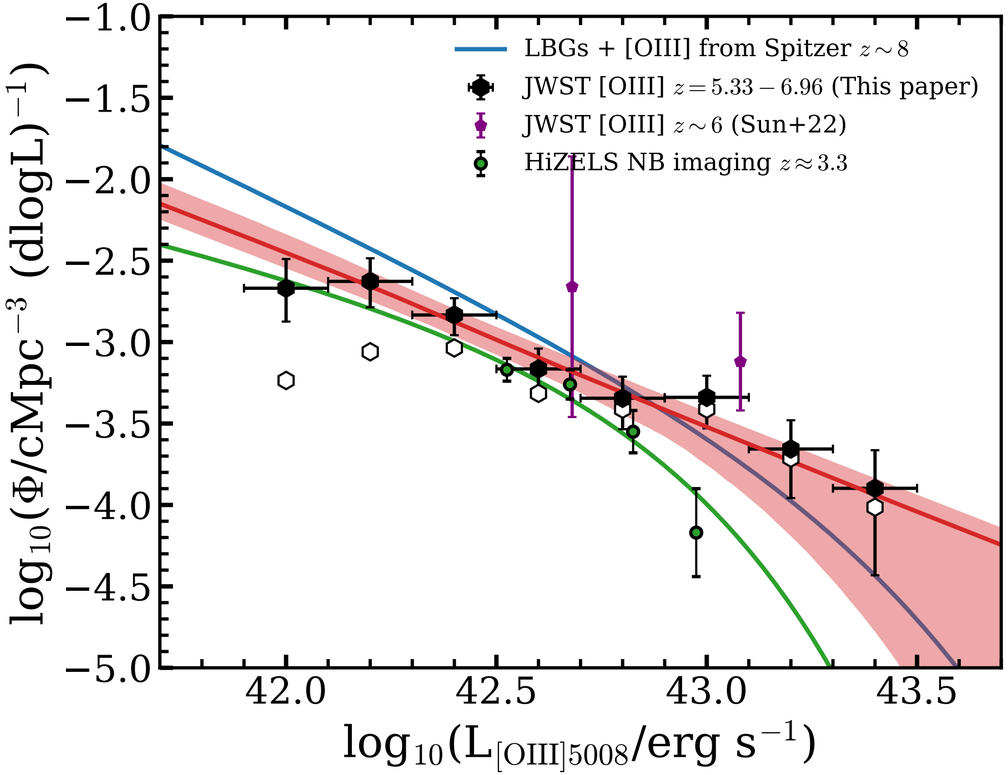
SED fit to F115W, F200W, and F356W + line fluxes with Prospector

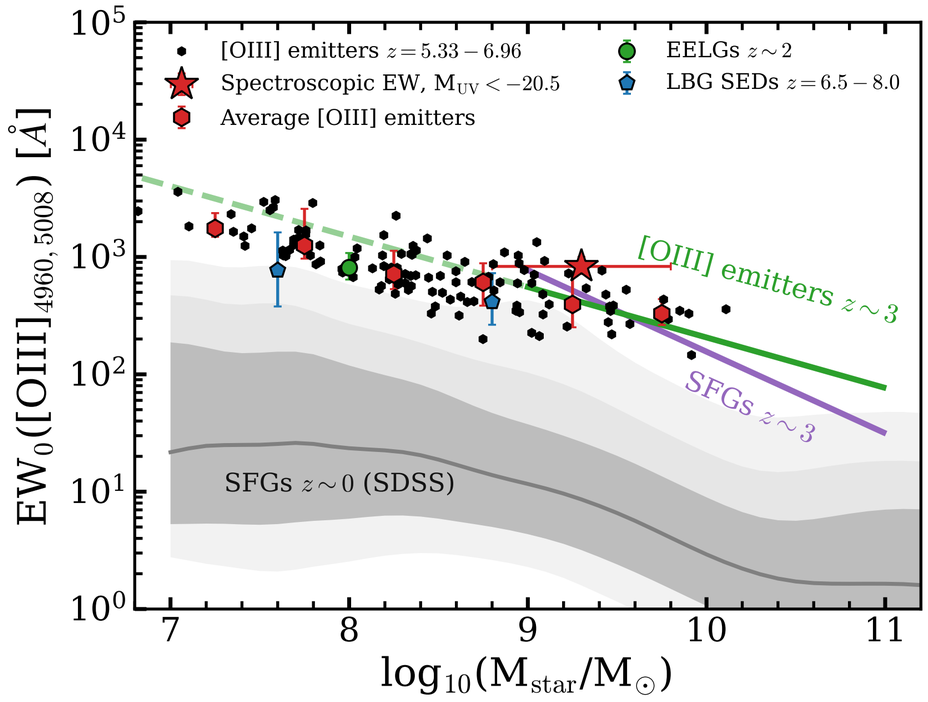
Existing photomeric data (e.g., HST) will be included in future papers.

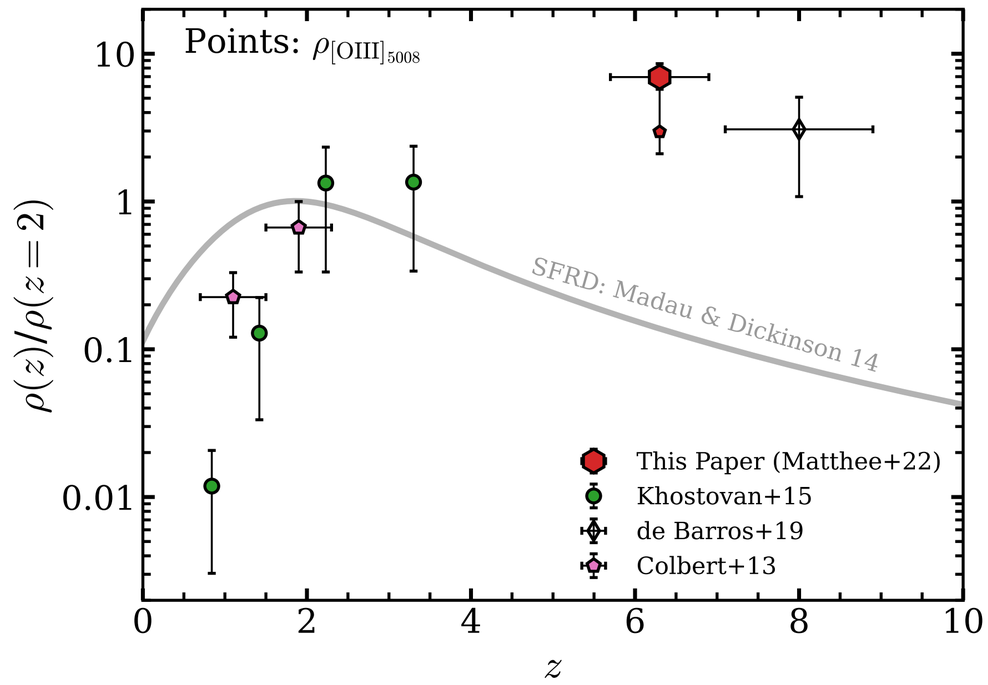


Paper II (Matthee+)

Bright [OIII] emissions

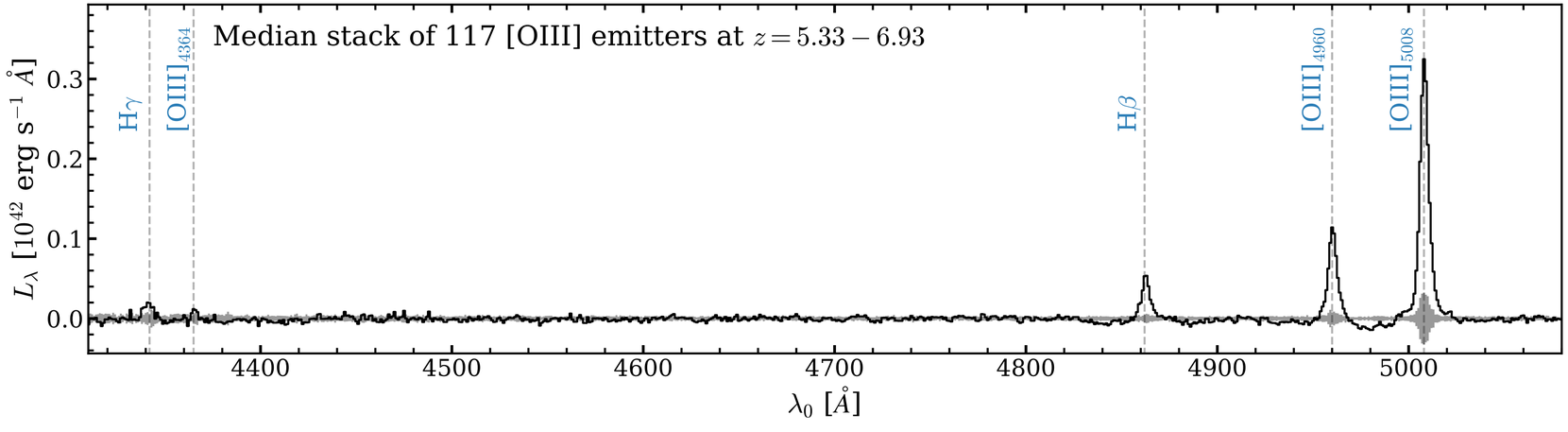


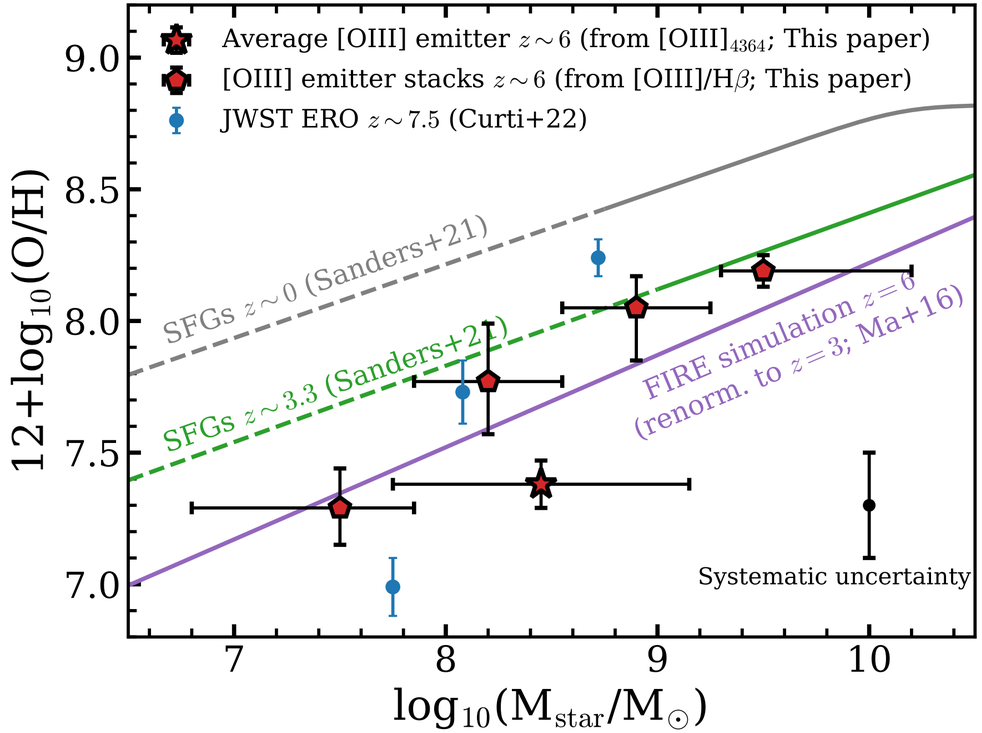




Paper II (Matthee+)

Metallicity: [OIII]4363 detected in the stack



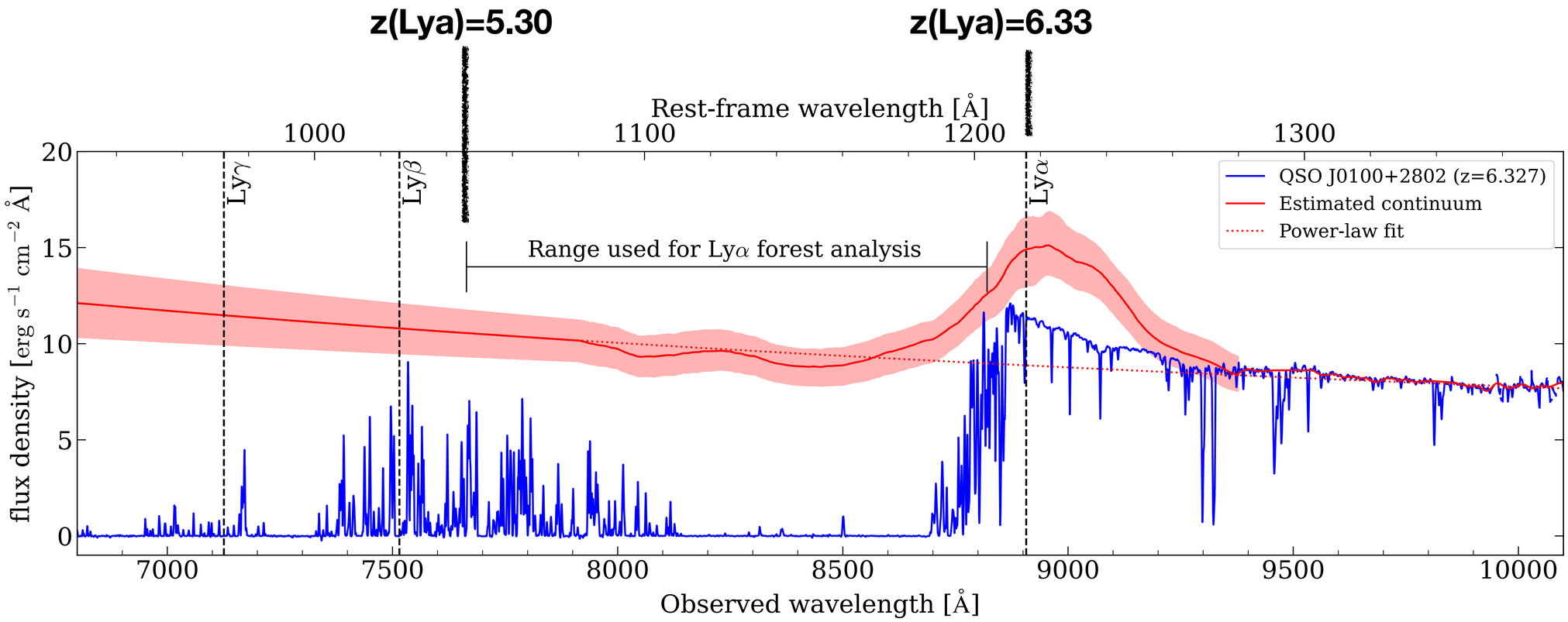


Paper II (Matthee+)

Correlation between IGM transmission and galaxies

Mainly based on Paper I (DK+)

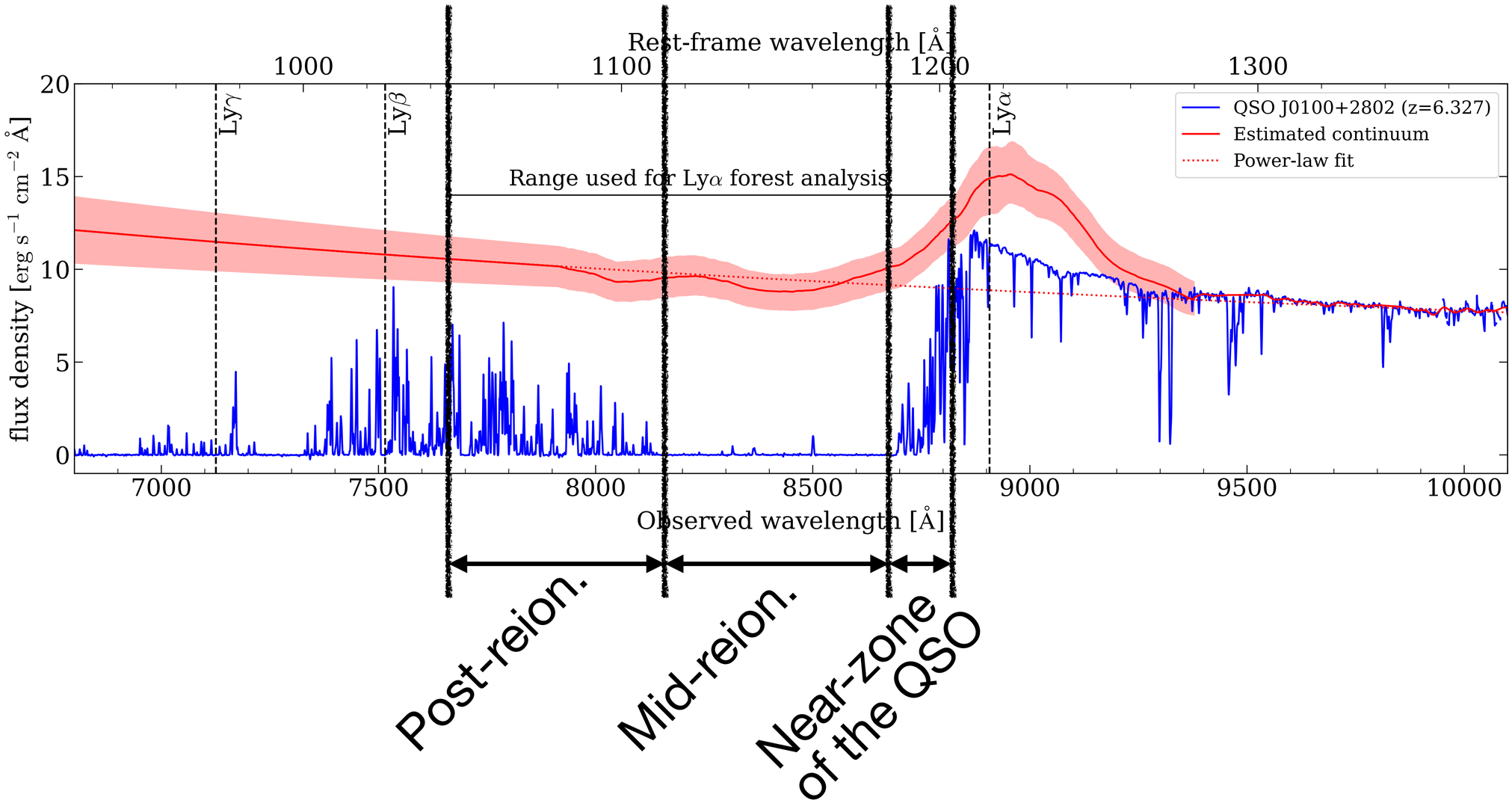
Lyα forest spectrum of QSO J0100+2802



Observed spectrum: 17-hr VLT/X-shooter spectrum, S/N~200 per 50 km/s (or ~0.5 Mpc)

Intrinsic continuum: estimated from a neural network trained by low-z QSOs

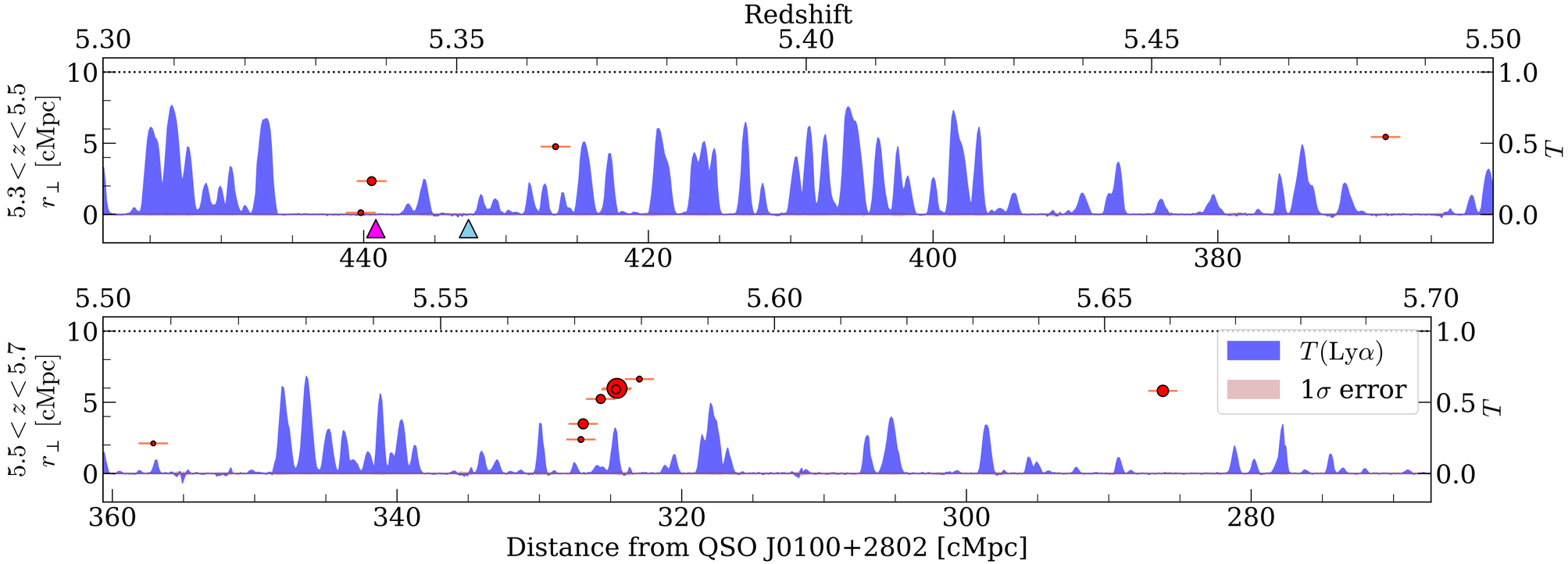
Lyα forest spectrum of QSO J0100+2802



Three redshift regimes

Galaxy – Lyα forest cross-correlation

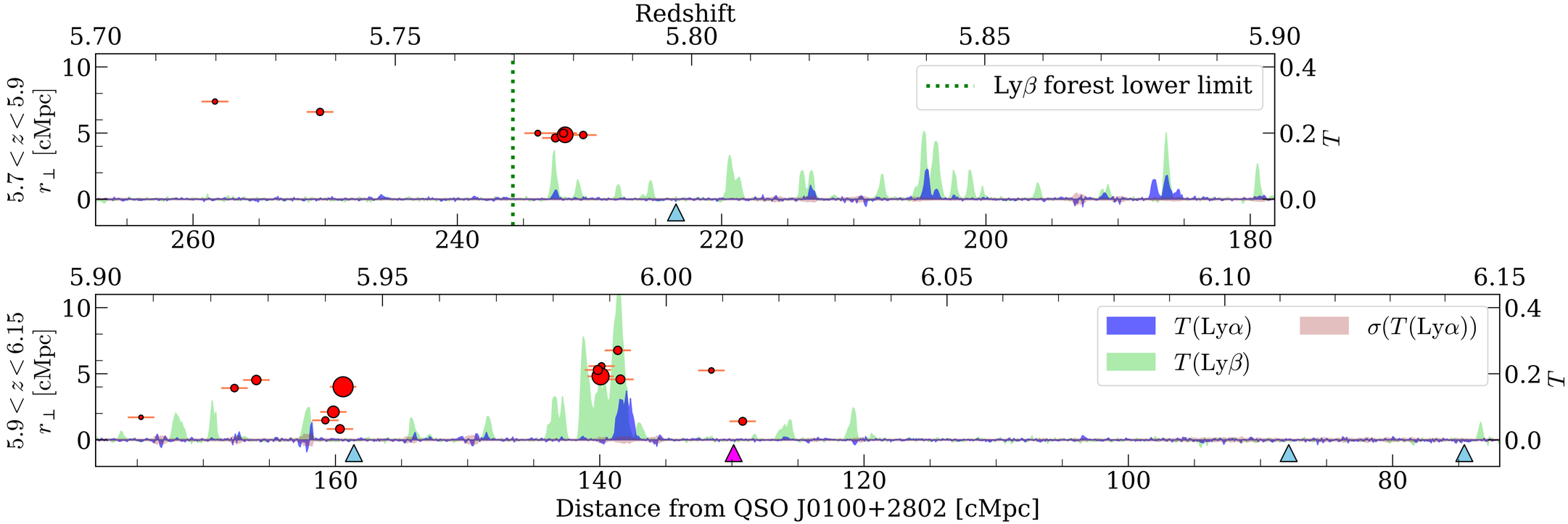
Post-reionization regime (z=5.3–5.7):
ubiquitous transmission of Lyα



Transmission appears to be suppressed near galaxies

Galaxy – Lyα forest cross-correlation

Mid-reionization regime (z=5.3–5.7):
with rare, distinct transmission spikes

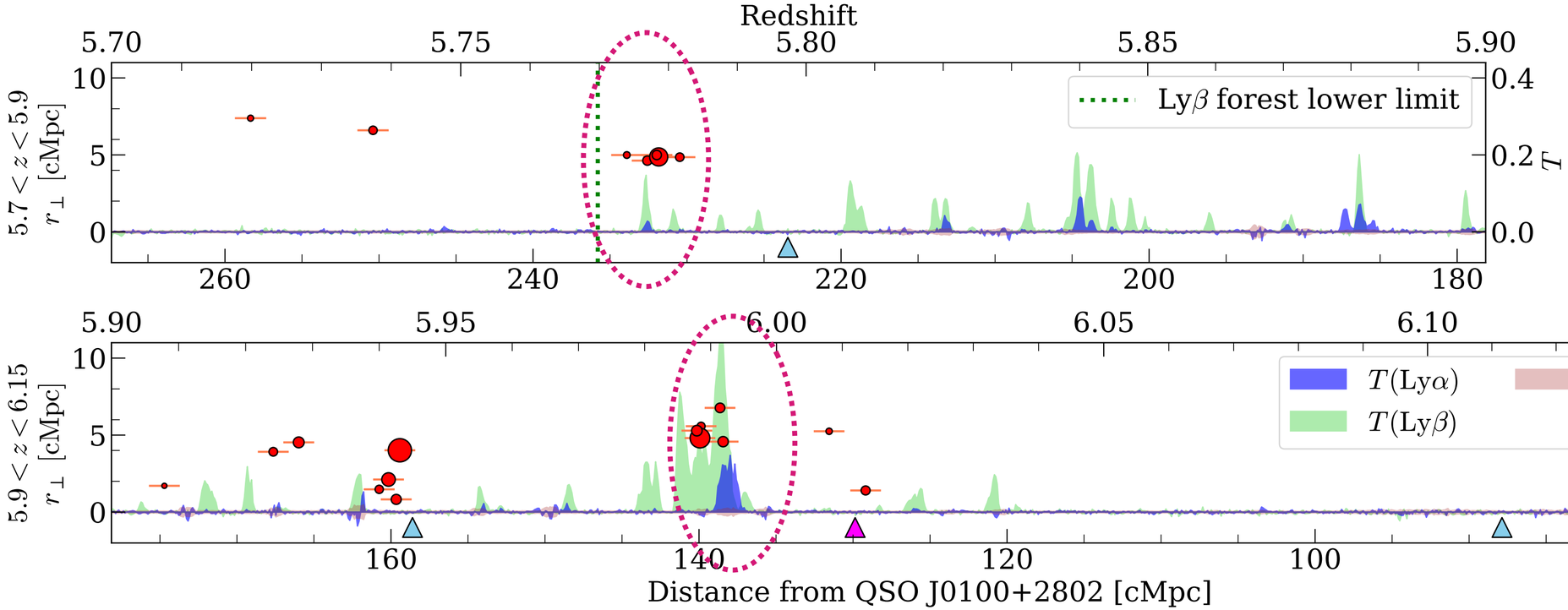


Galaxies are coincident with transmission spikes.

First direct evidence of local ionization of the IGM by galaxies

Galaxy – Lyα forest cross-correlation

Mid-reionization regime (z=5.3–5.7):
with rare, distinct transmission spikes

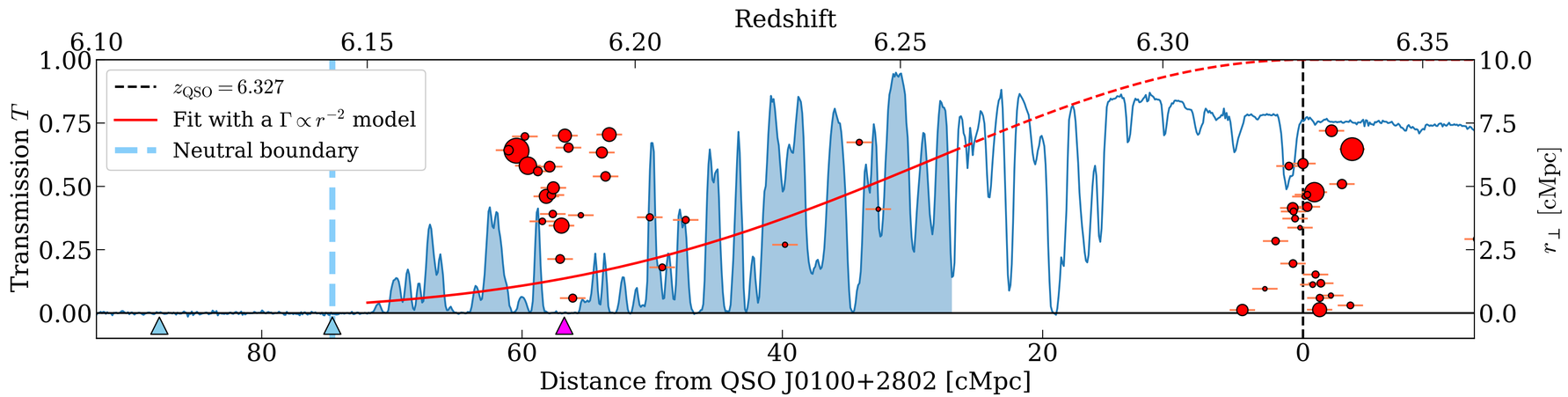


Galaxies are coincident with transmission spikes.

First direct evidence of local ionization of the IGM by galaxies

Galaxy – Lyα forest cross correlation

Quasar near-zone (z=6.15–6.25):
where the radiation from the QSO dominates.



Transmission is suppressed near the galaxy overdensities.

Galaxy – Lyα forest cross-correlation

Post-reionization:

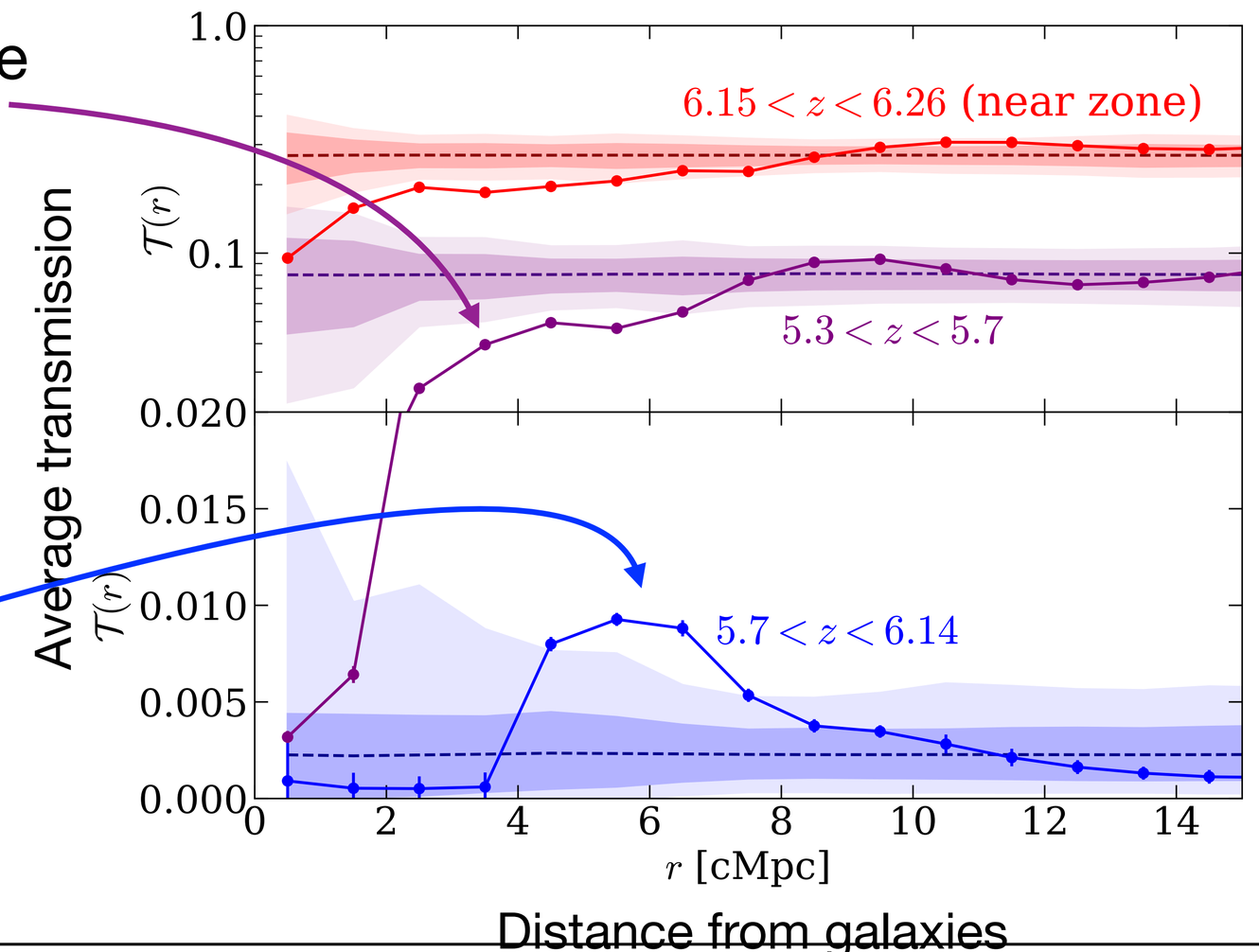
Transmission is suppressed due to dense gas around galaxies, and increases towards the level set by the more or less uniform background radiation

Mid-reionization:

Transmission peaks at ~ 5 cMpc, likely due to local ionization effect of galaxies, then decreases at larger distances, reflecting the low level of mean ionization of the universe

Quasar near zone:

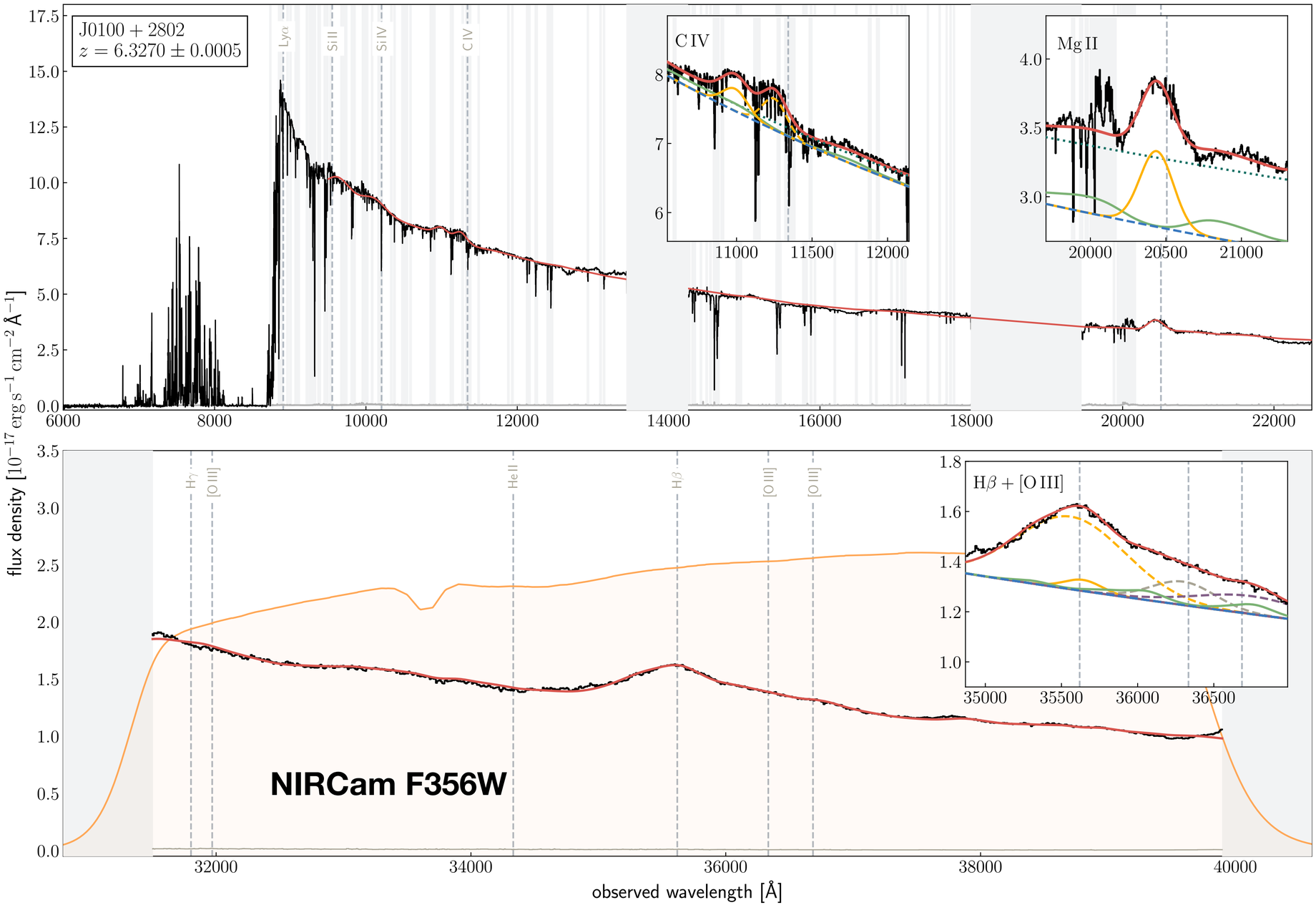
Dominating local but large-scale strong radiation from quasar leads the trend similar to what is seen at lowest-z (but with much higher T)



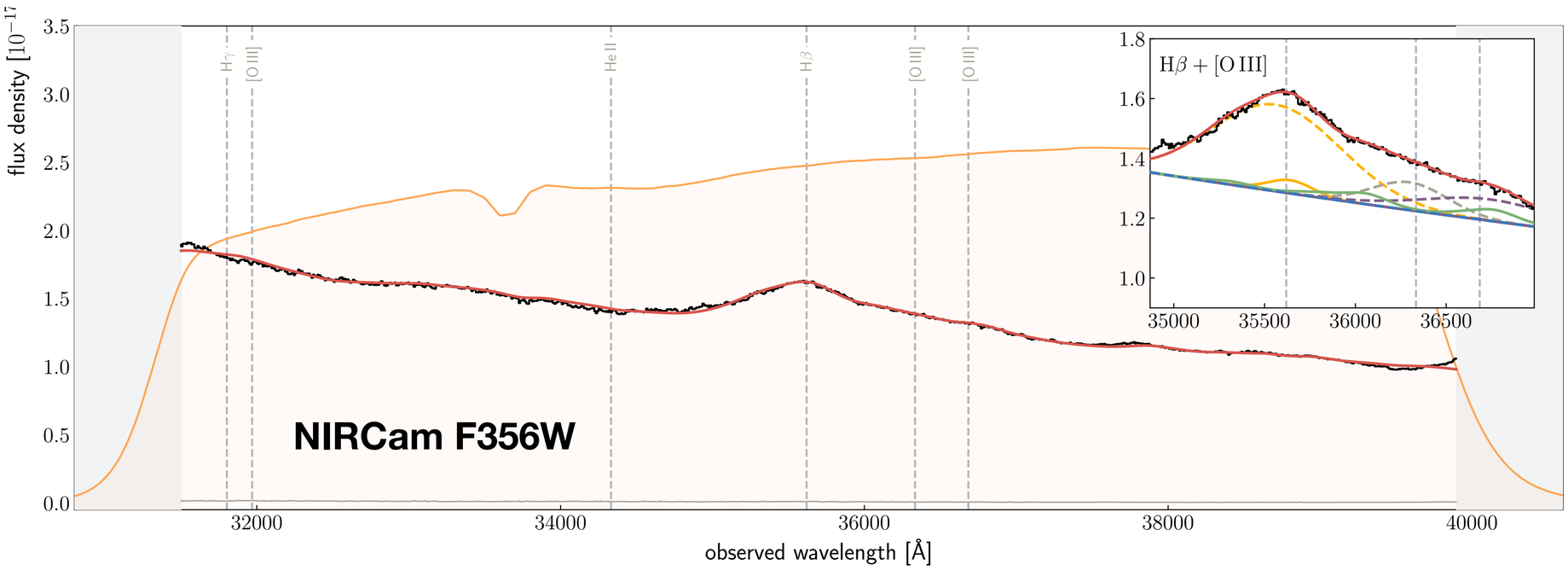
Results on the SMBH

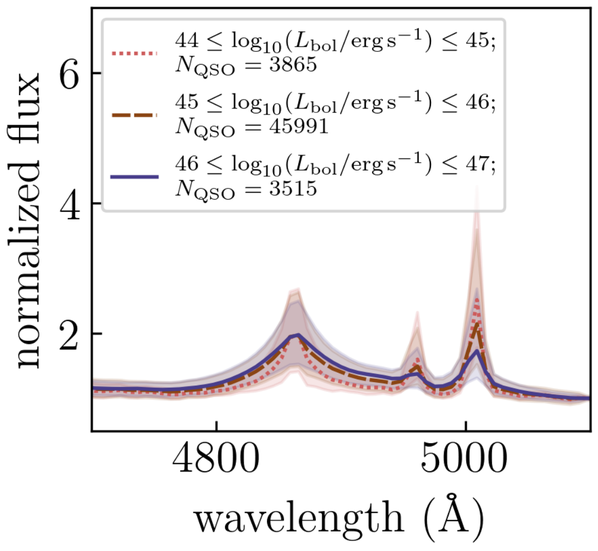
Mainly based on Paper III (Eilers+)

First rest-frame optical spectrum of z~6 QSO



First rest-frame optical spectrum of z~6 QSO





The [OIII] lines are surprisingly weak, with no significant narrow component, far different from typical SDSS quasars.

FWHM (Hβ) = 6480 ± 170 km/s

SMBH mass estimate

Hβ (+ $L_{5100Å}$) is considered as the best SMBH indicator, well calibrated at local universe.

Three empirical indicators, (Hβ, CIV, MgII) point to a SMBH mass logM●/Msun=9.7–10.2 , with Hβ yielding the highest.

Statistical errors are small, but the systematic uncertainties are large (~0.5 dex, or a factor of 3).

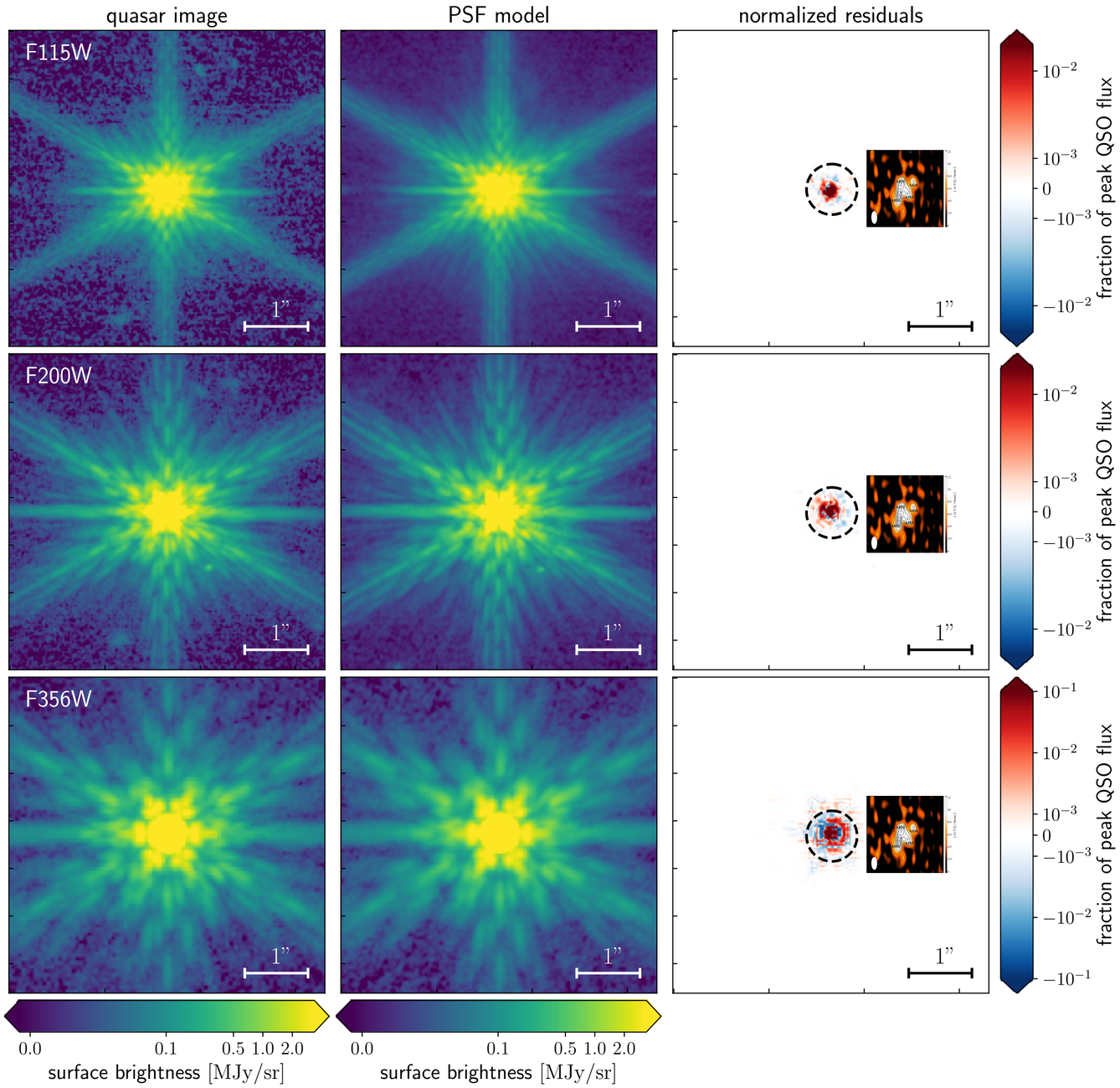
Table 2. Spectral properties of the quasar J0100+2802.

spectral property	measurement
$\mathrm{FWHM_{C\,IV}}$ $[\mathrm{km\,s^{-1}}]$ (corrected)	4270 ± 150
$\mathrm{FWHM_{Mg\,II}}$ $[\mathrm{km\,s^{-1}}]$	3790 ± 30
$\mathrm{FWHM_{H\beta}}$ $[\mathrm{km\,s^{-1}}]$	6480 ± 170
$\Delta v_{\mathrm{C\,IV}}$ $[\mathrm{km\,s^{-1}}]$	-2470 ± 80
$\Delta v_{\mathrm{Mg\,II}}$ $[\mathrm{km\,s^{-1}}]$	-980 ± 10
$\Delta v_{\mathrm{H\beta}}$ $[\mathrm{km\,s^{-1}}]$	-110 ± 20
1350Å $L_{1350\mathrm{Å}}$ $[10^{46}\,\mathrm{erg\,s^{-1}}]$	41.1 ± 0.1
3000Å $L_{3000\mathrm{Å}}$ $[10^{46}\,\mathrm{erg\,s^{-1}}]$	25.6 ± 0.1
5100Å $L_{5100\mathrm{Å}}$ $[10^{46}\,\mathrm{erg\,s^{-1}}]$	20.1 ± 0.1
$\log_{10}(M_\bullet/M_\odot)$ (C IV)	9.9 ± 0.1
$\log_{10}(M_\bullet/M_\odot)$ (Mg II)	9.7 ± 0.1
$\log_{10}(M_\bullet/M_\odot)$ (Hβ)	10.2 ± 0.1

No evidence of strong lensing

No multiple images at the diffraction limit 0.05".

Multi-image in ALMA 1mm reported by Fujimoto+20



Summary

- EIGER, a JWST GTO program of slitless spectroscopic survey of z~6 galaxies in the quasar fields.
- First observation was conducted in the field of ultraluminous QSO J0100+2802 z=6.33
- **First large sample of 117 [OIII]-selected galaxies over z=5.3–6.9**
  - EW_0~1000Å, stellar mass ~ 10^7–10^{10} Msun, metallicity ~ 0.1 Zsun
  - Strong overdensities (one at $z=z_{QSO}=6.33$)
- **Direct evidence for local ionization of the IGM by galaxies at z~5.9**
- **SMBH mass from Hβ log ~ 10.2, no evidence for strong lensing**

Check our papers on arXiv:

2211.08254 Kashino+: survey design, details of analysis, and correlation with the IGM transmission

2211.08255 Matthee+:characterization of the [OIII]-selected galaxies

2211.16261 Eilers+: SMBH measurement of QSO J0100+2802 from Hβ

More papers will come soon.