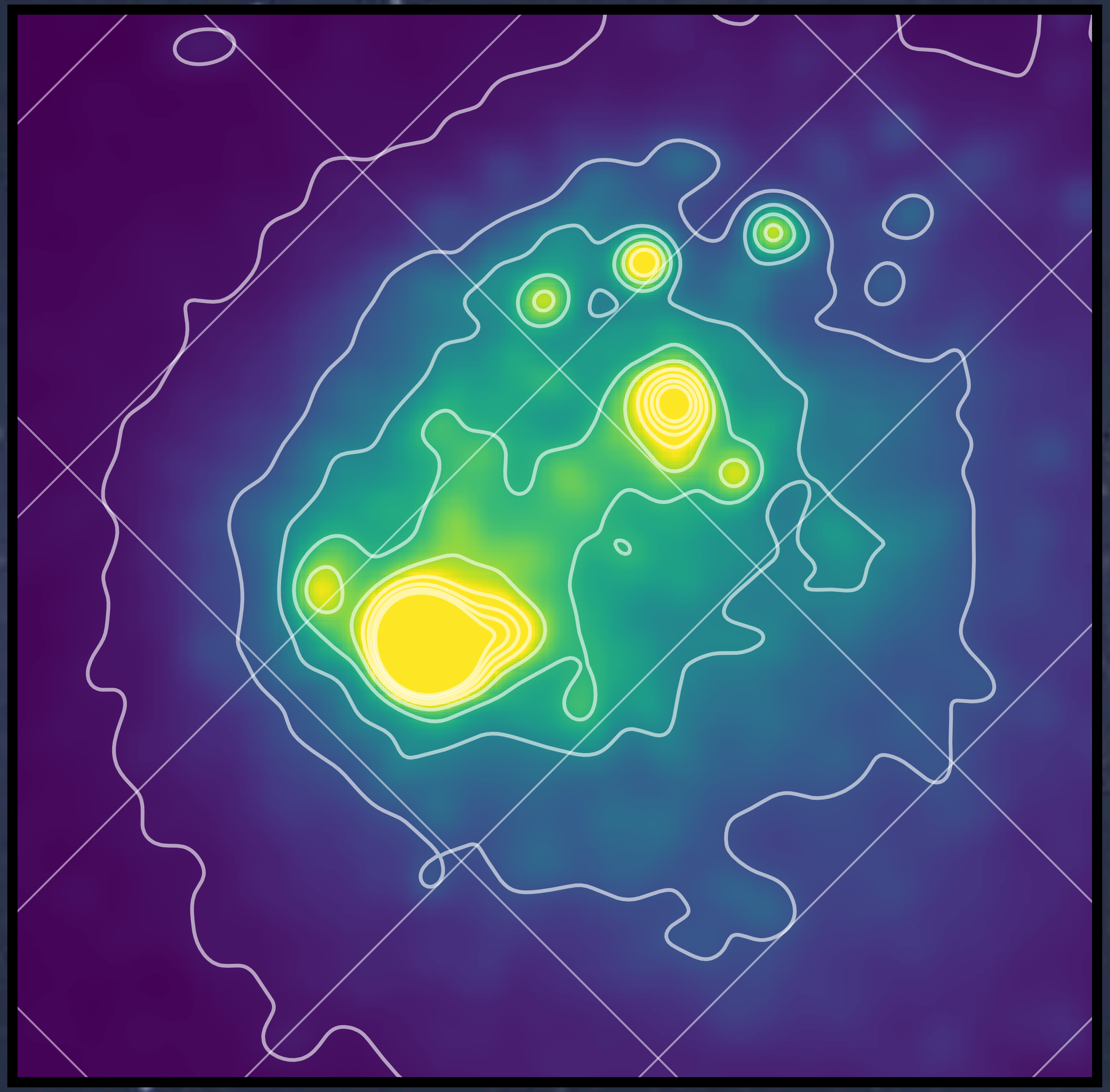
Unveiling the escape of ionizing photons: new insights from a 2D spatially-resolved study



Cristina Cabello (UCM)

TEAM: Nicolás Cardiel,
Jesús Gallego,
Sergio Pascual

Escape of Lyman radiation from galactic labyrinths - OAC, Crete - April 2023

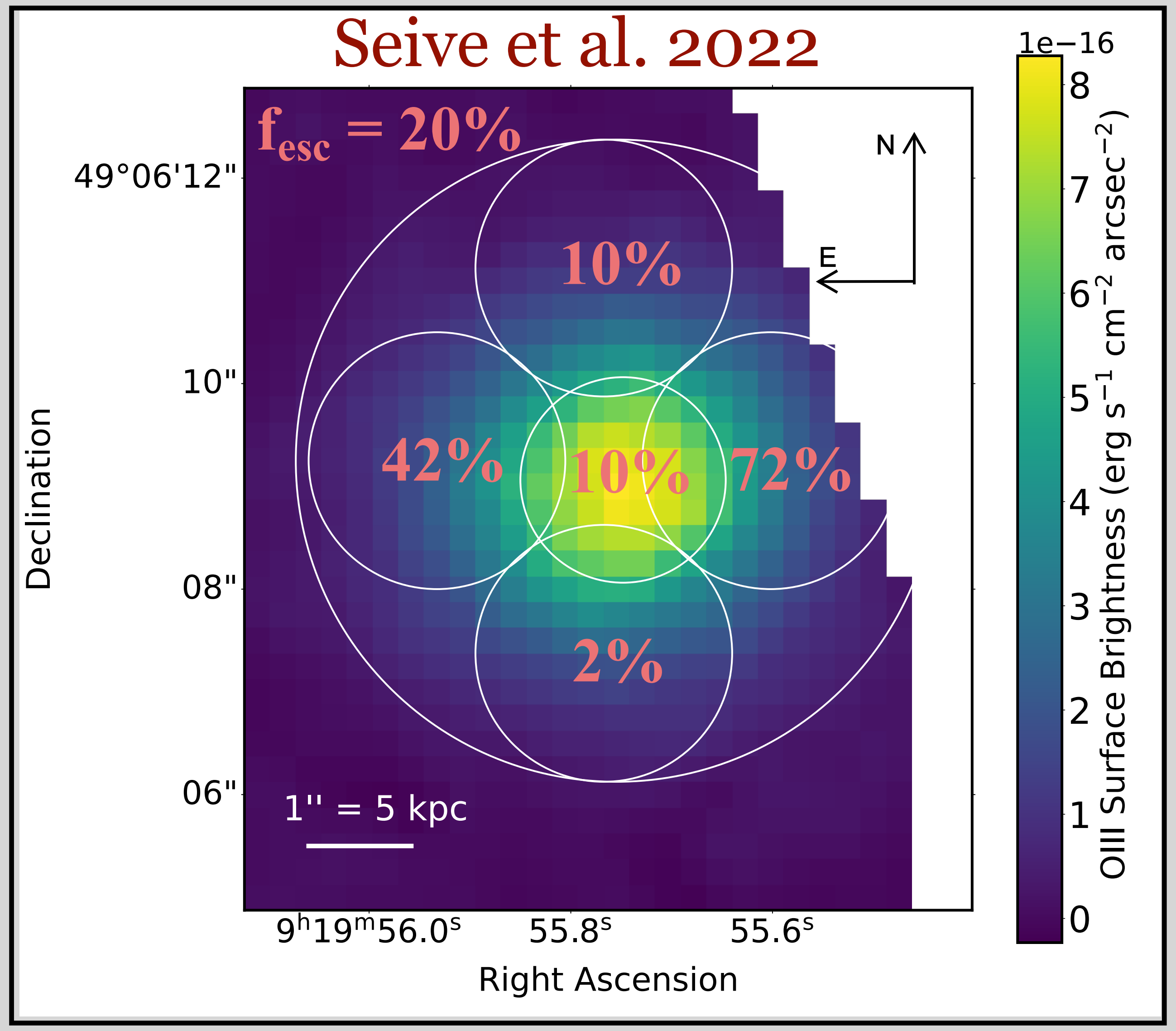
Outline

1. ✦ Introduction and motivation of the project
2. ✦ Instrumental setup and observations
3. ✦ Data reduction and processing
4. ✦ Estimation of random uncertainties
5. ✦ Analysis and preliminary results
6. ✦ General conclusions and final remarks

1 Introduction and motivation of the project

Lyman Continuum (LyC) leakers and reionization epoch analogs

The study of galaxies which may be representative of the high-z galaxy population can provide useful hints about cosmic reionization and the first galaxies.



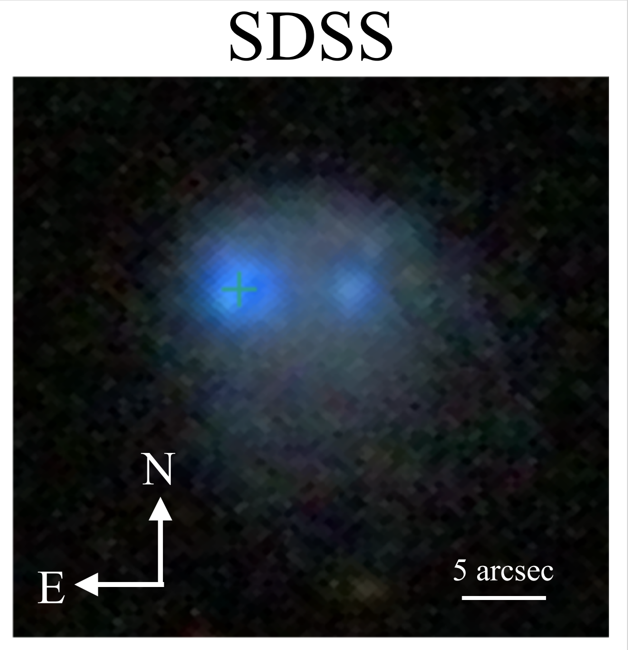
Properties of local analogs

- ✦ Small angular size
- ✦ Blue intrinsic color
- ✦ Irregular morphology
- ✦ Low stellar mass
- ✦ Low metallicity
- ✦ High SFR
- ✦ High gas content
- ✦ Spectrum dominated by strong emission lines

The importance of IFU observations

- Identification of different regions of low-z galaxies which are leaking LyC photons by performing a 2D spatially-resolved analysis of their physical properties.

- Testing of indirect indicators of LyC leakage: O32 vs R23 index, He I diagram, [SII] BPT diagram, mass dependency… (Nakajima et al. 2016, Izotov et al. 2017, 2018, Jaskot et al. 2019, Wang et al. 2021).



1

Introduction and motivation of the project

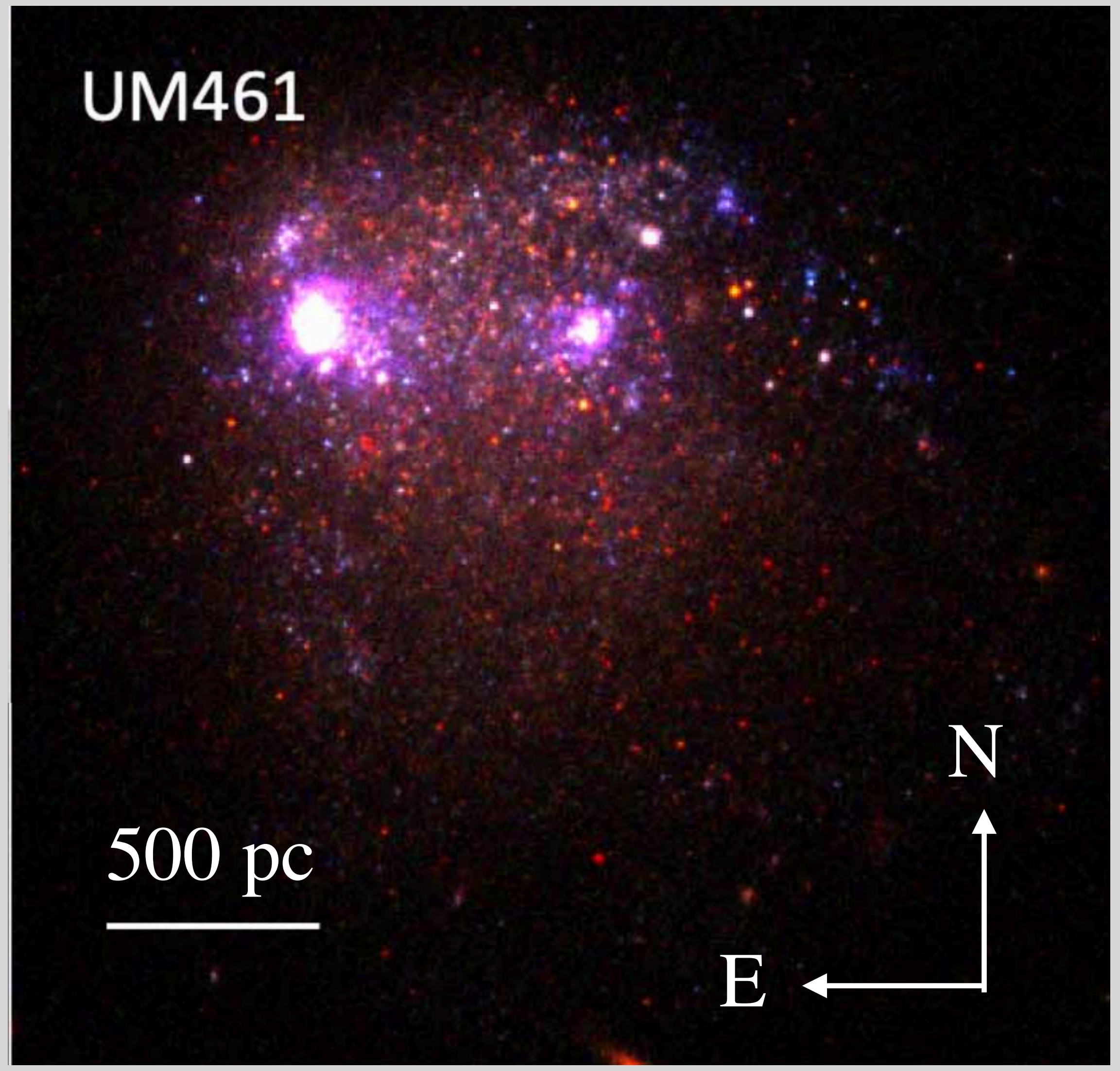
UM461: a potential LyC leaker candidate

- **Excellent local analog of high-z galaxies** (Motiño Flores et al. 2021)
- **Potential LyC leaker candidate** (Katz et al. 2020)

↓

We selected this star-forming galaxy for a
2D spatially-resolved study of its physical properties

Elmegreen et al. 2022



HST WFC3 and ACS observations
Filters: F390W, F574M, and F814W

Main goals:

- Shed light on the nature of UM461
- Map the ionization structure of the ISM.
- Test its resemblance with the high-z population of galaxies
- Investigate the mechanisms that allow LyC photons to escape in the first galaxies.

UM461 properties

$z = 0.003465$

$M_* = 7.6 \times 10^7\ M_\odot$

$12 + \log(O/H) = 7.78$

Size: 9 arcsec × 7 arcsec

2 Instrumental setup and observations

The MEGARA instrument

The first Integral-Field Unit (IFU) designed for the 10.4m GTC telescope

Composed of fibres.

↓

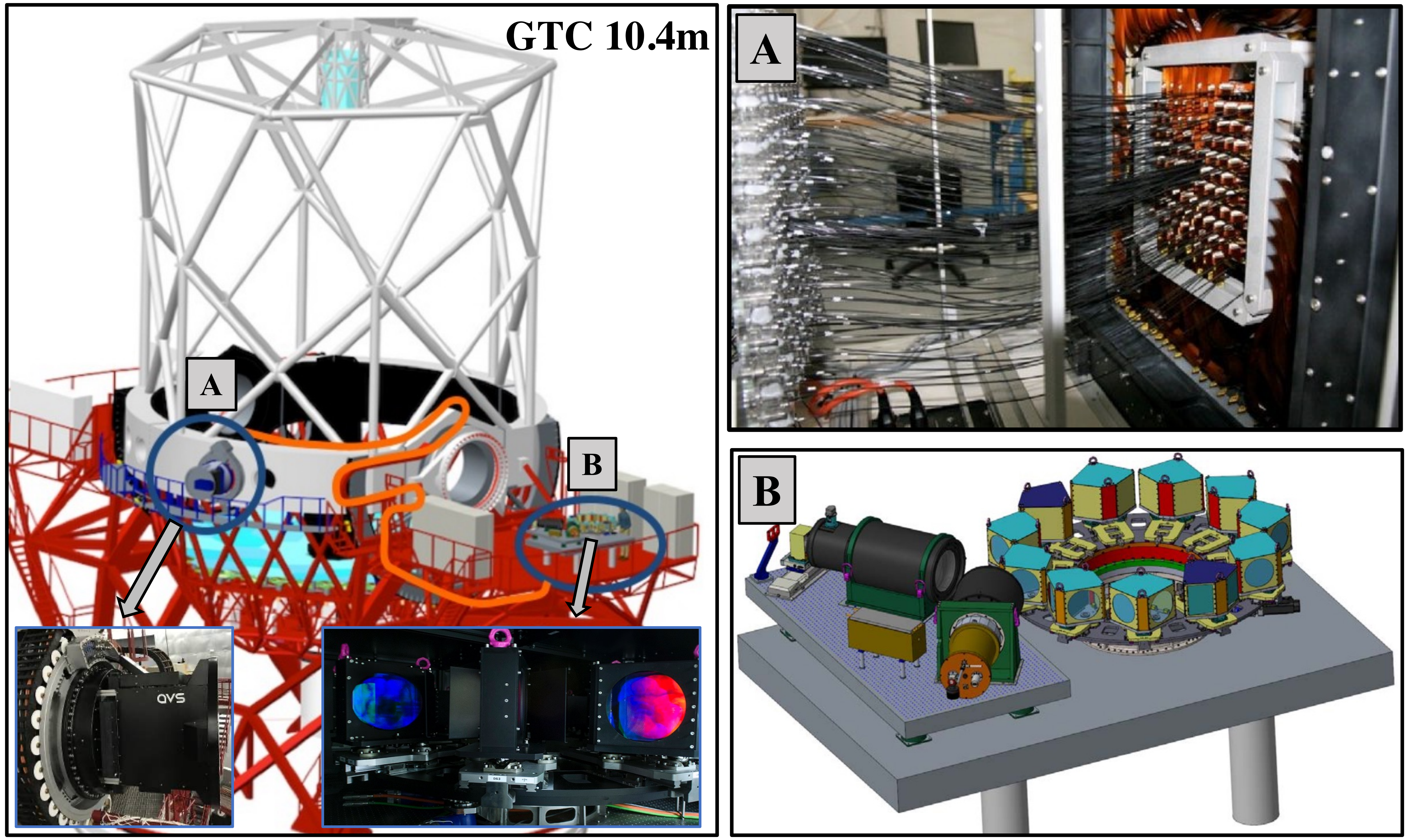
- **Large Compact Bundle (LCB) mode**

Main bundle with 567 fibers

8 minibundles (with 7 fibers each) that sample the sky background emission

- **MOS mode**

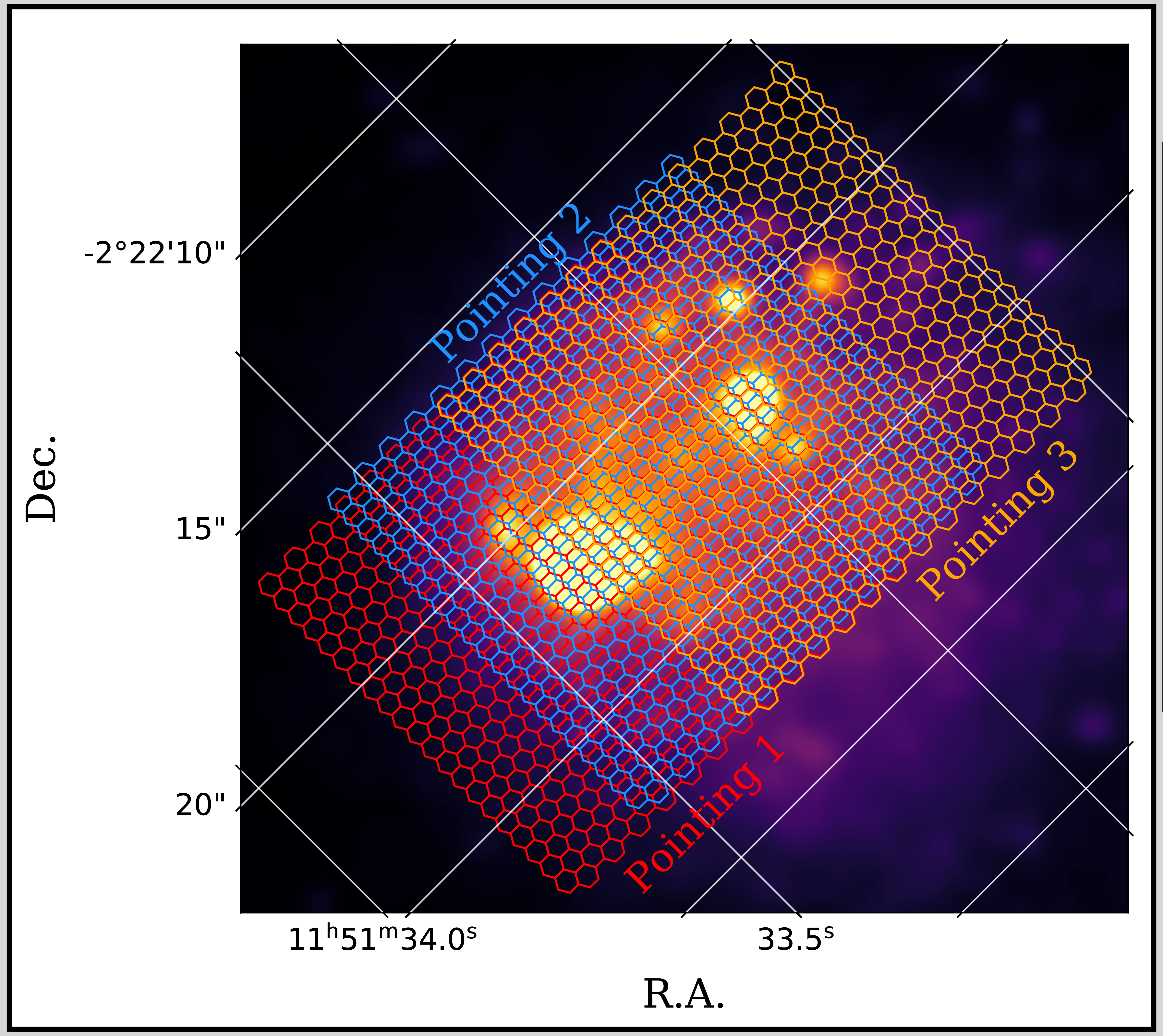
Robotic positioners that allow observing up to 92 objects



Detector:	E2V CCD231-84	**Readout noise:**	3.4 e^-
Spaxel size:	0.62″	**Gain:**	1.73 e^-/ADU
Spectral range:	0.37–0.97 μm	**FOV (IFU):**	12.5″ × 11.3″
Spectral resolution:	5 500, 12 500, and 20 000	**FOV (MOS):**	3.5′ × 3.5′

2 Instrumental setup and observations

UM461



GT + GTC proposal 62-GTC60/22A (PI: C. Cabello)

Point.	R.A.	Dec.	VPH	R ($\lambda/\Delta\lambda$)	Wave. range	Exp. Time	Obs. Date
1	11h 51m 33.34s	$-02°$ 22′ 21.9″	LR-U	5750	3654−4392 Å	3600 s	21/05/22
1	11h 51m 33.34s	$-02°$ 22′ 21.9″	LR-B	5000	4332−5200 Å	9600 s	22/02/21
1	11h 51m 33.34s	$-02°$ 22′ 21.9″	LR-R	5900	6097−7303 Å	3600 s	13/03/21
2	11h 51m 33.15s	$-02°$ 22′ 22.2″	LR-U	5750	3654−4392 Å	3840 s	05/05/22
2	11h 51m 33.15s	$-02°$ 22′ 22.2″	LR-B	5000	4332−5200 Å	3840 s	05/05/22
2	11h 51m 33.15s	$-02°$ 22′ 22.2″	LR-R	5900	6097−7303 Å	3840 s	05/05/22
3	11h 51m 32.93s	$-02°$ 22′ 22.1″	LR-U	5750	3654−4392 Å	7200 s	01/05/22
3	11h 51m 32.93s	$-02°$ 22′ 22.1″	LR-B	5000	4332−5200 Å	3600 s	06/03/22
3	11h 51m 32.93s	$-02°$ 22′ 22.1″	LR-R	5900	6097−7303 Å	3600 s	06/03/22

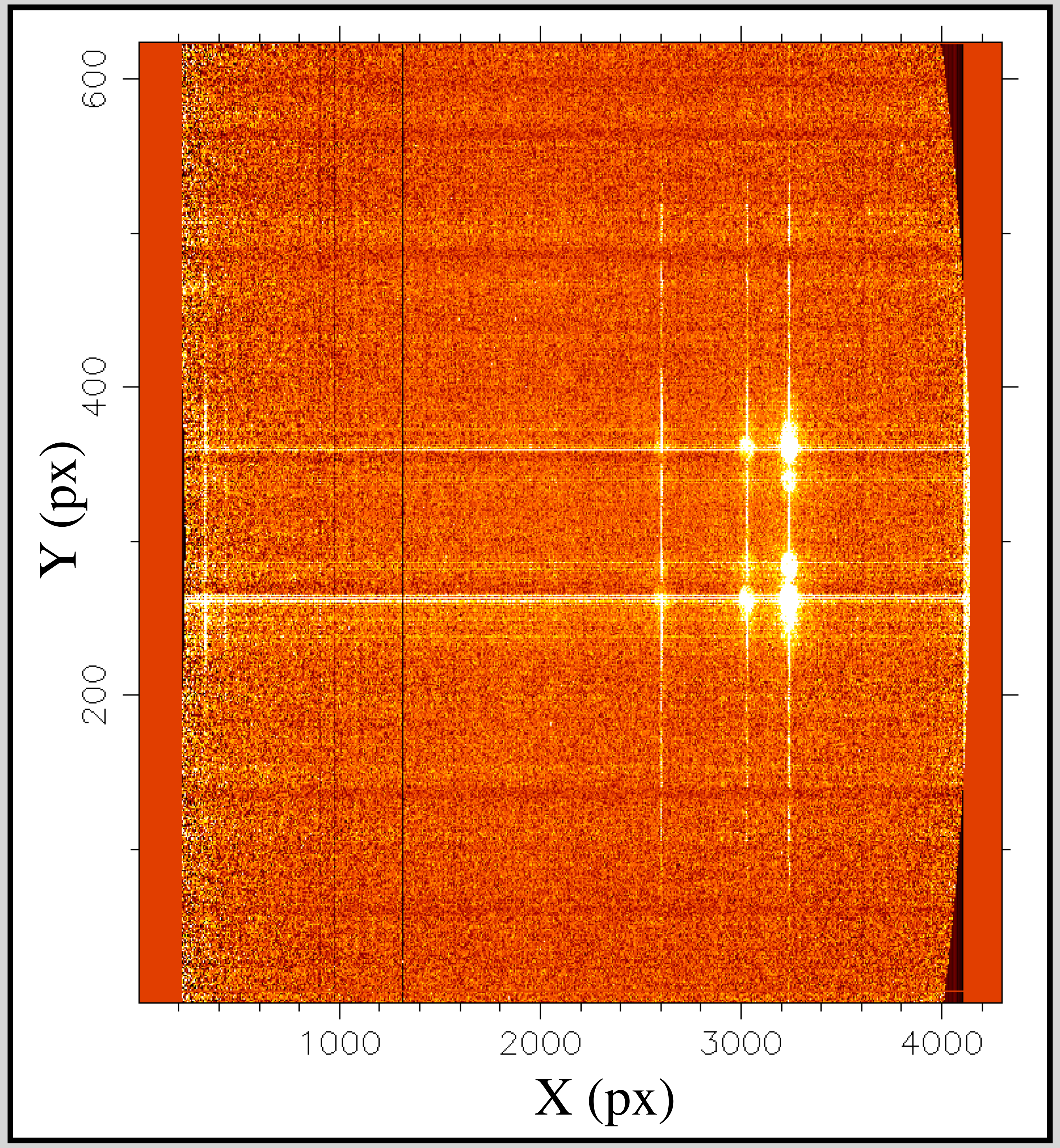
3 Data reduction and processing

MEGARA Data Reduction Pipeline (DRP)

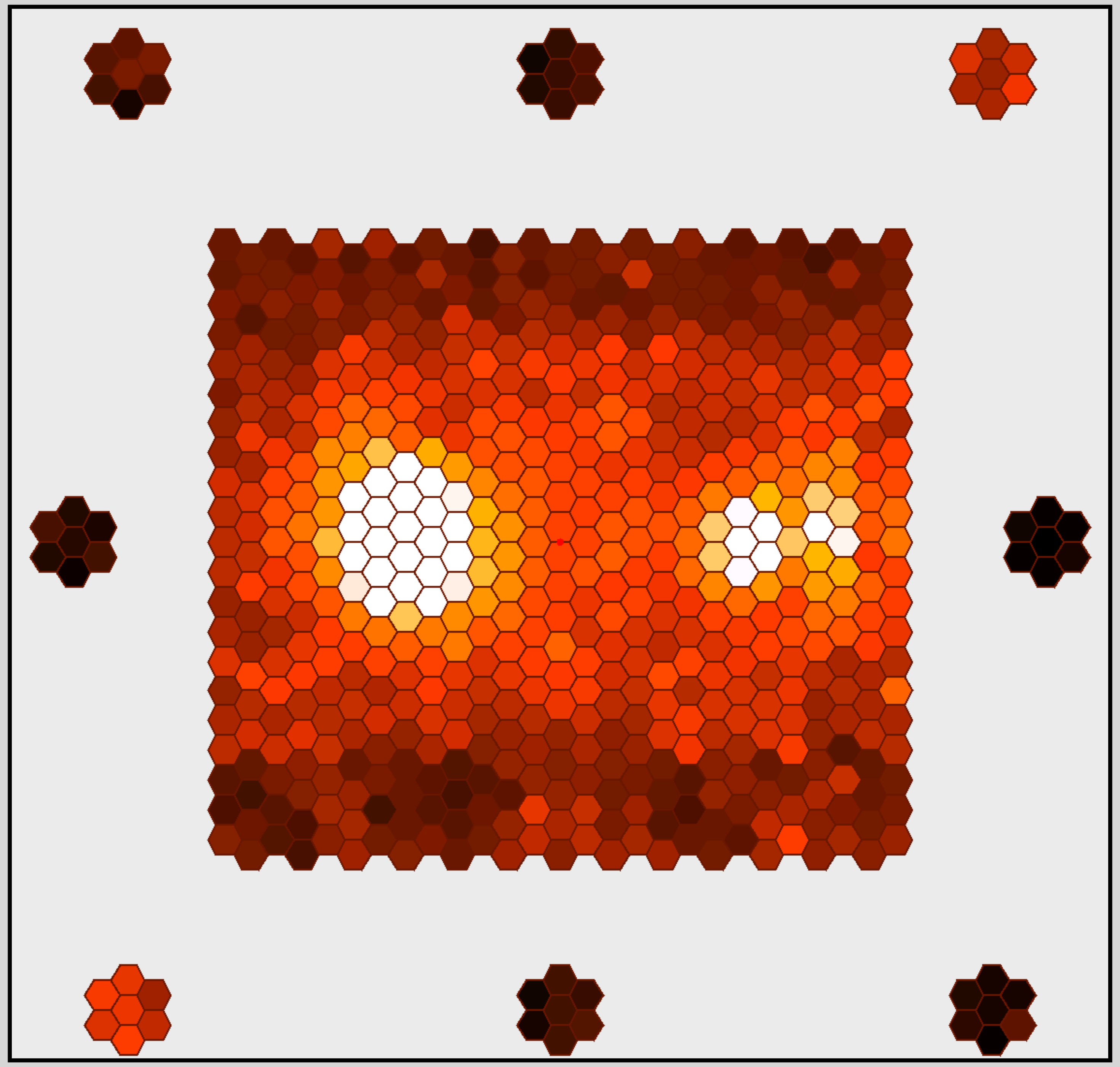
- **Master Bias image**
- **Tracemap**
- **Modelmap**
- **Wavelength calibration**
- **Master Fiberflat**
- **Master Twilight**
- **LCB acquisition**
- **Master Sensitivity**
- **LCB reduction**
  (combination, overscan removal, bias subtraction, extraction, wavelength calibration, flat-fielding, flux calibration, sky subtraction)

Sergio Pascual, Nicolás Cardiel
https://pypi.org/project/megaradrp/

Row-Stacked Spectra (RSS)

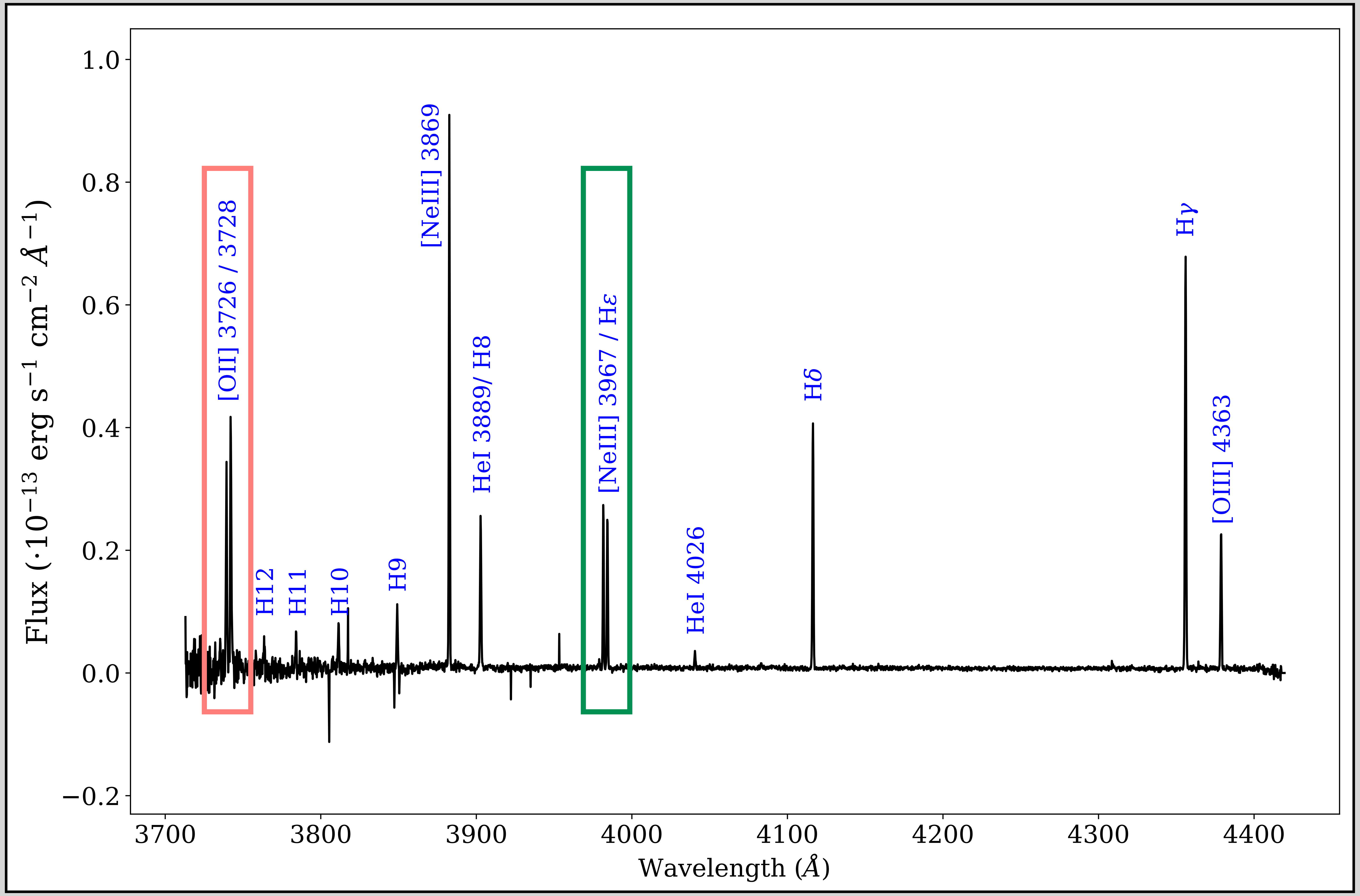


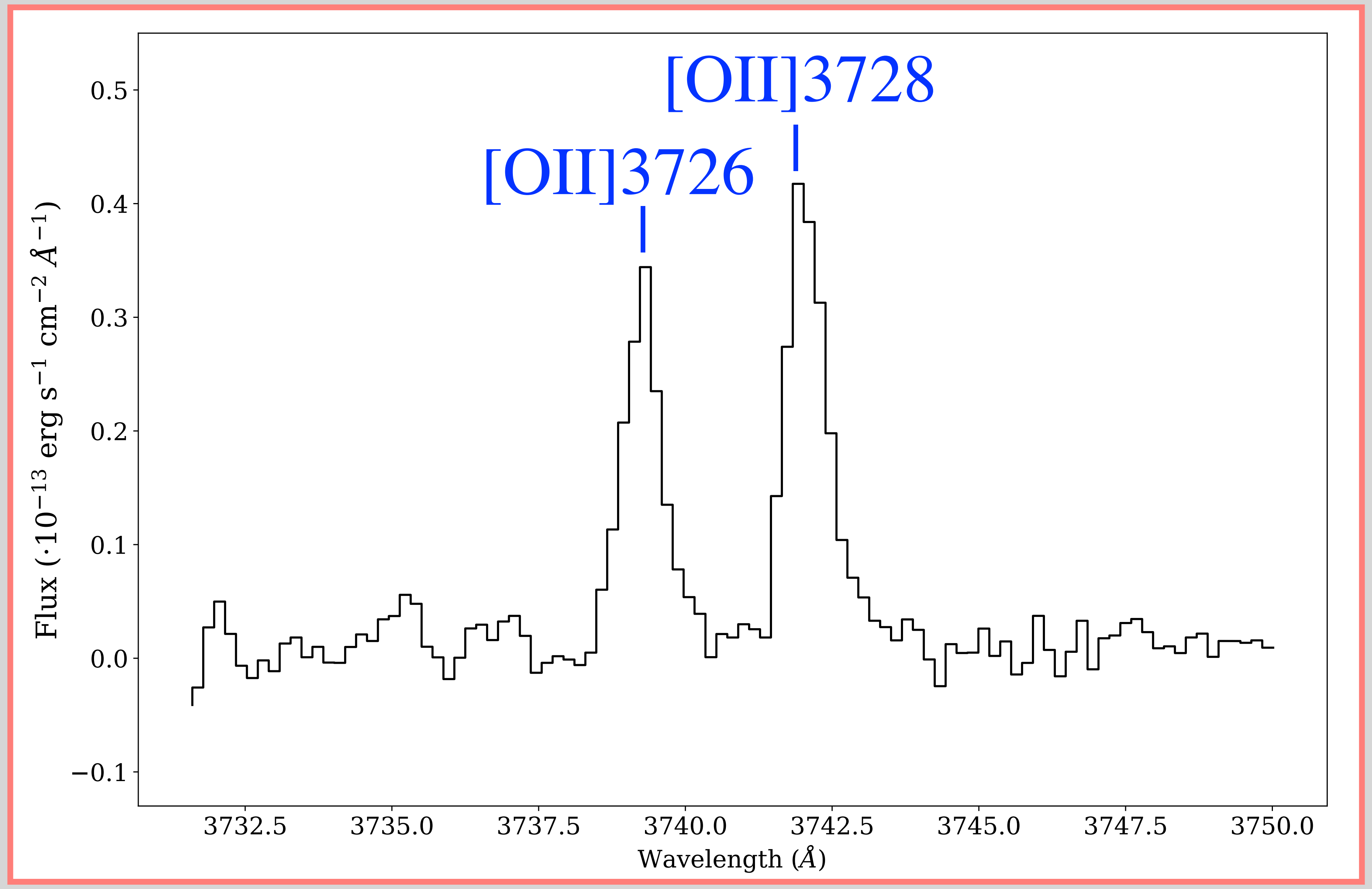
White light image

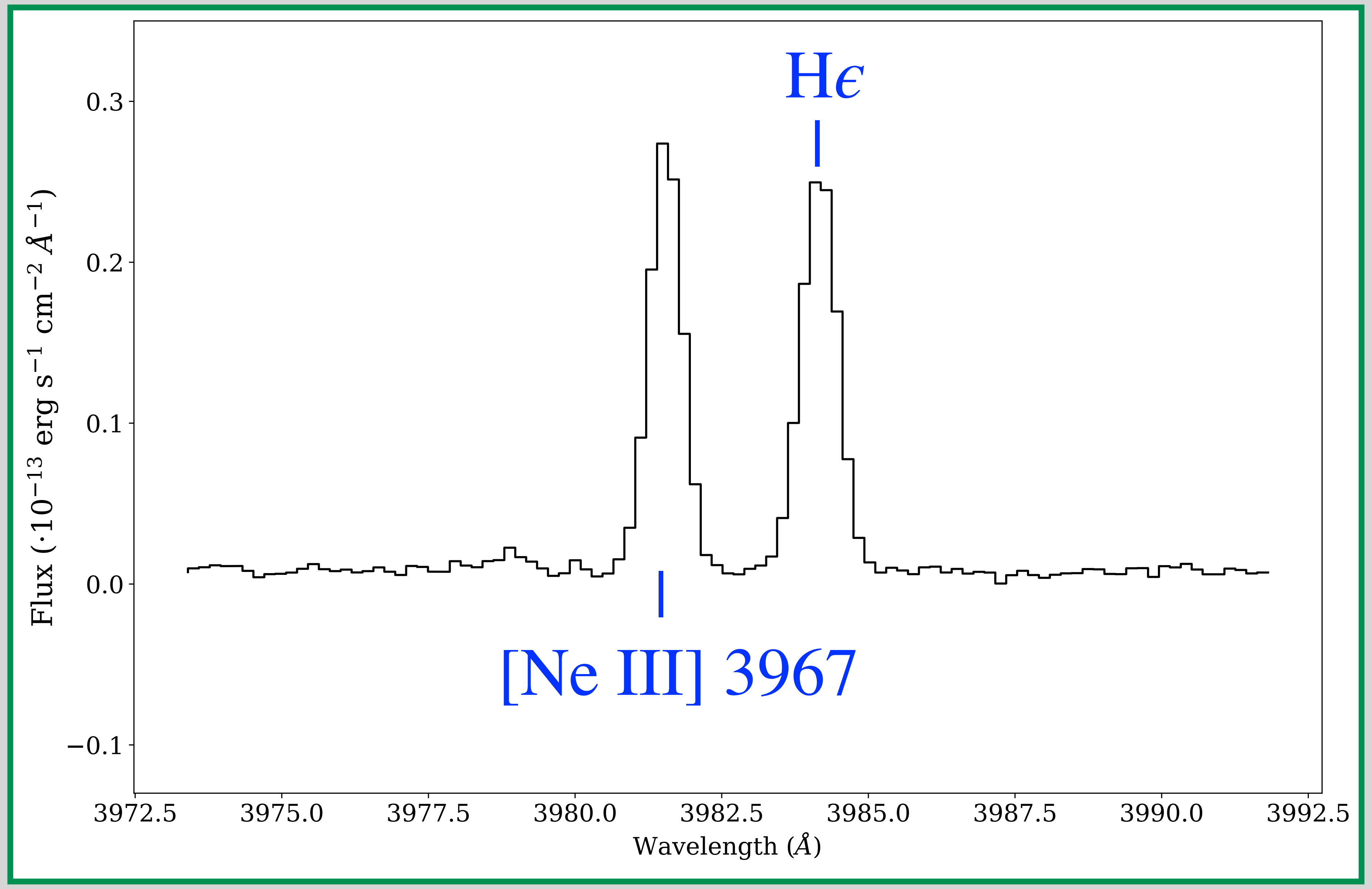


3 Data reduction and processing

LR-U

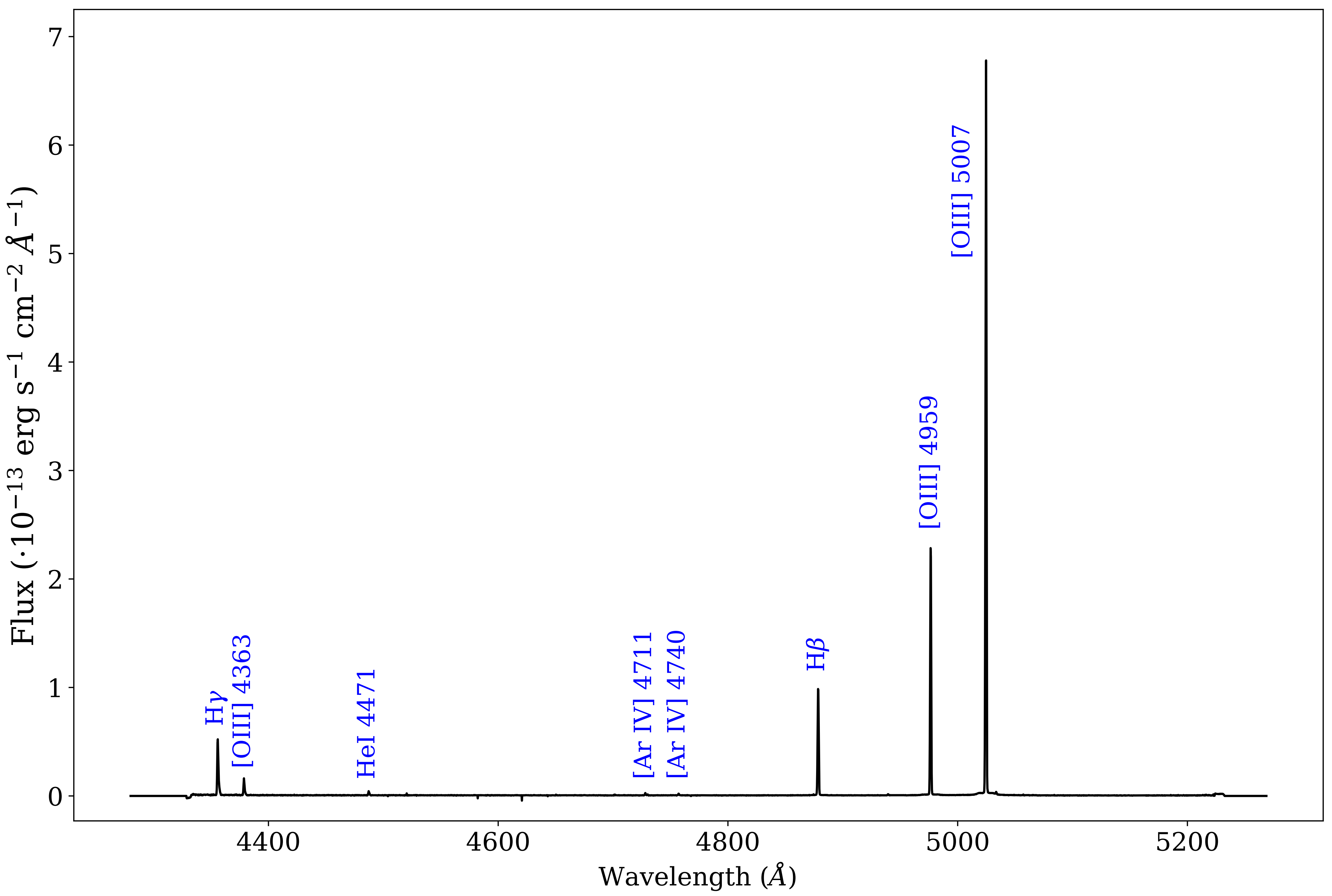




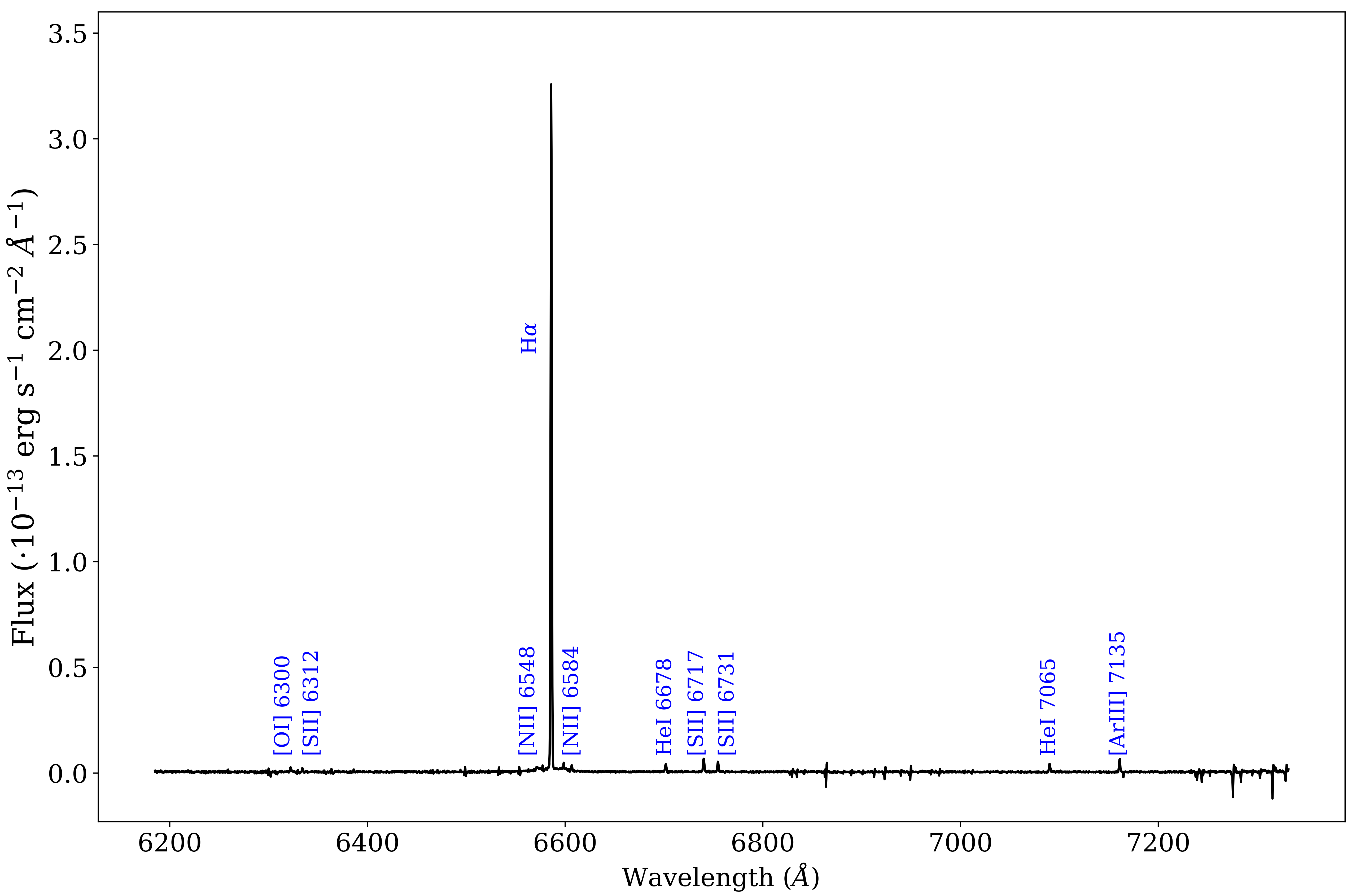


3 Data reduction and processing

LR-B



LR-R

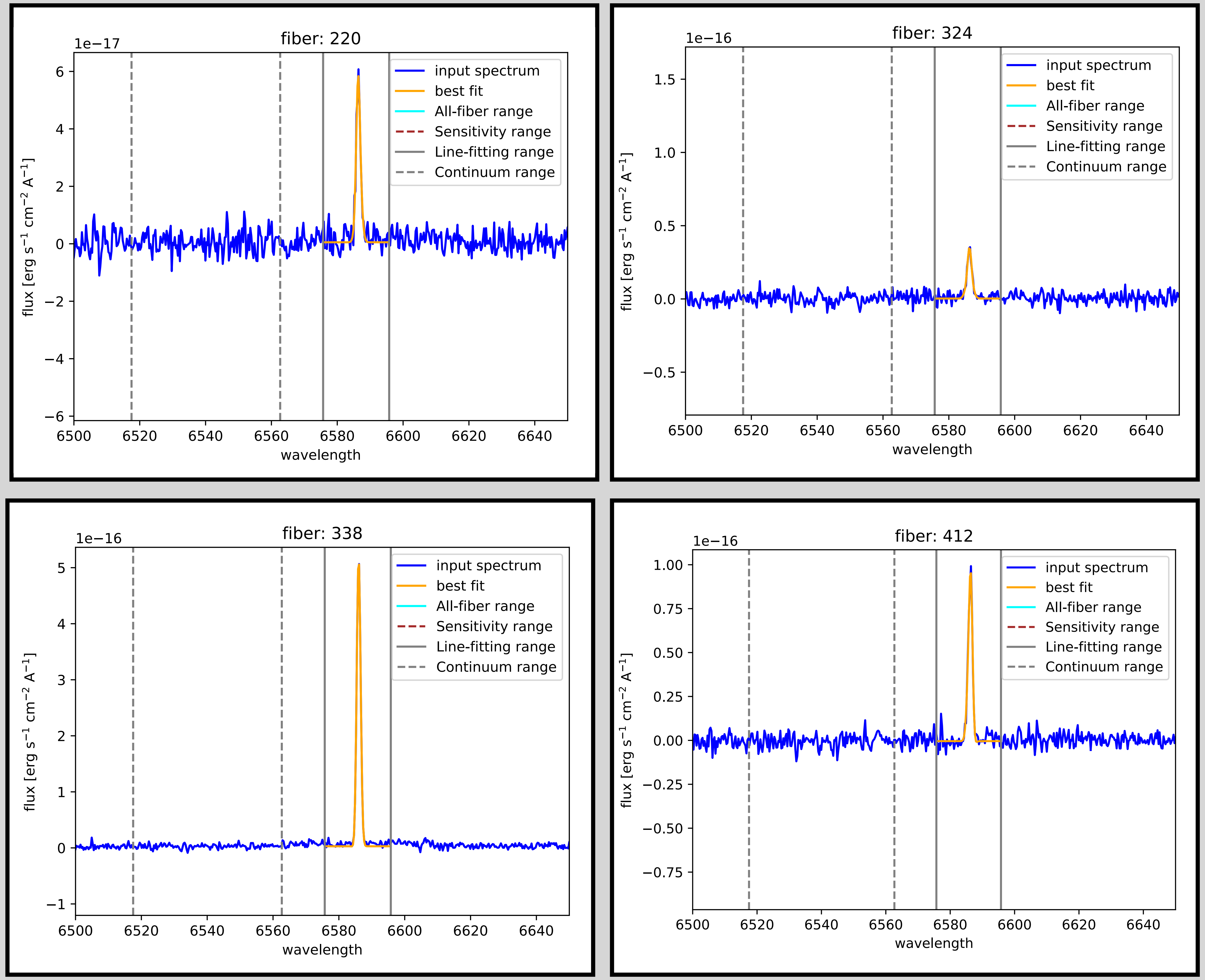


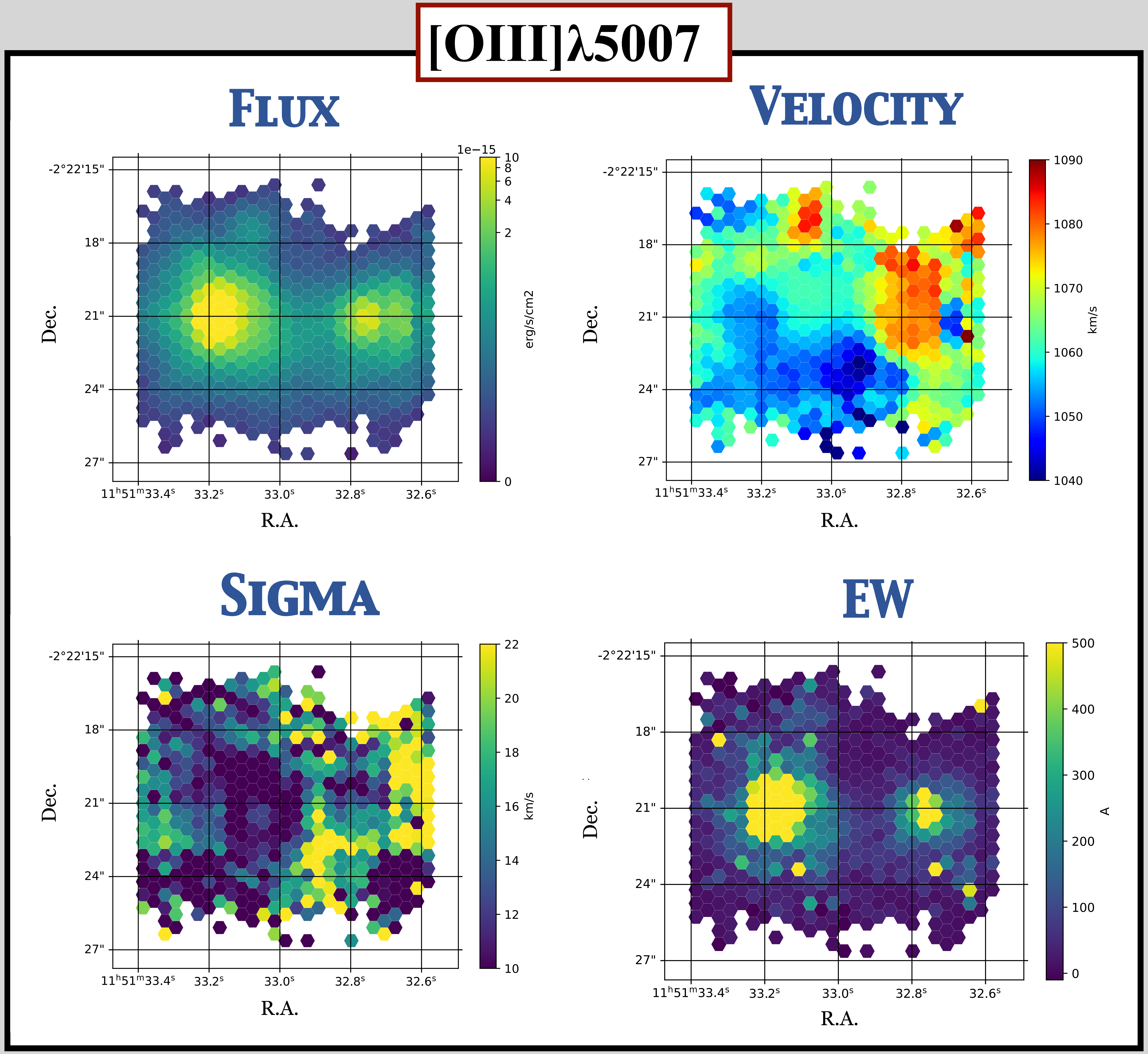
3 Data reduction and processing

MEGARA tools and Python codes

to derive the spatial distribution of properties

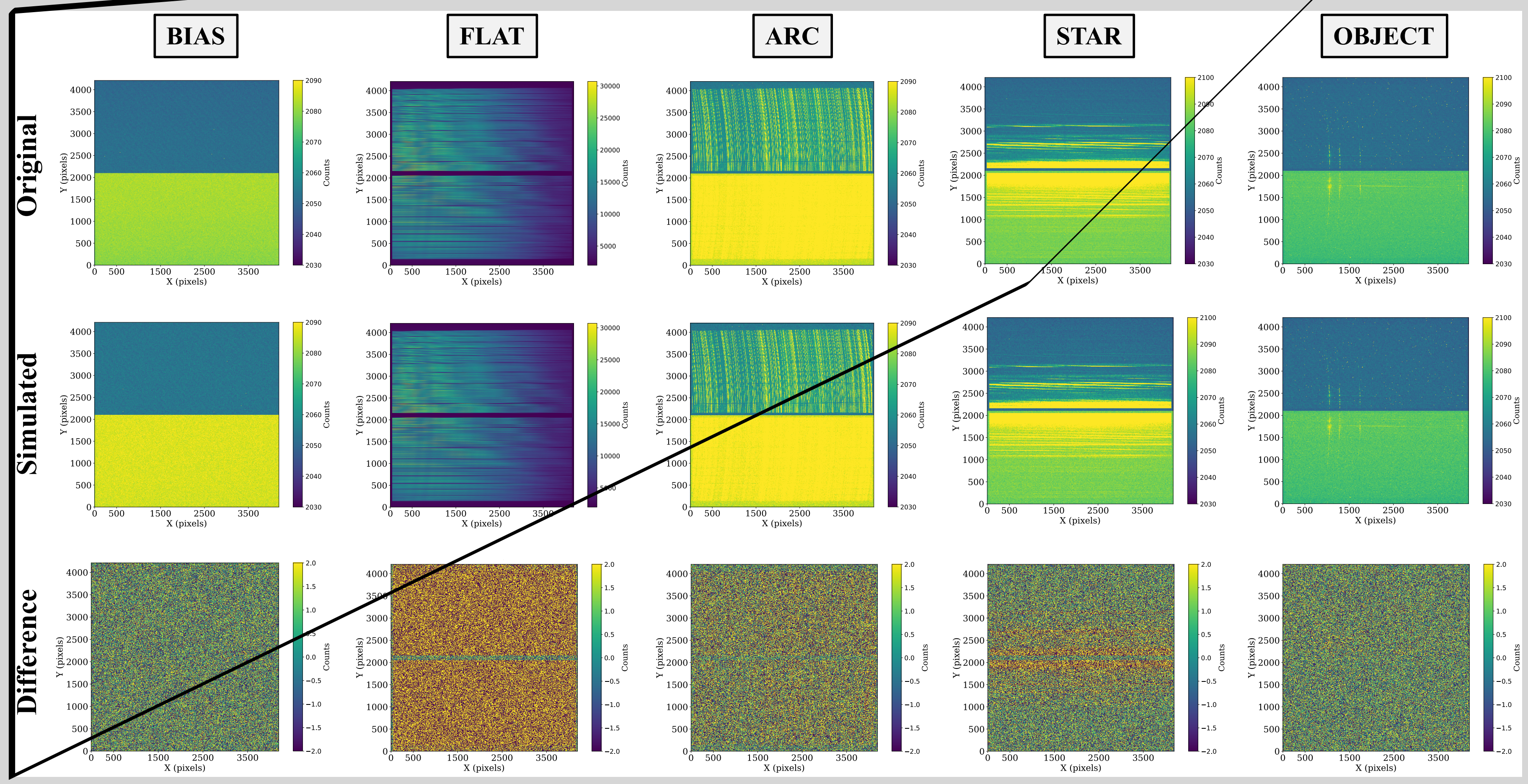
for each emission line detected in the UM461 spectra.





4 Estimation of random uncertainties

To overcome one of the limitations of the MEGARA DRP, which does not provide uncertainties during the calibration procedure, we developed a Python code based on the numerical approach described in Cardiel et al. (2002).



The signal of each pixel (i, j) due to the photons arriving at the detector:

$$\mathrm{Data}_{i,j}^{\mathrm{photon}} \simeq \mathrm{Data}_{i,j}^{\mathrm{measured}} - \mathrm{Bias}_{i,j} - \mathrm{DarkCurrent}_{i,j}$$

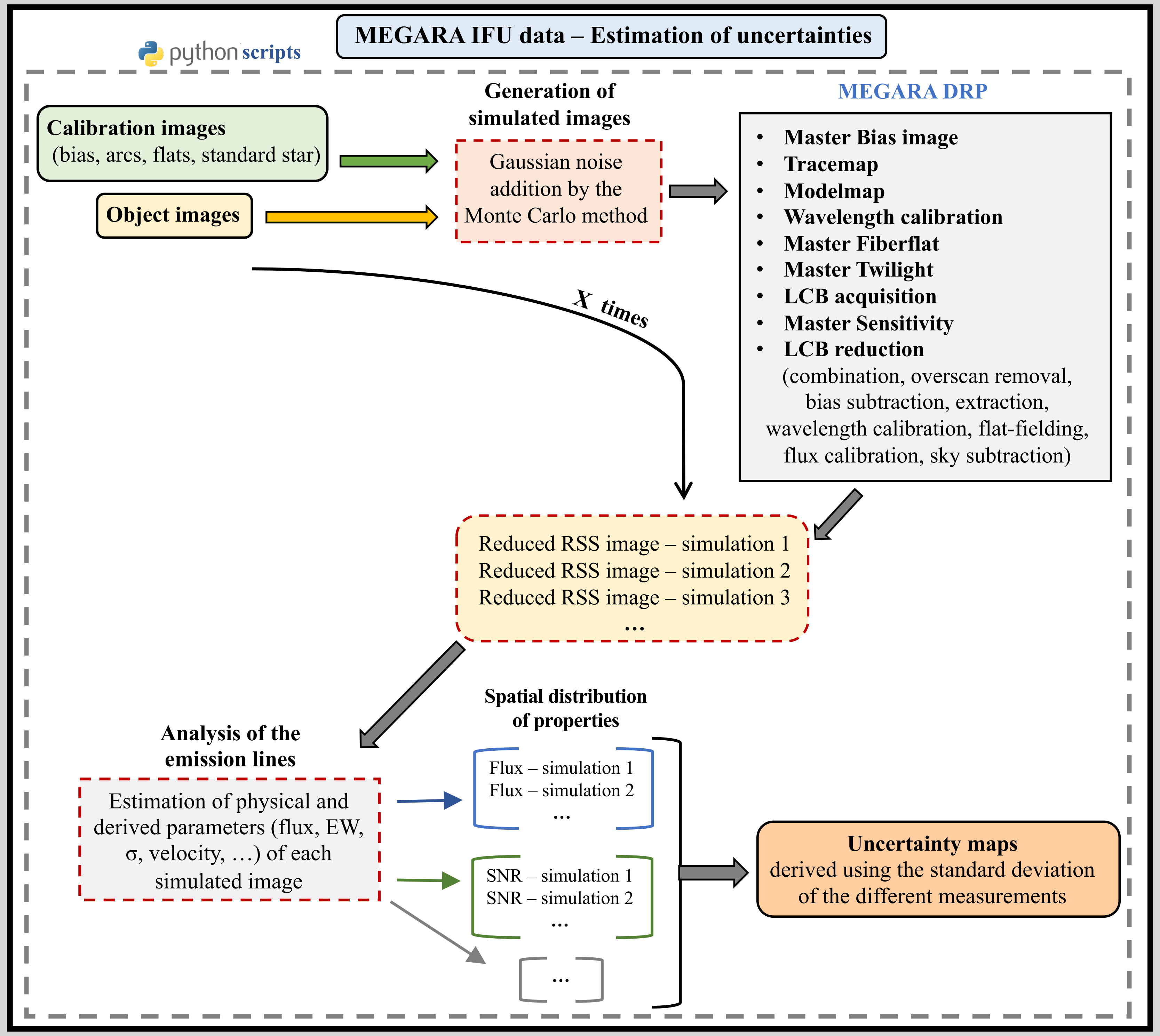
The uncertainty in the number of counts of each pixel:

$$(\mathrm{Noise}_{i,j})^2 = \frac{1}{\mathrm{g}_{i,j}} \cdot \mathrm{Data}_{i,j}^{\mathrm{photon}} + (\mathrm{RN}_{i,j})^2$$

Generation of Gaussian noise:

$$\mathrm{R}_{i,j} = \sqrt{2} \cdot \mathrm{Noise}_{i,j} \cdot \sqrt{-\ln(1 - z\_1)} \cdot \cos(2\pi \, z\_2), \qquad z\_1, z\_2 \in [0, 1).$$

$$\text{Simulated image} = \mathrm{Data}_{i,j}^{\mathrm{measured}} + \mathrm{R}_{i,j}$$



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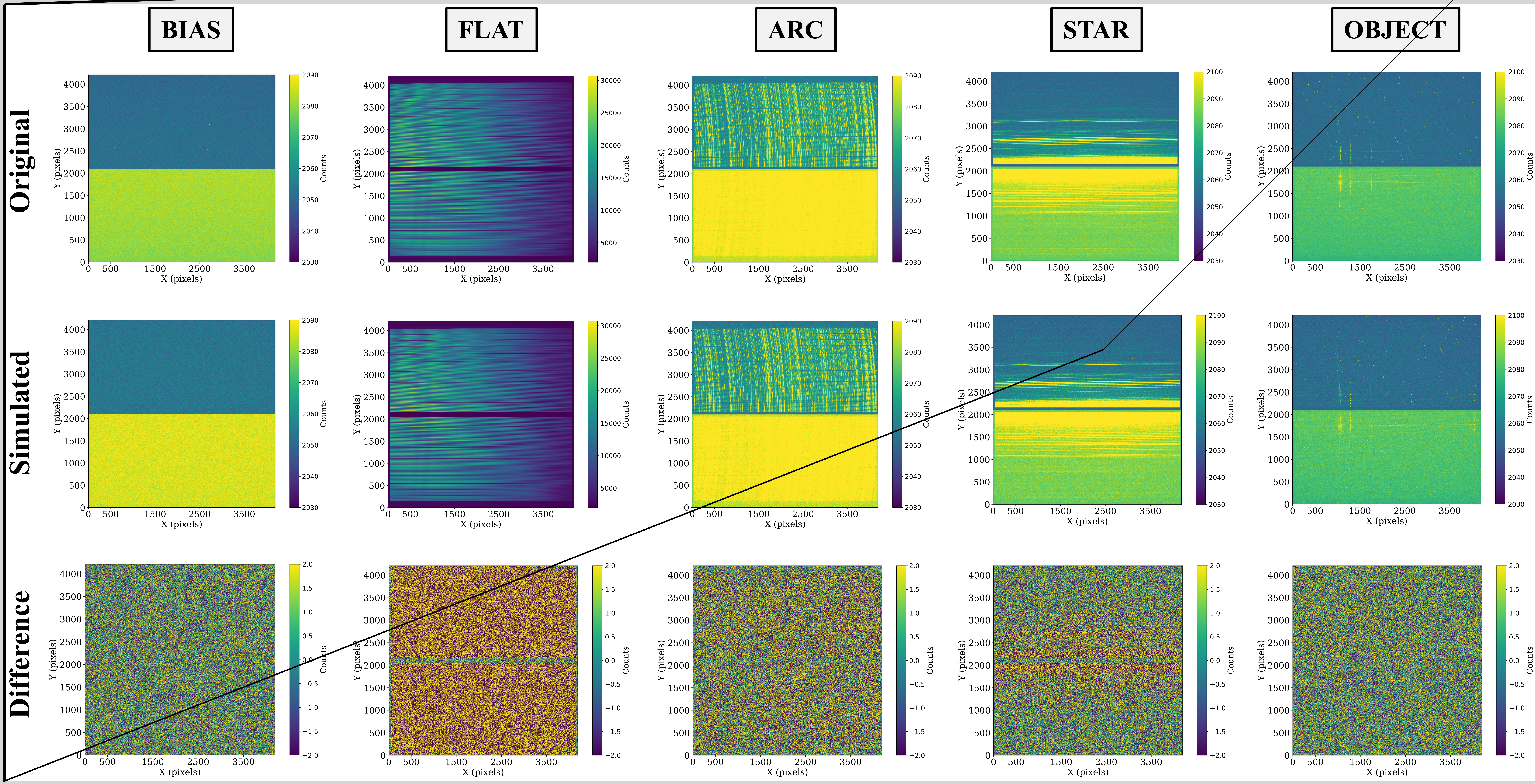
4 Estimation of random uncertainties



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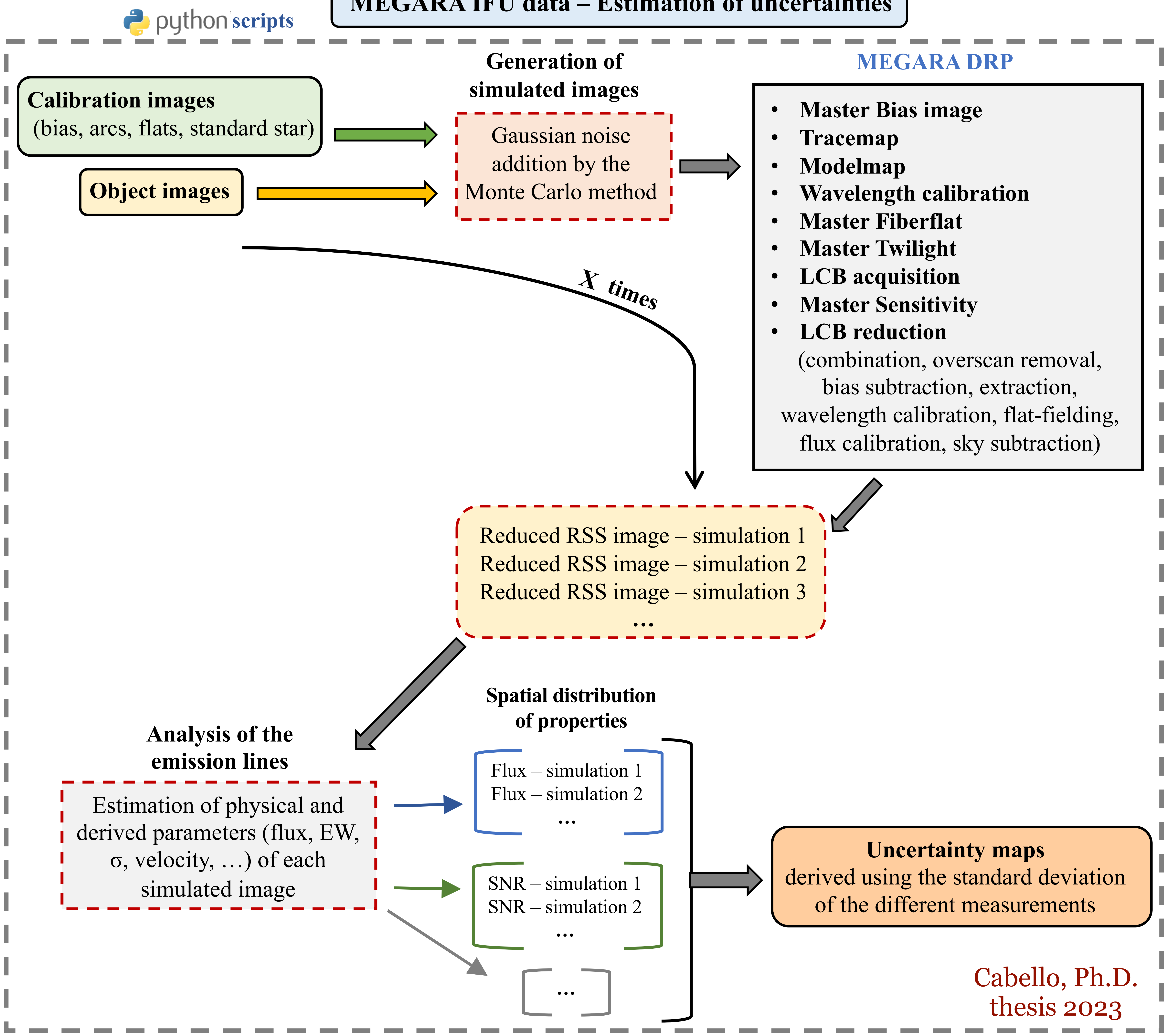
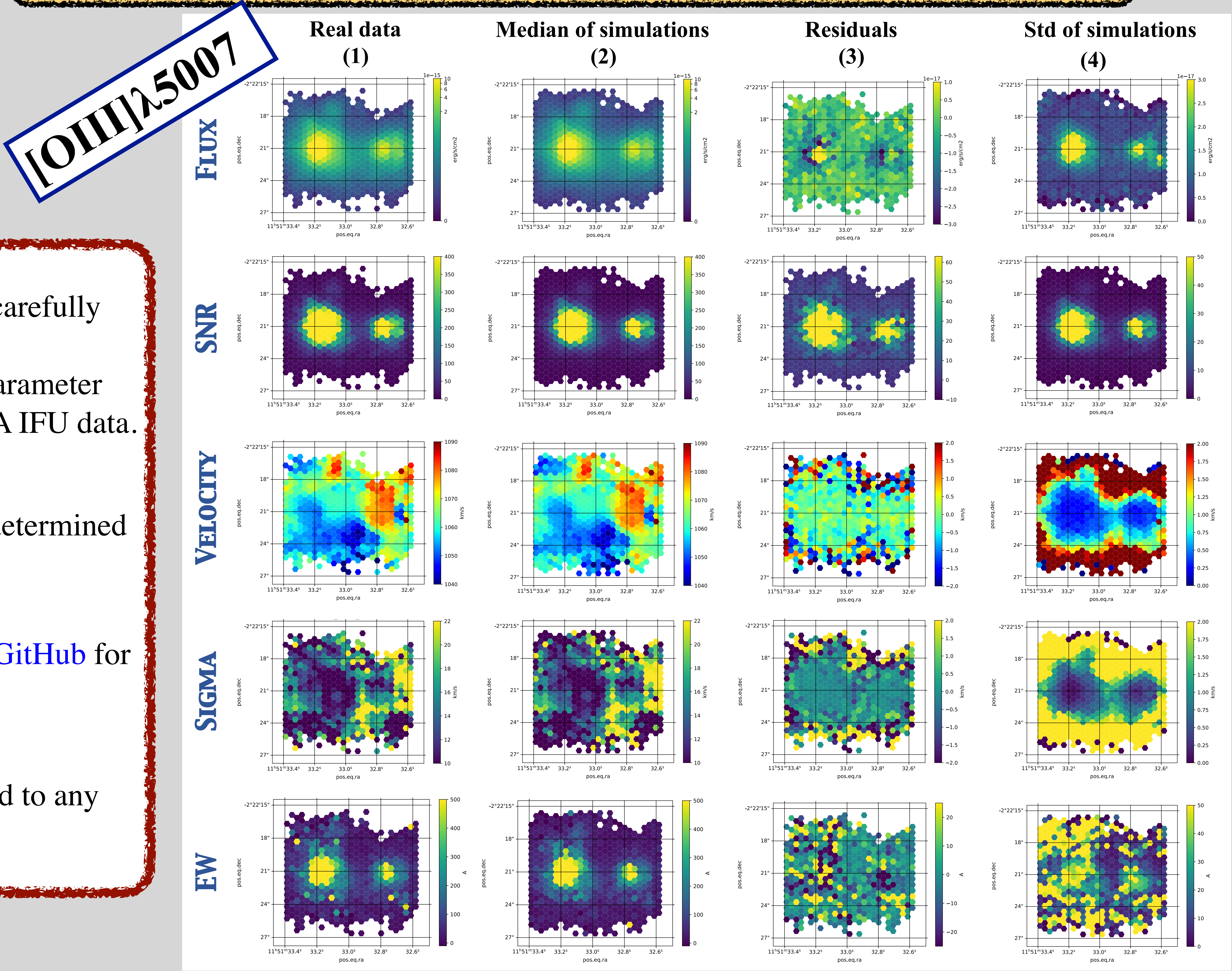
MEGARA IFU data – Estimation of uncertainties



4 Estimation of random uncertainties



- We developed a Python recipe to carefully estimate, for the first time, random uncertainties associated with any parameter that can be derived using MEGARA IFU data.
- The random uncertainties can be determined in a reasonable computation time.
- The code is publicly available on GitHub for the use of the community.
- This novel approach can be applied to any 2D spectroscopic dataset!

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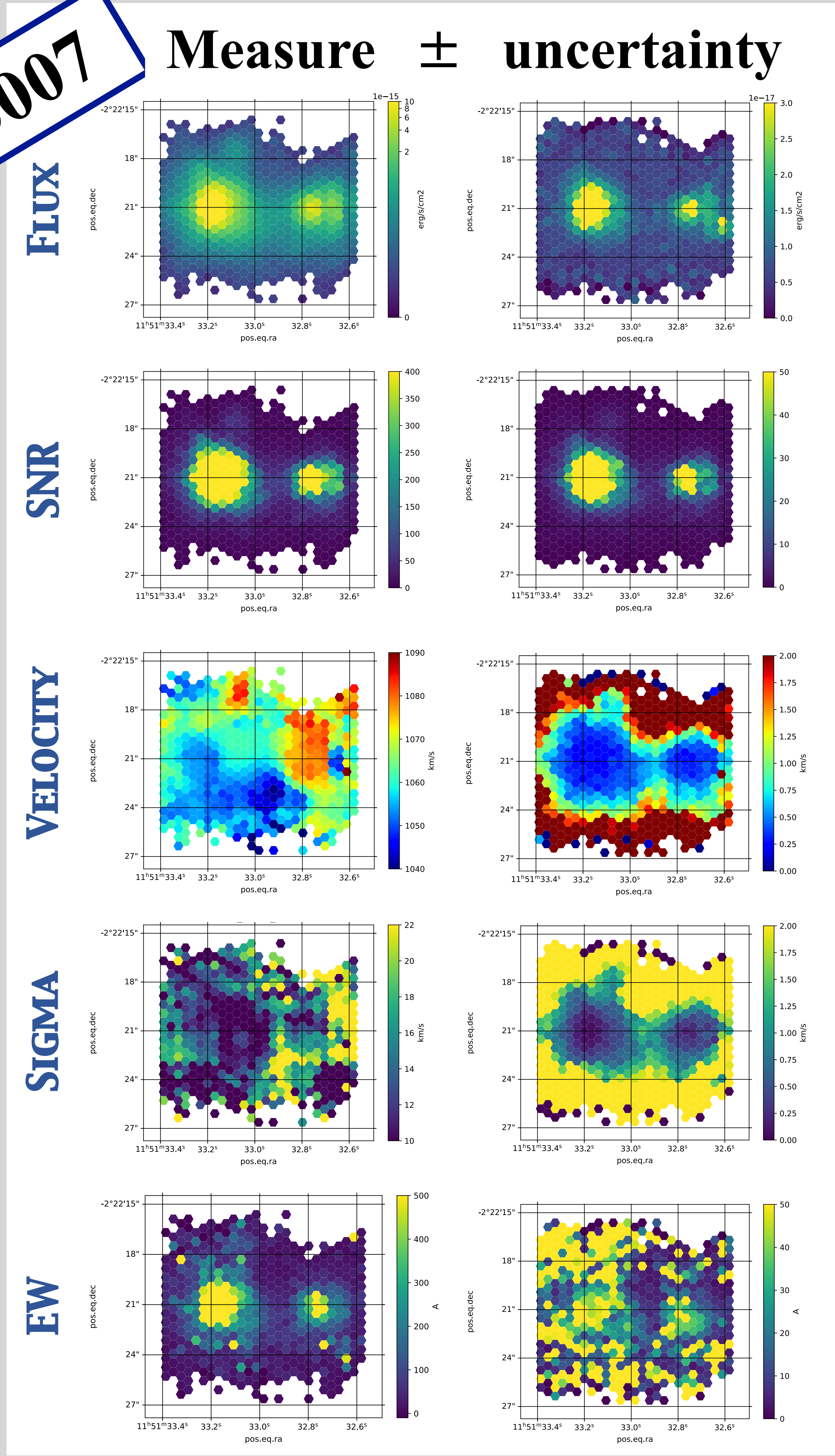
4 Estimation of random uncertainties

[OIII]λ5007



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GitHub

https://github.com/criscabe

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5 Analysis and preliminary results

Emission-line ratios: spaxel-by-spaxel analysis

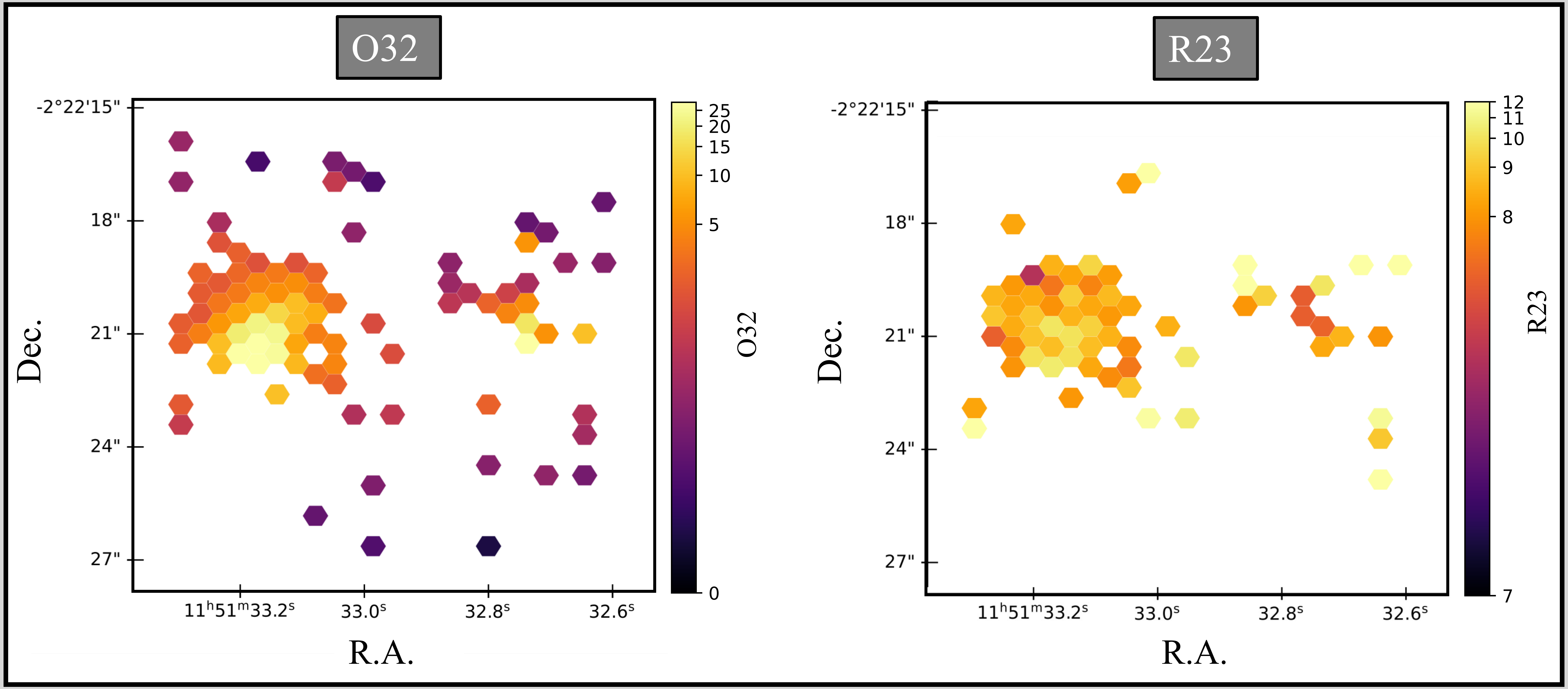
- Spaxels with SNR > 5 for Hβ, [OIII]λ4959, [OIII]λ5007, and Hα
- Spaxels with SNR > 3 for the rest of the emission lines

5 Analysis and preliminary results

$$O32 = \frac{[OIII]\lambda 5007}{[OII]\lambda\lambda 3726{,}3729}$$

Emission-line ratios spaxel-by-spaxel analysis

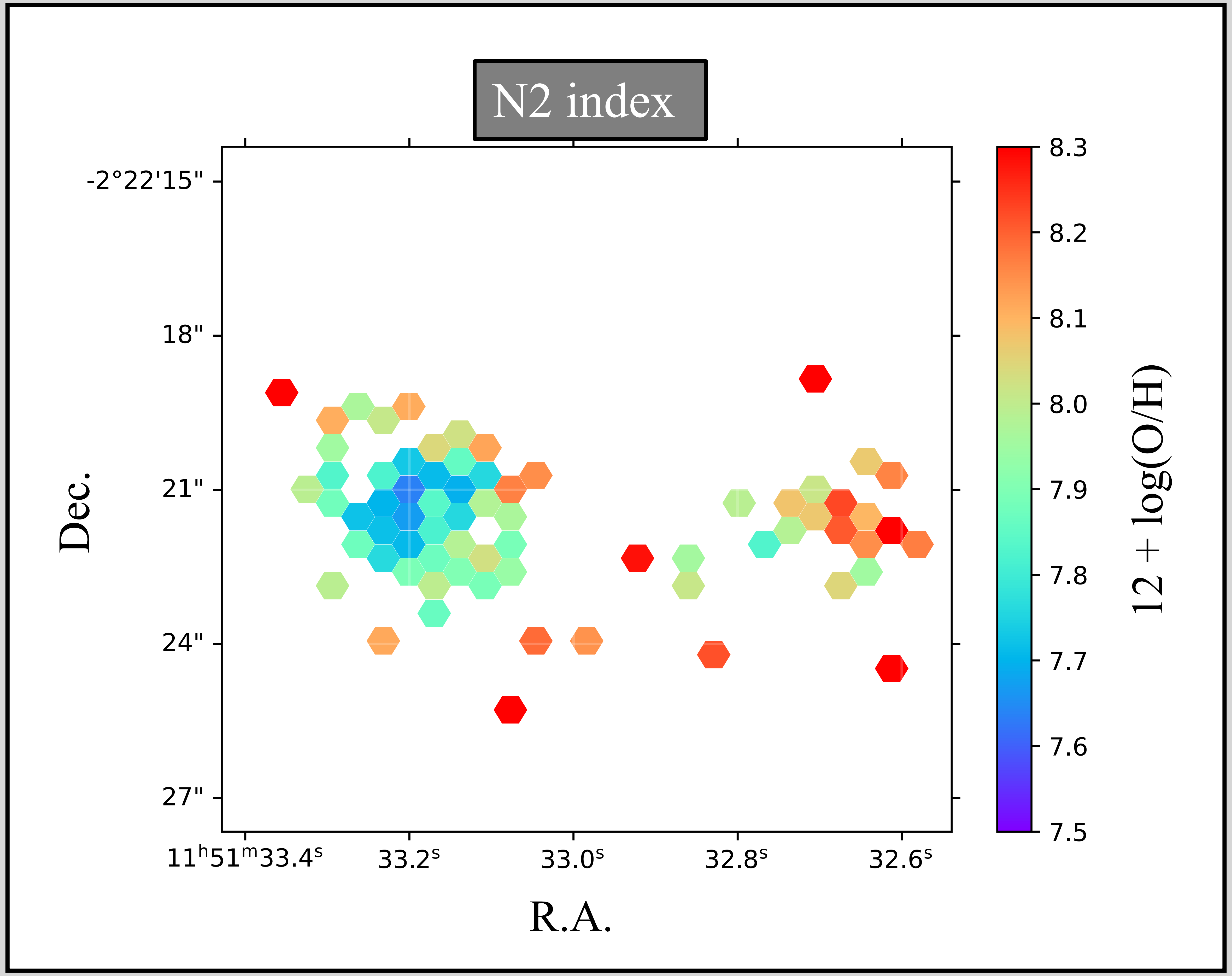
$$R23 = \frac{[OII]\lambda\lambda 3726{,}3729 + [OIII]\lambda\lambda 4959{,}5007}{H\beta}$$



5 Analysis and preliminary results

Metallicity abundance

The oxygen abundance was computed following the relation derived from Marino et al. 2013

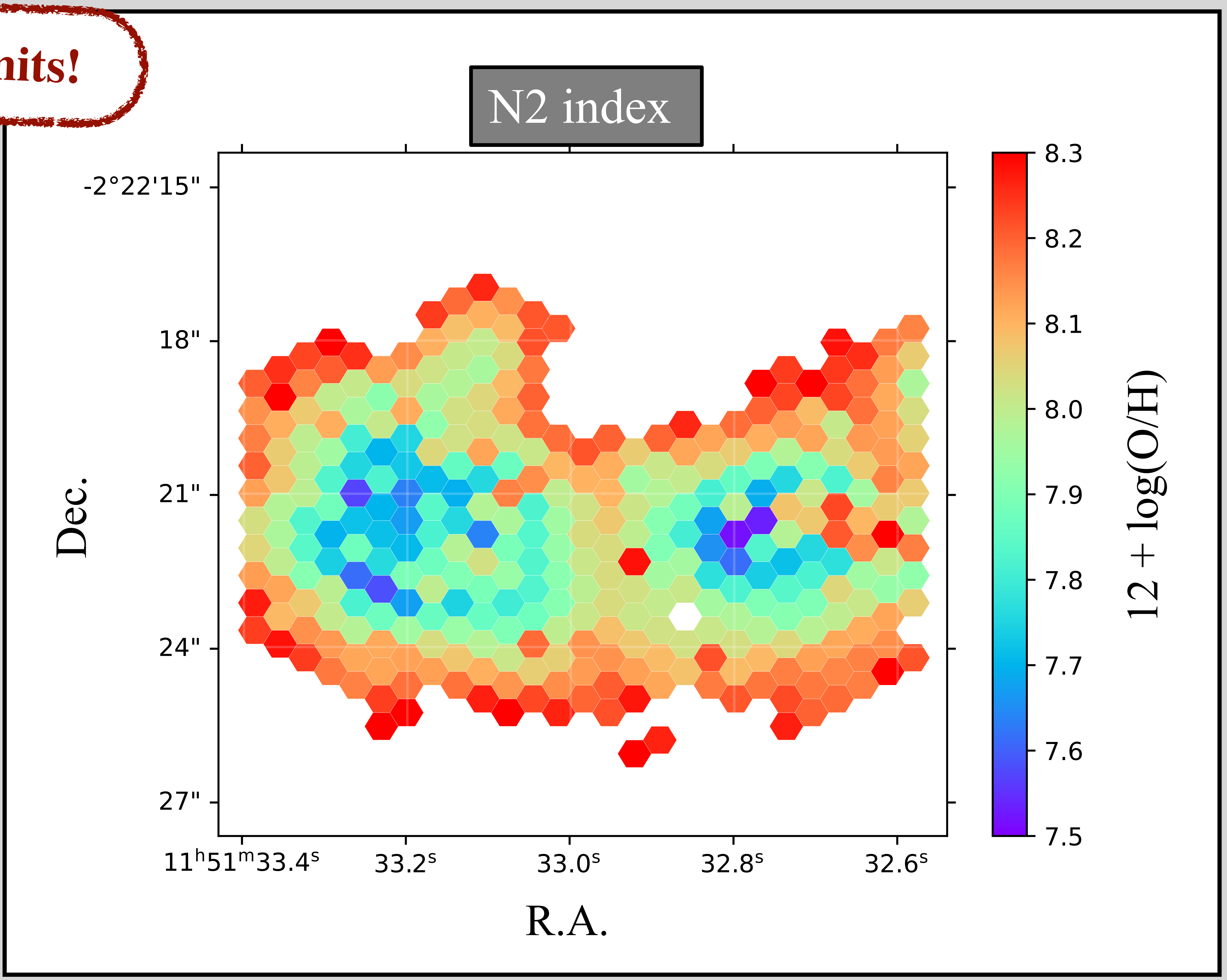


5 Analysis and preliminary results

Metallicity abundance

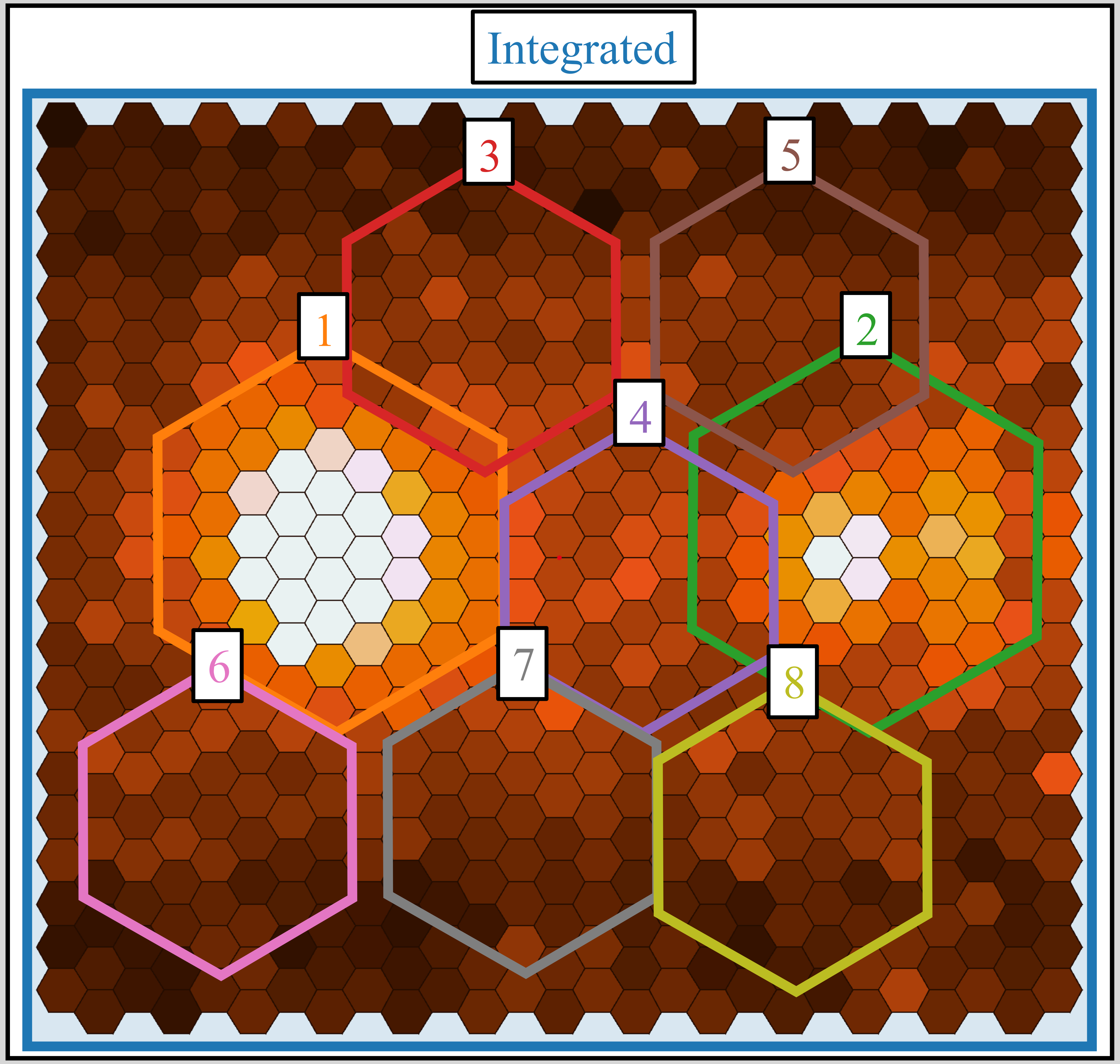
The oxygen abundance was computed following the relation derived from Marino et al. 2013

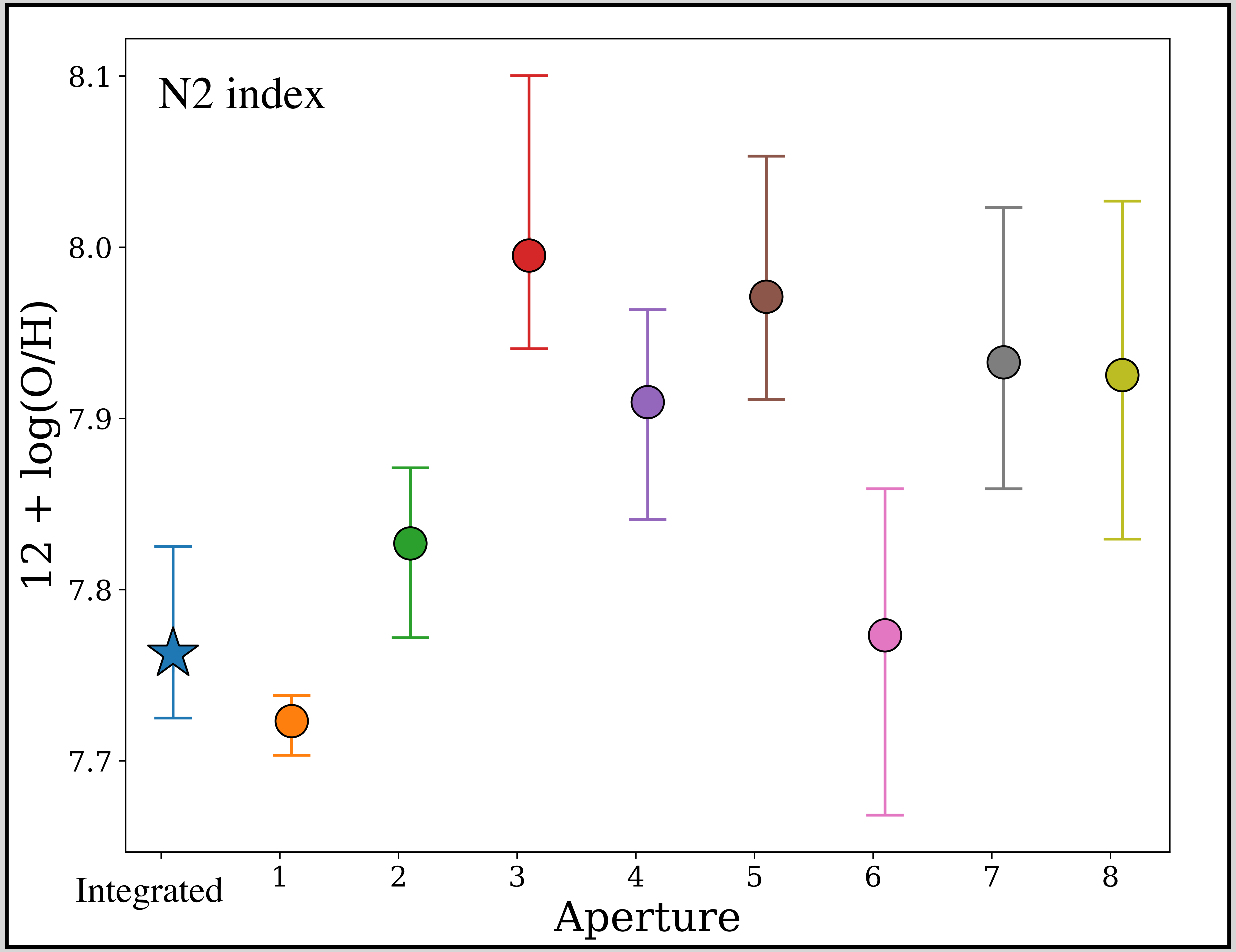
Upper limits!



5 Analysis and preliminary results

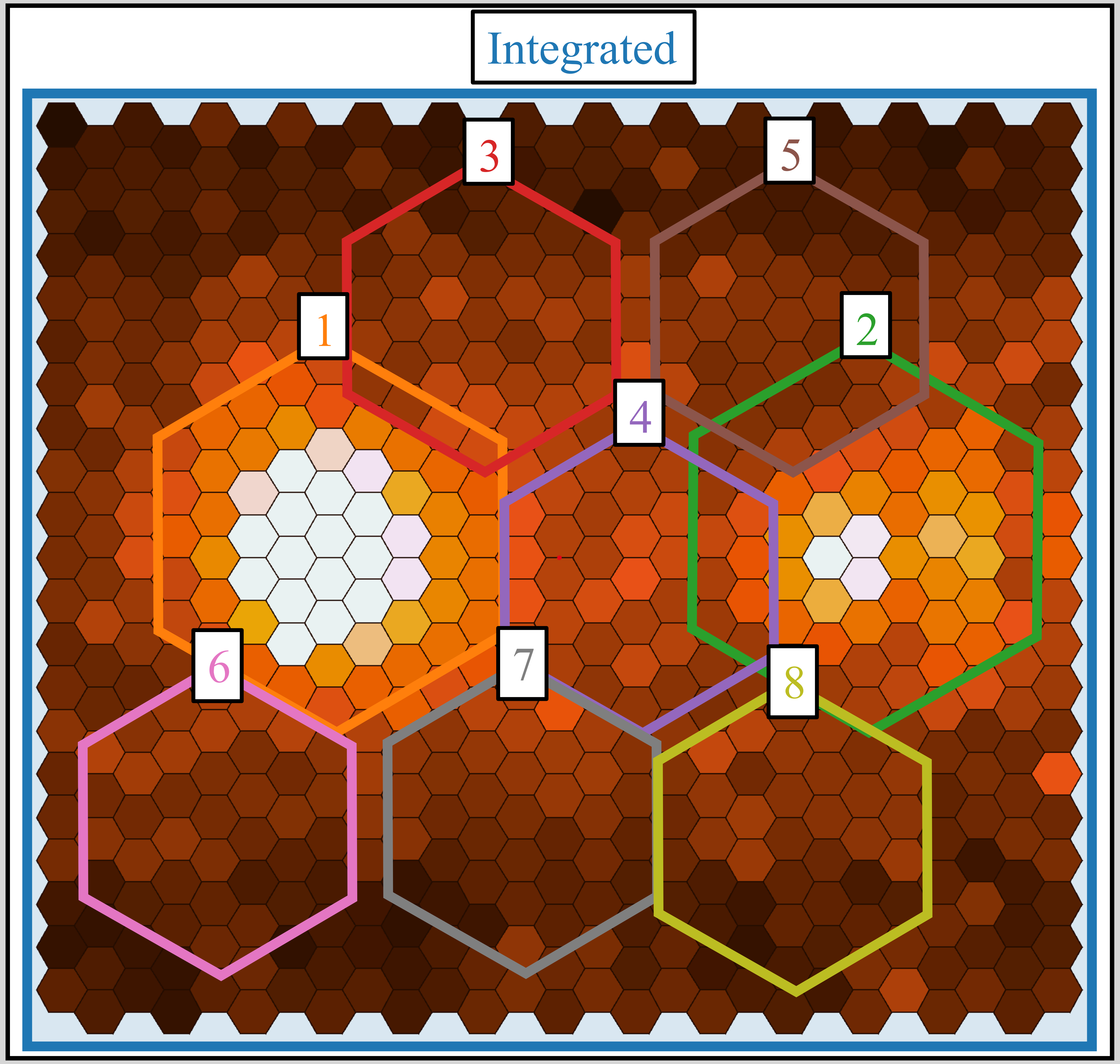
Metallicity abundance

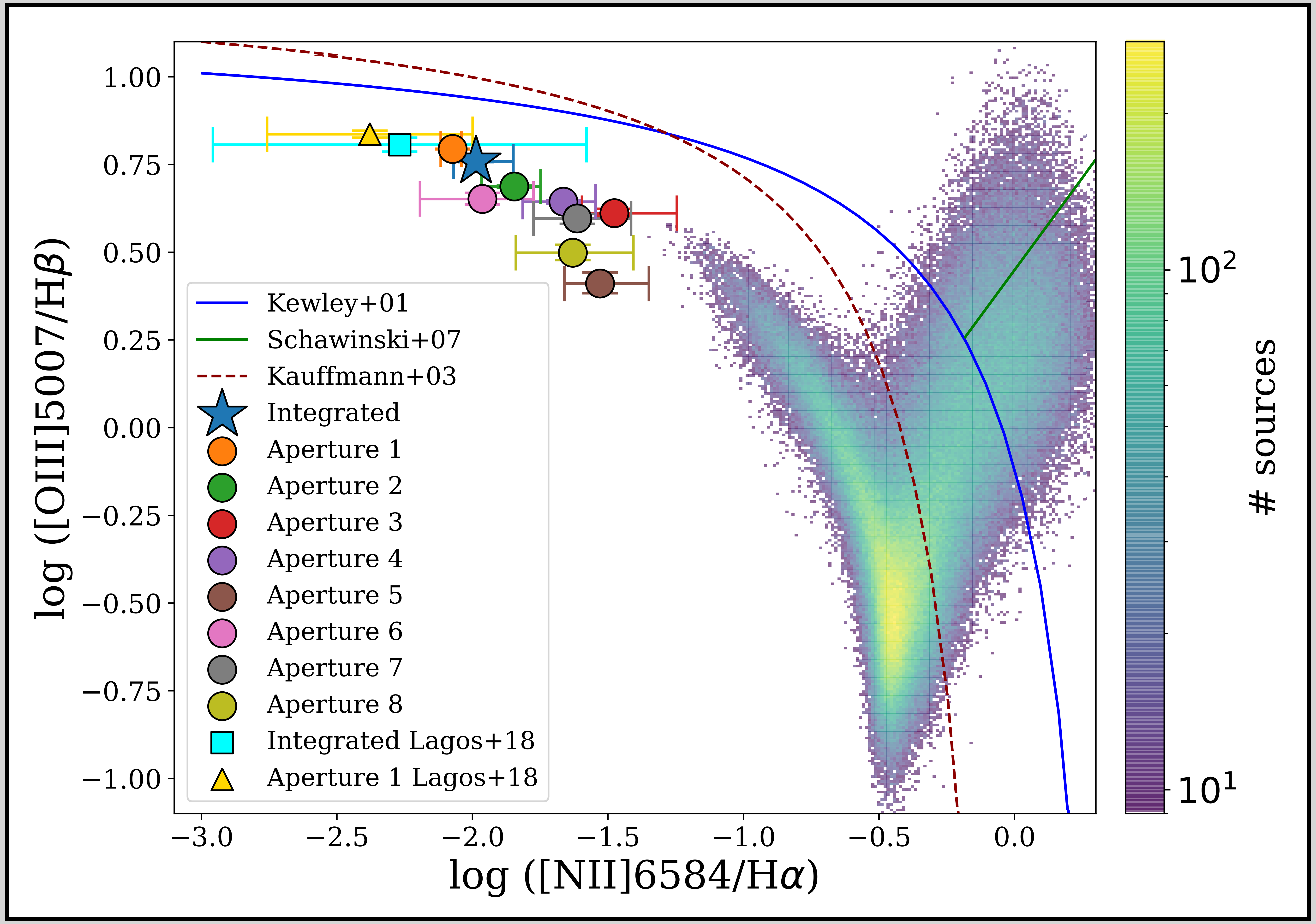




5 Analysis and preliminary results

BPT diagram





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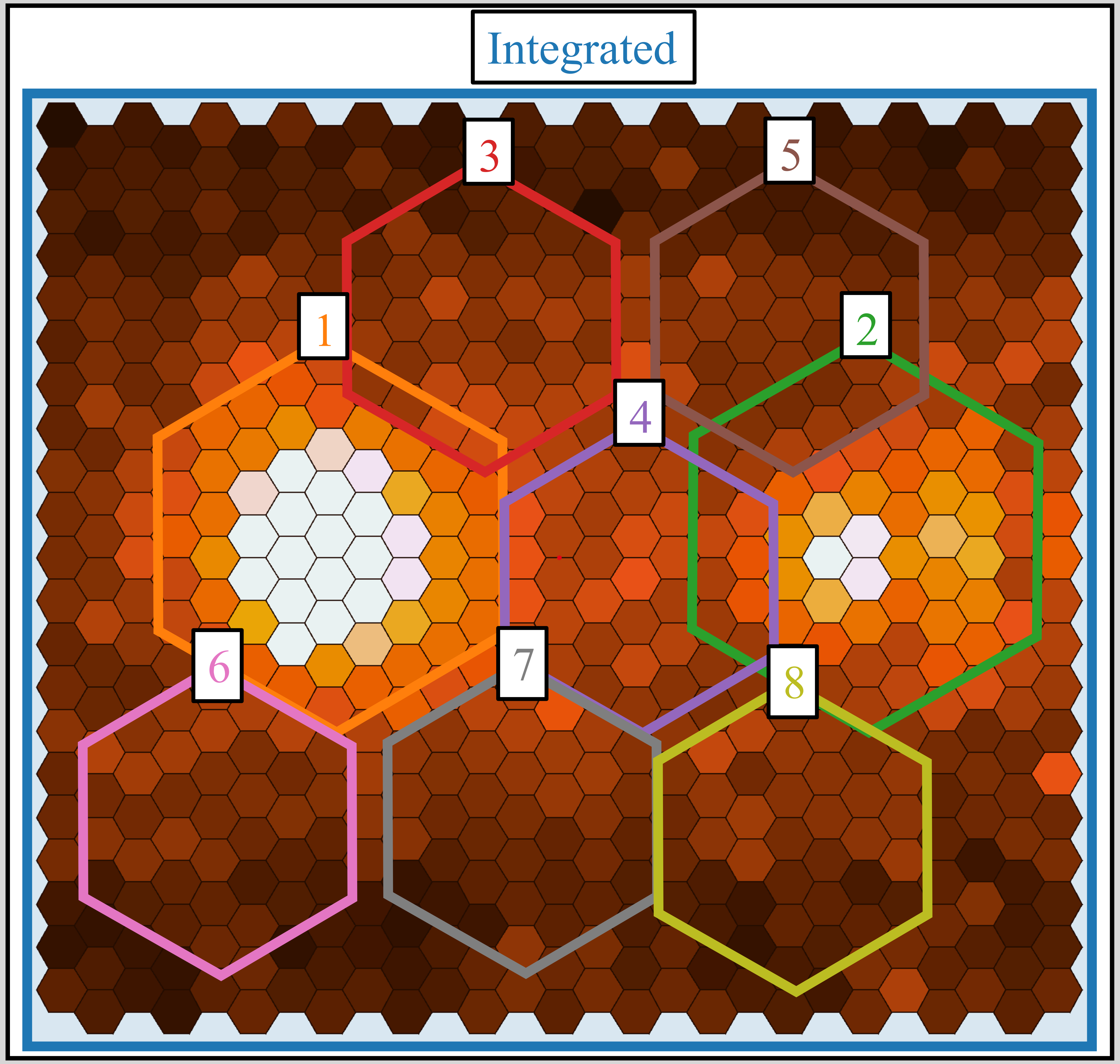
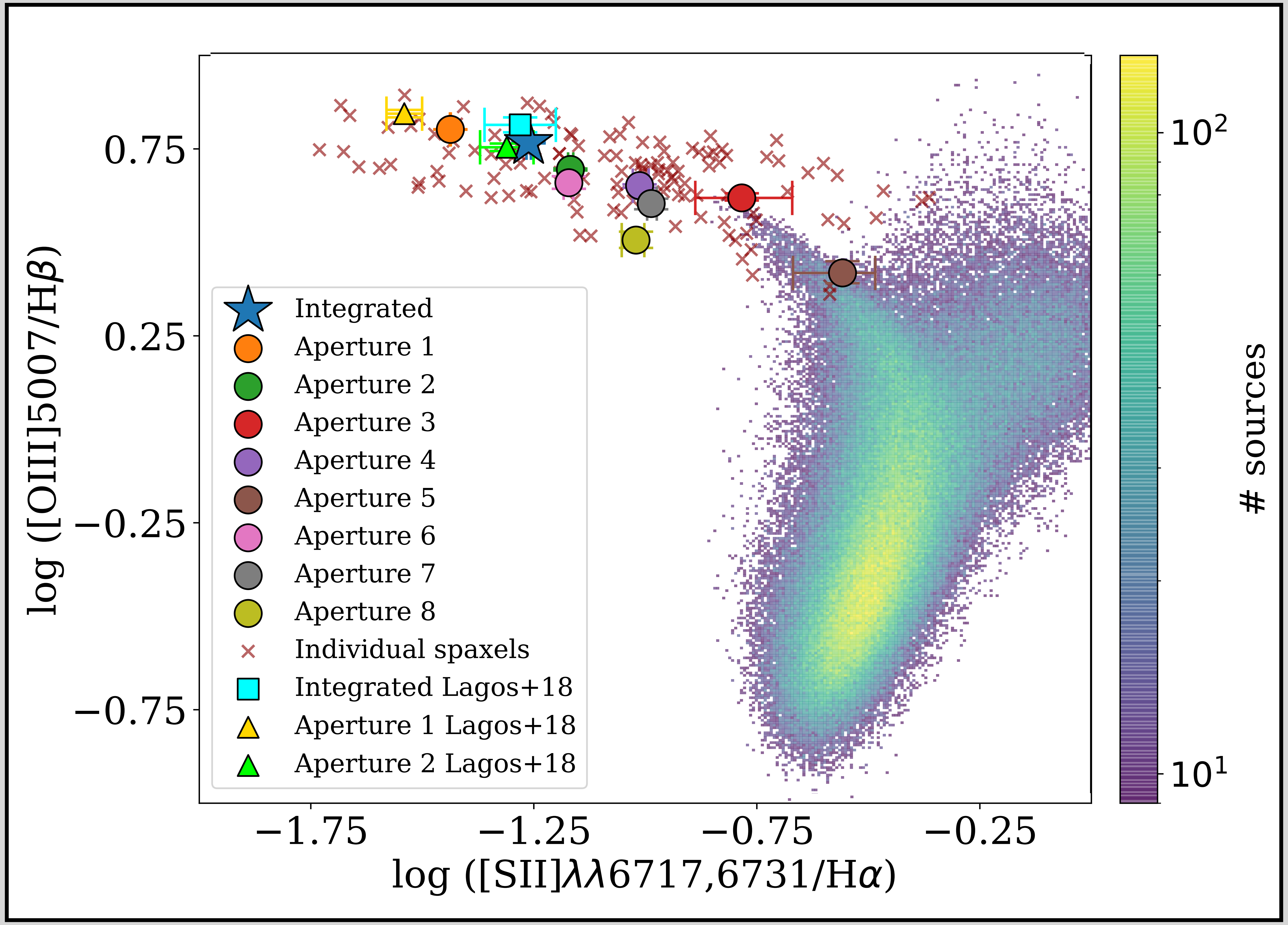
5 Analysis and preliminary results

[SII] BPT diagram

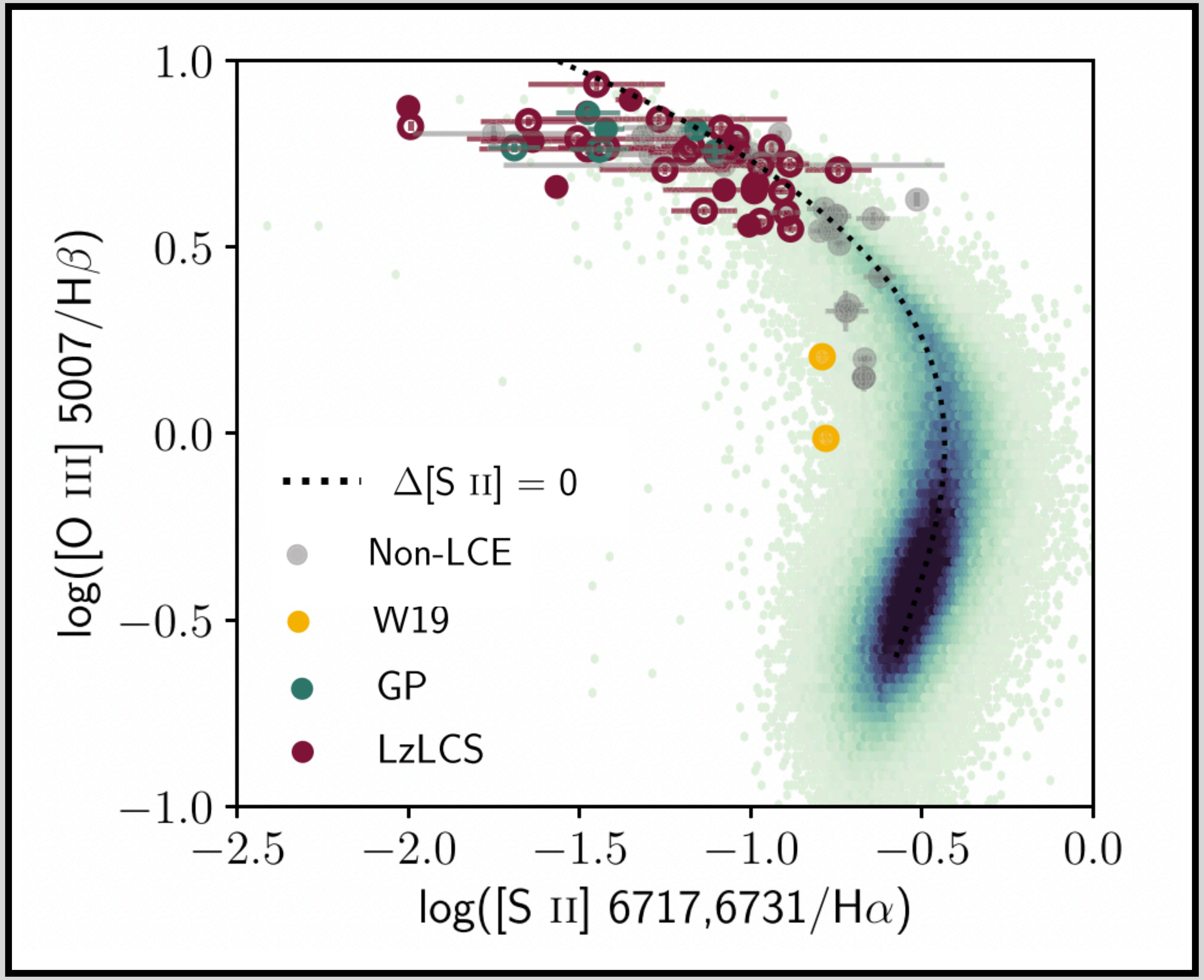




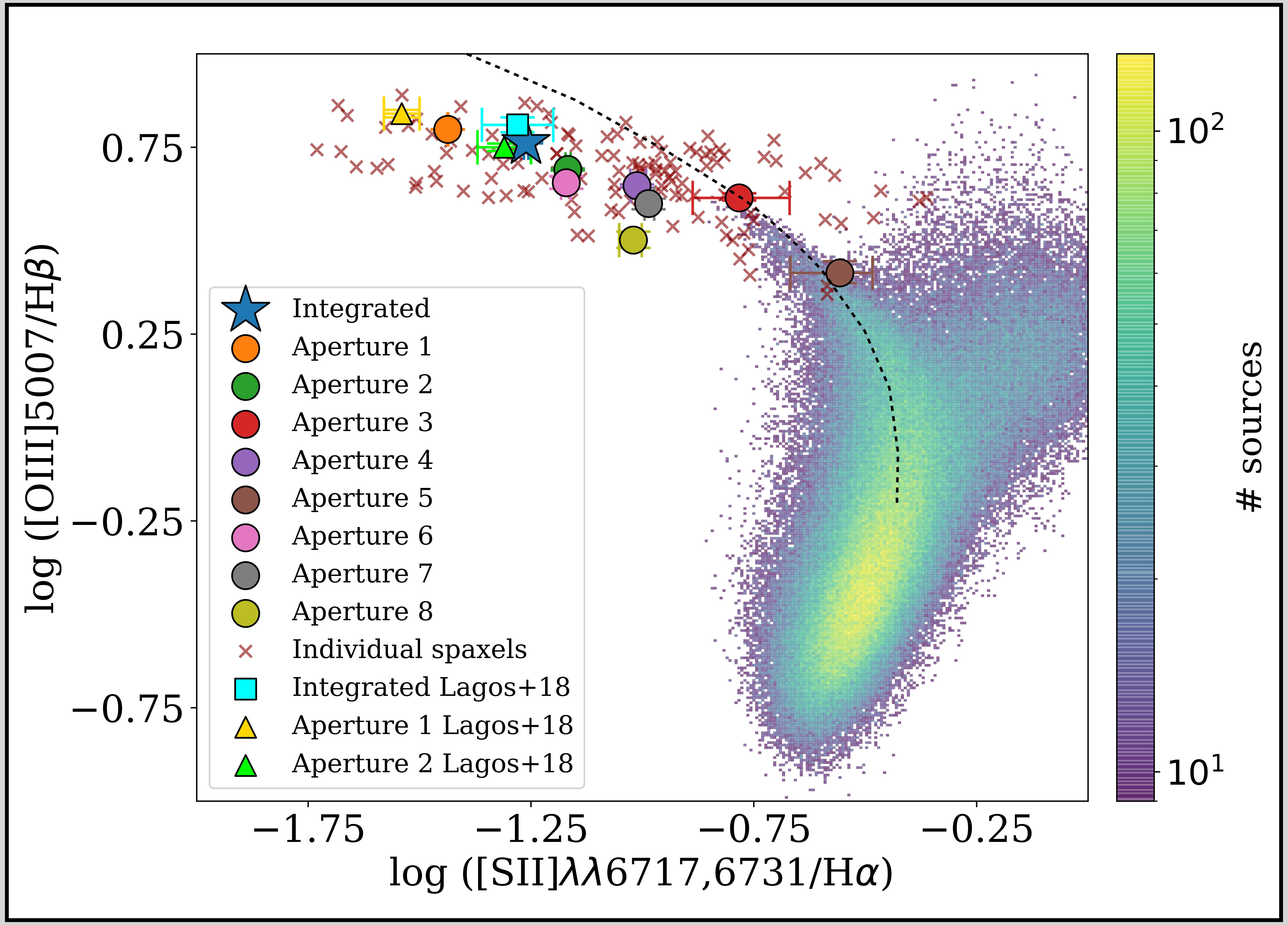
Cabello+23 *in prep.*

5 Analysis and preliminary results

[SII] BPT diagram



Wang+21

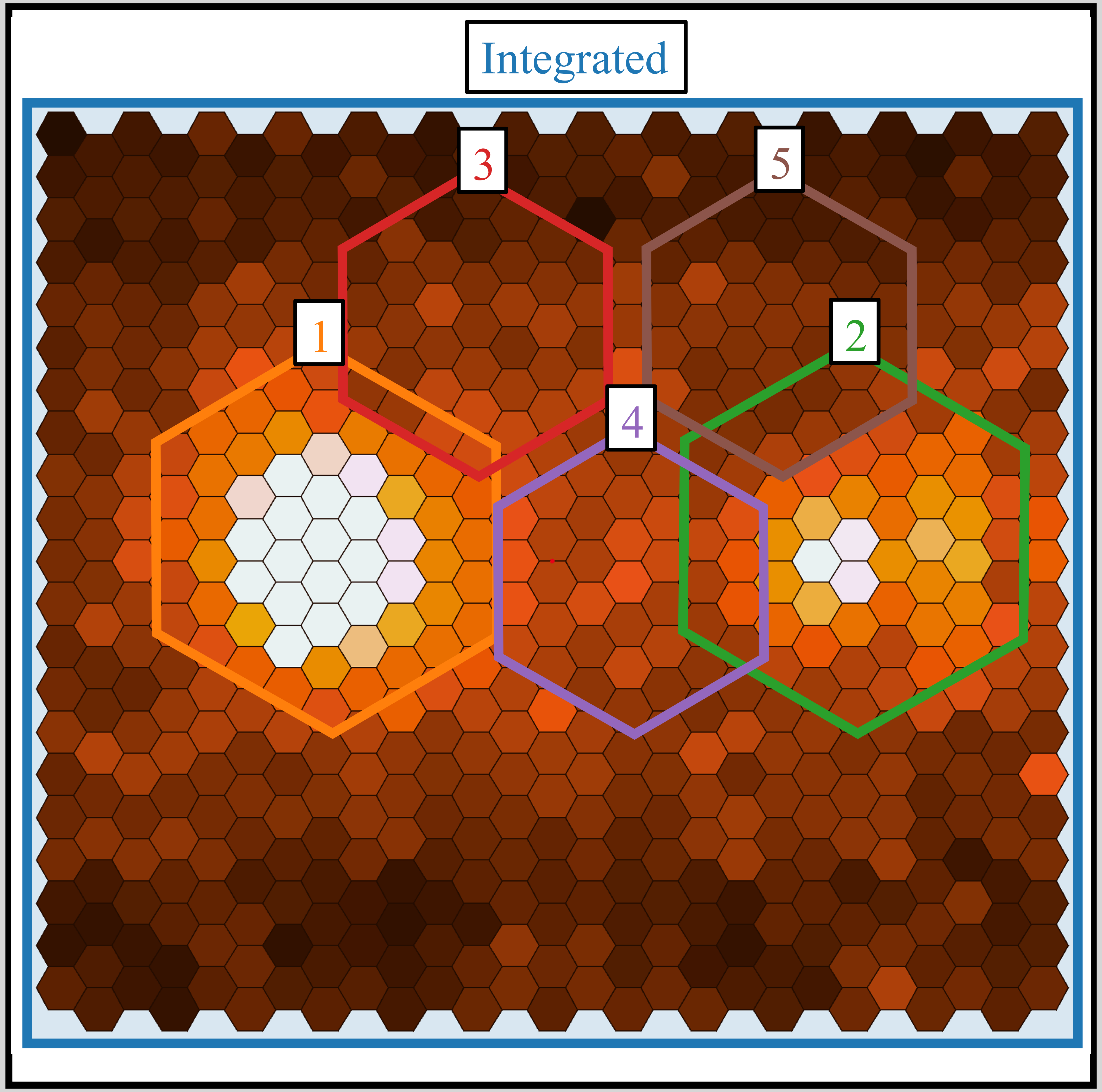


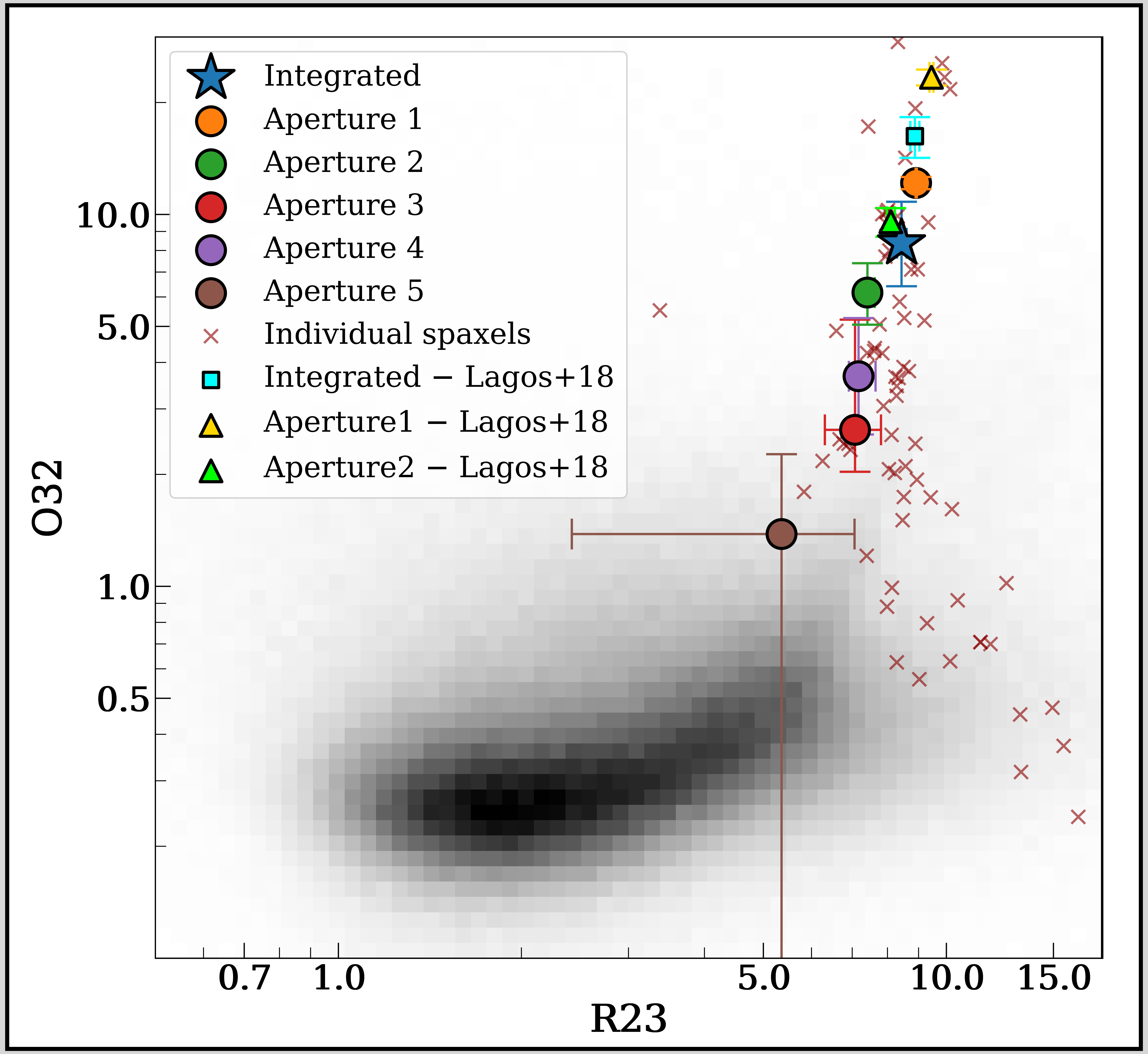
Cabello+23 *in prep.*

5 Analysis and preliminary results

O32 vs R23 diagram

Cabello+23 *in prep.*

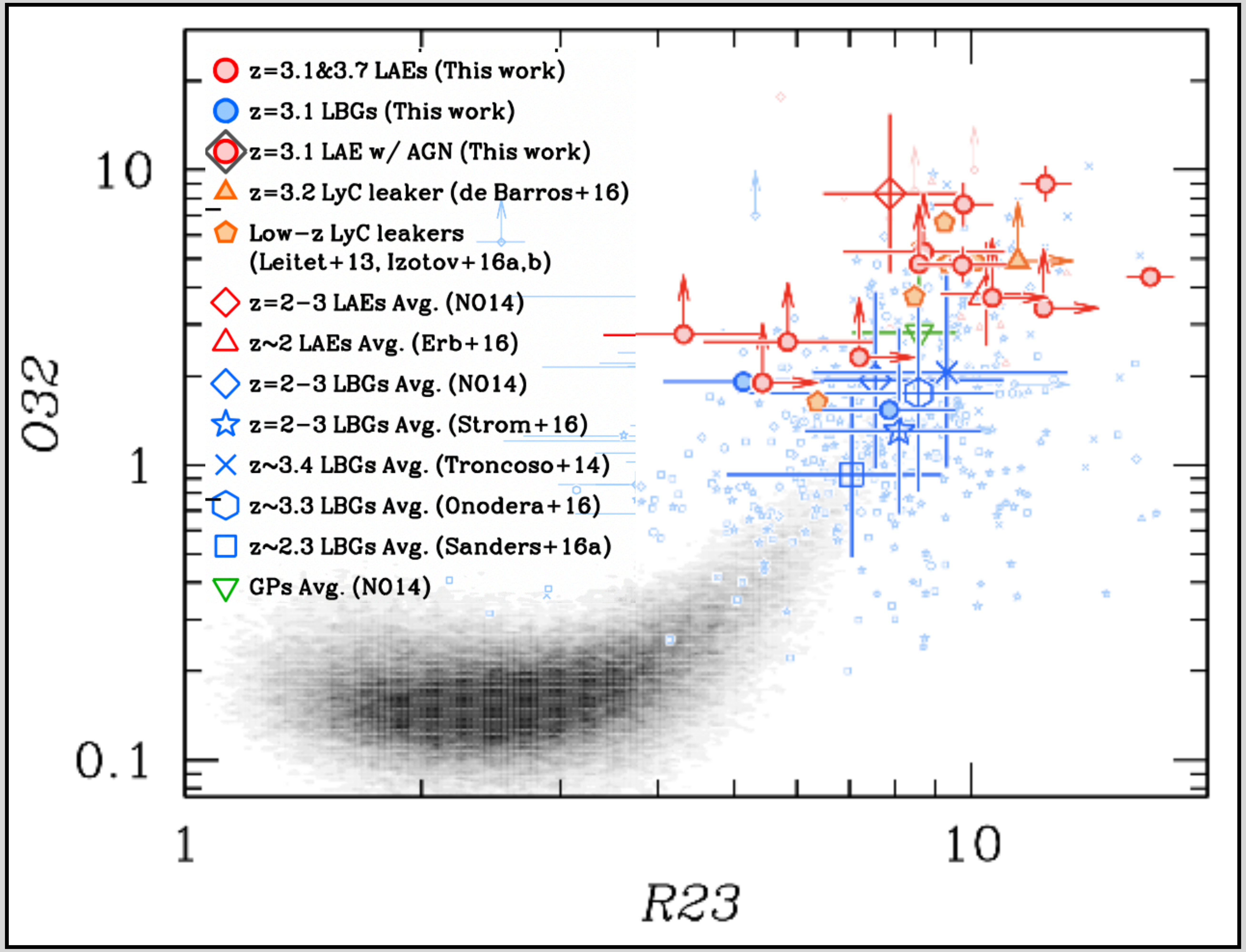




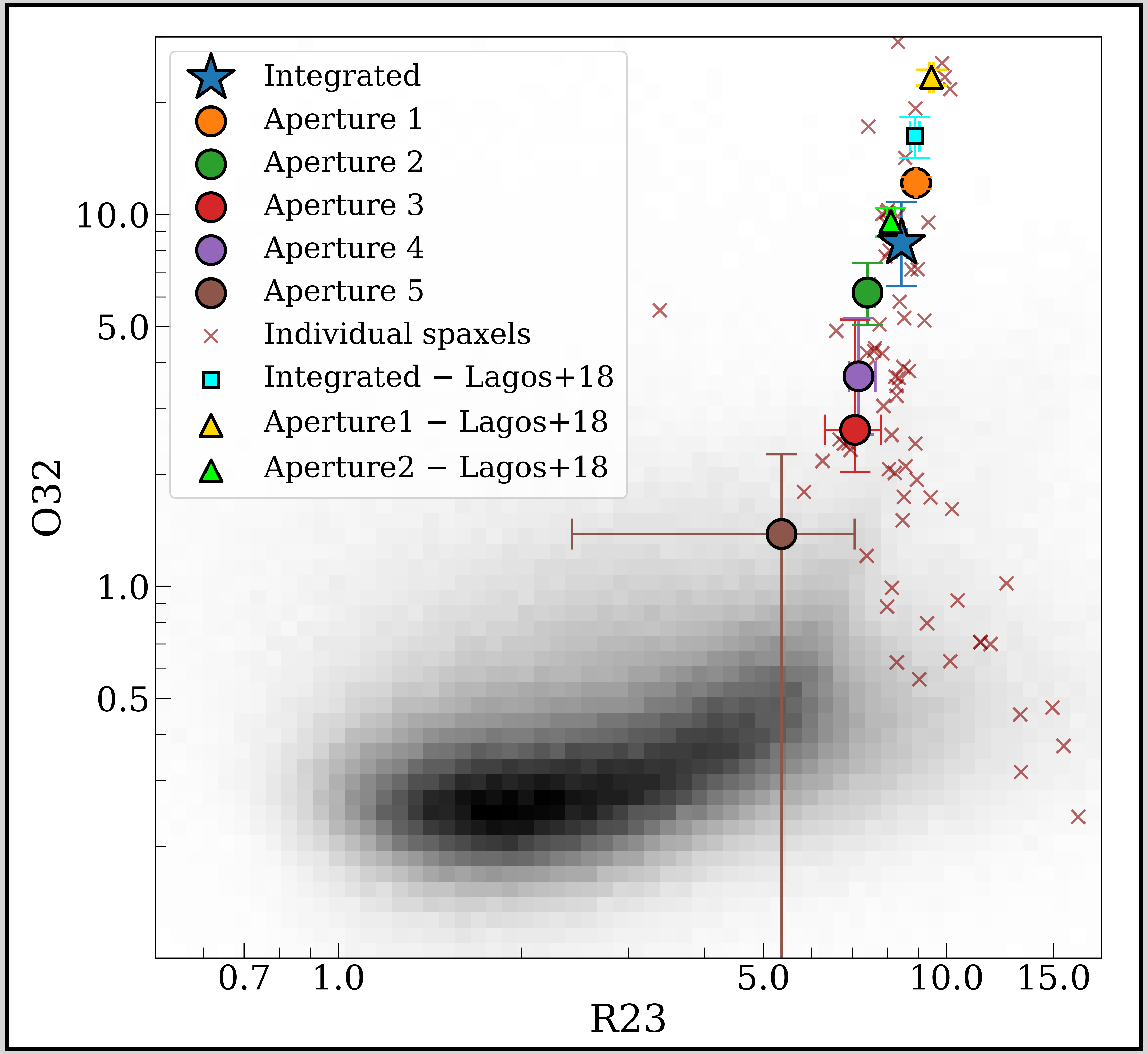
5 Analysis and preliminary results

O32 vs R23 diagram

Nakajima & Ouchi +14, Nakajima+16, Ouchi+20



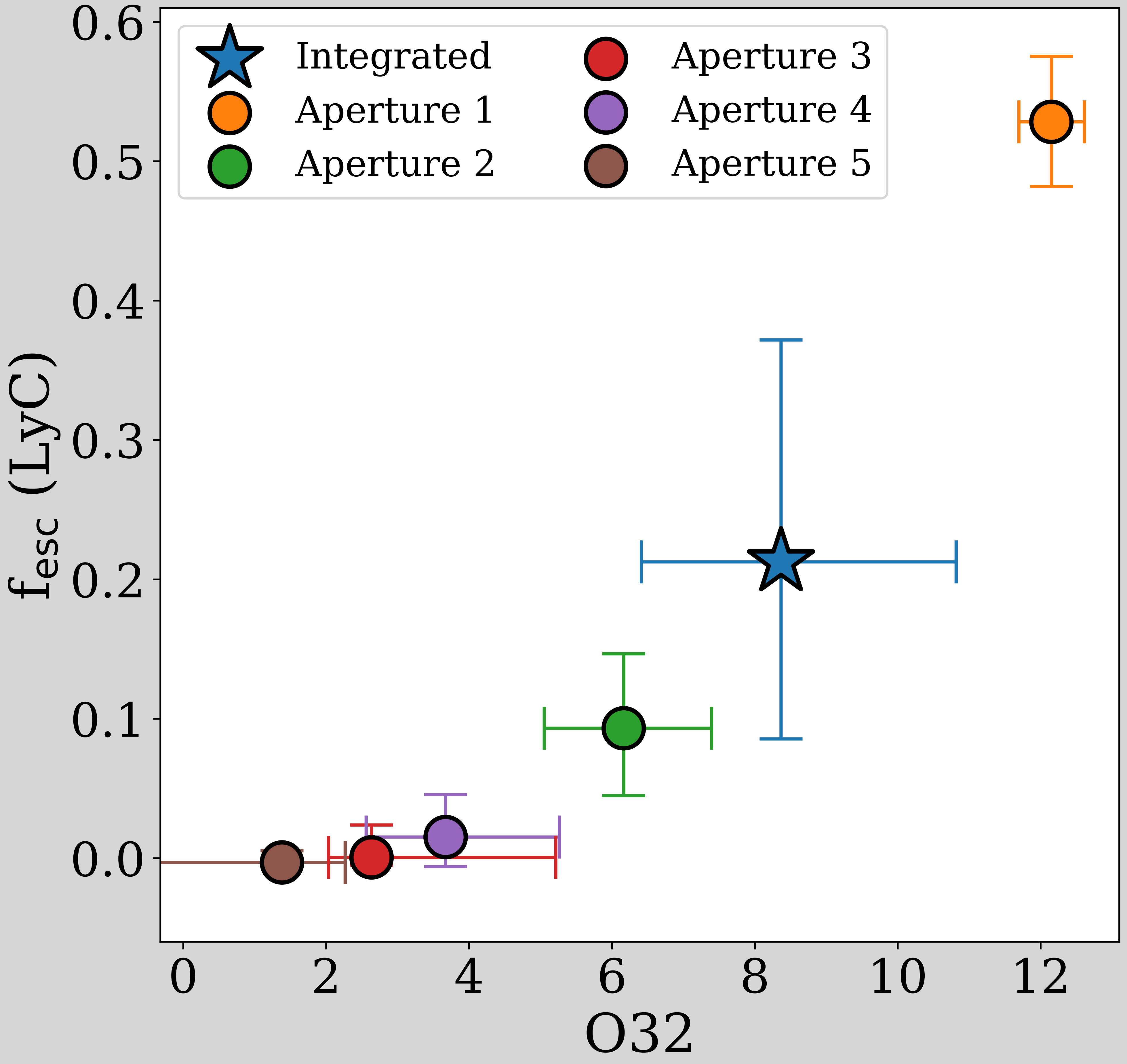
Cabello+23 *in prep.*



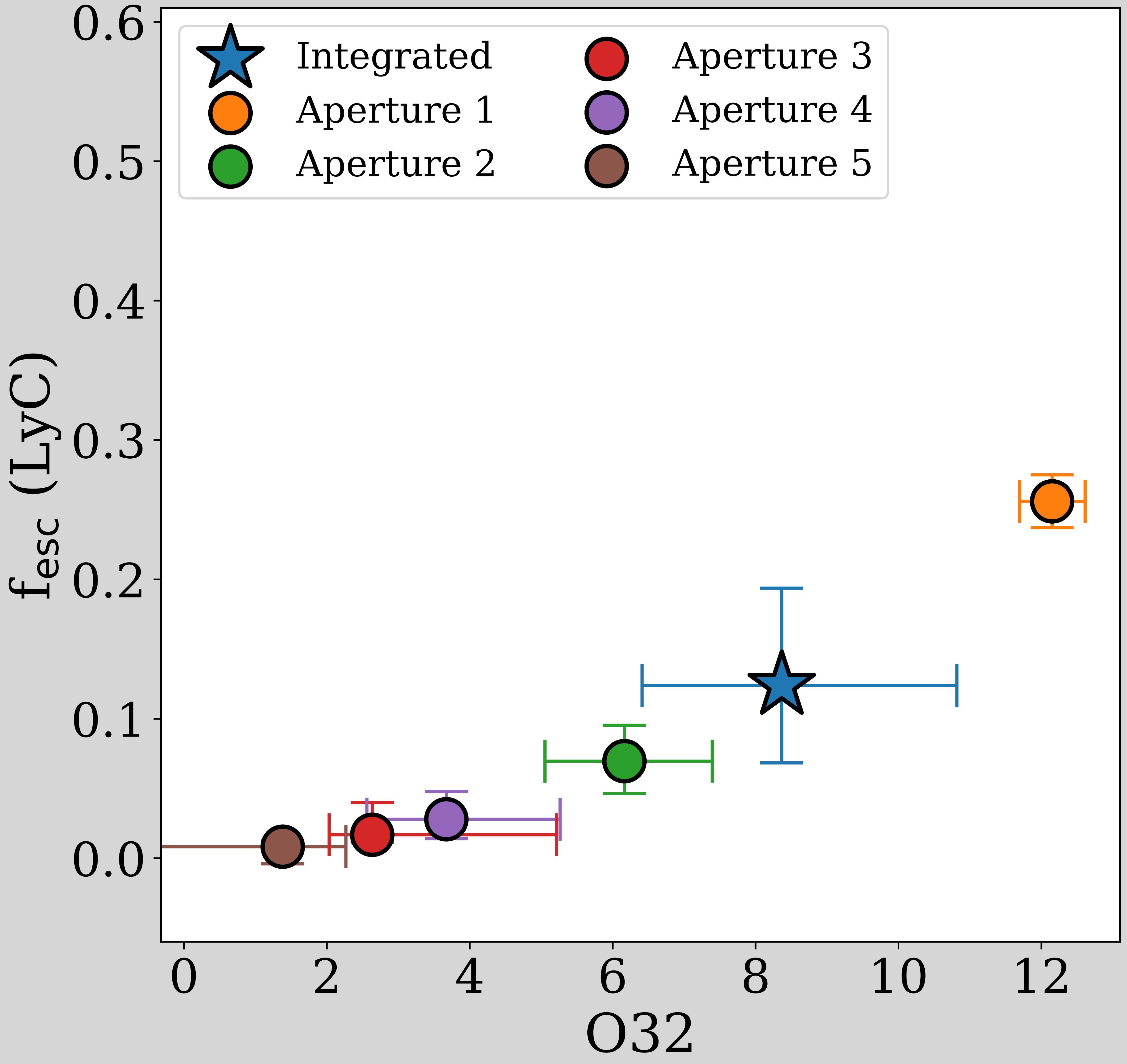
5 Analysis and preliminary results

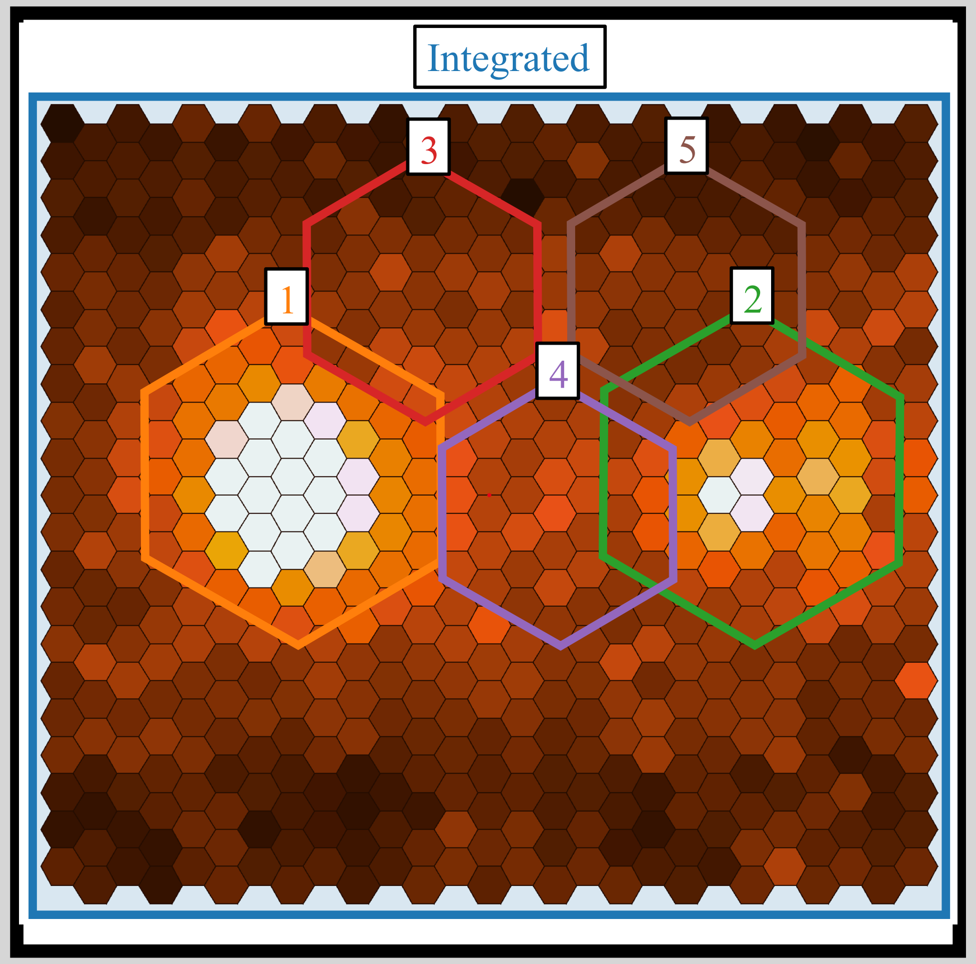
f_{esc}(LyC) estimation

O32 - f_{esc} (LyC) relation from Izotov+18a



O32 - f_{esc} (LyC) relation from Chisholm+18





Cabello+23 *in prep.*

6 General conclusions and final remarks

- Different indirect indicators of LyC leakage based on emission-line ratios revealed values consistent with those of high-z galaxies, Green Pea Galaxies, and low-z LyC leakers from the literature.

This outcome reinforces **the status of UM461 as an excellent local analog of the high-z population**.

- We found **significant spatial variations of LyC leakage**

Integrated properties do not fully represent the complex ionization structure of UM461

- **2D spectroscopic information is crucial for unveiling the mechanisms that allow LyC photons to escape.**

Representative of the whole population of local analogs?

Study of a larger sample of reionization era analogs

↓

MEGARA@GTC proposal GTC44-23A (PI: C. Cabello)

Thanks!

Contact: criscabe@ucm.es