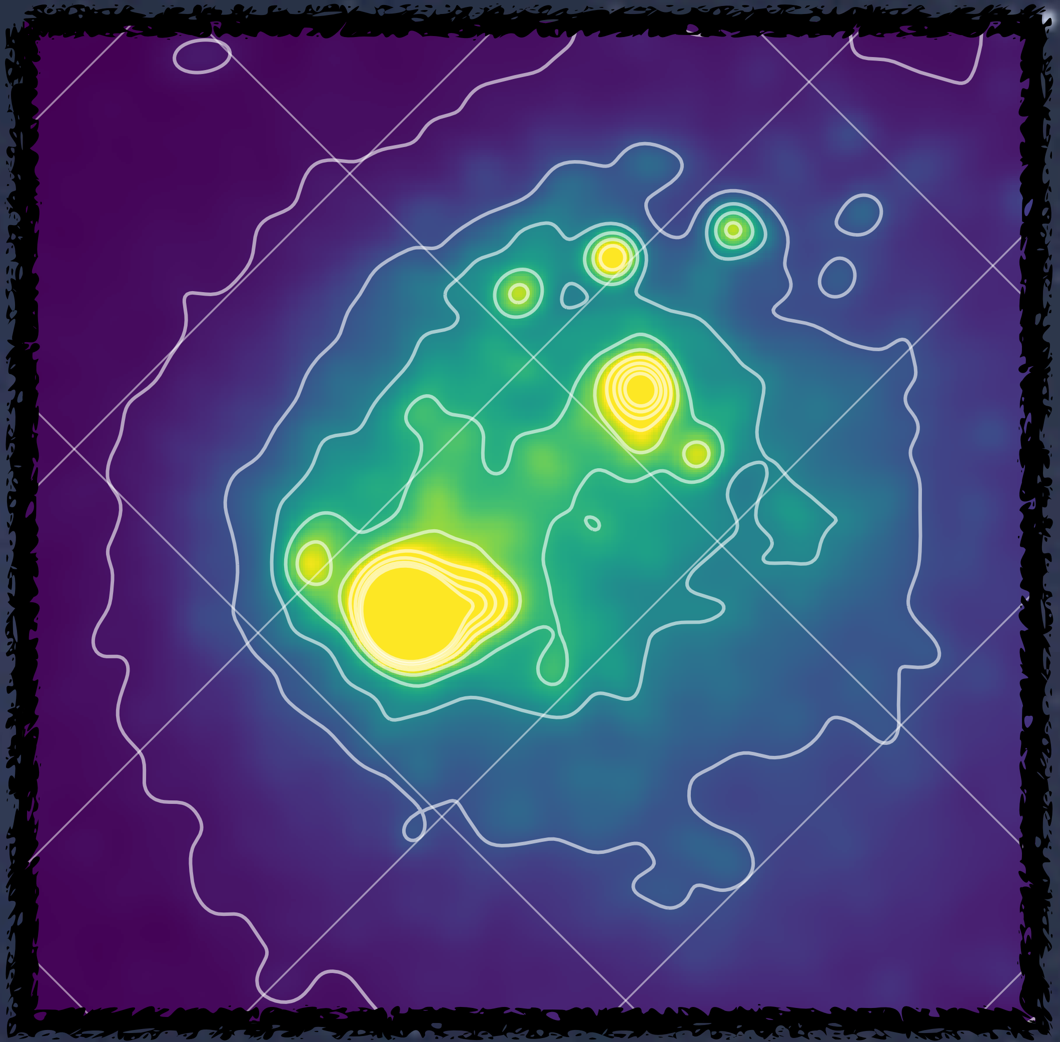
Mapping the ISM conditions of local analogs of primeval galaxies

OAC, Crete
Escape of Lyman radiation from galactic labyrinths
2025



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Comunidad de Madrid

Plan de Recuperación, Transformación y Resiliencia

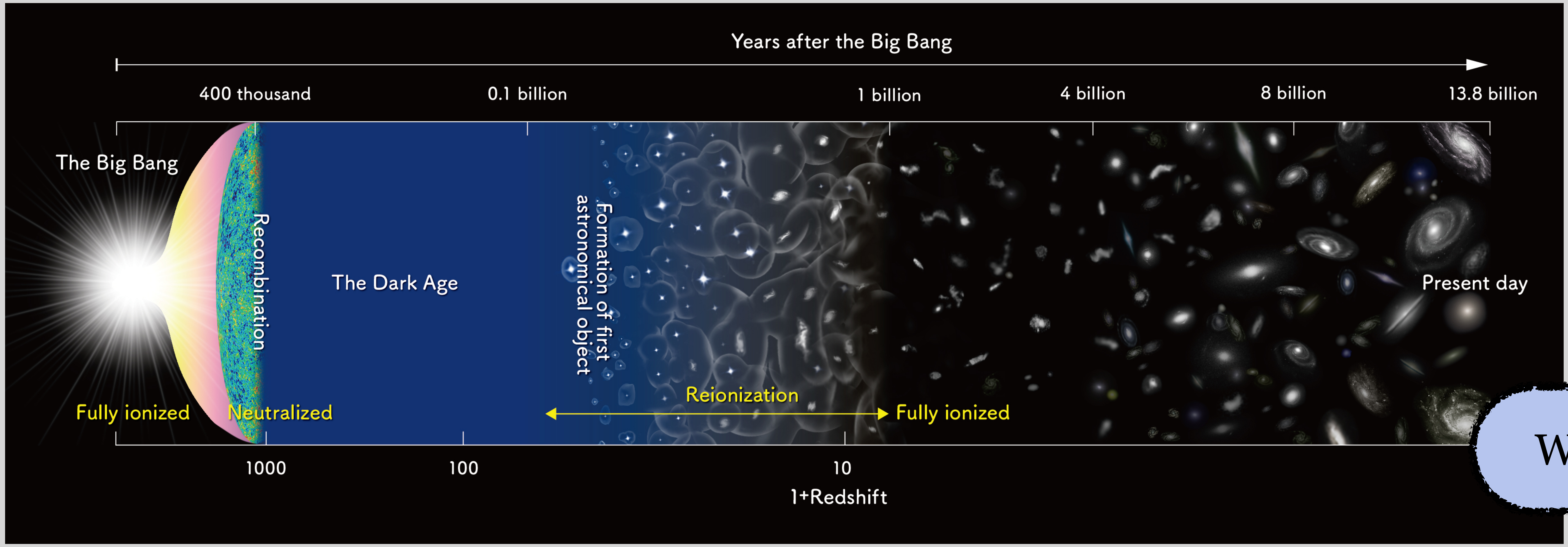
Financiado por la Unión Europea NextGenerationEU

Universidad Complutense Madrid

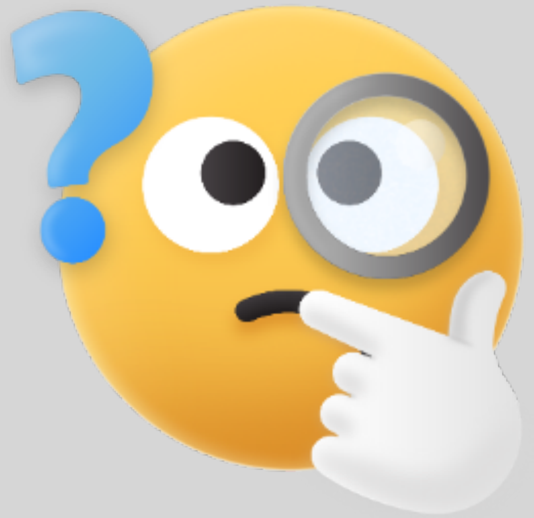
IPARCOS

GUAIX

The epoch of reionization



Credit: NAOJ



How was the process of reionization?

Which were the sources responsible for it?

When did it happen?

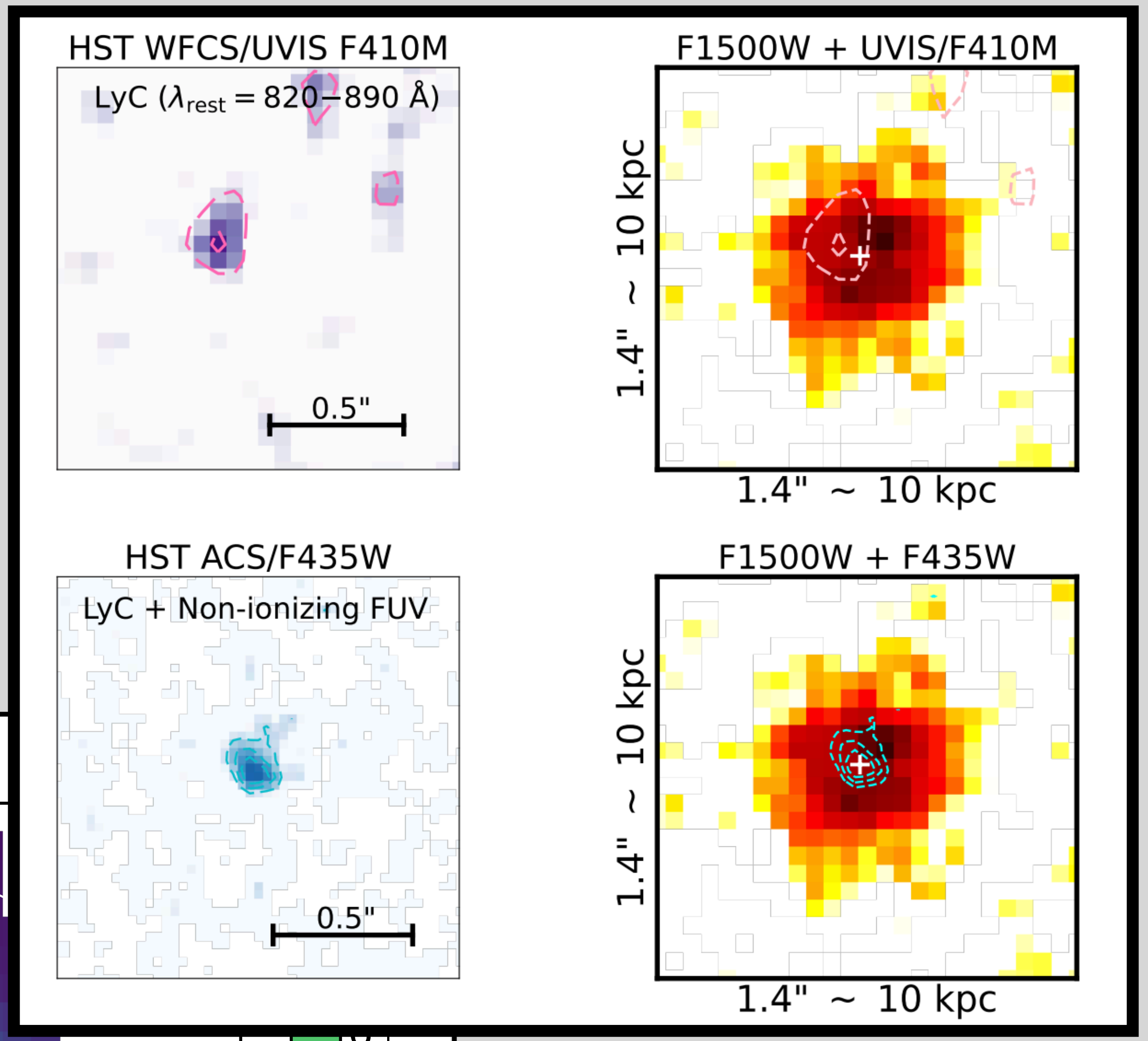
IGM opacity increases with redshift.

Direct detection of LyC photons is impossible for very high-z galaxies!

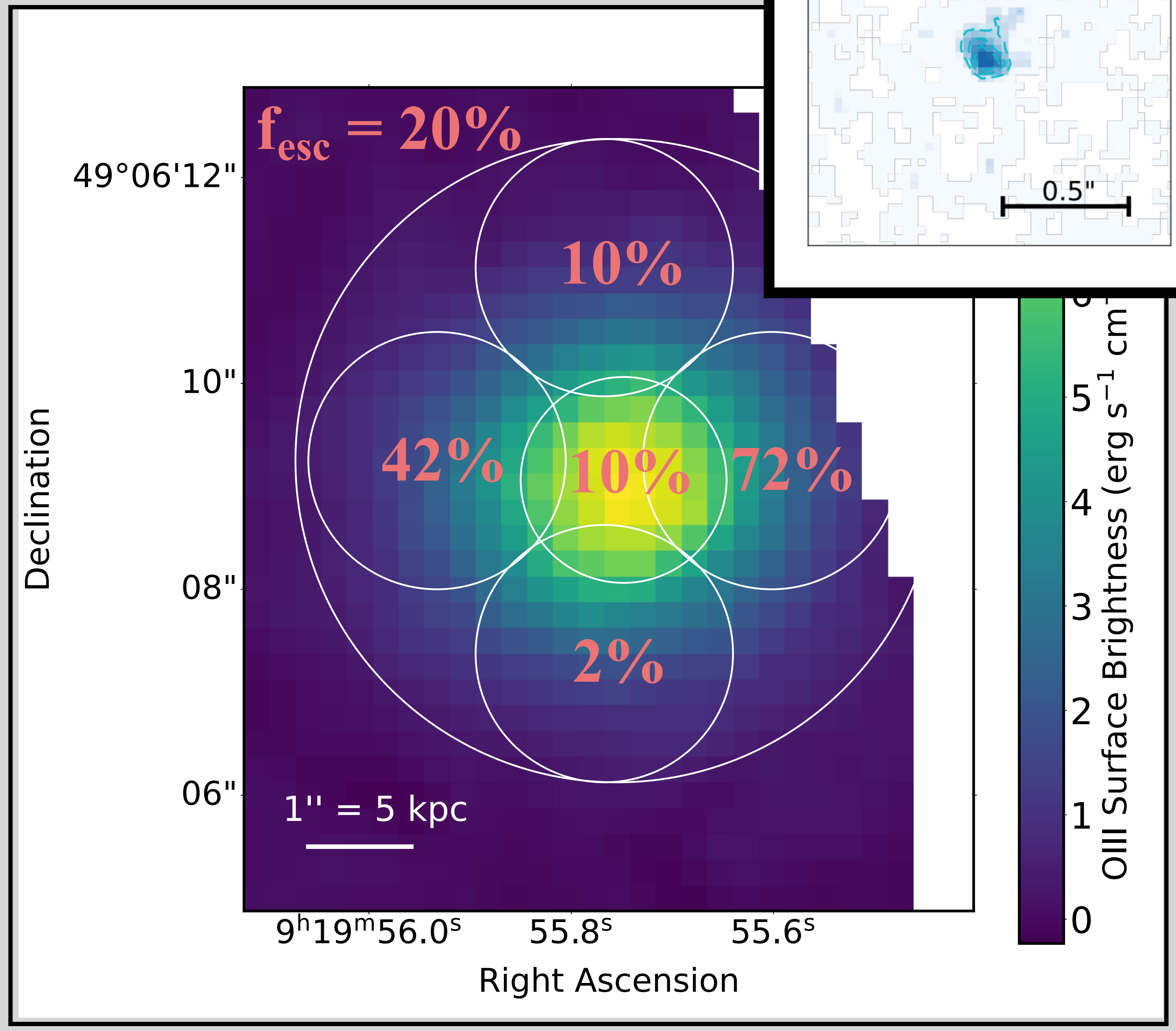
Need for indirect indicators of the physical mechanisms involved in LyC escape.

Need to find good analogs of primeval galaxies at lower redshifts

The importance of spatially resolved observations



Ji+25



Seive+22

f_{esc}(LyC) is highly sightline dependent.

Spatial variations may lead to large variations in both indirect and direct estimates of fesc(LyC).

LyC escape is a multi-parameter problem.

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

Scientific motivation of this project

The study of local analogs of high-z galaxies may provide useful hints about cosmic reionization and the first galaxies!

Main goals

- Identification of different regions of low-z galaxies leaking LyC photons (down to sub-kpc scales).
- 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).
- Map the ionization structure of the ISM and trace the chemical evolution.
- Test their resemblance with the high-z population of galaxies.
- Investigate the mechanisms that allow LyC photons to escape in the first galaxies.

Scientific motivation of this project

The sample of reionization-era analogs

- Excellent local analogs of high-z galaxies ("*gold*" sample)

(Motiño Flores et al. 2021, UV-FIR photometric data

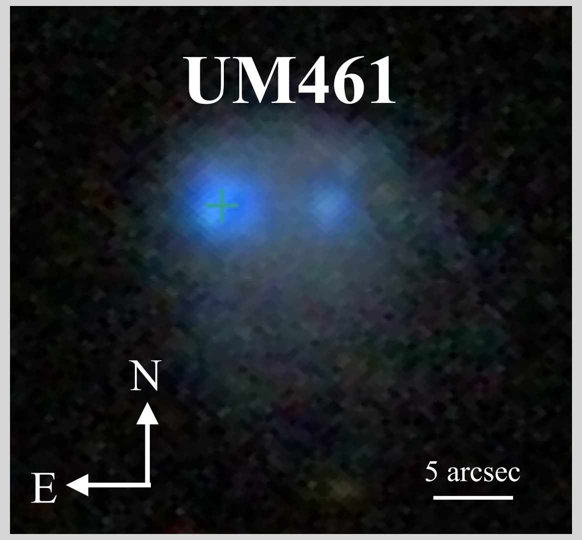
Yang et al. 2017)

- Potential LyC leaker candidates

(Katz et al. 2020, cosmological radiation hydrodynamics simulations)

Properties of local analogs

- ✦ Small angular size
- ✦ Irregular/compact morphology
- ✦ Low stellar mass
- ✦ Low metallicity
- ✦ Low dust attenuation
- ✦ High sSFR
- ✦ High gas content
- ✦ High nebular emission

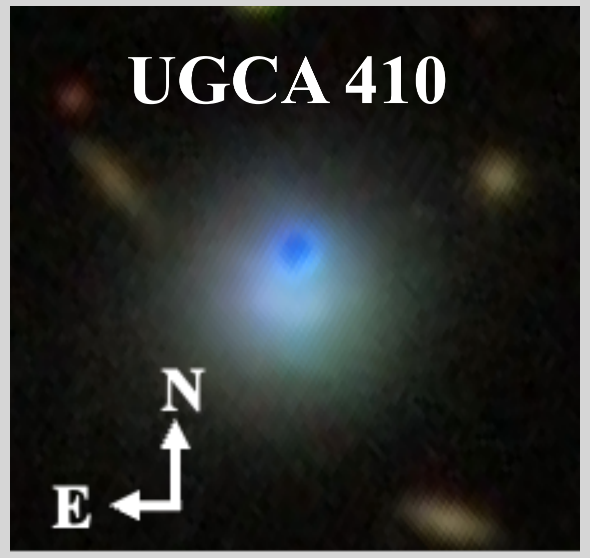


$z = 0.003465$

$\log(M_\star/M_\odot) = 7.88$

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

UM461

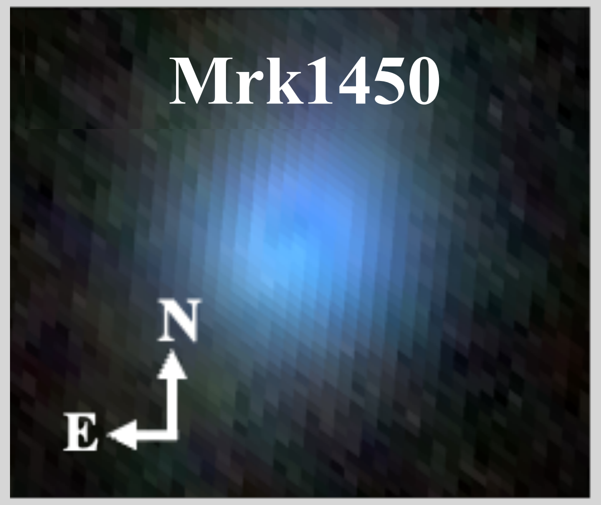


$z = 0.002148$

$\log(M_\star/M_\odot) = 7.26$

$12 + \log(O/H) = 8.10$

UGCA 410

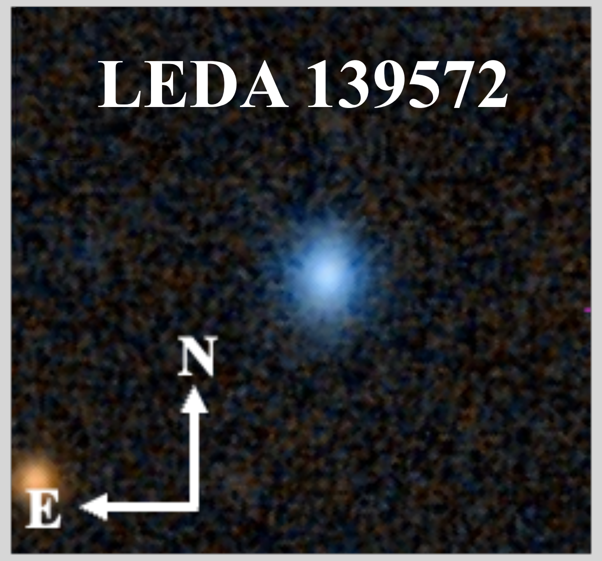


$z = 0.00317$

$\log(M_\star/M_\odot) = 7.27$

$12 + \log(O/H) = 7.96$

Mrk1450



$z = 0.03283$

$\log(M_\star/M_\odot) = 8.6$

$12 + \log(O/H) = 7.94$

LEDA 139572

Instrumental setup and observations

10.4 m - Gran Telescopio Canarias (GTC)

The MEGARA instrument

IFU mode - Large Compact Bundle

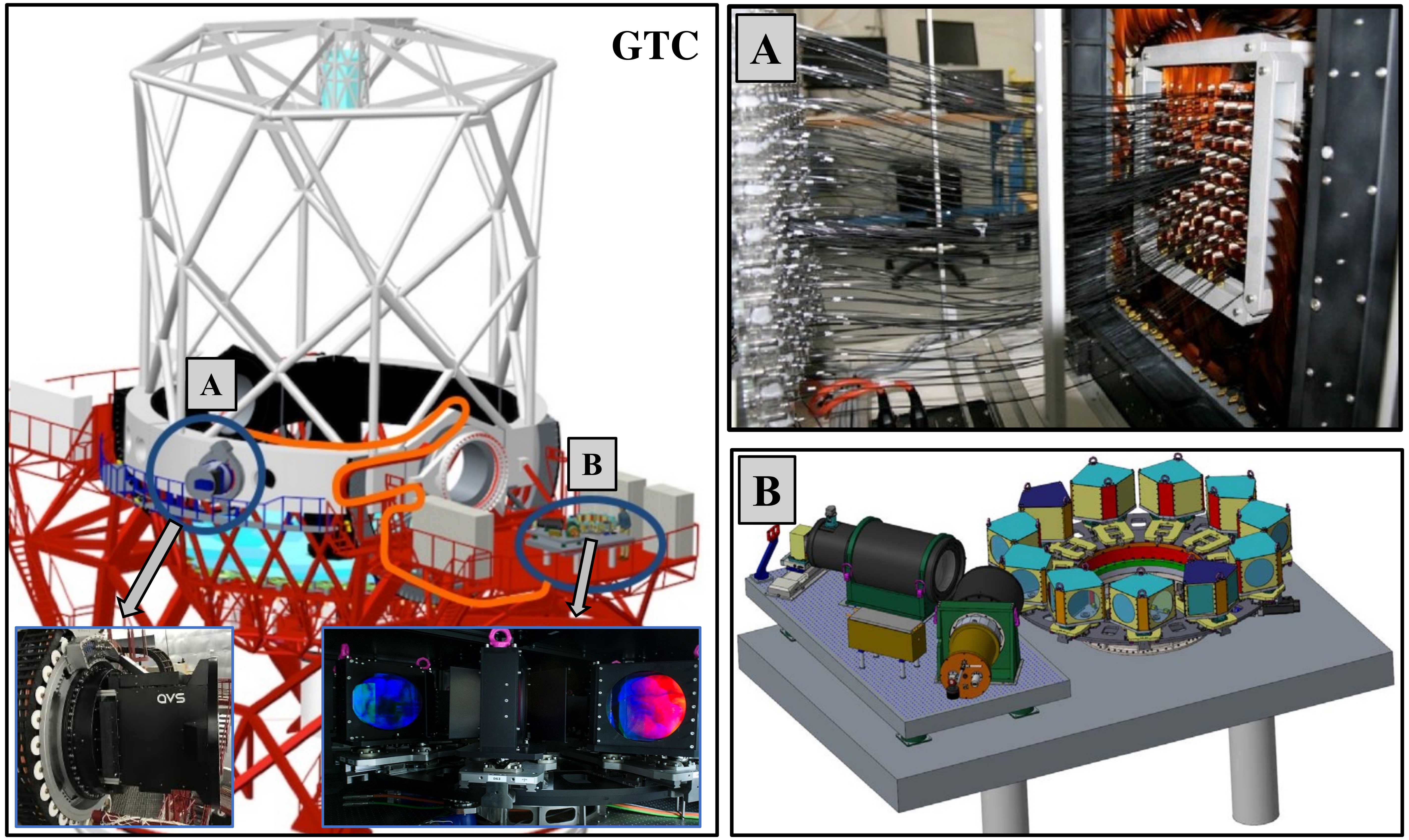
⇩

LR-U, LR-B, LR-R

MEGARA@GTC observations

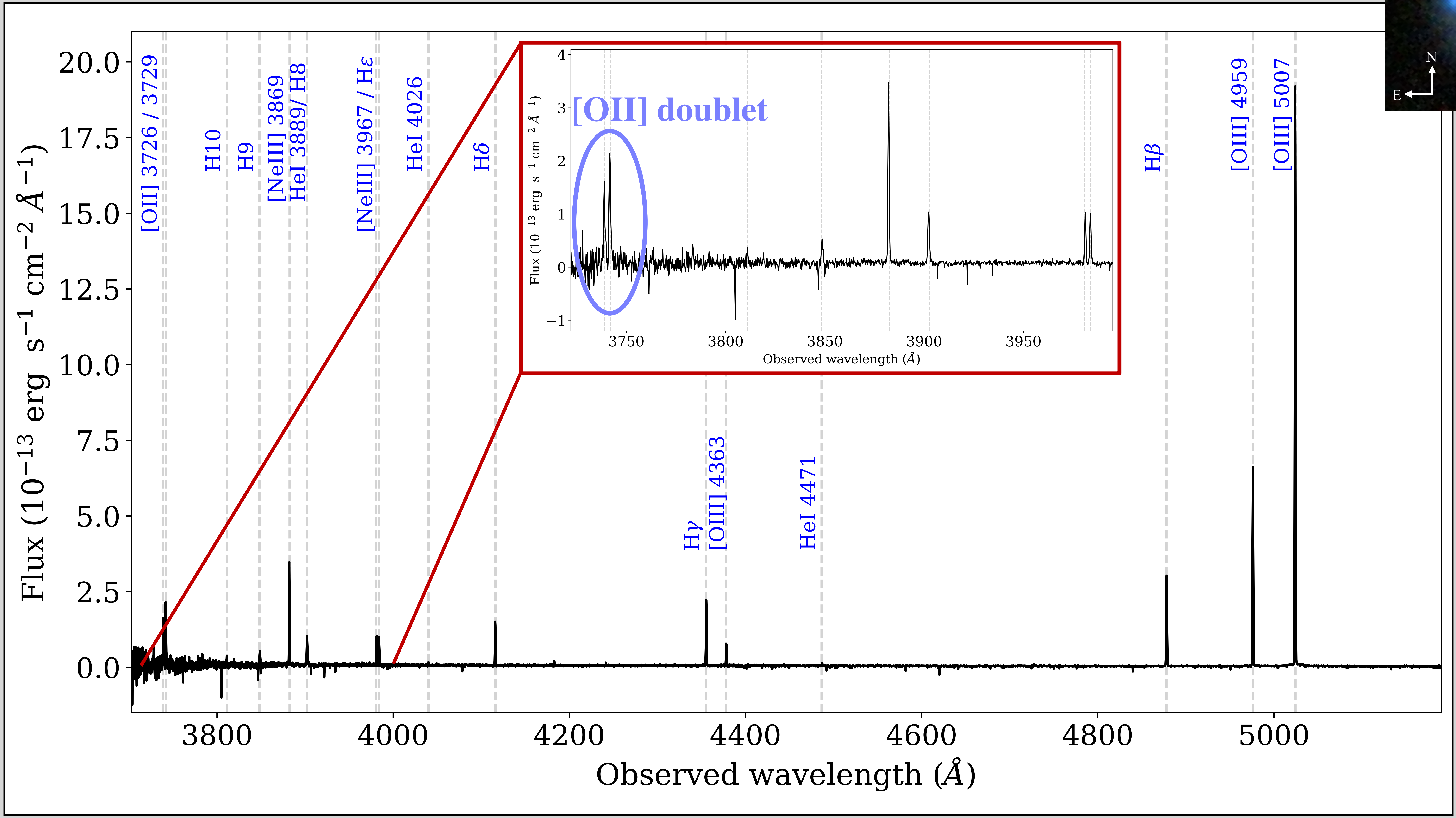
(PI: C. Cabello)

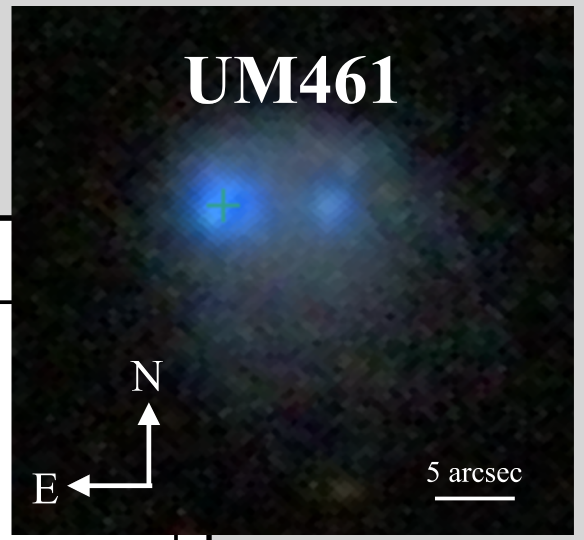
Semesters: 2022A, 2023A, 2024A



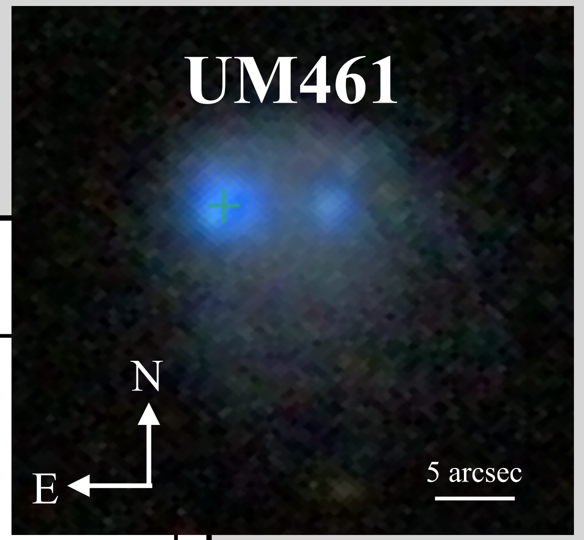
Detector:	E2V CCD231-84	**Readout noise:**	3.4 e^-
Spaxel size:	0.62″	**Gain:**	1.73 e^-/ADU
Spectral range:	0.37–0.97 μm	**FOV (IFU):**	12.5″ × 11.3″
Spectral resolution:	5 500, 12 500, and 20 000	**FOV (MOS):**	3.5′ × 3.5′

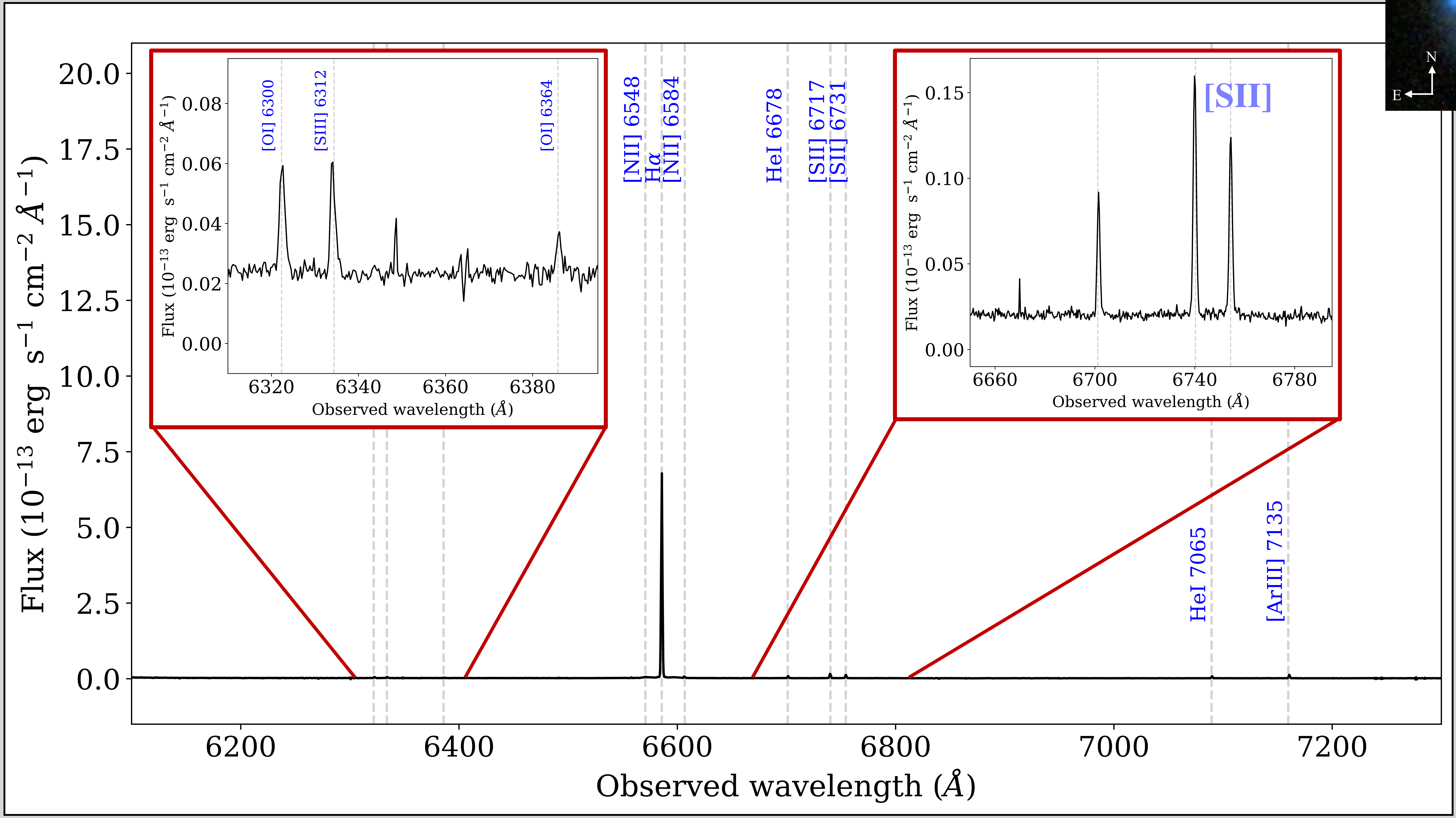
1D integrated spectra





1D integrated spectra

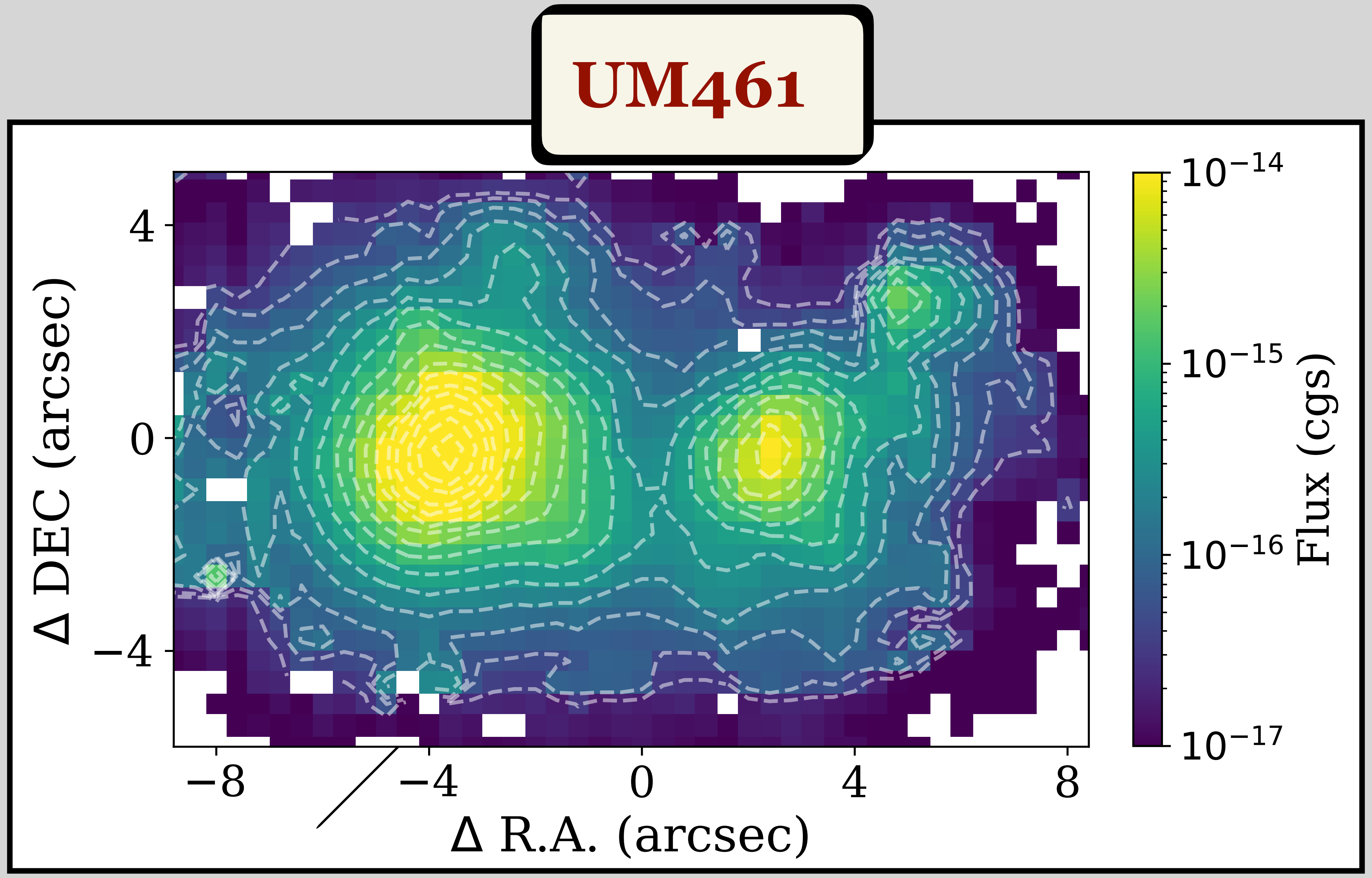


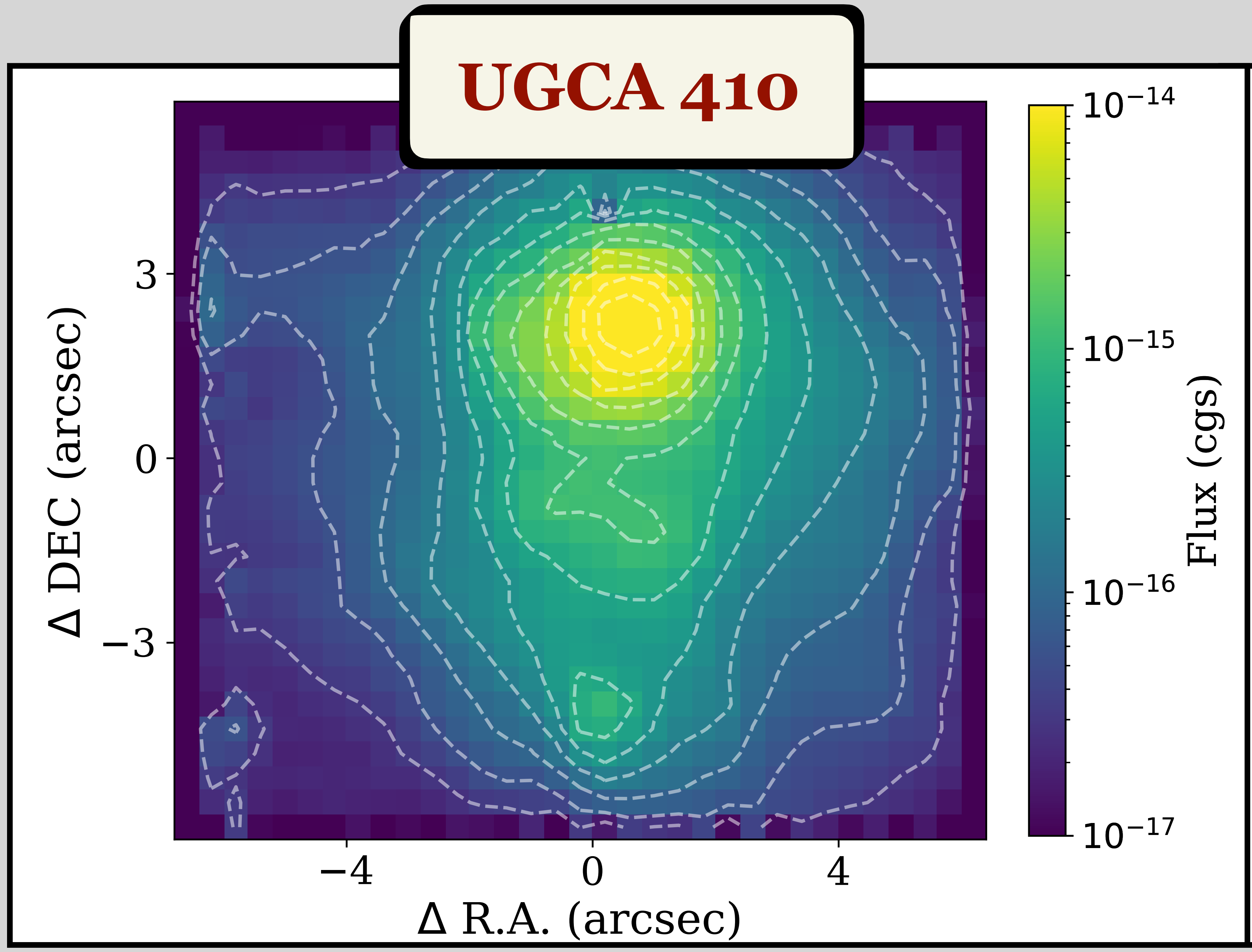


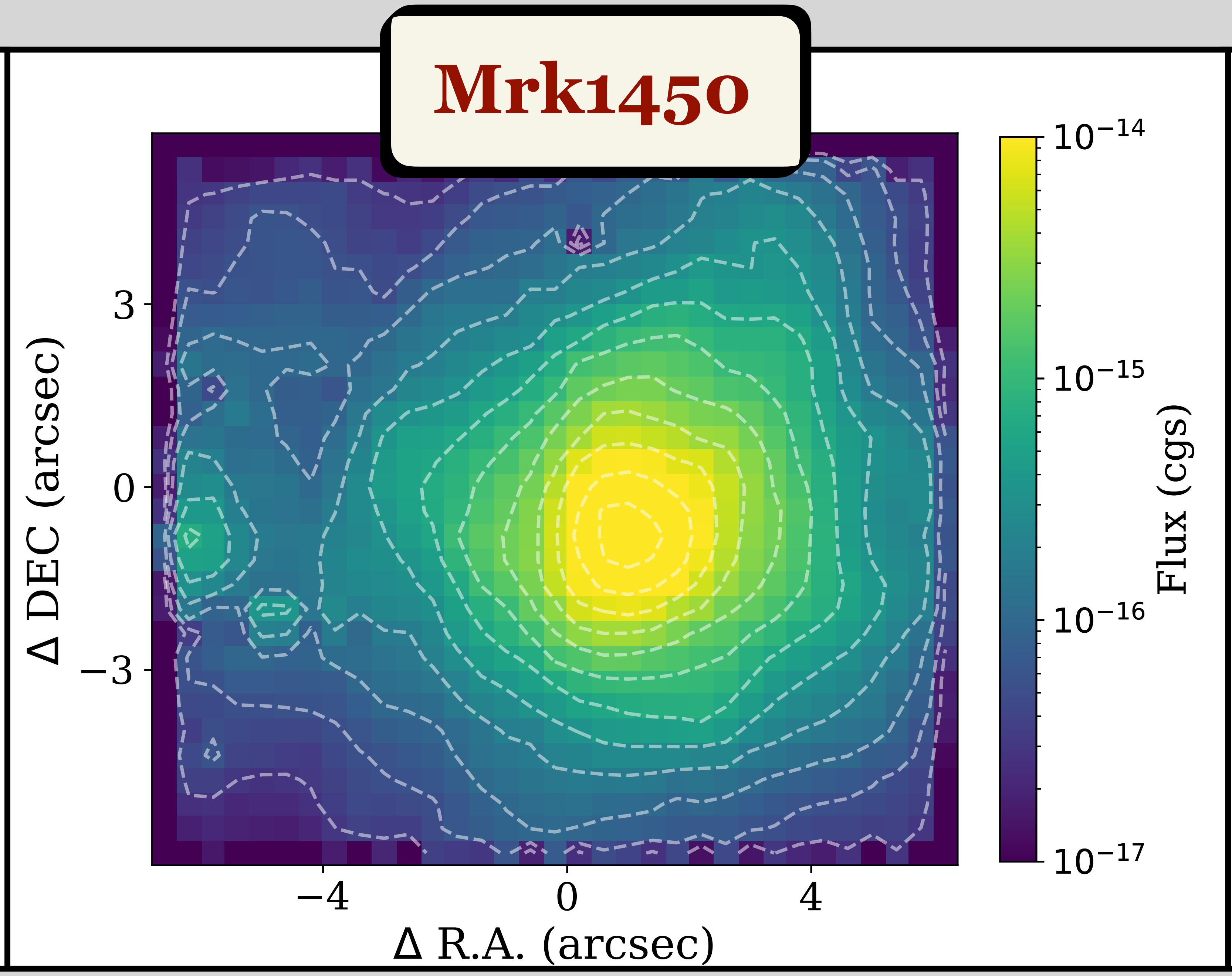
Physical properties of the sample

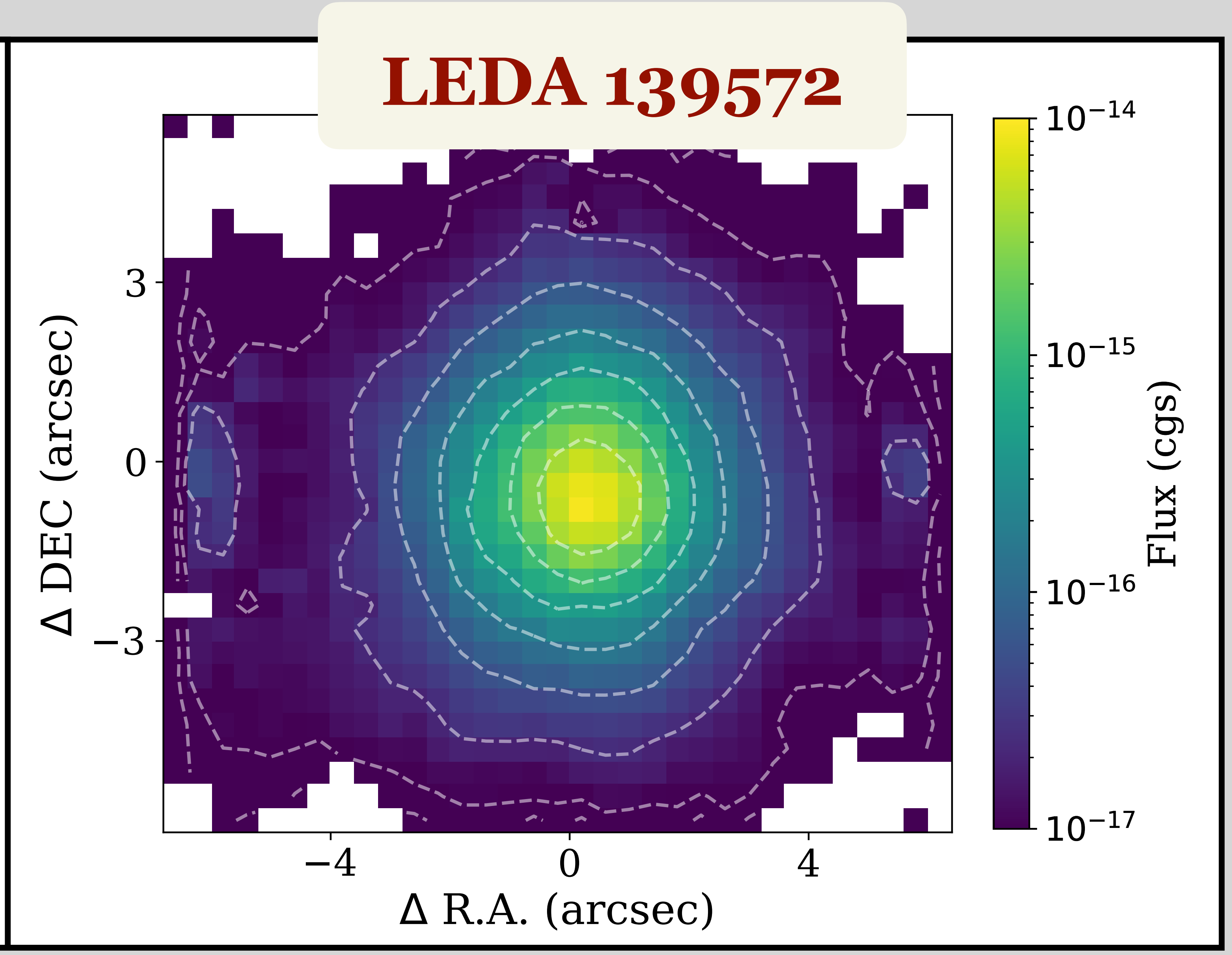
Our sample of low-*z* analogs seen through the MEGARA eyes

[OIII]5007 emission line flux









Physical properties of the sample

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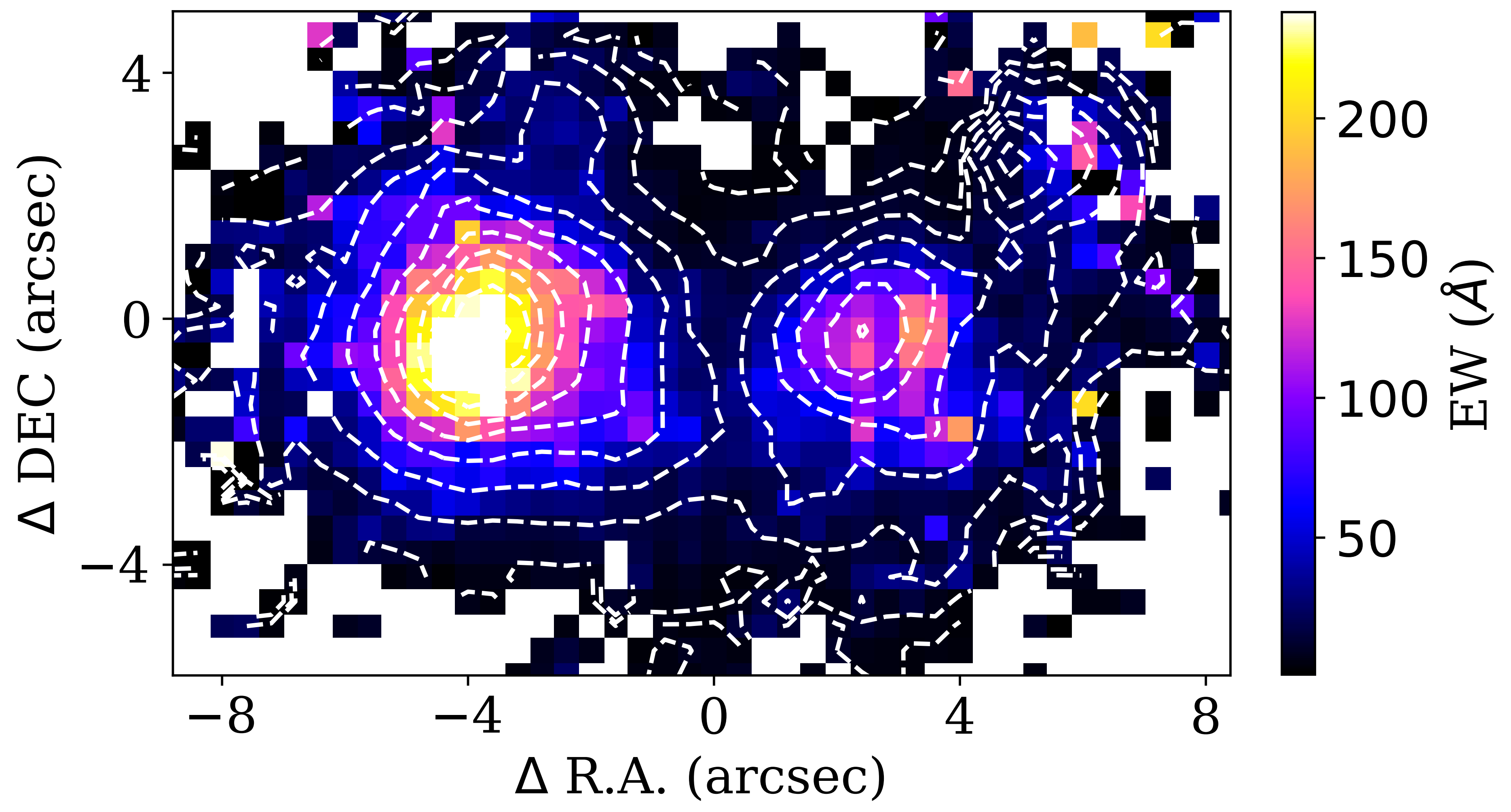
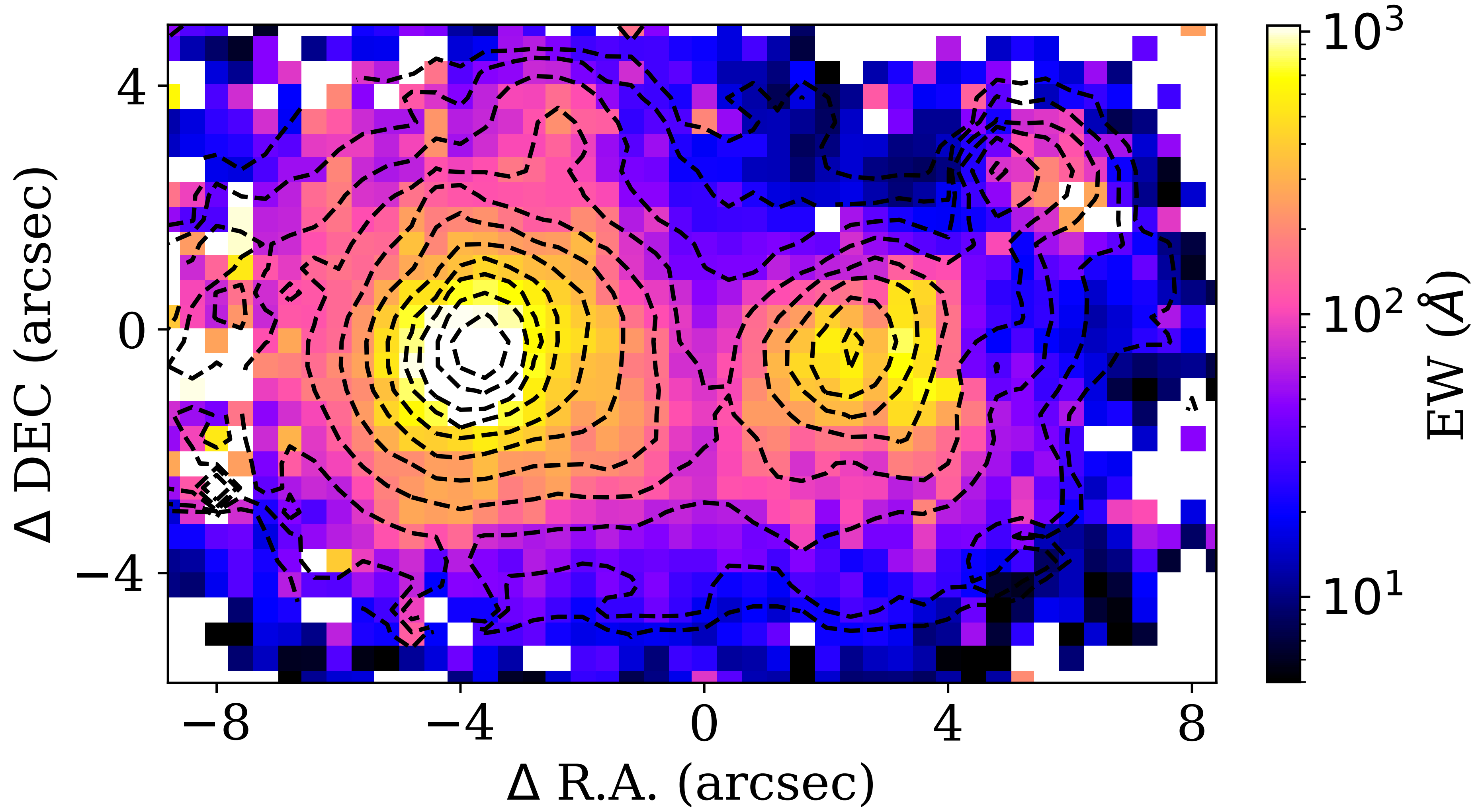
EW (Hβ)

- **Brightest knot: EW ~ 300 Å**
- **Second knot: EW ~ 100 Å**
- **External regions: EW < 50 Å**



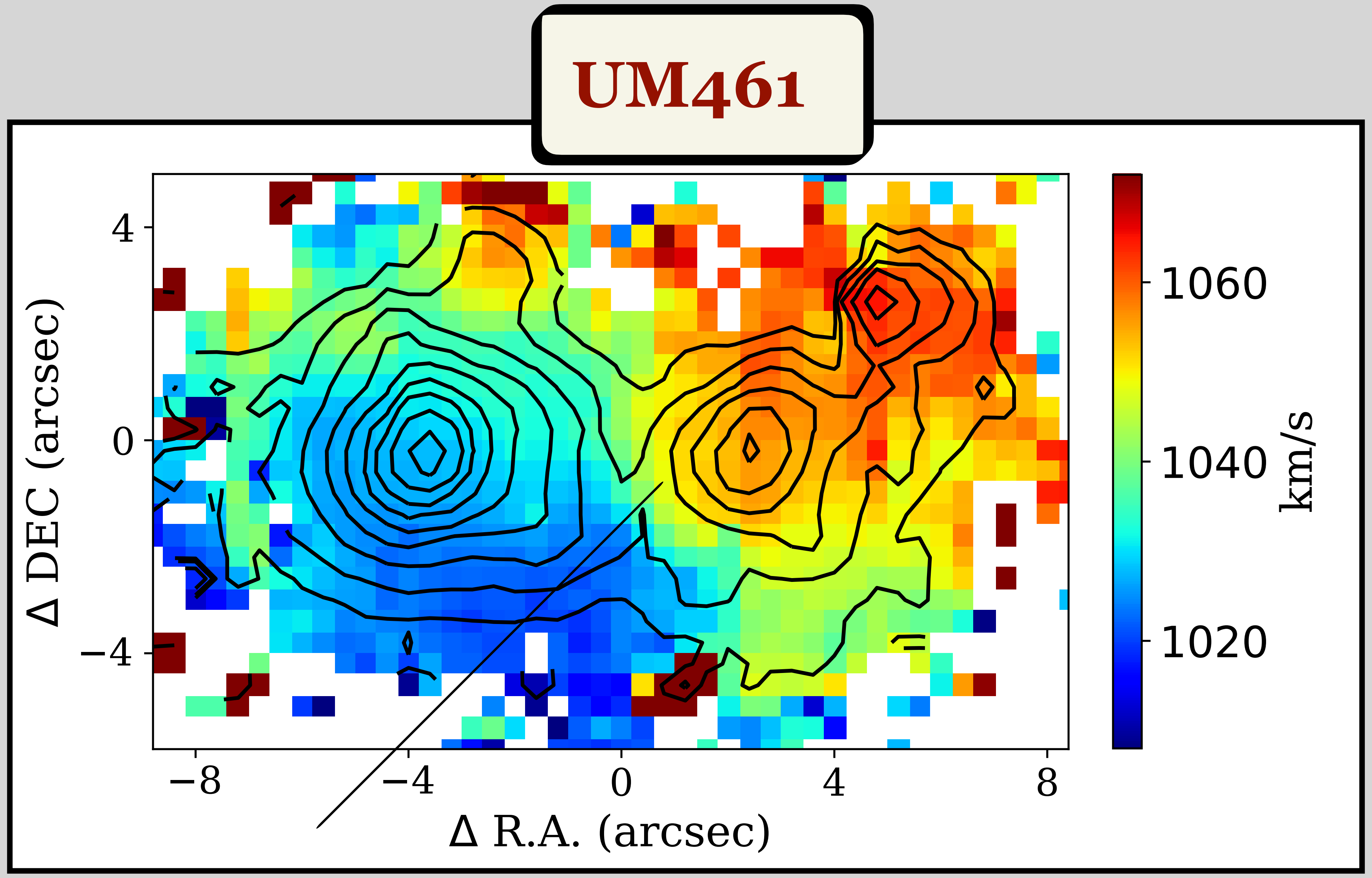
EW ([OIII]5007)

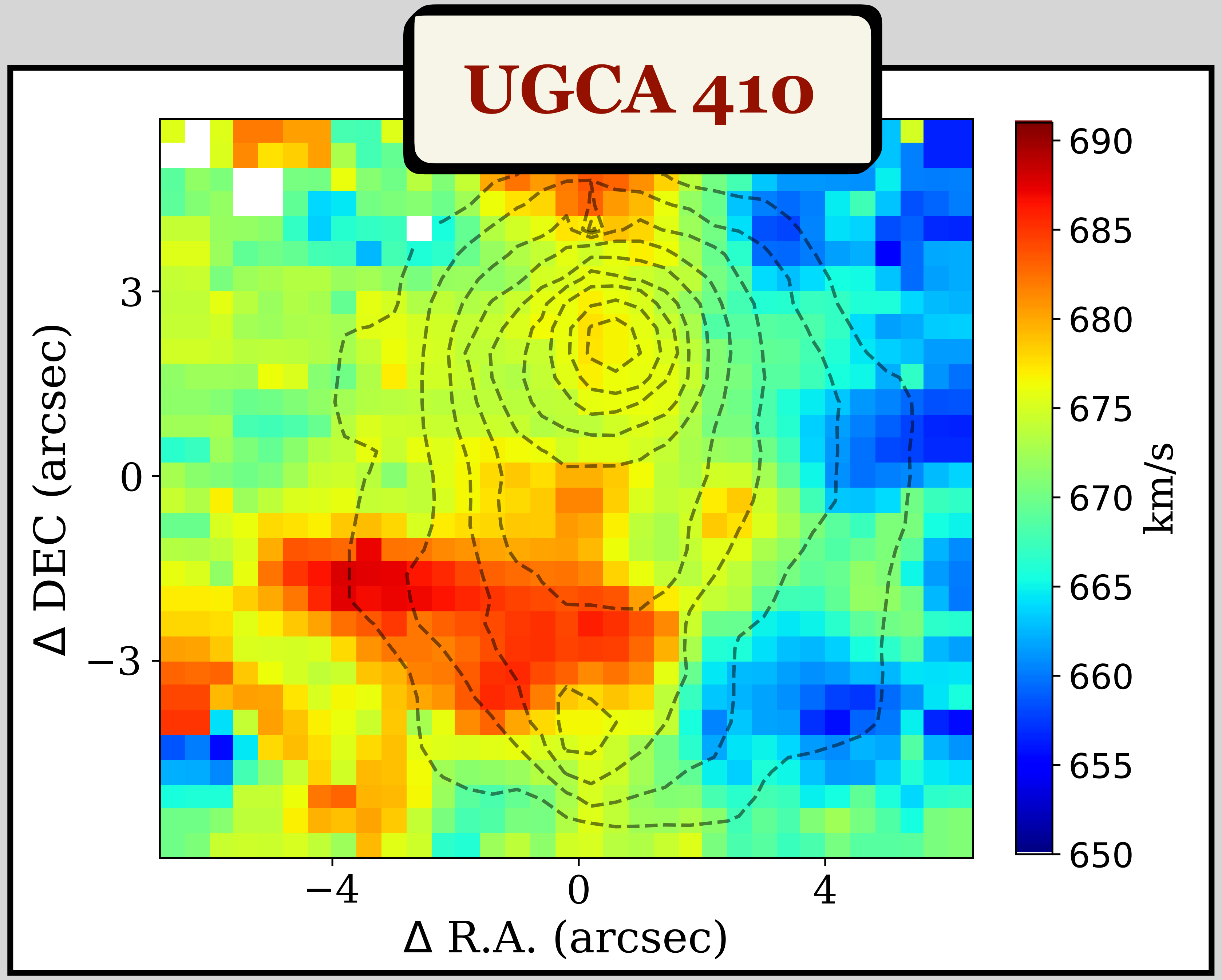
- **Brightest knot: EW ~ 1500 Å**
- **Second knot: EW ~ 500 Å**
- **External regions: EW < 100 Å**

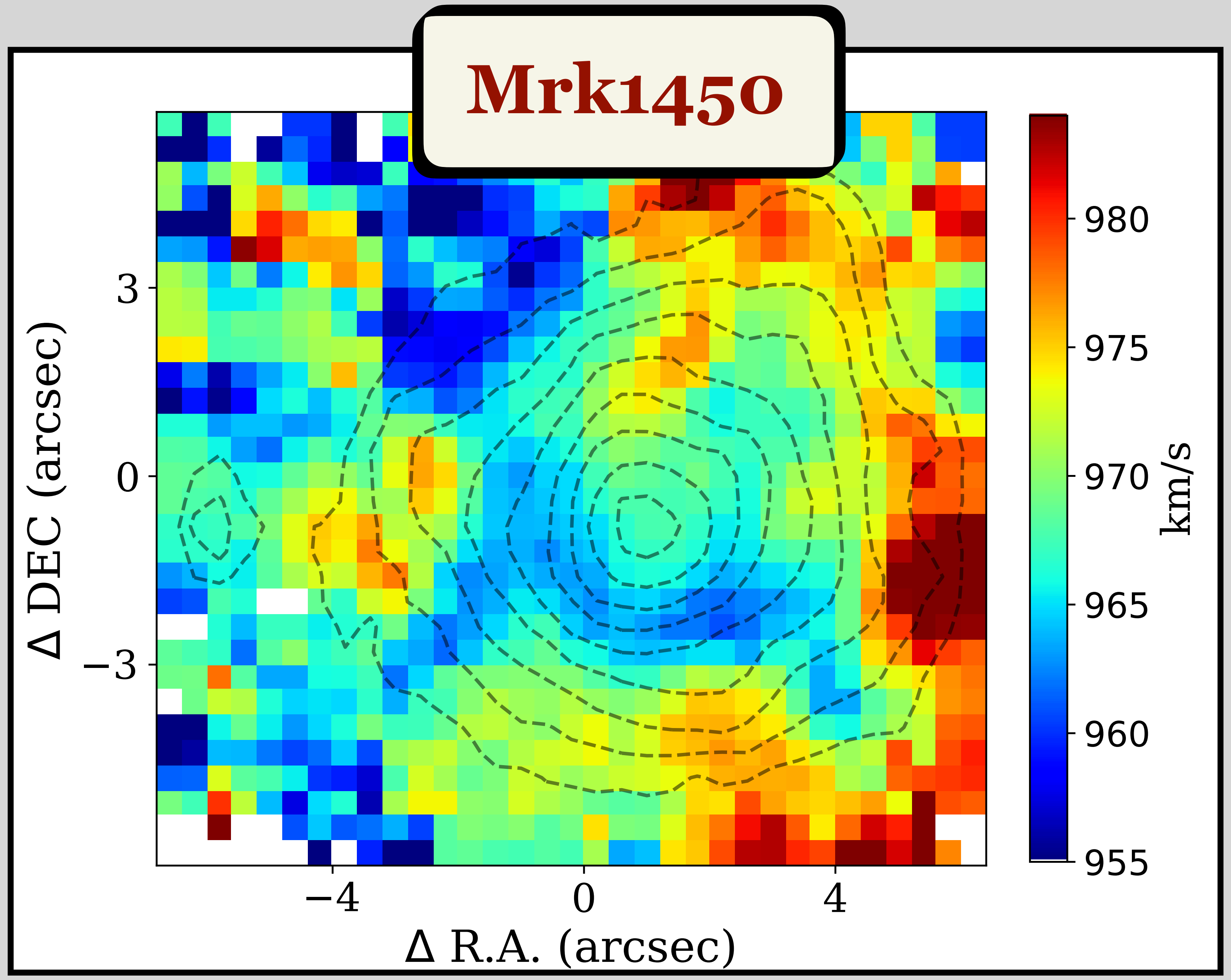


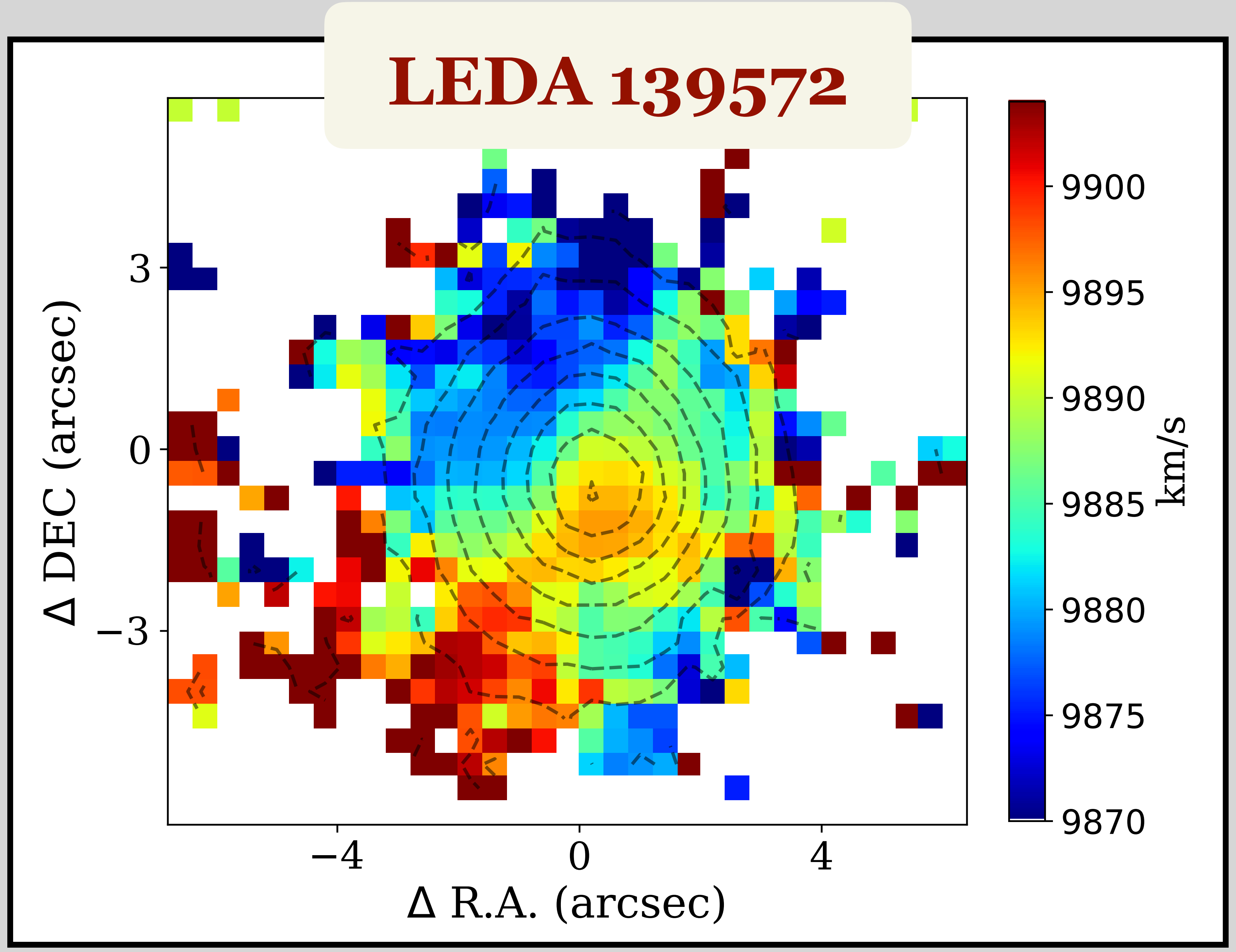
Ionized gas kinematics

- **No evidence of asymmetric line profiles or multiple components.**
- **Velocity dispersions ~ 10 - 20 km/s.**









Ionized gas kinematics

- **No evidence of asymmetric line profiles or multiple components.**
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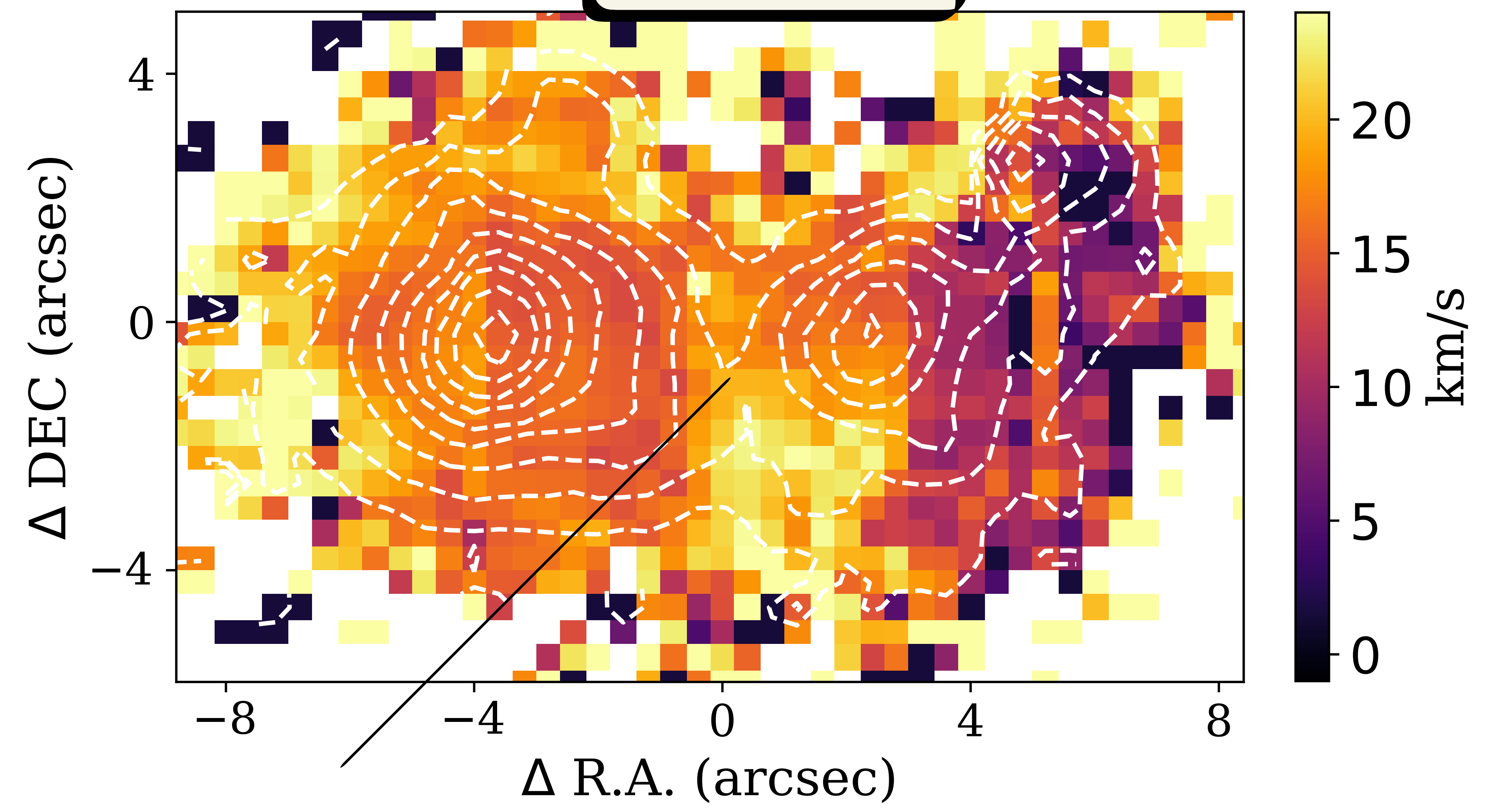
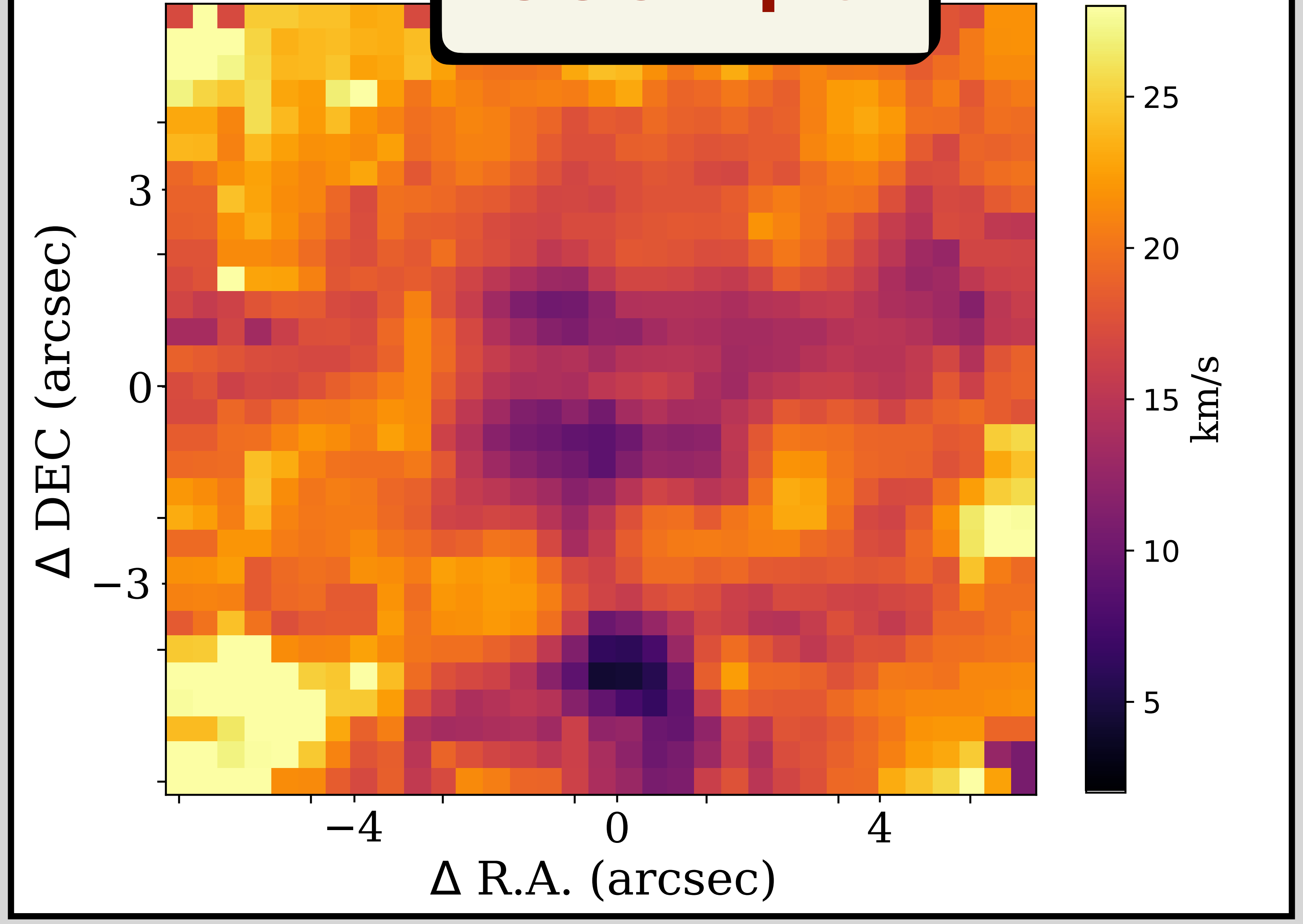
UM461



UGCA 410



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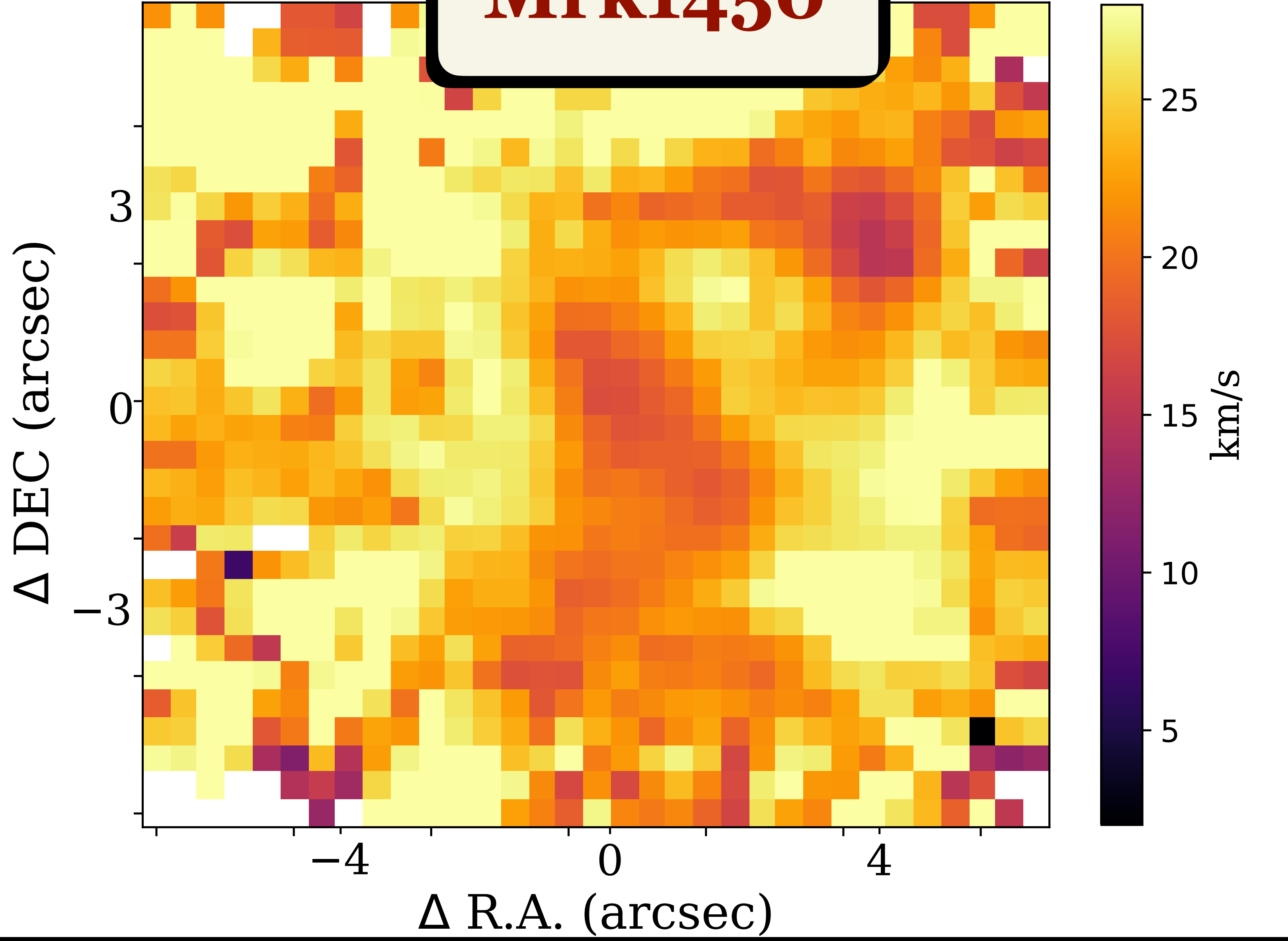

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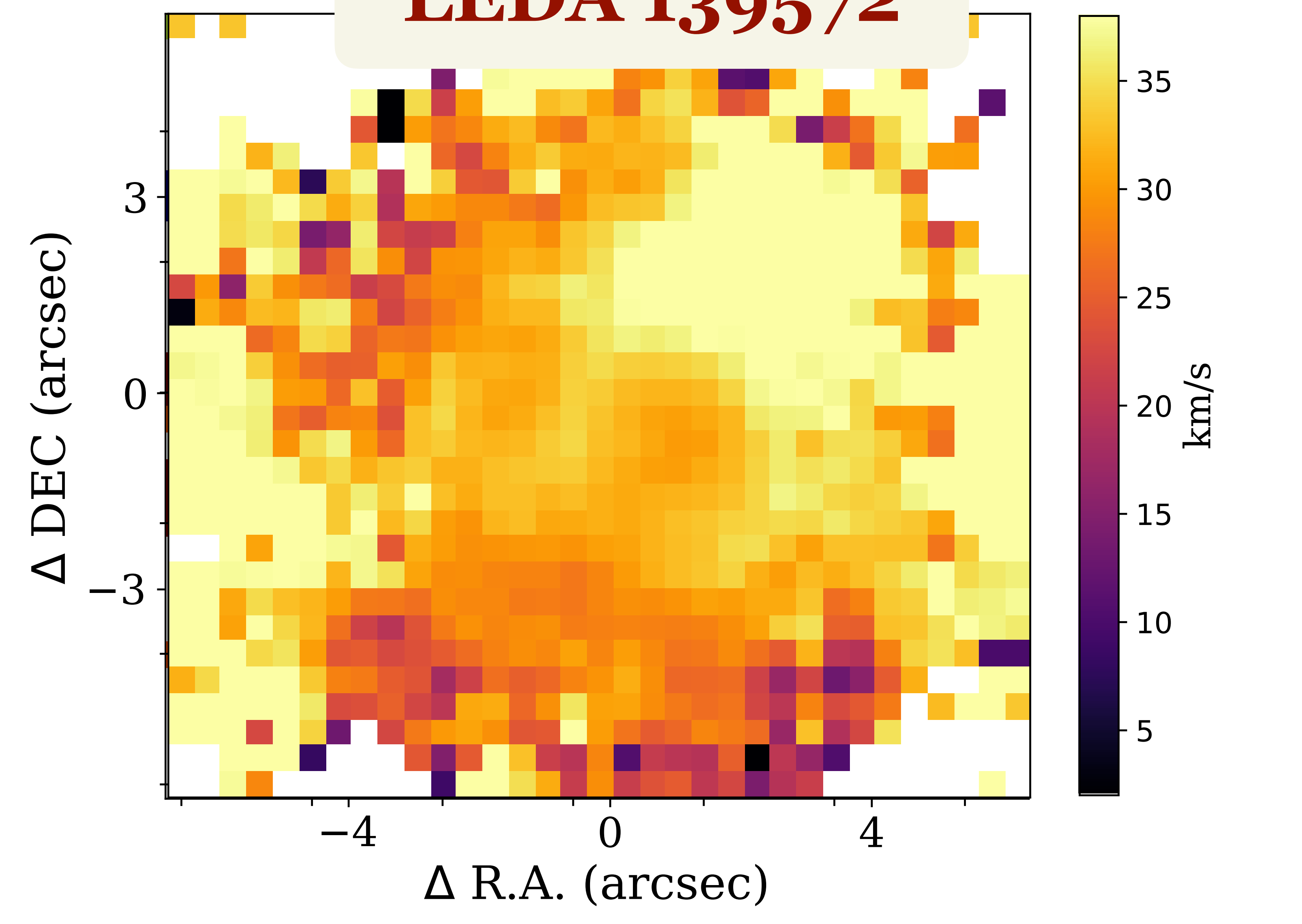
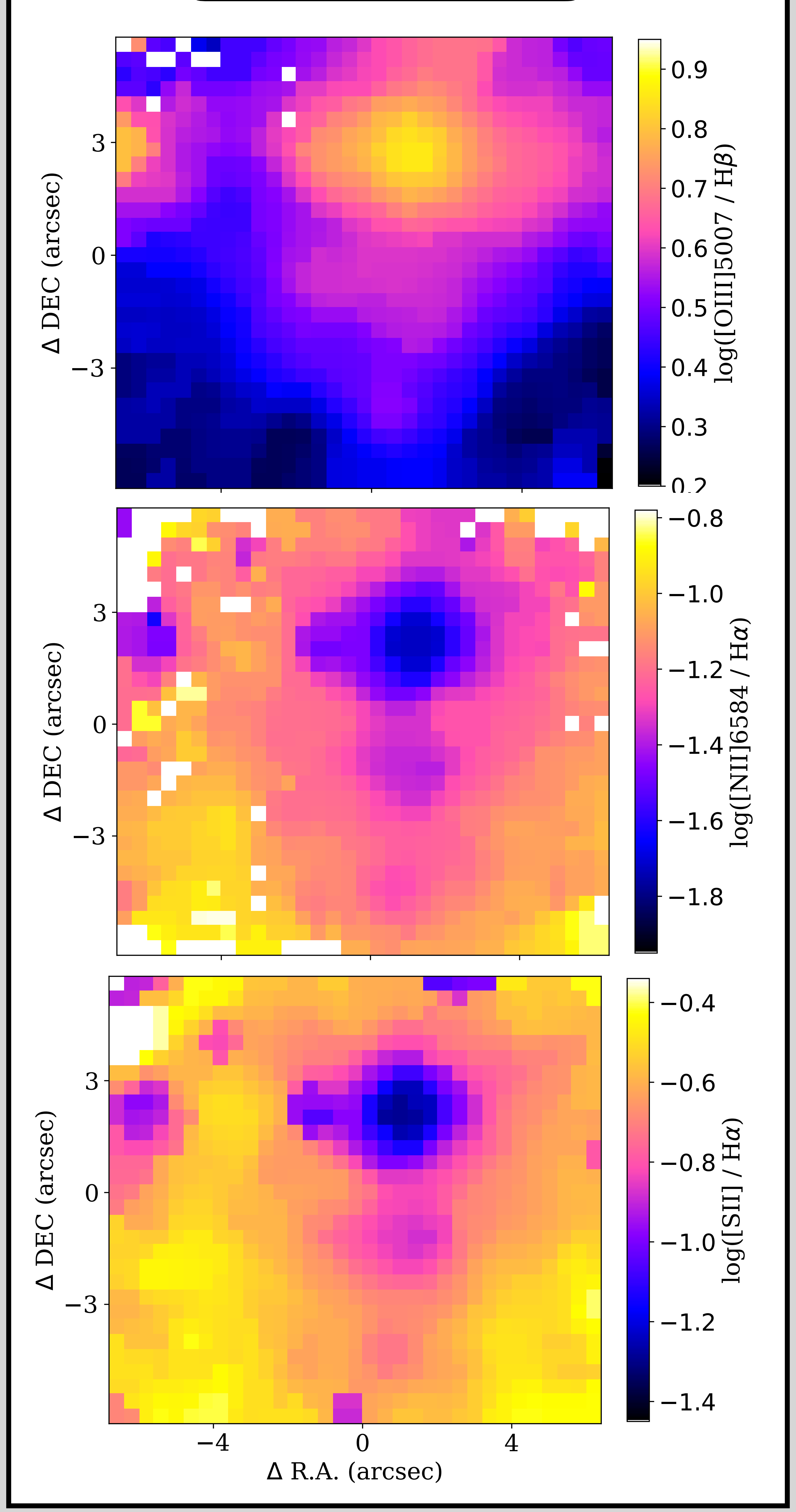


$$\frac{[OIII]\lambda 5007}{H\beta}$$

$$\frac{[NII]\lambda 6584}{H\alpha}$$

$$\frac{[SII]\lambda\lambda\, 6717{,}6731}{H\alpha}$$

UGCA 410



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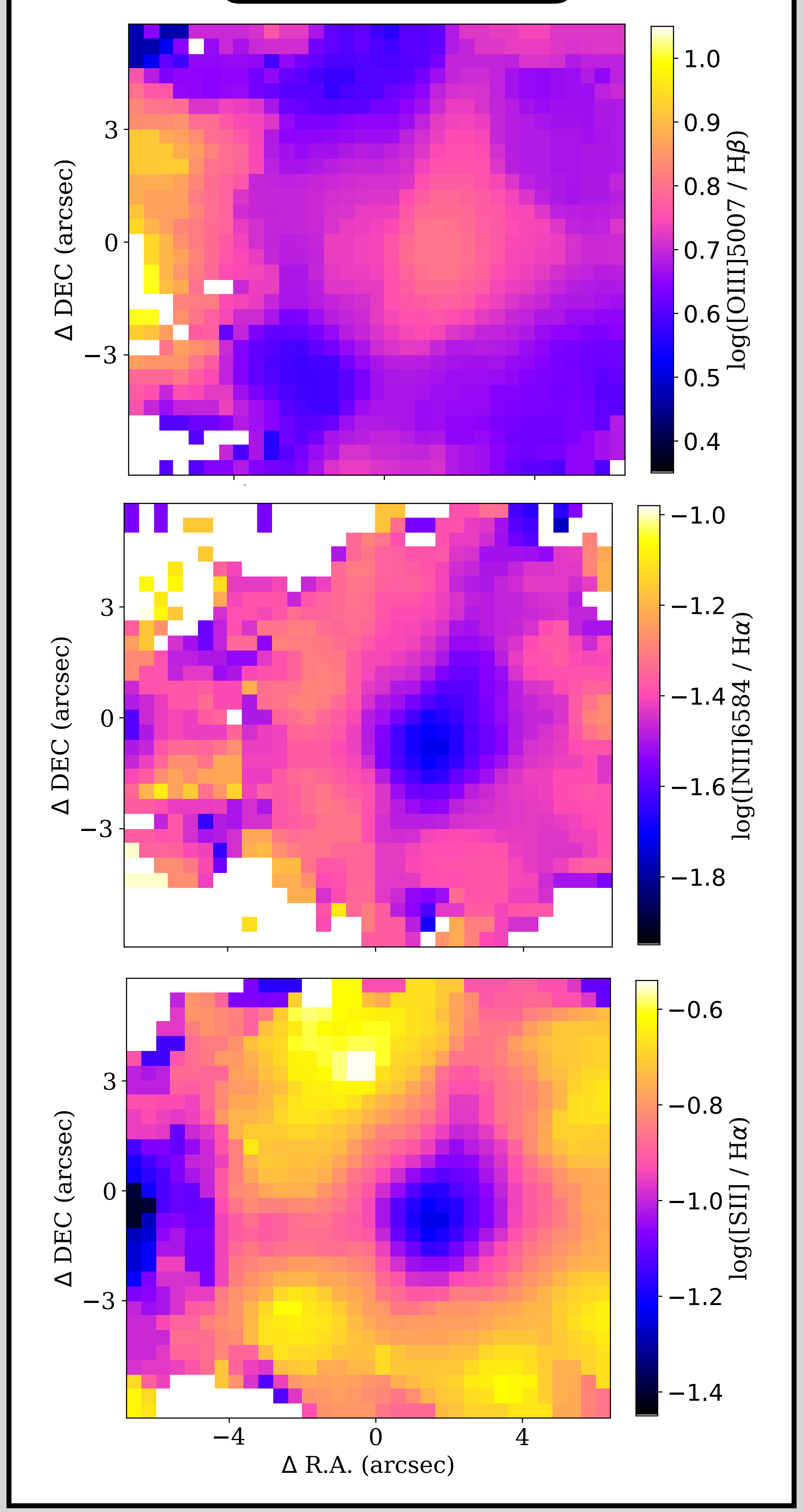

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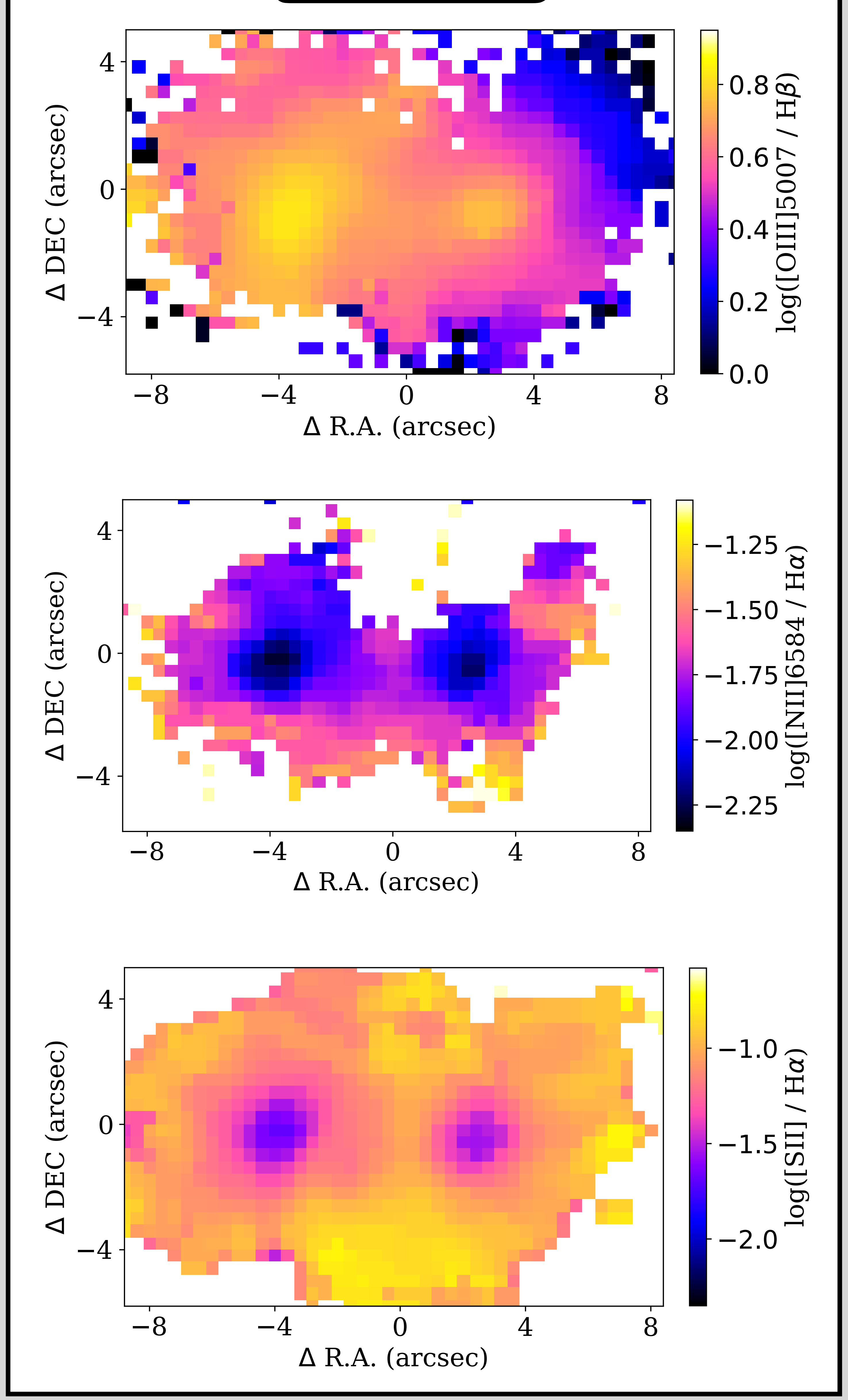
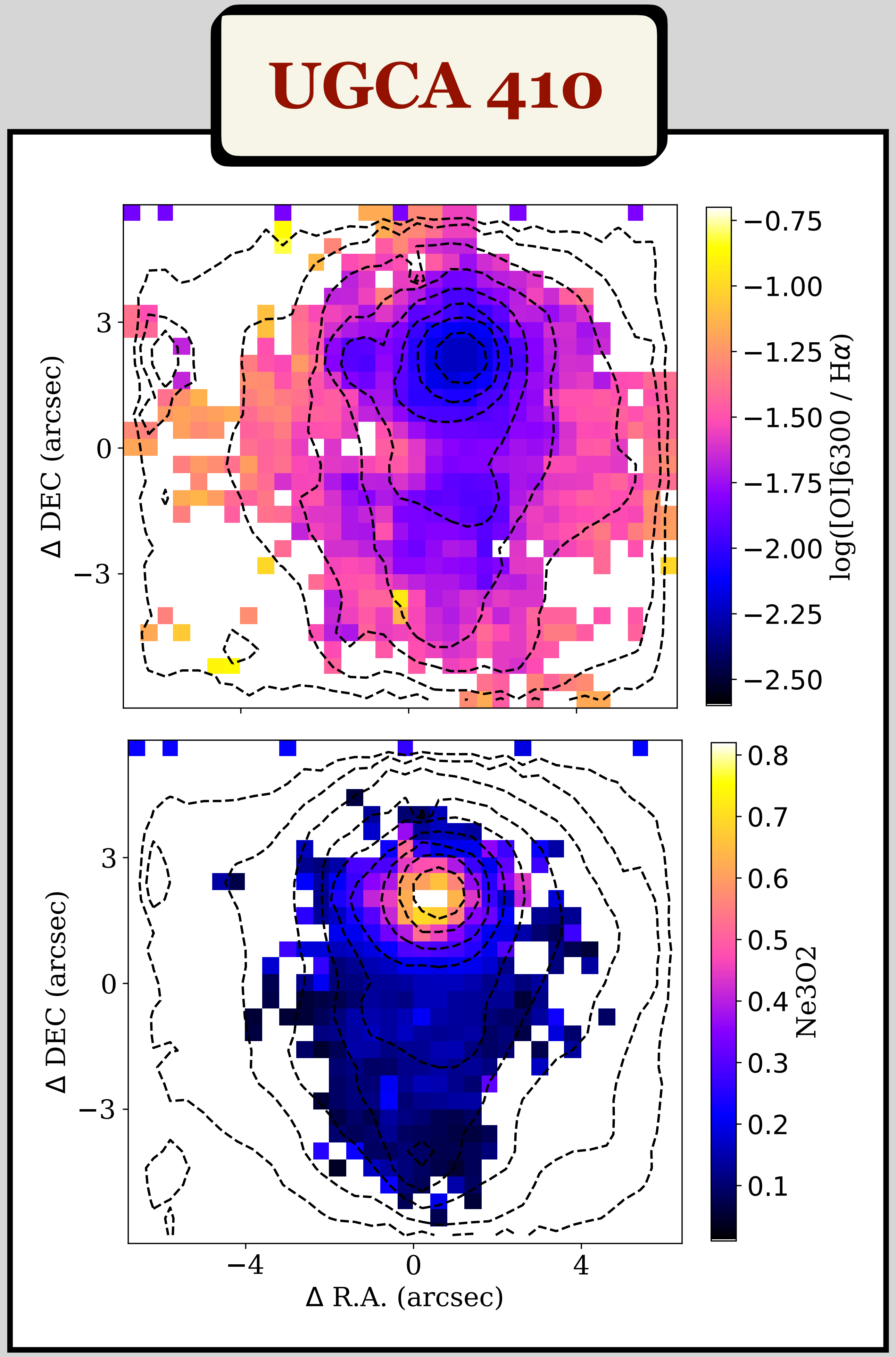
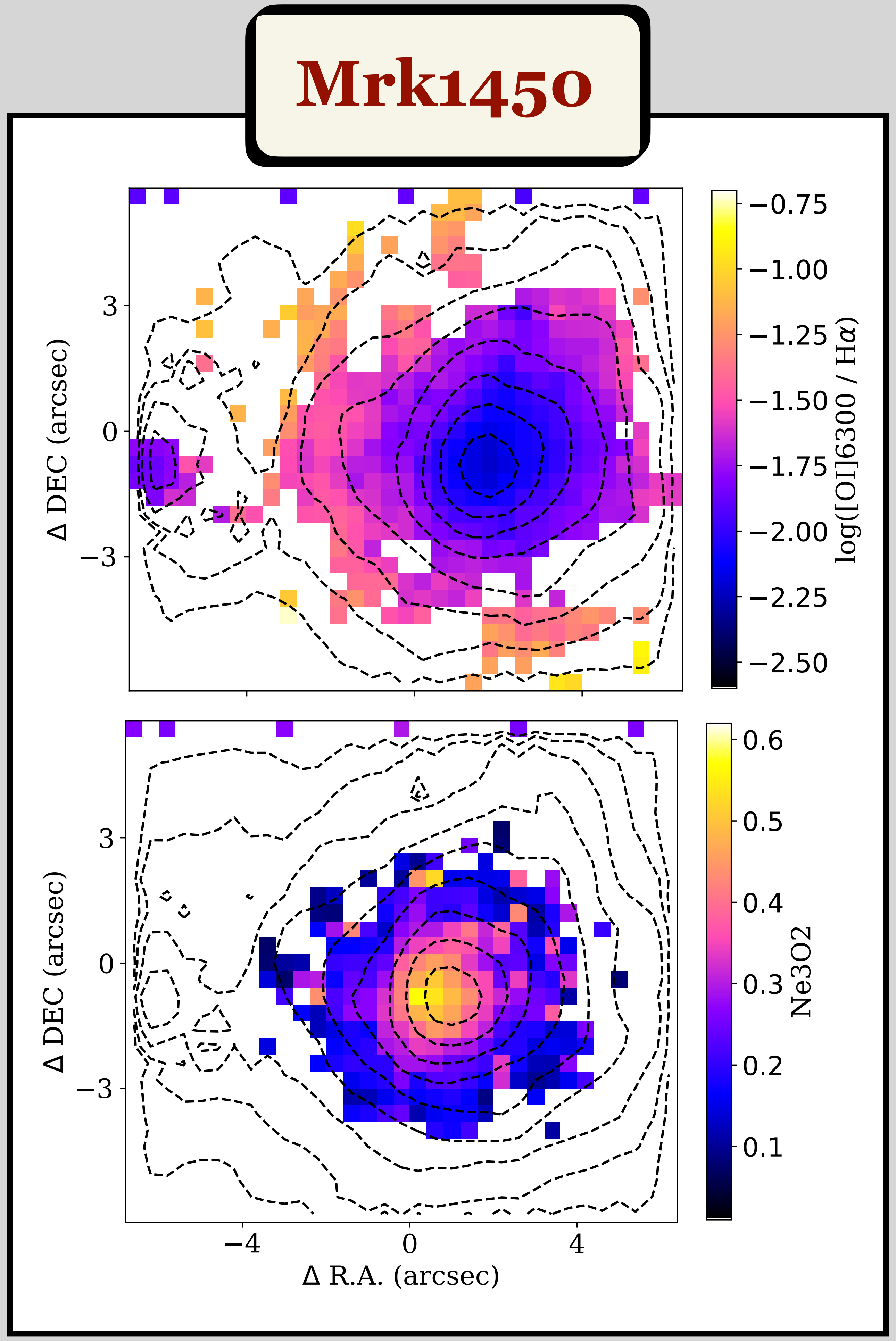
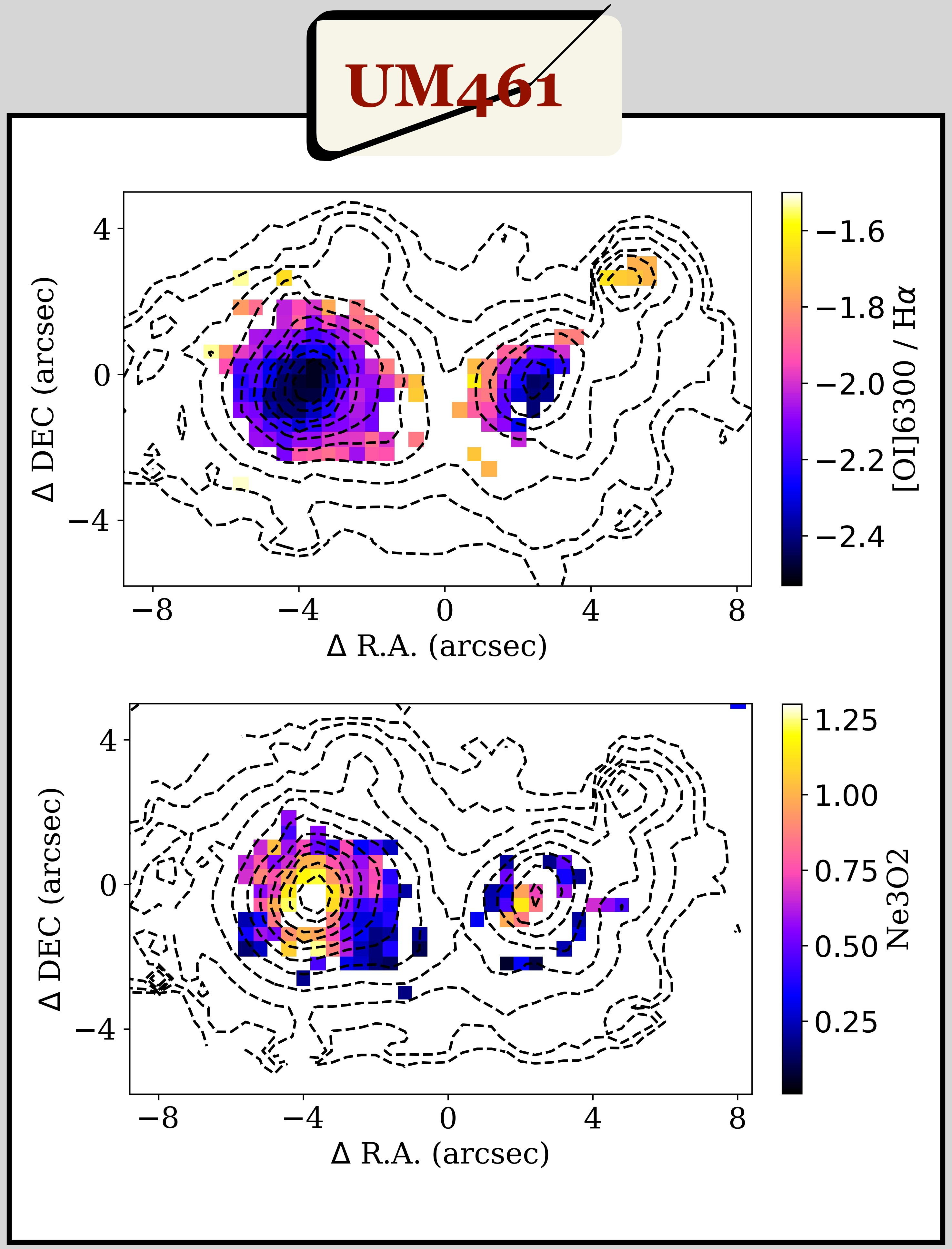


$$\frac{[OI]\lambda 6300}{H\alpha}$$

$$\frac{[NeIII]\lambda 3869}{[OII]}$$



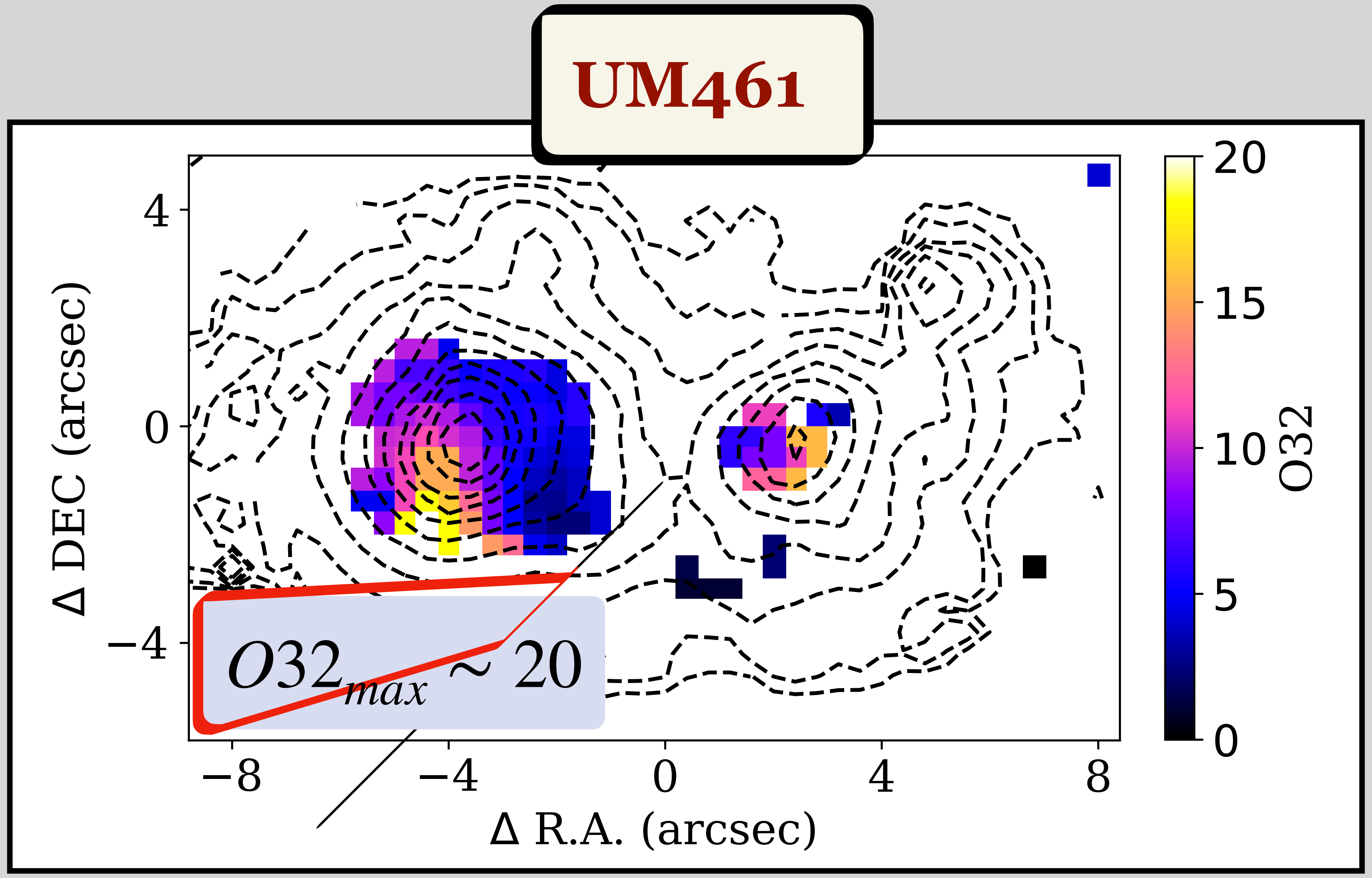


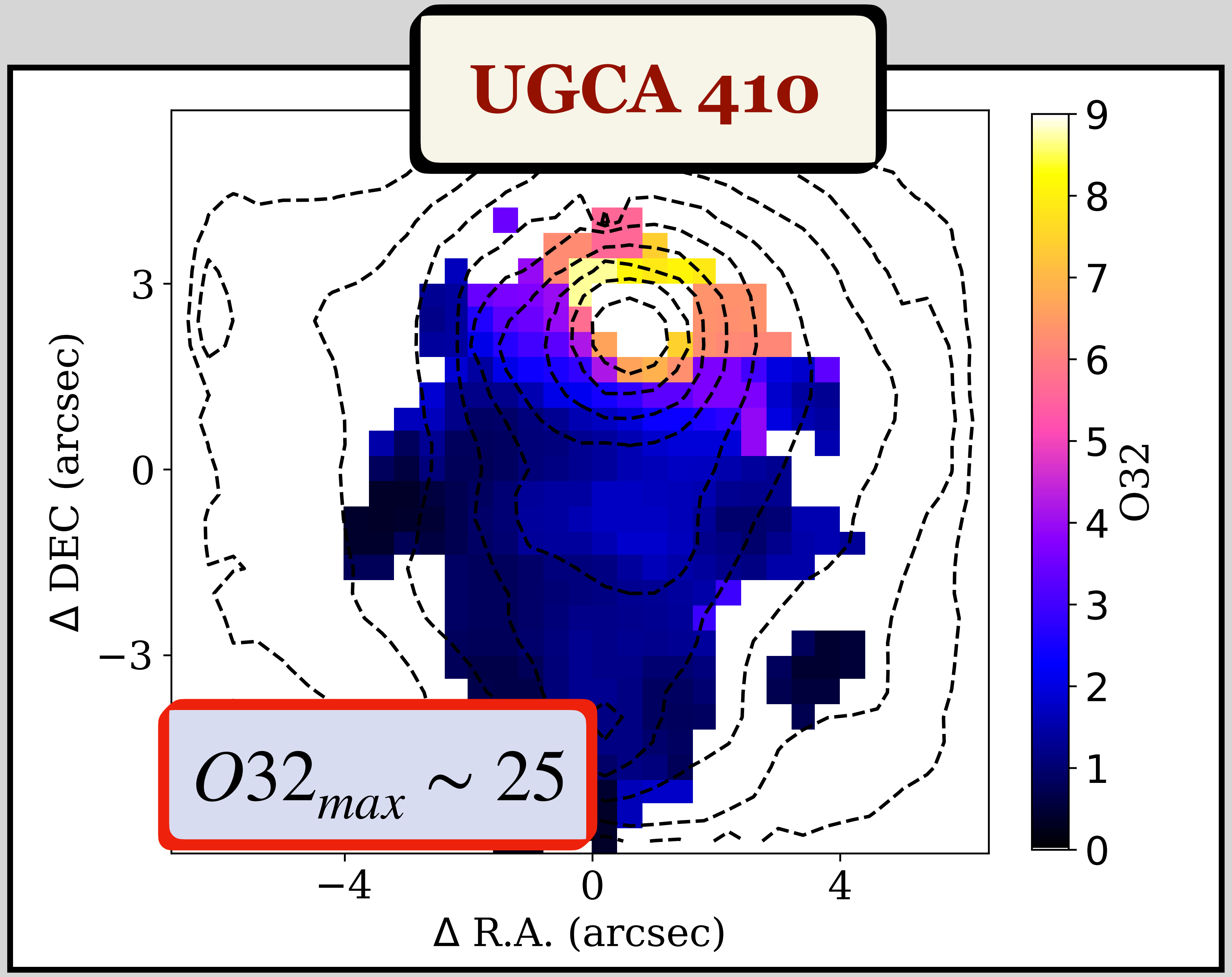


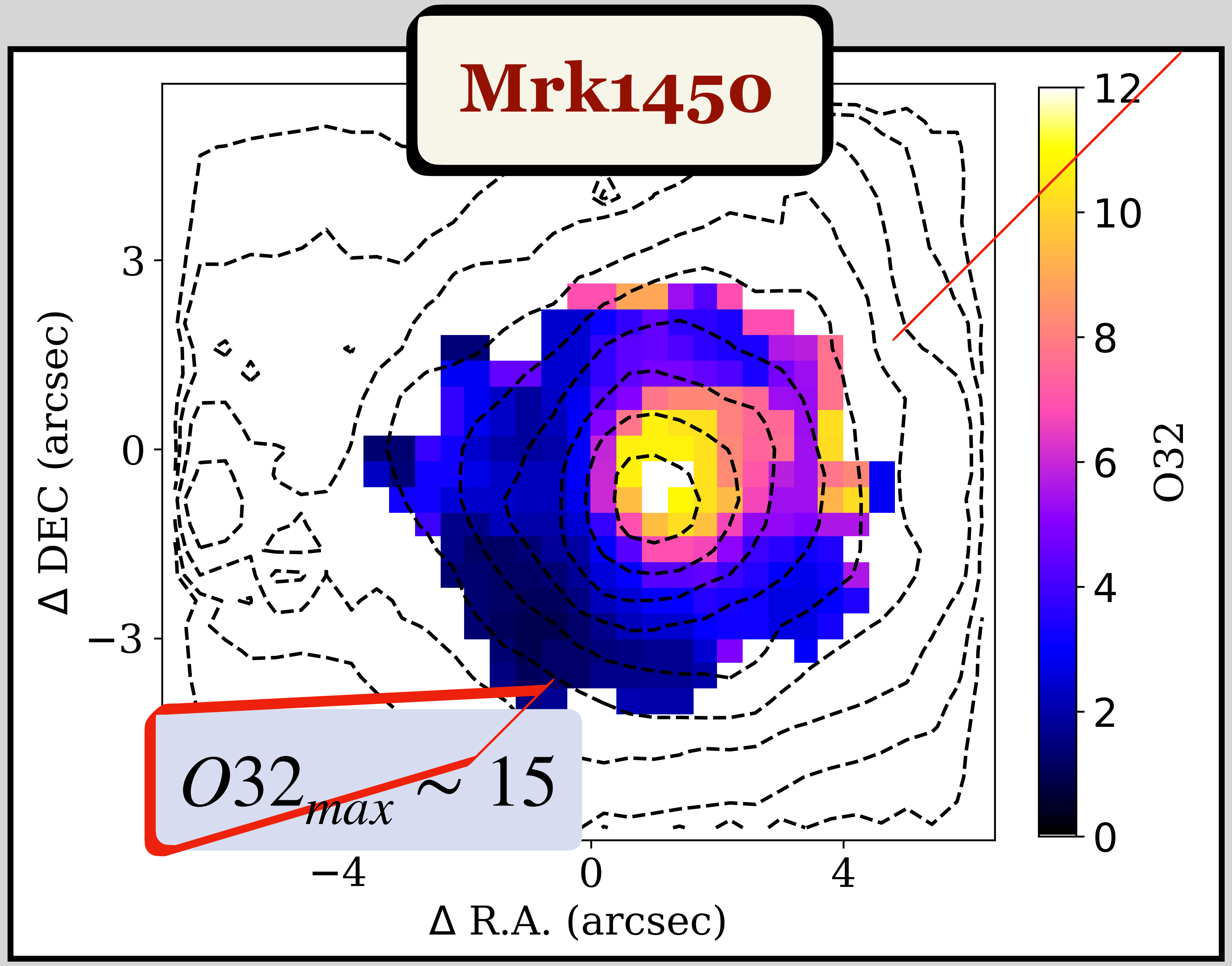
ISM conditions

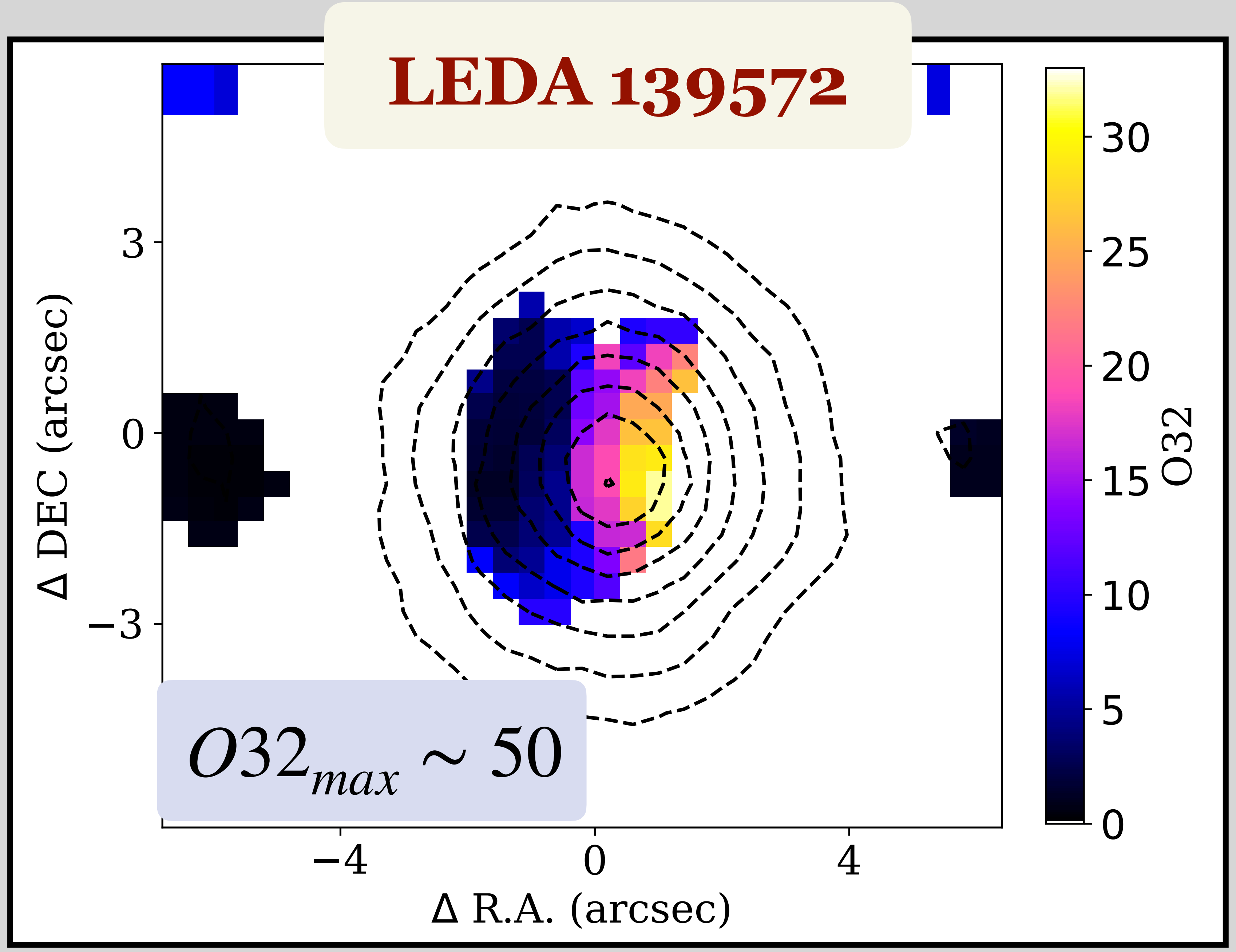
Emission-line ratios (pixel-by-pixel analysis)

$$O32 = \frac{[OIII]\lambda5007}{[OII]\lambda\lambda3726{,}3729}$$









ISM conditions

Emission-line ratios (pixel-by-pixel analysis)

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

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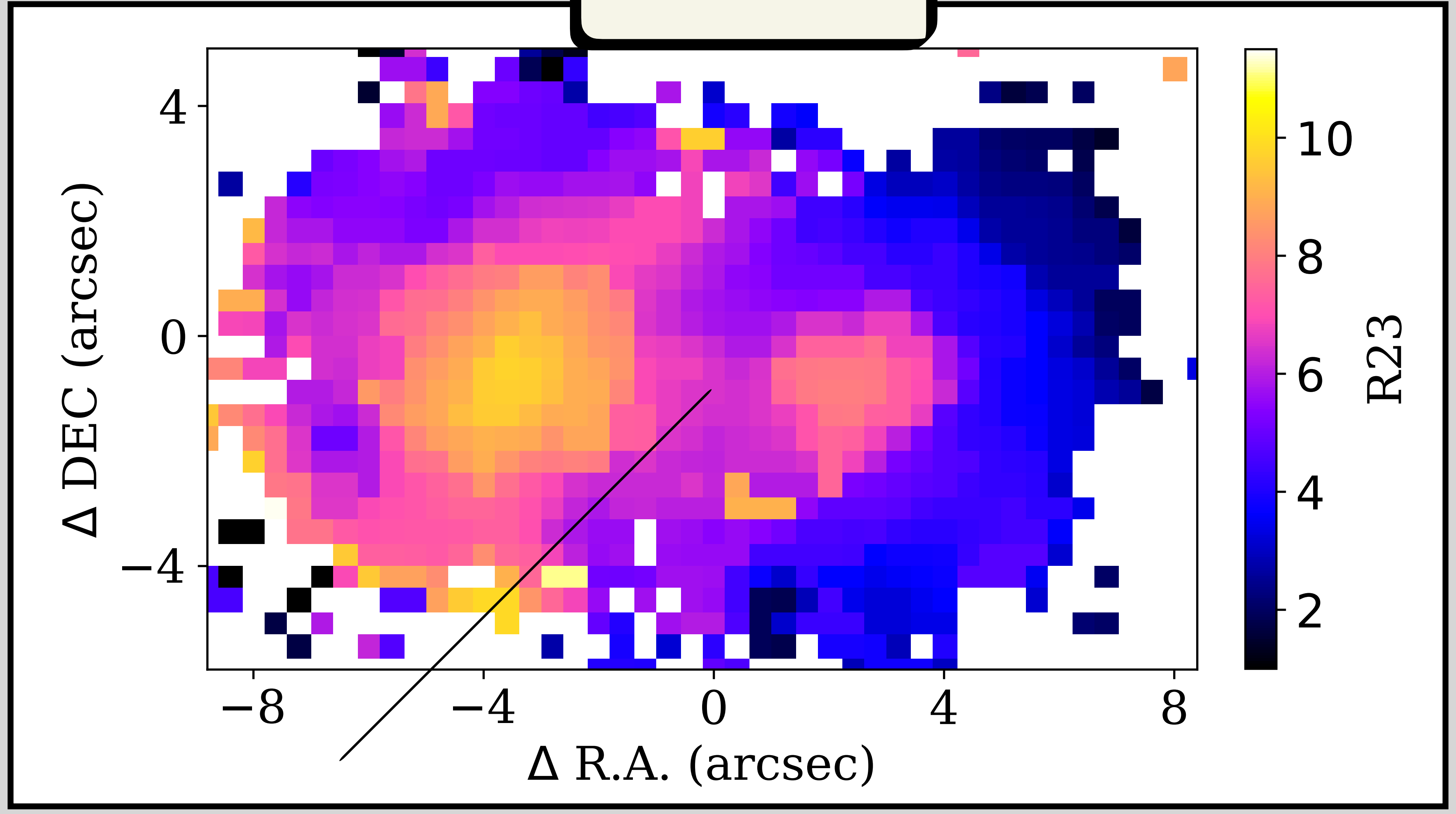
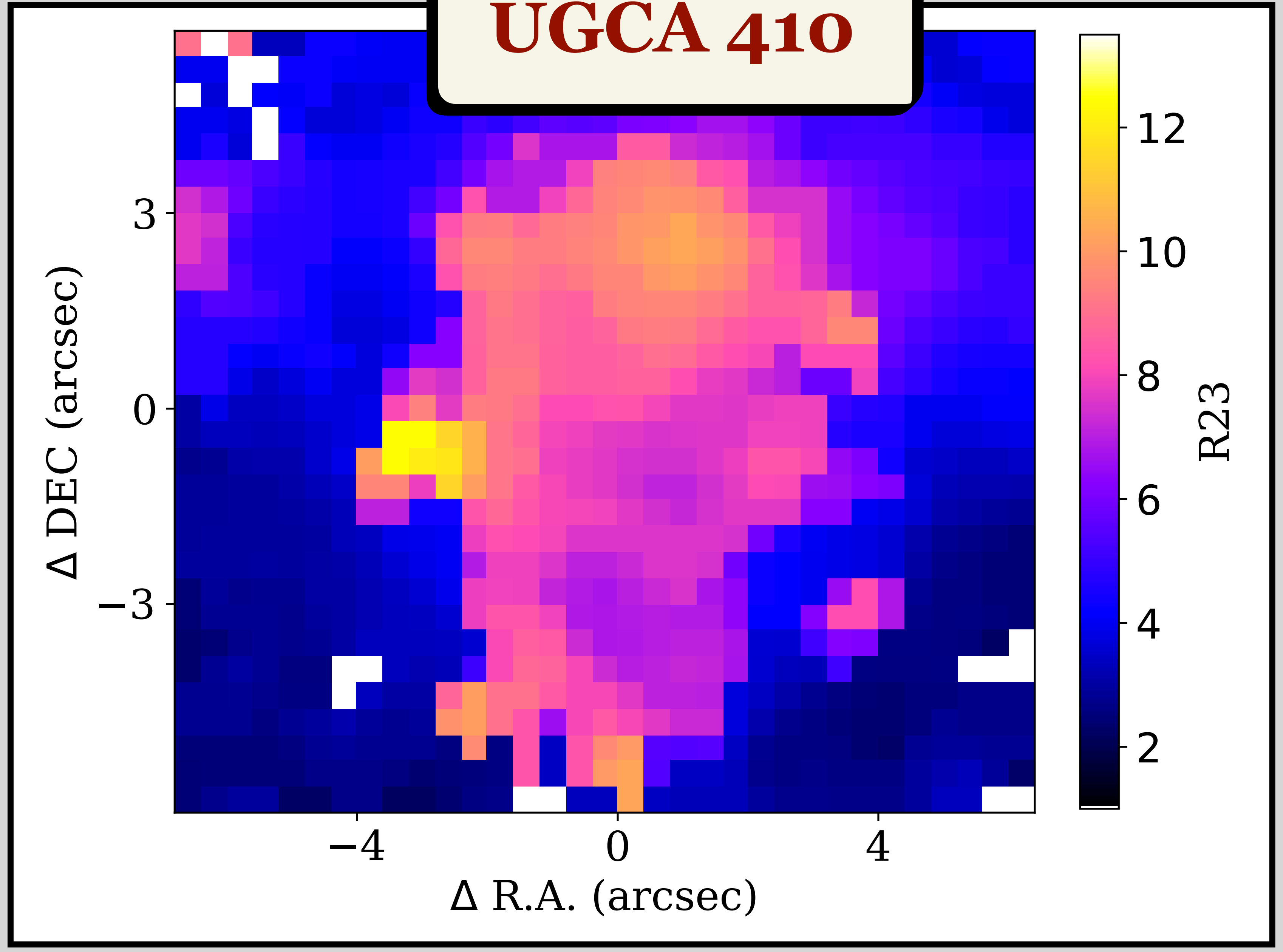


UGCA 410



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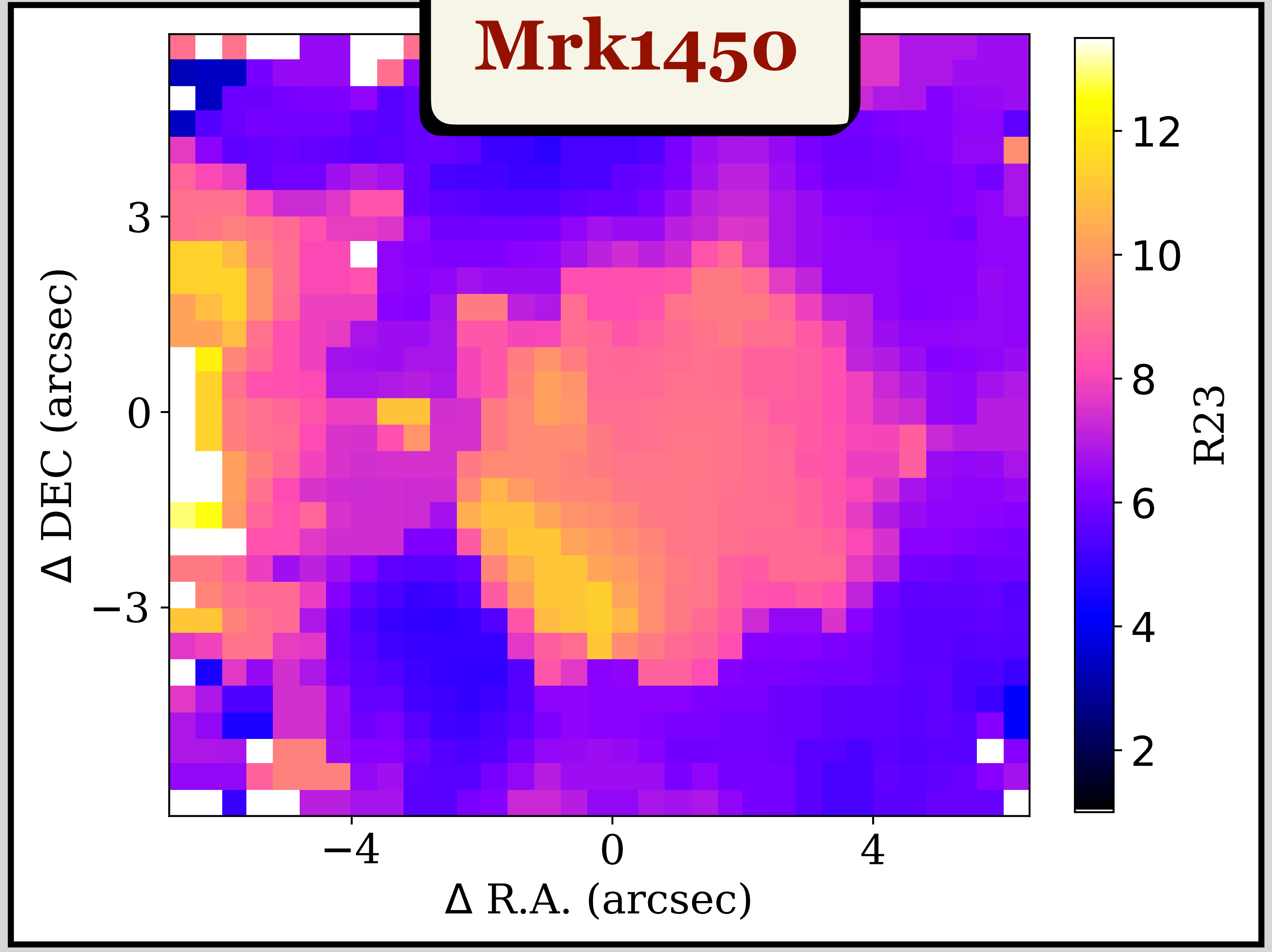

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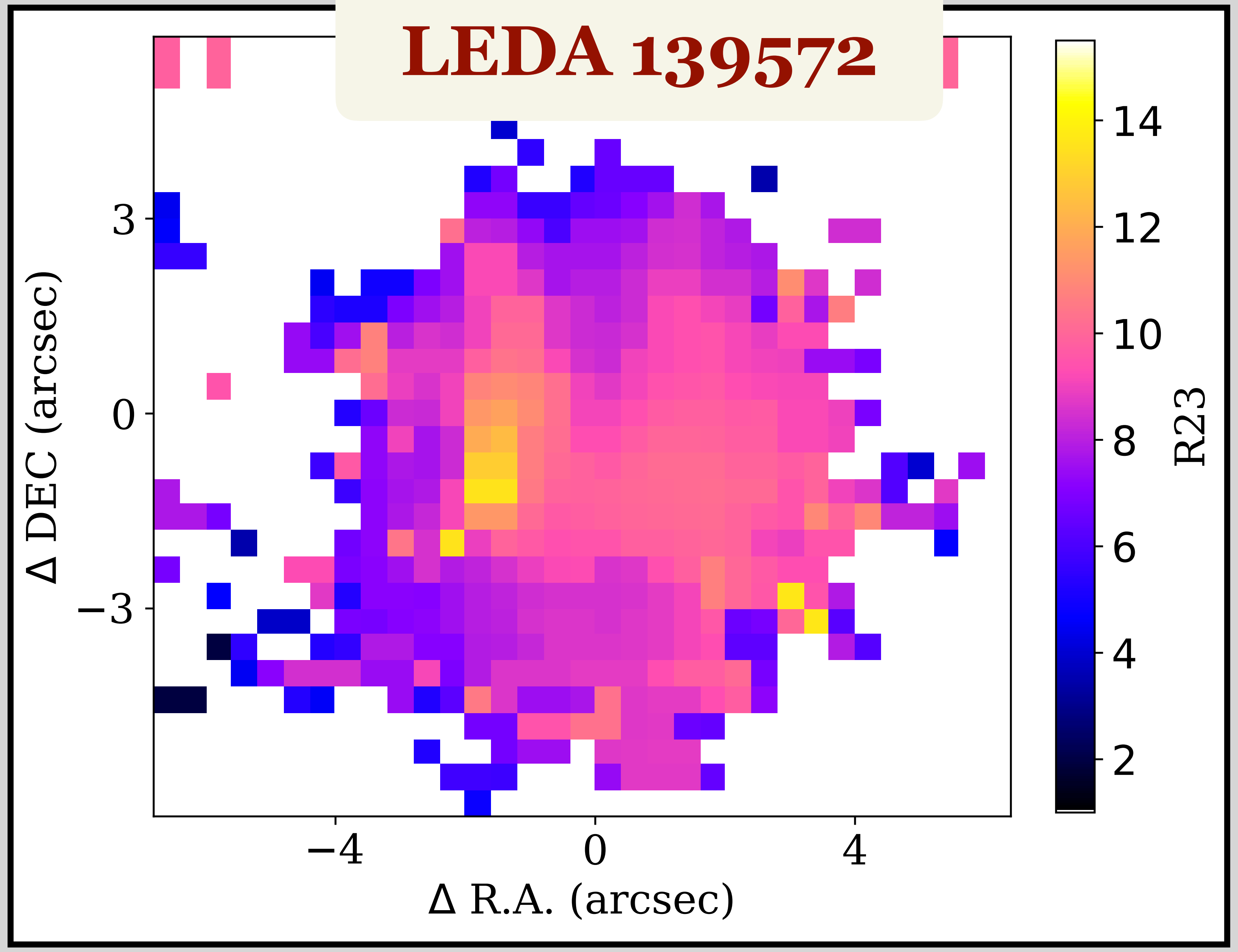


ISM conditions

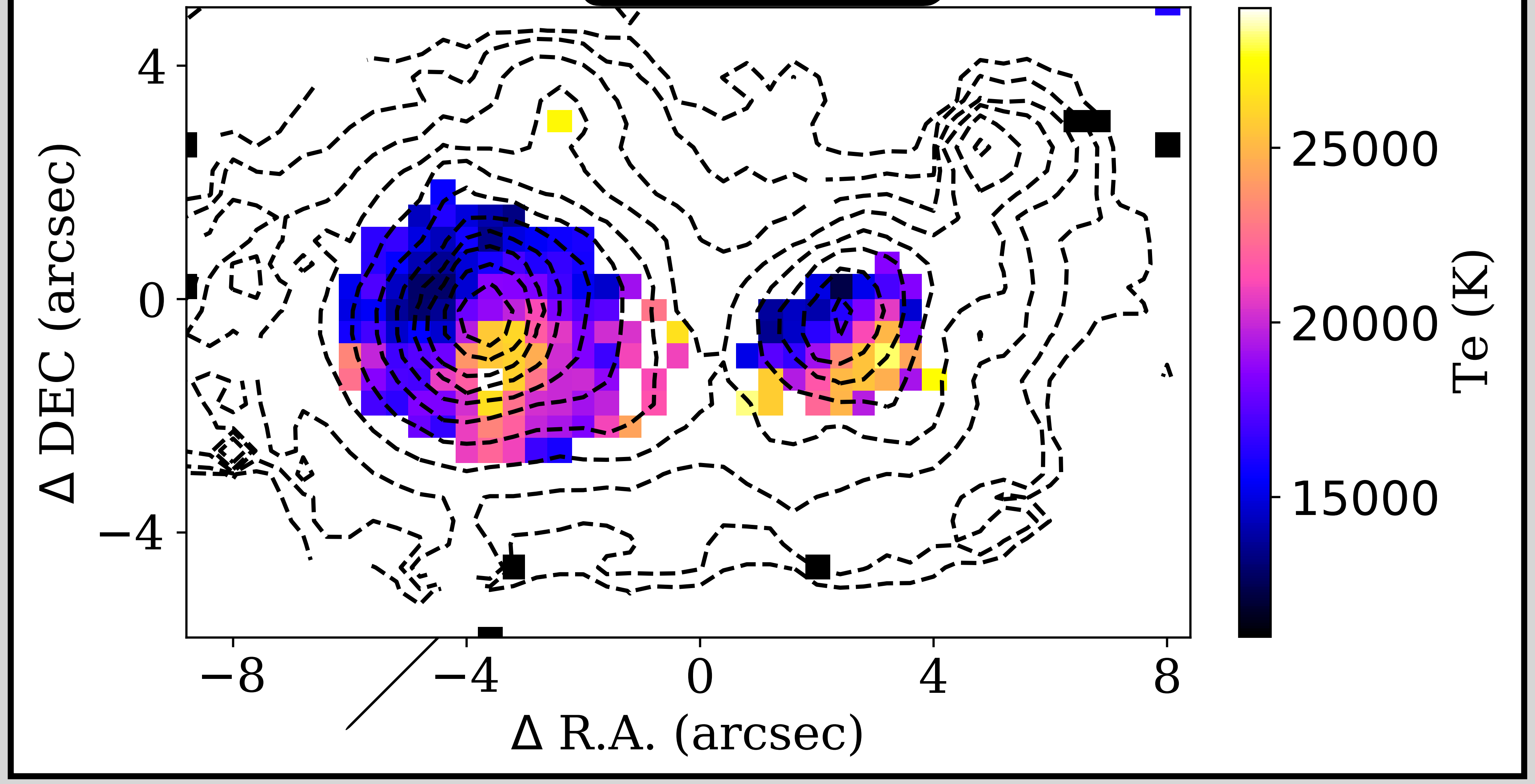
Electron temperature (Te)

PyNeb (Luridiana+15)

T_e was estimated using the measured $\frac{[OIII]4363}{[OIII]4959 + 5007}$ ratio

$$T_e \sim 12\,000 - 20\,000 K$$

UM461



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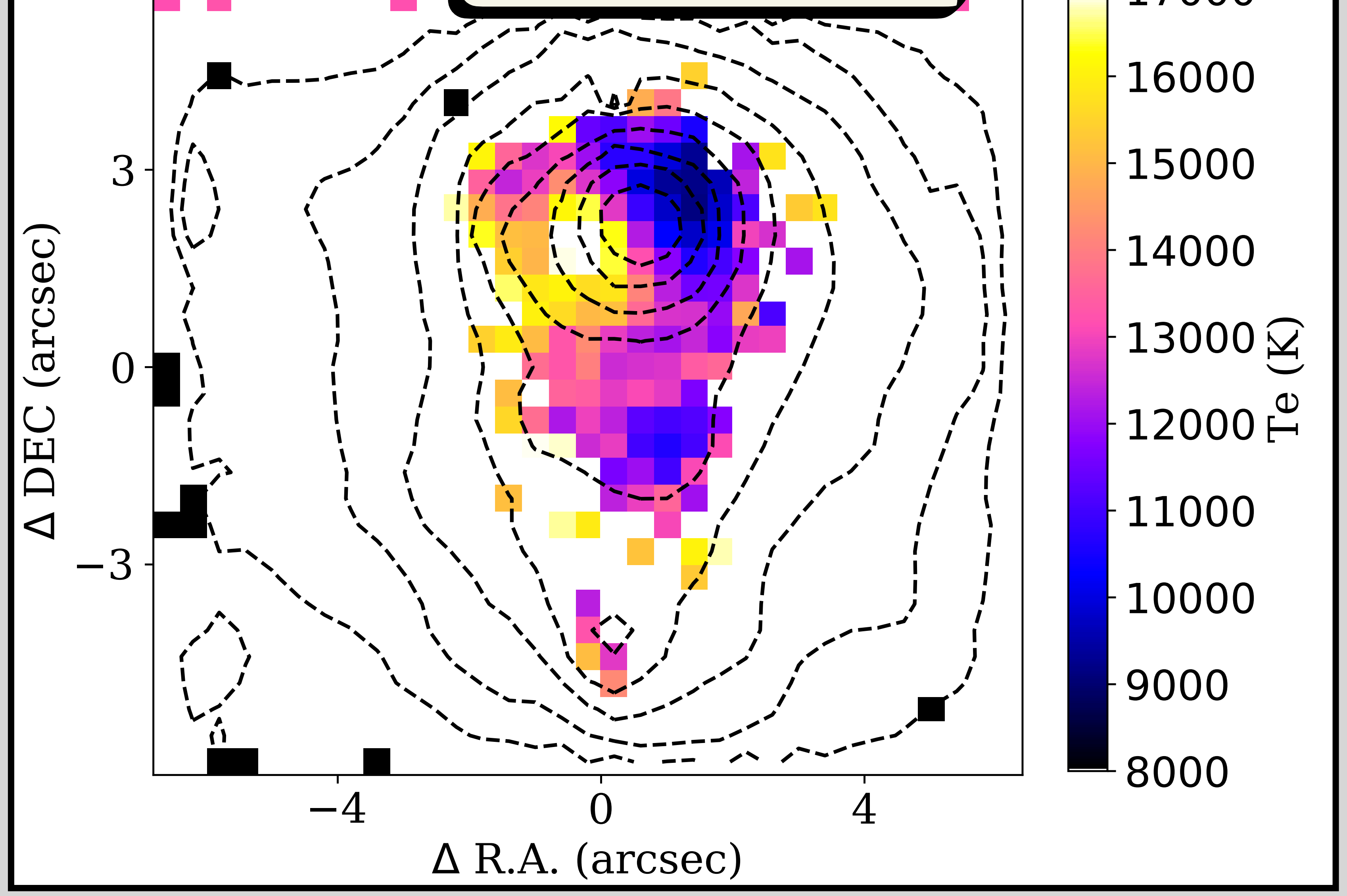

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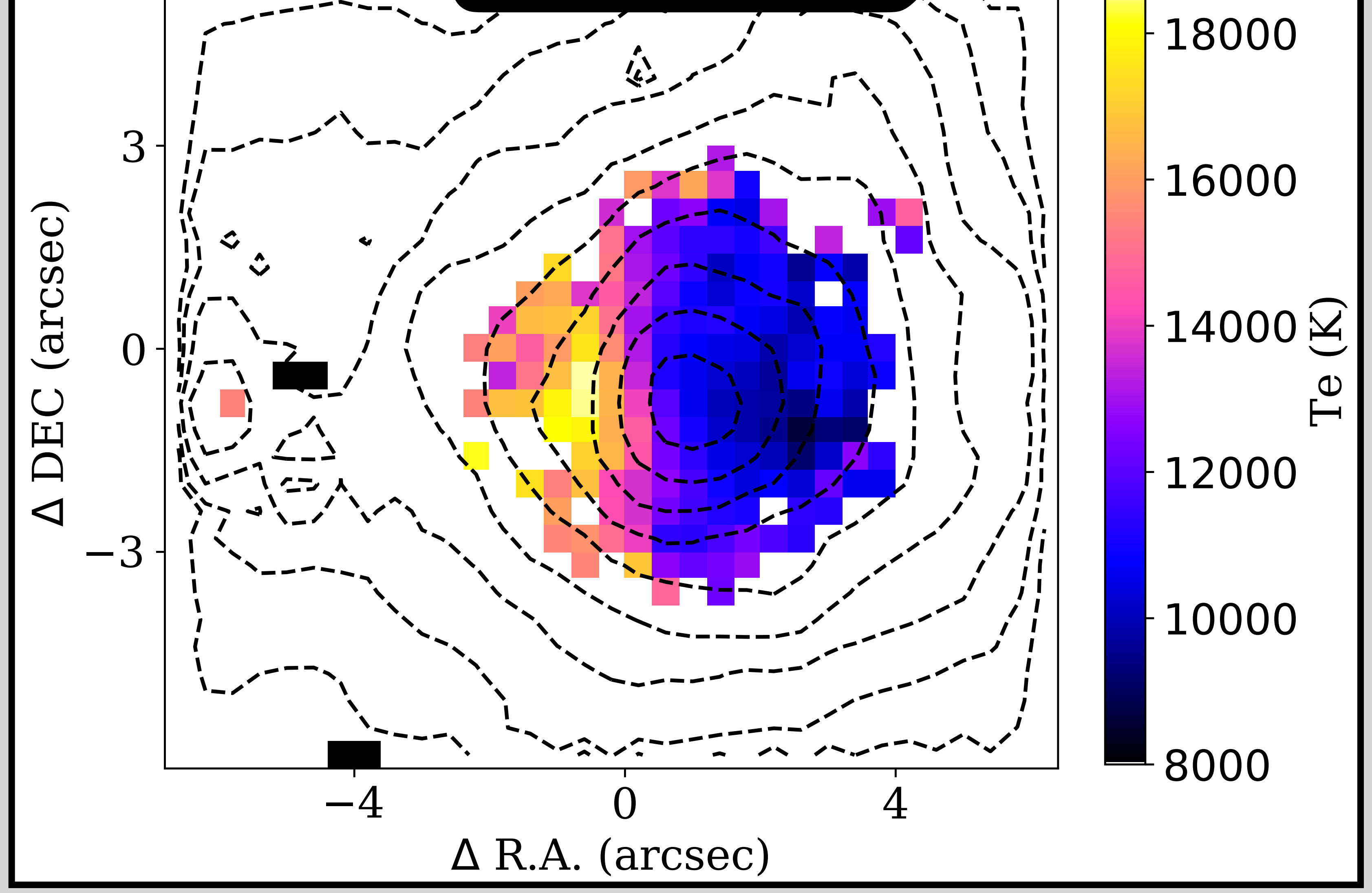

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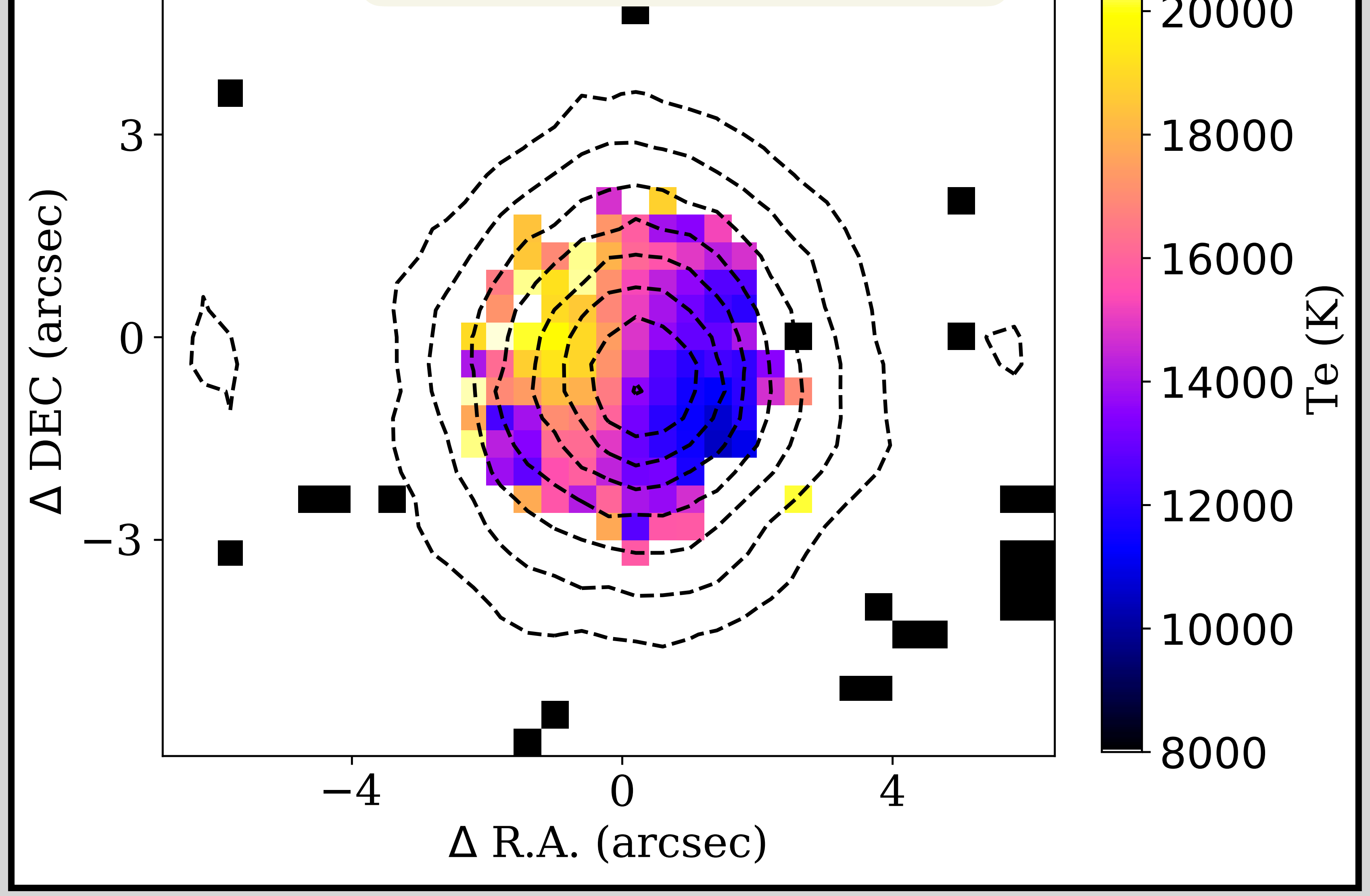
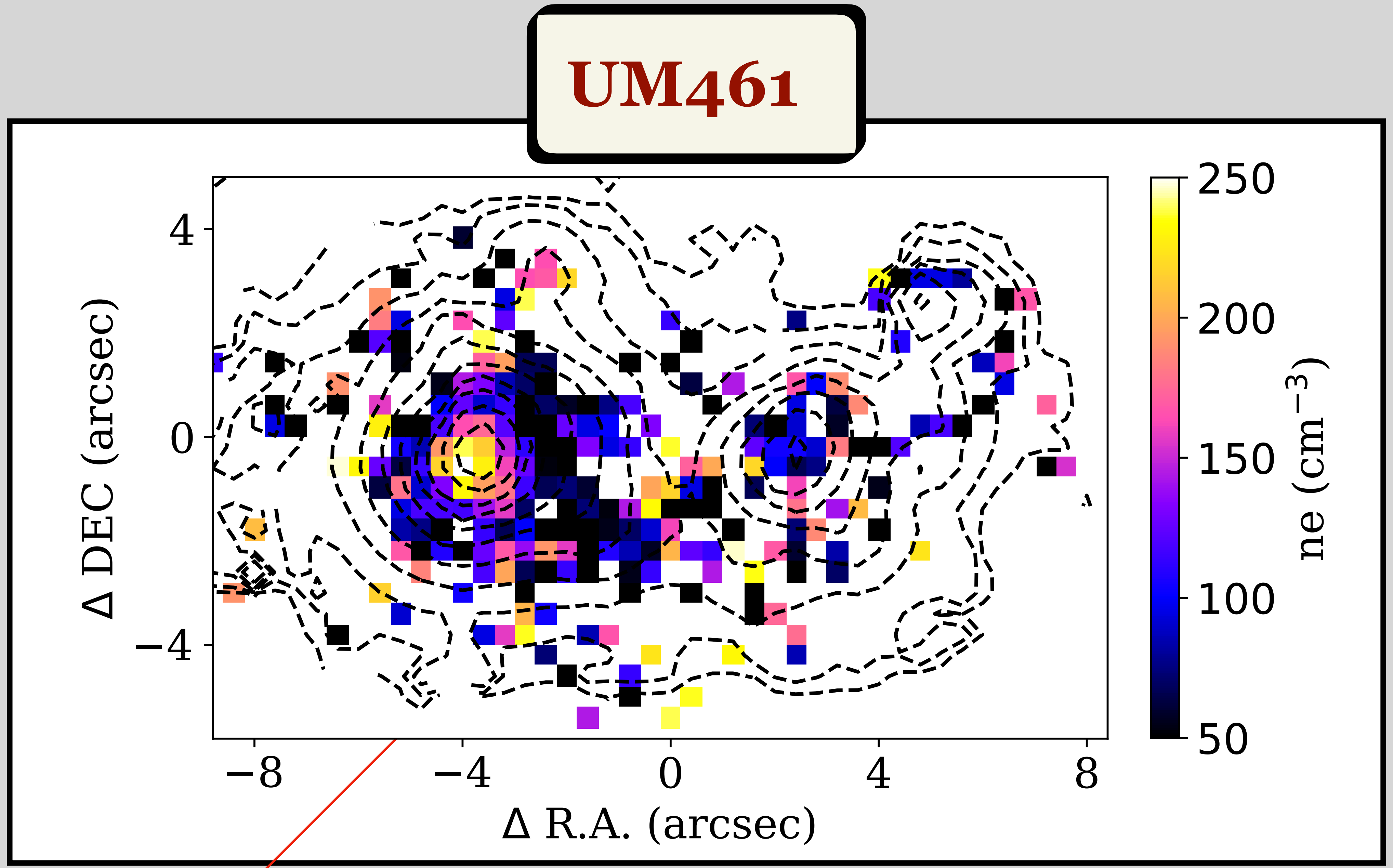


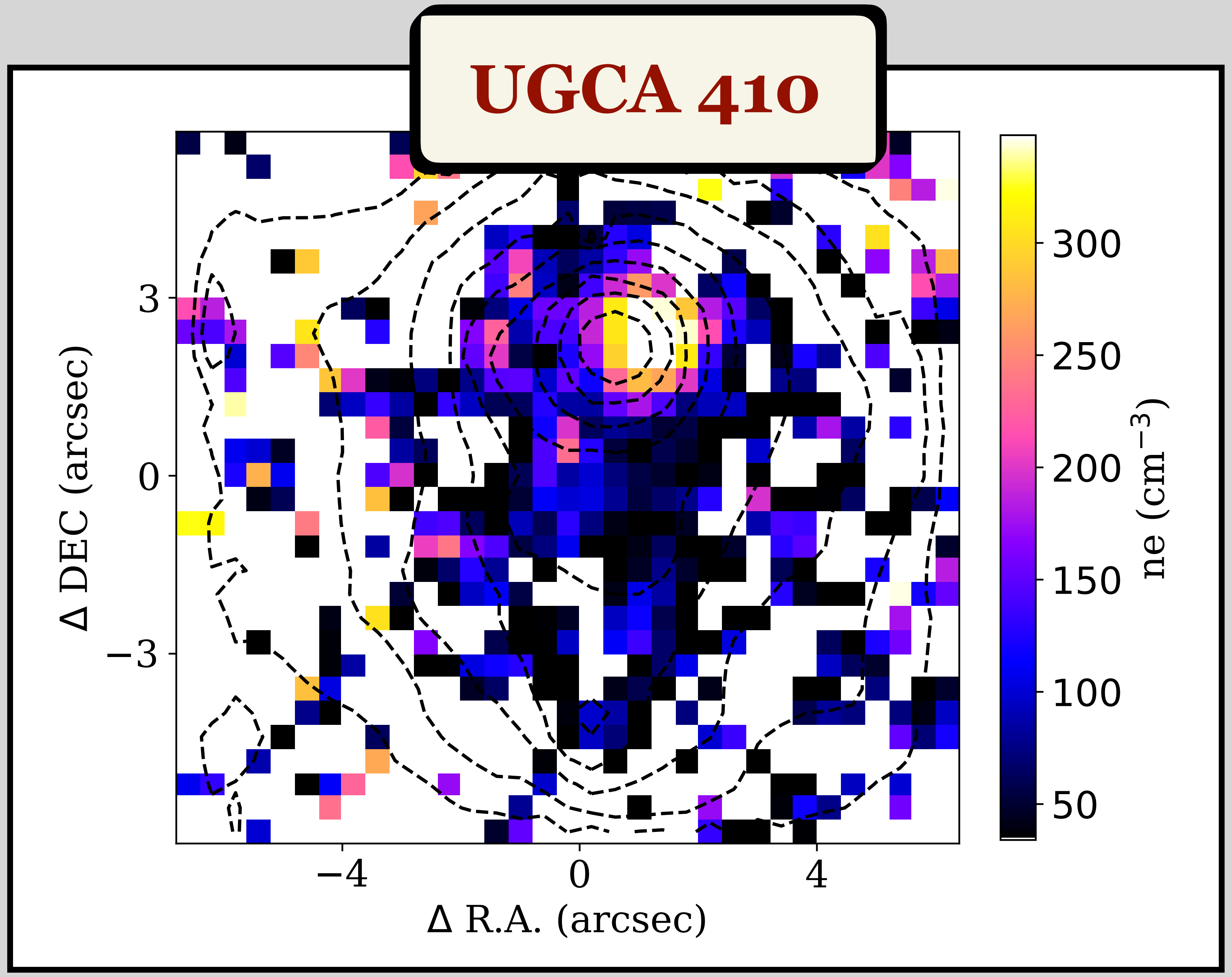
ISM conditions

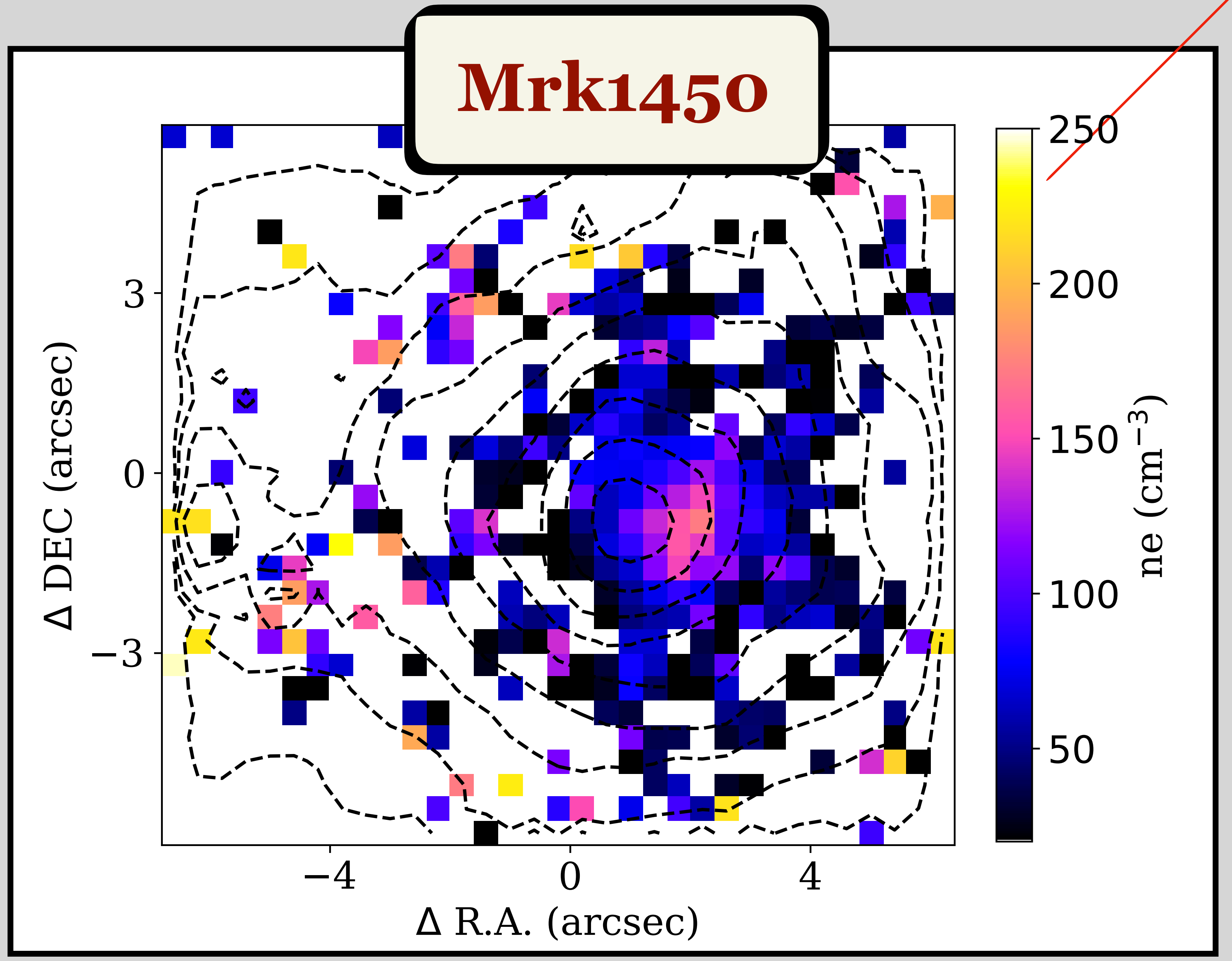
Electron density (n_e)

PyNeb (Luridiana+15)

n_e was computed from the $\frac{[SII]6717}{[SII]6731}$ ratio







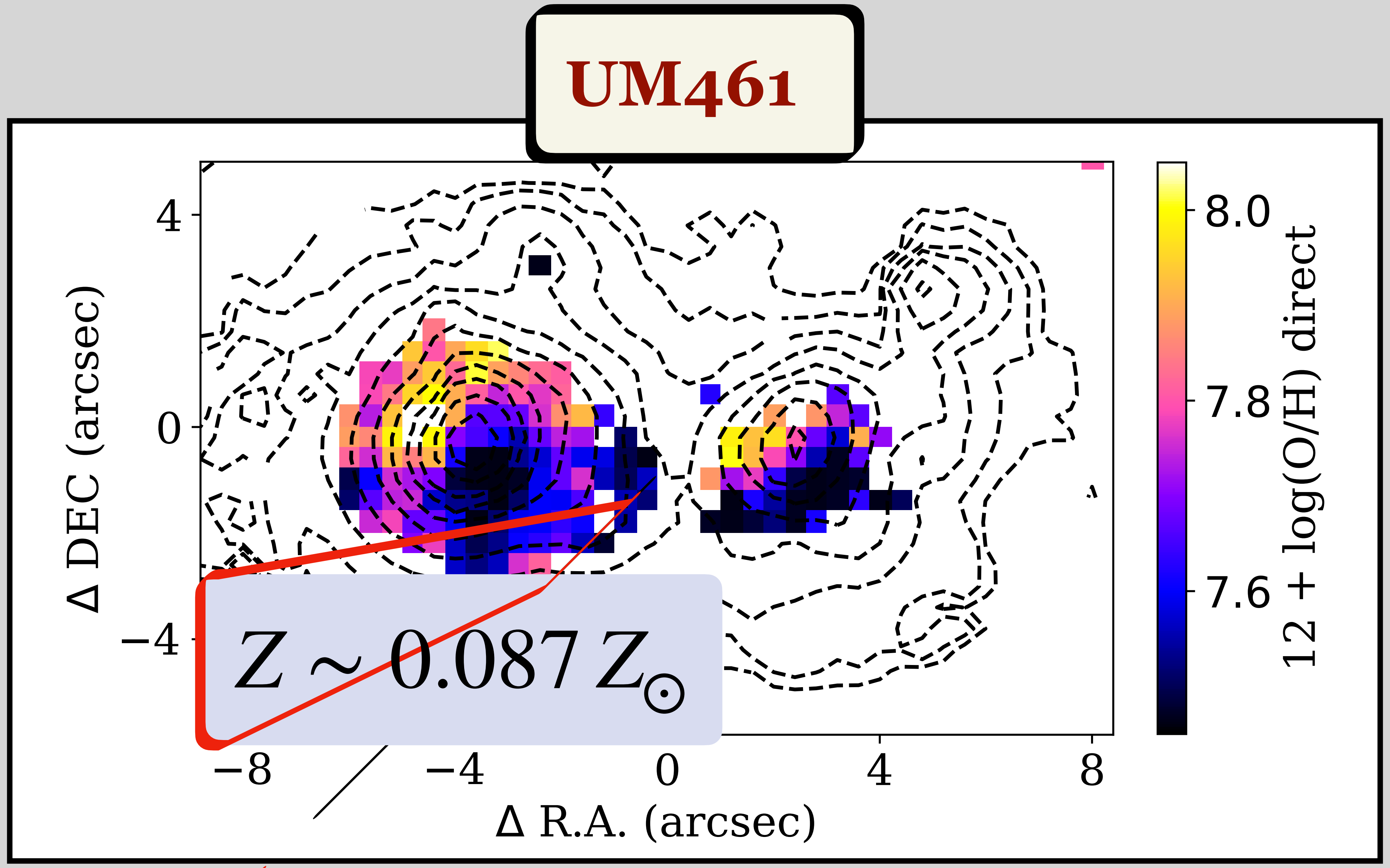
$$n_e \sim 100 - 300\, cm^{-3}$$

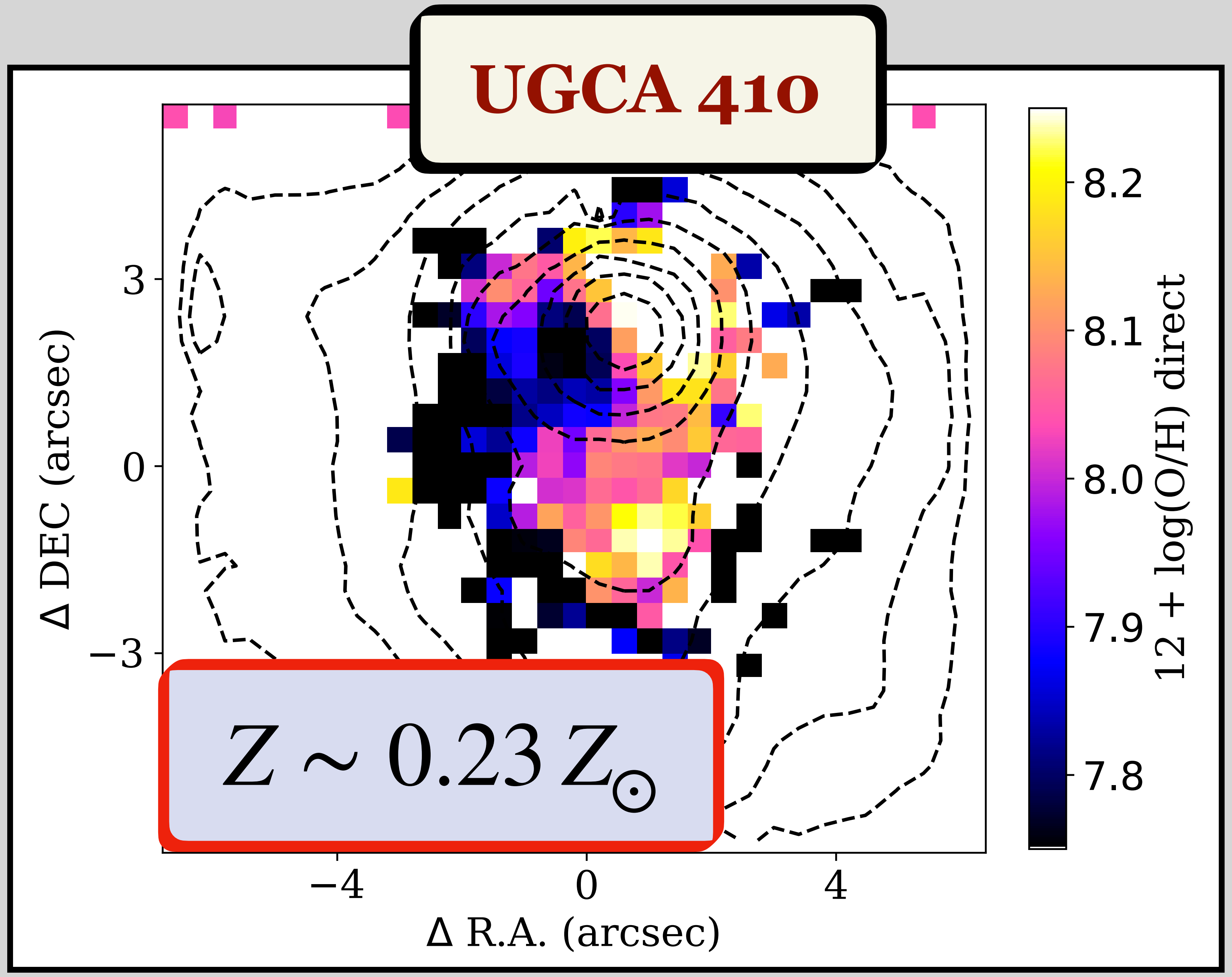
ISM conditions

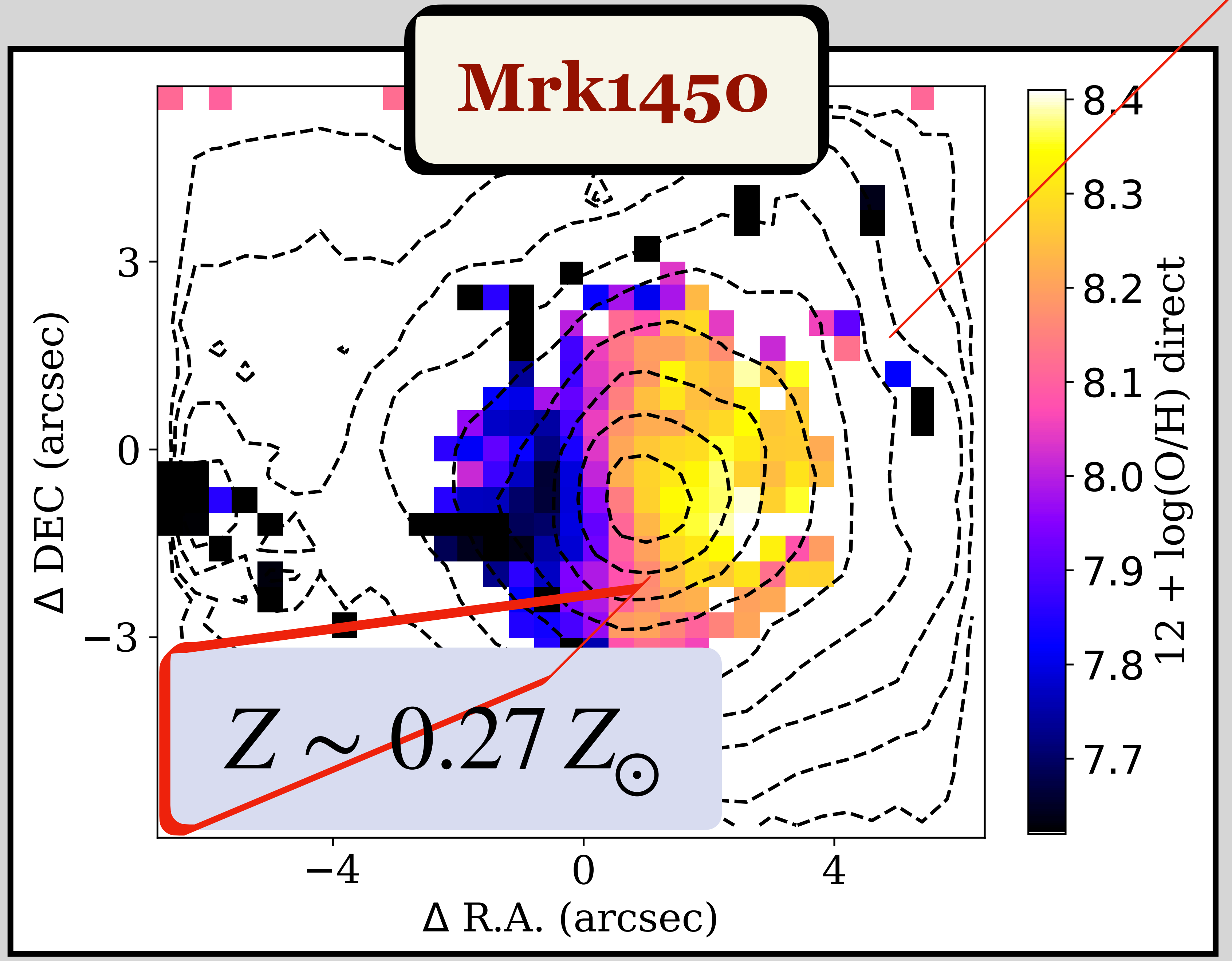
Metallicity (Te direct method)

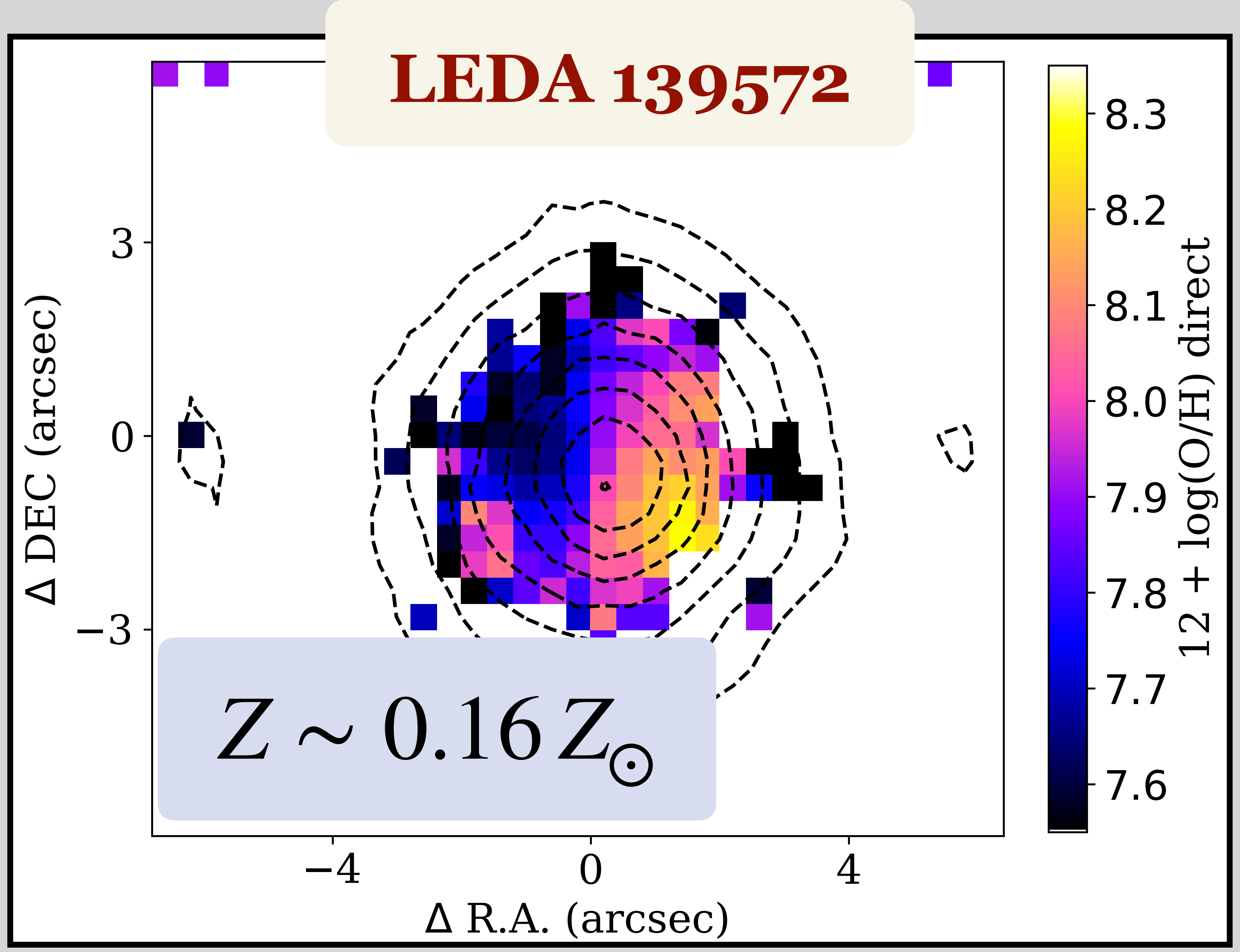
The gas phase oxygen abundance was estimated from Te following the relations derived from Pérez-Montero+21, Amorín+15

($Z_\odot = 8.69$, Asplund et al. 2021)





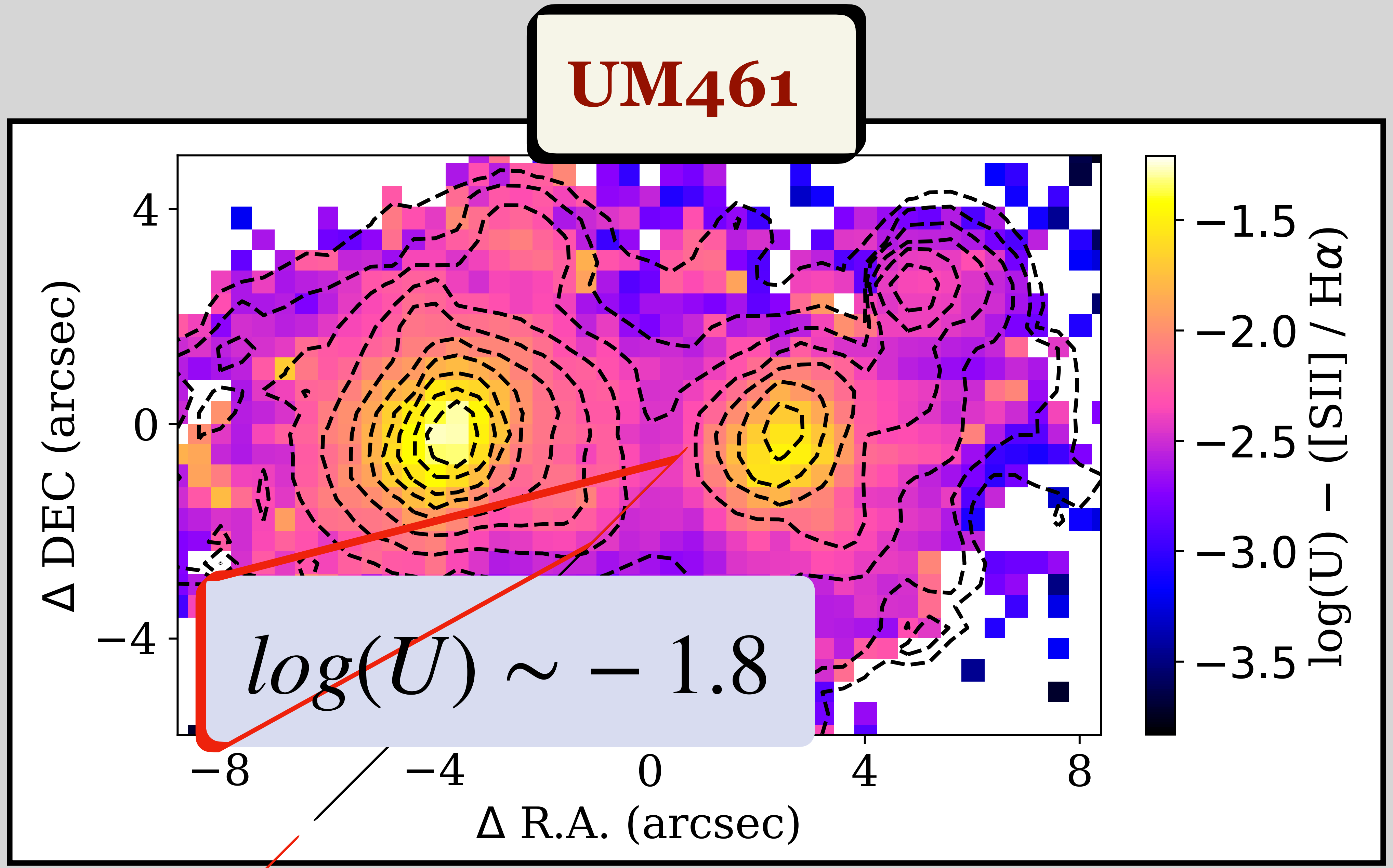


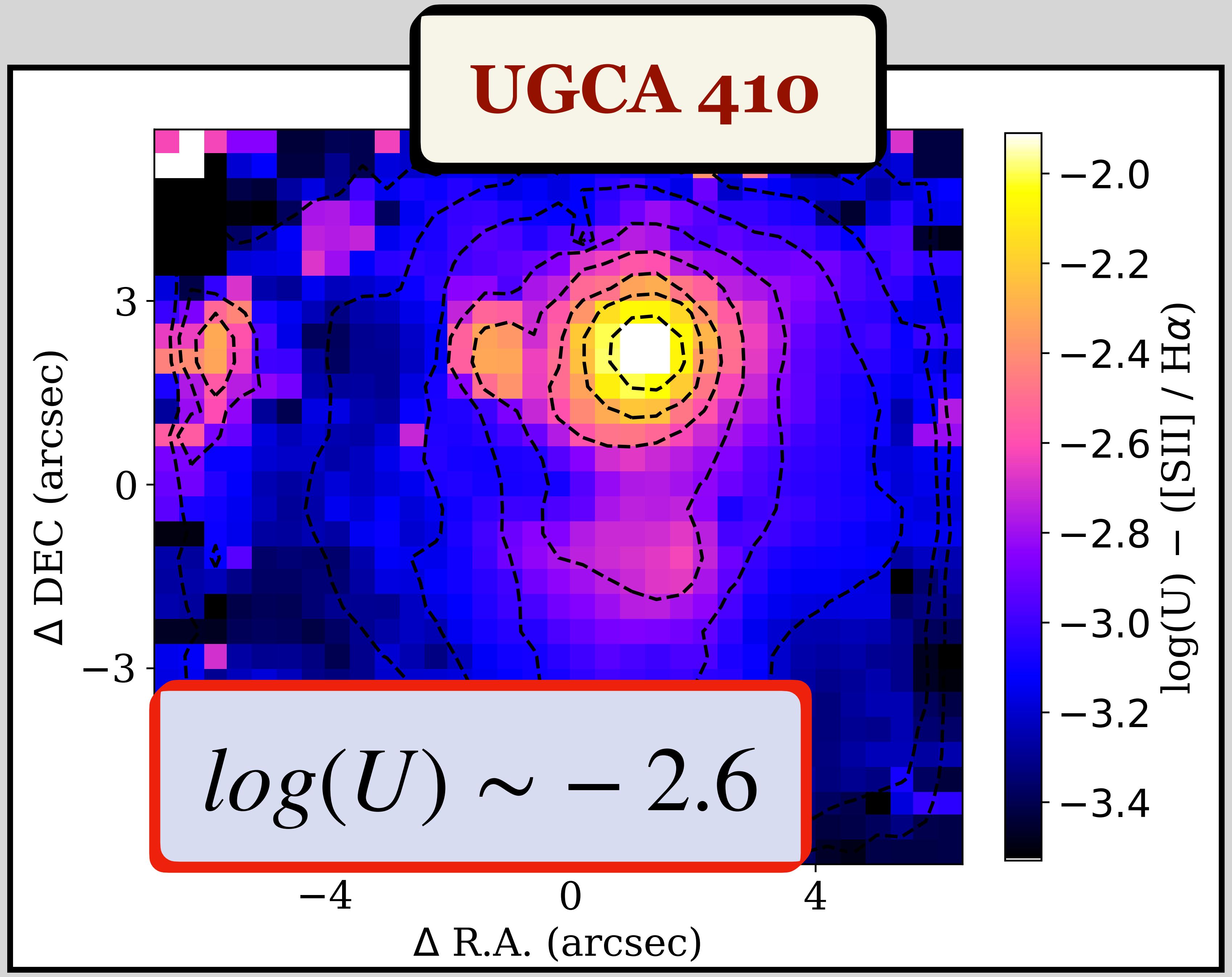


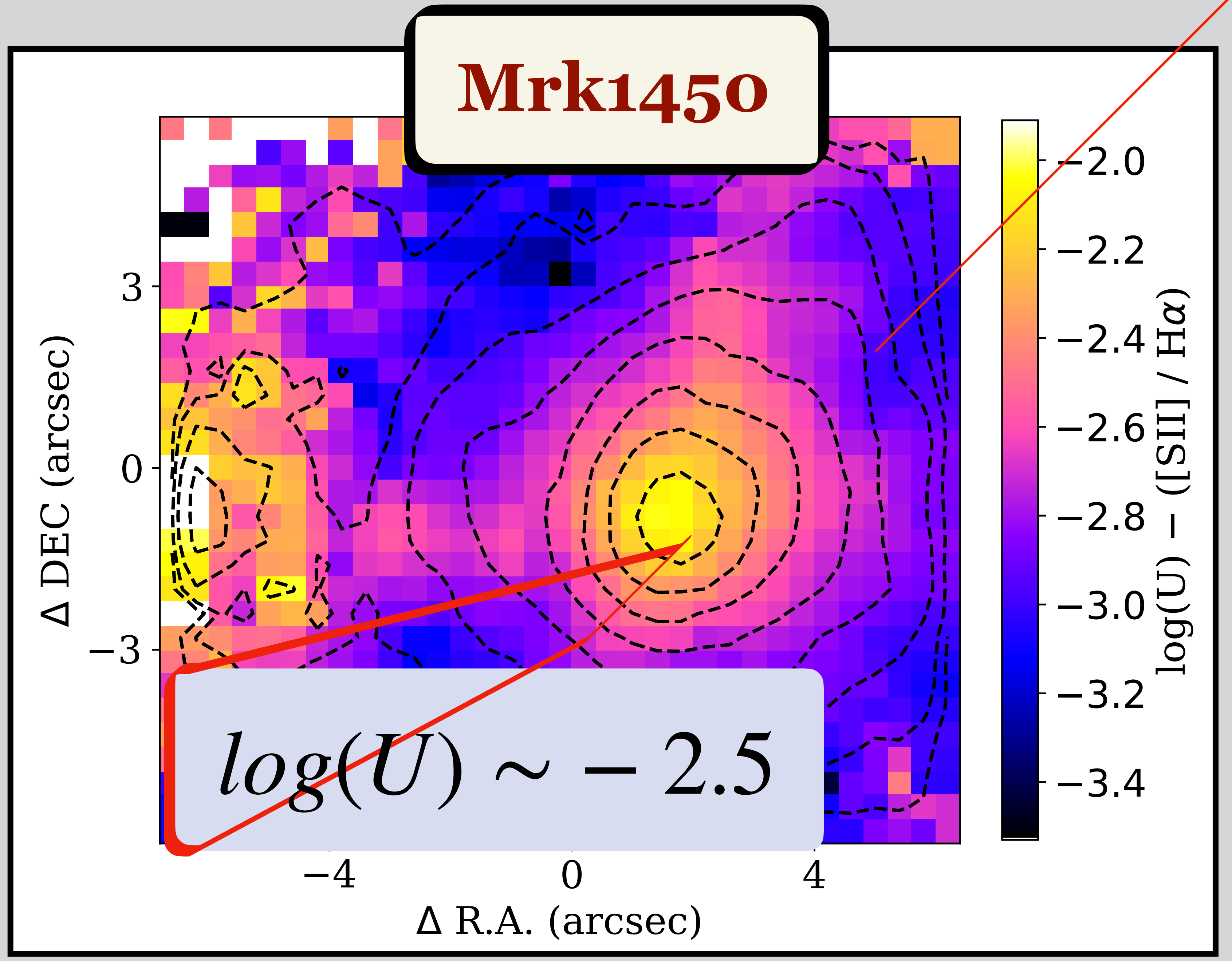
ISM conditions

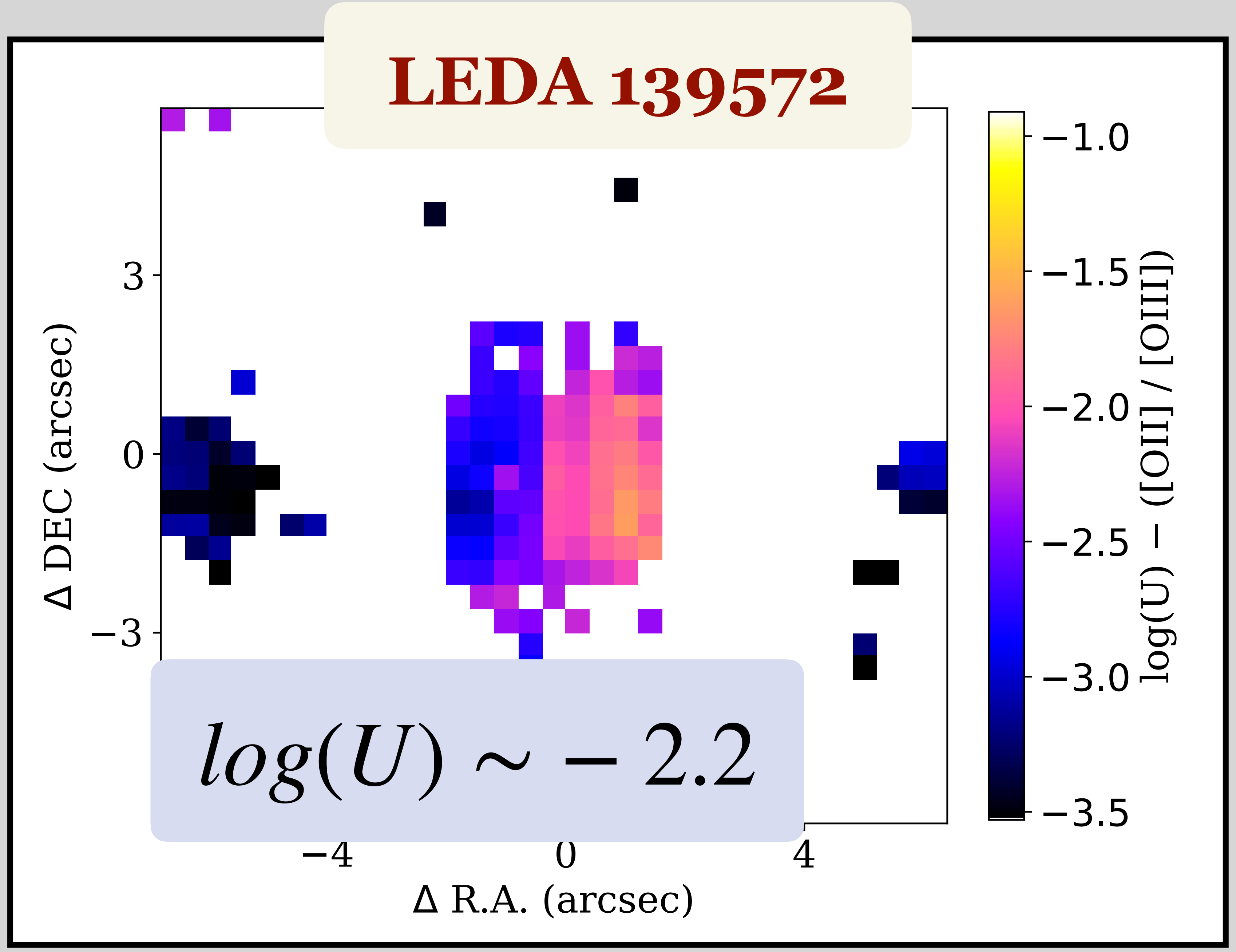
Ionization parameter log(U)

Different estimators of the ionization parameter based on emission-line ratios (Díaz+00, Dors+11)









ISM conditions

HII-CHI-mistry

Pérez-Montero+14, +21

Comparison with photoionization models

UM461

12+log(O/H) = 7.62 ± 0.04
log(N/O) = -1.19 ± 0.17
log(U) = -1.59 ± 0.01

Mrk1450

12+log(O/H) = 8.22 ± 0.08
log(N/O) = -0.92 ± 0.07
log(U) = -2.13 ± 0.05

UGCA 410

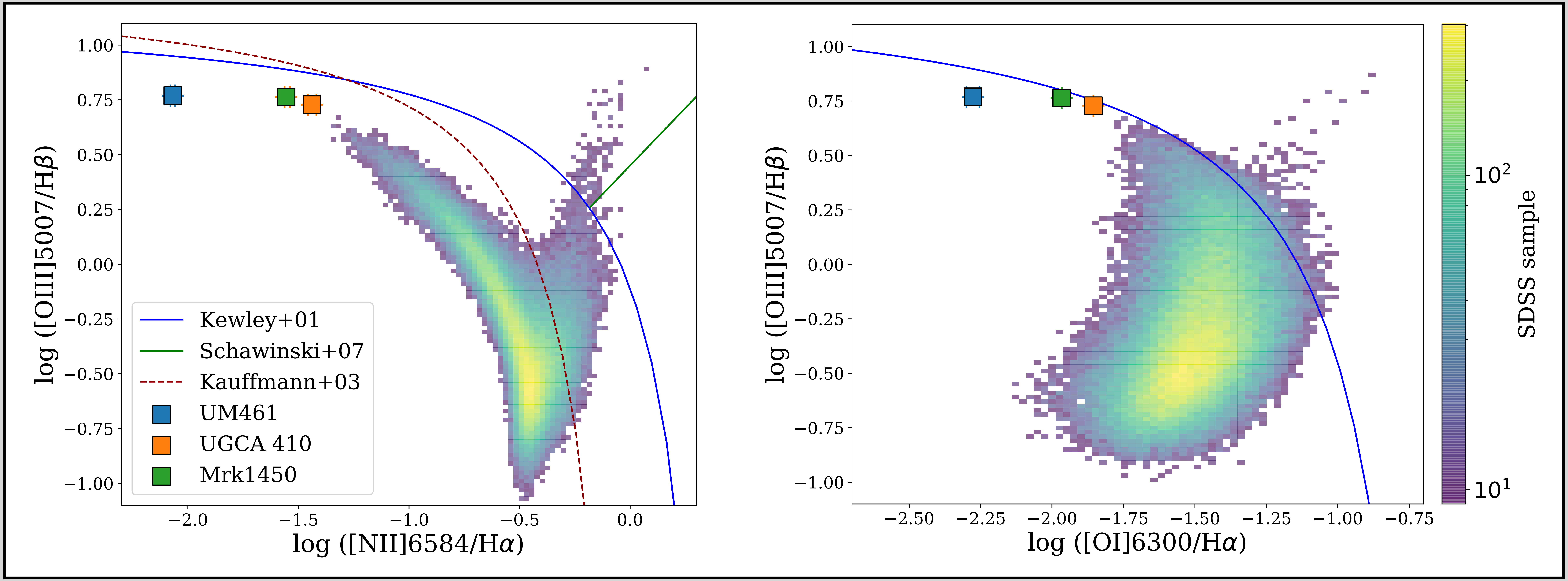
12+log(O/H) = 8.09 ± 0.11
log(N/O) = -0.93 ± 0.05
log(U) = -2.28 ± 0.06

Early stage of chemical evolution consistent with EELGs undergoing recent or ongoing starbursts.

Very high ionization state of the ISM driven by intense radiation fields from young, massive stars.

Emission-line diagnostics

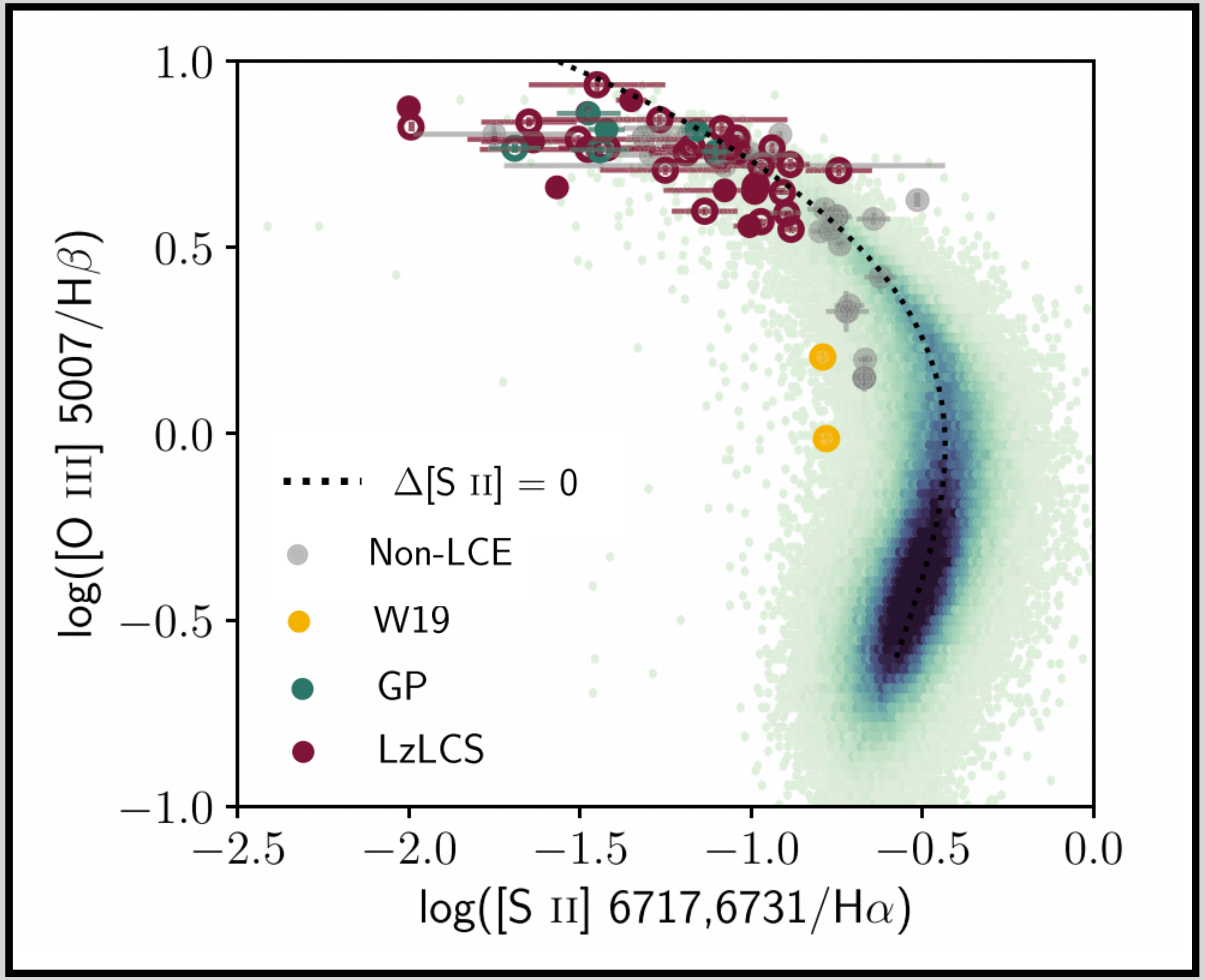
BPT diagrams



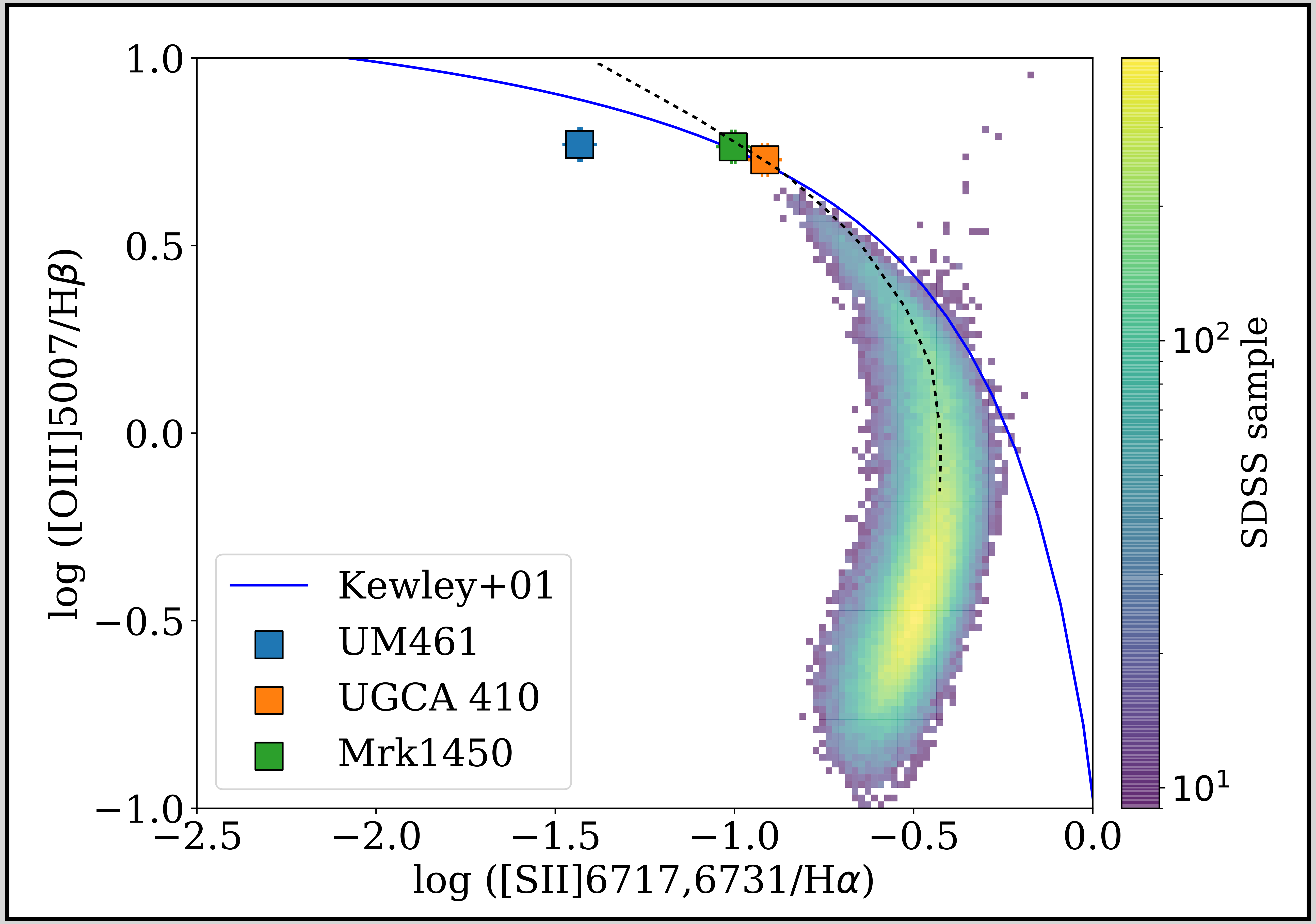
Cabello et al. *in prep.*

Emission-line diagnostics

[SII] BPT diagram



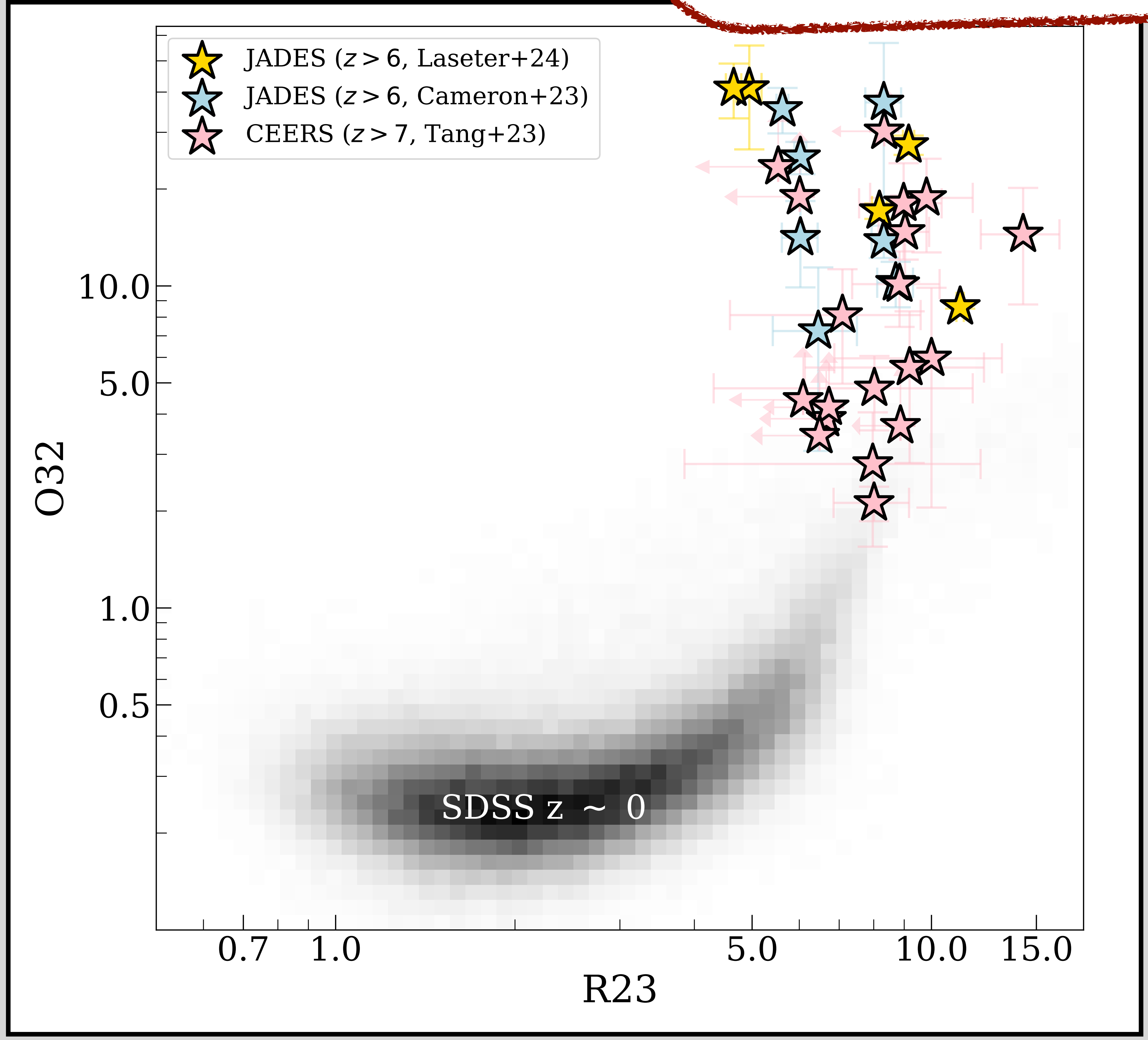
Wang+21

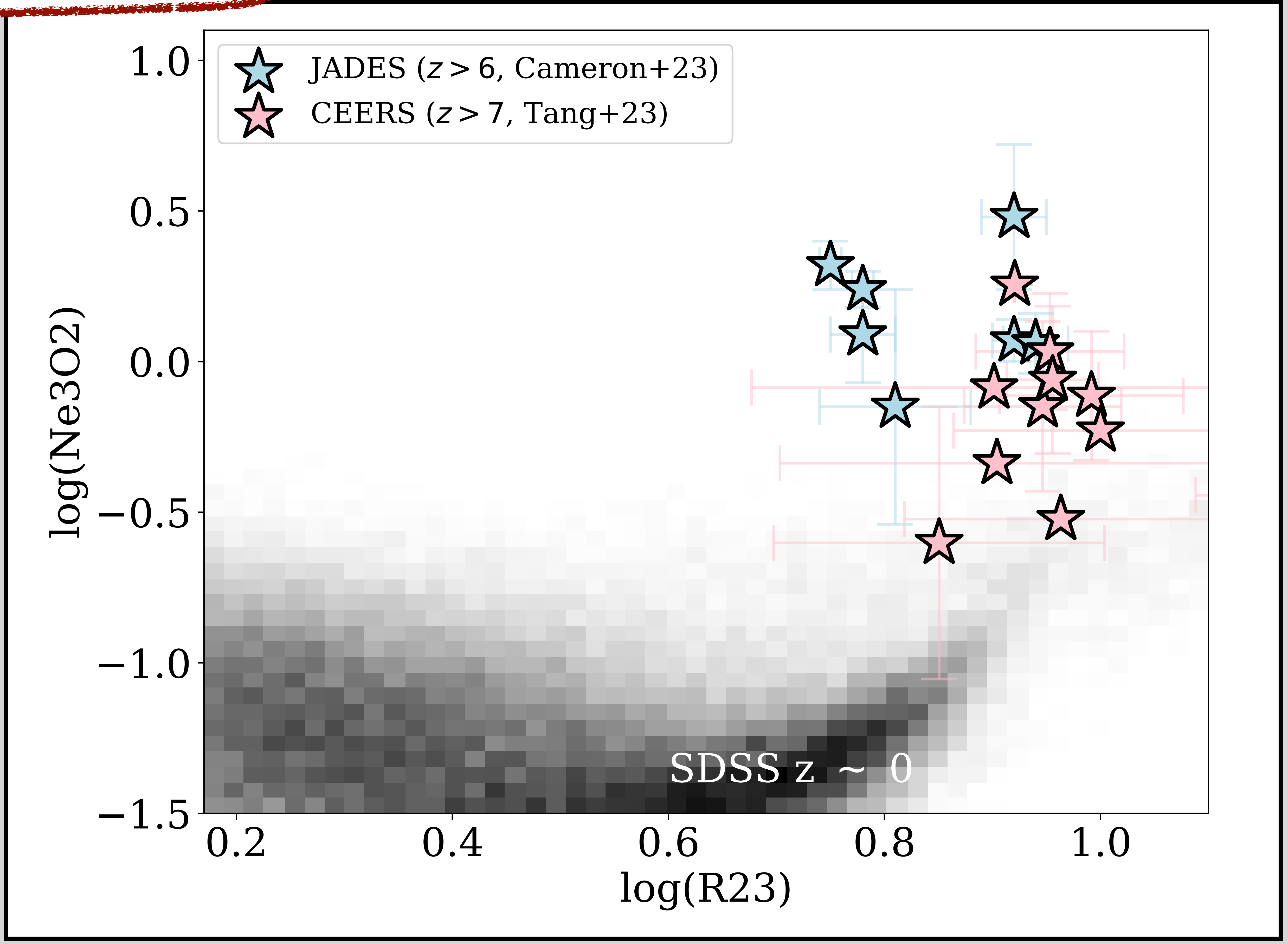


Cabello et al. *in prep.*

Ionization / excitation diagram

JWST (CEERS & JADES) galaxies in the range z = 6.0 - 9.5





Ionization / excitation diagram

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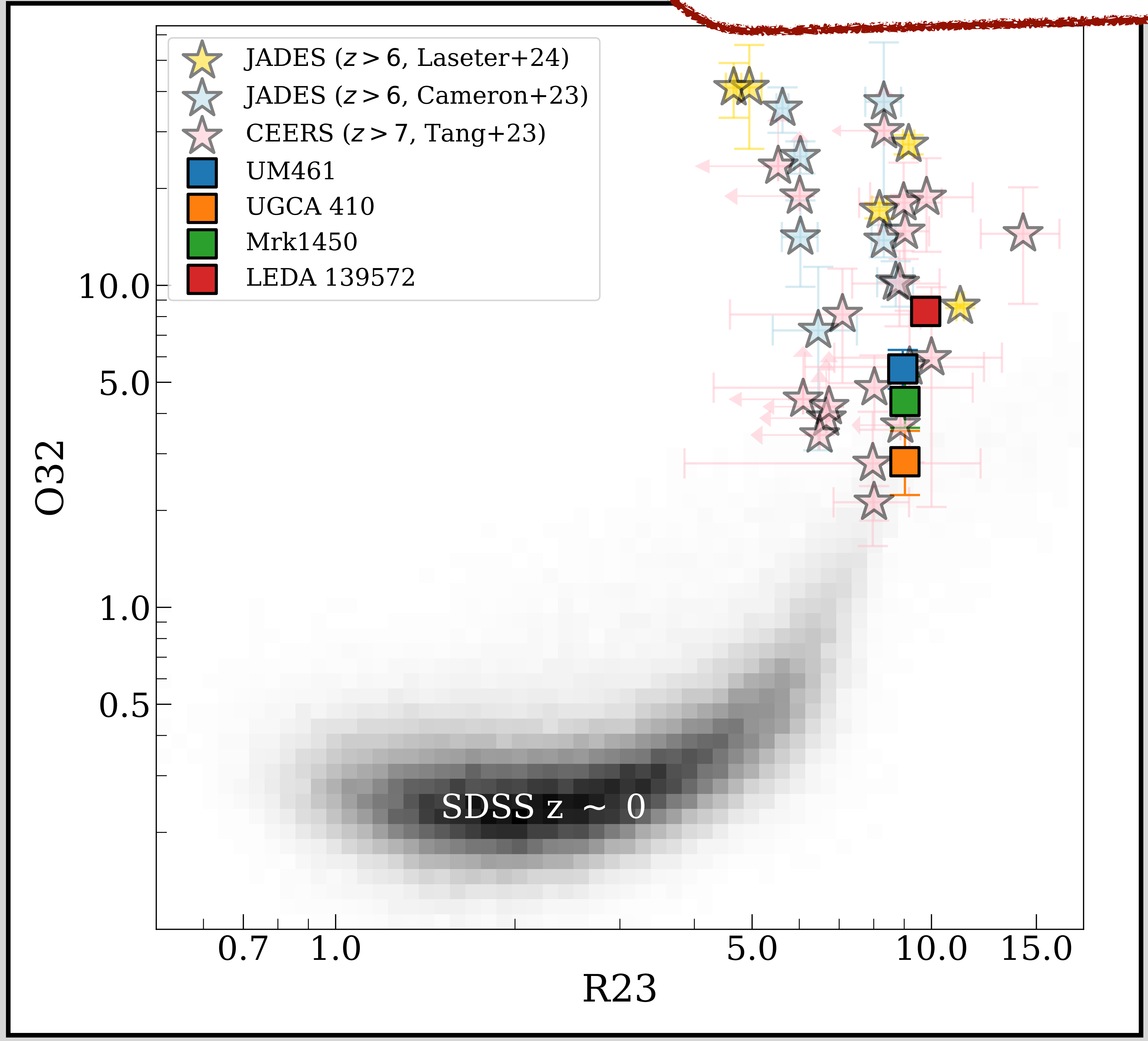
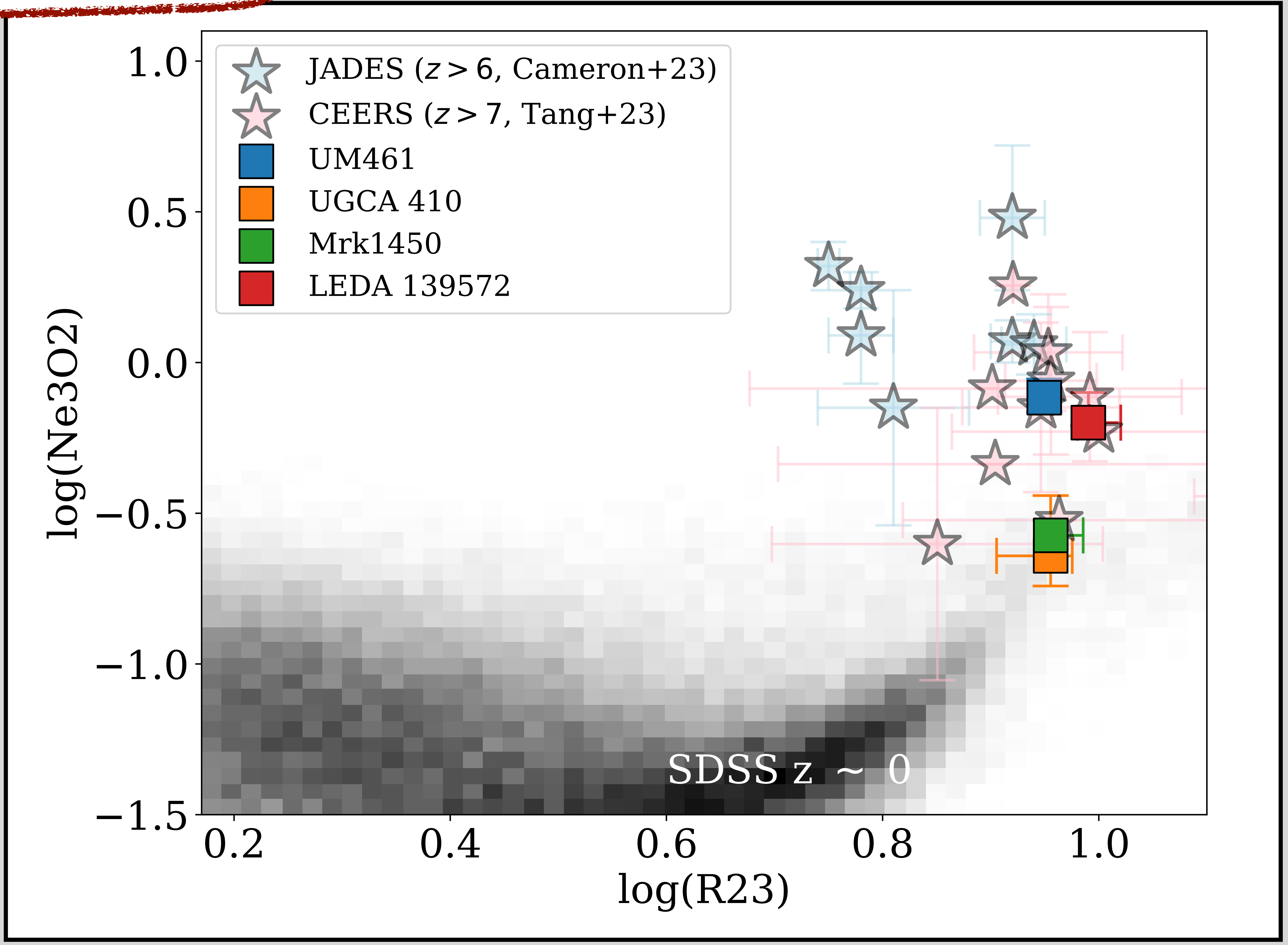
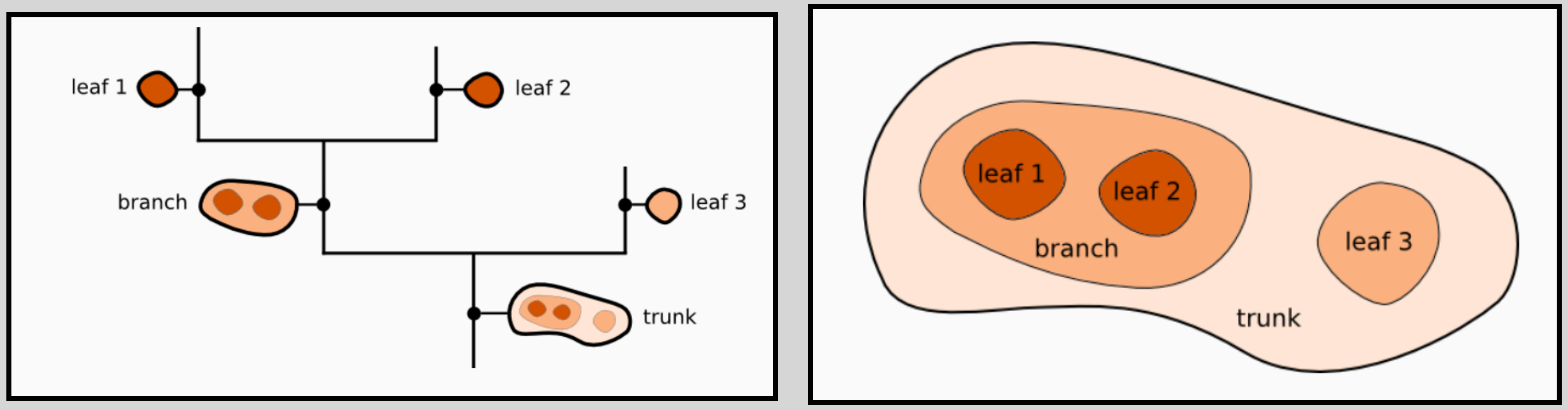




Cabello et al. *in prep.*

Analysis in multiple spatially distinct apertures

astrodendro finds structures in a set of data and groups them hierarchically

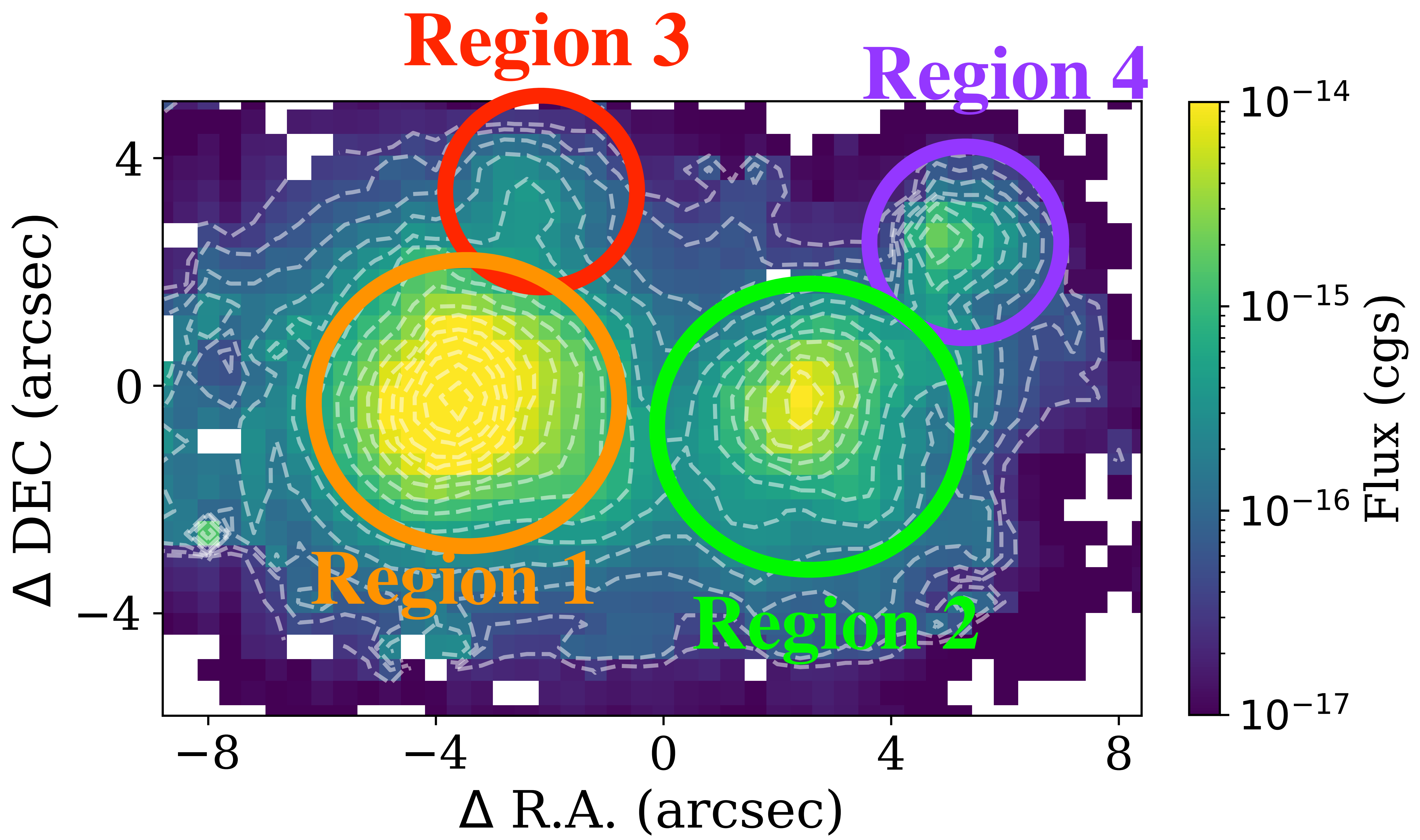


Identify HII regions corresponding to the diffuse component of the ionised gas at different levels of surface brightness.

(Monreal-Ibero +23, Goodman+09)

UM461

Hierarchical clustering provided by astrodendro



Analysis in multiple spatially distinct apertures

ISM conditions

Diagnostic diagrams:
Indirect indicators of LyC leakage
based on emission line ratios.

f_{esc} (LyC) estimation

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

Integrated value:
f_{esc} (LyC) ~ 5 - 8%

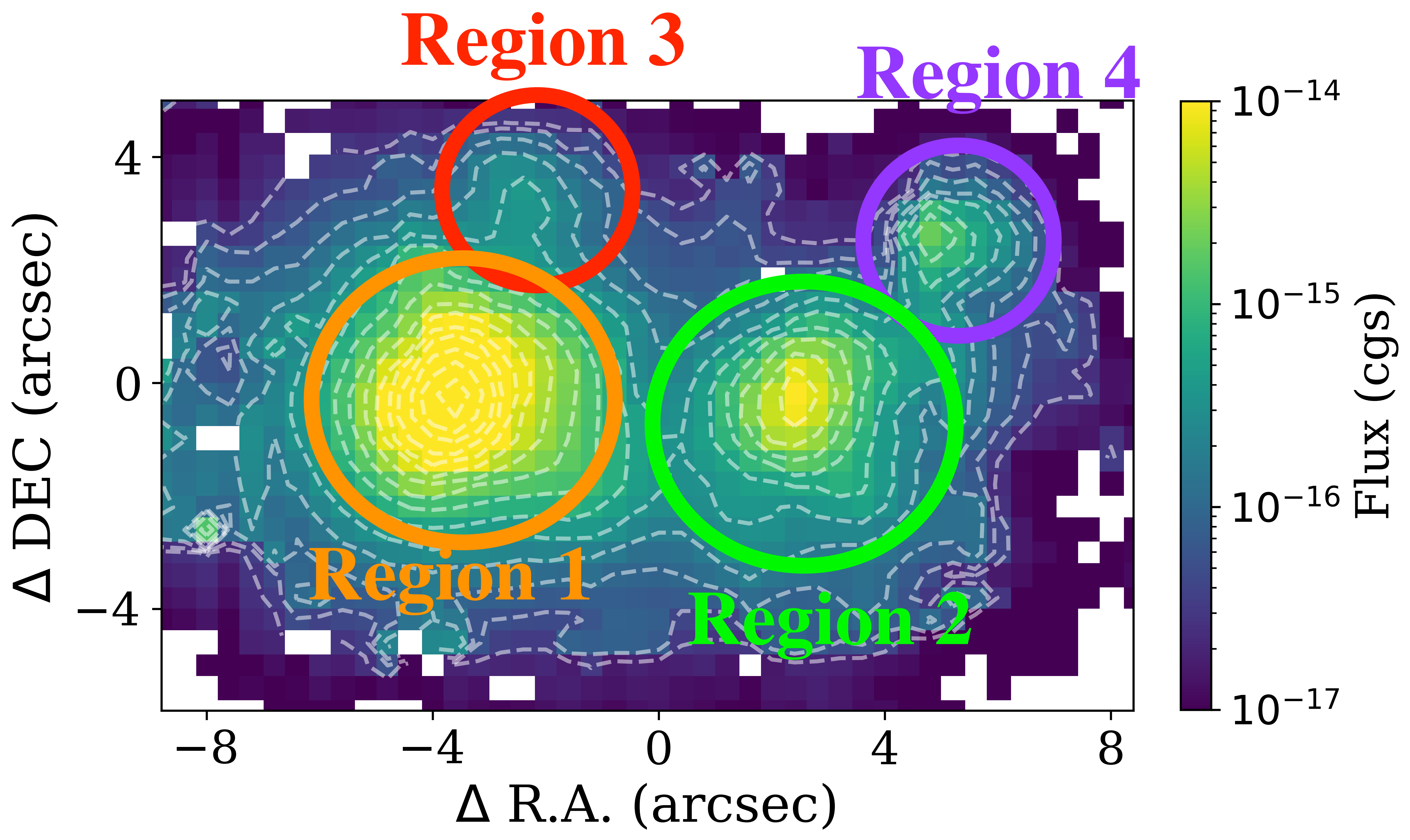
Aperture 1:
f_{esc} (LyC) ~ 10 - 15%

Aperture 2:
f_{esc} (LyC) ~ 2 %

Apertures 3 & 4:
f_{esc} (LyC) < 2 %

UM461

Hierarchical clustering provided by astrodendro



Conclusions

- We constrained the **predominant ionization mechanisms** of these extreme systems.

- Different indirect indicators of LyC leakage based on emission-line ratios reinforce **the status of our sample as excellent local analogs of the high-z population**.

- We identified regions with different behaviors, **mapping the ionization structure of the ISM** down to sub-kpc scales.

- The analysis of the ISM porosity provided important insights about **density-bounded regions** (optically thin gas with a high degree of ionization) from which the ionizing radiation may escape.

Final remarks

Analysis of the spatial variations:

The ISM conditions are not homogeneous

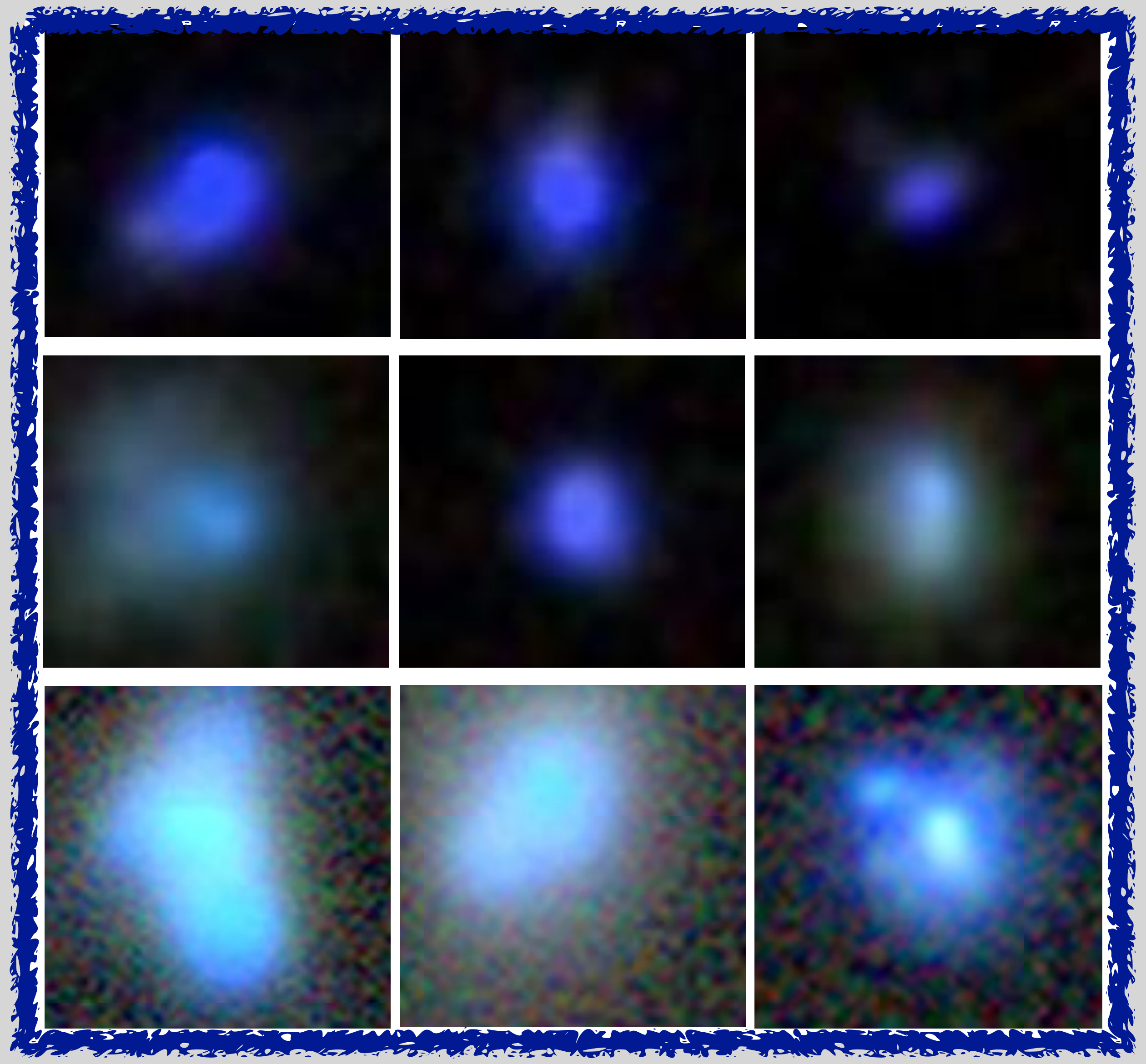
Integrated properties do not fully represent the complex ionization structure of some galaxies

↓

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

A larger sample of galaxies is needed!

A larger sample of local analogs



+50h of MEGARA/GTC (2025A)

(PI: C. Cabello)

In collaboration with: R. Amorín (CSIC-IAA), L. Costantin (CAB, CSIC-INTA), J. A. Fernández-Ontiveros (CEFCA), A. Lumbreras-Calle (CEFCA), E. Pérez-Montero (CSIC-IAA).

Spatially-resolved study of a large sample of reionization-era analogs

Extreme Emission Line Galaxies (EELGs)
selected from the
J-PLUS multiband survey (Cenarro+19)

$\log(M_*/M_\odot) < 9$
$12 + \log(O/H) < 8$
$O32 > 3$
$EW > 300$ Å

Stay tuned!

Thanks!

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