

High-definition imaging of an extended filament linking two active quasars at cosmic noon

Davide Tornotti

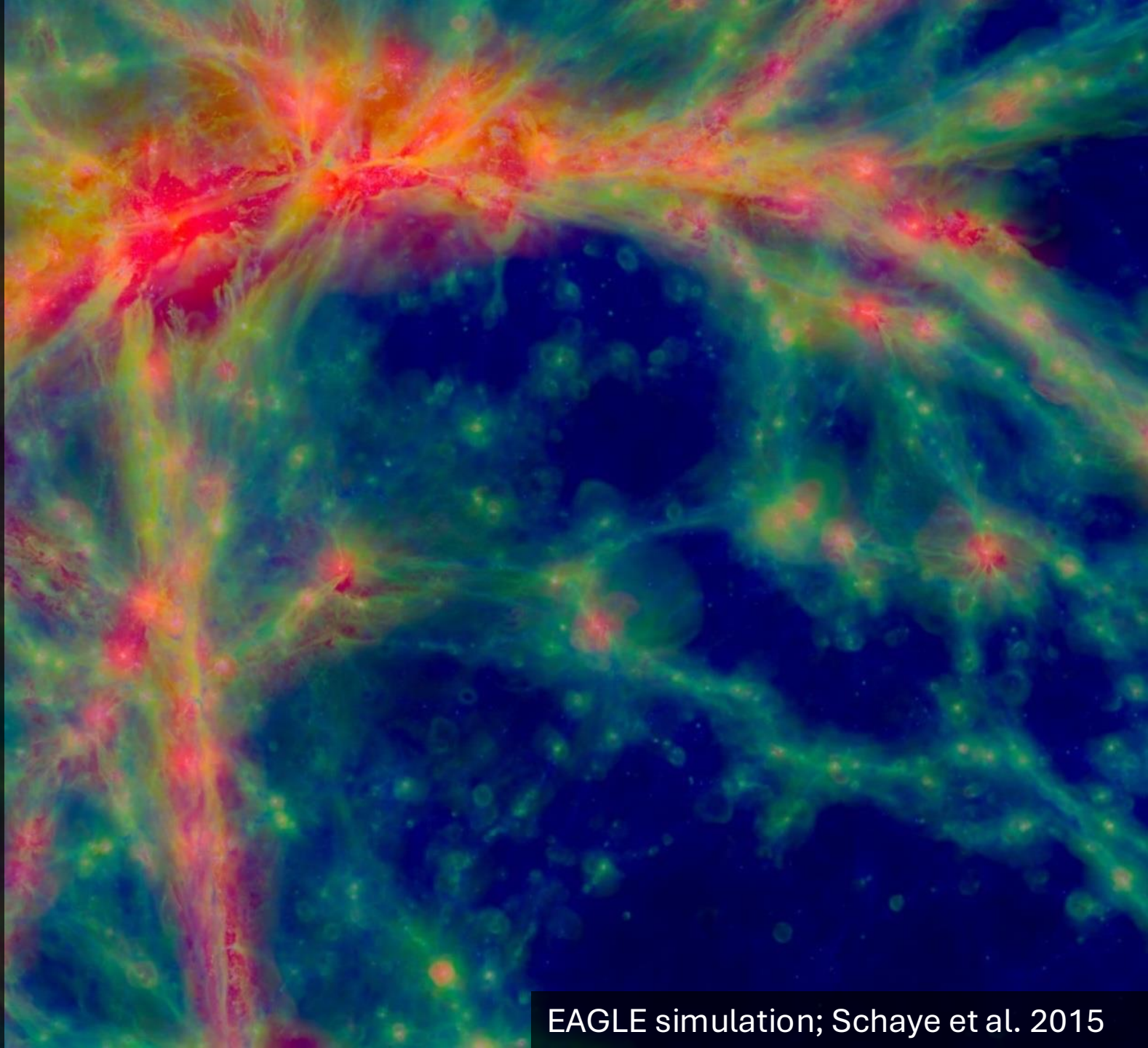
Supervisor: M. Fumagalli

Collaborators: M. Fossati, A. Benitez Llambay and the MUDF team

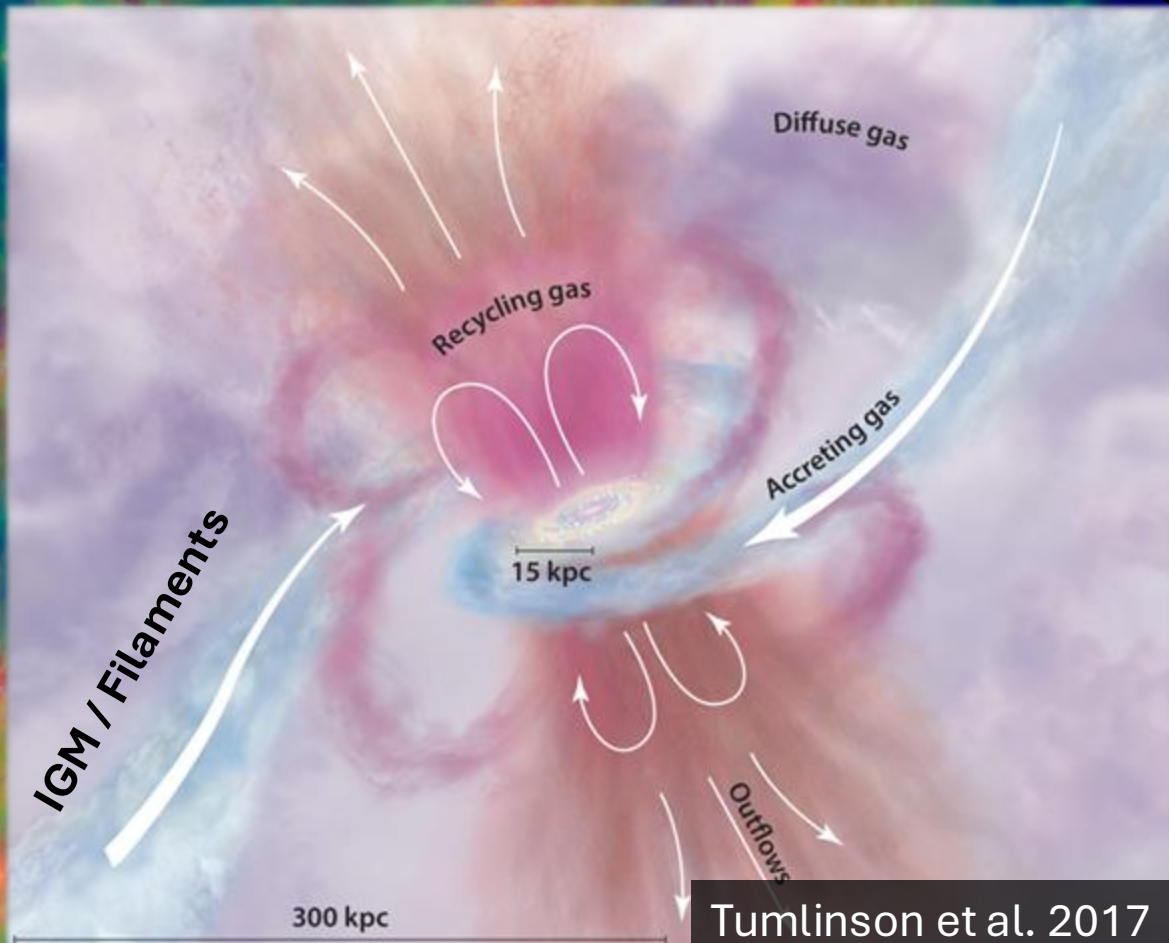
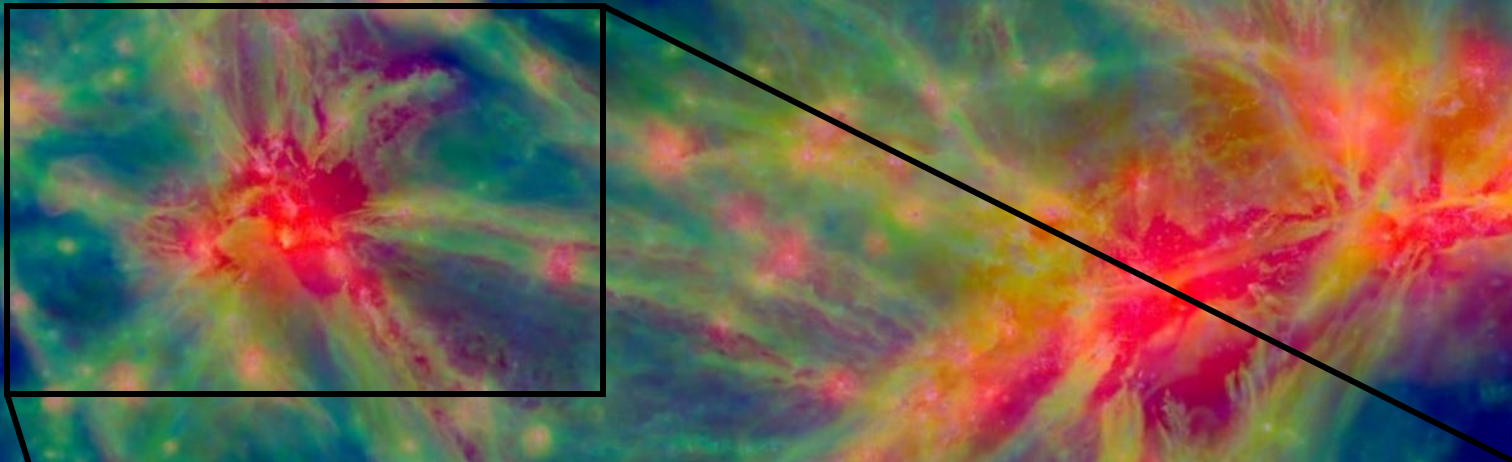
Λ CDM COSMOLOGICAL PARADIGM



FILAMENT-DOMINATED STRUCTURE ON
LARGE SCALES: «THE COSMIC WEB»



EAGLE simulation; Schaye et al. 2015



Tumlinson et al. 2017

FILAMENTS FEED THE CGM THAT REGULATES
THE GAS EXCHANGE BETWEEN GALAXIES AND
THE SURROUNDING IGM



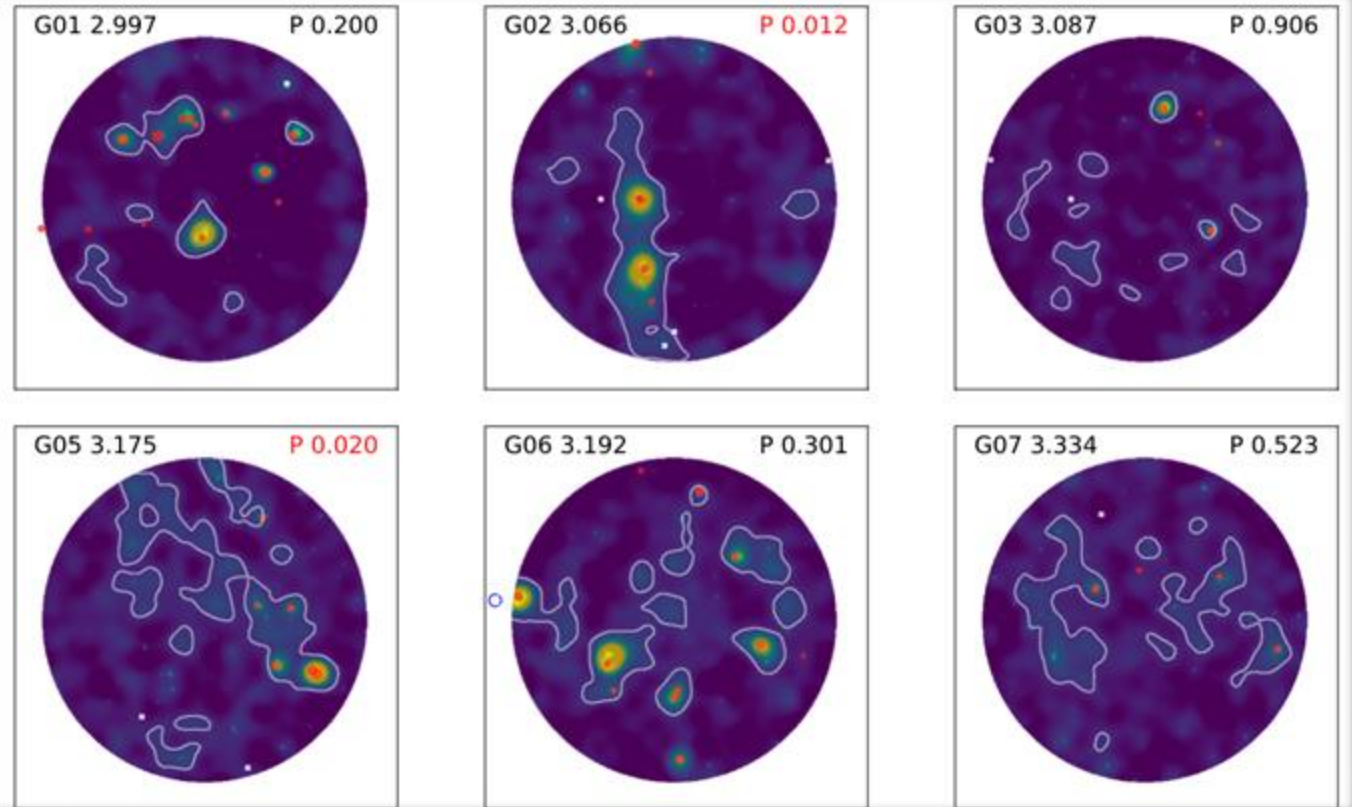
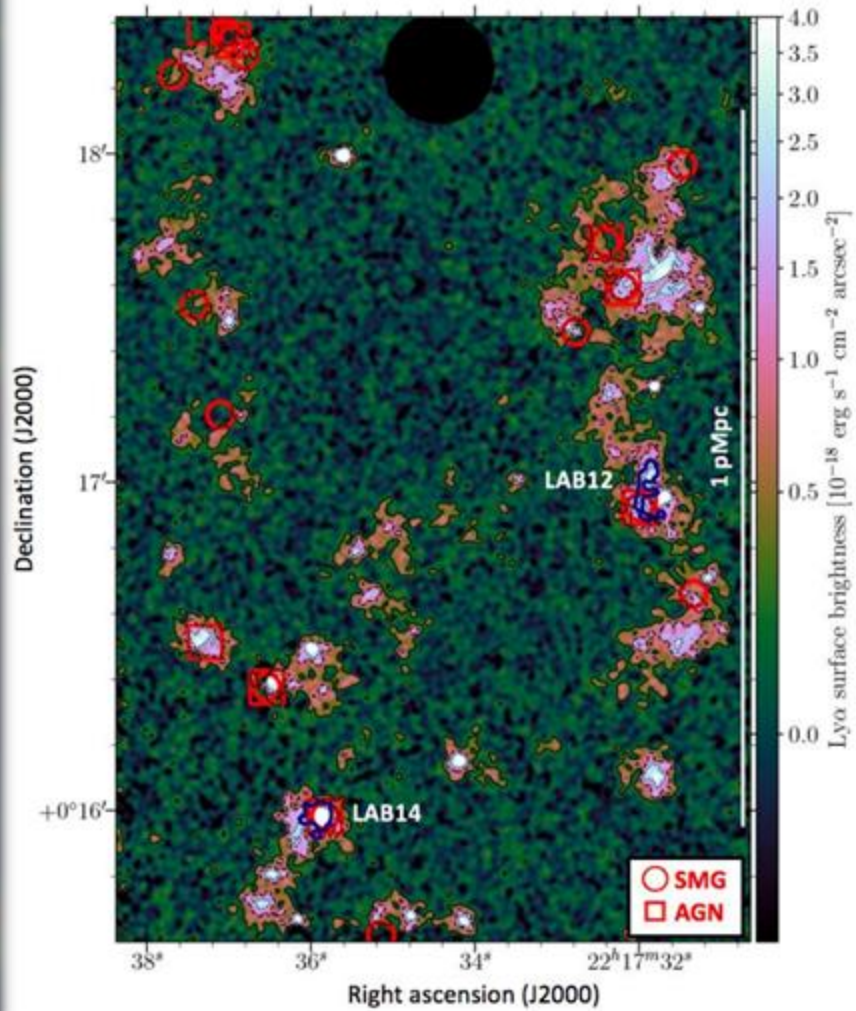
CONTROLS THE GALAXY GROWTH THROUGH
COSMIC TIME

A visualization of the cosmic web, showing a complex network of filaments and clusters of galaxies. The filaments are colored in shades of red, orange, and yellow, while the clusters are more densely packed and appear in darker colors. The background is a deep blue, suggesting the vastness of space.

GENERAL GOAL:

Study the properties of the large scale structures (filaments) and the link between galaxies and their circum/inter galactic medium at $z \approx 3 - 4$

The Cosmic Web in emission: some examples



MXDF – Bacon et al. 2021

SSA22 – Umehata et al. 2019

MXDF – Bacon et al. 2021

A visualization of the cosmic web, showing a complex network of dark matter filaments and galaxy clusters. The filaments are depicted as thin, elongated structures in shades of blue, green, and yellow, set against a dark background. The clusters are represented by denser, more colorful regions of red and orange. The overall structure is highly interconnected and hierarchical.

MUDF and the environment of the QSO pair

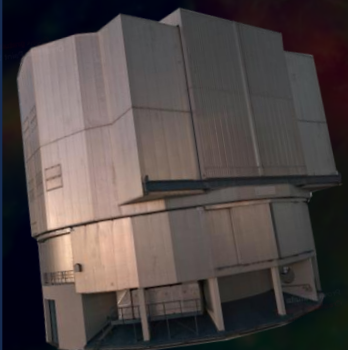
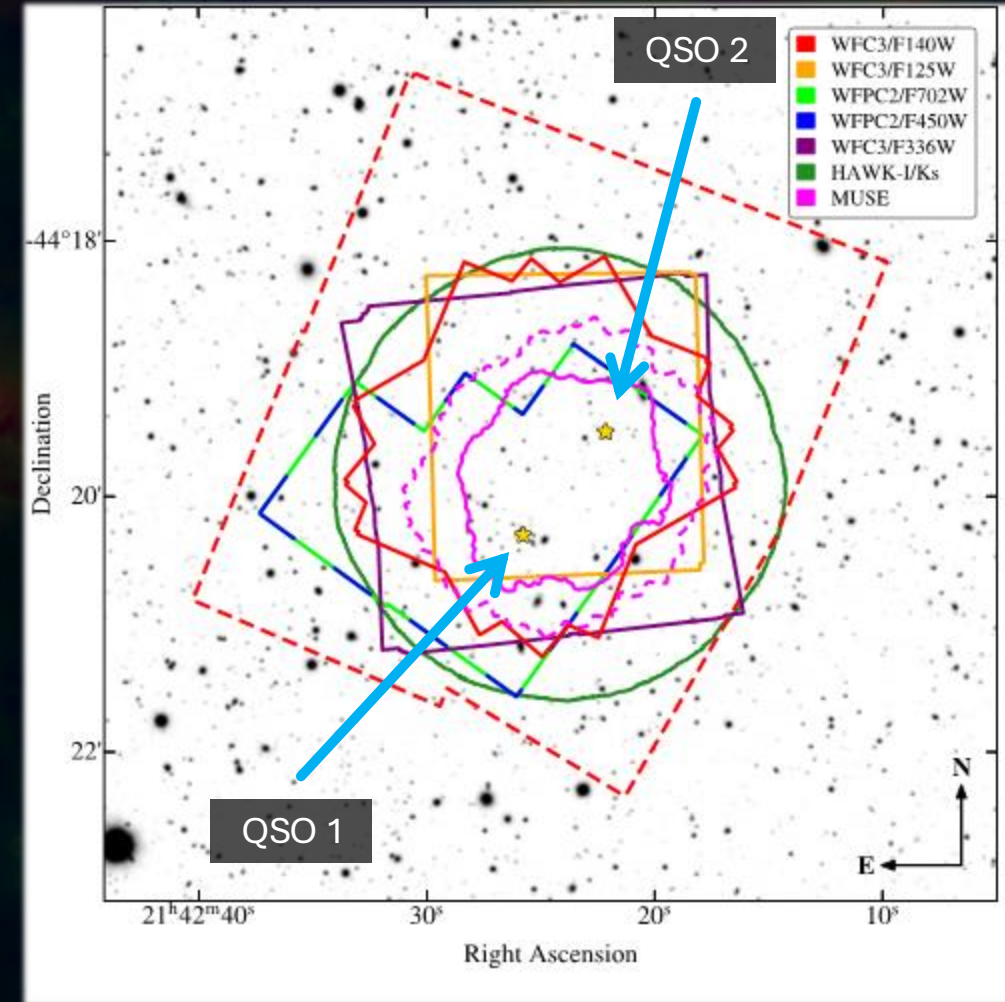
The MUSE Ultra Deep Field (MUDF)

ONE OF THE KEY GOALS:

image the Ly α emission from two massive nodes at $z \approx 3.22$

Observations:

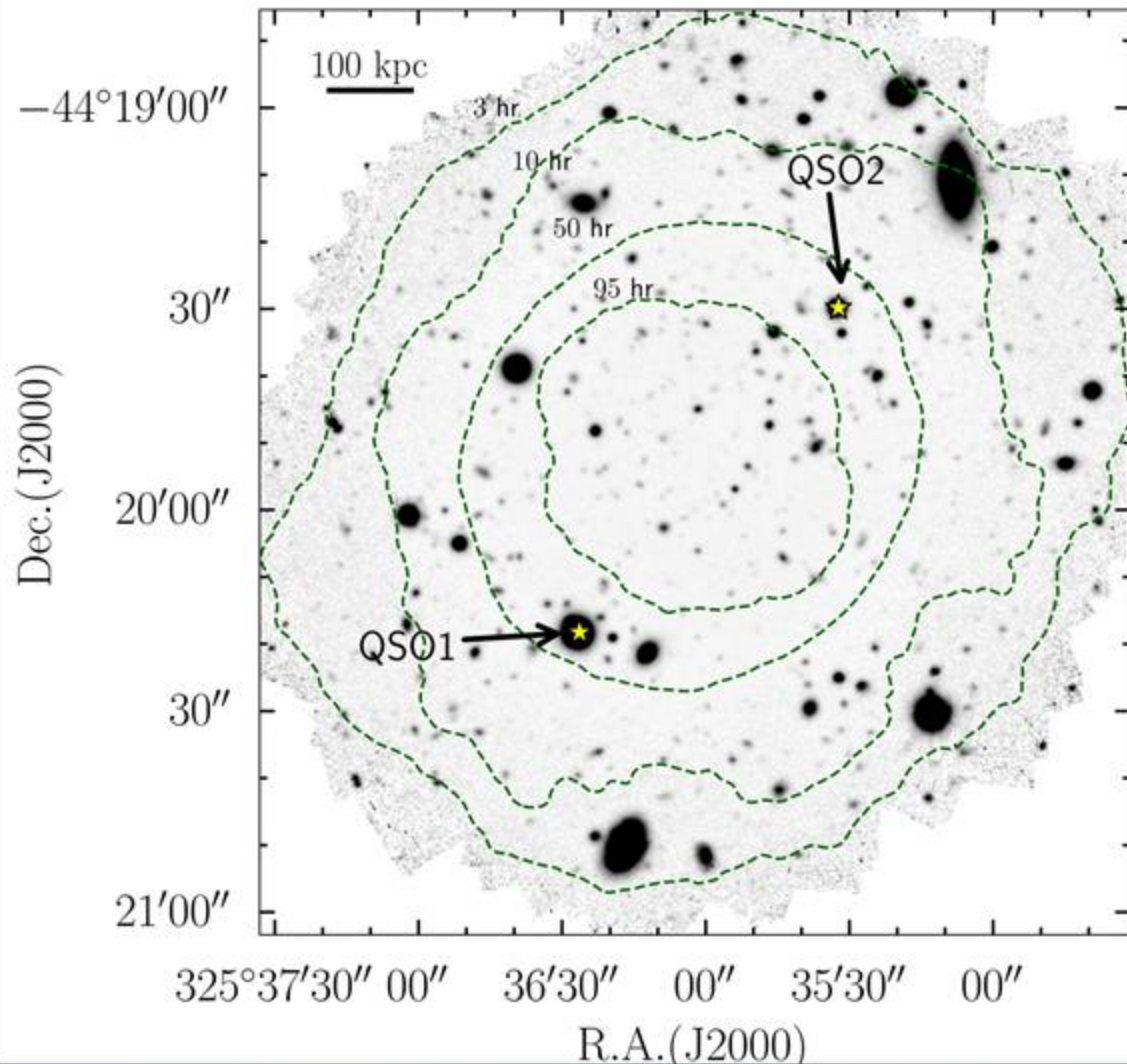
- **142h** MUSE (PI Fumagalli) similar to the MUSE GTO MXDF;
- 90 orbits HST WFC3 G141 spectroscopy ;
+ F125W, F140W imaging (PI Rafelski);
- 8 orbits HST UV imaging (PI Fossati);
- 30h UVES QSO spectroscopy (PI D'Odorico);
- 27h HAWK-I K-band imaging (PI Fossati);
- ALMA Band 3 and 6 programs (PI Fumagalli, Pensabene).



The environment of the QSO pair

Full dataset rms = $3 \times$

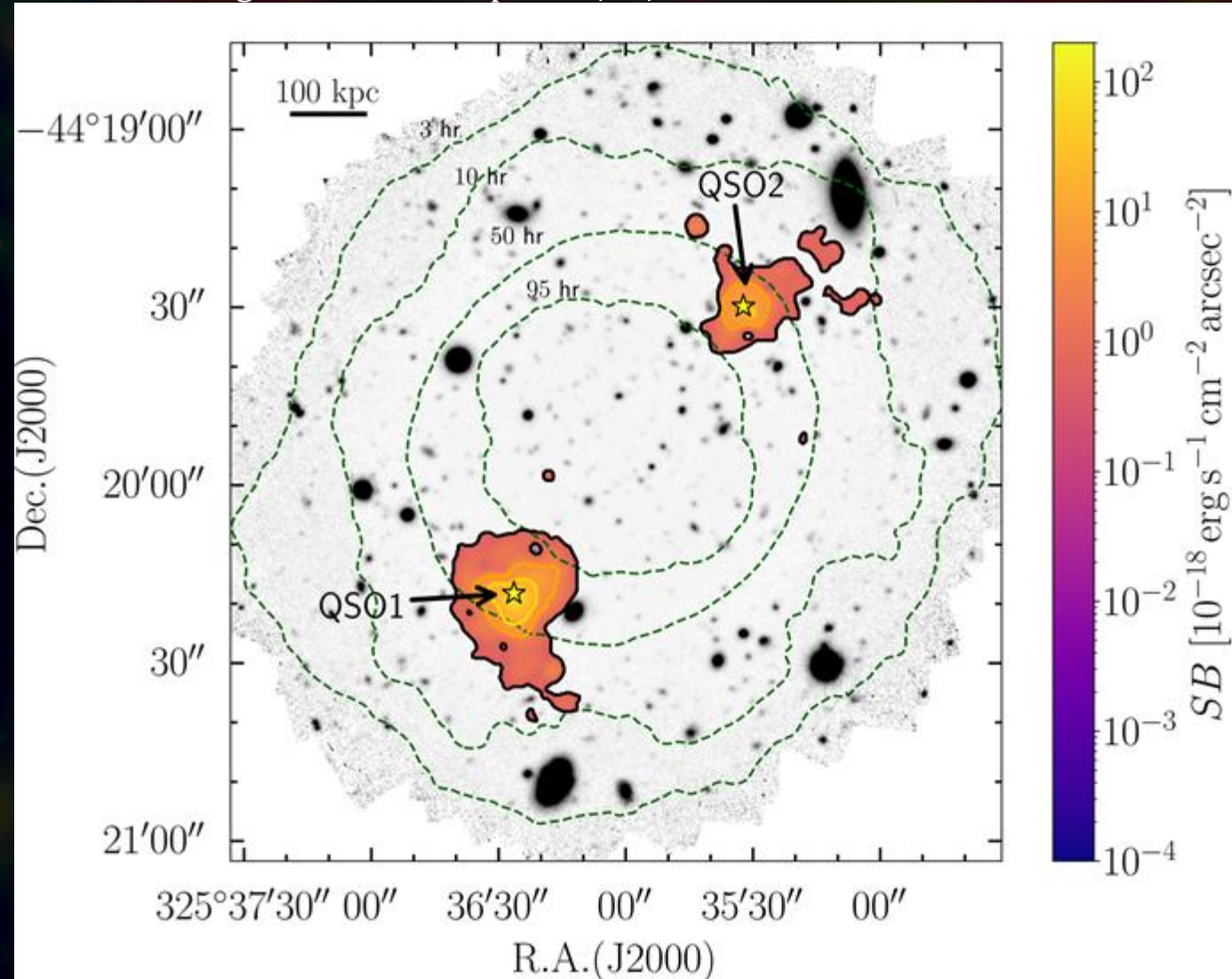
$10^{-21} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ \AA}^{-1} \text{ pix}^{-1} (1\sigma)$



The environment of the QSO pair

Full dataset rms = $3 \times$

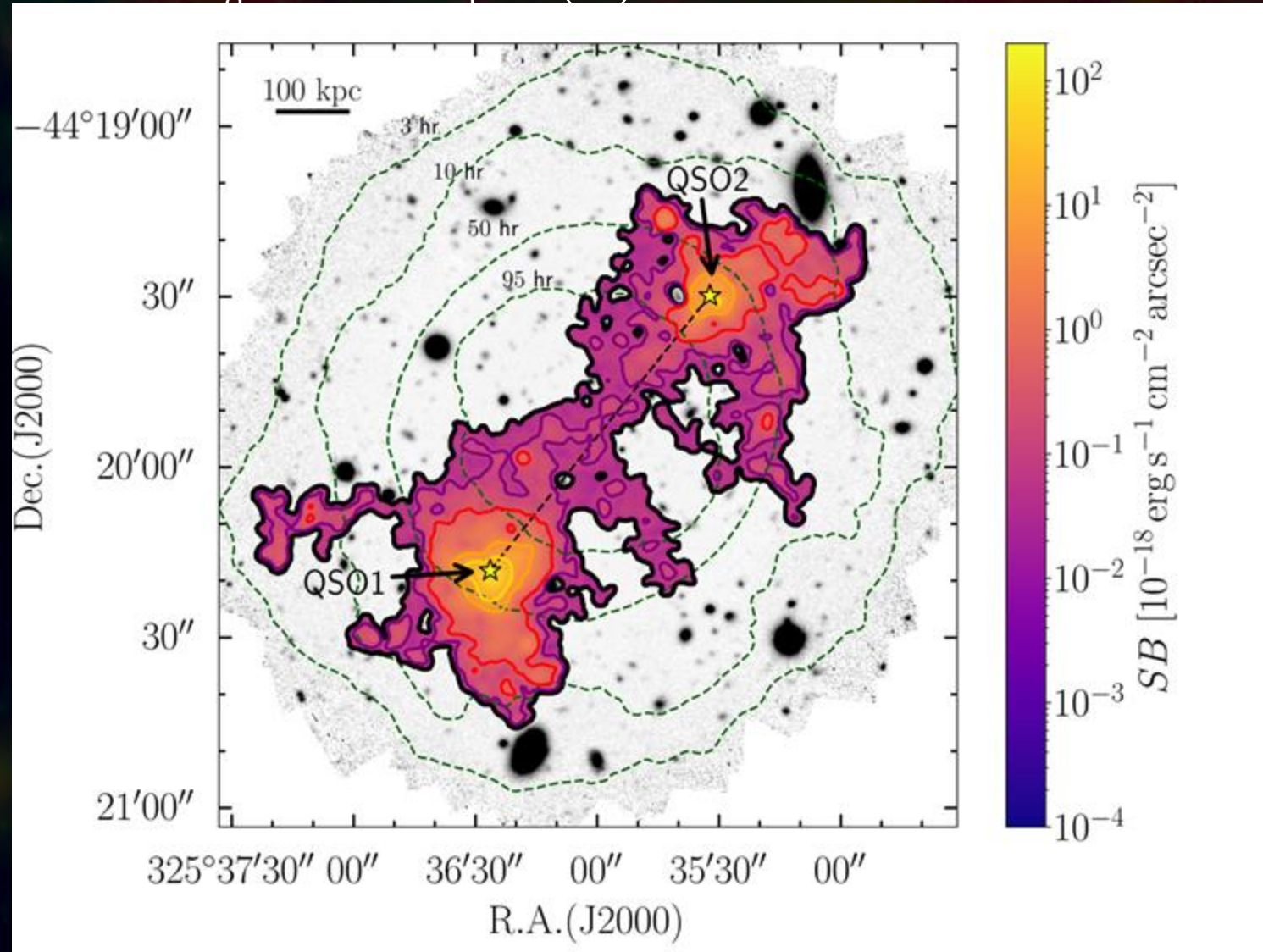
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The environment of the QSO pair

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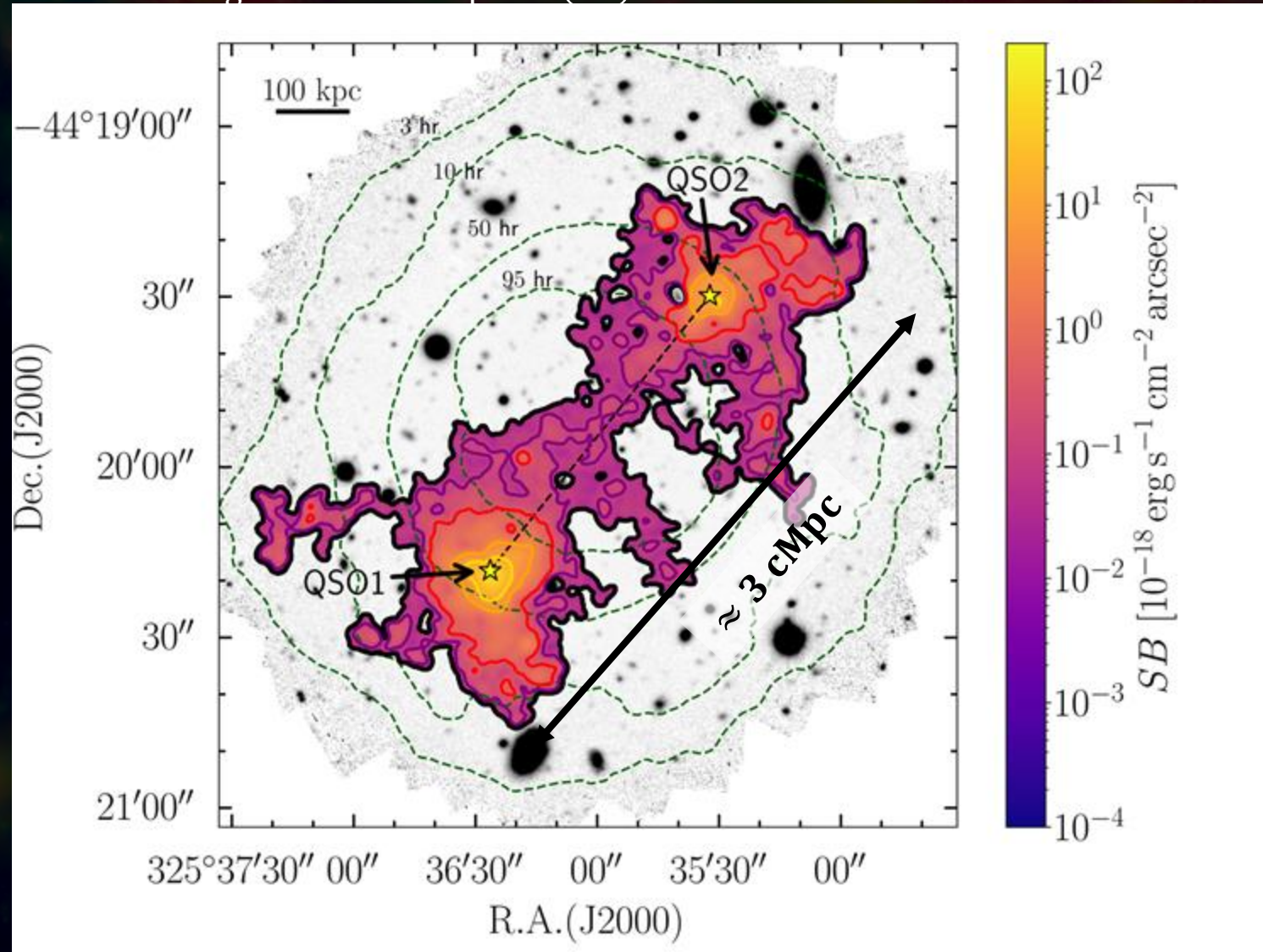
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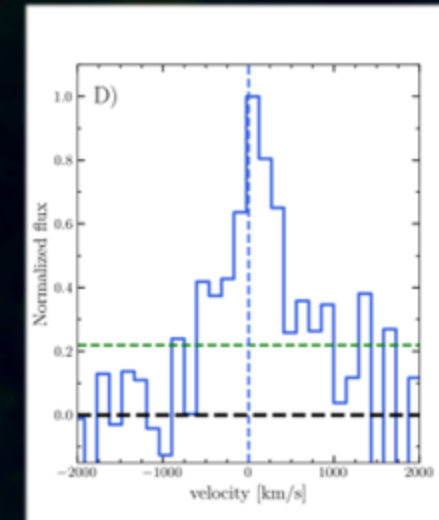
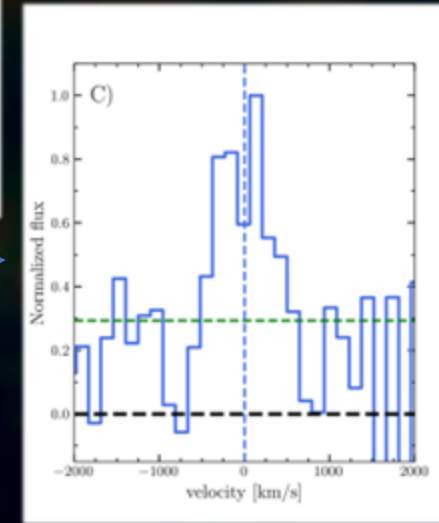
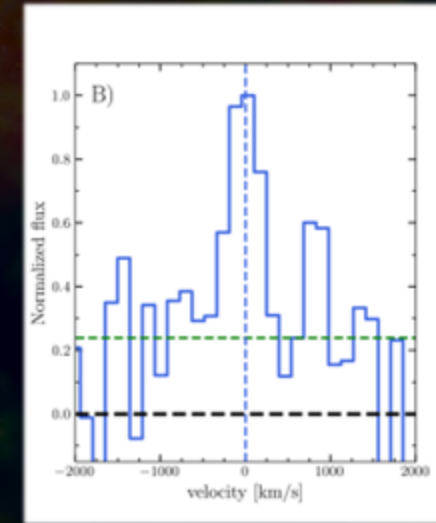
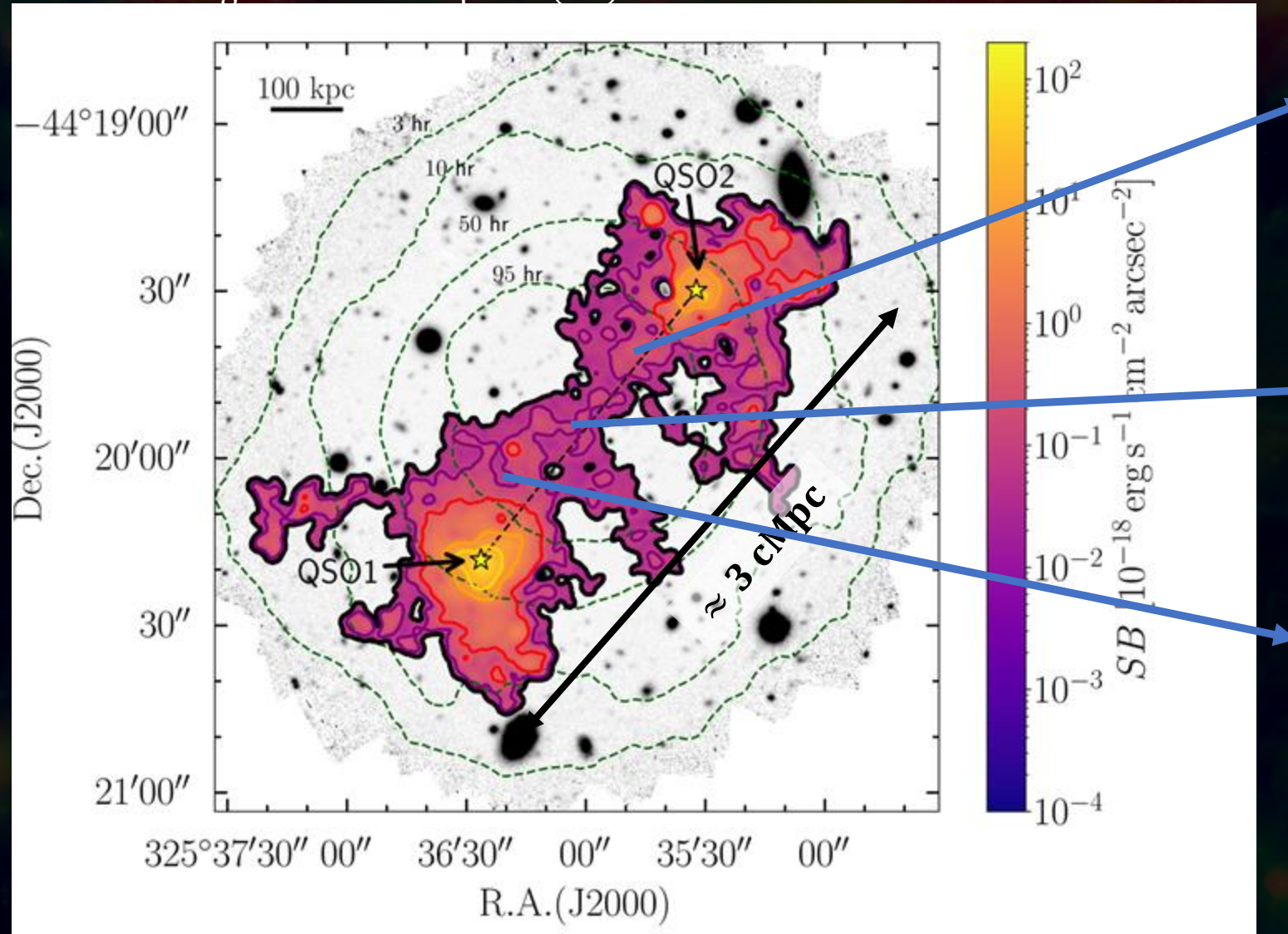
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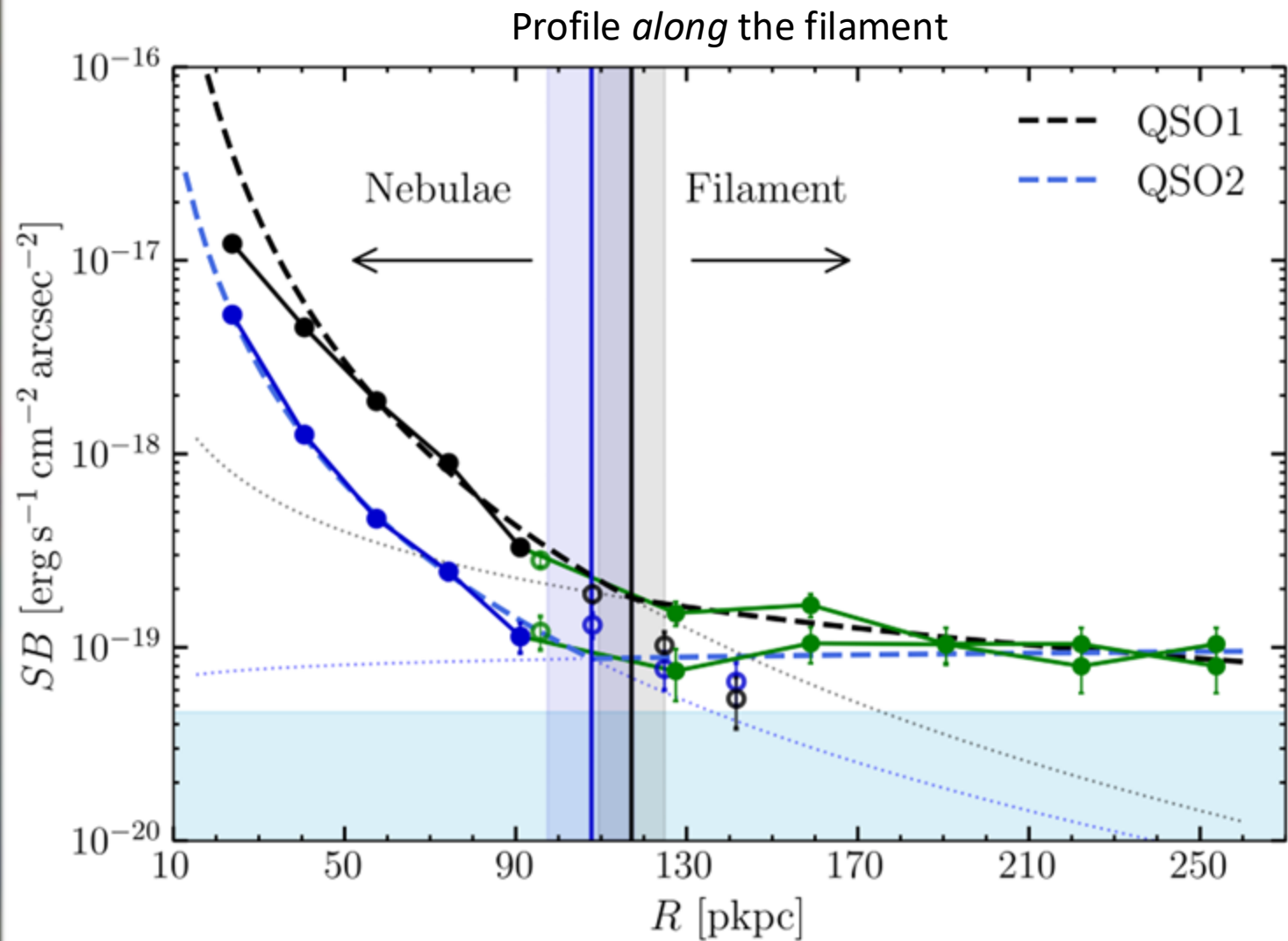
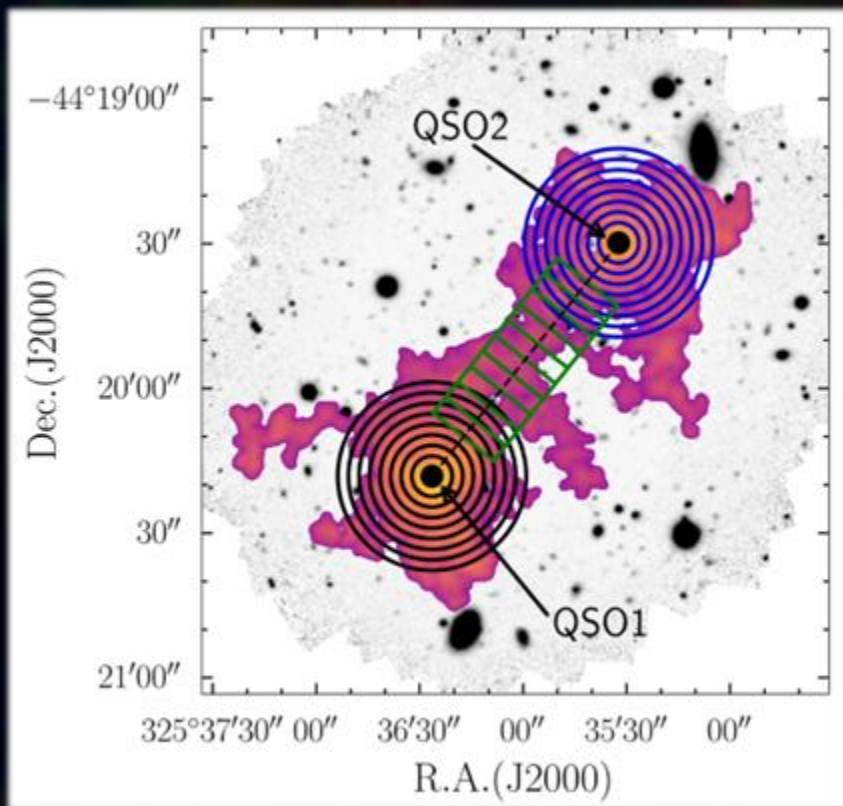
Full dataset rms = $3 \times$

$10^{-21} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ \AA}^{-1} \text{ pix}^{-1} (1\sigma)$

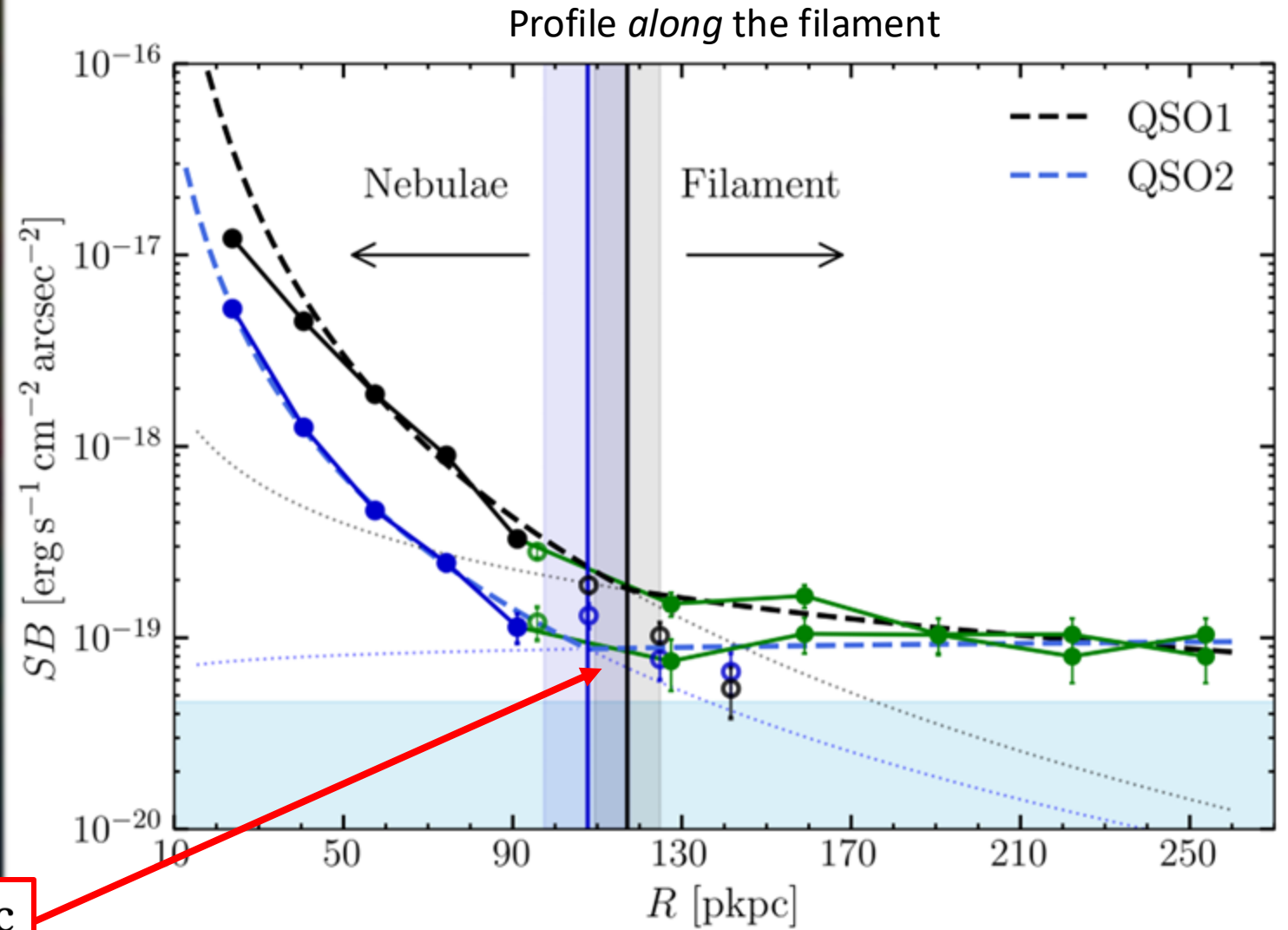
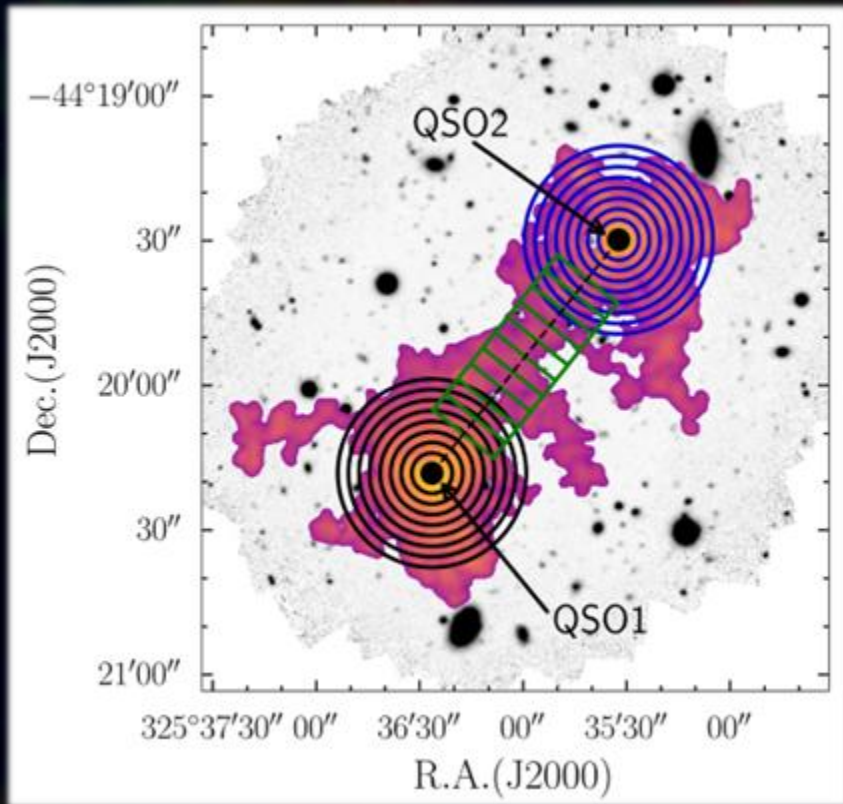


D. Tornotti et al. submitted

The environment of the QSO pair



The environment of the QSO pair

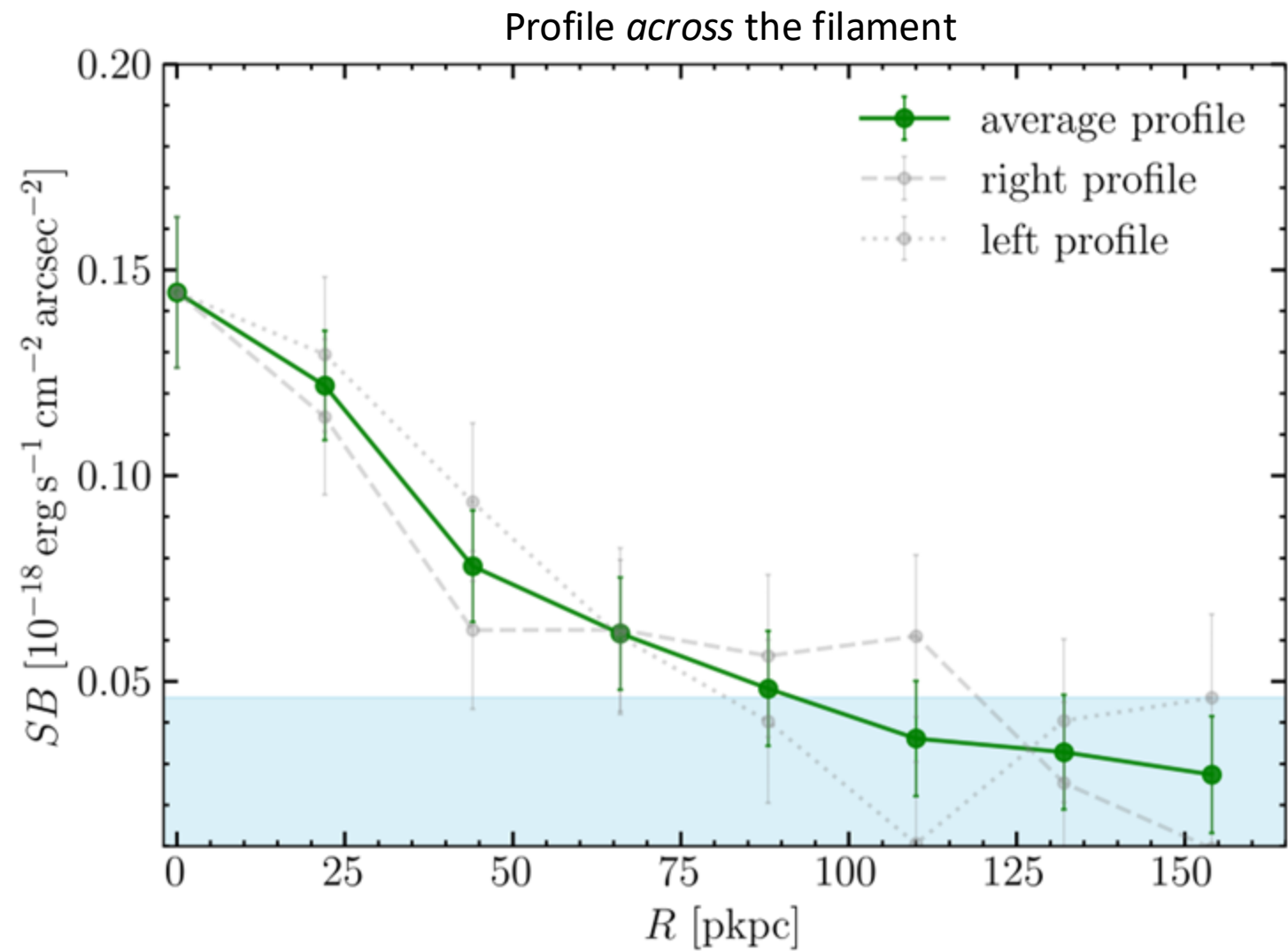
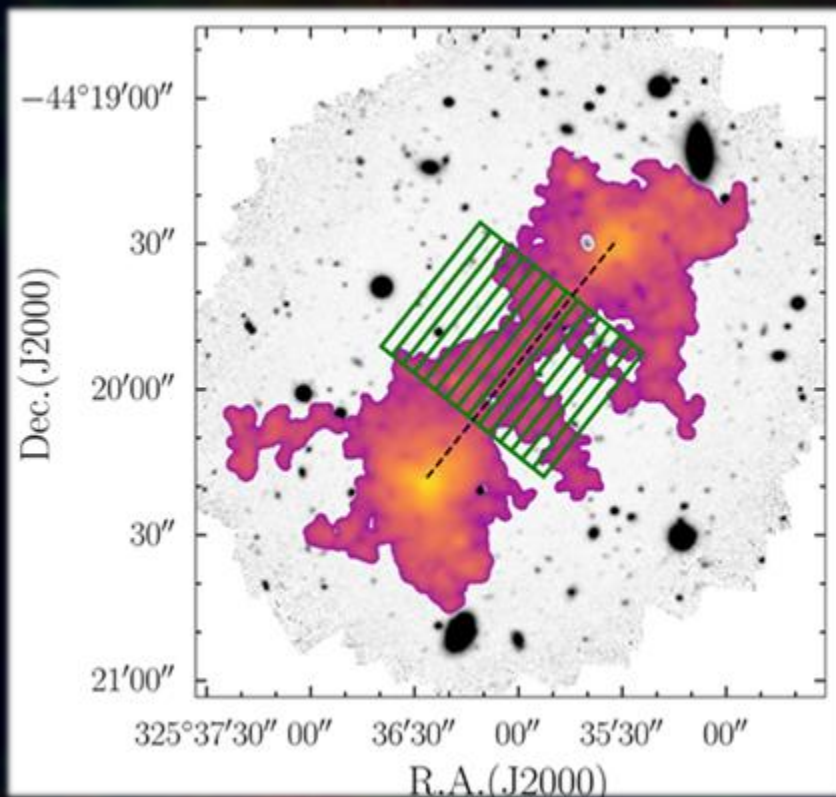


$$R_t \approx 100 \text{ pkpc}$$

e.g. Fossati et al 2021,
de Beer et al 2023

D. Tornotti et al. submitted

The environment of the QSO pair



The environment of the QSO pair

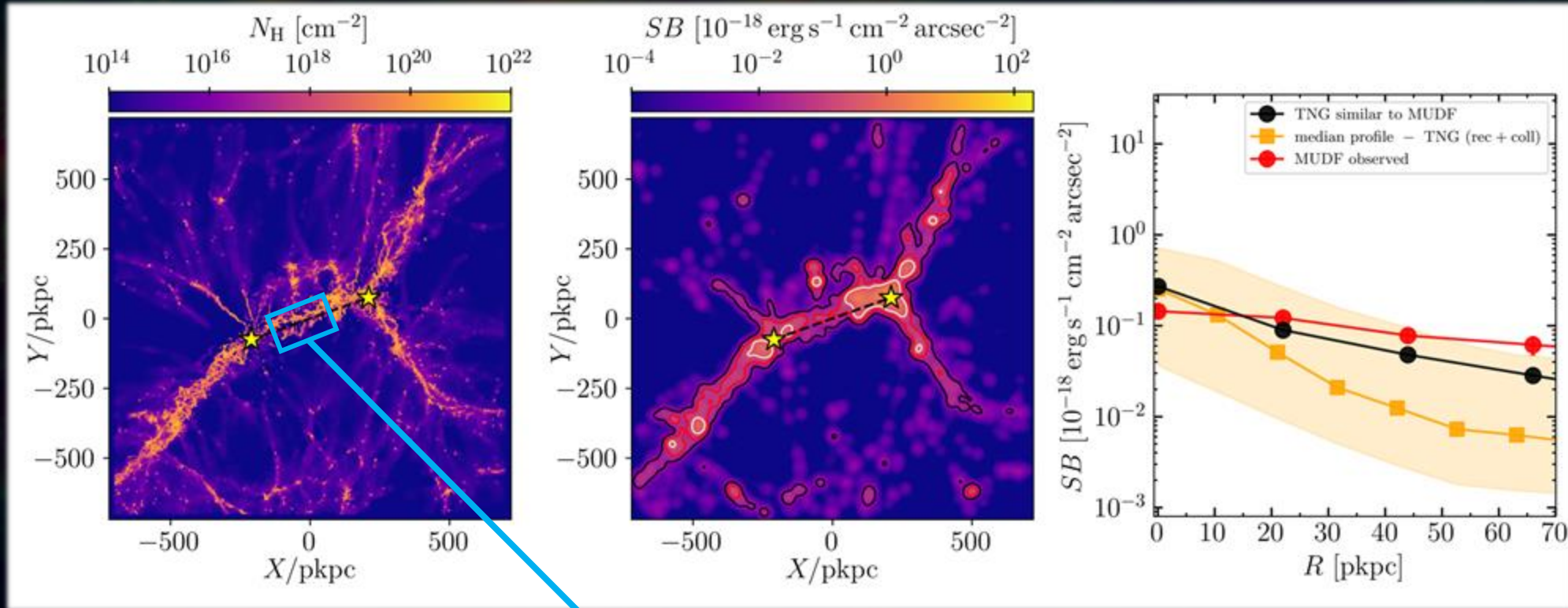
$$\text{QSO1: } \log\left(\frac{M_h}{M_\odot}\right) = 12.9 \pm 0.3$$

$$\text{QSO2: } \log\left(\frac{M_h}{M_\odot}\right) = 12.2 \pm 0.4$$

From L-Galaxies SAM with advanced QSO recipes
(Izquierdo-Villalba et al. 2020)

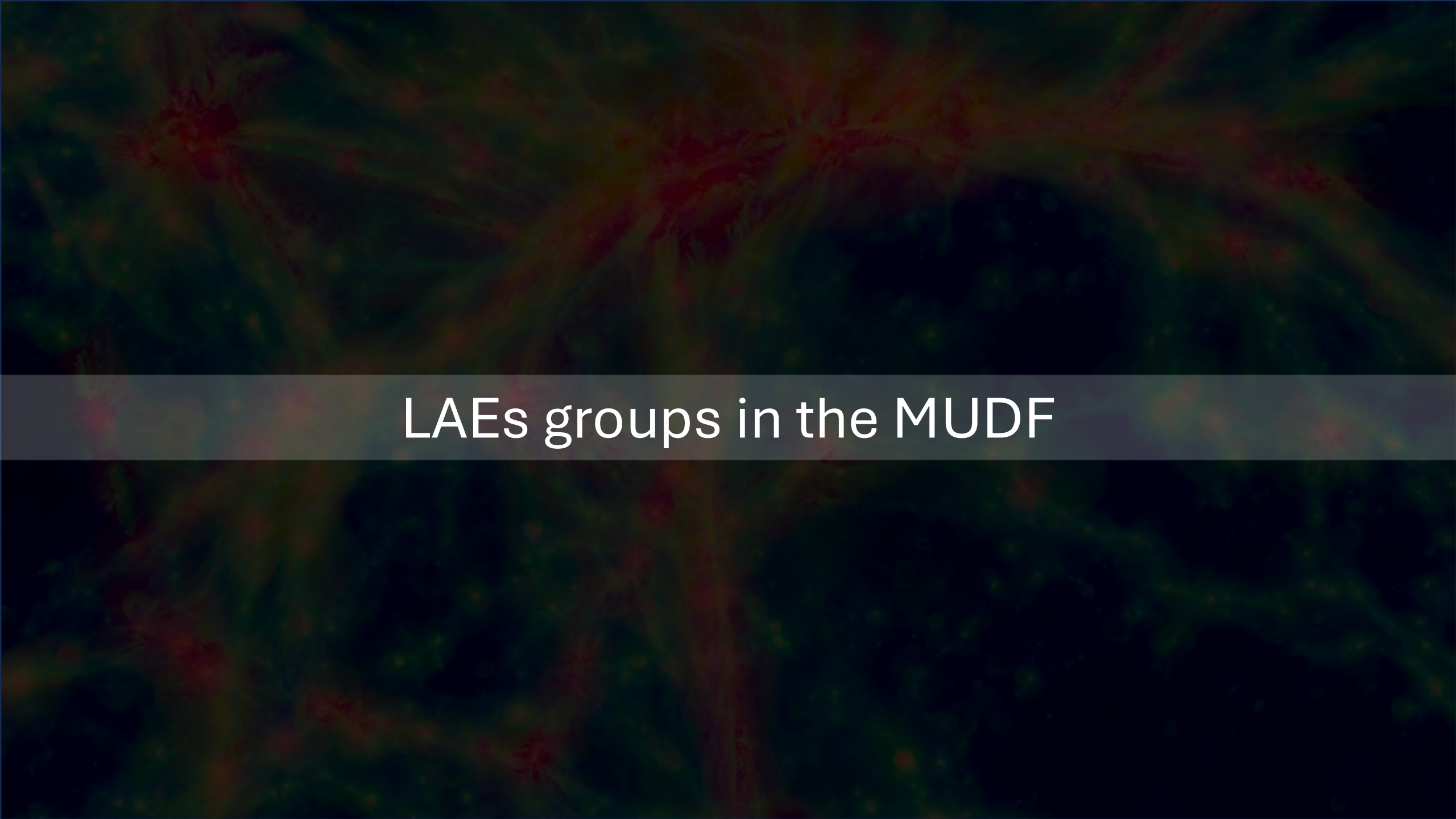
L - GALAXIES

Comparison with TNG-100



$$n_H^{\text{IGM}} \approx 10^{-3} \text{ cm}^{-3}$$

D. Tornotti et al. submitted

A visualization of the cosmic web, showing a complex network of filaments and clusters of galaxies. The filaments are colored in shades of blue, green, and yellow, while the clusters are more densely packed and appear in warmer colors like red and orange. The background is a deep black, representing the vastness of space.

LAEs groups in the MUDF

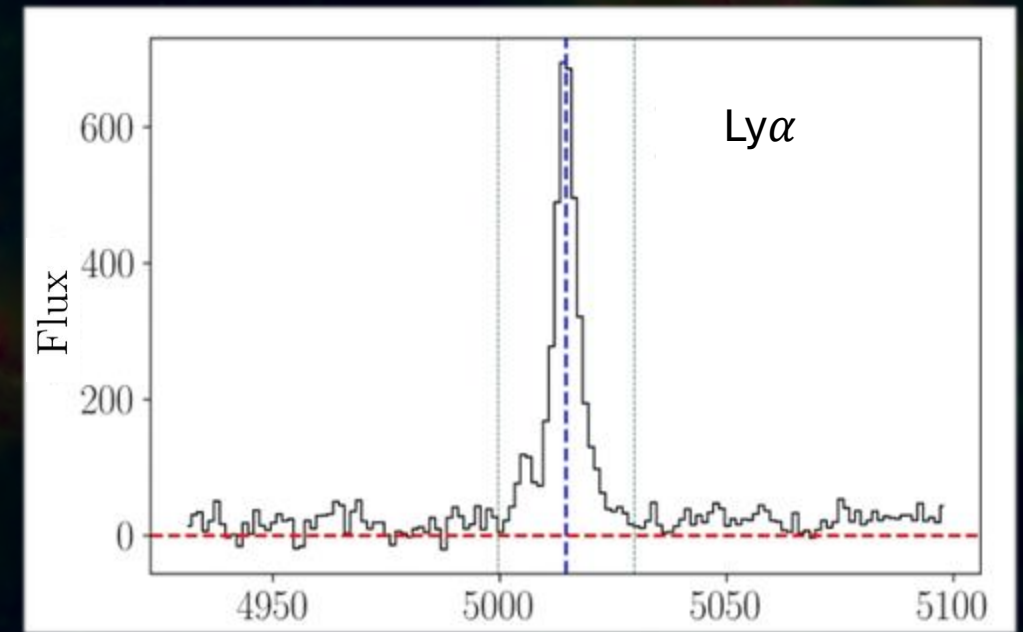
LAEs groups in the MUDF

Lyman-alpha emitters (LAEs): young , star forming and low mass galaxies showing Ly α emission line in their spectra.

Step 1: Catalogue of LAEs in the MUDF;

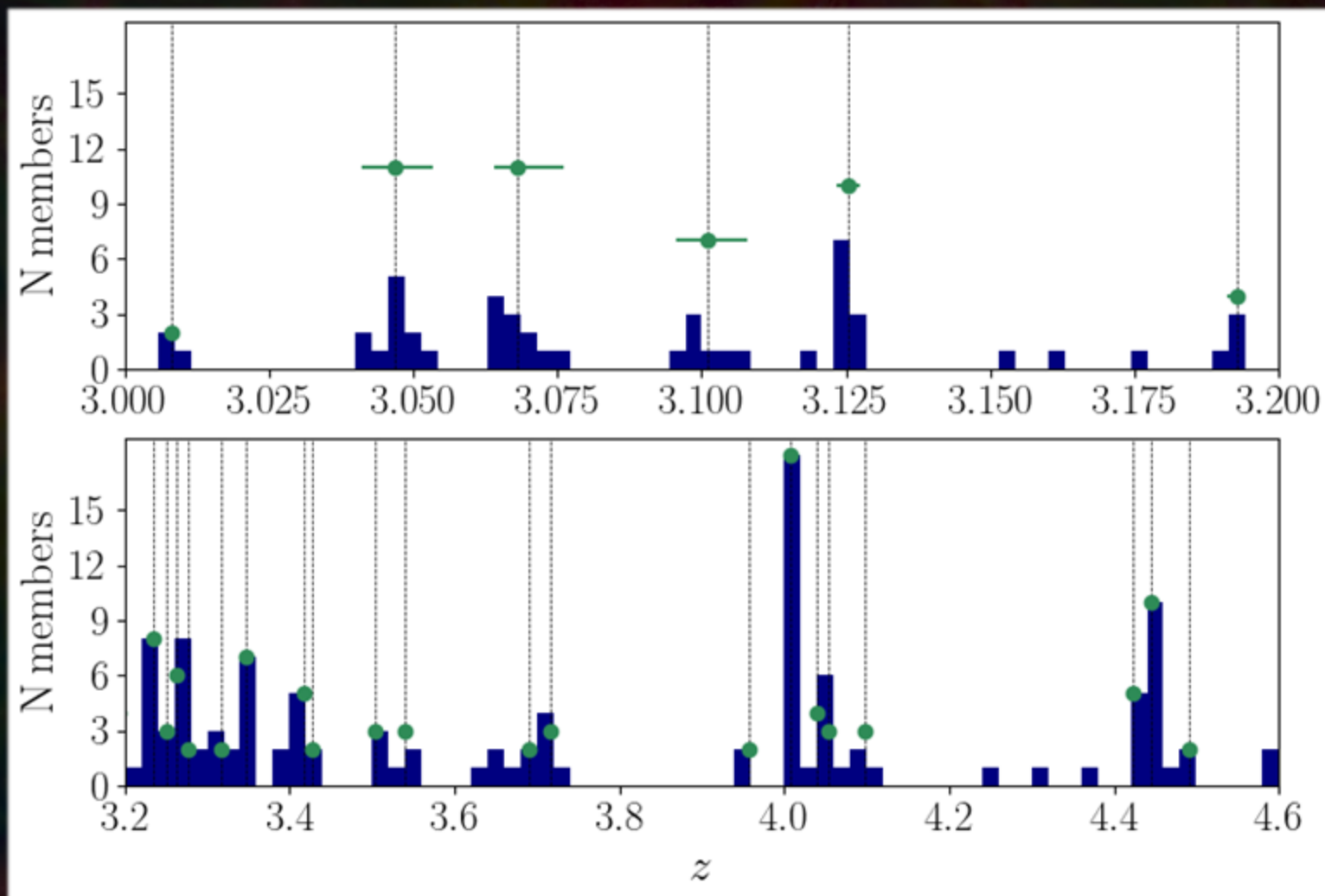
Step 2: Define overdense regions of LAEs;

Step 3: Search for extended Ly α emission tracing filamentary structures.



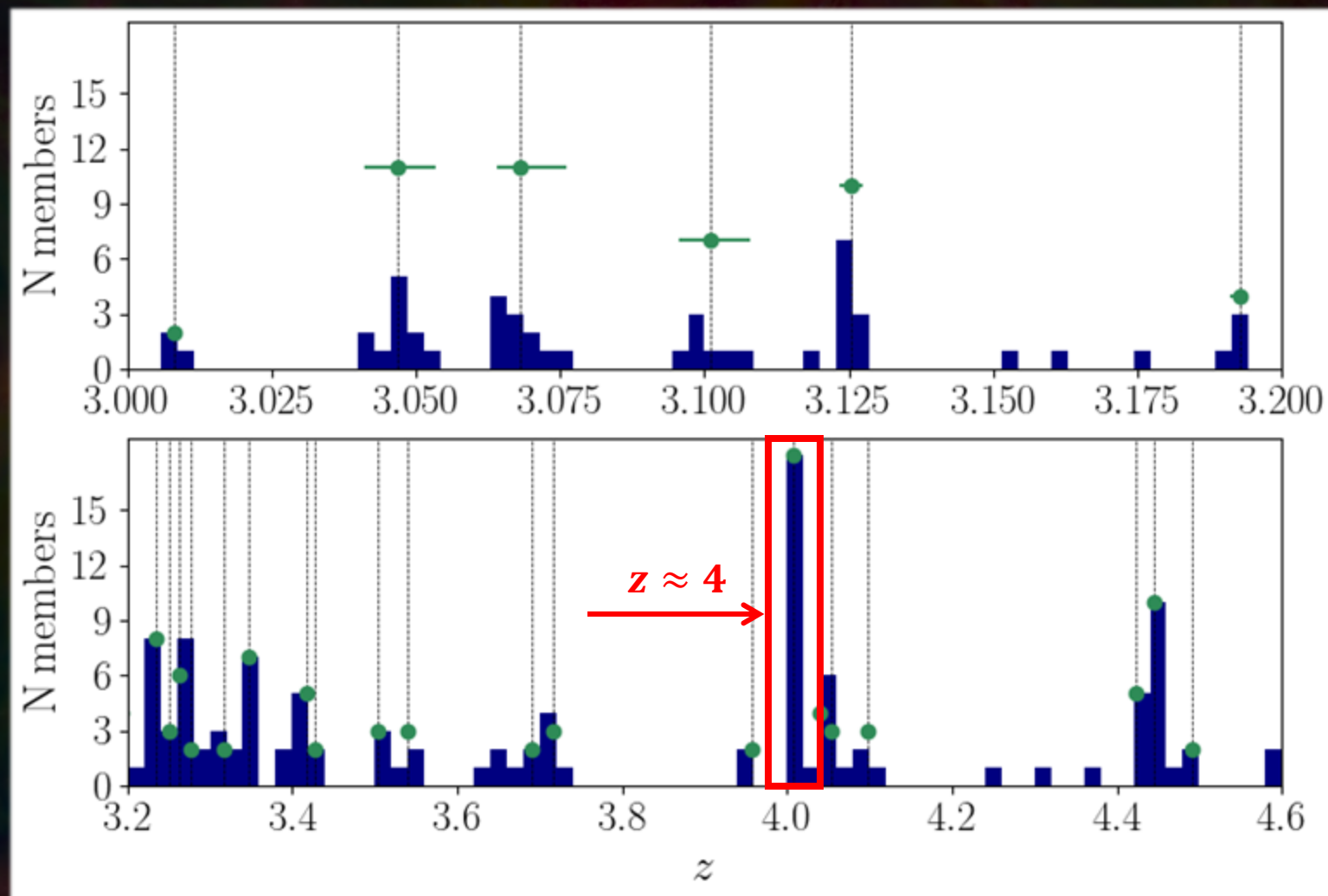
LAEs groups in the MUDF

More than 200 spectroscopically confirmed LAEs

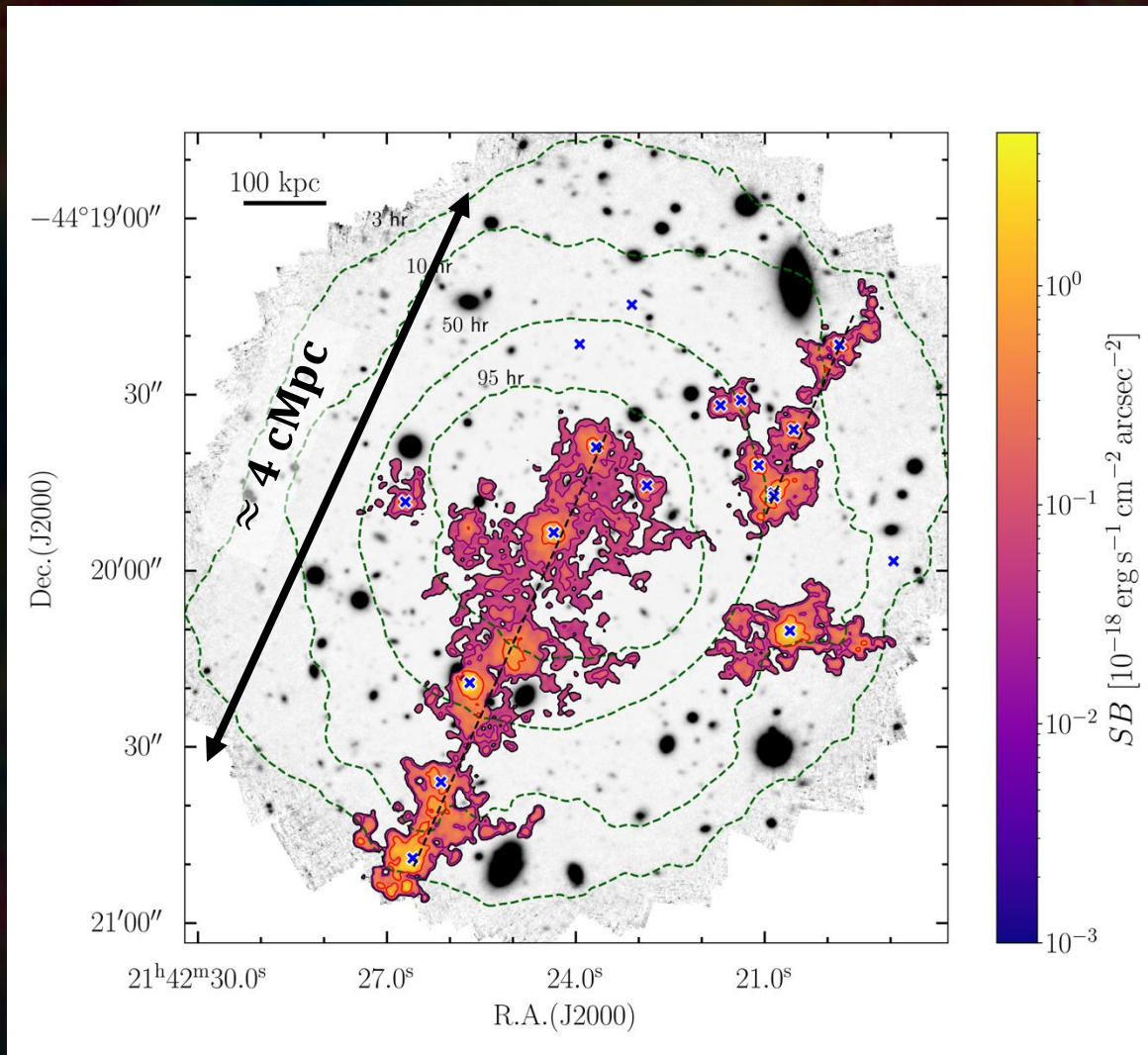


LAEs groups in the MUDF

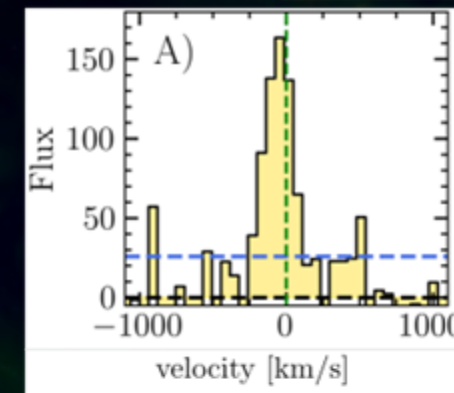
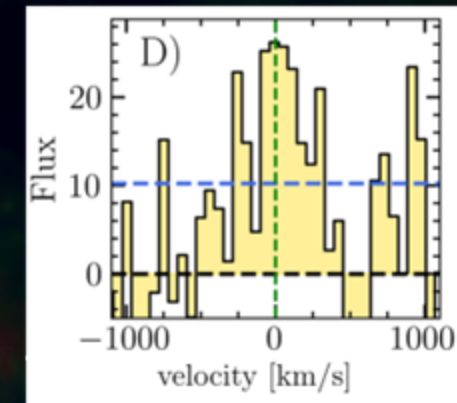
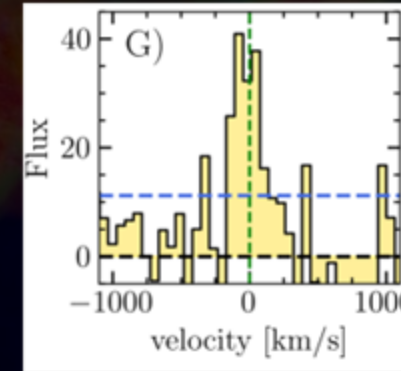
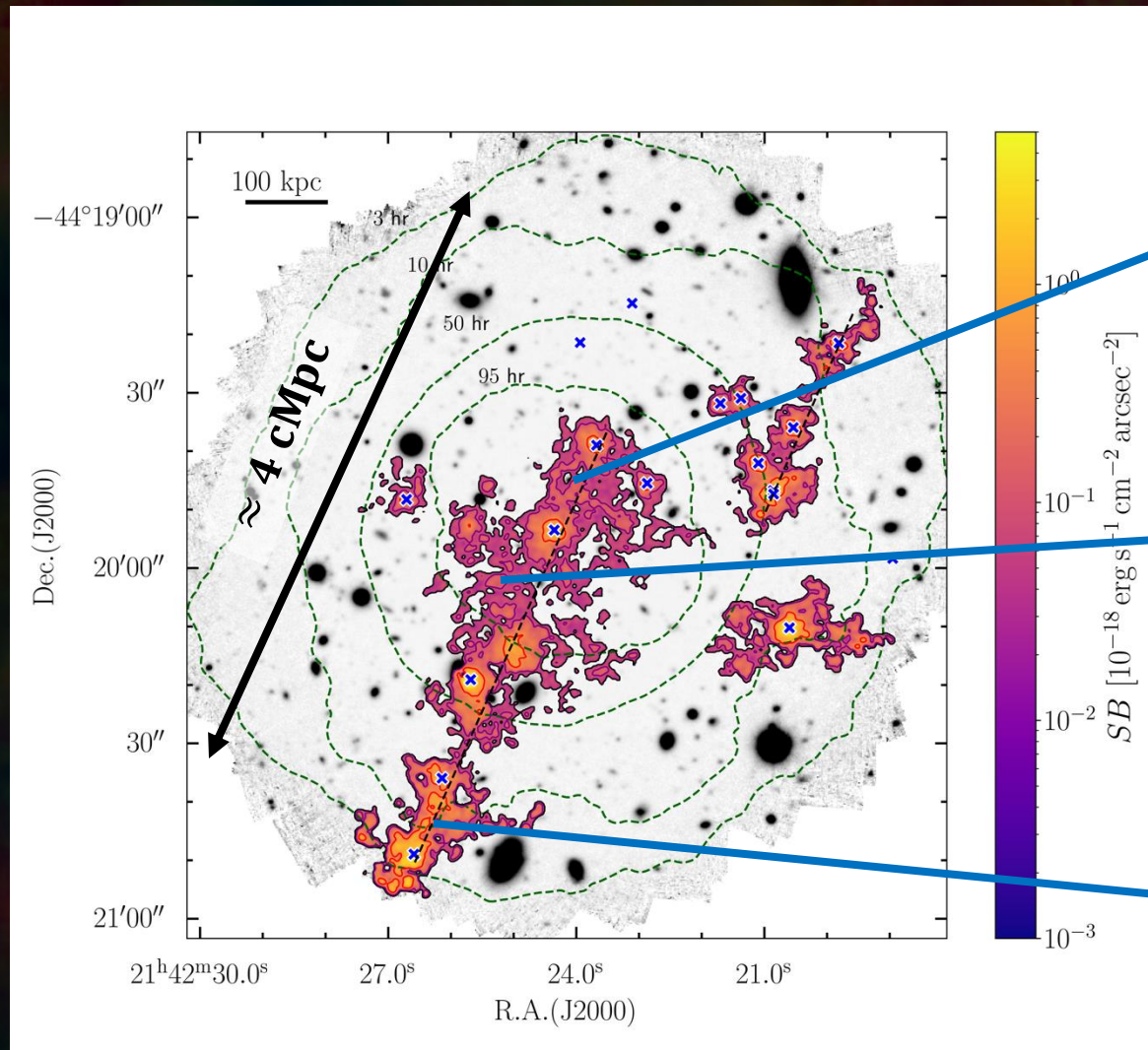
More than 200 spectroscopically confirmed LAEs



Filaments around normal galaxies at $z \sim 4$

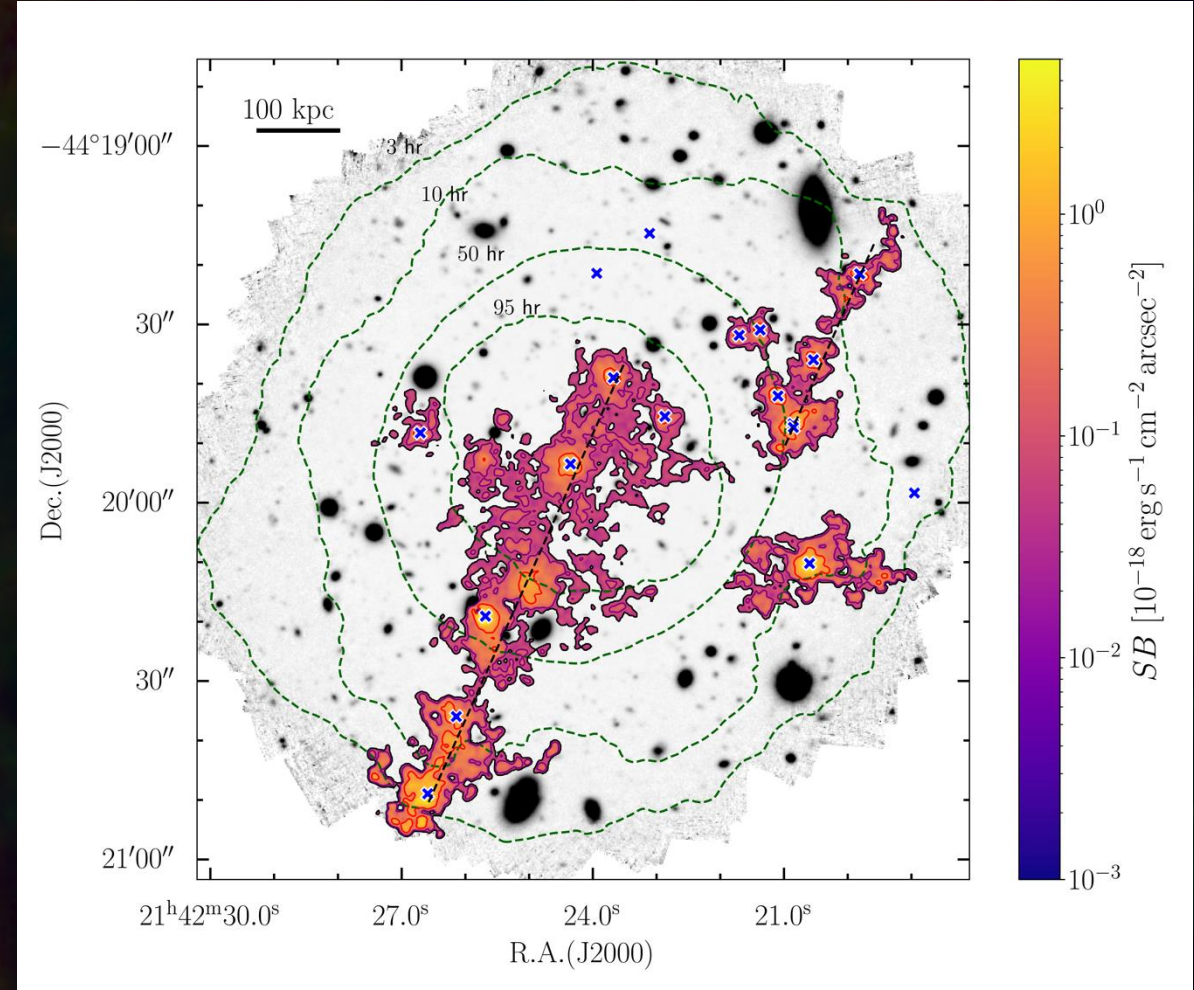
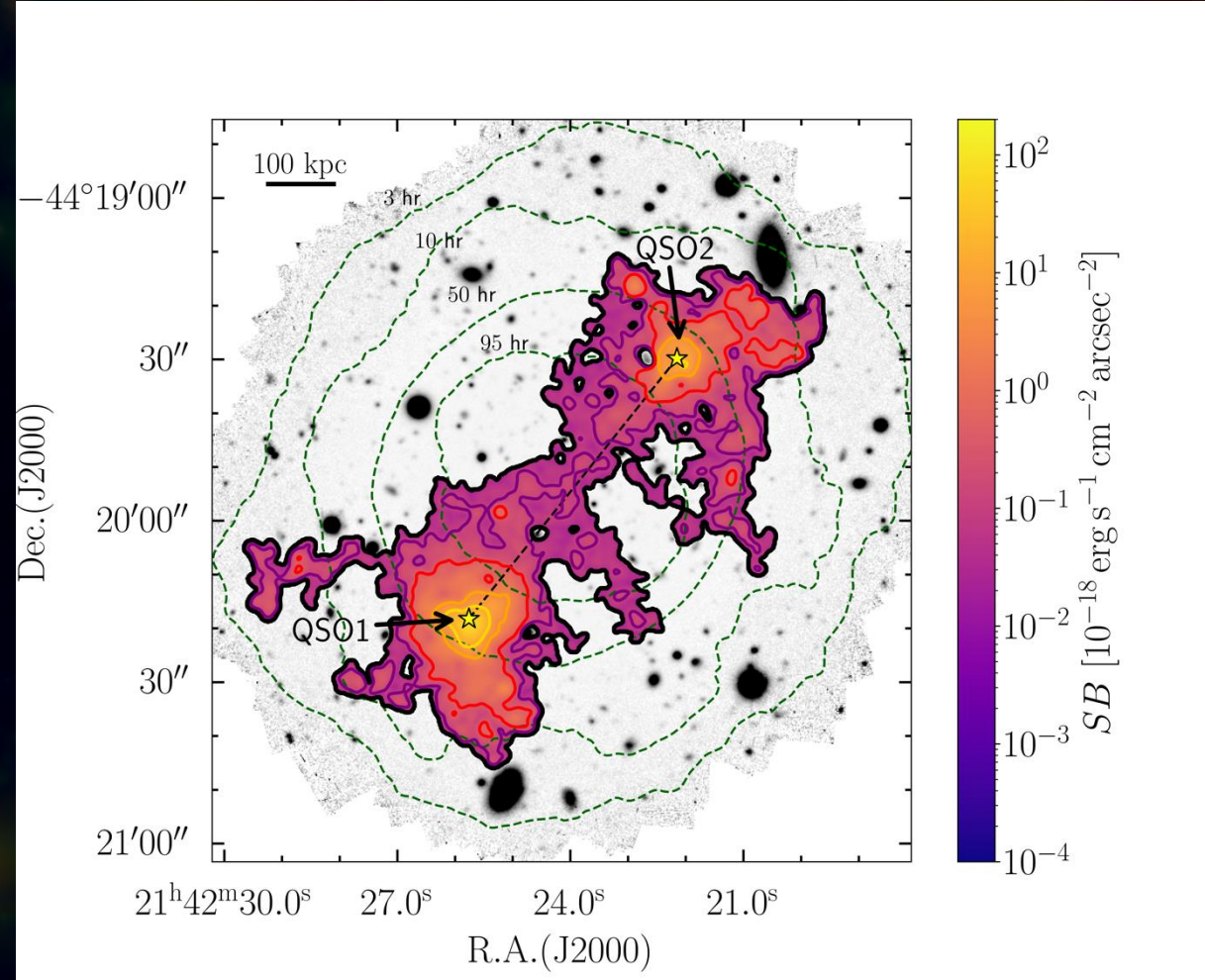


Filaments around normal galaxies at $z \sim 4$



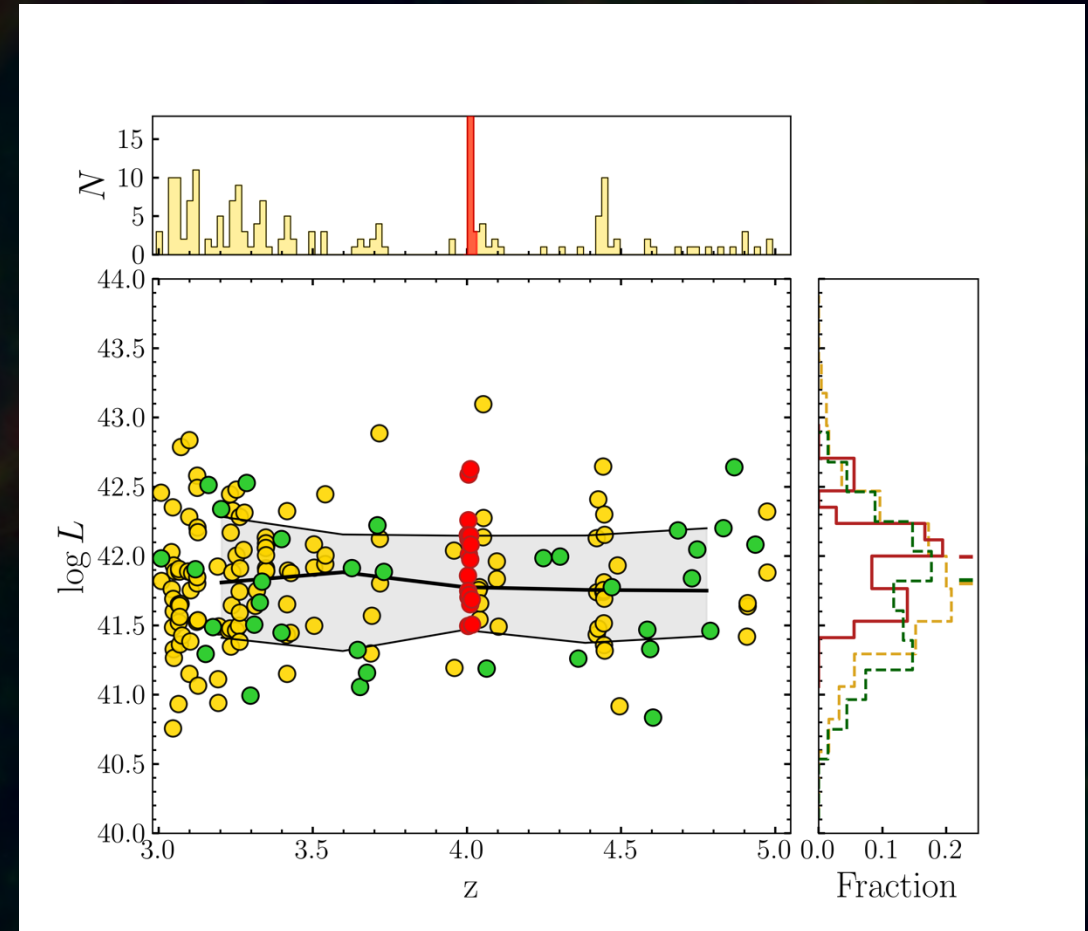
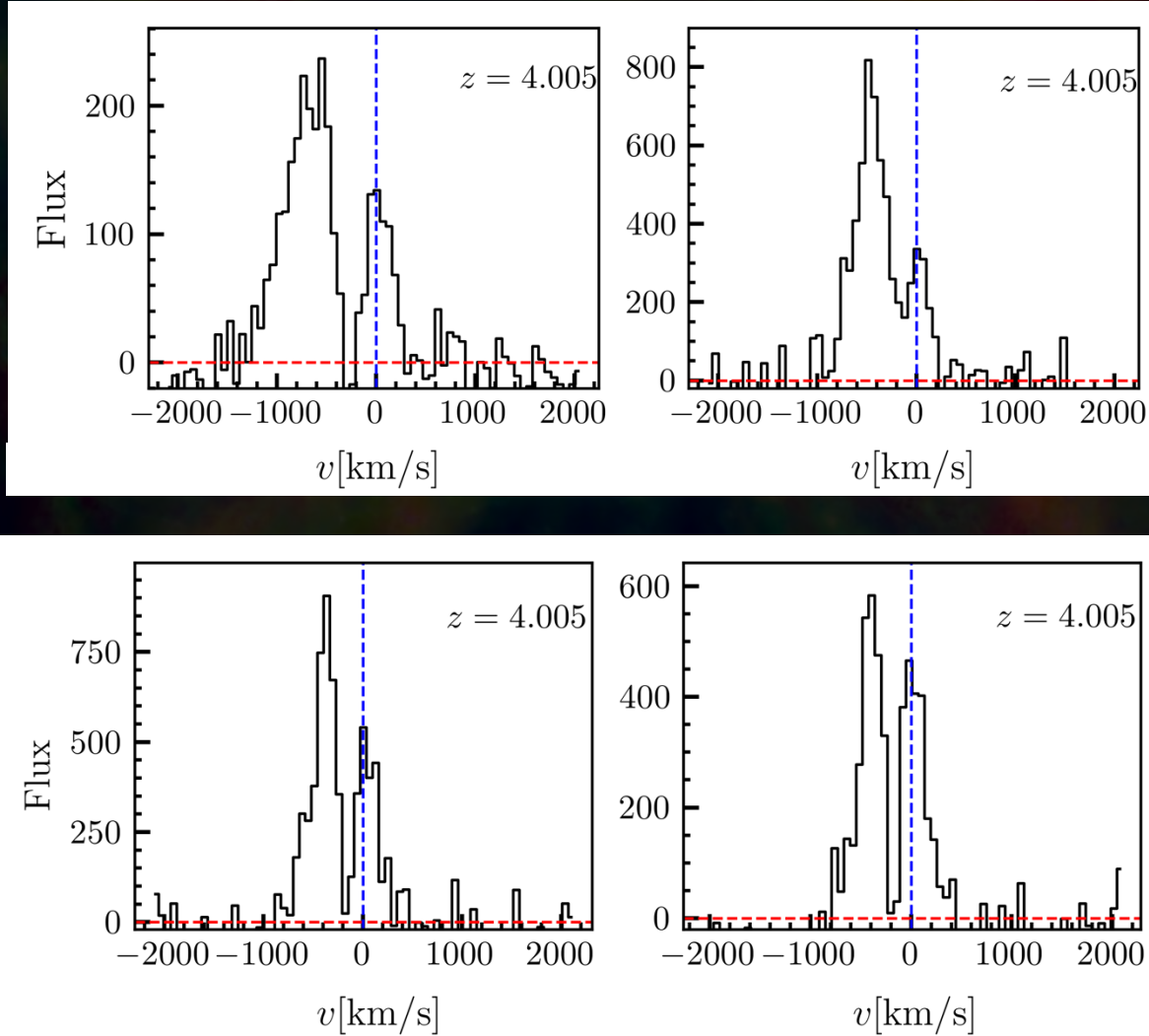
Filaments comparison

Similar surface brightness levels of $\approx 4 - 8 \times 10^{-20} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ arcsec}^{-2}$) in the IGM, even if **different environments** and **redshifts**



LAEs embedded in the filament $z \sim 4$

Blue dominated double peaked $\text{Ly}\alpha$ lines in $\sim 25\%$ of the LAEs in the group at $z \sim 4 \rightarrow$ synthon of inflow of gas? \rightarrow enhanced star formation rate? \rightarrow no evident shift in luminosity respect to a control sample.

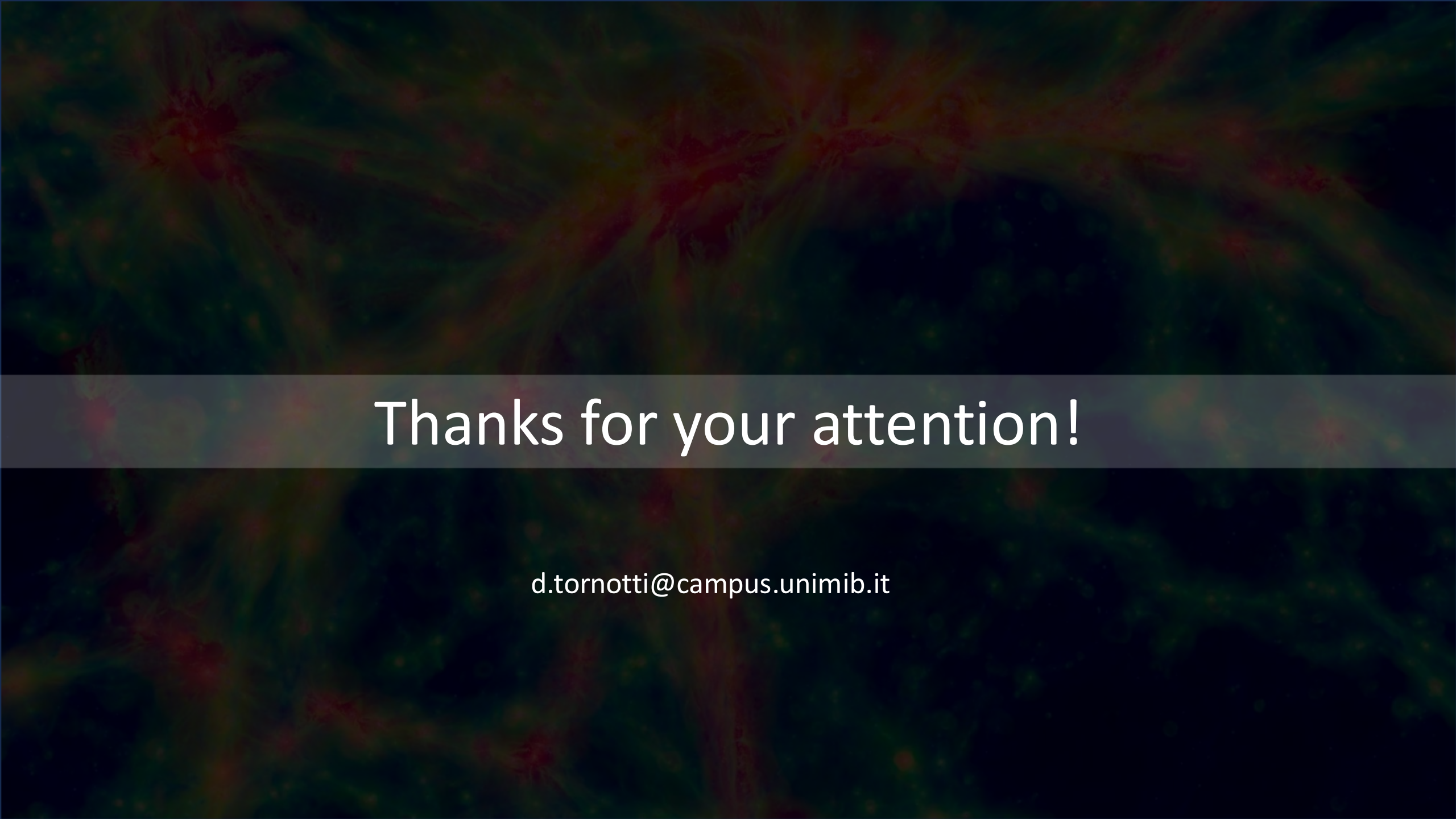


Summary

- The MUSE Deep Fields have unlocked the ability to study cosmic filaments on scales of the pMpc;
- We can now start to probe different environments (QSOs → LAEs) across different redshifts ($z \approx 3 - 4$);
- This breakthrough opens a completely new window, allowing us to start compiling **samples** of filaments and begin constraining their properties statistically.

QSO pair filament: <https://arxiv.org/abs/2406.17035>

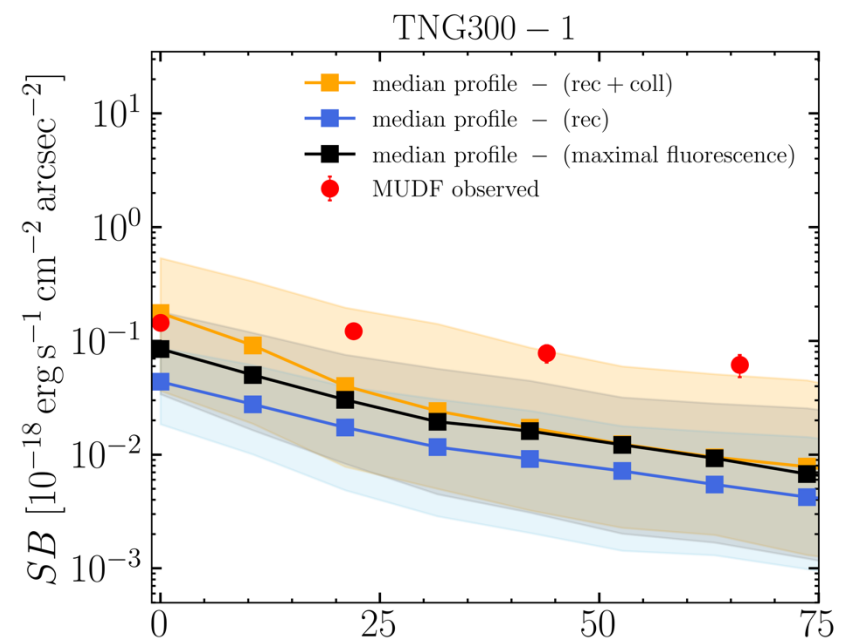
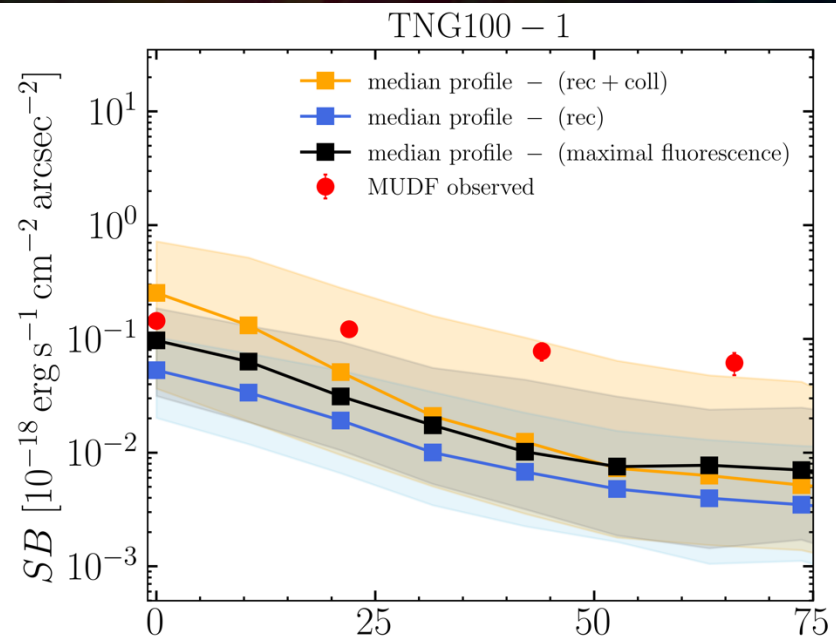
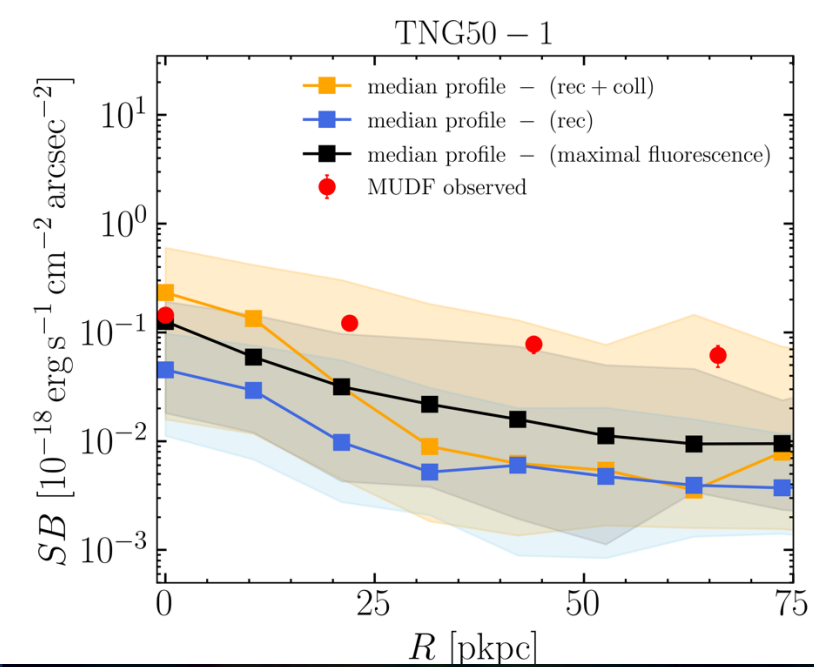
d.tornotti@campus.unimib.it

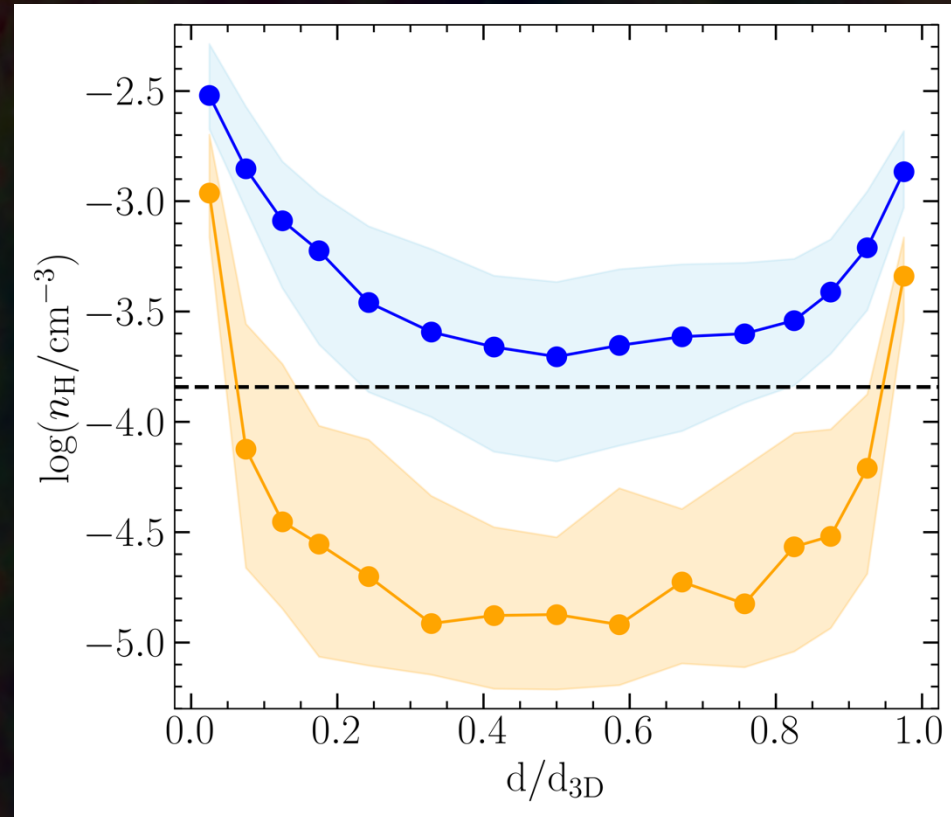
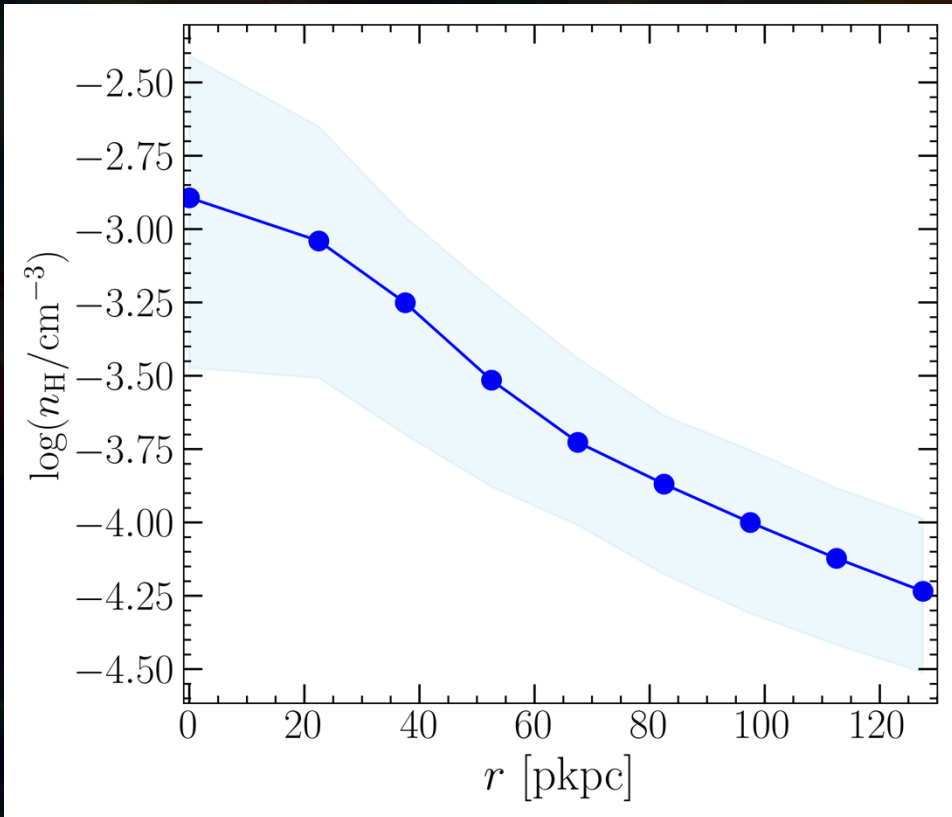


Thanks for your attention!

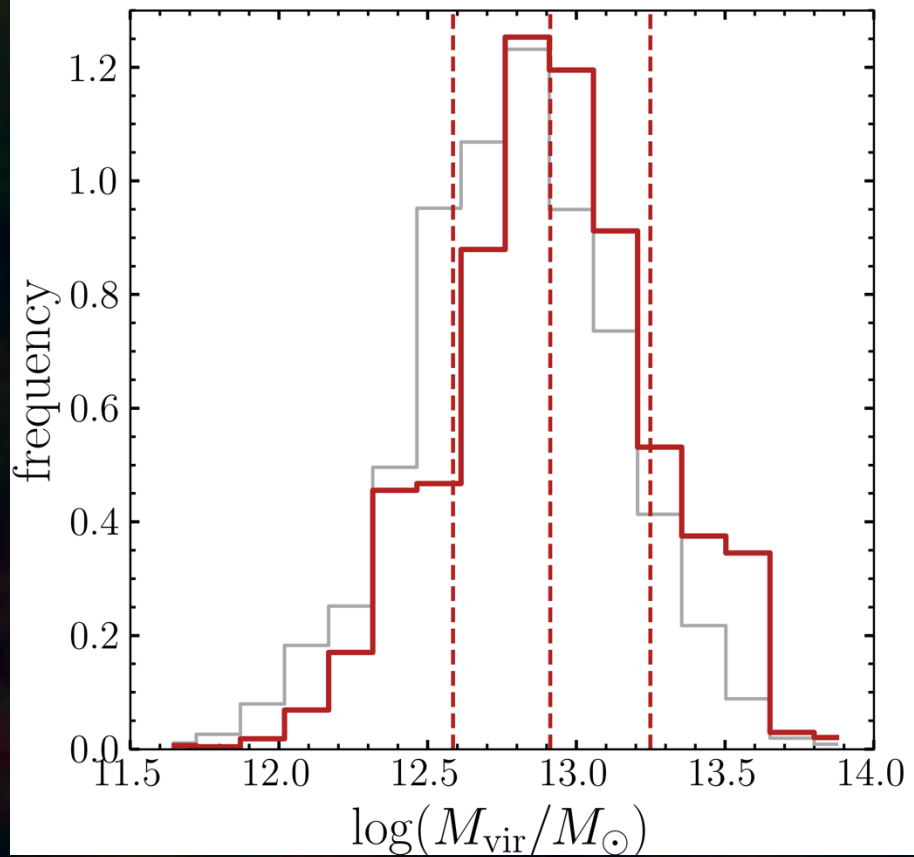
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Supplementary Slides

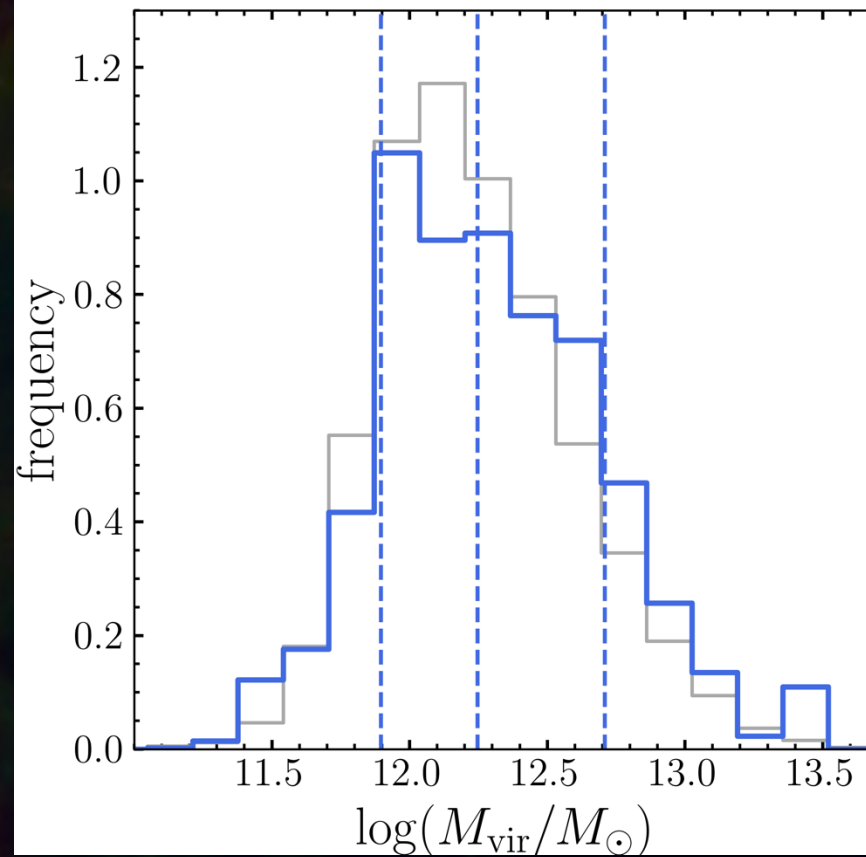


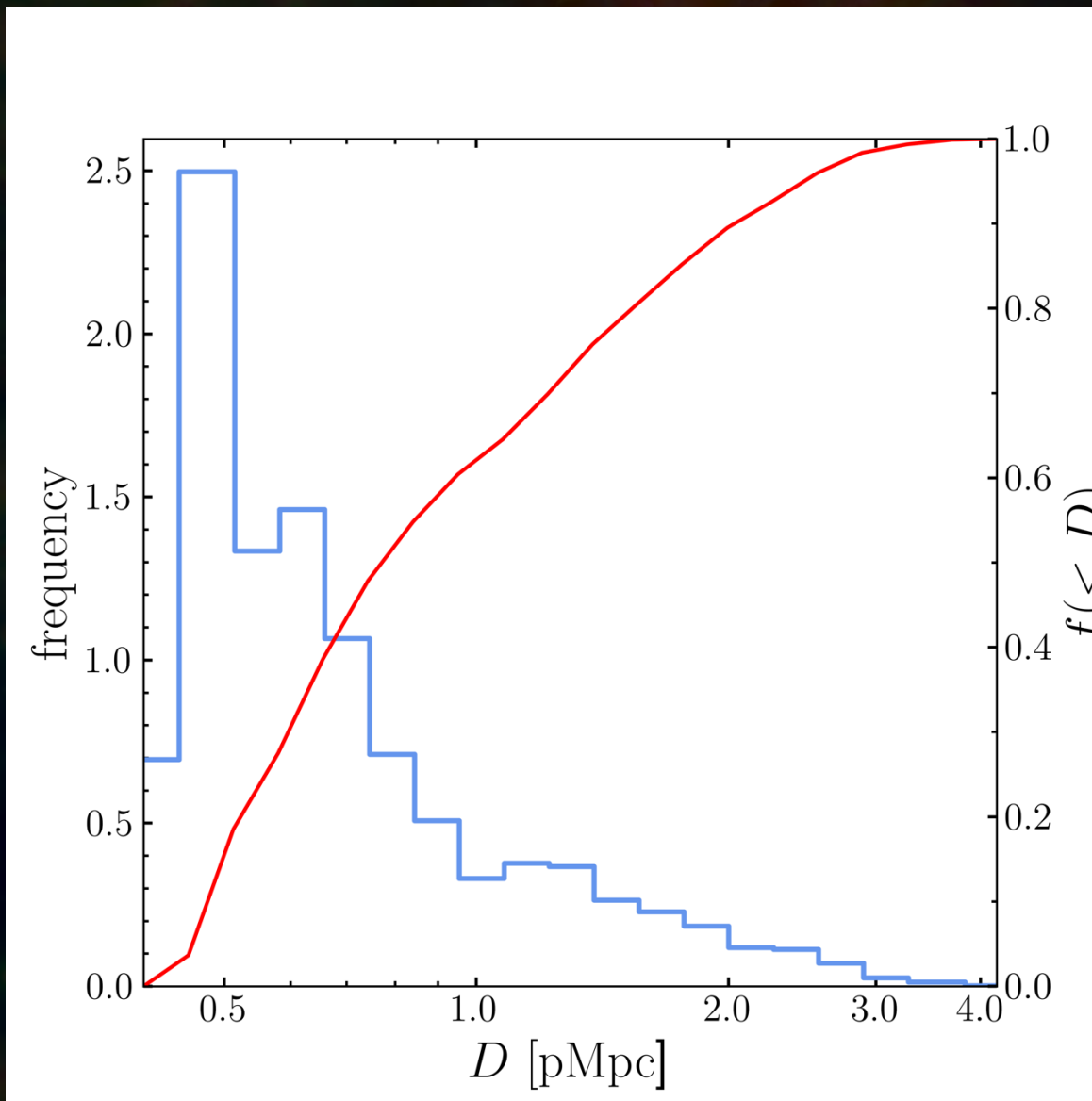


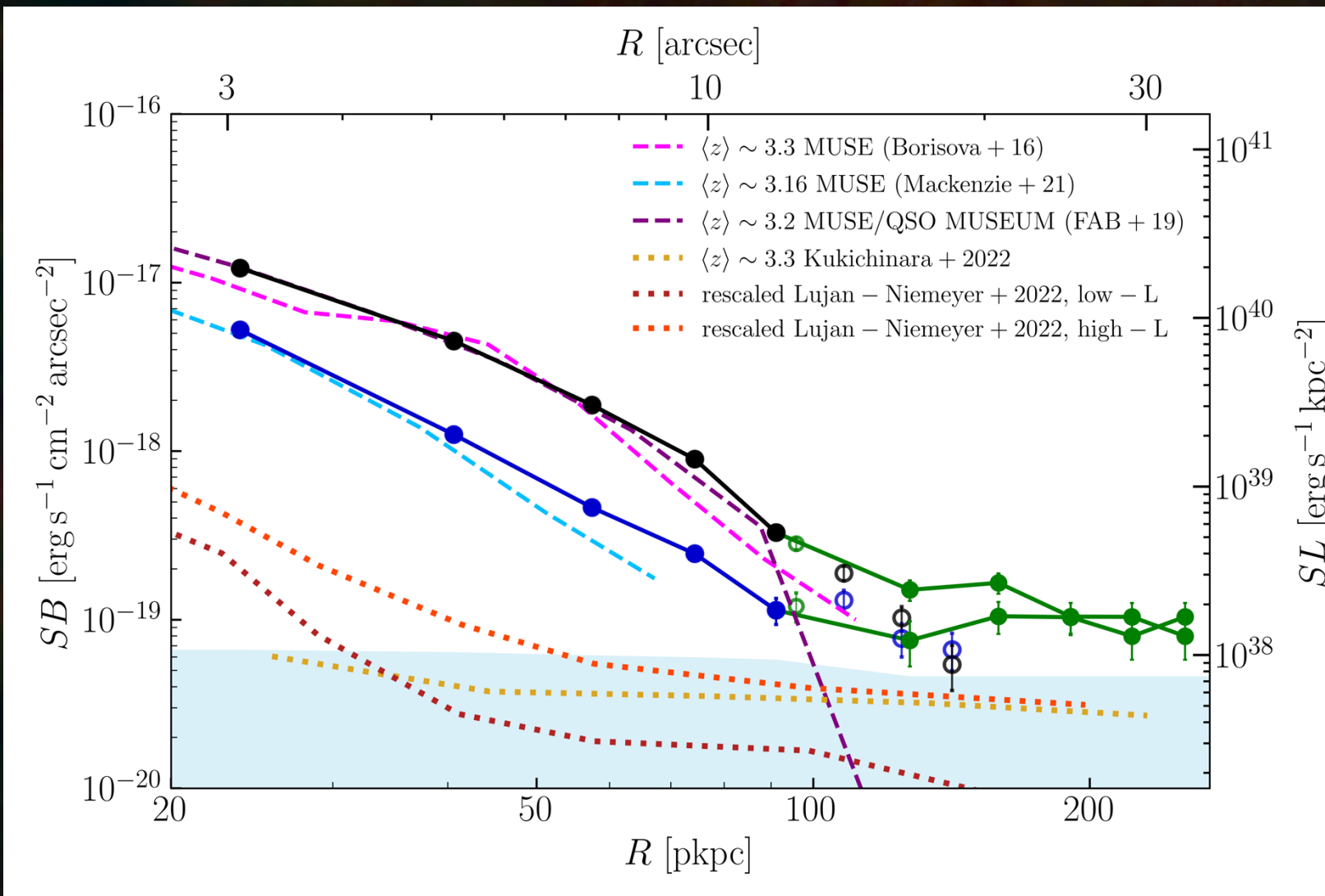
QSO1 (Bright)

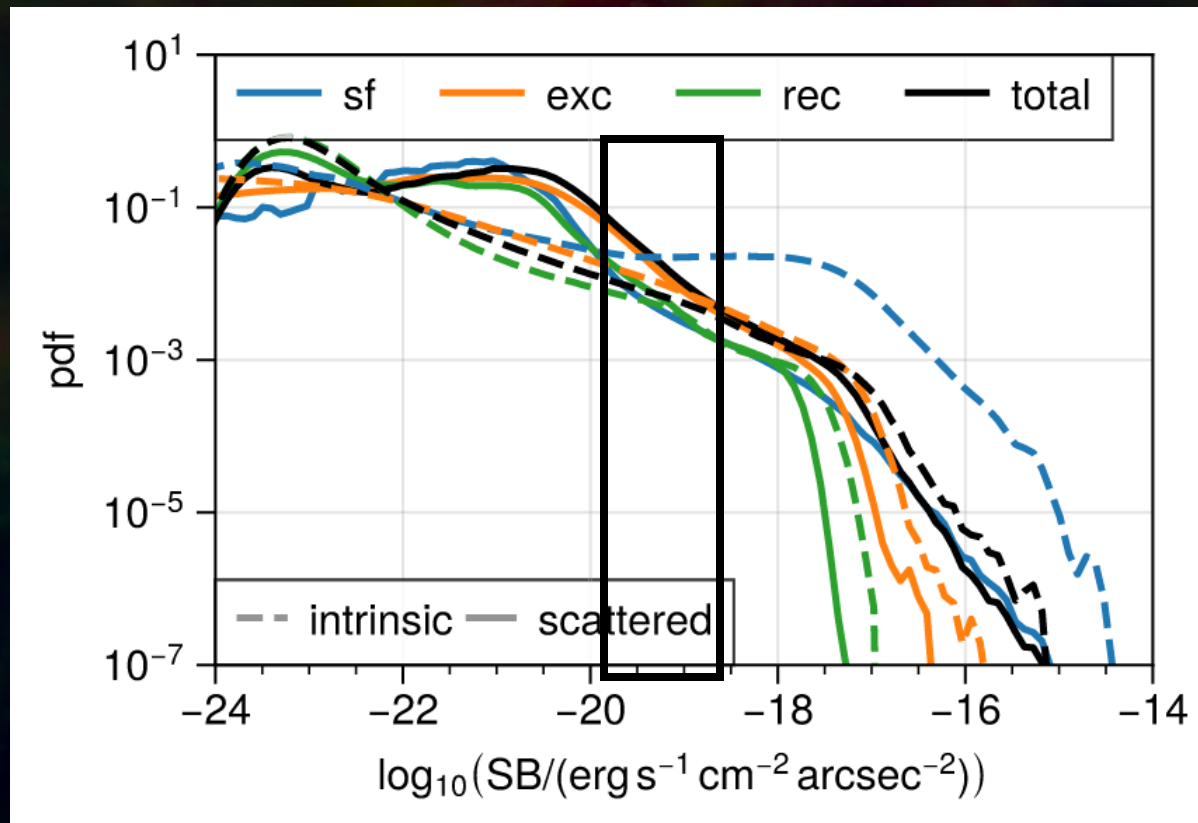


QSO2 (Faint)









Byrohl & Nelson 2023