Mapping the Cosmic Web in Lyα around QSOs and non-AGN galaxies

Davide Tornotti

Collaborators: M. Fumagalli, M. Fossati, A. Benitez Llambay, F. Arrigoni Battaia and the MUDF team

UNIVERSITÀ DEGLI STUDI DI MILANO BICOCCA

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Presentation Outline

- Introduction and key questions
- The MUSE Ultra Deep Field (MUDF) dataset
- Cosmic filament connecting a QSO pair
- LAE overdensities in the MUDF
- The LAE Luminosity Function
- The future: BlueMUSE and (possibly) WST
- Conclusions

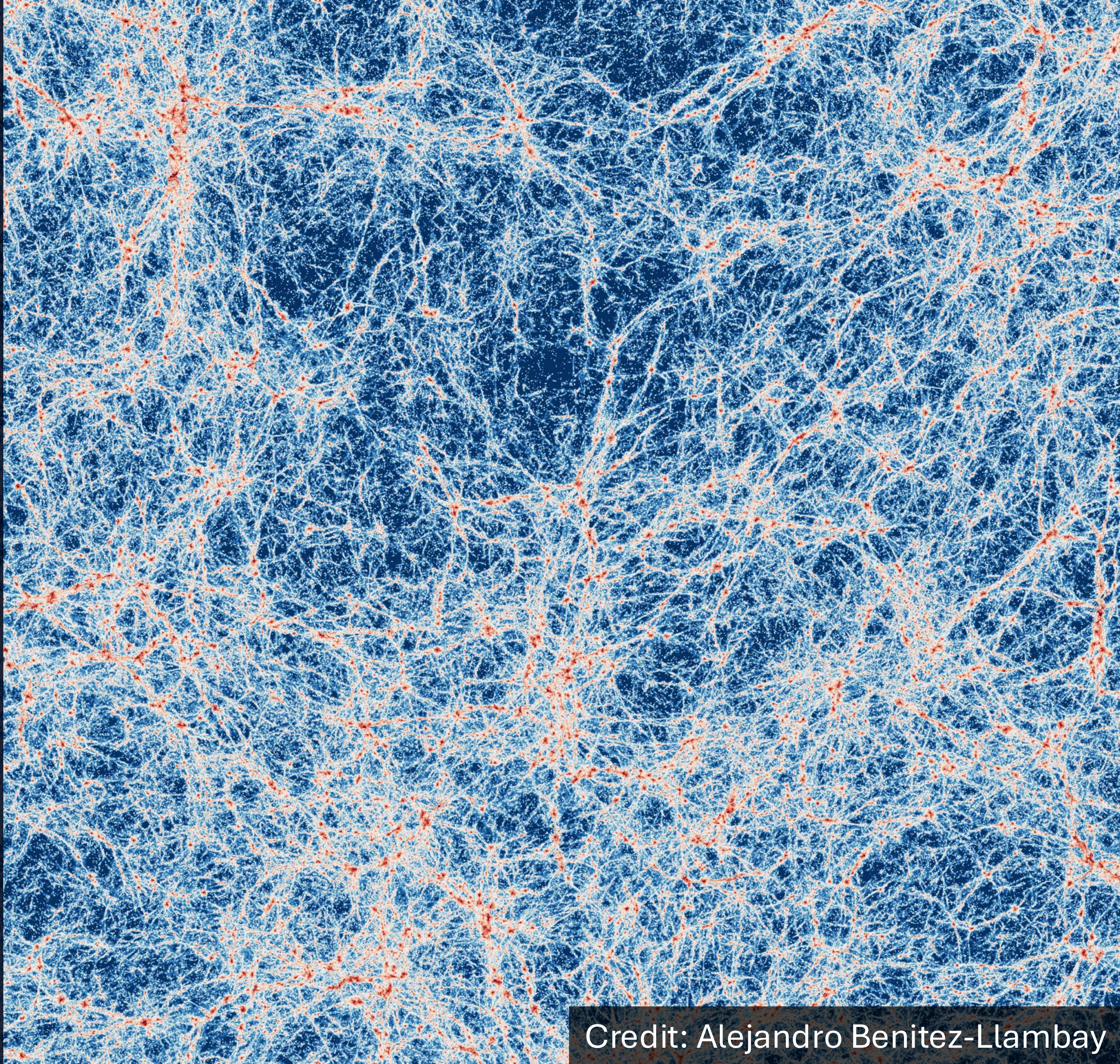
Introduction and key questions

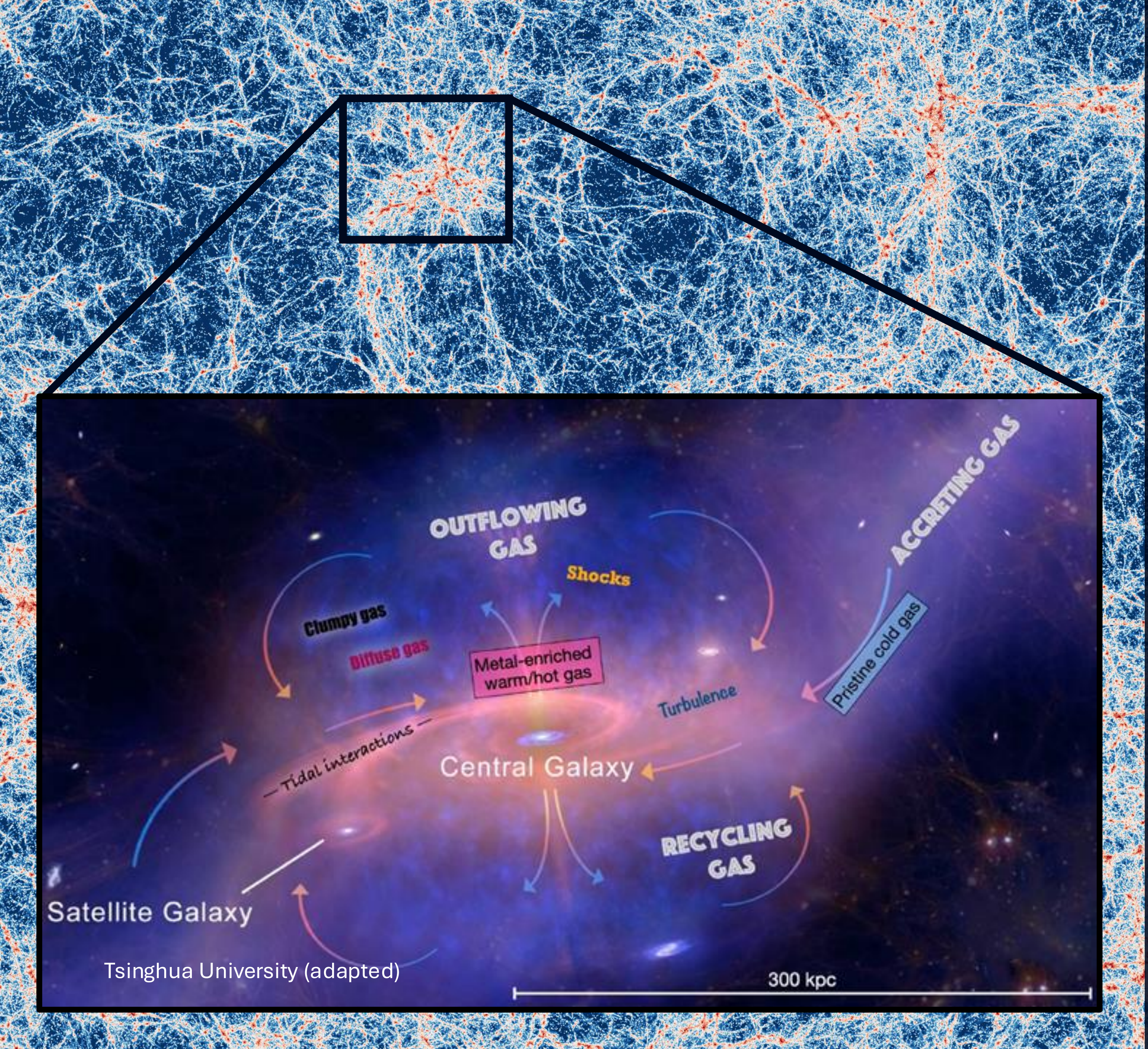
ΛCDM cosmological paradigm

↓

Matter on large scales organizes into a network of filaments, nodes, sheets and voids:

«THE COSMIC WEB»
(e.g. Bond et al 1996)





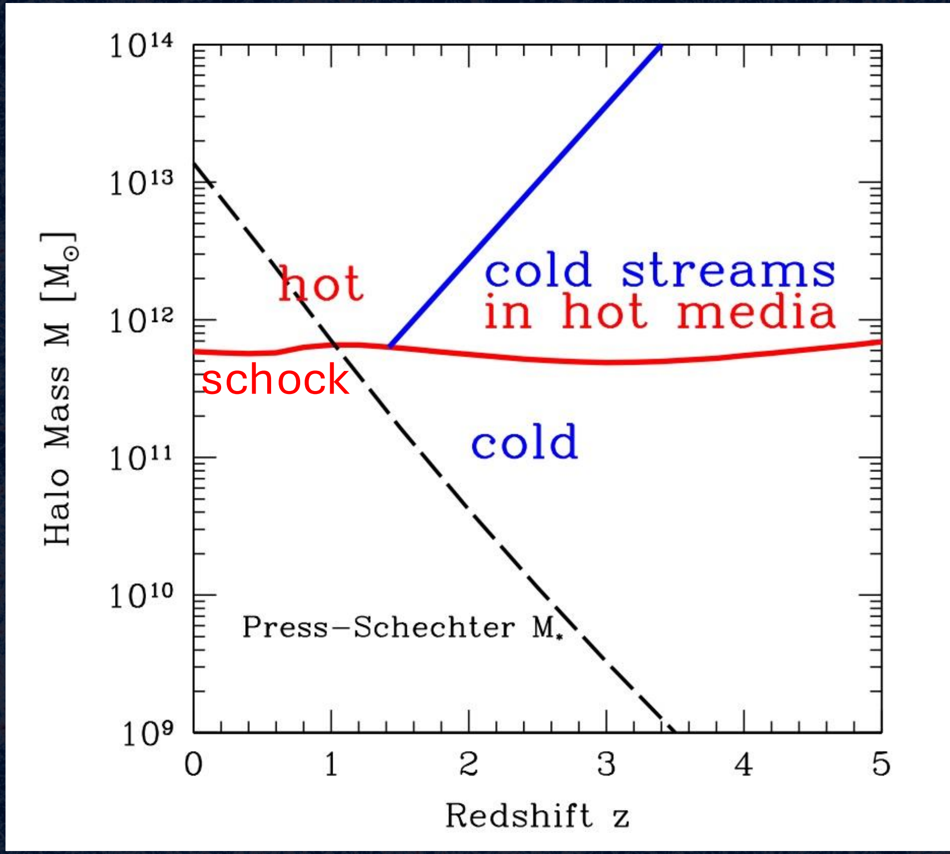
Filaments feed the CGM that regulates the gas exchange between galaxies and the sorrounding IGM
(e.g Tumlison et al 2017)

↓

Controls the galaxy growth across cosmic time

How do galaxies get their gas?

The gas accretion from the Cosmic Web is the dominant accretion mechanism
(e.g. Keres et al 2005, Dekel et al 2006)



Dekel et al 2006

- ***Hot mode***: $M_\mathrm{h} \gtrsim 6 \times 10^{11}\ \mathrm{M}_\odot$ accreted gas is schock heated and reaches $T \gtrsim 10^6\ \mathrm{K}$
- ***Cold mode***: $M_\mathrm{h} \lesssim 6 \times 10^{11}\ \mathrm{M}_\odot$ no stable schock
- ***Cold streams in hot media***: $z \gtrsim 2$ & $M_\mathrm{h} \gtrsim 10^{12}\ \mathrm{M}_\odot$ locally denser streams remain cold while penetrating the schocked medium

How do galaxies get their gas?

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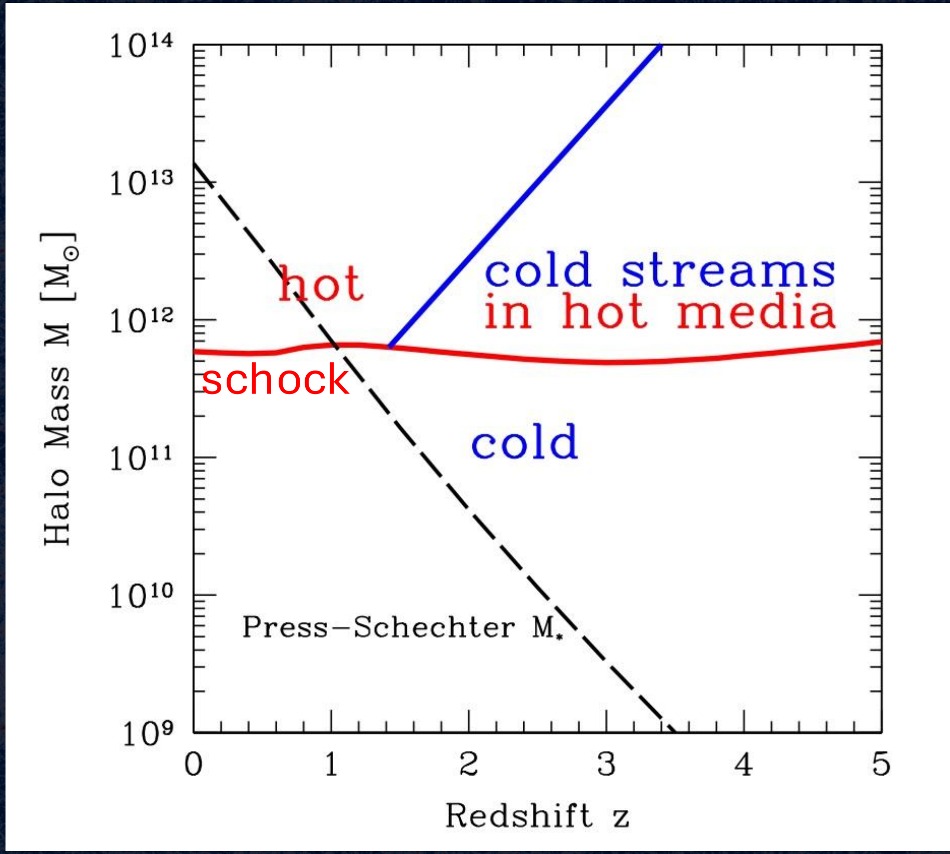
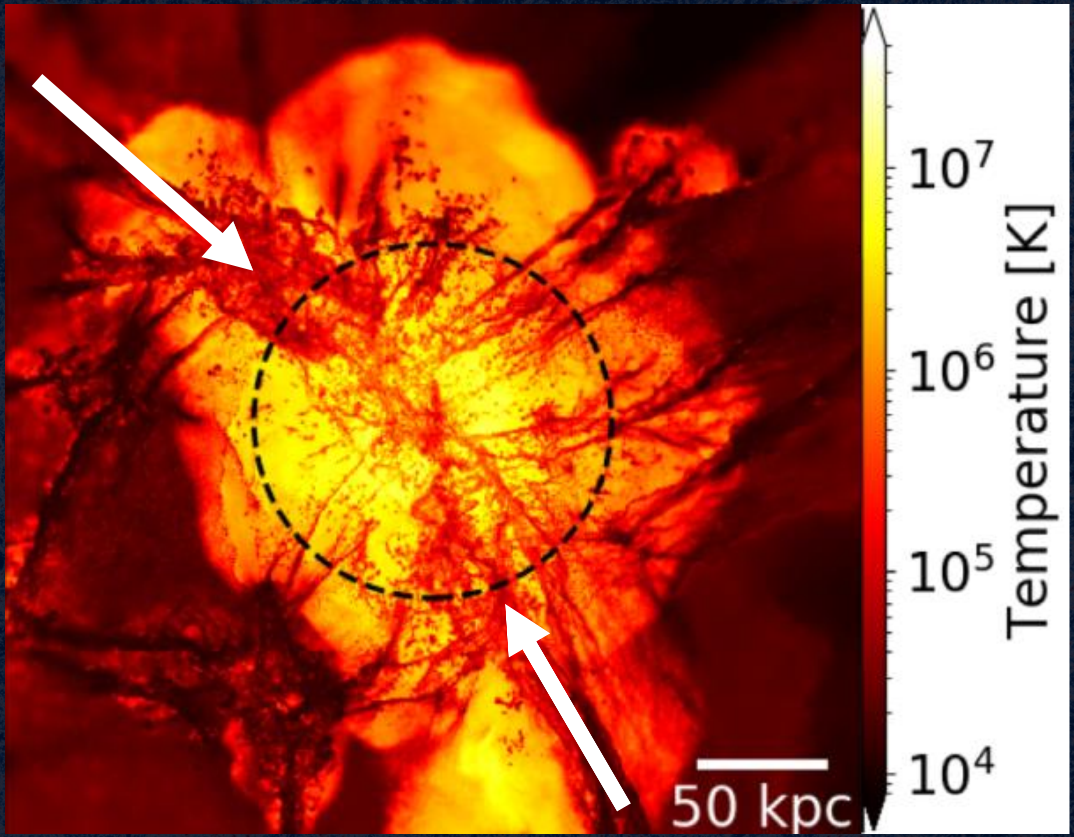


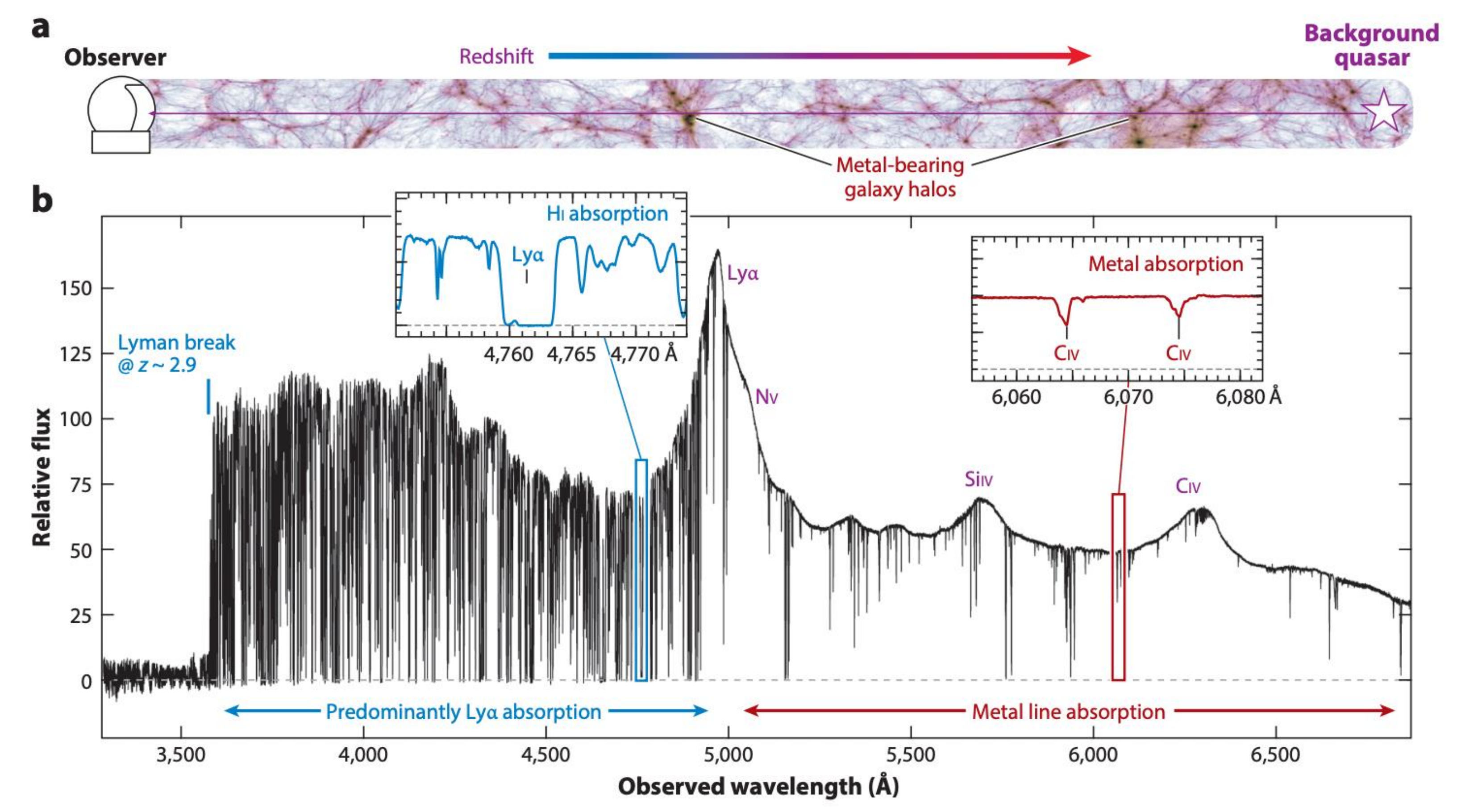
Dekel et al 2006



Bennett & Sijacki 2020

Observing both the multiphase CGM and the IGM in ***absorption***

Using background quasar to probe the foreground cosmic gas in absorption



Peroux & Howk 2020

Extremely powerful tool but provides only **one dimensional information**, limited to the line-of-sight direction

Observing both the multiphase CGM and the IGM in *emission*

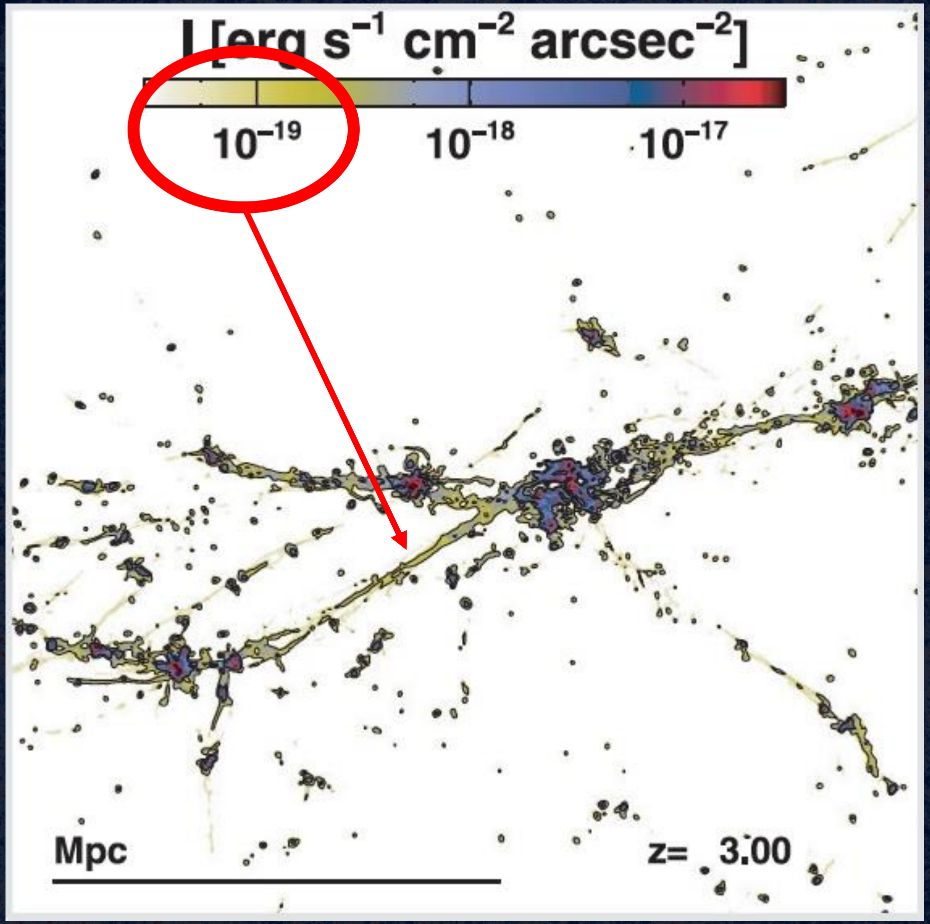
- The **gas** in the CGM is **diffuse** and even more in the IGM ($n_{\mathrm{H}} \ll 10^{-2}\ \mathrm{cm}^{-3}$) ⟶ hard to detect in emission

- **Hydrogen Lyα λ1215.67** Å map in emission the gas in both the CGM and IGM on large scales ($\gg 100$ kpc) at $z \approx 2-4$
  (e.g. Gould & Weinberg 1996, Cantalupo et al 2005, Kollmeier et al 2010, Rosdahl & Blaizot 2012, Elias et al 2020, Byrhol & Nelson 2023, Liu et al 2024);

- Main Lyα mechanisms:
  - recombination of a free proton and electron
  - collisional excitations (cooling radiation)

  \+ resonant scattering
  (e.g. Dijkstra et al 2019)

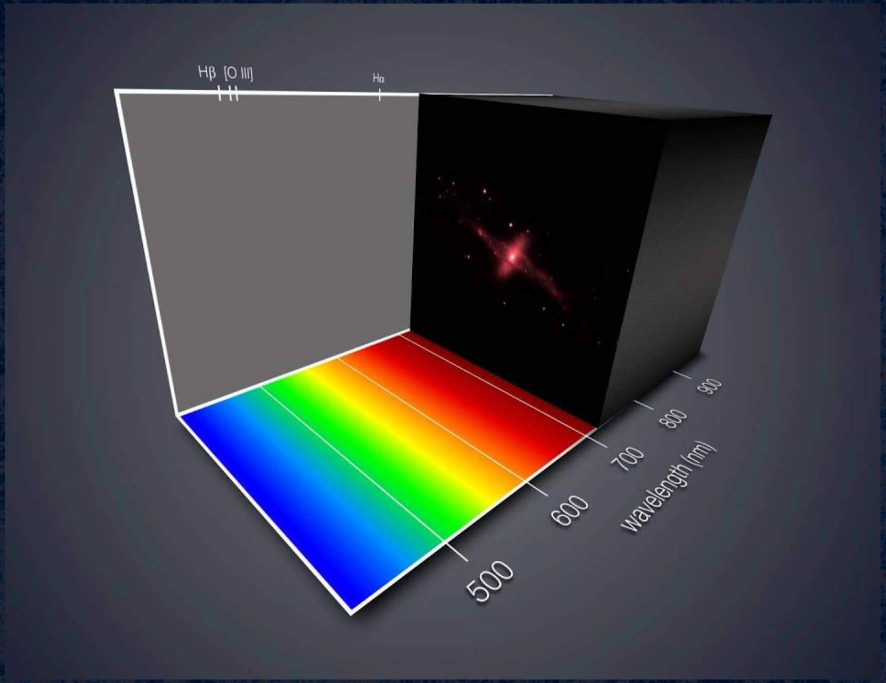
Simulated Lyα emission at $z = 3$



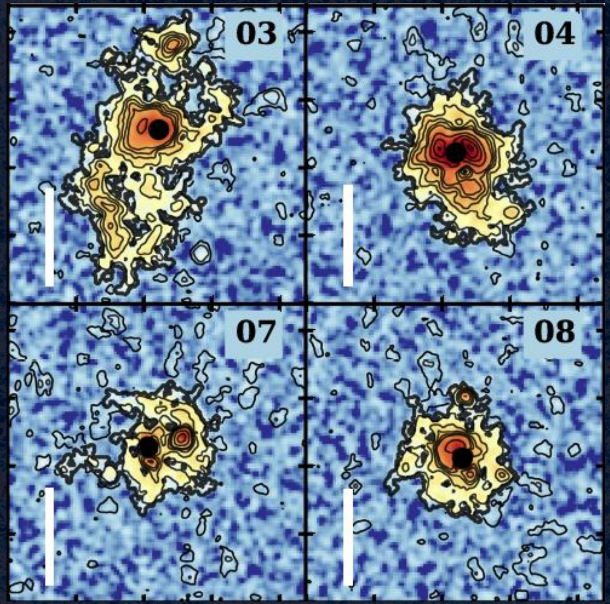
Rosdahl & Blaizot 2012

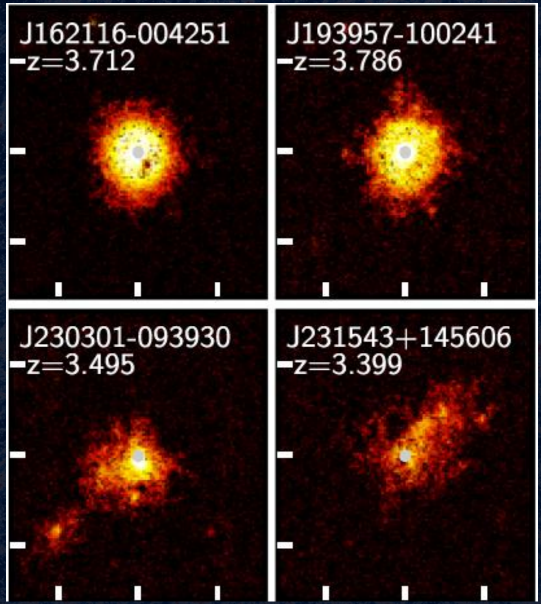
Observing both the multiphase CGM and the IGM in ***emission***

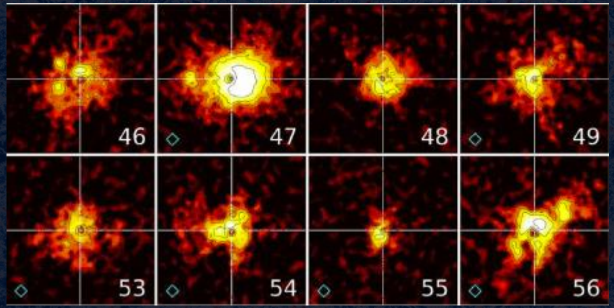
The advent of large-format integral field spectrographs at 8 m class:
Lyα emission tracing cold gas of CGM up to $\sim$100 kpc (so called **Lyα nebulae**)

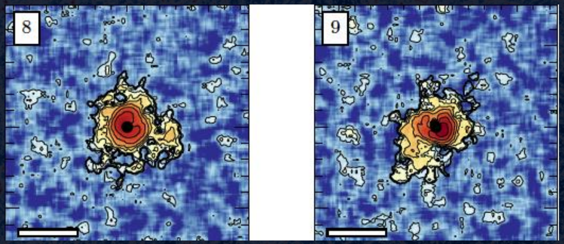


muse
multi unit spectroscopic explorer





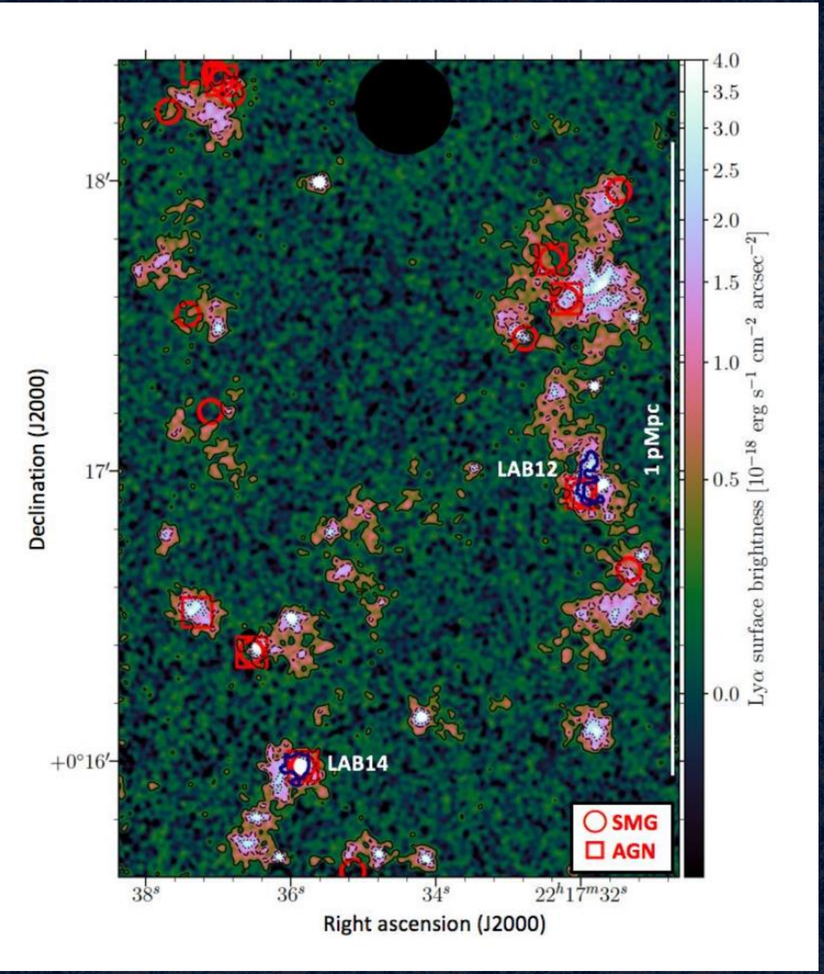




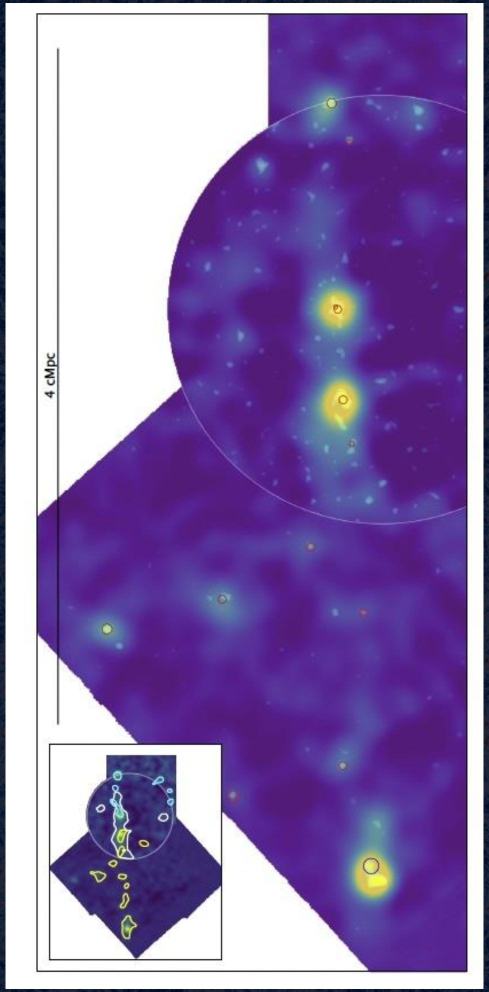
Borisova et al 2016, Arrigoni Battaia et al 2018, Fossati et al 2021, Mackenzie et al 2021

Observing both the multiphase CGM and the IGM in *emission*

The Cosmic Web in ***emission***: known examples



SSA22 – Umehata et al. 2019



MXDF – Bacon et al. 2021

Key questions

How are galaxies linked together and what is the morphology of the Cosmic Web?

What are the physical properties (e.g. density, ionization state) of the gas in the large scale filaments?

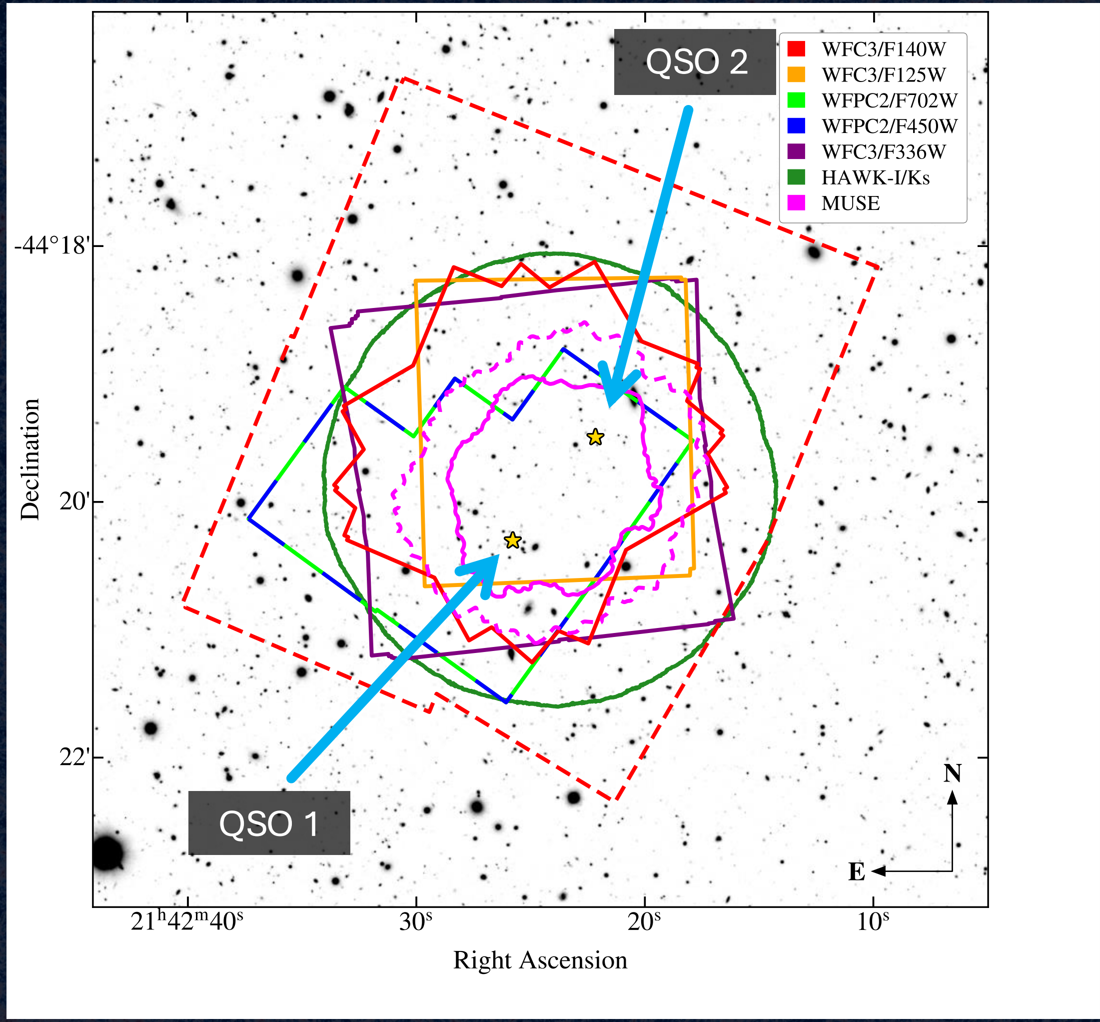
How do galaxies get their gas and are linked to their CGM/IGM?

The MUSE Ultra Deep Field survey

The MUSE Ultra Deep Field (MUDF)

Observations:

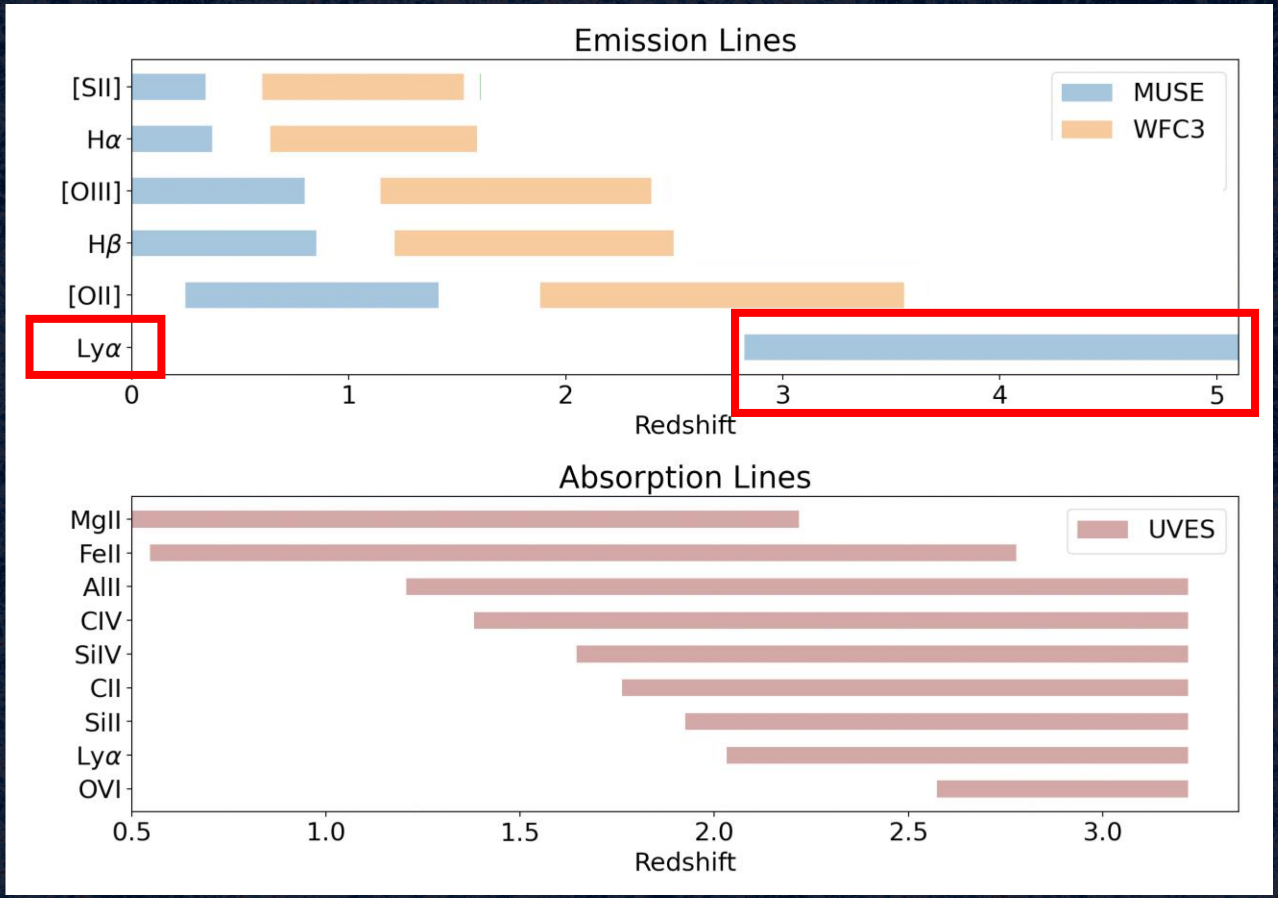
- **142h** MUSE (PI Fumagalli) similar to the MUSE GTO MXDF;
- 90 orbits HST WFC3 G141 spectroscopy ;
  + F125W, F140W imaging (PI Rafelski);
- 8 orbits HST UV imaging (PI Fossati);
- 30h UVES QSO spectroscopy (PI D'Odorico);
- 27h HAWK-I K-band imaging (PI Fossati);
- ALMA Band 3 and 6 programs (PI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



The MUSE Ultra Deep Field (MUDF)

Scientific goals:

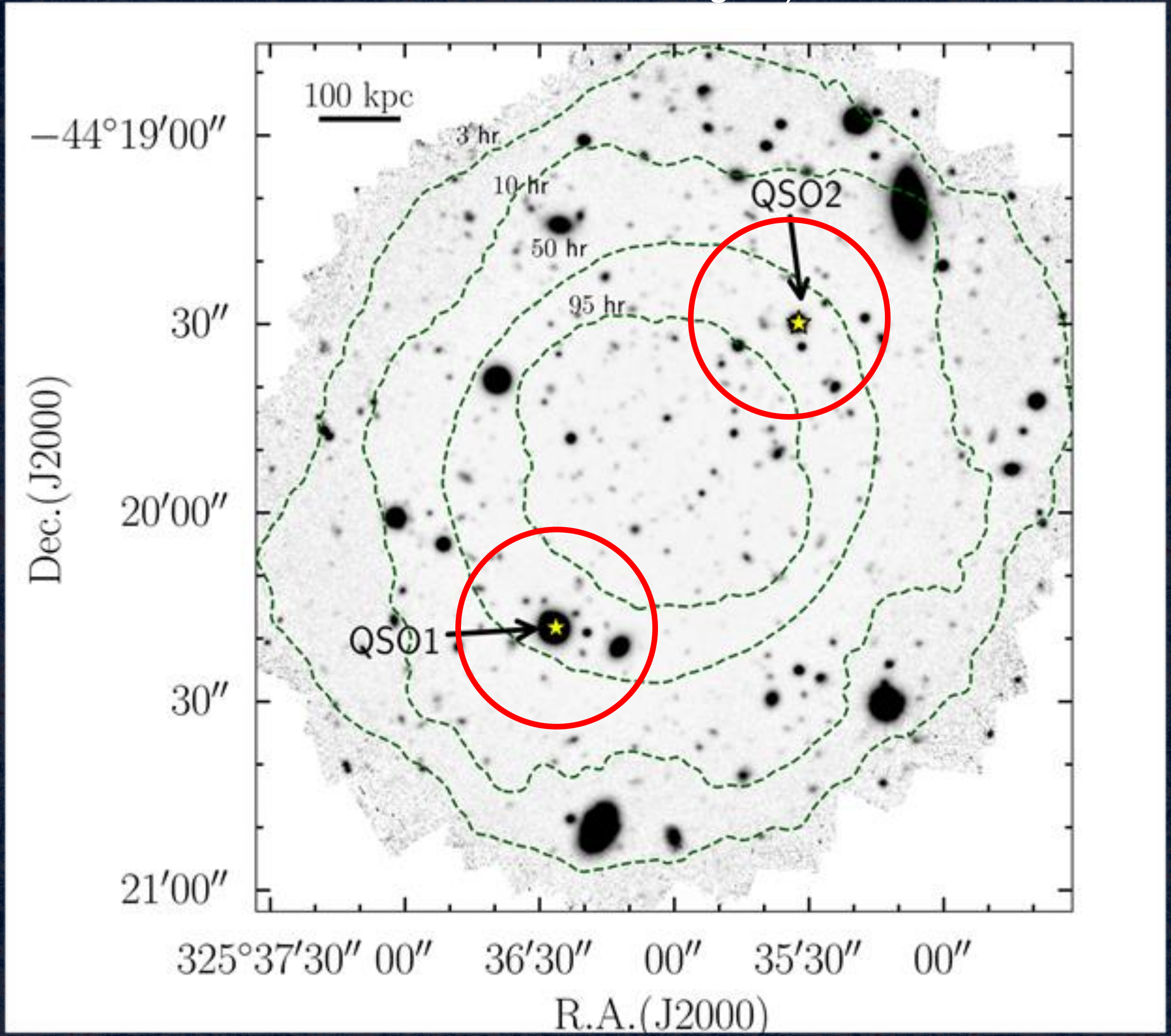
1. The environment of the QSO pair and LAE overdensities
2. Linking galaxies and the CGM with hydrogen and metal absorbers
3. Galaxy formation down to the dwarf regime



Cosmic filament connecting a QSO pair

The environment of the QSO pair

Full dataset rms $\approx 3 \times 10^{-20}$ erg s^{-1} cm^{-2} arcsec^{-2} (ultra-deep region)



D. Tornotti et al., 2025a, *Nature Astronomy*

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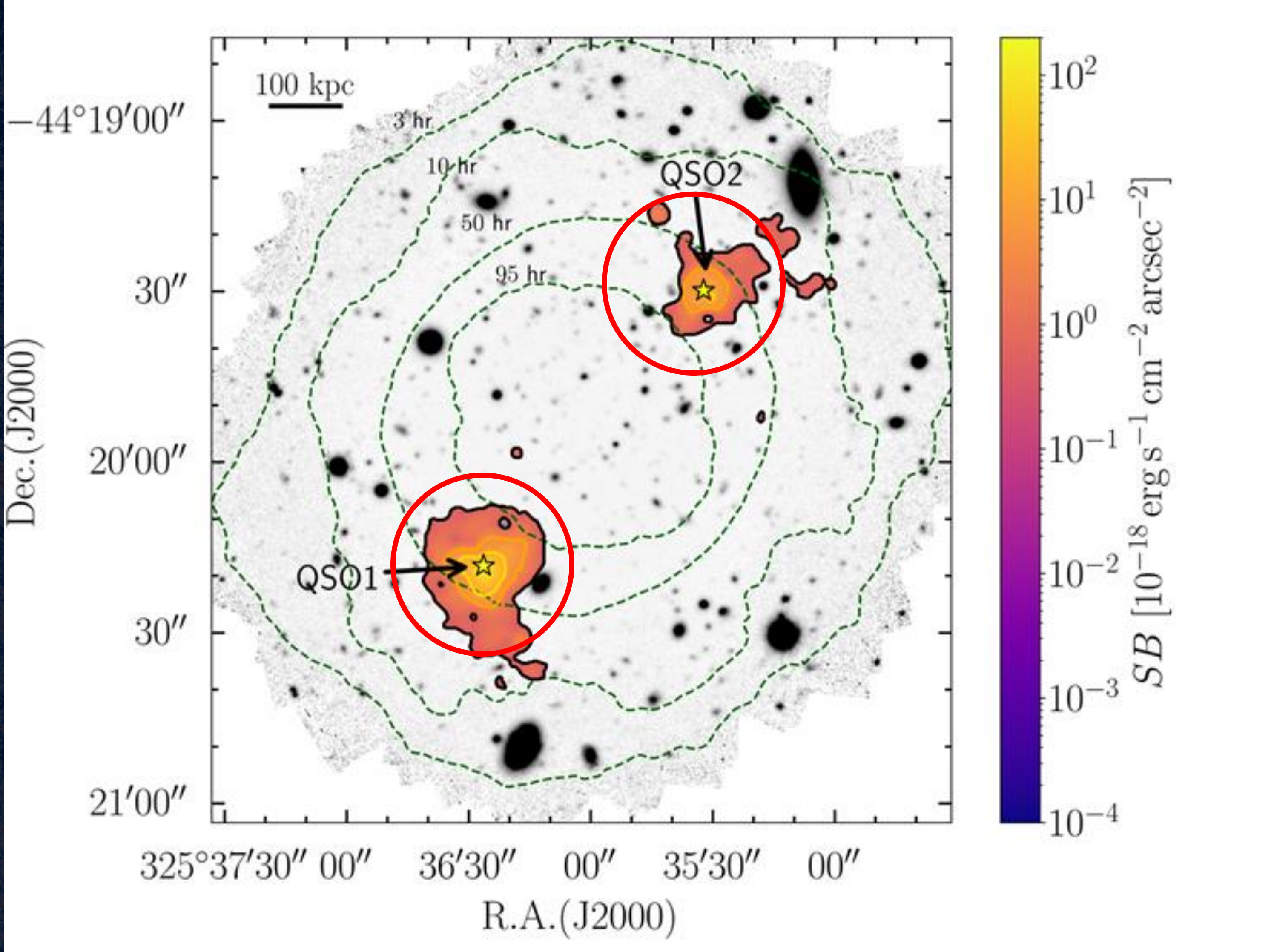

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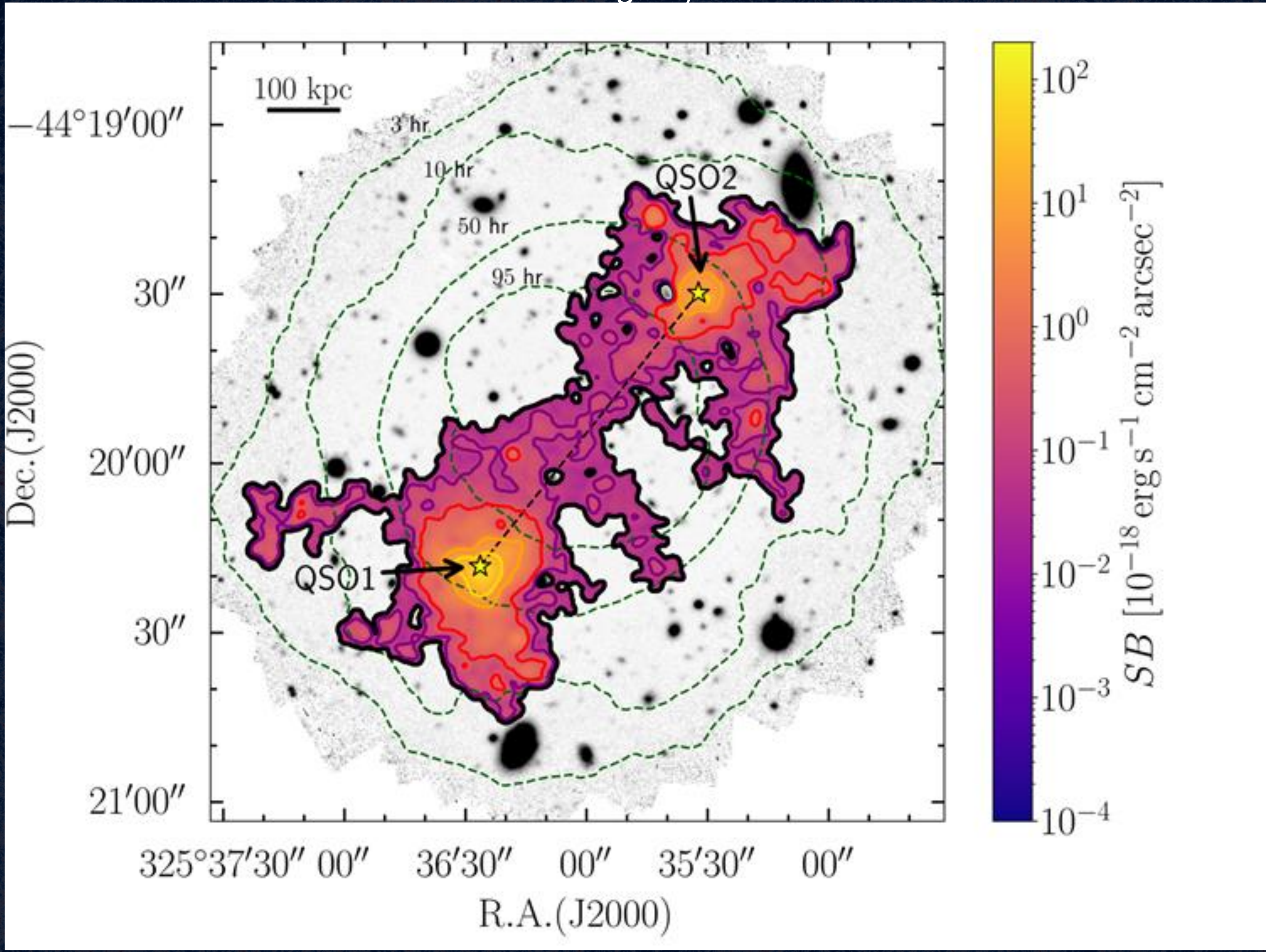

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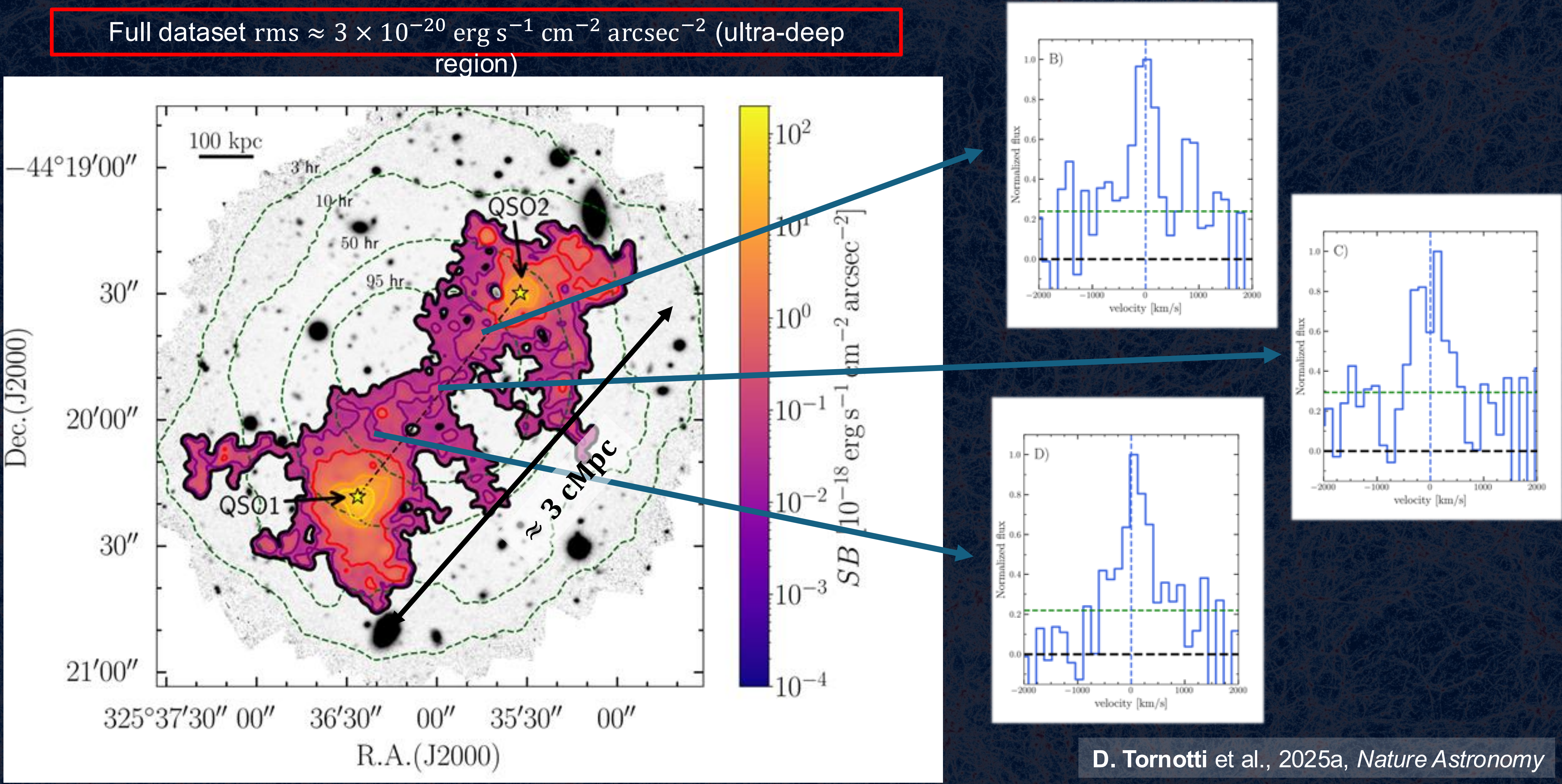

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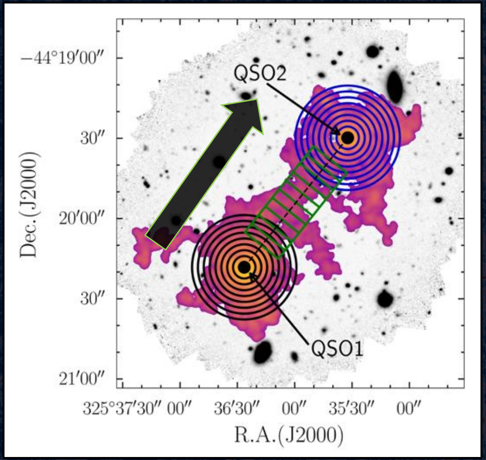
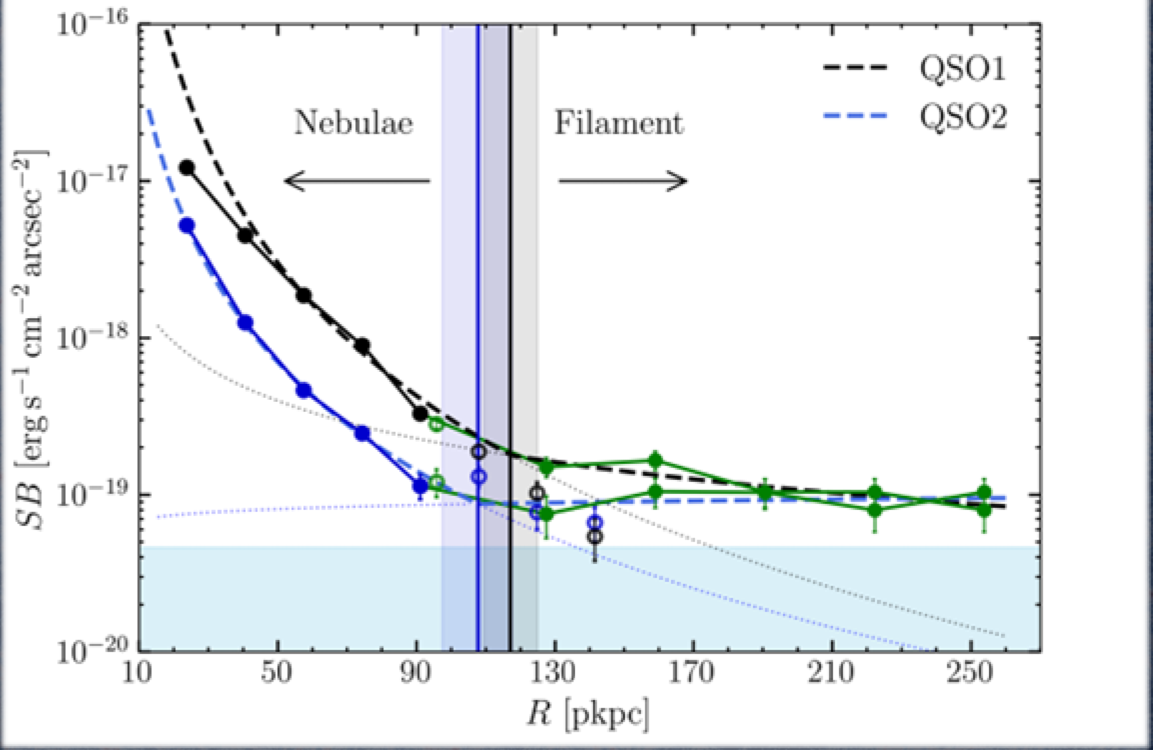


Profile *along* the filament



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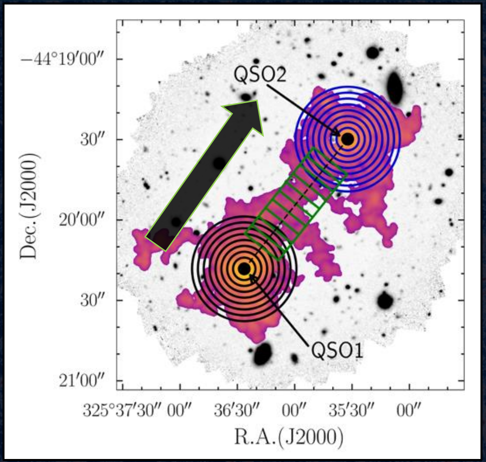
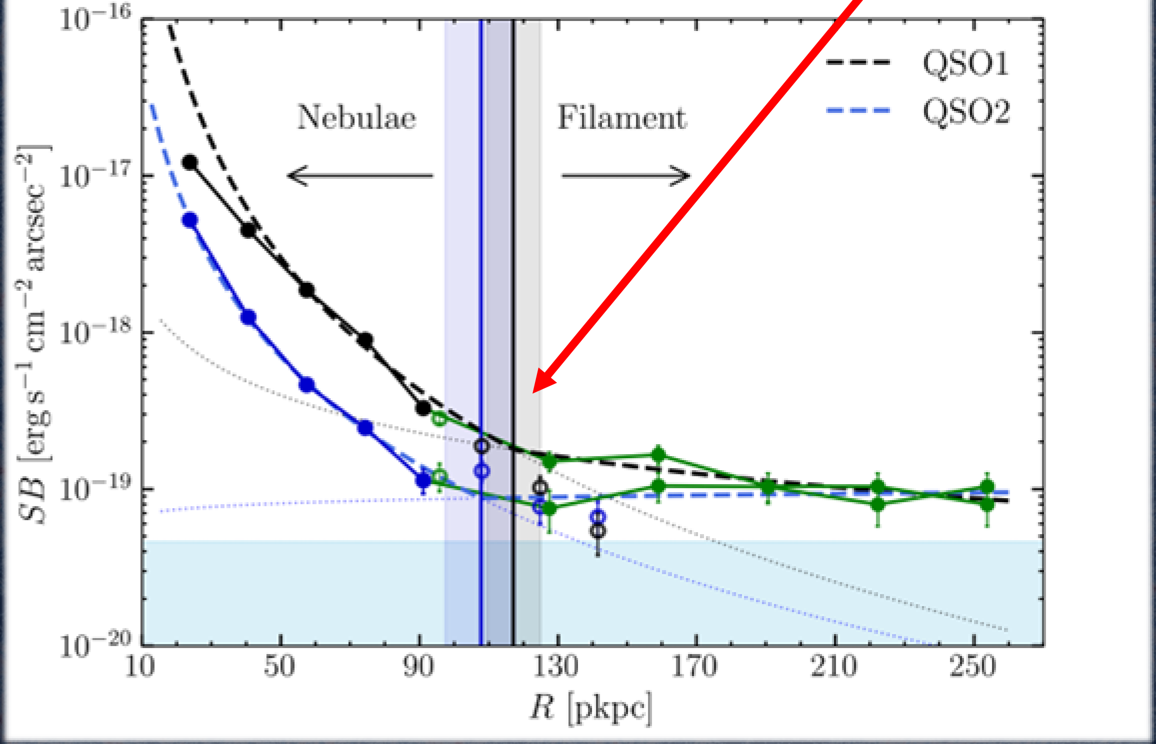


e.g. Fossati et al 2021, de Beer et al 2023

$R_t \approx 100$ pkpc

Profile *along* the filament



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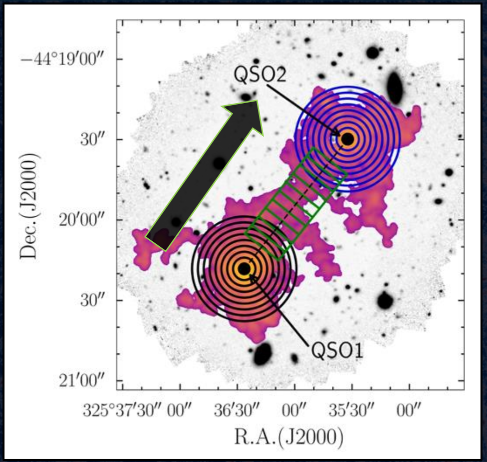

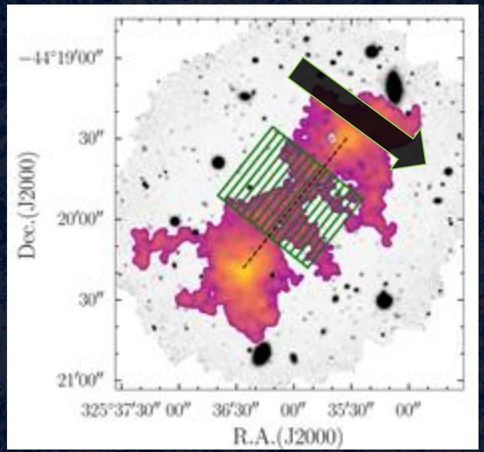

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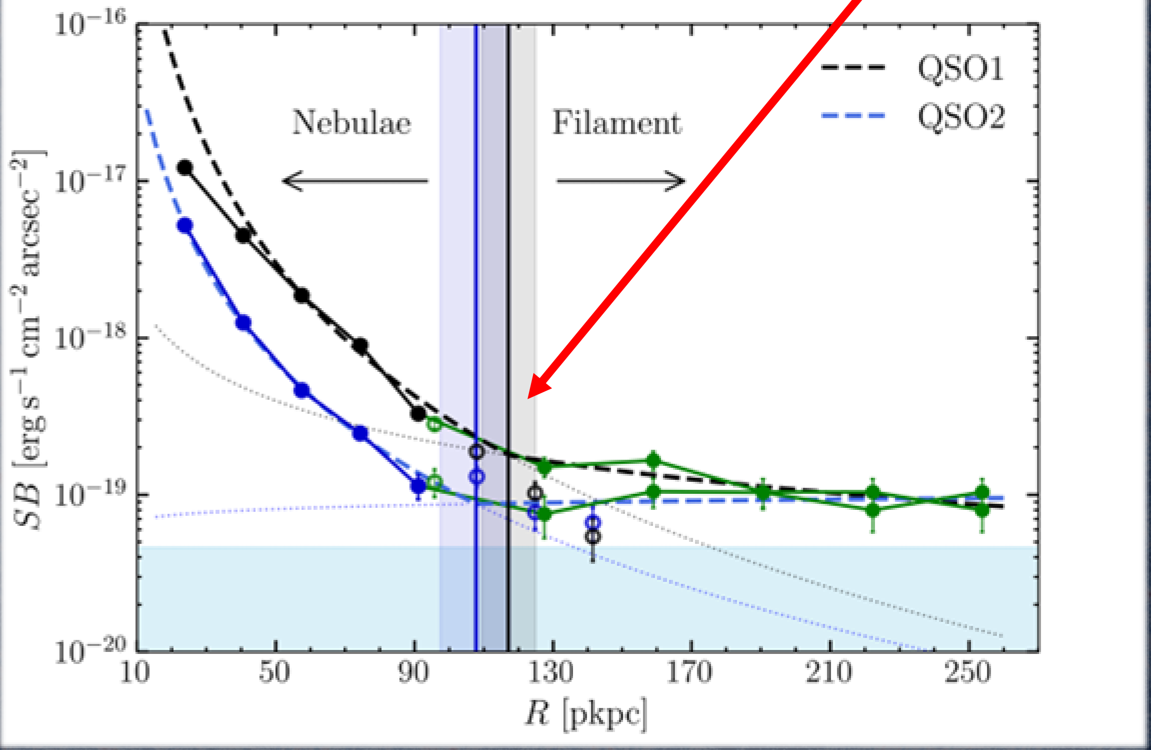
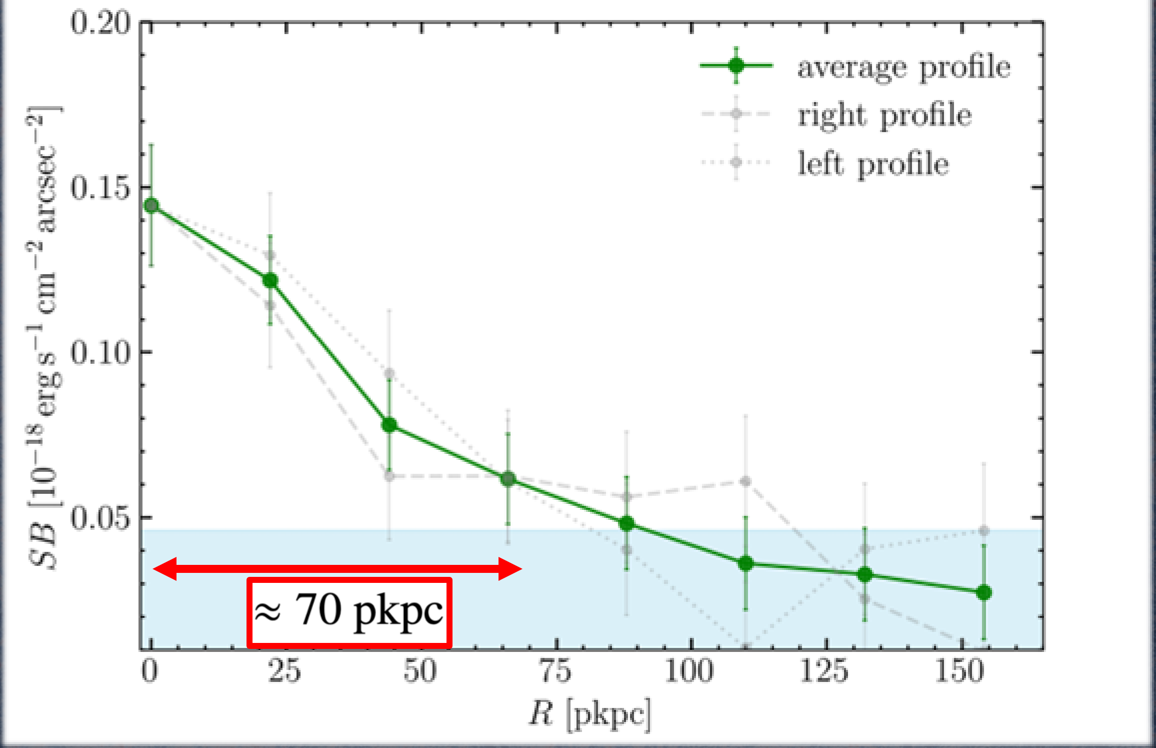
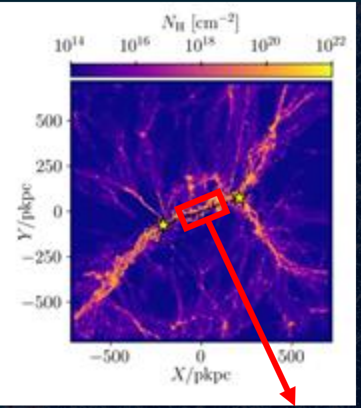


Profile *perpendicular* to the filament

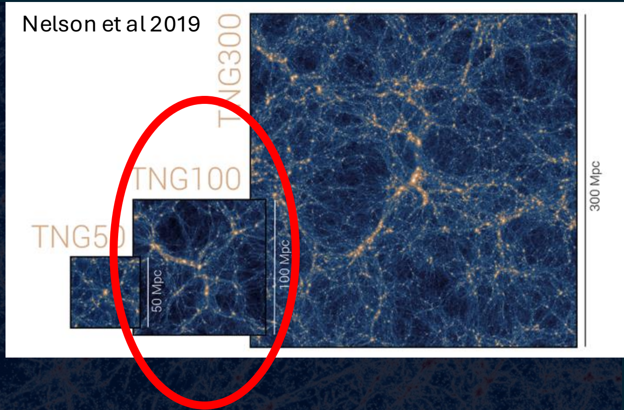


D. Tornotti et al., 2025a, *Nature Astronomy*

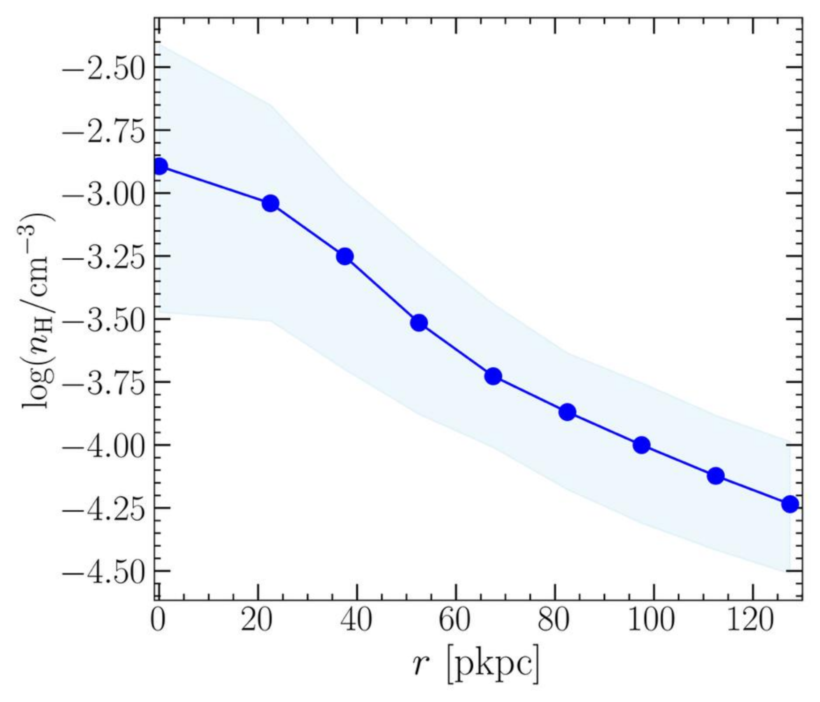
Comparison with simulations



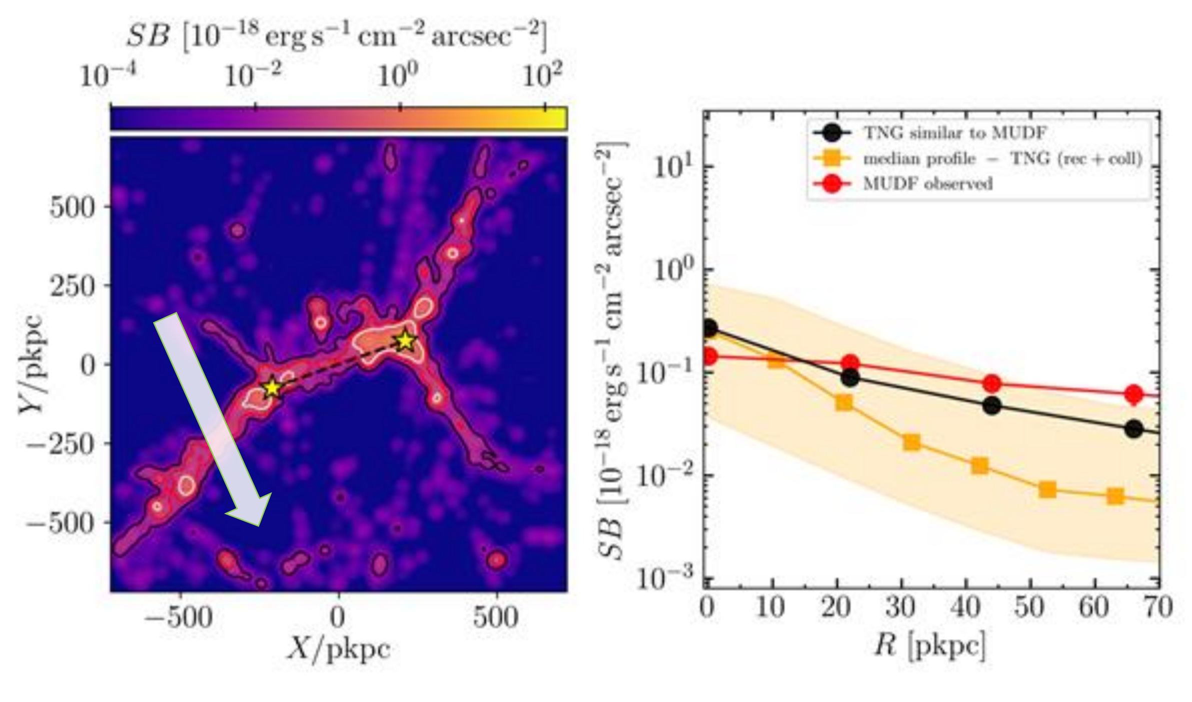
Halo pairs selected by using halo mass distributions obtained from L-Galaxies SAM with advanced QSO recipes (Izquierdo-Villalba et al. 2020)



Hydrogen density profile *perpendicular* to the simulated filaments



Simulated Lyα *perpendicular* SB profiles



→ $\text{SB} \propto n_H^2$

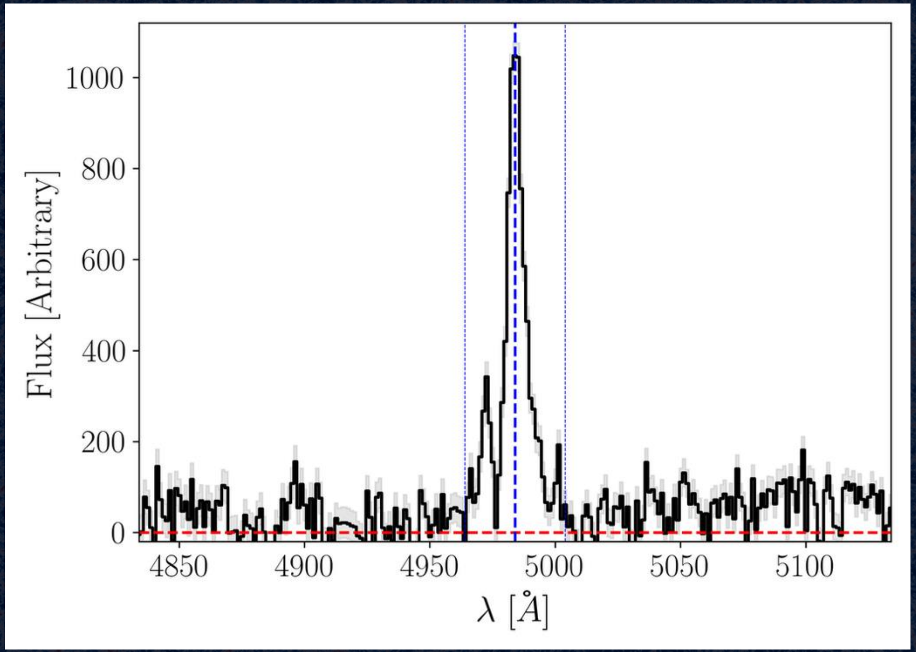
D. Tornotti et al., 2025a, *Nature Astronomy*

LAE Overdensities in the MUDF

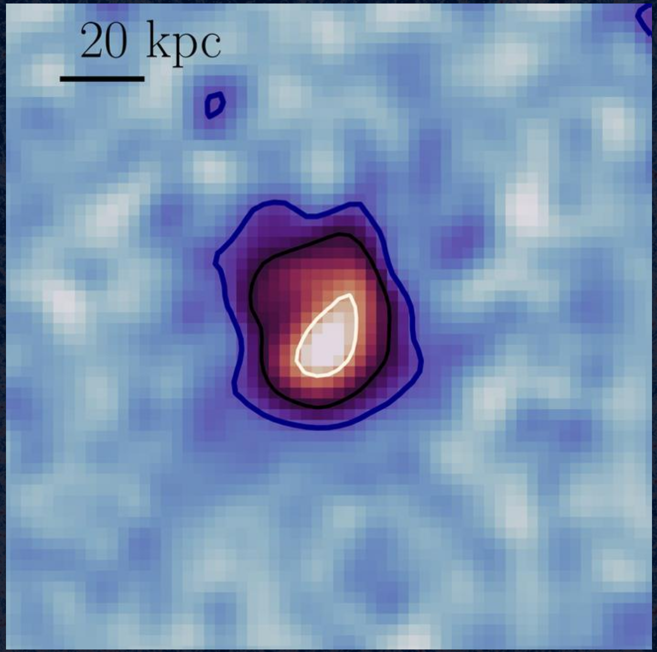
Tracing Large-Scale LAE Overdensities in the MUDF

Lyman-alpha emitters (LAEs):
young $(1 - 100\ \mathrm{Myr})$, **star forming** $(1 - 100\ \mathrm{M_\odot/yr})$, low mass $(10^7 - 10^{10}\ \mathrm{M_\odot})$ galaxies that show **Lyα emission**
(e.g. Dijkstra et al 2019)

Detected Lyα Emission in MUSE Spectrum



Lyα Narrow-Band Image

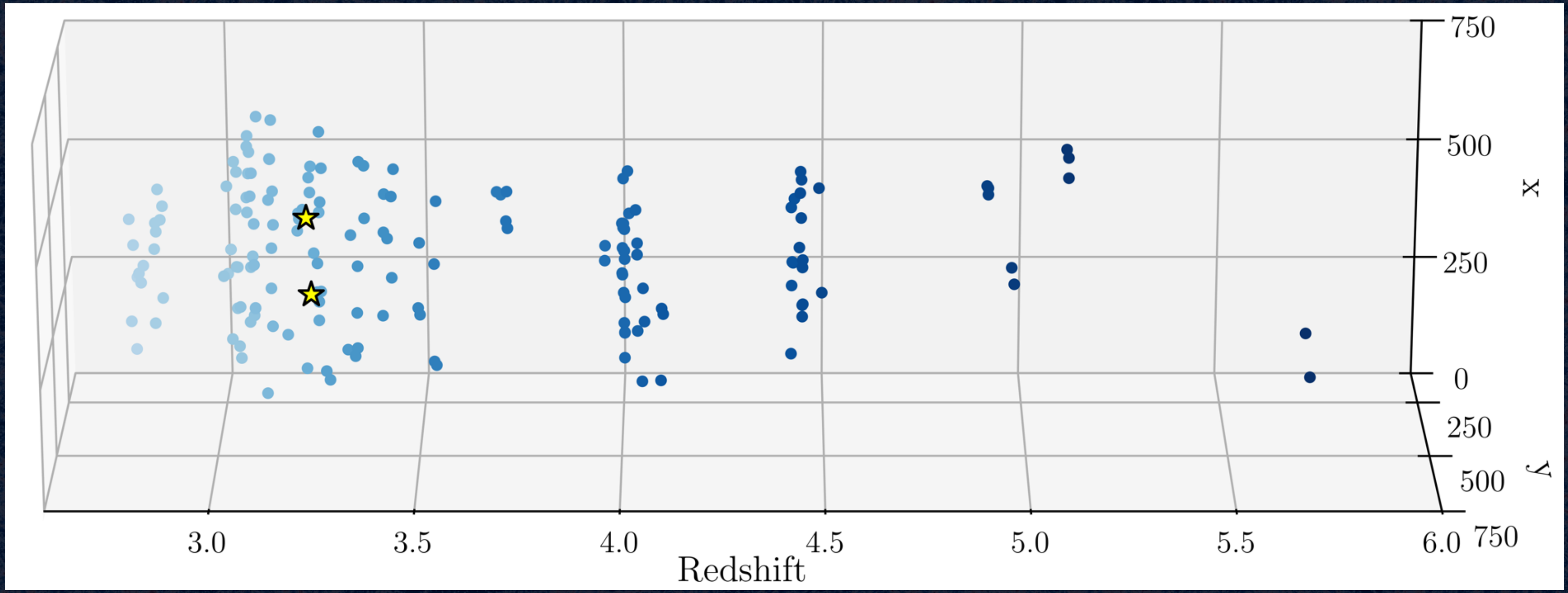


Overdensities of LAEs at $z \approx 3 - 4$ may trace early large-scale structures and galaxy protoclusters

D. Tornotti et al. in preparation

Tracing large-scale structures with LAE overdensities

- ***Step 1***: Build a catalog of LAEs in the MUDF (more than 200 LAEs spectroscopically confirmed)



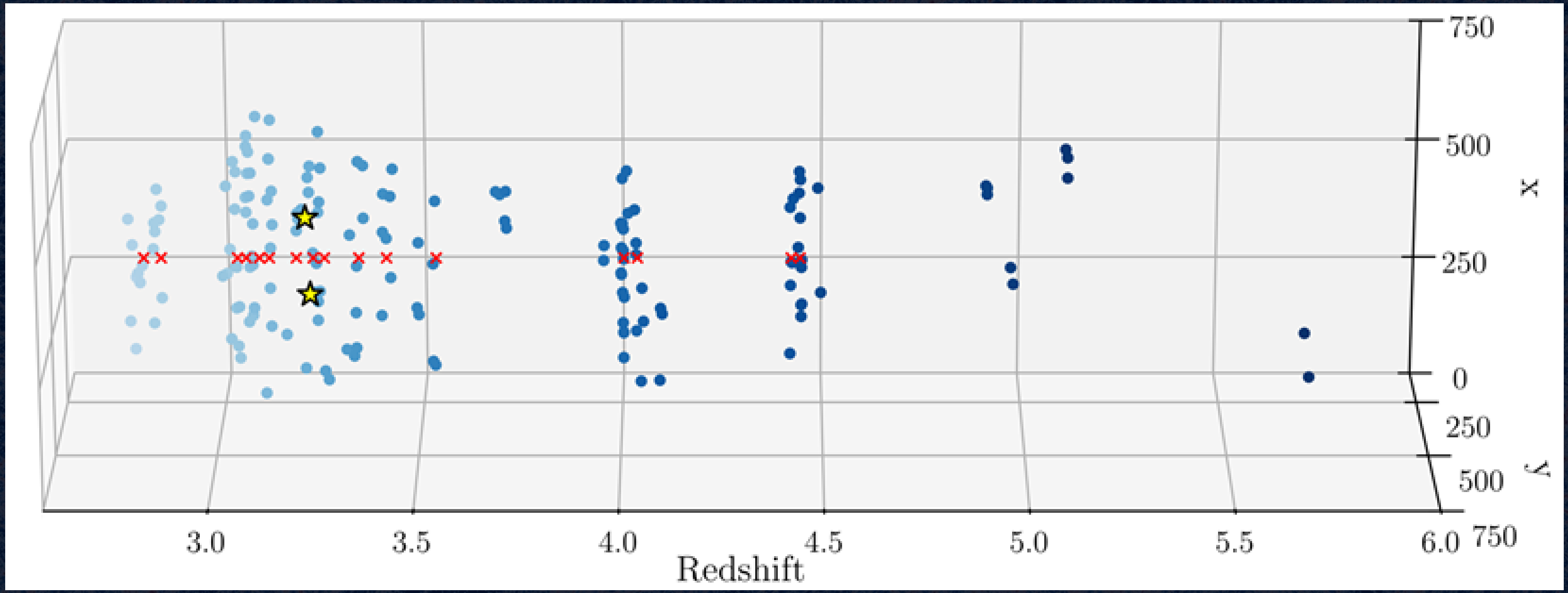
Median luminosity (all sample)

$$\log\left(\frac{L_{\mathrm{Lya}}}{\mathrm{erg\ s^{-1}}}\right) = 41.82$$

D. Tornotti et al. in preparation

Tracing large-scale structures with LAE overdensities

- ***Step 1***: Build a catalog of LAEs in the MUDF (more than 200 LAEs spectroscopically confirmed)
- **Step 2**: Identify overdense regions by grouping nearby LAEs



D. Tornotti et al. in preparation

Tracing large-scale structures with LAE overdensities

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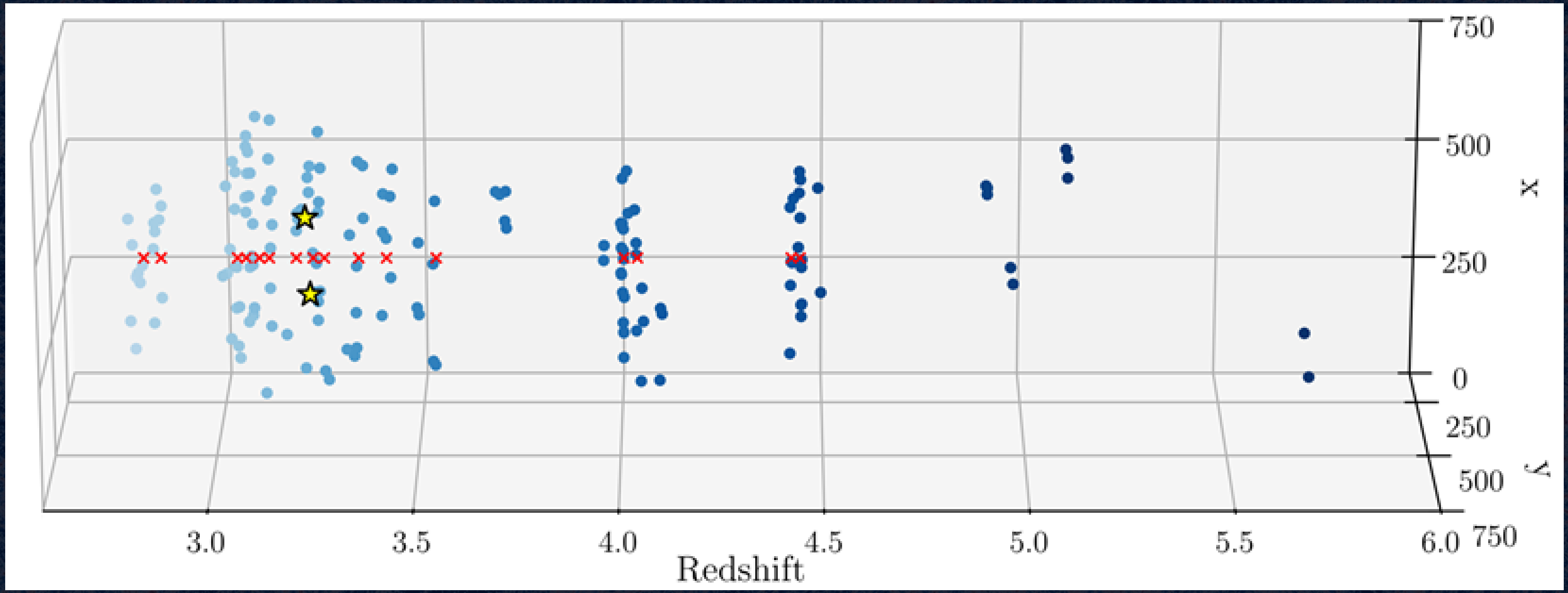
- **Step 3:** Search for potential extended Lyα emission associated with filamentary structures



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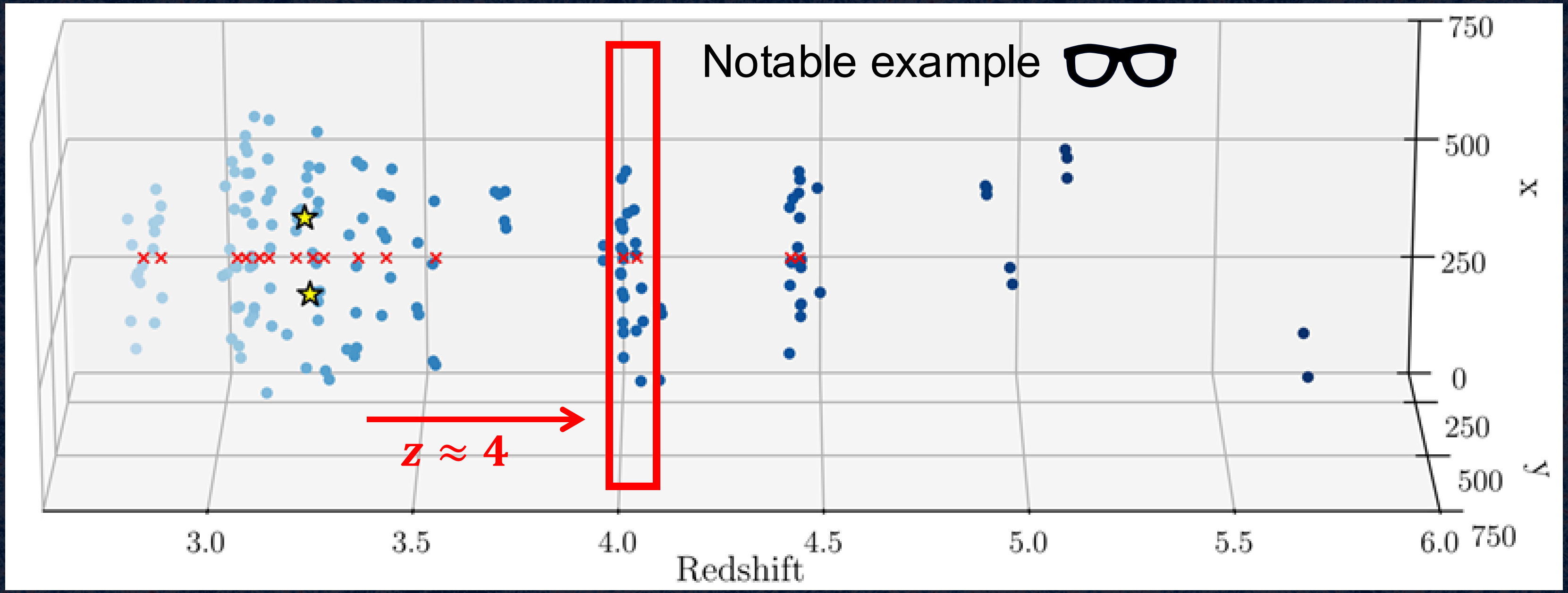
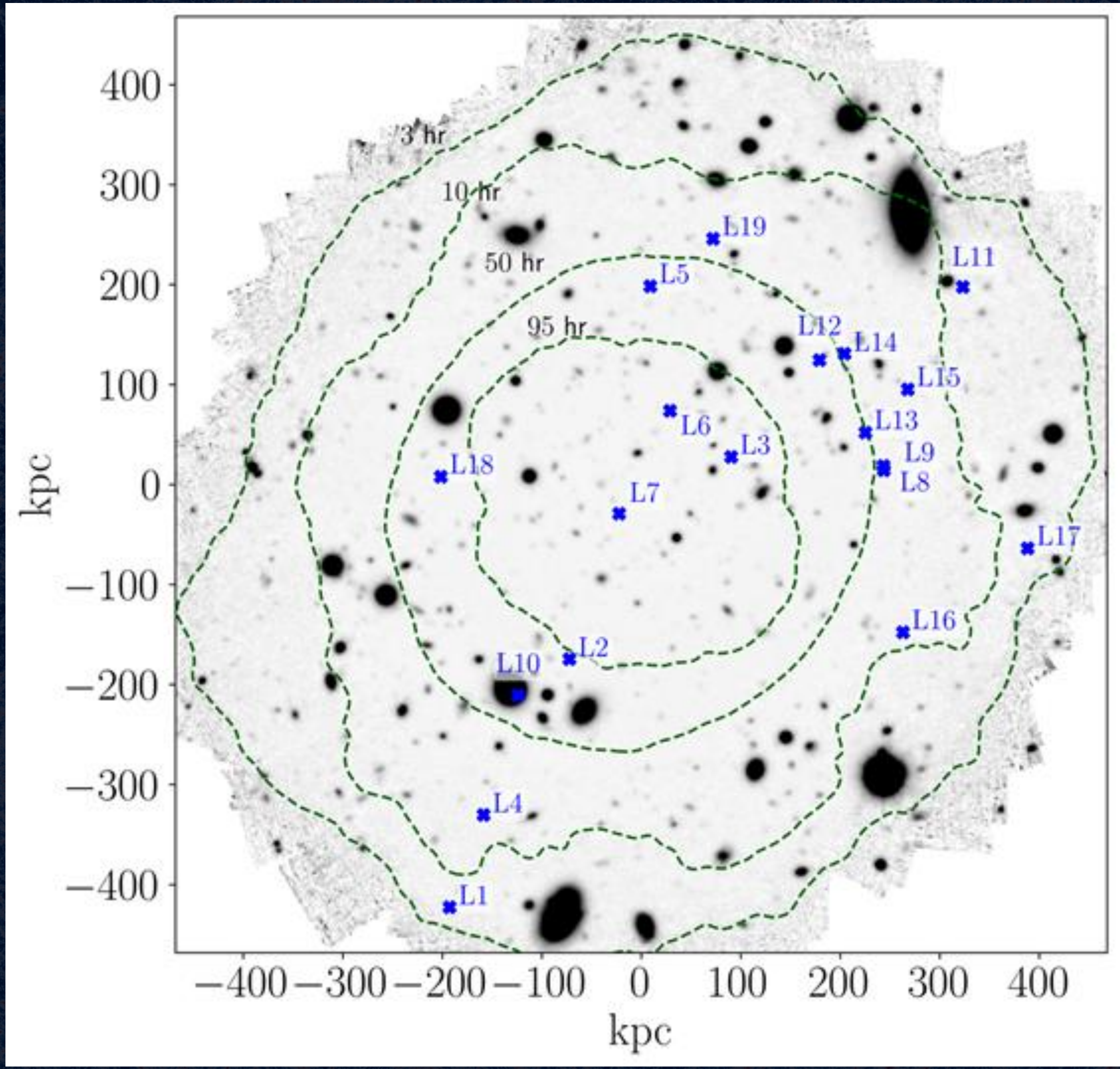


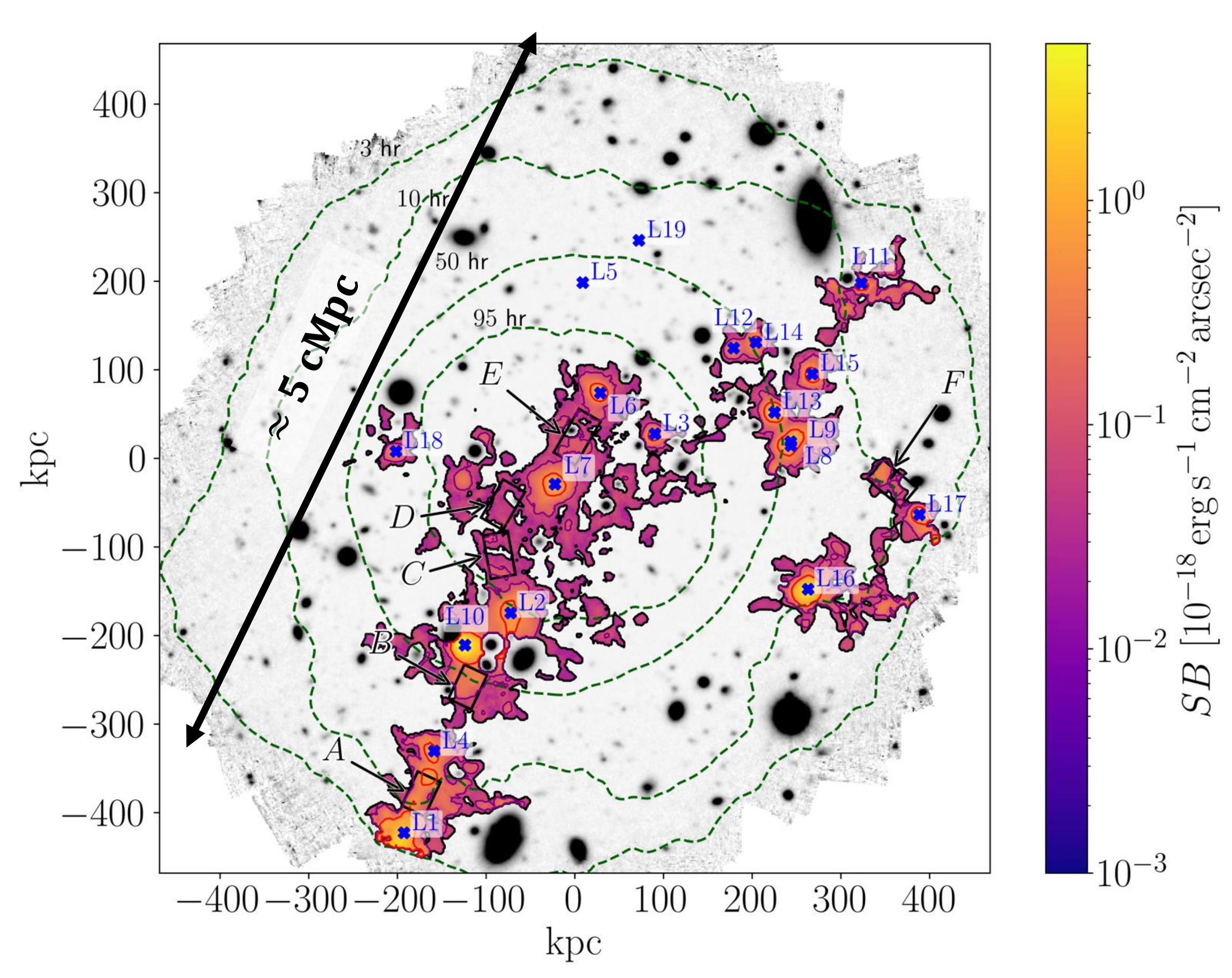
D. **Tornotti** et al. in preparation

Filaments around LAEs at $z{\sim}4$



D. Tornotti et al., 2025b, *ApJL*

Filaments around LAEs at $z \sim 4$



D. Tornotti et al., 2025b, *ApJL*

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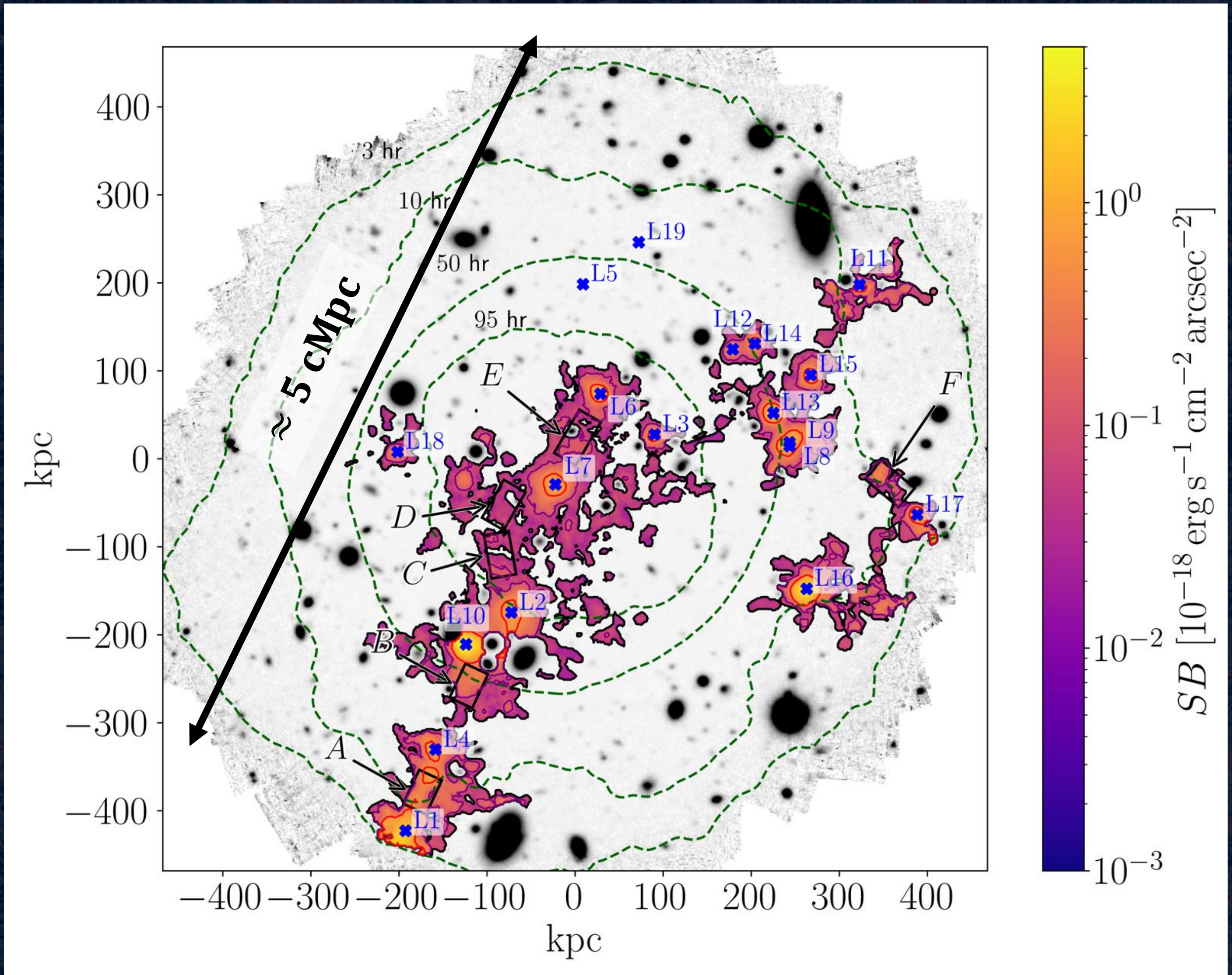
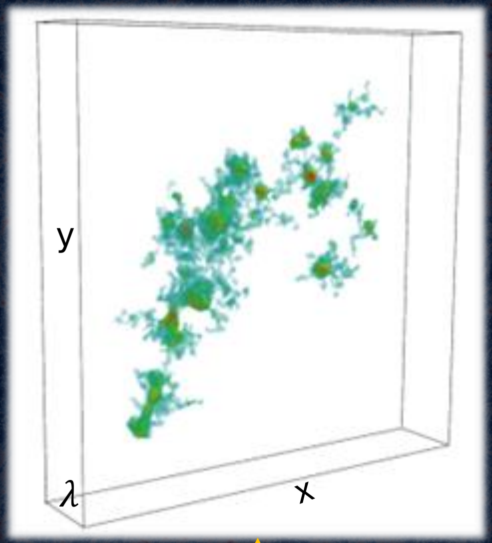




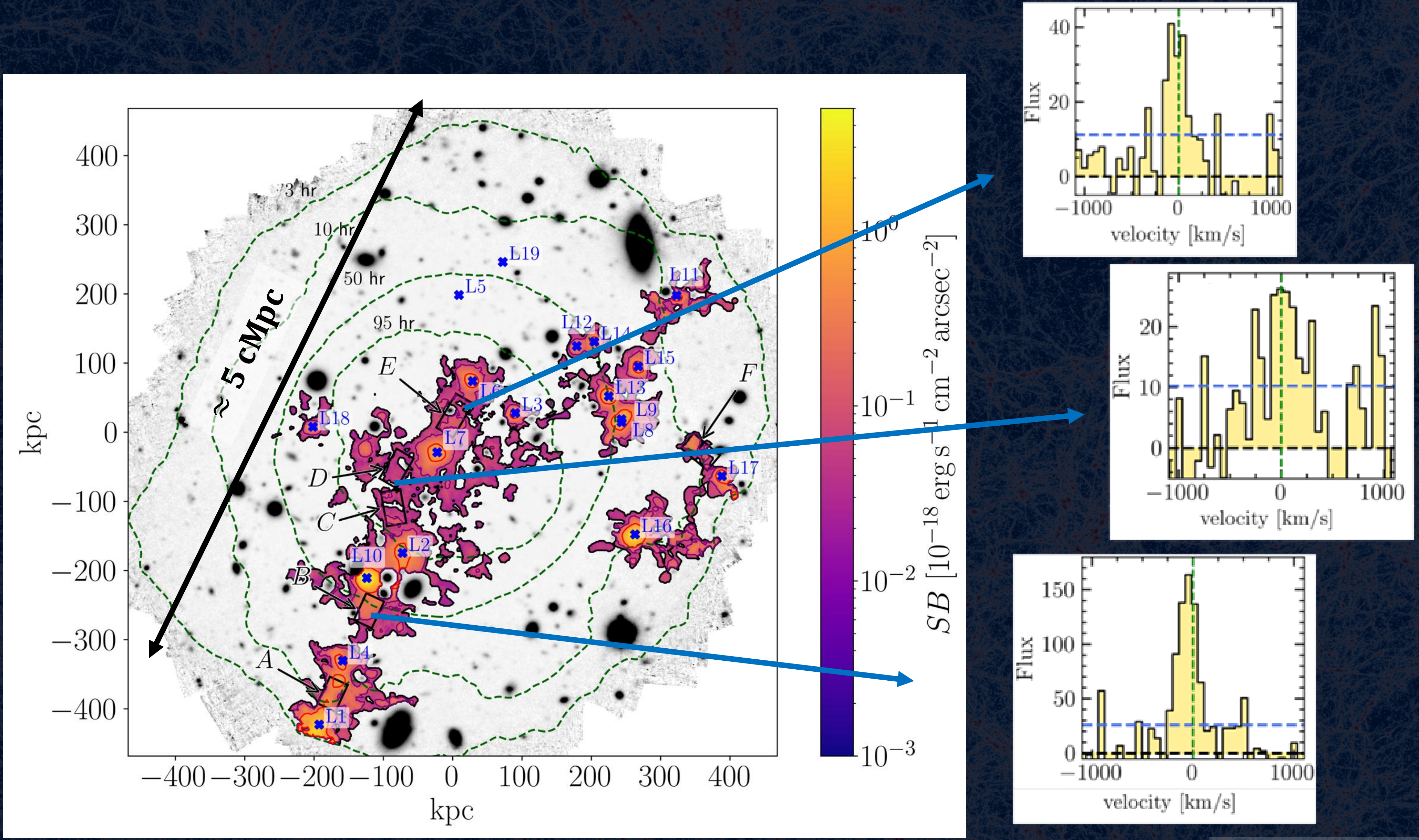
New extraction code:

SHINE

Fossati & Tornotti 2025

D. Tornotti et al., 2025b, *ApJL*

Filaments around LAEs at $z\sim4$



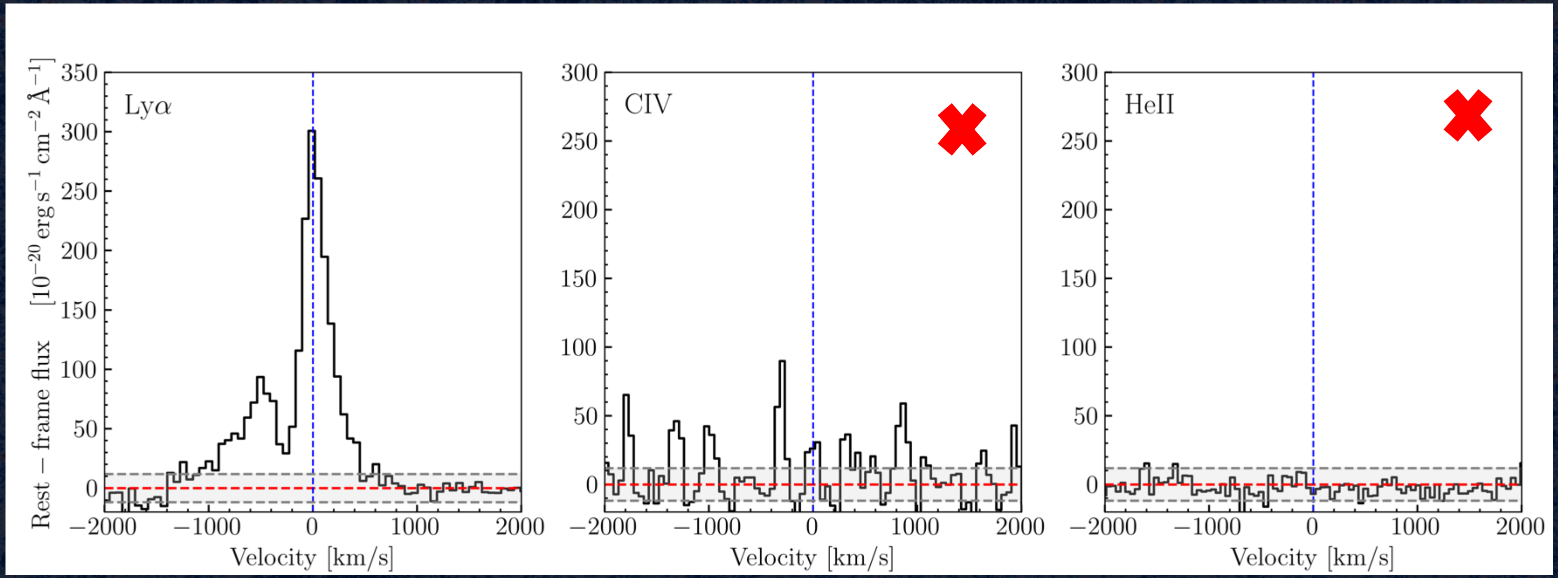
D. Tornotti et al., 2025b, *ApJL*

LAEs embedded in the filament $z\sim4$

Could AGN activity be a factor that boosts Lyα emission?

No clear evidence of AGNs both in individual spectra and in stacks

Stacks

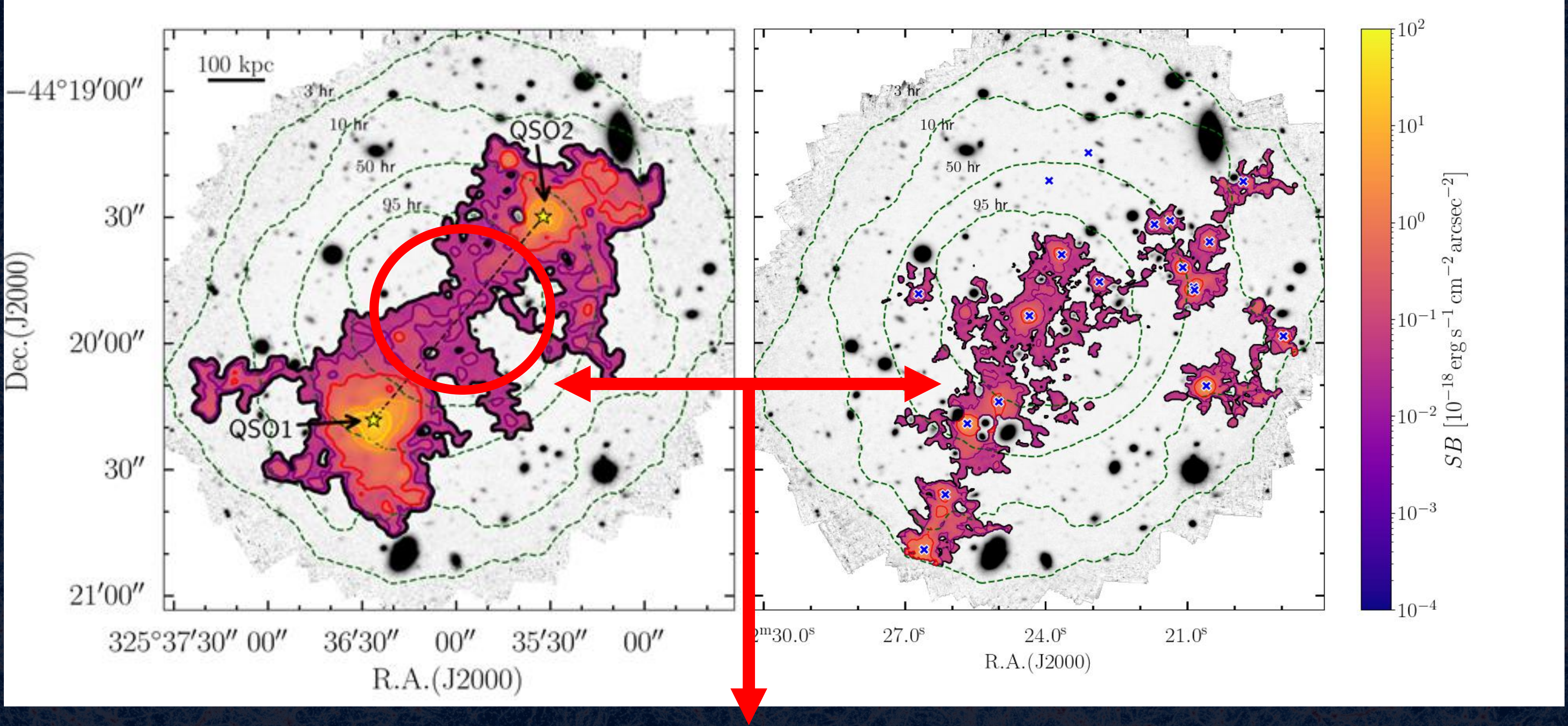


$\frac{\text{CIV}}{\text{Ly}\alpha} \lesssim 2\%$

$\frac{\text{HeII}}{\text{Ly}\alpha} \lesssim 1\%$

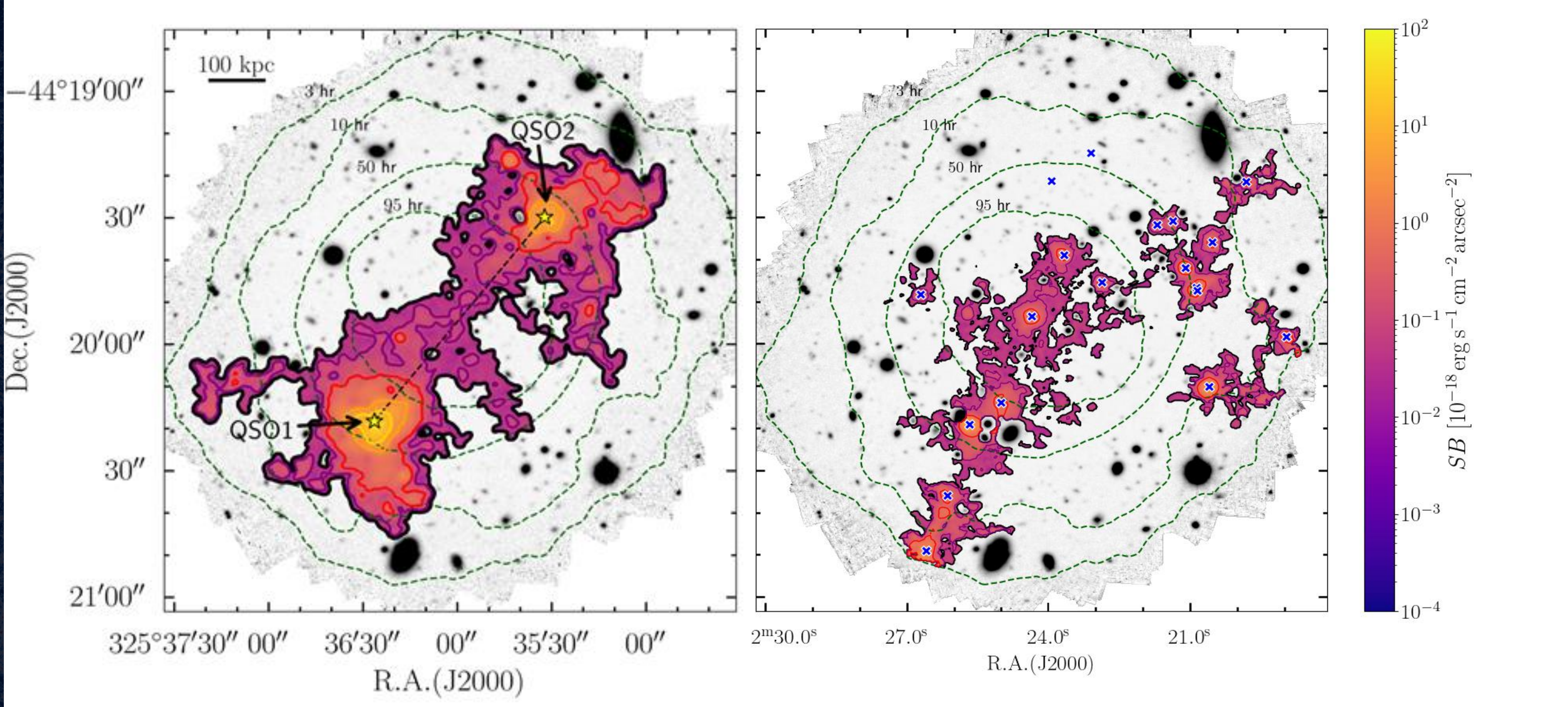
D. Tornotti et al., 2025b, *ApJL*

Comparison of the surface brightness levels



Intrinsic surface brightness levels **similar** in between the two quasars and within the rich group of LAEs

Comparison of the surface brightness levels

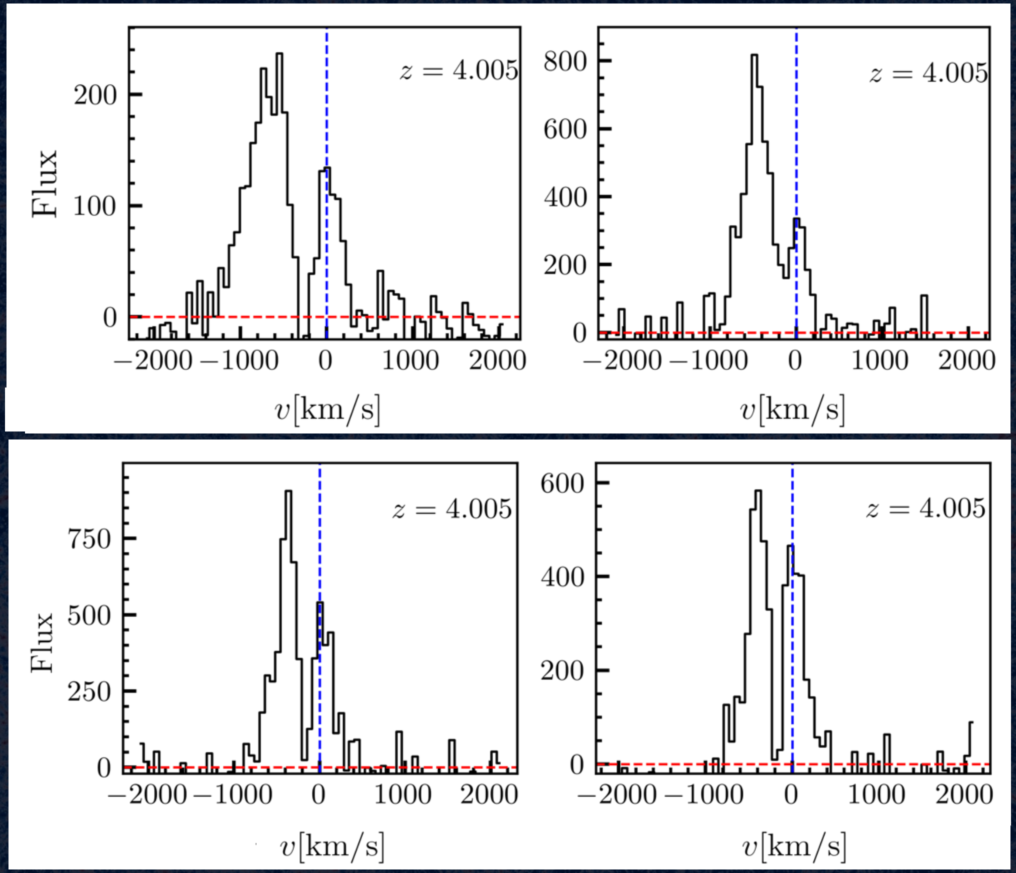


Is the presence of overdensities and dense gas more relevant then the radiation field?

?

LAEs embedded in the filament $z\sim4$

$7/19$ (~37 %) show double-peaked profiles and $5/7$ are blue peaked



D. **Tornotti** et al., 2025b, *ApJL*

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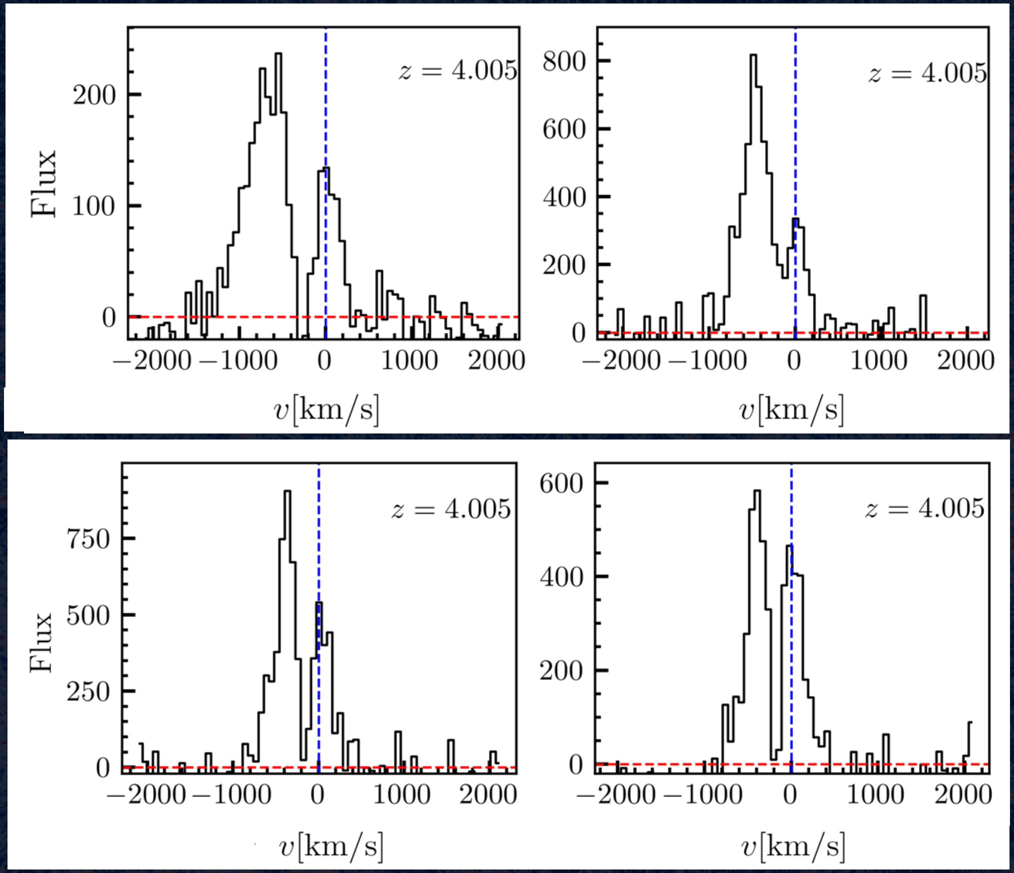
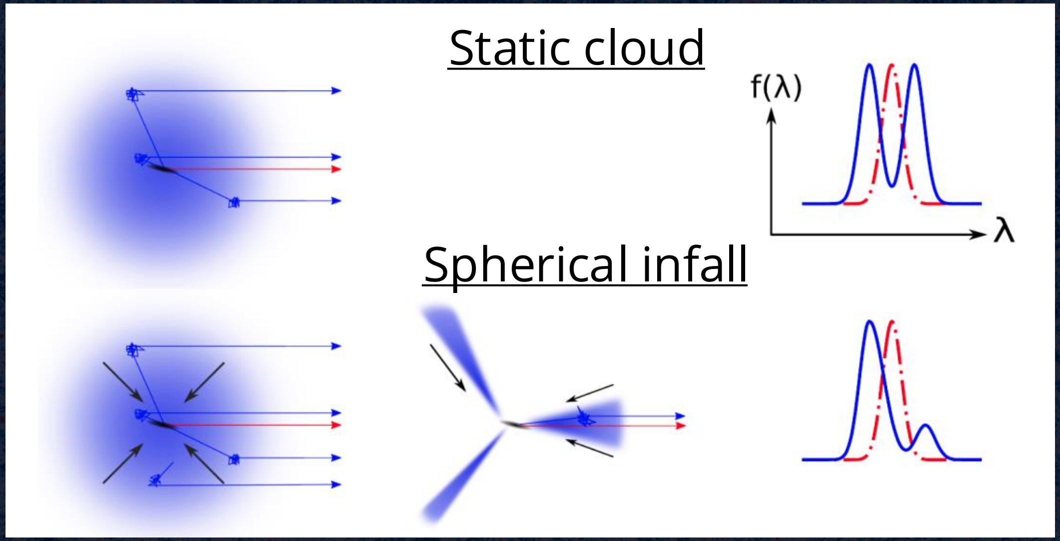


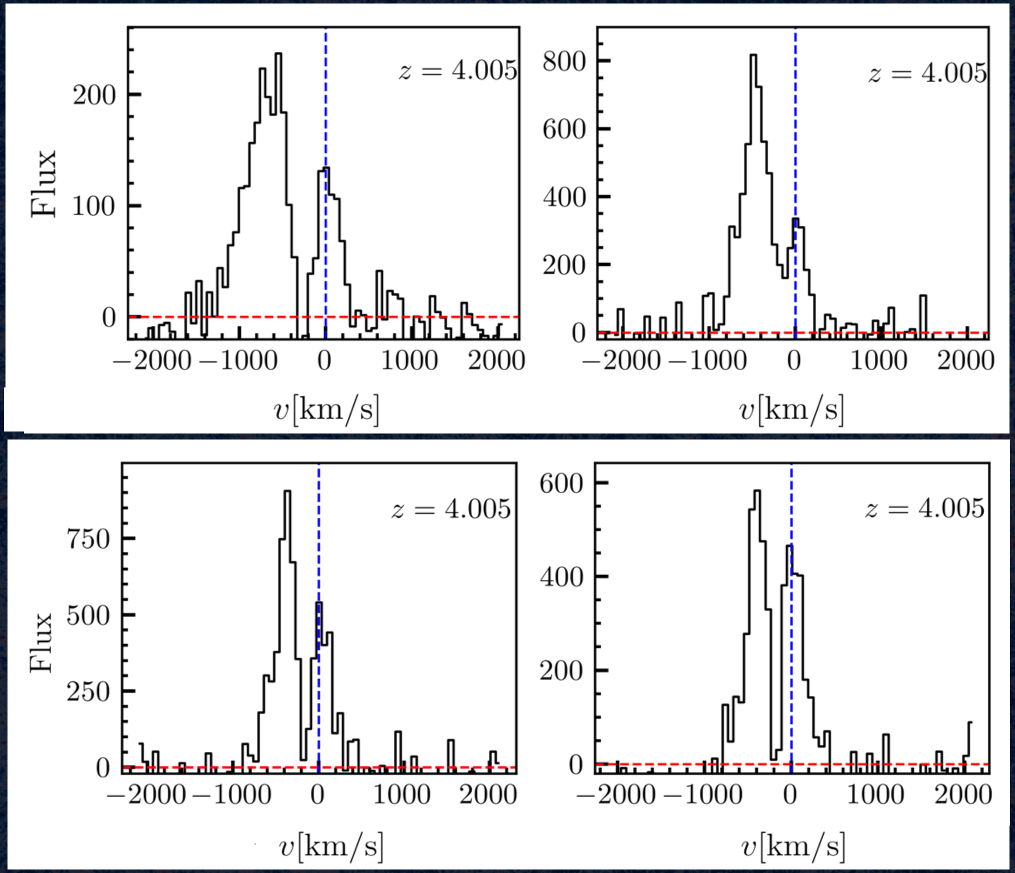


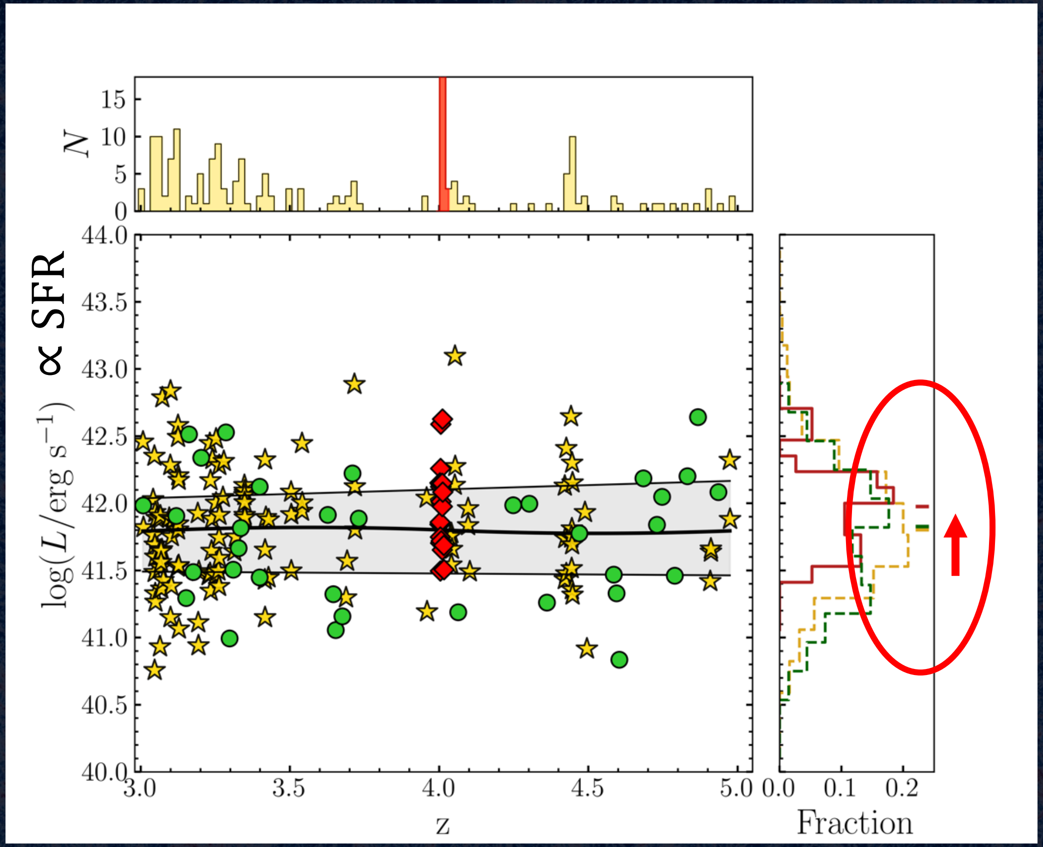
Enhanced star formation rate?

D. Tornotti et al., 2025b, *ApJL*

LAEs embedded in the filament $z\sim4$

7/19 (~37 %) show double-peaked profiles and 5/7 are blue peaked





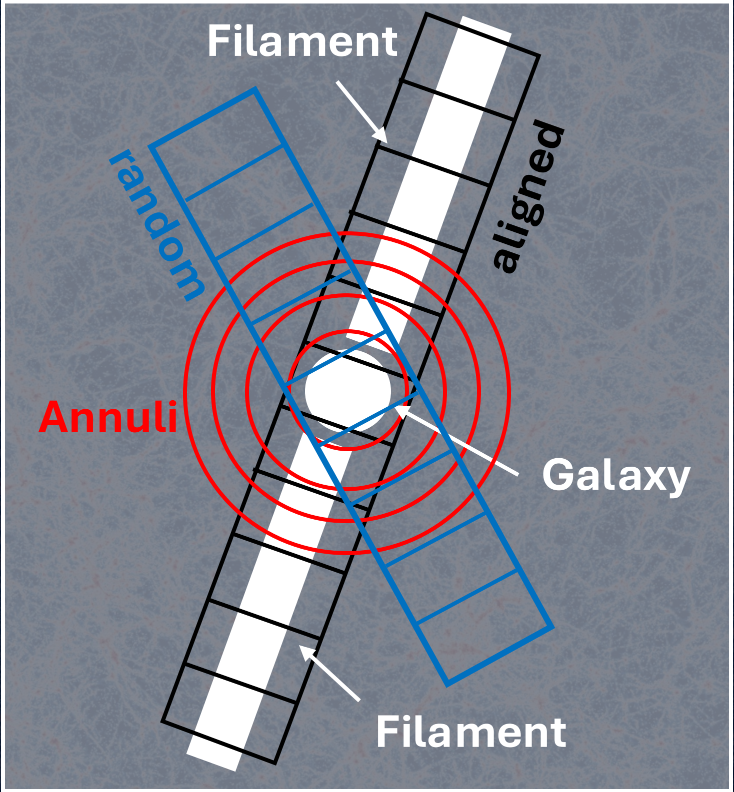
A population of active galaxies fuelled by prominent accretion?

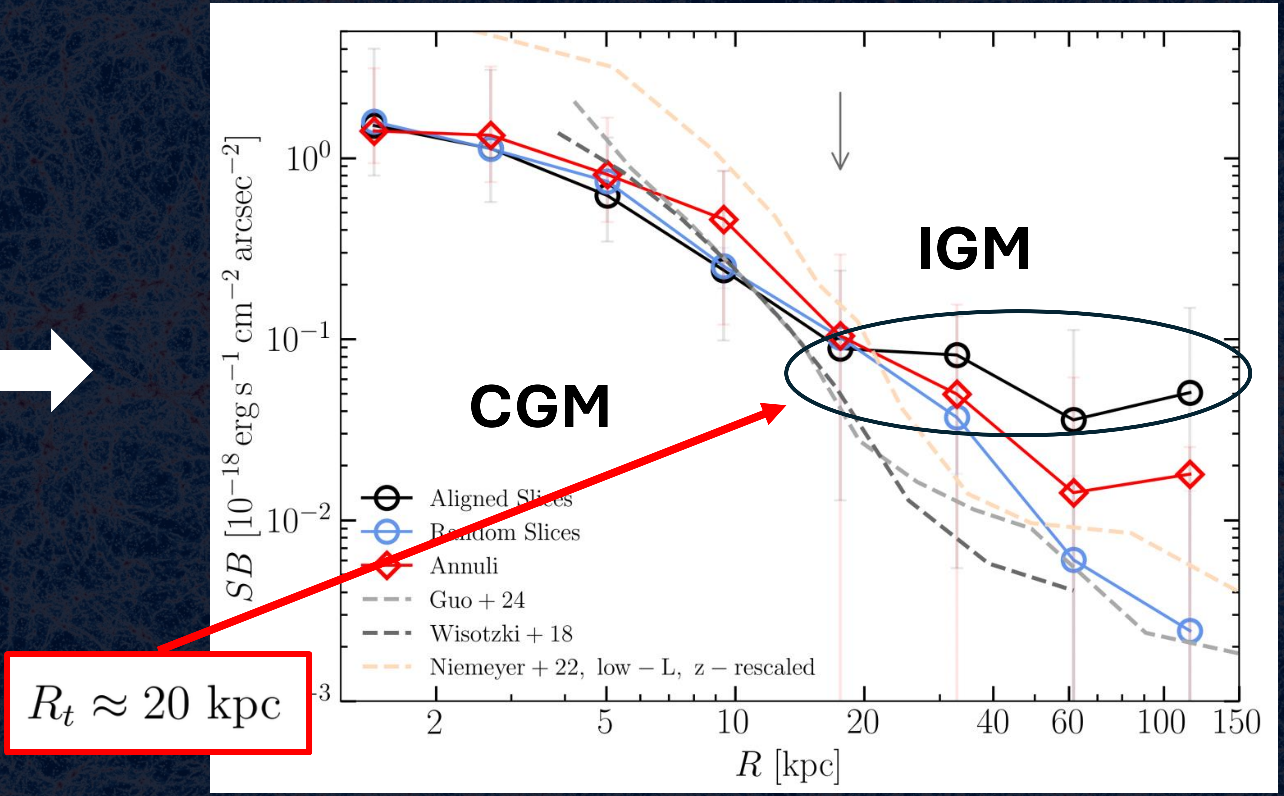
D. Tornotti et al., 2025b, *ApJL*

LAEs embedded in the filament $z \sim 4$

Evidence of **inflection point** in the SB profiles

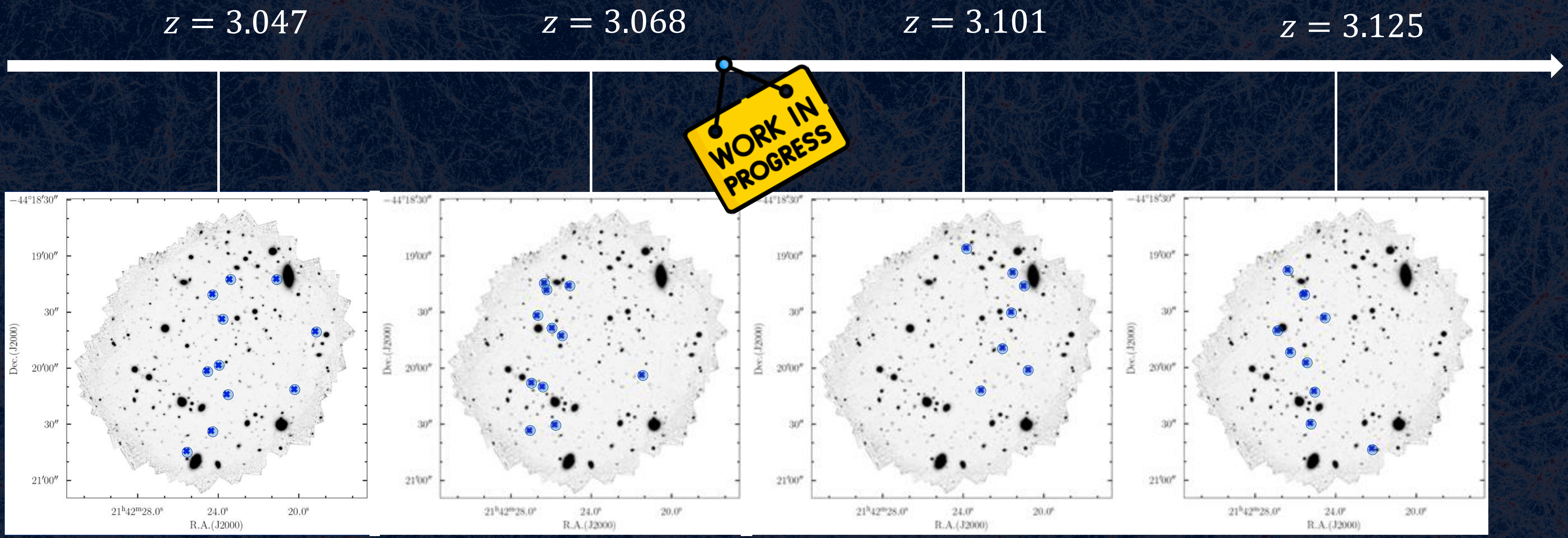
→ transition between CGM and IGM





D. Tornotti et al., 2025b, *ApJL*

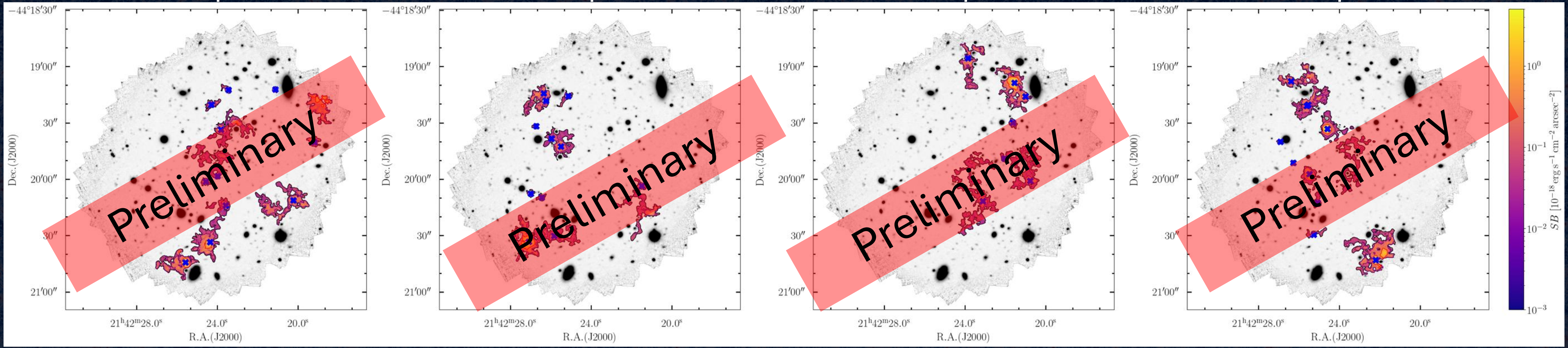
Extended emission around other LAE overdensities



D. **Tornotti** et al. in preparation

Extended emission around other LAE overdensities

$z = 3.047$ $z = 3.068$ $z = 3.101$ $z = 3.125$



D. Tornotti et al. in preparation

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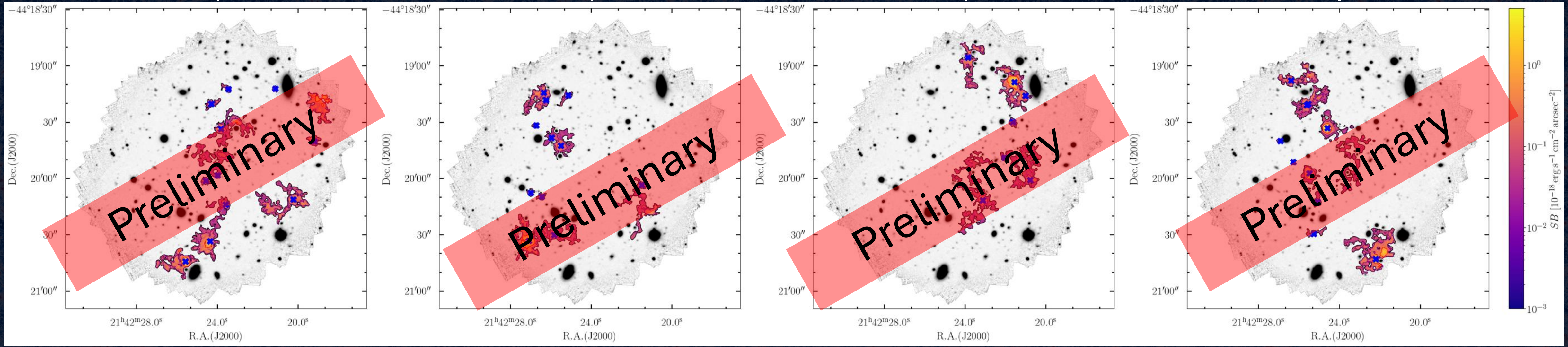

QSO pair

+ Constraints from QSOs absorptions

D. Tornotti et al. in preparation

LAE Luminosity Function

How can we characterize LAE groups and their properties?

Systematic study of the connection:

LAE overdensities ⟷ extended Lyα emission ⟷ galaxy population

We need to properly constrain the LAE luminosity function, especially the faint end

D. Tornotti et al. A&A submitted

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How?

Ultra-deep, small-area data
Exposure time: $\gtrsim 90\ \mathrm{hr}$
Area: $\approx 0.5 - 1\ \mathrm{arcmin}^2$

→ Constrains faint end: $\mathrm{L} \lesssim 10^{41}\ \mathrm{erg\ s^{-1}}$

+

Shallow, wide-area data
Exposure time: $(\approx 1 - 4\ \mathrm{hr})$
Area: $(\gtrsim 25\ \mathrm{arcmin}^2)$

→ Constrains bright end: $\mathrm{L} \approx 10^{43}\ \mathrm{erg\ s^{-1}}$

D. Tornotti et al. A&A submitted

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Area: ($\gtrsim 25$ arcmin^2)

→ Constrains bright end: $L \approx 10^{43}$ erg s^{-1}

⚠ We need to carefully account for the different selection effects, the area covered, and the uncertainties in the estimated quantities (e.g., luminosity)

D. Tornotti et al. A&A submitted

Hierachical Bayesian model for multidepths surveys

$$p(\lambda|\{\theta_i^{\mathrm{obs}}\}) = \frac{p(\{\theta_i^{\mathrm{obs}}\}|\lambda)\pi(\lambda)}{p(\{\theta_i^{\mathrm{obs}}\})}$$

k-th survey

$$p_k(\{\theta_i^{\mathrm{obs}}\}|\lambda', N) \propto e^{-N_{\mathrm{det,k}}} \prod_{i=1}^{N_{\mathrm{obs,k}}} \int \mathrm{d}\theta\, p(\theta_i^{\mathrm{obs}}|\theta)\, N\, p_{\mathrm{pop}}(\theta|\lambda')$$

population parametric model

uncertain observables

selection effects

$$N_{\mathrm{det,k}} = \frac{\Omega_k}{4\pi} N \int \mathrm{d}\theta\, P_{\mathrm{det,k}}(\theta)\, p_{\mathrm{pop}}(\theta|\lambda')$$

Survey 1: galaxy catalog with errors + selection function

Survey 2: galaxy catalog with errors + selection function

⋮

Survey *k*: galaxy catalog with errors + selection function

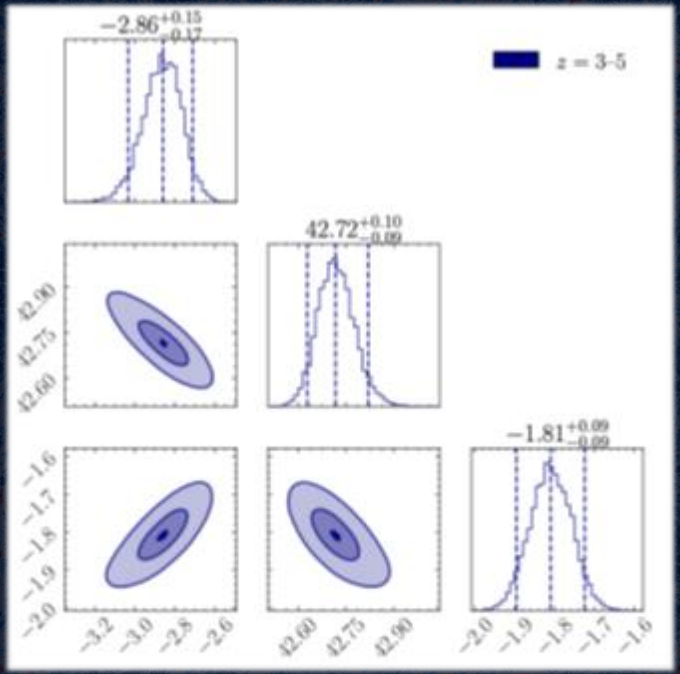
→ Bayesian model → Posterior distribution

D. Tornotti et al. A&A submitted

Application to the case of LAE population

Sample of LAEs:
- **1176** galaxies;
- $40.8 \lesssim \log\left(\frac{L}{\mathrm{erg\ s^{-1}}}\right) \lesssim 43.5$;
- $3 < z < 5$.

Schechter parametrization:
- $\Phi^{\star}$ normalization
- $L^{\star}$ charachteristic luminosity
- α slope



MUSE eXtremely Deep Field (MXDF, Bacon et al 2023)

MUSE Ultra Deep Field (MUDF, Lusso et al 2019)

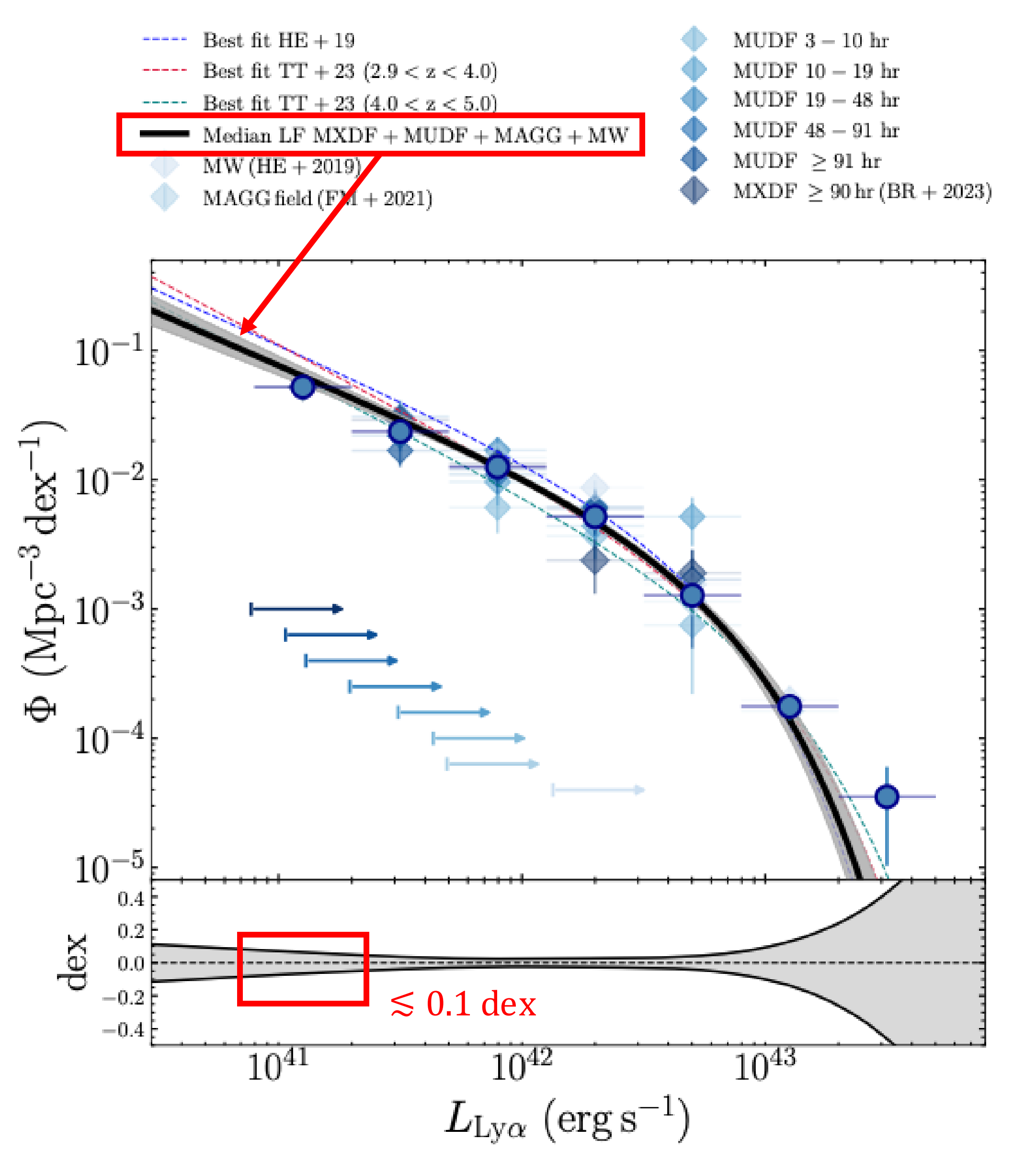
MUSE Analysis for Gas around Galaxies (MAGG, Lofthouse et al 2020)

MUSE-Wide survey (Herenz et al 2017)

→ Bayesian model → Posterior distribution

D. Tornotti et al. A&A submitted

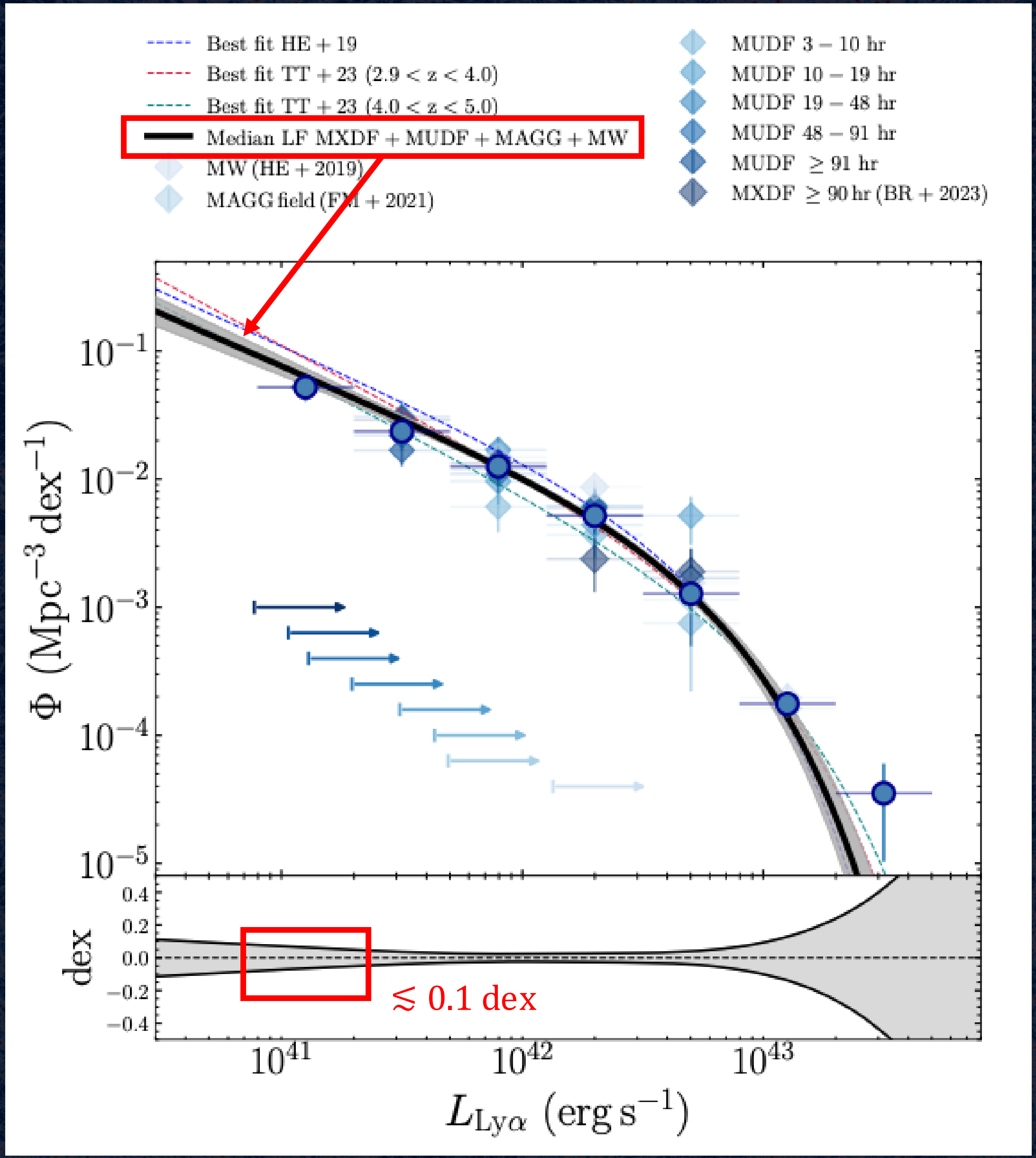
LAE luminosity function down to $\lesssim 10^{41}$ erg s^{-1}



General agreement with previous studies leveraging gravitational lensing (e.g. Thai et al 2023) to reach luminosities of $L \lesssim 10^{41}$ erg s^{-1}, although we report a slightly lower value for α

D. Tornotti et al. A&A submitted

LAE luminosity function down to $\lesssim 10^{41}$ erg s^{-1}



- Overdensity estimate;
- Calibration probe for simulations aiming to reproduce the LAE population;

D. Tornotti et al. A&A submitted

The future: BlueMUSE and (possibly) WST

muse
multi unit spectroscopic explorer

2014

BlueMUSE

Optical seeing-limited and blue-optimised IFU to be installed at VLT:

- FoV: $1\ \mathrm{arcmin}^2$
- wavelength range: $3500\ - 5800\ \text{Å}$
- $R \sim 3500$

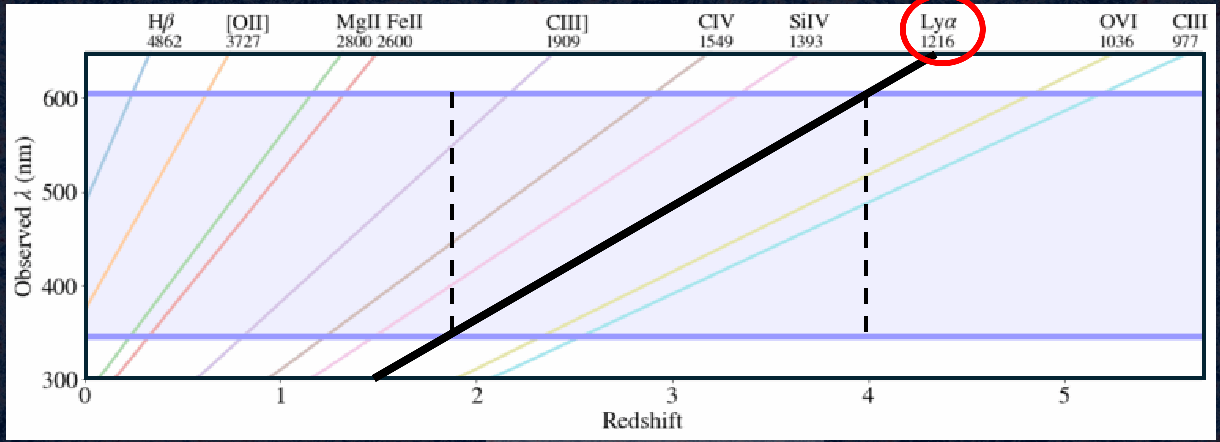
Lyα emission will be accessible **up to $z \sim 2$**

↓

Trace the Cosmic Web at lower redshift where the surface brightness dimming is weaker

↓

Easier to detect the CGM and IGM in emission



Richard et al 2019

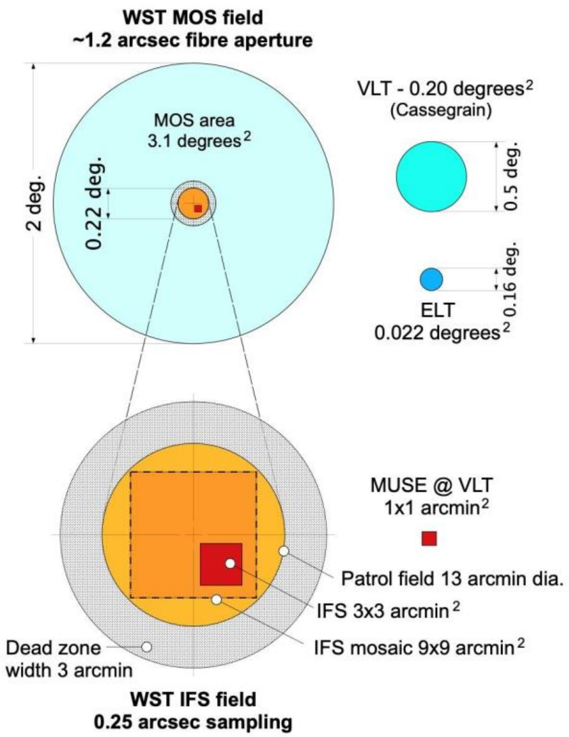
2014

2031

The next leap: Wide-Field Spectroscopic Telescope

https://www.wstelescope.com/

An innovative 12-m class **wide-field spectroscopic telescope (WST)** with simultaneous operation of a 3 sq. degree and 30 000 multi-object spectrograph plus a panoramic 3x3 sq. arcmin integral field spectrograph



Mainieri et al 2024

2014

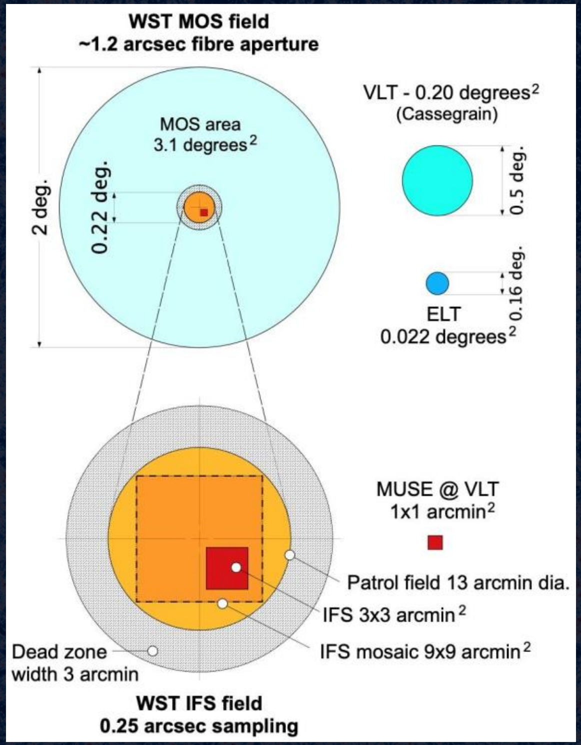
The next leap: Wide-Field Spectroscopic Telescope

«Detection era» → «Era of CW astrophysics»

Unlock the *unique potential* of WST, combining wide-area IFS with extreme MOS multiplexing

↓

WST Cosmic Web Survey
(including Tornotti et al, in prep)



Mainieri et al 2024

muse multi unit spectroscopic explorer — 2014

BLUE muse multi unit spectroscopic explorer — 2031

WST ? — 2040+

WST Cosmic Web Survey

SCIENCE GOALS

Across different redshifts ($\sim 2-5$) and environments (from rich groups to voids):

- **Mapping the cosmic web** through Lyα emission from filaments on ~ 35 cMpc scales (IFS);
- **Connecting the cosmic web to halos** on small scales by studying **embedded galaxies** (IFS);
- Linking the $\sim$ **35 cMpc cosmic web** to **large-scale structures** $\sim$ **200 cMpc** : large **coeval population** and **IGM tomography** using background galaxies (MOS);
- Testing the **nature of dark matter** by tracing matter distribution from small scales (~ 50 ckpc) to large scales (~ 200 cMpc).

D. Tornotti et al, in prep

WST Cosmic Web Survey

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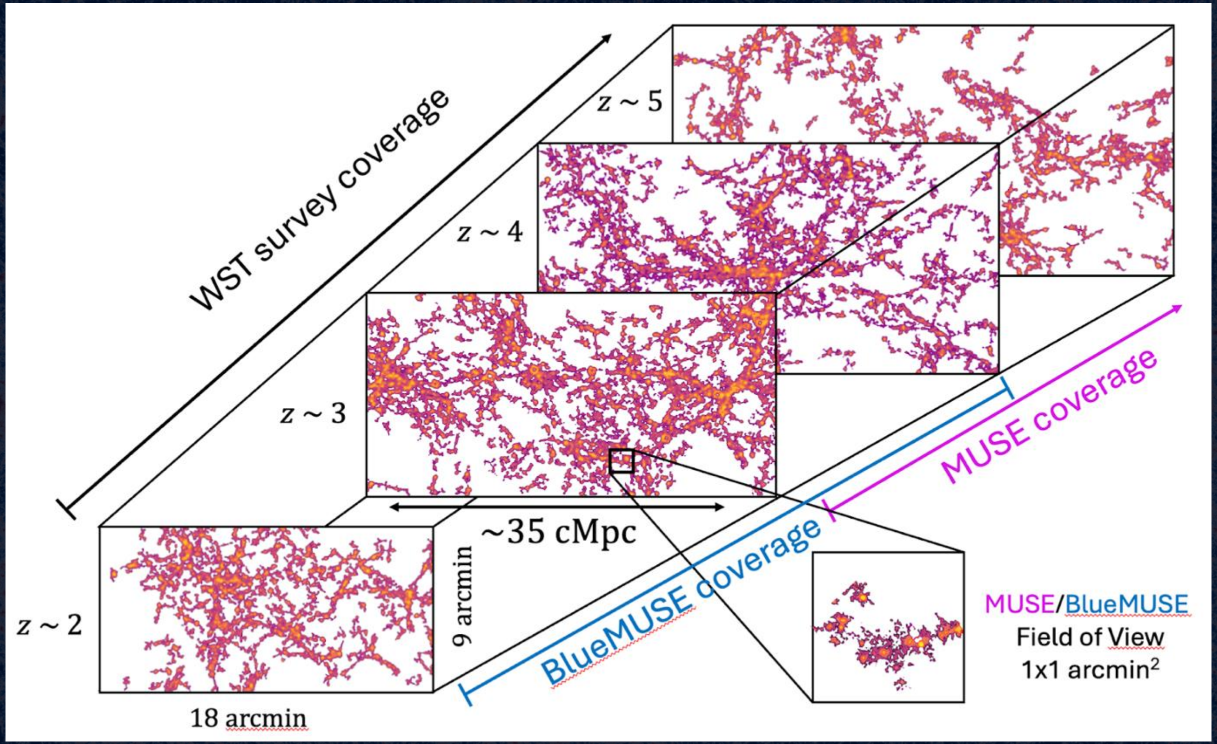
D. Tornotti et al, in prep

A multi-scale ($\sim 35-200$ cMpc) and multi-resolution ($\sim 50-800$ ckpc) experiment exploring a volume over 100x larger than previously achieved

WST Cosmic Web Survey

TRACING THE COSMIC WEB ON UNPRECEDENTED SCALES

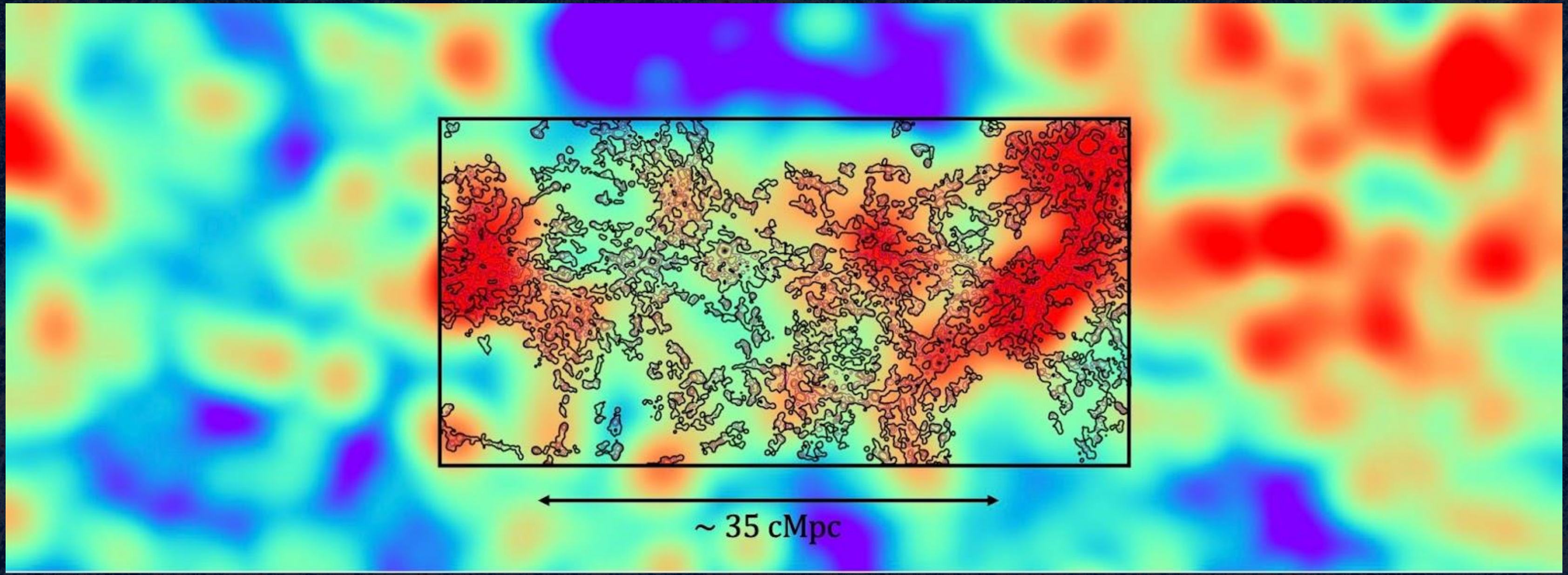


D .Tornotti et al, in prep

- Spectroscopic view of **matter distribution** in the IGM on $\sim$ 35 cMpc scales;
- Statistical characterization of **morphology** and **topology** (*e.g. number of nodes, lenght, thickness, …*);
- Constraining the **kinematics** of intergalactic gas;
- Study of the **CGM/IGM interface** in cosmic web galaxies. *Detailed analysis of **CGM properties** and constraints on temperature, density, ionization state using multiple tracers (e.g. Lyα, MgII).*

WST Cosmic Web Survey

LARGE SCALE IGM TOMOGRAPHY



D. Tornotti et al, in prep

- **Background galaxies** enable tomographic absorption mapping of the IGM with $\sim \mathbf{0.8\ cMpc}$ **resolution**;
- Reconstruction of **large-scale** (> 200 cMpc) structures from which the **cosmic web originates**.

Conclusions

- The MUSE Deep Fields have opened a new frontier: detecting cosmic web filaments in emission on $\sim$ **Mpc scales**;

- We are beginning to probe **different environments** (QSOs → LAEs) across different redshifts ($z \approx 3-4$) ⟶ **larger samples** are required

- The upcoming **BlueMUSE** will increase the observational window down to redshift $z \sim 2$ and possibly **WST** will deliver the transformative leap enabling **direct mapping of the cosmic web in emission** over large volumes ($z \approx 2-5$);

muse
multi unit spectroscopic explorer

BLUE muse
multi unit spectroscopic explorer

?

Thanks for your attention!

d.tornotti@campus.unimib.it