Mapping the Cosmic Web in Lyα emission

Davide Tornotti

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

Based on: Tornotti et al. 2025a, 2025b, 2025c, 2026 submitted

UNIVERSITÀ DEGLI STUDI DI MILANO BICOCCA

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Presentation Outline

- **Brief introduction and key questions**
  Why search for the faint glow of the intergalactic medium?
- **The MUSE Ultra Deep Field dataset**
  Pushing MUSE to its limits to detect diffuse Lyman-α emission
- **A cosmic filament between two quasars**
  A first glimpse of the web in emission
- **LAE overdensities as cosmic tracers**
  From galaxies to large-scale structure in the MUSE Deep Fields
- **Conclusions**

Brief introduction and key questions

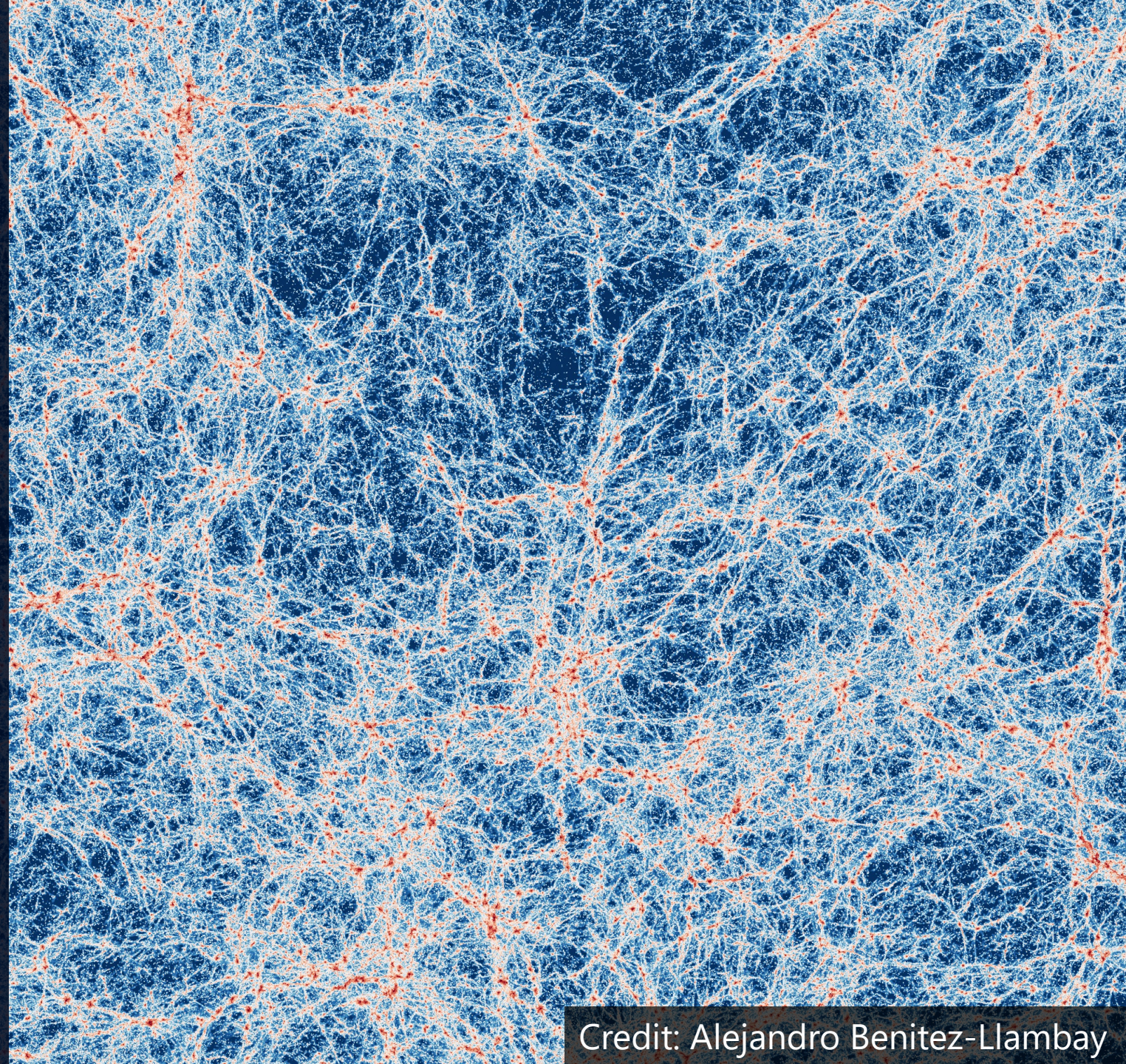
Why search for the faint glow of the intergalactic medium?

ΛCDM cosmological paradigm

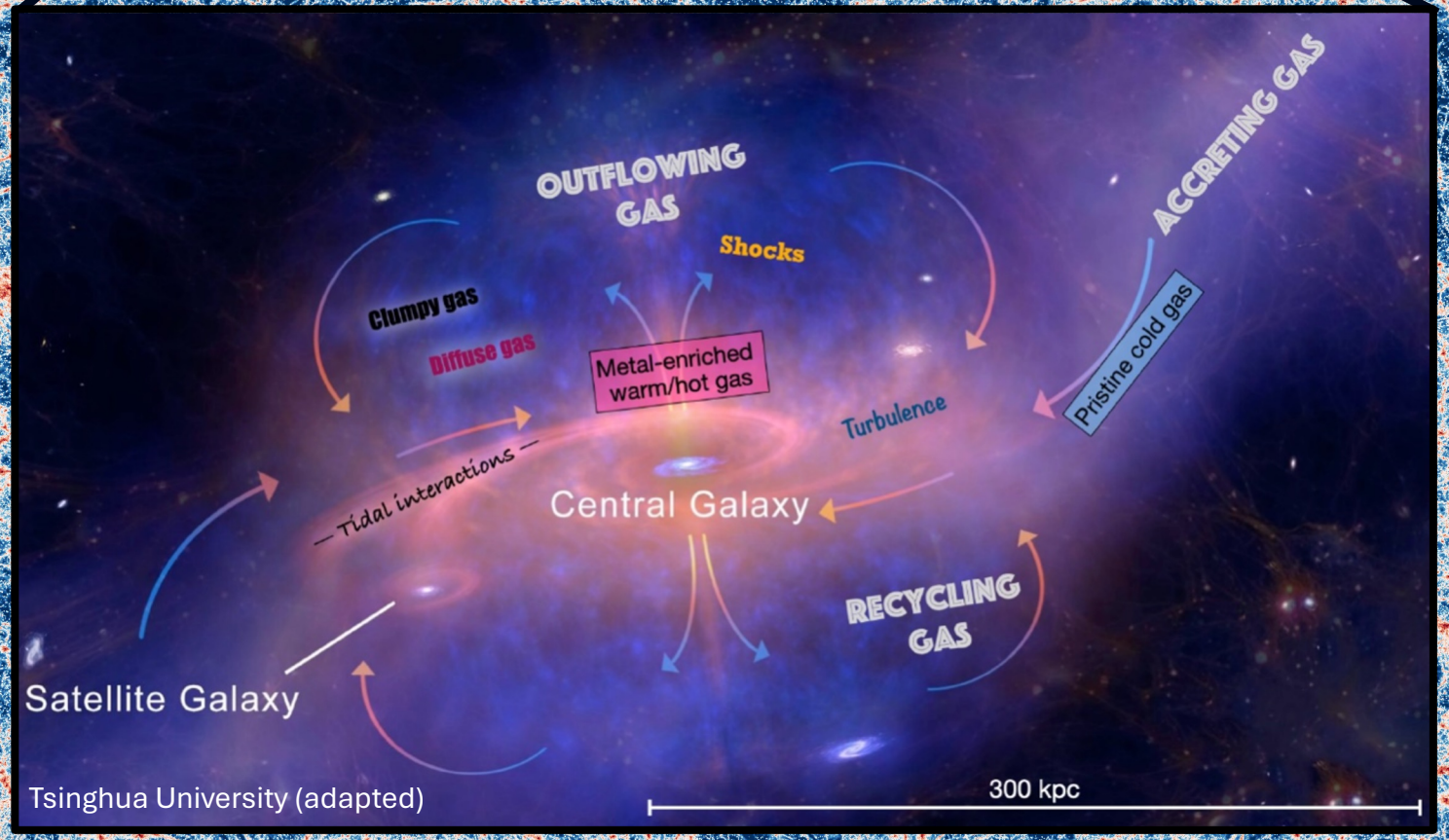
↓

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

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



Credit: Alejandro Benitez-Llambay



Filaments feed the CGM that regulates the gas exchange between galaxies and the sorrounding IGM

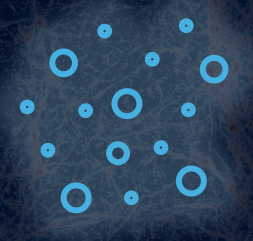
(e.g Tumlison et al 2017)

↓

Control the galaxy growth across cosmic time

(e.g. Davé et al 2012, Lilly et al 2013)

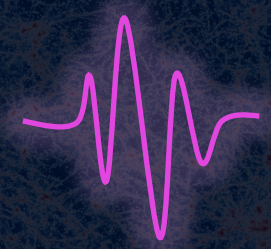
Observing the multiphase CGM and IGM in emission



Density challenge

The CGM and even more the IGM have low density

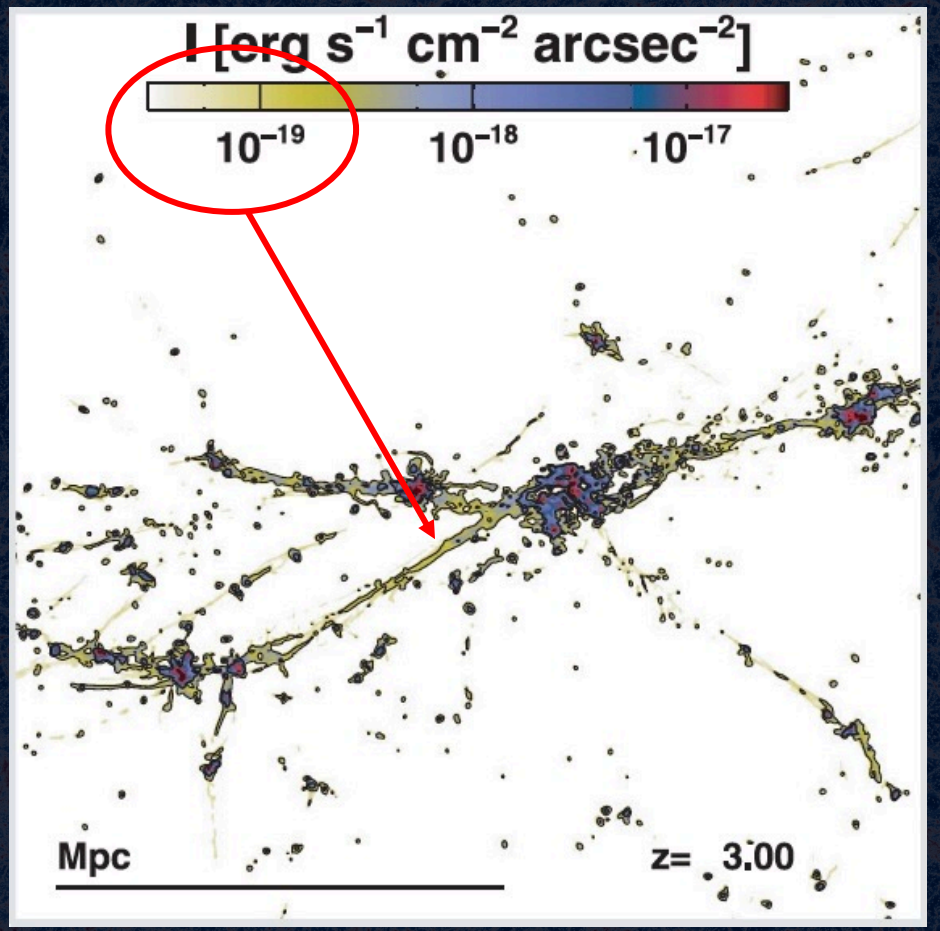
$$n_H \ll 10^{-2}\ \mathrm{cm}^{-3}$$



Hydrogen Lyα $\lambda 1215.67$ Å

Map in emission the **cool** gas in the CGM and IGM on large scales ($\gg 100$ kpc) at $z \approx 2-4$

Simulated Lyα emission at $z = 3$



Rosdahl & Blaizot 2012

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 affect the CGM/IGM?

The MUSE Ultra Deep Field

Pushing MUSE to its limits to detect diffuse Lyman-α emission

The MUSE Ultra Deep Field (MUDF)

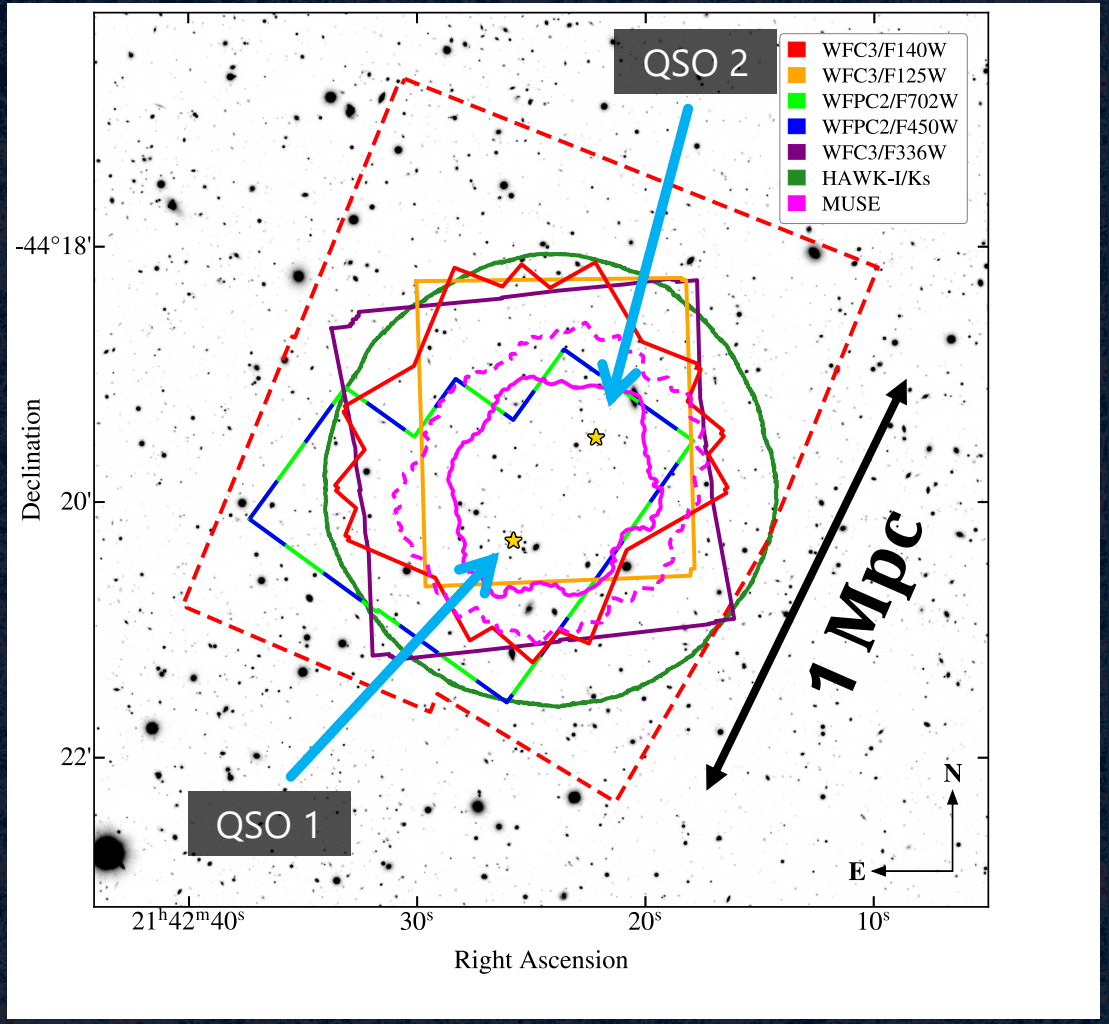
142h
Optical spectroscopy
(MUSE)

99 orb
HST WFC3 G141,
F140W, F125W, F336W

27h
I and K imaging
(HAWK)

14h
(sub-)millimiter
(ALMA Band 3 and 6)

30h
QSO spectroscopy
(UVES)



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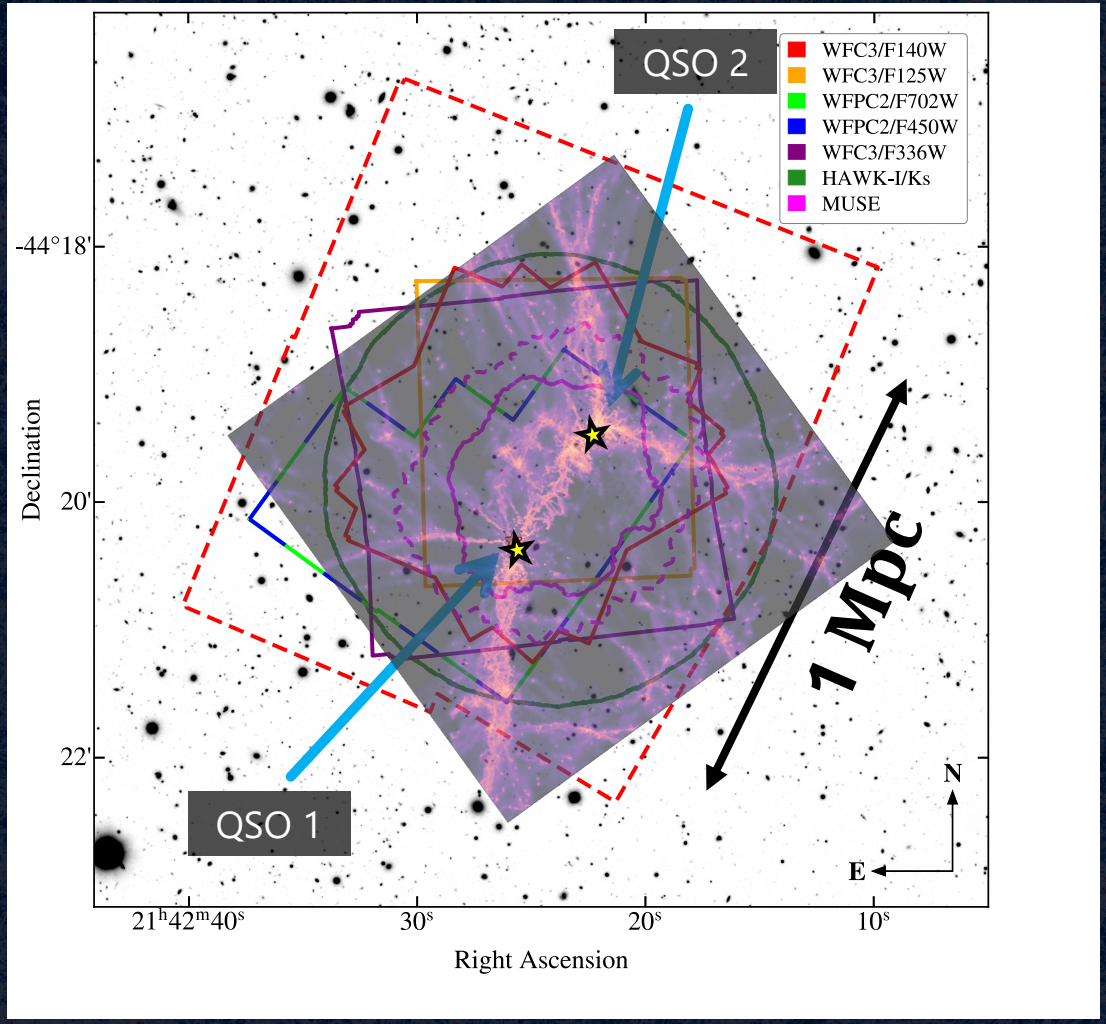
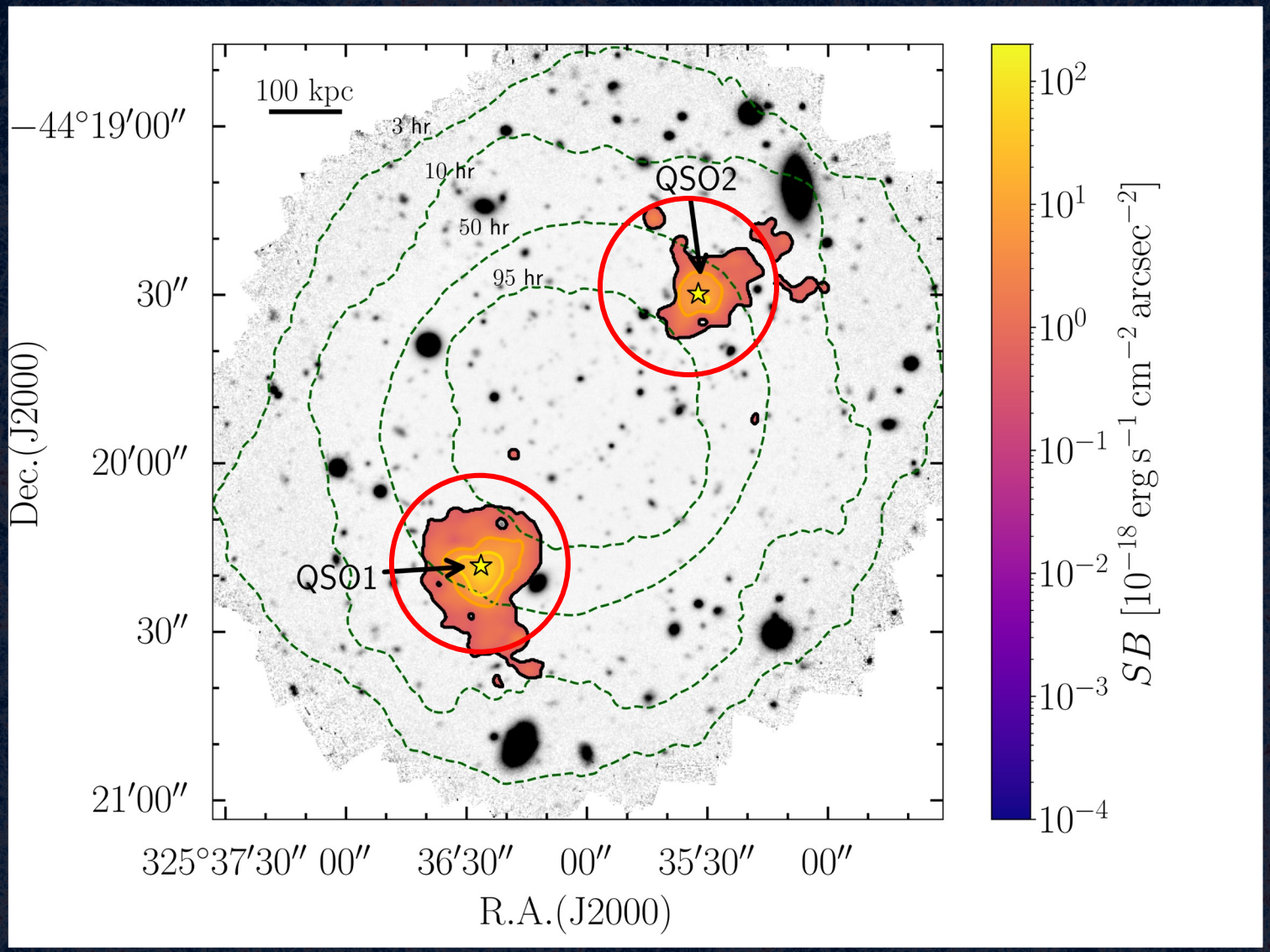


The environment of the QSO pair at z~3.22



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

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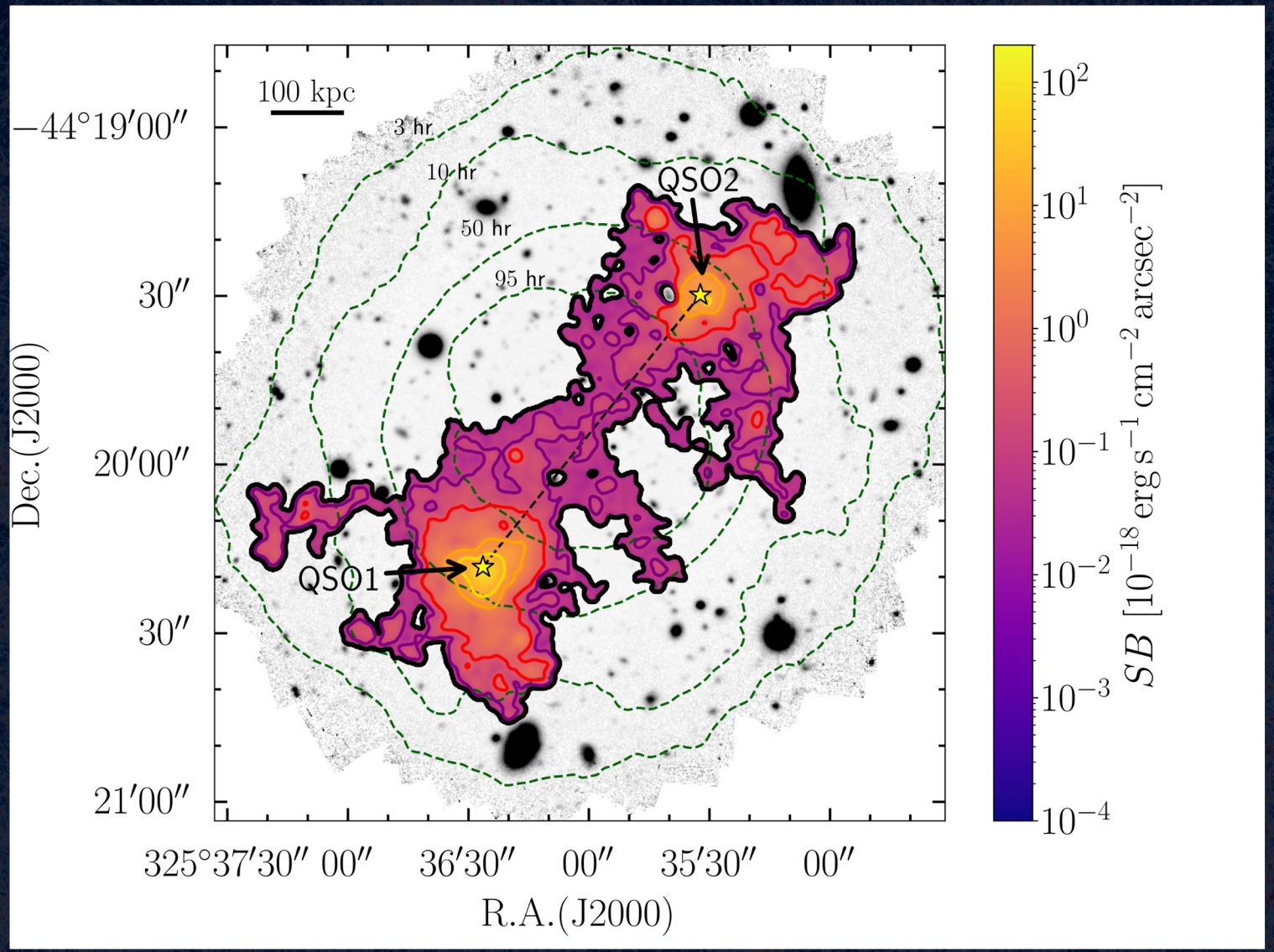

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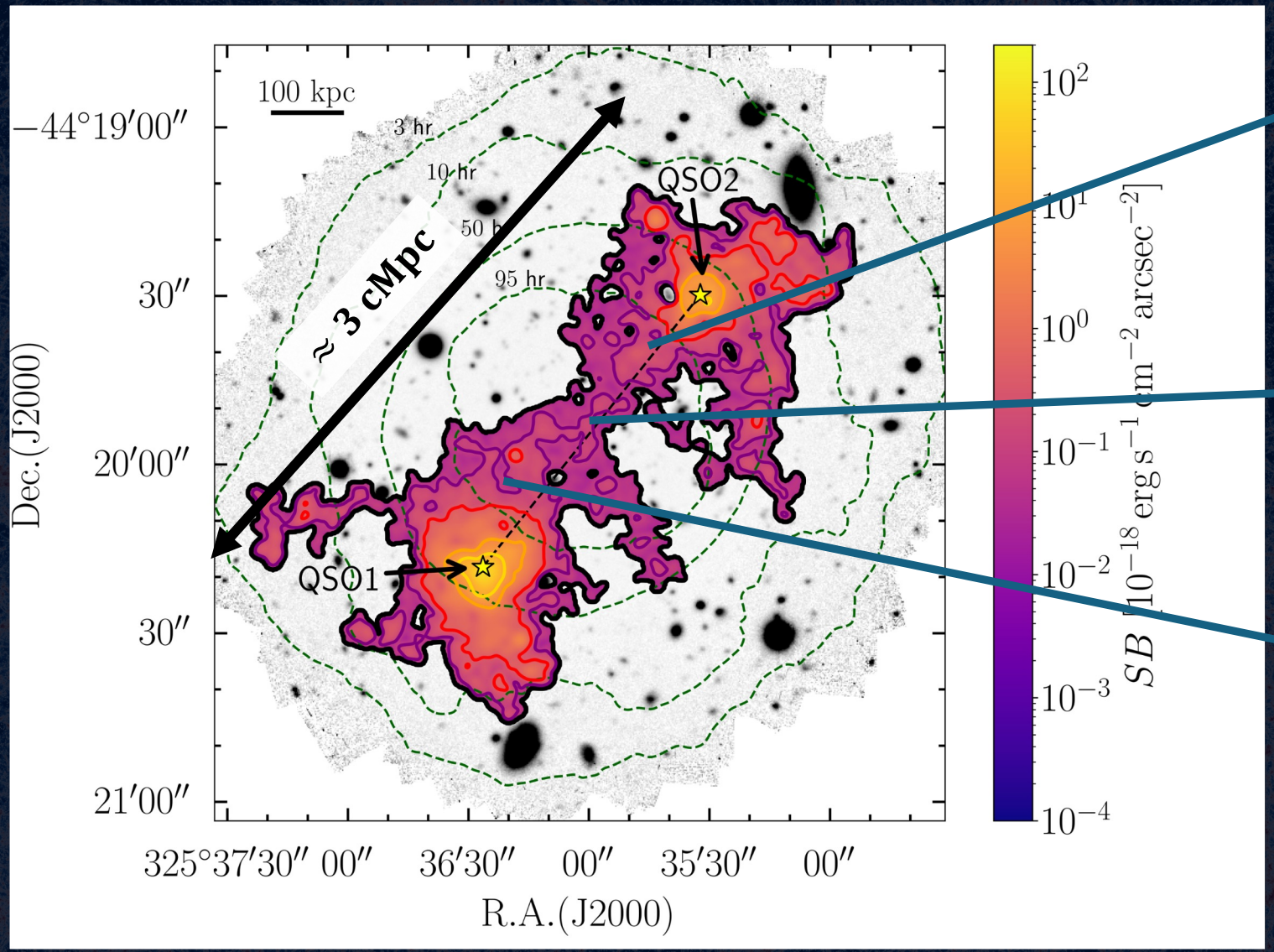

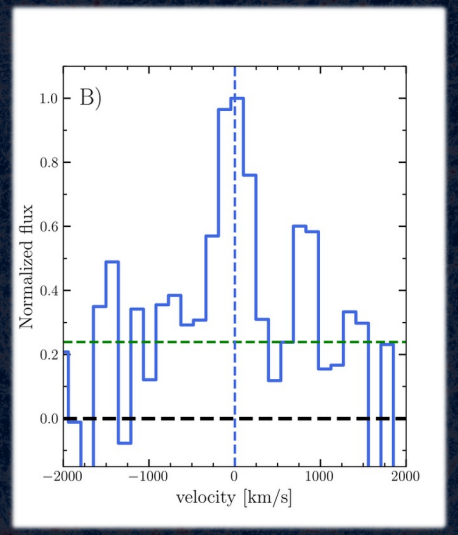

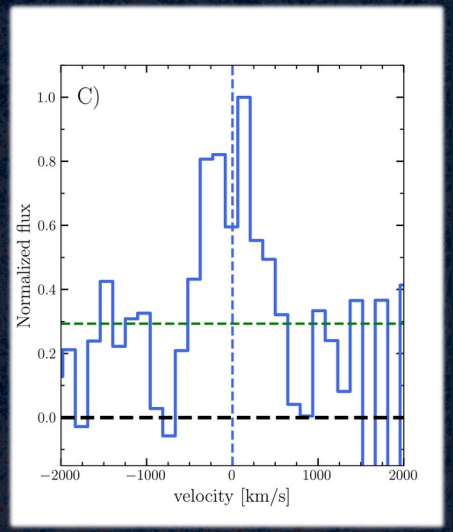

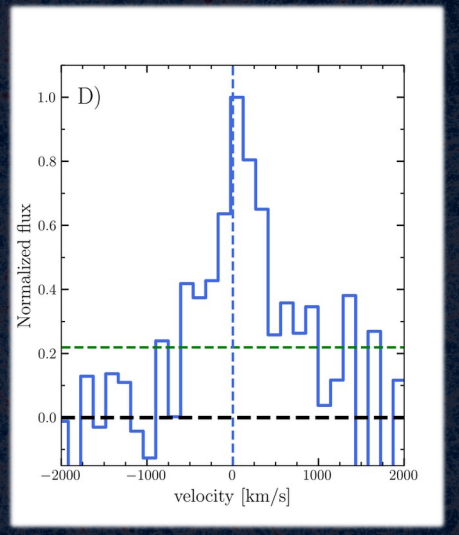

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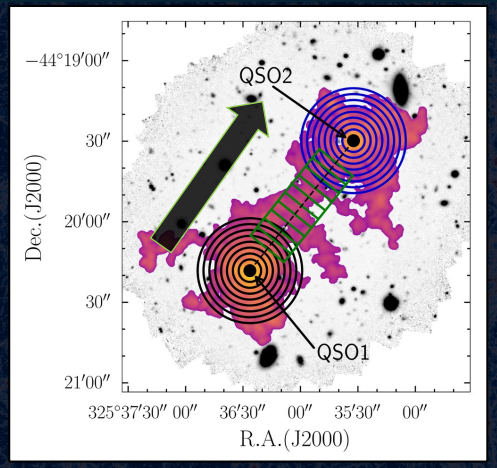
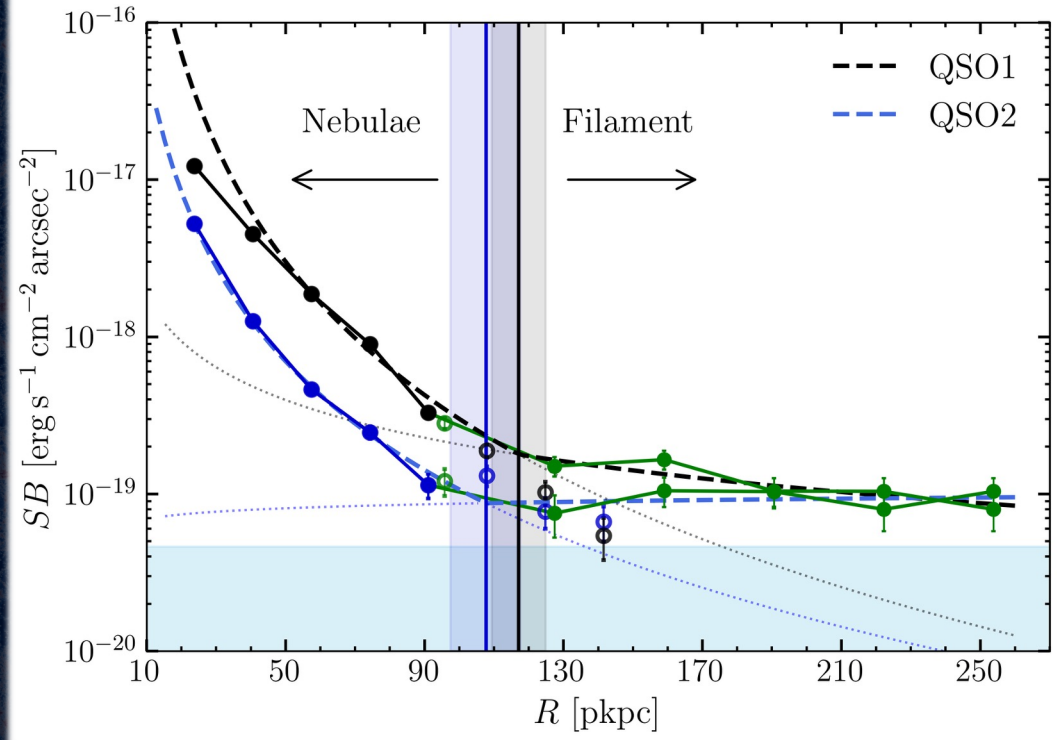


Profile *along* the filament



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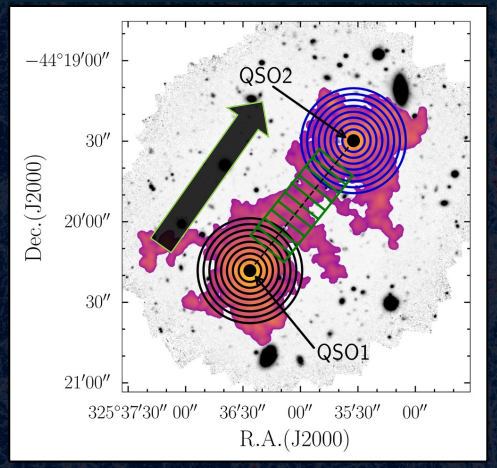

e.g. Fossati et al 2021,
de Beer et al 2023

$R_t \approx 100$ pkpc

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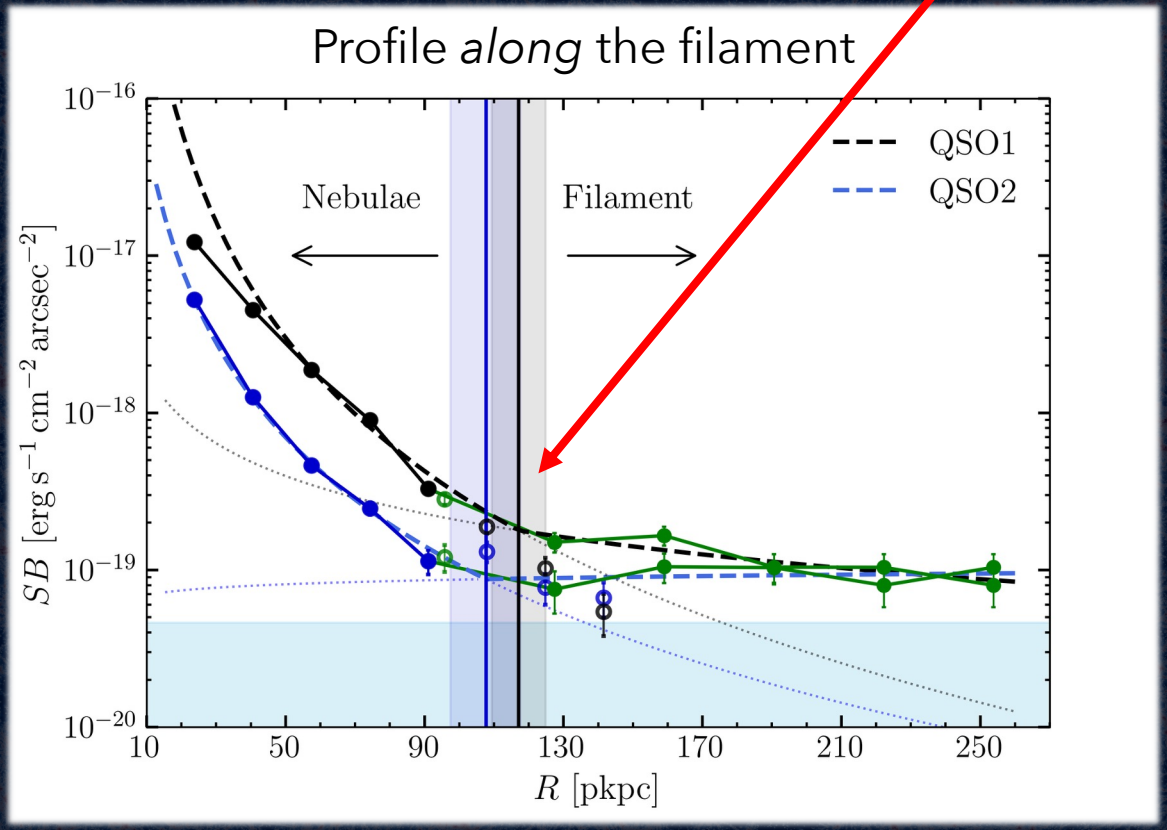

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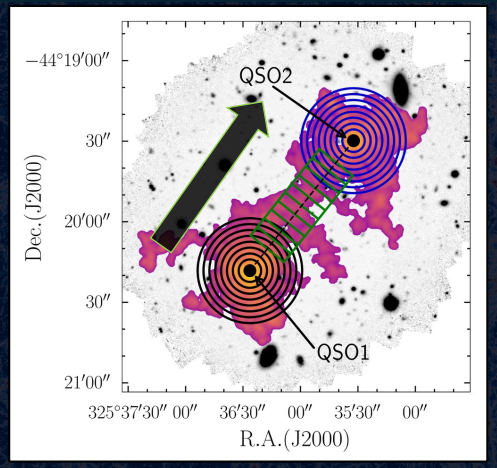

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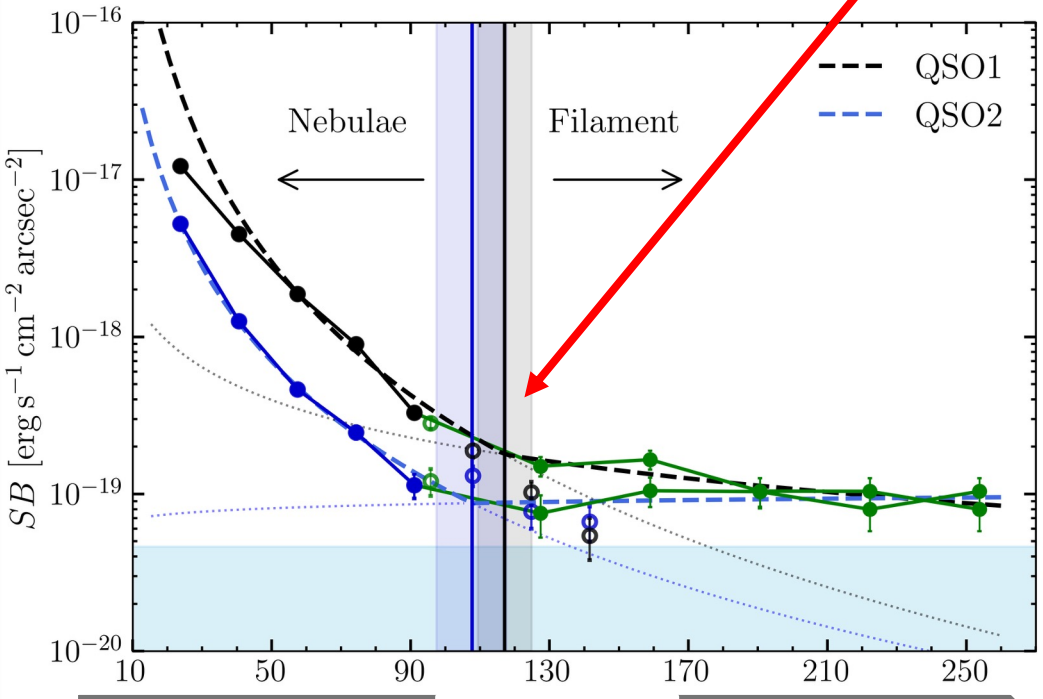

Transition between CGM and IGM happens at the expected virial radius

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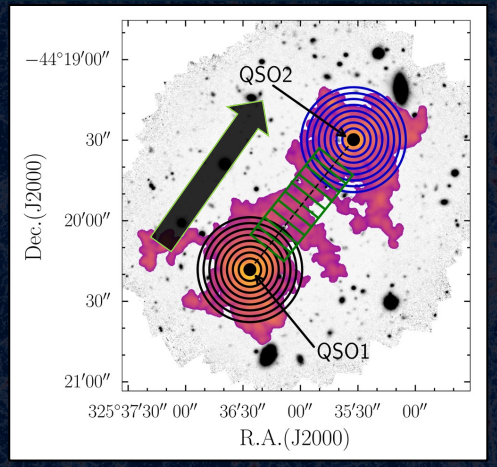

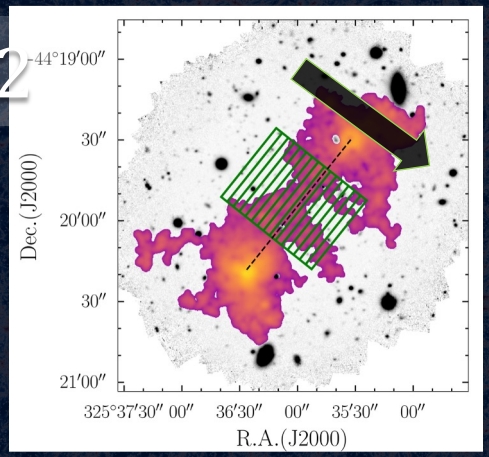

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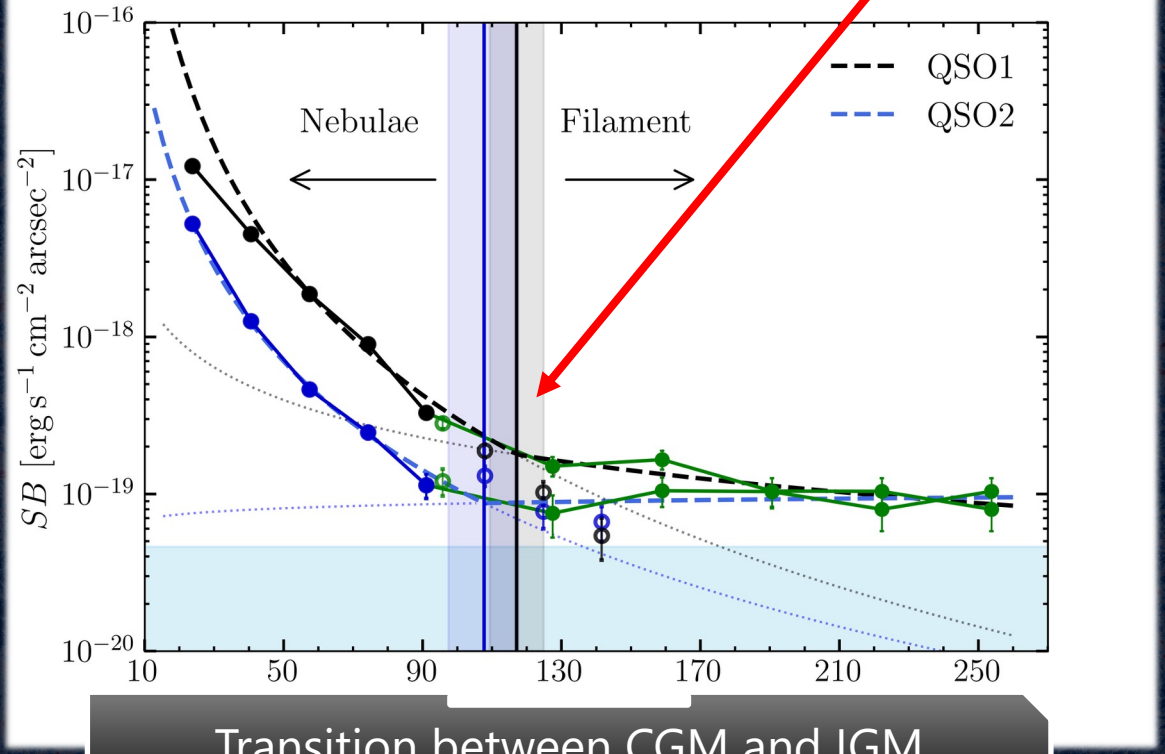

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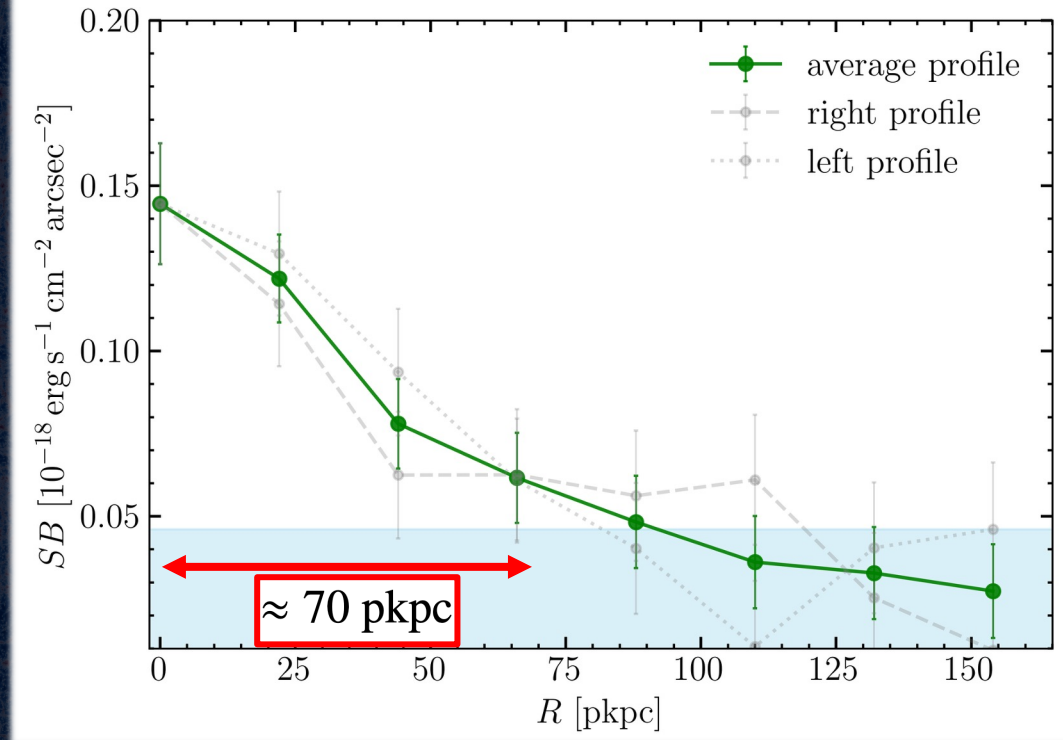
Profile *perpendicular* to the filament



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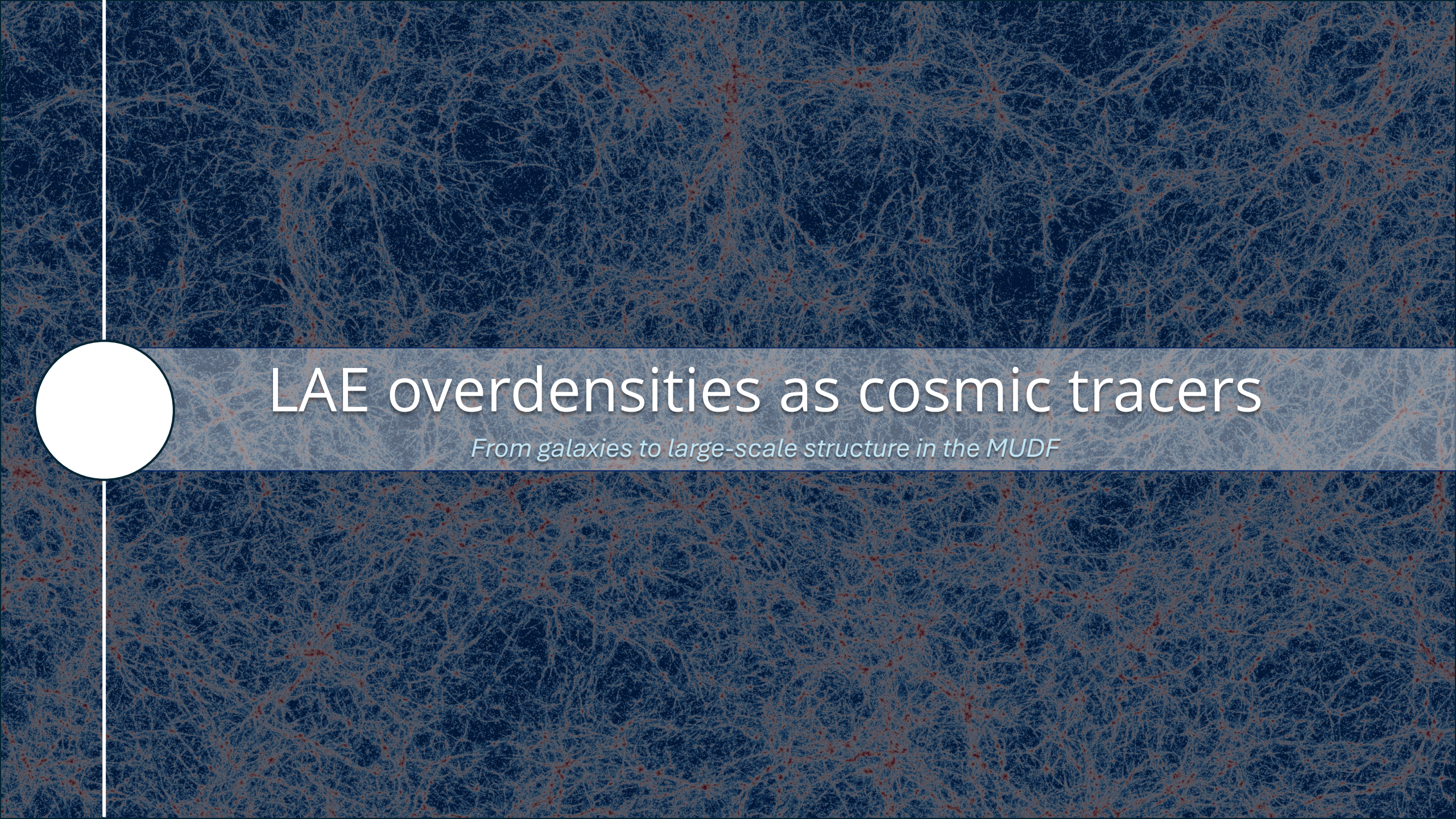

LAE overdensities as cosmic tracers

From galaxies to large-scale structure in the MUDF

Tracing large-scale structures with LAE overdensities

STEP 1: CATALOG

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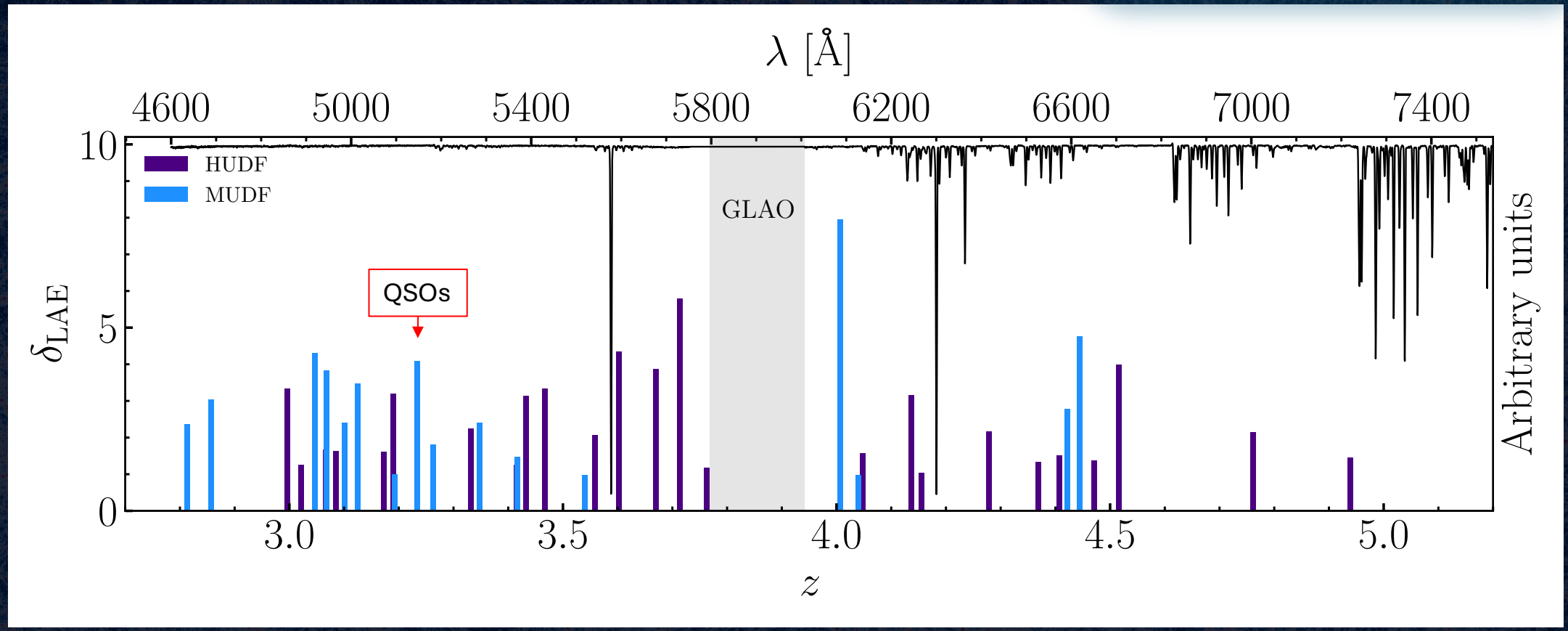

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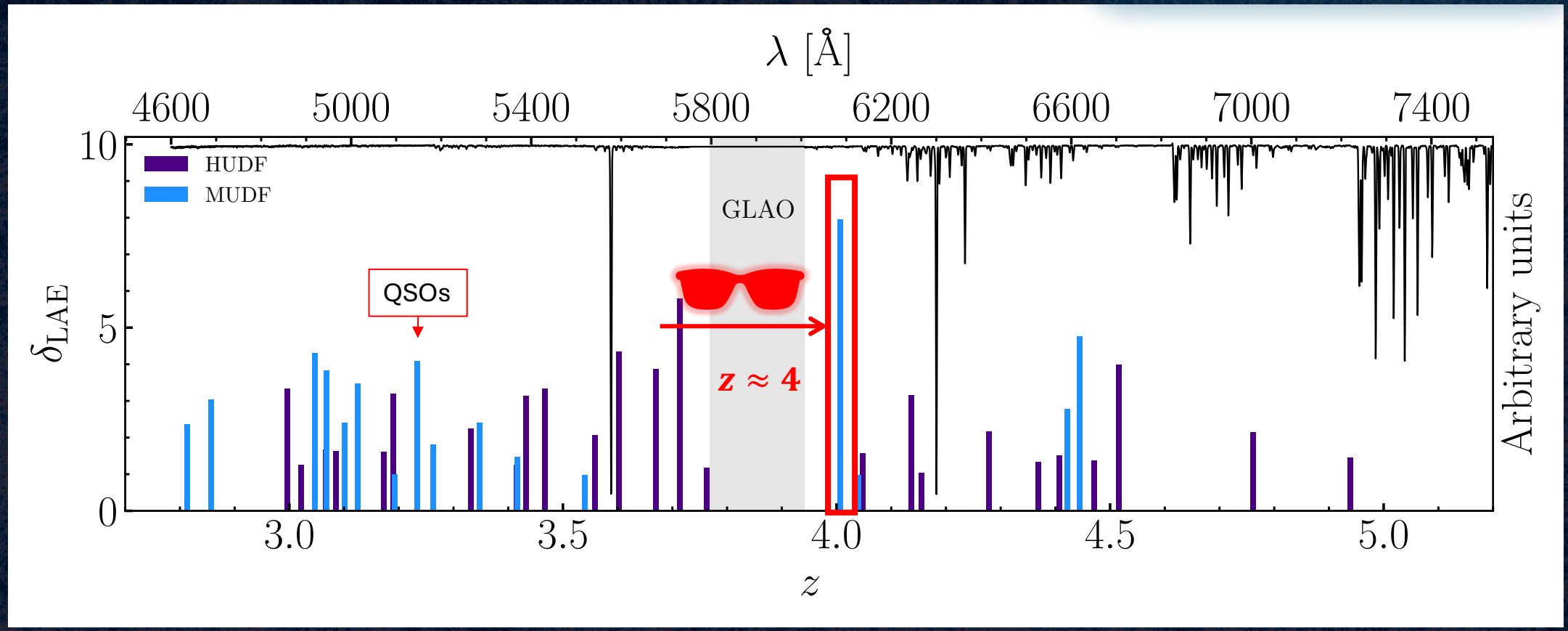
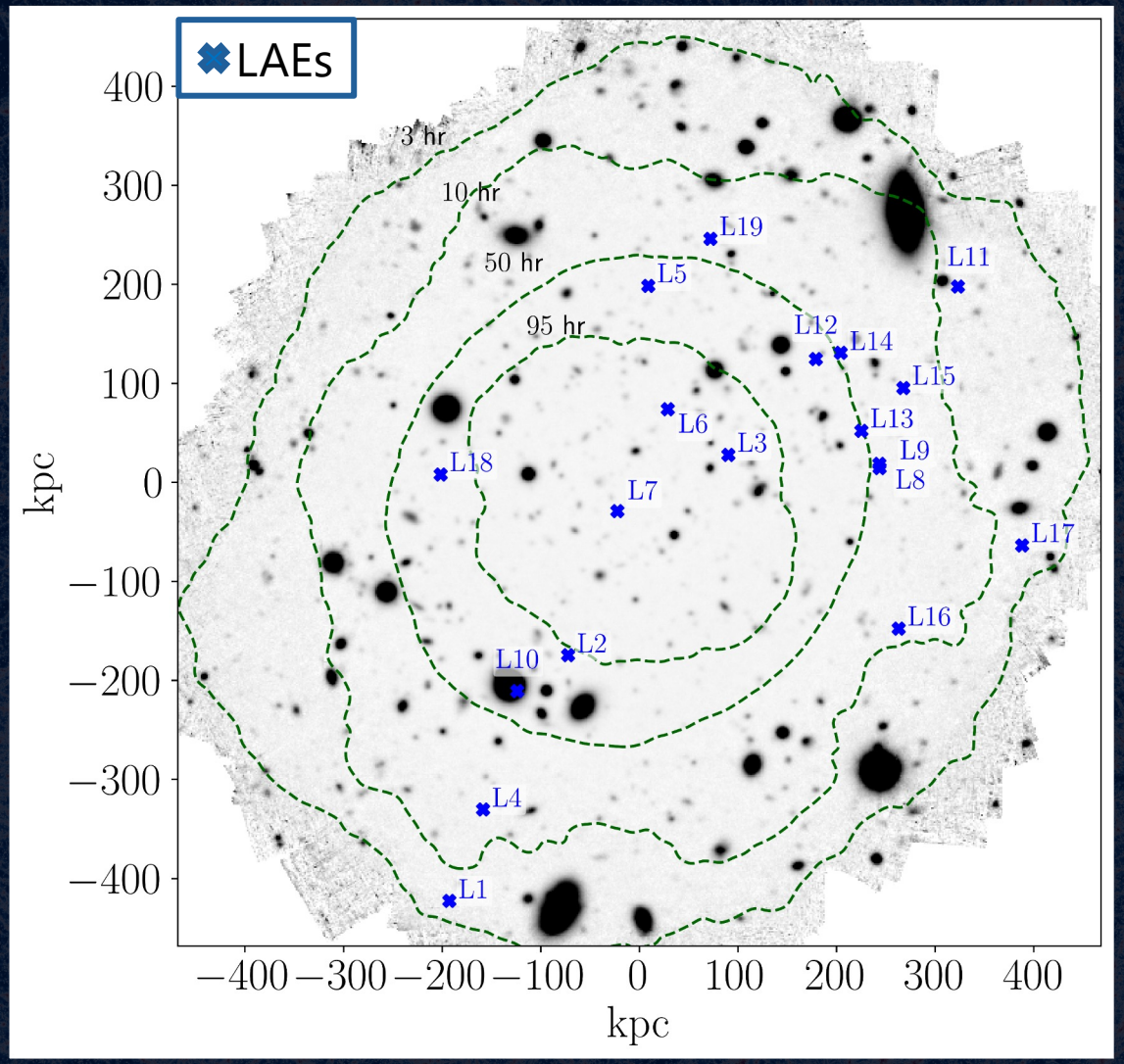


D. Tornotti et al., submitted

Filaments around LAEs at $z\sim4$



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

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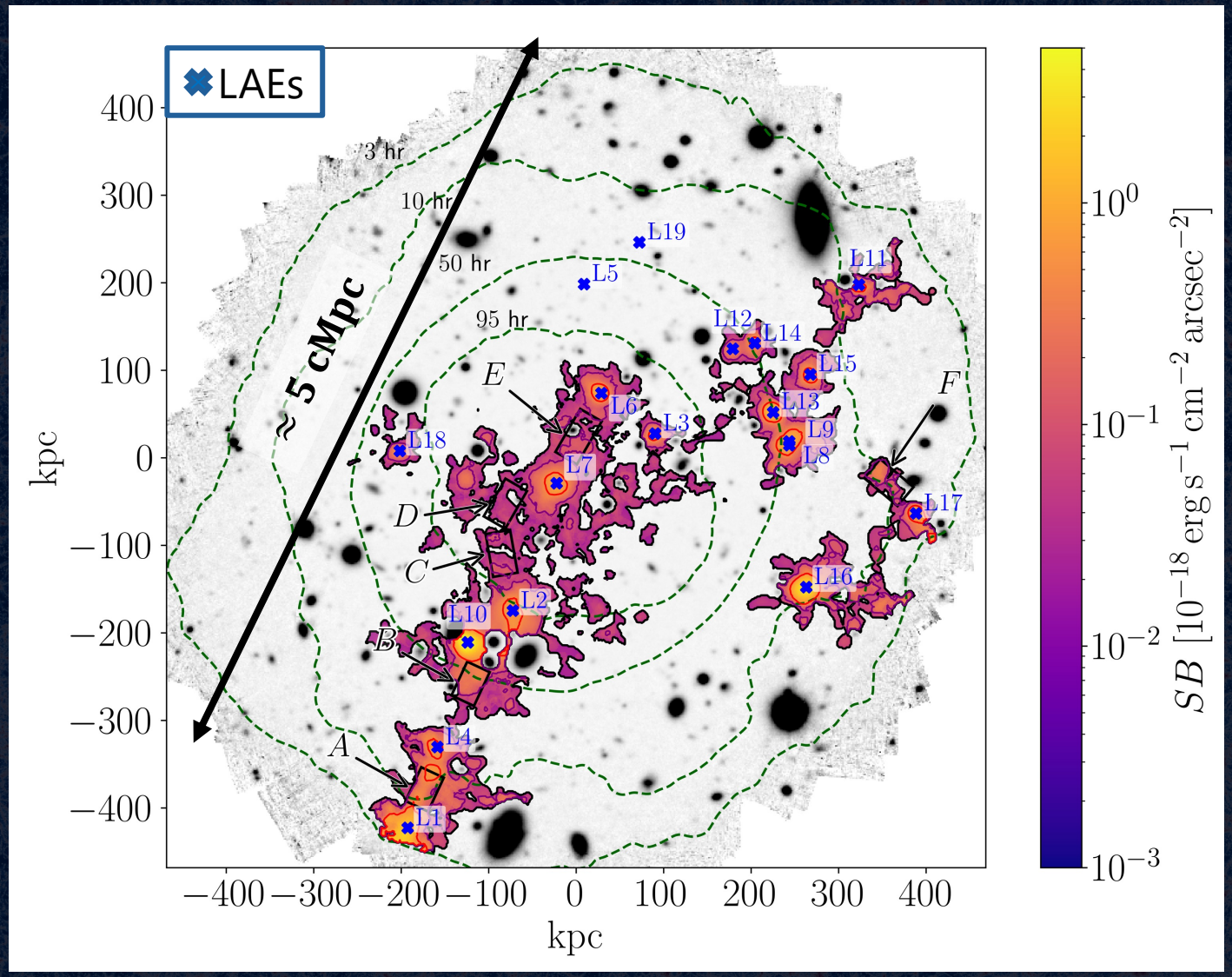

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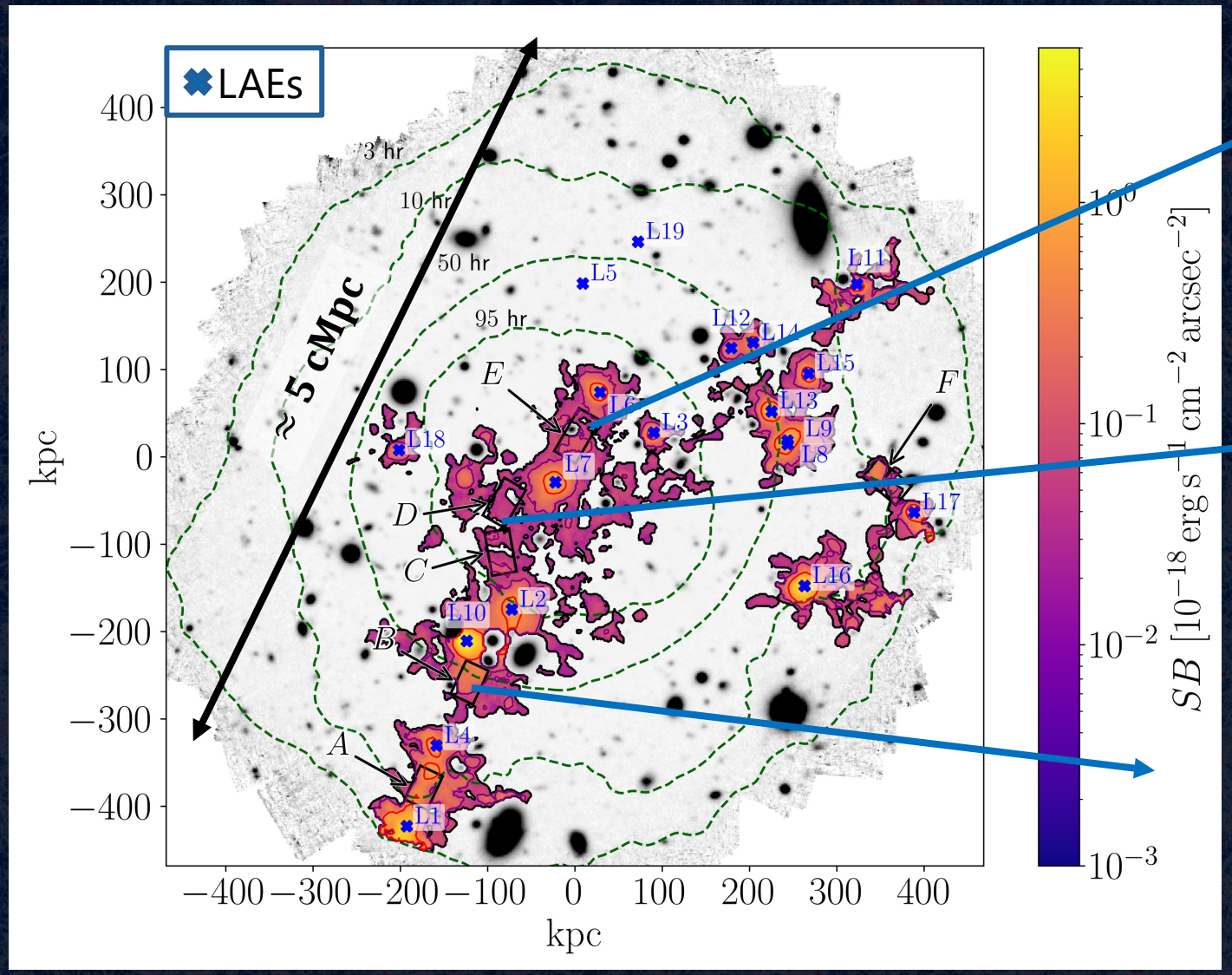
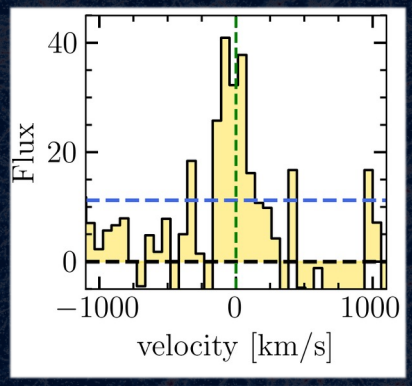
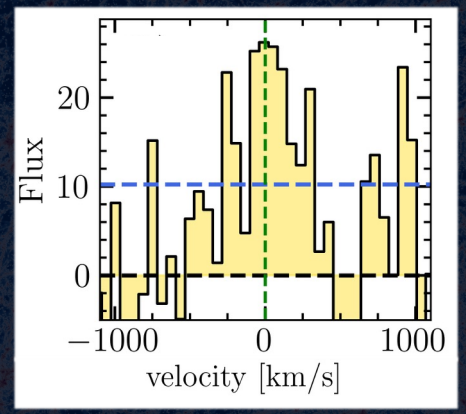
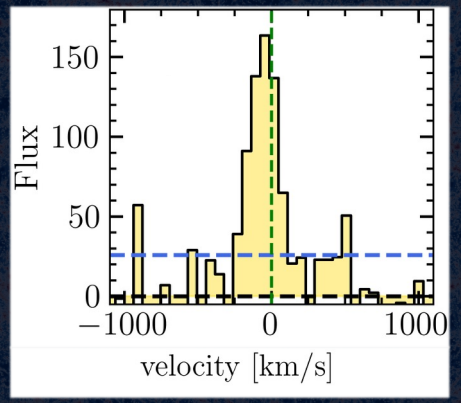


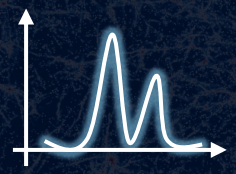






D. Tornotti et al., 2025b, *ApJL*

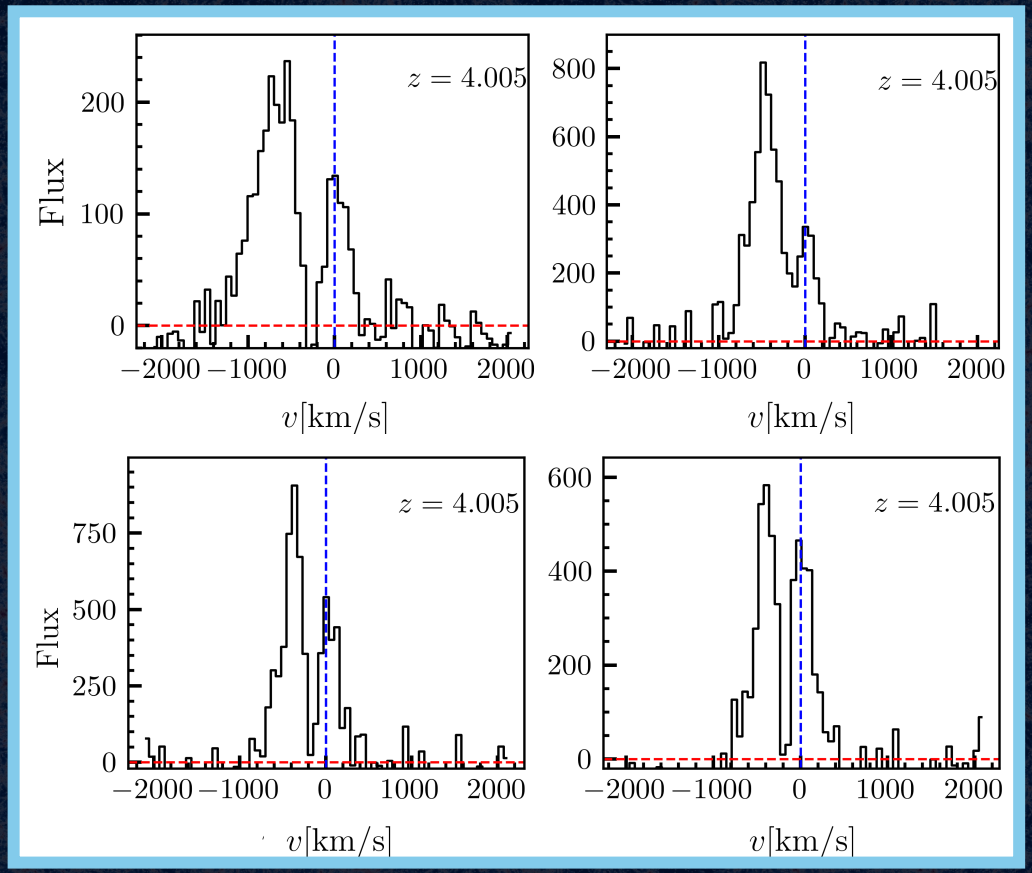
LAEs embedded in the filament $z\sim4$



37%
Double-peaked profiles

of which

71%
Blue-dominated



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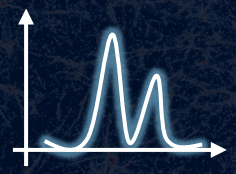

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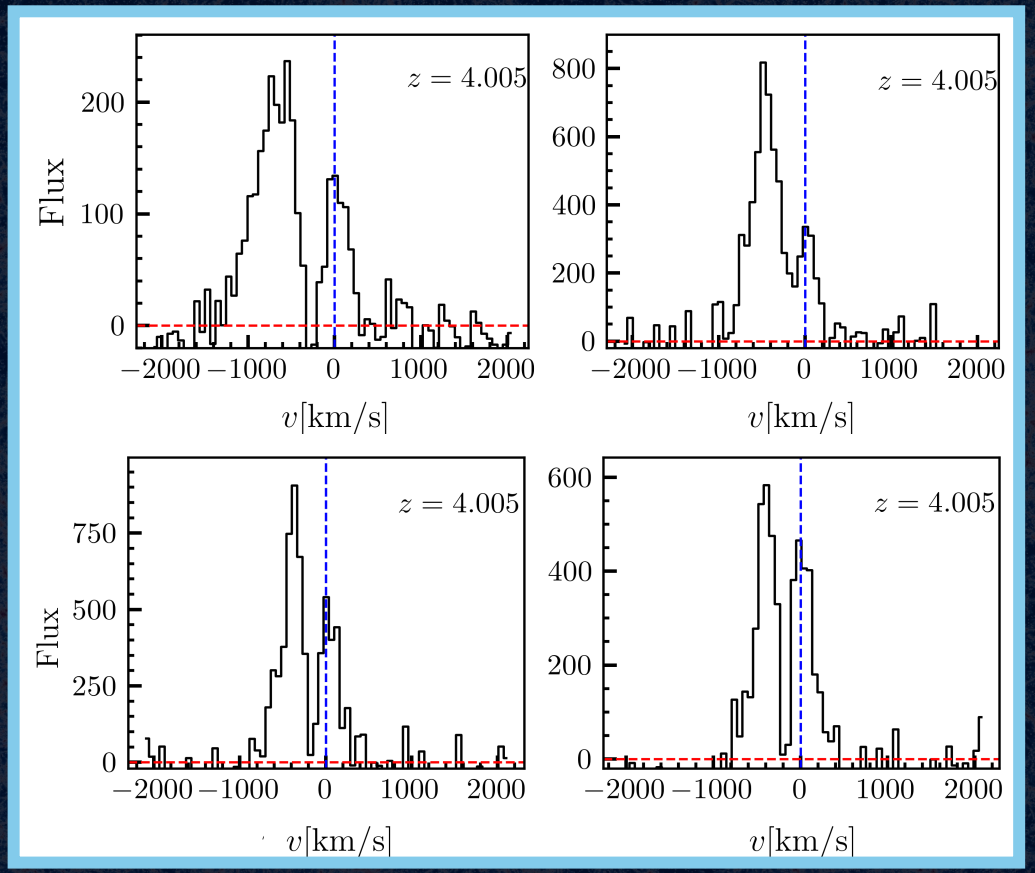

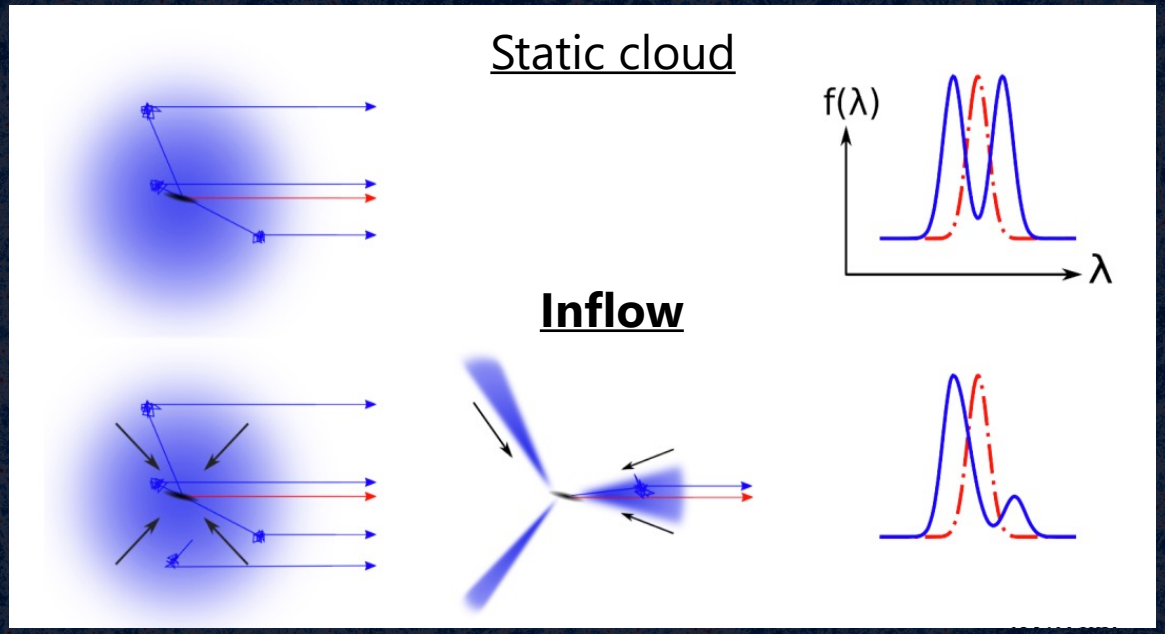

→ Enhanced star formation rate?

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

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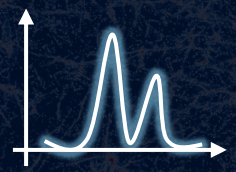

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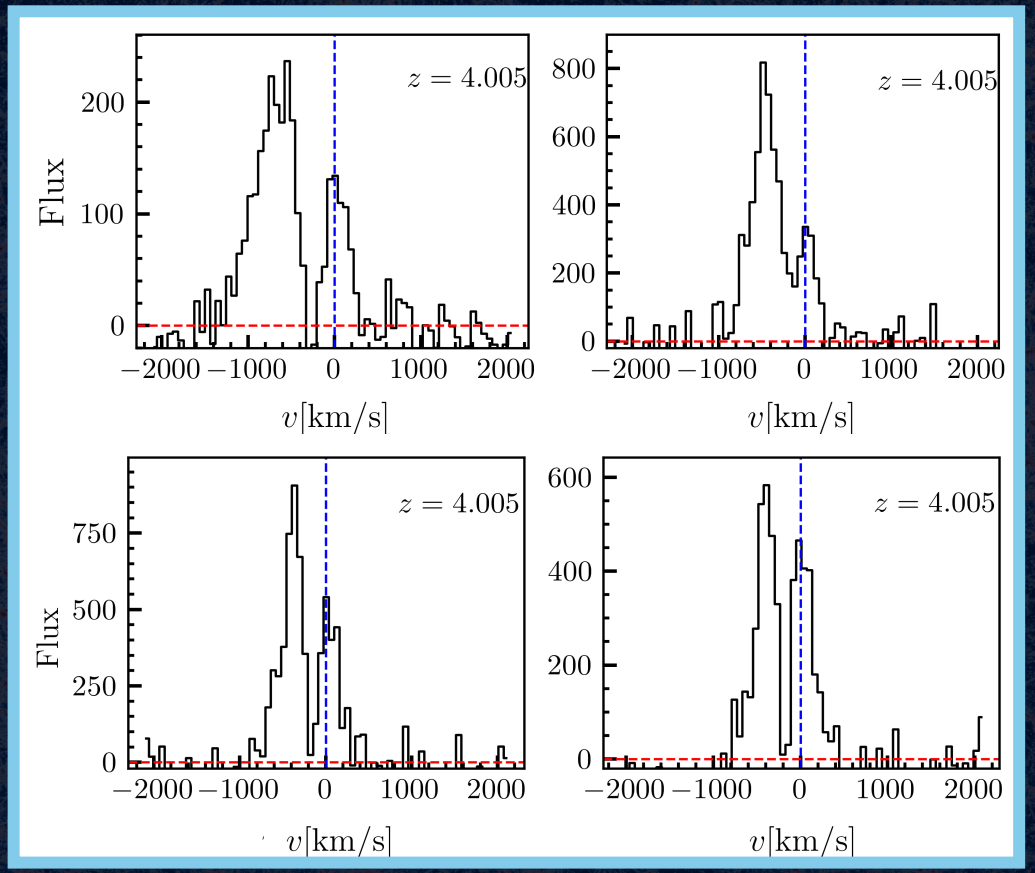
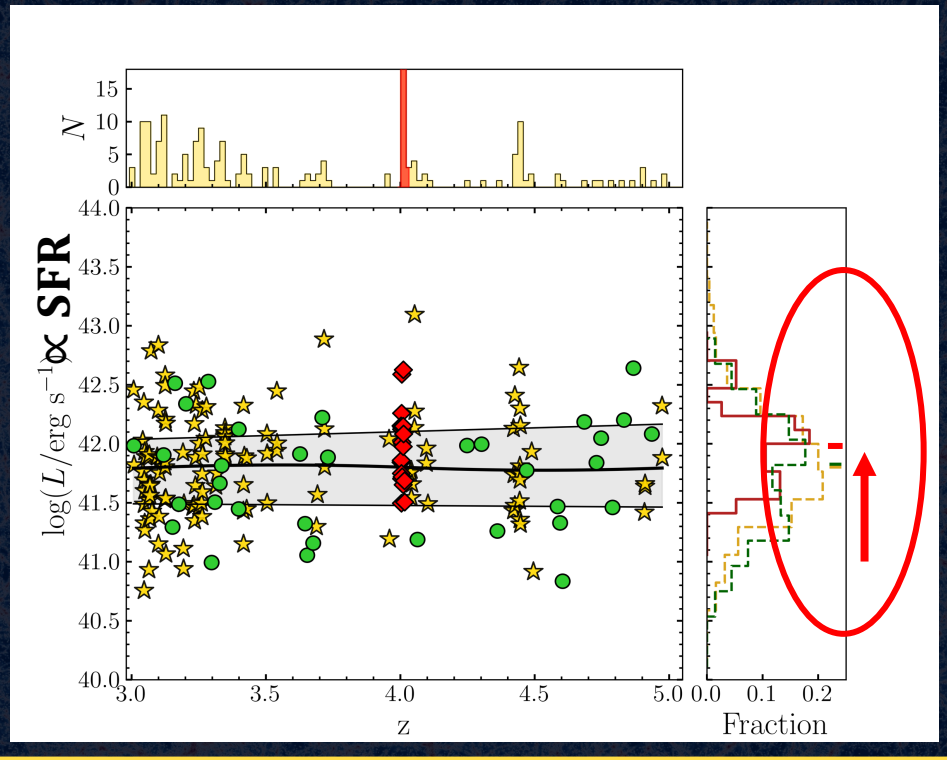




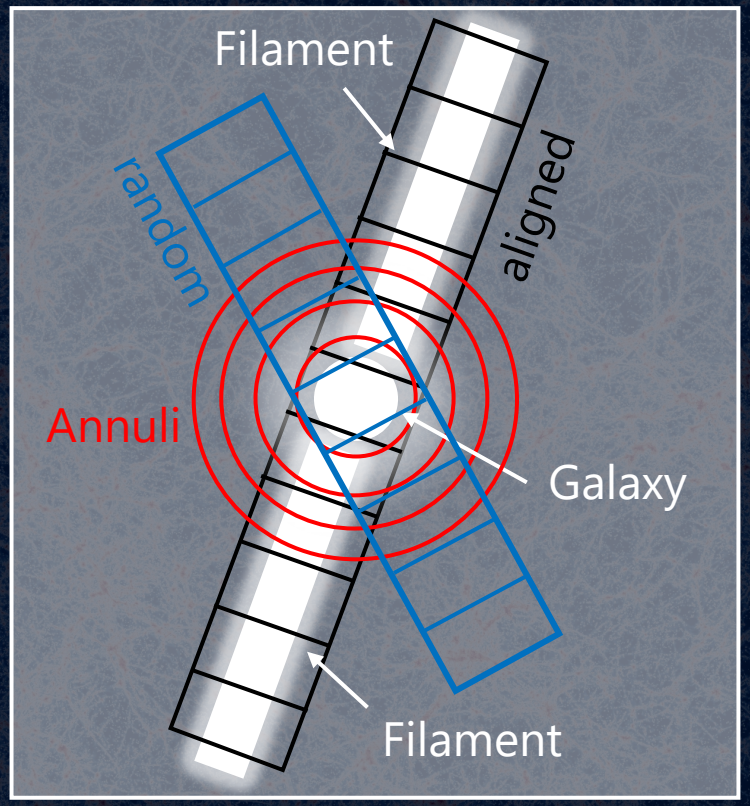
A population of active galaxies fuelled by prominent accretion?

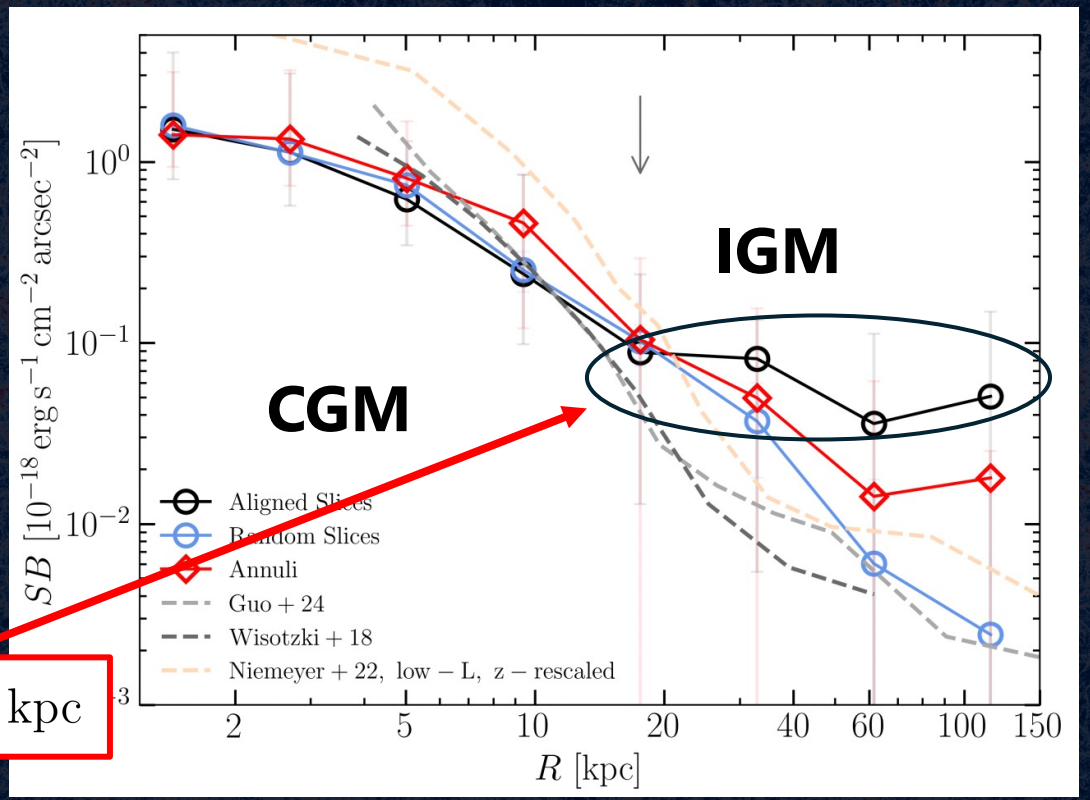
D. Tornotti et al., 2025b, *ApJL*

LAEs embedded in the filament $z\sim4$

Evidence of inflection point in the SB profiles

→ transition between CGM and IGM happens at the expected virial radius





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

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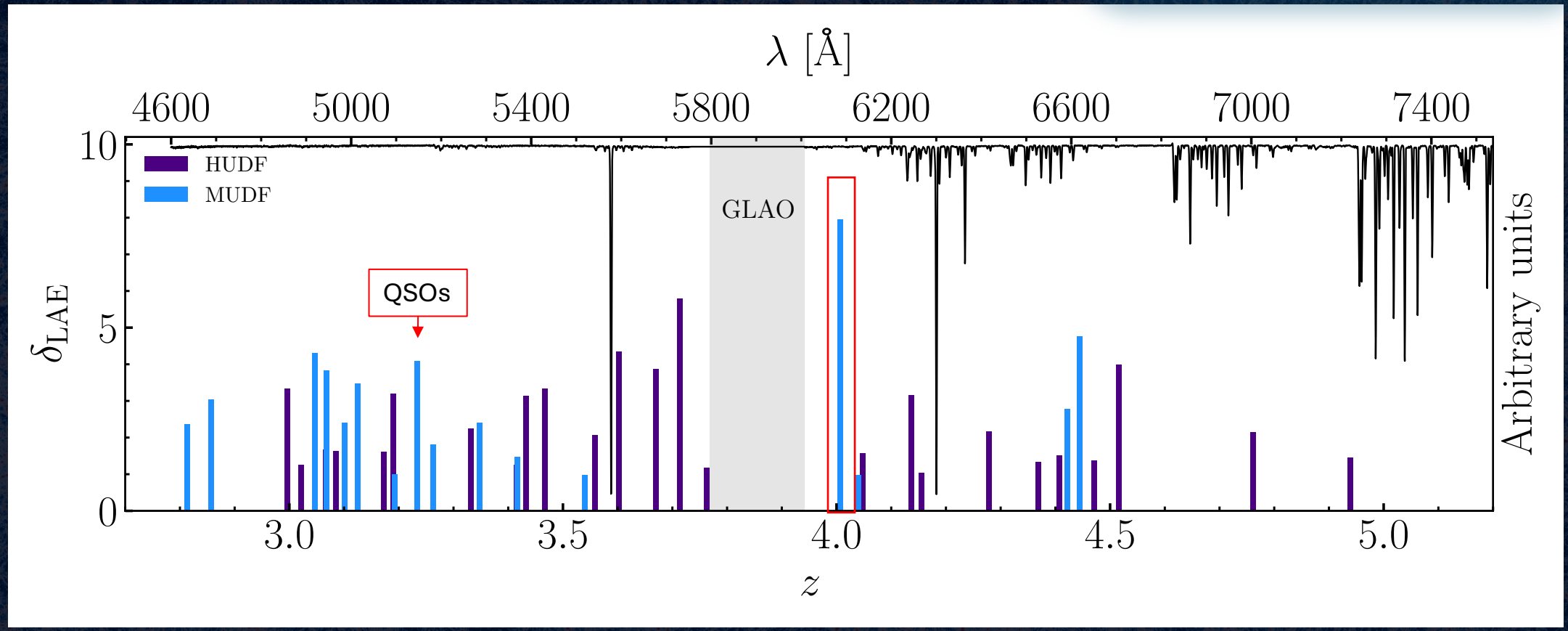
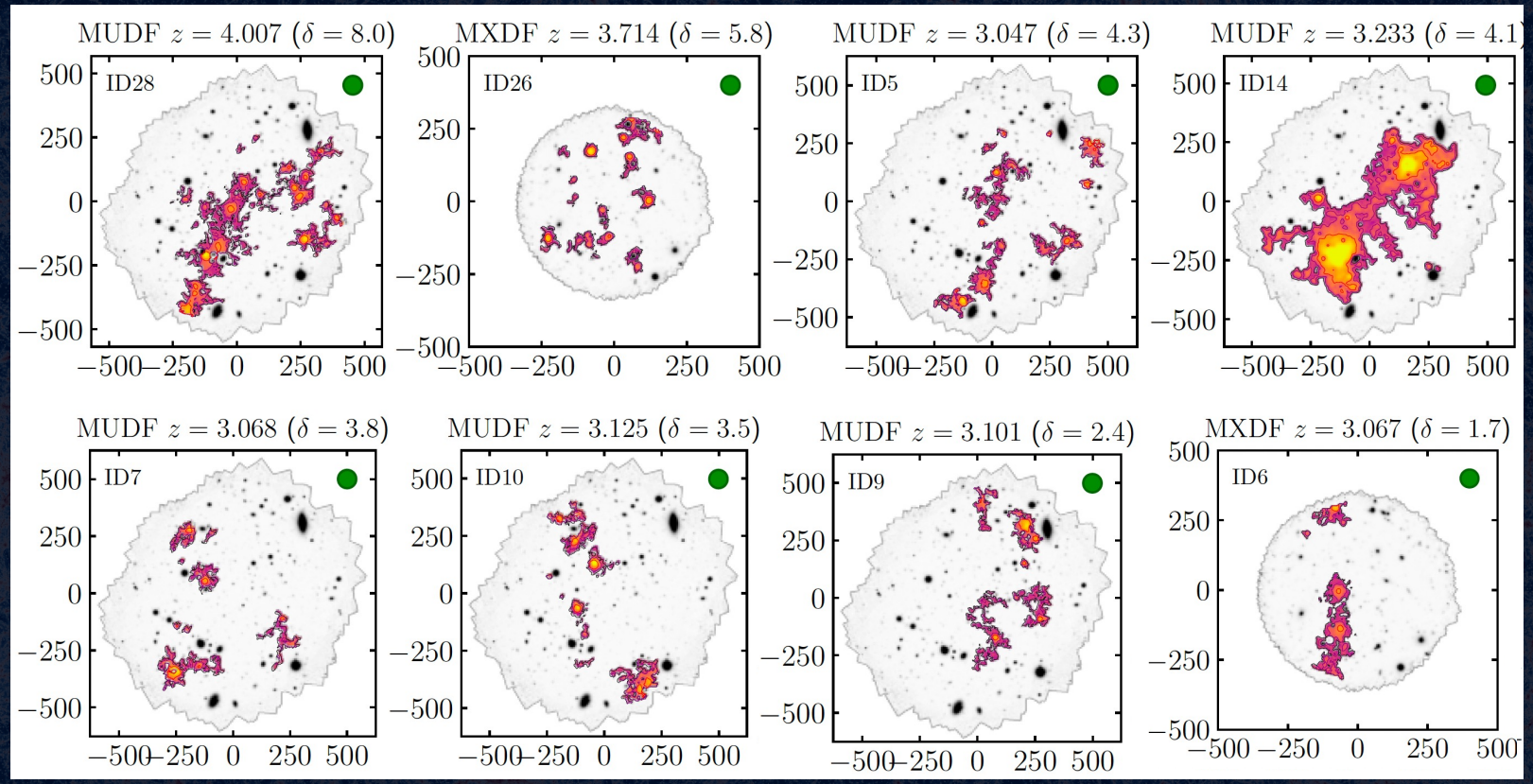
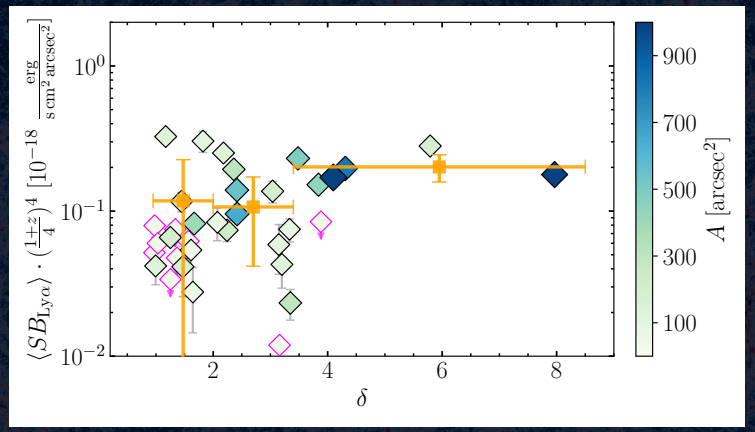


D. Tornotti et al., submitted

First samples of the cosmic web in Lyα emission



Regardless the overdensity and/or the presence of AGN activity, IGM show a maximum intrinsic SB of
$\approx 2{\times}10^{-19}$ erg s^{-1} cm^{-2} arcsec^{-2}



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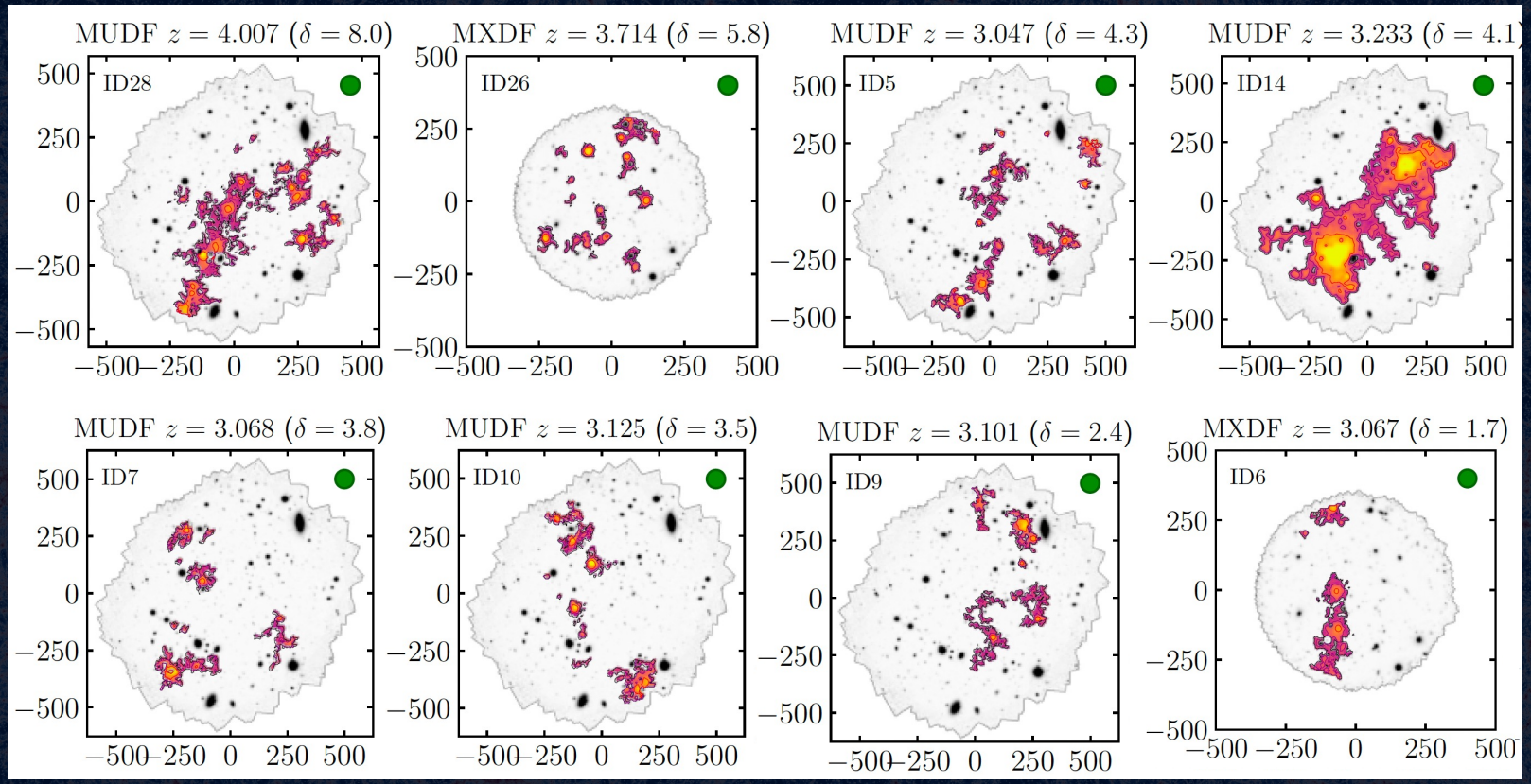
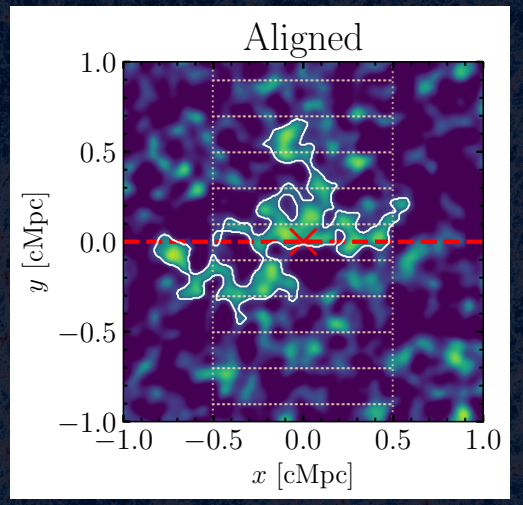


Stack aligned along the overdensity axis ($\delta > 3.5$)



Observed emission reveals a line of sight incidence consistent with that of LLSs

At z > 3 filaments are highly ionized but retain significant neutral patches

D. Tornotti et al., submitted

Conclusions

Tornotti+25a, Nat Ast | *Tornotti+25b, ApJL* | *Tornotti+25, A&A* | *Tornotti+25, submitted*

- The MUSE Deep Fields have opened a new frontier: detecting cosmic web filaments in emission on $\sim$ **Mpc scales** ⟶ morphology, SB profiles, CGM/IGM transition radii, embedded galaxy properties;
- We are beginning to probe **different environments** (QSOs ⟶ LAEs) across different redshifts ($z \approx 3-4$);
- We can start to compile first ***samples*** of filaments, probing **different environments,** across **different redshifts** ($z \approx 3-4$) ⟶ constrain their physical properties statistically;


Thanks for your attention!
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Supplementary Slides

The next leap: Wide-Field Spectroscopic Telescope

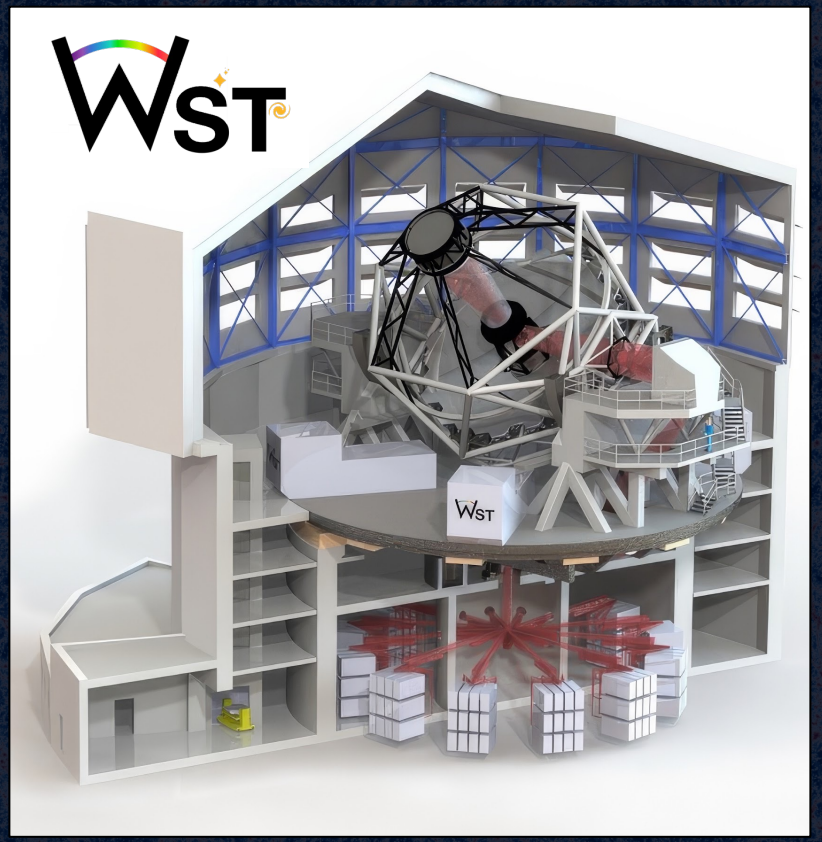
From the era of Cosmic Web detections to galaxy evolution in the Cosmic Web: complete mapping of the connection between ISM-CGM-filaments in WST era

An innovative 12-m class wide-field spectroscopic telescope (WST)

3'x 3'
Panoramic IFU

+

30k
MOS



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