Unveiling the cosmic web through Lyα emission: an ultra-deep observation with MUSE

Davide Tornotti

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

ΛCDM COSMOLOGICAL PARADIGM

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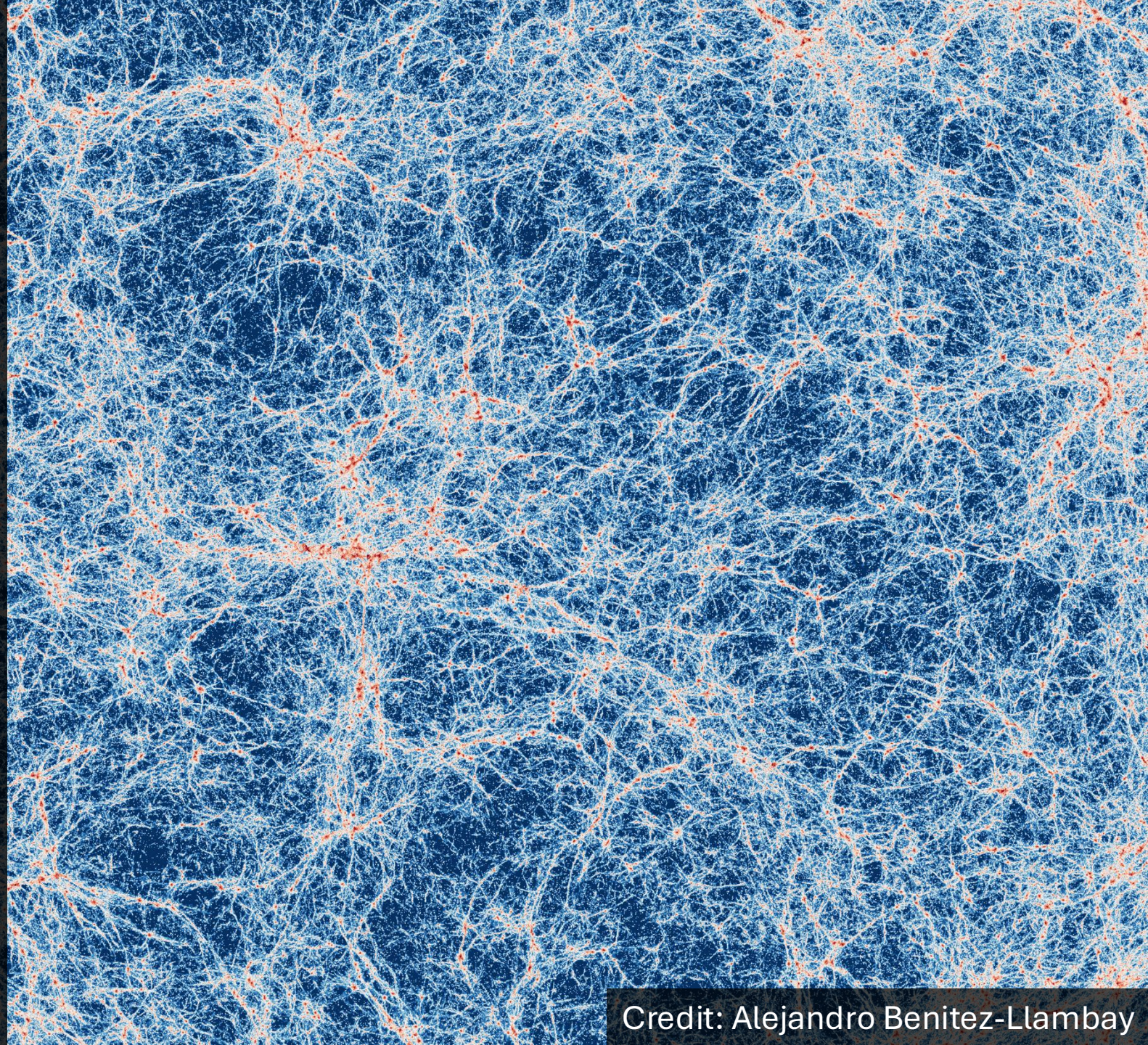
FILAMENT-DOMINATED STRUCTURE ON LARGE SCALES: «THE COSMIC WEB»



Credit: Alejandro Benitez-Llambay

ΛCDM COSMOLOGICAL PARADIGM

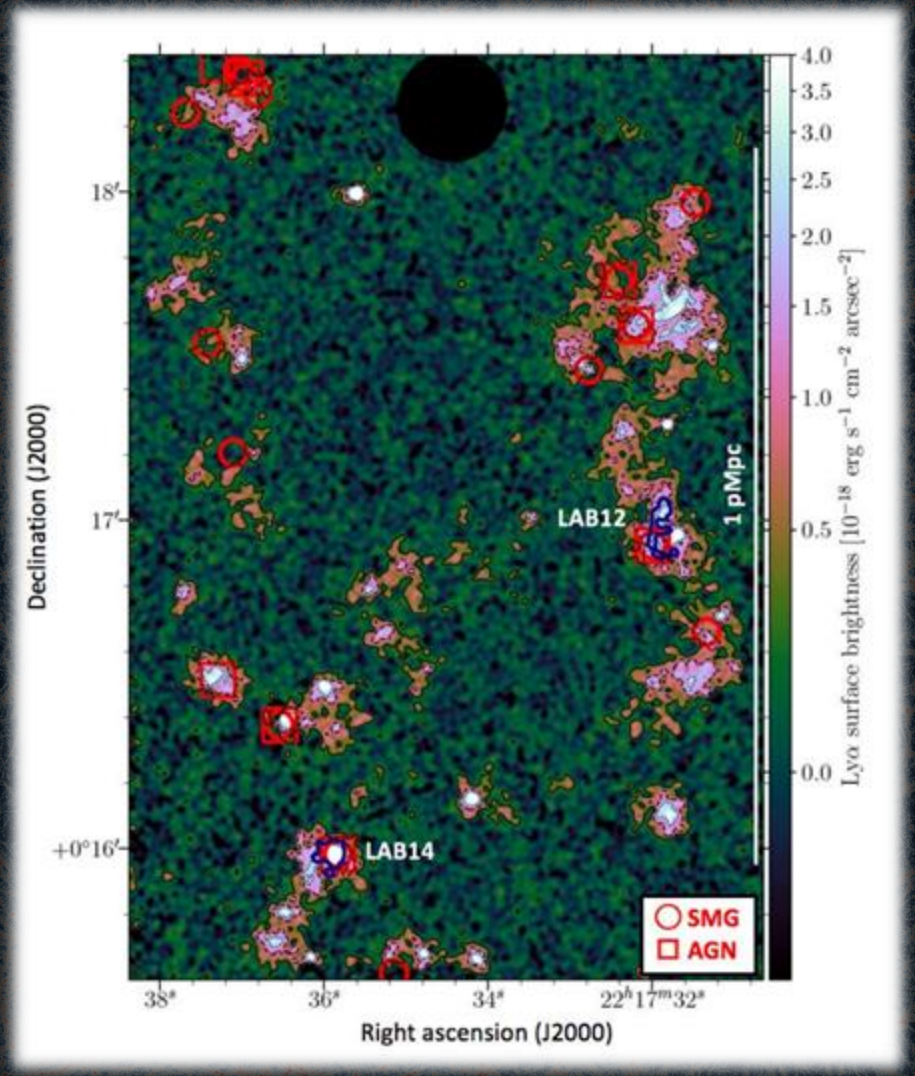
↓

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

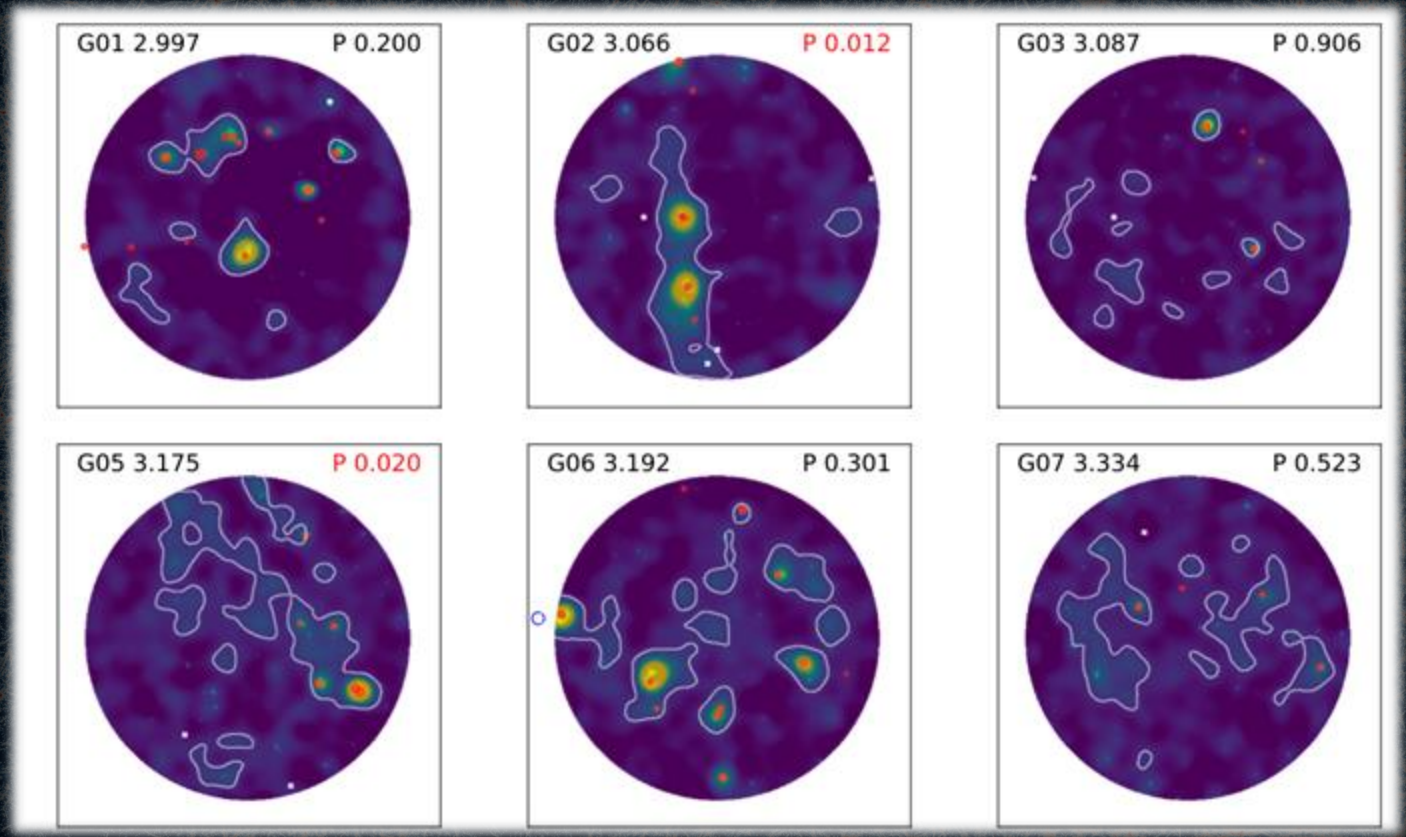
Can we see the cosmic web in emission at $z \sim 2 - 4$?

Credit: Alejandro Benitez-Llambay

The Cosmic Web in emission: known examples



SSA22 – Umehata et al. 2019

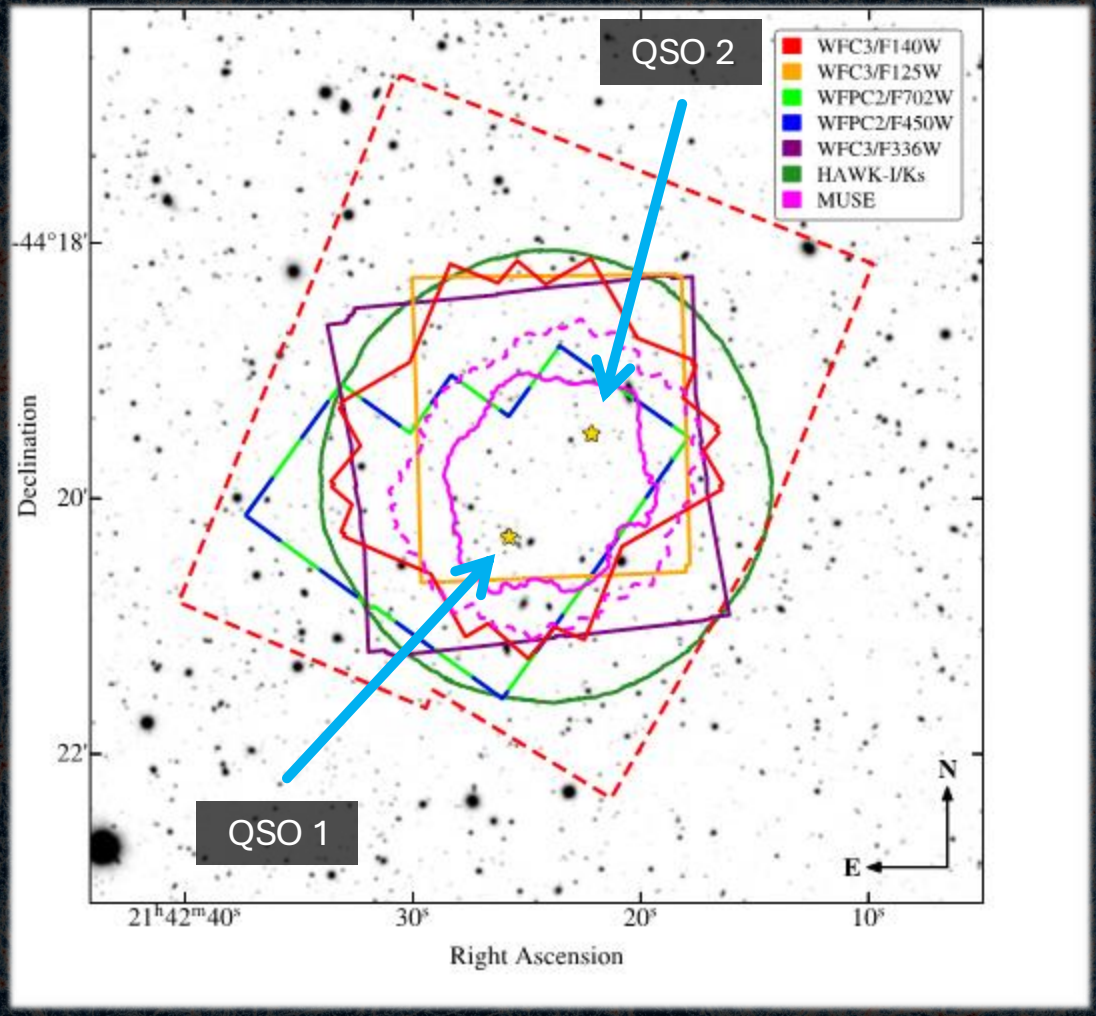


MXDF – Bacon et al. 2021

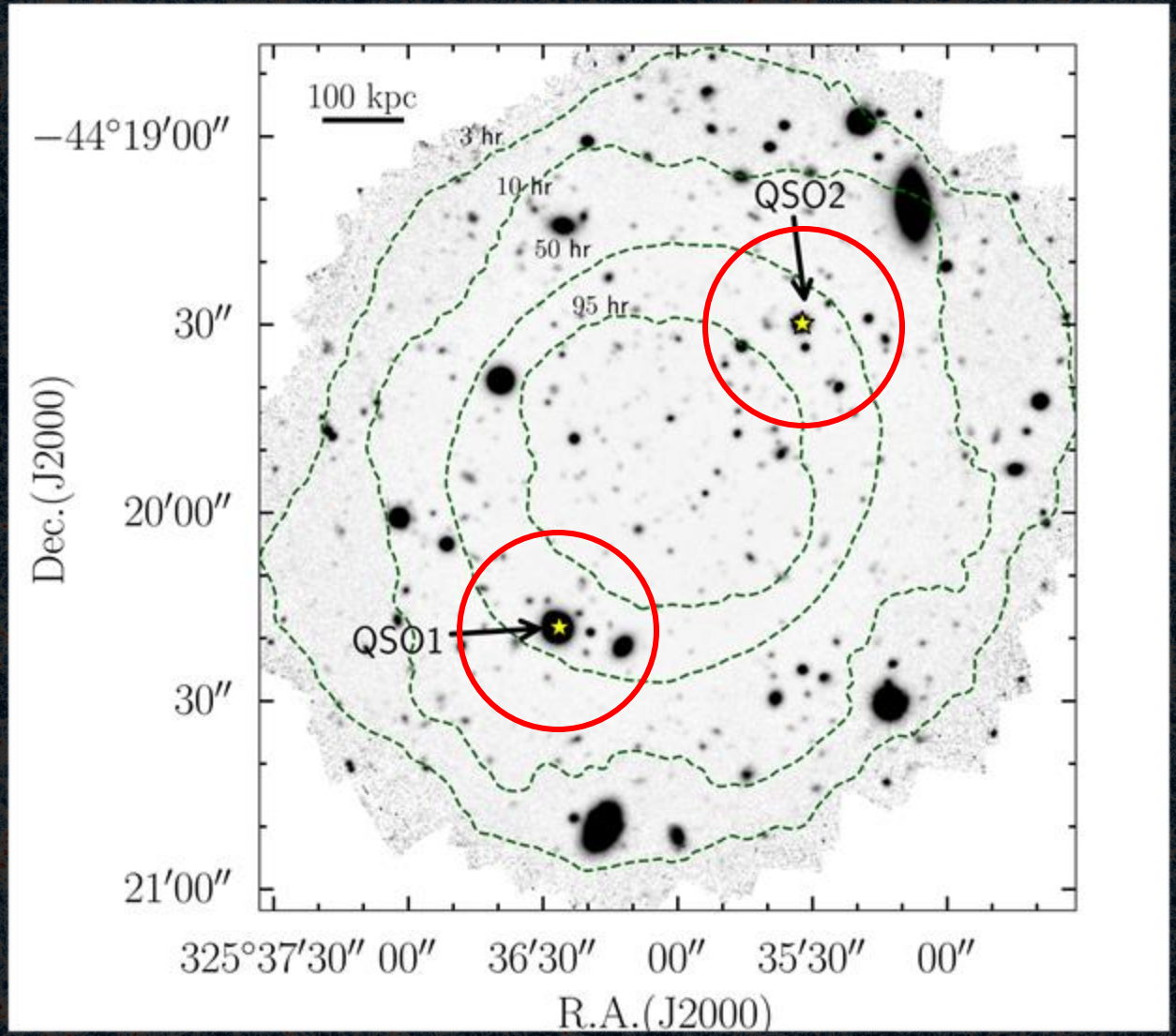
The MUSE Ultra Deep Field (MUDF)

ONE OF THE KEY GOALS:
image the Lyα 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).

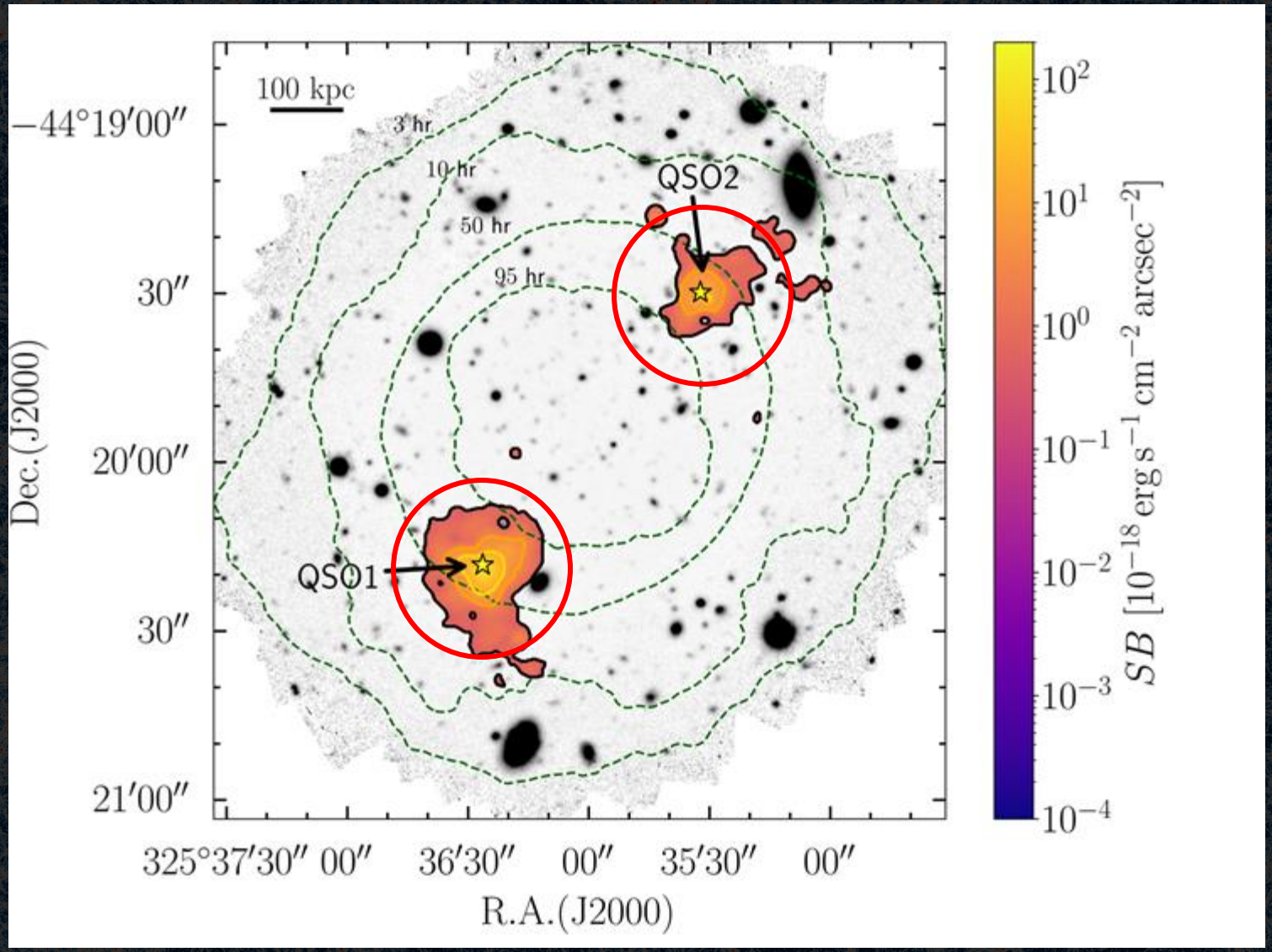


Lyα emission surrounding the QSO pair



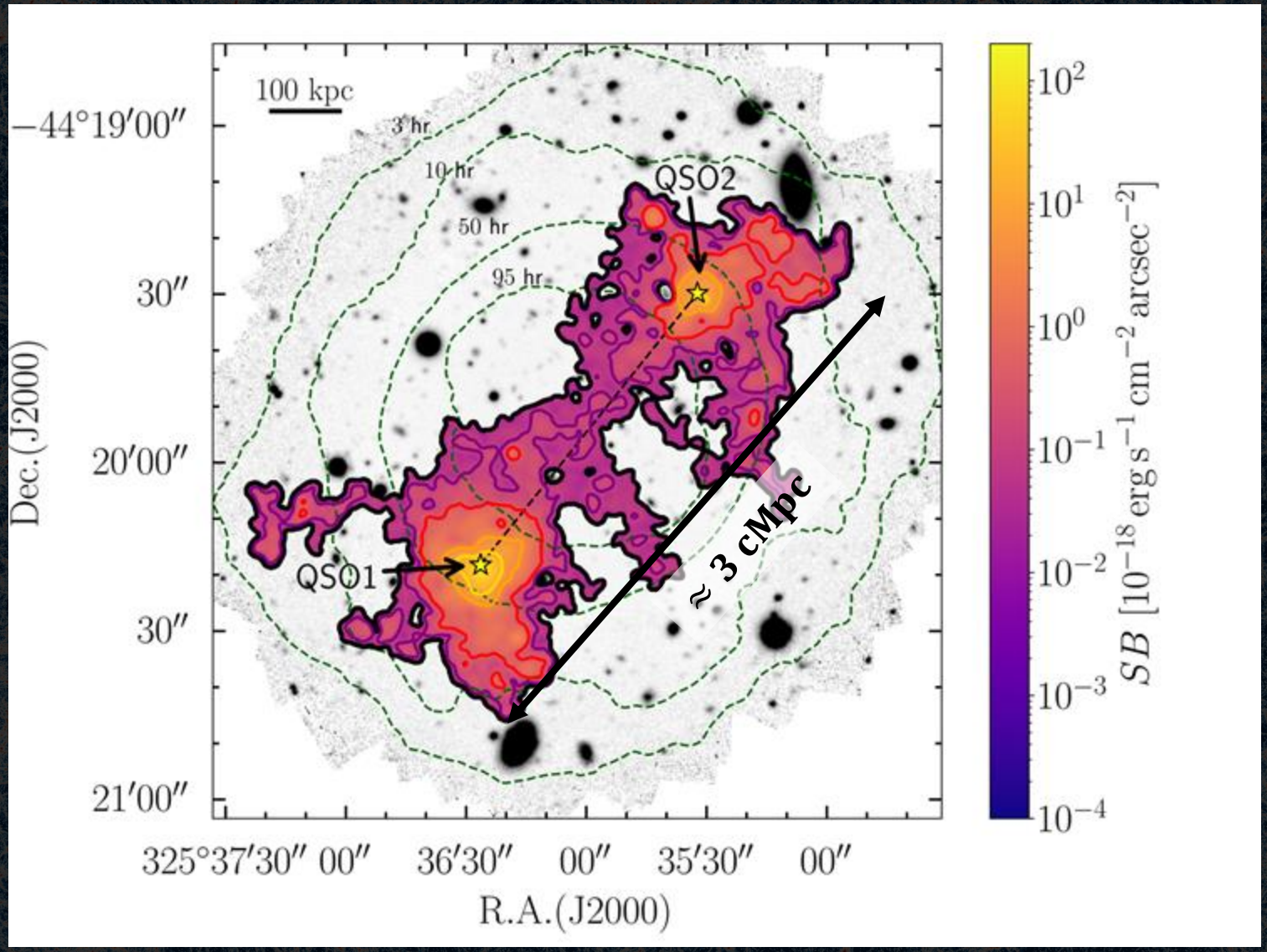
D. Tornotti et al., 2024, *Nature Astronomy*

Lyα emission surrounding the QSO pair



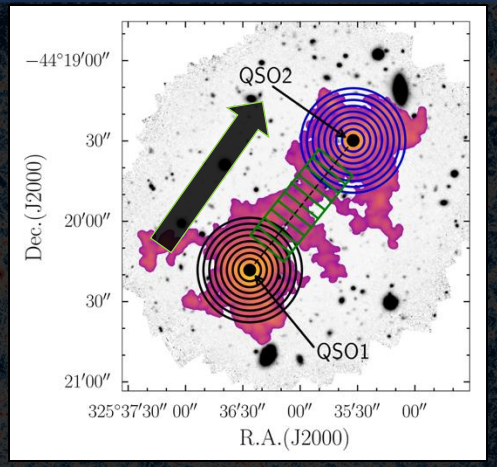
D. Tornotti et al., 2024, *Nature Astronomy*

Detection of a cosmic filament between the QSO pair

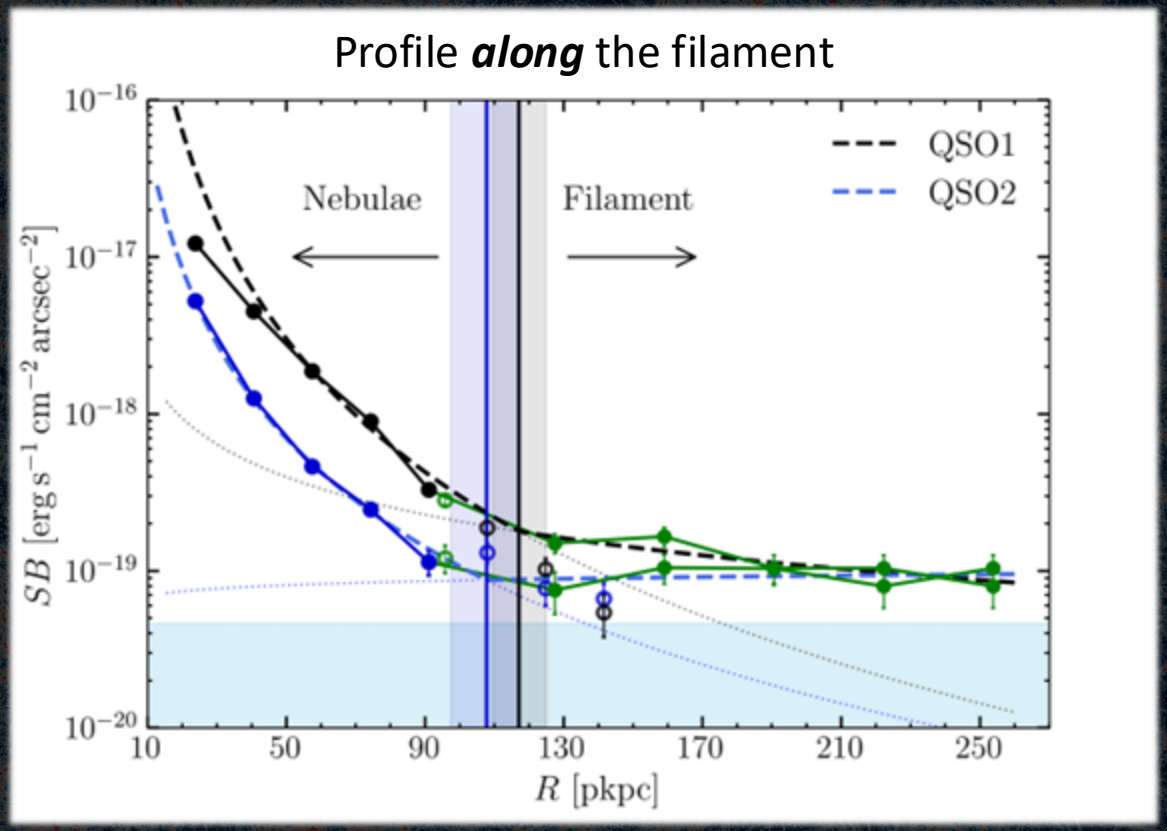


D. Tornotti et al., 2024, *Nature Astronomy*

Measurements of the filament SB profiles

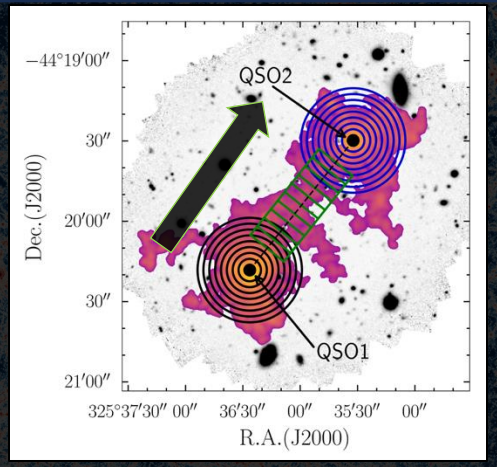


Profile ***along*** the filament



D. Tornotti et al., 2024, *Nature Astronomy*

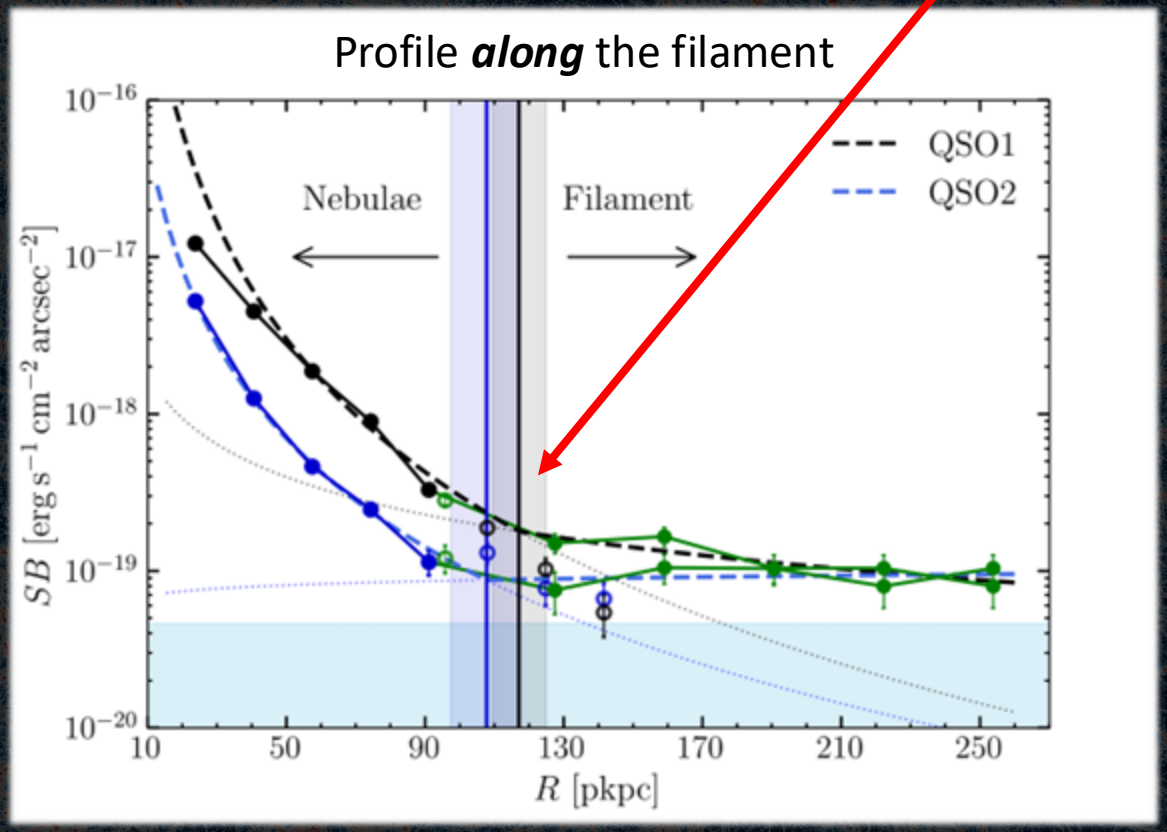
Measurements of the filament SB profiles



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

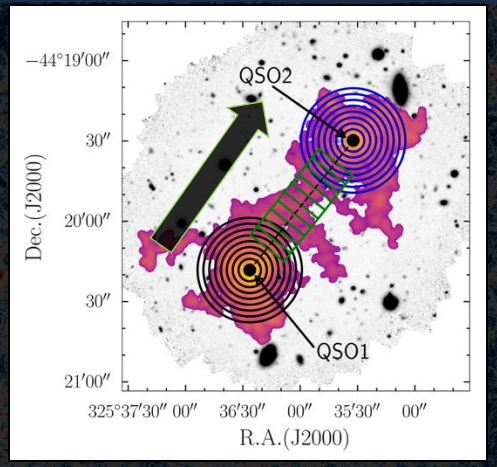
$R_t \approx 100$ pkpc

Profile ***along*** the filament



D. Tornotti et al., 2024, *Nature Astronomy*

Measurements of the filament SB profiles



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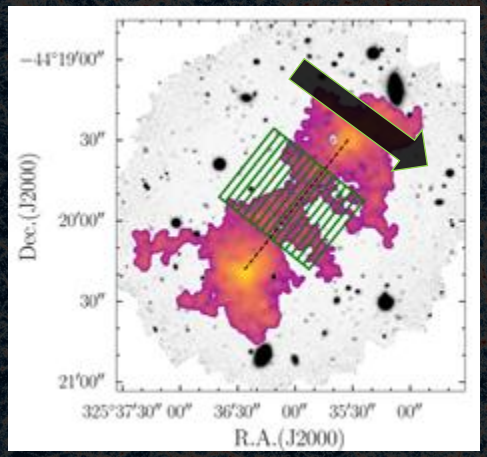
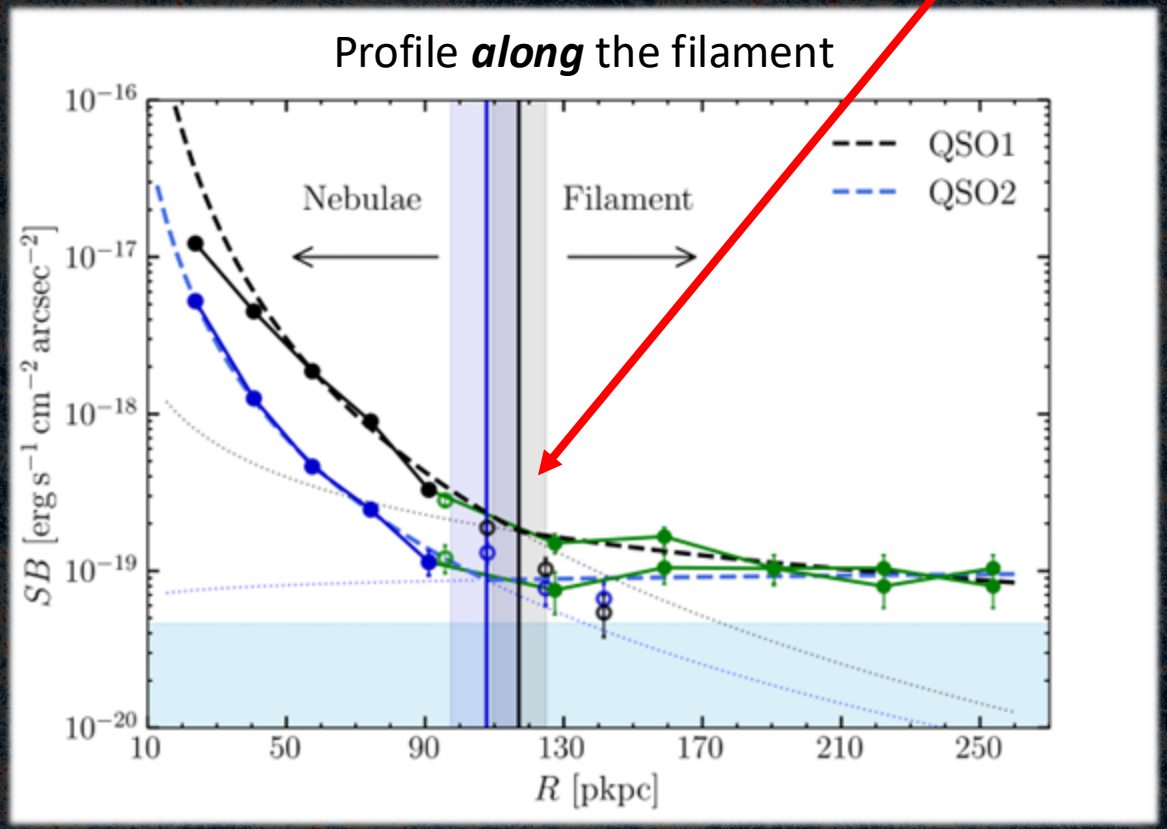
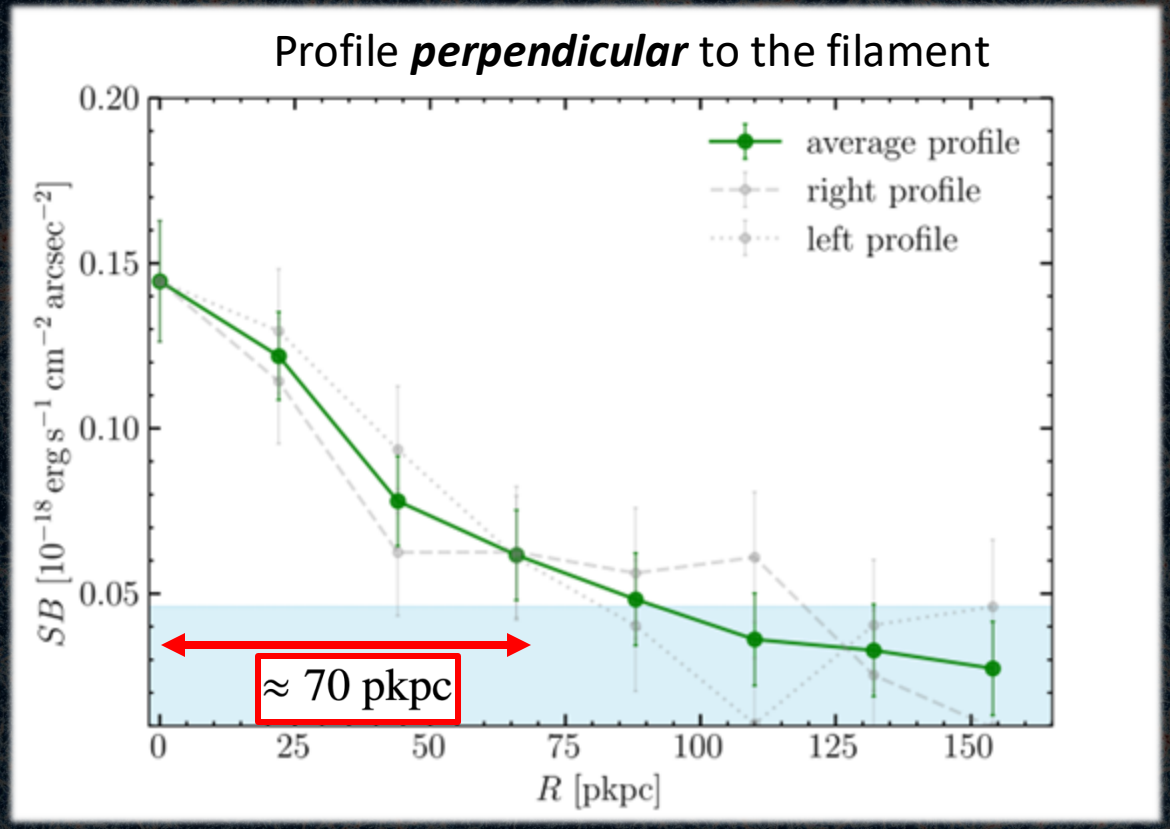


Profile ***along*** the filament



Profile ***perpendicular*** to the filament



D. Tornotti et al., 2024, *Nature Astronomy*

Constraining the filament density with numerical simulations

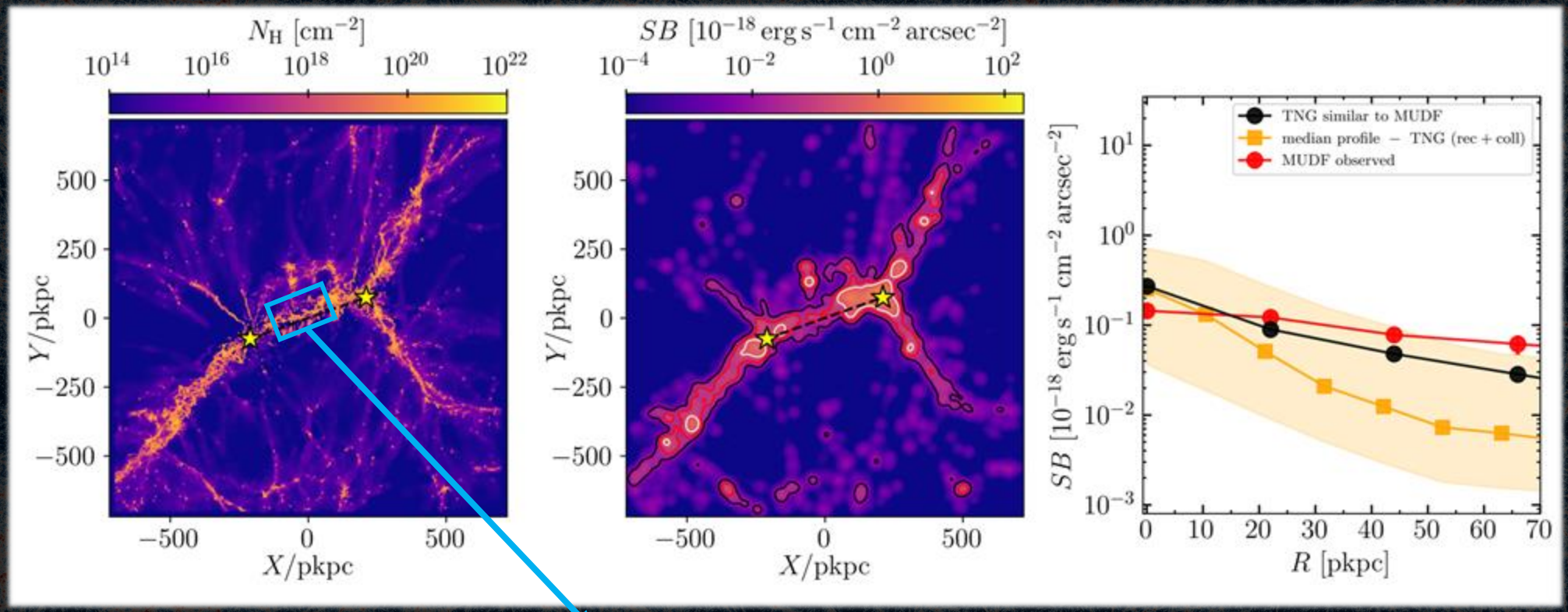
QSO1: $\log\left(\frac{M_h}{M_\odot}\right) = 12.9 \pm 0.3$

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

Typical halo mass from L-Galaxies SAM with advanced QSO recipes (Izquierdo-Villalba et al. 2020)

L - GALAXIES

Comparison with **TNG-100**

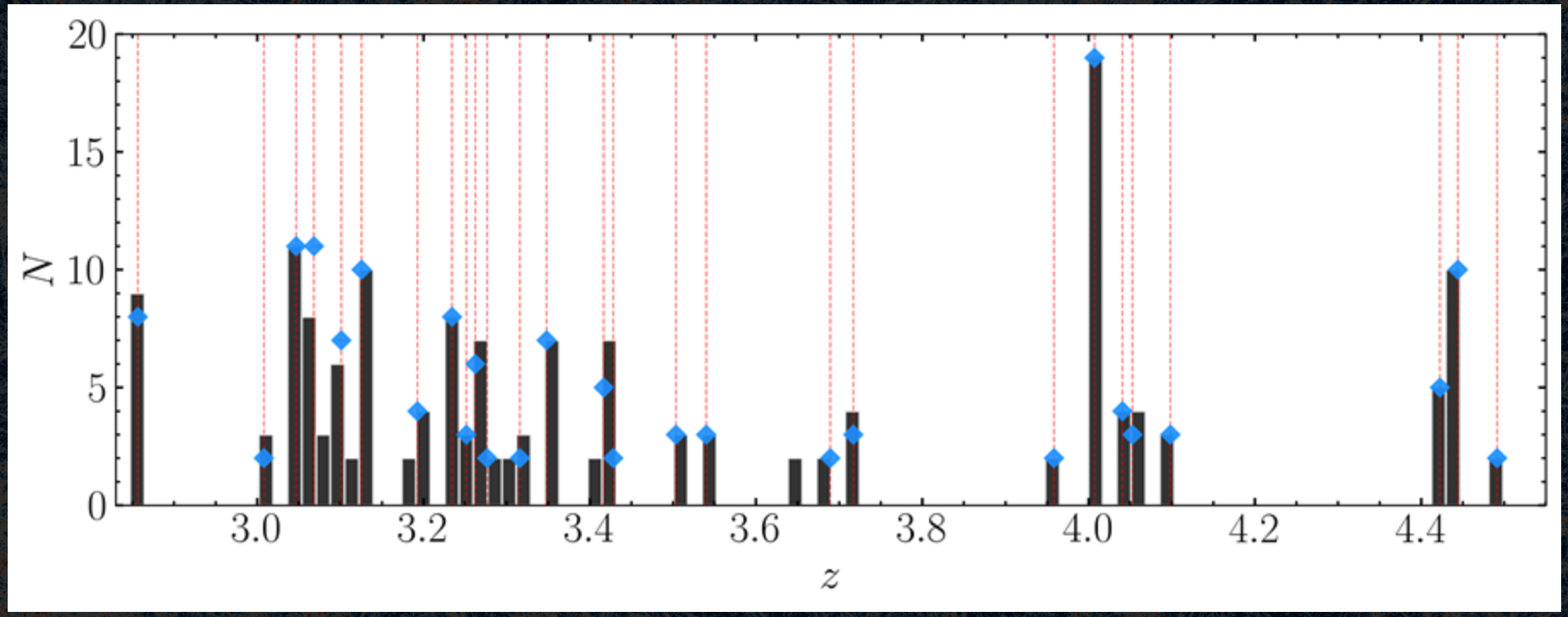


$n_H^{IGM} \approx 10^{-3}$ cm^{-3}

D. Tornotti et al., 2024, *Nature Astronomy*

LAEs overdensities in the MUDF

≳ **200** LAEs spectroscopically confirmed
various **overdensities** (up to ~ 25) where search for extended Lyα emission tracing **filamentary structures**



D. Tornotti et al. in preparation

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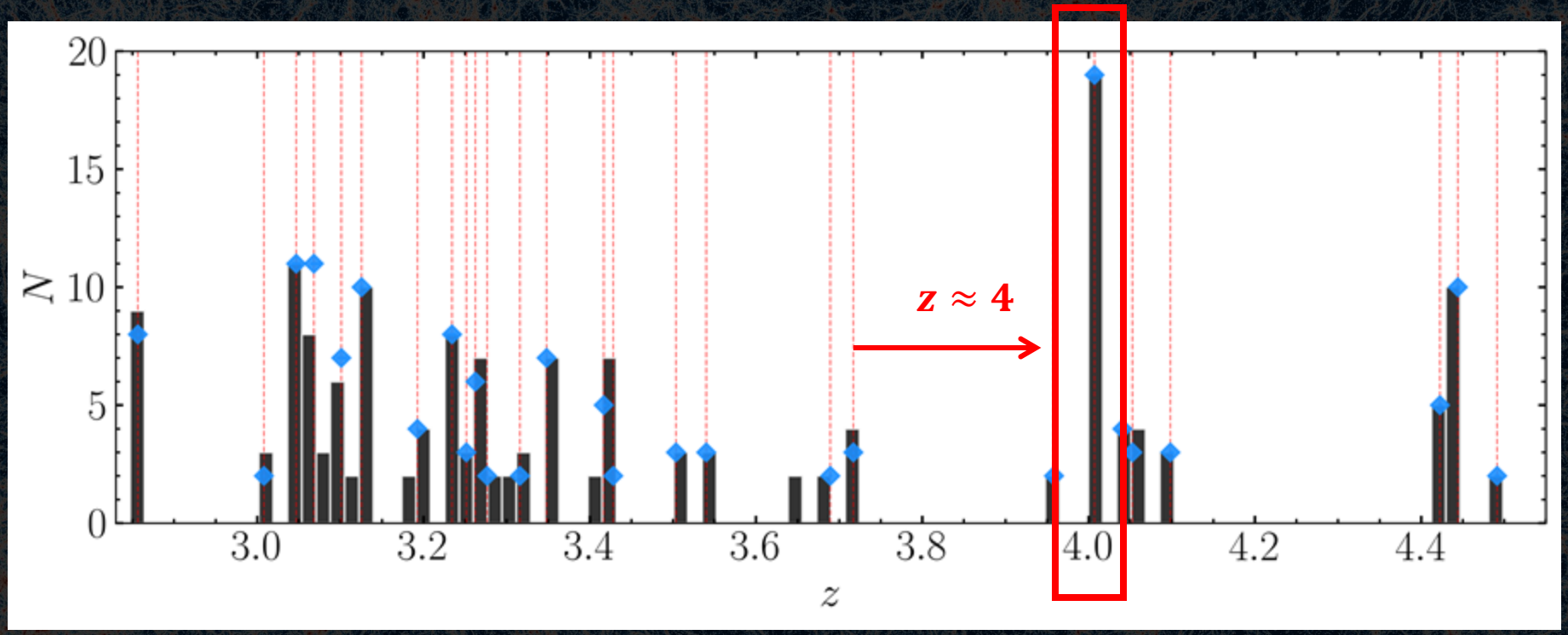
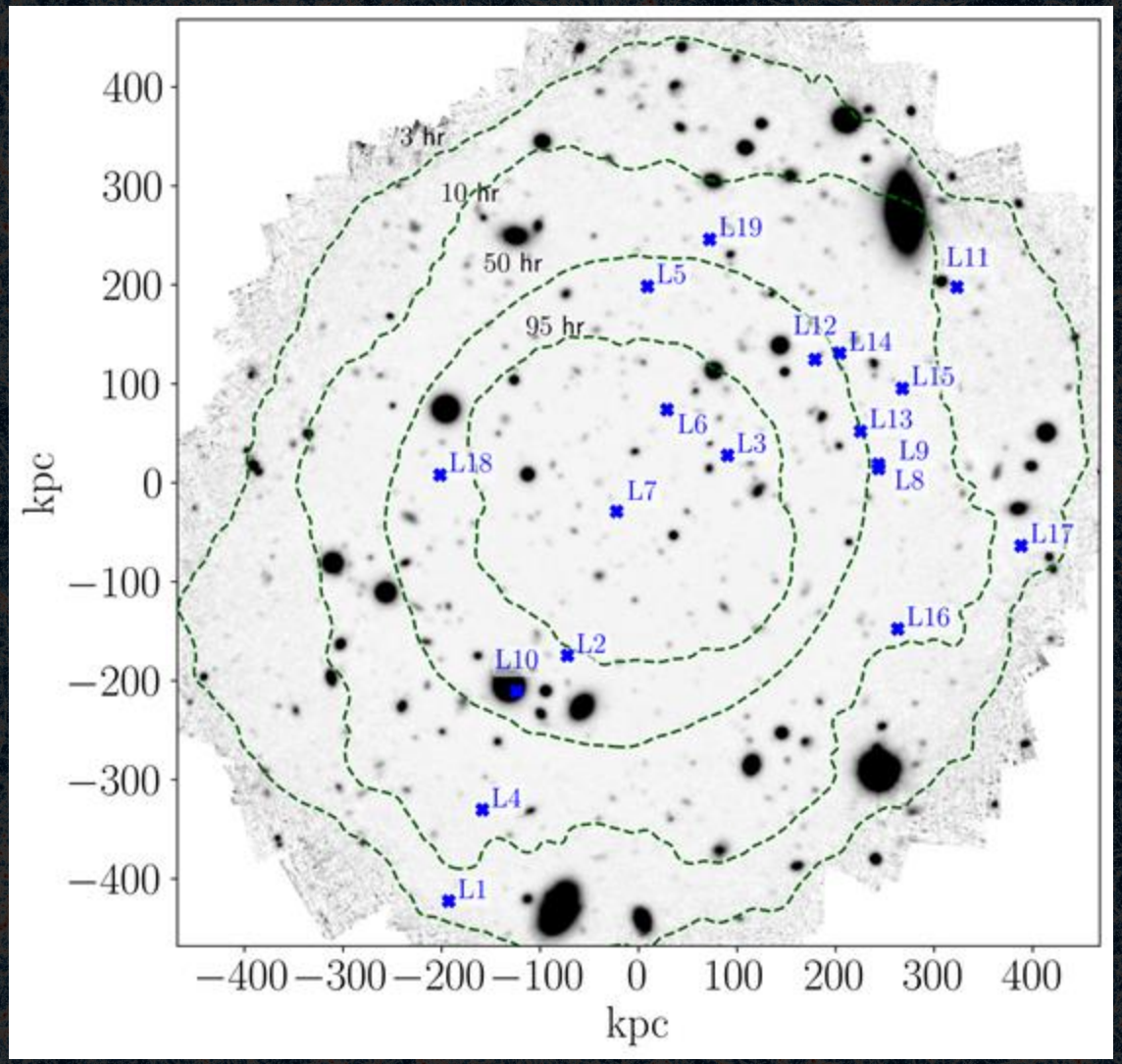


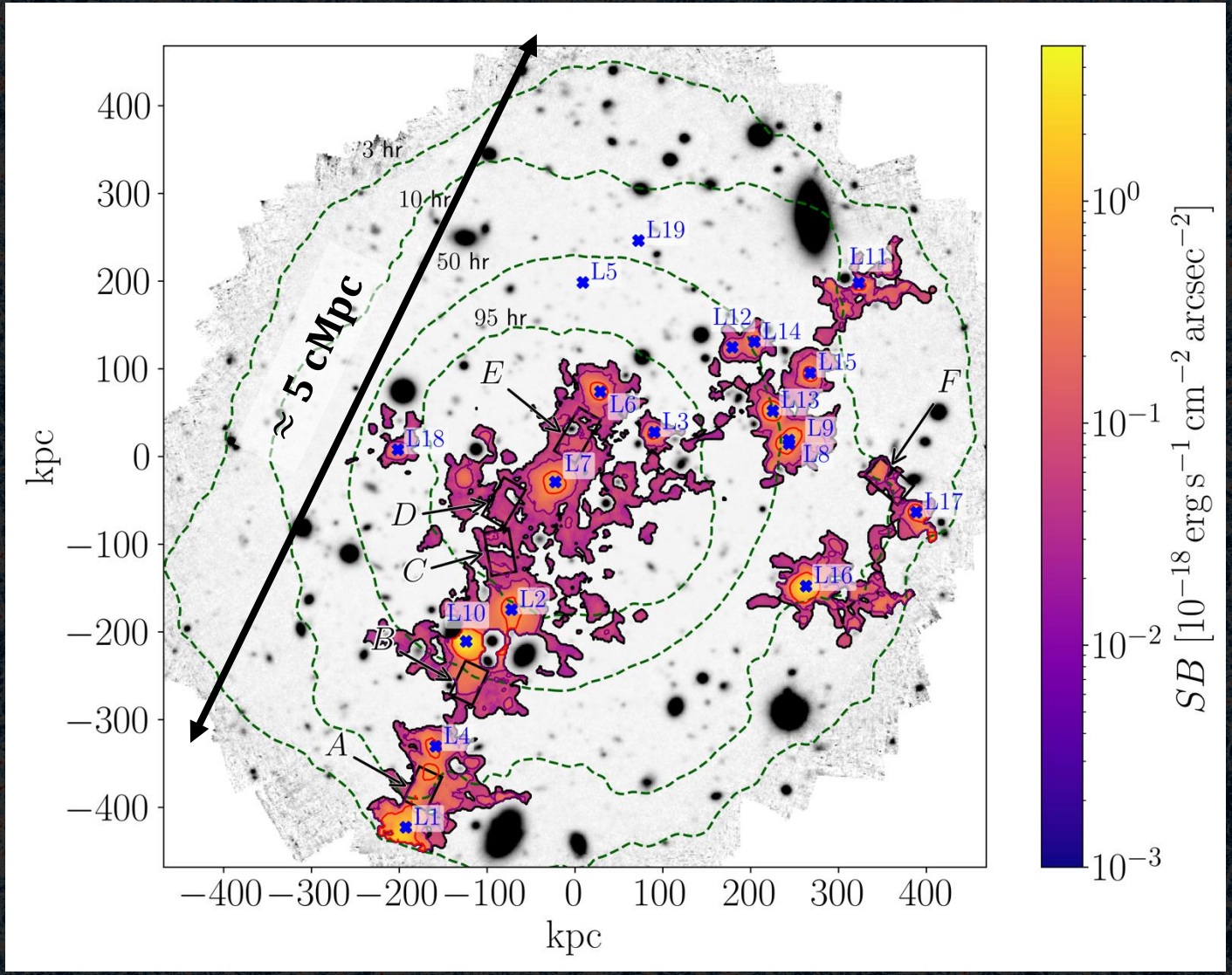
D. Tornotti et al. in preparation

Filaments around LAEs at $z\sim4$



D. Tornotti et al., 2024, *ApJL*

Filaments around LAEs at $z\sim4$



D. Tornotti et al., 2024, *ApJL*

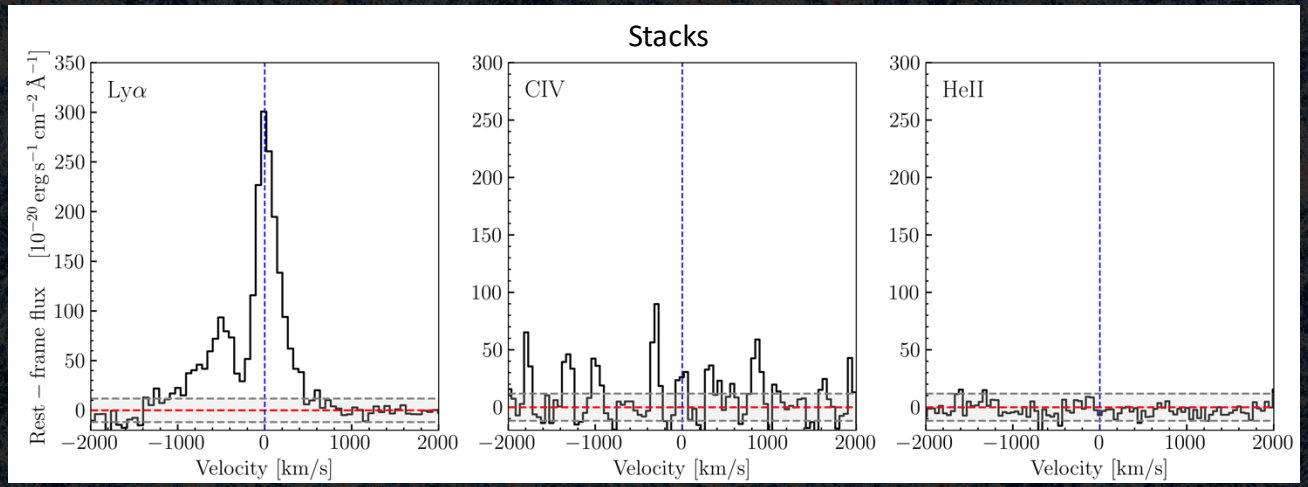
LAEs embedded in the filament z ~ 4

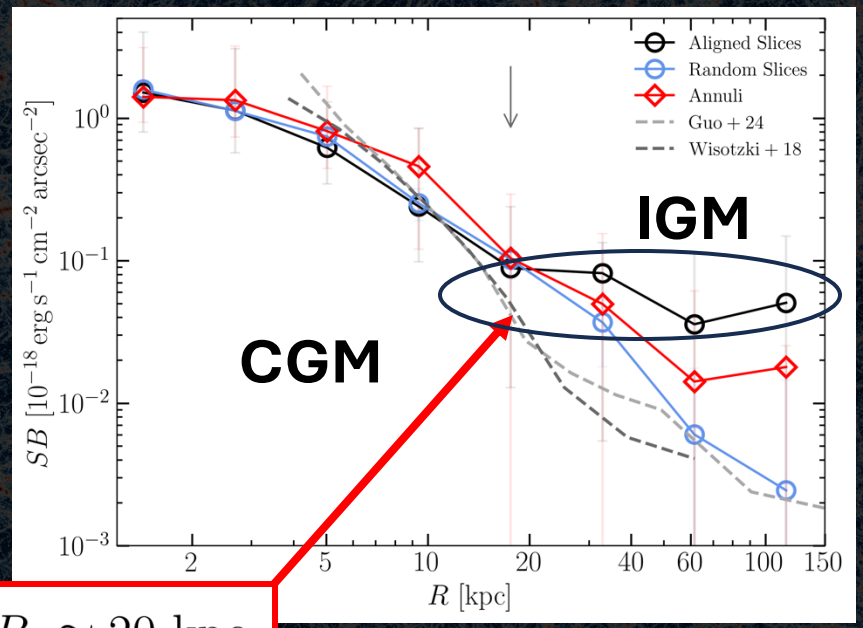
AGN activity?

No clear evidence of AGNs intrinsic surface brightness **similar** to the $z\sim3.2$ example near quasars

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

→ transition between CGM and IGM





$R_t \approx 20$ kpc

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

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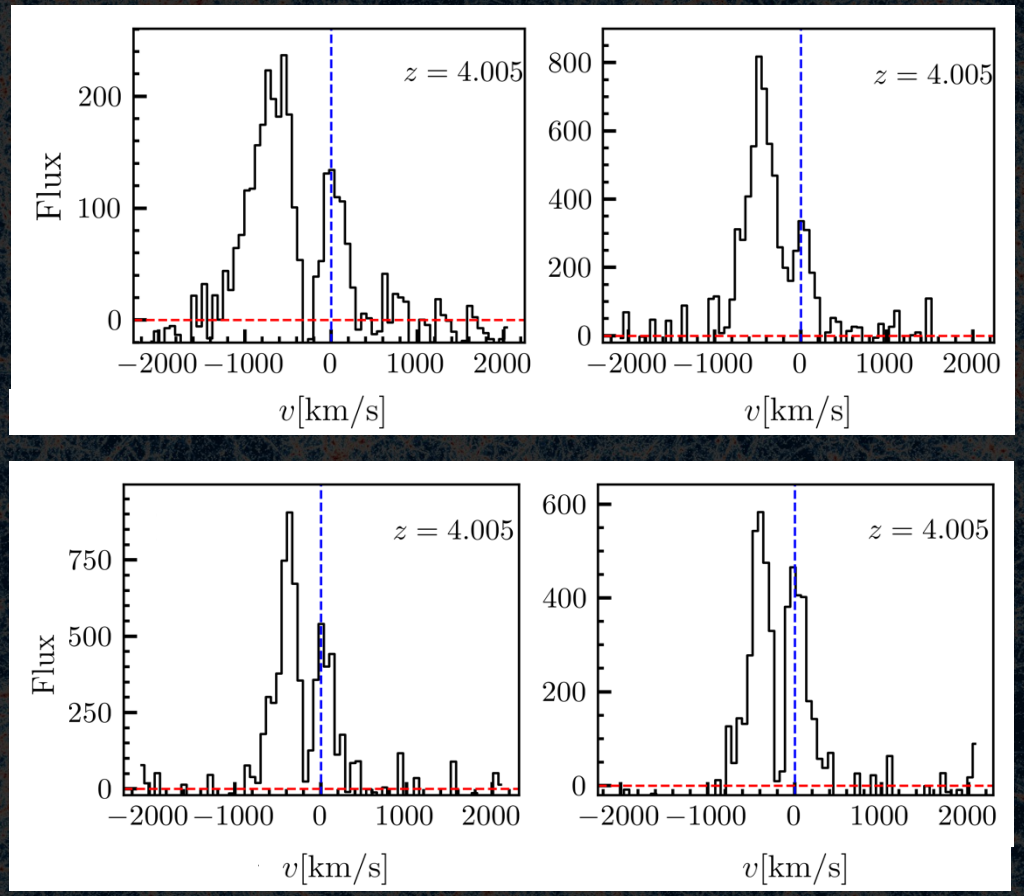
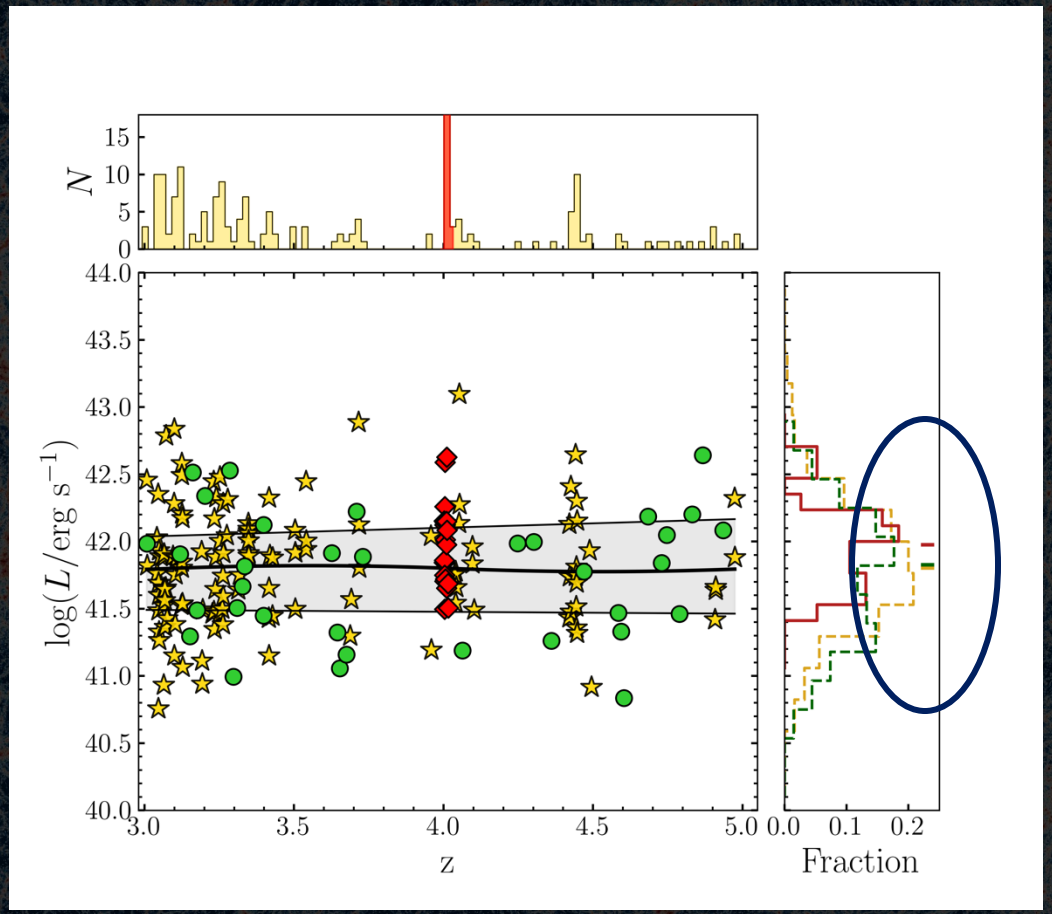
A population of active galaxies fuelled by prominent accretion?

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

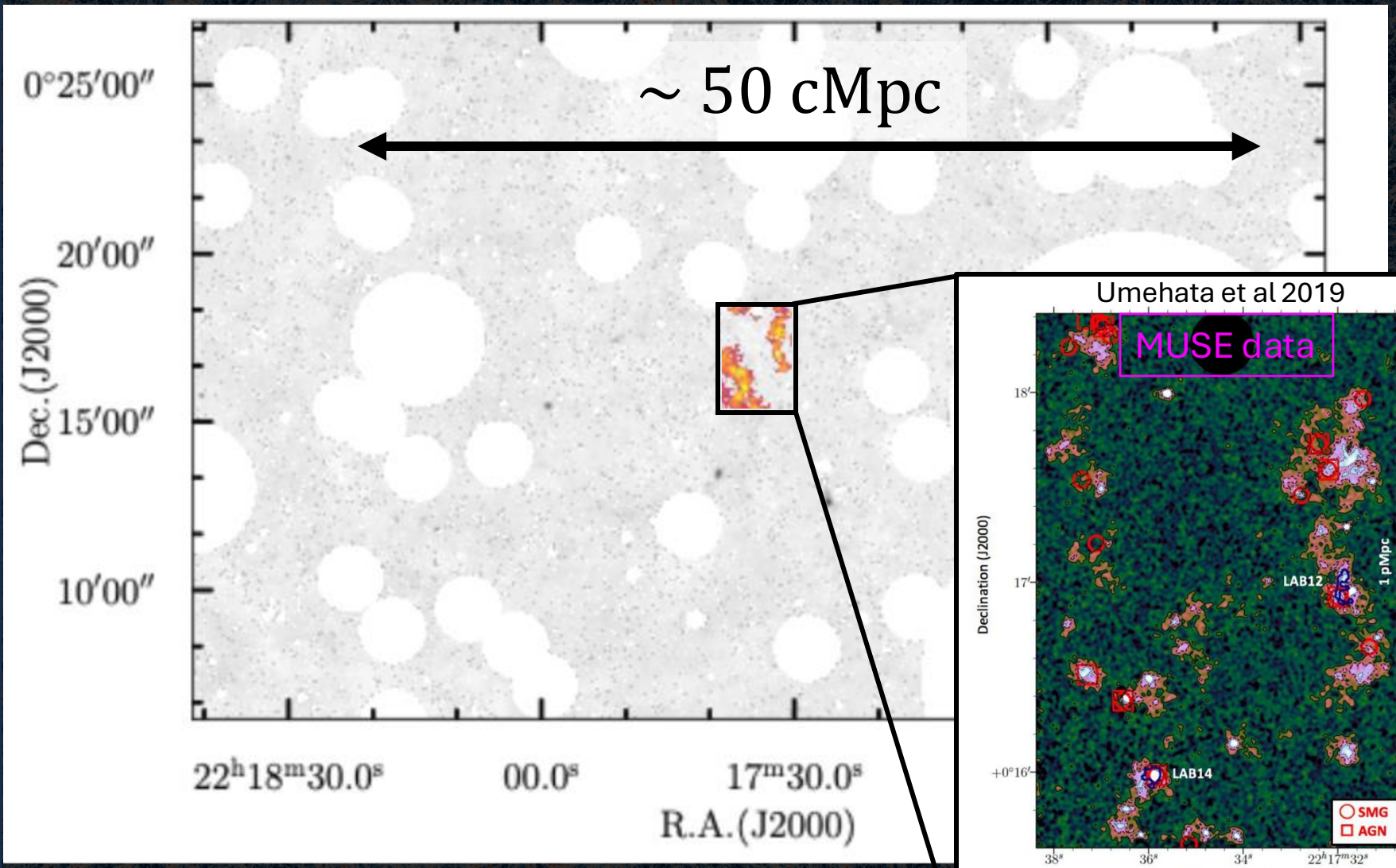




D. Tornotti et al., 2024, *ApJL*

The Cosmic Web in emission in the SSA22 protocluster

Matsuda Y. & MIRACLES team: **M**apping of **I**onizing **RA**diation on the **C**osmic web **L**yα **E**mission and **S**hadow



SSA22 protocluster (Steidel+00, Matsuda+04, Matsuda+11):
Narrow Band intensive SUBARU program on ~180 x 180 cMpc^2

SB
$\times 10^{-19}$ erg s^{-1}cm^{-2}arcsec^{-2}

Umehata et al 2019

The Cosmic Web in emission in the SSA22 protocluster

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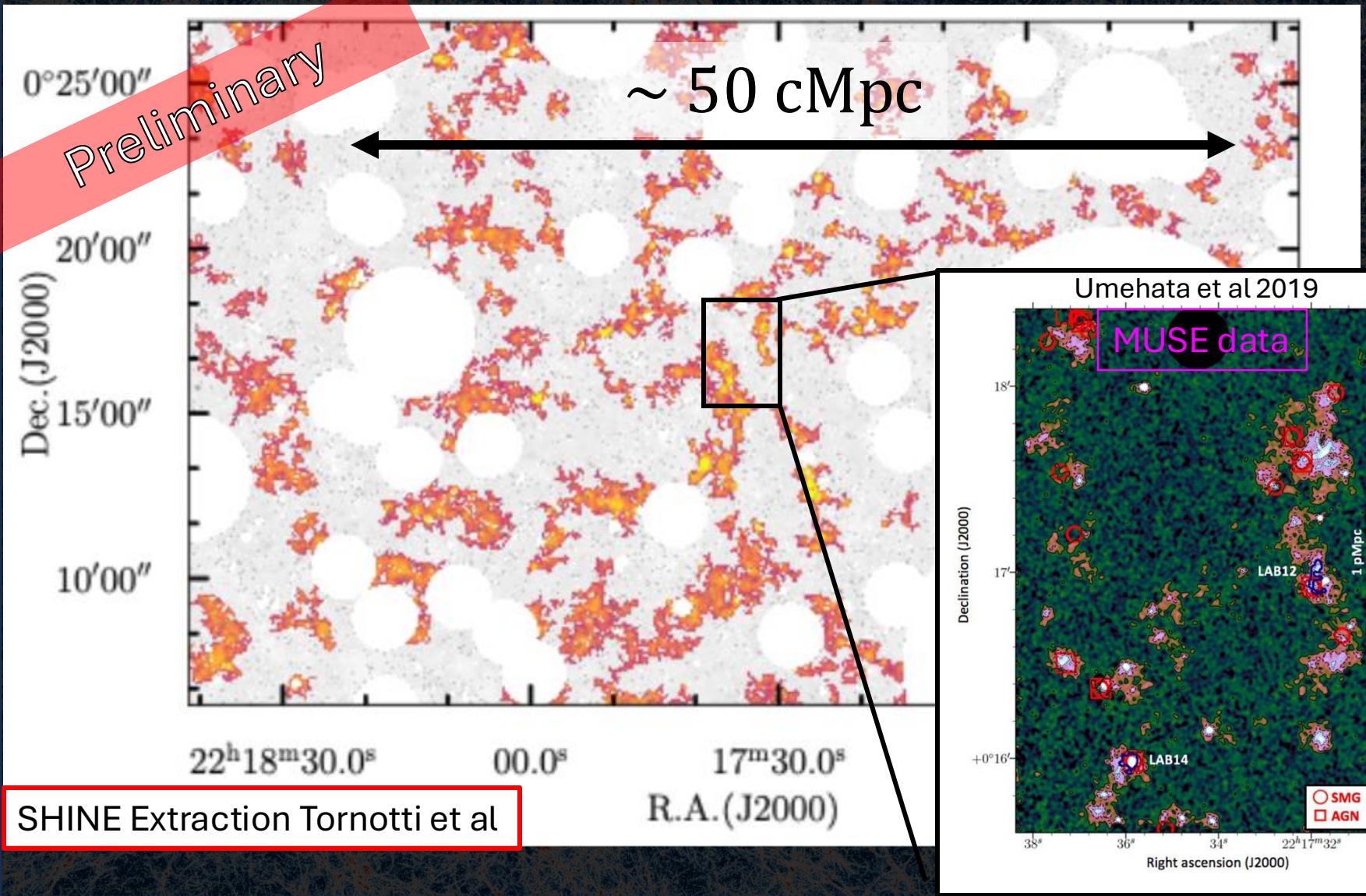

SHINE Extraction Tornotti et al

SSA22 protocluster (Steidel+00, Matsuda+04, Matsuda+11): **Narrow Band** intensive SUBARU program on ~180 x 180 $cMpc^2$

SB

$\times 10^{-19}$ erg $s^{-1}cm^{-2}arcsec^{-2}$

- Filament's morphology on cosmological scales. Test dark matter models?
- SB ⟷ Overdensity?

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;

Thanks for your attention!

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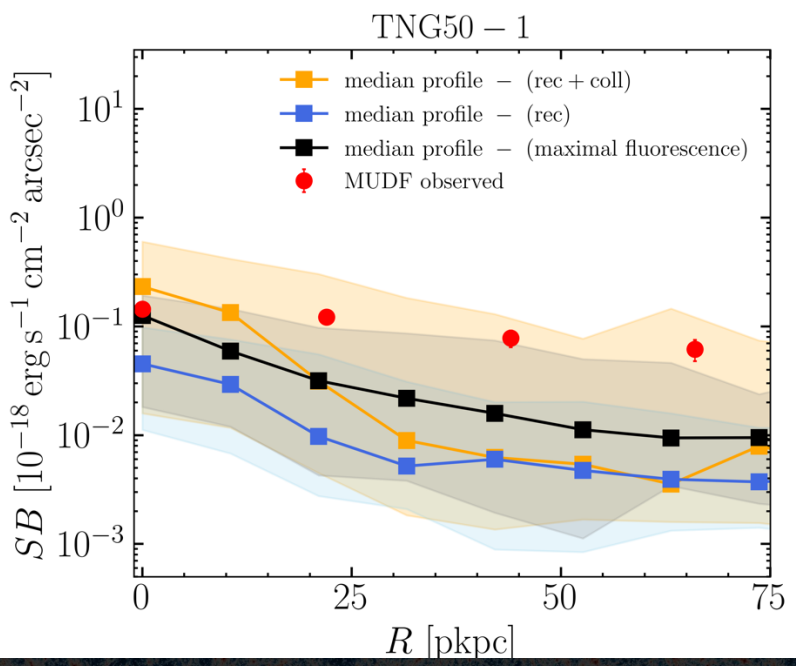
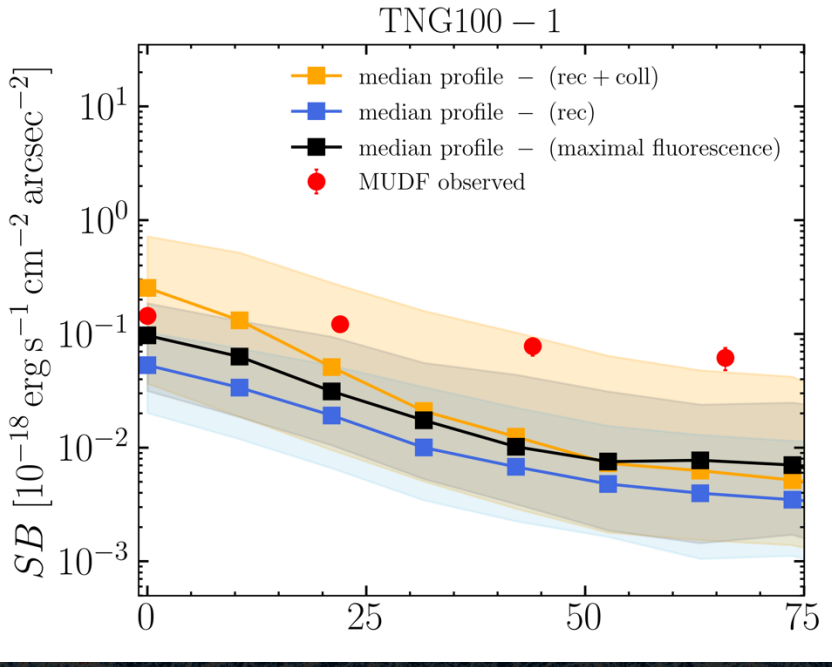
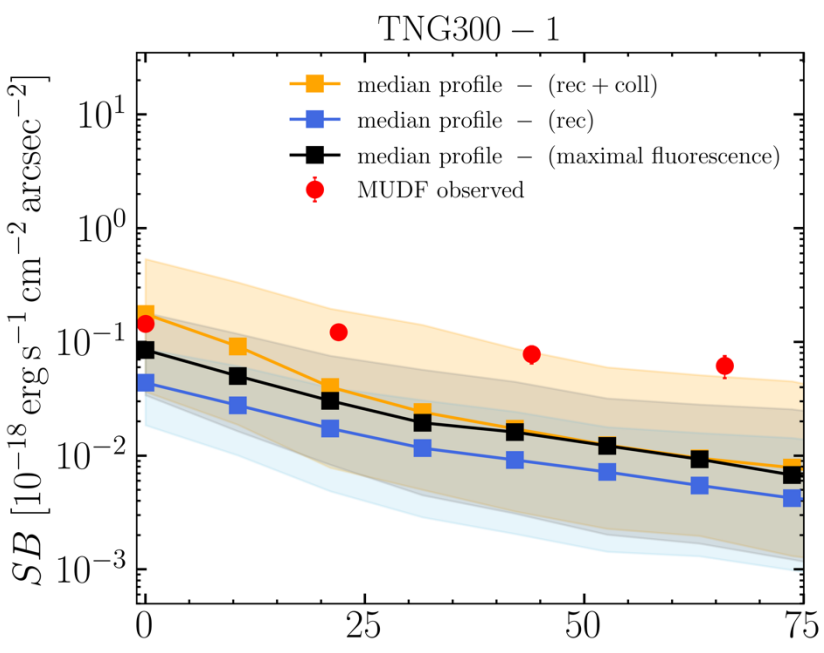
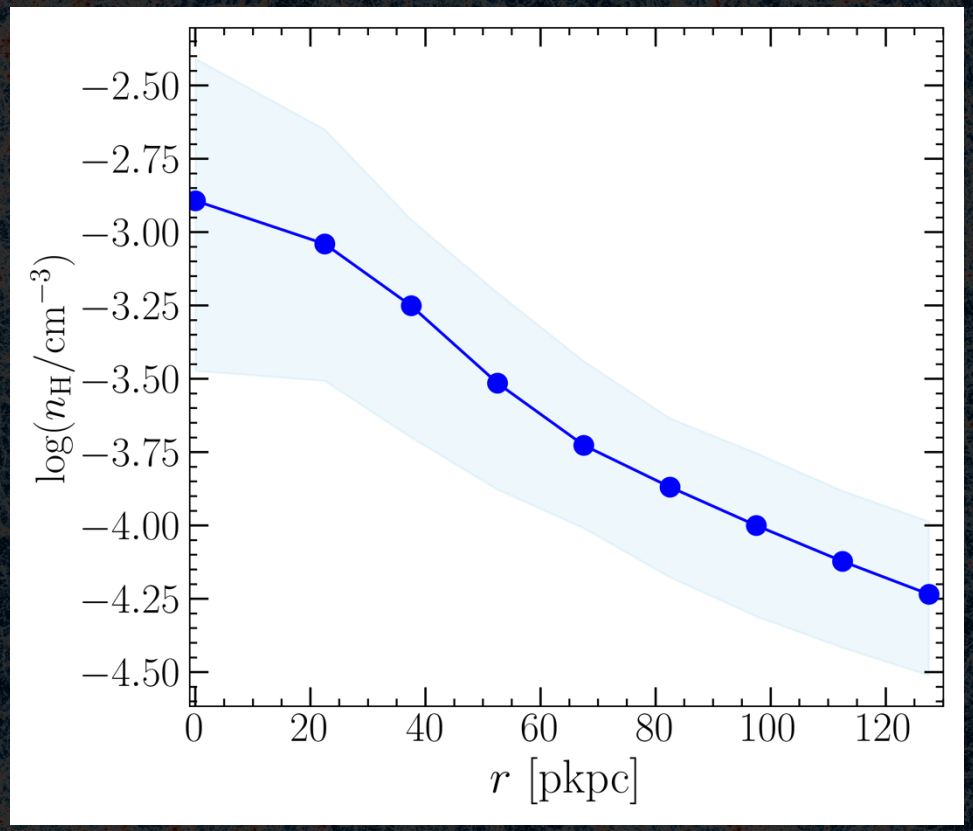
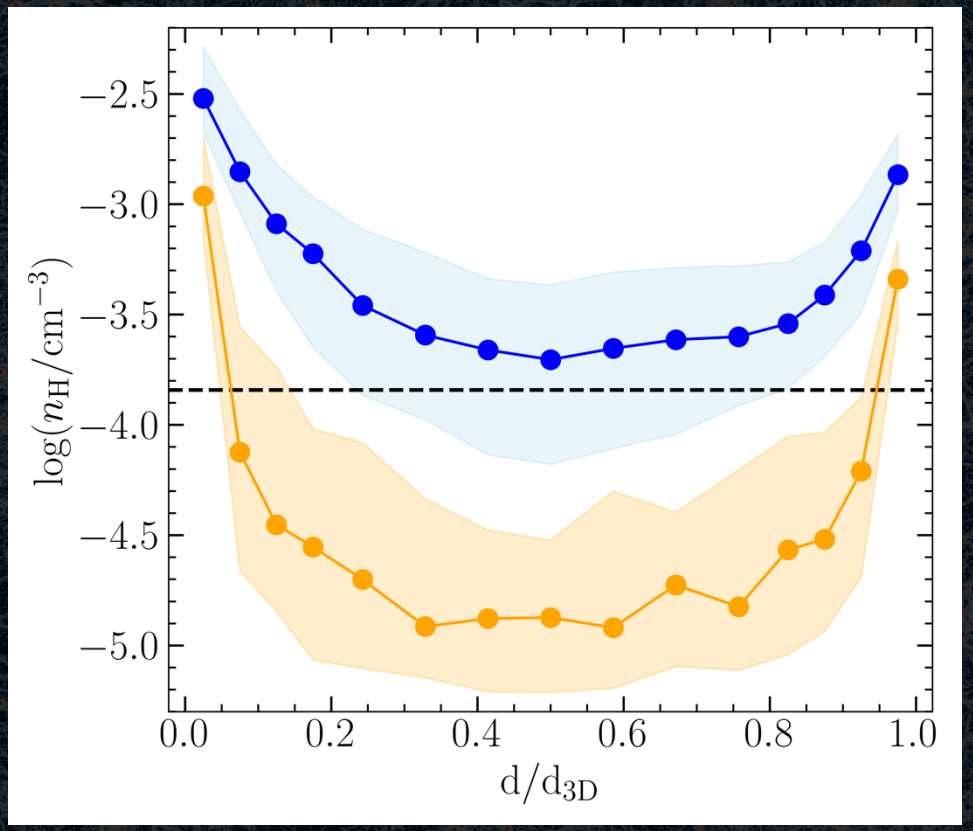
Supplementary Slides


TNG50 − 1
median profile − (rec + coll)
median profile − (rec)
median profile − (maximal fluorescence)
MUDF observed
SB [10^{-18} erg s^{-1} cm^{-2} arcsec^{-2}]
R [pkpc]

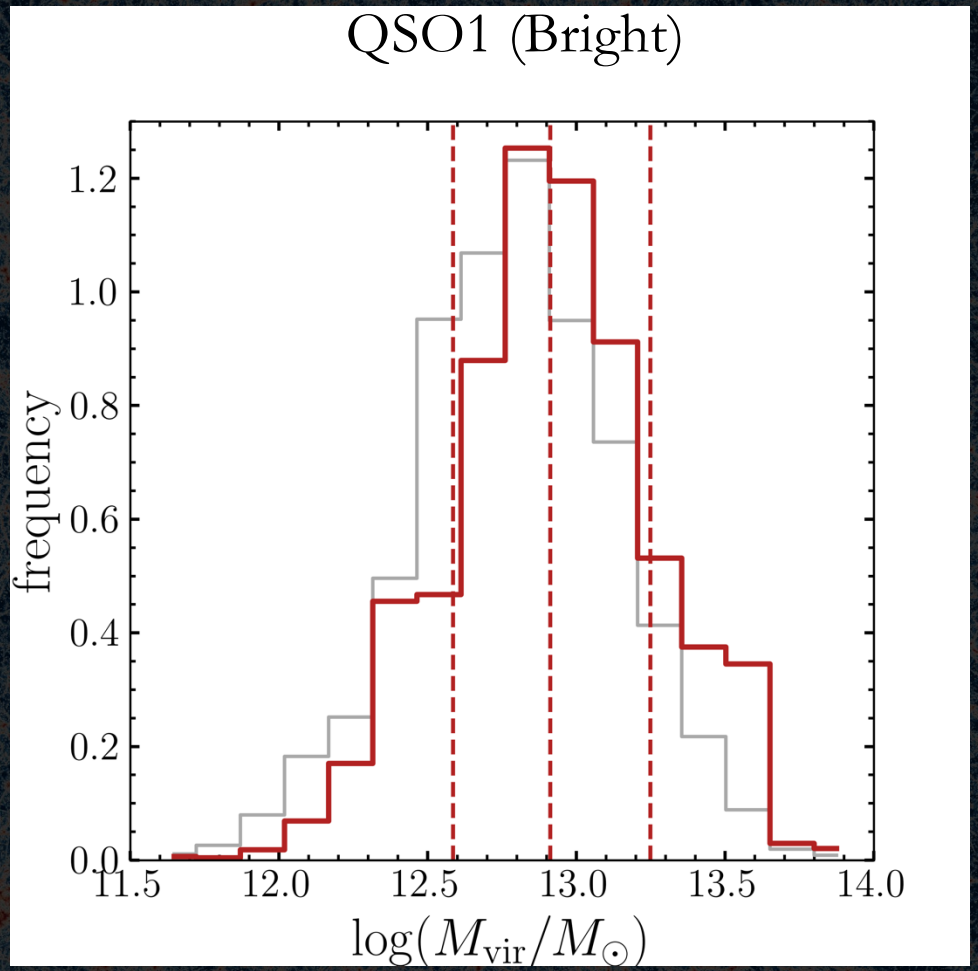

TNG100 − 1
median profile − (rec + coll)
median profile − (rec)
median profile − (maximal fluorescence)
MUDF observed
SB [10^{-18} erg s^{-1} cm^{-2} arcsec^{-2}]

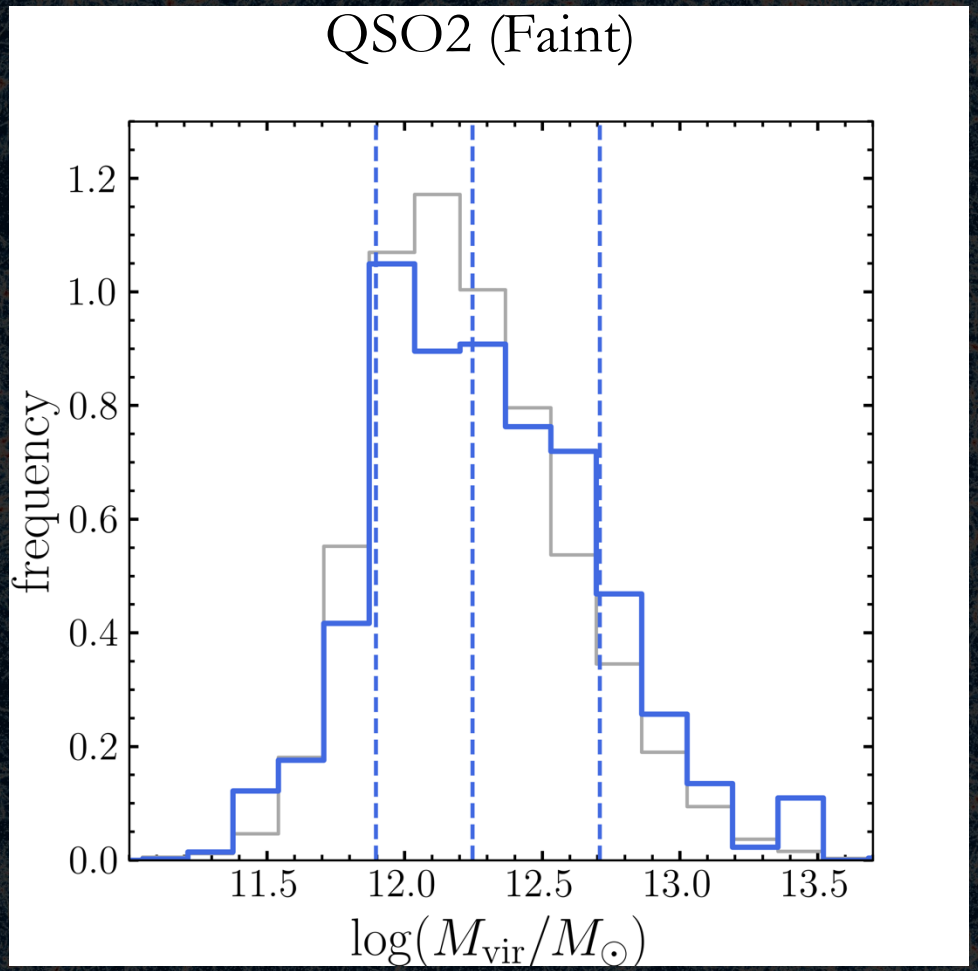

TNG300 − 1
median profile − (rec + coll)
median profile − (rec)
median profile − (maximal fluorescence)
MUDF observed
SB [10^{-18} erg s^{-1} cm^{-2} arcsec^{-2}]

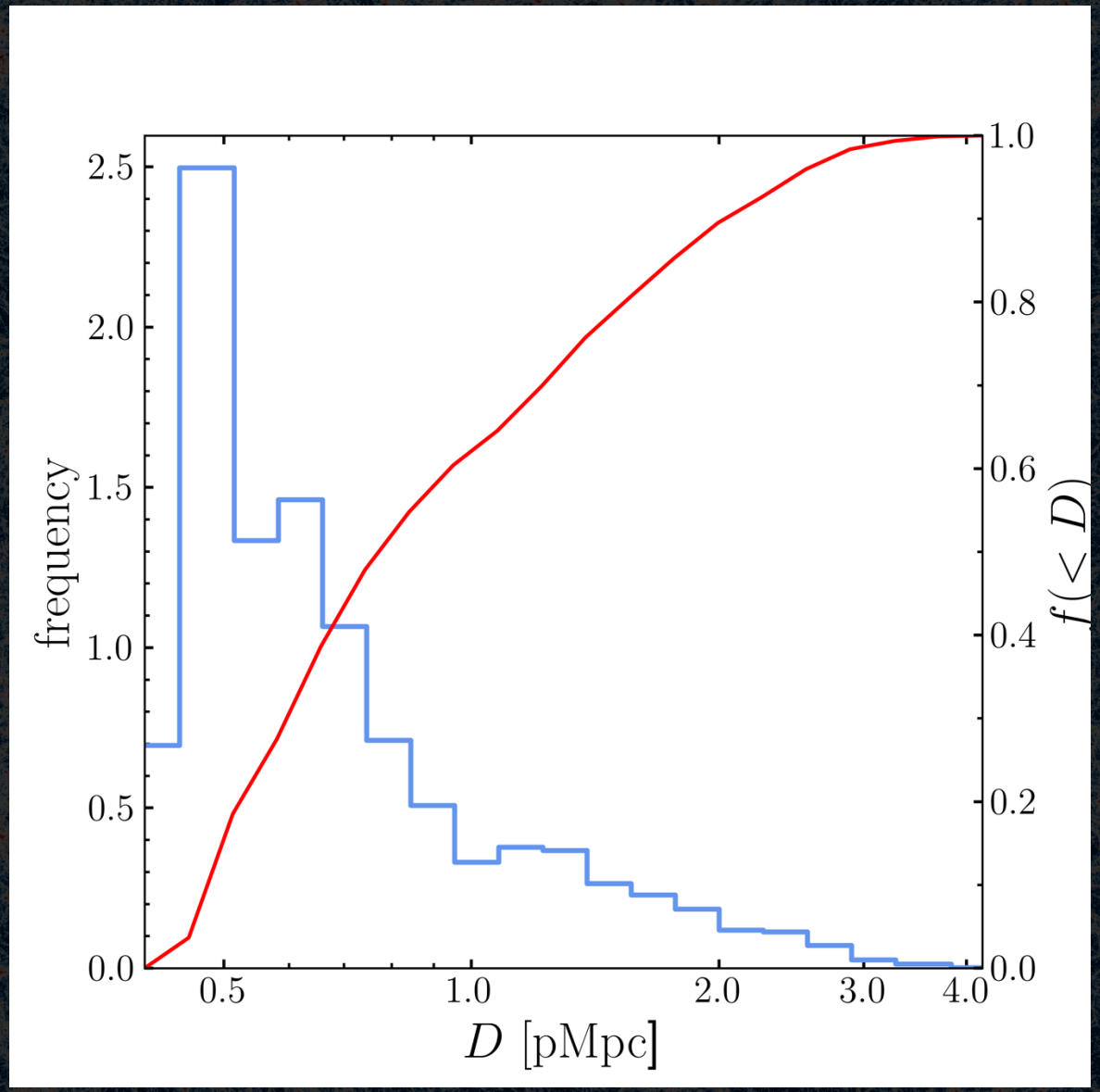


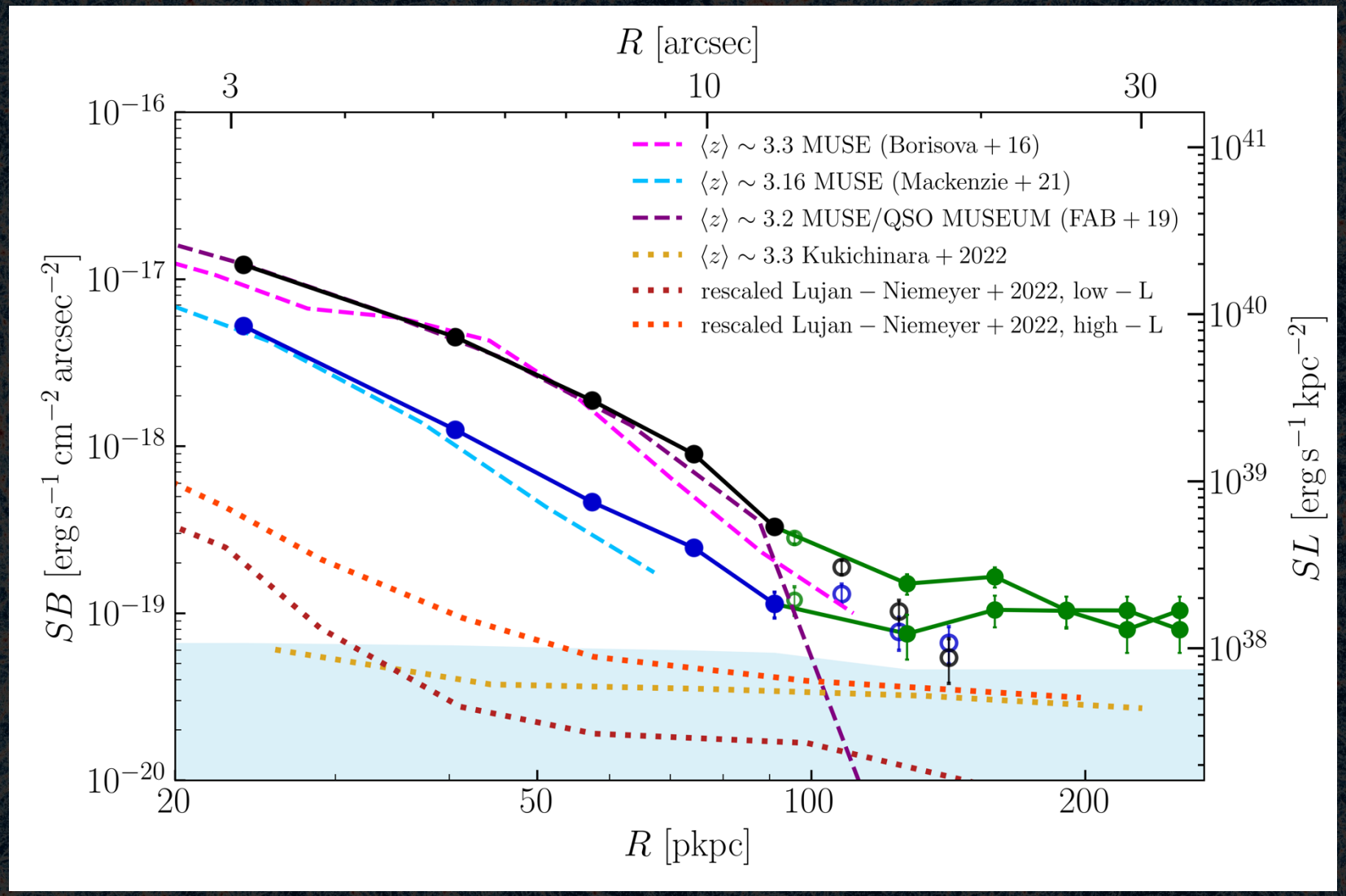


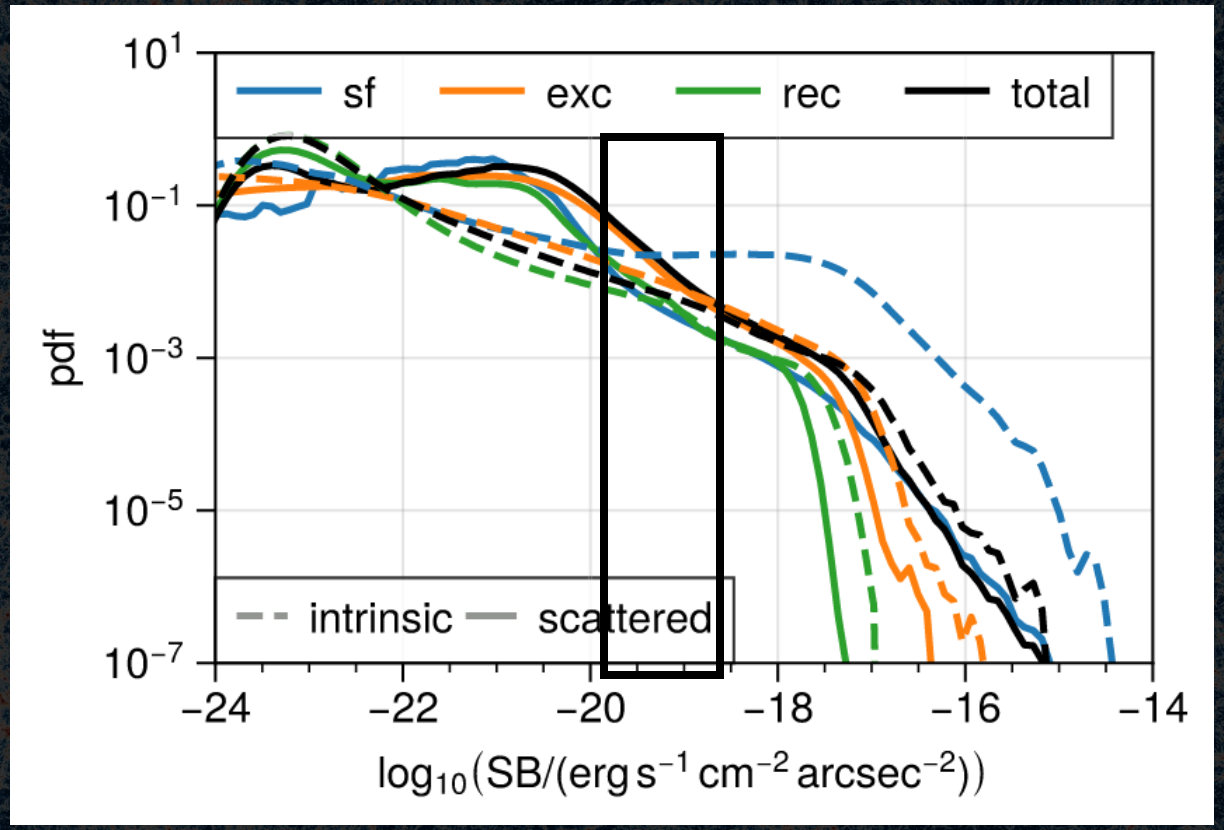
D. Tornotti et al. submitted


QSO1 (Bright)
frequency
0.0
0.2
0.4
0.6
0.8
1.0
1.2
11.5
12.0
12.5
13.0
13.5
14.0
log($M_{\rm vir}/M_\odot$)

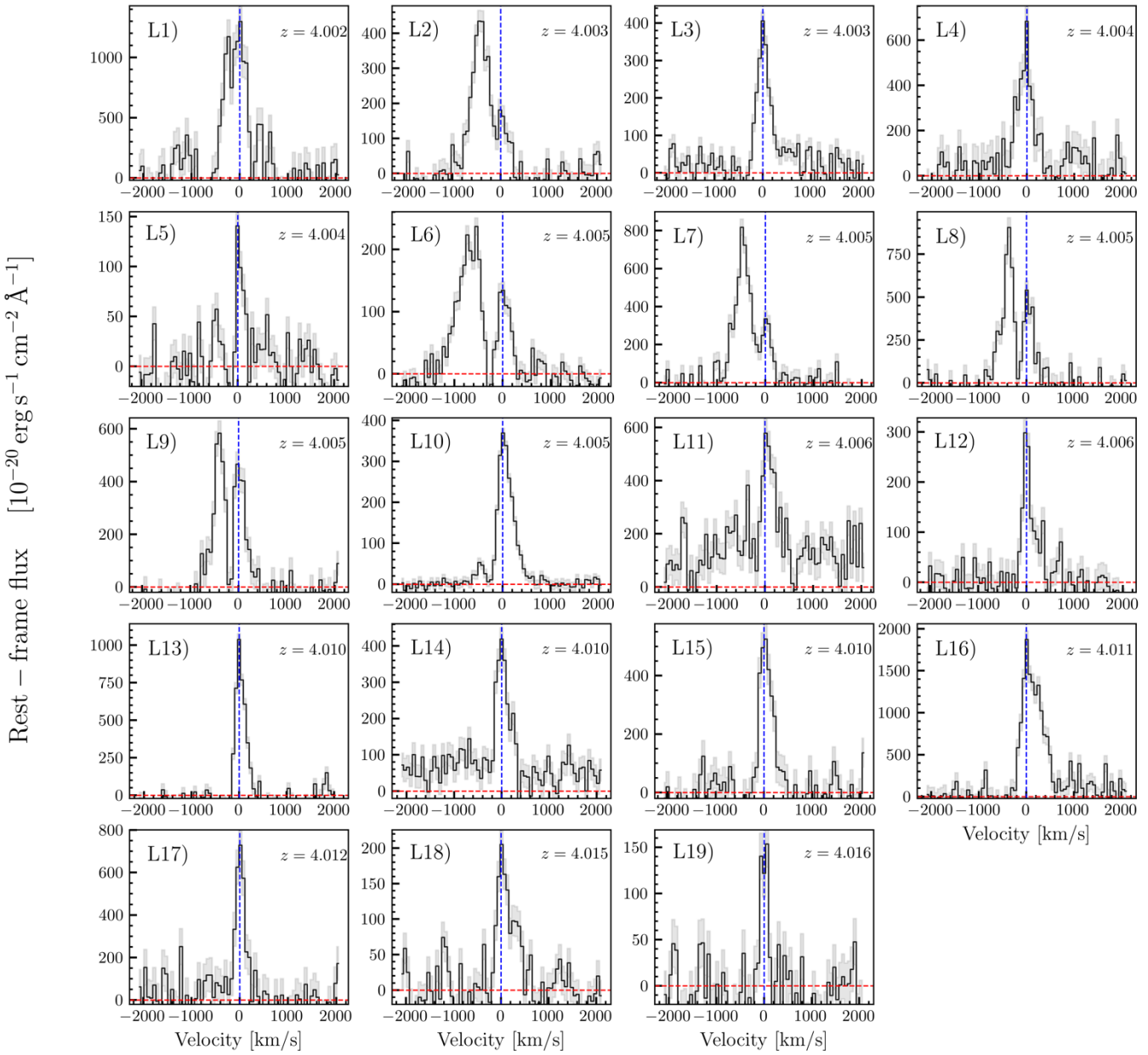

QSO2 (Faint)
frequency
0.0
0.2
0.4
0.6
0.8
1.0
1.2
11.5
12.0
12.5
13.0
13.5
log($M_{\rm vir}/M_\odot$)


frequency
$f(< D)$
D [pMpc]
0.0
0.5
1.0
1.5
2.0
2.5
0.2
0.4
0.6
0.8
1.0
0.5
1.0
2.0
3.0
4.0

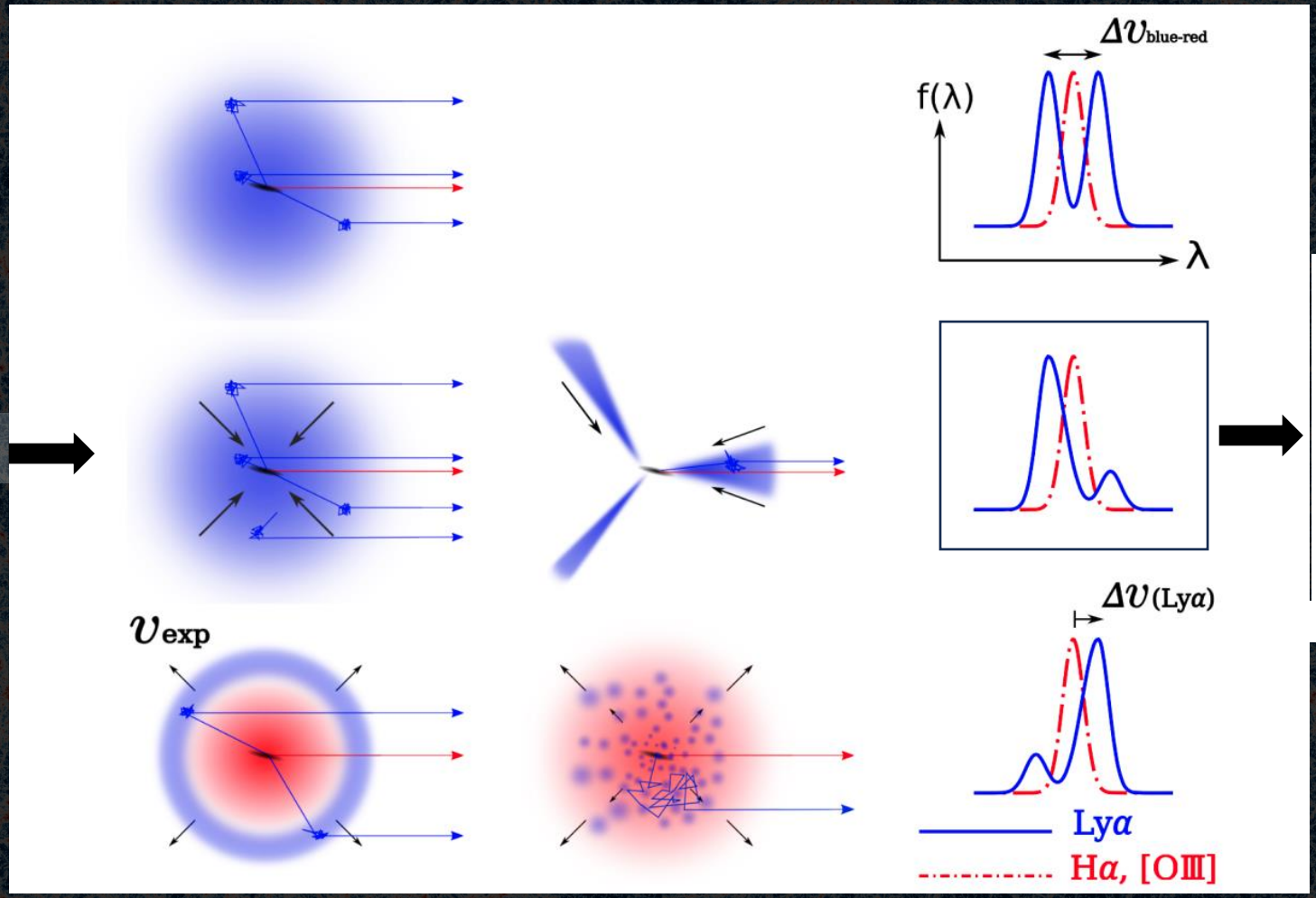

R [arcsec]
3
10
30
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
SB [erg s^{-1} cm^{-2} arcsec^{-2}]
10^{41}
10^{40}
10^{39}
10^{38}
SL [erg s^{-1} kpc^{-2}]
⟨z⟩ ∼ 3.3 MUSE (Borisova + 16)
⟨z⟩ ∼ 3.16 MUSE (Mackenzie + 21)
⟨z⟩ ∼ 3.2 MUSE/QSO MUSEUM (FAB + 19)
⟨z⟩ ∼ 3.3 Kukichinara + 2022
rescaled Lujan − Niemeyer + 2022, low − L
rescaled Lujan − Niemeyer + 2022, high − L
20
50
100
200
R [pkpc]

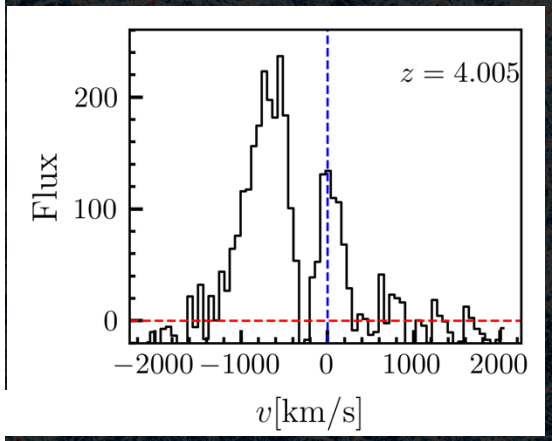


Byrohl & Nelson 2023

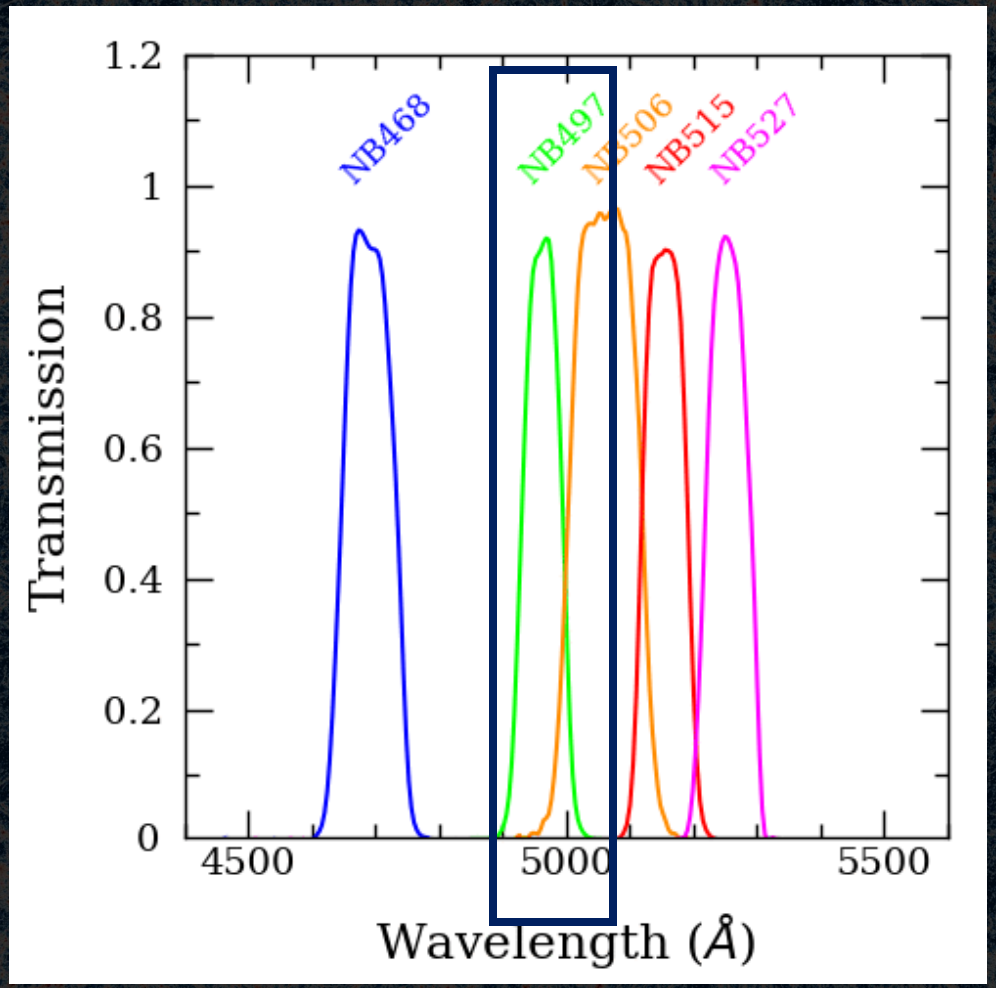

L1) $z = 4.002$
L2) $z = 4.003$
L3) $z = 4.003$
L4) $z = 4.004$
L5) $z = 4.004$
L6) $z = 4.005$
L7) $z = 4.005$
L8) $z = 4.005$
L9) $z = 4.005$
L10) $z = 4.005$
L11) $z = 4.006$
L12) $z = 4.006$
L13) $z = 4.010$
L14) $z = 4.010$
L15) $z = 4.010$
L16) $z = 4.011$
L17) $z = 4.012$
L18) $z = 4.015$
L19) $z = 4.016$
Rest − frame flux [10^{-20} erg s^{-1} cm^{-2} Å^{-1}]
Velocity [km/s]

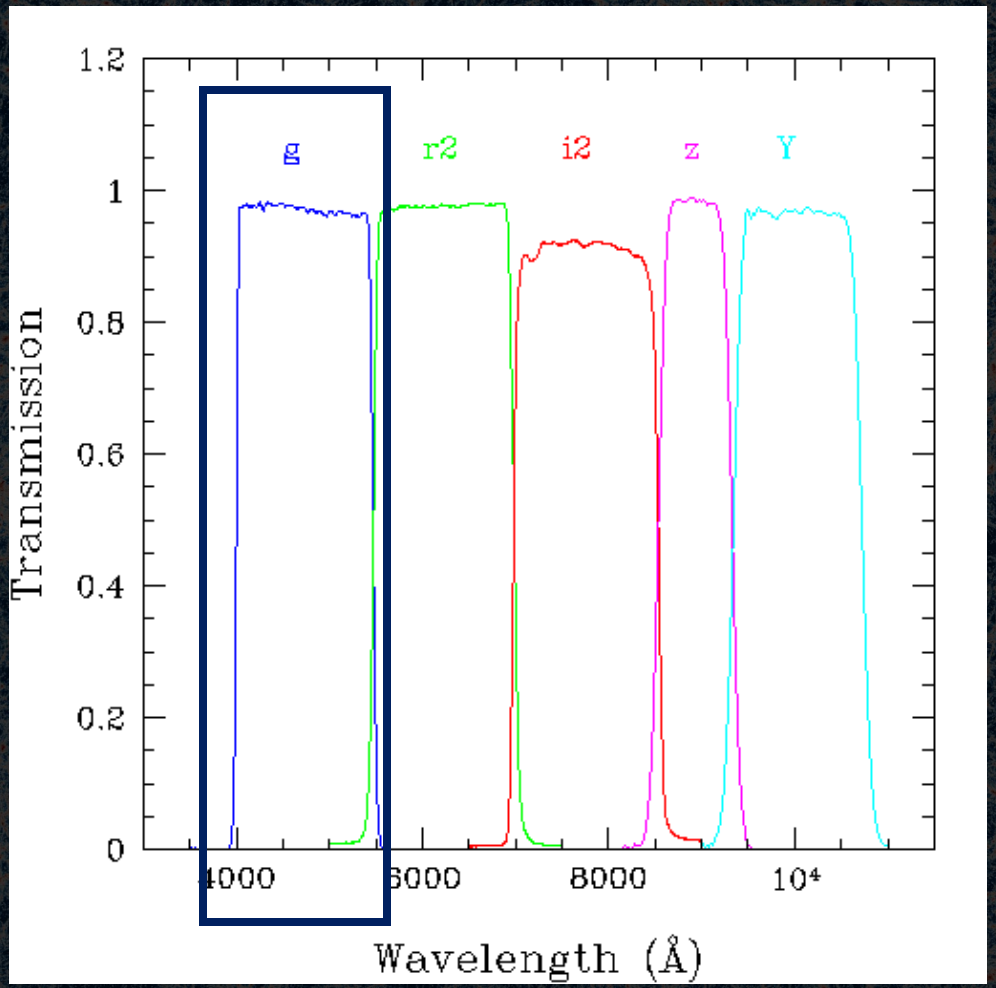
Spherical infall





Yang et al 2014


NB468
NB497
NB506
NB515
NB527
Transmission
Wavelength (Å)
0
0.2
0.4
0.6
0.8
1
1.2
4500
5000
5500


g
r2
i2
z
Y
Transmission
Wavelength (Å)
0
0.2
0.4
0.6
0.8
1
1.2
4000
6000
8000
10⁴