The MUSE contribution to mapping the cosmic baryon cycle over 10 billion years

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A decade of discoveries with MUSE and beyond
18–22 November 2024
Garching b. Muenchen

MUSE represents the transition from the dark ages to the enlightenment (literally) of studies of the baryon cycle

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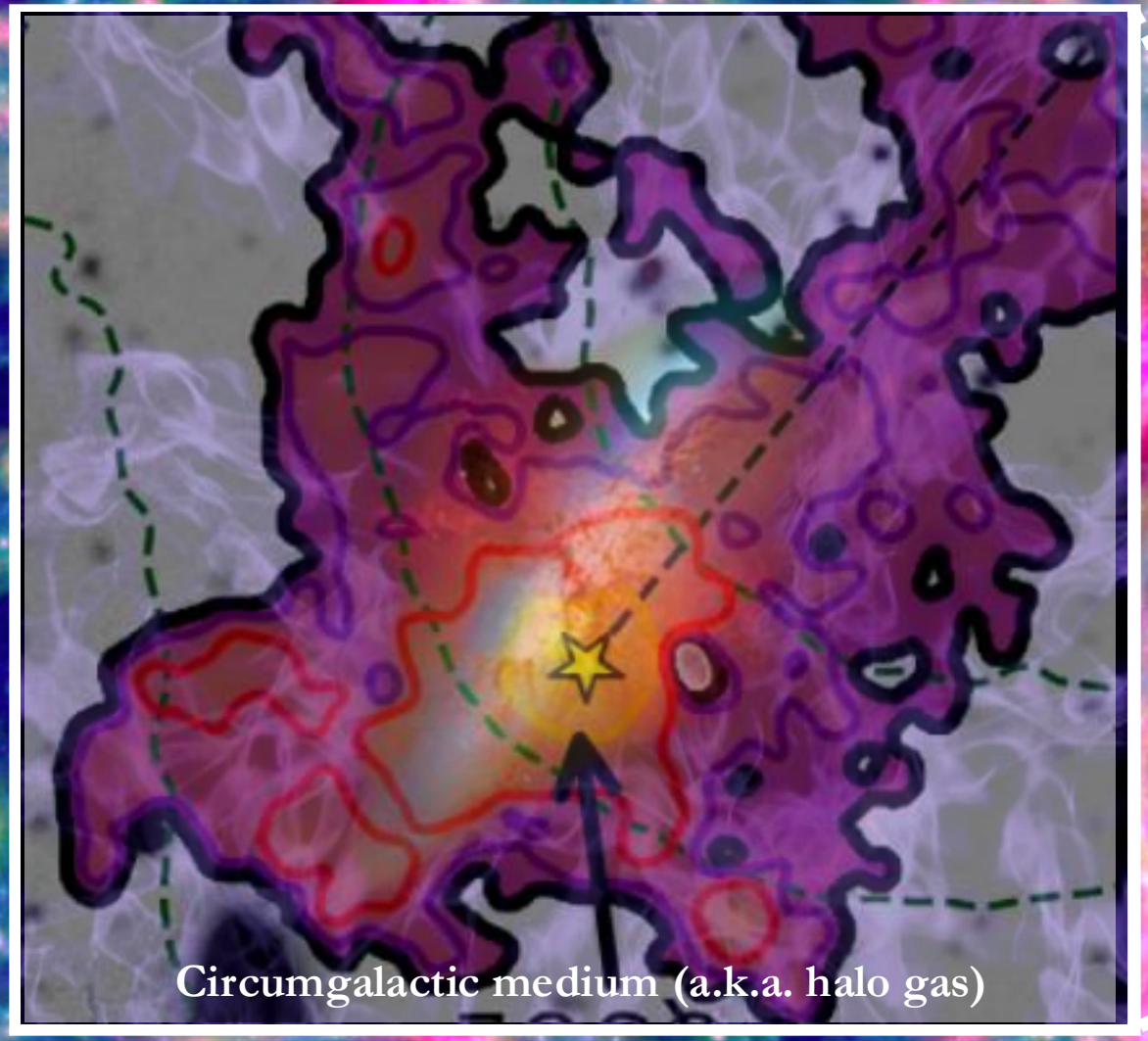
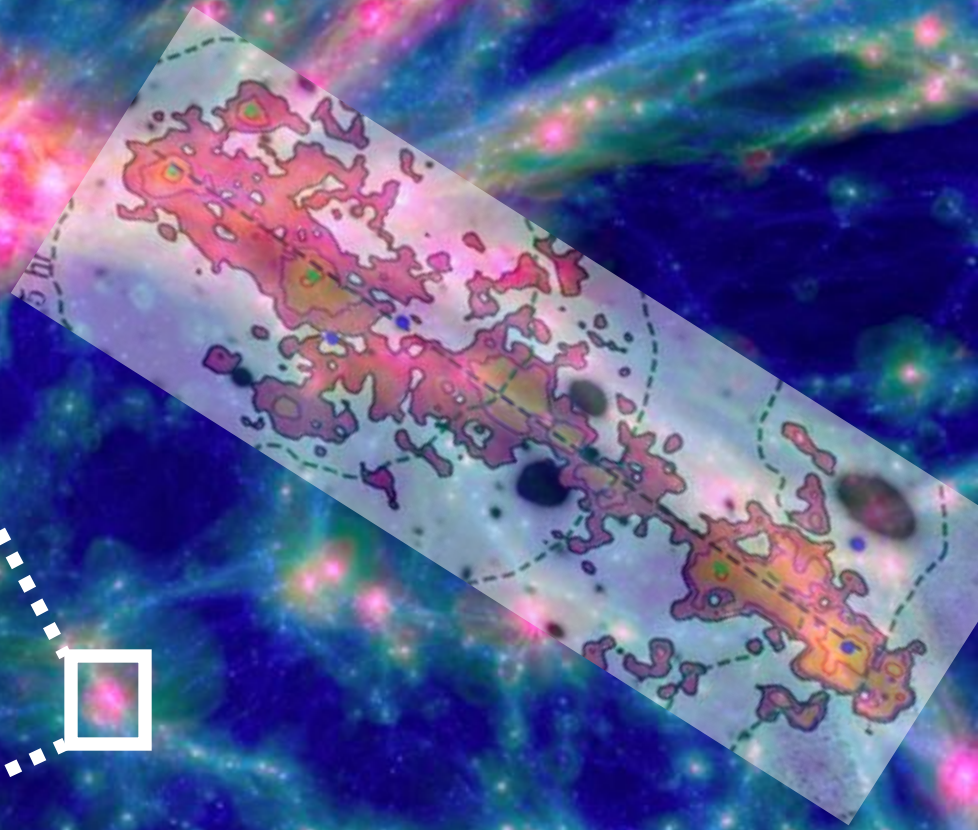


Circumgalactic medium (a.k.a. halo gas)



CGM is the "glue" between the ISM and surrounding environment

EAGLE simulation (Schaye et al. 2015) + MUSE data

THE EAGLE PROJECT

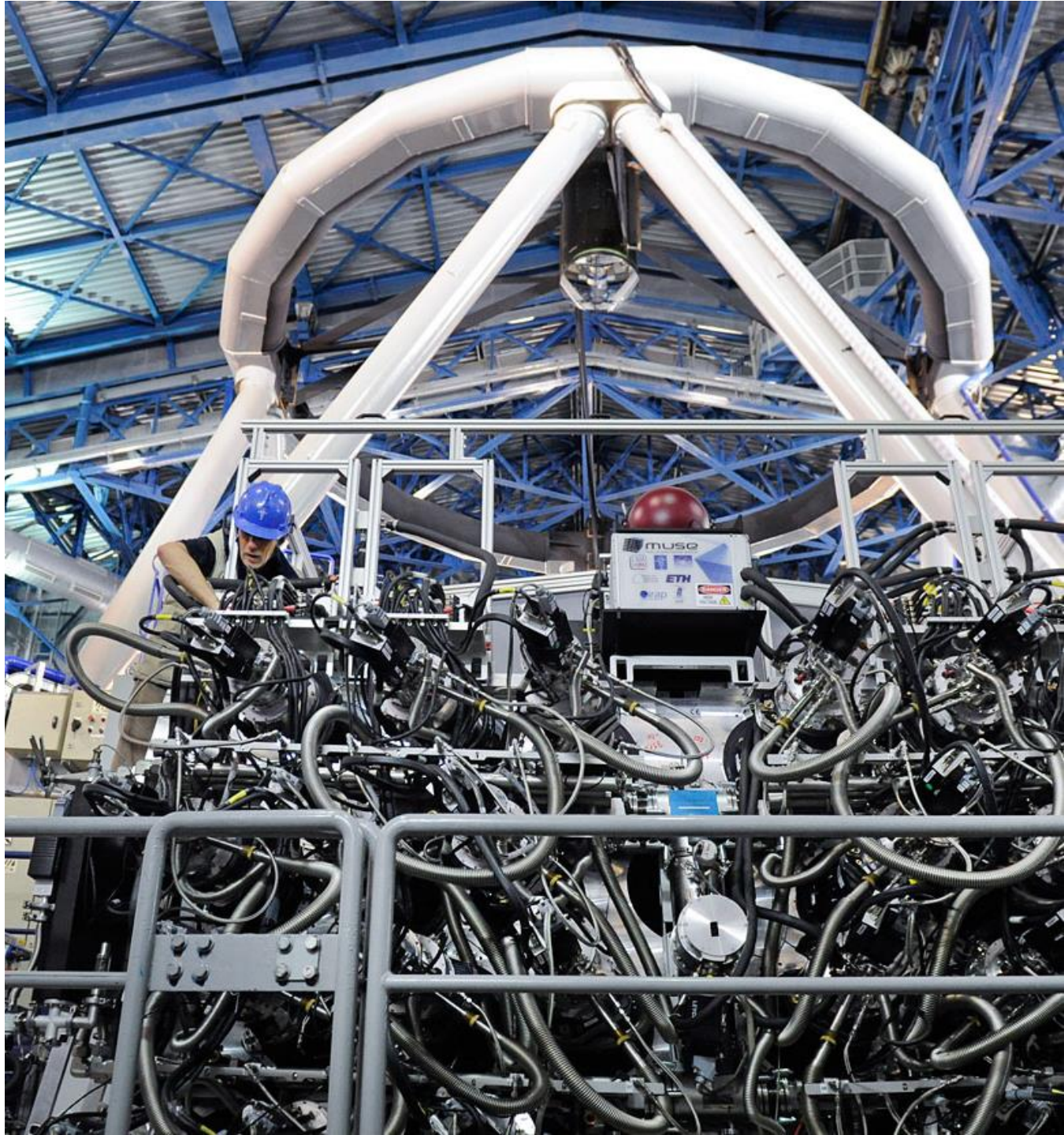
Three key contributions of MUSE in IGM/CGM studies (and the three parts of this talk)

1. Measure the gas (hydrogen plus metals) distribution outside galaxies in emission between z~0-4

2. Link the properties of the CGM to galaxies over >100x larger samples

3. Bridge the gap between galaxy evolution studies of the environment and the CGM community

Large community effort: I'll show hand-picked examples
But we will hear more exceptional science during the week



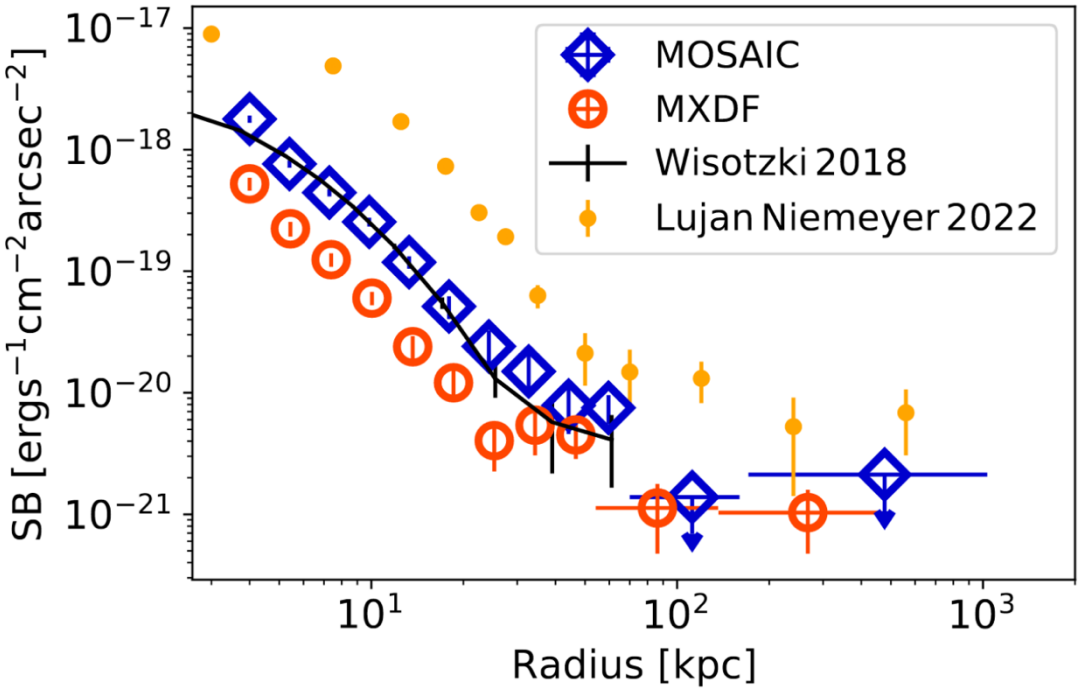
Key contribution #1

Measure the gas (hydrogen plus metals) distribution outside galaxies in emission between $z\sim0$-4

Mapping the HI gas in the CGM at z>3 in different halo masses

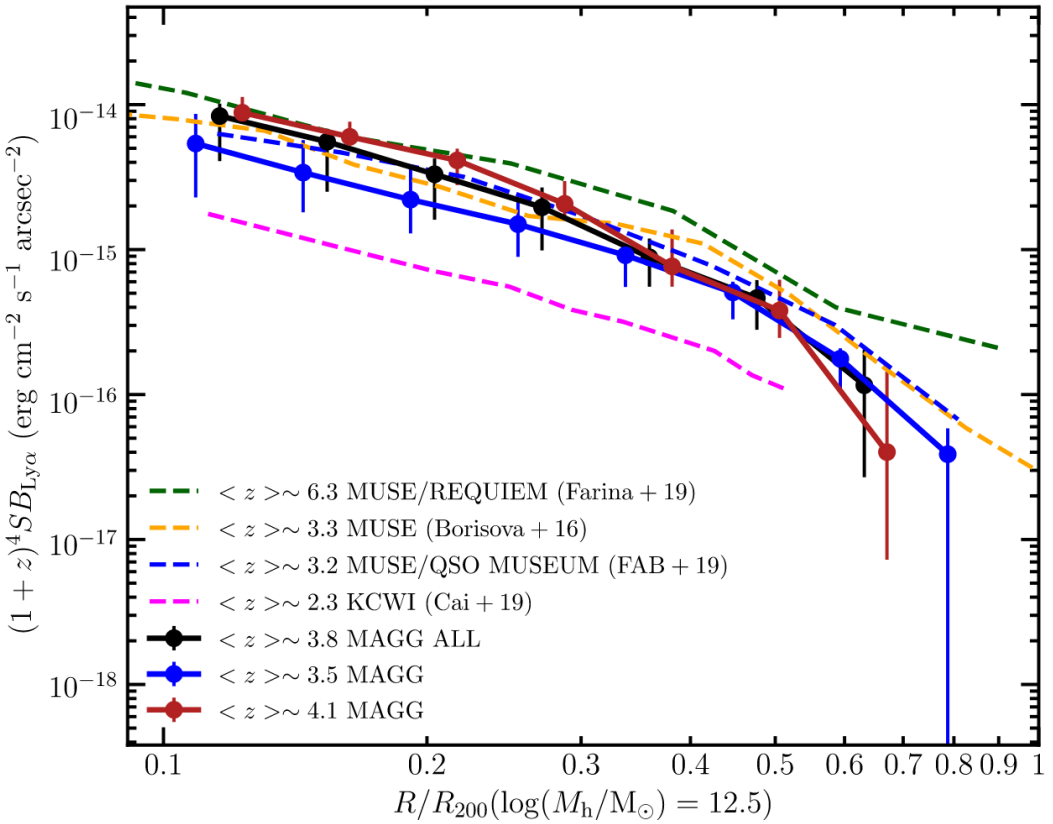
Lyα halos are ubiquitously detected and characterized around galaxies in a large range of halo masses at z>3

The CGM HI content of Lyα emission line galaxies (LAEs)



Guo et al. 2024, MXDF survey

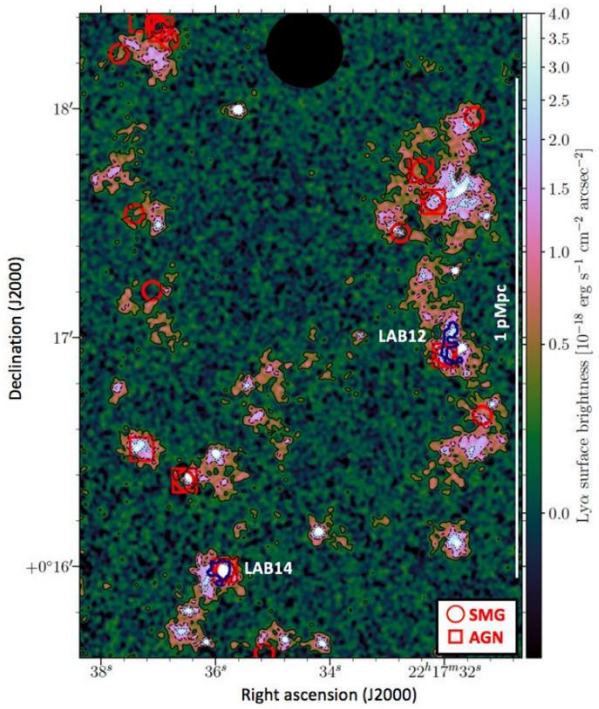
The CGM of HI content of quasar host galaxies



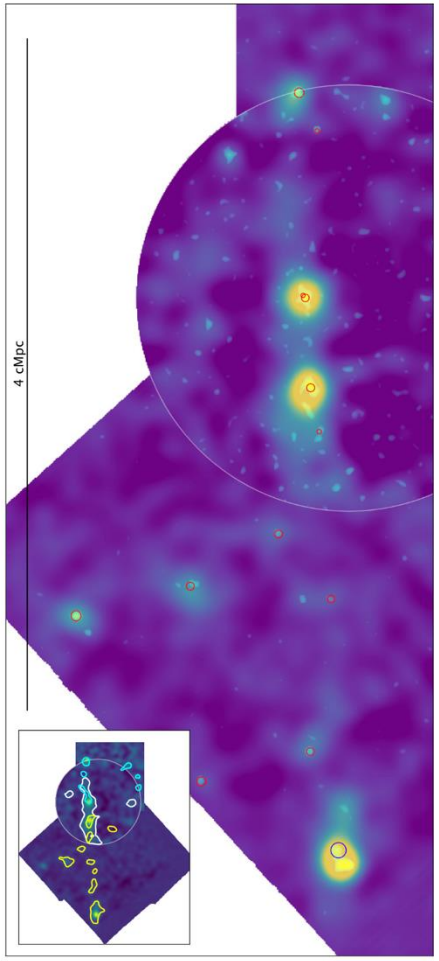
Fossati et al. 2021, MAGG survey

Opening a new view of the intergalactic medium

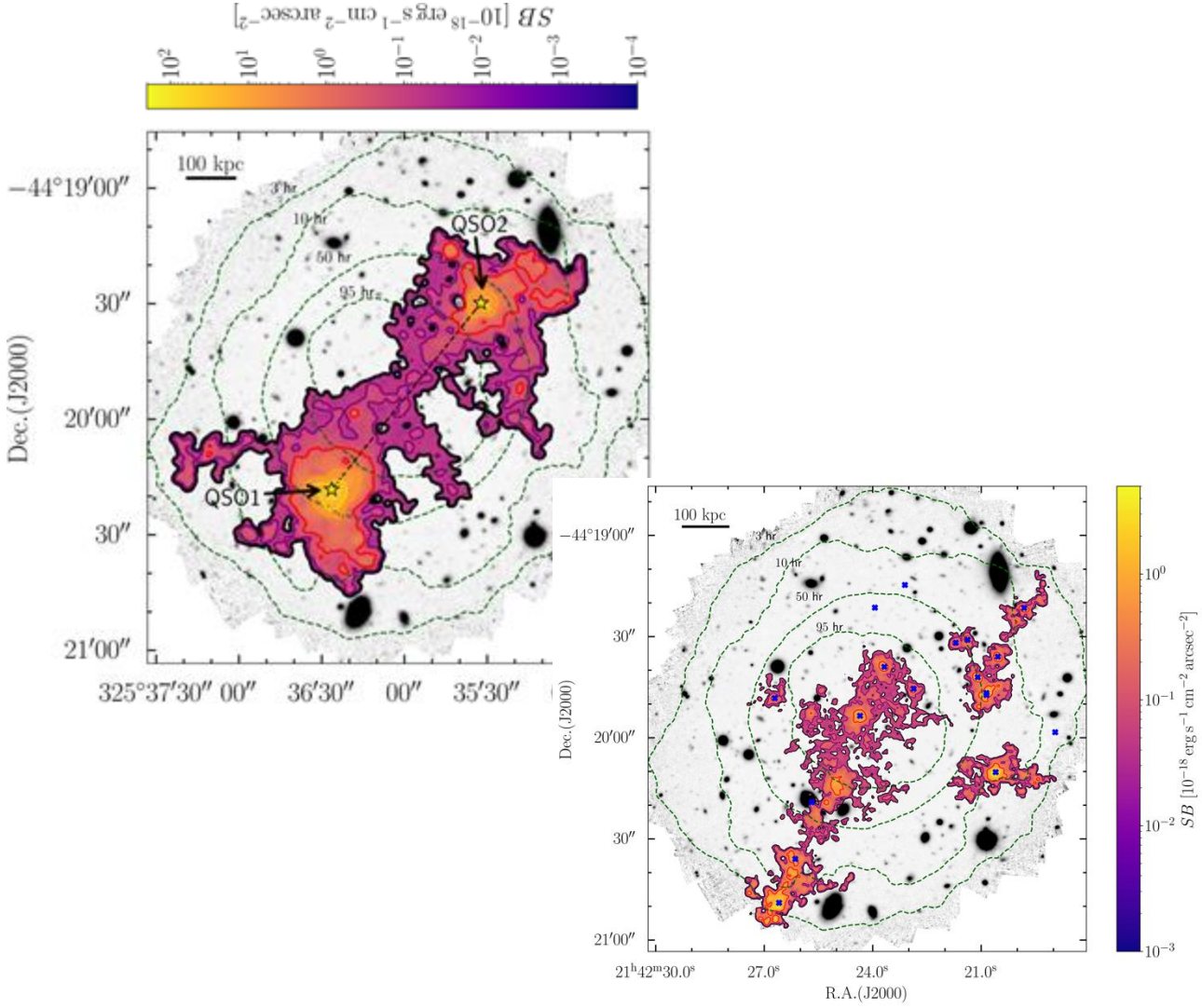
Lyα is now detected in samples of cosmic web filaments across various cosmic environments



Umehata, MF et al. 2019, SSA22 survey



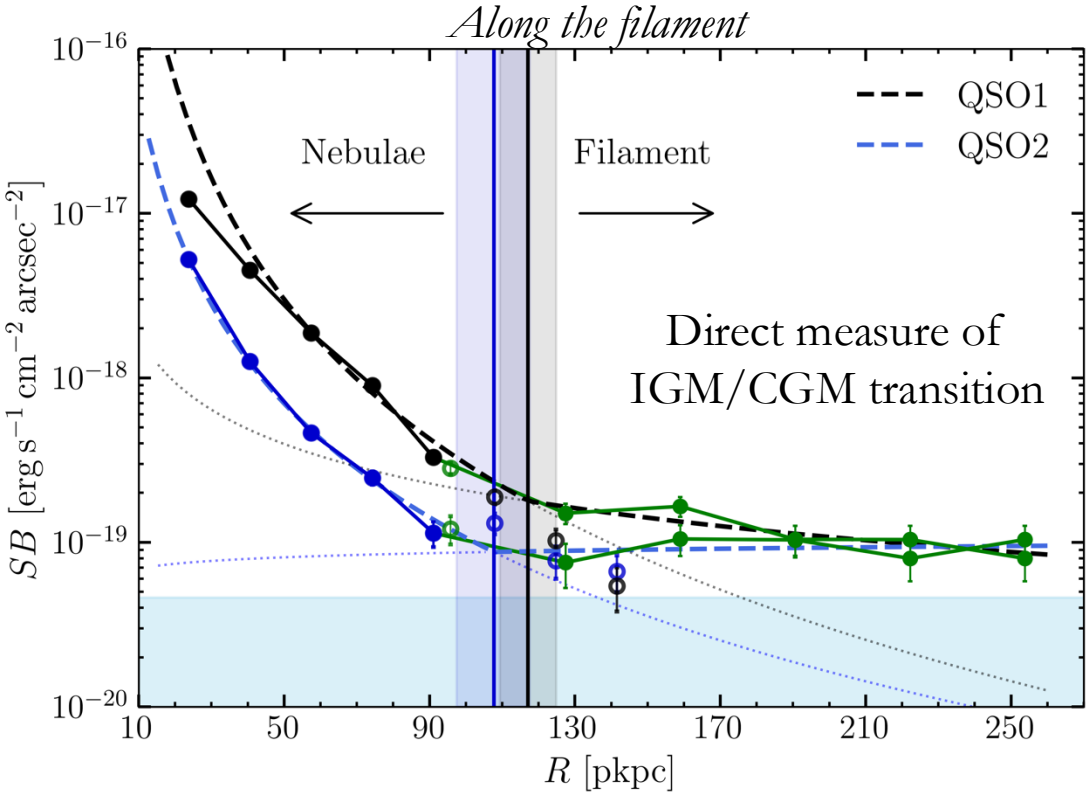
Bacon et al. 2021, MXDF survey

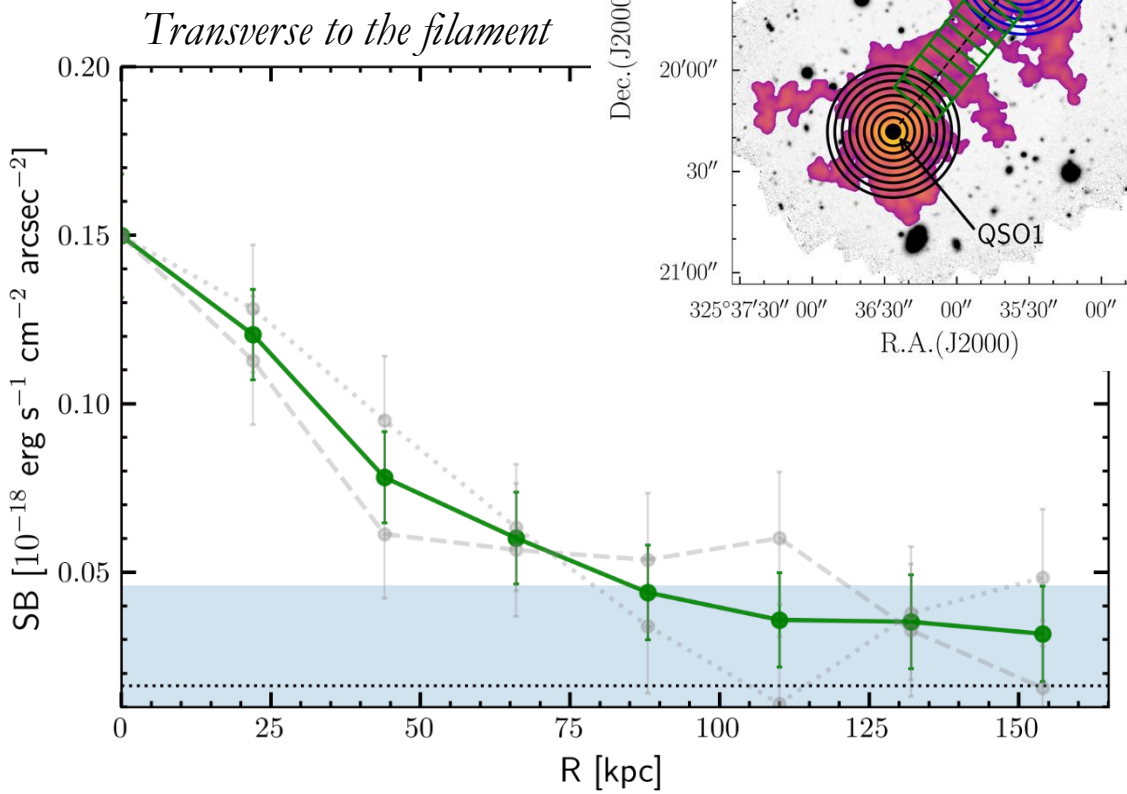


Tornotti et al. 2024a&b, MUDF survey

Opening a new view of the intergalactic medium

We can now measure properties of the cosmic web in emission

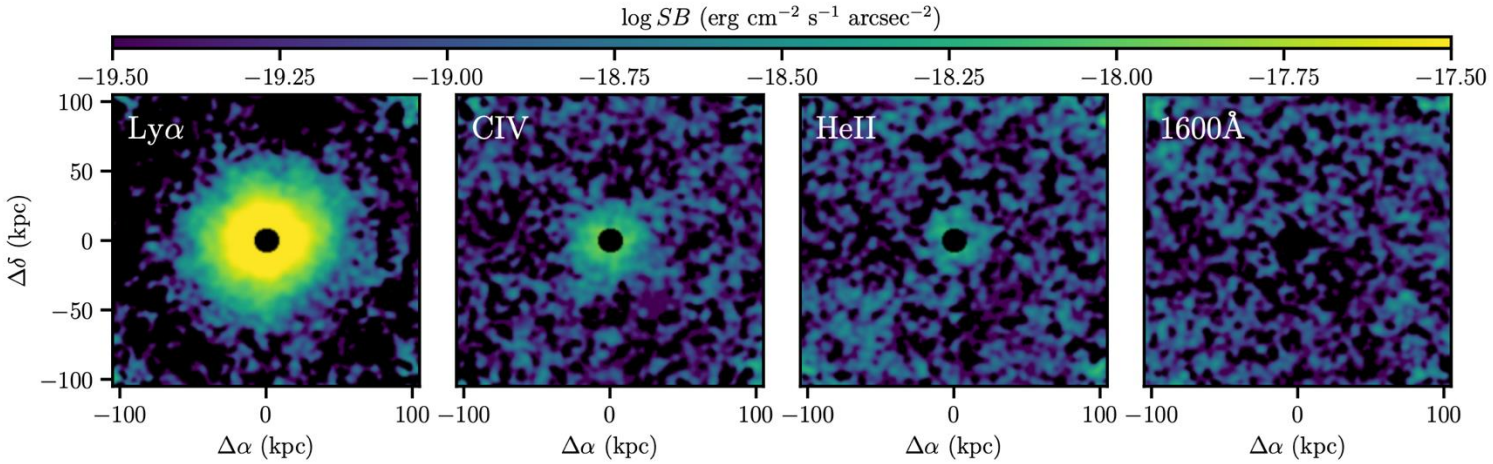




Tornotti et al. 2024a, MUDF survey

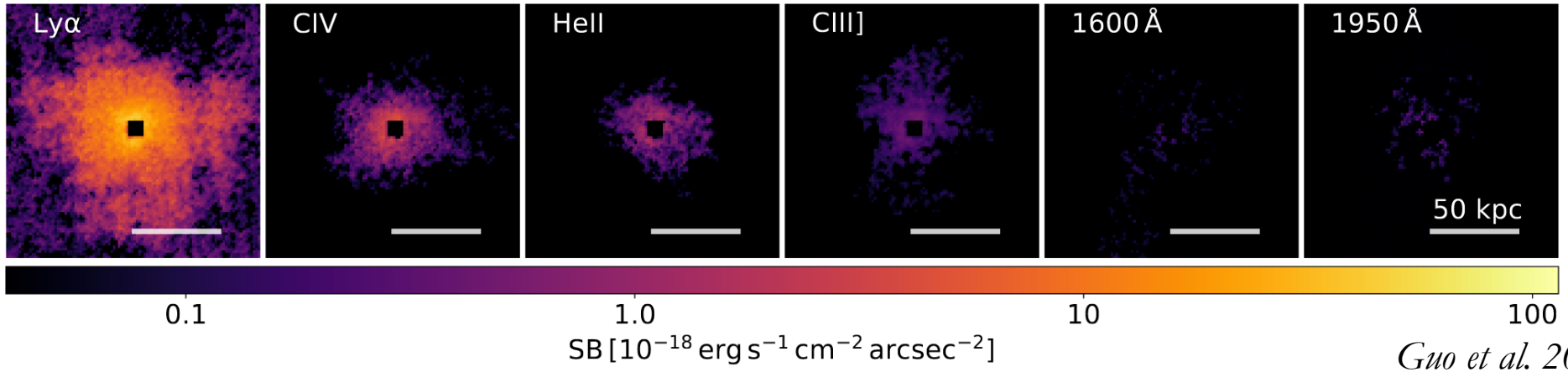
Metals are finally seen inside the CGM

CIV, CIII], (HeII) detections in the CGM of z~3-4 quasars



Evidence of enriched (inner) CGM to Z~0.1-0.5 Z_{sun}

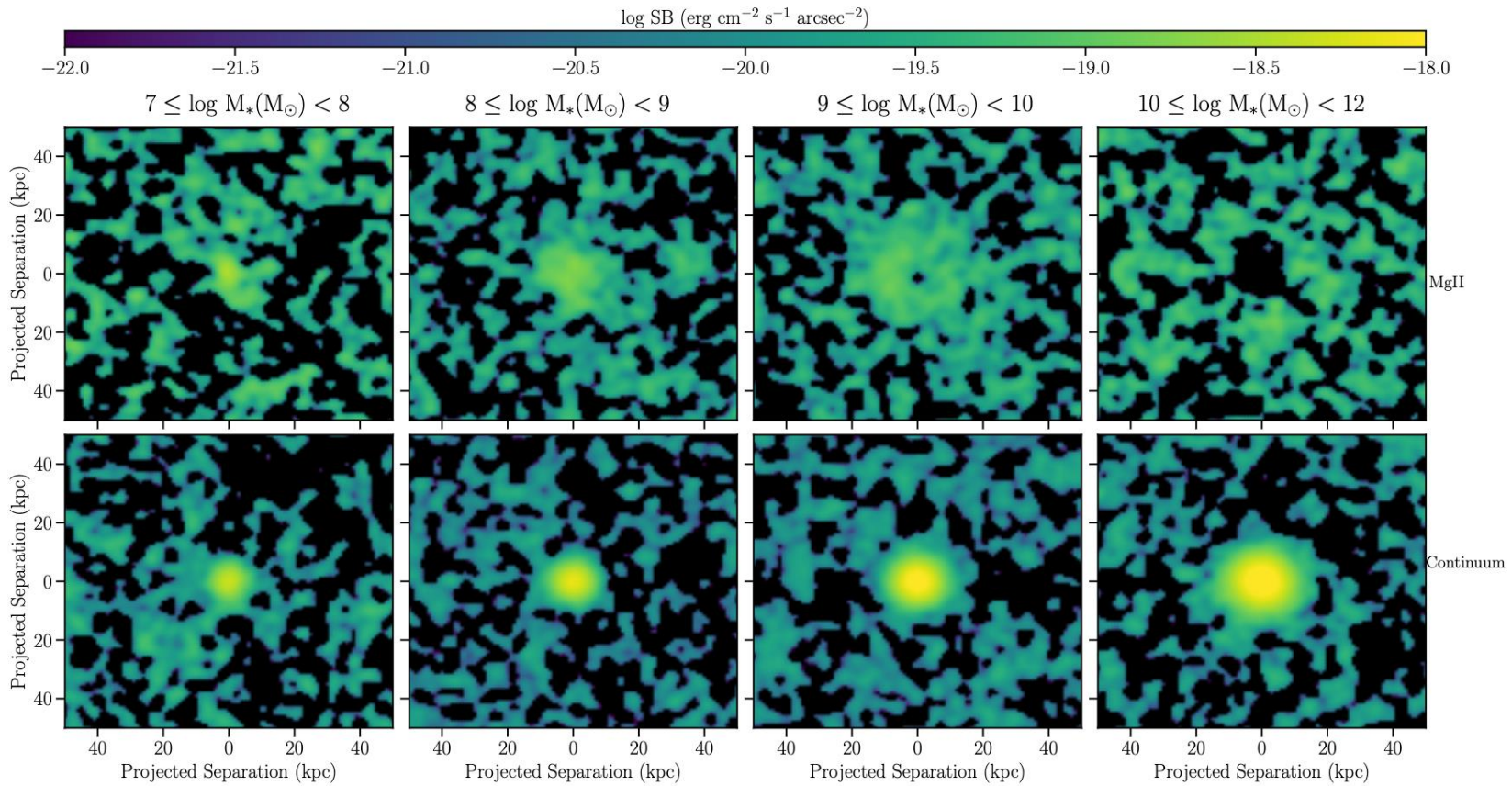
Fossati et al. 2021, MAGG survey

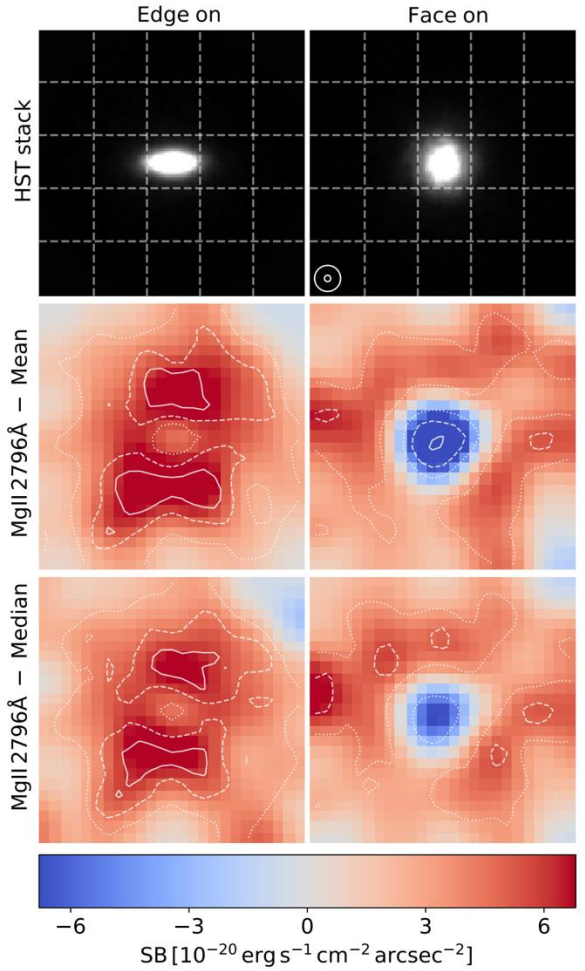


Guo et al. 2020

Metals are finally seen inside the CGM

Metal lines detections in the CGM of z~0.5-1.5 star-forming galaxies





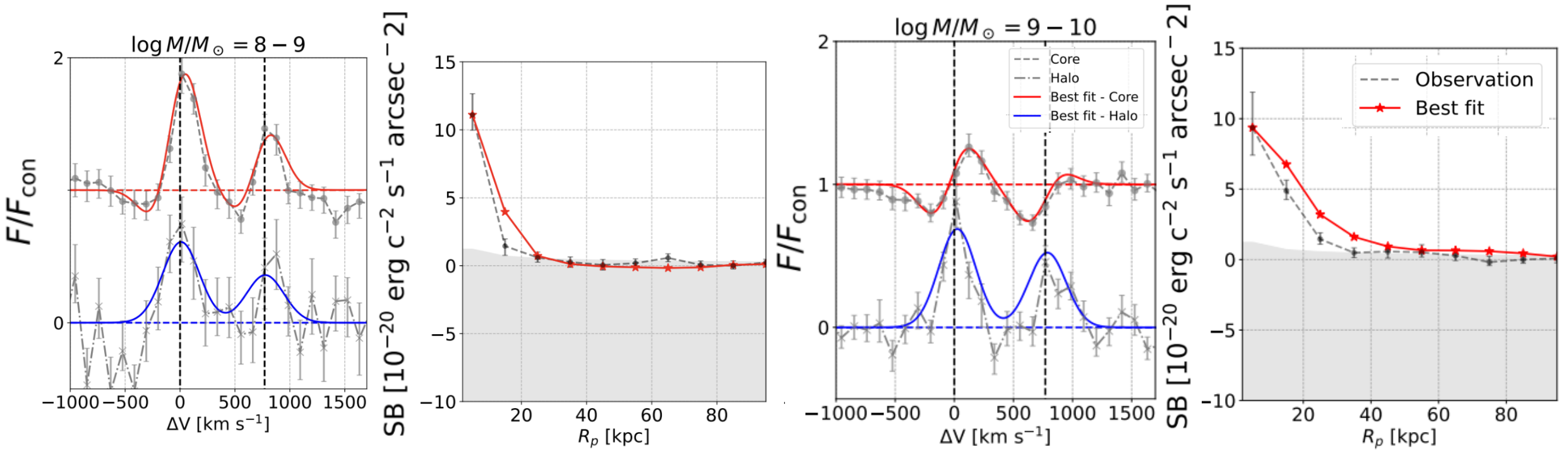
Dutta et al. 2023, MAGG+MUDF survey

Guo et al. 2023

Metals are finally seen inside the CGM

Metal lines detections in the CGM of z~0.5-1.5 star-forming galaxies: constraining halo models

Increasing mass



Slower outflows and cool gas accumulation at higher masses

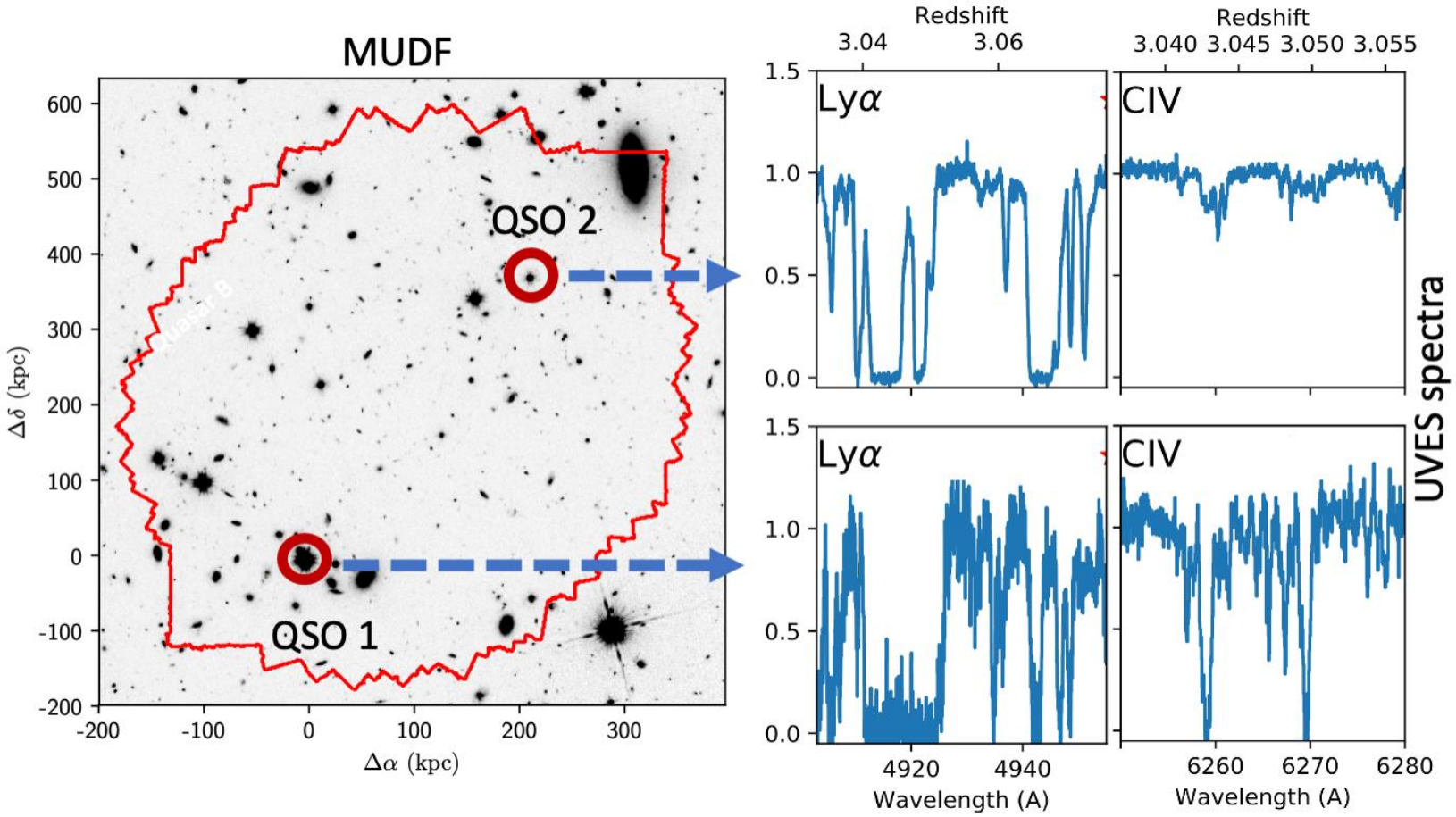
Chang, Dutta et al. 2024 (MAGG+MUDF)

Key contribution #2

Link the properties of the CGM to galaxies over >100x larger samples

MUSE has enabled a giant leap

IFUs (and slitless spectrographs) have the great advantage of avoiding pre-selection and thus allow for complete surveys including continuum-faint line emitters on scales <1 Mpc



MUDF: the MUSE Ultra Deep Field (Lusso et al. 2019, Fossati et al. 2019)

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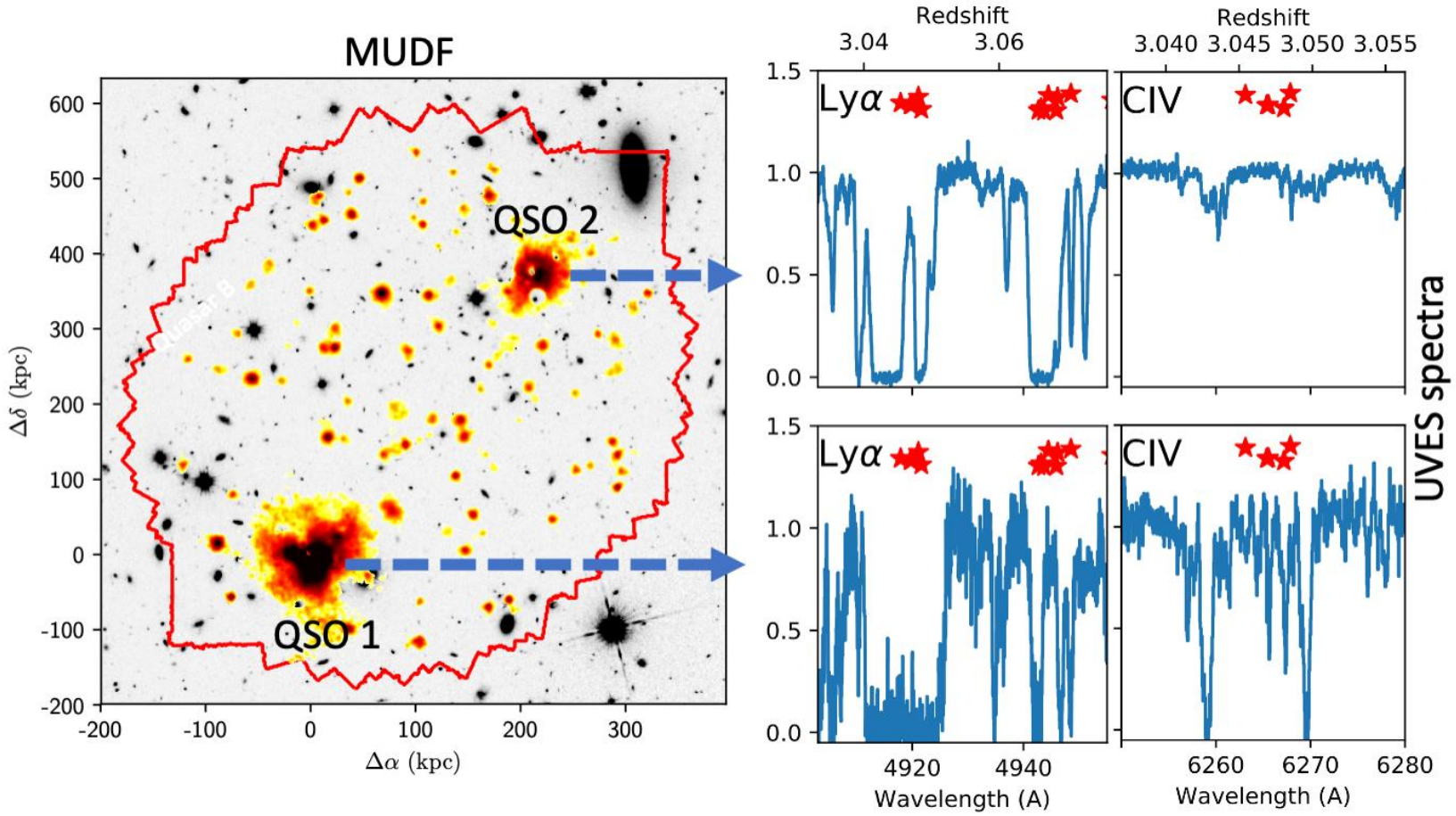
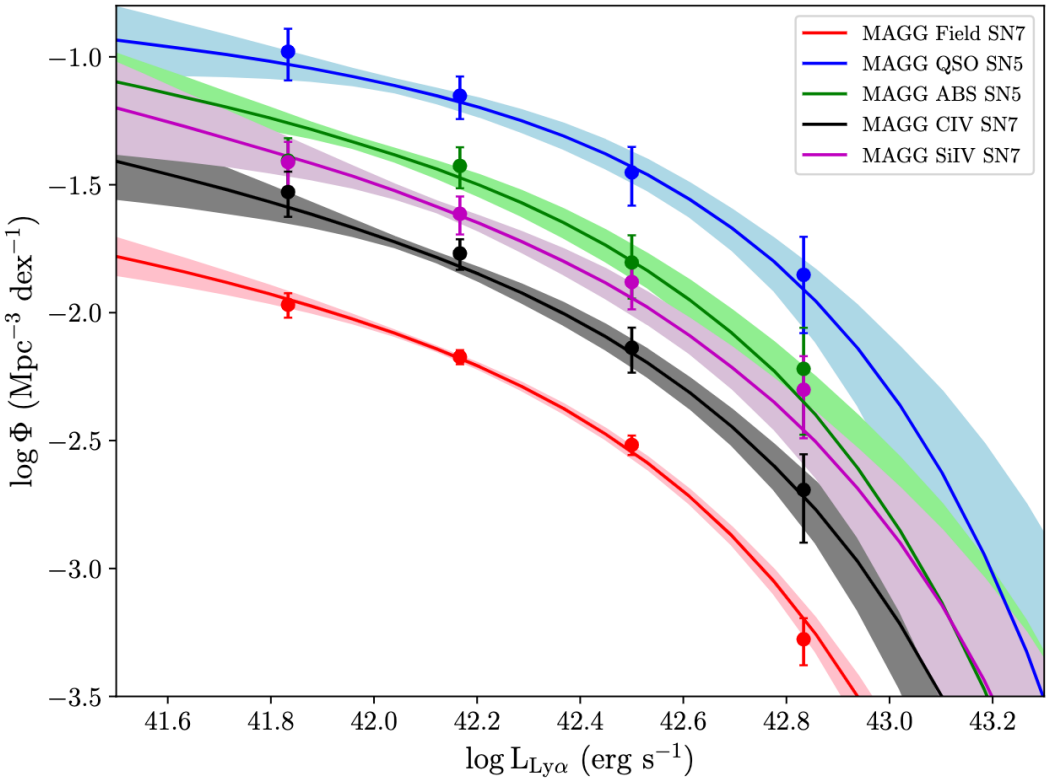
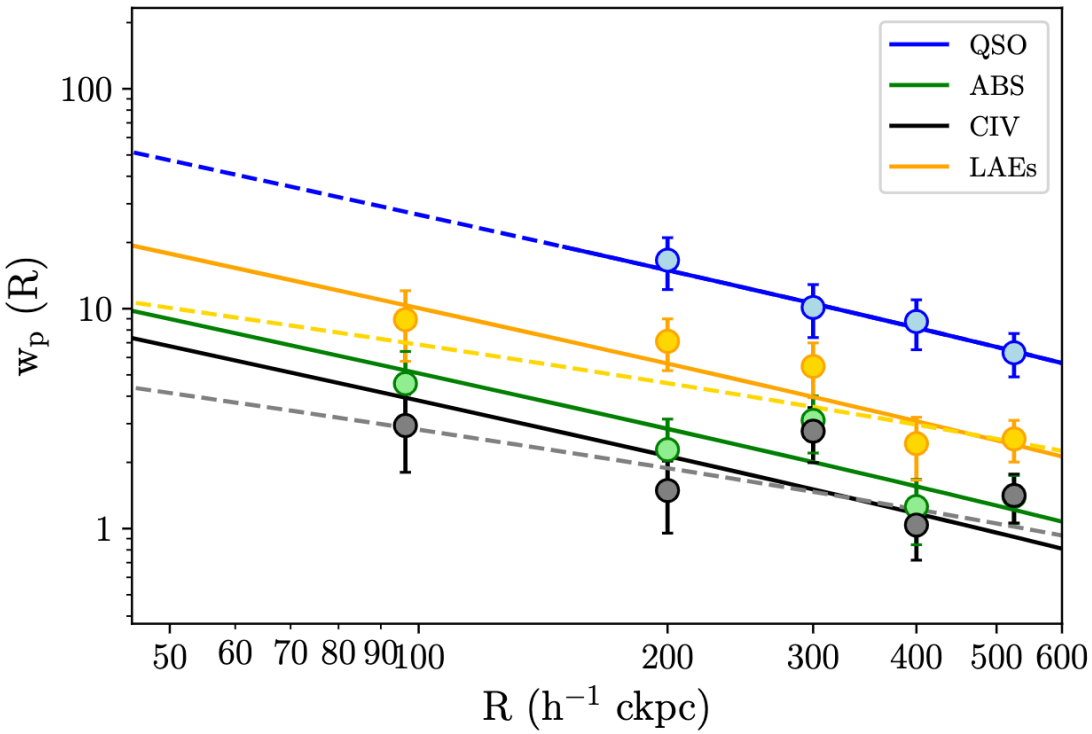


Many large surveys are contributing to this science: MAGG, MUSEQuBES, MEGAFLOW, MUSE-ALMA Haloes Survey…

Lower mass Lyα emitting galaxies (LAEs) trace metal enriched filaments

There is a clear excess of emission-line galaxies near HI and metals compared to field, highlighting a connection between strong absorbers and galaxies.

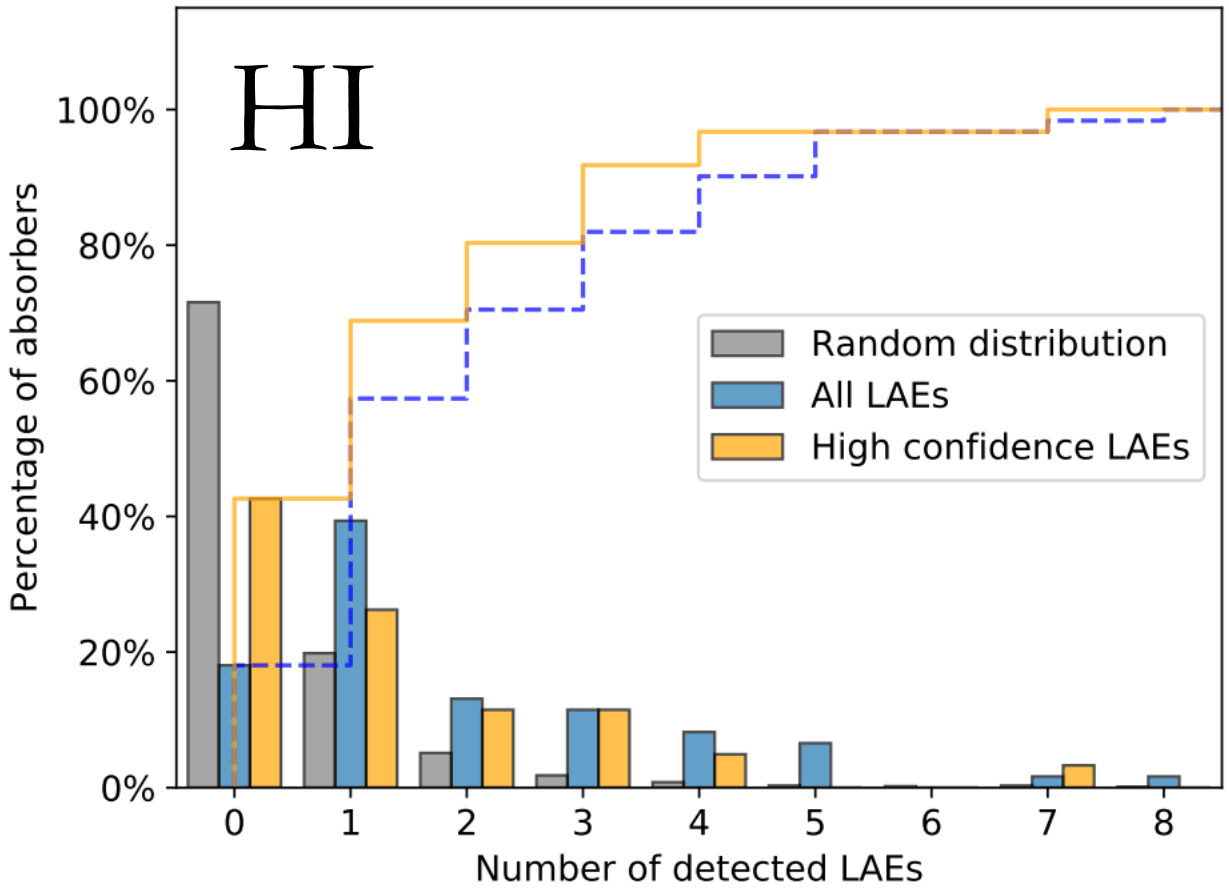


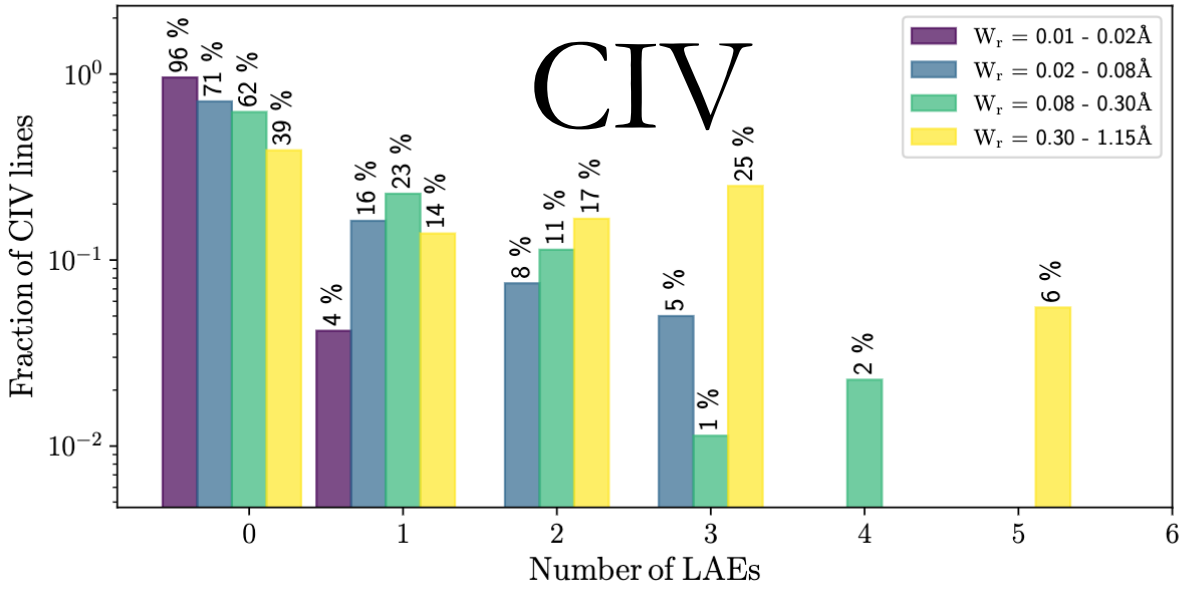


Lofthouse et al. 2023; Galbiati et al. 2023; Fossati et al. 2021 (MAGG survey)

Lower mass Lyα emitting galaxies (LAEs) trace metal enriched filaments

The detection rate is very high for strong HI absorbers, and strongly dependent on EW for CIV. Evidence of frequent instances of multiple LAEs connected to the same absorber.

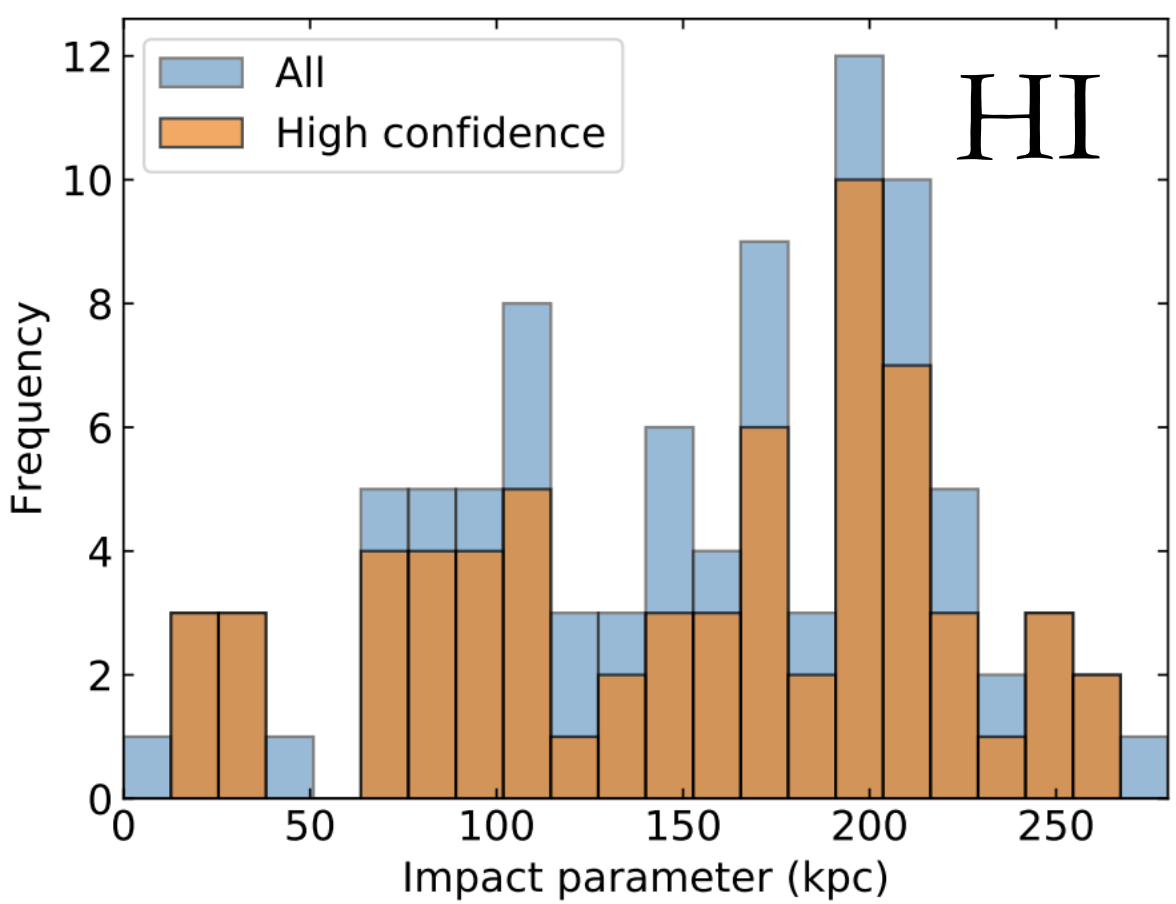


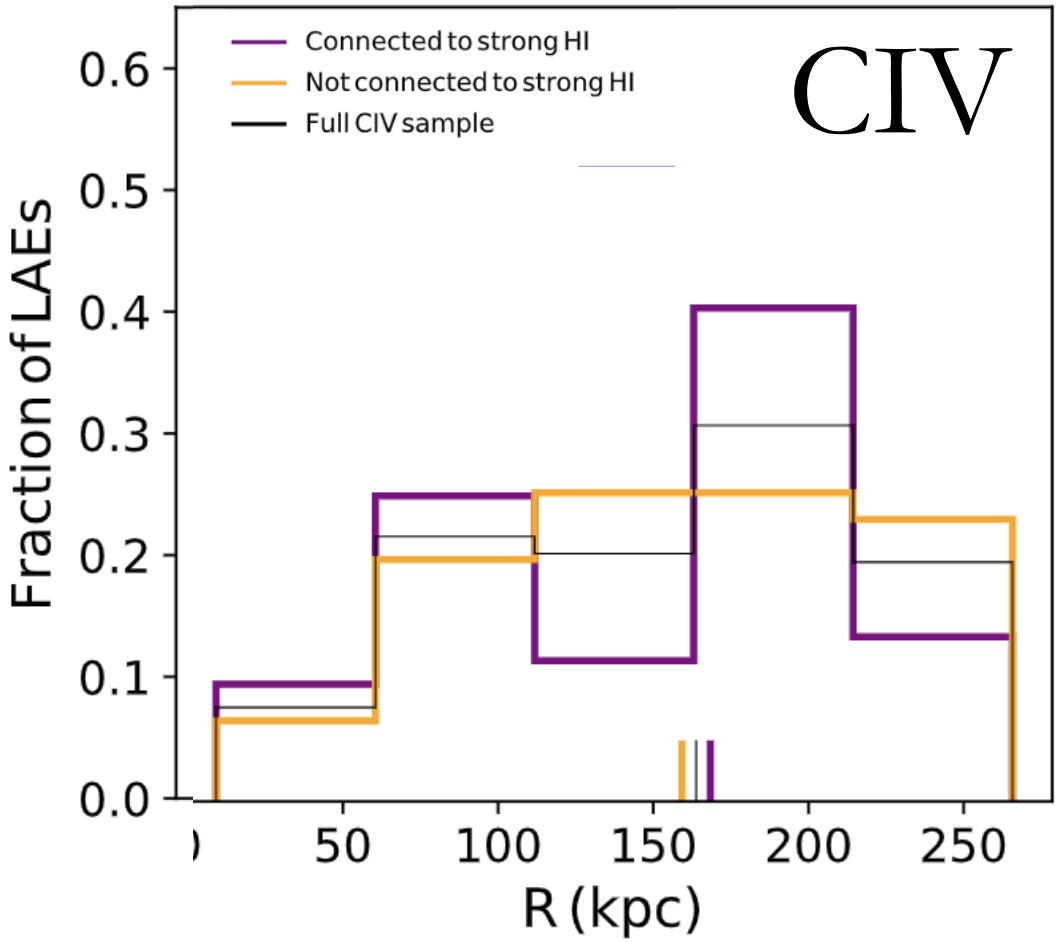


Lofthouse et al. 2023; Galbiati et al. 2023

Lower mass Lyα emitting galaxies (LAEs) trace metal enriched filaments

Associated LAEs are found typically at >2Rvir, ruling out the inner CGM as the origin of most of the observed absorption

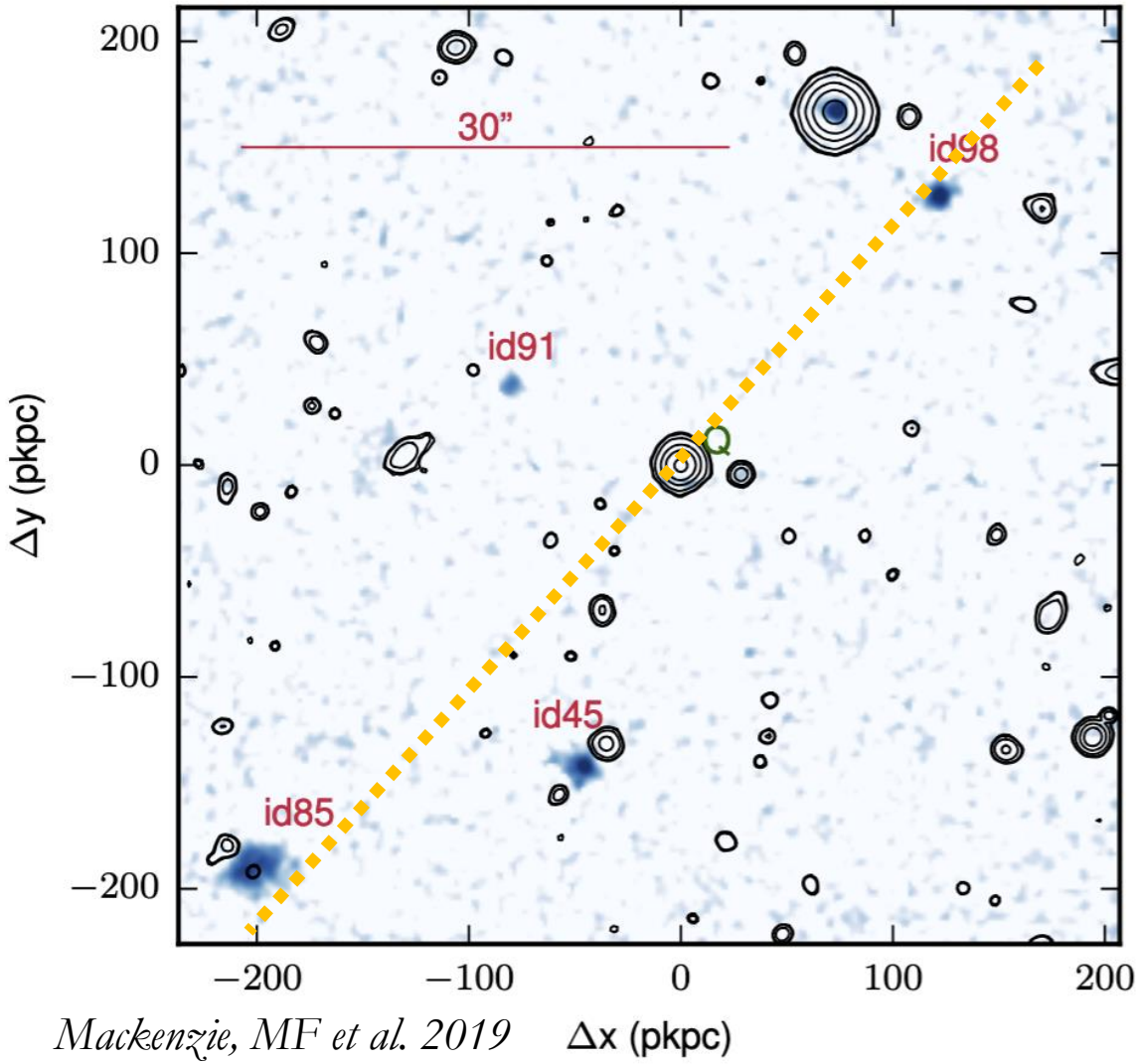




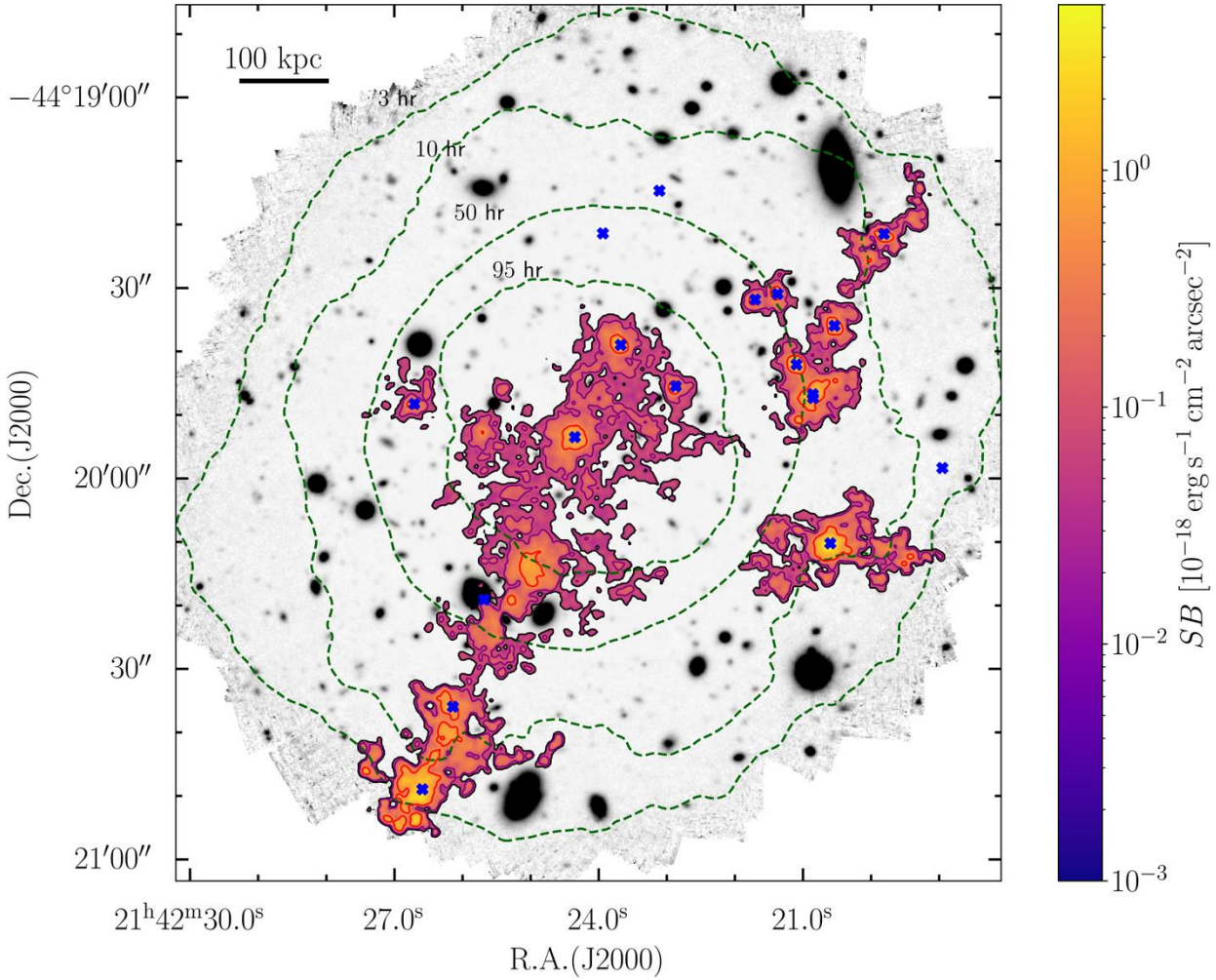
Lofthouse et al. 2023; Galbiati et al. 2023 (MAGG survey)

Lower mass Lyα emitting galaxies (LAEs) trace metal enriched filaments

The instances of multiple LAEs show preferential alignment between gas and galaxies: now also confirmed in emission



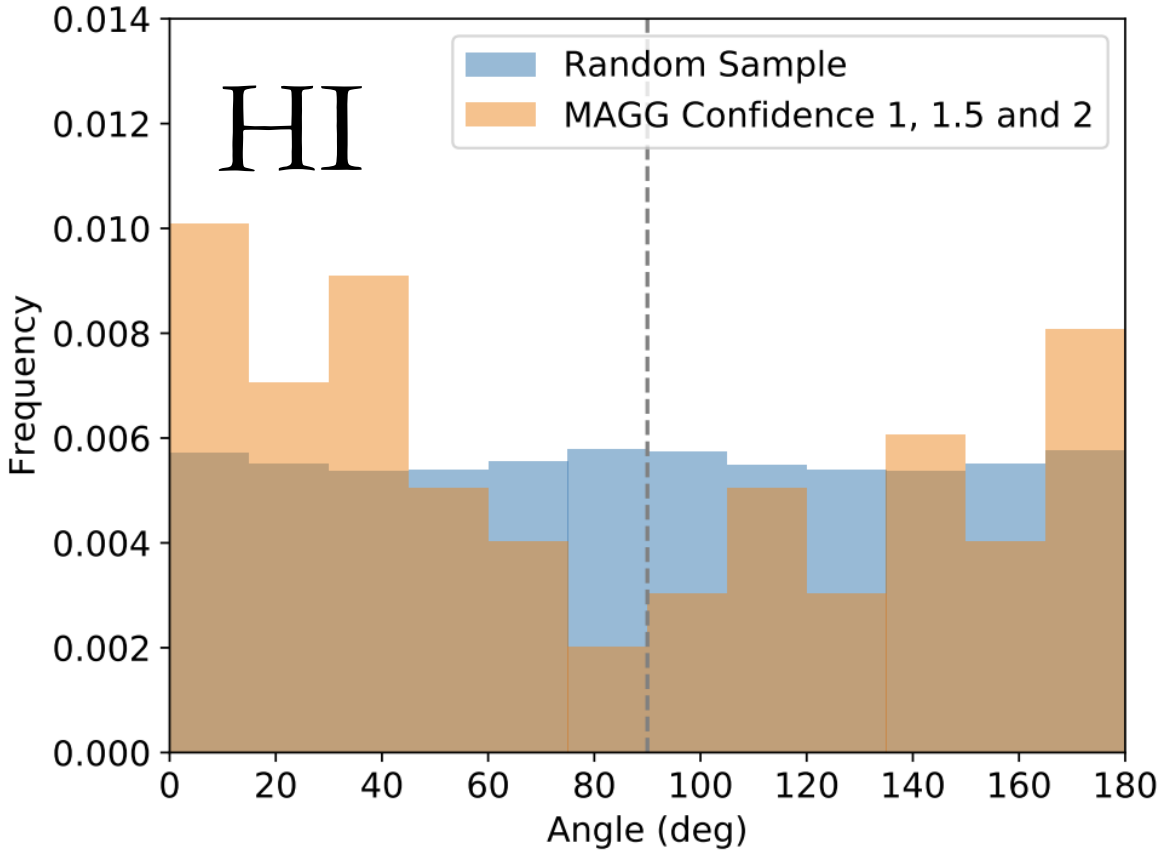
Mackenzie, MF et al. 2019

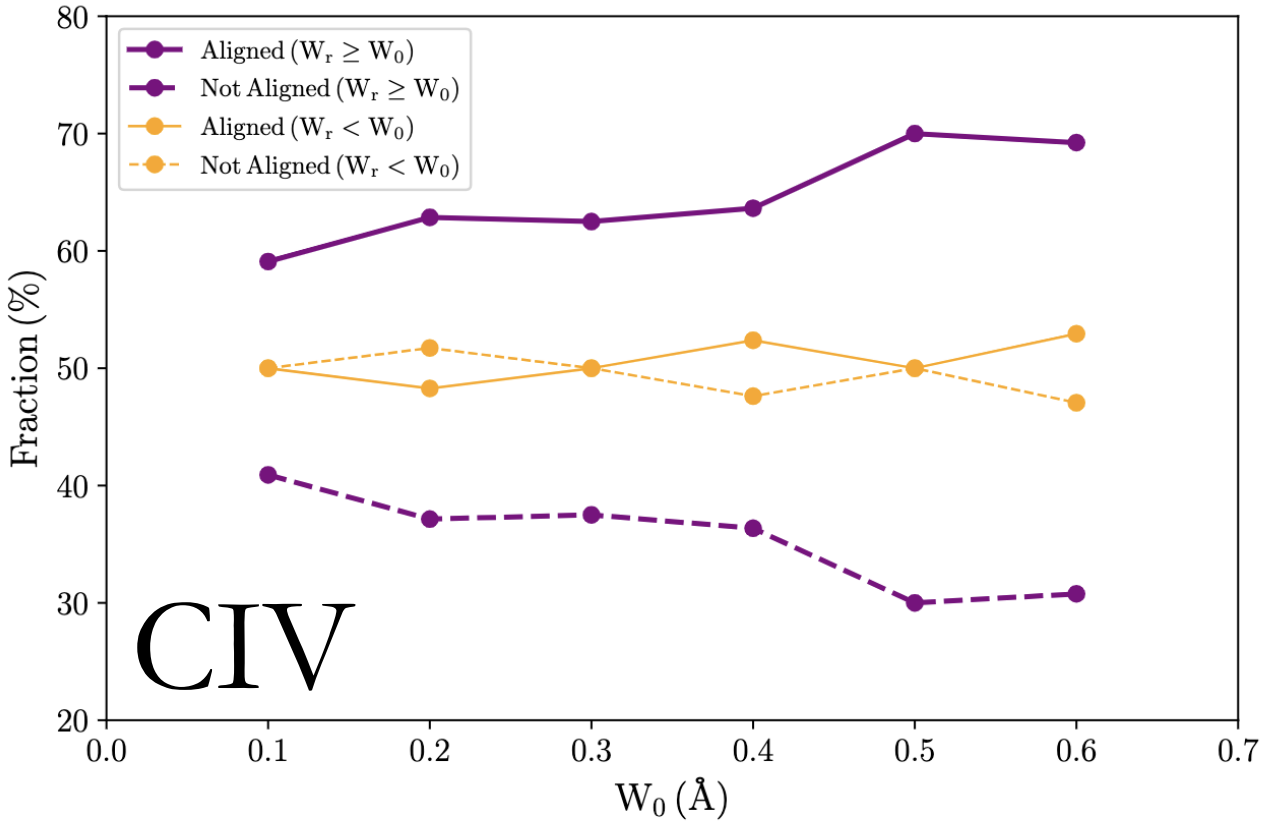


Tornotti et al. 2024b

Lower mass Lyα emitting galaxies (LAEs) trace metal enriched filaments

The instances of multiple LAEs show preferential alignment between gas and galaxies

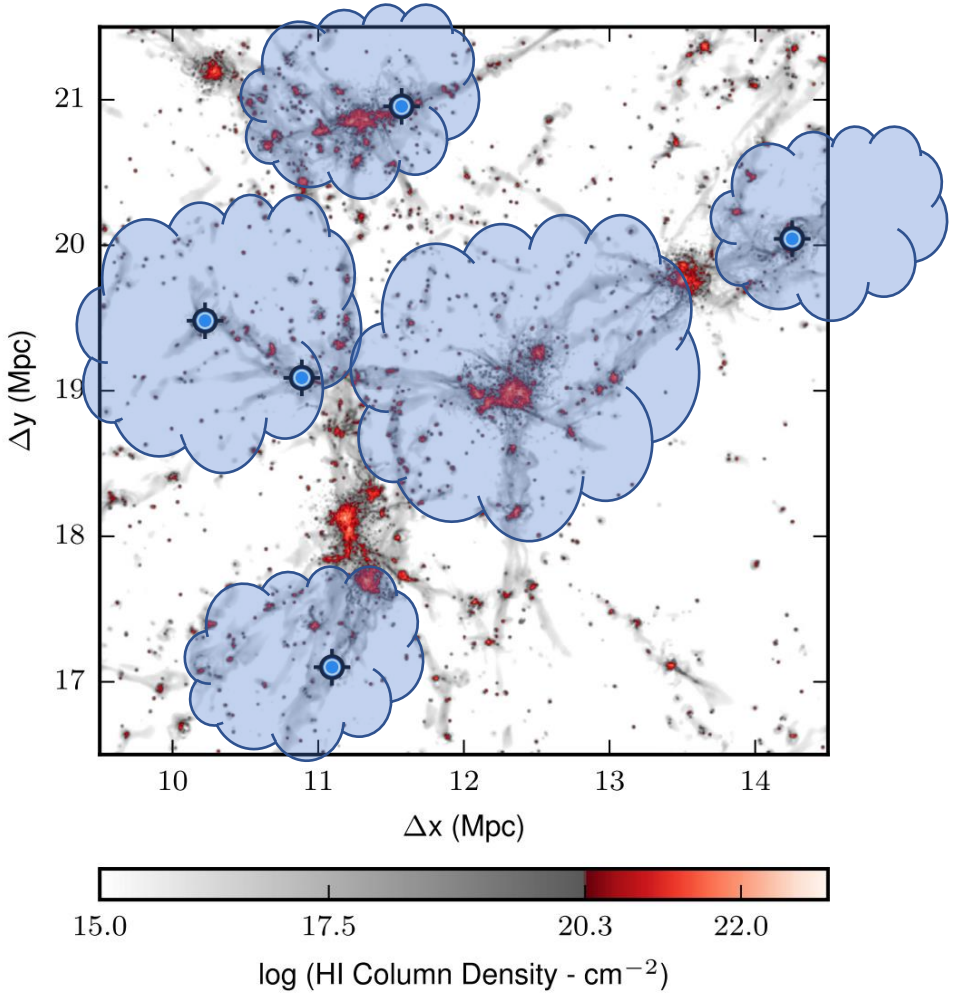




Lofthouse et al. 2023; Galbiati et al. 2023 (MAGG survey)

Lower mass Lyα emitting galaxies (LAEs) trace metal enriched filaments

The MAGG survey with >1,000 LAEs and >300 absorption lines reveals gas-rich and enriched filaments connecting multiple LAEs, and "older" enriched pockets of the IGM far from galaxies



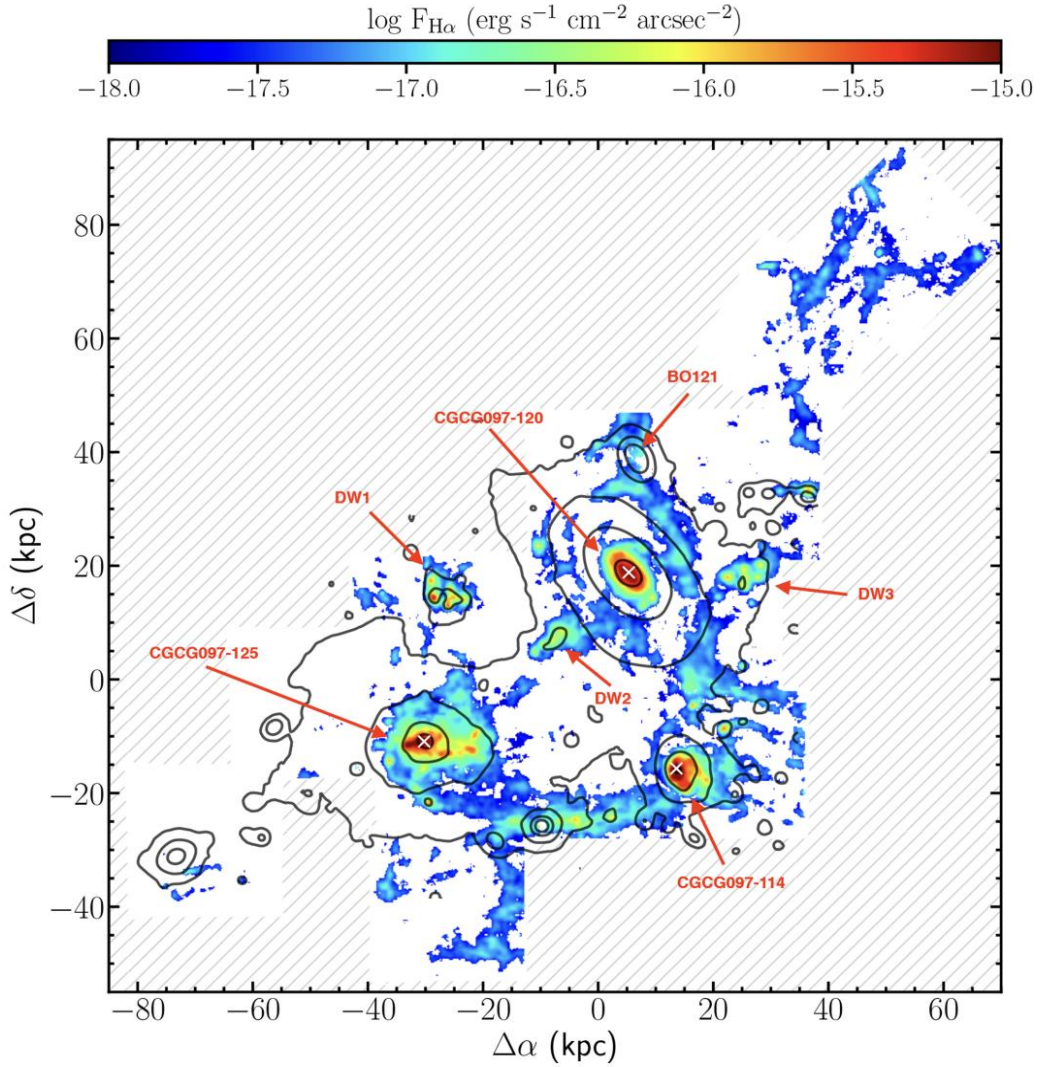
Lofthouse et al. 2023
Galbiati et al. 2023, 2024

Key contribution #3

Bridge the gap between galaxy evolution studies of the environment and the CGM community

The galaxy environment modifies the properties of the CGM

The combined MAGG, MUDF, and QSAGE surveys find a more extended metal cross-section in group galaxies. The gas environment near star-forming galaxies knows about the environment!



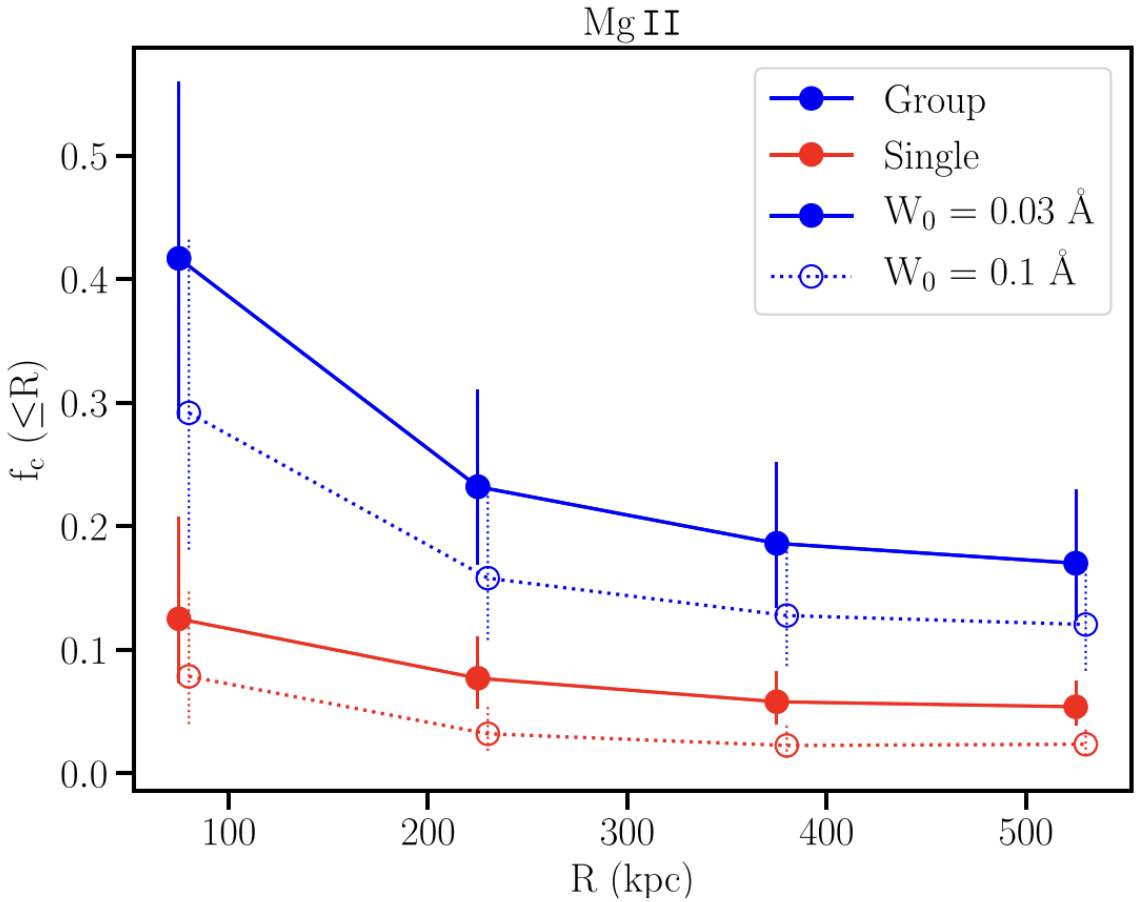
Lofthouse et al. 2023; Galbiati et al. 2023

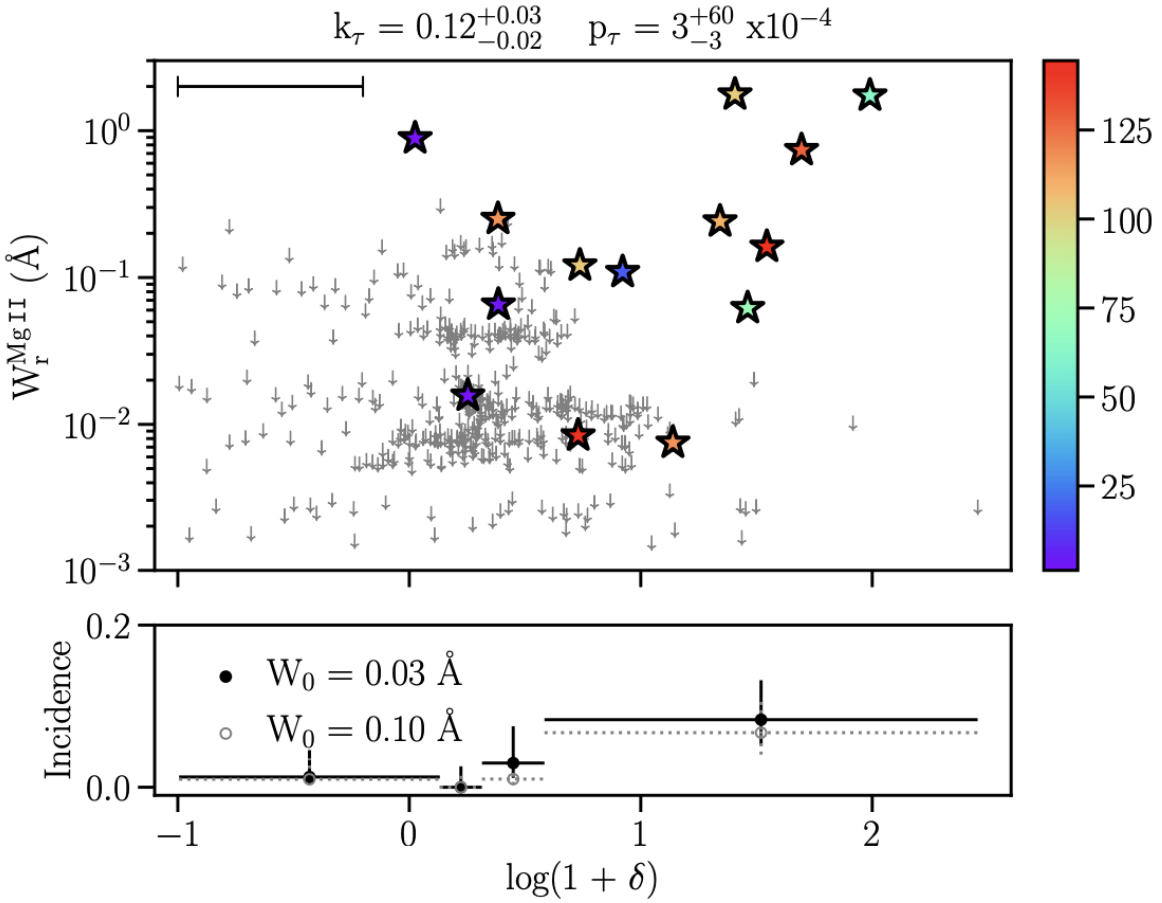
Dutta et al. 2020, 2022

Fossati et al. 2019

The galaxy environment modifies the properties of the CGM

At z~0.5-1.5, MgII absorption in group galaxies is ~2-3 times more prevalent/stronger than in isolation

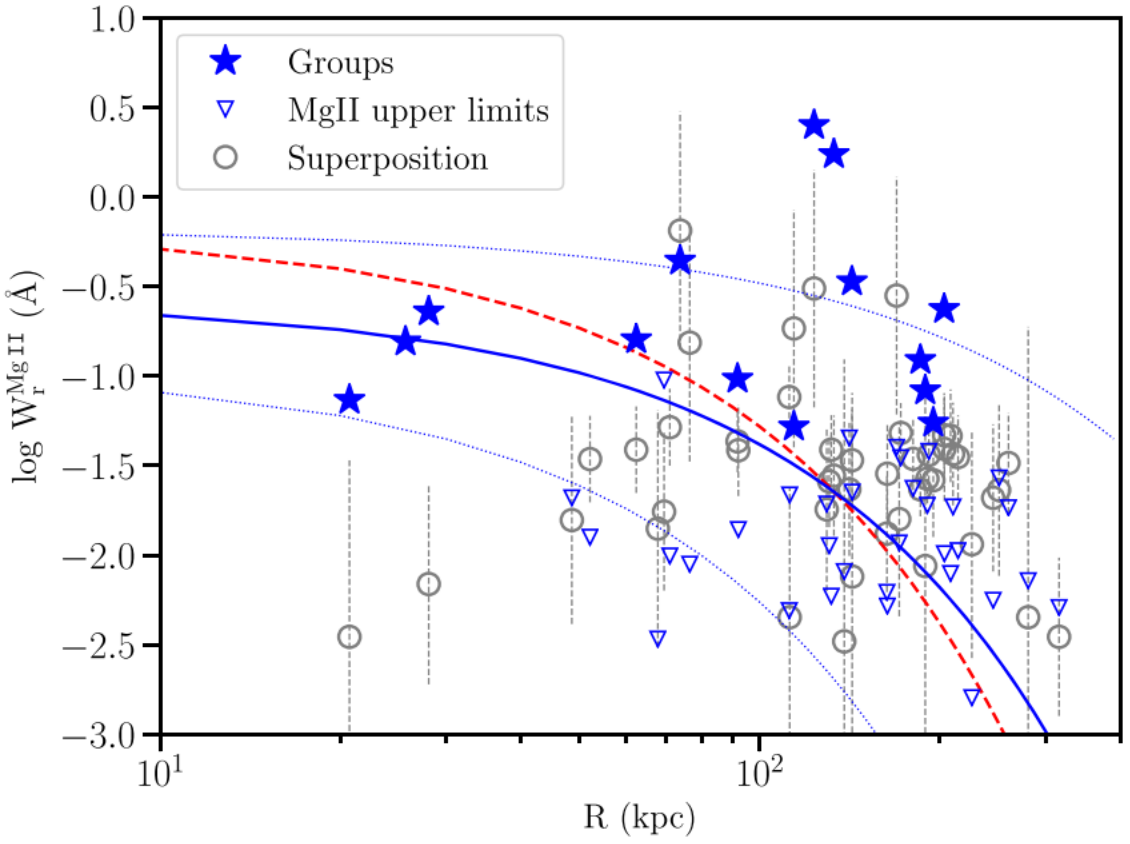


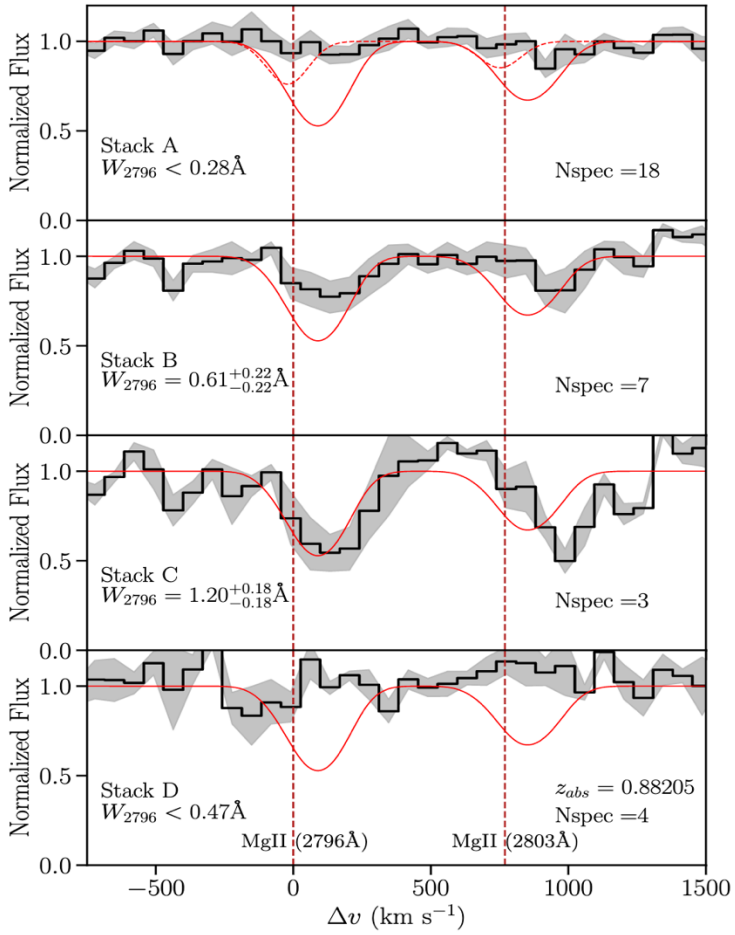


Dutta et al. 2020, 2022 (MAGG survey)

The galaxy environment modifies the properties of the CGM

A simple superposition model accounts for some but not all strong absorbers in groups. Deep stacks in MUDF hint that the CGM of group galaxies is perturbed.





All

Aligned with galaxies

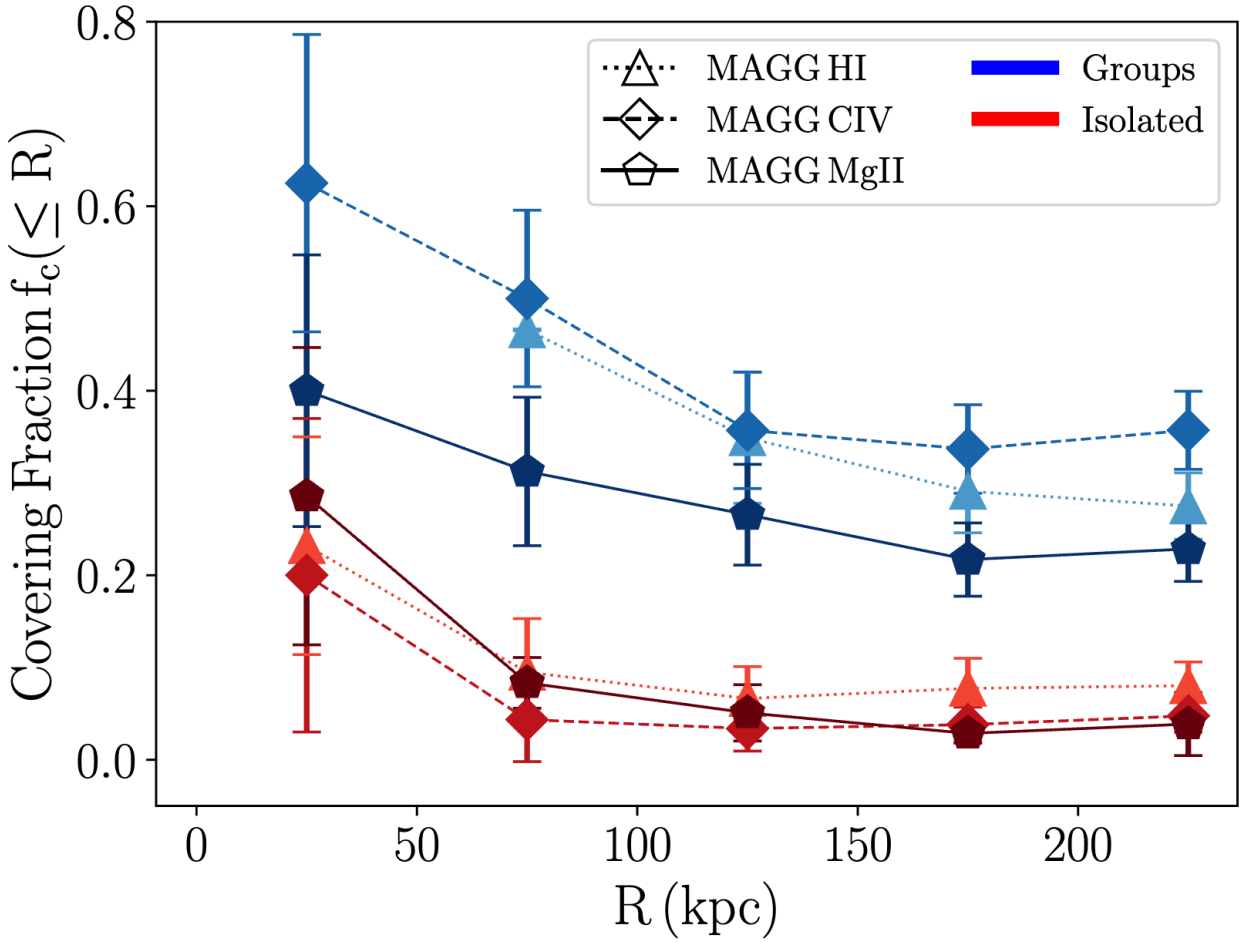
With MgII detections

Intragroup

Dutta et al. 2020, 2022 (MAGG survey)
Fossati et al. 2019 (MUDF survey)

The galaxy environment modifies the properties of the CGM

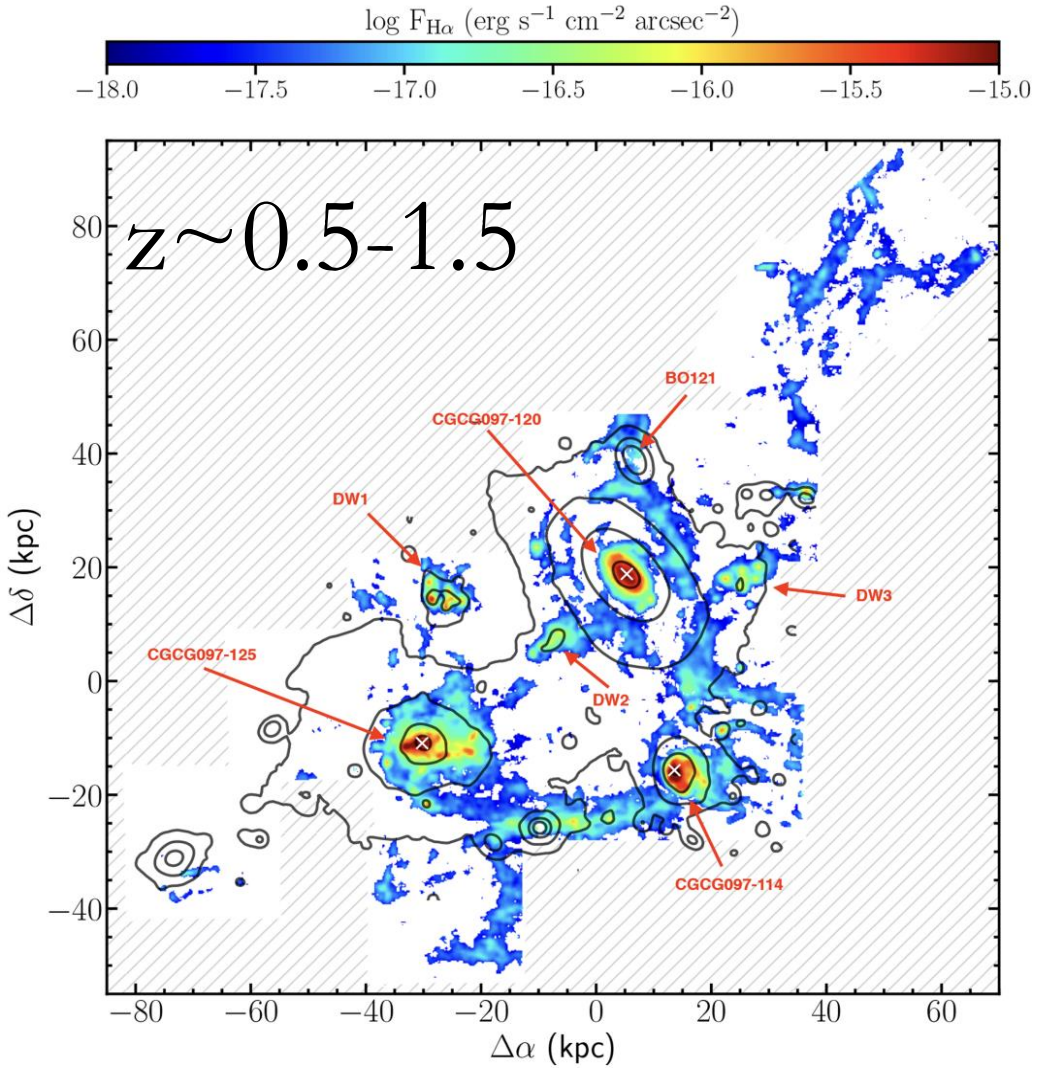
At z>3: HI, MgII, and CIV absorption are more prevalent in groups than in isolated galaxies

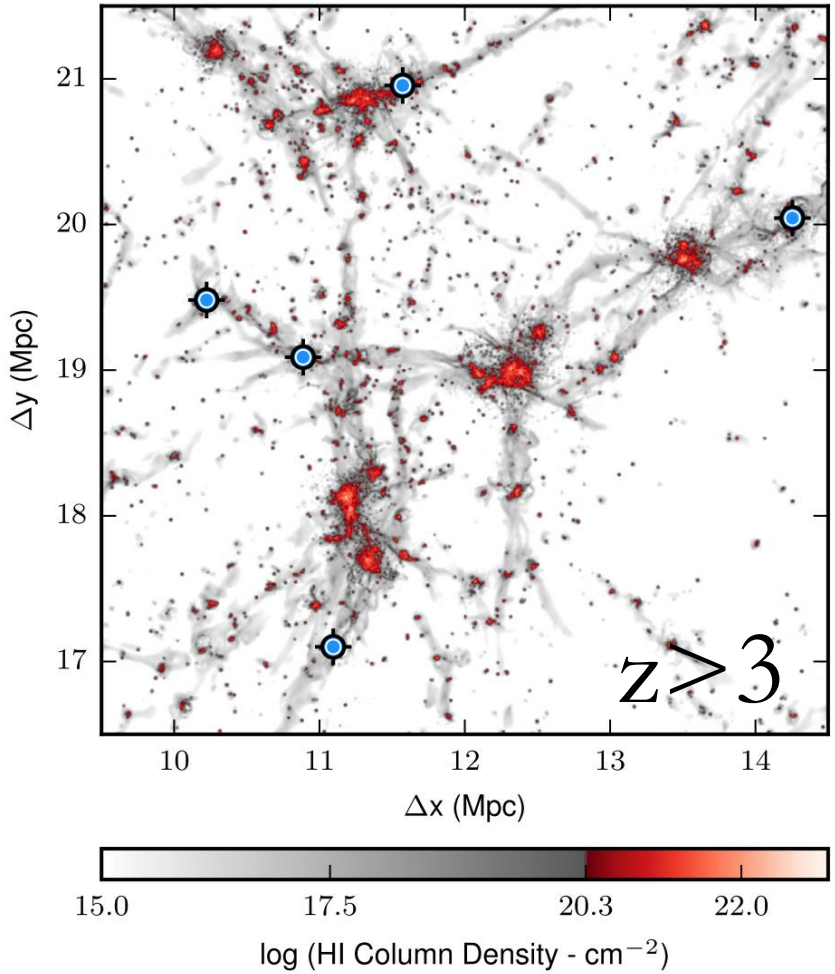


Lofthouse et al. 2023; Galbiati et al. 2023, 2024 (MAGG survey)

The galaxy environment modifies the properties of the CGM

The combined MAGG, MUDF, and QSAGE surveys find a more extended metal cross-section in group galaxies. Modelling effort needed to unveil the origin of this excess.





Three key contributions of MUSE in IGM/CGM studies

1. Measure the gas (hydrogen plus metals) distribution outside galaxies in emission between z~0-4

Map the hydrogen distribution in halos and filaments, measure the metallicity of the CGM, and constrain outflow models with novel observations.

2. Link the properties of the CGM to galaxies over >100x larger samples

LAEs reside in enriched HI filaments, with the presence of more diffuse enriched gas pockets.

3. Bridge the gap between galaxy evolution studies of the environment and the CGM community

At all redshifts probed, the CGM in group galaxies is more extended, suggesting environmental perturbation.

← *MUDF papers*

MAGG papers →

Ten incredible years of CGM/IGM science with MUSE… and more to come!

Thanks to Roland, the MUSE team, and ESO for bringing us out of the dark ages of CGM studies!