The gas environment of galaxies across 10 billion years

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European Research Council
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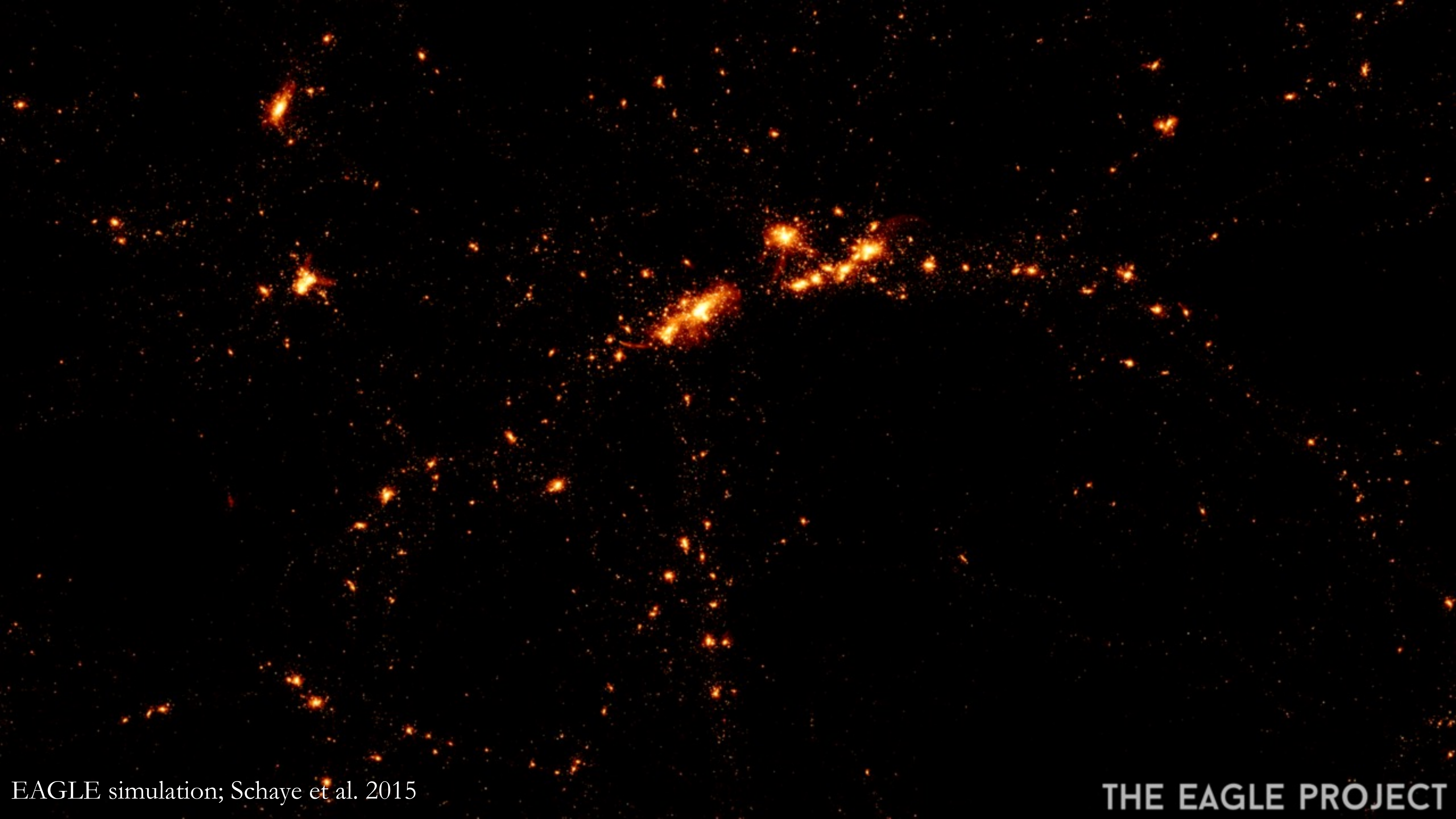
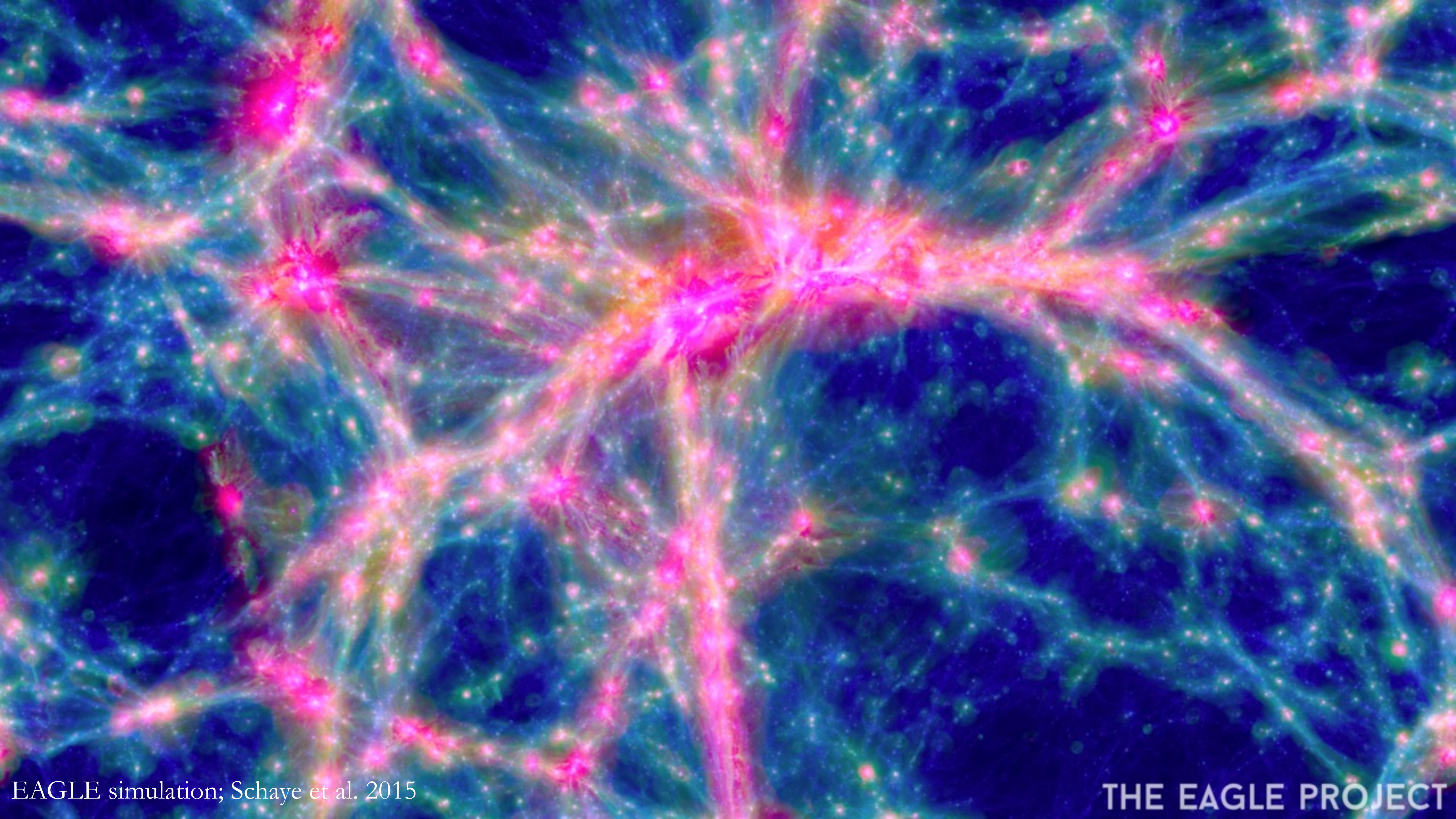
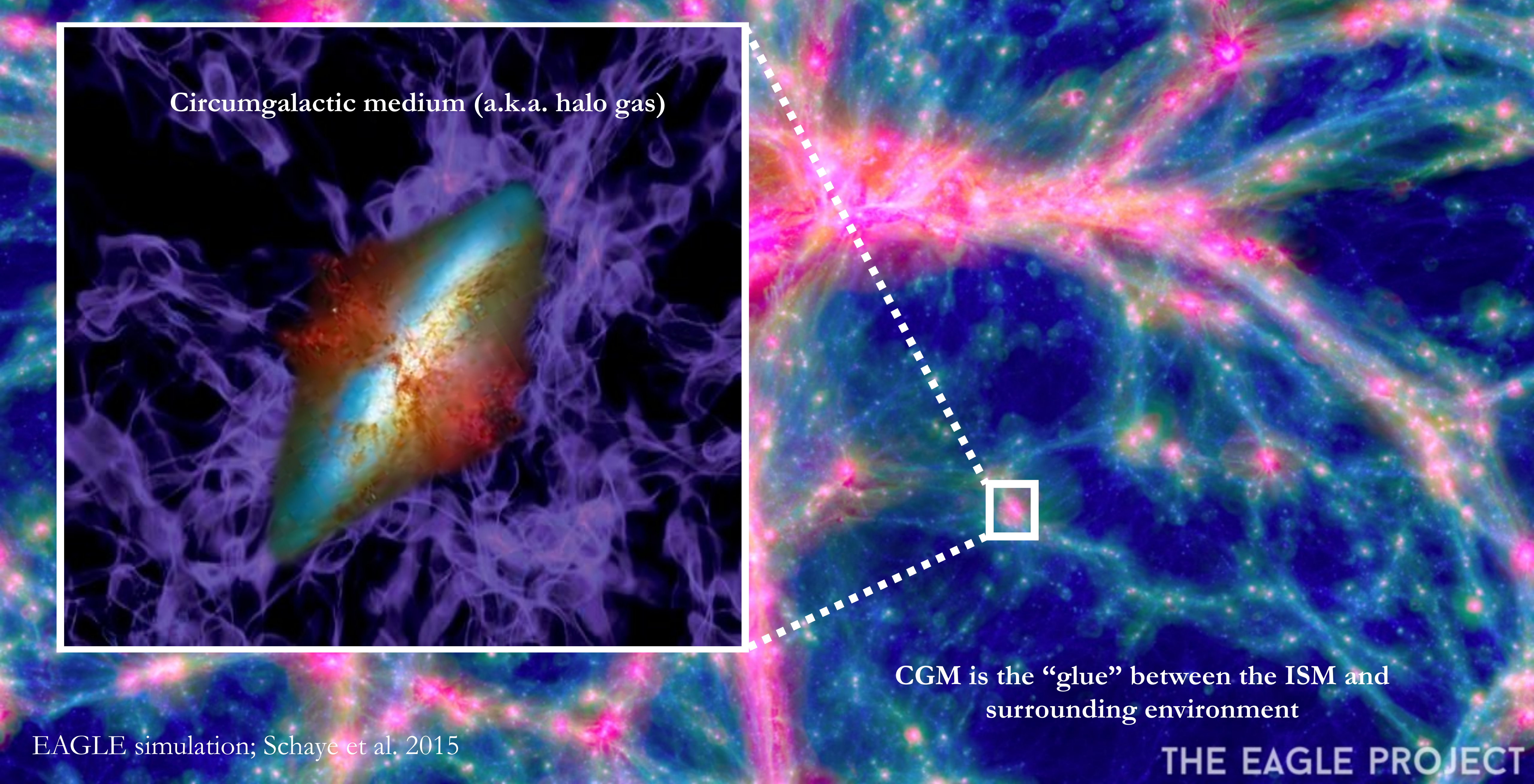


EAGLE simulation; Schaye et al. 2015



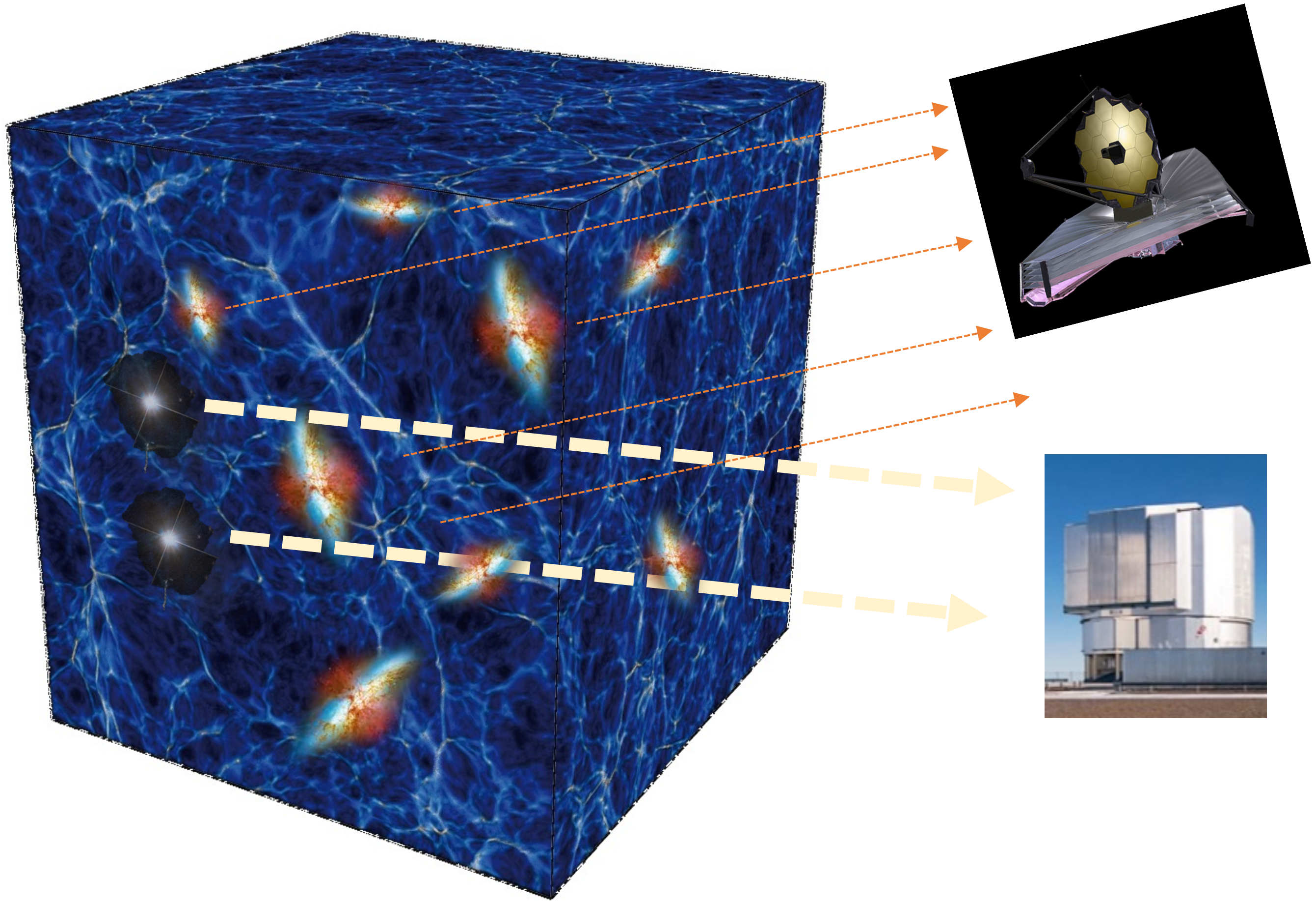
EAGLE simulation; Schaye et al. 2015

The baryon cycle through the circumgalactic medium



Linking gas and galaxies with redshift

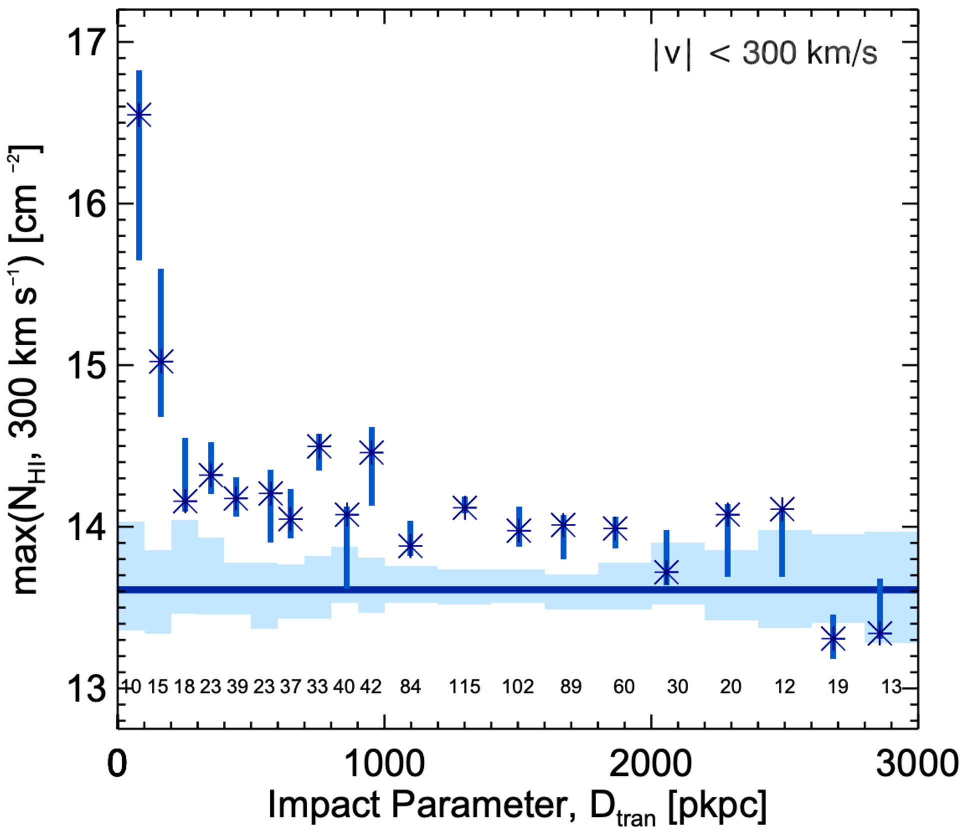
We want to constrain observationally the connection between galaxies and their IGM/CGM combining dense spectroscopic galaxy surveys with quasar absorption spectroscopy.



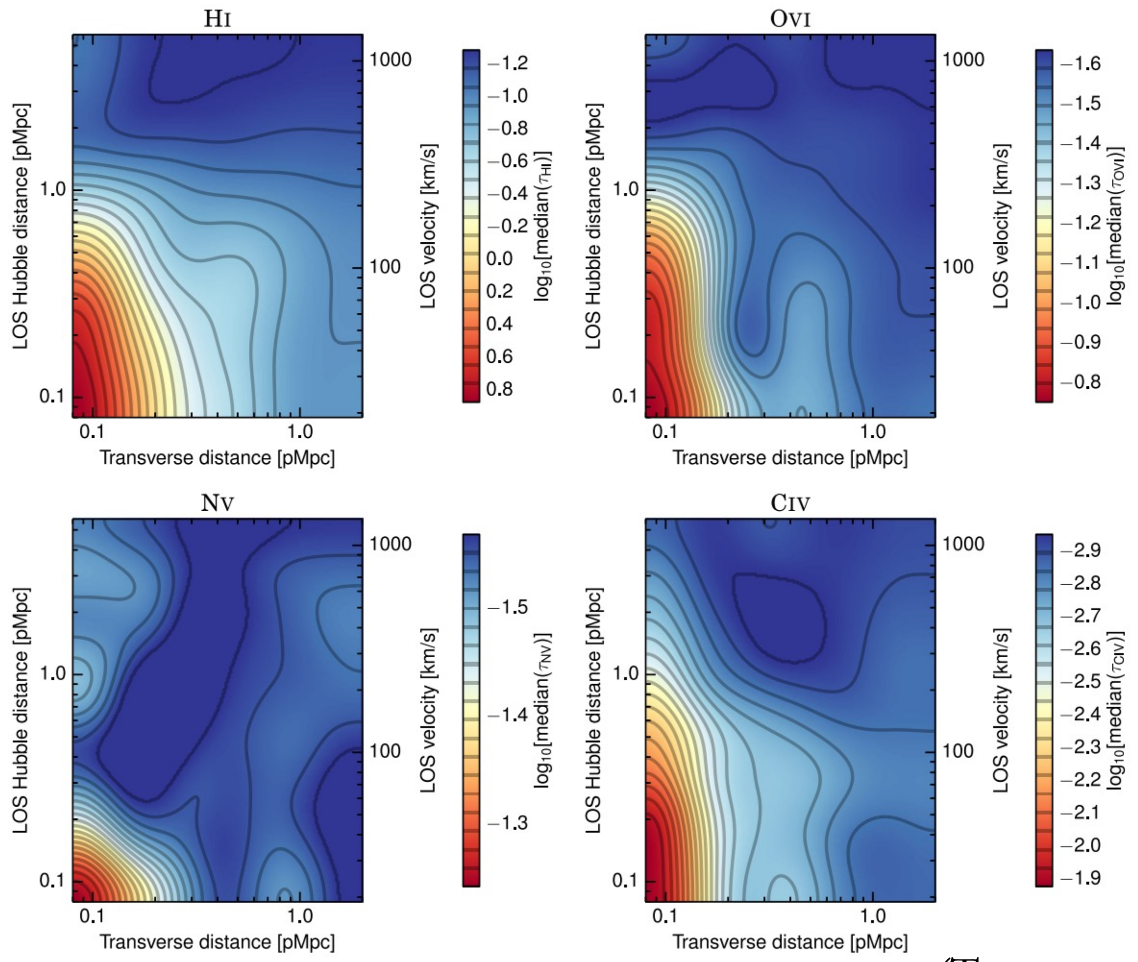
Multi-object spectrographs have paved the way

Targeted surveys to find galaxies associated to absorbers in the inner CGM (<20-30kpc)

Hydrogen and metals around galaxies in the KBSS – See also VLT-LBG survey by Bielby et al. 2011



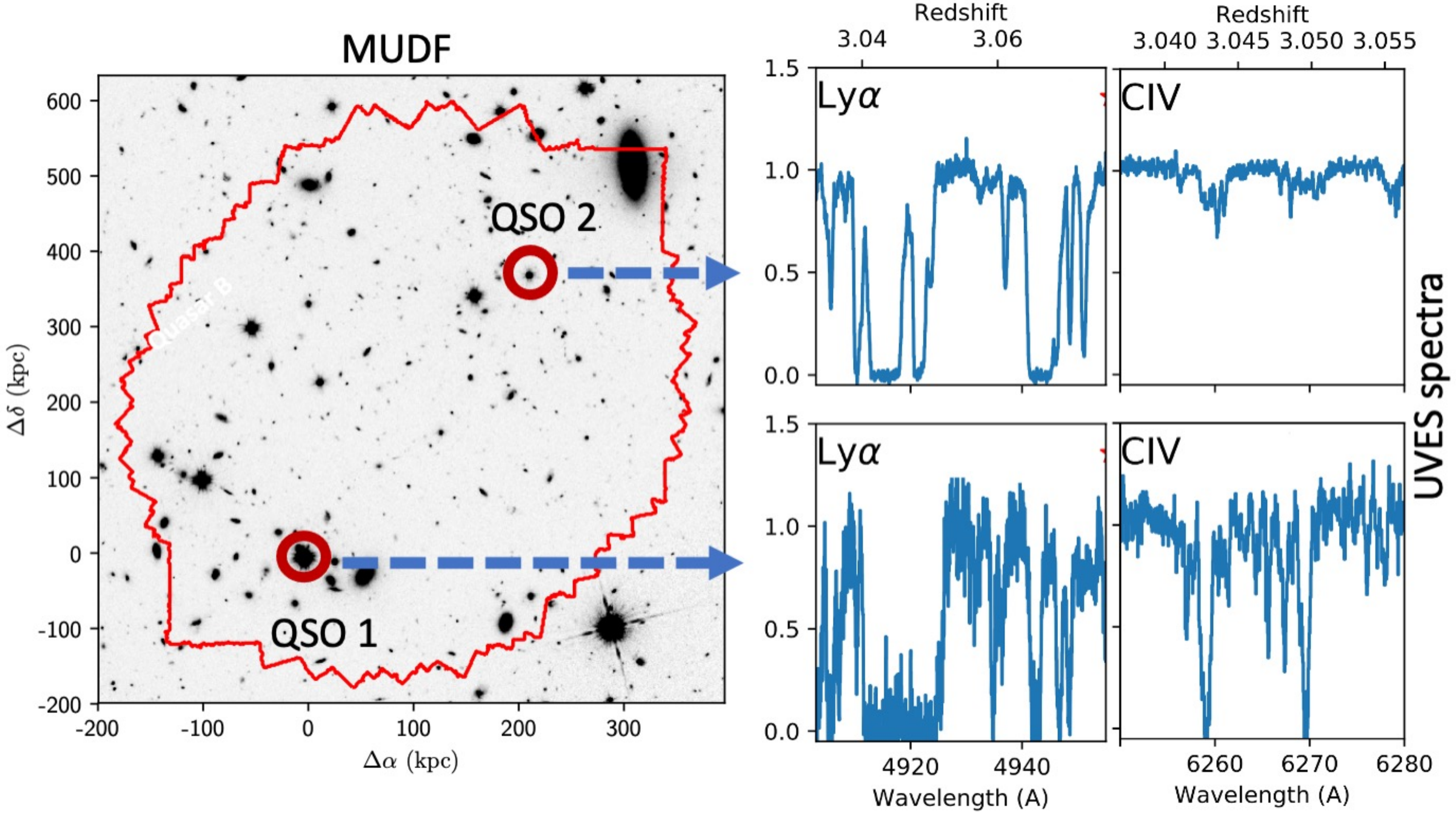
(Rudie et al. 2012)



(Turner et al. 2014)

IFUs at 8m telescopes are enabling the next 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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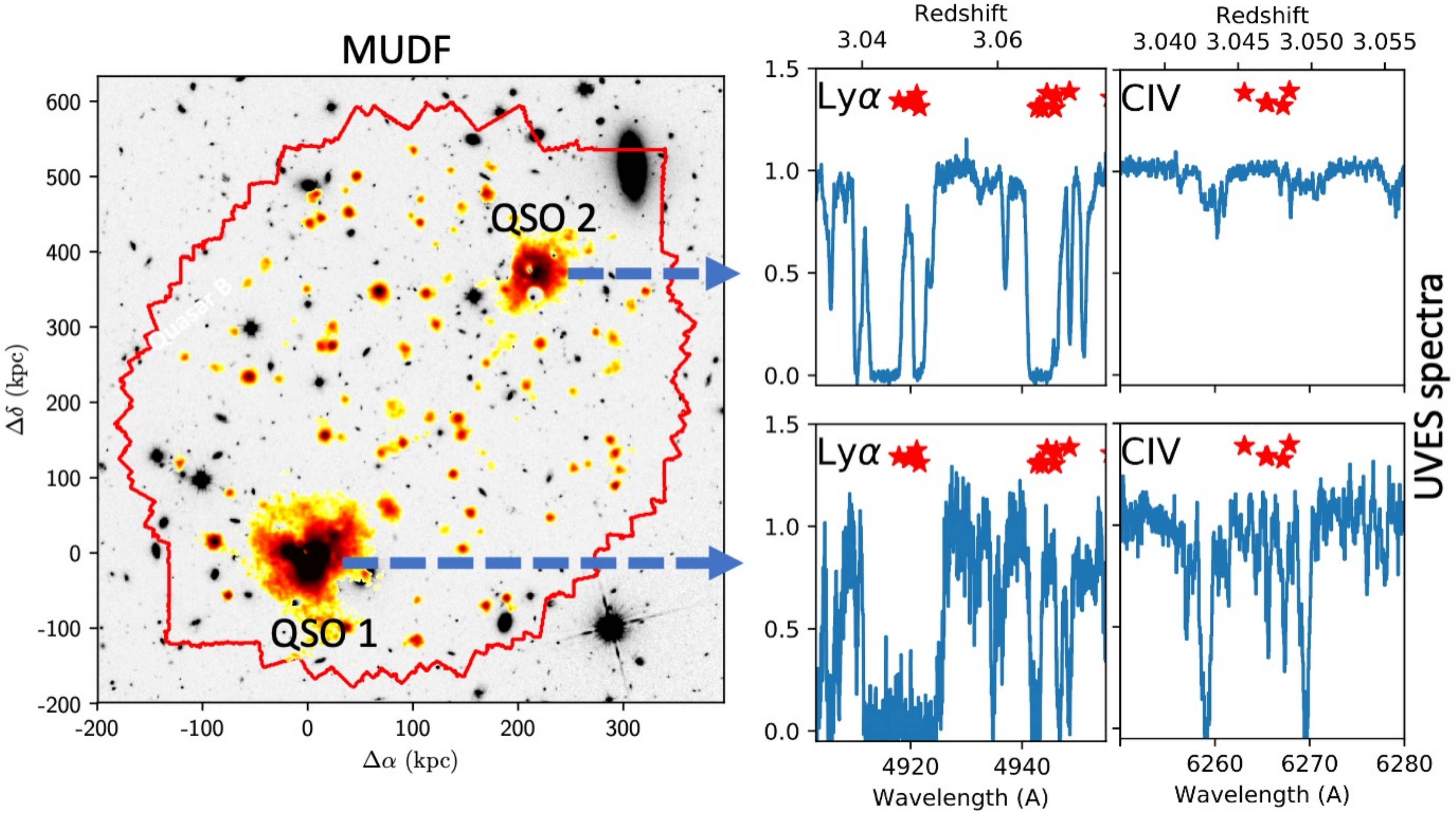
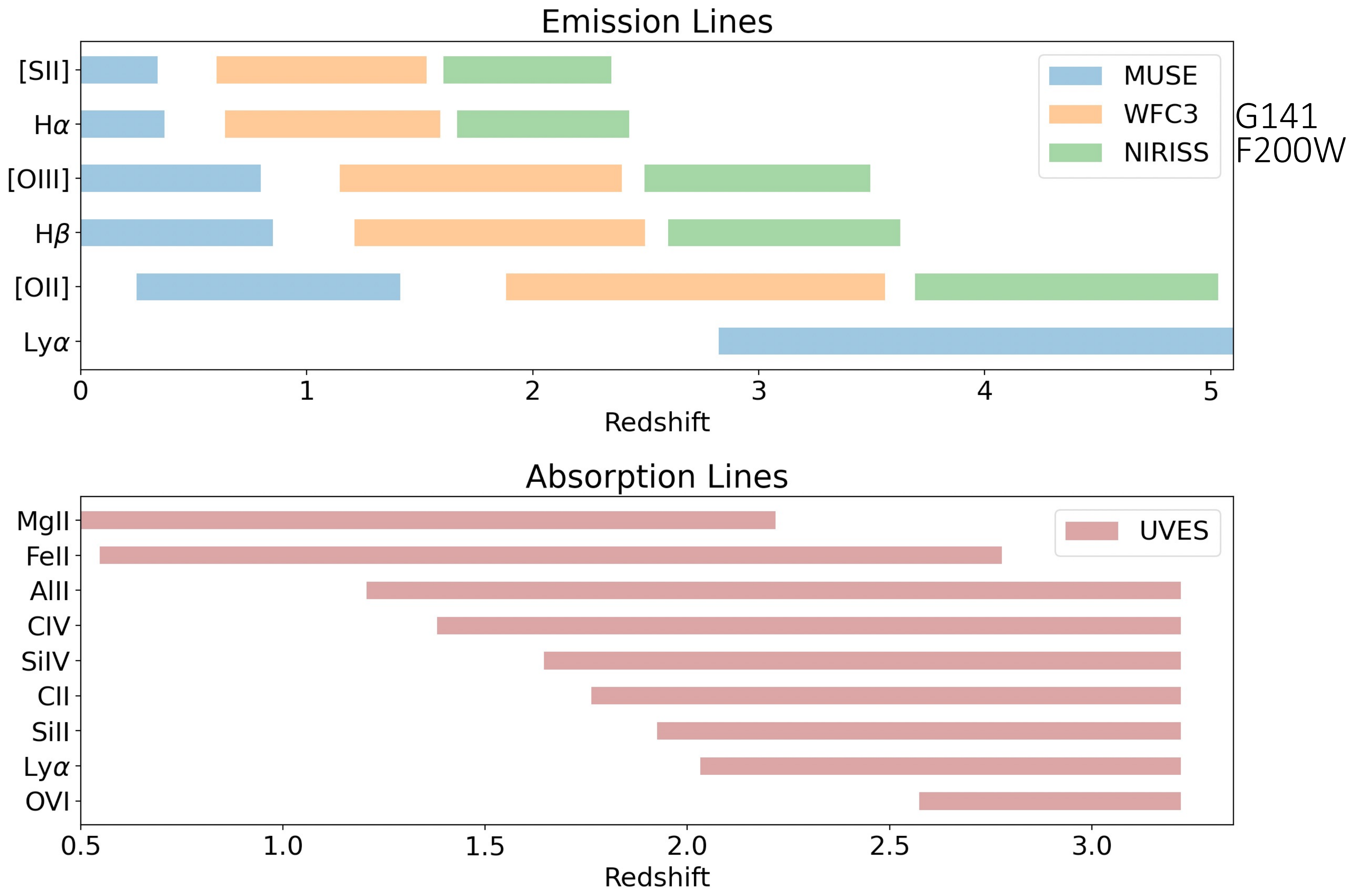
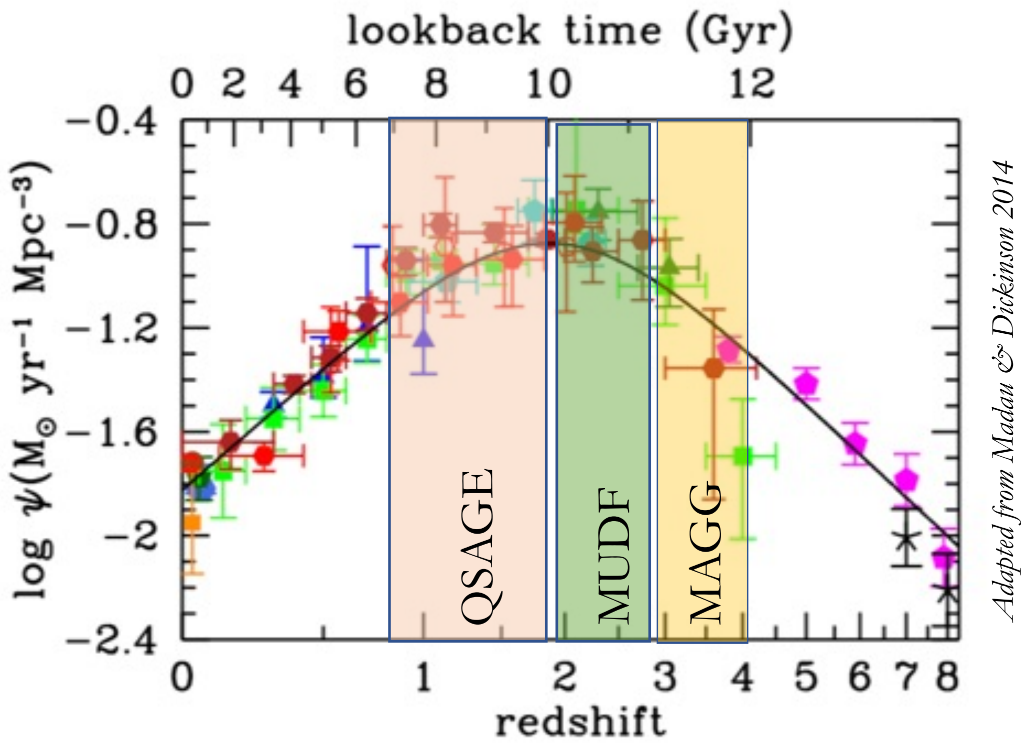


IFUs at 8m telescopes are enabling the next leap

Thanks to the ability to scan in redshift both quasar spectra and data cubes, we can access multiple tracers as a function of redshift both for intervening galaxies and the quasars themselves



The tools: large surveys at large telescopes



MF et al. 2016a; 2016b, 2017b
Lusso, MF et al. 2019
Mackenzie, MF et al. 2019
Lofthouse, MF et al. 2019,2022
Fossati et al. 2019,2020, 2021
Dutta, MF, et al. 2020,2021,2023
Galbiati, MF, et al. 2022

MAGG: a MUSE analysis of gas around galaxies

Medium-depth (5h) observations of 28 z>3.5 quasars with ~70 intervening DLAs/LLSs, 200 CIV, and 114 MgIIs

MUDF: the MUSE + HST ultra-deep field

Ultra-deep MUSE (250h) and HST/WFC3 G141 (90 orbits) observations of a z~3.2 quasar pair with 25 intervening absorbers

QSAGE: Quasar Sightline and Galaxy Evolution survey

Medium-deep HST/WFC3 G141 (8 orbits/quasar) observations of 12 z > 1.2 quasars with MUSE and UV+optical spectroscopy

Linking gas and galaxies with IFUs at z~0.5-4.5: take-home points

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

Evidence of gas-rich and enriched filaments connecting multiple LAEs, and "older" enriched pockets of the IGM far from galaxies

2. The galaxy environment modifies the properties of the CGM

Evidence of more extended metal cross section in group galaxies versus more isolated systems

3. Newly found ability to trace both hydrogen and metals in emission in the IGM/CGM

Detection of cosmic web filaments, and enriched halos of quasars and normal star-forming galaxies

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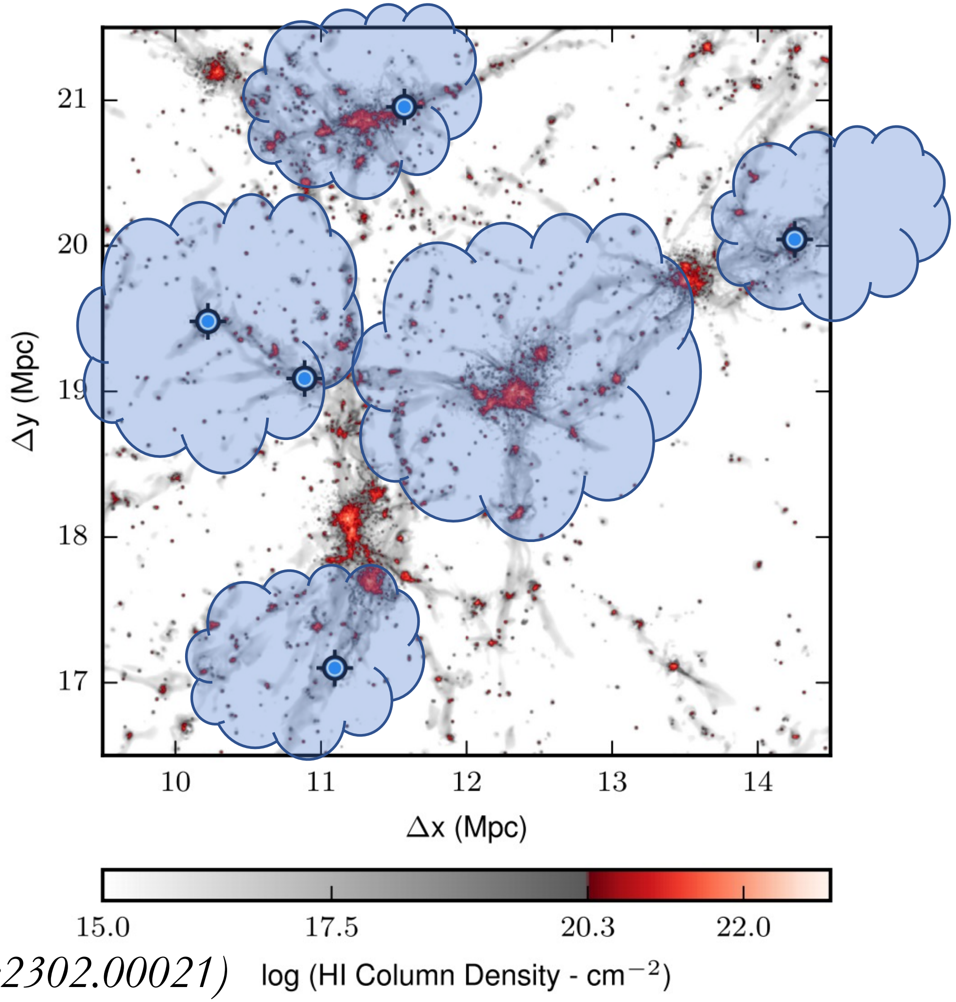
Our MAGG survey with >1,000 LAEs and >300 absorption lines reveals gas-rich and enriched filaments connecting multiple LAEs, and "older" enriched pockets of the IGM far from galaxies

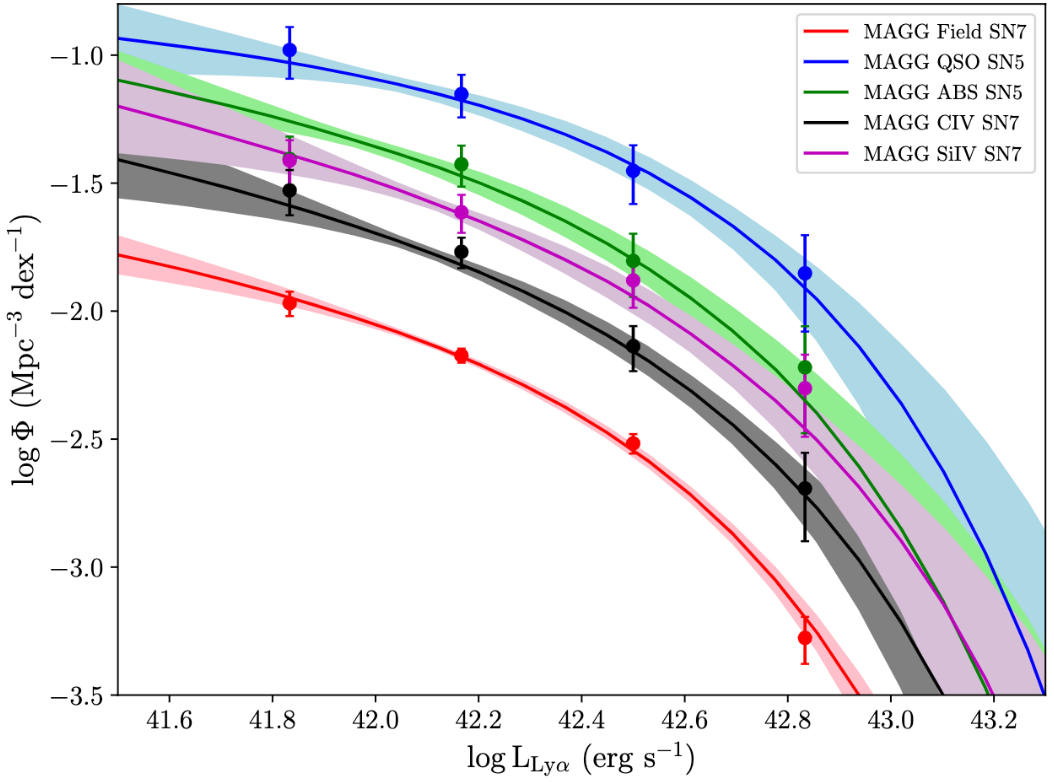


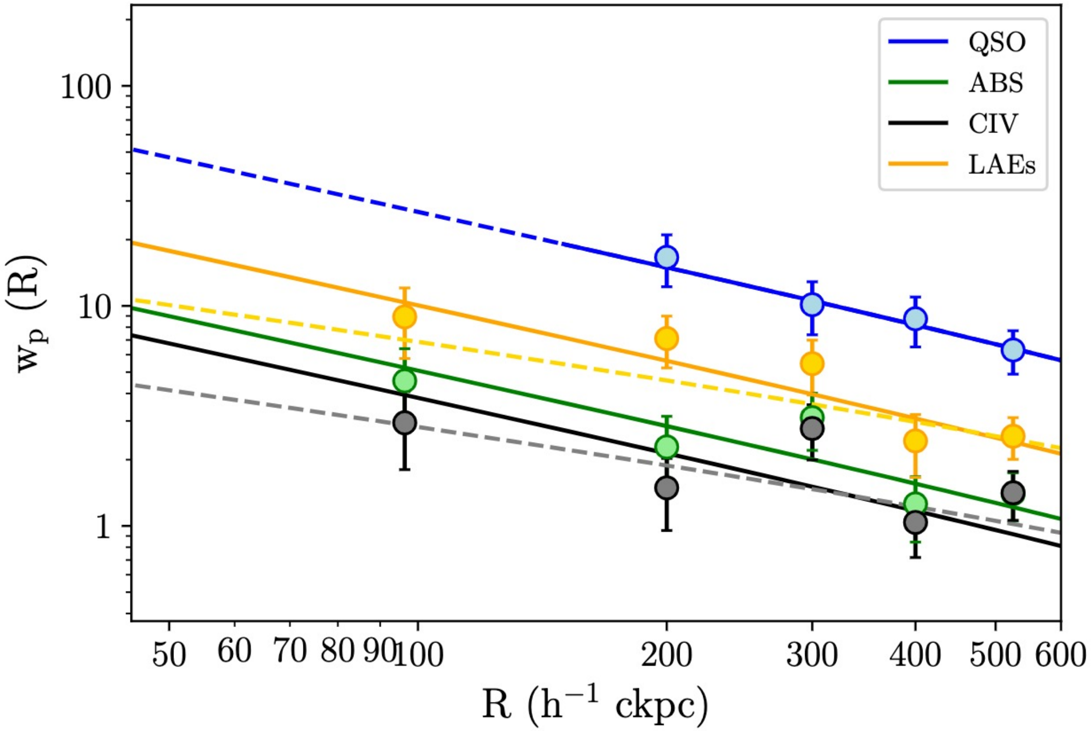
Lofthouse et al. 2023

Galbiati et al. 2023, MNRAS submitted (arXiv:2302.00021)

1. 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.

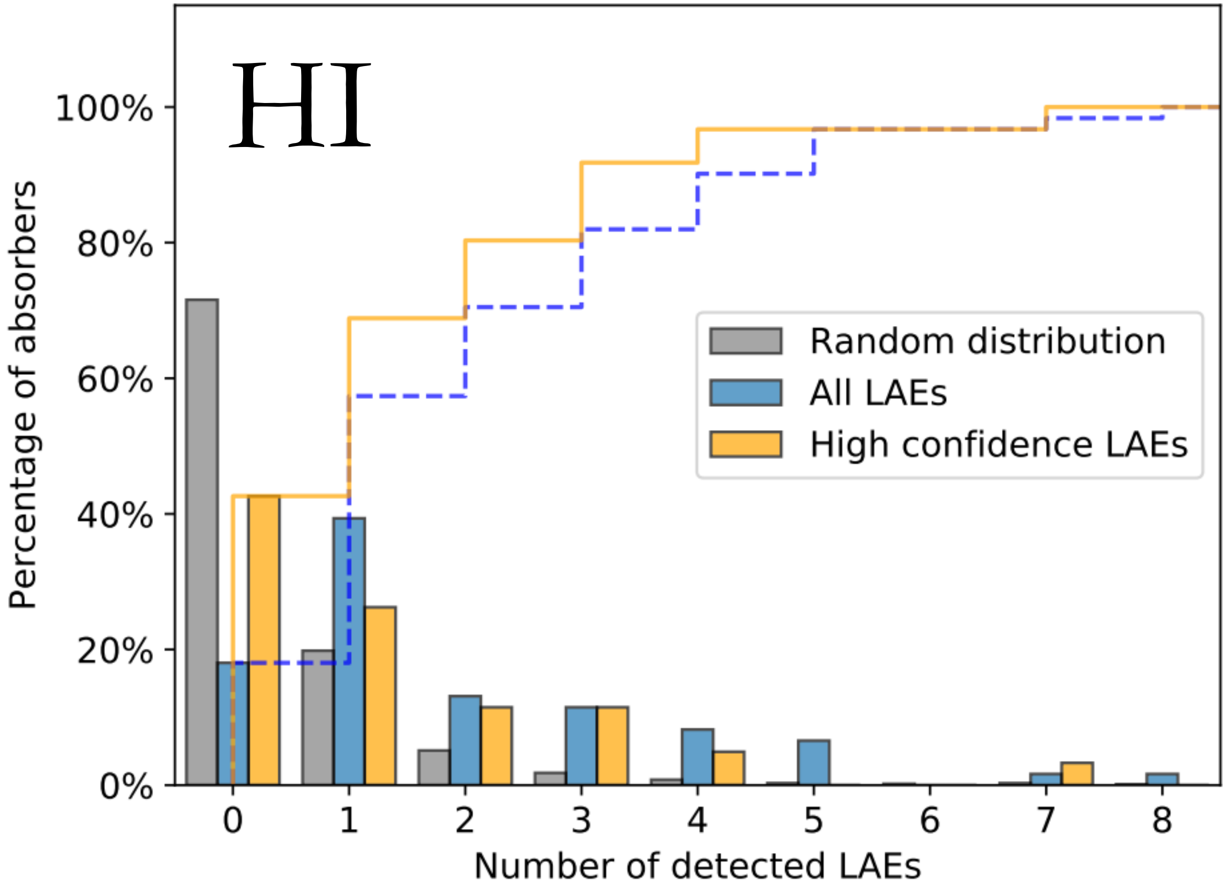


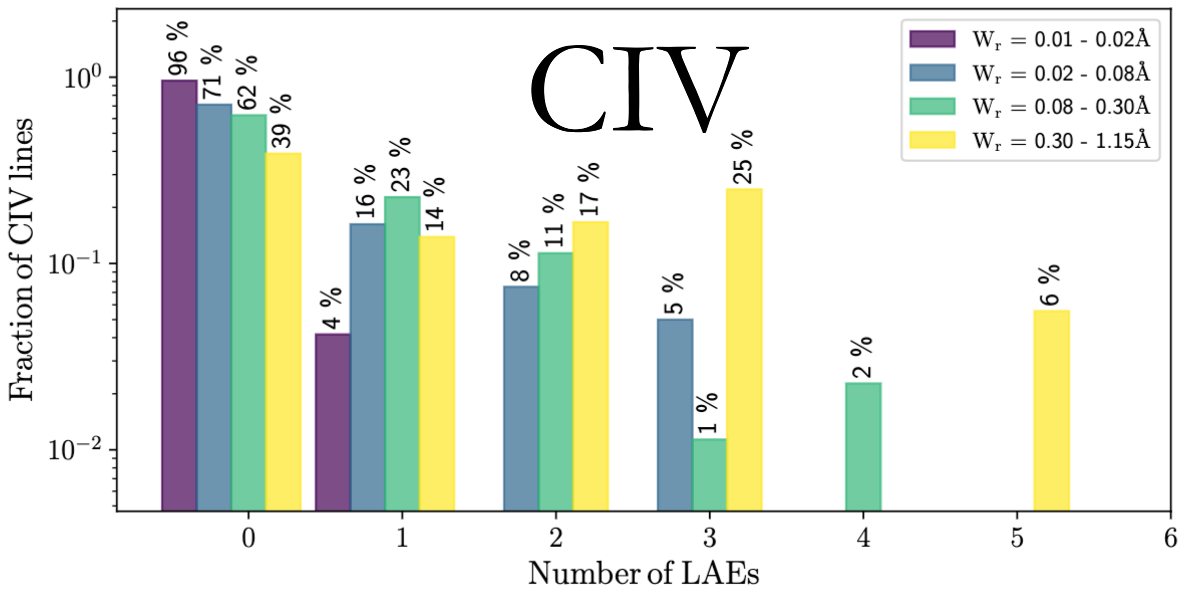


Lofthouse et al. 2023; Galbiati et al. 2023; Fossati et al. 2021

1. 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

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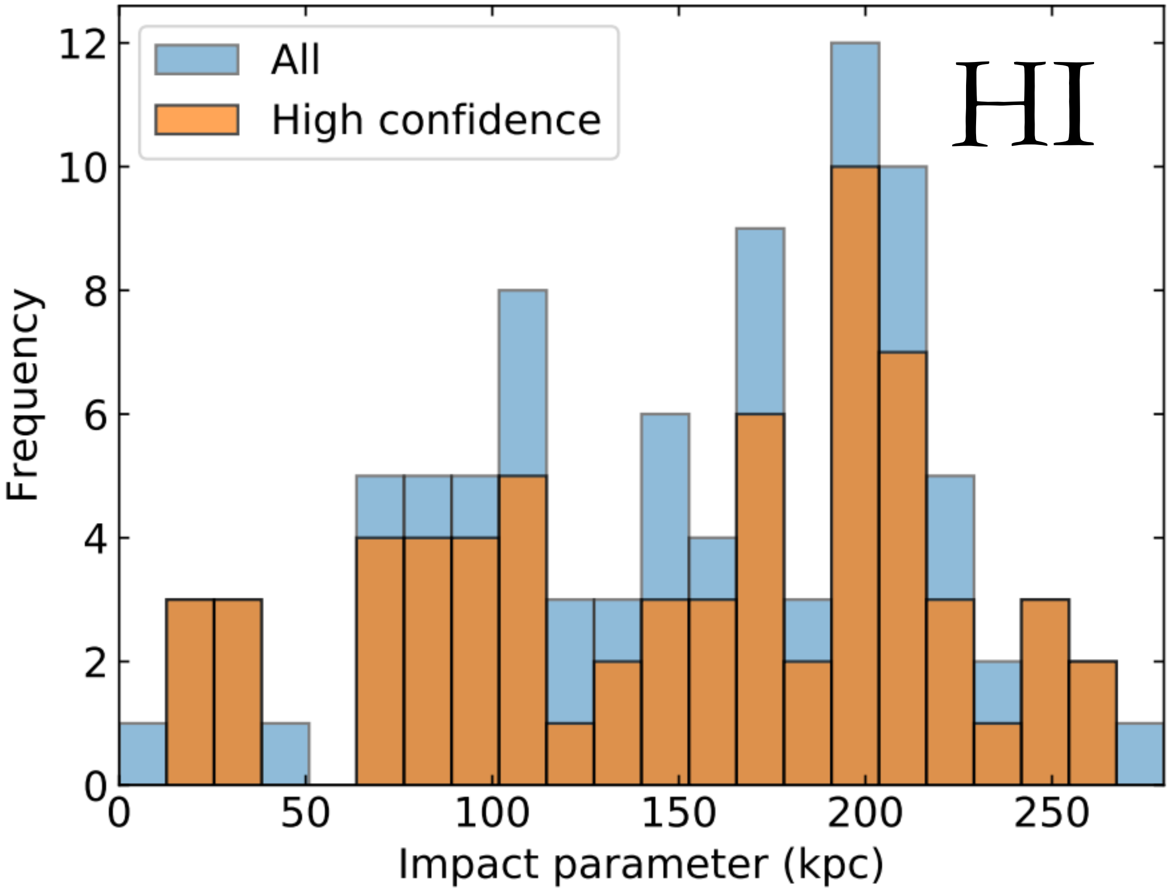
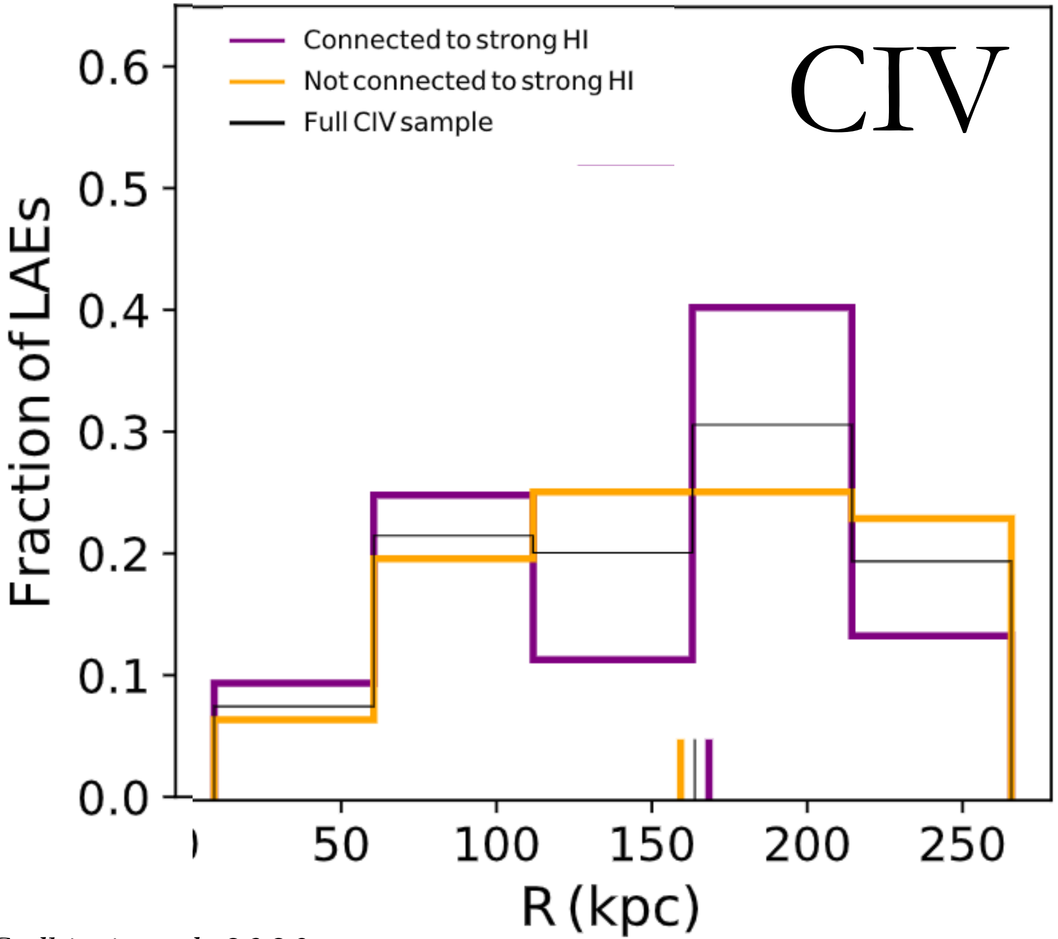
Associated LAEs are found typically at >2Rvir, ruling out the inner CGM as the origin of most of the observed absorption





Lofthouse et al. 2023; Galbiati et al. 2023

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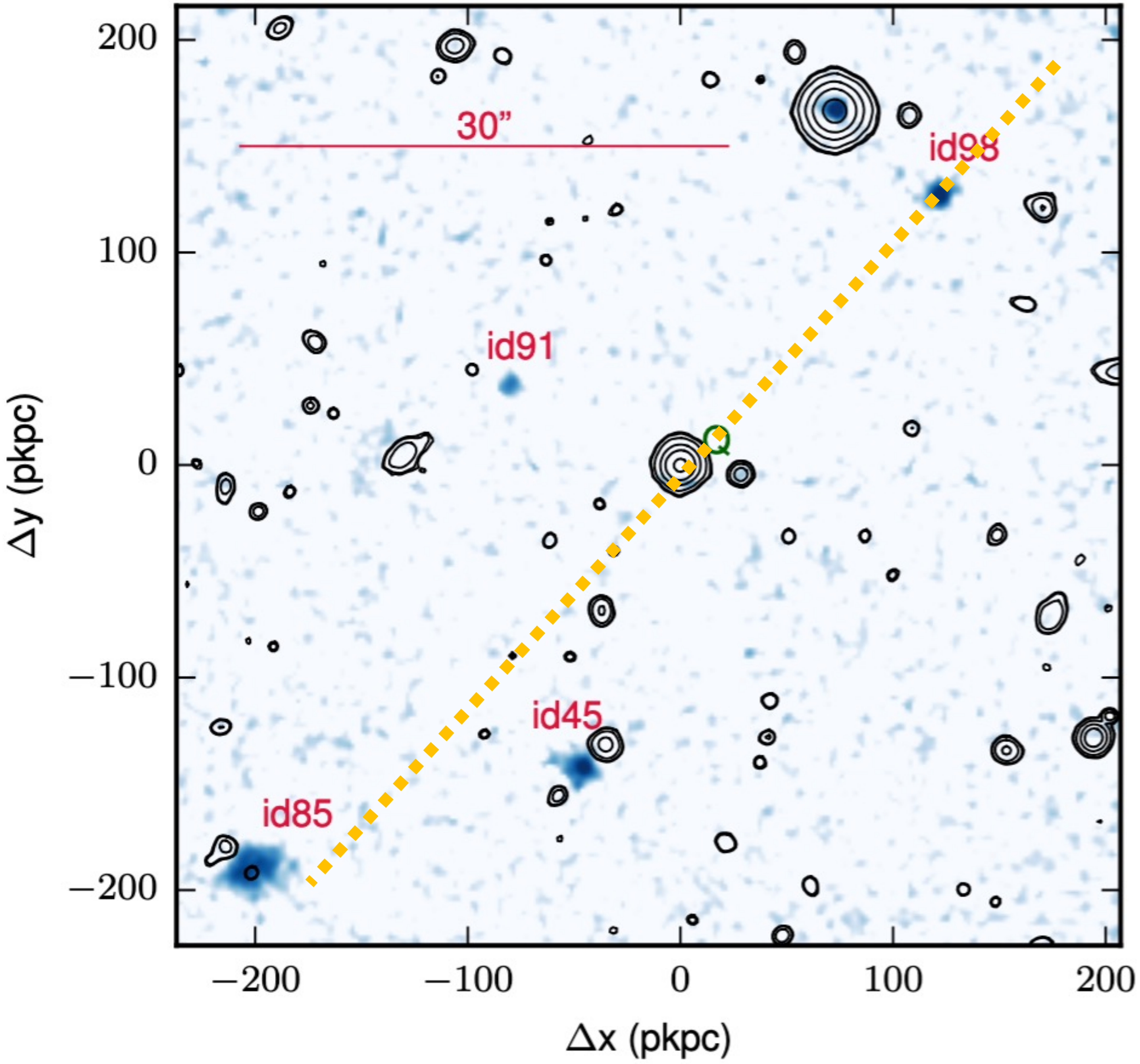
The instances of multiple LAEs show preferential alignment between gas and galaxies



Mackenzie, MF et al. 2019

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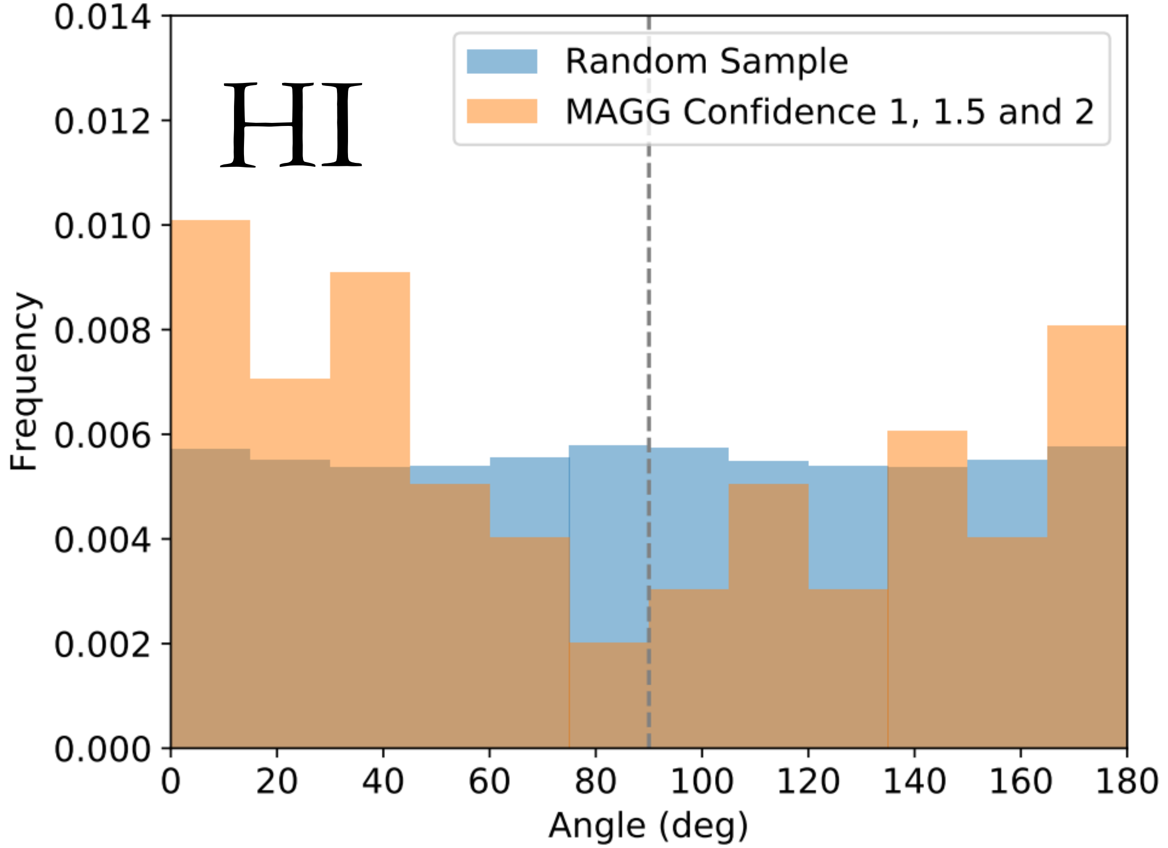
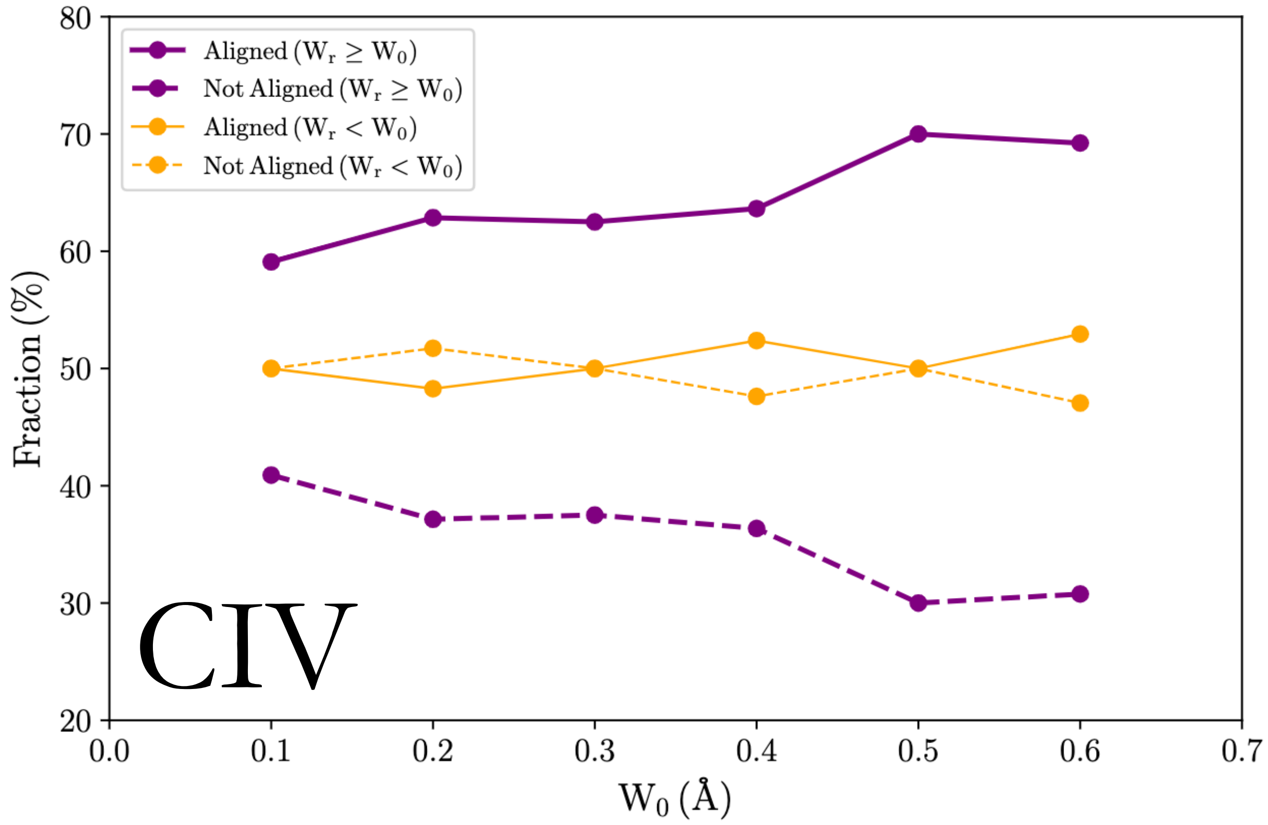


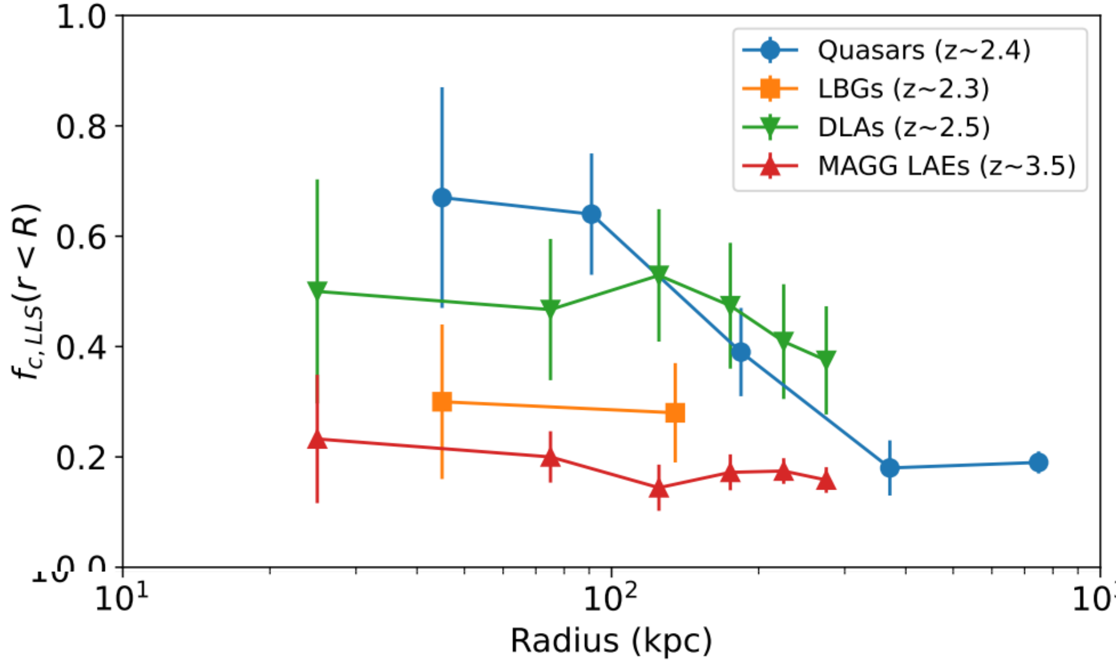


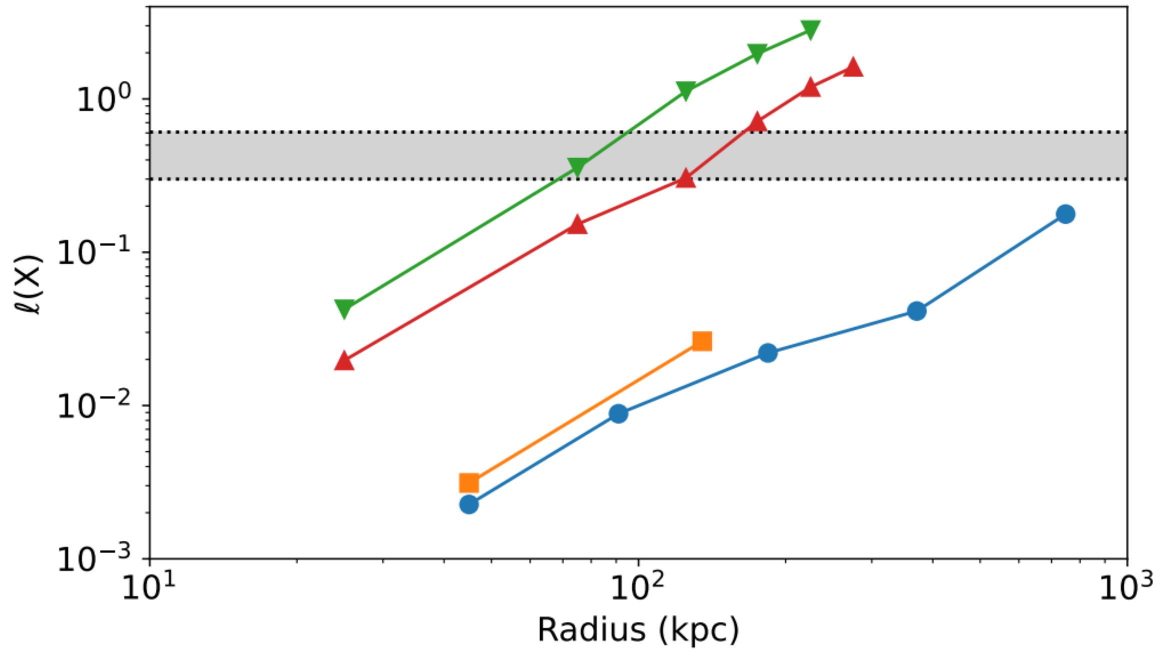
Lofthouse et al. 2023; Galbiati et al. 2023

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

LAEs are tracer of the optically-thick gas in the central regions of filaments connecting galaxies

HI



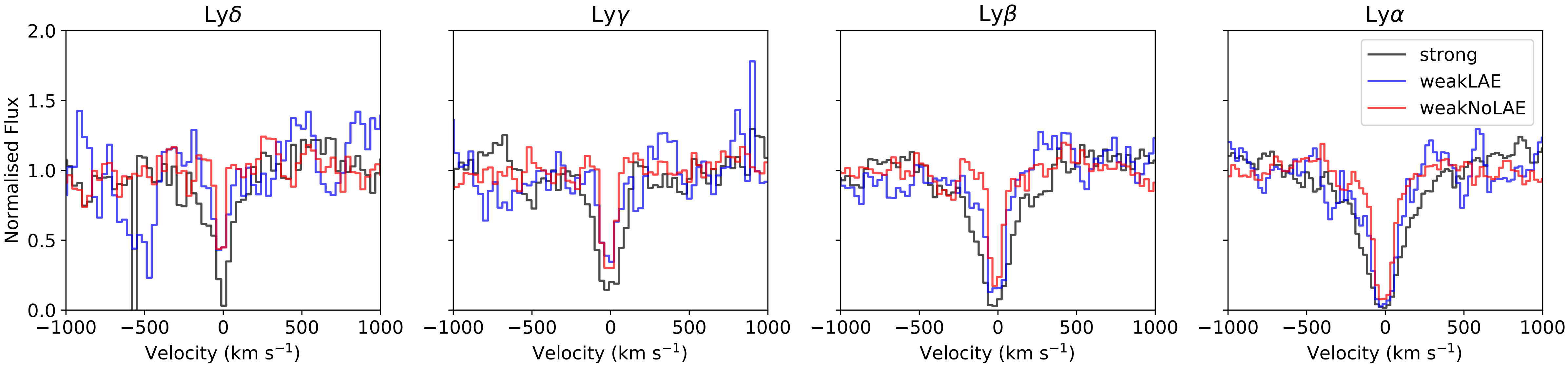


Lofthouse et al. 2023; Galbiati et al. 2023

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

For CIV, the strong (>0.1-0.2 A) population largely overlaps with strong HI systems.
The weaker absorbers, are instead tracing an enriched medium which is less directly connected with the filaments hosting LAEs

CIV



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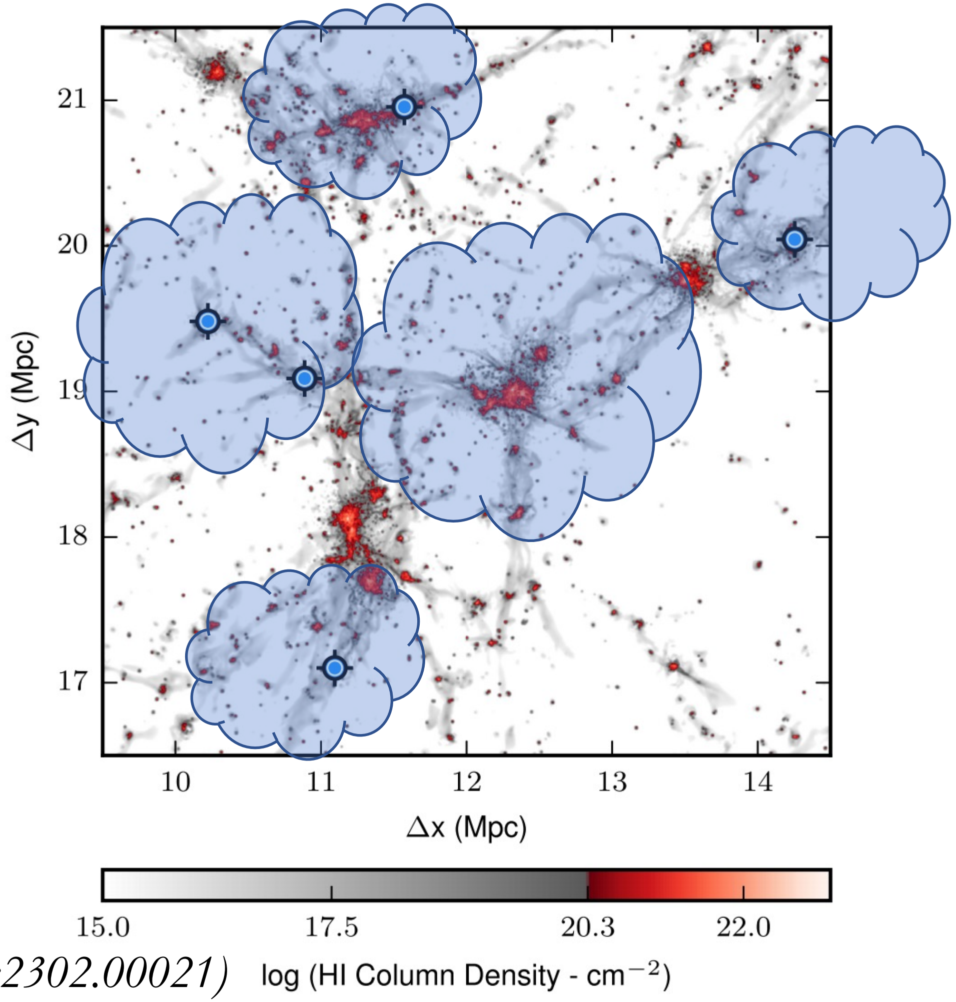

Lofthouse et al. 2023
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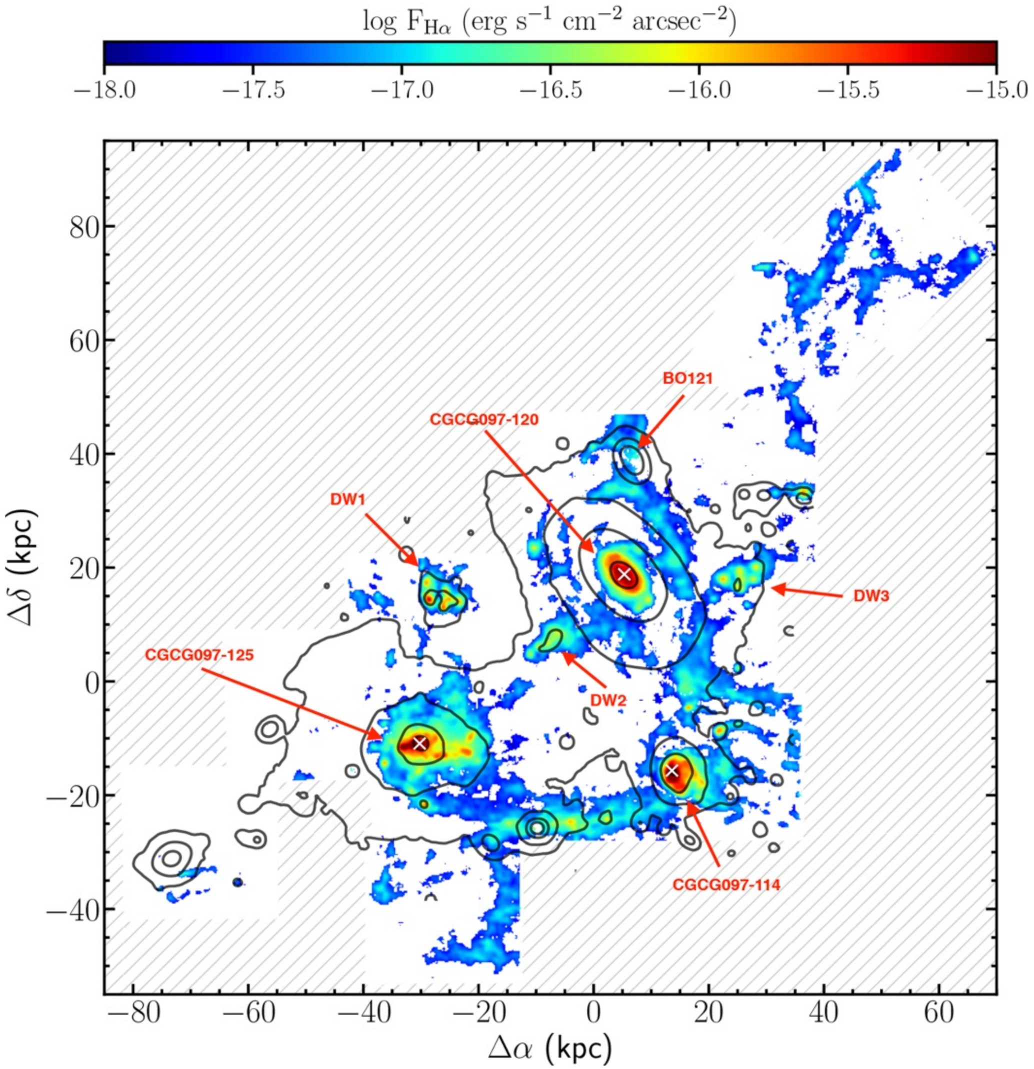
2. The galaxy environment modifies the properties of the CGM

Combining MAGG, MUDF, and QSAGE we are finding more extended metal cross section in group galaxies, supporting the idea that the gas environment near star-forming galaxies depends on the density



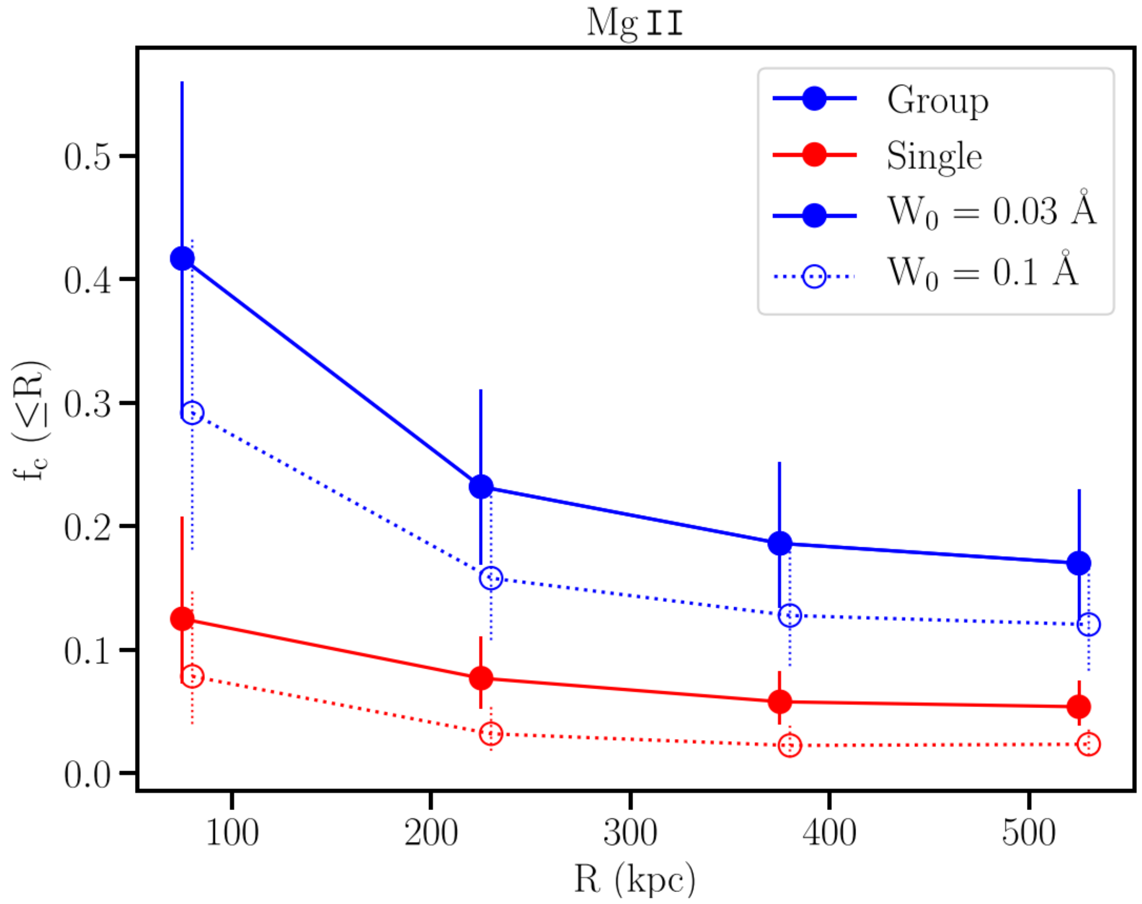
Lofthouse et al. 2023; Galbiati et al. 2023

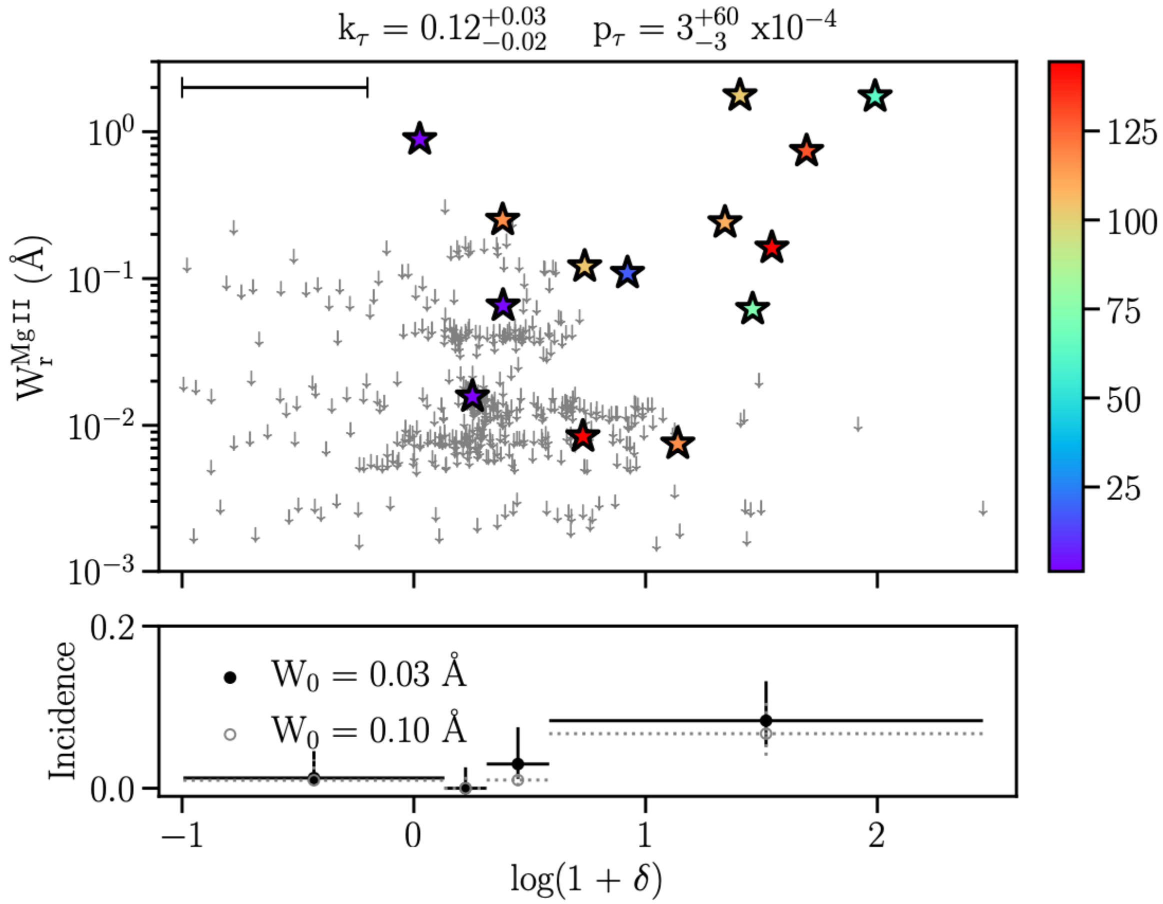
Dutta et al. 2020, 2022

Fossati et al. 2019

2. 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
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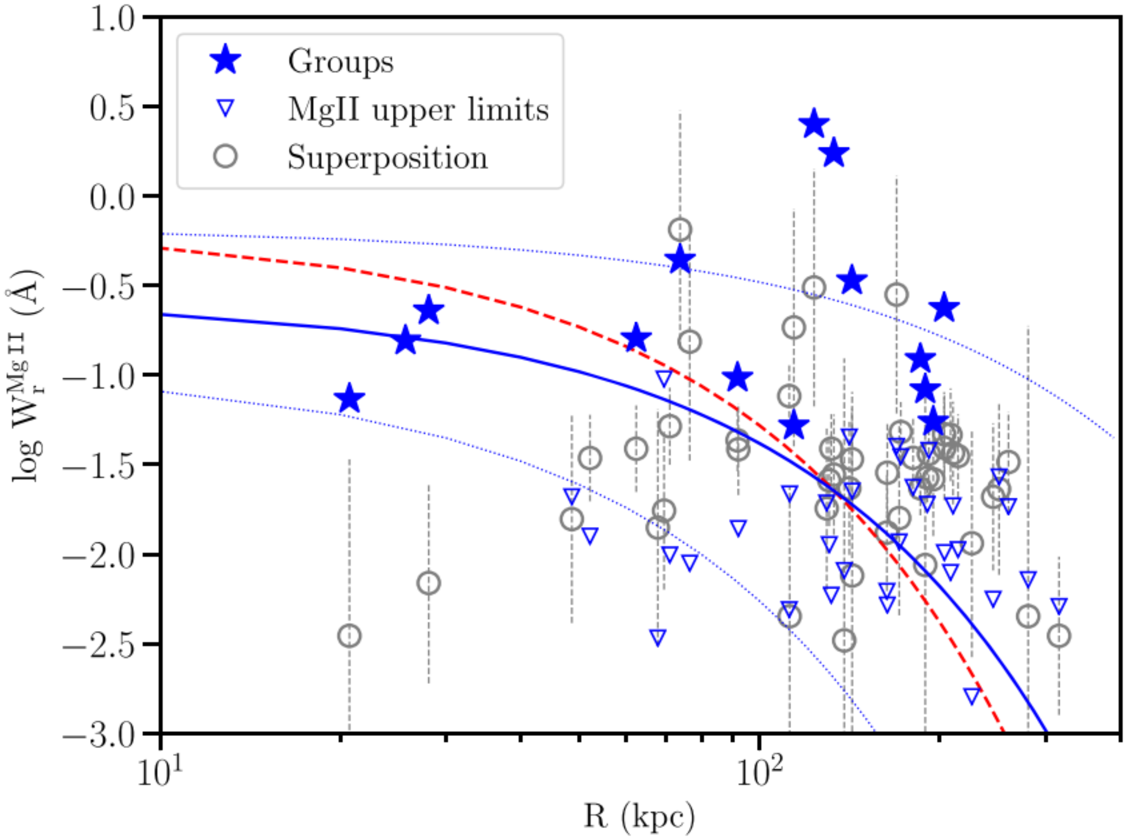
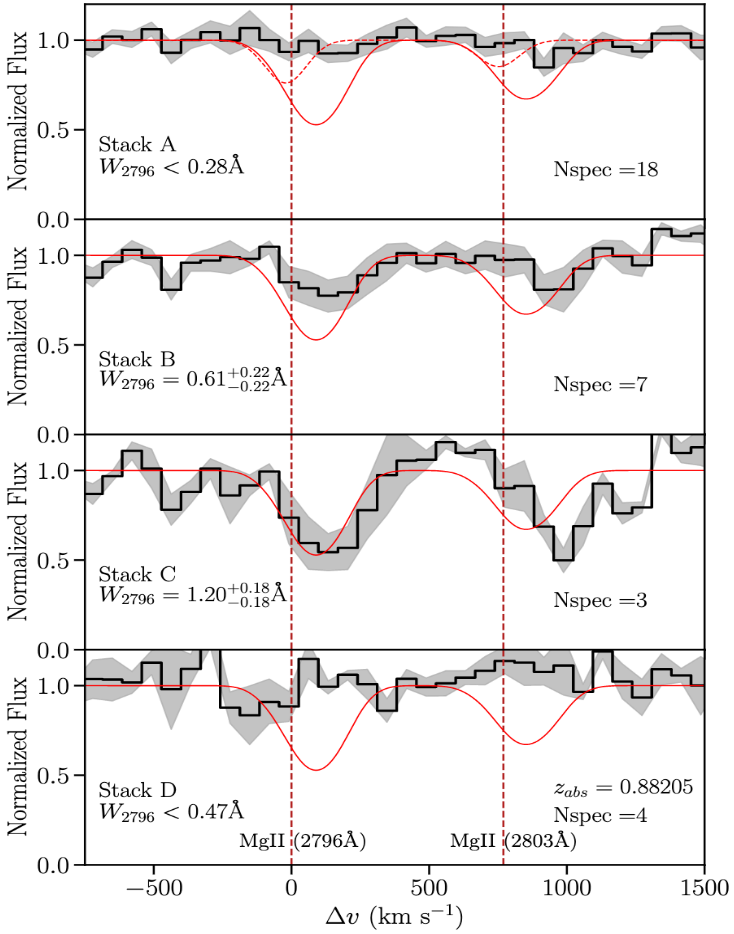
A simple superposition model account for some but not all strong absorbers in groups. Using deep stacks in MUDF, we report hints that the CGM of group galaxies is perturbed.





All

Aligned with galaxies

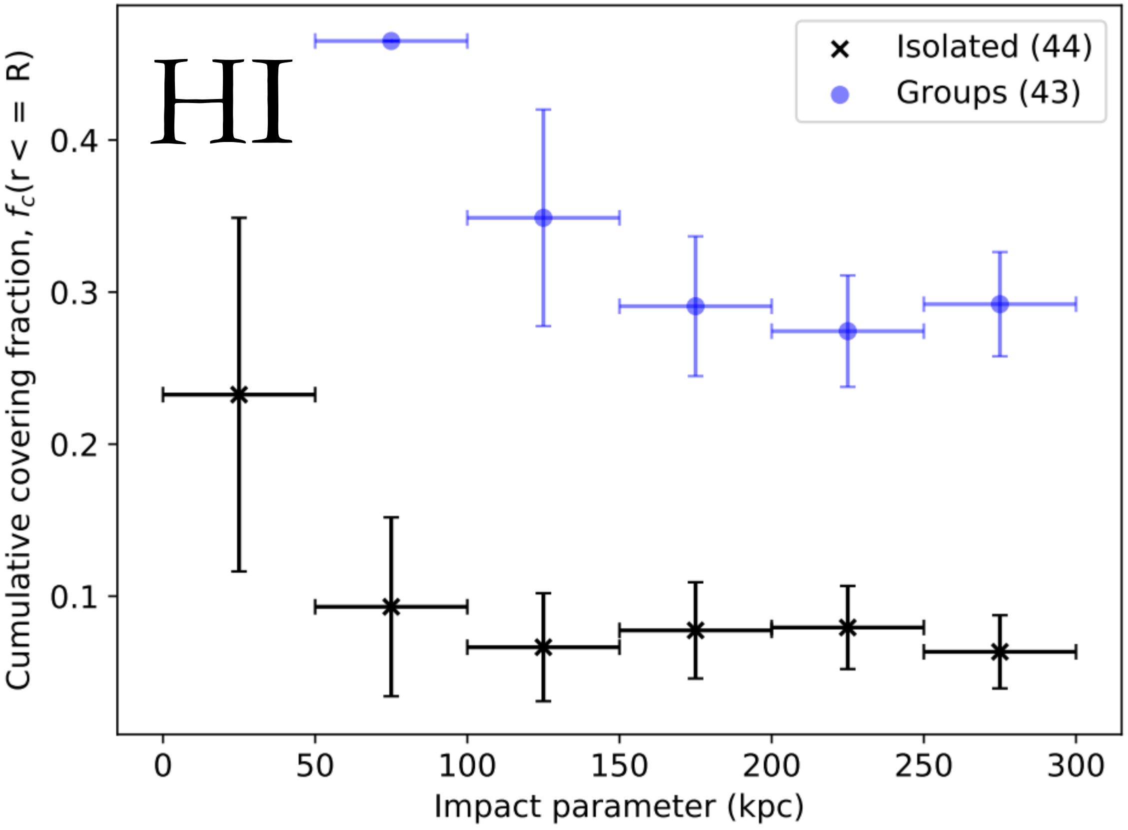
With MgII detections

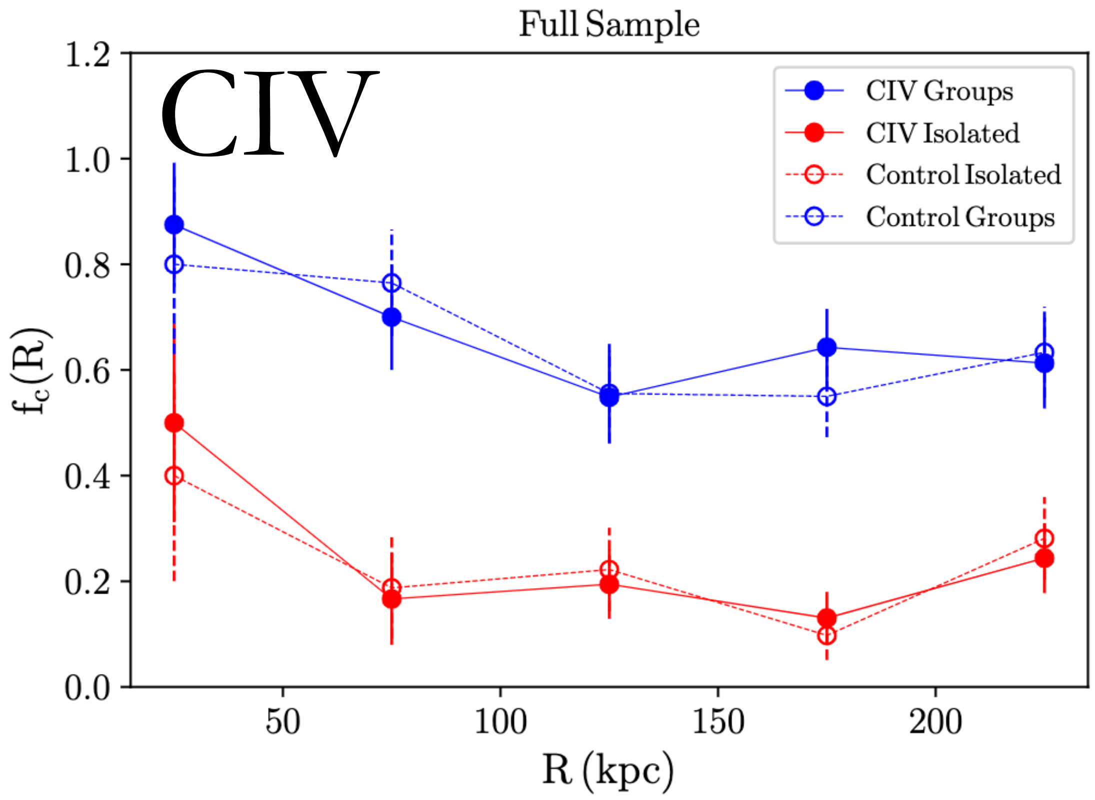
Intragroup

Dutta et al. 2020, 2022
Fossati et al. 2019

2. The galaxy environment modifies the properties of the CGM

At z>3, both HI and CIV absorption is more prevalent more prevalent in groups than in isolated galaxies





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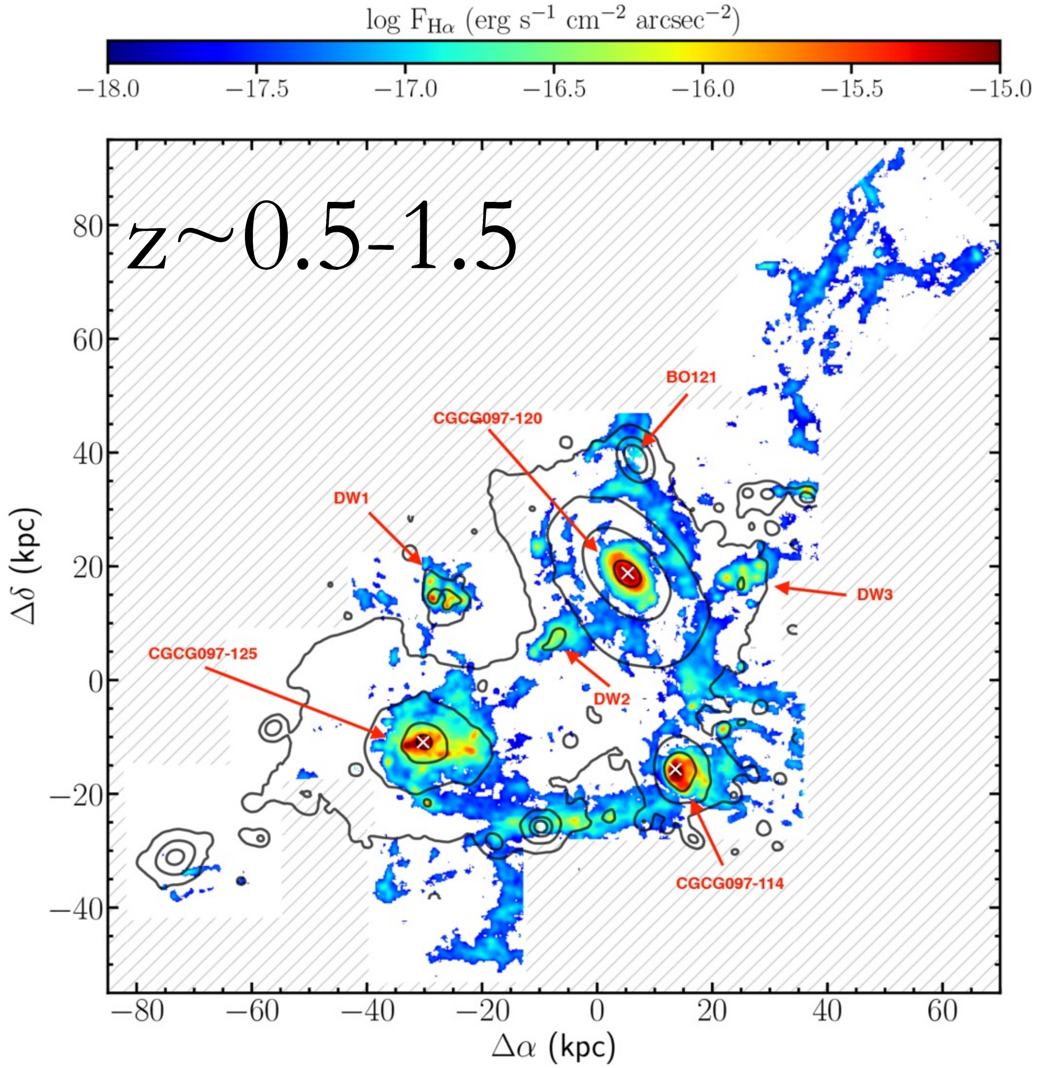
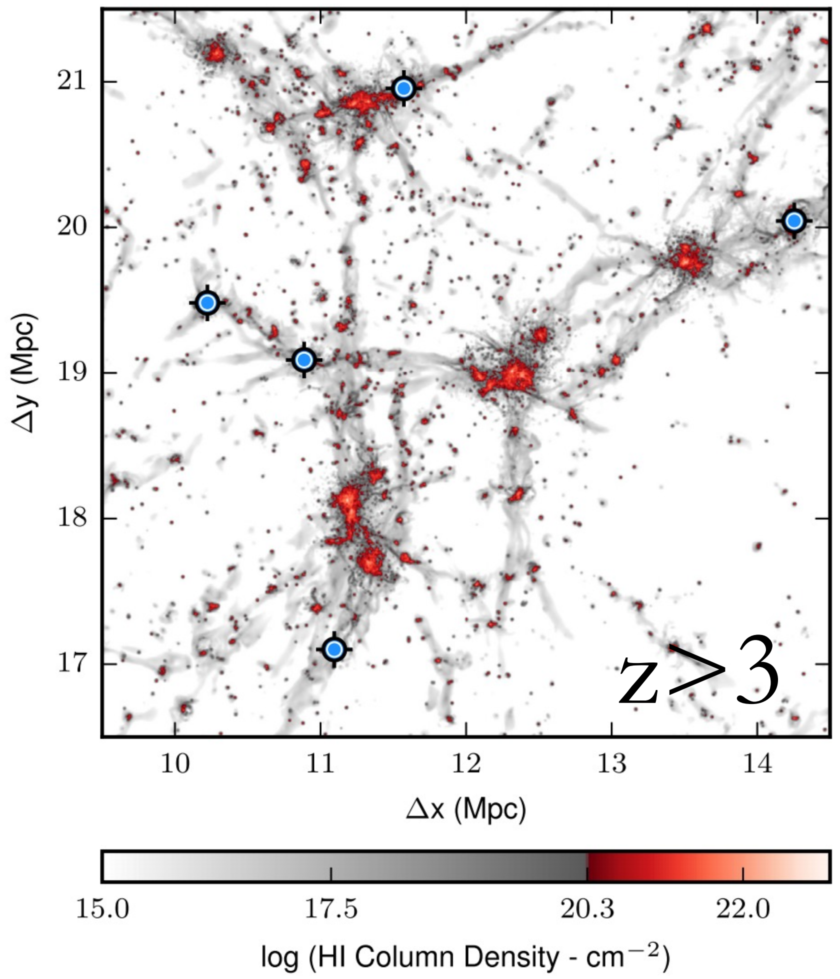
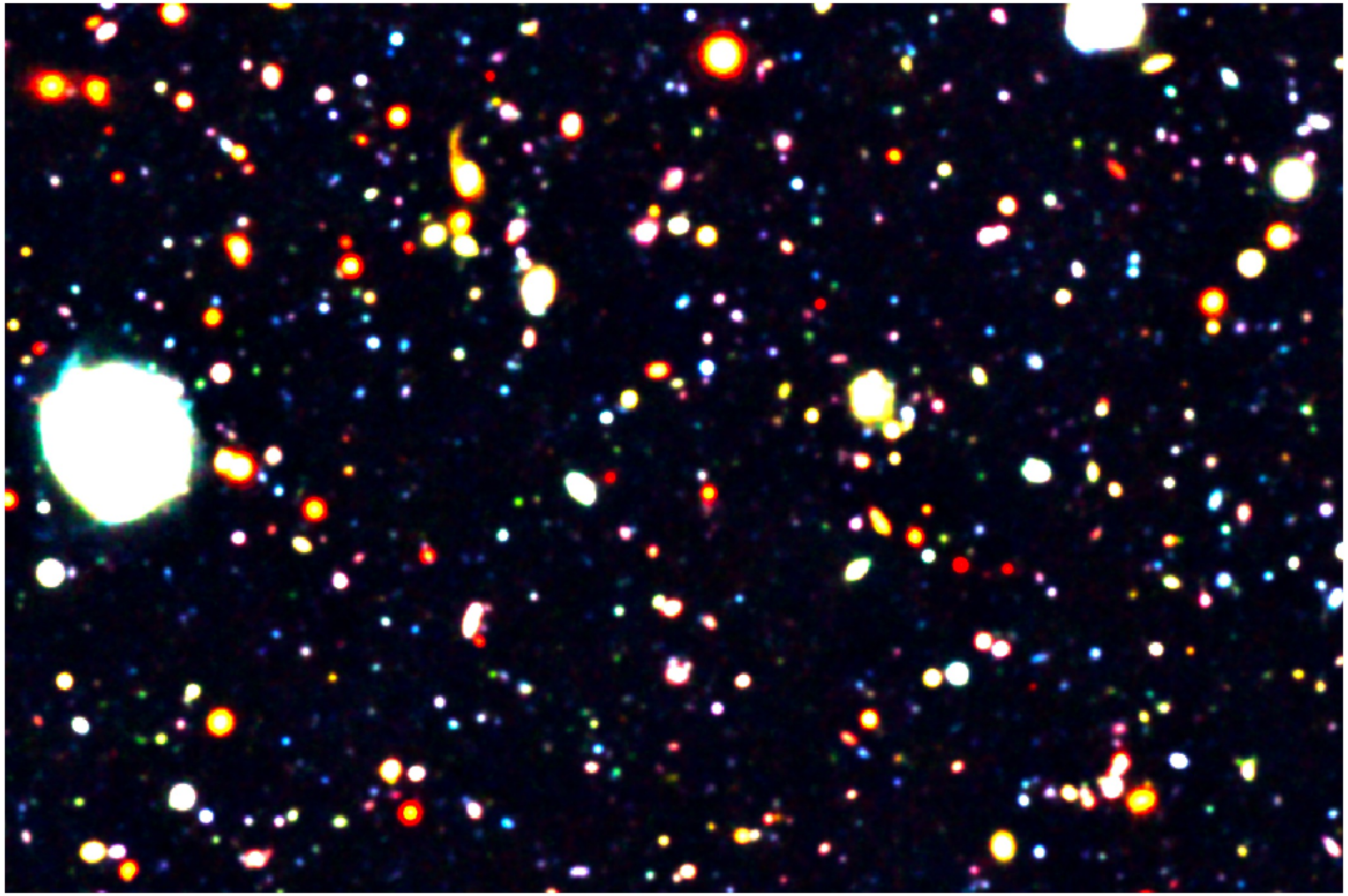




3. Hydrogen and metals in emission in the IGM/CGM

MUSE has enabled the detection of cosmic web filaments, and enriched halos of quasars and normal star-forming galaxies

Example of >1Mpc scale filaments in SSA22



Umehata, MF et al. 2019

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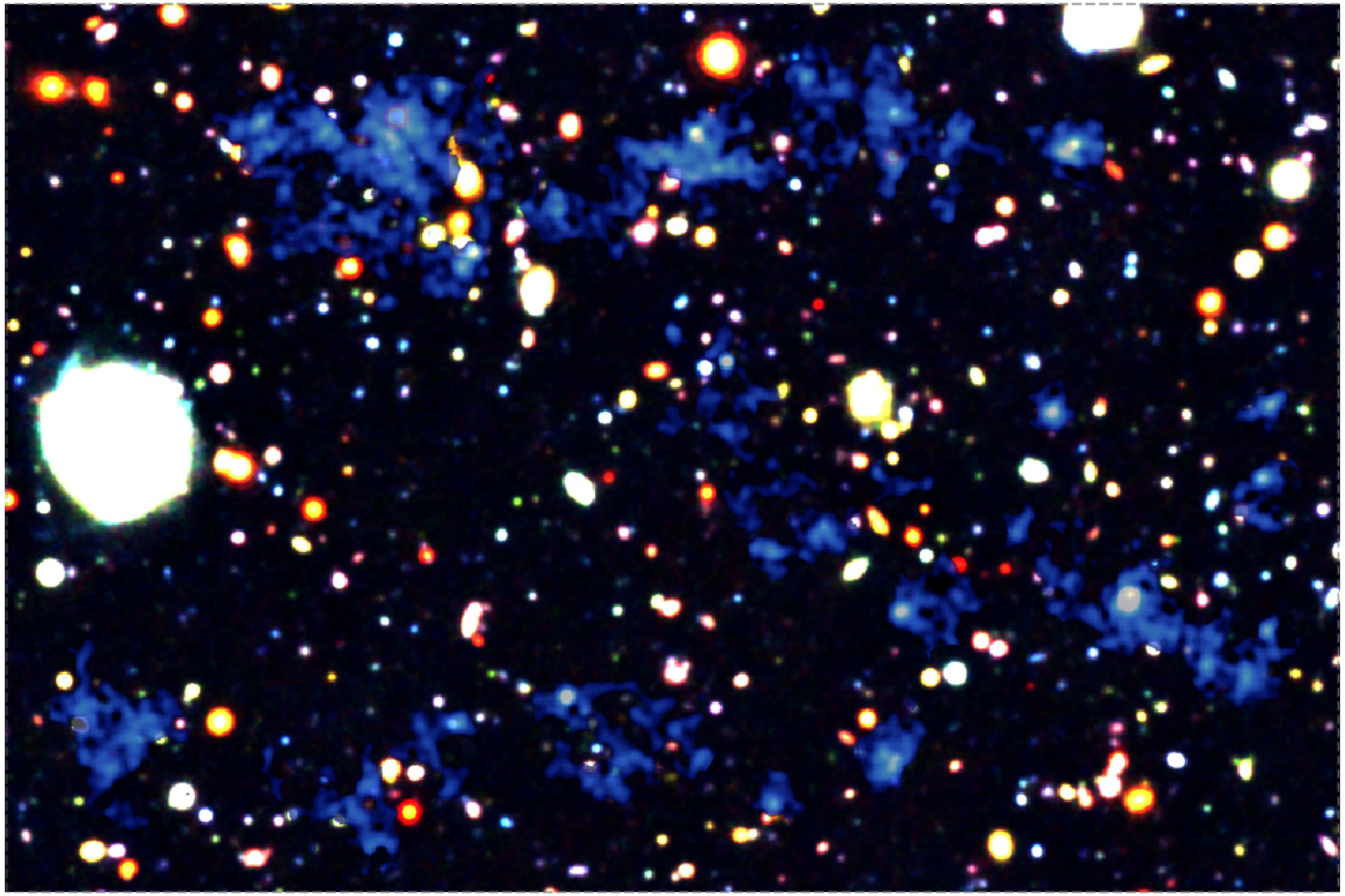

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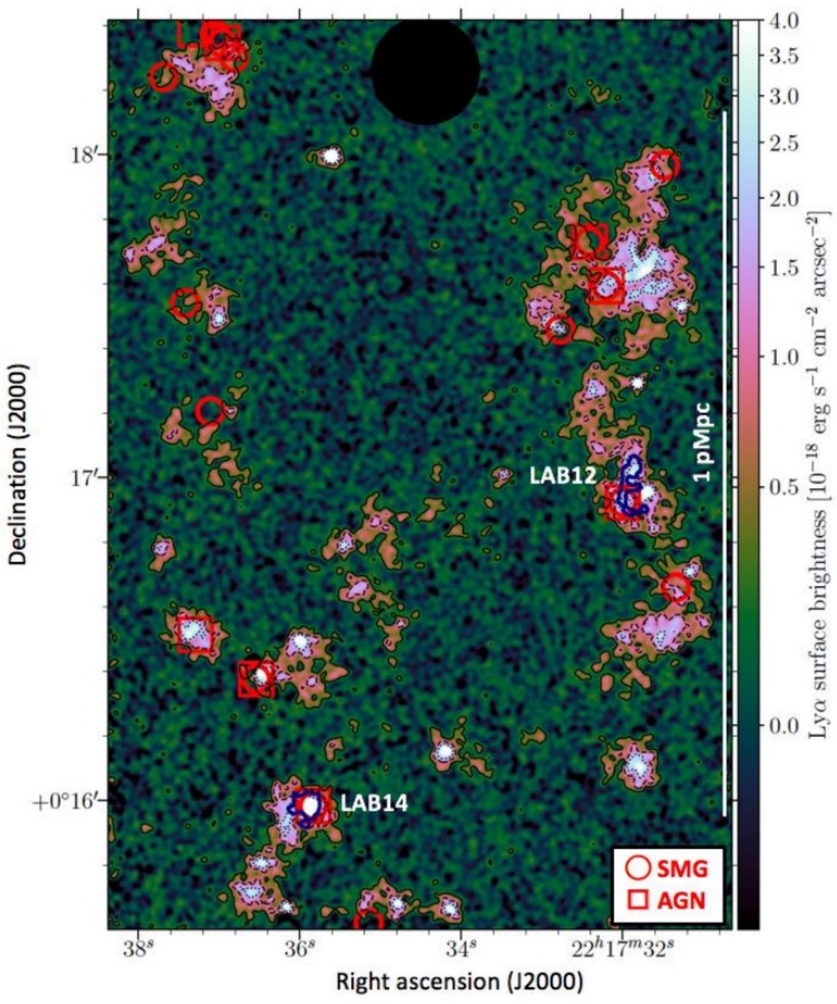
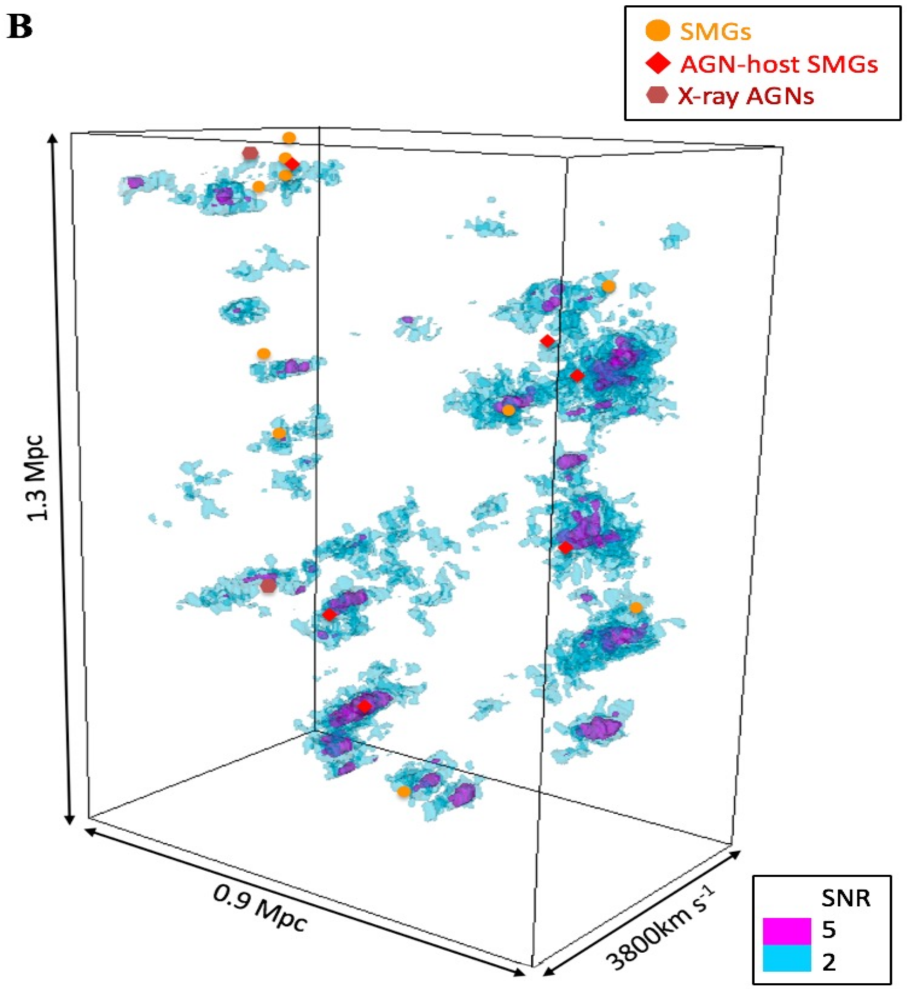
AGN and starburst galaxies appear embedded in this filamentary structure





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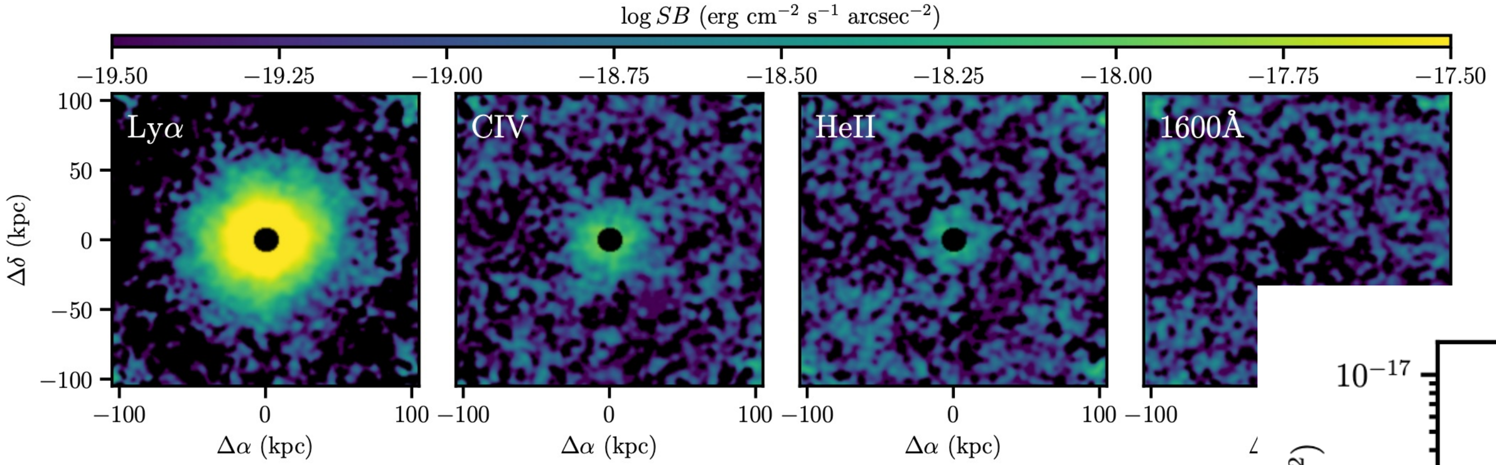
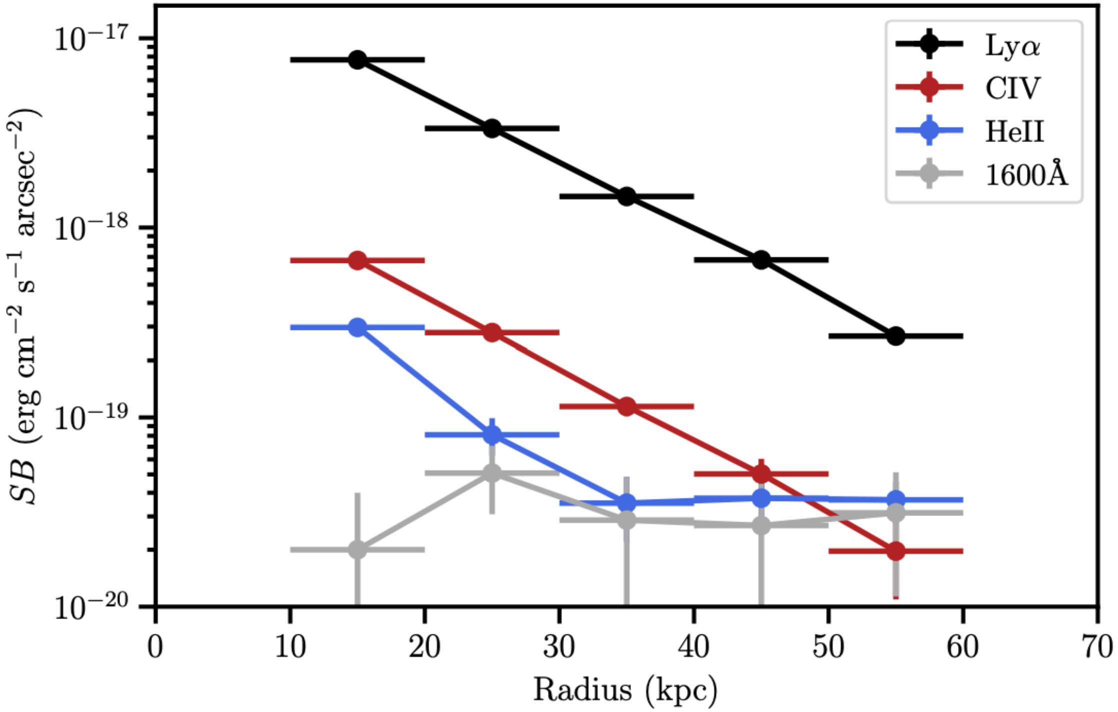
In MAGG, stacking reveals extended metal emission in the CGM of $z\sim3.5$ quasars



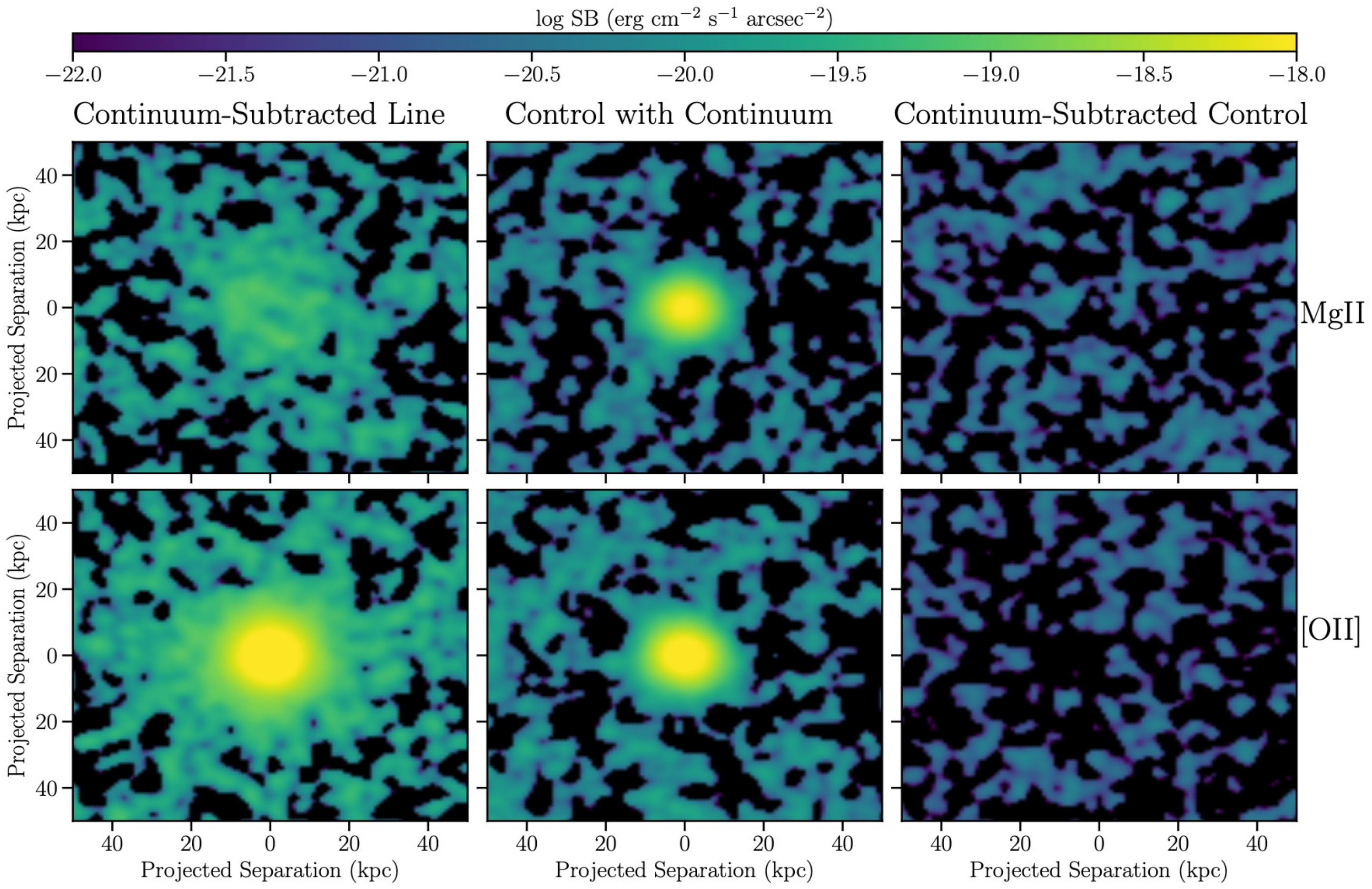


Barring difficulties in modeling the RT effects on CIV and Lyα, the CGM appears enriched to ~0.1Zsun

Fossati, MF et al. 2021

3. Hydrogen and metals in emission in the IGM/CGM

Stacks of ~500 galaxies and ~60 galaxies in MAGG and MUDF also reveal extended (>30-40 kpc) emission of [OII] and MgII in normal star-forming galaxies

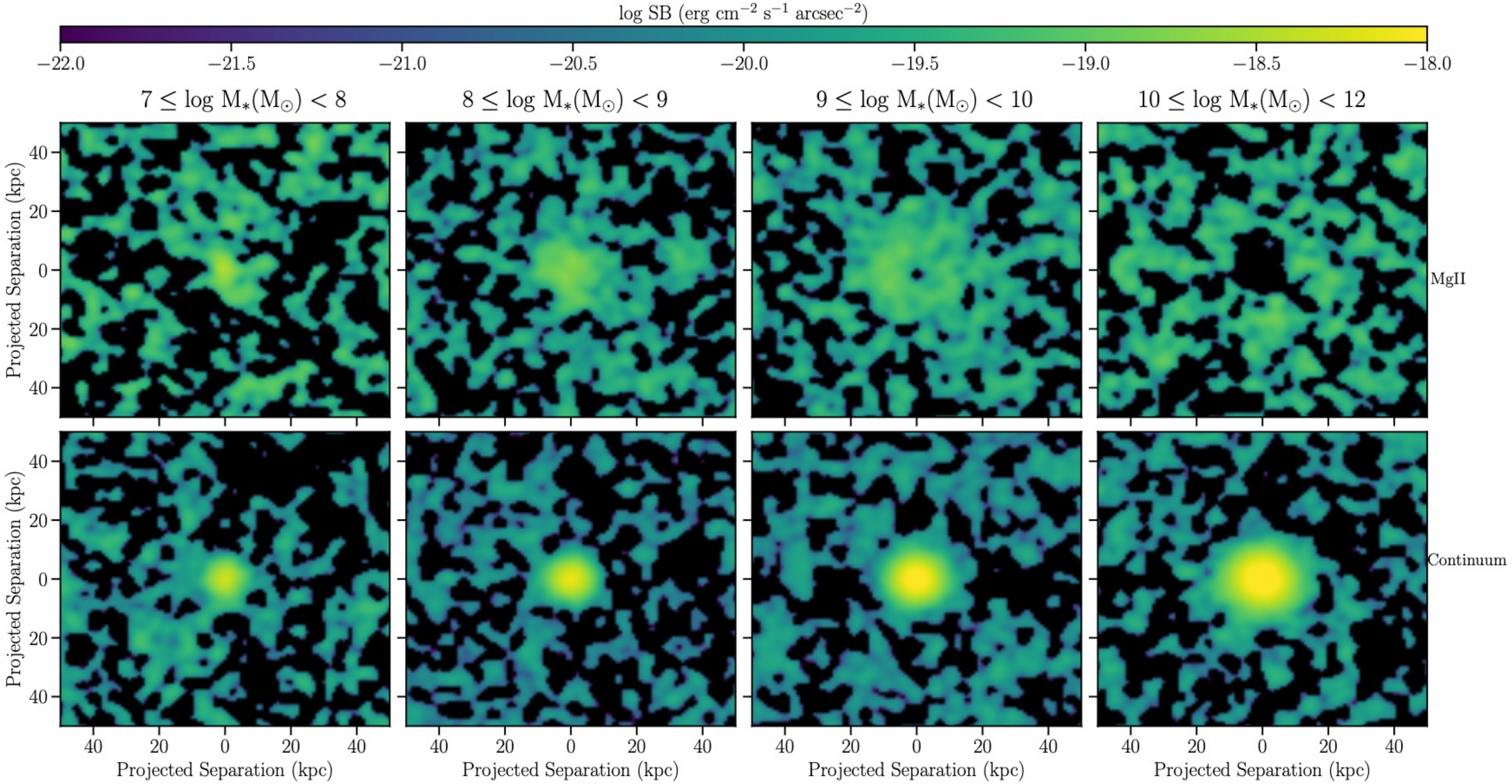


Dutta, MF et al. 2023

3. Hydrogen and metals in emission in the IGM/CGM

Extended emission of [OII] and MgII increases with redshift and stellar mass

MgII

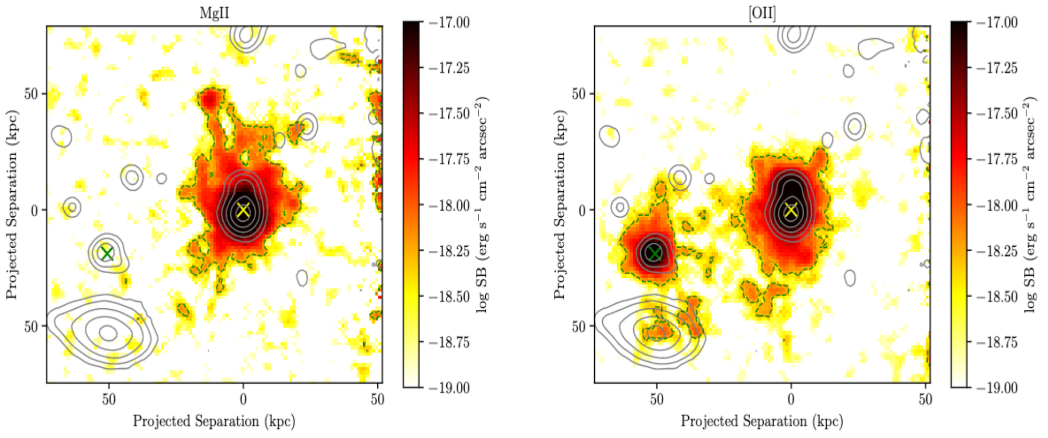


Dutta, MF et al., 2023

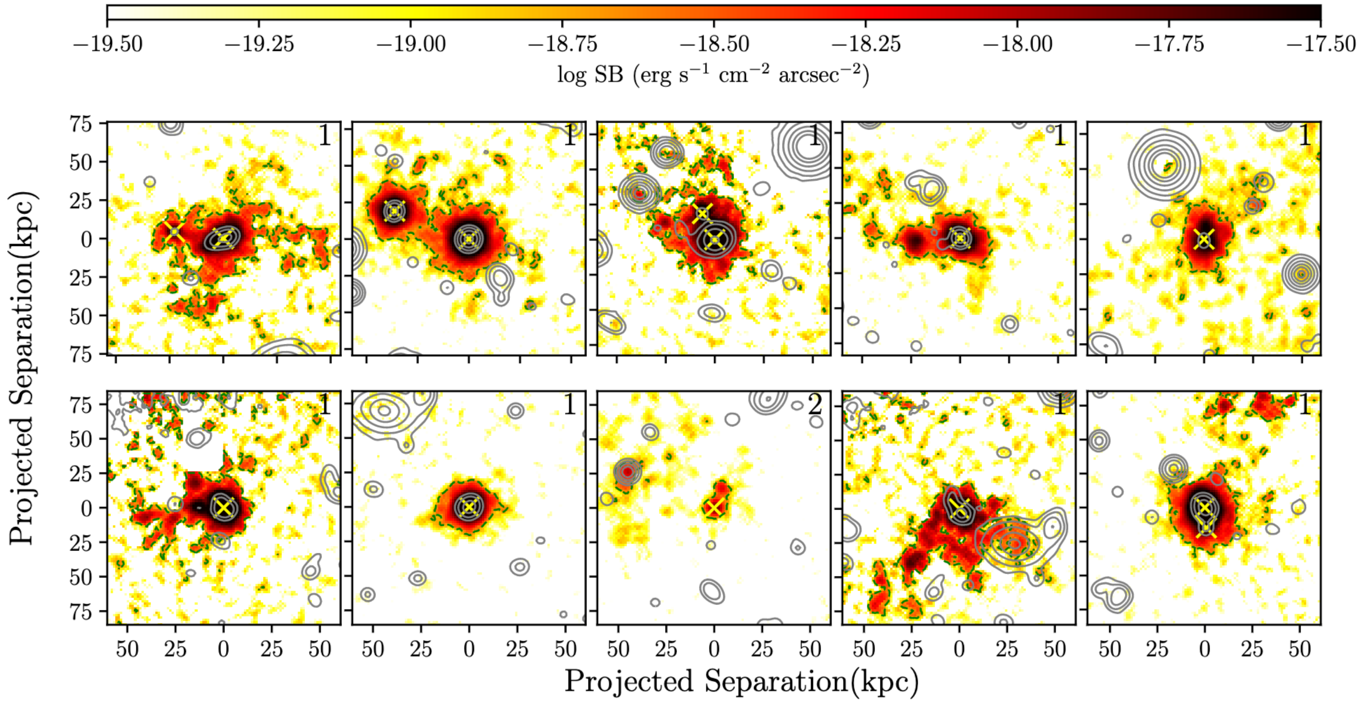
3. Hydrogen and metals in emission in the IGM/CGM

~30-40% of group galaxies show individual extended emission of [OII]
but MgII is detected only near active galaxies

Active galaxy – MgII emission



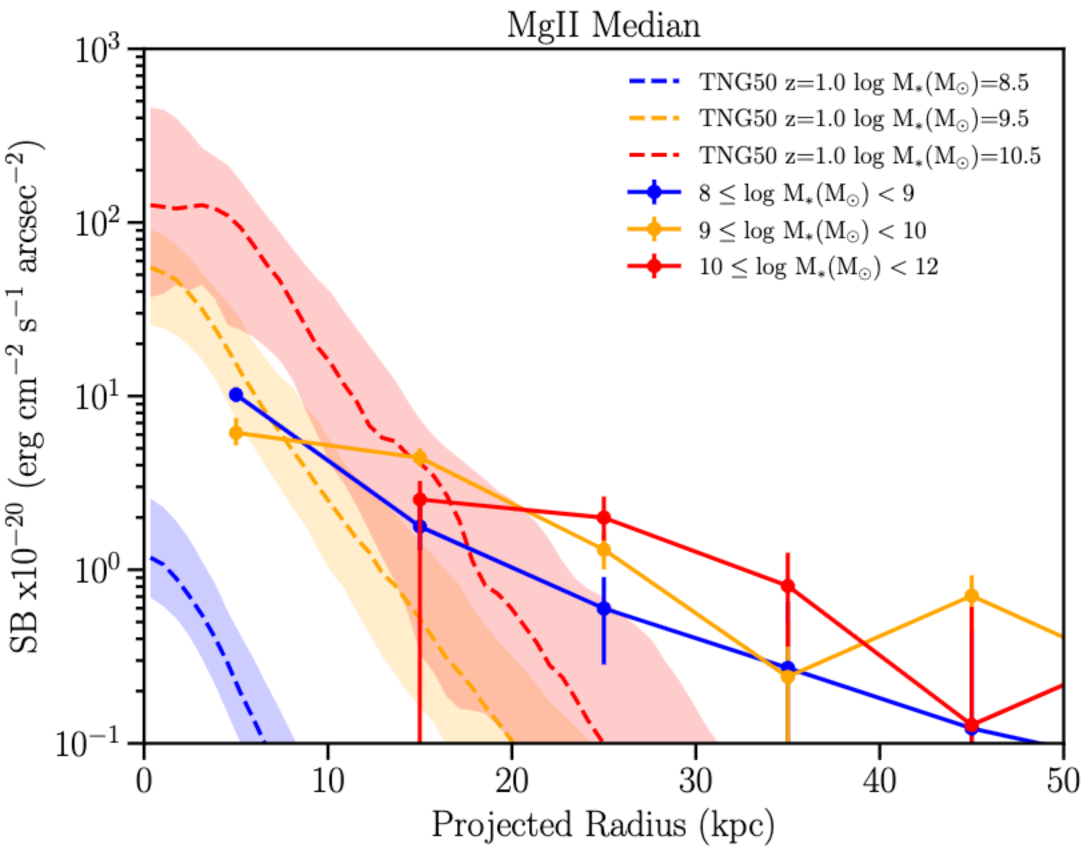
Normal galaxies – [OII] emission

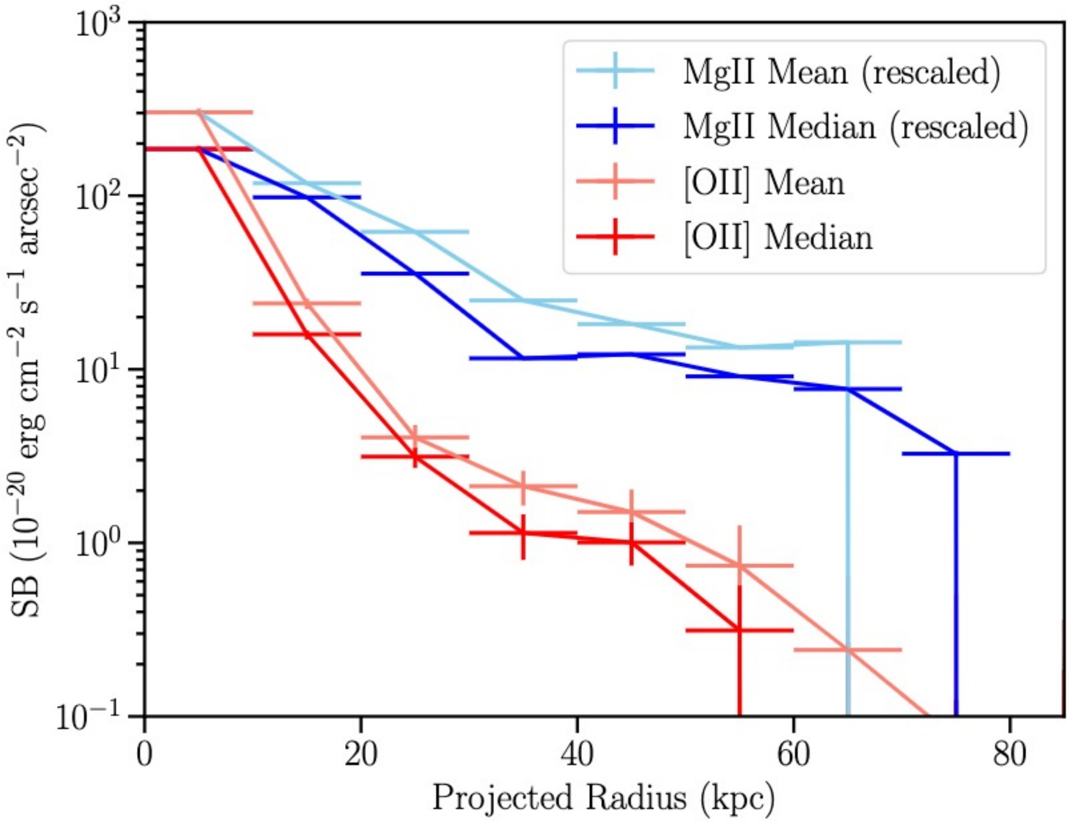


Dutta, MF et al. 2023

3. Hydrogen and metals in emission in the IGM/CGM

Comparison between observed MgII emission and results from simulations (Nelson et al. 2021) reveals broad agreement but emphasizes the need for detailed R.T. calculations

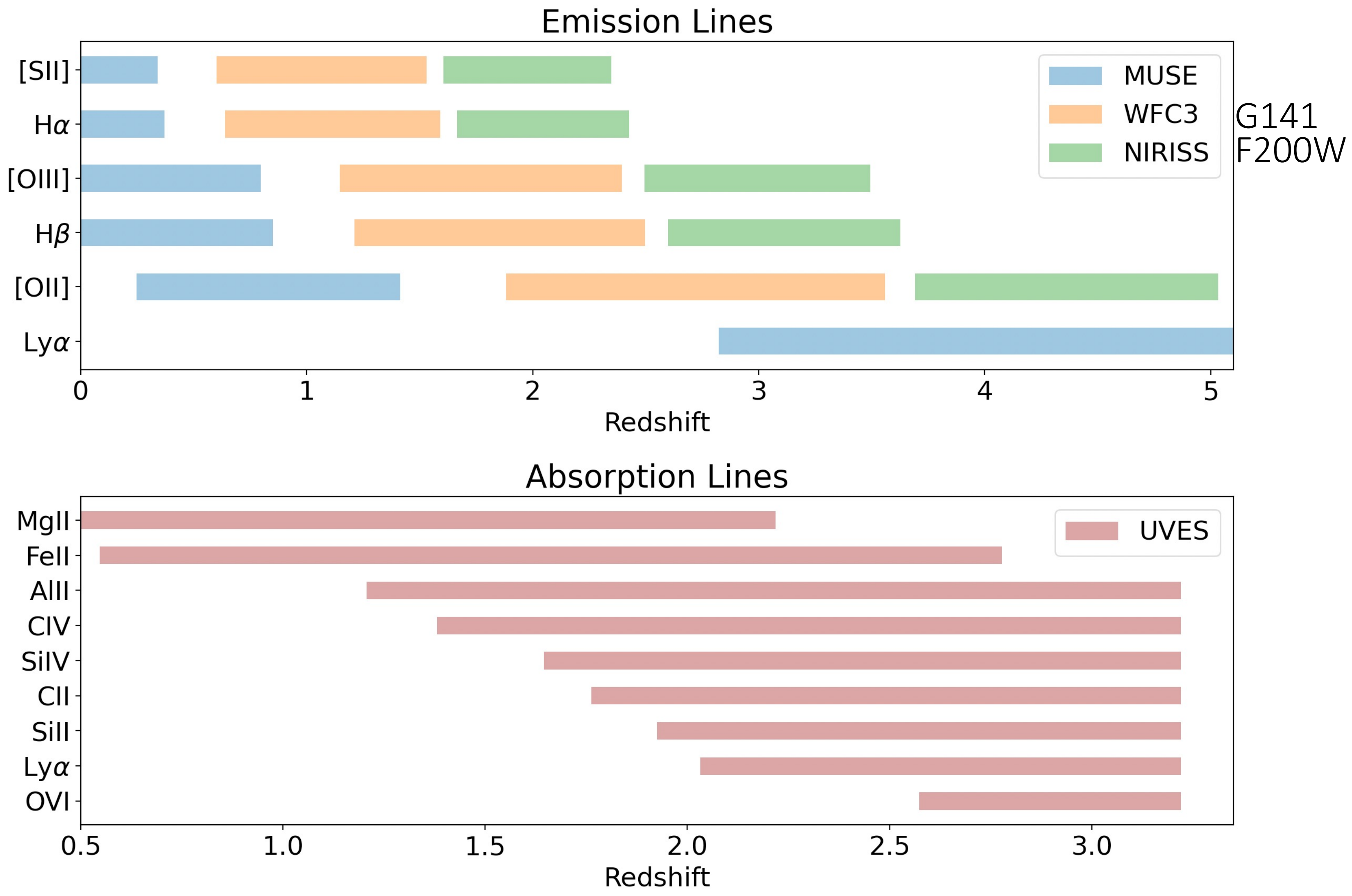




Dutta, MF et al. 2023

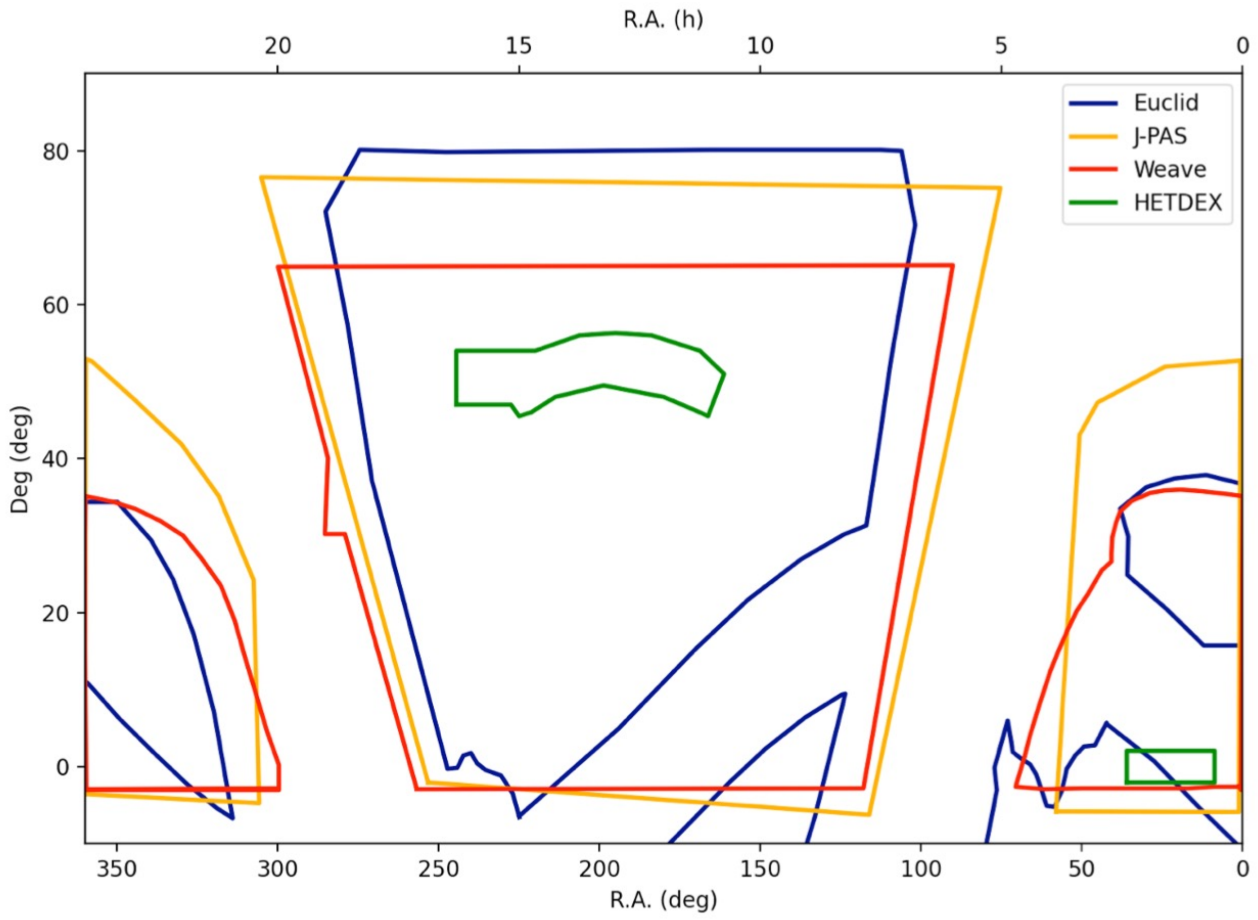
Looking ahead: large surveys and multiwavelength follow-up

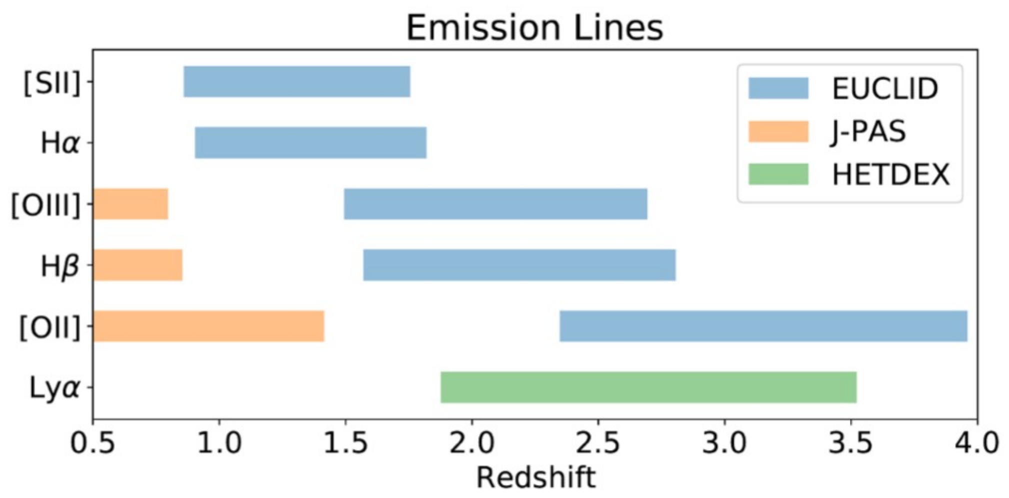
Extensions of these studies in the NIR/MIR will allow links between the physics of the ISM and CGM

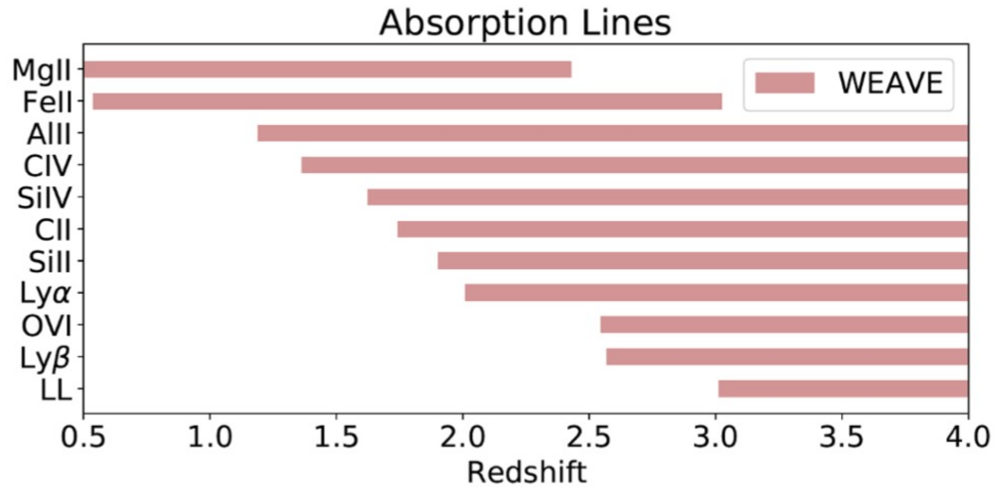


Looking ahead: large surveys and multiwavelength follow-up

Cosmology surveys are becoming "science grade" for CGM studies



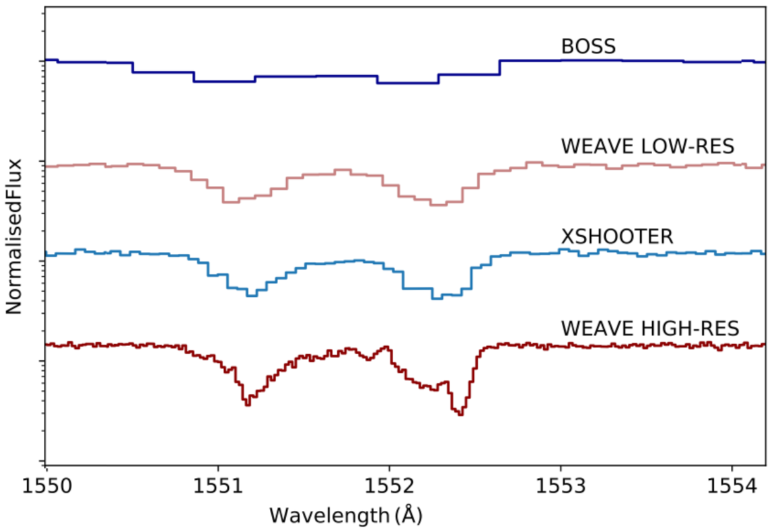


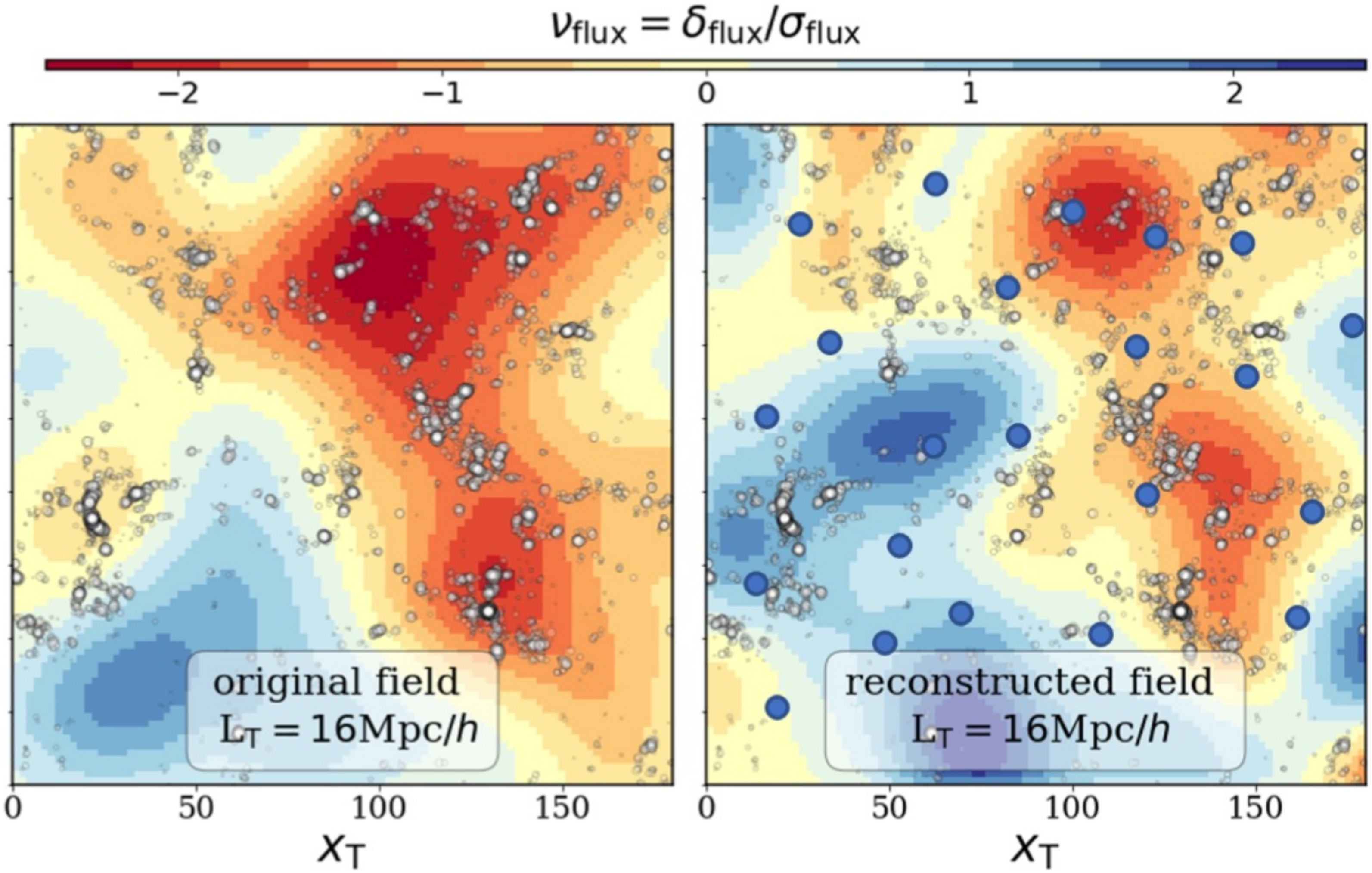


Looking ahead: large surveys and multiwavelength follow-up

WEAVE will build detailed metallicity information in fields with multiple quasars with reconstructed density distribution and known galaxy locations

Better resolution = 3x deeper survey in absorption





Courtesy of C. Laigle

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$\mathbf{W_0 = 0.10Å}$	Number of CIV	Number of LLS	% of LLS
Strong	98	39	$39/98 \approx 40\%$
Strong with LAEs	47	20	$20/47 \approx 43\%$
Strong w/o LAEs	51	19	$19/51 \approx 37\%$
Weak	122	4	$4/122 \approx 3\%$
Weak with LAEs	33	2	$2/33 \approx 6\%$
Weak w/o LAEs	89	2	$2/89 \approx 2\%$

Table 1: Weak $W_r < W_0$, Strong $W_r \geq W_0$. With $W_0 = 0.10$ Å.

$\mathbf{W_0 = 0.20Å}$	Number of CIV	Number of LLS	% of LLS
Strong	56	25	$25/56 \approx 45\%$
Strong with LAEs	33	16	$16/33 \approx 49\%$
Strong w/o LAEs	23	9	$9/23 \approx 11\%$
Weak	164	18	$18/164 \approx 11\%$
Weak with LAEs	47	6	$6/47 \approx 13\%$
Weak w/o LAEs	117	12	$12/117 \approx 10\%$

Table 2: Weak $W_r < W_0$, Strong $W_r \geq W_0$. With $W_0 = 0.20$ Å.