Title: The Lyman-Alpha Tomography IMACS Survey (IMACS)

Speakers: Andrew Newman

Collection/Series: Cosmic Ecosystems

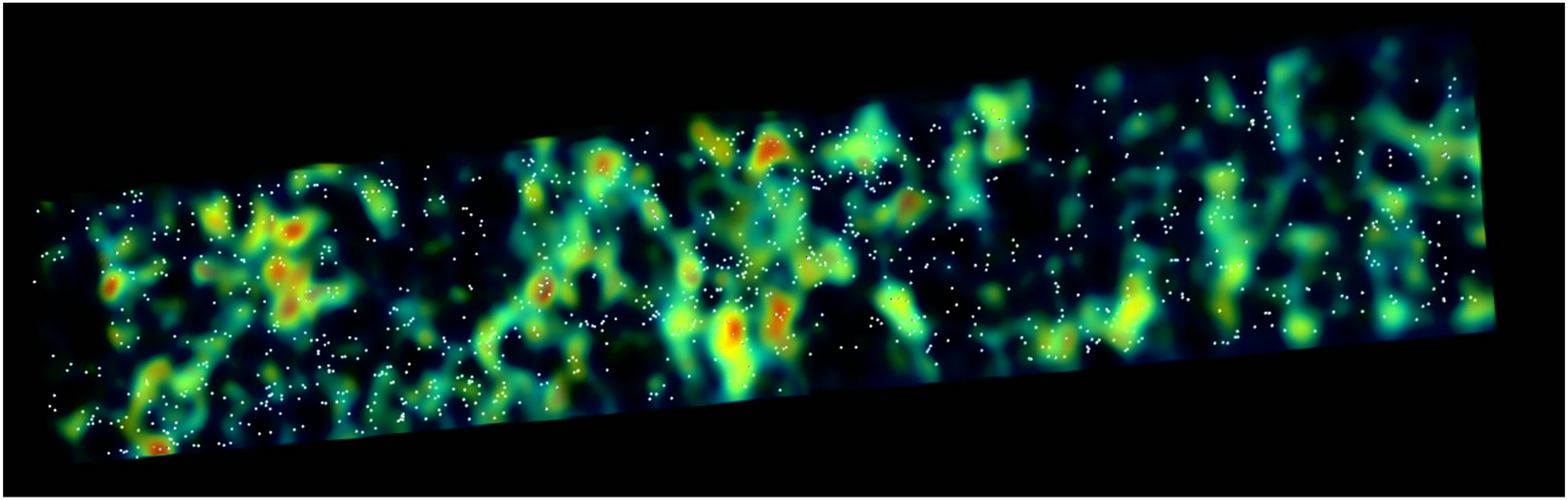
Subject: Cosmology

Date: August 01, 2025 - 9:35 AM

URL: https://pirsa.org/25080002

Abstract:

The cosmic web in the distant universe is generally mapped by observing the positions of galaxies. Recently a new perspective has been gained by mapping the diffuse gas in the intergalactic medium (IGM). The Lyman-Alpha Tomography IMACS Survey (LATIS) has now produced 3D maps of the IGM at redshift z~2.5, covering a volume of about 10^7 Mpc^3. I will present the LATIS maps and discuss how they inform our understanding of the interplay between early galaxies and their large-scale environments.



LATIS: The Lyα Tomography IMACS Survey

Drew Newman

Cosmic Ecosystems, Perimeter Institute (Aug. 1, 2025)

Together with Nima Chartab, Mahdi Qezlou, Gwen Rudie, Guillermo Blanc, Dan Kelson, Simeon Bird, Andrew Benson, Caitlin Casey, Enrico Congiu, Alan Dressler, Denise Hung, Brian Lemaux, John Mulchaey, Victoria Pérez, Jorge Zavala

CARNEGIE SCIENCE | Observatories

LATIS in a nutshell

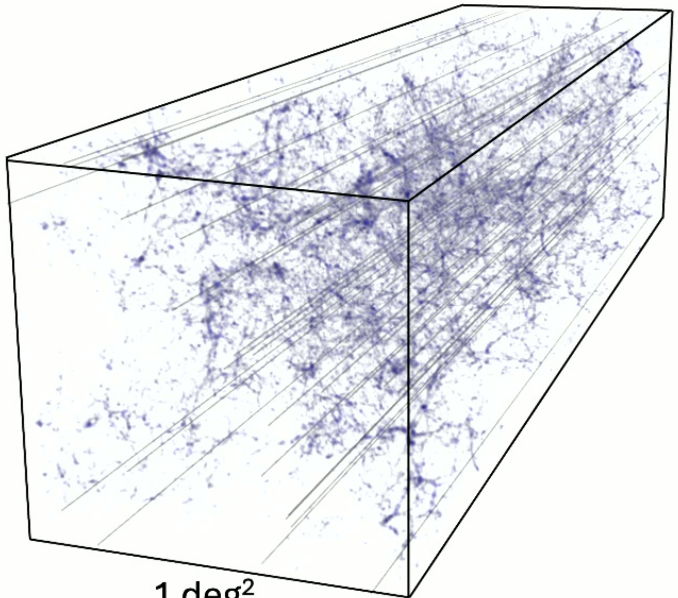
A survey designed to create **3D maps of IGM** around **z~2.5,** based on Lya absorption, with relatively high spatial resolution (few cMpc/*h*) and large volume ($\Delta z = 0.6$, 1.7 deg^2).

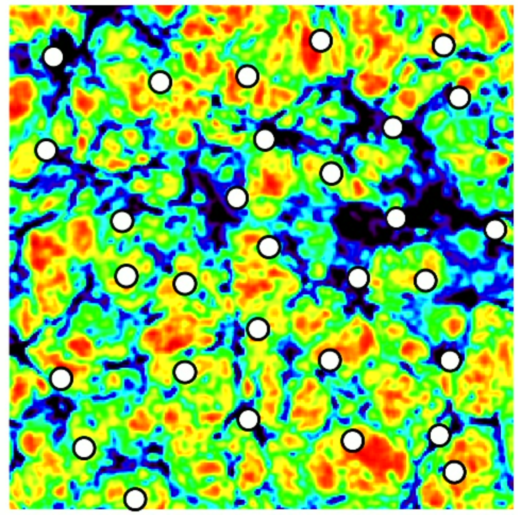
Some motivating applications:

- Map large-scale structure
- Study environment-dependent galaxy evolution
- Detect protoclusters independent of their galaxy populations
- Study influence of feedback on intergalactic gas

IGM Tomography

3D mapping using multiple sightlines
(e.g., Pichon et al 2001, Caucci et al 2008, Lee et al 2014)



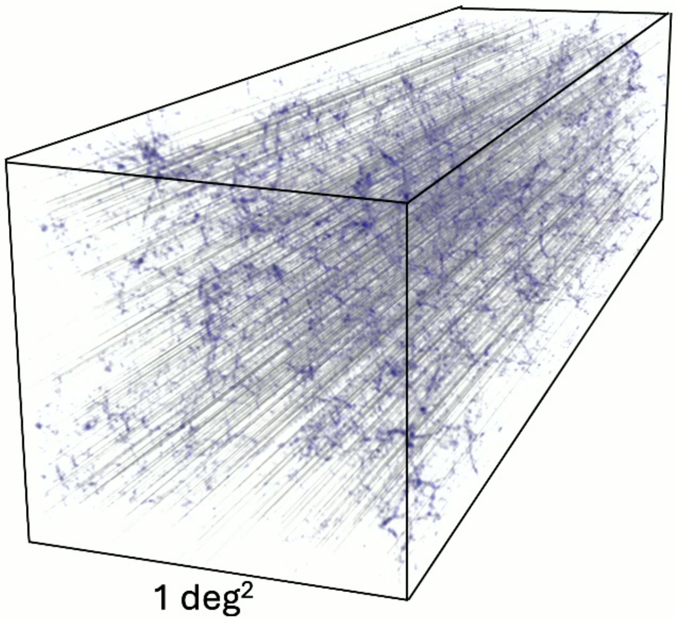


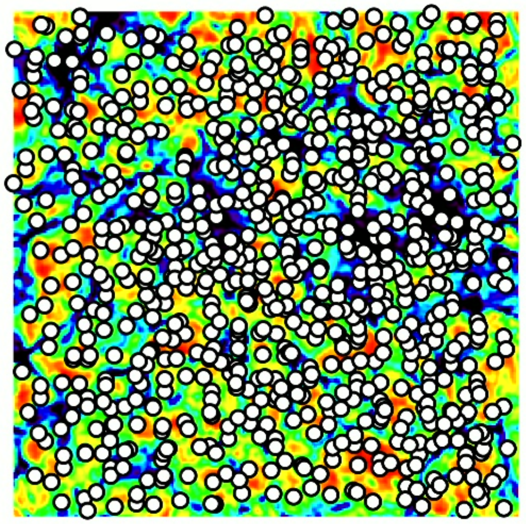
Color = Lyα transmission

Sightline density 30 deg^{-2} → Map resolution ~ mean separation ~ 13 h^{-1} cMpc
Feasible with QSOs, but sampling is very sparse. (e.g., Cai et al 2017, Shi et al 2021)

IGM Tomography

Lyman-break galaxies (LBGs) provide a sightline network with ~30x higher density





Color = Lyα transmission

Sightline density 800 deg^{-2} → Map resolution ~ mean separation ~ 2.5 h^{-1} cMpc

Resolution is better matched to scales of interest — but sources are far fainter.

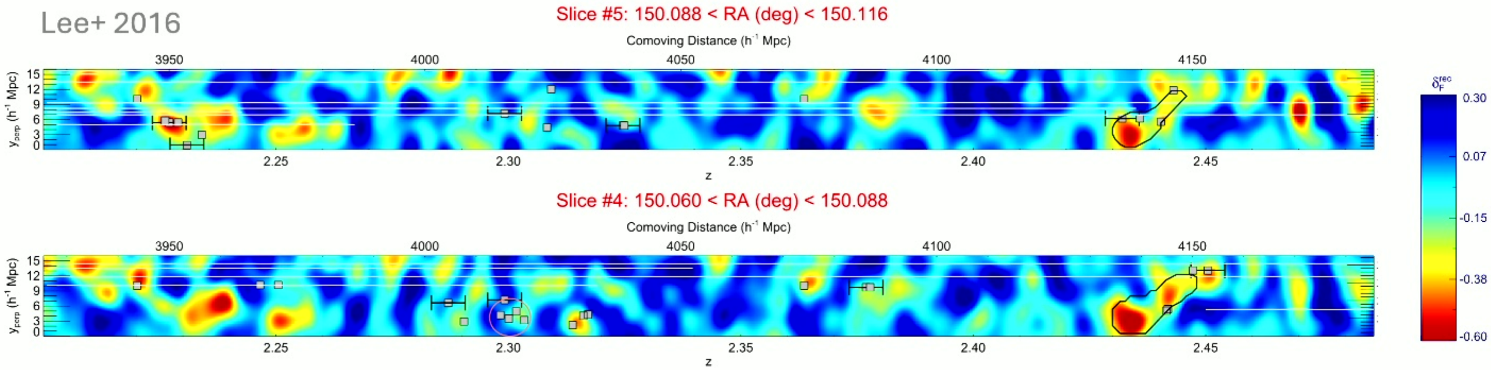
CLAMATO: COSMOS Lyα Mapping and Tomography Observations Survey

These techniques were developed by K-G Lee and collaborators (Joe Hennawi, Martin White, et al.) and implemented in the CLAMATO survey.

Lee et al 2014a,b, 2016, 2018; Stark et al 2015a,b; Krolewski et al 2017, 2018; Horowitz et al 2021

This work proved the viability of IGM tomography using Keck/LRIS observations covering an area of $\sim$0.2 deg^2.

Lee+ 2016

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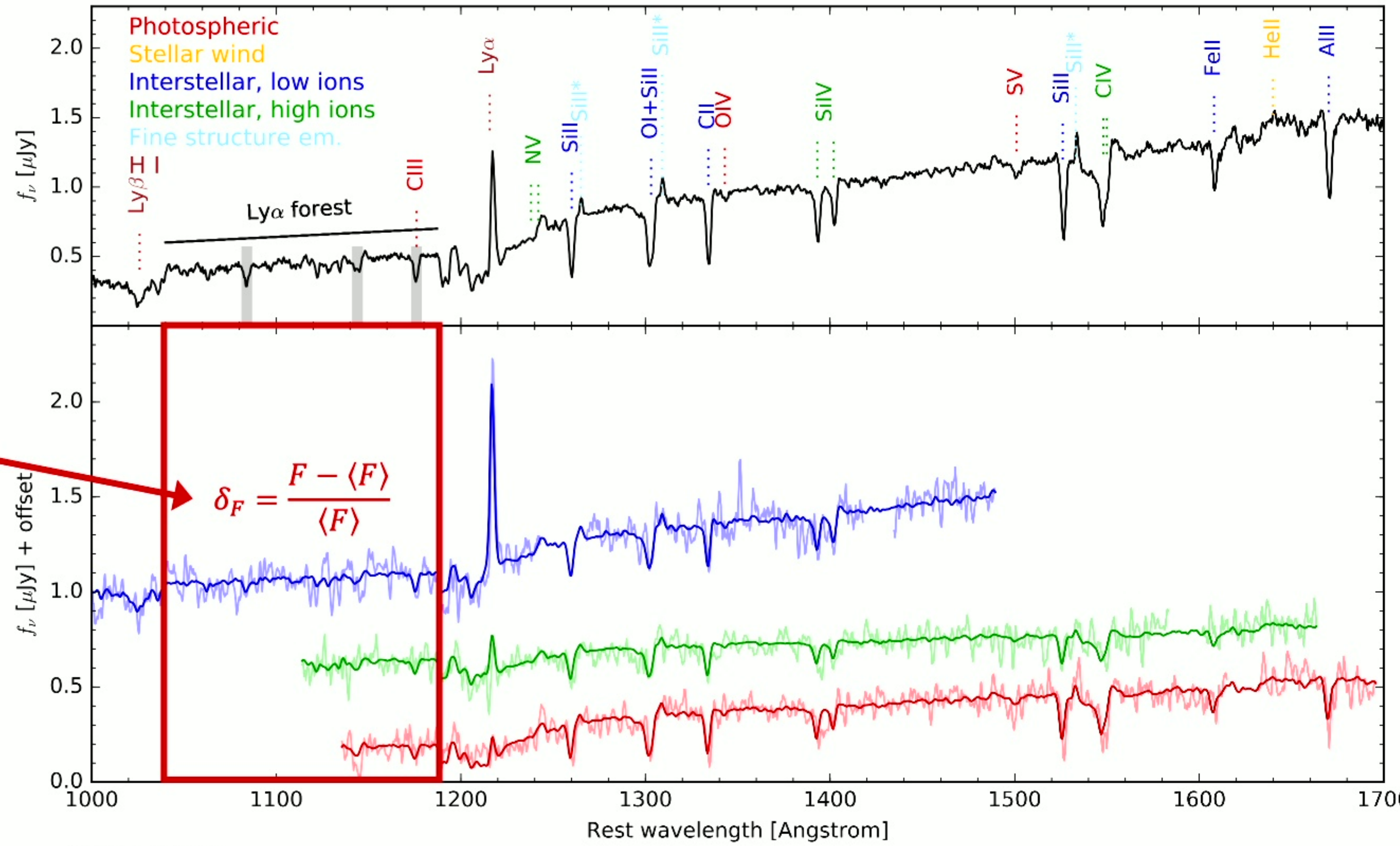
LATIS
Lyman-Alpha Tomography IMACS Survey
ABN+ 2020
- Mapped IGM from z=2.2-2.8 over 1.7 deg^2
- 3 surveys fields (COSMOS, CFHTLS D1 & D4)
- Targets are z ~ 2.2-3.2 LBGs and QSOs
- Limiting mag r < 24.8 (~0.7 L*)
- Obtained ~3600 spectra within this z range
- Typical 12 hr exposures, custom grism/grating
- Continuum-to-noise ratio ~ 2 in the forest @ R~1000
- Mean sightline separation is 2-3 h^{-1} cMpc
- 61 nights over 5 years
- Comparable to the pioneering CLAMATO survey but with ~10x volume (Lee+ 2014, 2016, 2018, Horowitz+ 2022)

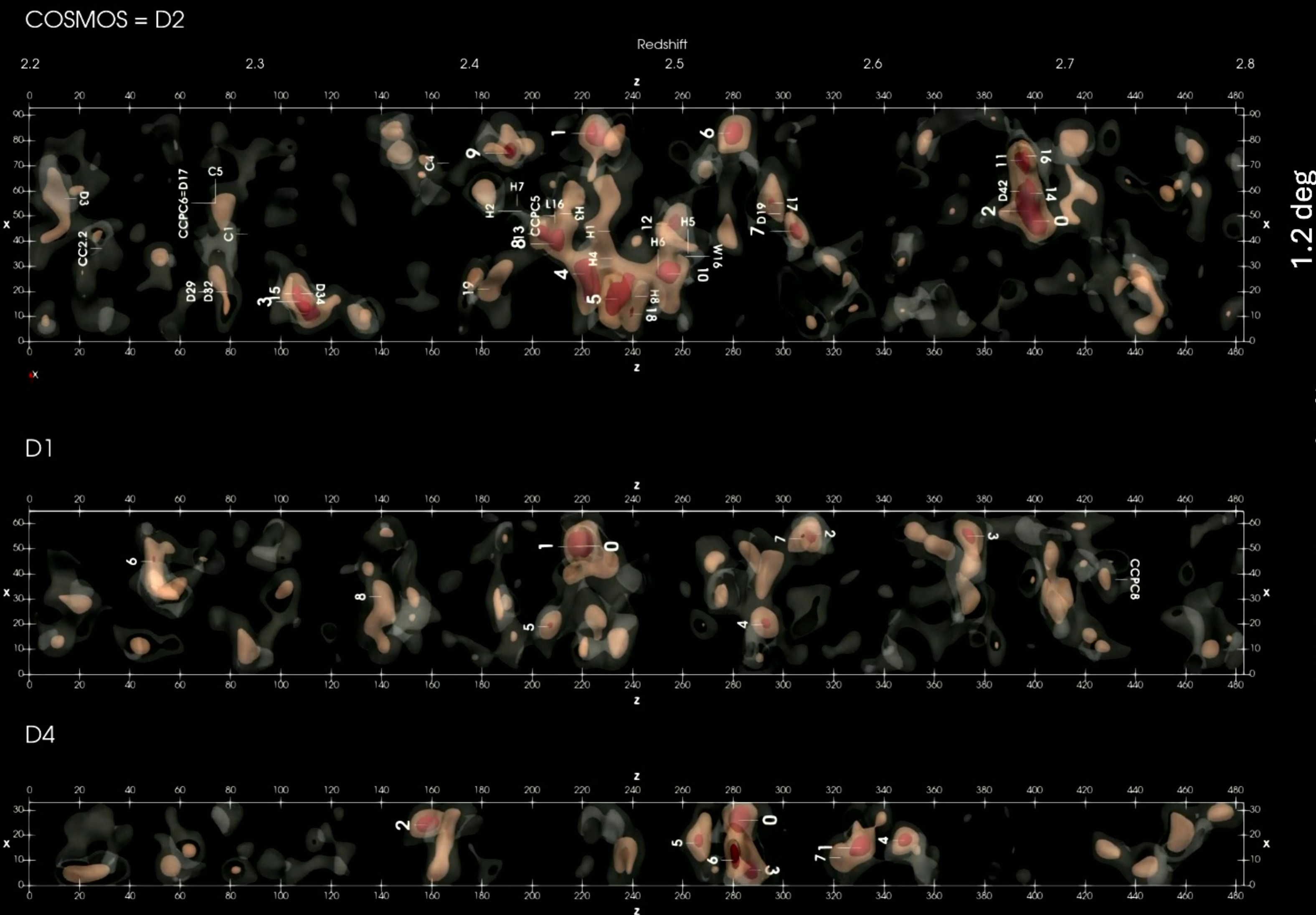
The Lyα Forest in Galaxy Spectra

<u>Key measurement:</u>

Lyα transmission fluctuation (or flux contrast)



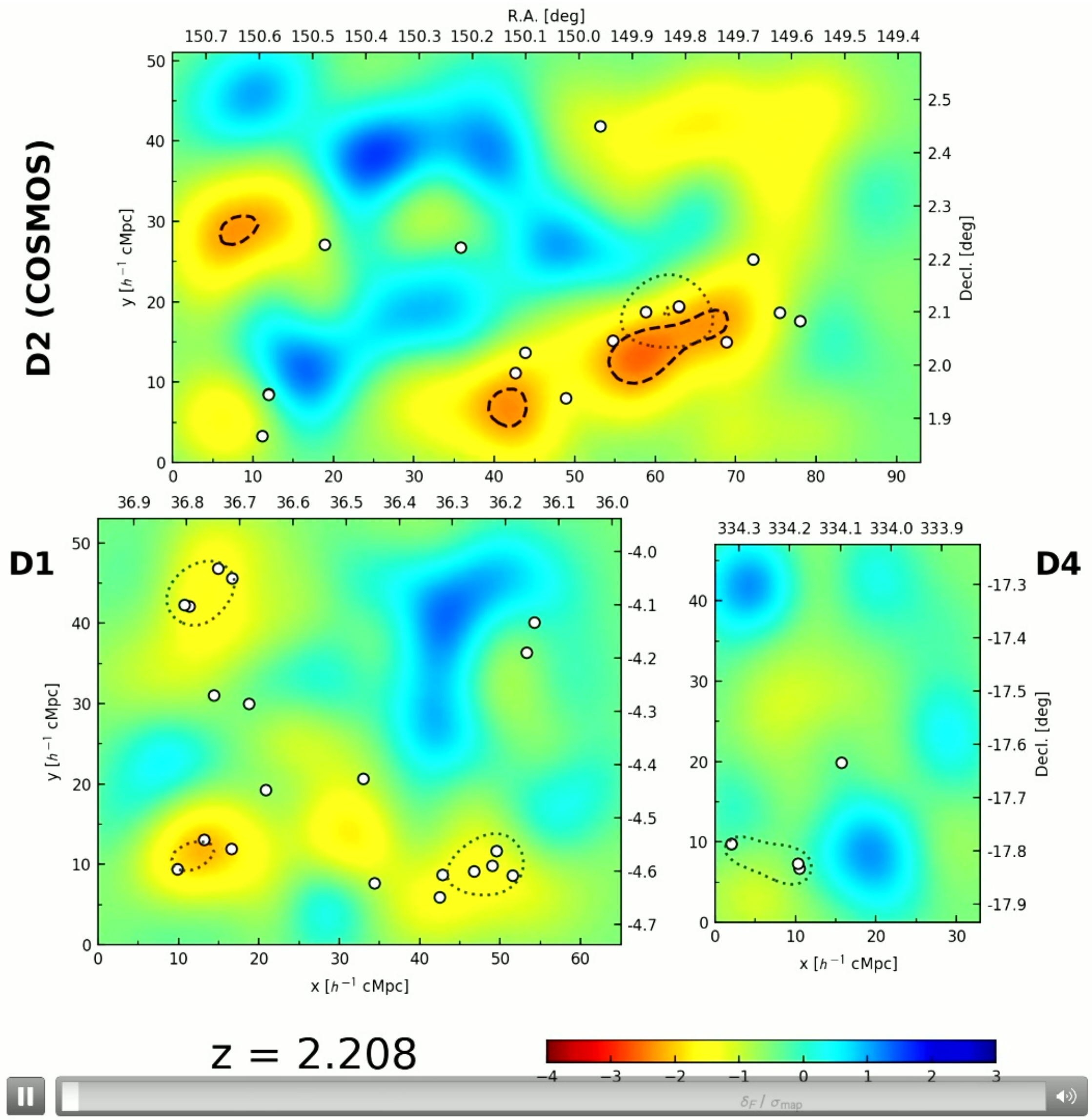
ABN+ 2020



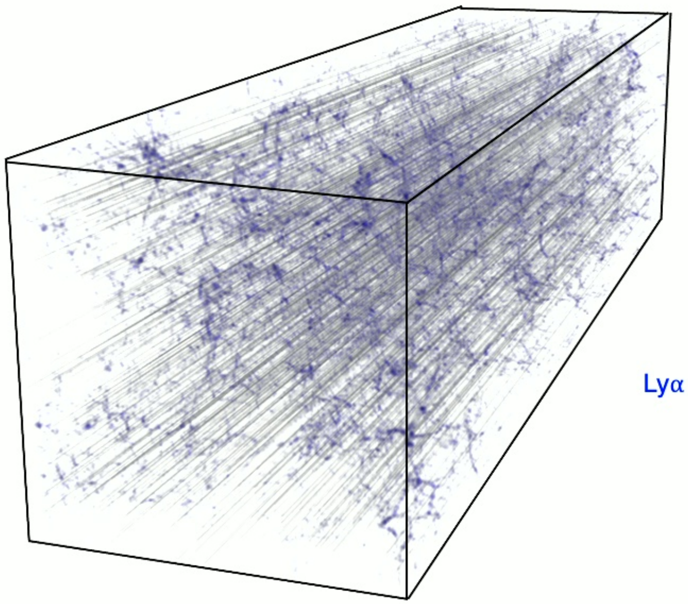
3D maps of IGM Lyα absorption in 3 fields

redder/darker → more absorption, higher density

Resolution
σ = 4 h^{-1} cMpc
FWHM ~ 14 cMpc


R.A. [deg]
D2 (COSMOS)
D1
D4
y [h^{-1} cMpc]
x [h^{-1} cMpc]
Decl. [deg]
z = 2.208
δ_F / σ_{map}

Mimicking LATIS in cosmological simulations



Dark matter only simulations (MultiDark)

We can estimate the Lyα absorption from the matter density with a simple analytic method that balances *photoionization* and H *recombinations*:

$$\tau \sim n_{HI} \sim \frac{\rho^2\, T^{-0.7}}{\Gamma}$$

Lyα optical depth

Density & temperature

Photoionization rate

For most of the IGM gas:

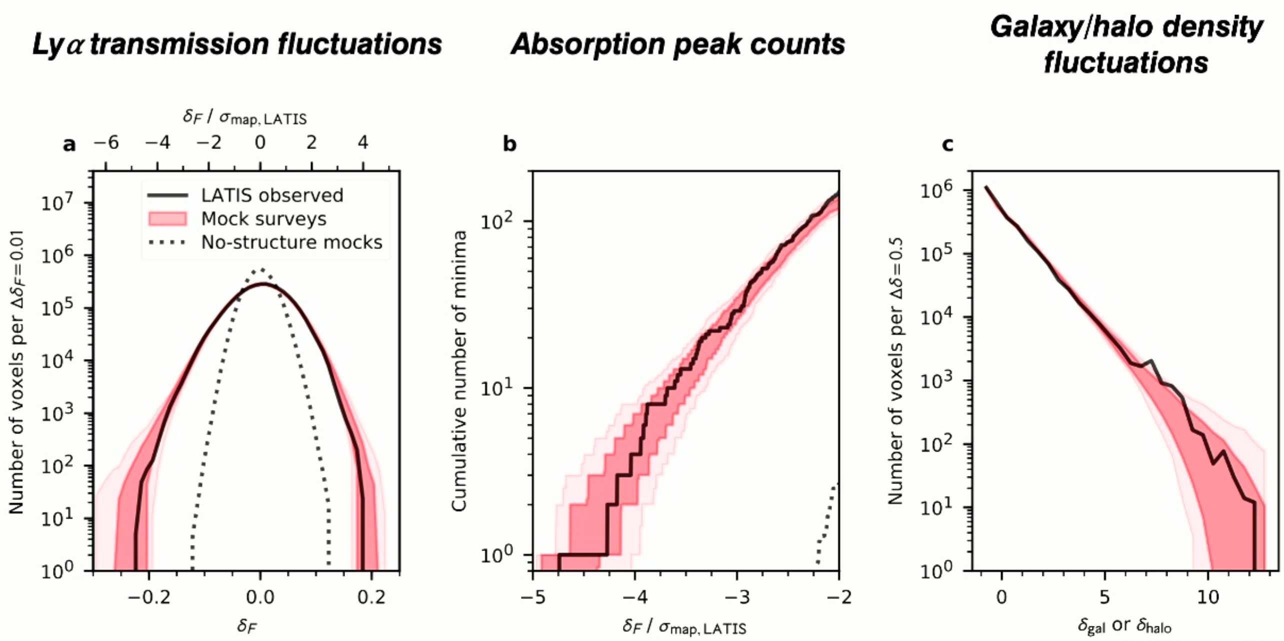
$$T \sim \rho^{0.5}, \Gamma \sim \text{constant}$$
$$\Rightarrow \tau \sim \rho^{1.6}$$

This *fluctuating Gunn-Peterson approximation (FGPA)* ignores hydrodynamics (shocks), local sources of ionizing radiation, etc. It's a useful "null hypothesis" – ***deviations indicate interesting astrophysics.***

Mimicking LATIS in cosmological simulations

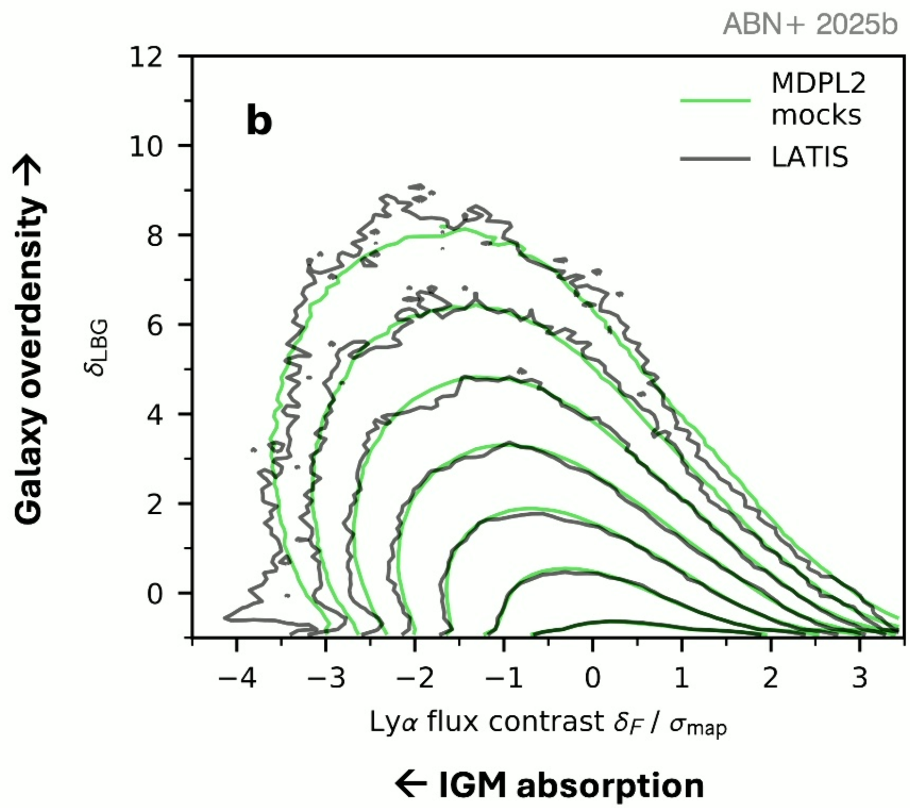
We mock observe sub-volumes of the several cosmological simulations, carefully matching the sightline distribution, S/N, spectral resolution, etc. to the observations.

The observed distributions of galaxy density and IGM opacity fluctuations are normal.



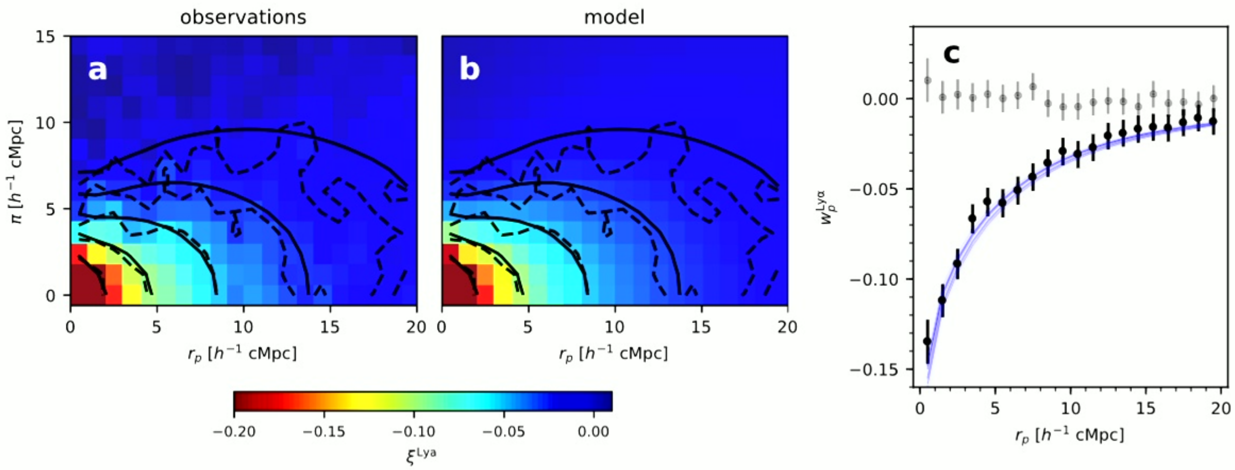
ABN+ 2022

The Galaxy-Lyα Connection



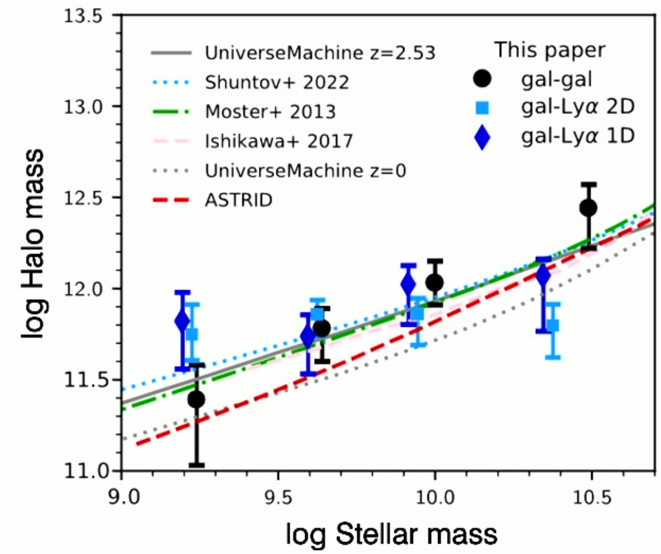
Overall, the joint distribution of Lyα absorption and LBG overdensity (on 4 cMpc/*h* scales) is well described by a very simple model (FGPA + observed galaxies trace their host halos).

The Galaxy-Lyα Connection



- We can measure and model (in the ASTRID simulations) the clustering of LBGs with Lyα absorption. (Bird+ 2021)
- Constraints on the stellar mass—halo mass relation are compatible with (and competitive with) galaxy-galaxy clustering → strict test of the Lyα absorption measurements.

ABN+ 2024; and see Kim & Croft 2008, Rakic+ 2013, Y. Chen+ 2020, Prusinski et al 2025

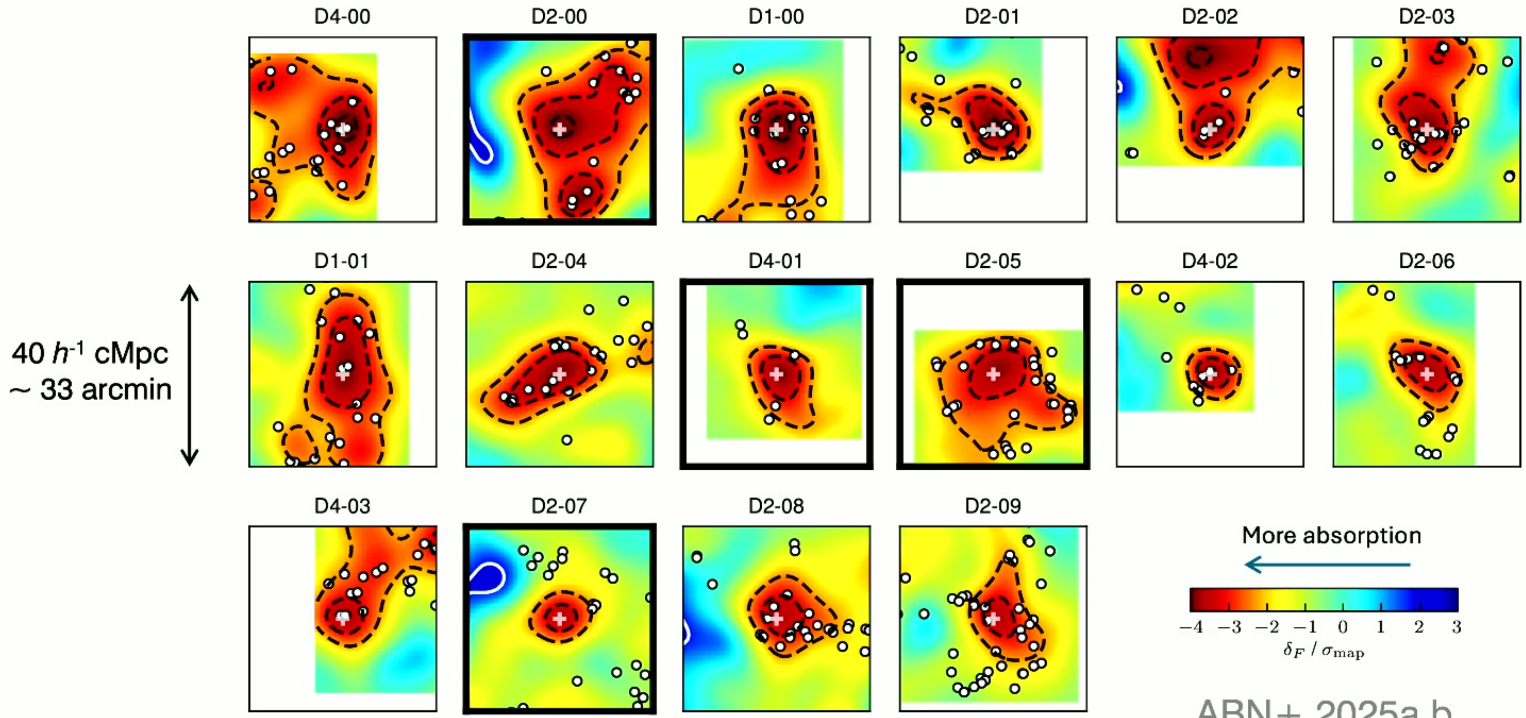


Things look pretty simple!

Things look pretty simple!

Are there any anomalies?

Protoclusters Identified in the LATIS Maps

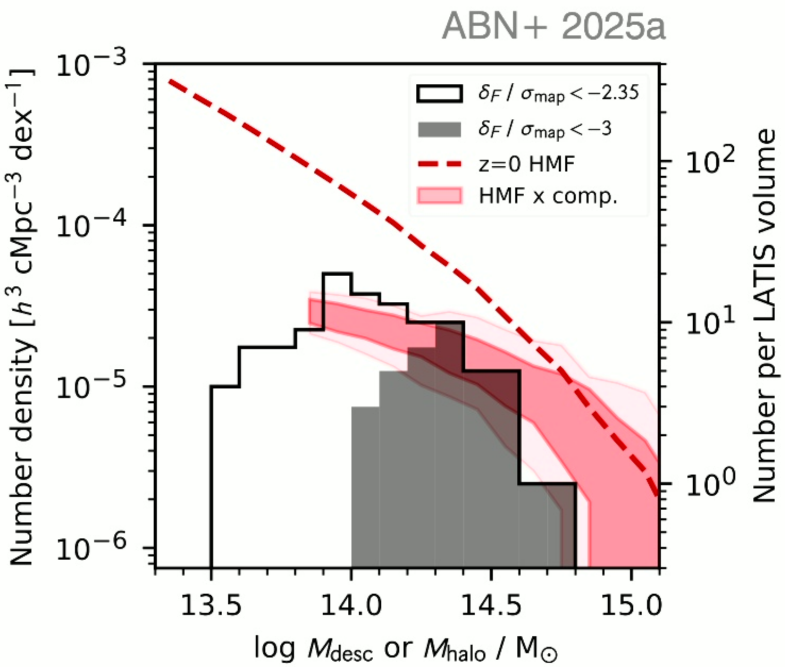


ABN+ 2025a,b

We find 37 overdense regions selected by $\delta_F / \sigma_{map} < -3$.

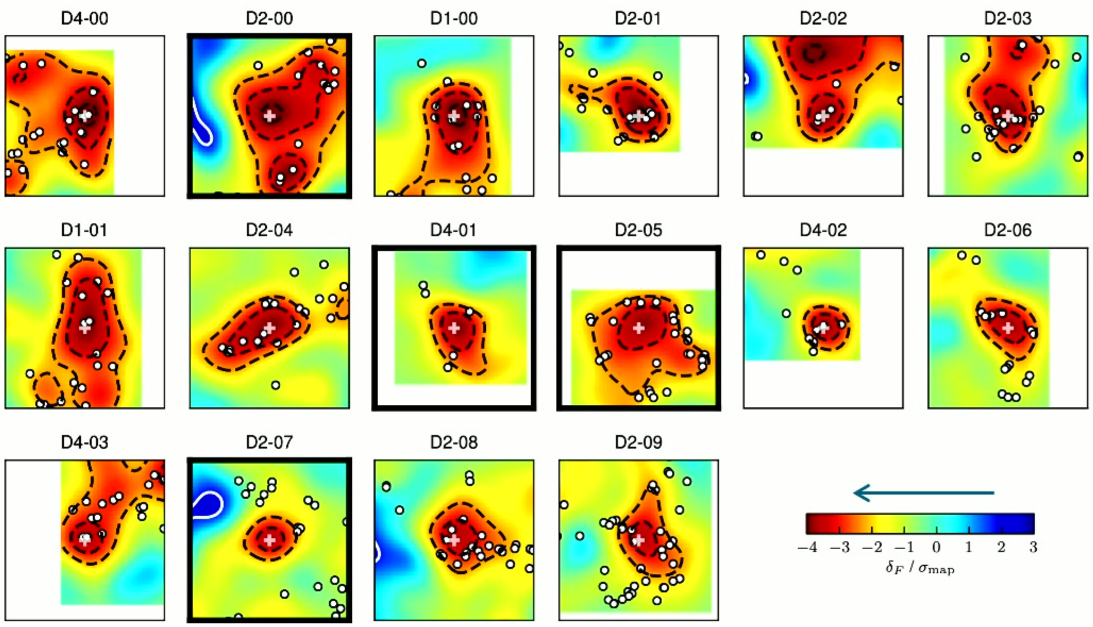
Mocks indicate that among the 16 strongest (shown above), 93% are associated with z=0 halos with masses $>10^{14}$ $M_\odot$ and so can be considered protoclusters.

Protocluster Masses and Counts



The space density and mass distribution are compatible with mocks. *Overall, nothing looks surprising about the IGM-selected protoclusters, as viewed in the IGM maps.*

Anomalies: Strong IGM absorption, Few galaxies?

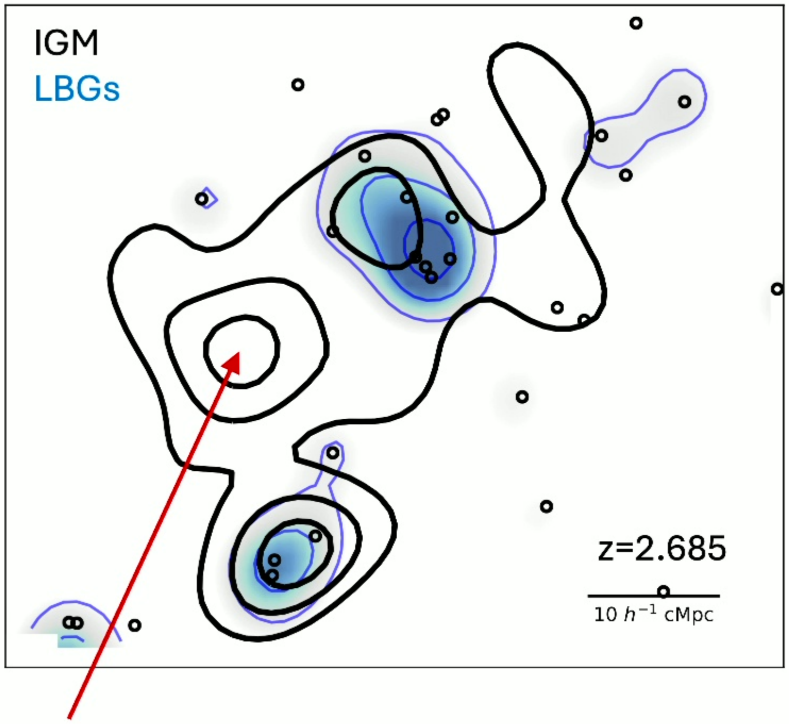


What is surprising: some regions look like massive protoclusters in IGM maps—but contain basically no overdensity of LBGs at their centers (r=4 cMph/h scales).

LATIS has 4 such outliers, more than ~99% of mocks.

Candidate UV-dim Protoclusters

- We think these are best explained as protoclusters with atypical, UV-faint galaxy populations.
  - Dustier or suppressed/quenched star formation
- This is plausible because LATIS rest-UV flux limits ($r \sim 24.8$) misses most galaxies at all stellar masses.
- However, it's hard to understand how a protocluster environment would affect galaxy properties across its full extent (diameter ~ 10 cMpc/h) and down to moderate galaxy masses $\sim 10^{10}\ M_{\odot}$.



Strongest absorption peak in LATIS COSMOS map.
No sign of LBGs in LATIS, VUDS, zCOSMOS.

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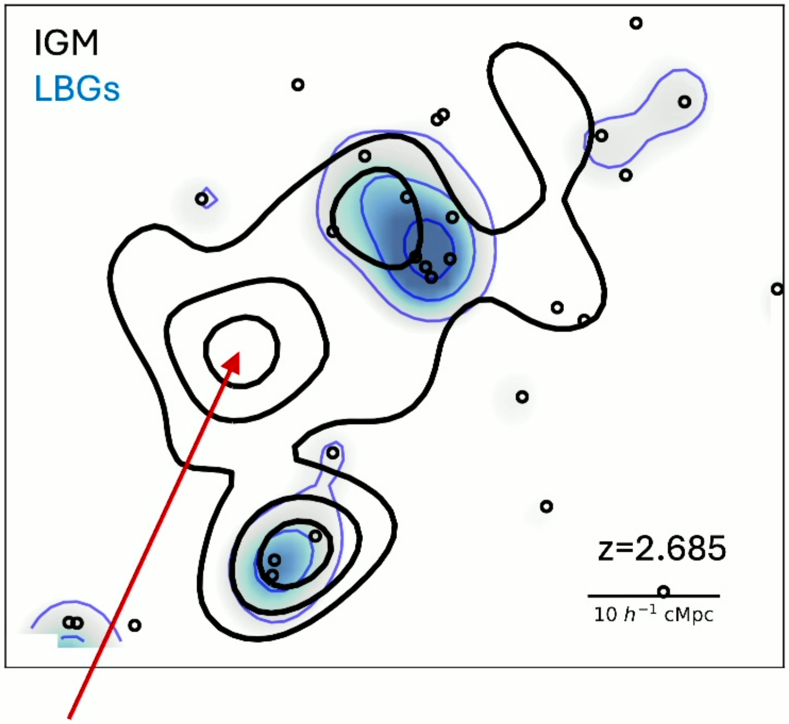
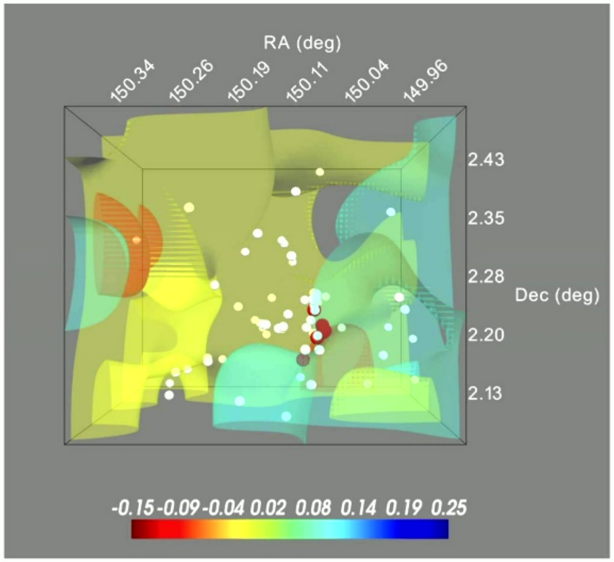
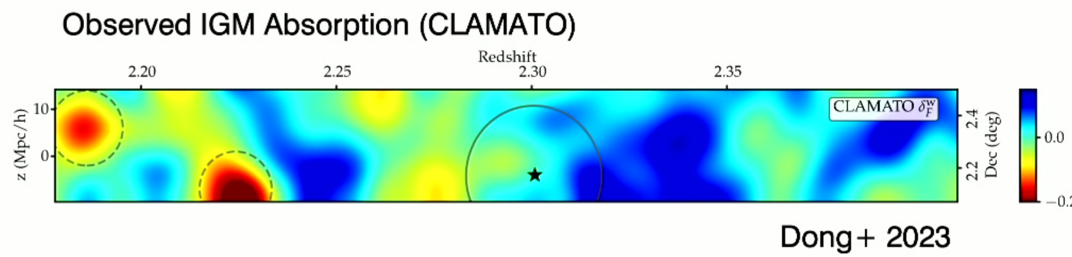
- However, it's hard to understand how a protocluster environment would affect galaxy properties across its full extent (diameter ~10 cMpc/*h*) and down to moderate galaxy masses $\sim 10^{10}\ M_\odot$.
- Need to confirm by locating the missing galaxies at other wavelengths – underway!



Strongest absorption peak in LATIS COSMOS map. No sign of LBGs in LATIS, VUDS, zCOSMOS.

“Transparent” galaxy overdensities



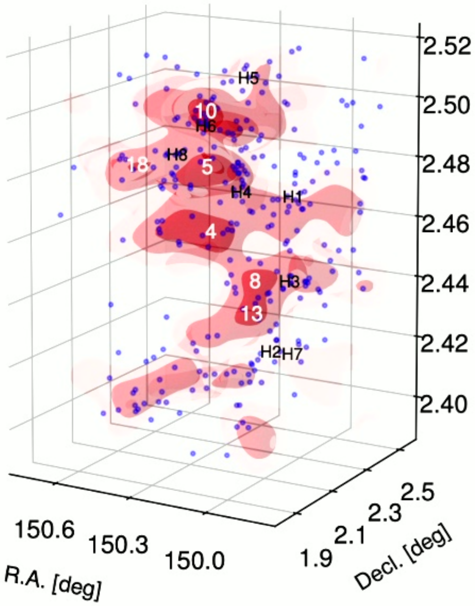


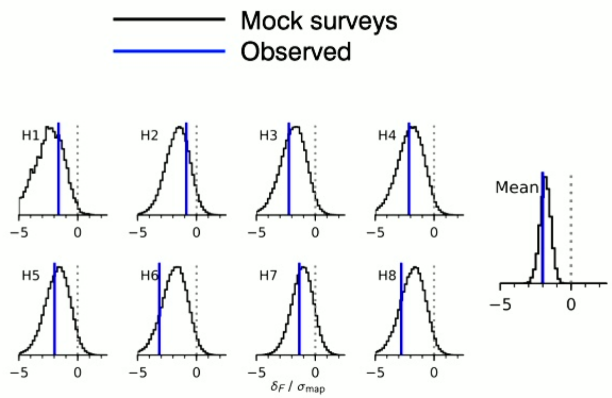
COSTCO-I: a puzzling example of a structure with a high galaxy overdensity yet no excess IGM absorption (Dong+ 2023)

- Hyperluminous QSO?
- AGN feedback over surprisingly large scales, e.g., collimated jets?

Testing Feedback on Protocluster Gas

Shading = IGM absorption
Points = Galaxies (LBGs)





IGM absorption conditioned on galaxy overdensity

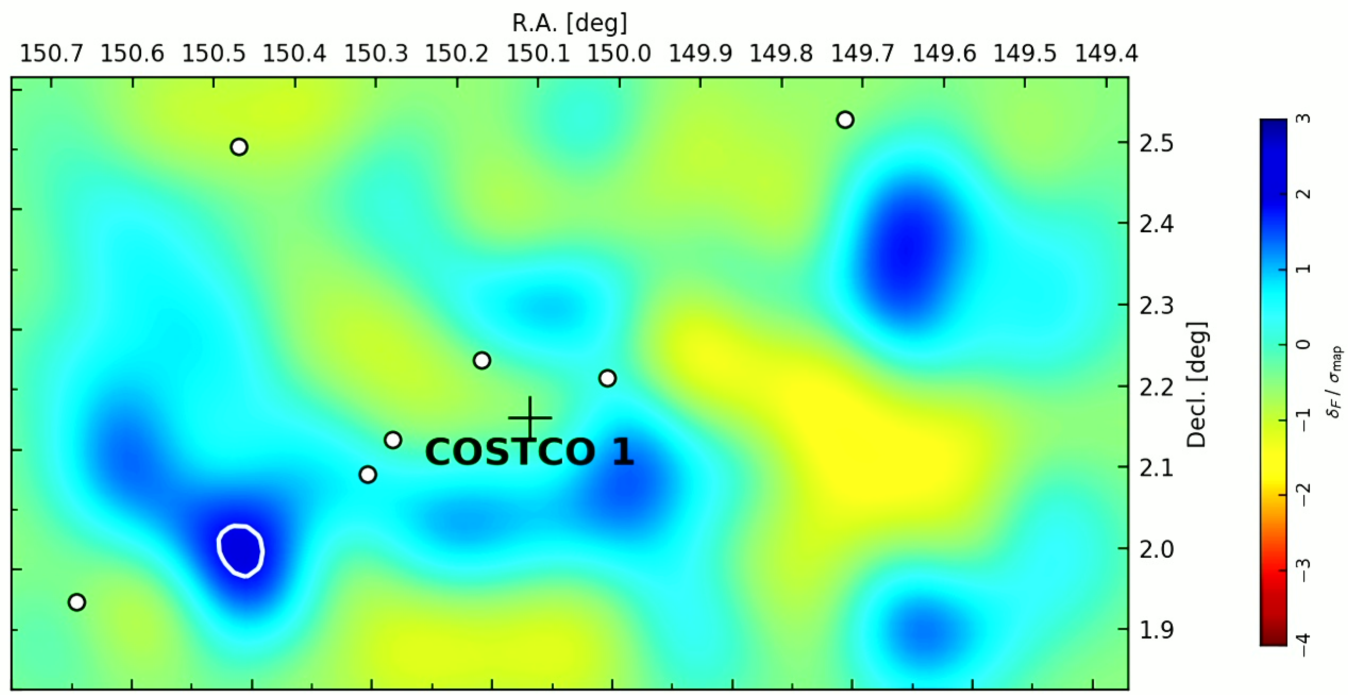
Hyperion is an enormous proto-supercluster at z~2.5 in the COSMOS field.
Cucciati+ 2018

No evidence that the gas within components of Hyperion is more transparent than expected based on the FGPA.

(If *all* dense regions were more transparent than the FGPA, LATIS would have too many strong Lyα absorption peaks.)
ABN+2025a,b

"Transparent protoclusters" like COSTCO-I are probably not very common but may be illuminating.

“Transparent” galaxy overdensities



The LATIS maps show no excess IGM absorption at COSTCO-I too—but also no galaxy overdensity. The Dong et al overdensity is detected in NIR-selected galaxies.
A better galaxy census in these fields might enable us to find more examples.

Data Release

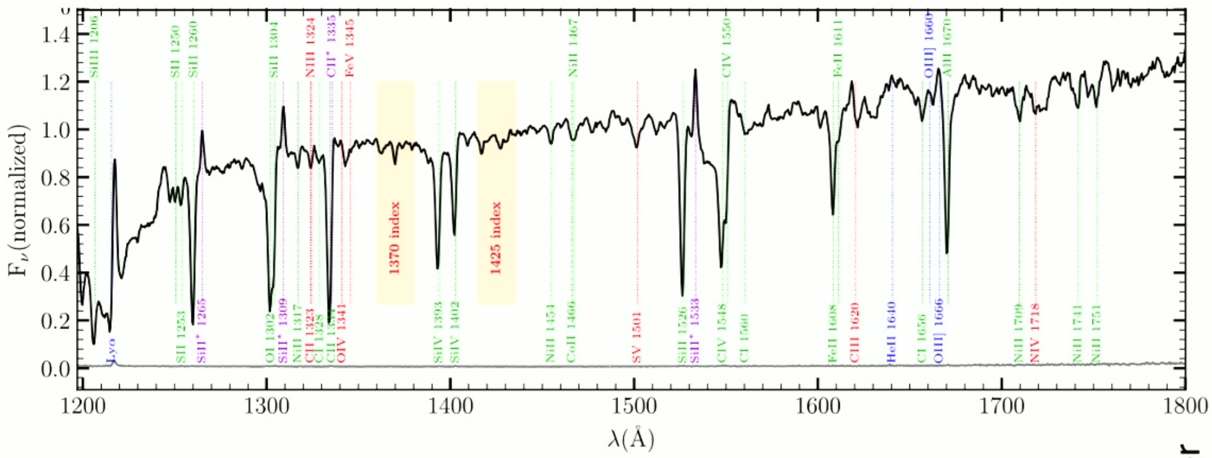
LATIS Data Release: ~ 4200 Spectra of $z \sim 2-3$ Galaxies, Redshifts, and IGM Tomography Maps

Andrew B. Newman[1] Gwen C. Rudie[1] Guillermo A. Blanc[1,2] Daniel D. Kelson[1] Nima Chartab[1,3]
Enrico Congiu[4] Victoria Pérez[2] Mahdi Qezlou[5] Simeon Bird[6] Brian C. Lemaux[7,8] and
Olga Cucciati[9]

In review now!

- $\sim$4200 spectra of $z > 1.7$ galaxies
- Calibrated redshifts with $\sim$100 km/s uncertainties
- Lyα transmission fluctuations in $\sim$470,000 pixels
- IGM tomography maps
- Mock surveys

Stellar Mass-Metallicity Relationship

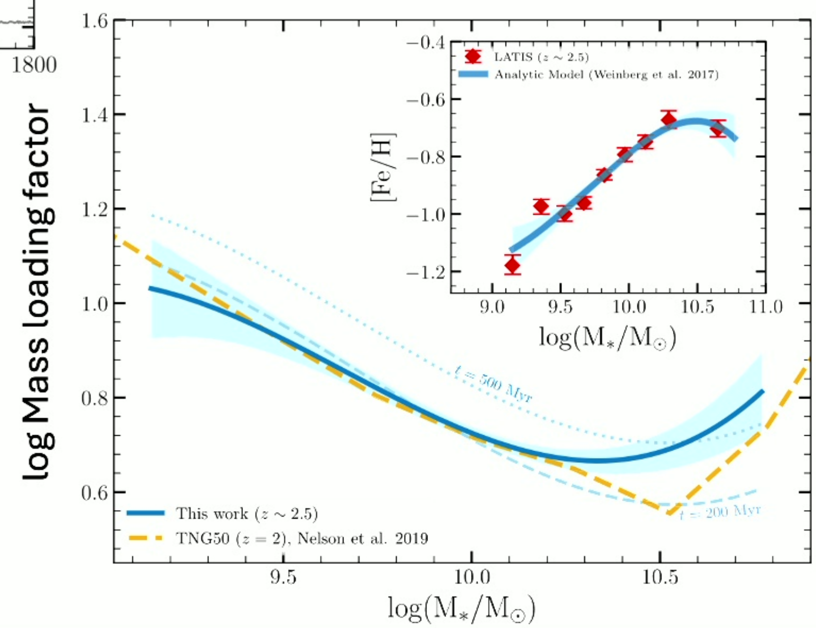


- Far-UV spectra constrain the *stellar* mass-metallicity relation at z~2.5.
- High-mass flattening of MZR is interpreted as change in the properties of galactic winds.
  - Consistent with IllustrisTNG and onset of AGN-driven outflows at high masses.

Chartab+ 2022

see also Steidel+ 2016, Cullen+ 2019, Kashino+ 2021

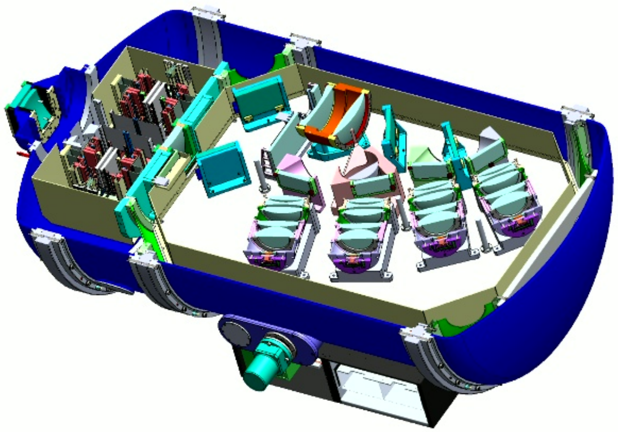
Nima Chartab



MIRMOS

The Magellan Infrared Multi-object Spectrograph

PI: N. Konidaris, Project Scientists: G. Rudie, ABN



A cryogenic multi-object spectrograph and IFU for Magellan

- Simultaneous coverage of 0.89-2.4 μm @ R~3700
- **MOS mode**: Wide 13'x3' field with 92 robotically placed slits
- **IFU mode**: 26"x19" slicer
- High efficiency (VPH gratings, fast optics)
- Diffuser for exoplanet transmission spectroscopy

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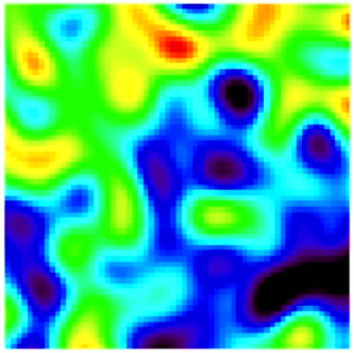
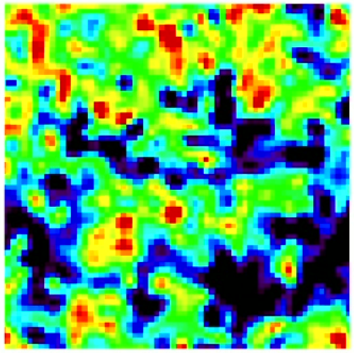
IDG INSTRUMENT DEVELOPMENT GROUP

Extremely Large Telescopes

Roughly simulated Lyα tomography maps



6-10m: LATIS/CLAMATO/PFS



ELTs

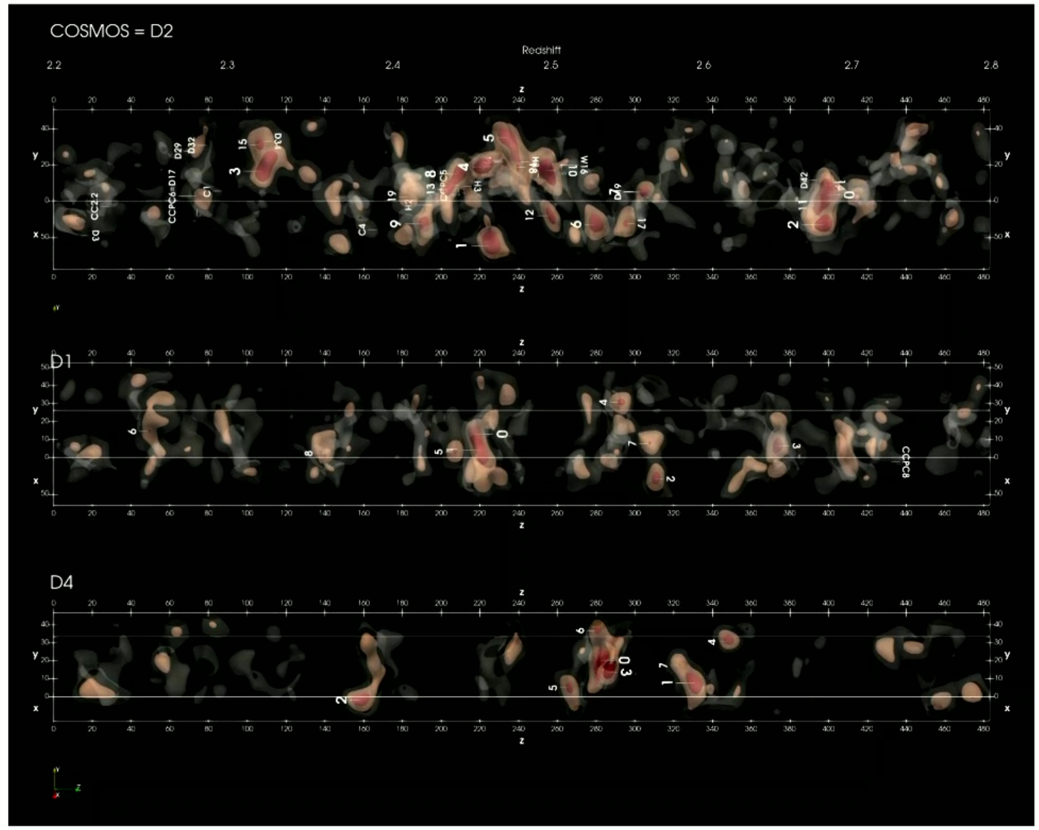
Just 1 mag more depth gives ~10x more galaxies and sightlines enabling:

- Drastically more detailed HI tomography
- Multi-sightline probes of metals and HI within individual galaxy halos: CGM tomography

Astro2020 white paper & US ELT example key project
Newman, Bezanson, Johnson, Rudie, et al.

Summary

- IGM tomography provides a new probe of the cosmic web in the distant universe with complementarity to galaxy surveys.
- Generally, galaxies and IGM absorption consistently trace the underlying large-scale structure according to simple models.
- But in some regions, we find disconnects among the distributions of IGM absorption and galaxy subpopulations, which we struggle to understand with current galaxy formation and feedback models.
- We are now using LATIS to examine the early stages of environment-dependent galaxy evolution, but more complete spectroscopic galaxy surveys are needed particularly in NIR.
- With ELTs, similar techniques can be applied on smaller scales to map gas/metal flows in the CGM.



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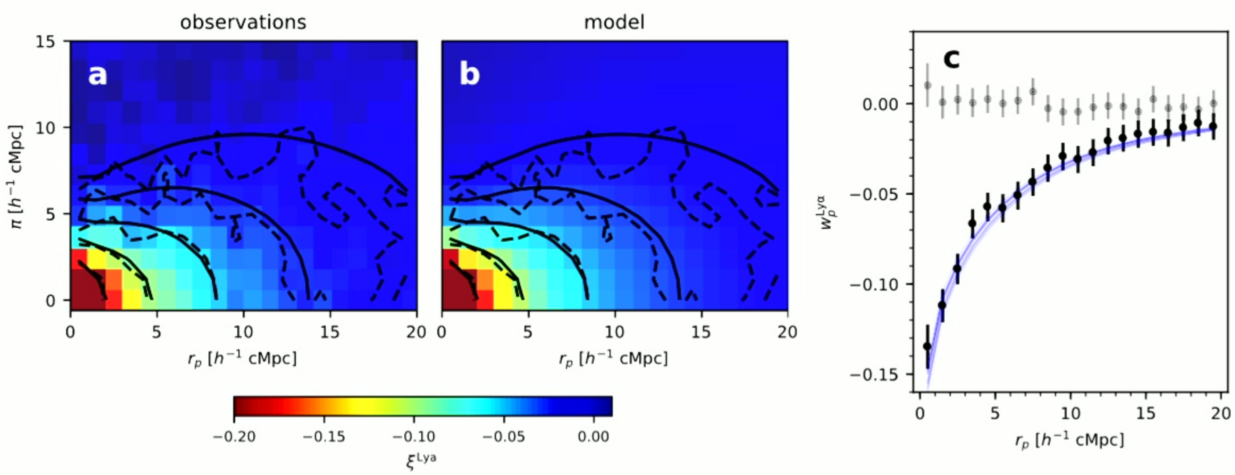

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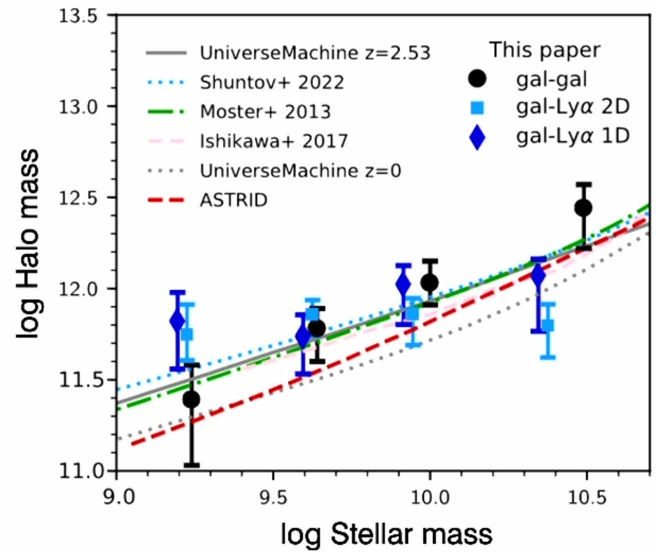
- Constraints on the stellar mass—halo mass relation are compatible with (and competitive with) galaxy-galaxy clustering → strict test of the Lyα absorption measurements.

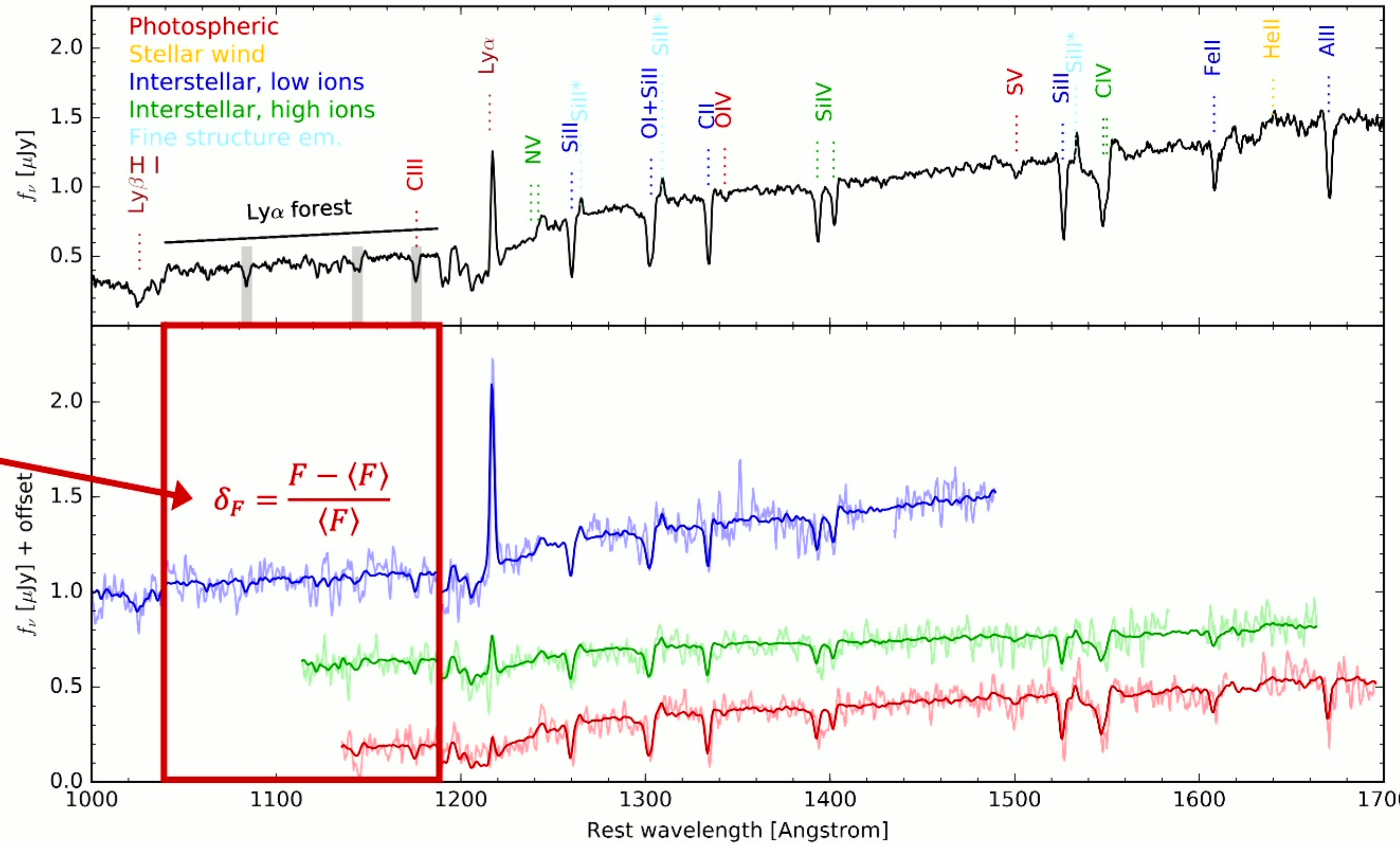
ABN+ 2024; and see Kim & Croft 2008, Rakic+ 2013, Y. Chen+ 2020, Prusinski et al 2025



The Lyα Forest in Galaxy Spectra

<u>Key measurement:</u>

Lyα transmission fluctuation (or flux contrast)



ABN+ 2020