



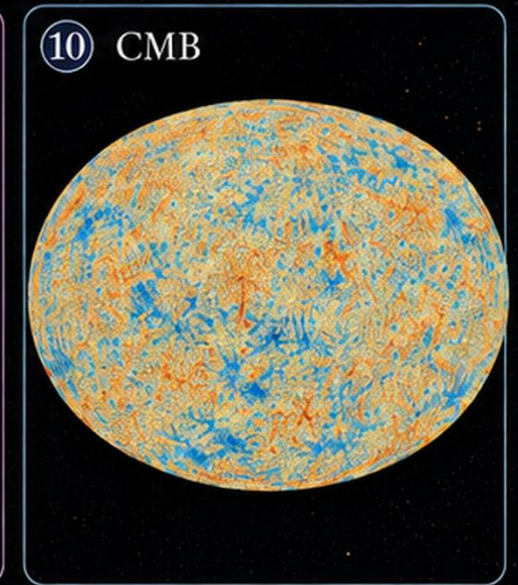
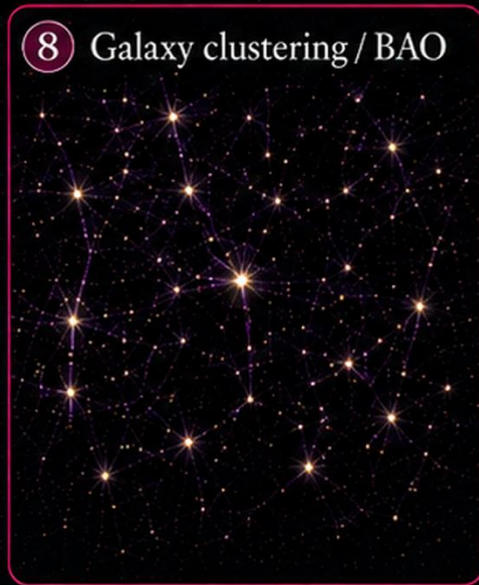
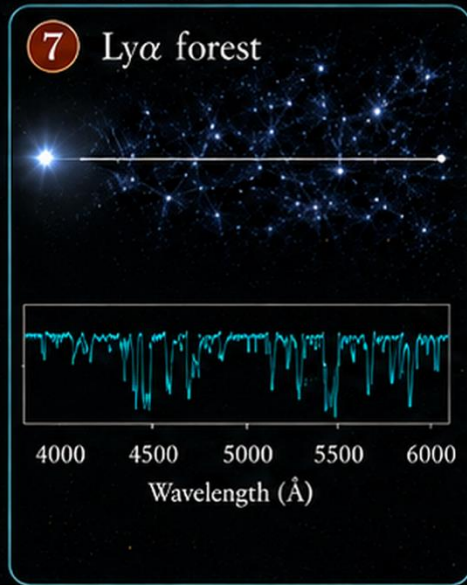
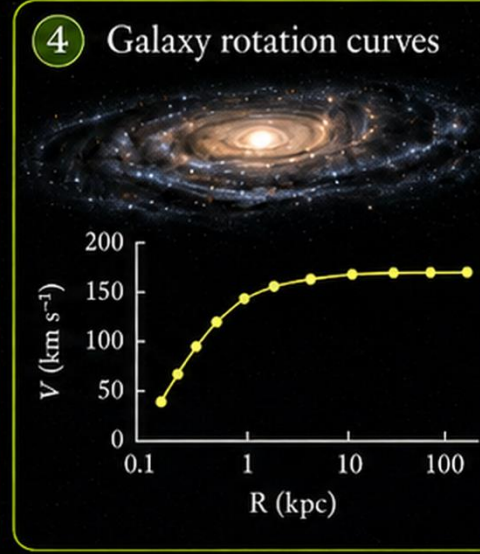
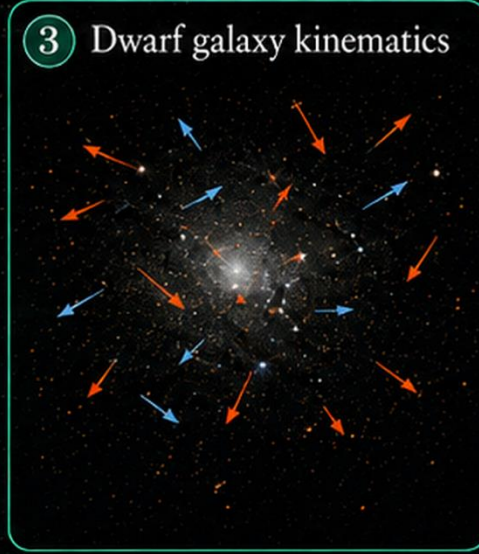
# Mapping Large-Scale Structure Using Intergalactic Gas

Drew Newman

BiCoQ Conference / 18 June 2026

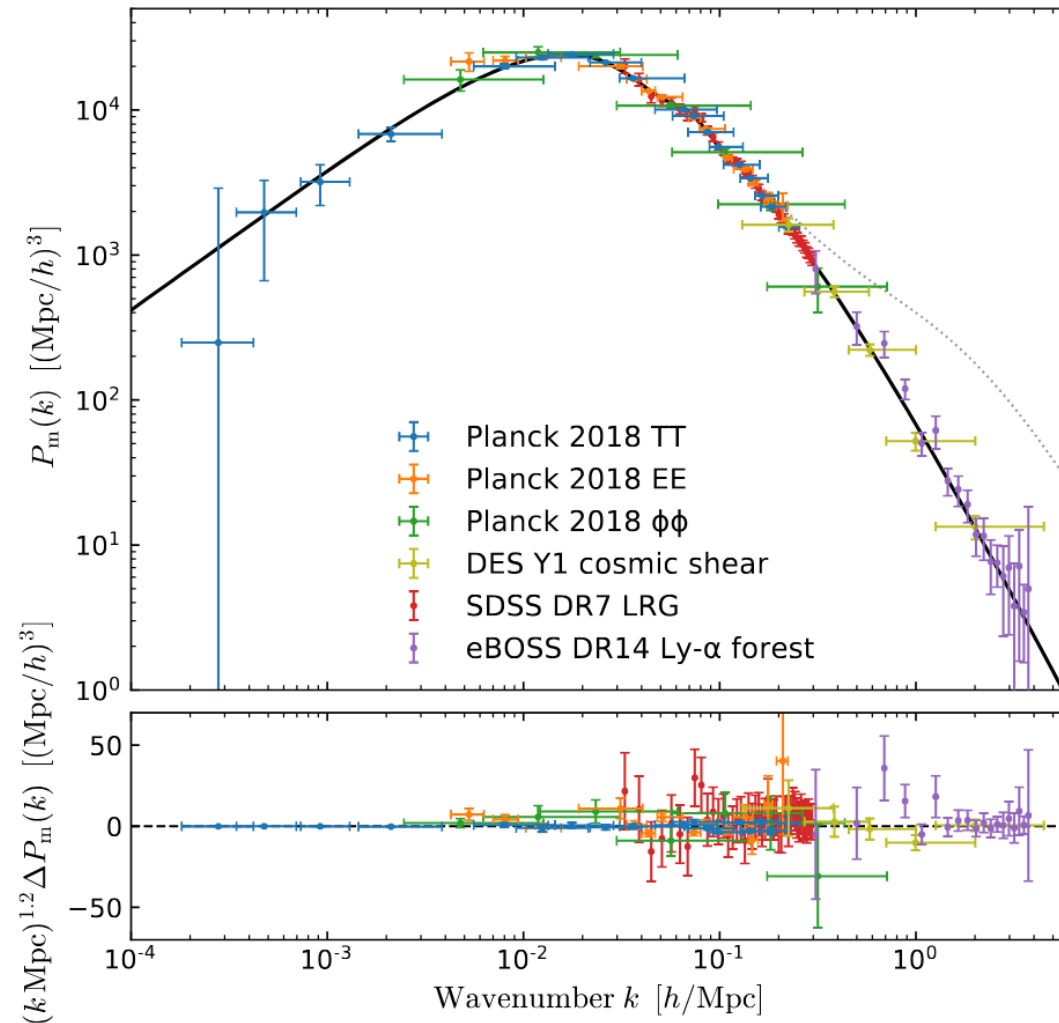
LARC and LATIS Collaborations including Nima Chartab, Mahdi Qezlou, Gwen Rudie, Guillermo Blanc, Ian McConachie, Hossein Hatamnia, Simeon Bird, Vera Gluscevic, Brian Lemaux, Dan Kelson, Andrew Benson, Caitlin Casey, Jorge Zavala, Alan Dressler





Many astronomical probes constrain the amount and spatial distribution of dark matter, from sub-galactic to cosmological scales.

# Matter power spectrum



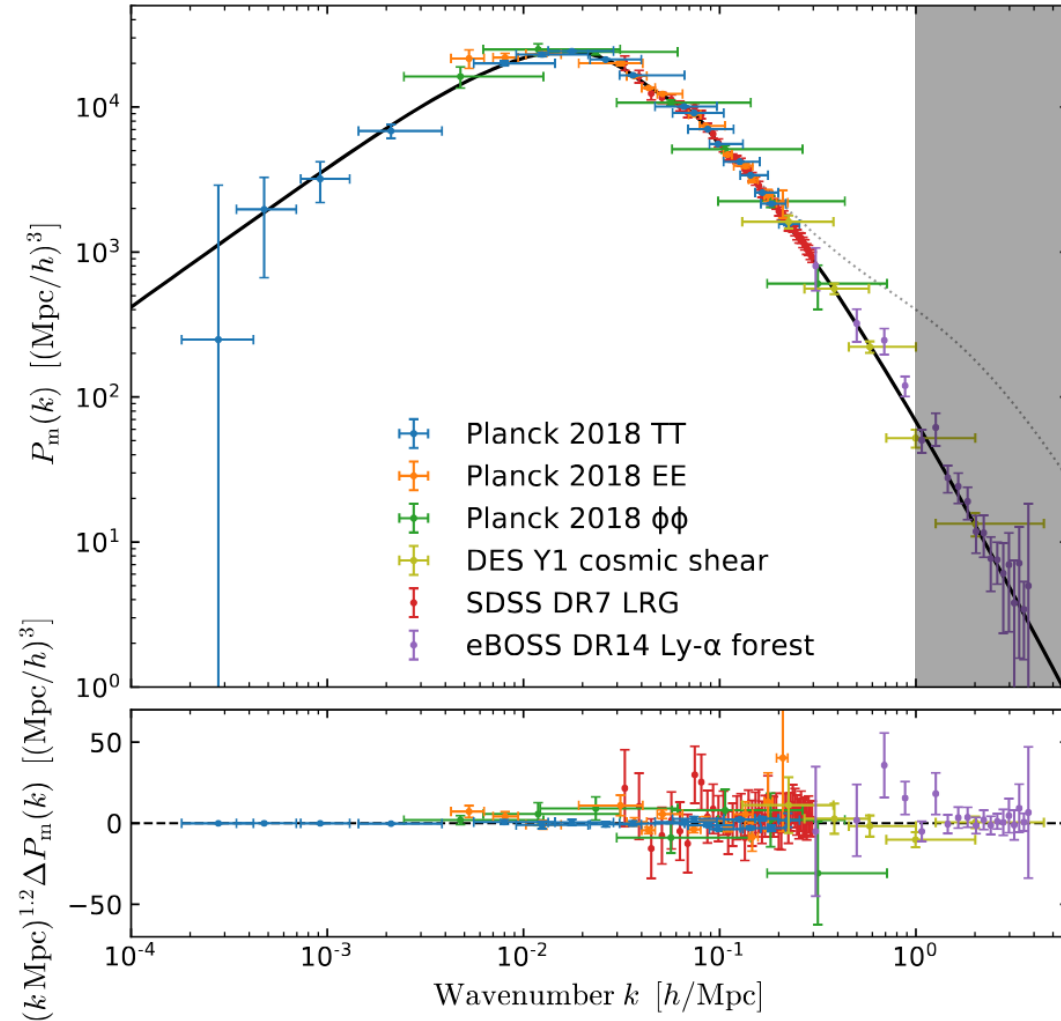
Chabanier+ 2019

The variance of matter density fluctuations on different spatial scales is represented by the *matter power spectrum*.

It is now tightly constrained on “large” scales ( $k < 0.3 h/\text{Mpc}$ ) by multiple probes and is well fit by  $\Lambda$ CDM.

(There is some possible  $\sim 2\sigma$  tension on the amplitude.)

# Density fluctuations on small scales



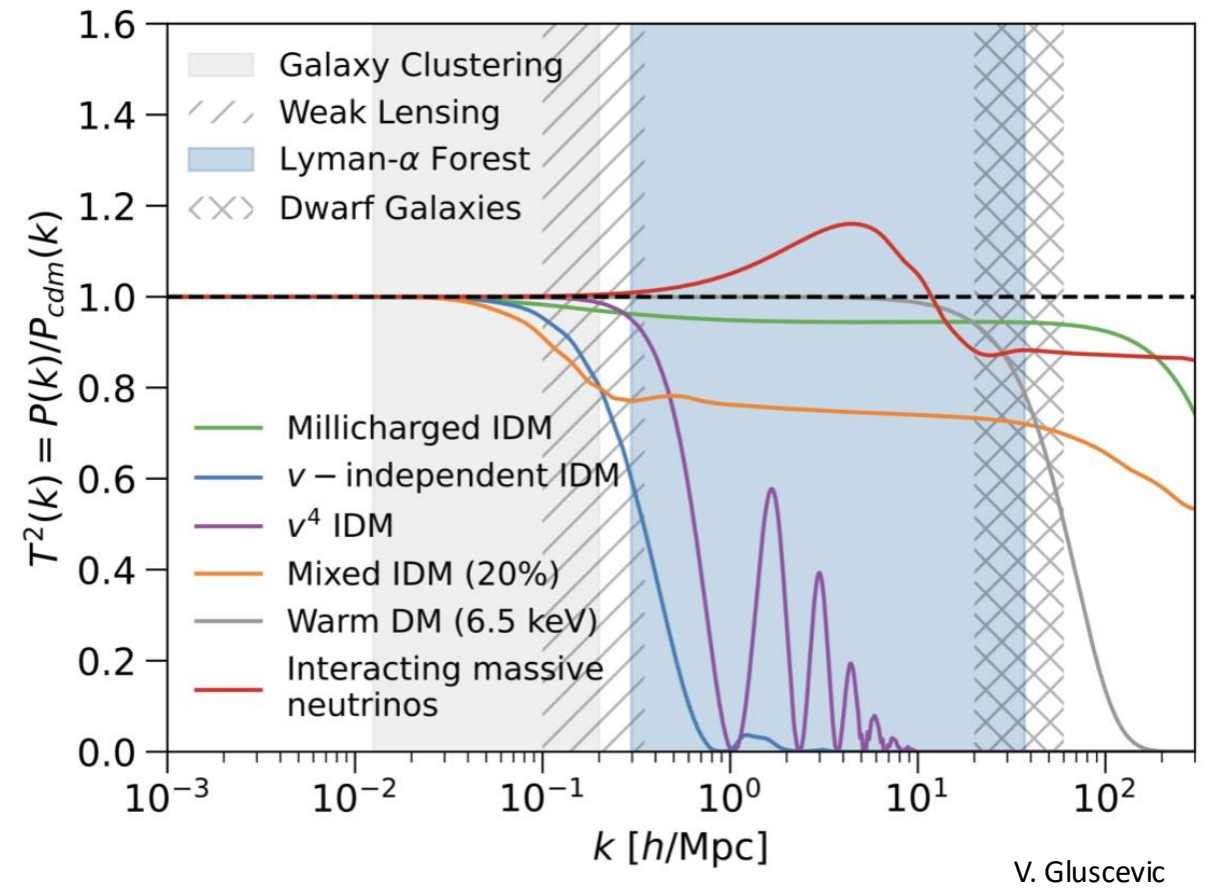
Small scales contain information on the “clumpiness” and interaction history of dark matter.

They are also less observationally constrained.

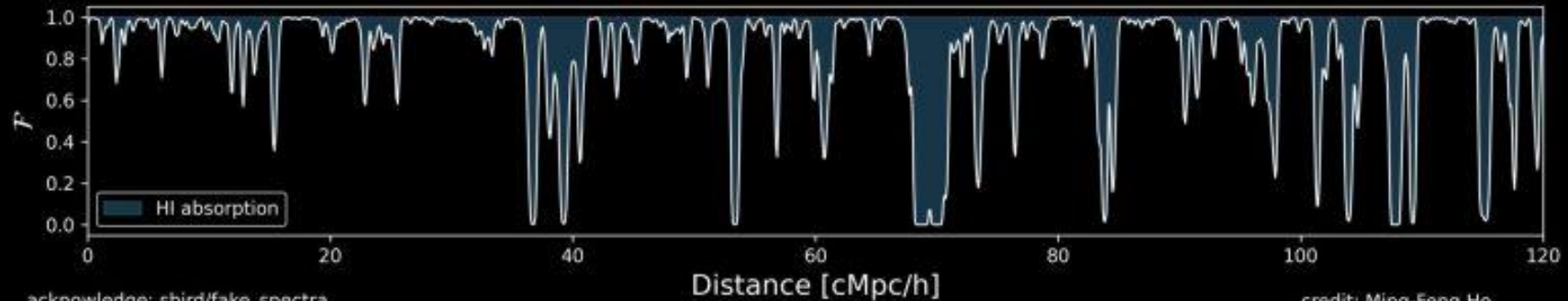
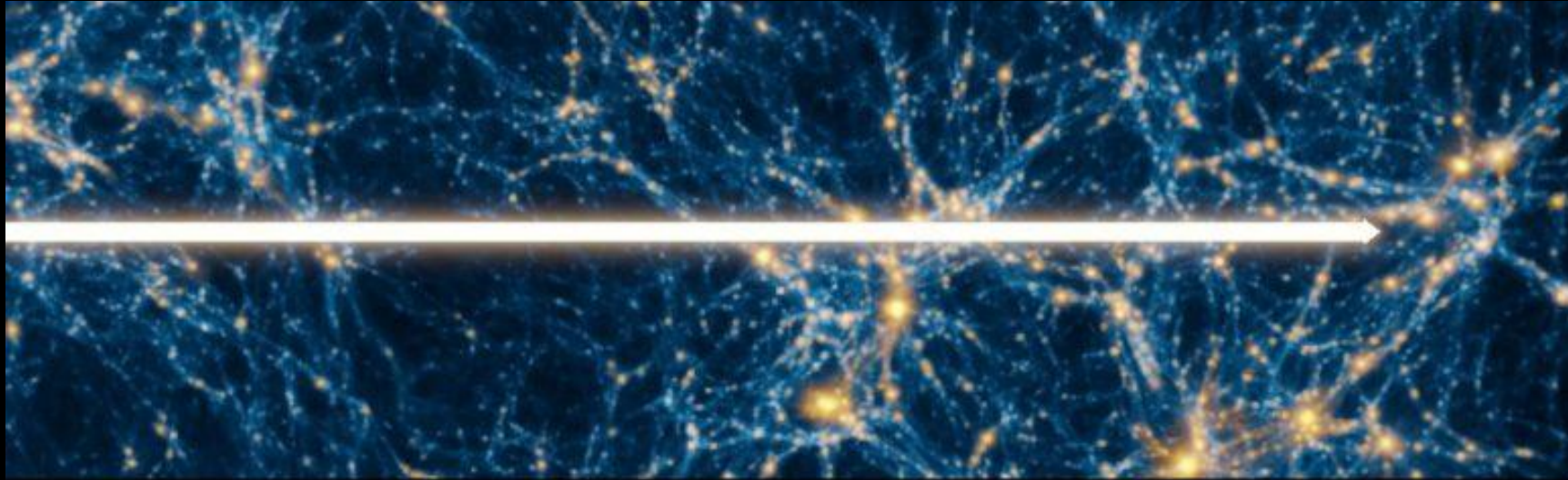
Are density fluctuations suppressed or modified (relative to  $\Lambda$ CDM) below a certain scale?

# What can be constrained?

- Thermal relic mass
- Sterile neutrino mass and production mechanism
- Ultralight/fuzzy particle mass
- DM-DM and DM-baryon scattering
- Coupling to dark radiation
- Annihilation/decay rates
- Mixtures of multiple types of DM



# Lyman- $\alpha$ Forest

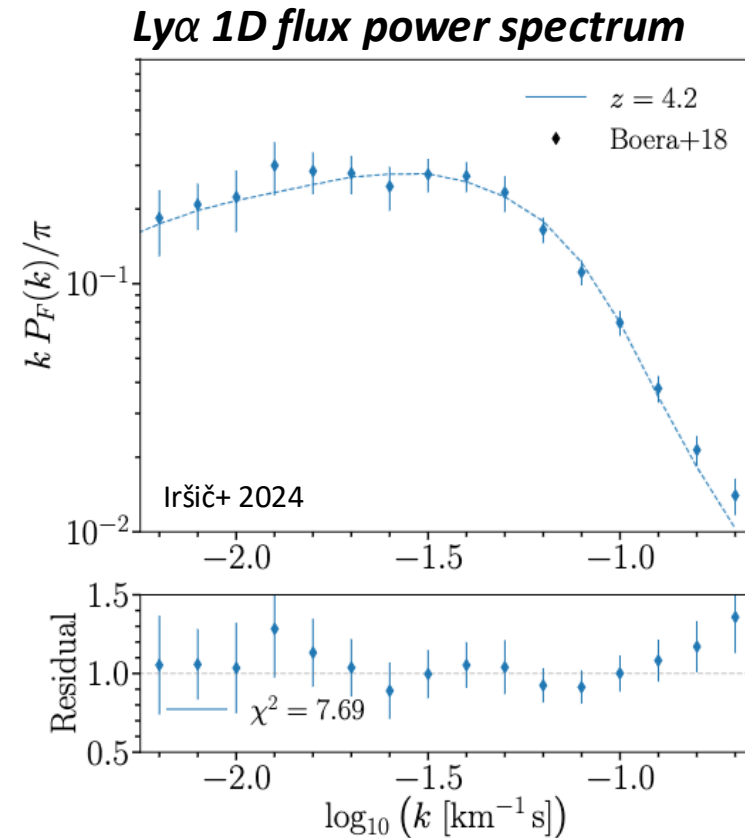
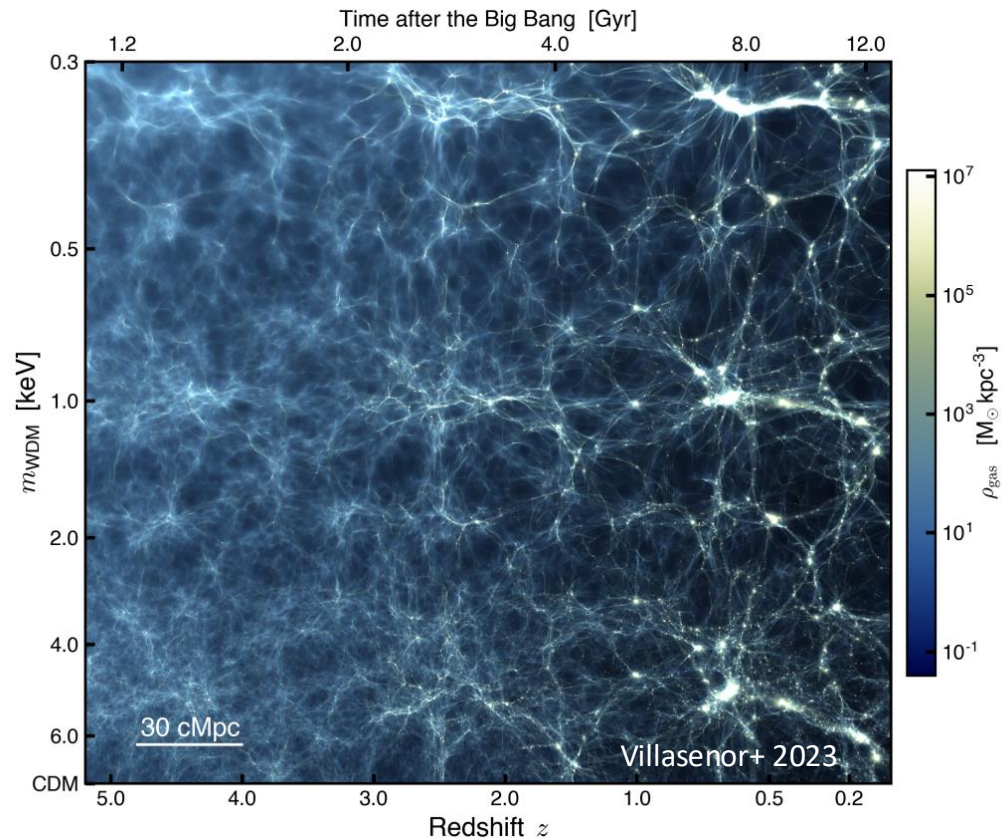


Along with dark matter, hydrogen pervades the intergalactic medium. A small fraction is atomic and absorbs light from a background source at the wavelength of Ly $\alpha$  (and other transitions).

# Why is the Lyman- $\alpha$ forest powerful?

- **Huge statistical weight:**  $\sim 3\text{M}$  quasar spectra in DESI
- **Diffuse, intergalactic gas:** Mostly sensitive to gas near mean density, wide range of linear to mildly non-linear scales
- **Small-scale matter clustering:** Sensitive to dark matter physics and accessible to only a few astronomical probes
- **Observable in distant universe ( $z \sim 2-5$ ):** Minimizes small-scale power from non-linear gravitational clustering and complications from galaxy formation.

# Constraints on warm dark matter



Free-streaming of warm dark matter truncates the power spectrum on small scales. Recent Ly $\alpha$  forest analyses give lower limits  $m_{\text{WDM}} > 5.7$  keV (Iršič+ 2024) to 3.1 keV (Villasenor+ 2023).

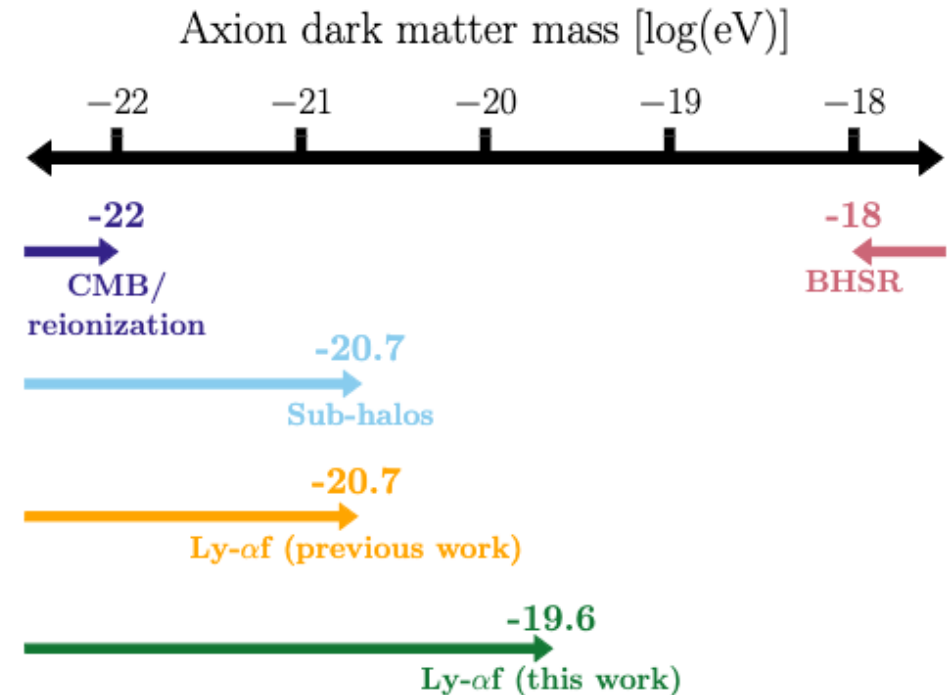
Difficult because gas also filters out small-scale perturbations due to *Doppler broadening* and *pressure smoothing*, which requires knowing about the *temperature* and thermal *history* of the gas.

# Constraints on other dark matter candidates

from 1D Ly $\alpha$  forest data:

- Sterile neutrinos
- DM-baryon scattering
- Dark sector interactions
- Fuzzy dark matter
- Ultralight axion dark matter

e.g., Murgia, Iršič & Viel 2018, Xu, Dvorkin & Chael 2018, Garny+ 2018, Nori+ 2019, Murgia+ 2019, Rogers & Peiris 2021, Decant+ 2022, Rogers, Dvorkin & Peiris 2022, Hooper+ 2022, Buen-Abad+ 2022, ...



*Constraints on “vanilla” ultralight axion mass if it comprises all the dark matter*

Rogers & Peiris 2020

# Limitations

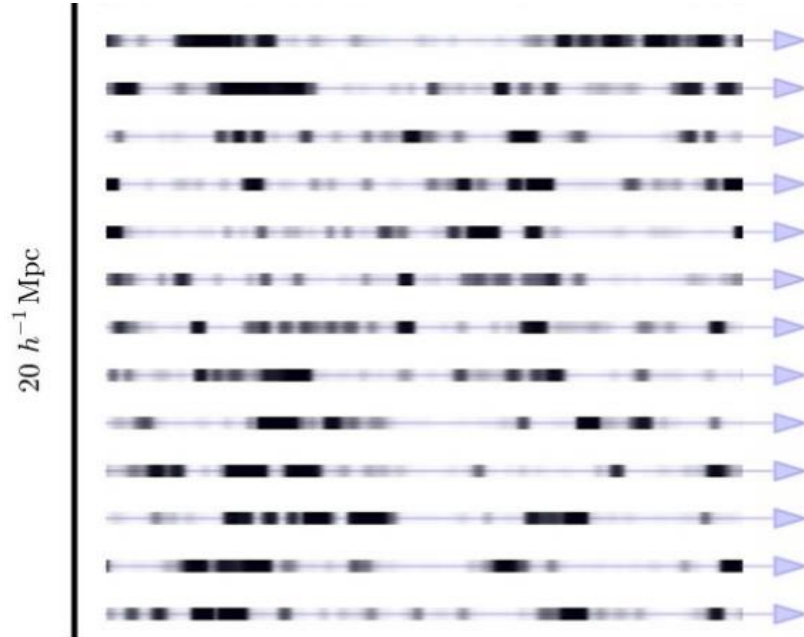
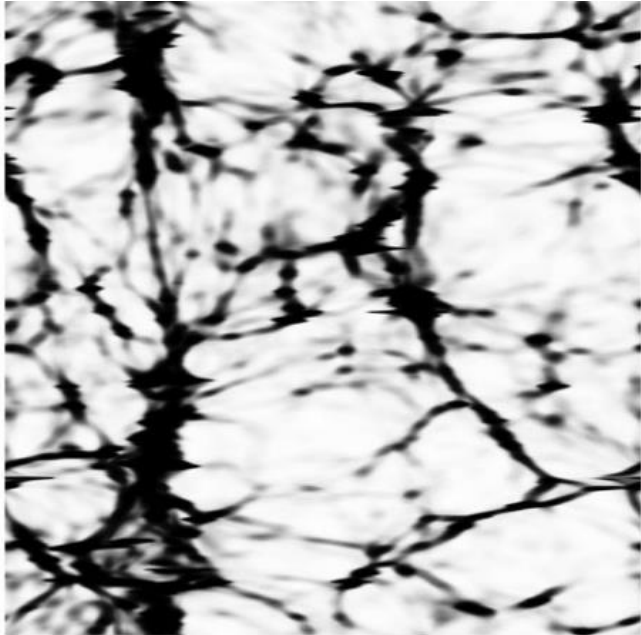
The forest has mostly been a **sparse, 1D** probe (especially on DM-relevant scales):

- **$P_{1D}$  mixes modes**, blurring features in matter power spectrum
- $P_{1D}$  measurements are approaching **systematics limit**
- **Thermal history** and **ionization** of gas depends on galaxy formation physics.
- The power spectrum does not capture **geometry/connectivity of the cosmic web**.

Theoretical limitations:

- **Simulations** that resolve forest scales + large volumes, with varied new physics, marginalizing over baryon uncertainties

# IGM Tomography: From 1D to 3D

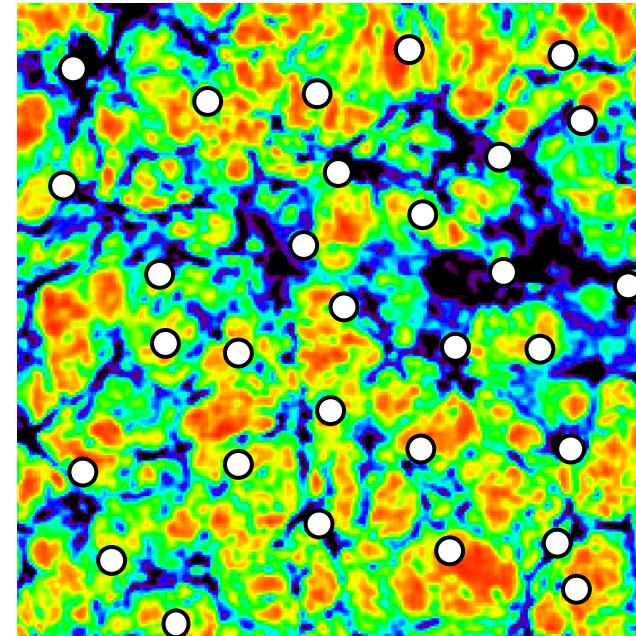
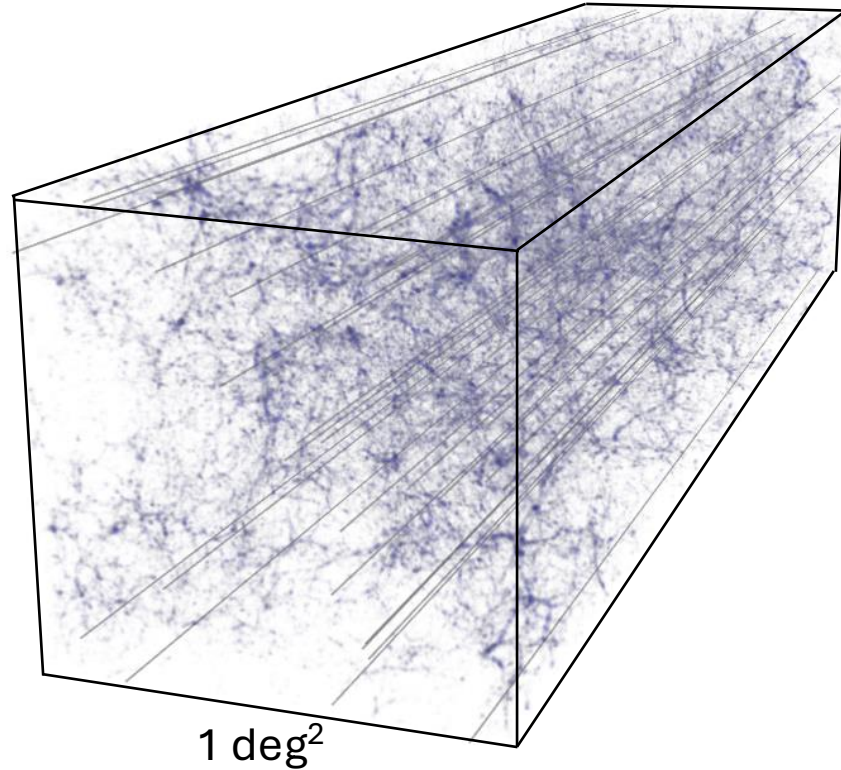


Observing the Ly $\alpha$  forest along multiple sightlines piercing the same volume — IGM tomography — enables 3D mapping of the absorbing gas.

Pichon et al (2001), Caucci et al (2008), Lee et al (2014)

Credit: Casey Stark

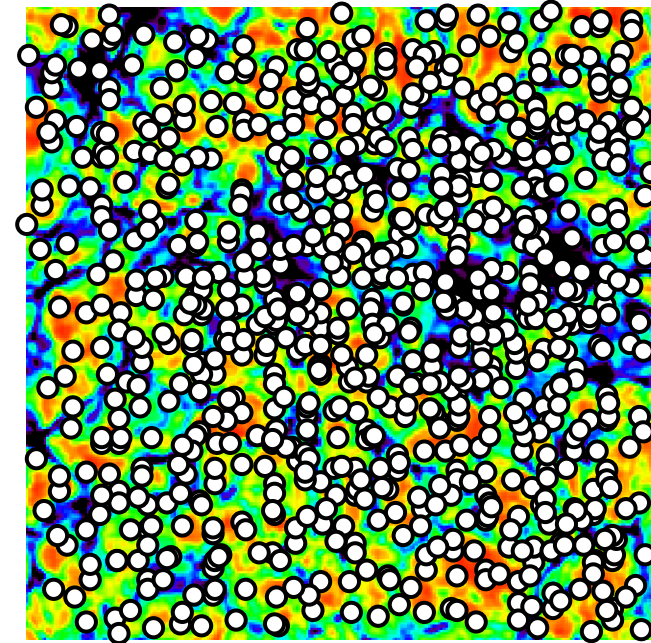
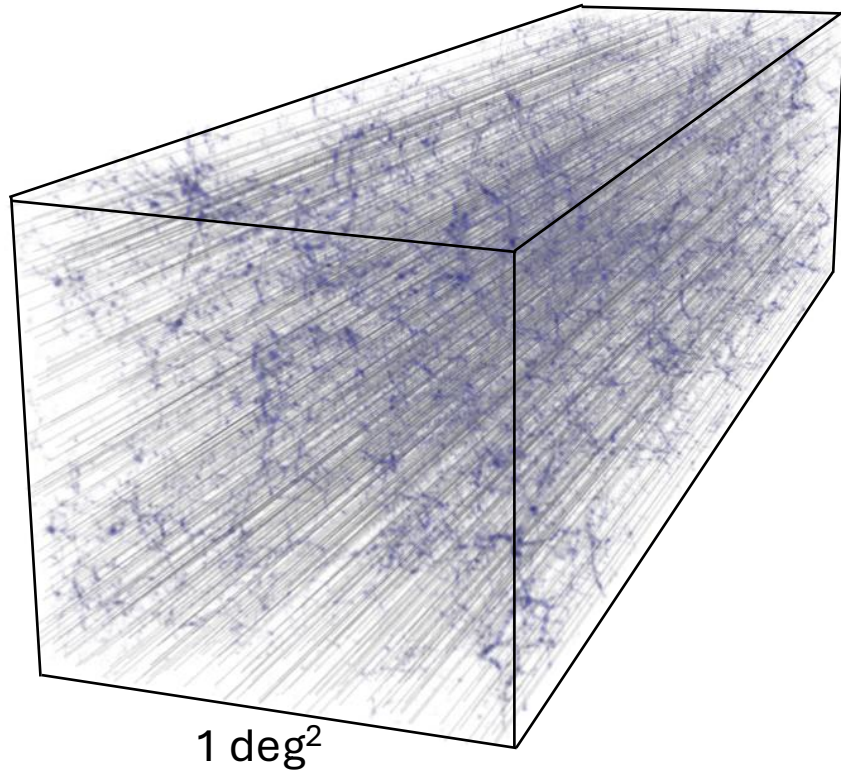
# IGM Tomography Using Quasars



**Sightline *density* is map *resolution*.**

Quasars are typically separated on sky by  $\sim 13 h^{-1} \text{ cMpc}$ . Transverse sampling is very sparse.

# IGM Tomography Using Galaxies



Color = Ly $\alpha$  transmission

For accessible galaxies, the transverse separation shrinks to  $\sim 2.5 h^{-1} \text{ cMpc}$ ---far better suited to mapping the cosmic web. *But* galaxies are  $>10x$  fainter!

(Lee et al 2014)

# IGM Tomography Using Galaxies

## Why go 3D?

- Access the **underlying 3D density fluctuations** on  $\sim$ Mpc scales ( $P_{3D}$ , not  $P_{1D}$ ).
- Transverse correlations reduce **systematics**.
- Map **cosmic web**, not just power spectrum.
- Test influence of **galaxies/black holes** on intergalactic gas.

For accuracy, 3D tomography is better

suited to mapping the cosmic web. *But* galaxies are  $>10x$  fainter!

(Lee et al 2014)

# IGM Tomography: A Nascent Technique

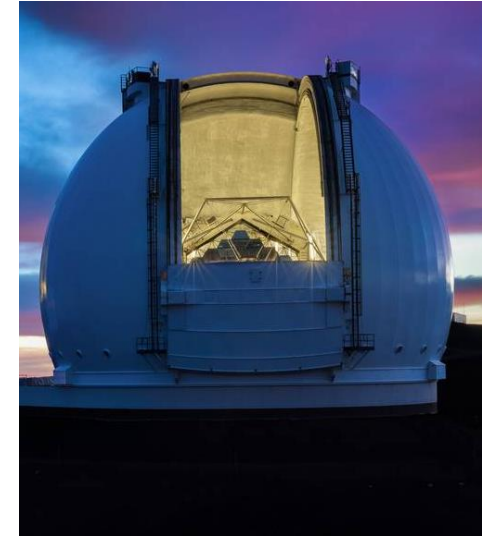
- (1) We have the first data sets and have starting to make **3D IGM maps**.
- (2) We have compared **basic map statistics to LCDM** expectations.
- (3) We have started to examine field-level **correlations with galaxy tracers**.
- (4) **No dark matter constraints** yet! Future surveys will be more powerful.

# IGM Tomography Surveys at Mpc Scales

## CLAMATO

The first Mpc-scale IGM tomography survey. Mapped 0.2 deg<sup>2</sup> with Keck. Led by K.G. Lee, Joe Hennawi, Martin White, and collaborators.

Lee et al 2014a,b, 2016, 2018; Stark et al 2015a,b; Krolewski et al 2017, 2018;  
Horowitz et al 2019, 2021; Kooistra et al 2022; Dong et al 2023, 2024; Momose et al 2024;  
Zhang et al 2026



## LATIS: Ly $\alpha$ Tomography IMACS Survey

Mapped 1.7 deg<sup>2</sup>, from redshift  $z=2.2-2.8$ , using 59 nights at Magellan to observe 3052 sightlines toward background galaxies and quasars.

Newman et al 2020, 2022, 2024, 2025a, 2025b, 2025c, Chartab et al 2024, 2025,  
Qezlou et al 2022, 2023

# The Ly $\alpha$ Forest in Galaxy Spectra

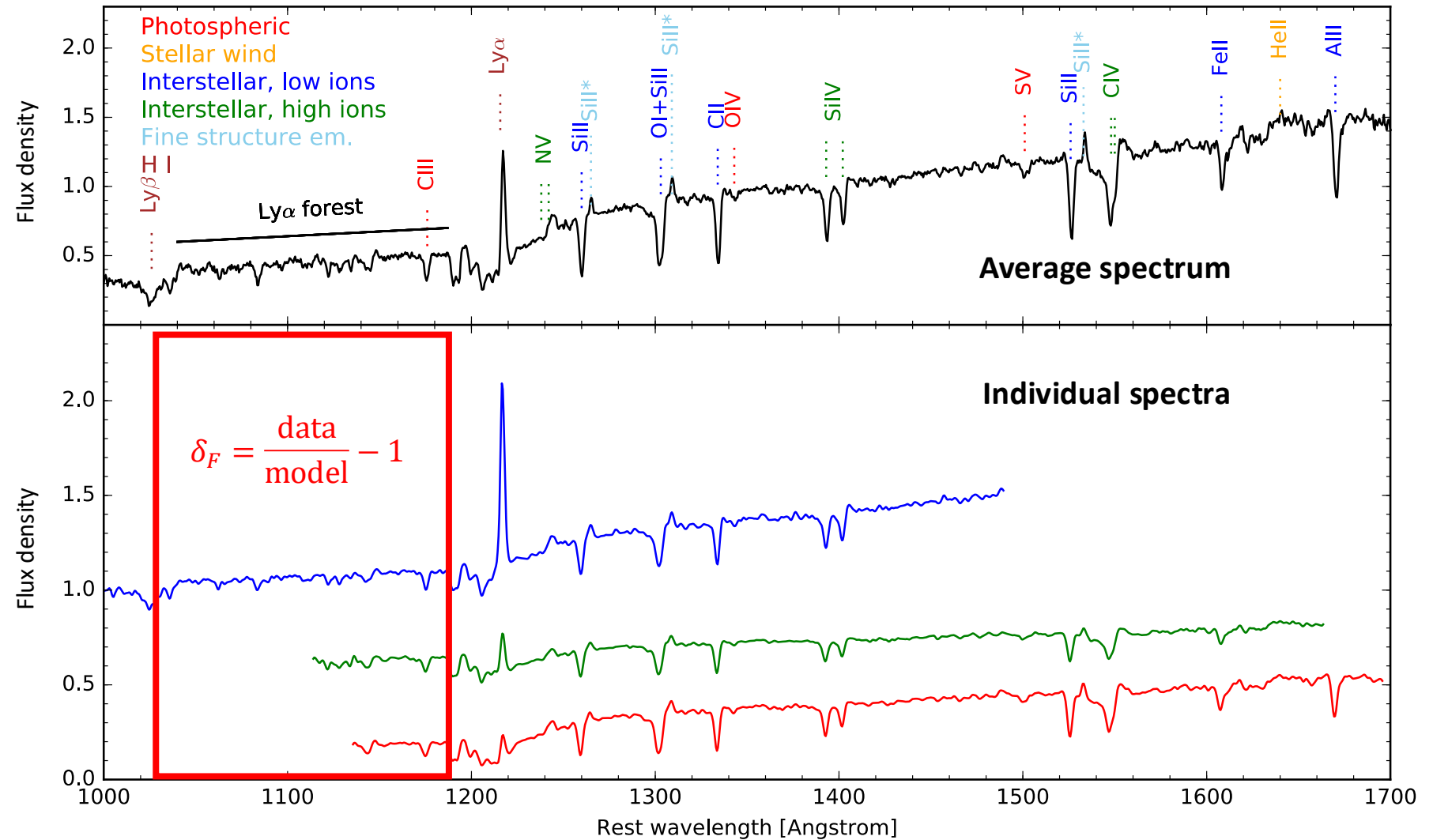
Key measurement is the Ly $\alpha$  transmission fluctuation or flux contrast:

$F$ : transmitted Ly $\alpha$  flux (between 0 and 1)

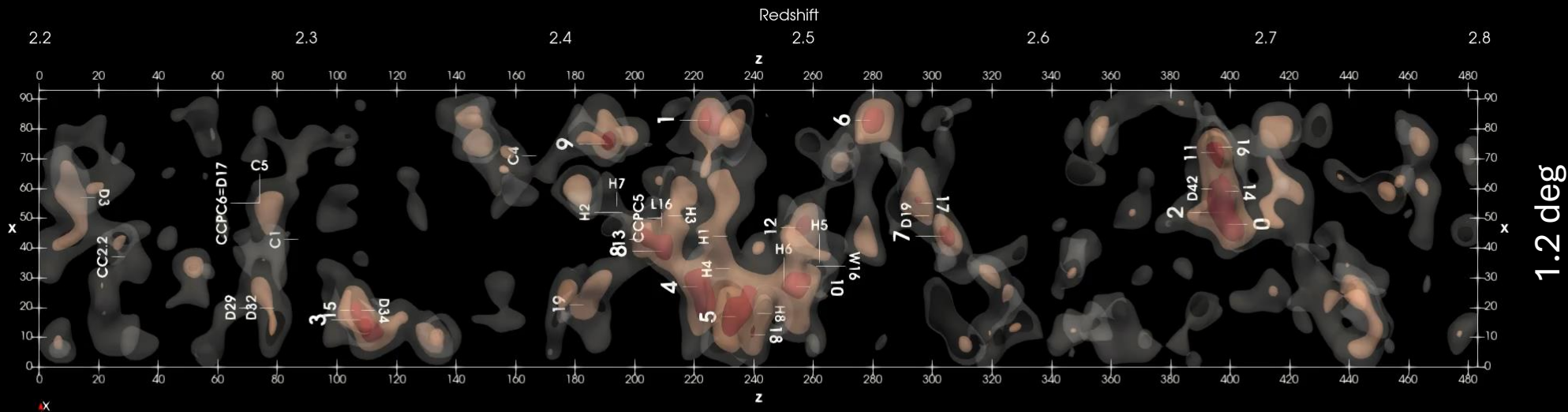
$$\delta_F = \frac{F - \langle F \rangle}{\langle F \rangle}$$

$\delta_F < 0$ : More than average absorption

$\delta_F > 0$ : Less than average absorption



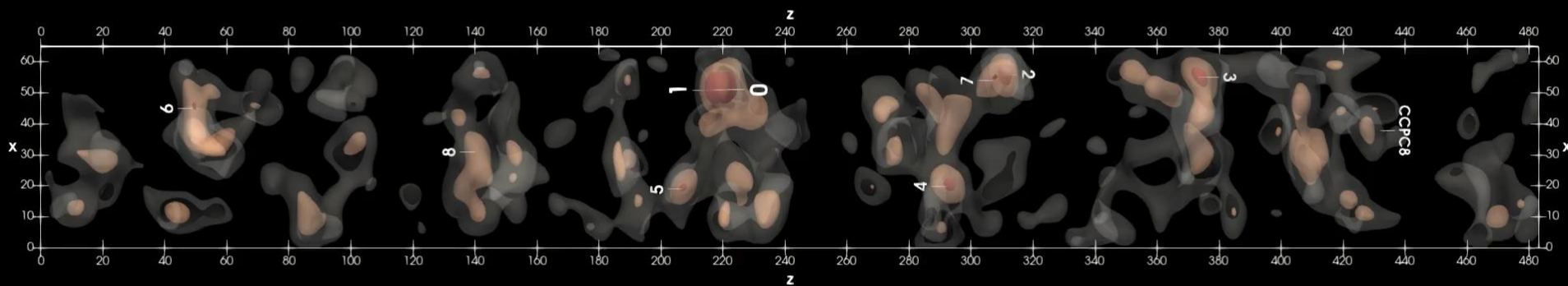
COSMOS = D2



1.2 deg

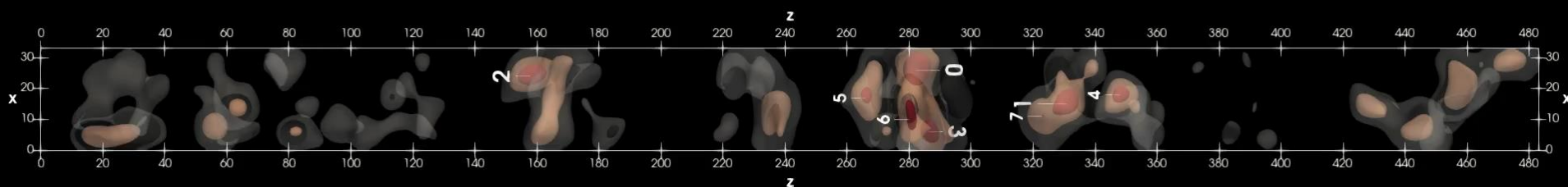
3D maps of IGM Ly $\alpha$  absorption in 3 fields

D1

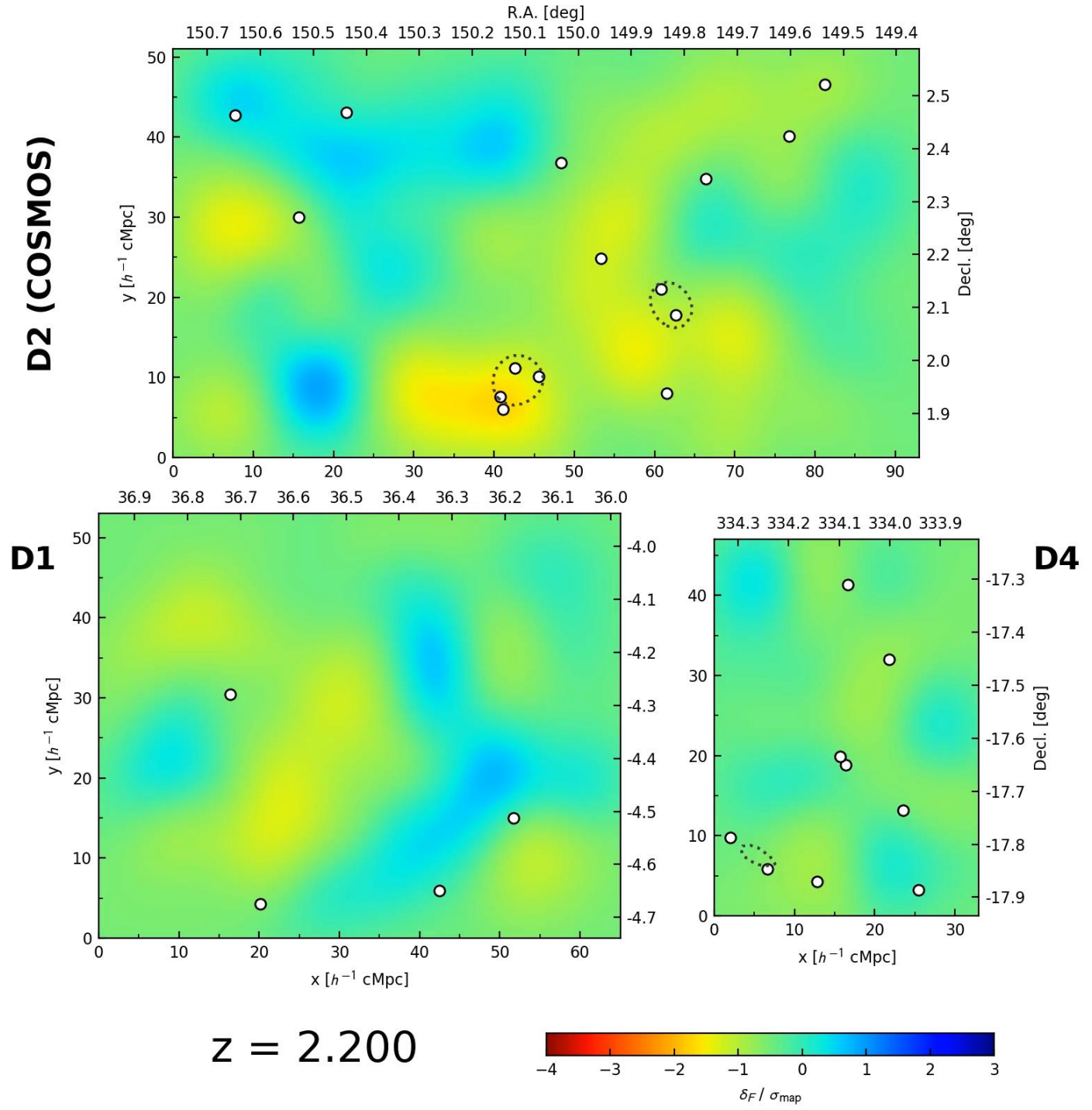


redder/darker  
→  
more absorption,  
higher matter density

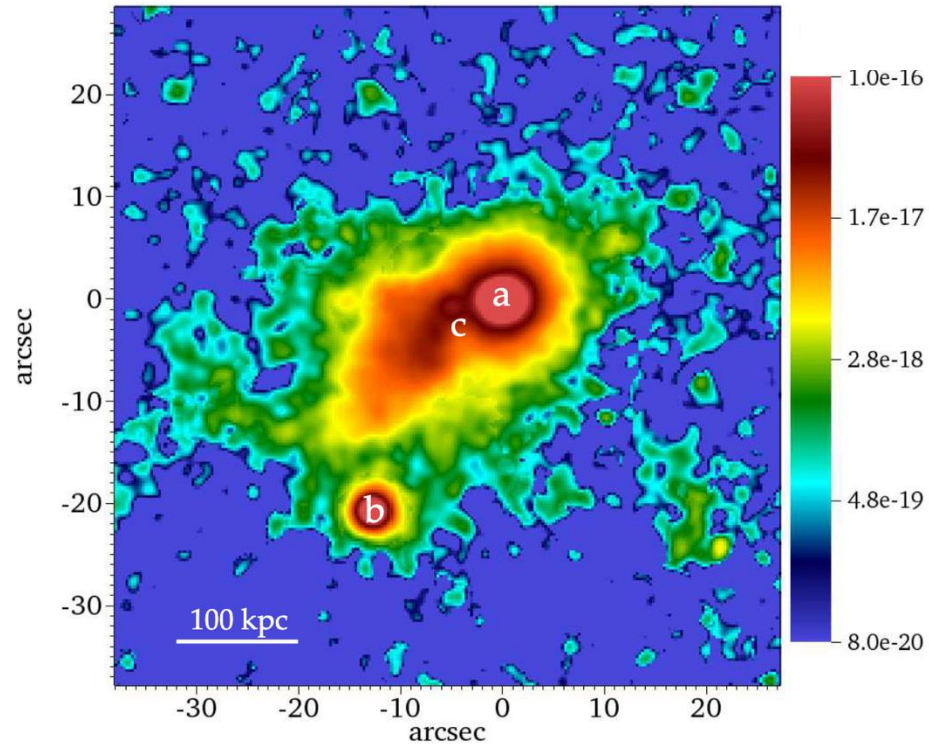
D4



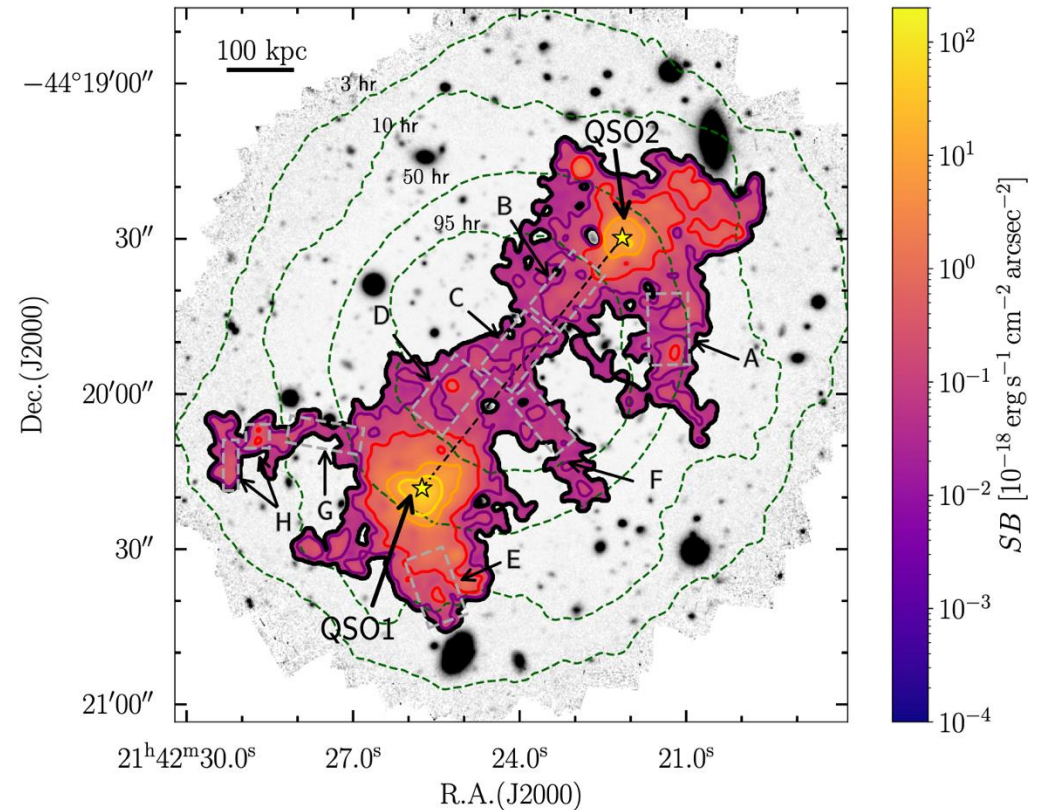
Resolution:  
 $\sigma = 4 h^{-1} \text{ cMpc}$   
FWHM  $\sim 14 \text{ cMpc}$



# Absorption/emission



Cantalupo+ 2018

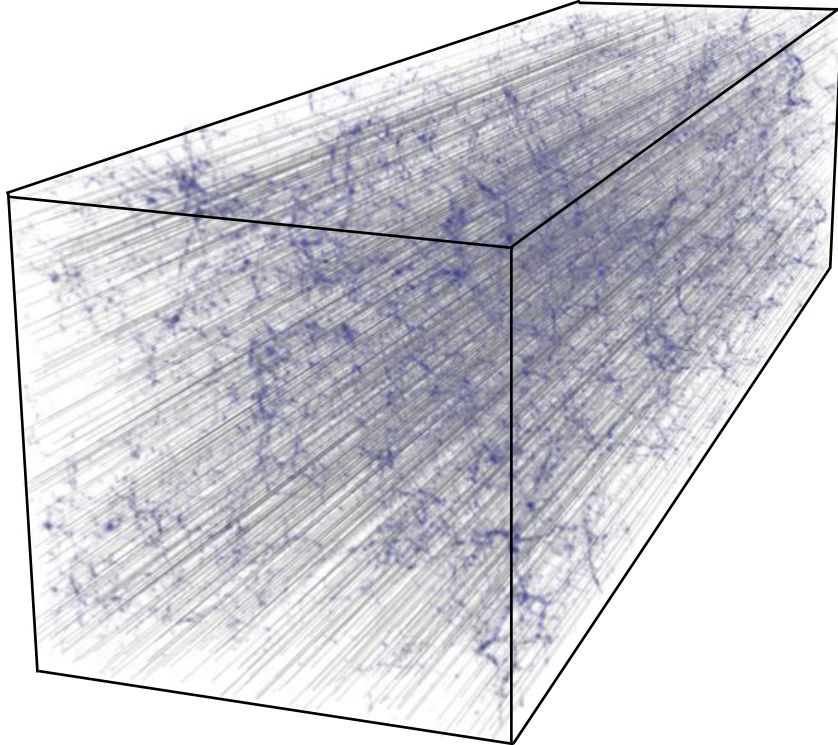


Tomotti+ 2025

$\text{Ly}\alpha$  emission observations are sensitive to higher density, highly illuminated gas (e.g., near quasars). Absorption probes gas near the mean density over large volumes – but at much lower spatial resolution.

Are the LATIS maps consistent with the cosmological model and simple IGM physics?

# Simulating LATIS



The largest cosmological simulations follow the growth of the cosmic web over much larger volumes than observed by LATIS.

We shoot many “sightlines” through such simulations to perform mock LATIS surveys.

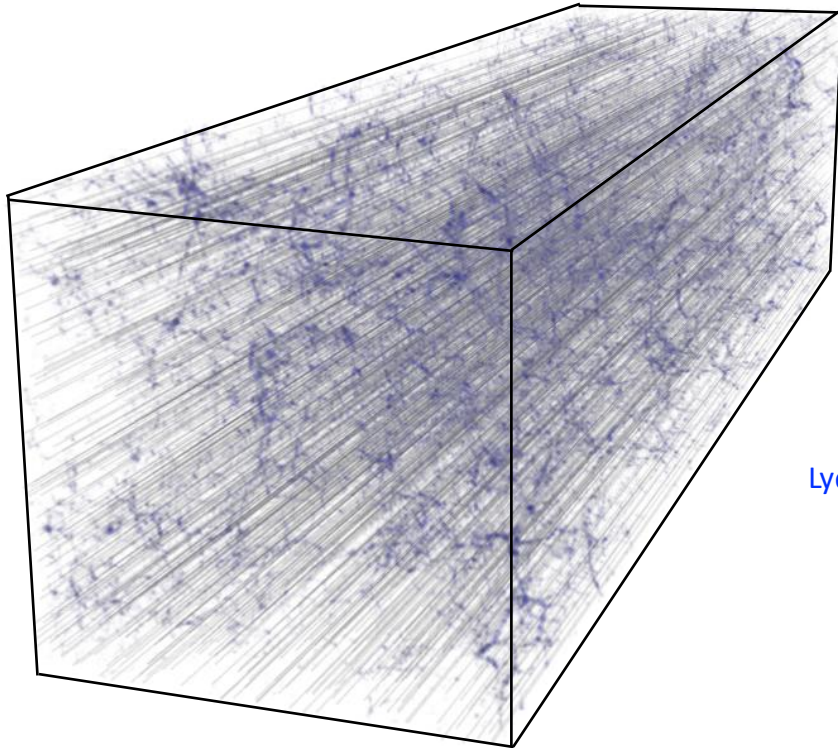
## **Hydrodynamic simulations** (ASTRID, IllustrisTNG)

$\text{Ly}\alpha$  absorption can be computed fairly directly.

## **Dark matter only simulations** (MultiDark)

We can estimate the  $\text{Ly}\alpha$  absorption from the matter density with a simple analytic method.

# Simulating LATIS



Ly $\alpha$  optical depth



## Dark matter only simulations

We can estimate the Ly $\alpha$  absorption from the matter density by balancing *photoionization* and H *recombinations*:

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

Density & temperature

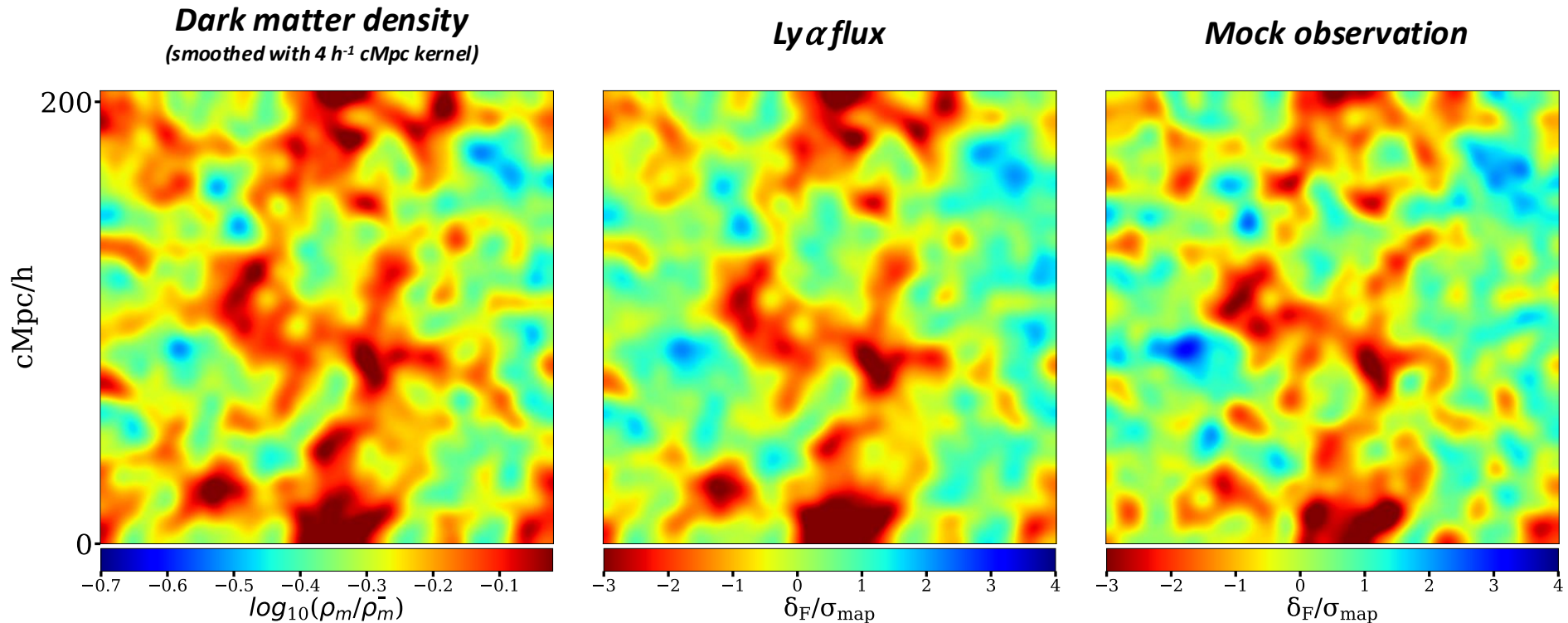
Photoionization rate

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 is a useful “null hypothesis” – ***deviations indicate interesting astrophysics.***

# IGM Tomography Maps ~ Dark Matter Maps



*Cross-sections through TNG-300; Qezlou+ 2022*

Mock surveys show that LATIS-like surveys can trace the density field at  $z \sim 2.5$  well on scales of several cMpc/h.

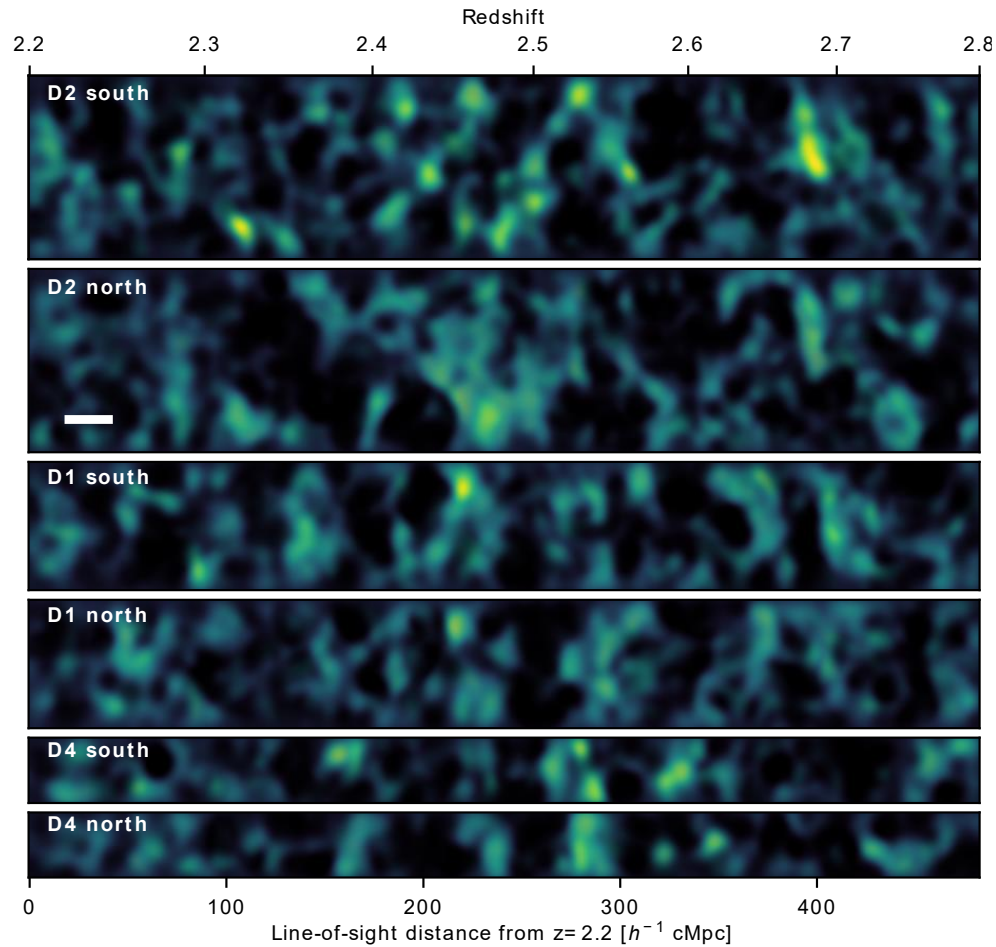


Mahdi Qezlou  
(UCR/Carnegie  $\rightarrow$  UT Austin)

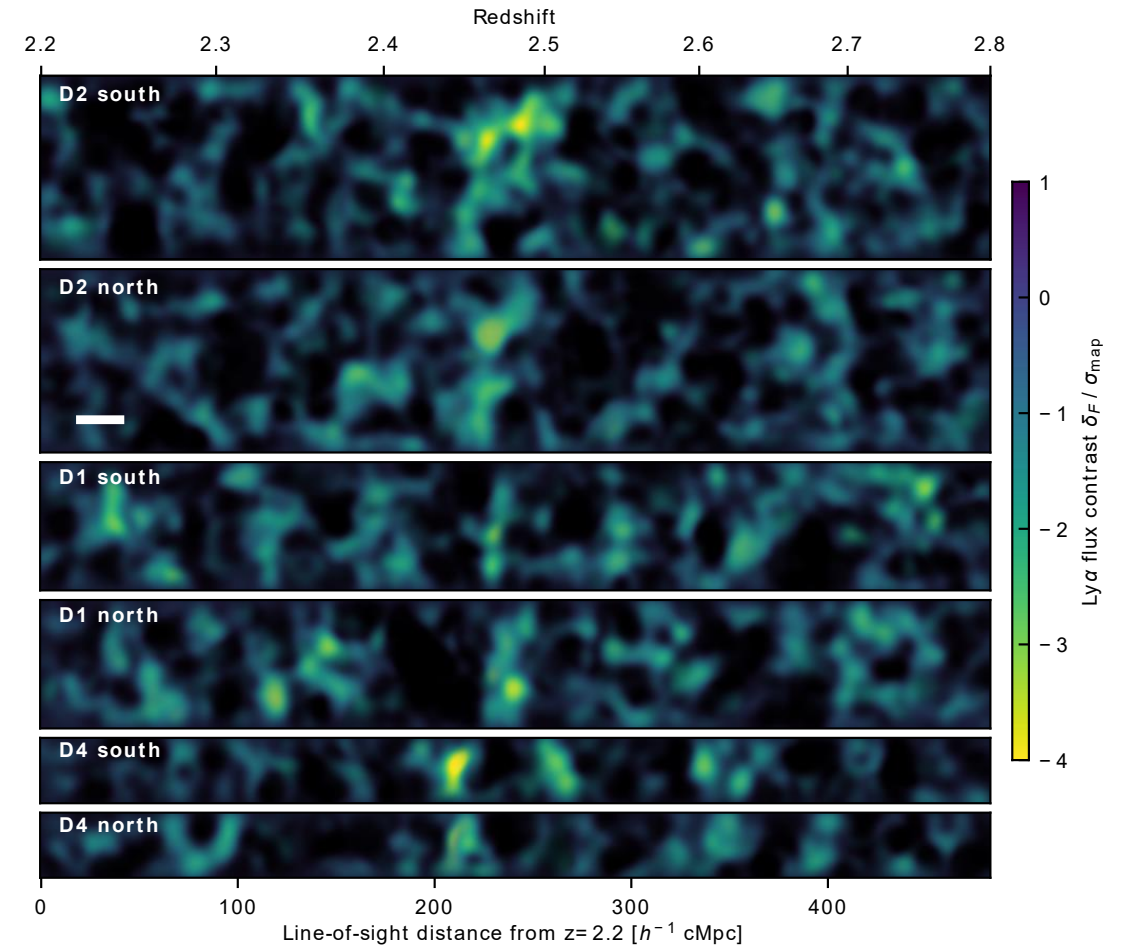
*See initial calculations & simulations by Lee et al 2014 and Stark et al 2015*

# Simulated vs observed IGM maps

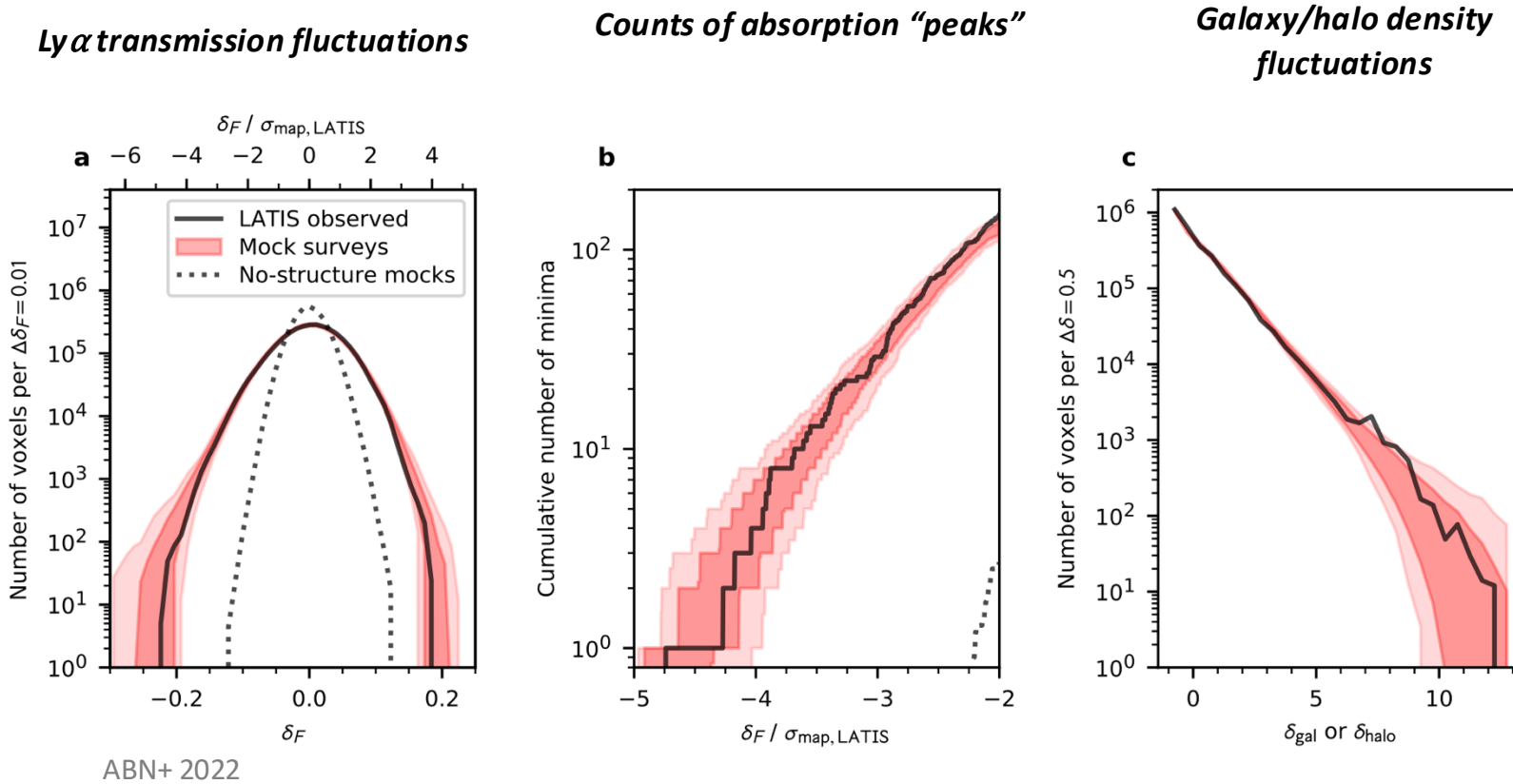
## Observed maps



## Mock survey (one realization)



# Global statistics of the IGM maps are nominal

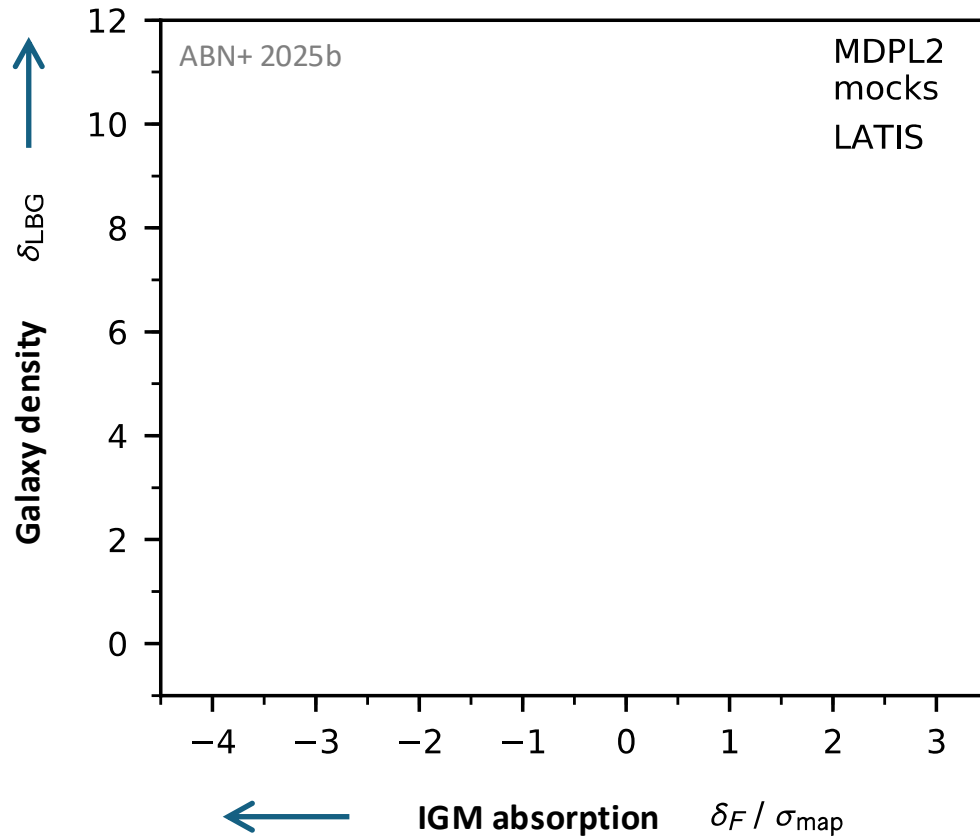


The observed fluctuations in Ly $\alpha$  transmission and galaxy counts are consistent with the mock surveys, i.e., LCDM + simple models (FPGA).

Do IGM and galaxy maps consistently trace the cosmic web?



# Do IGM and galaxy maps consistently trace the cosmic web?



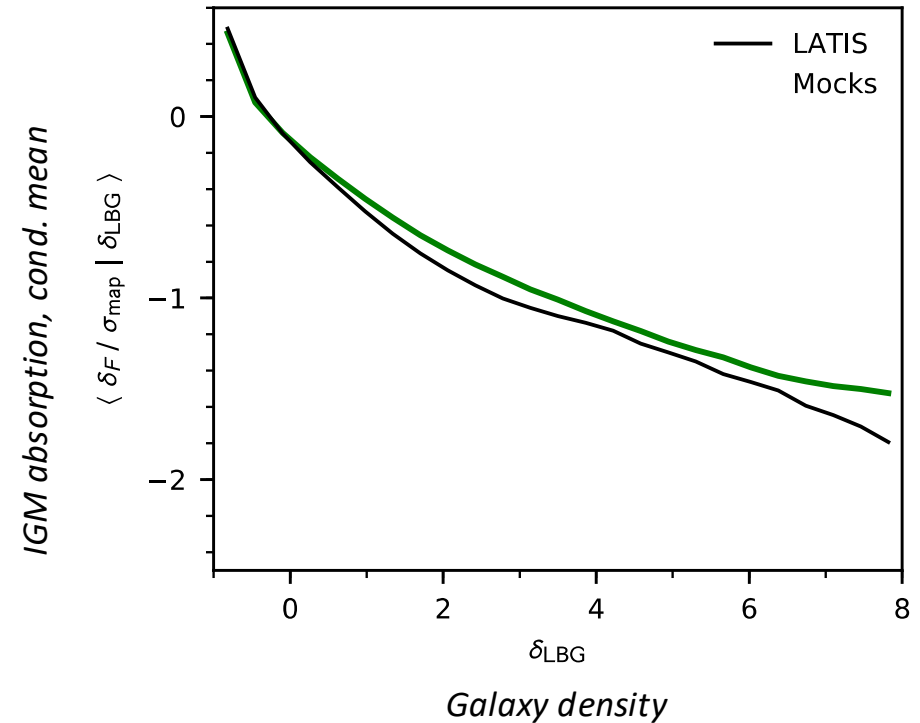
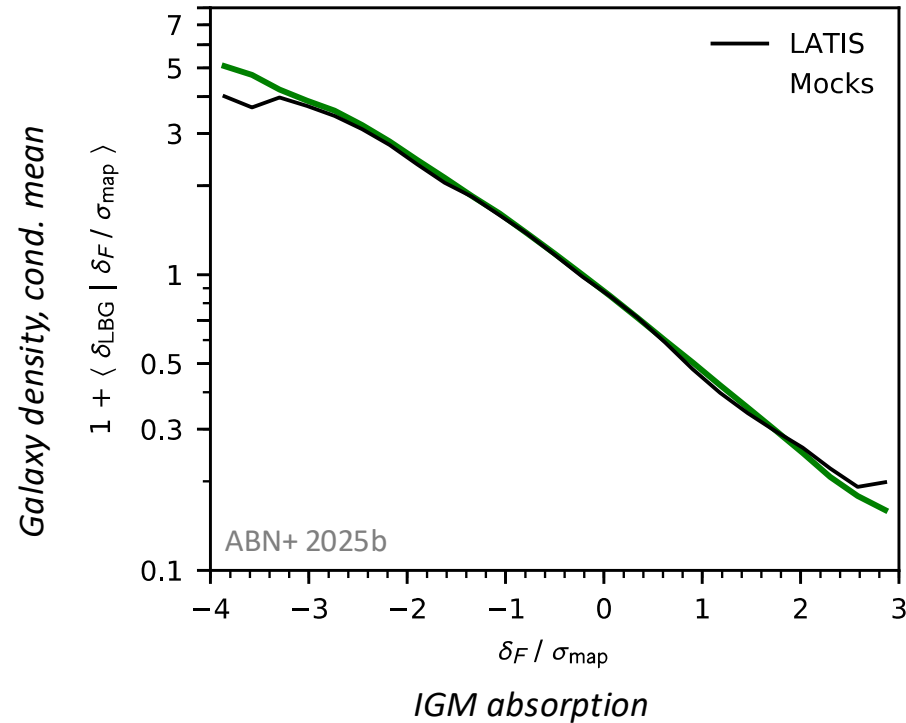
**Yes, at least overall.**

We can compare the joint distribution of IGM absorption and galaxy overdensity at the field level.

The LATIS data match the mocks well. Simple models of IGM physics are adequate at this resolution.

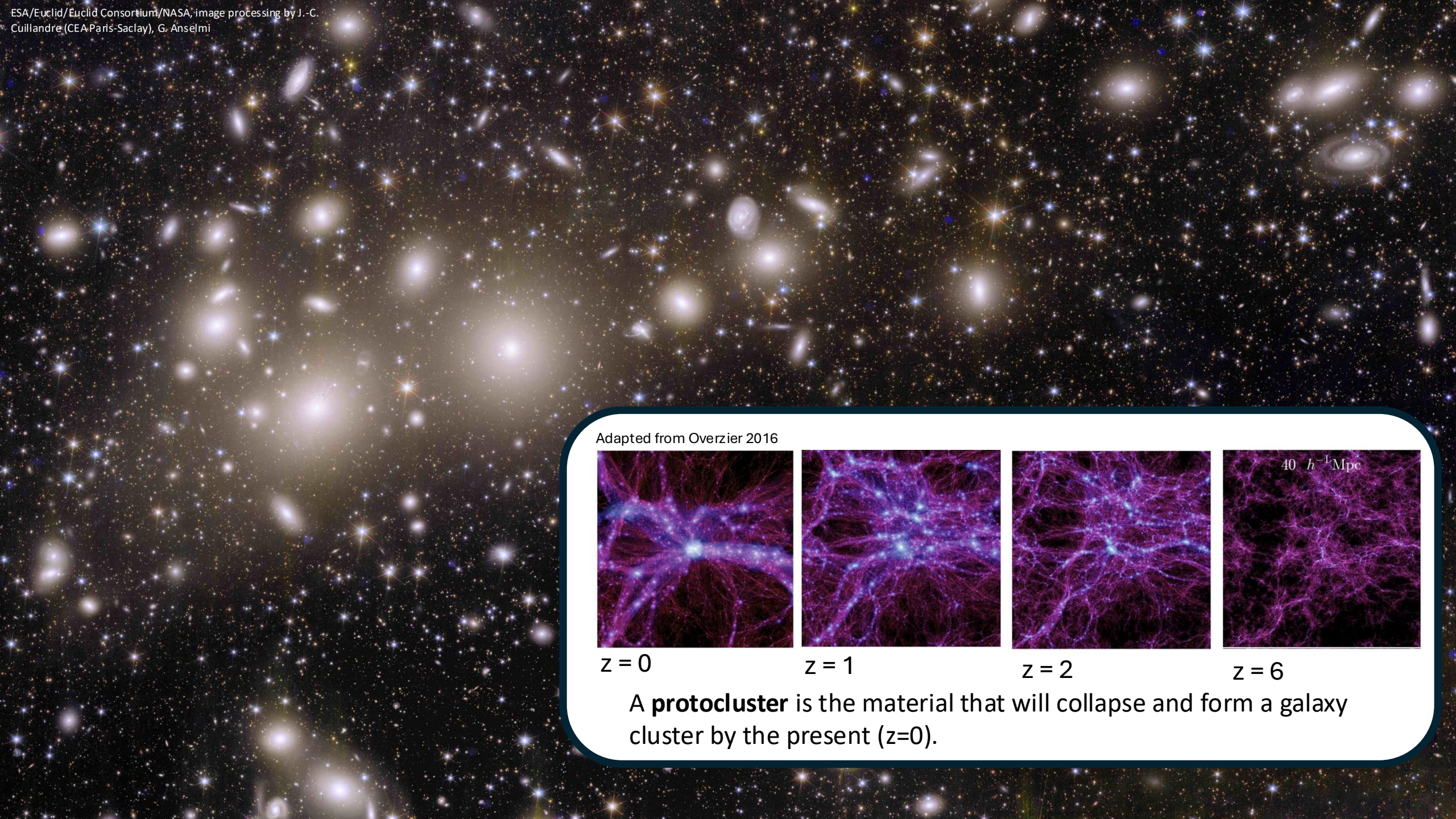
\* Galaxies are matched to dark matter halos in simulations using our clustering measurements.

# Do IGM and galaxy maps consistently trace the cosmic web?

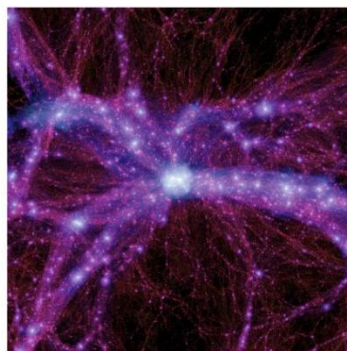


The conditional relationships between galaxy density and IGM absorption match the simple mock surveys well, again supporting a simple connection over most of the volume.

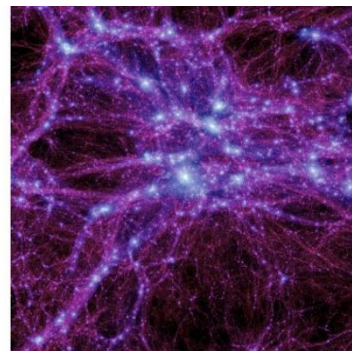
Are there places where IGM and galaxy tracers appear inconsistent?



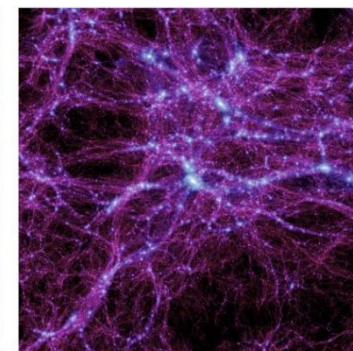
Adapted from Overzier 2016



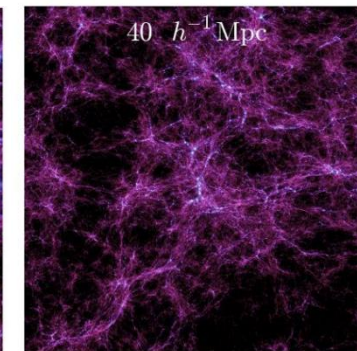
$z = 0$



$z = 1$



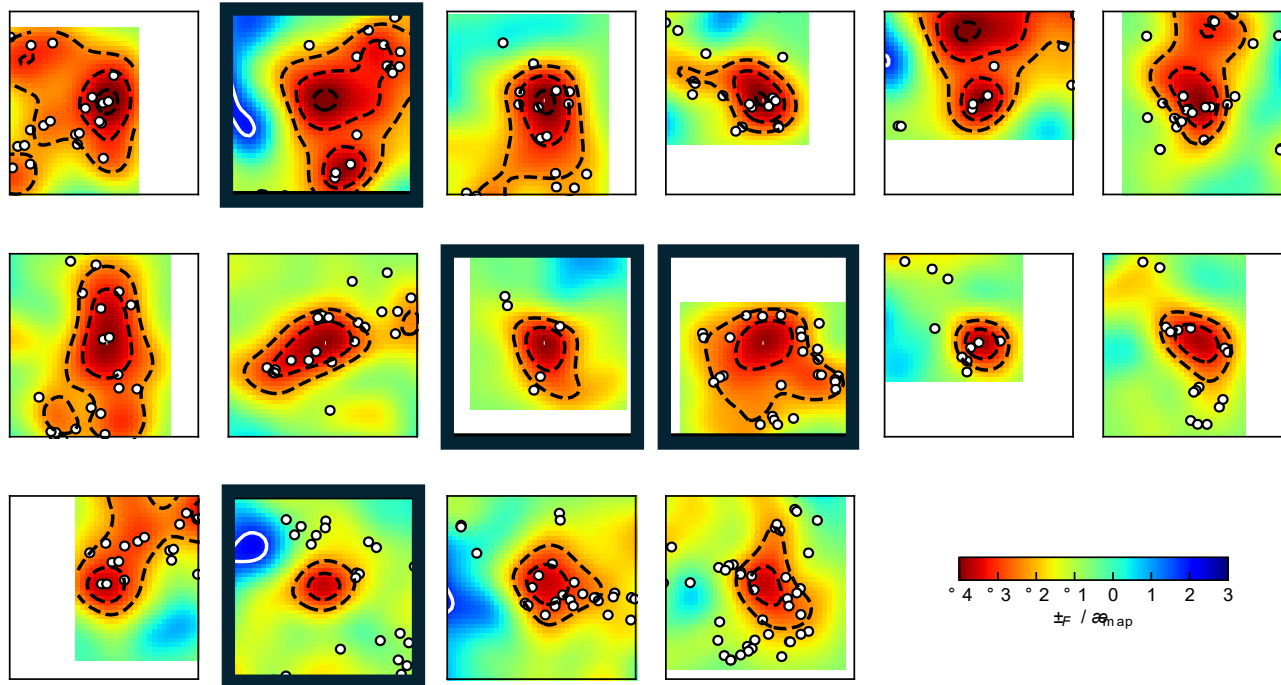
$z = 2$



$z = 6$

A **protocluster** is the material that will collapse and form a galaxy cluster by the present ( $z=0$ ).

# Protoclusters Detected in IGM Maps

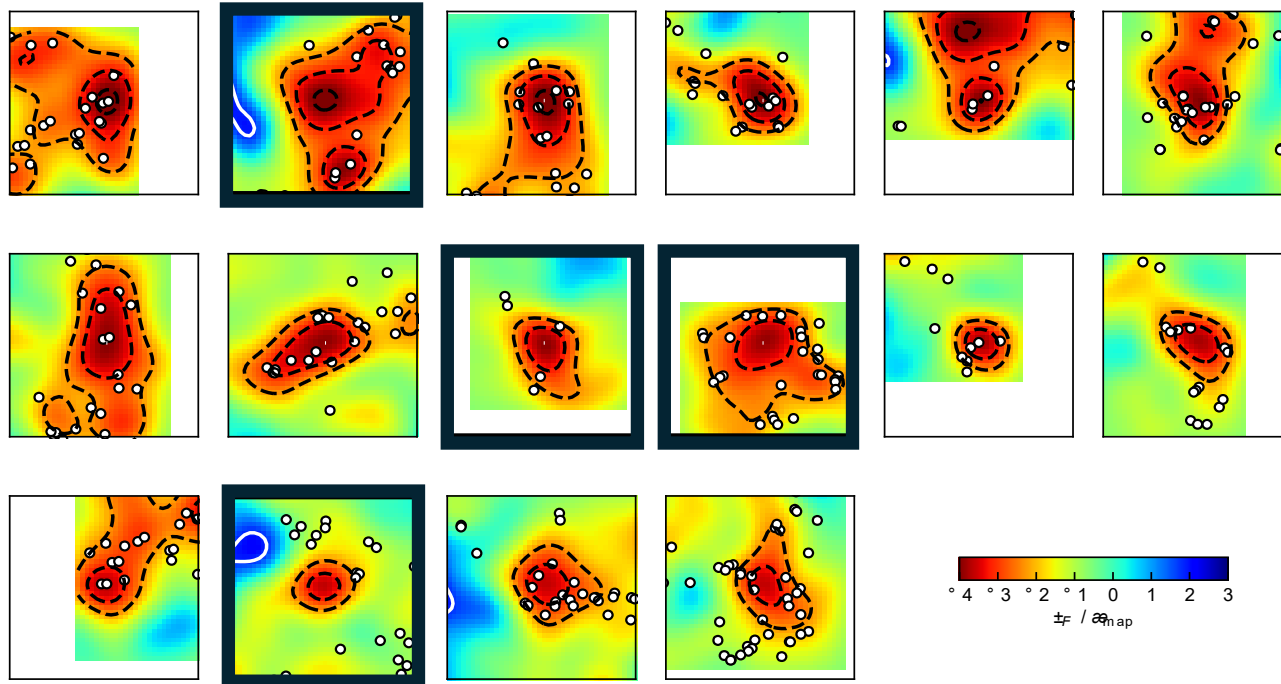


ABN+ 2025b

*Redder = More IGM absorption*

In the LATIS maps, we can find protoclusters based on the strong IGM Ly $\alpha$  absorption that they produce over scales of several Mpc. The largest are shown here.

# Anomalies? Strong IGM absorption, few galaxies



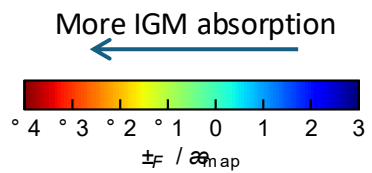
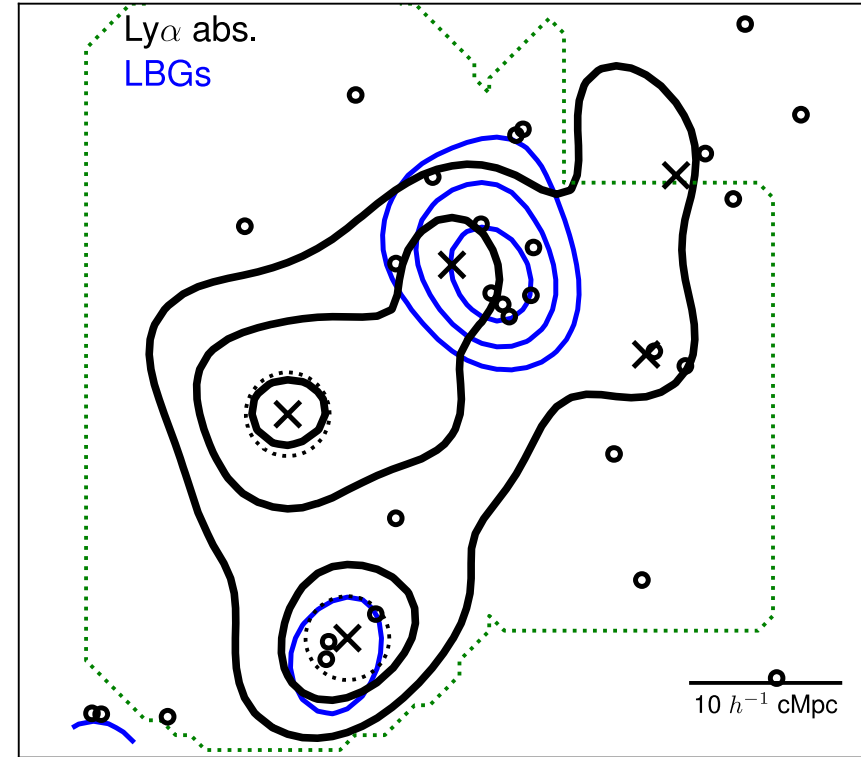
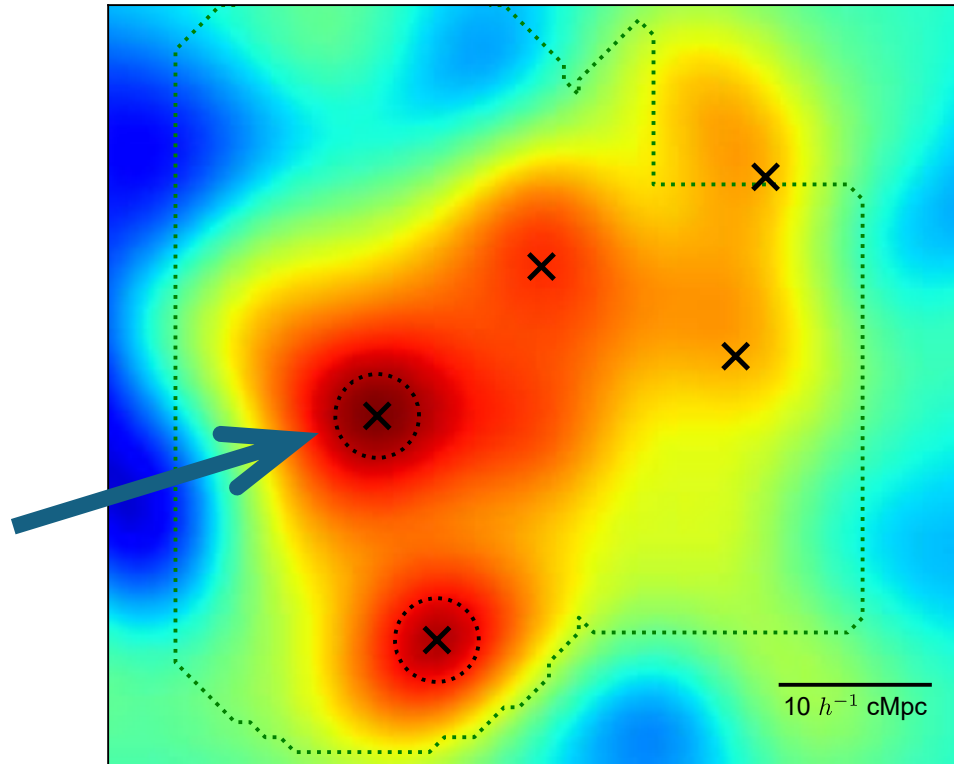
ABN+ 2025b

*Redder = More IGM absorption*

Most of these protoclusters contain many galaxies—as expected!

But 4 / 16 (thick boxes) have **few detected galaxies**, particularly near peak IGM absorption. <1% of mock surveys have as many outliers.

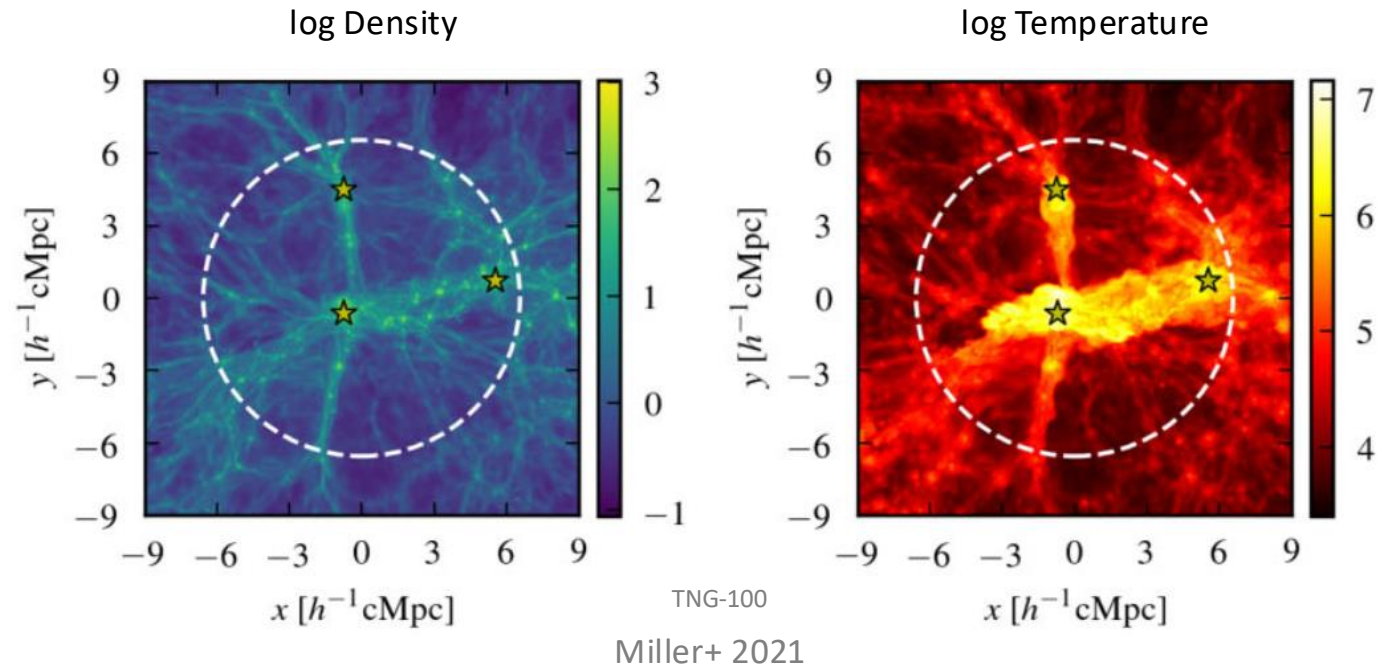
# A Prototypical Anomalous Protocluster: Antu



ABN+ 2025b

- The strongest absorption in our COSMOS IGM map is highlighted (left).
- Surprisingly, the region is essentially devoid of galaxy members in LATIS and similar optical spectroscopy surveys.

# Protoclusters as Probes of IGM Heating



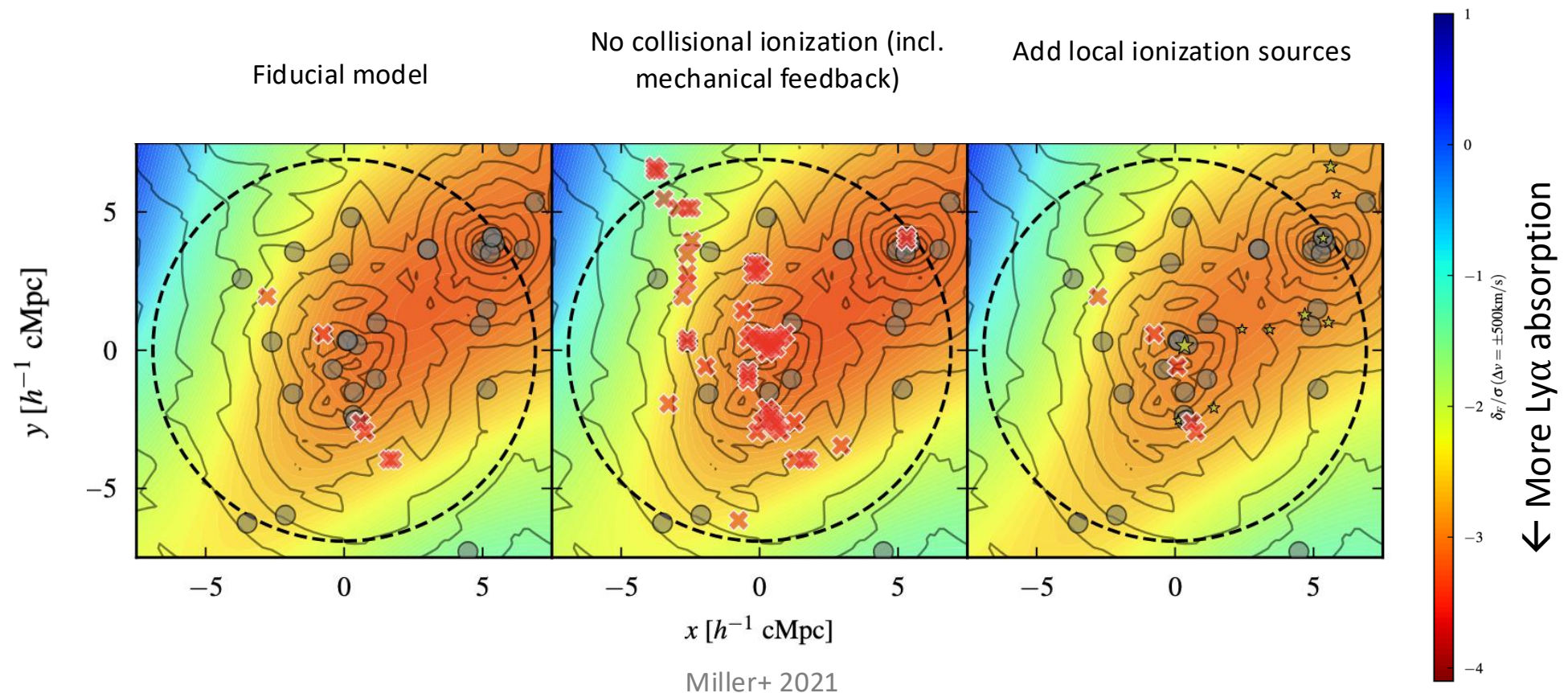
Protoclusters contain many massive galaxies and supermassive black holes.

**Radiation** and **jets** can heat the surrounding gas on Mpc scales, reducing the neutral H fraction and thus Ly $\alpha$  absorption.

*Can this erase protoclusters from IGM maps?*

*Can we learn about feedback from black holes on the IGM?*

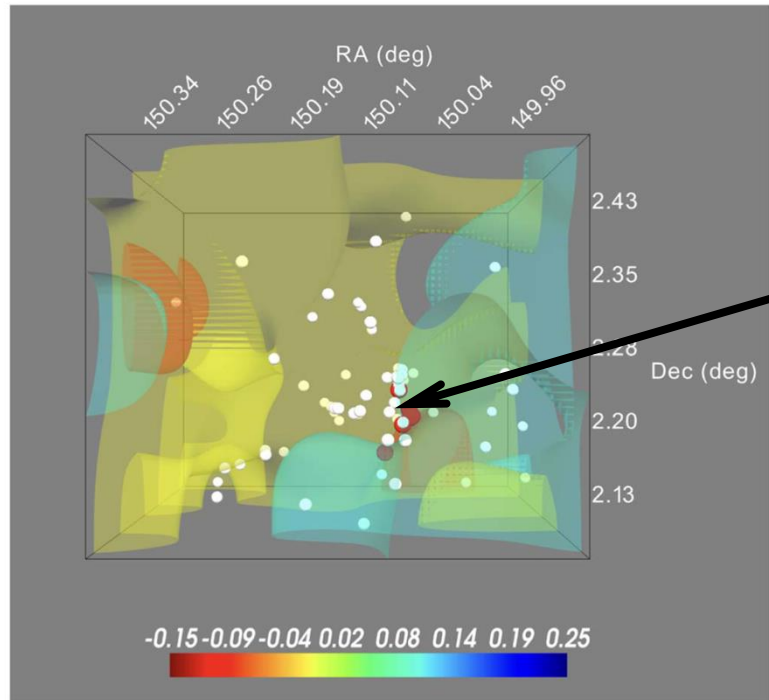
# Protoclusters as Probes of IGM Heating



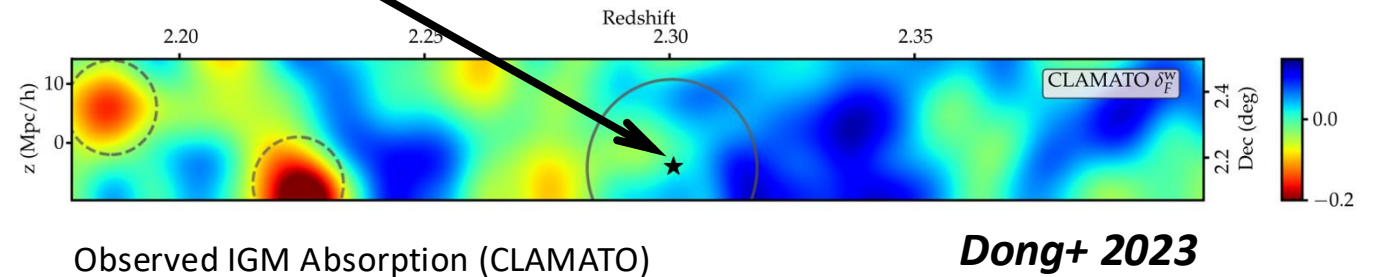
But this feedback is within a  $\sim \text{Mpc}$  of massive galaxies. At the  $\sim 4 \text{ cMpc}/h$  resolution of current IGM tomography maps, Miller et al. expect no major effects—at least for the feedback implemented in the IllustrisTNG cosmological simulation.

# Another type of anomaly?

## Strong galaxy overdensity, no IGM absorption



COSTCO-I: a puzzling example of a galaxy overdensity with no excess IGM absorption, in CLAMATO or LATIS. Dong+ 2023

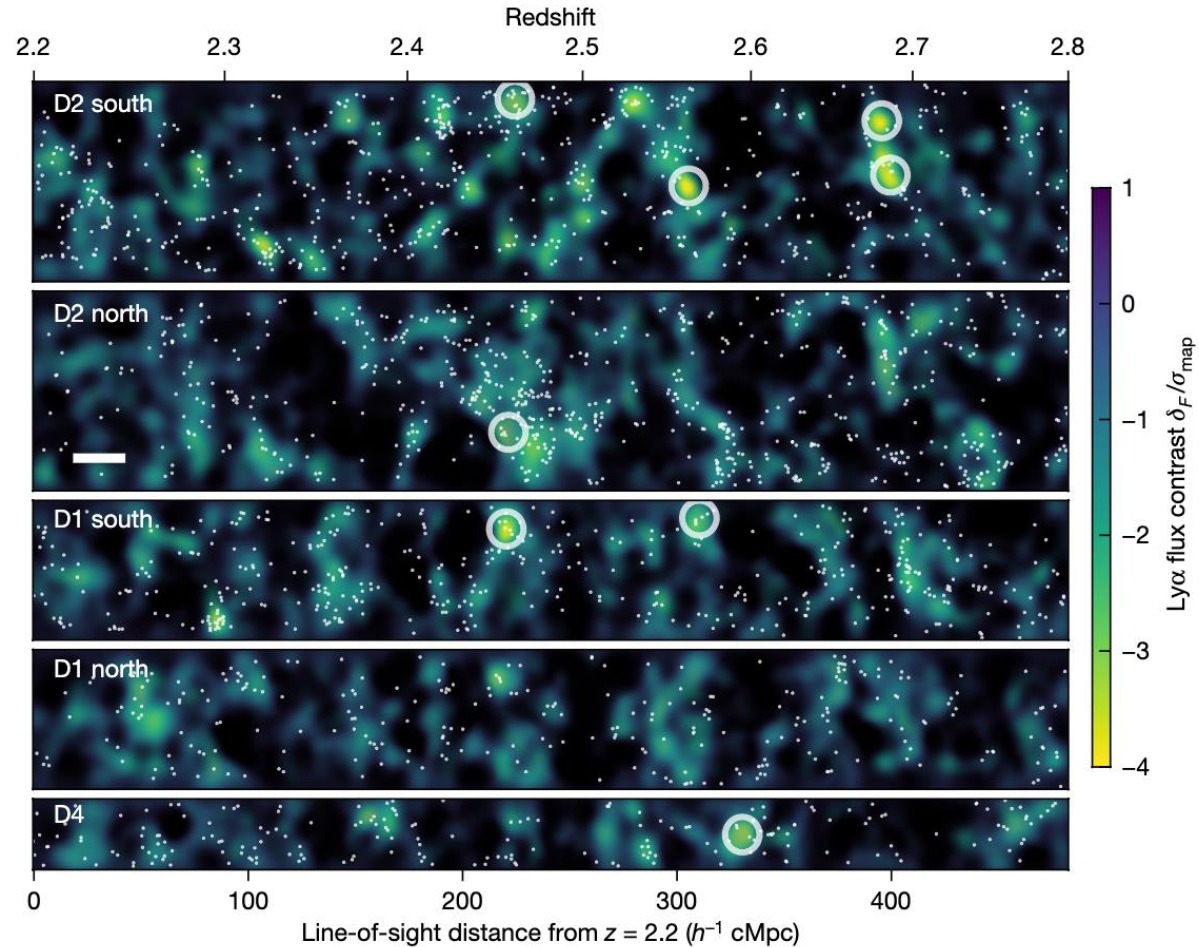


# IGM / Galaxy Anomalies

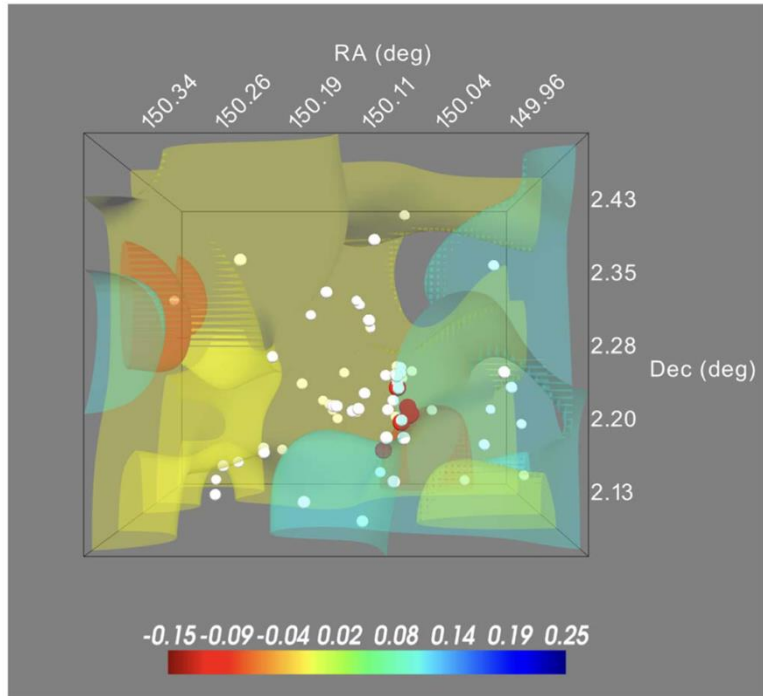
## IGM absorption lacking galaxies?

- It's hard to see how strong IGM absorption is produced without a matter overdensity.
- More likely: galaxies are present but currently missed due to survey selection effects coupled with galaxy evolution differences in some protoclusters.
- However, the evolutionary differences are much larger than expected, so the resolution remains unclear.

ABN+ 2022, 2025b



# IGM / Galaxy Anomalies



Dong+ 2023

## Galaxy overdensities lacking IGM absorption?

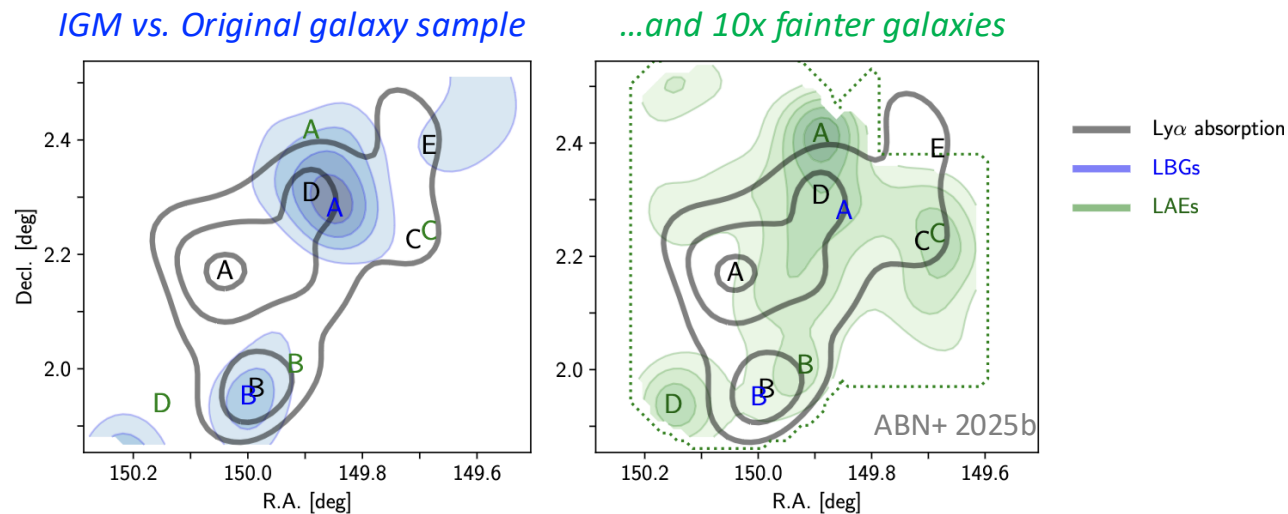
- In principle, this is easier to explain: ionize the gas.
  - But a surprisingly large volume needs to be ionized, which seems to require extreme feedback
- Dong+ 2023
- It's unclear how common these anomalies are; most current galaxy surveys might miss them.

ABN+ 2025b

# IGM / Galaxy Anomalies? Next steps

## Are the anomalies real, and what are their causes?

The main barrier now is less IGM maps and more *galaxy samples*, particular with accurate redshifts so that we can situate galaxies within the IGM maps. We are using observations at Magellan, Keck, JWST, etc. to build *larger and more representative* galaxy samples.



# Lyman Alpha Research Collaboration



A cross-institutional effort across the University of Southern California, the University of California, Riverside, and Carnegie Observatories

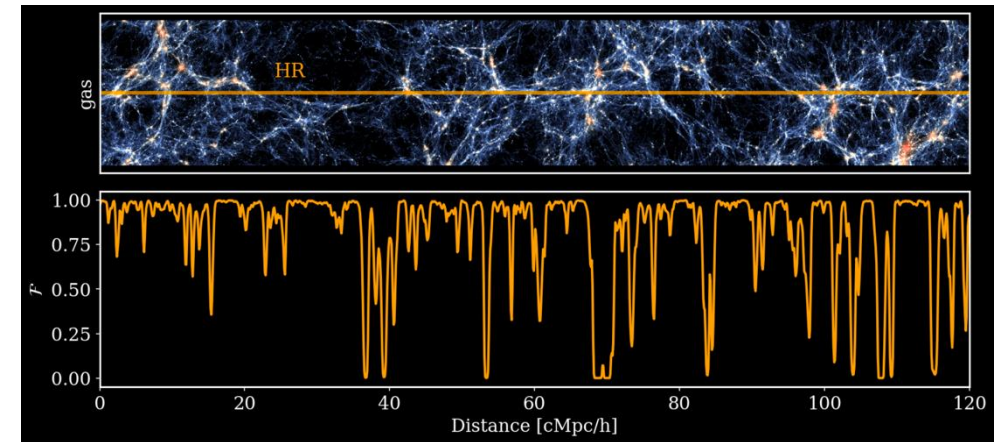
*Science leads: Vera Gluscevic, Simeon Bird, Drew Newman, Gwen Rudie*

- **Dark Matter & Neutrinos** — Constrain DM models and neutrino masses using the Lyman- $\alpha$  forest, in 1D and 3D, along with other probes
- **Simulations & AI** — High-res. cosmological simulations and ML emulators/neutral nets
- **Public Engagement** — games and interactive visualization

# Lyman Alpha Research Collaboration

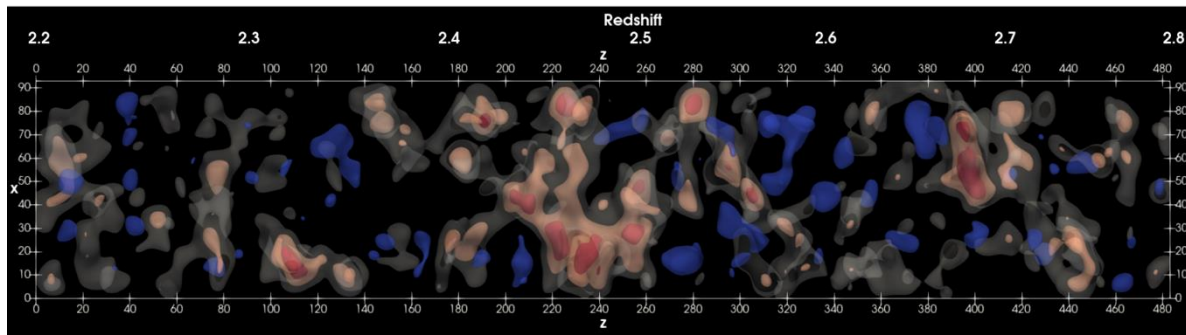
## Modeling Structure with New Physics

- Develop cosmological, hydrodynamic simulations with DM-baryon interactions, neutrino interactions, and general initial conditions
- Simulate the Ly $\alpha$  forest to the smallest scales including calibrated galaxy feedback models
- Deploy new emulator and neural network techniques to connect range of spatial scales across simulations
- Combine constraints from multiple probes and scales (Milky Way, Ly $\alpha$  forest, galaxy surveys, weak lensing, CMB)



## Tracing Gas Structure with Novel Observations

- Measure the “sphere of influence” of galaxies on the surrounding gas (chemistry, temperature) and calibrate “subgrid” models used in simulations.
- Understand the relationship between the Ly $\alpha$  forest and galaxy populations, including anomalies.
- Develop tools to turn IGM tomography into a cosmological probe.

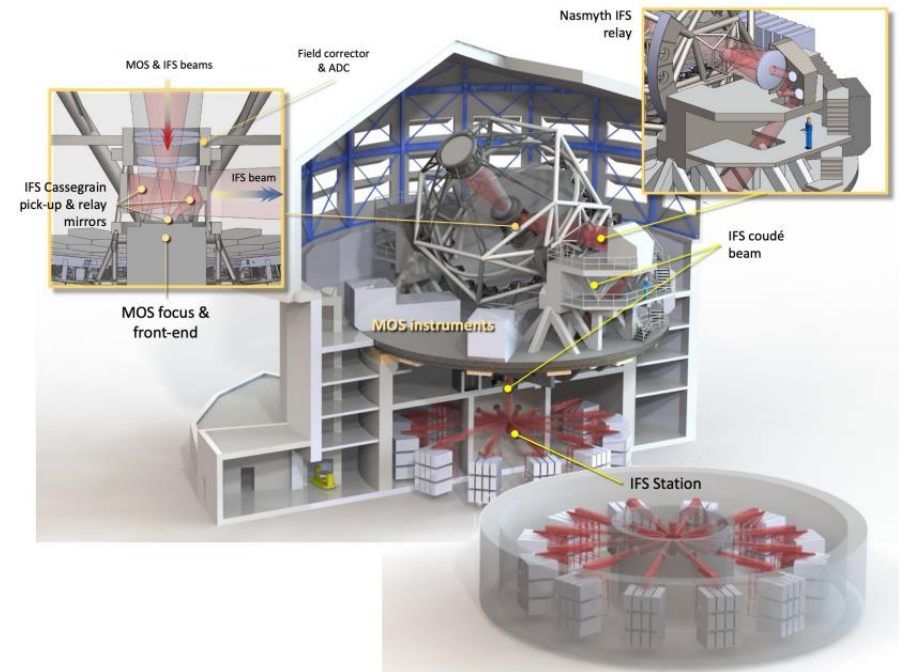


# Future: Massively parallel spectroscopy

Massively parallel spectroscopic platforms on large telescopes are now operating (Subaru PFS) and under various stages of concept/development to study dark energy, inflation, neutrinos, and dark matter.

They could be engines for 3D Ly $\alpha$  forest tomography over **Gpc-scale volumes**.  
(For comparison: LATIS multiplex was  $\sim 300$  with  $0.2 \text{ deg}^2$  FoV)

Platform	Telescope / aperture	Multiplex (# fibers)	Field of view ( $\text{deg}^2$ )
Subaru PFS	Subaru 8.2 m (Mauna Kea)	$\approx 2,400$	1.3
DESI-II	Mayall 4 m (Kitt Peak)	$\approx 5,000$	8
Spec-S5	6 m (Kitt Peak & Cerro Tololo)	$\approx 13,000 \times 2$	7
MUST	6.5 m (Saishiteng, China)	$\approx 20,000$	7
WST	12 m	$\approx 20,000$	3
MSE	11 m (Mauna Kea)	$\approx 18,000?$	1.5
MegaMapper	6.5 m	$\approx 26,000$	7

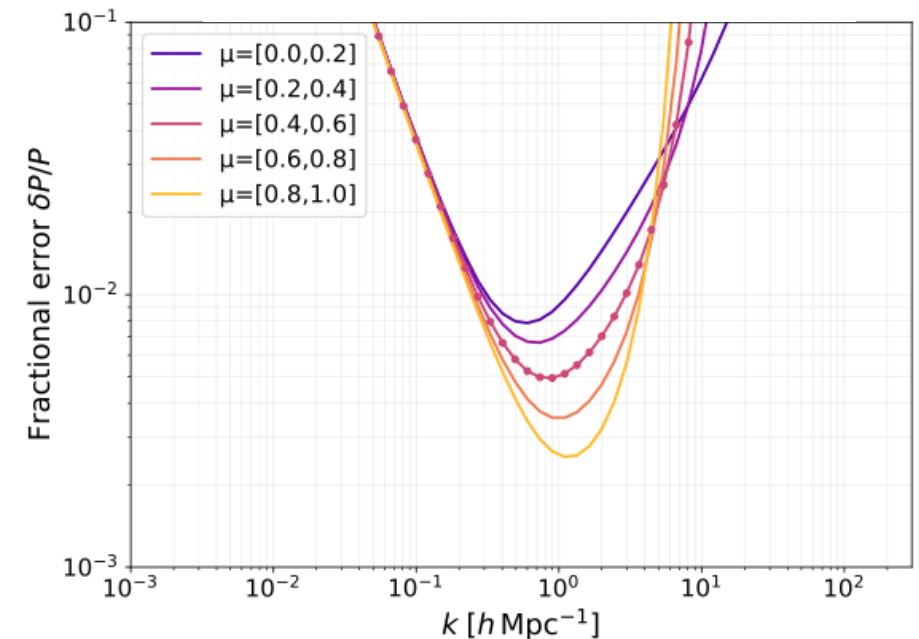
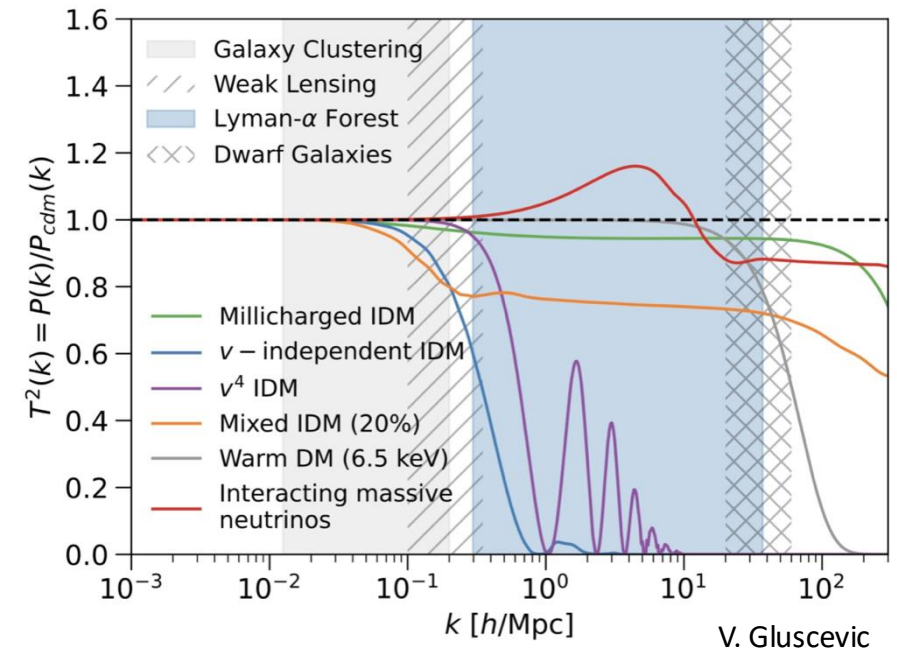


WST White paper v1

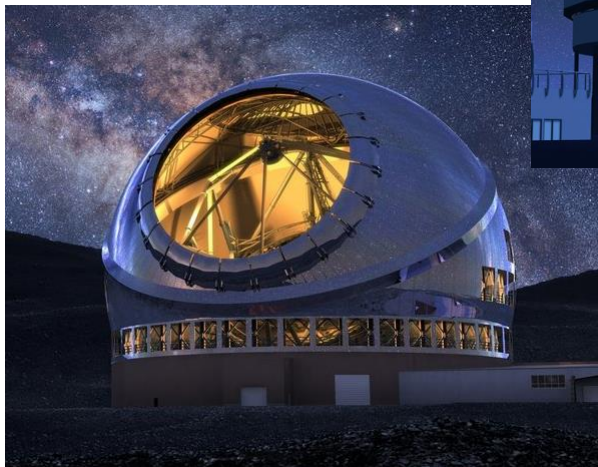
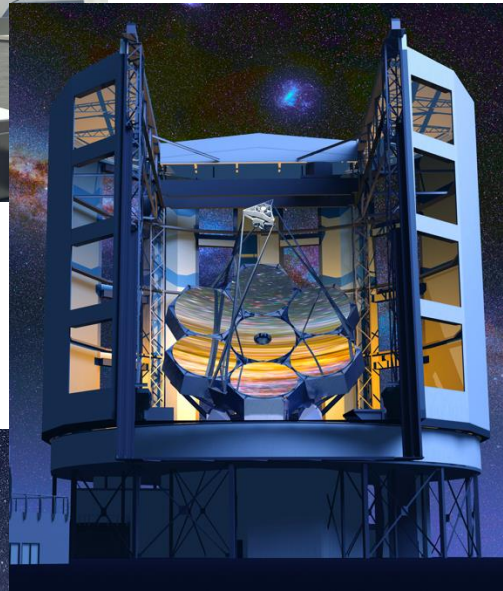
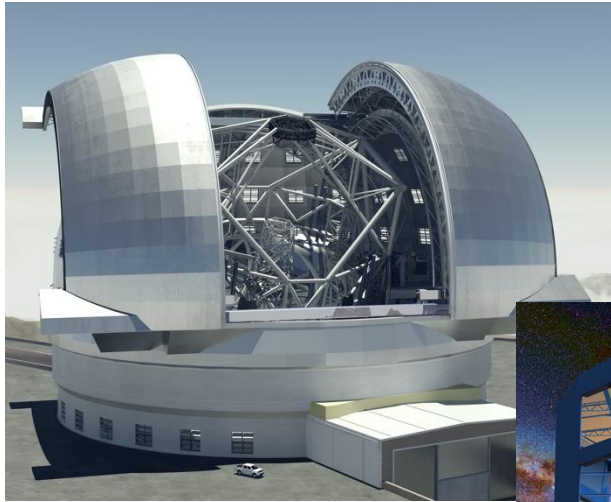
# Future: Massively parallel spectroscopy

A 200 deg<sup>2</sup> IGM tomography survey, similar to what is proposed for the Wide-field Spectroscopic Telescope (WST), could measure the Ly $\alpha$   $P_{3D}$  to  $\sim 1\%$  precision at scales relevant for dark matter constraints.

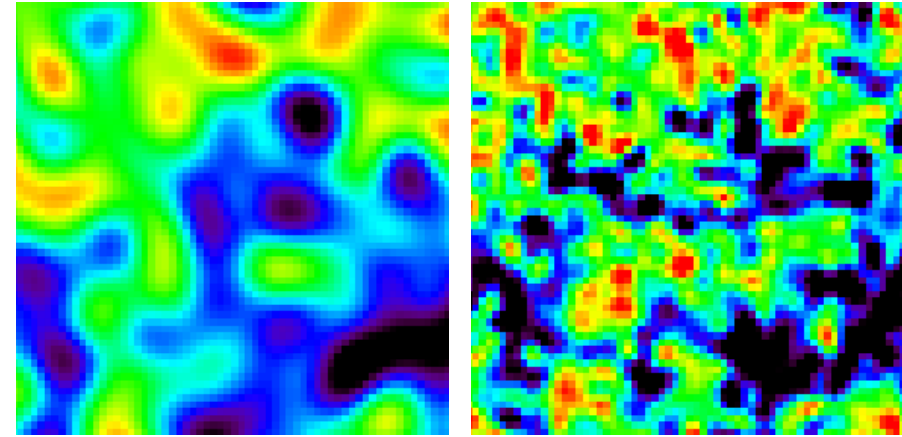
Correlations across different sightlines should have *reduced systematics*, and  $P_{3D}$  accesses the *underlying density fluctuations* (without 1D mode mixing).



# Large ground-based telescopes



Cross-section of simulated IGM tomography maps



6-10m: LATIS/CLAMATO/PFS

ELTs

Gain in sensitivity gives access to **~10x more galaxies and sight lines** enabling drastically more detailed IGM mapping over limited volumes, as well as *multi-sightline measurements of the “sphere of influence” around galaxies* to constrain astrophysics.

# Conclusions

- **The Ly $\alpha$  forest is a powerful probe** of many dark matter models.
- **Ly $\alpha$  constraints have historically been mostly 1D.** Moving to 3D can reduce measurement systematics, open up new statistics, and help separate dark matter physics from galaxy/IGM astrophysics.
- **The first 3D Ly $\alpha$  maps are now in hand.** They do not have statistical power for cosmology, but they already show interesting anomalies compared to galaxy maps. Understanding these will teach us about galaxy–environment–IGM co-evolution.
- **Future surveys will make 3D Ly $\alpha$  tomography much more powerful.** They will enable cosmological and dark matter constraints, while also constraining relevant astrophysics by mapping the circum- and intergalactic environments of galaxies in detail.