The Lyman-alpha cosmic web in TNG50

CB & Nelson, arXiv:2212.08666

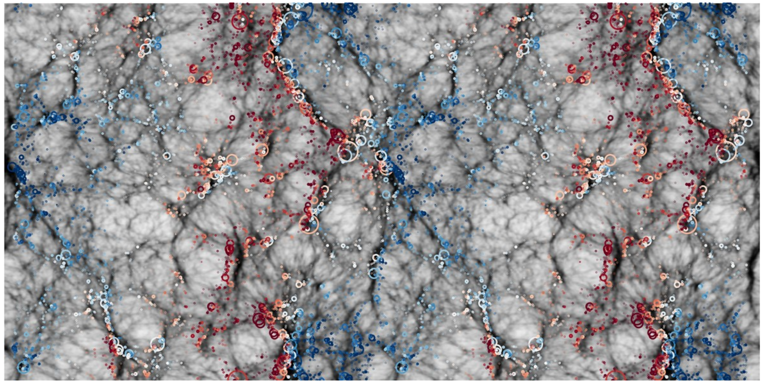
Chris Byrohl
Institute for Theoretical Astrophysics, Heidelberg

Escape of Lyman radiation from galactic labyrinths, Crete, April 18, 2023

Observing the cosmic web: How is it done?

Galaxy clustering

- Use galaxy clustering to indirectly infer filamentary structure, but cannot trace gas



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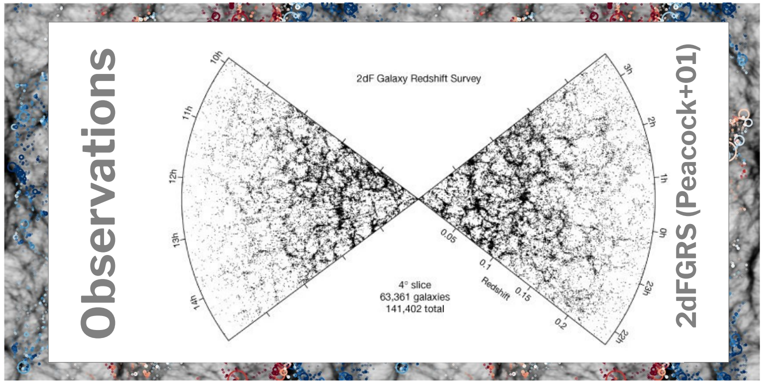

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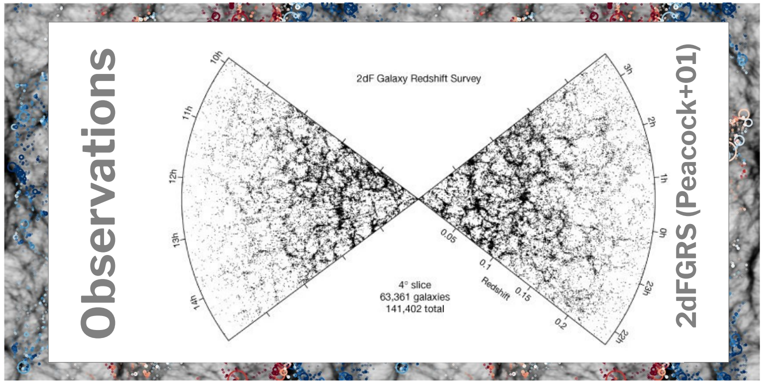

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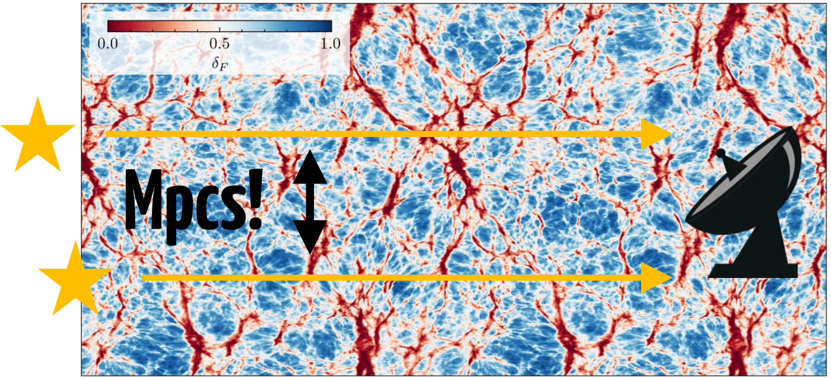

Lyman-alpha absorption

- Use absorption in bright continuum spectra to reconstruct the neutral hydrogen density field
- sparse sampling, resolution ~1 Mpc

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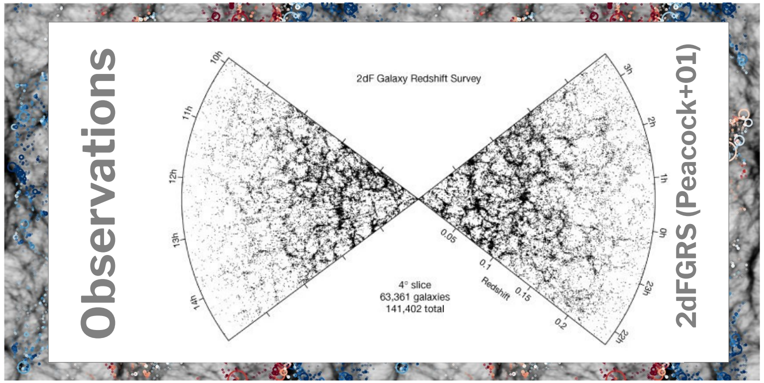

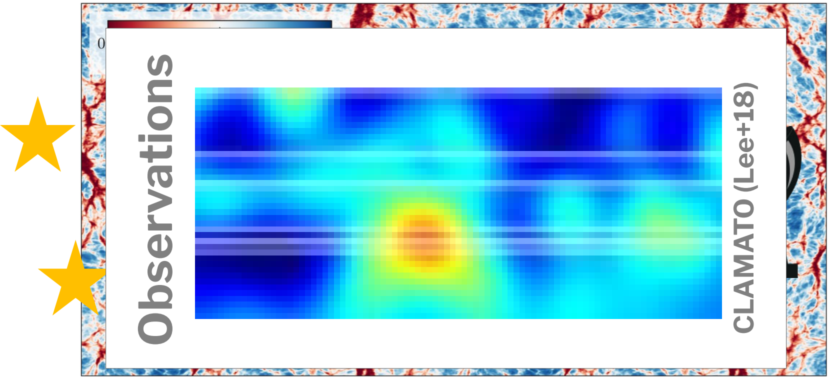

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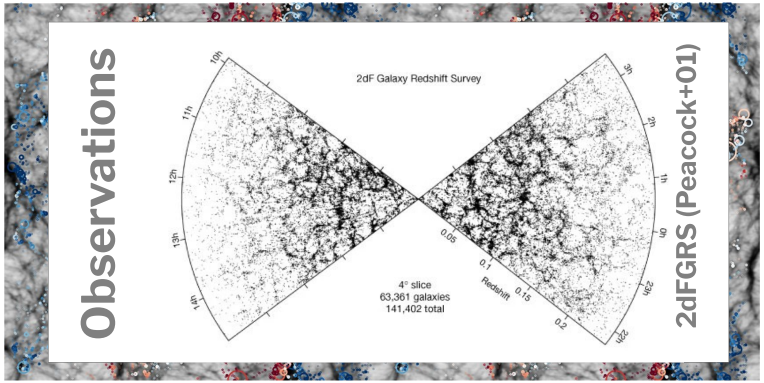

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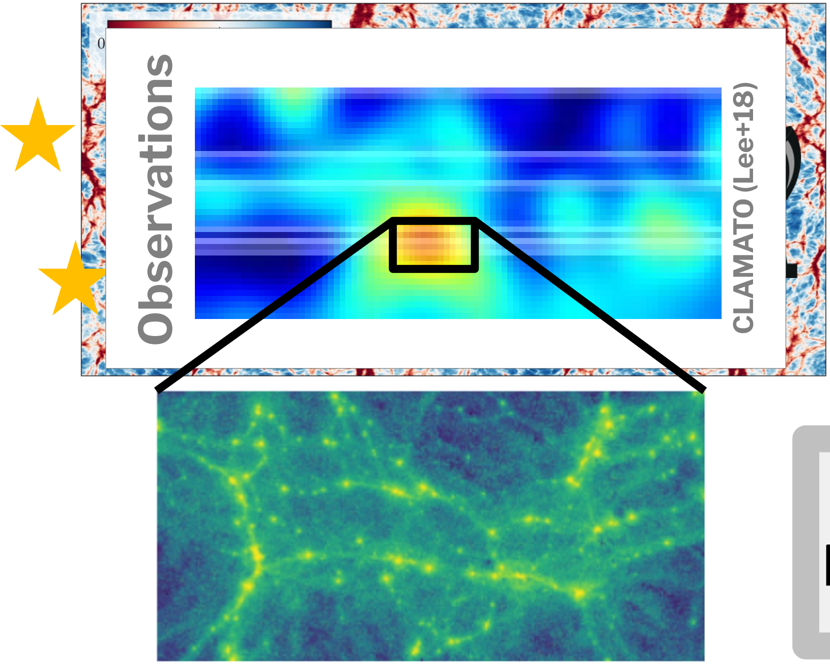

Color coding: log Lya surface brightness

Lyman-alpha absorption

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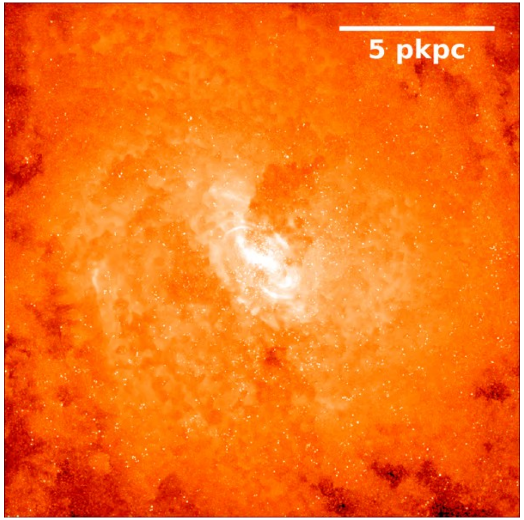
Lyman-alpha emission

Model Lya emission and radiative transfer of the cosmic web
Determine distribution of Lya filaments and their underlying props

Lyman-alpha emission: A multi-scale tracer

(CB, Nelson+21)



Galaxy/ISM

Lyman-alpha radiative transfer simulations on top of the MHD cosmological galaxy formation simulation TNG50

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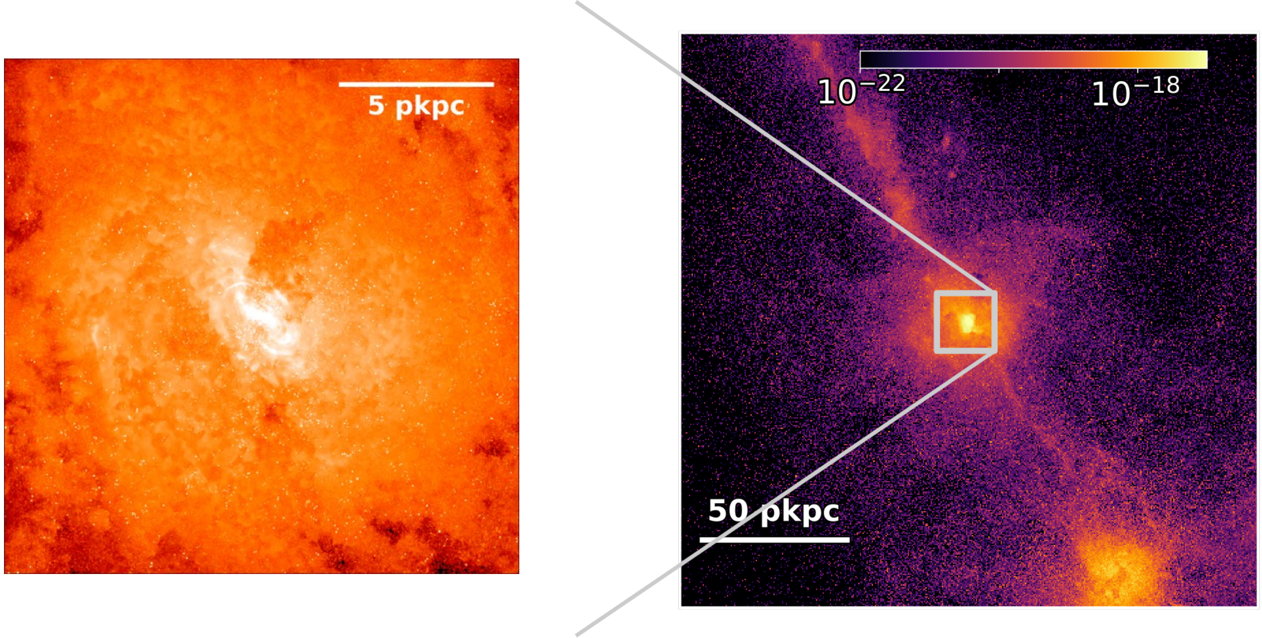

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CGM

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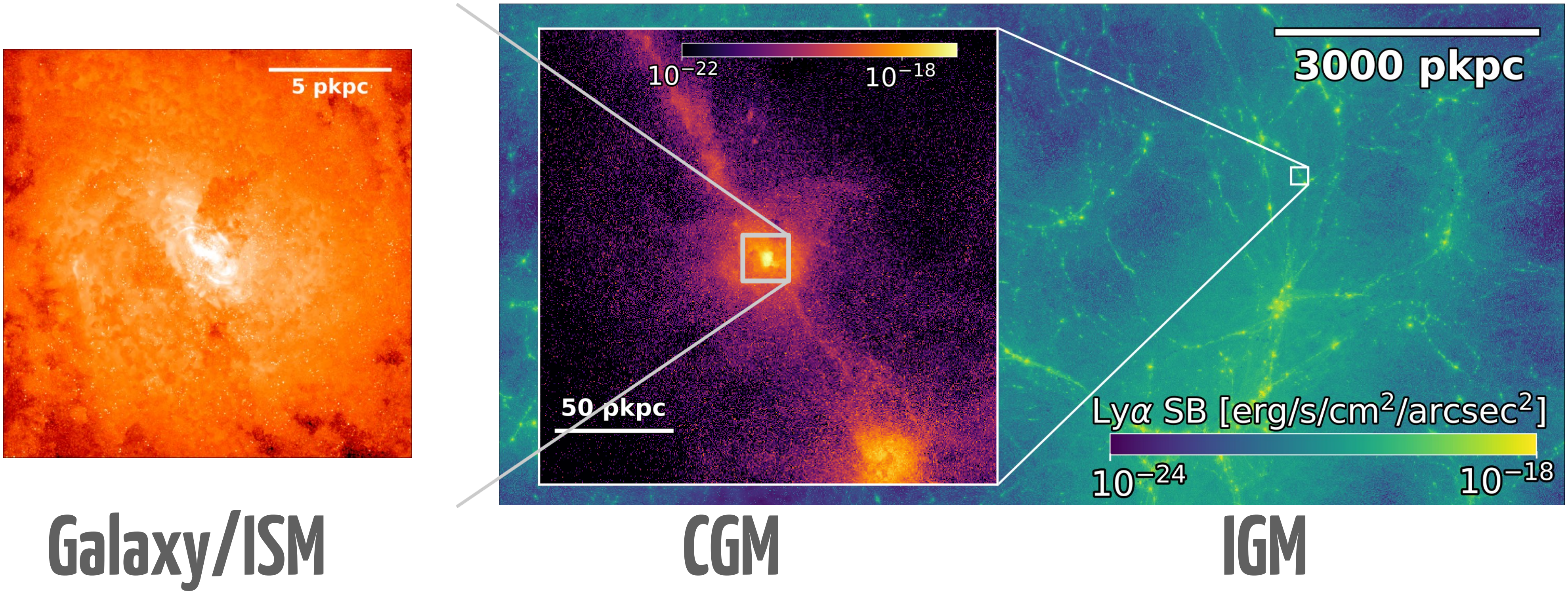


Lyman-alpha radiative transfer simulations on top of the MHD cosmological galaxy formation simulation TNG50

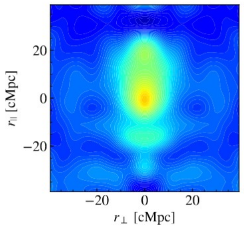
Imaging of the CGM and CW

Observations

LABs/LANs

LAHs

LAF/LCW



(Croft+16, Lin+22)

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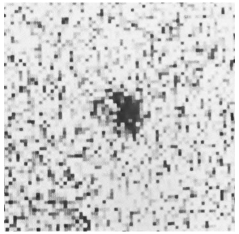

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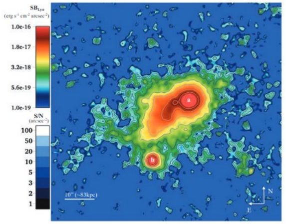

(Cantalupo+14)

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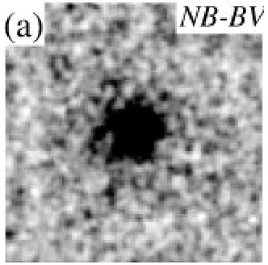

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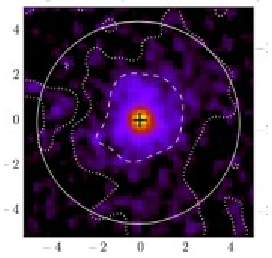

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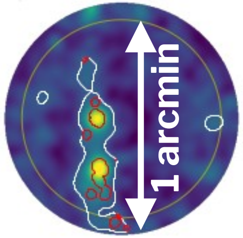

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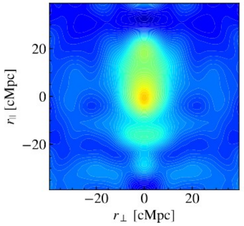

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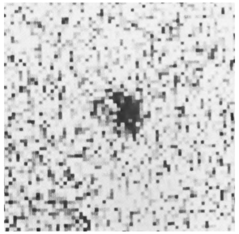

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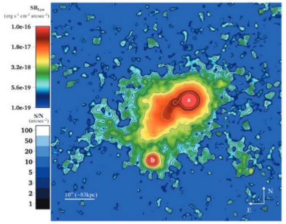

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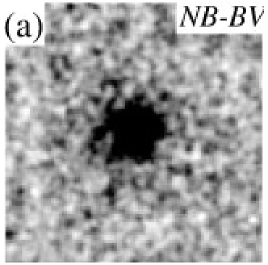

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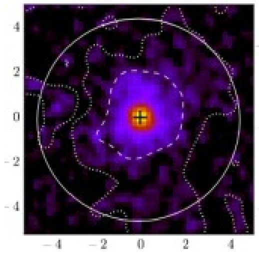

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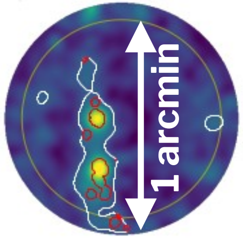

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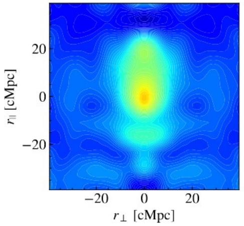

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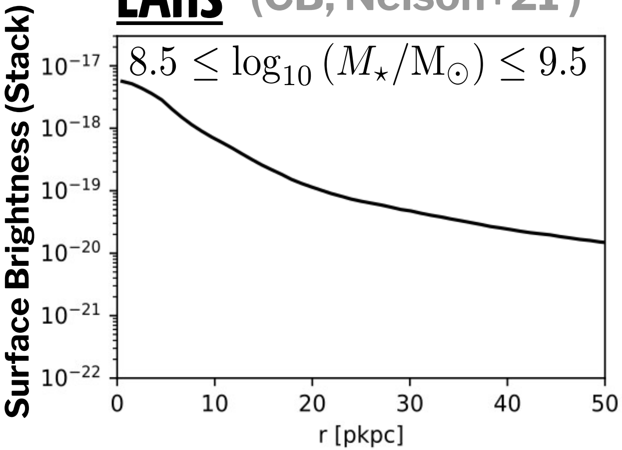

Simulated stacked radial profiles at z=3.0

Imaging of the CGM and CW

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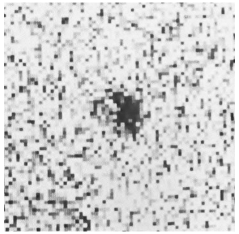

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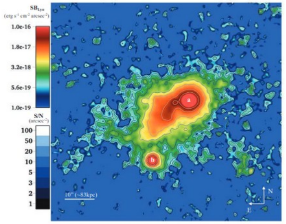

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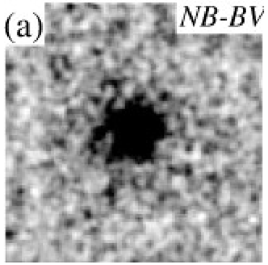

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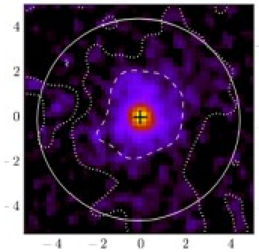

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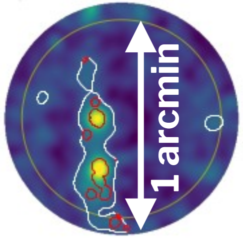

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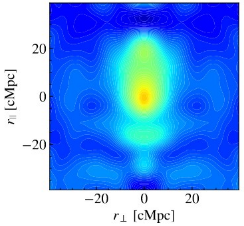

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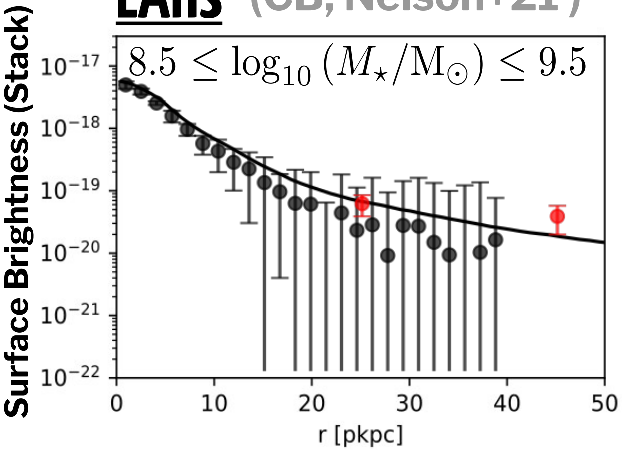

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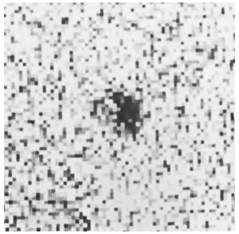

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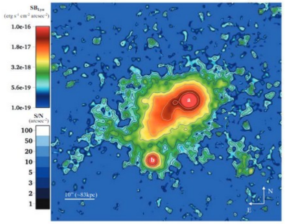

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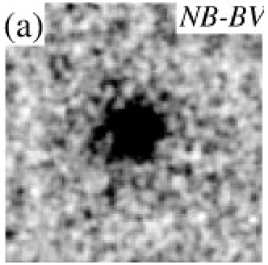

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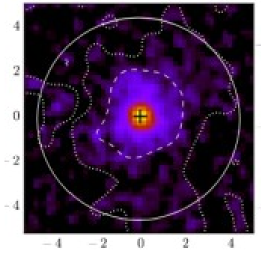

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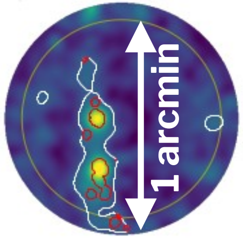

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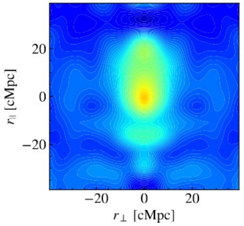

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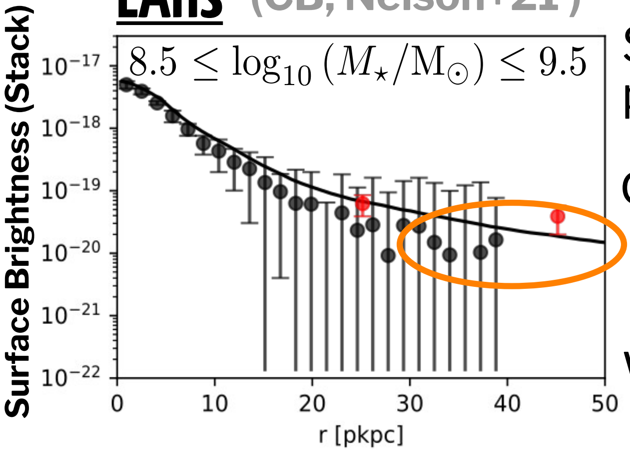

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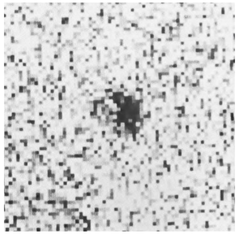

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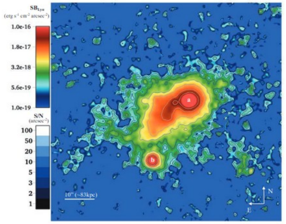

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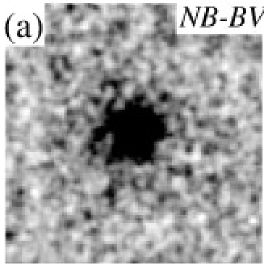

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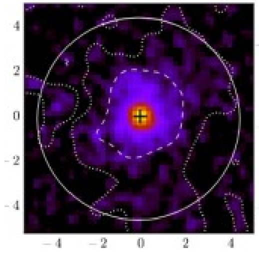

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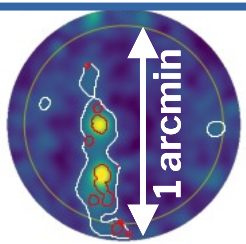

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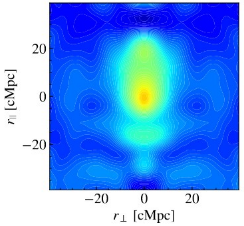

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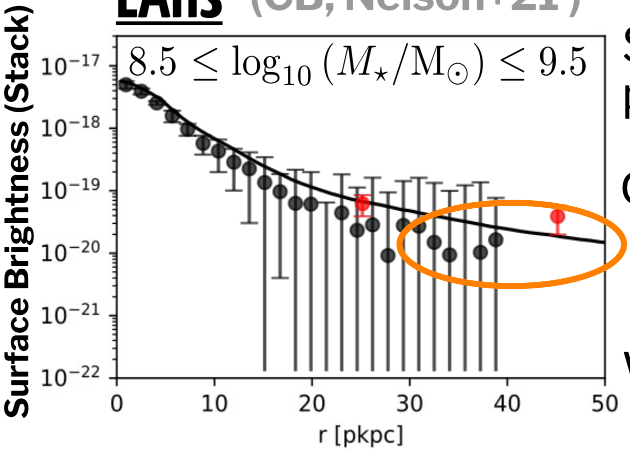

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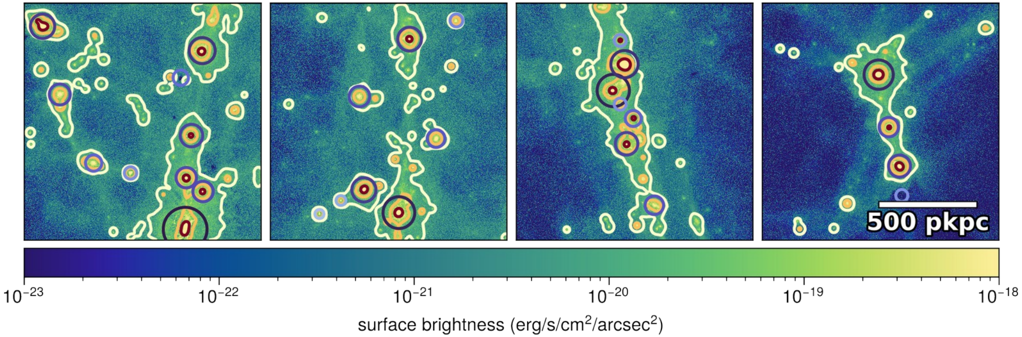
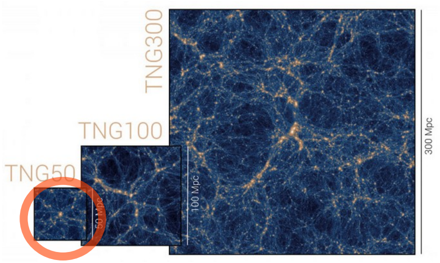
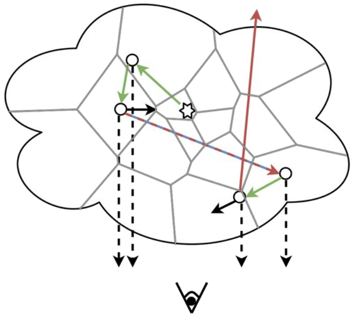


Modeling the Lya cosmic web

Galaxy formation simulation → **Lyα radiative transfer code**



(TNG Collaboration)



Paint on the emission from stellar populations and diffuse gas

$$\epsilon_{\rm exc} = \gamma_{\rm 1s2p}(T)\ n_e\ n_{HI}\ E_{{\rm Ly}\alpha}$$

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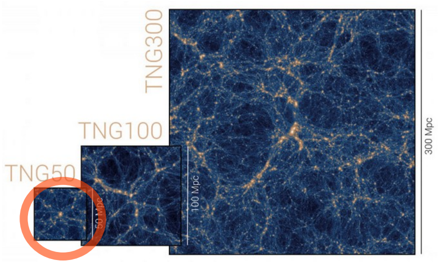

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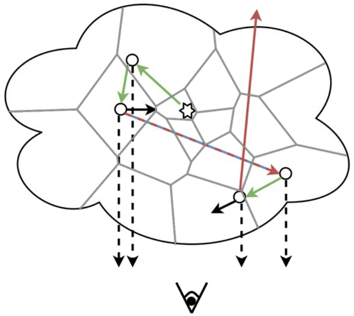

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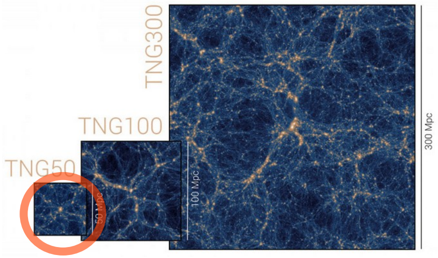

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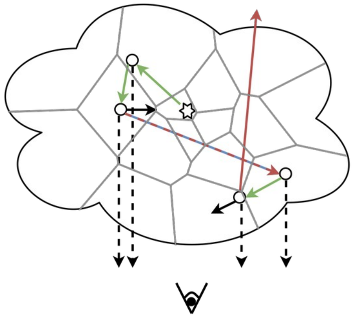

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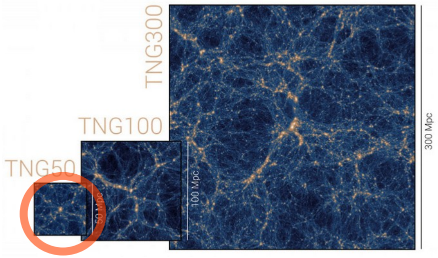

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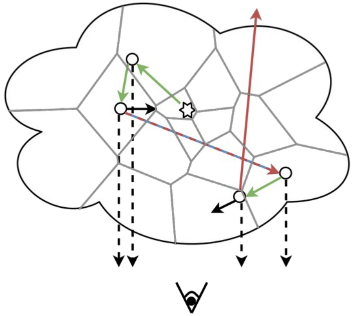

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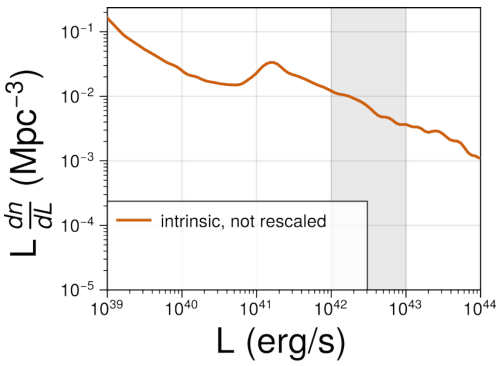
Post-processing & analysis @ z=2



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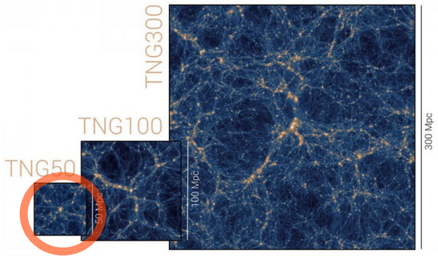

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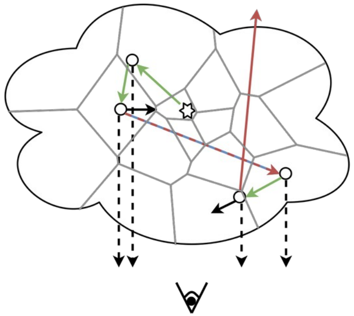

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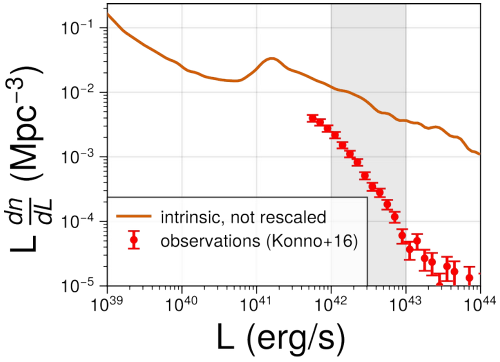
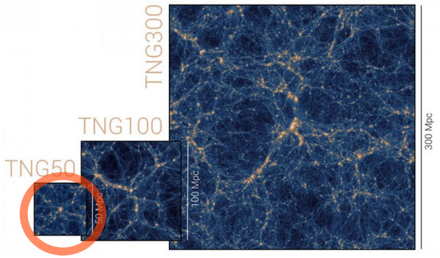
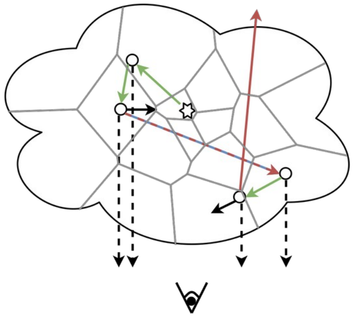


Modeling the Lya cosmic web

Galaxy formation simulation → **Lyα radiative transfer code**



(TNG Collaboration)



Paint on the emission from stellar populations and diffuse gas

$$\epsilon_{\rm exc} = \gamma_{\rm 1s2p}(T)\ n_e\ n_{HI}\ E_{\rm Ly\alpha}$$

$$\epsilon_{\rm rec} = f_{\rm rec}(T)\ n_e\ n_{HII}\ \alpha(T)\ E_{\rm Ly\alpha}$$

$$\epsilon_{SF} = \sout{10^{42}\ ({\rm erg/s})/(M_\odot/{\rm yr})\ \cdot\ {\rm SFRd}}$$

Stellar synth. code BPASS + calibrated dust attenuation model

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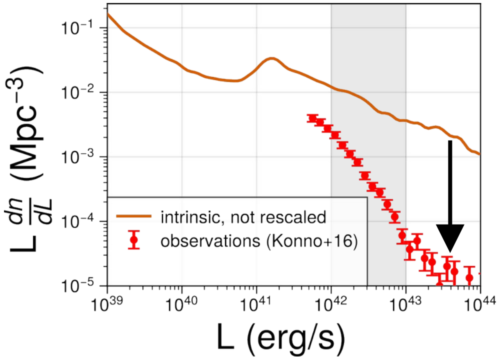

IGM interaction + dust destruct.

Modeling the Lya cosmic web

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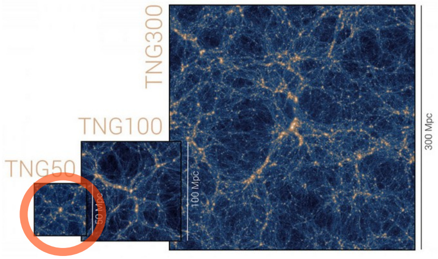

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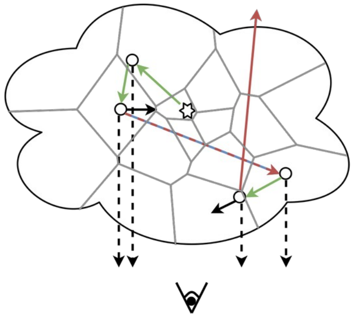

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Stellar synth. code BPASS + calibrated dust attenuation model

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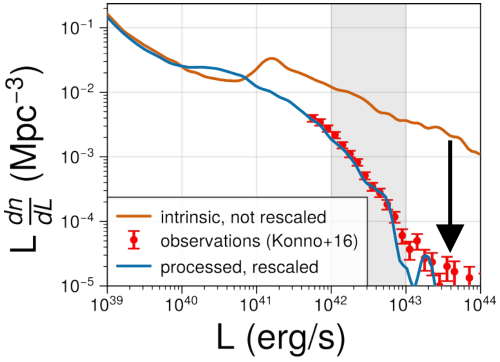

IGM interaction
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Rescale each scattered photon according to the dust content at its origin to capture both effects!

Modeling the Lya cosmic web

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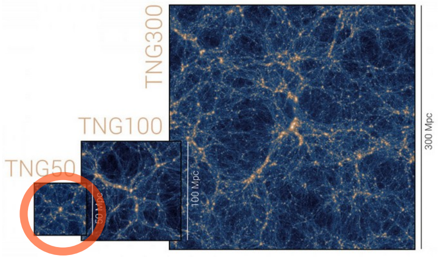

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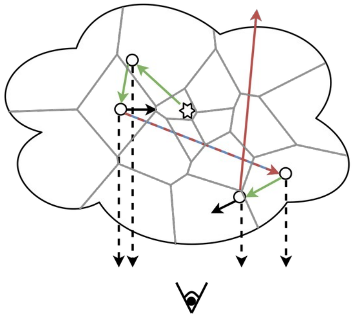

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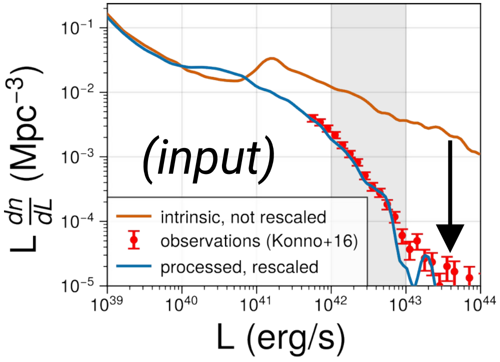

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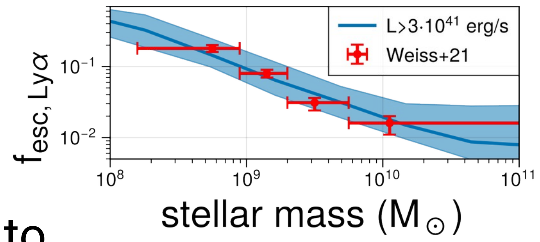
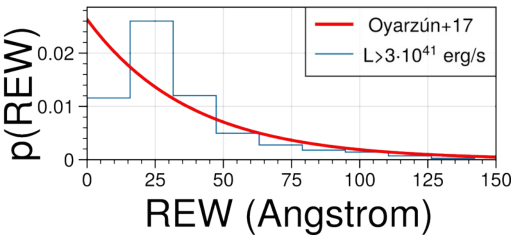
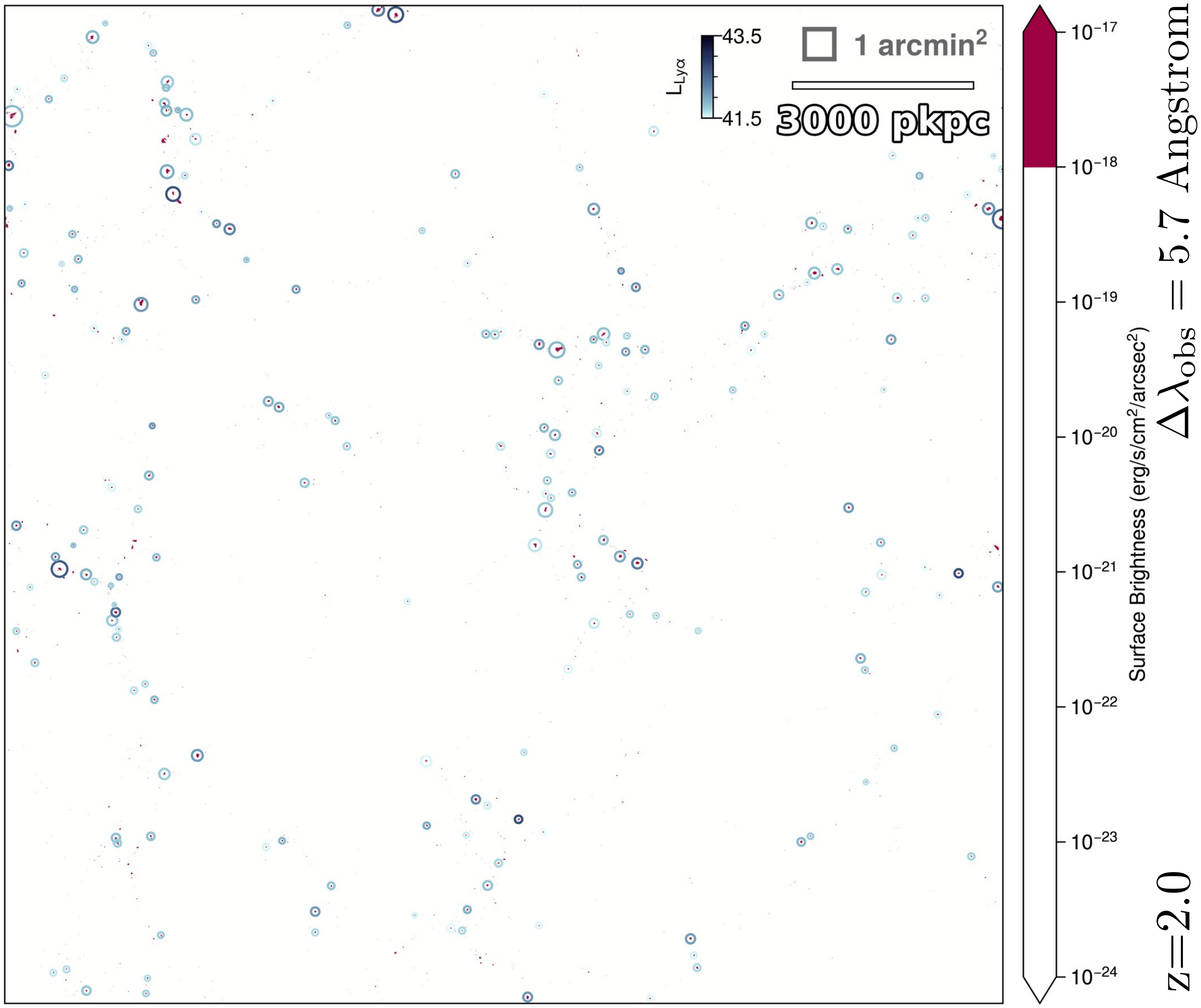
Rescale each scattered photon according to the dust content at its origin to capture both effects!

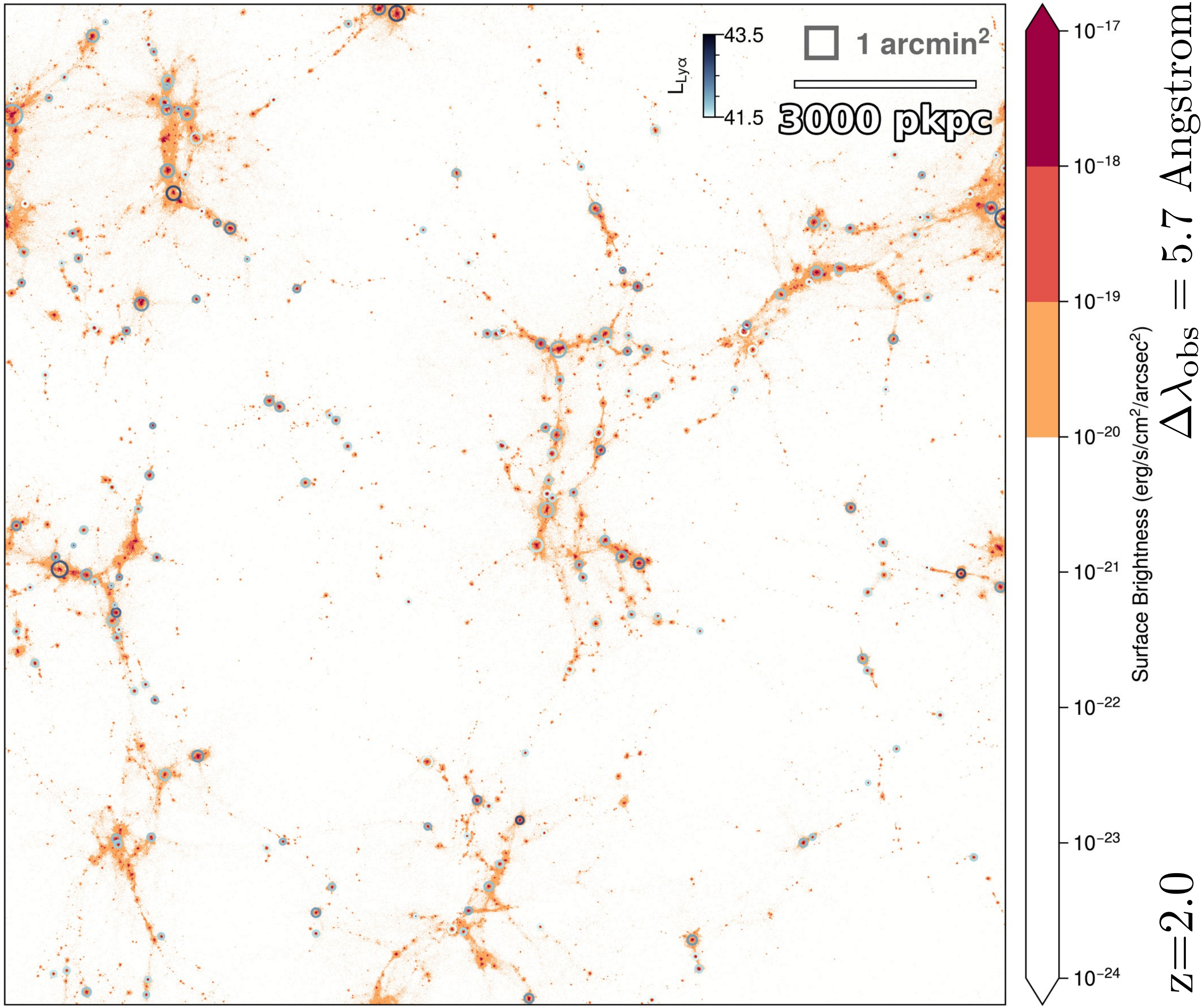
Consistency check on galaxies *(output)*







$L_{Ly\alpha}$
43.5
41.5
1 arcmin²
3000 pkpc
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
Surface Brightness (erg/s/cm²/arcsec²)
$\Delta\lambda_{\rm obs} = 5.7$ Angstrom
z=2.0



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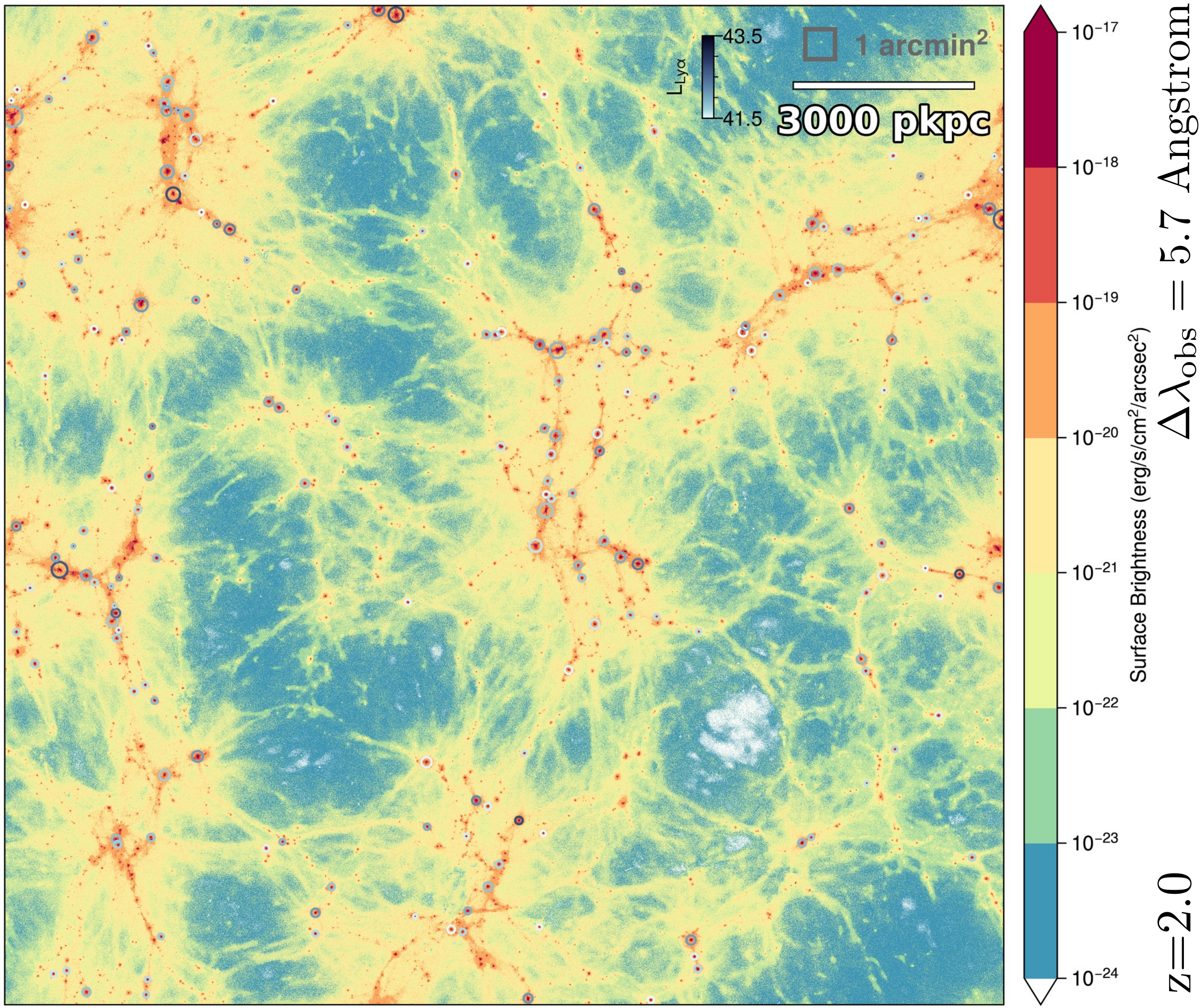

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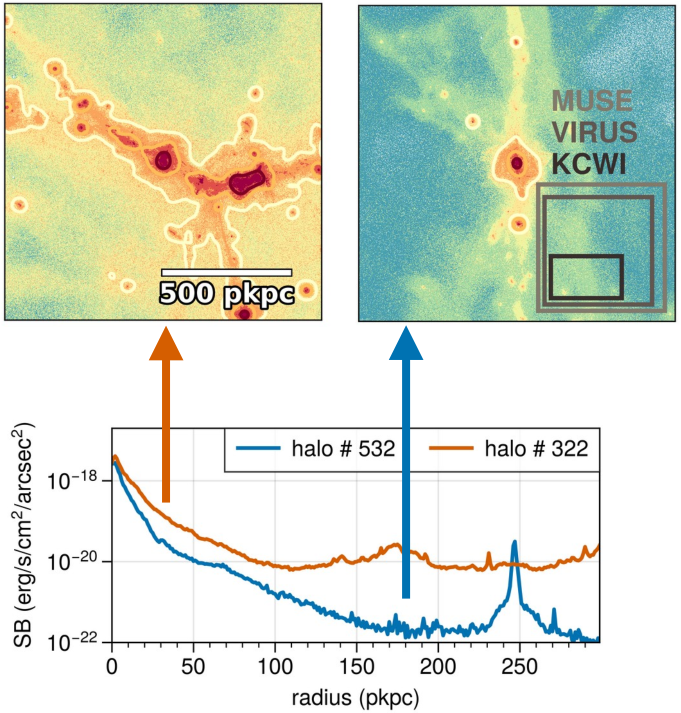
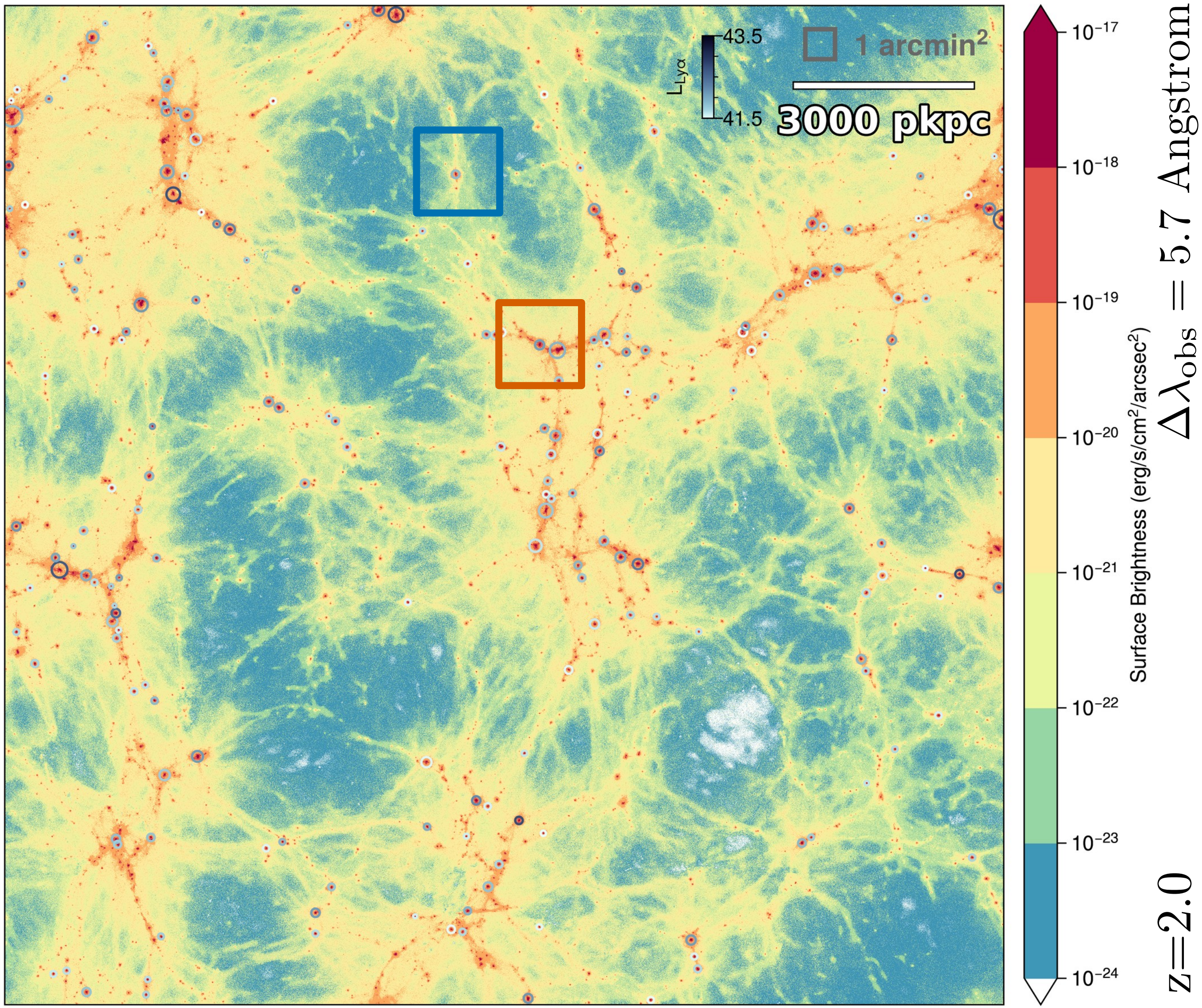
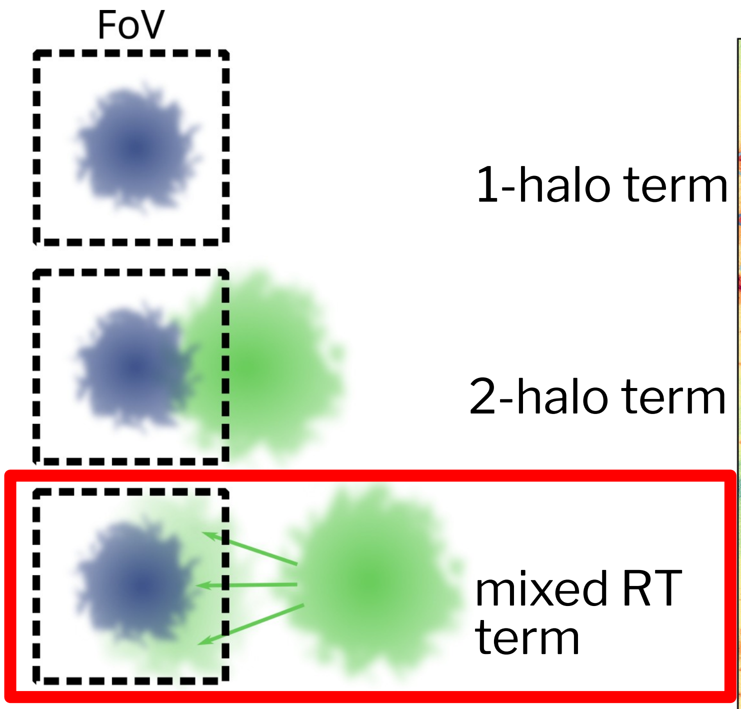
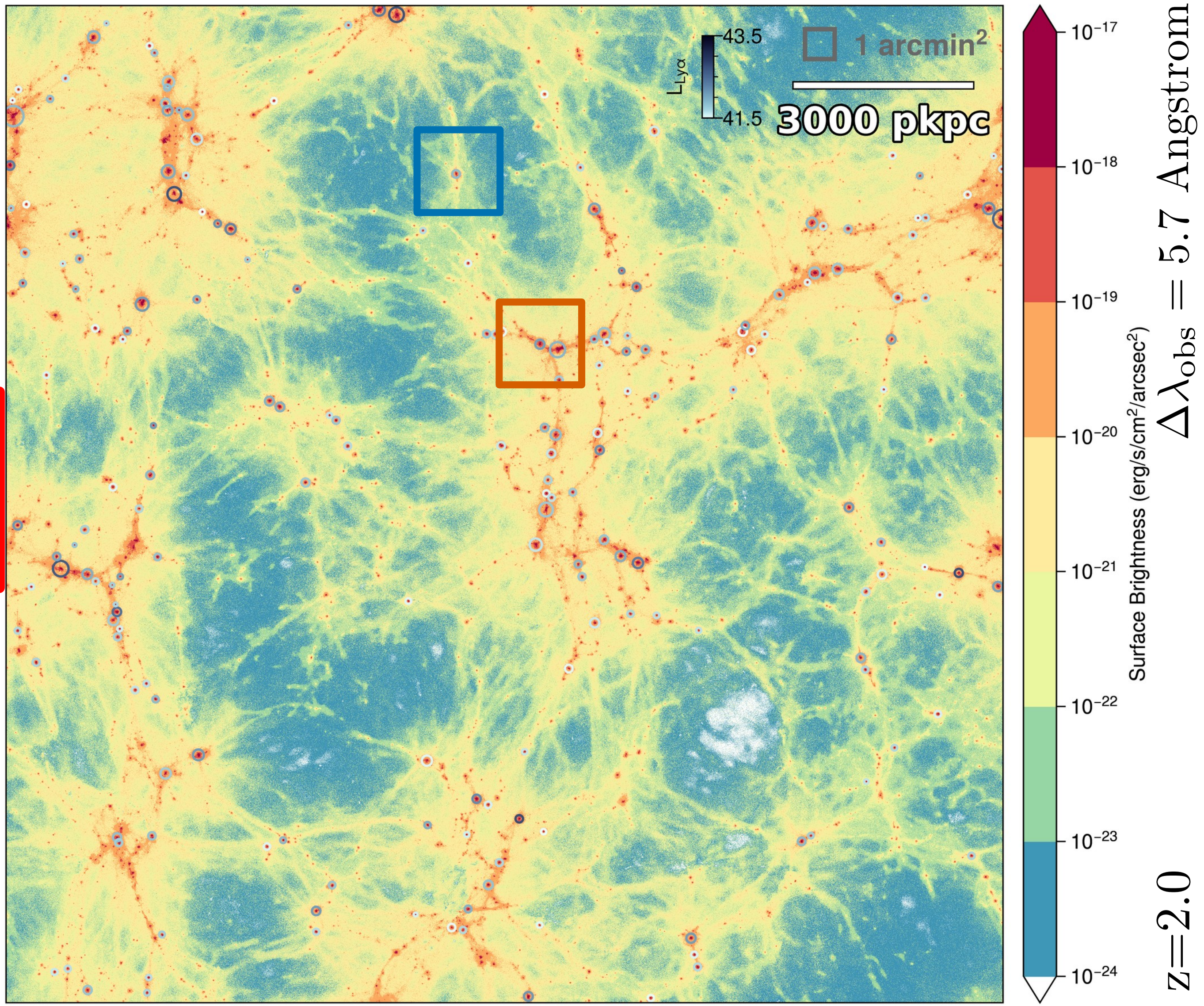




Flattening in observed radial profiles (Wisotzki+18, Kikuchihara+21, Niemeyer+22) explained by scattered photons of nearby galaxies (Byrohl+21)

→ environmental effect





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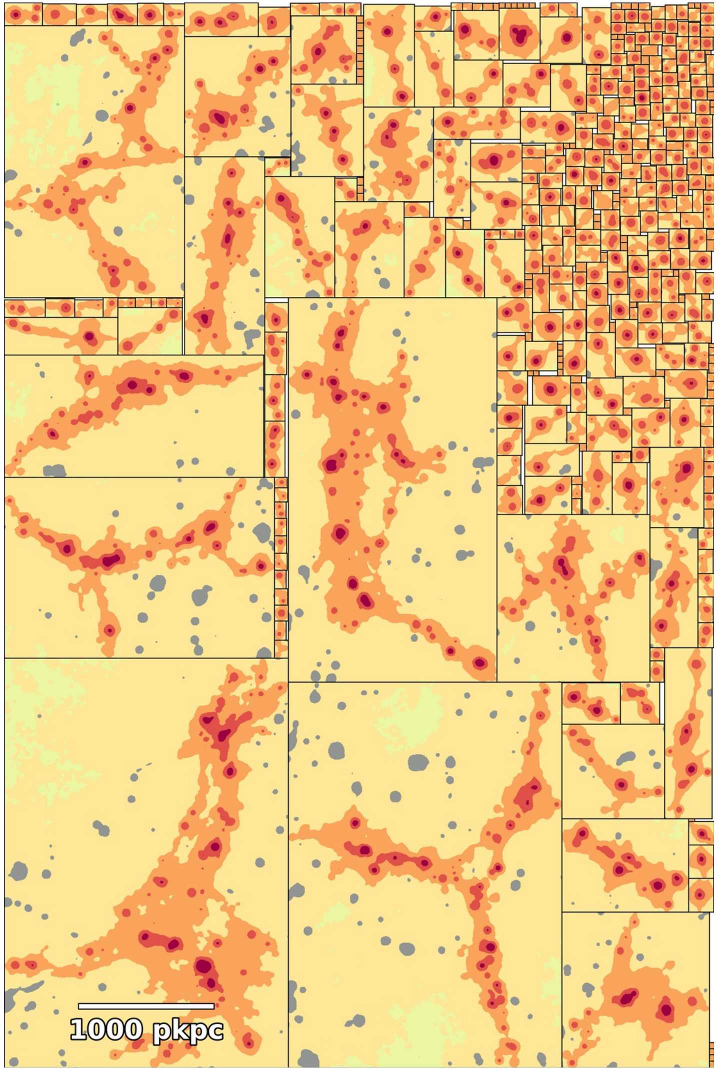
Lya filament identification



Lya nebula for scale (Cantalupo+14): 

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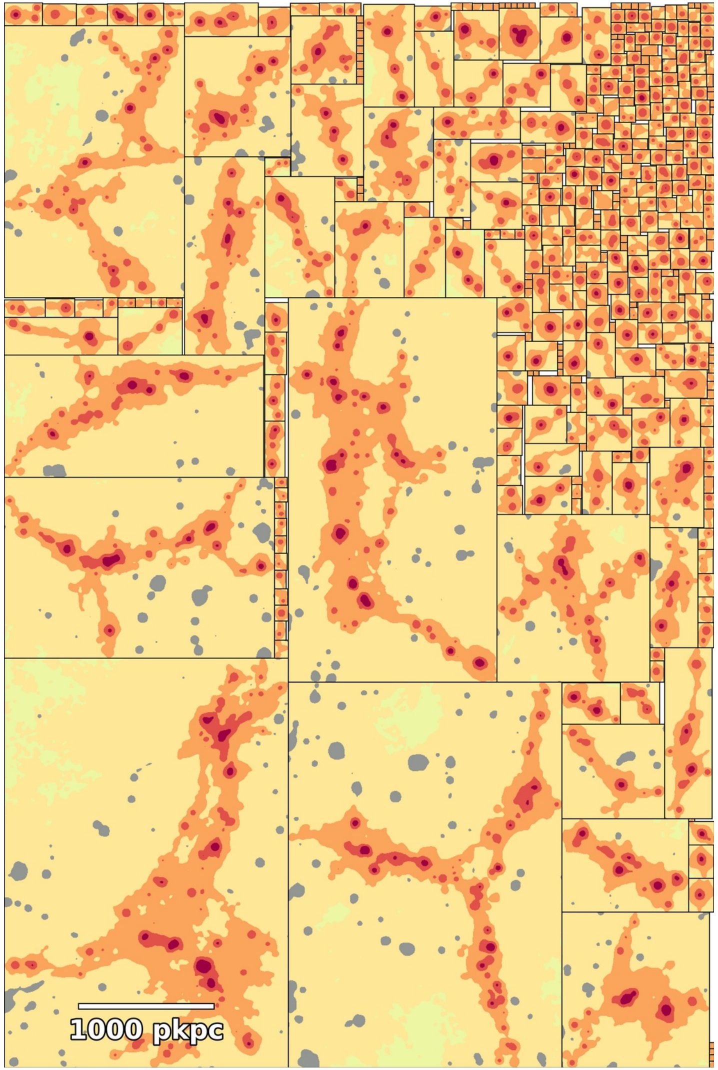

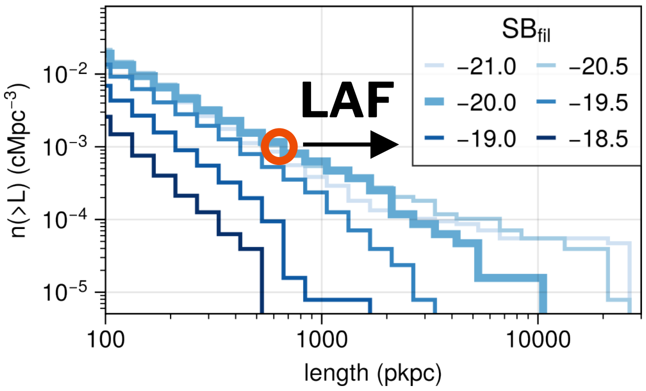

$$n_{LAF} = 10^{-3}\,\mathrm{cMpc}^{-3}$$

Between 2<z<2.4 for footprint:

blueMUSE/KCWI: $\langle N \rangle \approx 1$

HET-VIRUS: $\langle N \rangle \approx 300$

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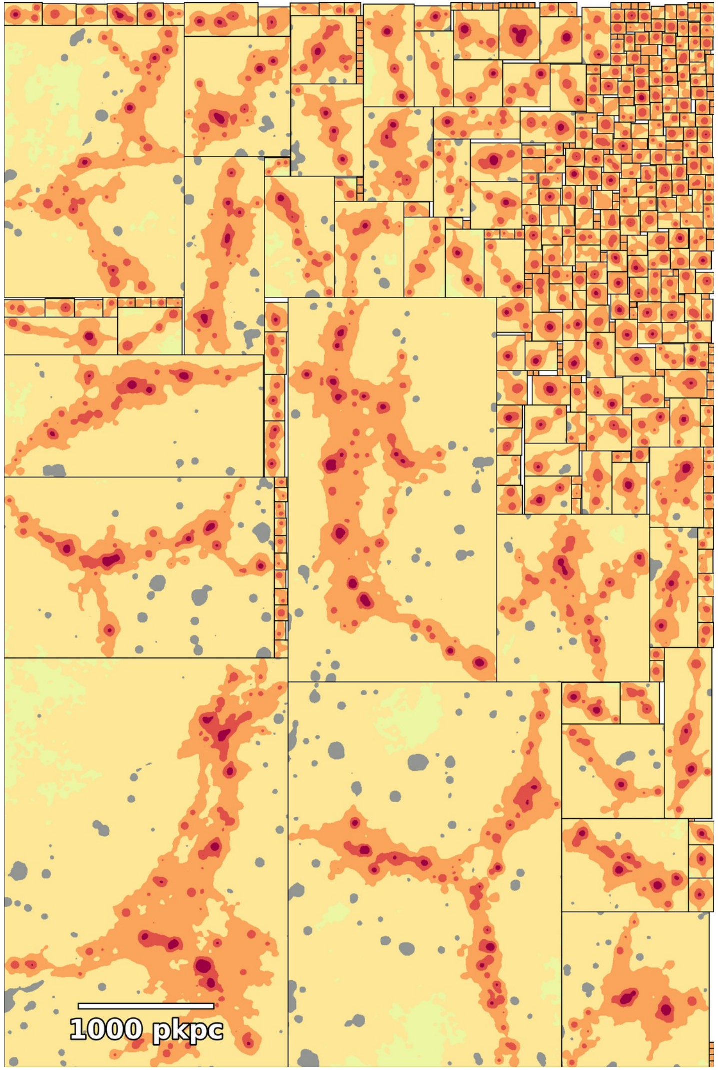

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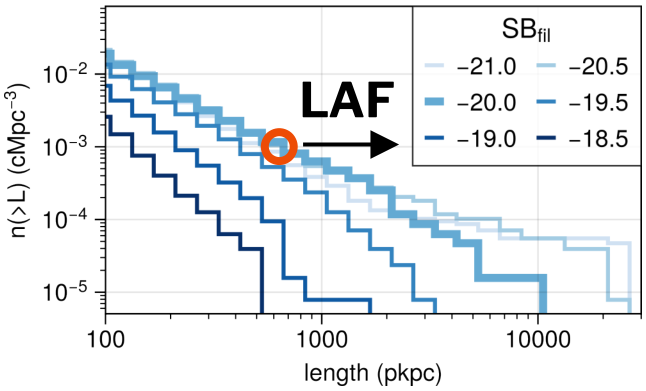

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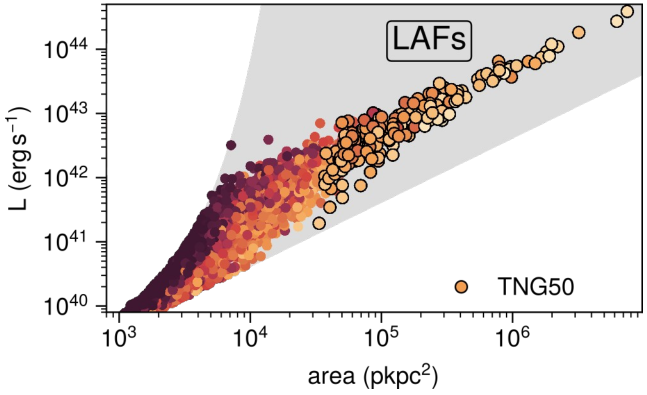
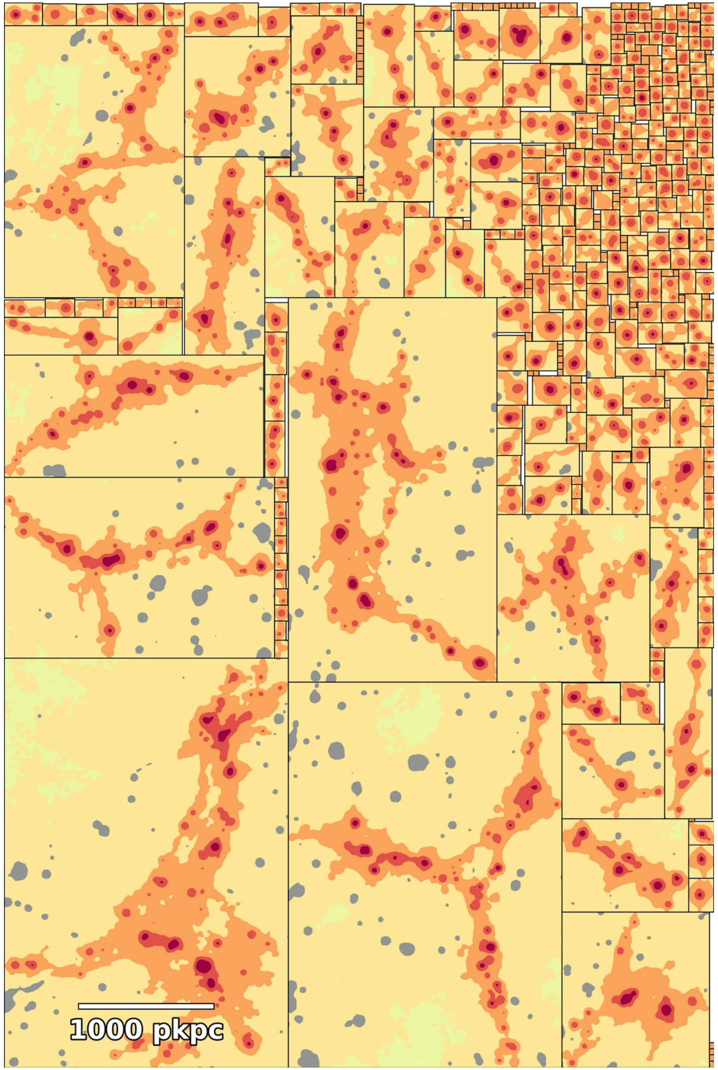


Lyman-alpha filaments (LAF): Elongated structures with L > 400pkpc at SB threshold $\sim 10^{-20}\,\mathrm{erg\,s^{-1}\,cm^{-2}\,arcsec^{-2}}$



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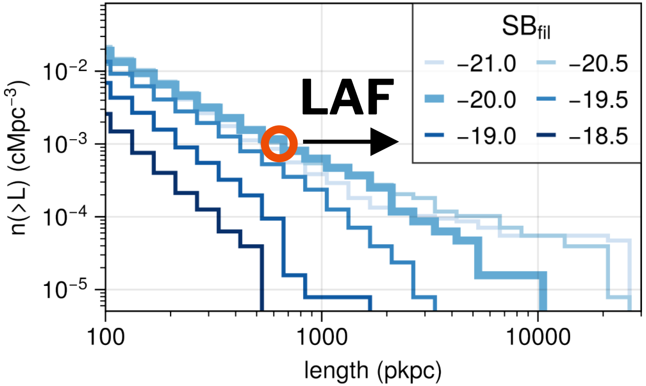

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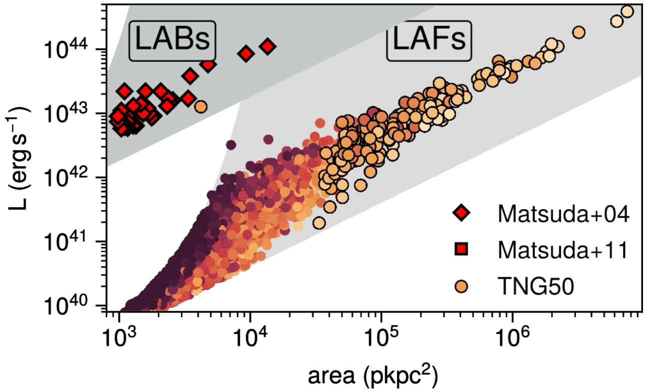
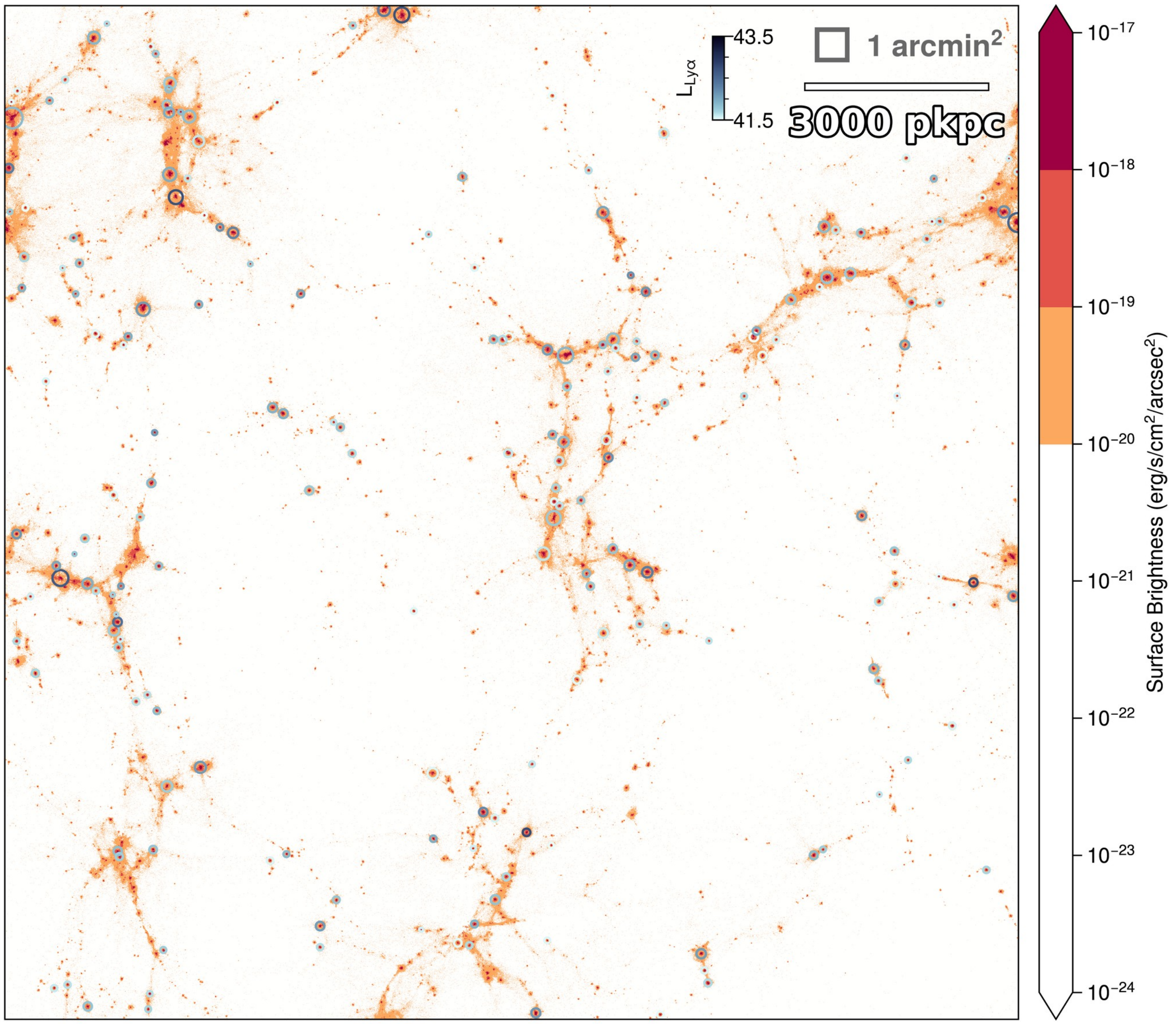


Lyman-alpha filaments (LAF):
Elongated structures with
L > 400pkpc at SB threshold

$$\sim 10^{-20}\,\mathrm{erg\,s^{-1}\,cm^{-2}\,arcsec^{-2}}$$

→ significantly more common than LABs, for which we find one candidate in TNG50 consistent with LAB number densities

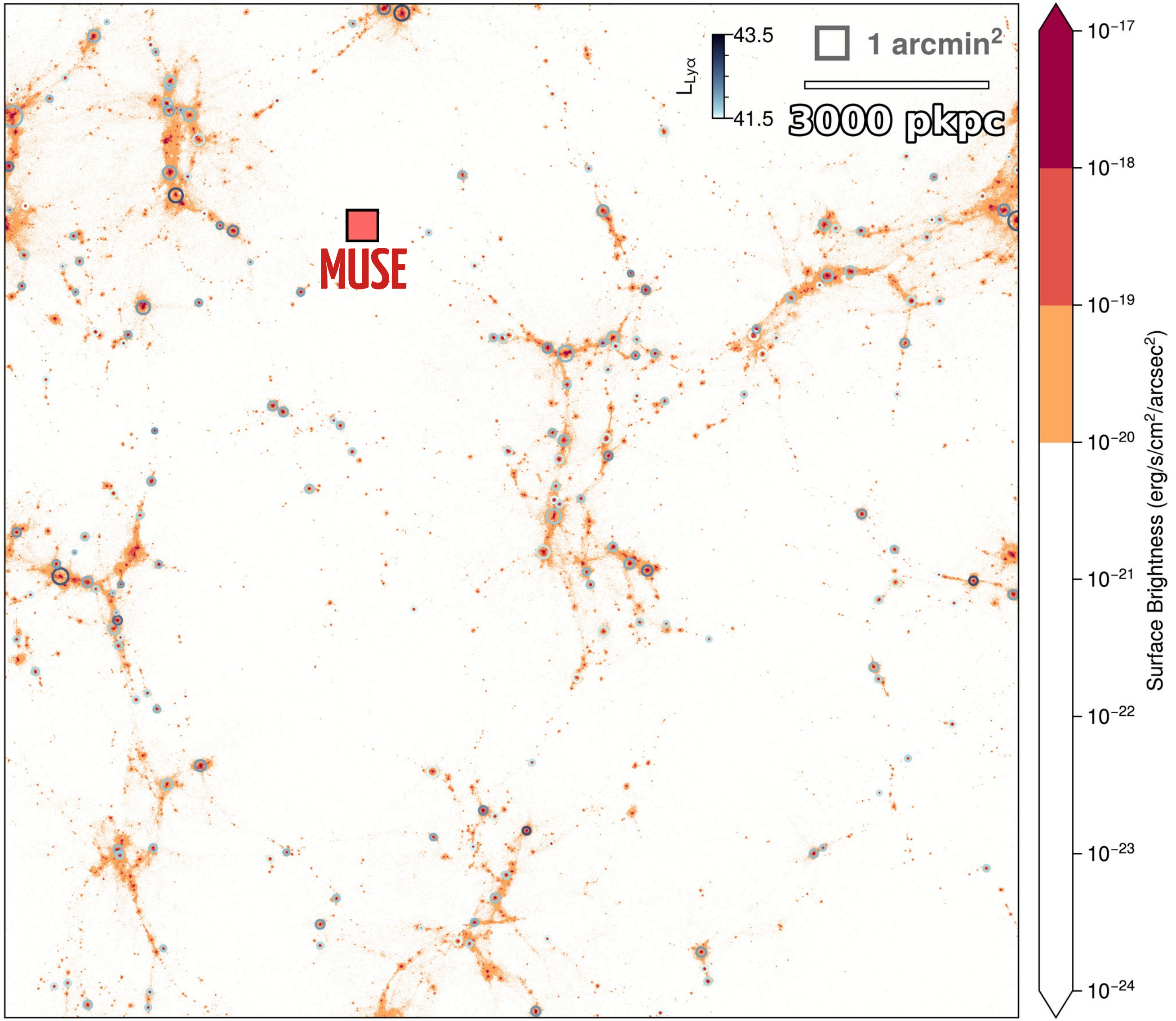
Observations



Observations

ESO/P. Horálek

MUSE-EDF:
1×400pkpc fil @ z=3,
selected around $\delta_{\mathrm{LAE}} \gg 1$
100h alloc (Bacon+21)
$1\ \sigma \sim 2 \cdot 10^{-20} \mathrm{erg/s/cm^2/arcsec^2}$



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ⓘ McDonald Obs./ Martin Harris

34h alloc
$1\ \sigma \sim 7 \cdot 10^{-20} \mathrm{erg/s/cm^2/arcsec^2}$

HET-VDF (proposed):
48h alloc in EGS 2023-2024
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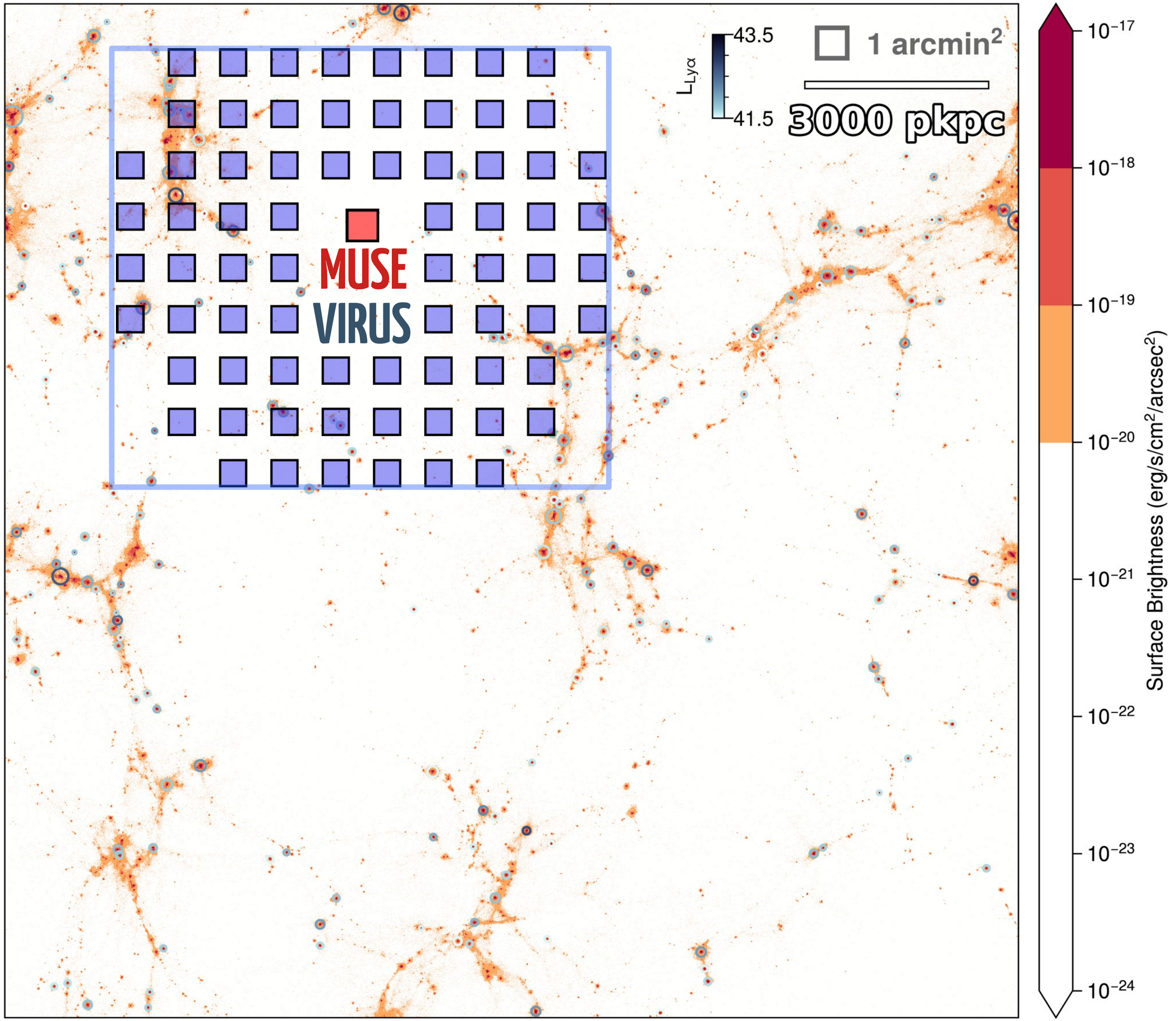

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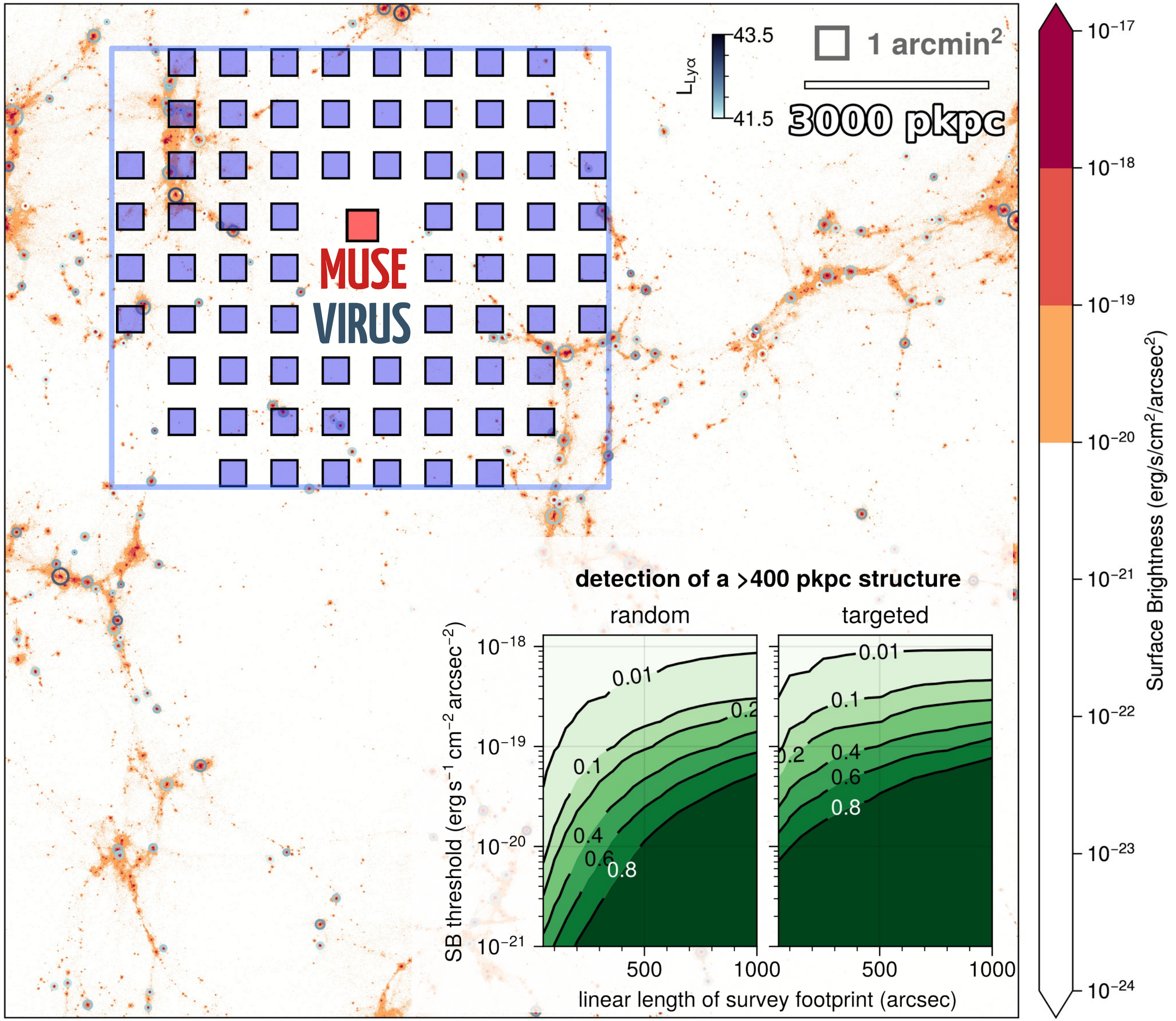
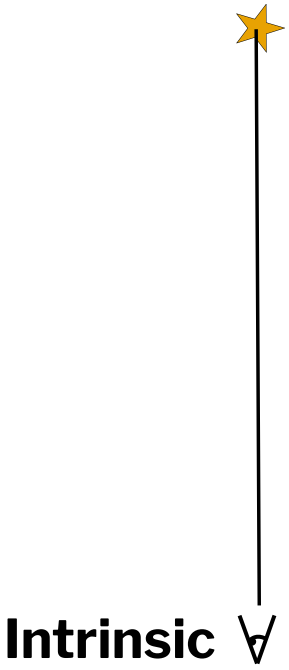


Keeping track of Lyman-alpha radiative transfer



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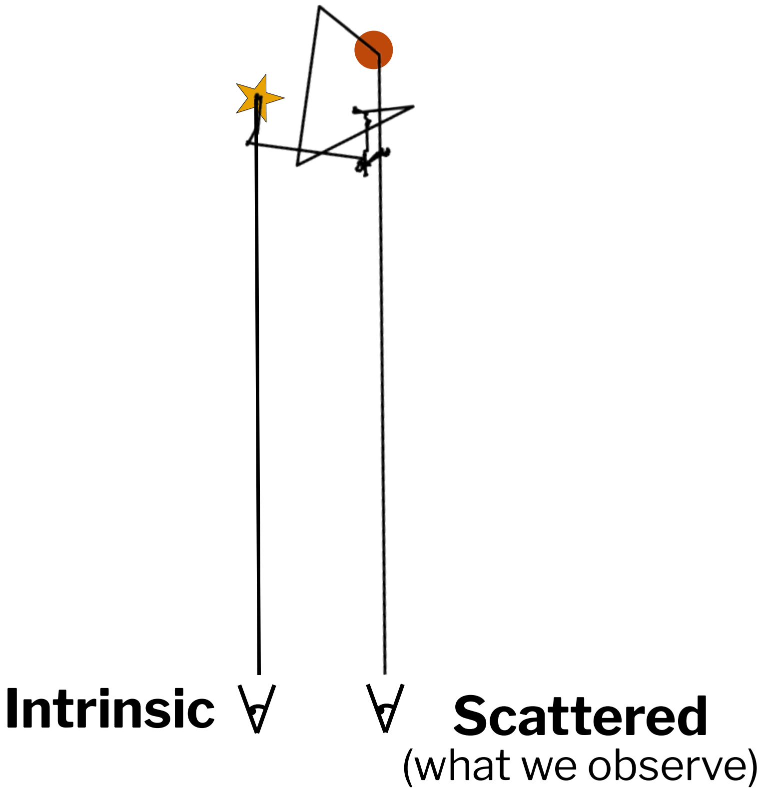

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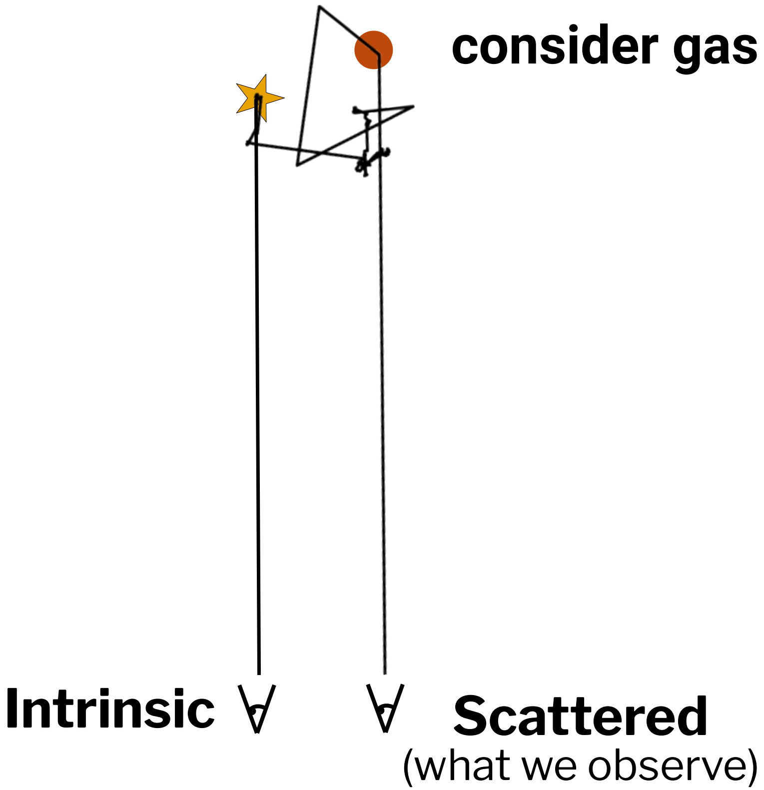

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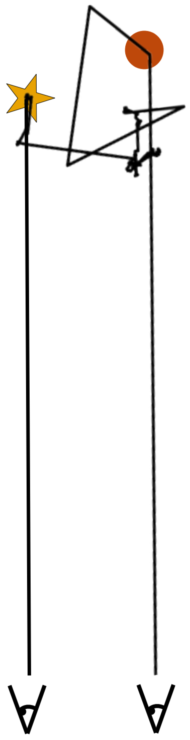


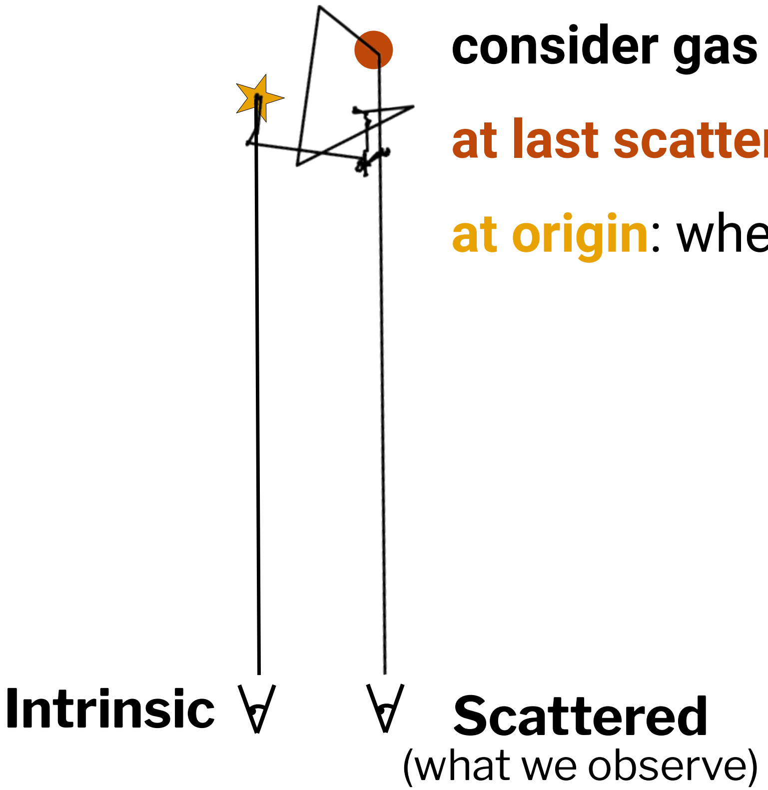
consider gas state

at last scattering: from where the photons reach us

Intrinsic

Scattered
(what we observe)

Keeping track of Lyman-alpha radiative transfer



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at last scattering: from where the photons reach us

at origin: where the photons are emitted

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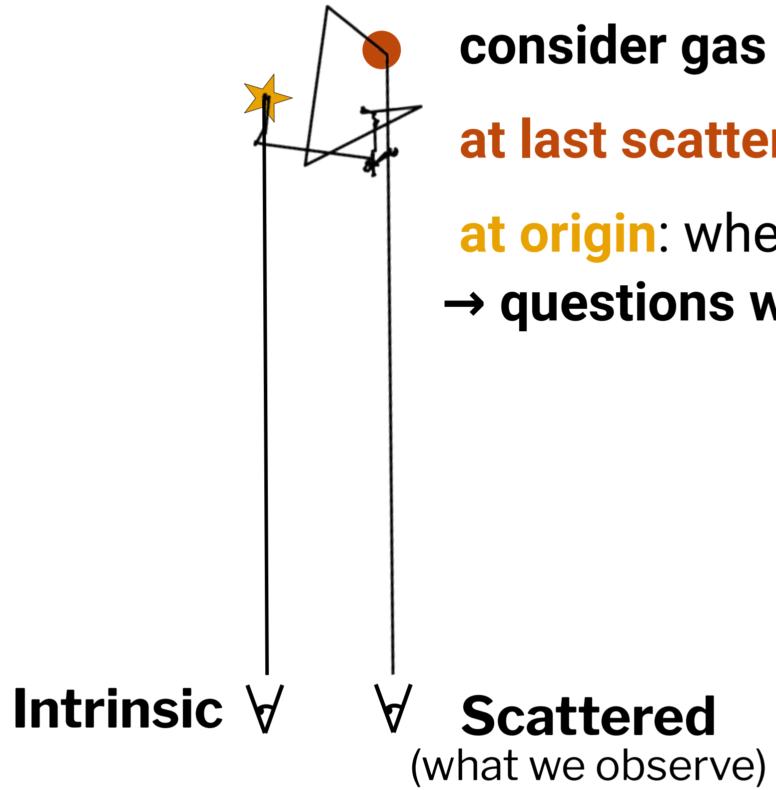

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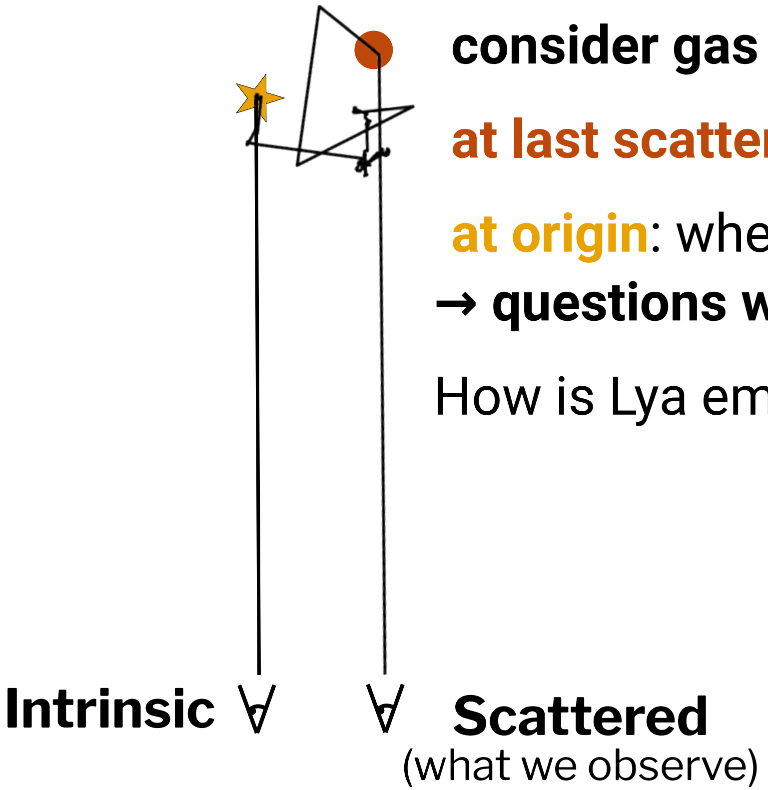
→ **questions we can answer**

Keeping track of Lyman-alpha radiative transfer



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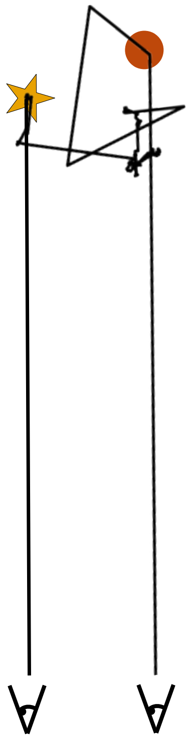
How is Lya emission distributed? (**intrinsic**, **at origin**)

Keeping track of Lyman-alpha radiative transfer



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at last scattering: from where the photons reach us

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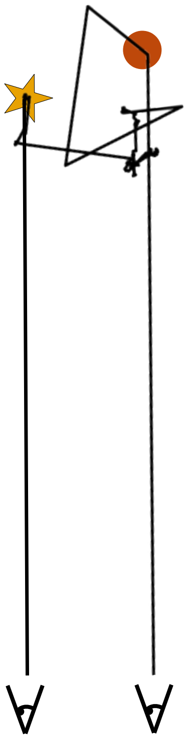
Where does the observed radiation originate? (**scattered**, **at origin**)

Intrinsic

Scattered
(what we observe)

Keeping track of Lyman-alpha radiative transfer



consider gas state

at last scattering: from where the photons reach us

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→ questions we can answer

How is Lya emission distributed? (**intrinsic**, **at origin**)

Where does the observed radiation originate? (**scattered**, **at origin**)

What gas does the observed radiation trace? (**scattered**, **at last scattering**)

Intrinsic

Scattered
(what we observe)

Emission mechanism

- **collisions**: in diffuse gas, cooling via Lyman-alpha emission following collisions
- **recombinations**: in diffuse gas, recombinations following ionization, particularly by nearby AGN and UV background
- **star-formation**: nebular emission sourced by ionizing radiation around stellar populations

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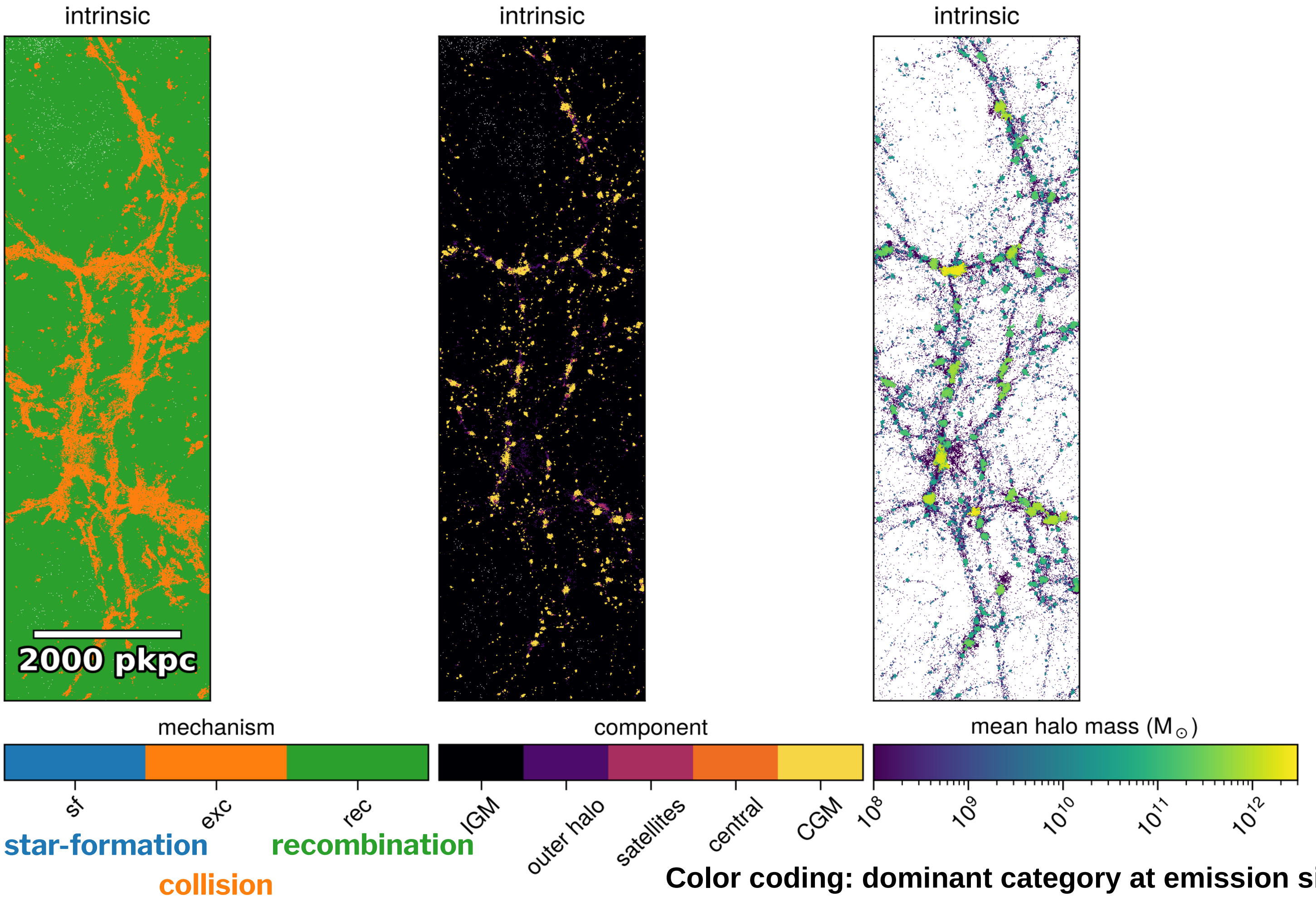
Spatial component

- **IGM**: intergalactic medium gas, i.e. does not belong to any collapsed halo.
- **outer halo**: gas which is part of a dark matter halo, but gravitationally unbound, i.e. on the outskirts.
- **satellite**: gas gravitationally bound to a satellite galaxy in the orbit within a larger host halo
- **CGM**: gas in the halo, gravitationally bound to the central galaxy, and outside 10% of the halo virial radius
- **central**: gas in the halo, gravitationally bound to the central galaxy, and inside 10% of the halo virial radius

Lyα filament boosting by its radiative transfer



Color coding: dominant category at emission site

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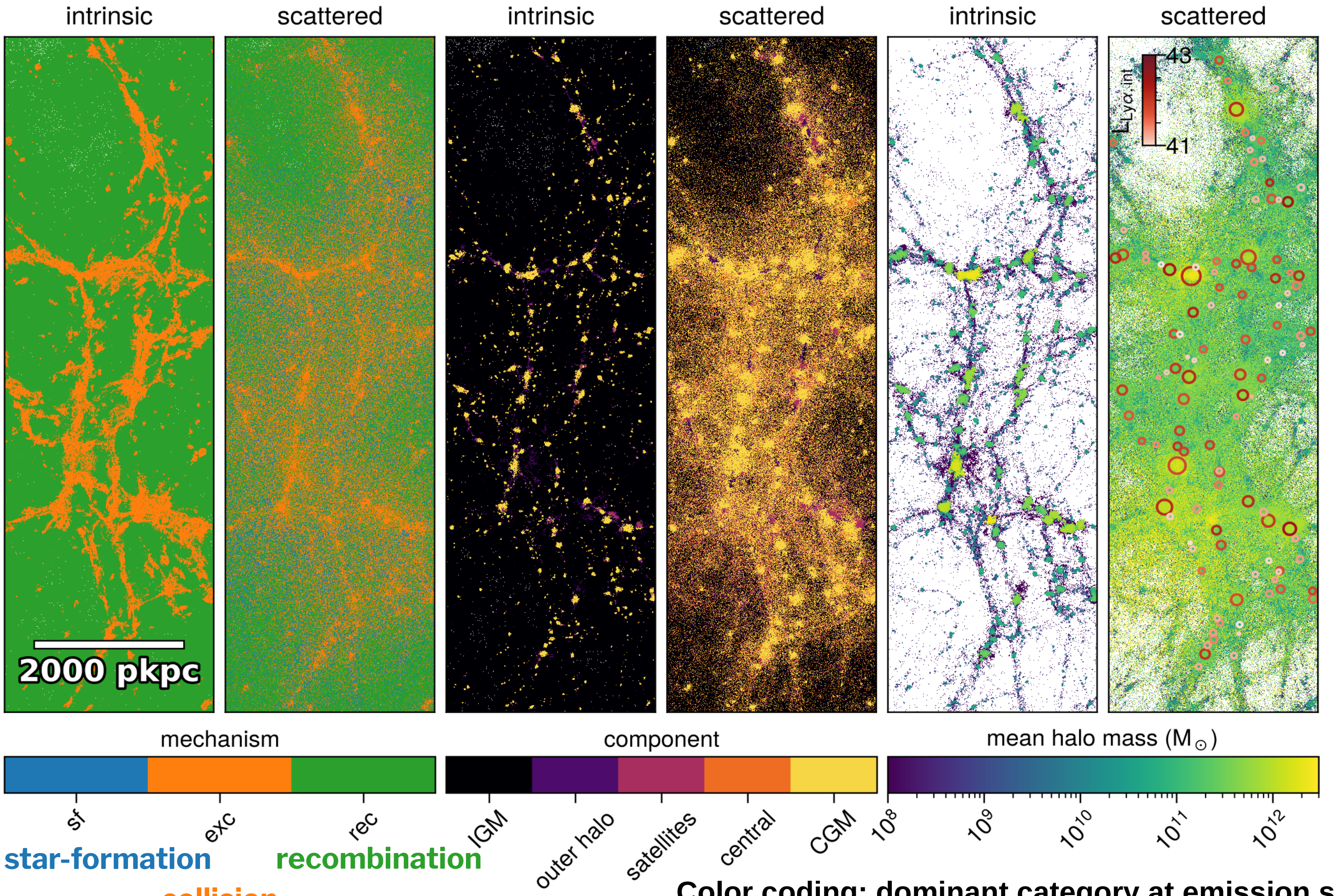

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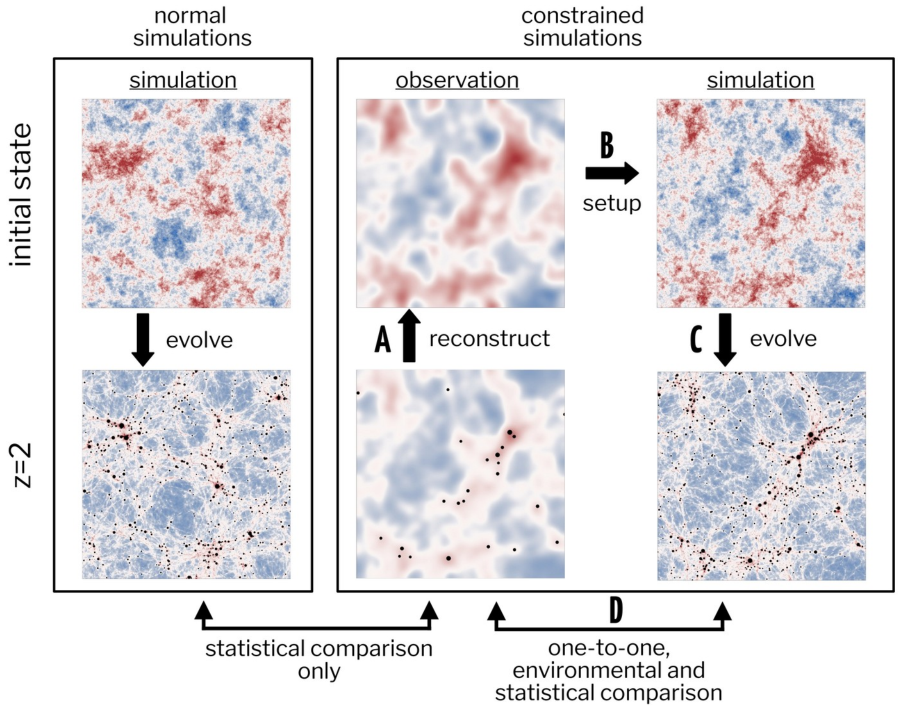
Lya halos and hosting filaments are boosted by **central galaxies** and their **CGM**, sourced by **sf**/**coll** with halo masses of $10^{10} - 10^{11} M_\odot$ scattering into their **IGM**

Work-in-progress and future directions

Galaxy formation simulation → Lyα radiative transfer code → Post-processing & analysis



- Constrained cosmological simulations, testing galaxy formation models in their cosmological environment
- Evaluate at z=2.5 in order
  - test at high redshift
  - save ~80% of compute time

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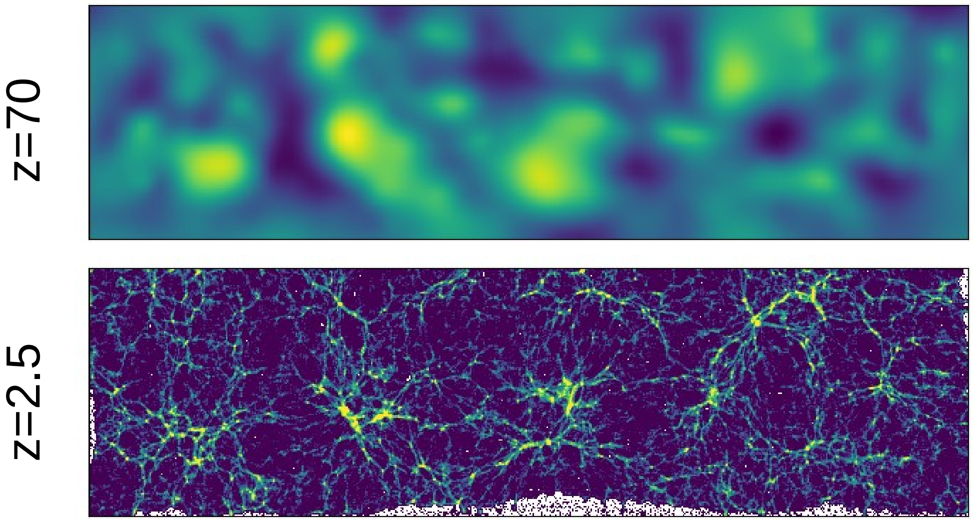
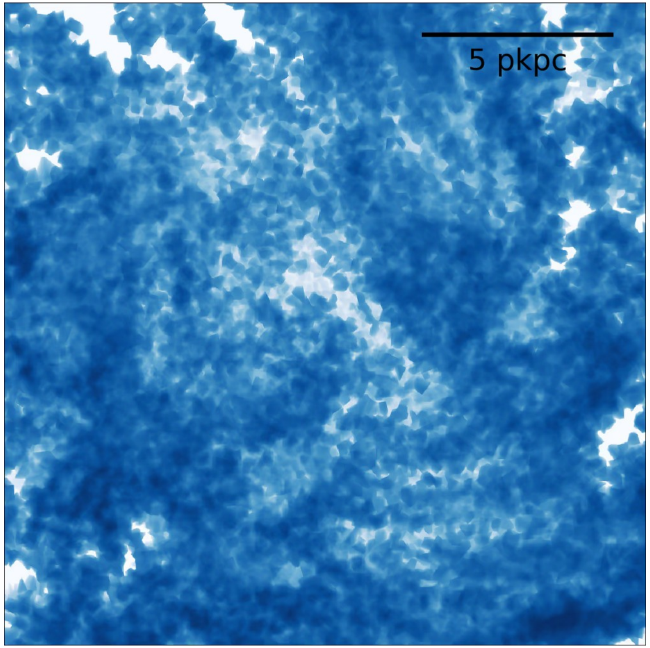


- Constrained cosmological simulations, testing galaxy formation models in their cosmological environment
- Evaluate at z=2.5 in order
  - test at high redshift
  - save ~80% of compute time
- Use the ICs from the CLAMATO survey in the COSMOS field
- Currently have the DMO runs at target resolution; awaiting allocation for baryon runs

Work-in-progress and future directions

Galaxy formation simulation → **Lyα radiative transfer code** → Post-processing & analysis

HI column density for a TNG50 galaxy

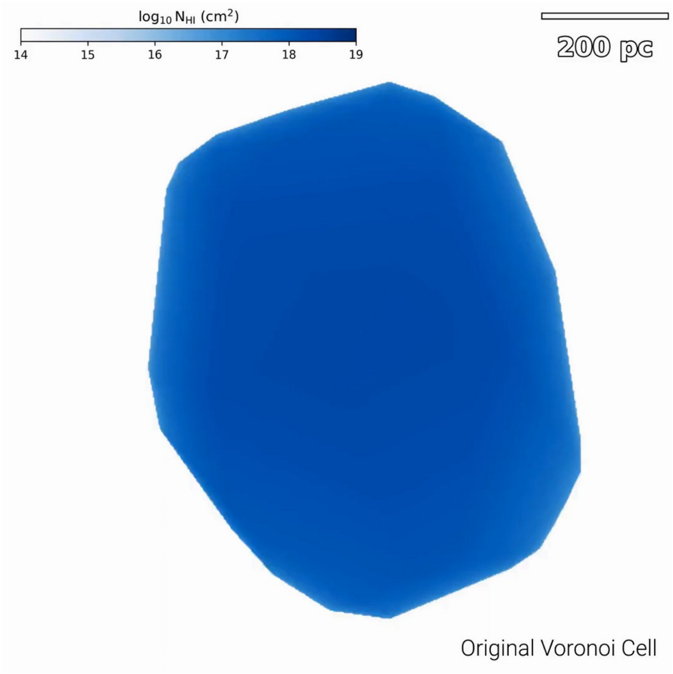


- Currently, we can only account for sub-resolution effects in the emission by *re-weighting photons' initial spectra and luminosities* for all photons
- How to test subgrid radiative transfer impact?

Work-in-progress and future directions

Galaxy formation simulation → **Lyα radiative transfer code** → Post-processing & analysis

An individual cell in TNG50

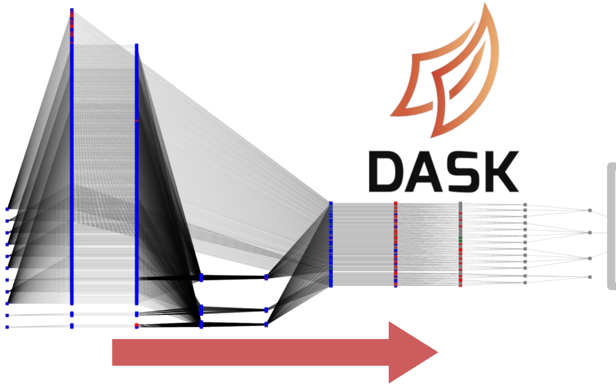


- Currently, we can only account for sub-resolution effects in the emission by *re-weighting photons' initial spectra and luminosities* for all photons
- How to test subgrid radiative transfer impact?
- Combine toy models on subgrid scales
- Procedural generation to efficiently model subgrid

Work-in-progress and future directions

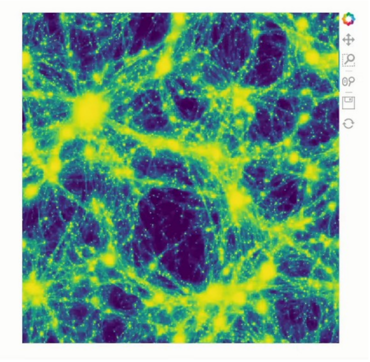
Galaxy formation simulation → Lyα radiative transfer code → **Post-processing & analysis**

Particle data



Scalable, *distributed*, *out-of-core*, *interactive*

Observables



- Manipulate and interact with TBs of hydro/RT sim outputs
- Use the distributed dask framework on HPC/cloud resources

Summary

- Combine TNG50 + emission + RT to simulate Lyman-alpha filaments
- Lyα filaments trace IGM illuminated by scattered photons from central galaxies and their CGM residing in $10^{10} - 10^{11} \mathrm{M}_\odot$ halos
- Largest structures are filamentary in shape, with $\mathrm{n_{LAF}} = 10^{-3}\,\mathrm{cMpc}^{-3}$ for $\mathrm{SB_{thresh}} = 10^{-20}\,\mathrm{erg\,s^{-1}\,cm^{-2}\,arcsec^{-2}}$ and $\mathrm{FWHM{=}3.5''}$
- Vary the fiducial galaxy formation model, the emission model and RT