The faint Lyman-alpha cosmic web in TNG50

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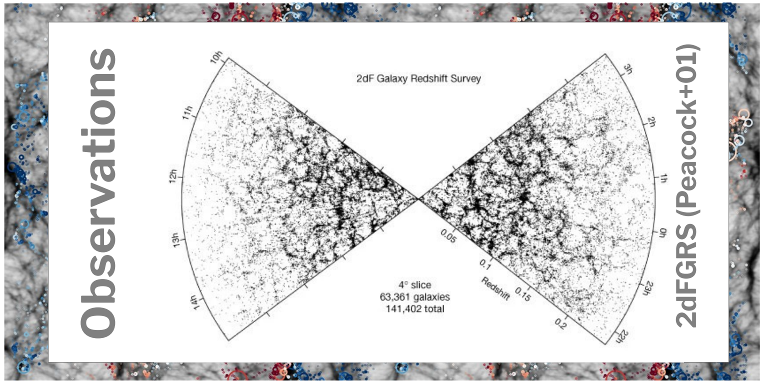
Cosmic Web @ KITP, Santa Barbara, February 7, 2023

Observing the cosmic web

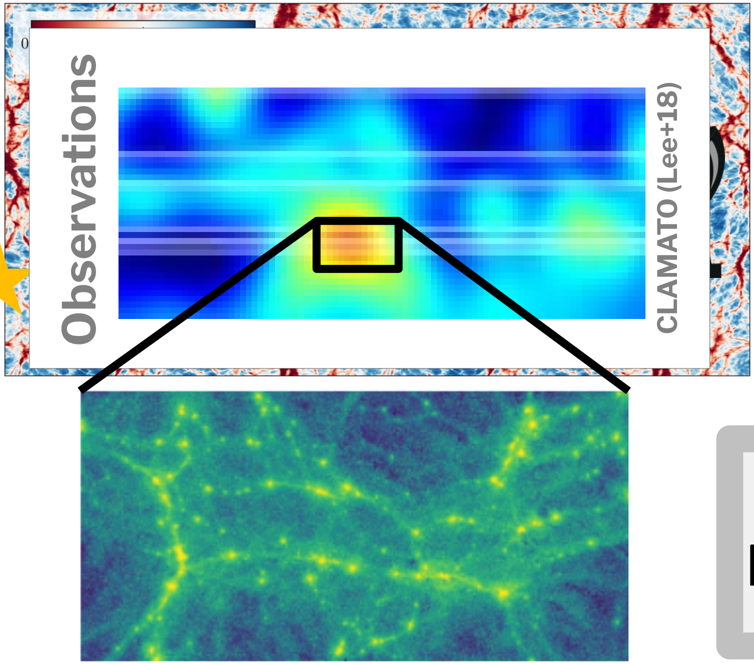
Galaxy clustering

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



Lyman-alpha absorption

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

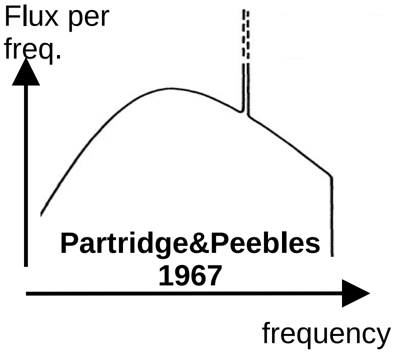


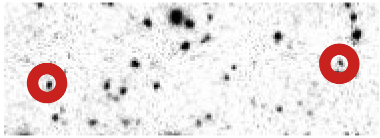
Color coding: log Lya surface brightness

Lyman-alpha emission

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

Lyman-alpha – A tracer of neutral gas in the high-z Universe





Lya in direct emission (Cowie+98)

- Trace the high-z Universe, particularly young galaxies with Lyα line (n=2→n=1) of hydrogen

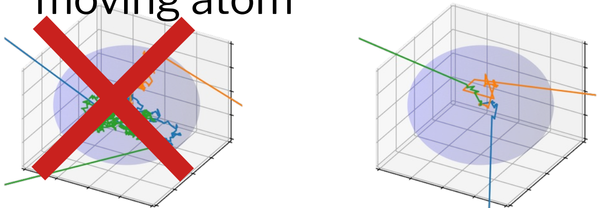
Lots of potential with Lyα line (e.g.):
Cosmology, ISM/IGM structure in spectra, CGM constraints

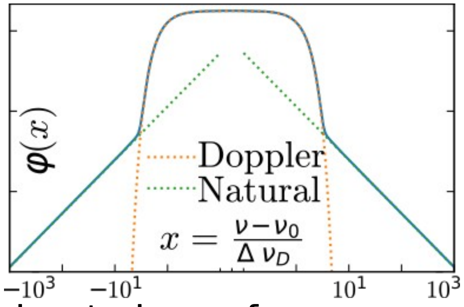
Theoretical challenge linking Lyα observations to underlying physics:

- Lyα: resonant line with high optical depths (→scatterings)
  →Complex radiative transfer (RT) → Numerical simulations

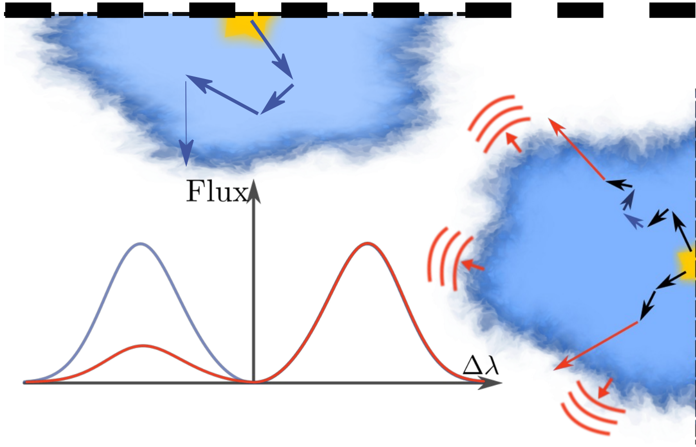
Lya RT crash course

- **Not** a random walk!
- Escape scattering by fast-moving atom



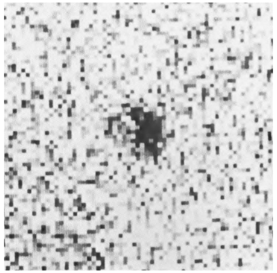


...due to large frequency dependency for line profile

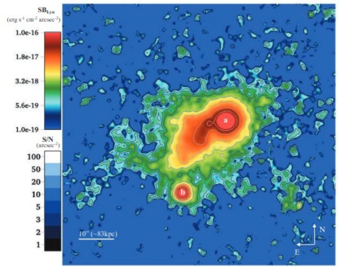


A first hint of the Lyα cosmic web?

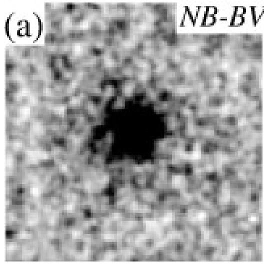
- 1967: prediction of Lyα as tracer of young high-z galaxies
- ≳ 1990: extended Lyα emission in form of blobs/nebulae
- ≳ 2005: extended Lyα around (stacked) galaxies
- ≳ 2015: integral field spectroscopy around galaxies
- ≳ 2021: faint filaments (?, MUSE-EDF, HET-VIRUS-GAMA)



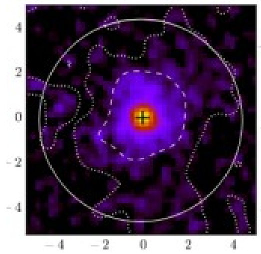
(McCarthy+87)



(Cantalupo+14)

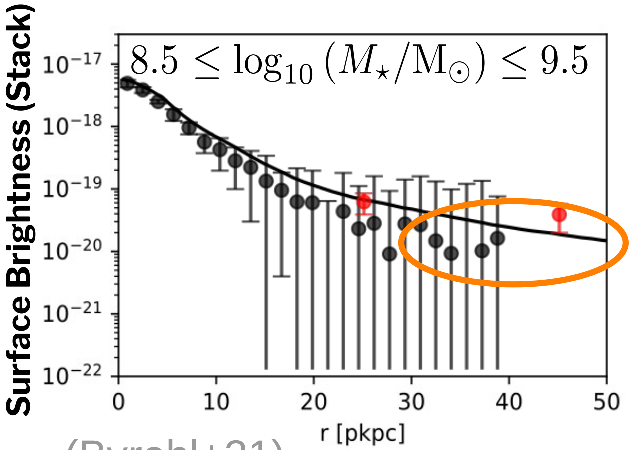


(Hayashino+04)



(Leclercq+17)

Simulations



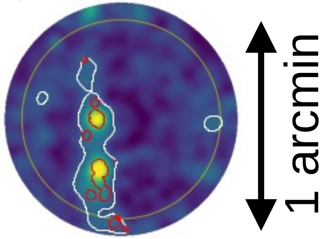
(Byrohl+21)

Simulated stacked radial profiles at z=3.0

Observations:

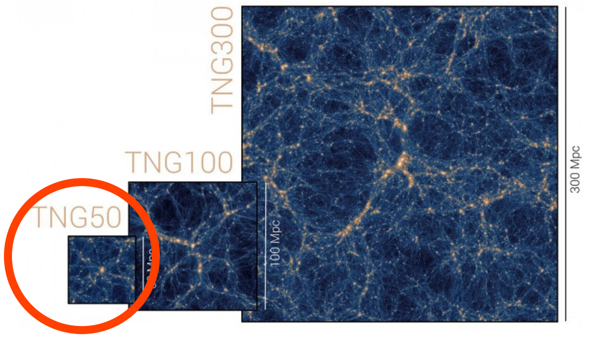
- Leclercq+17
- Kikuchihara+21

Why do these profiles flatten?

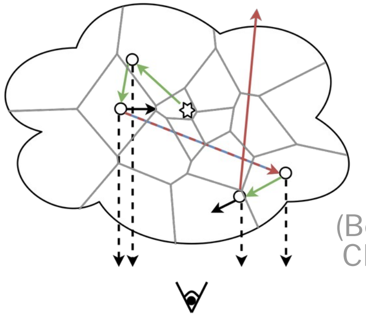


(Bacon+21)

Galaxy formation simulation → **Lyα radiative transfer code** → **Results @ z=2**

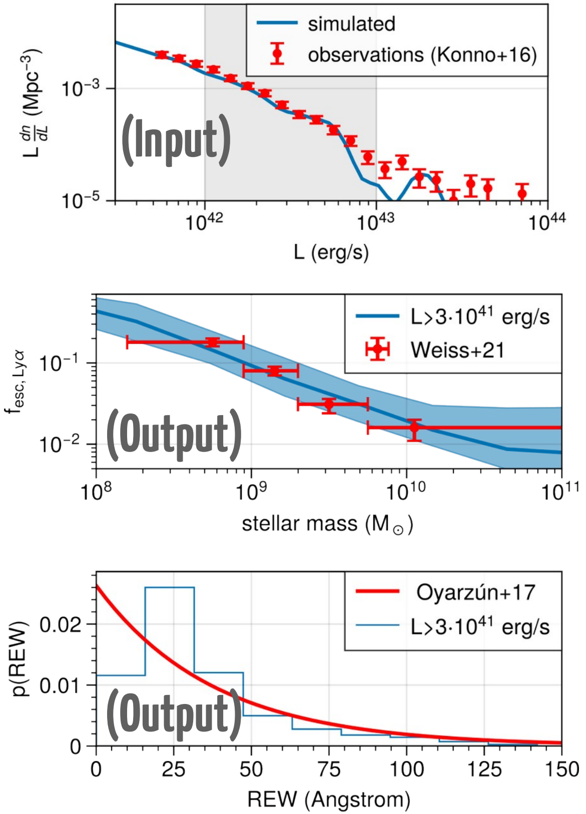


(TNG Collaboration)



"Iltis"

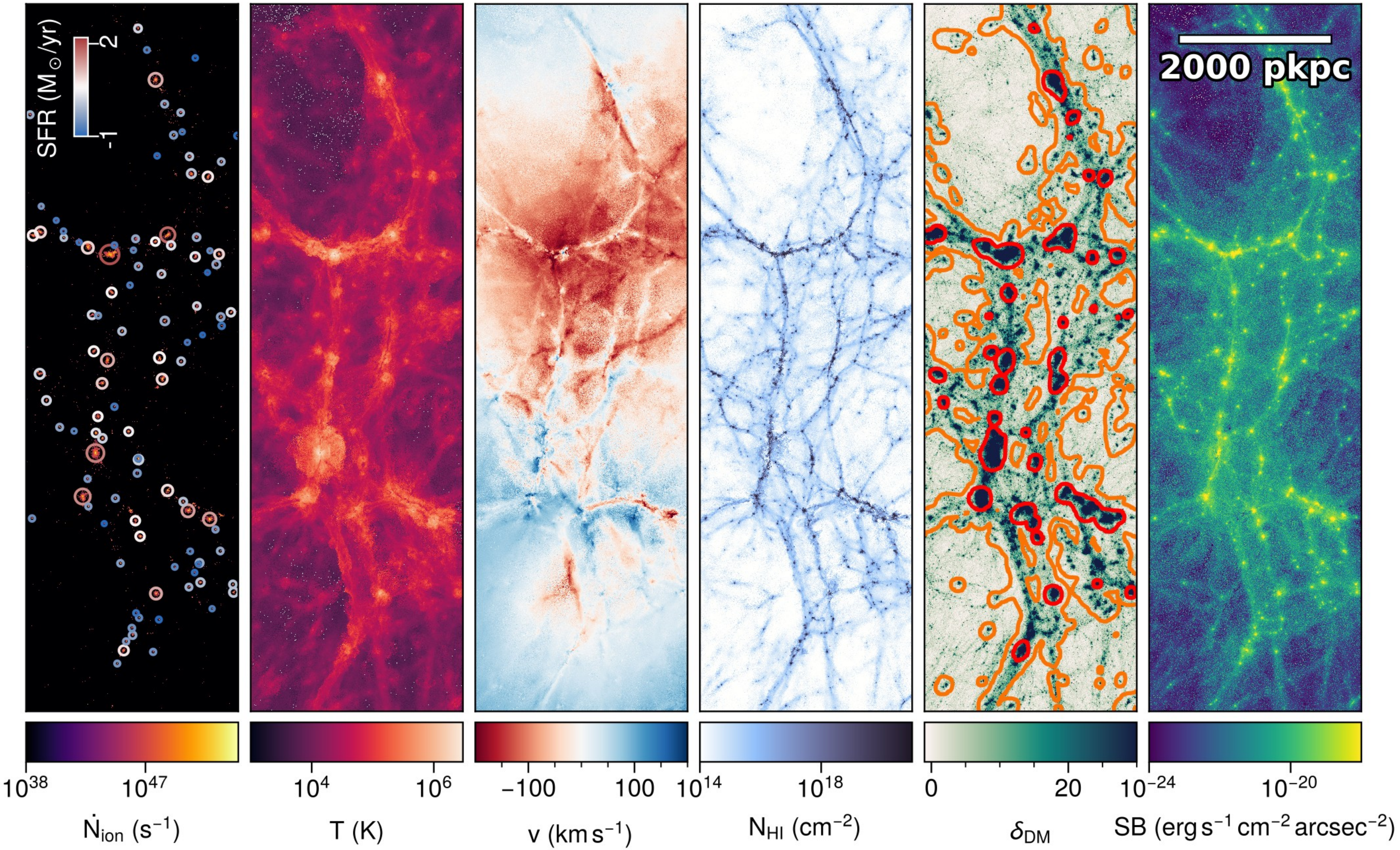
(Behrens et al. 19; CB et al. 21)

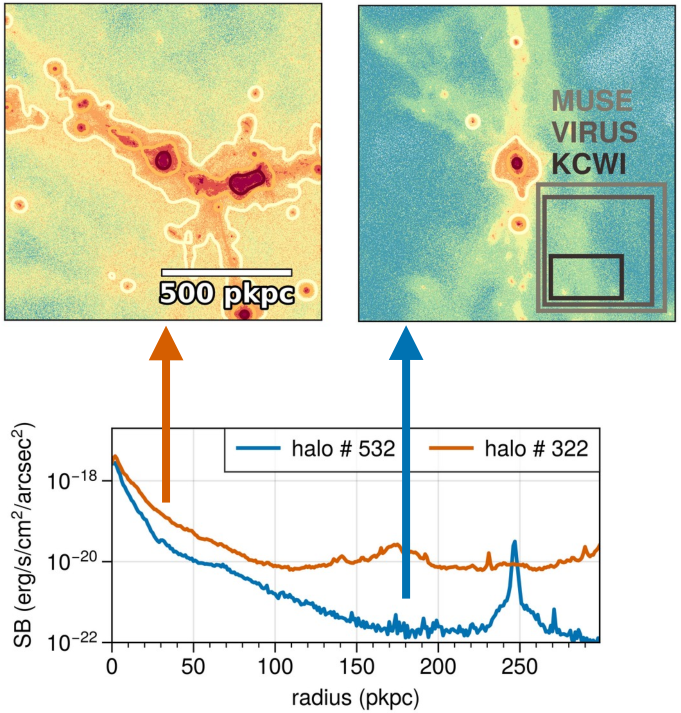


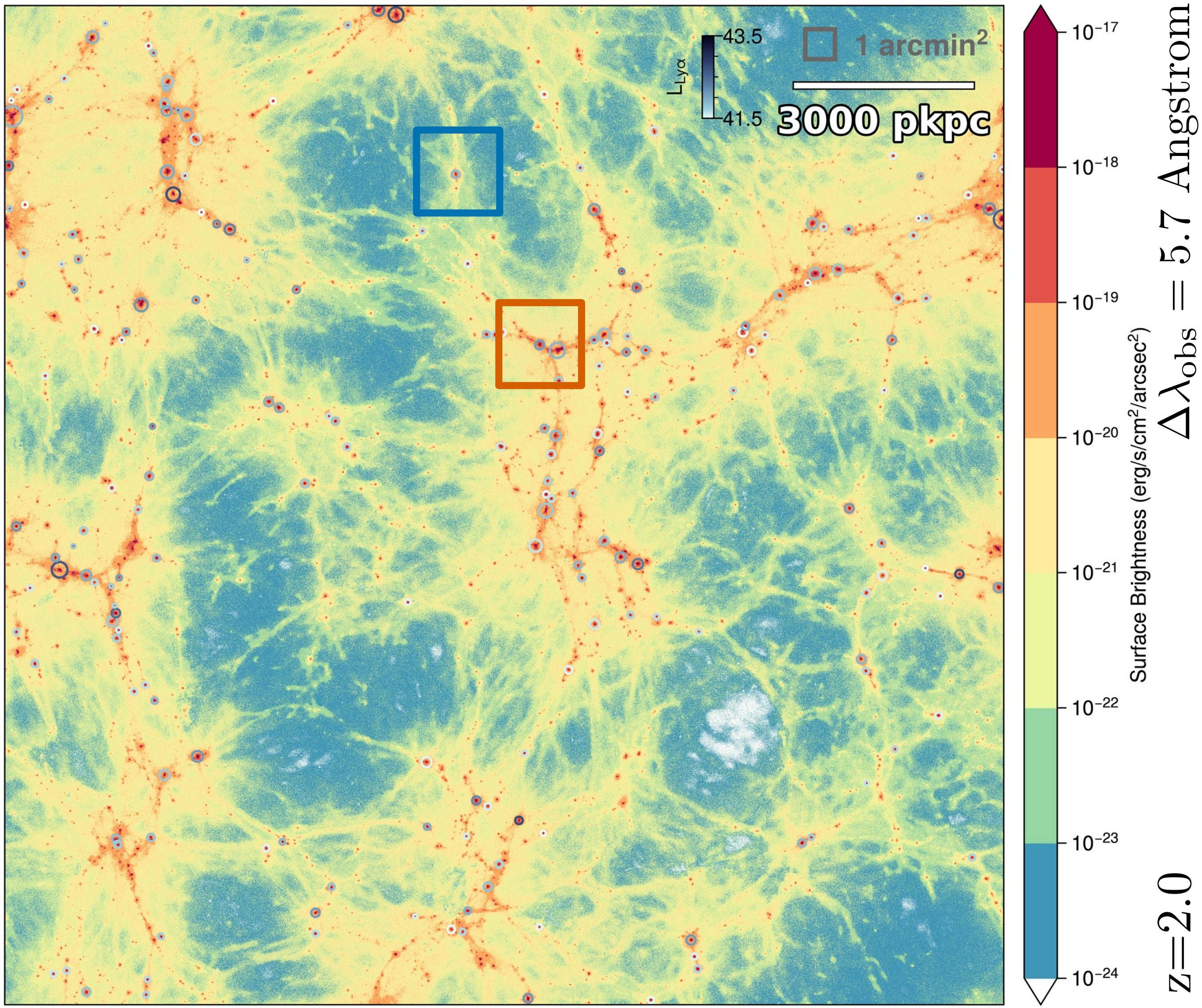
- galaxy formation sims with a comprehensive physical model including s.s. UVB + AGN radiation on-the-fly
- Emission from recombinations and collisions in diffuse gas; stellar populations in ISM (using BPASS spectral synthesis code)

- Monte Carlo approach propagating, scattering and destructing weighted photon packages
- Track trajectory for each photon
- In ISM, account for dust by matching luminosity function

Next: spatial distribution →

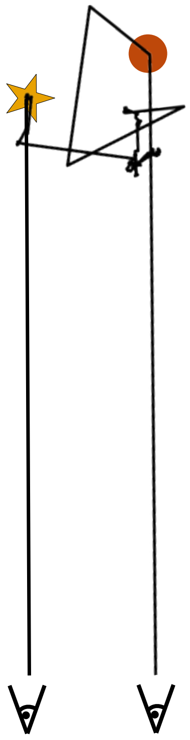

SFR ($M_\odot$/yr)
2
-1
2000 pkpc
10^{38}
10^{47}
$\dot{N}_{ion}$ (s^{-1})
10^4
10^6
T (K)
−100
100
v ($km\,s^{-1}$)
10^{14}
10^{18}
N_{HI} (cm^{-2})
0
20
δ_{DM}
10^{-24}
10^{-20}
SB ($erg\,s^{-1}\,cm^{-2}\,arcsec^{-2}$)





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

Keeping track of Lyman-alpha radiative transfer



consider gas state

at last scattering: from where the photons reach us

at origin: where the photons are emitted

→ 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)

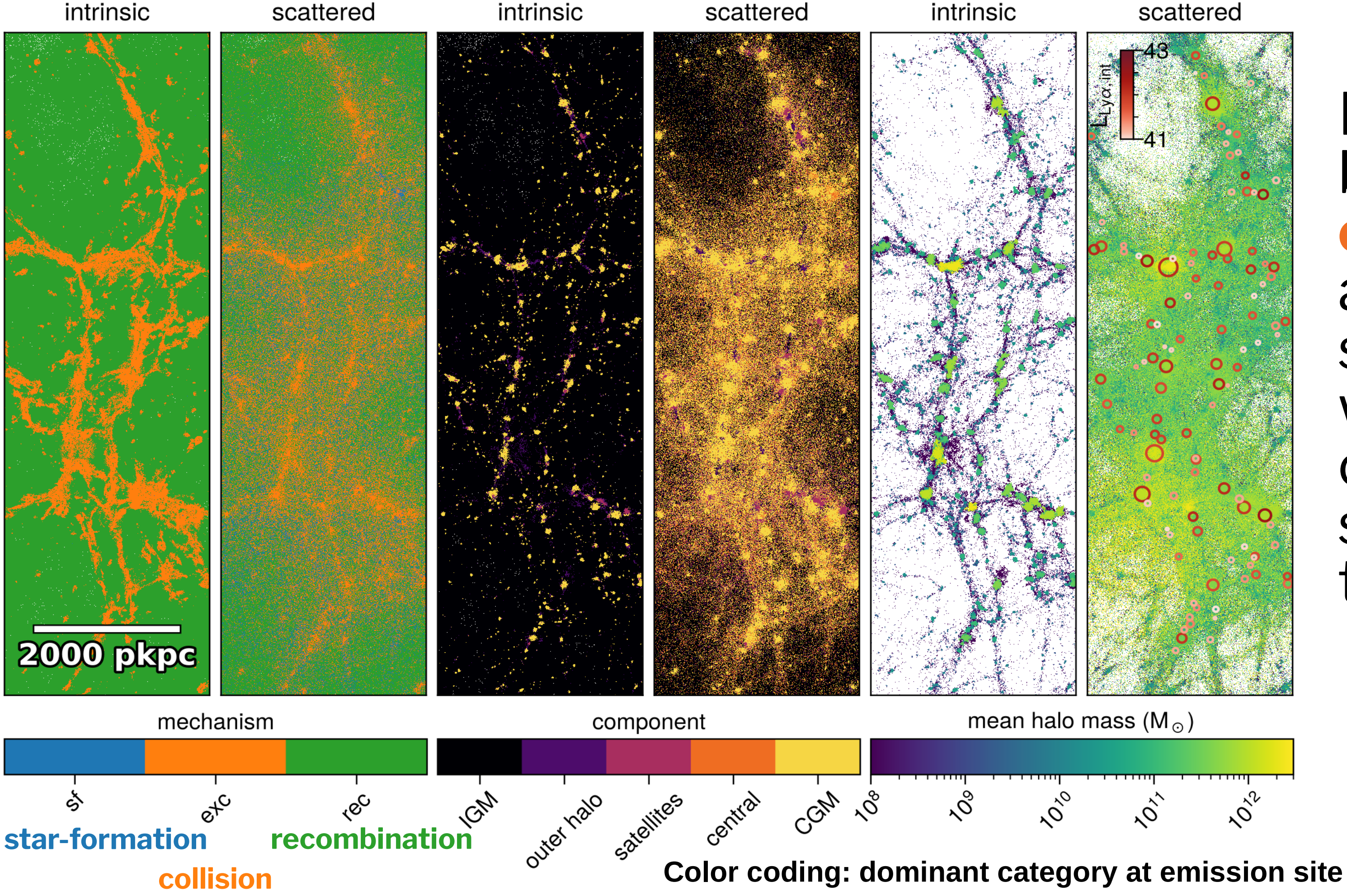
Emission mechanism

- **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

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

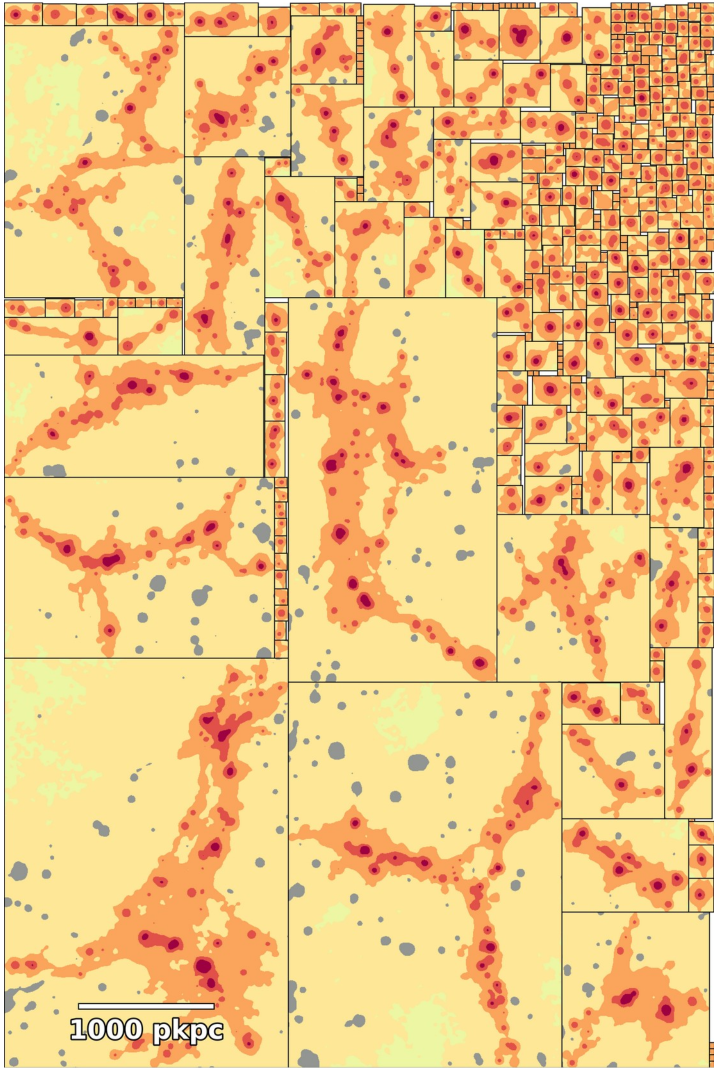
Lyα filament boosting by its radiative transfer

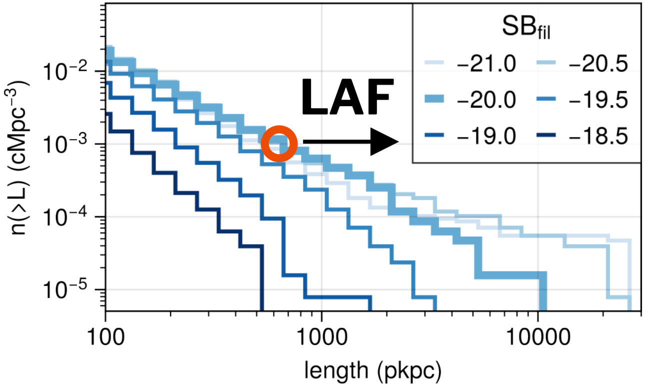


Color coding: dominant category at emission site

Lya 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**

Lya filament identification





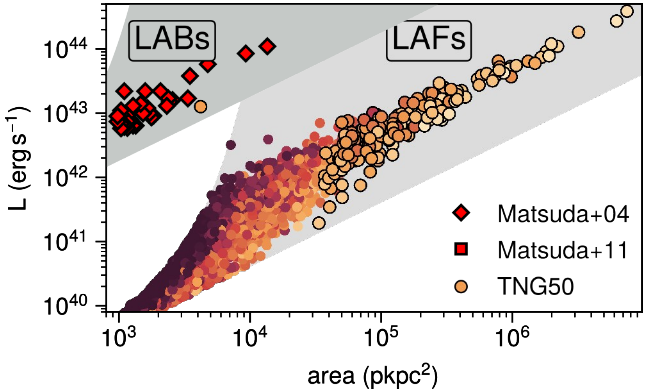
$$n_{LAF} = 10^{-3}\,\mathrm{cMpc}^{-3}$$

Between 2<z<2.4 for footprint:

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

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

Color coding: circular – filamentary shape



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)

Lya nebula for scale (Cantalupo+14): 

Observations

ESO/P. Horálek

<u>MUSE-EDF</u>:
1×400pkpc fil @ z=3,
selected around $\delta_{\rm LAE} \gg 1$
100h alloc (Bacon+21)

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

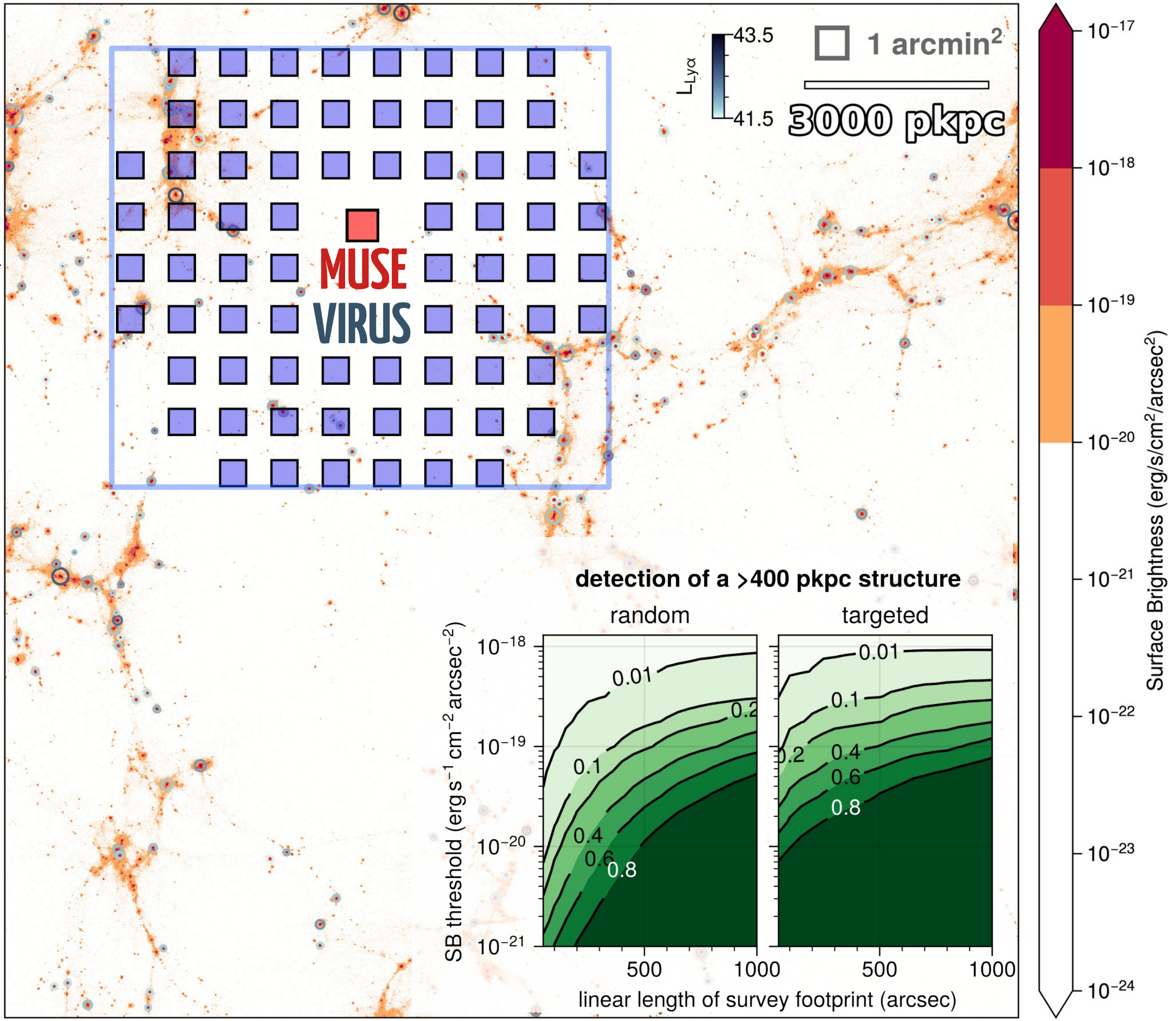
<u>HET-GAMA09</u>:
1 × 2Mpc fil @ z=2.4
selected by eye
(Fabricius+23, in prep.)
34h alloc

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

McDonald Obs./
Martin Harris

<u>HET-VDF</u> (proposed):
48h alloc in EGS 2023-2024

$1\ \sigma \sim 3 \cdot 10^{-20} \mathrm{erg/s/cm^2/arcsec^2}$



Summary

- Combine TNG50 + emission + RT to simulate Lyman-alpha filaments at z=2
- 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 $\mathrm{FWHM{=}3.5"}$
- Observational measurements will allow to refine the fiducial TNG model, the emission model and RT