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Surveying the cosmic web: multi-scale tomography of the IGM

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RAMSES User Meeting

Geometry/connectivity of the cosmic web

Structures multiply connected at large scale, cluster scale and CGM scale

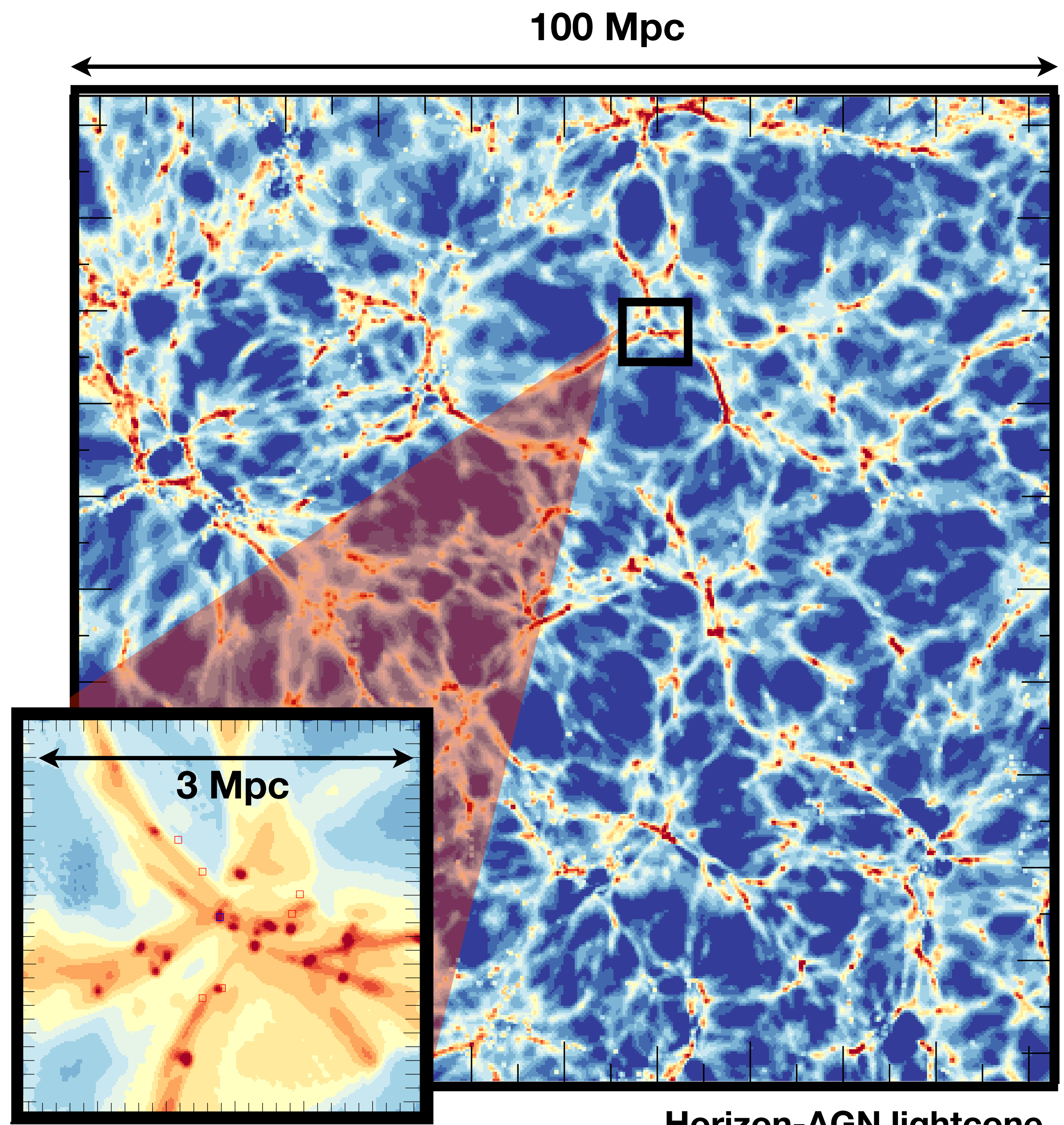
- Cosmological context:
large scale connectivity characterizes the topology of the matter field
e.g.: **Colombi+01, Pogosyan+in prep.**

- Astrophysical context:
  - Halo mass/spin dependent on the geometry and connectivity of their large-scale environment

e.g.: **Codis+12**, **Malavasi+16, Gonzalez+16**

  - Cluster/galaxy scale: geometry of gas inflow connected to galaxy properties (SFR, spin, morphology)

e.g.: **Ocvirk+08**, **Dekel+08, Pichon+11, Danovich+11**



Horizon-AGN lightcone

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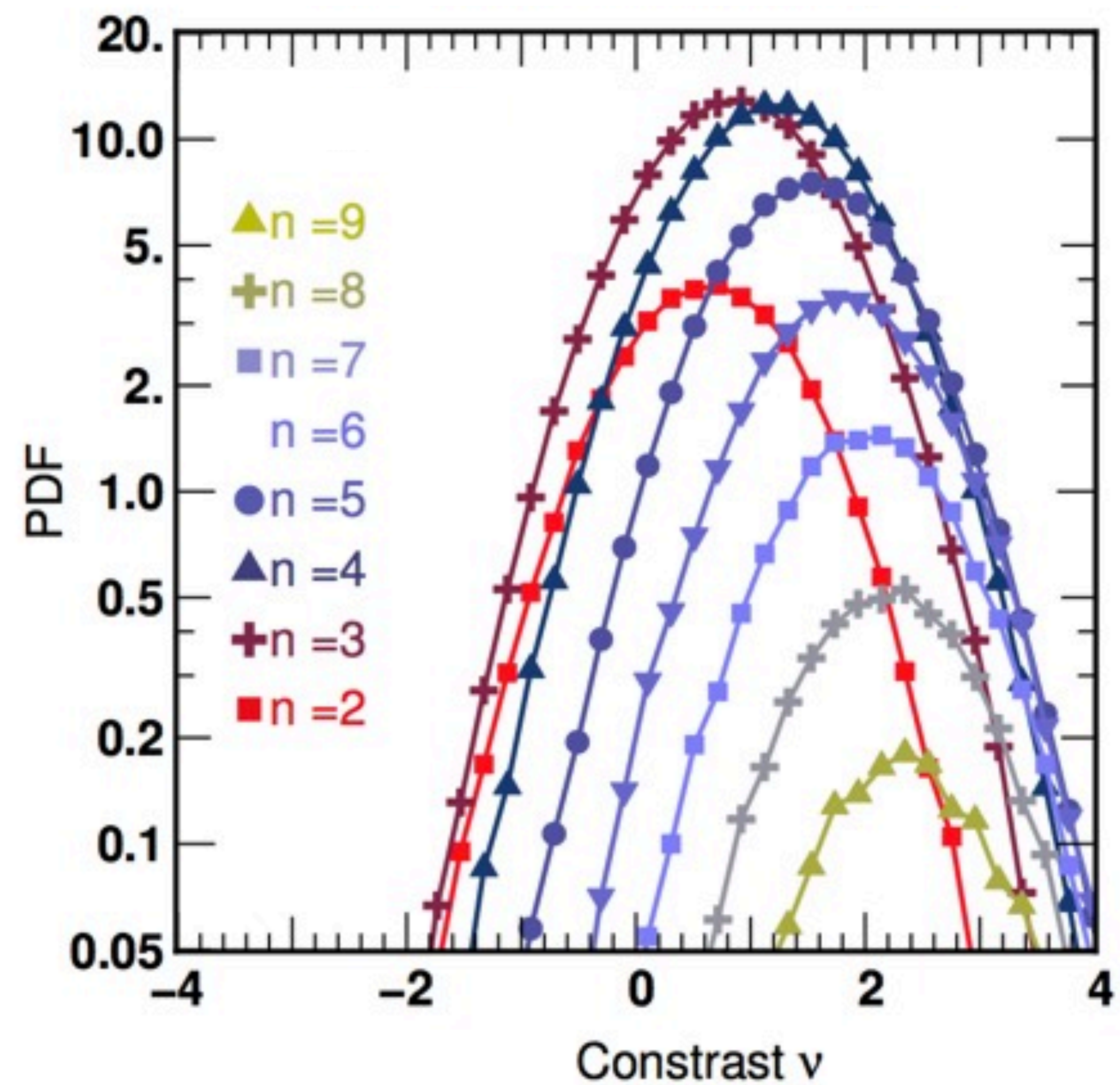

Number of connected filaments as a function of density contrast for a 2D gaussian random field

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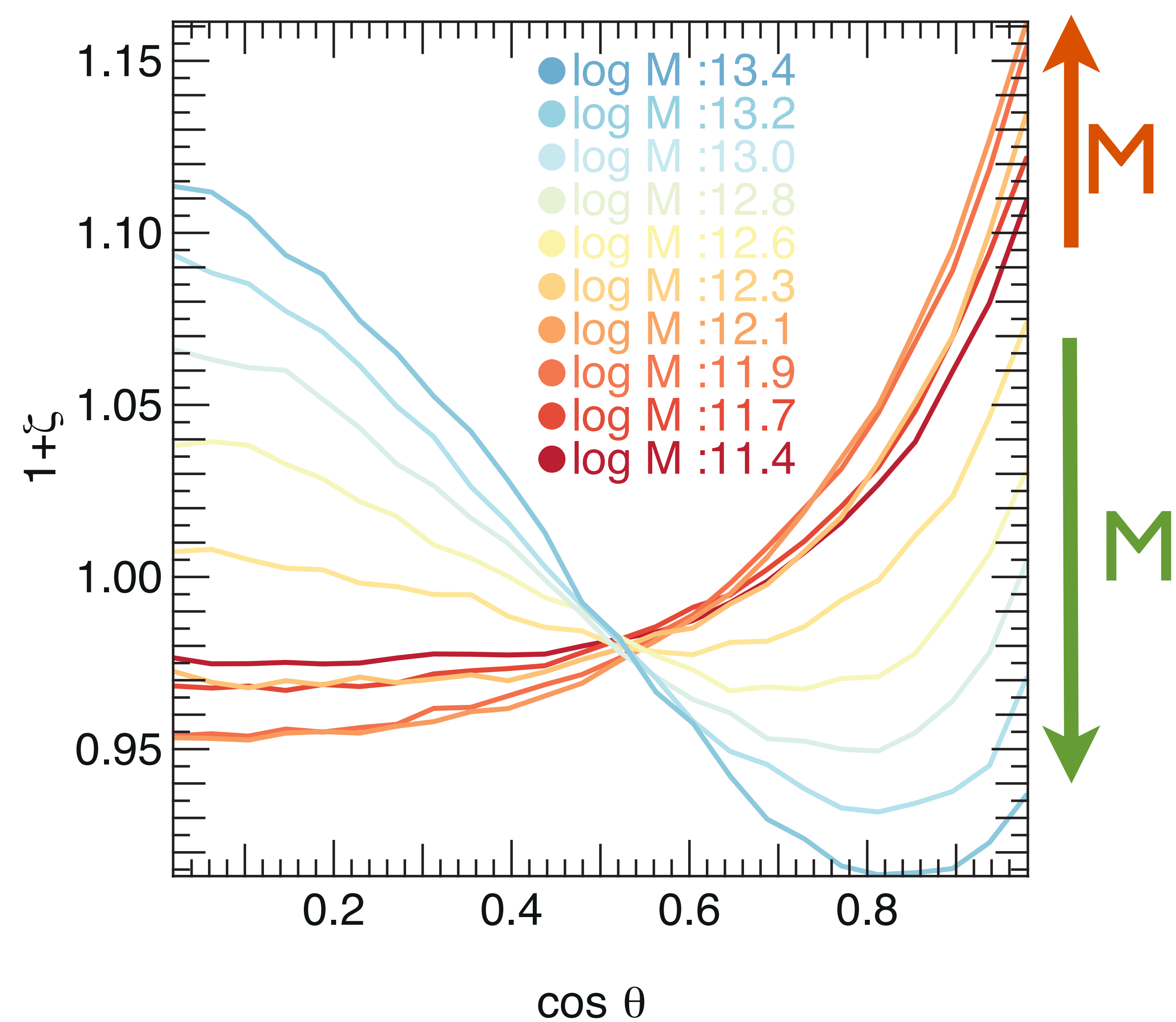
Codis+12, Laigle+15



halo angular momentum alignment with the filaments as a function of halo mass

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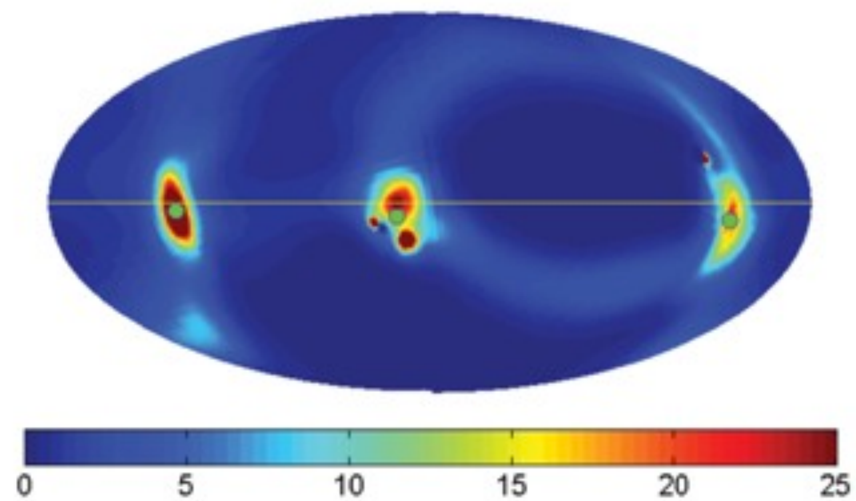
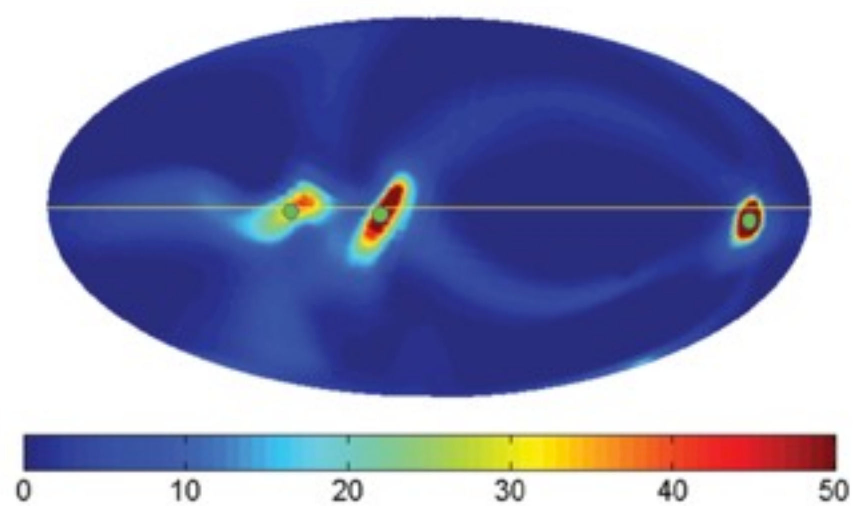
Danovich+11

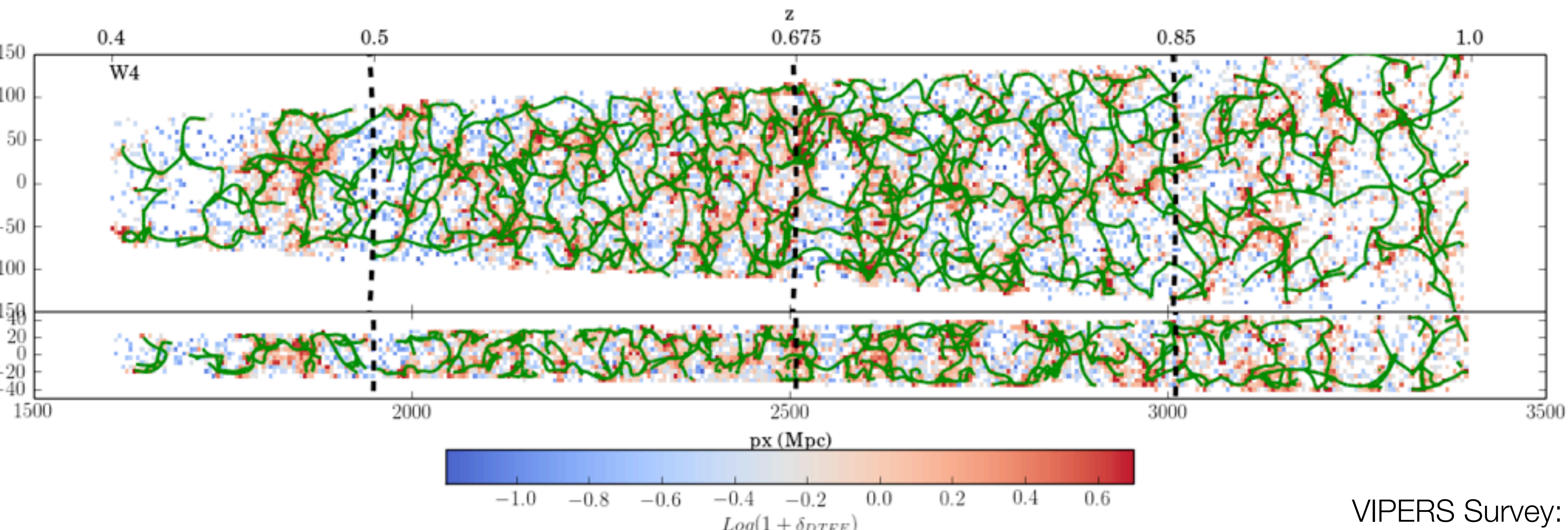




Inflowing streams in galaxies at 1~R_{vir}, at z~2.5

Reconstructing the cosmic web: galaxy distribution

Skeleton extraction in VIPERS W1, 0.4<z<1, i_{AB}<22.5, scale of ~10cMpc (**Malavasi+16**)

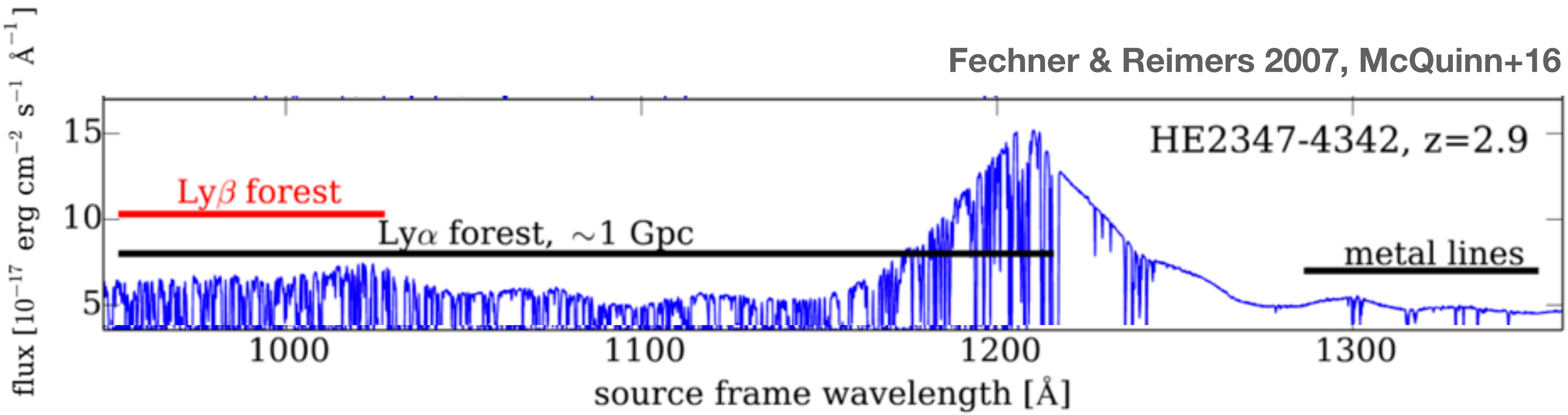


VIPERS Survey:
24 deg^2 on ESO VLT, 8m (see **Guzzo+14**)

At z>1, very costly (telescope time) to probe the cosmic web at ~Mpc scale

Reconstructing the cosmic web: tomography

Fechner & Reimers 2007, McQuinn+16



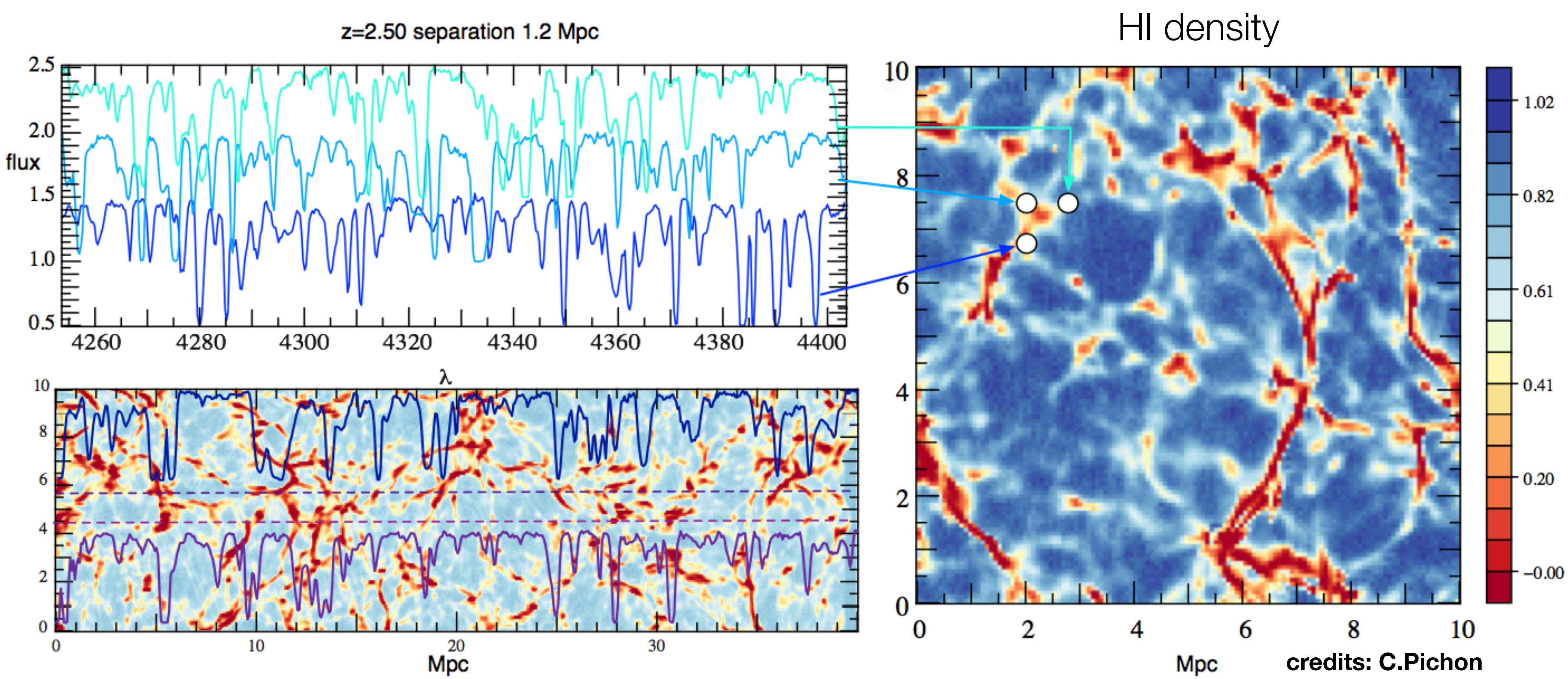
Residual neutral hydrogen in the filamentary IGM causes absorption lines in the spectra of background objects

Excellent tracer of filamentary dark matter at large scale

(**Cen+94, Zhang+95, Hernquist+96, Miralda-Escude+96, Theuns+98**)

Lyman-α wavelength redshifted towards optical bands at z>2

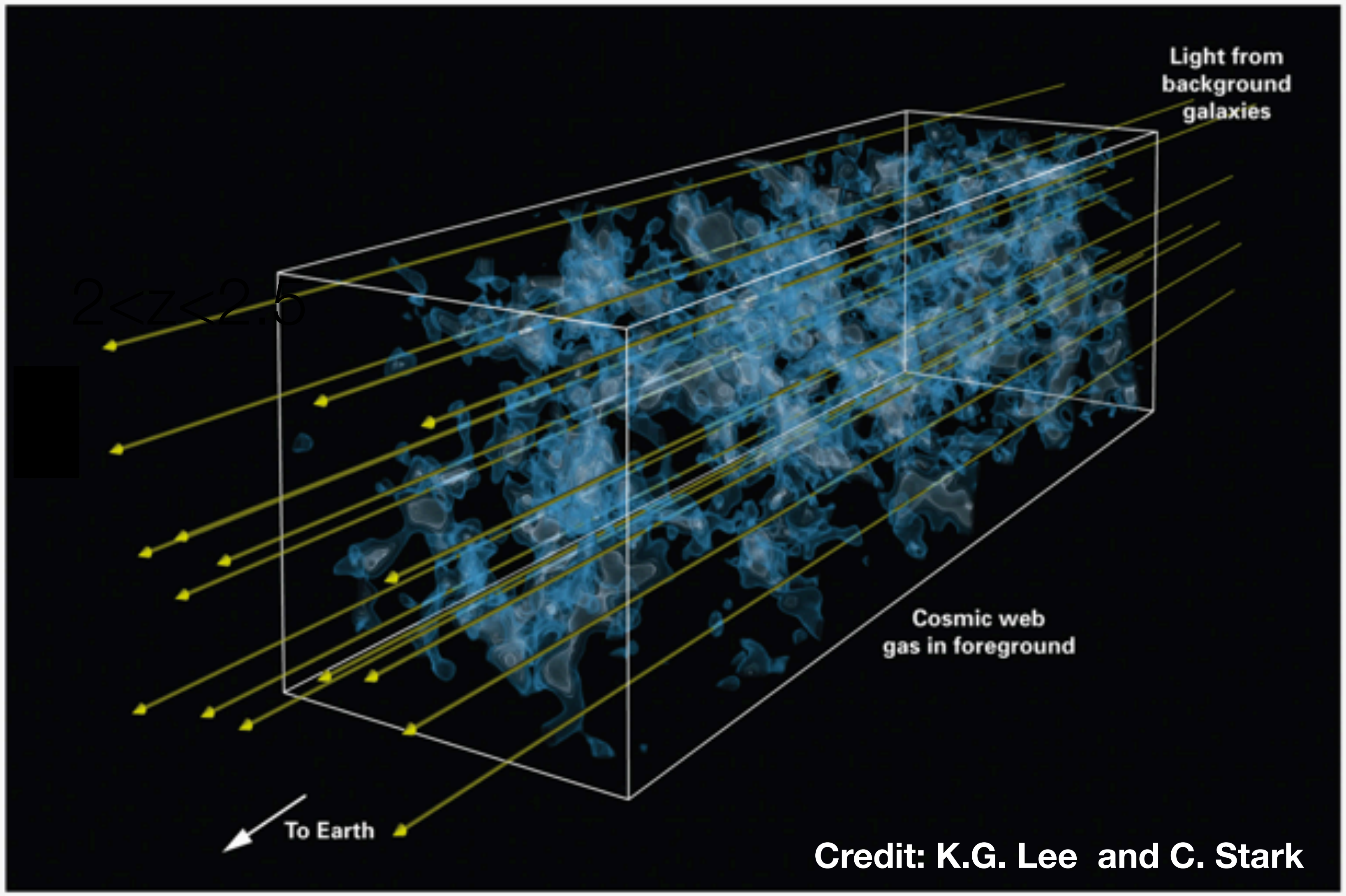
Reconstructing the cosmic web: tomography



Transmitted flux $F(\nu_0) = e^{-\tau_\alpha(\nu_0)}$ depends on the neutral hydrogen (HI) density:

$$\tau_\alpha(\nu_0) = \int_0^{x_s} \mathrm{d}x \frac{\sigma_\alpha n_{\rm HI}(x, z)}{1 + z}$$

Reconstructing the cosmic web: tomography



Inversion of the Lyman-α forest through Wiener filtering: interpolation between line-of-sights (los)

Transverse correlation length (map resolution) set by the mean inter-los distance

see **Pichon+01, Caucci+08**

To reach ~Mpc scales, use bright galaxies (selected on their r-band photometry at z~2) in addition to quasars

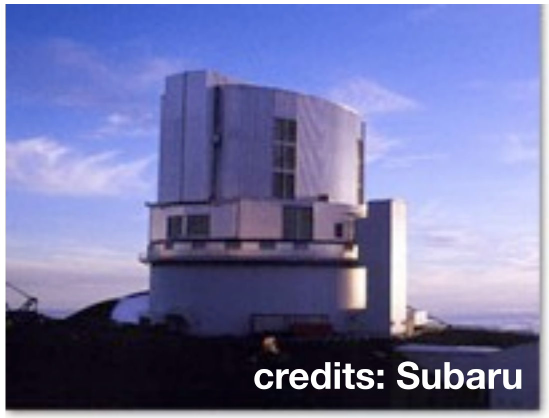
Tomography with current and future surveys

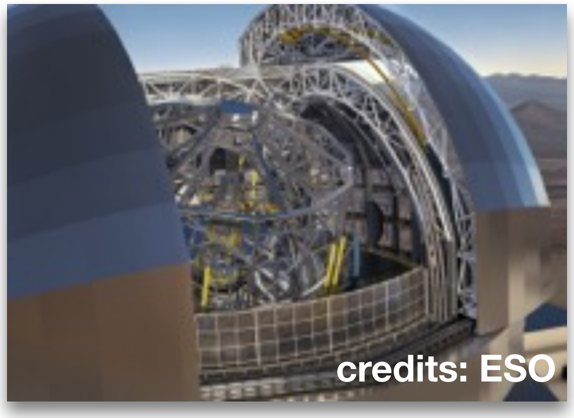
Ly- α with quasars: not a new idea (see e.g. BOSS, **McDonald+01, Slosar+13**)
Tomography with bright galaxies: new (see e.g. CLAMATO, **Lee+14**) and requires robust tests

PFS (**Takada+14**) E-ELT (**Evan+12**)

Prime focus Spectrograph on Subaru Telescope

spectra of 2400 targets at the same time over 1.3deg diameter field





European-Extremely Large Telescope

39-meter main mirror

We are in the planification phase for future surveys: use the Horizon-AGN lightcone to make predictions

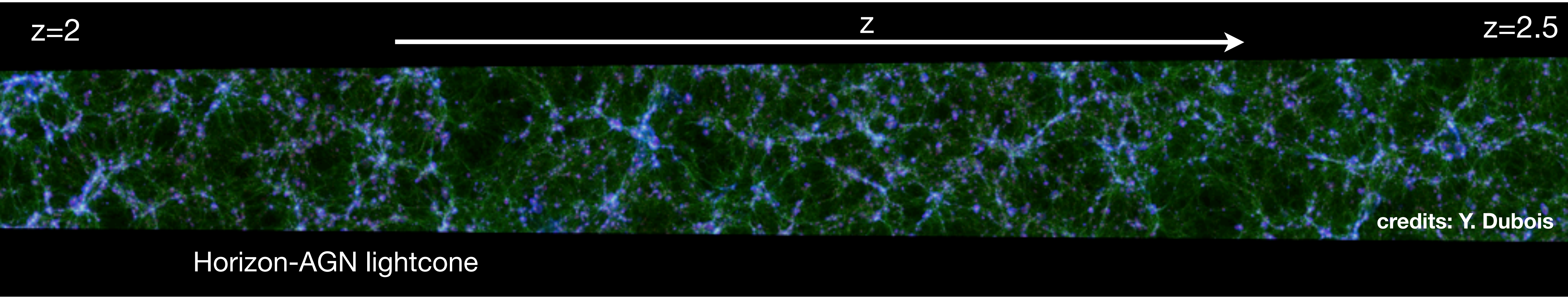
- realistic IGM modeling + ligthcone geometry
- realistic source photometry and clustering
- source spectrum modeling + realistic noise

The Horizon-AGN simulation

Dubois+14

- Hydrodynamical simulation run with RAMSES
- Cosmological volume (100 Mpc/h) + a lightcone (1deg^2 above z>1)
- Not calibrated on the local Universe
- Subgrid physics (below ~1kpc): stellar evolution and feedback, BH formation, BH growth, AGN feedback
- Galaxies and haloes extracted with AdaptaHop (**Aubert+04**)

- Hydro simulations model consistently the IGM
- 1-point statistics well reproduced in Hz-AGN: colors, luminosity and mass functions (**Kaviraj+16**)
  - ➡ Important for background source selection



Modeling HI absorption in Hz-AGN

HI density: balance between photoionisation, collisional ionization and recombination (**Black+81**):

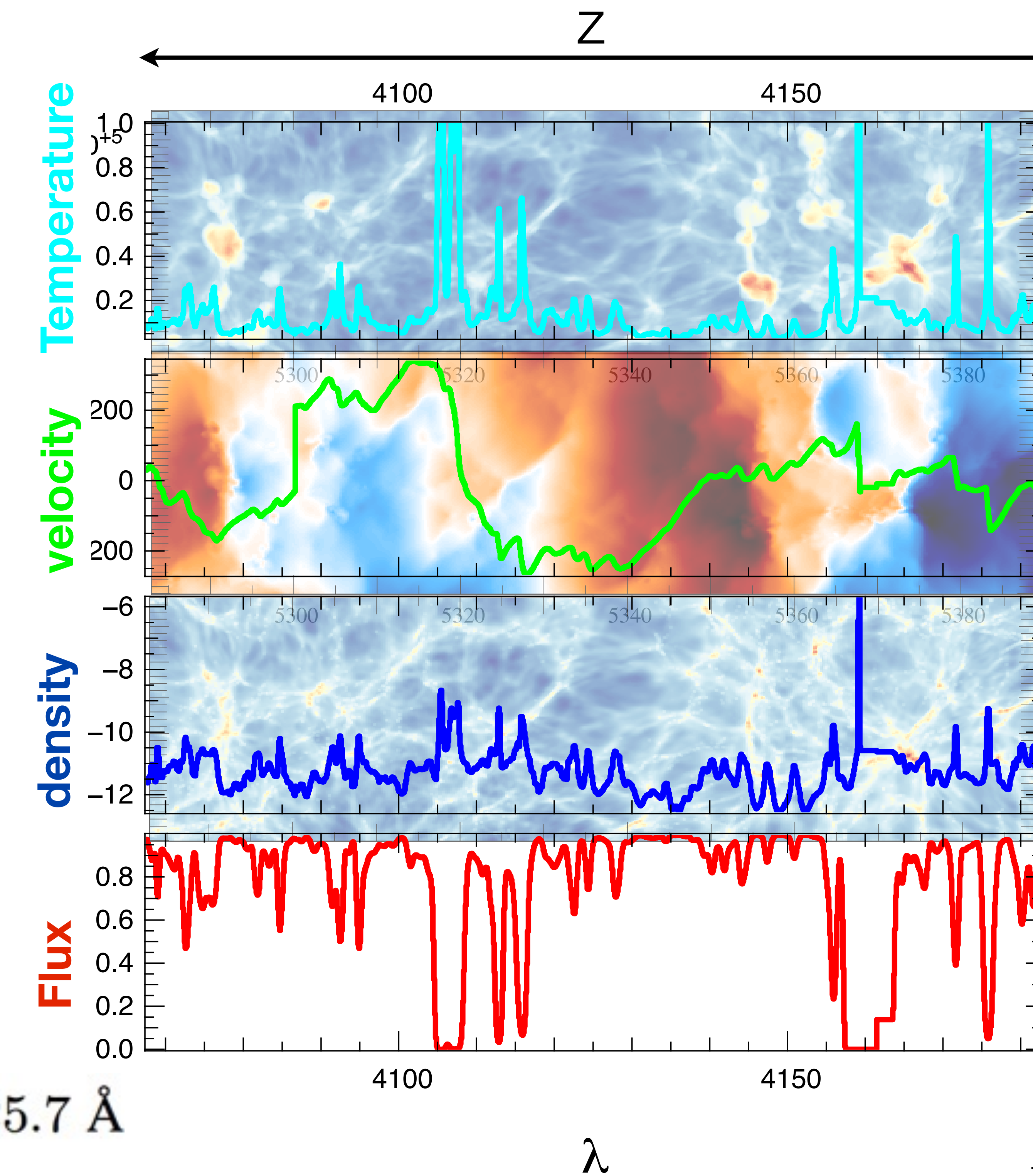
$$\alpha(T)n_e(1 - x_{HI}) = \gamma(T)n_e x_{HI} + \Gamma x_{HI}$$

$$x_{HI} = \frac{\alpha(T)}{\alpha(T) + \gamma(T) + J_{22}G_1 n_e^{-1}}$$

Line profile: Doppler profile

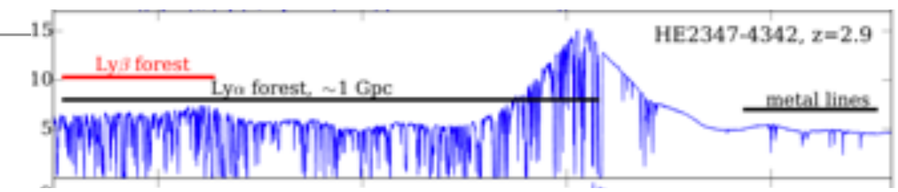
$$\sigma_\alpha = \frac{\sigma_{\alpha,0}\, c}{b(x,z)\sqrt{\pi}} e^{-\frac{(v(x,z)(1+z)\nu_0 - c\nu_\alpha + c(1+z)\nu_0)^2}{\nu_\alpha^2 b^2(x,z)}}$$

Exploit the spectrum region between $\lambda_\alpha = 1215.7$ Å and $\lambda_\beta = 1025.7$ Å

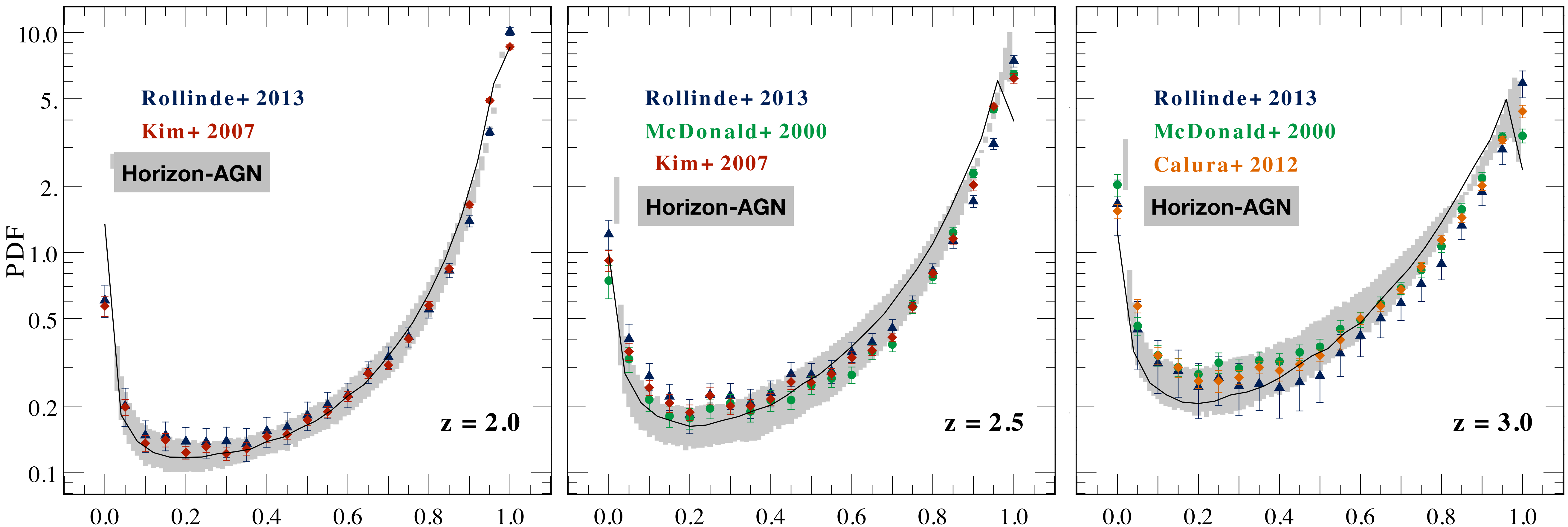


Statistics on the Lyman-α forest in Hz-AGN

- Adjust J22
- Assess the reliability of the Lyman-alpha forest



Laigle+ in prep.



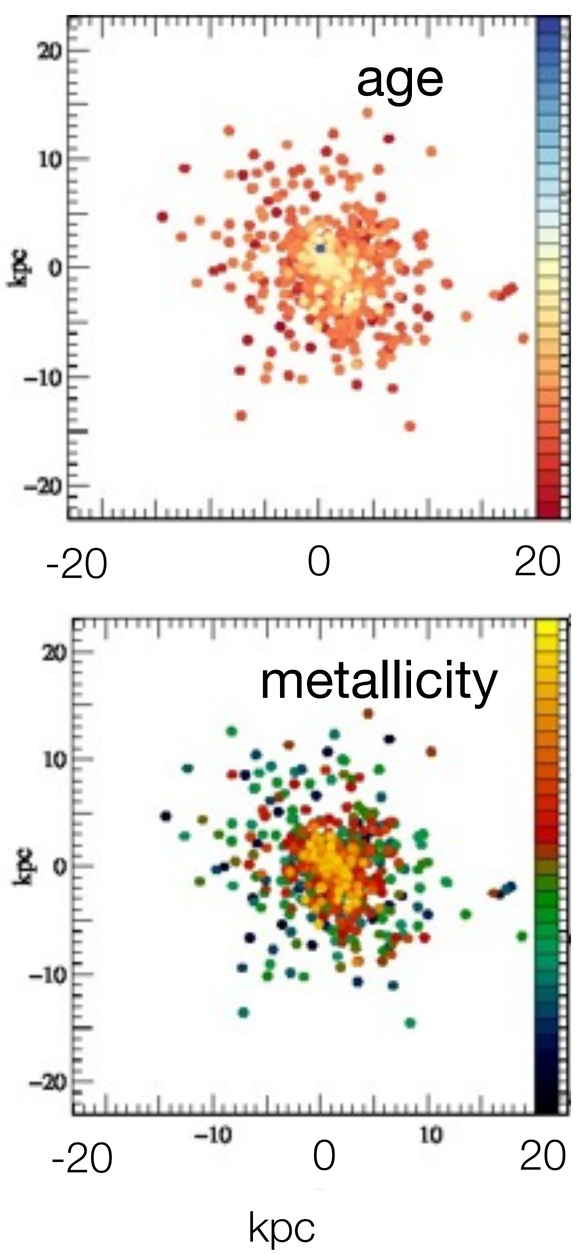
Transmitted flux along the line-of-sight

Other relevant statistics:

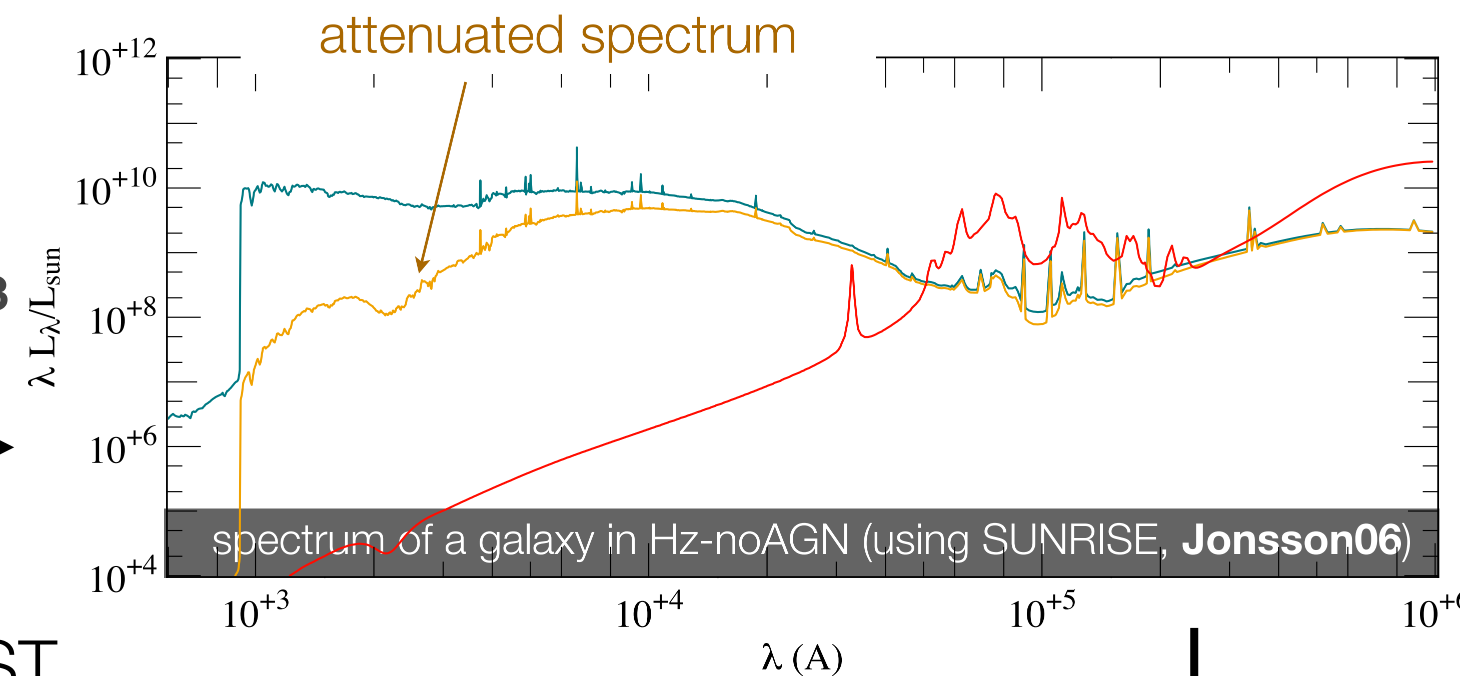
- line-of-sight power spectrum
- HI column density distribution

Realistic background of bright sources in Hz-AGN

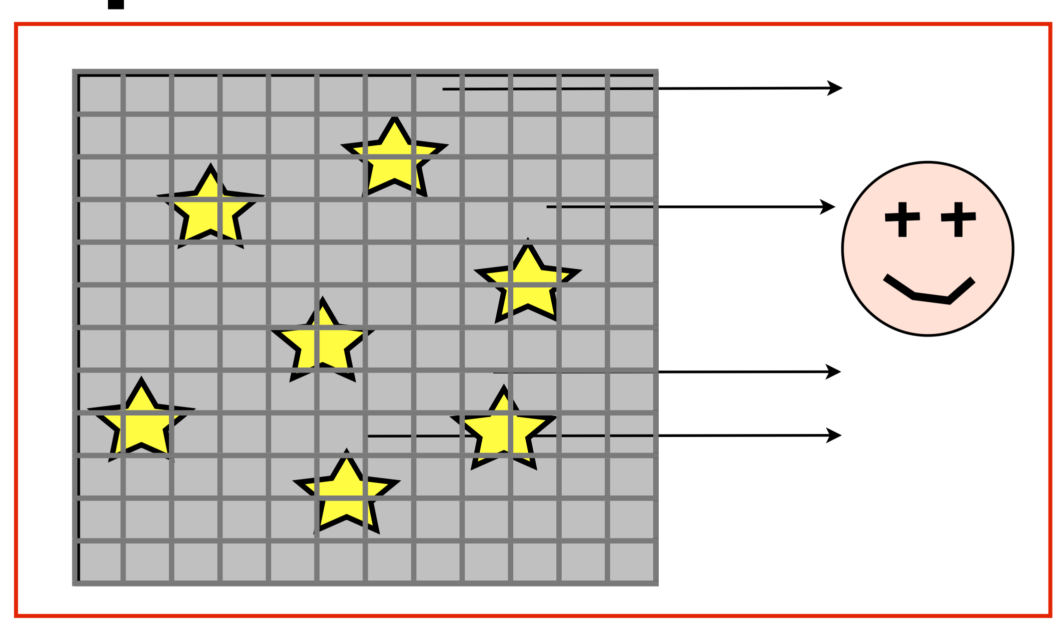
Bright background sources are selected based on their apparent magnitudes in the r-band



Bruzual&Charlot 03
SSP models

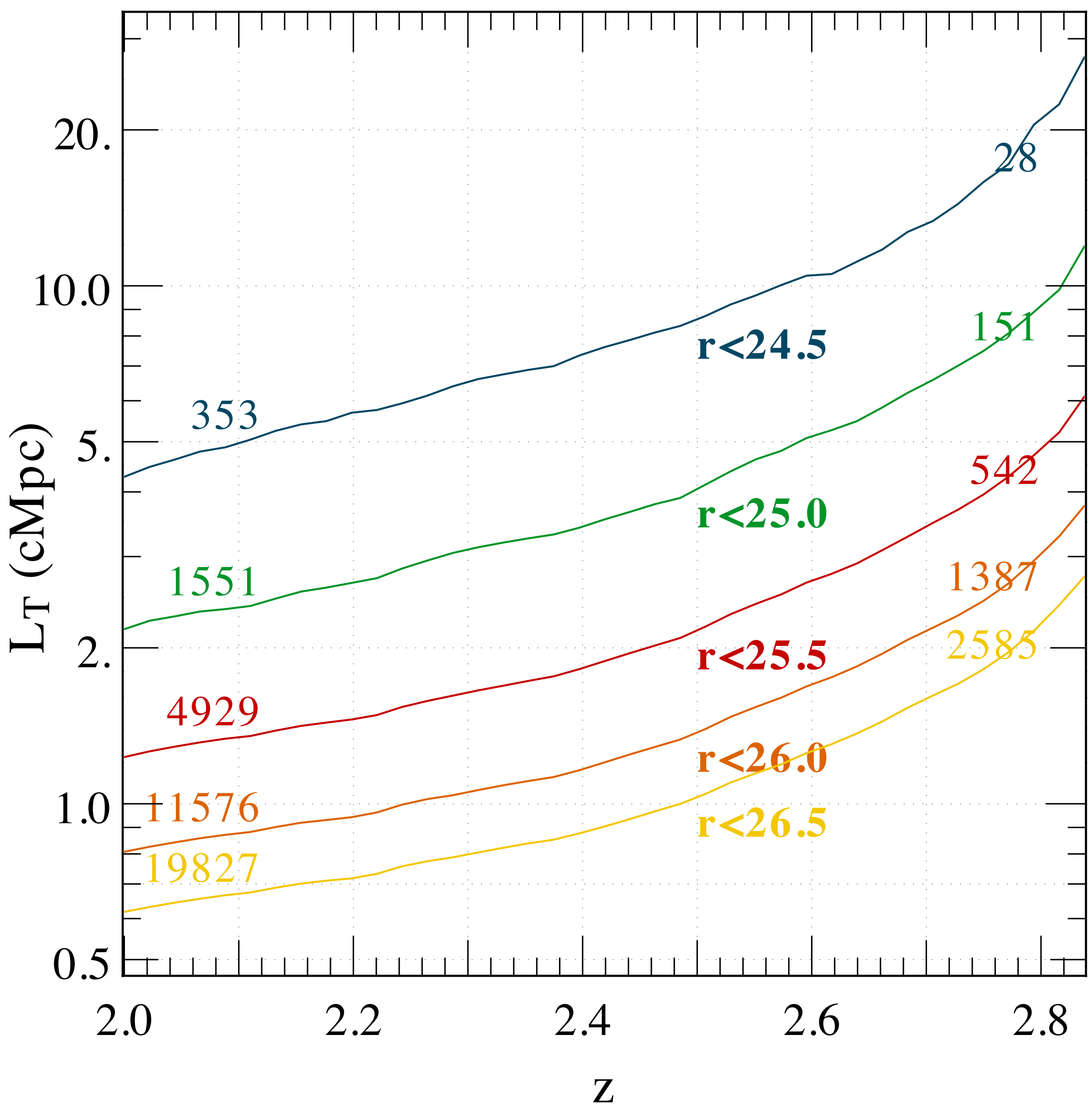


DUST



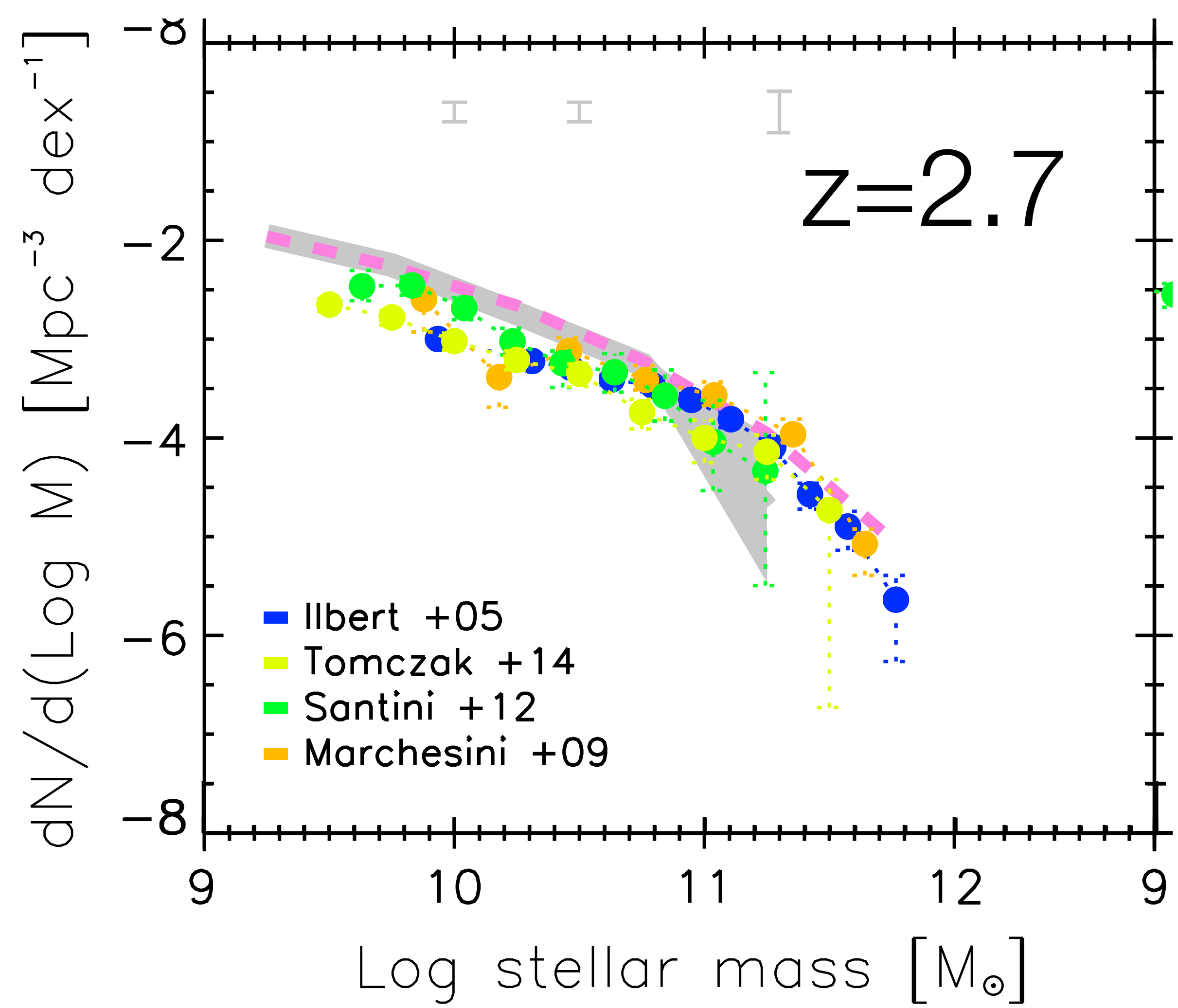
Photometric filter

Realistic background of bright sources in Hz-AGN



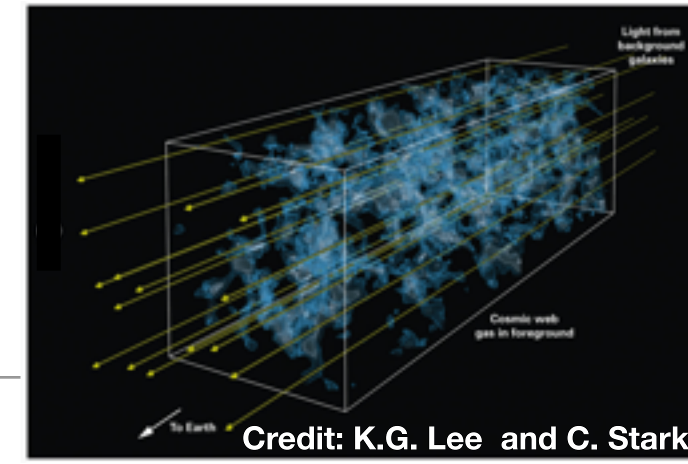
Mass function in Hz-AGN

Kaviraj+2016



Horizon-AGN well qualified to make robust predictions for IGM reconstruction

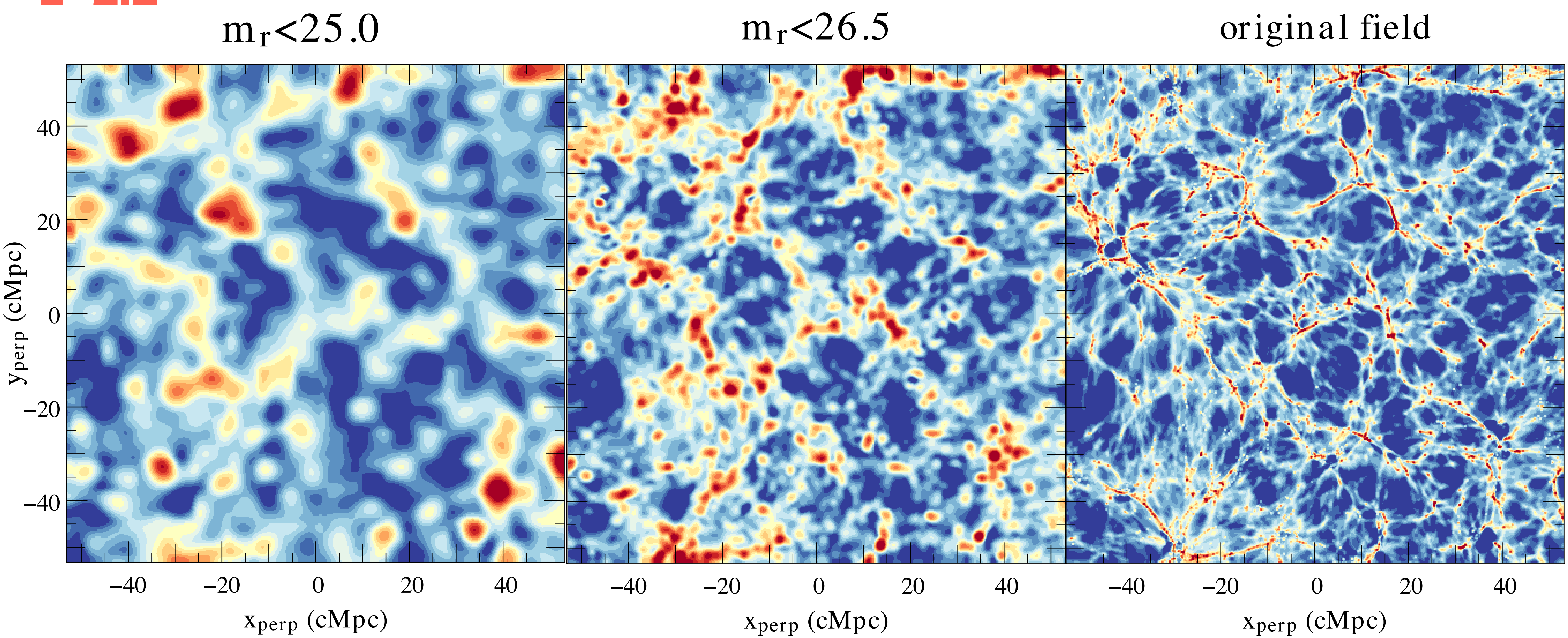
Tomographic reconstruction



Reconstruction is done on the logarithm of the density in comoving space
Resolution of reconstructed field directly set by the mean inter-LOS distance

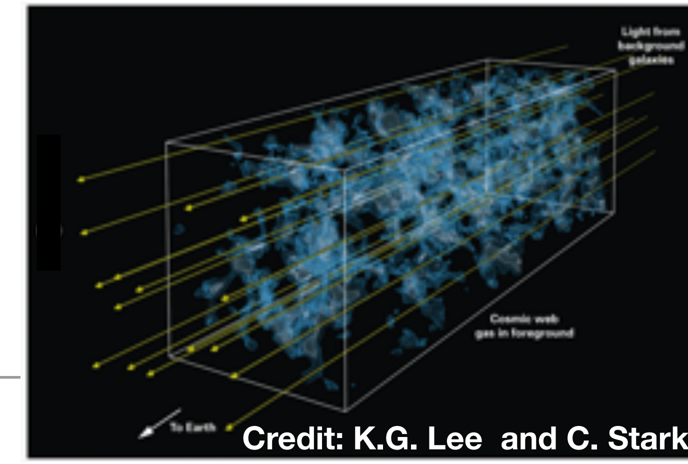
Laigle+ in prep.

z~2.2



Preliminary reconstruction (without contamination by intrinsic lines and noise)

Tomographic reconstruction

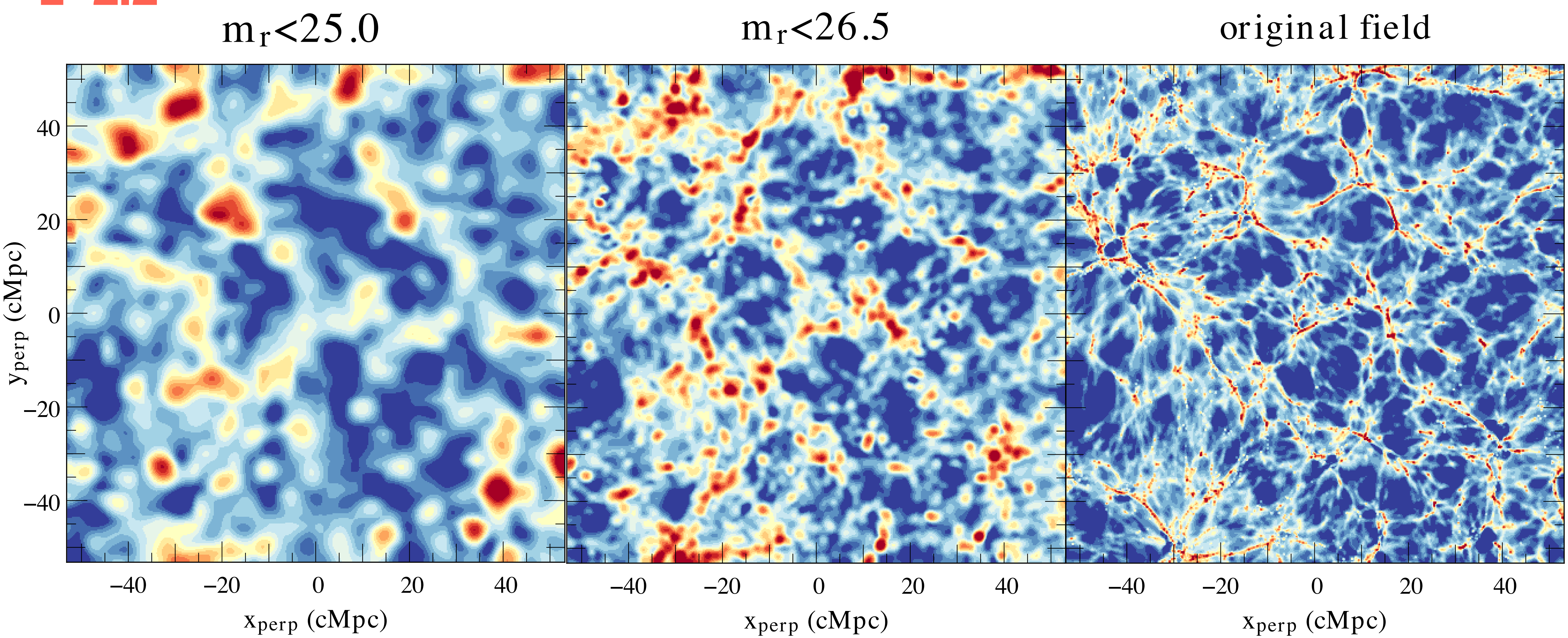


530 galaxies on 106^3 $cMpc^3$
~2000 LOS

4712 galaxies on 106^3 $cMpc^3$
~20000 LOS

Laigle+ in prep.

z~2.2



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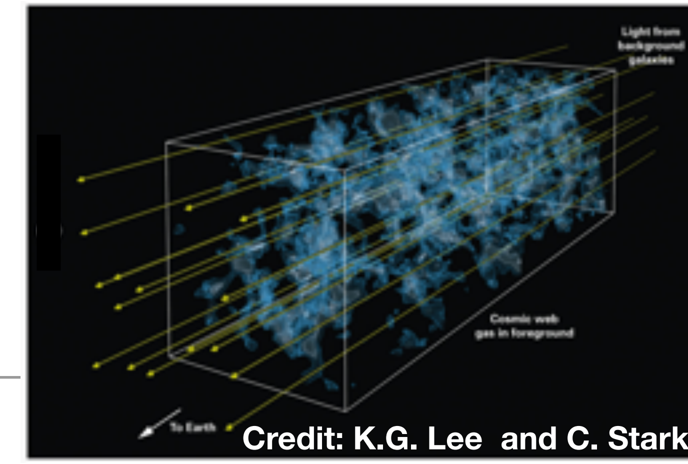
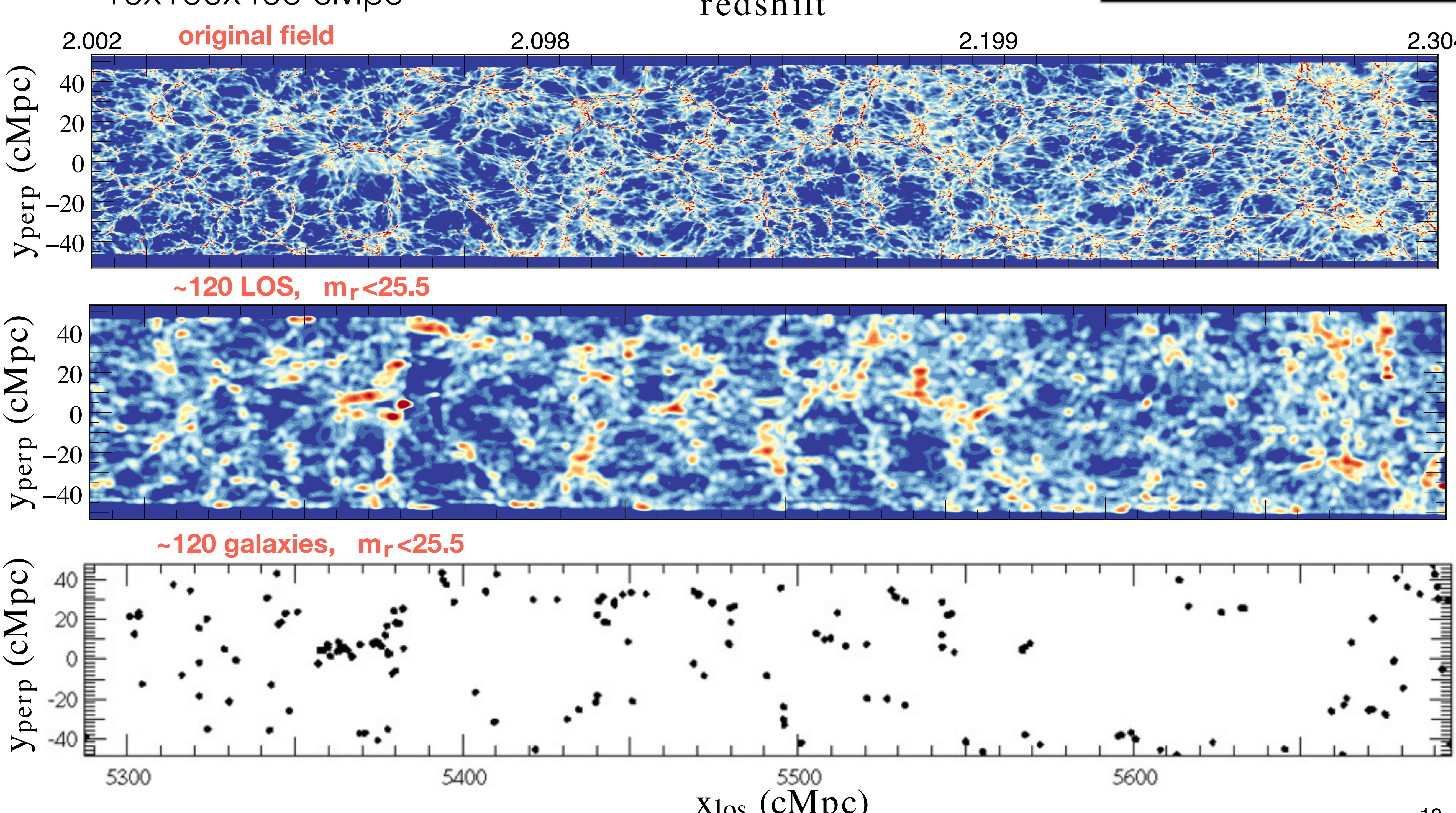
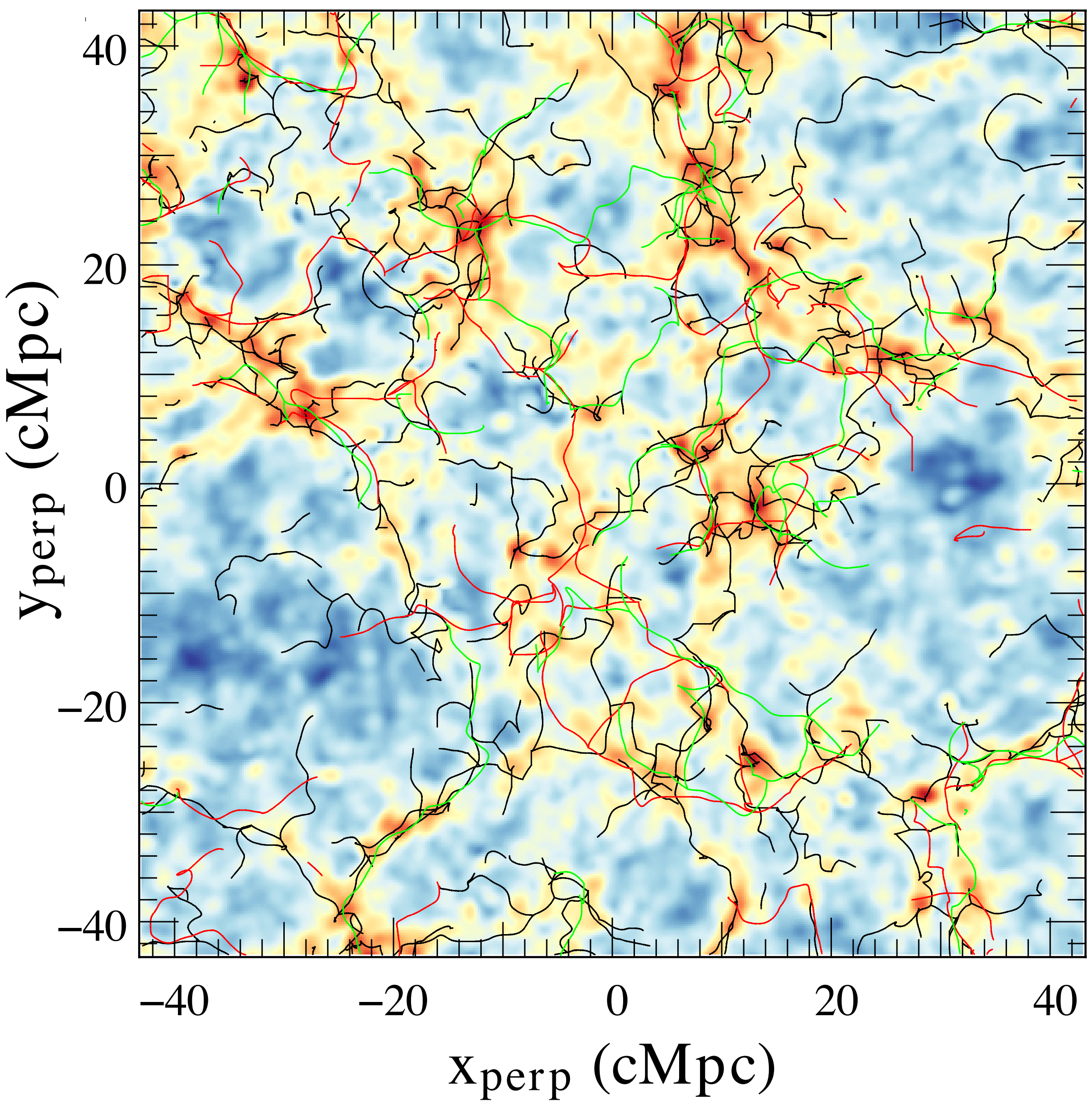


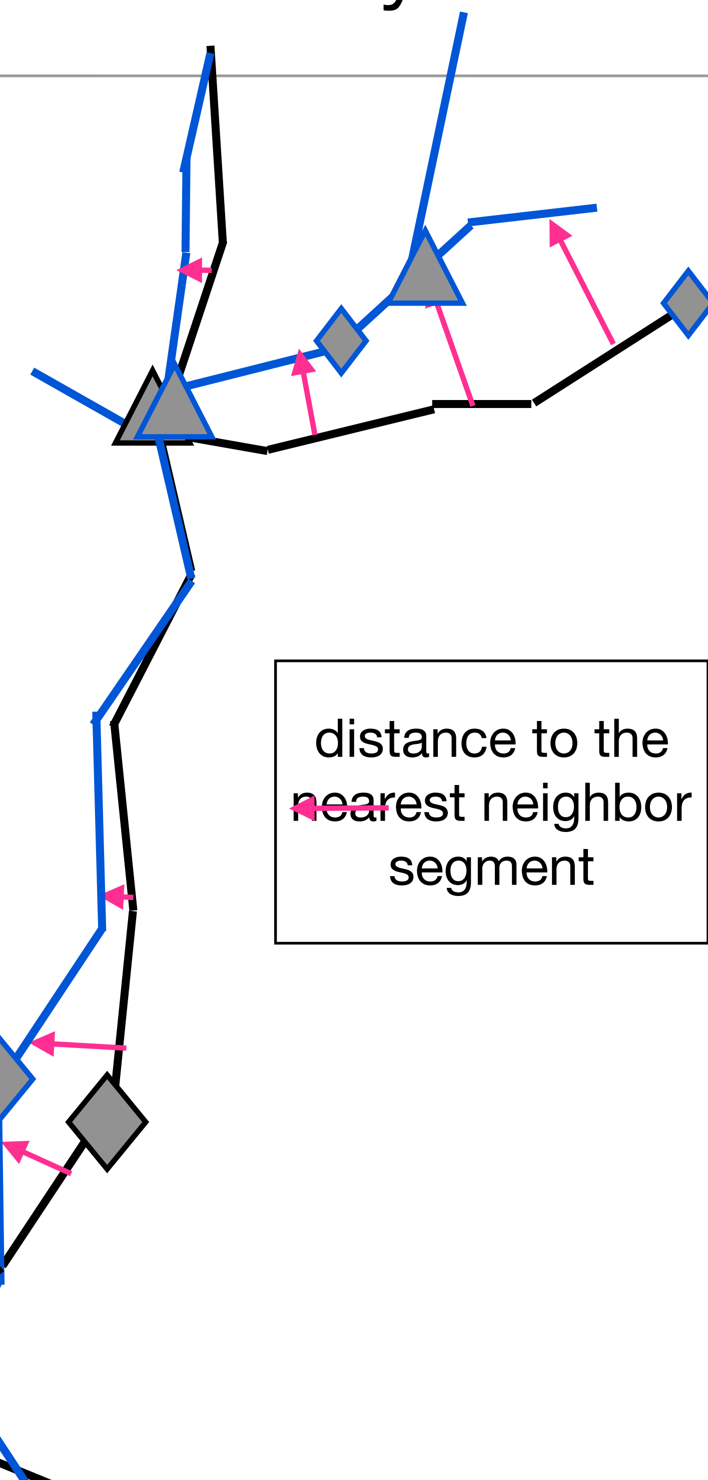
10x100x400 cMpc



Geometry of the large-scale field: preliminary results

Skeleton is extracted with DISPERSE (**Sousbie+11**)





At equivalent observation time: tomography allows to better qualify the geometry of the field than galaxy distribution

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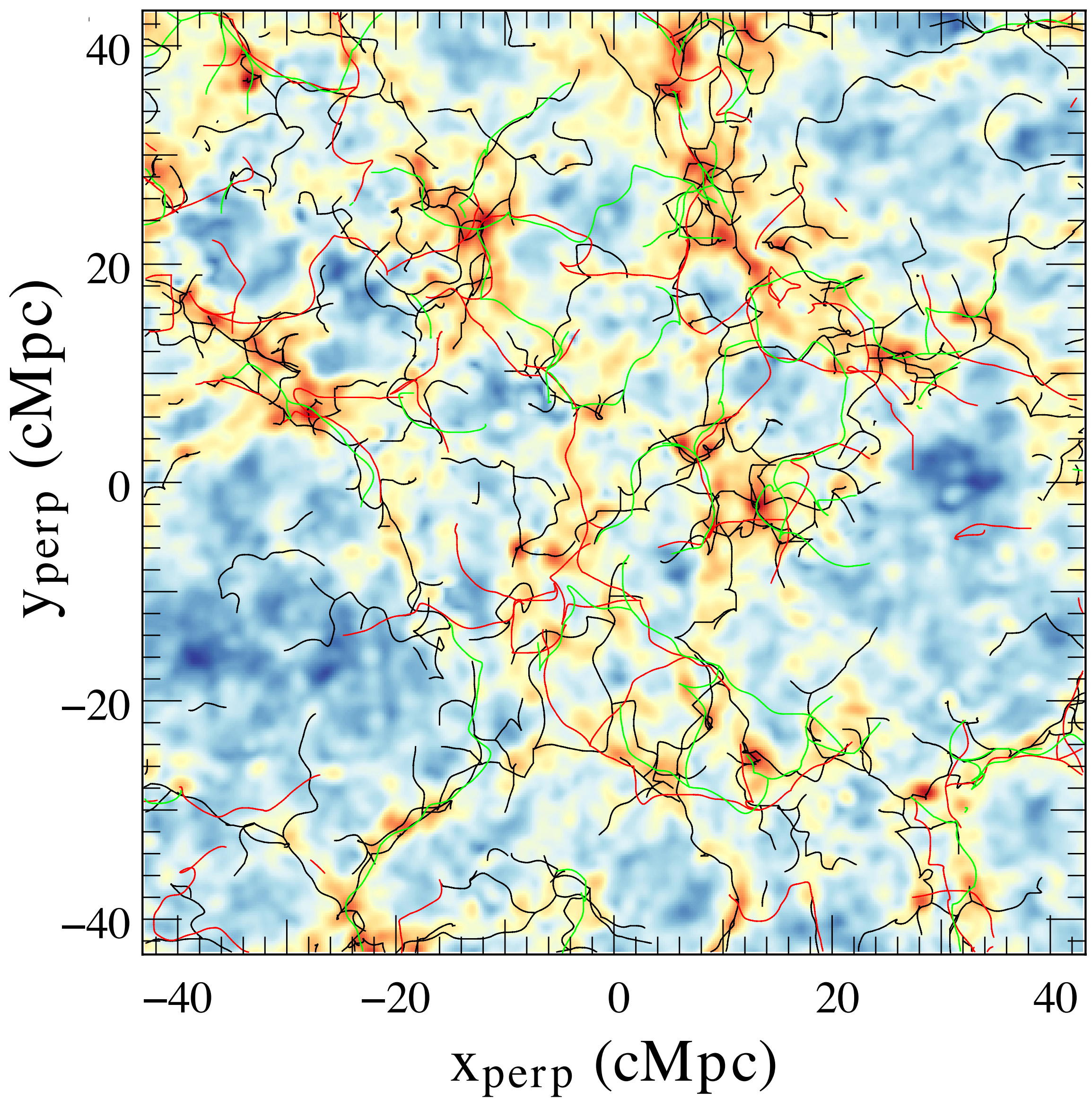
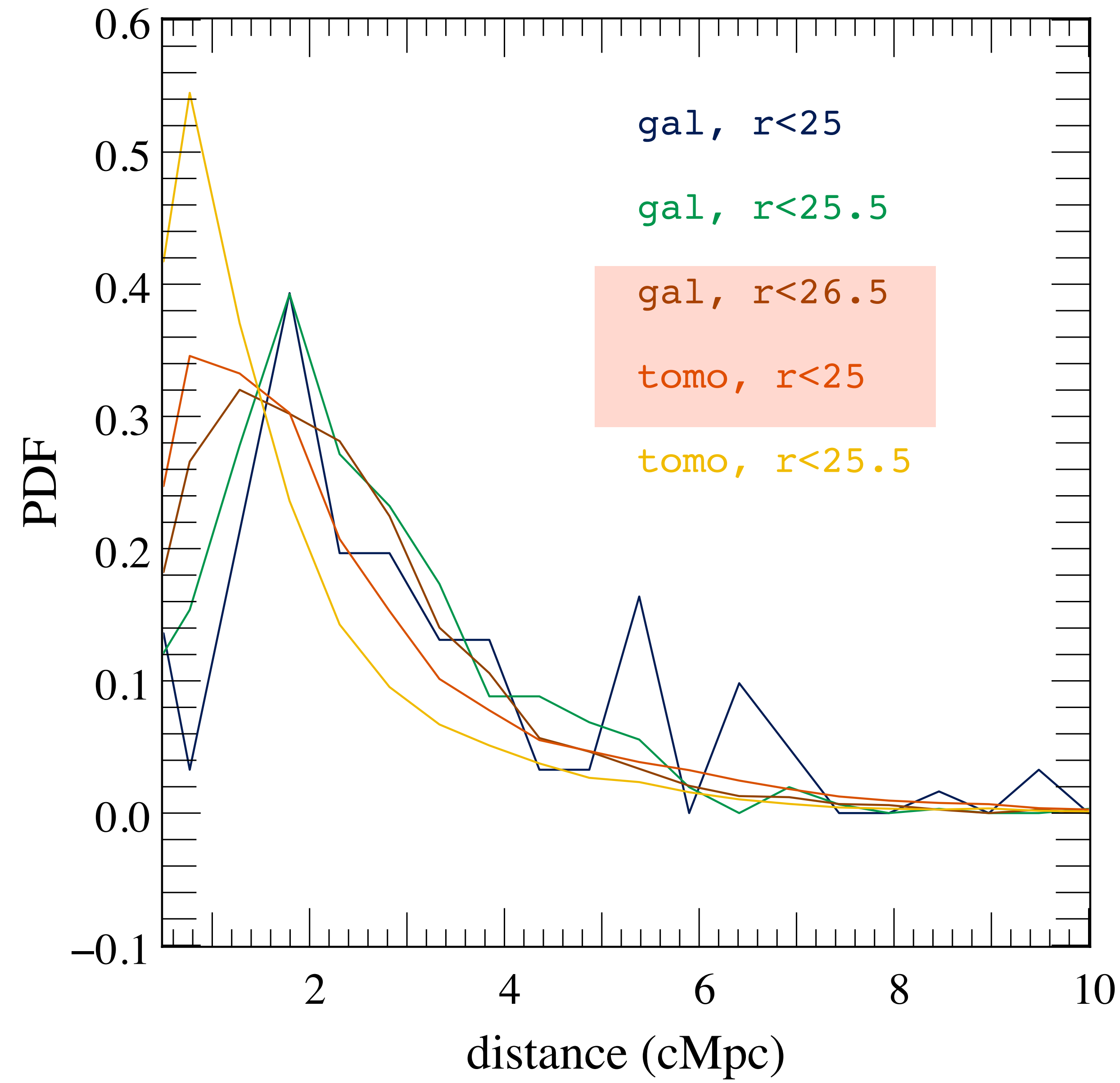




At equivalent observation time: tomography allows to better qualify the geometry of the field than galaxy distribution

Geometry of the large-scale field: preliminary results

Other relevant statistics:

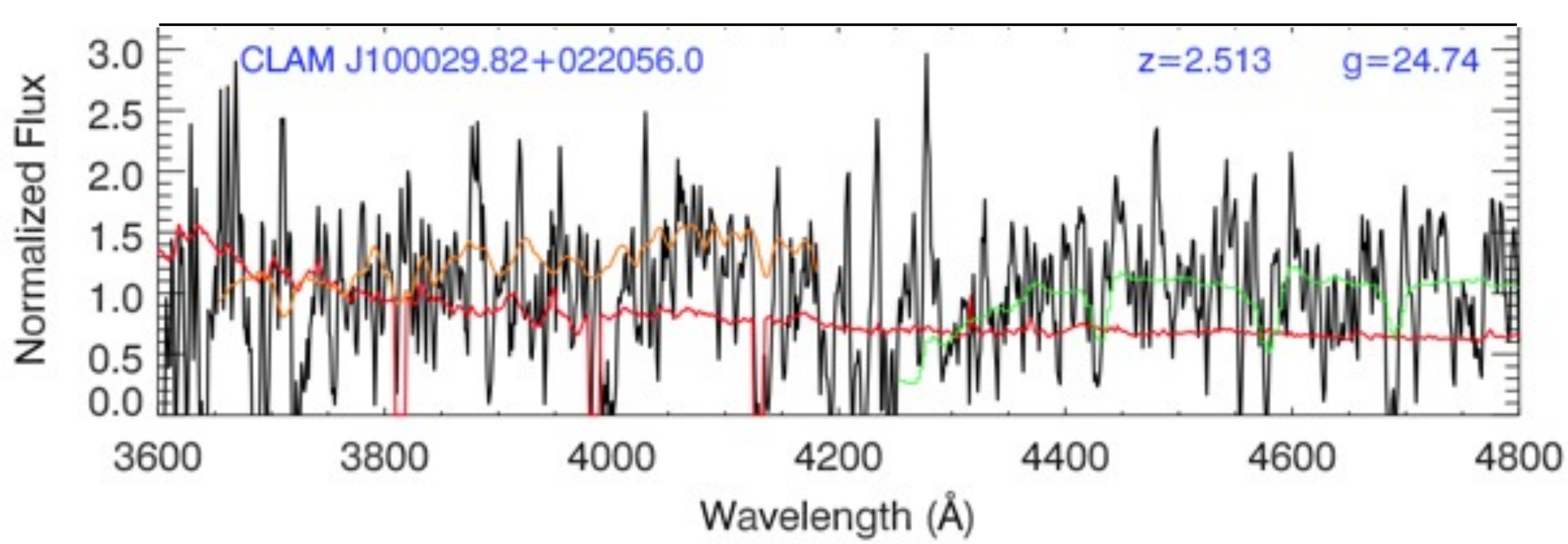
- critical point counts
- skeleton length
- connectivity

Other relevant measurements:

- How well do we recover galaxy environment?
- How well are we able to study galaxy alignment with filaments?

Find a reasonable balance between the required telescope time and the resolution
Use realistic galaxy spectra + add realistic noise

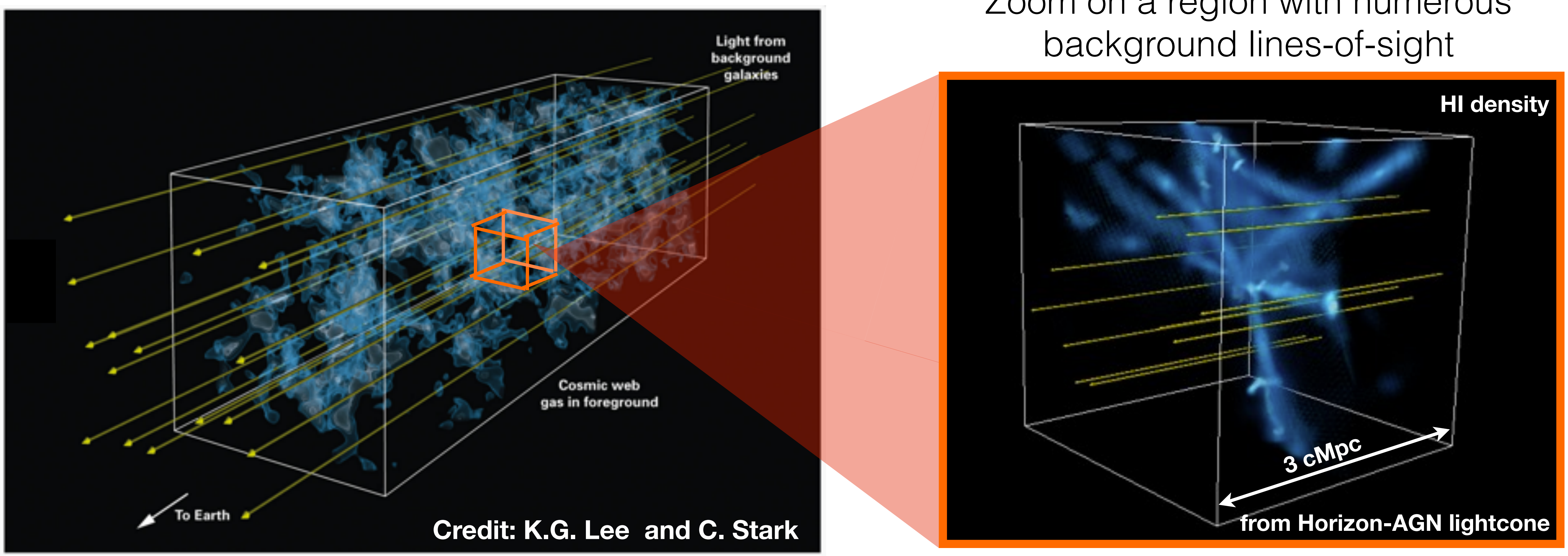
Lee+14



Probing the geometry of the CGM

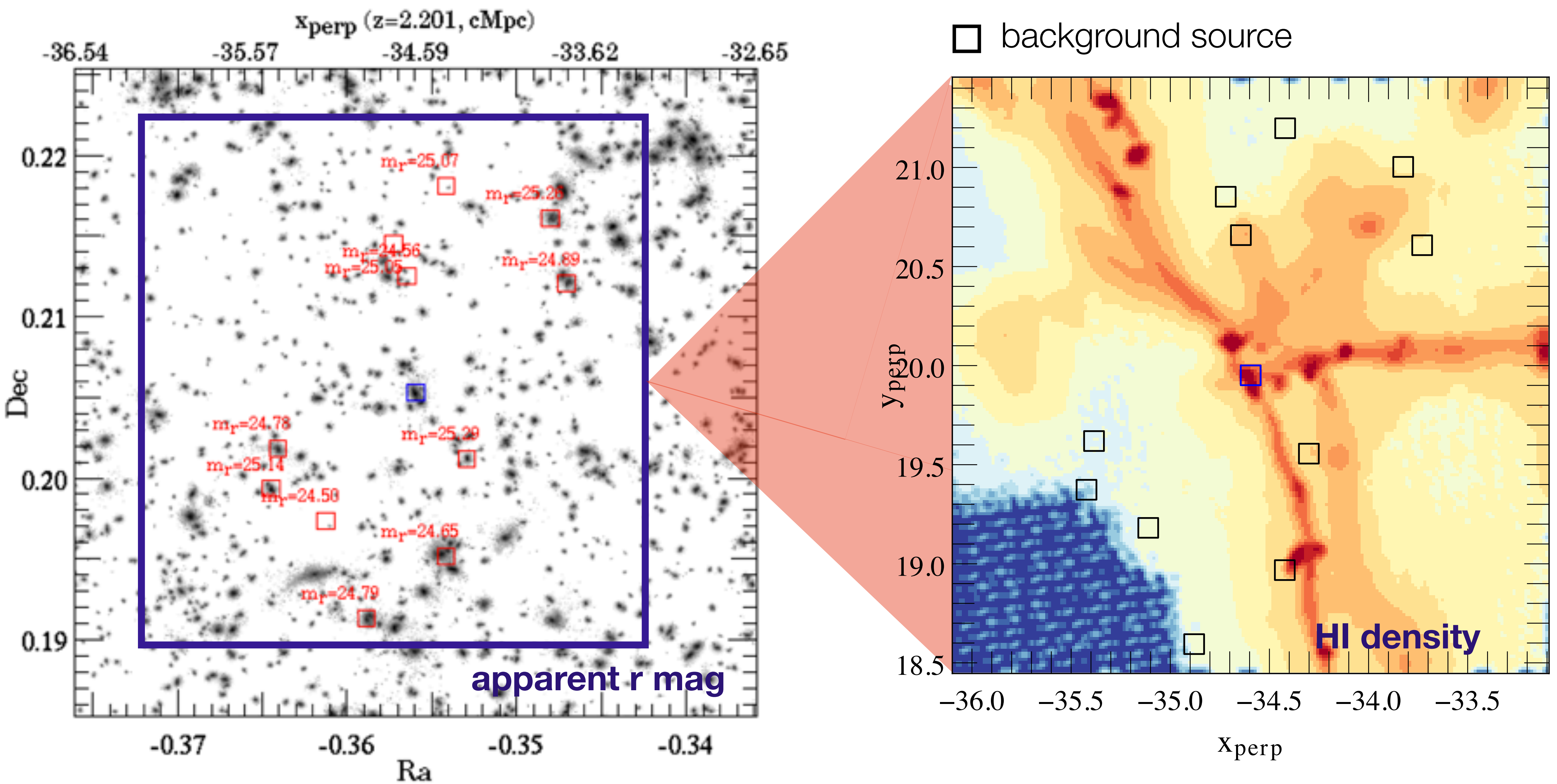
Tracing the cosmic web at large scales requires a relatively uniform distribution of sightlines

Zoom on a region with numerous background lines-of-sight



Inflows around clusters and galaxies can be inferred by punctually observing spectra of clustered background objects

Probing the geometry of the CGM: on-going work



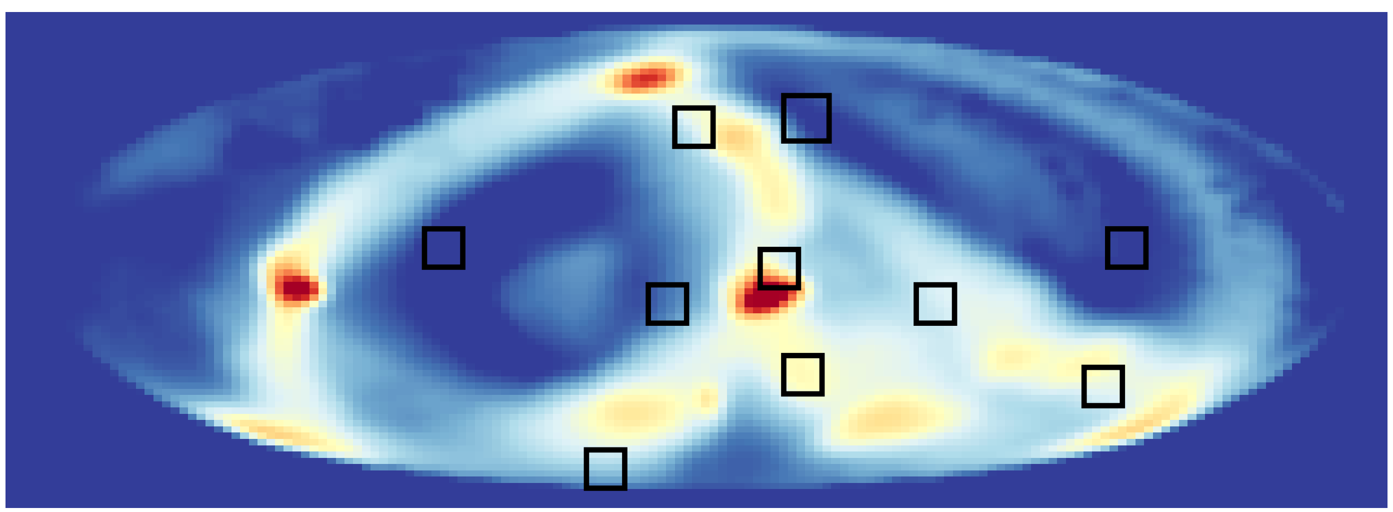
Background sources selected based on apparent r-band magnitudes and redshift (such that Ly-alpha forest probes foreground CGM)

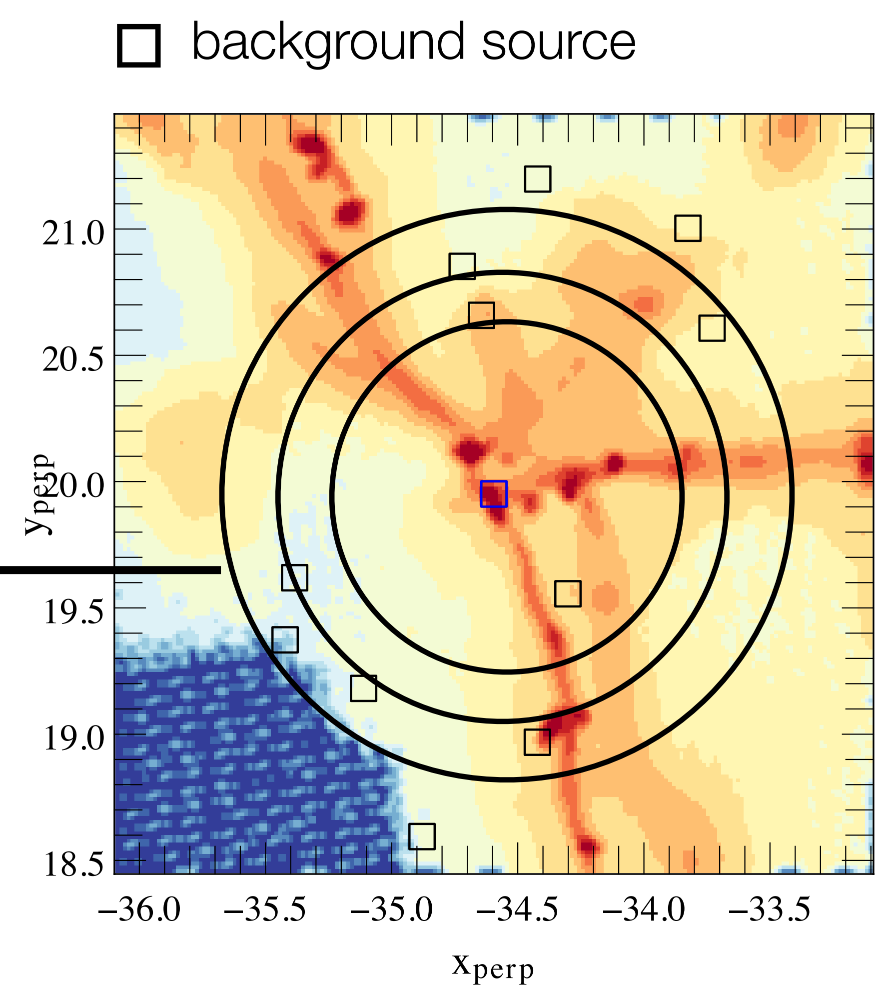
Can we determine the geometry of the gas inflow from a limited number of sightlines, at which scale? How many background sources are required?

Probing the geometry of the CGM: on-going work

log ($M_*/M_\odot$)=10.3, z-2.20

Hammer-Aitoff projection at R~1.2 Mpc
HI density





Multipolar development on the sphere at different radii could characterize gas inflow
Test the feasibility in observations (model all observational limitations)

Can we determine the geometry of the gas inflow from a limited number of sightlines, at which scale? How many background sources are required?

CONCLUSION

- Take advantage of the Lyman-alpha absorption on background objects to reconstruct at large-scale the cosmic web. At smaller scale, characterize the circum-galactic medium. Use bright UV galaxies in addition to quasars.
- Horizon-AGN: well qualified to make prediction for future surveys: e.g. PFS, E-ELT
- At equivalent observation time, tomography allows a better reconstruction than galaxy distribution.
- On-going work: characterizing gas inflow at smaller scale from a limited number of sightlines

Next steps:

- Make accurate predictions for future surveys, in particular including noise and using realistic galactic spectra (with intrinsic lines)
- Combine tomography and redshift distribution to improve the reconstruction