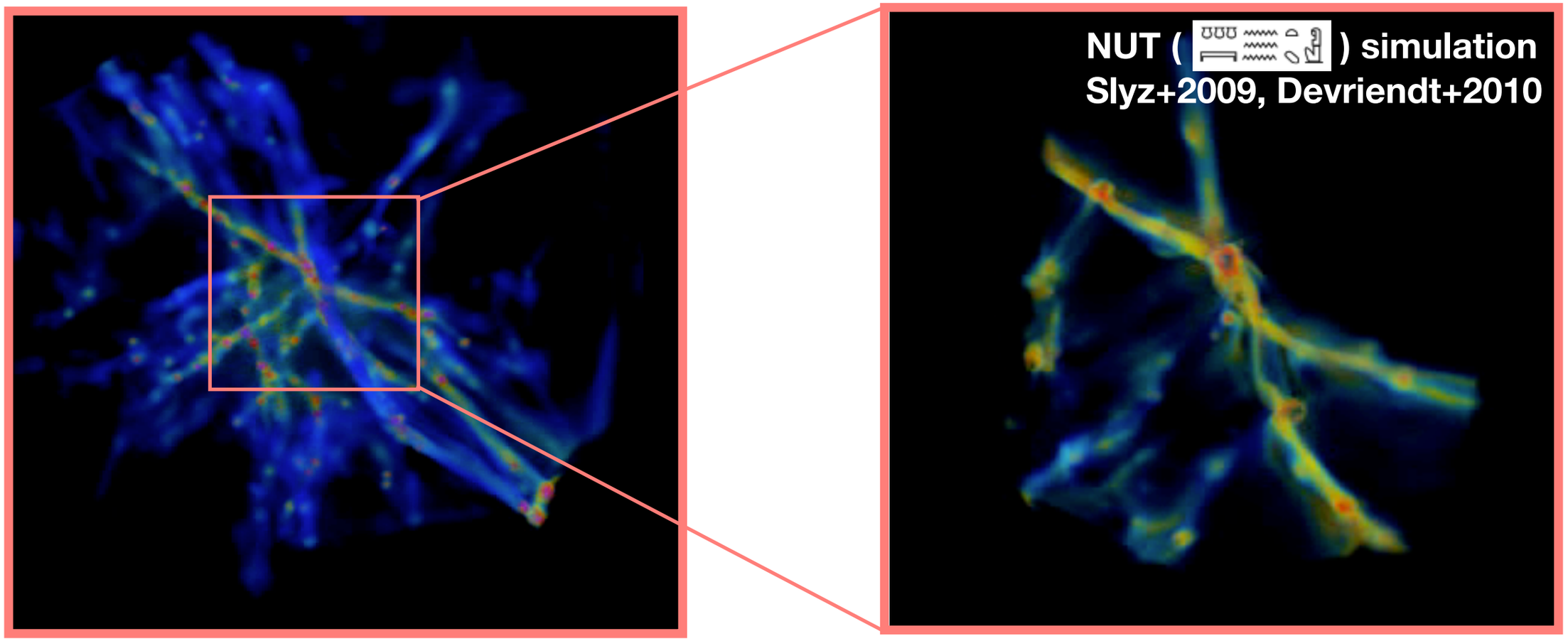
Clotilde Laigle

Devriendt, Japelj, Arnouts, Pichon, Slyz, Dubois, Park, Peirani

UNIVERSITY OF OXFORD

Probing the multi-scale cosmic web

forecasts for Lyman-alpha forest tomography



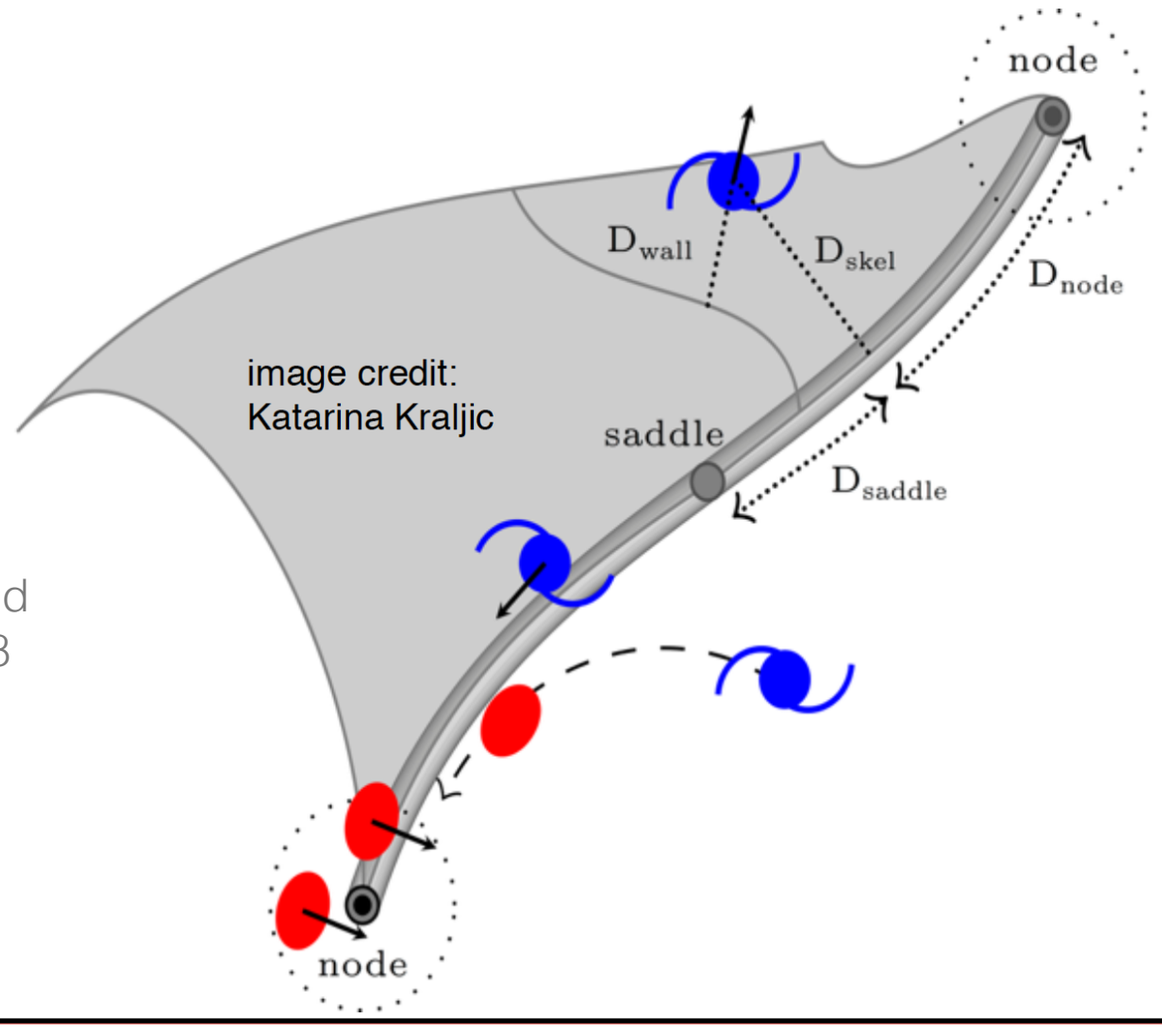
IGM: a multi-scale and multi-connected web

Gravity amplifies anisotropy: filaments are found at all scales
Connectivity: relevant both for cosmology and galaxy formation

GALAXY FORMATION

- Angular momentum acquisition
  Codis+12, Temple+13, Dubois+14, Libeskind +13, Laigle+15, Welker+17, Ganeshaiah+18

- Mass assembly
  Malavasi+16, Kraljic+18a,b, Laigle+18, Odekon+18, Chen+18



Impact of the **geometry** of the matter distribution **beyond density** on galaxy properties

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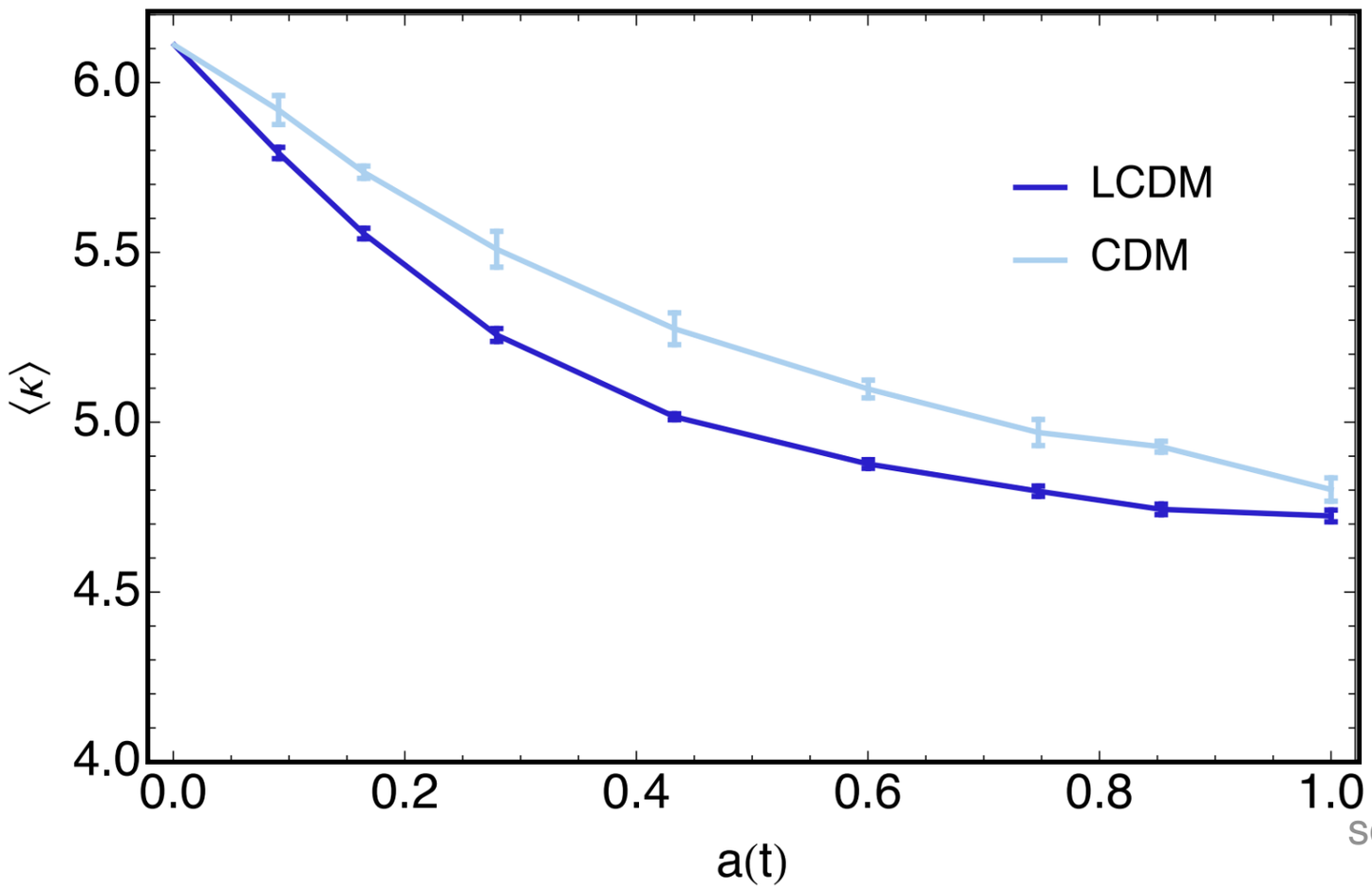
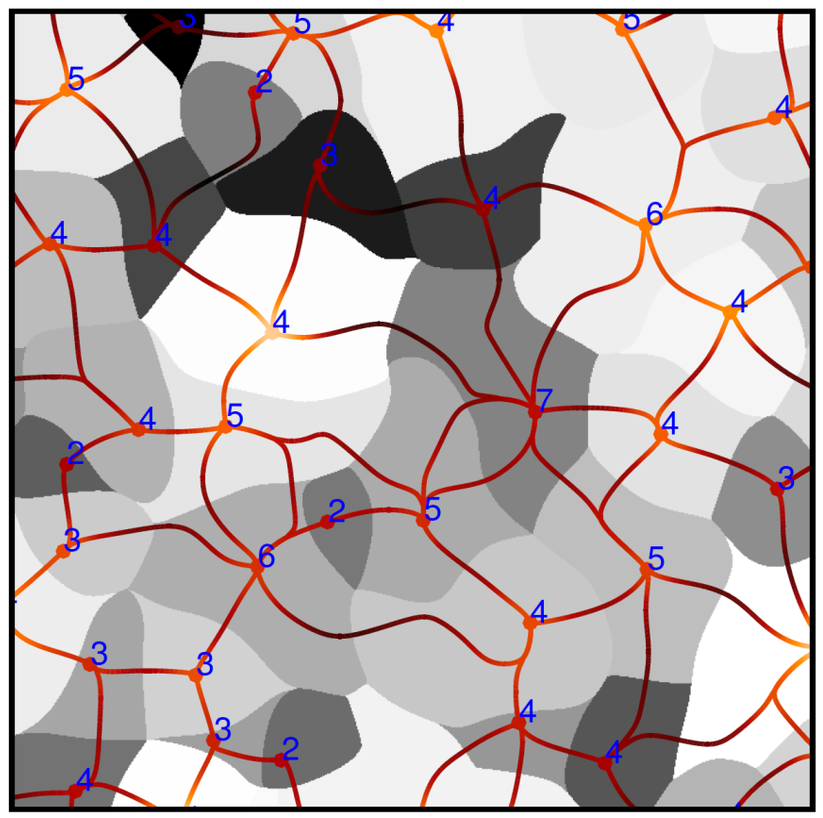
COSMOLOGY



Codis et al. 18



see also e.g. Park+09 Codis+13, Appleby+17

How many filaments a node of a given height is connected to depends on **cosmology**

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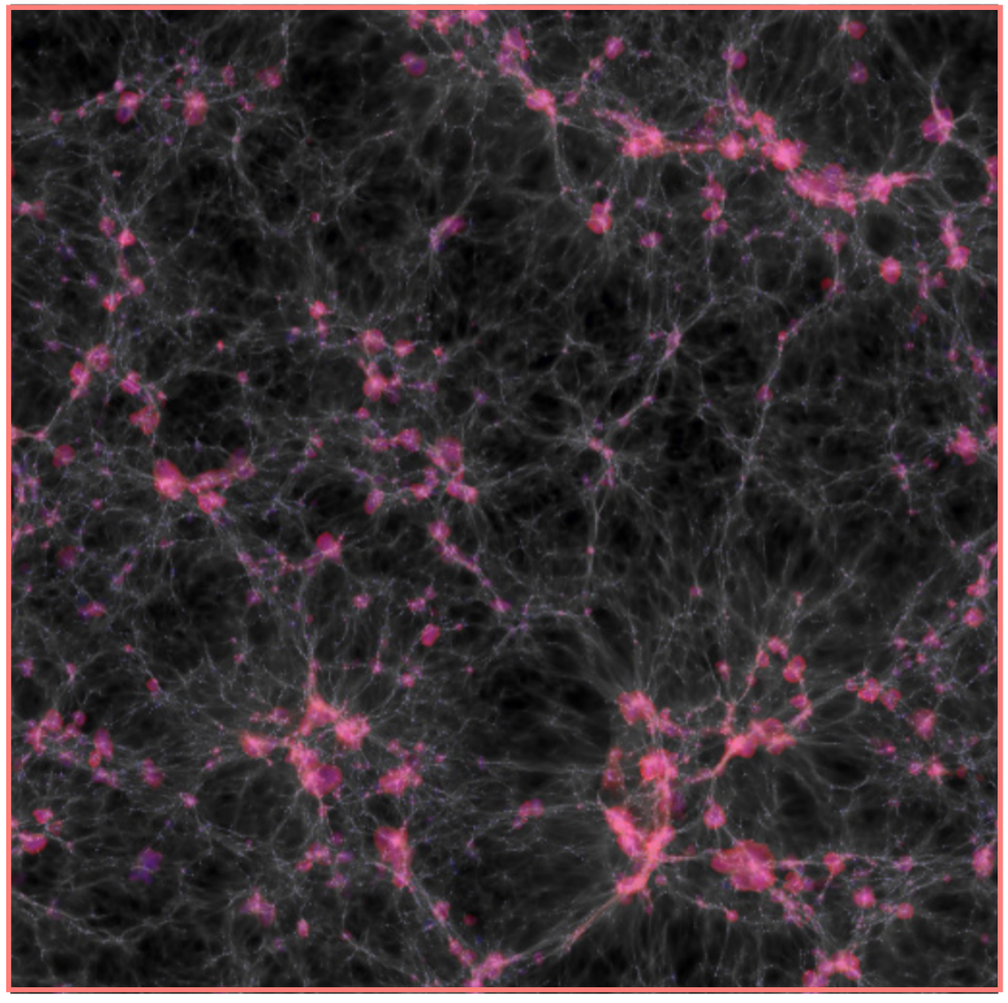
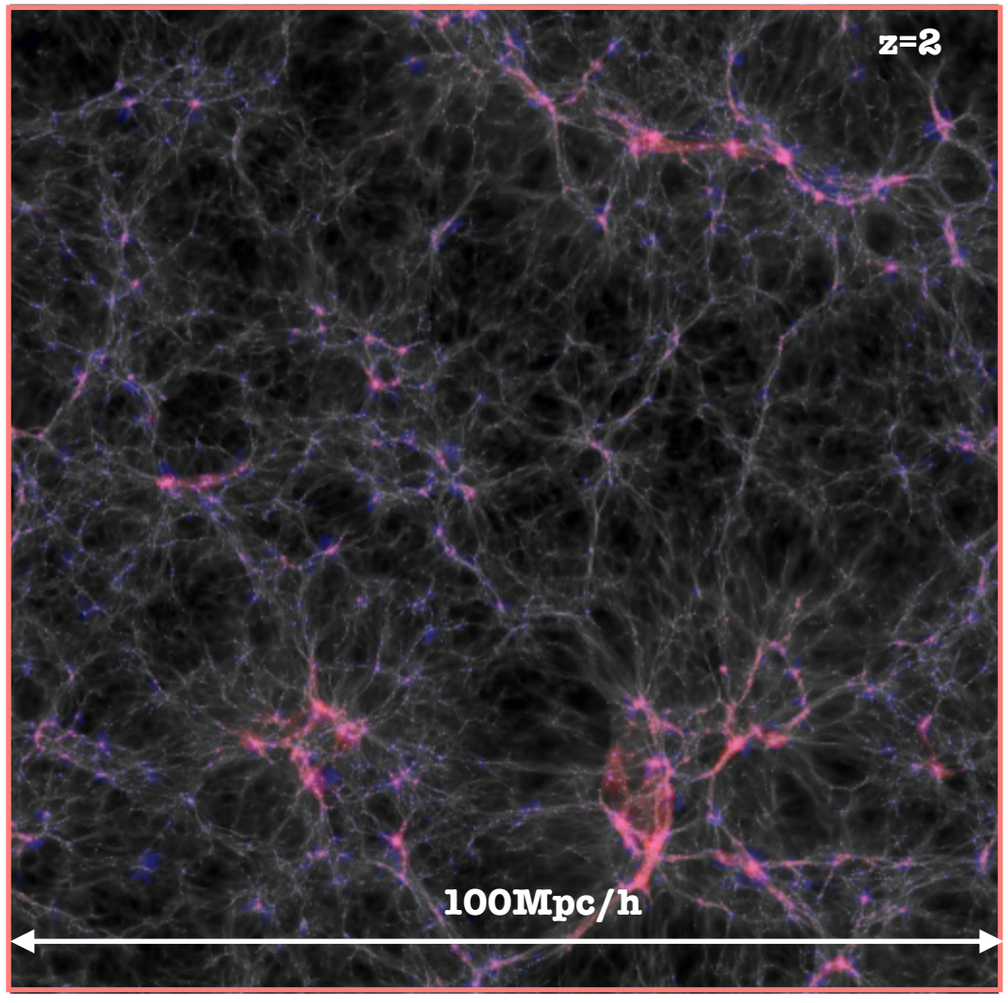
AGN FEEDBACK

Horizon-AGN simulation



Horizon-noAGN simulation



(**Disruption** of the) connectivity of the HI field might be a probe for **AGN feedback**

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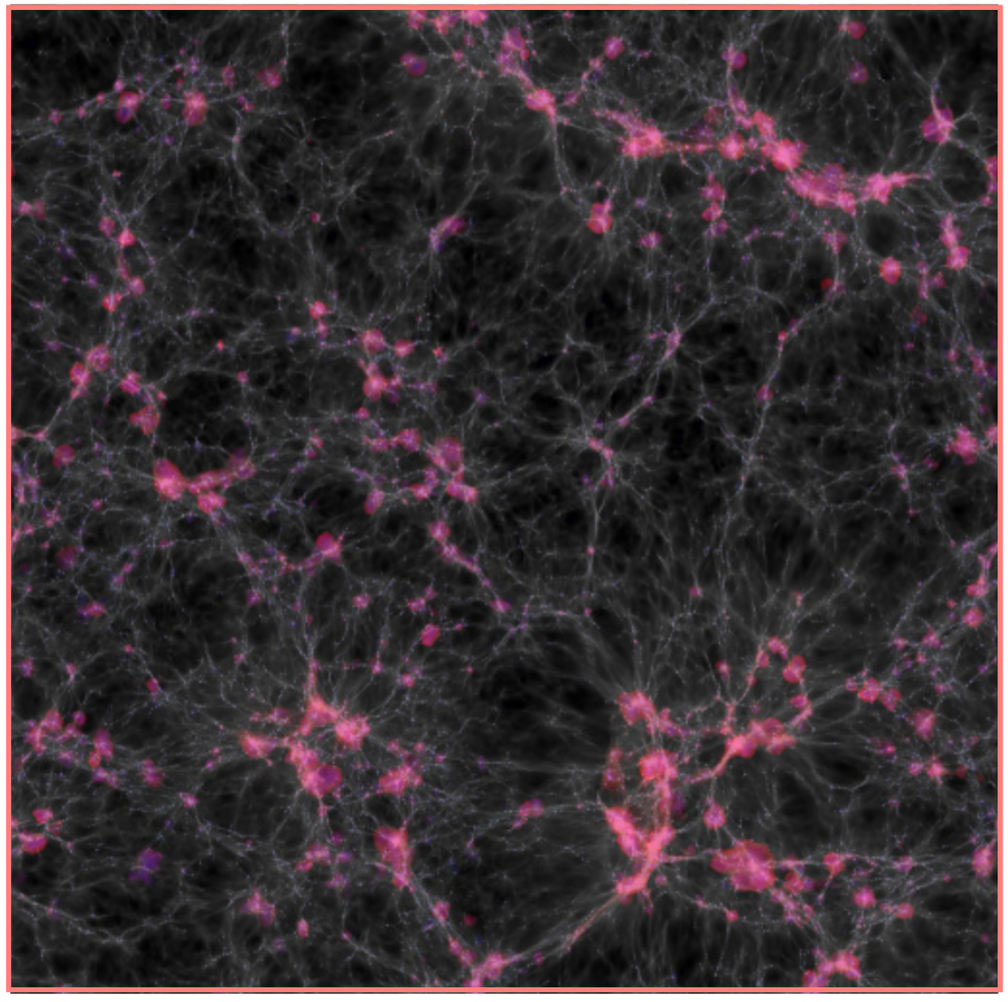

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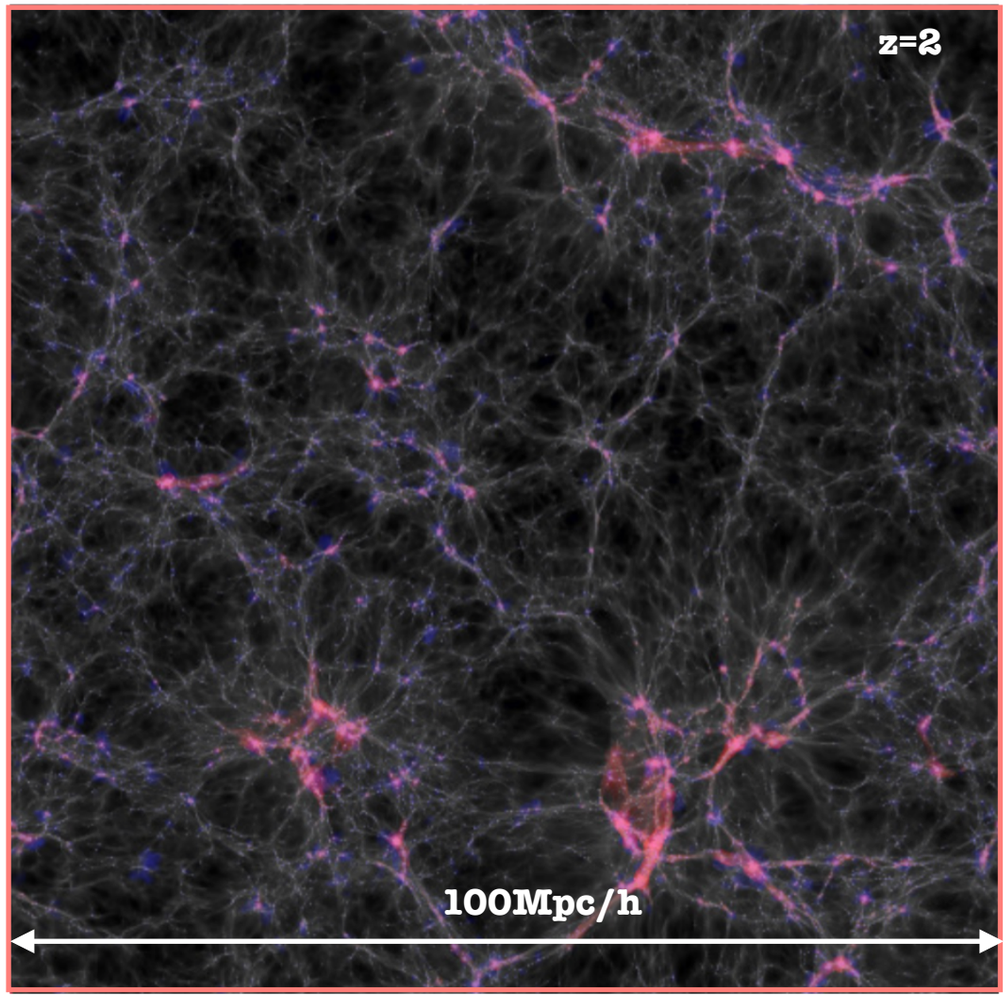

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Probing connectivity of the IGM → need to reconstruct the 3D distribution of matter

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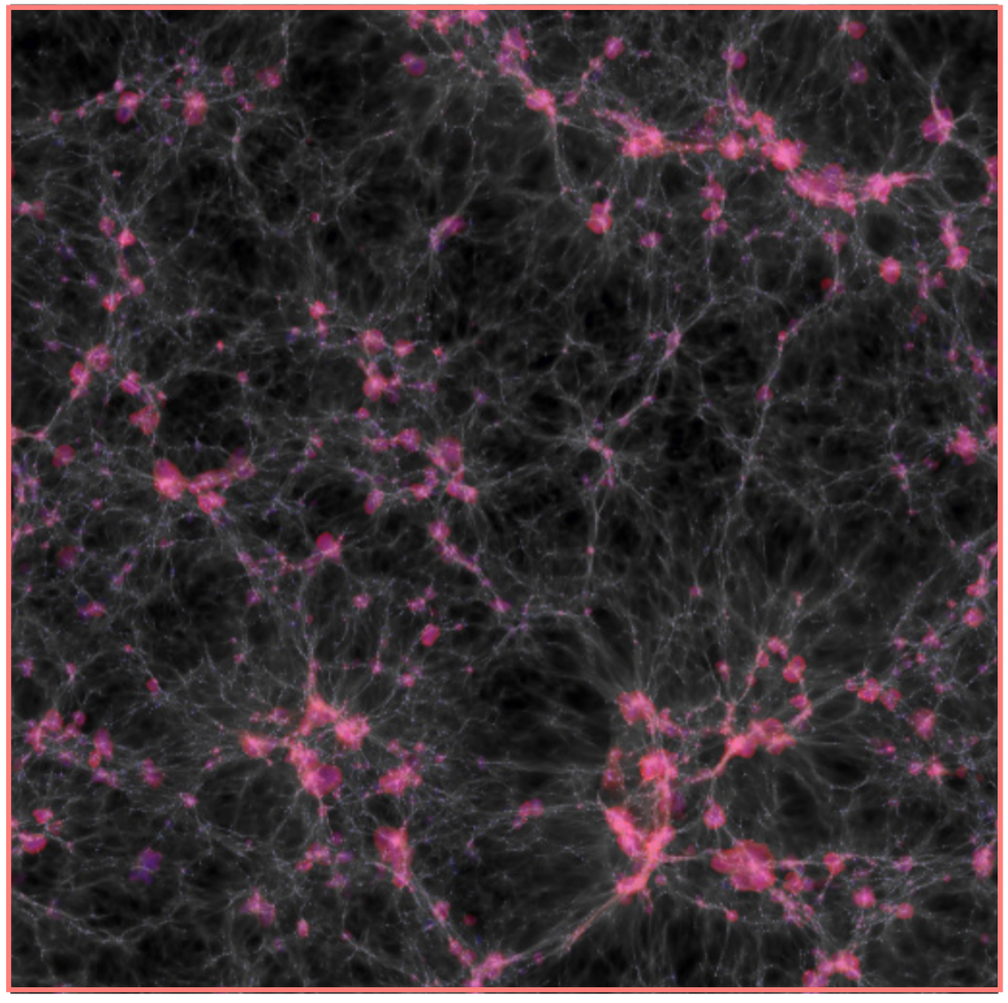

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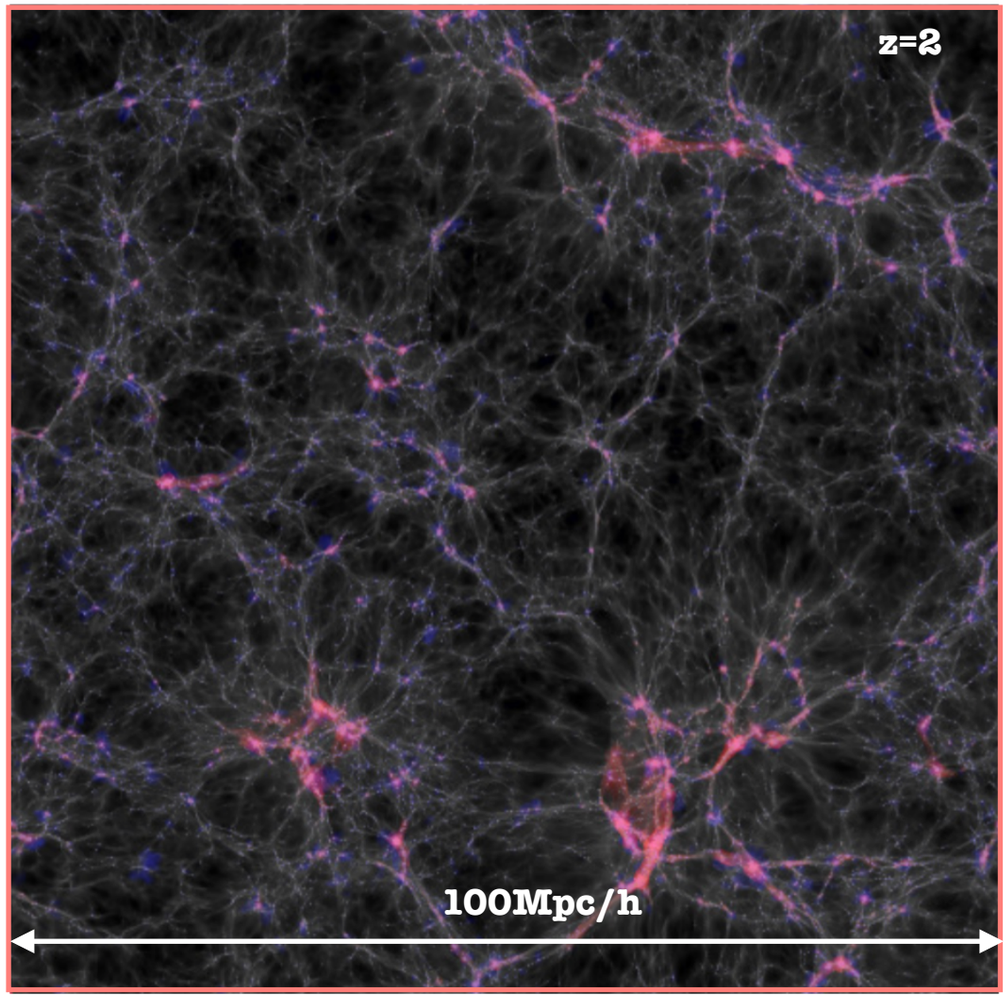


(**Disruption** of the) connectivity of the HI field might be a probe for **AGN feedback**

Probing connectivity of the IGM → need to reconstruct the 3D distribution of matter

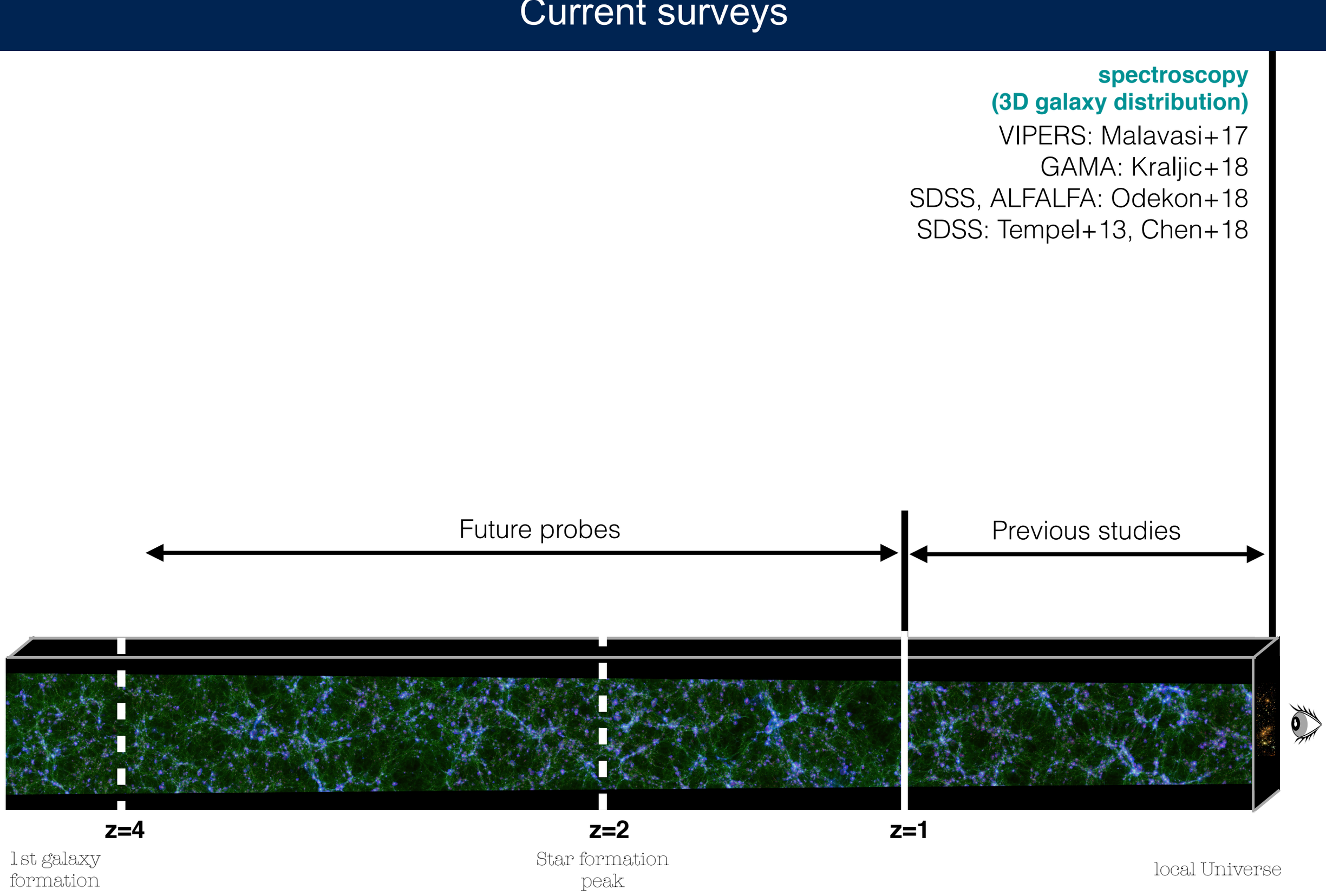
Focus on a global reconstruction (in absorption, cosmological volume, scale >Mpc)

Observing the multi-scale cosmic web

Current surveys

spectroscopy
(3D galaxy distribution)

VIPERS: Malavasi+17
GAMA: Kraljic+18
SDSS, ALFALFA: Odekon+18
SDSS: Tempel+13, Chen+18



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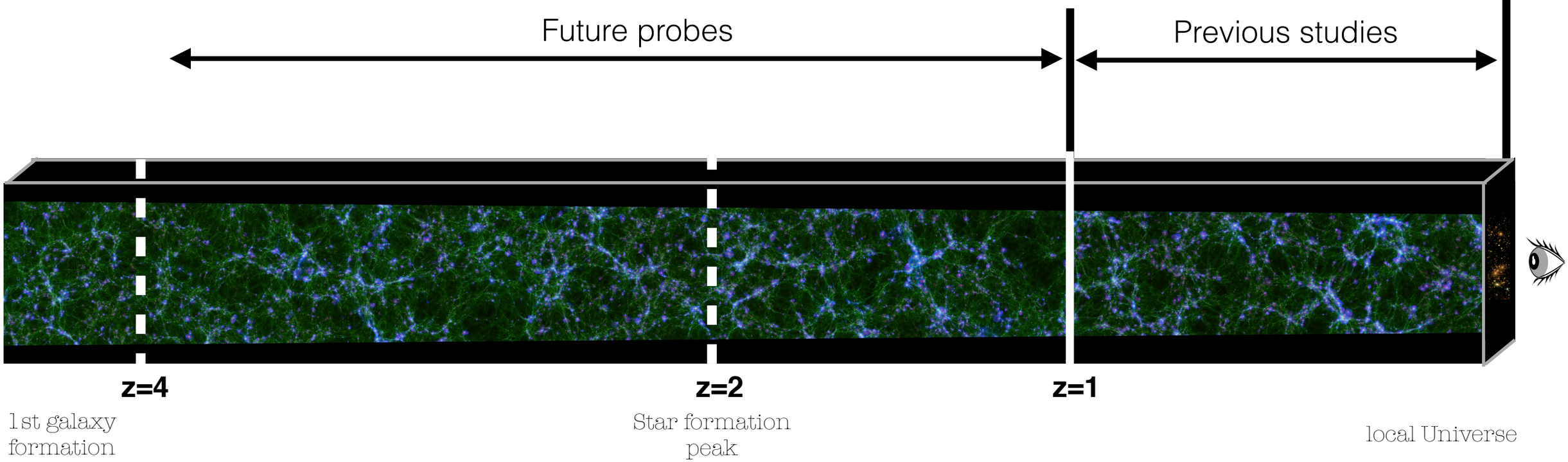
photometry
(2D galaxy distribution)

COSMOS: Laigle+18

Euclid, LSST

photometry



Observing the multi-scale cosmic web

Current surveys

Lyman-alpha forest tomography
CLAMATO (e.g. Lee+14,18, Krolewski+17)

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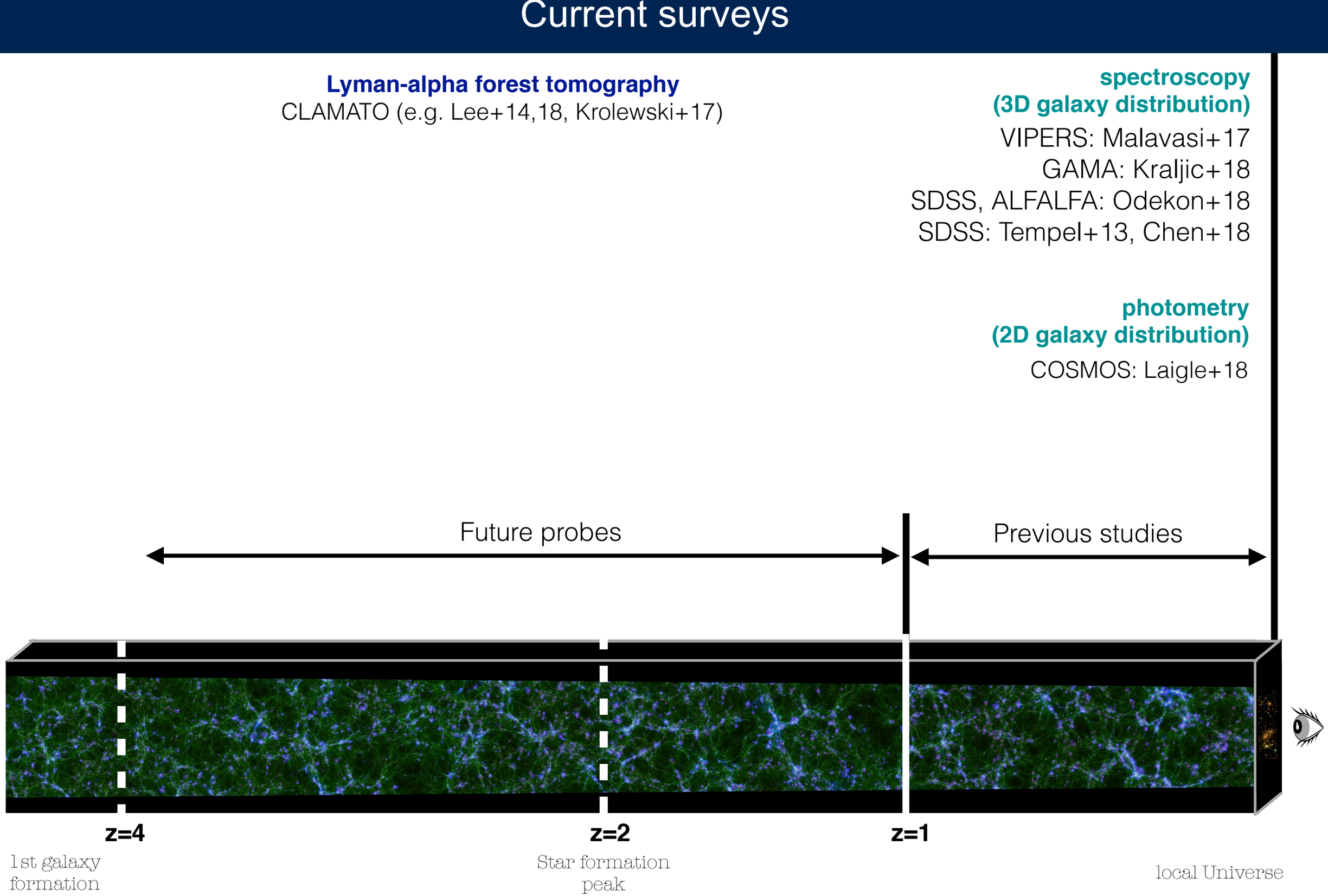
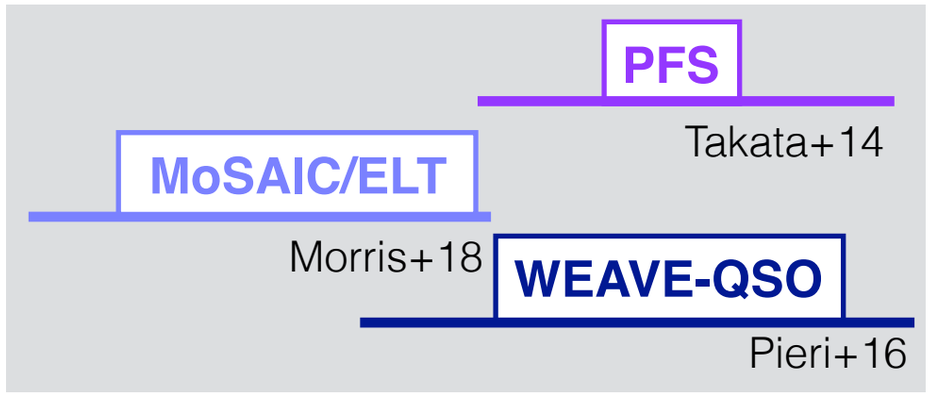


Observing the multi-scale cosmic web

Future surveys

Lyman-alpha forest tomography
CLAMATO (e.g. Lee+14,18, Krolewski+17)



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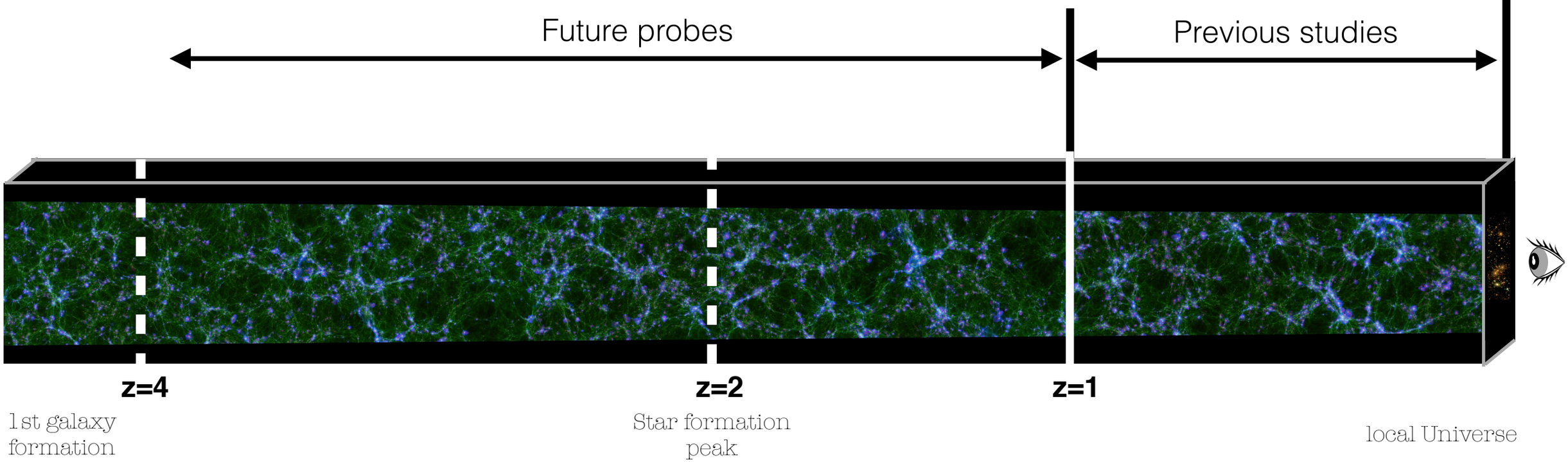
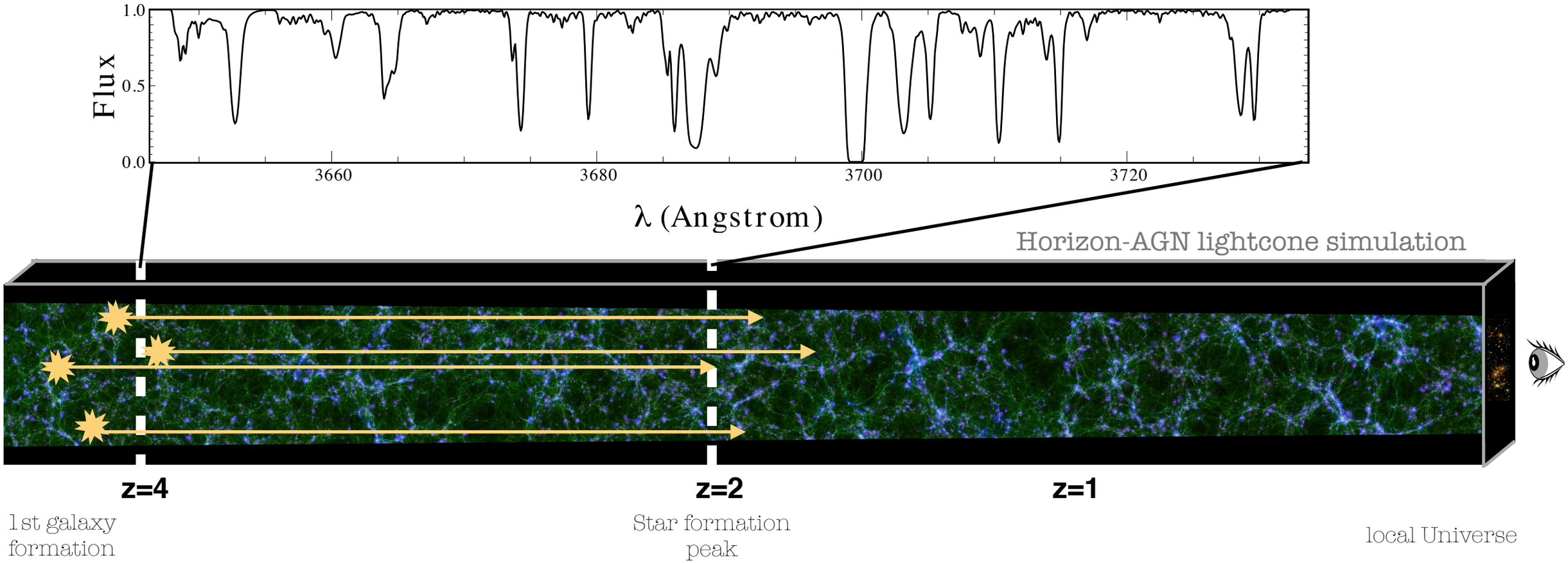


Observing the multi-scale cosmic web

Reconstruction from Lyman-alpha forest

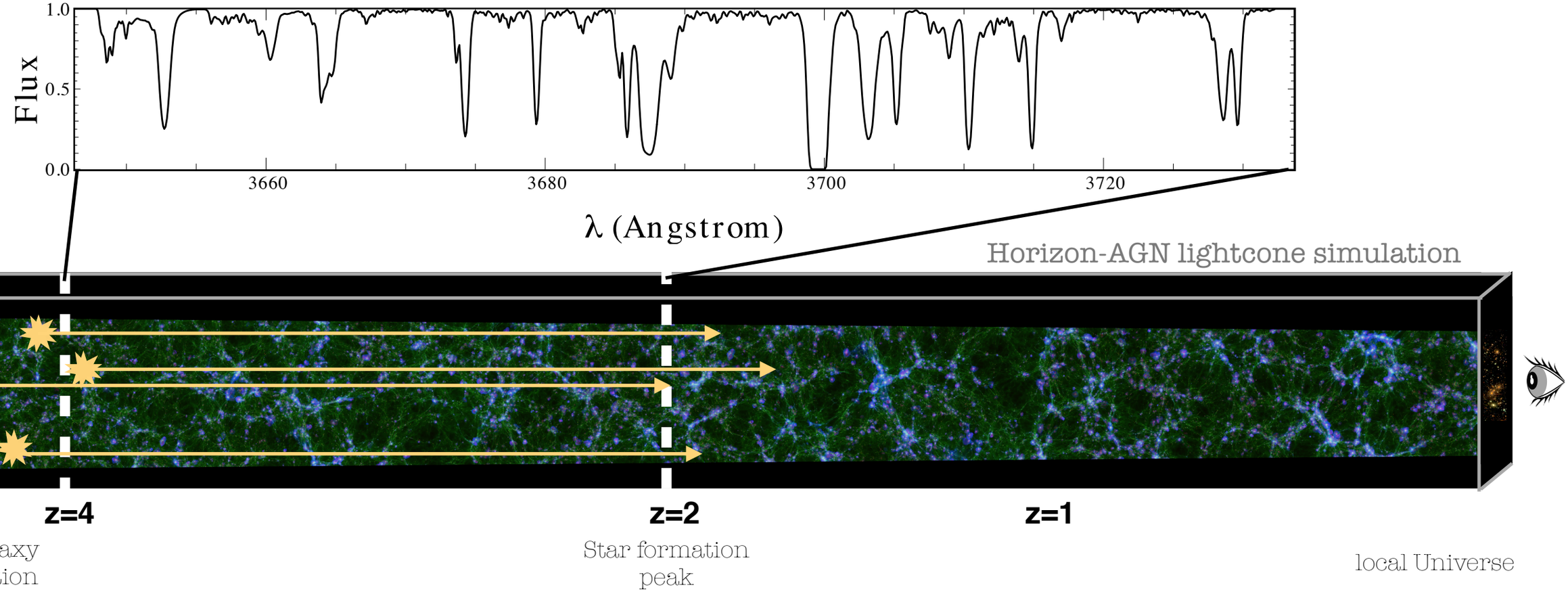


Observing the multi-scale cosmic web

Reconstruction from Lyman-alpha forest

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

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



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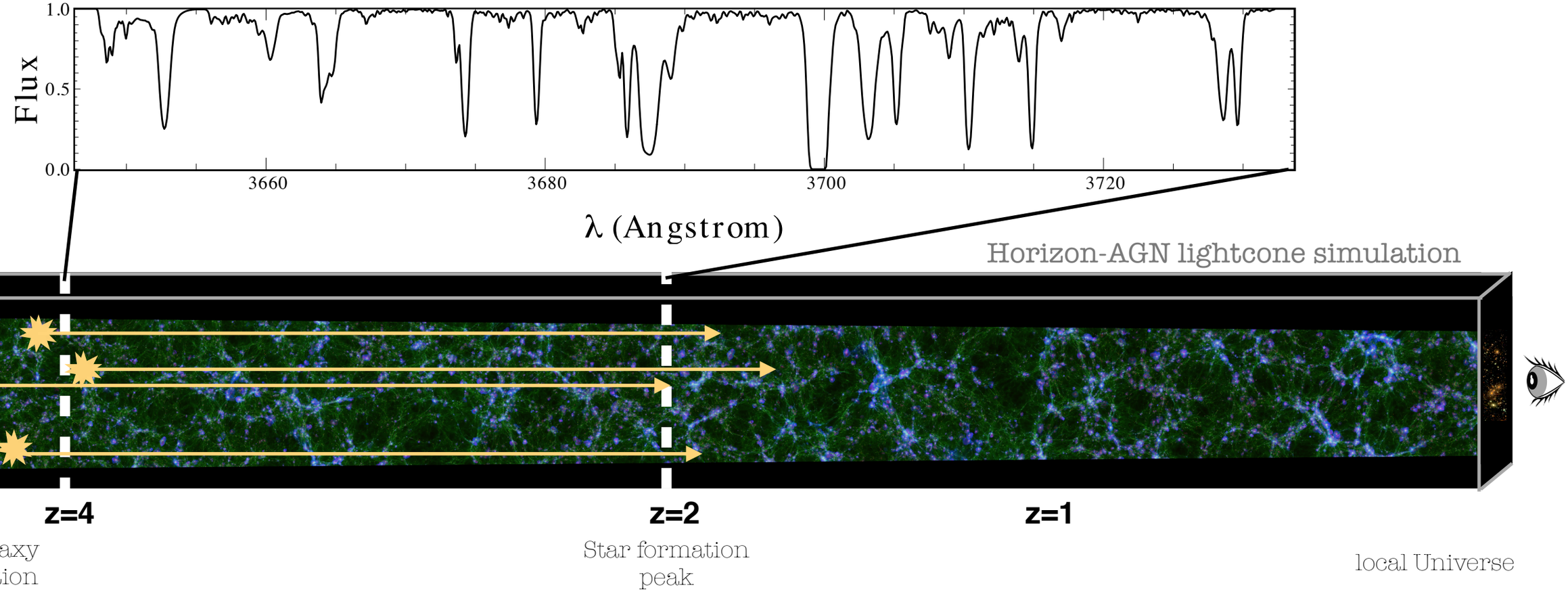
In order to probe the connectivity of the field: 3D reconstruction of the matter distribution

Interpolation between sightlines: Wiener filtering Pichon+01, Caucci+08, Lee+16, Stark+16

see also Cisewski+14, Ozbek+16



Observing the multi-scale cosmic web

Reconstruction from Lyman-alpha forest

$$\mathbf{M} = \mathbf{C}_{\delta \mathbf{3d}\, \delta}(\mathbf{C}_{\delta\delta} + \mathbf{N})^{-1}\mathbf{D}$$

$$\mathbf{C}_{\delta\delta}(x_1, x_2, \mathbf{x_{1T}}, \mathbf{x_{2T}}) = \sigma^2 e^{-\frac{|x_1 - x_2|^2}{2L_x^2}} e^{-\frac{|\mathbf{x_{1T}} - \mathbf{x_{2T}}|^2}{2L_{\mathrm{T}}^2}}$$

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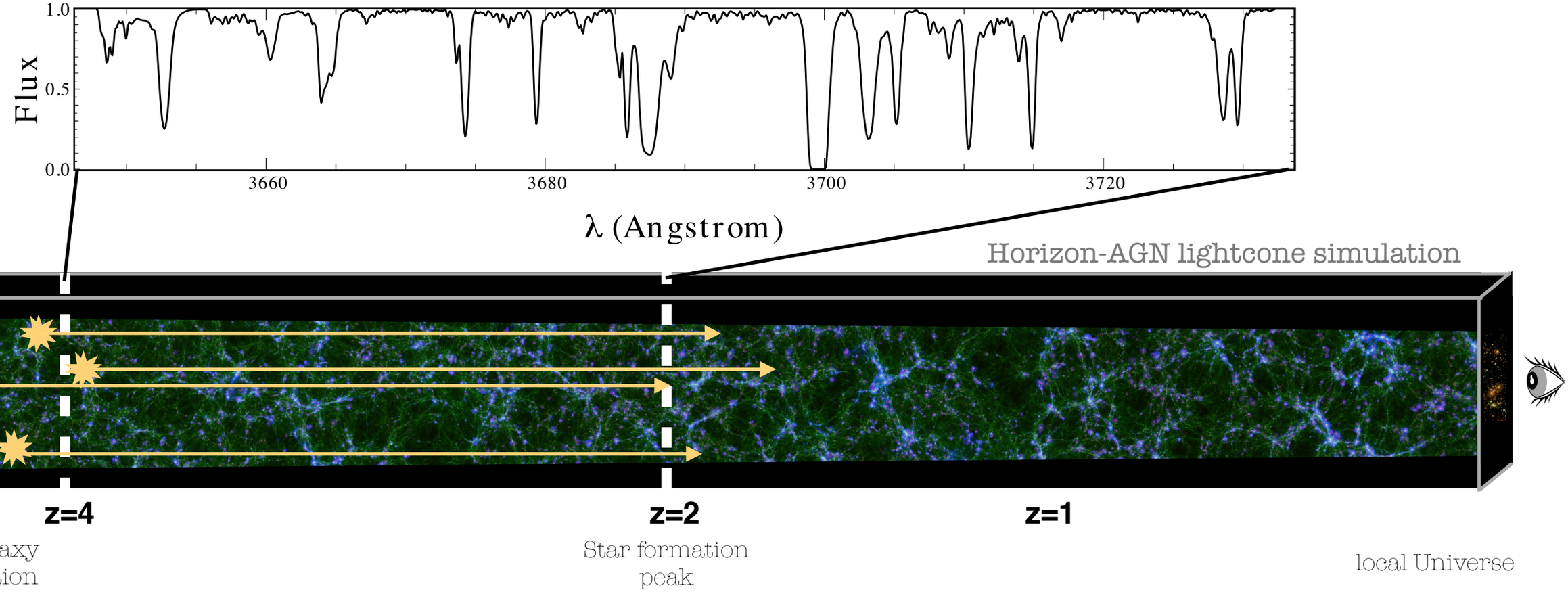

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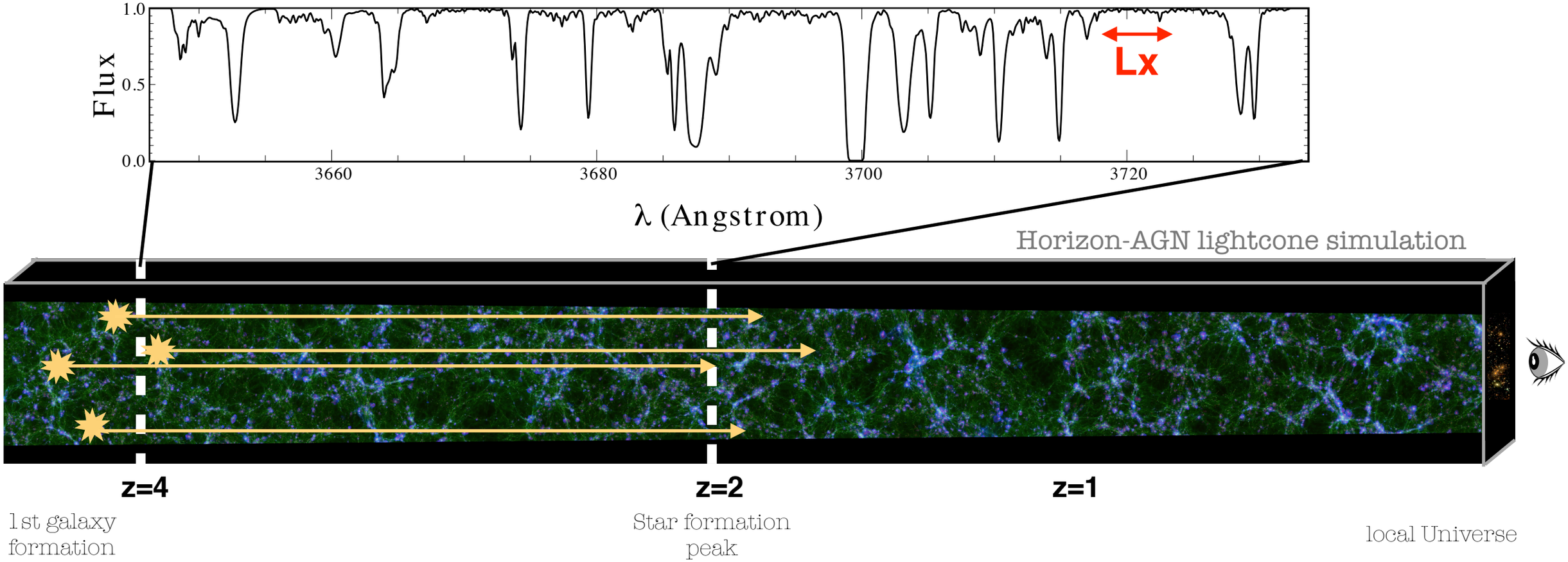

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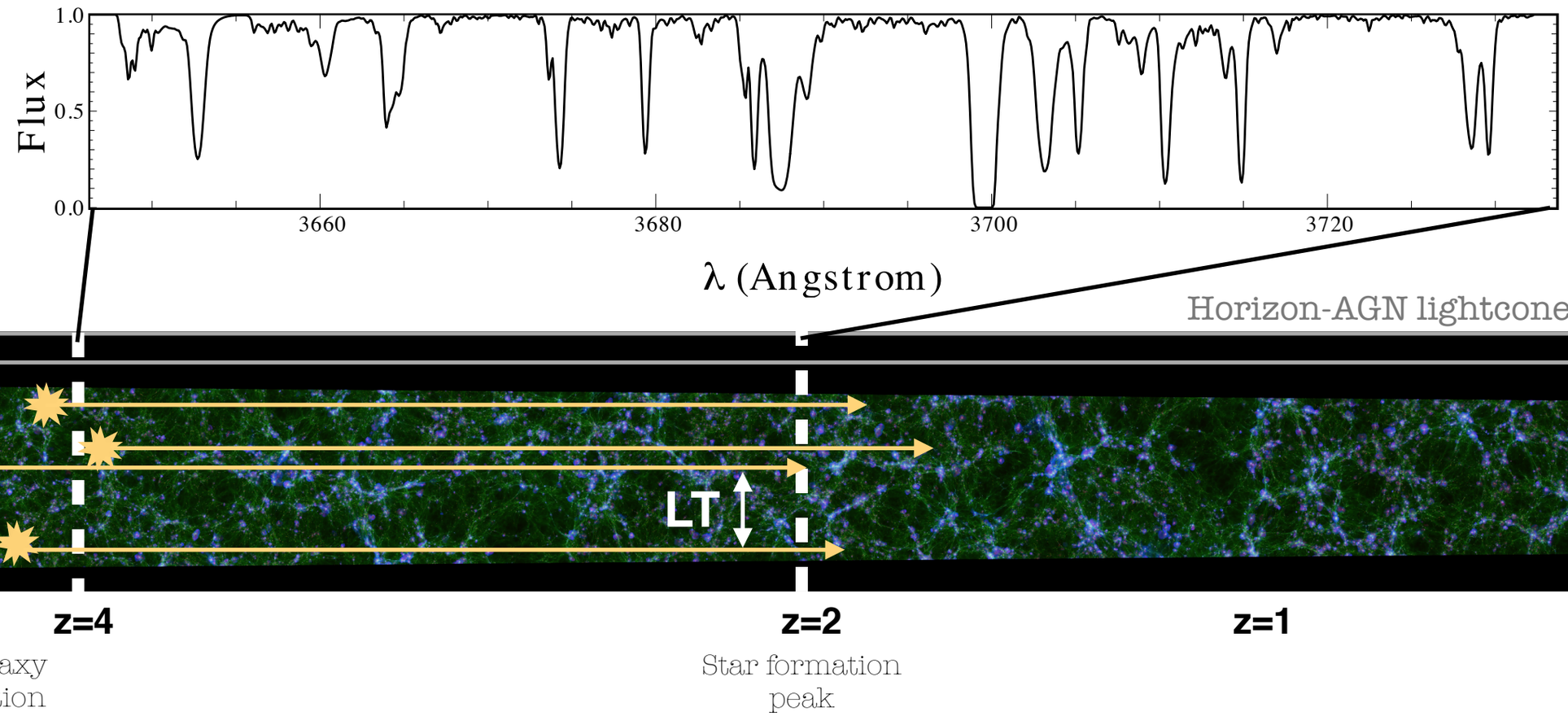
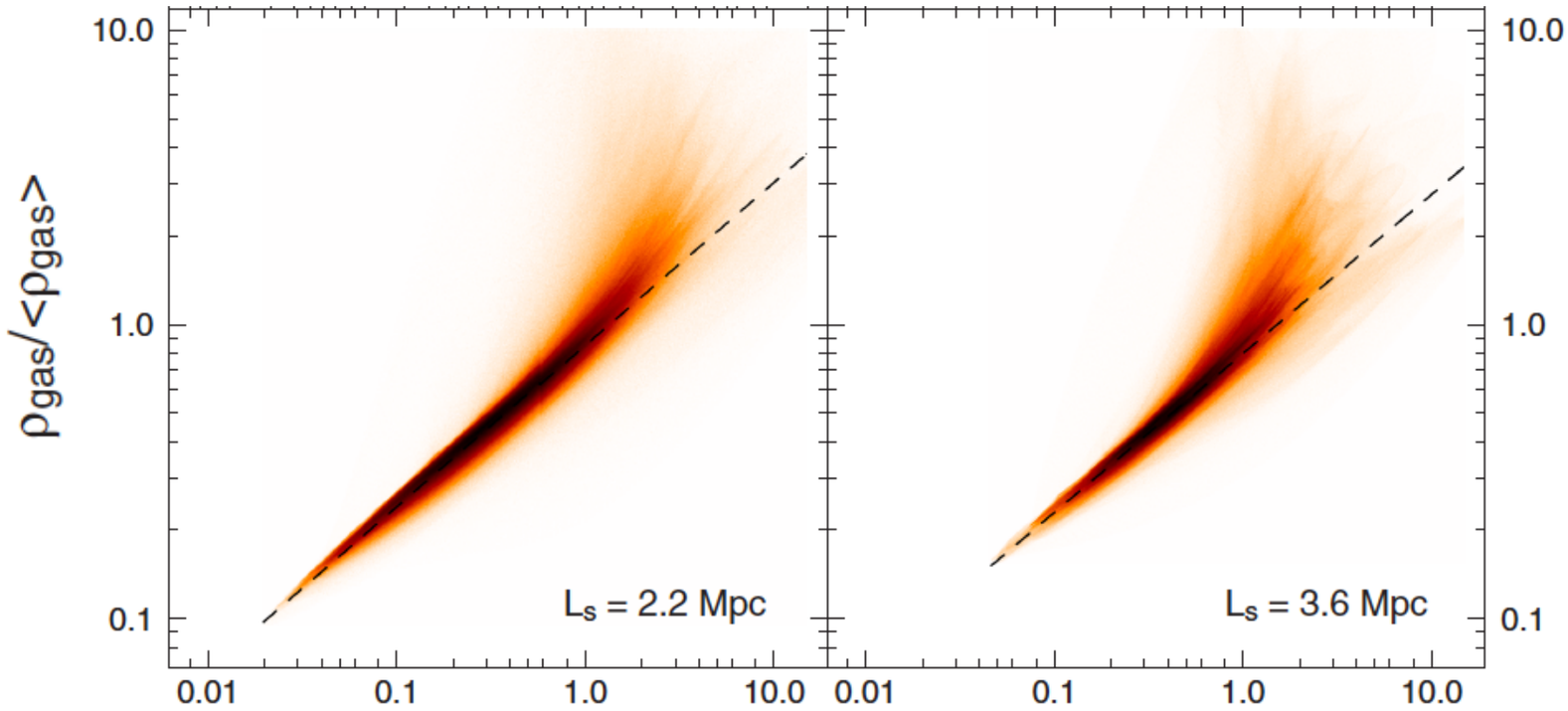


Observing the multi-scale cosmic web

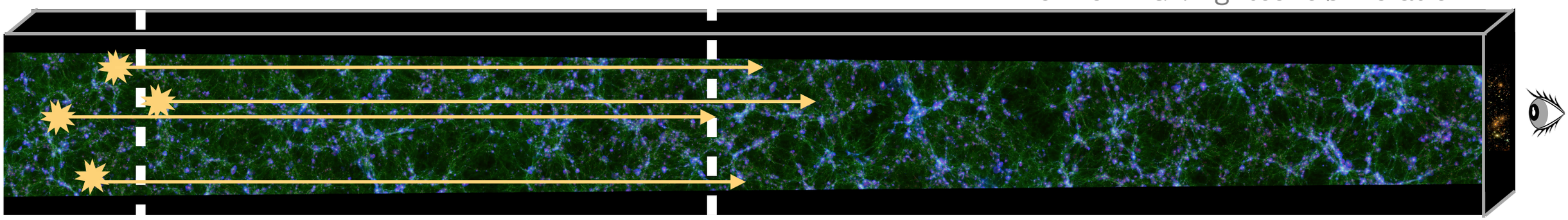
Sources of systematics and noise — 0th order tests

- HI biased tracer of total matter distribution

Caucci et al. 08



Horizon-AGN lightcone simulation



1st galaxy formation

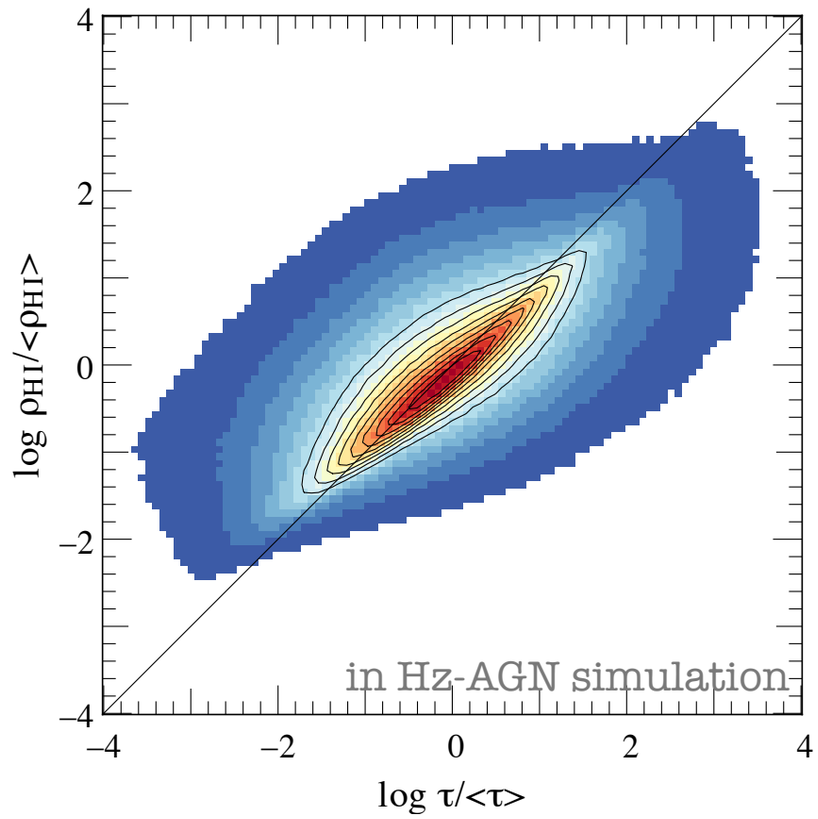
Star formation peak

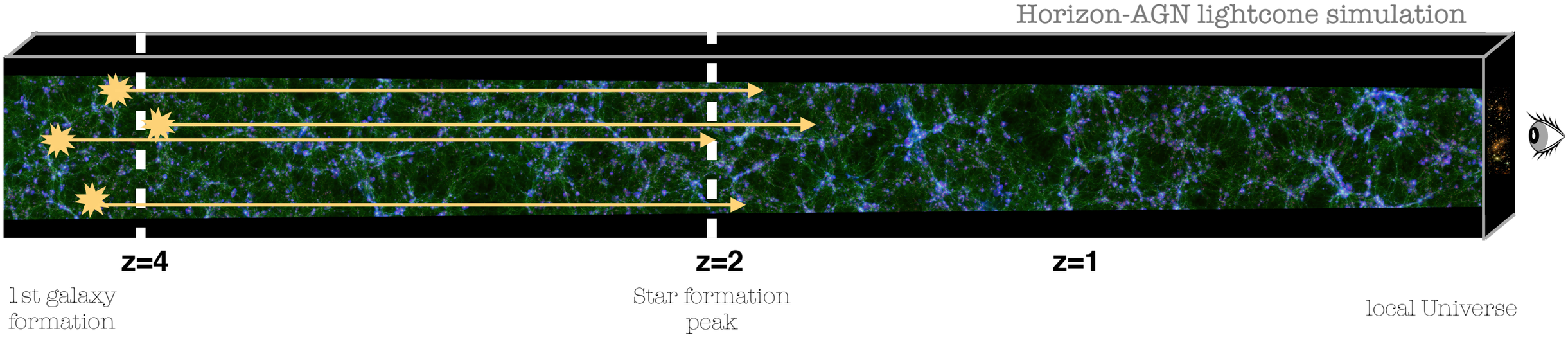
local Universe

Observing the multi-scale cosmic web

Sources of systematics and noise — 0th order tests

- Reconstruction better performed on log(Flux)

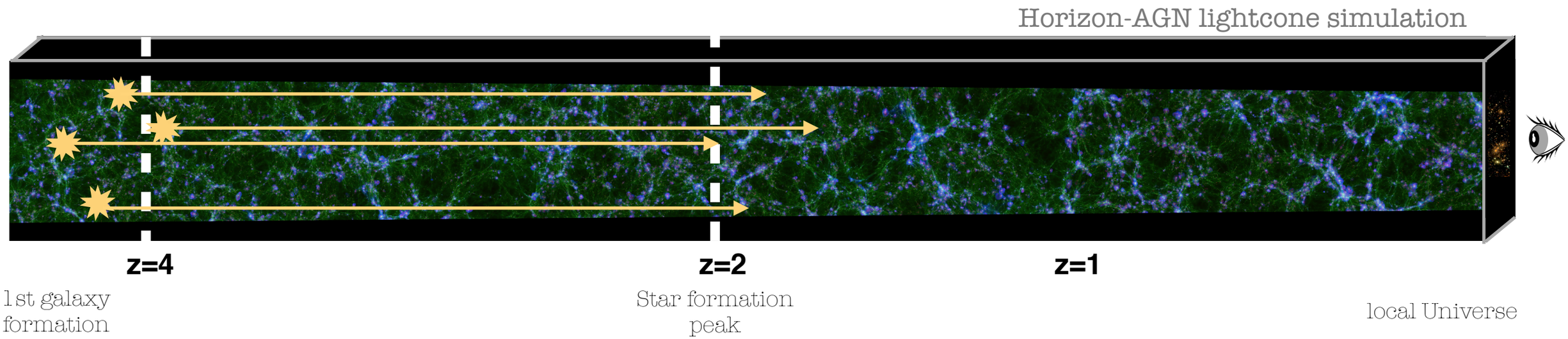




Observing the multi-scale cosmic web

Sources of systematics and noise — 0th order tests

- Reconstruction better performed on log(Flux)
- Finite resolution on spectra ➡ minimal longitudinal smoothing scale
- Finite number of sightlines ➡ minimal transverse smoothing scale



Observing the multi-scale cosmic web

Sources of systematics and noise — 0th order tests

- Reconstruction better performed on log(Flux)
- Finite resolution on spectra ➔ minimal longitudinal smoothing scale
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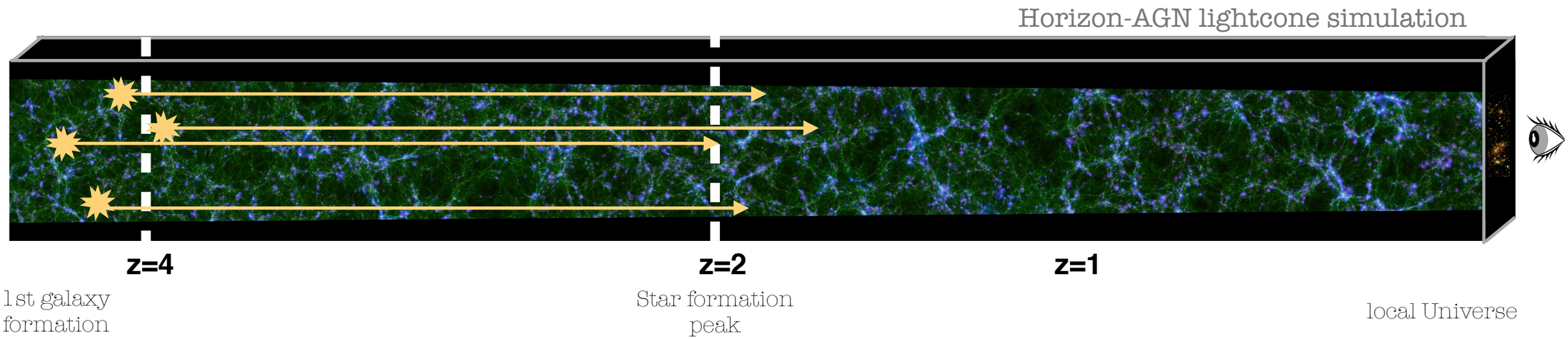
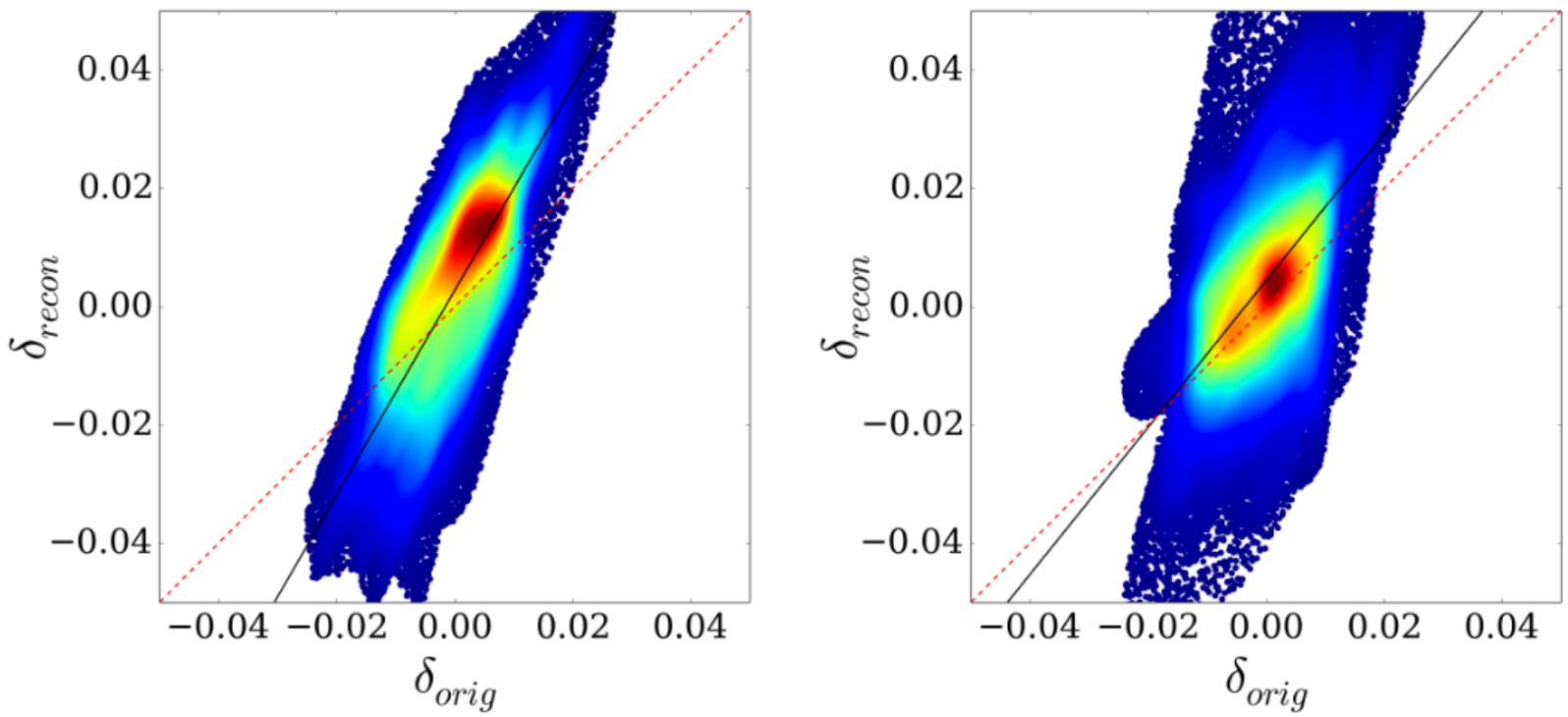
- Inhomogeneous coverage ➔ shot noise. Larger impact on over-densities
- Noise on spectra and saturated regions



Observing the multi-scale cosmic web

Sources of systematics and noise — 0th order tests

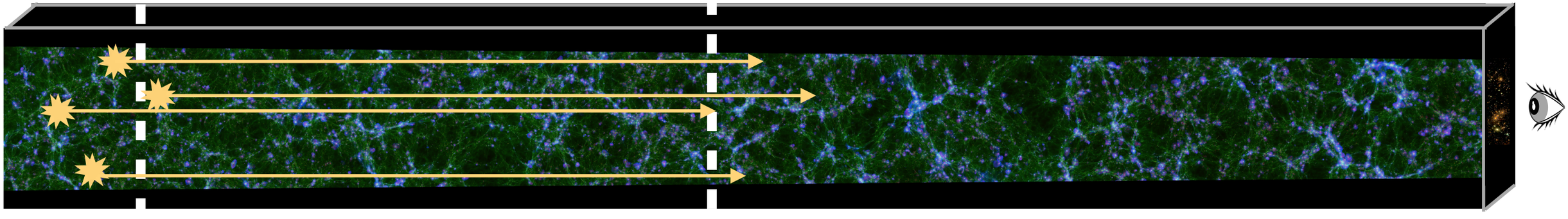
Ozbek et al. 16



(a) $z = 2$, $N_{\rm LOS} = 200$, Noiseless

(b) $z = 2$, $N_{\rm LOS} = 200$, S/N=2

Horizon-AGN lightcone simulation



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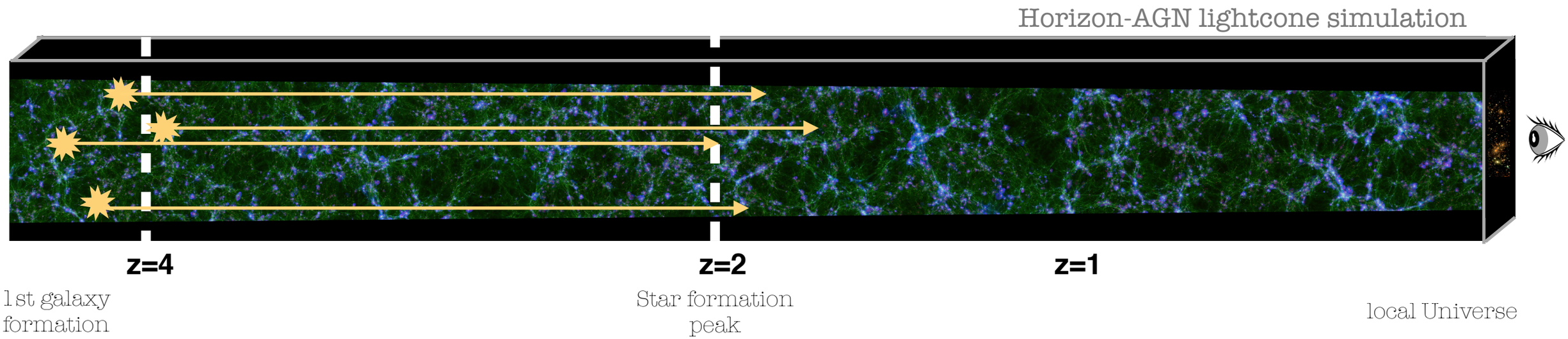
- Noise on spectra and saturated regions
- Baryonic physics: AGN feedback

End-to-end simulations required to make accurate forecasts for HI reconstruction

Realistic background source distribution — Realistic HI foreground — Realistic noise implementation

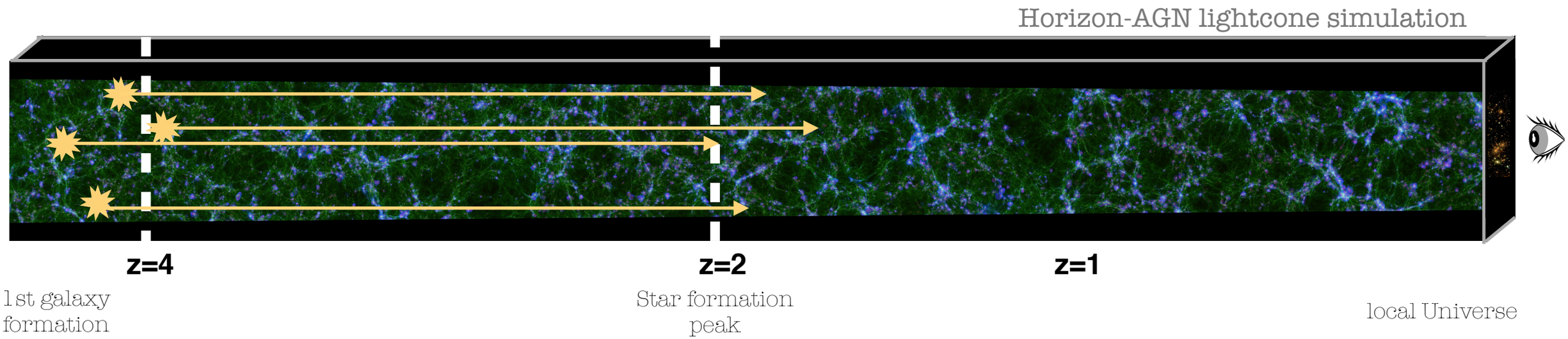


Observing the multi-scale cosmic web

End-to-end simulation

The Horizon-AGN suite (DM, AGN, noAGN) Dubois et al. 14

- Hydrodynamical simulation run with RAMSES on a cosmological volume (100 Mpc/h, finest cell 1kpc) +lightcone (1 deg)
- star formation, stellar winds, SNII, SNIa, and AGN feedback (radio/quasar)
- Gas cooling and UV background heating (uniform UV background, Haardt and Madau+96)



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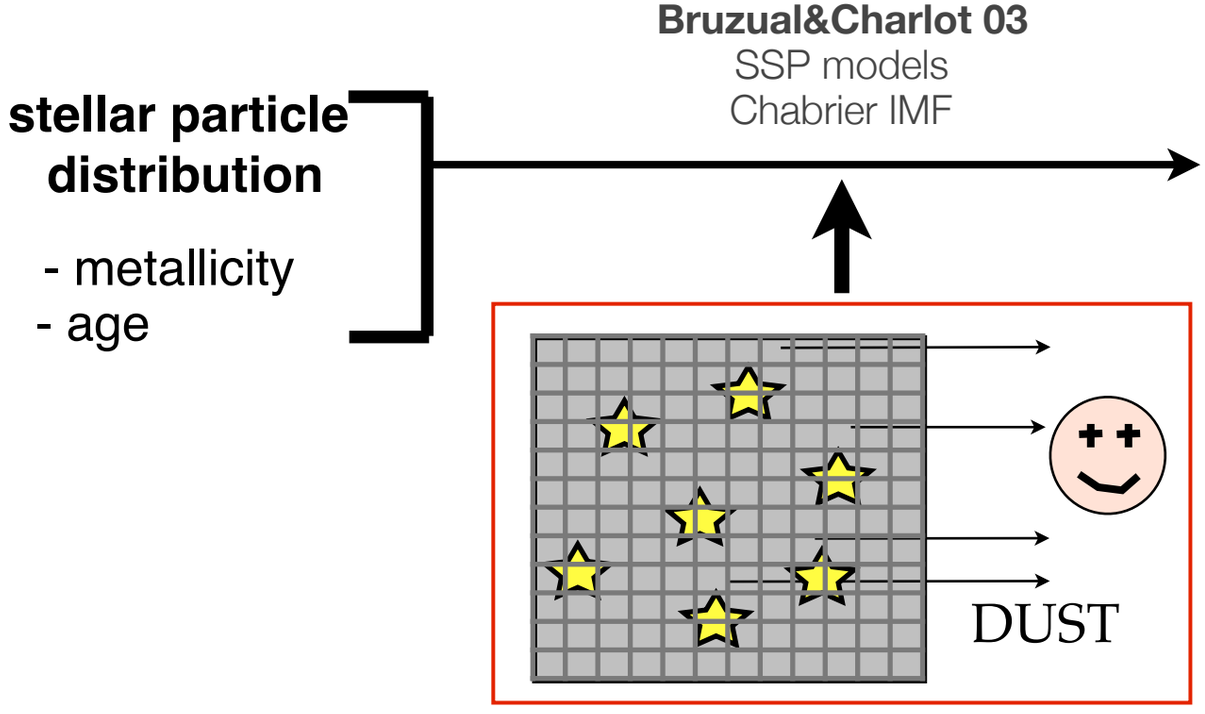
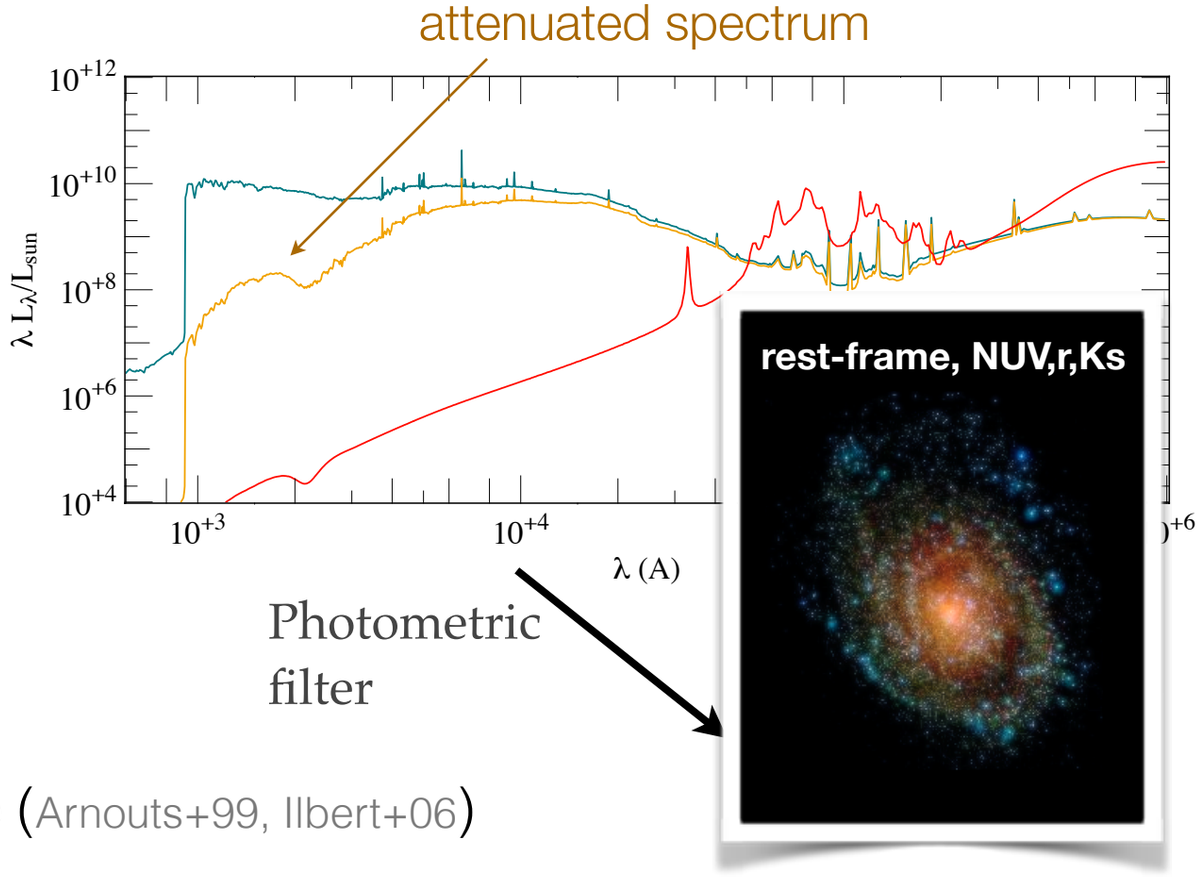
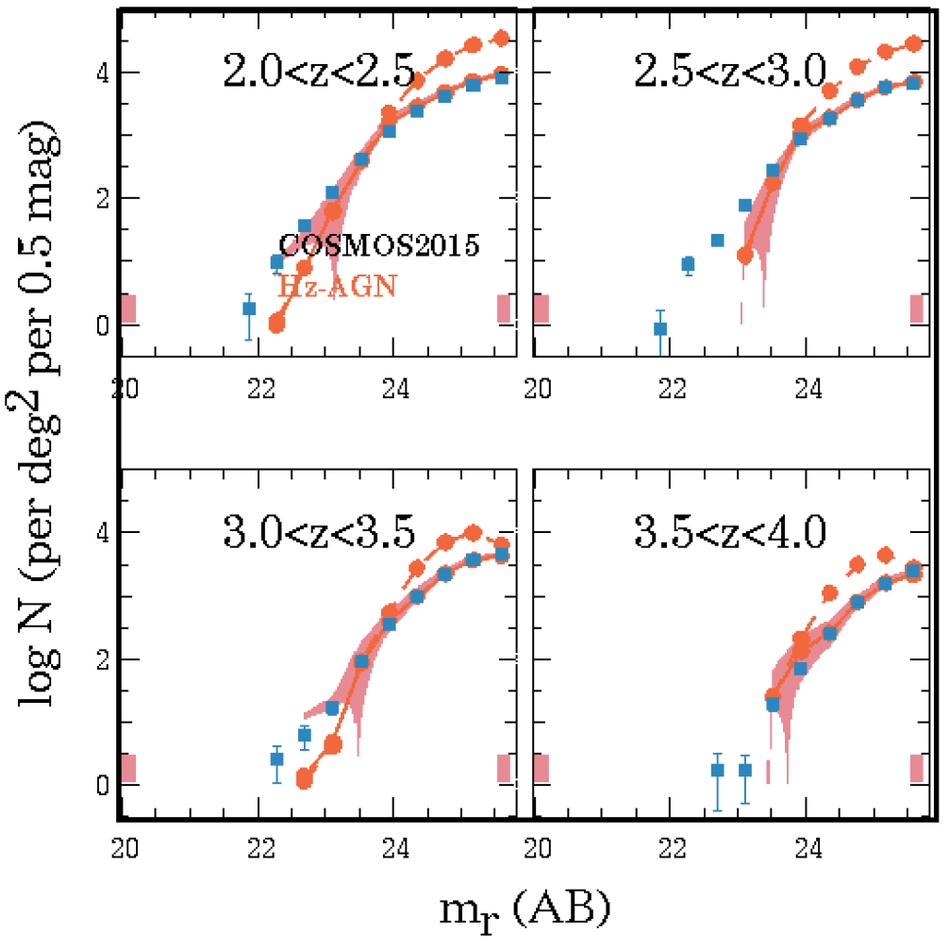




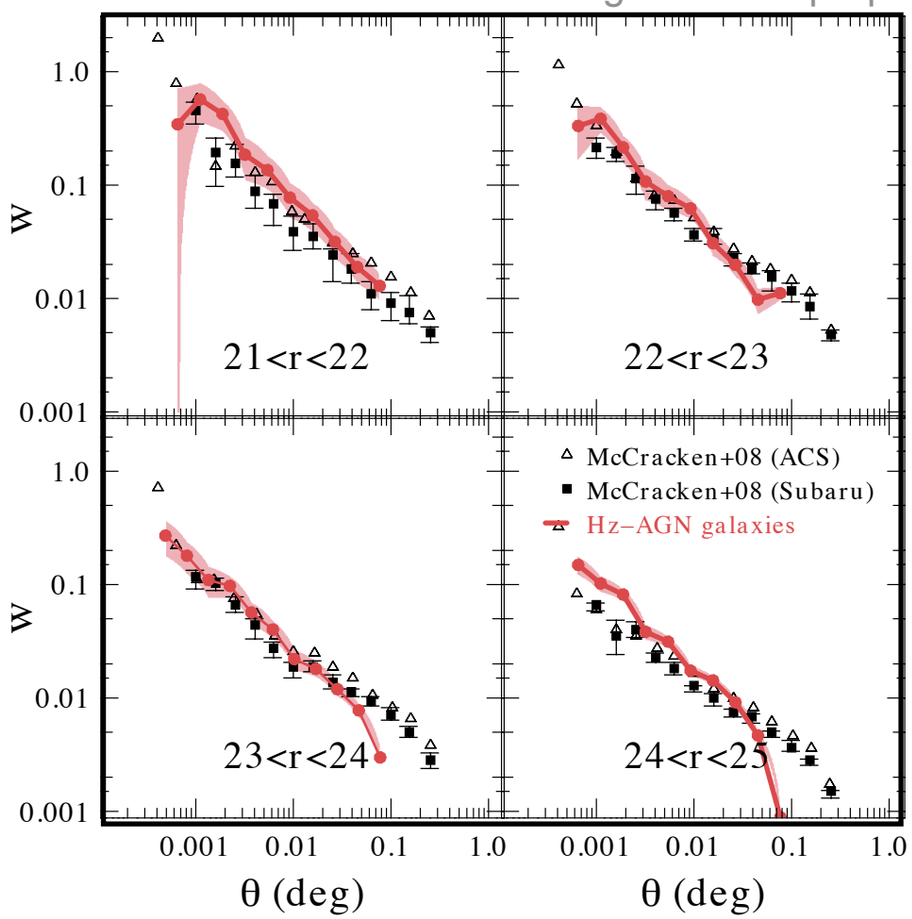
- Photometric redshifts derived with LePhare (Arnouts+99, Ilbert+06)

Observing the multi-scale cosmic web

End-to-end simulation



Laigle et al. in prep



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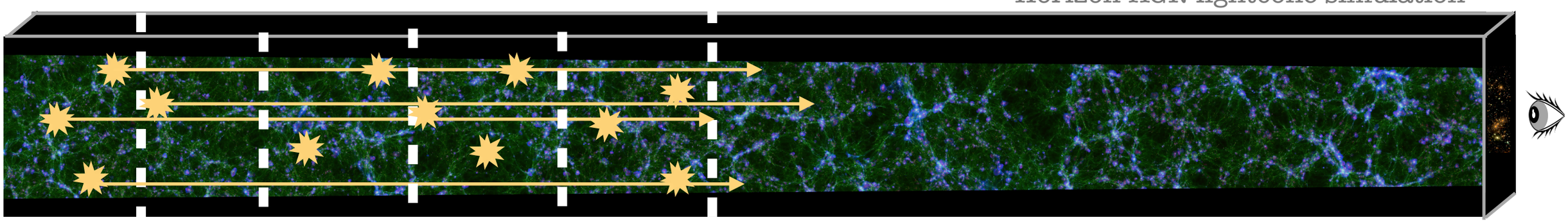

Observing the multi-scale cosmic web

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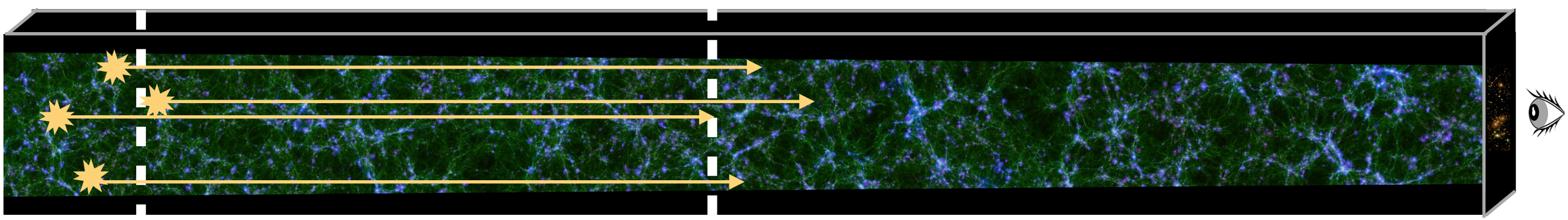
- star formation, stellar winds, SNII, SNIa, and AGN feedback (radio/quasar)
- Gas cooling and UV background heating (uniform UV background, Haardt and Madau+96)
- HI density: balance between photoionisation, collisional ionization and recombination (Black+81)

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

Larger scale HI simulations: see also Peirani+14, Lochhaas+16, Sorini+16, Ozbek+16



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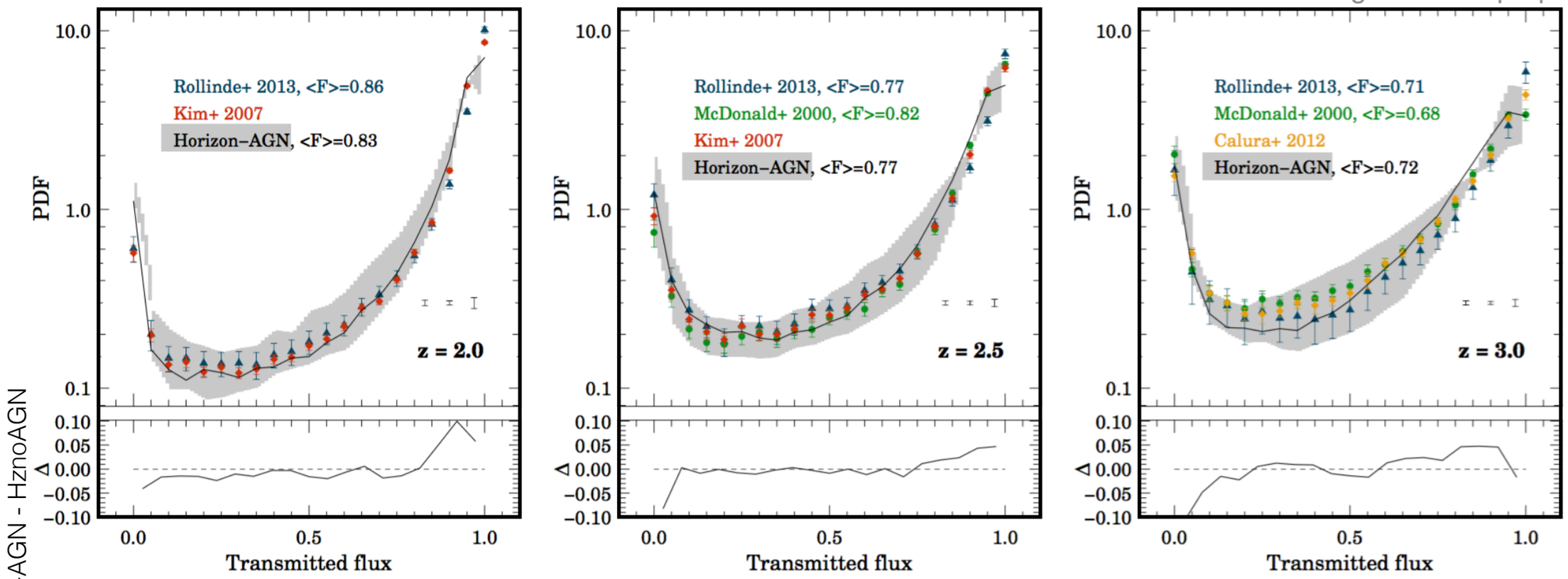
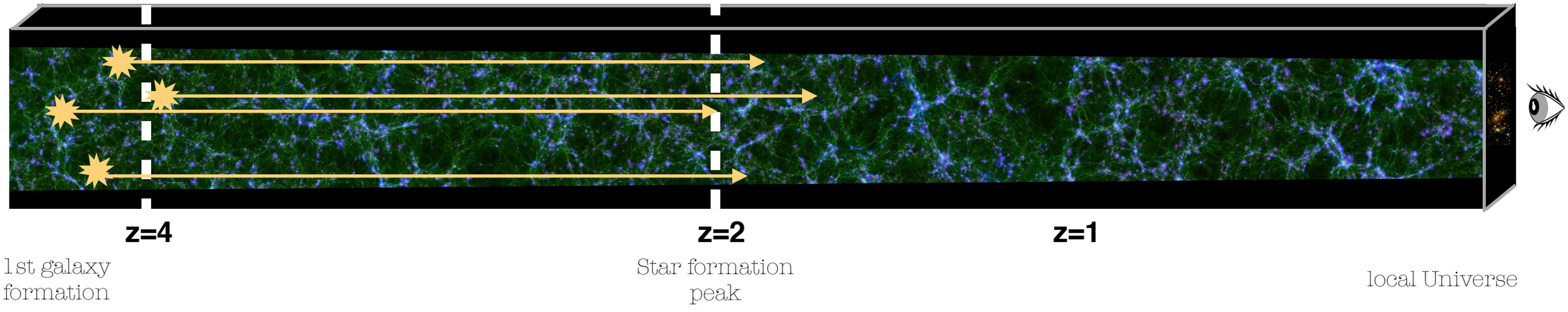


Impact of AGN feedback relatively small on the PDF of the flux: need for higher order statistics

see also e.g. Viel+12,13, Nasir+17, M. Brush's talk

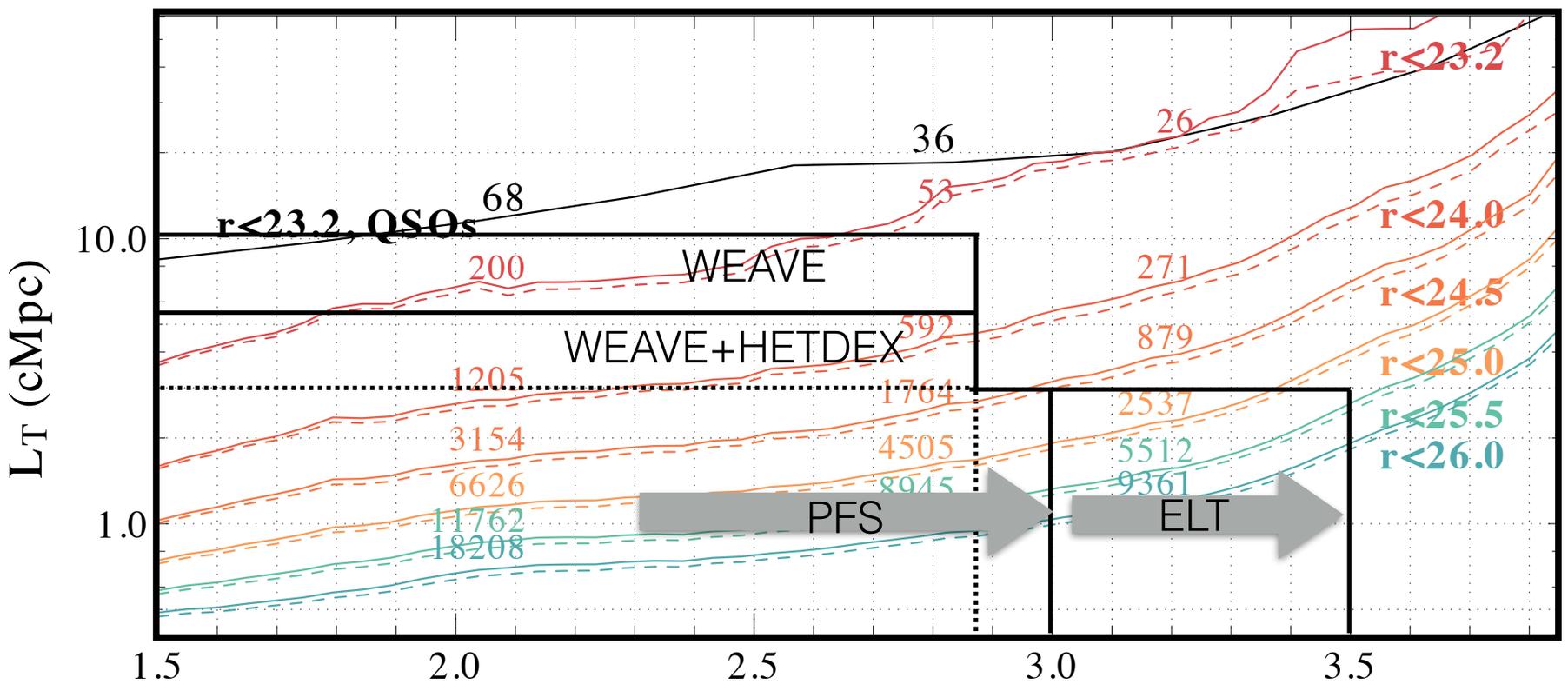
see also Lucik+15 for a convergence study



Observing the multi-scale cosmic web

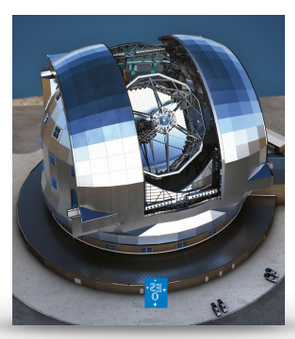
0th-order forecasts

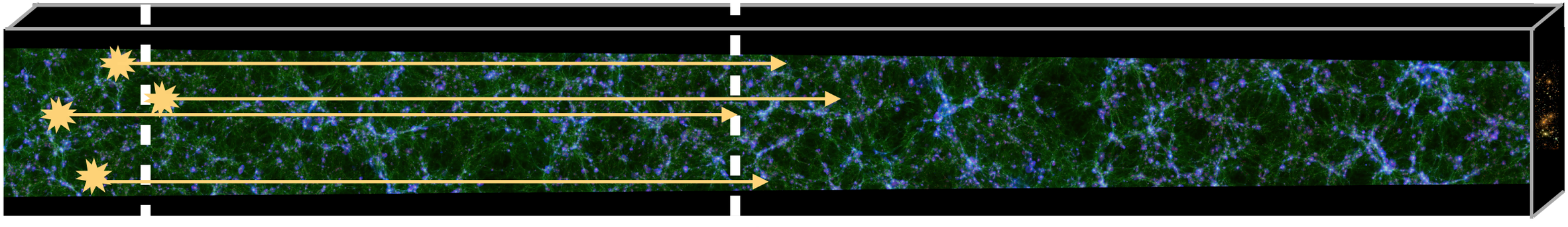
Predictions for GLOBAL reconstruction (Ly-alpha only)



PFS/subaru

ELT





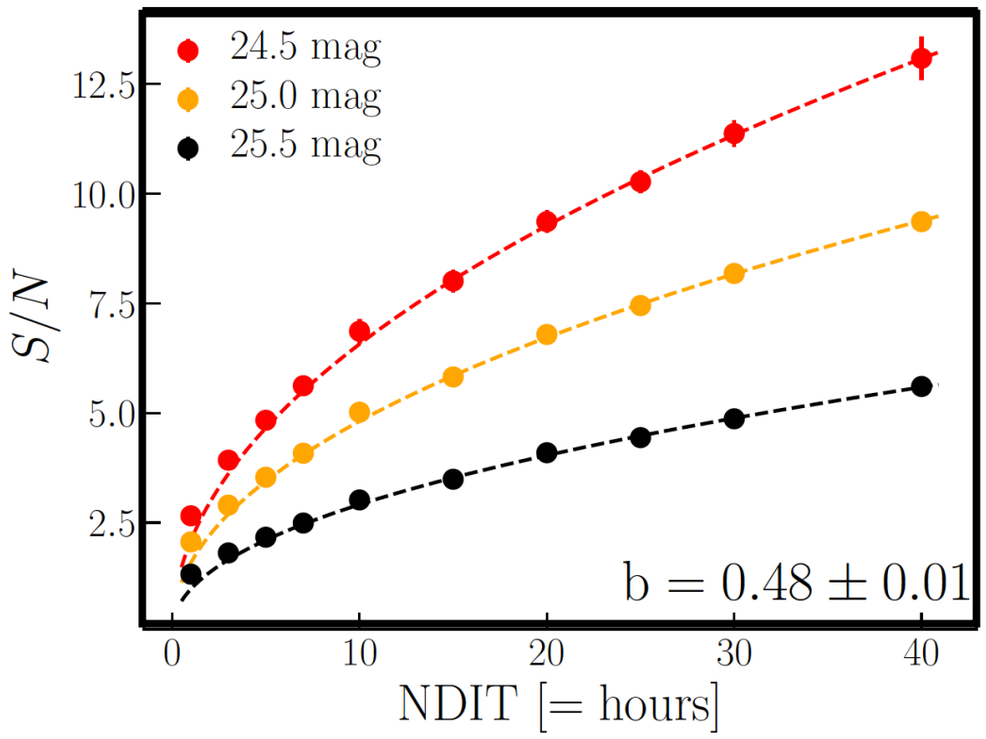
Observing the multi-scale cosmic web

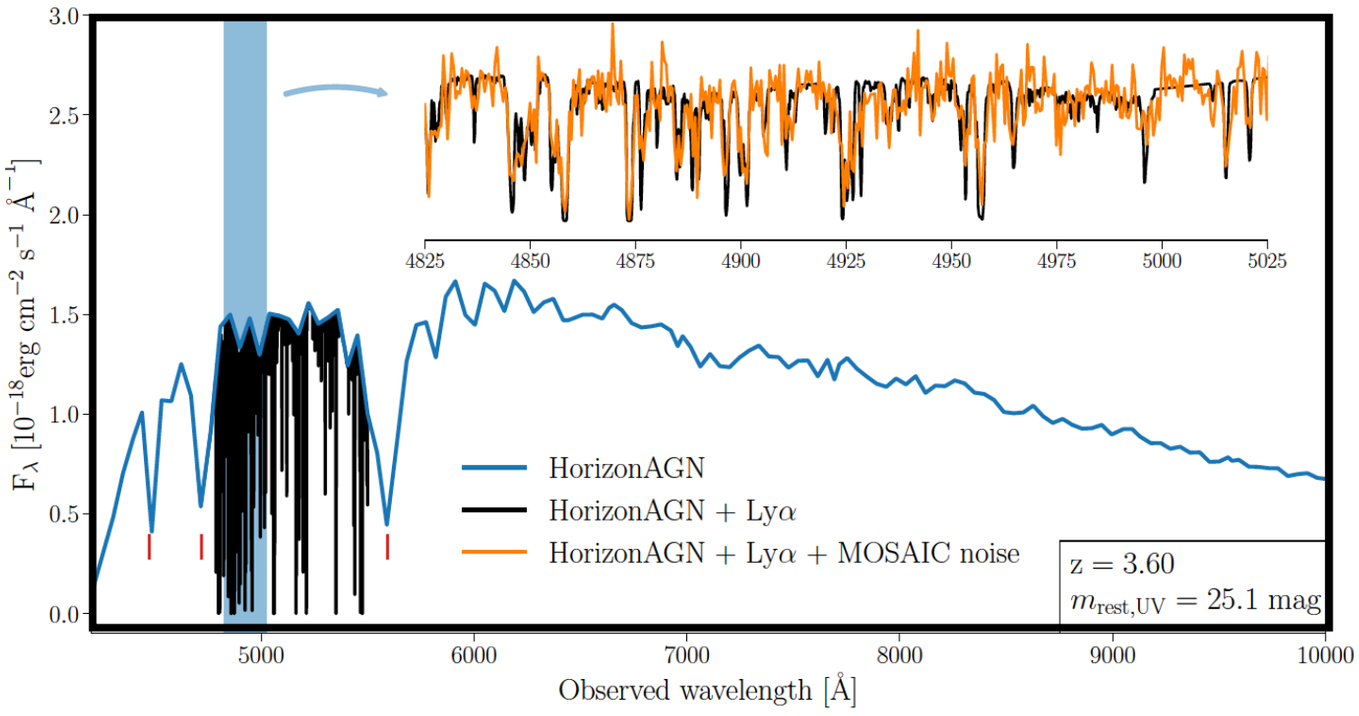
Forecasts for MOSAIC/ELT

Japelj, Laigle, Puech et al. in prep

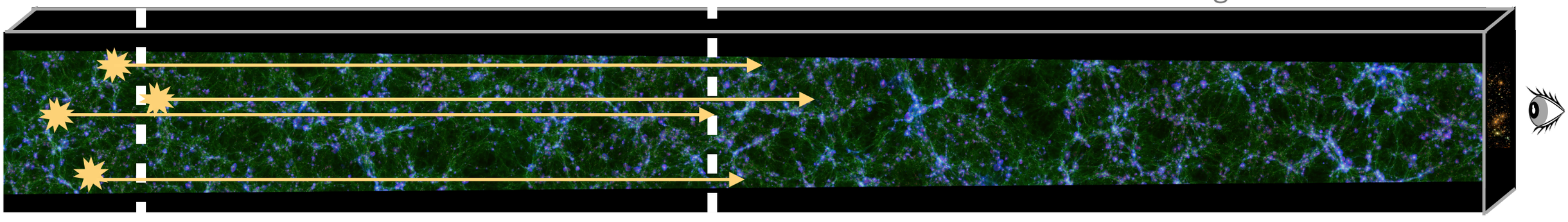
WEBSIM-COMPASS (Puech+10,+16)

in VIFU mode, R=5000 and <S/N>=5





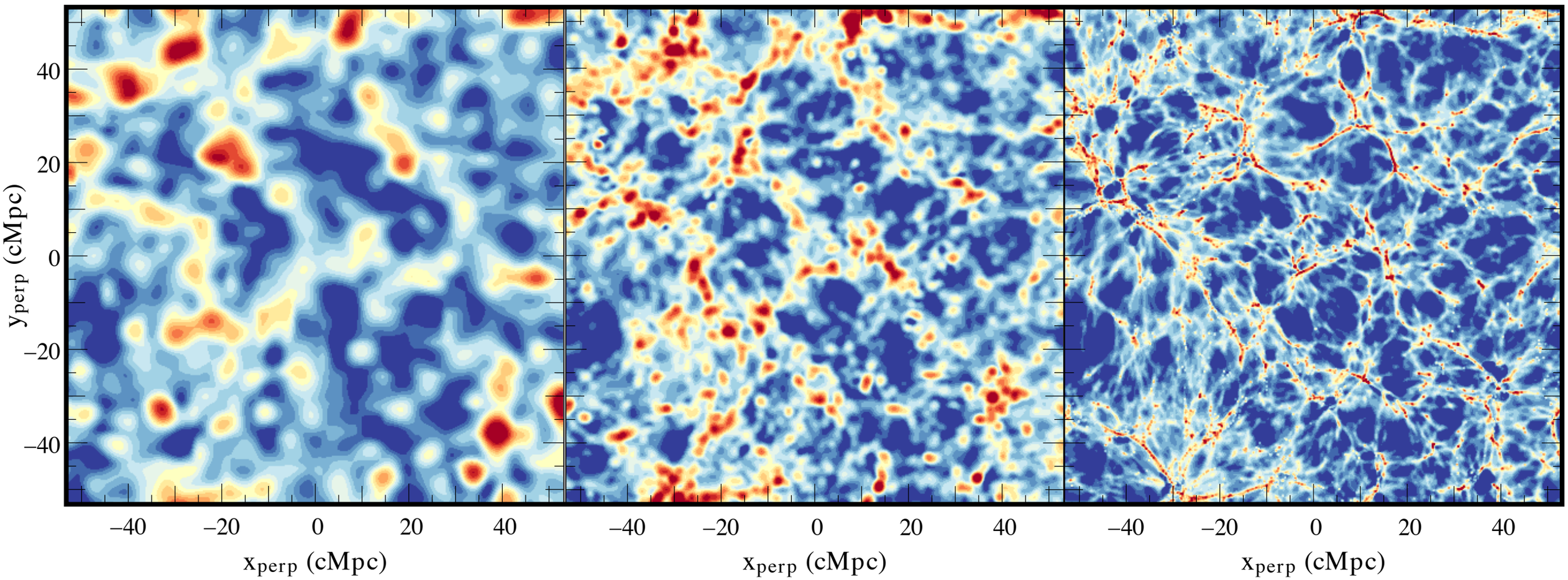
Horizon-AGN lightcone simulation



Observing the multi-scale cosmic web

Reconstruction

Laigle et al. in prep
see also e.g. Lee, White+16, Krolewski+17, Ozbek+16

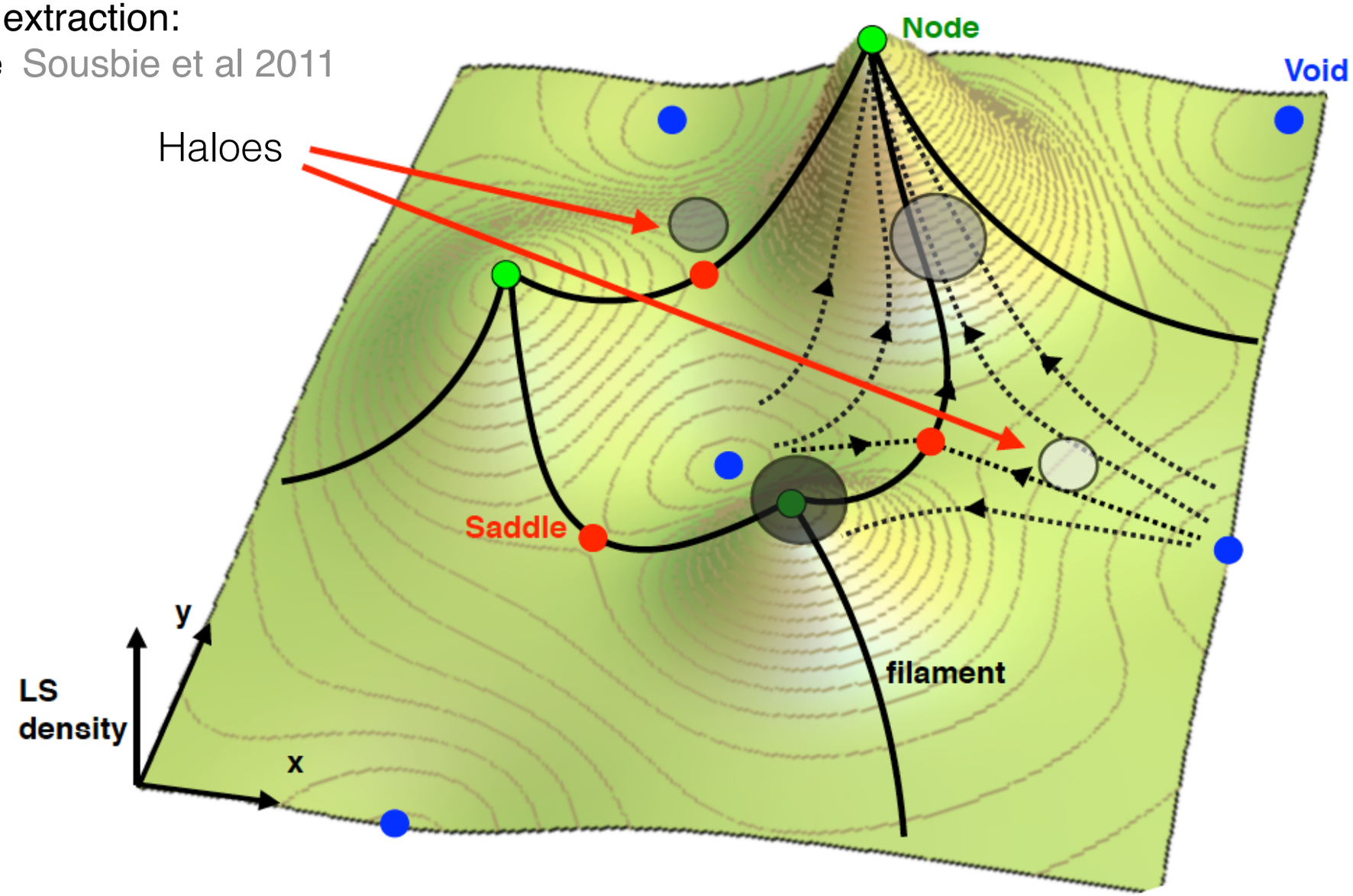


- How different are the original and reconstructed sets of cosmic filaments?
- Is the reconstructed skeleton still reliable for galaxy evolution/cosmology studies?

Observing the multi-scale cosmic web

Reconstruction of the global skeleton

Skeleton extraction:
Disperse Sousbie et al 2011



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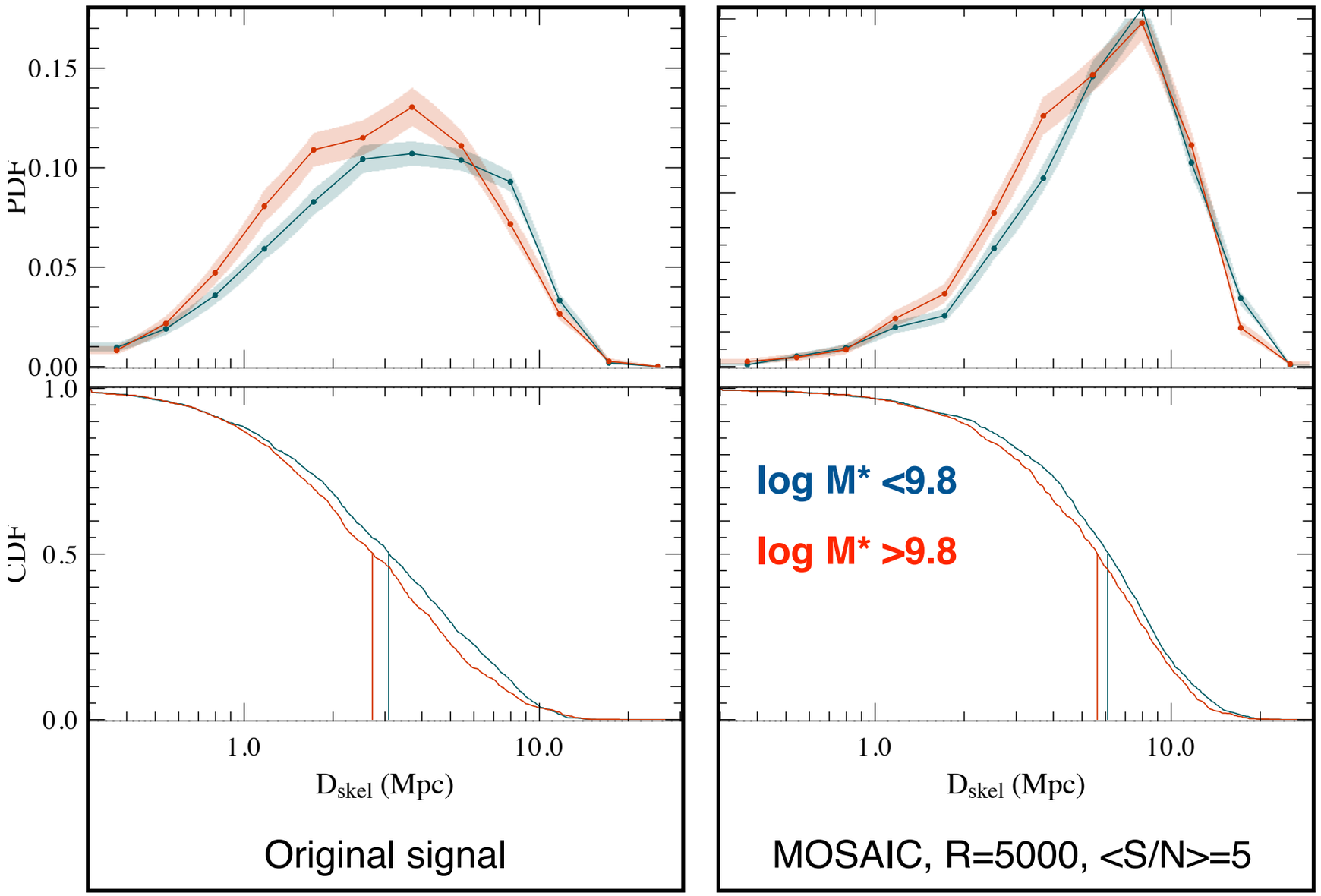
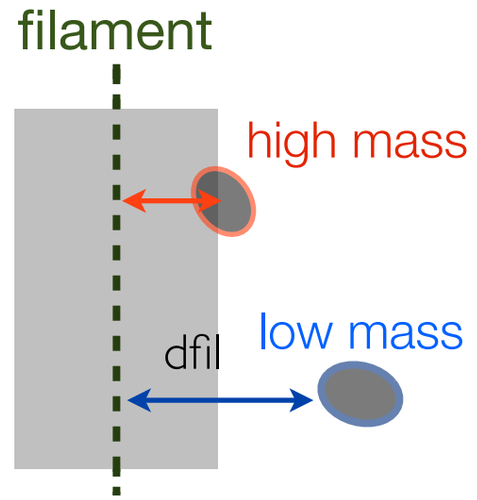
Observing the multi-scale cosmic web

Reconstruction of the global skeleton



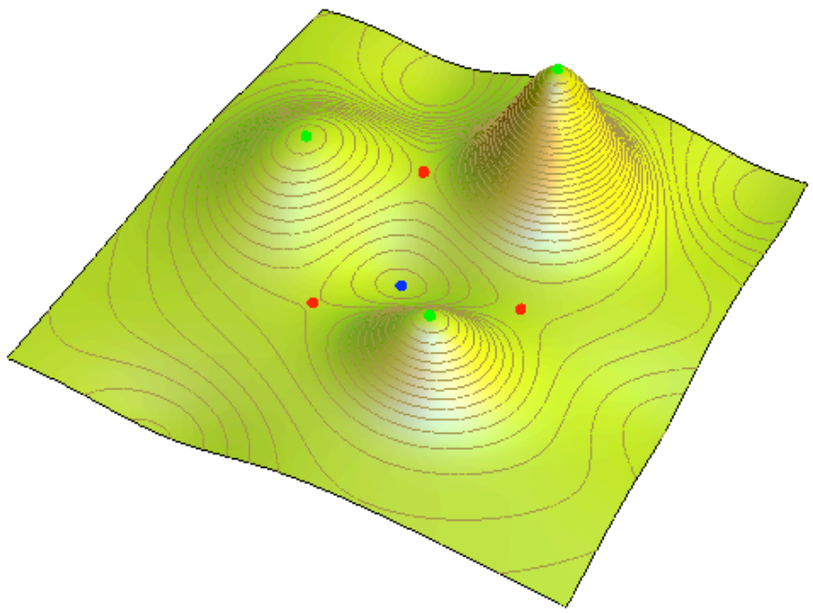


Segregation of galaxies in filaments is recovered from tomography

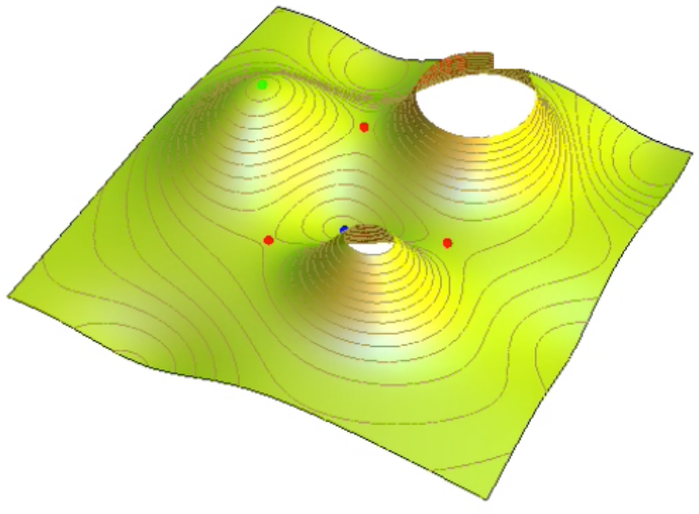
Observing the multi-scale cosmic web

Connectivity of the isocontour: genus

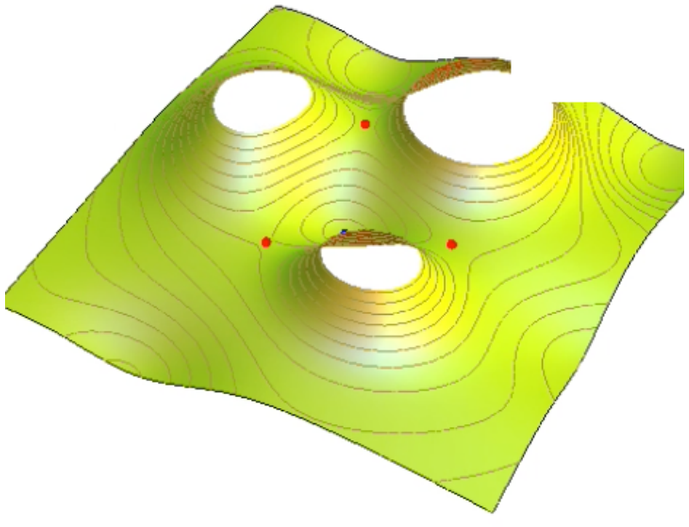
Genus = number of holes - number of isolated components -1



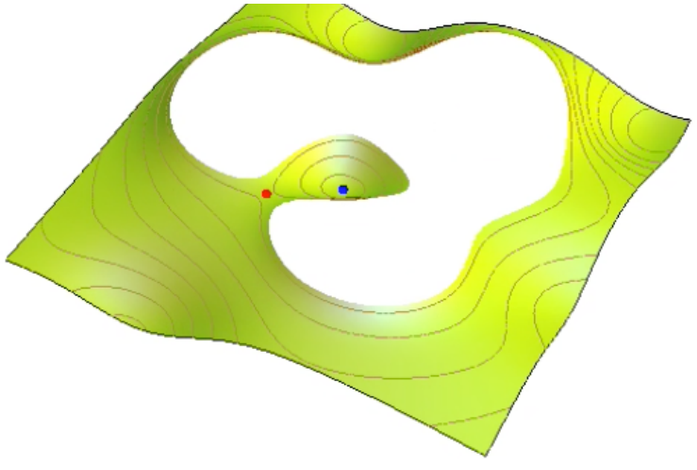
Genus = 0



Genus = 2



Genus = -1



Observing the multi-scale cosmic web

Connectivity of the isocontour: genus

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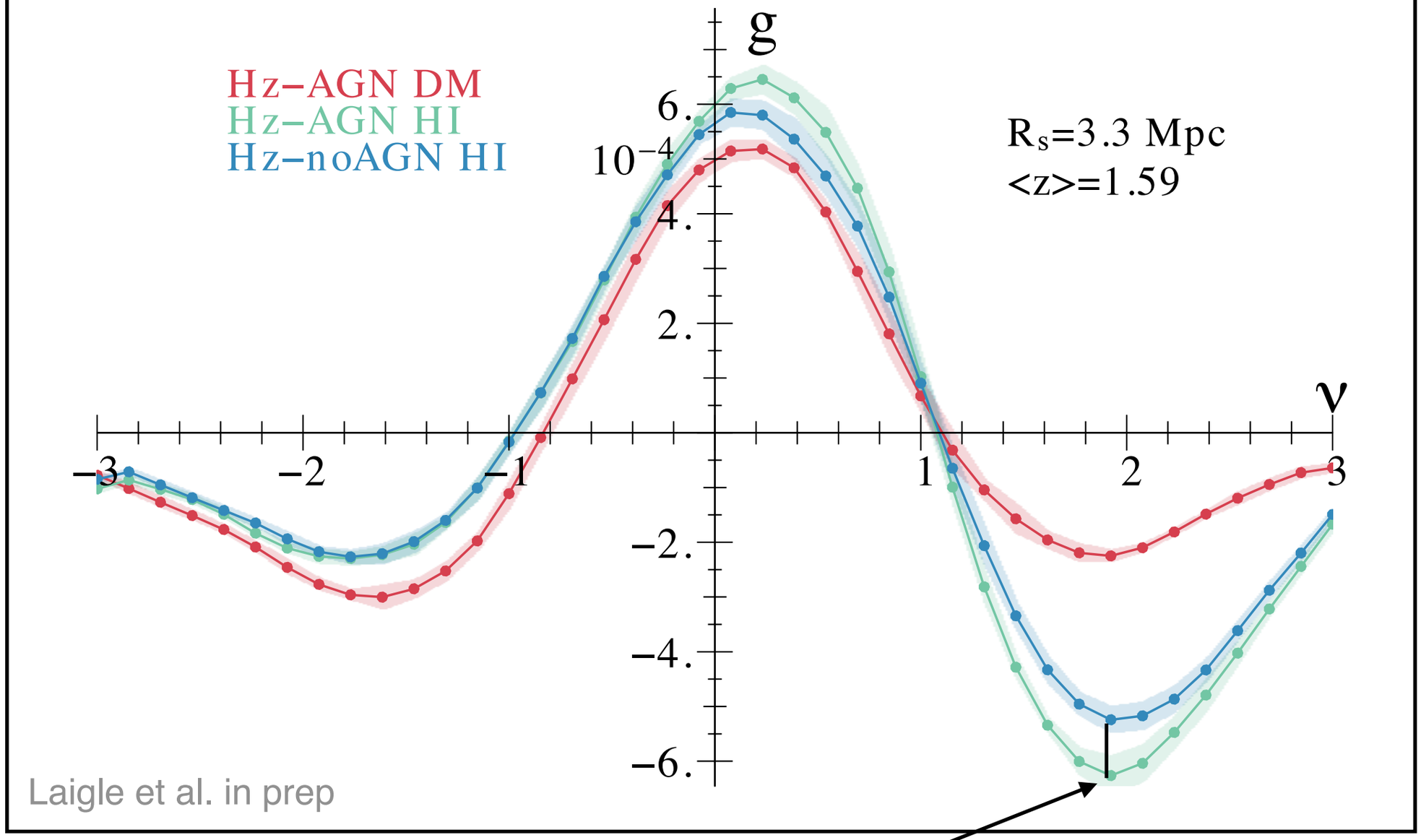
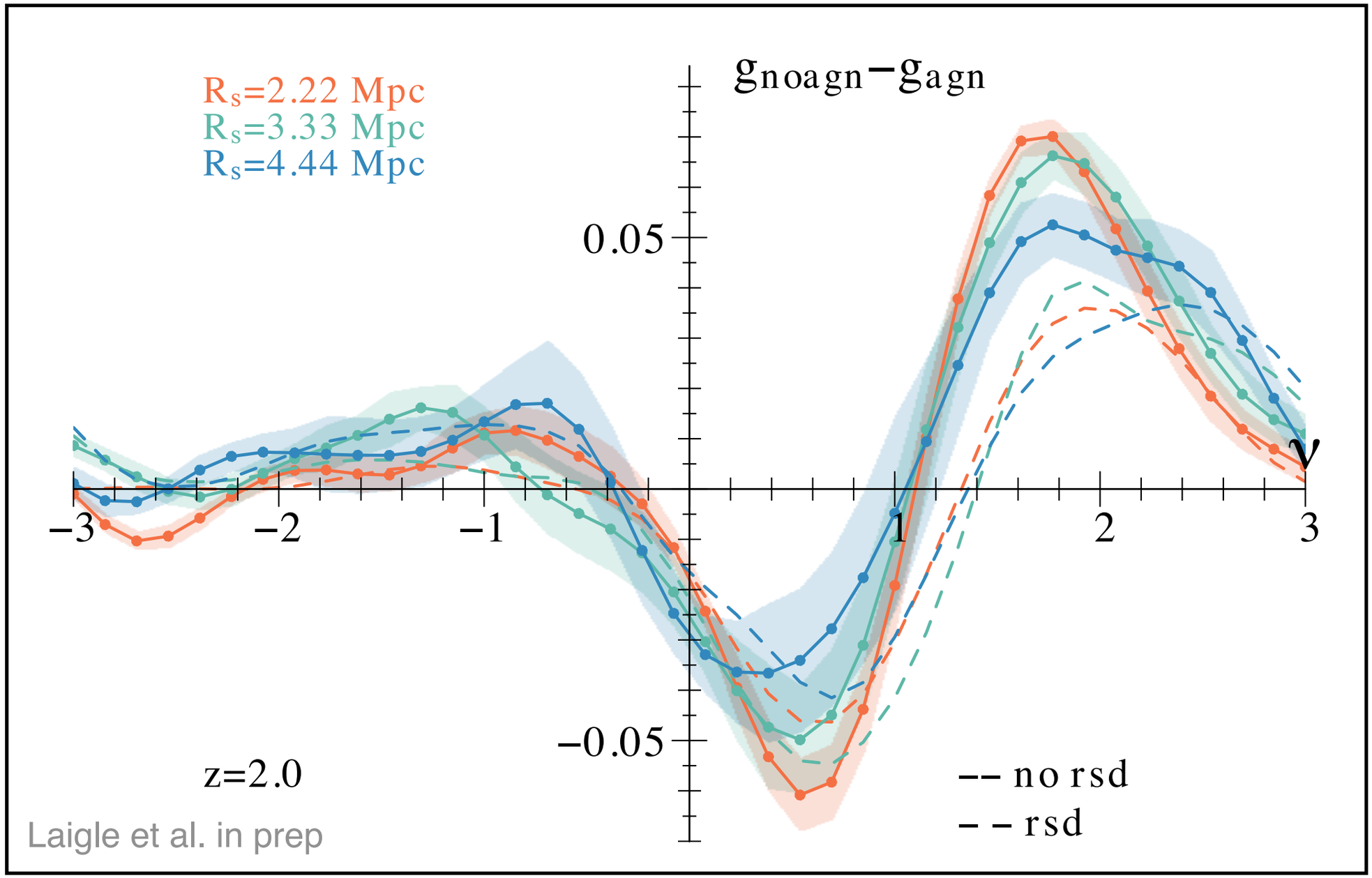


imprint of AGN feedback

Observing the multi-scale cosmic web

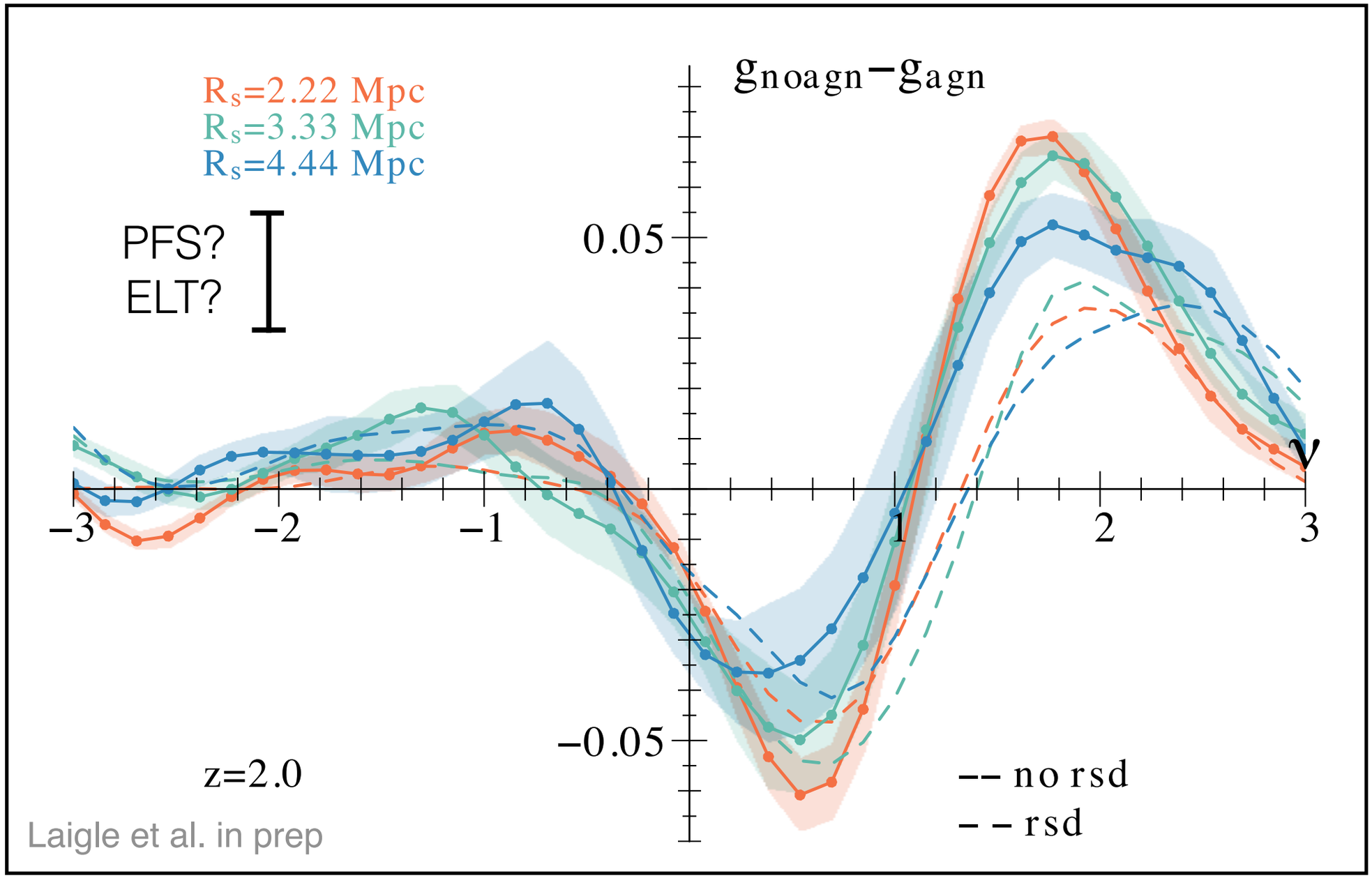
Connectivity of the isocontour: genus



The impact of AGN feedback on genus is lower with redshift-space distortion

Observing the multi-scale cosmic web

Connectivity of the isocontour: genus

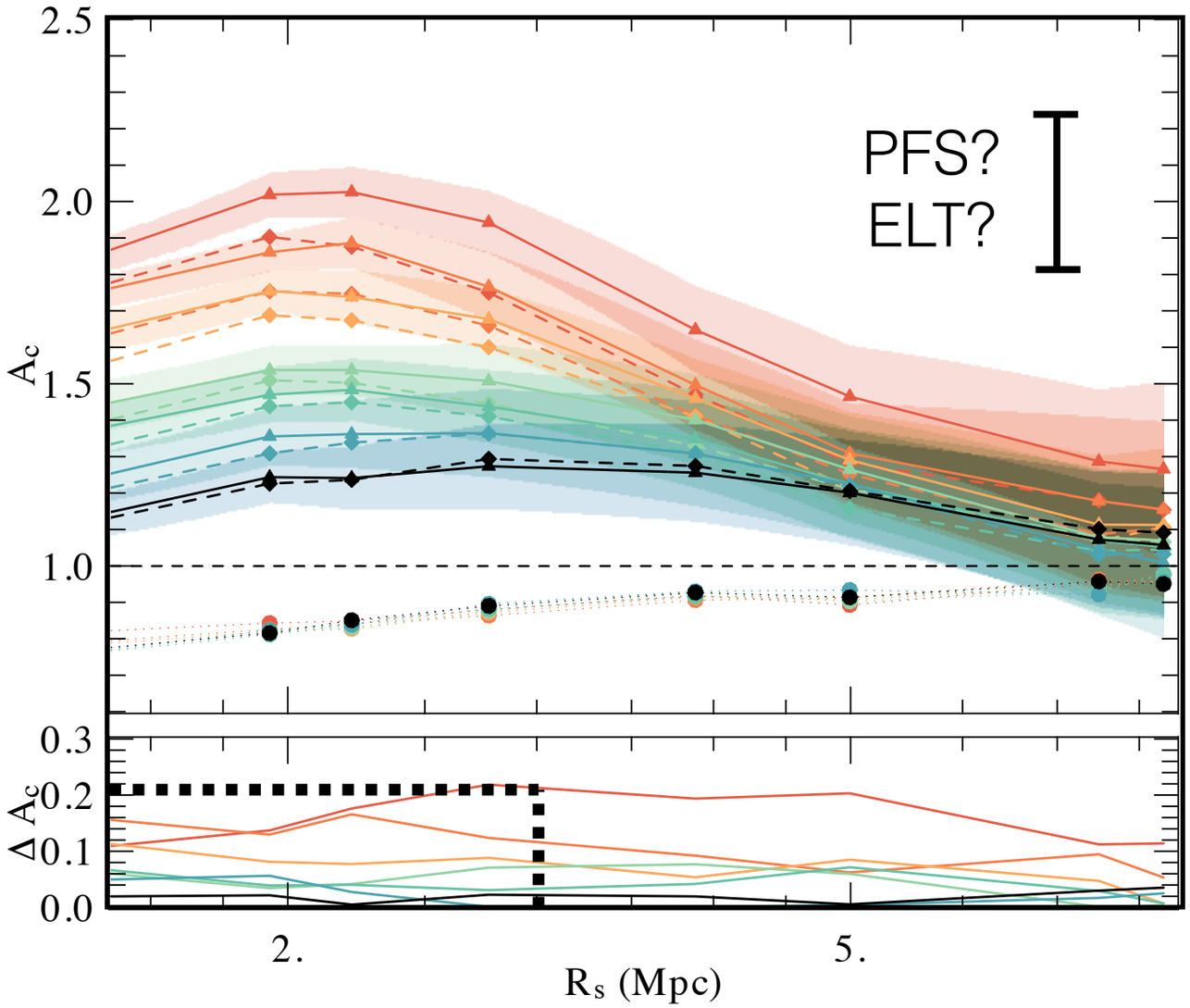


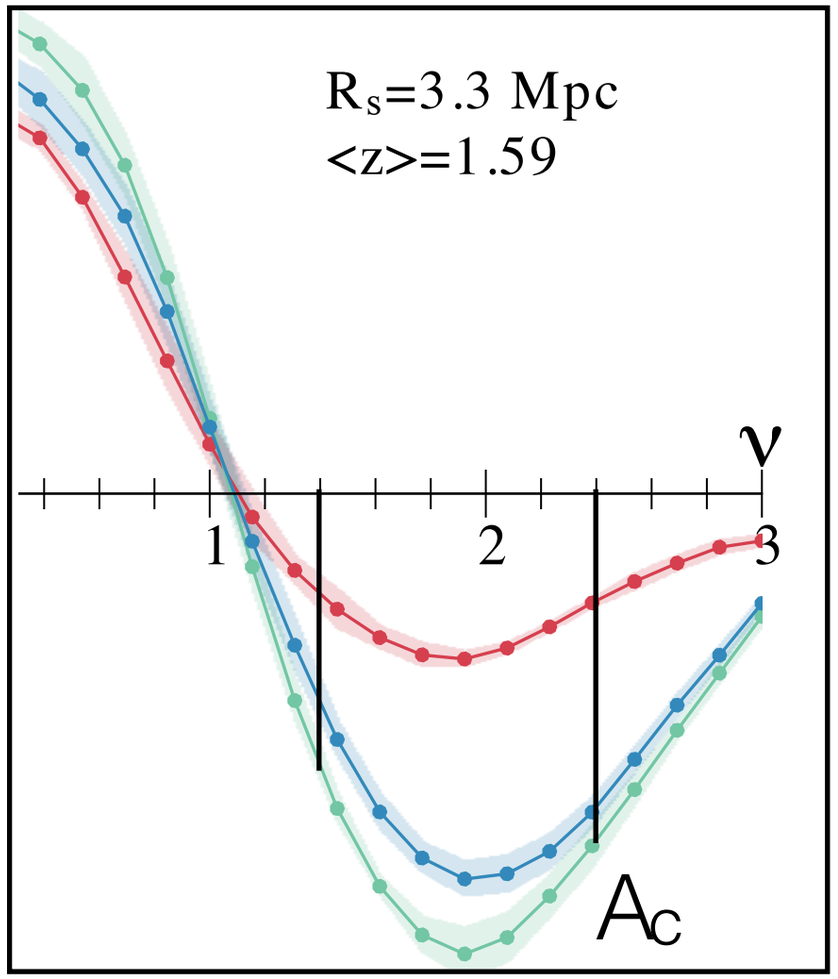
The impact of AGN feedback on genus is lower with redshift-space distortion

More analysis needed to quantify observational systematics

Observing the multi-scale cosmic web

Connectivity of the isocontour: genus





Scale and redshift evolution of the genus: upper limit on AGN feedback impact scale

up to ~ 20% effect on the cluster parameter at a scale of 3Mpc

SUMMARY: the cosmic web with Ly-alpha tomography

- **The connectivity of the cosmic network (as traced by HI) is**
  - an alternative probe of cosmology
  - essential to shape mass assembly & angular momentum acquisition
  - an indirect tracer of AGN feedback

- **Lyman-alpha forest tomography allows to reconstruct the 3D HI distribution**
  - End-to-end simulations are useful to make high-precision forecasts and design observational strategies

- **Some first results**
  - The global skeleton is robust with respect to tomographic reconstruction to study galaxy properties (MOSAIC configuration)
  - The genus of HI field is an indirect probe of AGN feedback