Mapping the Large Scale Structures through Lyman-alpha Forest

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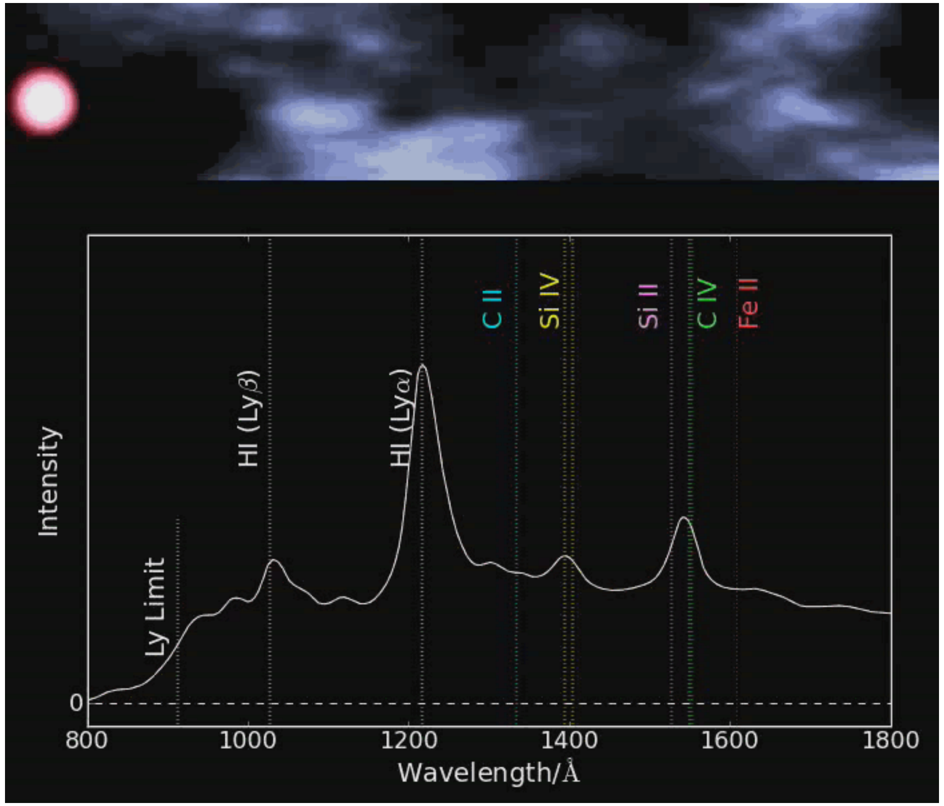
Background

- **Lyman alpha forest**

  The absorption phenomenon seen in the spectra of high redshift QSOs and galaxies, showing a forest of HI Lyα (1216Å) absorption lines.

  It' s the direct observational evidence of intergalactic medium (IGM).

  Flux of Lyα forest probes the density fluctuation along sightlines.



Background

- **Large scale structure (LSS)**

It refers to the patterns of galaxies and matter at very large scales (>Mpc), and is also called cosmic web.

It grows due to gravitational instability.

Measurements of LSS allows us to constrain cosmology and study physics of galaxy evolution.

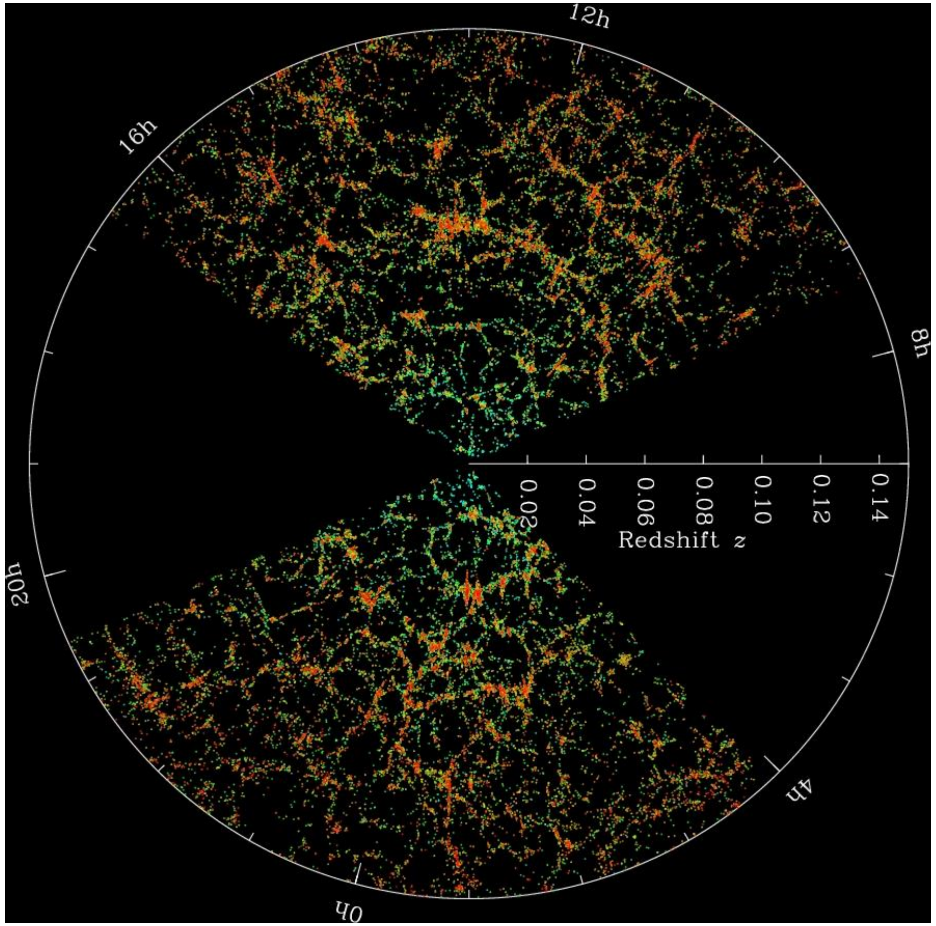


Figure Credit: M. Blanton and SDSS

How can we map the LSS?

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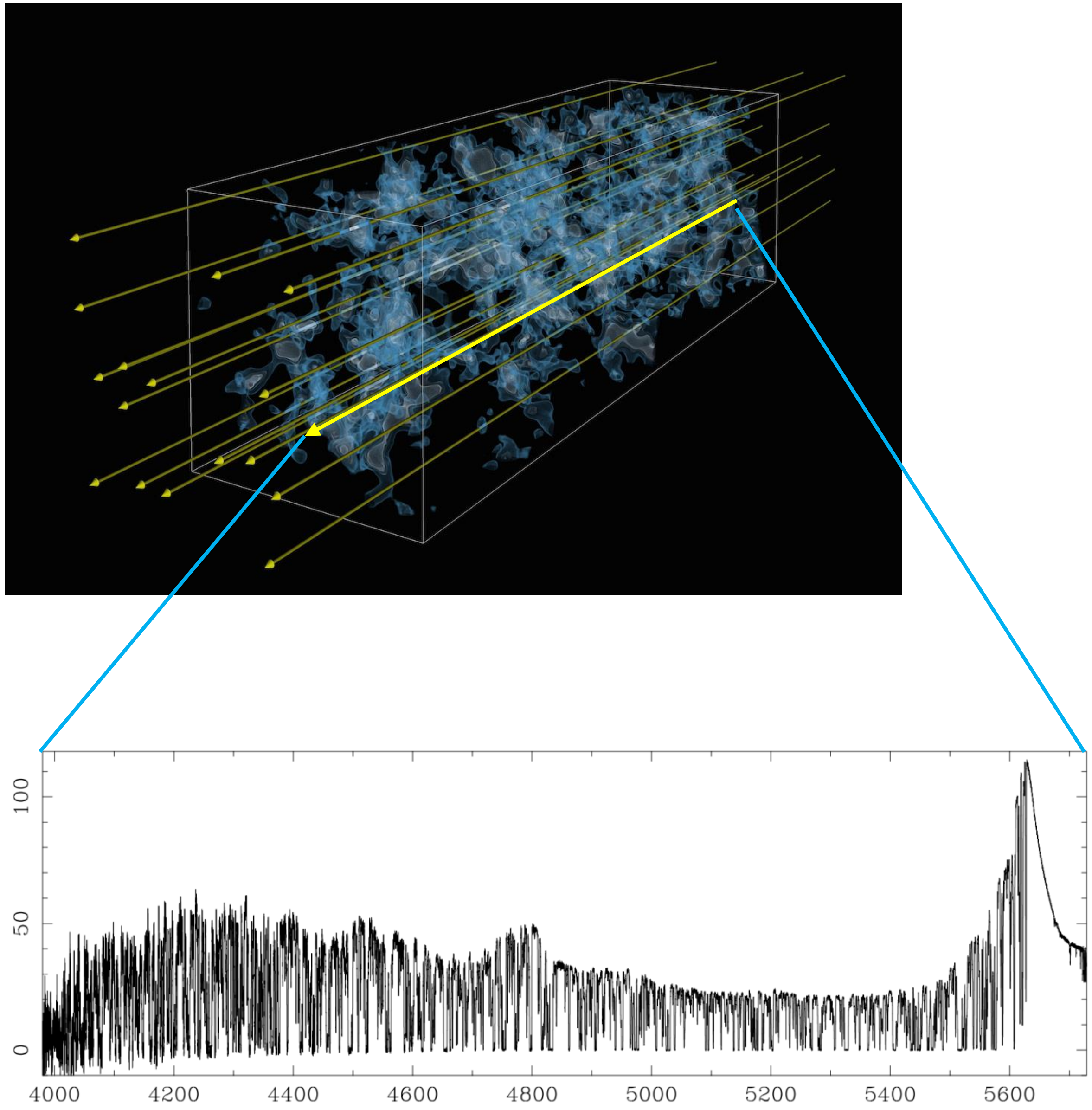
Lyα Tomography

- Lyman alpha forest in each individual sightline provides 1-d information of density.
- We can infer the 3-D structure using multiple sightlines from background QSOs and galaxies.

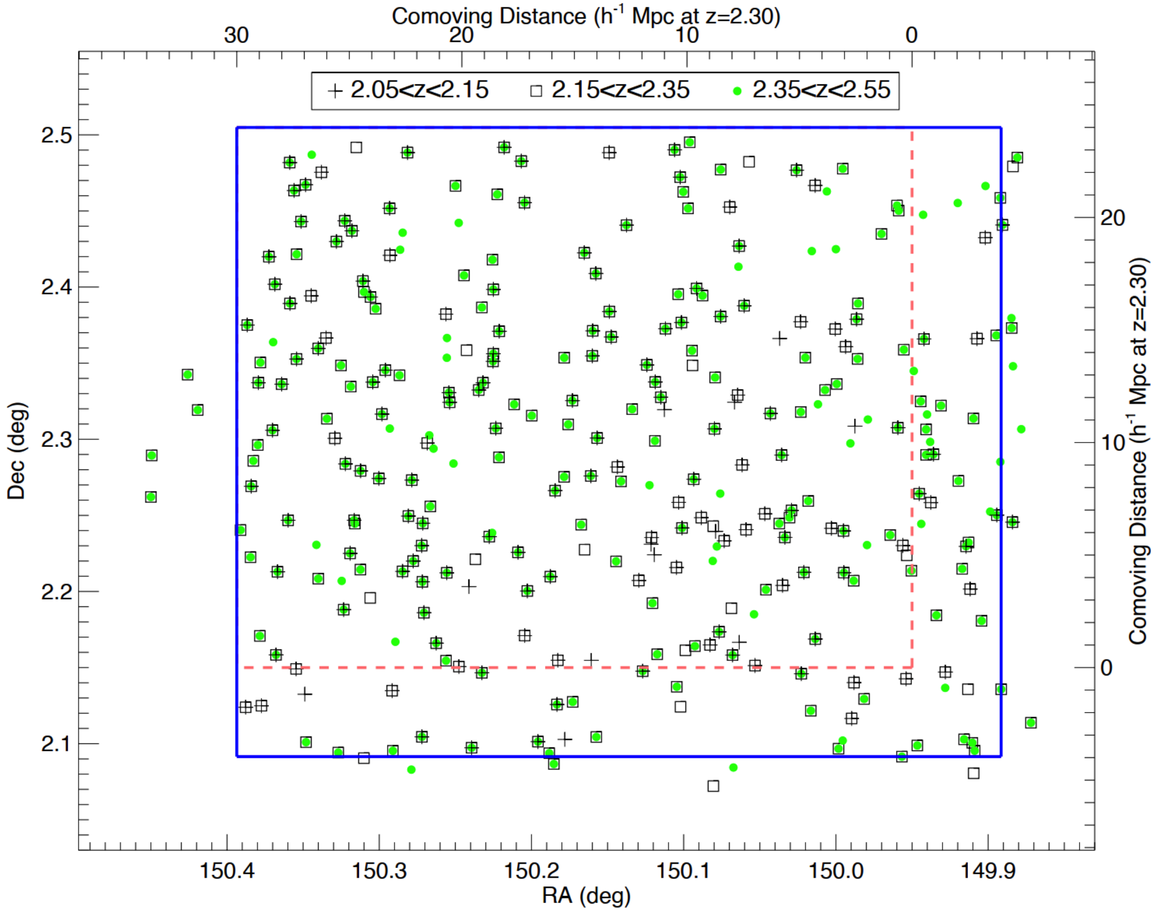


Observations

CLAMATO Survey (Horowitz et al. 2021):

(COSMOS Lyman-Alpha Mapping And Tomography Observations)

- Instrument: Keck-I/LRIS
- Cover the Lyα line at $2.1 \lesssim z \lesssim 2.6$
- Spatial resolution: ~3 Mpc/h
- Mean sightline density: 856 deg^2
- Mean sightline separation: 2.35 Mpc/h
- Survey volume: $34 \times 28 \times 438$ Mpc^3/h^3



Tomographic reconstruction

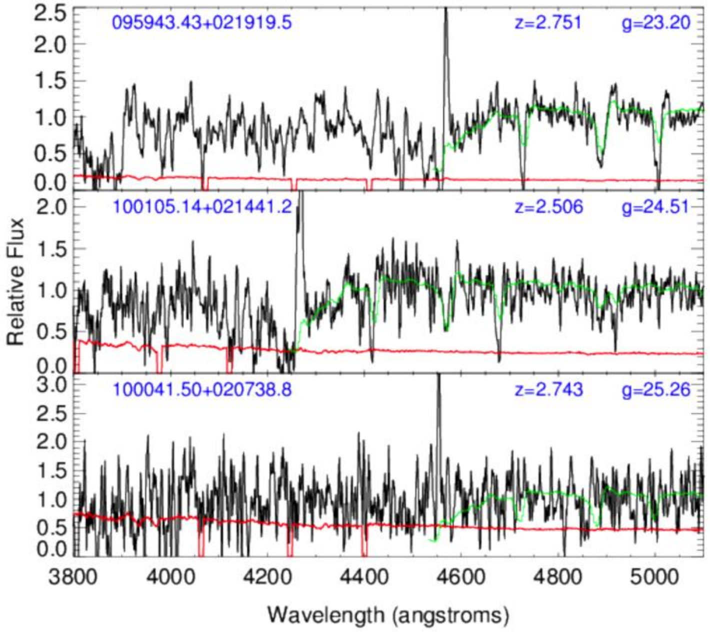
Wiener Filter (Stark et al. 2015)

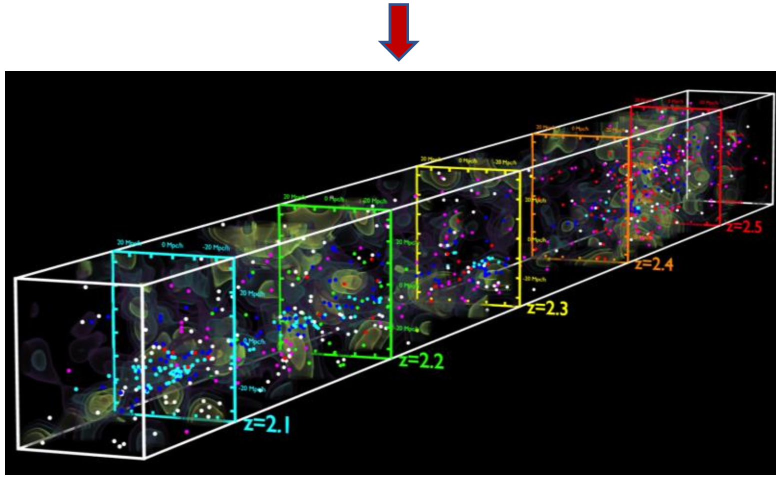
$$M = C_{MD} * (C_{DD}+N)^{-1} * \mathrm{d}$$

N: noise covariance matrix
C_{MD}: map-data covariance matrix
C_{DD}: data-data covariance matrix
d: spectra containing Lyman-alpha forest
M: reconstructed 3-d map
Assuming gaussian data-data covariance matrix:

$$C_{DD} = C_{MD} = \mathrm{C}(\mathrm{r}_1, \mathrm{r}_2) = \sigma_F^2 \exp\left[-\frac{(\Delta r_{\parallel})^2}{L_{\parallel}^2}\right] \exp\left[-\frac{(\Delta r_{\perp})^2}{L_{\perp}^2}\right]$$

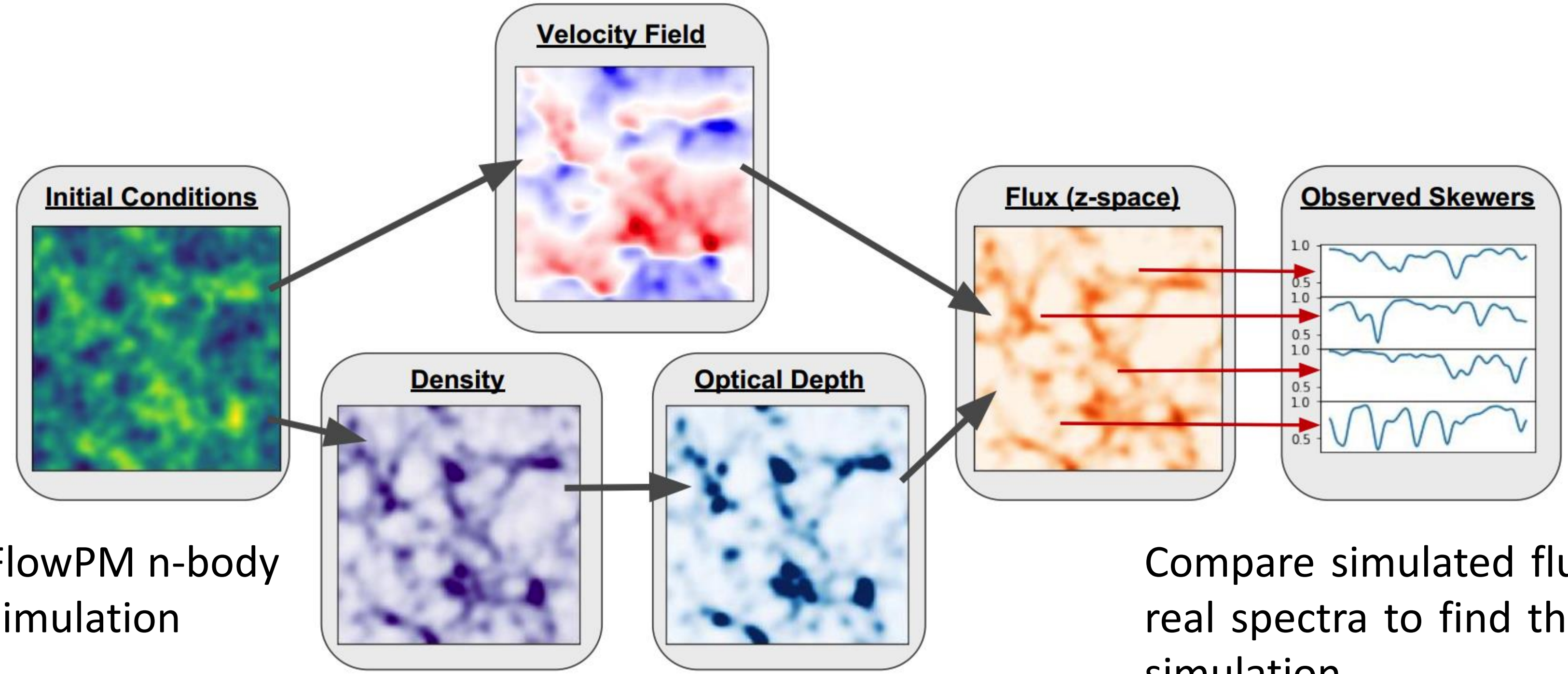
where $\Delta r_{\parallel}$ and $\Delta r_{\perp}$ are distance between r_1 and r_2 along, and transverse, to the line-of-sight, respectively.





Tomographic reconstruction

TARDIS (Horowitz et al. 2019 2020)
Tomographic Absorption Reconstruction and Density Inference Scheme



FlowPM n-body simulation

Convert matter density to optical depth through Fluctuating Gunn Peterson approximation

Compare simulated flux and real spectra to find the best simulation.

$$\chi^2 = \boldsymbol{s}^\dagger \boldsymbol{S}^{-1} \boldsymbol{s} + (\boldsymbol{d} - \boldsymbol{R}(\boldsymbol{s}))^\dagger \boldsymbol{N}^{-1} (\boldsymbol{d} - \boldsymbol{R}(\boldsymbol{s}))$$

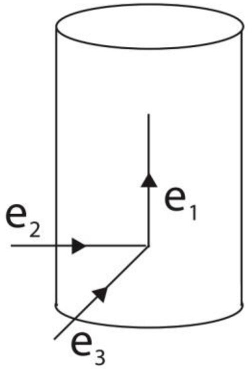
Cosmic web classification

Hessian of gravitational potential: $\mathrm{H}_{ij} = \frac{\partial^2 \phi}{\partial x_i \partial x_j}$

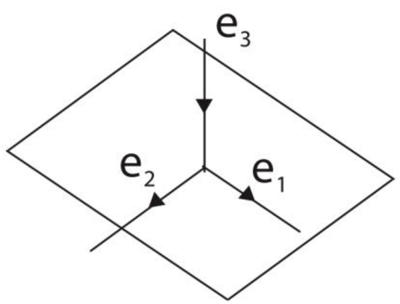
Eigenvectors: $\hat{e}_1, \hat{e}_2, \hat{e}_3$

Eigenvalues: $\lambda_1, \lambda_2, \lambda_3$

- Extrema
  - $+\ +\ +$ Peaks (nodes, clusters)
  - $-\ -\ -$ Voids
- Saddle points
  - $-\ +\ +$ Filaments
  - $+\ -\ -$ Walls (Sheets)



Filament



Sheet

How to calculate Hessian:

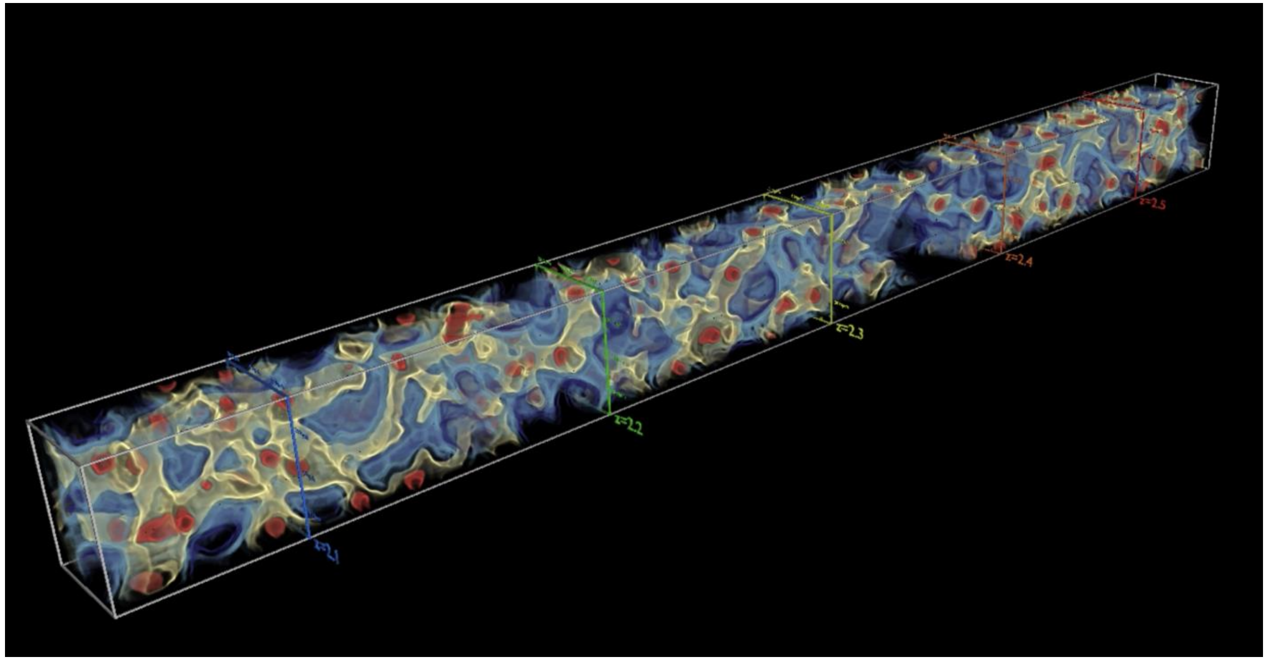
Fourier transformation of H_{ij}: $\widetilde{H}_{ij} = k_i k_j \phi_k$

Poisson 's eq: $\nabla^2 \phi = \rho \Rightarrow k^2 \phi_k = \delta_k$

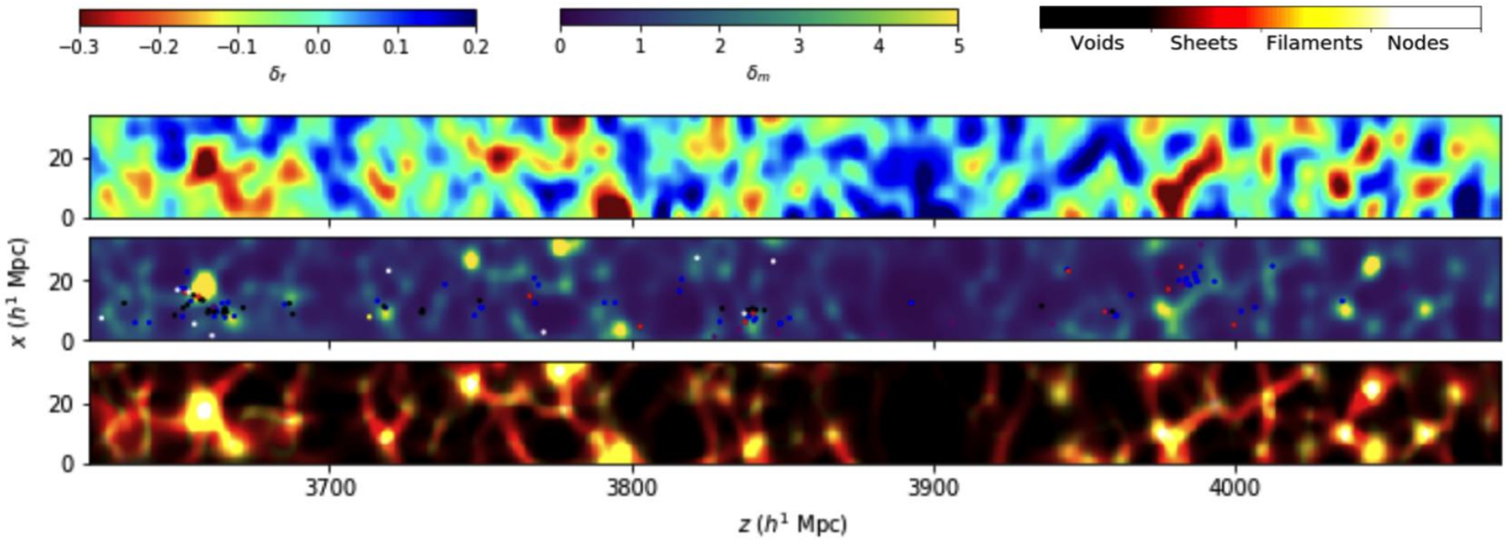
$\Rightarrow\ \widetilde{H}_{ij} = \frac{k_i k_j}{k^2} k^2\ \delta_k$

Matter overdensity, inferred from tomography

Visualization



3-D map of the CLAMATO field



Lyman-alpha flux field reconstructed by Wiener Filter

Matter density field reconstructed by TARDIS

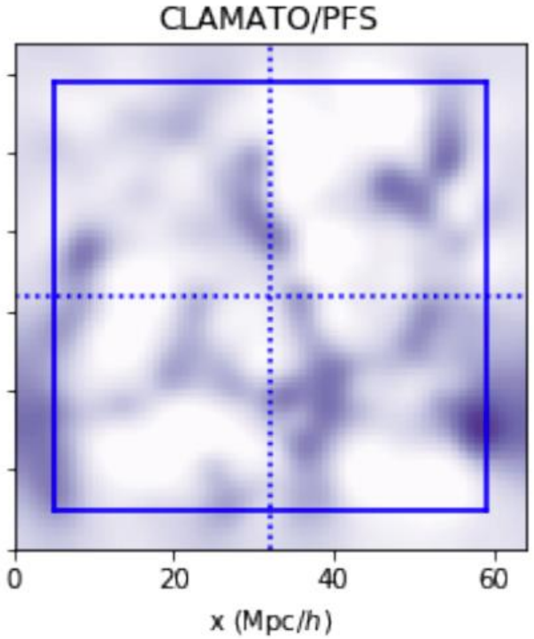
Cosmic web classification

What can tomography tell?

On “small” scale (~ Mpc/h)

Investigate galaxy evolution and it’s dependencies on cosmic web environments.

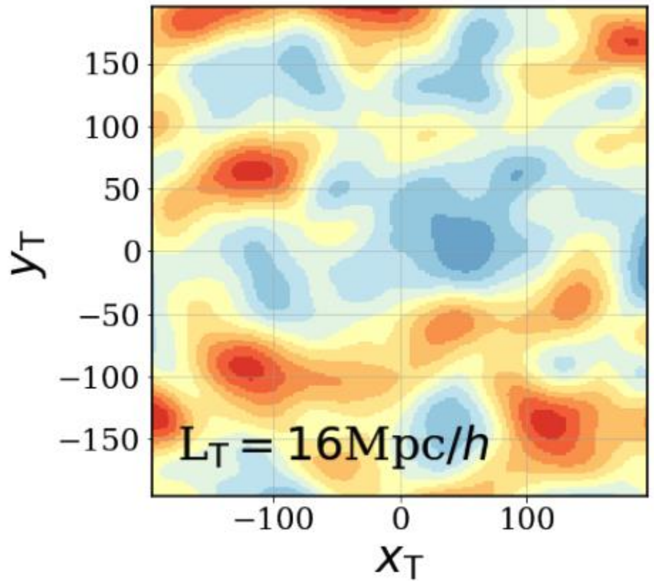
e.g., DESI, CLAMATO, PFS (~3 Mpc/h); TMT (~1 Mpc/h)



On “large” scale (>10 Mpc/h)

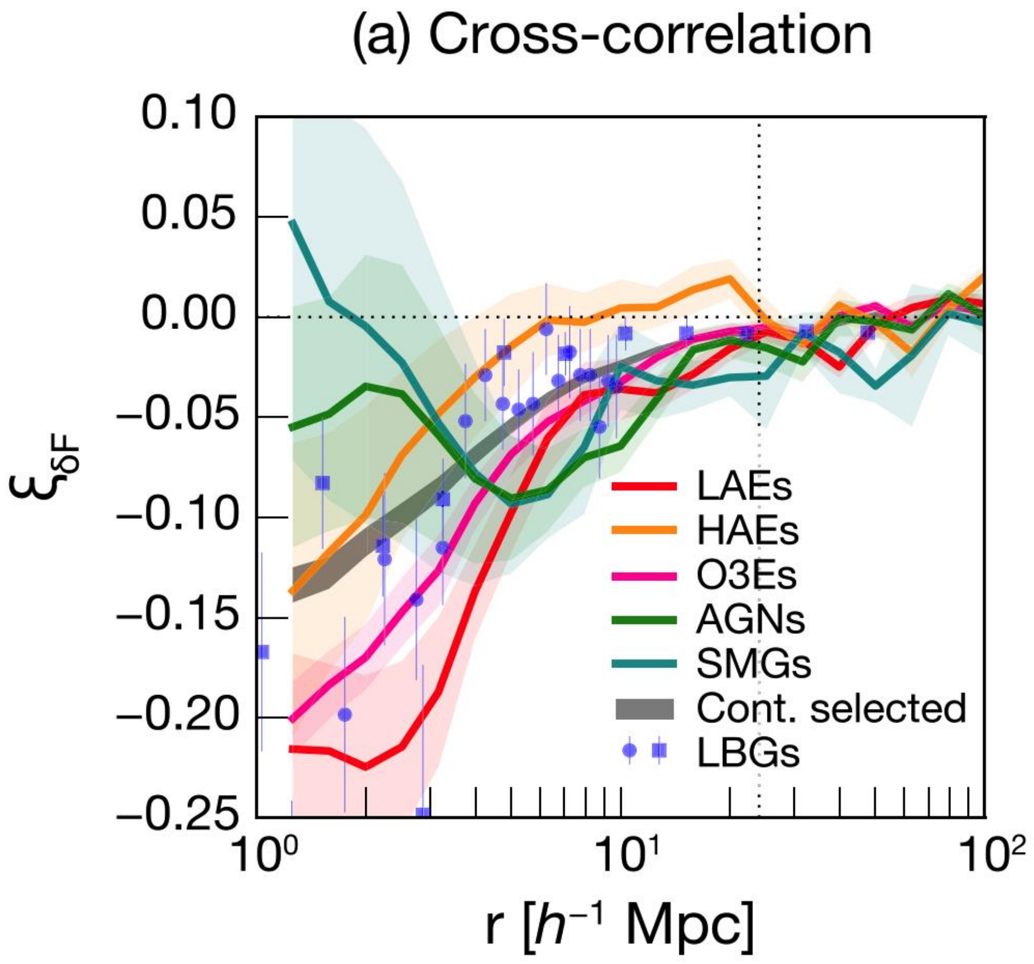
Study and constrain cosmology by measuring the clustering of matter.

e.g., WEAVE-QSO (~16 Mpc/h)



Cross correlation of tomographic flux and galaxies

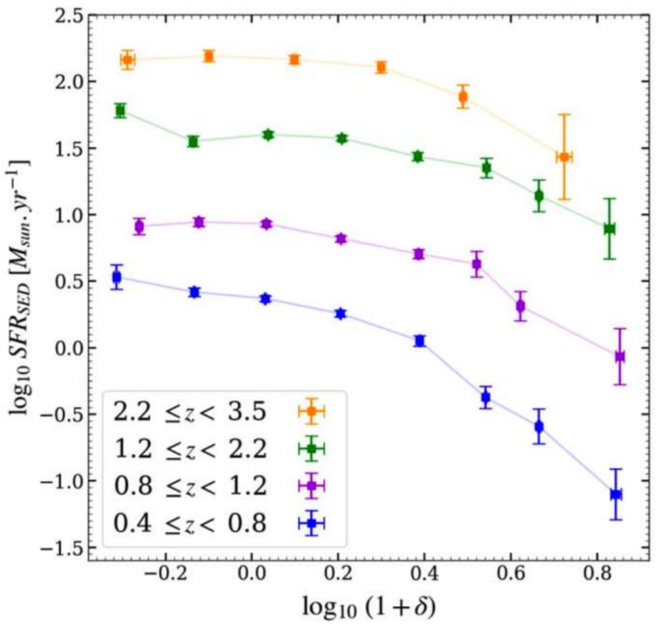
- The cross correlation functions (CCF) of tomographic flux between LAEs, HAEs and O3Es increase monotonically with radius. It indicates that the strongest HI absorption is around those galaxies, and the absorption decreases with distance.
- The CCFs of AGNs and SMGs have minima at ~5Mpc. It could be explained by the hypothesis that the AGN photoionizes surrounding HI gas and suppresses HI absorption (proximity effect)



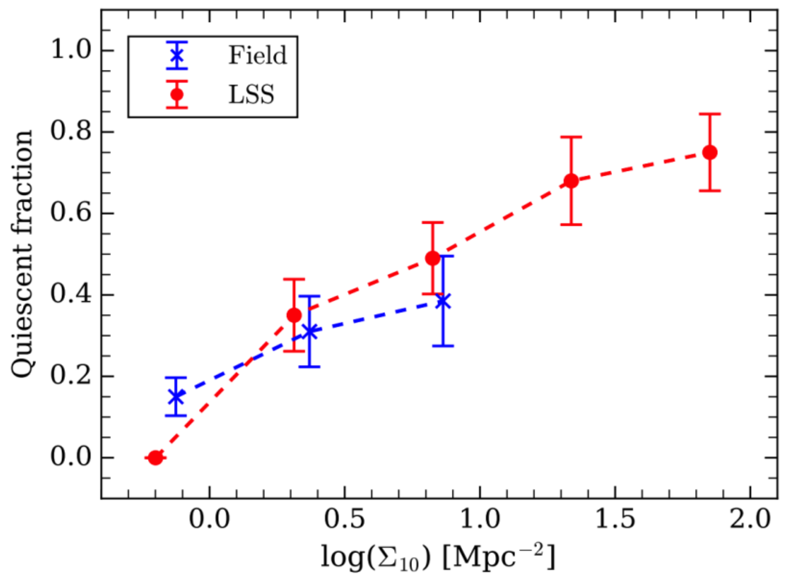
Momose et al. (2021)

Impact of LSS on Star Formation Activity

- Evidence of environmental quenching for massive galaxies in overdense region.
- Overdense environment hosts more quiescent galaxies than underdense regions.
- Dense environment prevents the accretion of cool gas into the galaxy.



Chartab et al. (2020)

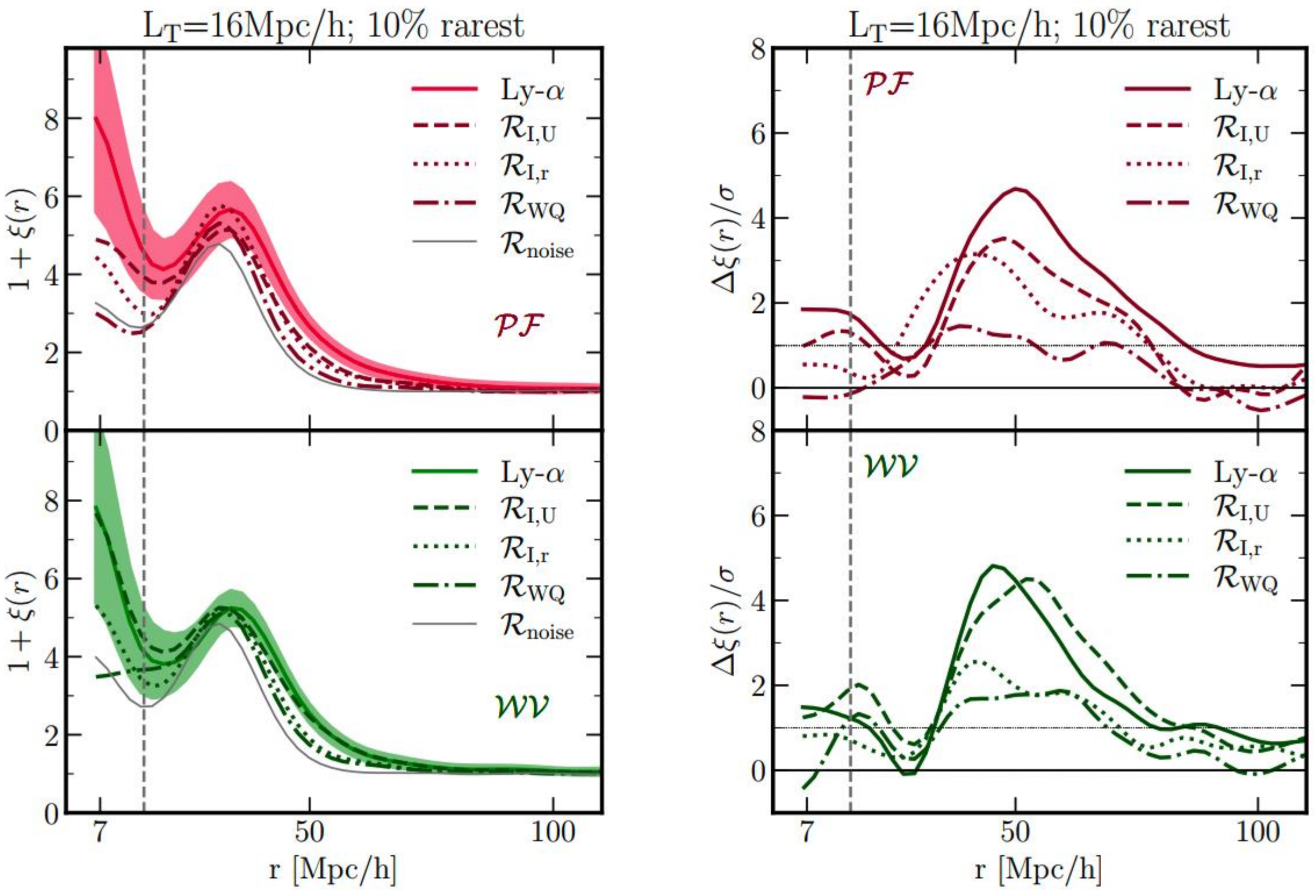


Ren et al. (2022)

Still not well understood, and see Wang et al. (2022) and Li et al. (2022 APJL in press) for a seemingly contradictory (?) opinion.

Cross correlation of cosmic web structures

- The clustering scales of the LSSs can only match the theoretical prediction given correct cosmology.
- E.g., Maximum of the Peak-Filament and Wall-Void CCF can be used to constrain cosmology, similar to BAO but at smaller scale.



K. Kraljic et al. 2022

Take home message

- Tomography techniques can convert Lyman-alpha forest in multiple sightlines to a 3-D map of the universe.
- The reconstructed map can be classified into 4 different cosmic web structures (nodes, filaments, sheets and voids)
- The correlation between galaxies and large scale structures can help us study galaxy evolution in different environments.
- The correlation between large scale structures themselves can help us constrain cosmology.