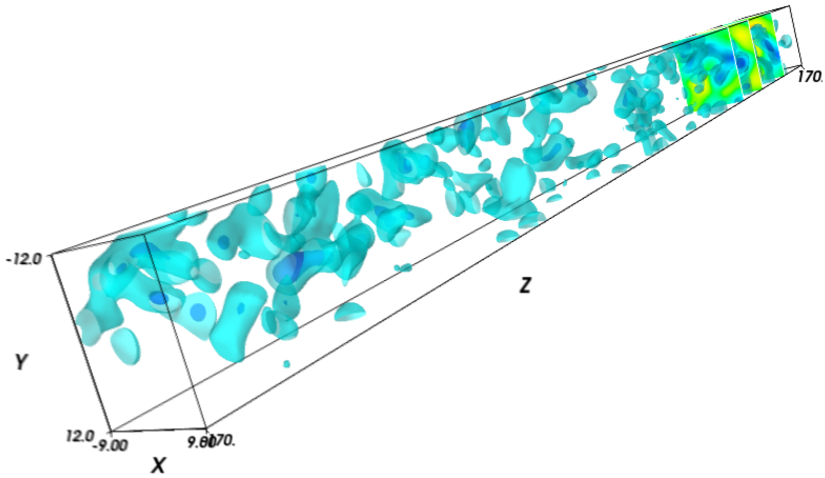
The mystery figure



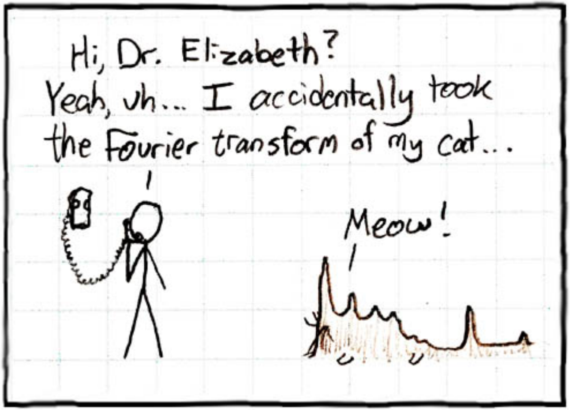
Cosmic Web, IGM tomography and *Clamato*

Martin White
with
K-G Lee, J. Hennawi, E. Kitanidis, P. Nugent, J. Prochaska,
D. Schlegel, M.Schmittfull, C. Stark, et al.

http://clamato.lbl.gov

Beyond power spectra ...

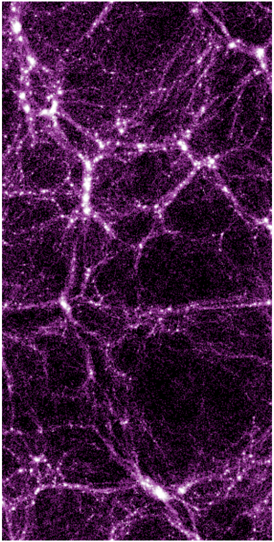
Give a cosmologist a map and they will reflexively take it's Fourier transform then throw away the phases ...



xkcd.com/26

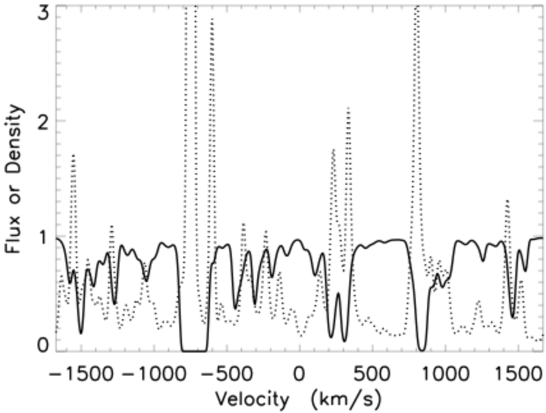
The cosmic web

- Sometimes you want a map!
- A natural outcome of gravitational instability from Gaussian ICs is a beaded filamentary network of voids, sheets, filaments and knots known as the cosmic web.
- All of galaxy and structure formation occurs in this context!
- Can we make a map of the large-scale structure with Mpc resolution over a representative volume of the Universe ($10^6\,h^{-3}\mathrm{Mpc}$) with existing telescopes … at $z > 2$?
- It's hard with galaxies, but …



Lyα forest tomography

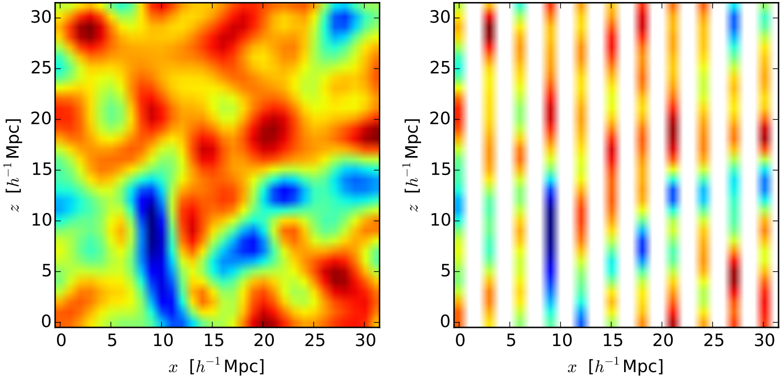
If we take a spectrum of a background source, neutral H along the line of sight imprints (absorption) features: Lyα forest.



Spectrum = "flipped density"

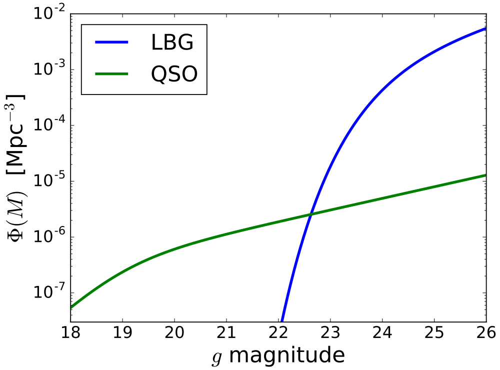
Lyα forest tomography

With the Lyα forest we get the line-of-sight sampling "for free", so we just need to get the transverse sampling high enough.



Source luminosity functions

To increase the sightline density we need to go beyond QSOs as backlights. Beyond $g \sim 22 - 23$ LBGs dominate over QSOs.



Exponential increase in sightline density beyond $g \simeq 23$!

Requirements?

- By $g \simeq 24$ sources (galaxies) are separated by arcmin on the sky! Can get S/N$\sim$few per $\AA$ with 3 hr integrations on Keck / LRIS-B.
- BOSS taught us that you can get a lot of information from low resolution spectra with low S/N – if you have a lot of them!
  - We're closer to measuring a "mean absorption" than individual absorption features.
- Moderate resolution and S/N means that what looks like 30 m class science can be done (now!) with a 10 m!

What can you do with $\mathcal{O}(10^3)$ sightlines per deg^2 at S/N $\sim$few per $\AA$?

Science with IGM tomography

- Finding protoclusters and (high z) voids.
  - Stark et al. (2015a,b) study the counts, profiles, radii, etc. of $z \simeq 2.5$ protoclusters and voids as seen in Lyα tomography.
  - Find high completeness ($> 75\%$) and purity ($> 90\%$) for massive cluster progenitors.
  - Similarly good completeness and purity for large voids.
- Improving photo zs.
  - Low density regions occupy most of the volume of the Universe, but host essentially no massive halos (or galaxies).
  - Schmittfull & White (2016) show can improve photo zs for massive galaxies.
- Cosmic web classification
  - One can use a deformation tensor approach to characterize the cosmic web.
  - Lee & White (2016) show, in simulations, comparable performance at $z \simeq 2.5$ to GAMA, using the same method, at $z \simeq 0.25$.
- ... and some other stuff ...

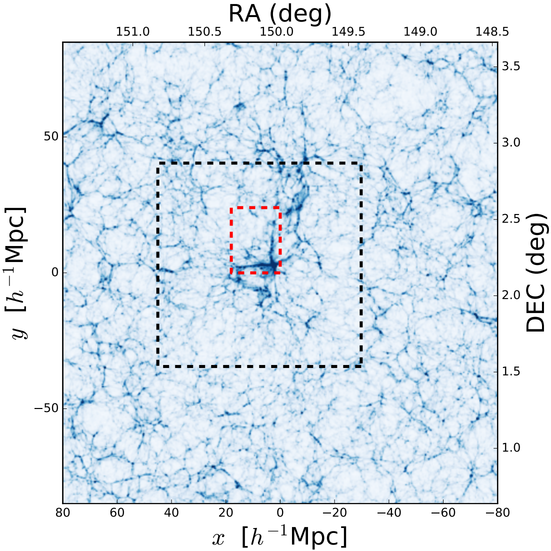
CLAMATO

COSMOS **L**y-**A**lpha **M**apping **A**nd **TO**mography

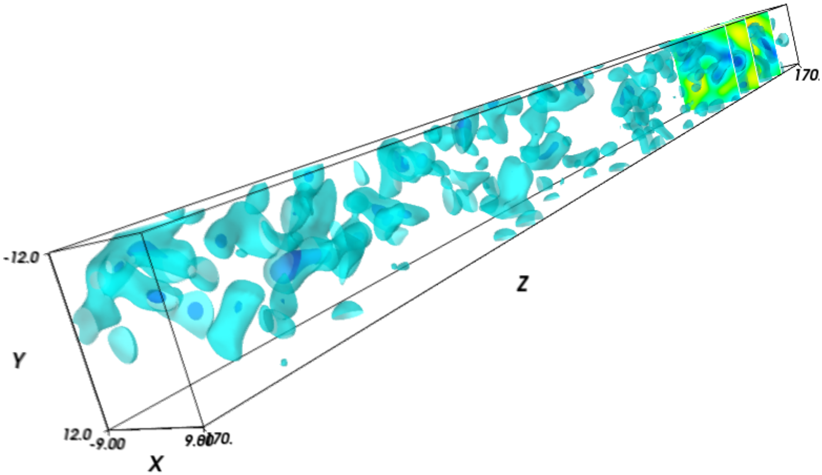
- Survey to do Lyα forest tomography in the central $1\,\mathrm{deg}^2$ of the COSMOS field.
  - Overlaps CANDELS/3D-HST. Allows study of colors, morphology, SF rate, AGN activity, etc., as a function of large-scale environment.
  - Survey for protoclusters and voids.
  - Improved photo-z for galaxies in COSMOS.
  - Cosmic web classification.
  - Study CGM in protocluster foregrounds.
  - Cross-correlations and small-scale Lyα forest.
- Need $1\,\mathrm{deg}^2$ in order to sample large structures, like protoclusters and voids.
- Goal: $\left(60\,h^{-1}\mathrm{Mpc}\right)^2 \times 300\,h^{-1}\mathrm{Mpc} \sim 10^6\,h^{-3}\mathrm{Mpc}^3$.
- Survey in progress ...
  - Currently have 124 sightlines.
  - Mean separation $2.5\,h^{-1}\mathrm{Mpc}$.
  - Lee et al. (2014ab, 2016)

Context and scales

Conveniently $1'$ and $1\,\AA$ are (about) a comoving Mpc at $z \simeq 2.5$



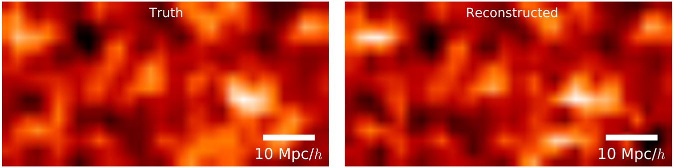
CLAMATO: Current status



Contours of the flux (overdensities are more blue) in our current data set ($18 \times 24 \times 340\, h^{-1}$Mpc). Slices are placed at the redshifts of previously known proto-clusters.

Joint fitting & Sampling

We have implemented a high-dimensional minimization and sampling scheme that allows us to generate (Gaussian) initial conditions which (when evolved and turned into Lyα flux) are consistent with the observed data and noise model.



We can use these to run constrained N-body simulations, jointly fit Lyα and galaxy data sets, and propagate errors consistently.

Conclusions

- IGM tomography is 'ideal' for measuring large-scale environments of galaxies and QSOs.
- Can find large, coherent objects spanning Mpc
  - Protoclusters
  - Voids
- Map LSS and decompose into filaments, sheets and halos.
- Improve photo-zs of galaxies using topology.
- Medium scale 3D Lyα clustering.
- Cross-correlations.

Clamato is underway, and so far things look good ...

References and links

- Observational papers
  - Lee et al. (2014b; ApJ, 795, L12)
  - Lee et al. (2016a; ApJ, 817, 160)
  - Lee et al. (2016b; in prep.)
- Theory/Simulation papers
  - Lee et al. (2014a; ApJ, 788, 49)
  - Stark et al. (2015a; MNRAS, 453, 311)
  - Stark et al. (2015b; MNRAS, 453, 4311)
  - Lee & White (2016; ApJ, in press)
  - Schmittfull & White (2016; MNRAS, in press)
- Mock data sets and code
  - `http://clamato.lbl.gov`
- Movies and 3D visualizations
  - Video of 2015 map: `https://youtu.be/KeW1UJOPMYI`
  - 3D/Cardboard video of 2016 map: `https://youtu.be/xV2Ng8n61Xc`

The End!

Backup Slides

Technical details

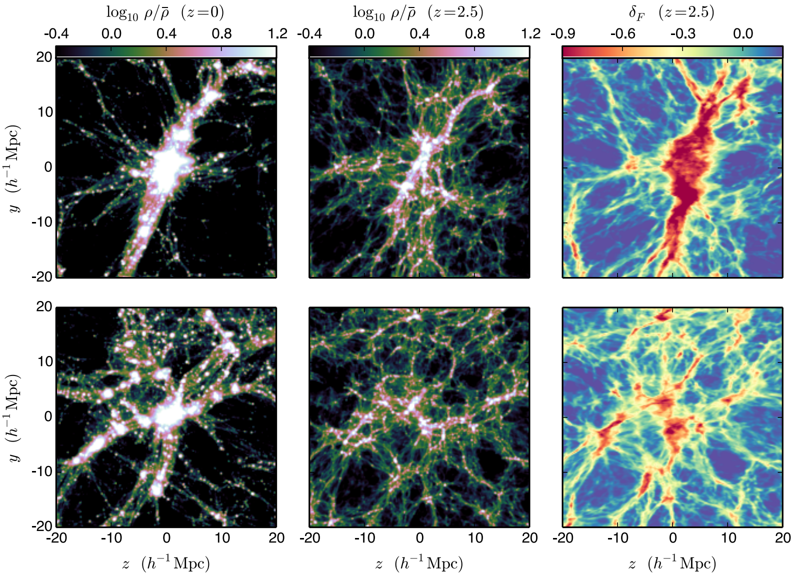
- Program on Keck-I/LRIS-B ($4' \times 7'$ FOV)
- Covers central $0.8\,\mathrm{deg}^2$ in 90 pointings.
- Nominal limit $g = 24.5$ (about 25 per mask) with 3 hr exposures.
- Yields $10 - 15$ targets with proper z and S/N for reconstructing the $2.2 < z < 2.5$ Lyα forest.

Physics of the forest

- The physics of the forest is relatively straightforward.
- Gas making up the IGM is in photo-ionization equilibrium with a (uniform?) ionization field which results in a tight $\rho - T$ relation for the absorbing material.
- The neutral H density is proportional to a power of ρ_B.
- Since pressure forces are subdominant on "large" scales, the gas traces the DM.
- The structure in the spectrum traces, in a calculable way, the fluctuations in the density along the line of sight.
- Ab initio calculations of the forest perform quite well compared to observations.

e.g. Meiksin (2009)

Protocluster finding

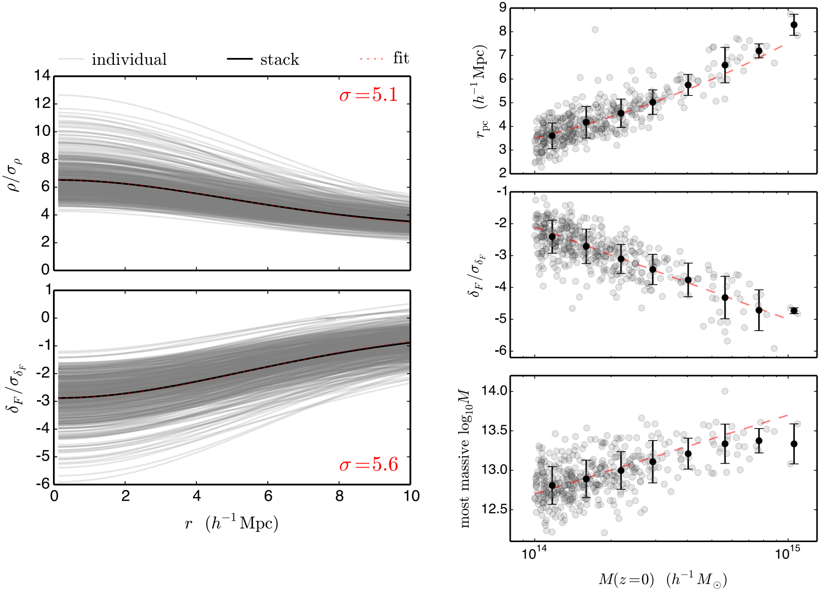


Stark et al. (2015a)

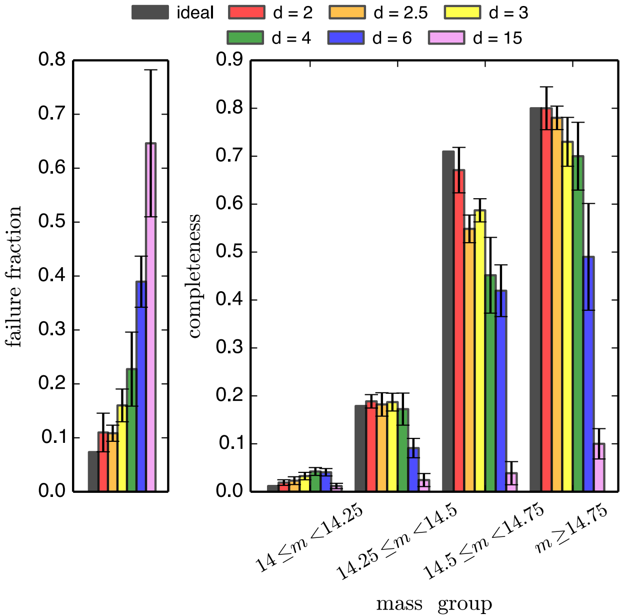
Completeness and purity

- Stark et al. (2015a, 2015b) study the counts, profiles, radii, etc. of $z \simeq 2.5$ protoclusters and voids as seen in Lyα tomography.
- Find high completeness ($> 75\%$) and purity ($> 90\%$) for tomographically selected samples of massive ($> 3 \times 10^{14}\, h^{-1} M_\odot$) cluster progenitors for sightline separations at or better than $4\, h^{-1}$Mpc.
- Even sightline separations above $10\, h^{-1}$Mpc can be used to find the largest, earliest assembling protoclusters.
- Find similarly good completeness and purity for voids with radii $> 6\, h^{-1}$Mpc ($\sim 10^2$ such voids per $1\,\mathrm{deg}^2$ at $z = 2.5$).

Protocluster Properties

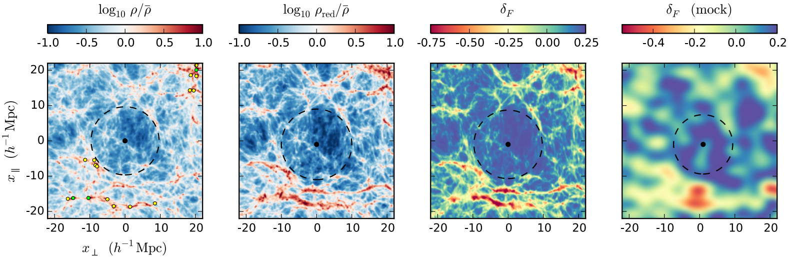


Protocluster Completeness and Purity



Void finding

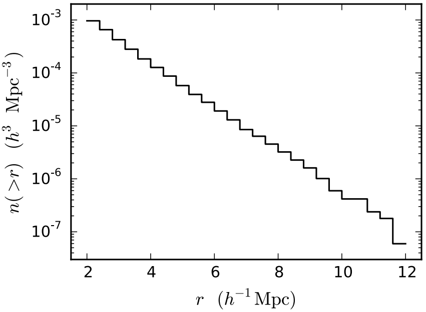
It is also possible to find large underdensities – in fact this is somewhat easier since voids aren't really empty, just underdense in galaxies (dots in left panel).



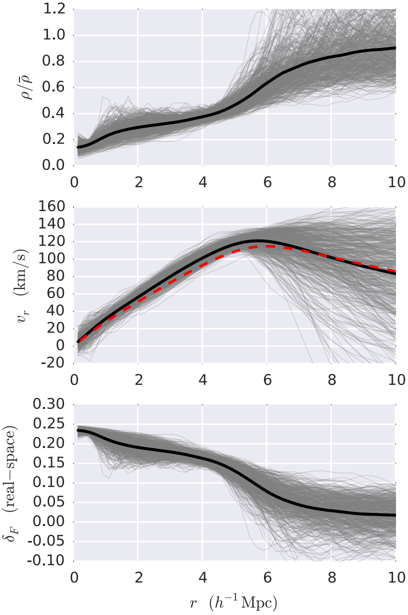
Stark et al. (2015b)

Voids at high z

Voids counts at $z = 2.5$

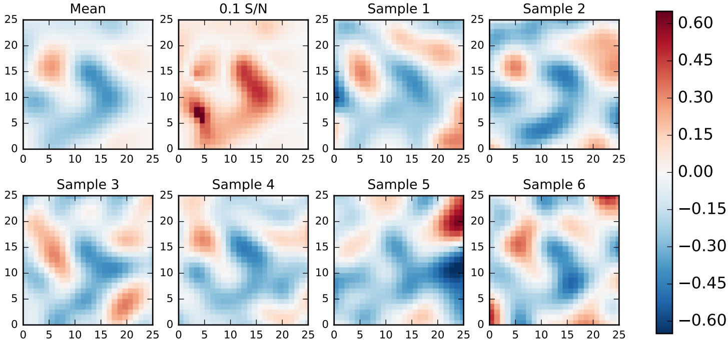


Synergistic with JWST-NIRSPEC to study sub-$L_\star$ void galaxies at $z \simeq 2 - 3$.



Protocluster Candidate: $z = 2.44$

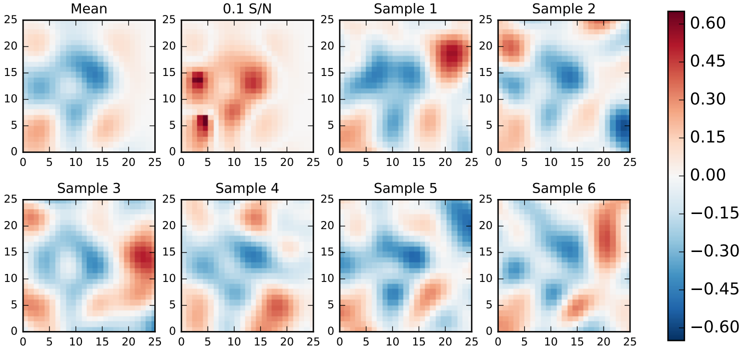
Diener et al. (2015; LBG) and Chiang et al. (2015; LAE).



Lee et al. (2016): See a large overdensity in our absorption map at high significance, correlated with LBG and LAE overdensities. Comparison with sims gives $M(z=0) \simeq (3 \pm 1.5) \times 10^{14}\ h^{-1}\mathrm{Mpc}$ (Virgo). Possible fragmentation into two $z \simeq 0$ clusters.

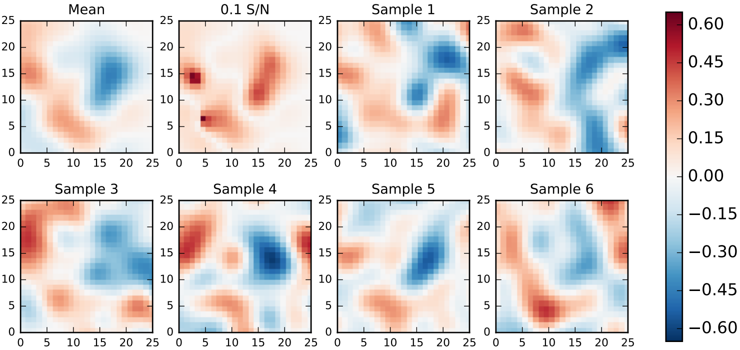
Protocluster Candidate: $z = 2.47$

Casey et al. (2015), Hershel sub-mm overdensity (also seen in LBGs).



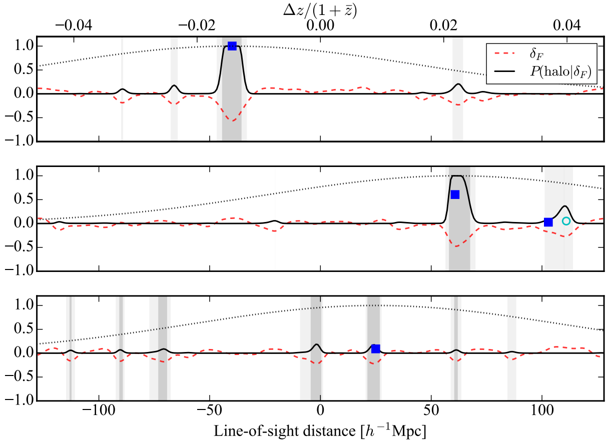
Protocluster Candidate: $z = 2.51$

X-ray detected (proto-)cluster: Wang et al. (2016)



Improving photo-zs

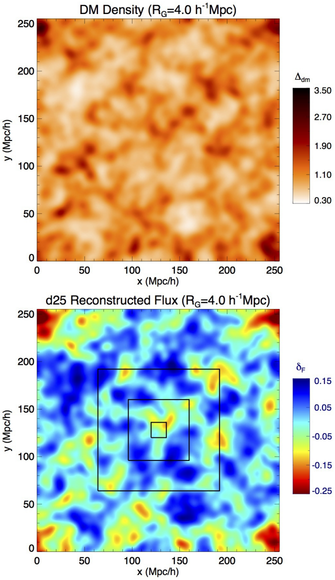
Low density regions occupy most of the volume of the Universe,
but host essentially no massive halos (or galaxies).
Knowledge of the density field can improve photo-zs!



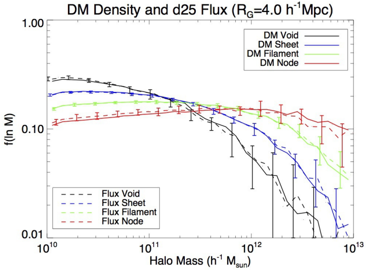
Cosmic web classification

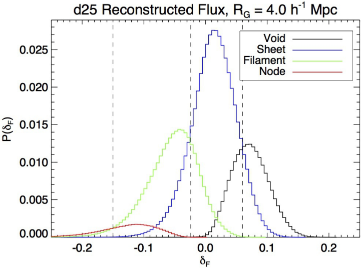
- One can use a deformation tensor approach to characterize the cosmic web.
  - Compute $T_{ij}(\mathbf{k}) = (k_i k_j/k^2)\ \delta_F(\mathbf{k})$
  - Solve for e-values, λ_k, count number less than a given threshold, $\lambda_{\rm th}$.
- For achievable resolution and S/N we can classify 70% of the volume correctly compared to the DM, and 99% within 1 eigenvalue.
- Our performane at $z \simeq 2.5$ is comparable to the performance of GAMA, using the same method, at $z \simeq 0.25$.

Cosmic web classification



Cosmic web classification





Halo multiplicity function and (normalized) distribution of overdensities (in 1 $h^{-3}\mathrm{Mpc}^3$ voxels) classified by cosmic web component.