Cosmic Web, IGM tomography and *Clamato*

Martin White
with

Quasar

z = 2.1

z = 2.5

z = 2.6

505 Mpc
The cosmic web

- All of the structure in our Universe arose from small, initially Gaussian (quantum) fluctuations (generated during inflation) amplified by gravitational instability in a (cold) dark matter dominated Universe.
- A natural outcome of this process, when viewed on Mpc scales, 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!
- What are the observational requirements for making a map of the cosmic web at high $z$?
The physics of gravitational instability, the initial fluctuation spectrum and the cosmic constituents provide natural definitions for “large”, “dense”, “representative”.

- Natural length scale set by the horizon at matter-radiation equality ($k_{eq} \simeq 0.0103(1)\, \text{Mpc}^{-1}$, i.e. 100 Mpc).
- Amplitude of fluctuations (power spectrum) sets requirements on tracer density.

Can we make a map of the large-scale structure with Mpc resolution over a representative volume of the Universe ($10^6 \, h^{-3}\text{Mpc}$) with existing telescopes?

Can we survey massive volumes to find extreme objects (protoclusters, voids, ...)?

Can we measure the “environment” of galaxies at high $z$?
Galaxy redshifts at $z \approx 0$ and $z \approx 2.5$

Locally we do cosmography with galaxy redshift surveys – but redshifts get expensive at high $z$!

Note we’ve isolated a thin slice in $z$
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Galaxy density

- Ability to map LSS depends on galaxy separations.
- SDSS main sample ($z < 0.2 - 0.3$) has a mean inter-galaxy separation of $\sim 8 \, h^{-1}\text{Mpc}$.
- At $z = 0.5$ need to go to $I_{AB} = 22.5$ to reach the same mean separation.
- At $z = 1.0$ need $I_{AB} = 24.2$.
- At $z = 2.0$ need $I_{AB} = 25.7$.
- Direct mapping of $z > 1$ LSS at Mpc resolution is a 30 m telescope project!

Galaxies aren’t the only tracer of large-scale structure: if we use HI we get line-of-sight “for free”.
Source luminosity functions

With the Ly$\alpha$ forest we get the line-of-sight sampling “for free”, so we just need to get the transverse sampling high enough. 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 below $g \sim 23$!
By 24th magnitude sources are separated by arcminutes on the sky.
Requirements?

- The standard in the field of IGM studies is to work with very high S/N spectra at high resolution.
- 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!

How well can you do with $O(10^3)$ sightlines per deg$^2$ at $S/N \sim \text{few}$ per Å? Look for structures coherent over Mpc scales ...
Protocluster finding

Stark et al. (2015a)
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)
Completeness and purity

- Stark et al. (2015a, 2015b) study the counts, profiles, radii, etc. of $z \approx 2.5$ protoclusters and voids as seen in Ly$\alpha$ 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 $4 \, h^{-1} \text{Mpc}$.
- Even sightline separations above $10 \, h^{-1} \text{Mpc}$ can be used to find the largest, earliest assembling protoclusters.
- Find similarly good completeness and purity for voids with radii $> 6 \, h^{-1} \text{Mpc}$. We estimate $\sim 10^2$ such voids per $1 \, \text{deg}^2$ at $z = 2.5$. 
CLAMATO

COSMOS Ly-\textit{Al}pha M\textit{apping} A\textit{nd} T\textit{O}mography

- Survey to do Ly\textalpha{} forest tomography in the central 1\,deg\textsuperscript{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.
  - Study CGM in protocluster foregrounds.
  - Improved photo-z for galaxies in COSMOS.
  - Cosmic web classification (as well as e.g. GAMA at low z)
  - Survey for protoclusters and voids.

- Need 1\,deg\textsuperscript{2} in order to sample large structures, like protoclusters and voids.

- Goal: \((60\,h^{-1}\text{Mpc})^2 \times 300\,h^{-1}\text{Mpc} \sim 10^6\,h^{-3}\text{Mpc}^3\).

- Survey in progress ...
  - Currently have 124 sightlines.
  - Mean separation 2.5\,\(h^{-1}\text{Mpc}\).
  - Lee et al. (2014ab, 2016)
CLAMATO: Current status

Contours of the flux (overdensities are more blue) in our current data set ($18 \times 24 \times 340 \, h^{-1}\text{Mpc}$). Slices are placed at the redshifts of previously known proto-clusters.
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 $M(z = 0) \simeq (3 \pm 1.5) \times 10^{14} \, h^{-1}\text{Mpc}$ (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)
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 Ly$\alpha$ flux) are consistent with the observed data and noise model.

We can use these to run constrained N-body simulations, jointly fit Ly$\alpha$ and galaxy data sets, and propagate errors consistently.
Conclusions

- IGM tomography is ‘ideal’ for measuring large-scale environments of galaxies and QSOs.
- Map LSS and decompose into filaments, sheets and halos.
- Medium scale 3D Ly$\alpha$ clustering.
- Cross-correlations.
- Improve photo-zs of galaxies using topology.
- From such a map ideally want to look for large, coherent objects spanning Mpc
  - Protoclusters
  - Voids

Clamato is underway, and preliminary indications are very promising!
The End!
Backup Slides
Protocluster Properties

\[ \sigma = 5.1 \]

\[ \sigma = 5.6 \]
Protocluster Completeness and Purity

![Graph showing protocluster completeness and purity across different mass groups and distances.](image-url)
Voids at high $z$

Voids counts at $z = 2.5$

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

- Program on Keck-I/LRIS-B (4′ × 7′ FOV)
- Covers central 0.8 deg² 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 $2.2 < z < 2.5$ Ly$\alpha$ forest.
Ly\(\alpha\) forest tomography

With the Ly\(\alpha\) forest we get the line-of-sight sampling “for free”, so we just need to get the transverse sampling high enough.