Mapping the $z > 2$ Cosmic Web with 3D Ly$\alpha$ Forest Tomography

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The Cosmic Web and Cosmology

- Pattern of voids, filaments and nodes in the large-scale distribution of DM + baryons
- Caused by gravitational evolution of Gaussian random-phase initial conditions from inflation
- Detection of cosmic web in the 1980s was key evidence supporting inflationary cold dark matter paradigm
- Galaxy formation and evolution is influenced by cosmic web environment
- The evolution over time probes gravity models and the cosmological constant

Credit: Anatoly Klypin (NMSU) & Andrei Kravtsov (Chicago)
Cosmic Web from GAMA Redshift Survey

- 100k galaxy redshifts with AAOMega on 4m AAT

Only feasible in nearby Universe (z < 0.3)!

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Why study cosmic web at ‘Cosmic Noon’?

Peak of cosmic star-formation + AGN activity occurred at $z \sim 2 - 3$

Bouwens+2011

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Lyα Forest Tomography
Cosmic Web with Galaxy Redshifts at $z \sim 2$?

$D < 100 \text{ Mpc Local Universe}$
$(\Delta v = 2000 \text{ km s}^{-1} \text{ slice})$

Courtois et al 2013
Cosmic Web with Galaxy Redshifts at $z \sim 2$?

$D < 100 \text{ Mpc Local Universe}$
($\Delta v = 2000 \text{ km s}^{-1} \text{ slice}$)

Courtois et al 2013

$z = 2.3$
(COSMOS spectro-z’s)

COSMOS Collaboration

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Ly$\alpha$ Forest Tomography
Lyman-α Forest as Probe of $z > 2$ Universe

- Seen in quasar spectra in their restframe, $\lambda < 121.6\text{nm}$ wavelengths
- Caused by neutral hydrogen in the IGM
- Absorption is non-linear tracer of underlying LSS density in mildly overdense regime ($\rho/\langle \rho \rangle \sim \text{few}$), approximately:

$$\tau(x) \propto \frac{T_0^{0.7}}{\Gamma} \left( \frac{\rho(x)}{\langle \rho \rangle} \right)^{2-0.7(\gamma-1)}$$

- $T_0$, $\Gamma$, $\gamma$ are parameters governing the astrophysics of the photoionized IGM
- In this talk, I will ignore astrophysics and pretend the absorption is a direct tracer of density

Credit: AmSci/R. Simcoe

Ellison+2000
Ly$\alpha$ Forest Tomography

If the quasars have arcmin ($\sim$ Mpc) separations, can enable tomographic reconstruction full 3D absorption field (Pichon et al 2001, Caucci et al 2008, Lee et al 2014a)

But quasars (rare!) aren’t enough to pull this off. Need to also target faint (> 23rd mag) UV-bright star-forming galaxies!
Pilot Tomography Survey in COSMOS

- Pilot observations in 2014-2015 on COSMOS field (Lee+2014b, Lee+2016)
- LRIS spectrograph on 10.3m Keck-I telescope, Hawai’i
- Total $\sim 15$ hrs on-sky, $\sim 2$hr exposures per pointing
- 49 galaxies+QSOs within blue area $(11.8' \times 13.5')$
  $\rightarrow \sim 1100 \text{deg}^{-2}$ (c.f. $\sim 15 \text{deg}^{-2}$ in BOSS Ly$\alpha$)
Example Spectra

First systematic use of LBGs for Lyα forest analysis!

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Tomographic Reconstruction

Measure Lyα forest transmission $\delta_F = F/\langle F \rangle - 1$ ('data'), pixel noise estimates $\sigma_F$, and $[x, y, z]$ positions. Perform Wiener filtering on these inputs to estimate the map:

$$M = C_{MD} \cdot (C_{DD} + N)^{-1} \cdot D$$

The noise term provides some noise-weighting to the data. We assume Gaussian correlation function in the map, where $C_{DD} = C_{MD} = C(r_1, r_2)$, and

$$C(r_1, r_2) = \sigma_F^2 \exp \left[ -\frac{(\Delta r_\parallel)^2}{2L_\parallel^2} \right] \exp \left[ -\frac{(\Delta r_\perp)^2}{2L_\perp^2} \right], \quad (1)$$

with $L_\perp = 2.5 \, h^{-1} \, \text{Mpc}$ and $L_\parallel = 2.0 \, h^{-1} \, \text{Mpc}$, and $\sigma_F = 0.8$ (Note average sightline separation $\langle d_\perp \rangle \approx 2.5 \, h^{-1} \, \text{Mpc}$).
3D Map of Cosmic Web at $2.2 < z < 2.5$

$260 \, h^{-1} \, \text{Mpc along LOS}; \, 14 \, h^{-1} \, \text{Mpc} \times 16 \, h^{-1} \, \text{Mpc} \, \text{transverse} \rightarrow \\
V = 5.8 \times 10^4 \, h^{-3} \, \text{Mpc}^3 \sim (39 \, h^{-1} \, \text{Mpc})^3$

To watch online: https://youtu.be/KeW1UJ0PMYI
Correlations with Foreground Galaxies?

There are some known galaxies with spectroscopic redshifts overlapping the map volume. We can compare locations of 31 MOSDEF galaxies with the overall map PDF:

Galaxies clearly live in high-density regions of our map!
A Galaxy Protocluster at $z = 2.44$

See one large ($\sim 20 \, h^{-1} \, \text{Mpc})$ overdensity in our absorption map ($3\sigma$ significance)

Correlated with $z = 2.45$ galaxy protocluster from LBGs and LAEs (Diener+2015, Chiang+2015)

Comparison to sims gives descendant mass estimates:

$$M(z = 0) = (3 \pm 1.5) \times 10^{14} \, h^{-1} \, \text{Mpc}$$

($\sim$ Virgo cluster)

Elongated morphology suggests possible fragmentation into two $z \sim 0$ clusters

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*HETDEX Pilot LAEs (stars, Chiang+2015); LBGs (squares, Diener+2015); Open circles: sightline positions*
CLAMATO Survey
(COSMOS Lyman-Alpha Mapping And Tomography Observations)

- Co-PIs: Schlegel & White
- Upcoming LMAP proposal targeting \(~ 1\) sq deg of COSMOS field
- Require \(~ 240\)hrs on-sky with Keck-LRIS \(\rightarrow\) \(~ 30\) nights over 3 years
- Target \(~ 1000\) LBGs at \(2.3 \lesssim z \lesssim 3\) for \(R \sim 1000\) spectroscopy
  \(\rightarrow \langle z \rangle \sim 2.3\) LSS map over \(10^6 h^{-3}Mpc^3 \sim (100 h^{-1} Mpc)^3\)
- Similar spatial resolution \(\sim 3 h^{-1} Mpc\) and volume \(\sim 10^6 h^{-3} Mpc^3\) to GAMA survey at \(z < 0.3\)!
CLAMATO Survey
(COSMOS Lyman-Alpha Mapping And Tomography Observations)

- Co-PIs: Schlegel & White
- Upcoming LMAP proposal targeting $\sim 1$ sq deg of COSMOS field
- Require $\sim 240$hrs on-sky with Keck-LRIS $\rightarrow \sim 30$ nights over 3 years
- Target $\sim 1000$ LBGs at $2.3 \lesssim z \lesssim 3$ for $R \sim 1000$ spectroscopy
  $\rightarrow \langle z \rangle \sim 2.3$ LSS map over $10^6 h^{-3} \text{Mpc}^3 \sim (100 h^{-1} \text{Mpc})^3$
- Similar spatial resolution ($\sim 3 h^{-1} \text{Mpc}$) and volume ($\sim 10^6 h^{-3} \text{Mpc}^3$) to GAMA survey at $z < 0.3$!

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Lyα Forest Tomography
Casey Stark (UC Berkeley) studied detectability of $z \sim 2.5$ protoclusters and voids with Ly$\alpha$ forest tomography in sims (Stark+2015a, 2015b)

- **L** = $256 \, h^{-1} \, \text{Mpc}$ TreePM sim with IGM absorption from FGPA
- Generated DM density field and mock tomographic maps with sightline sampling + noise consistent with real data
- **Protoclusters**: Look for $3\sigma$ peaks in smoothed map, which gives $>90\%$ completeness and $\sim 75\%$ purity for $M > 3 \times 10^{14} \, h^{-1} \, M_\odot$ progenitors
- **Voids**: Search for spherical low-density regions in DM field and tomographic map $\rightarrow \sim 65\%$ volume overlap for $\sim 15\%$ filling factor
Voids and Protoclusters in CLAMATO

Right: Central part of COSMOS Field

- **Magenta**: CLAMATO 0.8 sq deg
- **Blue**: Pilot field (2014-2015)
- **Dots**: Photo-z and spectro-z

\[ z = 2.4 - 3.0 \text{ LBG targets} \]

Below: Simulated **protoclusters and voids** (approx to scale)

*Large area (> 1 sq deg) needed to resolve large structures!*

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Lyα Forest Tomography
Pushing Towards Cosmological Volumes

Lyα tomography will push towards large volumes over the next few years...

**CLAMATO (2016-2018):**
- LRIS Spectrograph on 10.3m Keck-I
- FOV: 7’ × 5’ (∼0.01deg²)
- Target ∼20 sources per FOV (g ≤ 24.7)
- Time: ∼40 nights to cover 0.8deg²
  → 2.3 < z < 2.5 Tomographic map probing
  ∼2.5 h⁻¹ Mpc over V ∼10⁶ h⁻³ Mpc

IGM Tomography Survey on Subaru-PFS (2019- )?
- Prime Focus Spectrograph on 8.2m Subaru Telescope
- FOV: 1.2deg²
- Target ∼2000 sources per FOV (g ≤ 24.0)
- Time: 10 nights to cover 15deg² with 6hrs per pointing
  → 2.5 < z < 3.2 Tomographic map probing
  ∼5 h⁻¹ Mpc over V ∼10⁸ h⁻³ Mpc
Pushing Towards Cosmological Volumes

Ly\(\alpha\) tomography will push towards large volumes over the next few years...

**CLAMATO (2016-2018):**
- LRIS Spectrograph on 10.3m Keck-I
- FOV: 7’ \(\times\) 5’ (\(\sim\) 0.01deg\(^2\))
- Target \(\sim\) 20 sources per FOV (\(g \leq 24.7\))
- Time: \(\sim\) 40 nights to cover 0.8deg\(^2\)
  \(\rightarrow\) \(2.3 < z < 2.5\) Tomographic map probing
  \(\sim 2.5\ h^{-1}\ Mpc\) over \(V \sim 10^6\ h^{-3}\ Mpc\)

**IGM Tomography Survey on Subaru-PFS (2019- )?**
- Prime Focus Spectrograph on 8.2m Subaru Telescope
- FOV: 1.2deg\(^2\)
- Target \(\sim\) 2000 sources per FOV (\(g \leq 24.0\))
- Time: 10 nights to cover 15deg\(^2\) with 6hrs per pointing
  \(\rightarrow\) \(2.5 < z < 3.2\) Tomographic map probing
  \(\sim 5\ h^{-1}\ Mpc\) over \(V \sim 10^8\ h^{-3}\ Mpc\)
Tomographic Survey Planning for PFS

- Exposure times required to make tomographic maps at various resolutions. Different curves show different map quality.

- Black dotted line: 3 hr exposures from PFS Galaxy Evolution Survey of $i < 24$ LBGs (Takada+2013).

- Red dashed line: Additional exposures → 6 hrs to build up S/N will enable a good-quality map sampling 5 $h^{-1}$ Mpc in same volume as PFS galaxy redshifts!
Classifying the Cosmic Web (Lee & White 2016)


Analyze deformation tensor of density field:

\[
T_{ij} = \frac{\partial^2 \Phi}{\partial x_i \partial x_j}
\]

Easy to do in Fourier space, since \( \nabla^2 \tilde{\Phi} = k^2 \tilde{\Phi} = 4\pi G \delta_k \):

\[
\tilde{T}_{ij} = \frac{k_i k_j \delta_k}{k^2}
\]  \hspace{1cm} (2)

Compute 3 eigenvalues at each point, and count \# above eigenvalue threshold \( \lambda_{th} \):

- No eigenvalue above threshold: void
- 1 eigenvalue above threshold: sheet
- 2 eigenvalues above threshold: filament
- 3 eigenvalues above threshold: node/knot

For Ly-a forest flux field \( \delta_f = F/\langle F \rangle - 1 \), just flip the signs!
Classifying the $z = 2.5$ Cosmic Web with CLAMATO

Analyzed $L = 256 \, h^{-1} \, \text{Mpc}$ FGPA sim to find voids (white), sheets, filament, nodes

CLAMATO-like: $\langle d_\perp \rangle = 2.5 \, h^{-1} \, \text{Mpc}$
Classifying the $z = 2.5$ Cosmic Web with PFS Tomography

Voids (white), sheets, filament, nodes

PFS-like: $\langle d_\perp \rangle = 4.0 \, h^{-1} \, \text{Mpc}$
Flux-Mass Relationship on $4\, h^{-1}\text{ Mpc}$ Scales

DM Overdensity

Flux in Mock CLAMATO Map

K.G. Lee Lyα Forest Tomography
Halo Abundances in Different Densities

Computed halo multiplicity function as function of different overdensities/flux (Error bars: 1σ scatter from CLAMATO-like subvolumes)

\[ f(\ln M) \, d\ln M = \frac{M}{\bar{\rho}} \frac{dn}{d\ln M} \, d\ln M \]

DM Density and d25 Flux (R_g=4.0 h^-1 Mpc)
Halo Abundances in Different Densities

Computed halo multiplicity function as function of different overdensities/flux (Error bars: 1σ scatter from CLAMATO-like subvolumes)

$$f(\ln M) \, d\ln M = \frac{M}{\bar{\rho}} \frac{dn}{d\ln M} \, d\ln M$$

CLAMATO map will deliver estimates of local density/halo-mass scale at any point within its volume!
Conclusion

- Observations of $z \sim 2 - 3$ QSOs + LBGs at high area densities allow 3D reconstructions of foreground Ly$\alpha$ forest absorption
- Ideal for detecting extended $z \sim 2$ structures: voids + protoclusters
- Good recovery of cosmic web sheets and filaments — comparable to $z \sim 0.1$ galaxy surveys!
- Ly$\alpha$ absorption is proxy for density $\rightarrow$ halo mass!
  - Will deliver Ly$\alpha$ absorption maps of $2.2 < z < 2.5$ cosmic web with high fidelity probing $\sim 3 \, h^{-1} \, \text{Mpc}$ scales
  - Cover cosmological volume ($V \sim 10^6 \, h^{-3} \, \text{Mpc}^3$) while simultaneously
  - $\sim 500$ coeval galaxies from other surveys will enable studies of galaxy evolution in context of Cosmic Web
- Subaru-PFS will be very powerful for large-volume surveys of $z = 2.5 - 3.5$ IGM, and together with coeval galaxies will reveal the interplay between the Cosmic Web and galaxy evolution.