Mapping the $z > 2$ Cosmic Web with 3D Lyα Forest Tomography

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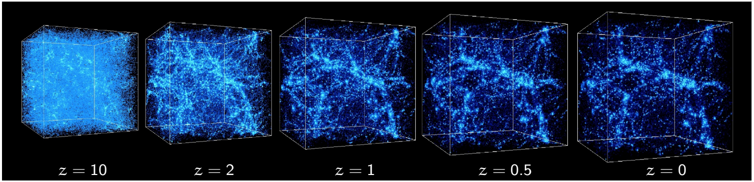
The Cosmic Web and Cosmology

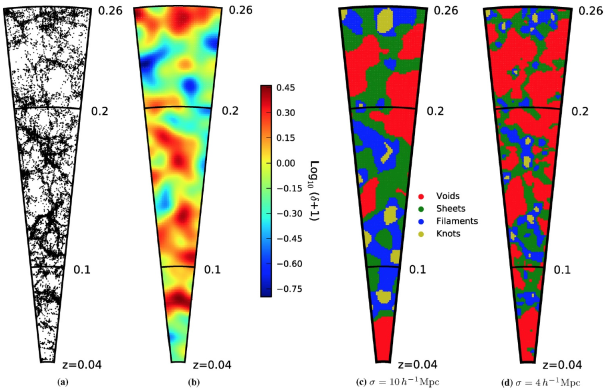


Credit: Anatoly Klypin (NMSU) & Andrei Kravtsov (Chicago)

- 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

Cosmic Web from GAMA Redshift Survey

- 100k galaxy redshifts with AAOMega on 4m AAT

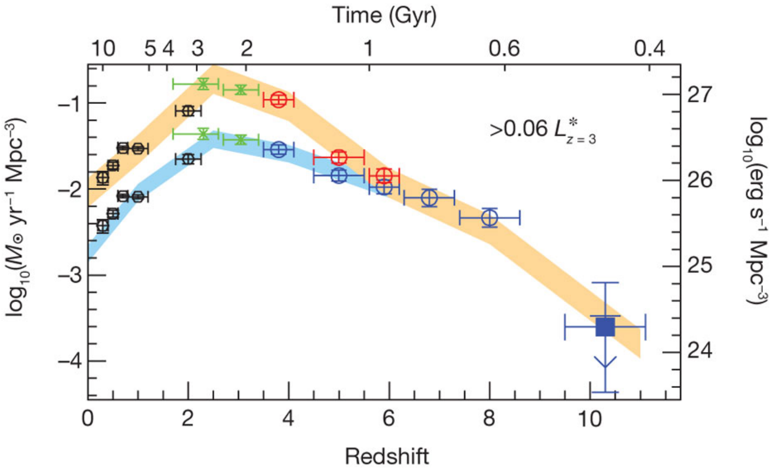


Eardley+ 2015

Only feasible in nearby Universe ($z < 0.3$)!

Why study cosmic web at 'Cosmic Noon'?

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

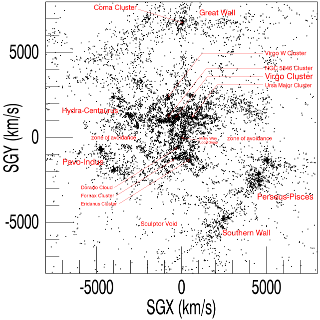


Bouwens+2011

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

D < 100 Mpc Local Universe

($\Delta v = 2000$ km s^{-1} slice)



Courtois et al 2013

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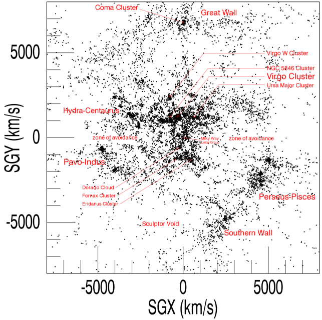
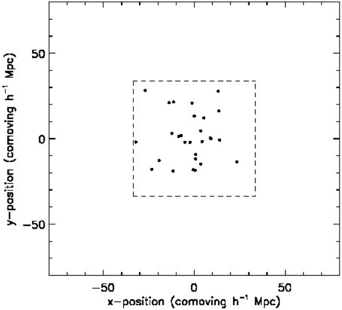


Courtois et al 2013

$z = 2.3$
(COSMOS spectro-z's)



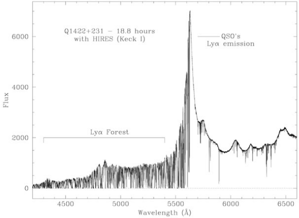
COSMOS Collaboration

Lyman-α Forest as Probe of $z > 2$ Universe

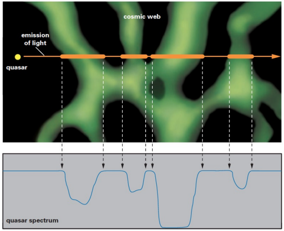
- Seen in quasar spectra in their restframe $\lambda < 121.6$nm wavelengths
- Caused by neutral hydrogen in the IGM
- Absorption is non-linear tracer of underlying LSS density in mildly overdense regime ($\rho/\langle\rho\rangle \sim$ few), approximately:

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

- T_0, Γ, γ 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**



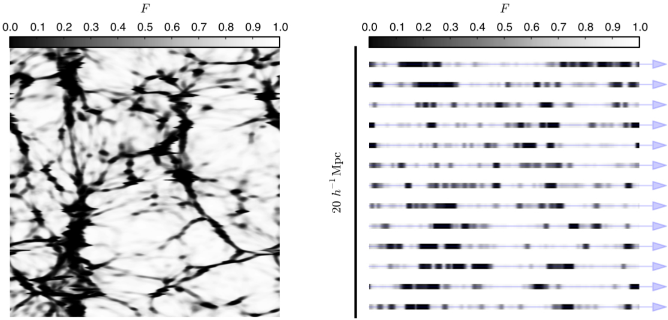
Ellison+2000



Credit: AmSci/R. Simcoe

Lyα 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)

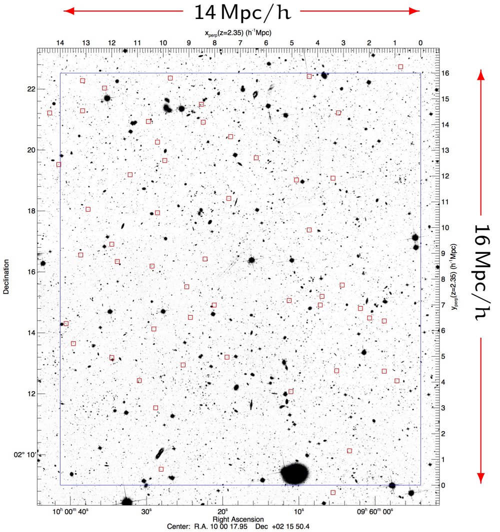


Credit: Casey Stark (Berkeley)

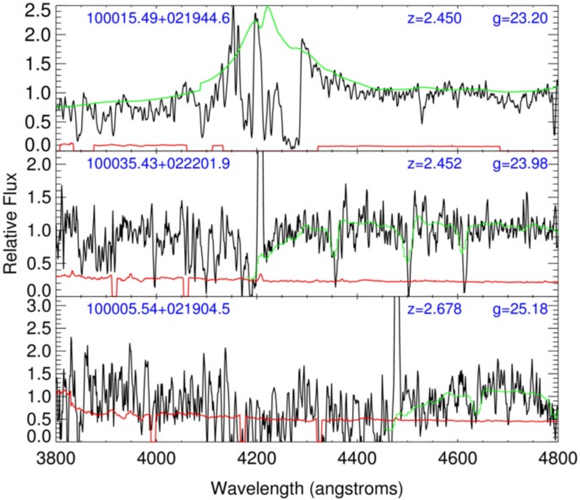
But quasars (rare!) aren't enough to pull this off. Need to also target faint (> 23rd mag) UV-bright star-forming galaxies!

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, $\sim$ 2hr exposures per pointing
- 49 galaxies+QSOs within blue area ($11.8' \times 13.5'$) $\rightarrow \sim 1100\,\mathrm{deg}^{-2}$ (c.f. $\sim 15\,\mathrm{deg}^{-2}$ in BOSS Lyα)



Example Spectra



First systematic use of LBGs for Lyα forest analysis!

Tomographic Reconstruction

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

$$\mathbf{M} = \mathbf{C}_{\mathrm{MD}} \cdot (\mathbf{C}_{\mathrm{DD}} + \mathbf{N})^{-1} \cdot \mathrm{D}$$

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

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

with $L_{\perp} = 2.5h^{-1}$ Mpc and $L_{\parallel} = 2.0\,h^{-1}$ Mpc, and $\sigma_F = 0.8$ (Note average sightline separation $\langle d_{\perp} \rangle \approx 2.5\,h^{-1}$ Mpc).

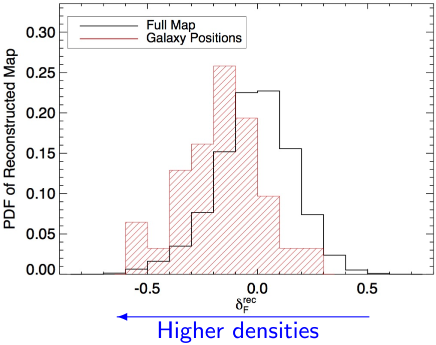
3D Map of Cosmic Web at $2.2 < z < 2.5$

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

To watch online: `https://youtu.be/KeW1UJOPMYI`

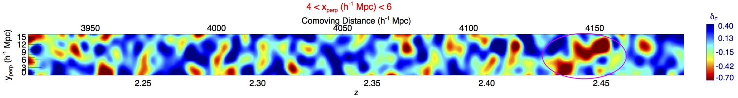
Correlations with Foreground Galaxies?

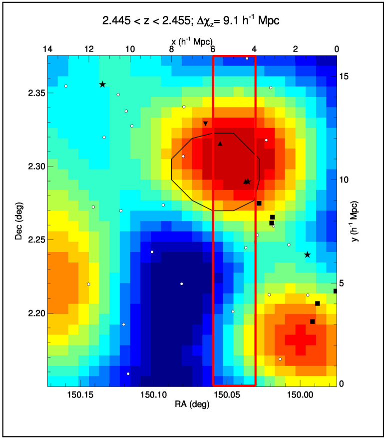
There are some known galaxies with spectroscopic redshifts overlapping the map volume. We can compare locations of 31 MOSDEF galaxies with the overall map PDF:



Galaxies clearly live in high-density regions of our map!

A Galaxy Protocluster at $z = 2.44$





HETDEX Pilot LAEs (stars, Chiang+2015); LBGs (squares, Diener+2015); Open circles: sightline positions

- See one large ($\sim 20\,\mathrm{h}^{-1}$ Mpc) overdensity in our absorption map (3σ significance)
- Correlated with $z = 2.45$ galaxy protocluster from LBGs and LAEs (Diener+2015, Chiang+2015)
- Comparison to sims gives descendant mass estimates: $M(z=0) = (3 \pm 1.5) \times 10^{14}\,\mathrm{h}^{-1}$ Mpc ($\sim$ Virgo cluster)
- Elongated morphology suggests possible fragmentation into two $z \sim 0$ clusters

CLAMATO Survey
(COSMOS Lyman-Alpha Mapping And Tomography Observations)

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

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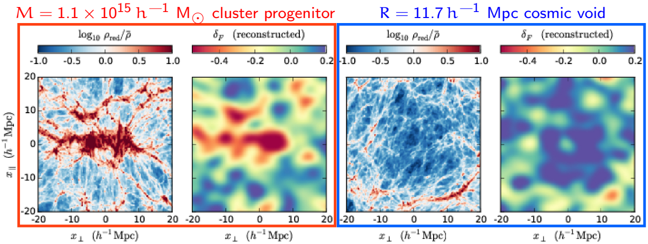
Voids and Protoclusters



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

- $L = 256\,h^{-1}$ 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 3σ 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

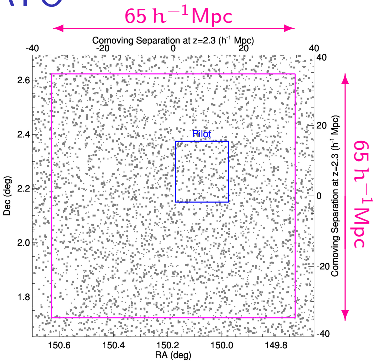
Voids and Protoclusters in CLAMATO

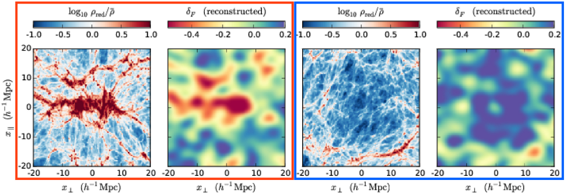
Right: Central part of COSMOS Field

Magenta	CLAMATO 0.8 sq deg
Blue	Pilot field (2014-2015)
Dots	Photo-z and spectro-z $z = 2.4 - 3.0$ LBG targets

Below: Simulated protoclusters and voids (approx to scale)

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

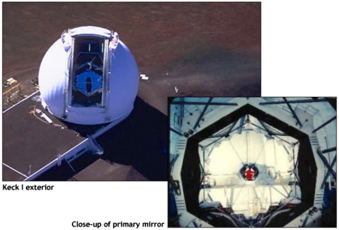




Pushing Towards Cosmological Volumes

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

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



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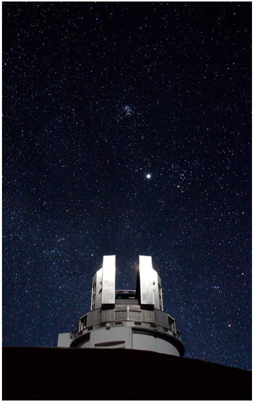
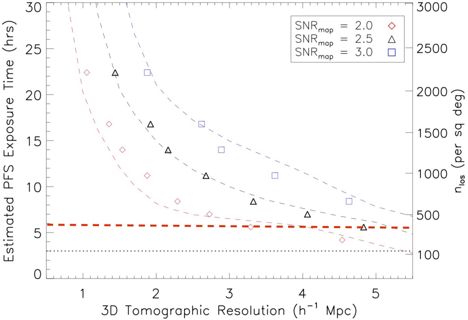
- IGM Tomography Survey on **Subaru-PFS (2019-)?**
  - Prime Focus Spectrograph on 8.2m Subaru Telescope
  - FOV: $1.2\mathrm{deg}^2$
  - Target ~ 2000 sources per FOV ($g \leqslant 24.0$)
  - Time: 10 nights to cover $15\mathrm{deg}^2$ with 6hrs per pointing
    $\rightarrow 2.5 < z < 3.2$ Tomographic 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: 3hr exposures from PFS Galaxy Evolution Survey of $i < 24$ LBGs (Takada+2013).
- Red dashed line: Additional exposures → 6hrs 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)

After Zel'dovich 1970 (... Hahn+2007, Forero-Romero+2009, Eardley+2015).
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 $\nabla^2 \tilde{\Phi} = k^2 \tilde{\Phi} = 4\pi G \delta_k$:

$$\tilde{T}_{ij} = \frac{k_i k_j \delta_k}{k^2} \quad (2)$$

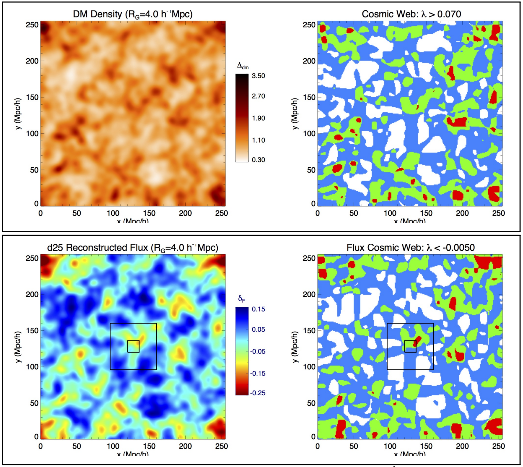
Compute 3 eigenvalues at each point, and count # above eigenvalue threshold λ_{th}:

- 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

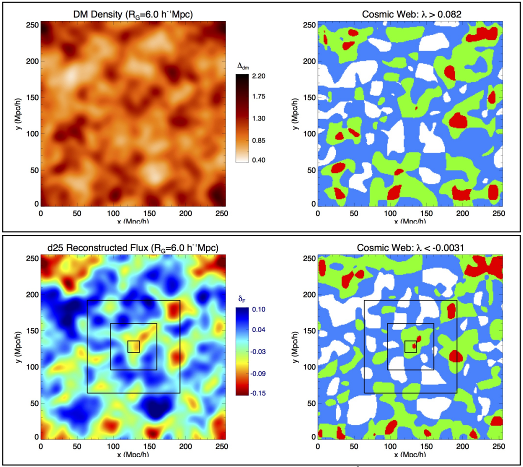
Analyzed $L = 256\,h^{-1}$ Mpc FGPA sim to find voids (white), sheets, filament, nodes



CLAMATO-like: $\langle d_\perp \rangle = 2.5\,h^{-1}$ Mpc

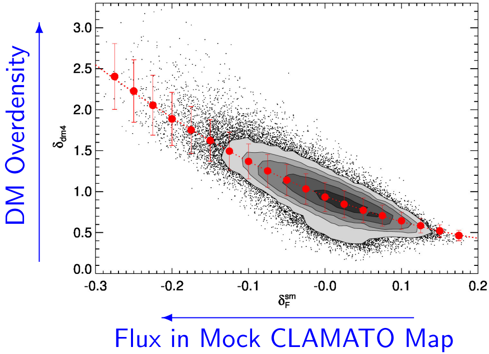
Classifying the $z = 2.5$ Cosmic Web with PFS Tomography

Voids (white), sheets, filament, nodes



PFS-like: $\langle d_\perp \rangle = 4.0\, h^{-1}$ Mpc

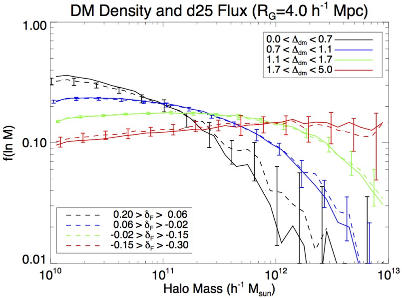
Flux-Mass Relationship on $4\,h^{-1}$ Mpc Scales



Halo Abundances in Different Densities

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

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



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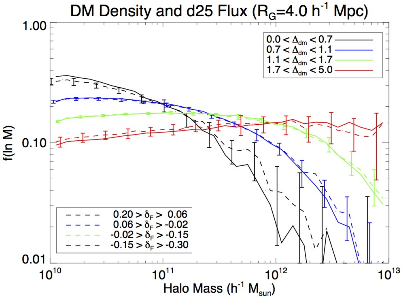

CLAMATO map will deliver estimates of local density/halo-mass scale at any point within its volume!

Conclusion

- Observations of $z \sim 2-3$ QSOs + LBGs at high area densities allow 3D reconstructions of foreground Lyα 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!
- Lyα absorption is proxy for density $\rightarrow$ halo mass!
- CLAMATO Survey on Keck-I/LRIS (2015-2019):
  - Will deliver Lyα absorption maps of $2.2 < z < 2.5$ cosmic web with high fidelity probing $\sim 3\,\mathrm{h}^{-1}$ Mpc scales
  - Cover cosmological volume ($V \sim 10^6\ \mathrm{h}^{-3}\,\mathrm{Mpc}^3$) while simultaneously
  - ~ 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.