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

IGM@50 Conference, Spineto, Italy

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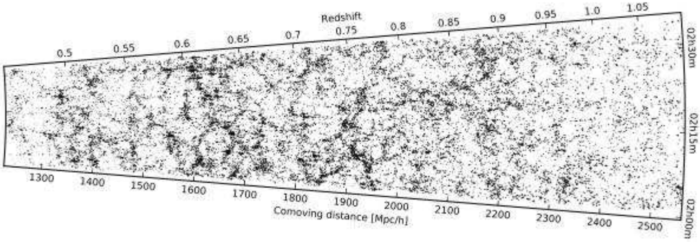
Mapping the Cosmic Web wth Galaxy Redshift Surveys

Ability to map LSS depends on the average galaxy separations, e.g. SDSS Main Galaxy Sample ($z \leqslant 0.3$) has average galaxy separation $\sim 8\,\mathrm{h}^{-1}$ Mpc. At $z = [0.5, 1.0, 2.0]$, need to go to $\mathrm{I} \approx [22.5, 24.2, 25.7]$ to reach same separation.



24 deg^2 VIPERS Survey on the ESO VLT, Guzzo et al 2014

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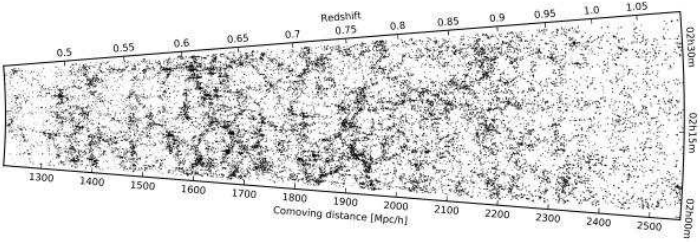
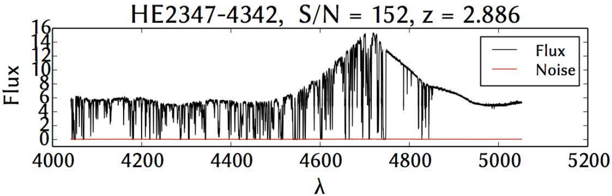


$24\,\mathrm{deg}^2$ VIPERS Survey on the ESO VLT, Guzzo et al 2014

Direct mapping of $z > 1$ LSS with galaxy redshifts only feasible with 30m telescopes!

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

Restframe 1215.67 Å Lyman-α absorption caused by neutral hydrogen in front of background QSO. This transition redshifts into optical wavelengths at $z > 2$.



Credit: Michael Walther (MPIA)

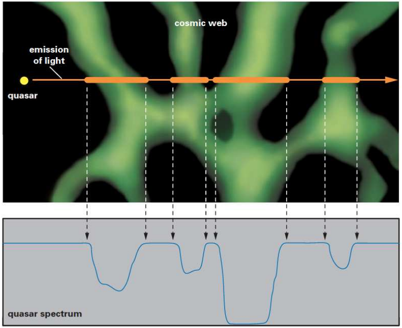
We observe the transmitted flux $F = f/C = \exp(\tau)$ caused by optical depth τ. This absorption is seen over $\sim 300 - 500$ Mpc along the quaar line-of-sight before Lyβ kicks in.

Lyα Forest as a Probe of the Cosmic Web

In the modern 'fluctuating Gunn-Peterson' model, the Lyα absorption traces the quasi-linear matter overdensity, $\Delta \equiv \rho_{dm}(x)/\langle\rho_{dm}\rangle$, probing the range $0 \gtrsim \Delta \gtrsim 10$. This is modulated by IGM astrophysics

$$\tau(x) \propto \frac{T_0^{-0.7}}{\Gamma}\Delta(x)^{2-0.7(\gamma-1)}$$

- IGM temperature at mean density, T_0
- UV background ionization rate, Γ
- Temperature-density relationship, γ (where $T(\Delta) \propto \Delta^{\gamma-1}$)



Credit: AmSci/R. Simcoe

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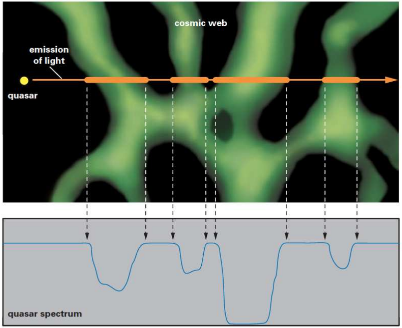
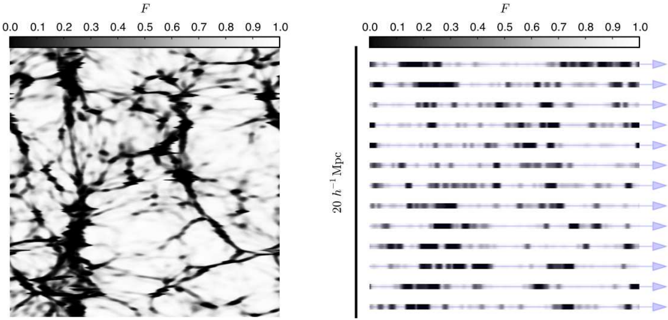


Credit: AmSci/R. Simcoe

In this talk, I assume that the Lyα forest traces large-scale structure **not** *'gas'!*

Lyα Forest Tomography

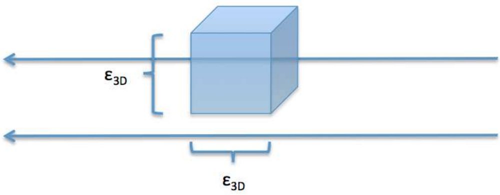
Collection of closely-separated sightlines enable tomographic reconstruction of 3D absorption field on scales comparable to sightline separation (Pichon et al 2001, Caucci et al 2008, Lee et al 2014)



Credit: Casey Stark (Berkeley)

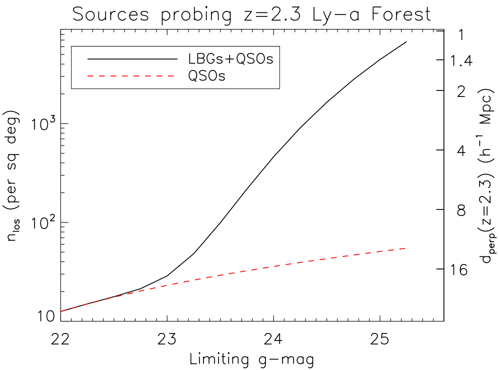
Source separation vs map resolution

The sightline separation, $\langle d_\perp \rangle$, is the basic consideration for IGM tomography. For maps with 3D resolution ϵ_{3D}, expect to need $\langle d_\perp \rangle \lesssim \epsilon_{3D}$.



LBGs as Lyα Forest Background Sources?

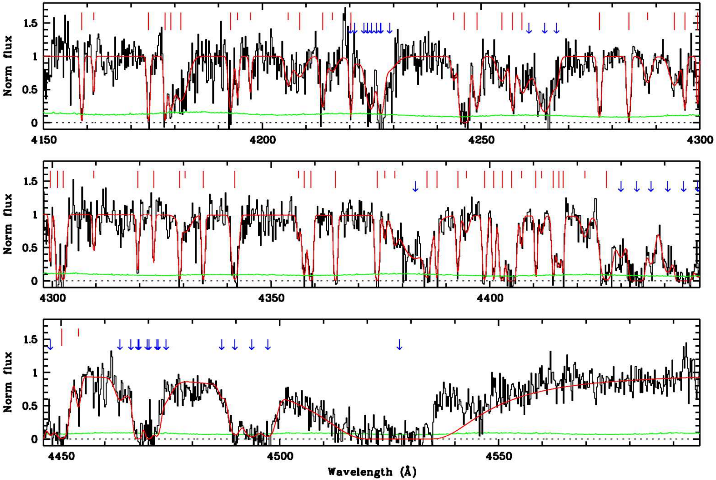
QSO luminosity function (Palanque-Delabrouille +2013) rises too slowly to provide sufficient background sources to sample the Lyα forest.



With LBGs, exponential increase of source density, $n_{\rm los} \propto 10^{m}$. Source separation is $\langle d_{\perp} \rangle \sim 2.5\, h^{-1}$ Mpc at $g \leqslant 24.5$.

High-Resolution Spectrum of a Lensed LBG

The $z = 2.724$ LBG MS 1512-cB58 is lensed ($\sim 50\times$) to V ~ 20.6



Savaglio et al 2001 (12hrs exposure per order on VLT-UVES)

Observational Requirements for Lyα Forest Tomography

LBGs are much fainter than QSOs ($m \sim 24$), so it was assumed that 30m-class telescopes would be required for tomography, but never any detail analysis of requirements.

In Lee et al 2014a (ApJ 788, 49), I argued using sims and analytic calculations:

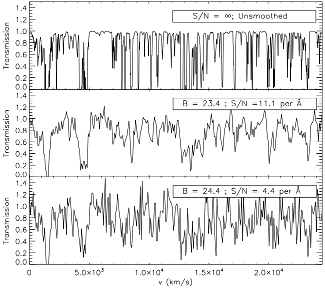
- No need to resolve individual Lyα absorbers: $R \sim 1000$ is adequate
- $S/N \sim 3-4$ per Å is sufficient at the survey limit
- At reconstruction scales of $\epsilon_{3D} > 2\,h^{-1}$ Mpc, still in shot-noise limited regime so $\langle d_\perp \rangle < \epsilon_{3D}$ is helpful

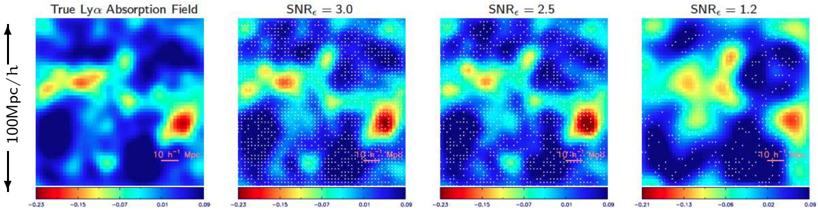
Simulated Tomographic Reconstructions

Reconstructions using mock spectra with realistic sampling and spectral S/N. Transverse maps smoothed on $\sigma = 3.5\,h^{-1}$ Mpc scale (left to right):

- $n_{\rm los} = 971{\rm deg}^{-2}$, $t_{\rm exp} = 8{\rm hrs}$
- $n_{\rm los} = 657{\rm deg}^{-2}$, $t_{\rm exp} = 6{\rm hrs}$
- $n_{\rm los} = 112{\rm deg}^{-2}$, $t_{\rm exp} = 2{\rm hrs}$

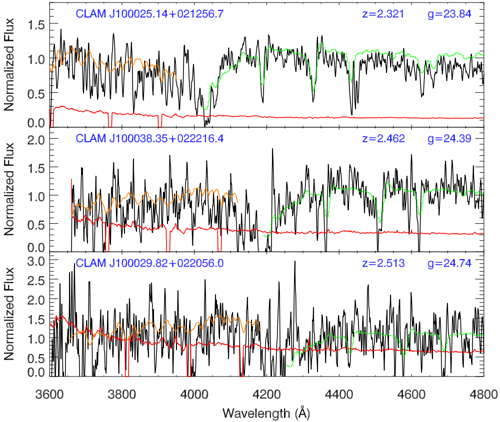
(Exposure times assuming VLT VIMOS spectrograph)





Pilot Observations on Keck, March 2014

Observing run with LRIS spectrograph on 10m Keck-I telescope, Hawai'i. Suffered $\sim 70\%$ weather loss, but from 4hrs on-sky obtained 24 LBG spectra at $2.3 < z < 2.8$

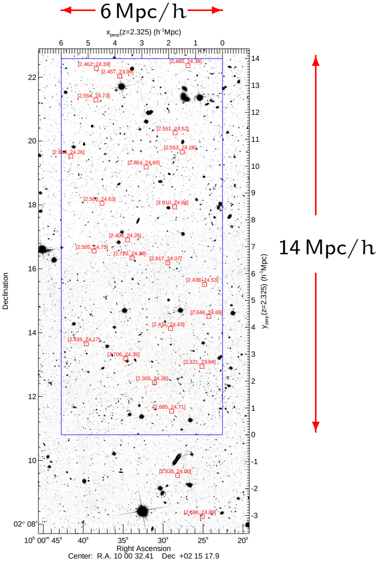


Brightest: $g = 23.84$

Median: $g = 24.39$

Faintest: $g = 24.74$

COSMOS/CANDELS/3D-HST Field



Tomographic Reconstruction

We now have extracted 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:

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

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

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

with $L_\perp = 3.5h^{-1}$ Mpc and $L_\parallel = 2.7\,h^{-1}$ Mpc, and $\sigma_F = 0.8$.

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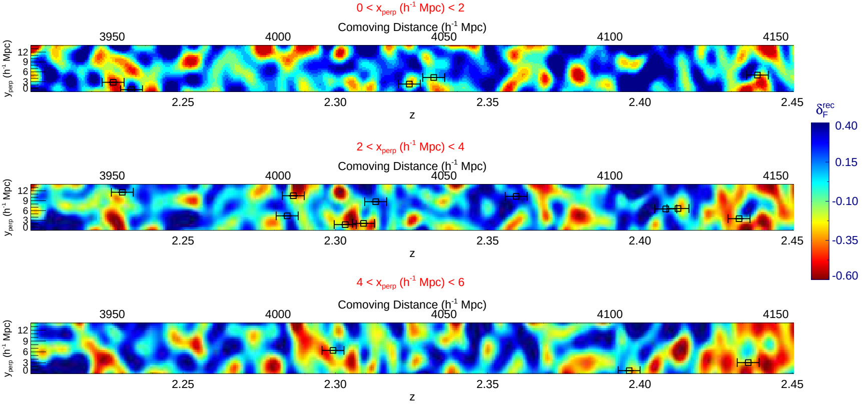
with $L_{\perp} = 3.5h^{-1}$ Mpc and $L_{\parallel} = 2.7\,h^{-1}$ Mpc, and $\sigma_F = 0.8$.

Super-efficient implementation by Casey Stark (Berkeley), see (arXiv:1412.1507), I just wait 1 min on my laptop....

First 3D Map of Cosmic Web at $z > 2$

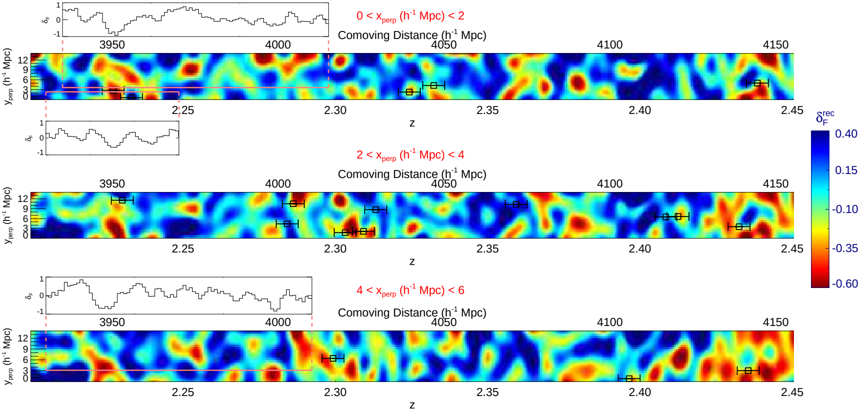
$$V = (6 \times 14)\,\mathrm{h}^{-2}\mathrm{Mpc}^2 \times 230\,\mathrm{h}^{-1}\ \mathrm{Mpc} \approx 1.93 \times 10^4 \mathrm{h}^{-3}\mathrm{Mpc}^3 \approx (27\,\mathrm{h}^{-1}\ \mathrm{Mpc})^3$$

Pilot Map in Slices



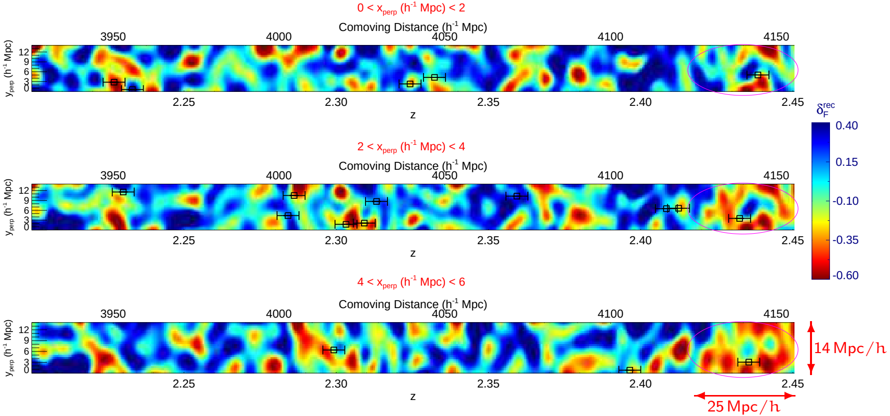
Squares: 18 coeval galaxies (mostly zCOSMOS-Deep) with known spectro-z's within map, error bars are estimated 1σ redshift errors.

Pilot Map in Slices



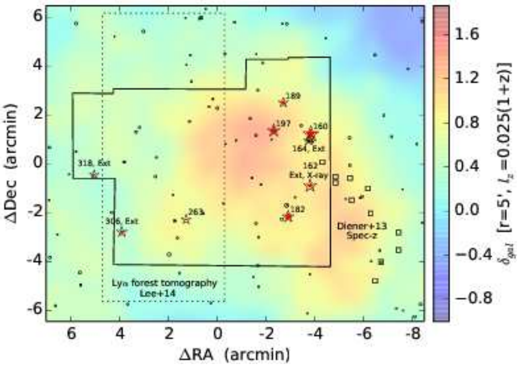
Overdensities seen in the map are typically probed by multiple independent sightlines

Pilot Map in Slices



Hints of a huge overdensity at z=2.43?

A Large Protocluster at $z = 2.44$?



Credit: Yi-Kuan Chiang (UT Austin)

Color Scale	Overdensity of photo-z candidates
Stars	HETDEX Pilot Survey (Chiang et al, submitted)
Squares	zCOSMOS spectro-z's from Diener et al 2015

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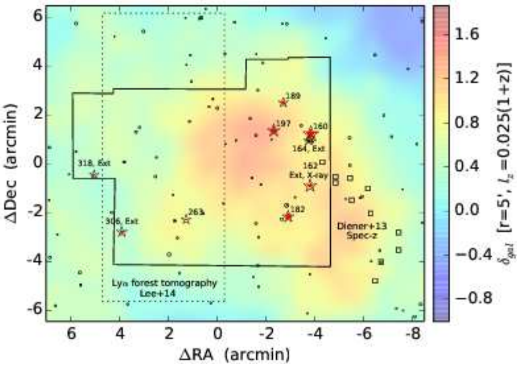

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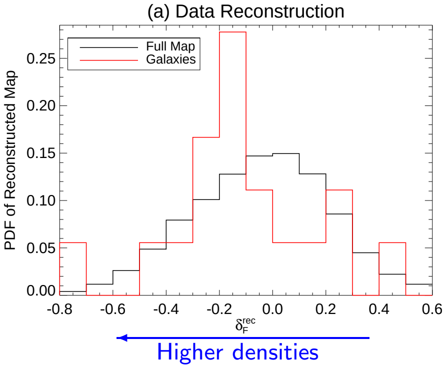
See Yi-Kuan Chiang's poster!

Do Galaxies Live in Overdensities on $3 - 4$ Mpc Scales?

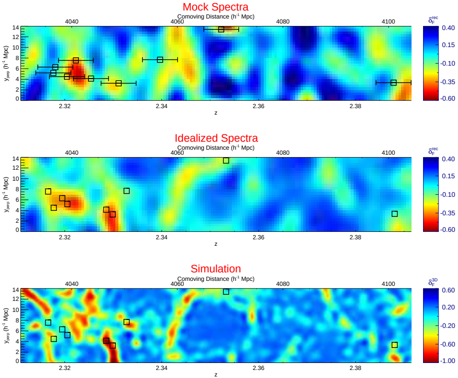
We evaluate the δ_F values at the 18 galaxy positions, and compare with the full map. Bias towards higher overdensities, but also a few in lower-density regions.



This is due to redshift uncertainties in the foreground galaxies + reconstruction errors. **More volume + galaxies needed for better measurements!**

Comparison with Simulations

We took Lyα forest skewers from sims, and created mock data with exactly the same sightline geometry and S/N as real data. We also have positions of DM halos corresponding to $R \leqslant 25.5$ (abundance-matched)



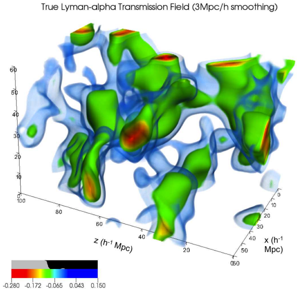
- There are reconstruction errors, but our data quality should reproduce broad LSS features
- Redshift errors will also scatter galaxies out of overdensities

CLAMATO Survey

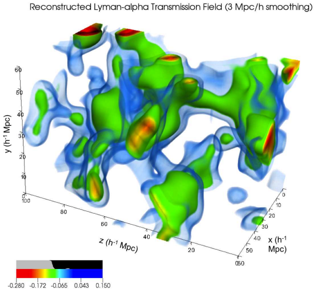
(COSMOS Lyman-Alpha Mapping And Tomography Observations)

- Proposed survey targeting 0.8 sq deg of COSMOS field (~ 30 nights on Keck)
- 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 $10^6 h^{-3} \mathrm{Mpc}^3 \sim (100\, h^{-1}\ \mathrm{Mpc})^3$

Simulation Field



Mock CLAMATO Reconstruction

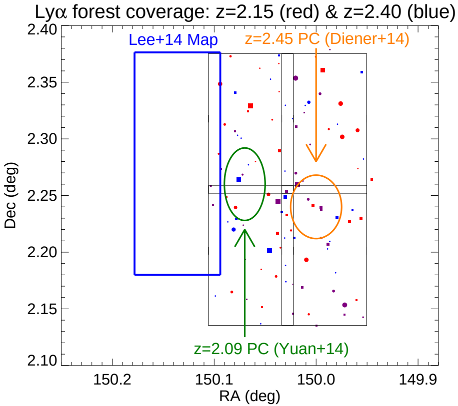


Dimensions: $(65\ \mathrm{Mpc})^2 \times (100\ \mathrm{Mpc})$


Cóctel de Tomate
Clamato
60
32FL.OZ (1QT) 946mL

CLAMATO: State of the Union

Keck/LRIS Run 2015 April 16-21: 4 masks targeting $z = 2.15 - 2.40$ and 1 mask targeting $z = 2.09$ protocluster



Upcoming large program proposal beginning 2016A.

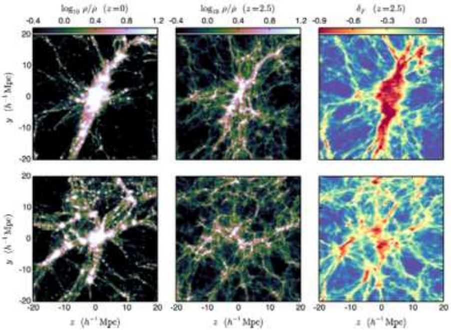
Hunting Protoclusters with Lyα Tomography

Stark, White, Lee & Hennawi (arXiv:1412.1507): studied progenitors of simulated $M > 10^{14} M_\odot$ clusters at $z = 2.5$

$z = 0$ DM $z = 2.5$ DM $z = 2.5$ Lyα

$M = 9 \times 10^{14} M_\odot$

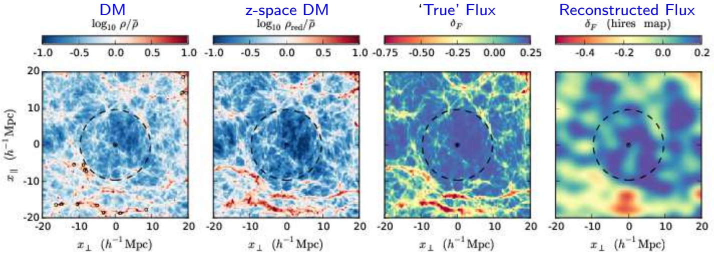
$M = 3 \times 10^{14} M_\odot$



- Protoclusters are $r \sim 5$ Mpc overdensities in Lyα absorption
- CLAMATO will find $M > 3 \times 10^{14} M_\odot$ progenitors with $\sim 90\%$ purity and $\sim 75\%$ completeness $\rightarrow N \sim 5$ in $10^6\ h^{-3}\mathrm{Mpc}^3$
- Even with known protoclusters, can characterize full 3D morphology, e.g. collapsing along single axis vs more isotropically

Detecting High-z Voids with CLAMATO

Stark, Font-Ribera, White & Lee (submitted): look for LSS voids with simulated Lyα forest tomography



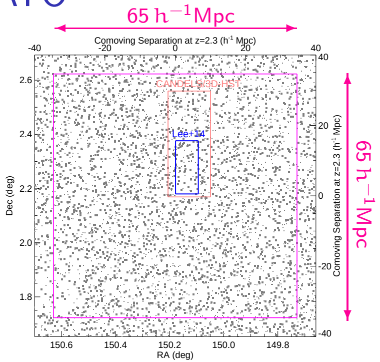
R $= 11.7\,\mathrm{h}^{-1}$ Mpc void, Stark+2015

- Used simple spherical finder: grow spheres around minima until some $\bar{\rho}$.
- CLAMATO will be able to pick up $\mathrm{R} \geqslant 6\,\mathrm{h}^{-1}$ Mpc voids with $\sim 70\%$ purity and $\sim 60\% \rightarrow \sim 100$ voids within CLAMATO volume
- Synergy with JWST-NIRSPEC to study sub-L_* void galaxies in the $z \sim 2-3$ accretion era?

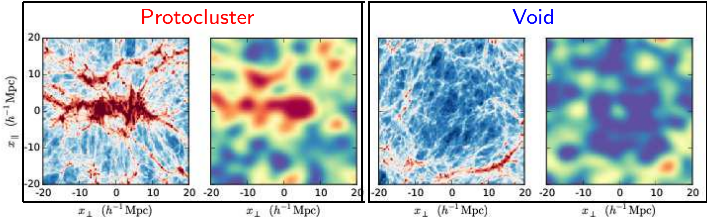
Voids and Protoclusters in CLAMATO

Right: Central part of COSMOS Field

Magenta	CLAMATO 0.8 sq deg
Orange	CANDELS/3D-HST footprint
Blue	Lee+2014 Pilot field
Dots	Photo-z and spectro-z $z = 2.4 - 3.0$ LBG targets



Below: Simulated protoclusters and voids (approx to scale)



Other Science with CLAMATO

- *Finding and characterizing high-z protoclusters*
- *Finding and characterizing high-z voids*
- *Galaxy Environments: How do high-z galaxy properties (e.g. SFR, metallicity, AGN activity) correlate with their large-scale IGM environment*
- *Decomposing high-z LSS into filaments, sheets and nodes*
- *First measurement of LSS topology at $z > 2$, e.g. genus or Euler characteristics*
- *Cross-correlating Lyα forest with LBGs and LAEs: first detections of RSD from these population + better bias measurements*
- *Small-scale 3D power spectrum of the Lyα forest: independent constraints on cosmological parameters e.g. σ_8 and m_ν*
- *Refining photometric redshifts with tomographic LSS as a prior*

Pushing Tomography Towards Smaller Scales

8-10m class telescopes can perform IGM tomography down to scales of $\sim 3-4\,\mathrm{h}^{-1}$ Mpc or $\sim 1.5-2$pMpc, too coarse to resolve IGM/CGM interface ($\sim$ 100pkpc). This will require 30m-class telescopes.

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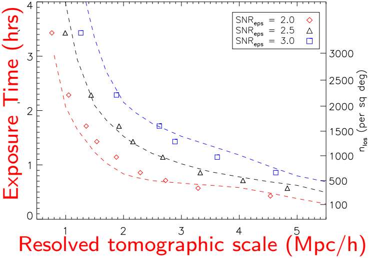
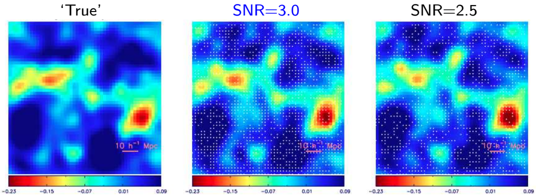
- Right: Exposure time required to achieve different tomographic resolutions with GMT/GMACS
- Different curves are different 'map SNR' (e.g. below) defined by Var(true)/Var(map-true).
- 4hr integrations will push down to 500pkpc scales

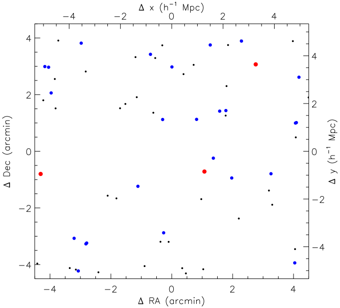




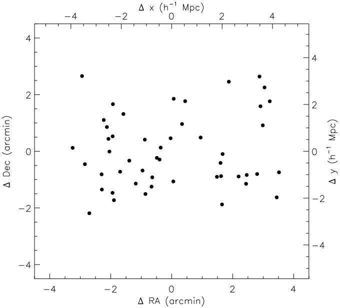
Protocluster Galaxies as Background Sources

In addition to studying protoclusters in the foreground, we can also use known protocluster galaxies as background sources for high-resolution tomography in the foreground.

COSMOS Field



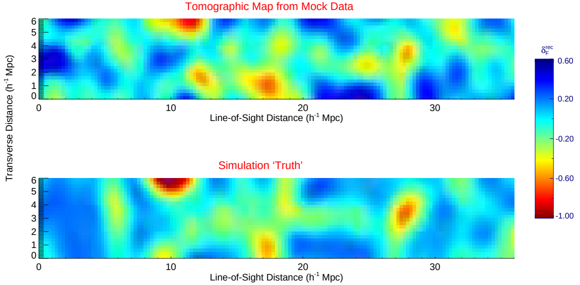
HS1549+19 $z = 3.1$



Average source separation of $g < 25$ galaxies is $\langle d_\perp \rangle \sim 1.5\,h^{-1}$ Mpc from protocluster sources vs $\langle d_\perp \rangle \sim 3-4\,h^{-1}$ Mpc in field.

Detailed IGM Mapping through Protocluster Lines-of-Sight (DIMPLS)

Reconstructions resolving scales of 400kpc, directly detect cosmic web filaments at $z \sim 2.6$



Simulated reconstructions resolving $\epsilon_{3D} \sim 1.5\,h^{-1}$ Mpc *(400pkpc)*

Upcoming observations:

- 35hrs (Priority 'B') on HS1549 with VLT-FORS2
- 6 nights on SSA22 with Keck-DEIMOS

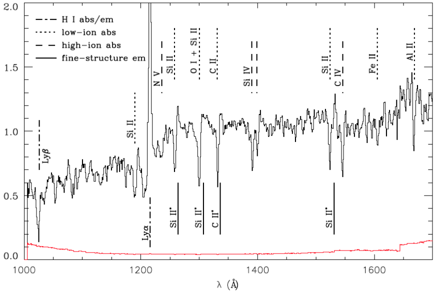
Summary

- **First** exploitation of LBGs as Lyα forest background sources
  - Faintest-ever ($g \sim 24.5$ vs $g \sim 21.5$ for BOSS) and densest-ever source densities ($\sim 1000\,\mathrm{deg}^{-2}$ vs $\sim 10\,\mathrm{deg}^{-2}$ for BOSS)
- **First** large-scale structure map of the $z > 2$ universe (from 1/2 night of data!)
- Ongoing CLAMATO survey:
  - Survey ~ 1000 LBGs ($z \sim 2 - 3$) in $0.8\,\mathrm{deg}^2$ field
  - Will yield 3D Lyα forest tomographic map with $\sim 3\,h^{-1}$ Mpc spatial resolution over $\sim (100\,h^{-1}\ \mathrm{Mpc})^3$
  - Time requirement: ~ 30 nights on Keck-LRIS (inc weather overhead)
  - Science: cosmic web studies at $z > 2$, hunting galaxy protoclusters and high-z voids, galaxy properties as function of environment....
- Over the next few years, use protoclusters as background sources to probe IGM-CGM interface before 30m-class telescope come online

All simulation products available at
`http://tinyurl.com/lya-tomography-sim-data`

Continuum Estimation

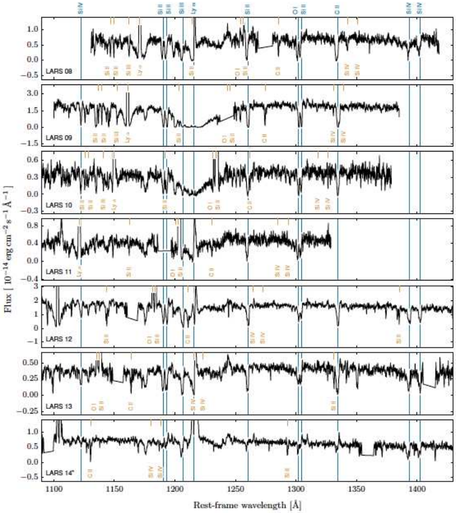
The Lyα forest transmission $F = f/C$ is observed flux, f, divided by estimated intrinsic 'continuum', C. Fortunately there are few strong absorbers in the Lyα forest region, which we can mask.



Berry et al 2012

We perform 'mean-flux regulation' (Lee et al 2012) using the Berry et al 2012 composite at $1040 - 1190$ Å, i.e. adjust amplitude and slope until the resulting $\langle F \rangle$ matches measurements from quasars.

UV spectra of Low-z Starforming Galaxies



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