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

"Theoretical & Observational Progress on the Large-Scale Structure of the Universe", Garching bei München

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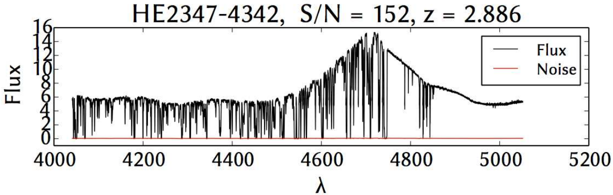
Lyman-α Forest as Probe of $z > 2$ Universe

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



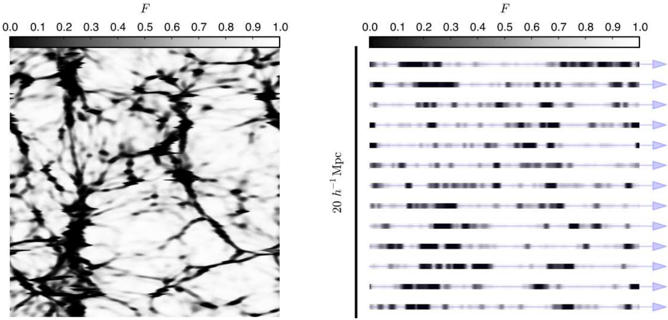
Credit: Michael Walther (MPIA)

On $\gtrsim 100\mathrm{kpc}$ scales, the absorption is a good non-linear tracer for the underlying LSS in the mildly overdense ($0 \gtrsim \rho(x)/\langle\rho\rangle \gtrsim 10$) regime:

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

Lyα Forest Tomography

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

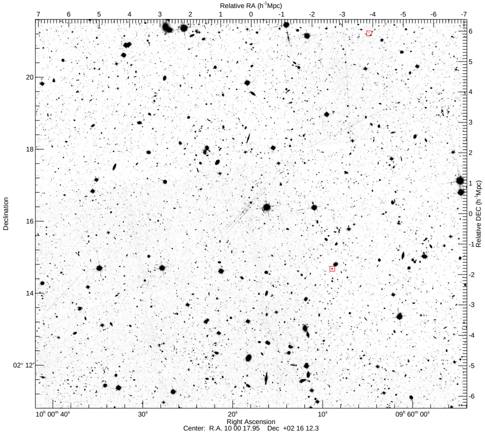


Credit: Casey Stark (Berkeley)

But quasars aren't enough to pull this off....

Availability of Background Sources

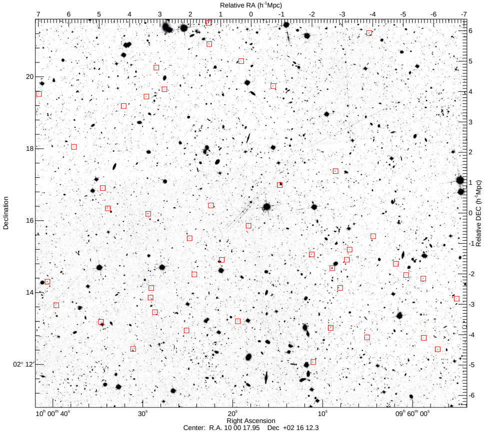
$g \leqslant 22.5$ sources at $2.3 < z < 3.0$



$12' \times 10.8'$ Hubble ACS Image (Koekemoer+2007)

Availability of Background Sources

$g \leqslant 24.7$ sources at $2.3 < z < 3.0$

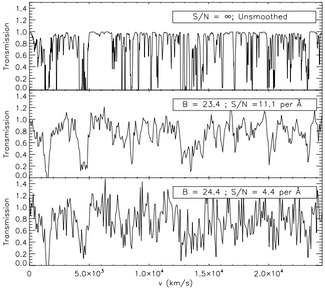


$12' \times 10.8'$ Hubble ACS Image (Koekemoer+2007)

It is necesary to target faint background LBGs for tomography!

Feasibility of Lyα Forest Tomography

In Lee+2014a, I argued that existing 8-10m class telescopes can collect sufficient S/N from $\sim$ 24th mag LBGs to map $z > 2$ LSS on scales of several Mpc.



Right: Examples of mock spectra from simulations. Below: Simulated tomographic maps smoothed on $\sigma = 3.5\,\mathrm{h}^{-1}$ Mpc *scale.*

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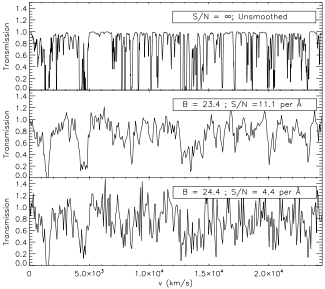
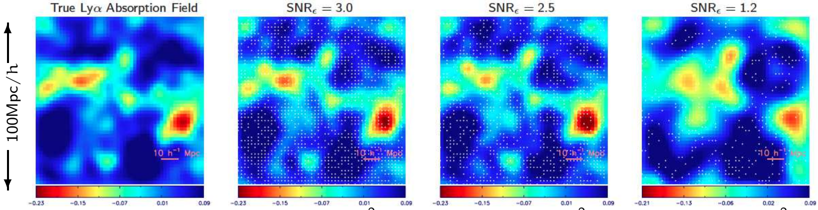
Right: Examples of mock spectra from simulations. Below: Simulated tomographic maps smoothed on $\sigma = 3.5\,\mathrm{h}^{-1}$ Mpc *scale.*





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

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

$n_{\rm los} = 112\mathrm{deg}^{-2}$, $t_{\rm exp} = 2$hrs

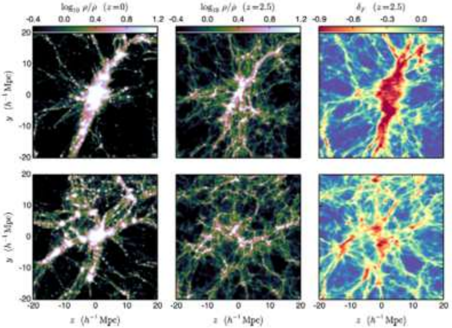
Hunting Protoclusters with Lyα Tomography

Stark, White, **Lee** & Hennawi (arXiv:1412.1507): studied progenitors of simulated $M > 10^{14} M_\odot$ clusters at $z = 2.5$ in a N-body simulation ($L = 250\,h^{-1}$ Mpc)

$z = 0$ DM　　$z = 2.5$ DM　　$z = 2.5$ Lyα

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

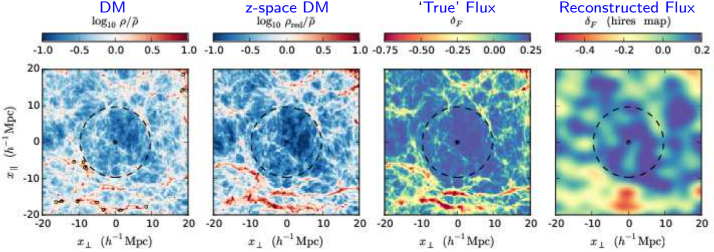
$M = 3 \times 10^{14} M_\odot$



- Protoclusters are $r \sim 5\,h^{-1}$ Mpc overdensities in Lyα absorption
- Can find $M > 3 \times 10^{14} M_\odot$ progenitors with $\sim 90\%$ purity and $\sim 75\%$ completeness $\rightarrow N \sim 5$ per $10^6\,h^{-3}\mathrm{Mpc}^3$
- Even with known protoclusters, can characterize full 3D morphology, e.g. collapsing along single axis vs more isotropically

Detecting High-z Voids

Stark, Font-Ribera, White & **Lee** (1504.03290): look for LSS voids with simulated Lyα forest tomography

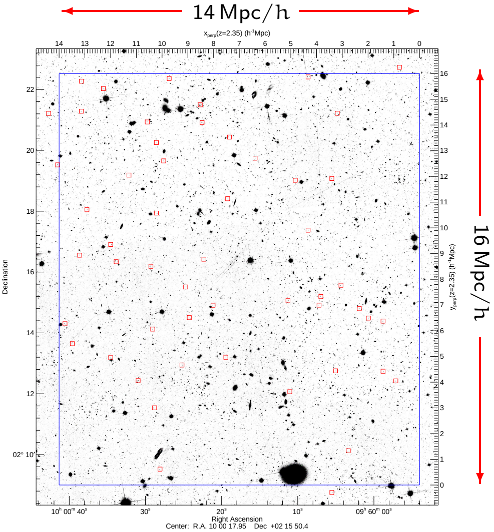


R = 11.7 h^{-1} Mpc void, Stark+2015

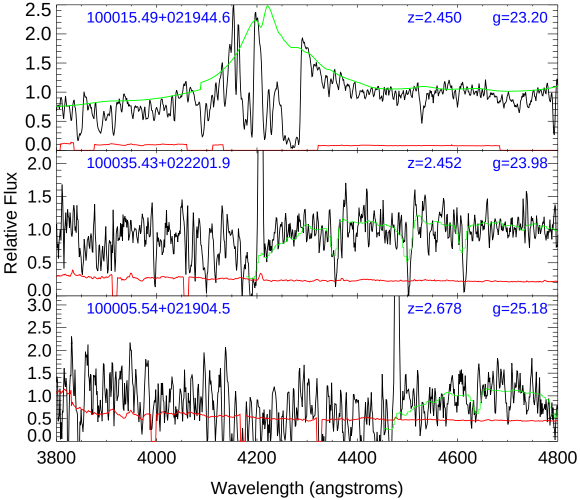
- Used simple spherical finder: grow spheres around minima until some $\bar{\rho}$.
- Able to pick up $R \geqslant 6\,h^{-1}$ Mpc voids with $\sim 70\%$ purity and $\sim 60\%$ completeness $\rightarrow \sim 100$ voids per $10^6\,h^{-3}\,\mathrm{Mpc}^3$ volume
- Synergy with JWST-NIRSPEC to study sub-L_* void galaxies in the $z \sim 2-3$ accretion era?

Pilot Survey in COSMOS

- Pilot observations in 2014/2015 on COSMOS field
- LRIS spectrograph on 10.3m Keck-I telescope, Hawai'i
- Total $\sim$ 15 hrs on-sky, $\sim$ 2hr exposures per pointing
- Targeted known spec-z's and 30-band multi-wavelength photo-z's at $2.3 < z < 3.0$ down to $g \sim 25.0$
- 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



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

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

with $L_{\perp} = 3.5 h^{-1}$ Mpc and $L_{\parallel} = 2.7\, h^{-1}$ Mpc, and $\sigma_F = 0.8$ (Note average sightline separation $\langle d_{\perp} \rangle \approx 2.8\, h^{-1}$ Mpc).

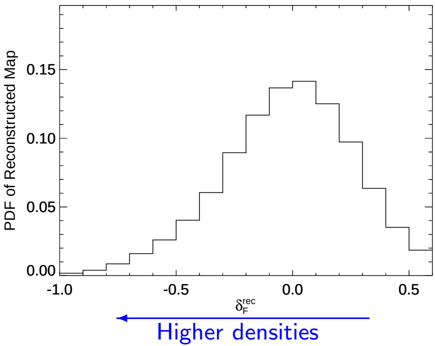
3D Map of Cosmic Web at $2.2 < z < 2.5$

$260\,\mathrm{h}^{-1}$ Mpc along LOS; $14\,\mathrm{h}^{-1}$ Mpc $\times$ $16\,\mathrm{h}^{-1}$ Mpc transverse $\rightarrow$

$V = 5.8 \times 10^4\,\mathrm{h}^{-3}\,\mathrm{Mpc}^3 \sim (39\,\mathrm{h}^{-1}\ \mathrm{Mpc})^3$

Correlations with Foreground Galaxies?

There are 61 known galaxies with spectroscopic redshifts overlapping the map volume. We can compare their locations with the overall map PDF:



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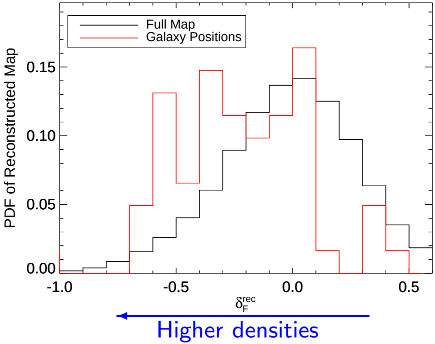

Systemic redshift uncertainties ($\sigma_{los} \sim 3 - 4\,h^{-1}$ Mpc) in galaxies' LOS position are comparable to our $\sim 3 - 4\,h^{-1}$ Mpc map smoothing, weakening the correlation...

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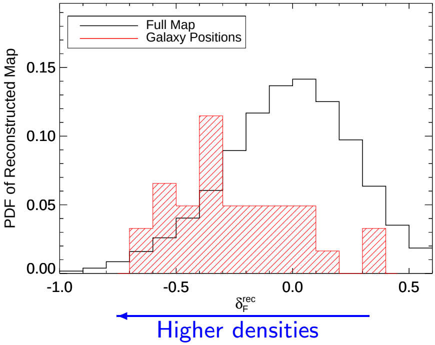
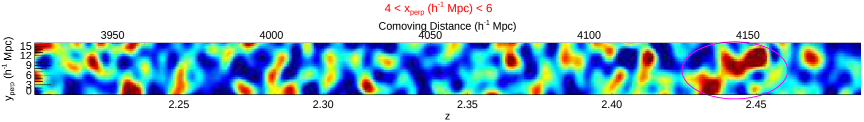


If we plot only NIR redshifts from MOSFIRE, these have smaller redshift uncertainties: even more clearly associated with high-density regions in the tomography.

A Galaxy Protocluster at $z = 2.44$?



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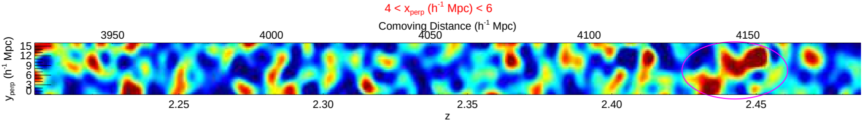
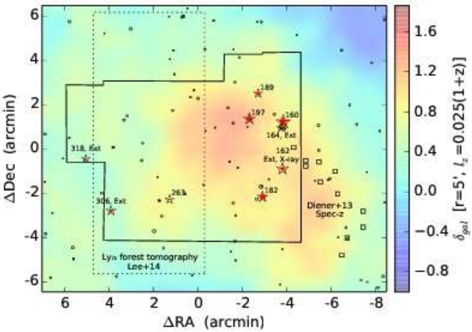


Photo-z (color, Chiang+2014); HETDEX Pilot (stars, Chiang+2015); LBGs (squares, Diener+2015)



Credit: Chiang+2015

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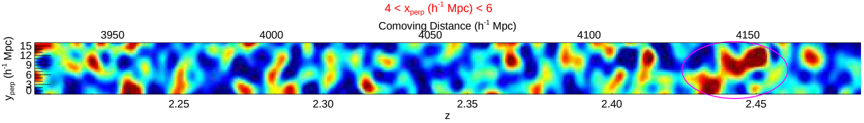

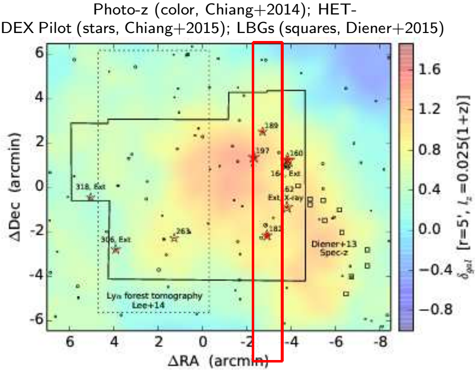

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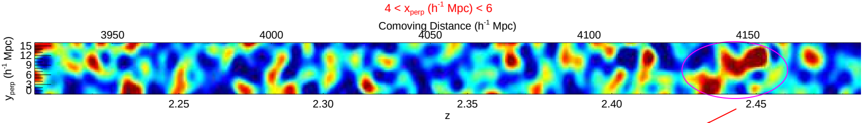

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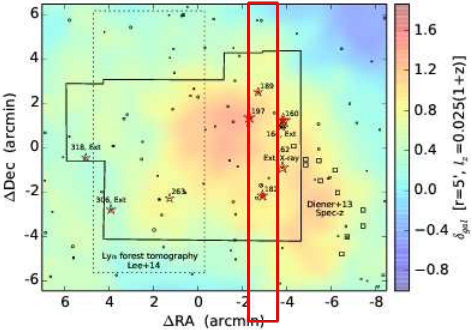

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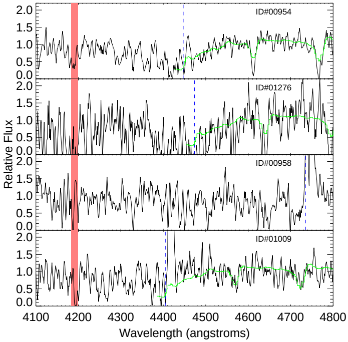
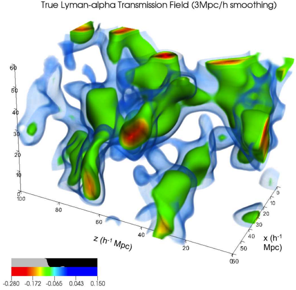


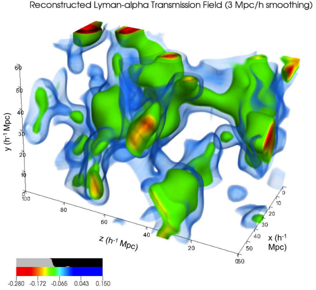
CLAMATO Survey
(COSMOS Lyman-Alpha Mapping And Tomography Observations)

- Proposed survey targeting 0.8 sq deg of COSMOS field ($\sim$ 30 nights on Keck)
- Target ~ 1000 LBGs at $2.3 \lesssim z \lesssim 3$ for R ~ 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: $(65\ \mathrm{Mpc})^2 \times (100\ \mathrm{Mpc})$

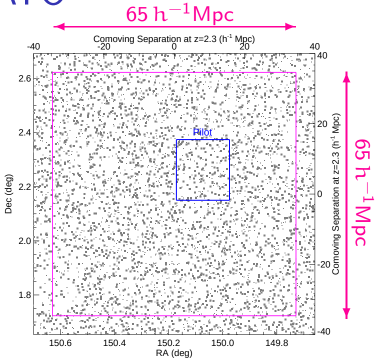

Cóctel de Tomate
Clamato
60
32FL OZ (1QT) 946mL

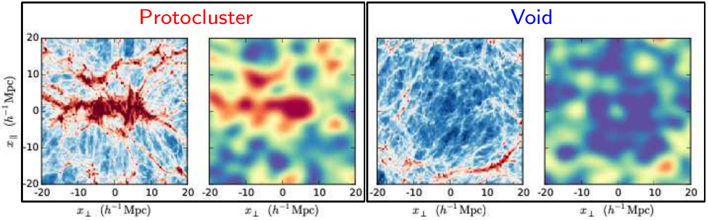
Voids and Protoclusters in CLAMATO

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)

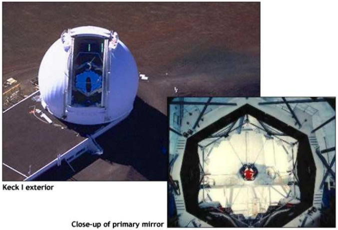




Pushing Towards Cosmological Volumes

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

- **CLAMATO (2016-2018):**
  - LRIS Spectrograph on 10.3m Keck-I
  - FOV: $7' \times 5'$ ($\sim 0.01\text{deg}^2$)
  - Target ~ 20 sources per FOV ($g \leqslant 24.7$)
  - Time: ~ 40 nights to cover 0.8deg^2
    $\rightarrow 2.3 < z < 2.5$ Tomographic map probing
    $\sim 3.5\,\mathrm{h}^{-1}$ Mpc over $V \sim 10^6\,\mathrm{h}^{-3}$ Mpc



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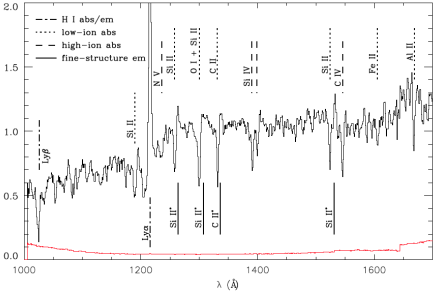
    $\sim 3.5\, h^{-1}$ Mpc over $V \sim 10^6\, h^{-3}$ Mpc
- Strawman Tomography Survey on **Subaru-PFS (2018-):**
  - Prime Focus Spectrograph on 8.2m Subaru Telescope
  - FOV: $1.2\mathrm{deg}^2$
  - Target ~ 2000 sources per FOV ($g \leqslant 24.0$)
  - Time: 10 nights to cover $20\mathrm{deg}^2$
    $\rightarrow 2.5 < z < 3.2$ Tomographic map probing
    $\sim 5\, h^{-1}$ Mpc over $V \sim 10^8\, h^{-3}$ Mpc

Conclusion

- First exploitation of $z > 2$ faint LBGs as Lyα forest background sources to probe Lyα forest absorption
- First direct 3D map of LSS at $z > 2$ probing several Mpc scales in COSMOS field
  - Clearly see overdensities and voids
  - Good correlation of known spec-z galaxies with overdensities
  - Clear signature of known $z = 2.44$ galaxy protocluster
- Upcoming CLAMATO Survey on Keck-I
  - Survey central $\sim 0.8\,\mathrm{deg}^2$ region of COSMOS
  - Will map out $V \sim (100\,\mathrm{h}^{-1}$ Mpc$)^3$ down to scales of $\sim 3 - 4\,\mathrm{h}^{-1}$ Mpc
  - Good synergy with multiwavelength data in COSMOS
- Future wide-field spectrographs on 8m class telescopes will be able to cover $\sim \mathrm{Gpc}^3$ volumes
- Science: Protoclusters, voids, high-z galaxy environments, small-scale Lyα forest clustering.... **YOU TELL ME!**

Continuum Estimation

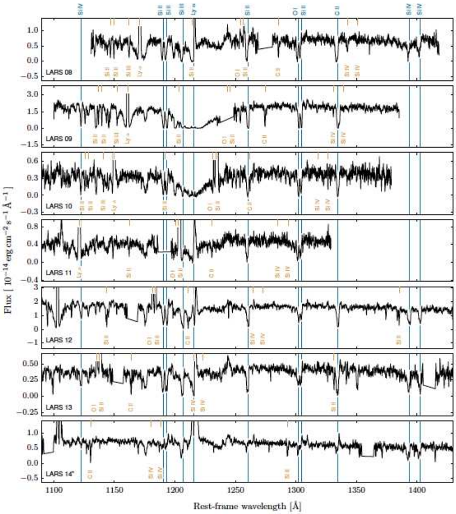
The Lyα forest transmission $F = f/C$ is observed flux, f, divided by estimated intrinsic 'continuum', C. Fortunately there are few strong absorbers in the Lyα forest region, which we can mask.



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



Rivera-Thorsen+ 2015