3D Mapping of the $z > 2$ Universe with Lyα Forest Tomography

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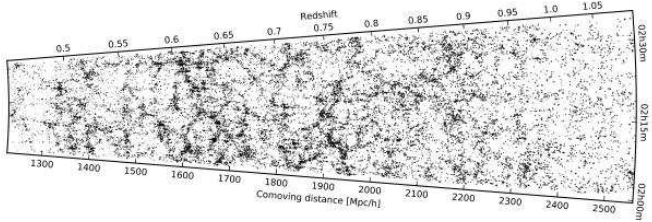
Mapping the Cosmic Web wth Galaxy Redshift Surveys

Galaxy redshift surveys need to measure 3D positions for galaxies down to at least $\mathrm{L} \sim 0.3\mathrm{L}^*$ to map the cosmic web on ∼Mpc scales **including absorption line redshifts**. But at $z = [0.5, 1.0, 2.0]$, L_* is $\mathrm{R} \approx [20.6, 21.8, 24.5]\mathrm{mag}$.



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

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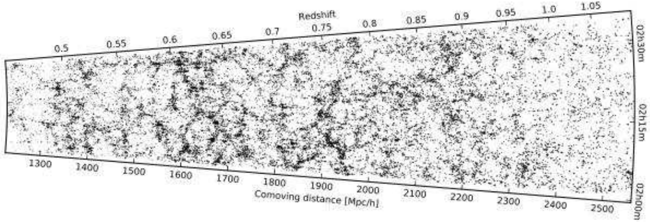
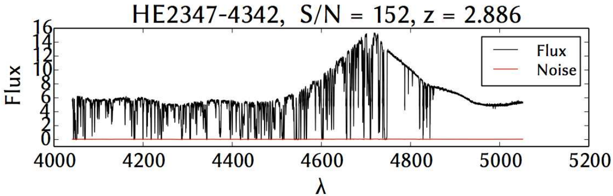


24 deg^2 VIPERS Survey on the ESO VLT, Guzzo et al 2014

Redshift survey at $z = 2$ with same number density as VIPERS requires 30hr exposures on VLT. *Direct mapping of $z > 1$ LSS with galaxy positions 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)

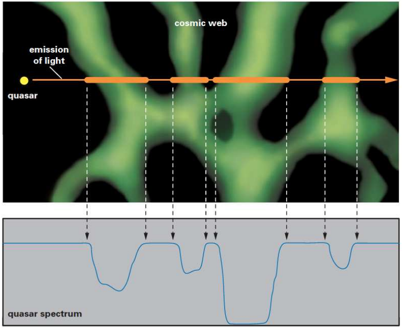
We observe the transmitted flux $F = f/C = \exp(\tau)$ caused by optical depth τ. This absorption is seen over $\sim 300 - 500$ Mpc along the quaar line-of-sight before Lyβ kicks in.

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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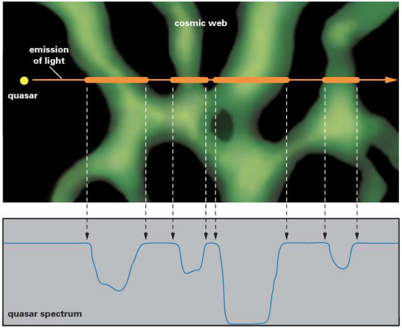
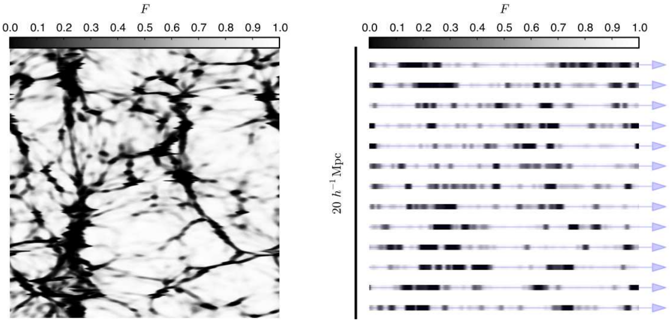


Credit: AmSci/R. Simcoe

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)

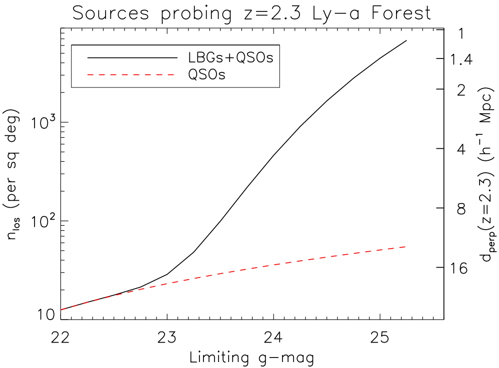


Credit: Casey Stark (Berkeley)

To map the Lyα forest on scales of few Mpc, the transverse separation of background sources also needs to be a few Mpc. But BOSS quasars ($g \sim 21$) are separated by ~ 15 Mpc!

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.



At g $\gtrsim$ 23, LBGs take over as the most common UV-bright sources at $z > 2$ (e.g. Reddy et al 2008). Source separation is only a few Mpc at g $\sim$ 24, but can we obtain sufficient S/N on such spectra?

Resolution and S/N

Lyα tomography is not a new idea (Pichon et al 2001, Caucci et al 2008), but what is actually required to resove spatial scales of $\epsilon_{3\mathrm{D}}$? Lee et al 2014a attempts to address this...

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- Moderate resolution spectra is sufficient, since we want resolution FWHM $> \epsilon_{3D}$:

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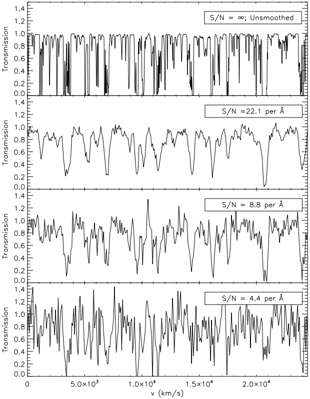
- Spectral S/N (e.g. on $R = 24.5$ LBG):
  - If $S/N \sim 30$ required, need $\sim$ 10hr exposures on 30m!
  - If $S/N \sim 3$ is required, can be done with 2hr exposures on Keck
  - Highly-dependent on desired ϵ_{3D}: coarser scales require brighter sources $\rightarrow$ less exposure time.

Testing Requirements with Sims (Lee et al 2014a)

Test reconstructions with mock Lyα forest absorption spectra generated from N-body simulations, *incorporating resolution and noise effects assuming e.g. 2hr exposures on LRIS spectrograph on Keck*



Raw Simulation

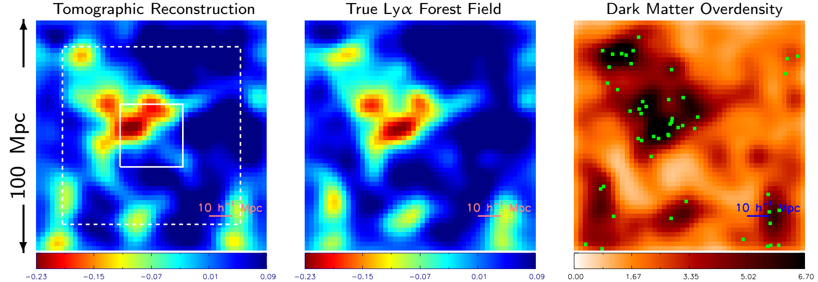
g = 22.0

g = 23.4

g = 24.0

Perform Wiener filtering on mock data set...

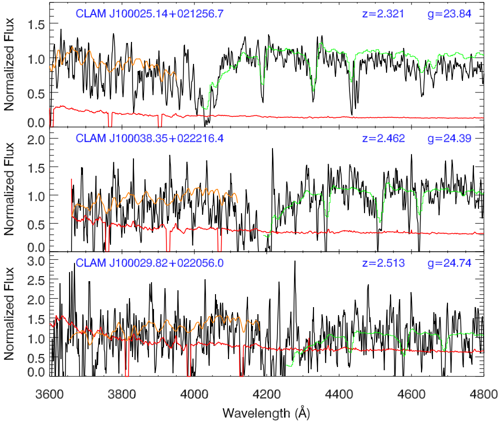
Simulation of Lyα Forest Tomography at $z \sim 2.3$



- $(100\ \text{Mpc})^2 \times 2\ \text{Mpc}$ slices, redshift direction is into page
- Smoothing scale $\epsilon_{3D} = 3.5\ \text{Mpc}$ (~ 2 pMpc).
- Includes realistic instrumental effects assuming survey depth of $g \leqslant 24.5$ and $t_{exp} = 2$hrs on Keck LRIS
- Green dots on DM map: coeval $\mathcal{R} = 25.5$ galaxies ($L \approx 0.4L_*$, 30hrs on VLT!)

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 spectra from 24 LBGs at $2.3 < z < 2.8$ in $5' \times 14'$ field ($\sim 2\,\mathrm{h}^{-1}$ Mpc transverse separation)

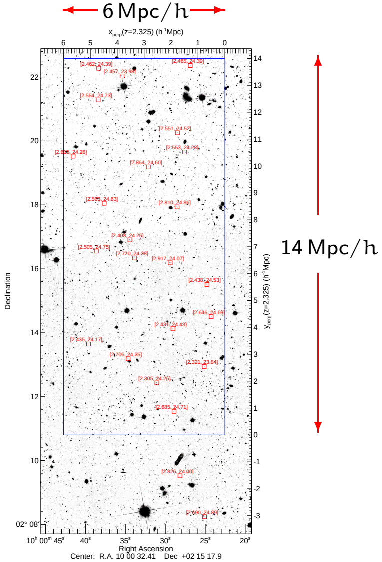


Brightest: $g = 23.84$

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:

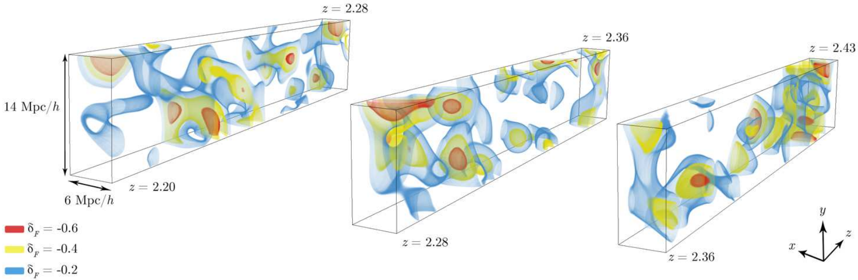
$$\mathbf{M} = \mathbf{C}_{\mathrm{MD}} \cdot (\mathbf{C}_{\mathrm{DD}} + \mathbf{N})^{-1} \cdot \mathrm{D}$$

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

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

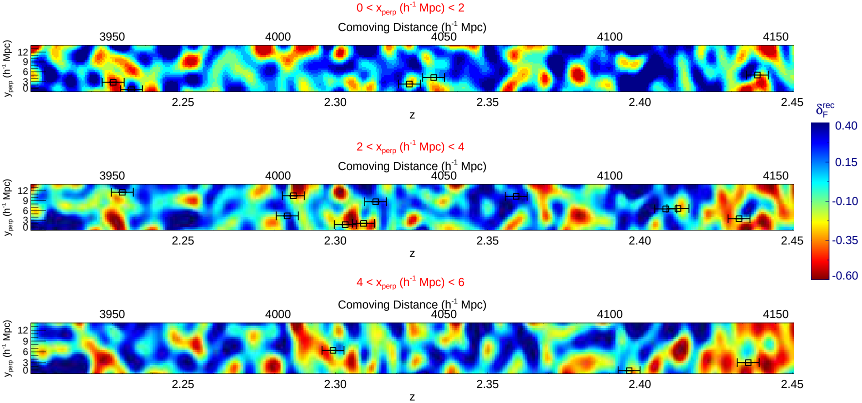
with $L_{\perp} = 3.5h^{-1}$ Mpc and $L_{\parallel} = 2.7\,h^{-1}$ Mpc, and $\sigma_F = 0.8$.

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



Note: Negative δ_F corresponds to higher densities

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.

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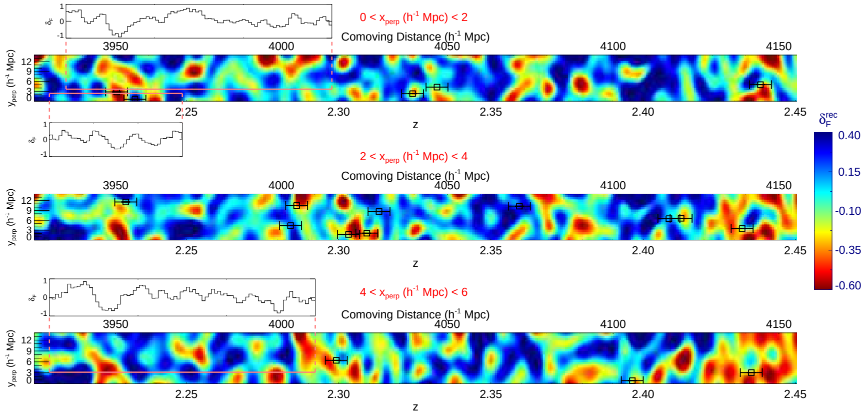
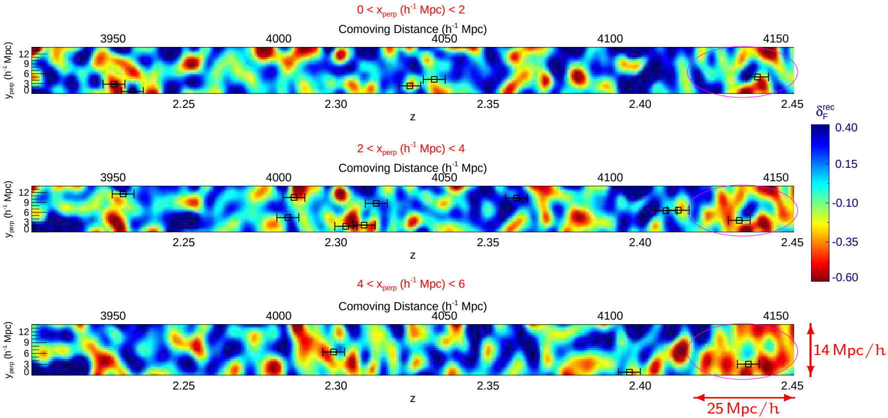


Overdensities seen in the map are typically probed by multiple independent sightlines

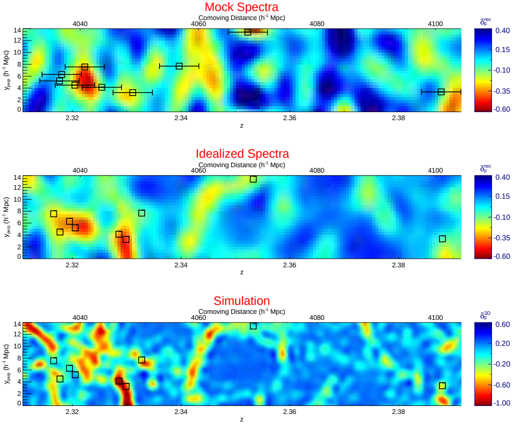
Pilot Map in Slices



Hints of a huge overdensity at z=2.43?

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.

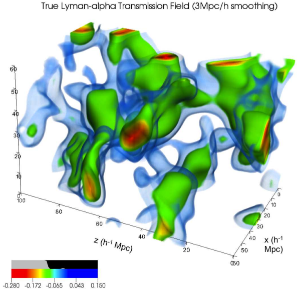


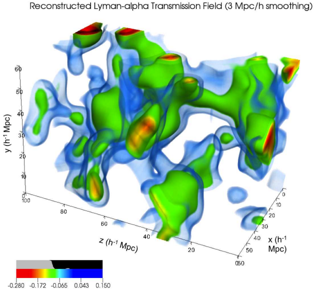
- There are reconstruction errors, but our data quality should reproduce broad LSS features

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

- Full survey targeting 1 sq deg of COSMOS field (150-200hrs on Keck)
- Target ~ 1000 LBGs at $2.3 \lesssim z \lesssim 2$ 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
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Science with $z \sim 2$ Lyα Forest Tomography

- Galaxy Environment Studies
  - Plenty of co-eval COSMOS galaxies with redshifts, multi-wavelength observations (X-ray to radio), deep Hubble imaging etc
  - Characterize $z \sim 2$ galaxy properties (SFR, color, morphology etc) as function of their environment
- Galaxy Protoclusters
  - Progenitors of massive ($M \sim 10^{15} M_{\odot}$) present-day clusters are extended ($\gtrsim 10$ Mpc) overdensities at $z \sim 2$ (Chiang et al 2013)
  - Should be straightforward to identify these protoclusters directly through LSS in tomographic map (Stark et al, in prep)
  - This will be 'cleanest' way to look for high-z protoclusters (well-understood selection function etc)
- Structures/Cosmology at high-z
  - How filamentary is $z \sim 2$ LSS on scales of few Mpc?
  - Power spectrum, bispectrum etc to constrain primordial non-Gaussianity, neutrino masses, IGM astrophysics etc

Summary

- **First** exploitation of LBGs as background sources for Lyα forest analysis. If have enough S/N to measure absorption-line redshift, enough S/N to exploit Lyα forest.
- **First** large-scale structure map of the $z > 2$ universe (from 1/2 night of data!) probing scales of a few Mpc
- CLAMATO survey:
  - Obtain spectra for ~ 1000 LBGs ($z \sim 2-3$) over 1sq deg in COSMOS field
  - Will yield 3D Lyα forest tomographic map with $\sim 3\,\mathrm{h}^{-1}$ Mpc spatial resolution over $\sim (100\,\mathrm{h}^{-1}\ \mathrm{Mpc})^3$
  - Time requirement: 160hrs on Keck and/or VLT
  - Science: cosmic web studies at $z > 2$, hunting galaxy protoclusters, galaxy properties as function of large-scale environment....

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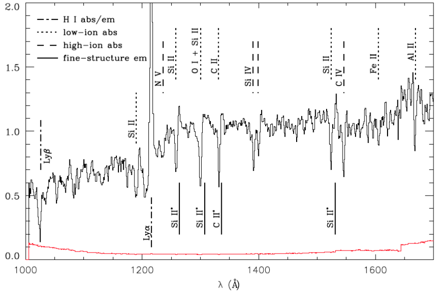
There is still time for theorists to make **predictions**!

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.

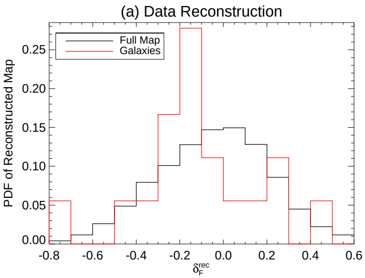


Berry et al 2012

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.

Maps vs Real Data

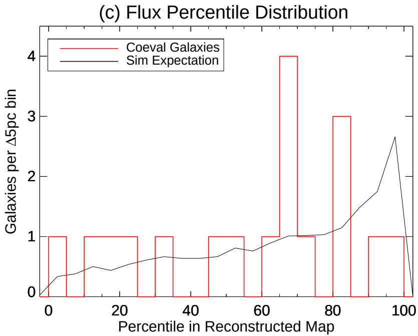
We can compare the map vs galaxy PDFs in both data and sim:



Reconstruction errors + galaxy redshift errors cause many sim galaxies to also reside in underdensities.

Maps vs Real Data (II)

We can rank the δ_F values by percentile, and then plot the values sampled by the galaxies



Two-sample KS test gives 22% probability of being drawn from same distribution.