Mapping the $z \sim 2$ Large-Scale Structure with 3D Lyα Forest Tomography

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1. Introduction
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   - Lyman-α Forest in Quasars
2. Lyman-α Forest Tomography
   - Feasibility - Need background galaxies!
   - Pilot Observations
3. Possible Science Applications
   - Searching for galaxy protoclusters
   - Void Alcock-Paczynski test
   - LSS topology as distance measure

Collaborators

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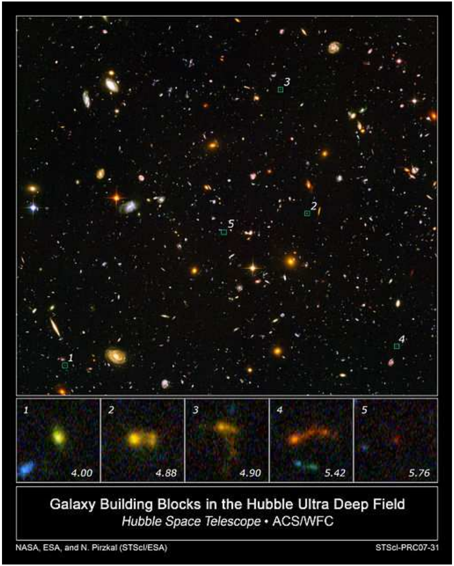
Images are pretty, but...



Measuring Redshifts → 3D Positions

Given a cosmological model, measuring the **redshift** of an extragalactic object provides information on radial/line-of-sight distance.

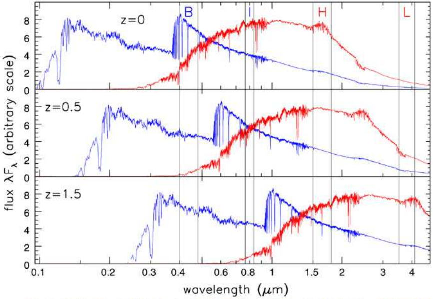


Fig 8.12 (S. Charlot) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

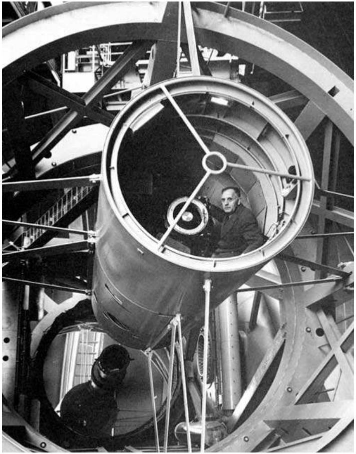
This gives 3D information on the object but requires measuring a spectrum which is:

- Requires much longer observations
- Can typically only be measured one at a time (or a few at a time)

An Example from Early Days...

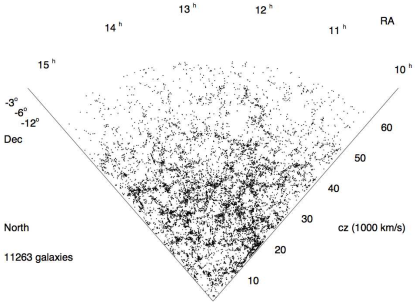
Humason et al 1956 measurement of Hubble expansion

- Used the largest telescope in the world at the time (Palomar 5m)
- Measured ~ 800 spectra of nearby galaxies to determine redshifts
- Took 10 years!!!



Mapping the Universe with Galaxy Redshifts

- In 1980s, CCD technology dramatically improves the efficiency of astronomical observations
- Late 1980s/Early 1990s: Galaxy redshift surveys can now observe $O(10^{3-4})$ galaxies, e.g. CfA2, SSRS surveys
- Since galaxies trace the underlying matter density field, large numbers of 3D galaxy positions allow the study of large-scale structure (LSS).
- The first confirmation of 'cosmic web' that arises from gravitational evolution of primordial random-phase fluctuations predicted by inflation

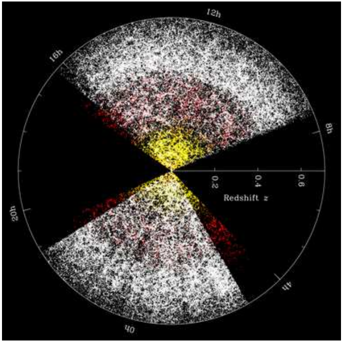


Las Campanas Redshift Survey

Shechtman et al 1996

Wide-Field Surveys circa 2014

With advances in CCD technology and fiber-optic spectrographs, there are now $\sim 2.5 \times 10^6$ galaxies with known spectroscopic redshifts.

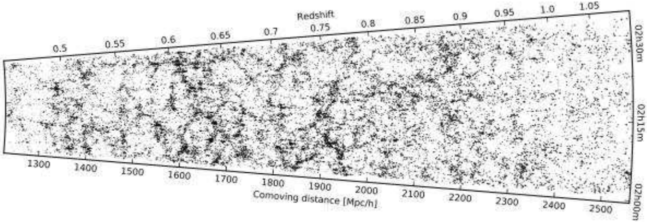


SDSS (yellow/red), BOSS (white)

Mostly from wide surveys on 2-4m diameter telescopes, e.g. SDSS, 2dF, BOSS etc, out to redshifts of $z \leqslant 0.6$ ($t_{\rm look} < 5\,$Gyr)

Pushing to Higher-Redshifts is Hard!

To trace LSS, need to go faint and observe large density of galaxies ($L \sim 0.3L^*$) to map the cosmic web on $\sim$Mpc scales. But at $z = [0.5, 1.0, 2.0]$, L_* is $R \approx [20.6, 21.8, 24.5]$mag.



24 deg^2 VIPERS Survey on the 8m ESO VLT, Guzzo et al 2014

Pushing to Higher-Redshifts is Hard!

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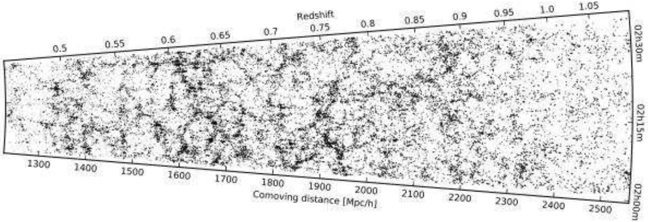
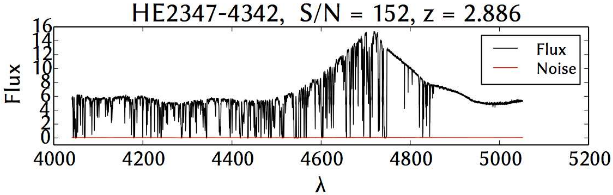


24 deg^2 VIPERS Survey on the 8m ESO VLT, Guzzo et al 2014

Redshift survey at $z = 2$ ($t_{look} > 10$ Gyr) with same number density as VIPERS requires 30hr exposures on the 8m Very Large Telescopes. *Direct mapping of $z > 1$ LSS with galaxies only feasible with 30m telescopes!*

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

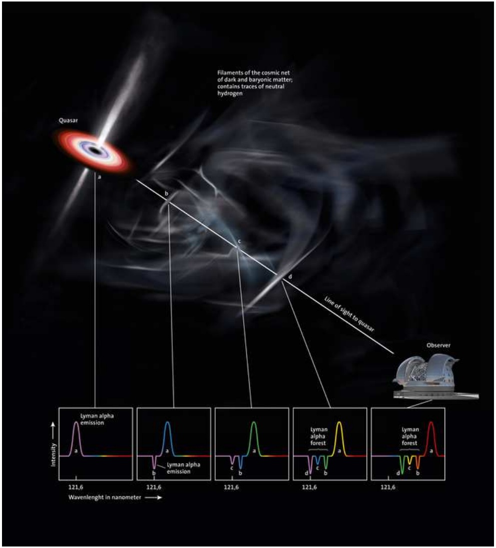
For $z \gtrsim 2$ ($t_{\rm look} > 10\,$Gyr) objects, the hydrogen Lyman-series transitions stretches into optical wavelengths. The most prominent is Lyman-α ($\lambda = 1216\,\mathring{A}$).



Credit: Michael Walther (MPIA)

When we observe background quasars, we see a pattern of Lyα absorption lines bluewards of the quasar's own Lyα emission. This is caused by residual neutral hydrogen ($\sim 10^{-4}$) in the intergalactic medium (IGM).

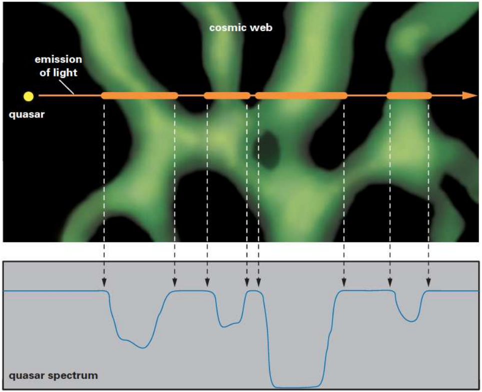
IGM Lyα Forest Absorption



The Nature of the Lyα Forest

Inflation-seeded, CDM-dominated gravitational collapse became widely accepted as standard picture for growth of structure in late 1980s

Residual HI directly traces DM inhomogeneities in 'cosmic web' (Bi et al 1992, Cen et al 1994, Miralda-Escudé et al 1996)



Credit: AmSci/R. Simcoe

Lyα Forest & the IGM

Can think of Lyα forest absorption as $F \equiv e^{-\tau}$. If assume photoionization equilibrium,

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

- Matter overdensity $\Delta \equiv \rho_{dm}(x)/\langle\rho_{dm}\rangle$
  - Caused by $\Delta \sim 0-10$ overdensities, i.e. sheets and filaments in cosmic web

  $\rightarrow$ Matter $\xi(r), P(k)$ etc
- Intergalactic medium (IGM) gas parameters:
  - T_0: IGM temperature at mean density (~ 20000 K)
  - Γ: Photoionizing UV background ($\sim 10^{-12}$ erg s^{-1})
  - γ: Temperature-density relation ($T \propto \Delta^{\gamma-1}$)

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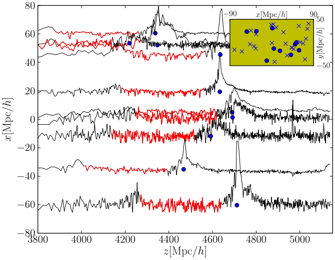
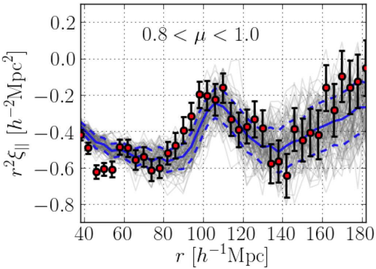
Cosmology $\leftrightarrow$ IGM

BOSS Lyα Forest Survey

- BOSS has just completed main survey, with $\sim 160,000$ Lyα forest quasars ($g \lesssim 21.5$) over 10,000 sq deg on the 2.5m Sloan Telescope
- Important recent cosmology results, e.g.
  - Constraints on growth of matter at $z > 2$ from measuring 1D Lyα forest power spectrum (McDonald et al 2006)
  - Measuring baryon acoustic oscillation (BAO) clustering signal in 3D and constraining expansion rate of universe at $z > 2$ (e.g. Busca et al 2013, Slosar et al 2013)



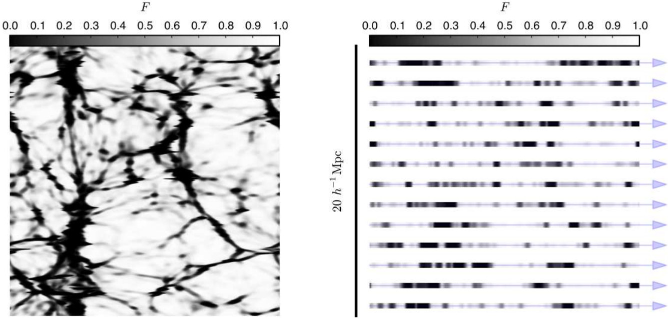
Slosar et al 2011



Delubac et al 2014

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)

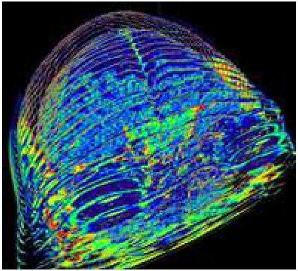


Credit: Casey Stark (Berkeley)

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!

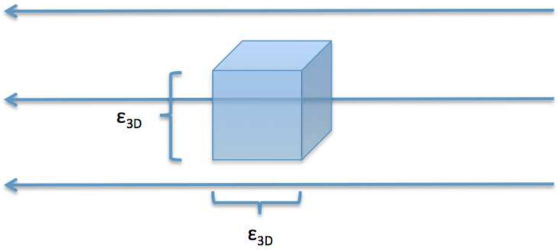
'Tomography'

Tomography is the reconstruction of higher-dimension images from lower-dimensional data, e.g. X-ray computed tomography (CT) scans



Source separation vs map resolution

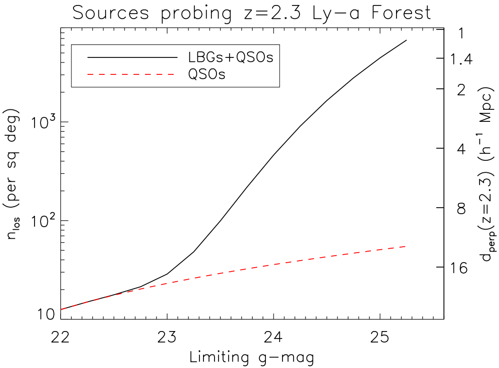
The sightline separation, $\langle d_\perp \rangle$, is the basic consideration for IGM tomography. For maps with 3D resolution ϵ_{3D}, expect to need $\langle d_\perp \rangle \lesssim \epsilon_{3D}$.



There are more fainter objects, so by targeting fainter background quasars we can decrease ϵ_{3D}.

Galaxies as Lyα Forest Background Sources?

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

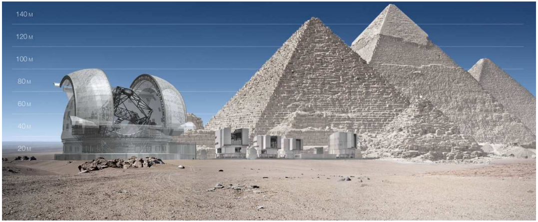


If go to fainter magnitudes, starting getting UV-bright star-forming galaxies (SFGs) with exponential increase of source density with magnitude, $n_{los} \propto 10^m$. Source separation is $\langle d_\perp \rangle \sim 2.5$ Mpc at $g \leqslant 24.5$.

We need bigger telescopes?

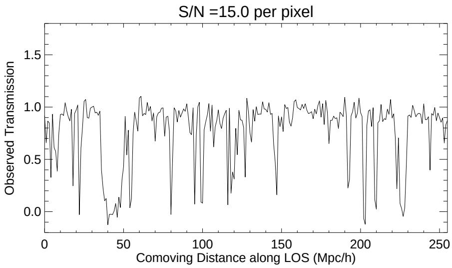
Lyα forest tomography is not a new idea, but people assume that 30m telescopes are needed, because of high assumed S/N and spectral resolution, $R \equiv \lambda/\Delta\lambda$:

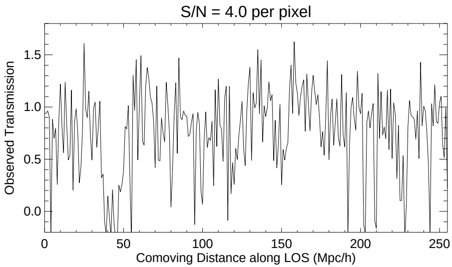
- **"Multi-Object Spectroscopy with the European ELT"** (Evan et al 2012)
  S/N$\geqslant$ 8 per $R = 5000$ resolution element for $r = 24.8$ sources
- **"Mapping the 'Cosmic Web' During the Peak Epoch of Galaxy Formation"** (Steidel et al 2009)
  S/N=30 per pixel at $R = 5000$ for $R = 24.5$ sources



39m diameter European Extremely Large Telescope

What noise does to the Lyα forest





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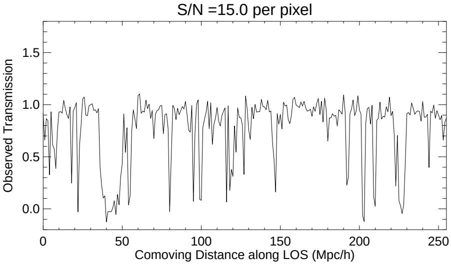
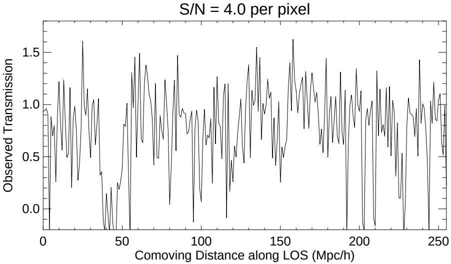


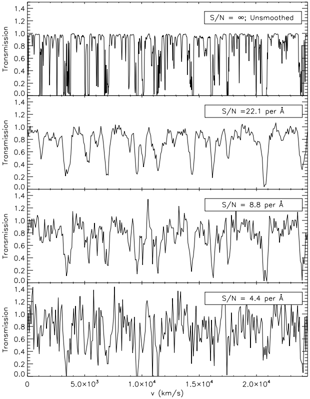
2hr exposure on $V = 24$ galaxy
with 30m telescope



2hr exposure on $V = 24$ galaxy
with 8m telescope

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

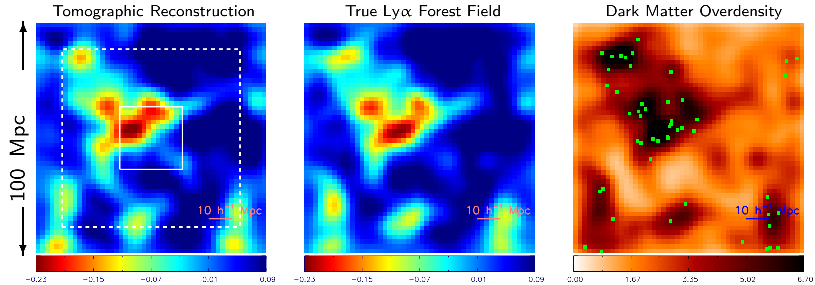
g = 22.0

g = 23.4

g = 24.0

Perform Wiener filtering on mock data set...

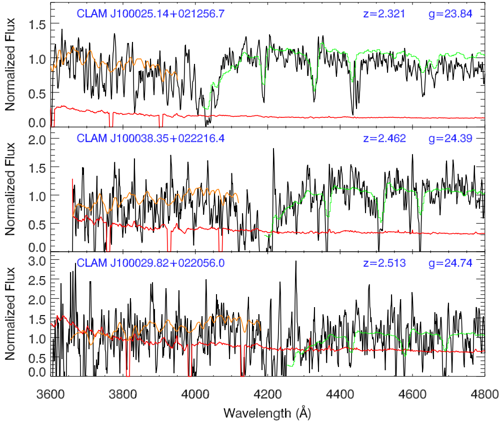
Simulation of Lyα Forest Tomography at $z \sim 2.3$



- $(100\ \text{Mpc})^2 \times 2\ \text{Mpc}$ 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)

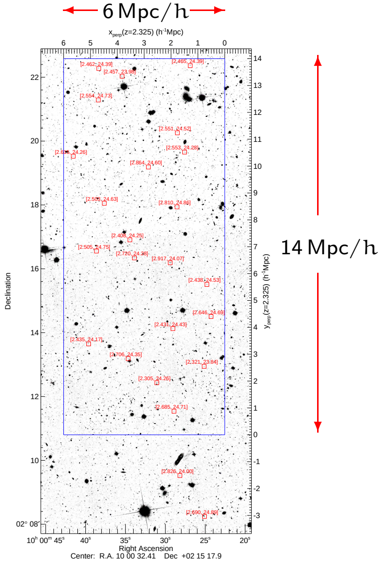


Brightest: $g = 23.84$

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:

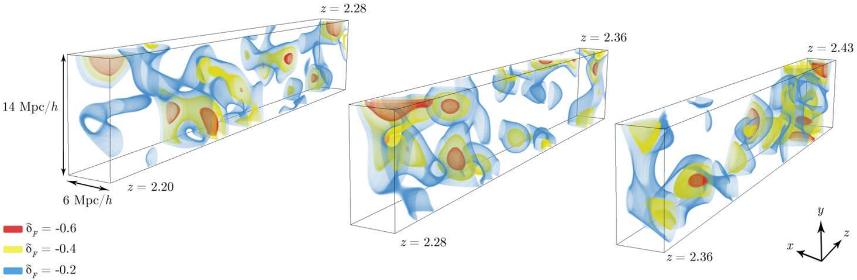
$$\mathbf{M} = \mathbf{C}_{\mathrm{MD}} \cdot (\mathbf{C}_{\mathrm{DD}} + \mathbf{N})^{-1} \cdot \mathrm{D}$$

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

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

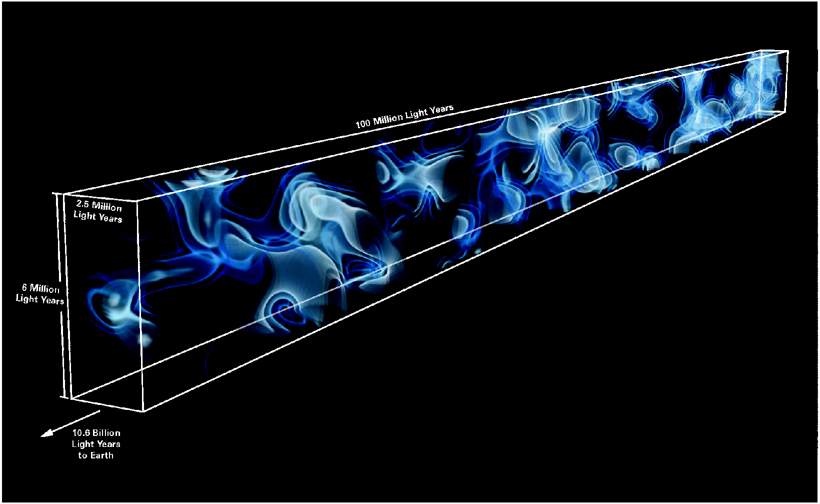
with $L_{\perp} = 3.5h^{-1}$ Mpc and $L_{\parallel} = 2.7\,h^{-1}$ Mpc, and $\sigma_F = 0.8$.

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

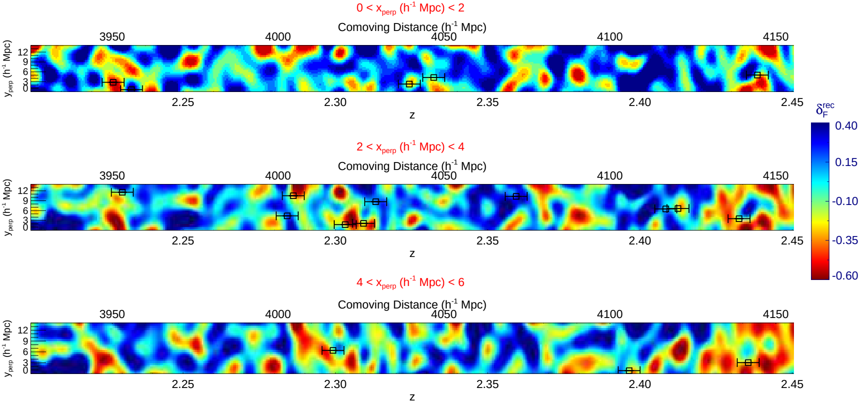


Note: Negative δ_F corresponds to higher densities

… and the public version

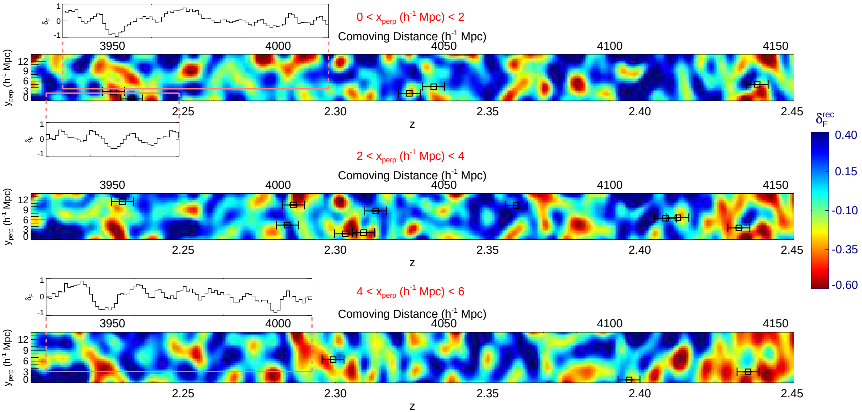


Pilot Map in Slices



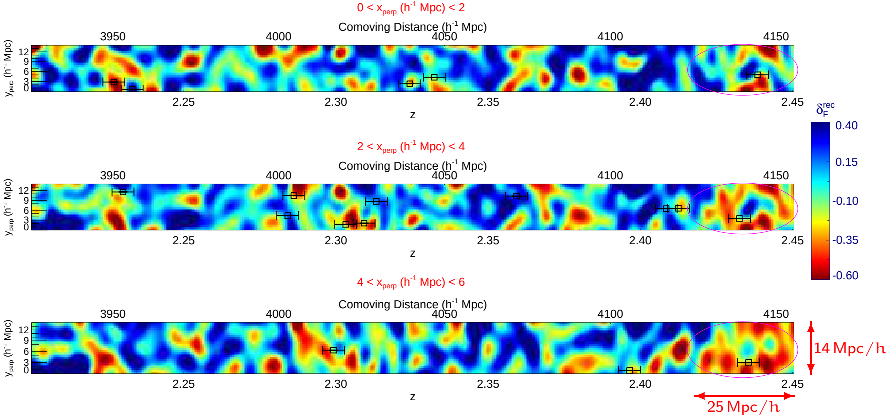
Squares: 18 coeval galaxies (mostly zCOSMOS-Deep) with known spectro-z's within map, error bars are estimated 1σ redshift errors.

Pilot Map in Slices



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

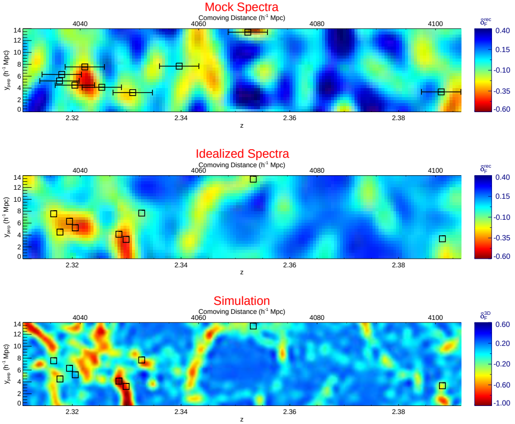
Pilot Map in Slices



Hints of a huge overdensity at z=2.43?

Comparison with Simulations

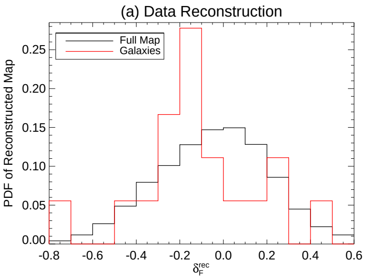
We took Lyα forest skewers from sims, and created mock data with exactly the same sightline geometry and S/N as real data.

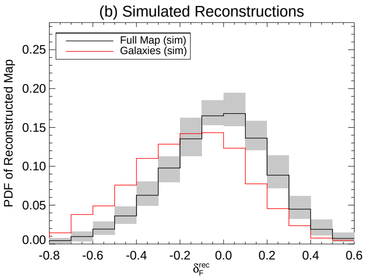


- There are reconstruction errors, but our data quality should reproduce broad LSS features

Comparison with Galaxies

We can evaluate the absorption at the galaxy positions, in both data and sim:

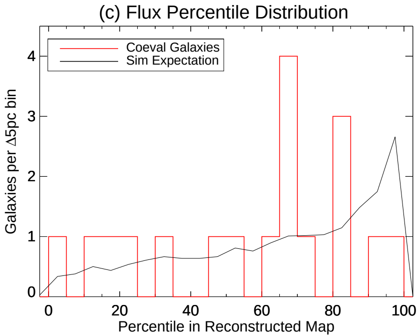




Reconstruction errors + galaxy redshift errors cause many sim galaxies to also reside in underdensities.

Maps vs Real Data (II)

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

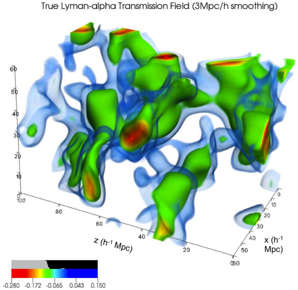


Two-sample KS test gives 22% probability of being drawn from same distribution.

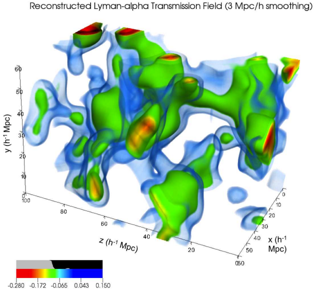
CLAMATO Survey
(COSMOS Lyman-Alpha Mapping And Tomography Observations)

- Full survey targeting 1 sq deg of COSMOS field (150-200hrs on Keck)
- Target ~ 1000 LBGs at $2.3 \lesssim z \lesssim 3$ 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: $(65\ \mathrm{Mpc})^2 \times (100\ \mathrm{Mpc})$

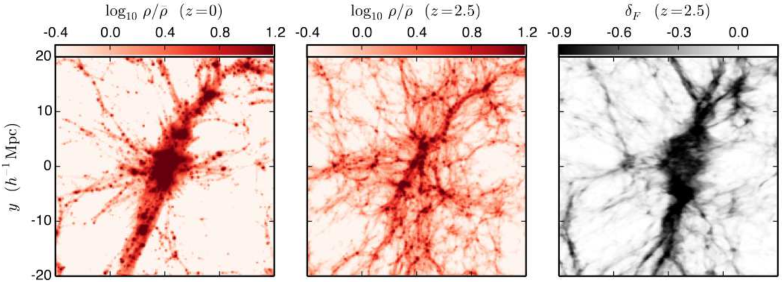

Cóctel de Tomate
Clamato
60
32FL.OZ (1QT) 946mL

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

Hunting Galaxy Protoclusters

It is important to study the formation of $z = 0$ massive galaxy clusters, since they are used for various cosmological constraints. At $z = 2.5$, their ancestors are large-scale overdensities that can detected with Lyα forest tomography

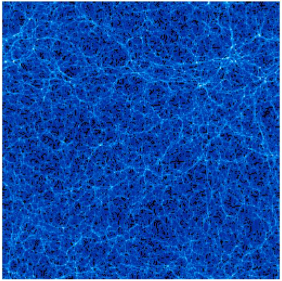


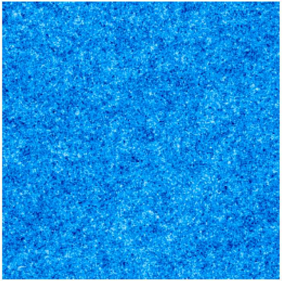
Stark et al., in prep

With CLAMATO survey we should find $\sim 10 - 20$ progenitors of modern-day $\mathrm{M} > 10^{14}\mathrm{M}_{\odot}$ clusters. Only 15 currently known at high-z.

Understanding Structure Formation

The most common large-scale structure statistic is 2pt clustering (power spectrum or correlation function). **This neglects a lot of information!**



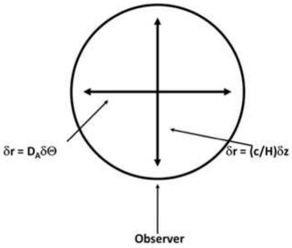


Peter Coles (U. of Sussex)

With Lyα forest tomography, we can go into more exotic methods to study structure formation...

Studying Cosmology with Spherical Cows (Alcock-Paczynski test)

- Measure stacked shape of intrinsically isotropic objects in expanding universe $\rightarrow$ observed anisotropy between radial and angular dimensions give the ratio $\mathrm{D}_A(z)/\mathrm{r}(z)$ (Alcock & Paczynski 1979)
- Most structures are also affected by gravitational effects, but underdense voids are much less affected
- Voids are hard to define in Local Universe from finite galaxy points
- Lyα forest tomography should make it straightforward to detect voids at $z > 2$



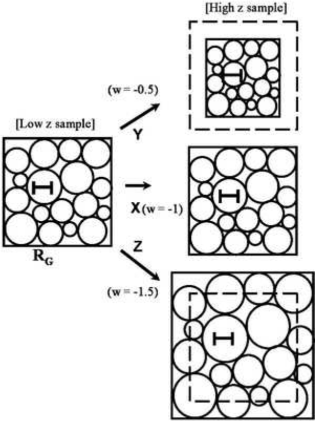
LSS Topology as a Standard Ruler (I)

- Inflationary CDM predicts a specific topology for LSS ('cosmic web')
- Can be quantified using the genus, which is just integrating Gaussian curvature K over surfaces defined by a given threshold:

$$G_s = \frac{-1}{4\pi} \int K \, dA$$

Geometric interpretation is:
G_s = (no. of holes) - (no, of separate regions)

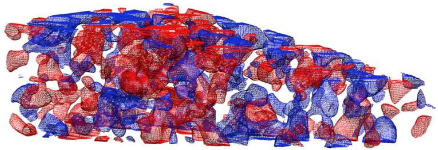
- Genus per unit volume is fully specified within a cosmological model (primarily Ω_M), so it can be used as a standard ruler to measure expansion rate and dark energy (Park & Kim 2010).

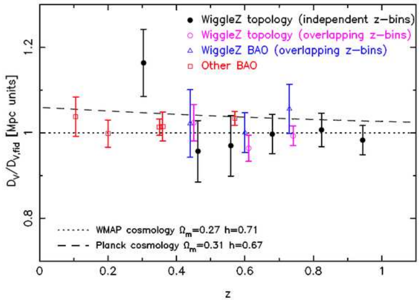


Park & Kim 2010

LSS Topology as a Standard Ruler (II)

Measurement at $z < 0.9$ using 160k WiggleZ galaxies by Blake et al 2014:





This technique can be applied to Lyα forest tomographic maps at $z > 2$!

Summary

- **First** exploitation of LBGs as background sources for Lyα forest analysis
  - Faintest-ever ($\mathrm{g} \sim 24.5$ vs $\mathrm{g} \sim 21.5$ 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!)
  - Clearly see transverse structure; unlikely to be caused to systematics
  - Good correlation with coeval galaxies
- Full survey (CLAMATO):
  - Obtain spectra for ~ 1000 LBGs ($z \sim 2 - 3$) in 1sq deg field
  - Will yield 3D Lyα forest tomographic map with $\sim 3\,\mathrm{h}^{-1}$ Mpc spatial resolution over $\sim (100\,\mathrm{h}^{-1}\ \mathrm{Mpc})^3$
- Science applications: Studying galaxy environments, studying galaxy protoclusters, void Alcock-Paczynski test (future), LSS topology as distance measure (future)