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

IPMU ACP Seminar

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Heidelberg, Germany

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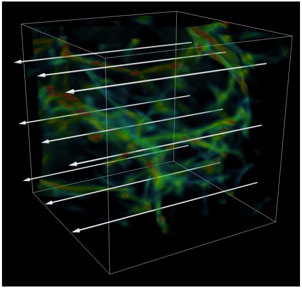
Today's talk is based on
Lee, Hennawi, White, Croft & Ozbek 2013, arXiv:1309.1477



Casey Stark, UC Berkeley

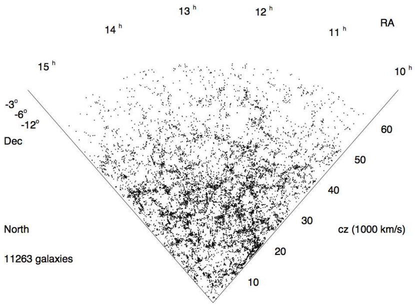
Collaborators

Joe Hennawi (MPIA), David Schlegel (LBL), Martin White (Berkeley), Xavier Prochaska (UCSC), Nao Suzuki (IPMU), Eric Gawiser (Rutgers), Rupert Croft (CMU), Casey Stark (Berkeley), Jean-Paul Kneib (EPFL)

+ more please!

Cosmography: Mapping the Universe

- Cosmography is the most intuitive way of studying the universe
- Filamentary 'cosmic web' topology of the Universe was one of the key predictions of inflationary CDM
- Provides environmental context for galaxy formation/evolution studies
- Late 1980s/Early 1990s: first redshift surveys deep enough to test this: CfA2, SSRS surveys
- Late 1990s/2000s: $\sim$ 1 million redshift surveys of $z \sim 0.1$ universe: 2dF-GRS, SDSS



Las Campanas Redshift Survey

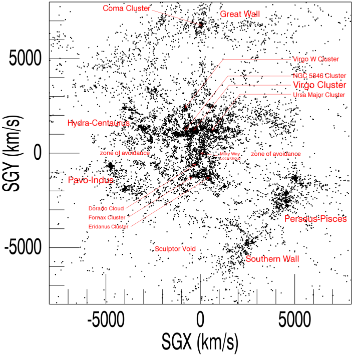
Schechtman et al 1996

Galaxy Redshift Maps at $z \sim 0$ and $z \sim 2$

But redshifts are expensive since surface brightness $\propto (1+z)^{-4}$, e.g. going from $z = 0.5$ to $z = 2$ requires 16x more exposure time

Local Universe

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



Courtois et al 2013

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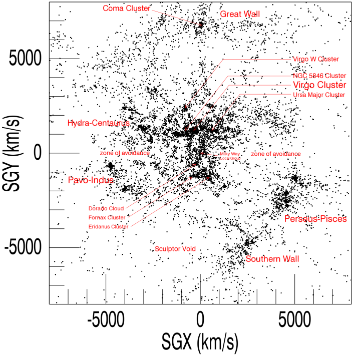
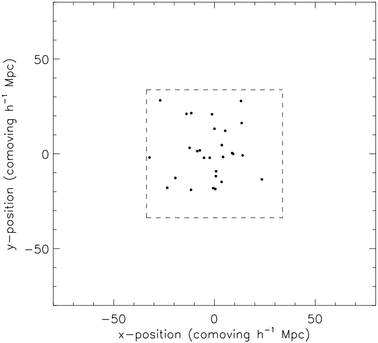


Courtois et al 2013

COSMOS spectro-z's at $z = 2.3$
(Same comoving volume)



COSMOS Collaboration

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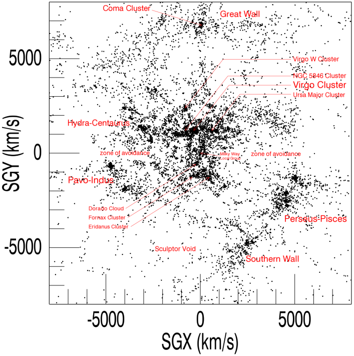

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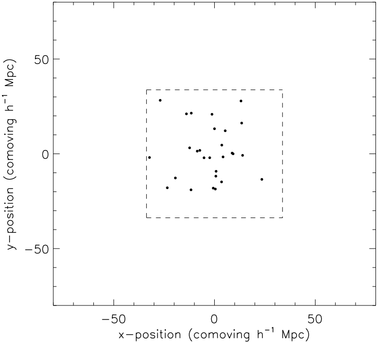


COSMOS Collaboration

The Lyα forest allows an easy way to study higher-z!

Lyman-α Absorption Lines

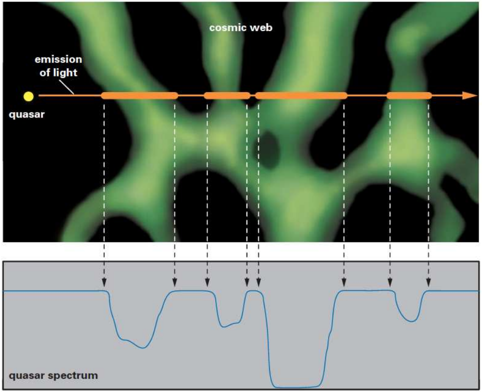
Credit: Andrew Pontzen, Cambridge

Lyman-α forest	Optically thin, from photoionized IGM ($N_{HI} < 10^{16}\,\mathrm{cm}^{-2}$). ($\gtrsim$ 95% of absorption pathlength)
Lyman-limit systems	$\tau \gtrsim 1$ from circumgalactic medium of galaxies ($10^{17}\,\mathrm{cm}^{-2} \lesssim N_{HI} \lesssim 10^{20}\,\mathrm{cm}^{-2}$)
Damped Lyα Absorbers	Strong absorption with clear damping wings, from Milky Way-like disks ($N_{HI} \gtrsim 10^{20.3}\,\mathrm{cm}^{-2}$)

Probing the Cosmic Web

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
  - *Allows probe of large-scale structure at high-z*
- Intergalactic medium (IGM) parameters:
  - T_0: IGM temperature at mean density (~ 20000 K)
  - Γ: Photoionizing UV background ($\sim 10^{-12}$ erg s^{-1})
  - γ: Temperature-density relation ($T \propto \Delta^{\gamma-1}$)
  - *Allows study of thermal history of Universe, H I/He II reionization + radiative sources etc*

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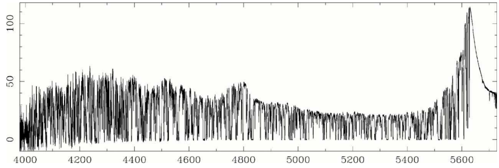
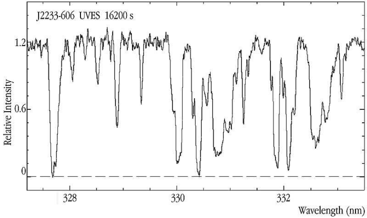
Cosmology $\leftrightarrow$ IGM

Lyα Forest Data Sets: High-Resolution Echelle Data

- Fully resolve individual Lyα absorbers, e.g. can study velocity profiles
- Taken with echelle spectrographs ($R \sim 30,000 - 40,000$)
- Require long-exposures on 8-10m class telescopes
- Limited to the brightest (< 17 mag) quasars — few hundred in whole sky
- These days mostly used for studying IGM astrophysics and circum-galactic medium (CGM) around galaxies



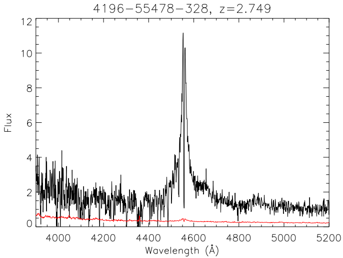
Q1422+2309; $z = 3.63$



Credit: ESO

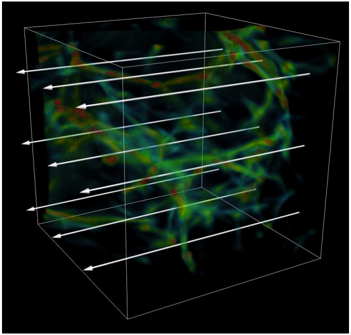
Lyα Forest Data Sets: Massive Survey Data

- Moderate resolution spectra ($R \sim 1000 - 2000$) that do not resolve individual lines
- Can be observed in bulk by multi-object spectrographs, e.g. SDSS/BOSS
- BOSS has just completed main survey, with $\sim 160,000$ Lyα forest quasars ($g \lesssim 21.5$) over 10,000 sq deg
- 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) signal in 3D and constraining expansion rate of universe at $z > 2$ (e.g. Busca et al 2013, Slosar et al 2013, Delubac et al 2014)



IGM Tomography

The Lyα forest in each quasar spectrum is a 1D tracer of the IGM, but with an extremely dense distribution of background sources it's possible to 'tomographically' map out the IGM in full 3D (Pichon et al 2001, Caucci et al 2008).



Casey Stark, UC Berkeley

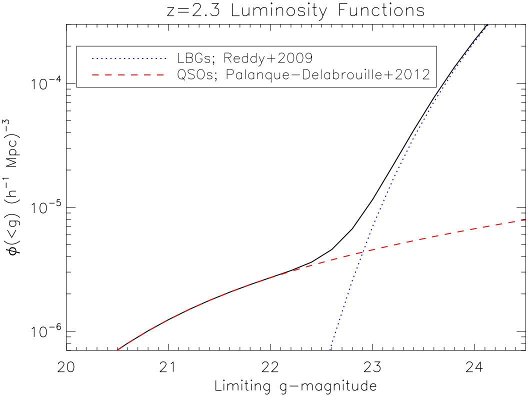
This will require using LBGs as background sources allowing $\lesssim 1\ \mathrm{h}^{-1}$ *Mpc mapping. This is part of the science case for all the 30m-telescopes.*

Some questions to ask:

- What is *meant* by IGM tomography, i.e. what are the scales we are interested in probing?
- What are the practical requirements for IGM tomography in terms of:
  - Resolution
  - Exposure time
  - Multiplexing
- What are the science applications for IGM tomography, and how do they relate to the observational requirements?

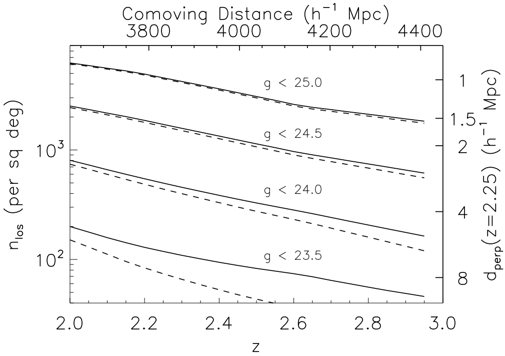
Source Luminosity Functions

At $g \gtrsim 23$, the LBG luminosity function dominates over QSOs and rises steeply with observing depth.



Density of sightlines

I can then compute projected density of sightlines as a function of z and limiting magnitude.

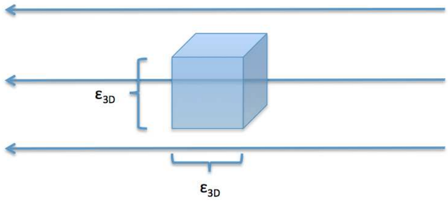


- Solid lines: LBG+QSO; Dashed-lines: LBGs only
- Exponential increase in sightline density: $\log_{10}(n_{los}) \propto g_{lim}$
- Characteristic sightline separation: $\langle d_\perp \rangle \sim \sqrt{A/n_{los}^2}$
- At limiting magnitudes of $g = [23.5, 24.0, 24.5]$, we get $\langle d_\perp \rangle \approx [7, 3.5, 2]$, h^{-1} Mpc

This takes into account the finite length of the Lyα forest absorption in each sightline (between restframe Lyα and Lyβ)

Source separation vs map resolution

The sightline separation, $\langle d_\perp \rangle$, is the basic consideration for IGM tomography. To make a map with 3D resolution ϵ_{3D}, we expect a requirement of $\langle d_\perp \rangle \lesssim \epsilon_{3D}$.



- But this says nothing about the S/N requirements. We only know $0 < S/N < \infty$.
- Also if we have multiple sightlines probing each 'voxel' $(\langle d_\perp \rangle < \epsilon_{3D})$, they all contribute to the signal.

A back-of-the-envelope calculation (I)

How does the typical source separation scale with exposure time? In background-limited regime, exposure time scales as

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Therefore

$$t_{\mathrm{exp}} \propto \langle d_\perp \rangle^{-1.6} \text{ at fixed spectral S/N}$$

A back-of-the-envelope calculation (II)

$$t_{exp} \propto \langle d_\perp \rangle^{-1.6} \text{ at fixed S/N}$$

- To go deep enough such that sources ($g \approx 24$) are separated by 5 h^{-1} Mpc requires 1/13 the exposure time to get 1 h^{-1} Mpc separations from $g > 25$ sources
- But the ratio of collecting area of between 8m and 30m mirror is $(8/30)^2 \approx 1/14$!
- If you agree that 30m telescopes can do 1 h^{-1} Mpc tomography, then we can already do 5 h^{-1} Mpc mapping with 8-10m telescopes. There is interesting science to be done at such scales!

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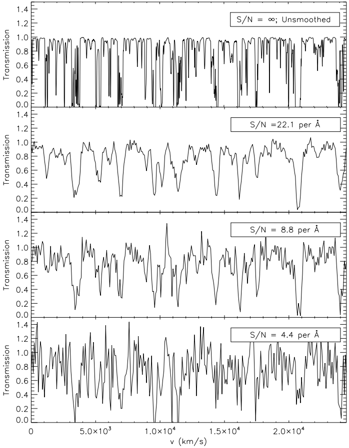
For a more detailed view we need to turn to simulations

Testing IGM Tomography with Simulations

Use Martin White's N-body TreePM simulation with 2048^3 particles in $250^3\,h^{-3}\,\mathrm{Mpc}^3$ volume.

- Generate Lyα forest absorption skewers through fluctuating GP approx, $\tau \propto (\rho/\langle\rho\rangle)^{2-0.7(\gamma-1)}$ — with peculiar velocities and Jeans' smoothing
- Extract random number of sightlines corresponding to n_{los}
- Assign source magnitudes according to luminosity functions and add pixel noise assuming some t_{exp}
- Right: Smoothed to $R = 1000$, and assuming $t_{exp} = 2$hrs on Keck LRIS on $g = [22.3, 23.3, 24.0]$ sources



Resolution Requirements

Moderate resolution spectrographs are sufficient, since we just need mapping scale ϵ_{3D} to be resolved:

$$R > 1000 \left(\frac{1.4 \ h^{-1} \, \text{Mpc}}{\epsilon_{3D}} \right) \left[\frac{(1+z)}{3.25} \right]^{-1/2}$$

(Think of it as measuring local mean-absorption, rather than studying individual Lyα absorbers)

Wiener Filtering Algorithm

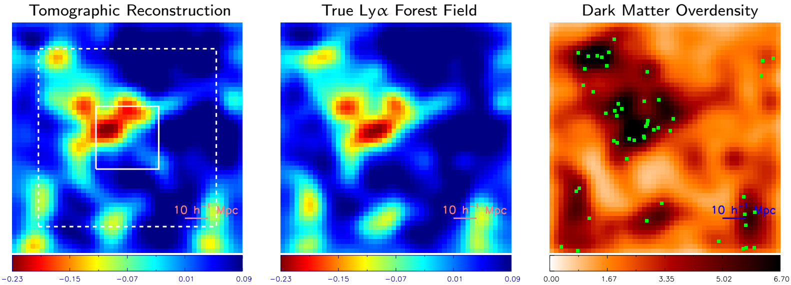
Wiener filtering can be applied to grid of Lyα forest skewers to reconstruct the underlying 3D field (Picchon et al 2001, Caucci et al 2008)

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

- $\mathbf{D}$ and $\mathbf{M}$ are the data and reconstructed vectors.
- $\mathbf{C}_{\mathrm{MD}}$ and $\mathbf{C}_{\mathrm{DD}}$ describe 2-pt correlations — split into LOS and transverse parts
- $\mathbf{N}$ is noise vector — we assume diagonality
- Gaussian smoothing at scale of $\epsilon_{3\mathrm{D}}$ as final step to remove small-scale reconstruction noise

Rupert Croft and Melih Ozbek (CMU) have written an implementation of this algorithm to create a large-scale map of the BOSS Lyα Forest at $\sim 20\ \mathrm{h}^{-1}$ Mpc scales

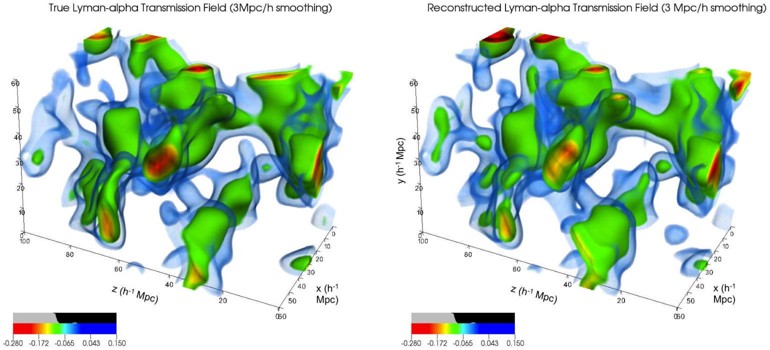
Simulation of Lyα Forest Tomography



- $(100\ \mathrm{h}^{-1}\,\mathrm{Mpc})^2 \times 2\ \mathrm{h}^{-1}\,\mathrm{Mpc}$ slices, redshift direction is into page
- Smoothing scale $\epsilon_{3D} = 3.5\ \mathrm{h}^{-1}\,\mathrm{Mpc}$.
- Assumes survey depth of $g = 24.5$ and $t_{exp} = 2$hrs on LRIS
- Green dots on DM map: coeval $\mathcal{R} = 25.5$ galaxies ($L \approx 0.4 L_*$)
- Large rectangle: 1 sq deg; Small rectangle: Area of pilot program (see later).

3D Visualization

Similar reconstruction as previous slide.



Dimensions: $(65\ h^{-1}\,\mathrm{Mpc})^2 \times (100\ h^{-1}\,\mathrm{Mpc})$

Cosmic Lyman-Alpha Program for the Tomographic Reconstruction of Absorption Probes (CLAPTRAP)

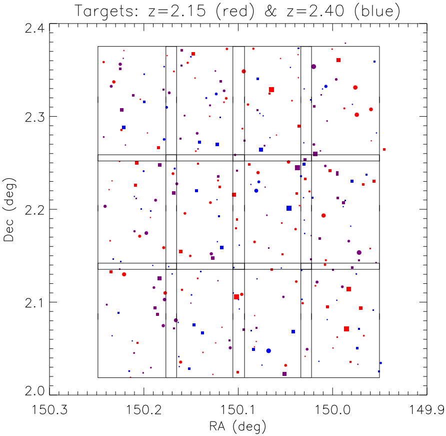
- Survey to do Lyα forest tomography in central sq deg of COSMOS, using Keck-LRIS and (possibly) VLT-VIMOS
- $\epsilon_{3D} = 3.5\ h^{-1}\,\mathrm{Mpc}$ mapping with nominal $n_{los} = 500\,\mathrm{deg}^{-2}$ and $g \leqslant 24.0$
- $(60\ h^{-1}\,\mathrm{Mpc})^2 \times 300\ h^{-1}\,\mathrm{Mpc} \sim 10^6\,h^{-3}\,\mathrm{Mpc}^3$ volume
- Total time requirements: $t_{exp} \sim$ 2hrs per LRIS pointing — 160hrs total including overheads
- Observing run at Keck LRIS last week!

CLAPTRAP-Pilot Observations

- 3 nights awarded on Keck-LRIS in Mar 25-26 (Subaru-Keck exchange) and Mar 29-30 (UC).
- Designed 12 masks ($\sim 5' \times 7'$ each) in COSMOS and 4 masks in AEGIS
- 2hrs exposure per mask on $g \sim 23.5 - 25.0$ LBGs at $2.3 < z < 3$
- Bad weather: only observed 3 COSMOS masks and 2 AEGIS masks $\rightarrow \sim$ 100 LBG spectra

COSMOS masks

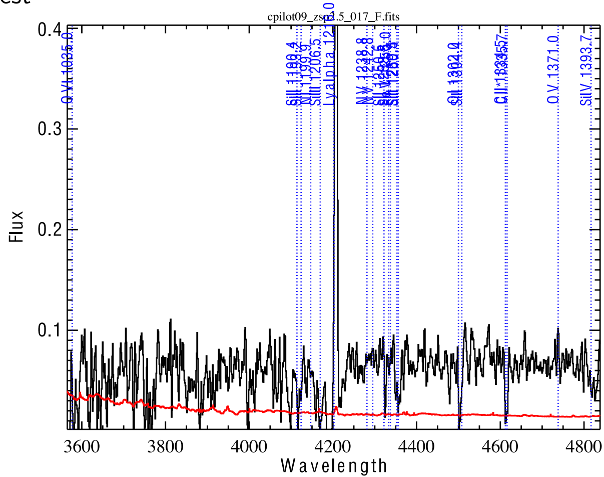
Targets were selected by g-magnitude from COSMOS catalogs to maximize forest coverage at $2.15 < z < 2.40$.



- Colors indicate forest redshift coverage NOT source redshift; Purple = full forest coverage over $2.15 < z < 2.40$, i.e. $z \sim 2.5 - 2.6$ sources
- Symbol size reflect source mags. Largest: $g \leqslant 23.4$; smallest: $g \geqslant 24.9$
- Square = spectroscopically confirmed source redshift
- Circle = photo-z's from Ilbert et al 2008 (from ~ 40 band photometry $\rightarrow < 10\%$ catastrophic errors)

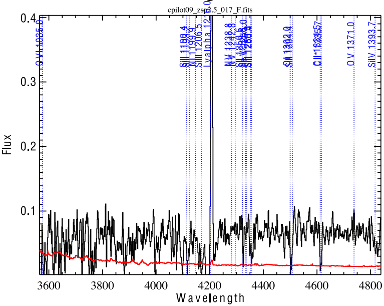
Preliminary Spectra

$g = 23.98$ LBG at $z = 2.456$ (one of our brighter objects!) with $S/N \approx 3$ in the forest

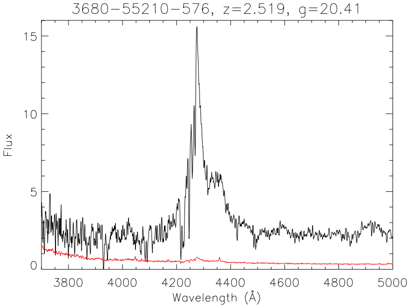


CLAPTRAP vs BOSS

$z = 2.456, \; g = 23.98$



CLAPTRAP



BOSS

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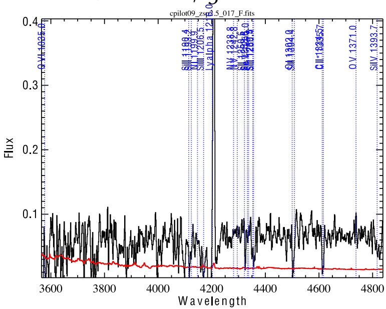

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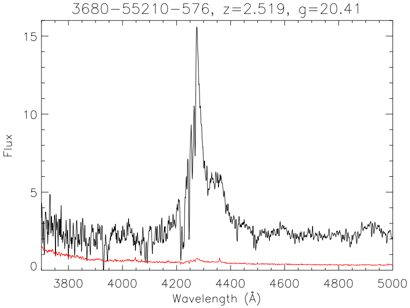
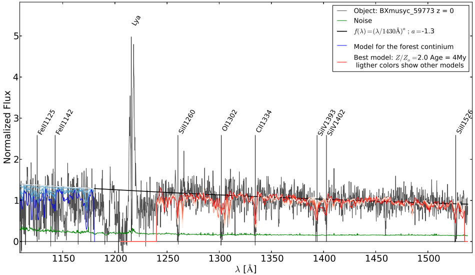


BOSS

In 6hrs on-sky we have ~ 100 BOSS-like Lyα forest spectra in 0.04deg^2
$\rightarrow$ *2500 per sq deg!*

Continuum Fitting

- Unlike QSO accretion disks, we understand stellar astrophysics $\rightarrow$ detailed physical models exist for LBG spectra (e.g. Starburst99)
- LBG spectra have intrinsic absorption lines, but at moderate resolution they are not prominent in the Lyα forest region
- Below: best-fit model (solid color), and *random* models (all from Starburst99) $\rightarrow$ the continuum estimation can't possibly be worse than $\sim$ 10% RMS



Andreu Ariño-i-Prats (Barcelona);

Spectrum observed with VLT-FORS by Gawiser et al

Science with CLAPTRAP

Lyα forest tomography with CLAPTRAP can generate LSS maps at $z \sim 2$ at $\approx 3\ \mathrm{h}^{-1}$ Mpc scales over $10^6\ \mathrm{h}^{-3}$ Mpc^3

- Galaxy Environment Studies
  - Will overlap with CANDELS/3D-HST field in COSMOS
  - Study colors, morphology, SF rates, AGN activity etc as function of large-scale environment.
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- Galaxy Protoclusters
  - Progenitors of low-z $> 10^{14.5} M_\odot$ clusters are $\rho/\langle\rho\rangle \sim 3-4$ overdensities at $\sim 10\ h^{-1}$ Mpc scales (Chiang et al 2013)
  - Expect $\sim 10-20$ protoclusters within 1 sq deg CLAPTRAP volume
  - Follow-up with imaging and spectroscopy to study member galaxies

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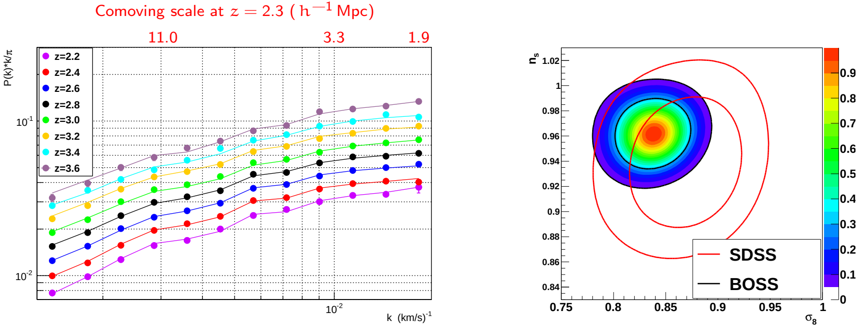
- Clustering Measurements
  - Can measure $< 10\ \mathrm{h}^{-1}$ Mpc Lyα forest autocorrelation in 3D: more 3D pixel pairs in CLAPTRAP than 1D in BOSS
  - Constrain σ_8, neutrino mass etc
  - Also: cross-correlation with CMB lensing, WL magnification etc

Small-scale Lyα Forest Power

- Measuring small-scale power ($\lesssim 10\ h^{-1}$ Mpc) in the Lyα forest allows powerful constraints on cosmological parameters such as σ_8, n_s and neutrino mass
- With BOSS, this measurement was accessible only through 1D since transverse separations too large for 3D ($\gtrsim 20\ h^{-1}$ Mpc)

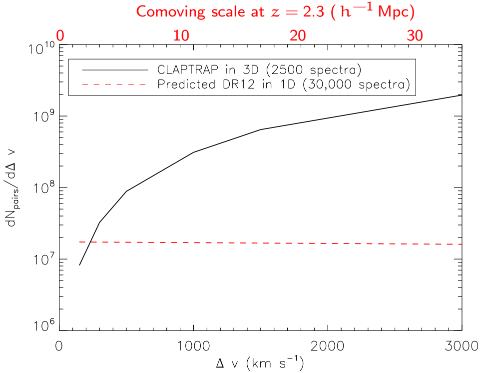


Palanque-Delabrouille et al 2013

Small-scale Lyα Forest Power with CLAPTRAP

CLAPTRAP sightlines will be sufficiently closely separated for forest autocorrelation or power spectrum to be measured in 3D

- The number of pixel pairs will be much larger than BOSS 1D
- 3D measurements will allow breaking of various systematics that affect 1D, e.g. resolution, pixel correlations, continuum

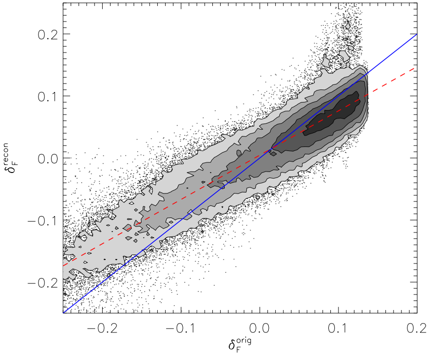


Looking Ahead: Planning Considerations for Future Lyα Forest Tomography Surveys

Survey Planning: Defining a Map S/N

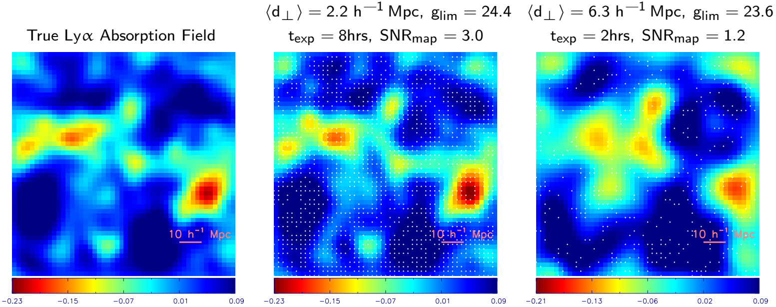
Using simulated reconstructions, we can compare the reconstructed fluxes with the true flux to define a reconstruction SNR as

$$S/N_{map} = [Var(\delta_{true})/Var(\delta_{true} - \delta_{recon})]^{-1/2}$$



Note: bias in slope is probably artifact in reconstruction algorithm

Survey Considerations: t_{exp} vs ϵ_{3D} vs $\langle d_\perp \rangle$



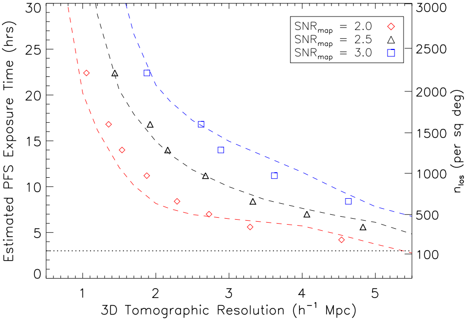
- For a given set of data, we choose the final map resolution, ϵ_{3D}.
- Above maps have $\epsilon_{3D} = 3.5\ h^{-1}$ Mpc generated from different mock data sets (dots show skewer positions).
- Need $\langle d_\perp \rangle \lesssim \epsilon_{3D}$ for a good reconstruction, smaller $\langle d_\perp \rangle$ and/or higher t_{exp} gives better maps
- Exact map quality will need to depend on science goals, but $SNR_{map} \sim 2 - 3$ is a good rule-of-thumb

Looking Ahead: Subaru PFS

Prime-Focus Spectrograph on 8.2m Subaru Telescope (Mauna Kea, Hawai'i) would be ideal for Lyα forest tomography!

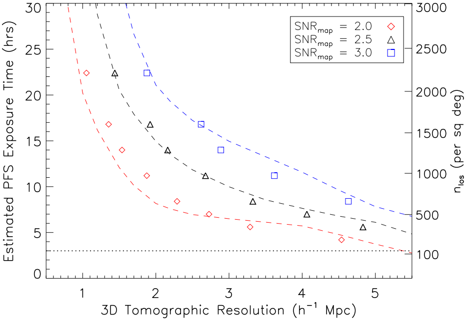
- Wide FOV: $\approx 1\text{deg}^2$ c.f. $\sim (1/80)\,\text{deg}^2$ on Keck-LRIS!)
- Massive Multiplexing: $2400\ \text{fibers deg}^{-2}$
- Ideal for deep pointings on Lyα forest background sources on continuous fields to do Lyα forest tomography

Tomographic Survey Planning for PFS



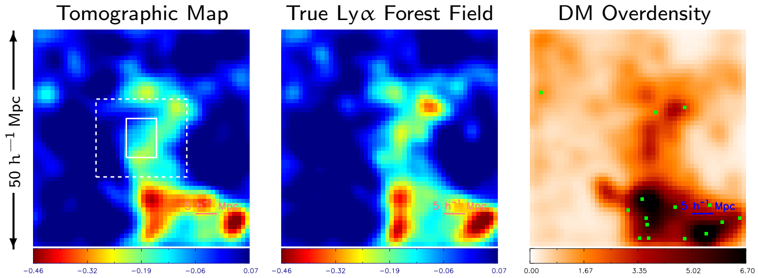
- Exposure times required to make tomographic maps at various resolutions, assuming minimum S/N = 4 per angstrom at survey limit. Different colors show different map SNR.

Tomographic Survey Planning for PFS



- Exposure times required to make tomographic maps at various resolutions, assuming minimum $S/N = 4$ per angstrom at survey limit. Different colors show different map SNR.
- Horizontal dashed line: $16\,\mathrm{deg}^2$ PFS Galaxy Evolution Survey (Takada et al 2013) will observe $i < 24$ LBGs with 3hrs exposures. Overall target density of $\sim 300\,\mathrm{deg}^{-2}$ or $n_{los} \sim 100\,\mathrm{deg}^{-2}$
$\rightarrow \epsilon_{3D} \approx 6 - 7\ h^{-1}$ Mpc map over $\sim (0.35 h^{-1} \mathrm{Gpc})^3$

Deep Tomography on PFS



- Dedicated fields with $t_{\mathrm{exp}} \approx$ 20hrs on PFS should be able to pick up S/N $\sim$ 4 per Å on $g \approx 24.9$ LBGs $\rightarrow$ $\epsilon_{3D} \sim 1.5\ h^{-1}$ Mpc
- This corresponds to $\sim 500 - 600$ kpc physical, close to circumgalactic medium scales
- Possibly directly see cold-flow accretion?
- Even just 1 single PFS field ($\sim 65\ h^{-1}$ Mpc $\times$ $65\ h^{-1}$ Mpc in transverse coverage) will be very exciting

Summary/Conclusions

- Cosmography with galaxies is difficult at $z \gtrsim 1$
- At $\mathrm{g} \gtrsim 23$, LBGs dominate the $z \sim 2$ UV luminosity function, at sufficient area densities to enable direct 3D tomography of IGM $\rightarrow$ direct mapping of the $z \sim 2$ cosmic web
- Requirements not as stringent as previously thought: Moderate resolution spectra with $S/\mathrm{N} \sim$ a few are adequate
- CLAPTRAP: Mapping 0.9 sq deg in COSMOS at $\sim 3.5\ \mathrm{h}^{-1}$ Mpc resolution with Keck LRIS $\rightarrow \sim$ 160hrs total
- Science: Galaxy environments, galaxy protoclusters, topology of LSS....
- Subaru-PFS will be amazing for IGM tomography!

For more details, please see arXiv:1309.1477