Constraining the IGM Temperature-Density Slope with the BOSS Flux PDF

Edinburgh 'Intergalactic Interactions' Workshop

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Collaborators

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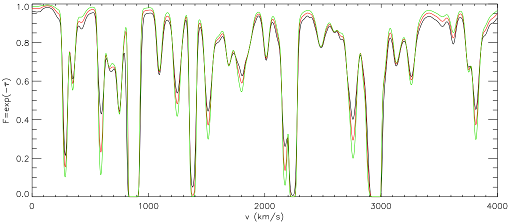
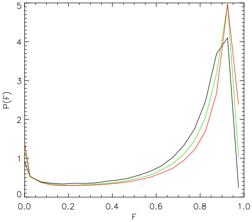
Lyα forest Flux PDF

The Lyα forest probability distribution function (PDF) is sensitive to temperature-density relation, $T \propto \rho^{\gamma - 1}$

$\gamma = 1.5$, $\gamma = 1.0$, $\gamma = 0.5$





Different implications for thermal history:

- $\gamma = 1.5$: Relaxed state after hydrogen reionization at high-z
- $\gamma = 1.0$: Expected from inhomogeneous HeII reionization at $z = 3 - 4$
- $\gamma = 0.5$: Inverted, requires preferential heating of voids!

Observational Constrants

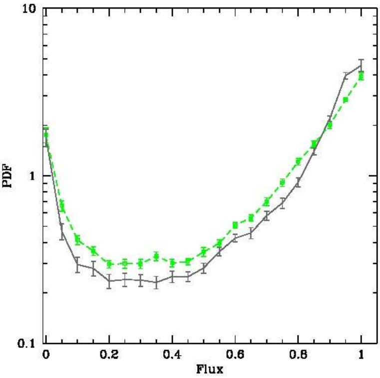
No consensus on γ at $2 \lesssim z \lesssim 3$!

- McDonald et al 2000: $\rightarrow \gamma \approx 1.6$ (PDF)
- Bolton et al 2008/Viel et al 2010: $\gamma = 0.44 - 0.67$ from Kim et al 2007 measurement! (PDF)
- Calura et al 2012: $\gamma \approx 1$ (PDF)
- Rollinde et al 2012: consistent with $\gamma \approx 1.5$ (PDF)
- Rudie et al 2012: $\gamma \approx 1.3$ ($\mathrm{b} - \mathrm{N_{HI}}$ cutoff)

Motivation I: Current measurements don't converge

Flux PDF is so far measured with small numbers (~ 5) of high-resolution spectra per z-bin. Sample variance + methodology variance is significant

$z = 3$ PDF from Calura et al 2012 (green) and Kim et al 2012



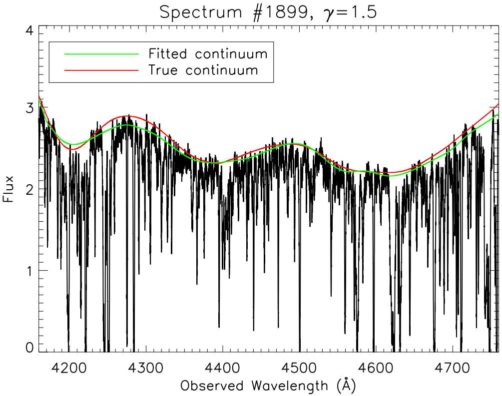
Calura et al 2012

Rollinde et al 2012 also suggests error bars tend to be underestimated.

Motivation II: Continuum-fitting bias

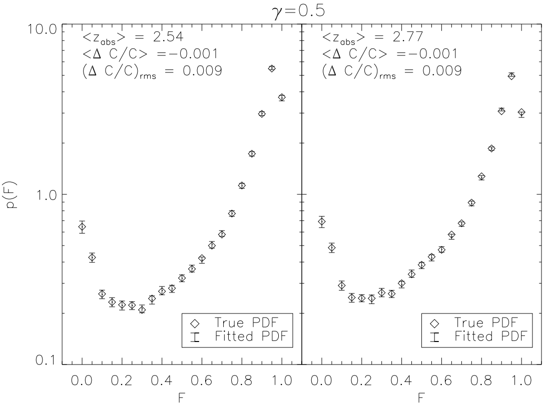
I showed in Lee 2012 how uncertainty in continuum-fitting affects flux PDF constraints on $T - \rho$ slope.

But high-resolution spectra are continuum-fitted by hand. This can give a biased flux PDF towards lower γ.



More complicated than simple up/down rescaling of continuum

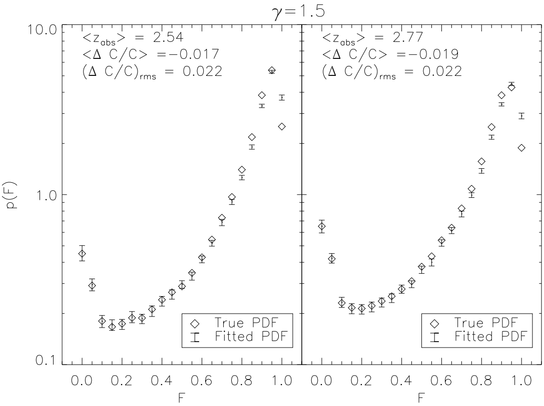
Continuum-fitting bias on PDF



Diamonds: True PDF; Error bars: Recovered PDF

Continuum-fitting bias on PDF

- High-γ values more likely to suffer from continuum bias
- Even F $\lesssim$ 0.9 potion of PDF affected



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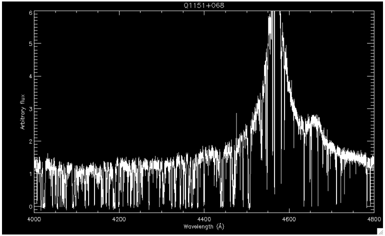
An unlikely proposition?



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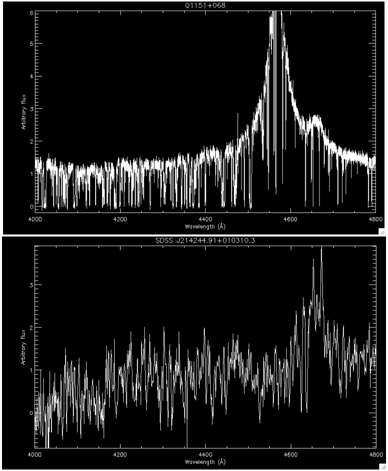

Let's measure the Lyα forest flux PDF with BOSS spectra!

Flux PDF measurement with BOSS

This motivates an independent measurement from previous methods. We carry out a measurement of the Lyα forest flux PDF from high-SNR subset of BOSS spectra, at $\langle z \rangle = [2.3, 2.6, 3.0]$.

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- Large numbers ($\gtrsim 100,000$) to beat down sample variance
- Full automation — allows marginalization of nuisance parameters

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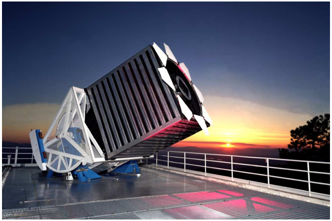
- Large numbers ($\gtrsim 100,000$) to beat down sample variance
- Full automation — allows marginalization of nuisance parameters

Disadvantages:

- Noisy (median $S/N \sim 1$ per pixel) and moderate resolution $R \approx 2000$ require careful modelling
- Requires model for forest contaminants (metals + LLS)

Baryon Oscillation Spectroscopic Survey

- 1000-fiber multi-object spectrograph on the 2.5m SDSS Telescope, Apache Point NM
- Wavelength coverage: $3600 - 10400$ Å with resolution $R = \lambda/\Delta\lambda \approx 2000$
- Survey will run from Dec 2009-July 2014
- Eventual goal:
  - 1.5×10^6 galaxy redshifts at $\langle z \rangle \sim 0.5$
  - 1.7×10^5 Lyman-α forest quasars with $\langle z \rangle \sim 2.3$
- DR9 publicly available;



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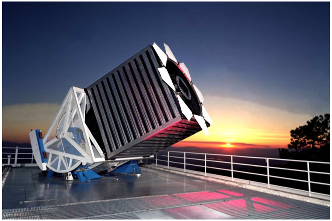
- DR9 publicly available; DR10 to be released July 2013 with $\sim 2\times$ data



BOSS DR9 Lyα Forest Sample

Lee et al 2013 (AJ 145, 69) released a value-added set of BOSS DR9 spectra specially for Lyα forest analysis.

Intended for comparison purposes and as 'starter package'. Includes:

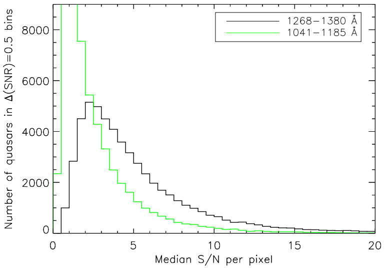
- Continua (see later)
- Masks: Pixel, sky, DLA
- Noise corrections
- DLA damping wing corrections
- Corrections for artifacts in spectrophotometric calibration

Available in per-spectrum format at
http://www.sdss3.org/dr9/algorithms/lyaf_sample.php

Data Cuts

Used DR9 Quasar Catalog (Paris et al 2012 A&A, 548, 28) as parent sample.

- Quasar redshift: $z > 2.15$
- Non-BAL quasars
- $S/N > 0.5$ per pixel ($S/N > 6$ for PDF analysis)
- Less than 80% of pixels flagged by pipeline
- Fitted continua (see later) must be be positive (see later)
- Outliers in spectral dispersion rejected for PDF analysis

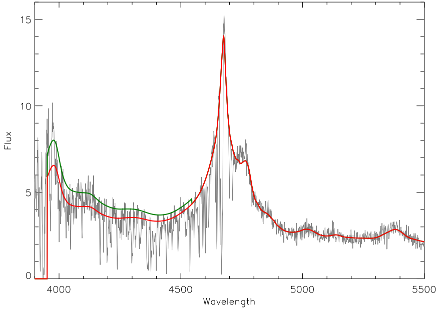


Final count: 54,468 spectra; 3,387 used in PDF analysis

Mean-Flux Regulated PCA Continuum Fitting

- Described in Lee, Suzuki & Spergel 2012
- Fit PCA templates redwards of quasar Lyα line (restframe $1216 - 1600$ Å) to guess *shape* of quasar continuum
- Regulate the continuum with a linear function such that it yields the $\langle F \rangle(z)$ from external measurements, to give correct amplitude and slope

Gives only 4% RMS errors at $S/N \gtrsim 5$ per pixel



Forward Modelling Approach

We make 'noisy' measurement and do forward modeling on simulation:

$$\textit{(Sims with IGM Model} \xrightarrow[\text{Systematics model}]{} \textit{BOSS Data)}$$

BOSS Data:

- Normalize by continuum
- Evaluate histogram

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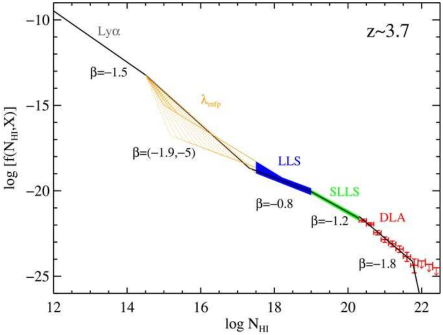
Model:

- Use simulations as basis — GADGET2-based hydro sims by M. Viel & J. Bolton
- Generate realistic mock skewers from simulations:
  1. Add LLS
  2. Add metals
  3. Smooth to BOSS resolution
  4. Add realistic pixel noise
- Compare directly with data measurement

Step I: Lyman-limit Systems

$N_{HI} \gtrsim 10^{16}\,\mathrm{cm}^{-2}$ absorbers are self-shielding and are not normally captured in sims above this threshold. We discard DLAs ($N_{HI} > 10^{20.3}\,\mathrm{cm}^{-2}$) from our sample, but LLS are hard to identify.



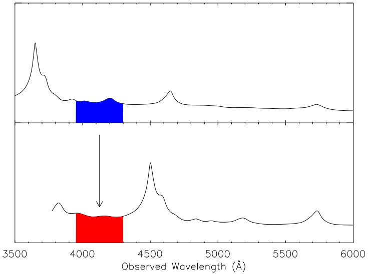
Prochaska, O'Meara & Worseck 2010

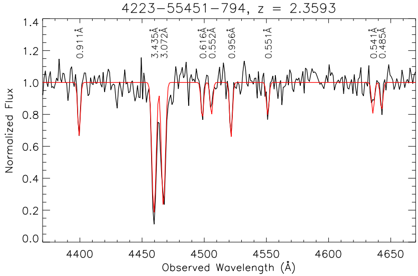
Draw absorbers in the range $10^{17.2}\,\mathrm{cm}^{-2} < N_{HI} < 10^{20.3}\,\mathrm{cm}^{-2}$, then add Voigt profiles on top of mock spectra.

Step II: Metal Absorbers

At BOSS resolution, only stronger absorption associated with MgII absorbers, low-z LLS/DLAs are seen We use a 'side-band' approach to add metals to our mock spectra in a model-independent way.

- Britt Lundgren (Wisconsin) provided a raw catalog of $\lambda_{rest} > 1216$ Å absorbers
- Draw absorbers from restframe $\lambda \approx 1260 - 1390$ Å in lower-z quasar at same observed wavelength range that matches each forest segment

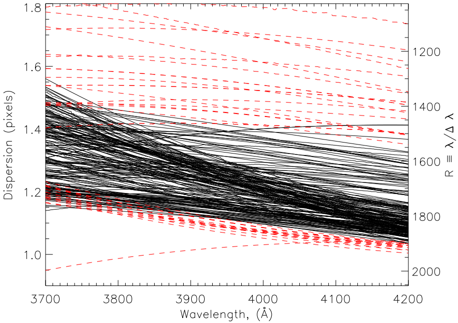




This agnostically includes all absorbers with $\lambda_{rest} \gtrsim 1400$ Å, i.e. Si IV onwards.

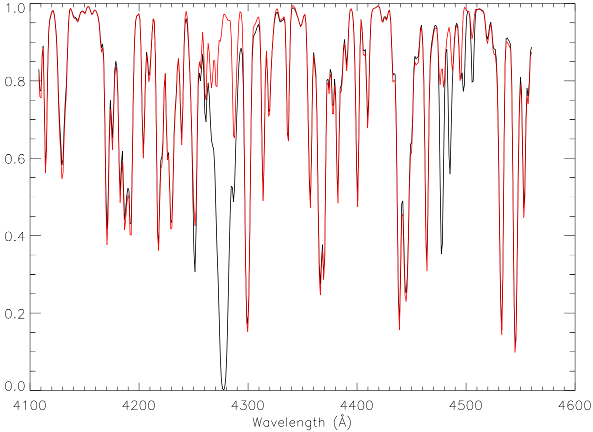
Step III: Resolution

BOSS pipeline reports a per-pixel dispersion for each spectrum.



- We cut below 5th percentile and above 90th percentile in median dispersion within each redshift bin
- Smooth each mock spectrum by median dispersion within the relevant wavelength range

Effect of LLS+metals+smoothing on sim spectra



(Noiseless spectra, but smoothed to BOSS resolution)

Step IV: Noise

BOSS pipeline noise estimates suffer from 2 problems:

1. Known to give biased estimate, at up to $\sim 15\%$ at blue end
2. Does not give separation of 'signal' and CCD components — required to add accurate noise to mock spectra with different absorption field

In the DR9 Lyα forest 'package' we have included per-spectrum noise corrections that deal with #1 but not #2

MCMC Noise Estimation

Carry out our own co-addition of BOSS individual exposures, with MCMC resampling to solve for the 'true' observed flux, F_λ and fudge factors A, B, C, D.

$$\sigma^2_{\lambda i} = B\hat{S}_{\lambda i}\left(F_\lambda + s_{\lambda_i}\right) + A\hat{S}^2_{\lambda i}\sigma^2_{\mathrm{RN,eff}}\sigma_{disp}(\lambda)$$

where

$$\hat{S}_{\lambda i} = S_{\lambda i}\left(1 - exp(-C\lambda + D)\right)$$

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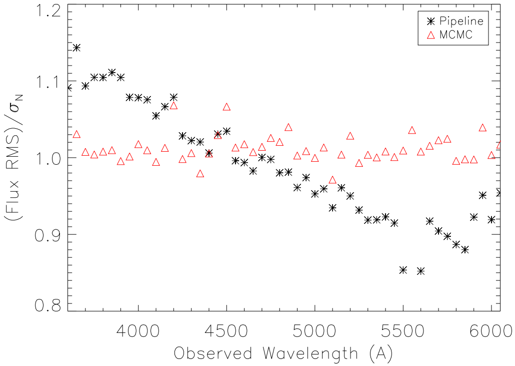
This effectively separates out the two terms in σ. We can simply plug in F_λ from our mock spectra to introduce *self-consistent noise that matches properties of each individual spectrum*

Noise dispersion test

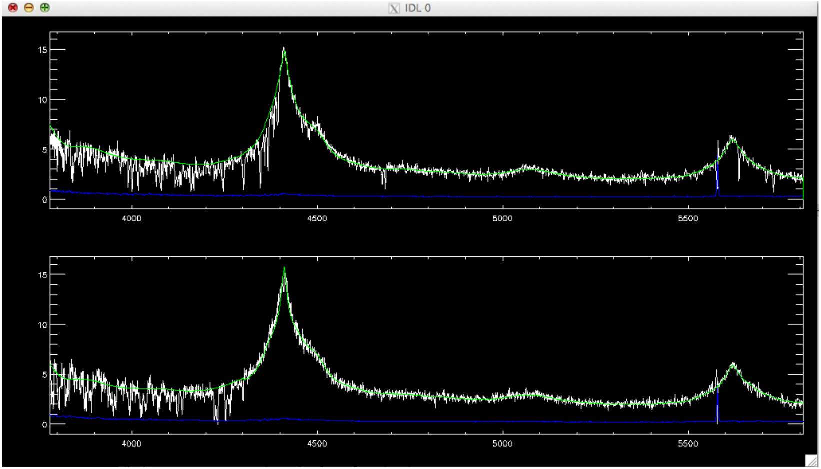
Compare flux RMS in absorption-free 1450-1470 Å region, to noise estimate. If noise estimate is good, this should average to unity.



- (Flux RMS)/$\sigma_N > 1$: Underestimated noise
- (Flux RMS)/$\sigma_N < 1$: Overestimated noise

Full co-added mocks

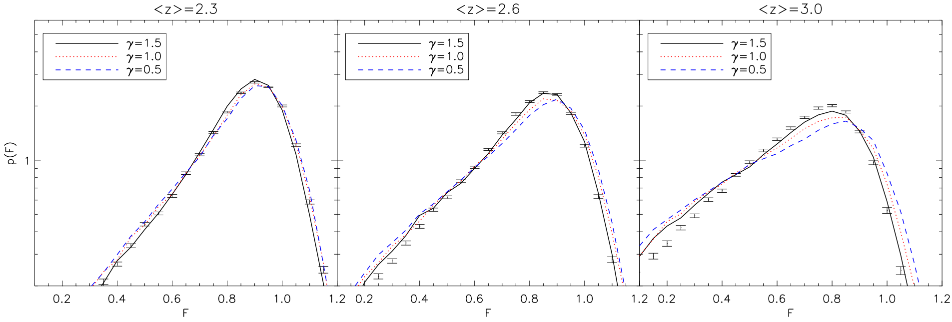
Mock spectra are embedded onto actual continuum-fit of each quasar before adding noise. We then re-fit continuum to introduce realistic continuum errors.



Results...

We do this for ~ 2500 high-SNR DR9 spectra ($\langle S/N \rangle > 6$), in $\langle z \rangle = [2.3, 2.6, 3.0]$ bins.

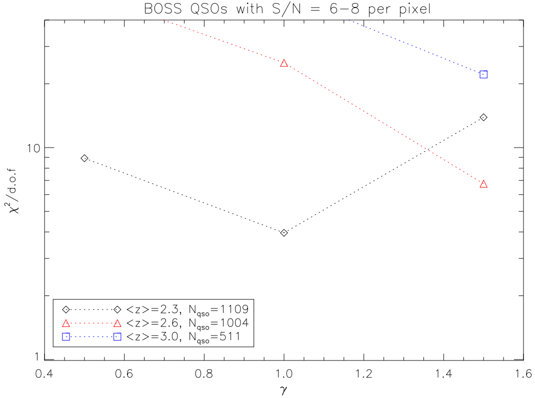
$8 > \langle S/N \rangle > 10$ bin:



$\gamma = 1.5$ is favored at $\langle z \rangle = 2.6, 3.0$, but isothermal model preferred at $\langle z \rangle = 2.3$. Don't seem to get good fit in $z = 3$ bin... something off with my LLS model?

Consistency across SNR bins

Reduced χ^2 as a function of temperature-density slope γ, at differerent redshifts



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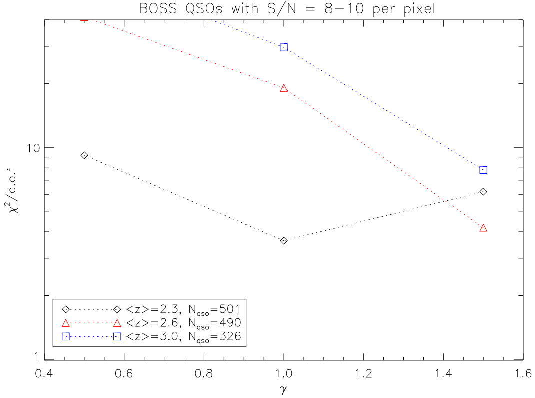

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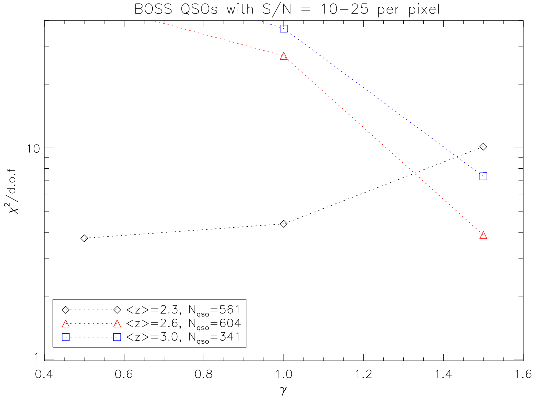


Consistency across SNR bins indicates noise model is robust

Next Steps

- Must sort out LLS model — LLS should be correlated with forest?
- Need sims that cover broader range of IGM thermal histories, for comparison
- Marginalization over nuisance parameters: continuum errors, $\langle F \rangle(z)$, LLS abundance etc
- Future plans: Deconvolution of intrinsic flux PDF

Conclusions/Summary

- Flux PDF measurements with high-resolution data do not agree + could suffer from continuum bias
- We have developed a model for BOSS spectra that allows us to exploits statistical power of BOSS:
  - Accurate continuum fitting
  - Robust noise model enables realistic noise in mock spectra
  - Automation will allow marginalization over nuisance parameters
- *Tentative:* Results indicate $\gamma \approx 1.5$ at $\langle z \rangle = 3.0$, evolution to $\gamma \approx 1$ at $\langle z \rangle \sim 2$?


MONTY PYTHON'S
And Now For Something
COMPLETELY DIFFERENT
DVD

CLAPTRAP

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

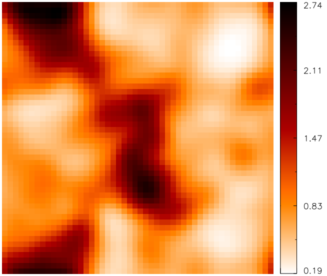
Deep + dense Lyα forest survey on VLT-VIMOS

- $\mathrm{B} < 24.5$ LBGs and QSOs
- Sightline densities of ~ 1000 per sq deg ($100\times$ BOSS)
- 3D Tomographic mapping of the $z \sim 2$ Lyα forest on $\sim 3\,\mathrm{h}^{-1}$ Mpc scales

Pilot program proposed for upcoming period to cover 0.25 sq deg in COSMOS field

Right: $(100\,\mathrm{h}^{-1}$ *Mpc*$)^2 \times 2\,\mathrm{h}^{-1}$ *Mpc sim slices*

DM Distribution smoothed to $4\,\mathrm{h}^{-1}$ Mpc



Lyα forest absorption map from CLAPTRAP