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

IAU 308 "Zel'dovich Universe", Tallinn, Estonia

Khee-Gan ("K.G.") Lee
@kheegster

Max Planck Institut für Astronomie
Heidelberg, Germany

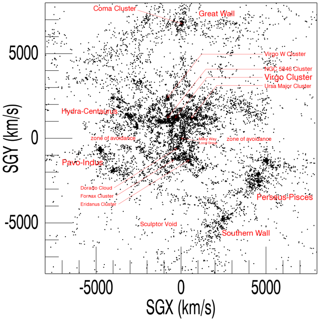
June 26, 2014

Collaborators: *Joe Hennawi (MPIA), Casey Stark (Berkeley), Martin White (Berkeley), Xavier Prochaska (UCSC), David Schlegel (LBNL), Andreu Ariño-i-Prats (Barcelona), COSMOS collaboration, + Your Name Here*

Direct Mapping of 3D LSS with Galaxy Redshift Surveys

- Mapping the 3D cosmic web requires galaxy spec-z's (best photo-z's give $\sigma_z = 0.1$ or $\delta r_{los} \sim 100\,h^{-1}$ Mpc at $z \sim 2$)
- Probing ~Mpc-scales require spec-z's to $L \gtrsim 0.1 L_*$, but $SB \propto (1+z)^{-4}$ (i.e. need $R \sim 27$ at $z > 2$)

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



Courtois et al 2013

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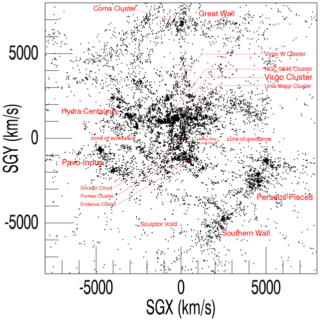
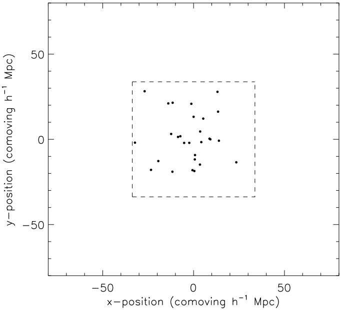


Courtois et al 2013

$z = 2.3$
(COSMOS spectro-z's)

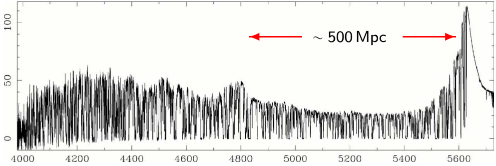


COSMOS Collaboration

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

In the photoionized intergalactic matter (IGM), the Lyα transmission $F = exp(-\tau)$ traces underlying matter density, $\Delta \equiv \rho_{dm}(x)/\langle\rho_{dm}\rangle$, modulated by IGM astrophysics :

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



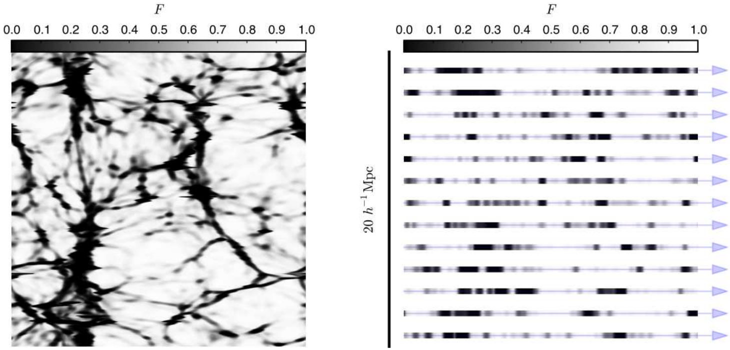
Q1422+2309; $z = 3.63$

The Lyα forest....

- ... is a LSS probe at $z \gtrsim 2$ ($>$ 10 Gyr lookback times)
- ... each background source probes a huge path-length along the LOS between Lyα and Lyβ
- ... probes near mean cosmic density ($0 \lesssim \Delta \lesssim 10$)

Lyα Forest Tomography

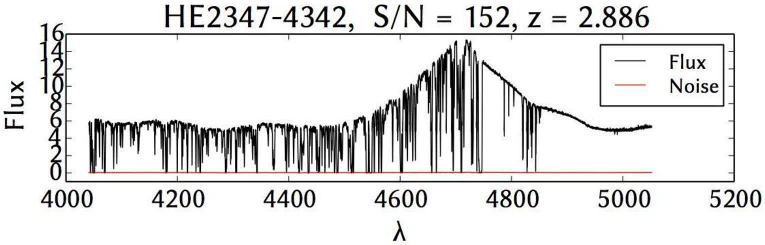
Individual Lyα forest spectra probe the IGM in 1D, but a dense collection of closely-separated sightlines will enable 3D reconstruction of absorption field (e.g. Pichon et al 2001, Caucci et al 2008, Lee et al 2014)



Credit: Casey Stark (Berkeley)

Bright Quasars are *Rare!*

Traditional Lyα forest analysis use high-SNR, high-resolution echelle spectra of bright quasars ($V \lesssim 18$) — requires many hours of 8-10m time.



Credit: Michael Walther (MPIA)

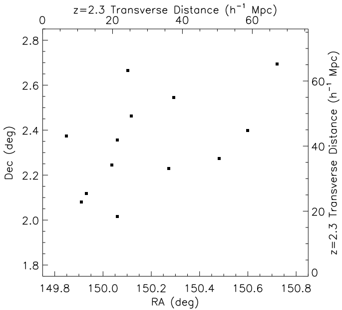
(Few hundred in whole sky)

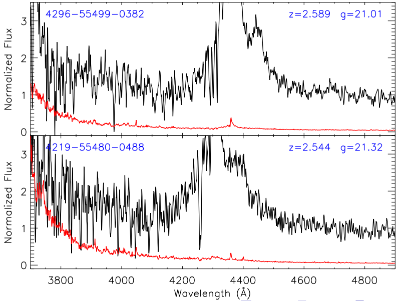
Availability of Background Quasar Sources

"Количество - это само по себе качество" - Иосиф Сталин.

BOSS survey first to exploit 3D information by incorporating tranverse correlations to measure the $r \sim 100\ h^{-1}$ Mpc BAO signal.

- For $g \lesssim 21.5$ QSOs, area density of $\sim 15\,\mathrm{deg}^{-2}$ over $10^5\mathrm{deg}^2$
- $R \equiv \lambda/\Delta\lambda \sim 2000$ spectra with $S/N \sim 2$ with 2.5m telescope





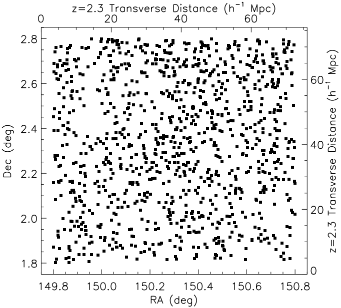
Availability of Background ~~Quasar~~ LBG Sources

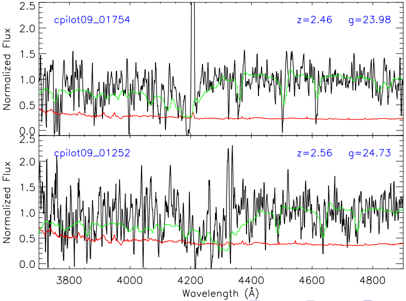
"Количество - это само по себе качество" - Иосиф Сталин.

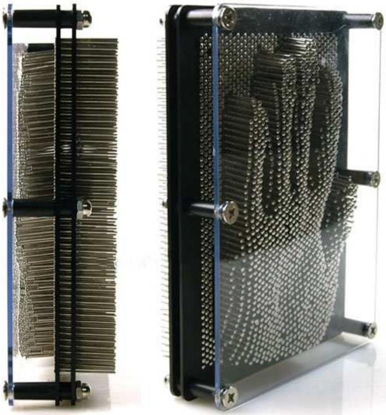
"Quantity has a quality all its own", Joseph Stalin

By going to > 23rd mag, we start picking up $z > 2$ star-forming galaxies as background sources

- For $g \lesssim 24.5$ LBGs, area density of $\gtrsim 1000\,\mathrm{deg}^{-2}$ ($\langle d_\perp \rangle \sim 2\ h^{-1}\,\mathrm{Mpc}$)
- $R \sim 1000$ spectra with $S/N \sim 2-3$ doable with 8-10m telescopes

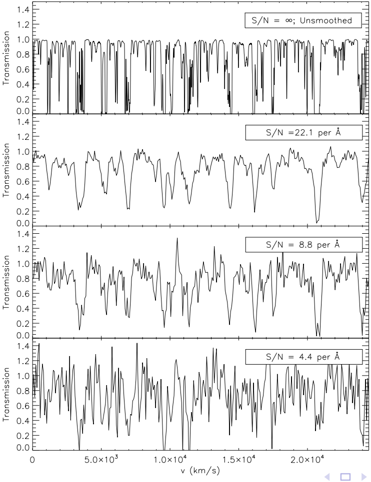






Testing Requirements with Sims (Lee et al 2014)

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

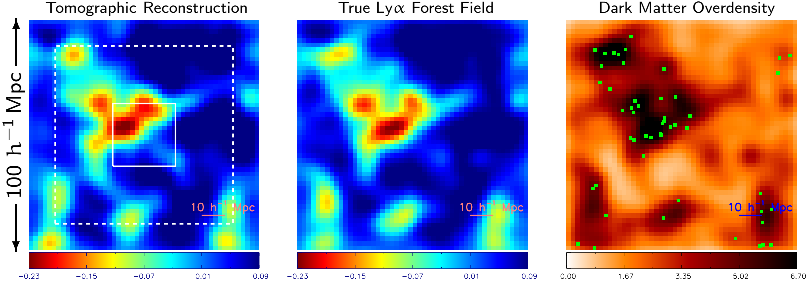
Wiener Filtering Algorithm

Wiener filtering can be applied to grid of Lyα forest skewers to reconstruct the underlying 3D field (Pichon 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 — this allows us to weigh data by pixel SNR
- Use very fast PCG implementation written by Casey Stark & Martin White

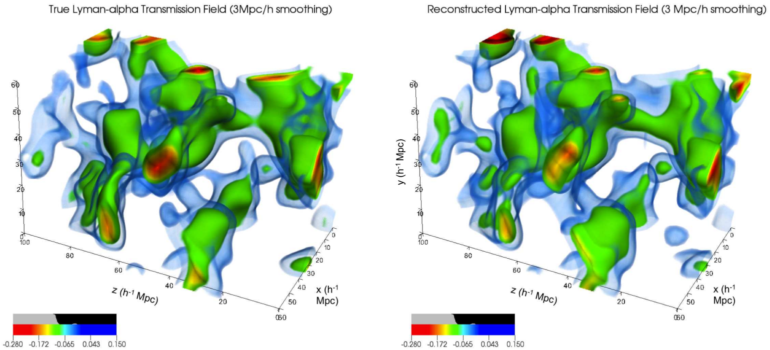
Simulation of Lyα Forest Tomography at $z \sim 2.3$



- $(100\ \mathrm{h}^{-1}\,\mathrm{Mpc})^2 \times 2\ \mathrm{h}^{-1}\,\mathrm{Mpc}$ slices, redshift direction is into page
- Smoothing scale $\epsilon_{3D} = 3.5\ \mathrm{h}^{-1}\,\mathrm{Mpc}$ (~ 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 ($L \approx 0.4 L_*$)

3D Visualization of IGM Tomography

'True' 3D absorption field at left; reconstruction from noisy mock spectra at right (Similar reconstruction as previous slide).



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

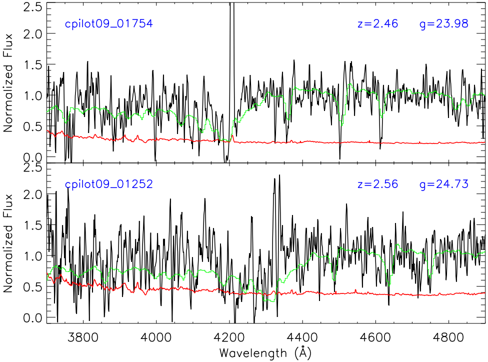
COSMOS Lyman-Alpha Mapping And Tomography Observations (CLAMATO)

- Survey to do Lyα forest tomography in central sq deg of COSMOS field, using Keck-LRIS and VLT-VIMOS (currently in TAC)
- $\epsilon_{3D} \sim 4\ h^{-1}\,\mathrm{Mpc}$ 3D mapping at $\sim 1000\,\mathrm{deg}^{-2}$ and $g \leqslant 24.7$
- $(60\ h^{-1}\,\mathrm{Mpc})^2 \times 300\ h^{-1}\,\mathrm{Mpc} \sim 10^6\,h^{-3}\,\mathrm{Mpc}^3$ volume
- Total time requirements: $t_{exp} \sim$ 2hrs per LRIS pointing — 160hrs total including overheads
- Pilot run with Keck LRIS in March 2014 through UC (PI: Schlegel) and NAOJ (PI: Lee). 2 night on COSMOS + 1 night on AEGIS $\rightarrow$ lost $\sim 75\%$ to weather

COSMOS Lyman-Alpha Mapping And Tomography Observations (CLAMATO)

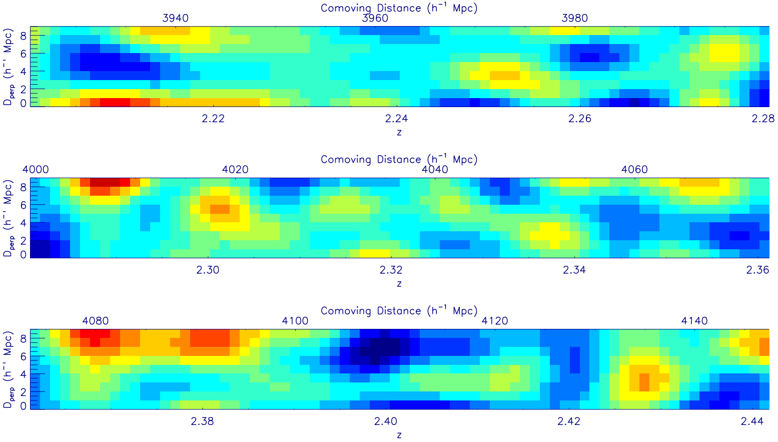
Preliminary Spectra

Reduced 12 spectra from one $\sim 5' \times 7'$ mask ($\langle d_\perp \rangle \sim 2\ h^{-1}$ Mpc separations) with sufficient SNR for tomography. (Shapley et al 2003 LBG composite spectrum in green)



Preliminary Map

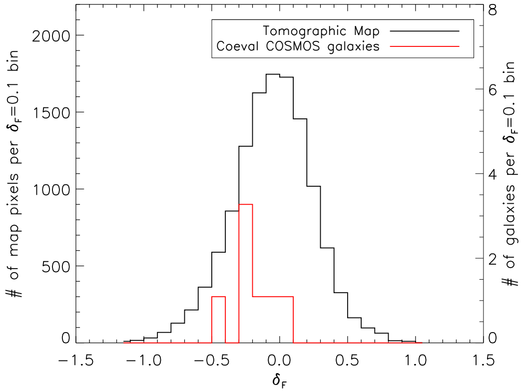
Preliminary tomographic reconstruction with smoothing scale of $\sim 5\ h^{-1}$ Mpc.
Only 2hrs of data!!



Map shows reconstructed $\delta_F = F/ < F > -1$, red is overdensities

Comparison with COSMOS galaxies

- There are 7 galaxies with solid spectro-z's within the map volume
- Can check the δ_F at the location of these galaxies.
- Preferentially located in higher-δ_F regions: 5/7 of galaxies reside in the top $\sim$ 30th percentile high-absorption regions



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 ($\gtrsim 10\,\mathrm{h}^{-1}$ 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)
- Structures/Topology at high-z
  - How filamentary is $z \sim 2$ LSS on scales of few Mpc?
  - Use topology (genus, voids AP etc) as standard ruler? (probably next-gen surveys with DESI, PFS etc)

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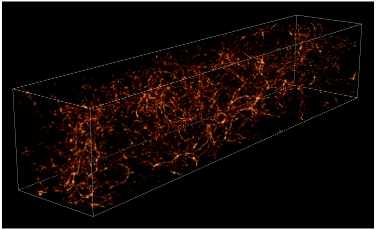
YOU tell me!

Summary/Conclusions

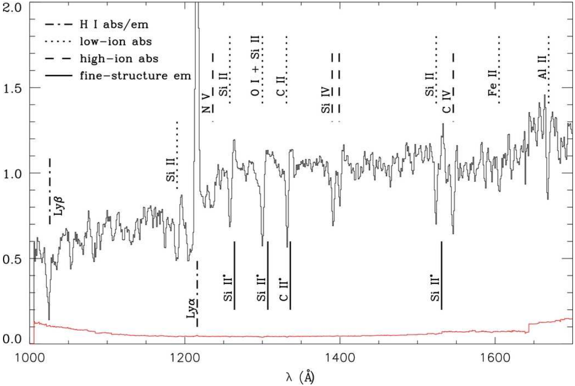
- High area density of relatively noisy Lyα forest spectra are sufficient to create 3D LSS maps at $z \gtrsim 2$, feasible with existing 8-10m telescopes
- CLAMATO: Lyα forest spectroscopy aimed at observing ~ 1000 LBG/QSOs in COSMOS 1 sq deg with $\langle \mathrm{d}_\perp \rangle \sim$ 2pMpc separation
  $\rightarrow$ (65 h^{-1} Mpc)^2 $\times$ 200 h^{-1} Mpc $\sim$ (100 h^{-1} Mpc)^3 at $2.15 \leqslant z \leqslant 2.40$
- **This is happening over the next couple of years!**
- Science: Galaxy environments, cluster progenitors, LSS topology, cosmology...
- Happy to collaborate!



Credit: Casey Stark (Berkeley)

Composite LBG Spectrum

By stacking multiple LBG spectra in their restframe, the Lyα forest fluctucations average out and we can see the intrinsic absorption.

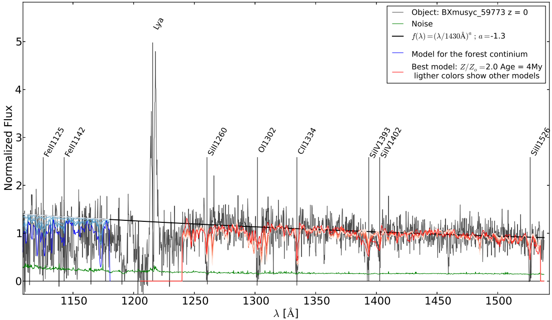


Berry et al 2012

Intrinsic spectrum of high-z star-forming galaxies is relatively free from strong emission lines in the $1040\text{Å} - 1190\text{Å}$ Lyα forest region.

Continuum Fitting

- Unlike QSOs, 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 Starburst99 model (solid color) fitted to MUSYC spectrum, and *random* Starburst99 model



Andreu Ariño (Barcelona)