# Cosmic Web, IGM tomography and *Clamato*

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with
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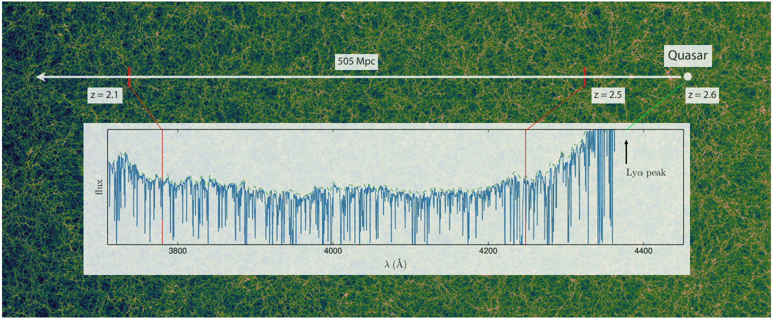
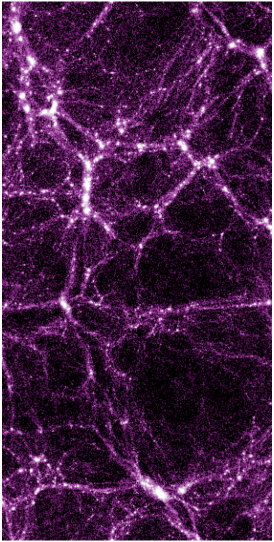


# The cosmic web

- All of the structure in our Universe arose from small, initially Gaussian (quantum) fluctuations (generated during inflation) amplified by gravitational instability in a (cold) dark matter dominated Universe.
- A natural outcome of this process, when viewed on Mpc scales, is a beaded filamentary network of voids, sheets, filaments and knots known as the cosmic web.
- All of galaxy and structure formation occurs in this context!
- What are the observational requirements for making a map of the cosmic web at high $z$?

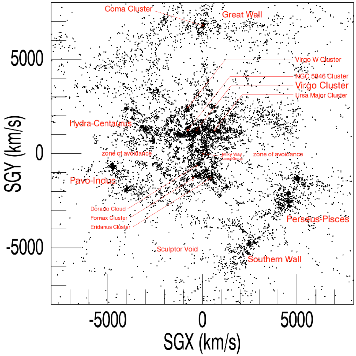


# Mapping the web

- The physics of gravitational instability, the initial fluctuation spectrum and the cosmic constituents provide natural definitions for "large", "dense", "representative".
  - Natural length scale set by the horizon at matter-radiation equality ($k_{\rm eq} \simeq 0.0103(1)\,\mathrm{Mpc}^{-1}$, i.e. 100 Mpc).
  - Amplitude of fluctuations (power spectrum) sets requirements on tracer density.
- Can we make a map of the large-scale structure with Mpc resolution over a representative volume of the Universe ($10^6\,h^{-3}\mathrm{Mpc}$) with existing telescopes?
- Can we survey massive volumes to find extreme objects (protoclusters, voids, ...)?
- Can we measure the "environment" of galaxies at high $z$?

# Galaxy redshifts at $z \simeq 0$ and $z \simeq 2.5$

Locally we do cosmography with galaxy redshift surveys – but redshifts get expensive at high $z$!




Courtois et al. (2013)

Note we've isolated a thin slice in $z$

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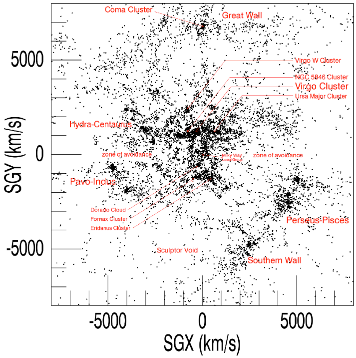


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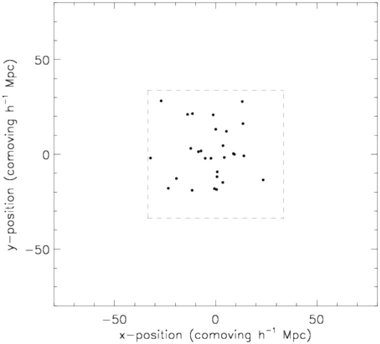



COSMOS collaboration

Note we've isolated a thin slice in $z$

# Galaxy density

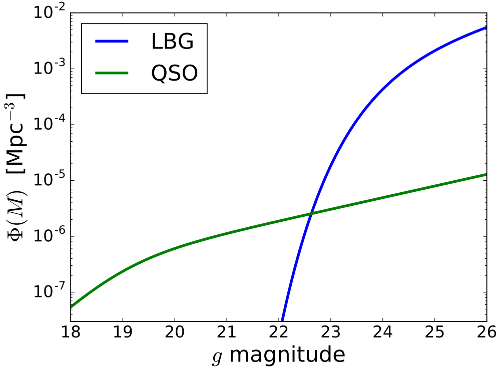
- Ability to map LSS depends on galaxy separations.
- SDSS main sample ($z < 0.2 - 0.3$) has a mean inter-galaxy separation of $\sim 8\,h^{-1}$Mpc.
- At $z = 0.5$ need to go to $I_{AB} = 22.5$ to reach the same mean separation.
- At $z = 1.0$ need $I_{AB} = 24.2$.
- At $z = 2.0$ need $I_{AB} = 25.7$.
- Direct mapping of $z > 1$ LSS at Mpc resolution is a 30 m telescope project!

Galaxies aren't the only tracer of large-scale structure: if we use HI we get line-of-sight "for free".

# Source luminosity functions

With the Ly$\alpha$ forest we get the line-of-sight sampling "for free", so we just need to get the transverse sampling high enough.

To increase the sightline density we need to go beyond QSOs as backlights. Beyond $g \sim 22 - 23$ LBGs dominate over QSOs.




Exponential increase in sightline density below $g \simeq 23$!

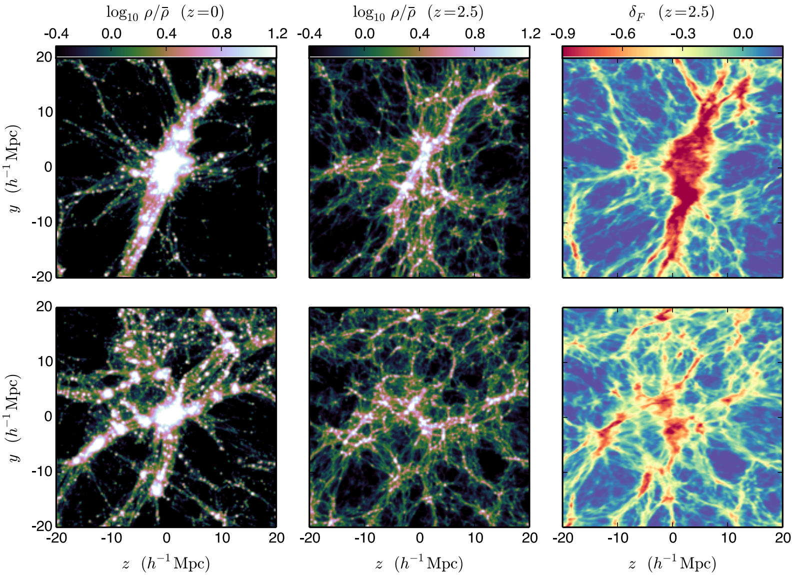
By 24$^{\mathrm{th}}$ magnitude sources are separated by arcminutes on the sky.

# Requirements?

- The standard in the field of IGM studies is to work with very high S/N spectra at high resolution.
- BOSS taught us that you can get a lot of information from low resolution spectra with low S/N – if you have a lot of them!
  - We're closer to measuring a "mean absorption" than individual absorption features.
- Moderate resolution and S/N means that what looks like 30 m class science can be done (now!) with a 10 m!

How well can you do with $\mathcal{O}(10^3)$ sightlines per deg$^2$ at $S/N \sim$few per $\AA$? Look for structures coherent over Mpc scales ...

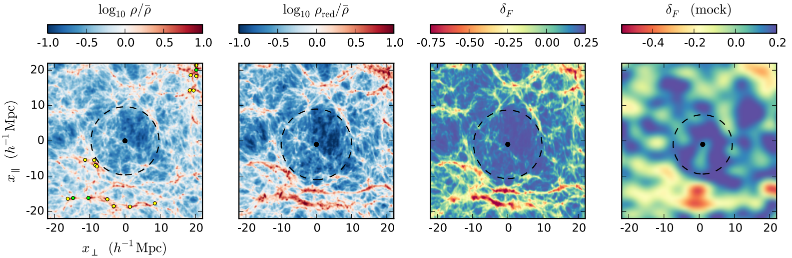
# Protocluster finding




Stark et al. (2015a)

# Void finding

It is also possible to find large underdensities – in fact this is somewhat easier since voids aren't really empty, just underdense in galaxies (dots in left panel).




Stark et al. (2015b)

# Completeness and purity

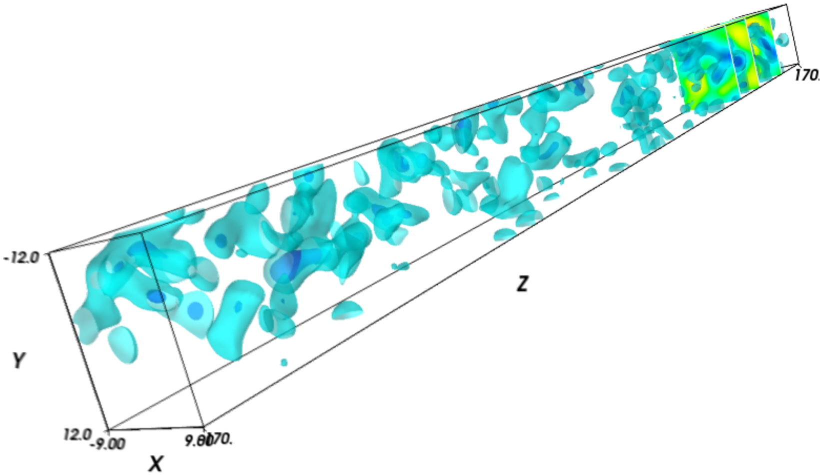
- Stark et al. (2015a, 2015b) study the counts, profiles, radii, etc. of $z \simeq 2.5$ protoclusters and voids as seen in Ly$\alpha$ tomography.
- Find high completeness ($> 75\%$) and purity (90%) for tomographically selected samples of massive ($> 3 \times 10^{14}\, h^{-1} M_{\odot}$) cluster progenitors for sightline separations at or better than $4\, h^{-1}$Mpc.
- Even sightline separations above $10\, h^{-1}$Mpc can be used to find the largest, earliest assembling protoclusters.
- Find similarly good completeness and purity for voids with radii $> 6\, h^{-1}$Mpc. We estimate $\sim 10^2$ such voids per $1\,\mathrm{deg}^2$ at $z = 2.5$.

# CLAMATO

**C**OSMOS **L**y-**A**lpha **M**apping **A**nd **TO**mography

- Survey to do Ly$\alpha$ forest tomography in the central $1\,\mathrm{deg}^2$ of the COSMOS field.
  - Overlaps CANDELS/3D-HST. Allows study of colors, morphology, SF rate, AGN activity, etc., as a function of large-scale environment.
  - Study CGM in protocluster foregrounds.
  - Improved photo-$z$ for galaxies in COSMOS.
  - Cosmic web classification (as well as e.g. GAMA at low $z$)
  - Survey for protoclusters and voids.
- Need $1\,\mathrm{deg}^2$ in order to sample large structures, like protoclusters and voids.
- Goal: $(60\,h^{-1}\mathrm{Mpc})^2 \times 300\,h^{-1}\mathrm{Mpc} \sim 10^6\,h^{-3}\mathrm{Mpc}^3$.
- Survey in progress ...
  - Currently have 124 sightlines.
  - Mean separation $2.5\,h^{-1}$Mpc.
  - Lee et al. (2014ab, 2016)

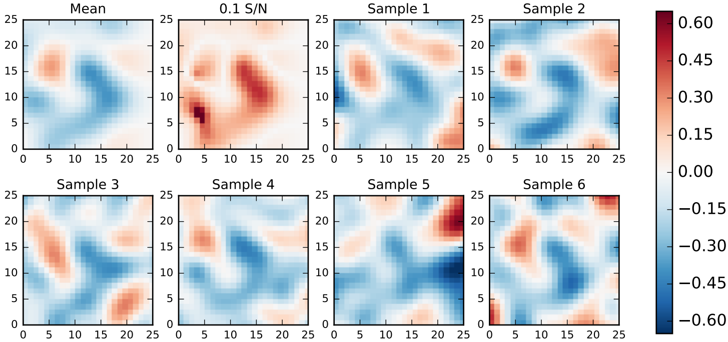
# CLAMATO: Current status




Contours of the flux (overdensities are more blue) in our current data set ($18 \times 24 \times 340\, h^{-1}$Mpc). Slices are placed at the redshifts of previously known proto-clusters.

# Protocluster Candidate: $z = 2.44$

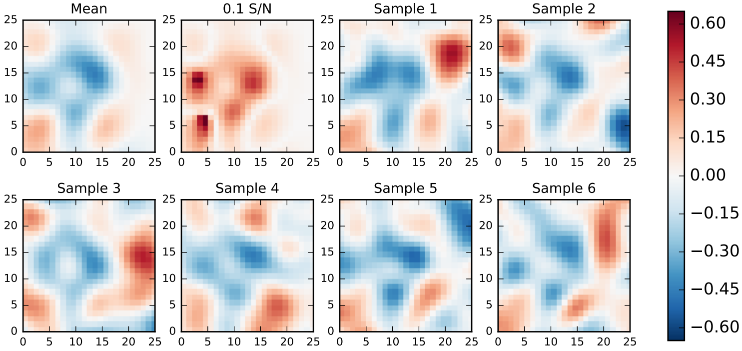
Diener et al. (2015; LBG) and Chiang et al. (2015; LAE).




Lee et al. (2016): See a large overdensity in our absorption map at high significance, correlated with LBG and LAE overdensities. Comparison with sims gives $M(z=0) \simeq (3 \pm 1.5) \times 10^{14}\ h^{-1}\mathrm{Mpc}$ (Virgo). Possible fragmentation into two $z \simeq 0$ clusters.

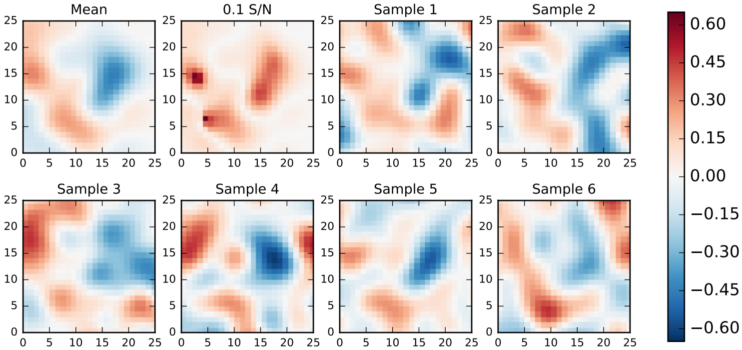
# Protocluster Candidate: $z = 2.47$

Casey et al. (2015), Hershel sub-mm overdensity (also seen in LBGs).



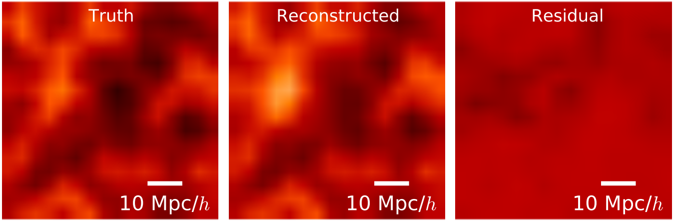
# Protocluster Candidate: $z = 2.51$

X-ray detected (proto-)cluster: Wang et al. (2016)



# Joint fitting & Sampling

We have implemented a high-dimensional minimization and sampling scheme that allows us to generate (Gaussian) initial conditions which (when evolved and turned into Ly$\alpha$ flux) are consistent with the observed data and noise model.




We can use these to run constrained N-body simulations, jointly fit Ly$\alpha$ and galaxy data sets, and propagate errors consistently.

# Conclusions

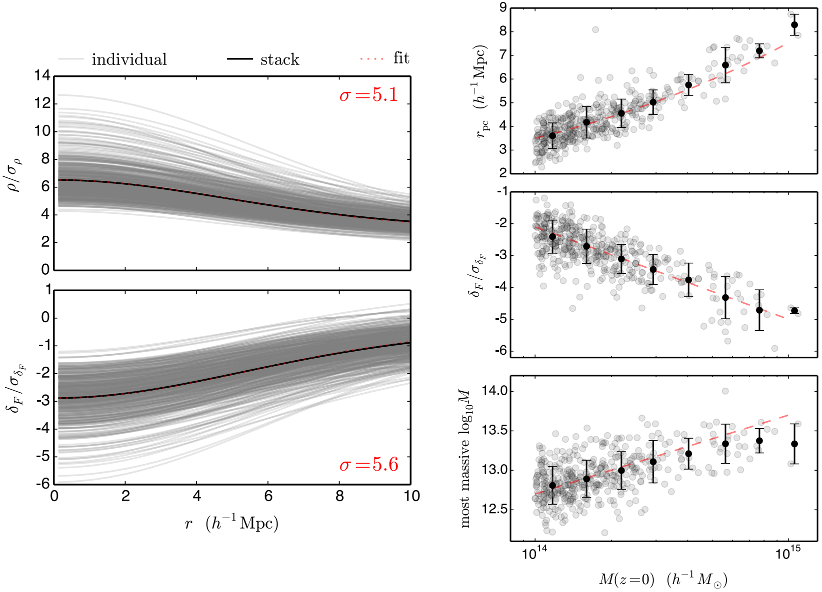
- IGM tomography is 'ideal' for measuring large-scale environments of galaxies and QSOs.
- Map LSS and decompose into filaments, sheets and halos.
- Medium scale 3D Ly$\alpha$ clustering.
- Cross-correlations.
- Improve photo-$z$s of galaxies using topology.
- From such a map ideally want to look for large, coherent objects spanning Mpc
  - Protoclusters
  - Voids

Clamato is underway, and preliminary indications are very promising!

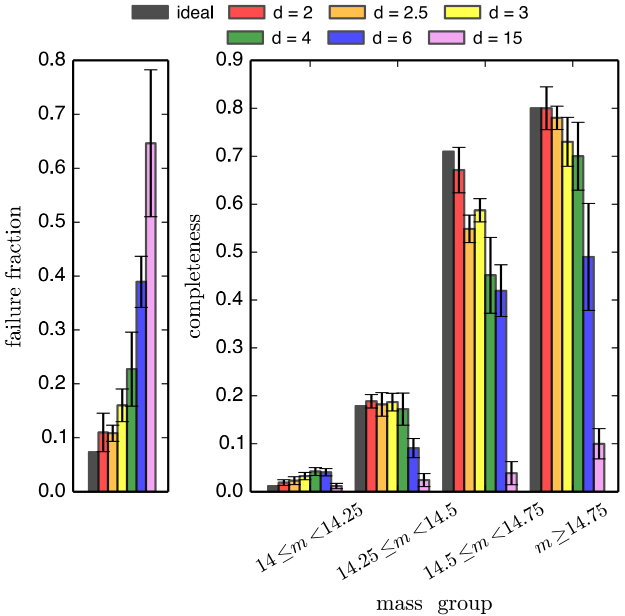
*The End!*

*Backup Slides*

# Protocluster Properties

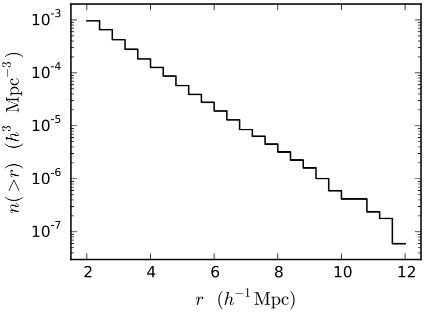


# Protocluster Completeness and Purity

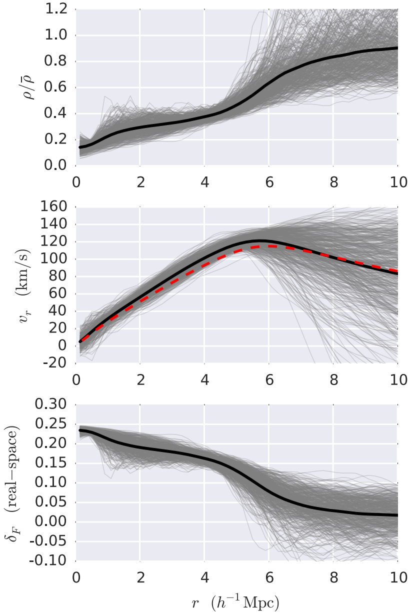


# Voids at high $z$

Voids counts at $z = 2.5$




Synergistic with JWST-NIRSPEC to study sub-$L_\star$ void galaxies at $z \simeq 2 - 3$.



# Technical details

- Program on Keck-I/LRIS-B ($4' \times 7'$ FOV)
- Covers central $0.8\,\mathrm{deg}^2$ in 90 pointings.
- Nominal limit $g = 24.5$ (about 25 per mask) with 3 hr exposures.
- Yields $10 - 15$ targets with proper $z$ and S/N for reconstructing the $2.2 < z < 2.5$ Ly$\alpha$ forest.

# Ly$\alpha$ forest tomography

With the Ly$\alpha$ forest we get the line-of-sight sampling "for free", so we just need to get the transverse sampling high enough.