Mapping the $z > 2$ Cosmic Web with 3D Lyα Forest Tomography

TMT Science Forum 2016, Kyoto

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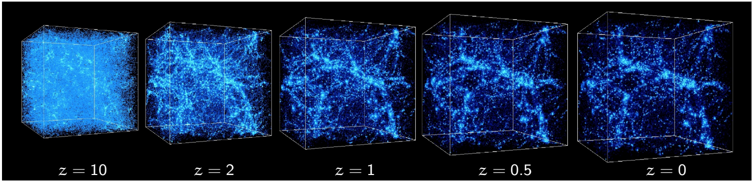
The Cosmic Web and Cosmology

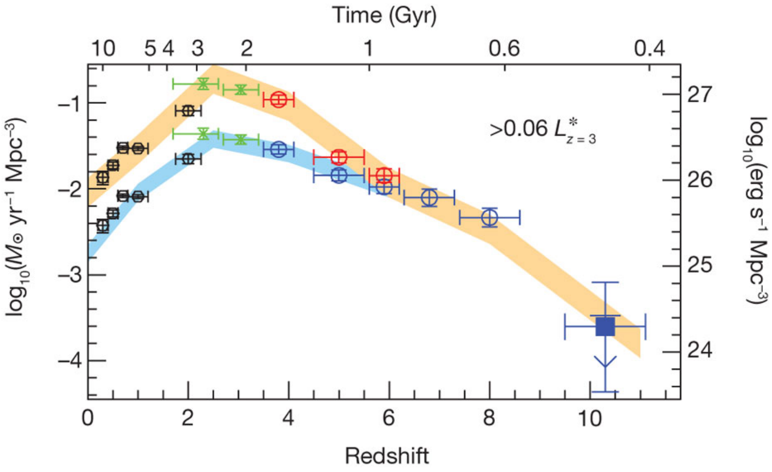


Credit: Anatoly Klypin (NMSU) & Andrei Kravtsov (Chicago)

- Pattern of voids, filaments and nodes in the large-scale distribution of DM + baryons
- Caused by gravitational evolution of Gaussian random-phase initial conditions from inflation
- Detection of cosmic web in the 1980s was key evidence supporting inflationary cold dark matter paradigm
- Galaxy formation and evolution is influenced by cosmic web environment
- The evolution over time probes gravity models and the cosmological constant

Why study cosmic web at 'Cosmic Noon'?

Peak of cosmic star-formation + AGN activity occured at $z \sim 2-3$

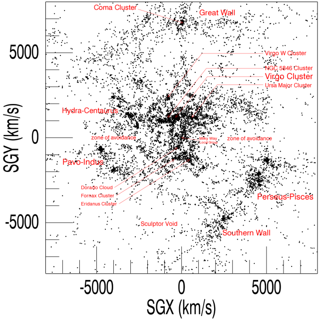


Bouwens+2011

Galaxy Redshifts at $z \sim 2$

D $<$ 100 Mpc Local Universe

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



Courtois et al 2013

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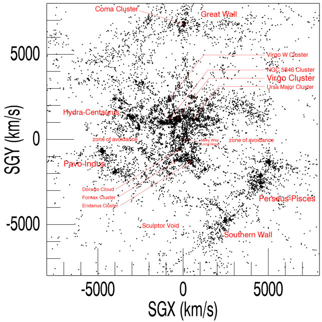
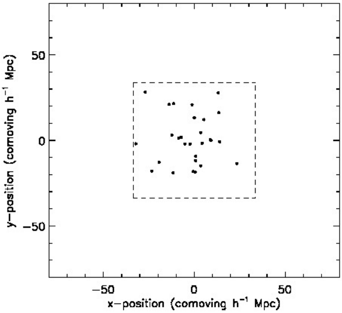


Courtois et al 2013

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



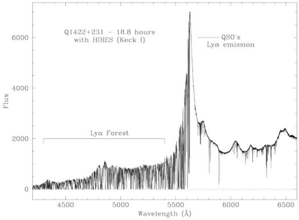
COSMOS Collaboration

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

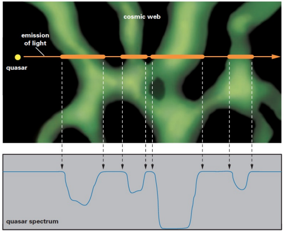
- Seen in quasar spectra in their restframe $\lambda < 121.6$nm wavelengths
- Caused by neutral hydrogen in the IGM
- Absorption is non-linear tracer of underlying LSS density in mildly overdense regime ($\rho/\langle\rho\rangle \sim$ few):

$$\tau(x) \propto \frac{T_0^{-0.7}}{\Gamma} \left(\frac{\rho(x)}{\langle\rho\rangle} \right)^{2-0.7(\gamma-1)}$$

- In this talk, I will ignore astrophysics! Absorption $\leftrightarrow$ Cosmic Web Density



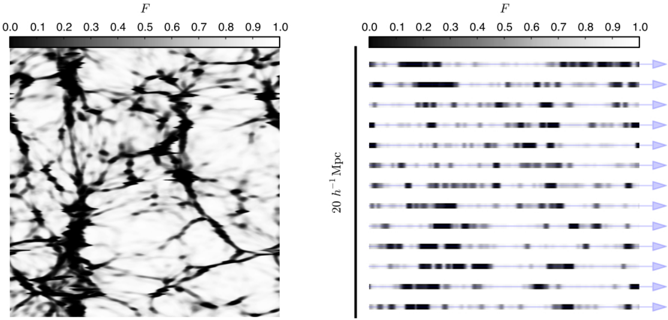
Ellison+2000



Credit: AmSci/R. Simcoe

Lyα Forest Tomography

If the quasars have arcmin ($\sim$ Mpc) separations, can enable tomographic reconstruction full 3D absorption field (Pichon et al 2001, Caucci et al 2008, Lee et al 2014a)

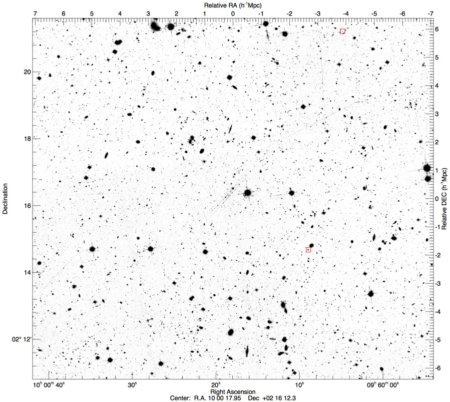


Credit: Casey Stark (Berkeley)

But quasars (rare!) aren't enough to pull this off. Need to also target faint ($>$ 23rd mag) UV-bright star-forming galaxies!

Availability of Background Sources

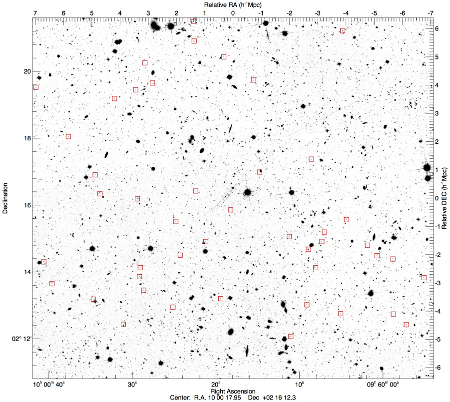
$g \leqslant 22.5$ sources at $2.3 < z < 3.0$



$12' \times 10.8'$ Hubble ACS Image in COSMOS (Koekemoer+2007)

Availability of Background Sources

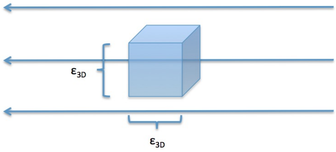
$g \leqslant 24.7$ sources at $2.3 < z < 3.0$



$12' \times 10.8'$ Hubble ACS Image in COSMOS (Koekemoer+2007)

It is necesary to target faint background LBGs for tomography!

S/N Requirements for Tomography? (Lee+2014a)



Imagine chopping up $z \sim 2.3$ survey volume into 'voxels' with similar size to desired map sampling, ϵ_{3D}

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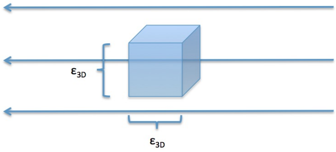

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- In transverse plane, sightline separation $\langle d_{\perp} \rangle$ needs to be equivalent to ϵ_{3D}, so $\epsilon_{\mathrm{3D}} \sim 3\,h^{-1}$ Mpc $\leftrightarrow \langle d_{\perp} \rangle \sim 2.5'$: ($g \leqslant 24.5$ LBGs + QSOs required!)

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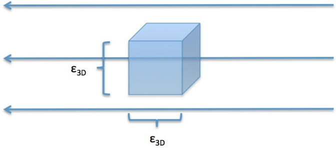

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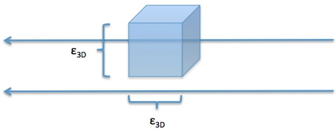

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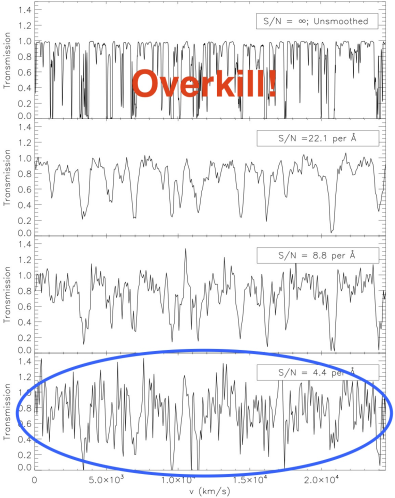
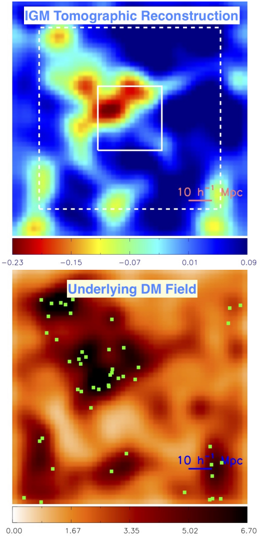
Moderate resolution spectra with modest S/N are sufficient for IGM tomography!

Reconstructions with low-S/N Spectra

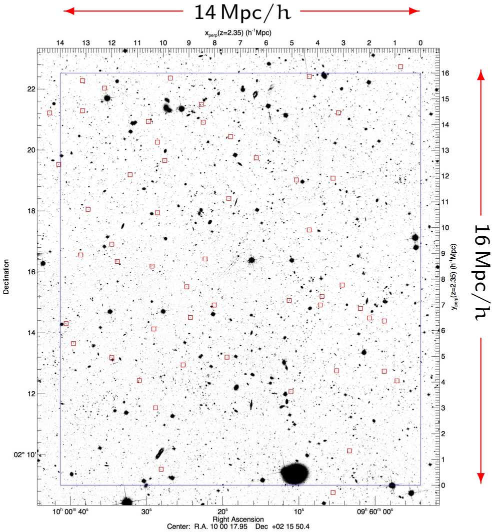
Simulated reconstructions from Lee+2014a on $L = 100\,h^{-1}$ Mpc box



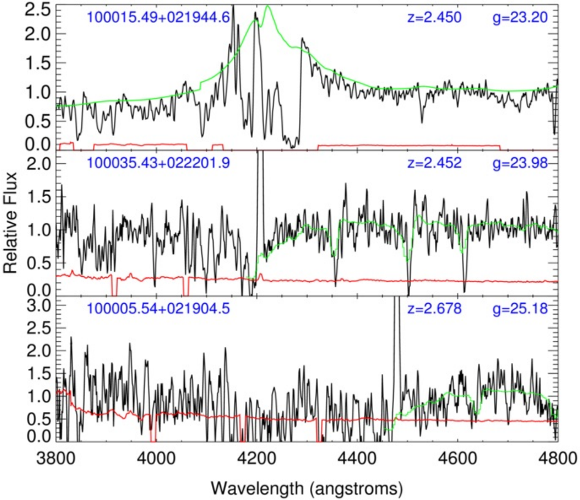


Pilot Tomography Survey in COSMOS

- Pilot observations in 2014-2015 on COSMOS field (Lee+2014b, Lee+2016)
- LRIS spectrograph on 10.3m Keck-I telescope, Hawai'i
- Total $\sim$ 15 hrs on-sky, $\sim$ 2hr exposures per pointing
- 49 galaxies+QSOs within blue area ($11.8' \times 13.5'$) $\rightarrow \sim 1100\,\mathrm{deg}^{-2}$ (c.f. $\sim 15\,\mathrm{deg}^{-2}$ in BOSS Lyα)



Example Spectra



First systematic use of LBGs for Lyα forest analysis!

Tomographic Reconstruction

Measure Lyα forest 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:

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

The noise term provides some noise-weighting to the data. We assume Gaussian correlation function in the map, where
$\mathbf{C}_{\rm DD} = \mathbf{C}_{\rm MD} = \mathbf{C}(\mathbf{r_1}, \mathbf{r_2})$, and

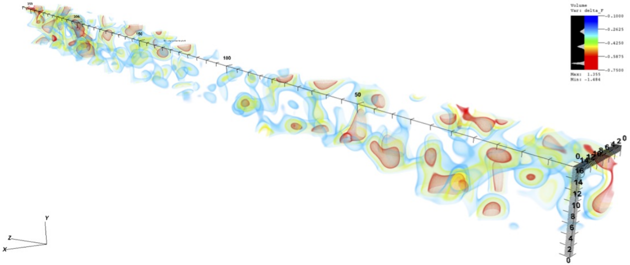
$$\mathbf{C}(\mathbf{r_1}, \mathbf{r_2}) = \sigma_F^2 \exp\left[-\frac{(\Delta r_{\parallel})^2}{2L_{\parallel}^2}\right] \exp\left[-\frac{(\Delta r_{\perp})^2}{2L_{\perp}^2}\right], \quad (1)$$

with $L_{\perp} = 2.5 h^{-1}$ Mpc and $L_{\parallel} = 2.0\, h^{-1}$ Mpc, and $\sigma_F = 0.8$ (Note average sightline separation $\langle d_{\perp} \rangle \approx 2.5\, h^{-1}$ Mpc).

3D Map of Cosmic Web at $2.2 < z < 2.5$

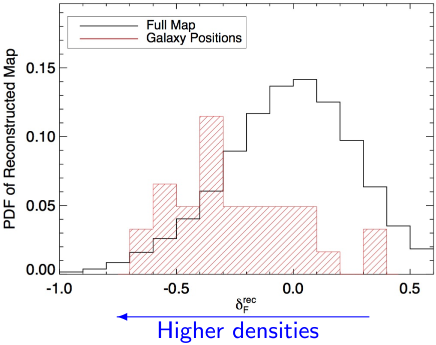
$260\,h^{-1}$ Mpc along LOS; $14\,h^{-1}$ Mpc $\times$ $16\,h^{-1}$ Mpc transverse $\rightarrow$

$V = 5.8 \times 10^4\,h^{-3}\,\mathrm{Mpc}^3 \sim (39\,h^{-1}\ \mathrm{Mpc})^3$



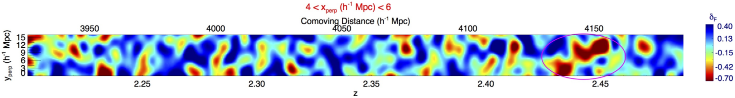
Correlations with Foreground Galaxies?

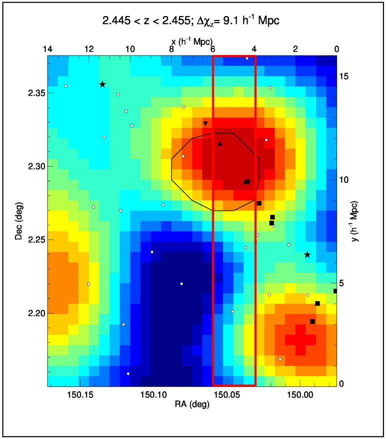
There are some known galaxies with spectroscopic redshifts overlapping the map volume. We can compare locations of 31 MOSDEF galaxies with the overall map PDF:



Galaxies clearly live in high-density regions of our map!

A Galaxy Protocluster at $z = 2.44$





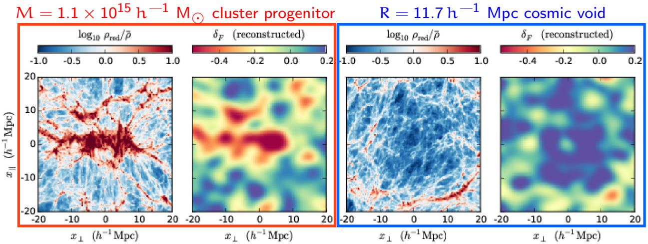
HETDEX Pilot LAEs (stars, Chiang+2015); LBGs (squares, Diener+2015); Open circles: sightline positions

- See one large ($\sim 20\,\mathrm{h}^{-1}$ Mpc) overdensity in our absorption map (3σ significance)
- Correlated with $z = 2.45$ galaxy protocluster from LBGs and LAEs (Diener+2015, Chiang+2015)
- Comparison to sims gives descendant mass estimates: $M(z = 0) = (3 \pm 1.5) \times 10^{14}\,\mathrm{h}^{-1}$ Mpc ($\sim$ Virgo cluster)
- Elongated morphology suggests possible fragmentation into two $z \sim 0$ clusters

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

- Co-PIs: Schlegel & White
- Upcoming LMAP proposal targeting ~ 1 sq deg of COSMOS field
- Require ~ 240hrs on-sky with Keck-LRIS $\rightarrow \sim 30$ nights over 3 years
- Target ~ 1000 LBGs at $2.3 \lesssim z \lesssim 3$ for R ~ 1000 spectroscopy
  $\rightarrow \langle z \rangle \sim 2.3$ LSS map over $10^6 \mathrm{h}^{-3}\mathrm{Mpc}^3 \sim (100\,\mathrm{h}^{-1}\ \mathrm{Mpc})^3$
- Similar spatial resolution ($\sim 3\,\mathrm{h}^{-1}$ Mpc) and volume ($\sim 10^6\,\mathrm{h}^{-3}\,\mathrm{Mpc}^3$) to GAMA survey at $z < 0.3$!

Voids and Protoclusters



Casey Stark (UC Berkeley) studied detectability of $z \sim 2.5$ protoclusters and voids with Lyα forest tomography in sims (Stark+2015a, 2015b)

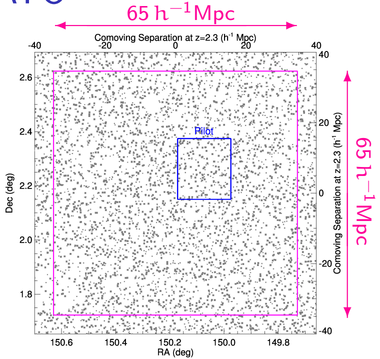
- $L = 256\,h^{-1}$ Mpc TreePM sim with IGM absorption from FGPA
- Generated DM density field and mock tomographic maps with sightline sampling + noise consistent with real data
- Protoclusters: Look for 3σ peaks in smoothed map, which gives $> 90\%$ completeness and $\sim 75\%$ purity for $M > 3 \times 10^{14}\,h^{-1}\,M_\odot$ progenitors
- Voids: Search for spherical low-density regions in DM field and tomographic map $\rightarrow \sim 65\%$ volume overlap for $\sim 15\%$ filling factor

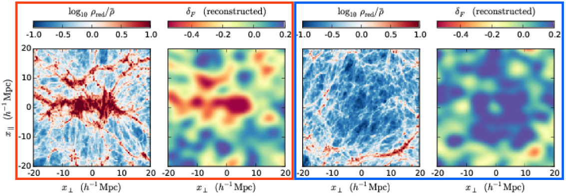
Voids and Protoclusters in CLAMATO

Right: Central part of COSMOS Field

Magenta	CLAMATO 0.8 sq deg
Blue	Pilot field (2014-2015)
Dots	Photo-z and spectro-z $z = 2.4 - 3.0$ LBG targets

Below: Simulated protoclusters and voids (approx to scale)

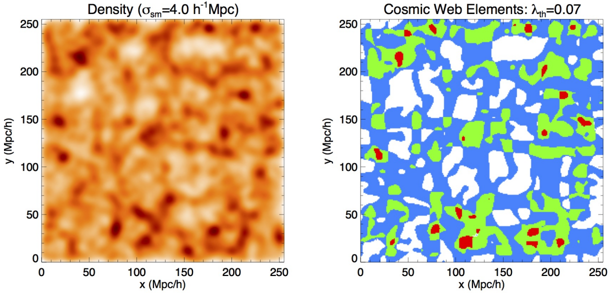




Sheets and Filaments in $z \sim 2.5$ Cosmic Web (Lee & White 2016)

Analyze eigenvalues of gravitational deformation tensor $T_{ij} \equiv \partial^2\Phi/\partial x_i \partial x_j$ (e.g. Forero-Romero+2009) to identify sheets, filaments and nodes in cosmic web:

$z = 2.5$ DM Field



- Excellent recovery of sheets and filaments: $\sim 60-70\%$ volume overlaps between DM and tomographic map (**Comparable to GAMA galaxy cosmic web recovery at $z \sim 0.2$!**)
- Significant contiguous sky area required, motivates 1deg^2 CLAMATO

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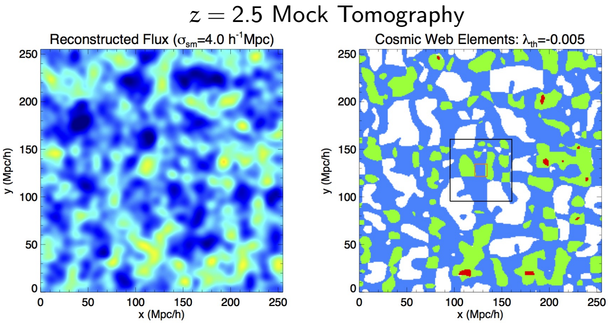

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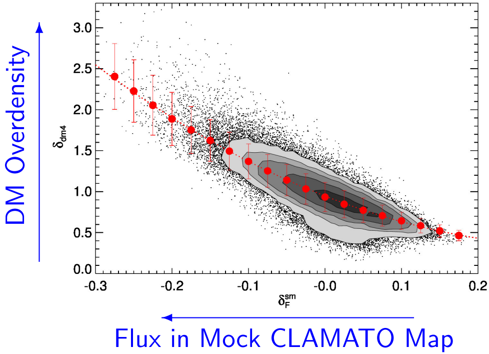
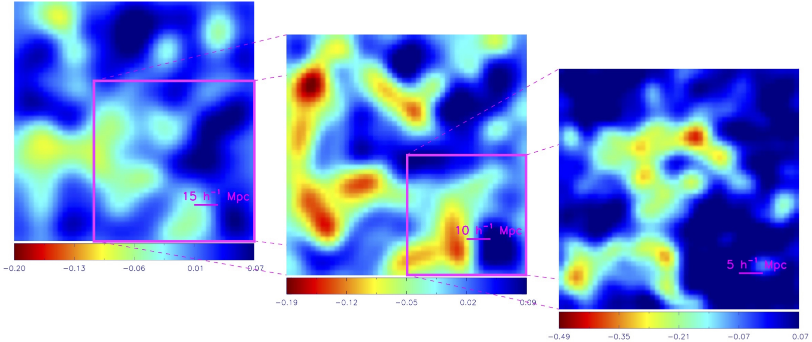
Flux-Mass Relationship on $4\,h^{-1}$ Mpc Scales



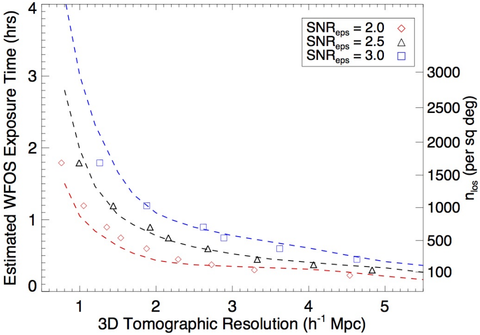
IGM Tomography and TMT

30m aperture will allow much fainter sources → higher sightline densities → better spatial resolution



Lee+ 2014

An ‘ETC’ for IGM Tomography



- 2-3hr integrations on TMT/WFOS will allow IGM tomography to scales of $\sim 1\,\mathrm{h}^{-1}$ Mpc (300-400 pkpc)
- Target densities of $\sim 1\,\mathrm{arcmin}^{-2}$ (approx. WFOS slit density)
- WFOS will be powerful but require many pointings to cover interesting volumes $\rightarrow$ 2nd generation wide-field MOS on TMT would be great!

Conclusion

- Observations of $z \sim 2-3$ QSOs + LBGs at high area densities allow 3D reconstructions of foreground Lyα forest absorption
- Ideal for detecting extended $z \sim 2$ structures: voids + protoclusters
- Good recovery of $z \sim 2$ cosmic web sheets and filaments — comparable to $z \sim 0.1$ galaxy surveys!
- **IGM Tomography already works!** CLAMATO Survey on Keck-I/LRIS (2016-2019) to map $\sim 10^6\,\mathrm{h}^{-3}\,\mathrm{Mpc}^3$ probing scales of $\sim 3\,\mathrm{h}^{-1}$ Mpc
- Similar program TMT/WFOS will allow tomographic mapping down to scales of $\sim 1\,\mathrm{h}^{-1}$ Mpc or 300-400 pkpc
  $\rightarrow$ *synergy with individual halo CGM scales!*
- A lot of theory work needed to interpret and exploit observations!