Mapping the z~2-3 IGM with Optical Spectroscopy on Keck and Subaru

"Massively Parallel Large Area Spectroscopy from Space"

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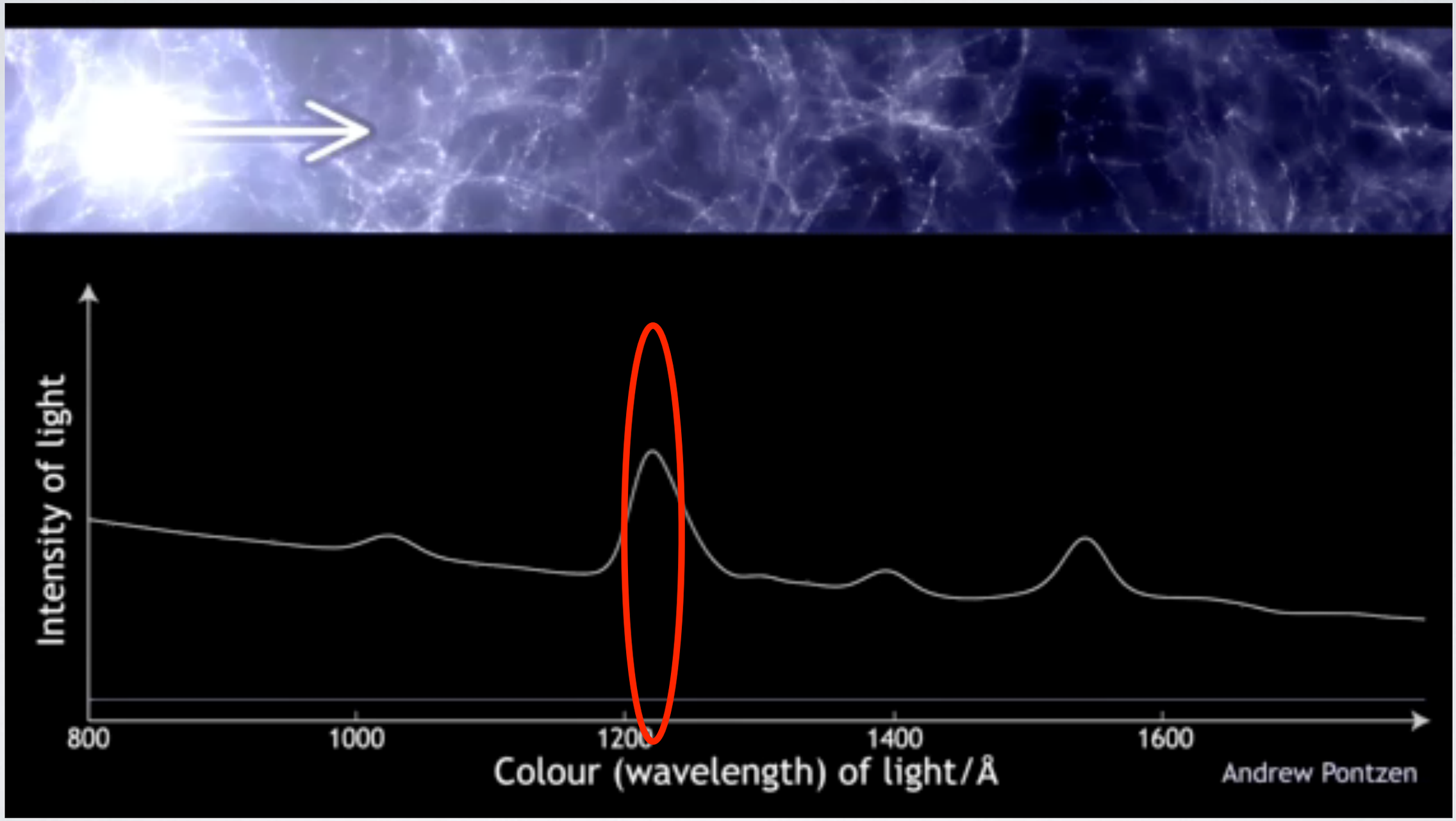
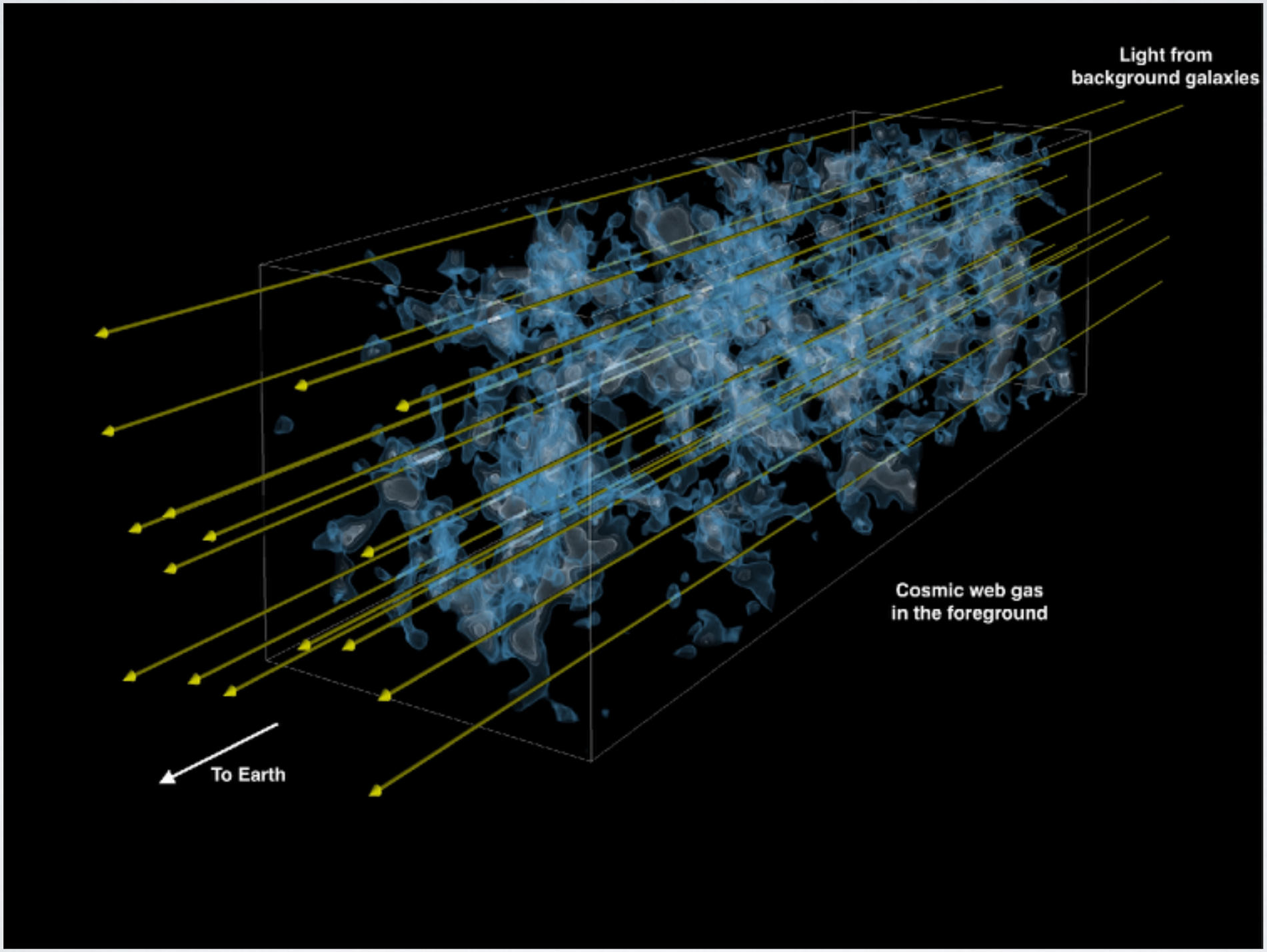
The Lyman-alpha Forest at Cosmic Noon (2<z<4)

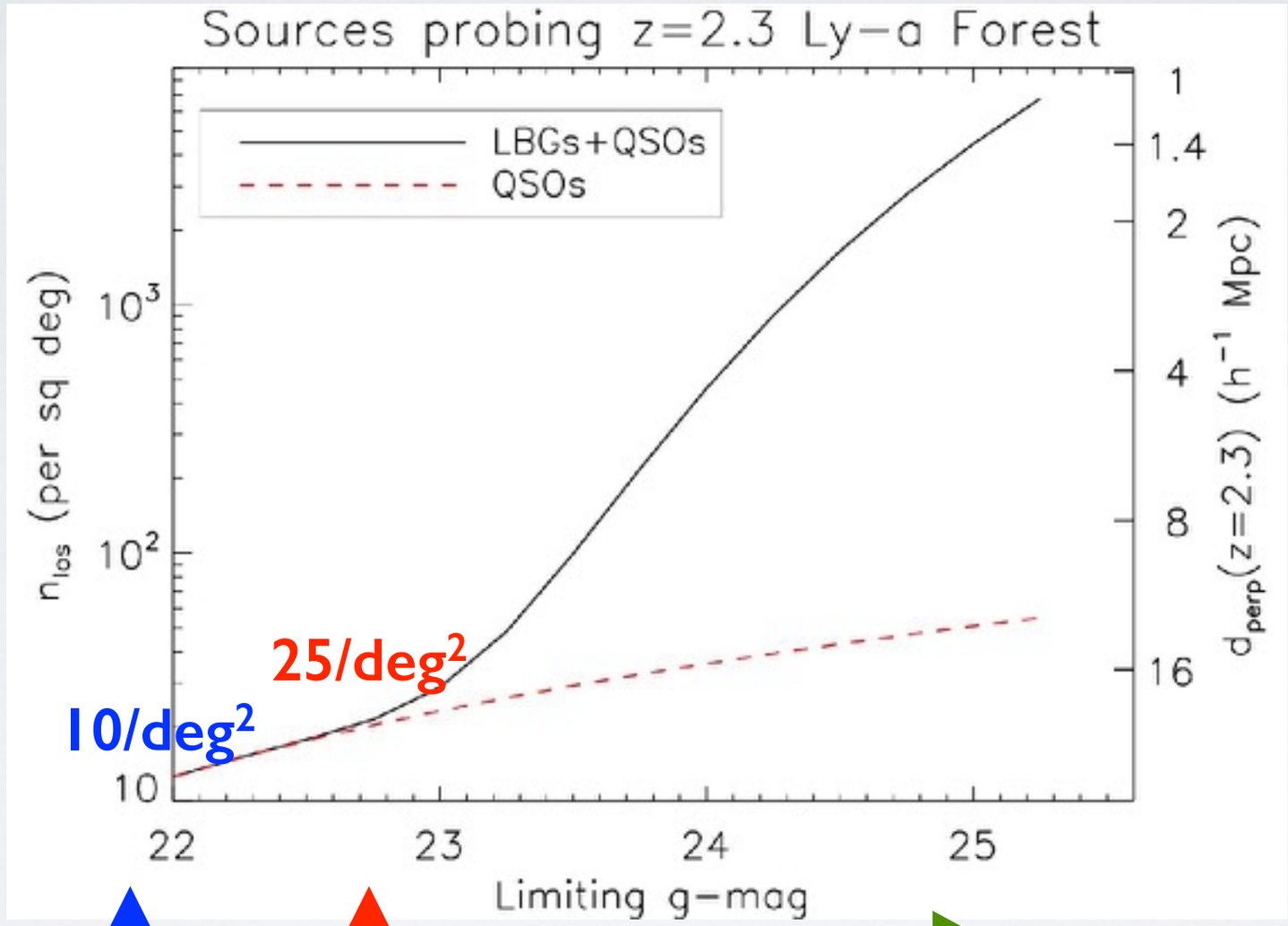


Restframe 1215.67Å absorption from neutral HI in intergalactic medium redshifts into the optical at 2<z<6

Tomographic Mapping of 3D Absorption



Going beyond quasars for Ly-α forest



# of Ly-a forest sightlines per sq deg

Average sightline separation

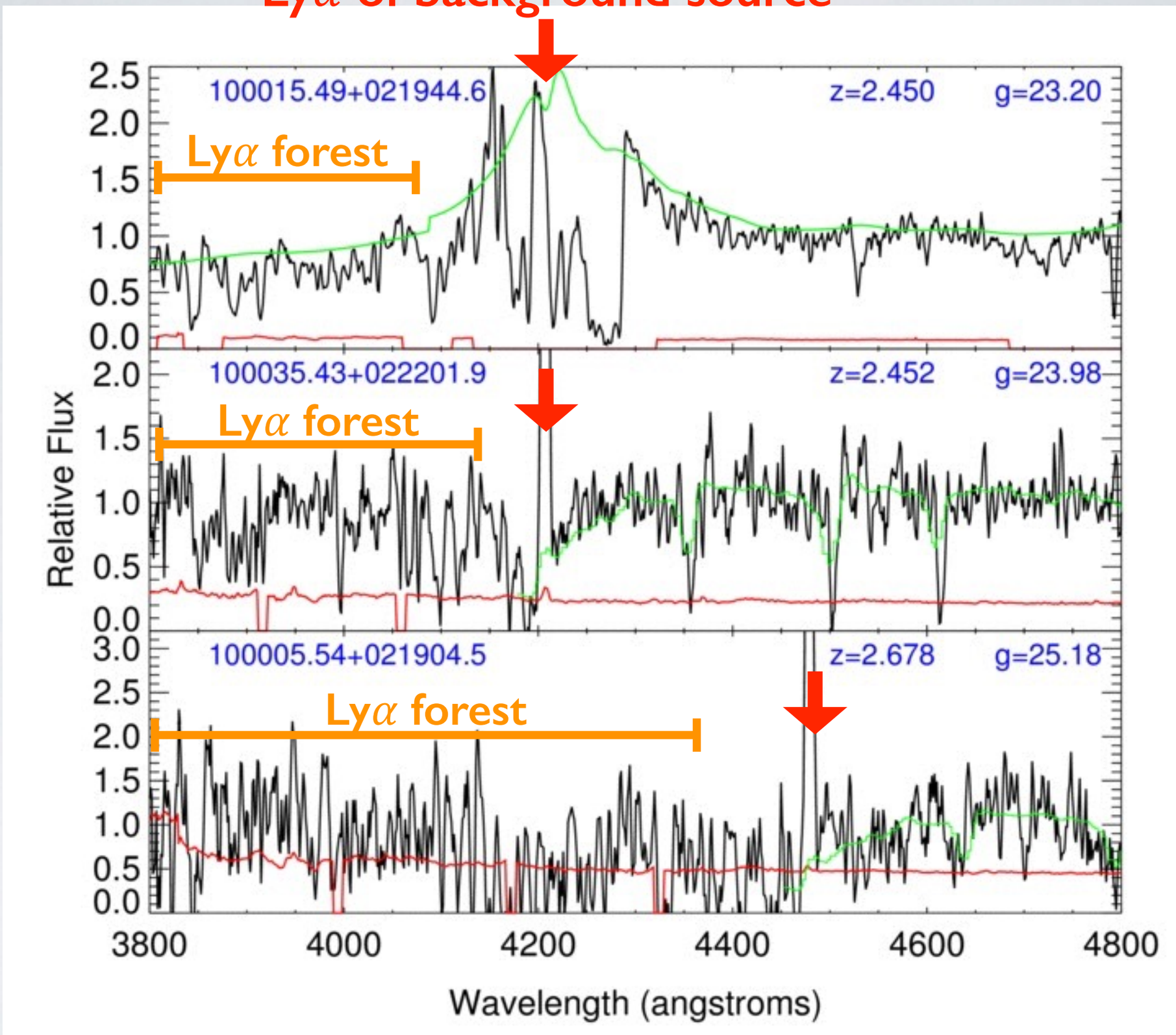
BOSS (2.5m)

DESI (4m)

Huge jump in sightline availability with LBGs/star-forming galaxies!

COSMOS LYMAN-ALPHA MAPPING AND TOMOGRAPHY OBSERVATIONS (CLAMATO)

- Keck survey on COSMOS field (10hr, +02deg)
- Aim to get spectra LBGs+QSOs at z~2-3, to sample 2.1<z<2.5 $Ly_{-1}a$ forest with sightline separations of ~2.5h^{-1} Mpc
- ***First systematic use of galaxies as Lyα forest background sources***
- 2-4hr integrations with Keck-I/LRIS spectrograph down to g<24.8
- ~60hrs on-sky observations so far (13.5 nights allocated from 2014-2017)
- Full public data release (Lee+2018, ApJS, 237, 31))



Color scheme: **spectrum**, noise vector, spectral template

Wiener Filtering Of Sightlines

- We have the flux δ_F, pixel noise, and their [x,y,z] positions. Estimate map, **M**, using Wiener filter applied to data D and noise matrix **N**

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

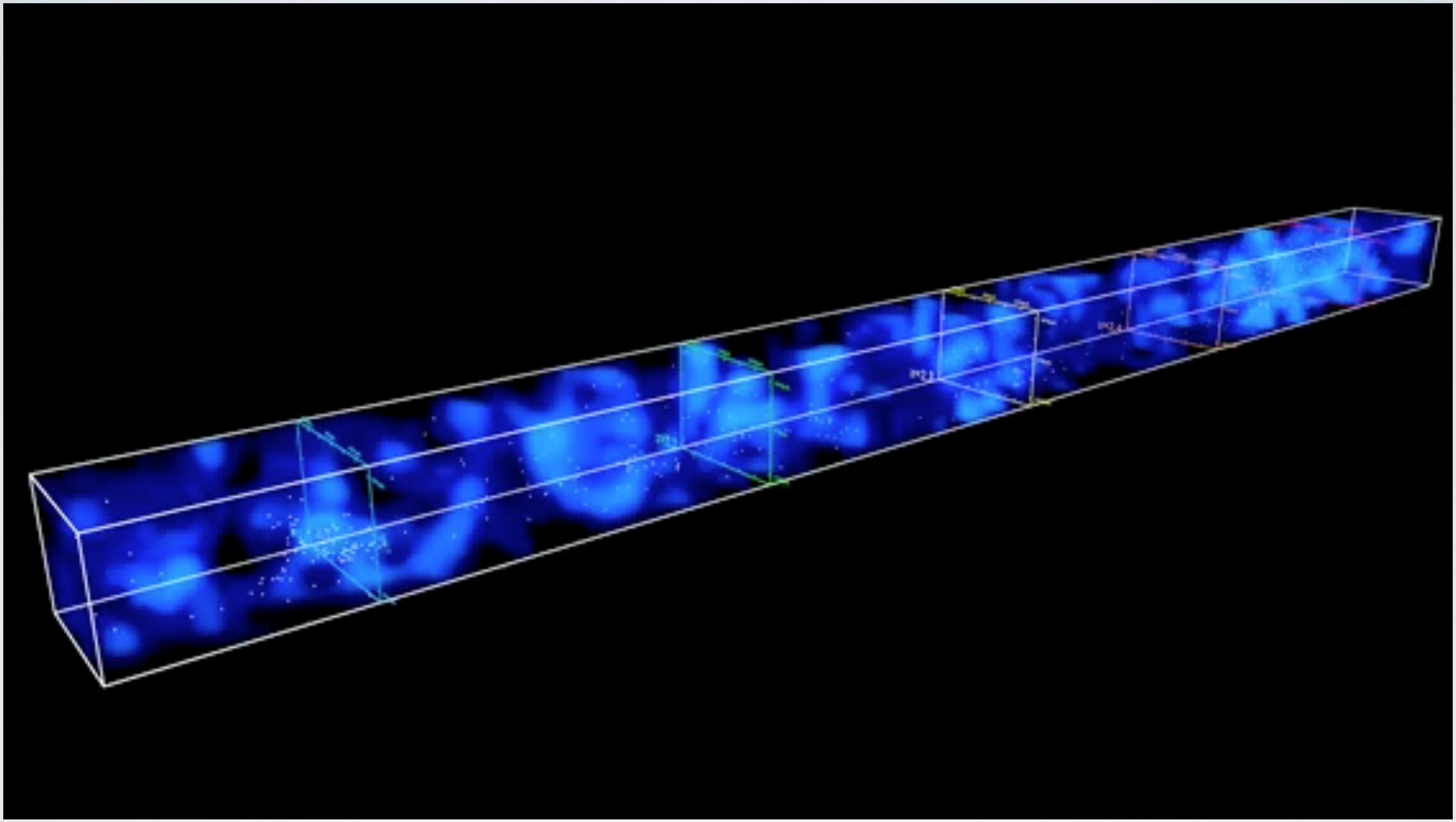
- Assume a correlation matrix of the form $C_{DD}=C_{MD}=C(r_1,r_2)$

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

-1 -1

- $L_\parallel$=2.5h Mpc and $L_\perp$=2.0h Mpc are set by the sightline separation and resolution, σ_F=0.8 is the variance of the map

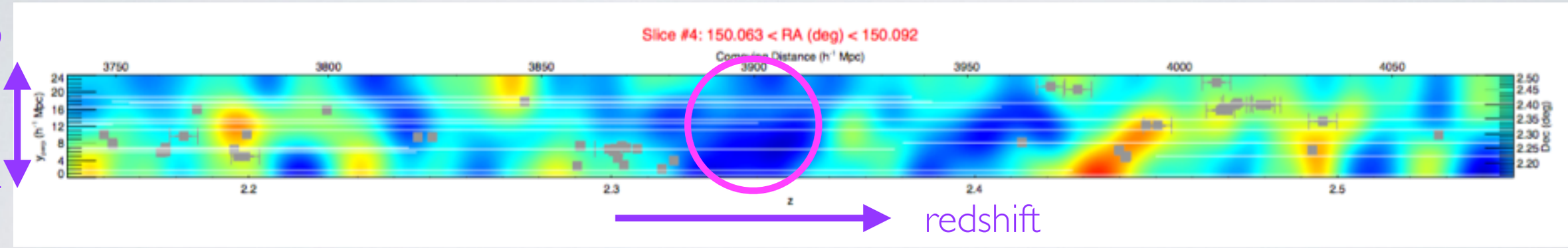
340 Mpc/h along LOS (2.05>z<2.55), 21Mpc/h x 27Mpc/h transverse.
Reconstructed from 240 background sightlines



YouTube: *http://tinyurl.com/clamatovid-v2*

First Detection Of Cosmic Voids At High-z

Krolewski, KGL, et al 2018, arXiv:1710.02612

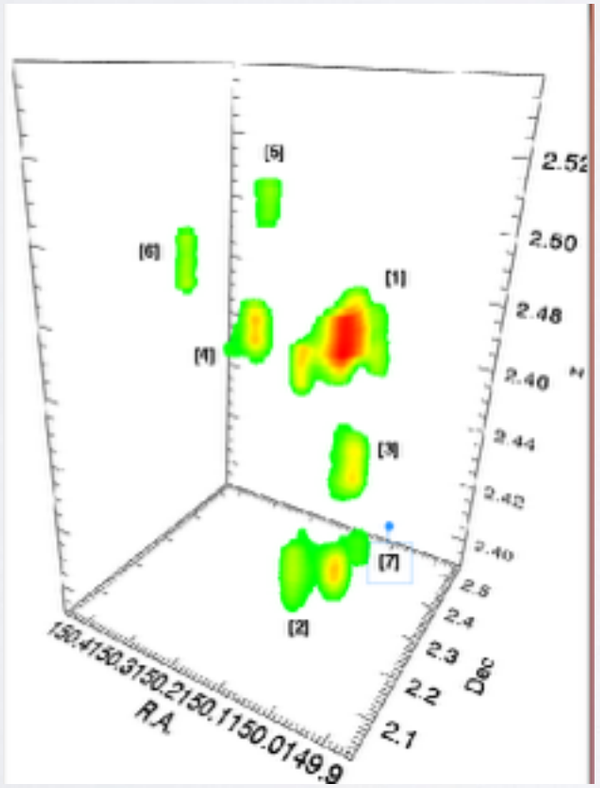


- Most distant-known cosmic voids from galaxy redshift surveys are at z~0.9 (VIPERS Survey, Hawken+2016)
- Obvious coherent underdensities in the CLAMATO map at 2.05<z<2.55
- Search for 3D voids in CLAMATO using simple "spherical underdensity" void finder (e.g. Stark, Font-Ribera, White, KGL, 2015)
- Cross-validation with 432 galaxies with spectroscopic redshifts show the IGM voids are underdense in galaxies at 6-sigma significance
- Found ~48 cosmic voids ranging with R>5 Mpc/h (work done by UC Berkeley grad student A. Krolewski)

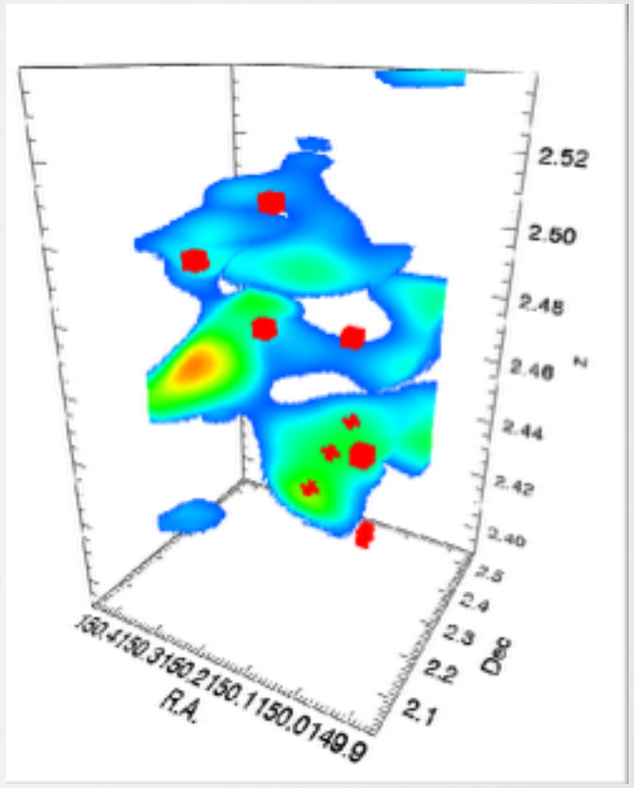
‘Hyperion’ Overdensity At z~2.5

- z~2.4-2.5 superstructure discussed in Cucciati+2018 from VUDS spectroscopic survey (arXiv:1806.06073)
- Spans >100 cMpc and potentially a progenitor of ~3×10^{15} $M_{\odot}$ present-day cluster
- Clearly see excess Ly-alpha absorption in same region, but galaxy and Ly-alpha absorption don’t match up exactly:
  - Boundary effects in CLAMATO?
  - Intracluster medium pre-heating suppresses Ly-alpha absorption?

VUDS Overdensity (Cucciati+2018)



CLAMATO Excess Ly-alpha Absorption (2-sigma threshold)

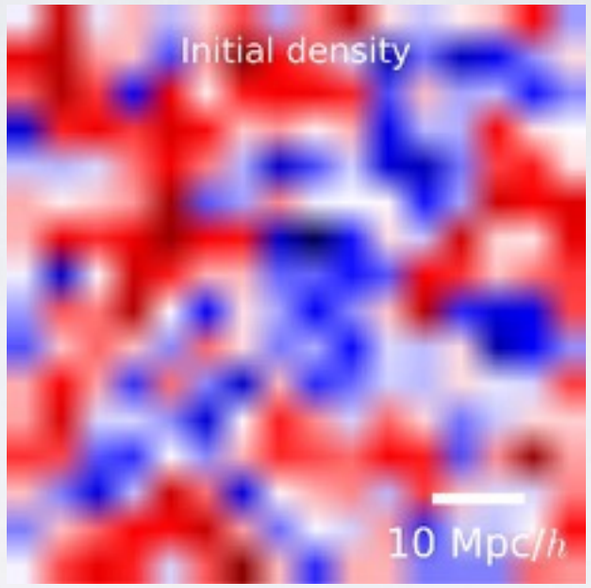


Figures courtesy of Olga Cucciati

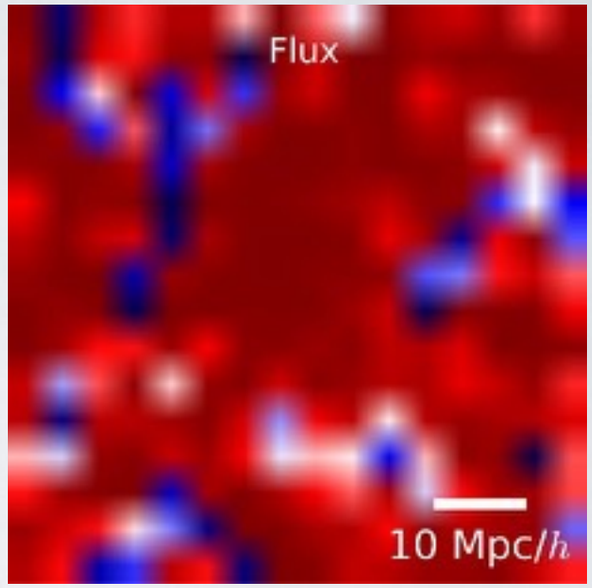
In Progress: Inferring Map Initial Conditions

- Simple log-normal model for Ly-a forest flux as function of density
- Limited-memory Broyden-Fletcher-Goldfarb-Shanno (L-BFGS) algorithm to minimize likelihood
- Inferred initial conditions (z=∞) can be used as a seed to run a sim to z=0 to infer fate of z~2.5 overdensities detected with tomography
- Lead by B. Horowitz (UCB) and M. White(UCB)

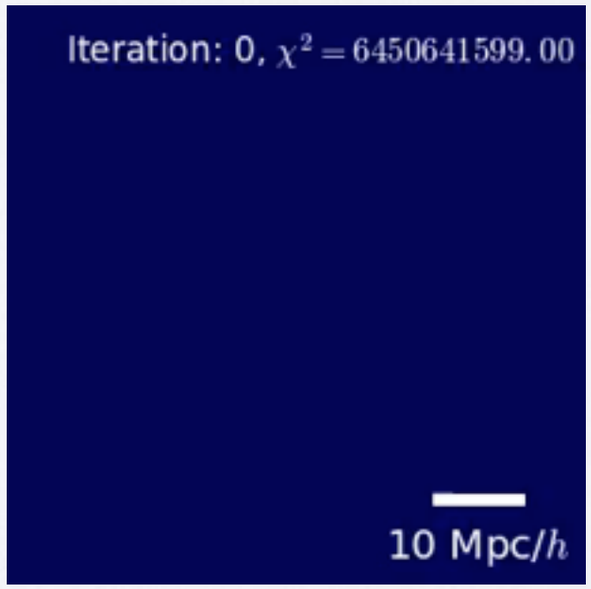
"True" Initial Conditions



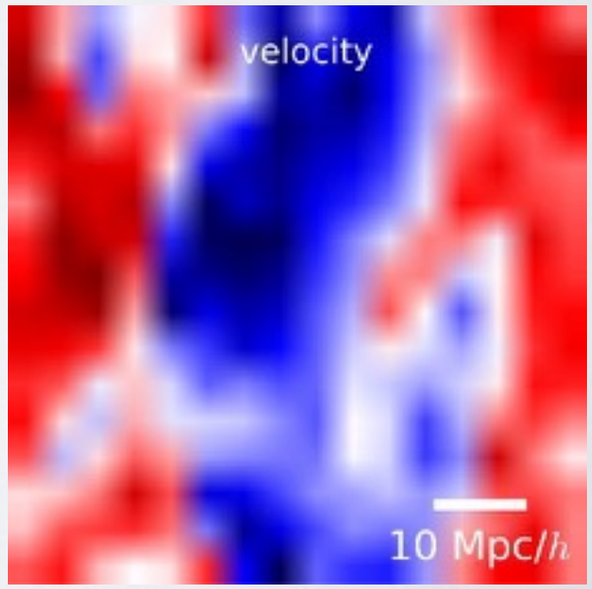
Toy "observations" at z~2.5



Inferred Initial Conditions



Inferred velocities at z~2.5



Preliminary!

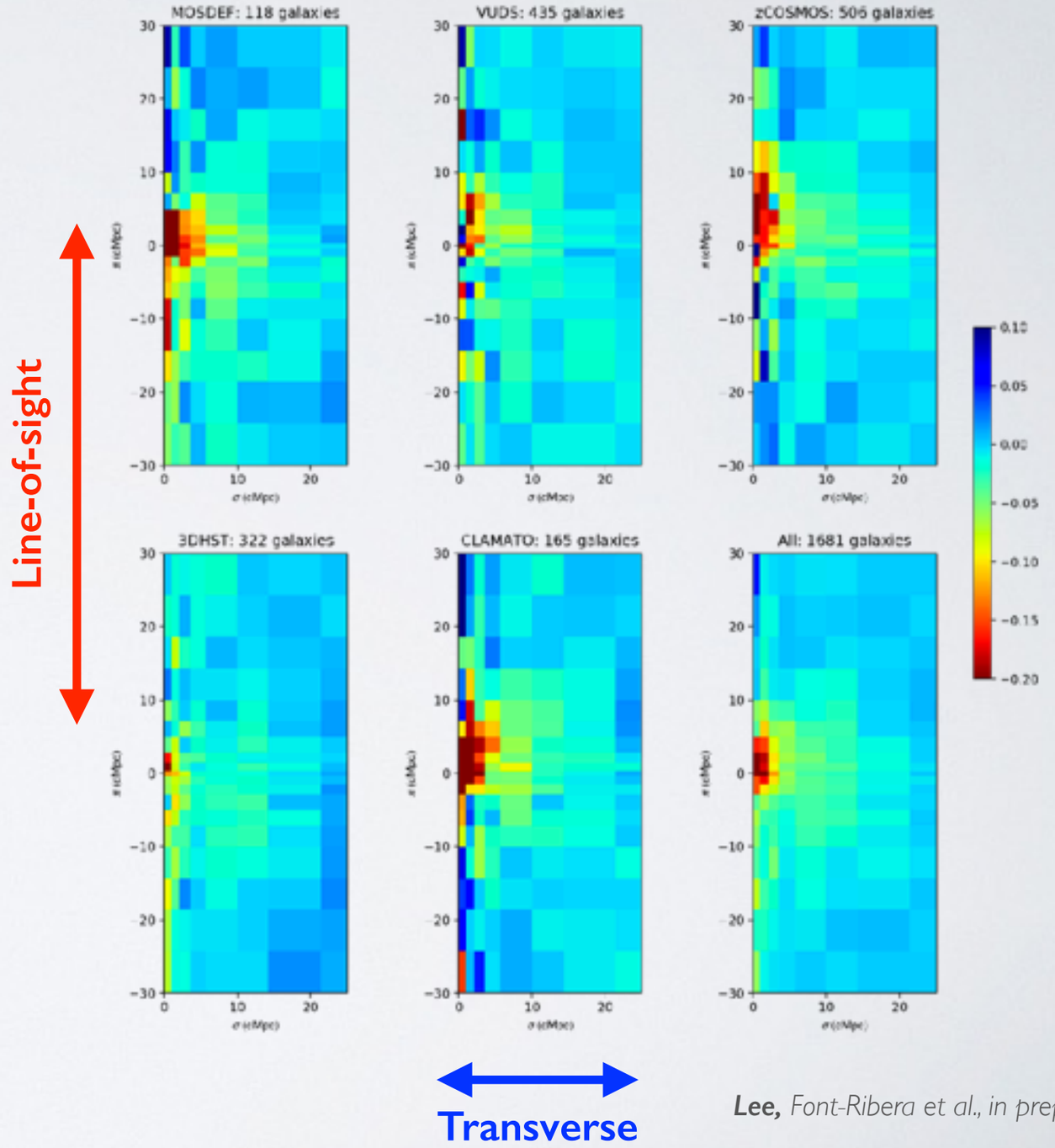
In Progress: Cross-correlation with Galaxies

- Use simple inverse variance estimator in configuration space (Font-Ribera et al 2012):

$$\xi_A = \frac{\sum_{i\in A} w_i \delta_{Fi}}{\sum_{i\in A} w_i}; w_i = \left[\sigma_F^2(z_i) + \frac{\sigma_{N,i}^2}{C_i^2 \bar{F}^2(z_i)}\right]^{-1}$$

- Overall ~21 **σ** detection from all samples
- Current analysis assumes Lyα forest parameters are known
- Model galaxies with linear model. with free parameters:
  - bias, b
  - LOS offset, δz
  - LOS dispersion, $\boldsymbol{\sigma}_z$ (combination of redshift error + FoG)

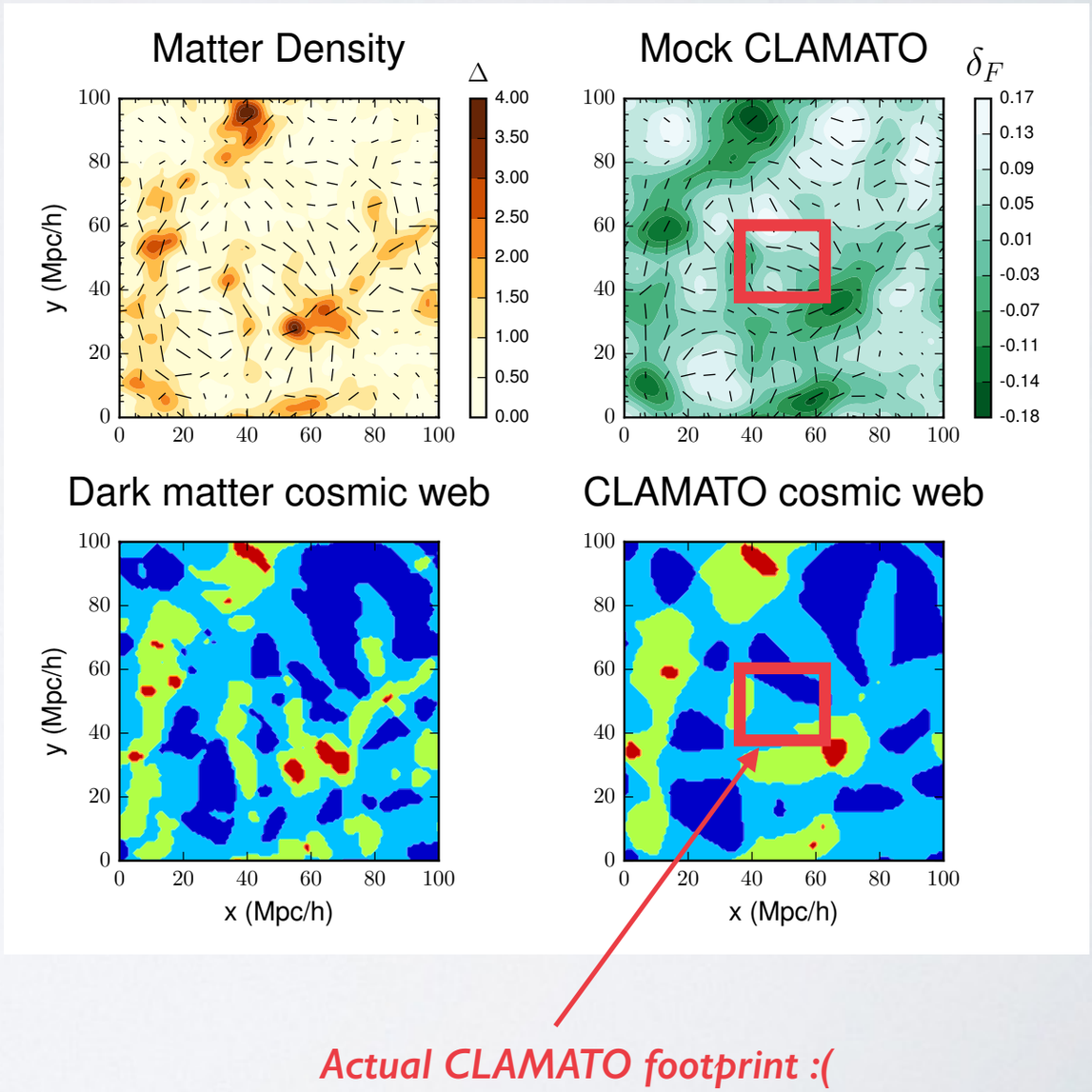
Different spectroscopic galaxy surveys (100-500 galaxies per sample)



Lee, *Font-Ribera et al., in prep.*

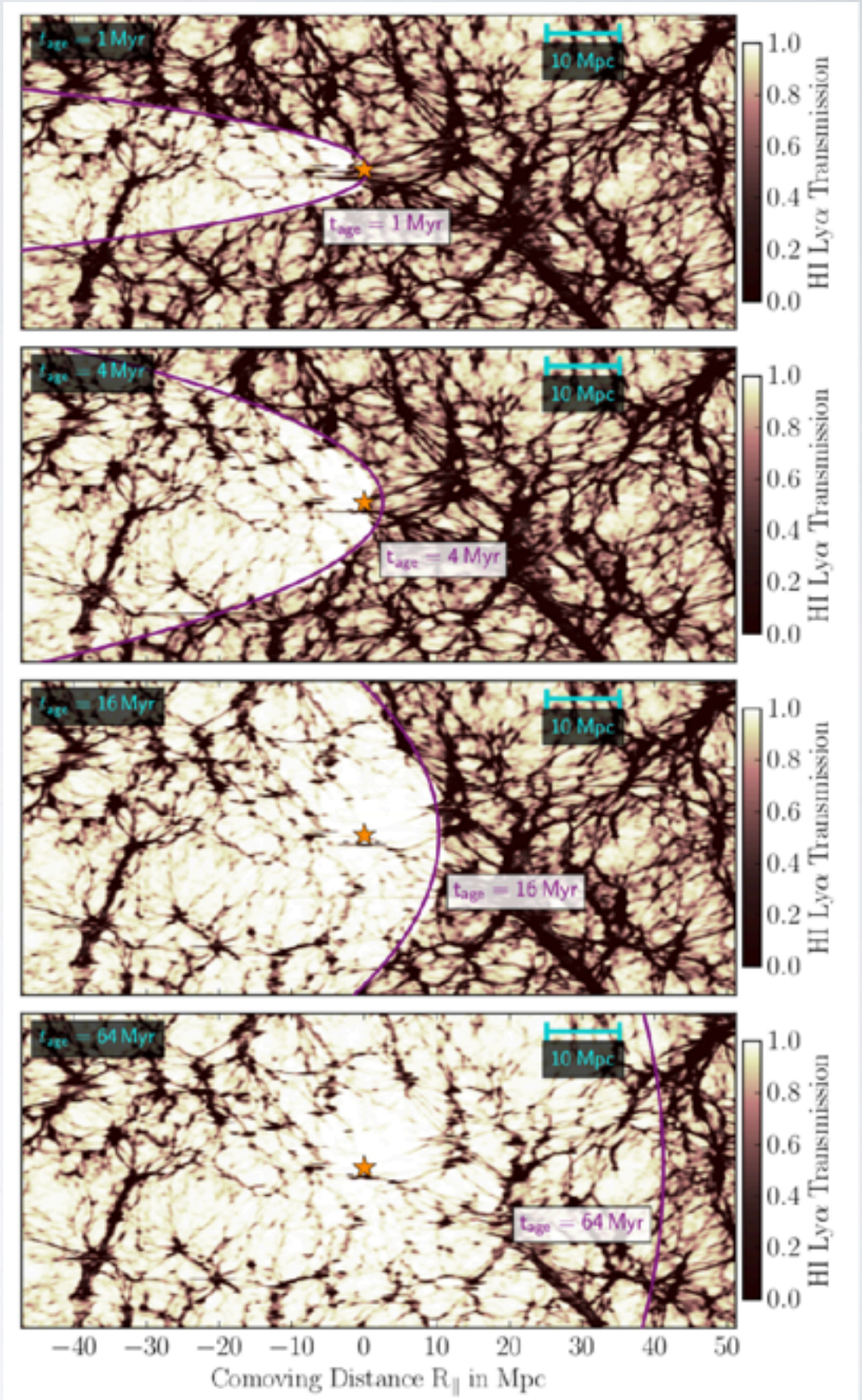
Studying The High-z Cosmic Web With IGM Tomography

- **KGL** & White 2016, ApJ, 817,160
- Krolewski, **KGL**, Lukic & White 2017, ApJ, 837,31
- Zel'dovich-like approach: eigenvalue analysis of the gravitational tidal tensor $d^2\Phi/dx_i dx_j$
- tl;dr: IGM tomography provide good recovery of the eigenvectors in the DM cosmic web on ~3-4cMpc scales
- With sufficient data volume, can constrain intrinsic alignments from galaxies at z~2-3
- Not being done with CLAMATO since boundary effects would alias the cosmic web recovery



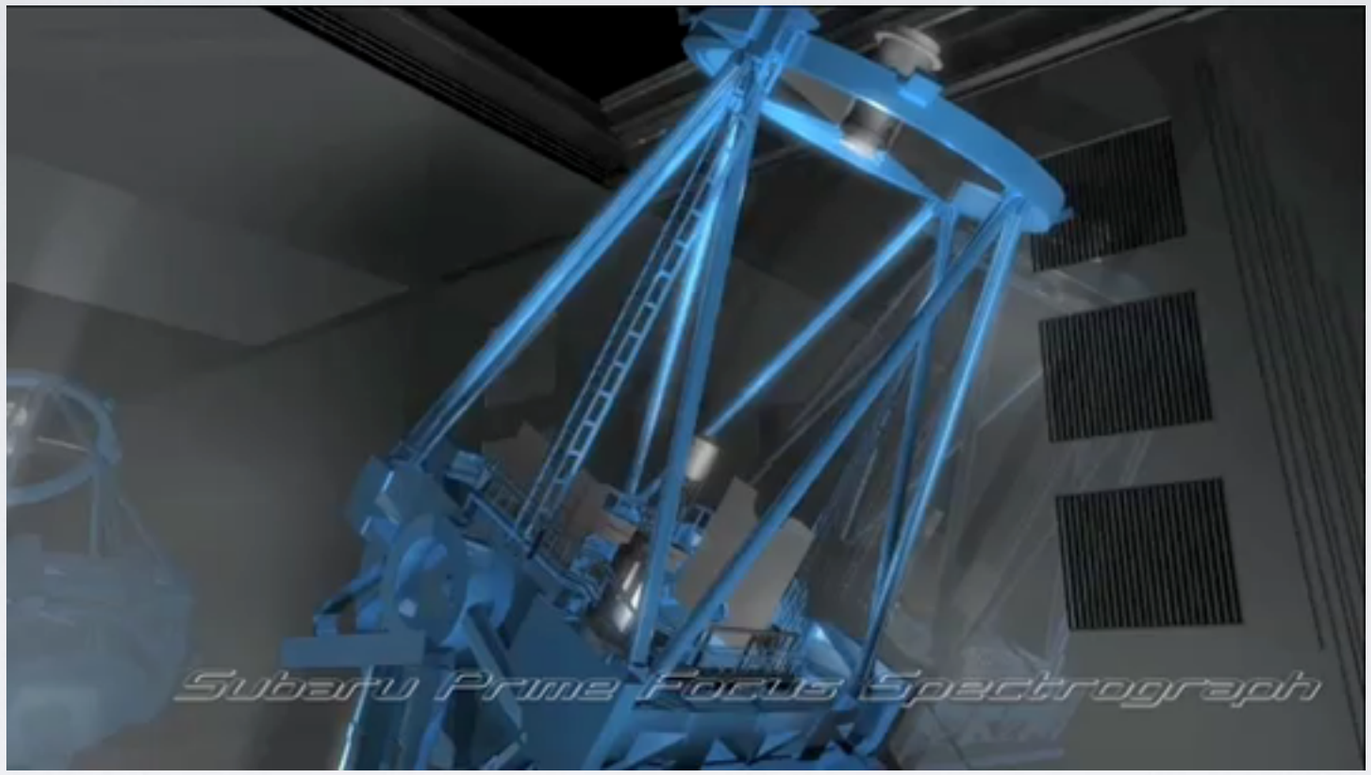
Quasar Light echoes

- Luminous quasars at z~3-4 will ionize their surroundings on ~10 Mpc scales ("proximity effect")
- IGM tomography with background galaxies will reveal this light echo around ultra-luminous quasars (Schmidt, Hennawi, **KGL**+, arXiv:181005156)
- Very challenging (r~25 background sources) but doable on 8-10m class telescopes
- 20% constraints on lifetimes of *individual quasars*! (assuming isotropic emission)



Schmidt et al 2018, arXiv:181005156

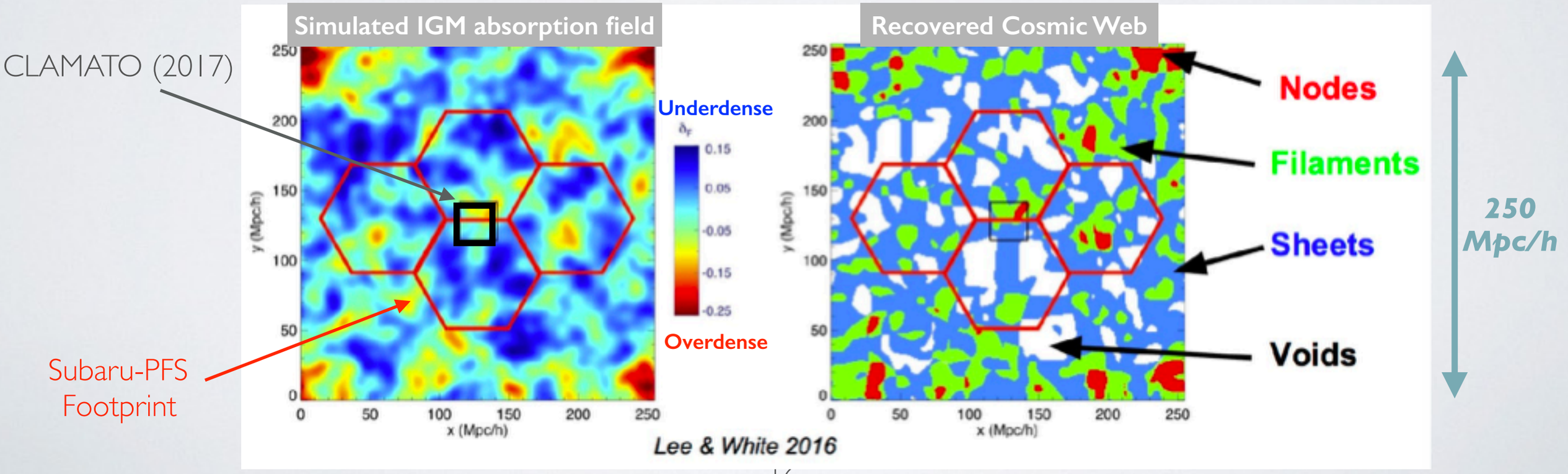
Future Surveys: Subaru-Prime Focus Spectrograph



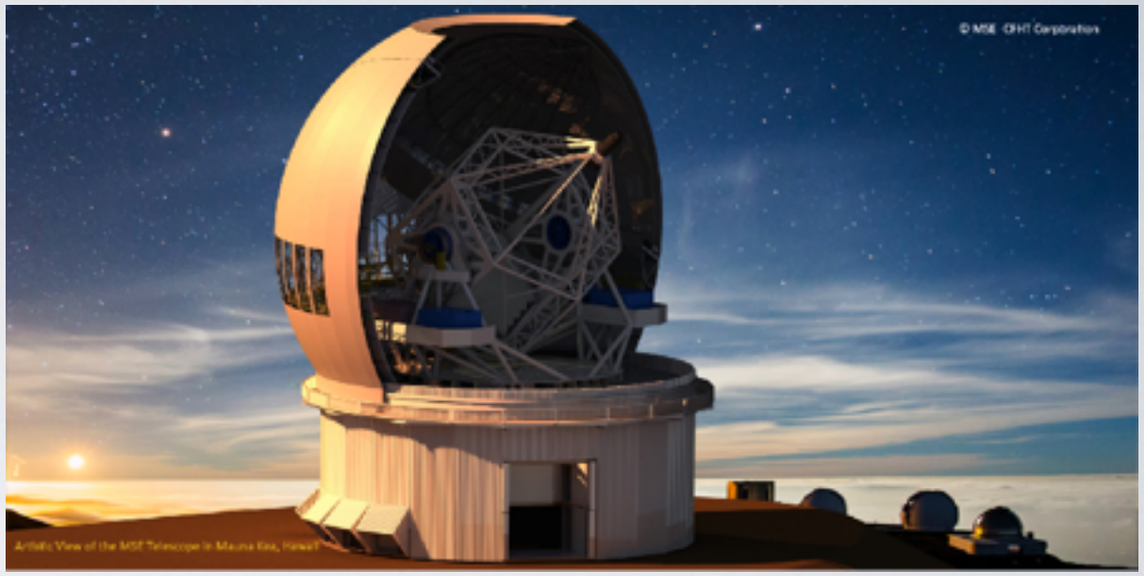
- Simultaneously observe ***~2000 targets over 1.3deg^2 FOV*** (c.f. Keck-LRIS: ~20 objects over 0.01deg^2)
- Broadband wavelength coverage: 380nm-1.3 micron
- Proposed Subaru Strategic Program (SSP) proposal for ~300 nights covering:
  - Cosmology
  - Galactic Archeology
  - Galaxy Evolution
- Projected to begin survey operations in 2021

IGM Tomography in PFS Galaxy Evolution Survey

- ~20 nights of the survey will be targeted at IGM tomography at 2.0<z<2.5
  - Area: 3 × 5 deg^2 = 15deg^2 fields
  - Background sources with 5 cMpc sightline separation at 2.5<z<3.5 (g<24.7)
  - 1000/deg^2 of foreground sources at 2.2<z<2.6 for cross-correlation



Maunakea Spectroscopic Explorer



- 11.5m telescope to replace the 3.5m in the CFHT dome on Maunakea
- Timescale: first-light ~2030
- 1.5 deg^2 FOV with multiplex of 3000 at medium resolution
- Factor ~few improvement in capability, but main advantage is that it will be dedicated survey telescope unlike PFS on Subaru
- Can easily carry out ~200 deg^2 program for IGM tomography at z~2-3 at comparable spatial resolution as CLAMATO

IGM Tomography in future surveys

	CLAMATO (Keck-I/ LRIS)	Subaru-PFS Galaxy Evolution SSP	MSE
Timescale	2014-2020	2021-2026	2030+
Area	0.17 deg^2 (in 2017)	15 deg^2	~100 deg^2
Map Volume	9×10^5 $cMpc^3$	4.4×10^7 $cMpc^3$	~10^9 $cMpc^3$
Background source density	1600 deg^{-2}	970 deg^{-2}	~1500 deg^{-2}
Transverse sightline separation	3.4 cMpc	3.9 cMpc	3.5 cMpc
Source magnitude limit	g<24.9	g<24.7	g<25, r<24.7
Map redshift	2.0<z<2.6	2.1<z<2.5	2.1<z<3.0

IGM Tomography and ATLAS

- IGM tomography was sold as much more efficient way to probe the cosmic web at z~2-3 compared to galaxy redshift surveys

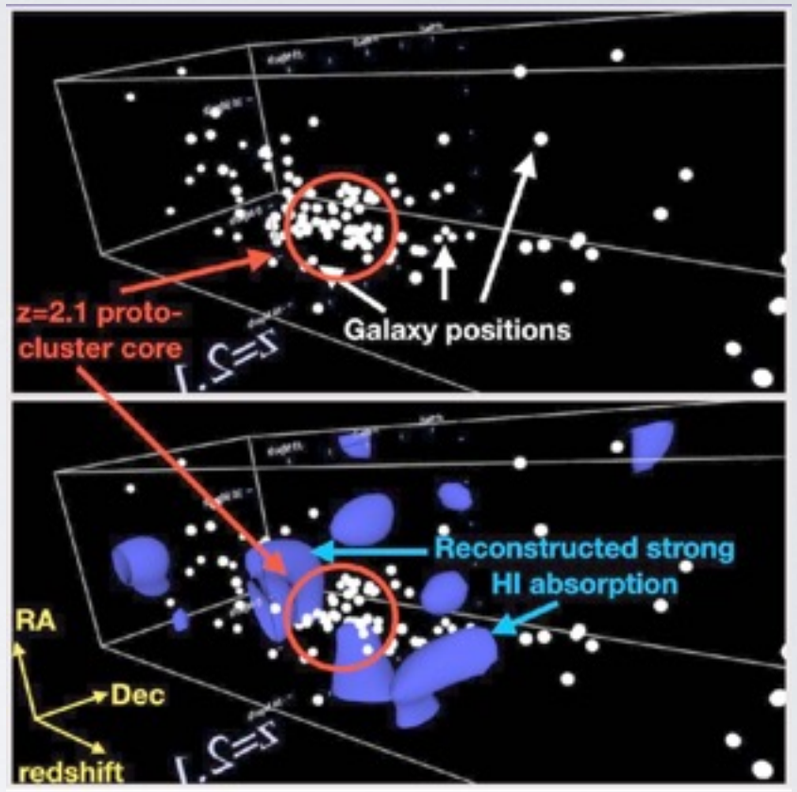
- But many of the exciting science that could be done with the data set comes from synergy with coeval galaxy spectroscopic samples

    - Currently, CLAMATO takes advantage of >100 nights of legacy COSMOS galaxy spectroscopy on large telescopes (i.e. zCOSMOS, VUDS, MOSDEF etc)

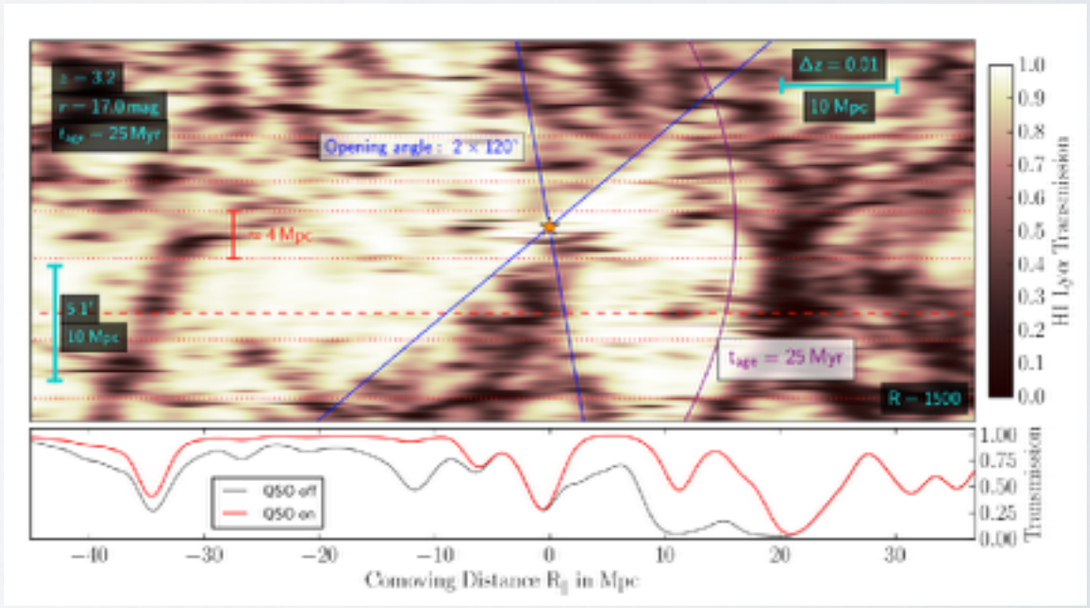
- ATLAS-Medium Survey will be well-matched with O(~100deg^2) surveys on MSE around ~2030 (or equivalent next-generation instrument)

IGM Tomography and Spectroscopic Galaxies

- Study deviations between 'fluctuating Gunn-Peterson' mapping between Lyα absorption and DM field:
    - Pre-heating in high-z protoclusters will be obvious with galaxy sample - can study galaxy evolution effects in pre-heated regions
    - Quasar ionizing light cones: LSS prior from galaxy field allow constraints on *lifetime, opening angle and inclination* for individual quasars!
- Lyα forest is most sensitive probe of small-scale cosmology at 2<z<5 (e.g. WDM, neutrinos constraints), but believability is limited by 'astrophysical systematics'.



Very preliminary from CLAMATO!



Courtesy of Toby Schmidt (UCSB)

Summary

- Ly-alpha forest using background LBGs lets us probe several-Mpc-scale cosmic web at z>2
- CLAMATO Survey on Keck-I is now approaching ~0.2sq deg:
  - Unique view of a (possible) forming supercluster at z=2.5
  - First detection of cosmic voids at z>1 at 6 sigma confidence
  - Cross-correlation measurements with foreground MOSDEF, 3D-HST and VUDS galaxy redshifts
- High-z SSP survey (~15 nights) with Subaru PFS will map out large volumes over 15 sq deg starting 2021
- ATLAS will be synergistic with ~100 sq deg surveys at 2<z<3 IGM tomographic mapping surveys on MSE (or equivalent)
  - Reveal the Ly-alpha forest connection with galaxies and DM field in detail