Exploring the z~2-3 Cosmic web with 3D Lyman-alpha Forest absorption tomography

Intergalactic Interconnections @ Aix-Marseille Université

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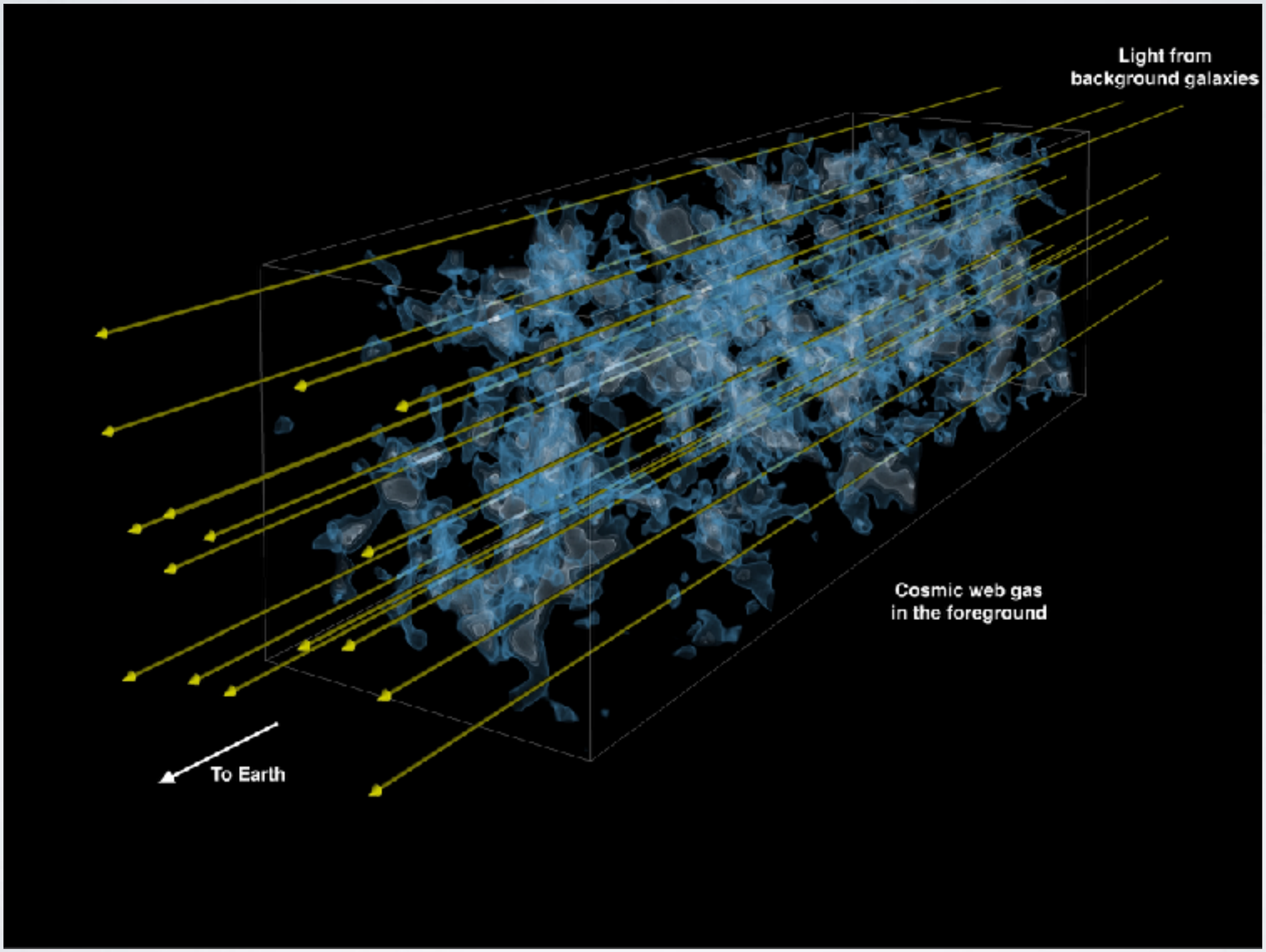
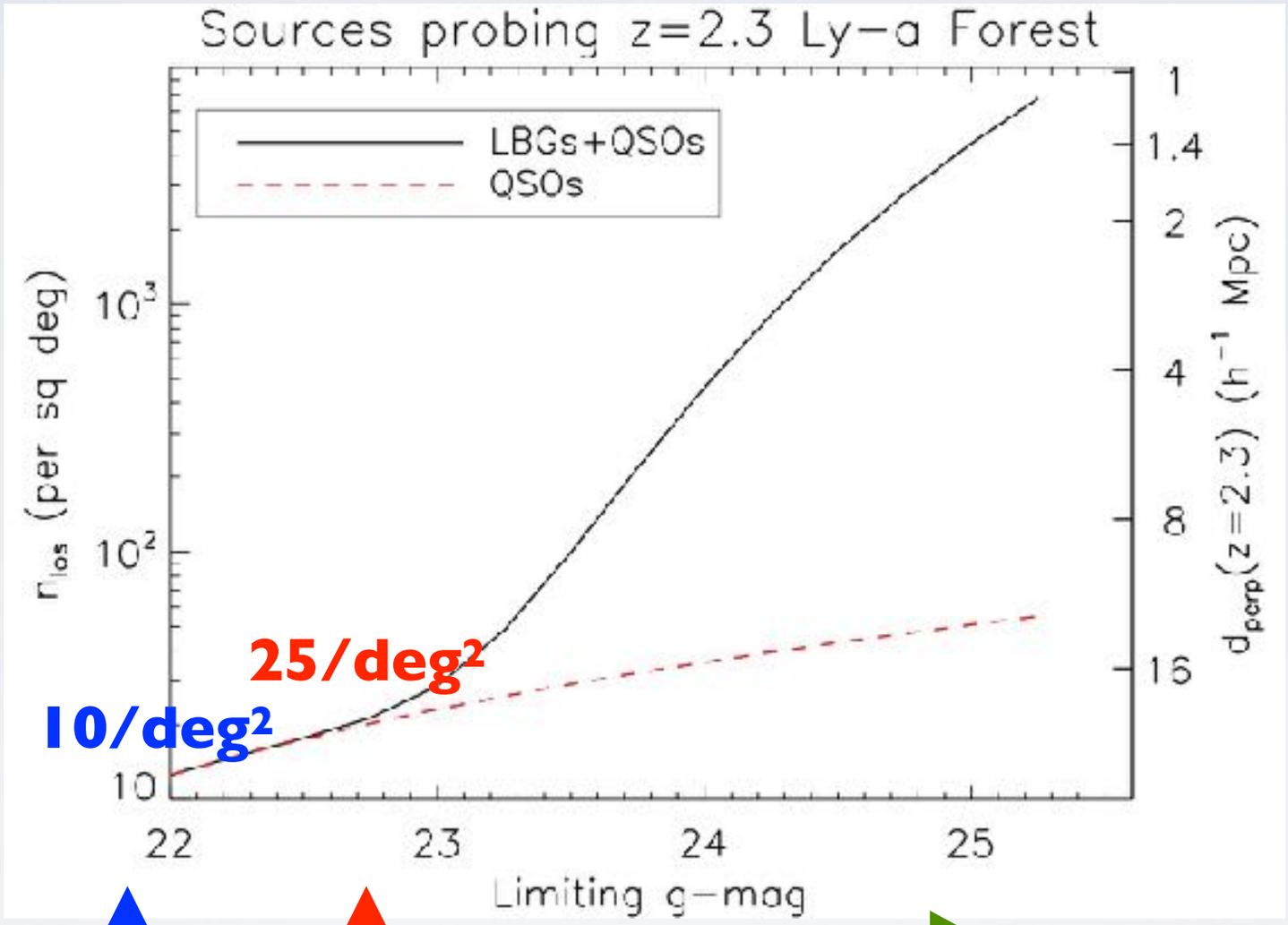
Tomographic Reconstruction of 3D Absorption



Going beyond quasars for Ly-α forest



# of Ly-a forest sightlines per sq deg

Average sightline separation

BOSS (2.5m)

DESI (4m)

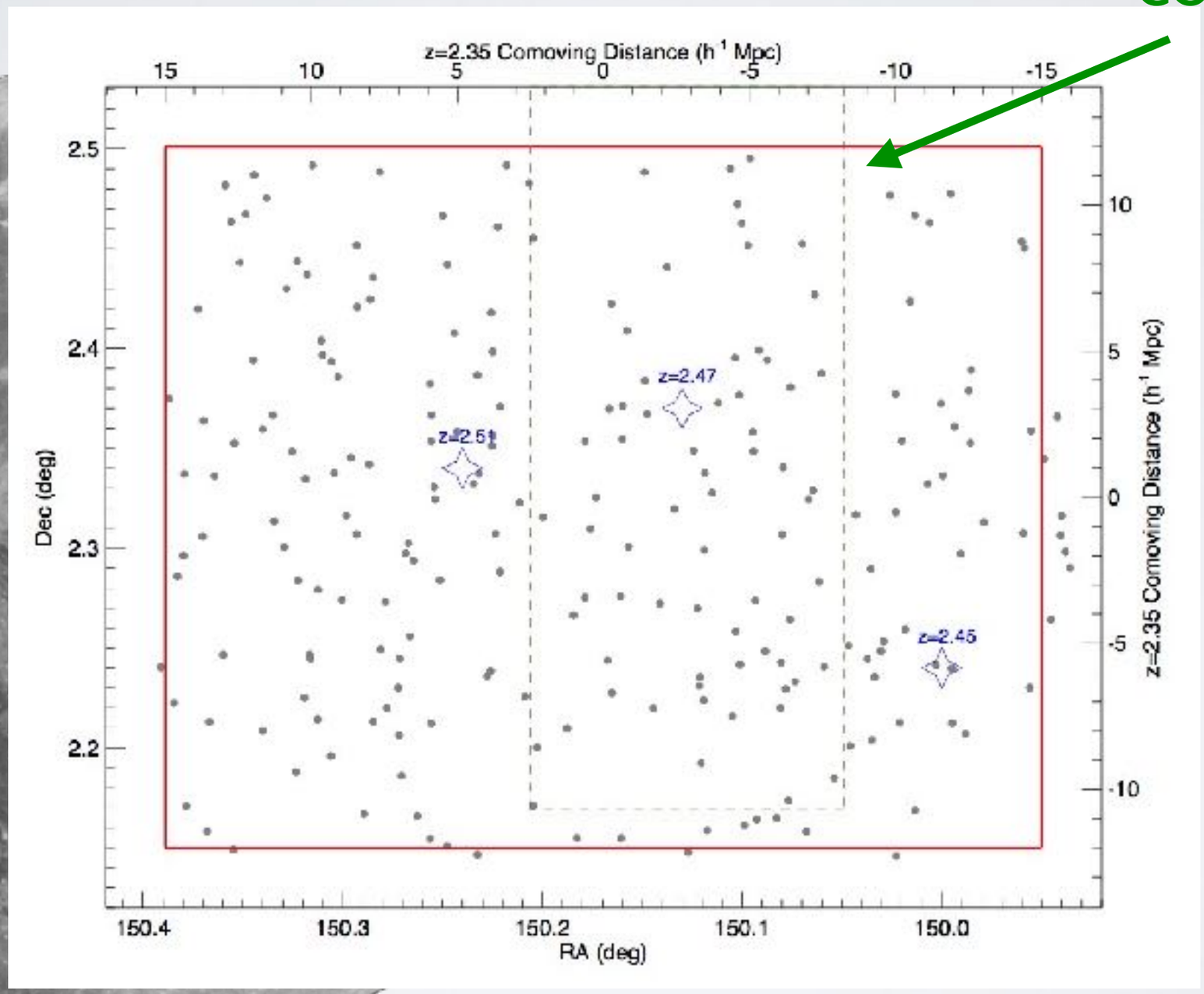
Huge jump in sightline availability with LBGs/star-forming galaxies!

COSMOS LYMAN-ALPHA MAPPING AND TOMOGRAPHY OBSERVATIONS (CLAMATO)

- Keck survey on COSMOS field (10hr, +02deg)
- Aim to get spectra LBGs+QSOs at $z\sim2$-3, to sample $2.1<z<2.5$ Ly-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

Current Status: 230 sightlines over 27' × 21' area (0.17 deg^2), covering 2.05<z<2.55 with mean transverse separation $d_\perp$=2.4h^{-1}Mpc

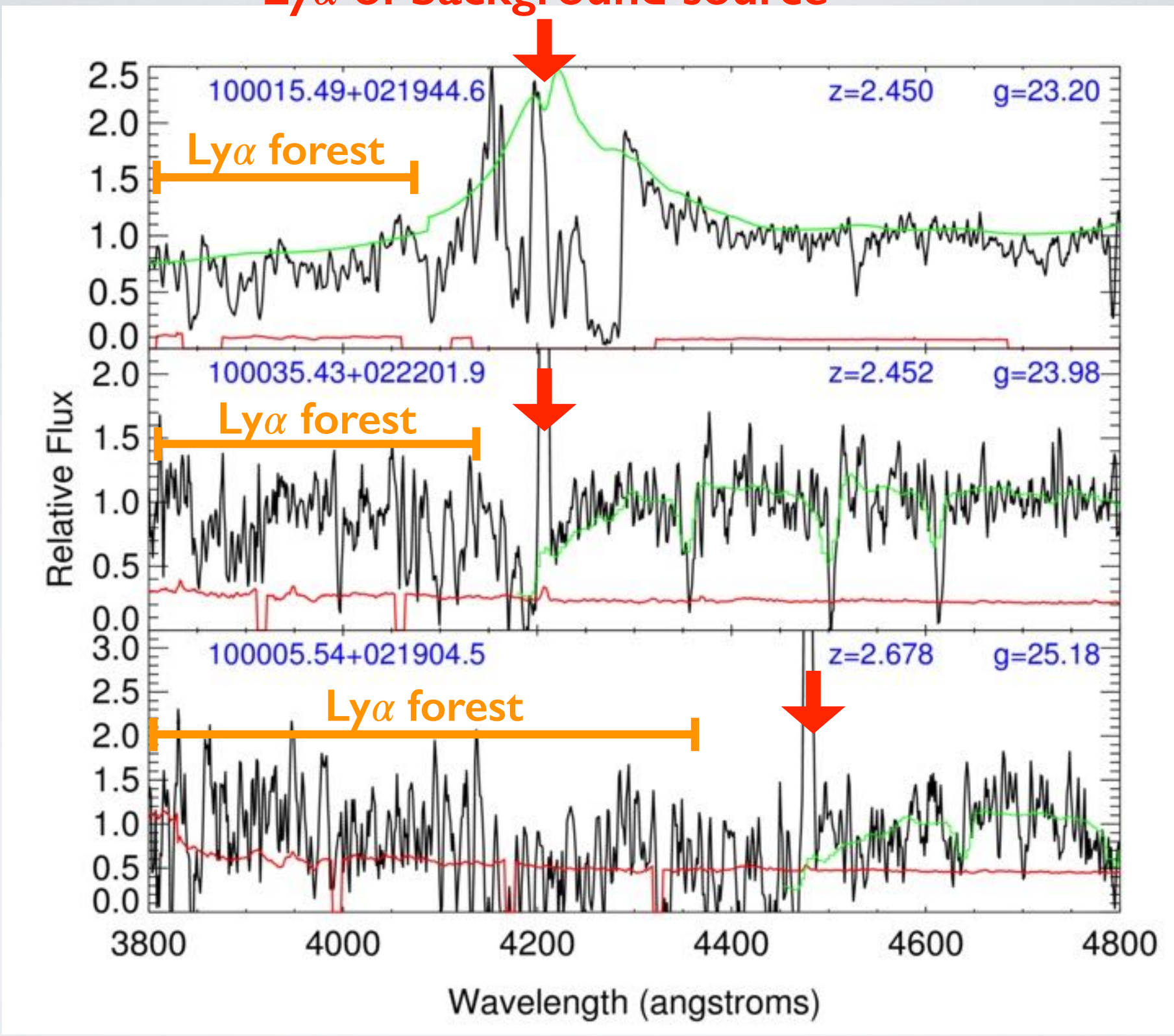
30 h^{-1}Mpc



COSMOS/CANDELS Field

24 h^{-1}Mpc

Lyα of background source



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**

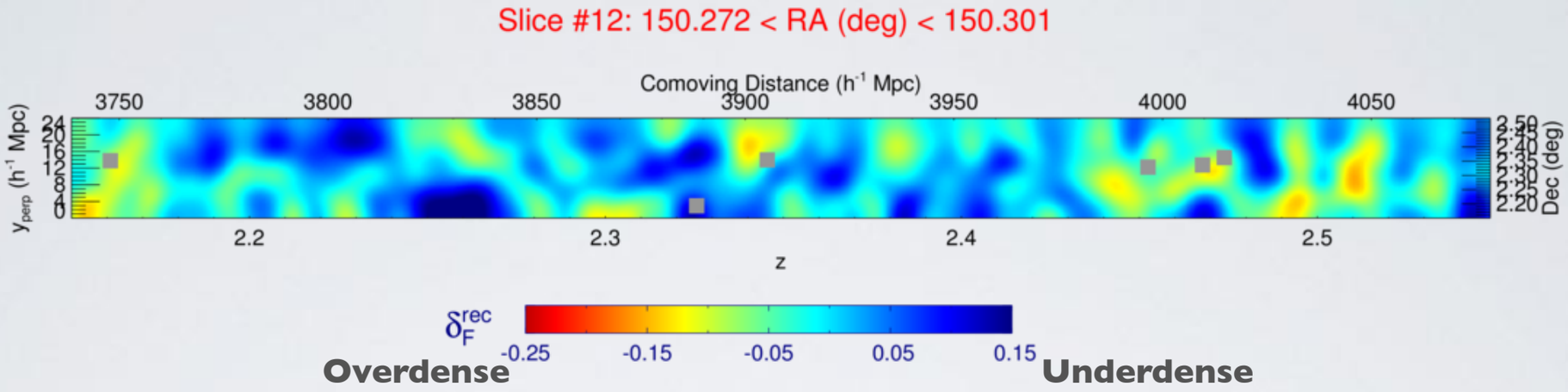
$$\mathbf{M} = \mathbf{C}_{MD} \cdot (\mathbf{C}_{DD} + \mathbf{N})^{-1} \cdot D$$

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

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

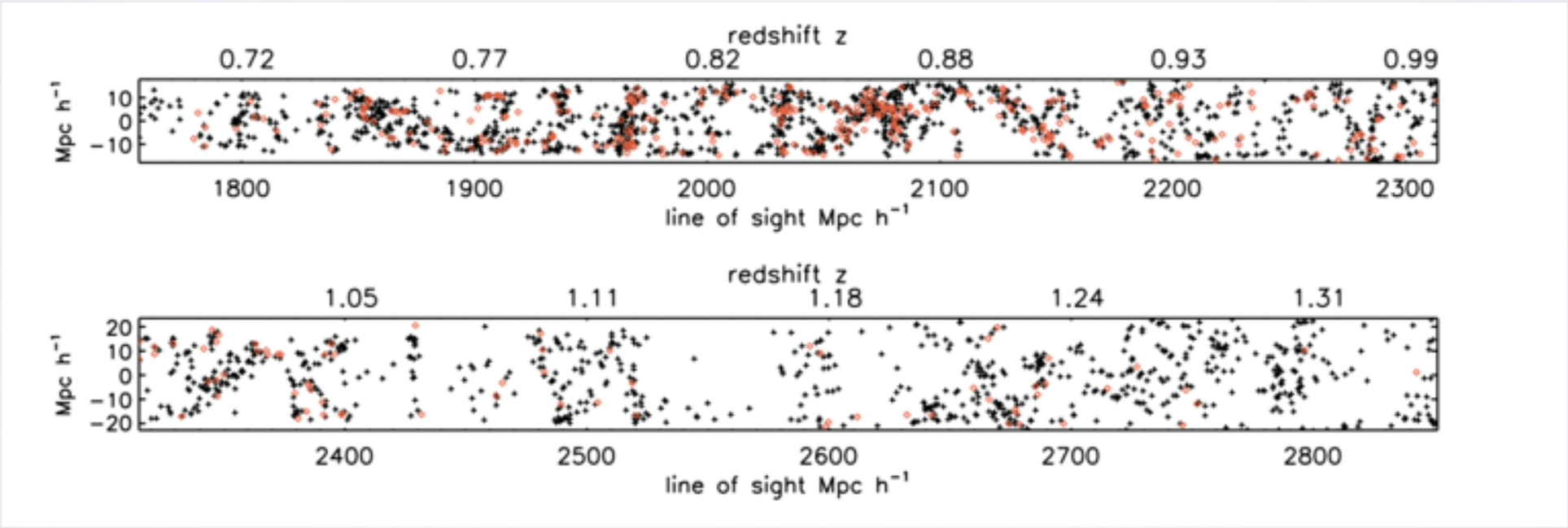
- $L_\parallel=2.5h^{-1}$Mpc and $L_\perp=2.0h^{-1}$Mpc are set by the sightline separation and resolution, $\sigma_F=0.8$ is the variance of the map

CLAMATO IGM Survey at z~2.3 (Keck-I)



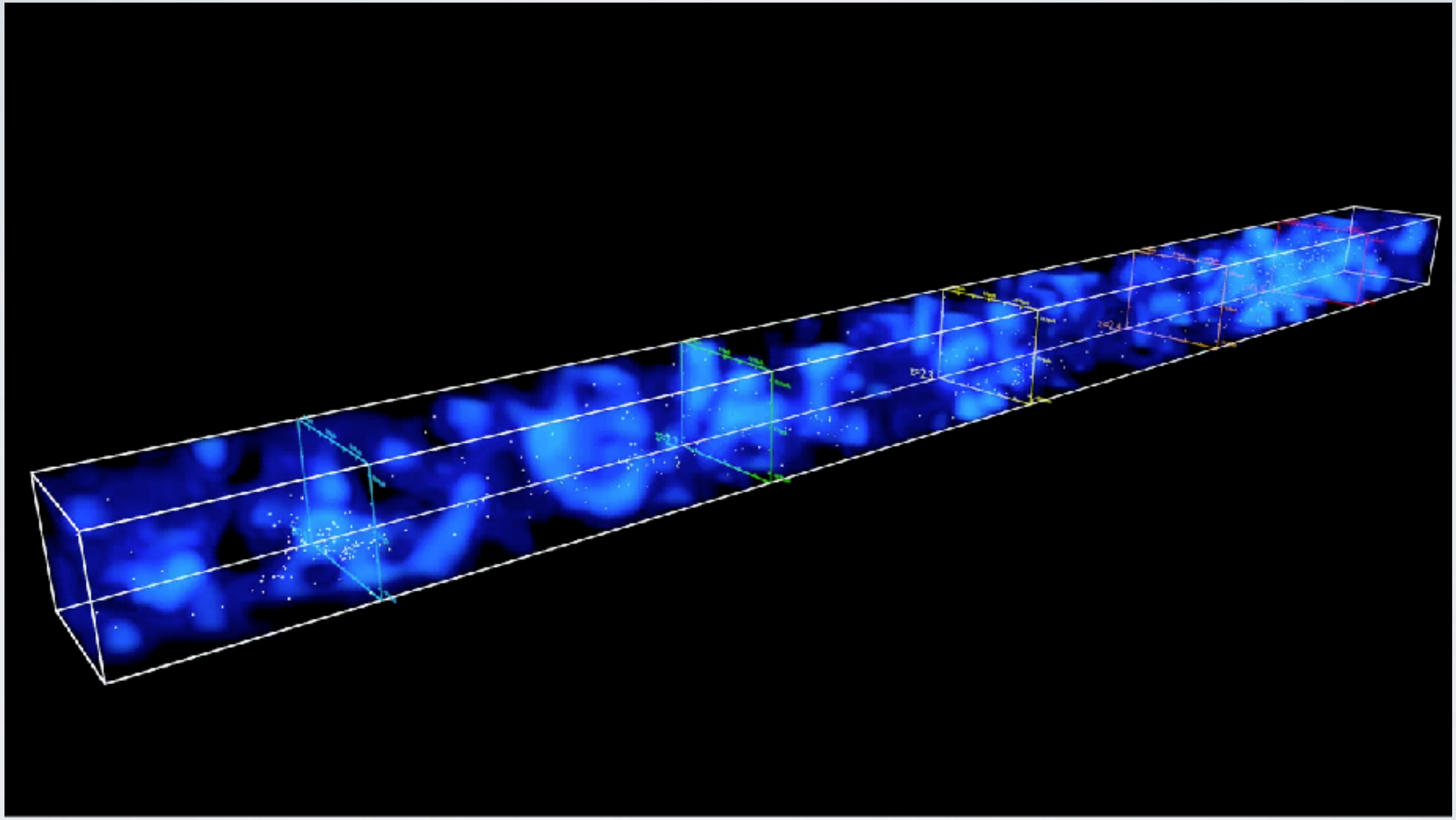
Lee et al, 2017

DEEP2 Redshift Survey at z~1 (Keck-II)



Coil et al, 2004

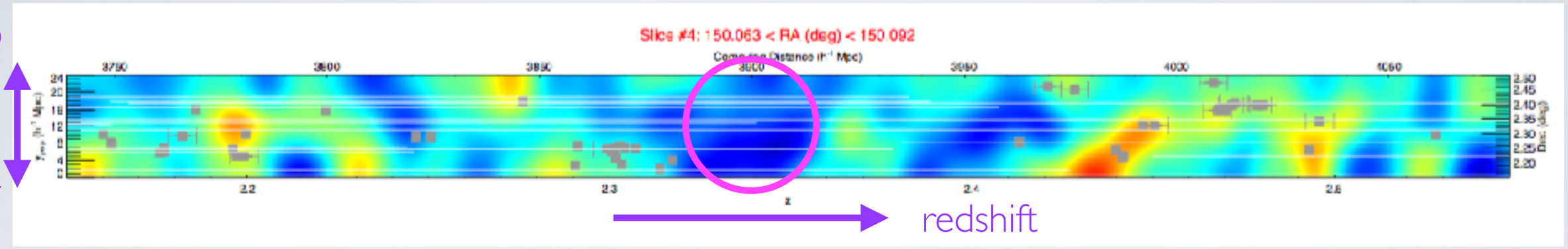
340 Mpc/h along LOS (2.05>z<2.55), 21Mpc/h x 27Mpc/h transverse



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

First Detection Of Cosmic Voids At High-z

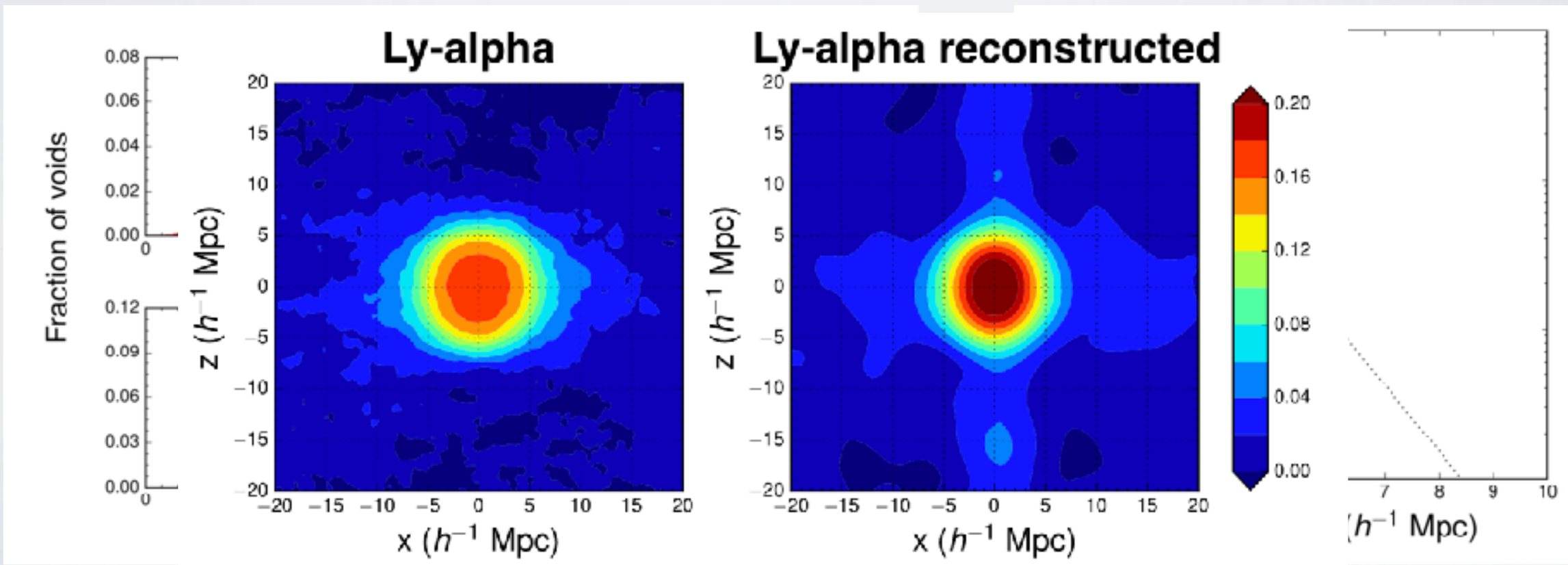
Krolewski, KGL, et al 2018, arXiv:1710.02612



- 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 voids in CLAMATO using simple "spherical underdensity" void finder (e.g. Stark, Font-Ribera, White, KGL, 2015)
- Found ~48 cosmic voids ranging with R>5 Mpc/h (work done by UC Berkeley grad student Alex Krolewski)

z~2 Void Characterization

- Cross-validation with 432 galaxies with spectroscopic redshifts show the IGM voids are underdense in galaxies at 6-sigma significance
    - Shuffle voids randomly N times to get expectation value for null detection
- Radius distribution is consistent with excursion set models
- Volume still too small to detect quadrupole; also need detailed modeling of continuum errors

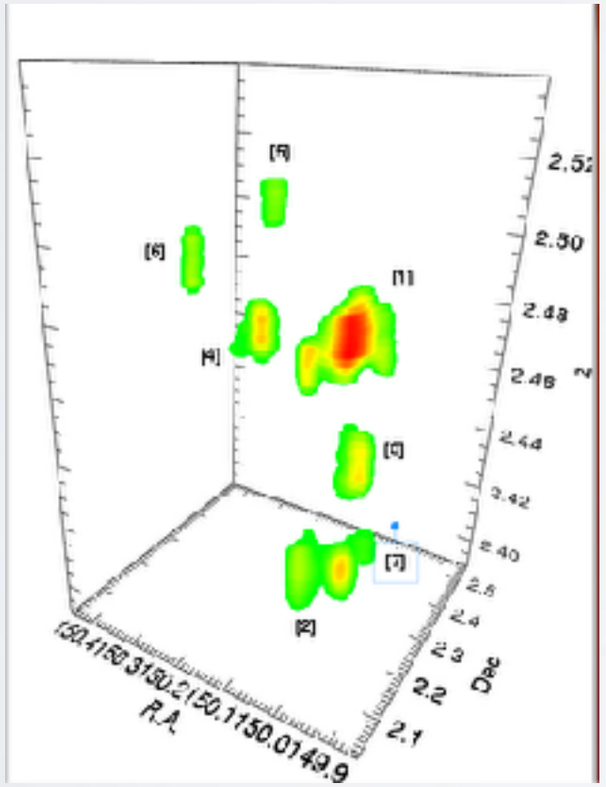


Krolewski, **KGL**, et al 2018

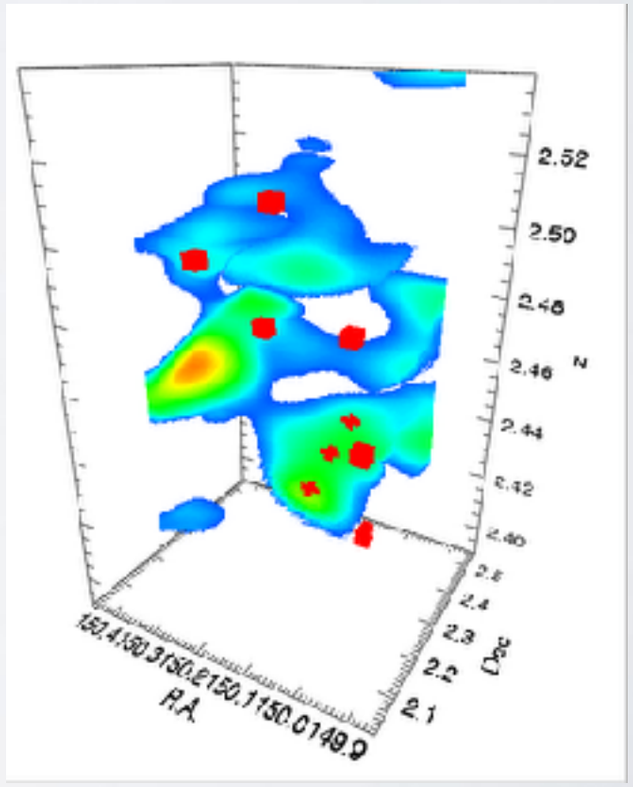
‘Titan’ Overdensity At z~2.5

- 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)

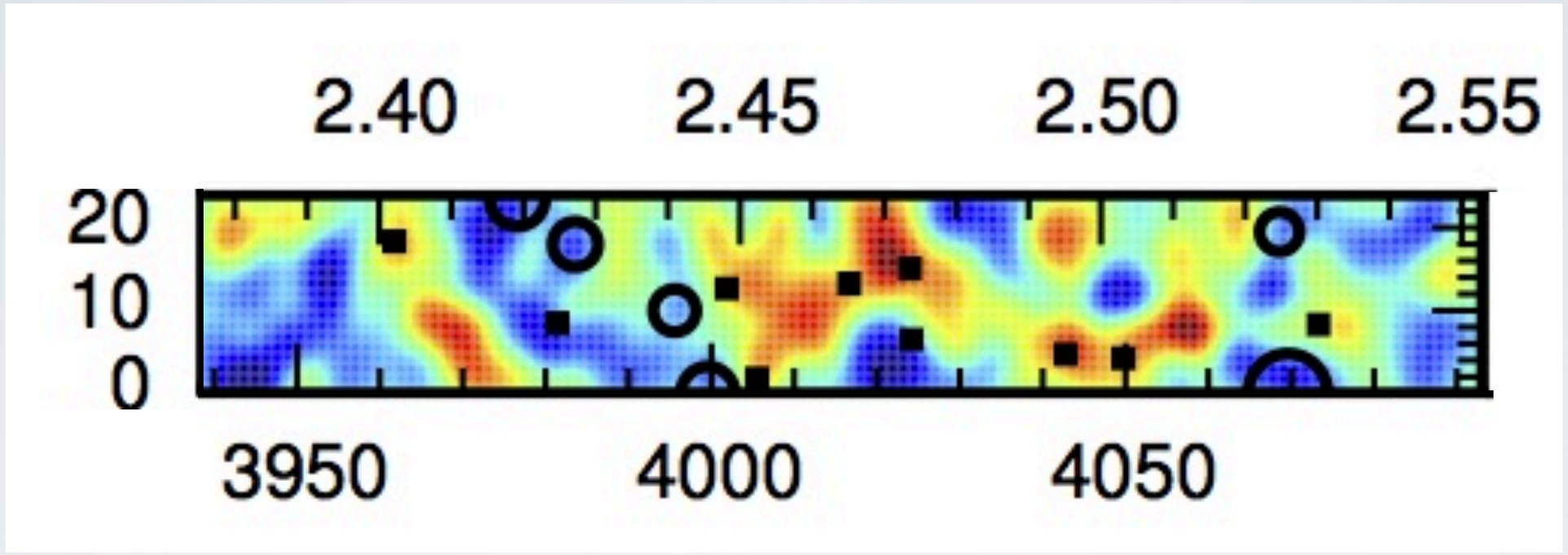


CLAMATO Excess Ly-alpha Absorption (2-sigma threshold)



Figures courtesy of Olga Cucciati

A forming supercluster at z=2.51?

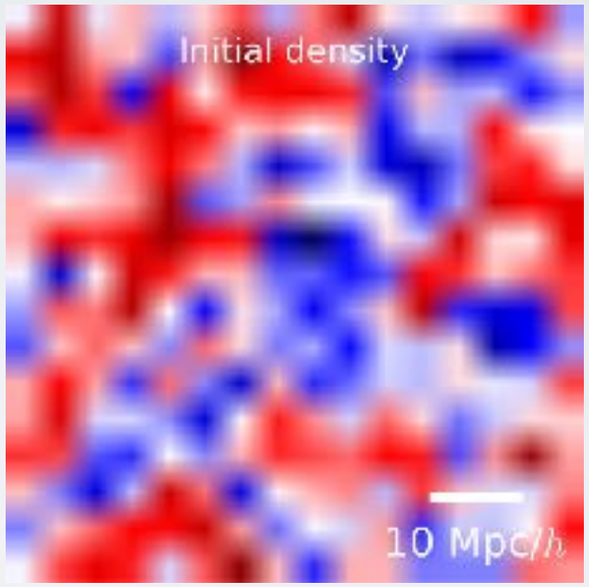


- Known galaxy protoclusters at z=2.44 (Diener+2015, Chiang+2015), z=2.48 (Casey+2016) and z=2.51 (Wang+2016) are <100 cMpc from each other.
- CLAMATO is resolving real filamentary sub-structure at z~2.5!

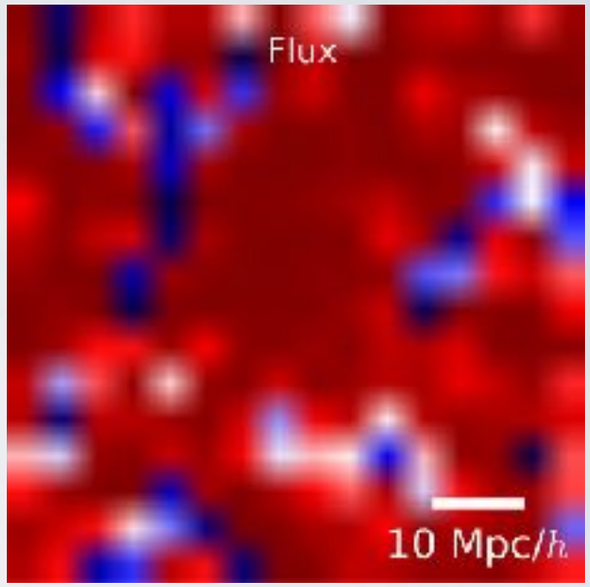
Inferring Map Initial Conditions

- 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 structures observed at z~2.5 with tomography
- Lead by B. Horowitz (UCB) and M. White(UCB)

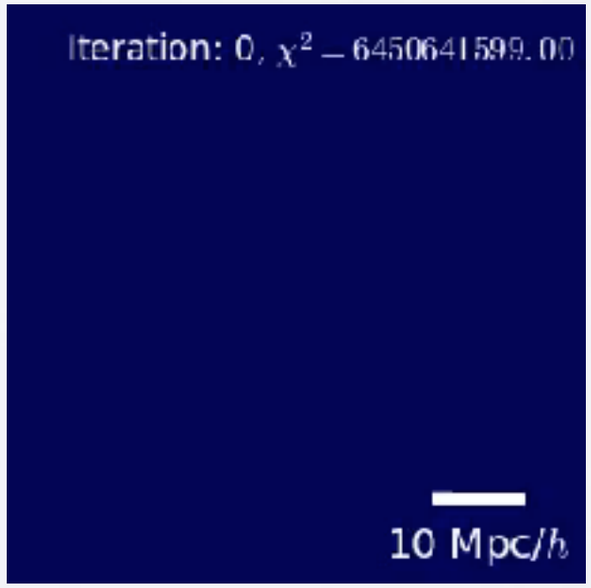
"True" Initial Conditions



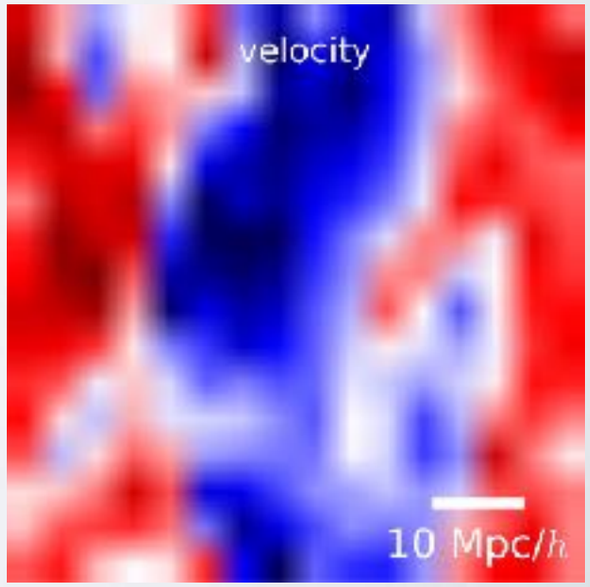
Toy "observations" at z~2.5



Inferred Initial Conditions

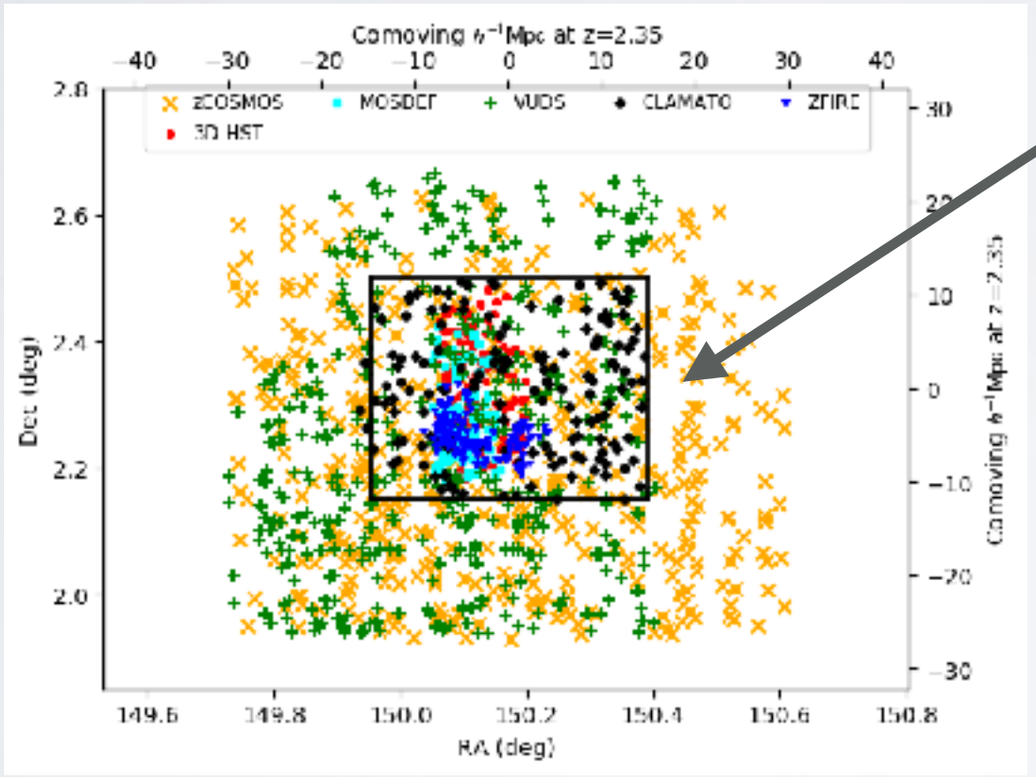


Inferred velocities at z~2.5



Galaxy-Forest Cross-Clustering

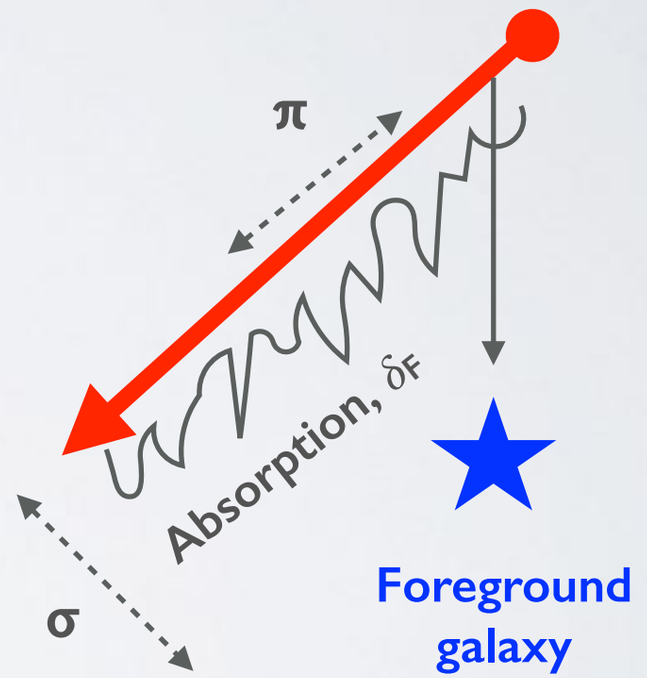
- Cross-correlate CLAMATO forest pixels with spectroscopic surveys in COSMOS field (with Andreu Font-Ribera, UCL)
- ~**1500** galaxies at 2.0<z<2.6 within <15 Mpc/h transverse distance of at least 1 sightline, from zCOSMOS, VUDS, MOSDEF, ZFIRE, CLAMATO, 3D-HST
- Objective: assume that forest bias and beta is known to derive galaxy free parameters



Current CLAMATO Footprint

Dec

RA



$$P_{gal,f}(k,\cos\theta) = b_{gal}(1+\beta_{gal}\cos^2\theta)\, b_f(1+\beta_f\cos^2\theta)\, P_{lin}(k,\cos\theta)$$

Cross-power spectrum **Galaxy bias + RSD** **Ly-a forest bias + RSD (known)** **Linear theory power spectrum (known from cosmology)**

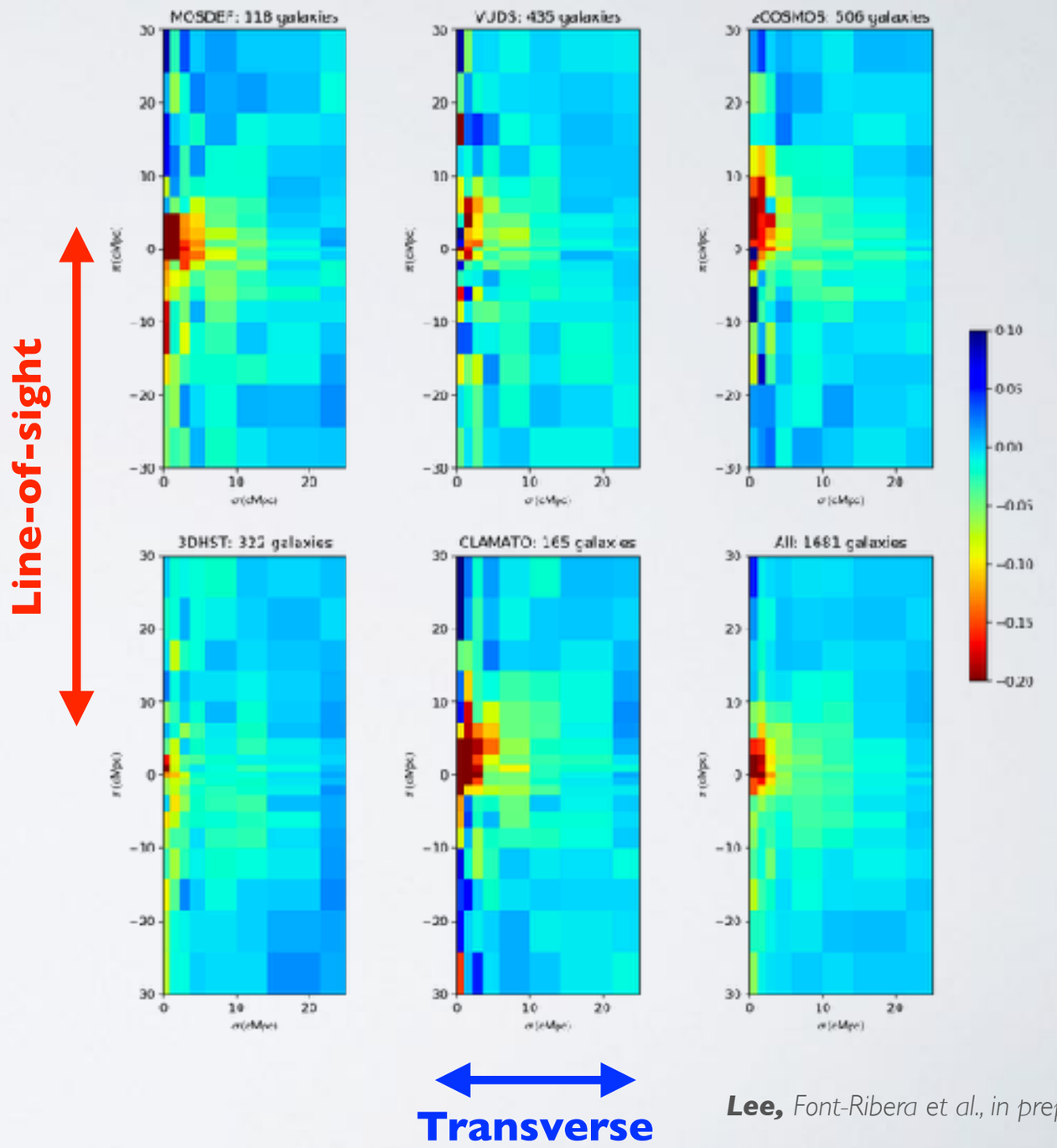
Preliminary!

Cross-correlation with Galaxies

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

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

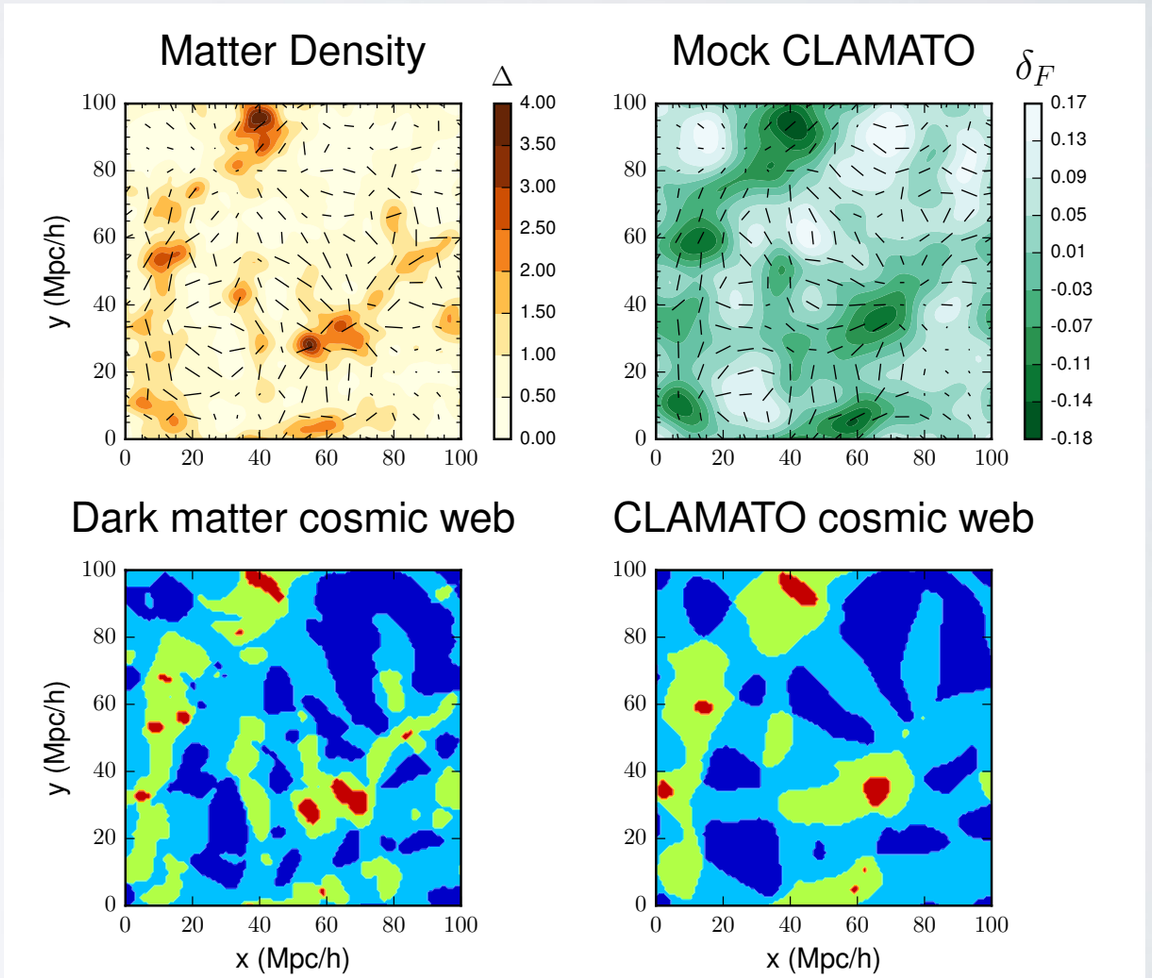
- Overall ~21 **σ** detection from all samples
- Current analysis assumes forest bias is fixed (known to ~3% from BOSS)
- Model galaxies with linear model. with free parameters:
  - bias, b
  - LOS offset, δz
  - LOS dispersion, $\boldsymbol{\sigma}_z$ (combination of redshift error + FoG)



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

Studying The High-Z Cosmic Web With IGM Tomography

- **Lee** & White 2016, ApJ, 817,160
- Krolewski, **Lee**, 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 the eigenvectors of the DM cosmic web
- With sufficient data volume, can constrain intrinsic alignments from galaxies at z~2-3



Future Surveys: Subaru-Prime Focus Spectrograph

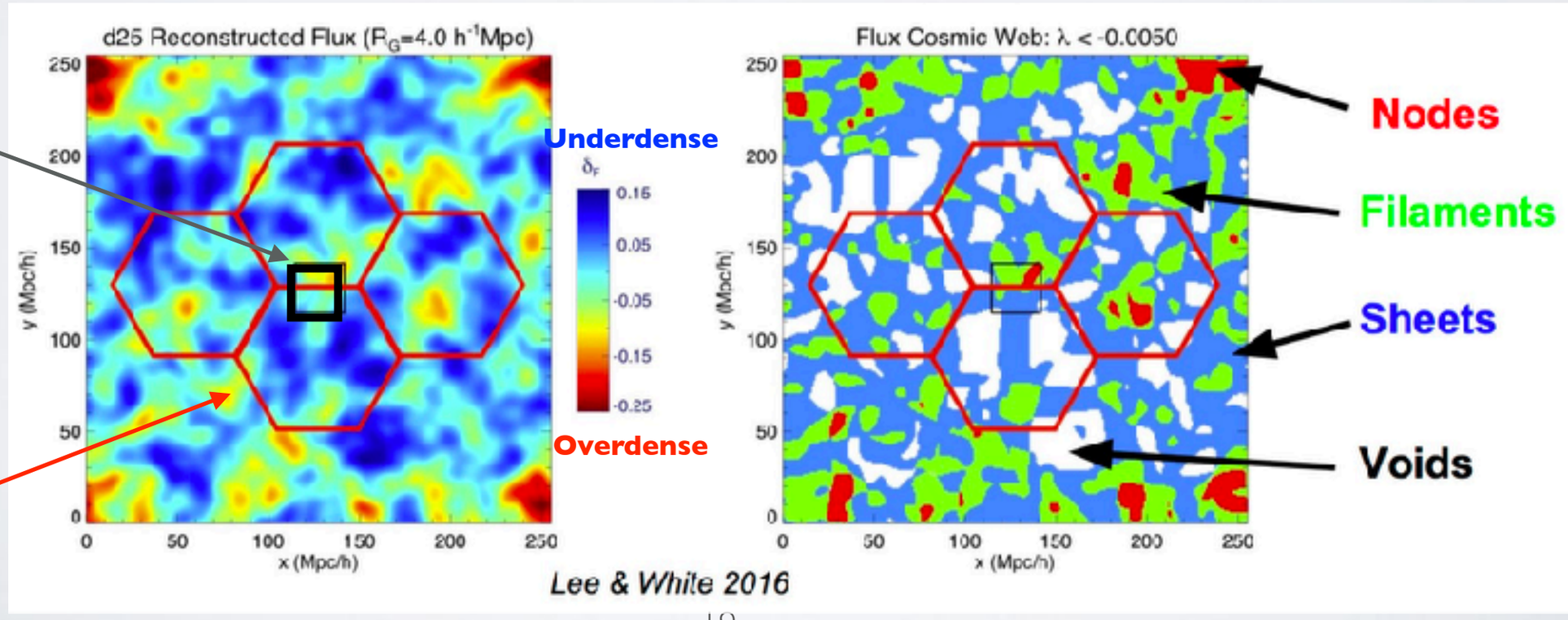
- Simultaneously observe ***~2000 targets over 1.3deg² FOV*** (c.f. Keck-LRIS: ~20 objects over 0.01deg^2)
- Broadband wavelength coverage: 380nm-1.3 micron
- Proposed Subaru Strategic Program (SSP) proposal for ~300 nights covering:
  - Cosmology
  - Galactic Archeology
  - Galaxy Evolution
- Projected to begin survey operations in 2021

IGM Tomography in PFS Galaxy Evolution Survey

- 50 nights of the survey will be targeted at 2<z<7 universe
  - Area: 3 × 5 deg^2 fields
  - 970/deg^2 background sources at 2.5<z<3.5 (g<24.7)
  - 1000/deg^2 of foreground sources at 2.2<z<2.6 for cross-correlation

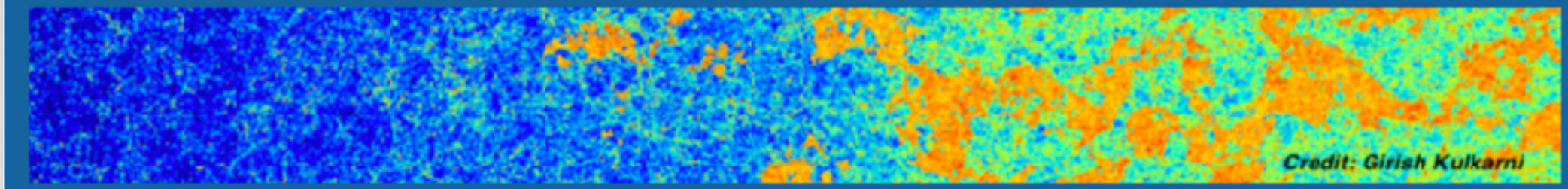
CLAMATO (2017)

Subaru-PFS Footprint



Summary

- Ly-alpha forest using background LBGs lets us probe ~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 (~50 nights) with Subaru PFS will map out large volumes over 15 sq deg starting 2021



IGM2018: Revealing Cosmology and Reionization History with the Intergalactic Medium

Kavli IPMU, Tokyo, Japan (2018 September 18-21)

http://ipmu.jp/igm2018

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Srianand Ragunathan
Matt McQuinn
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Confirmed Speakers

Emma Ryan-Weber
Fred Davies
Laura Keating
Andreu Font-Ribera
Naoki Yoshida
George Becker
Christina Eilers
Daniel Stark
Michael Walther
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