# Exploring the high-z Cosmic web with 3D Lyman-alpha Forest tomography

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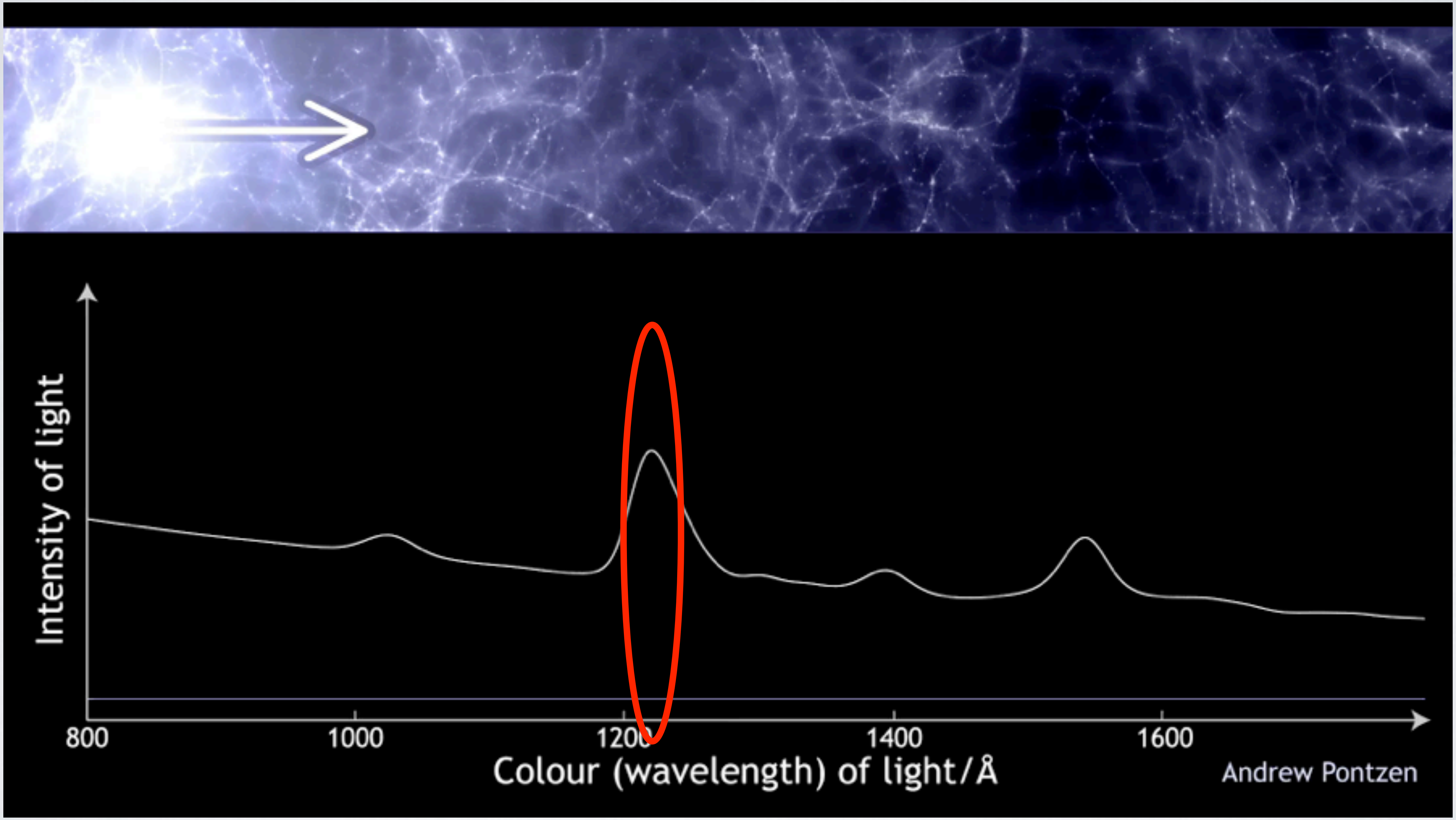
# The Lyman-alpha Forest at z>2



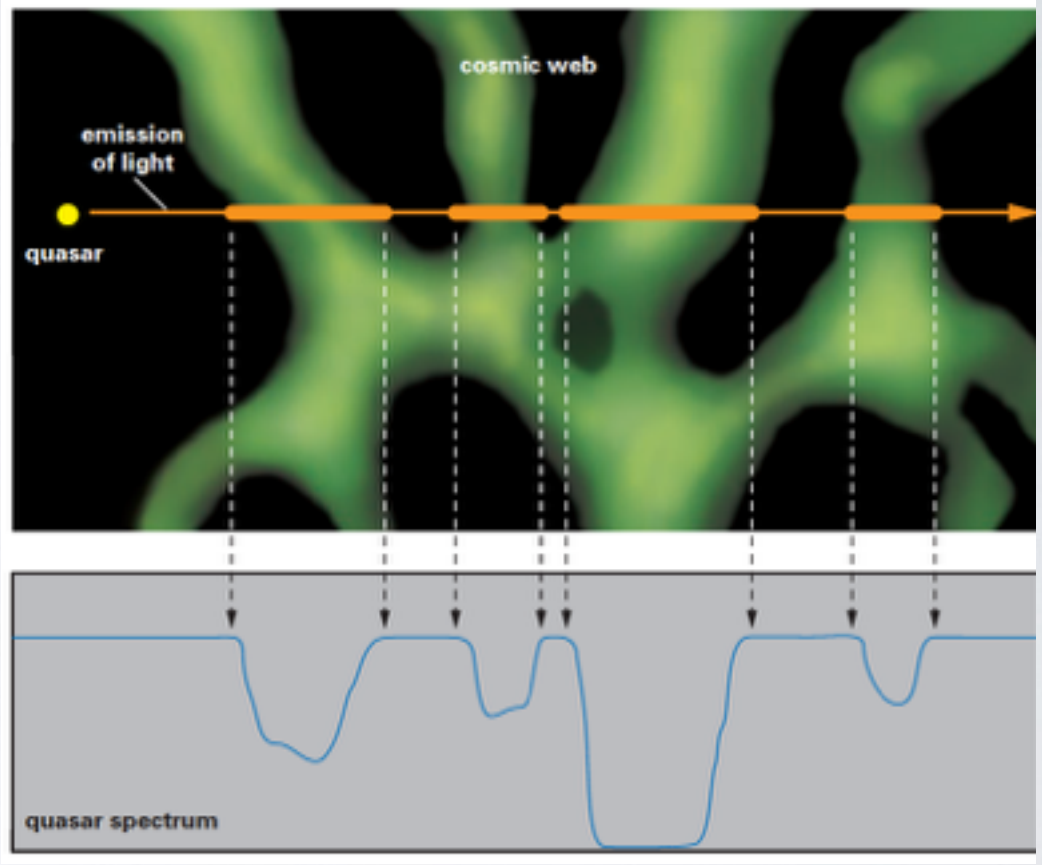

*Restframe 1215.67Å absorption from neutral HI in intergalactic medium*

# Fluctuating Gunn-Peterson Approximation (FGPA)

- Current paradigm for large-scale IGM: ~uniform optically-thin photo-ionization
- Lyman-alpha forest optical depth is modulated by IGM astrophysics and underlying large-scale structure overdensity

$$\tau_\alpha(x) \propto n_{HI}(x) \propto \frac{1}{\Gamma_{bg} T_0^{0.7}} \Delta(x)^{2-0.7(\gamma-1)}$$

- Optical depth is modulated by uniform UV background levels $\Gamma_{bg}$, IGM temperature $T_0$, slope of temperature-density relationship $\gamma$




*Credit: Rob Simcoe*

**In this talk, I assume**

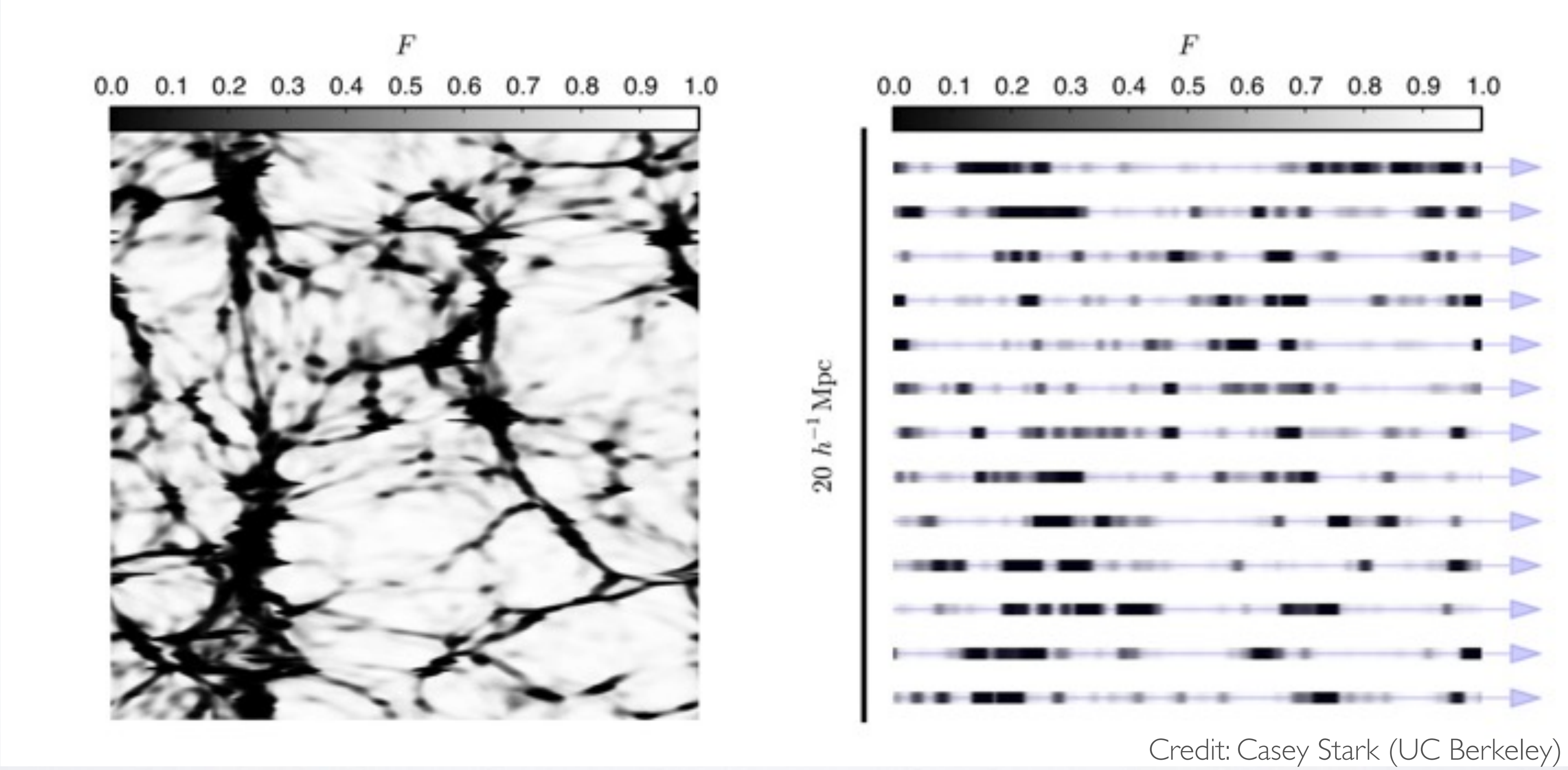
$$\tau_\alpha(x) \leftrightarrow \Delta(x)$$

**(absorption traces large-scale structure)**

*We observe transmitted flux, $F=F_0 \exp(-\tau)$*

# IGM Tomography:
# Mapping 3D Ly-alpha forest on small scales

- If have a grid of closely-separated sightlines, could allow reconstruction of 3D absorption field on scales comparable to sightline separation (*Pichon+2001*, *Caucci+2008*, ***Lee***+*2014*)



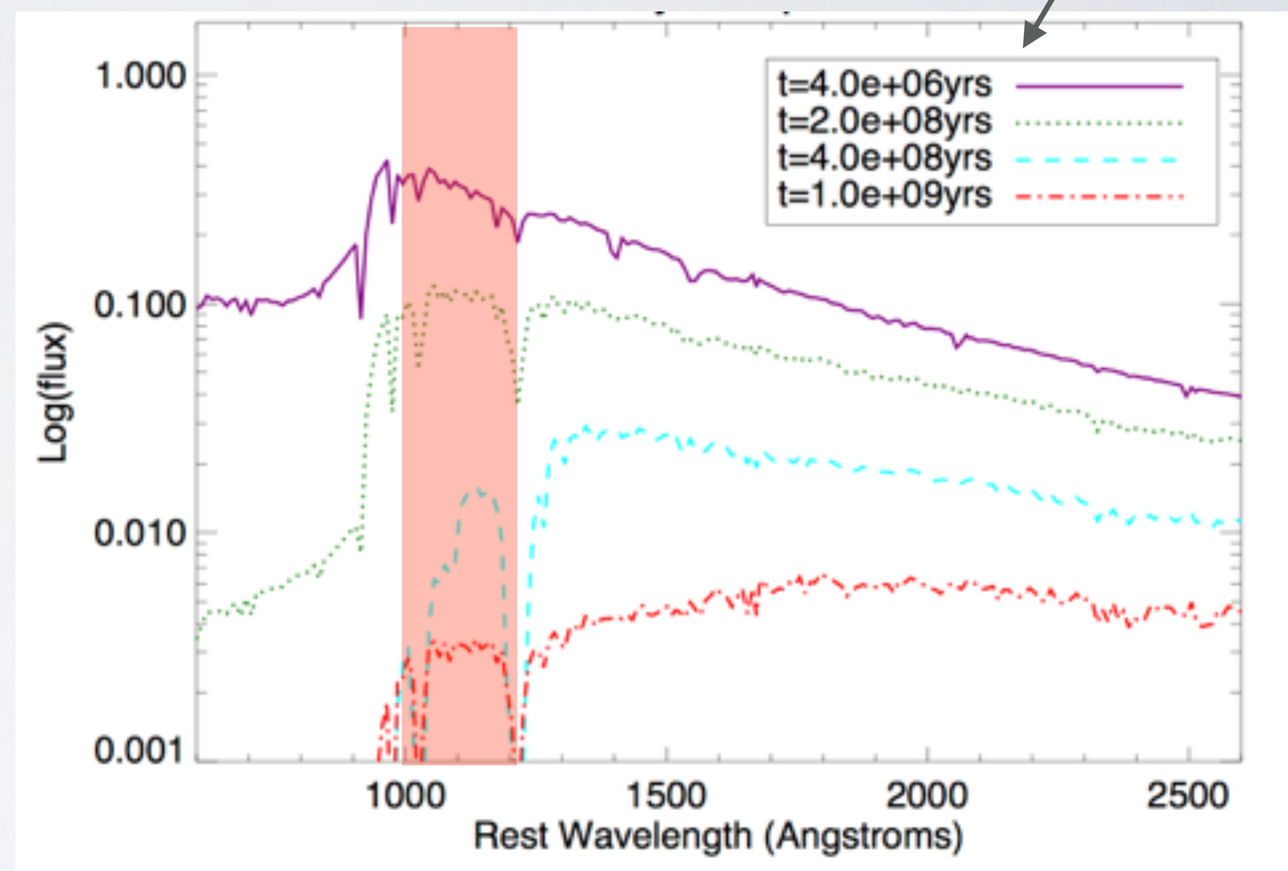

Going fainter → More sightlines → Smaller scales

# Going Beyond Quasars To Galaxies

- To probe the Lyman-$\alpha$ forest, need UV-bright background source
- Rest-frame UV coverage from ~1025A-1216A
- **Quasar** accretion disks are the brightest sources in the Universe
- **Star-forming galaxies** are also UV-bright from hot young stars, but generally much fainter — often called 'Lyman-Break Galaxies' (**LBGs**) due to selection method

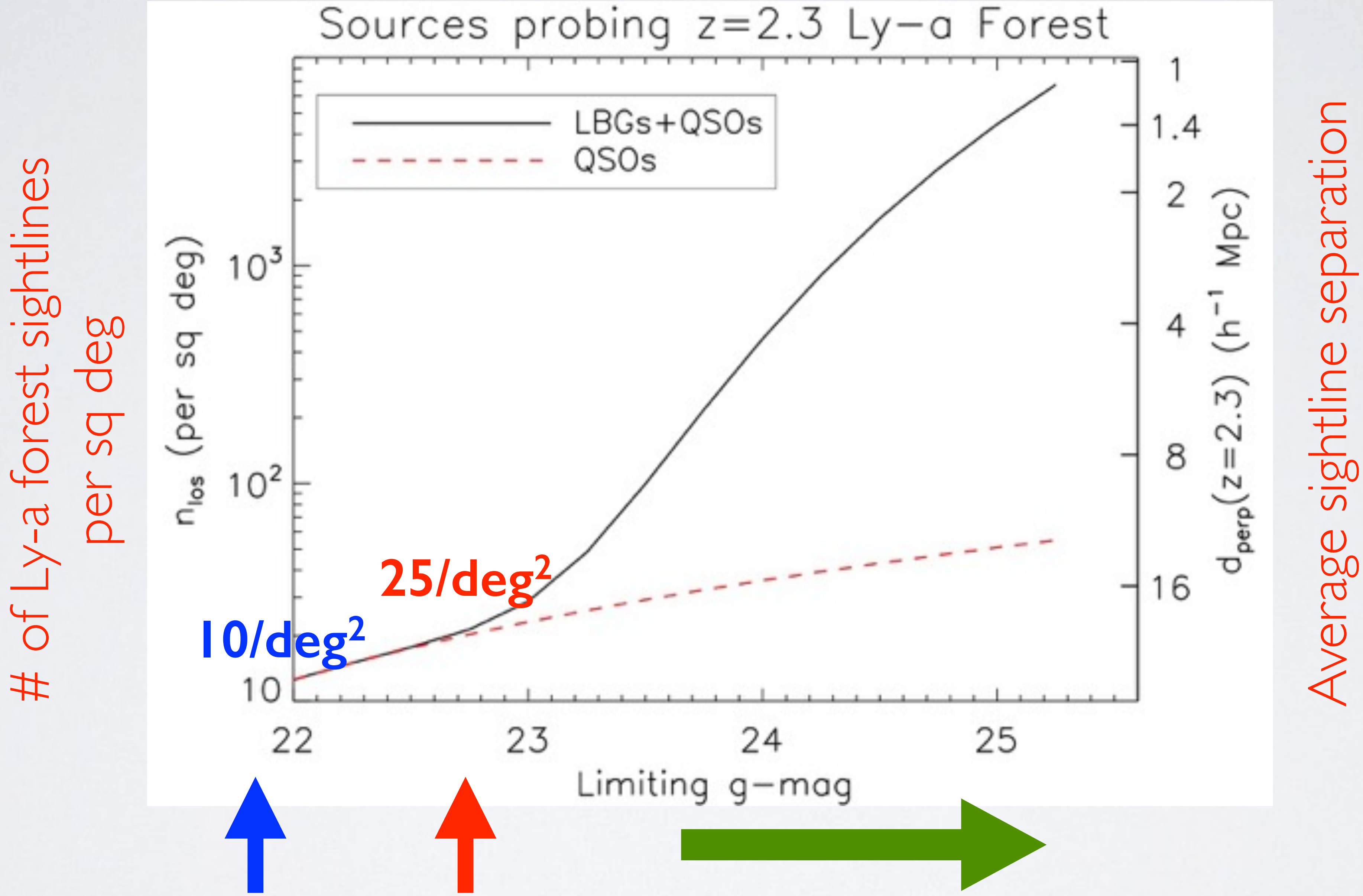
Time since star-formation

Galaxies




Lyman-alpha Forest

# GOING BEYOND QUASARS FOR LY-ALPHA FOREST

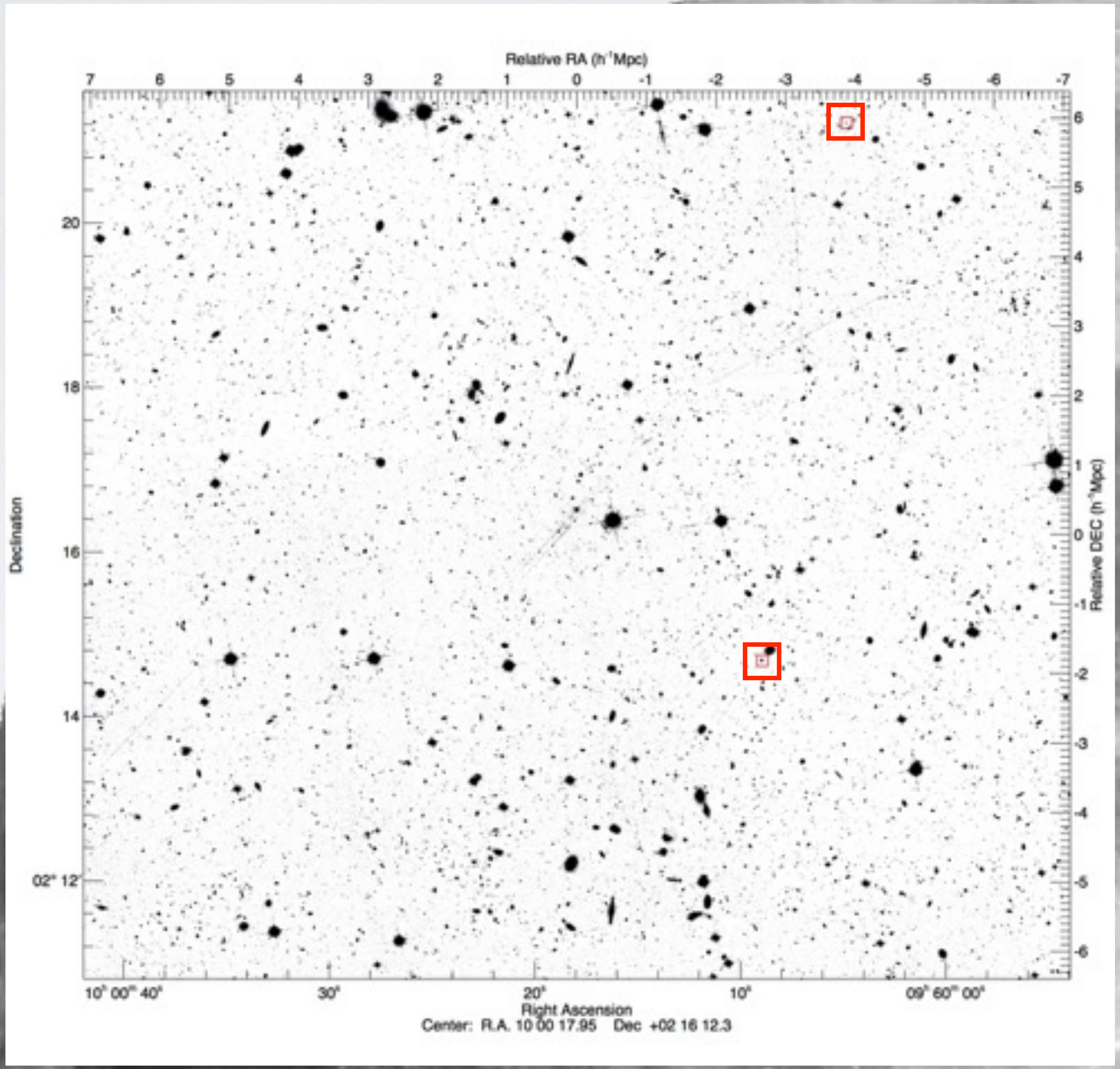



**BOSS (2.5m)**

**DESI (4m)**

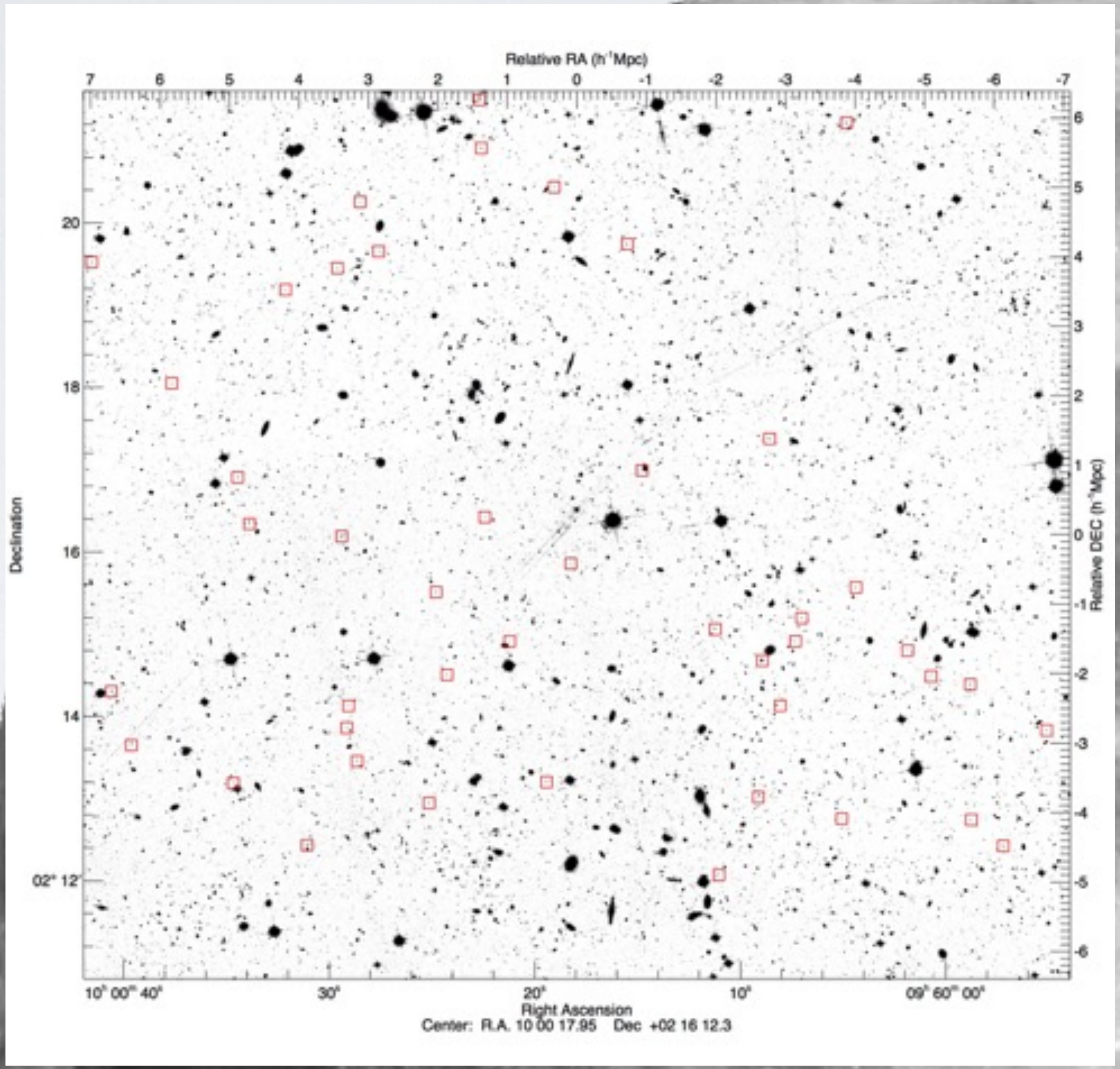
**Huge jump in sightline availability with LBGs/star-forming galaxies!**

# Sources Within A 12'x12' Field



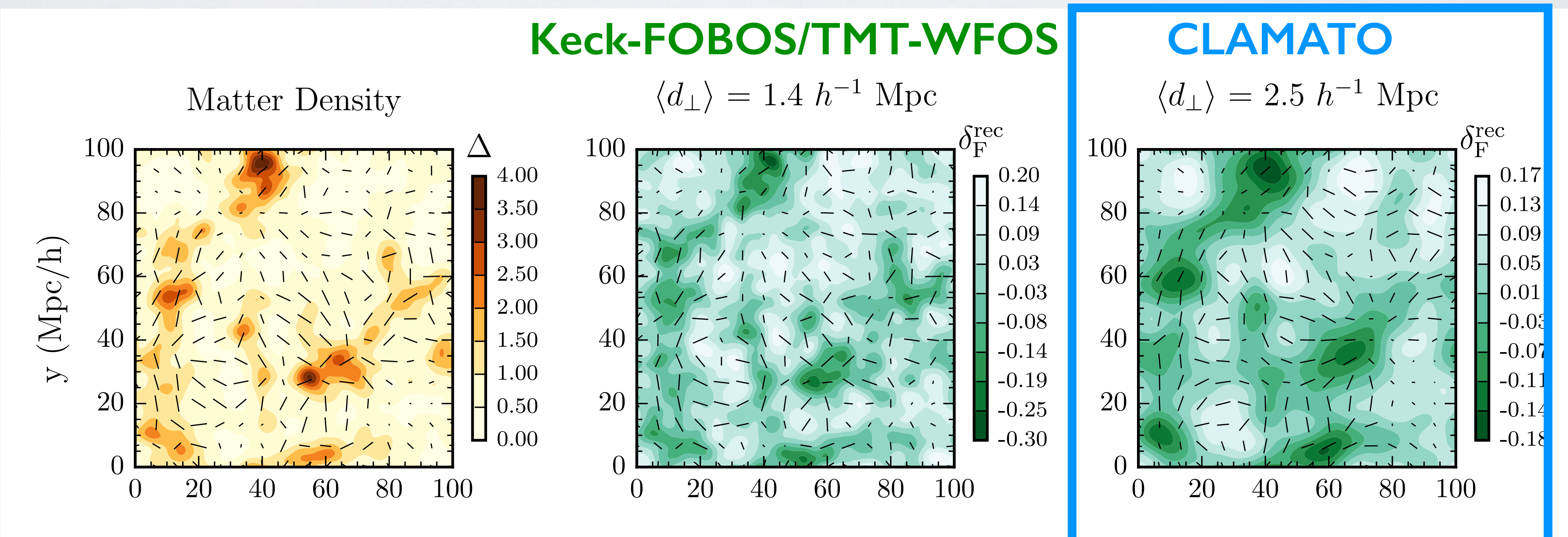

*mag<22.5 QSOs at 2.3<z<3.0*

# Sources Within A 12'x12' Field




*mag<24.5 QSOs+Galaxies at 2.3<z<3.0*

# IGM Tomography gives good cosmic web recovery in sims!

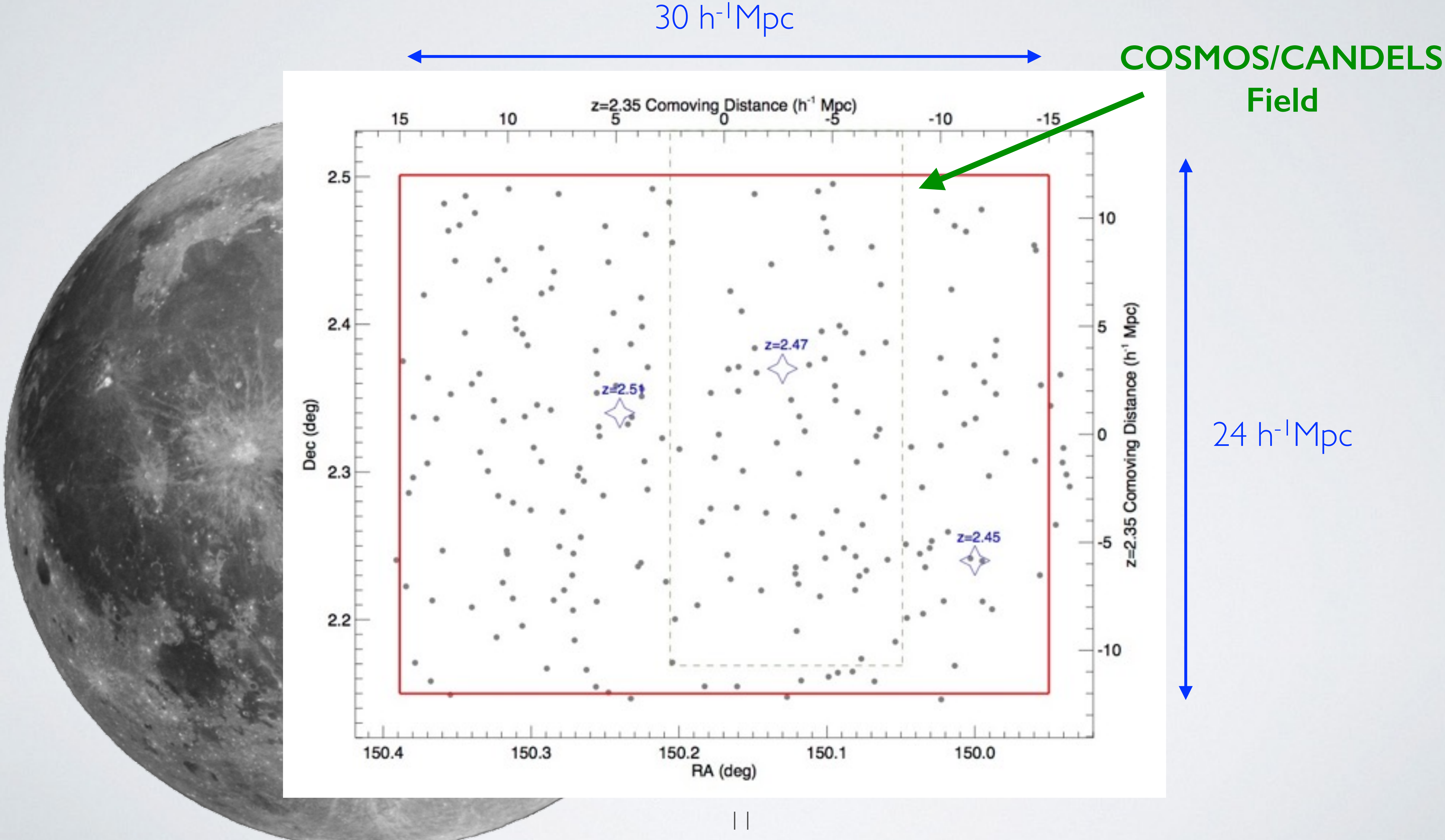


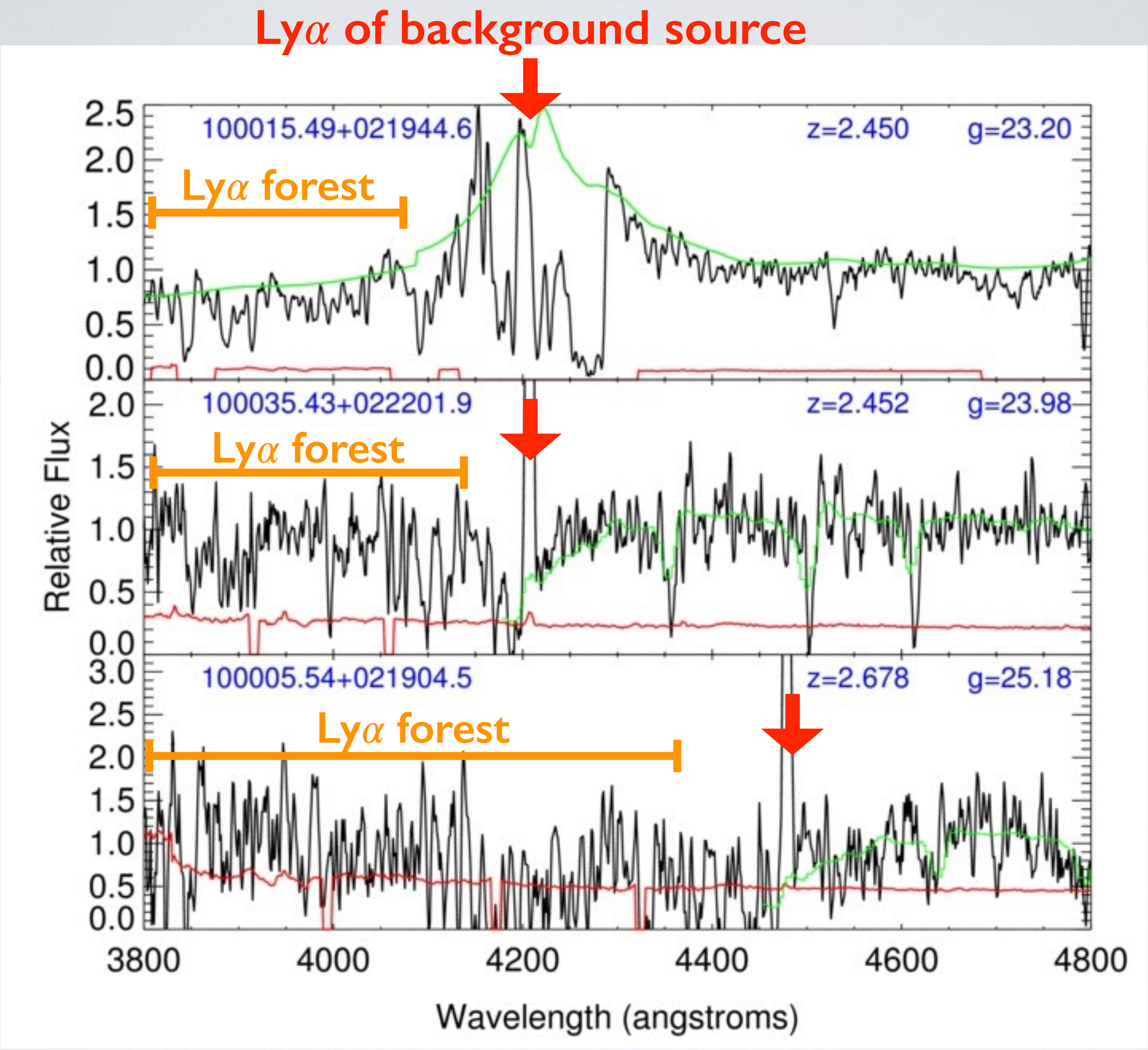

*Krolewski, Lee et al 2017 (see also Lee et al 2014)*

# 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-a forest with sightline separations of ~2.5$h^{-1}$Mpc
- *First systematic use of galaxies as Ly$\alpha$ forest background sources!*
- 2-4hr integrations with Keck-I/LRIS spectrograph down to g<24.8
- ~50hrs on-sky observations so far

**Current Status:** 230 sightlines over 26' × 20' area (0.14 $deg^2$), covering $2.15<z<2.55$ with mean transverse separation $d_\perp=2.5h^{-1}$ Mpc





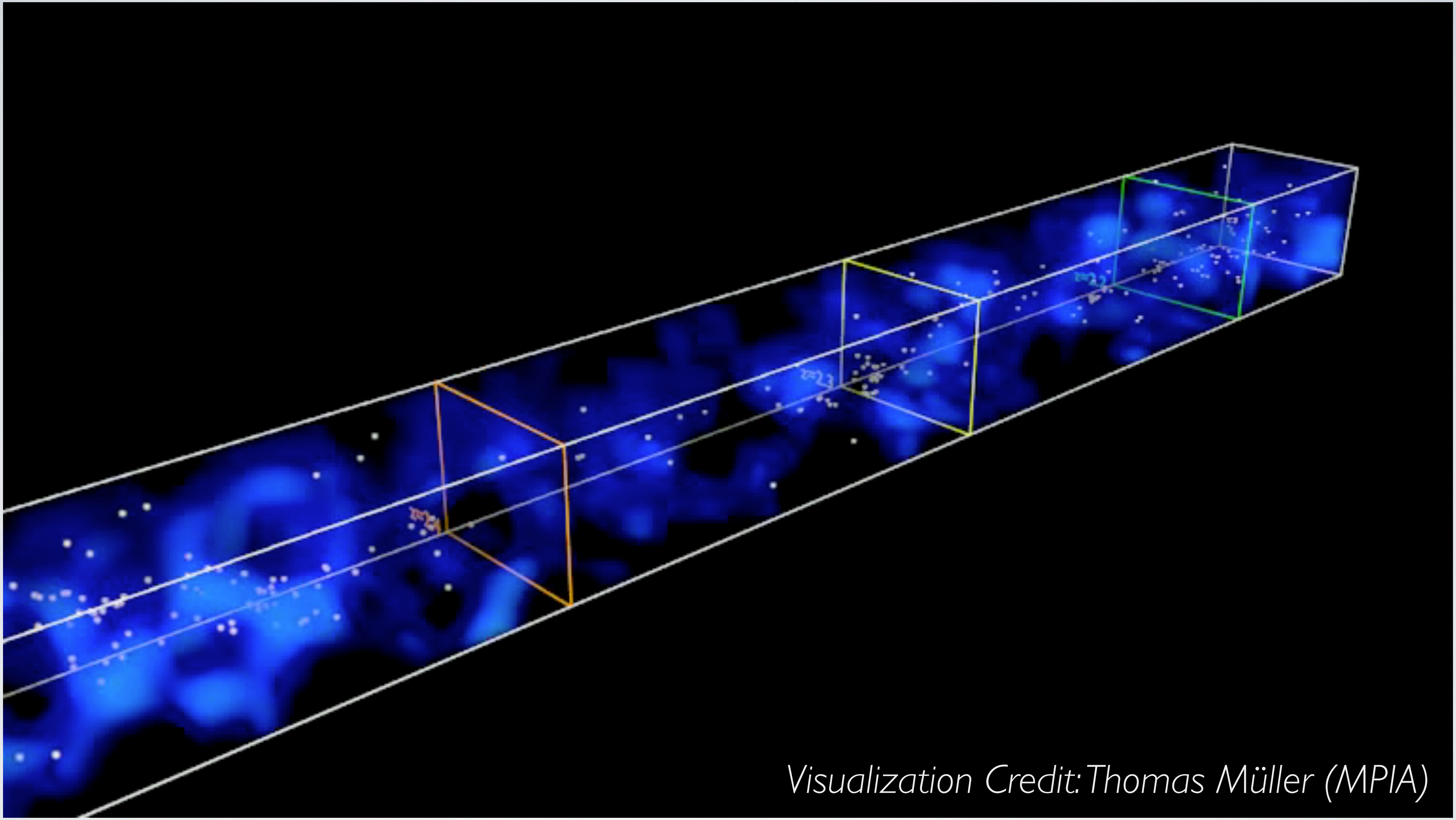

Color scheme: **spectrum**, noise vector, spectral template

# WIENER-FILTERING

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

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

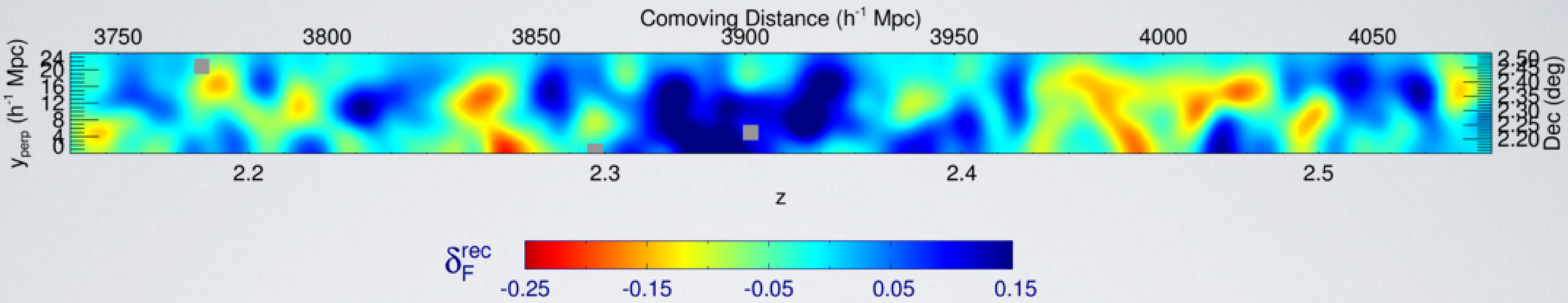
- Assume a Gaussian correlation matrix of the form $C_{DD}=C_{MD}=C(r_1,r_2)$ where $L_{||}=2.5h^{-1}$Mpc and $L_{\perp}=2.0h^{-1}$Mpc are set by the sightline separation and resolution



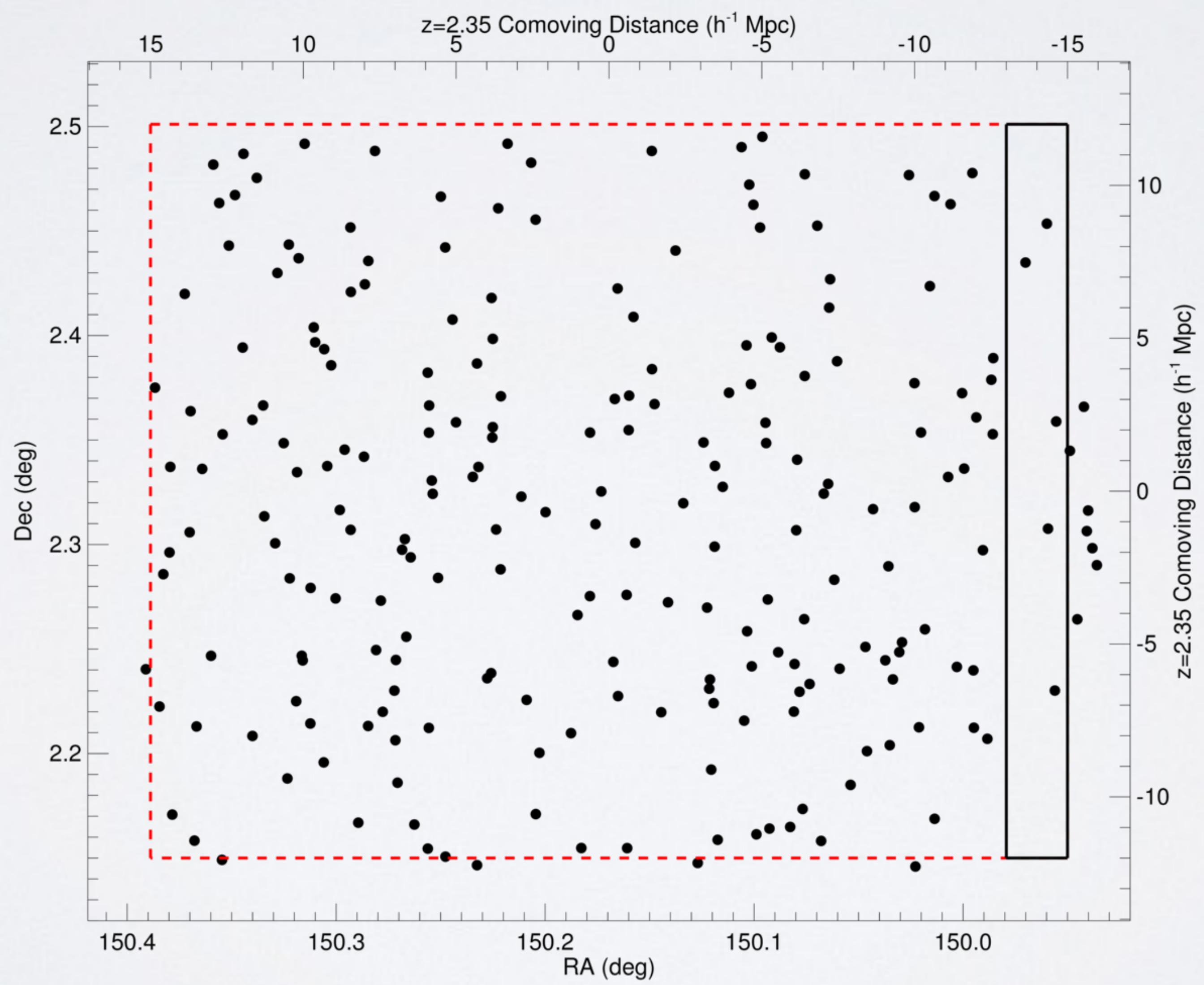

Long dimension: $340h^{-1}$Mpc.
Short dimensions: $24h^{-1}$Mpc x $30h^{-1}$Mpc

https://youtu.be/n1QuuDMPKiM

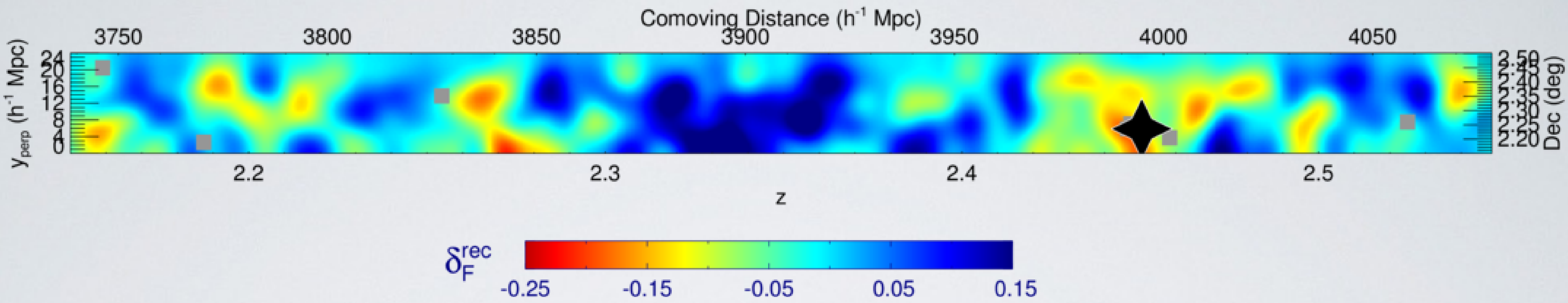
# Slice #1: 149.950 < RA (deg) < 149.979



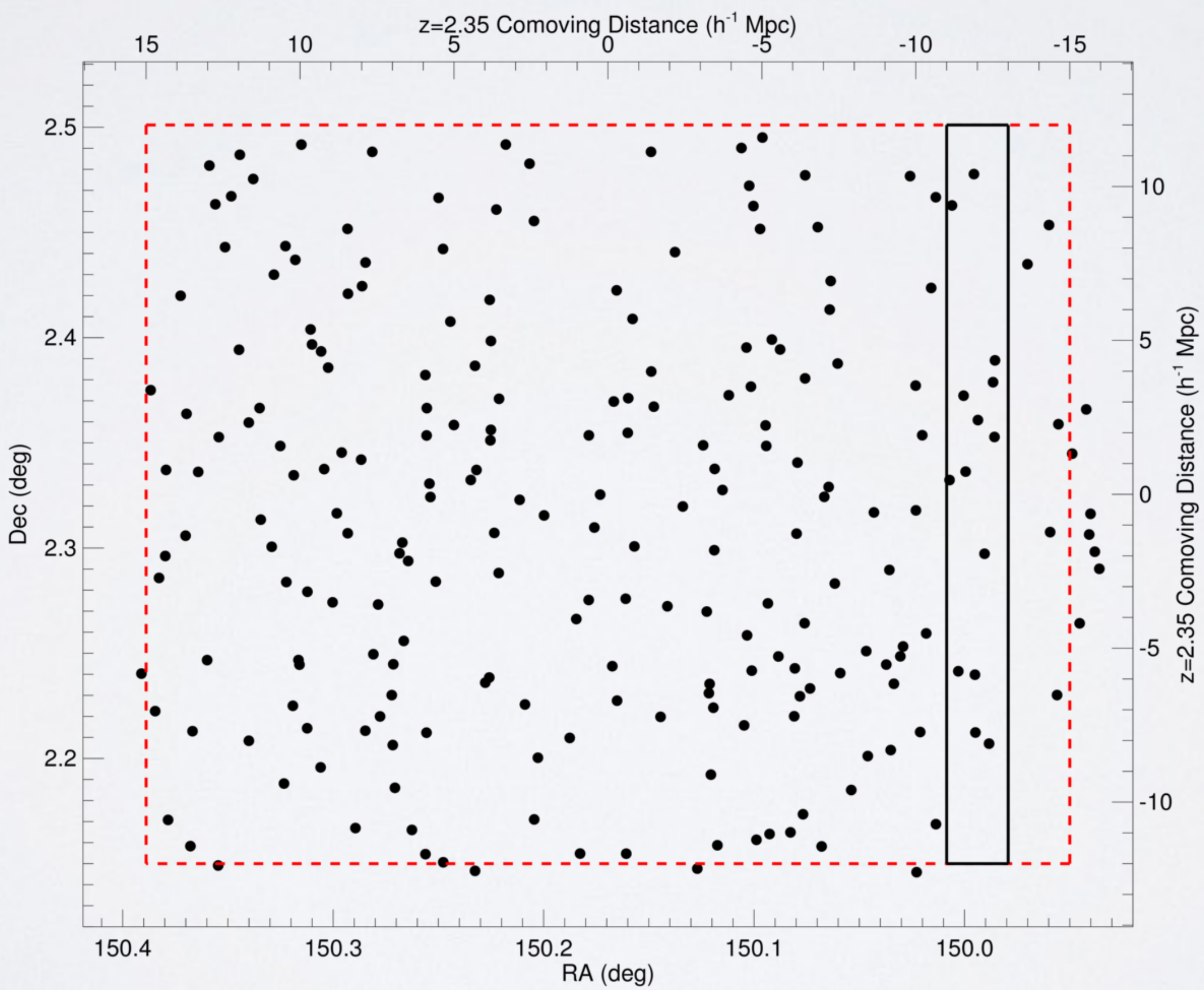

## 2.15 < z < 2.55 Sightlines



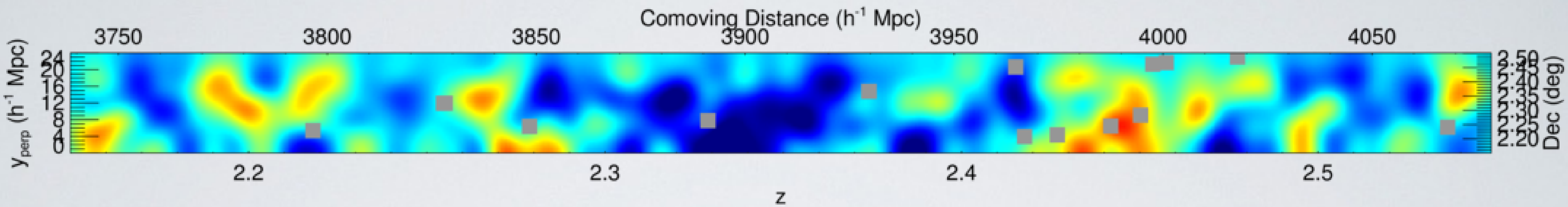
# Slice #2: 149.979 < RA (deg) < 150.009




## 2.15 < z < 2.55 Sightlines

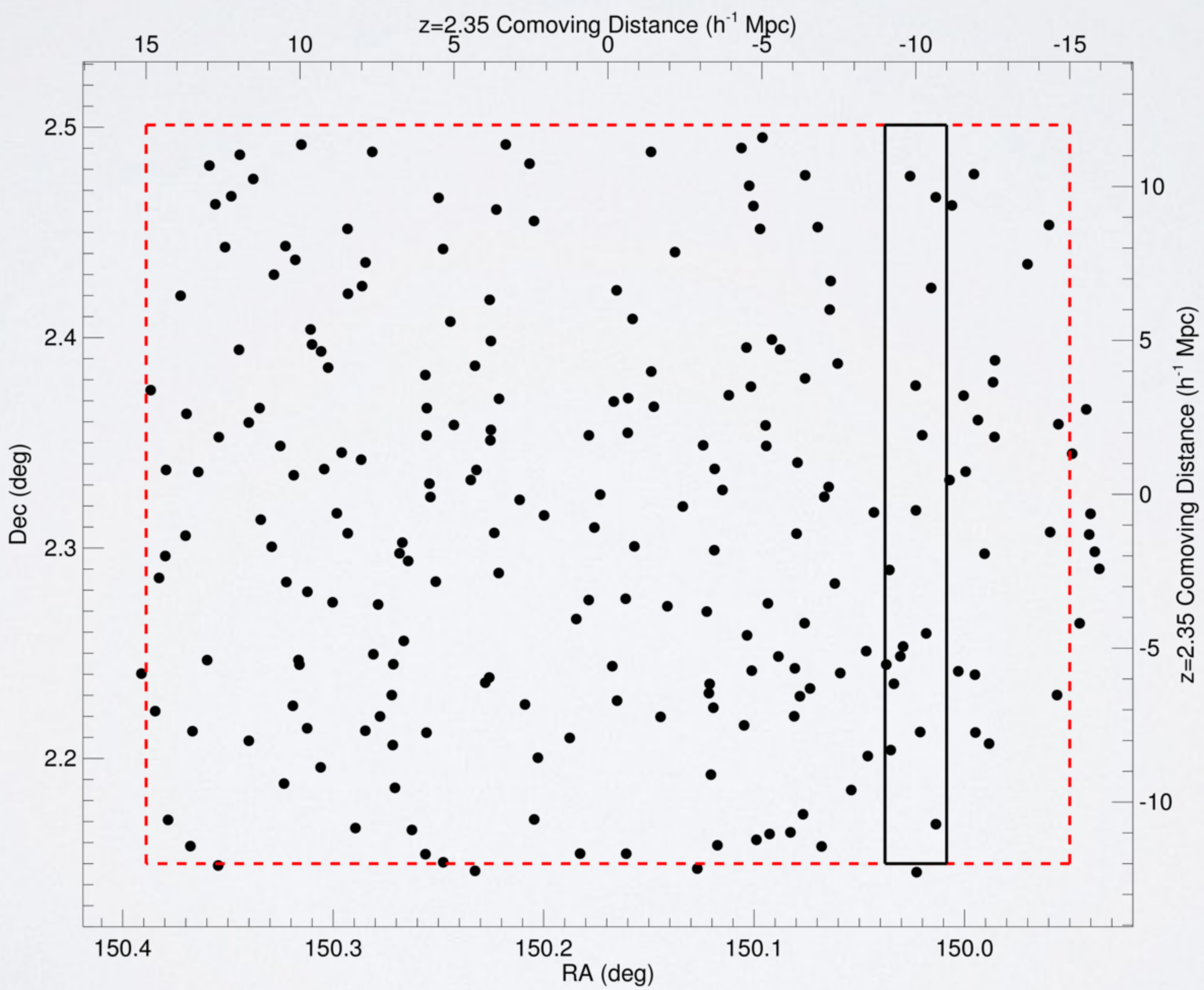


Slice #3: 150.009 < RA (deg) < 150.038

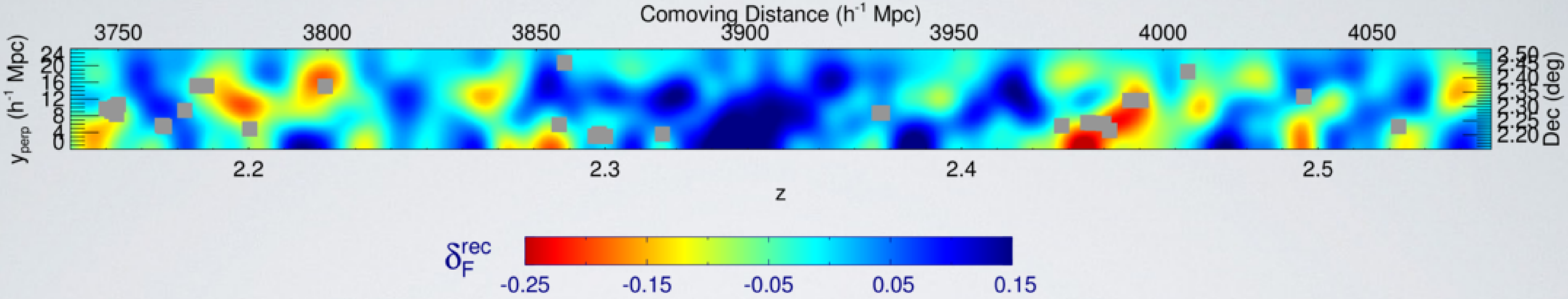




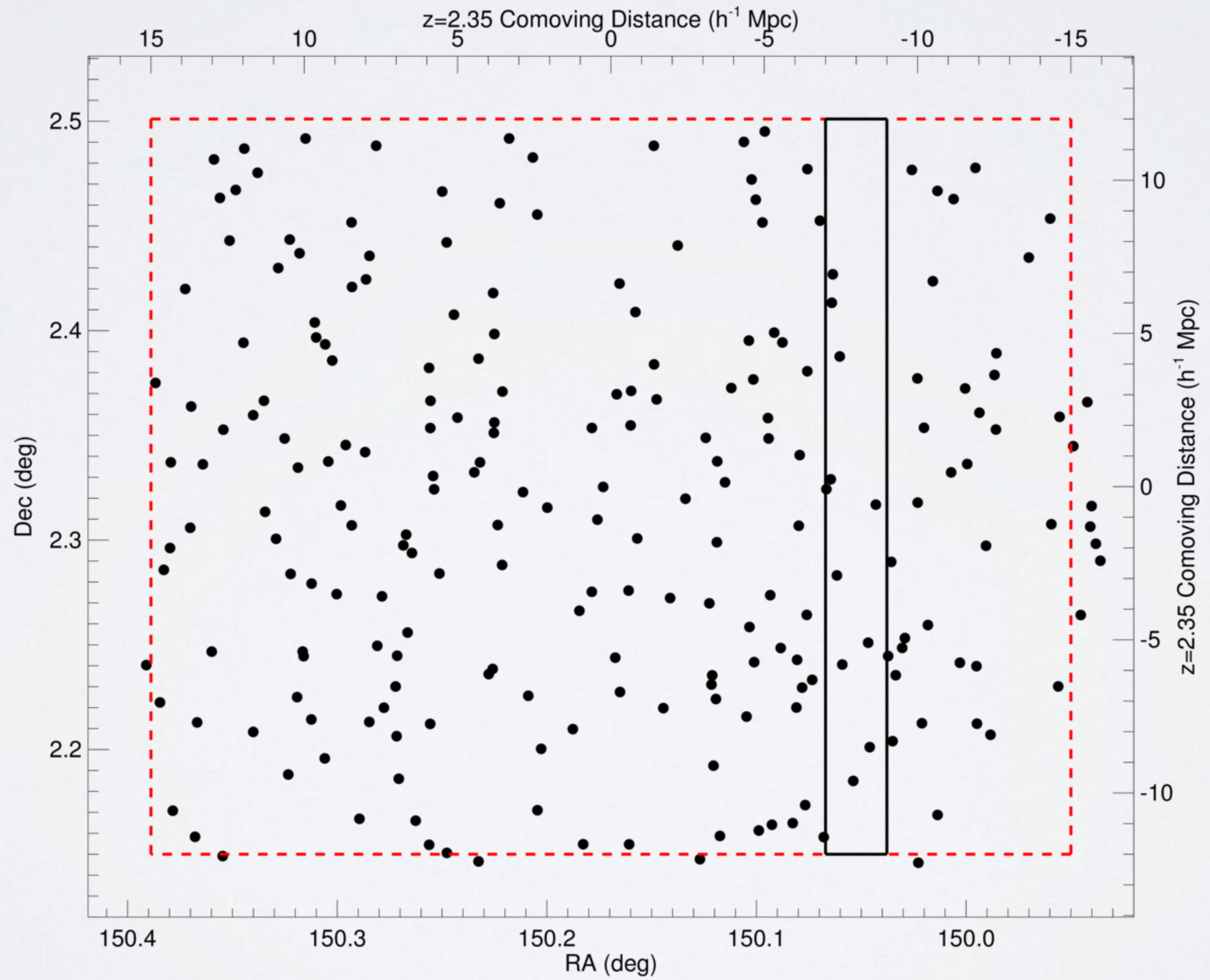
2.15 < z < 2.55 Sightlines



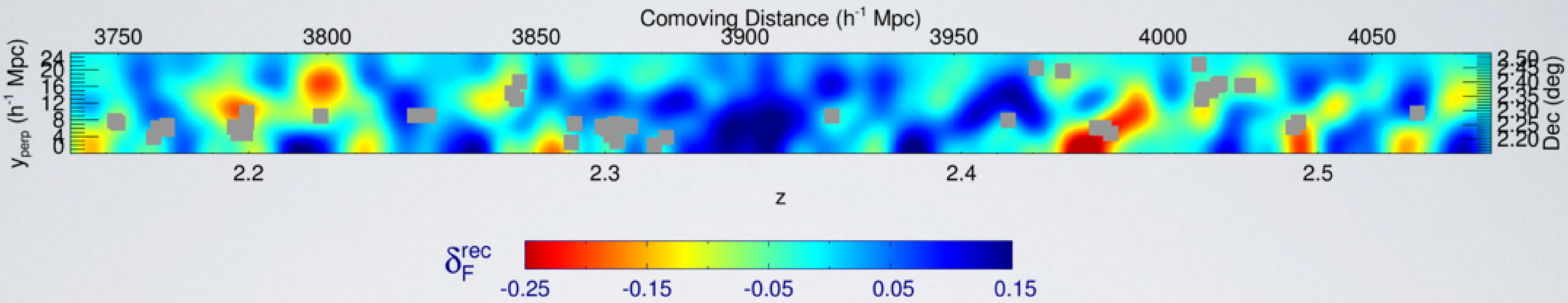
# Slice #4: 150.038 < RA (deg) < 150.067



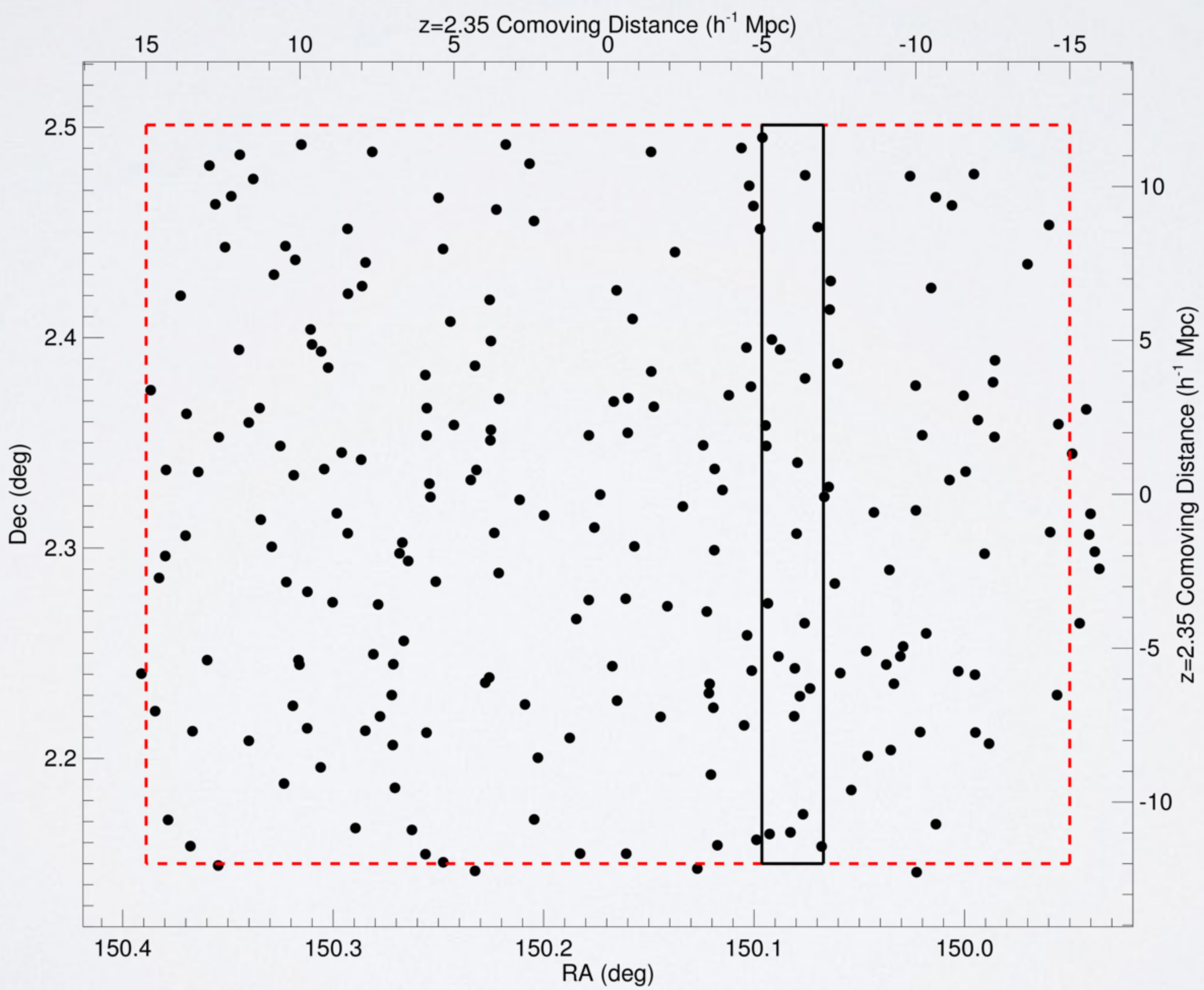

2.15 < z < 2.55 Sightlines



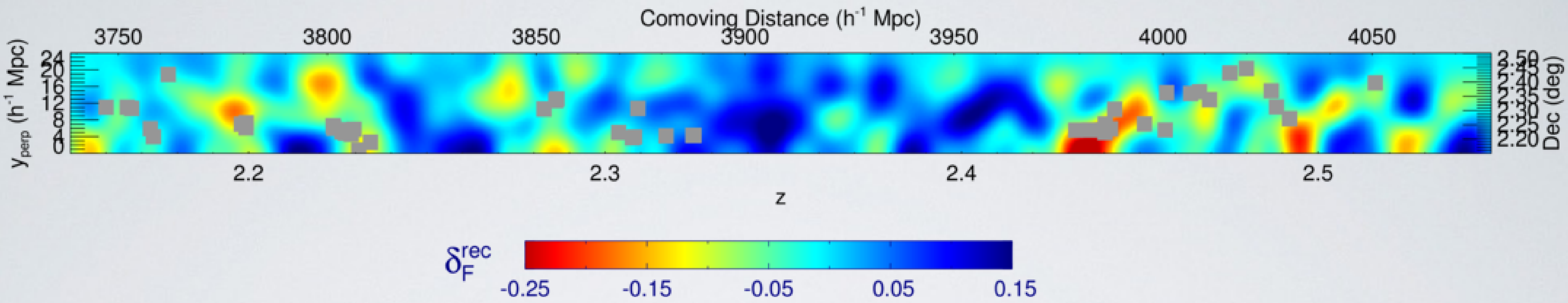
# Slice #5: 150.067 < RA (deg) < 150.096



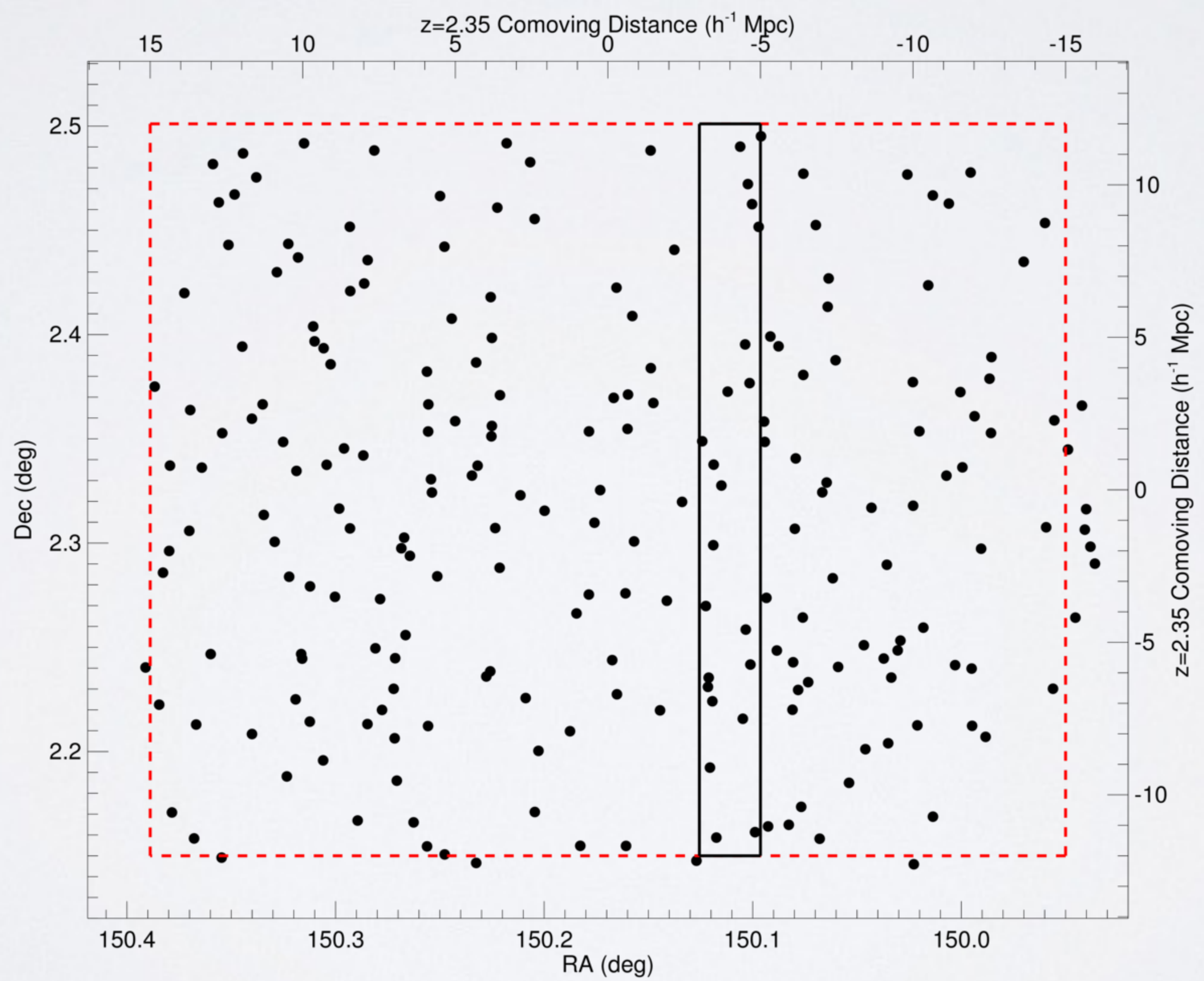

2.15 < z < 2.55 Sightlines



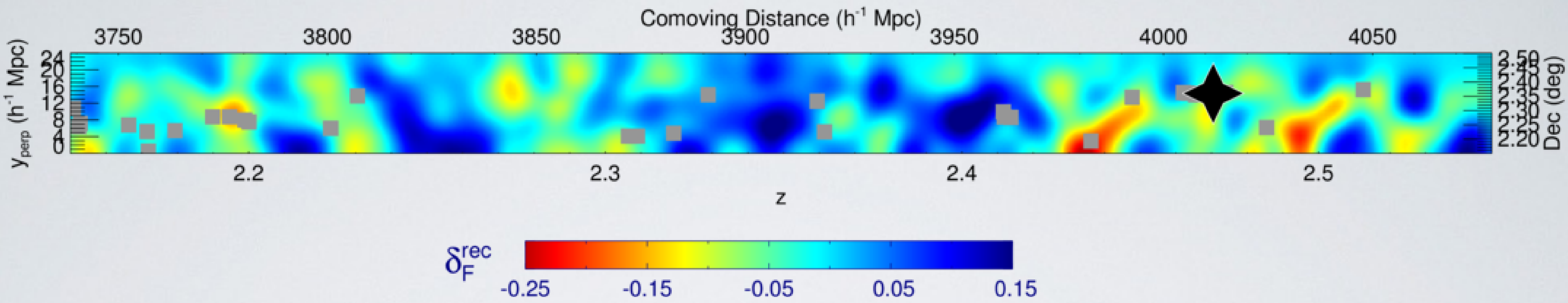
# Slice #6: 150.096 < RA (deg) < 150.126

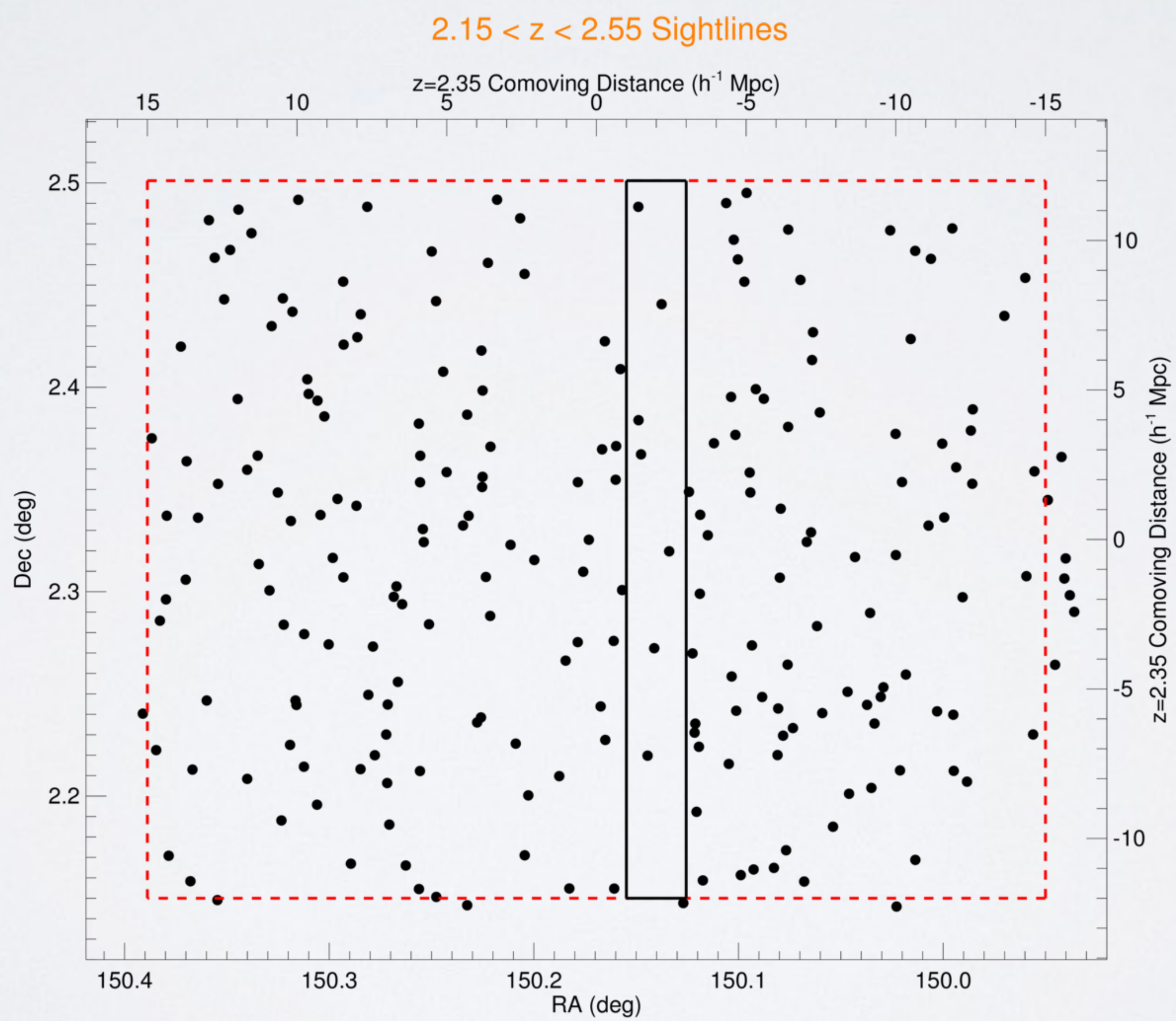



2.15 < z < 2.55 Sightlines

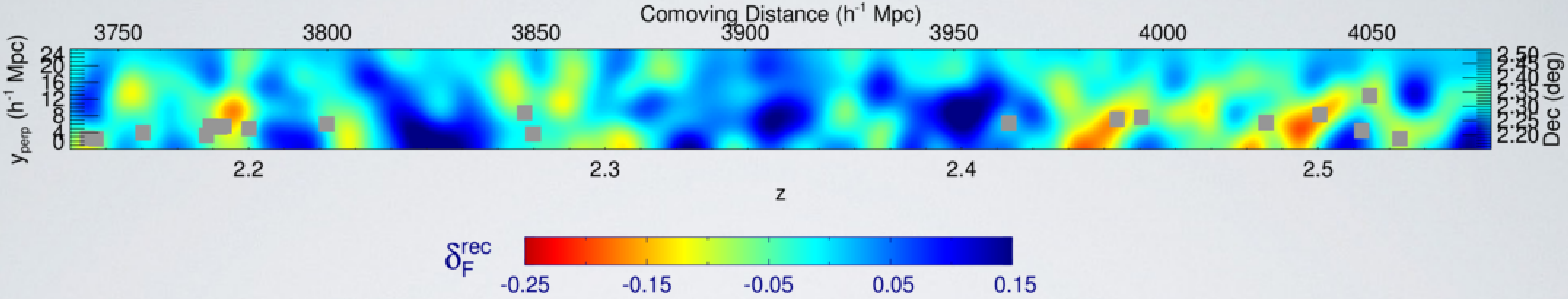


## Slice #7: 150.126 < RA (deg) < 150.155

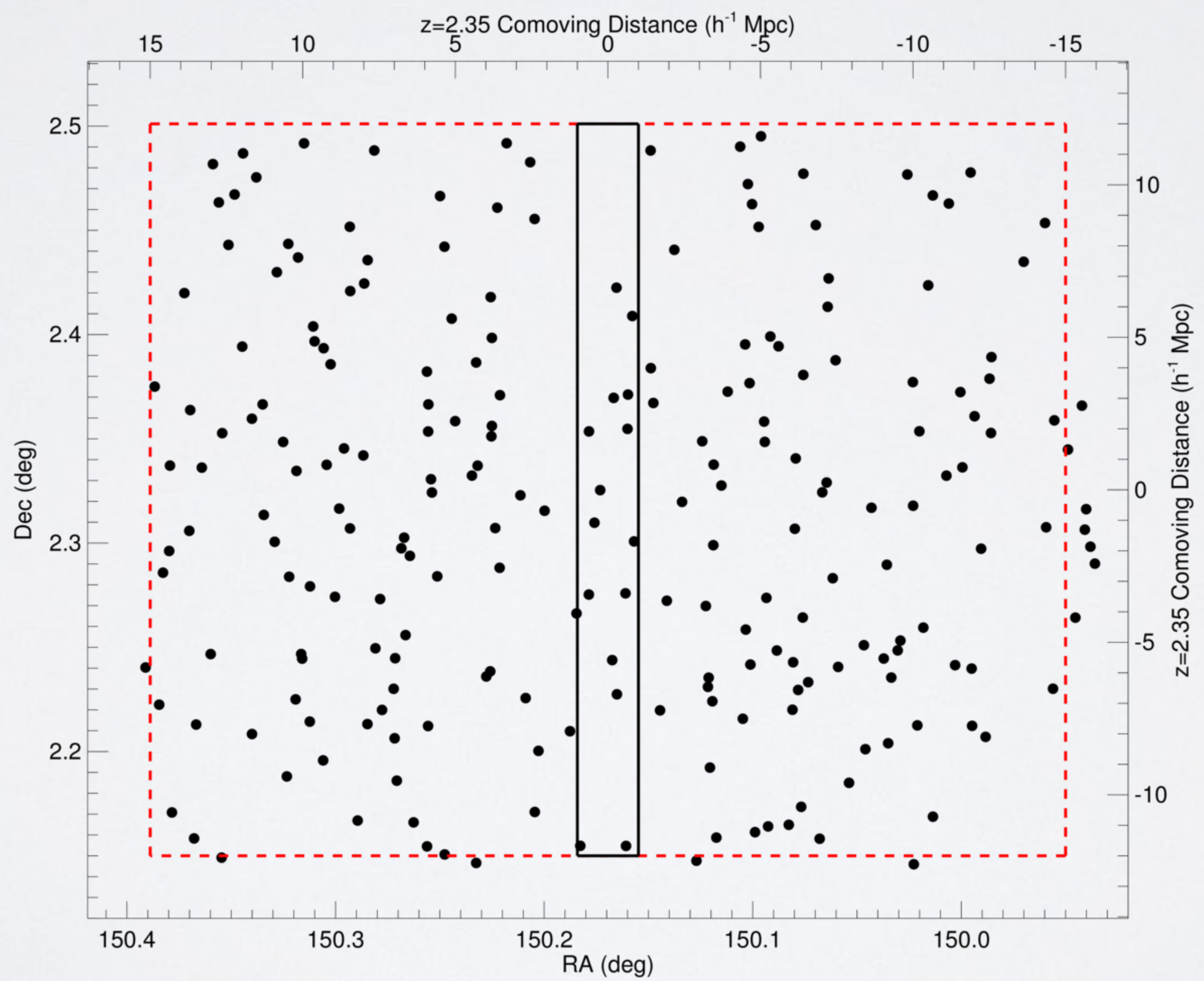


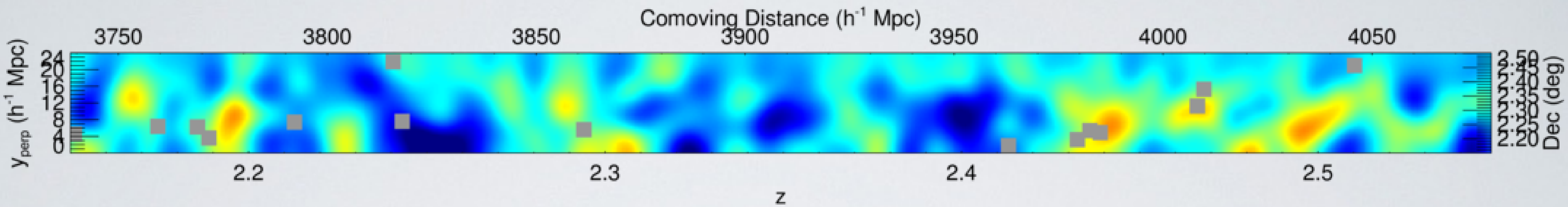
# Slice #8: 150.155 < RA (deg) < 150.184



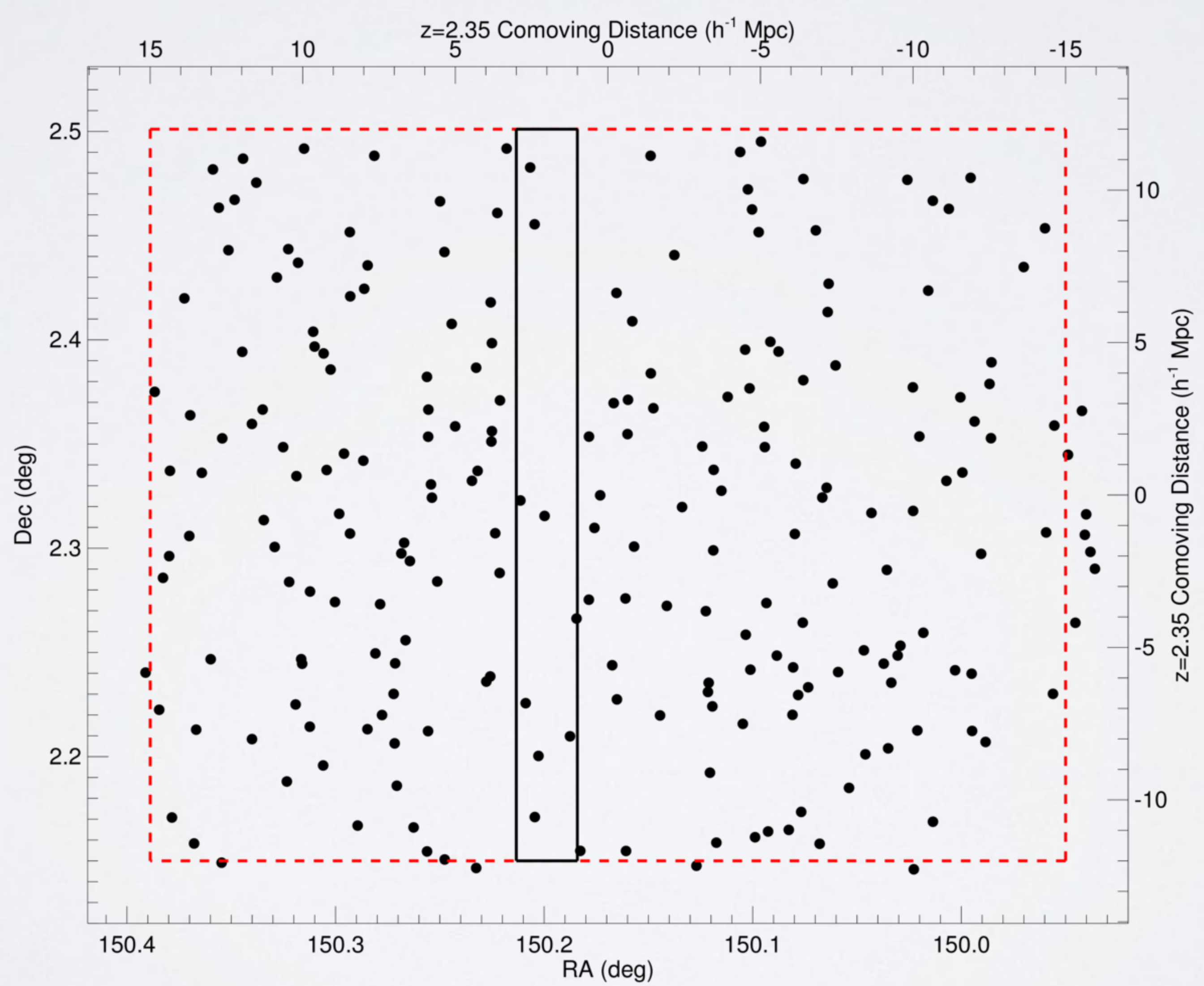

## 2.15 < z < 2.55 Sightlines



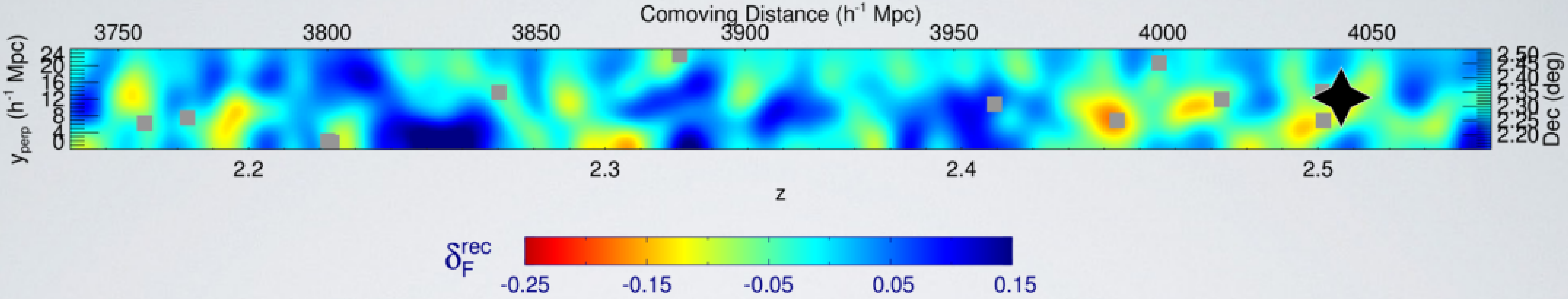
# Slice #9: 150.184 < RA (deg) < 150.213



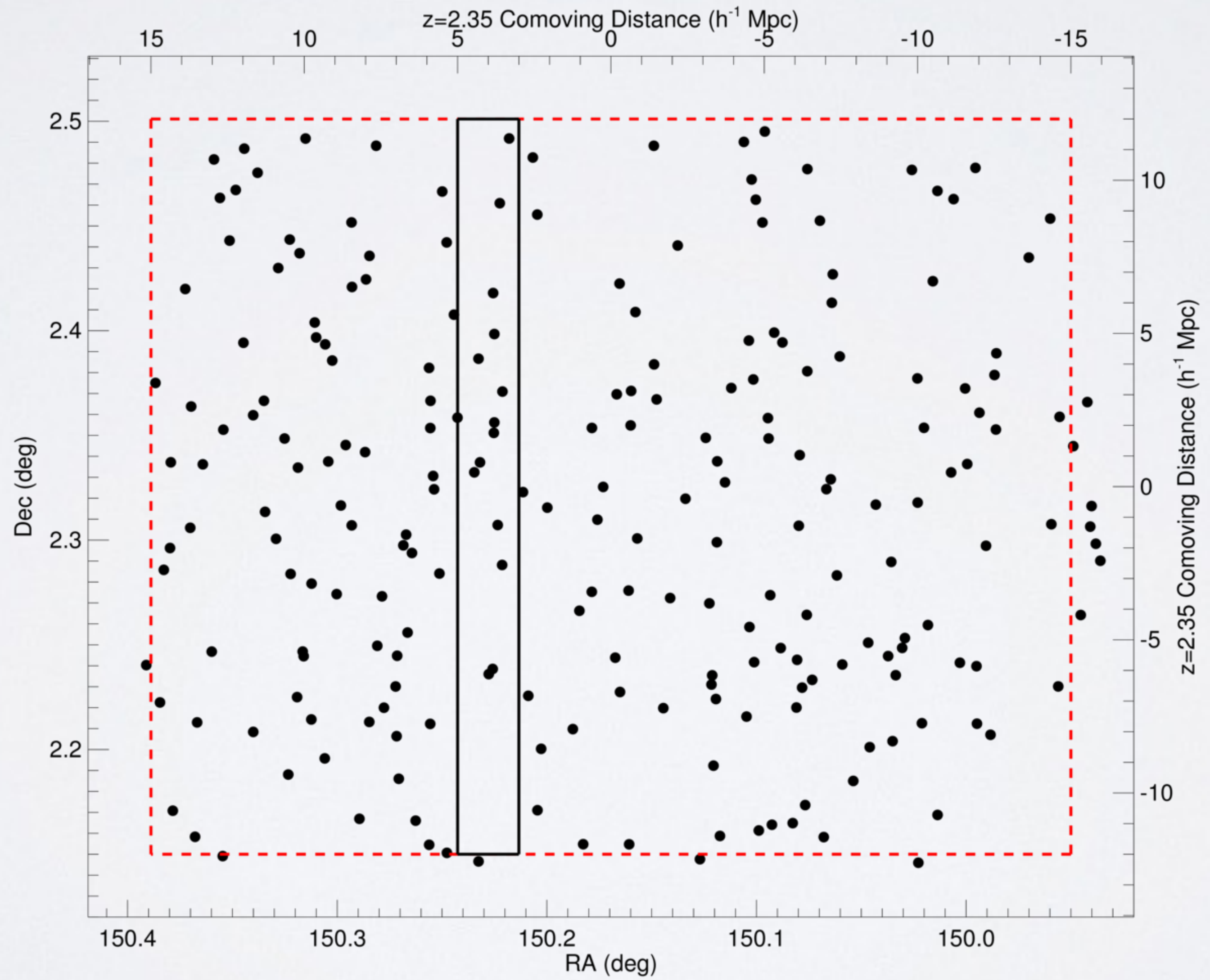

2.15 < z < 2.55 Sightlines



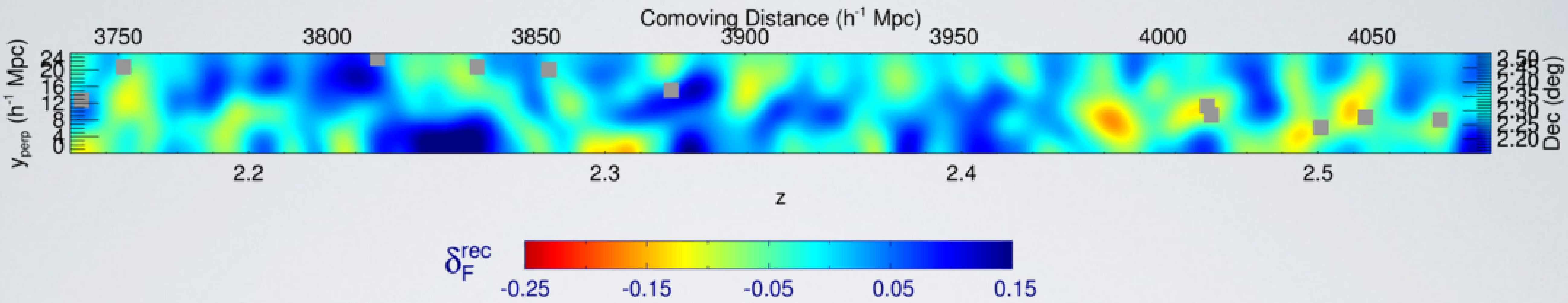
# Slice #10: 150.213 < RA (deg) < 150.243



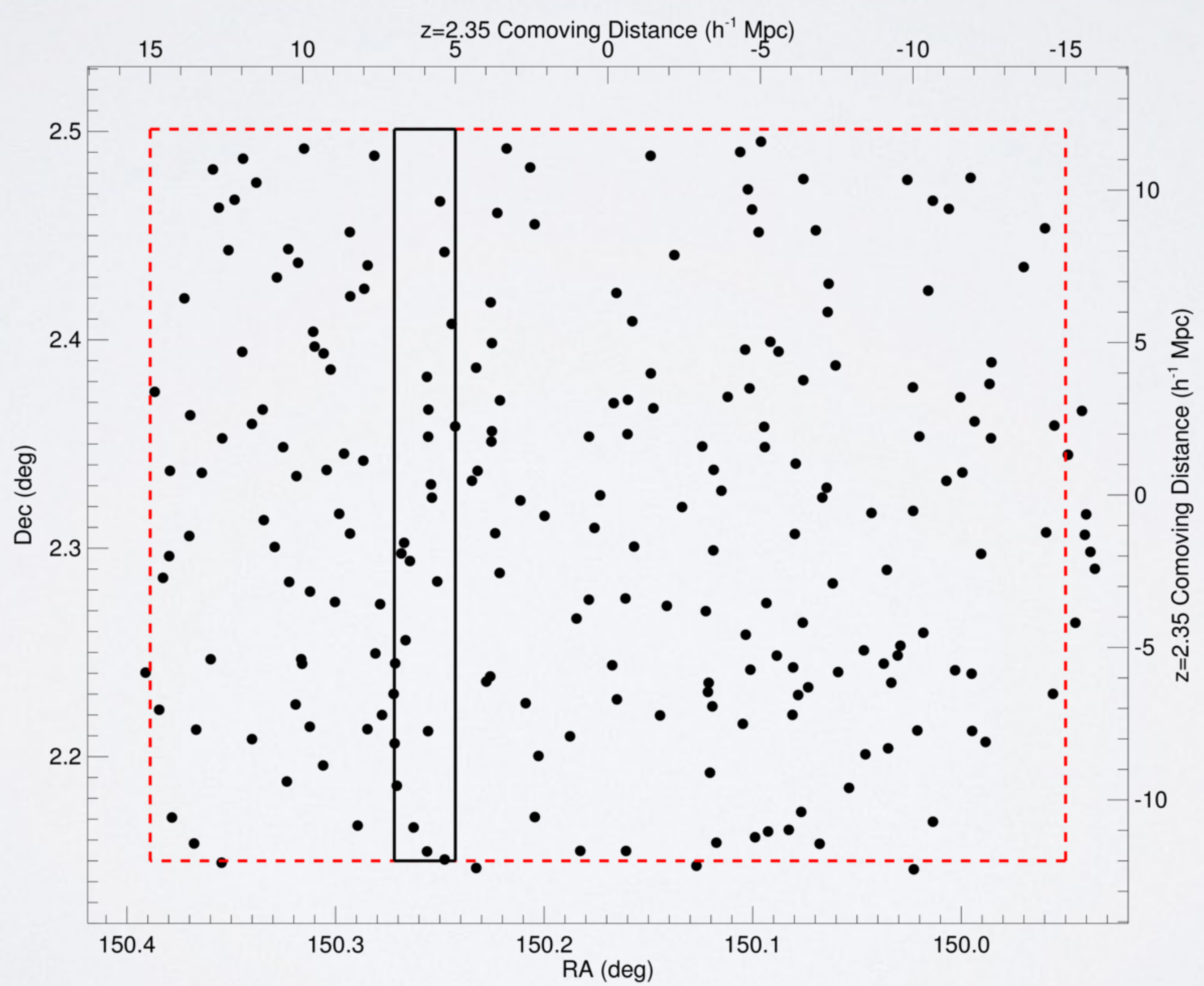

2.15 < z < 2.55 Sightlines



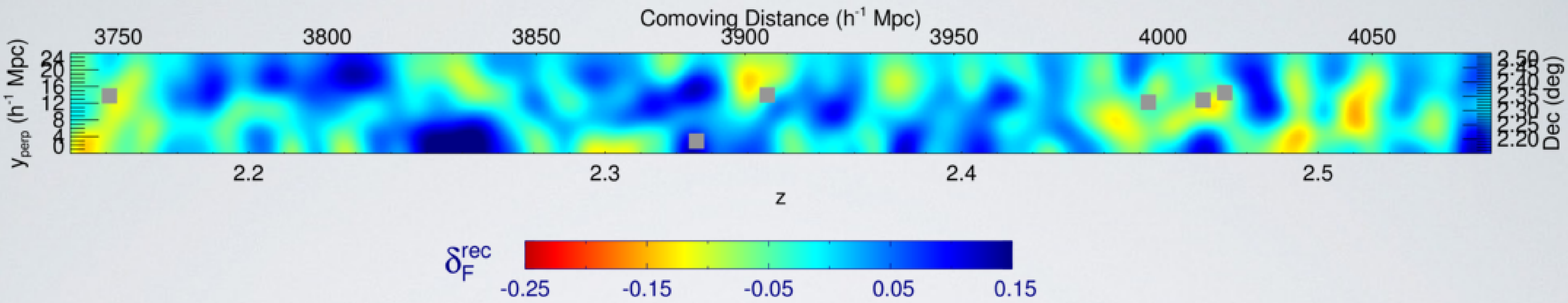
# Slice #11: 150.243 < RA (deg) < 150.272



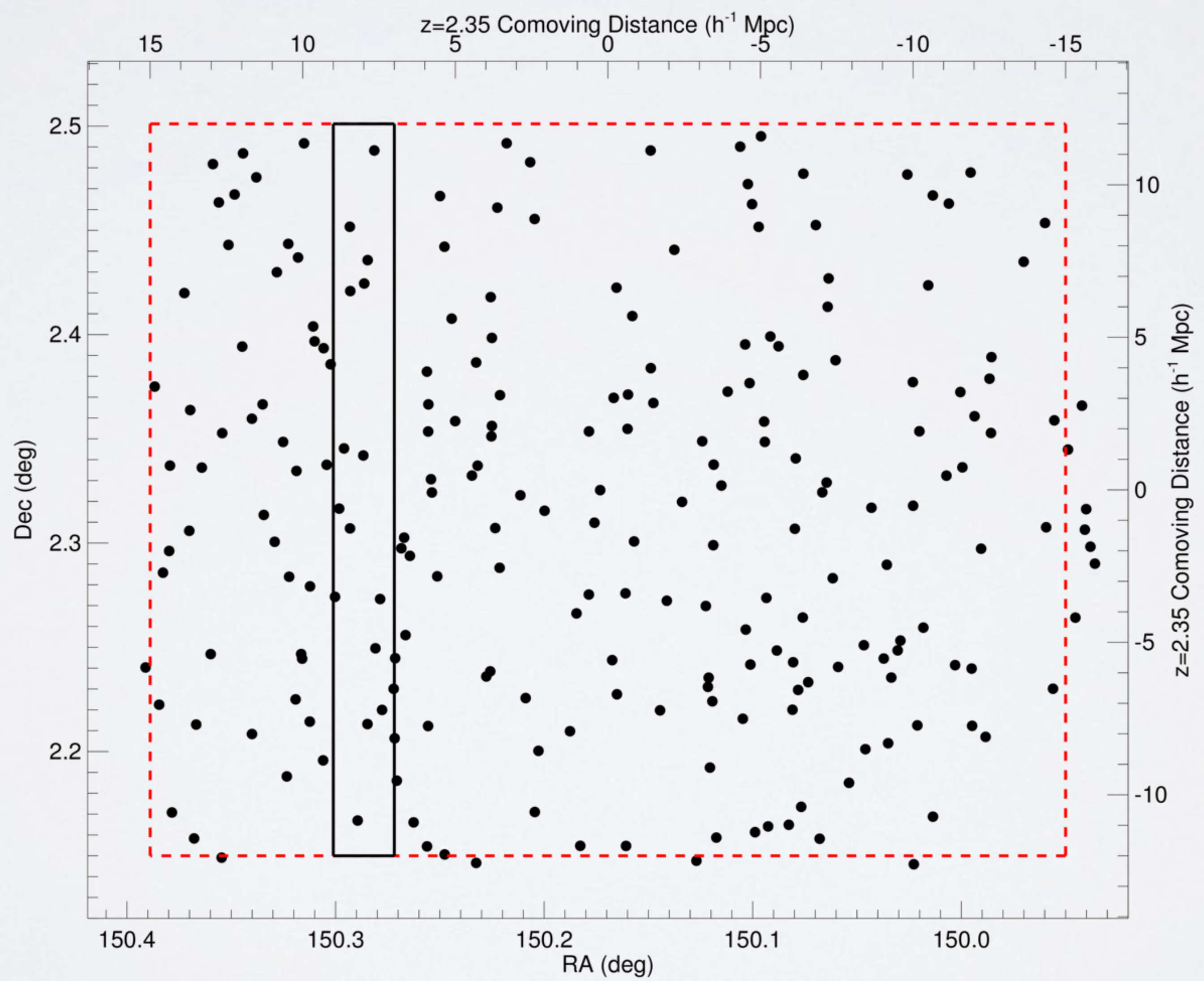

2.15 < z < 2.55 Sightlines



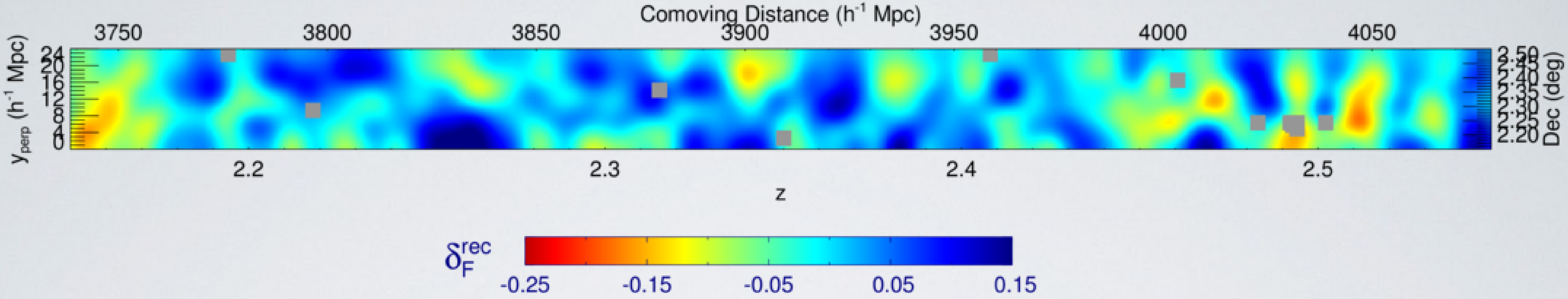
# Slice #12: 150.272 < RA (deg) < 150.301



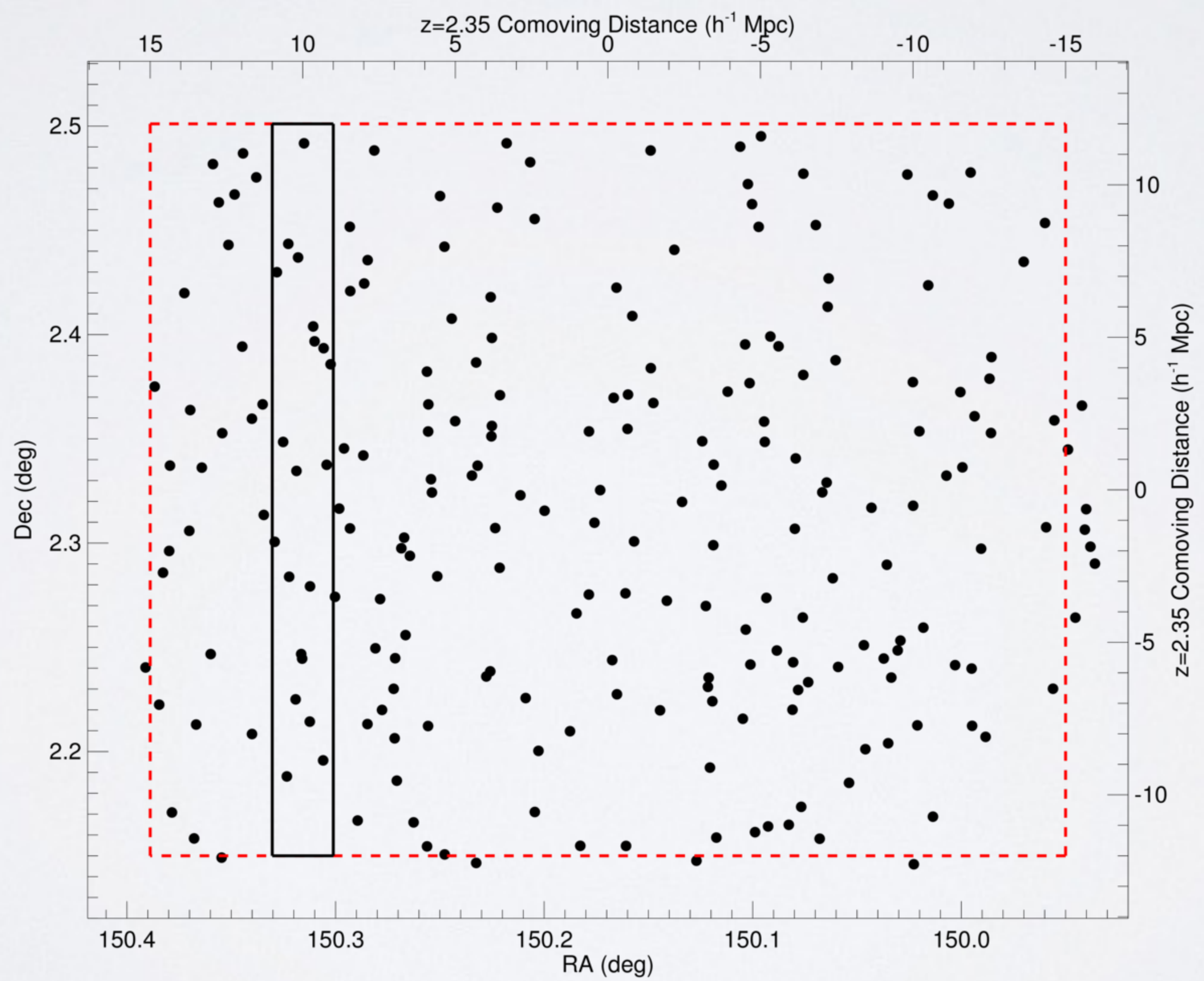

2.15 < z < 2.55 Sightlines



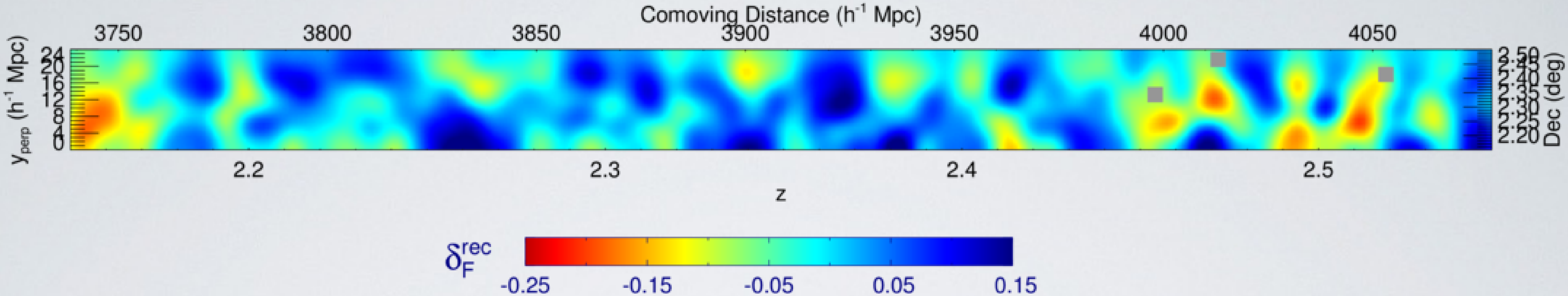
Slice #13: 150.301 < RA (deg) < 150.330



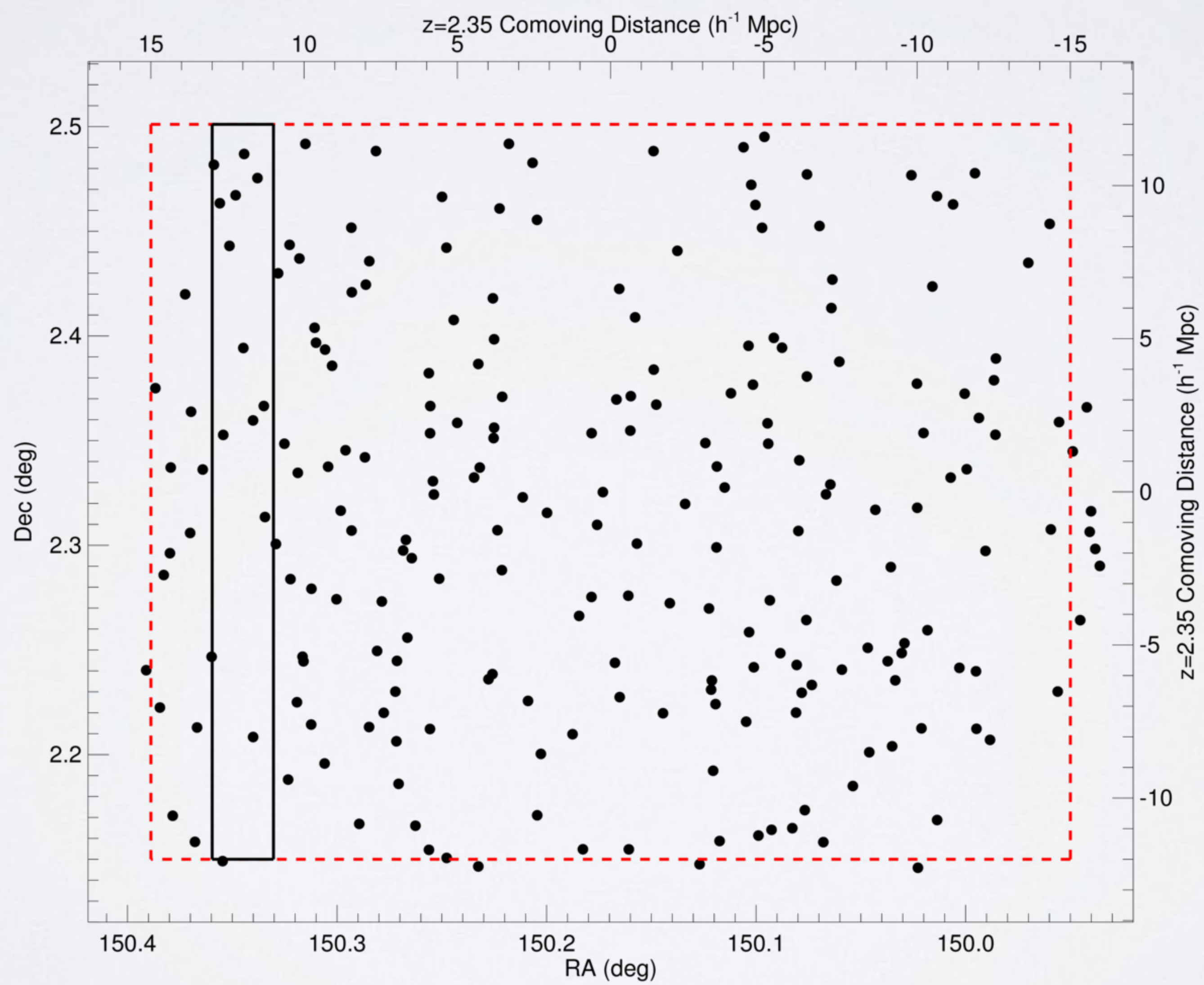

2.15 < z < 2.55 Sightlines



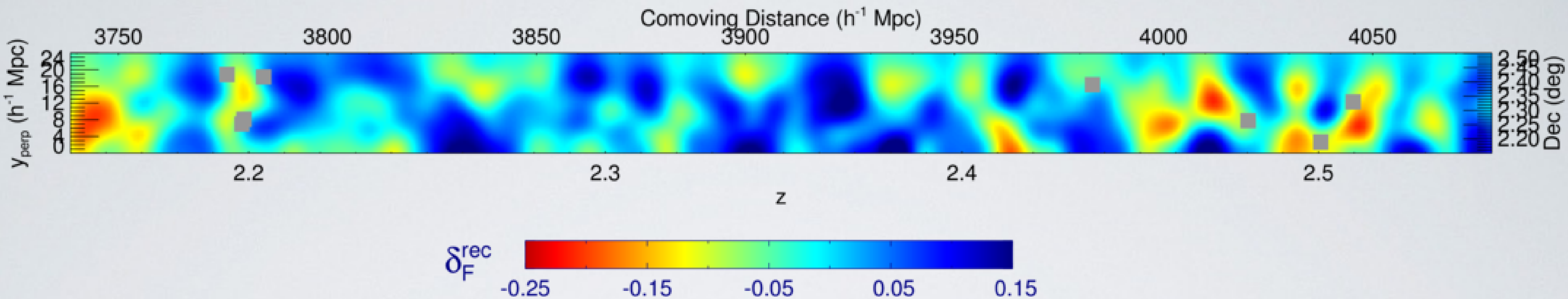
# Slice #14: 150.330 < RA (deg) < 150.360



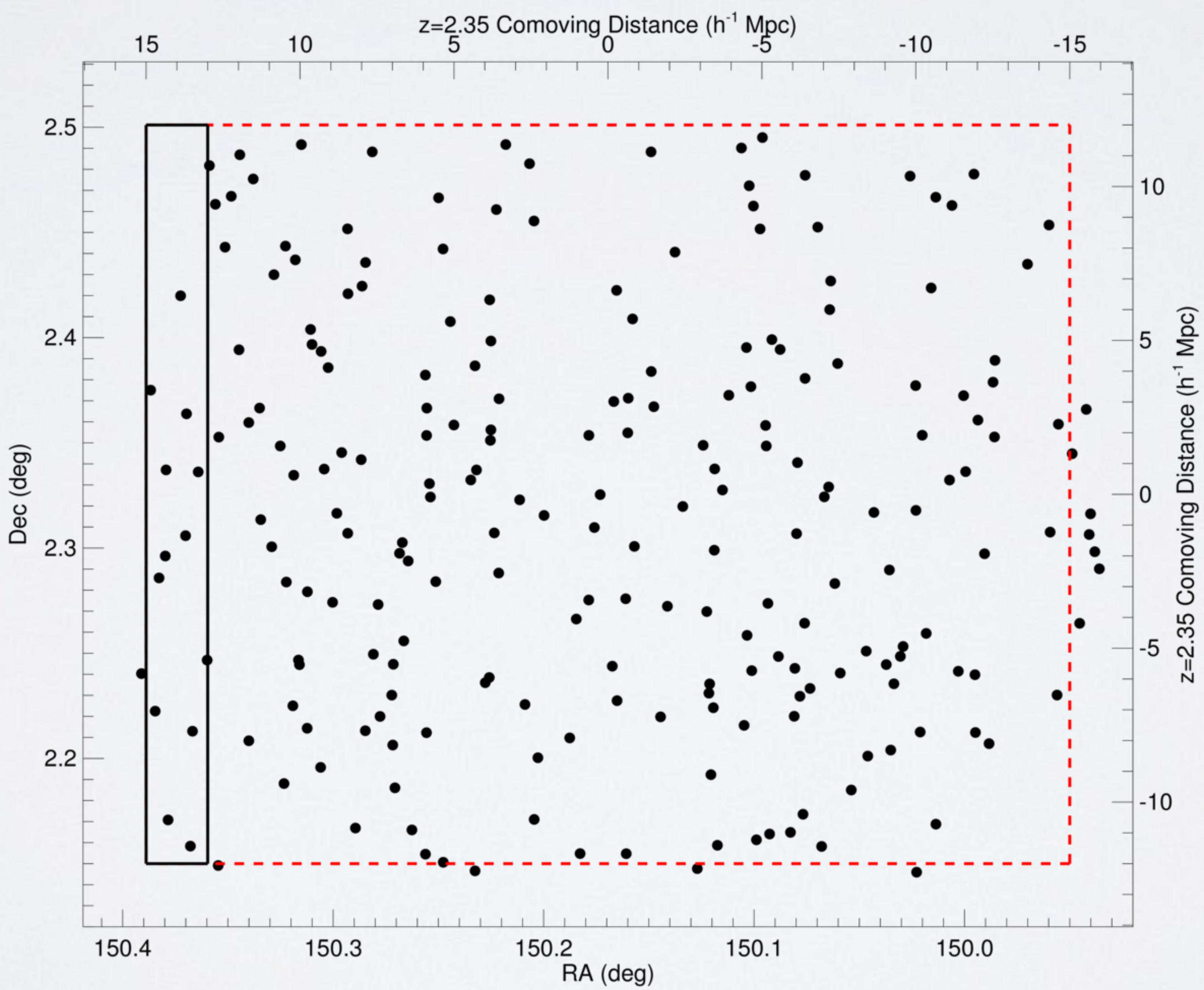

2.15 < z < 2.55 Sightlines



## Slice #15: 150.360 < RA (deg) < 150.389




2.15 < z < 2.55 Sightlines



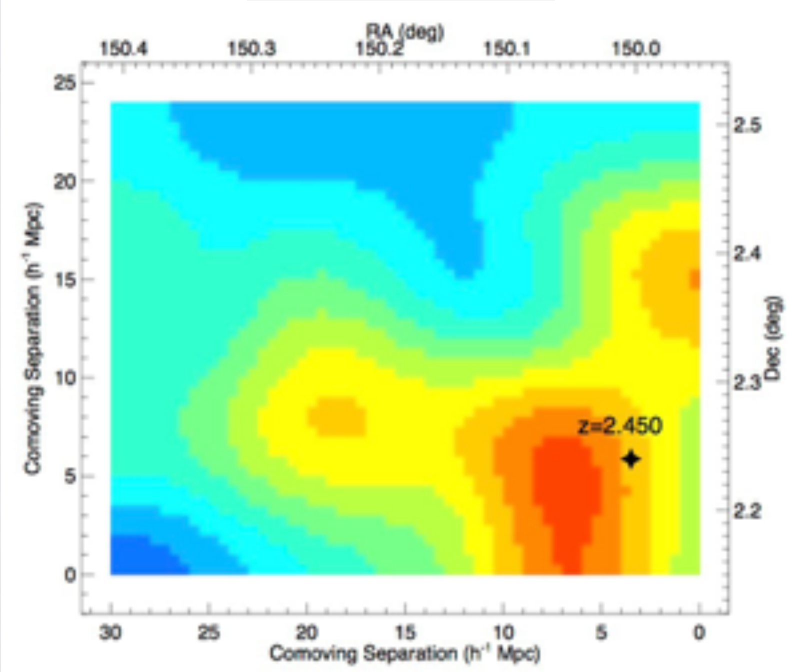
# A forming supercluster at z=2.5?

A little menagerie of overdensities:

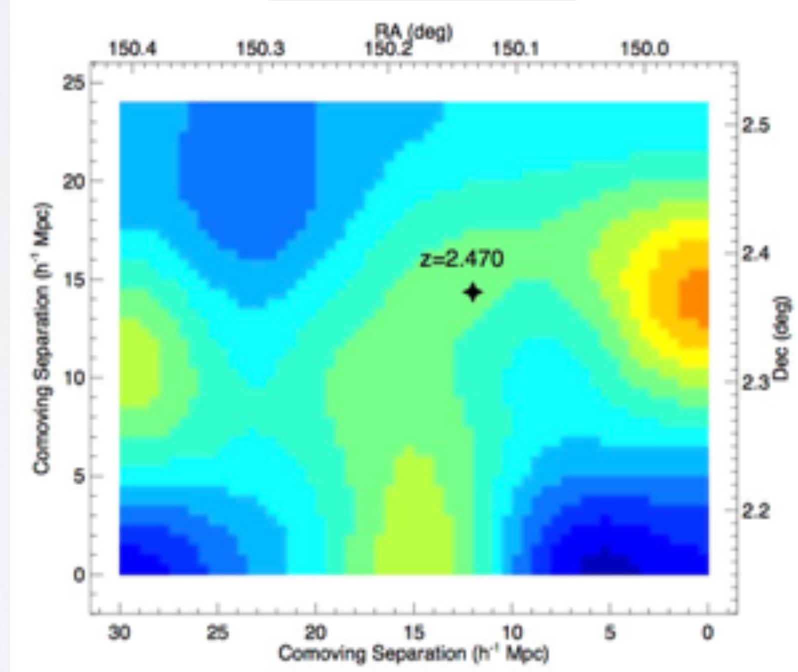
- z=2.44 LBG/LAE protocluster (Diener+2015, Chiang+2015)
- z=2.47 galaxy protocluster 'signposted' with sub-mm sources (Casey+2015)
- z=2.51 galaxy cluster **with X-ray detection (Wang+2015)**

**Overall span of ~100cMpc. Progenitor of z~0 supercluster?**

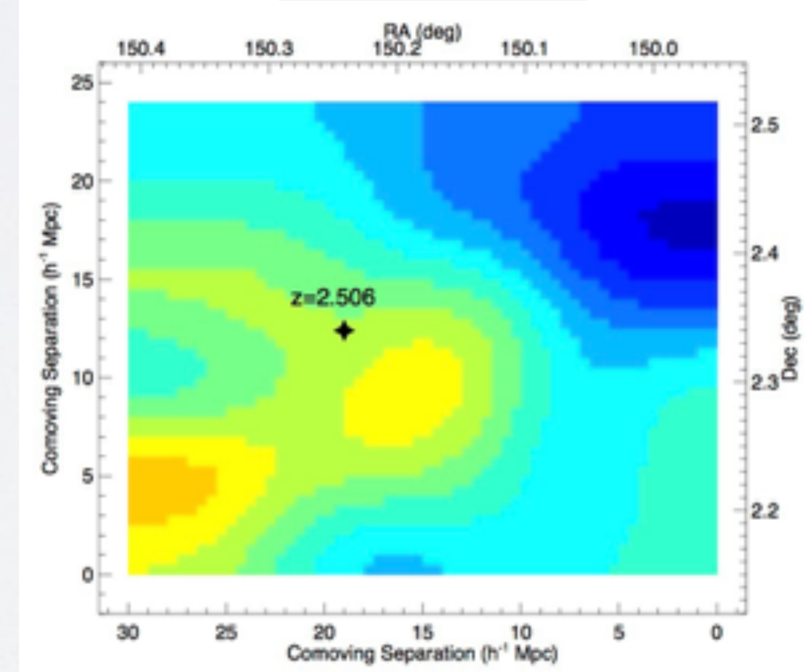
**2.431<z<2.461**




**2.461<z<2.490**

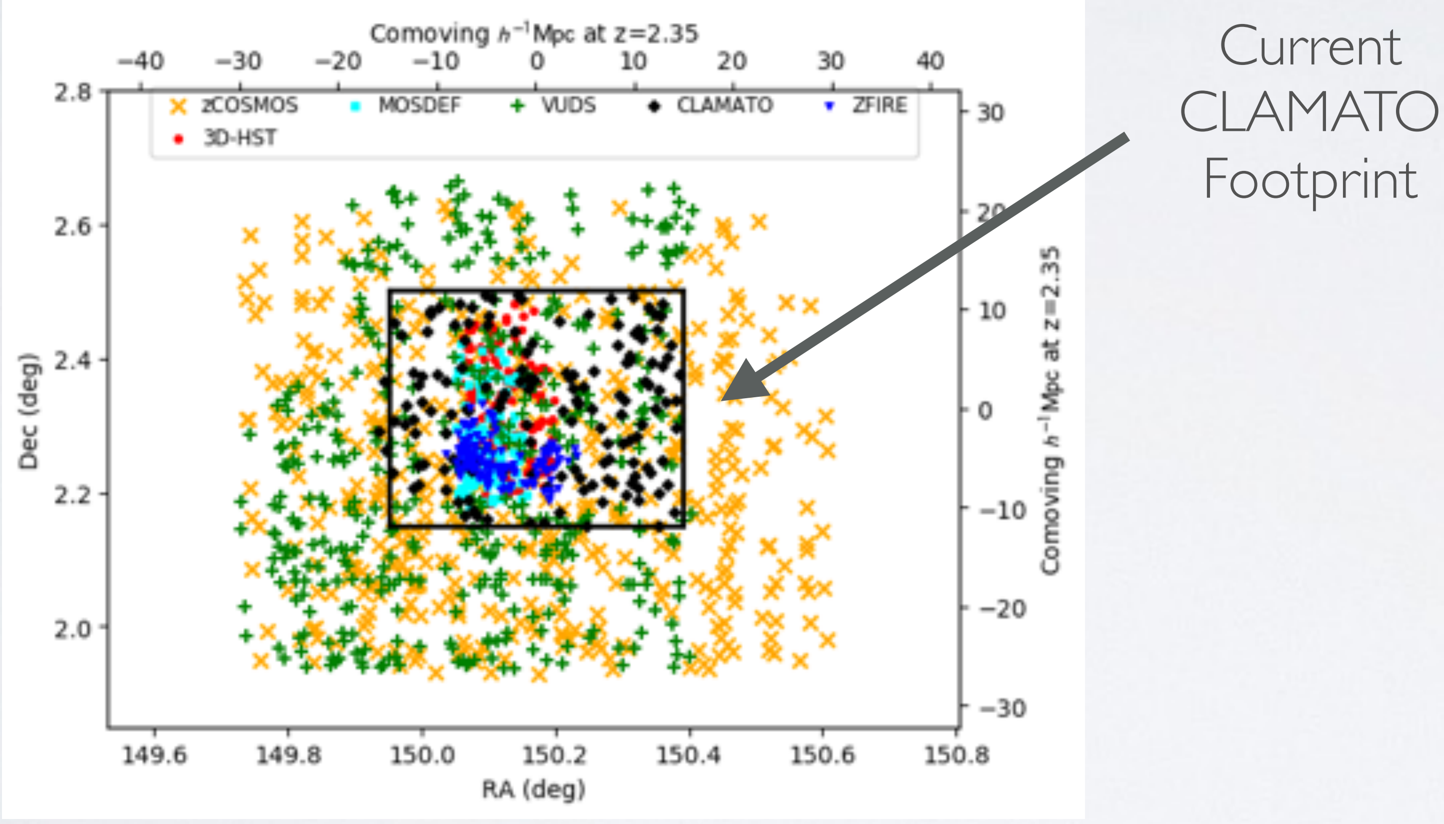


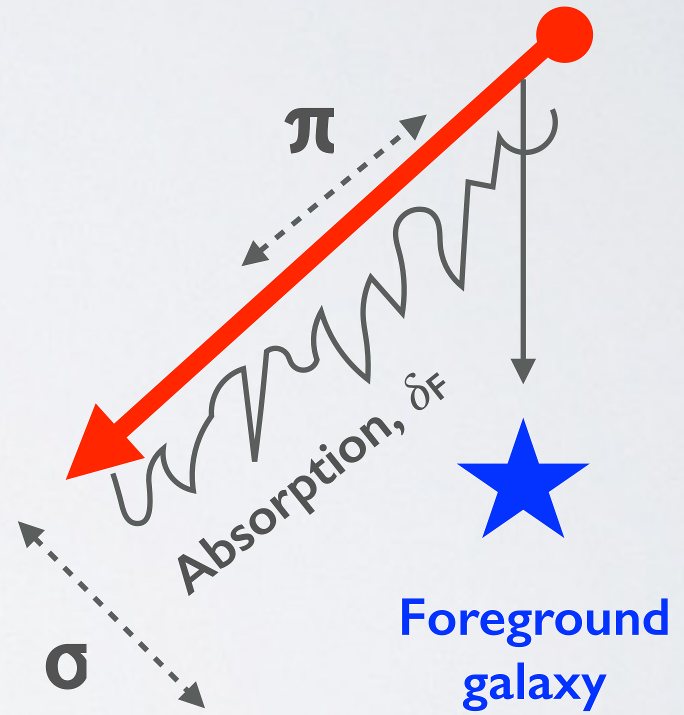

**2.490<z<2.519**



# Galaxy-Forest Clustering

- Cross-correlate CLAMATO forest pixels with spectroscopic surveys in COSMOS field (with Andreu Font-Ribera, UCL)
- ~1400 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




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

Cross-power spectrum

Galaxy bias + RSD

Ly-a forest bias + RSD (known)

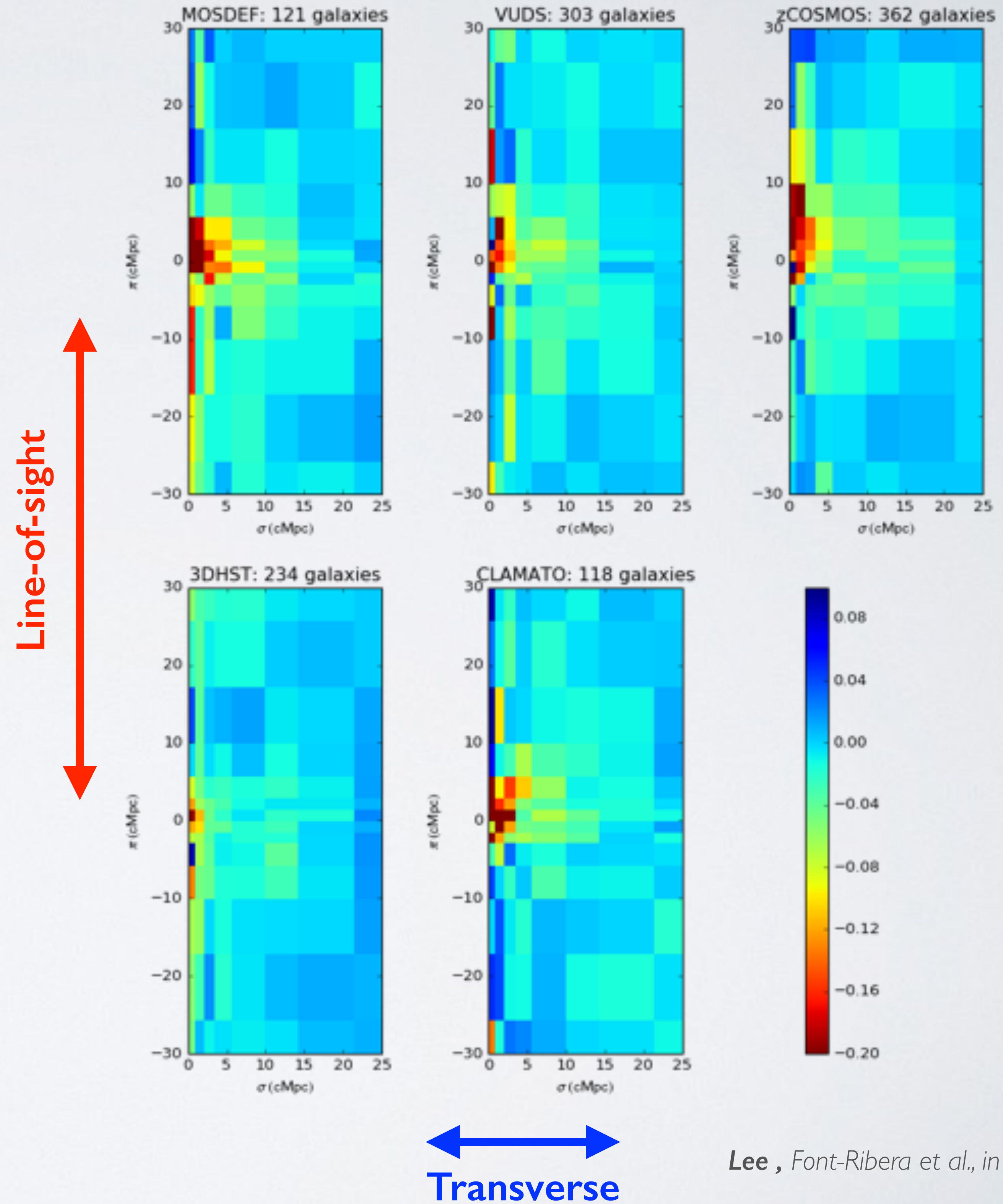
Linear theory power spectrum (known from cosmology)

# Cross-correlation with Galaxies

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

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

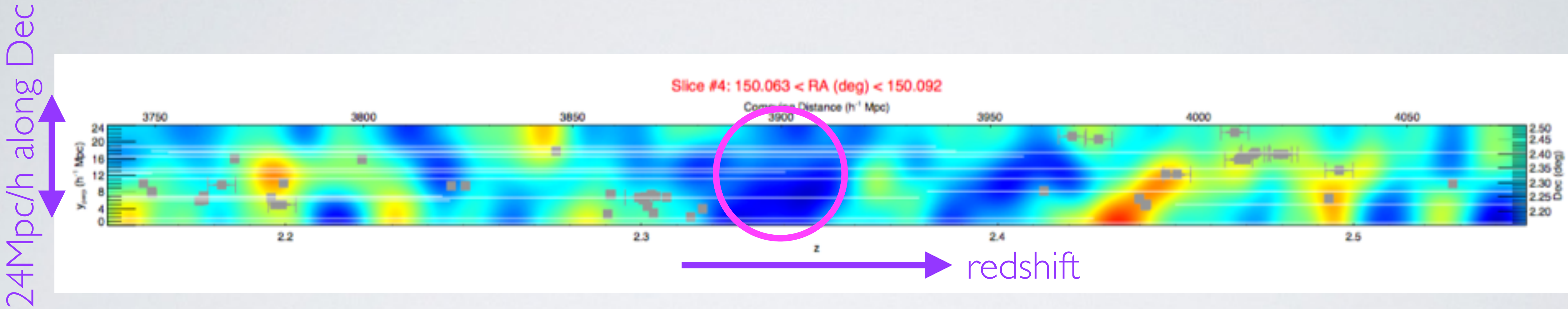
- Overall ~18 **σ** detection from all samples
- Current analysis: assume forest bias is fixed, constrain galaxy bias + spec-z offset/scatter of each survey




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

**Preliminary!**

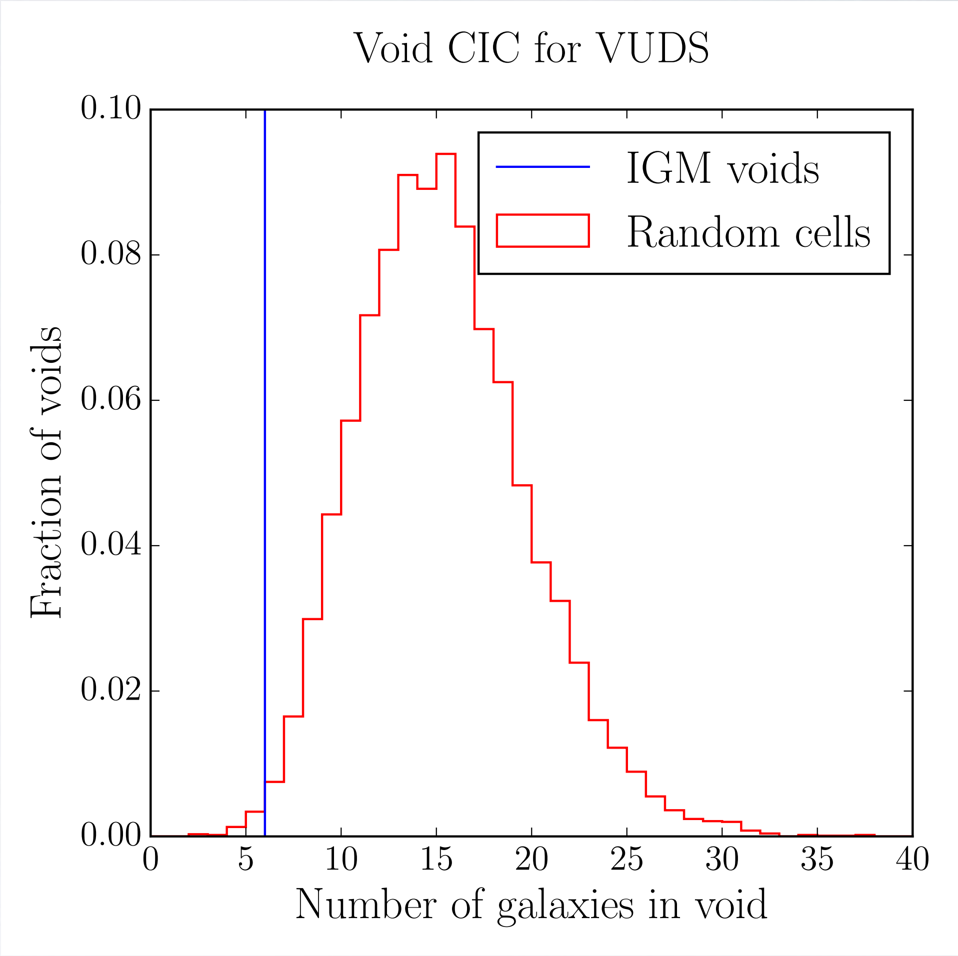
# First Detection Of Cosmic Voids At High-z?




- Currently most distant-known cosmic voids are at z~0.9 (VIPERS Survey, Hawken+2016)
- In CLAMATO map, already see coherent underdensities spanning large-scales (Krolewski, KGL, et al, in prep) at z~2.3
- Apply simple spherical void finder (e.g. Stark, Font-Ribera, White, KGL)

# Validation through galaxy counts-in-cells distribution

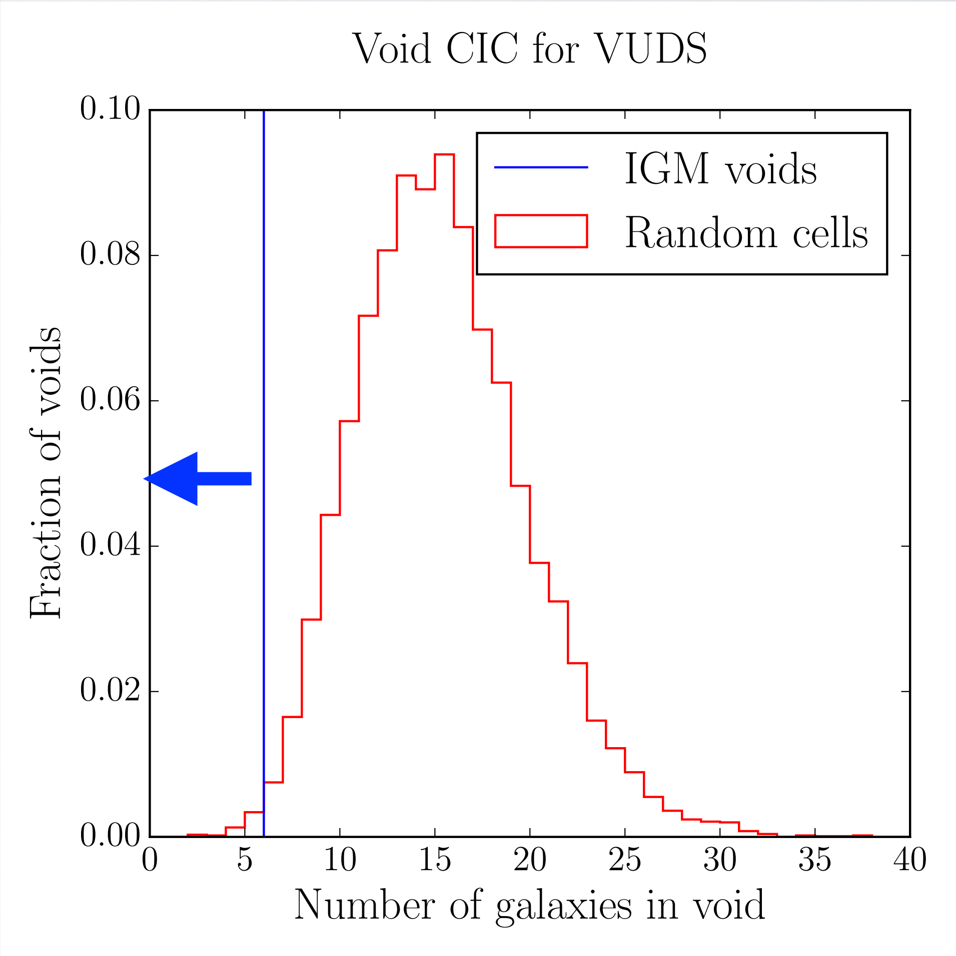
- Simple validation: count number of spectroscopic galaxies that fall within IGM voids
  - Generate random voids with same size distribution as void catalog
  - Count number of galaxies that fall within both IGM voids and random voids




*Krolewski, KGL, et al (in prep)*

# Void detection through galaxy counts-in-cells distribution

- Turn into p-value using 10,000 realizations of random catalog
- Significance for each galaxy survey:
  - VUDS: p = 0.0199
  - MOSDEF: p = 0.048
  - CLAMATO: p = 0.0732
  - zCOSMOS: p = 0.1836
  - 3DHST: p = 0.3459
  - Combined significance (assuming independence): p = 4.4e-6 (**~4.44σ**)



# Future Surveys: Subaru-PFS

- Subaru Prime Focus Spectrograph: wide-field fiber-fed optical spectrograph on 8.2m Subaru telescope
- Simultaneously observe ~2400 targets over 1.3deg^2 for IGM tomography (c.f. Keck-LRIS: ~20 objects over 0.01deg^2)
- 60-night program for IGM tomography will cover 30 deg^2 at 2.4<z<3.0: **Total comoving volume of ~7 x 10^7 (Mpc/h)^3,** c.f. ~5 x 10^7 (Mpc/h)^3 at z~0.7 for VIPERS
- Science case: galaxy cross-clustering, constraining intrinsic alignments, small-scale forest auto-correlation, characterizing extreme overdensities

# Future Surveys: Billion Object Apparatus

- (Next + 1) generation Optical-NIR spectroscopic survey facility
  - 10m-class telescope
  - >1.5deg$^2$ field-of-view
  - ~15,000-30,000 focal-plane fibers with robotic positioners
  - Moderate-resolution: R~4000 to resolve sky lines and split OII 3727A
  - First light: **>2032** (Post-LSST)
- Baseline 10-year cosmology survey over 10,000 deg$^2$
  - ~300M-500M galaxy redshifts from $0.4<z<1.6$ (~3 visits with 40min integrations)
  - ~25M background LBGs at $2.3<z<3.2$ for IGM tomography

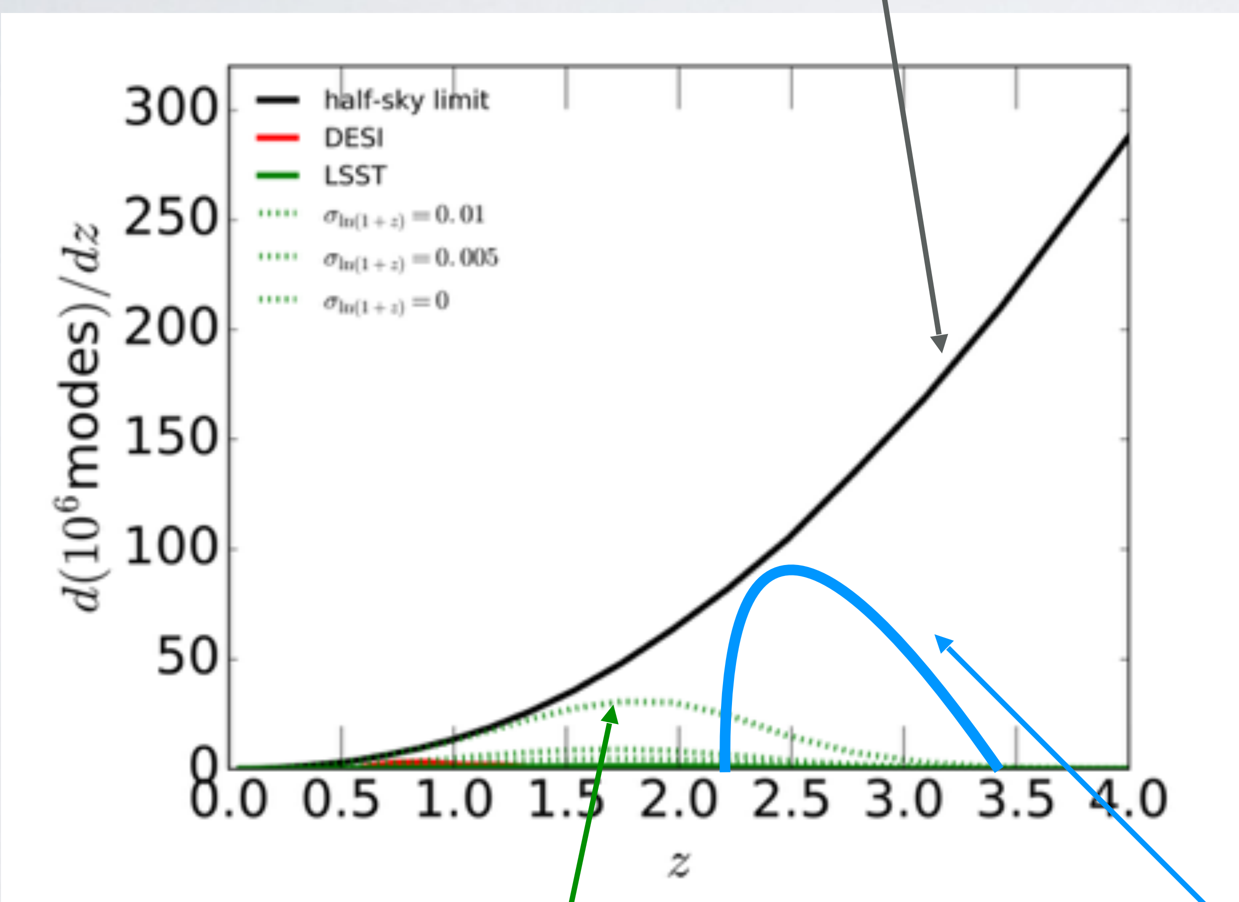
# A NOT-TOO-CRAZY EXTRAPOLATION…

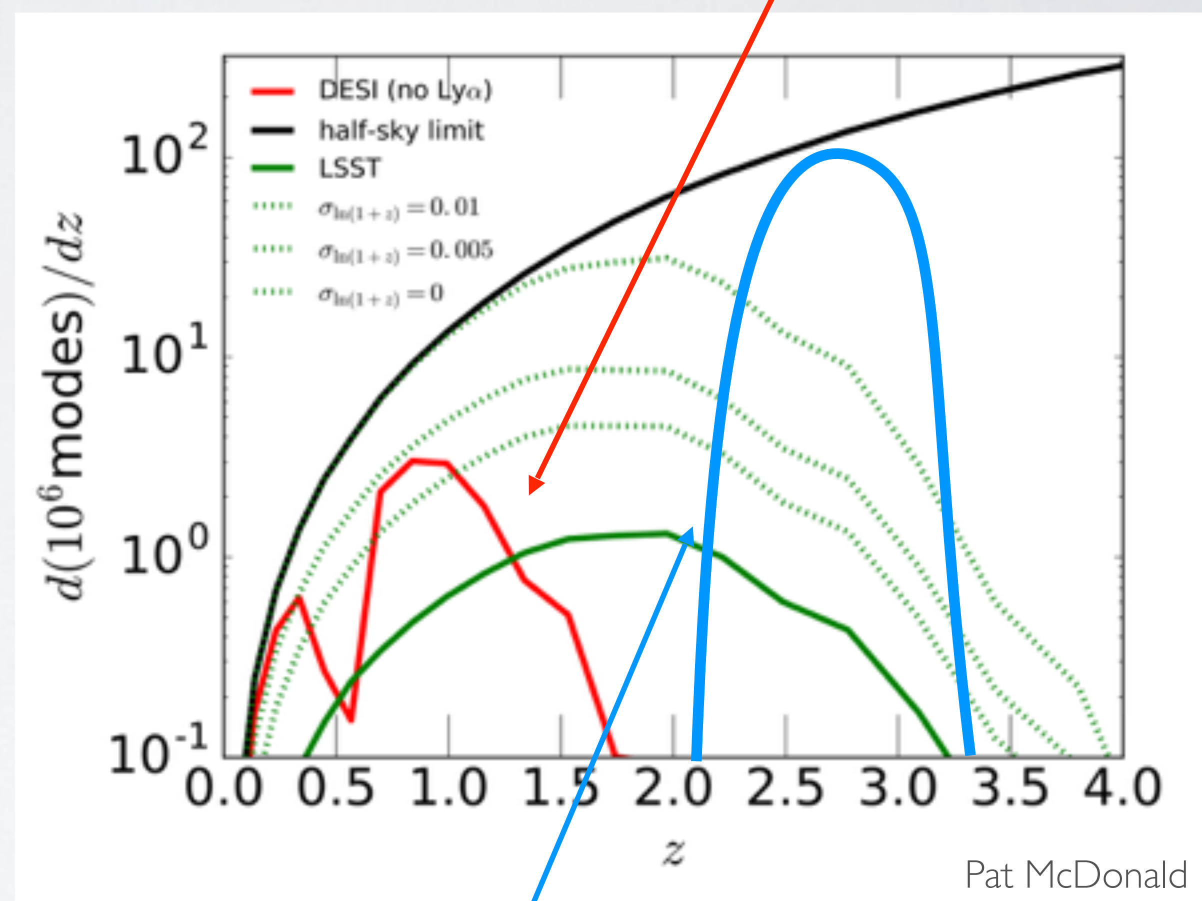
| | SDSS-III/BOSS (2009-2015) | DESI (2020-2025) | Subaru-PFS (2019-2024) | Billion Object Apparatus (2035+) |
|---|---|---|---|---|
| Telescope Diameter | 2.5m | 4m | 8.2m | 10+m |
| FOV | 7 deg$^2$ | 7 deg$^2$ | 1.3deg$^2$ | >1.5deg$^2$ |
| Total Multiplex | 1000 | 5000 | 2400 | 15,000 |
| Target Density | 140/deg$^2$ | 700/deg$^2$ | 2,000/deg$^2$ | >10,000/deg$^2$ |
| Cost | ~$10M (w/o telescope, limited upgrade) | ~$70M (w/o telescope) | ~$70M (w/o telescope) | ~$600M (telescope, instruments, ops) |

# Cosmological Information In Large-Scale Structure

*All linear modes within 14k sq deg*

*DESI Spectroscopic Survey on 4m Kitt Peak*



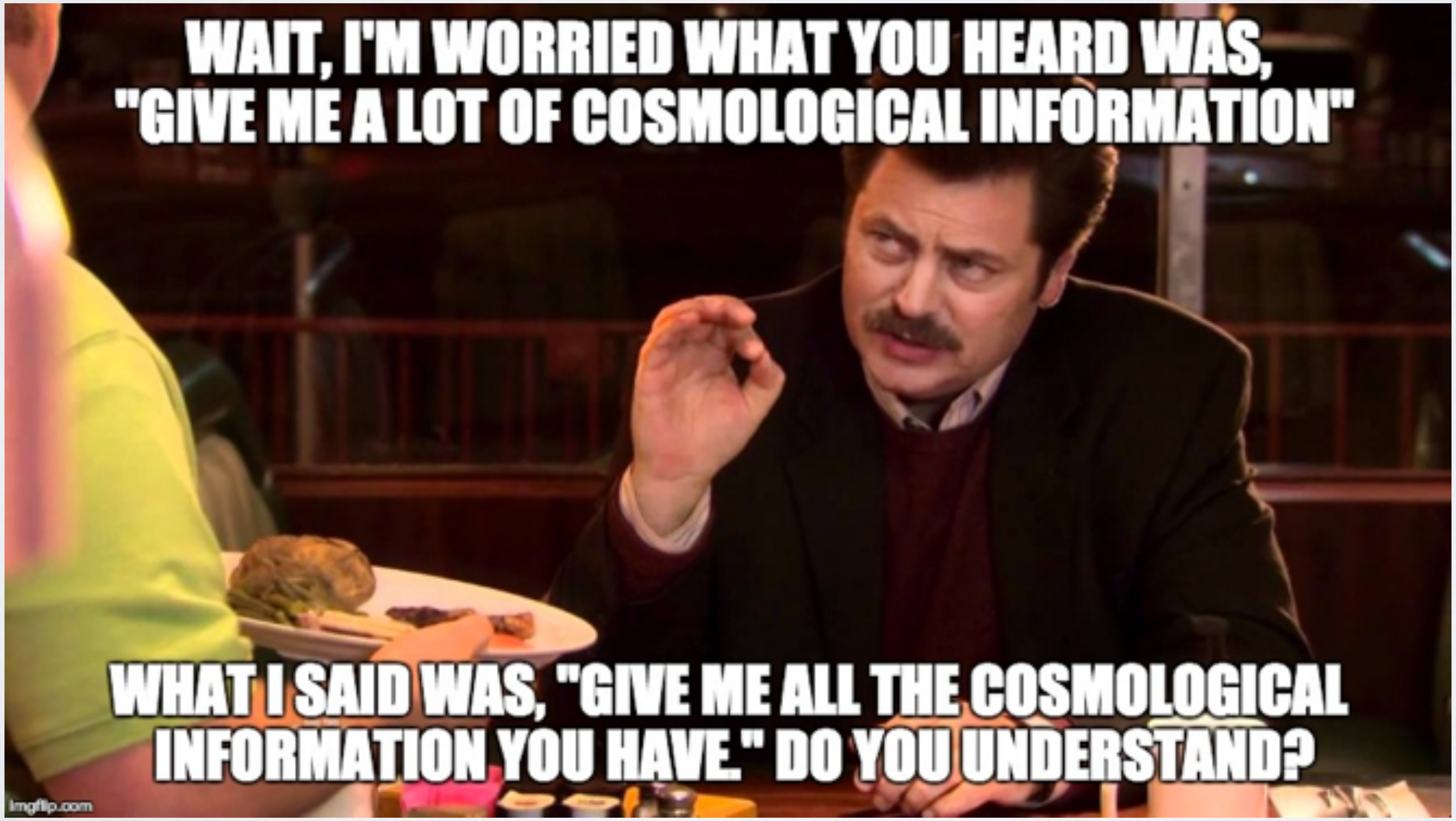

Pat McDonald (LBL)

*Spec-z's for all ~10^9 LSST galaxies!*

*~IGM tomography*

# Cosmology Goals

- Measuring nearly all cosmological linear modes in Universe out to z<3.5 within a hemisphere:
  - Galaxy redshift survey (0.5<z<2.0): ~30k galaxies per sq deg, probing kmax<0.6h/Mpc at z=1.5. At magnitude limits of r=24
  - IGM tomography survey (2.0<z<3.5) ~5k per sq deg of Ly-a forest backlights, kmax<1.5h/Mpc (similar to CLAMATO)



# 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
  - Cross-correlation measurements with foreground MOSDEF, 3D-HST and VUDS galaxy redshifts
  - Future projects: initial condition reconstruction, forest autocorrelation →cosmological parameters
- Future surveys with Subaru PFS (~2020) and Billion Object Apparatus (>2030) will extend this to cosmological volumes