Detection of z~2.3 voids from 3D Lyman-alpha forest tomography in the COSMOS field

Shedding Light on the Universe with Extremely Large Telescopes
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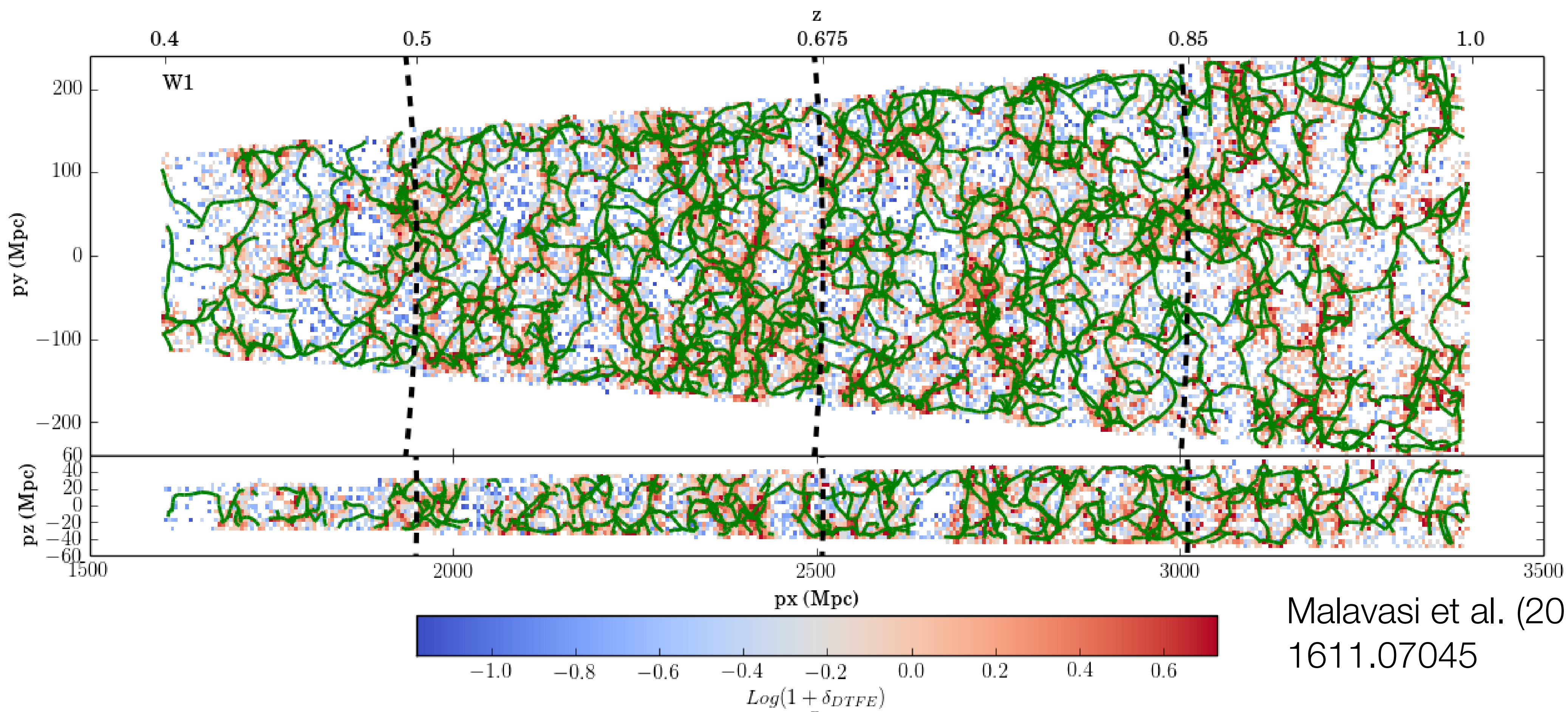
Based on arxiv:1710.02612

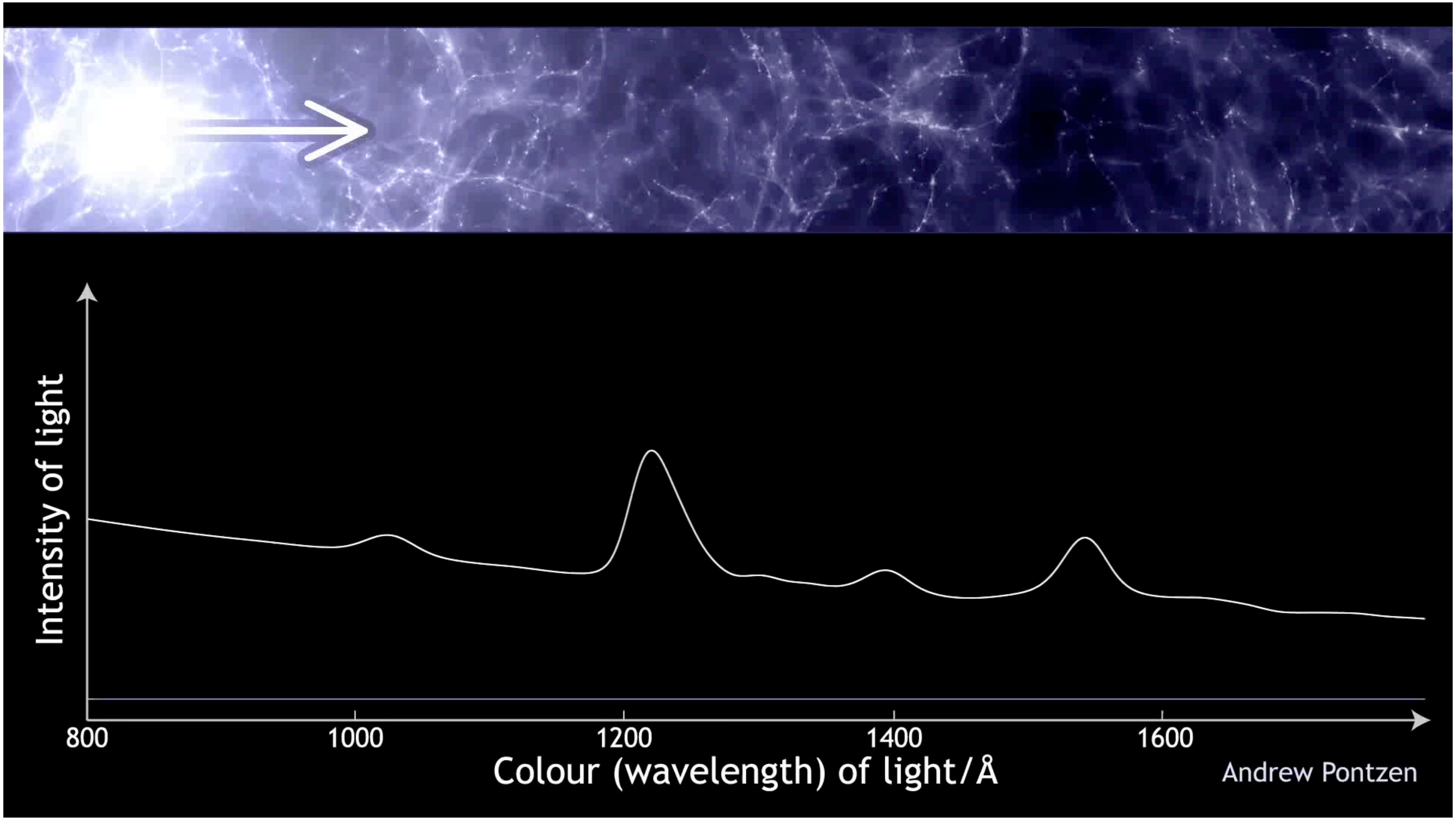
Mapping the z~2 universe at ~Mpc scales…



Malavasi et al. (2017), VIPERS 1611.07045

- up to z~1: VIPERS, GAMA, Sloan Main Galaxy Sample…but galaxy surveys are too sparse for z>1
- z~2 is epoch of peak star formation: what is relationship between cosmic web and galaxies as they form?

…with the Lyman-alpha forest



- Ly-alpha absorption traces large-scale structure

$$F = \bar{F}(z)\exp(-\tau)$$

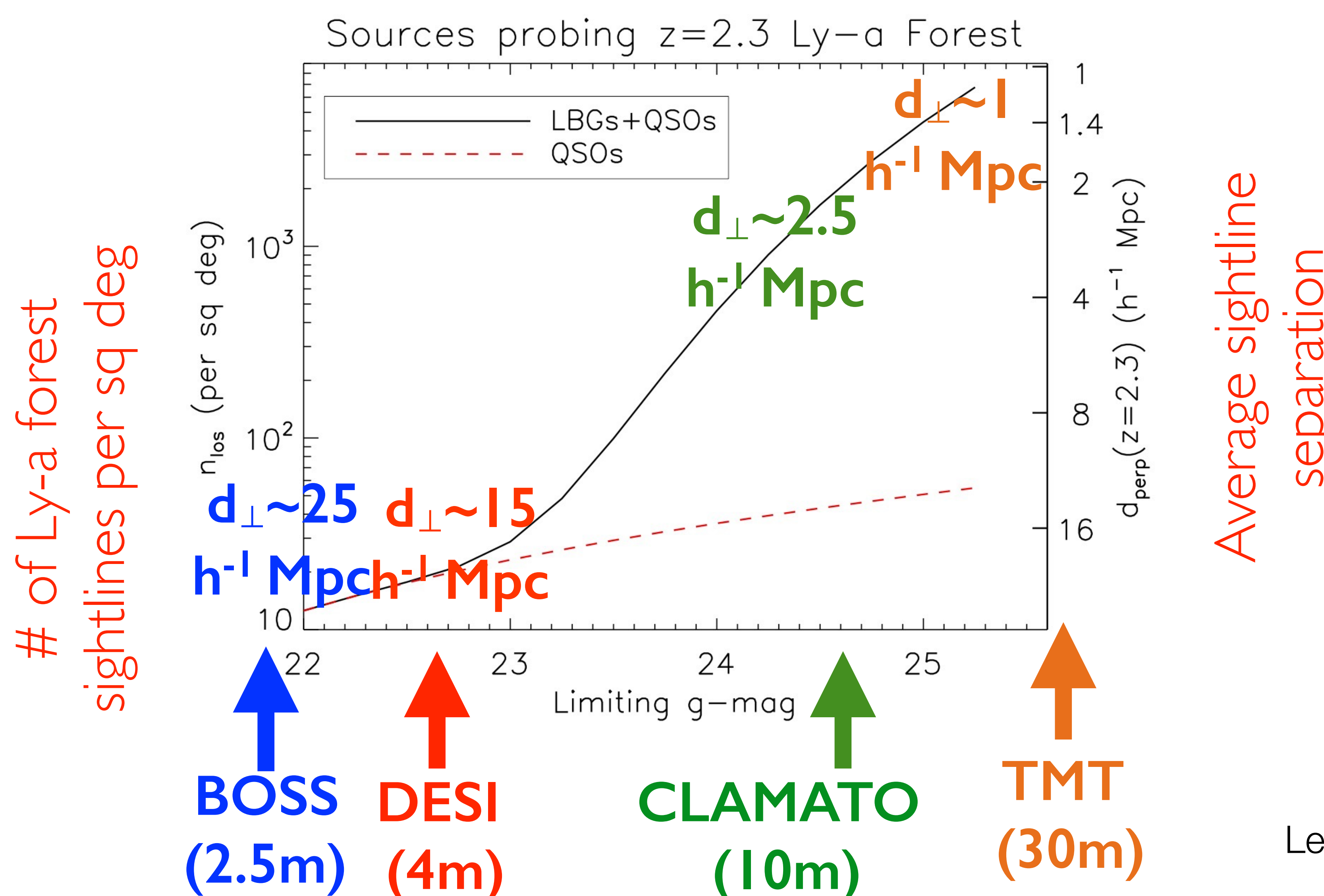
$$\tau(\lambda) \leftrightarrow \delta(z)$$

$$\delta_F = \frac{F}{\bar{F}(z)} - 1$$

- We quote fluctuations in flux field δ_F

IGM tomography: mapping 3D Ly-alpha forest on small scales

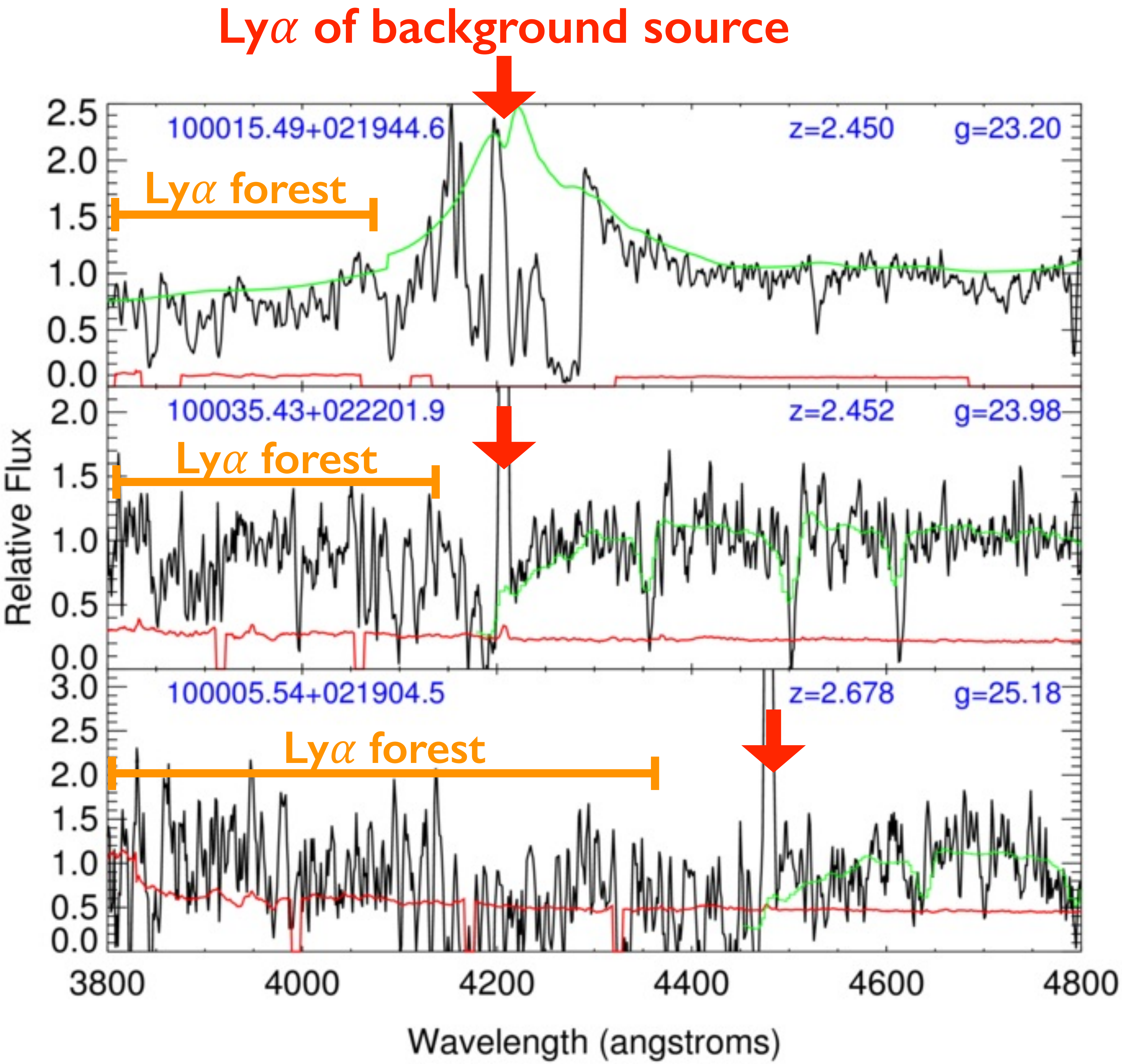
- With many closely-spaced sightlines, you can reconstruct 3D absorption field on scales comparable to the sightline separation $d_\perp$ (Pichon et al. 2001, Caucci et al. 2008, Lee et al., 2014)
- Small $d_\perp$ → More sightlines → Fainter background sources (g~24)
- Tomography requires big telescopes! We use Keck-I/LRIS (R ~ 1000)



Lee et al., 2014,

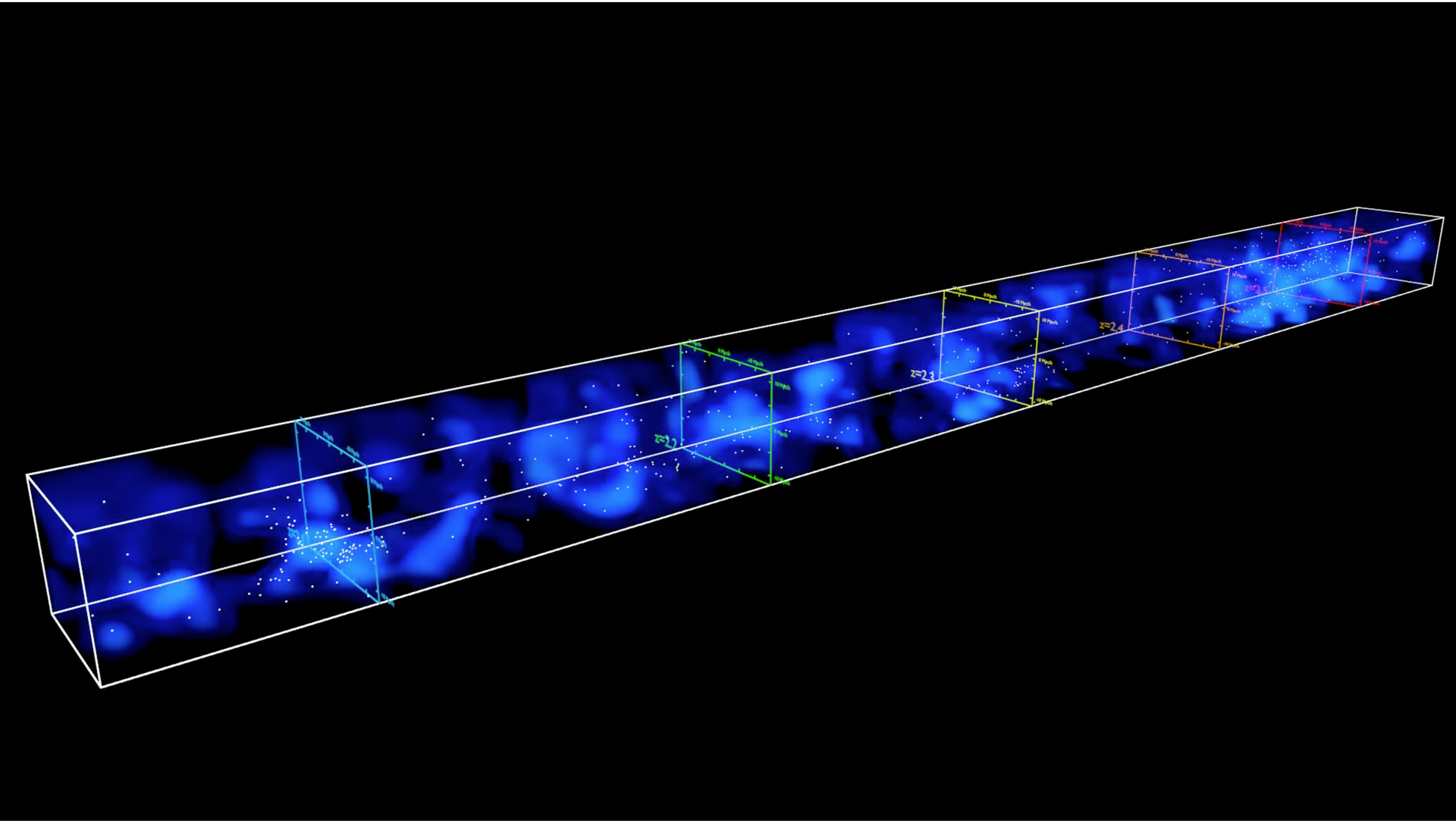
COSMOS Lyman-Alpha Mapping And Tomography (CLAMATO)

- **First systematic use of galaxies as Lyα forest background sources**
- Pathfinder for future IGM tomography on 30m-telescopes and multiplexed 10m-telescopes (e.g. Subaru PFS)
- Samples Lyα forest at 2.5 h^{-1} Mpc scales from $2.05 < z < 2.55$ over 0.157 deg^2 in COSMOS (230 sightlines)
  - $V = 30 \times 24 \times 438\ h^{-1}$ Mpc $= 3.1 \times 10^5\ h^{-3}$ Mpc^3
- Estimate 3D Ly-alpha absorption field using Wiener-filter map smoothed on 2-2.5 h^{-1} Mpc scales



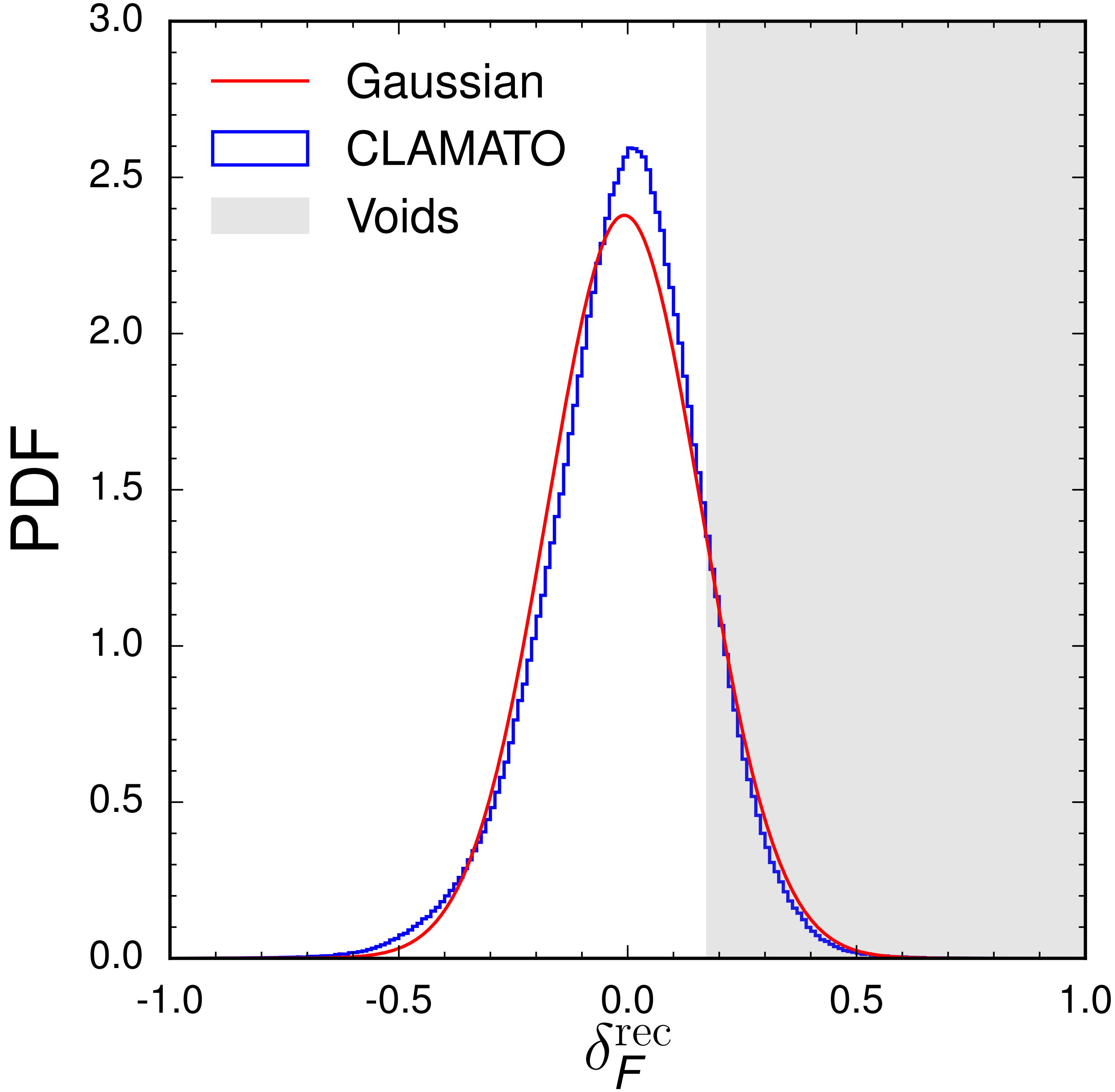
Color scheme: **spectrum**, noise vector, spectral template

2017 CLAMATO map



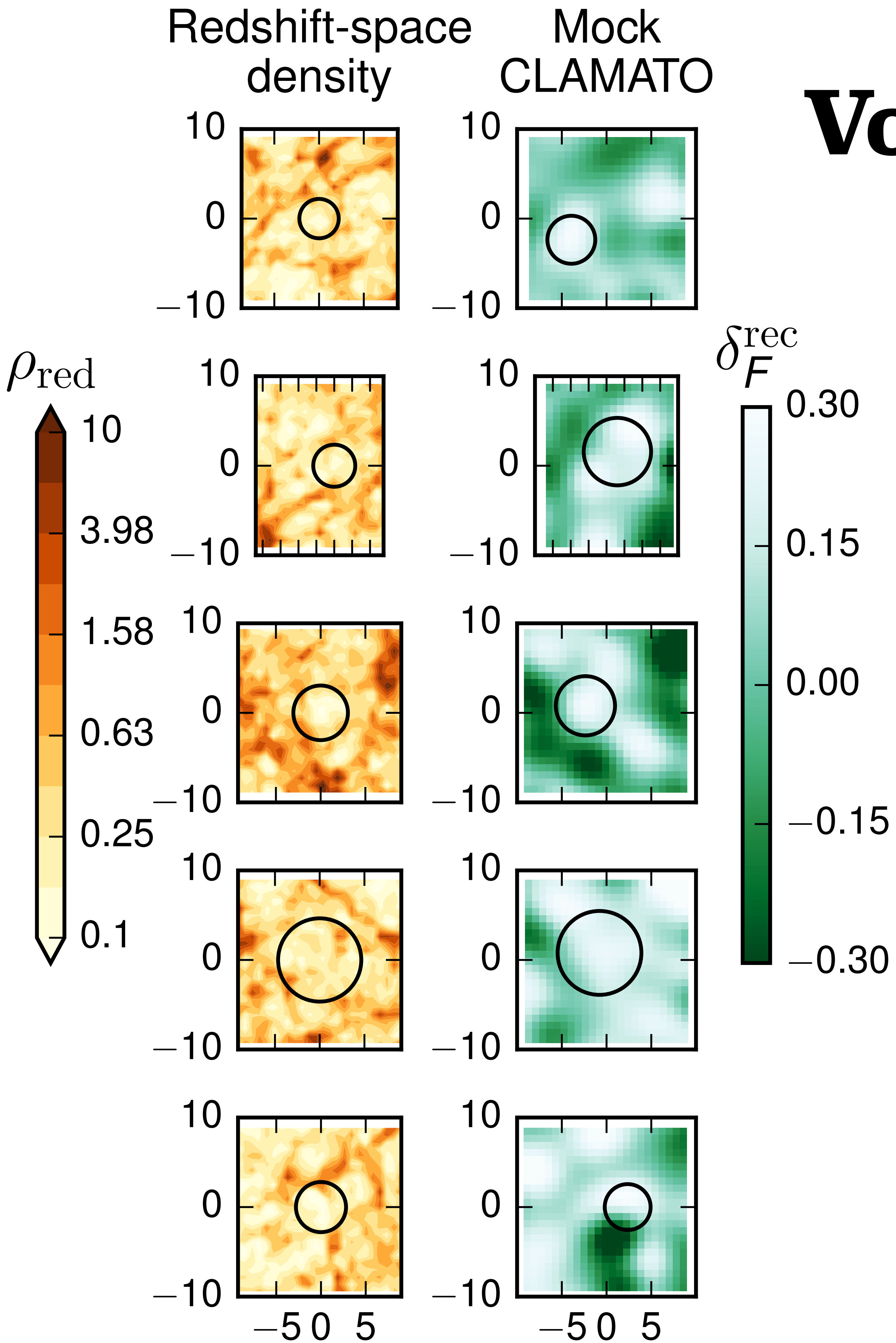
Visualization: Thomas Mueller (MPIA)

Why care about voids?



- Cosmology: voids sensitive to smooth components (dark energy, neutrinos)
- Void dynamics sensitive to modified gravity (screened in higher-density regions)
- Environmental dependence of galaxy properties: voids are most extreme regions

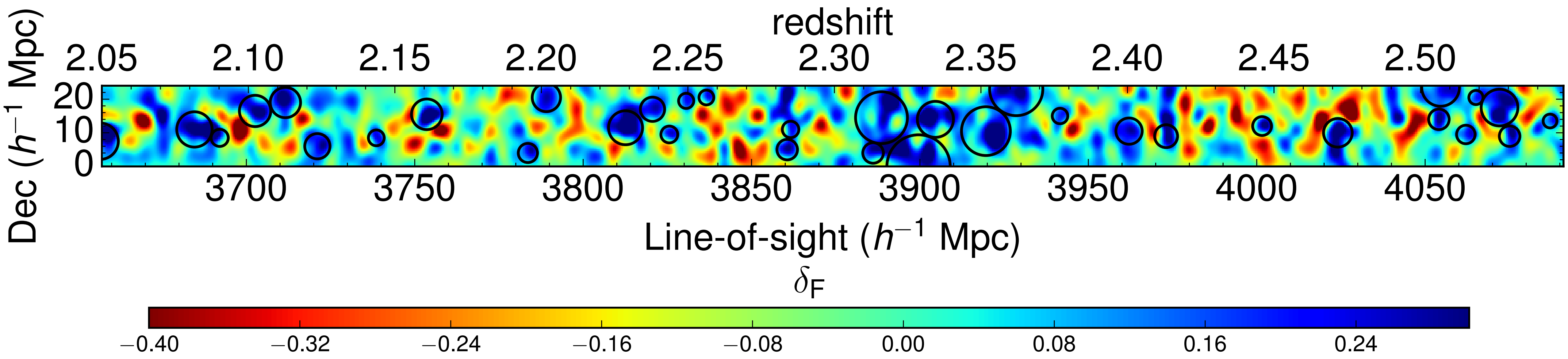
Voids in CLAMATO



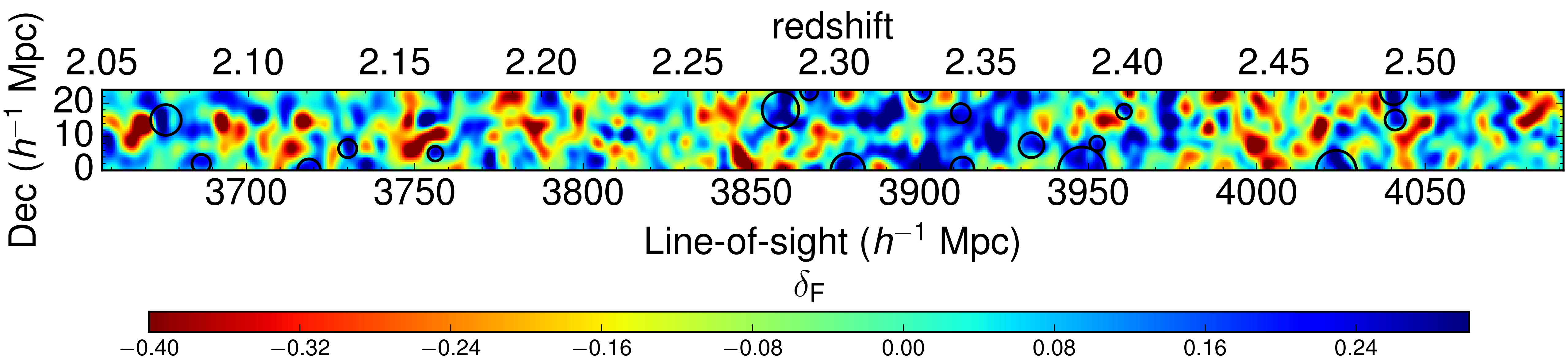
- First detection of voids beyond z~1
- Simple spherical overdensity finder can locate voids in simulated flux maps [Stark et al., 2016, 1504.03290]
- We use simulations to calibrate the SO thresholds to match void fraction of ~20% in density and flux

Krolewski et al., 2018

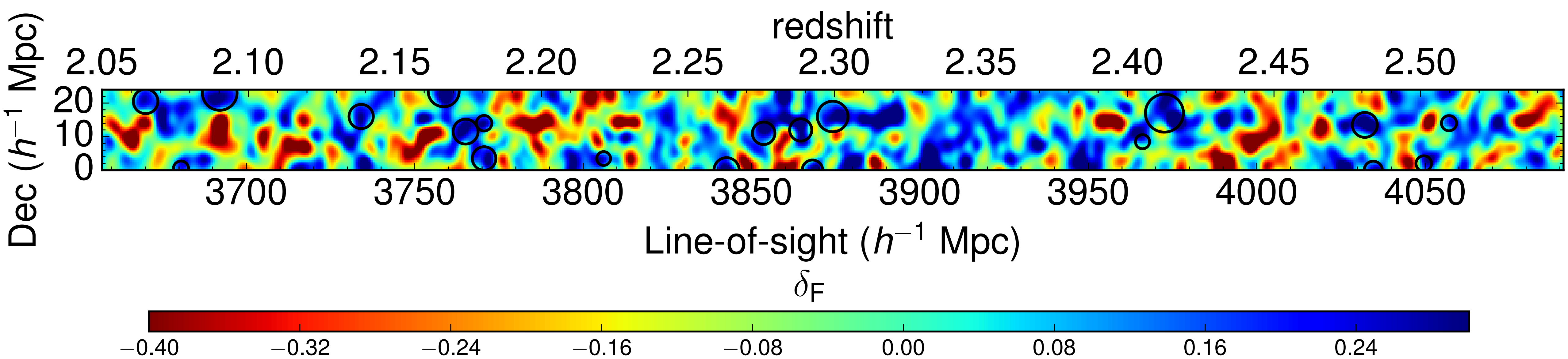
Voids in data



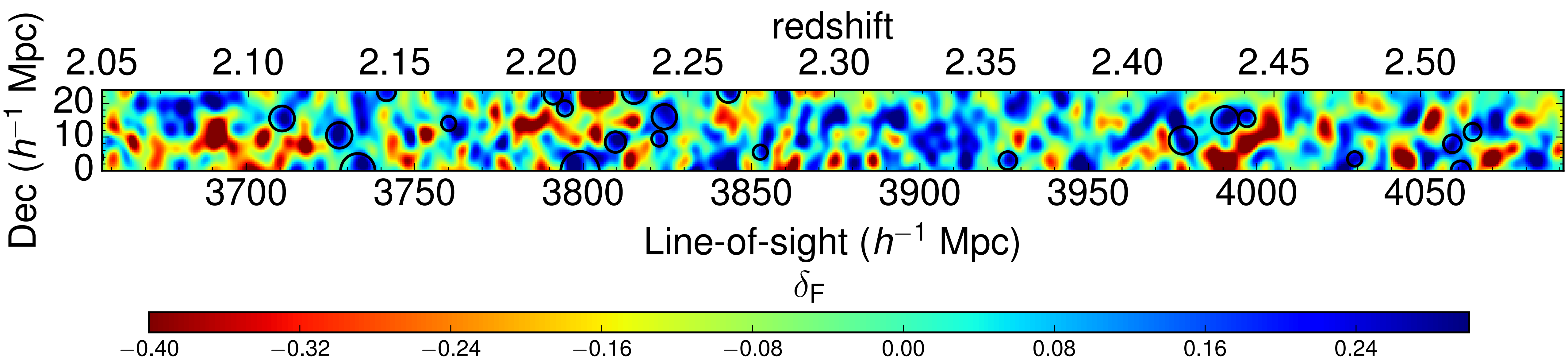
Voids in data



Voids in data

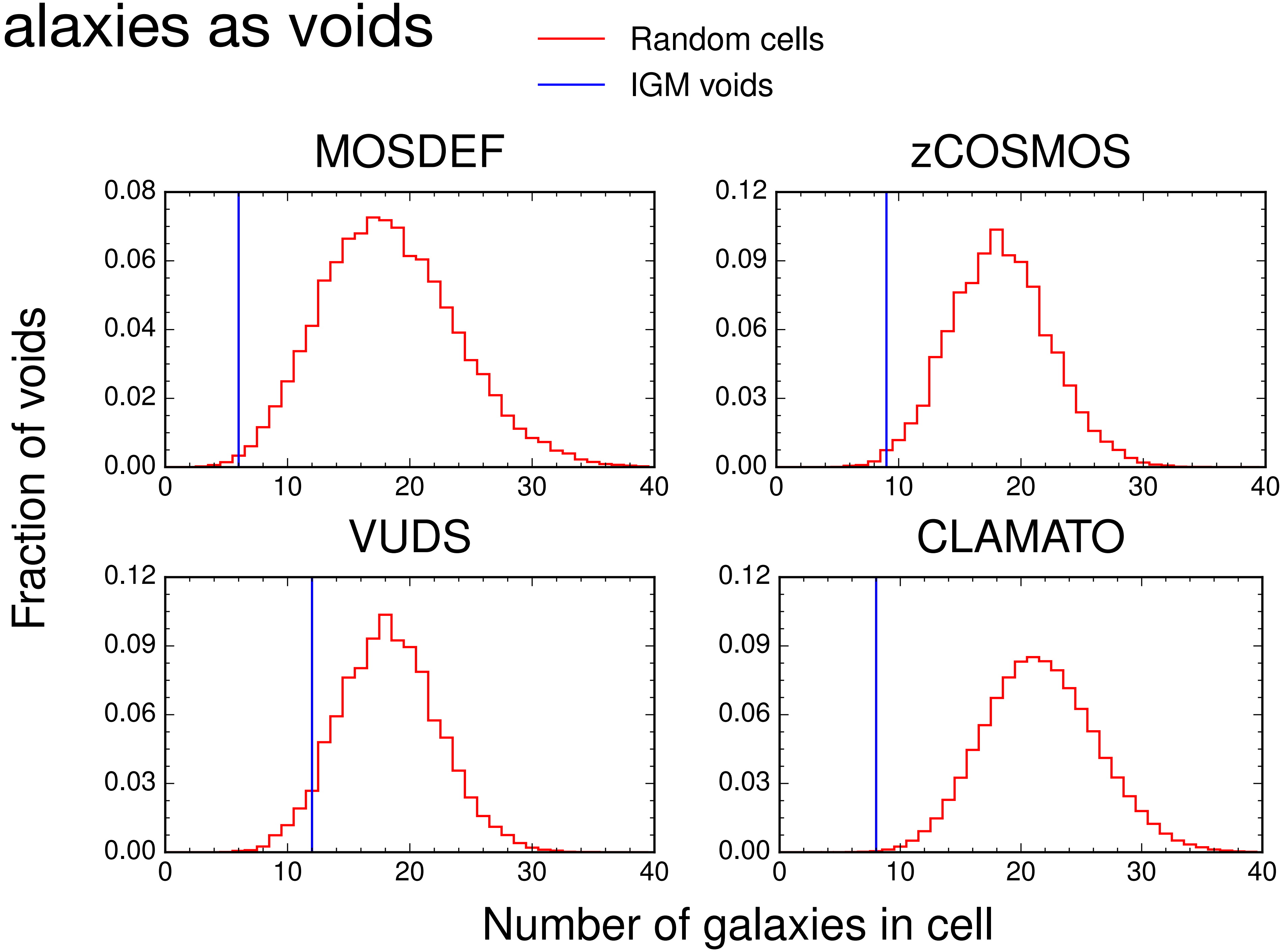


Voids in data



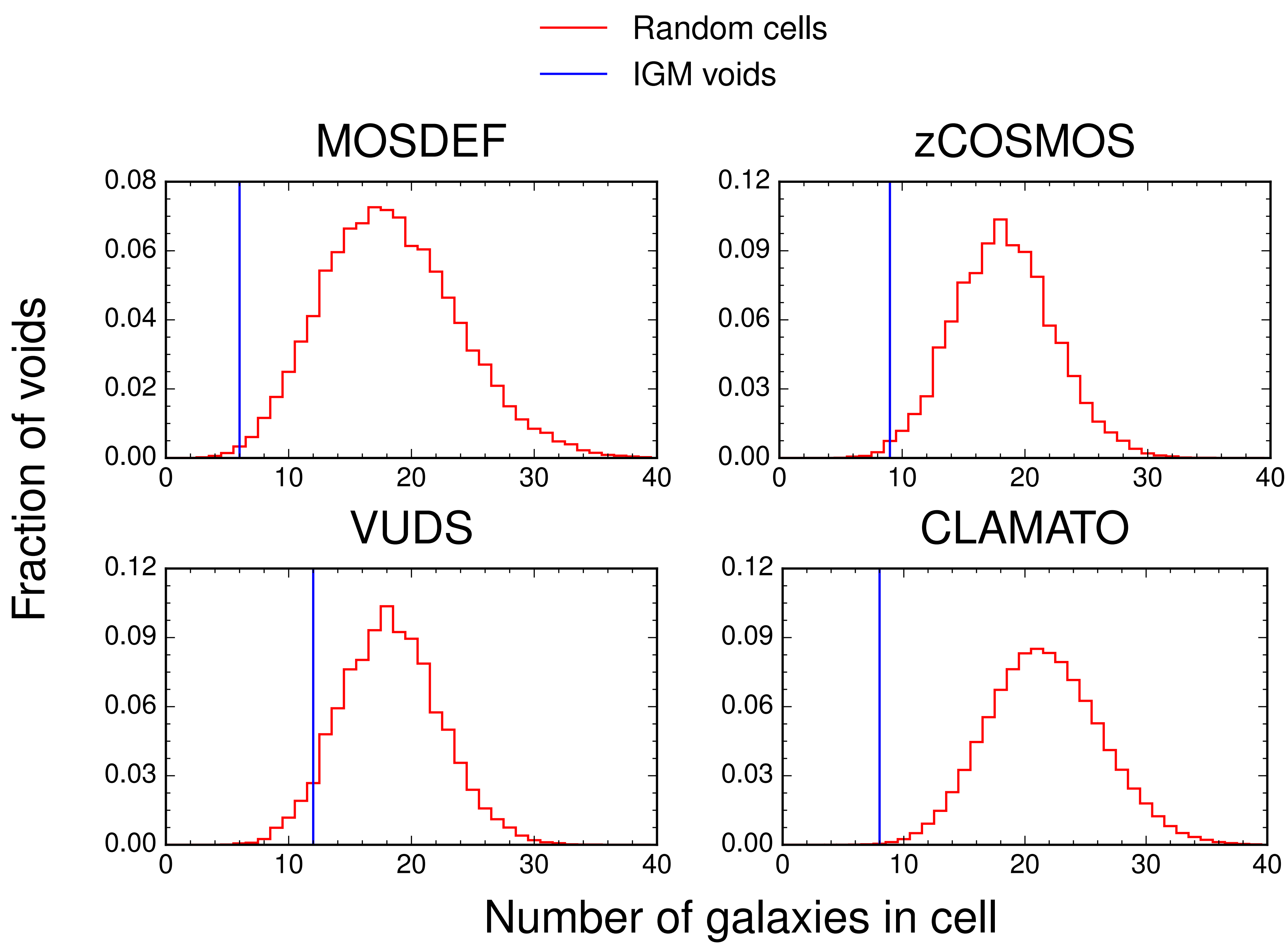
Validation: galaxies in tomographically-identified voids

- Voids have significantly fewer galaxies than random cells
- Significance = probability that random cells have as many galaxies as voids



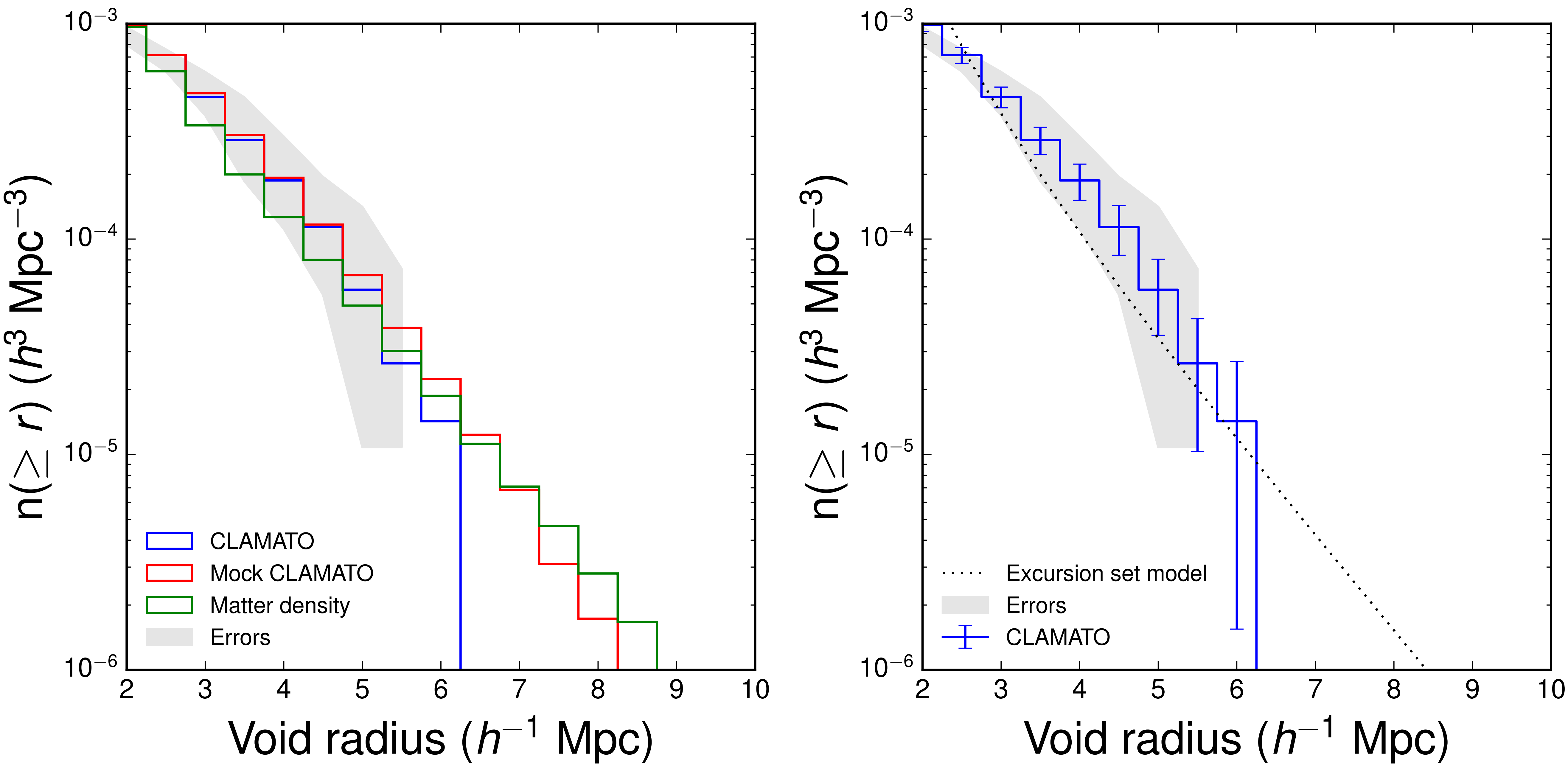
Galaxies in tomographically-identified voids

- Combined significance = 5.95σ



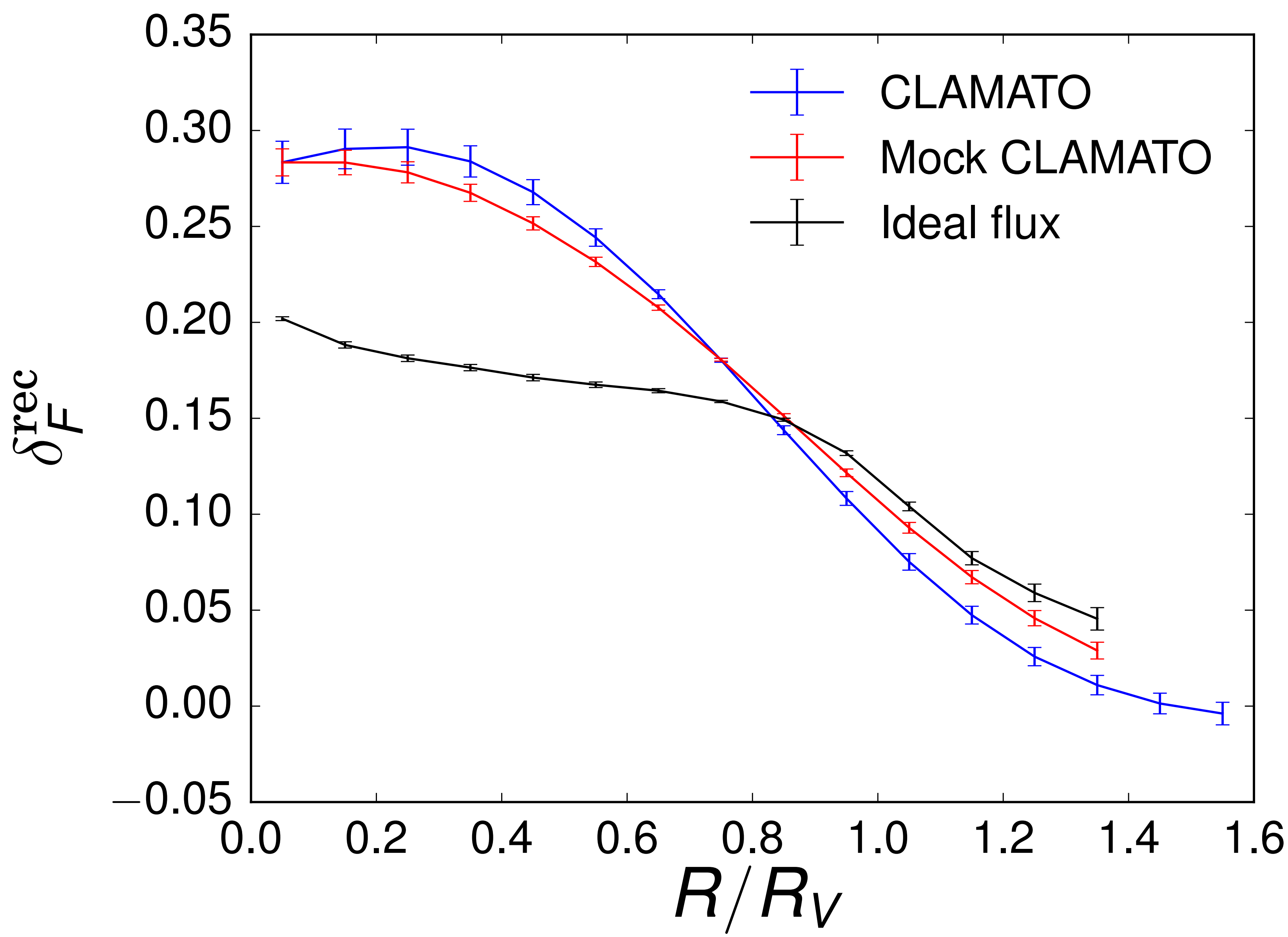
Void radius function

- Void radius function in data agrees with VRF in simulations
- Consistent with void abundance from excursion set models (though with void threshold as free parameter)



Stacked radial profile

- Good agreement between data and mock observations
- Unfortunately noise corrupts the profile on small scales-> hard to compare to low z profiles



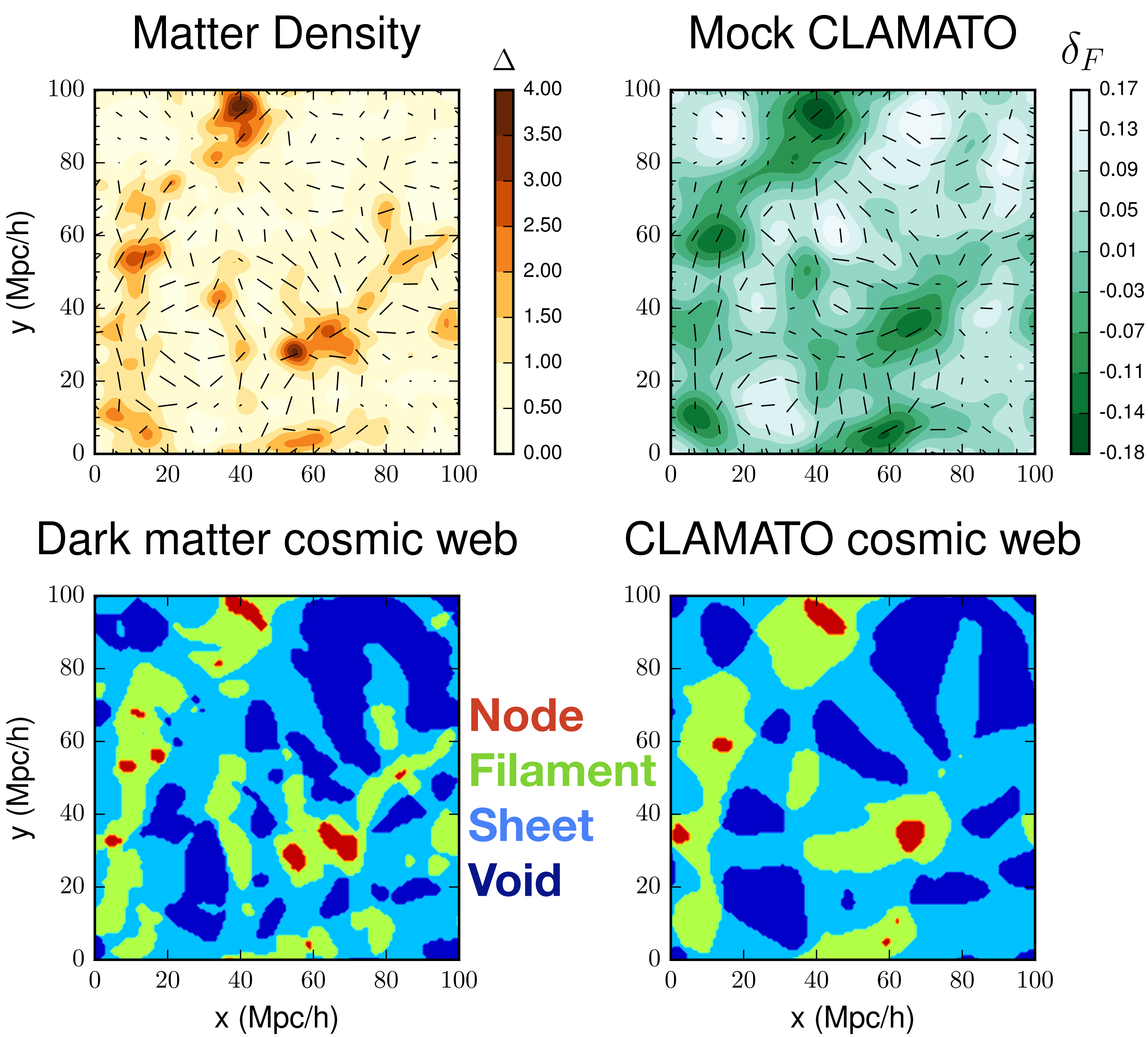
The future: IGM tomography on giant telescopes

- IGM tomography on 30 m telescopes can achieve ~1 Mpc resolution
  - Probing CGM around coeval galaxies
  - Thermal state of the IGM/CGM from AGN feedback, winds, galactic radiation field
  - Push 3D Ly-alpha power spectrum to very small scales
- Some science cases are better addressed in “survey mode” with massive multiplexing (e.g. Subaru-PFS, multiplexed fiber spectrographs on 30m telescopes?)
  - Ly-alpha voids require much larger sample sizes to be competitive cosmological probes

Summary

- CLAMATO: successful pathfinder on 10-m telescope for IGM tomography on future large telescopes
- First map of Mpc-scale universe at z~2 and first detection of voids at z~2
- 30m telescopes will push IGM tomography to resolve CGM and learn about galaxy feedback physics

Cosmic Web at z~2

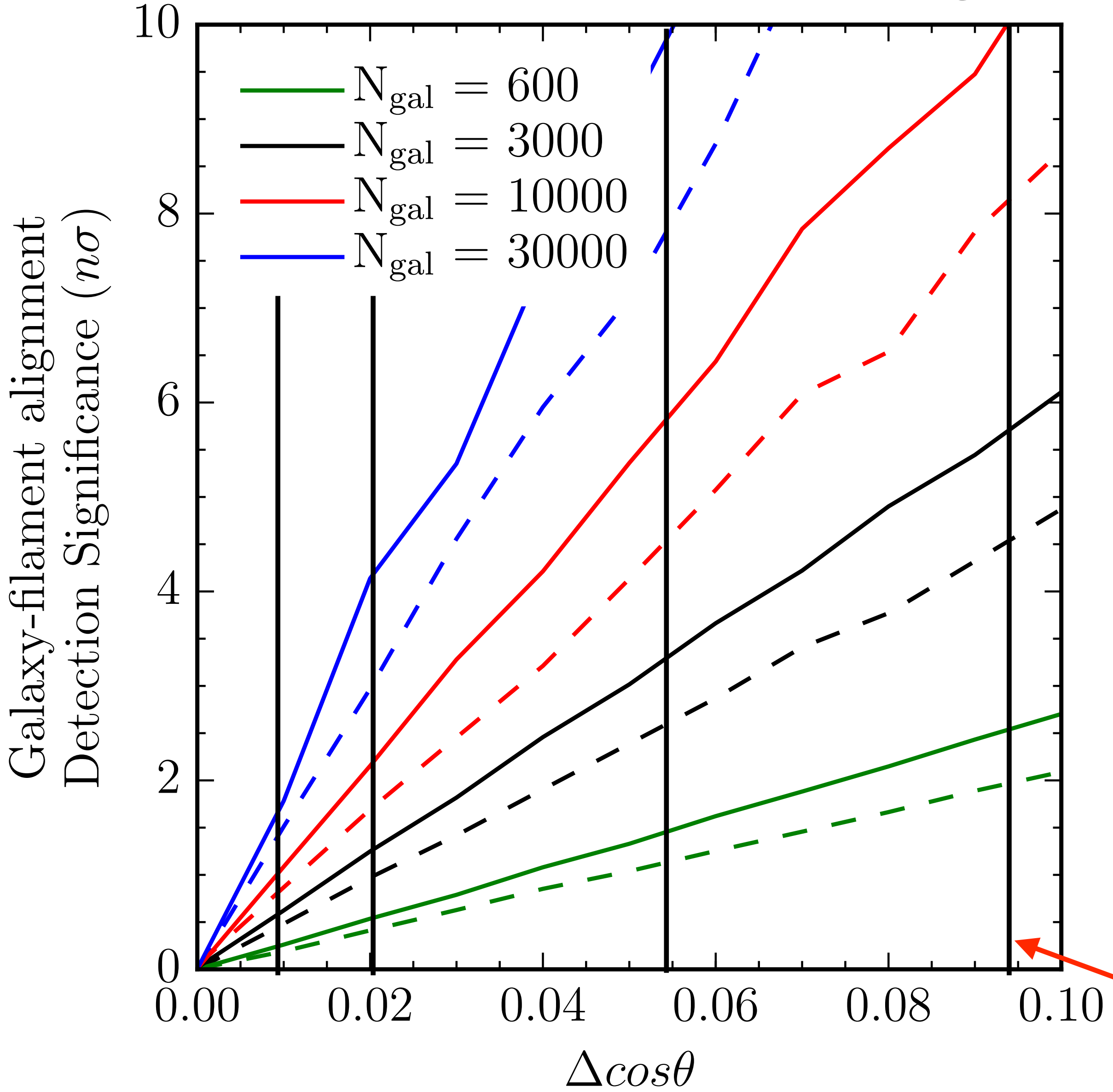


- IGM tomography can measure cosmic web with comparable fidelity to GAMA (z~0.2)
- Currently measuring cosmic web, but recovery will be significantly hampered by aliasing (Lee & White 2016)
- **Cosmic web will require full survey to measure**

Lee & White (2016), 1603.04441

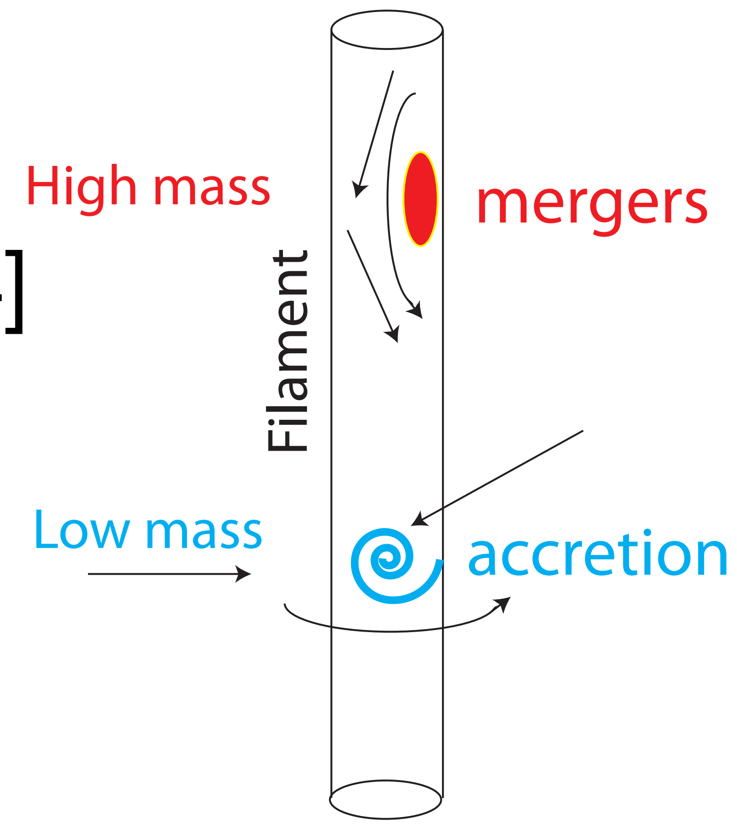
Galaxy alignments at z~2

- Studied feasibility of measuring alignments between galaxies and filaments at z~2 [e.g. Dubois et al., 2014]



True alignment with DM filaments

alignment models from simulations



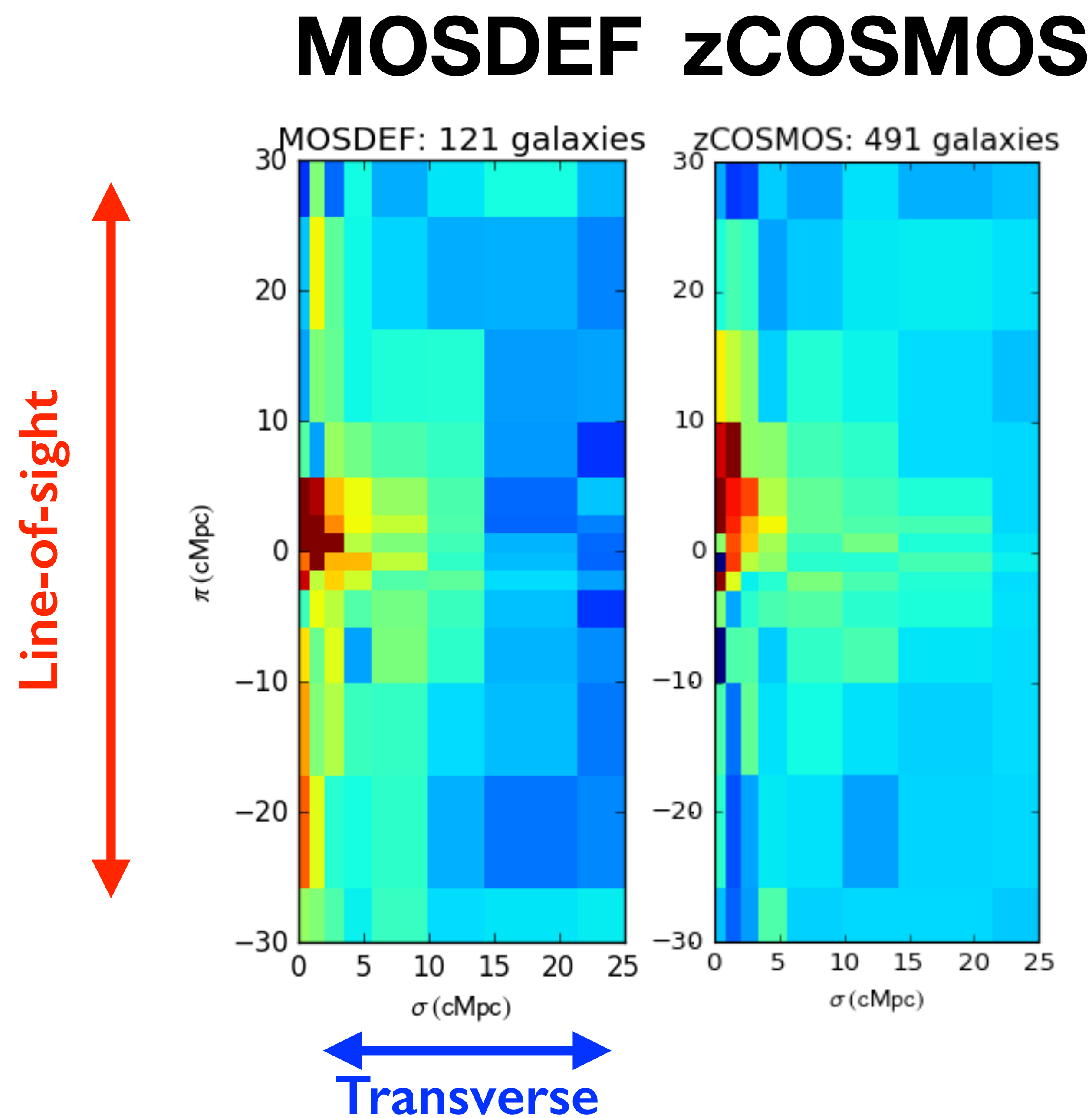
- 1200 coeval galaxies expected in full survey: 4-sigma constraint on most extreme models

Krolewski et al. (2017), 1612.00067

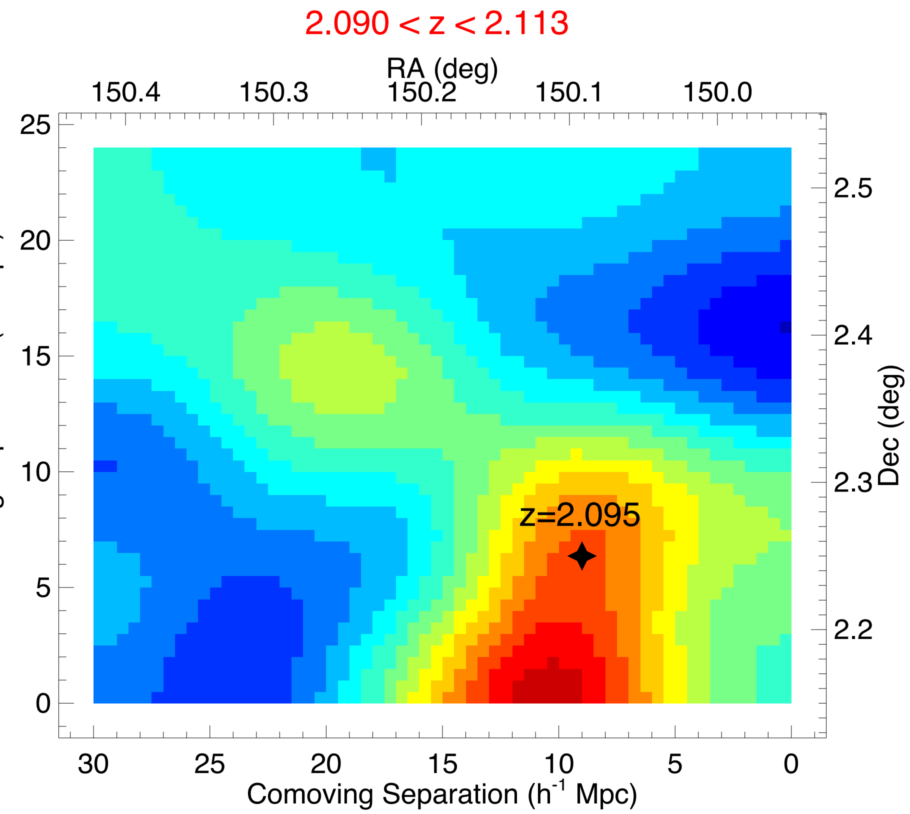
Cross-correlation with galaxies

Preliminary!

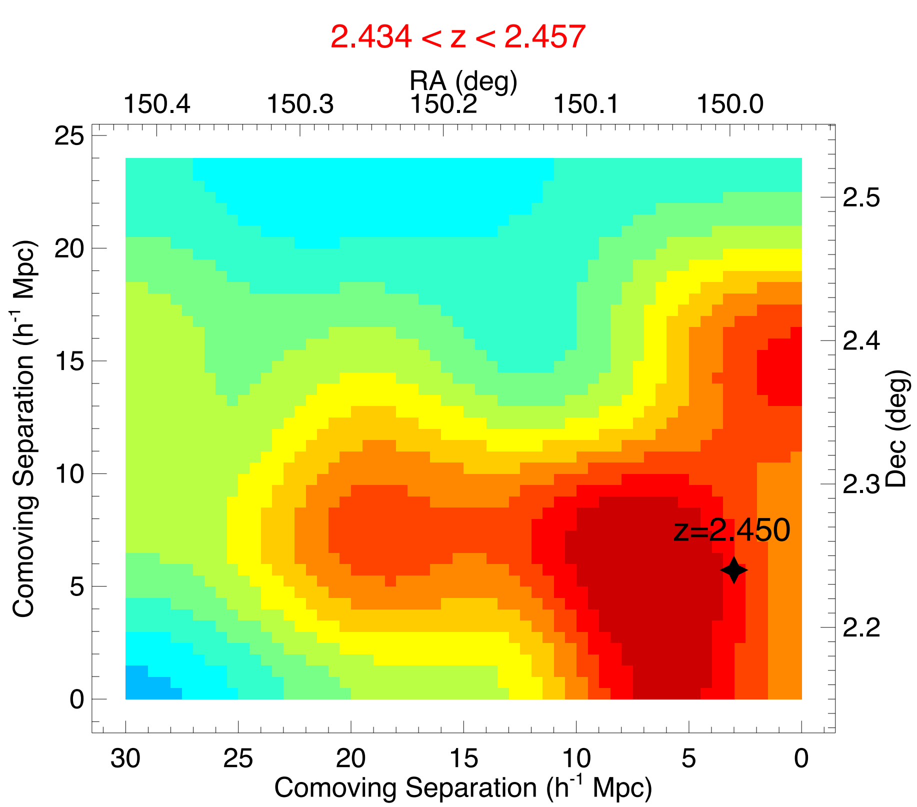
- Significant detections for cross-correlation with coeval galaxies
- With more data, we can measure bias as a function of galaxy properties and constrain redshift errors

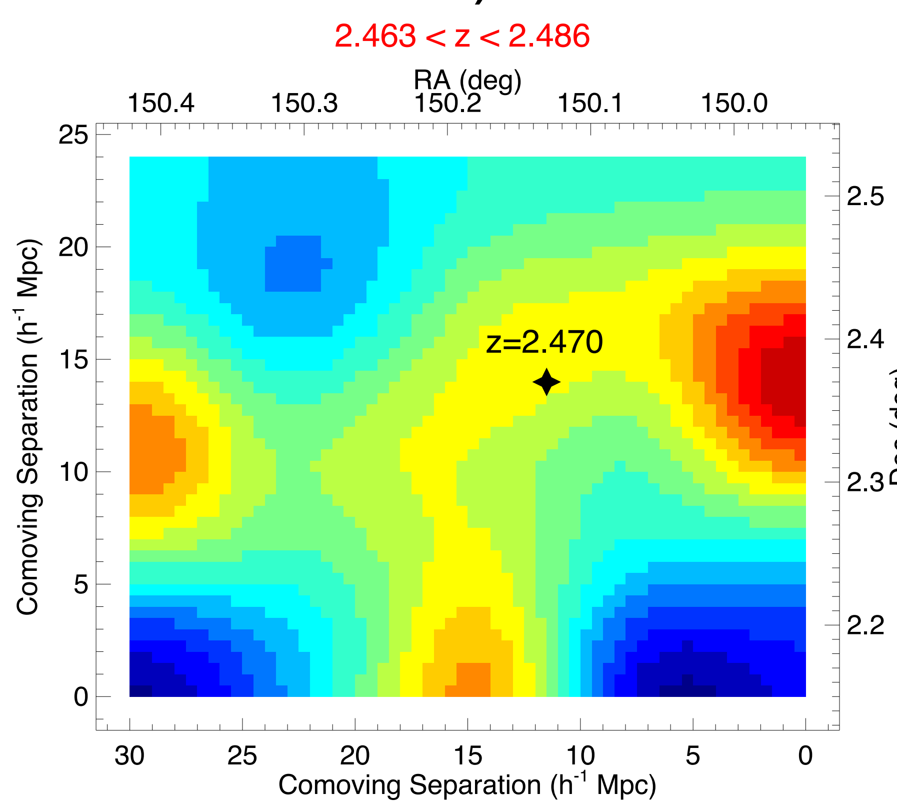


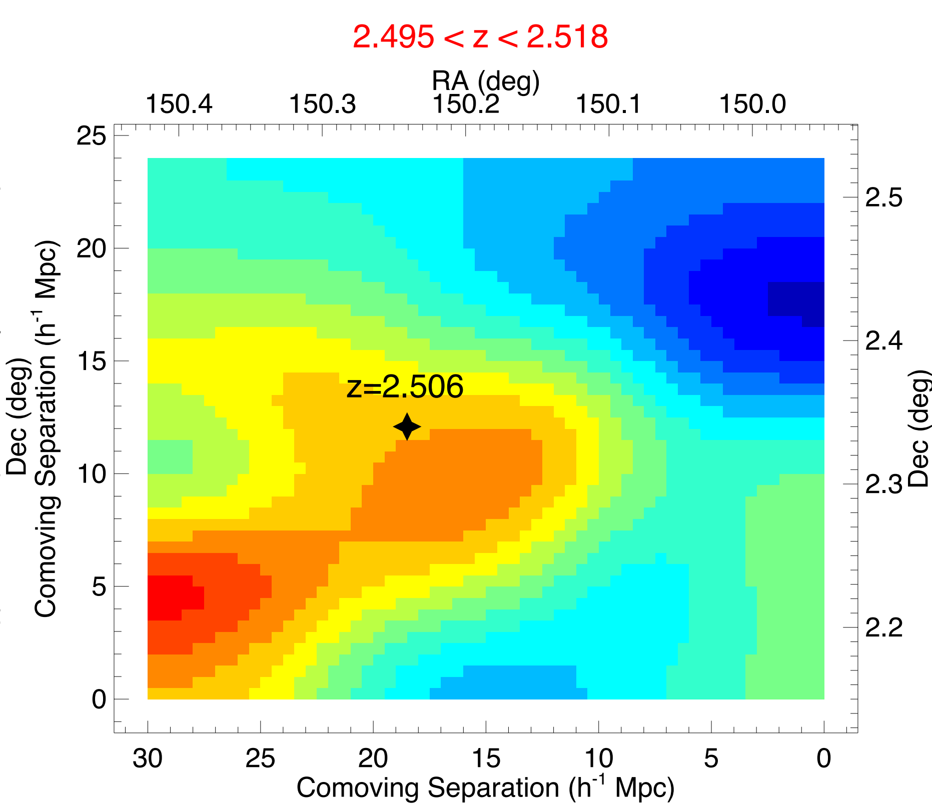
Lee, Font-Ribera, et al., in prep



- z = 2.1 cluster that will likely evolve into 10^{14} $M_\odot$ cluster (Yuan+2014)
- 3 protoclusters at z~2.48: progenitor of z~0 supercluster?
  - z=2.44 LBG/LAE protocluster (Diener+2015, Chiang+2015) [preliminary IGM analysis in Lee et al. 2016]
  - z=2.47 galaxy protocluster 'signposted' with sub-mm sources (Casey+2015)
  - z=2.51 galaxy cluster with X-ray detection (Wang +2015)

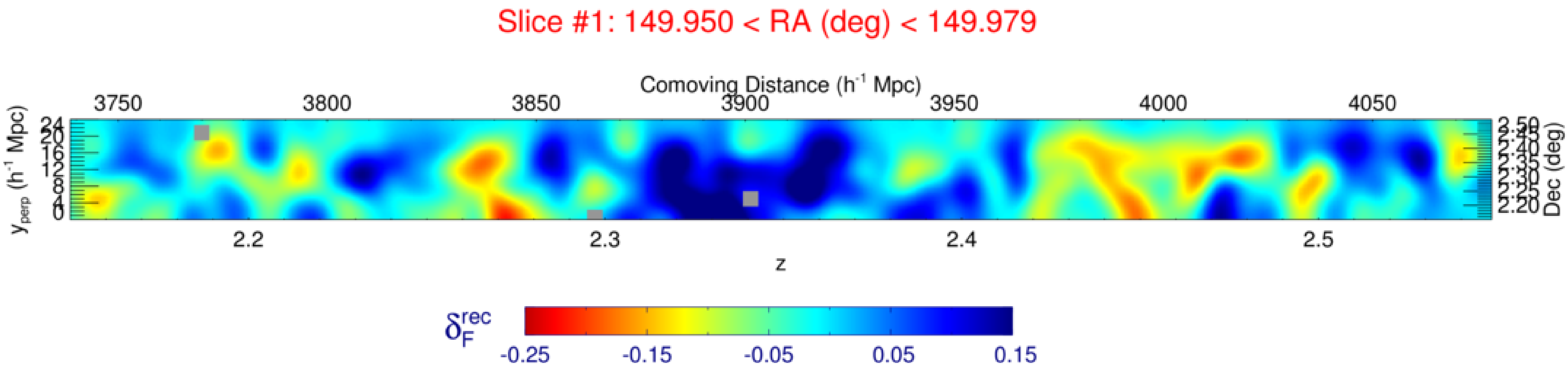


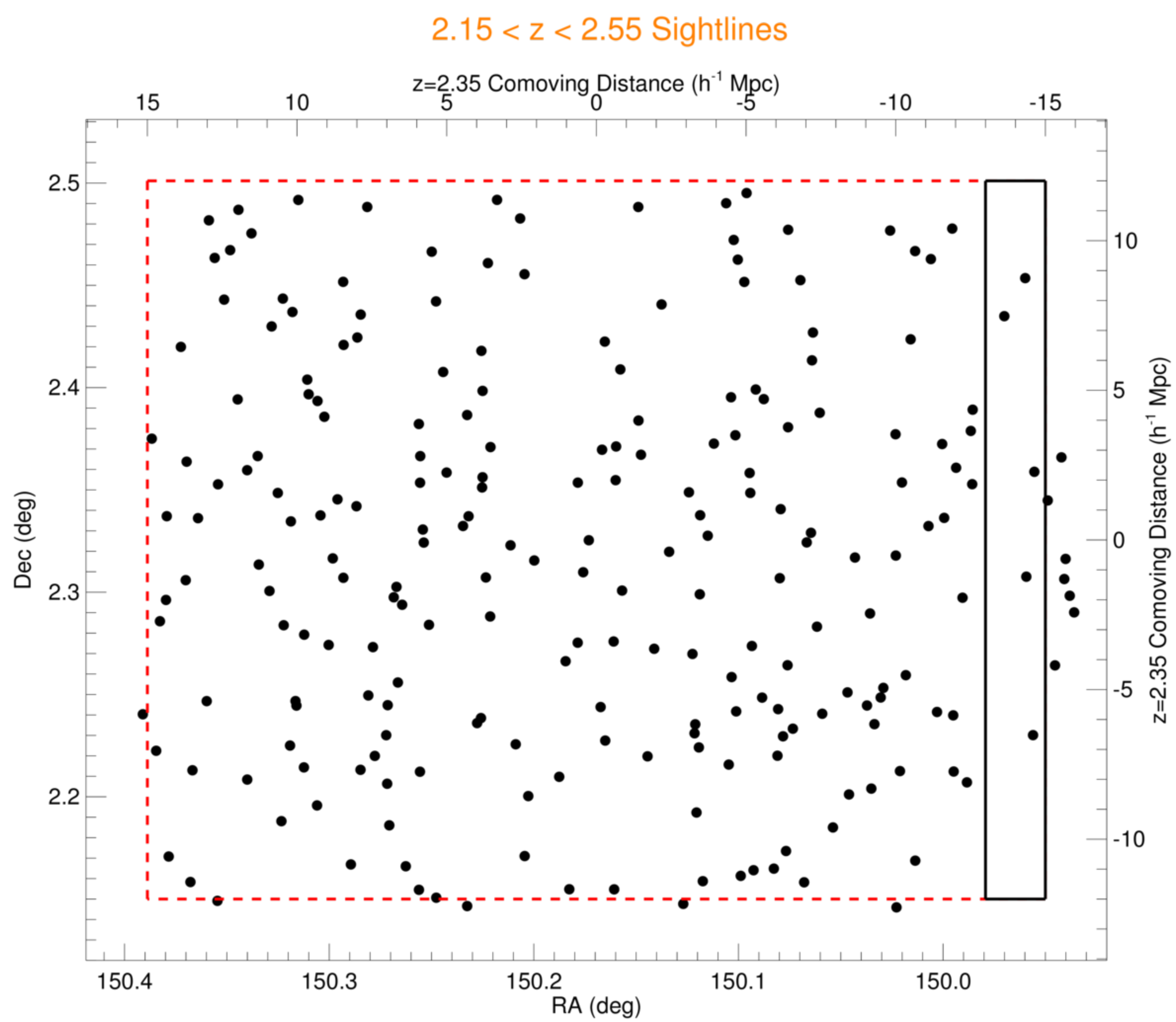


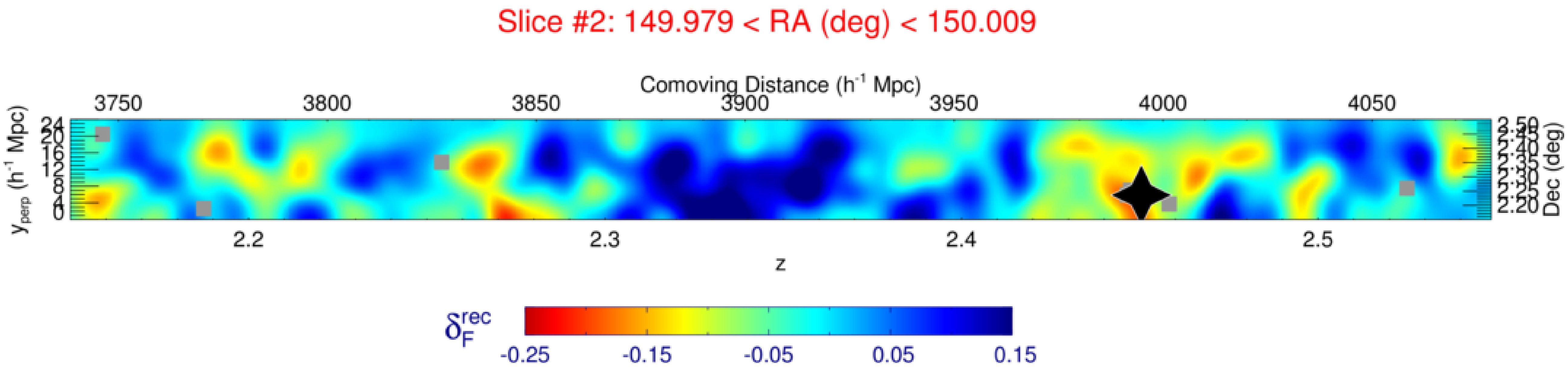


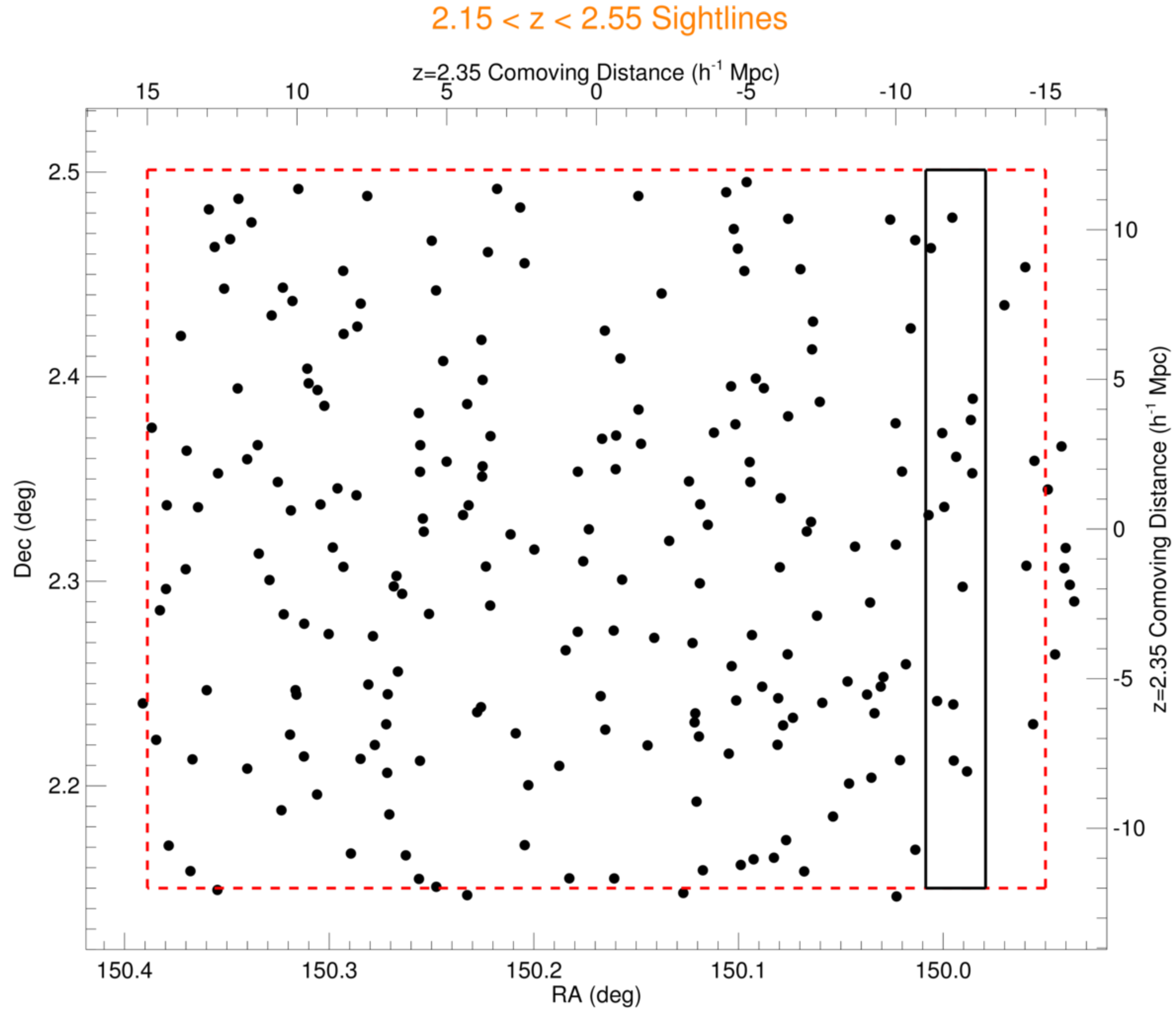
Summary

- IGM tomography uses the Lyman-alpha forest to make a map of the z~2 universe smoothed on 2.5 h^{-1} Mpc scales
- Keck-I/LRIS critical to our science: other instruments are insufficiently deep→poor map resolution (Lee et al., 2014)
- Projects in progress
  - Analysis of galaxy environments at z~2
  - Weak lensing of the Lyman-alpha forest (>5 sigma detection on full survey; Metcalf et al. 2017, Croft et al., 2017)
  - Constraints on galaxy feedback models (Sorini et al., 2017)
  - Neutrino mass: $\sigma(M_\nu) = 0.11$ eV (current Planck constraint: $\sigma(M_\nu) = 0.2$ eV)
- Use CLAMATO for your science!
  - Public data release of maps and spectra in Oct. 2017
- See me to look at our data in 3D with a VR headset!

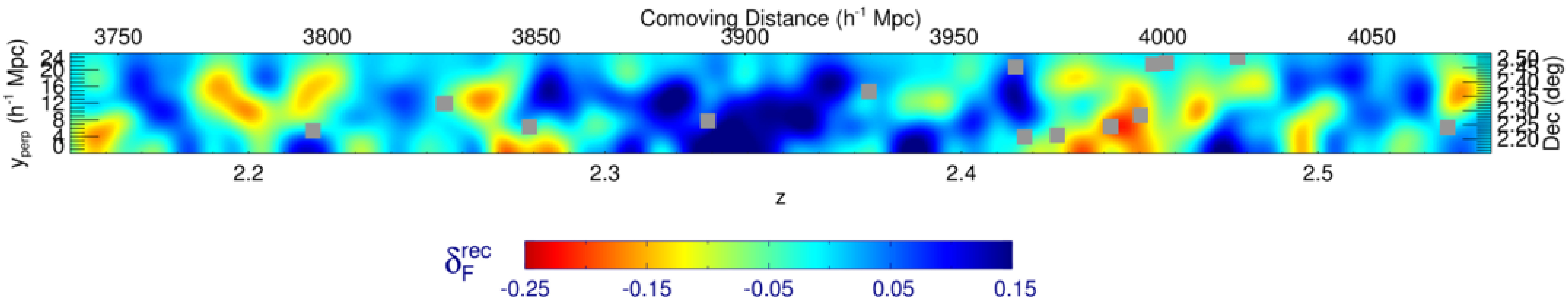

Slice #1: 149.950 < RA (deg) < 149.979
Comoving Distance (h⁻¹ Mpc)
3750
3800
3850
3900
3950
4000
4050
y_perp (h⁻¹ Mpc)
Dec (deg)
2.2
2.3
2.4
2.5
z
δ_F^rec
-0.25
-0.15
-0.05
0.05
0.15


2.15 < z < 2.55 Sightlines
z=2.35 Comoving Distance (h⁻¹ Mpc)
Dec (deg)
RA (deg)
150.4
150.3
150.2
150.1
150.0
2.2
2.3
2.4
2.5

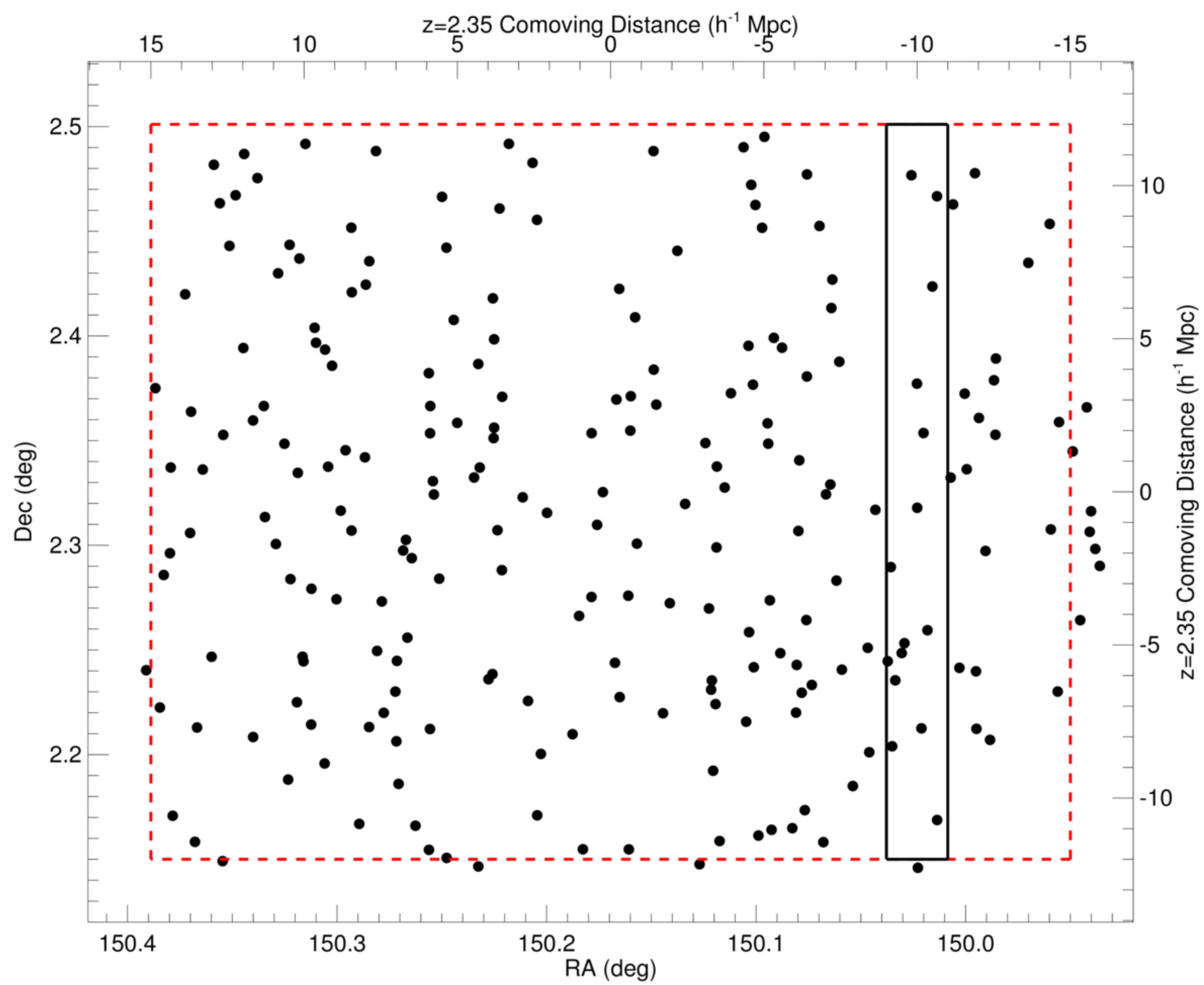

Slice #2: 149.979 < RA (deg) < 150.009
Comoving Distance (h^{-1} Mpc)
3750
3800
3850
3900
3950
4000
4050
y_{perp} (h^{-1} Mpc)
z
2.2
2.3
2.4
2.5
Dec (deg)
δ_F^{rec}
-0.25
-0.15
-0.05
0.05
0.15


2.15 < z < 2.55 Sightlines
z=2.35 Comoving Distance (h^{-1} Mpc)
15
10
5
0
-5
-10
-15
Dec (deg)
2.5
2.4
2.3
2.2
RA (deg)
150.4
150.3
150.2
150.1
150.0
z=2.35 Comoving Distance (h^{-1} Mpc)
10
5
0
-5
-10

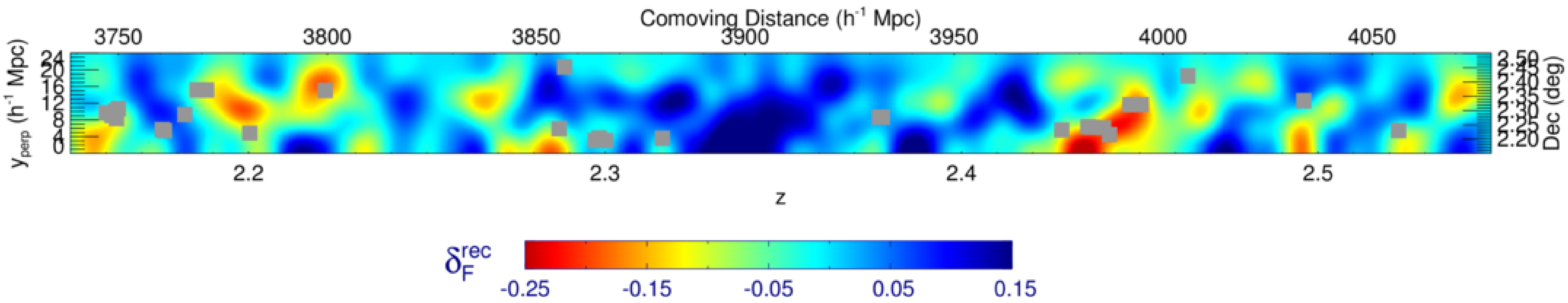
Slice #3: 150.009 < RA (deg) < 150.038



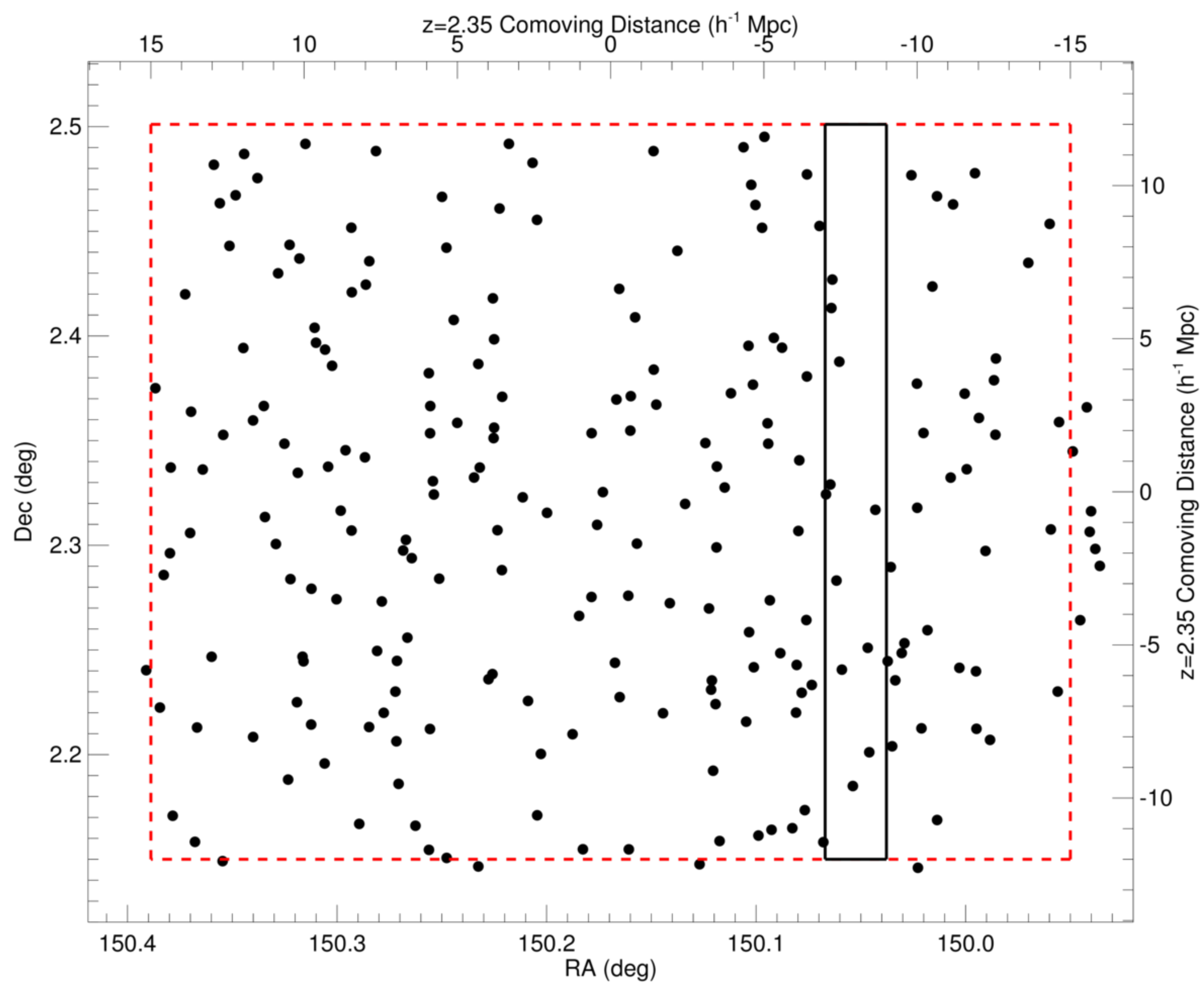
2.15 < z < 2.55 Sightlines

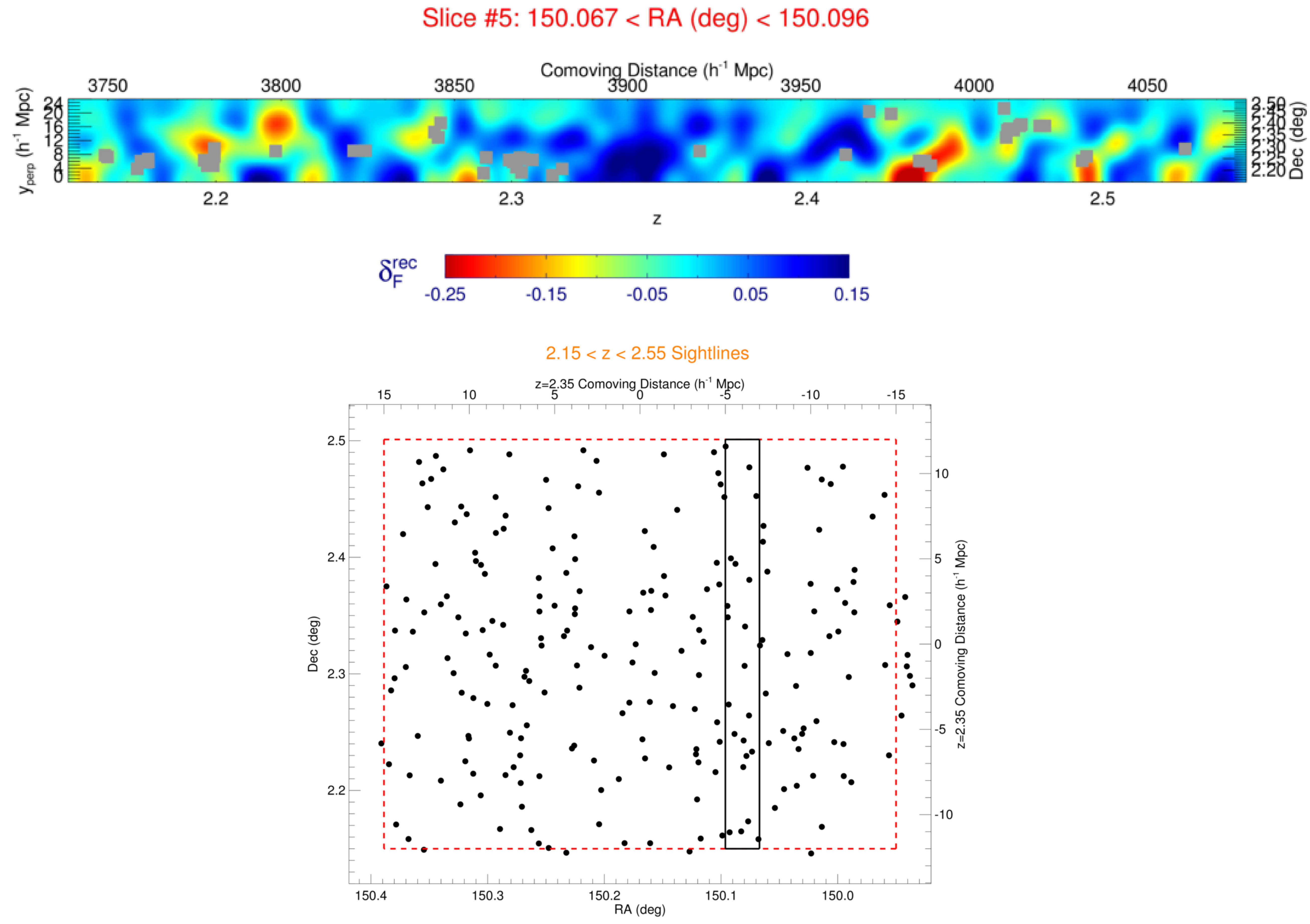


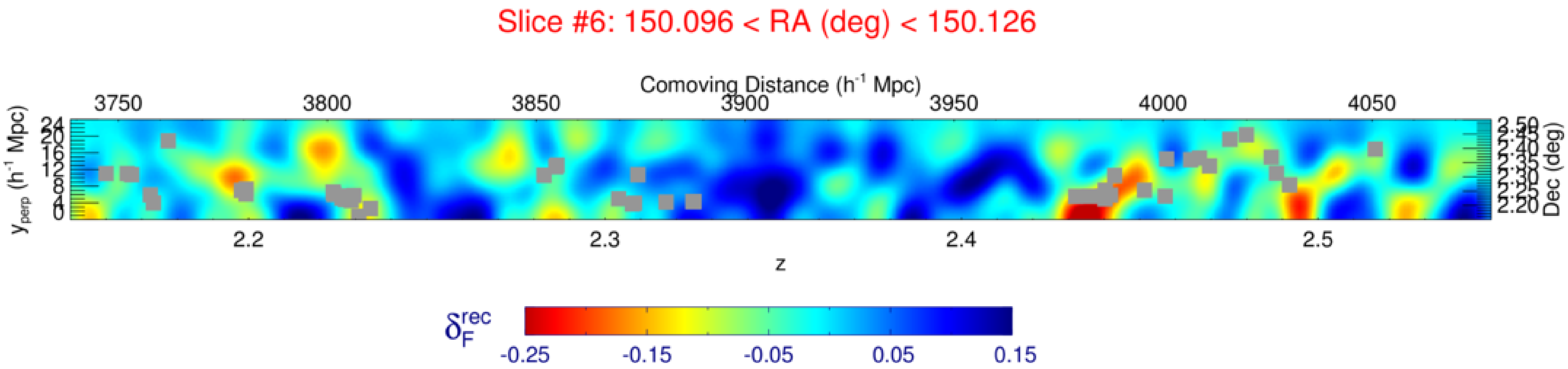
Slice #4: 150.038 < RA (deg) < 150.067

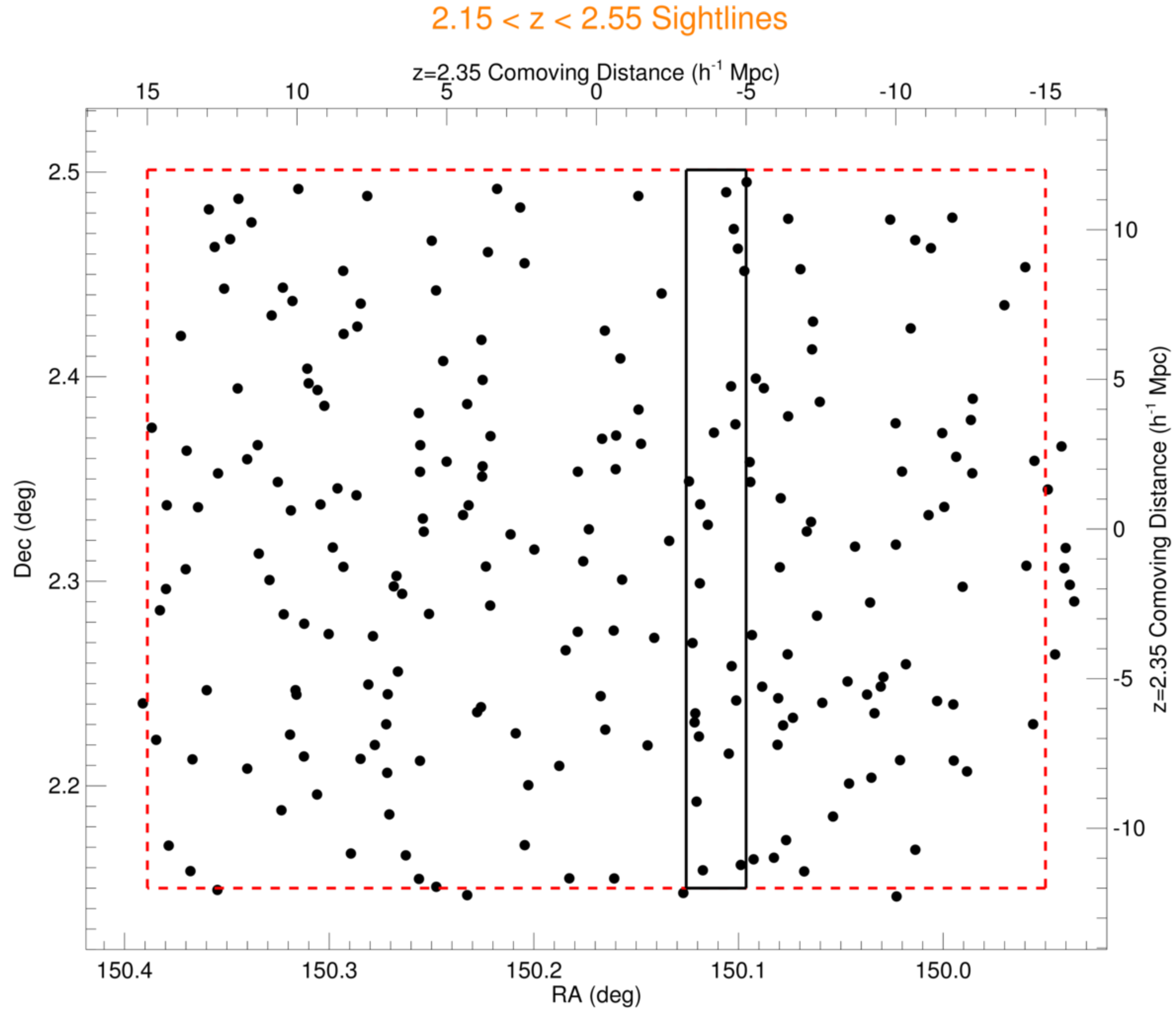


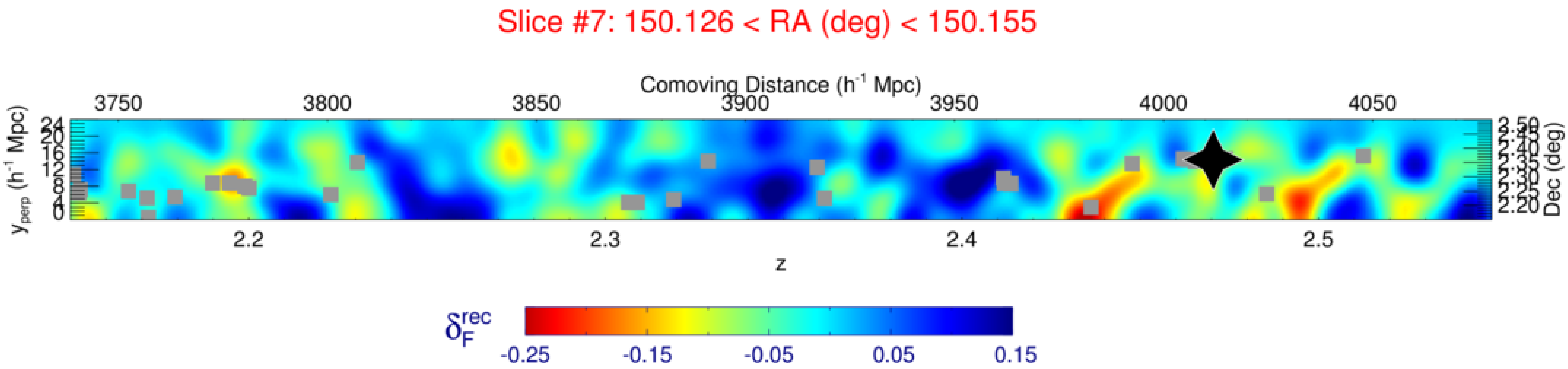
2.15 < z < 2.55 Sightlines

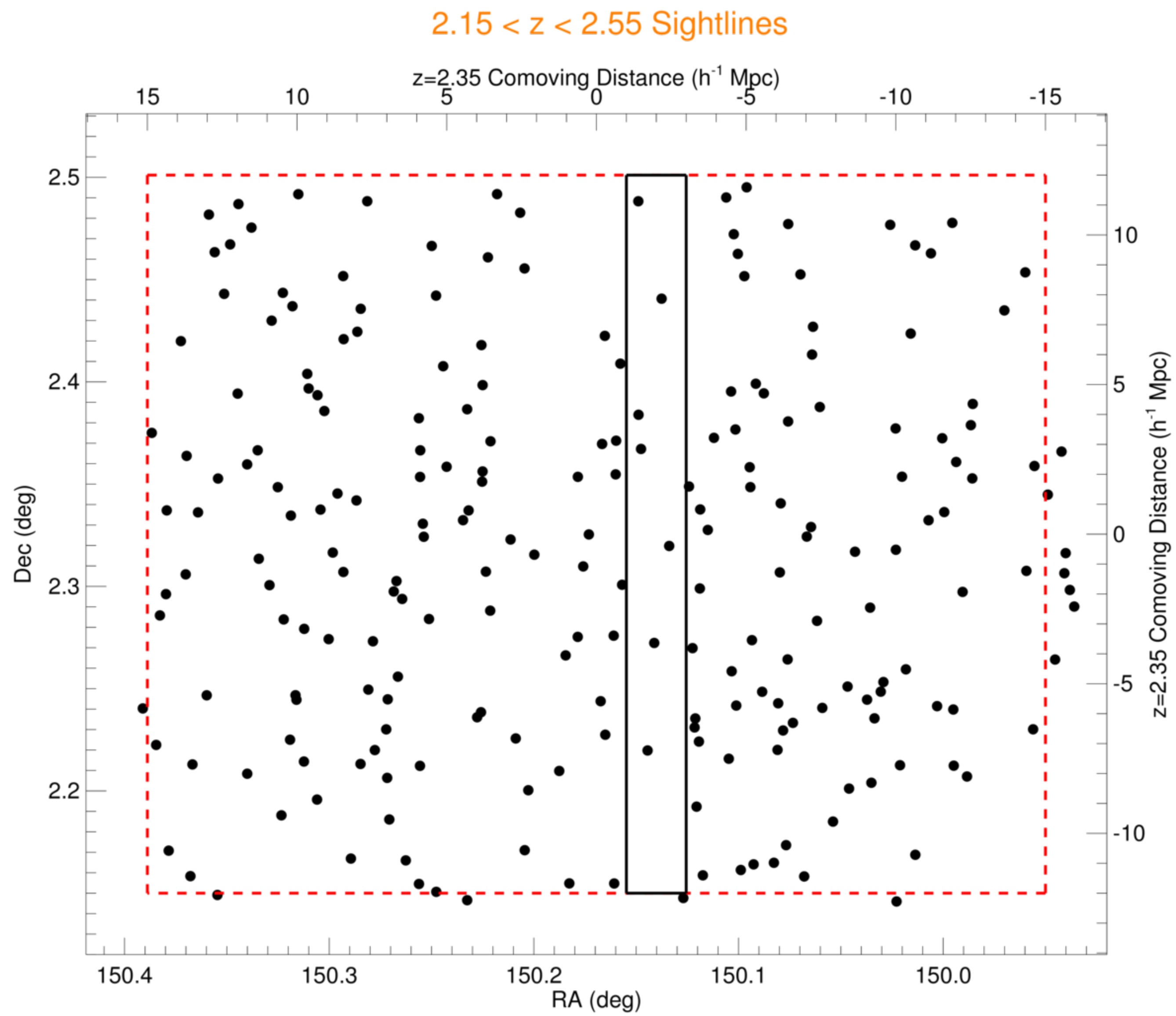



Slice #5: 150.067 < RA (deg) < 150.096
Comoving Distance (h⁻¹ Mpc)
3750
3800
3850
3900
3950
4000
4050
y_perp (h⁻¹ Mpc)
Dec (deg)
2.2
2.3
2.4
2.5
z
δ_F^rec
-0.25
-0.15
-0.05
0.05
0.15
2.15 < z < 2.55 Sightlines
z=2.35 Comoving Distance (h⁻¹ Mpc)
Dec (deg)
z=2.35 Comoving Distance (h⁻¹ Mpc)
RA (deg)
150.4
150.3
150.2
150.1
150.0

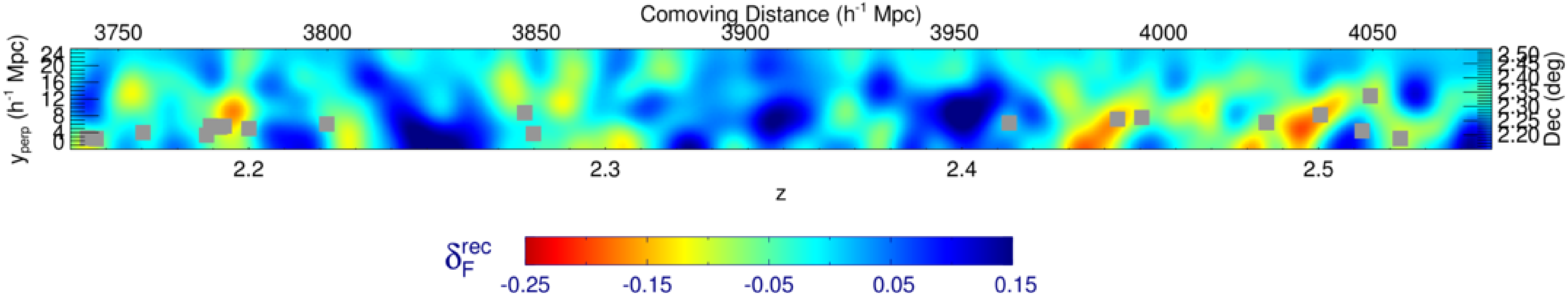

Slice #6: 150.096 < RA (deg) < 150.126
Comoving Distance (h⁻¹ Mpc)
3750
3800
3850
3900
3950
4000
4050
y_{perp} (h⁻¹ Mpc)
Dec (deg)
2.2
2.3
2.4
2.5
z
δ_F^{rec}
-0.25
-0.15
-0.05
0.05
0.15

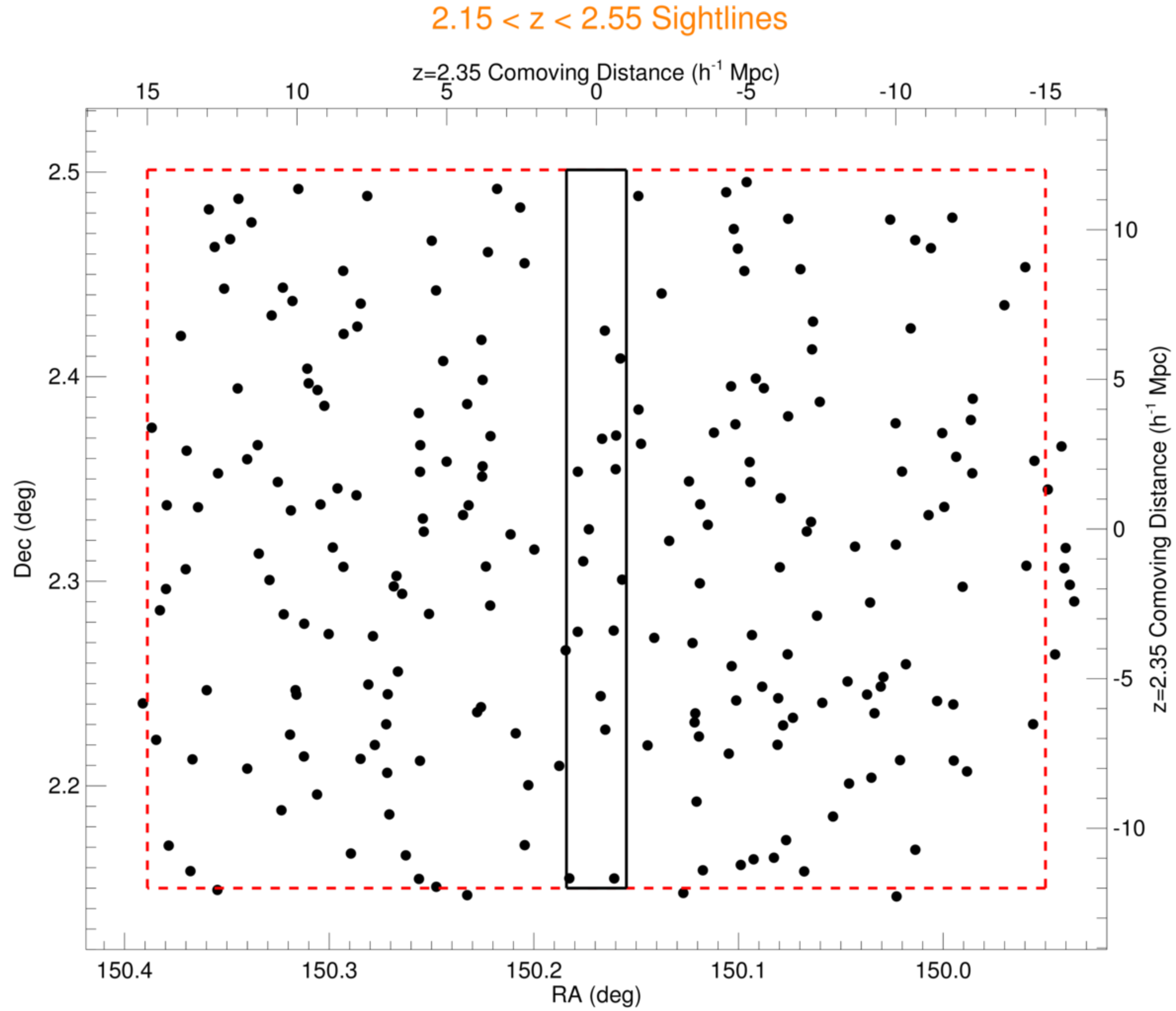

2.15 < z < 2.55 Sightlines
z=2.35 Comoving Distance (h⁻¹ Mpc)
15
10
5
0
-5
-10
-15
Dec (deg)
2.5
2.4
2.3
2.2
RA (deg)
150.4
150.3
150.2
150.1
150.0

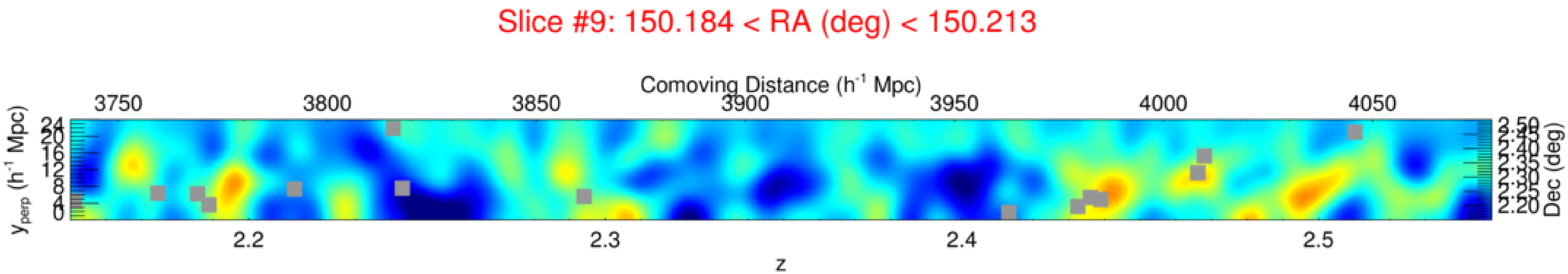

Slice #7: 150.126 < RA (deg) < 150.155
Comoving Distance (h^{-1} Mpc)
3750
3800
3850
3900
3950
4000
4050
y_{perp} (h^{-1} Mpc)
Dec (deg)
2.2
2.3
2.4
2.5
z
δ_F^{rec}
-0.25
-0.15
-0.05
0.05
0.15

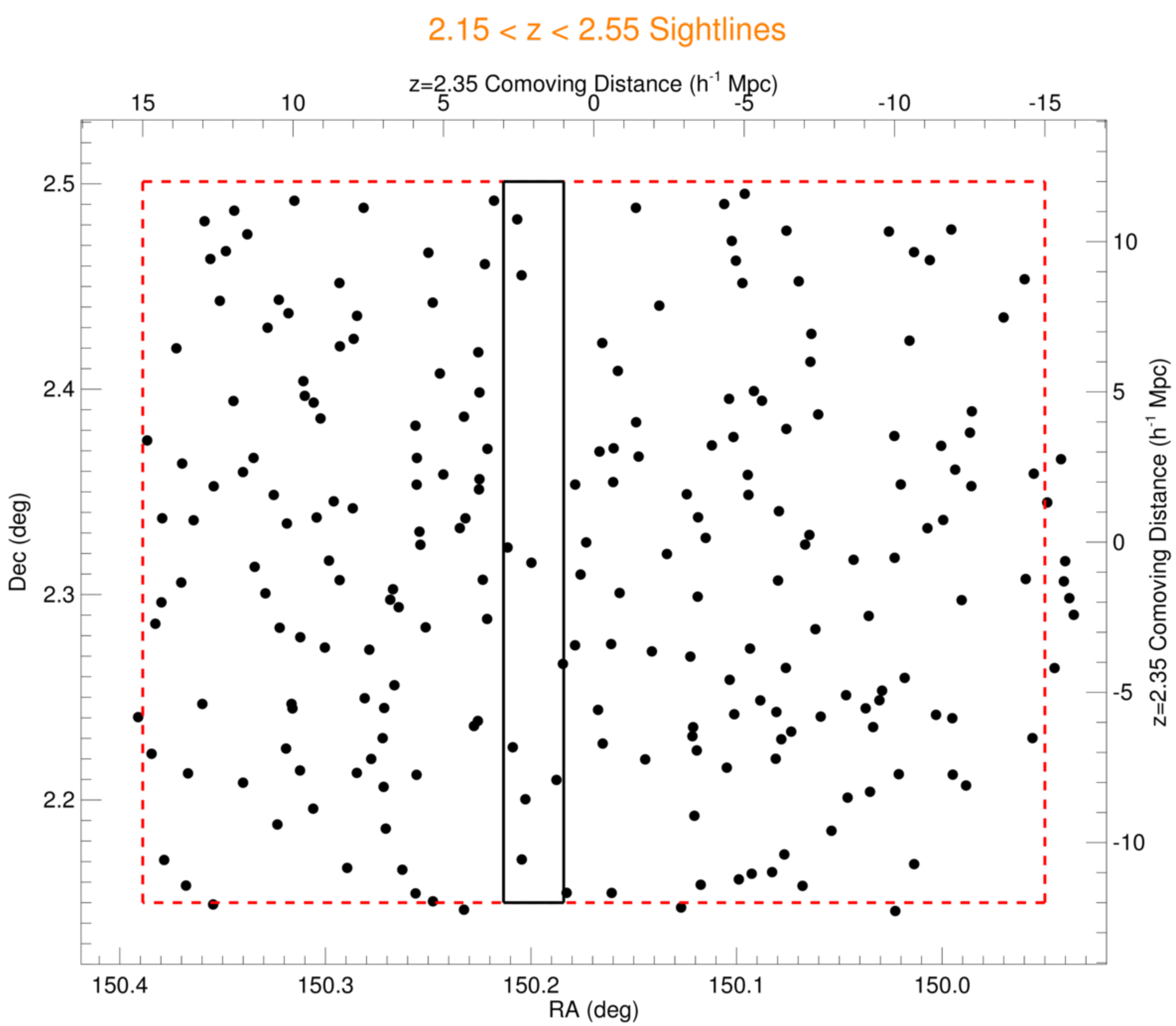

2.15 < z < 2.55 Sightlines
z=2.35 Comoving Distance (h^{-1} Mpc)
Dec (deg)
RA (deg)
150.4
150.3
150.2
150.1
150.0

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

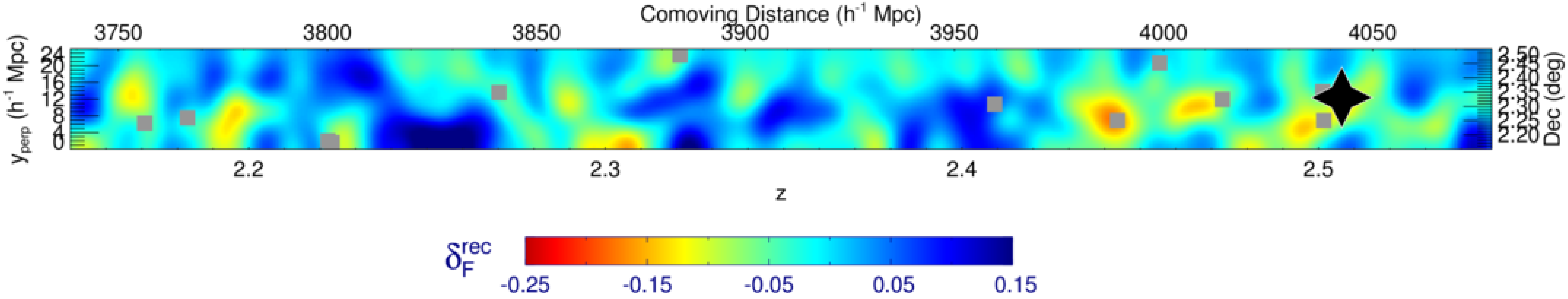




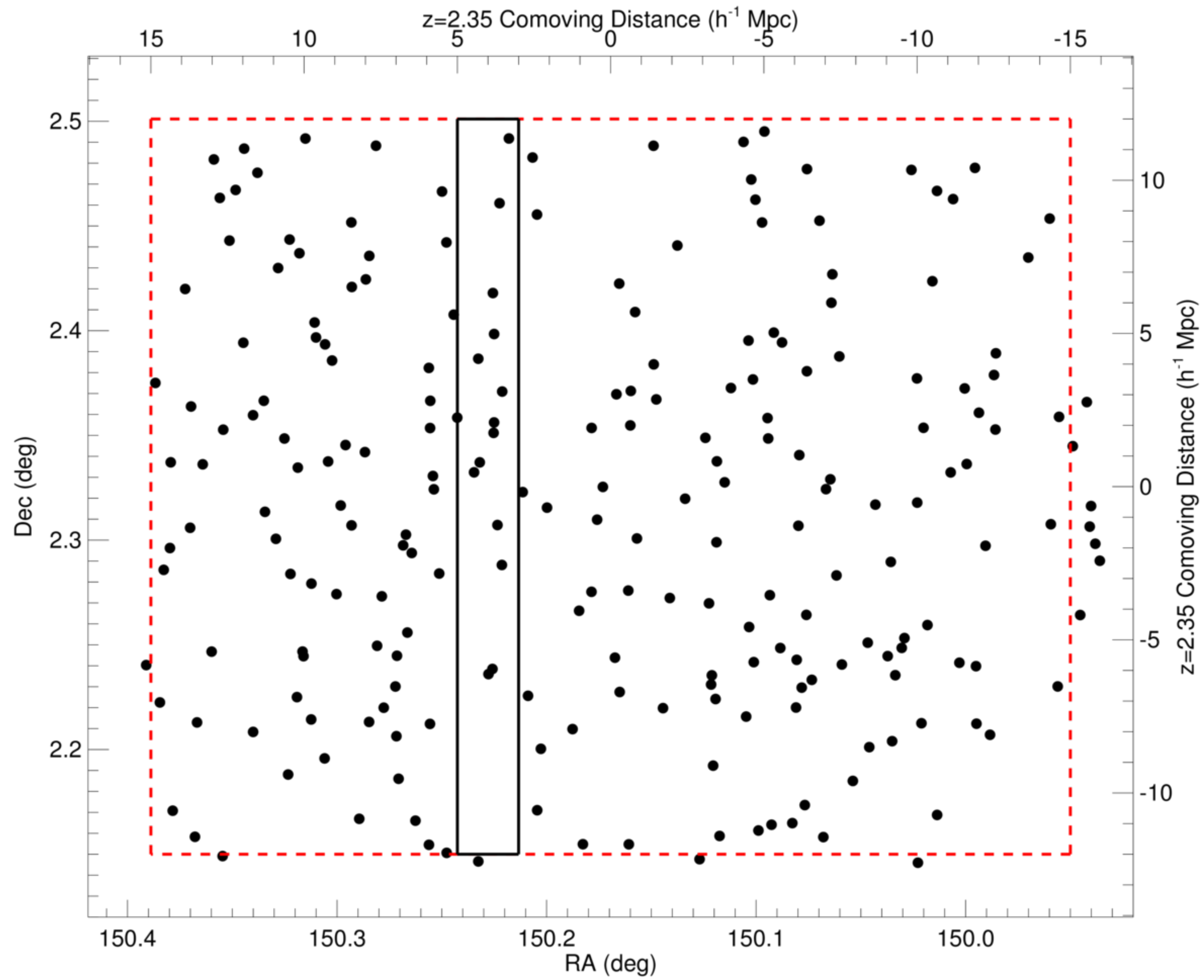

Slice #9: 150.184 < RA (deg) < 150.213
Comoving Distance (h⁻¹ Mpc)
3750
3800
3850
3900
3950
4000
4050
y_perp (h⁻¹ Mpc)
z
2.2
2.3
2.4
2.5
Dec (deg)
δ_F^rec
-0.25
-0.15
-0.05
0.05
0.15

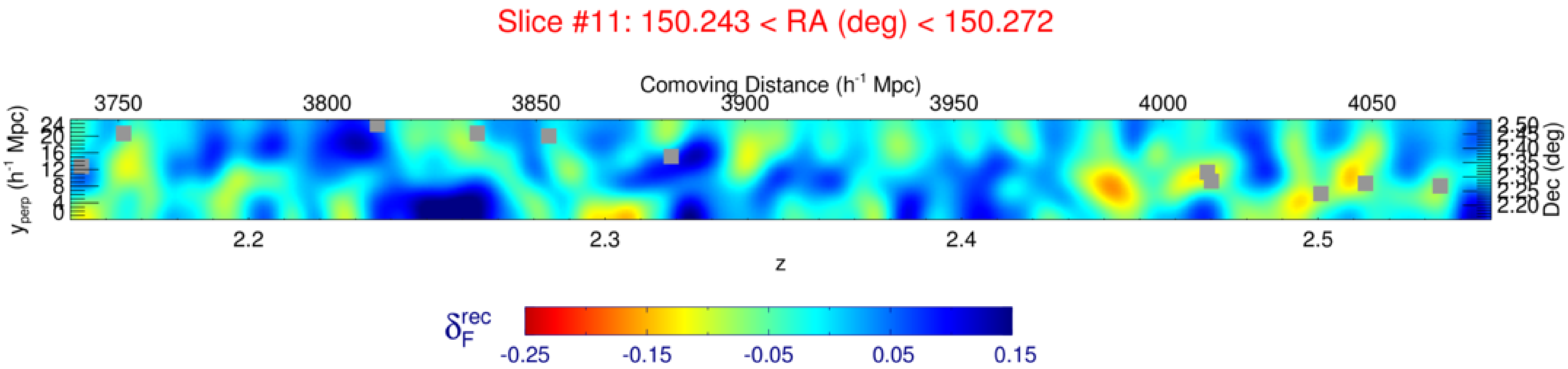

2.15 < z < 2.55 Sightlines
z=2.35 Comoving Distance (h⁻¹ Mpc)
15
10
5
0
-5
-10
-15
Dec (deg)
2.5
2.4
2.3
2.2
z=2.35 Comoving Distance (h⁻¹ Mpc)
RA (deg)
150.4
150.3
150.2
150.1
150.0

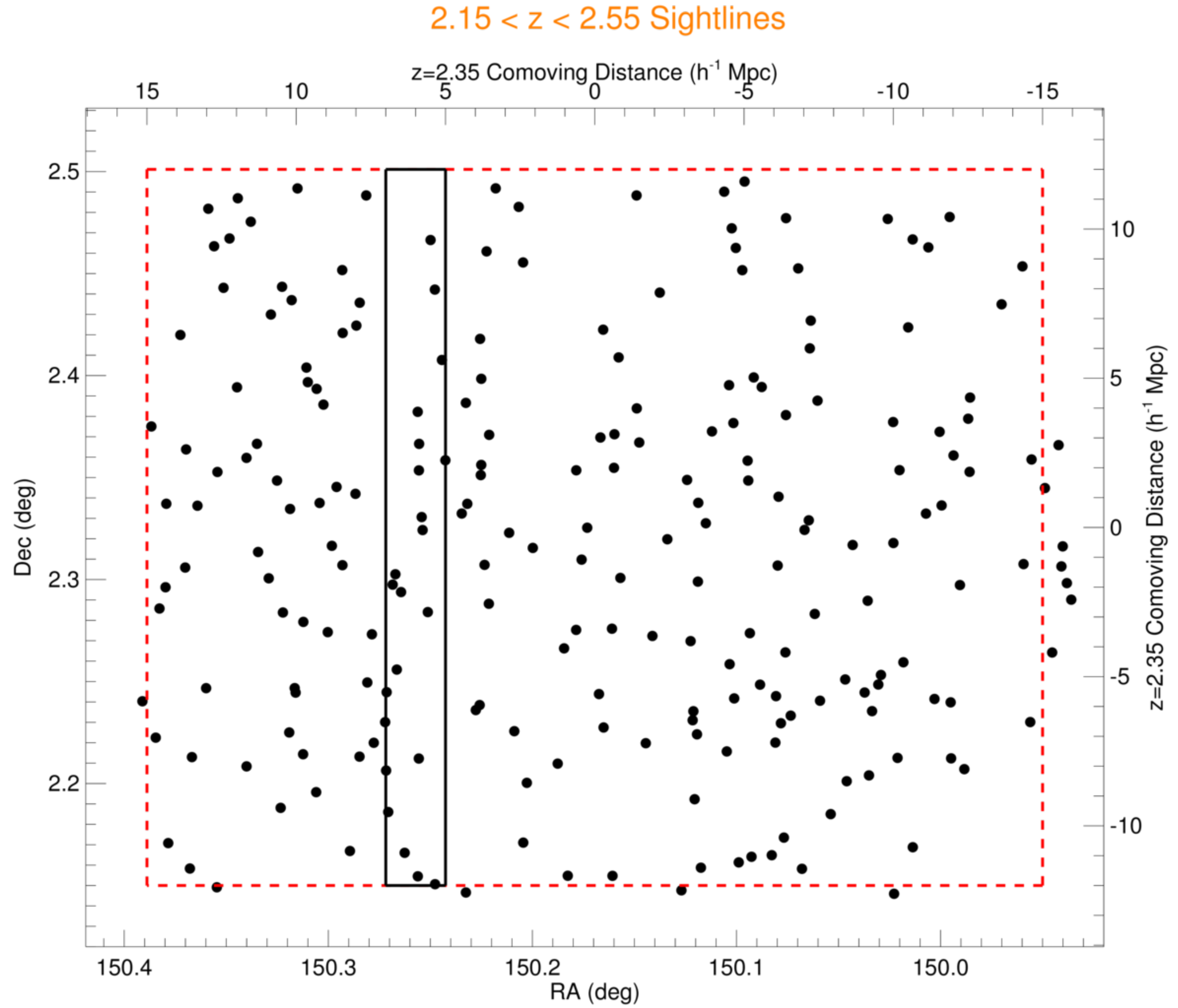
Slice #10: 150.213 < RA (deg) < 150.243



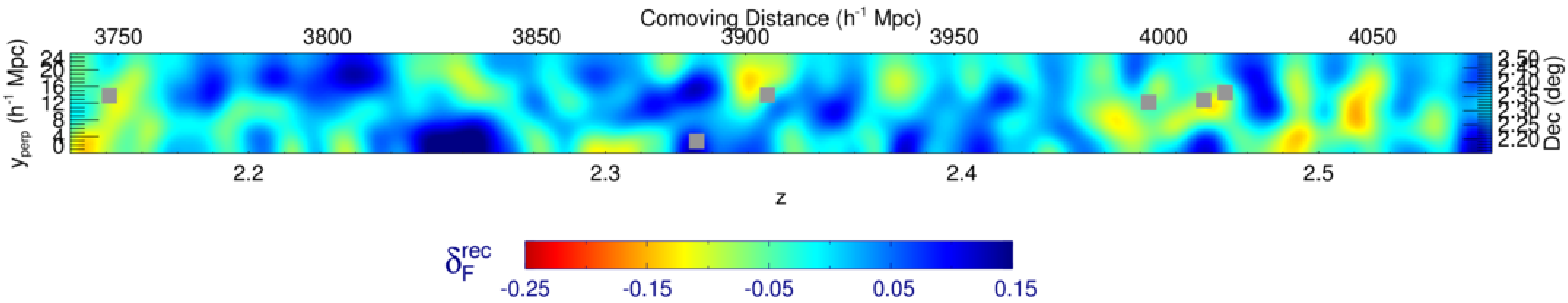
2.15 < z < 2.55 Sightlines



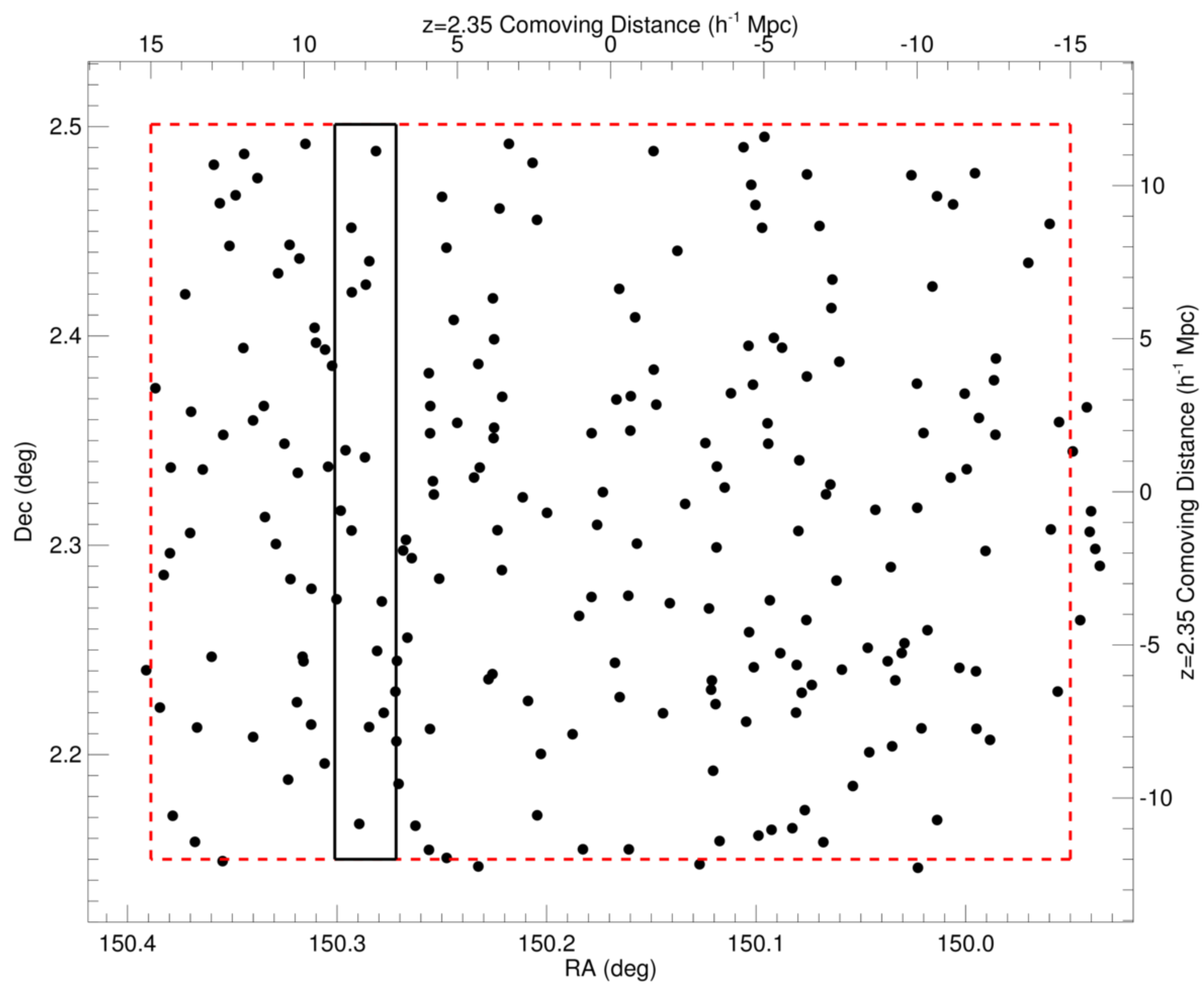

Slice #11: 150.243 < RA (deg) < 150.272
Comoving Distance (h⁻¹ Mpc)
3750
3800
3850
3900
3950
4000
4050
y_perp (h⁻¹ Mpc)
Dec (deg)
2.2
2.3
2.4
2.5
z
δ_F^rec
-0.25
-0.15
-0.05
0.05
0.15


2.15 < z < 2.55 Sightlines
z=2.35 Comoving Distance (h⁻¹ Mpc)
Dec (deg)
RA (deg)
150.4
150.3
150.2
150.1
150.0
z=2.35 Comoving Distance (h⁻¹ Mpc)

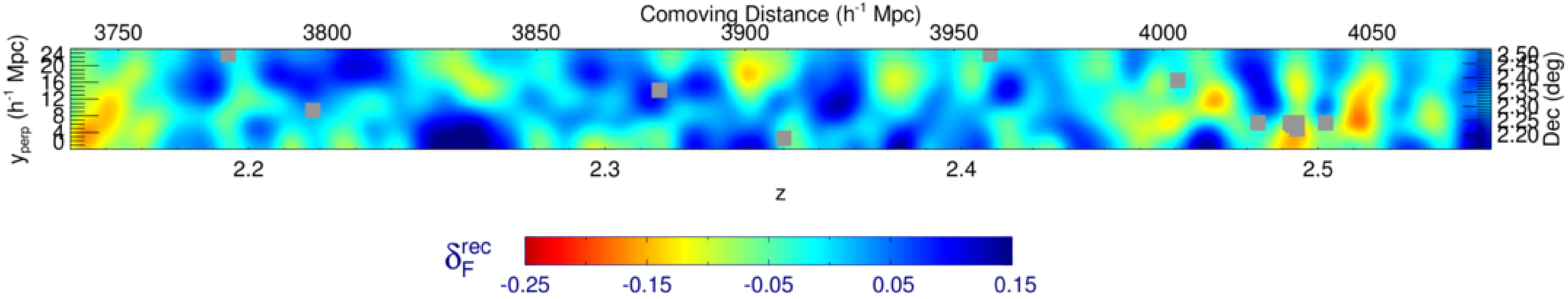
Slice #12: 150.272 < RA (deg) < 150.301



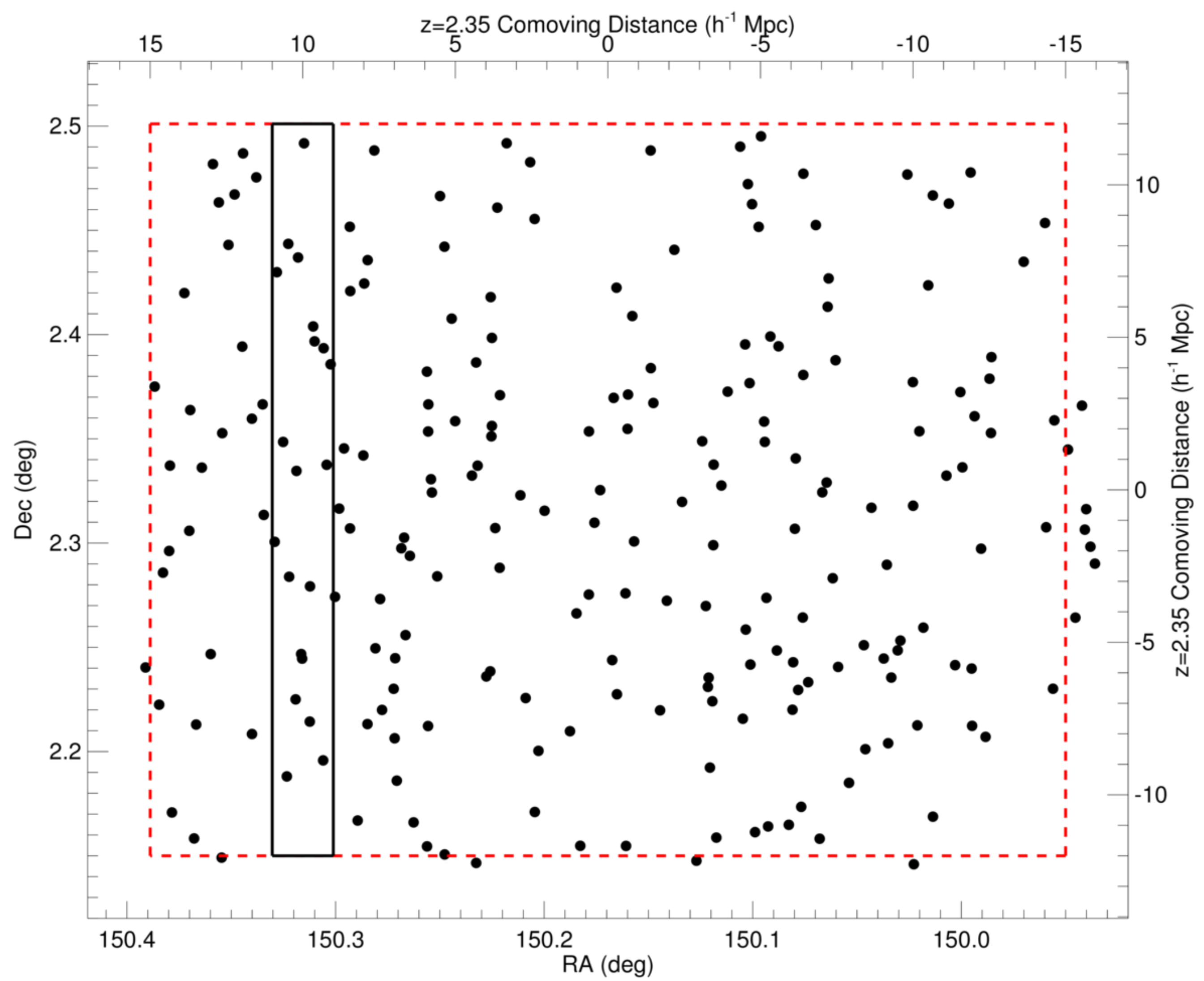
2.15 < z < 2.55 Sightlines

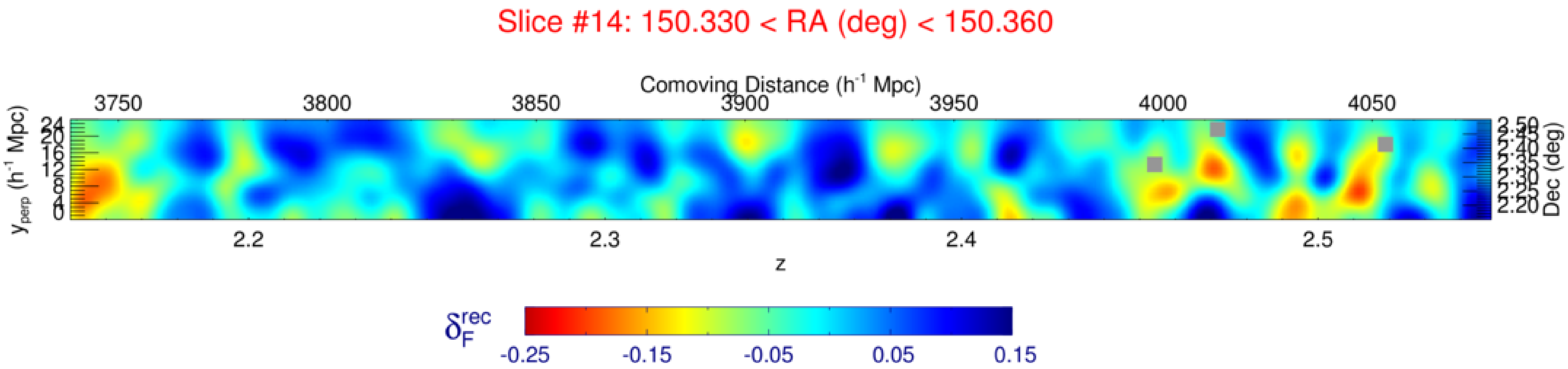


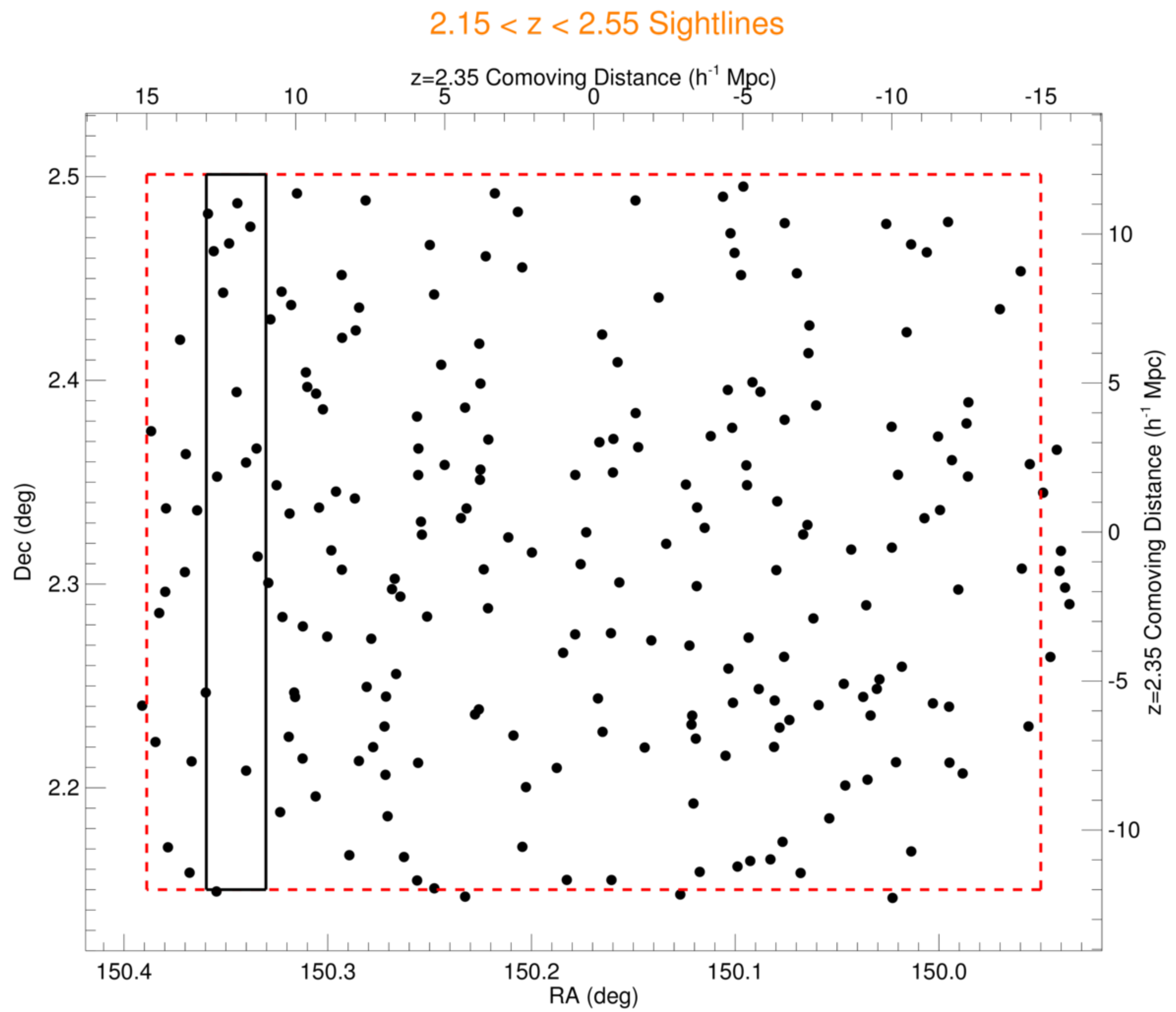
Slice #13: 150.301 < RA (deg) < 150.330



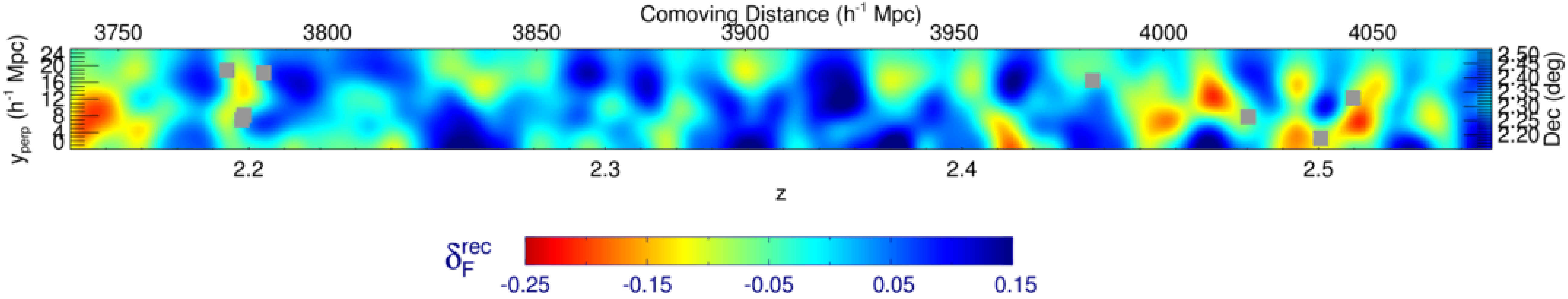
2.15 < z < 2.55 Sightlines




Slice #14: 150.330 < RA (deg) < 150.360
Comoving Distance (h^-1 Mpc)
3750
3800
3850
3900
3950
4000
4050
y_perp (h^-1 Mpc)
Dec (deg)
2.2
2.3
2.4
2.5
z
δ_F^rec
-0.25
-0.15
-0.05
0.05
0.15


2.15 < z < 2.55 Sightlines
z=2.35 Comoving Distance (h^-1 Mpc)
15
10
5
0
-5
-10
-15
Dec (deg)
2.5
2.4
2.3
2.2
z=2.35 Comoving Distance (h^-1 Mpc)
150.4
150.3
150.2
150.1
150.0
RA (deg)

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



2.15 < z < 2.55 Sightlines