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

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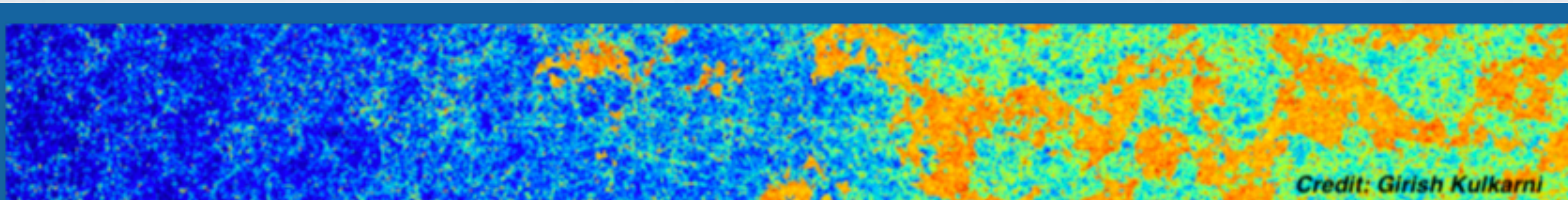
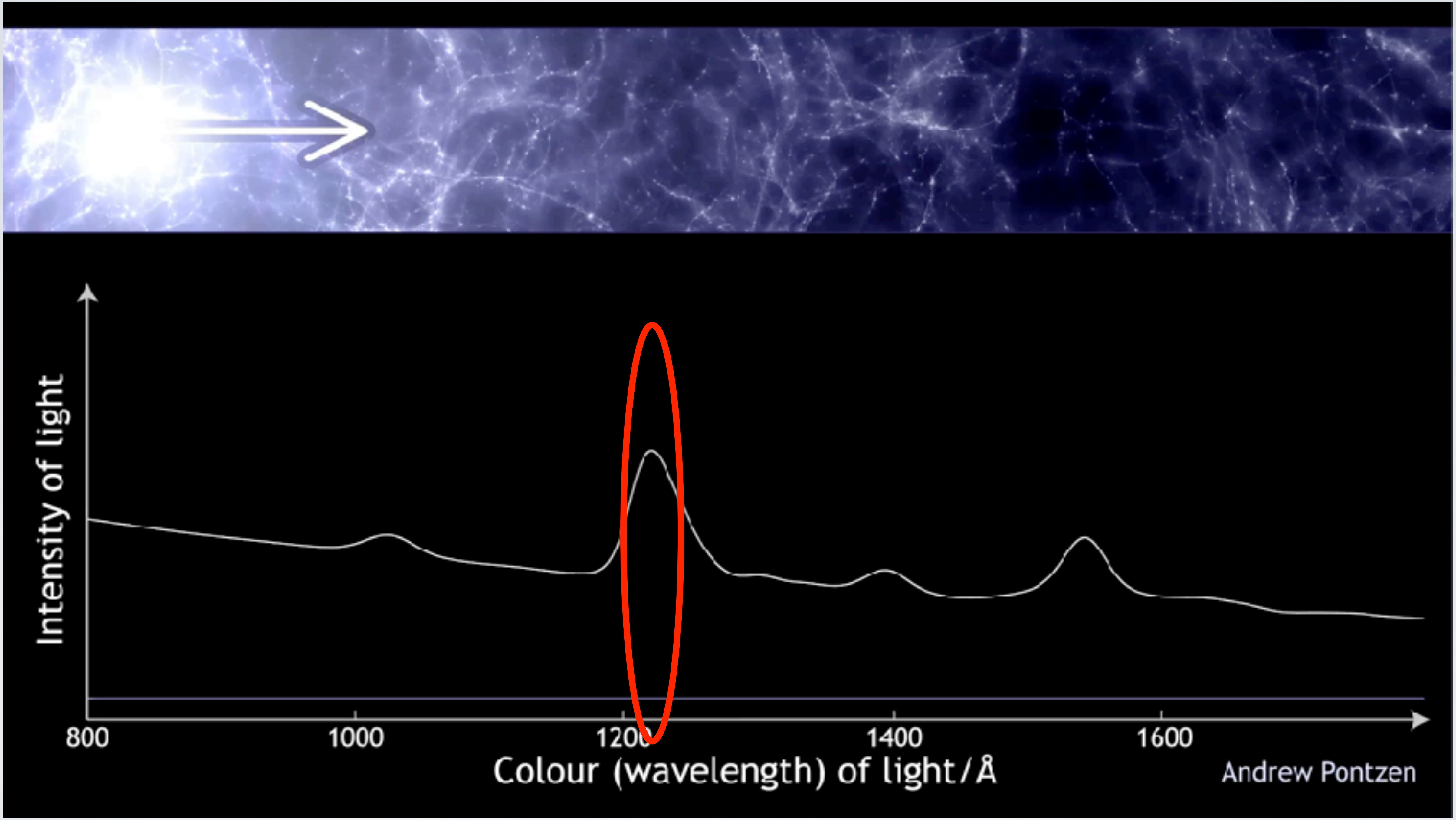


IGM2018: Revealing Cosmology and Reionization History with the Intergalactic Medium

18-21 September 2018
Kavli IPMU, Kashiwa, Japan

http://ipmu.jp/igm2018

The Lyman-alpha Forest Absorption at z>2



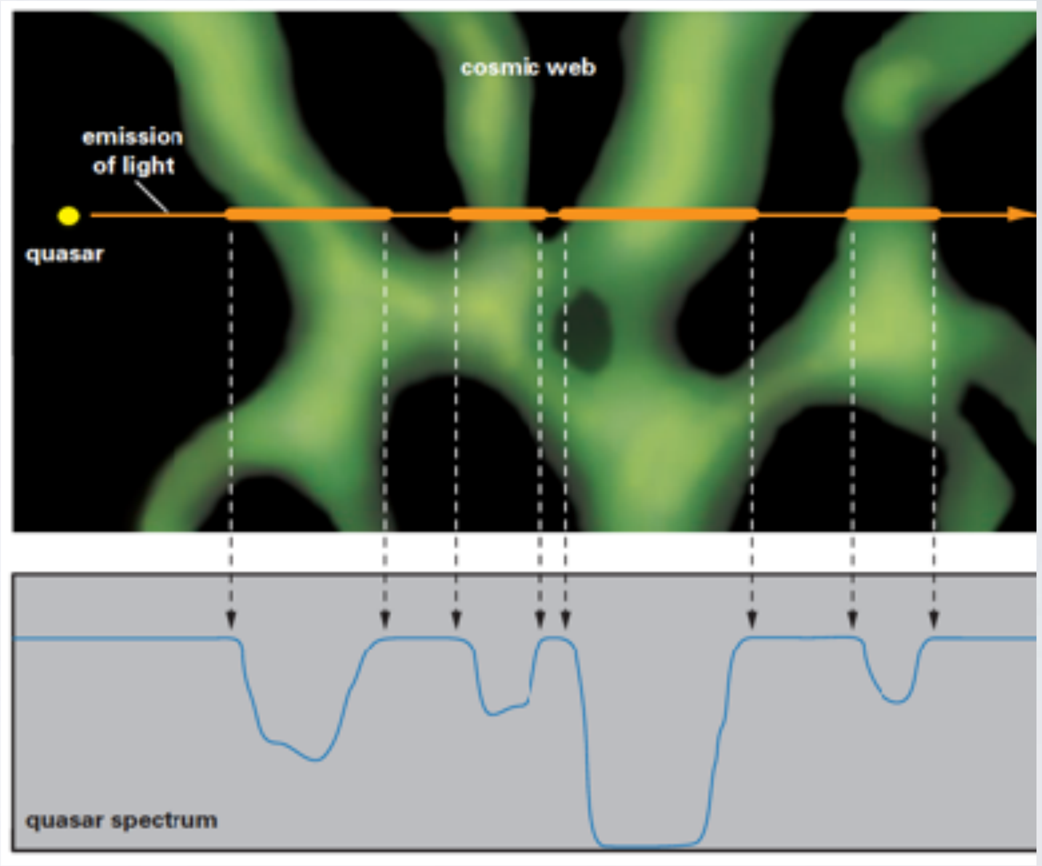
Restframe 1215.67Å absorption from neutral HI in intergalactic medium

Fluctuating Gunn-Peterson Approximation (FGPA)

- Current paradigm for large-scale IGM: ~uniform optically-thin photo-ionization (ignoring DLAs etc)
- 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 Γ_{bg}, IGM temperature T_0, slope of temperature-density relationship γ



Credit: Rob Simcoe

In this talk, I assume

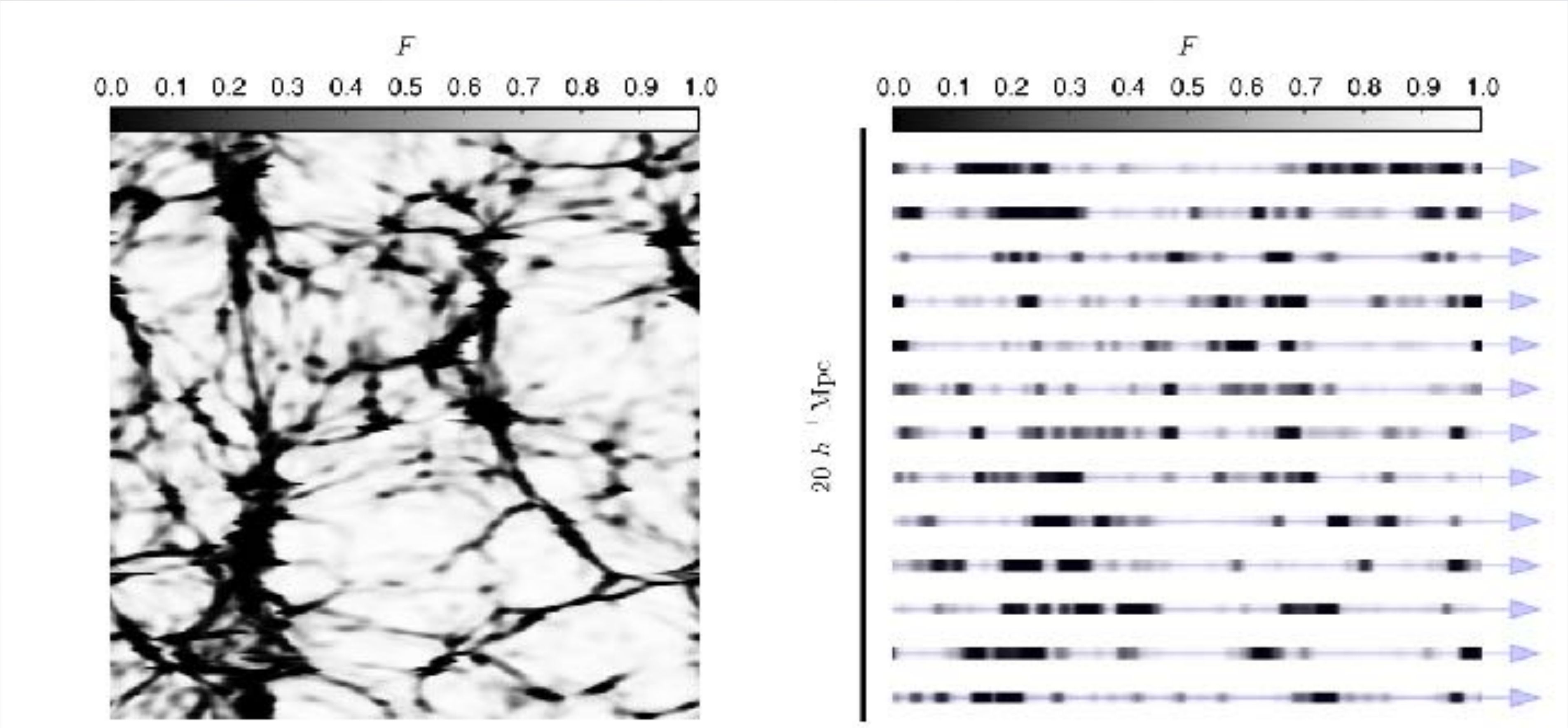
$$\tau_\alpha(x) \leftrightarrow \Delta(x)$$

(absorption traces large-scale structure)

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

IGM Tomography: Mapping 3D Ly-alpha forest

- 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*)

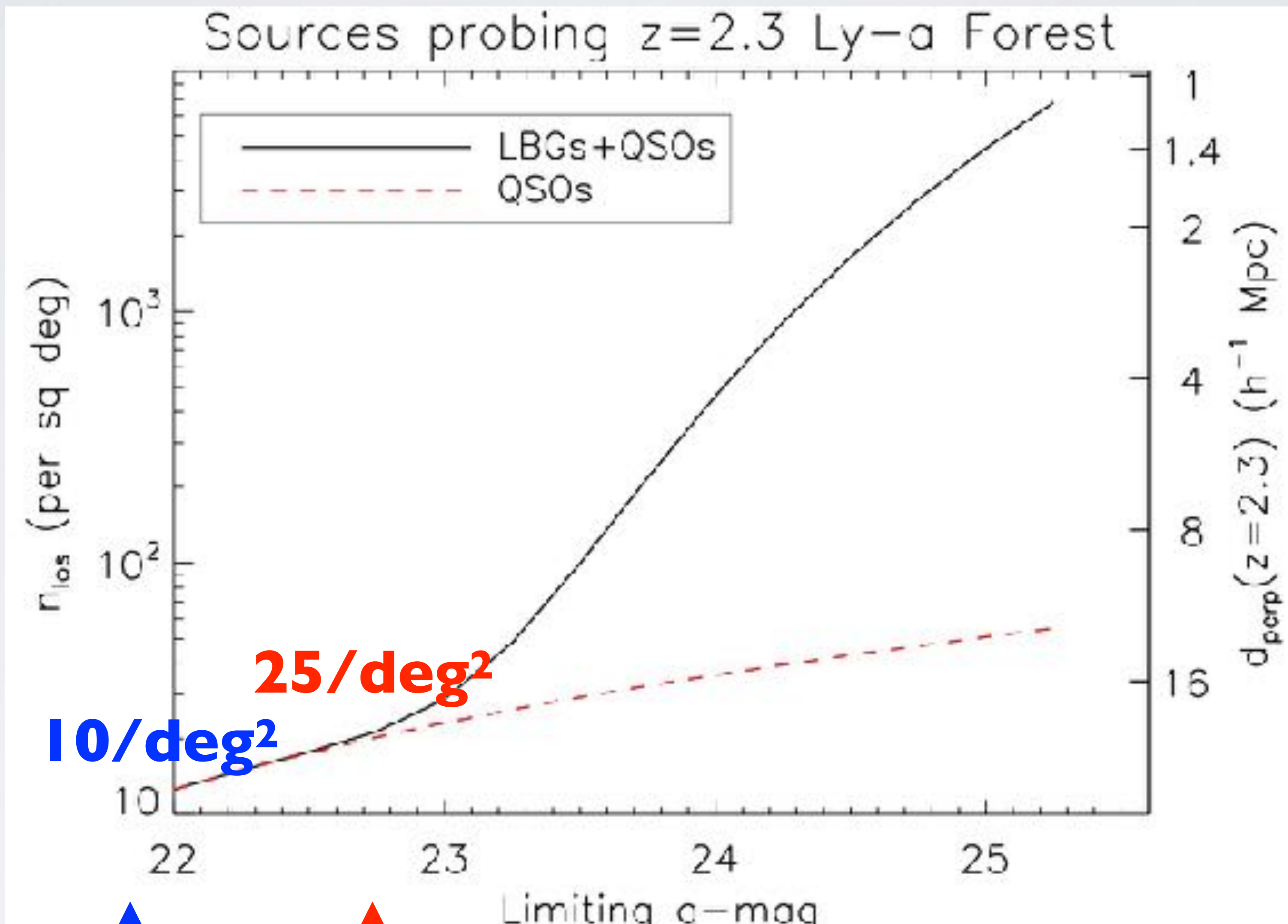


Credit: Casey Stark (UC Berkeley)

Going fainter → More sightlines → Smaller scales

GOING BEYOND QUASARS FOR LY-ALPHA FOREST

of Ly-a forest sightlines per sq deg



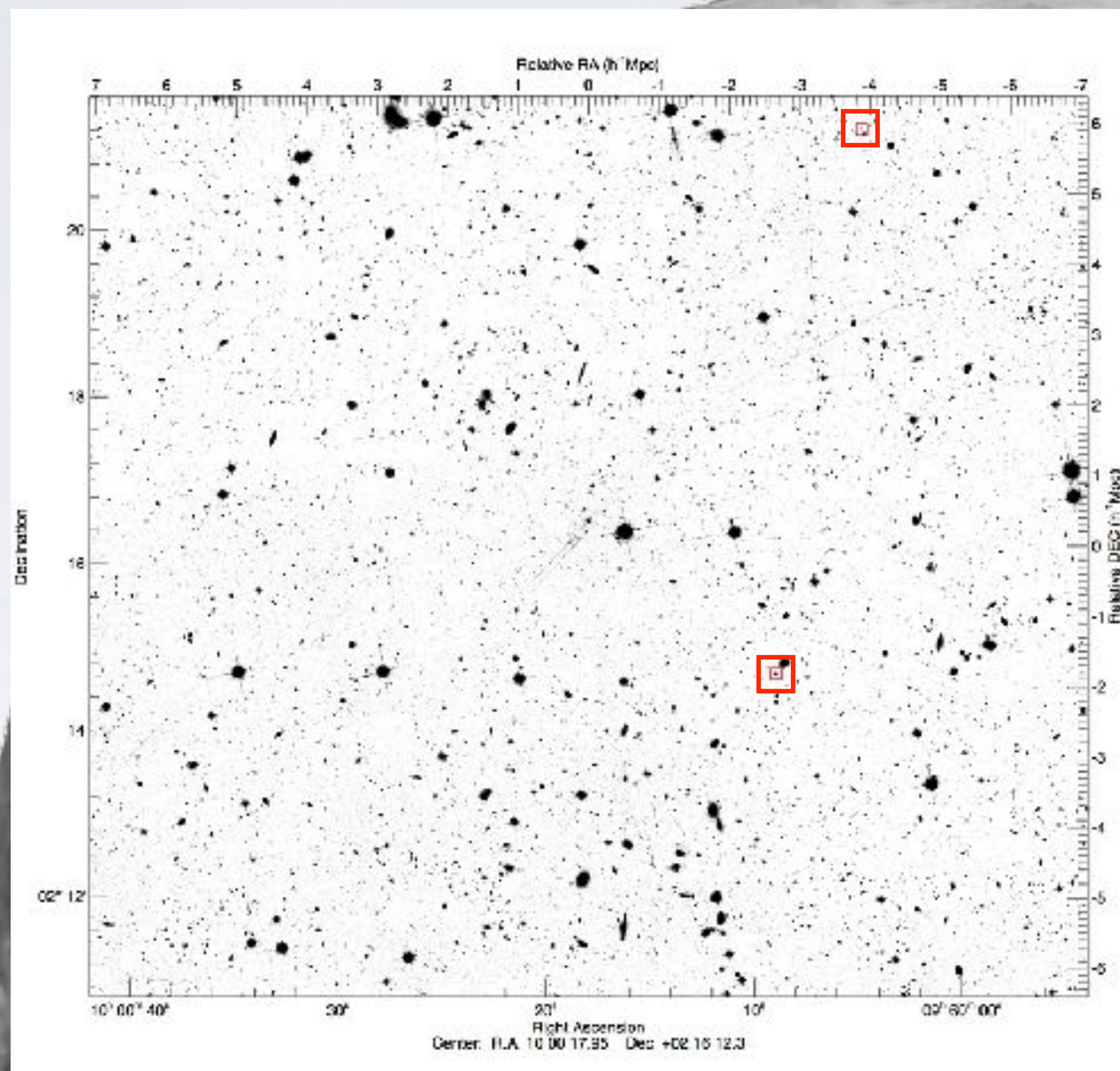
Average sightline separation

BOSS (2.5m)

DESI (4m)

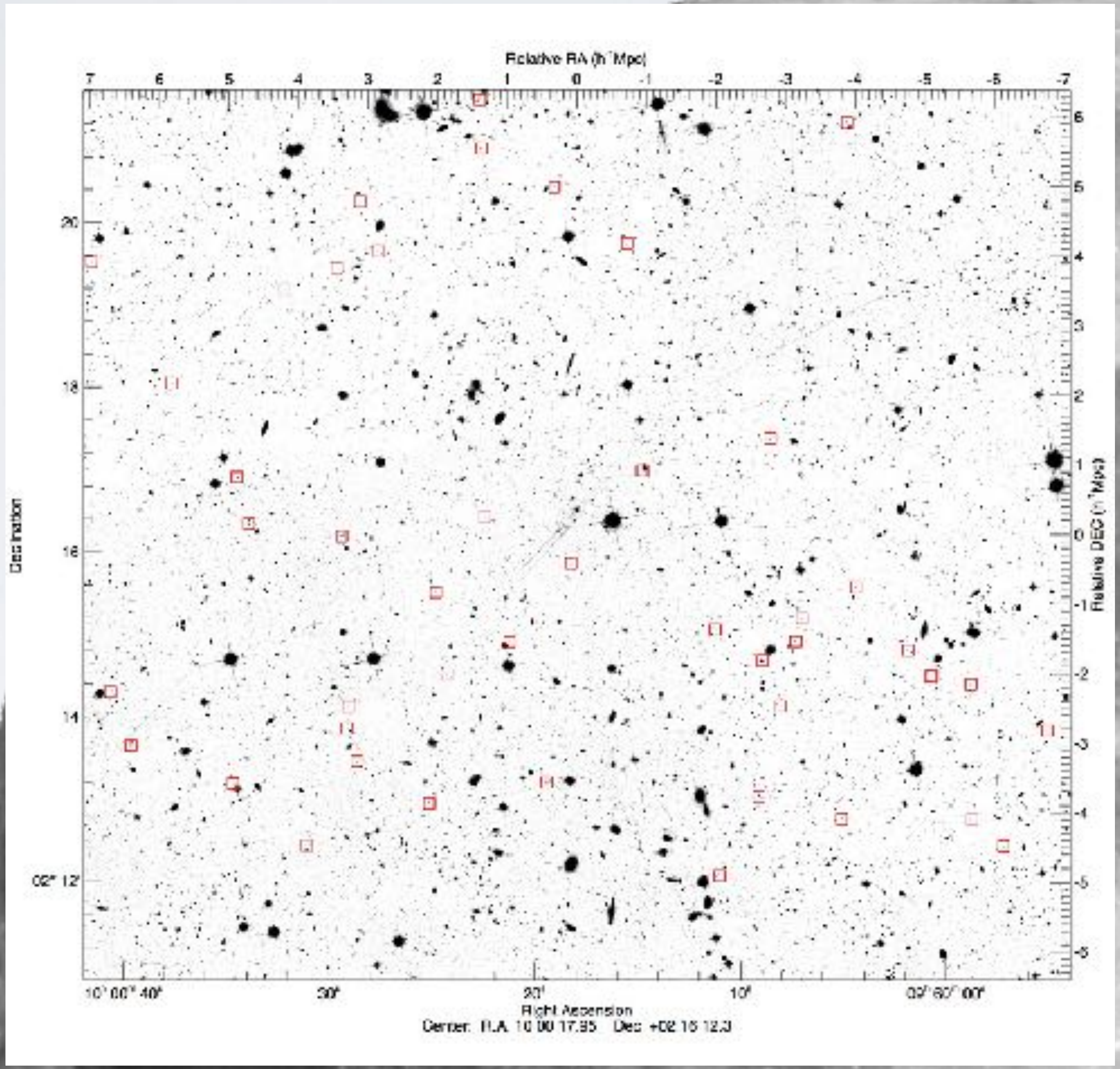
Huge jump in sightline availability with LBGs/star-forming galaxies!

Sources Within A 12’x12’ Field



mag<22.5 QSOs at 2.3<z<3.0

Sources Within A 12'x12' Field

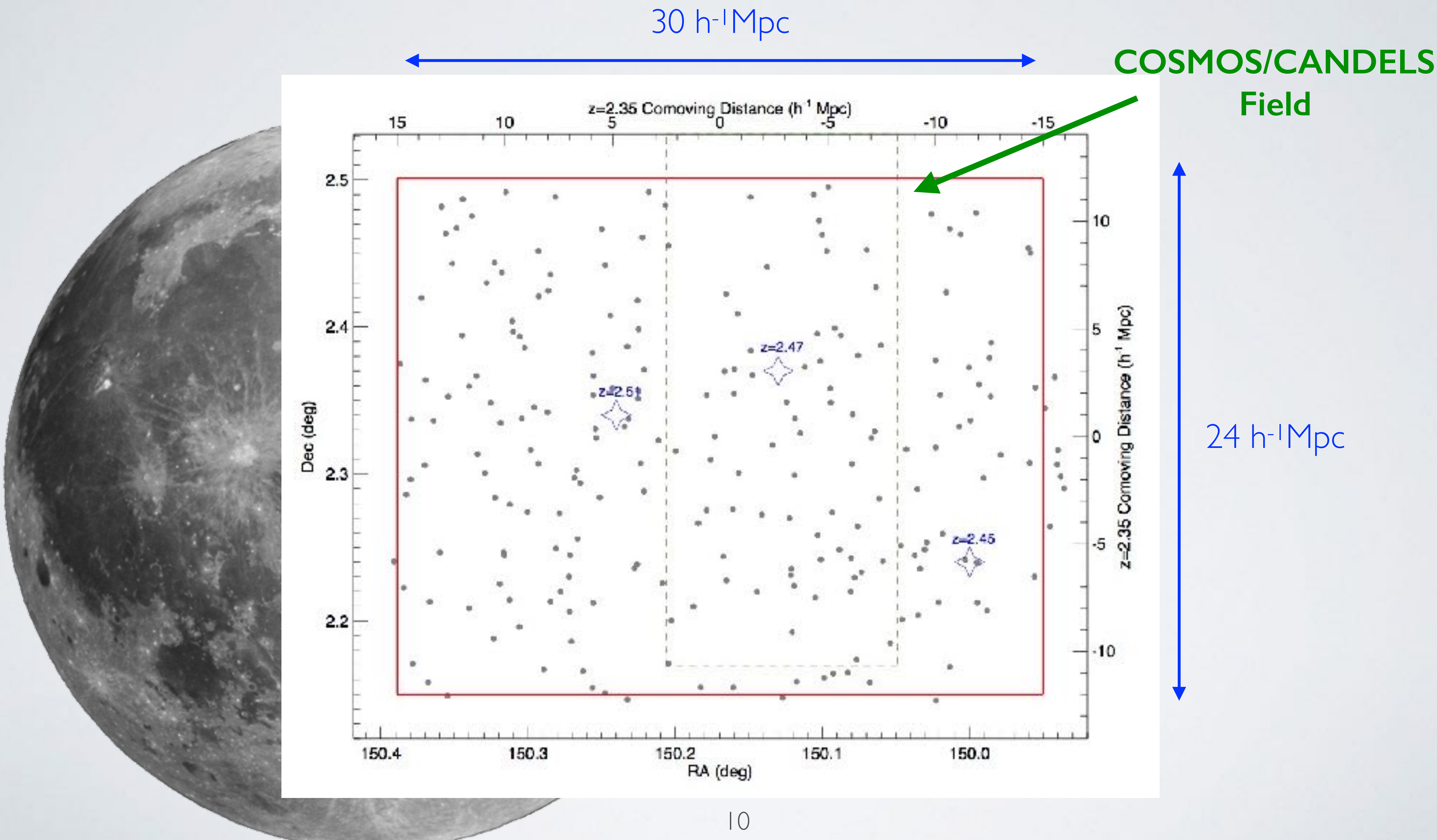


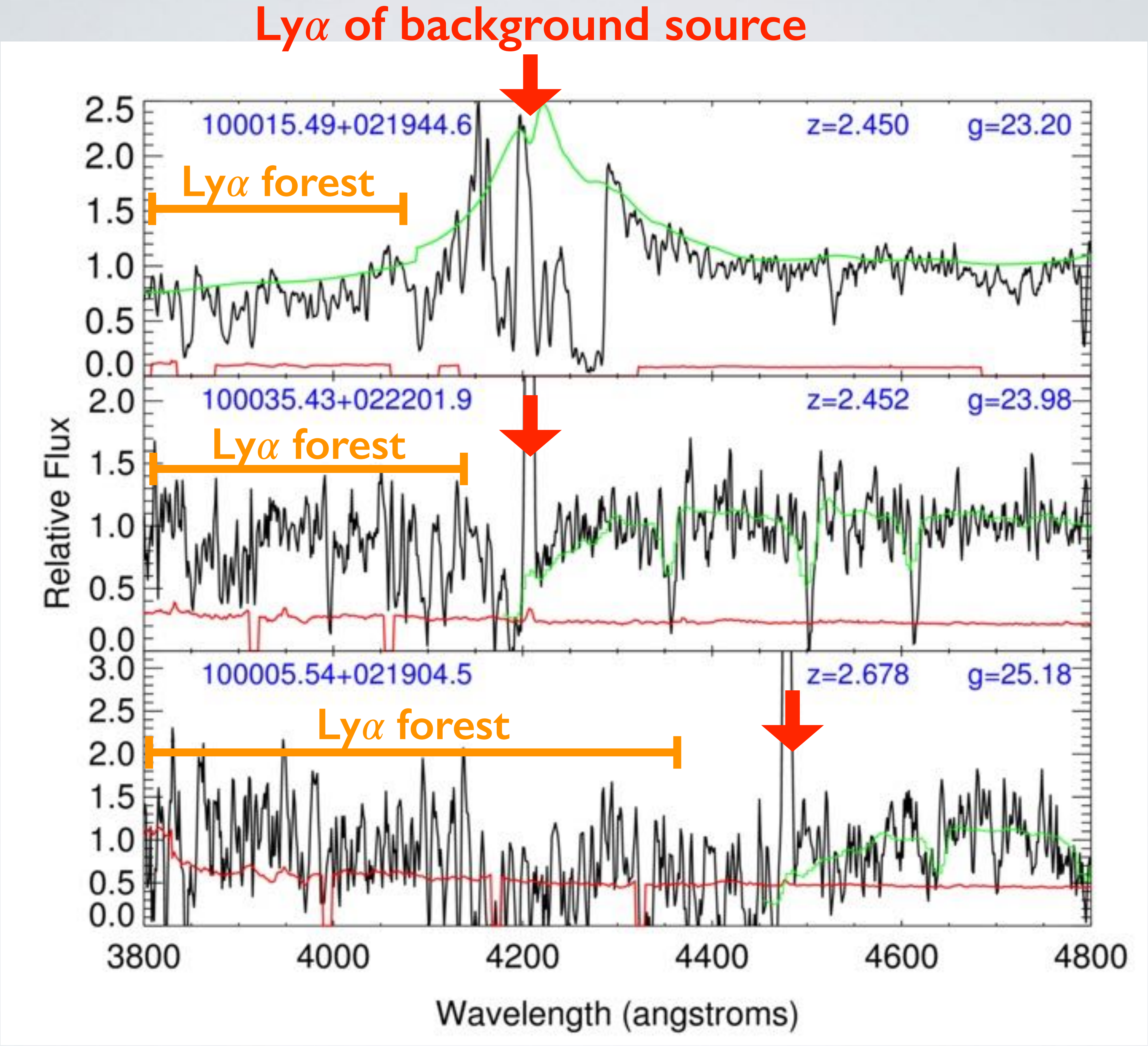
mag<24.5 QSOs+Galaxies at 2.3<z<3.0

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 ~2.5h^{-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 $d_\perp = 2.4 h^{-1}$Mpc





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**

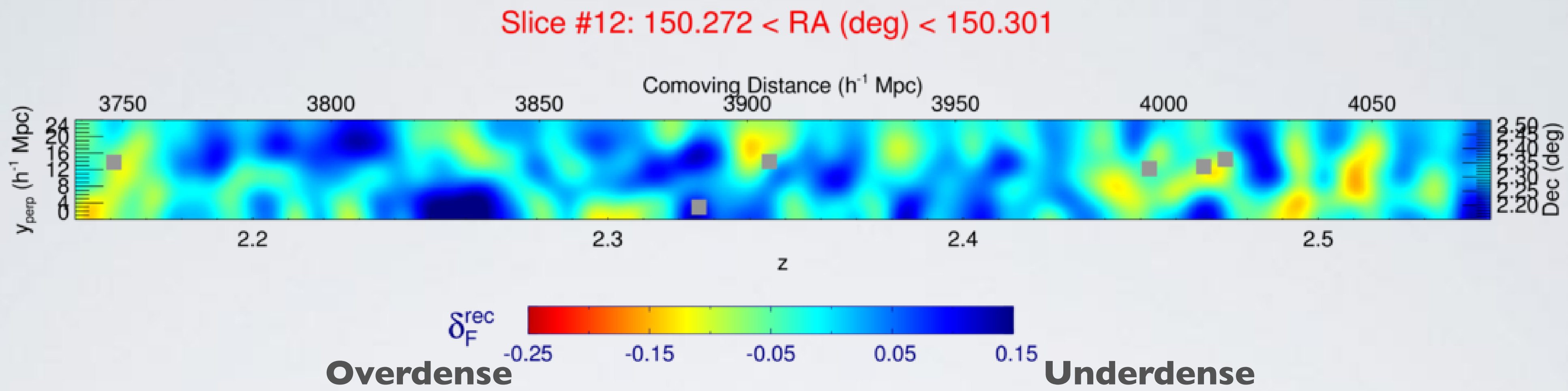
$$\mathbf{M} = \mathbf{C}_{MD} \cdot (\mathbf{C}_{DD} + \mathbf{N})^{-1} \cdot D$$

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

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

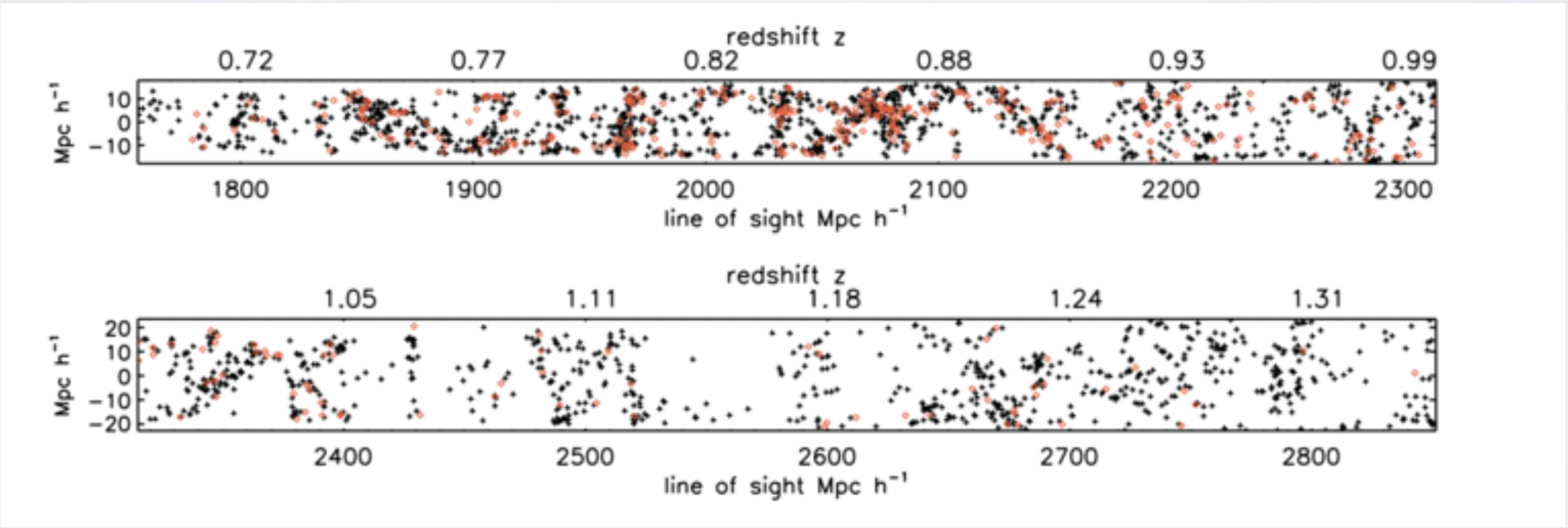
- $L_{||}=2.5h^{-1}$Mpc and $L_{\perp}=2.0h^{-1}$Mpc are set by the sightline separation and resolution, $\sigma_F=0.8$ is the variance of the map

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

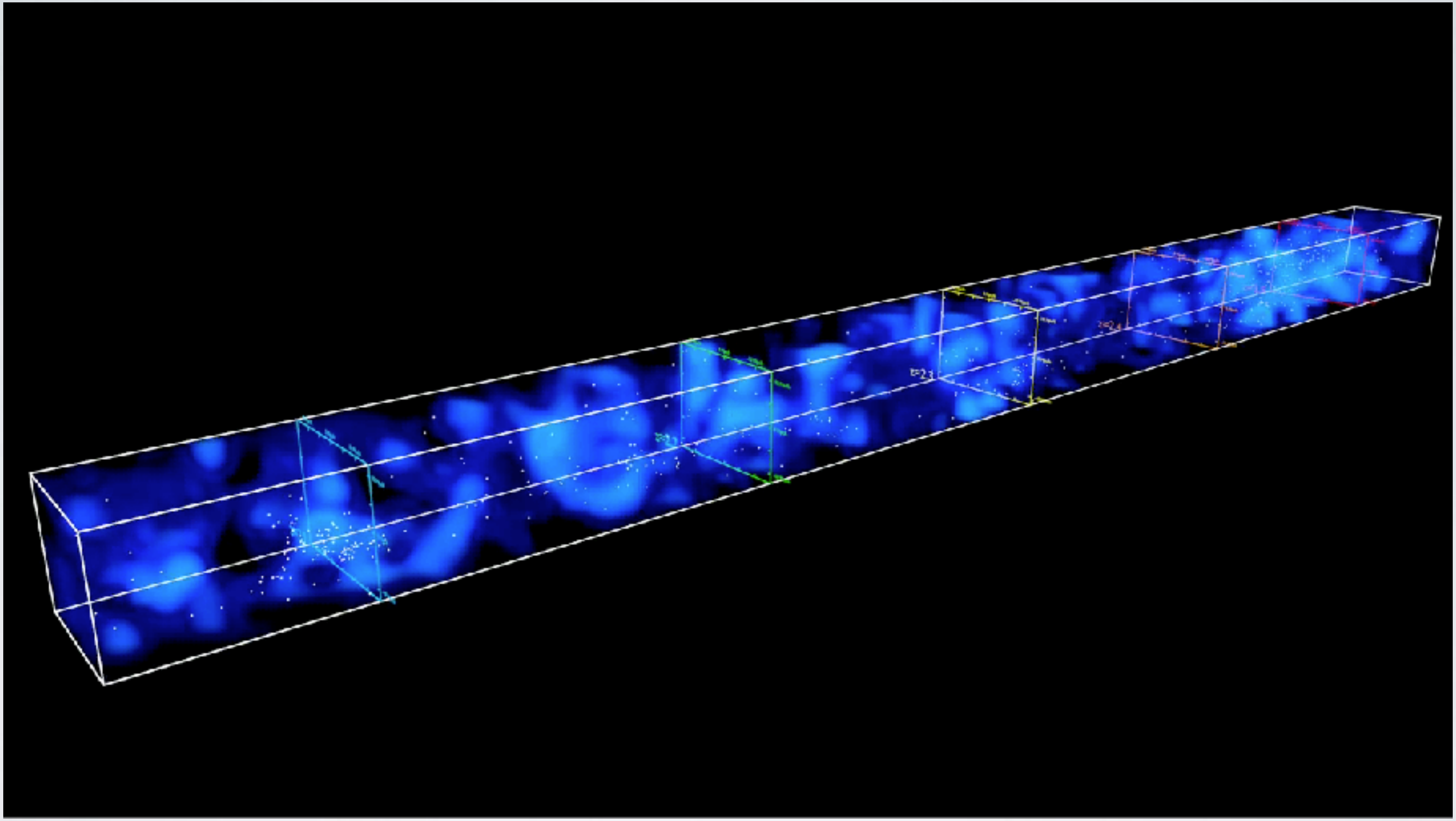


Lee et al, 2017

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



Coil et al, 2004

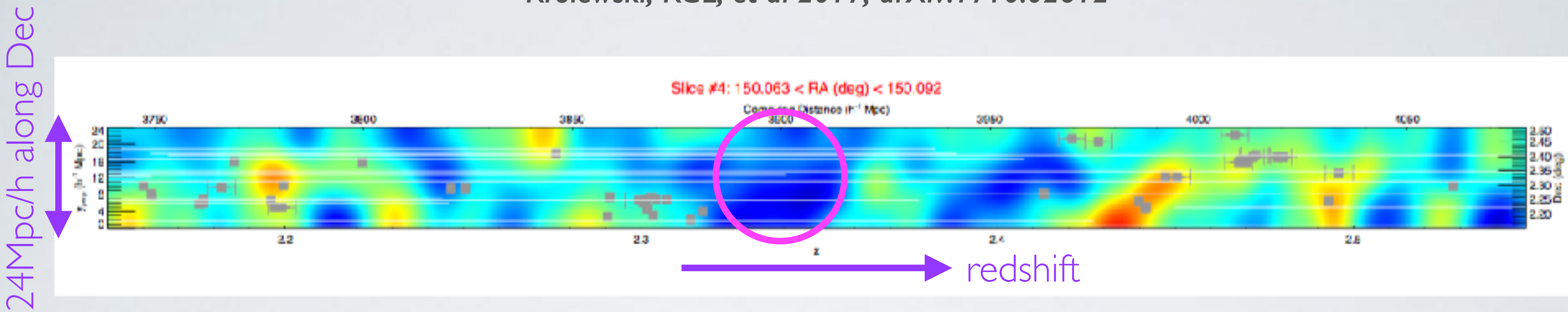


YouTube: *http://tinyurl.com/clamatovid-v2*

Come see the VR version at Alex Krolewski's poster!

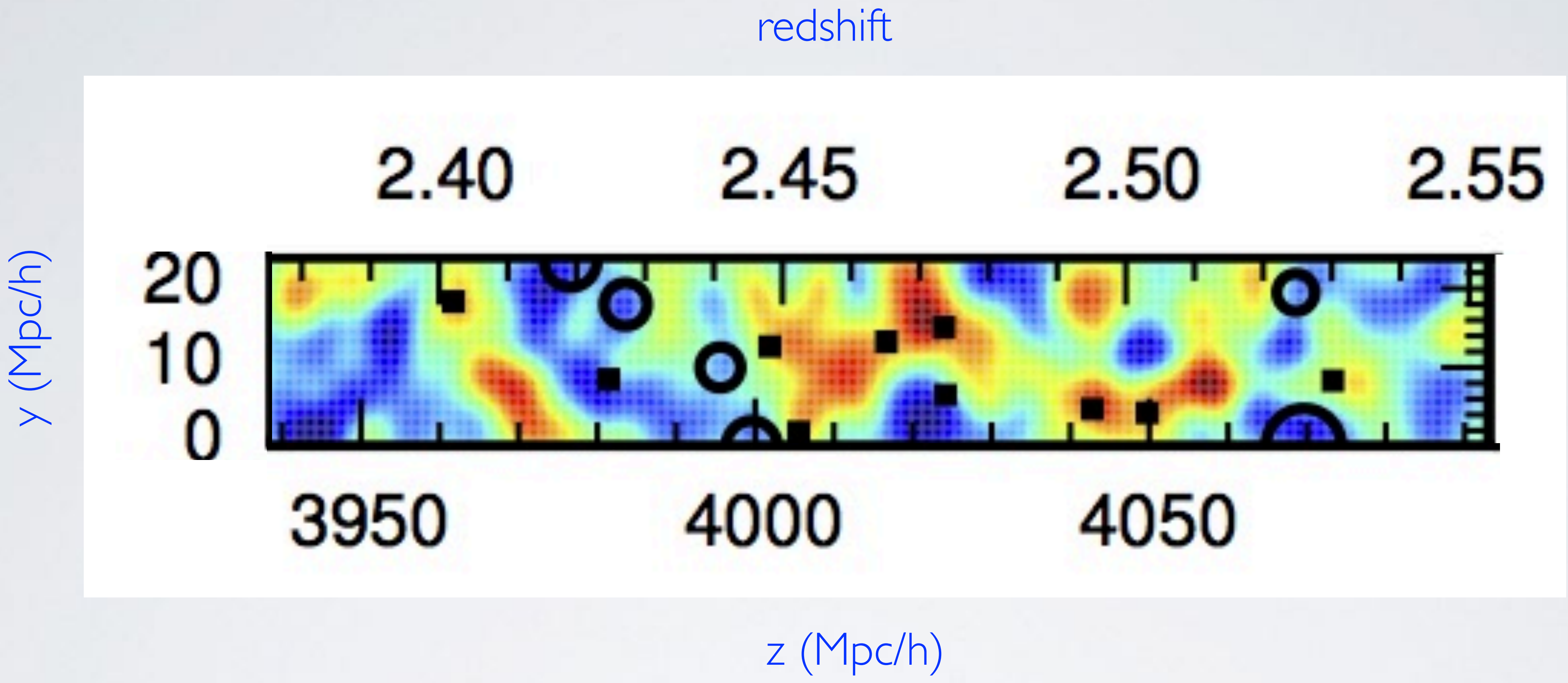
First Detection Of Cosmic Voids At High-z

Krolewski, KGL, et al 2017, arXiv:1710.02612



- Most distant-known cosmic voids from galaxy redshift surveys are at z~0.9 (VIPERS Survey, Hawken+2016)
- Clearly see 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)
- Voids identified in the tomographic map are $\sim 6\sigma$ underdense in spectroscopic galaxies
- See poster by Alex Krolewski outside!

A forming supercluster at z=2.51?

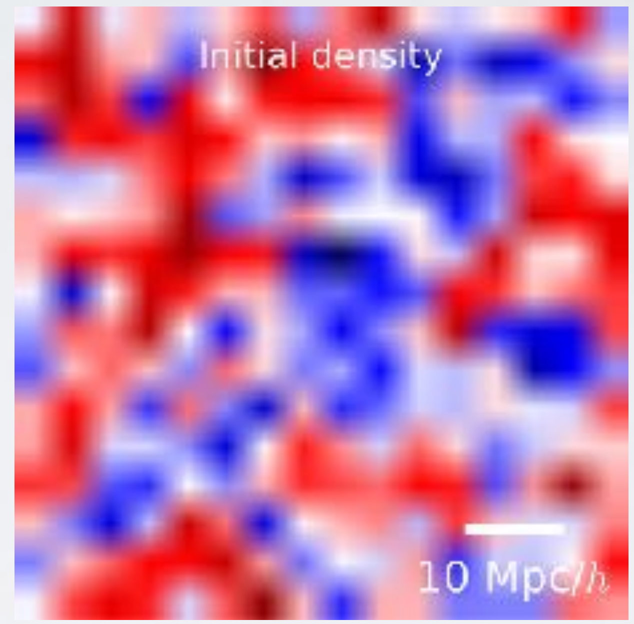


- Known galaxy protoclusters at z=2.44 (Diener+2015, Chiang+2015), z=2.48 (Casey+2016) and z=2.51 (Wang+2016) are <100 cMpc from each other.
- CLAMATO is resolving real filamentary sub-structure at z~2.5!

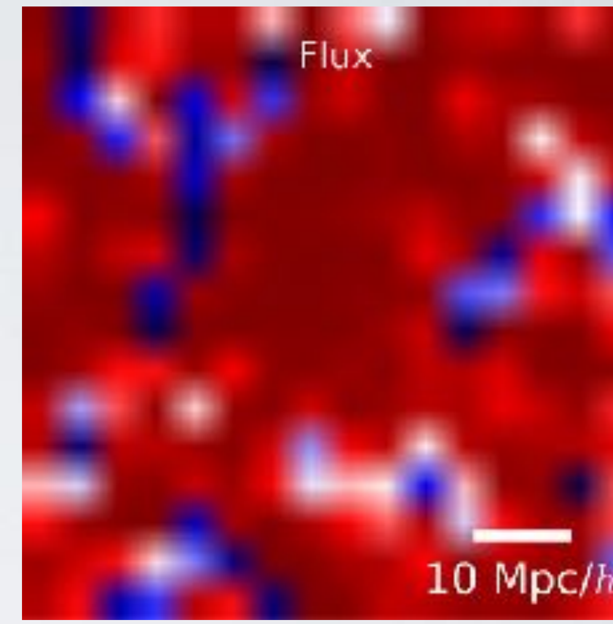
Inferring Map Initial Conditions

- 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)

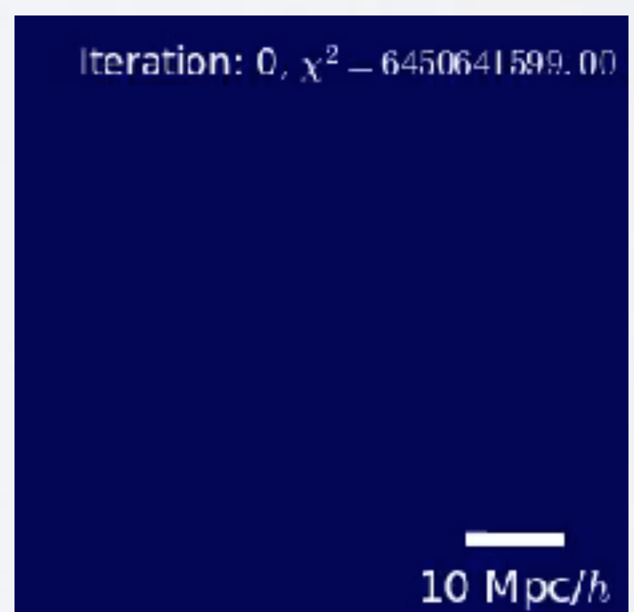
"True" Initial Conditions



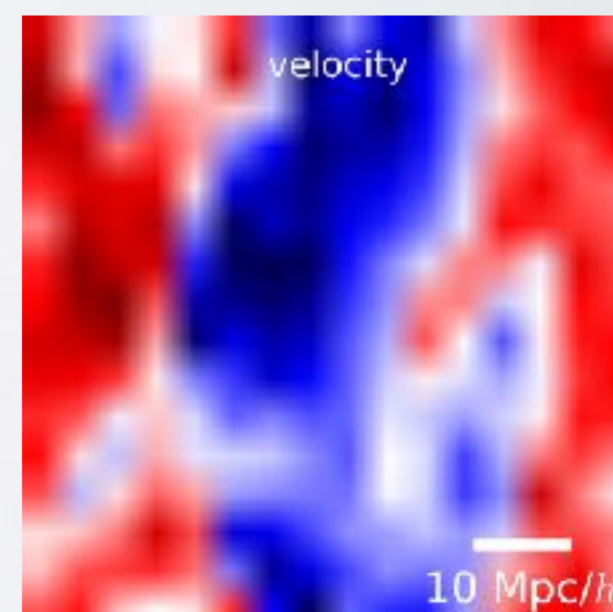
Toy "observations" at z~2.5



Inferred Initial Conditions

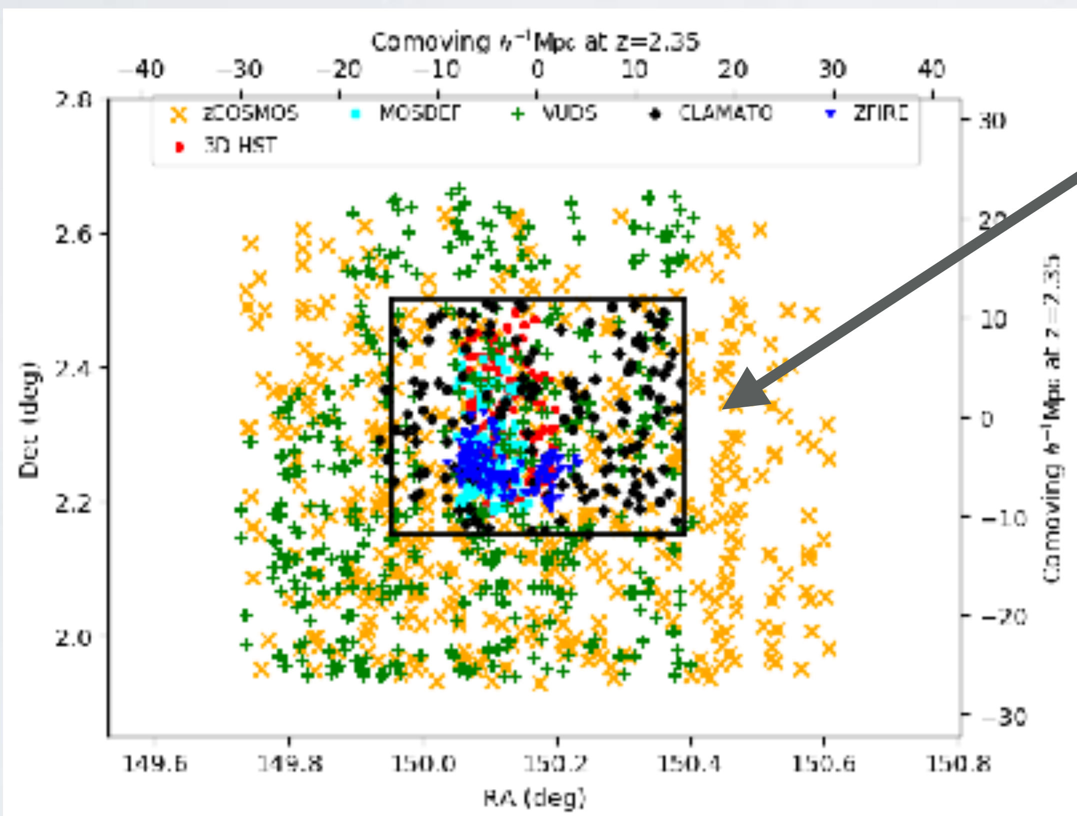


Inferred velocities at z~2.5

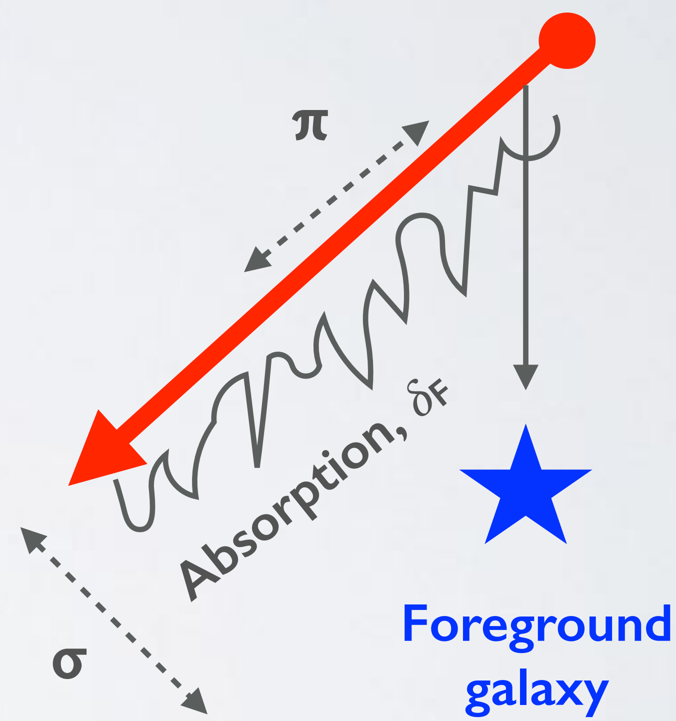


Galaxy-Forest Cross-Clustering

- 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



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

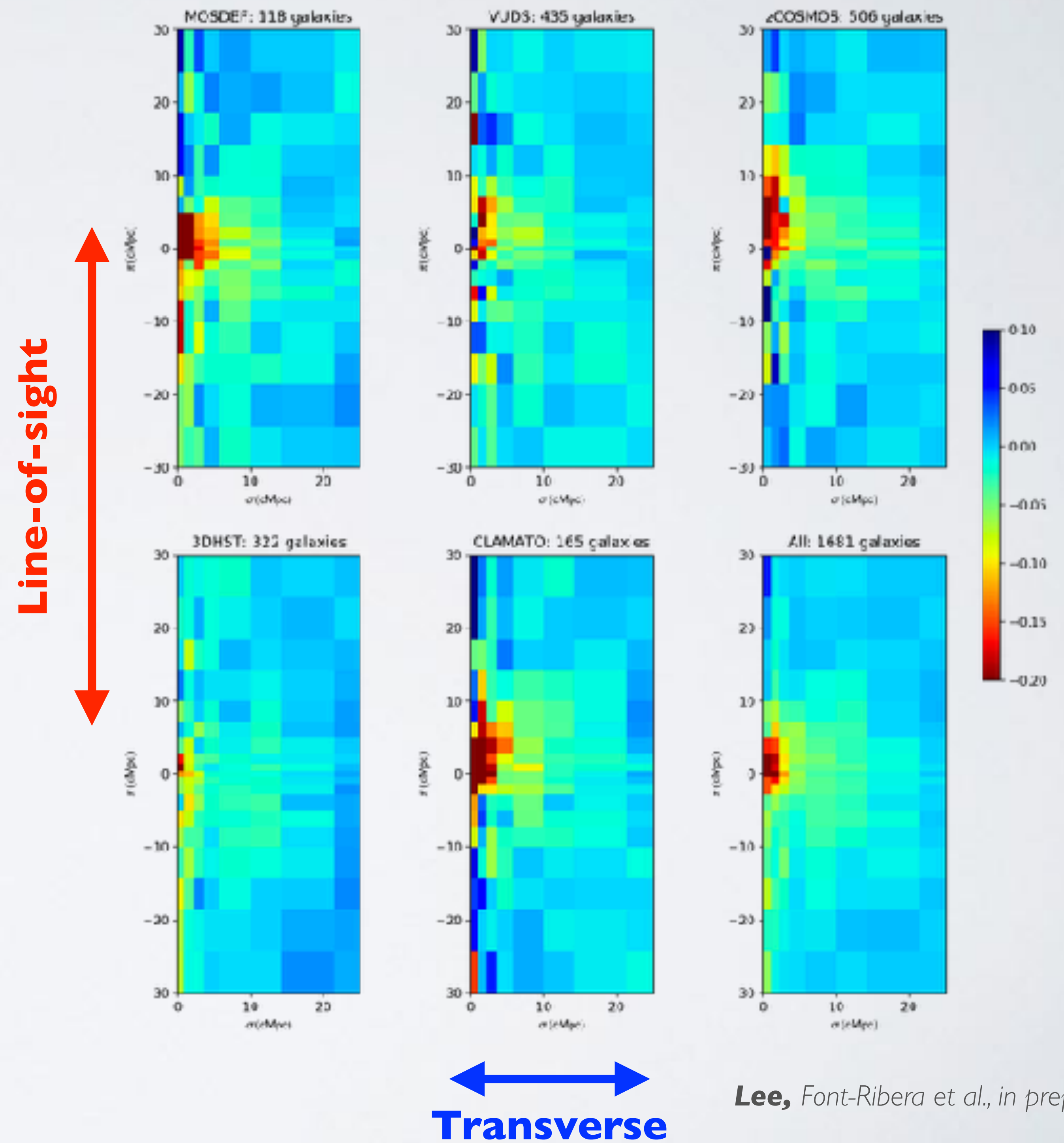
Cross-power spectrum **Galaxy bias + RSD** **Ly-a forest bias + RSD (known)** **Linear theory power spectrum (known from cosmology)**

Cross-correlation with Galaxies

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

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

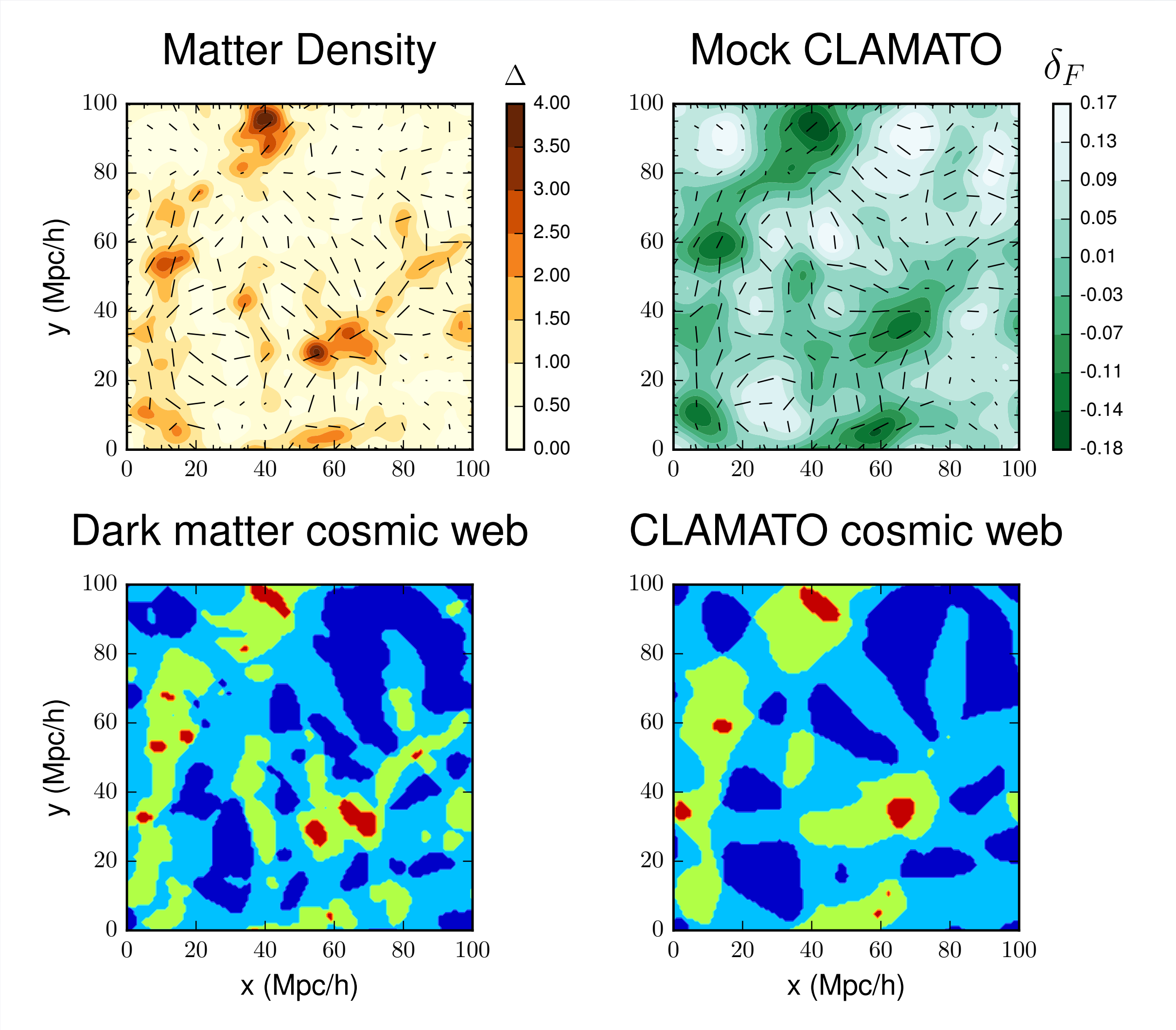
- Overall ~21 $\boldsymbol{\sigma}$ detection from all samples
- Current analysis assumes forest bias is fixed (known to ~3% from BOSS)
- Model galaxies with linear model. with free parameters:
  - bias, b
  - LOS offset, δz
  - LOS dispersion, $\boldsymbol{\sigma}_z$ (combination of redshift error +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

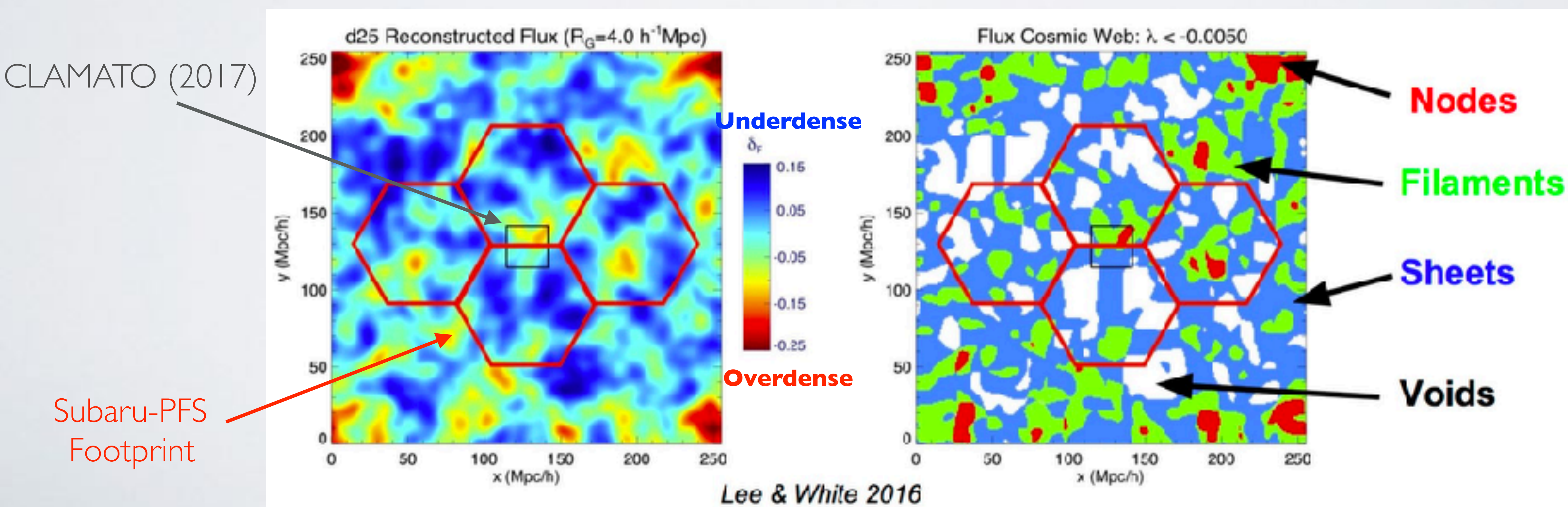


Future Surveys: Subaru-Prime Focus Spectrograph

- 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

- 50 nights of the survey will be targeted at 2<z<7 universe
  - Area: 3 × 5 deg^2
  - 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



Lee & White 2016

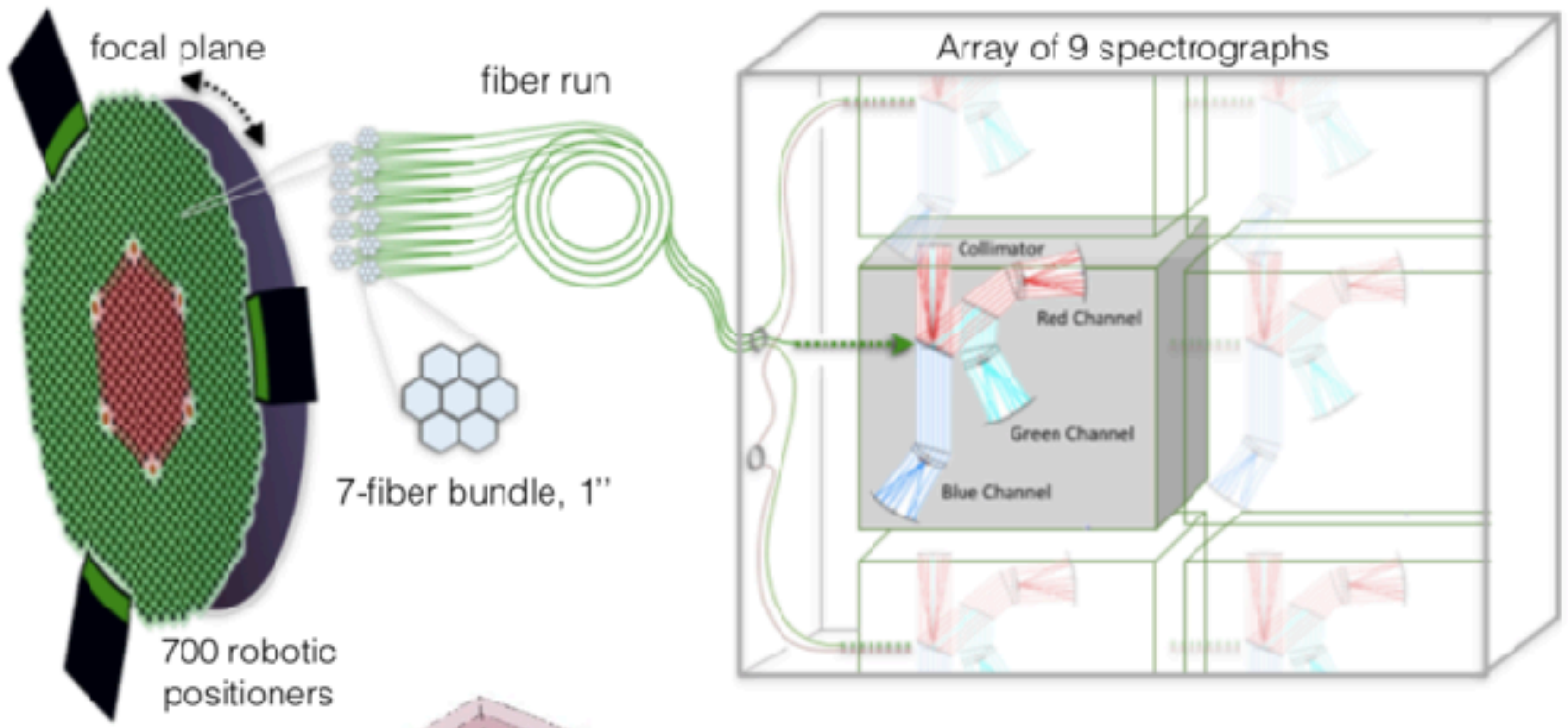
IGM Tomography with Keck vs PFS

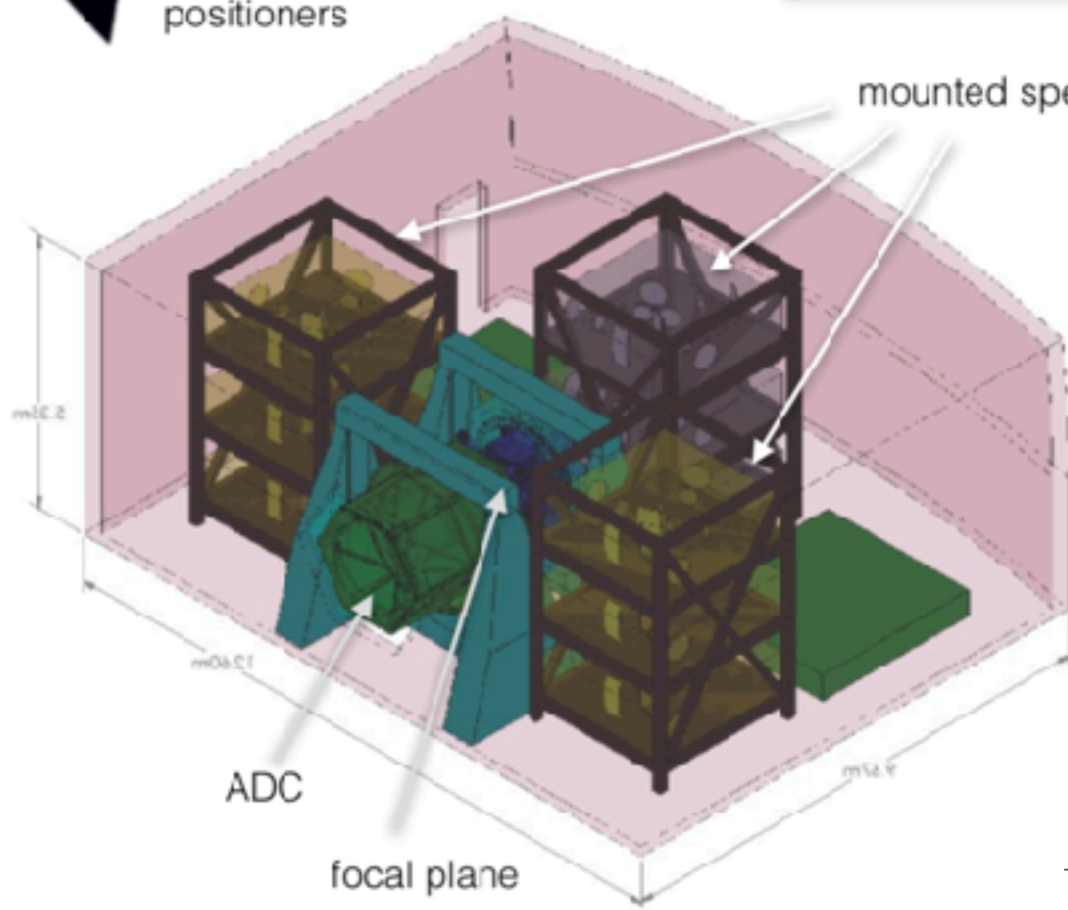
	CLAMATO (Keck-I/LRIS)	Subaru-PFS Galaxy Evolution SSP
Area	0.16 deg^2 (in 2017)	15 deg^2
Map Volume	9×10^5 $cMpc^3$	4.4×10^7 $cMpc^3$
Background source density	1600 deg^{-2}	970 deg^{-2}
Transverse sightline separation	3.4 cMpc	3.9 cMpc
Source magnitude limit	$g<24.9$	$g<24.7$
Map redshift	$2.0<z<2.6$	$2.1<z<2.5$

Future Fiber Instruments on Keck & TMT

- Blue throughput in PFS suffers from long fiber run from prime focus to spectrograph room
- Nasmyth robotic fiber feed + adjacent spectrograph can bypass this to provide superior throughput
- **Keck-FOBOS**:
  - 500 fibers over D=15 arcmin (10x LRIS FOV)
  - R~2500-5000 over 340nm-980nm
- **TMT-WFOS**:
  - Currently going through down-select between fiber version (recommended by team) and monolithic 'exchange' version
  - 700 fibers over D=10 arcmin
  - R>4000 over 310nm-1000nm
- Both concepts can exploit ground-layer AO deformable secondary mirror for consistent 0.4'' seeing in the optical

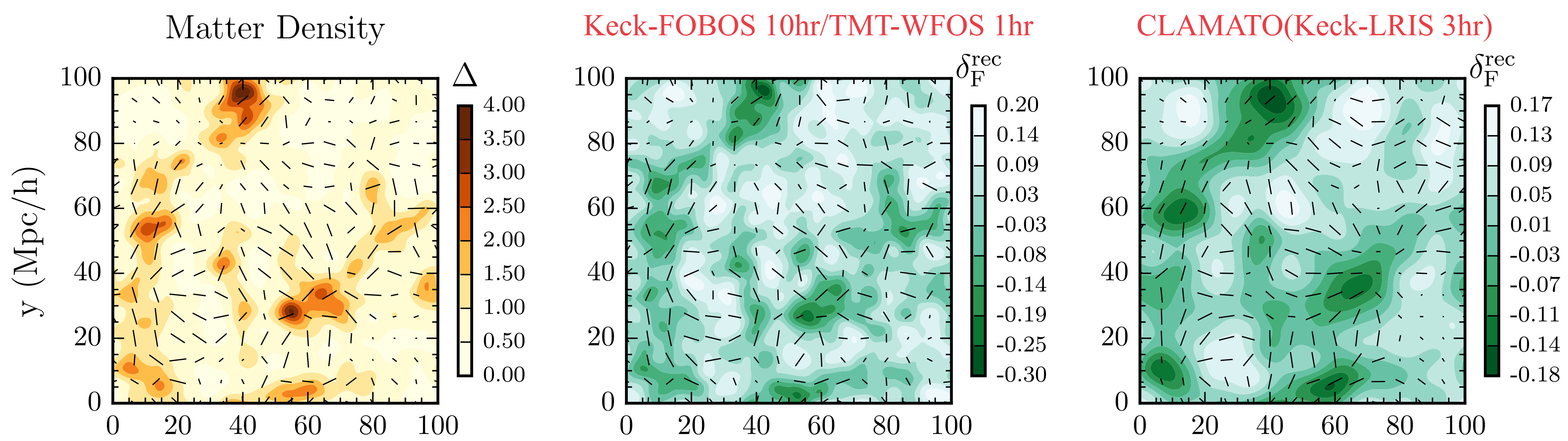
Fiber-WFOS Schematic layout





CAD rendering on Nasmyth platform

TMT-WFOS CoDP1 Down-Select Document



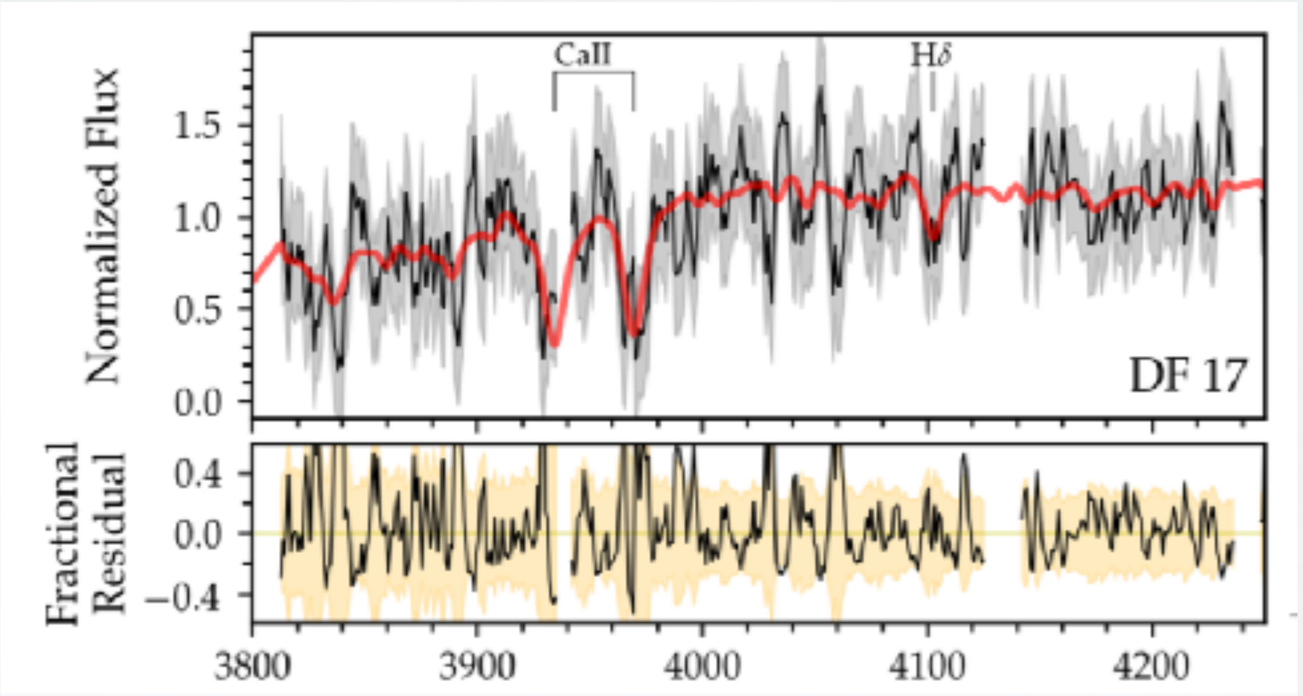
Adapted from Krolewski+2017a

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
  - 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

Sky Subtraction on Fiber Spectra

- Historically, fiber spectroscopy has been regarded as systematics limited for faint targets
- SDSS surveys, especially MaNGA, has worked hard in understanding and correcting for fiber systematics
- ***TMT-WFOS will need to achieve 0.1% sky subtraction to achieve its science goals. MaNGA is already achieving 0.2%*** (in a 2.5m telescope never designed for faint spectroscopy!)
- See upcoming paper by Kevin Bundy on sky subtraction requirements



MaNGA stacked spectrum from μ=25.1 mag/arcsec^2 ultrafaint dwarf in Coma (Gu et al 2017, arXiv:1709.07003)

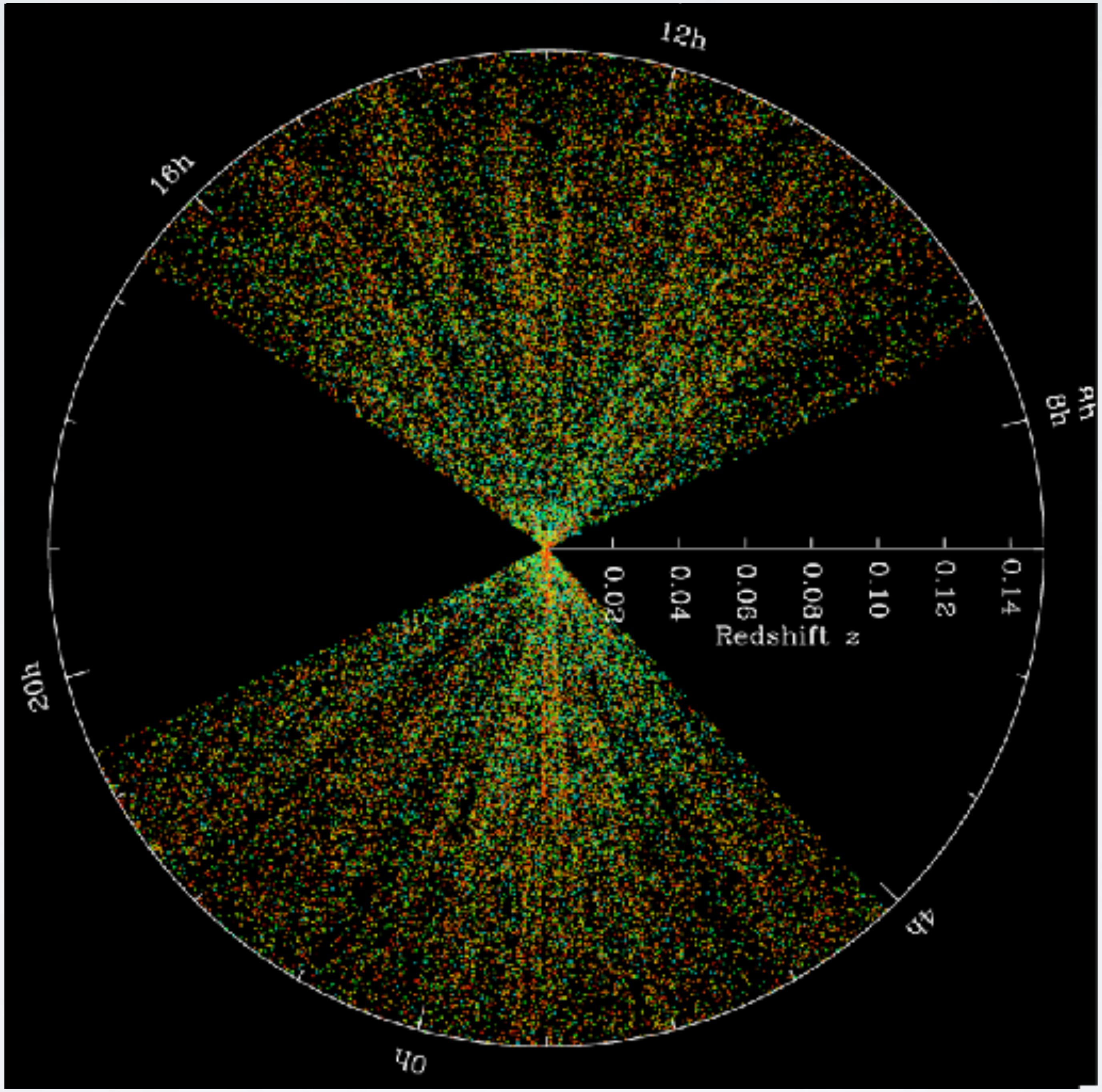
Context: Where are we after BOSS/eBOSS/DESI?

- Summary of cosmology yield:
  - BAO measured to nearly cosmic variance limit at z<1.5
  - Percent-level BAO at z>1.5
  - RSD measurements possible to kmax~0.2
  - Nearly **40M spectra**
- Limited fiber budget → require efficient target selection
  - Convolves complicated selection function across multiple imaging surveys
  - Sensitive to zero-point calibration and variation in imaging conditions
- Galaxies at higher-z are faint and hard to classify:
  - LRGs (passive galaxies) ID'ed by absorption, need high S/N
  - ELGs (optical SF galaxies) ID's by narrow emission lines, need to separate from sky residuals
  - Both rely on features at ~3700-3900A restframe, i.e. z<1.6 at λ<1micron

Statistical Limitations Of BOSS/ eBOSS/DESI

- BOSS/eBOSS: >$10^3\times$ smaller sample than LSST
  - Galaxy population demographics not well-sampled
- DESI: Science reach still not statistically limited
  - Lack mixed bias tracers and high-density sampling of small-scale modes
  - Room to improve RSD at small scales ($k>0.2\ hMpc^{-1}$)
- Statistics for future optical spectroscopic survey
  - More modes to explore
  - Can increase mix of tracer bias
  - Measure clustering to non-linear scales at $z<1.5$
  - Measure clustering to linear scales at $1.5<z<3.5$

Redshifts Are Crucial For Large-Scale Structure!

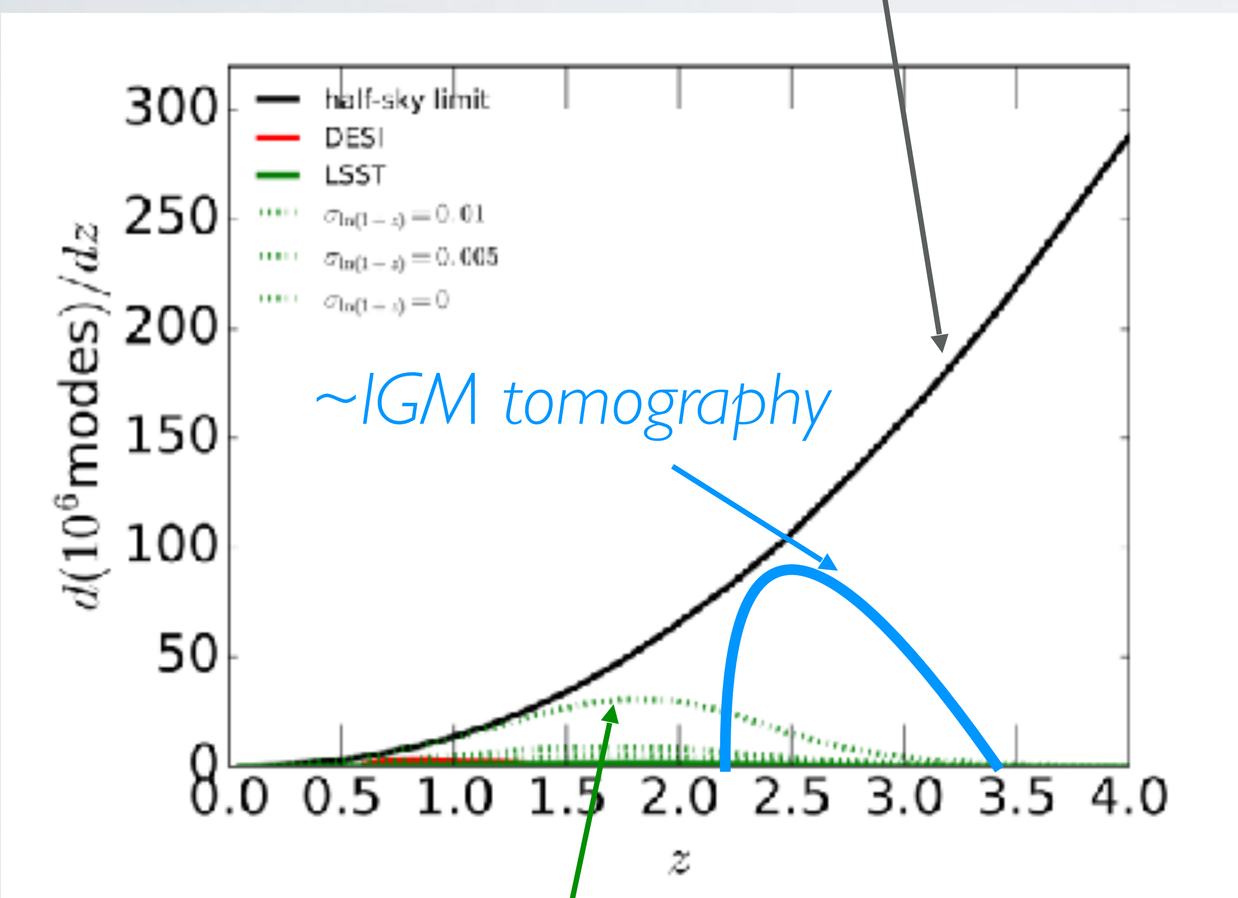


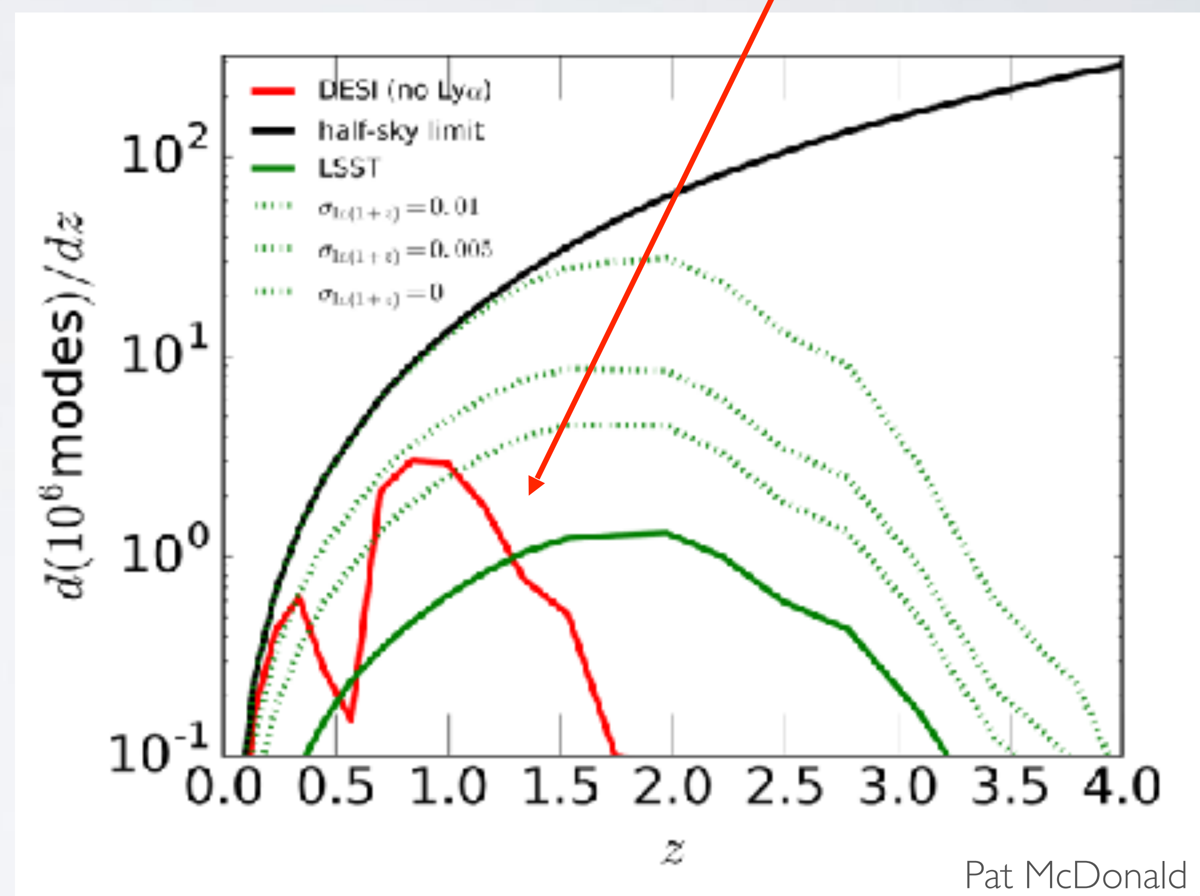
Photometric redshifts with 3% accuracy

Cosmological Information In Large-Scale Structure

All linear modes within 14k sq deg

DESI Spectroscopic Survey on 4m Kitt Peak





Pat McDonald (LBL)

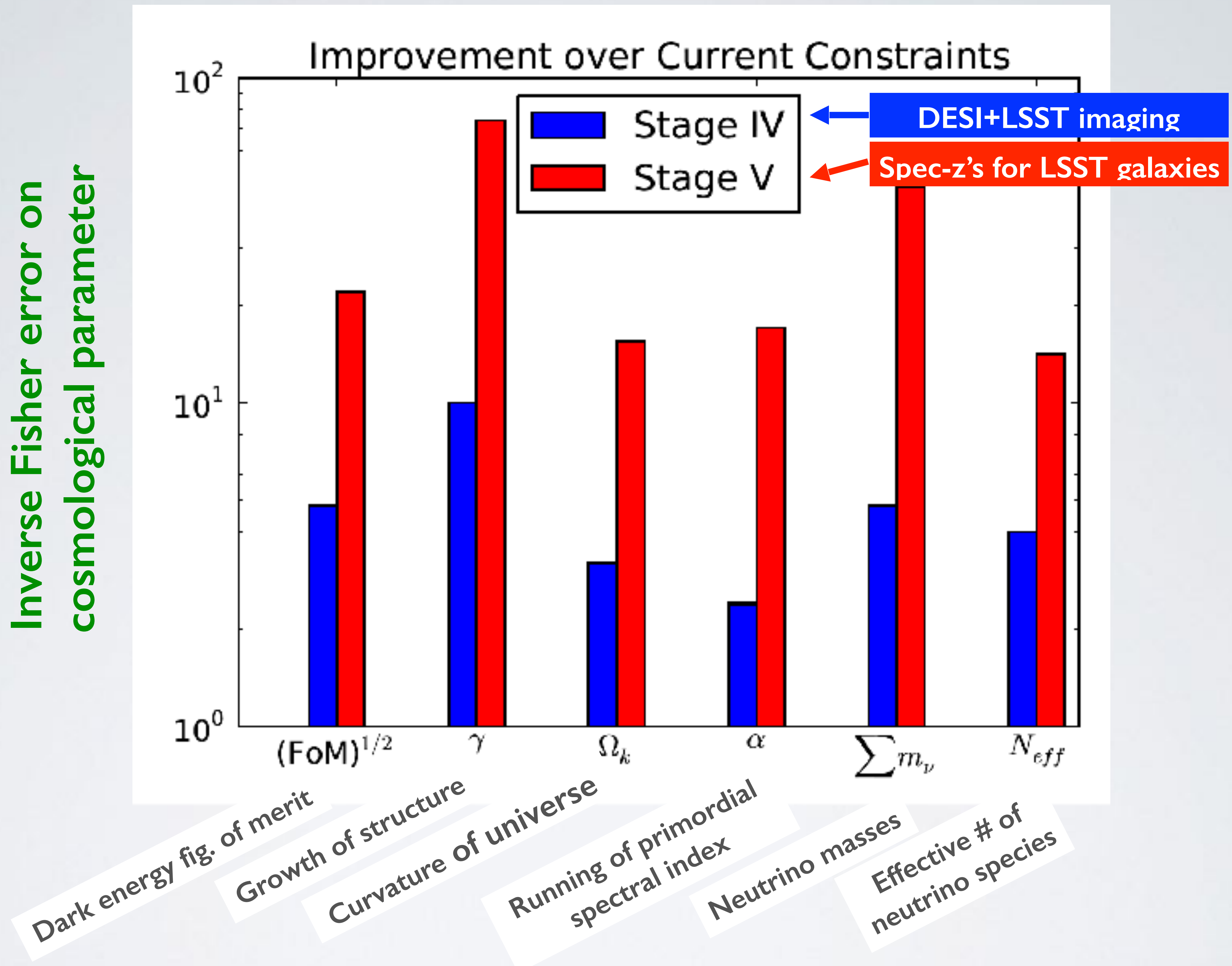
Spec-z's for all ~10^9 LSST Gold Sample galaxies!

Modes Available After DESI

- Assume in the linear regime: k_{max} evolves as 1/g (k_{max}=0.15 at z=0)
- Potential to explore non-linear regime
  - increasing kmax by 2x → 8x increase in N modes
  - Compare to **DESI: 10-15M modes**

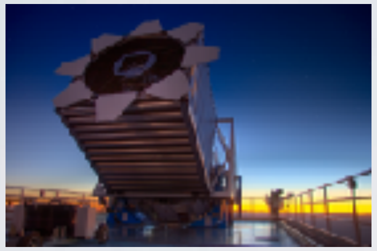
Redshift	kmax	Modes (Millions)	N (per sqdeg)	N (nonlinear)
0.25<z<0.75	0.19	1.75	500	2000
0.75<z<1.25	0.25	7.37	1500	6000
1.25<z<1.75	0.30	17.47	3000	12000
1.75<z<2.25	0.36	31.97	4000	
2.25<z<2.75	0.41	50.67	6000	
2.75<z<3.25	0.47	73.33	7000	
3.25<z<3.75	0.53	99.75	9000	

Assumptions: 14,000 sq deg of sky



Assumptions: k_{max}<0.5hMpc^{-1} at z<3.5

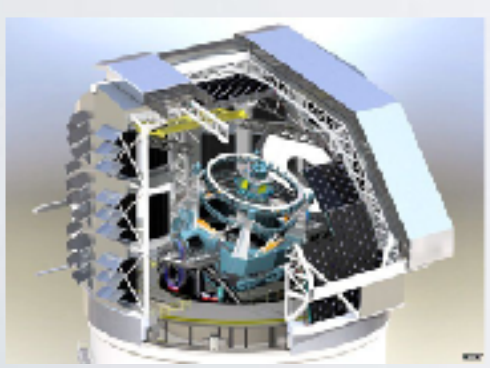
Imaging



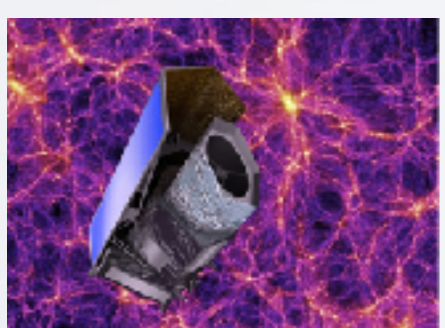
SDSS 2.5m, 7 deg^2 FOV

DECam, Blanco 4m,
7 deg^2 FOV

HSC, Subaru 8.2m,
1.5 deg^2 FOV



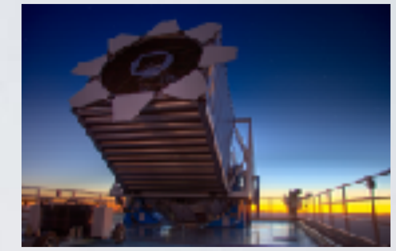
LSST 6.5m (effective),
9.5 deg^2 FOV



Euclid 1.2m (space),
0.5 deg^2 FOV

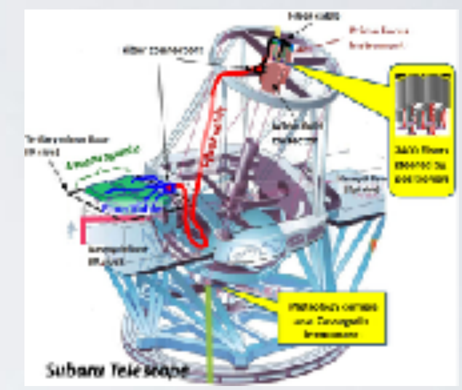
WFIRST 2.4m (space),
0.34 deg^2 FOV

Spectroscopy



SDSS 2.5m, N=1000

DESI, Mayall 4m,
N=5000



PFS, Subaru 8.2m,
N=2400

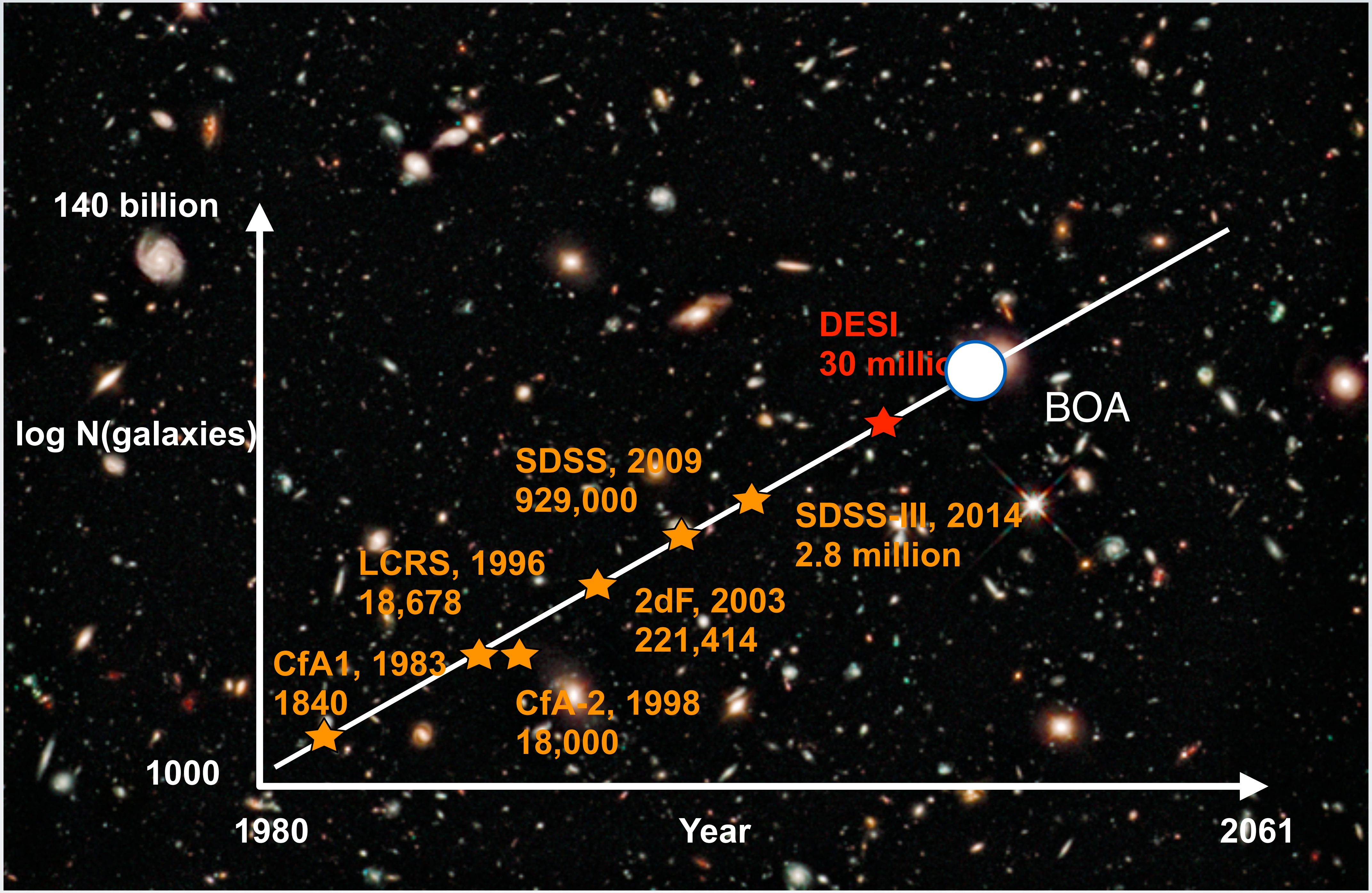
Billion Object Apparatus

Strawman Goals

- 30k deg^{-2} of galaxies to z<1.75 (**LOWZ)**
  - 20M modes (full sample)
  - Access non-linear regime
  - kmax=0.38 (z=0.5); kmax=0.6 (z=1.5)
  - Magnitude-limited selection (e.g. DEEP2, VVDS)
- 15k deg^{-2} of galaxies at 1.75<z<3.25 **(HIZ)**
  - 150M modes
  - New BAO, kmax=0.36 (z=2), kmax=0.47 (z=3)
  - IGM tomography from 2.3<z<3.0 galaxies will probe Ly-a forest absorption at 2.0<z<2.8 to non-linear scales
  - Color-color selection

45k galaxies per sq deg × 14k sq deg (10k sq deg)= 630M (450M) galaxies

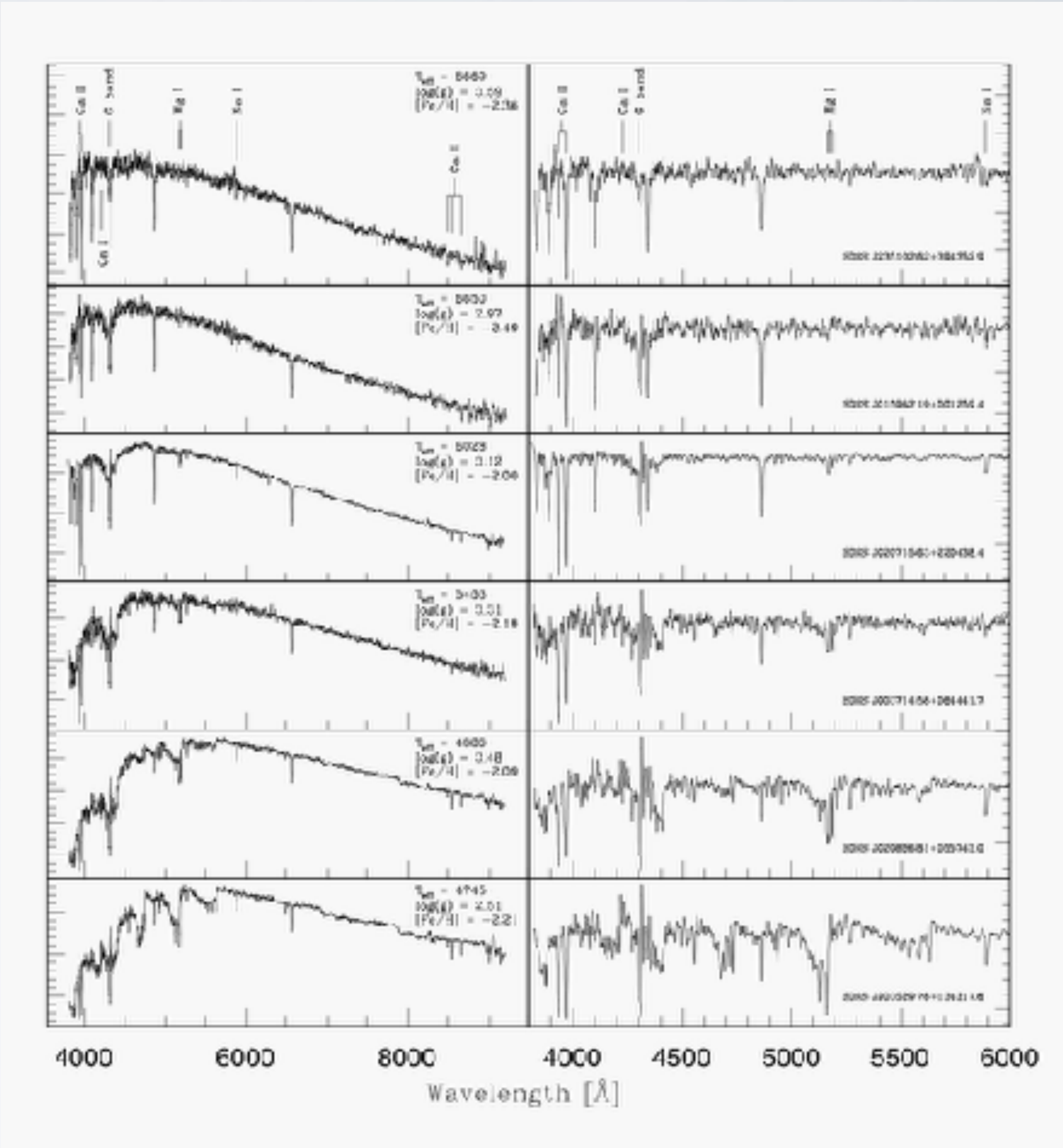
→ full galaxy power spectrum to k_{max}=0.35 at z<2 + full-sky CLAMATO-like IGM tomography to k_{max} ~1 at z~2-3



Credit: David Schlegel

Stellar Spectroscopy!

- Cosmology survey on BOA only on dark nights…observe Milky Way galaxies during bright time!
- Scaling from SDSS-SEGUE survey:
  - Integrate 15min to get S/N>10 on g=21.0 stars
  - **~700M stellar spectra over 10yrs**



http://classic.sdss.org/segue

Remarks On Instrumentation

Galaxy Redshift Surveys Are Multiplex Limited

- Traditionally, for astronomical surveys we define 'survey etendue' AΩ: telescope collecting area $\times$FOV
- This breaks down for high-density cosmological redshift surveys: *multiplexing/target density becomes important*
- In other words, large Ω is wasted if lower multiplexing requires returning to the same field (e.g. DESI is in this regime for its ELG survey). Better metric in this regime is A$\times$N, where N is multiplex
- This requires a new regime of ***hyper-multiplexed*** spectroscopic surveys, beyond "massively-multiplexed"

A Not-Too-Crazy Extrapolation…

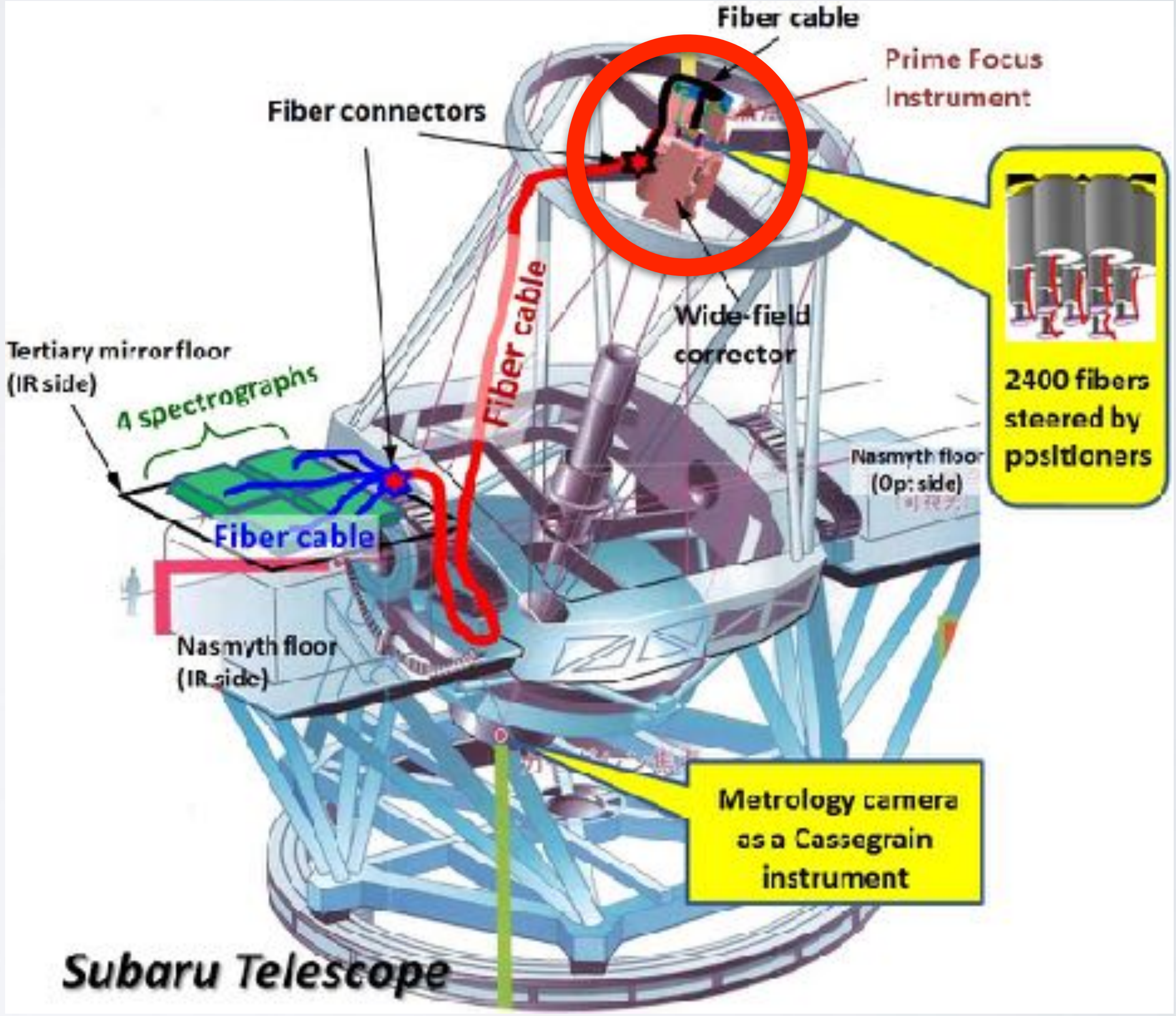
	SDSS-III/BOSS (2009-2015)	DESI (2020-2025)	Subaru-PFS (2019-2024)	Billion Object Apparatus (2035+)
Telescope Diameter	2.5m	4m	8.2m	10+m
FOV	7 deg^2	7 deg^2	1.3deg^2	>1.5deg^2
Total Multiplex	1000	5000	2400	15,000
Target Density	140/deg^2	700/deg^2	2,000/deg^2	>10,000/deg^2

Critical Tech Requirements

- **Smaller fiber positioners**: <5mm pitch (c.f. ~10mm pitch for DESI or PFS (or physically larger focal planes)
- **Cassegrain/Nasmyth wide-field 10m telescope design**: Huge number of positioners leads to heavy focal plane array (>4-5 tons) that cannot be put on prime focus. Also makes possible GLAO deformable secondary
- **Ground layer AO (optional):** Even 30% increase in encircled energy in R-band is a serious efficiency improvement! See 'imaka demonstrator on UH 88 inch (Jessica Lu (UCB) INPA talk May12)
- **Germanium CCDs (optional):** Push wavelength coverage to 1.3 micron, OII line to z~2.2… will straddle Ly-alpha emission for z~2 targets!

Upcoming 8-10m Spectroscopic Designs…

Maunakea Spectroscopic Explorer (McConnaghie+2016)



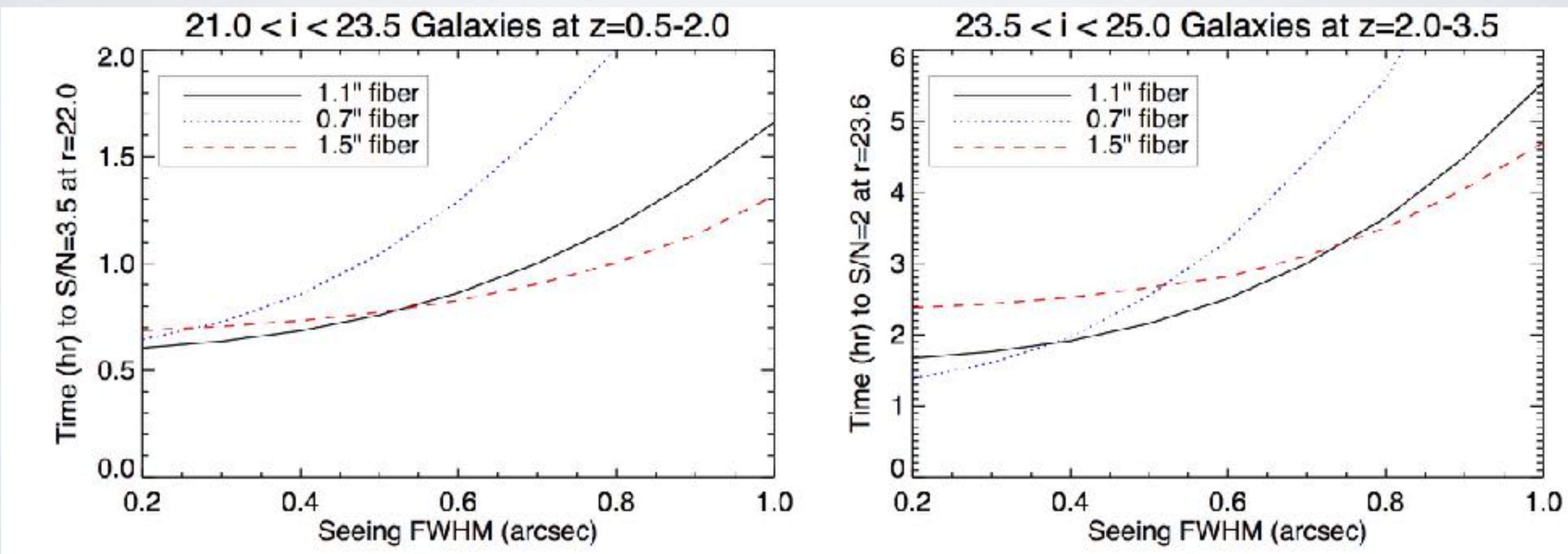
Subaru PFS (Sugai+2016)

Prime-focus undesireable:

- Cannot have more positioners than 5k
- No possibility for GLAO deformable secondary

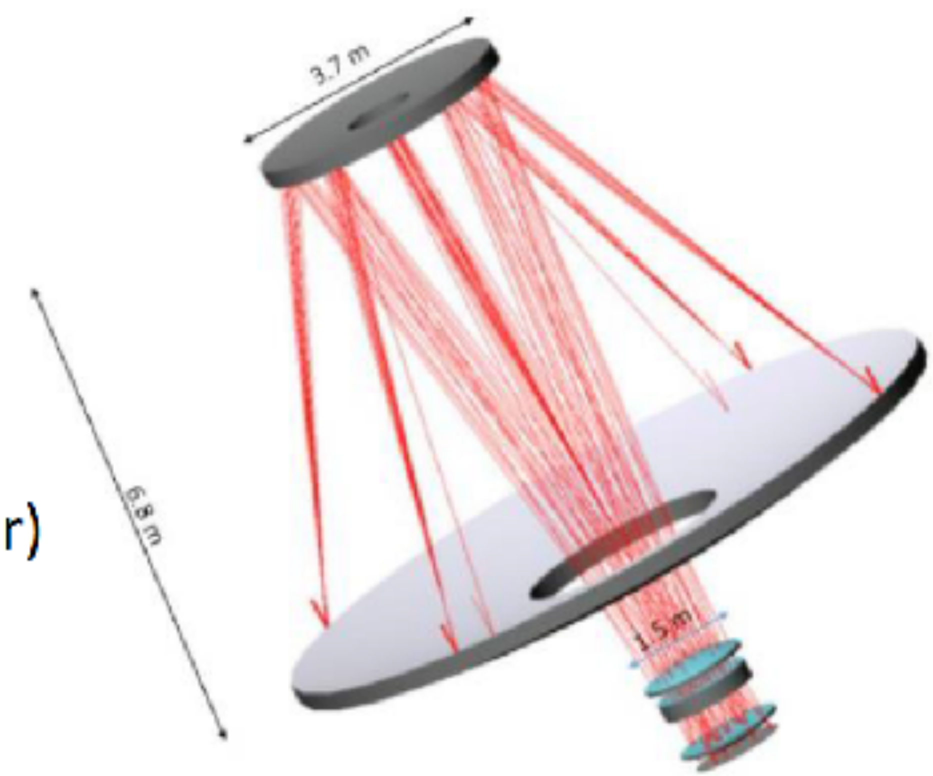
Ground Layer Adaptive Optics

- Correct for seeing caused by turbulence within ~100m above telescope
- Think of it as 'seeing improver', as opposed to diffraction-limited extreme AO
- Possibility of wide-fields: 'imaka demonstrator on UH 88' telescope gets consistent 0.4'' seeing on r-band over 0.3 sq deg
- Considerable gains in efficiency especially for high-z samples



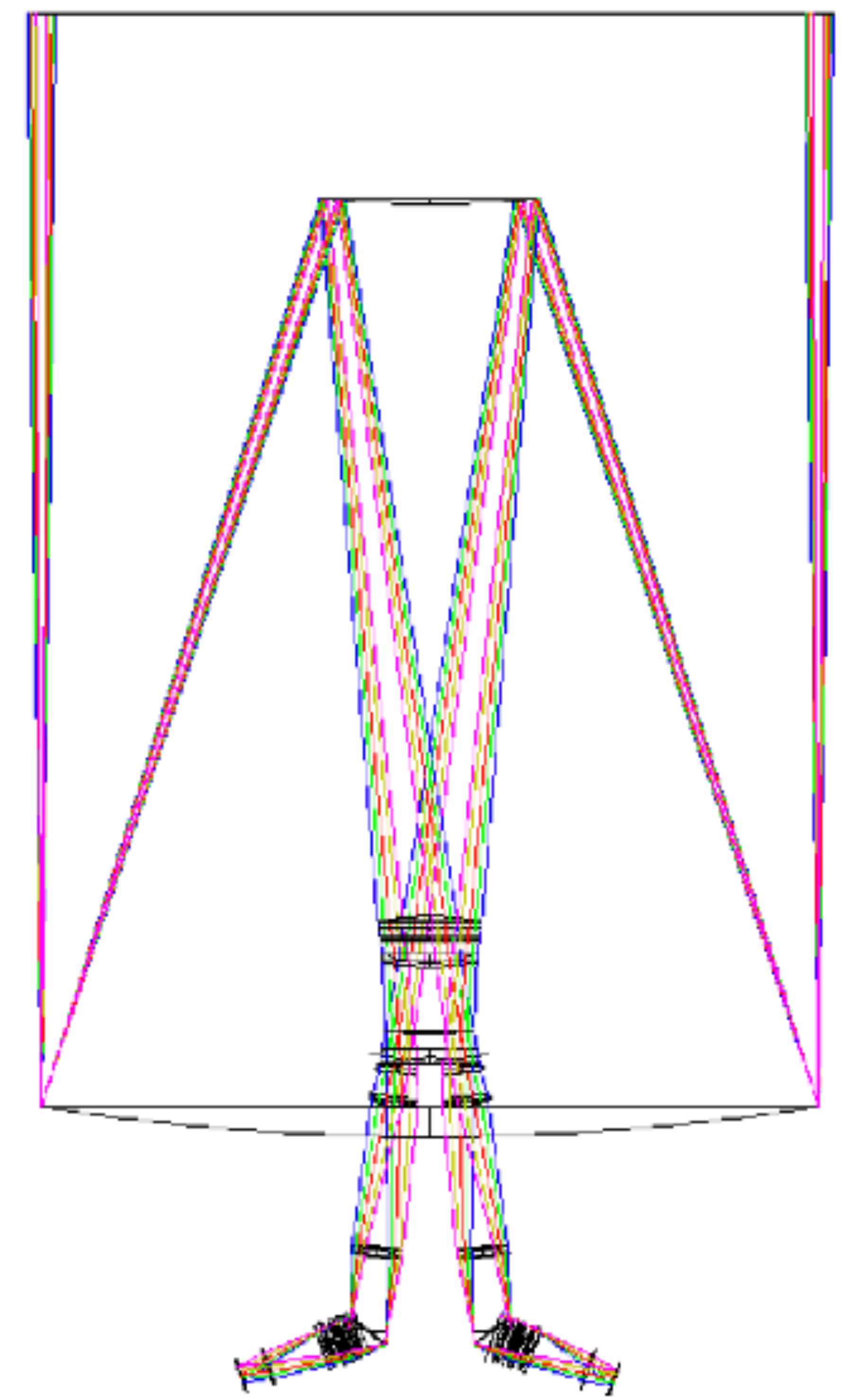
Possible Telescope Design (A)

- Design for Cass focus on 10-m class telescope
  - "Fiber Design" Pasquini et al., 2016
- 2.5 degree diameter FOV (4.9 sqdeg)
- F/3 beam
  - 145 micron/arcsec platescale
  - Well matched to SDSS fibers (180 micron diameter)
- 1.3 meter focal plane diameter
  - 2.6X DESI focal plane area
  - Hosts 13,000 fibers using DESI positioners
  - Increase to 50,000 fibers if decrease patrol radius from 6→3 micron
- 50,000 fibers over 4.9 sqdeg
  - Require average 4 visits per coordinate
  - ~12,000 observations for 14,000 sqdeg



Possible Telescope Design (B)

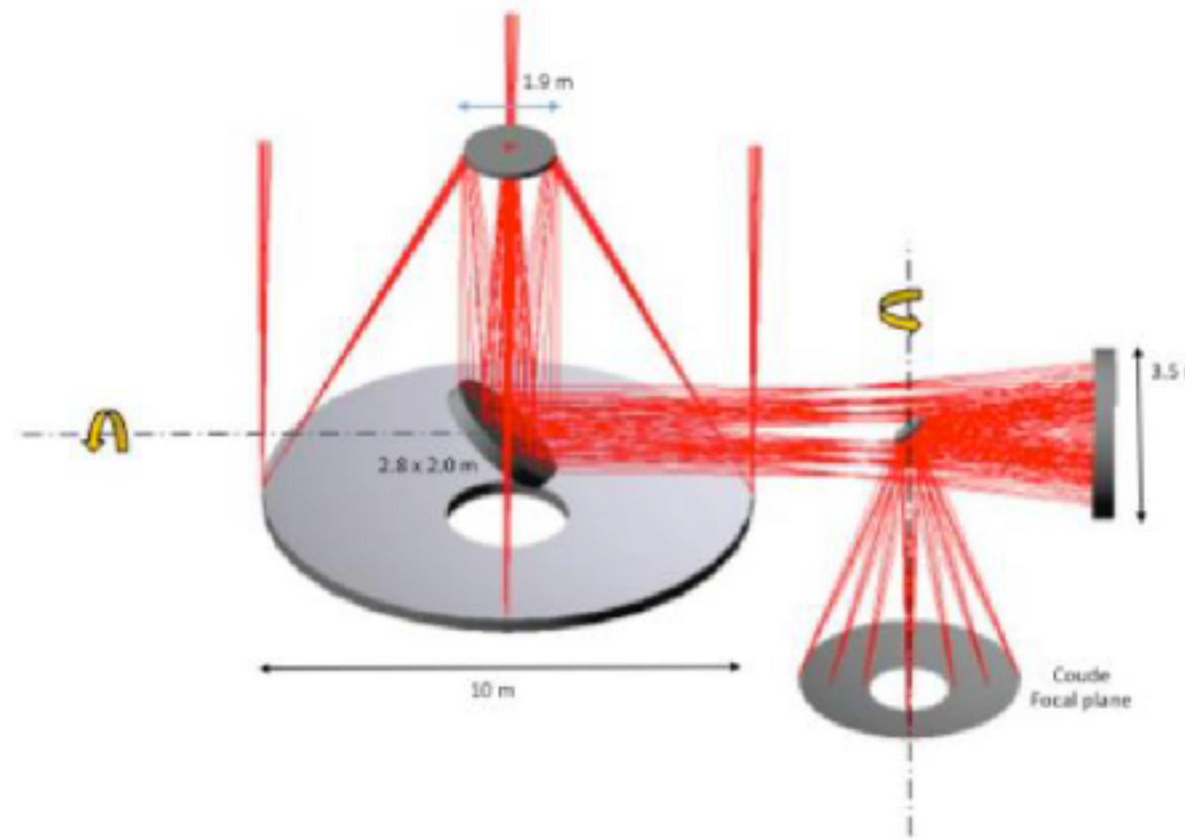
- Spectroscopic Wide Field Telescope (SWIFT)
  - NOAO 1999 proposal for 8.4-meter telescope
  - https://www.noao.edu/swift/proposal/swift.html
- 1.5 degree diameter FOV (1.75 sqdeg)
- F/4.3 beam
  - 188 micron/arcsec platescale
  - Well matched to SDSS fibers (180 micron diameter)
- 1.7 meter focal plane diameter
  - 3.5X DESI focal plane area
  - Hosts 17,500 fibers using DESI positioners
  - Increase to 70,000 fibers if decrease patrol radius from 6→3 micron
- 70,000 fibers over 1.75 sqdeg
  - Require average 1 visit per coordinate
  - ~8,000 observations for 14,000 sqdeg



Possible Telescope Design (C)

- Design for Coude focus on 10-m class telescope
  - “Ring Design” Pasquini et al., 2016
- Ring design
  - 1.5 degree diameter (1.0 sqdeg)
  - 4.6 meter focal plane diameter (Coude focus)
  - Three extra mirrors → reduced effective area due to <100% reflectivity
- 1.5 degree diameter FOV (1.0 sqdeg)
- F/17.7 beam
  - 857 micron/arcsec platescale
  - Poor match to any fiber system
- Microlenses for f-ratio conversion to F/4
  - DESI fibers → 0.6” on sky
  - e.g. Gemini: http://adsabs.harvard.edu/abs/2002PASP..114..892A
- 4.6 meter focal plane diameter
  - 30X DESI focal plane area
  - Hosts up to 150,000 fibers using DESI positioners
- Assume 50,000 fibers over 1.0 sqdeg
  - Require average 1 visit per coordinate
  - 14,000 observations for 14,000 sqdeg

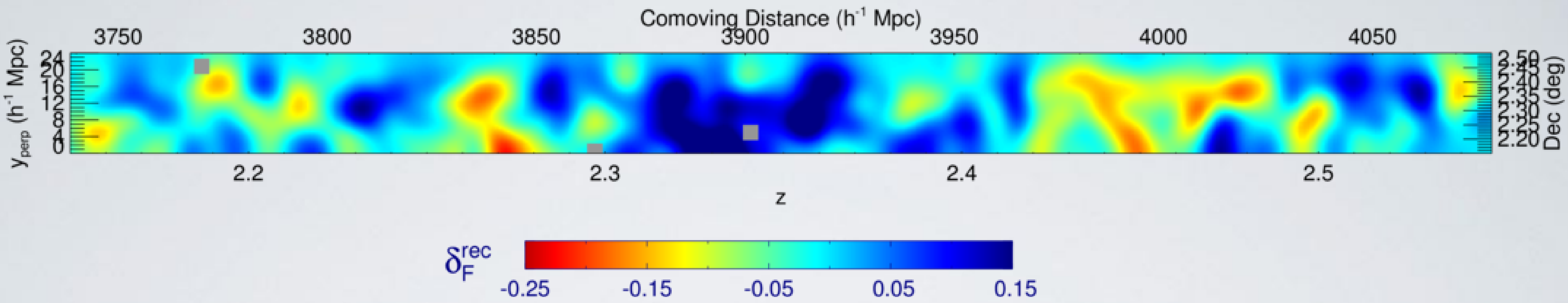
  (incomplete coverage due to central obscuration)



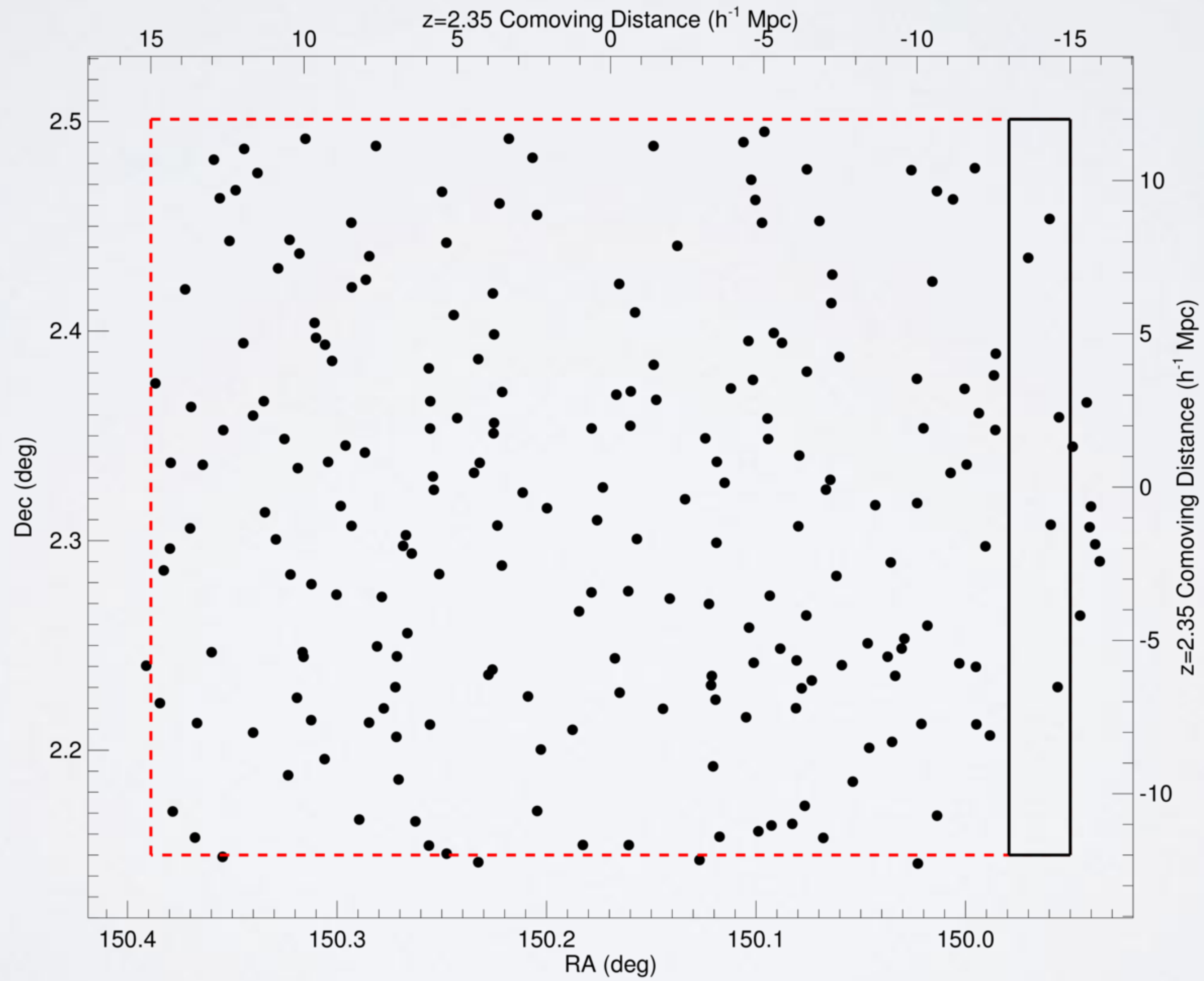
Landscape

- NSF (Najita+2016) and DOE (Dodelson+2016) are both calling for a Southern Spectroscopic Survey Instrument:
  - PFS- or MSE-like capability in the south to complement LSST by late-2020s
  - 6-10m class survey facility with N~5000 multiplex
- BOA would proceed most logically as an upgrade of SSSI in the 2030s
  - Requires a design that can support a >5-ton focal plane module, and ideally GLAO-ready
- "Cosmic Visions: Dark Energy" Workshop at LBL, Nov 14-15. Still time to register!

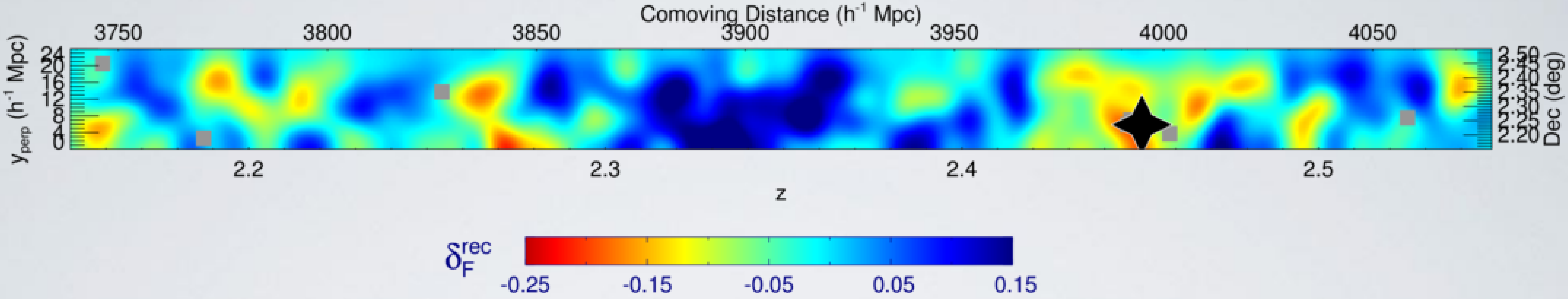
Slide #1: 149.950 < RA (deg) < 149.979



2.15 < z < 2.55 Sightlines



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



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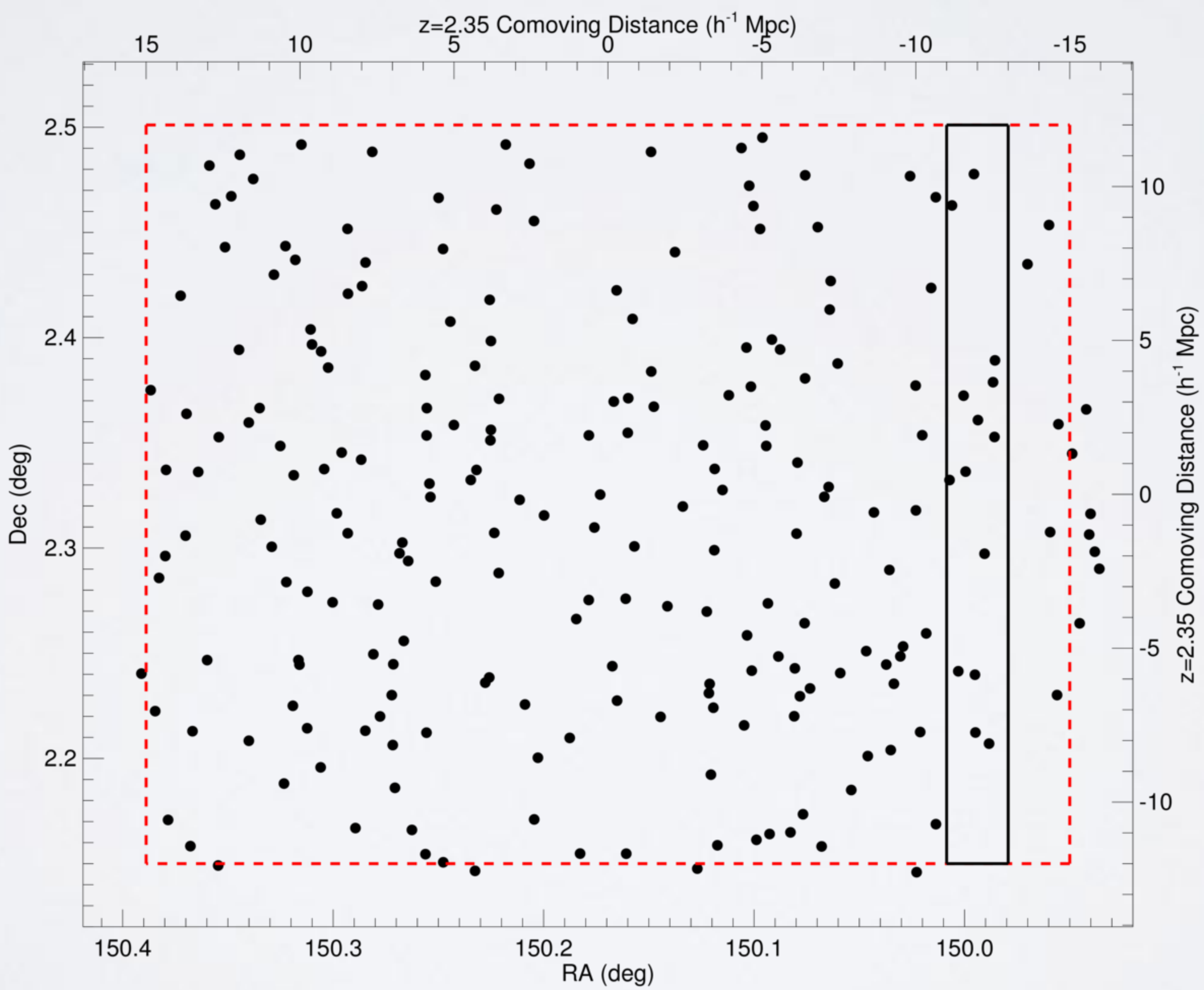
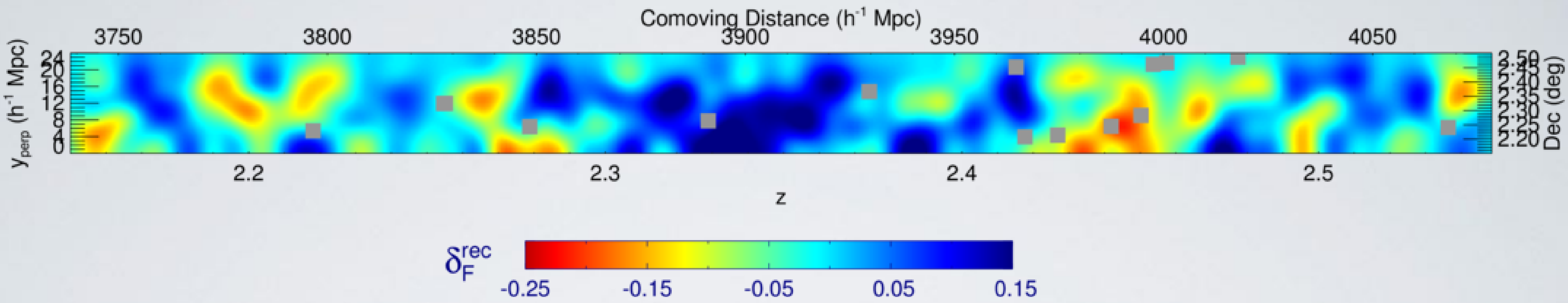


Slice #3: 150.009 < RA (deg) < 150.038



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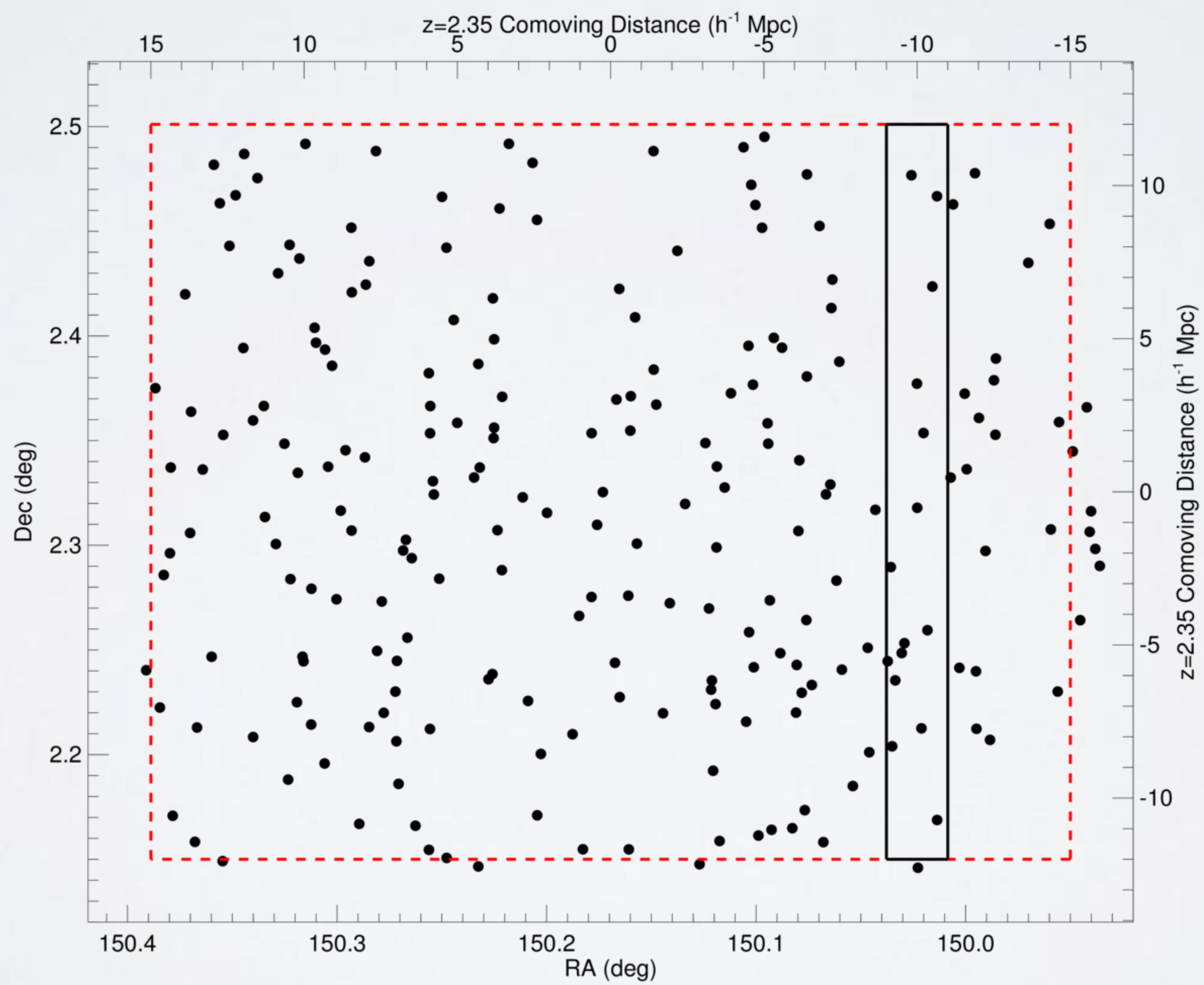
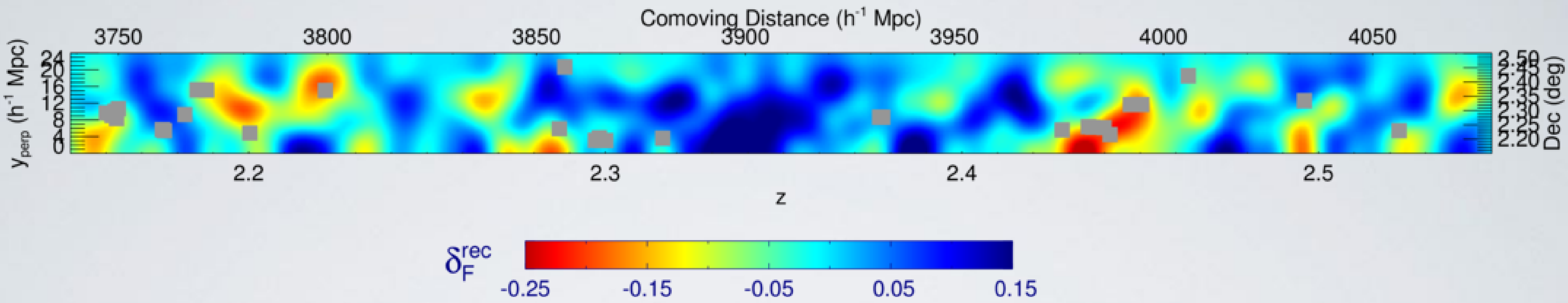


Slice #4: 150.038 < RA (deg) < 150.067



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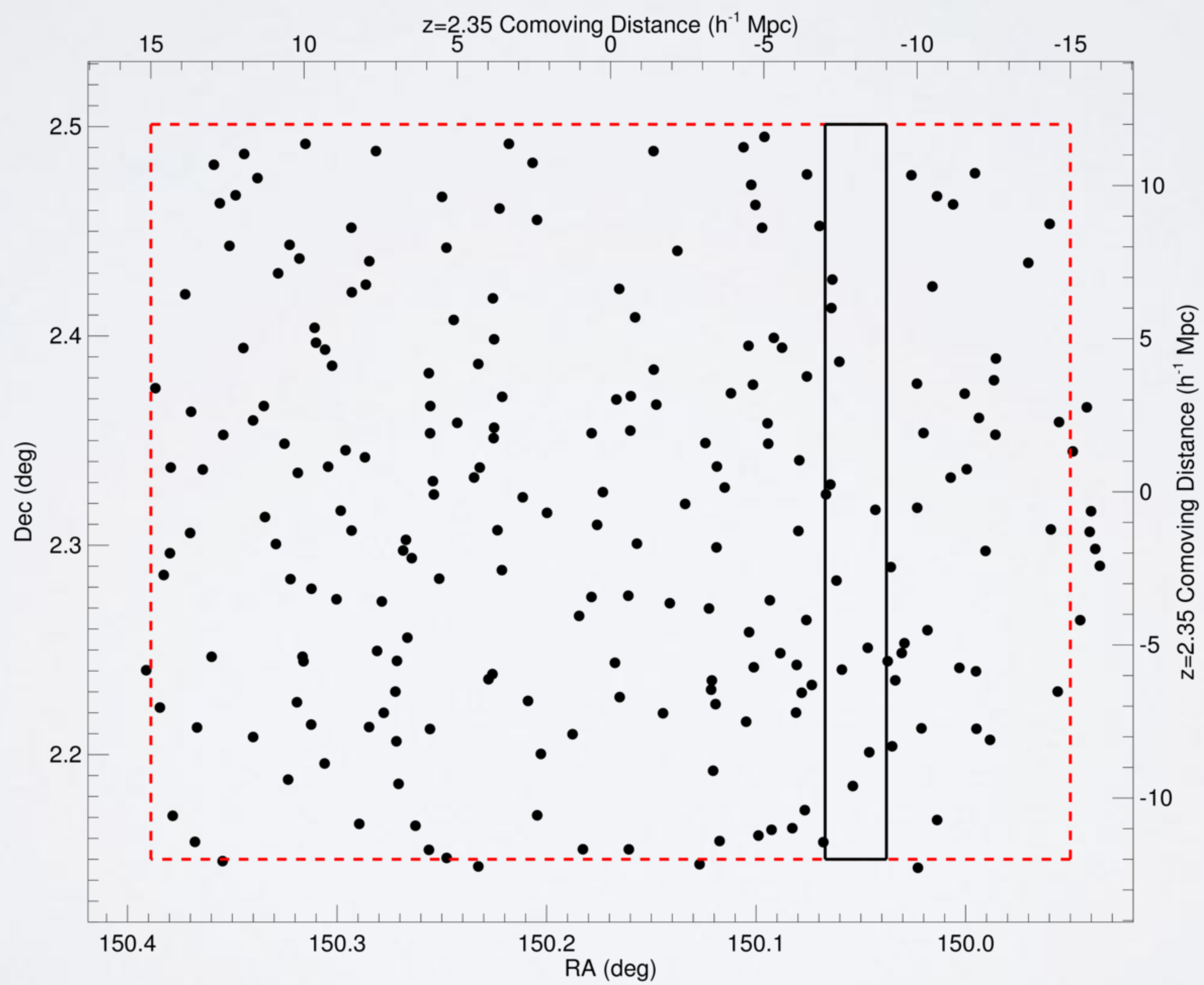
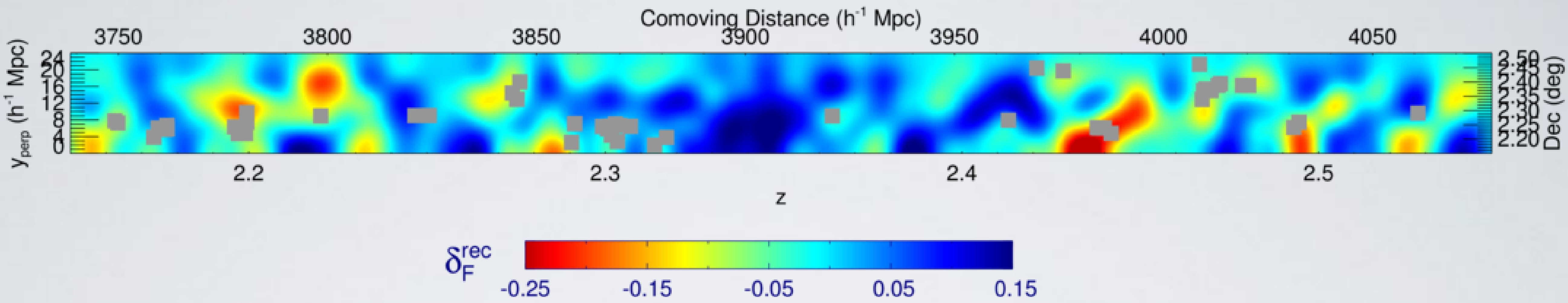
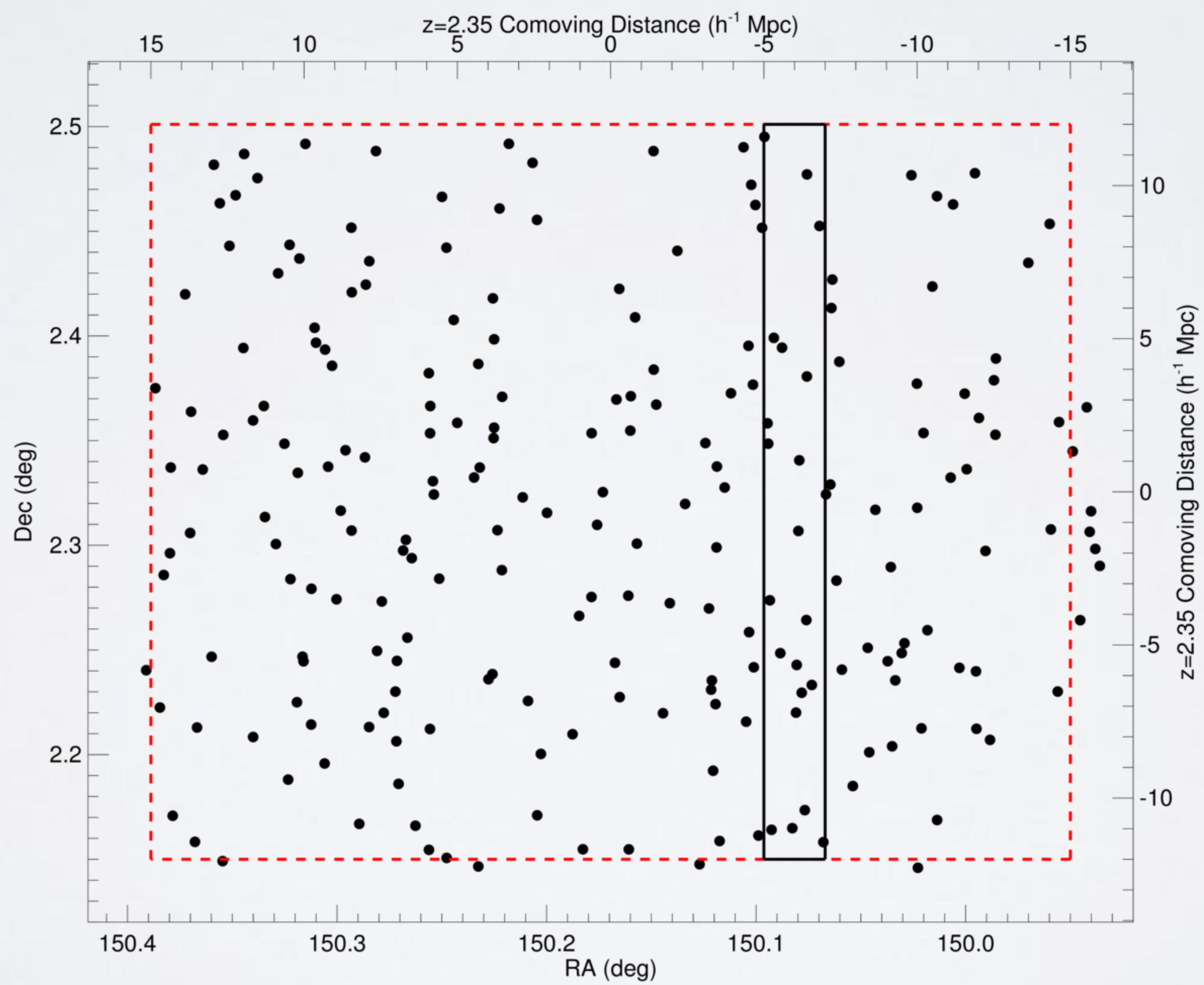


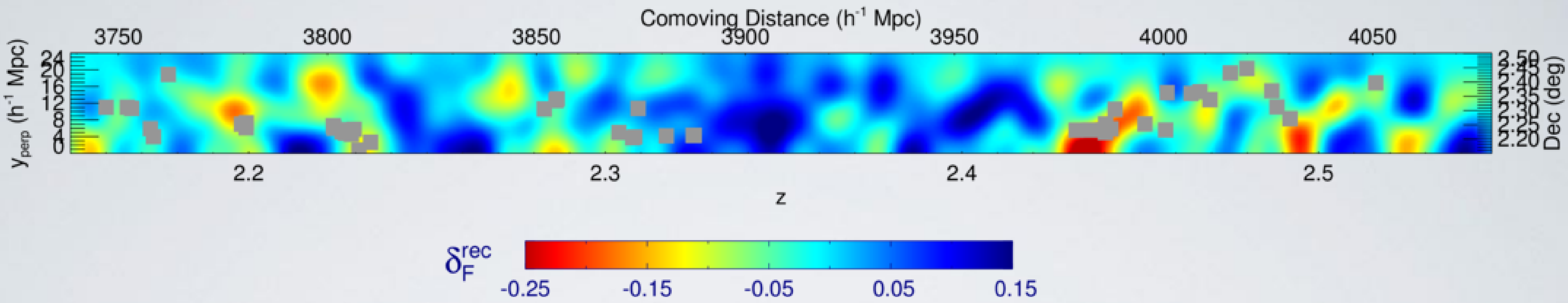
Slice #5: 150.067 < RA (deg) < 150.096



2.15 < z < 2.55 Sightlines



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



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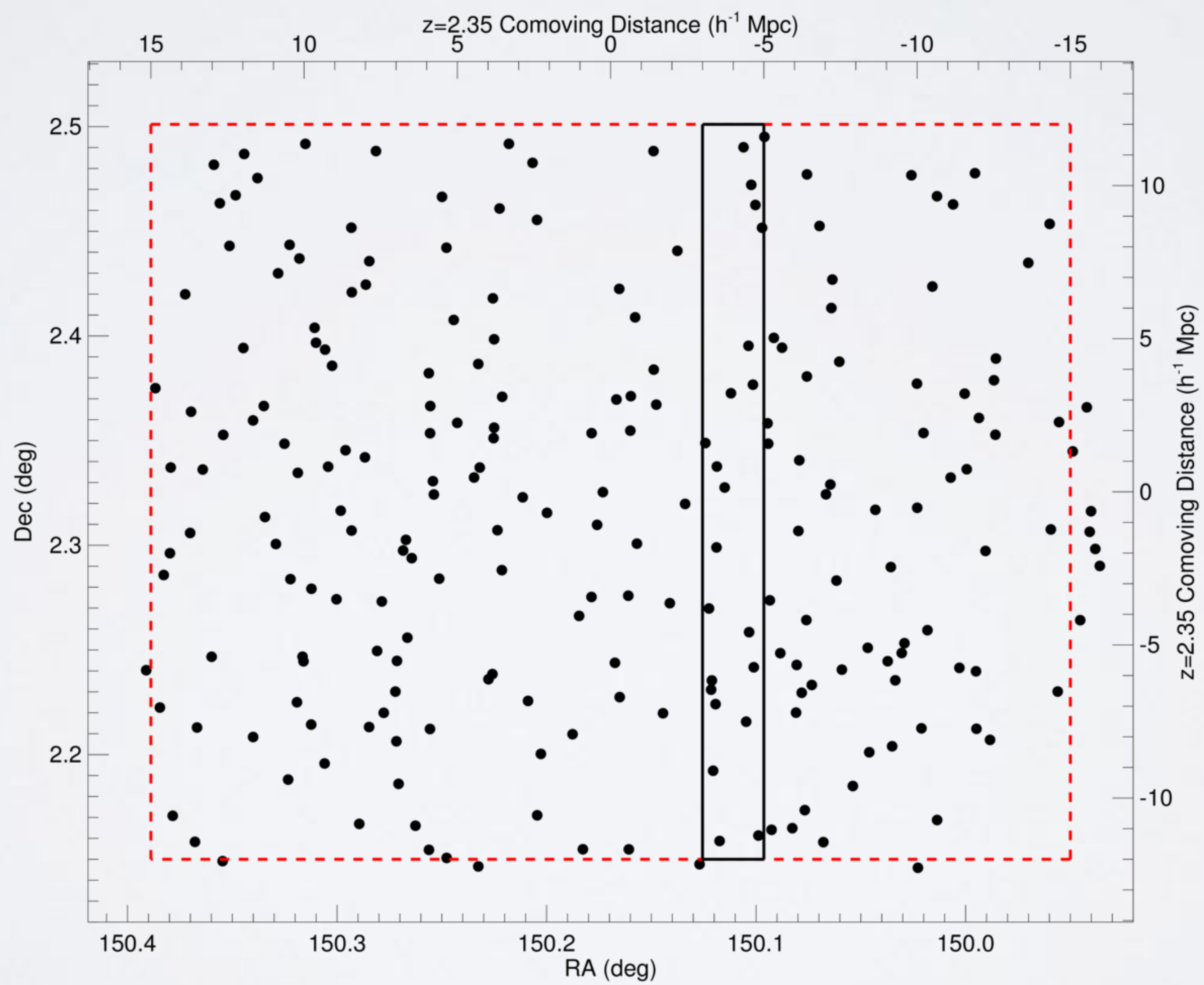
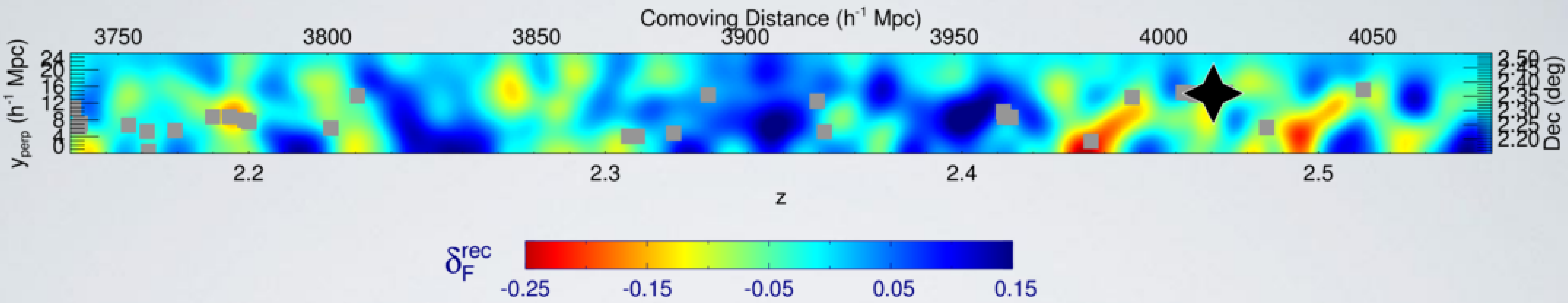
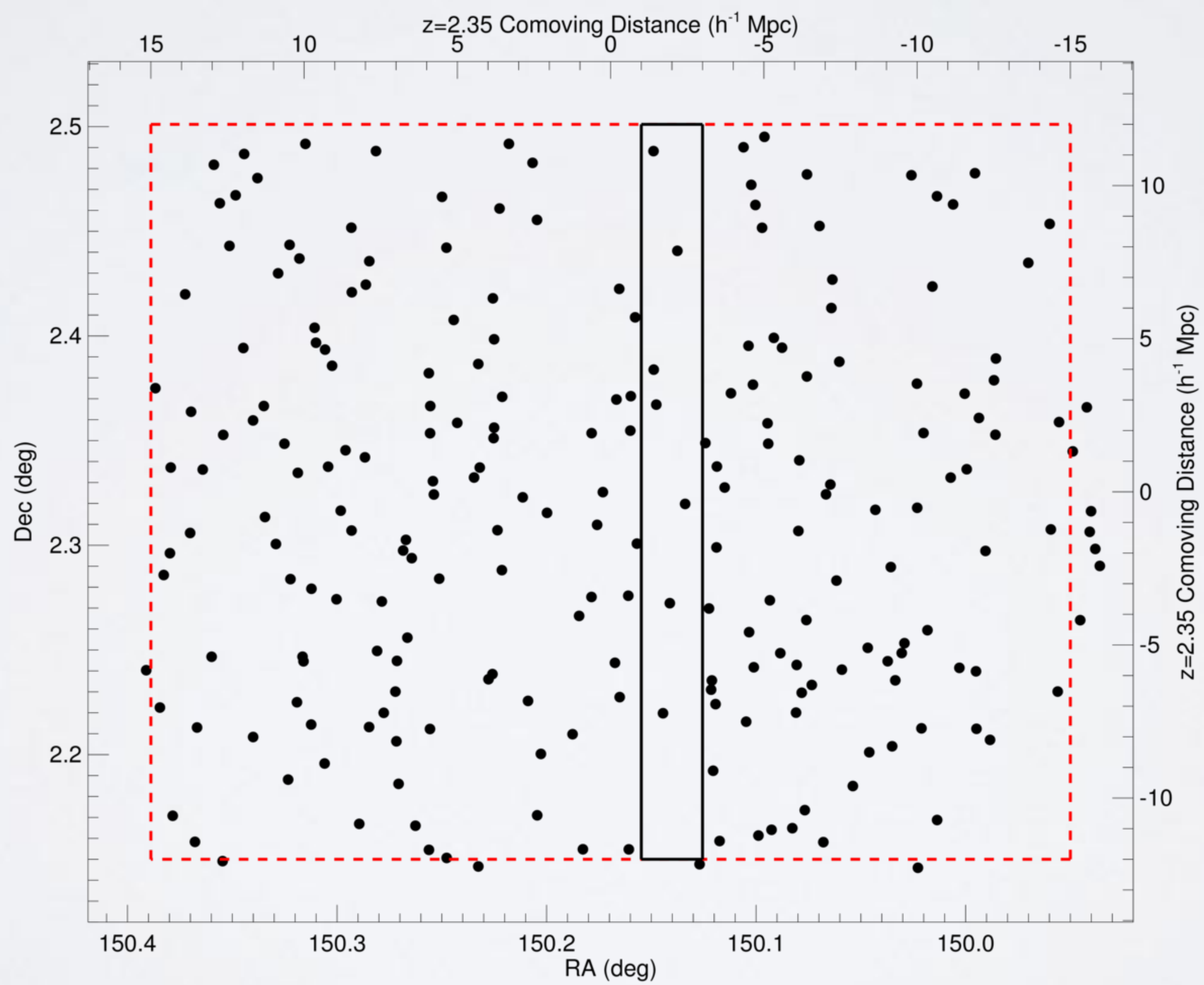


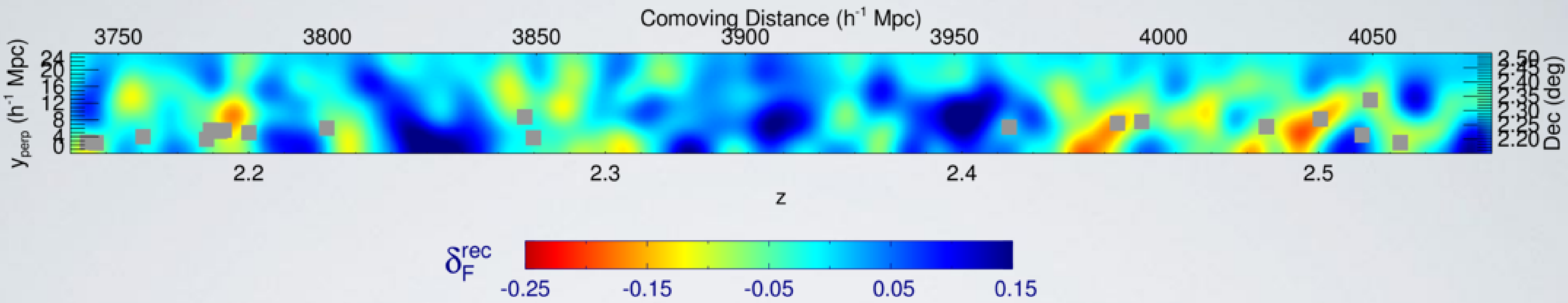
Slice #7: 150.126 < RA (deg) < 150.155



2.15 < z < 2.55 Sightlines



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



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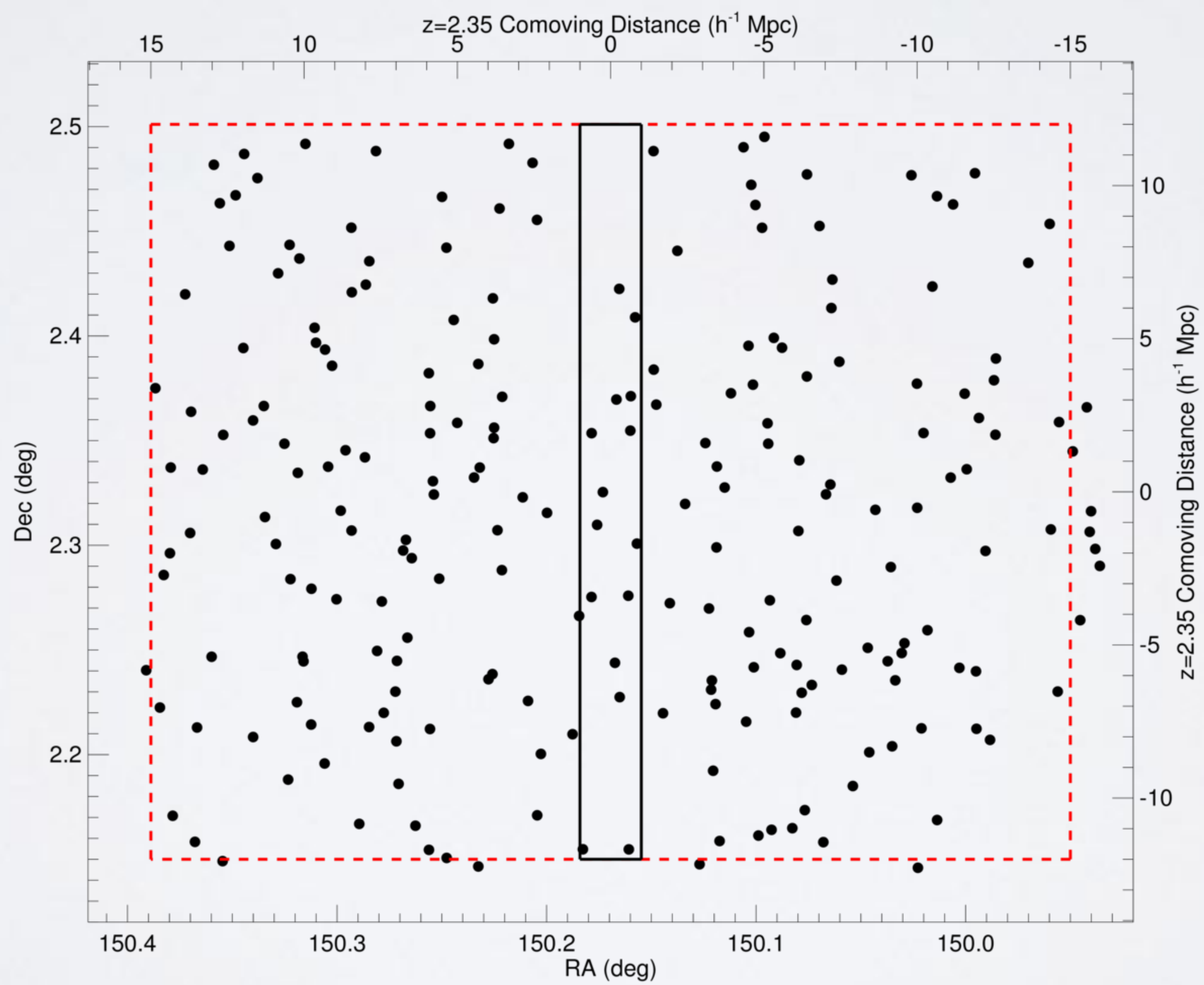
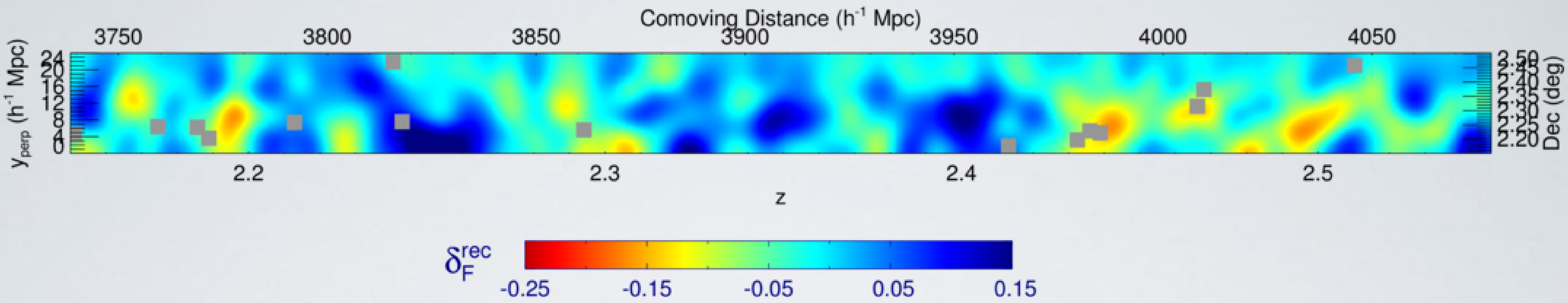
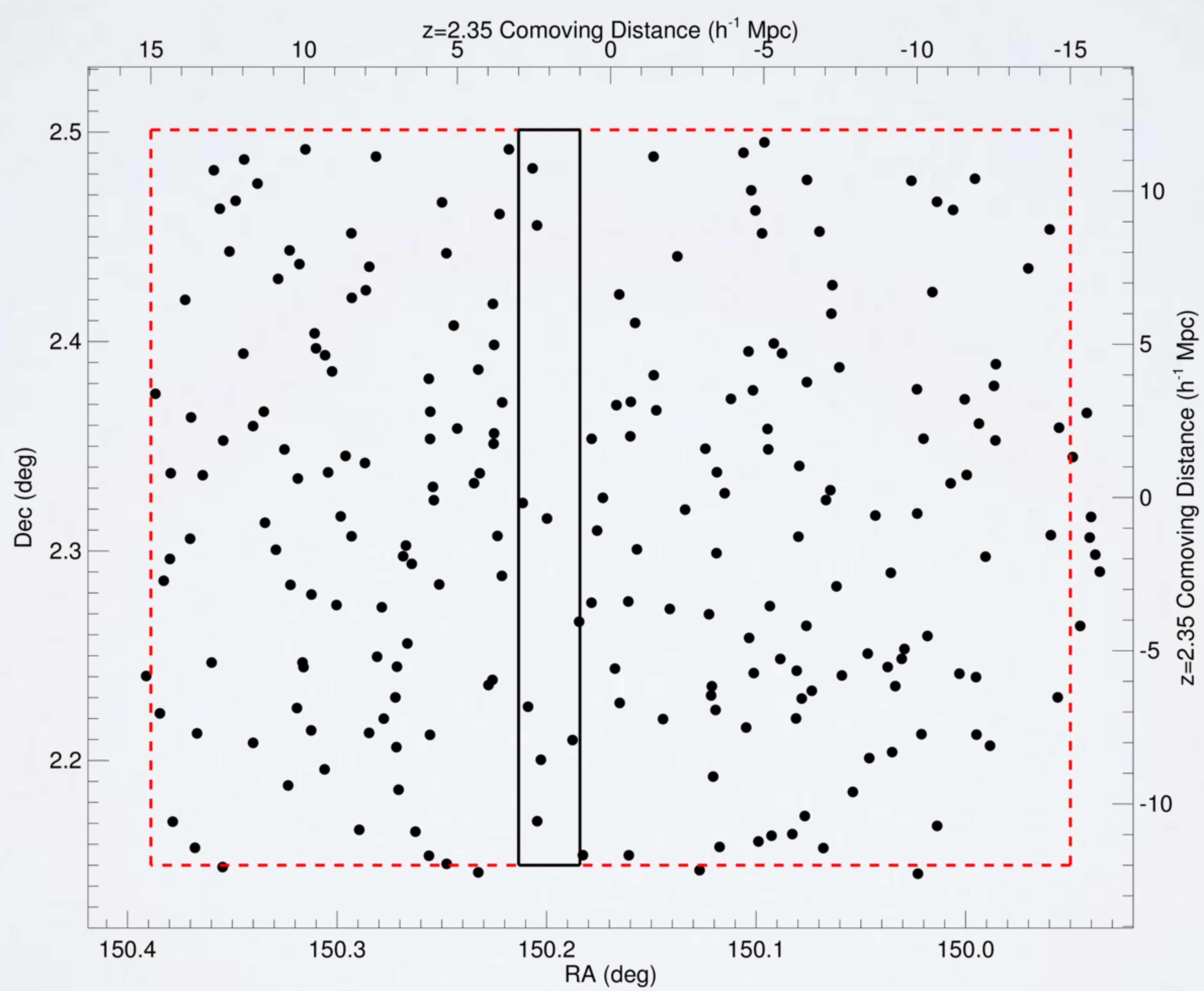


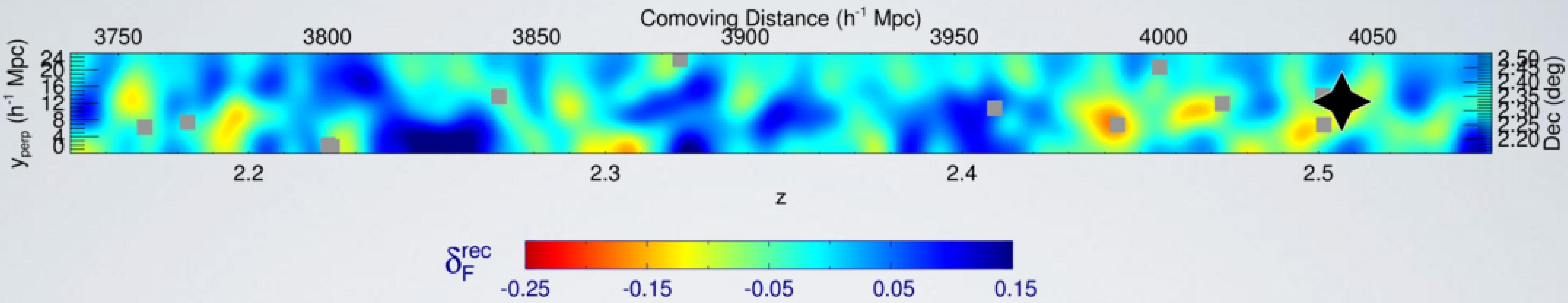
Slice #9: 150.184 < RA (deg) < 150.213



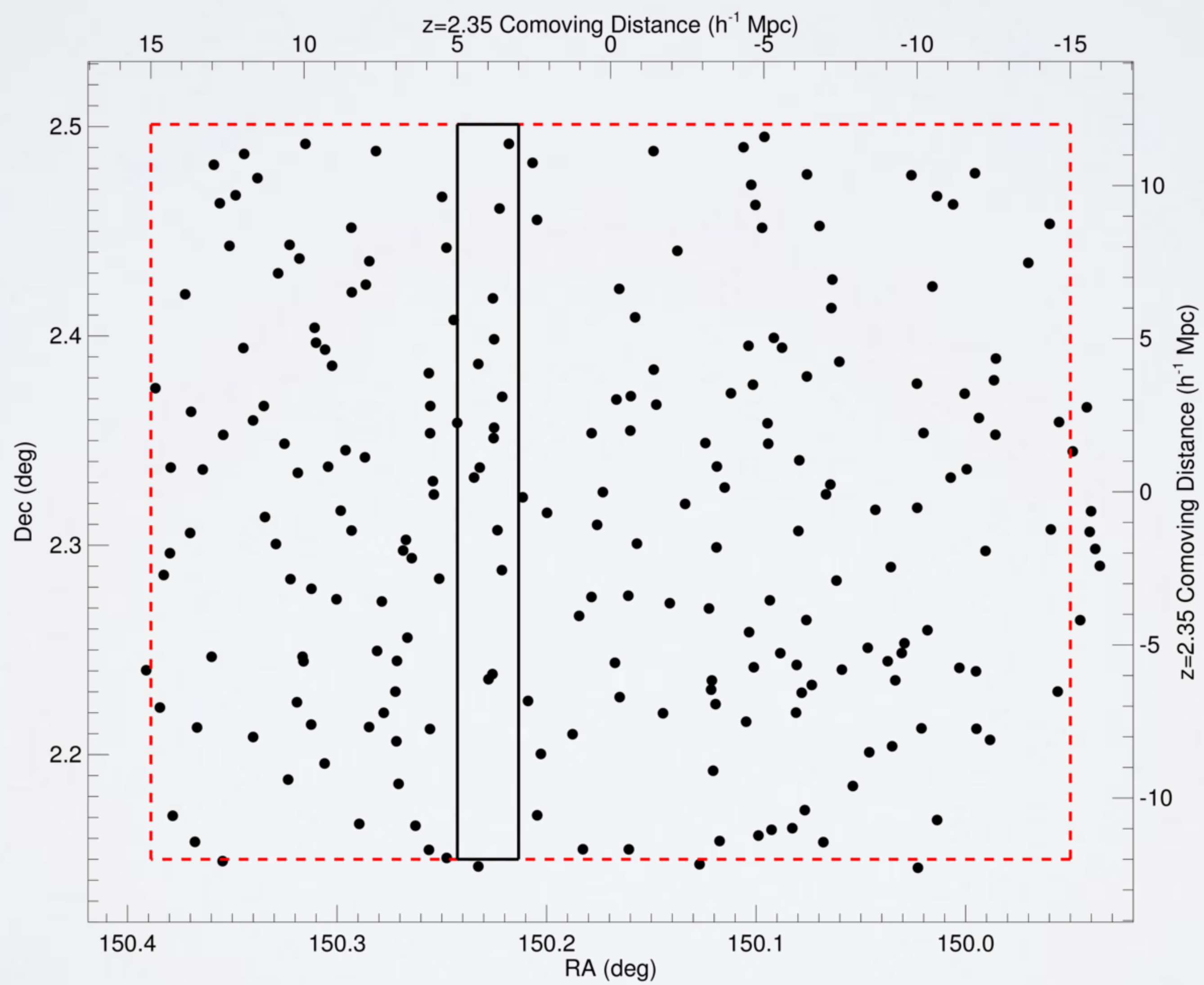
2.15 < z < 2.55 Sightlines



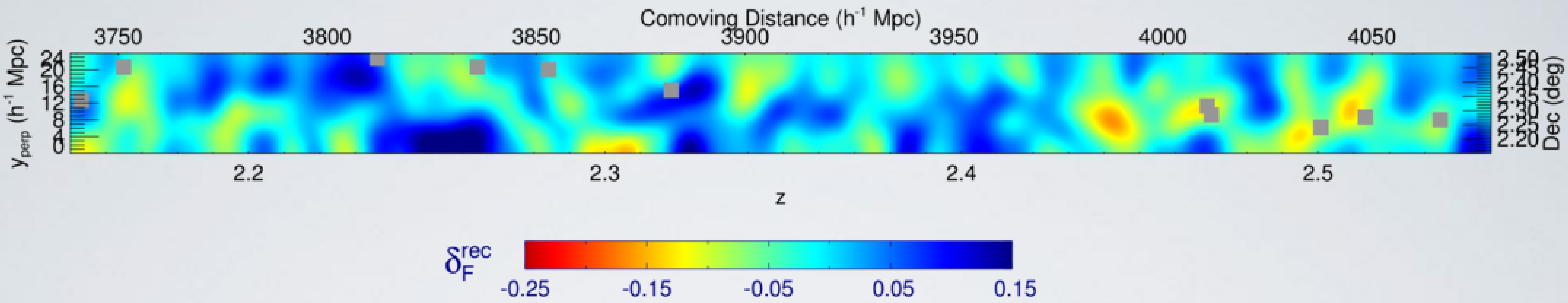
Slice #10: 150.213 < RA (deg) < 150.243



2.15 < z < 2.55 Sightlines



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



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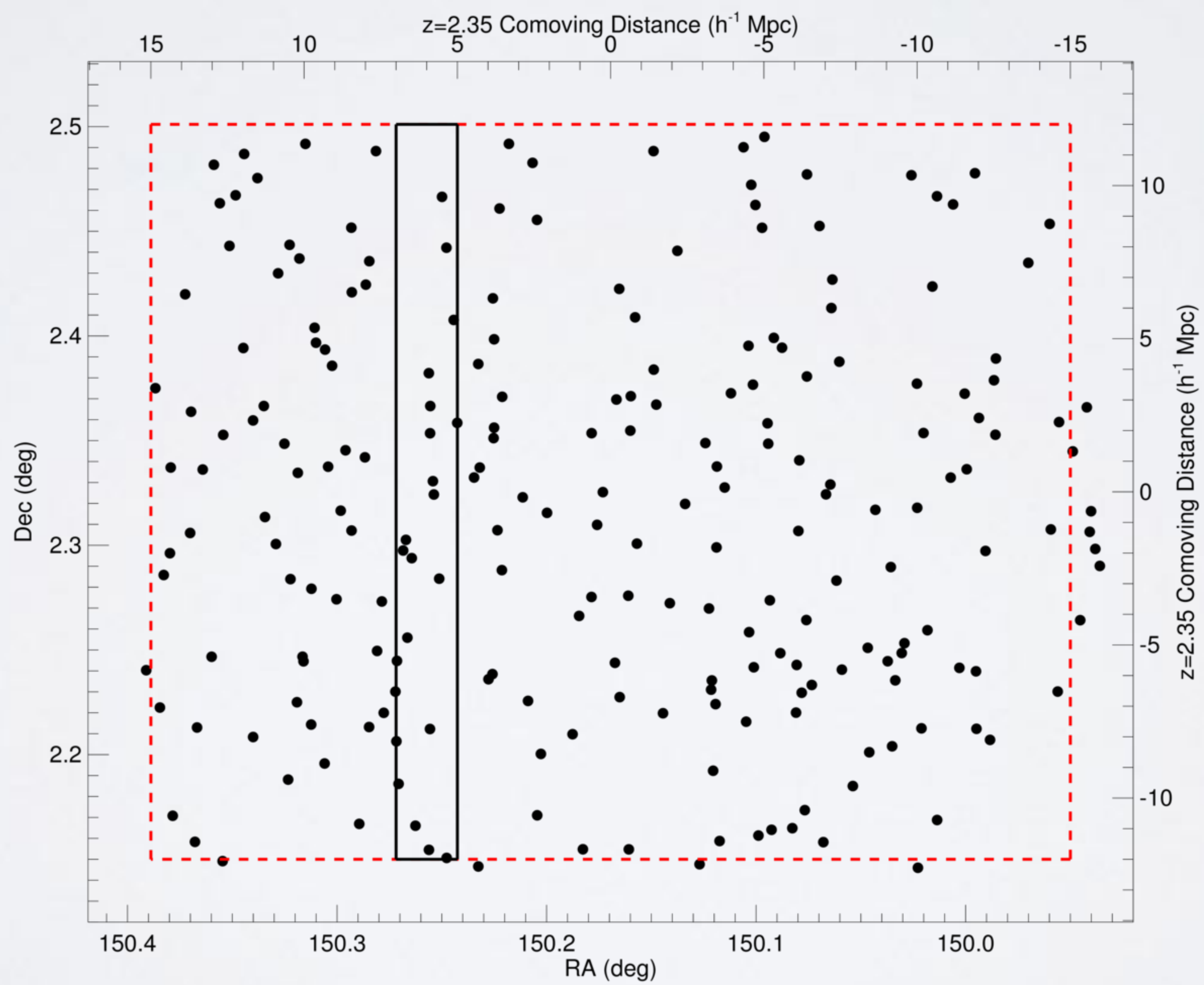
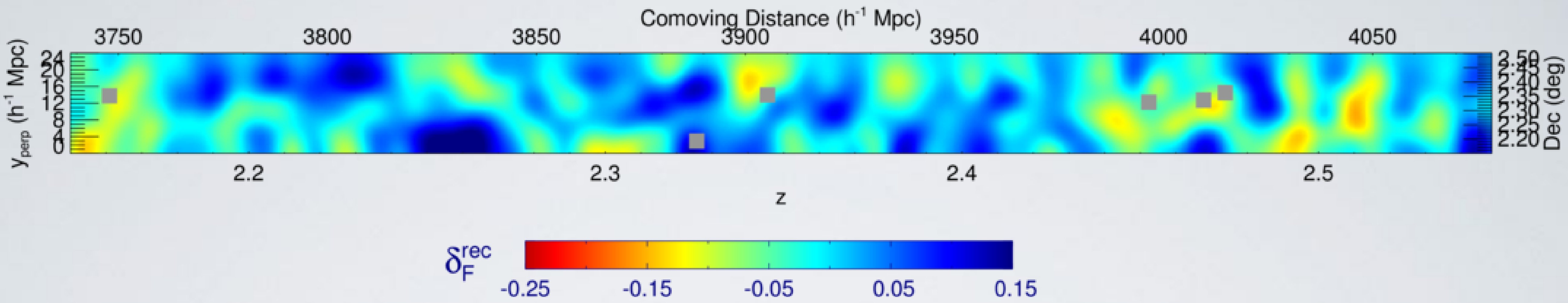


Slice #12: 150.272 < RA (deg) < 150.301



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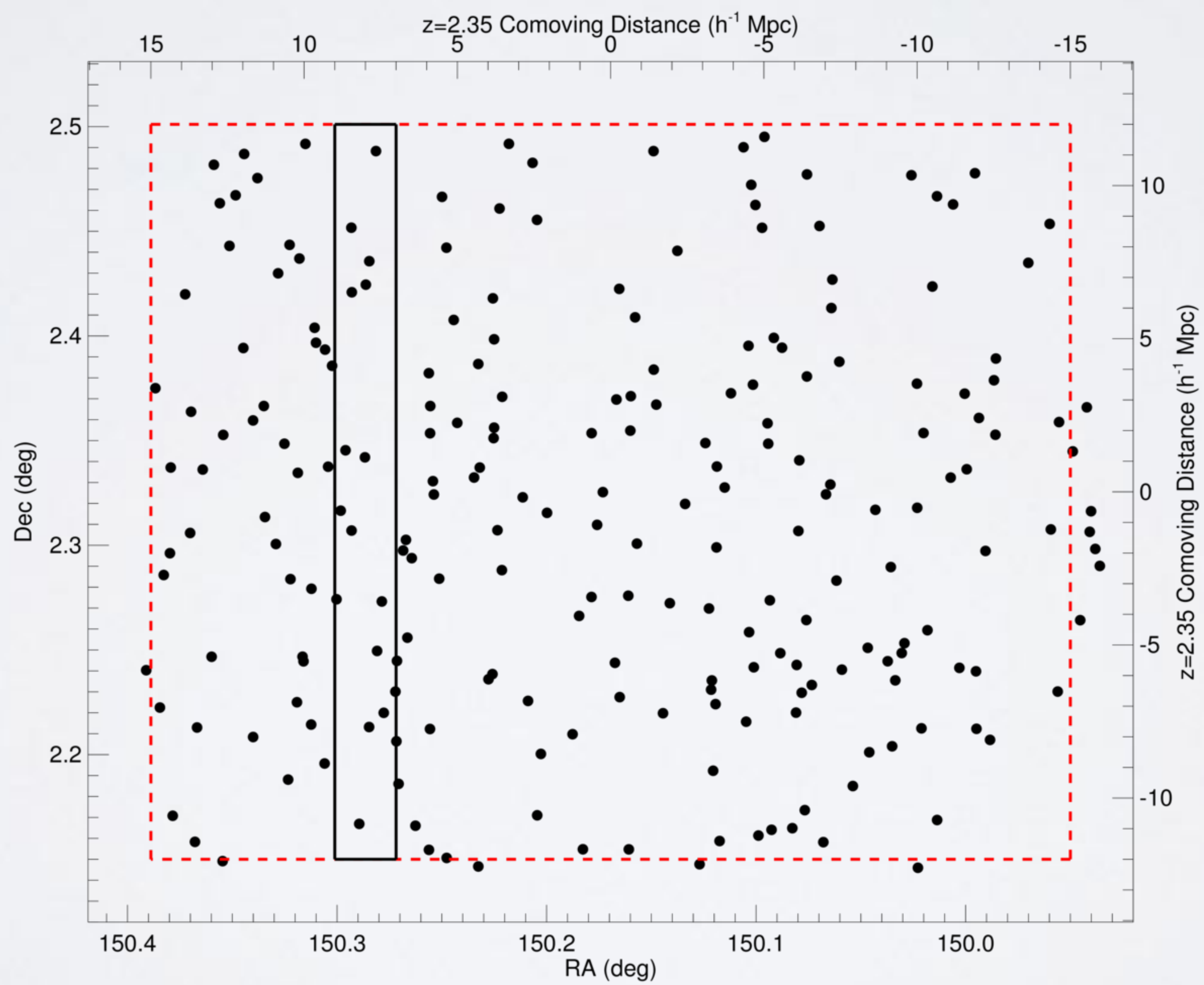
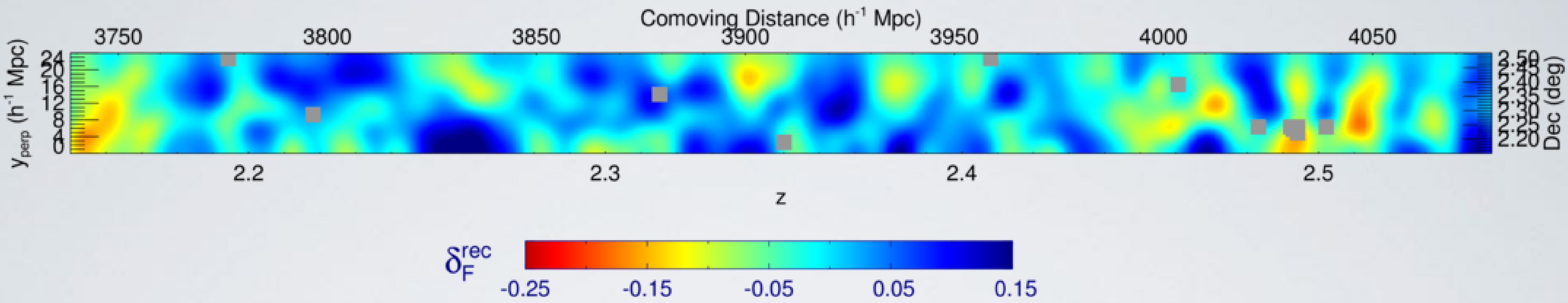
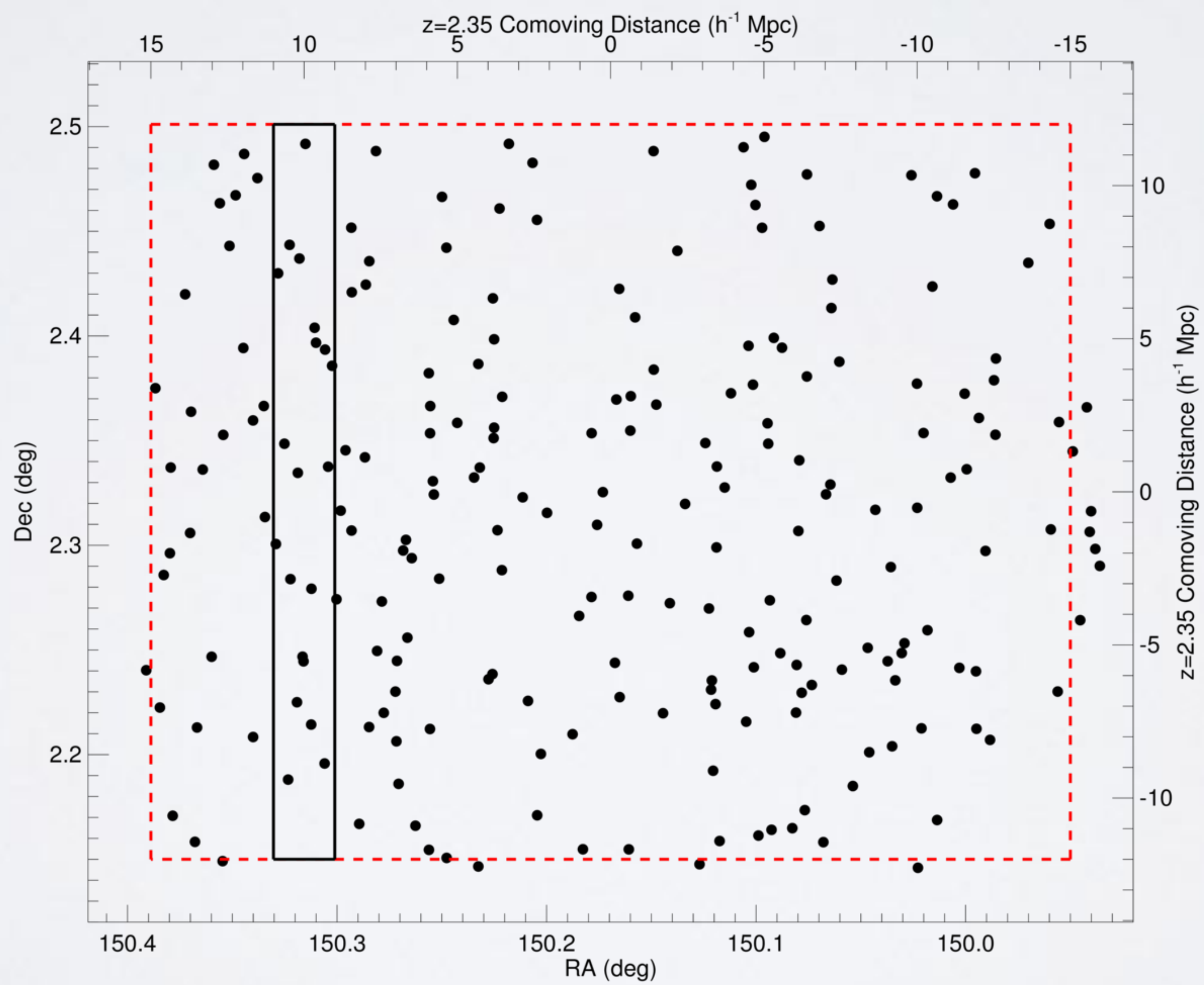


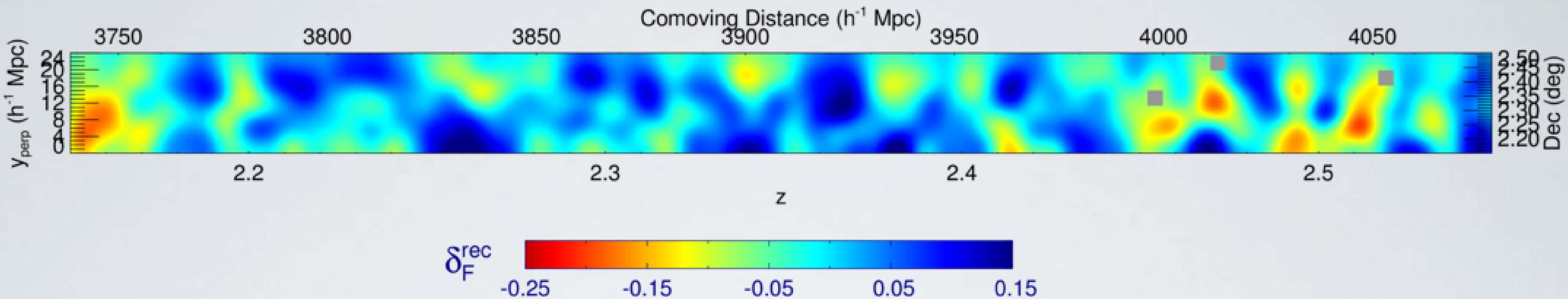
Slice #13: 150.301 < RA (deg) < 150.330



2.15 < z < 2.55 Sightlines



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



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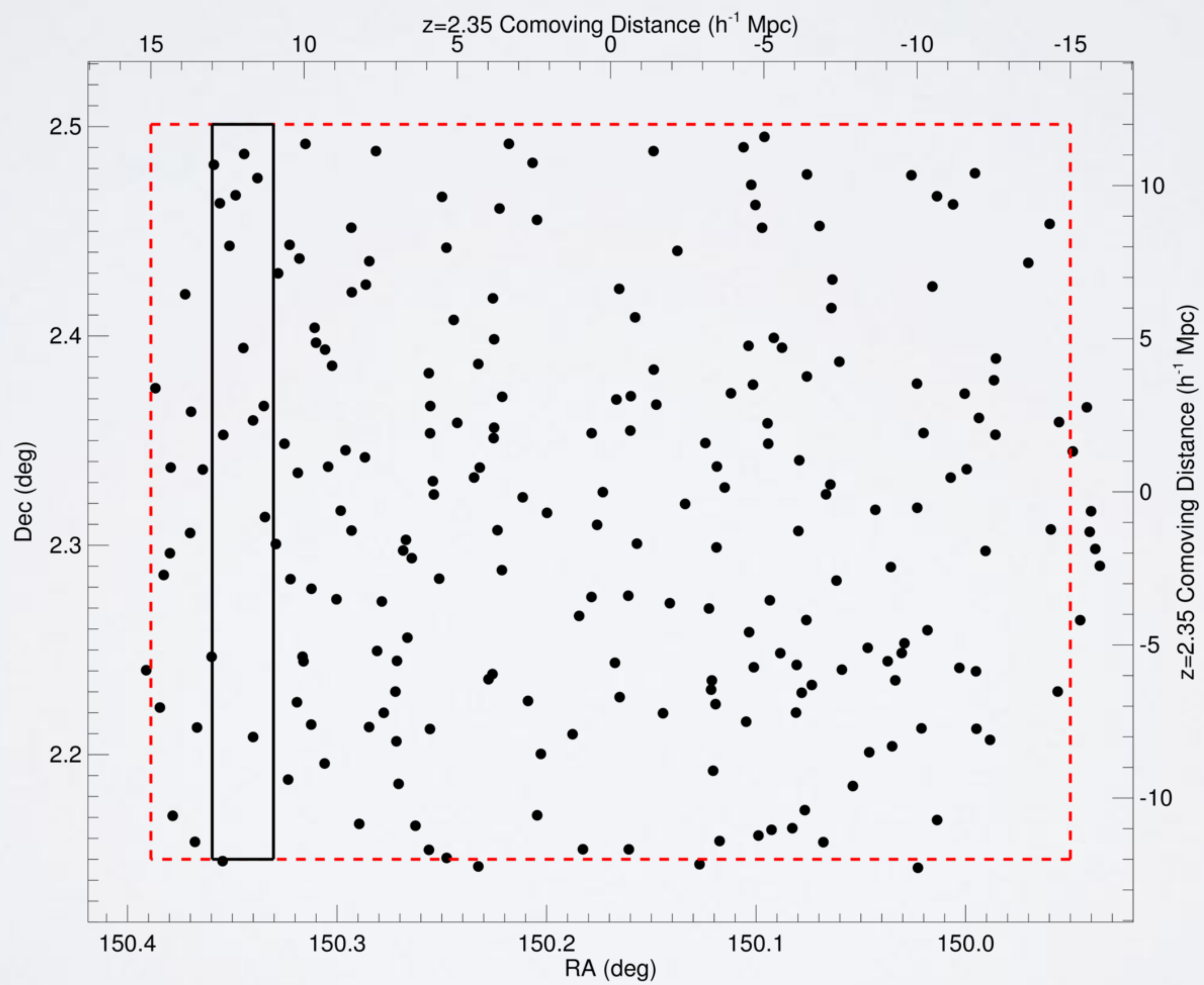

Slice #15: 150.360 < RA (deg) < 150.389