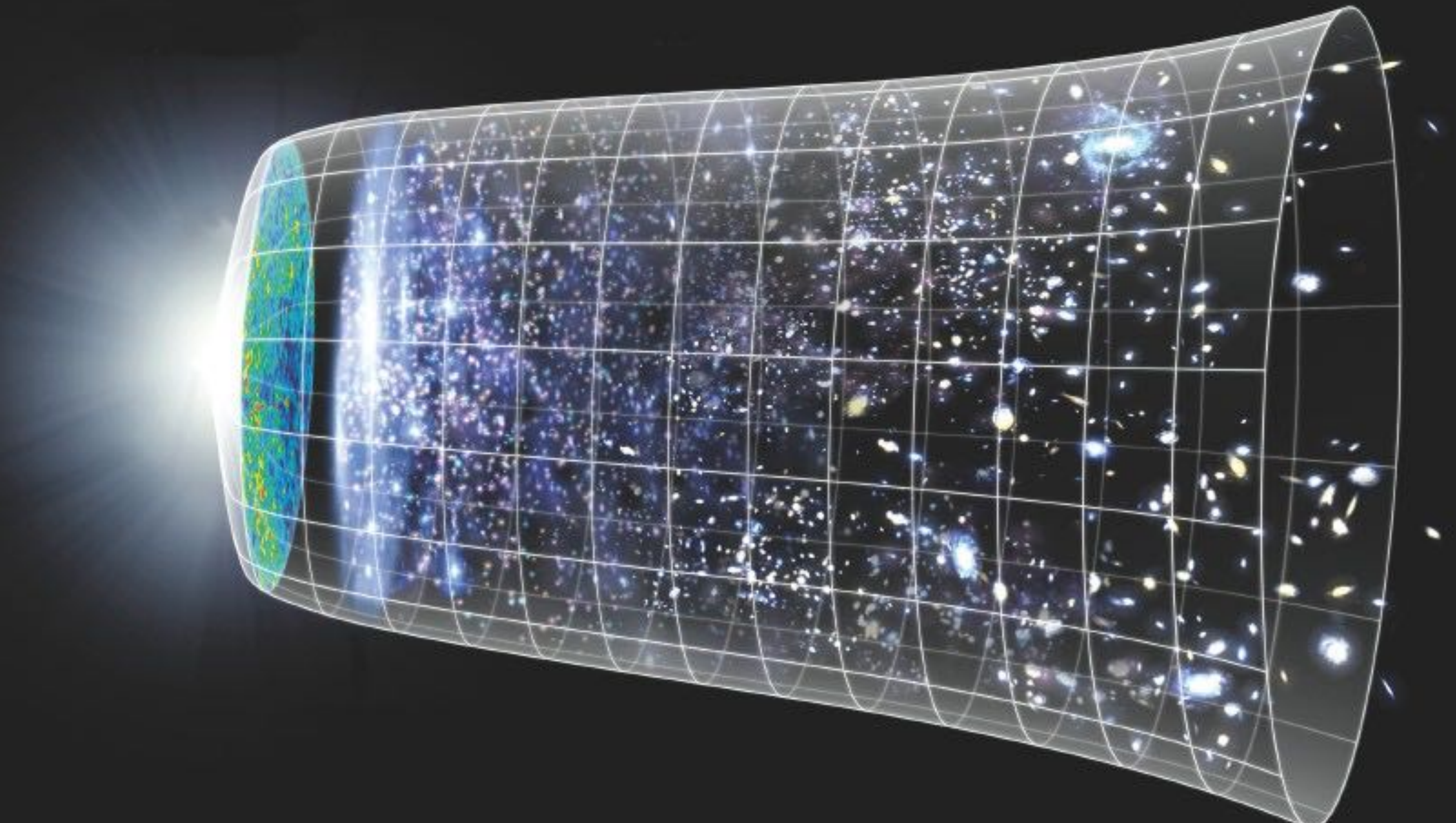
BERKELEY CENTER *for* COSMOLOGICAL PHYSICS

Efficient Optimal Reconstruction of Cosmological Density Fields

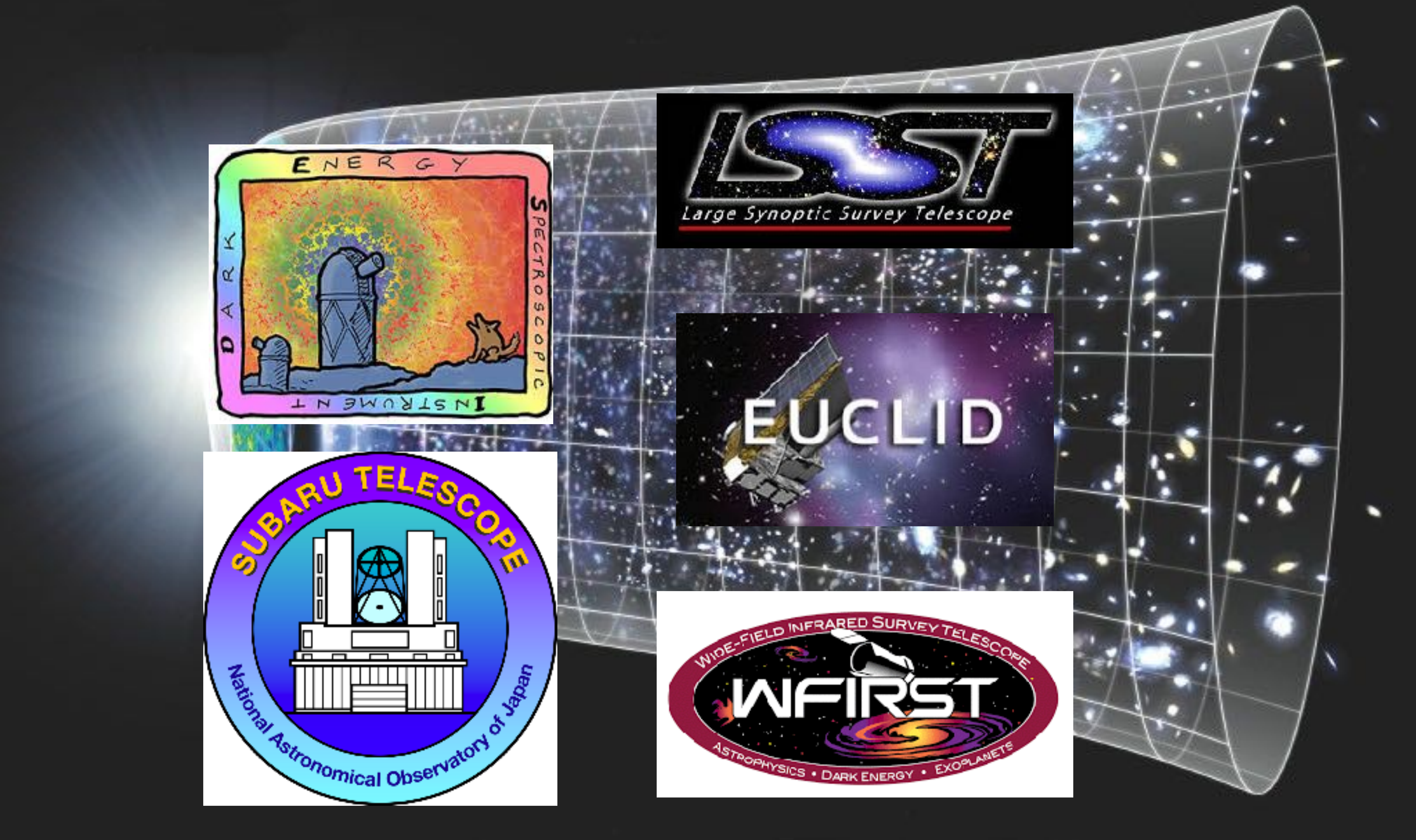
Benjamin Horowitz (UC Berkeley, NSF Graduate Research Fellow)

Accelerating Universe in the Dark

Linear → Nonlinear

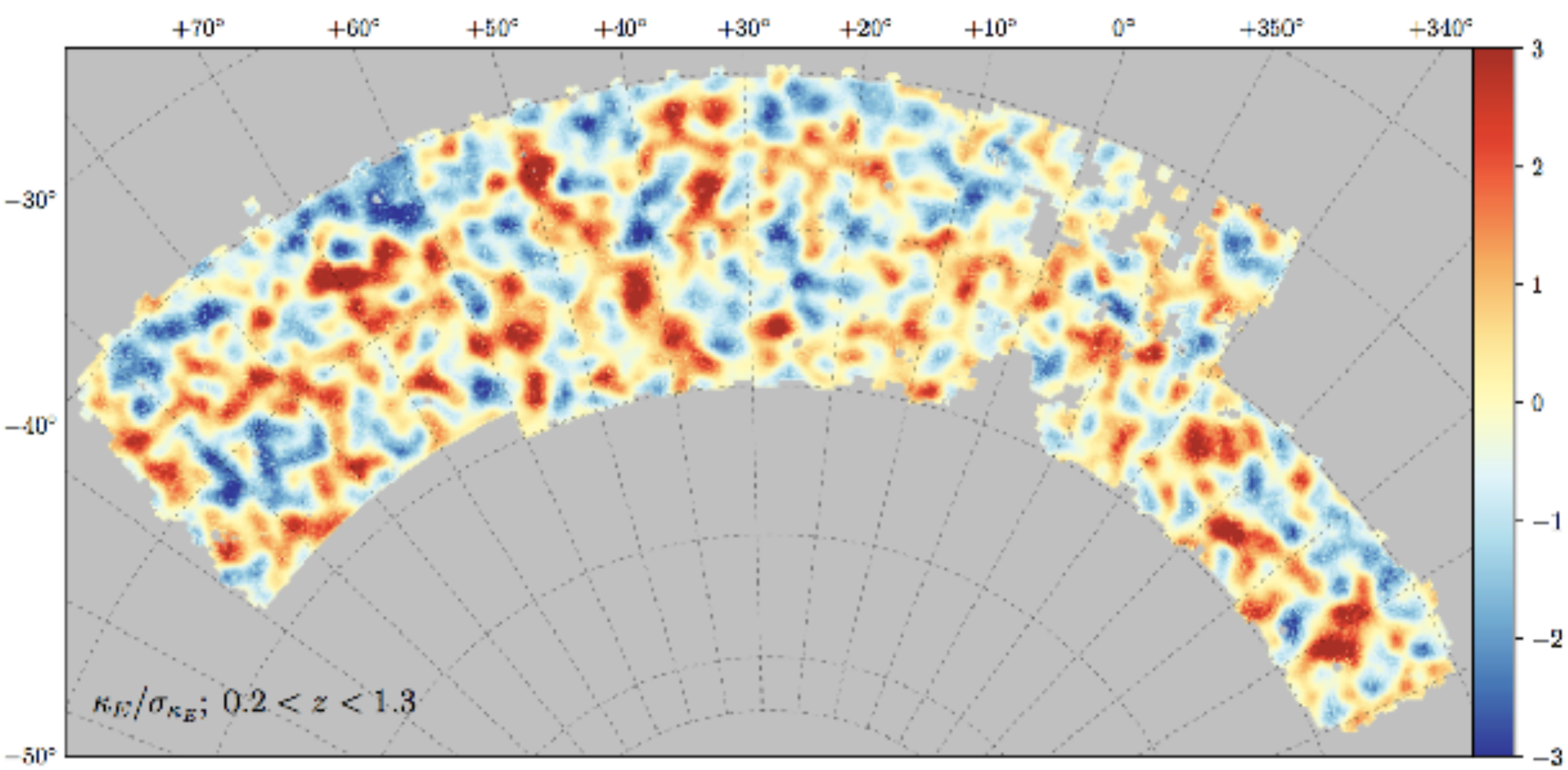


Linear → Nonlinear



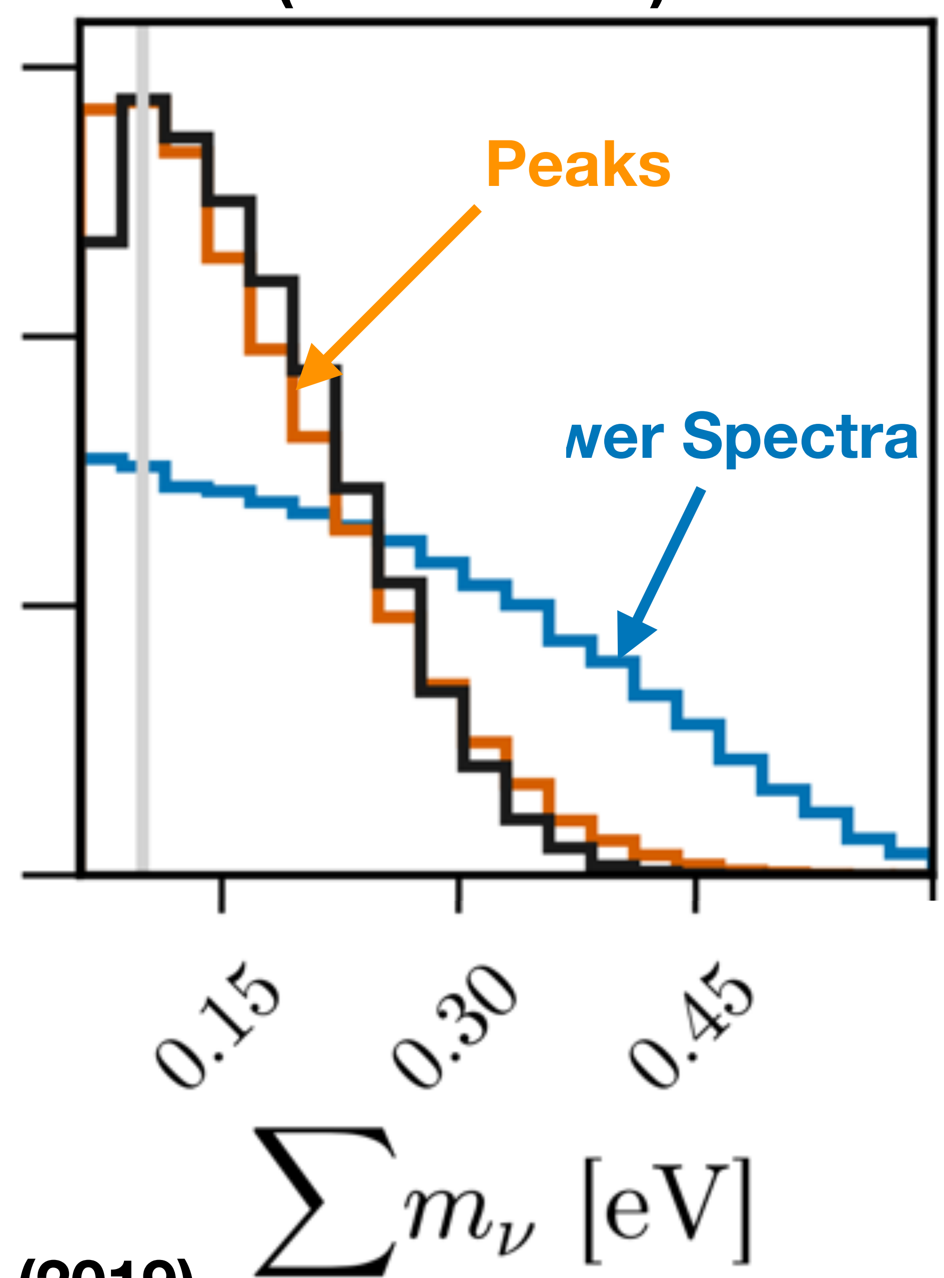
A Wealth of Information in the Beyond the Power Spectra: Motivating Example

Dark Energy Survey Mass Map



Weak Lensing Peak Counts

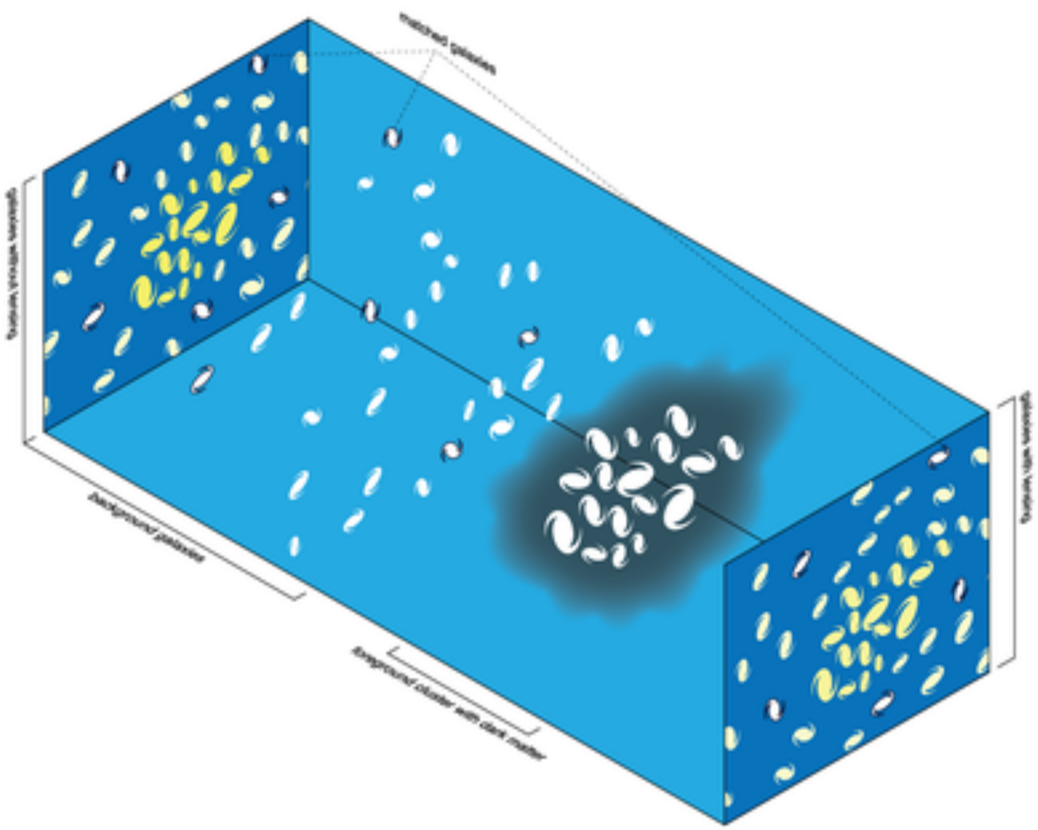
(Simulations)



Chang et al. (2017)

Li et al. (2019)

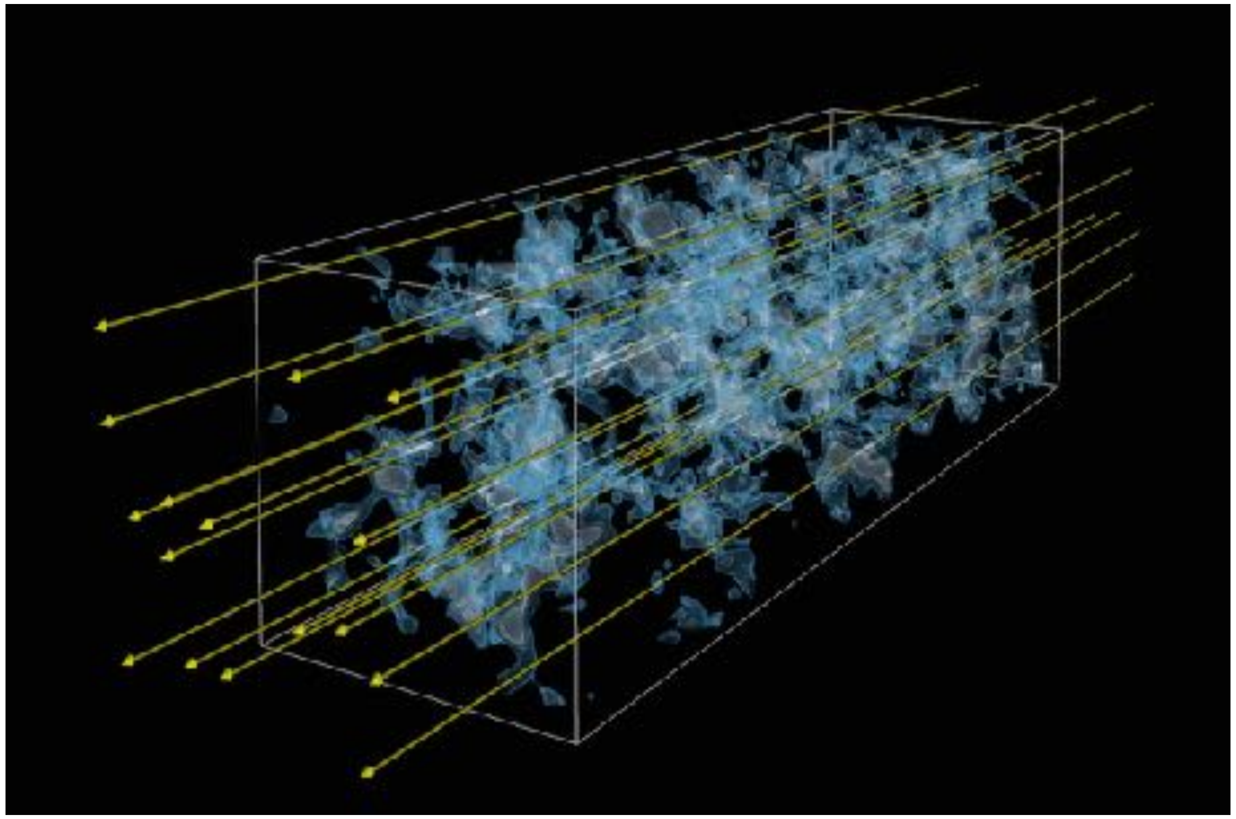
Weak Lensing



Uros Seljak and Grigor Aslanyan (UC Berkeley)

arXiv:1810:00503

Lyman Alpha Tomography



K.G. Lee (IPMU)
+ CLAMATO Collaboration

arXiv:190?:????

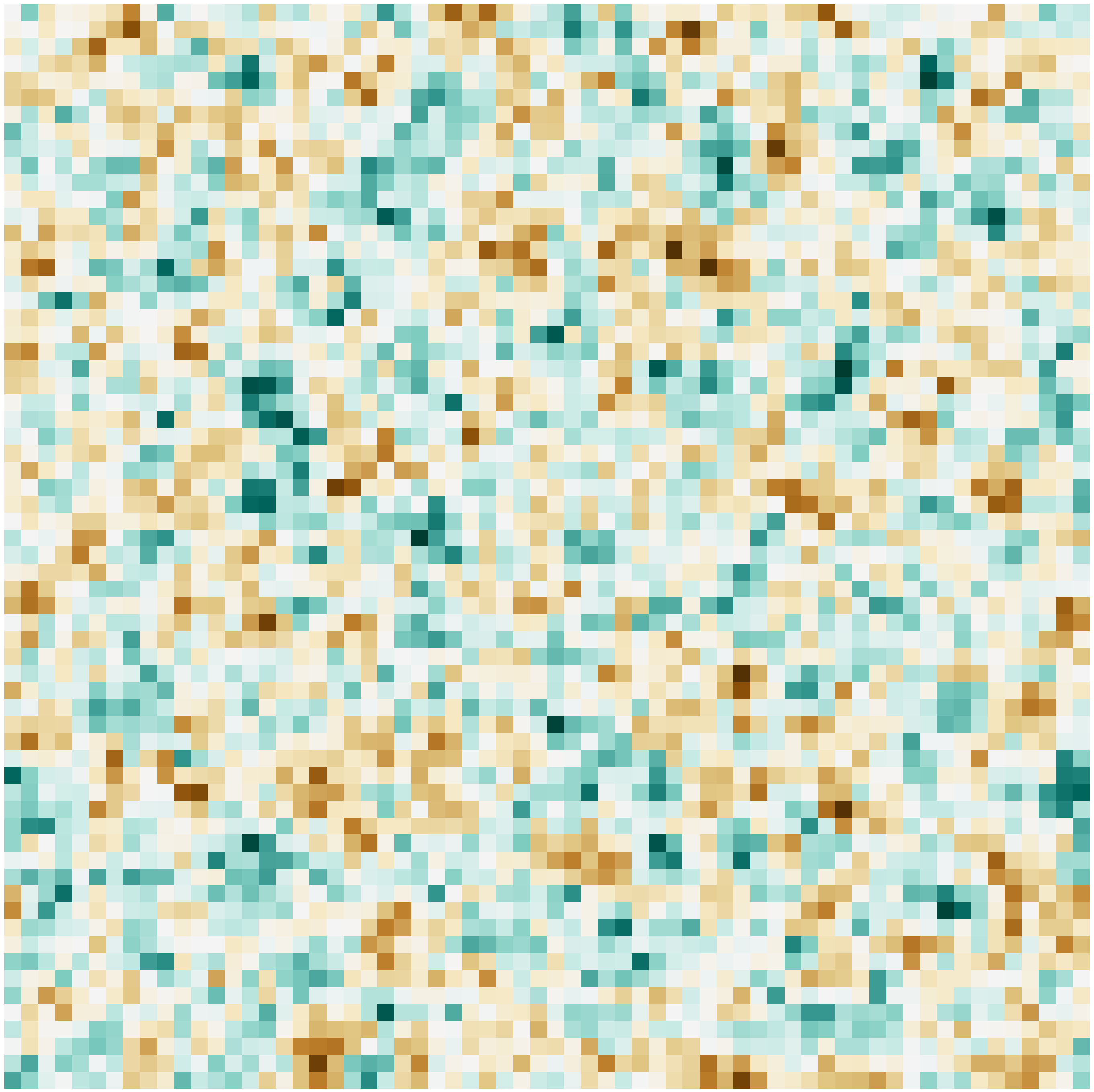
Notation

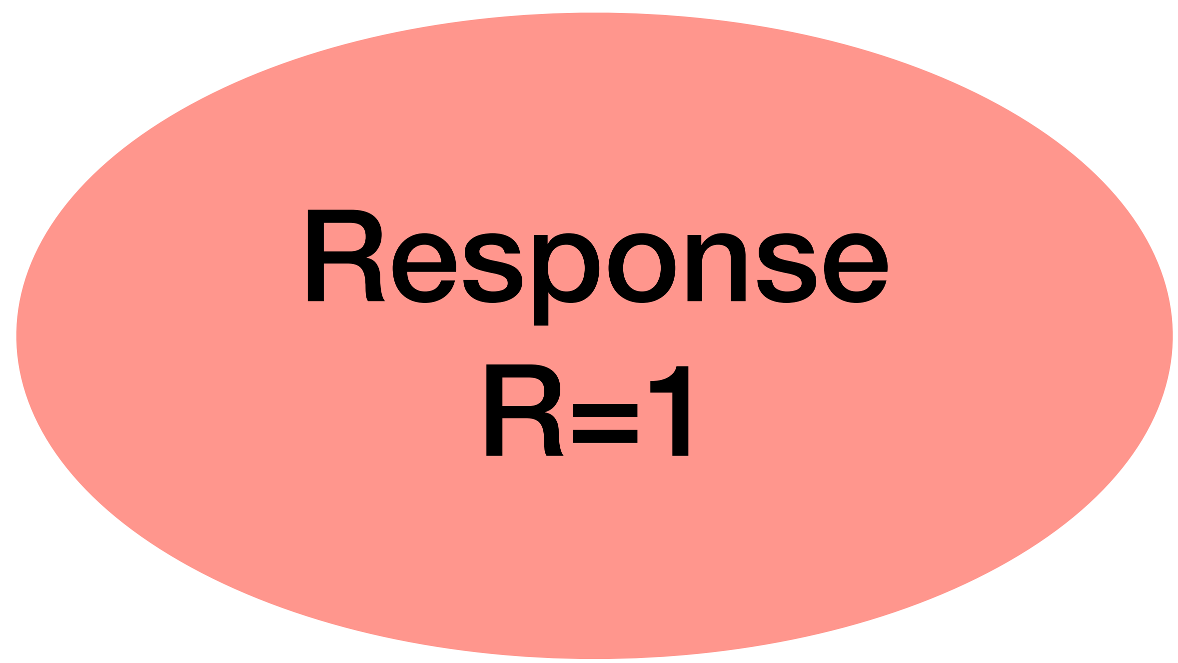
response **noise/mask**

$$\mathbf{d} = \mathbf{R}\mathbf{s} + \mathbf{n}$$

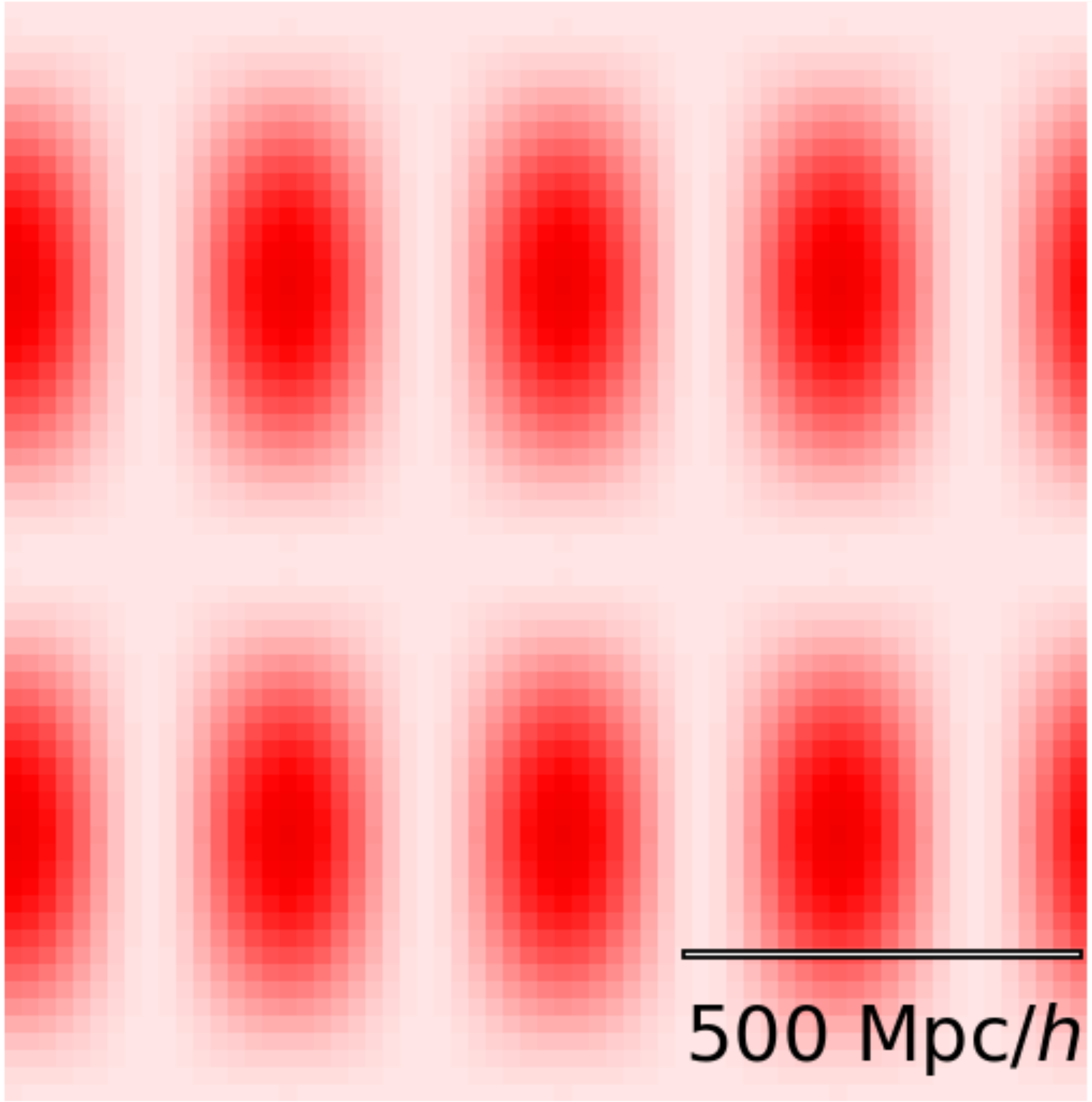
data **signal**

Toy Example: Signal Field
Linear Density Field (64x64)

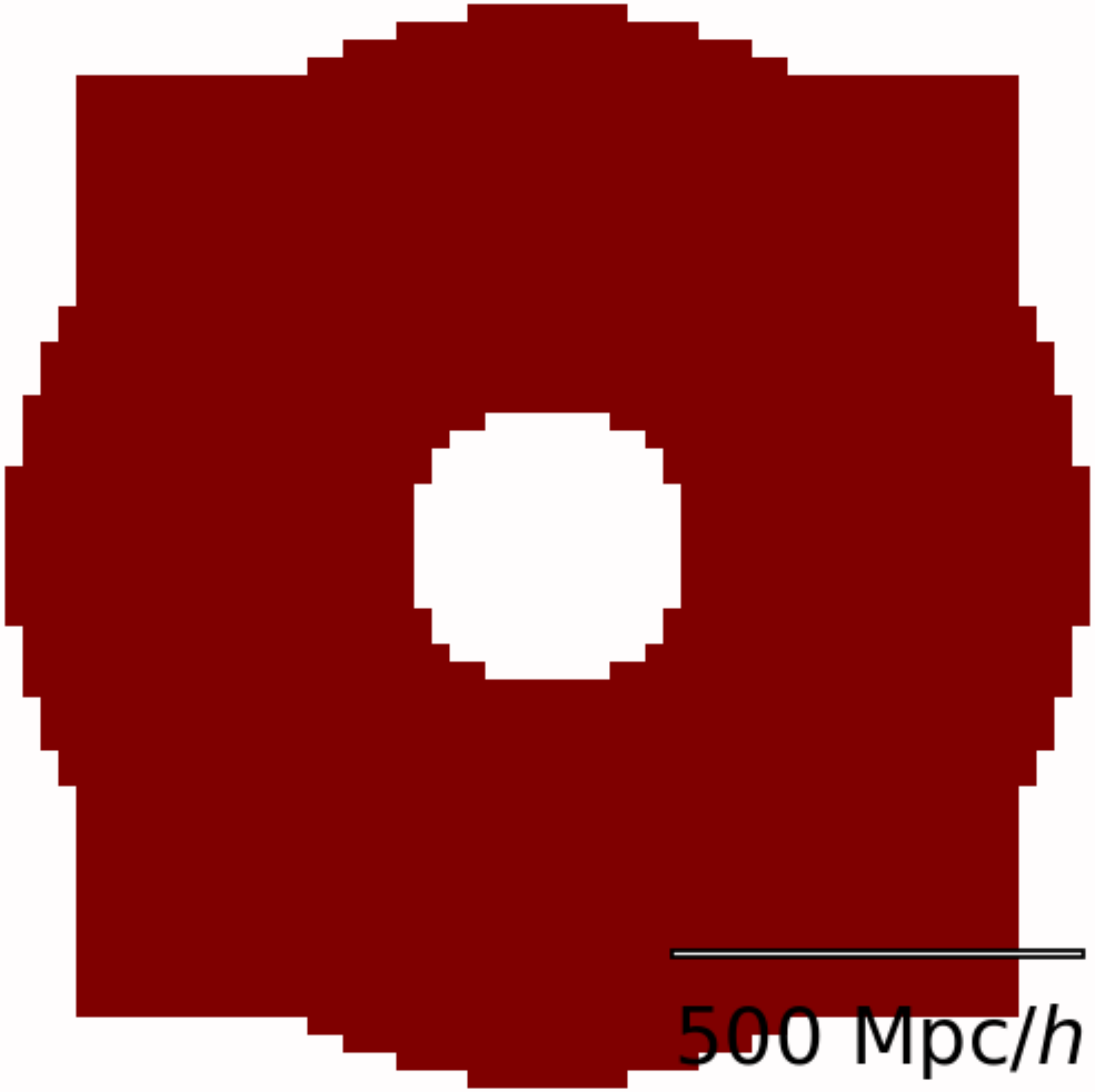




+ Noise



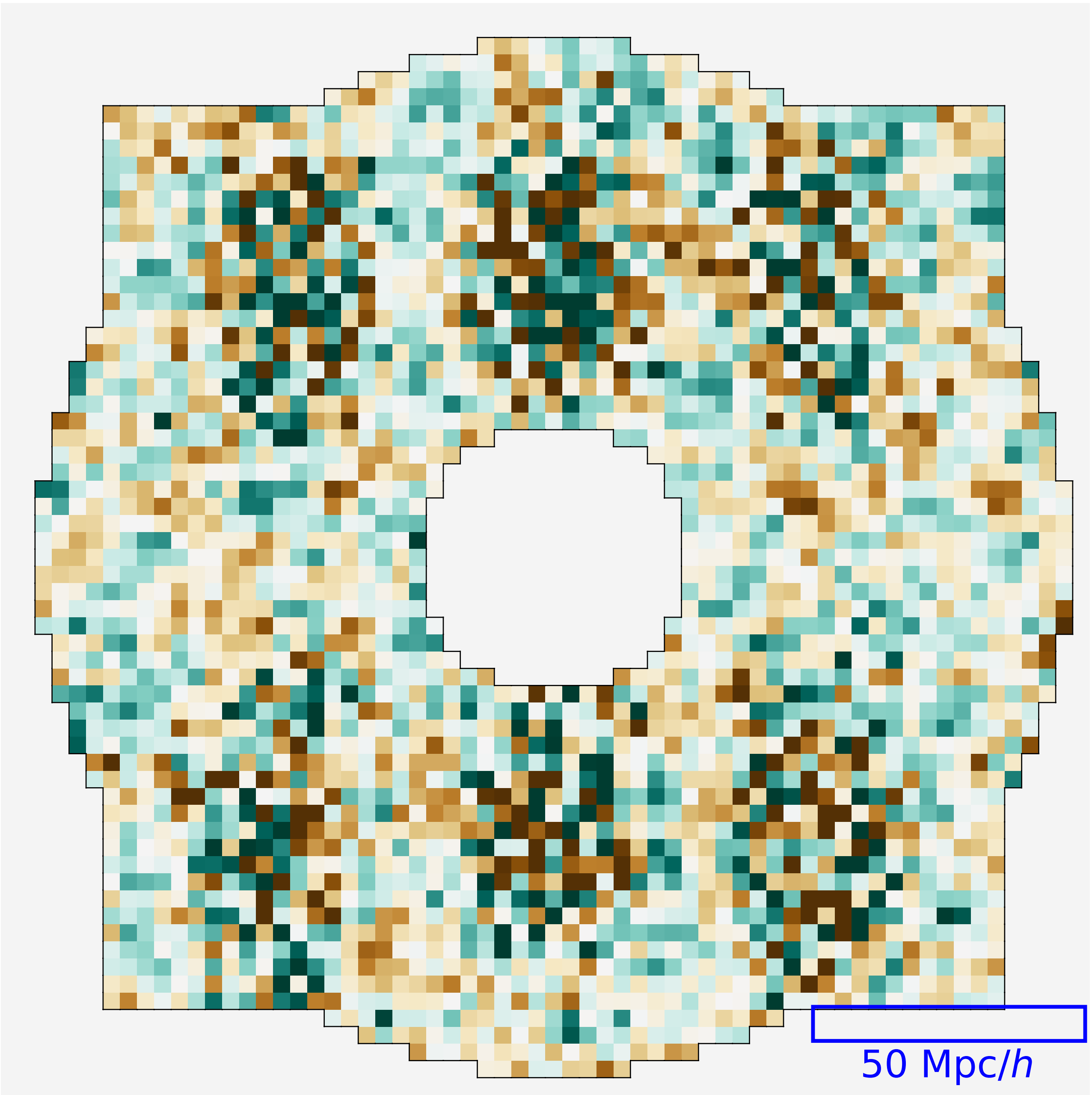
Anisotropic Noise



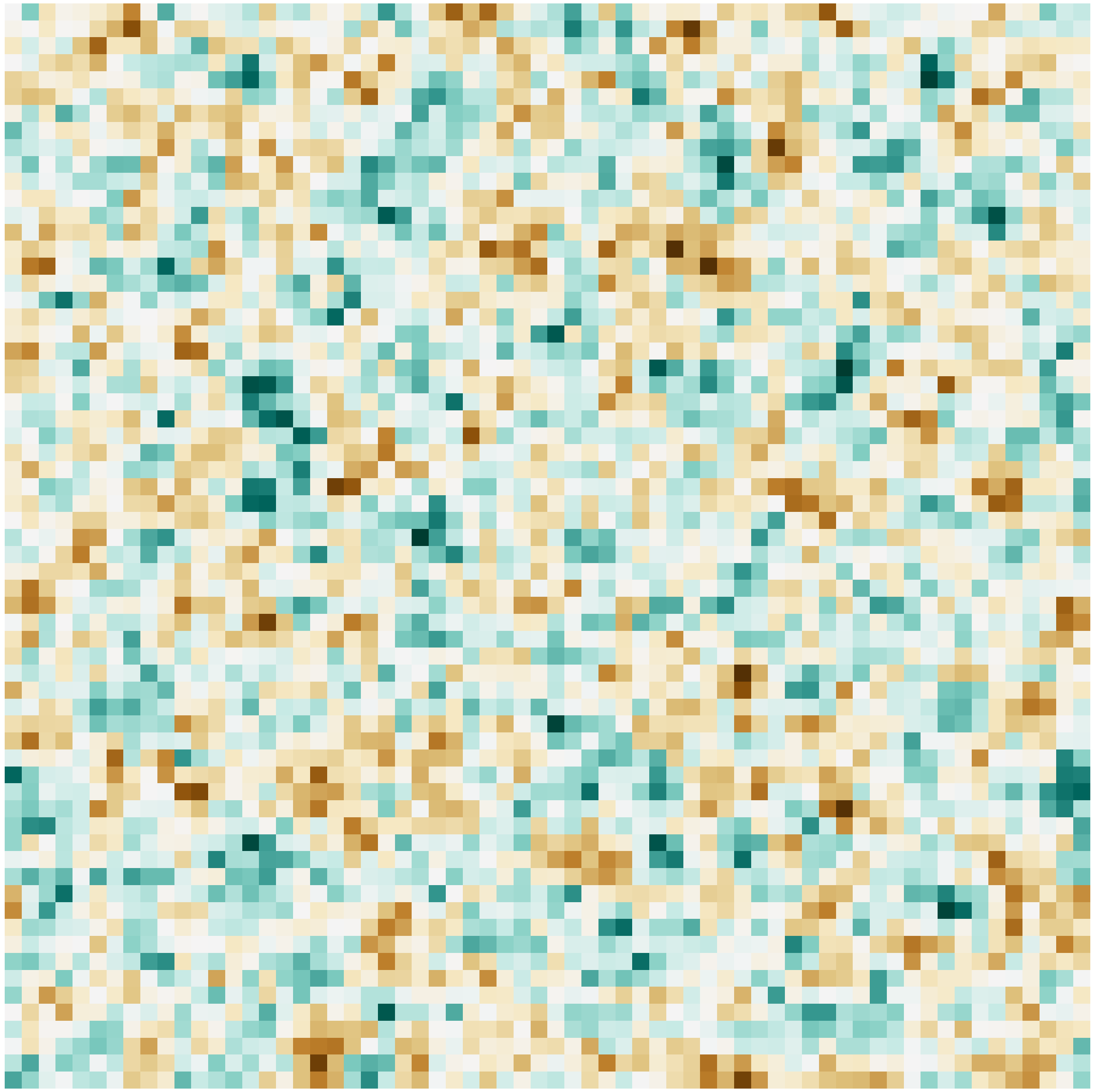
Mask

Horowitz et al. (2018)

Data Field



Data Field
Field + Noise/Mask



Signal Field

Horowitz et al. (2018)

Simple solution: Wiener Filter

Minimum variance estimator

$$\hat{\mathbf{s}} = \mathbf{S}\mathbf{R}^{\dagger}\mathbf{C}^{-1}\mathbf{d}$$

Covariances

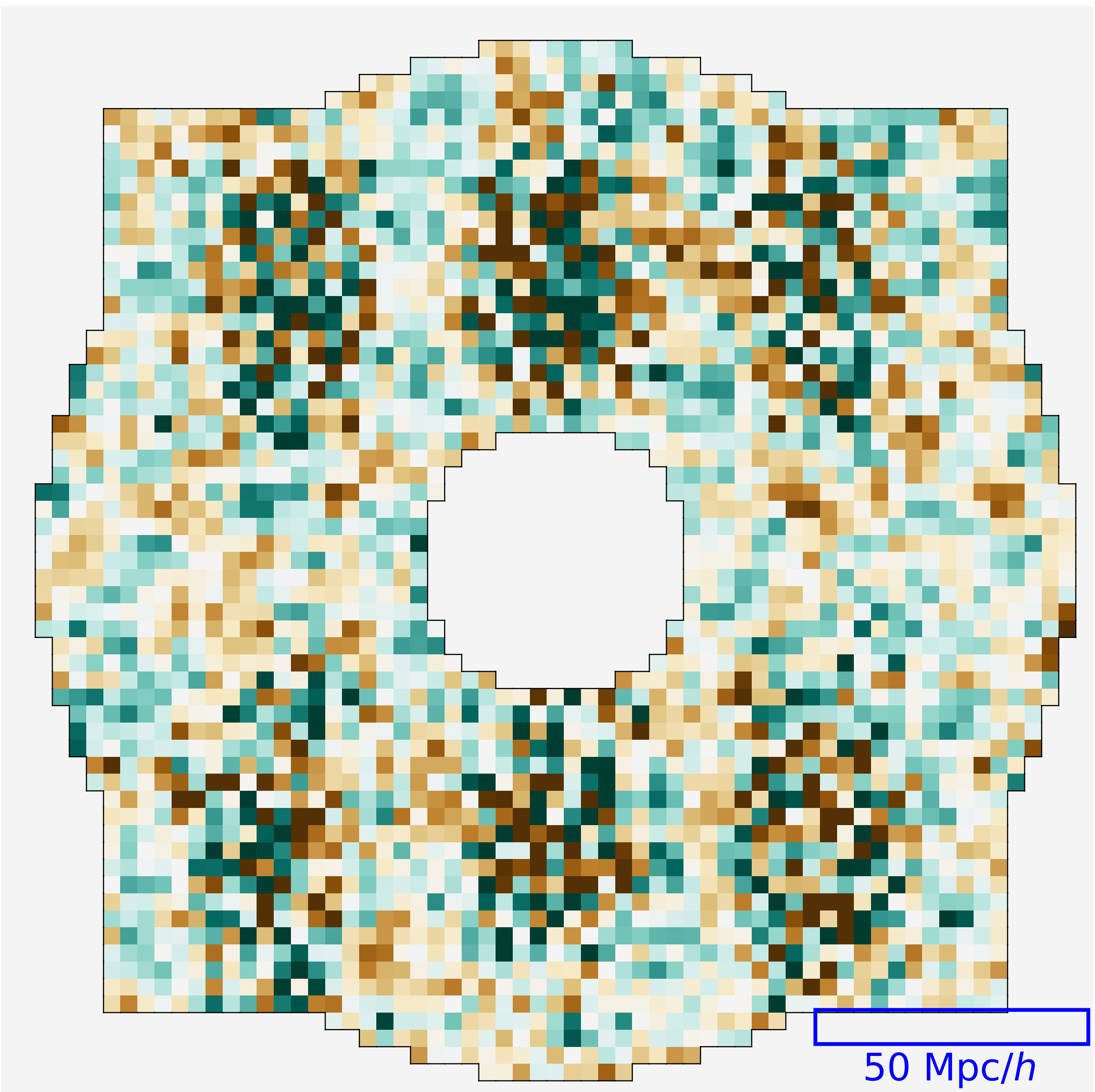
$$\mathbf{S} = \langle \mathbf{s}\mathbf{s}^{\dagger} \rangle \quad \mathbf{N} = \langle \mathbf{n}\mathbf{n}^{\dagger} \rangle$$

$$\mathbf{C} \equiv \langle \mathbf{d}\mathbf{d}^{\dagger} \rangle = \mathbf{R}\mathbf{S}\mathbf{R}^{\dagger} + \mathbf{N}$$

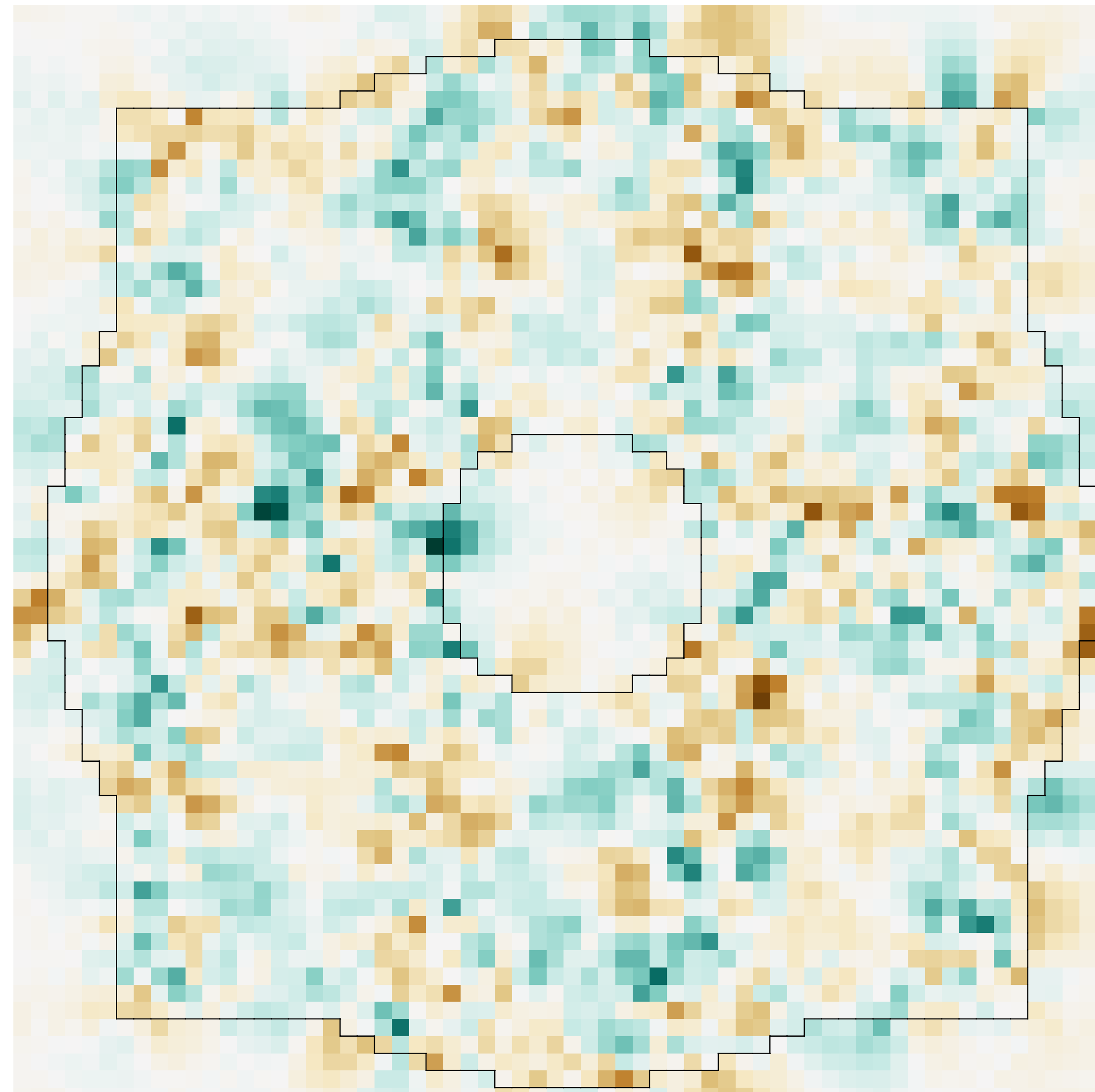
Size: $(64 \times 64)^2$

Rybicki and Press (1992)
Seljak (1997,1998)

Wiener Filter (64x64)



Observed "Data"
Field + Noise + Mask



Wiener Filtered

$$\hat{\mathbf{s}} = \mathbf{S}\mathbf{R}^{\dagger}\mathbf{C}^{-1}\mathbf{d}$$

Going to Smaller Scales

Smaller scales requires higher resolution -> larger covariance matrix

$$\hat{\mathbf{s}} = \mathbf{S}\mathbf{R}^{\dagger}\mathbf{C}^{-1}\mathbf{d}$$

$$\mathbf{C} \equiv \left\langle \mathbf{d}\mathbf{d}^{\dagger} \right\rangle = \mathbf{R}\mathbf{S}\mathbf{R}^{\dagger} + \mathbf{N}$$

$$\mathbf{N} = \left\langle \mathbf{n}\mathbf{n}^{\dagger} \right\rangle$$ **(Approximately diagonal in real space)**

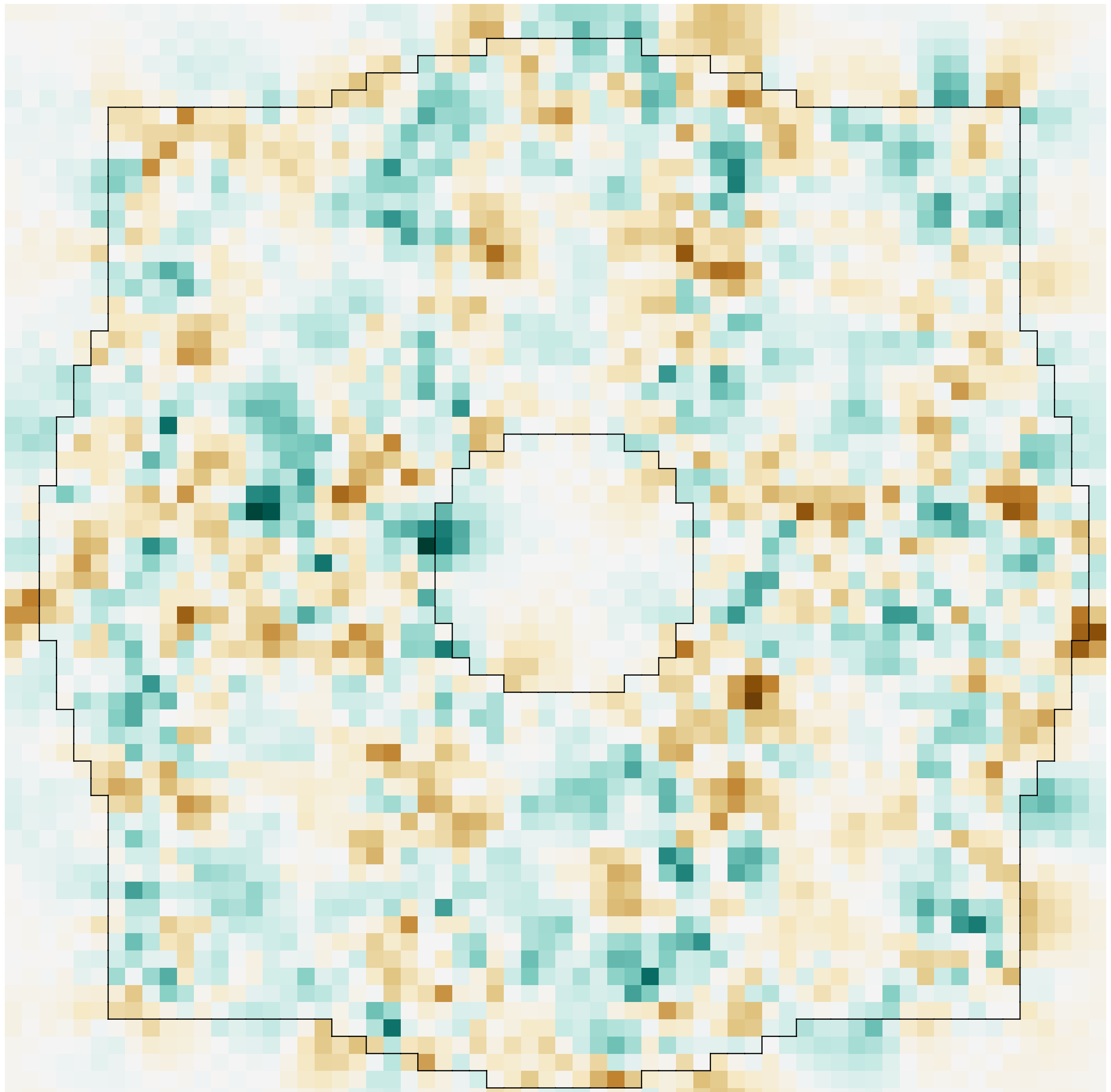
$$\mathbf{S} = \left\langle \mathbf{s}\mathbf{s}^{\dagger} \right\rangle$$ **(Approximately diagonal in Fourier space)**

Inverting generic matrices is hard work! (Best case O(n^3))

Optimize instead! $\chi^2 = \boldsymbol{s}^{\dagger}\boldsymbol{S}^{-1}\boldsymbol{s} + (\boldsymbol{d} - \boldsymbol{R}\boldsymbol{s})^{\dagger}\boldsymbol{N}^{-1}(\boldsymbol{d} - \boldsymbol{R}\boldsymbol{s})$

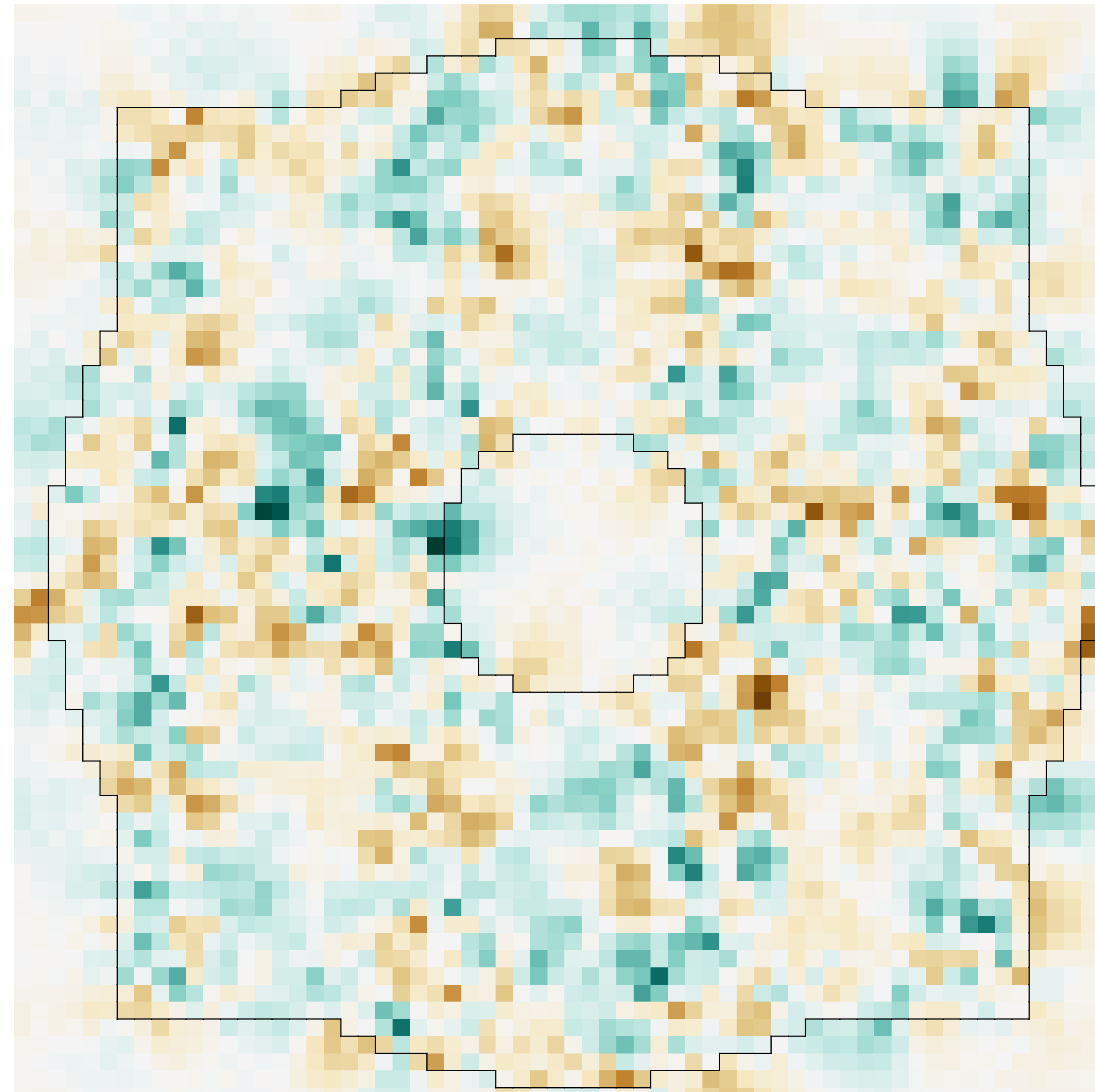
WF (64x64)

~0.5 second



Maximum Likelihood

~2 minute

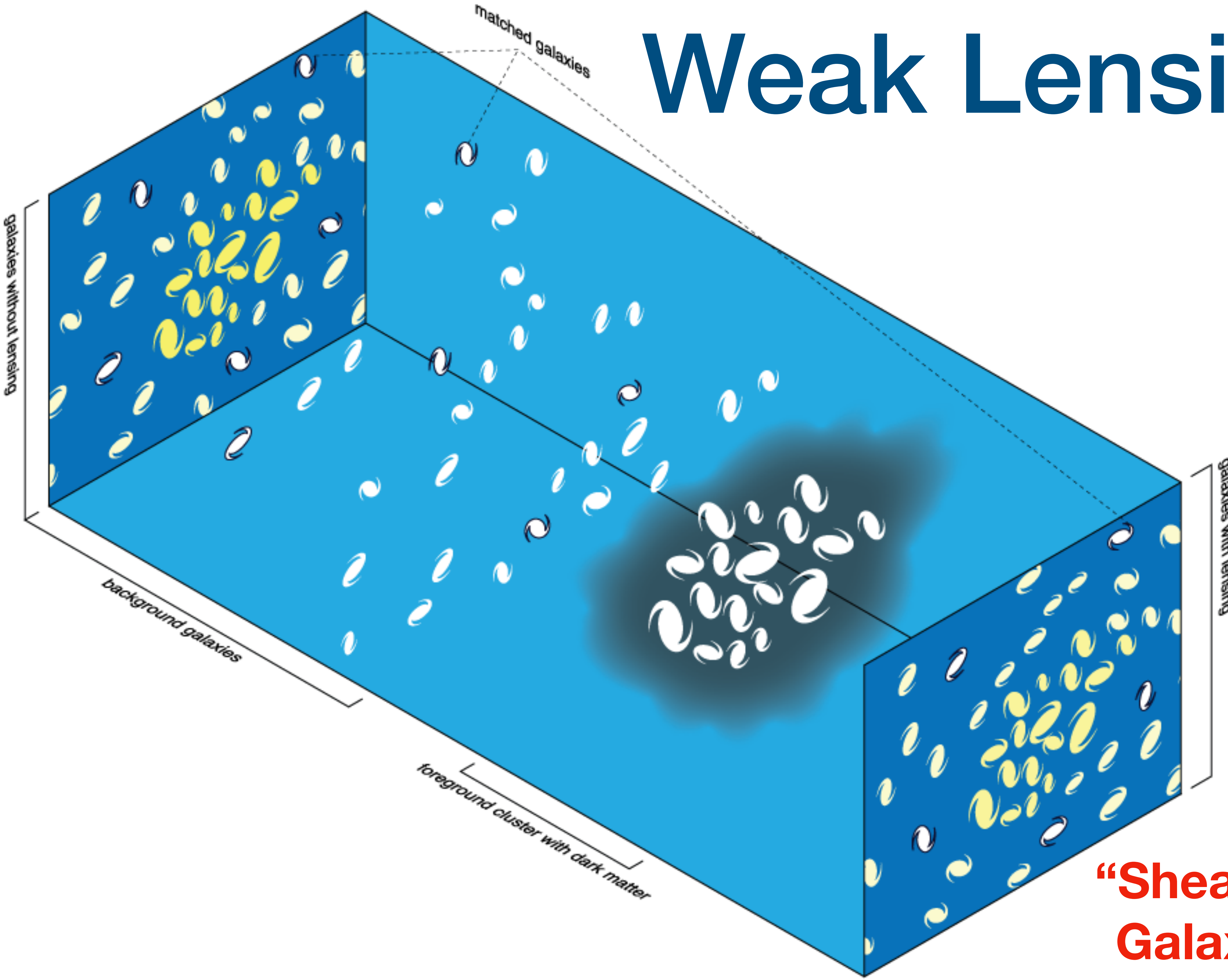


Wiener Filtered

$$\hat{\mathbf{s}} = \mathbf{S}\mathbf{R}^{\dagger}\mathbf{C}^{-1}\mathbf{d}$$

Horowitz et al. (2018)

Weak Lensing

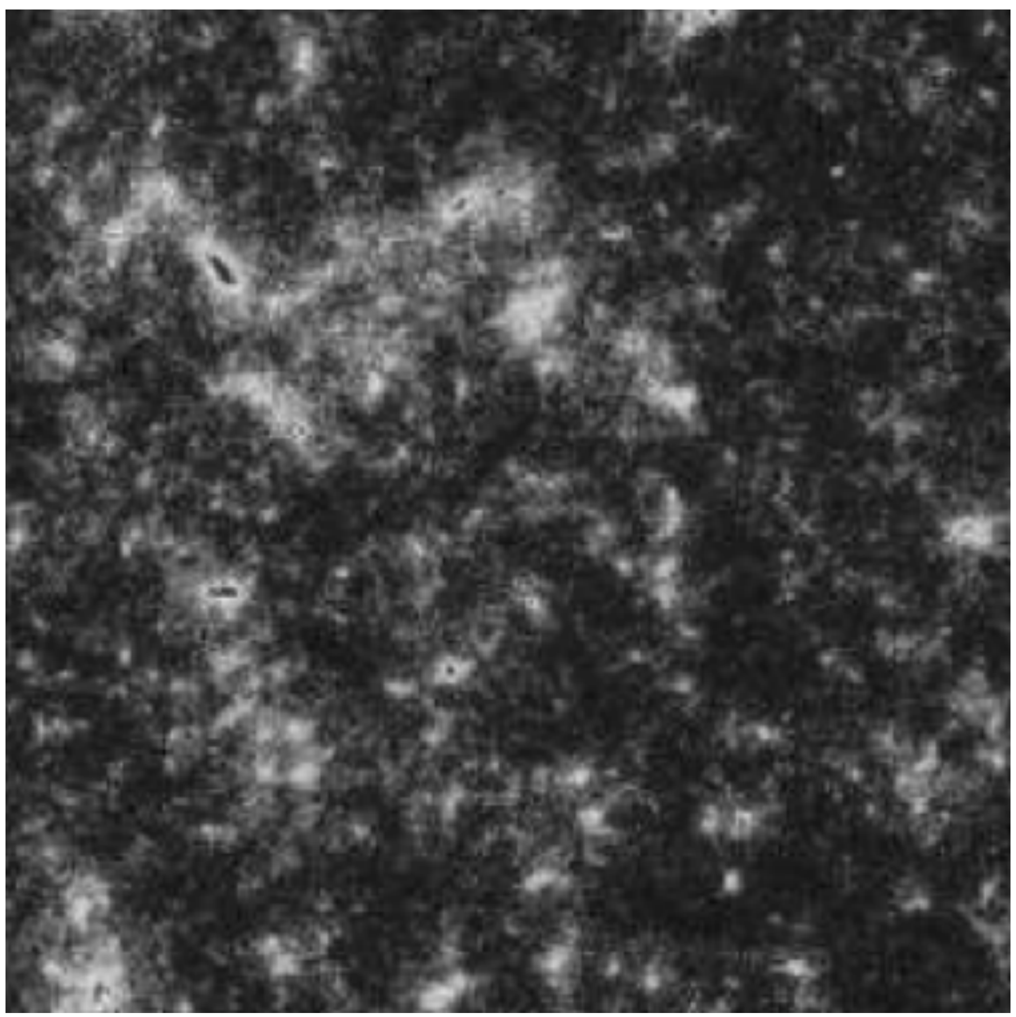


"Sheared" Galaxies

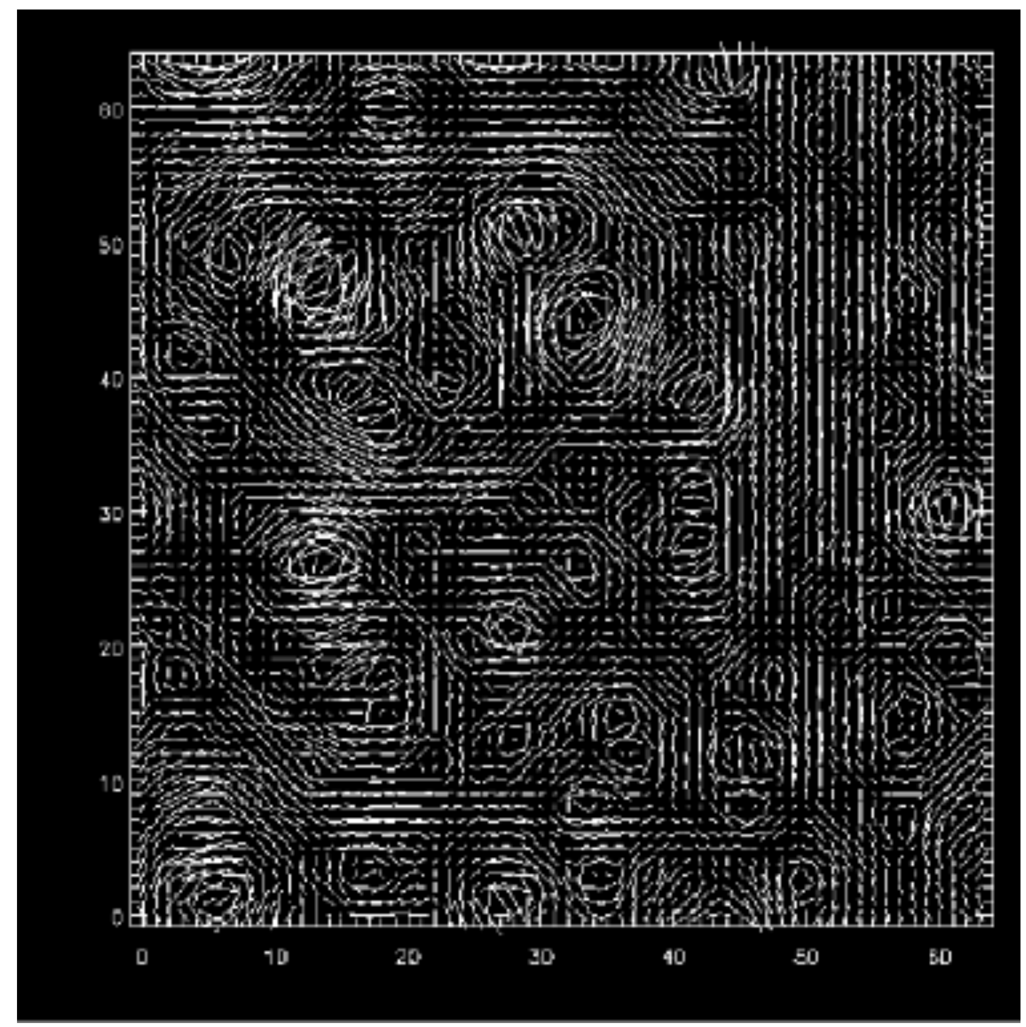
Jain, Seljak, White (1999)

Nontrivial Response Matrix: Weak Lensing

- The signal is still a density field, but the data is now 2 images of different shear components from the lensing.



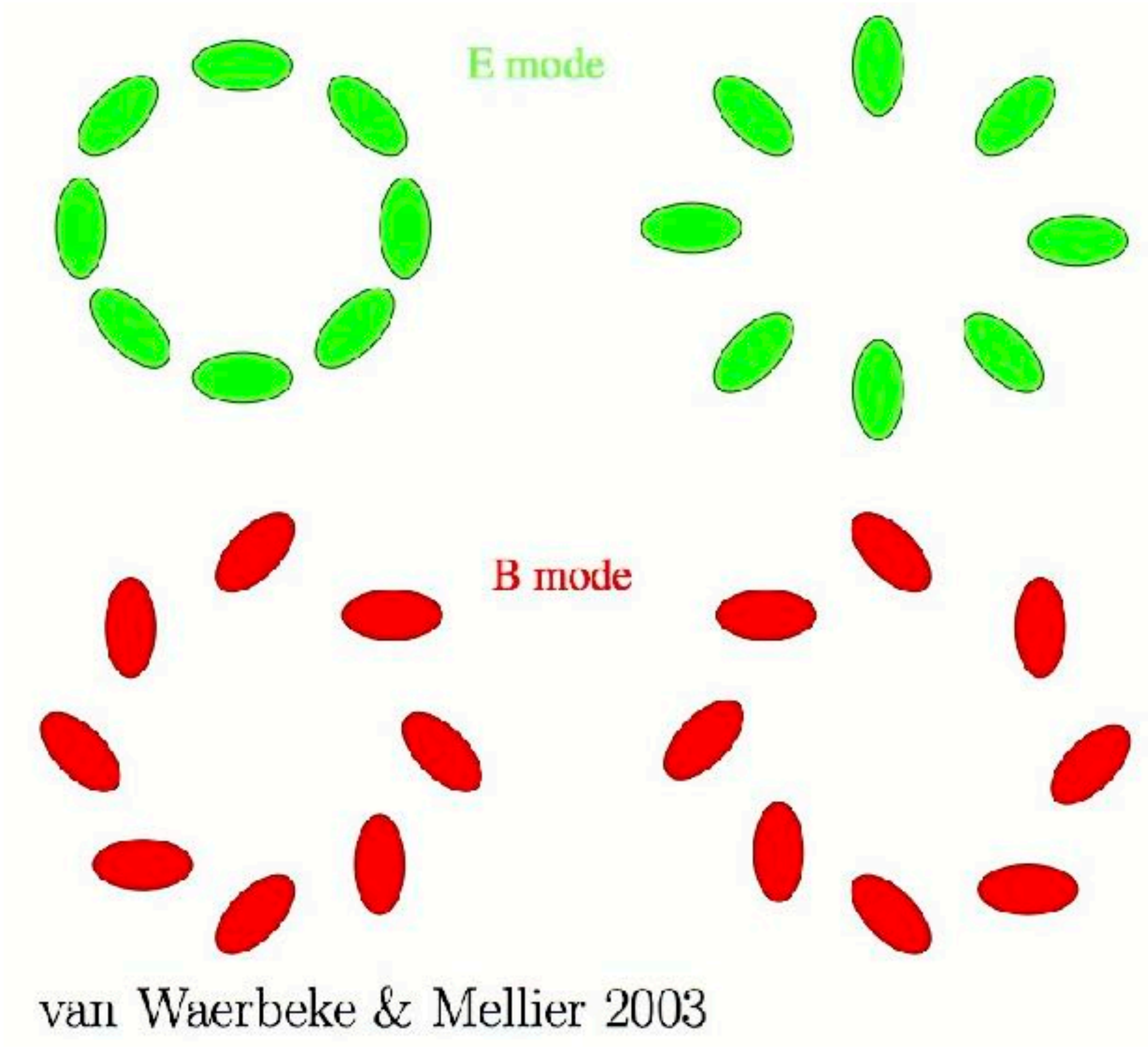
Potential



Shear

Generates pure E modes (curl free)

In addition… B-Modes!



Curl-free

Divergence-free

In addition… B-Modes!

Systematic effects from instrument/processing pipeline

“Physical” effects: Clustering in Redshift Space (Schneider et al. 2001), Intrinsic Alignments (Hirata and Seljak 2004), etc.

Directly related to LOS density

$$\underbrace{\begin{bmatrix} \gamma_1 \\ \gamma_2 \end{bmatrix}}_{\mathbf{d}} = \underbrace{\begin{bmatrix} (\partial_x^2 - \partial_y^2) & -2\partial_x\partial_y \\ 2\partial_x\partial_y & (\partial_x^2 - \partial_y^2) \end{bmatrix}}_{\mathbf{R}} \underbrace{\begin{bmatrix} \phi_E \\ \phi_B \end{bmatrix}}_{\mathbf{s}} + \textbf{Noise}$$

Approach is directly transferable to CMB polarization (Q/U)

Lanusse et al (2016)

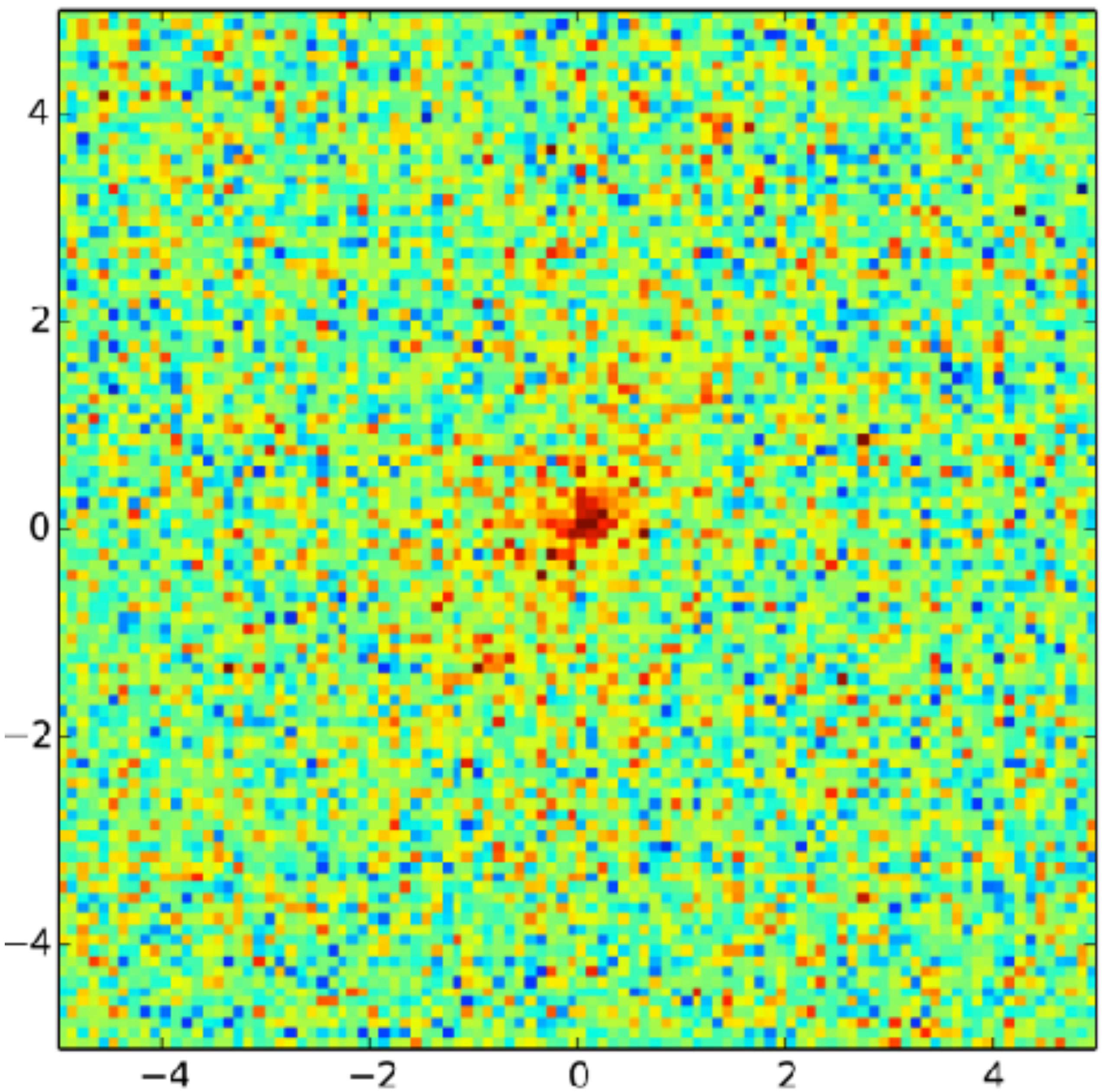
Kaiser, Squires (1992)

Kaiser-Squires

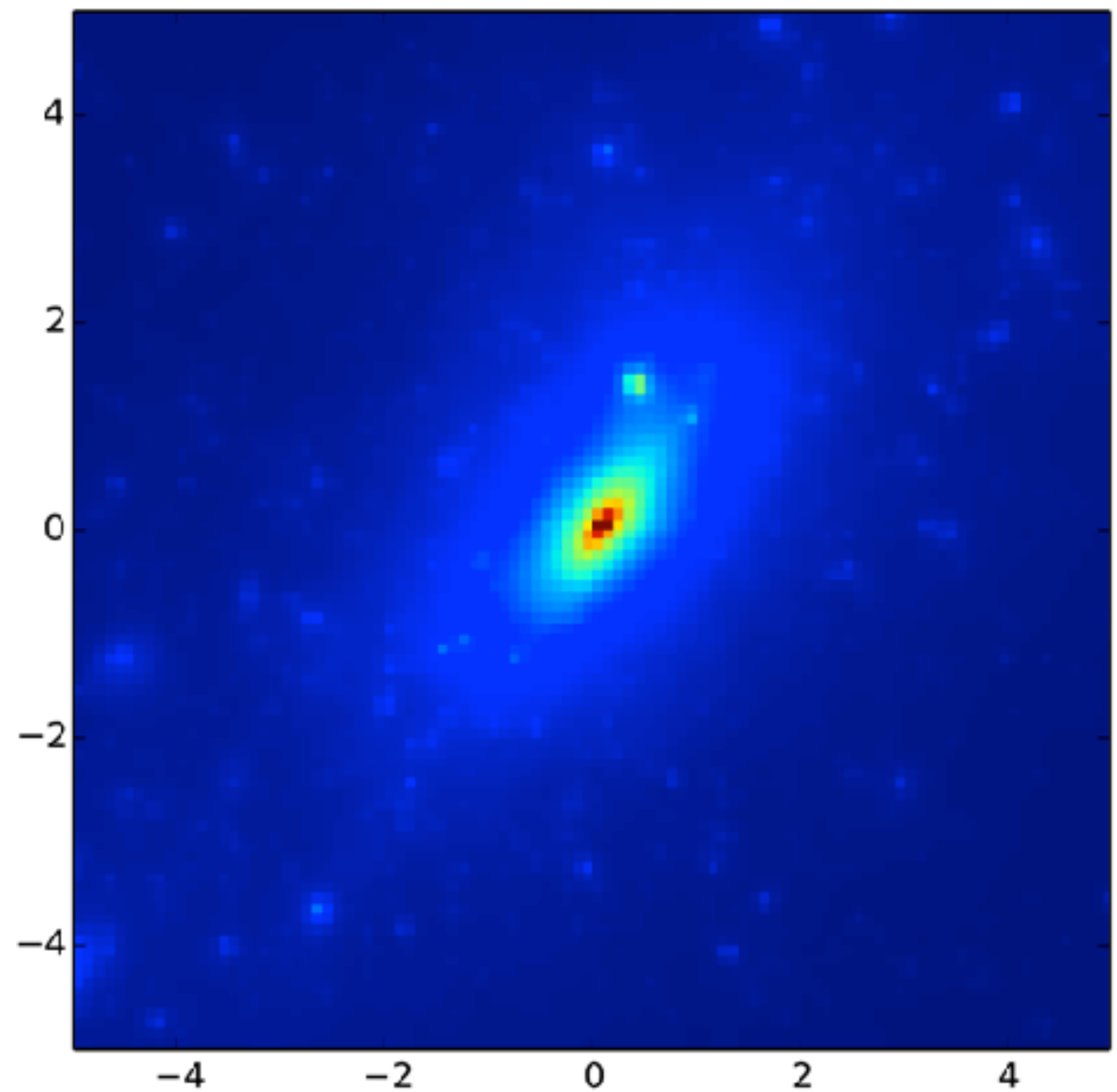
Shear relates to Convergence by:

$$\tilde{\gamma} = \tilde{\mathbf{A}}\tilde{\kappa}$$

$$[\tilde{\mathbf{A}}^{-1}]_{ij} = \frac{k_{1,i}^2 - k_{2,i}^2 - 2ik_{1,i}k_{2,i}}{k_{1,i}^2 + k_{2,i}^2}\delta_{ij}$$



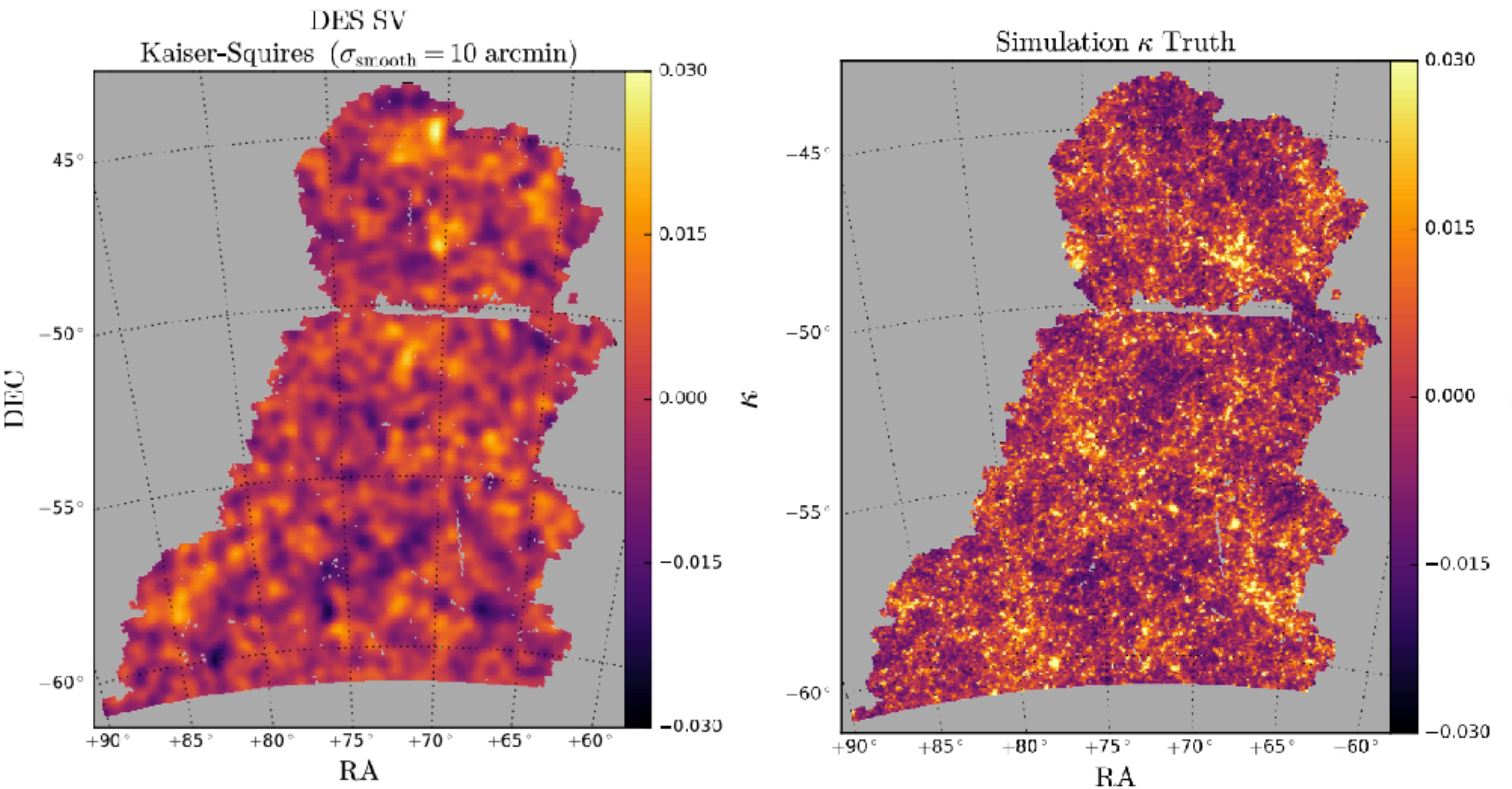
Kaiser-Squires



True Convergence

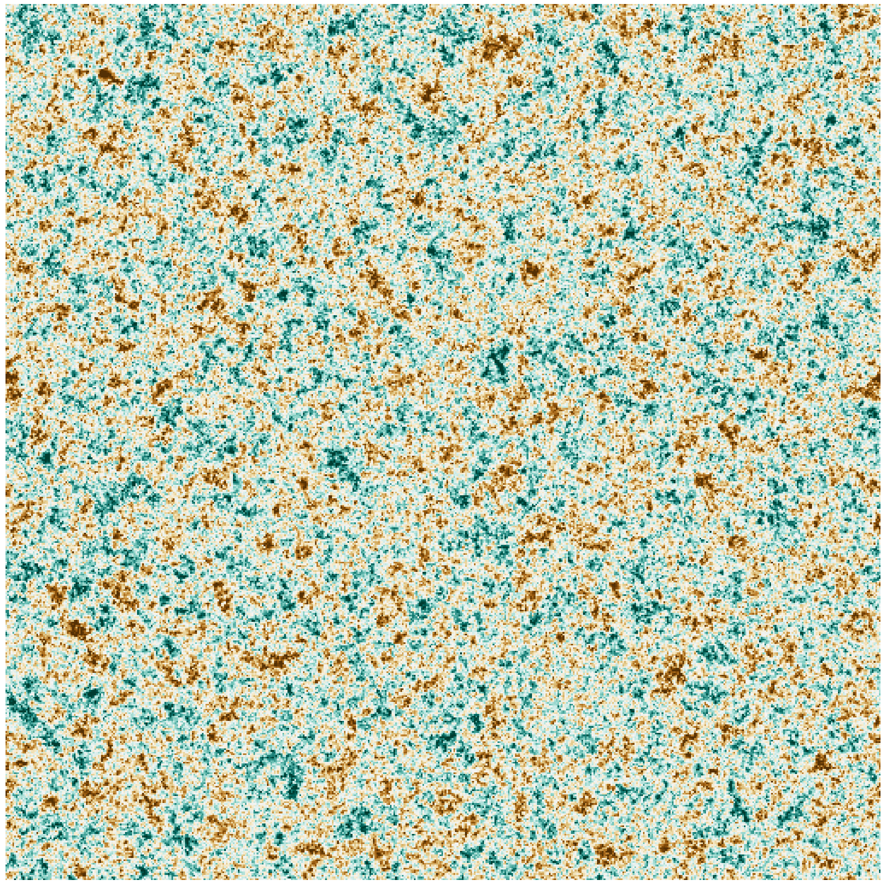
Jeffrey et al (2018)

Kaiser-Squires

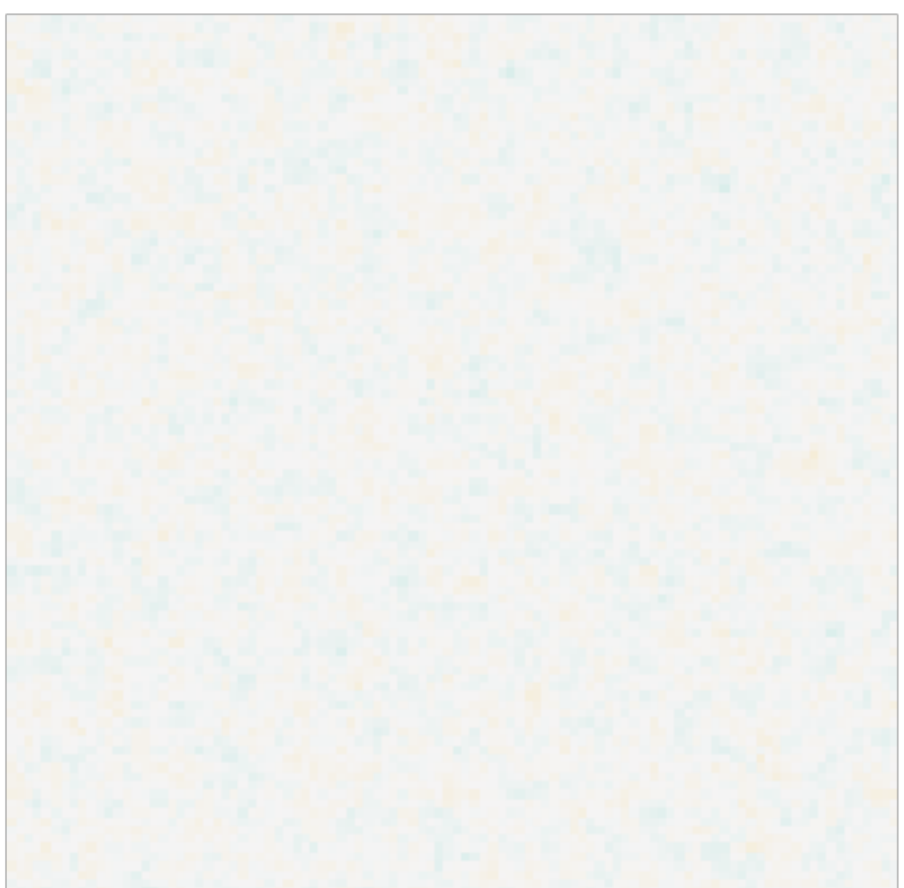


(Mock DES data)

E Potential (1024x1024)

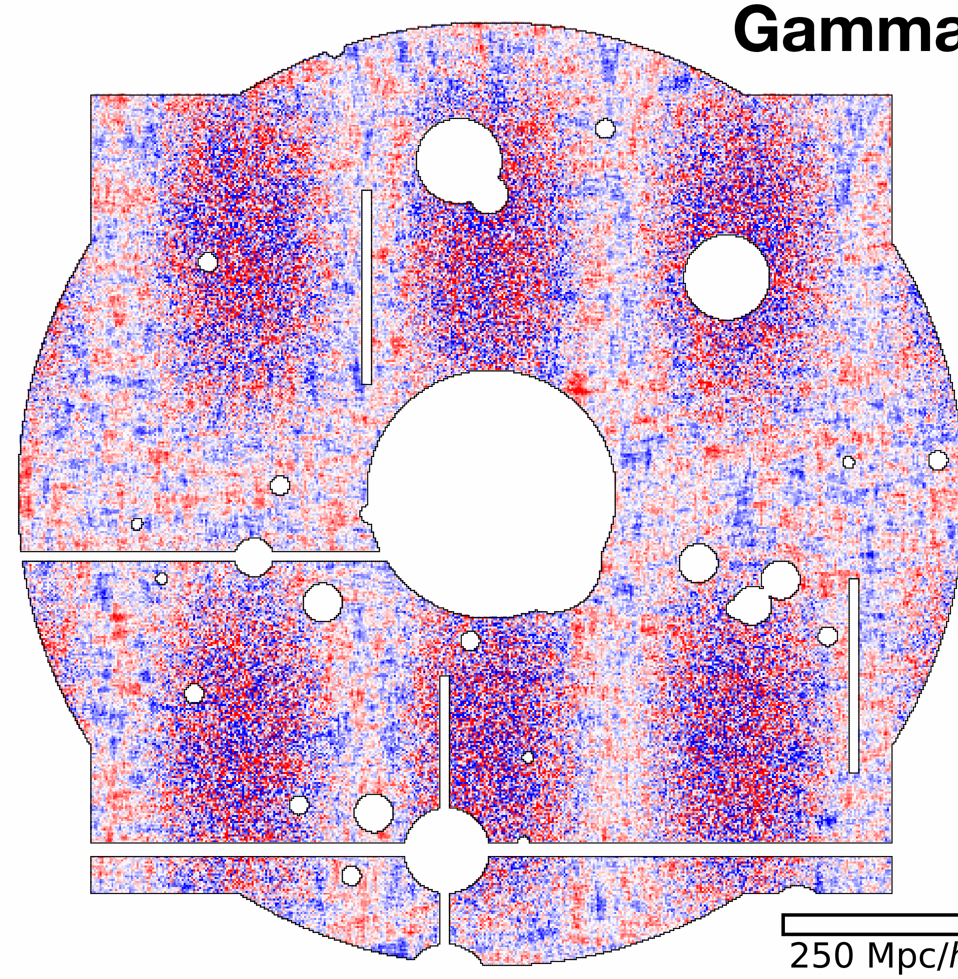


B Potential

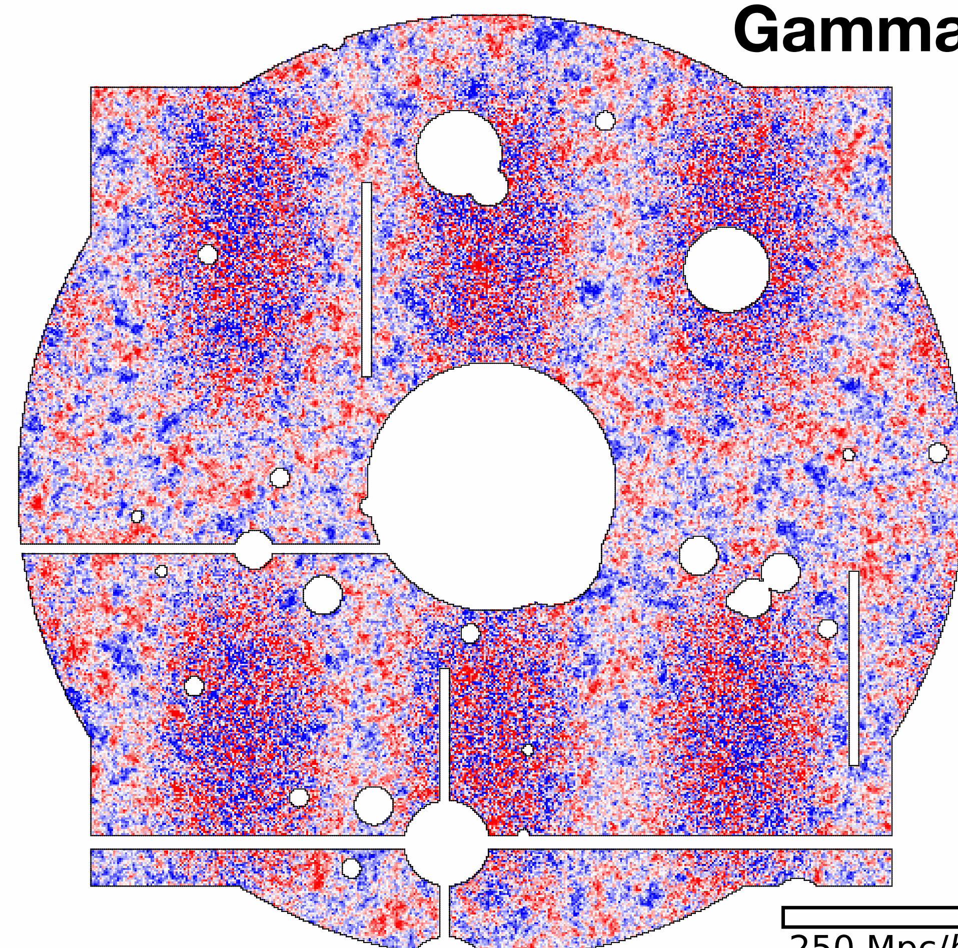


(has PS of E, but 10^-5 times amplitude)

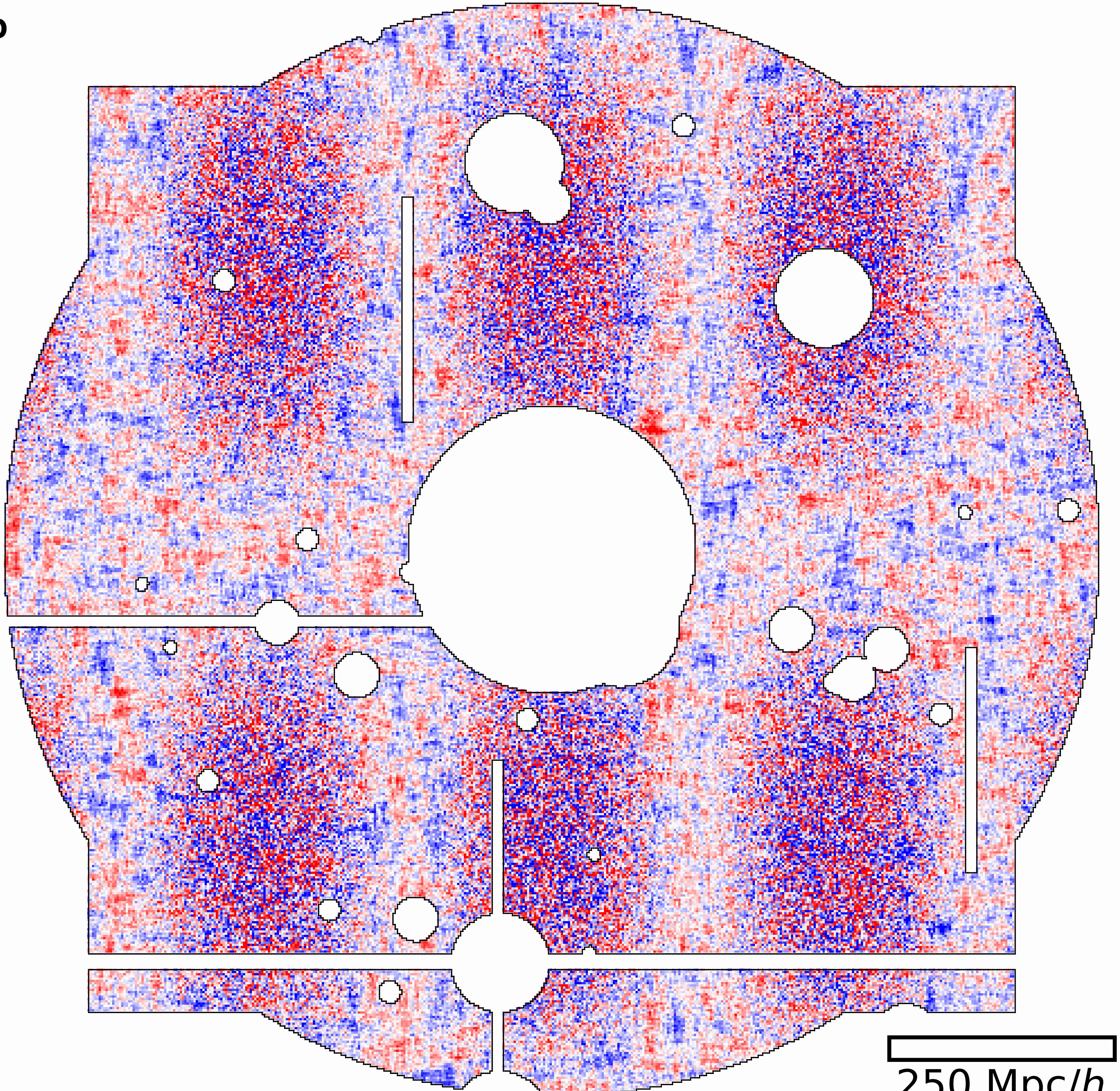
Gamma 1



Gamma 2

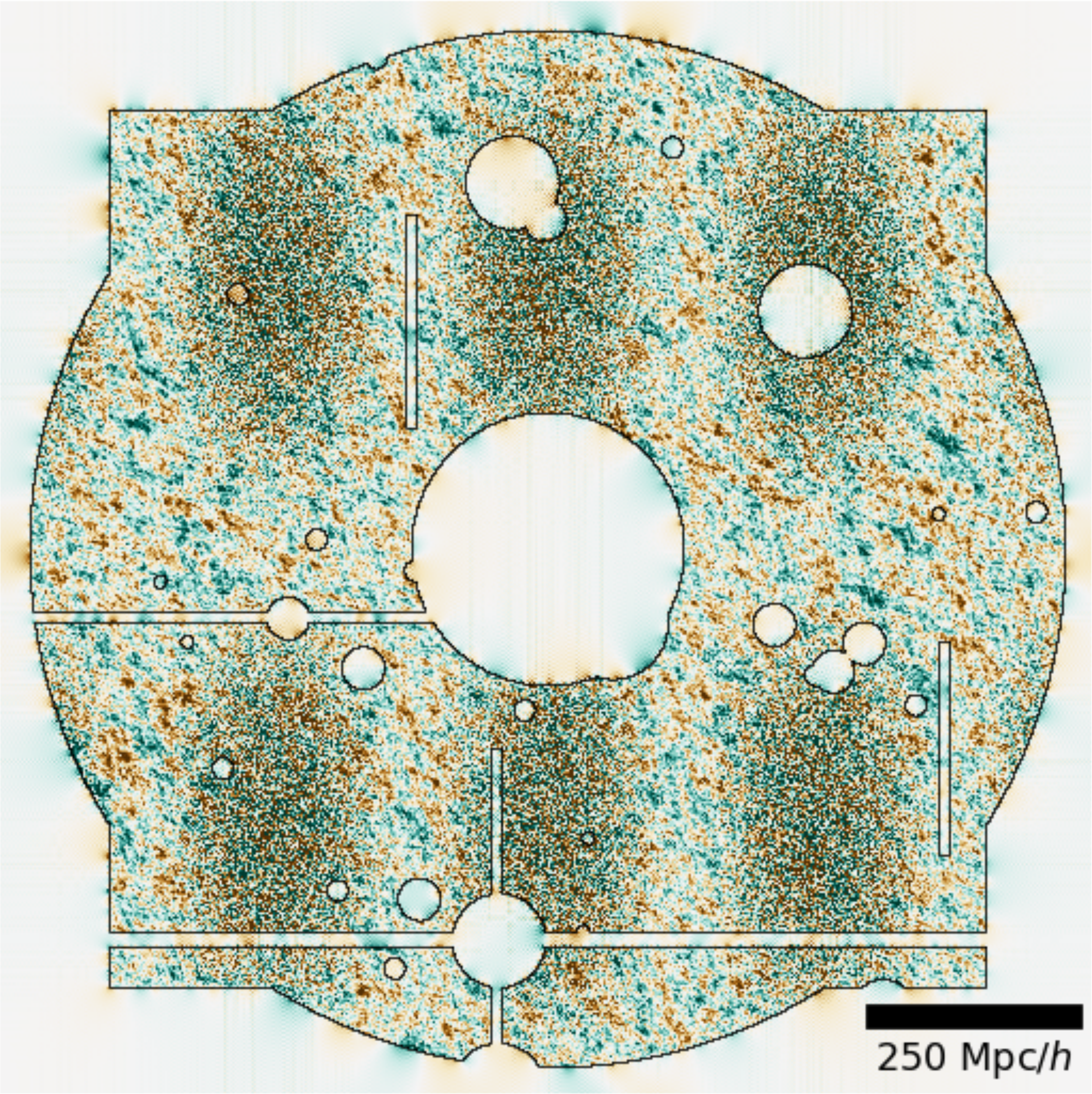


Shear Map

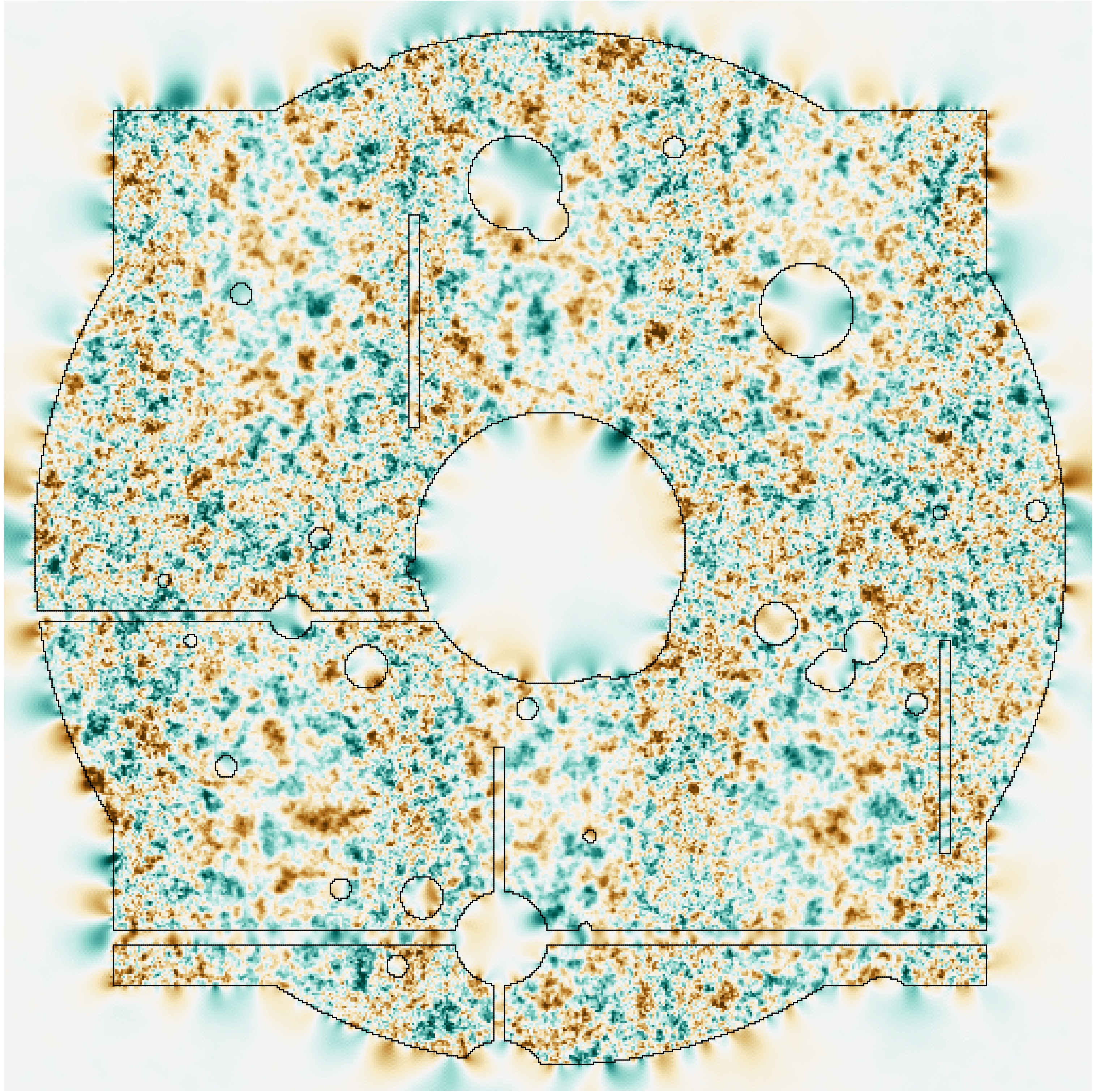


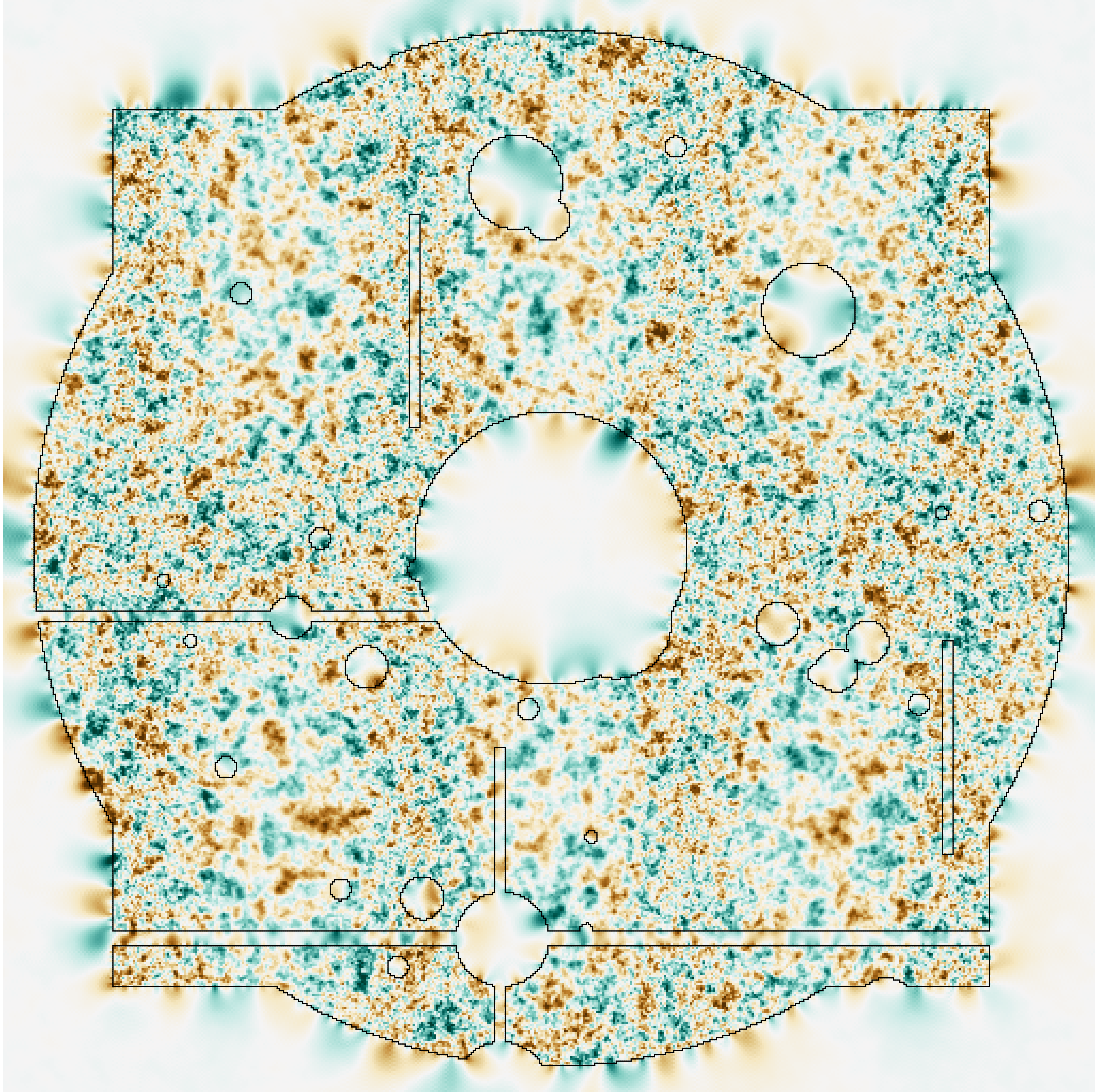
UGLY!

Kaiser Squires



Reconstructed E Potential (Density)



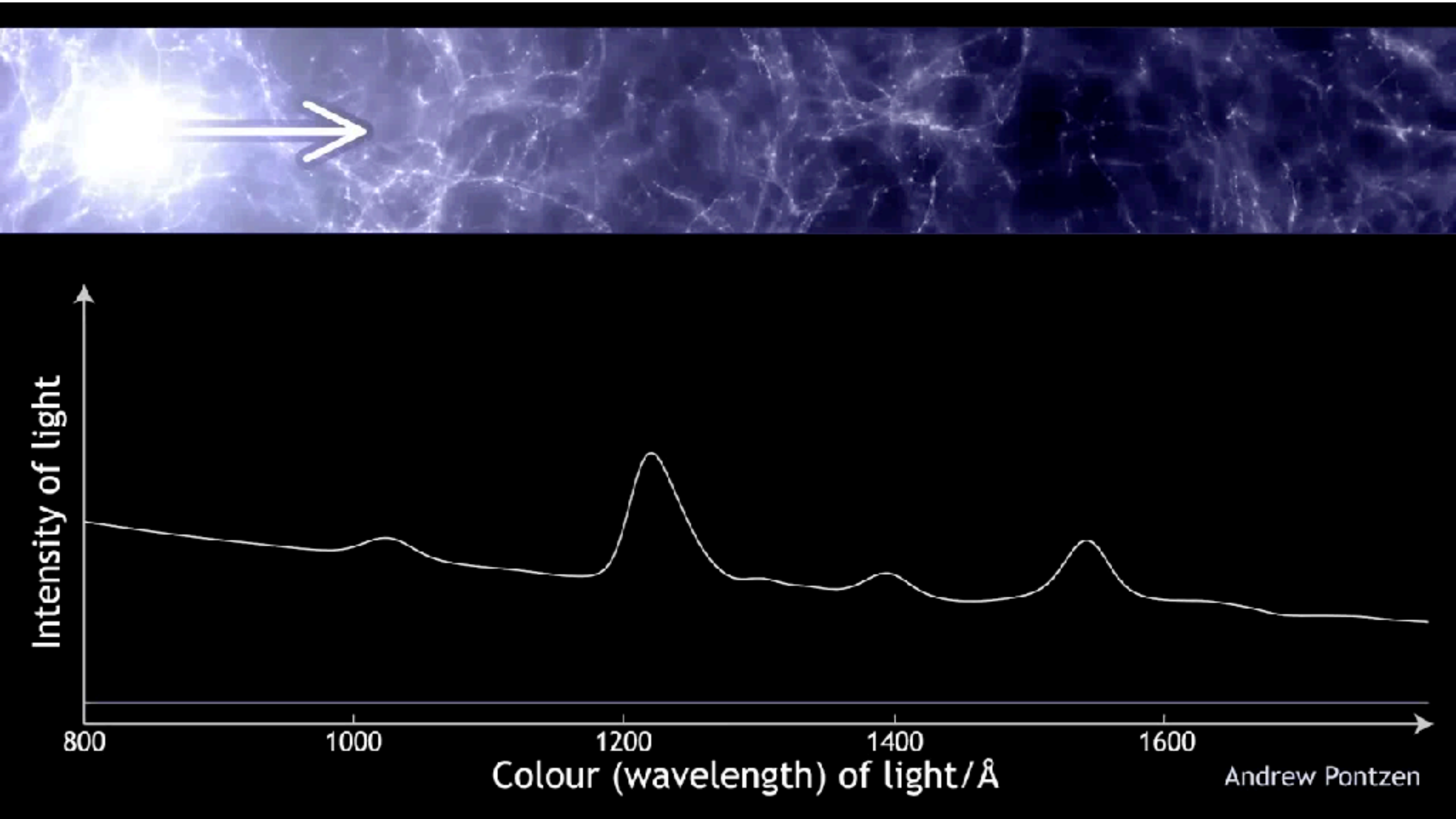


~1 minute

Preliminary!
Work in Progress!

Initial Density Reconstruction from Lyman Alpha Forest Tomography

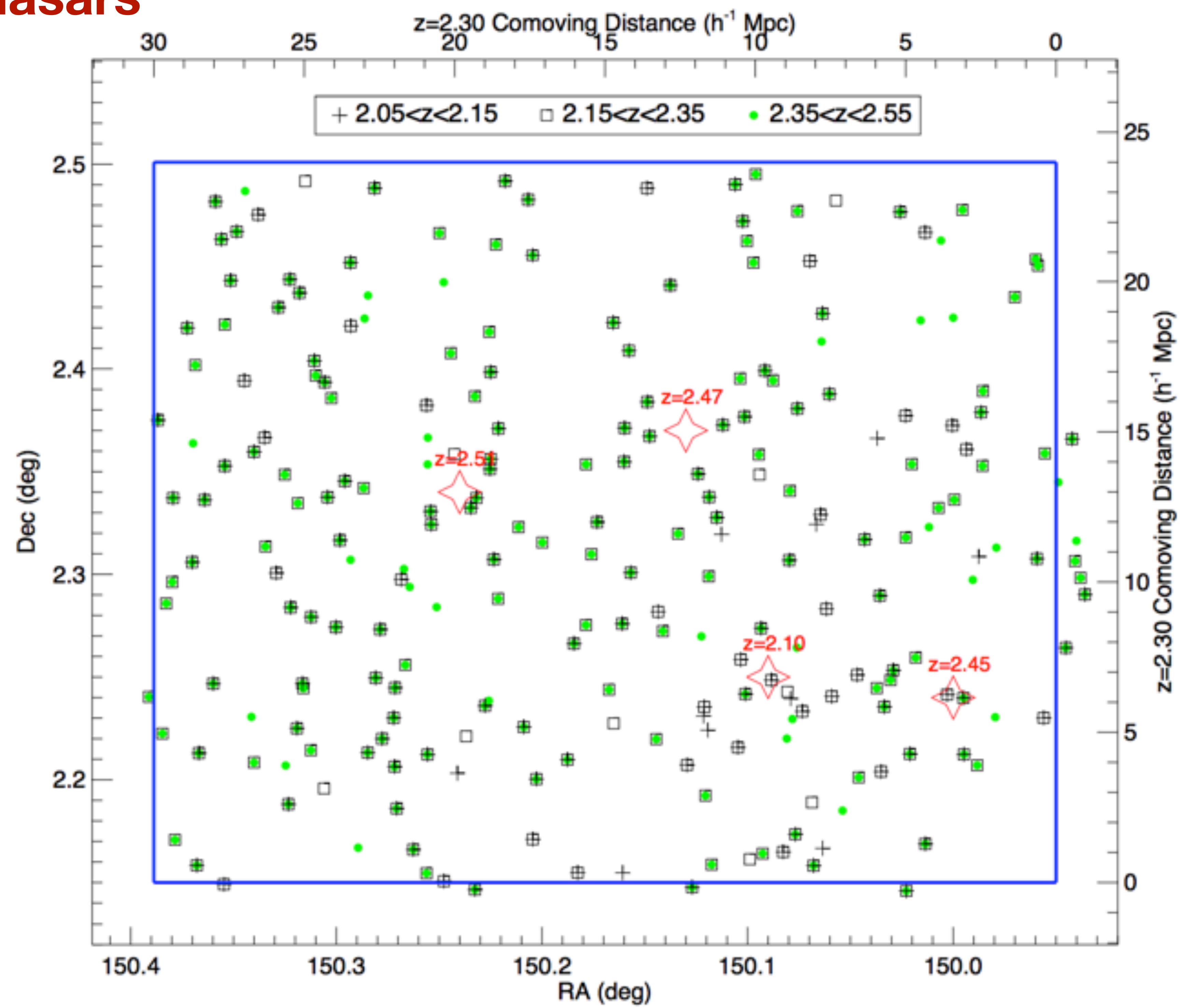
Lyman-α Forest as Probe of z > 2 Universe



COSMOS Lyman-Alpha Mapping And Tomography Observations

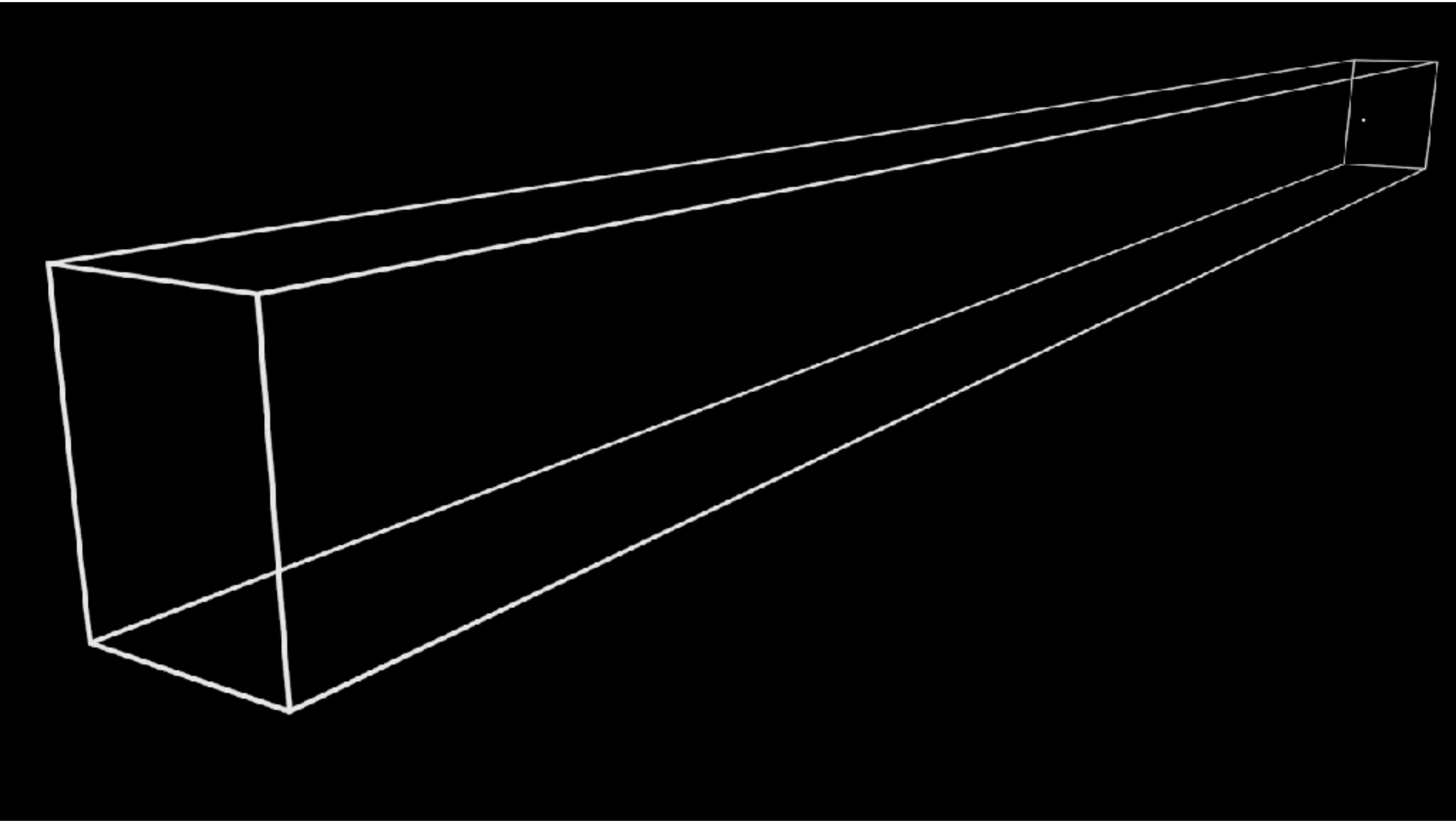
CLAMATO Survey

240 LBGs/quasars



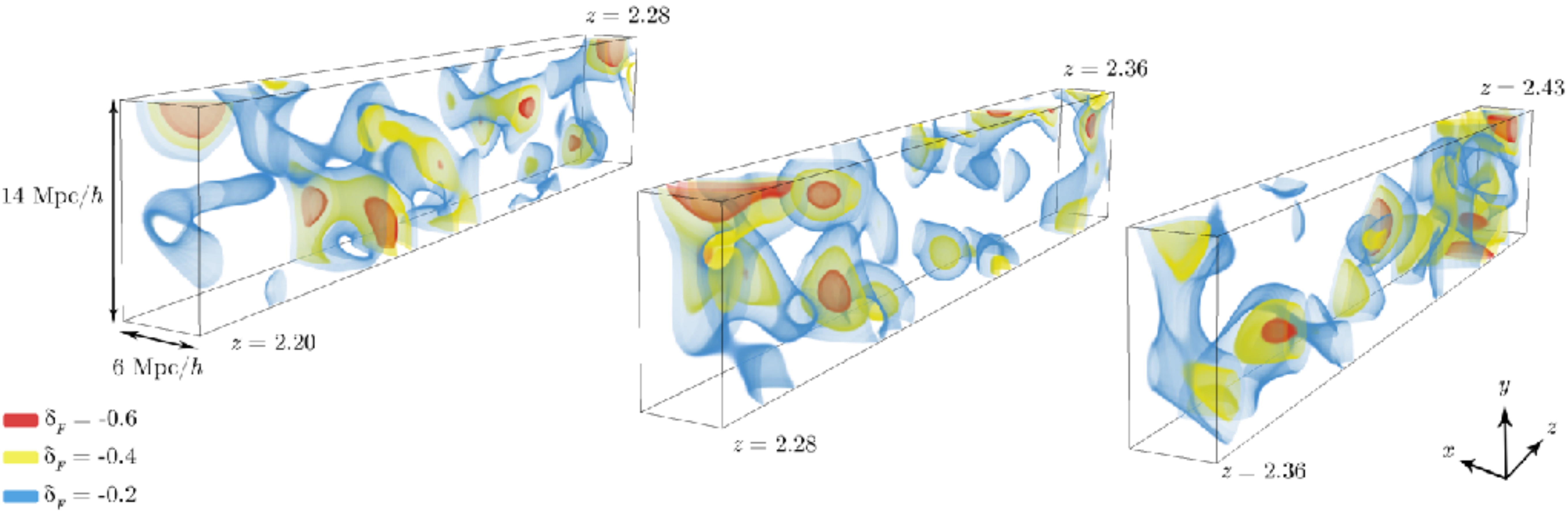
Volume: ~ 3.15 ×10^5 h^{-3} Mpc^3

Lee et al (2017)



Lee et al (2016)

CLAMATO Survey



Lee et al (2014)

Preliminary!

Initial Density Reconstruction

Reconstruct the initial (z~100) matter distribution to give rise to the observed structures.

- Easy to extract cosmological information from early time maps (i.e. BAO reconstruction).

- Will allow us to reconstruct more accurate z~2 density maps.

- All us to infer the z=0 fate of structures.

TARDIS: Tomographic Absorption Reconstruction and Density Inference Scheme

Response Modeling

Response operator now includes many components!

Initial Density Field

↓

Late Time Density Field

↓

Late Time Absorption Field

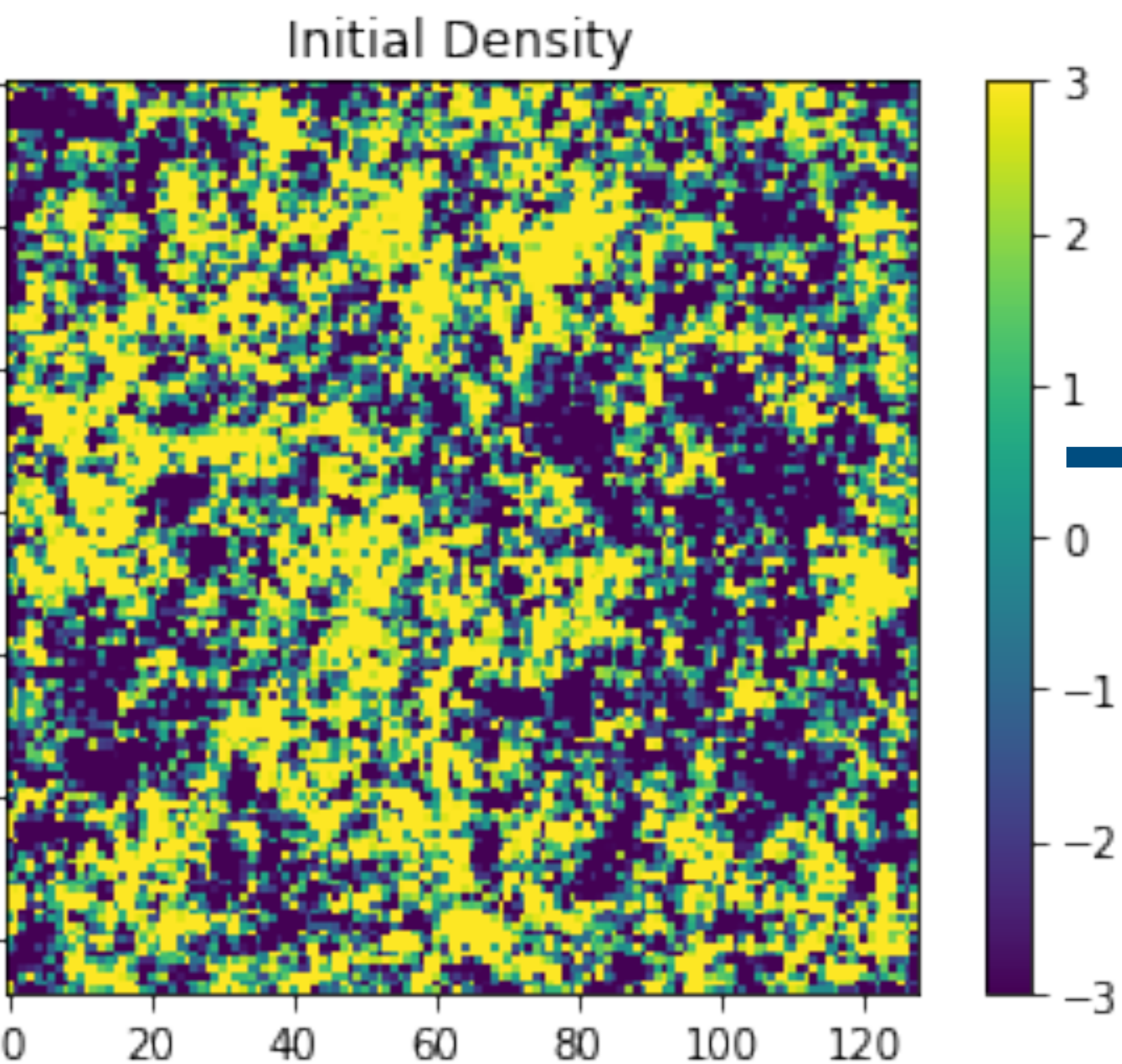
↓

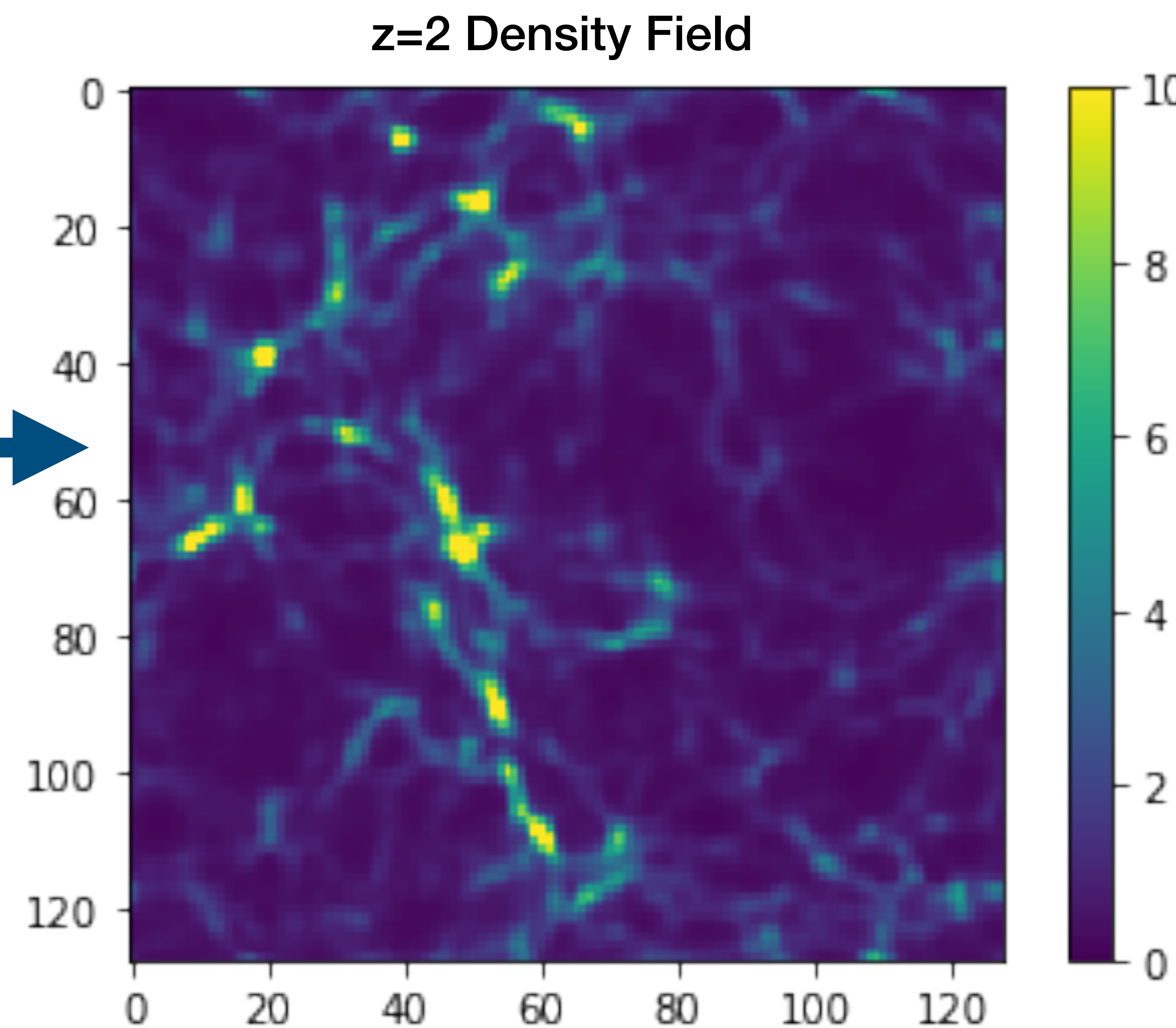
Redshift Space Absorption Field

↓

LOS Skewer Selection

Evolution w/ FastPM





(Planck 2015 Cosmology)

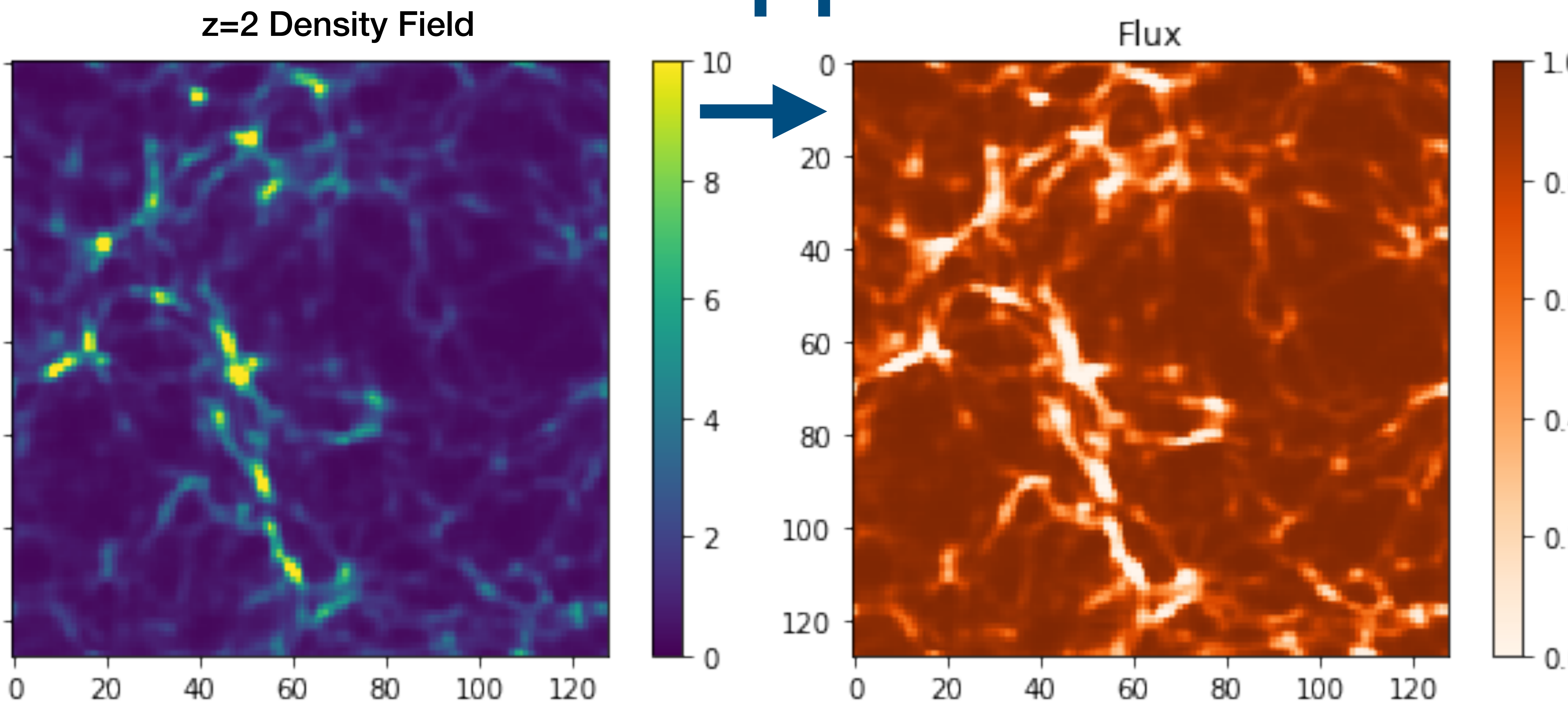
Side length: 45 Mpc h^{-1}

Resolution: 128^3 Particles

Periodic Boundary Conditions

FastPM: Feng et al. (2016)

Flux with Fluctuating Gunn-Peterson Approximation



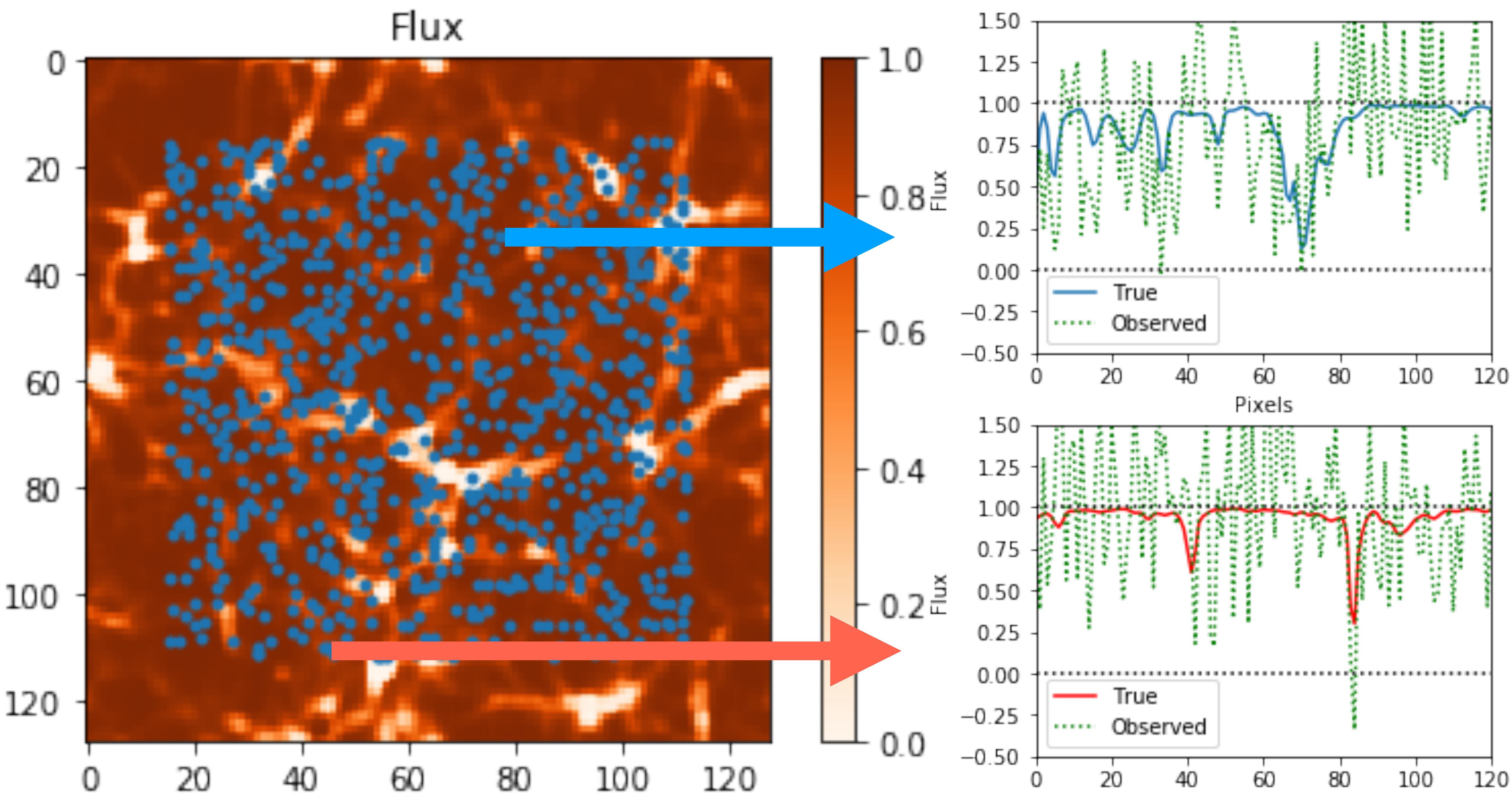
(Planck 2015 Cosmology)

FastPM: Feng et al. (2016)

Optical Depth $\tau(\lambda_{\rm obs}) \propto \left(\frac{\rho}{\bar{\rho}}\right)^{\beta}$

Observed Flux $F = \exp\left(-\tau\right)$

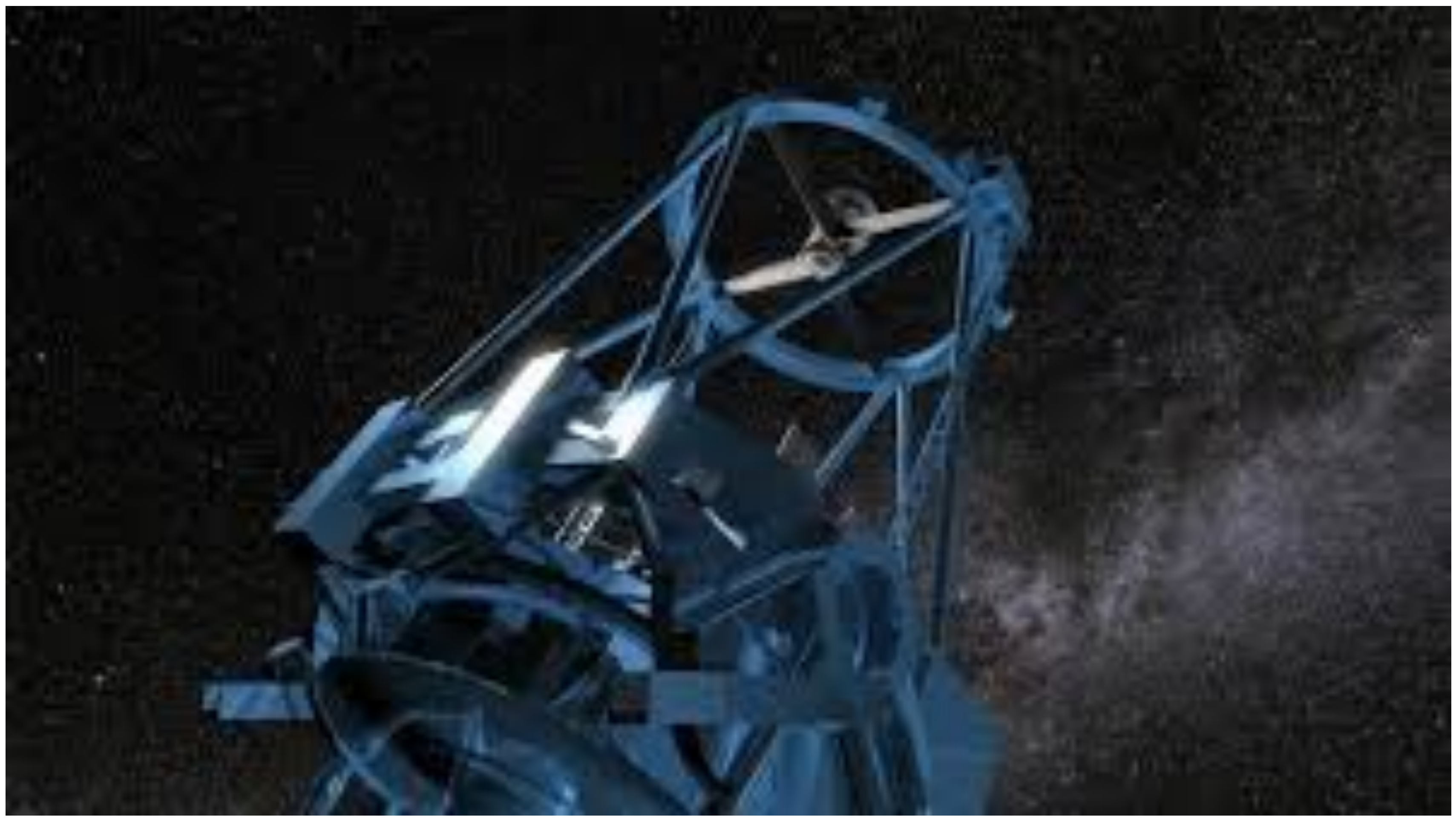
Sight-lines Selection



850 sight-lines

Example sight-lines
+ white noise

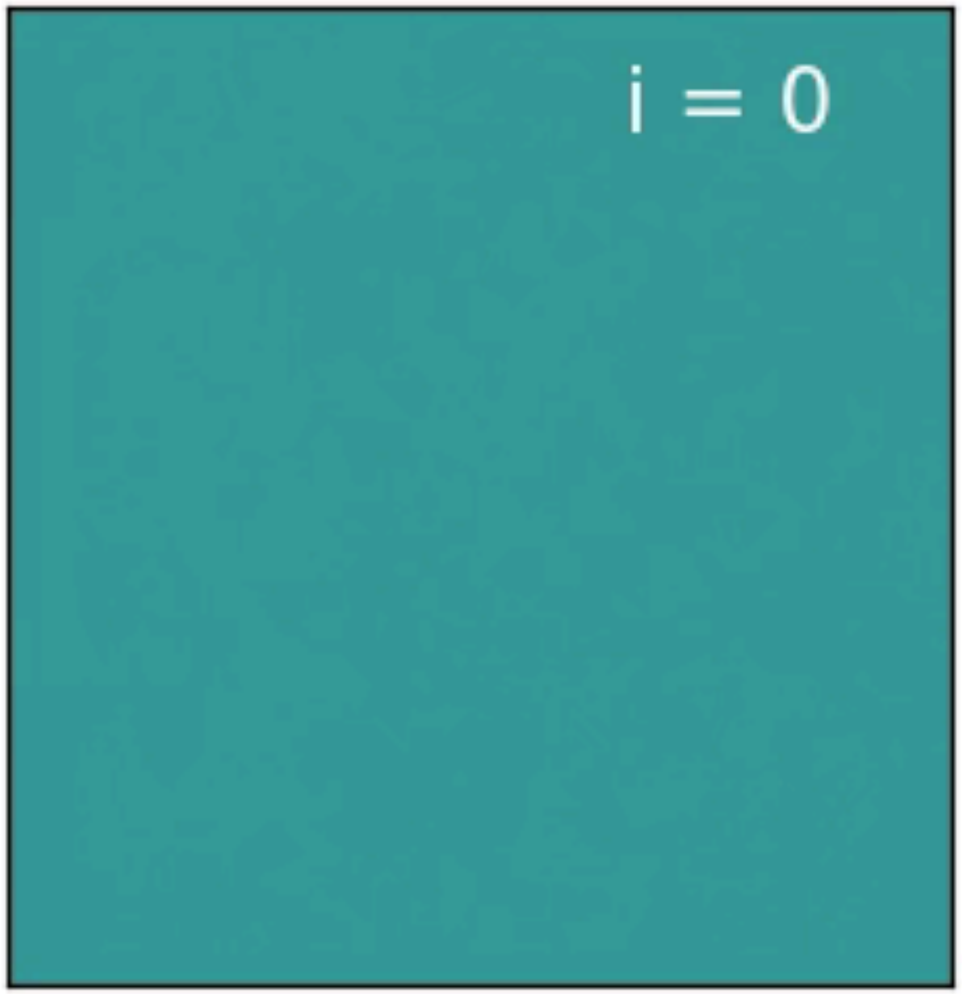
Configuration: Subaru Prime Focus Spectrograph



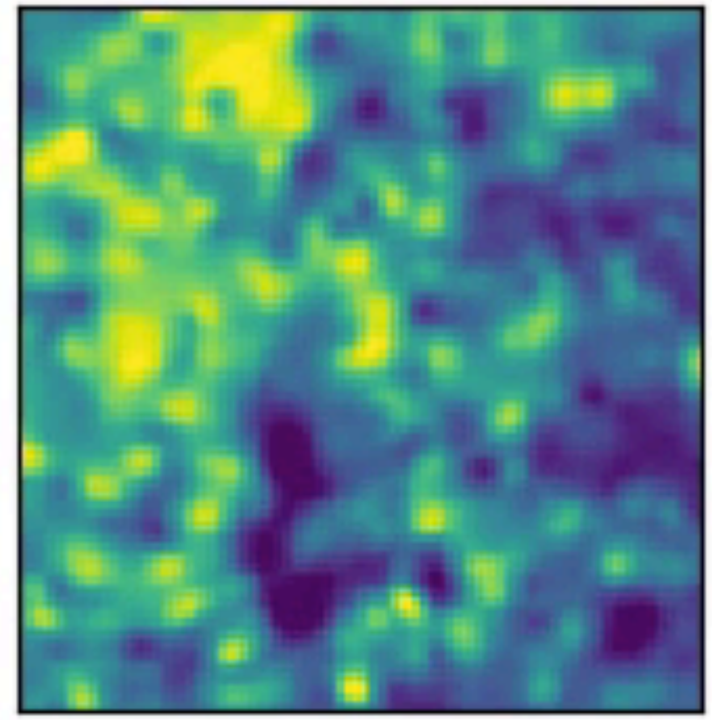
Name	N-body	Sight-line $(\mathrm{Mpc}/h)^{-2}$	SNR_{min}	SNR_{max}	Volume $(\mathrm{Mpc}/h)^3$	Particles
F-PFS	FastPM	0.5	2.4	5.0	64^3	128^3

Optimization (xy-slice)

Initial Density Field

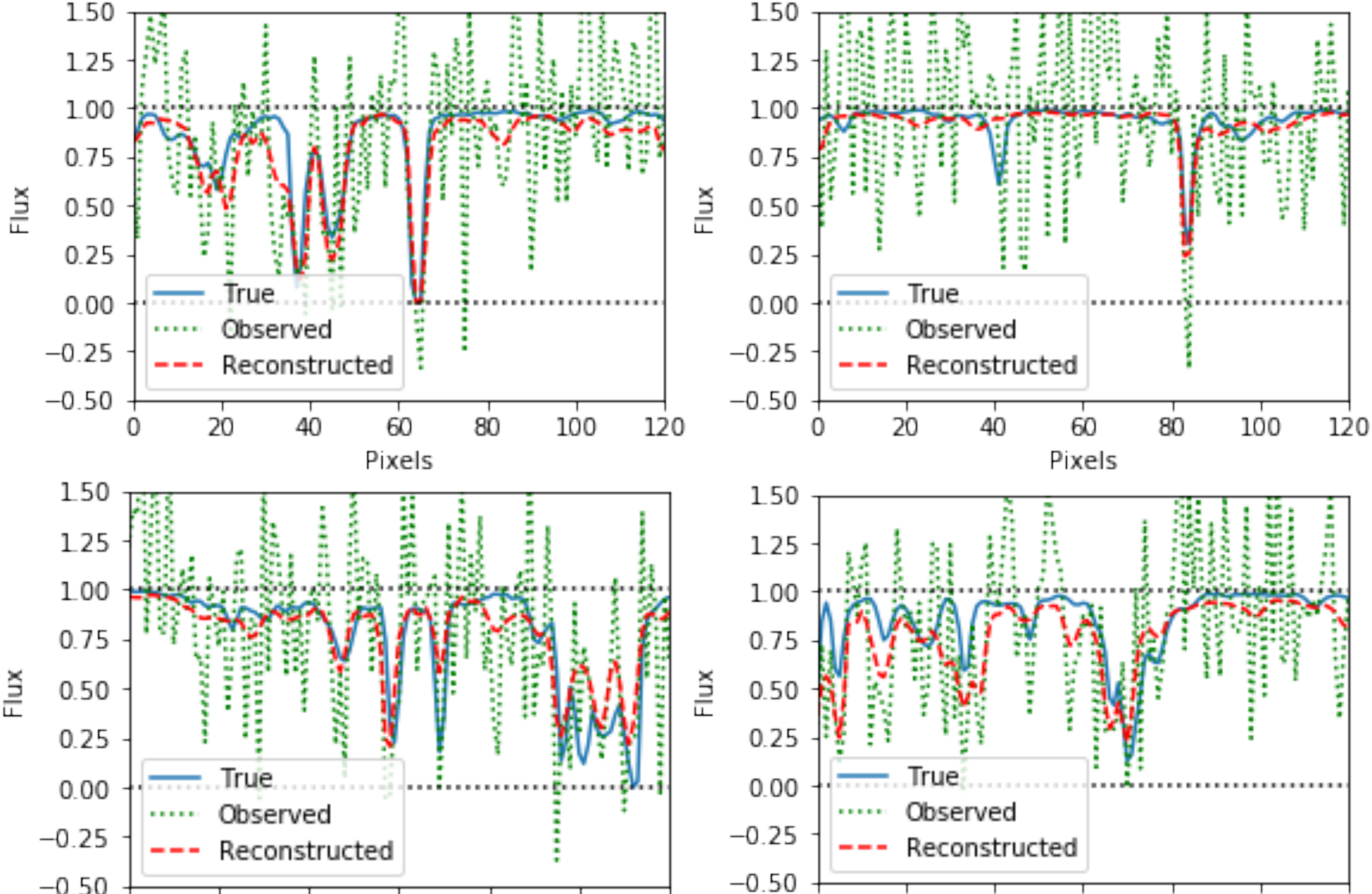


Converged Solution - Iteration IDF

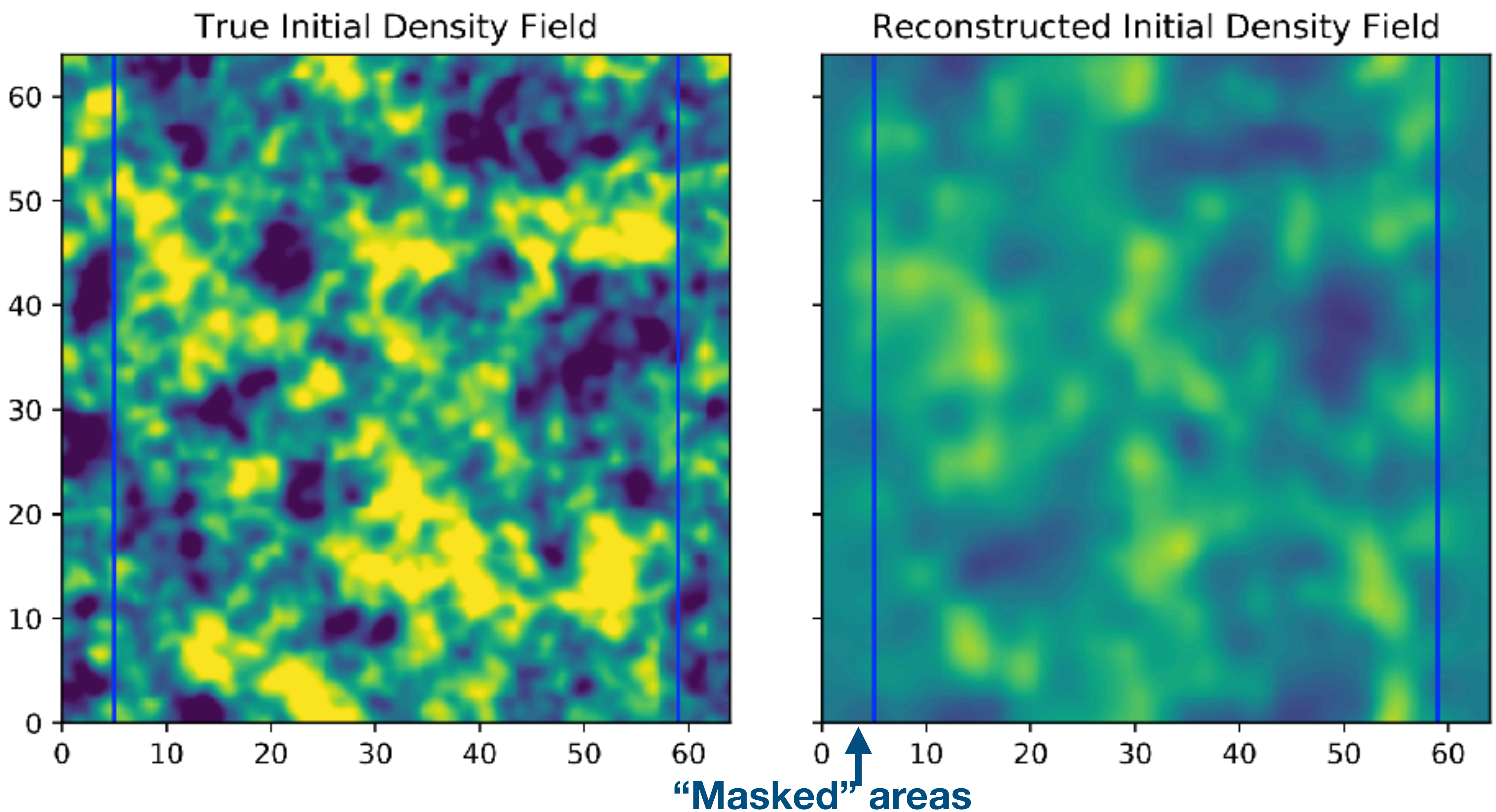


z=2 Density Field

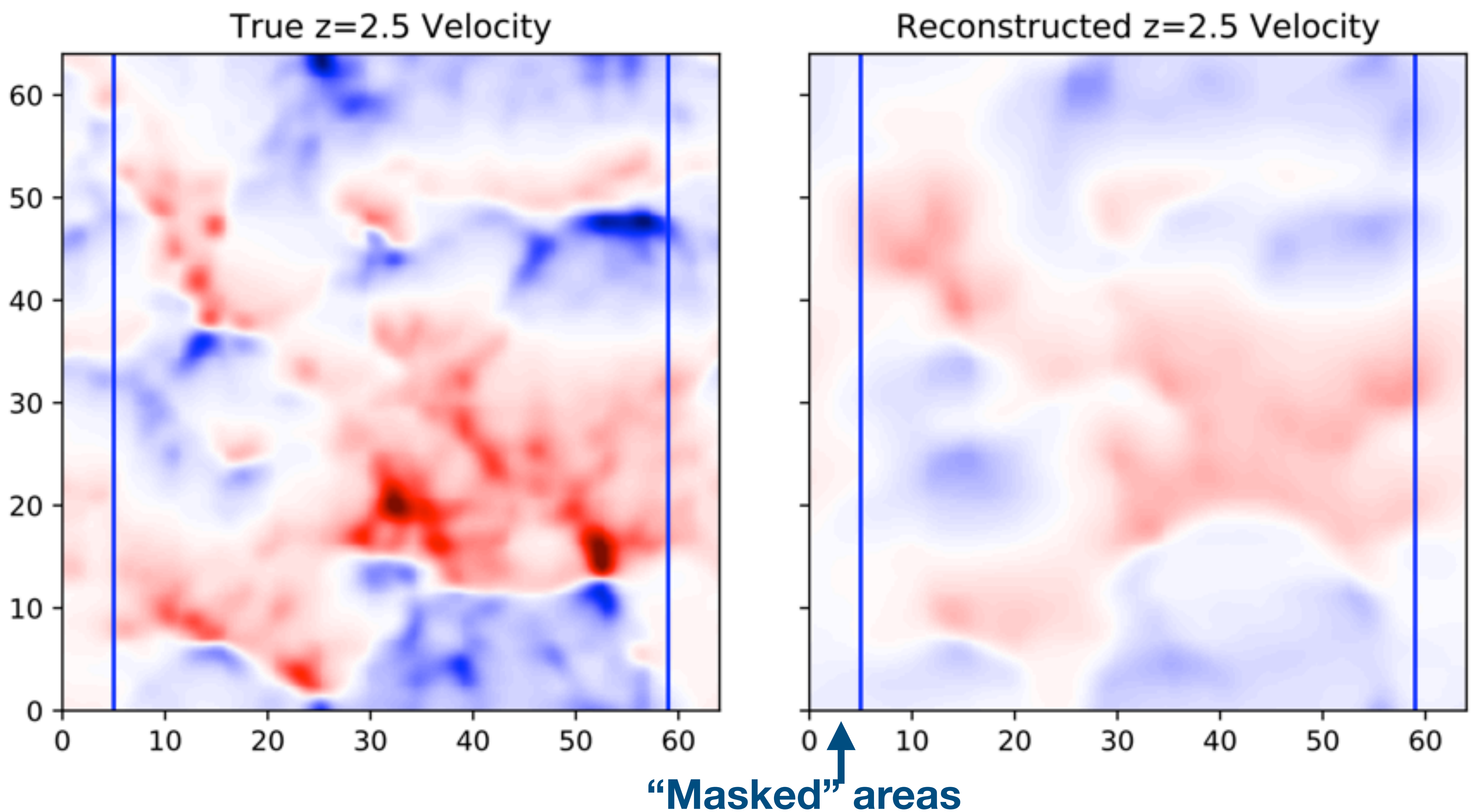
Skewer Results



Results : Initial Density (z~100) x-z plane

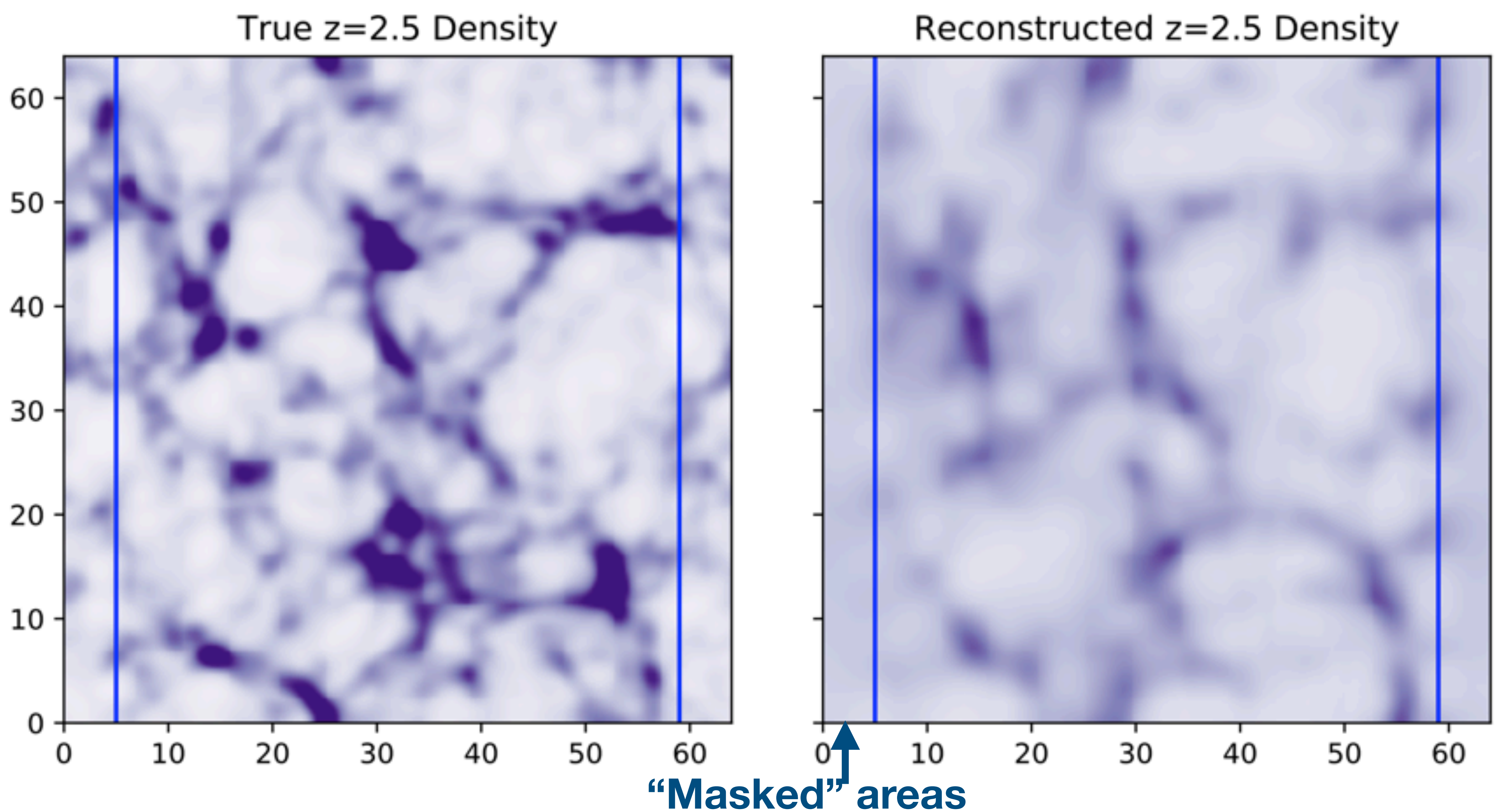


Velocity Results : x-z plane



- Velocity information is not normally reconstructed!

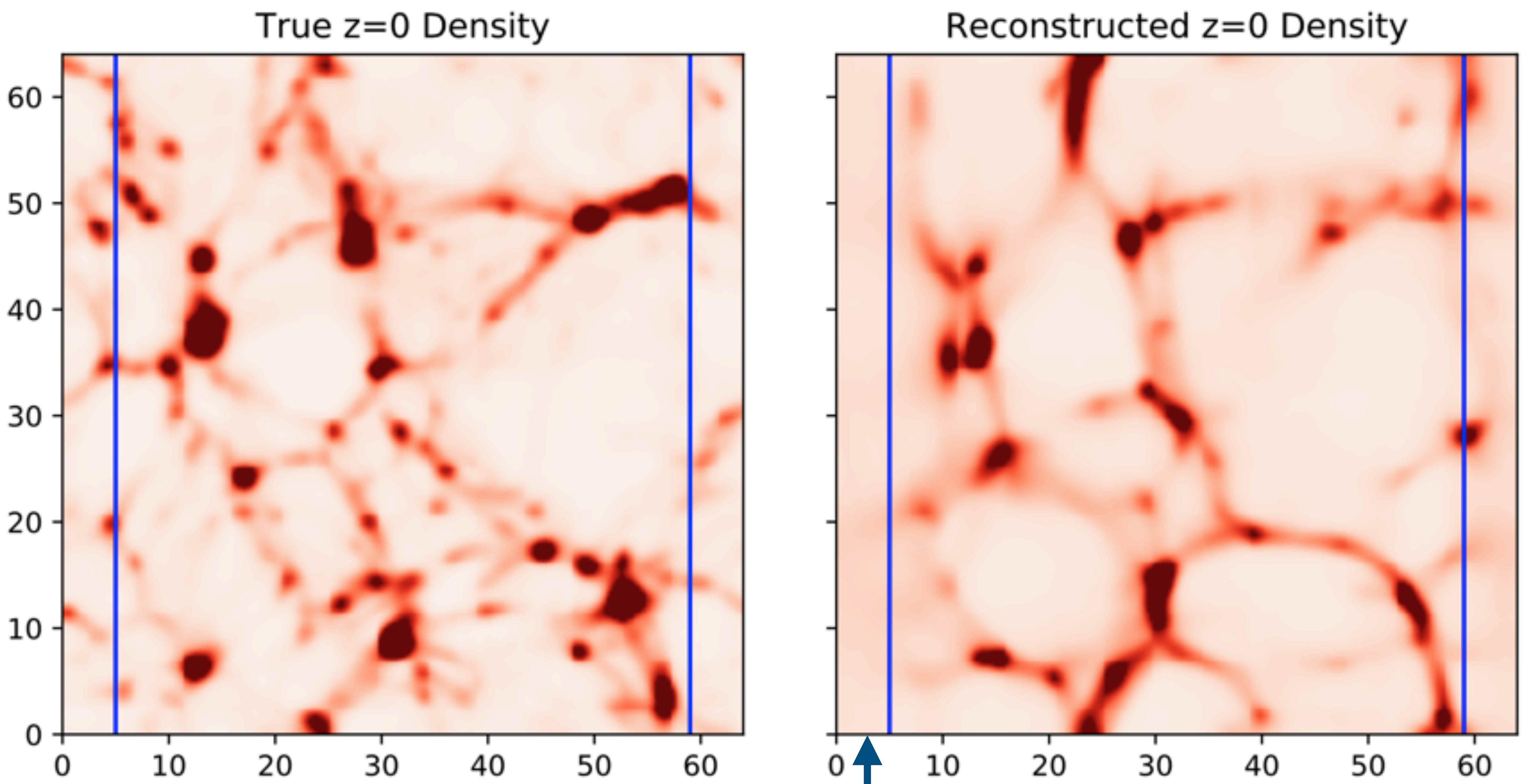
z~2 Density Results : x-z plane



- Cosmic web is well reconstructed, but some bias in high mass regions.

Preliminary!

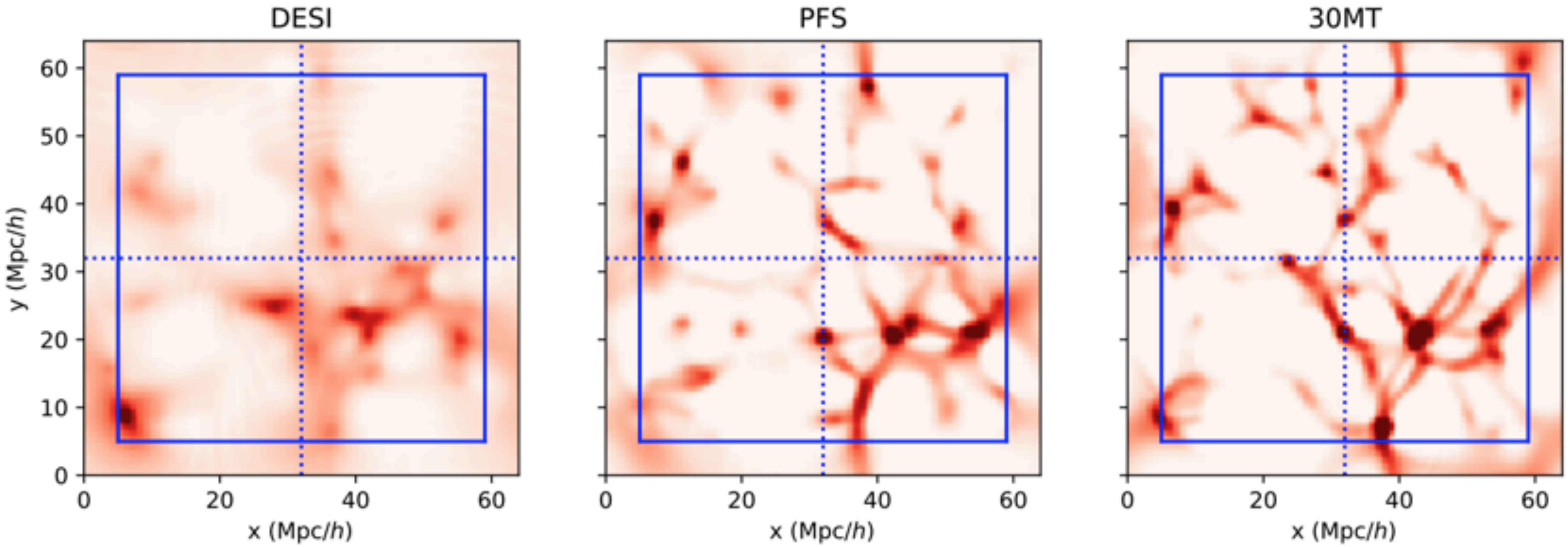
z~0 Density Results : x-z plane



"Masked" areas

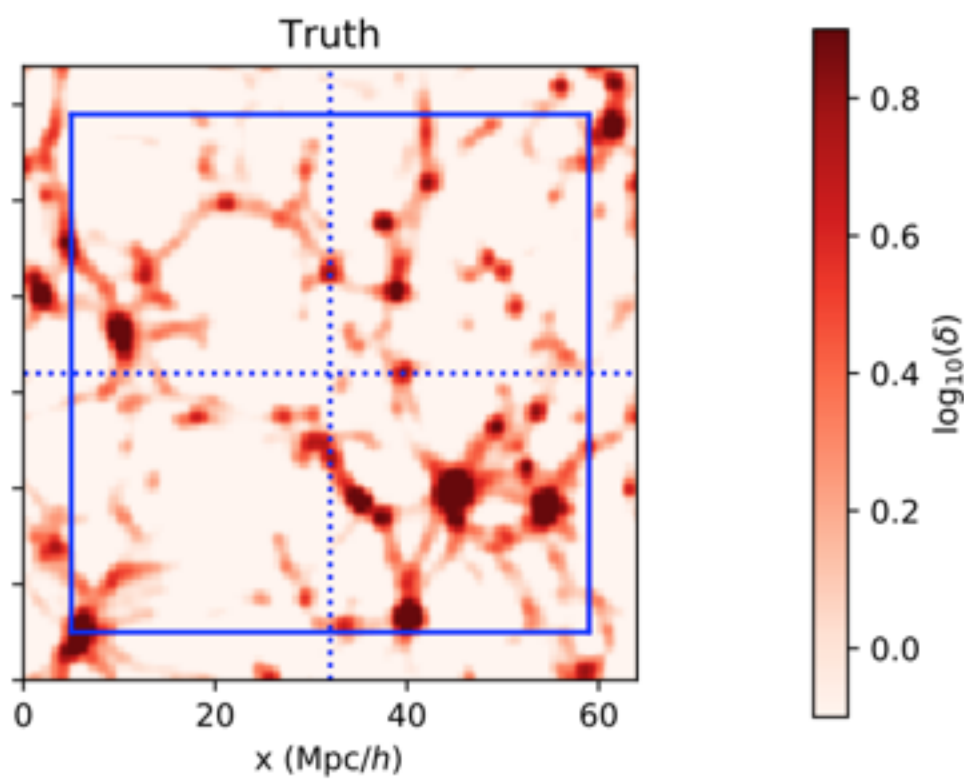
Preliminary!

z=0 Forecasted Reconstructions



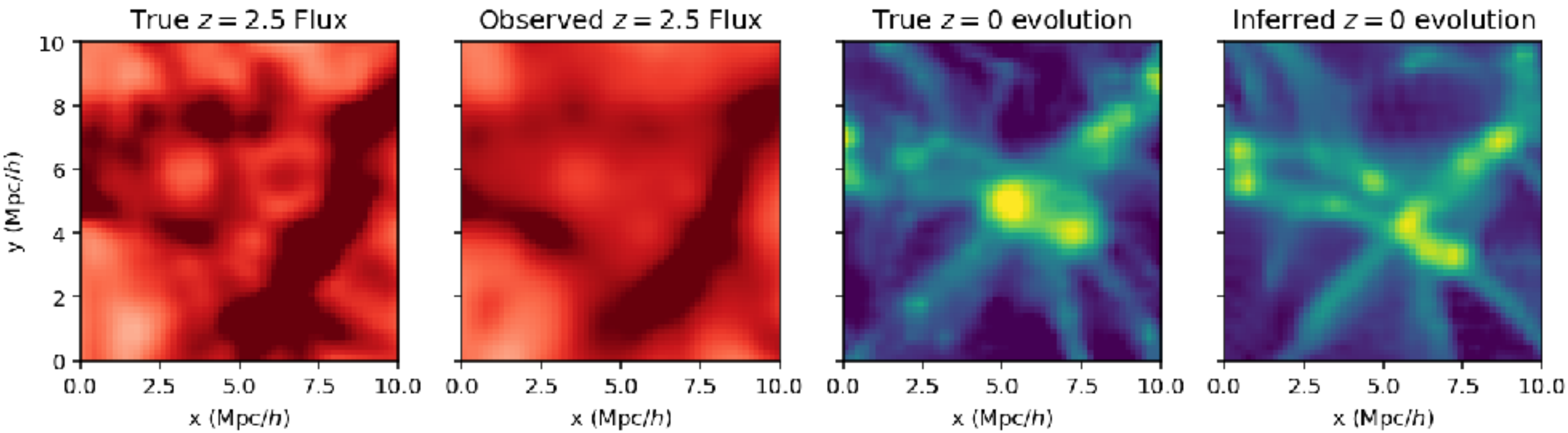
Subaru Prime Focus Camera

Dark Energy Spectroscopic Instrument



Thirty Meter Telescope

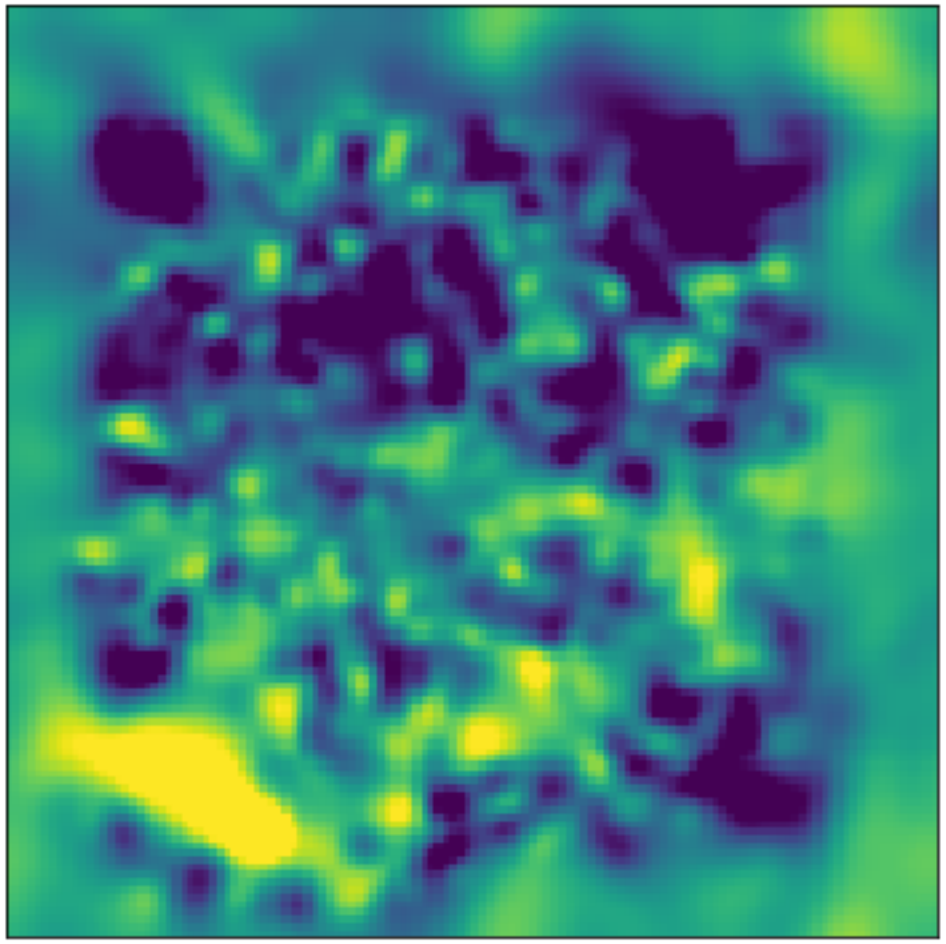
Halo Structure Reconstruction

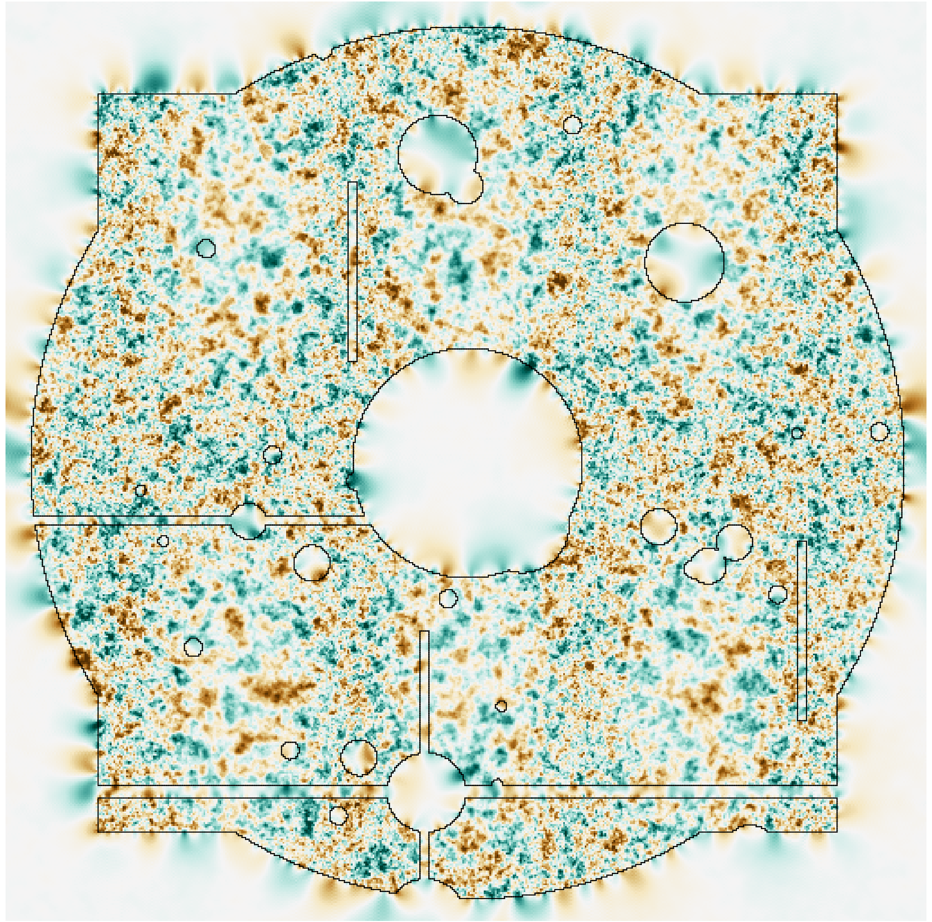


- Inference the late time fate of cosmic structures.

For ~TMT Noise Levels

Summary

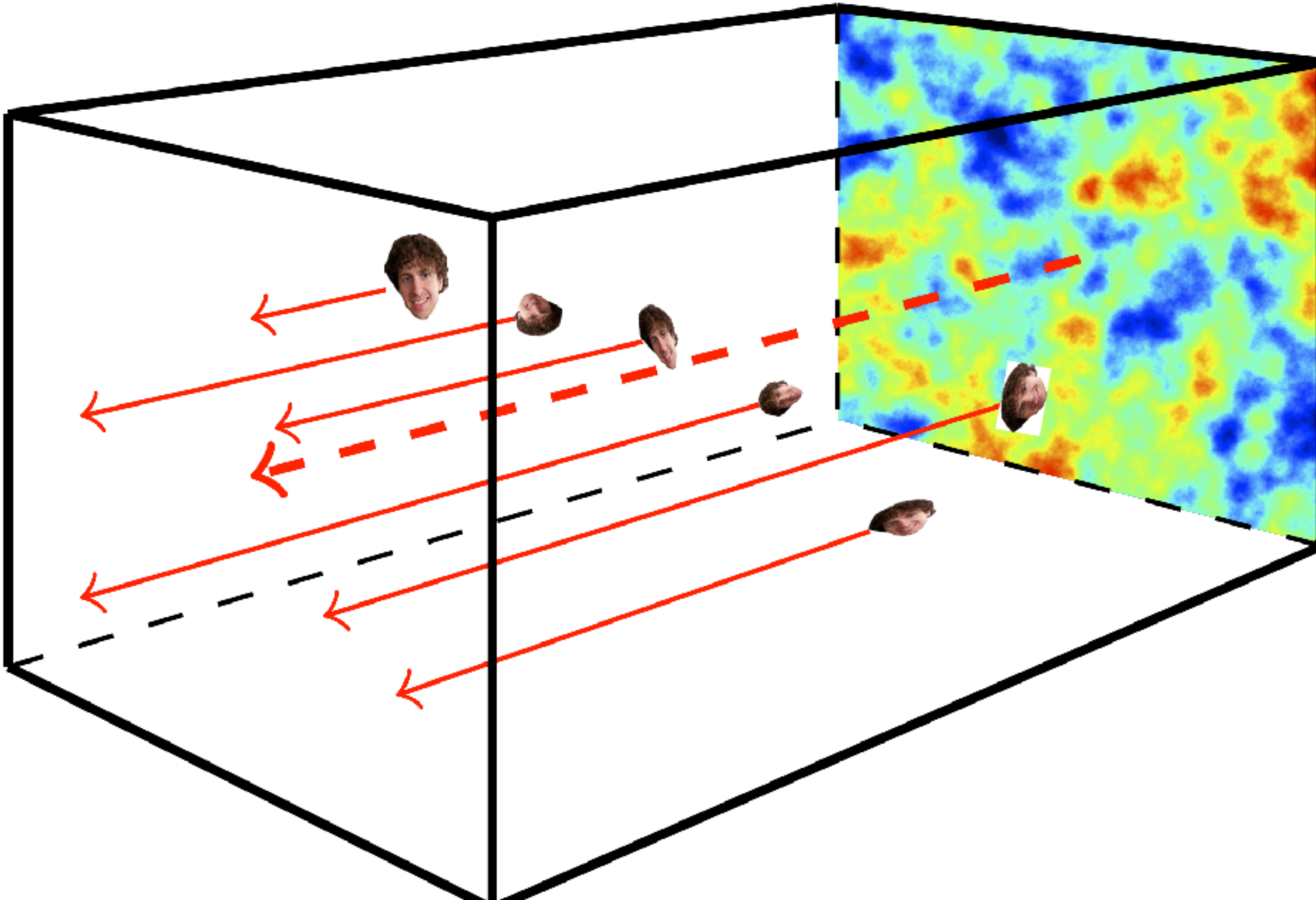




- It is possible to optimally reconstruct signal fields even with very complicated responses (such as gravitational evolution) and over wide survey volumes.

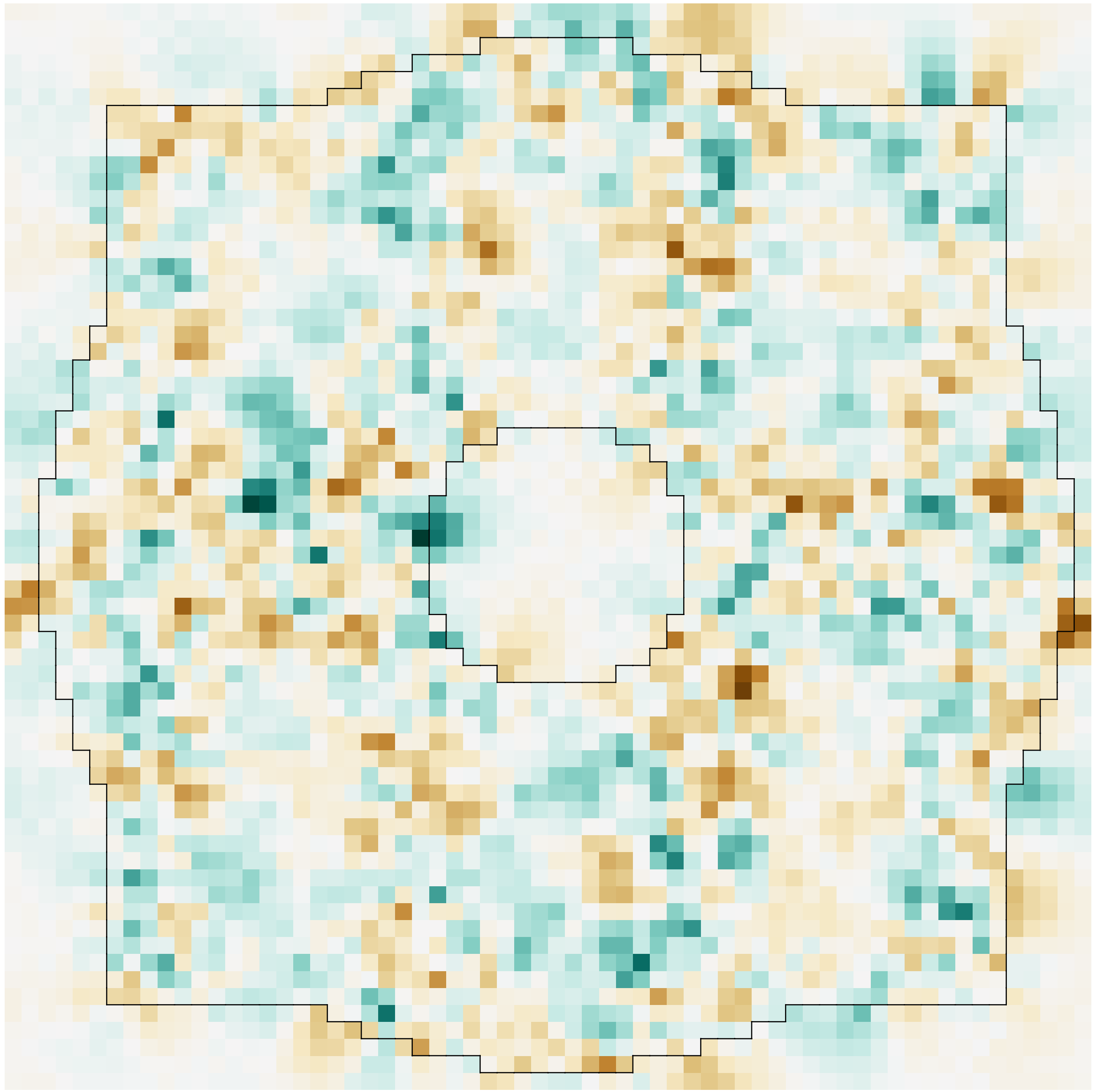
- Tools are being developed in time for next generation surveys which will no longer be statistics limited!

Backup Slides



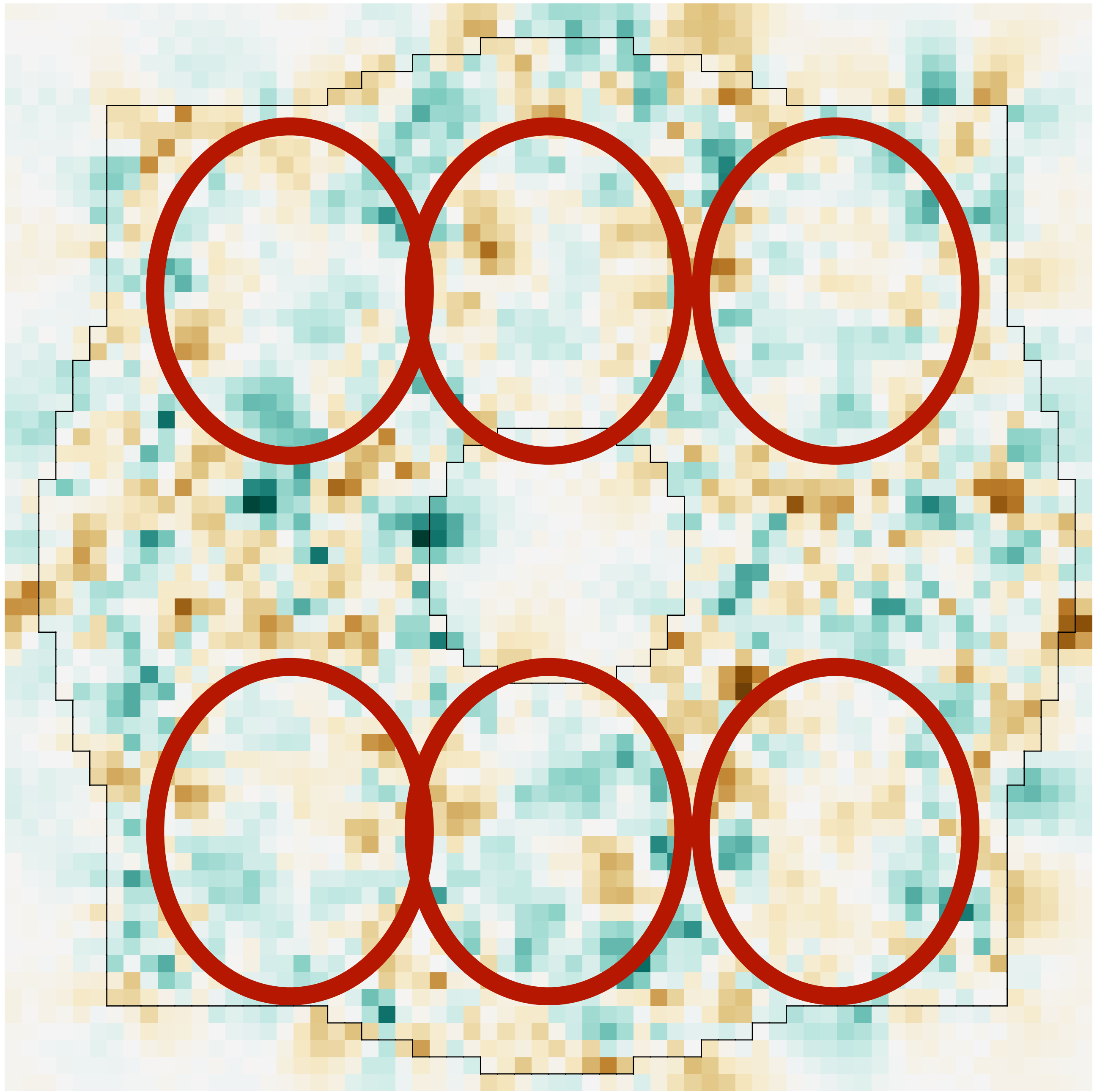
Optimization for Summary Statistics

Going to Summary Statistics



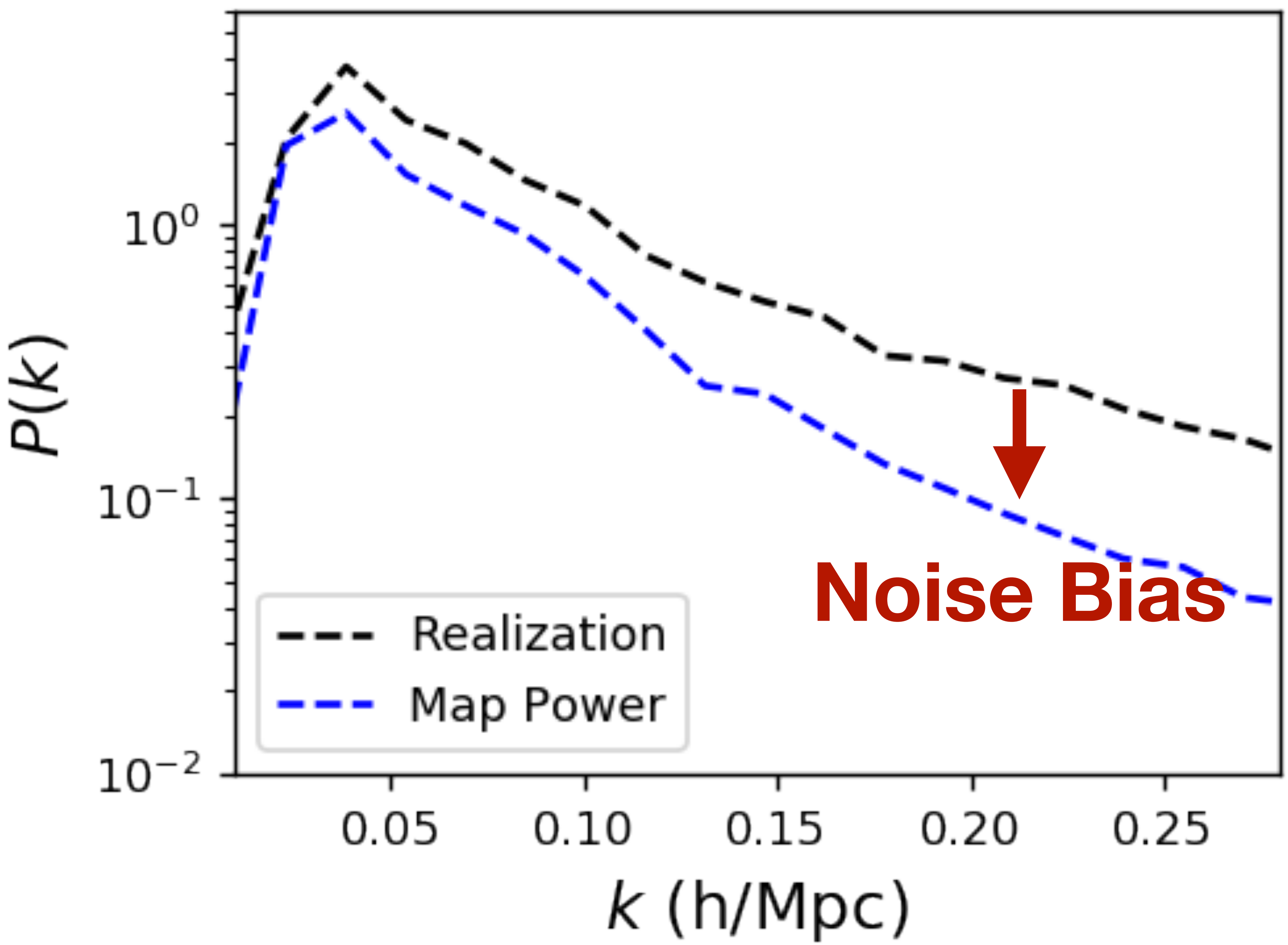
Power spectrum of minimum variance map isn't necessarily the most likely power spectrum.

Going to Summary Statistics



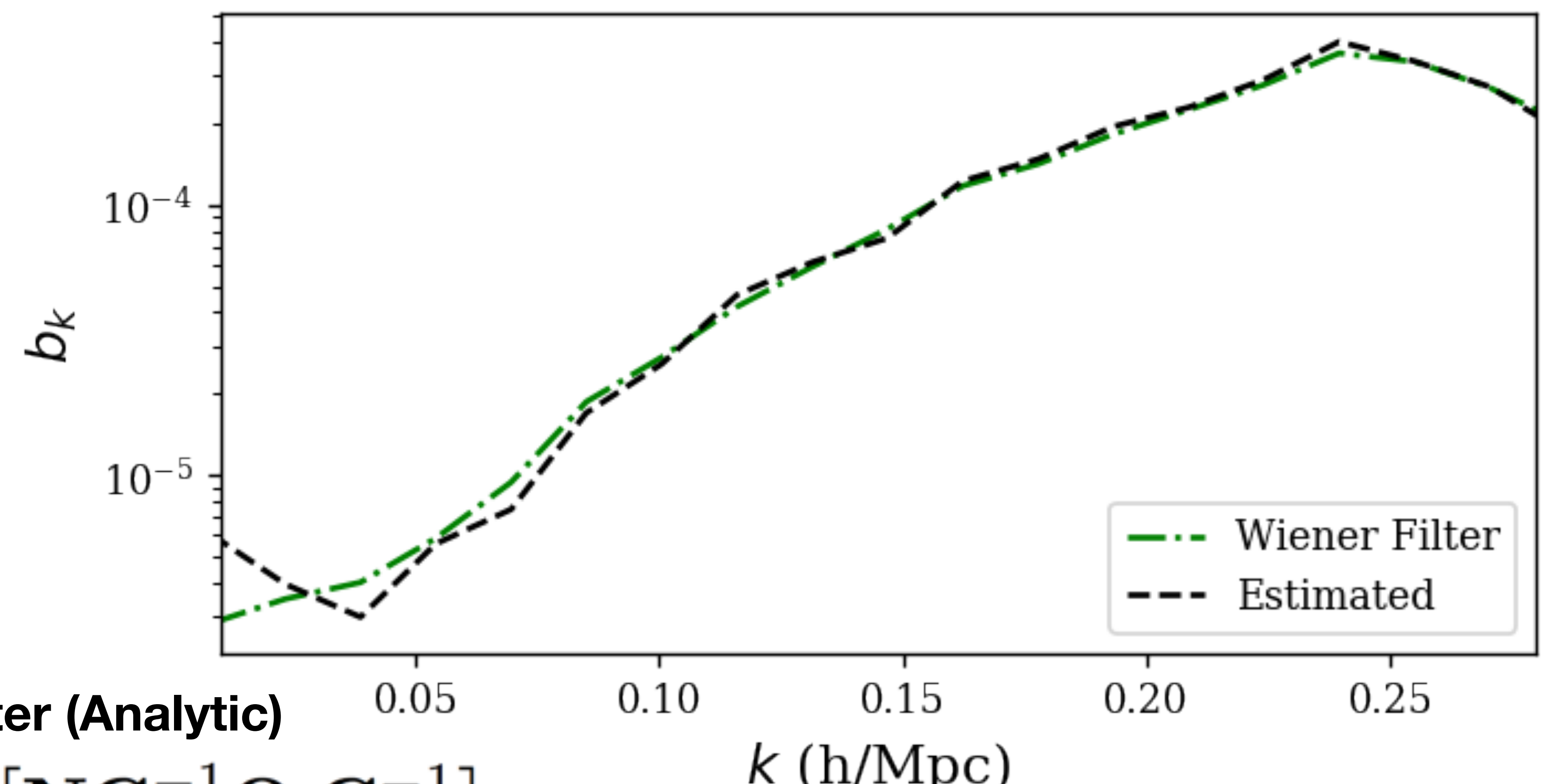
Power spectrum of minimum variance map isn't necessarily the most likely power spectrum.

Going to Summary Statistics



Power Spectrum Estimation: Noise Bias

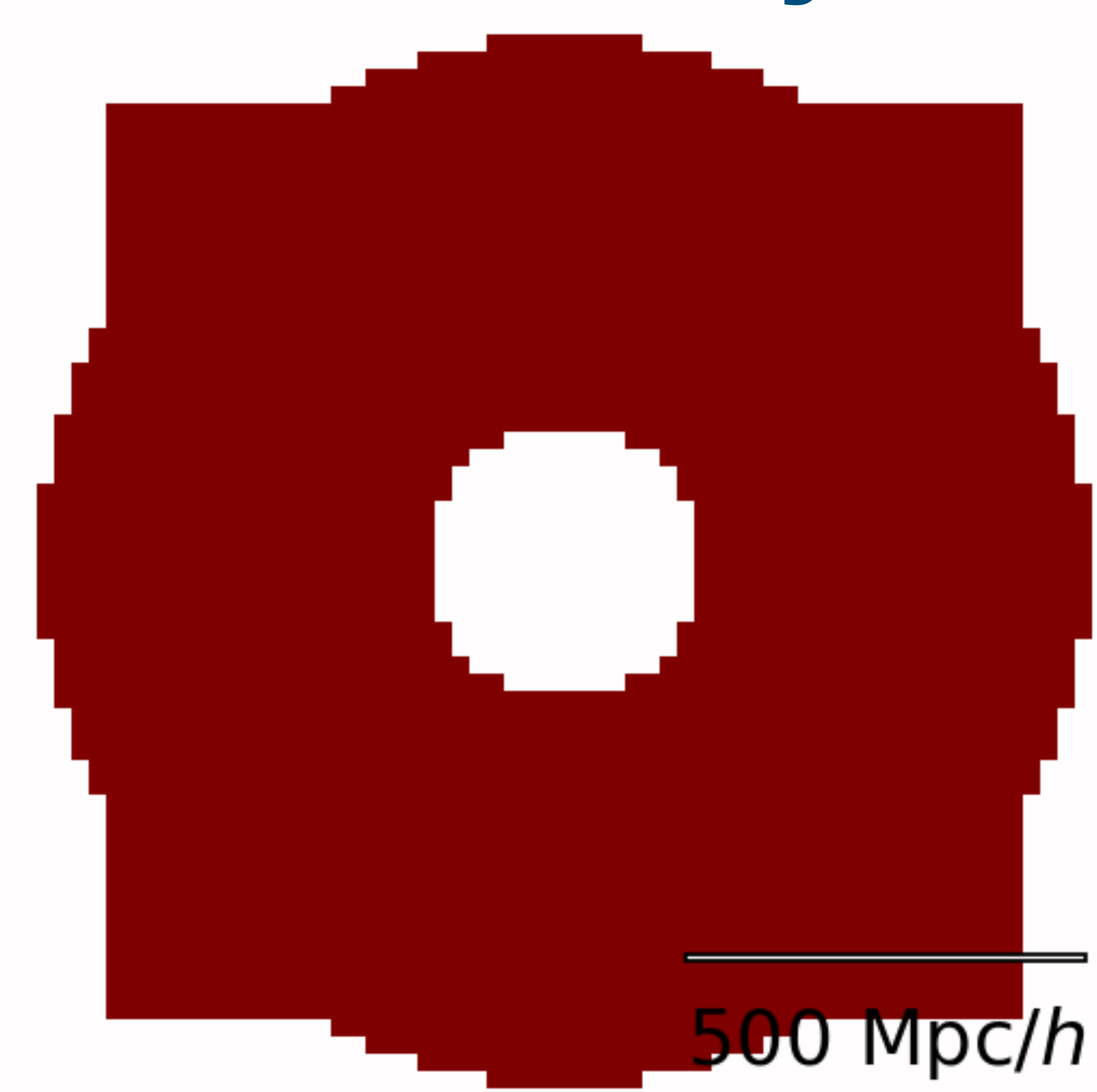
Inject additional noise, $\mathbf{d}_n$, and then rerun optimization $\hat{\mathbf{s}}_n$



Wiener Filter (Analytic)

$$b_l = tr\left[\mathbf{N}\mathbf{C}^{-1}\mathbf{Q}_l\mathbf{C}^{-1}\right]$$

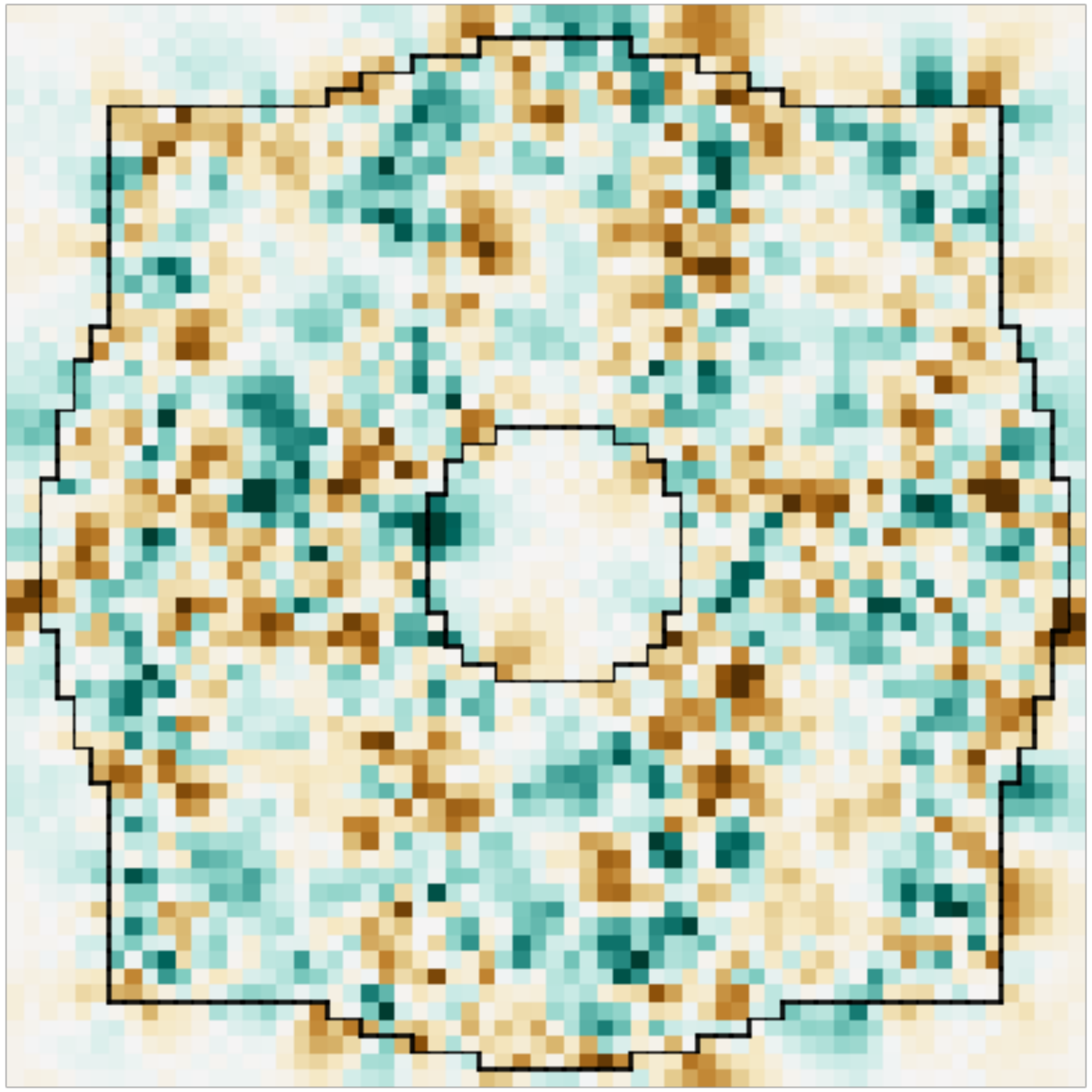
Going to Summary Statistics



Mask geometry can induce correlations between modes or suppression of certain modes

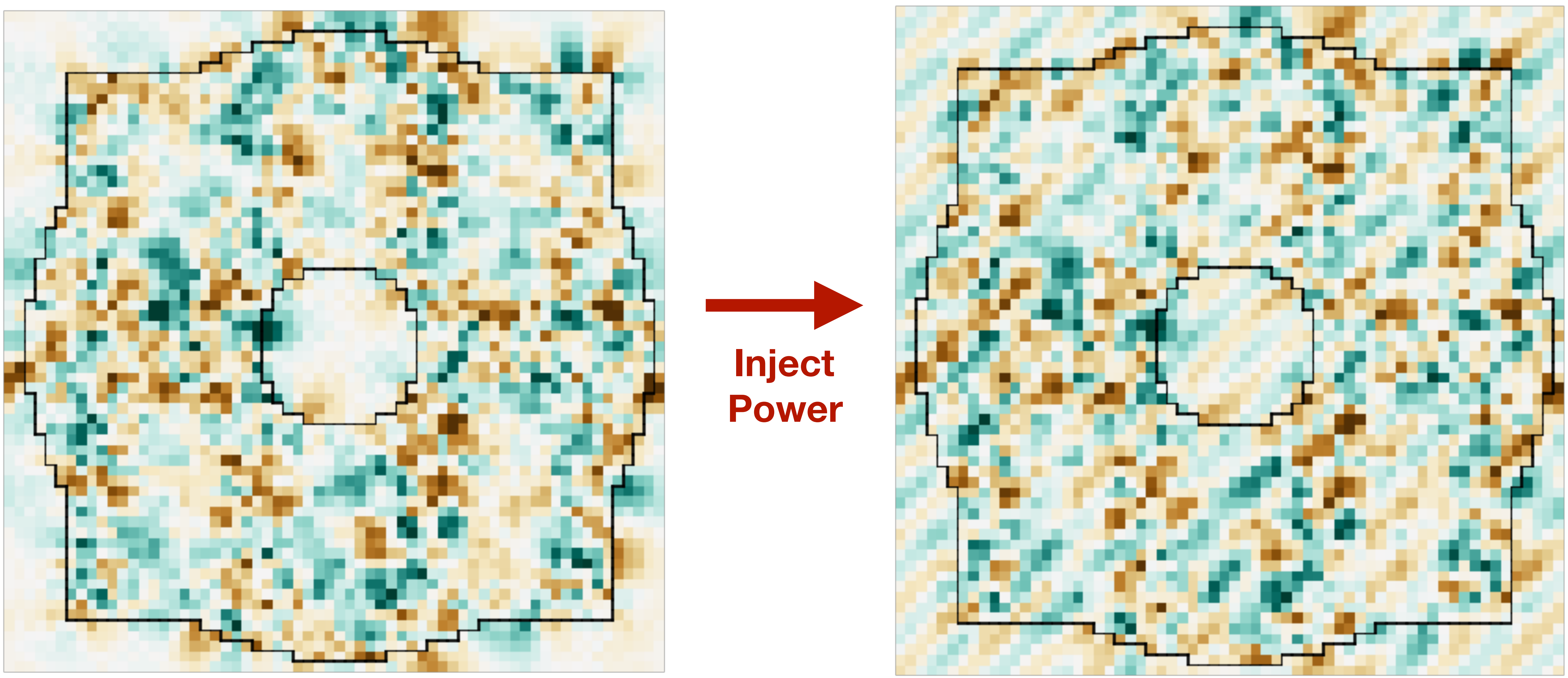
Power Spectrum Estimation: Fisher Matrix

Central Limit Theorem! For each band power there are many modes sampled, so the posterior for each band power should be Gaussian.



Power Spectrum Estimation: Fisher Matrix

Inject additional signal, $\Delta \mathbf{s}_{l'}$, to bin l' and optimize to get $\hat{\mathbf{s}}_{l'}$

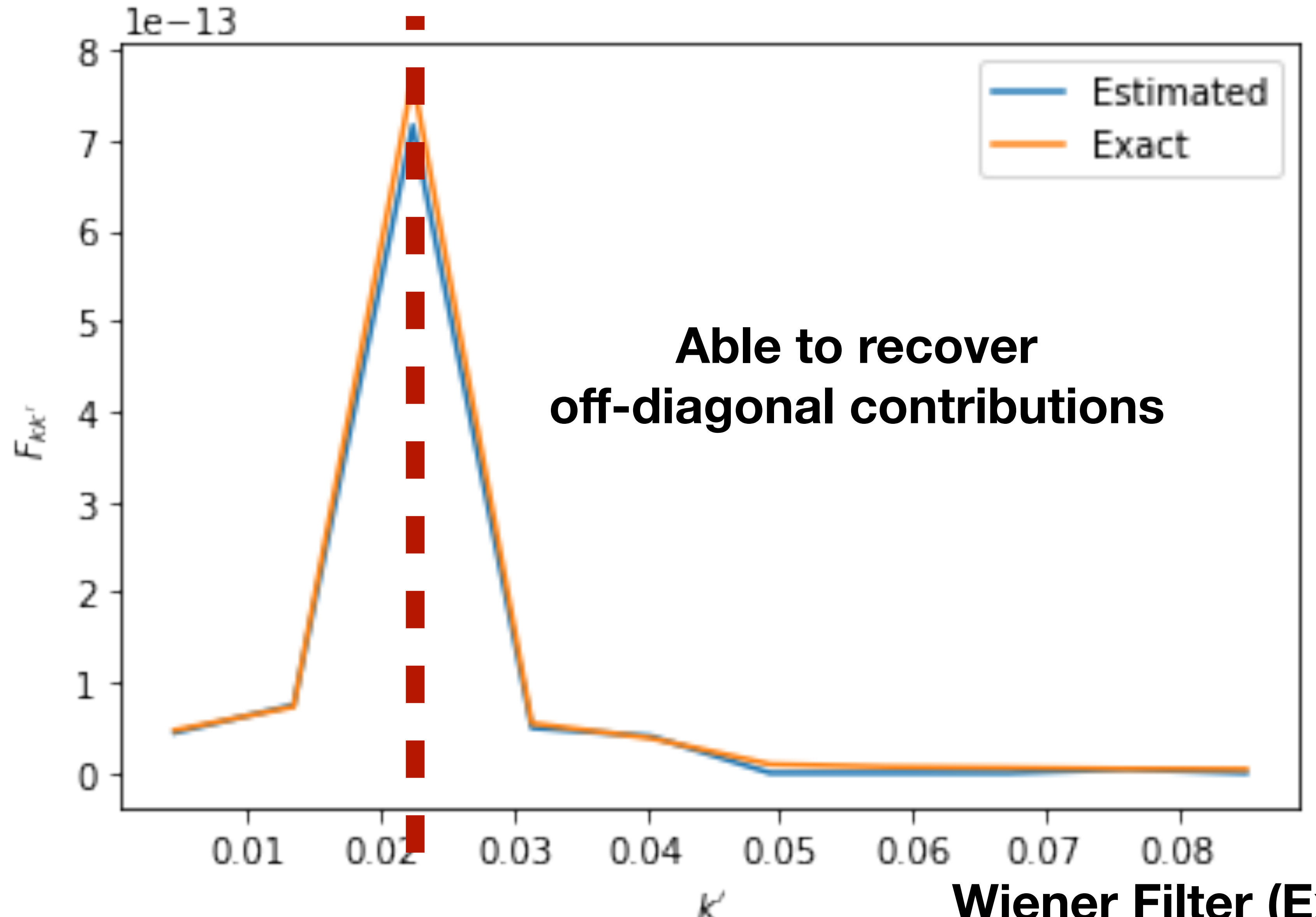


(Exaggerated Cartoon)

Power Spectrum Estimation: Fisher Matrix

Inject additional signal, $\Delta \mathbf{s}_{l'}$, to bin l' and optimize to get $\hat{\mathbf{s}}_{l'}$

Cut of Fisher Matrix:
k = 0.022

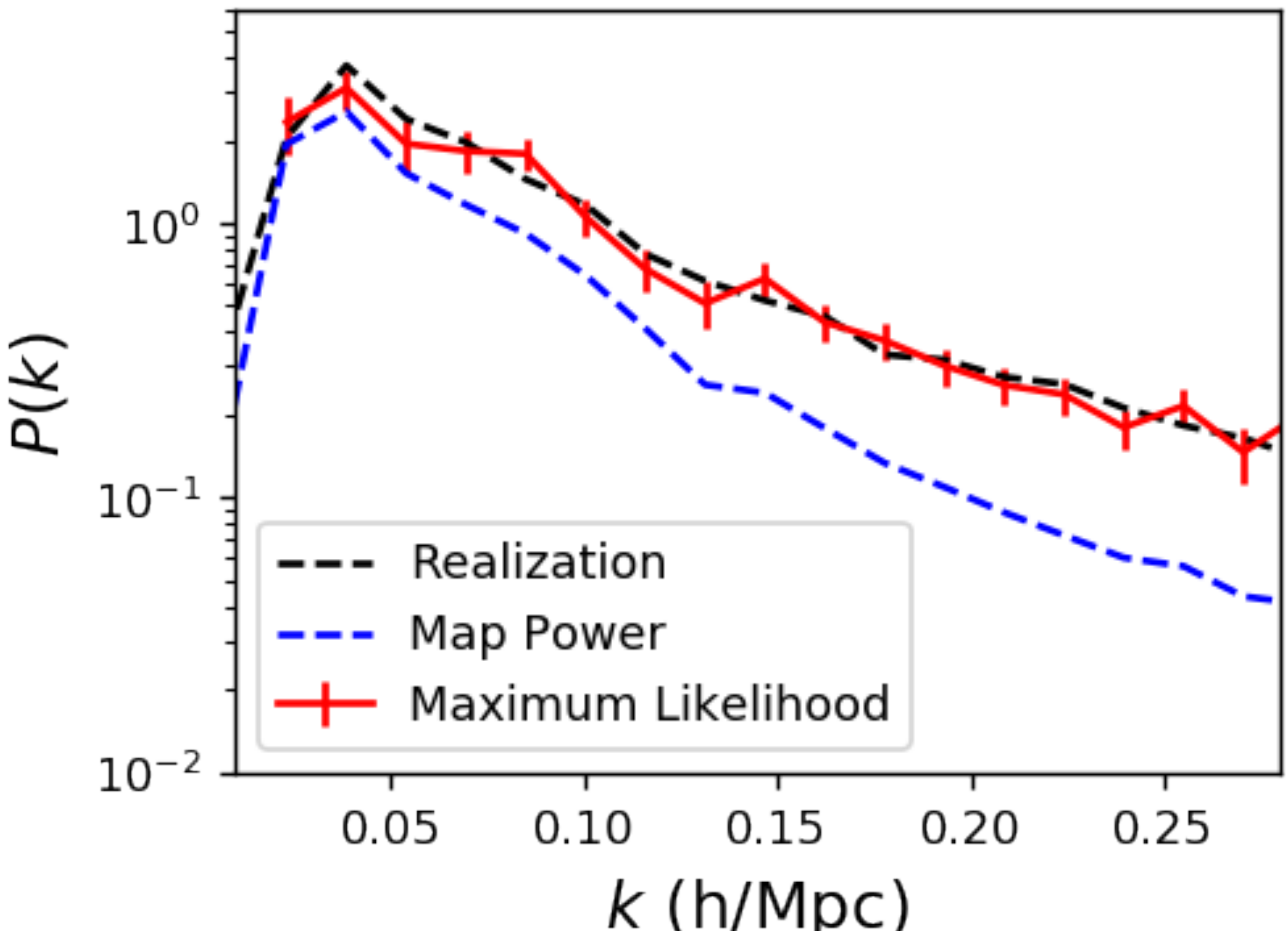


Wiener Filter (Exact)

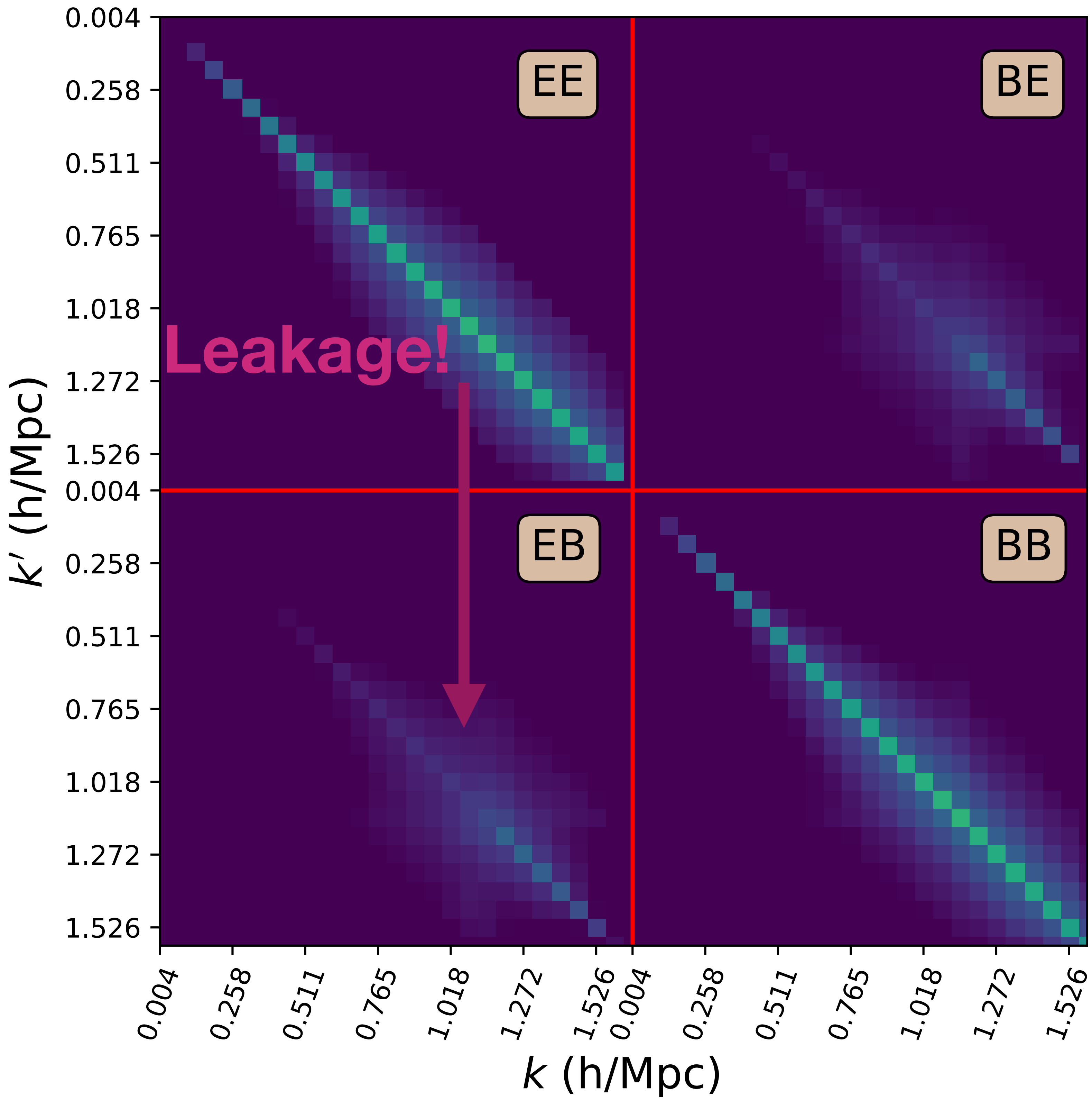
$$F_{ll'} = \frac{1}{2} tr\left(\mathbf{Q}_l \mathbf{C}^{-1} \mathbf{Q}_{l'} \mathbf{C}^{-1}\right)$$

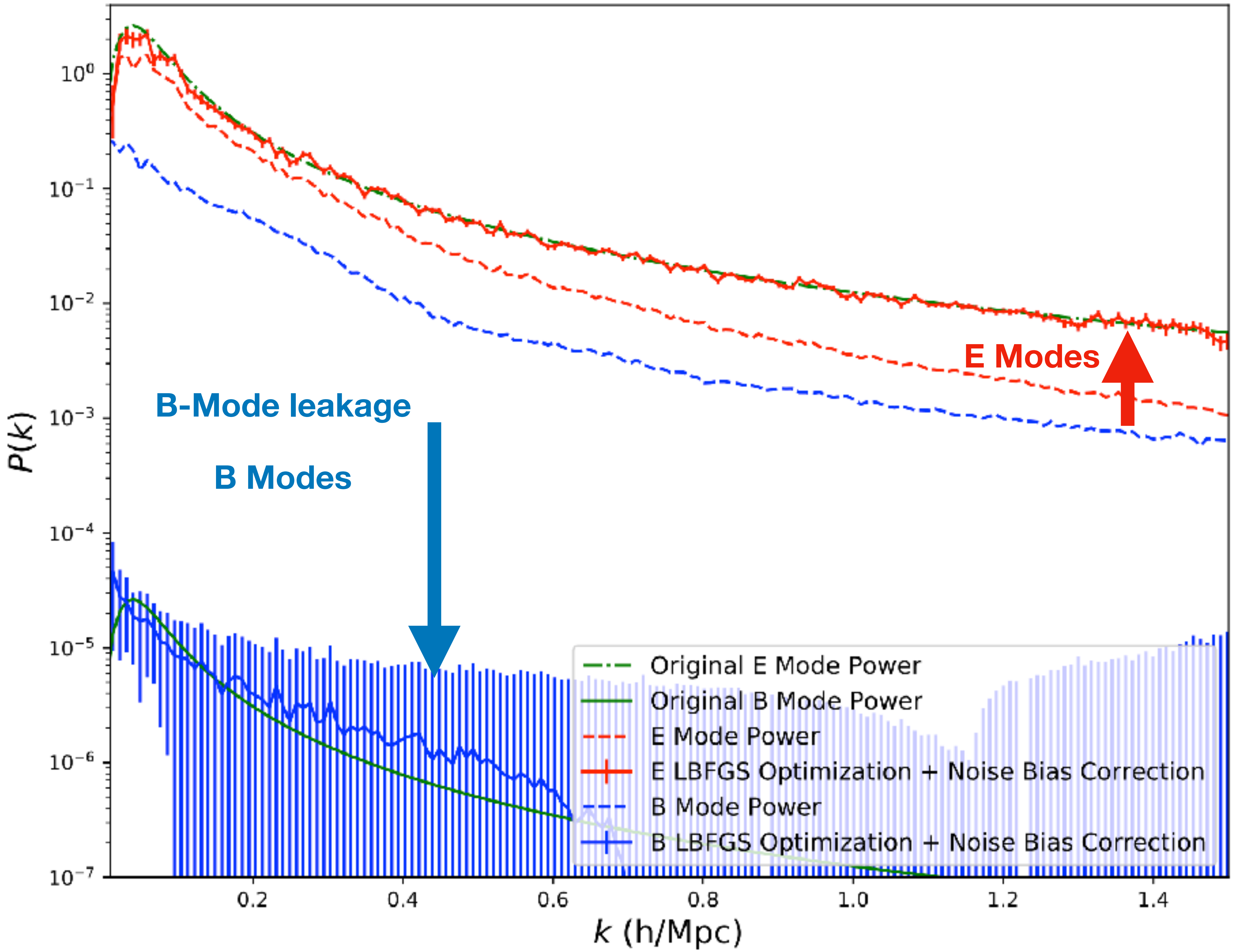
Also gives us error bars!

Power Spectrum



Fisher Matrix





E Modes
B-Mode leakage
B Modes
Original E Mode Power
Original B Mode Power
E Mode Power
E LBFGS Optimization + Noise Bias Correction
B Mode Power
B LBFGS Optimization + Noise Bias Correction
$P(k)$
k (h/Mpc)
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
0.2
0.4
0.6
0.8
1.0
1.2
1.4

Take-aways

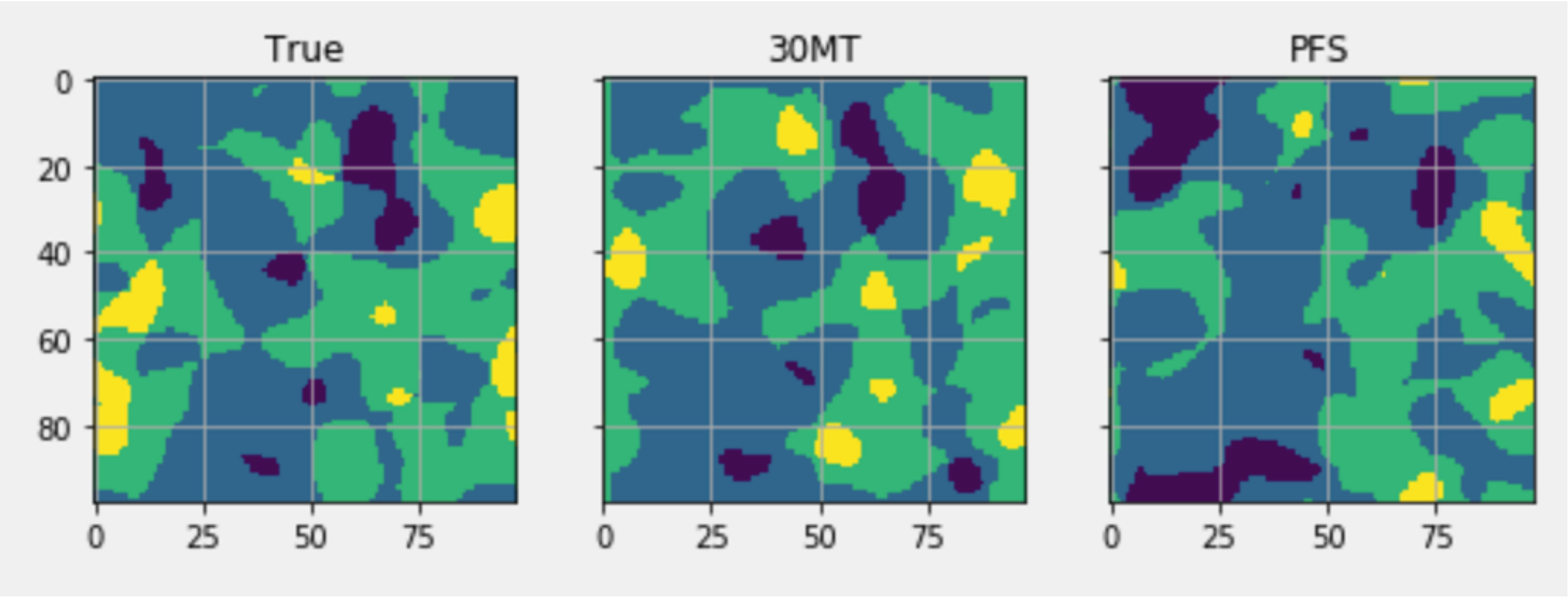
- It is possible to optimally reconstruct large maps in short time even with non-trivial noise, response matrix, and mask properties.

- Power-spectrum estimation is straightforward and optimal.

- Framework is extremely flexible and can be applied to many other observables.
  (Ask me later if interested in CMB reconstruction!)

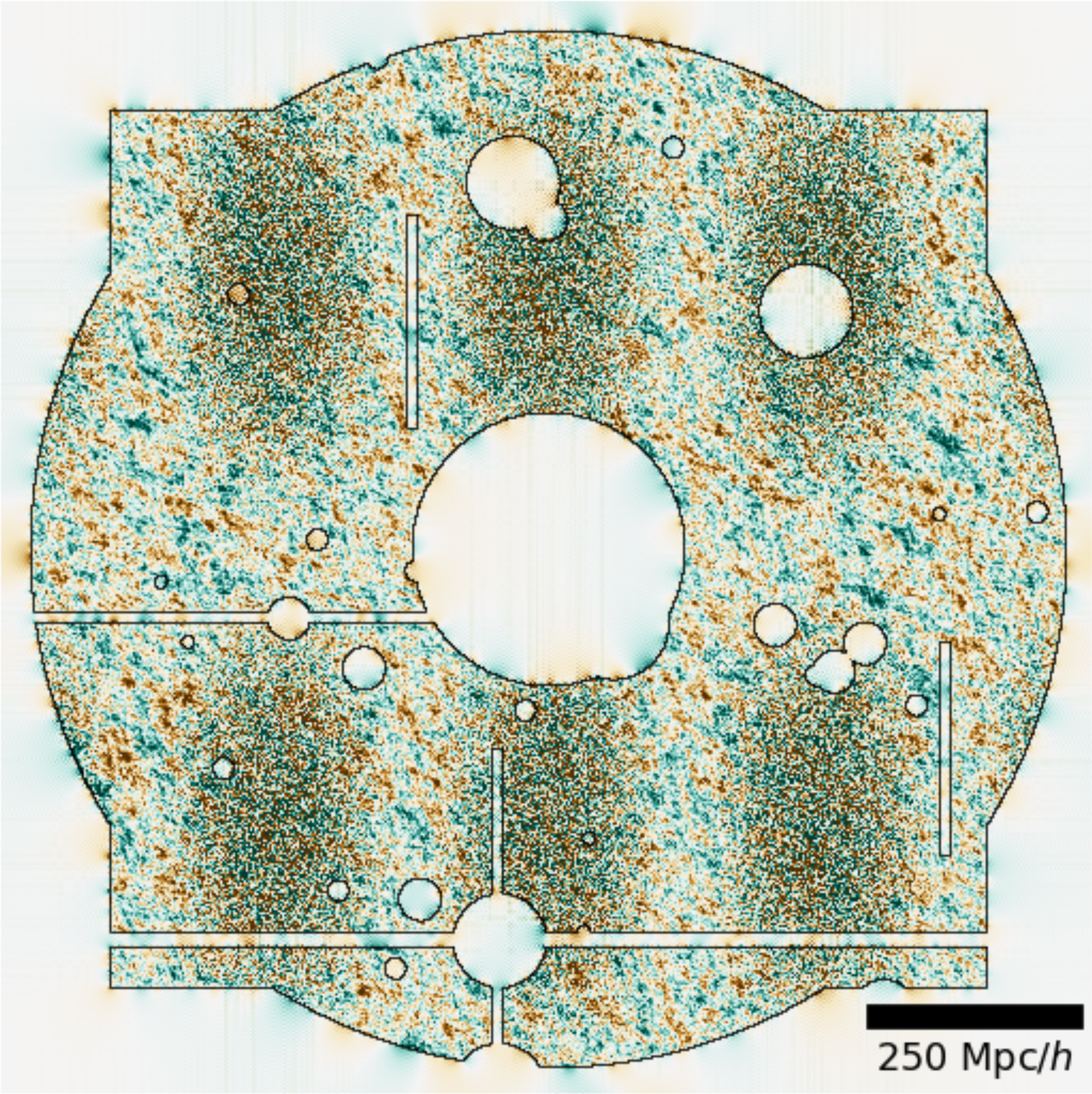
Preliminary!

z~0 Cosmic Web Structure



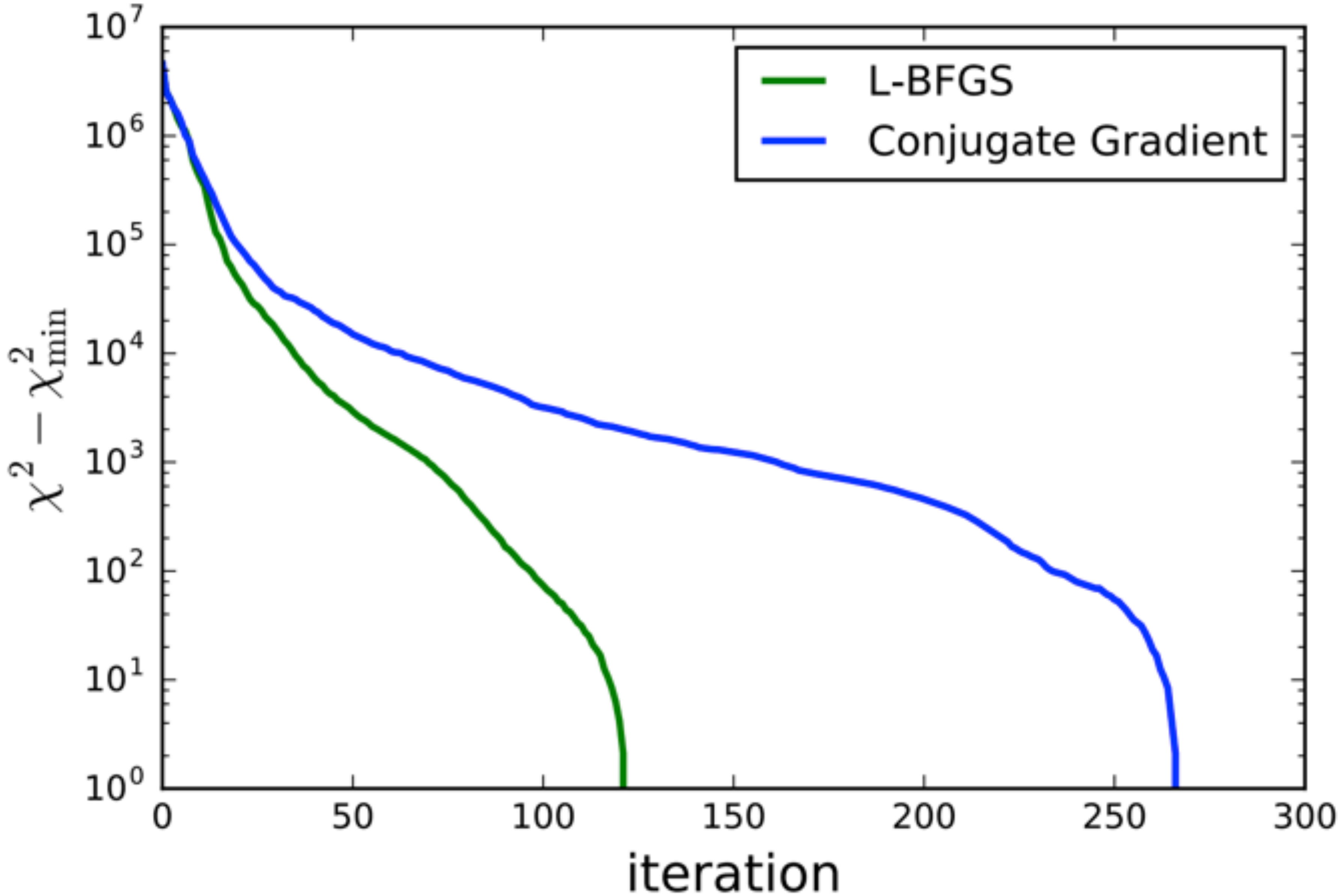
UGLY!

Kaiser Squires



Optimization over Initial Density Fields: Other Methods

(For nonlinear density only reconstruction)

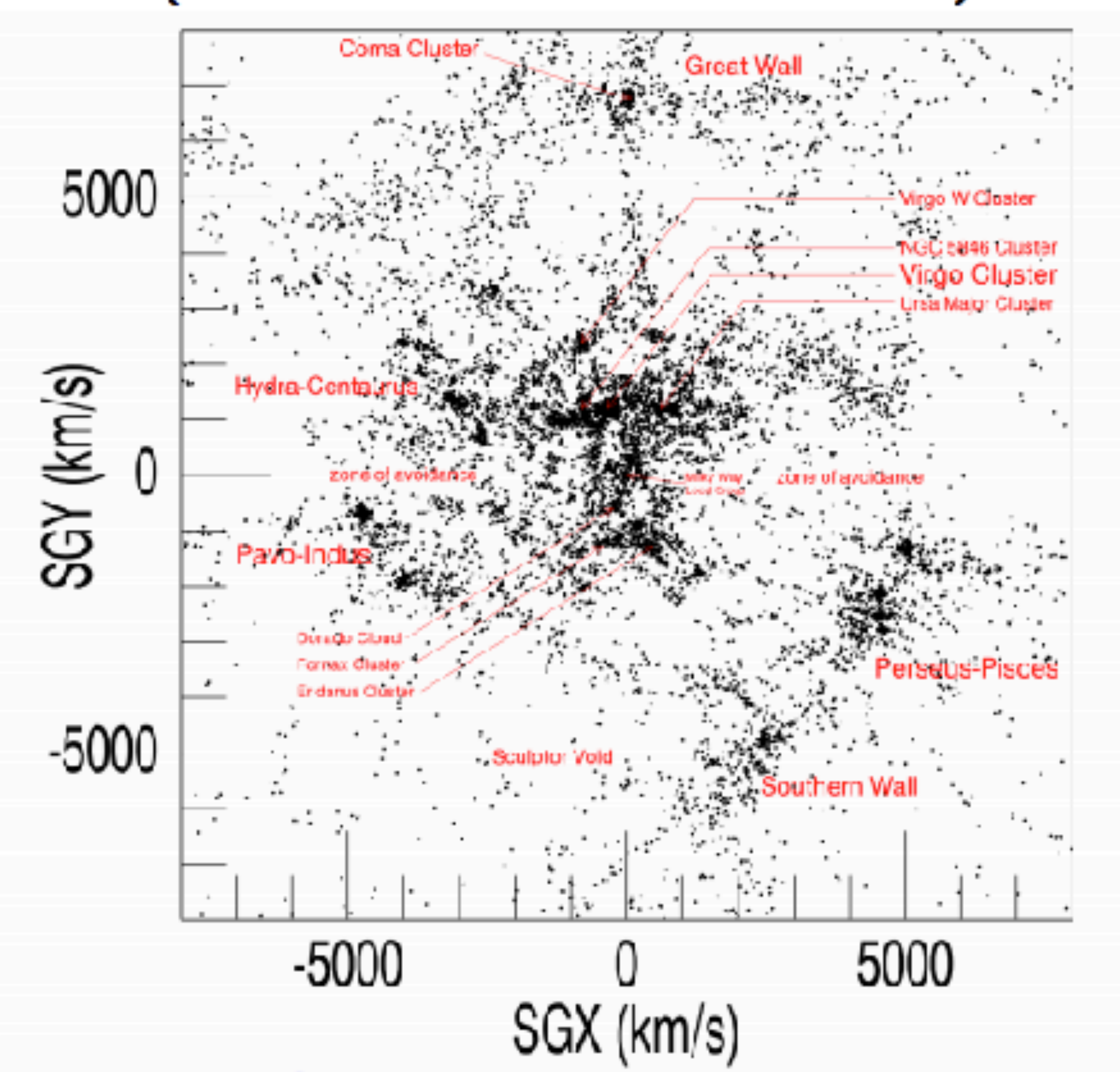


Very high dimensional parameter space; sampling is very costly computationally…

Seljak et al. (2017)

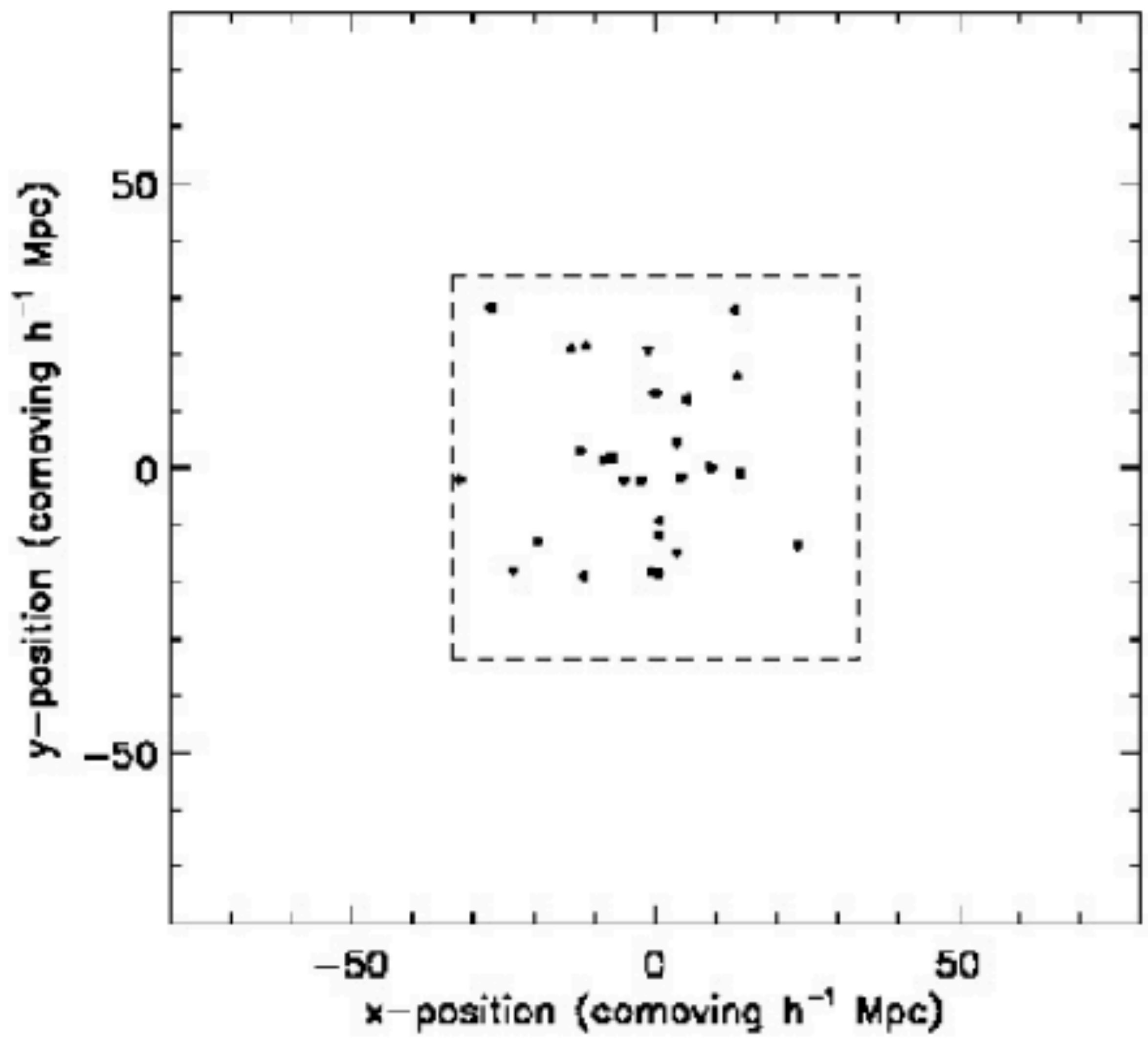
Density of galaxies in COSMOS Field

$D < 100$ Mpc Local Universe
($\Delta v = 2000$ km s^{-1} slice)



Courtois et al 2013

$z = 2.3$
(COSMOS spectro-z's)



COSMOS Collaboration

Slide from KG Lee