Probing Cosmology with the kSZ Effect

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KICP at the University of Chicago
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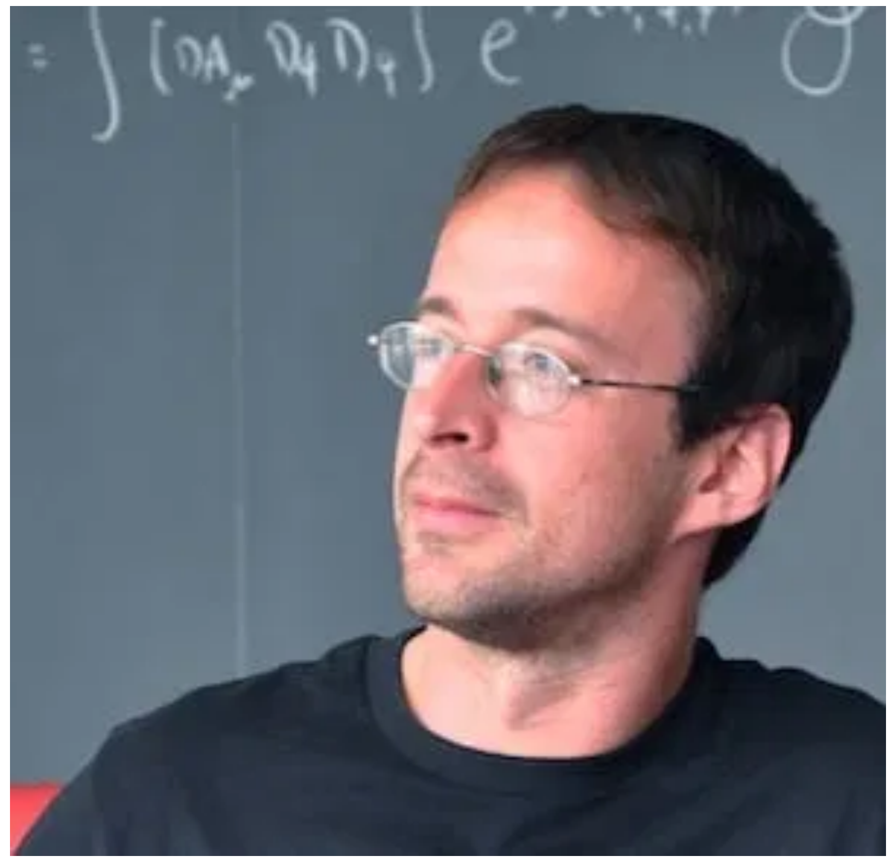
Outline



1. kSZ velocity reconstruction (recap)
2. The `kszx` reconstruction pipeline
3. DESI-LS LRGs & ACT DR5 analysis
4. Results: SNR and constraints on primordial non-Gaussianity

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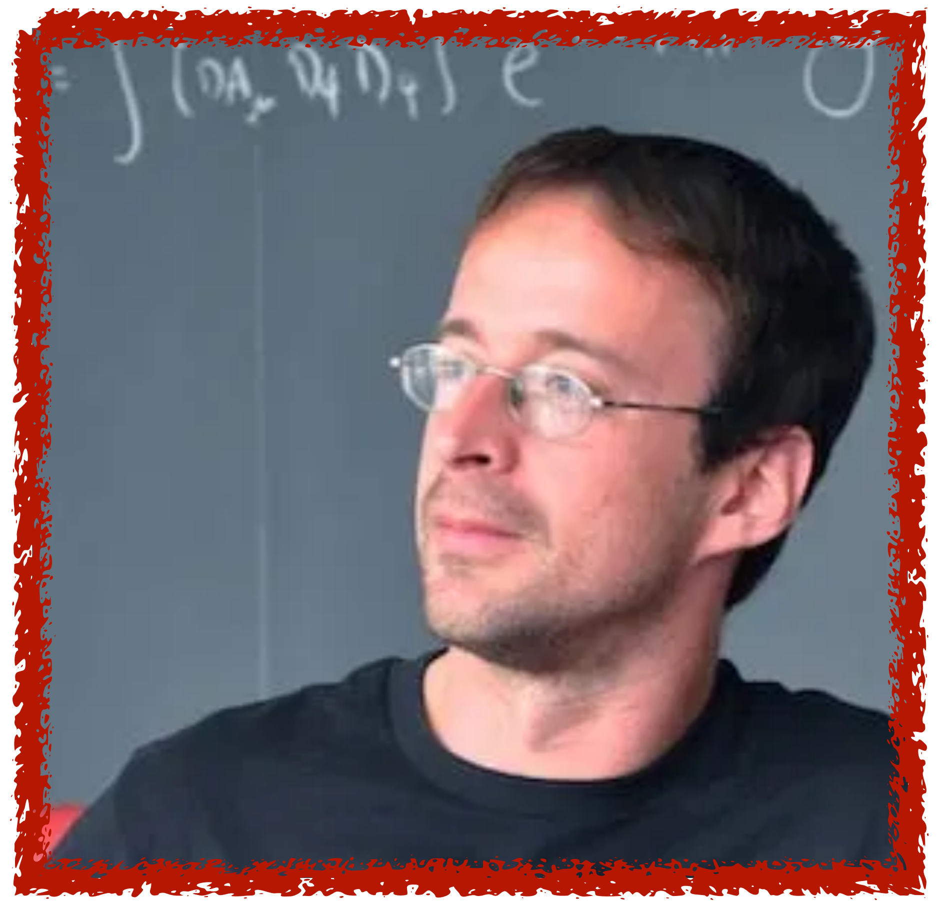

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2. The `kszx` reconstruction pipeline
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4. Results: SNR and constraints on primordial non-Gaussianity

`kszx:` https://github.com/kmsmith137/kszx

$$T_{\rm kSZ}(\boldsymbol{\theta}) = \int d\chi\, K(\chi)\, v_r(\chi\boldsymbol{\theta})\, \delta_e(\chi\boldsymbol{\theta})$$

$$K(z) \equiv -T_{\rm CMB}\, \sigma_T\, n_{e0}\, x_e(z)\, e^{-\tau(z)}\, (1+z)^2$$

Consider distribution of **free electrons**

…and a cosmological velocity fluctuation

Primary CMB + kSZ

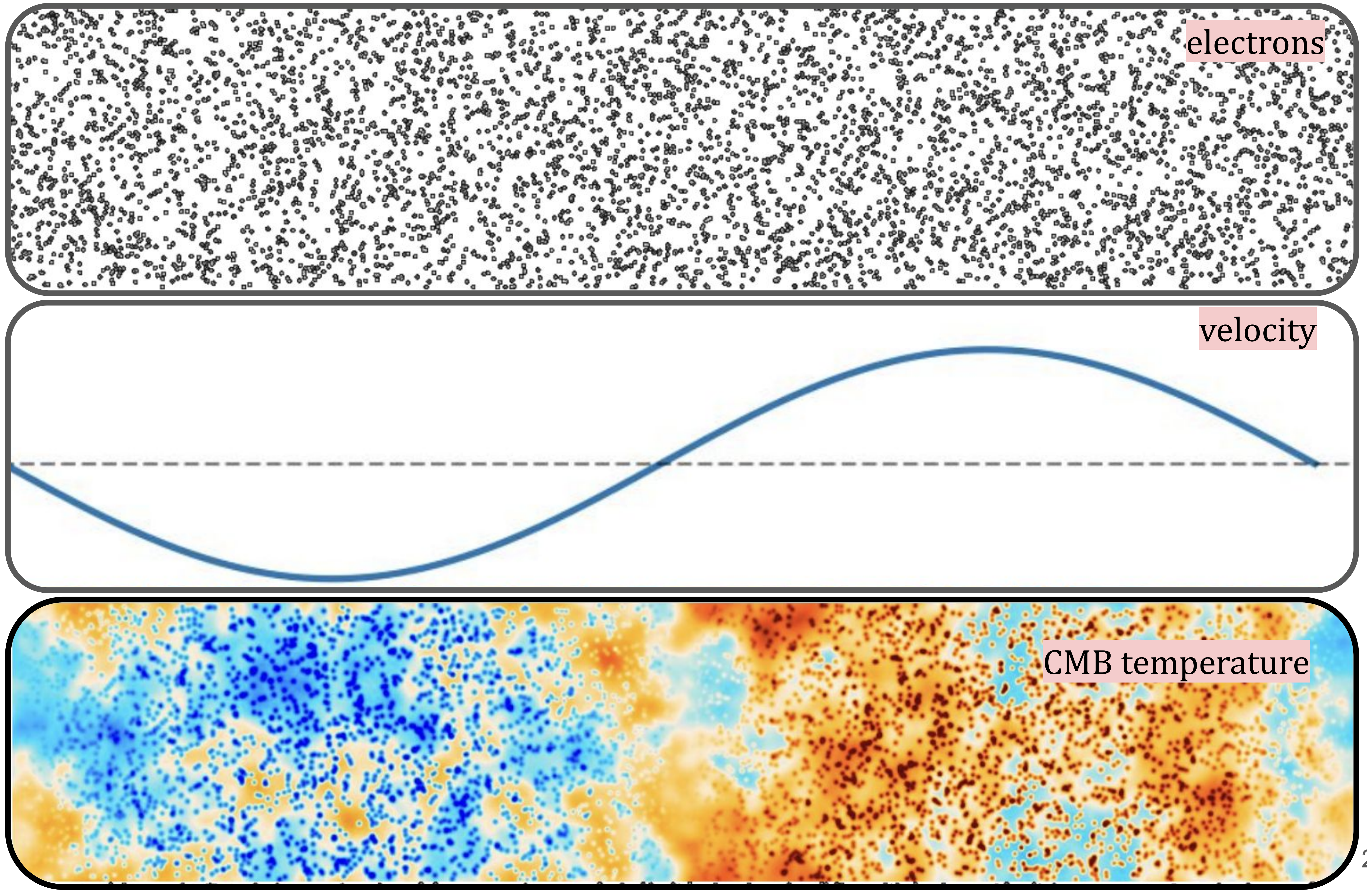

Figure curtesy: M. Madhavacheril

The kSZ quadratic estimator: Inputs 3-d galaxy field and 2-d CMB and outputs a 3-d reconstructed velocity field.

$$\hat{v}_r(\mathbf{k}_L) \propto \int_{\mathbf{k}_S+(\mathbf{l}/\chi_*)=\mathbf{k}_L} \frac{P_{ge}(l/\chi_*)}{P_{gg}^{\rm tot}(l/\chi_*)} \frac{1}{C_l^{\rm tot}} \left(\delta_g(\mathbf{k}_S) T_{\rm CMB}(\mathbf{l})\right)$$

Reconstructed velocity field (LHS) is evaluated at large scales ~0.01/Mpc, while RHS peaks on small scales (~1/Mpc)

Consider distribution of **free electrons**

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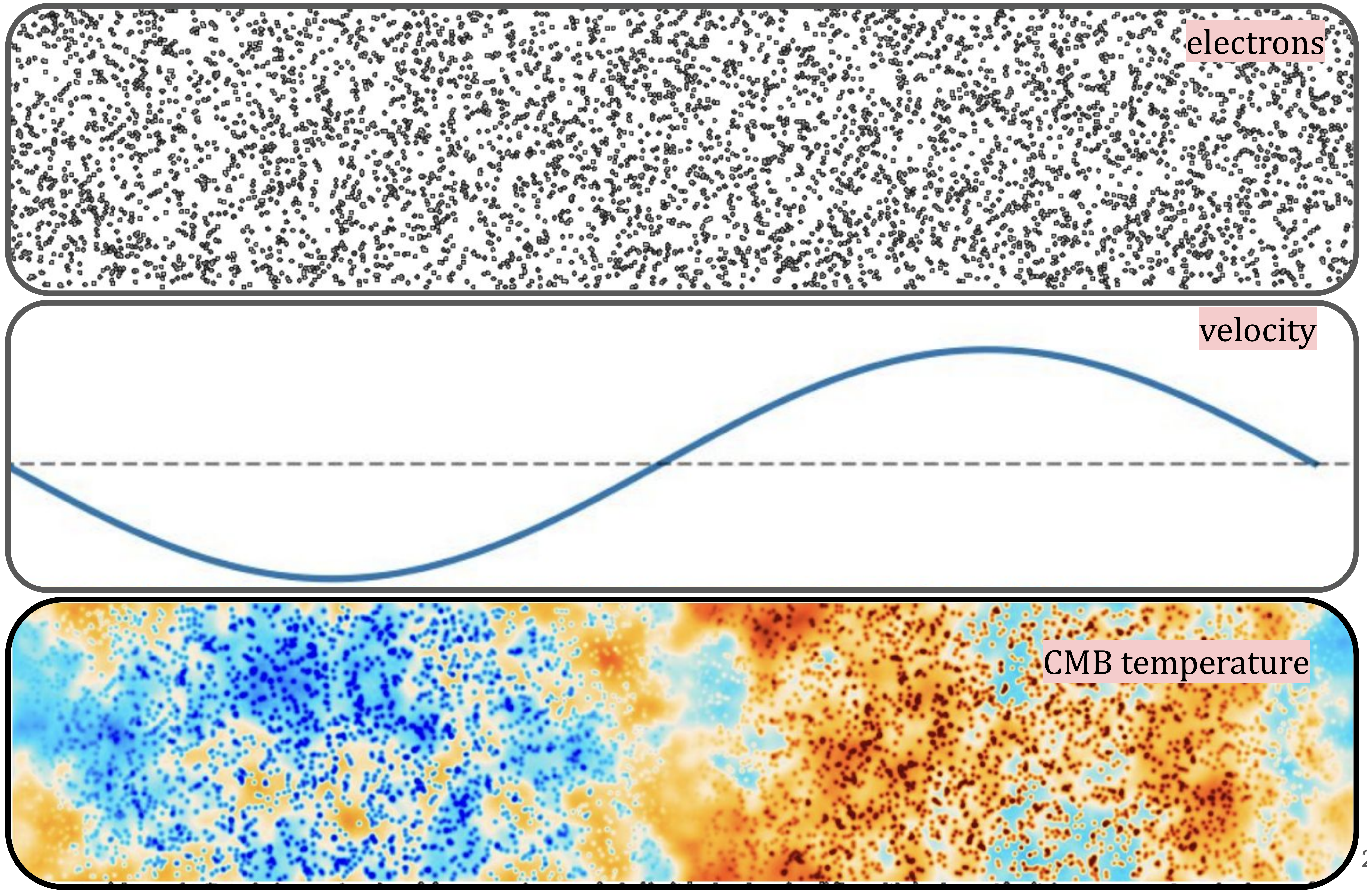
Primary CMB + kSZ



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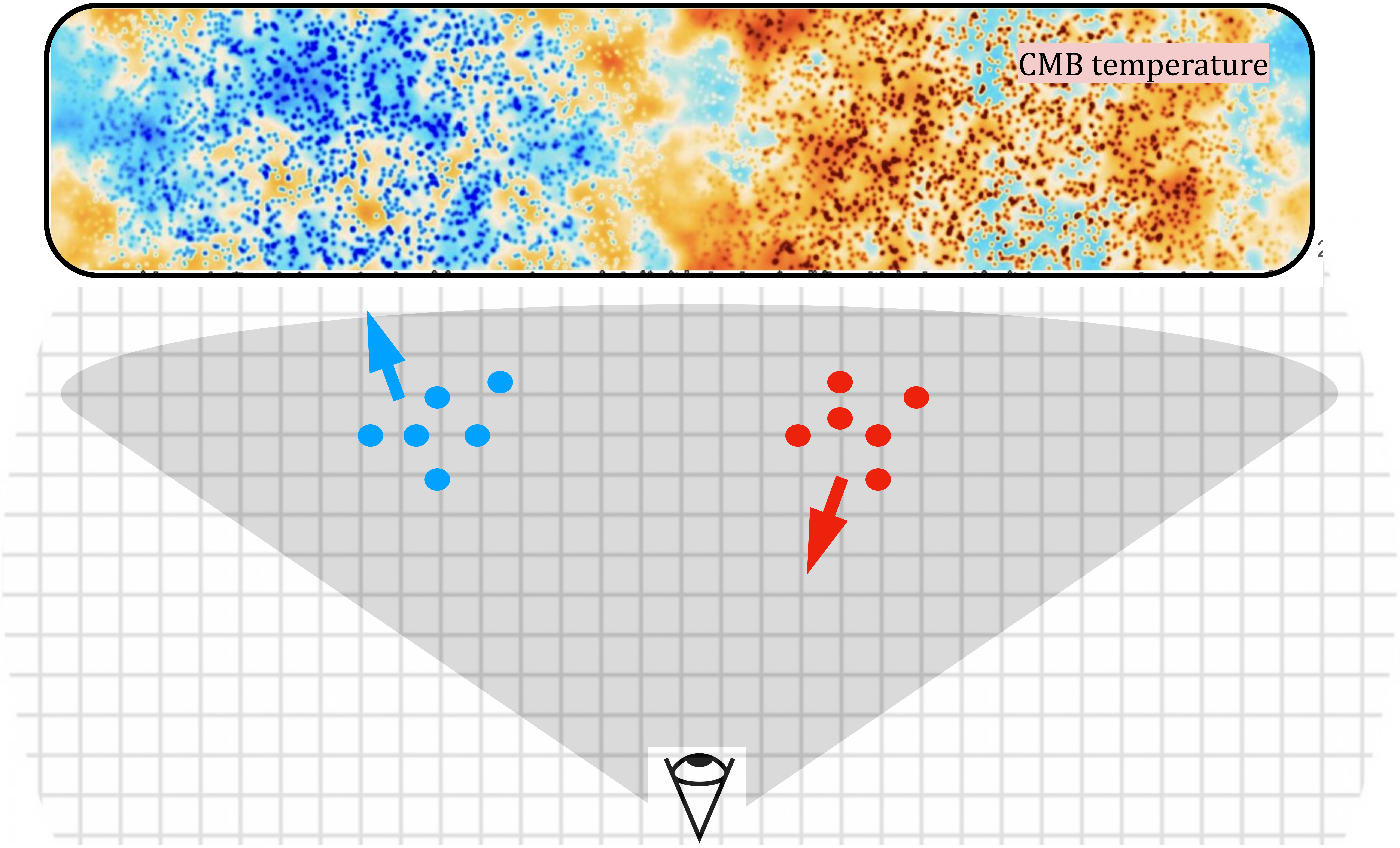
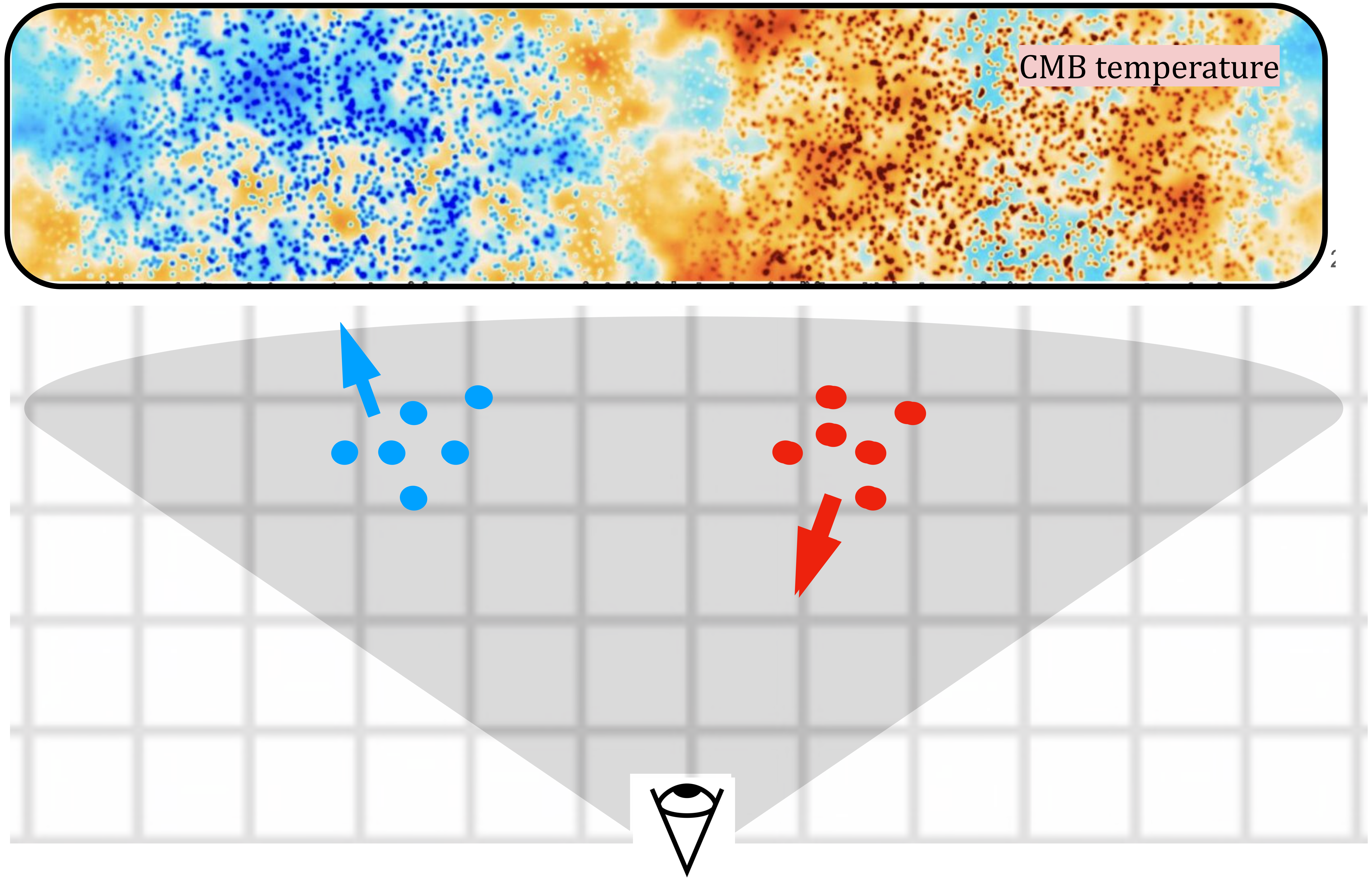
Primary CMB + kSZ



We can similarly see the estimated velocities in real space:

$$\hat{v}_r(\mathbf{x}) \propto \sum_{i \in \mathrm{gal}} \widetilde{T}(\boldsymbol{\theta}_i)\delta^3(\mathbf{x} - \mathbf{x}_i)$$

Primary CMB + kSZ

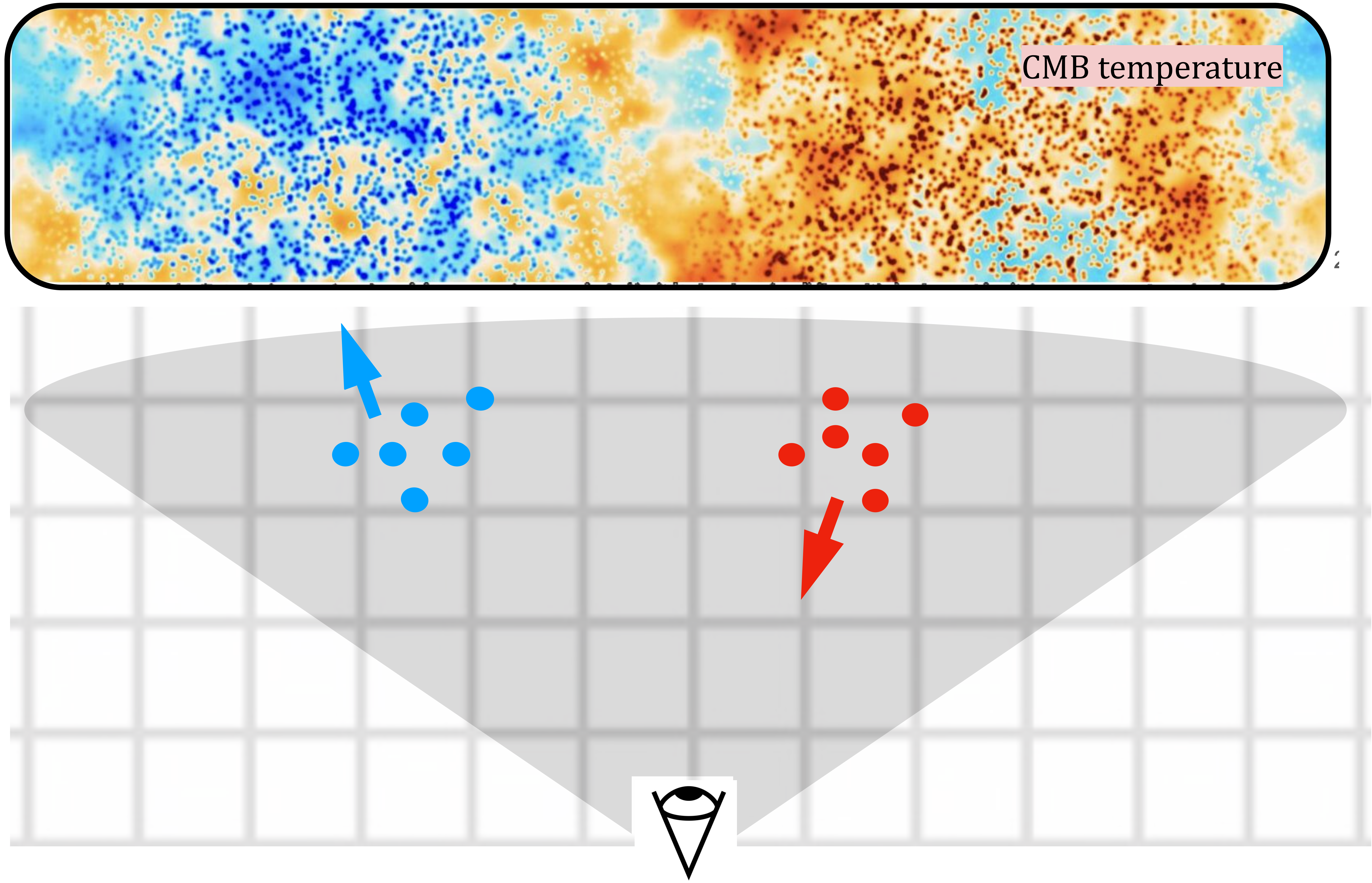


…where the indices run over galaxies and the CMB is *high-pass filtered* as below:

$$\hat{v}_r(\mathbf{x}) \propto \sum_{i \in \text{gal}} \widetilde{T}(\boldsymbol{\theta}_i)\delta^3(\mathbf{x} - \mathbf{x}_i)$$

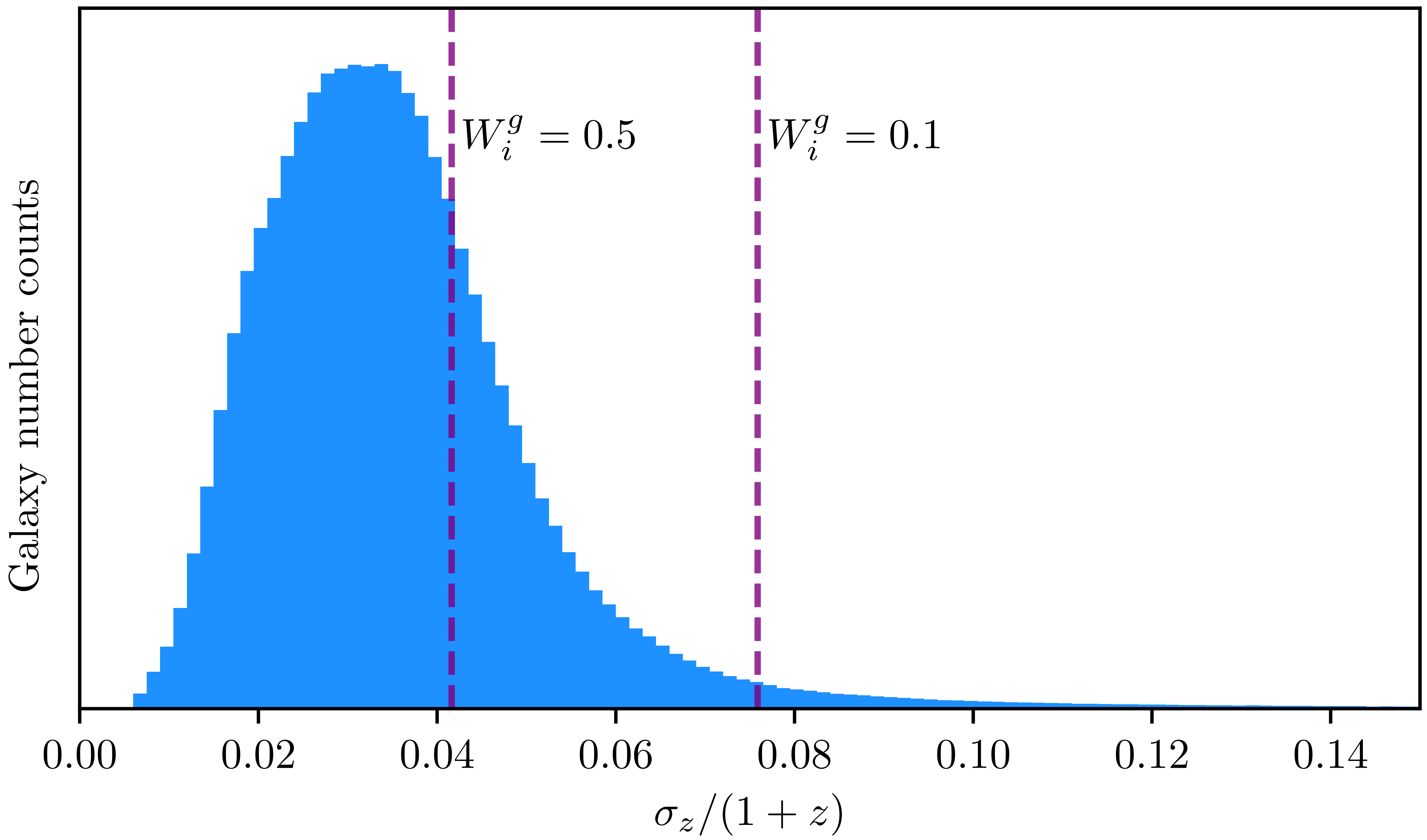
$$\widetilde{T}(\mathbf{l}) \equiv \frac{P_{ge}(l/\chi_*)}{P_{gg}(l/\chi_*)} \frac{1}{C_l^{\text{tot}}} T_{\text{CMB}}(\mathbf{l})$$

Primary CMB + kSZ



$$\hat{v}_r(\mathbf{x}) = \sum_{i \in \text{gal}} W_i^v \, \widetilde{T}(\boldsymbol{\theta}_i)\delta^3(\mathbf{x} - \mathbf{x}_i)$$

We define a *per-galaxy weight* function W_i^v that we will use to *down-weight* galaxies with large photo-z errors.



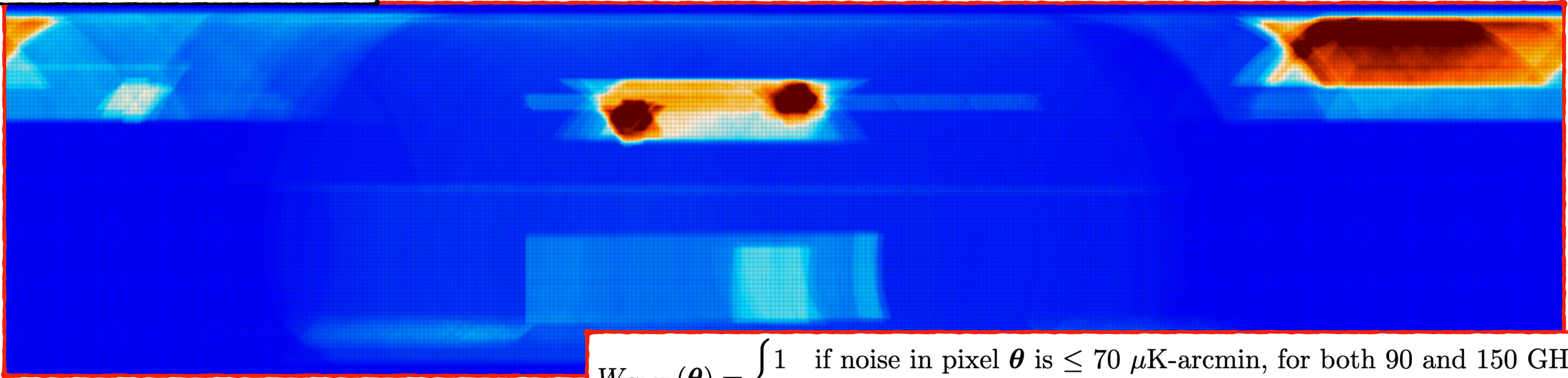
$$\hat{v}_r(\mathbf{x}) = \sum_{i \in \text{gal}} W_i^v \, \widetilde{T}(\boldsymbol{\theta}_i) \delta^3(\mathbf{x} - \mathbf{x}_i)$$

Mask out the galaxy.

0.7 sky-fraction galactic foreground mask from *Planck*

$$\hat{v}_r(\mathbf{x}) = \sum_{i \in \text{gal}} W_i^v \, \widetilde{T}(\boldsymbol{\theta}_i) \delta^3(\mathbf{x} - \mathbf{x}_i)$$

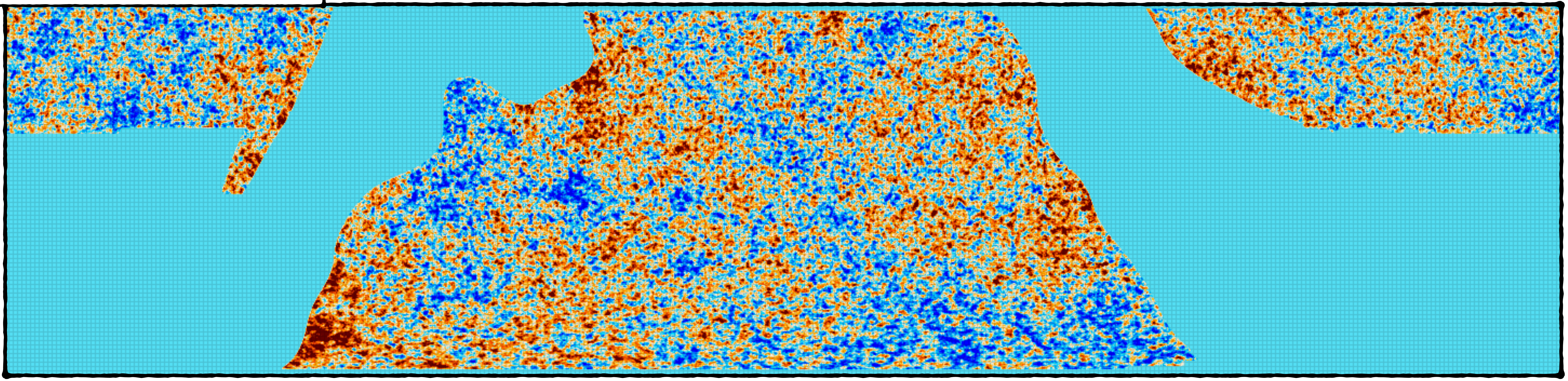
Mask out most noisy pixels.



$$W_{\text{CMB}}(\boldsymbol{\theta}) = \begin{cases} 1 & \text{if noise in pixel } \boldsymbol{\theta} \text{ is} \le 70 \ \mu\text{K-arcmin, for both 90 and 150 GHz} \\ 0 & \text{otherwise} \end{cases}$$

$$\hat{v}_r(\mathbf{x}) = \sum_{i \in \mathrm{gal}} W_i^v \, \widetilde{T}(\boldsymbol{\theta}_i) \delta^3(\mathbf{x} - \mathbf{x}_i)$$

Masked ACT DR5 map



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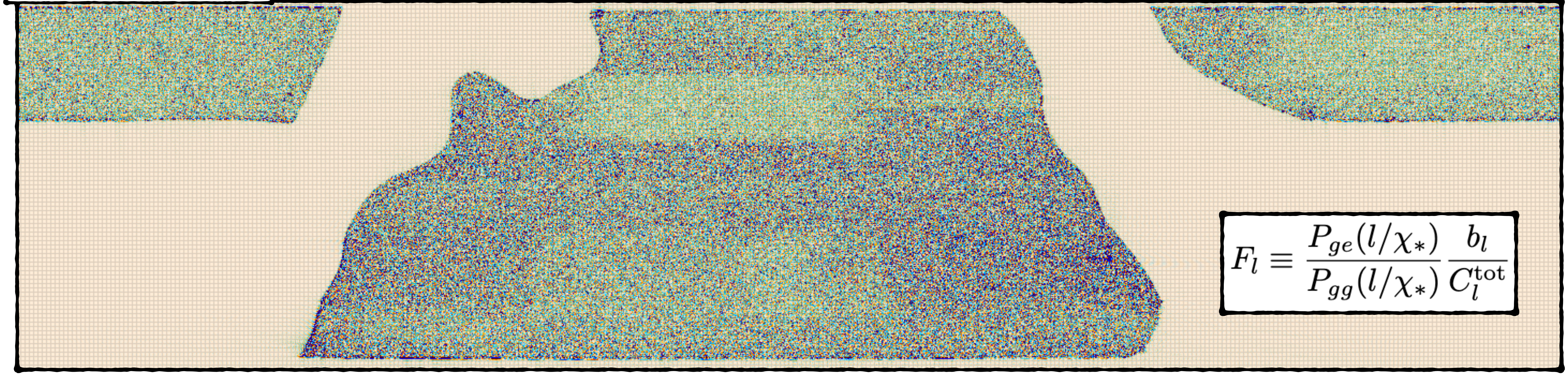
High-pass filtering



$$F_l \equiv \frac{P_{ge}(l/\chi_*)}{P_{gg}(l/\chi_*)} \frac{b_l}{C_l^{\mathrm{tot}}}$$

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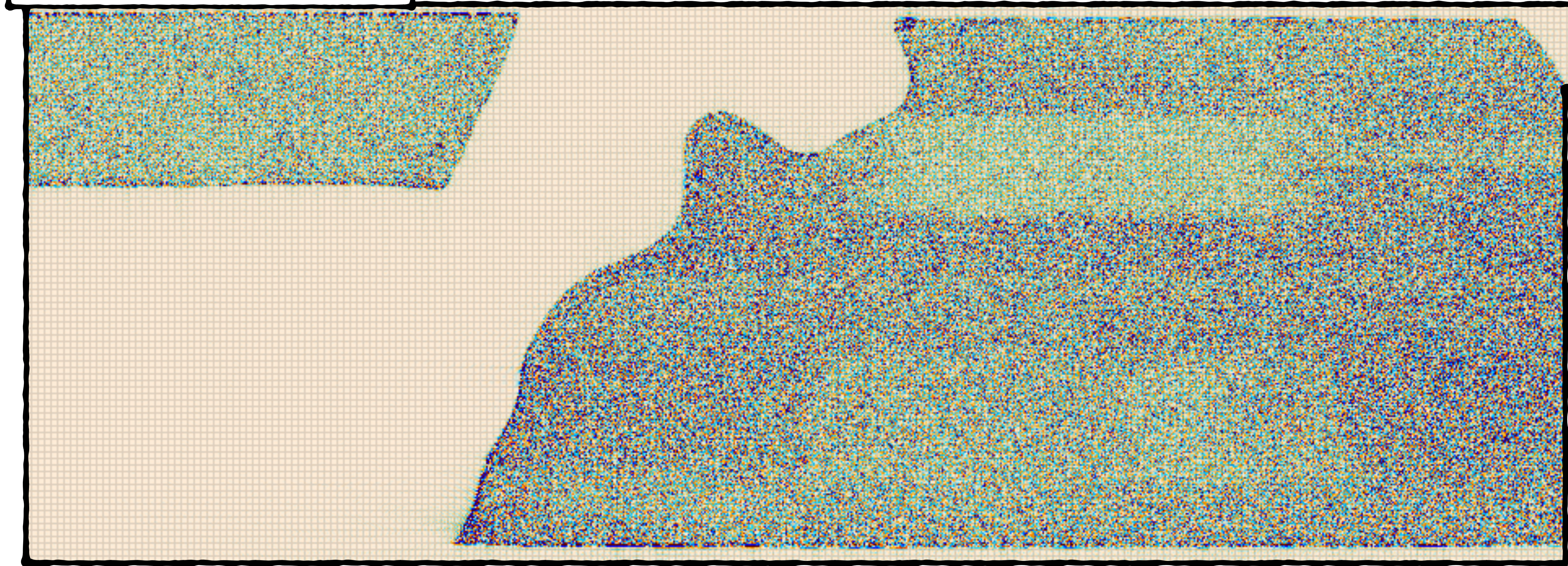

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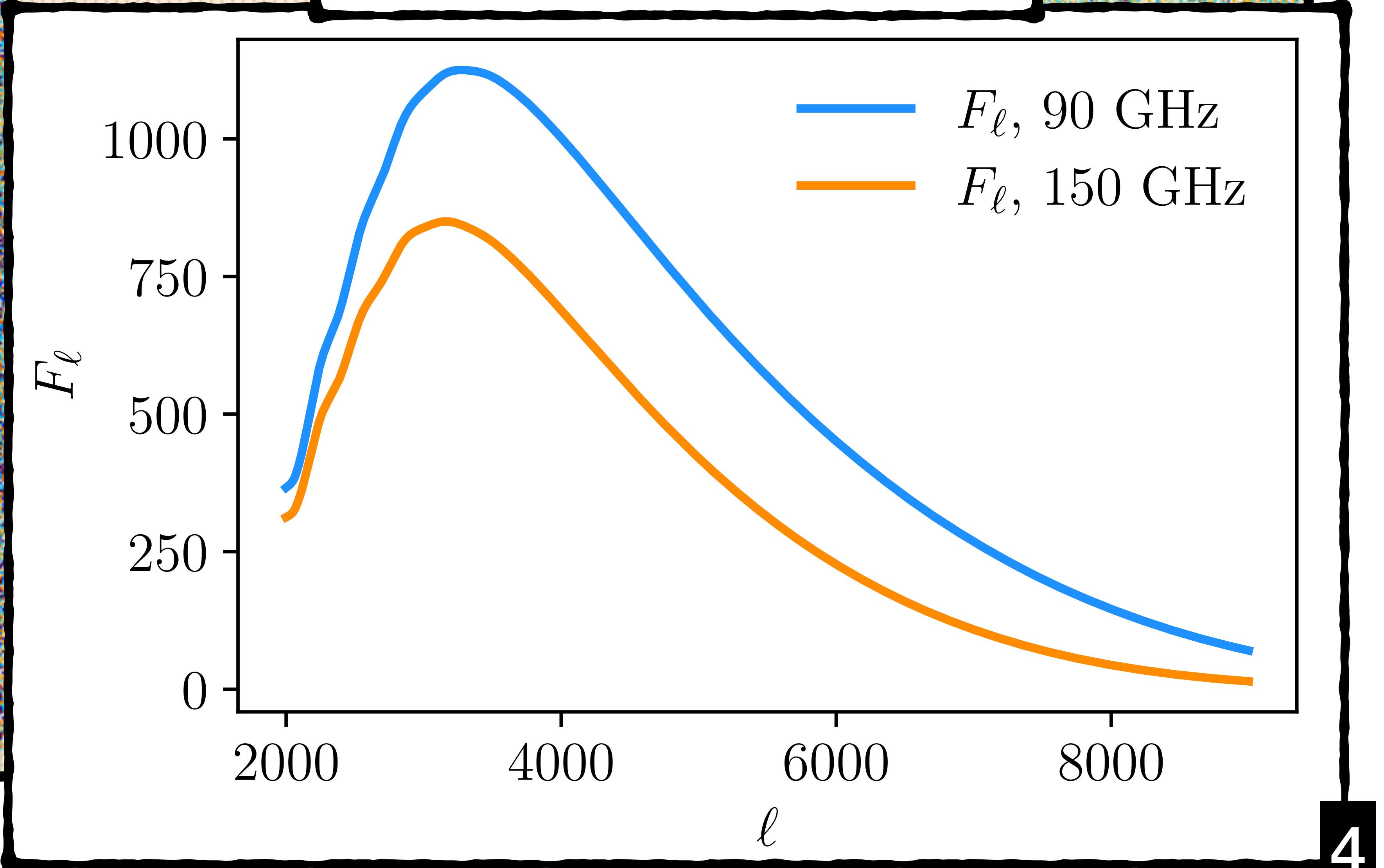

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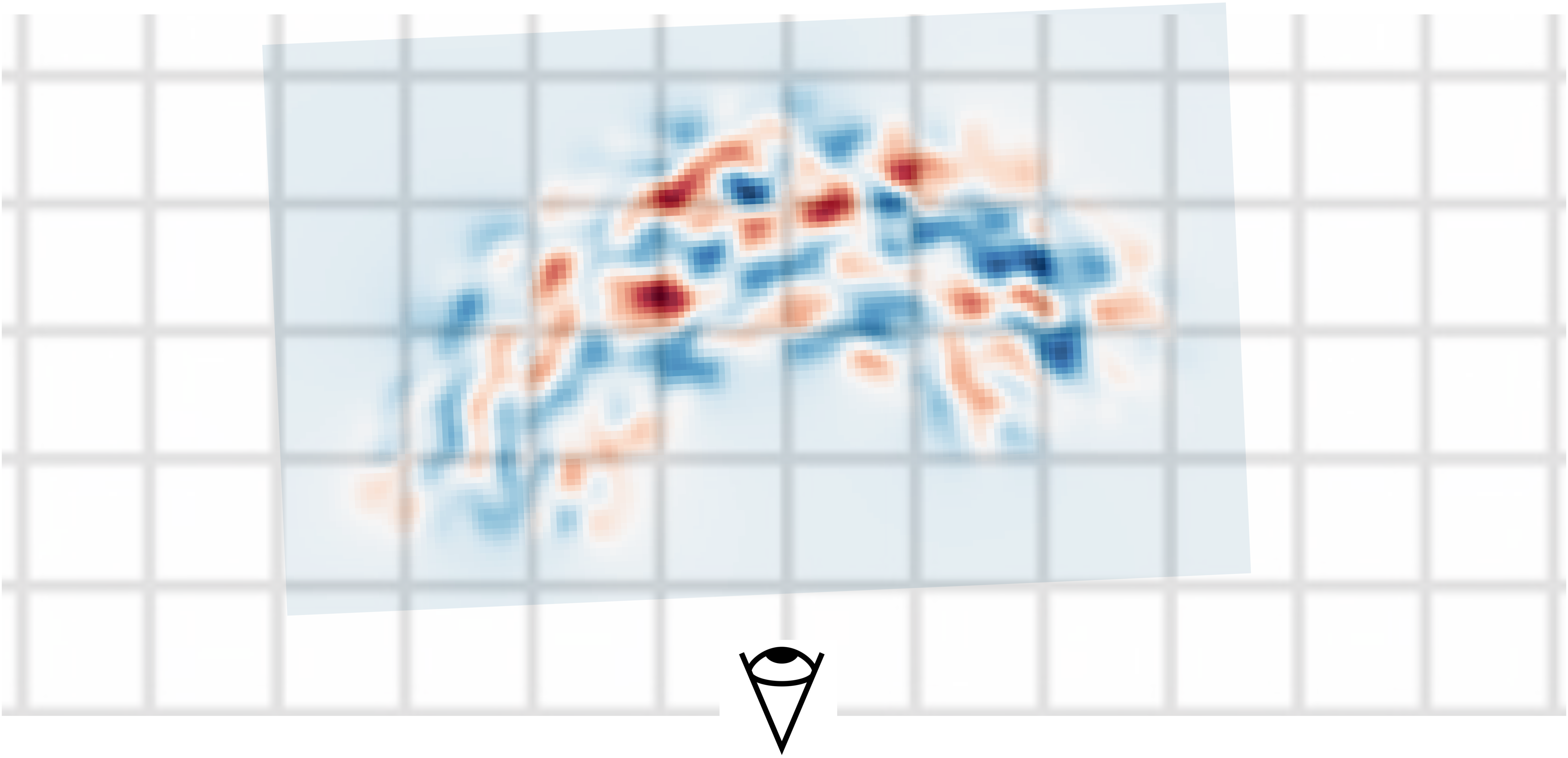

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The reconstructed velocity is a *biased* reconstruction of the *true* radial velocity field:

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mean reconstructed velocity = (bias terms) x (true velocity)

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The function $B(\mathbf{x})$ is a multiple of the CMB pixel mask and normalization that is set by the CMB high pass filter

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The b_v is the '*kSZ velocity bias*': An overall prefactor that is proportional to the ratio between the *true* and *fiducial* galaxy-electron power spectra.

For our purposes we currently consider parameter as a *nuisance* parameter, which we marginalize over.

However note it is in principle a measure of the *astrophysical baryonic feedback*.

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We define the 3-d large-scale galaxy density field using the '*galaxies-minus-randoms*' prescription.

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The velocity field in the '*dipolar*' power spectrum estimator is defined in terms of the reconstructed velocity:

$$\hat{v}_1(\mathbf{k}) \equiv \int_{\mathbf{x}} (i\hat{\mathbf{k}}_j \cdot \hat{\mathbf{x}}_j)\, \hat{v}_r(\mathbf{x})\, e^{-i\mathbf{k}\cdot\mathbf{x}}$$

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Here we will take a different approach: Convolving the model with the survey geometry using a ***new machinery***.

'Surrogate fields'

A '**surrogate field**' is a *random field* whose 2PCF matches to the same model.

We define the surrogate field as consisting of two terms: a signal term and a Poisson noise term:

$$S_g(\mathbf{x}) = S_g^{\text{sig}}(\mathbf{x}) + S_g^{\text{noise}}(\mathbf{x})$$

The *signal term*.

We simulate a Gaussian random field $\delta_G(\mathbf{k}, z)$ and *paint* it onto the randoms.

The *noise term*.

We add a Gaussian white noise with variance set to give the correct *Poisson galaxy power spectrum* at small scales:

$$S_v(\mathbf{x}) = S_v^{\text{sig}}(\mathbf{x}) + S_v^{\text{noise}}(\mathbf{x})$$

As before, we simulate the linear radial velocity and *paint* in onto randoms.

For the noise we use a *bootstrap procedure* based on real ACT maps.

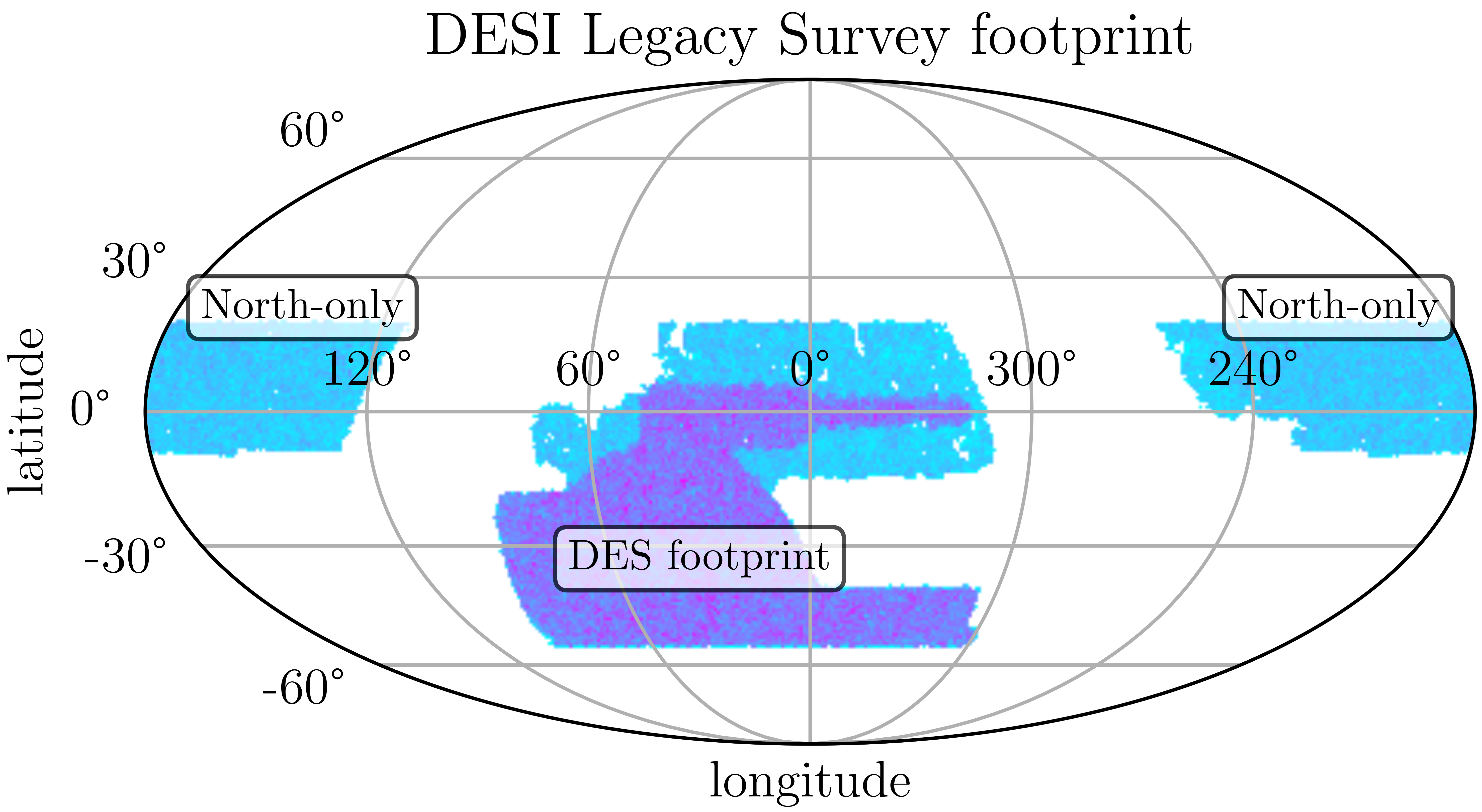
For each simulation we choose a random subset (of size galaxy survey) of the random catalog.

with Smith and Ferraro (to appear)

We use the LRG sample of DESI Legacy Imaging surveys DR9 after quality cuts. We use the "extended sample".

We restrict our analysis to the Galactic northern hemisphere in order to mitigate imaging systematics.

We find DES on the Galactic South patch lead to visible artifacts such as overdensities or color offsets, and result in systematic effects in our analysis.

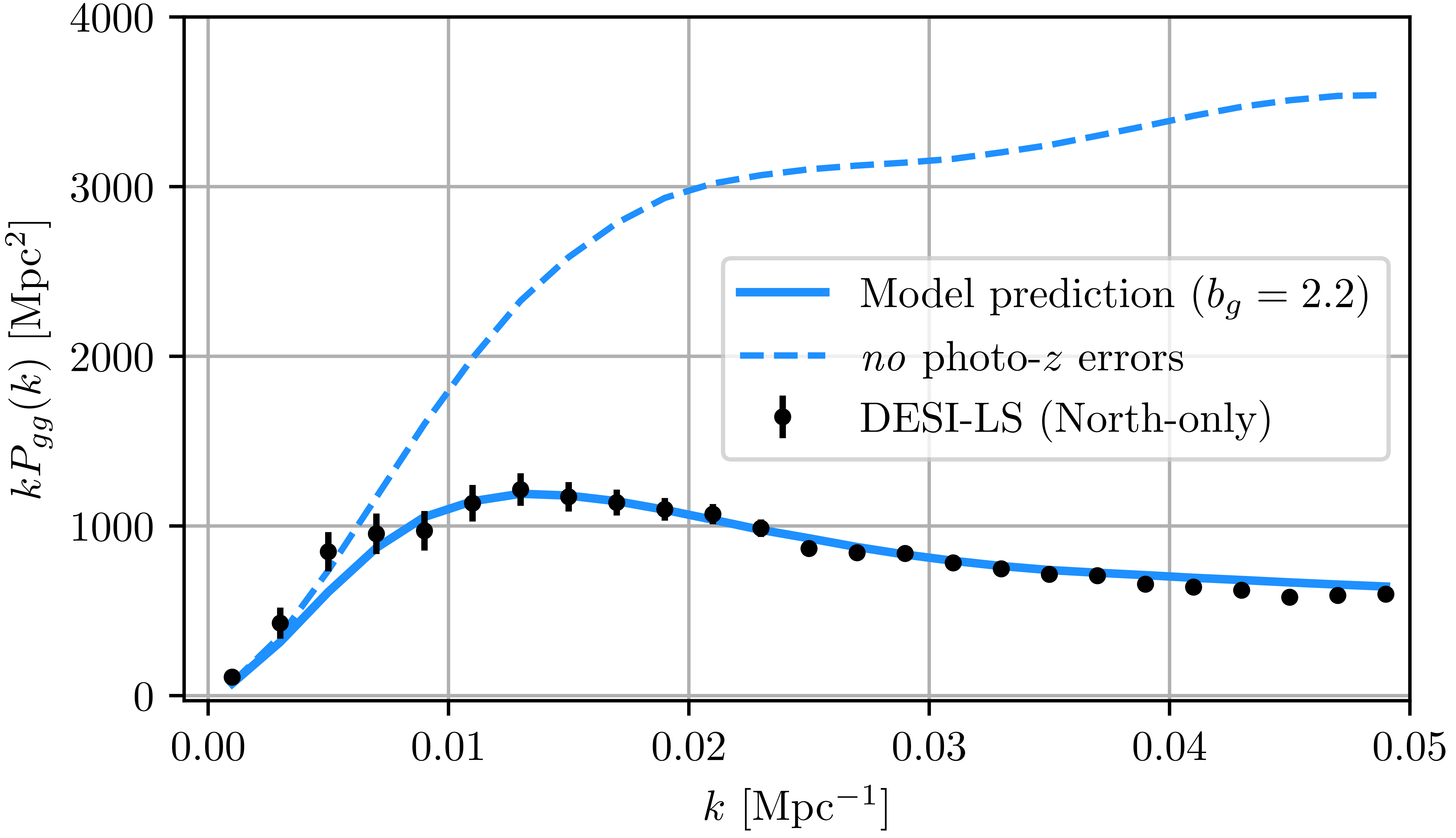


with Smith and Ferraro (to appear)

The galaxy power spectrum from DESILS-LRG Galactic North (black points).

Blue curves were computed by taking the mean power spectrum of simulated surrogates.

The dashed curve quantifies the impact of photometric redshift errors on the galaxy power spectrum



with Smith and Ferraro (to appear)

The dashed and dotted lines correspond to our model prediction with fNL = ±100

$$\text{SNR} = \begin{cases} 8.4 & \text{90 GHz only,} \\ 10.3 & \text{150 GHz only,} \\ 11.7 & \text{90+150 GHz joint analysis.} \end{cases}$$

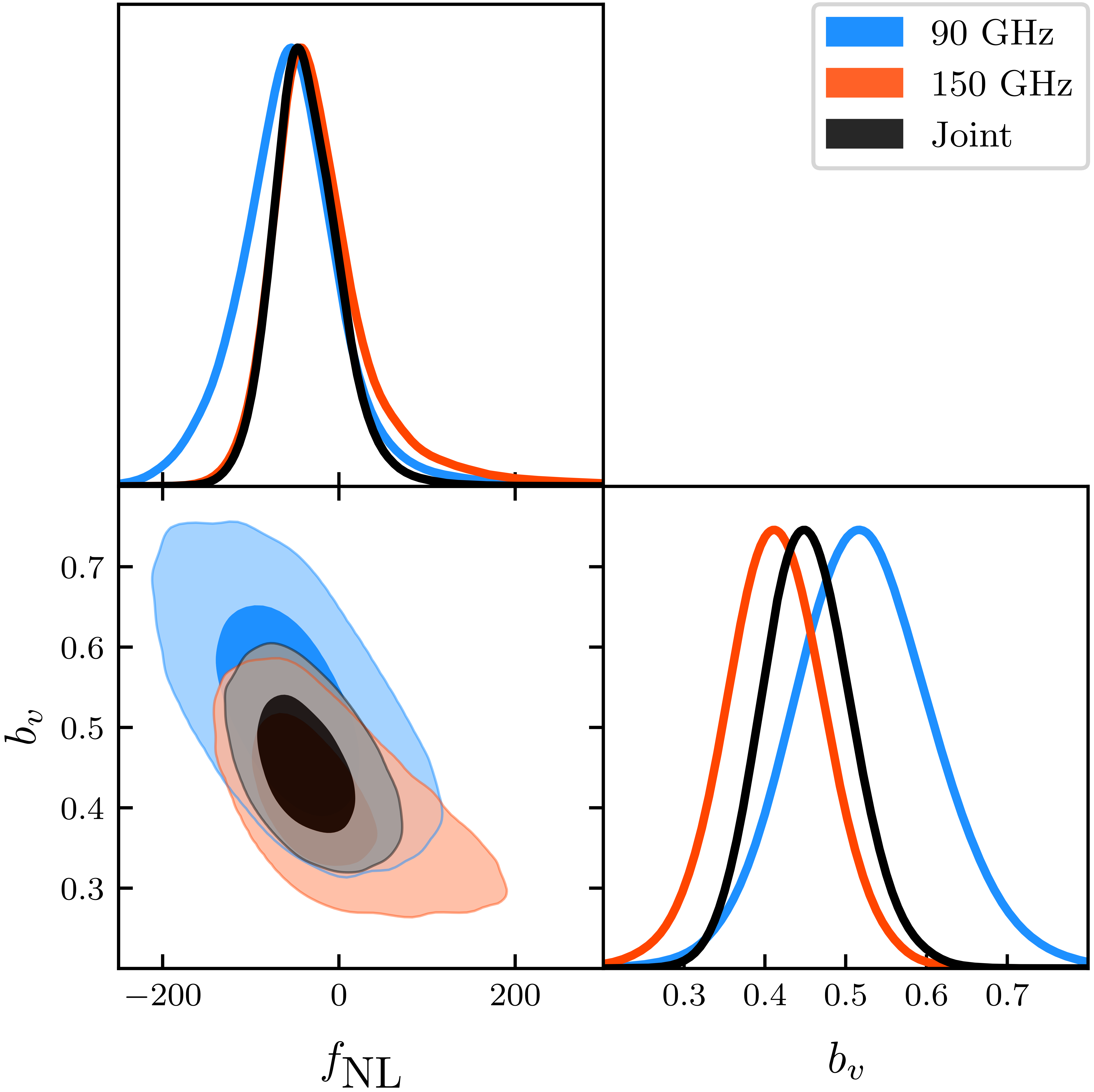
with Smith and Ferraro (to appear)

Results from our MCMC runs using DESI-LS 'North-only' patch and ACT DR5 *daynight* maps.

The black contour corresponds to our *joint* 90+150 analysis, where we include both 90 and 150 GHz bandpowers and their covariance.

$$b_v = \begin{cases} 0.52^{+0.09}_{-0.08} & \text{90 GHz only,} \\ 0.41^{+0.06}_{-0.06} & \text{150 GHz only,} \\ 0.45^{+0.06}_{-0.05} & \text{90+150 GHz joint analysis.} \end{cases}$$

$$f_{\rm NL} = \begin{cases} -55.4^{+52.9}_{-54.4} & \text{90 GHz only,} \\ -30.2^{+49.9}_{-39.5} & \text{150 GHz only,} \\ -39.3^{+40.2}_{-33.4} & \text{90+150 GHz joint analysis.} \end{cases}$$



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Conclusions

Our analysis is the first to use the *full three-dimensional* galaxy density field from photometric redshift data.

We achieve a signal-to-noise ratio of **11.7σ**, consistent with other kSZ analyses on similar datasets.

Our constraints on the **non-Gaussianity** parameter f_{NL} are the most precise to date from velocity tomography,

We also find the amplitude of the *galaxy-electron power spectrum* to be lower than halo model predictions.

Our measurements of pass multiple goodness-of-fit and null tests, including consistency between 90 and 150 GHz
(Feel free to ask me about this.)

This research introduces a reliable method for probing **fundamental physics**, such as models of the early universe and inflation paving the way for greater accuracy in cosmological studies.

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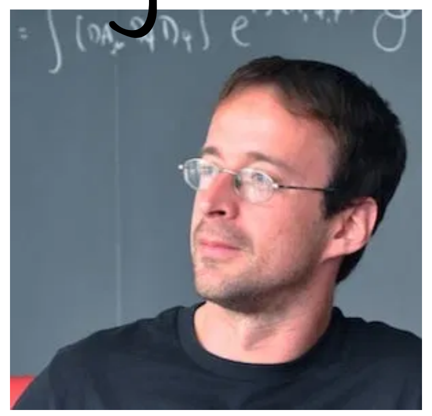
Many more projects ongoing with



and others

1. Small to large scales. 2. Hot gas to cold gas. 3. Galactic to intergalactic scales. 4. Diffuse to dense structures. 5. Past feedback processes to present-day observations.

Scientific Organization Committee

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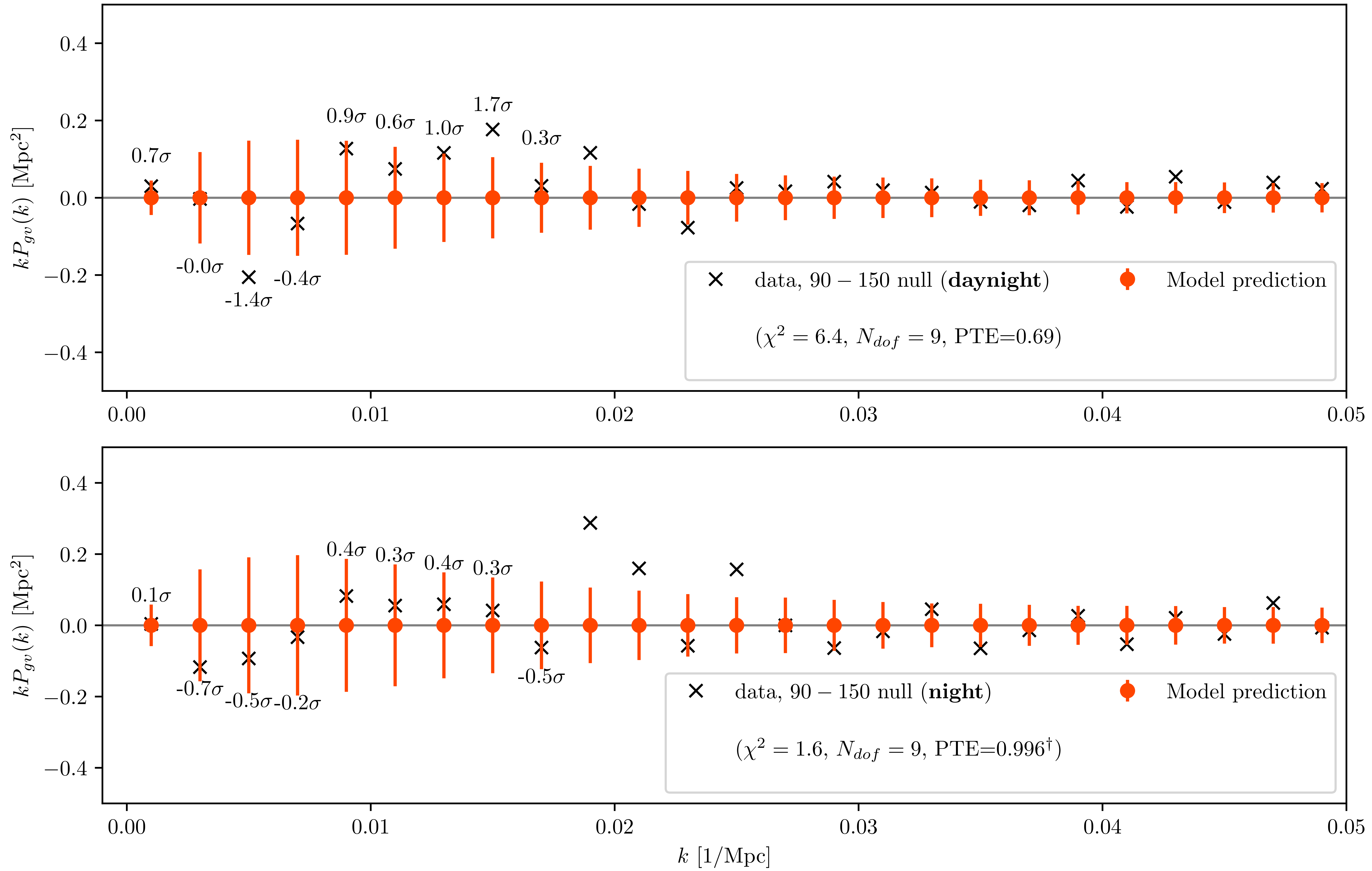
Extra slides

Since the kSZ signal has a black-body frequency dependence, the 'null' power spectra have zero contribution from kSZ, once we equalize the beams of the 90 and 150 GHz maps in our analysis



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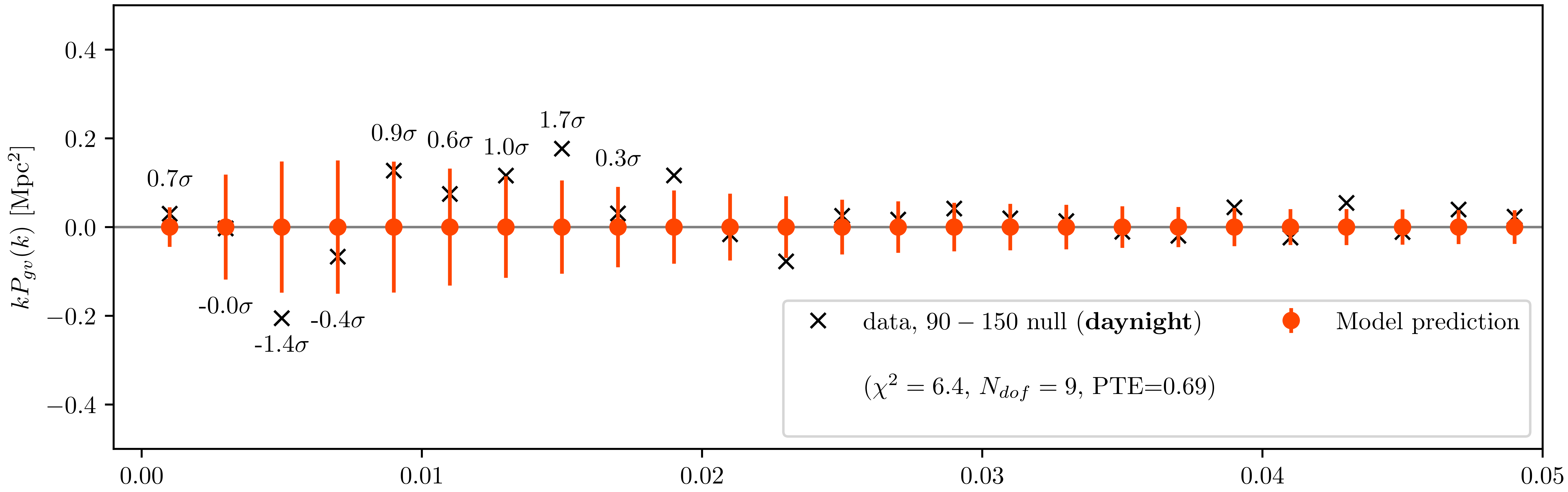
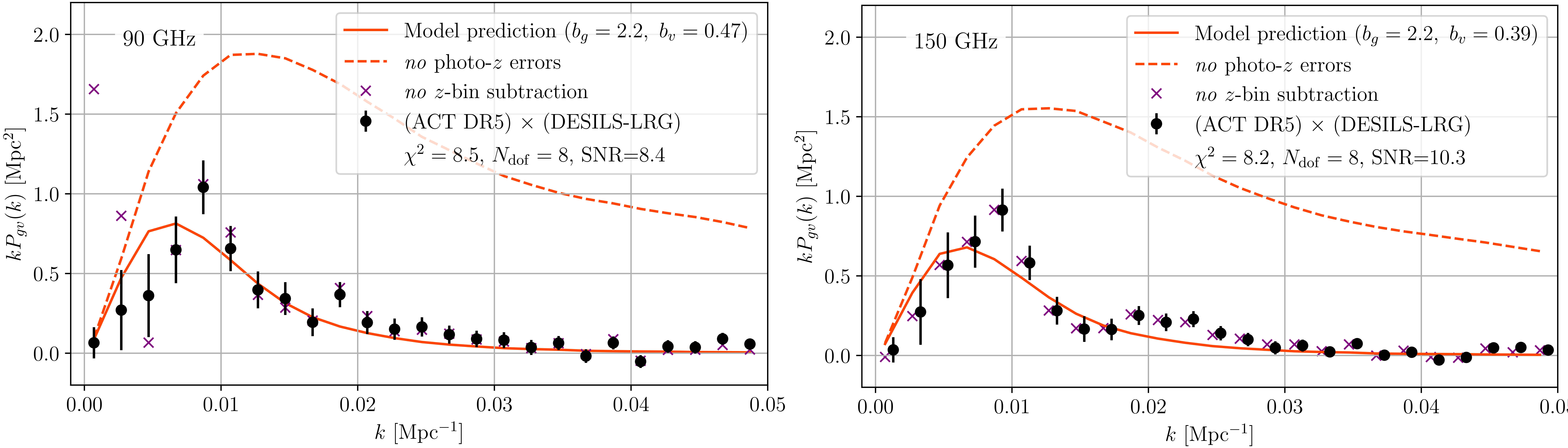


We define "mock" CMB maps obtained by rotating the daynight and night ACT CMB maps by 4 degrees north in declination. The corresponding joint region matches our baseline and we find the CMB-galaxy correlation to vanish while the galaxy auto-power spectrum remains the same.

CMB	Test Description	PTE (daynight)	PTE (night)
90	DESI-LS & mock CMB	0.67	0.85
150	DESI-LS & mock CMB	0.35	0.26
150 − 90	DESI-LS & mock CMB	0.53	0.22
Joint	DESI-LS & mock CMB	0.59	0.91

Galaxy-velocity cross-power spectra using the 90 GHz and 150 GHz CMB maps from ACT DR5 and the DESI Legacy Survey (black points with error bars).



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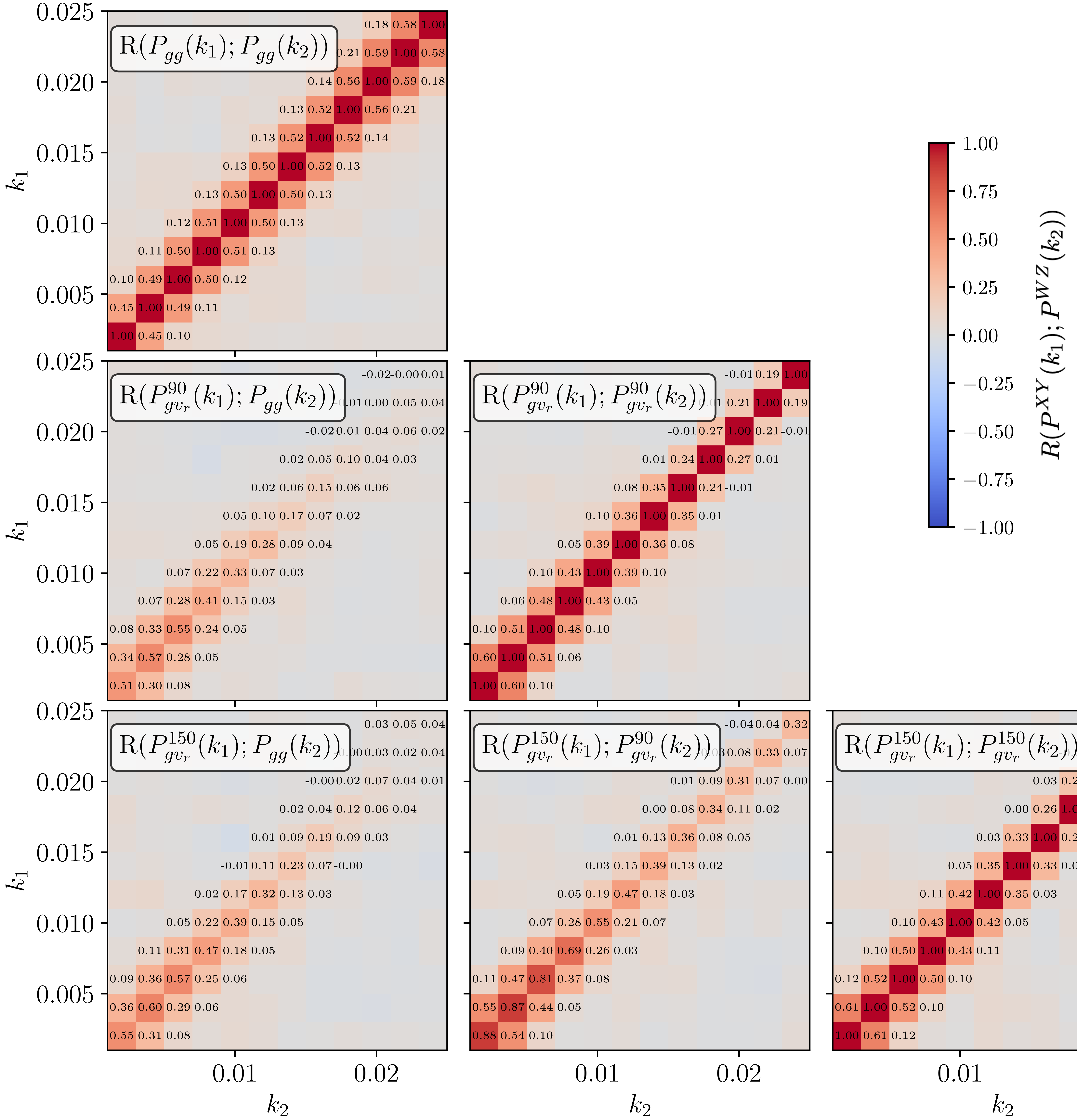

R($P_{gg}(k_1)$; $P_{gg}(k_2)$)
R($P^{90}_{gv_r}(k_1)$; $P_{gg}(k_2)$)
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k_1
k_2
$R(P^{XY}(k_1); P^{WZ}(k_2))$

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The reconstructed velocity is a <u>*biased*</u> reconstruction of the *true* radial velocity field:

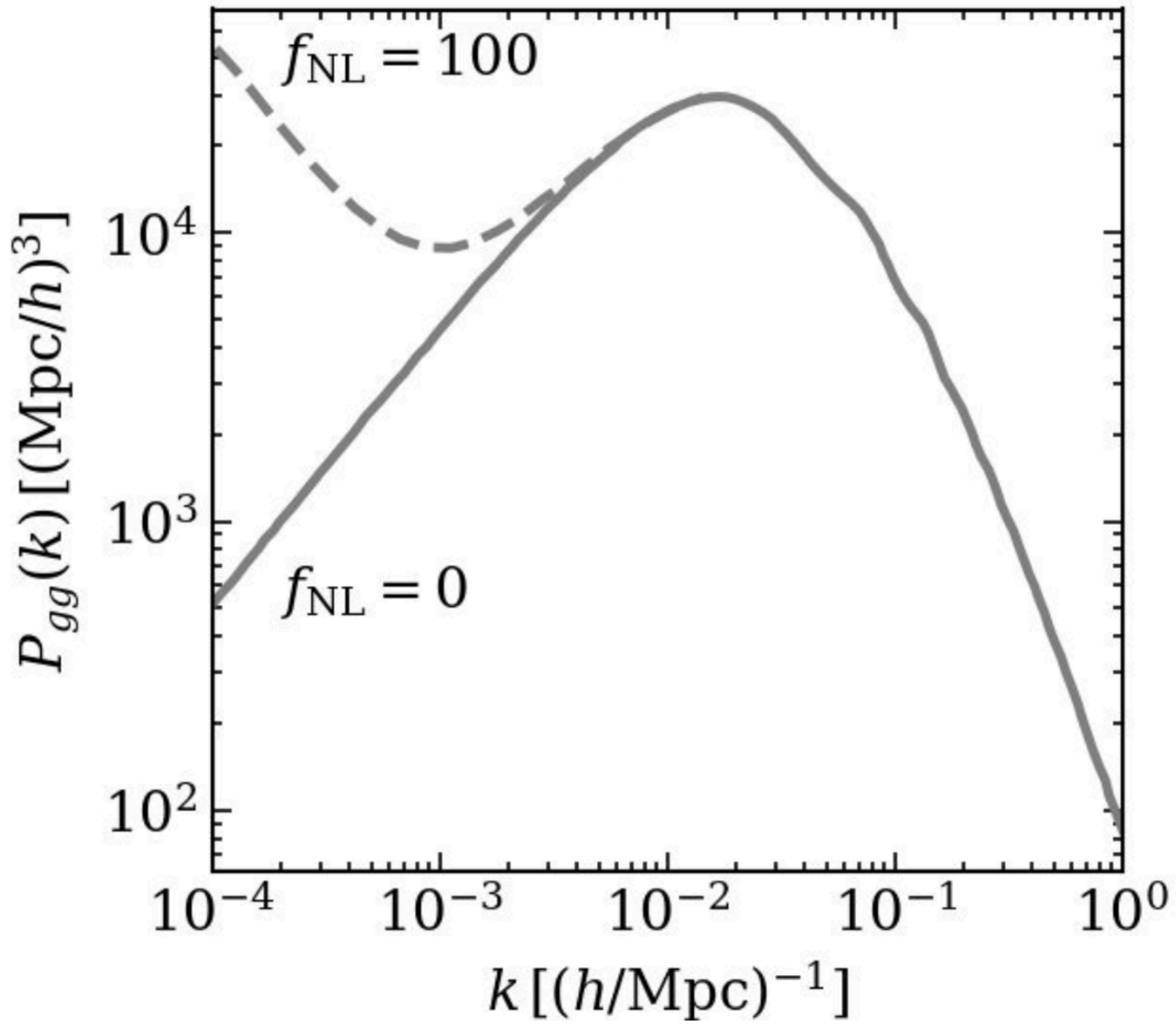
$$\langle \hat{v}_r(\mathbf{x}) \rangle = b_v \, \bar{n}_v(\mathbf{x}) \, B(\mathbf{x}) \, v_r^{\mathrm{true}}(\mathbf{x})$$

$$b_v(\chi) = \frac{\int (d^2\mathbf{L}/(2\pi)^2)) \, b_L F_L P_{ge}^{\mathrm{true}}(k, \chi)_{k=L/\chi}}{\int (d^2\mathbf{L}/(2\pi)^2)) \, b_L F_L P_{ge}^{\mathrm{fid}}(k, \chi)_{k=L/\chi}}$$

Surrogate fields, part 1: galaxy field

$$\rho_g(\mathbf{k}, z) = \bar{n}_g(z)\big[1 + \delta_G(\mathbf{k}, z)\big] + (\text{Poisson noise})$$

$$\delta_G(\mathbf{k}, z) \equiv \left(b_g(z) + f_{\rm NL} \frac{2\delta_c(b_g(z)-1)}{\alpha(k,z)} \right) \delta_{\rm lin}(\mathbf{k}, z)$$

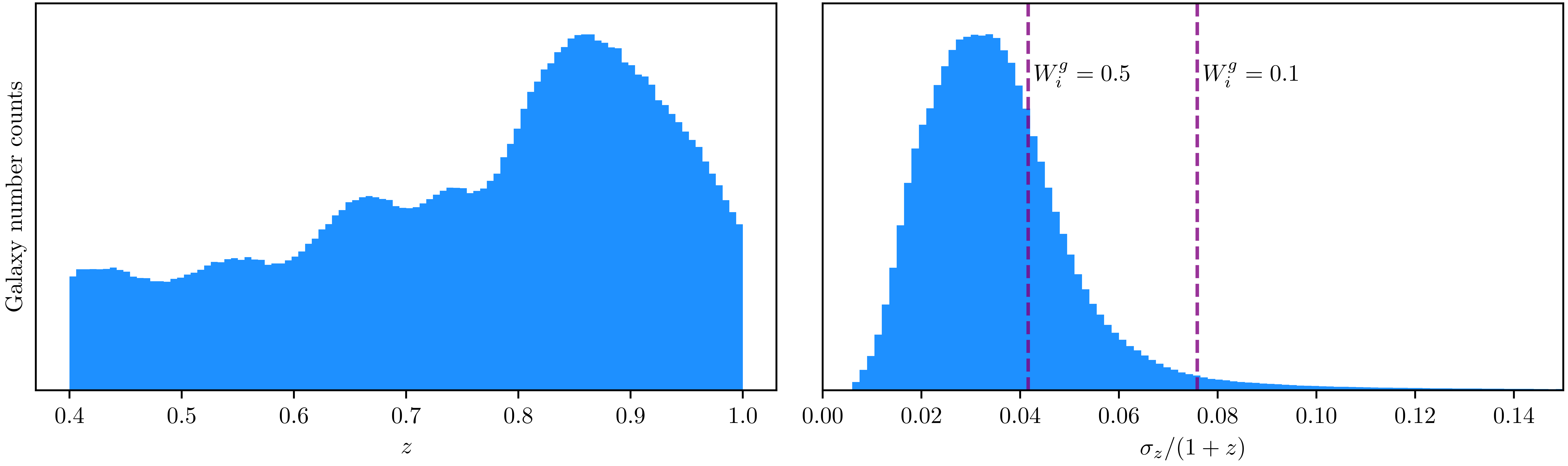


3. DESI-LS LRGs & ACT DR5 analysis

We choose an identical weighting for galaxy and reconstructed velocity.

This down-weights the galaxies with large photo-z errors compared to the correlation length of the velocity field.

$$W_i^g = W_i^v = \exp\left(-\frac{\sigma(z_i)^2}{\alpha(1+z_i)^2}\right) \qquad \text{where } \alpha = 0.0025$$

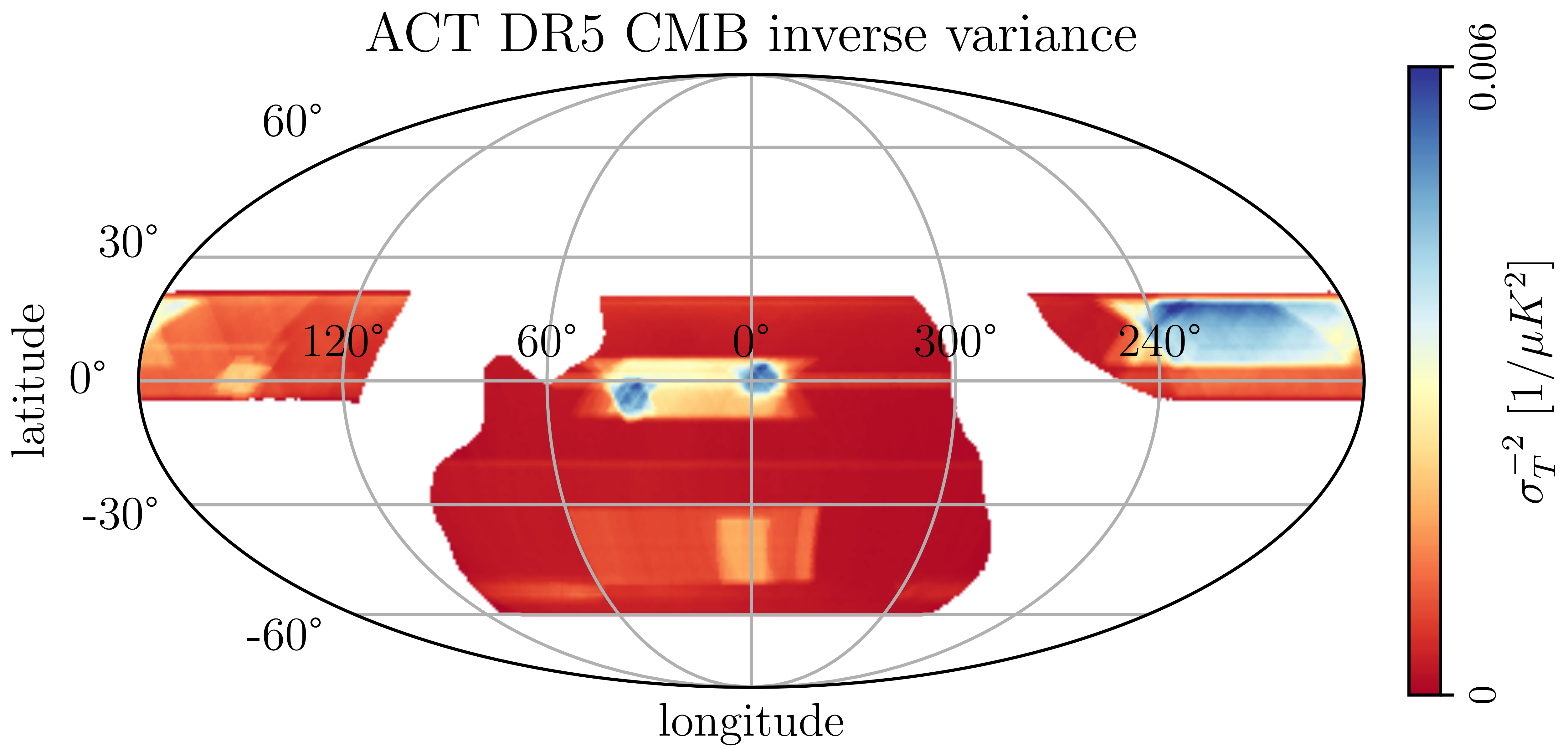


3. DESI-LS LRGs & ACT DR5 analysis

We mask out high-noise CMB regions and apply 0.7 sky-fraction galactic foreground mask from *Planck*.

$$W^{90}_{\rm CMB}(\boldsymbol{\theta}) = W^{150}_{\rm CMB}(\boldsymbol{\theta})$$

$$W_{\rm CMB}(\boldsymbol{\theta}) = \begin{cases} 1 & \text{if noise in pixel } \boldsymbol{\theta} \text{ is} \leq 70\ \mu\text{K-arcmin, for both 90 and 150 GHz} \\ 0 & \text{otherwise} \end{cases}$$



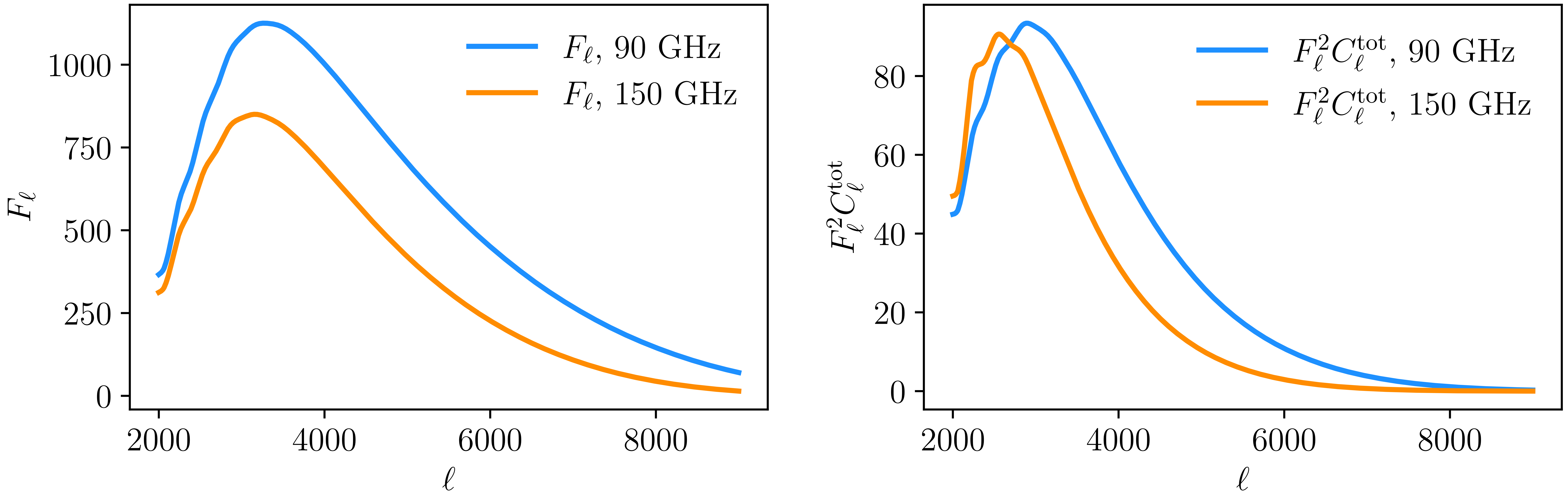
3. DESI-LS LRGs & ACT DR5 analysis

We *match* the 90 and 150 GHz filters by applying to the same beam and weights to 150 GHz ACT maps.

This looses some SNR but simplifies the analysis:

The reconstruction biases b_v are equal & difference between 90 and 150 GHz velocity maps are kSZ-free.

$$F_l^{90} = \frac{P_{ge}(l/\chi_*)}{P_{gg}(l/\chi_*)} \frac{b_l^{90}}{C_l^{\rm tot}} \qquad F_l^{150} = \frac{b_l^{90}}{b_l^{150}} F_l^{90}$$



Surrogate fields, part 1: galaxy field

$$\rho_g(\mathbf{k}, z) = \bar{n}_g(z)\big[1 + \delta_G(\mathbf{k}, z)\big] + (\text{Poisson noise})$$

We define the surrogate field as consisting of two terms: a signal term and a Poisson noise term:

$$S_g(\mathbf{x}) = S_g^{\text{sig}}(\mathbf{x}) + S_g^{\text{noise}}(\mathbf{x})$$

The *noise term*.

We add a Gaussian white noise with variance set to give the correct *Poisson galaxy power spectrum* at small scales:

$$S_g^{\text{noise}}(\mathbf{x}) = \frac{N_g}{N_r} \sum_{j \in \text{rand}} W_j^g \, \eta_j \, \delta^3(\mathbf{x} - \mathbf{x}_j)$$

$$\langle \eta_j^2 \rangle = \frac{N_r}{N_g} - \langle \delta_G(z_j)^2 \rangle$$

Surrogate fields, part 1: velocity field

$$\hat{v}_r(\mathbf{x}) = b_v\,\bar{n}_v(\mathbf{x})\,B(\mathbf{x})\,v_r^{\text{true}}(\mathbf{x}) + (\text{kSZ reconstruction noise})$$

We define the velocity surrogate field consisting of a *signal* and a *noise* term similarly:

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For the noise we use a ***bootstrap procedure*** based on real ACT maps.

For each simulation we choose a random subset (size N_g) of the random catalog.

$$S_v^{\text{noise}}(\mathbf{x}) \equiv \sum_{j\in\text{rand}} M_j\,W_j^v\,\widetilde{T}(\boldsymbol{\theta}_j)\delta^3(\mathbf{x}-\mathbf{x}_j)$$

$$\hat{v}_r(\mathbf{x}) = \sum_{i \in \text{gal}} W_i^v \, \widetilde{T}(\boldsymbol{\theta}_i) \delta^3(\mathbf{x} - \mathbf{x}_i)$$

The reconstructed velocity is a *biased* reconstruction of the *true* radial velocity field:

$$\langle \hat{v}_r(\mathbf{x}) \rangle = b_v \, \bar{n}_v(\mathbf{x}) \, B(\mathbf{x}) \, v_r^{\text{true}}(\mathbf{x})$$

$$n_v(\mathbf{x}) \equiv \left\langle \sum_i W_i^v \delta^3(\mathbf{x} - \mathbf{x}_i) \right\rangle$$

This is the 3-d galaxy *number density* including the weighting.

The function $B(\mathbf{x})$ is a multiple of the CMB pixel mask and normalization that is set by the CMB high pass filter

Our aim in this program is to measure the *galaxy-velocity correlation*, and compare it to our models.

$$\widehat{P}_{gv}(k) \equiv \frac{1}{\mathcal{N}_{gv}} \int \frac{d\Omega_k}{4\pi} \, \rho_g^*(\mathbf{k}) \, \hat{v}_1(\mathbf{k})$$

Note this is an *imperfect* relation since the normalization will generally depend on k subject to the *survey geometry*.

..more on this in a moment.

We define the 3-d large-scale galaxy density field using the '*galaxies-minus-randoms*' prescription:

$\rho_g(\mathbf{x}) \equiv$ *galaxies* *minus* *randoms*

$$\left(\sum_{i \in \mathrm{gal}} W_i^g \, \delta^3(\mathbf{x} - \mathbf{x}_i) \right) \qquad - \frac{N_g}{N_r} \left(\sum_{j \in \mathrm{rand}} W_j^g \, \delta^3(\mathbf{x} - \mathbf{x}_j) \right)$$

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$$S_g(\mathbf{x}) = S_g^{\text{sig}}(\mathbf{x}) + S_g^{\text{noise}}(\mathbf{x})$$

The *signal term.*

We simulate a Gaussian random field $\delta_G(\mathbf{k}, z)$ and *paint* it onto the randoms:

$$S_g^{\text{sig}}(\mathbf{x}) \equiv \frac{N_g}{N_r} \sum_{j \in \text{rand}} W_j^g \, \delta_G(\mathbf{x}_j) \, \delta^3(\mathbf{x} - \mathbf{x}_j)$$

Surrogate fields, part 1: velocity field

$$\hat{v}_r(\mathbf{x}) = b_v\, \bar{n}_v(\mathbf{x})\, B(\mathbf{x})\, v_r^{\rm true}(\mathbf{x}) + (\text{kSZ reconstruction noise})$$

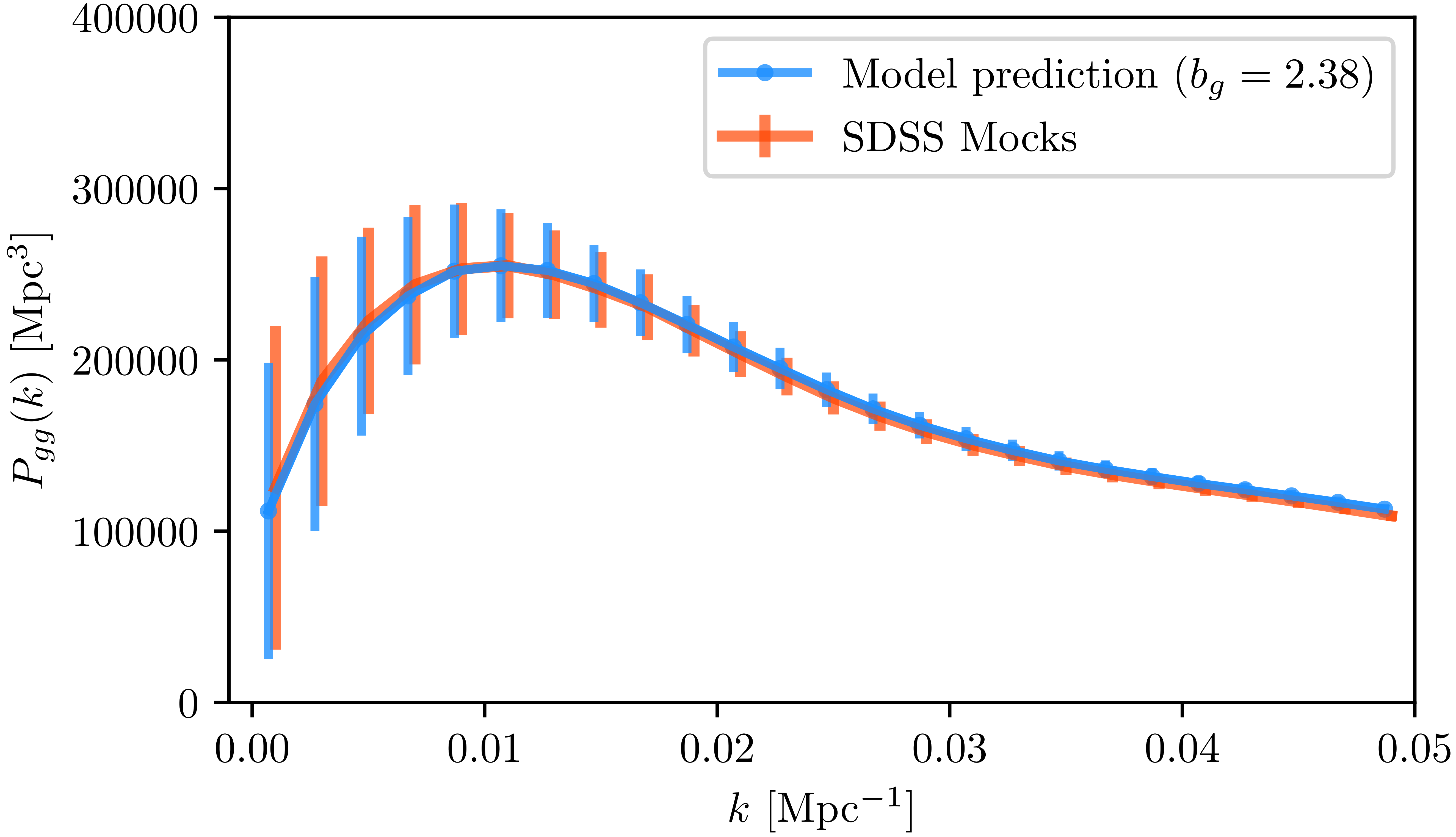
We define the velocity surrogate field consisting of a *signal* and a *noise* term similarly:

$$S_v(\mathbf{x}) = S_v^{\rm sig}(\mathbf{x}) + S_v^{\rm noise}(\mathbf{x})$$

As before, we simulate the linear radial velocity and *paint* in onto randoms:

$$S_v^{\rm sig}(\mathbf{x}) \equiv \frac{N_g}{N_r} \sum_{j \in \rm rand} W_j^v\, B(\mathbf{x}_j)\, v_r^{\rm sim}(\mathbf{x}_j)\, \delta^3(\mathbf{x} - \mathbf{x}_j)$$

Surrogates accurately approximate both the diagonal and off-diagonal power spectrum covariance on large scales. We use 1000 SDSS BOSS DR12 mocks galaxy samples and compare it with mean and variance of power spectra from 1500 surrogate simulations.



with Smith and Ferraro (to appear)

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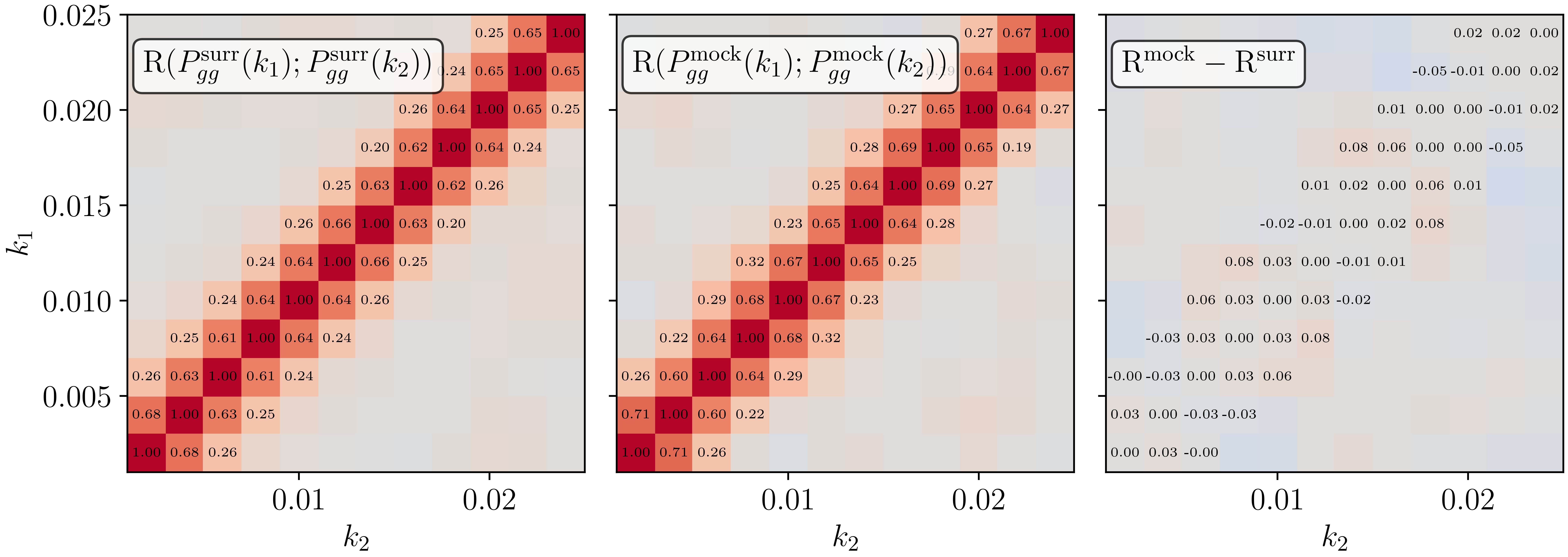

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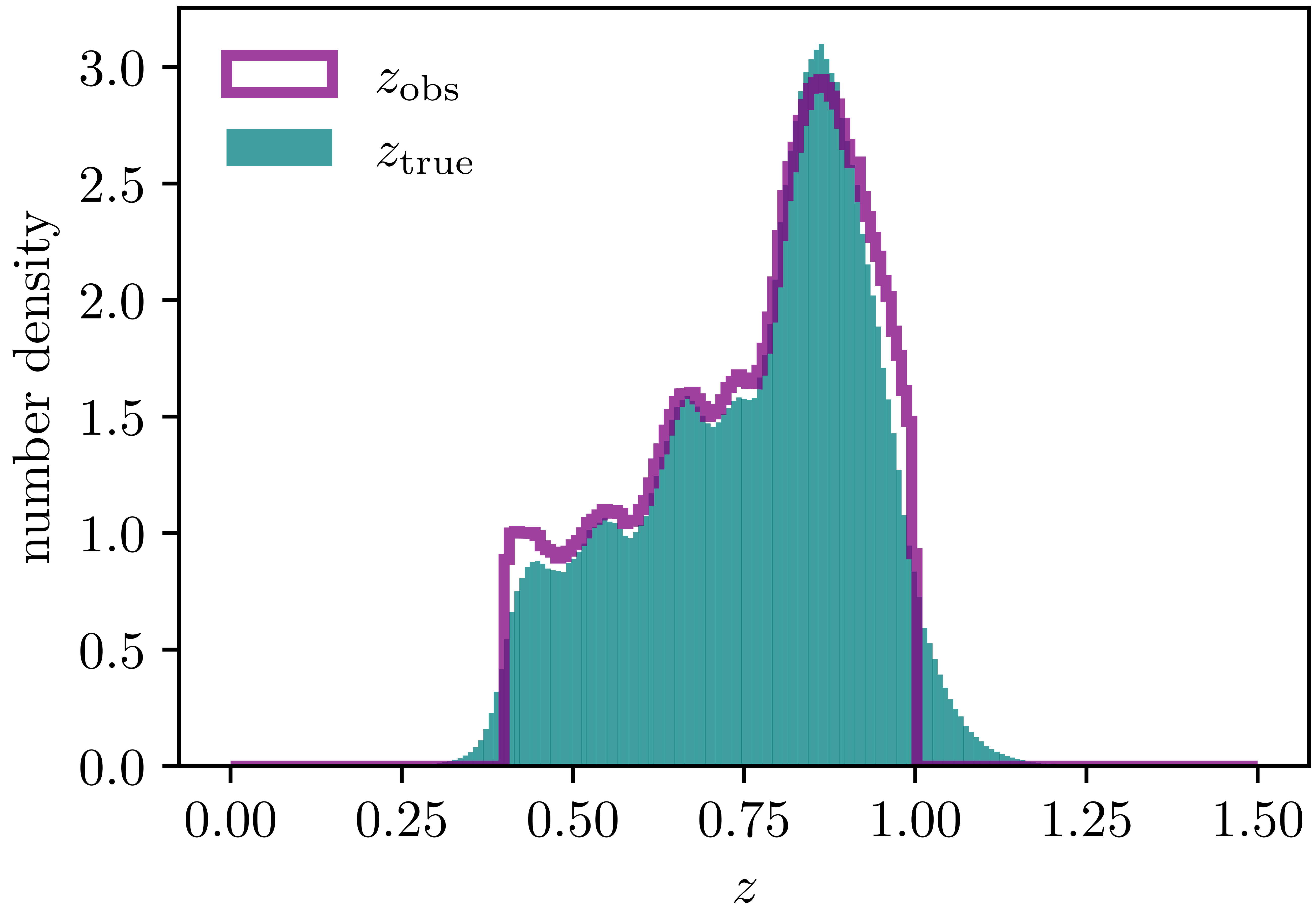
The galaxy catalog contains $(z_{\rm obs}, \sigma_z)$ values for each object, but $z_{\rm true}$ is unknown. For the random catalog, we randomly assign a $(z_{\rm obs}, z_{\rm true}, \sigma_z)$ triple to each object. To do this, we deconvolve the observed 2-d $(z_{\rm obs}, \sigma_z)$ galaxy catalog, in order to infer the underlying 3-d $(z_{\rm obs}, z_{\rm true}, \sigma_z)$ distribution.



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Note how a '**mock**' catalog of objects is defined:

As a *sum of delta functions* that is described on large scales by the galaxy field model above.

$$\sum_i W_i^g \delta^3(\mathbf{x} - \mathbf{x}_i)$$

A galaxy 'mock' field

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$\sum_i W_i^g \delta^3(\mathbf{x} - \mathbf{x}_i)$ A galaxy 'mock' field

Similarly a '**surrogate field**' is a *random field* whose 2PCF matches to the same model.

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