HI intensity mapping with MeerKLASS

Understanding the Galaxy/Matter Connection in the Era of Large Surveys

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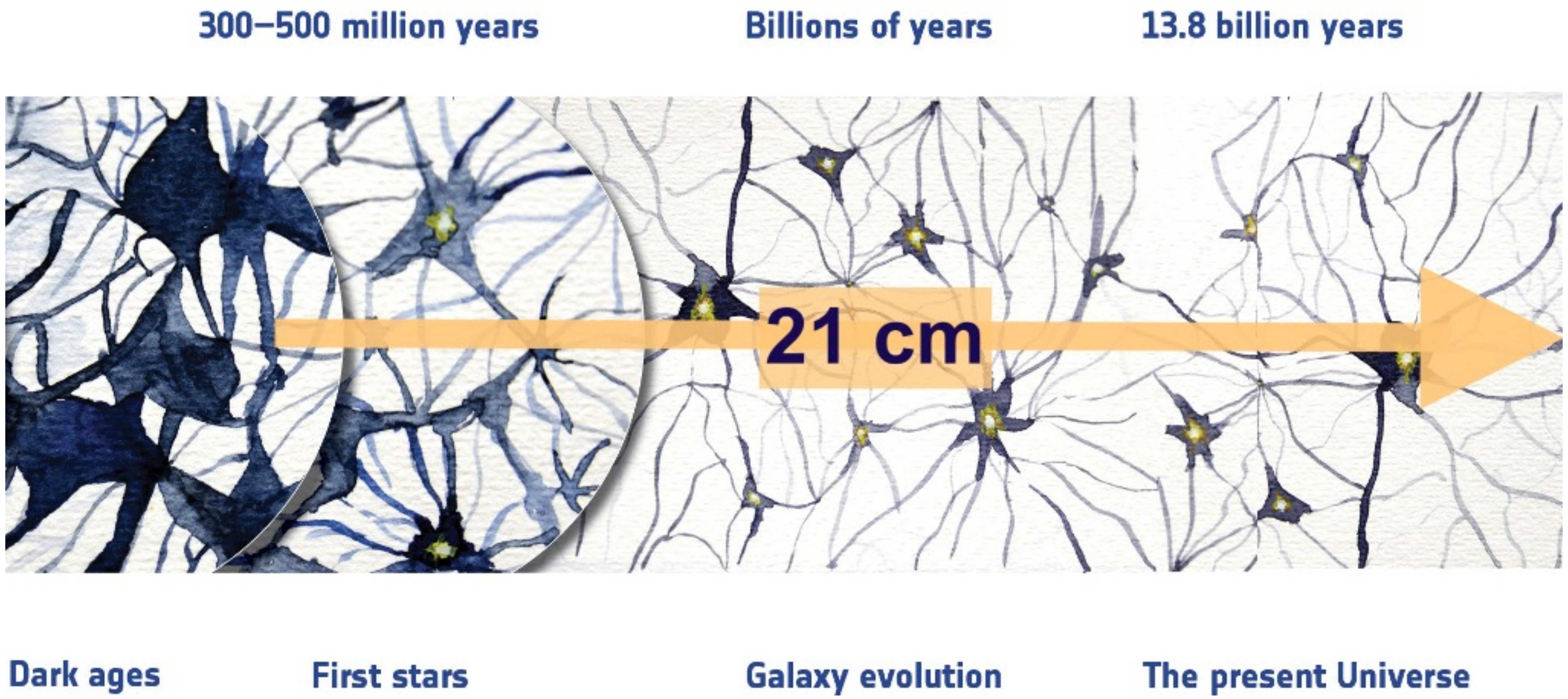
Matilde Barberi Squarotti - September 17th 2024

HI intensity mapping

- Hi as tracer of the matter distribution
- Emission from the hyperfine transition of HI
- Amplitude of the signal dependent on the clustering of HI
- Wide redshift range

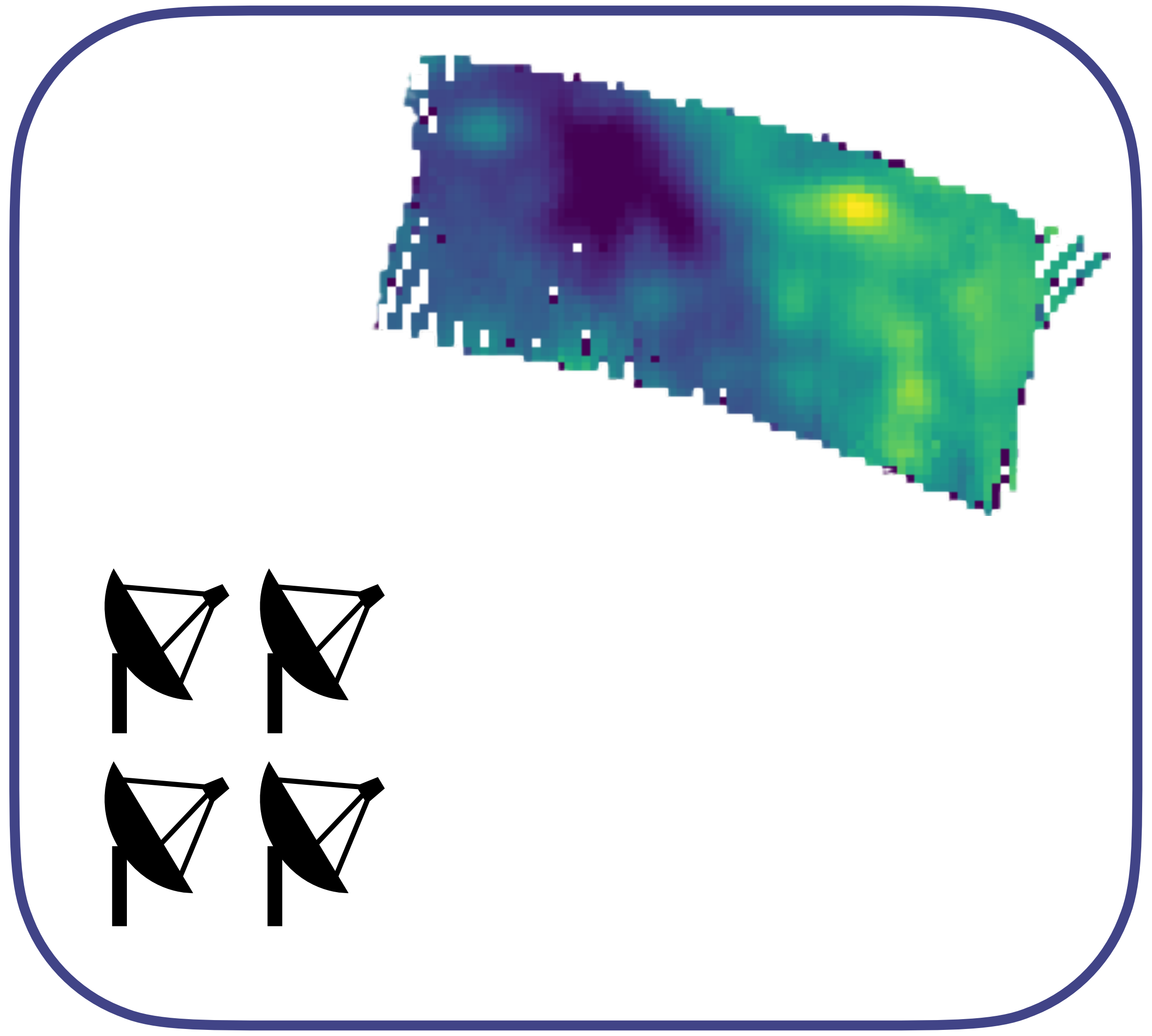


HI intensity mapping

- HI as tracer of the matter distribution
- Emission from the hyperfine transition of HI
- Amplitude of the signal dependent on the clustering of HI
- Wide redshift range
- Not only cosmological signal
    - Astrophysical foregrounds
        - Galactic foregrounds: synchrotron emission, free-free emission, point sources...
        - Extragalactic foregrounds
    - Contaminants: Radio Frequency Interference (RFI), instrumental contaminations...

Single dish technique

- All the antennas of the array observe the same region at the same
- Low angular-resolution survey of the total 21cm flux from unresolved sources
- High signal-to-noise ratio
- Large cosmic volumes covered



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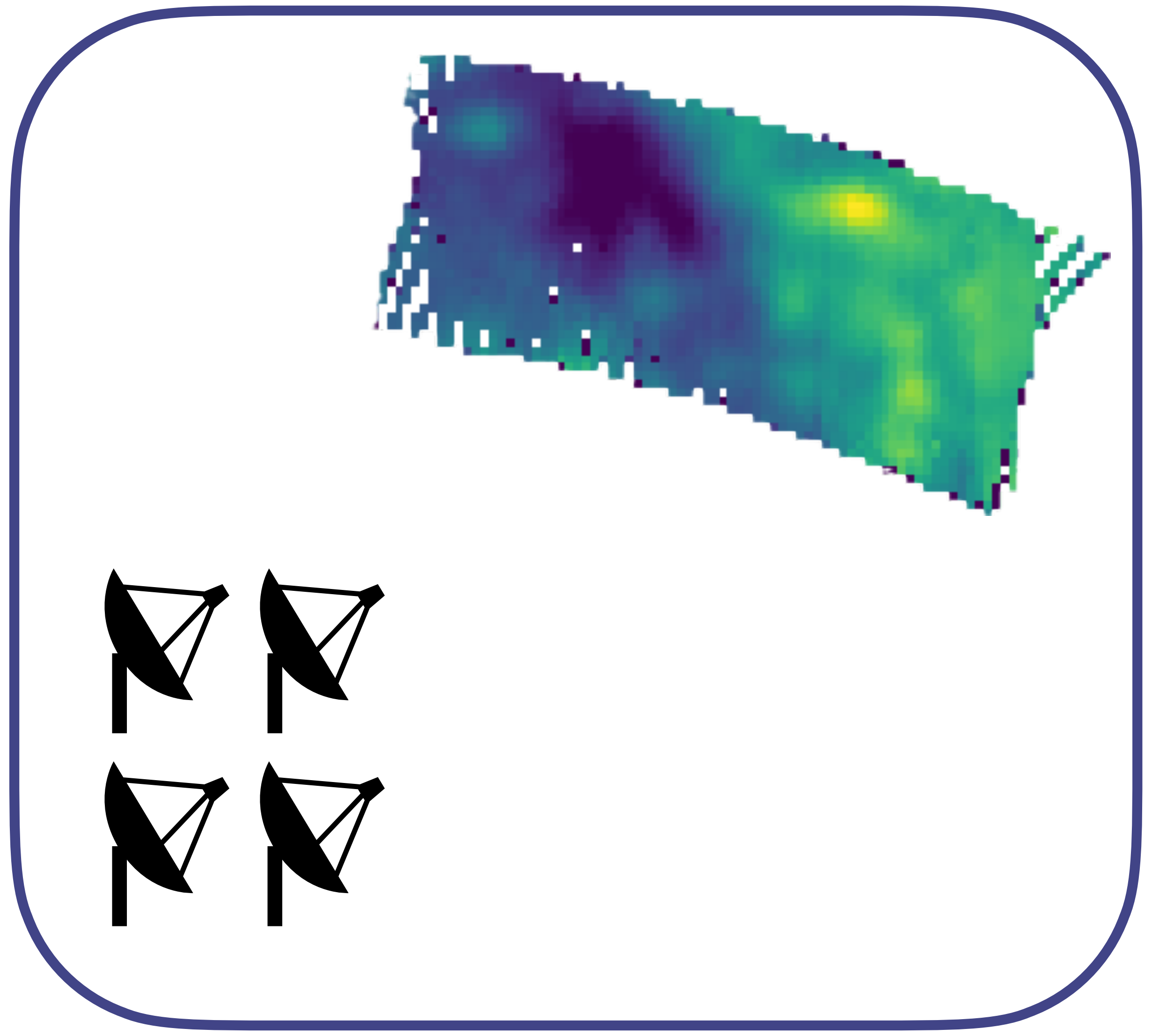

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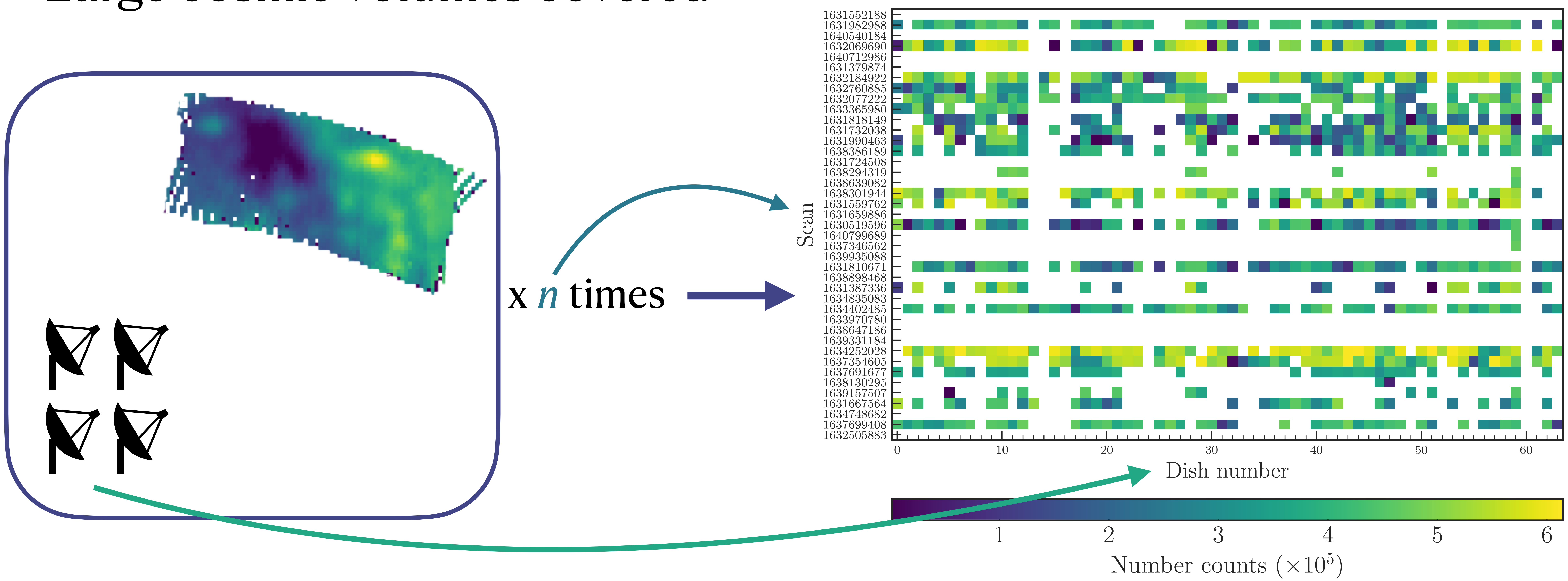

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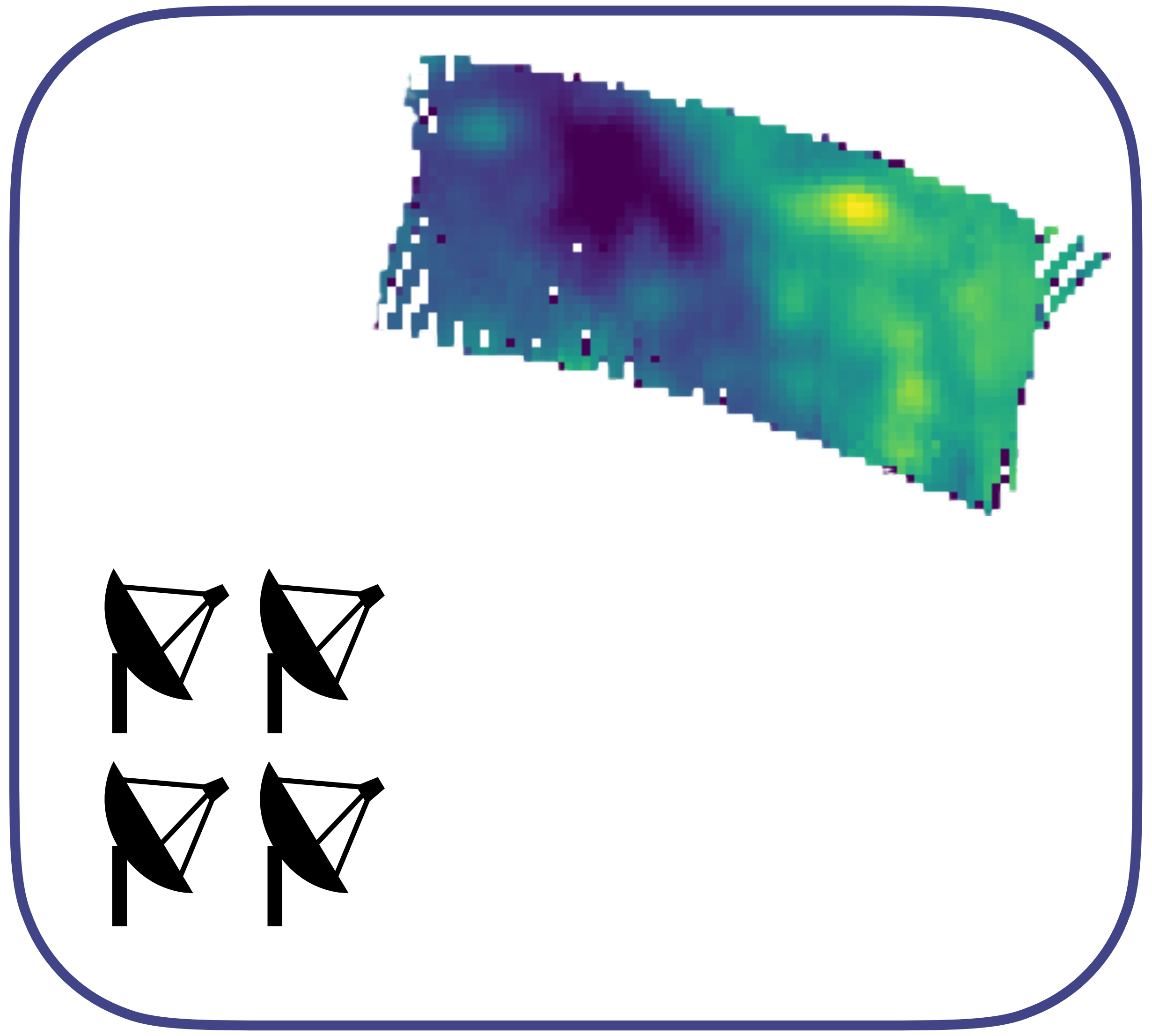
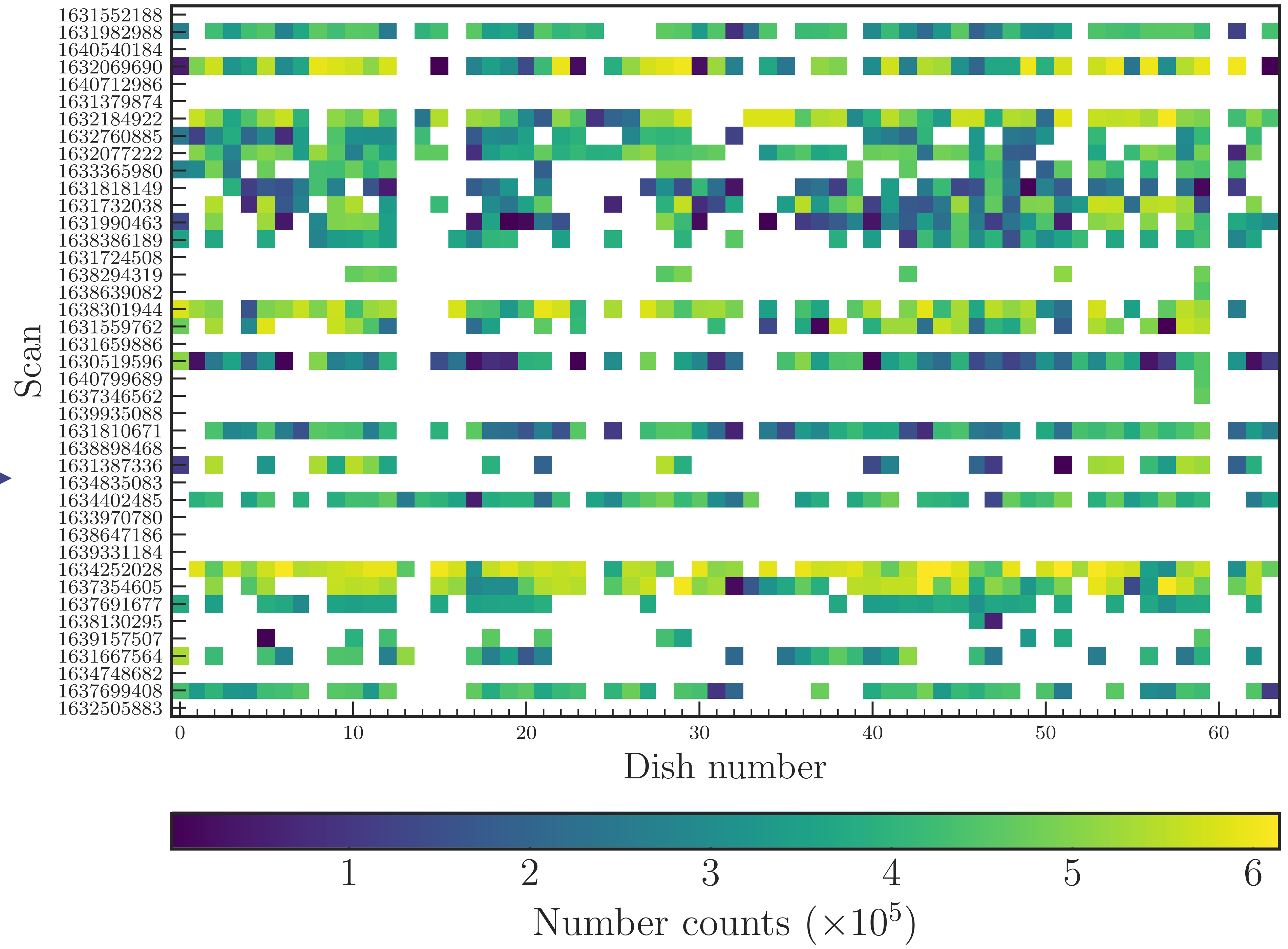


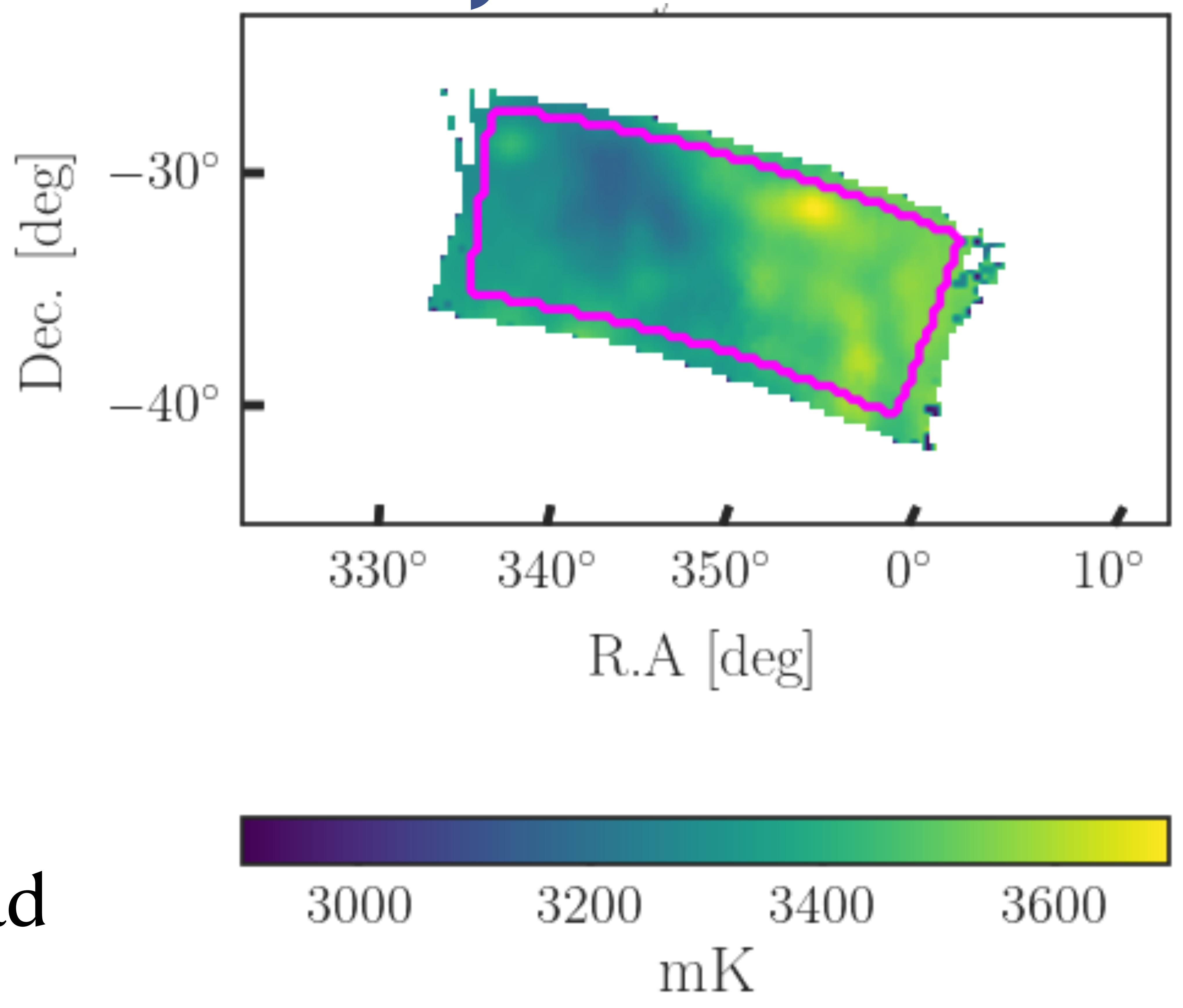
x *n* times →



→ Combined calibrated map

MeerKLASS 2021 survey

- MeerKAT Large Area Synoptic Survey
- Observations:
  - Area: 236 deg²
  - Time: 62 hours (41 scans with 64 dishes)
- Frequency and redshift range
  - 971.2 MHz < ν < 1023.6 MHz → 0.388 < z < 0.463
- Trimming performed to minimise the number of bad pixels
  - 334° < R.A. < 357°
  - 34.5° < dec < -27.5°

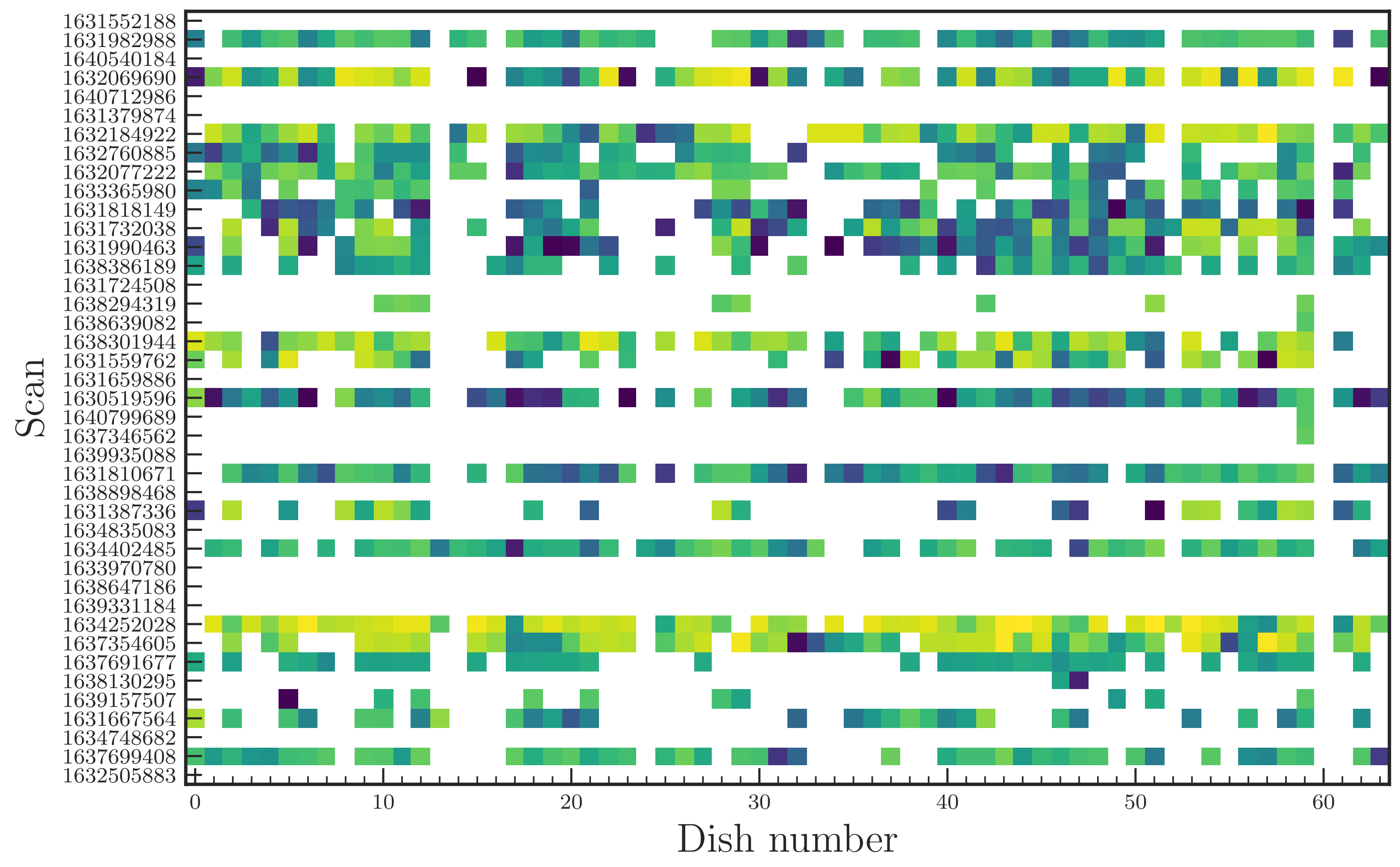


HI cosmological signal detected in cross-correlation with GAMA galaxies

[MeerKLASS Collaboration: Cunnington et al. (2024)]

Full data set auto-correlation

- HI cosmological signal
- Noise
  - Thermal noise
  - Shot noise
- Residuals foregrounds
- Contaminants



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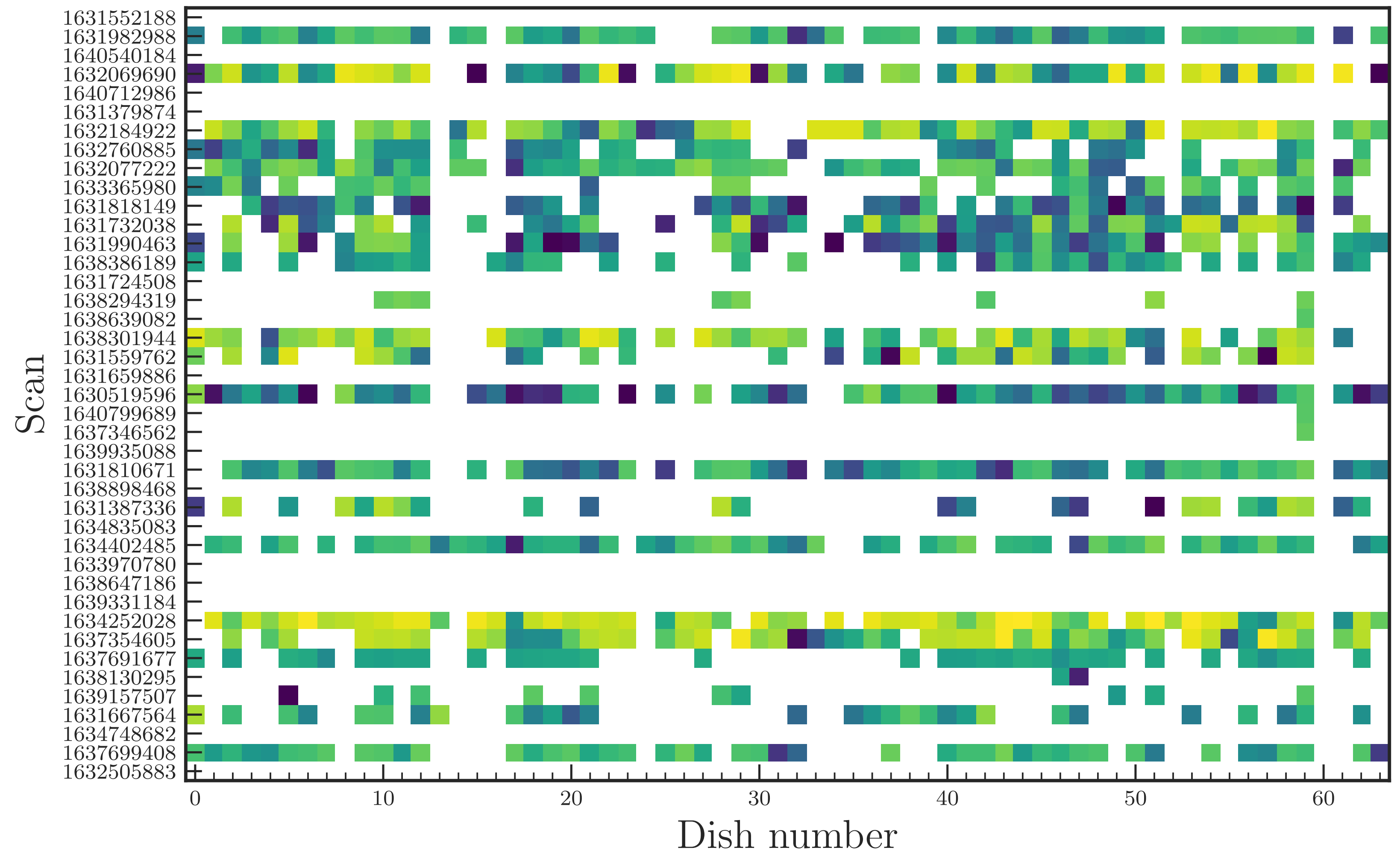

Splitting the data set

- Building independent data sets from the same survey [Wolz et al. (2021)]
  - Contaminants not correlated between subsets
  - Noise free cross-subset power spectra

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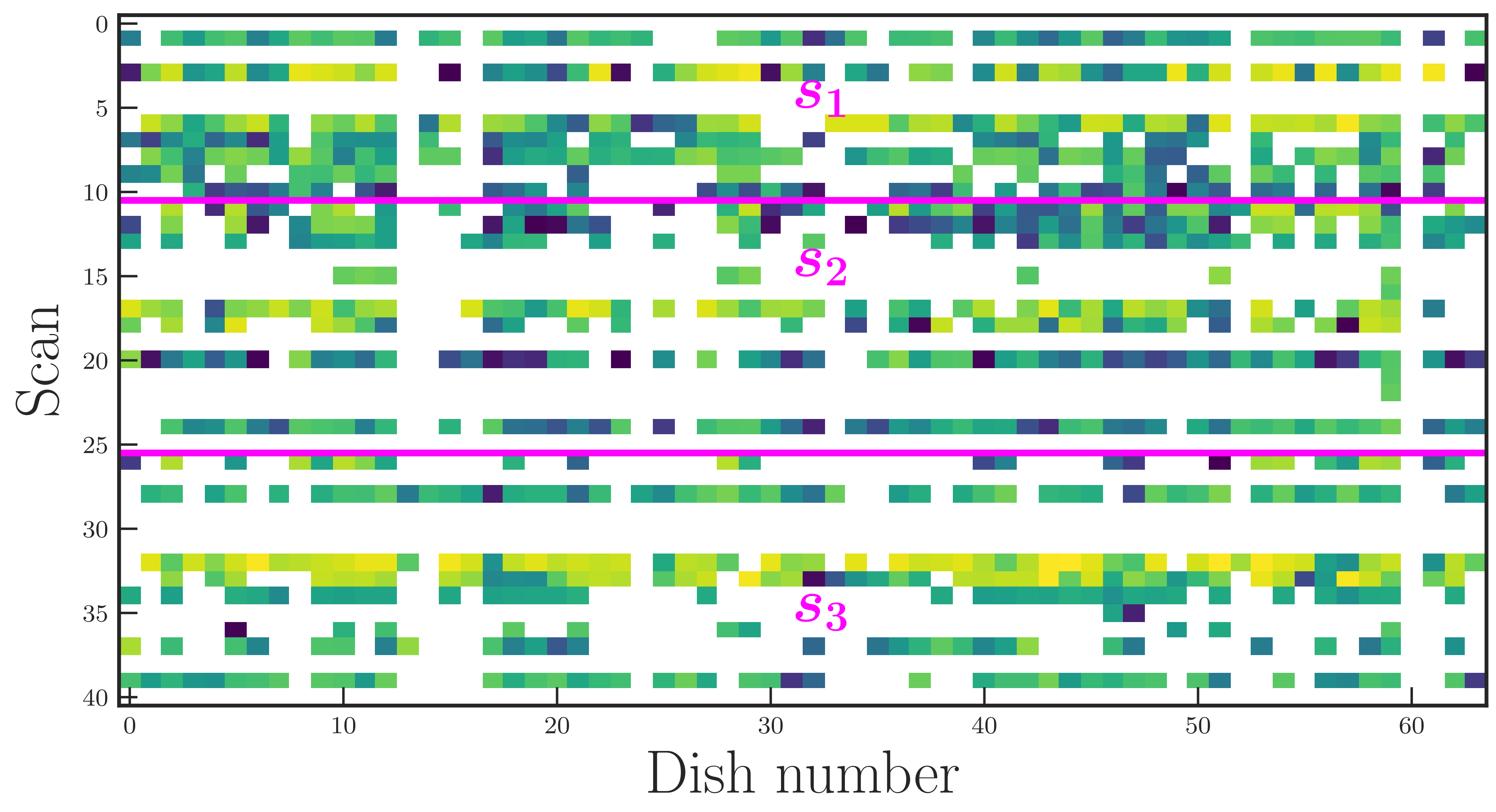

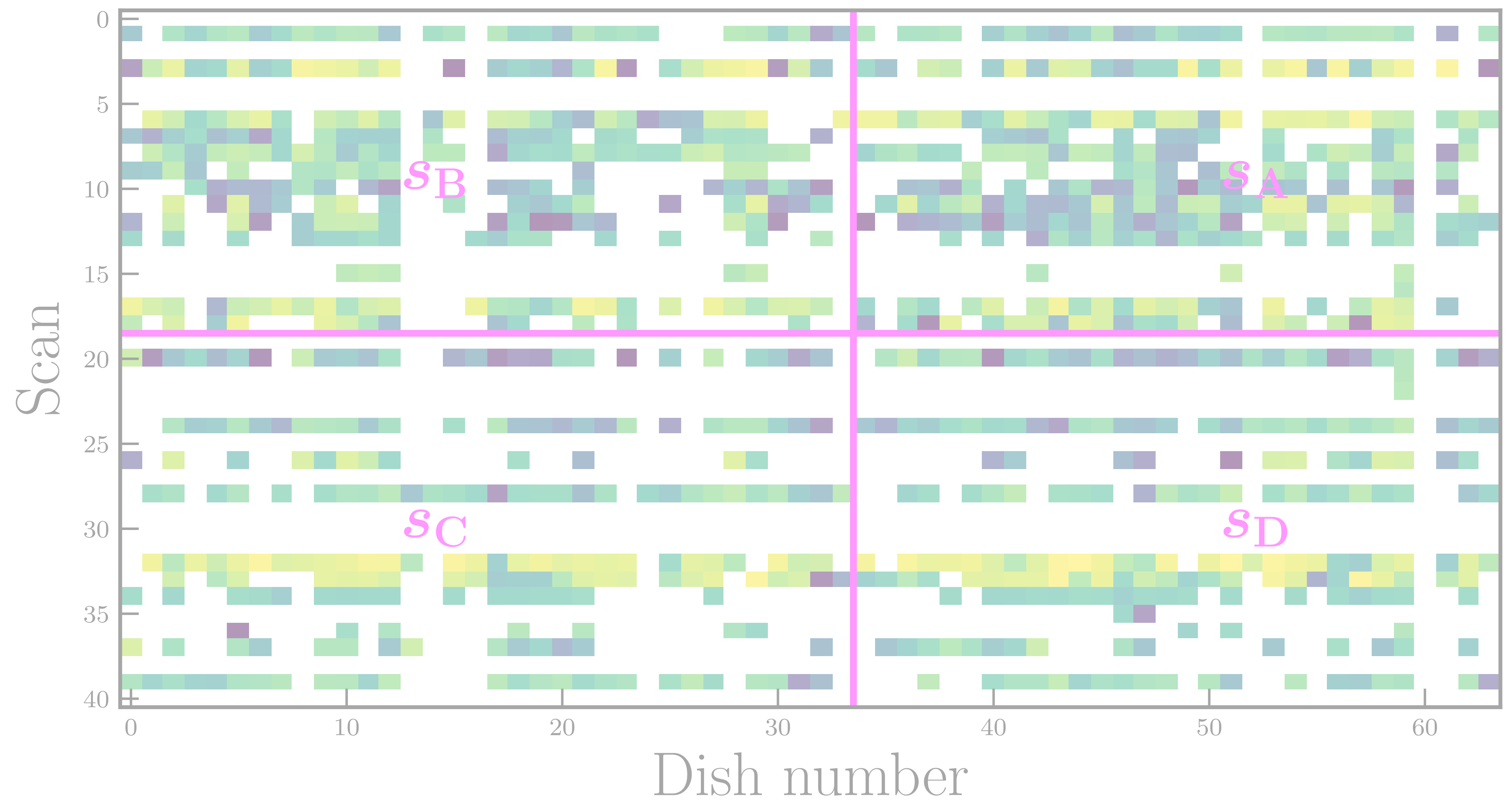

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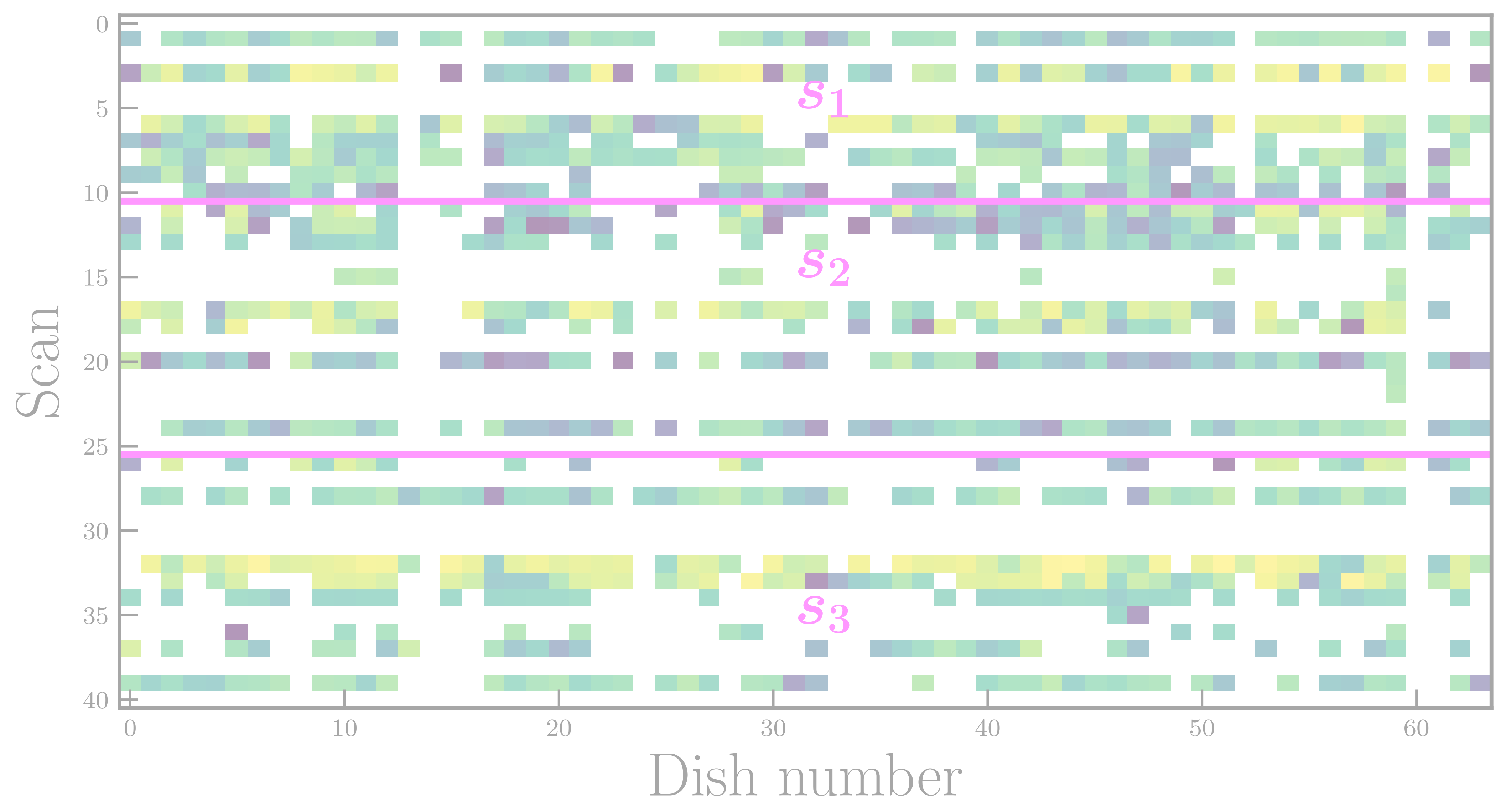

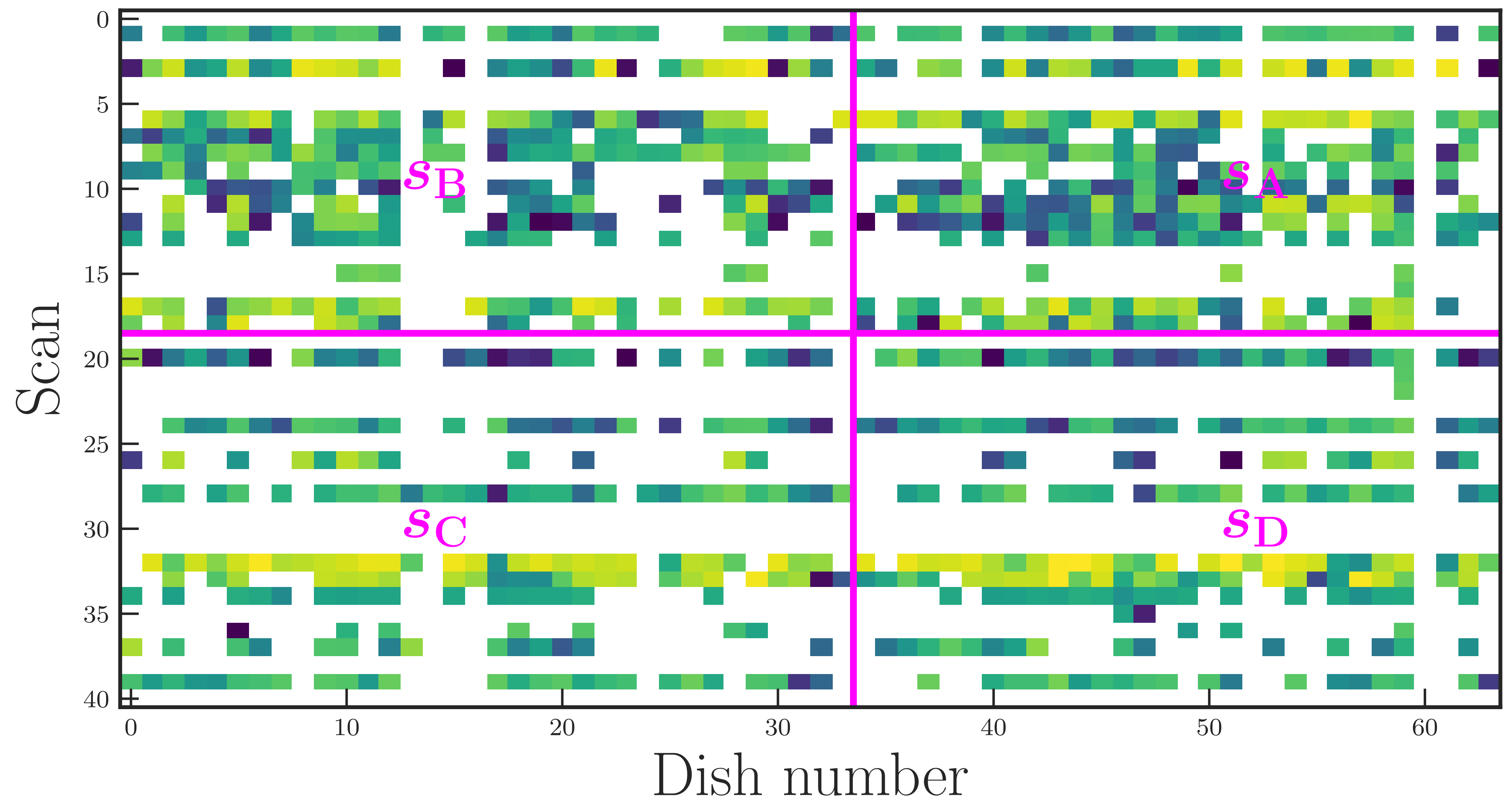

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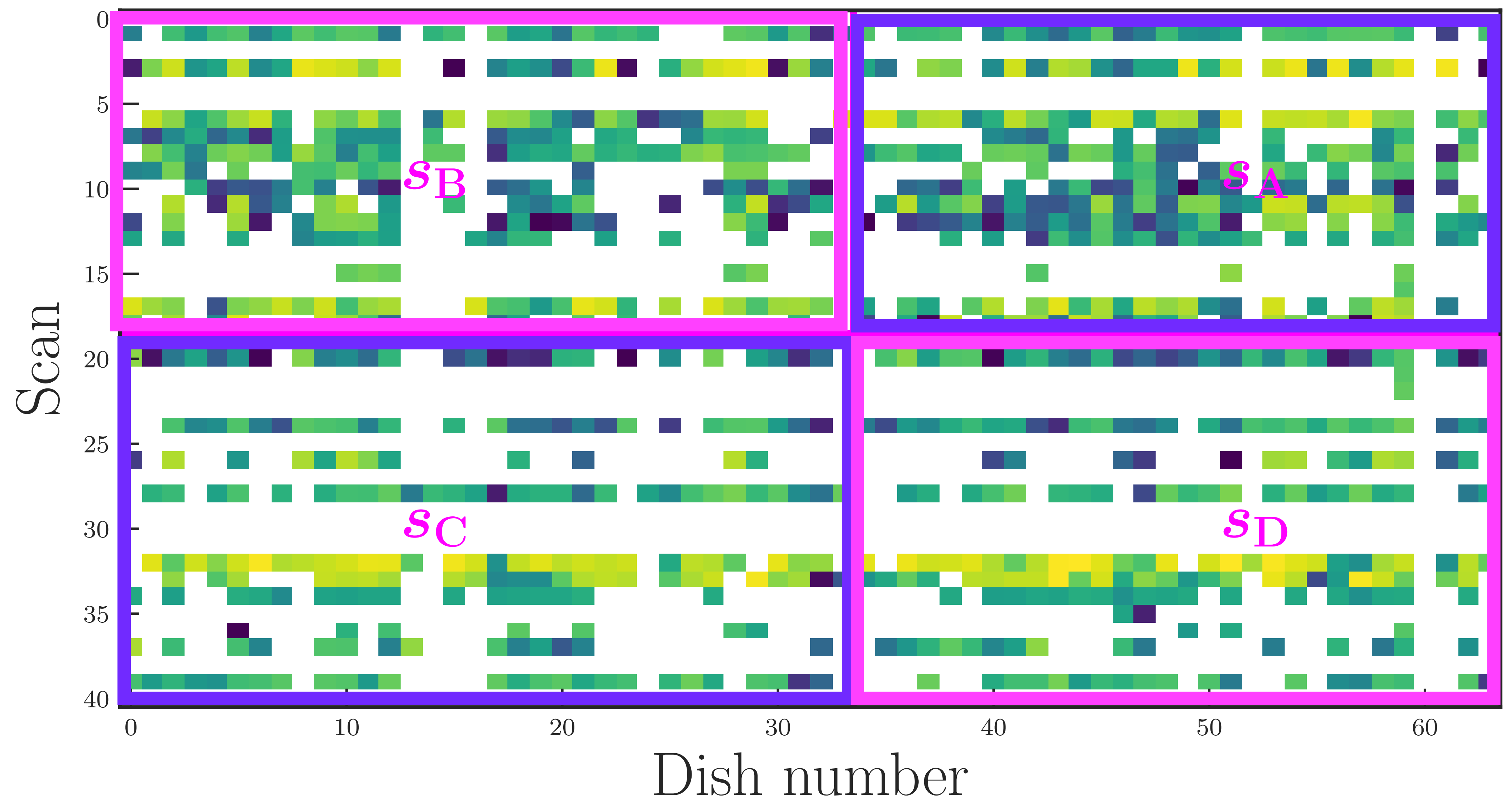


Foreground cleaning: mPCA

- Same principle of the PCA but large and small scales cleaned independently
- Scale separation through a wavelet filtering (using starlets)

Large scale fluctuations

$$\delta\mathbf{T}_{\mathrm{obs}} = \delta\mathbf{T}_{\mathrm{obs,L}} + \sum_{j=1}^{J} \delta\mathbf{T}_{\mathrm{obs},j} \overset{J=1}{=} \delta\mathbf{T}_{\mathrm{obs,L}} + \delta\mathbf{T}_{\mathrm{obs,S}}$$

Small scale fluctuations

- PCA analysis of the coarse and fine maps

$$\begin{cases} \delta\mathbf{T}_{\mathrm{clean,L}} = \delta\mathbf{T}_{\mathrm{obs,L}} - \hat{\mathbf{A}}_{\mathrm{L}}\mathbf{S}_{\mathrm{L}} \\ \delta\mathbf{T}_{\mathrm{clean,S}} = \delta\mathbf{T}_{\mathrm{obs,S}} - \hat{\mathbf{A}}_{\mathrm{S}}\mathbf{S}_{\mathrm{S}} \end{cases} \longrightarrow \delta\mathbf{T}_{\mathrm{clean}} = \delta\mathbf{T}_{\mathrm{clean,L}} + \delta\mathbf{T}_{\mathrm{clean,S}}$$

Power spectrum measurements

- (R.A., dec, ν) maps regridded into a coming cartesian box (x,y,z)
  - $(n_{\rm R.A.}, n_{\rm dec.}, n_\nu)=(n_x, n_y, n_z)$
  - Nearest Grid Point assignment: correction for the smoothing
  - Interlacing included
- Optimisation of k range and k binning
  - $0.08\,h/{\rm Mpc} < k < 0.24\,h/{\rm Mpc}$: avoid the largest scales (at least $2k_{\rm f}$) and the smallest scales (dominated by the beam)
  - $n_k = 9$ k bin: wide enough Δk to avoid loss of information and noise

Power spectrum measurements

- FFT of the cleaned regridded maps

$$\tilde{F}(\mathbf{k}) = \sum_{\mathbf{x}} \delta T(\mathbf{x}) w(\mathbf{x}) \exp(i\mathbf{k} \cdot \mathbf{x})$$

- Power spectrum estimator

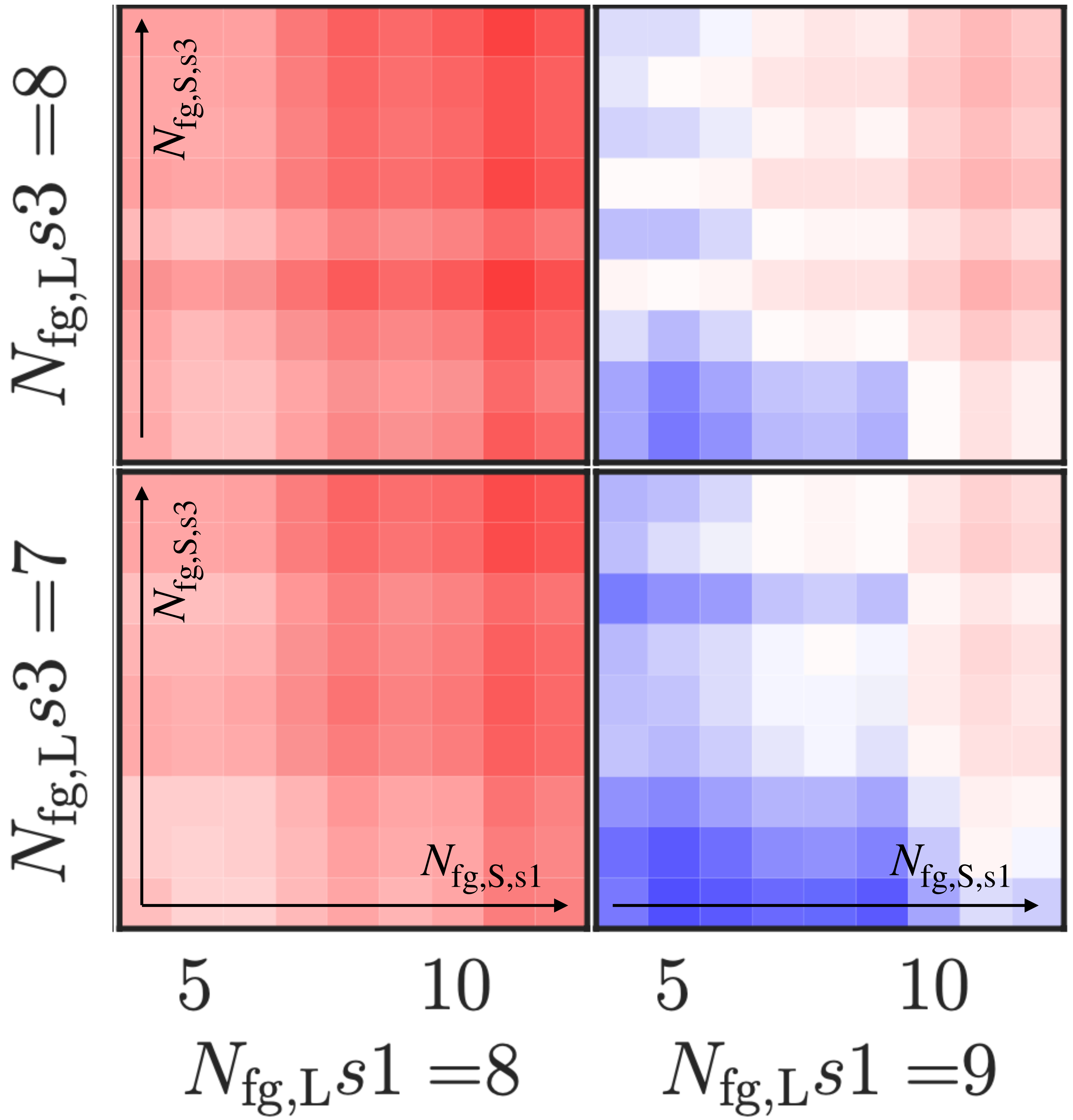
$$\hat{P}_{i\,j}(\mathbf{k}) = \frac{V_{\text{cell}}}{\sum_{\mathbf{x}} w_i(\mathbf{x}) w_j(\mathbf{x})} \text{Re}\left\{ \tilde{F}_i(\mathbf{k}) \tilde{F}_j^*(\mathbf{k}) \right\}$$

subsets i and j

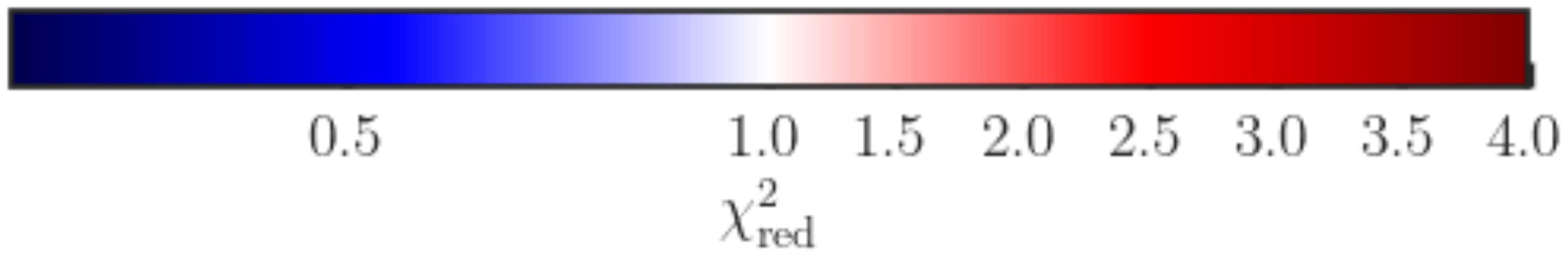
Guidance fits

- Fit of each cross power spectrum against the model
- $P_{ij}(\mathbf{k}) = \mathscr{D}^2(\mathbf{k}) T_{\mathrm{HI}}^2 b_{\mathrm{HI}}^2 \left(1 + f\mu^2\right)^2 P_{\mathrm{matter}} \qquad i \neq j$
- Least Square Error method to constrain the overall amplitude (parameterized by $\Omega_{\mathrm{HI}} b_{\mathrm{HI}}$)
- Best cleaning identified according to the quality of the fit (the metric is the reduced χ^2) [Carucci et al. (2020)]
  - Too mild cleaning → residuals contributing to the power spectra with a different trend compared to the cosmological clustering → fit fails
  - Too aggressive cleaning → the signal is almost completely erased → fit fails

Guidance fits

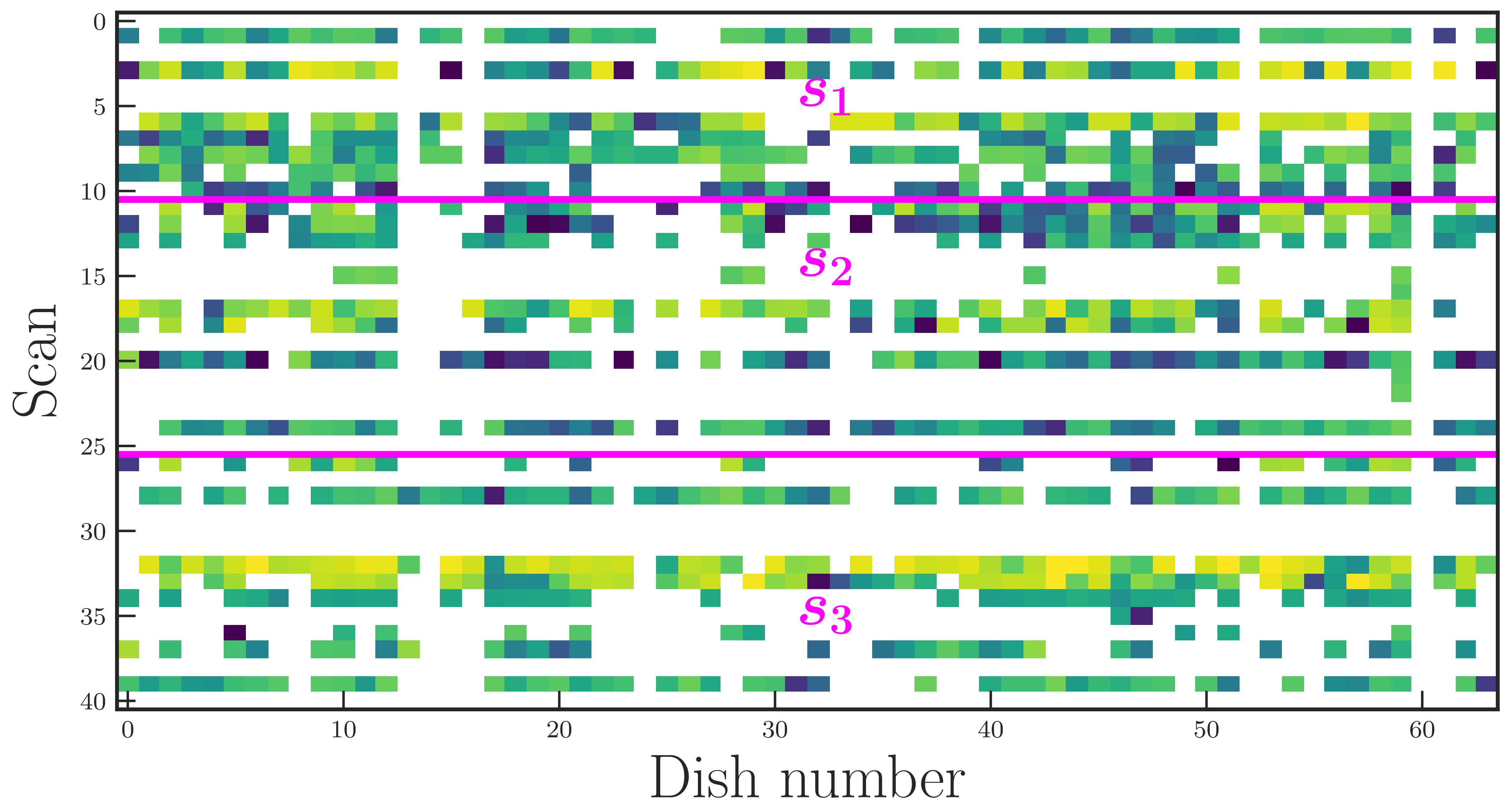


- Columns: cleaning of the large scales in one of the subsets
- Rows: cleaning of the large scales in one of the subsets
- Block axes: cleaning of the small scales
- Color map:



Global fits

- Multi-tracer like formalism
- Subsets auto-correlations discarded: shown with Fisher forecast that they would not provide additional information (noise level still too high)
- Data vector built with all the available subsets cross-correlations
  - Stripe division: $\mathbf{P} = \{P_{12}, P_{23}, P_{13}\}$
  - Chess-board division: $\mathbf{P} = \{P_{AC}, P_{BD}\}$
- Full Gaussian/jackknife covariance matrix



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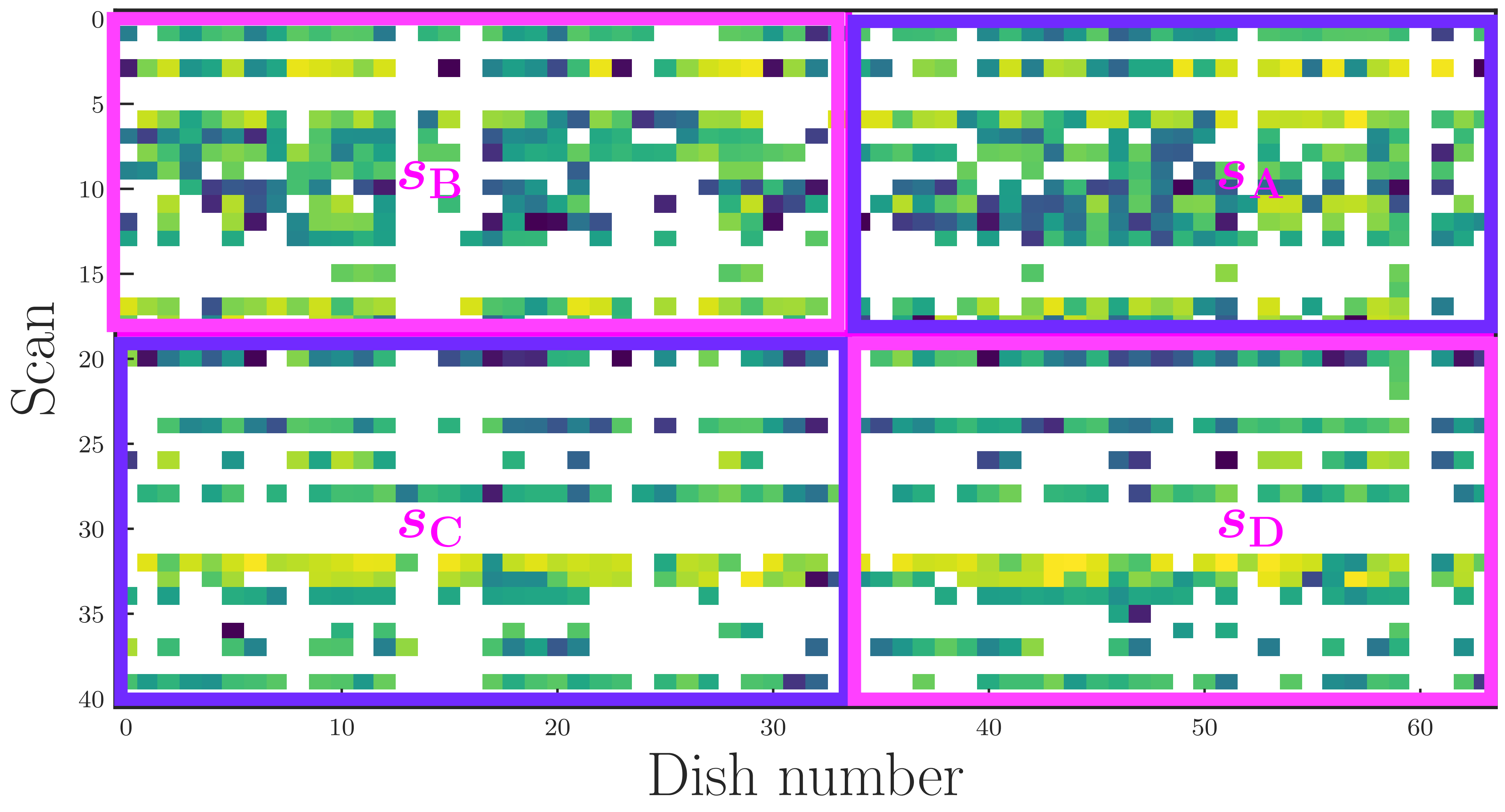
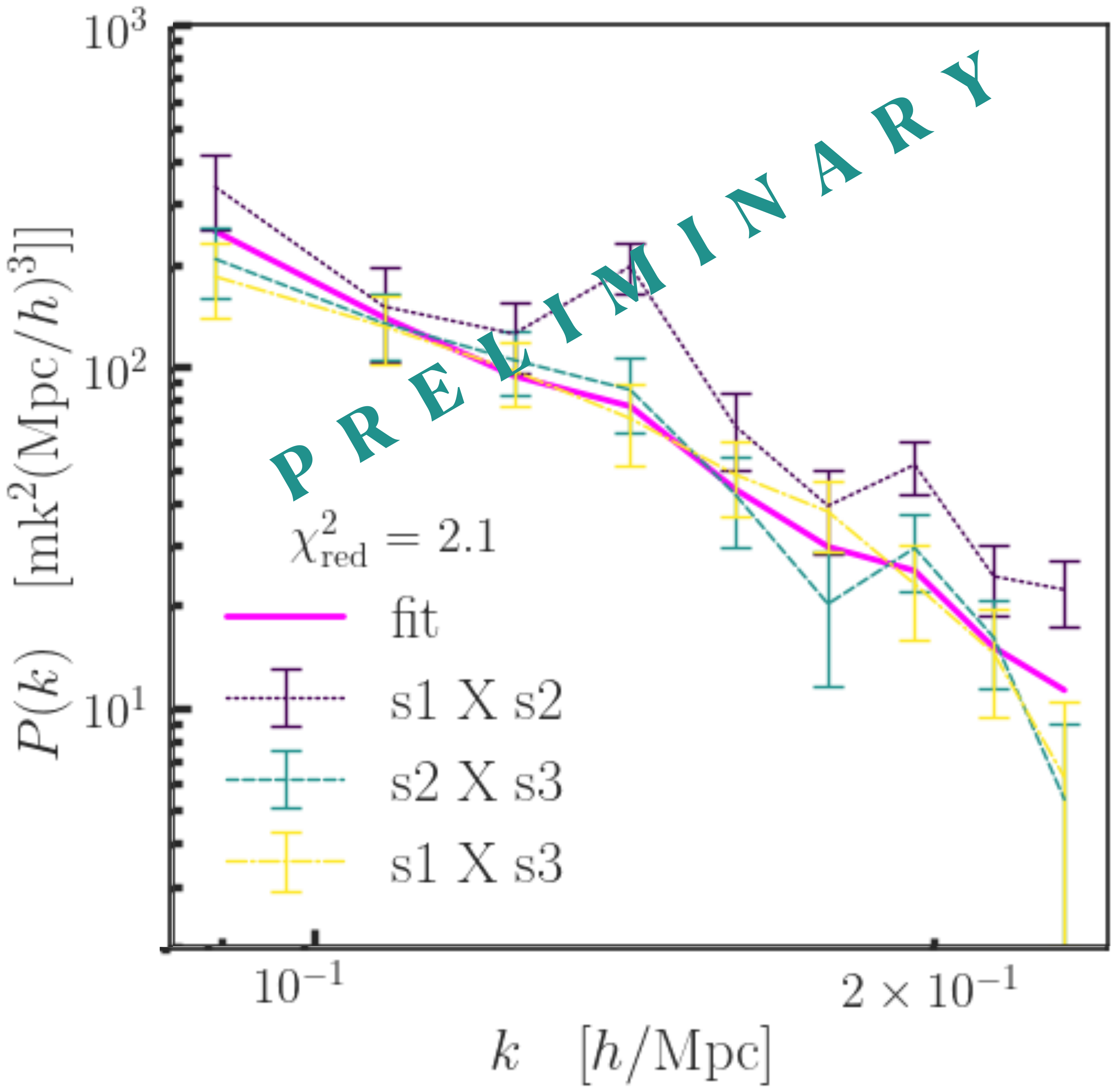


Global fits: the data vector

- Fix a cleaning for each subset by looking at the guidance fits
  - Criterium: $\chi^2_{\rm red} - 1 \;\; < 0.05$
  - The cleaning of one subset has to be the same for its possible the cross-correlations (e.g. if I chose for s_1 $N_{\rm fg,L} = 7, N_{\rm fg,S} = 6$, I use that cleaning both in $P_{s_1 s_2}$ and $P_{s_1 s_3}$)
- Build the data vector with the good cleaning combinations

Global fits: the analysis

- Only one free common parameter: $\Omega_{\rm HI} b_{\rm HI}$



Conclusions

- The MeerKLASS 2021 survey in the L-band, being the deepest single-dish survey, carry a relaevant amout of information
- Internal cross-correlations:
  - Help in mitigating systematics that affect HI intensity mapping observation
  - Possibility to detect the power spectrum without the need of a cross-correlation with a spectroscopic galaxy survey
- Successful robustness tests
- Stay tuned!

Back-up slides

Foreground cleaning: PCA

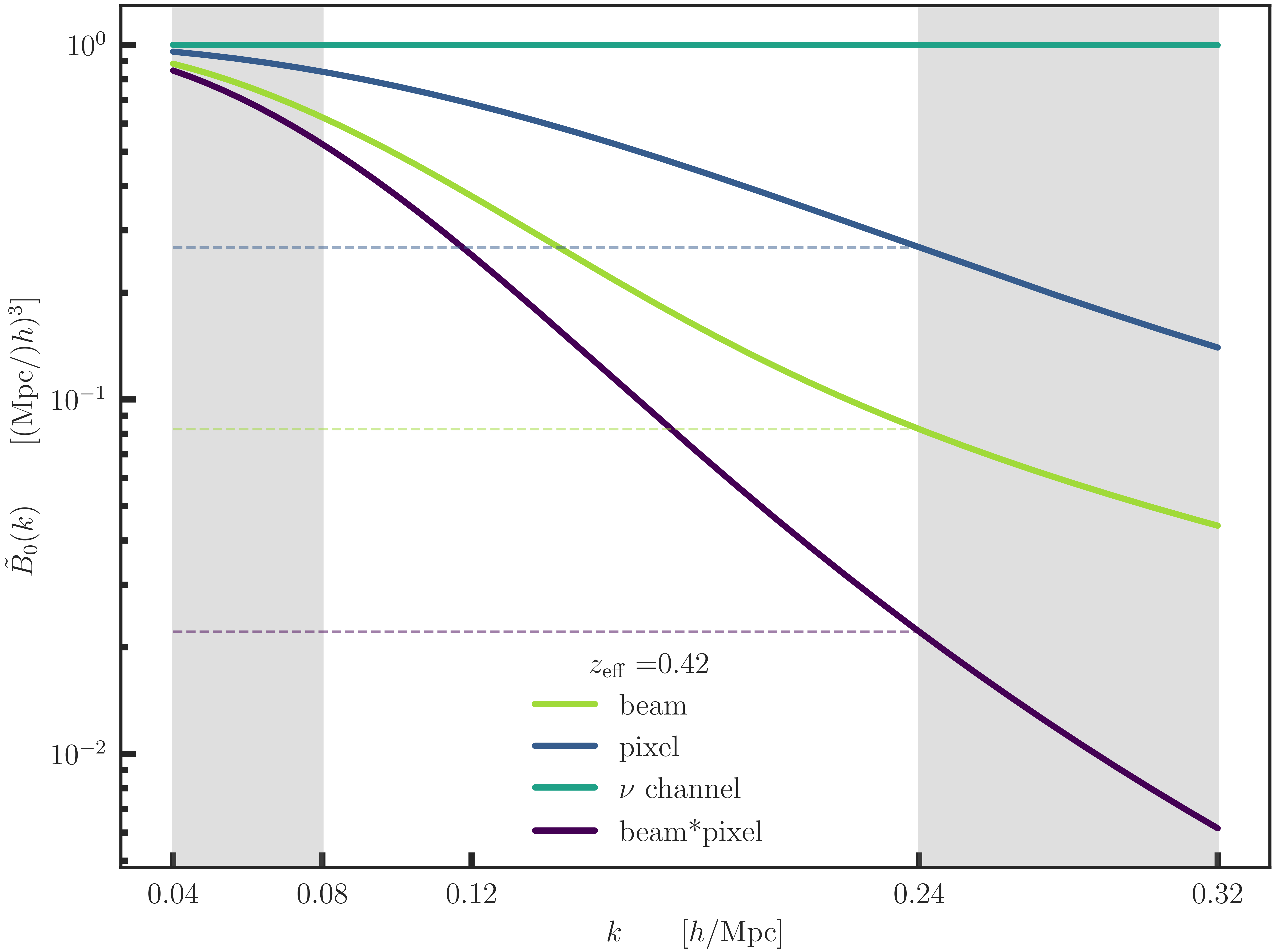
- The observed data cube can be decomposed in a set of sources $\mathbf{S}$ in pixel space modulated in frequency by a mixing matrix $\hat{\mathbf{A}}$, plus some residuals (the cosmological signal)

$$\underbrace{\delta\mathbf{T}_{\rm obs}}_{[\nu,\,\text{pixel}]} = \underbrace{\hat{\mathbf{A}}}_{[\nu,\,\#]}\,\underbrace{\mathbf{S}}_{[\#,\,\text{pixel}]} + \mathbf{R}\;[\nu,\,\text{pixel}]$$

- Computation of the mixing matrix $\hat{\mathbf{A}}$ and choise of the number $N_{\rm fg}$ of components to remove

$$\mathbf{X}_{\rm clean} \equiv \mathbf{R} = \delta\mathbf{T}_{\rm obs} - \underbrace{\hat{\mathbf{A}}}_{[\nu,\,N_{\rm fg}]}\,\underbrace{\mathbf{S}}_{[N_{\rm fg},\,\text{pixel}]}$$

Damping effects



Multi-scan data vectors

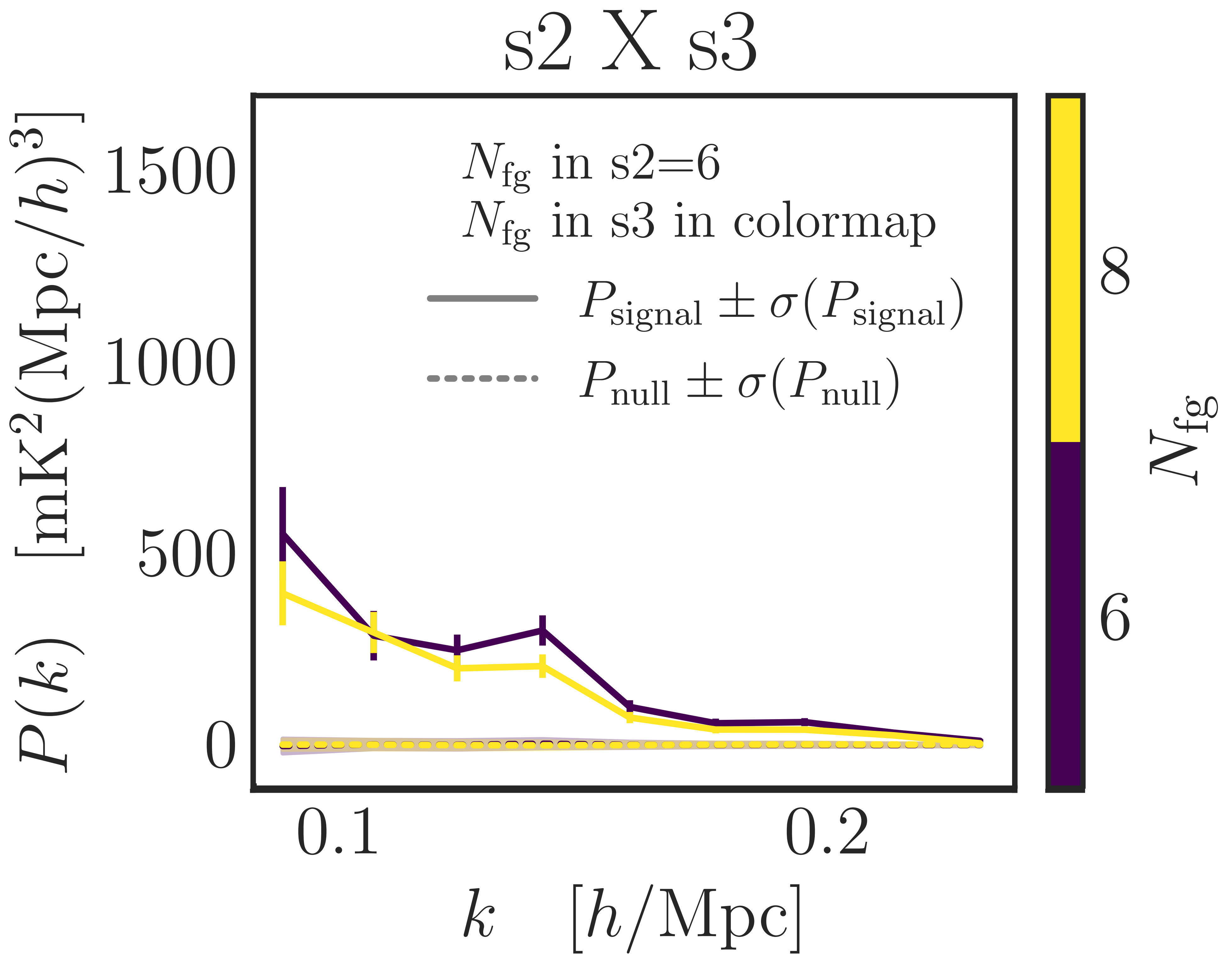
$$\boldsymbol{P} = \{P_{12}, P_{23}, P_{13}\}$$

$$\mathsf{Cov}(\boldsymbol{P}, \boldsymbol{P}) = \frac{1}{2\,N_{\rm m}} \begin{vmatrix} (P_{11}P_{22} + P_{12}P_{12}) & (P_{13}P_{22} + P_{12}P_{23}) & (P_{11}P_{23} + P_{12}P_{13}) \\ & (P_{22}P_{33} + P_{23}P_{23}) & (P_{12}P_{33} + P_{13}P_{23}) \\ & & (P_{11}P_{33} + P_{13}P_{13}) \end{vmatrix}$$

$$\mathsf{Cov}(\boldsymbol{P}, \boldsymbol{P}) = \frac{1}{2\,N_{\rm m}} \begin{vmatrix} (P_{AA}P_{DD} + P_{AD}^2) & (P_{AB}P_{CD} + P_{AC}P_{BD}) \\ & (P_{BB}P_{CC} + P_{BC}^2) \end{vmatrix}$$

Robustness tests

- Null test
  - Reshuffling along the radial direction of one of the intervening maps
  - Cross-power spectra between an original map and a reshuffled one



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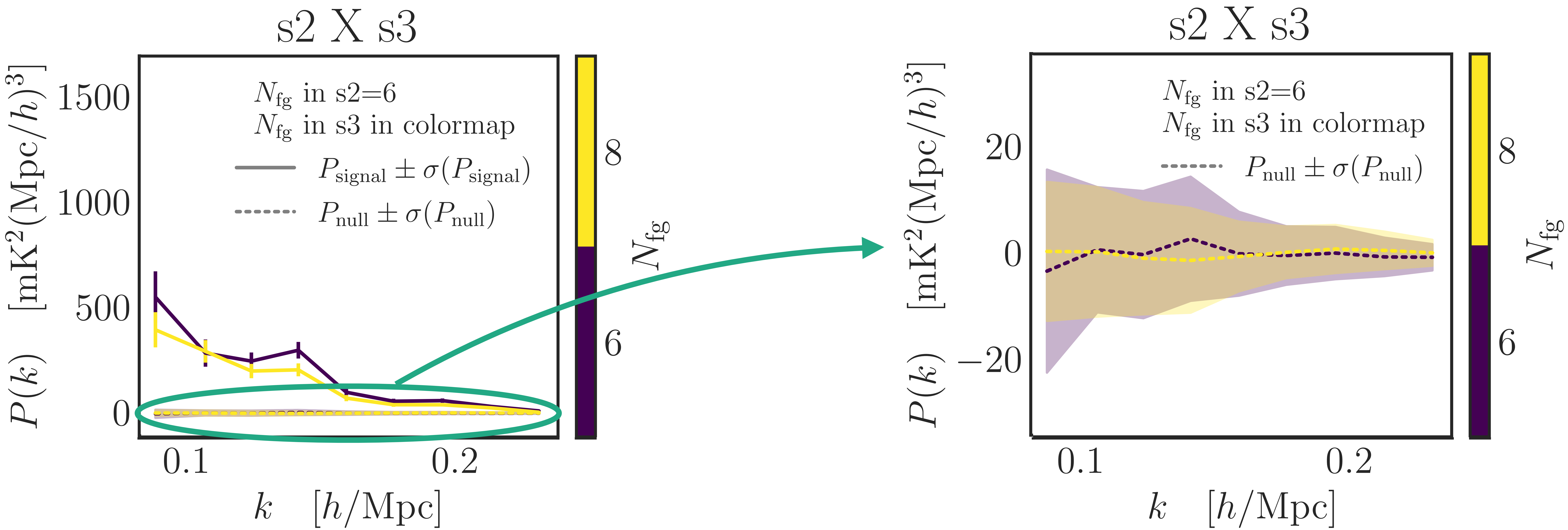
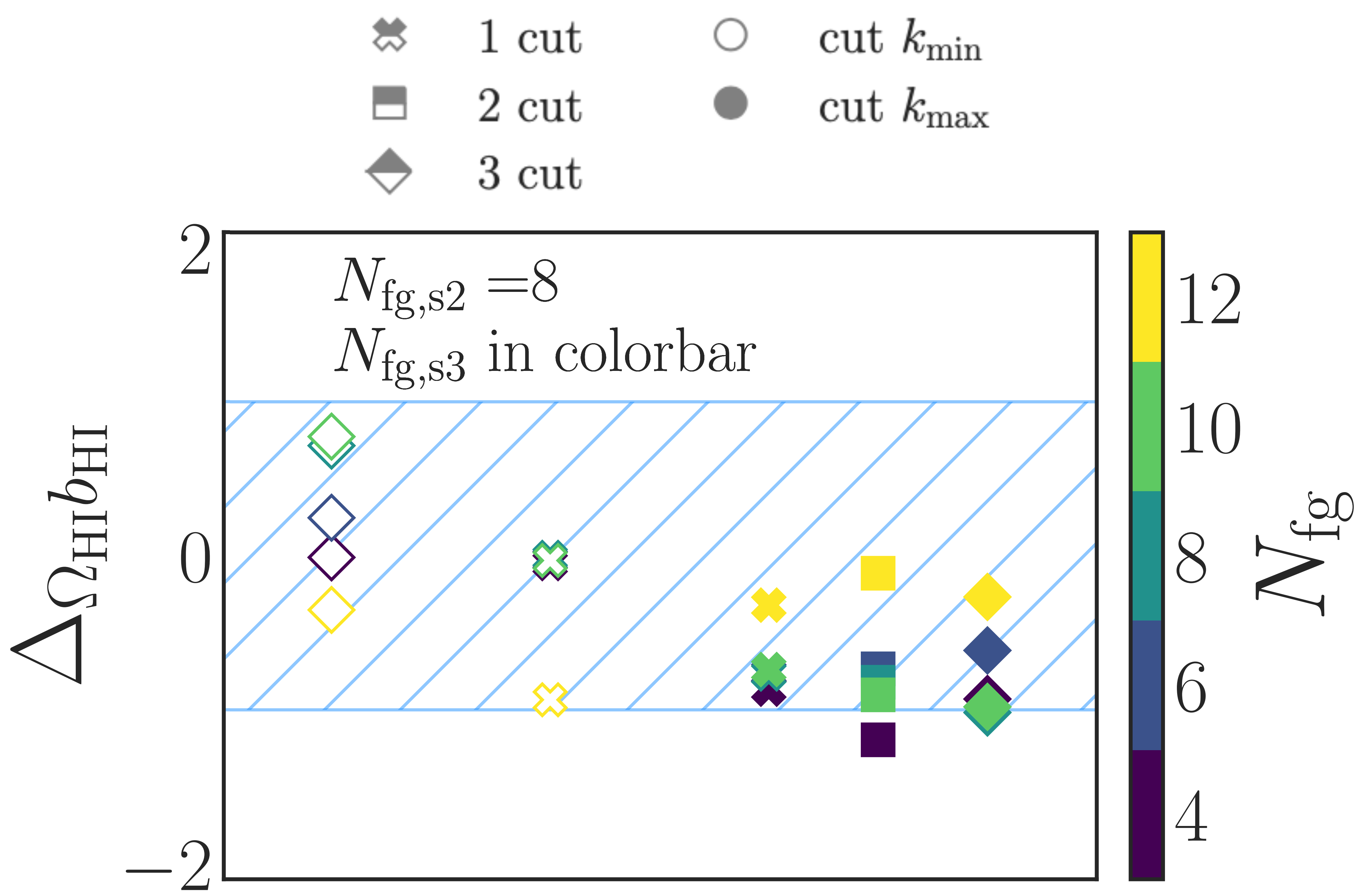


Robustness tests

- Null test ✔
- Scale cuts
  - Repeat the fits discarding k bins at large or small scales

$$\Delta_{\Omega_{HI} b_{HI}} = \frac{\Omega_{HI} b_{HI}^{\text{no}k-\text{cuts}} - \Omega_{HI} b_{HI}^{k-\text{cuts}}}{\sigma_{\Omega_{HI} b_{HI}}^{\text{no}k-\text{cuts}}}$$



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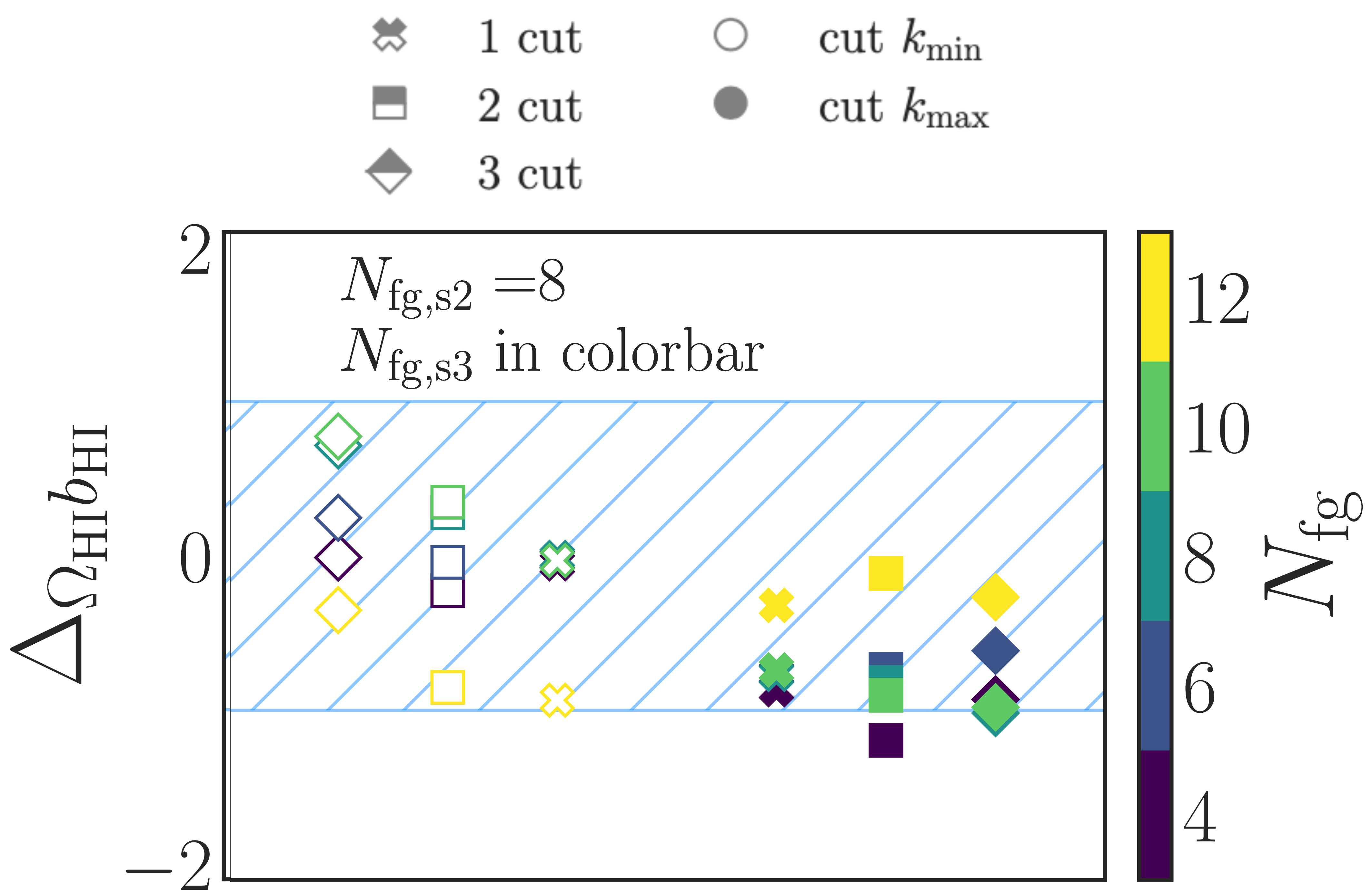
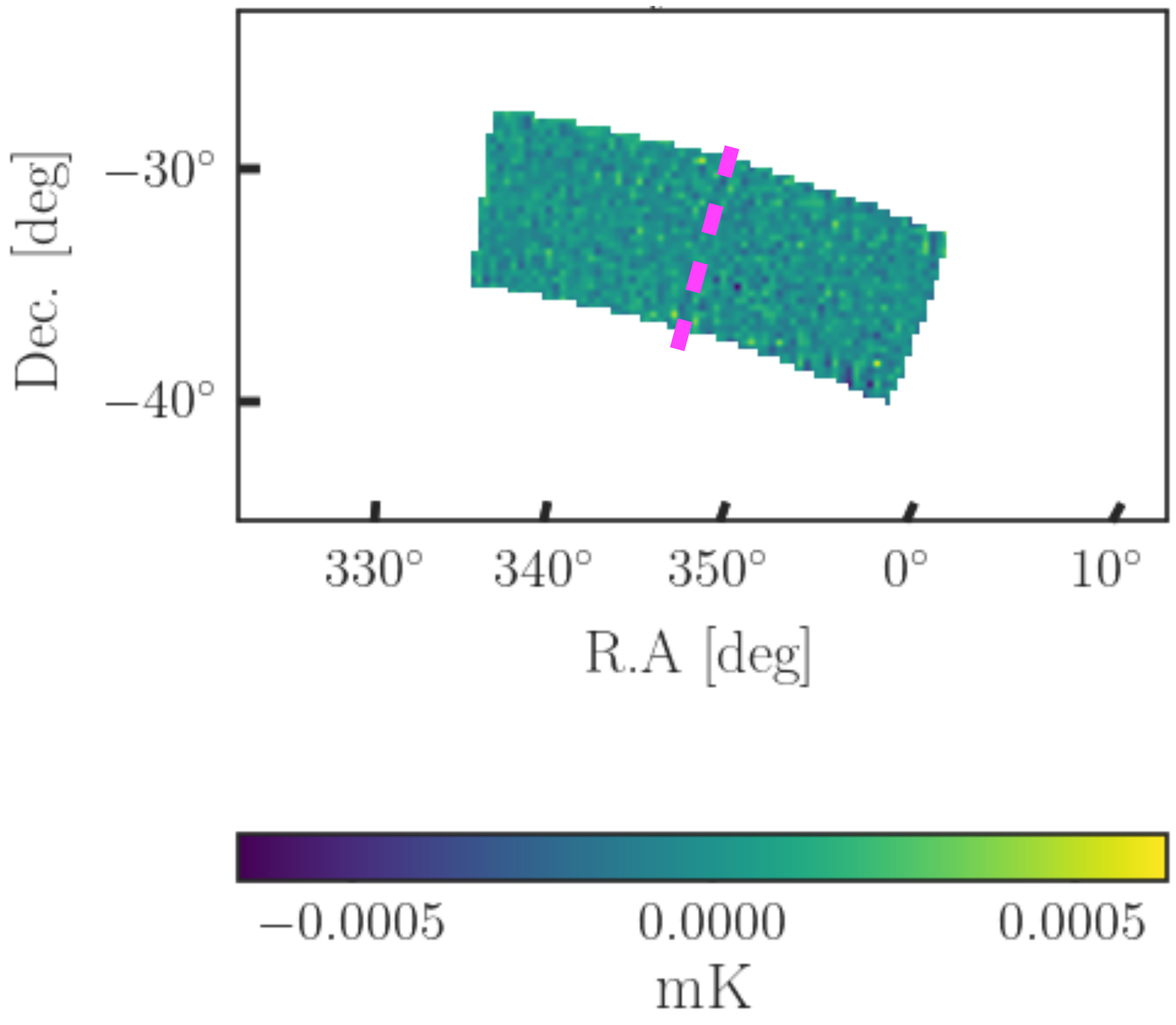


Robustness tests

- Null test ✓
- Scale cuts ✓
- Map division in R.A.
  - Independent foreground cleaning for left and right patches
  - Power spectra measurements
  - $\left[\Omega_{\rm HI} b_{\rm HI}\right]_{ij,\rm left}$ vs $\left[\Omega_{\rm HI} b_{\rm HI}\right]_{ij,\rm right}$ vs $\left[\Omega_{\rm HI} b_{\rm HI}\right]_{ij,\rm all}$



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- Estimate of the signal loss due to foreground cleaning ✓