Unveiling the HI power spectrum with MeerKLASS

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LIM25

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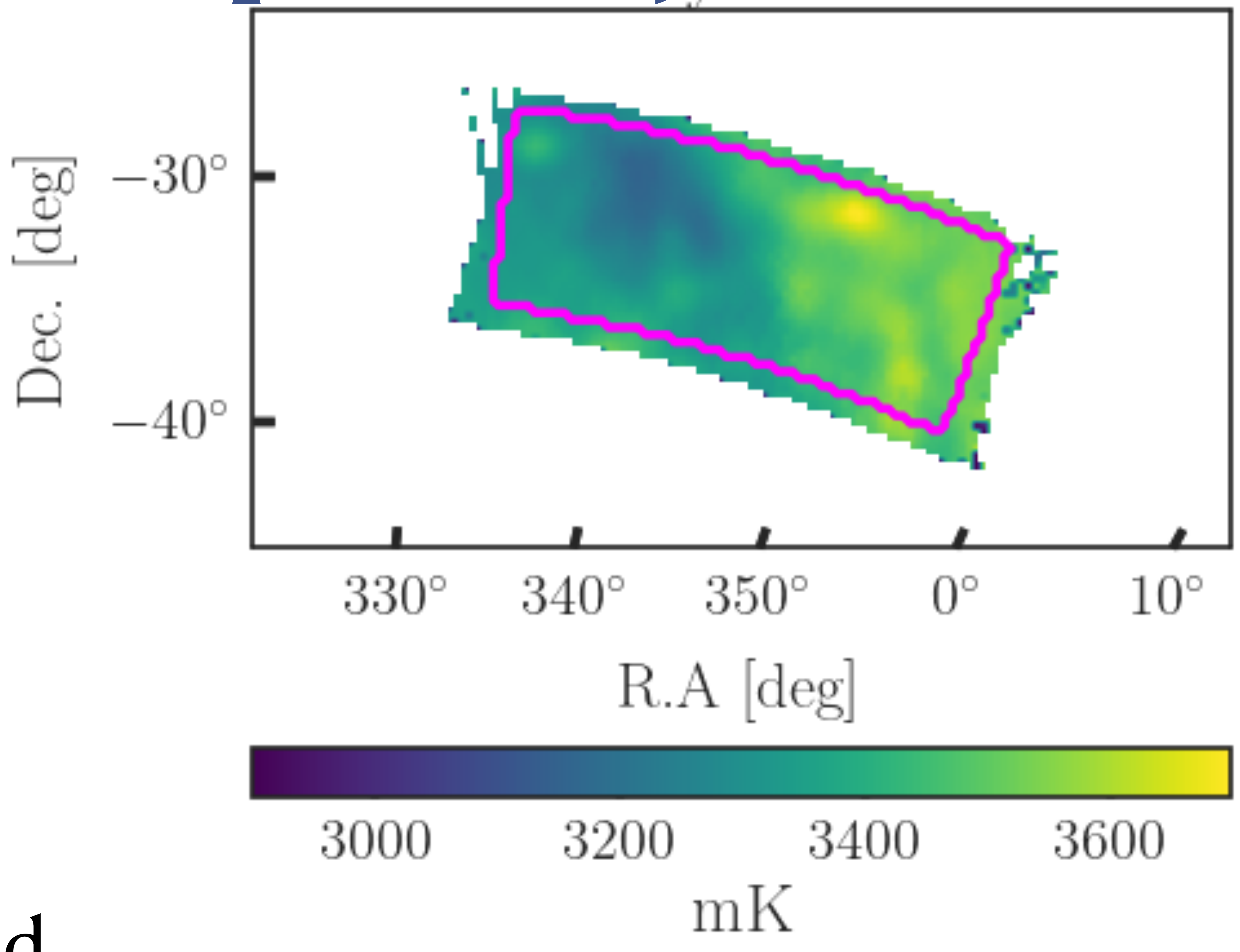
MeerKLASS 2021 deep survey

- MeerKAT Large Area Synoptic Survey
- Observations:
  - Area: 236 deg^2
  - Time: 62 hours (41 scans with 64 dishes)
- Frequency and redshift range
  - $971.2 \text{ MHz} < \nu < 1023.6 \text{ MHz} \rightarrow 0.388 < z < 0.463$
- Trimming performed to minimise the number of bad pixels
  - $334^\circ <$ R.A. $< 357^\circ$
  - $-34.5^\circ <$ dec $< -27.5^\circ$

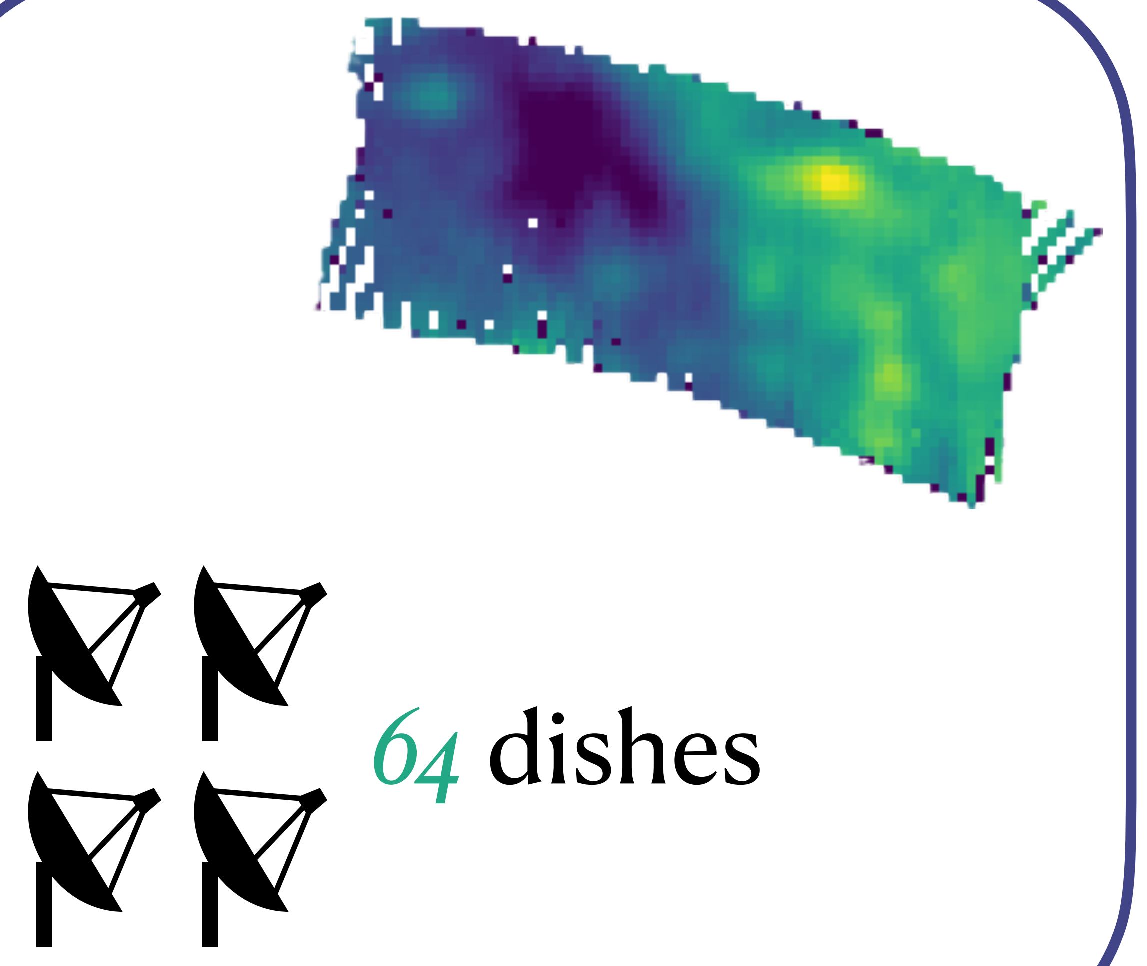


HI cosmological signal detected in cross-correlation with GAMA galaxies

[MeerKLASS Collaboration: Cunnington, Wang et al. (2025)
MeerKLASS Collaboration: MBS et al. (in prep.)]

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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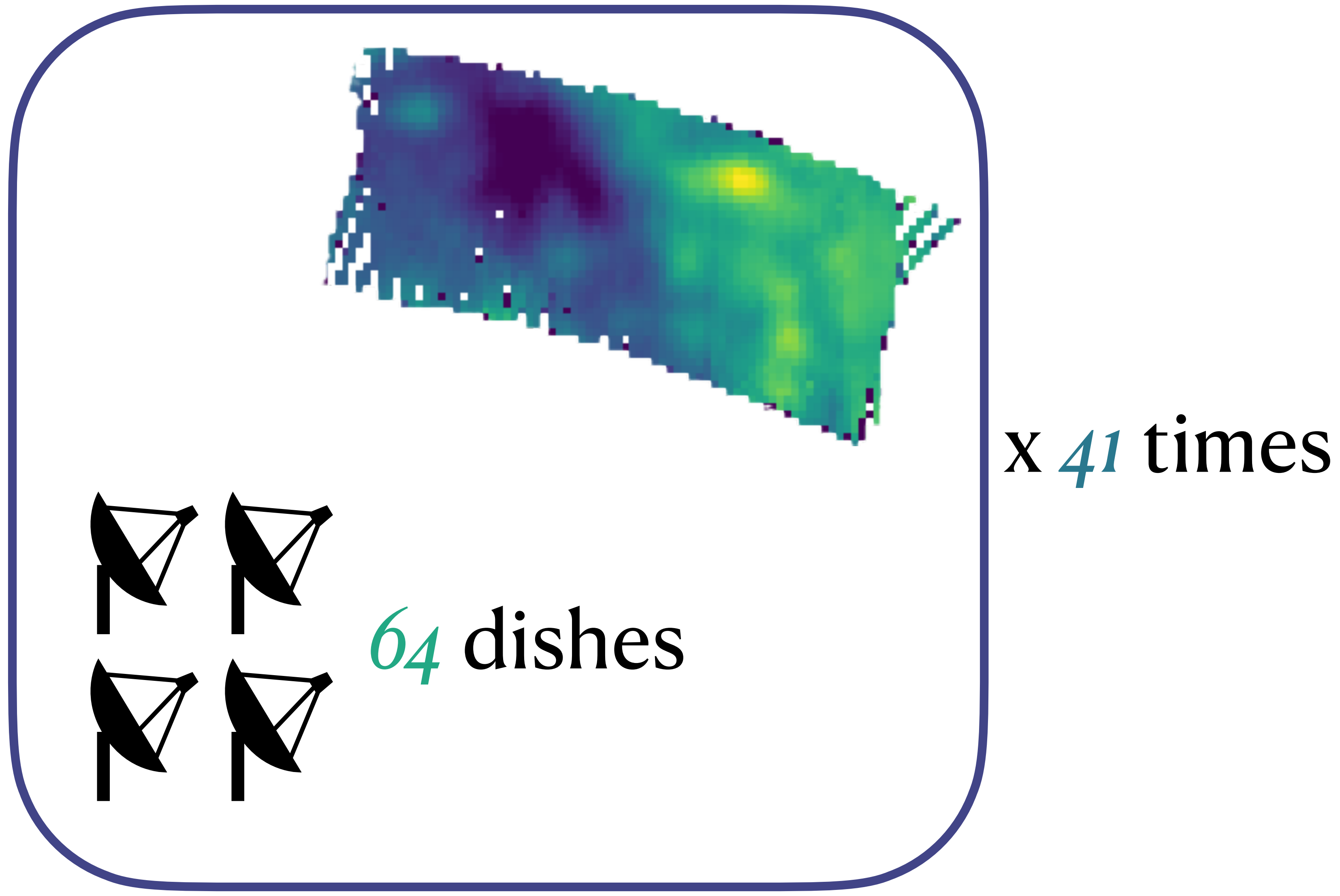

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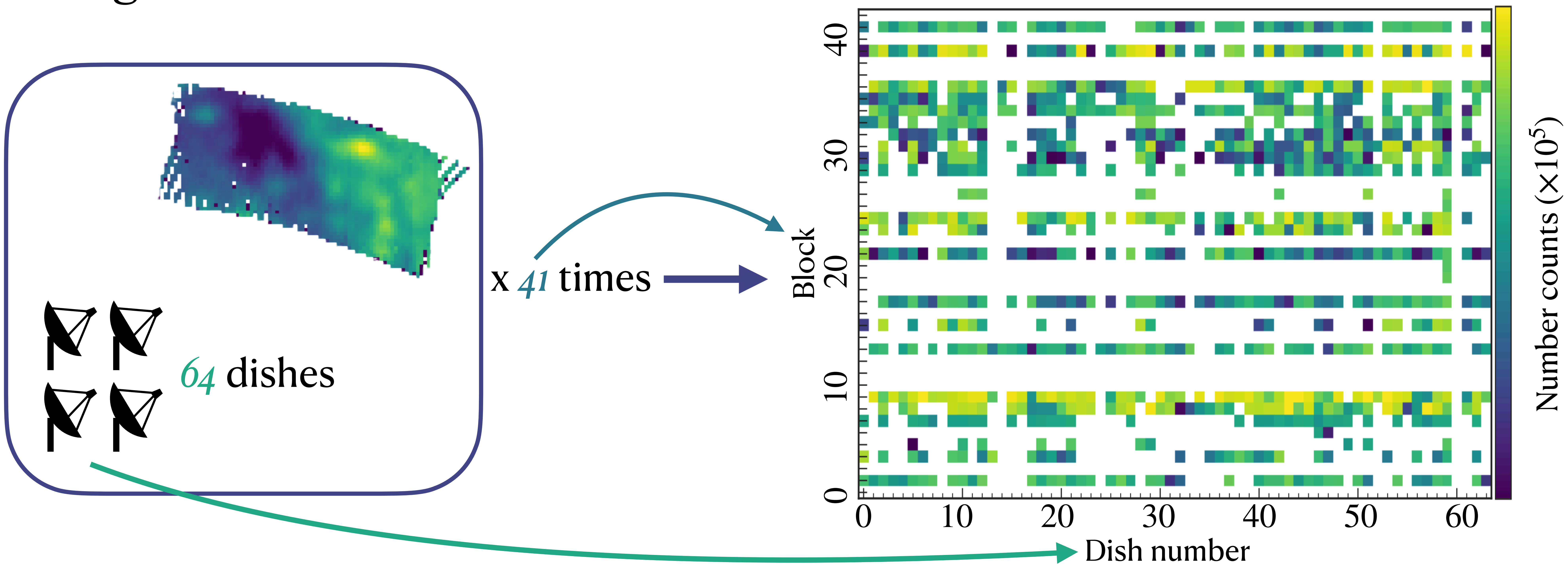

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Splitting the data set

- Building independent data sets from the same survey [Wolz et al. (2021)]
  - Contaminants not correlated between subsets
  - Noise free cross-subset power spectra
- Definition of subset with an equivalent signal-to-noise ratio

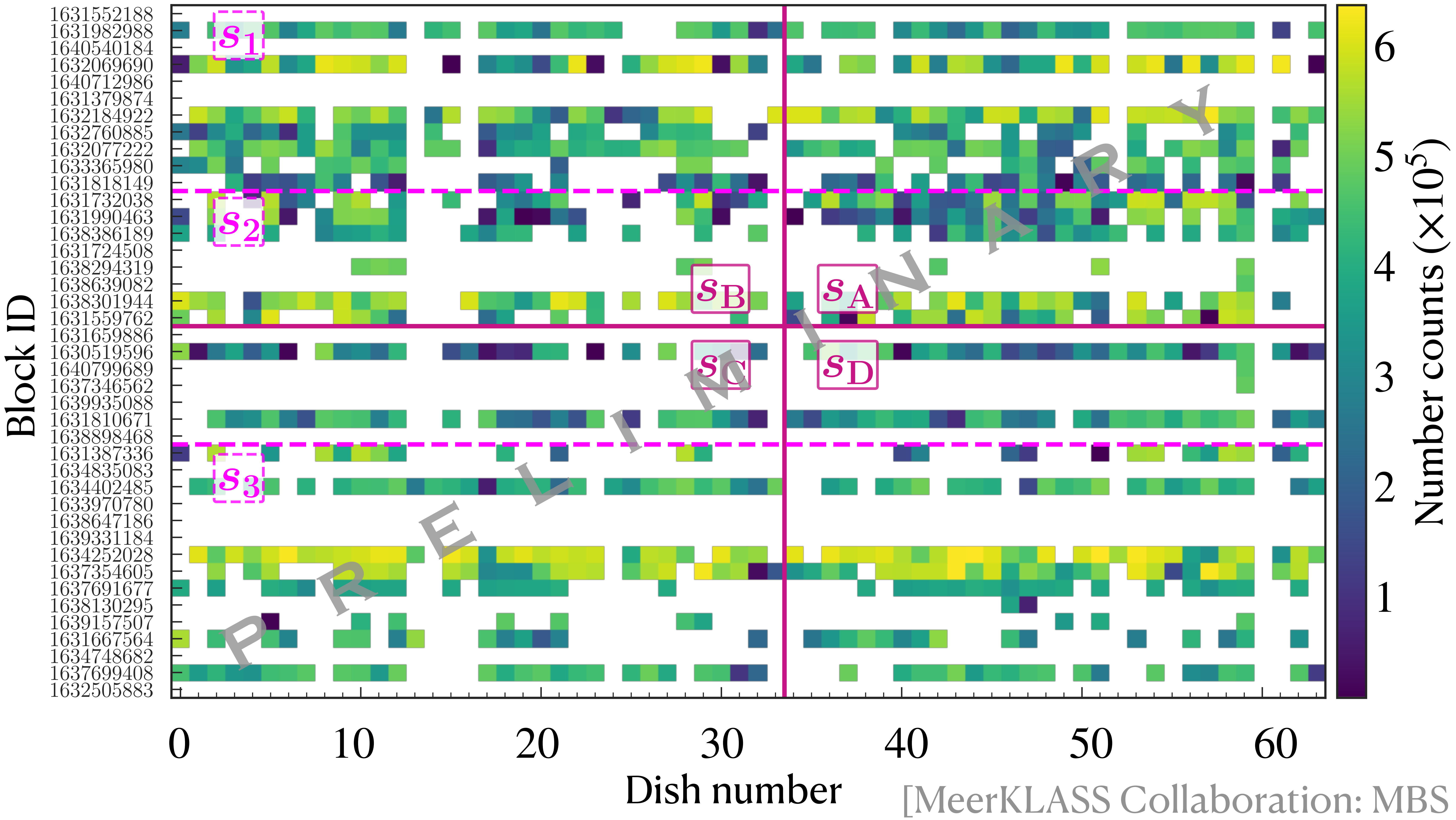
Splitting the data set

Chess-board division

- Block- and dish-wise splitting: s_A, s_B, s_C, s_D

Stripe division

- Block-wise splitting: s_1, s_2, s_3



→ ~ amount of information

[MeerKLASS Collaboration: MBS et al. (in prep.)]

Foreground cleaning: mPCA

- Blind cleaning method: PCA applied on large and small scales independently

- Scale separation through a wavelet filtering (using starlets) on the observed map of the subset s_i

Large scale fluctuations

$$s_i^{\mathrm{obs}} = s_i^{\mathrm{obs,L}} + s_i^{\mathrm{obs,L}}$$

Small scale fluctuations

- PCA analysis of the coarse and fine maps: removal of the first eigenmodes at large and small scales ($N_{\mathrm{fg,L}}$ and $N_{\mathrm{fg,S}}$)

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

- Successfully adopted for MeerKLASS 2019 L-Band data [Carucci et al. (2024)]

- Optimal cleaning level identified through guidance fits

[MeerKLASS Collaboration: MBS et al. (in prep.)]

Power spectrum estimation

- More processing: $s_i^{\text{clean}}(\text{R.A.}, \text{dec.}, \nu) \xrightarrow{\text{regridding}} s_i^{\text{clean}}(\mathbf{x}) \xrightarrow{\text{FFT}} \tilde{F}_i(\mathbf{k})$
- Power spectrum estimator (applied on the subsets i and j)

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

- Scale range
  - $n_k = 9$ k-bins
  - $0.095\, h\,\text{Mpc}^{-1} < k < 0.245\, h\,\text{Mpc}^{-1}$
  - $k_{\parallel,\text{min}} = 0.07\, h\,\text{Mpc}^{-1}$ $k_{\perp,\text{min}} = 0.02\, h\,\text{Mpc}^{-1}$ to avoid the region where signal loss and potential foreground residuals are more prominent

[MeerKLASS Collaboration: MBS et al. (in prep.)]

Global fits

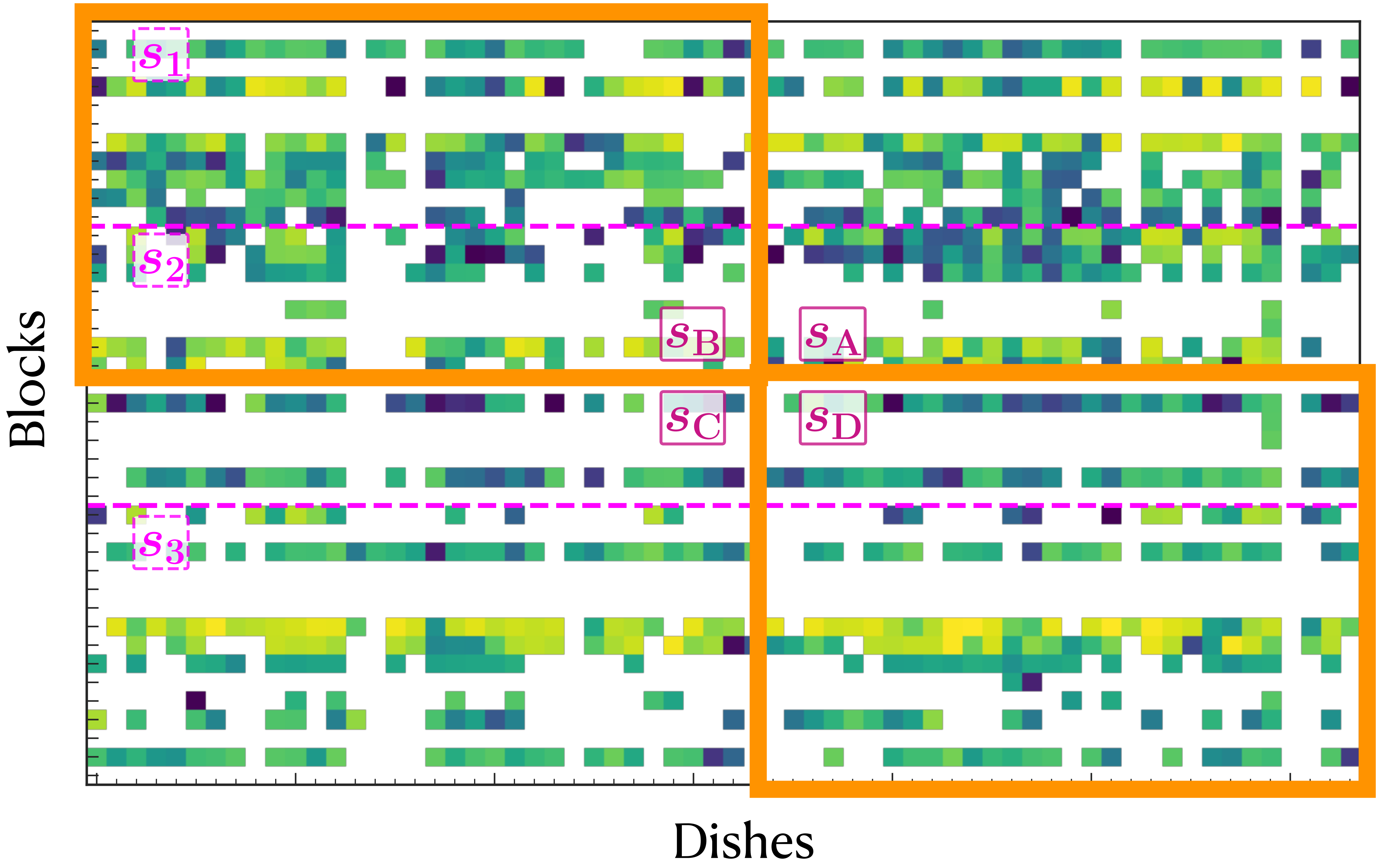
- Multi-tracer formalism translated to the multi-subset formalism to enhance the constraining power and robustness of the analysis
  - Cross-$P_{ij}(k)$ combined in a single data-vector
  - Auto-$P_{ii}(k)$ excluded from the analysis because noise dominated

[MeerKLASS Collaboration: MBS et al. (in prep.)]

Global fits: *Chess-board* division

- Multi-subset data vector including only "super" cross-$P_{ij}(k)$
  - Power spectra involving subsets that do not share nor blocks nor dishes
  - Most robust combinations available

$$P_{\text{xchess}} = \{P_{BD}, P_{AC}\}$$



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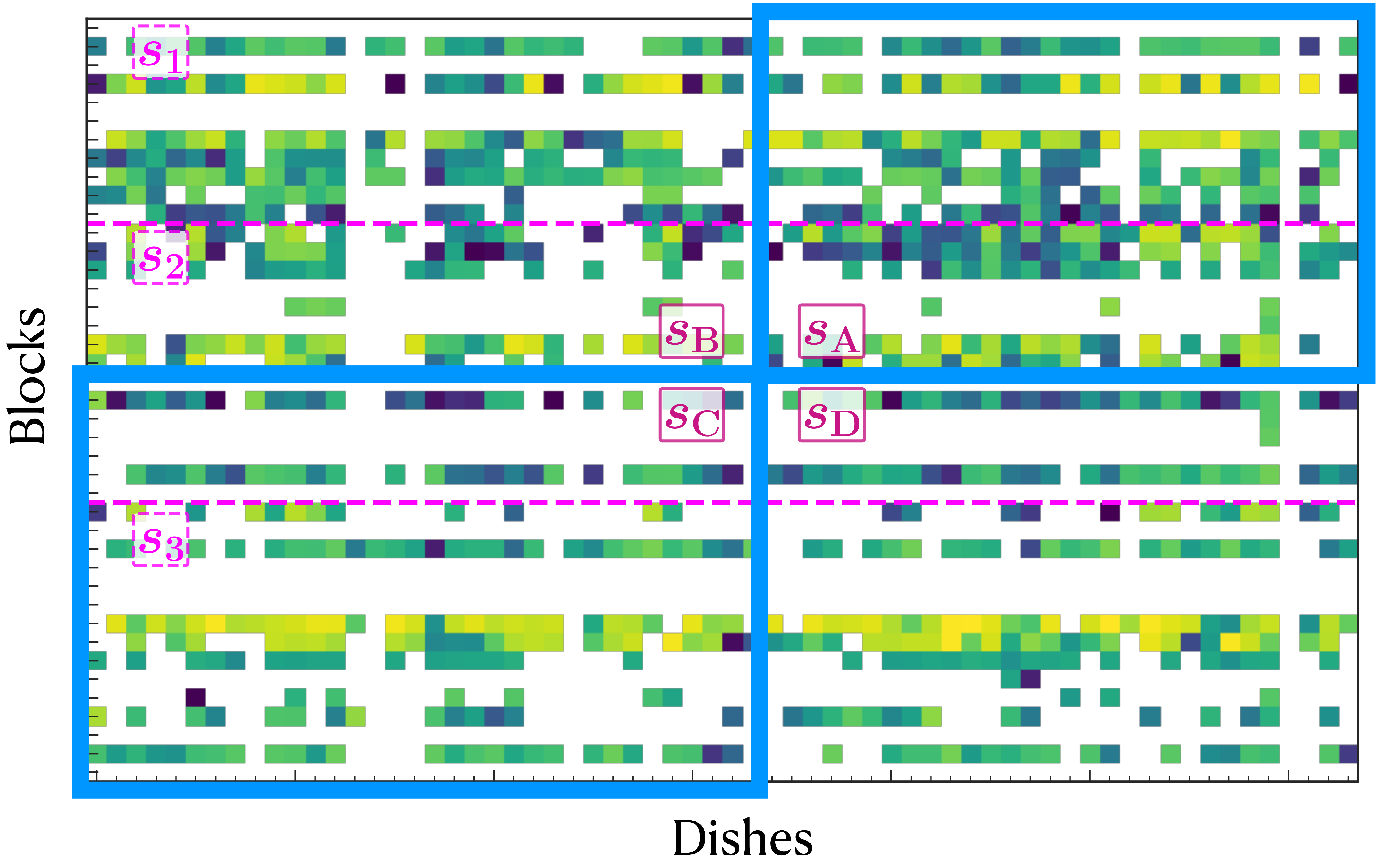

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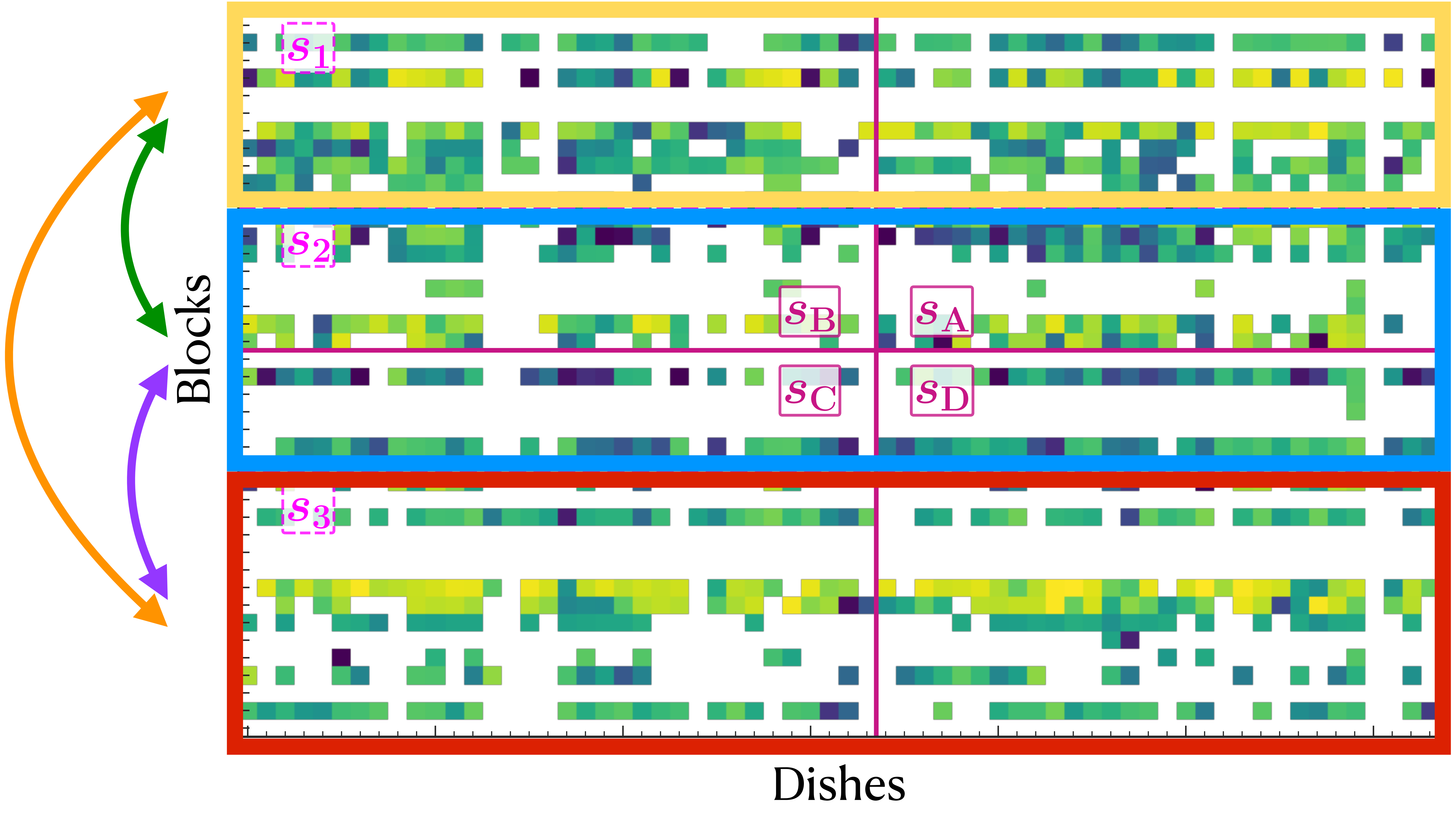
$$\mathsf{C}\left(P_{\rm xchess}, P_{\rm xchess}\right) = \begin{bmatrix} \mathsf{C}\left(P_{BD}, P_{BD}\right) & \mathsf{C}\left(P_{BD}, P_{AC}\right) \\ & \mathsf{C}\left(P_{AC}, P_{AC}\right) \end{bmatrix}$$

[MeerKLASS Collaboration: MBS et al. (in prep.)]

Global fits: *Stripes* division

- Multi-subset data vector including all the three available cross-$P_{ij}(k)$
- Potentially more prone to residual (dish-dependent) systematics

$$P_{\text{stripes}} = \{P_{12}, P_{13}, P_{23}\}$$



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Global fits

- MCMC fits of the multi-subsets data vectors against the model

$$P_{ij}(\mathbf{k}) = \mathscr{D}_{\mathrm{sl}}(k)\left[\mathscr{B}^2(\mathbf{k})T_{\mathrm{HI}}^2 b_{\mathrm{HI}}^2 \left(1+f\mu^2\right)^2 P_{\mathrm{m}}(k)\right] \text{ where } \begin{cases} T_{\mathrm{HI}}^2 b_{\mathrm{HI}}^2 = \text{HI brightness temperature } (\propto \Omega_{\mathrm{HI}}) \\ \qquad \text{and linear bias} \\ \mathscr{B}^2(\mathbf{k}) = \text{instrumental damping (mostly beam)} \\ \mathscr{D}_{\mathrm{sl}}(k) = \left(\frac{k}{h\,\mathrm{Mpc}^{-1}}\right)^{\beta} = \text{signal loss damping} \end{cases}$$

- $P_{ij}(\mathbf{k})$ spherically averaged $\rightarrow$ $P_{ij}(k)$
- Signal loss taken into account with a forward model approach
  - No reconstruction of the signal at the power spectrum level
  - Extra nuisance parameter in the model: β

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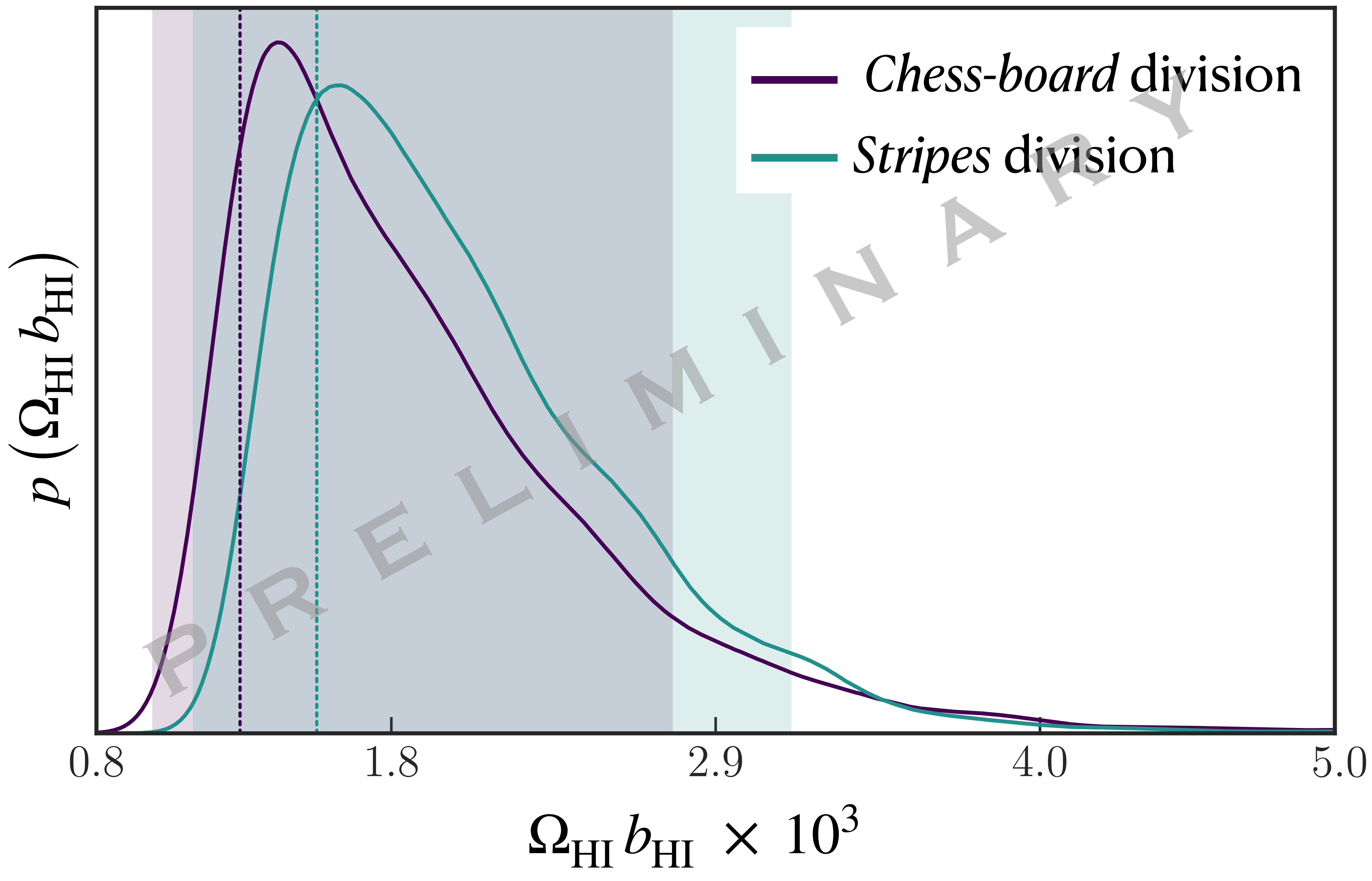
- $P_{ij}(\mathbf{k})$ spherically averaged $\rightarrow$ $P_{ij}(k)$
- Fit parameters
  - $\Omega_{\rm HI} b_{\rm HI}$ common to all cross-$P_{ij}(k)$
  - One nuisance β for each cross-$P_{ij}(k)$ in the data vector
- Jackknife covariance matrix

[MeerKLASS Collaboration: MBS et al. (in prep.)]

Results

- High detection significance
- Good internal consistency (but *chess-board* division confirmed to be more robust than the *stripe* division)
- Positive outcomes from stress tests performed
- Agreement with previous detections:
  - MeerKLASS 2019 L-band survey in cross-correlation with WiggleZ galaxies [Cunnington, Li et al. (2022), Carucci et al. (2024)]
  - MeerKLASS 2021 L-band survey in cross-correlation with GAMA galaxies [MeerKLASS Collaboration: Cunnington, Wang et al. (2025)]



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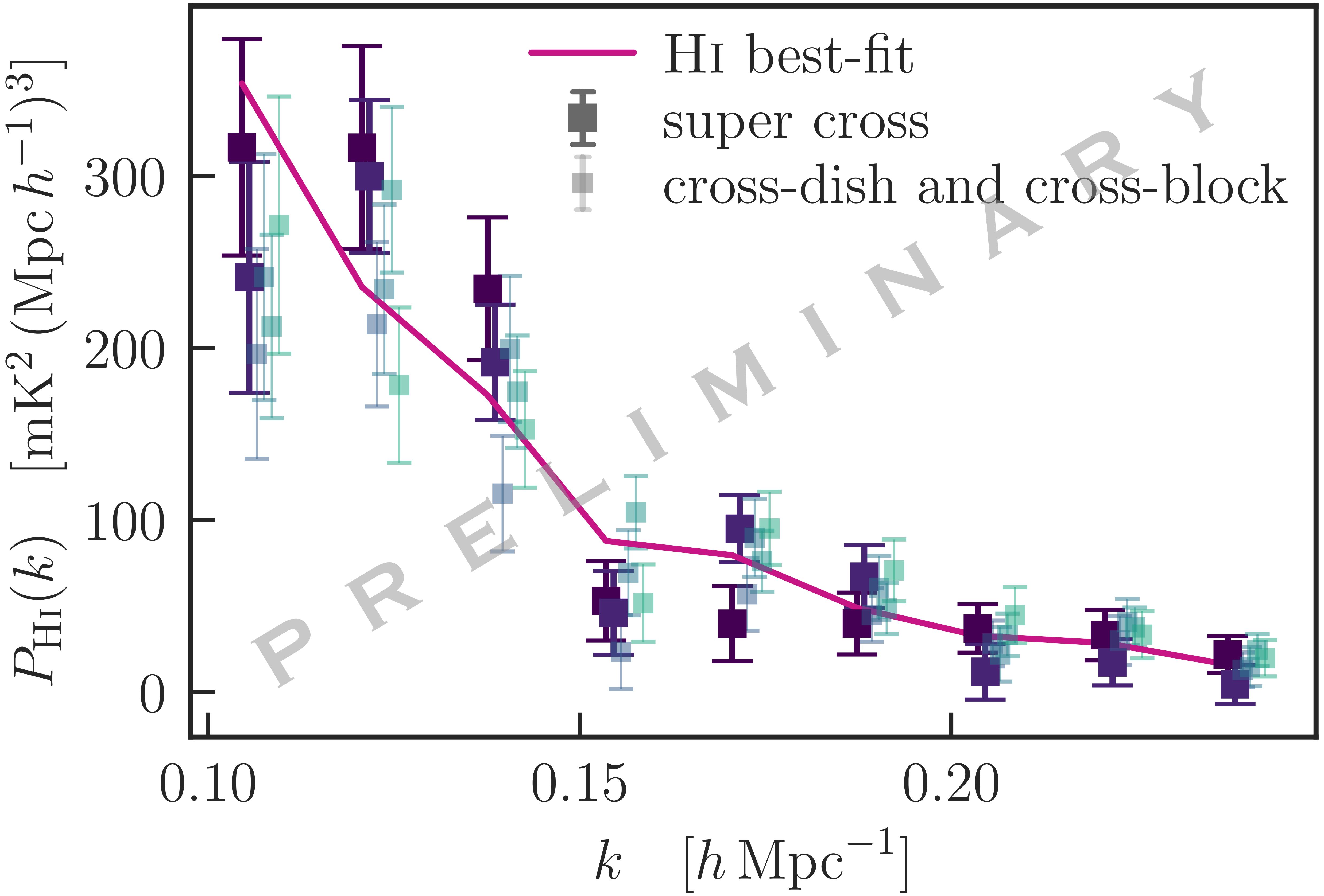
Focus on the *chess-board* division

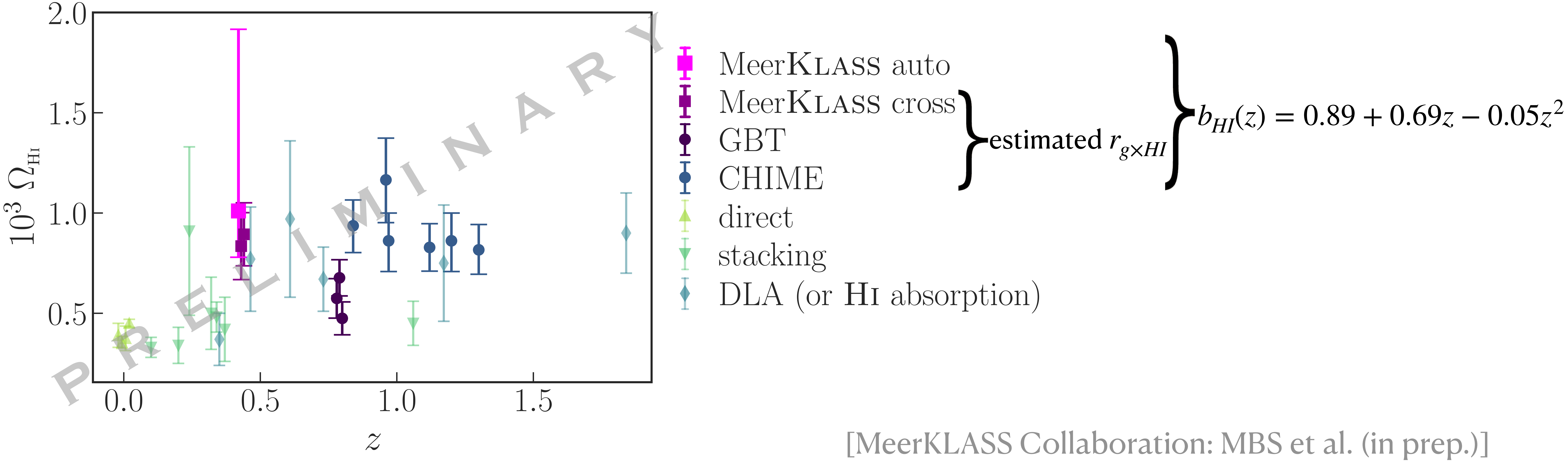
$\chi^2_{\text{red}} \sim 1.00$ SNR ~ 10.1



[MeerKLASS Collaboration: MBS et al. (in prep.)]

MeerKLASS in the HI landscape

- A comparison with other measurements of the abundance of HI
  - Other intensity mapping measurements (but in cross correlation with galaxies) $\rightarrow$ $\Omega_{\rm HI}\, b_{\rm HI}\, r_{g\times \rm HI}$
  - Direct measurements $\rightarrow$ $\Omega_{\rm HI}$
  - Staking measurements $\rightarrow$ $\Omega_{\rm HI}$
  - Damped Lyman-α measurements $\rightarrow$ $\Omega_{\rm HI}$
  - HI absorption measurements $\rightarrow$ $\Omega_{\rm HI}$



[MeerKLASS Collaboration: MBS et al. (in prep.)]

Conclusions

- 21 cm intensity mapping is challenging but it has a great potential for probing the large scale structure of the Universe
- The MeerKLASS collaboration is successfully demonstrating the feasibility of such a technique, paving the way for SKAO
  - Development of calibration pipelines [Wang et al. (2021), MeerKLASS Collaboration: Cunnington, Wang et al. (2025)]]
  - Development of optimized foreground cleaning techniques [Carucci et al. (2024)] and methods to extract the information embedded in the data [Cunnington et al. (2023), Chen et al. (2025), ...]
  - Detections of the HI signal in cross-correlation with galaxies [Cunnington, Li et al. (2022), Carucci et al. (2024), MeerKLASS Collaboration: Cunnington, Wang et al. (2025)]
  - Detection of the HI signal independently on external data sets [MeerKLASS Collaboration: MBS et al. (in prep.)]