Unveiling the HI power spectrum with MeerKLASS

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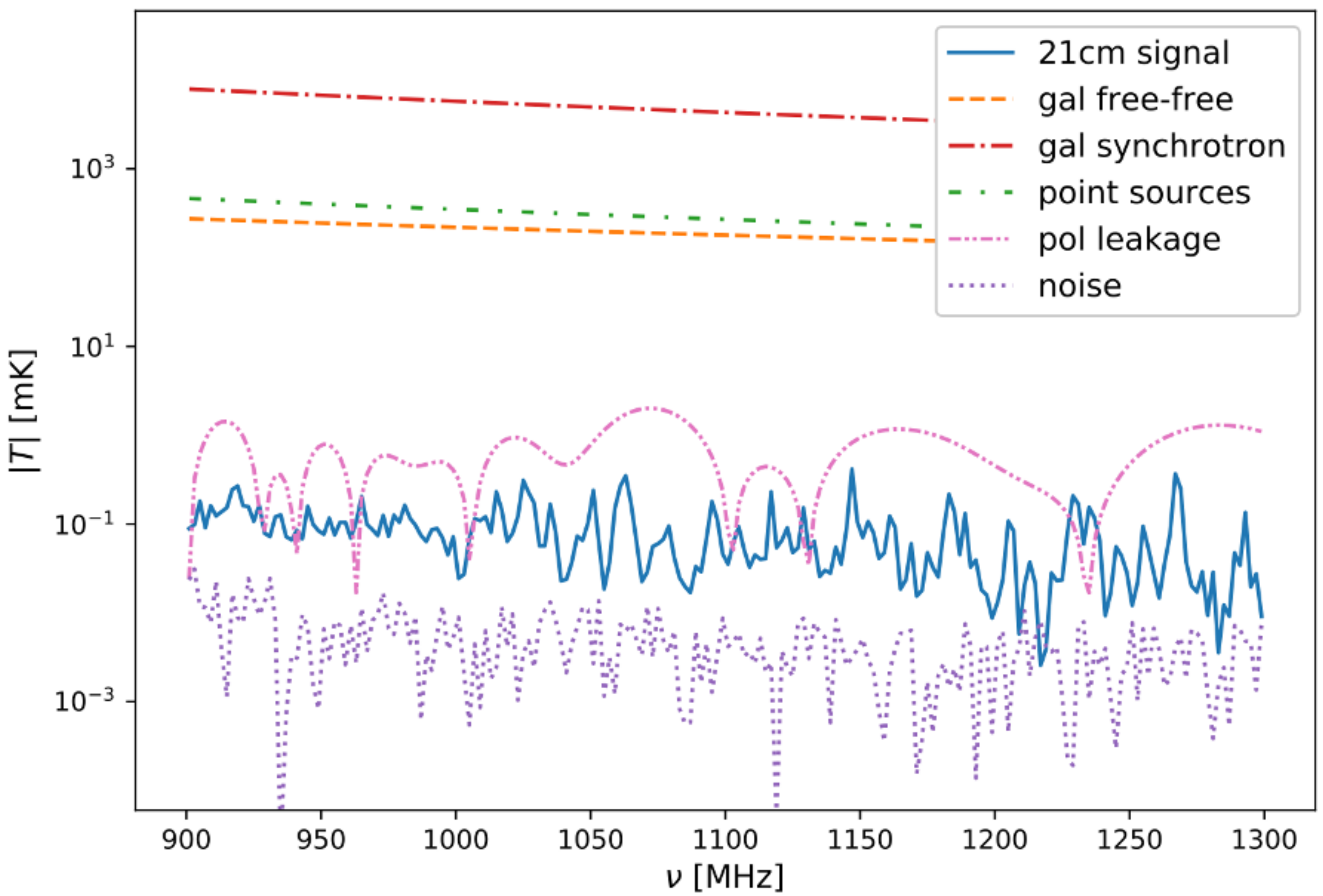
New Physics from Galaxy Clustering at GGI

Firenze, October 2nd 2025

HI intensity mapping

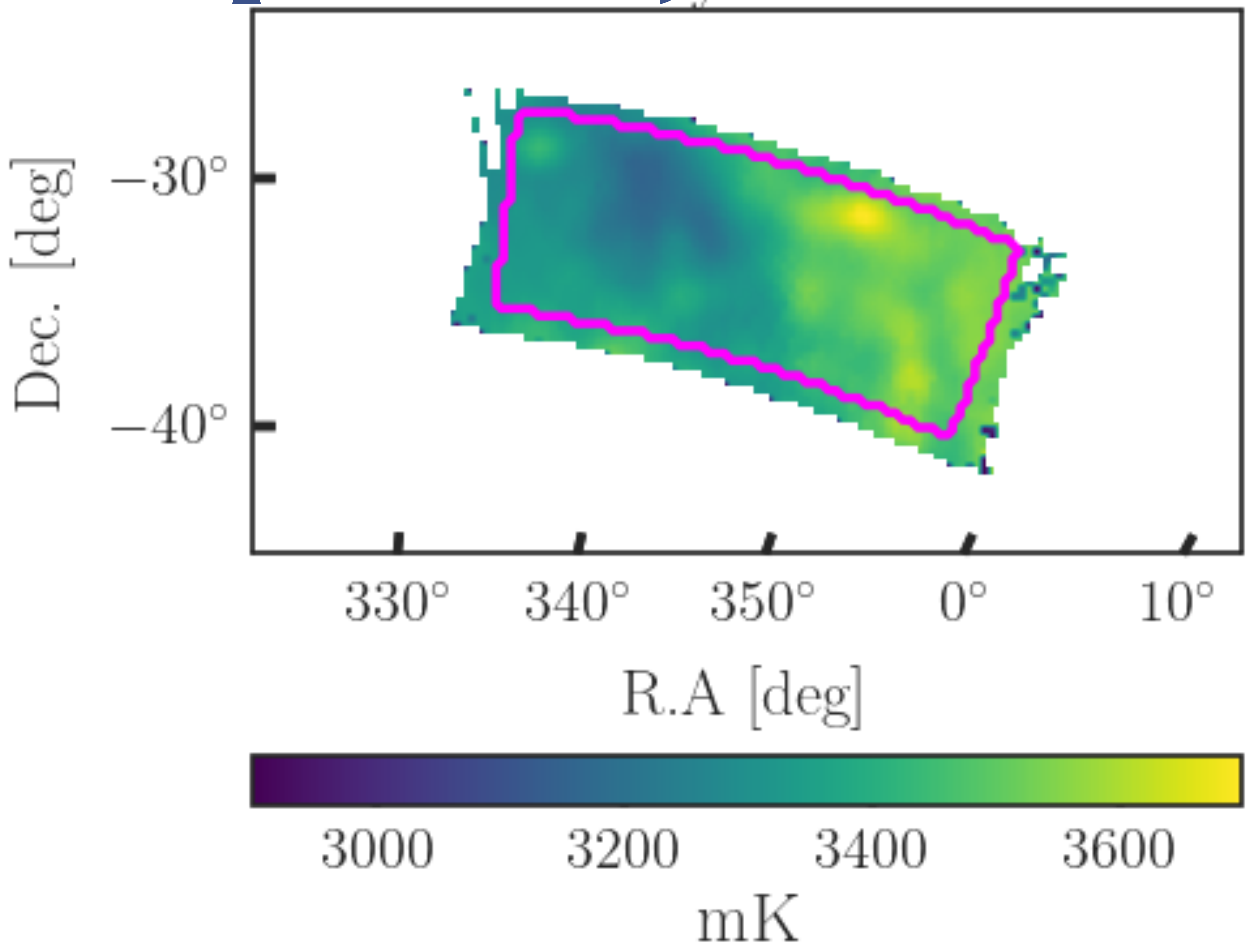
- HI as tracer of the matter distribution
- Emission from the hyperfine transition of HI
- Amplitude of the signal dependent on the clustering of HI
- Wide redshift range
- Not only cosmological signal
  - Astrophysical foregrounds: galactic and extragalactic
  - Contaminants: Radio Frequency Interference (RFI), instrumental contaminations...

[Carucci et al. (2020)]



MeerKLASS 2021 deep survey

- MeerKAT Large Area Synoptic Survey
- Observations in single dish mode:
  - Area: 236 deg^2
  - 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, Wang et al. (2025)
MeerKLASS Collaboration: MBS et al. (in prep.)]

Single dish technique

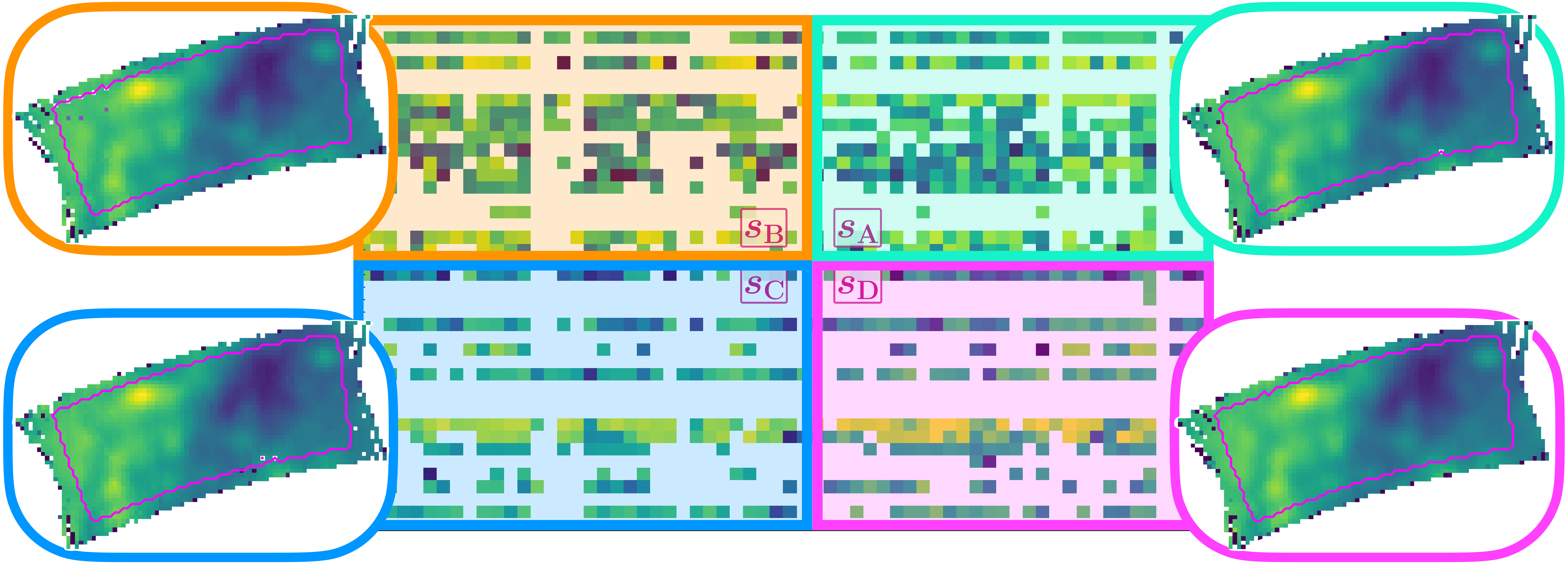
- All the antennas of the array observe the same region at the same
- Low angular-resolution survey of the total 21cm flux from unresolved sources
- High signal-to-noise ratio (SNR)
- Large cosmic volumes covered

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 (SNR)

Splitting the data set

- *Chess-board* division: block- and dish-wise splitting: s_A, s_B, s_C, s_D
- Minimum number of subset (highest SNR) to cover all possible cross-correlations



[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

$$s_i^{\text{obs}} = \underbrace{s_i^{\text{obs,L}}}_{\text{Large scale fluctuations}} + \underbrace{s_i^{\text{obs,L}}}_{\text{Small scale fluctuations}}$$

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

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

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

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

Power spectrum estimation

- More processing: $s_i^{\mathrm{clean}}(\mathrm{R.A.}, \mathrm{dec.}, \nu) \xrightarrow{\text{regridding}} s_i^{\mathrm{clean}}(\mathbf{x}) \xrightarrow{\text{FFT}} \tilde{F}_i(\mathbf{k})$

- Power spectrum estimator (applied on the subsets i and j)

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

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

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

Global fits

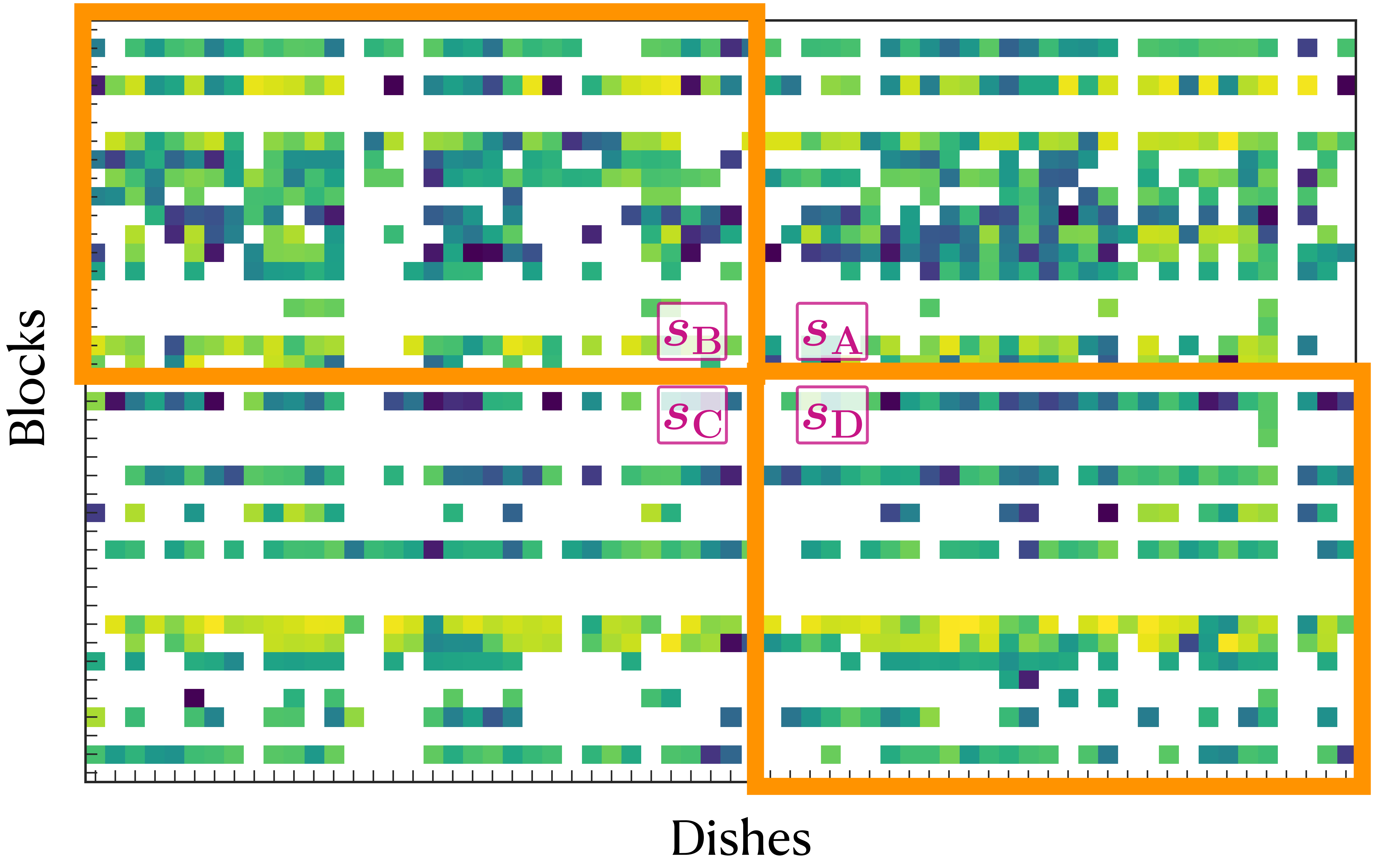
- Multi-tracer formalism translated to the multi-subset formalism to enhance the constraining power and robustness of the analysis
  - Cross-$P_{ij}(k)$ combined in a single data-vector
  - Auto-$P_{ii}(k)$ excluded from the analysis because noise dominated

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

Global fits

- 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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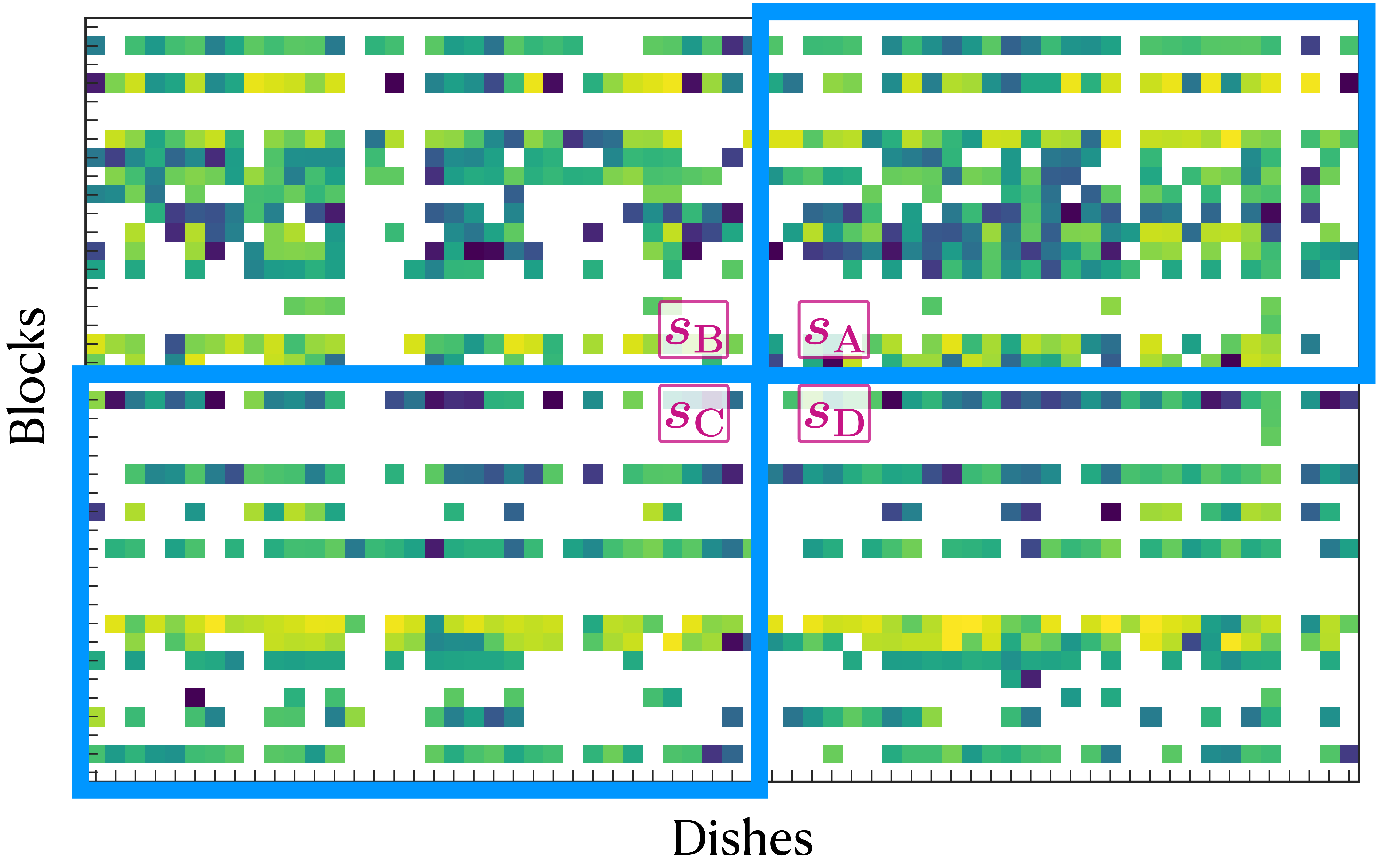

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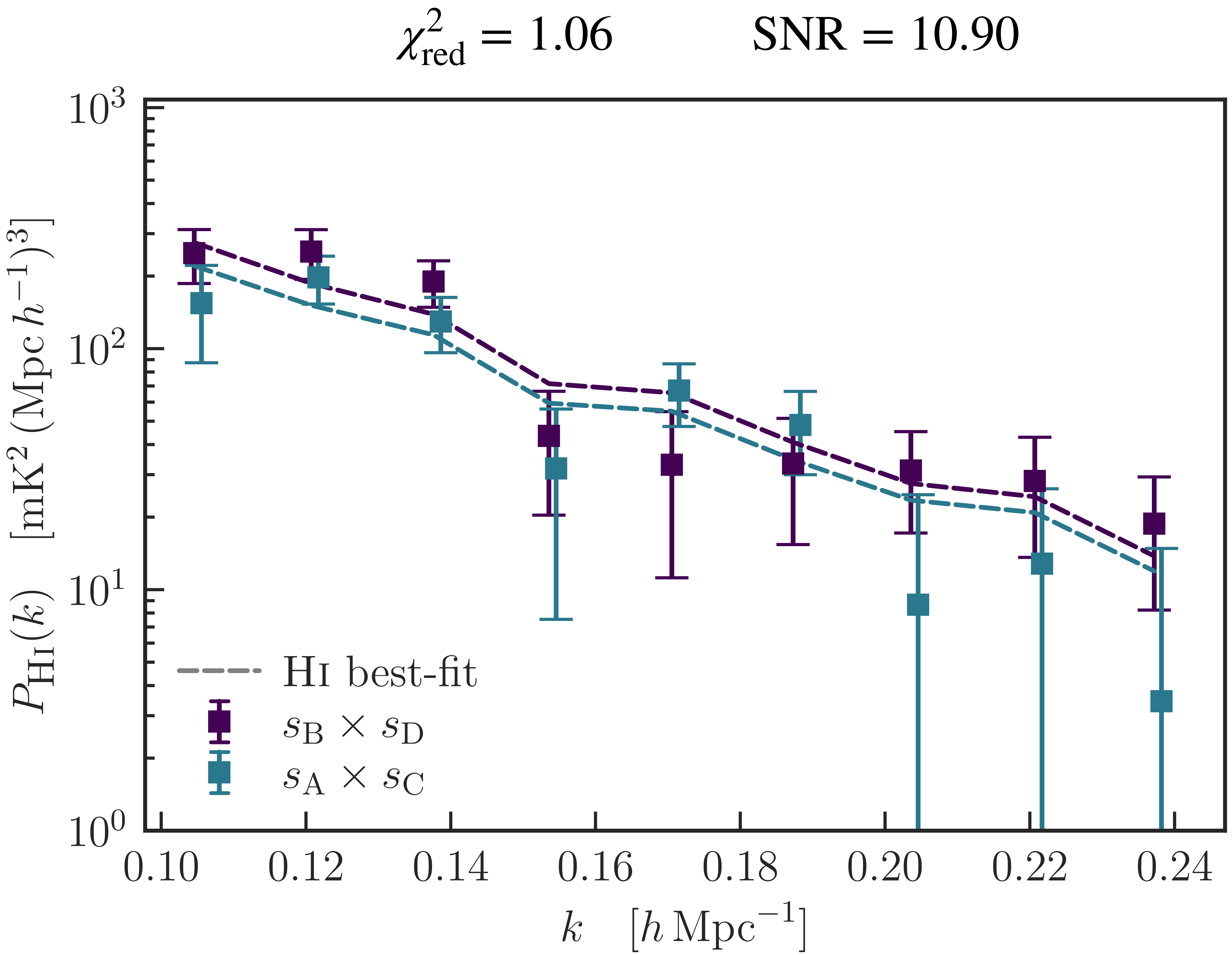
$$\mathsf{C}\left(P_{\text{xchess}}, P_{\text{xchess}}\right) = \begin{bmatrix} \mathsf{C}\left(P_{BD}, P_{BD}\right) & \mathsf{C}\left(P_{BD}, P_{AC}\right) \\ & \mathsf{C}\left(P_{AC}, P_{AC}\right) \end{bmatrix}$$ with jackknife method

- Free parameters
  - Power spectrum amplitude common to all cross-$P_{ij}(k)$: $\Omega_{\text{HI}} b_{\text{HI}}$ (HI abundance and linear bias)
  - One signal loss nuisance parameter for each cross-$P_{ij}(k)$ in the data vector

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

Results

- High detection significance
- Good internal consistency
- 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)]



[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 demonstrating the feasibility of this technique
  - Development of calibration pipelines [Wang et al. (2021), MeerKLASS Collaboration: Cunnington, Wang et al. (2025)], 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)]
  - First data release (2019 L-band pilot survey): meerklass.org/data
  - **Direct measurement of the HI cosmological signal independently on external tracers** [MeerKLASS Collaboration: MBS et al. (in prep.)]