Launching the *ultra*-large-scale era with radio intensity mapping

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Cosmology in the Alps

Les Diablerets - 18th March 2024

MANCHESTER 1824

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Image: SOUTH AFRICAN RADIO ASTRONOMY OBSERVATORY

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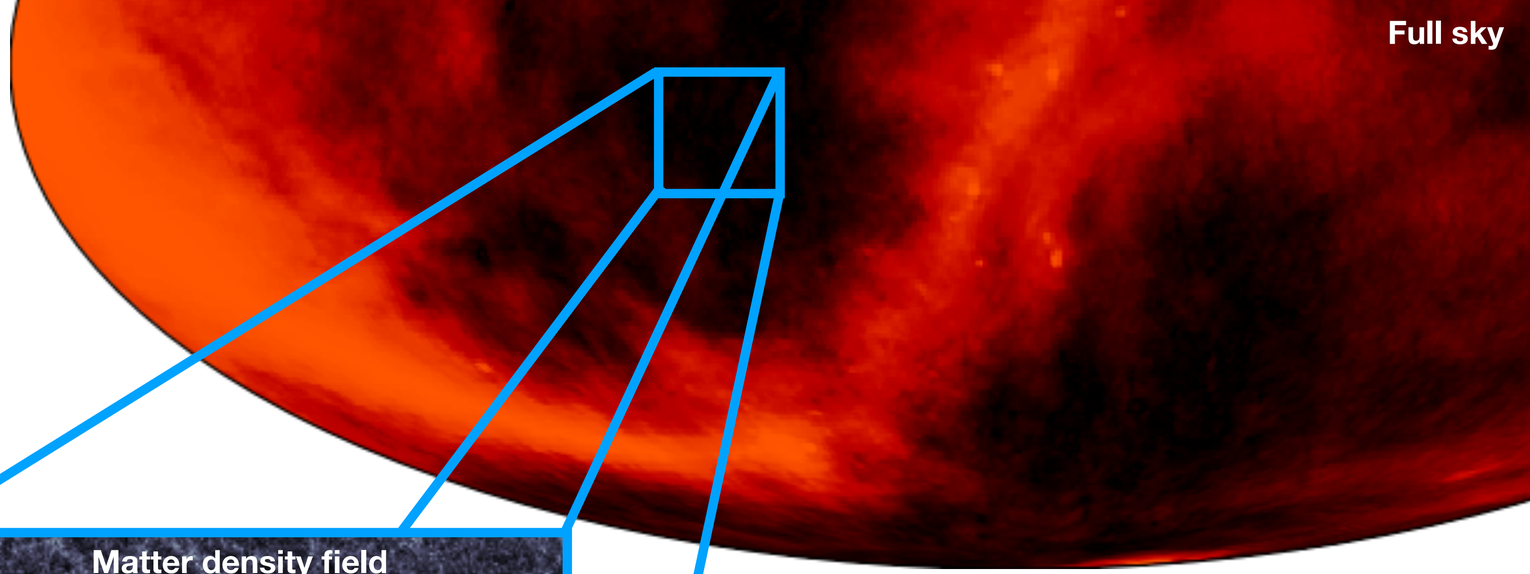
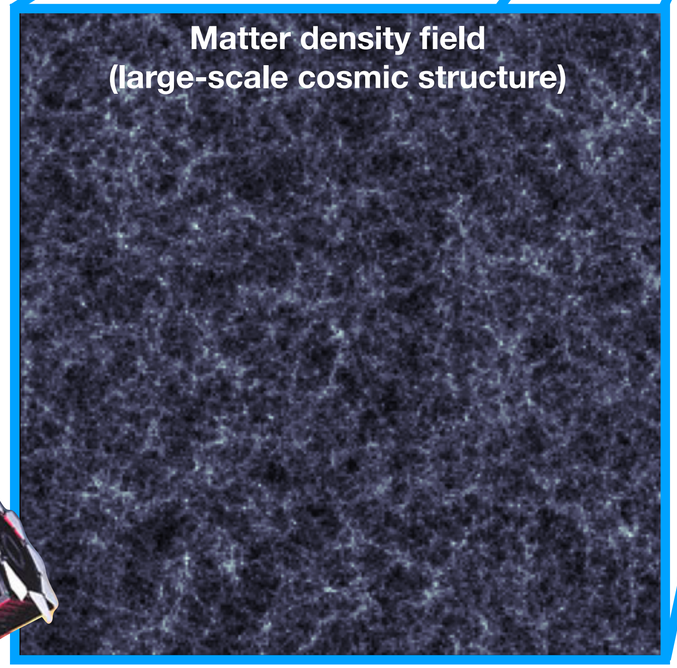
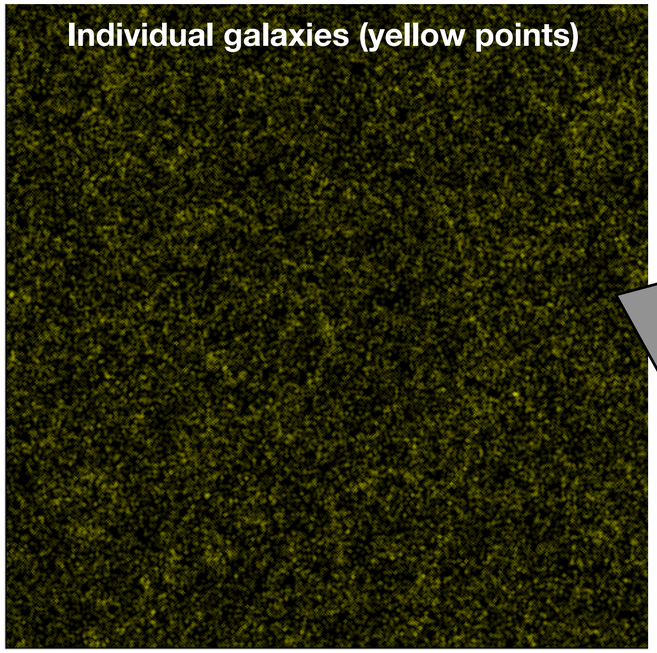
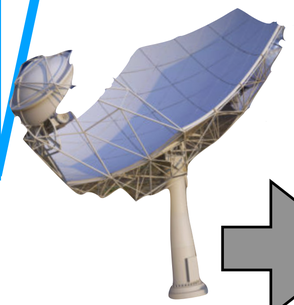
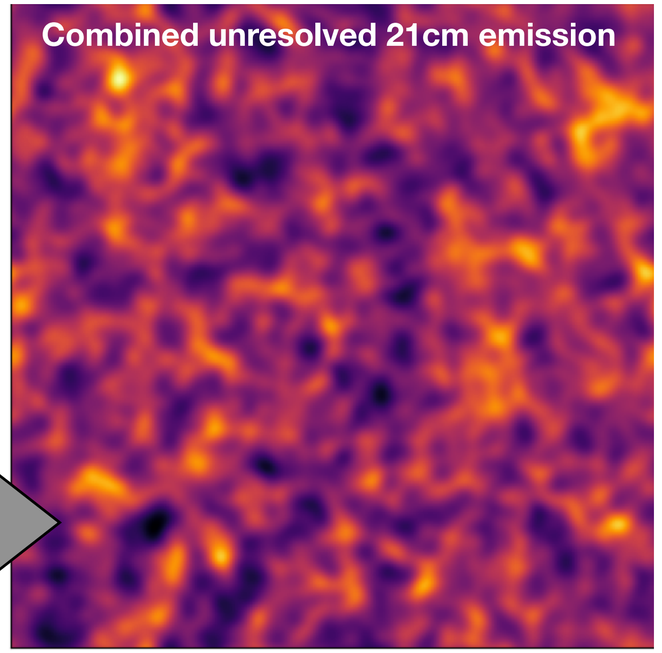
Intensity mapping
instead of galaxy cataloguing











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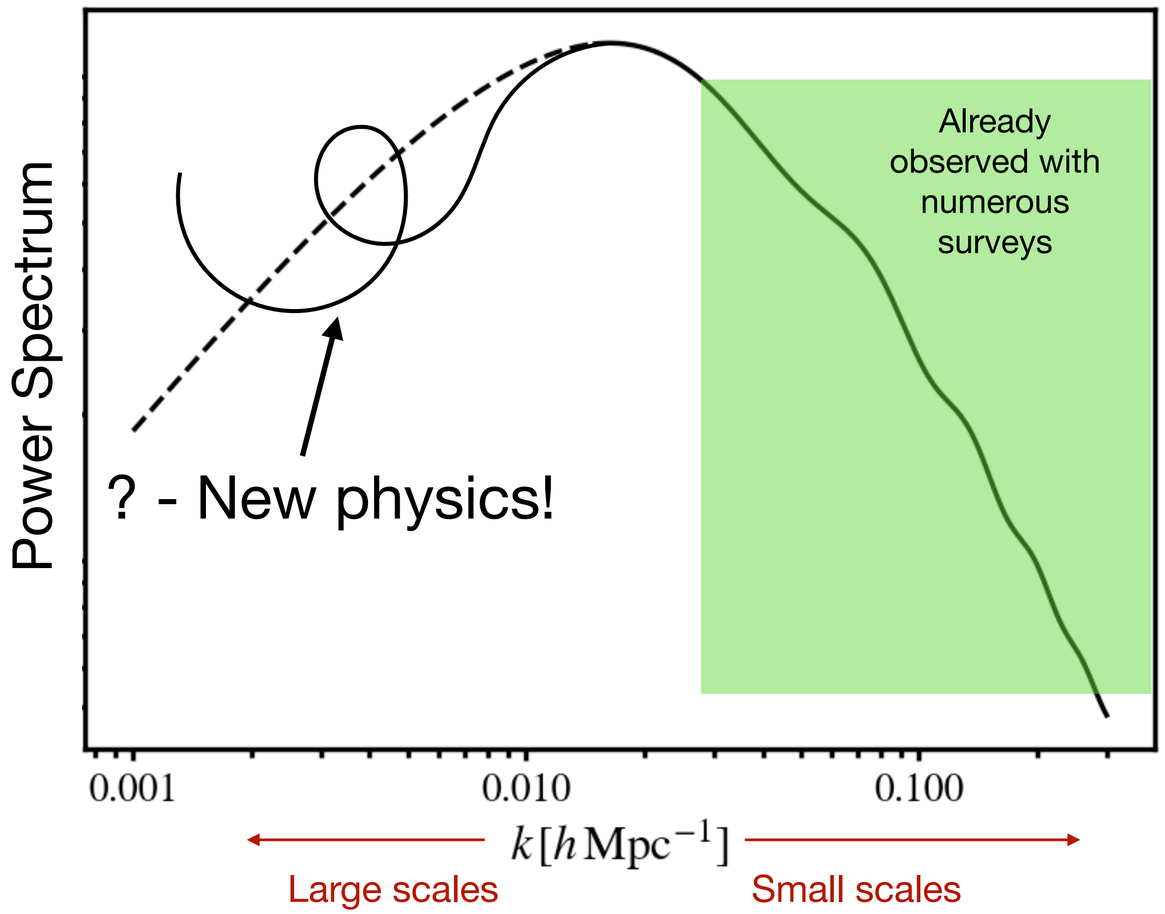
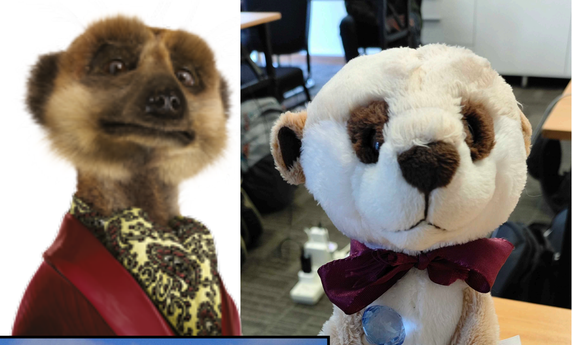
Why aim to probe the largest cosmological scales?

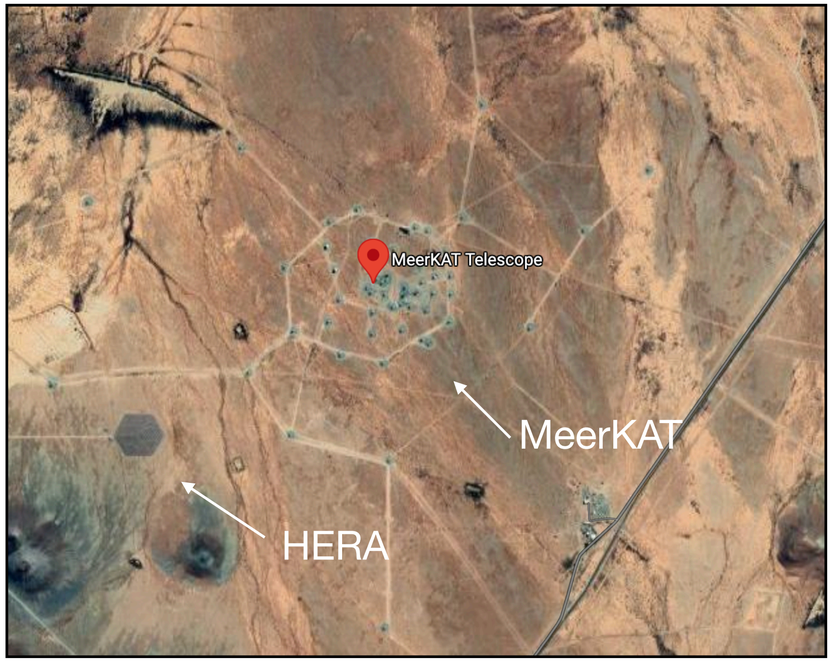


- ☑ Probe primordial inflation
- ☑ New test of general relativity
- ☑ Access to *linear* scales

SKAO pathfinder: MeerKAT



- 64 dishes to merge with full SKA-MID
- $0.2 < z < 0.58$ (L-band)
- $0.4 < z < 1.45$ (UHF-band)



MeerKLASS
(MeerKAT Large Area Synoptic Survey)
- rely on single-dish mode observations (not interferometer)

- Several pilot surveys already complete
- 10,000 deg^2 survey **commencing now/early 2024**

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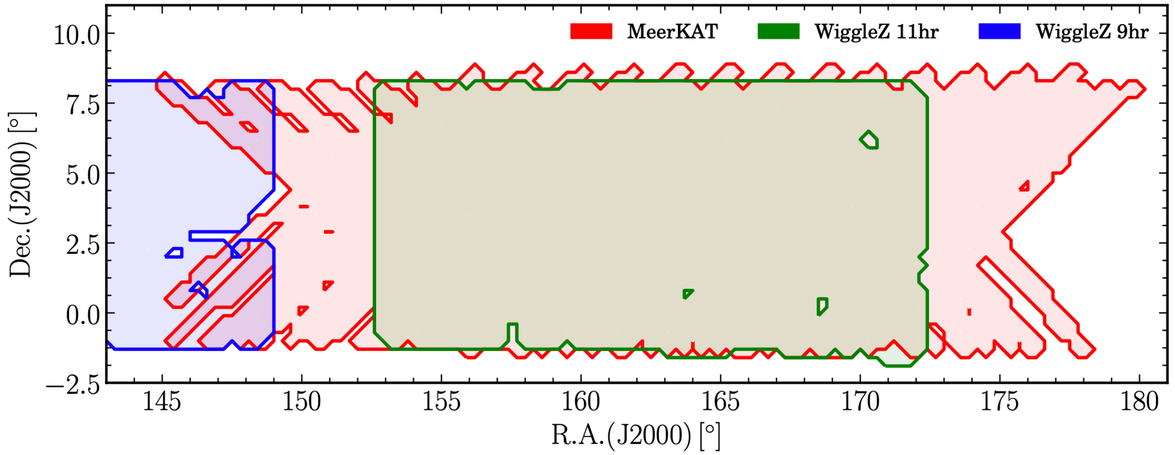
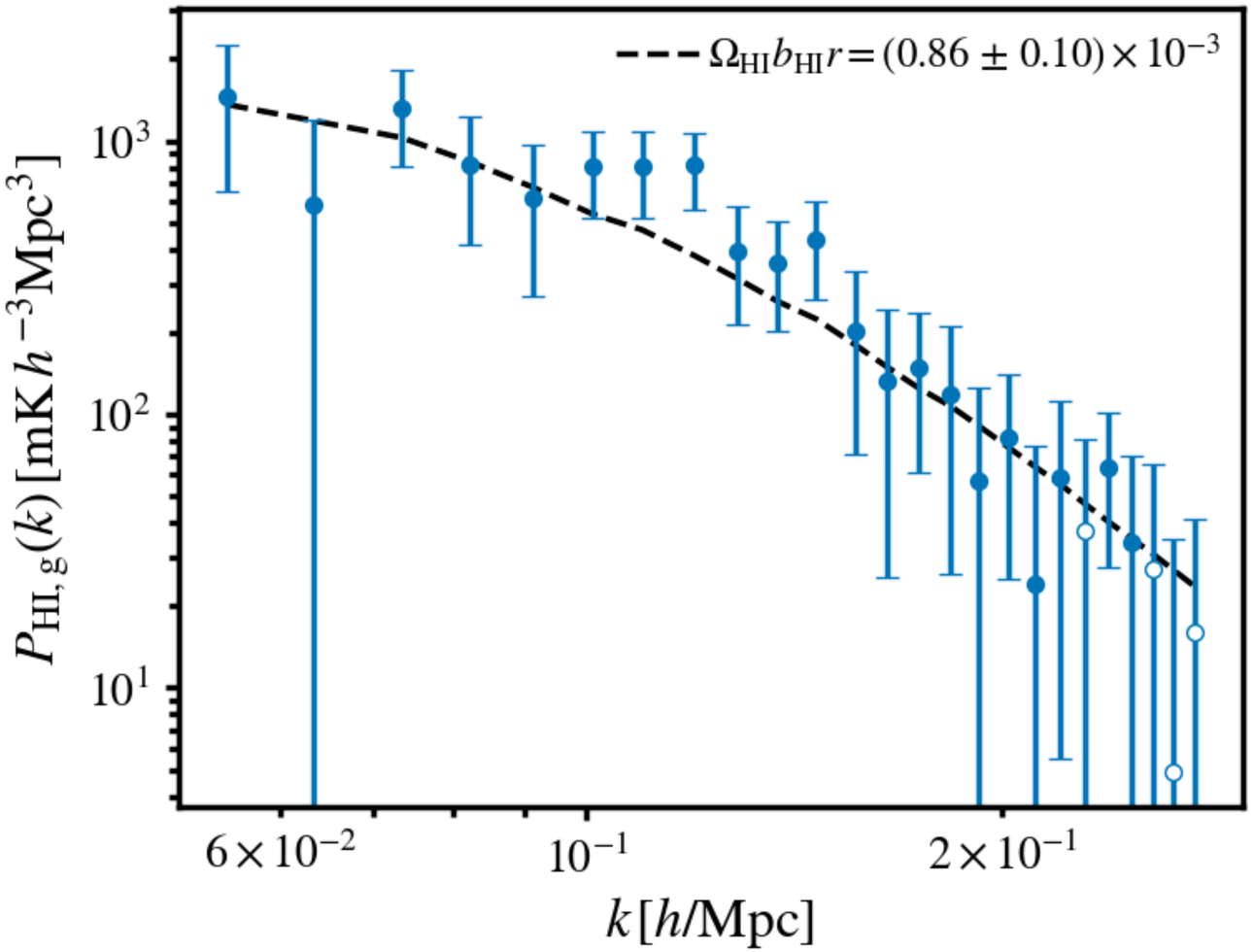
Detecting cosmological clustering with MeerKLASS pilot intensity mapping survey



- Positive correlation (7.7σ) between galaxy survey and array of dishes in single-dish mode
- The first detection of its kind
- Important milestone for doing LSS cosmology with SKA intensity mapping

S.Cunnington+23 [arXiv:2206.01579]



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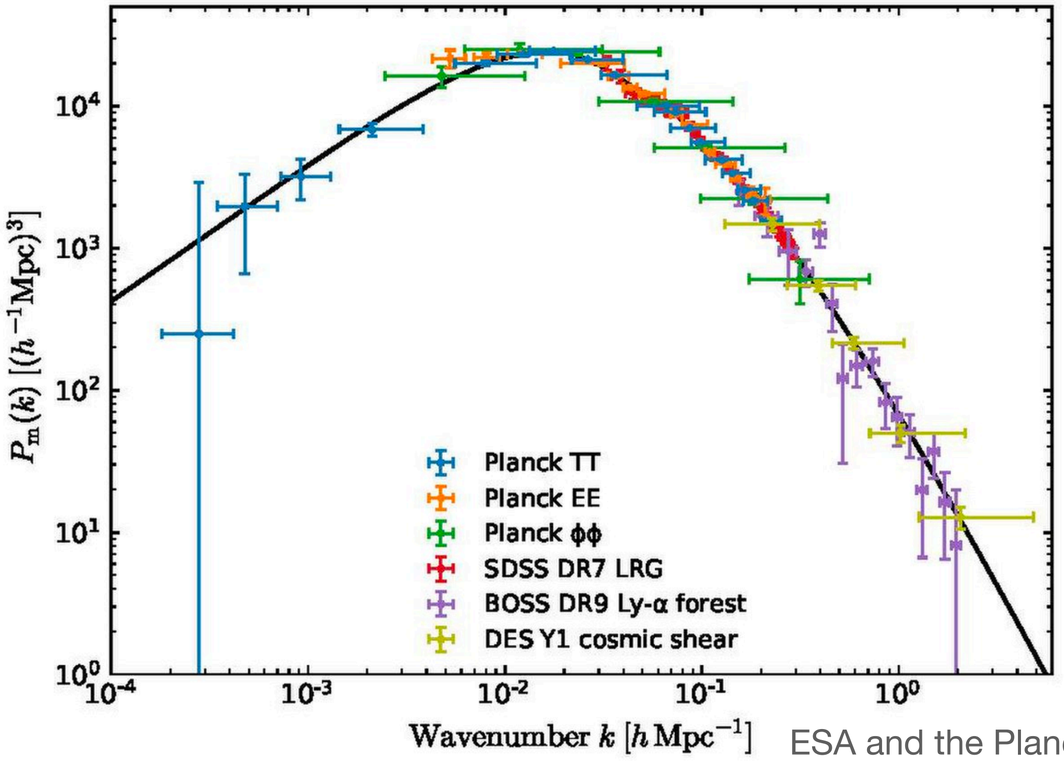
Observations on the sky

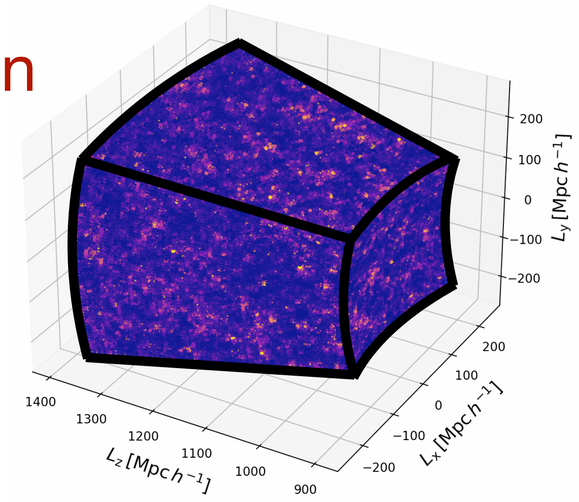
Analysis in Cartesian space



ESA and the Planck Collaboration

3D **Fourier-space** clustering analysis require observations in **Cartesian** *comoving* (Mpc/*h*) space

➡ Require transformation of voxel intensities



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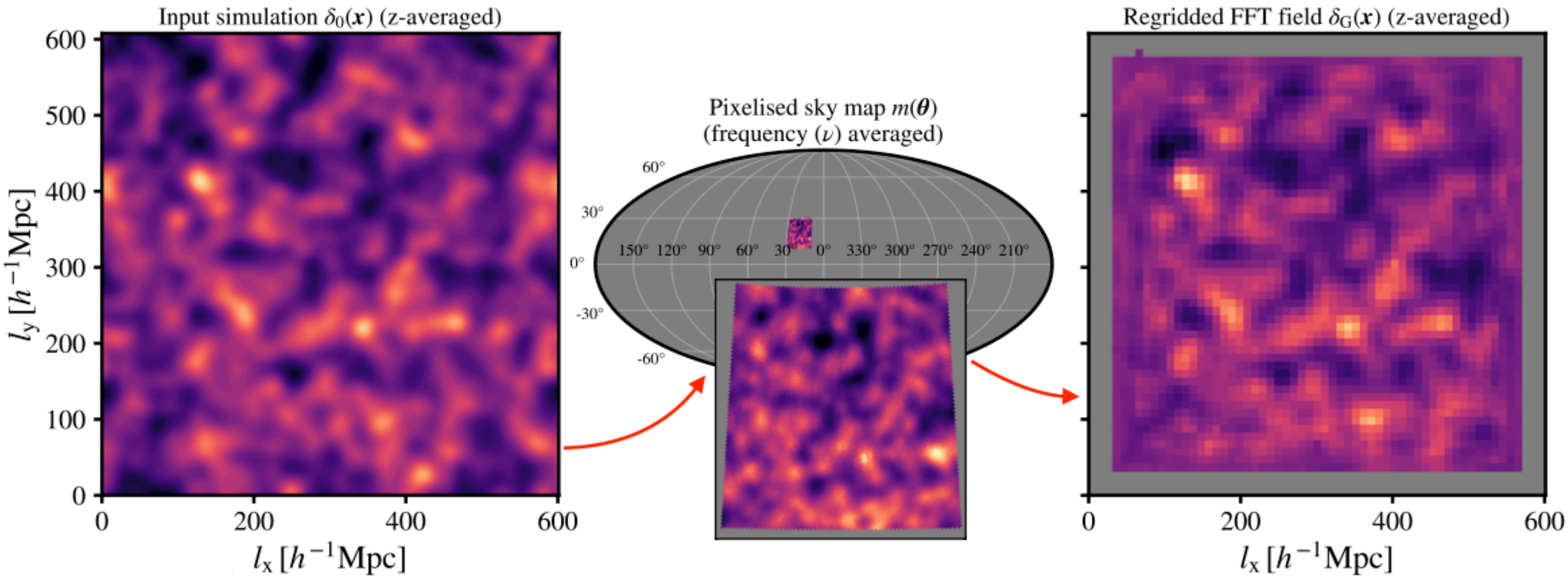
Testing regridding pipeline with simulations



➡ https://github.com/stevecunnington/gridimp

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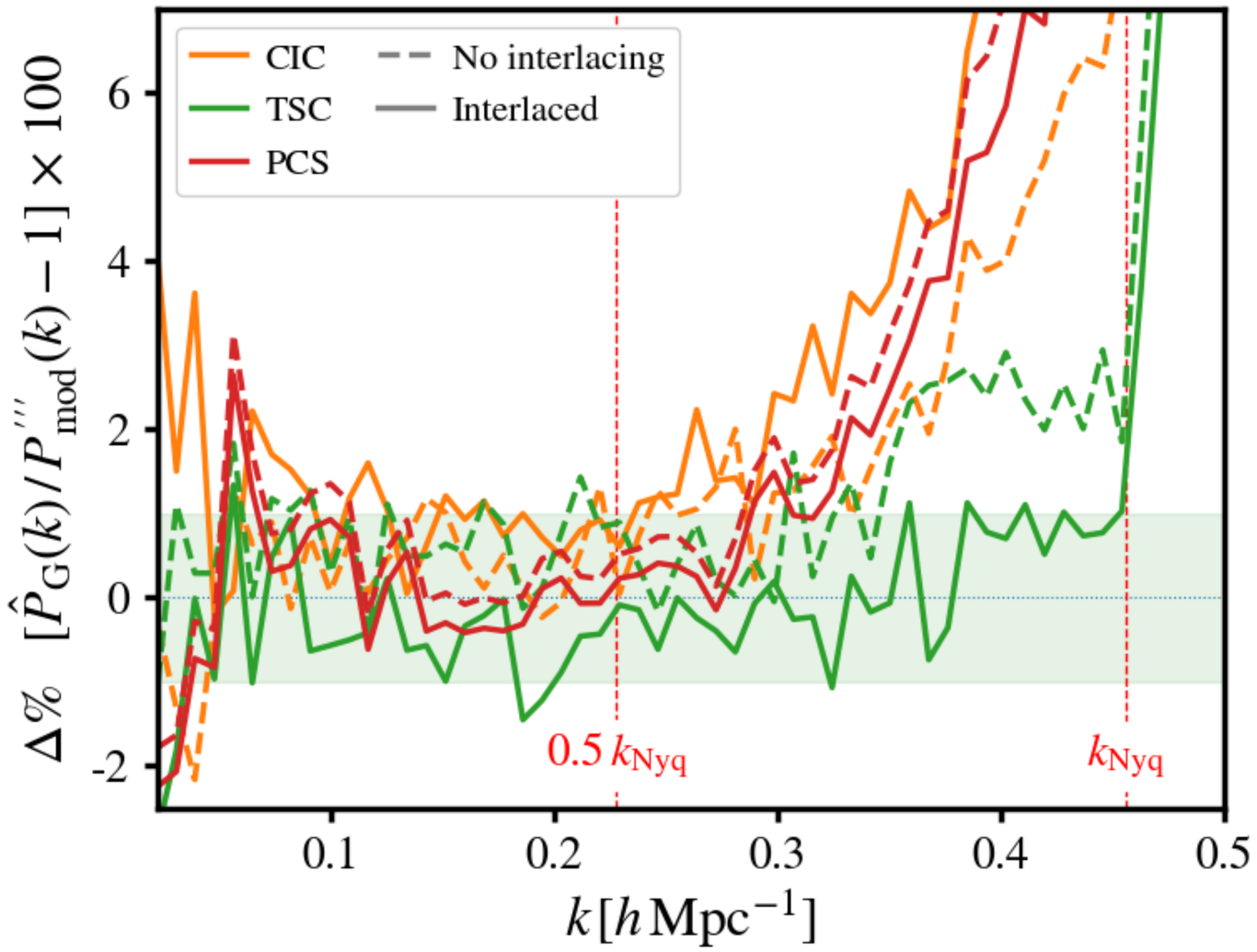
Mitigating regridding effects with modelling and higher-order *mass* assignment



Results include:

- modelling power damping from HEALPix pixelisation
- modelling power damping from frequency channels
- higher-order mass-assignement to test suppression of **aliasing**

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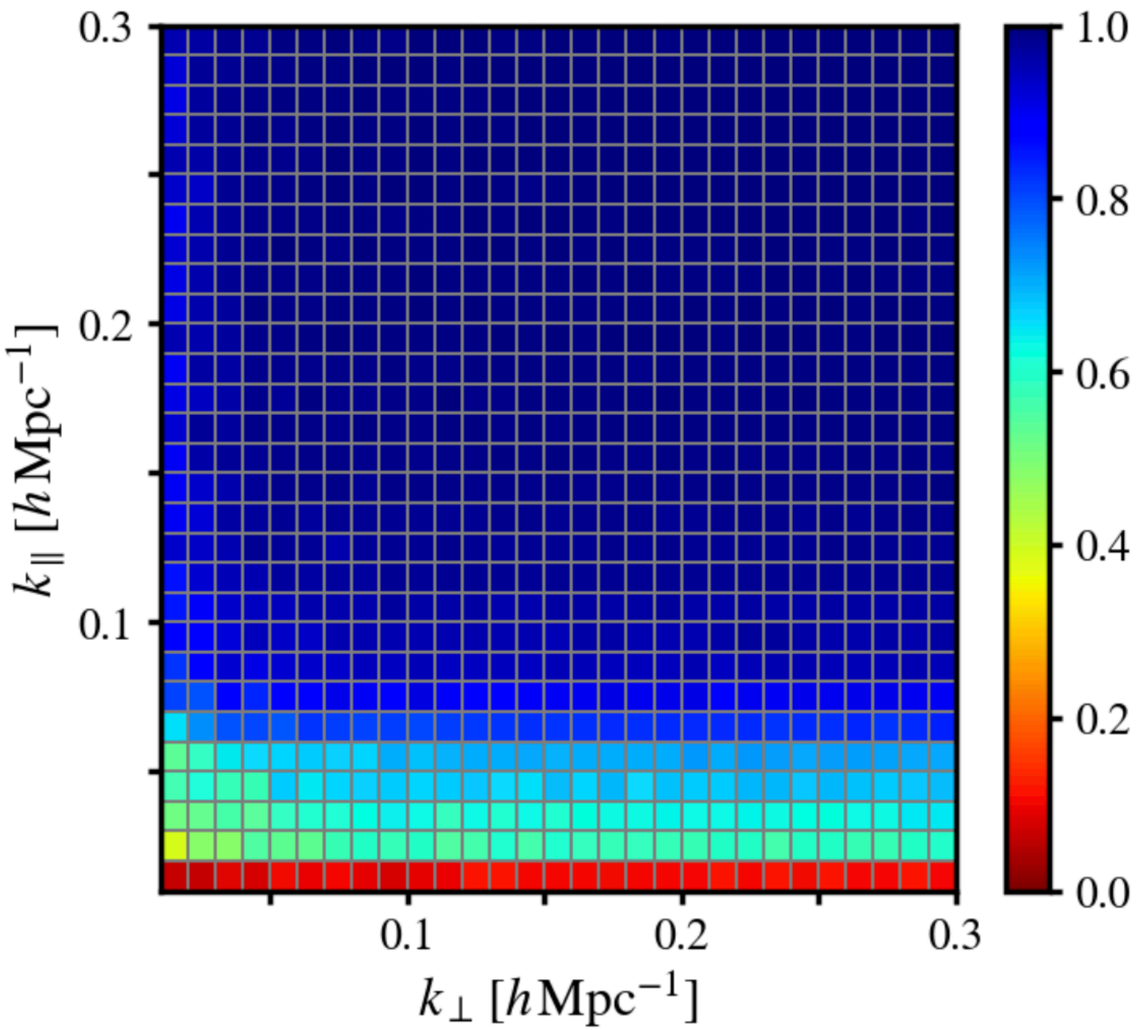
How much (HI) signal is lost in foreground cleaning?



Not known with real data

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Testing signal loss reconstruction with simulations

Constructing a foreground cleaning transfer function for signal reconstruction:

Inject mocks into real observational data and clean:

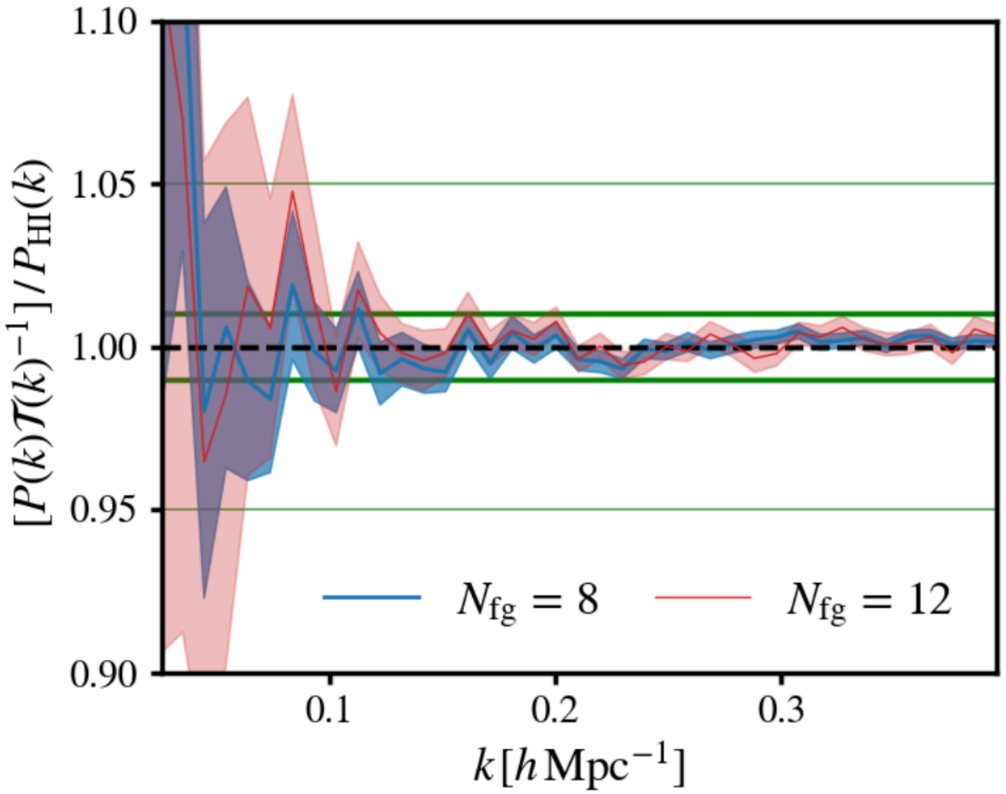
$$\mathbf{X}^{\mathrm{m}}_{\mathrm{clean}} = \mathbf{X}_{\mathrm{f+s+m}} - \mathbf{U}_{\mathrm{f+s+m}}\mathbf{S}\mathbf{U}^{\mathrm{T}}_{\mathrm{f+s+m}}\mathbf{X}_{\mathrm{f+s+m}}$$

"Cleaned" mock

Uncleaned (original) mock

$$\mathcal{T}(k) = \left\langle \frac{\mathcal{P}(\mathbf{X}^{\mathrm{m}}_{\mathrm{clean}}, \mathbf{X}_{\mathrm{m}})}{\mathcal{P}(\mathbf{X}_{\mathrm{m}}, \mathbf{X}_{\mathrm{m}})} \right\rangle$$

$$P_{\mathrm{corrected}}(k) = P_{\mathrm{cleaned}}(k) \,/\, \mathcal{T}(k)$$



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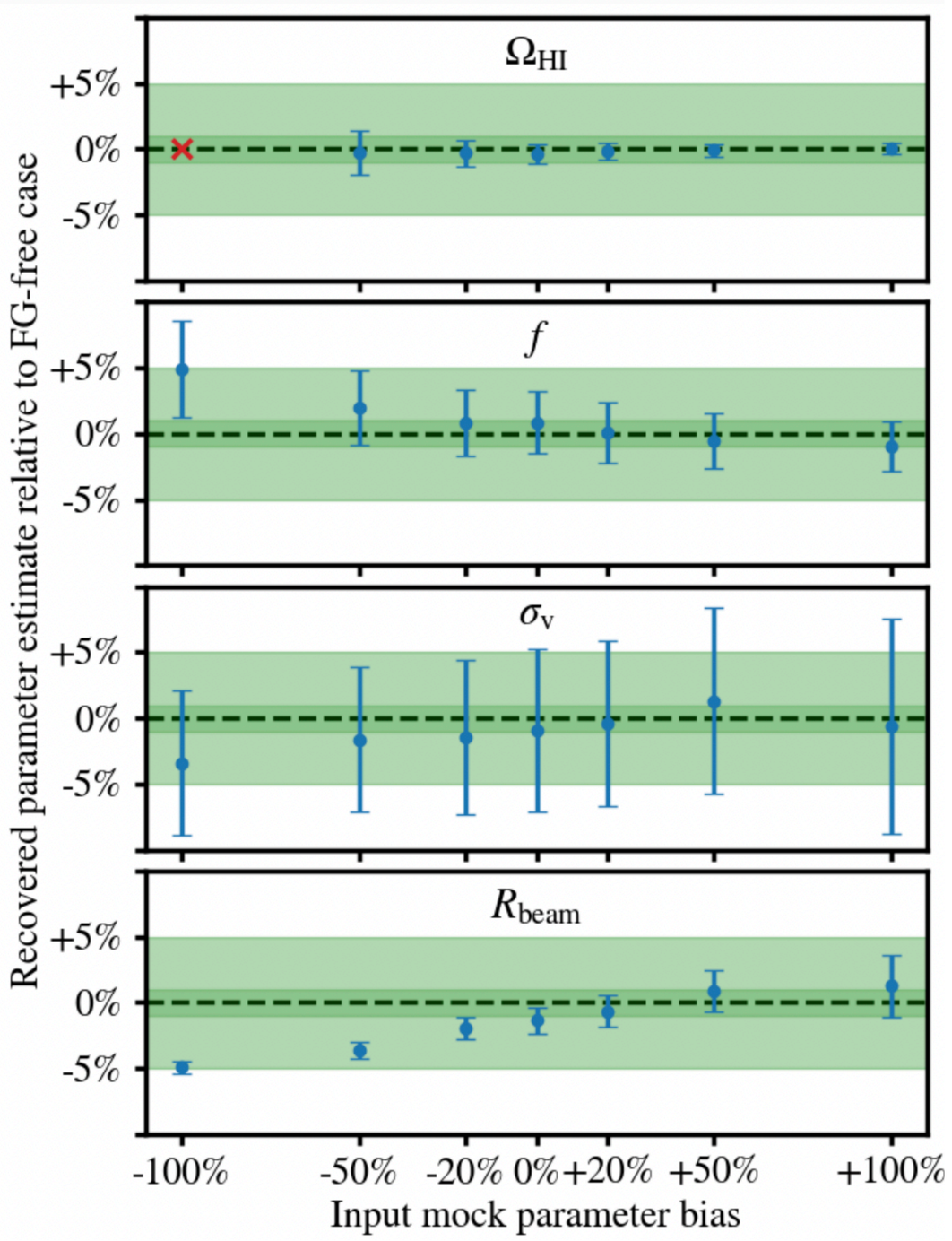
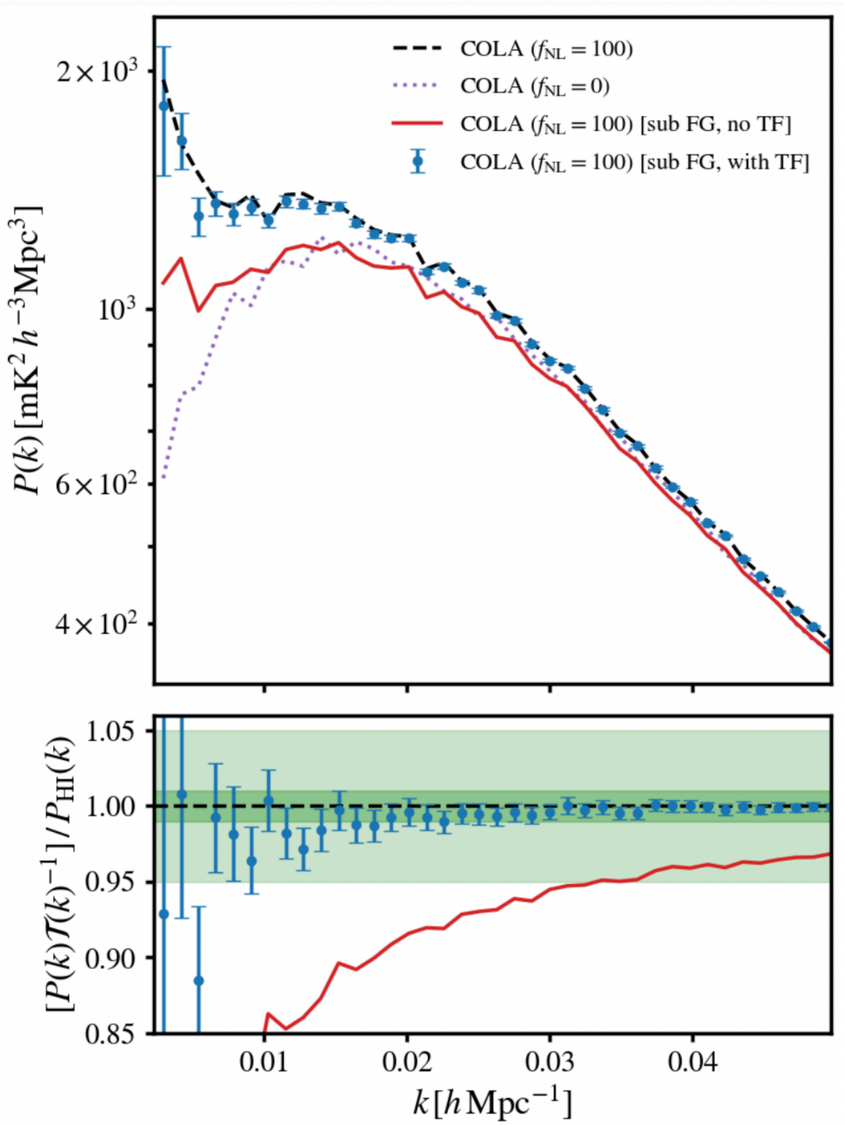
Foreground cleaning signal loss reconstruction for precision cosmology





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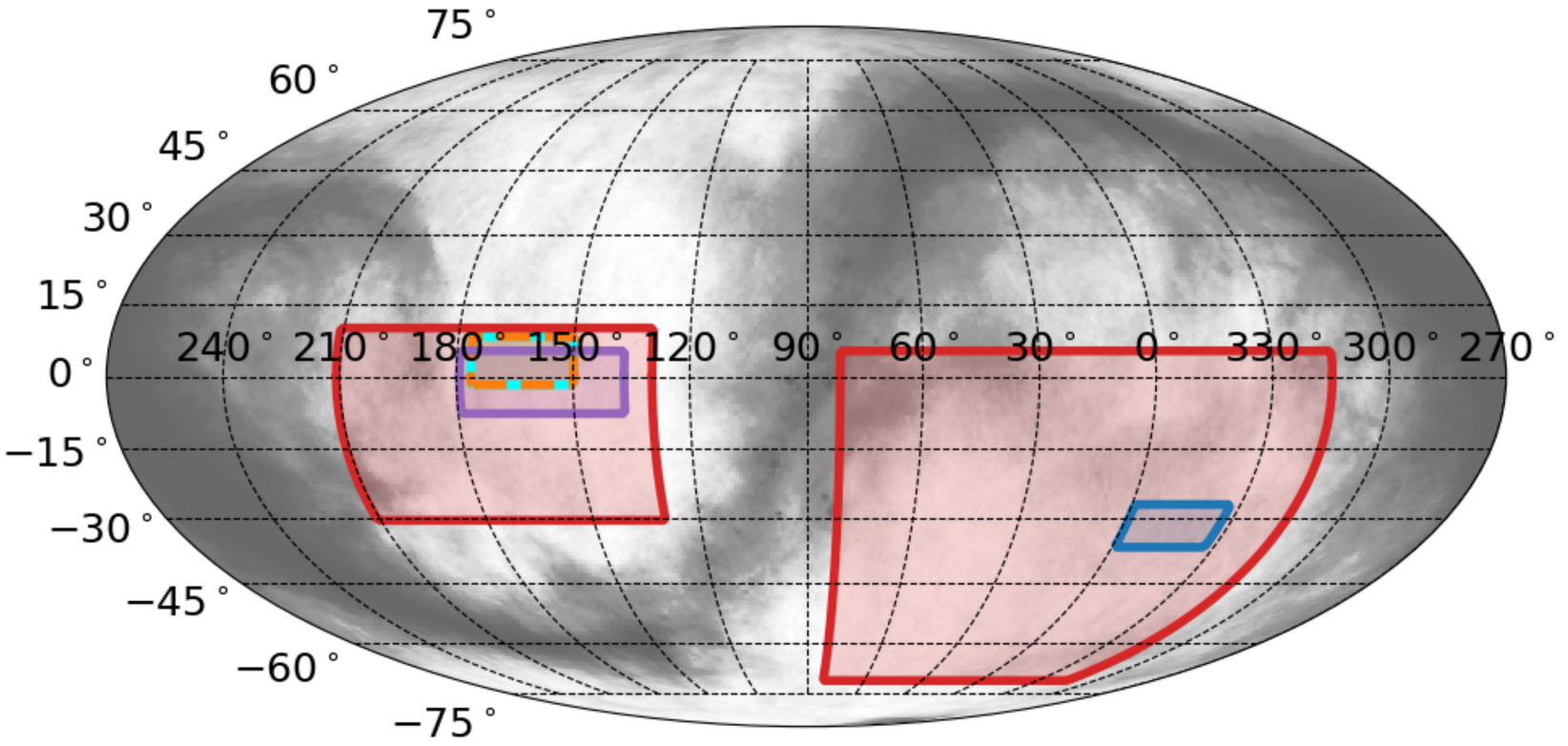
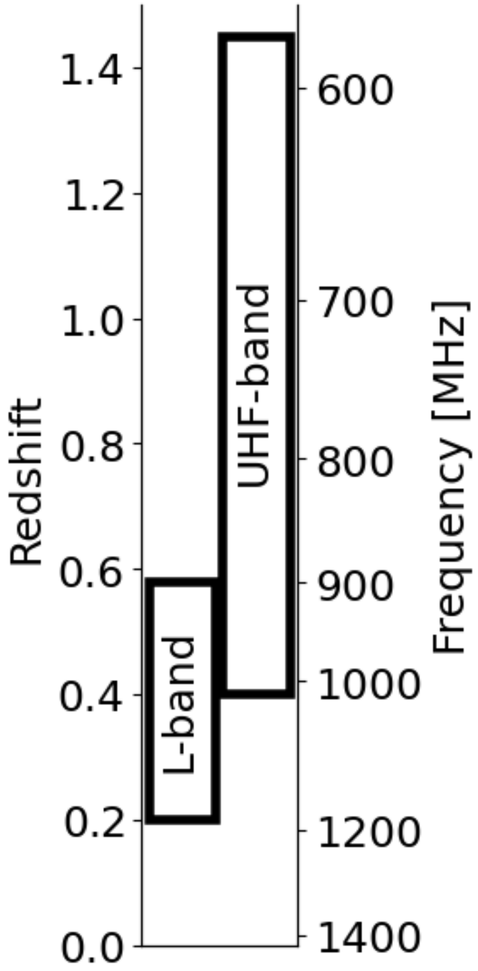
Future and current observations with MeerKLASS (MeerKAT Large Area Synoptic Survey)





2019 L-band OT1 (10.5 hrs)

2021 L-band OT2 (61.5 hrs)

2022 UHF-band DDT (12.5 hrs)

2023 UHF-band OT3 (105 hrs)

Full MeerKLASS 10,000 deg^2 UHF-band proposal (2480hrs)

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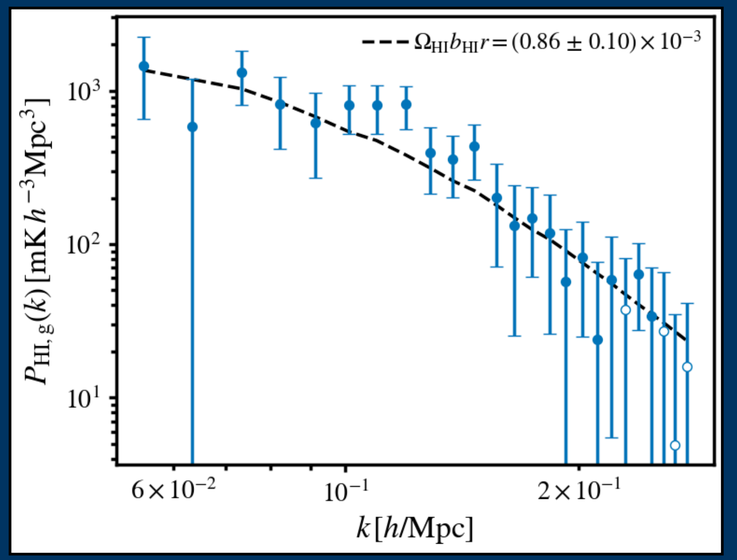
In Summary…

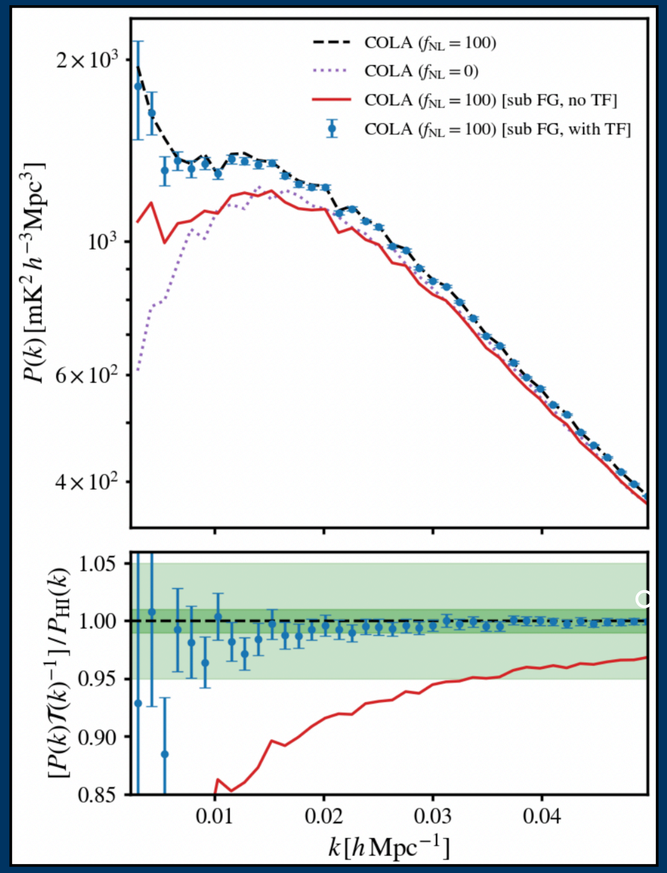
- Probing **ultra-large scales** can be efficiently achieved with 21cm intensity mapping

- Pilot surveys with **MeerKLASS** have demonstrated the **single-dish** intensity mapping method



[arXiv:2206.01579]

- Validation of **regridding to Cartesian** space for Fourier-based clustering statistics has begun
[arXiv:2312.07289]



[arXiv:2302.07034]

- **Signal loss from foreground cleaning** does not appear to be a limitation for *ultra*-large intensity mapping campaigns which are now underway…

Thank you!

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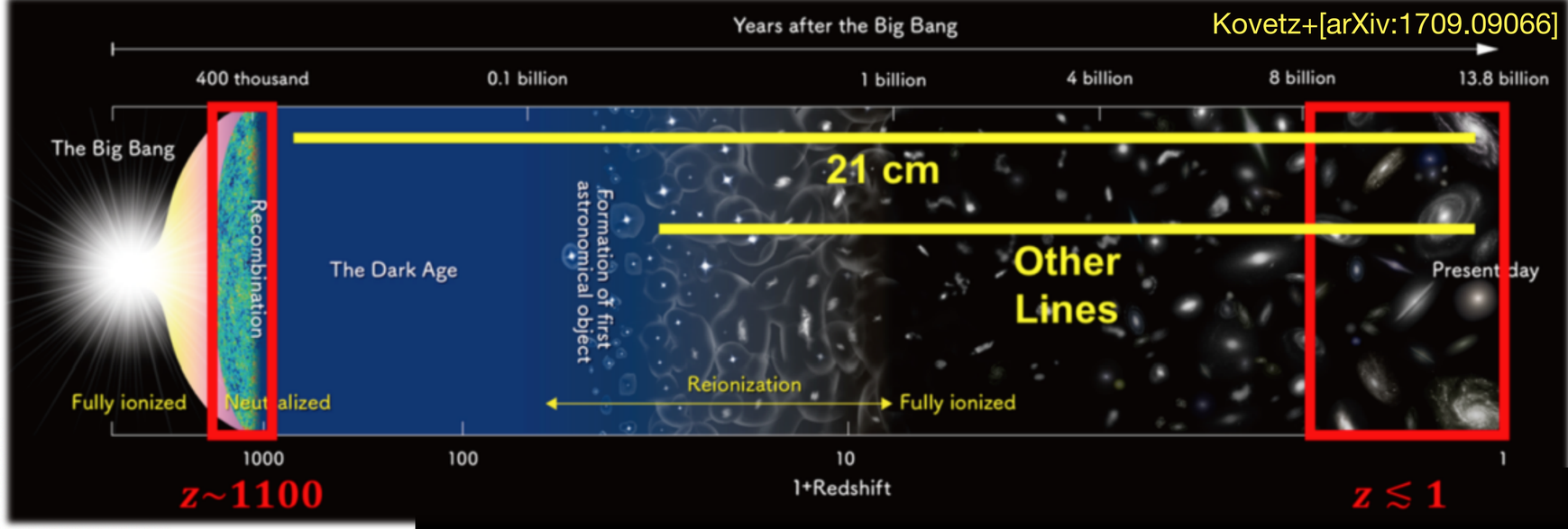
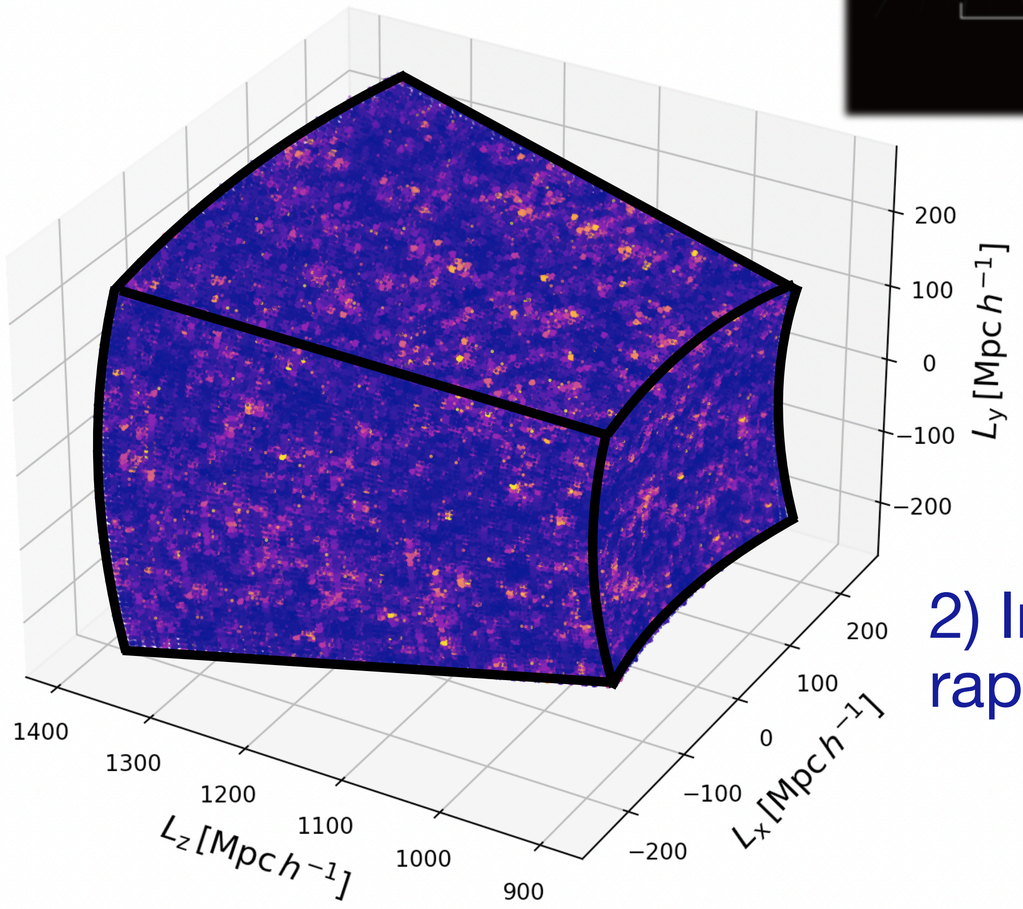
Backup Slides

Advantages of 21cm intensity mapping



1) Neutral hydrogen is rare tracer of early cosmic epochs



2) Intensity mapping can rapidly survey large volumes

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Key project milestone	LOW Telescope	MID Telescope
Start of construction (T0)	1st July 2021	1st July 2021
Earliest start of major contracts (C0)	August 2021	August 2021
Array Assembly 0.5 finish (AA0.5) SKA-Low: 6-station array SKA-Mid: 4-dish array	Q1 2024	Q1 2024
Array Assembly 1 finish (AA1) SKA-Low: 18-station array SKA-Mid: 8-dish array	Q1 2025	Q1 2025
Array Assembly 2 finish (AA2) SKA-Low: 64-station array SKA-Mid: 64-dish array	Q1 2026	Q4 2025
Array Assembly 3 finish (AA3) SKA-Low: 256-station array SKA-Mid: 133-dish array	Q1 2027	Q3 2026
Array Assembly 4 finish (AA4) SKA-Low: full array SKA-Mid: full array, including MeerKAT dishes	Q4 2027	Q2 2027
Operations Readiness Review (ORR)	Q1 2028	Q4 2027
End of Construction	July 2029	July 2029

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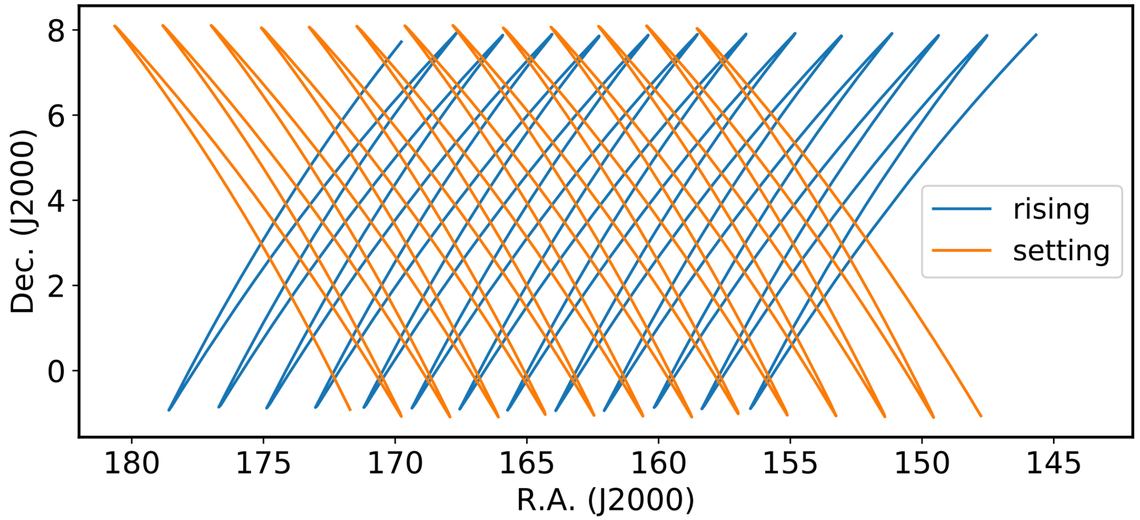
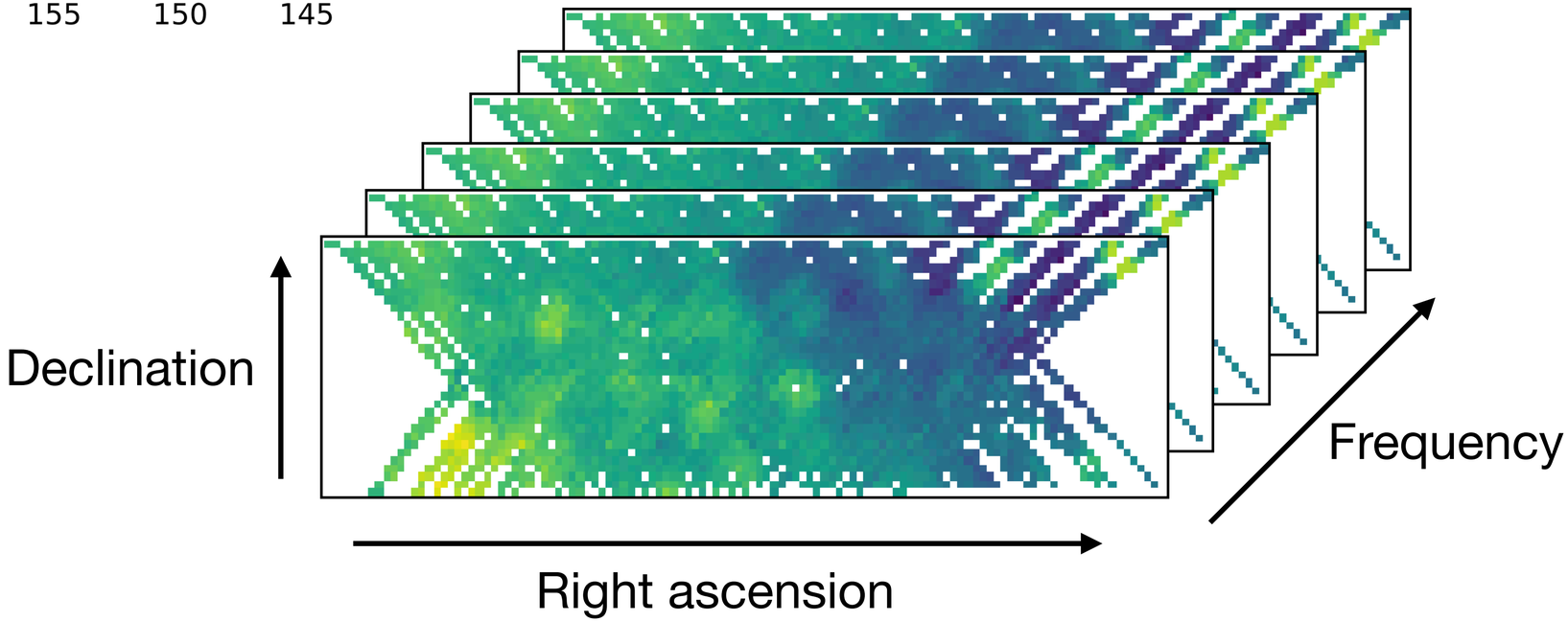
Observations on the sky



MeerKAT 2019 pilot survey scanning strategy
Wang+21 [arXiv:2011.13789]



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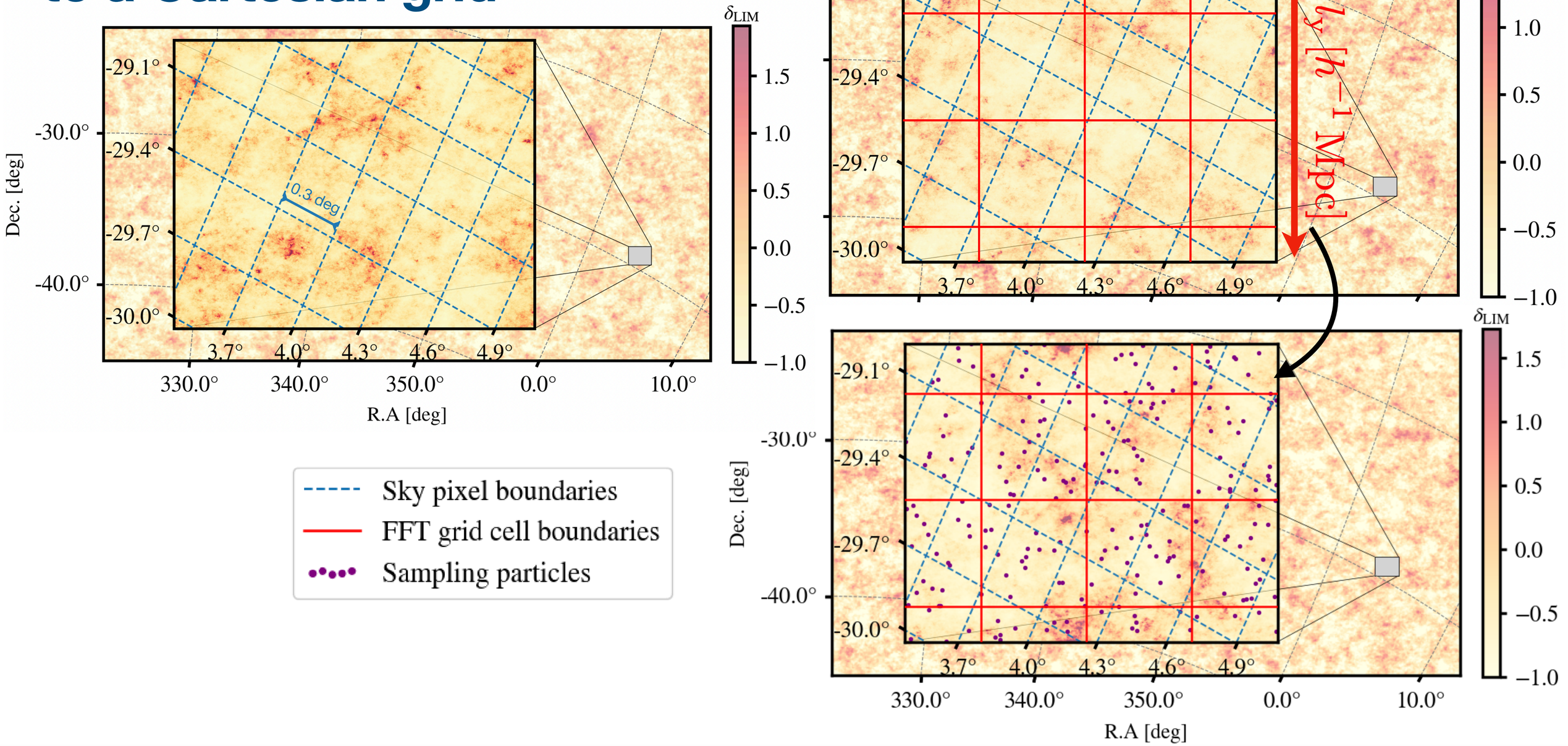
Monte Carlo sampling to a Cartesian grid



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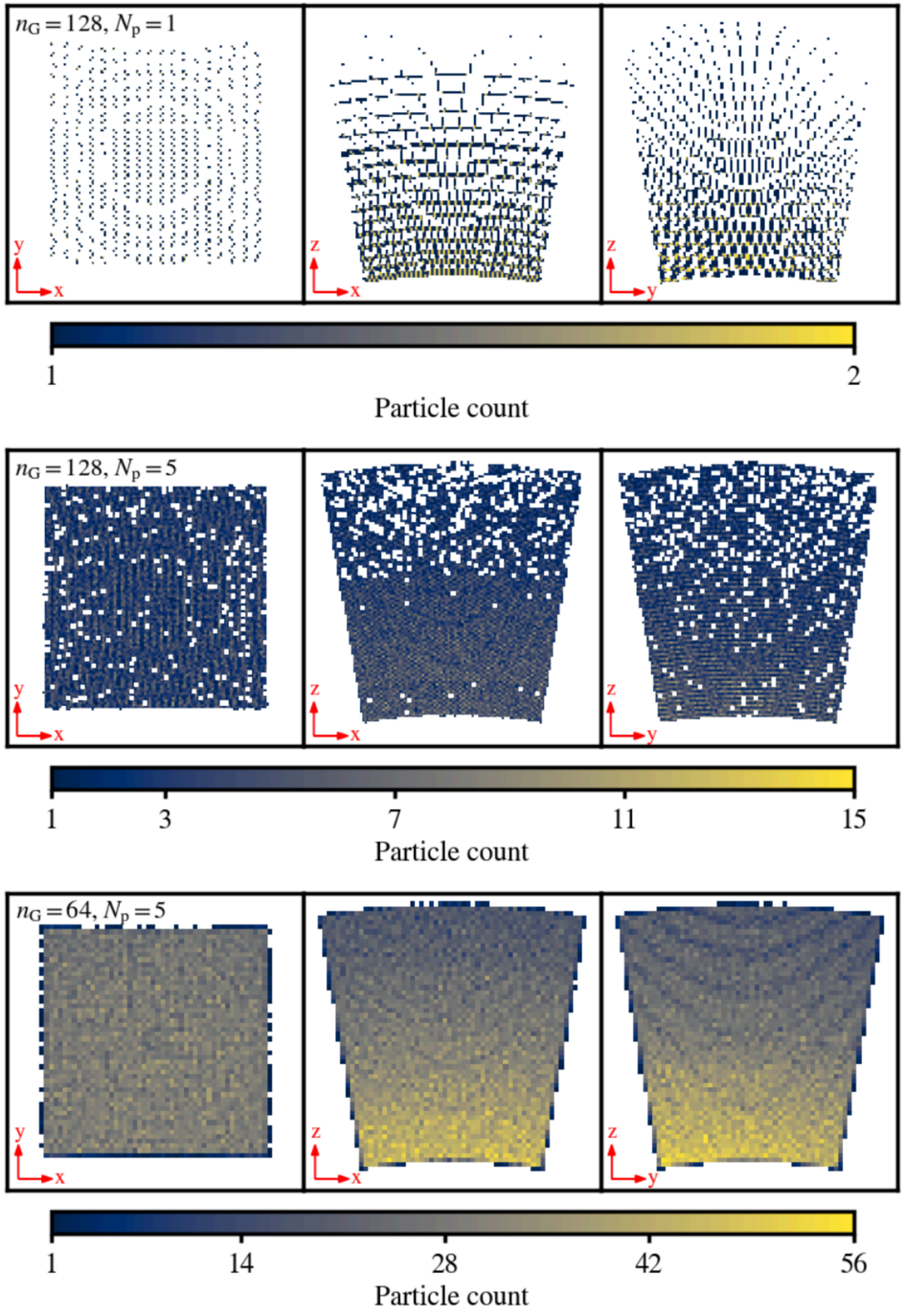
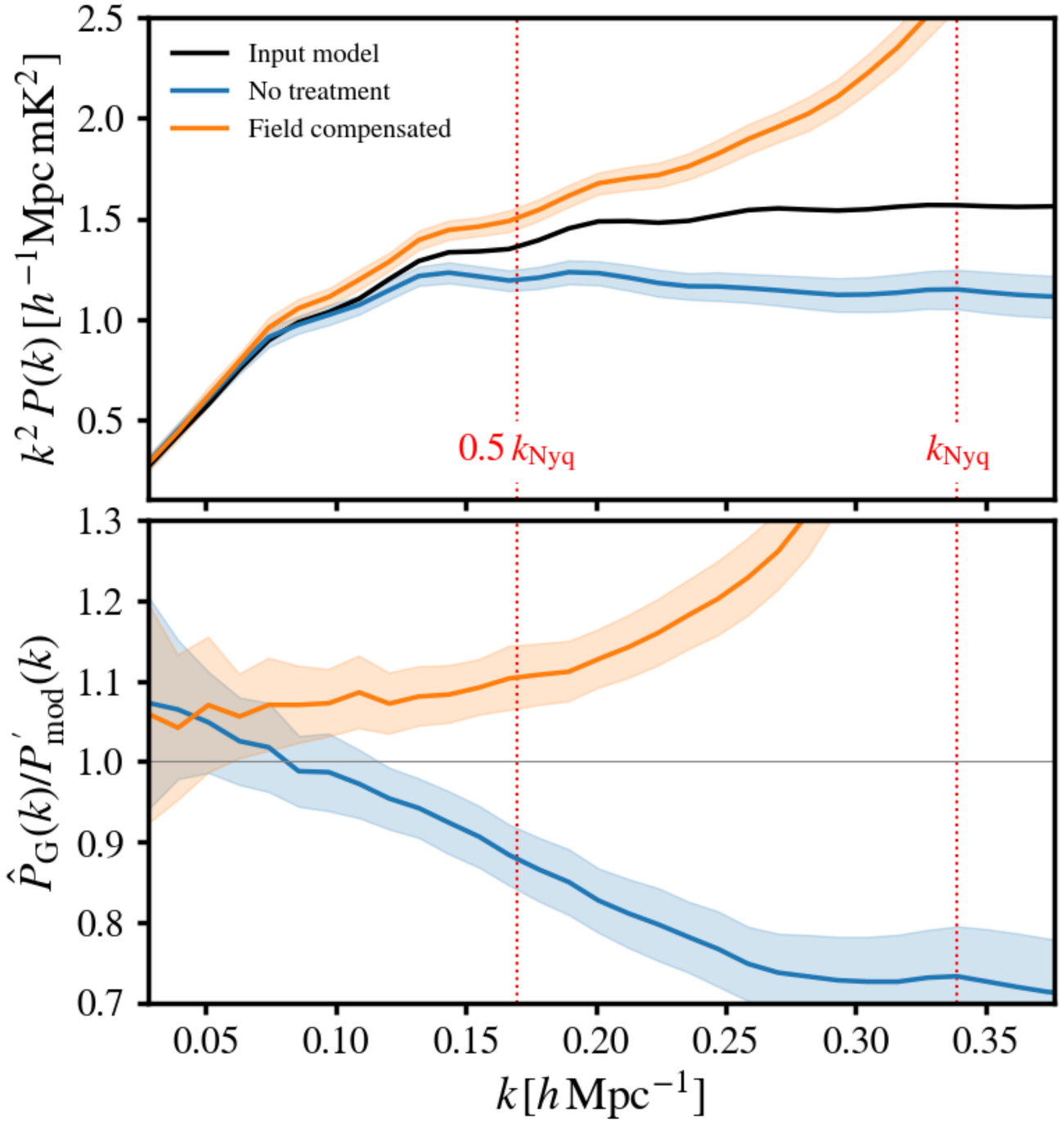


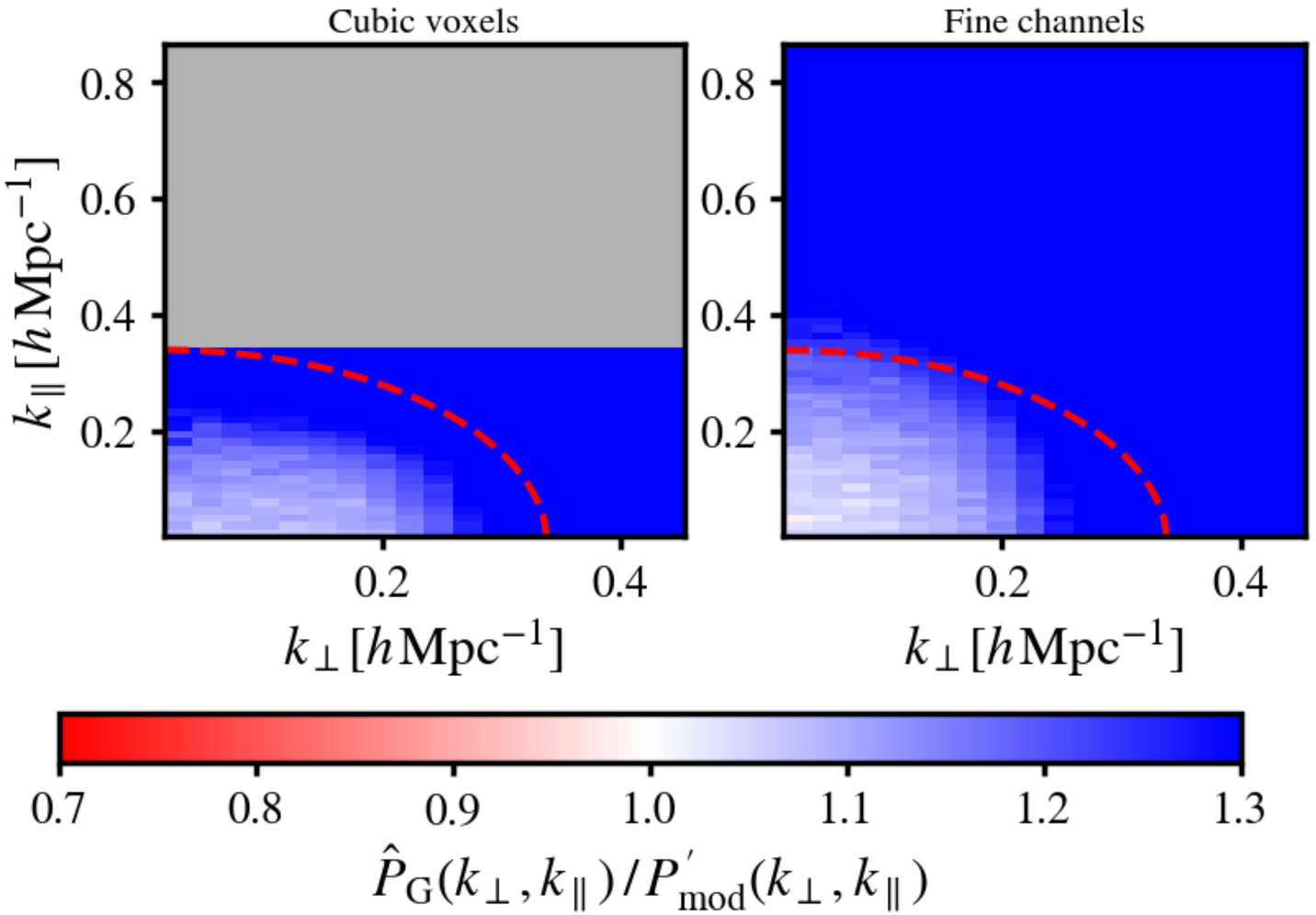
- ☑ Enough sampling particles
- ☑ Well chosen grid resolution
- ➡ footprint in Cartesian space with no holes



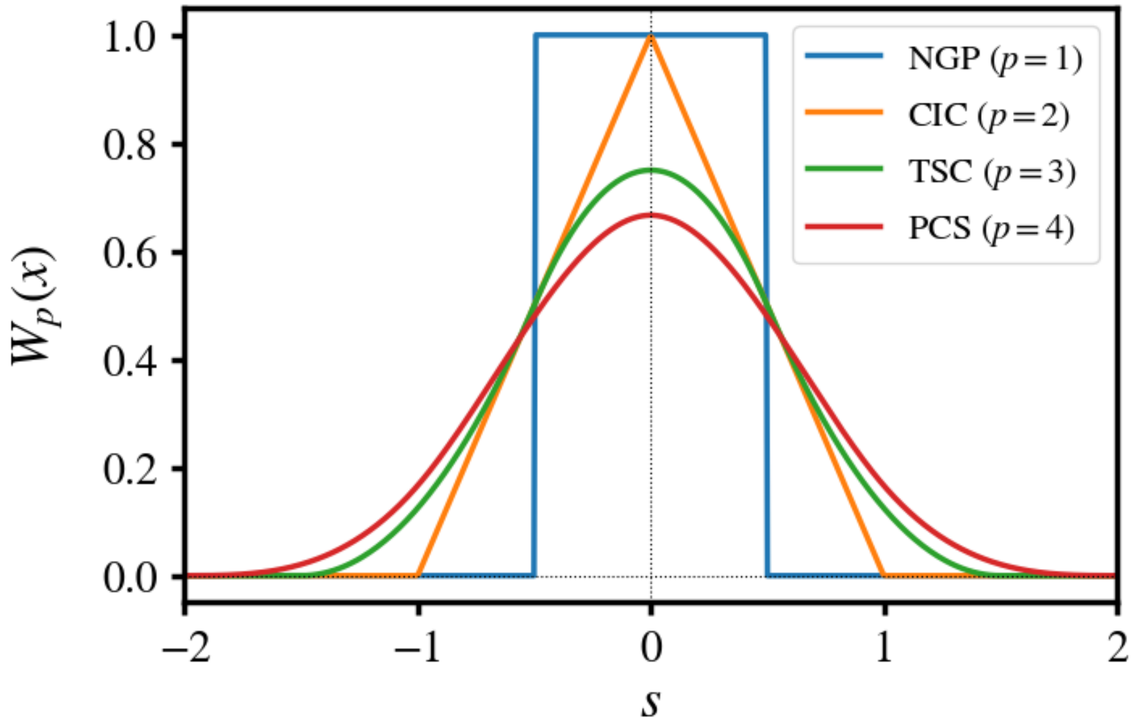
To **compensate** for smoothing from resampling, the Cartesian field is deconvolved with the Fourier transform of **top-hat** functions

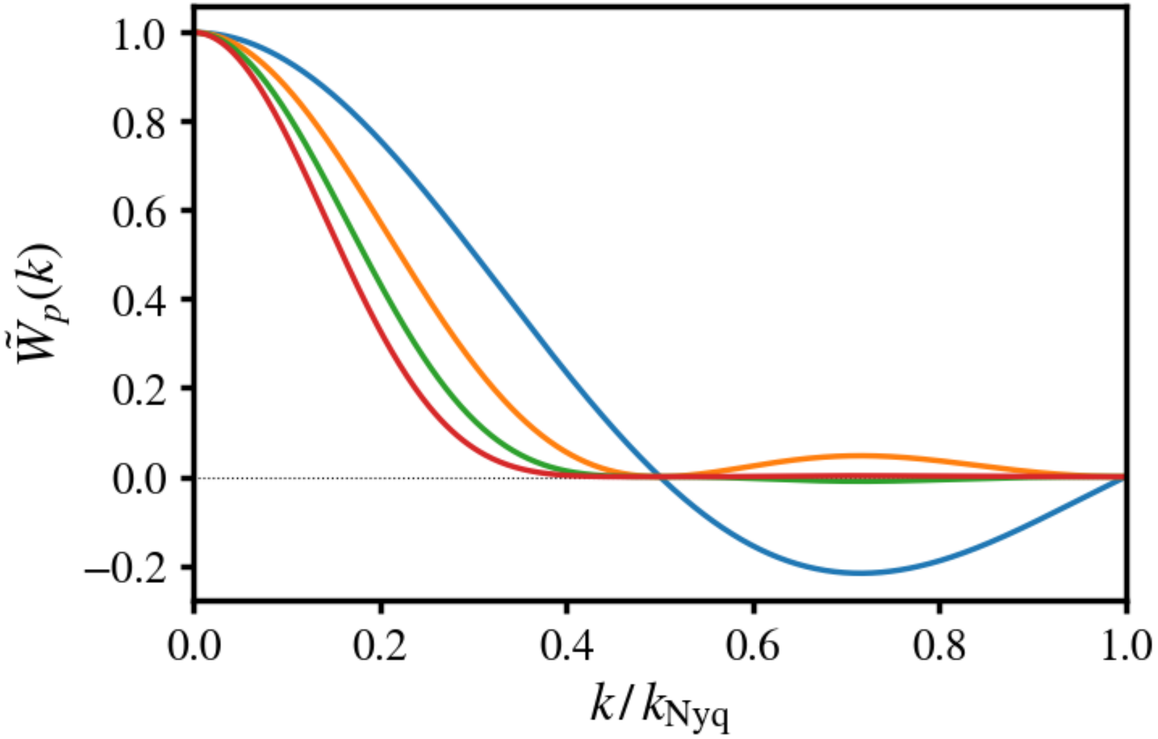
$$\tilde{W}_{\mathrm{ngp}}(\boldsymbol{k}) = \mathrm{sinc}\left(\frac{k_{\mathrm{x}}H_{\mathrm{x}}}{2}\right)\mathrm{sinc}\left(\frac{k_{\mathrm{y}}H_{\mathrm{y}}}{2}\right)\mathrm{sinc}\left(\frac{k_{\mathrm{z}}H_{\mathrm{z}}}{2}\right)$$

High resolution channels



Can we mitigate aliasing with higher-order assignment schemes

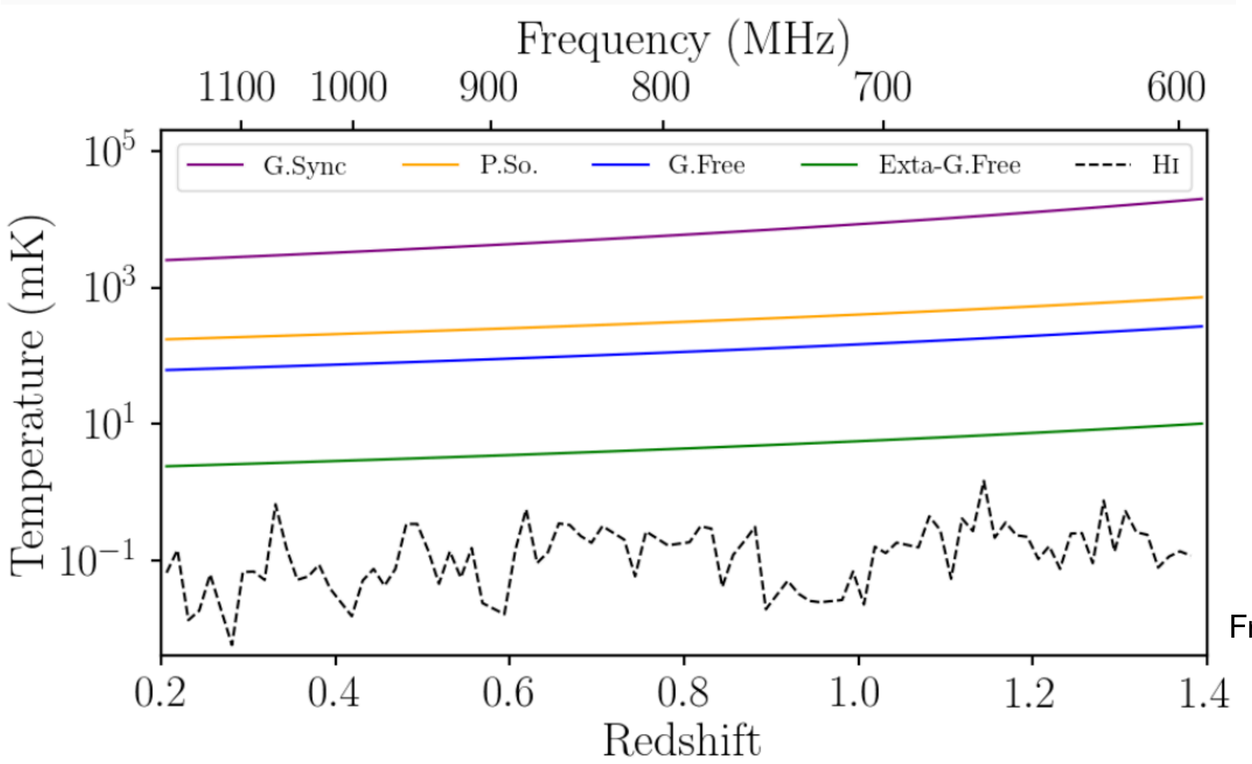




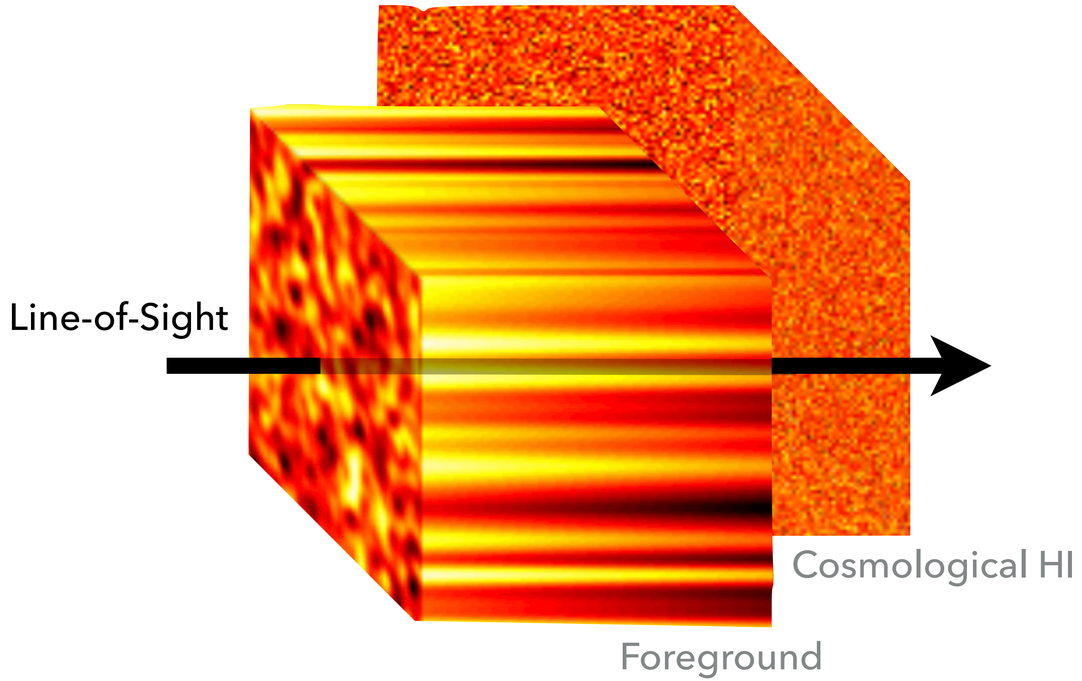
$$\tilde{W}_p(\boldsymbol{k}) = \left[\mathrm{sinc}\left(\frac{k_\mathrm{x}H_\mathrm{x}}{2}\right)\mathrm{sinc}\left(\frac{k_\mathrm{y}H_\mathrm{y}}{2}\right)\mathrm{sinc}\left(\frac{k_\mathrm{z}H_\mathrm{z}}{2}\right)\right]^p$$

Foreground cleaning MeerKAT HI intensity maps

Idealised simulation demo:

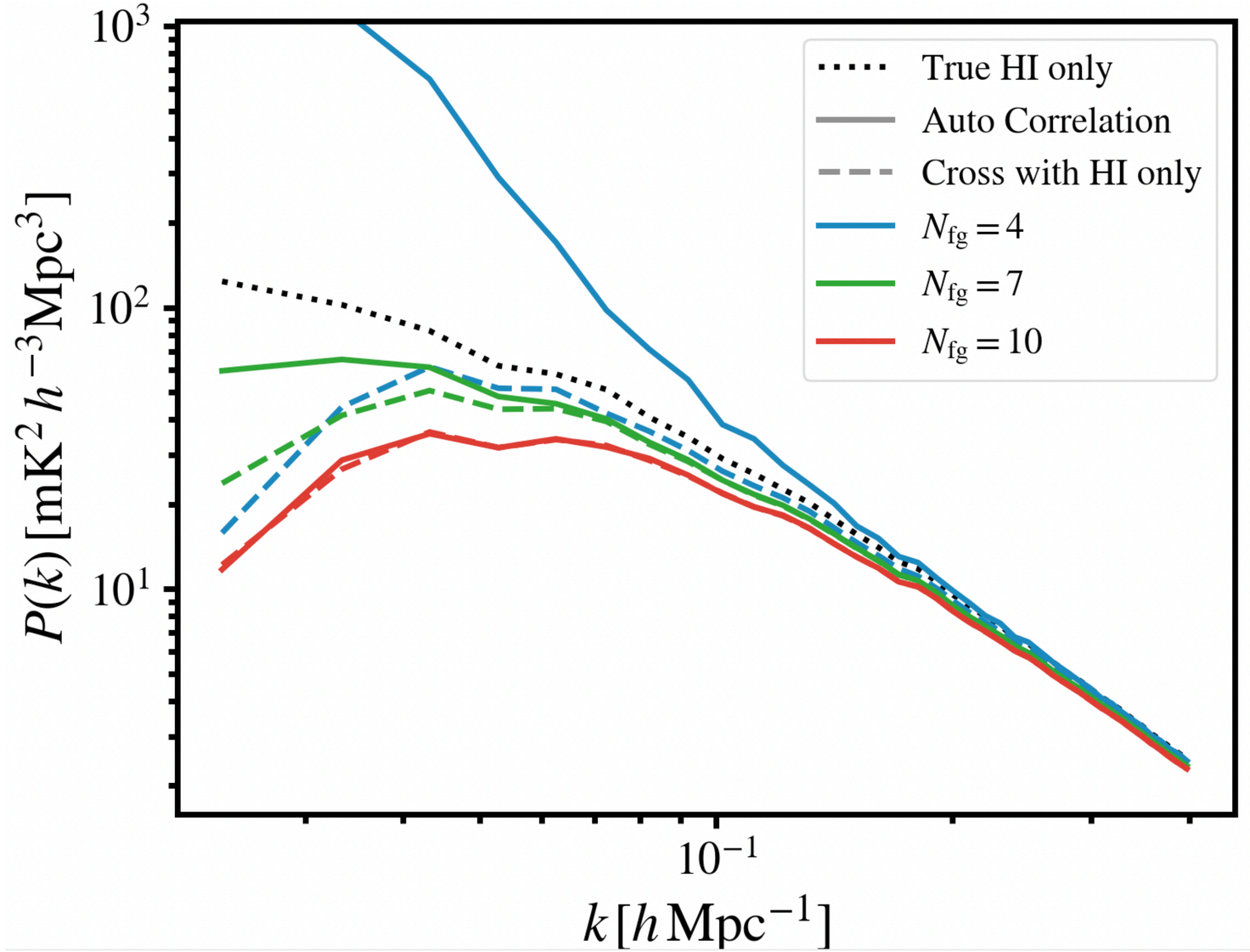


From S.Cunnington+19 [arXiv:1904.01479]



- We utilise smooth foreground spectra to distinguish them from cosmological signal

Foreground cleaning the simulations



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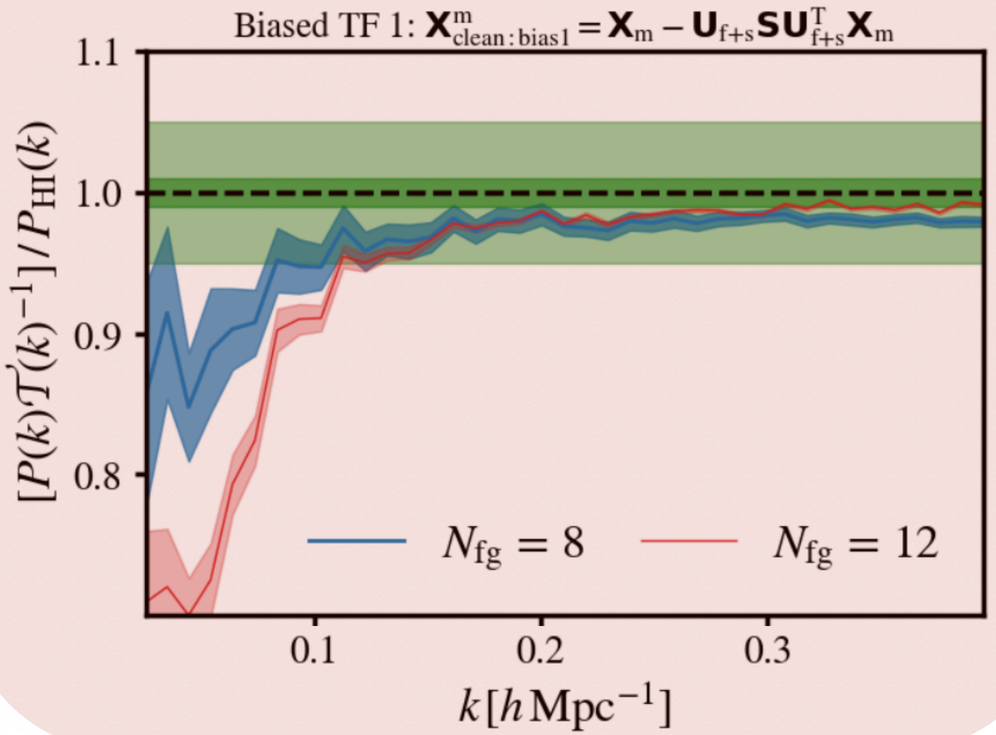
Biased transfer functions: What to avoid

Unbiased approach

$$\mathbf{X}^{\rm m}_{\rm clean} = \mathbf{X}_{\rm f+s+m} - \mathbf{U}_{\rm f+s+m}\mathbf{S}\mathbf{U}^{\rm T}_{\rm f+s+m}\mathbf{X}_{\rm f+s+m}$$

$$\mathcal{T}(k) = \left\langle \frac{\mathcal{P}(\mathbf{X}^{\rm m}_{\rm clean}, \mathbf{X}_{\rm m})}{\mathcal{P}(\mathbf{X}_{\rm m}, \mathbf{X}_{\rm m})} \right\rangle_{N_{\rm mock}}$$



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