SKAO HI Intensity Mapping:

Blind Foreground Subtraction Challenge

Isabella Paola Carucci

Università degli Studi di Torino

The Third National Workshop on the SKA Project
The Italian Route to the SKAO Revolution
5th October 2021

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A collective effort of (a subset of) the IM Focus Group, within the SKA Cosmology SWG

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Marta Spinelli,[1,2,3★] Isabella P. Carucci,[4,5,6†] Steven Cunnington,[7] Stuart E. Harper,[8] Melis O. Irfan,[3,7] José Fonseca,[7,3,9,10] Alkistis Pourtsidou,[7,3] Laura Wolz[8]

ABSTRACT

Neutral Hydrogen Intensity Mapping (HI IM) surveys will be a powerful new probe of cosmology. However, strong astrophysical foregrounds contaminate the signal and their coupling with instrumental systematics further increases the data cleaning complexity. In this work, we simulate a realistic single-dish HI IM survey of a 5000 deg^2 patch in the 950 – 1400 MHz range, with both the MID telescope of the SKA Observatory (SKAO) and MeerKAT, its precursor. We include a state-of-the-art HI simulations and explore different foreground models and instrumental effects such as non-homogeneous thermal noise and beam side-lobes. We perform the first Blind Foreground Subtraction Challenge for HI IM on these synthetic data-cubes, aiming to characterise the performance of available foreground cleaning methods with no prior knowledge of the sky components and noise level. Nine foreground cleaning pipelines joined the Challenge, based on statistical source separation algorithms, blind polynomial fitting, and an astrophysical-informed parametric fit to foregrounds. We devise metrics to compare the pipeline performances quantitatively. In general, they can recover the input maps' 2-point statistics within 20 per cent in the range of scales least affected by the telescope beam. However, spurious artefacts appear in the cleaned maps due to interactions between the foreground structure and the beam side-lobes. We conclude that it is fundamental to develop accurate beam deconvolution algorithms and test data post-processing steps carefully before cleaning. This study was performed as part of SKAO preparatory work by the HI IM Focus Group of the SKA Cosmology Science Working Group.

arXiv: 2107.1081

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- HI IM: an innovative cosmological probe
  (Matteo's talk)

- Contaminants are **THE** problem
  - How to simulate them?
  - How to subtract them?

- The blind challenge

- MeerKLASS as testbed
  (me, Marta Spinelli, Gianni Bernardi, Stefano Camera)

MeerKAT

64+ dishes with single pixel feeds

- HI IM with MeerKAT: MeerKLASS
- calibration paper —> Wang+ 2021
- Analysis of the Science Verification Data in progress

MeerKAT

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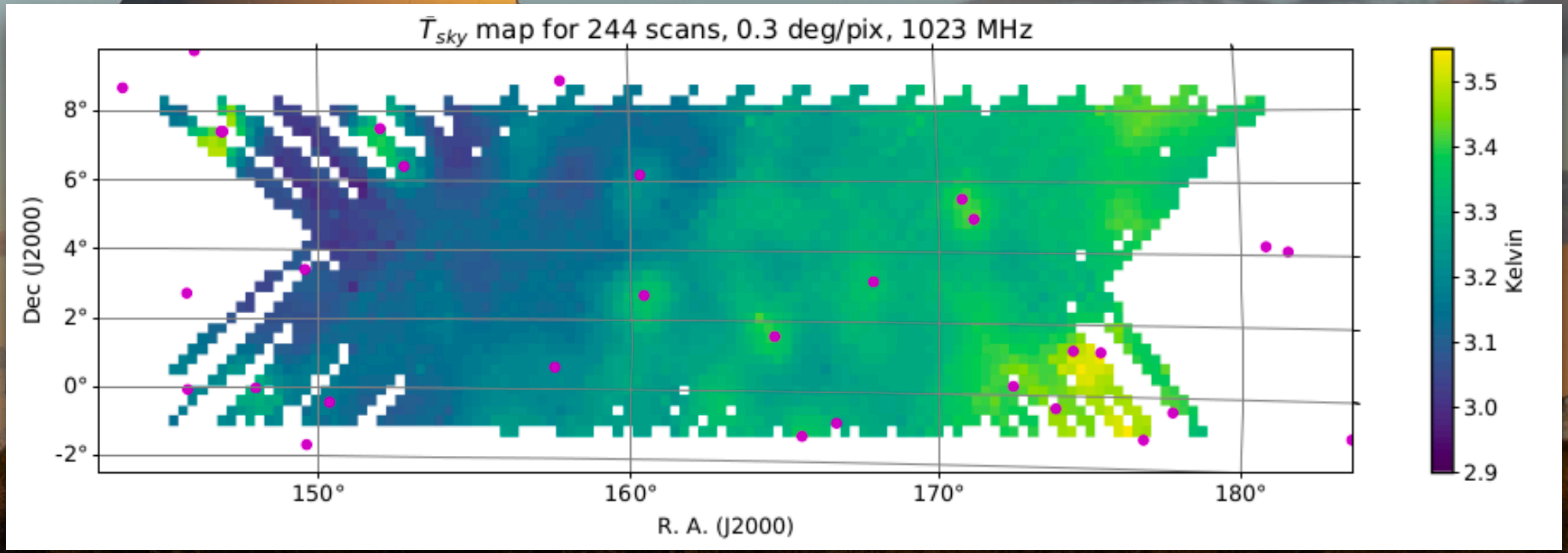

- **HI IM with MeerKAT: MeerKLASS**
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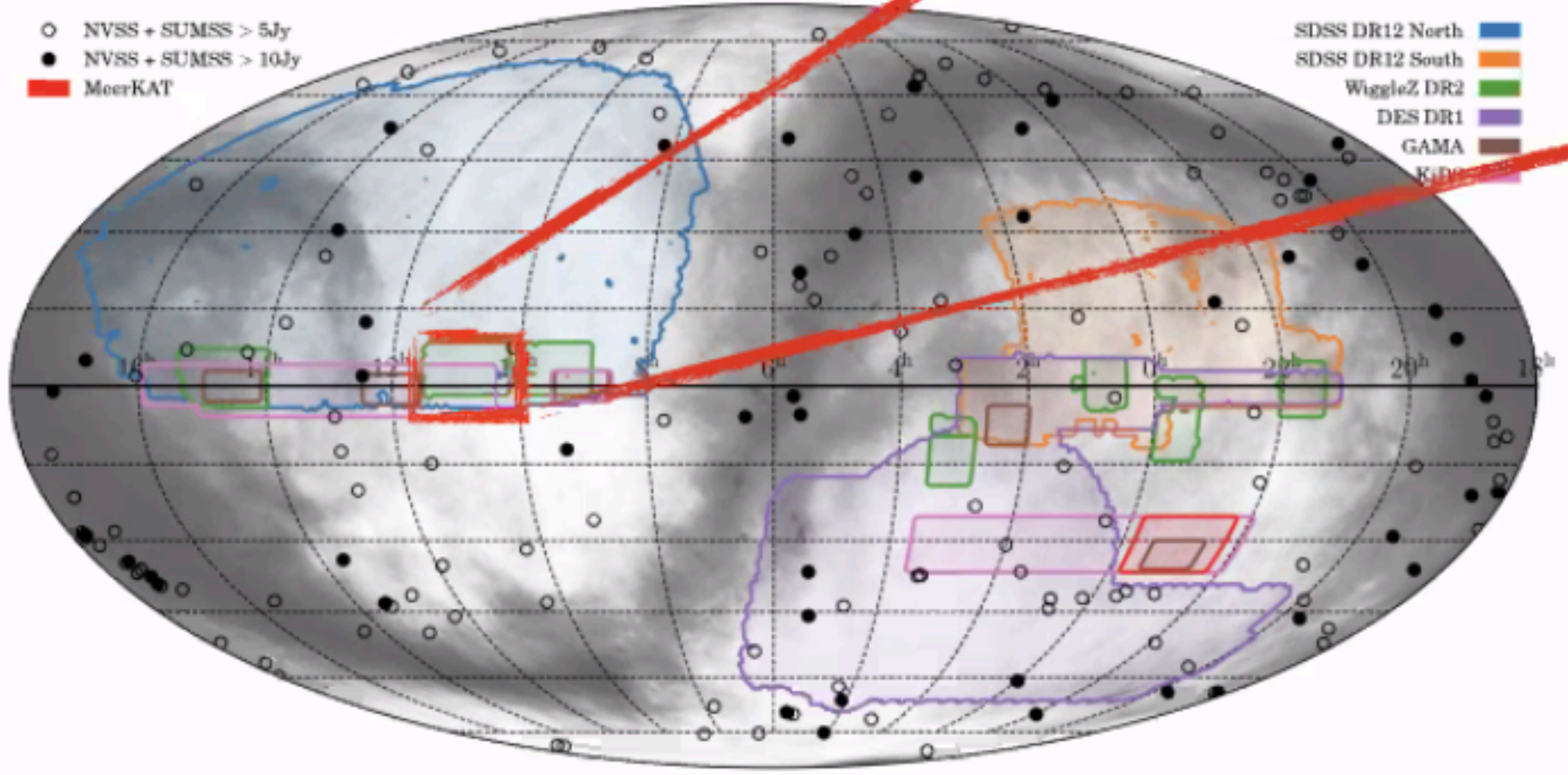
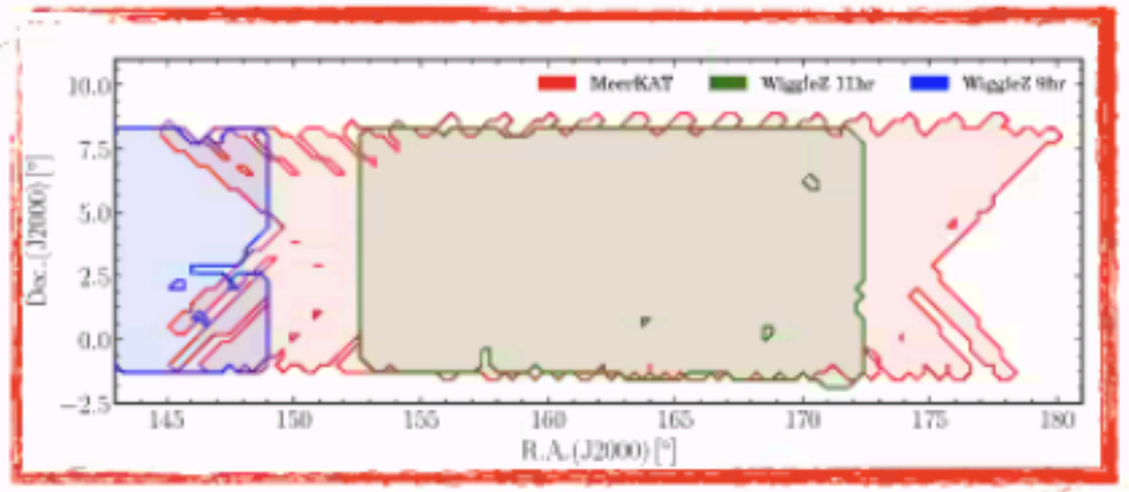
MeerKAT

- MeerKAT Large Area Synoptic Survey (MeerKLASS, PI: Mario Santos)

M. G. Santos et. al. arXiv:1709.06099

- MeerKAT HI IM Pilot survey
  - ~170 square deg, ~10 hours, ~60 dishes
  - Fix Alt ~ 45deg
  - L-band (856-1712MHz)
  - Overlap with WiggleZ/SDSS
  - Test system, training pipeline





J. Wang et. al. arXiv:2011.13789

Credit: Yichao Li

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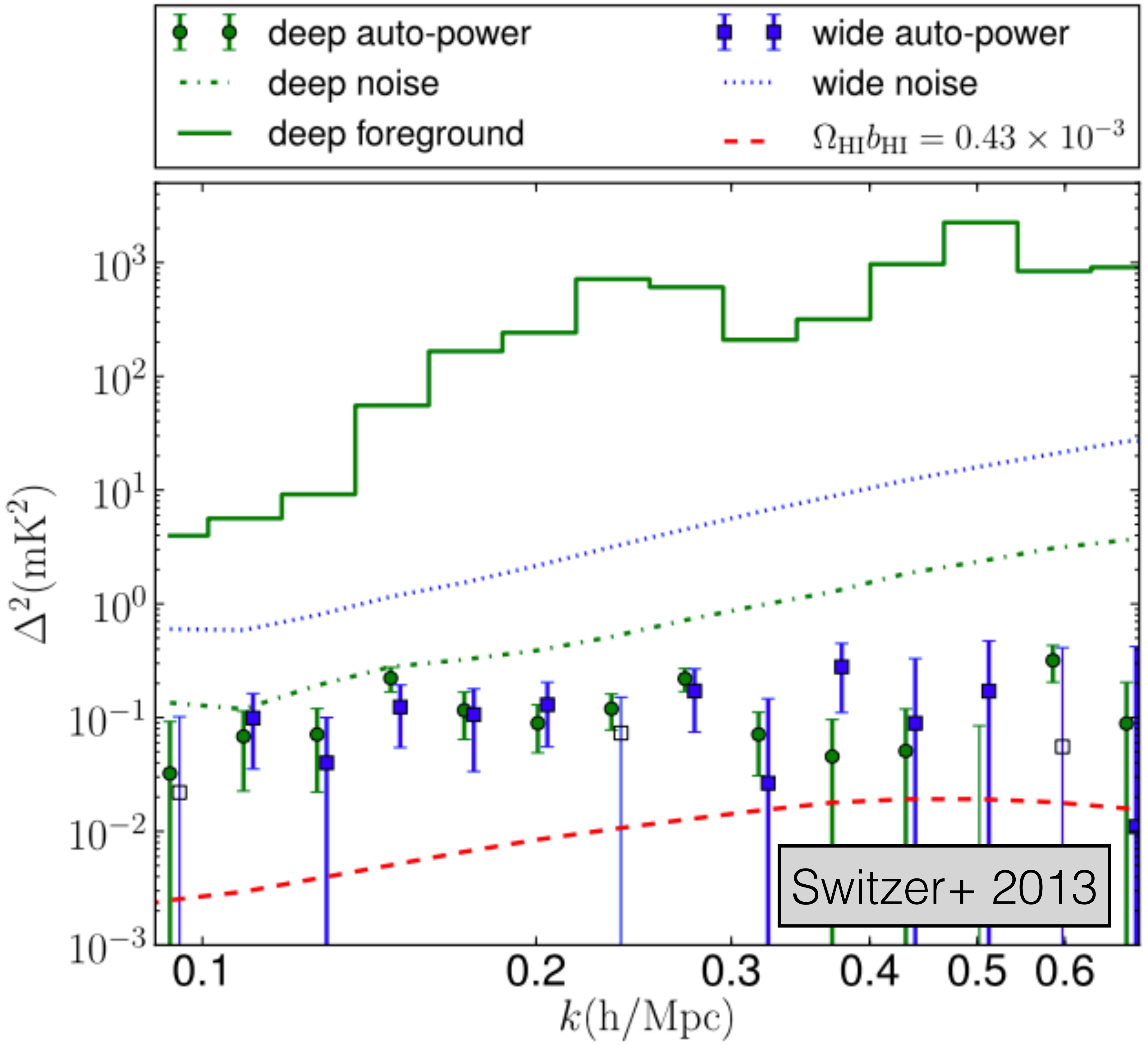
Contaminants are THE problem

HI intensity mapping: state-of-the-art

1. **Chang+ 2010**
   Green Bank Telescope
   X WiggleZ galaxies
   z~0.8

   (also Masui+ 2013, Wolz+ 2017,2021)

2. **Anderson+ 2018**
   Parkes telescope
   X 2dF optical galaxies



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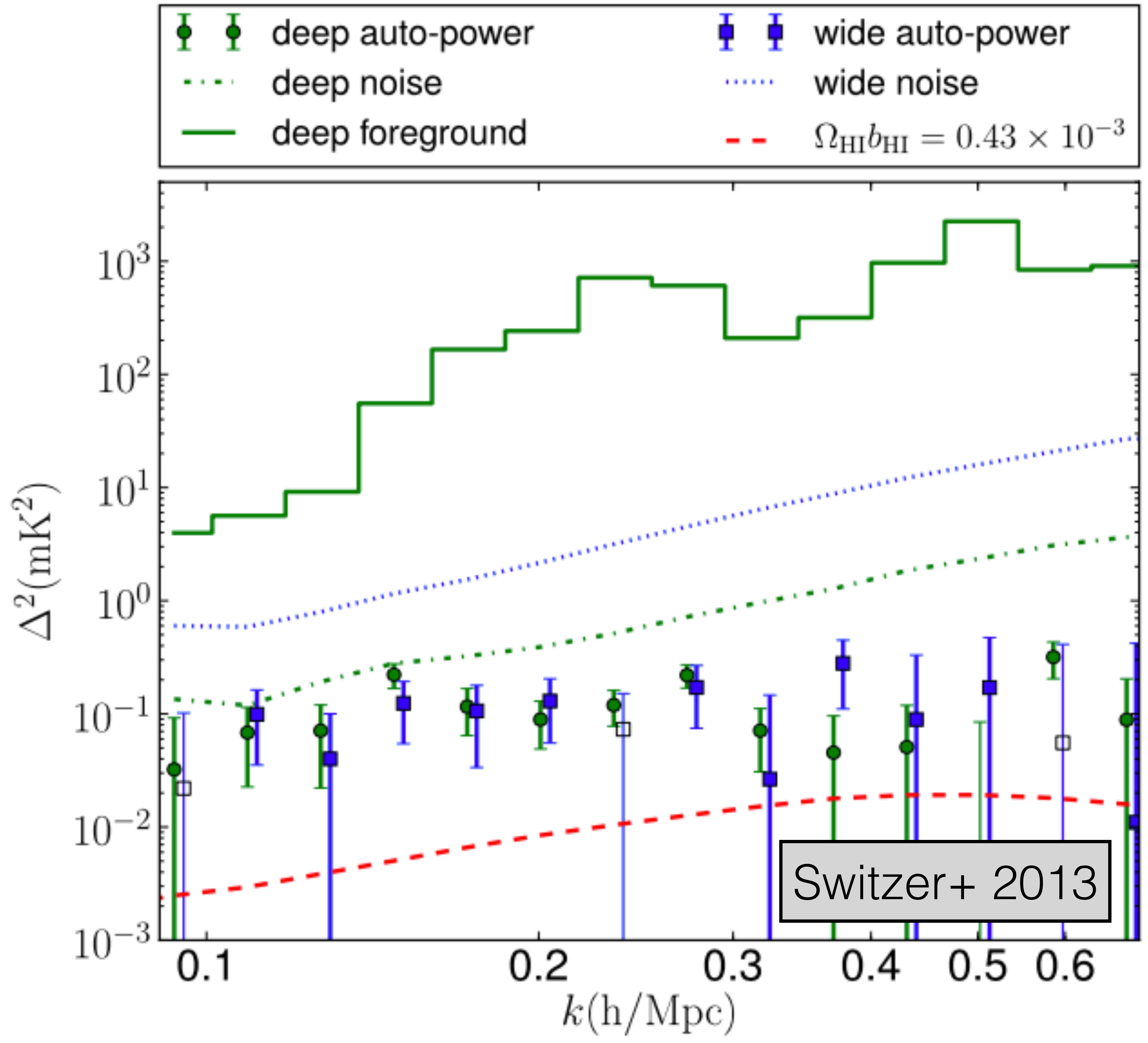
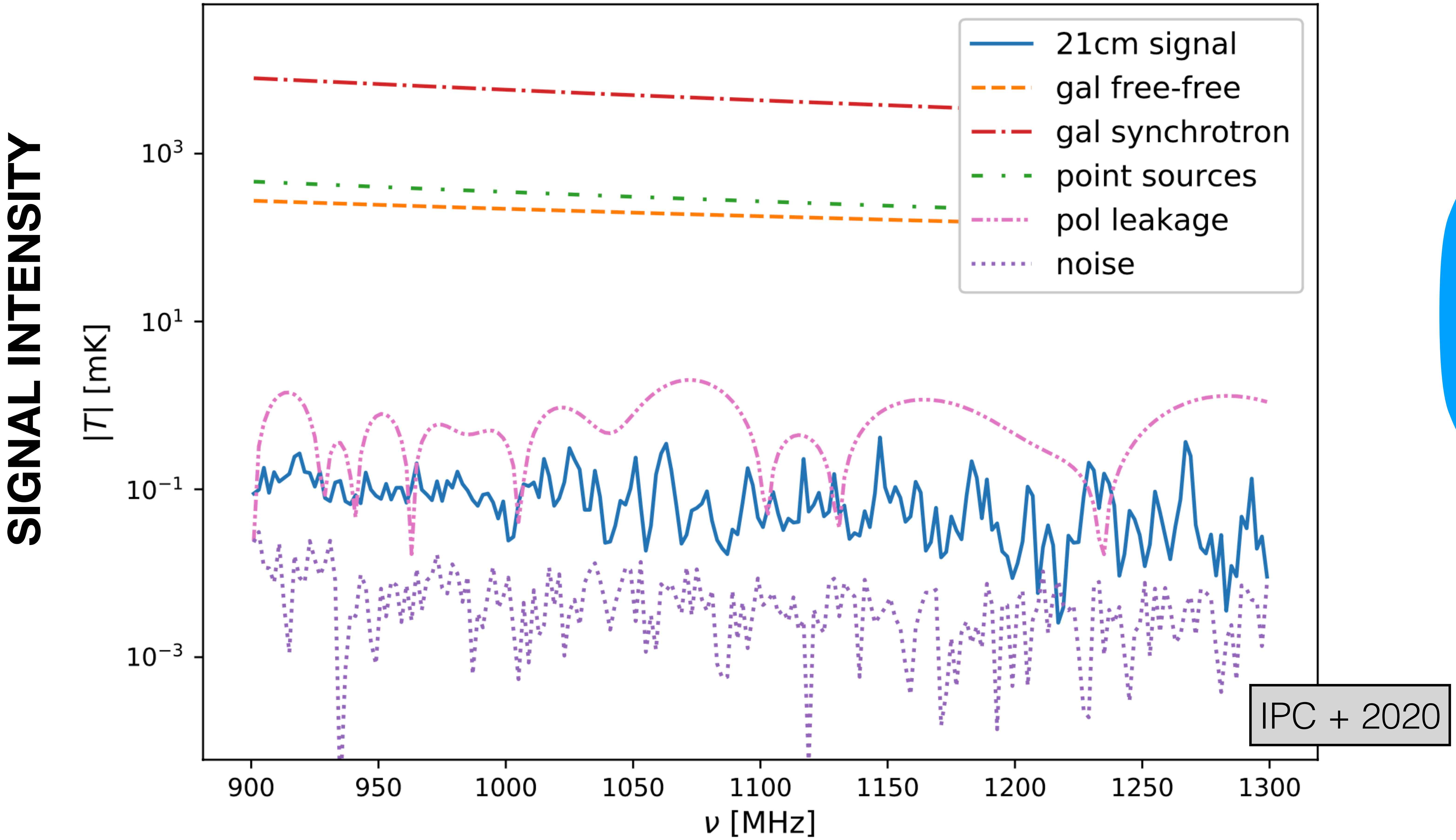


CHALLENGES:

- Foregrounds
- Systematics

HI intensity mapping: buried under the foregrounds



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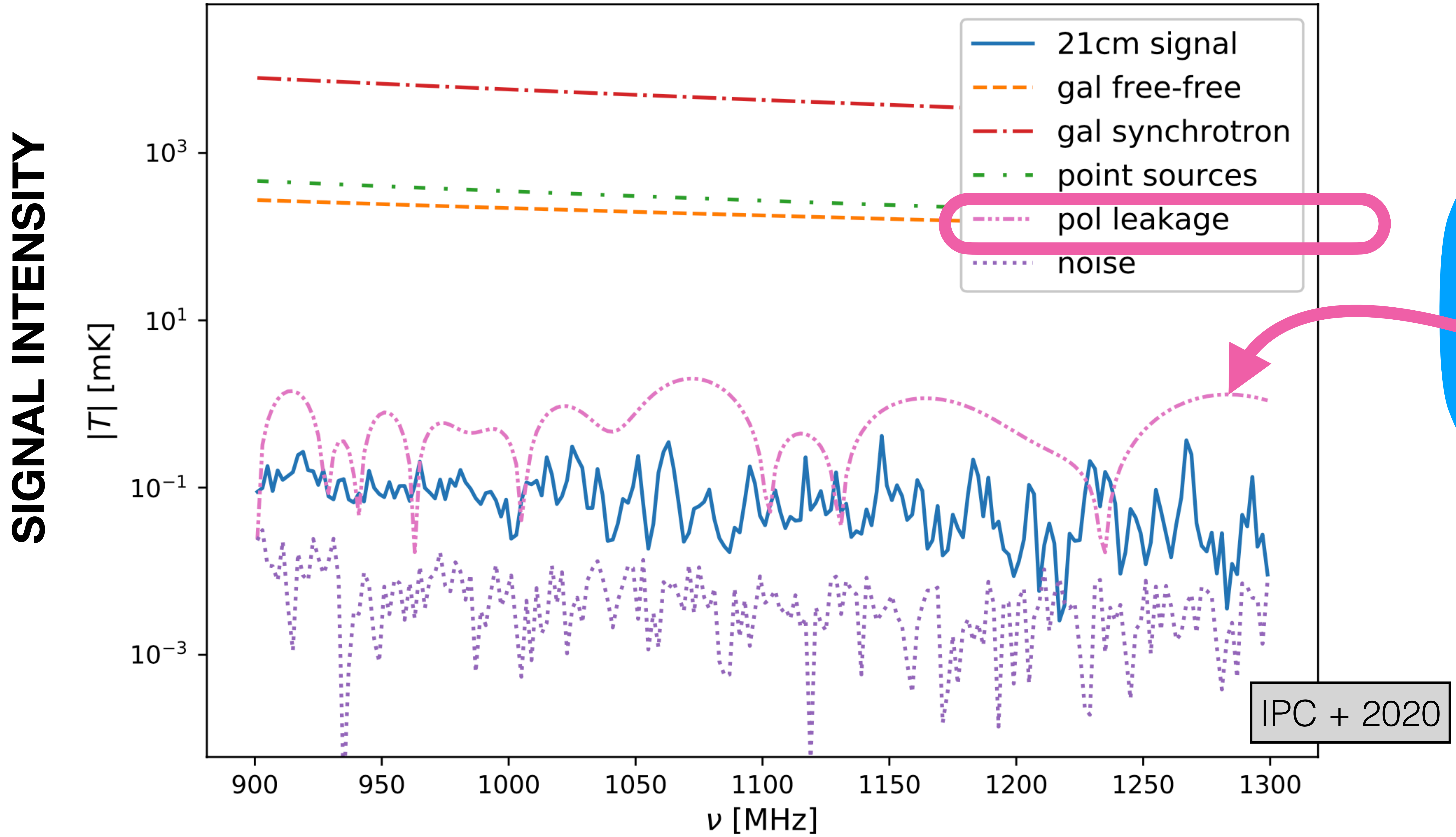

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- Foregrounds
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Blind Source Separation algorithms

The separation of a set of source signals (contaminants) from a set of mixed signals (the maps), with little or no info about the source signal or the mixing process.

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$$\mathbf{X} = \mathbf{A}\ \mathbf{S} + \mathbf{N}$$

- $\mathbf{X}$: signal (f,p)
- $\mathbf{A}$: mixing matrix (f,n)
- $\mathbf{S}$: sources (n,p)
- $\mathbf{N}$: HI signal!

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mixing matrix (f,n)

HI signal!

signal (f,p)

sources (n,p)

- **Decorrelation** —> diagonalise the covariance matrix
- **Independence** —> as more independent sources are mixed the signal becomes more Gaussian (central limit theorem). So, let's maximise the non-gaussianity of the sources to *unmix* them.

Principal Component Analysis (**PCA**)

Independent Component Analysis (**ICA**)

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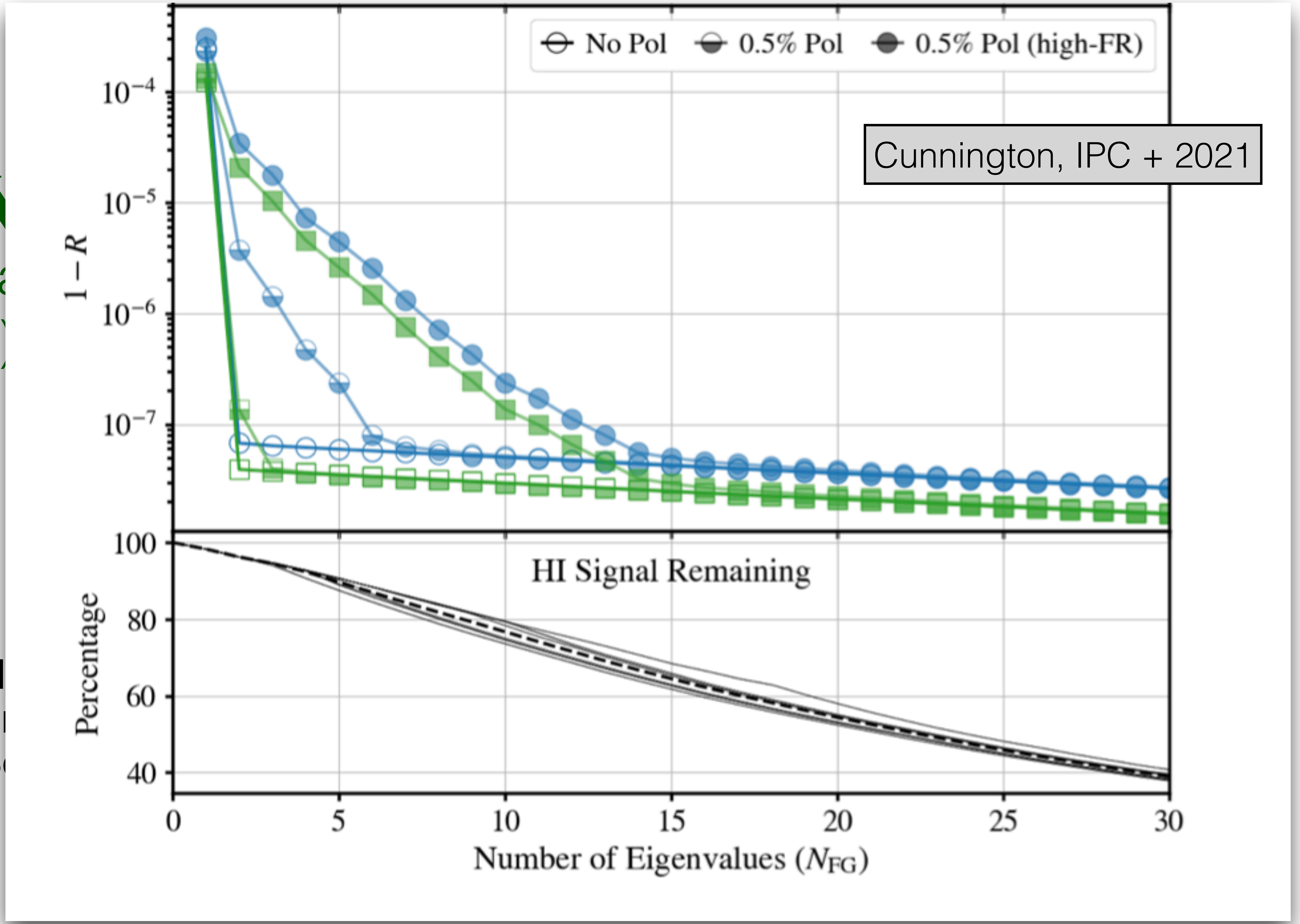

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"Instrumental effects such as passband calibration and **polarization leakage** couple bright foregrounds into new degrees of freedom […]. The spectral functions describing these systematics cannot all be modelled in advance, so we take an **empirical approach to foreground removal by estimating dominant modes** from the covariance of the map itself."

Switzer+ 2013

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- no noteworthy difference between PCA or ICA
- ~**4** components removed are enough

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GMCA (sparsity-based) —> **mixGMCA**

(Carucci+ 2020, Cunnington+ 2021, The SKAO Blind Challenge , work in progress…)

a quick interlude on GMCA

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- **Sparsity —>** mixtures are less sparse than sources!

Principal Component Analysis (**PCA**)

Independent Component Analysis (**ICA**)

Generalised Morphological Component Analysis (**GMCA**)

Bobin + 2007, 2008, 2012

why sparsity?

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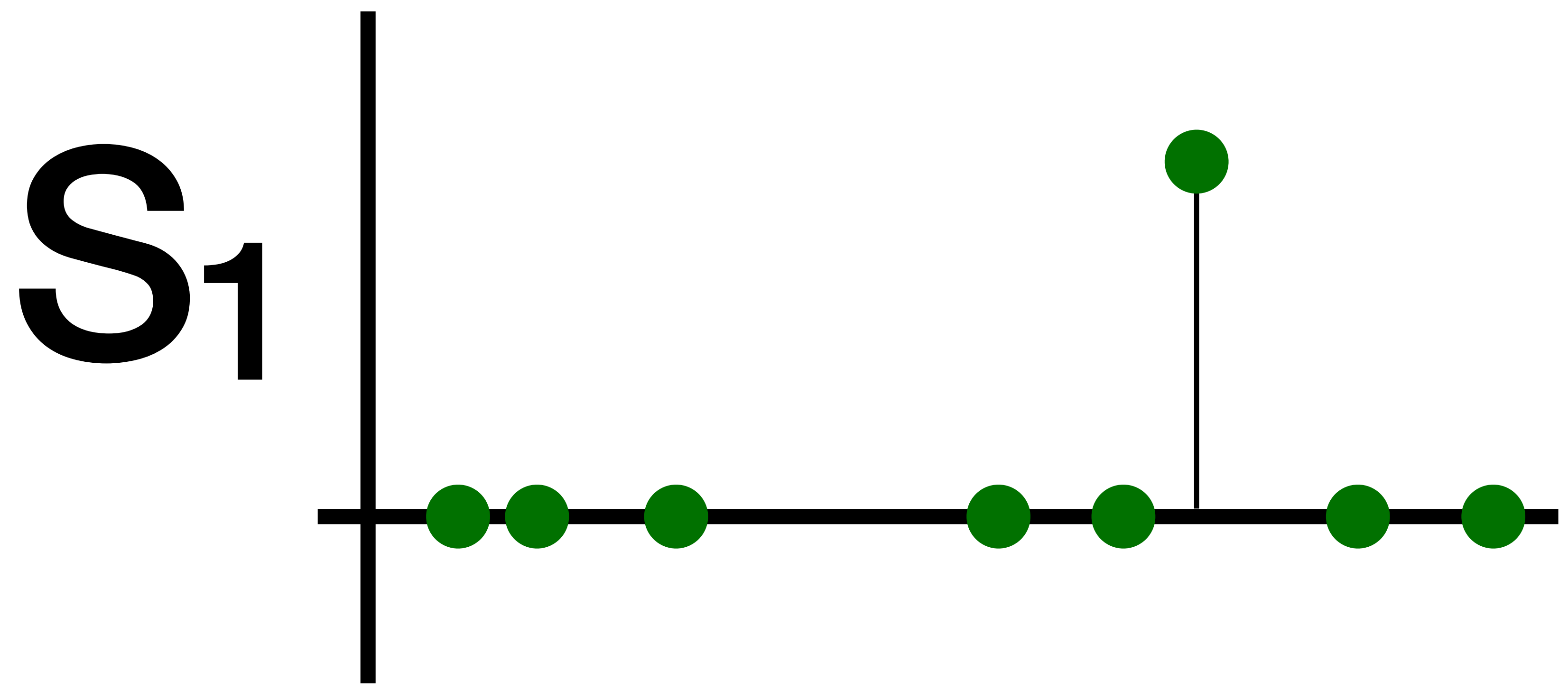

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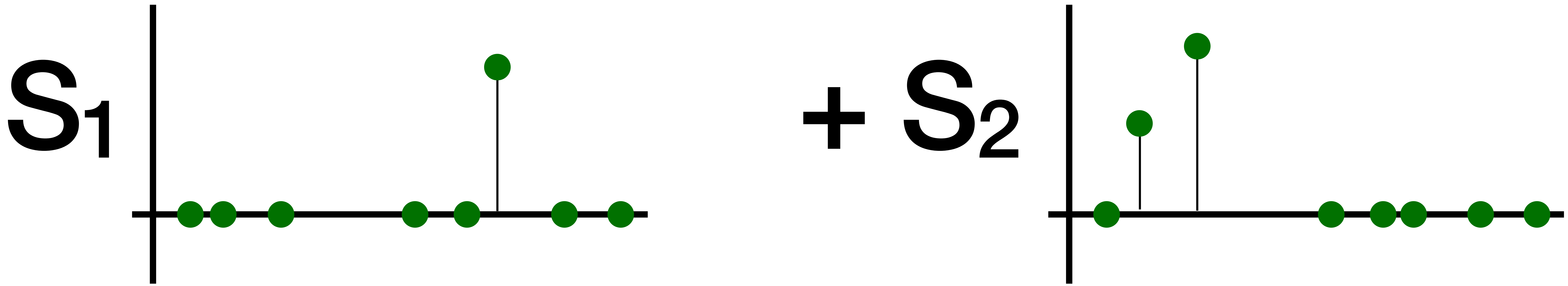

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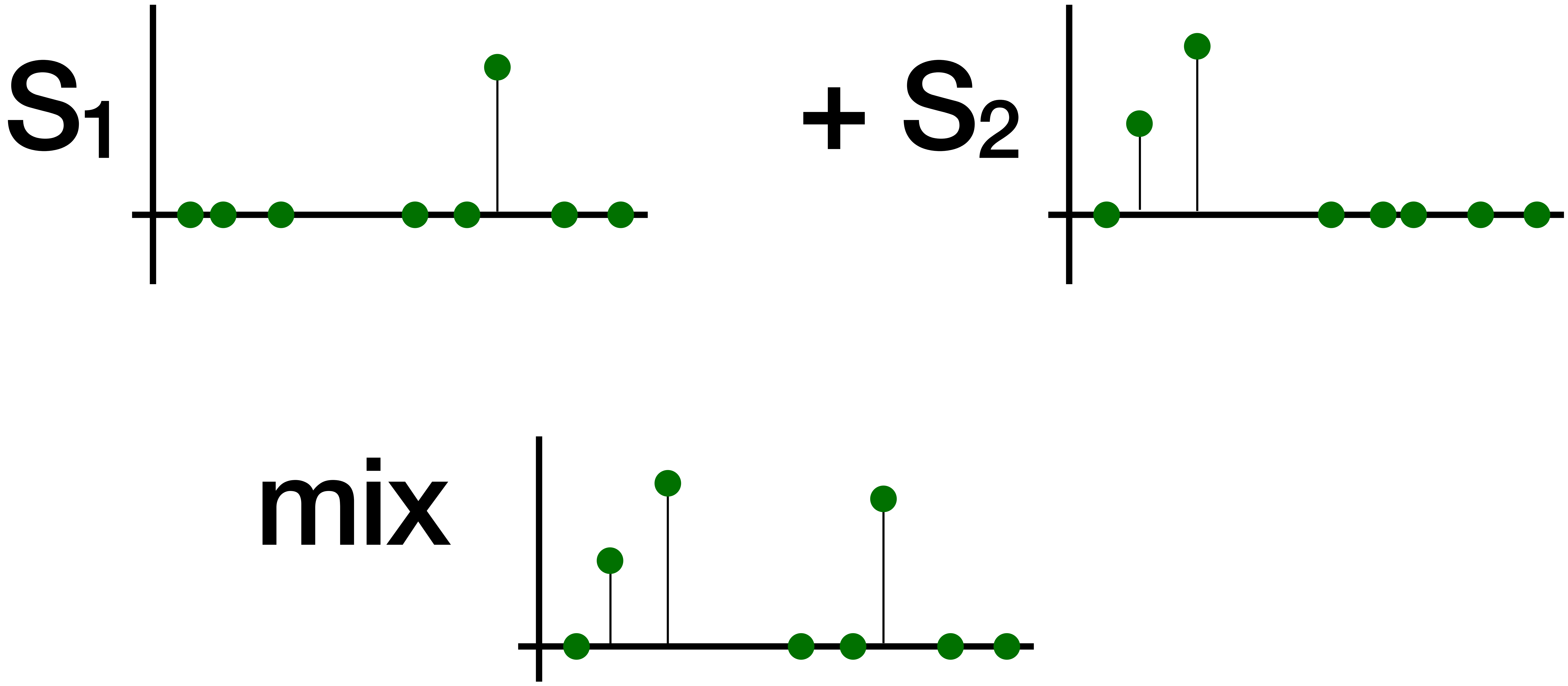
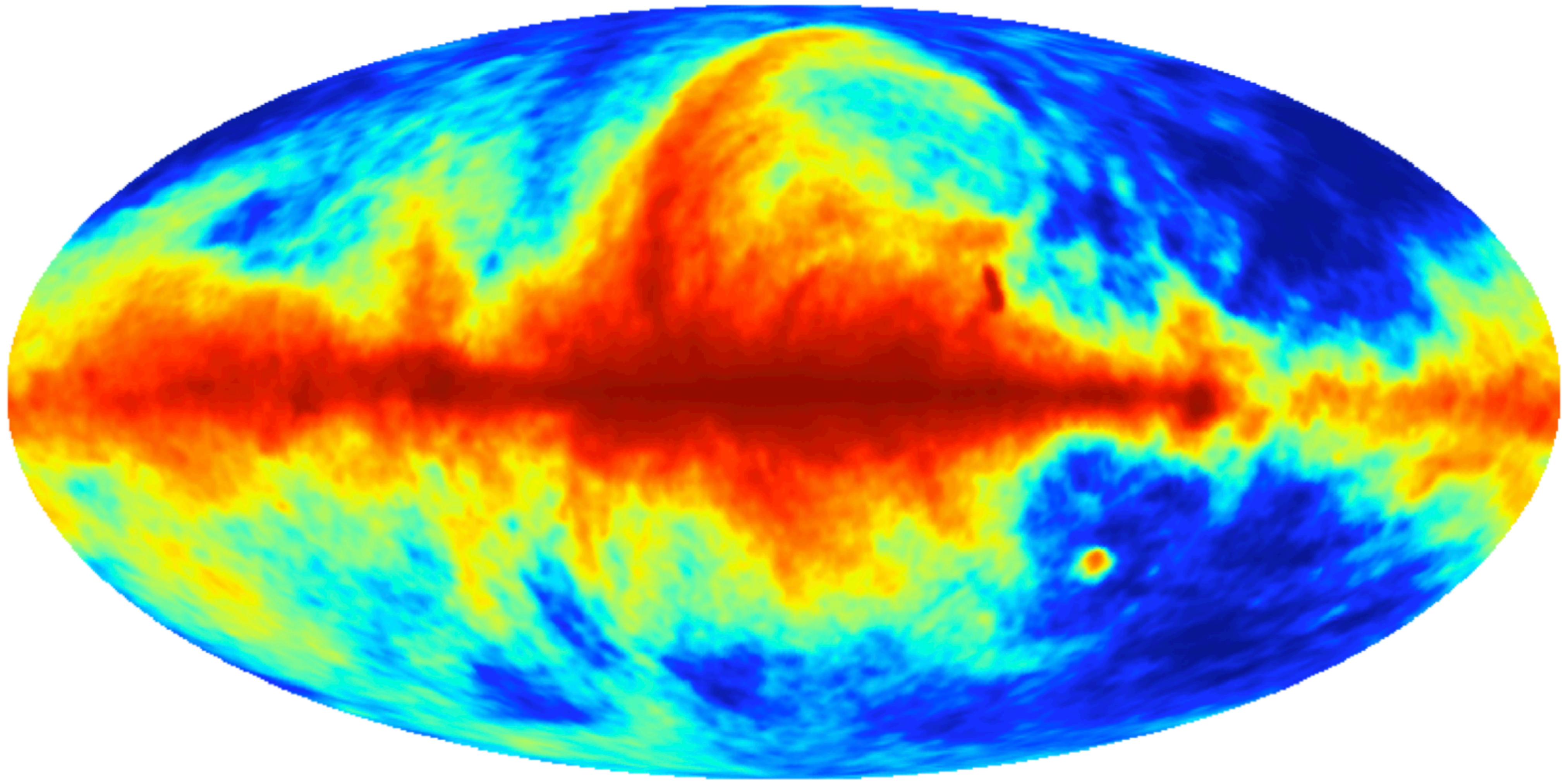


Enforcing sparsity: in which domain?



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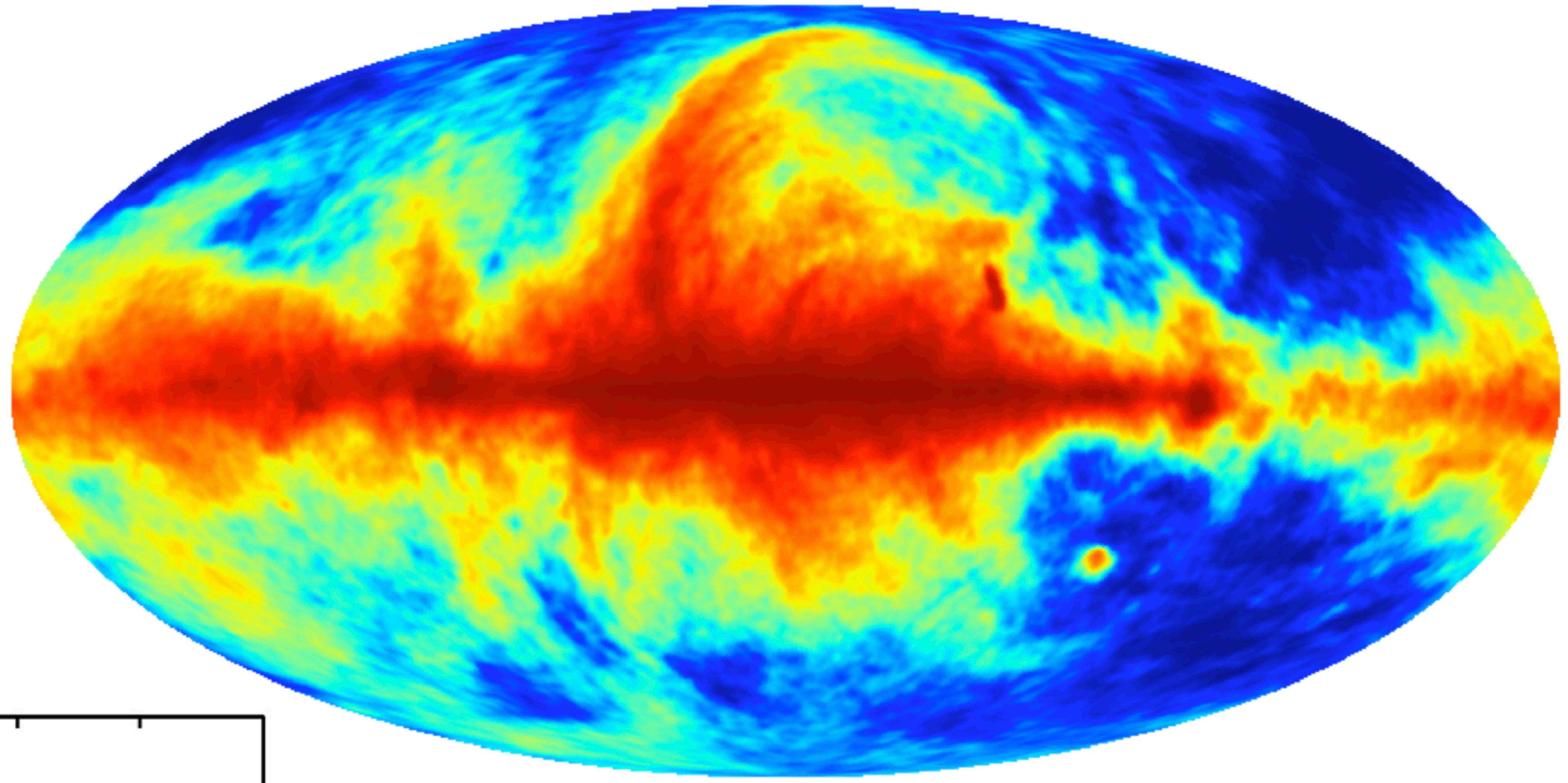

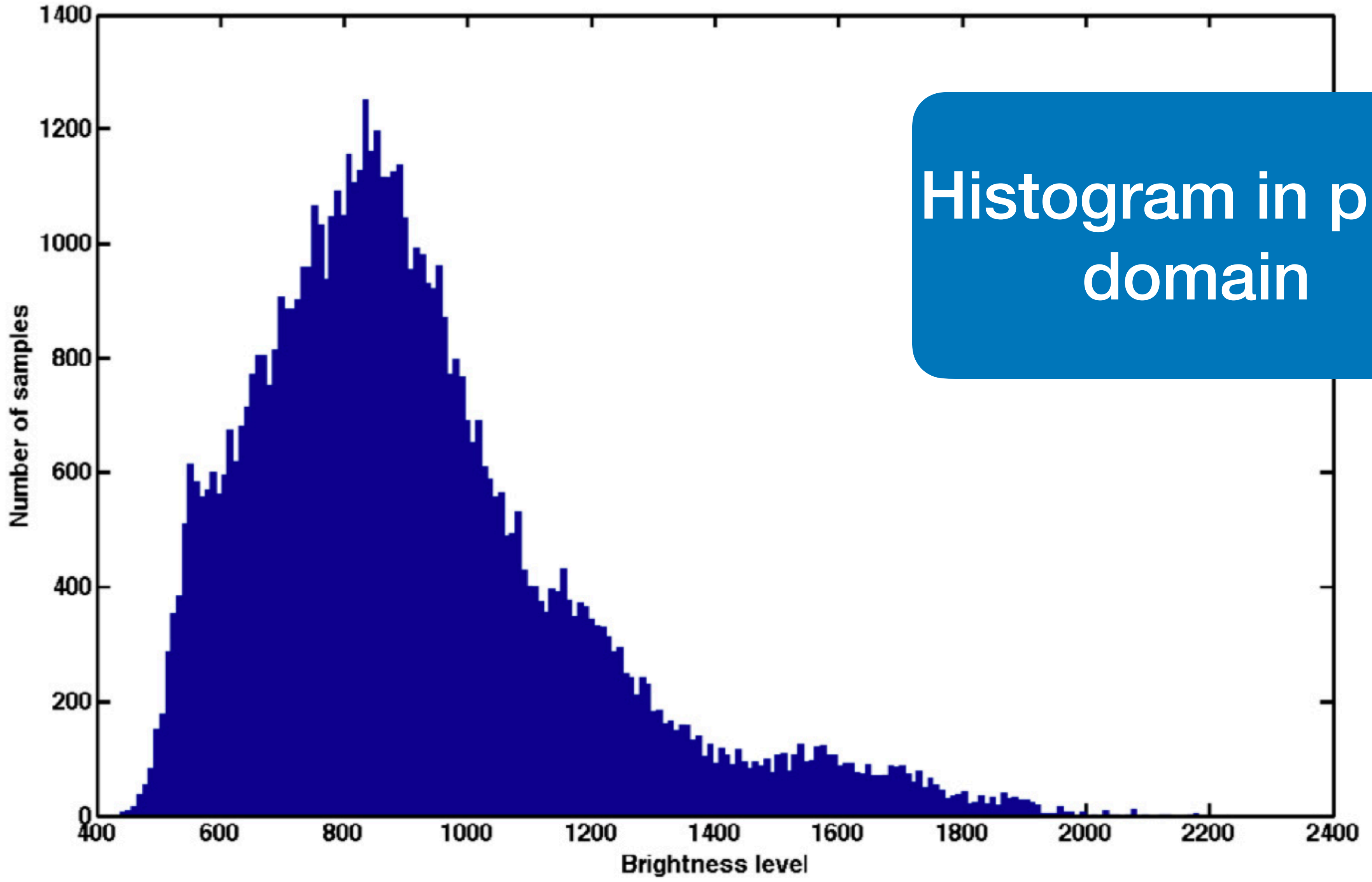

Histogram in pixel domain

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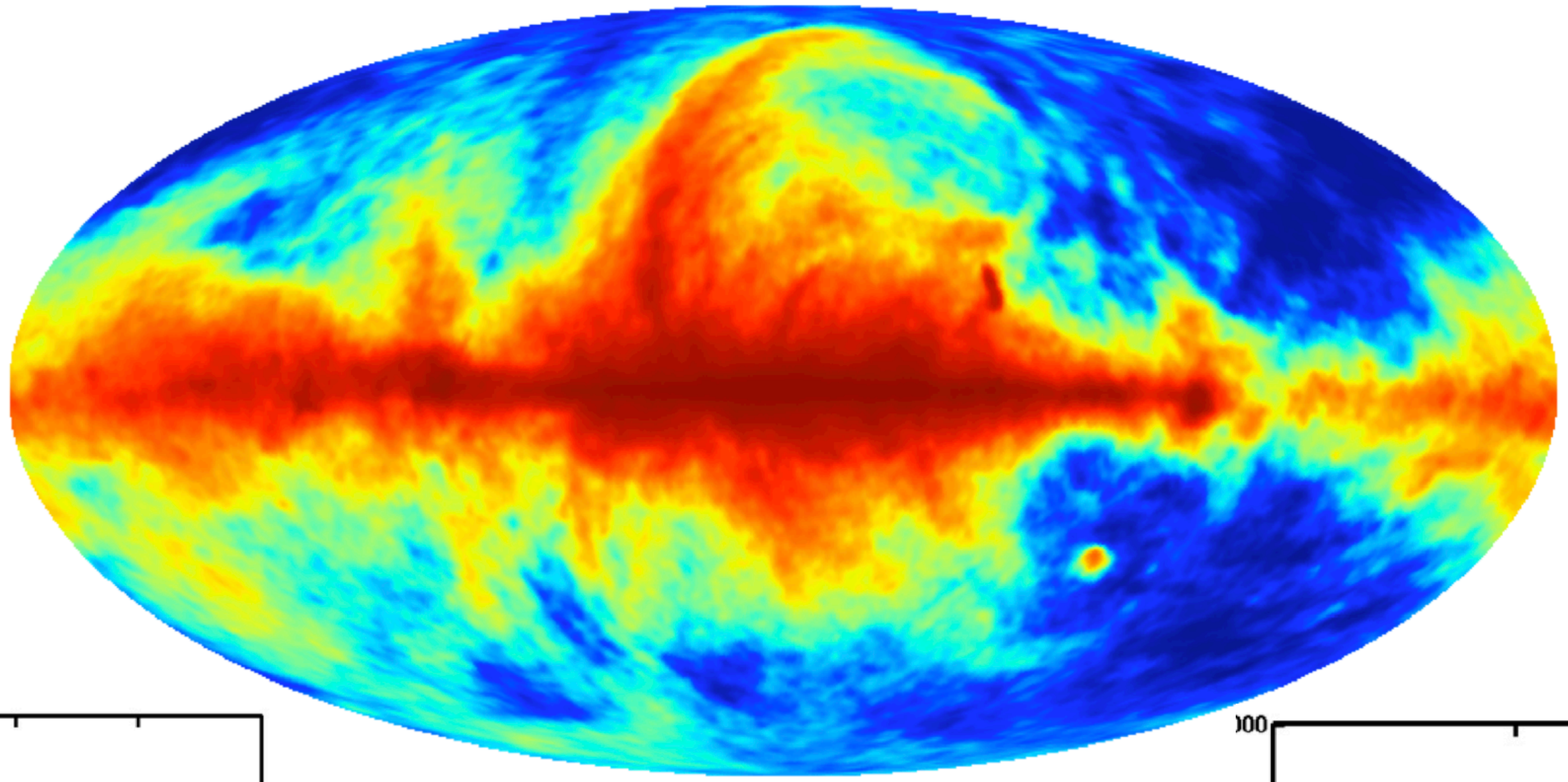

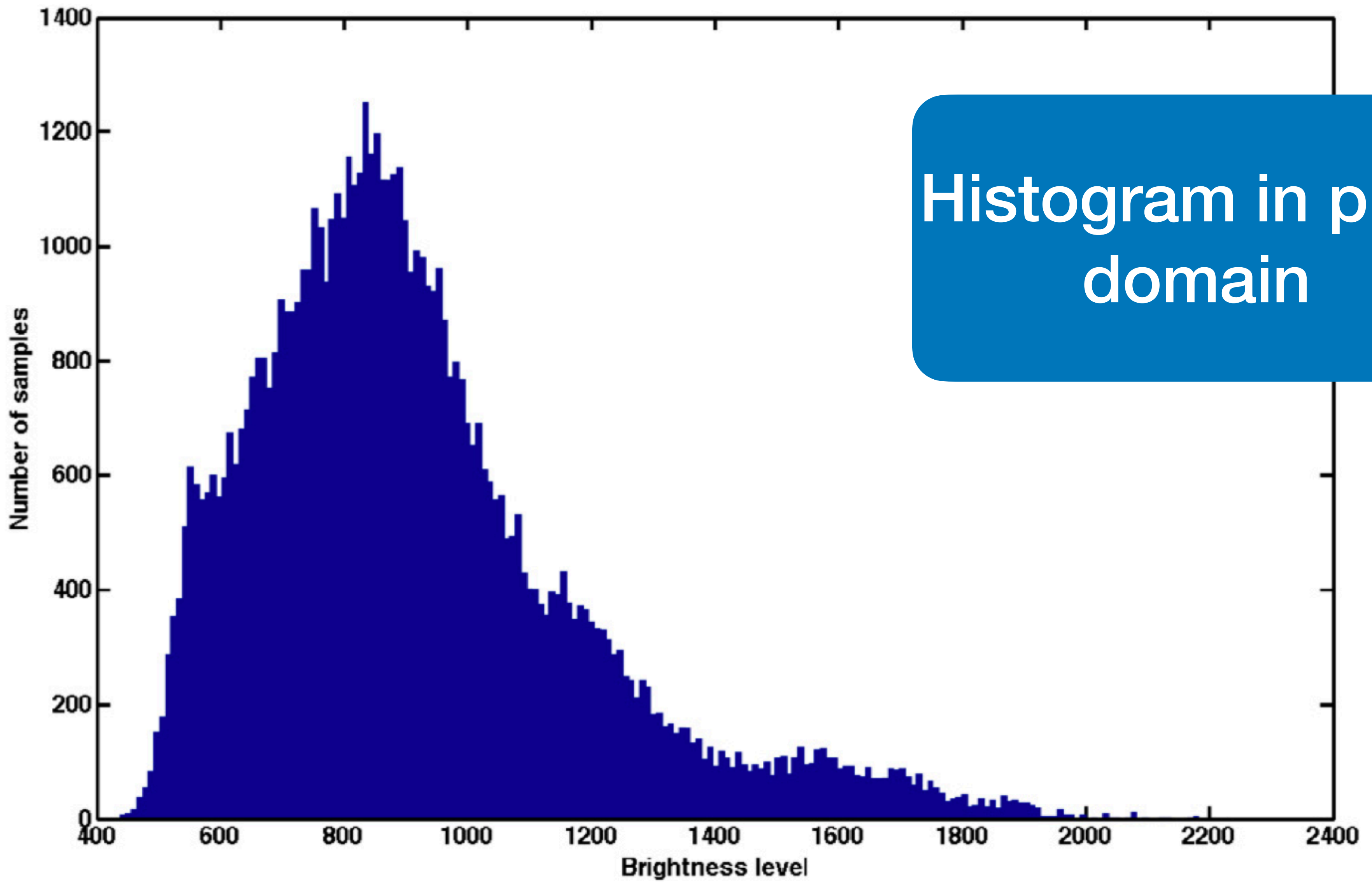

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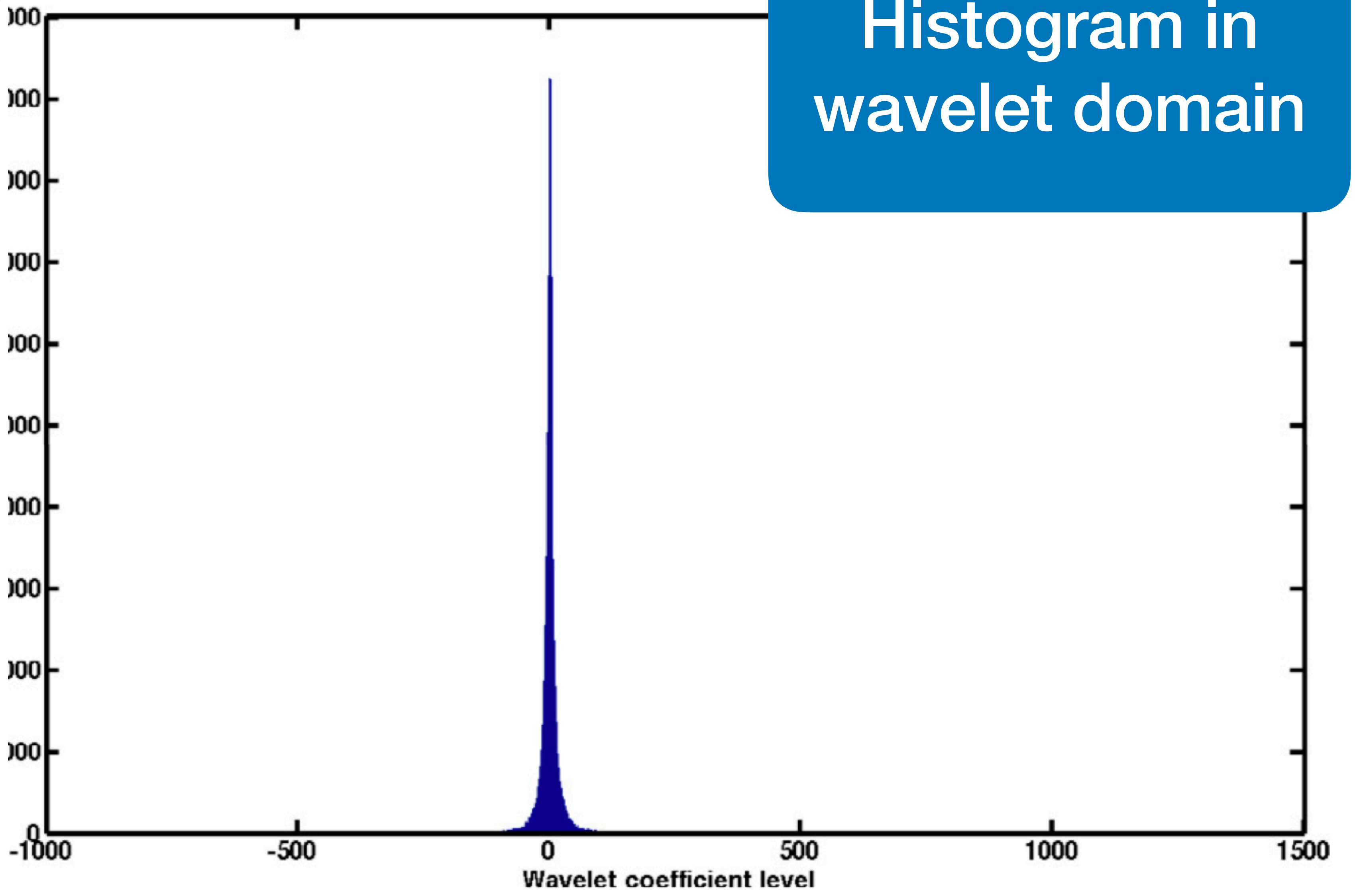


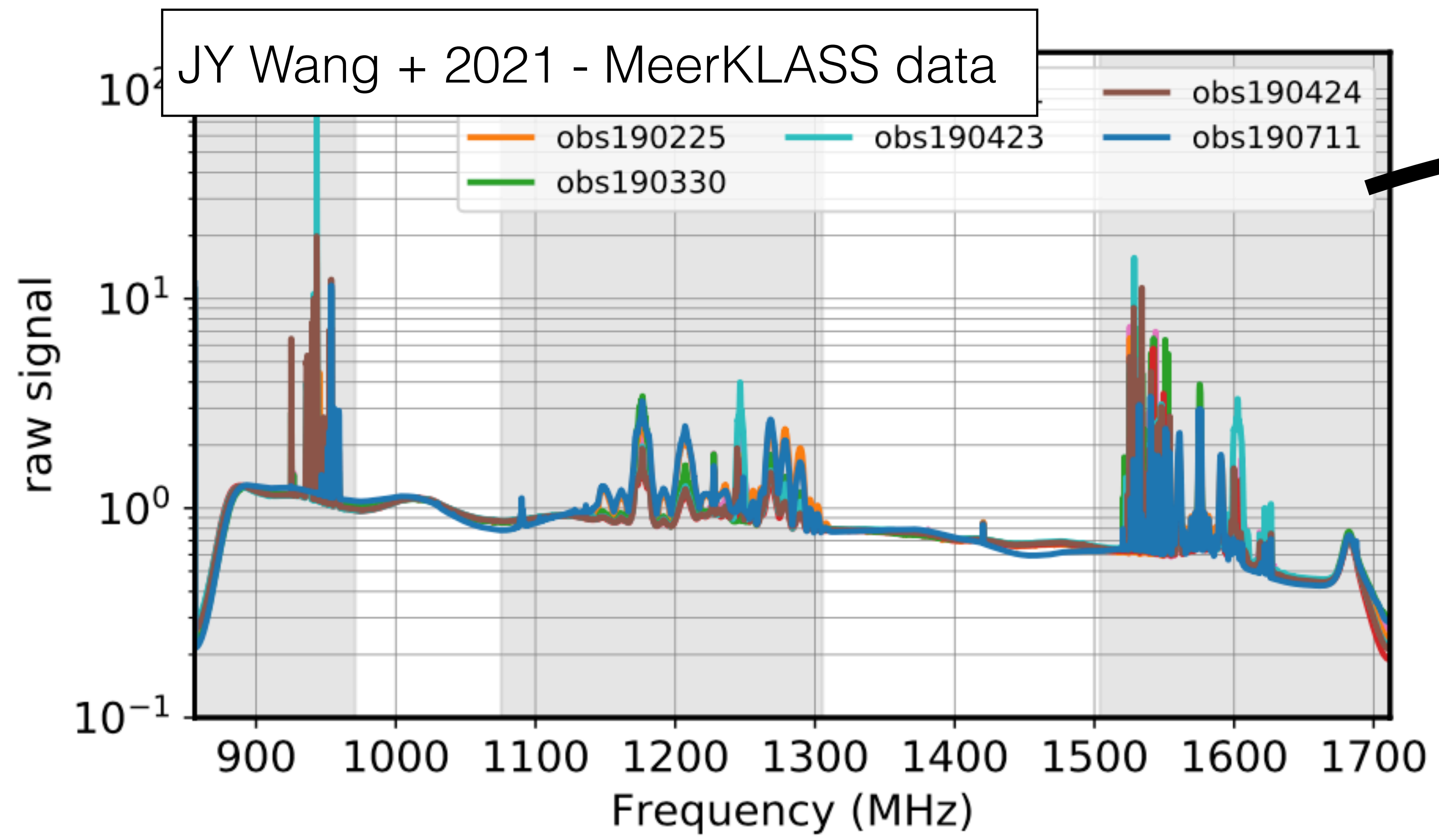
Histogram in wavelet domain

Sparsity-based component-separation for 21-cm IM

GMCA: Generalised Morphological Component Analysis

Bobin+ 2007, 2008, 2012,.. Applied on data in different astro-context: CMB (e.g. Bobin+2016), EoR (e.g. Hothi+2020), X-ray (Picquenot+2019), …

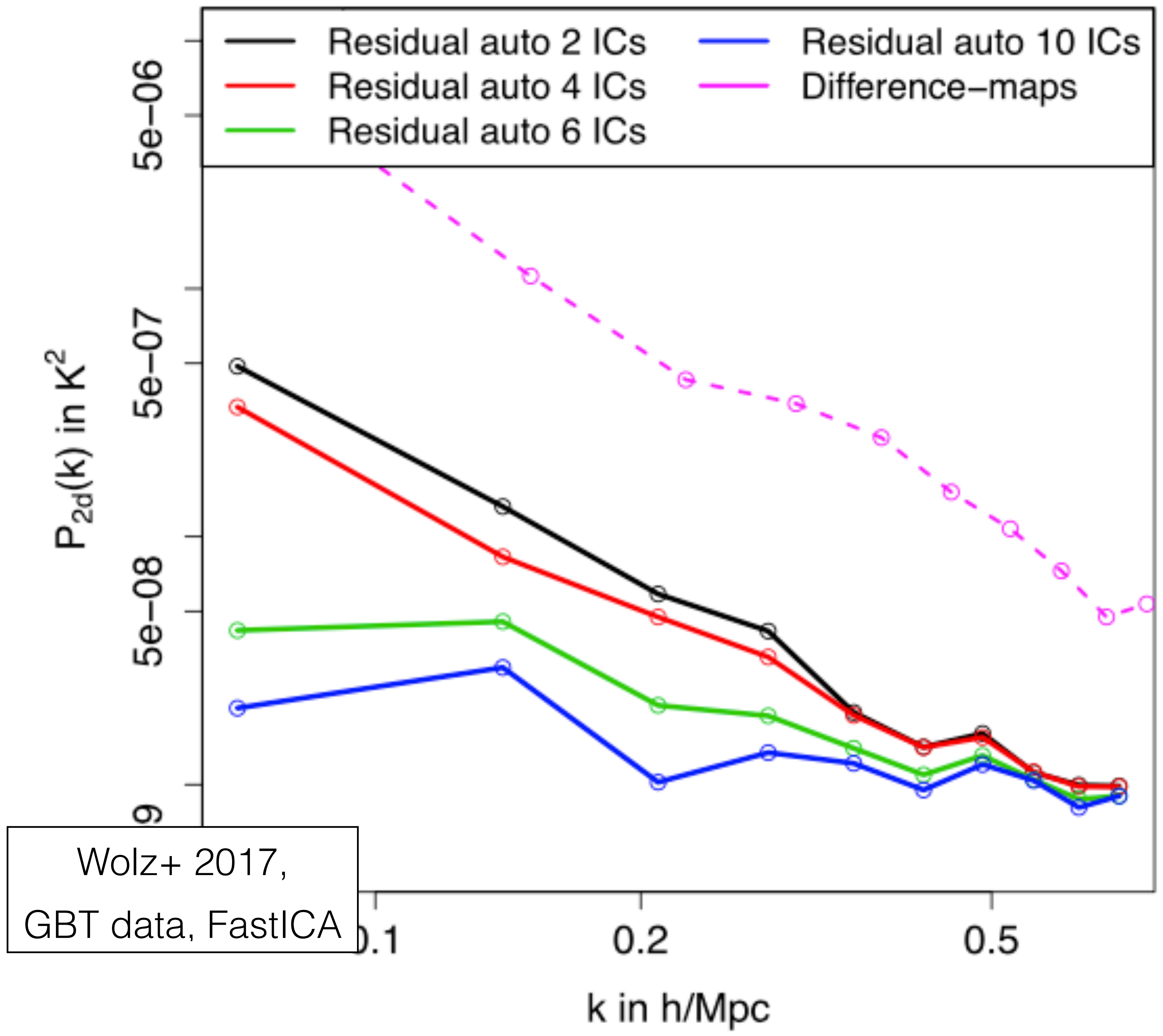
- wavelet decomposition —> **multi-scale** approach
- **No priors on signal**



in Carucci+ 2020, for the fist time in the literature:

1. Good performance also with **RFI-flagged** data cubes!
   (TV stations, telecommunication, satellites,..)
2. **Pol leakage:** greater complexity of data
   (higher number of sources needed, convergence not assured, mode-mixing assured)

Different scales need different care



Wolz+ 2017,
GBT data, FastICA

See also Hothi+2020 with LOFAR data

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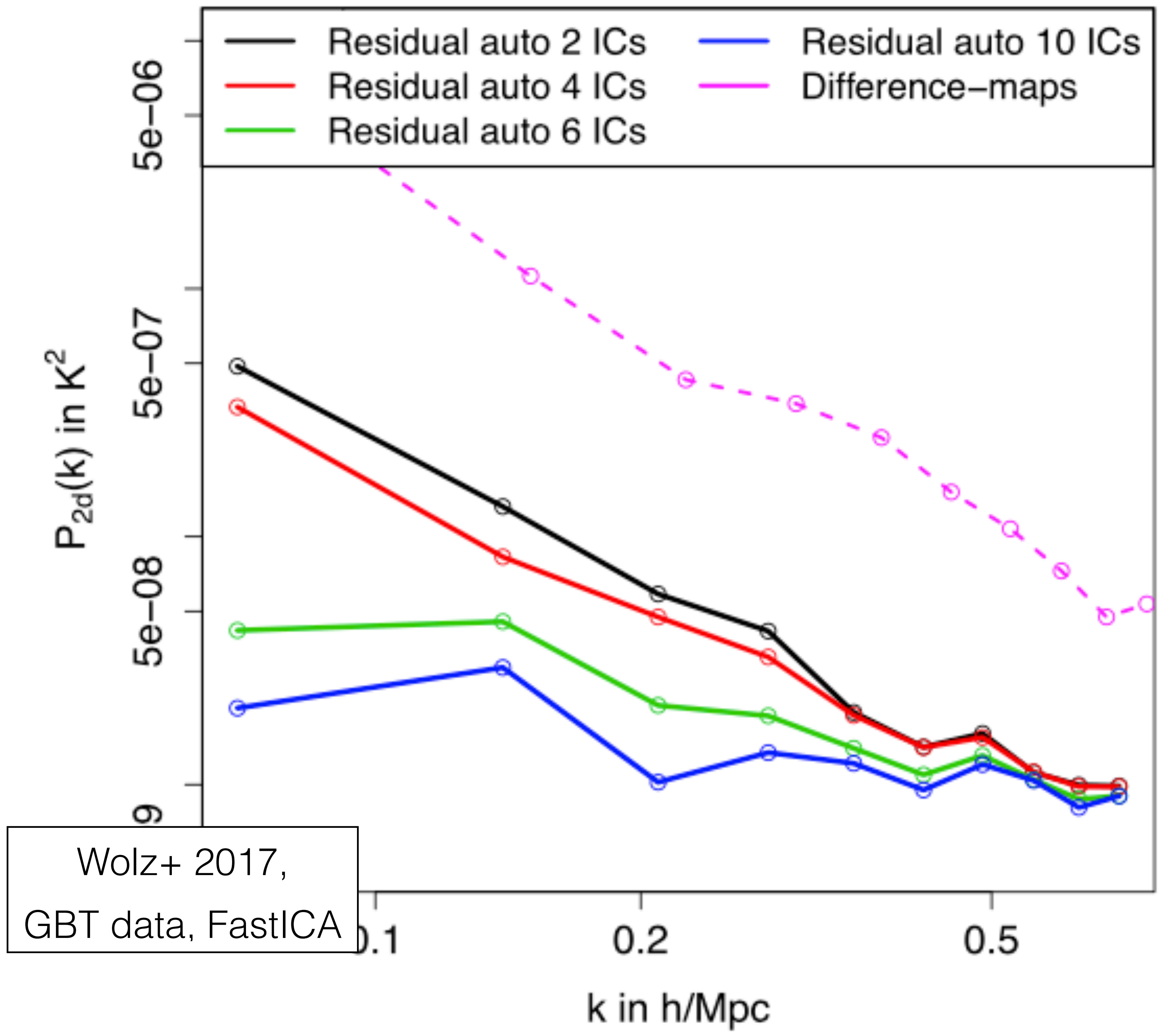

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- GMCA performs very well on small scales, can fail at the large scale
- PCA / ICA —> overfit the large scales

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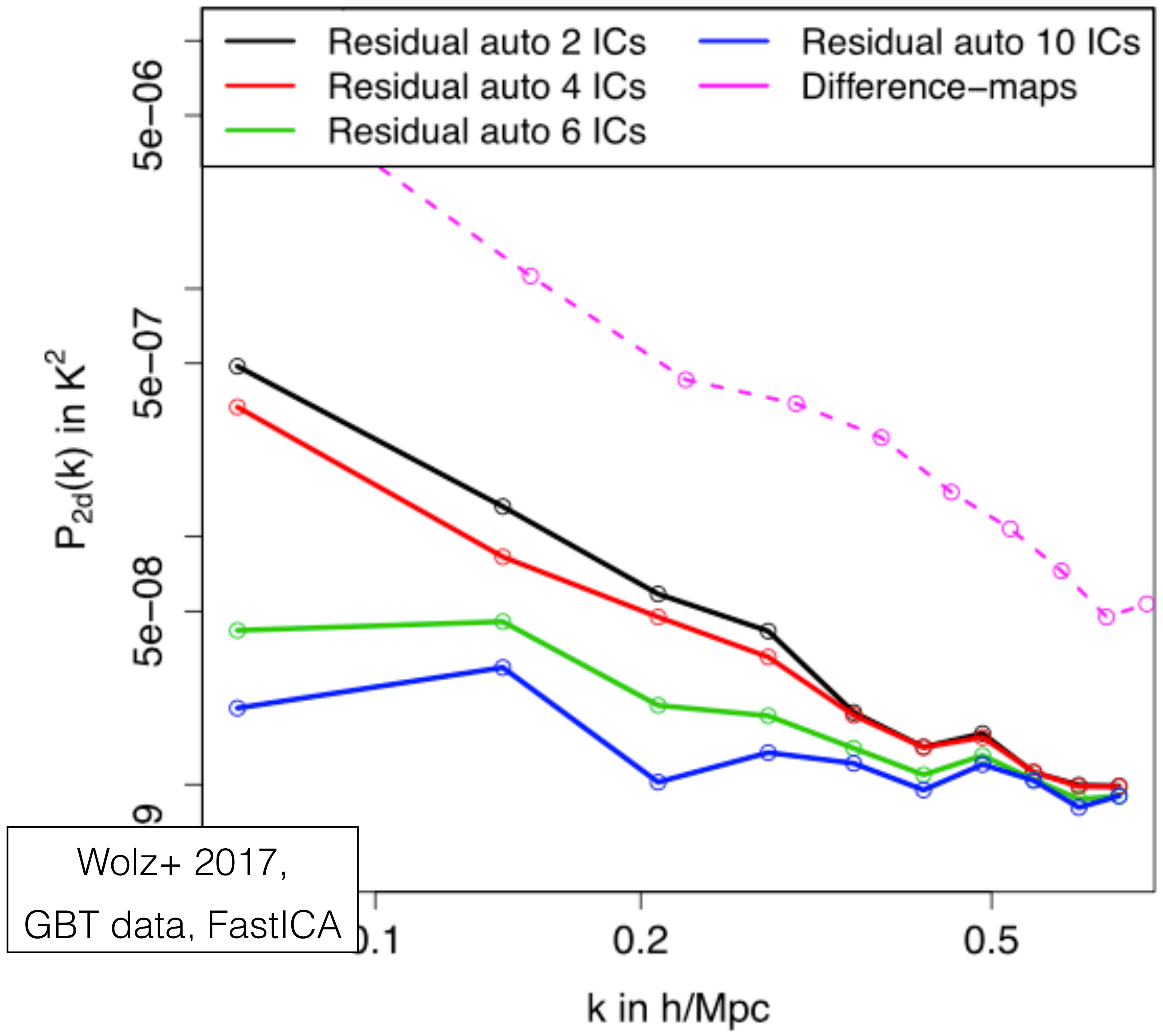
The wavelet domain is a multi-scale framework!



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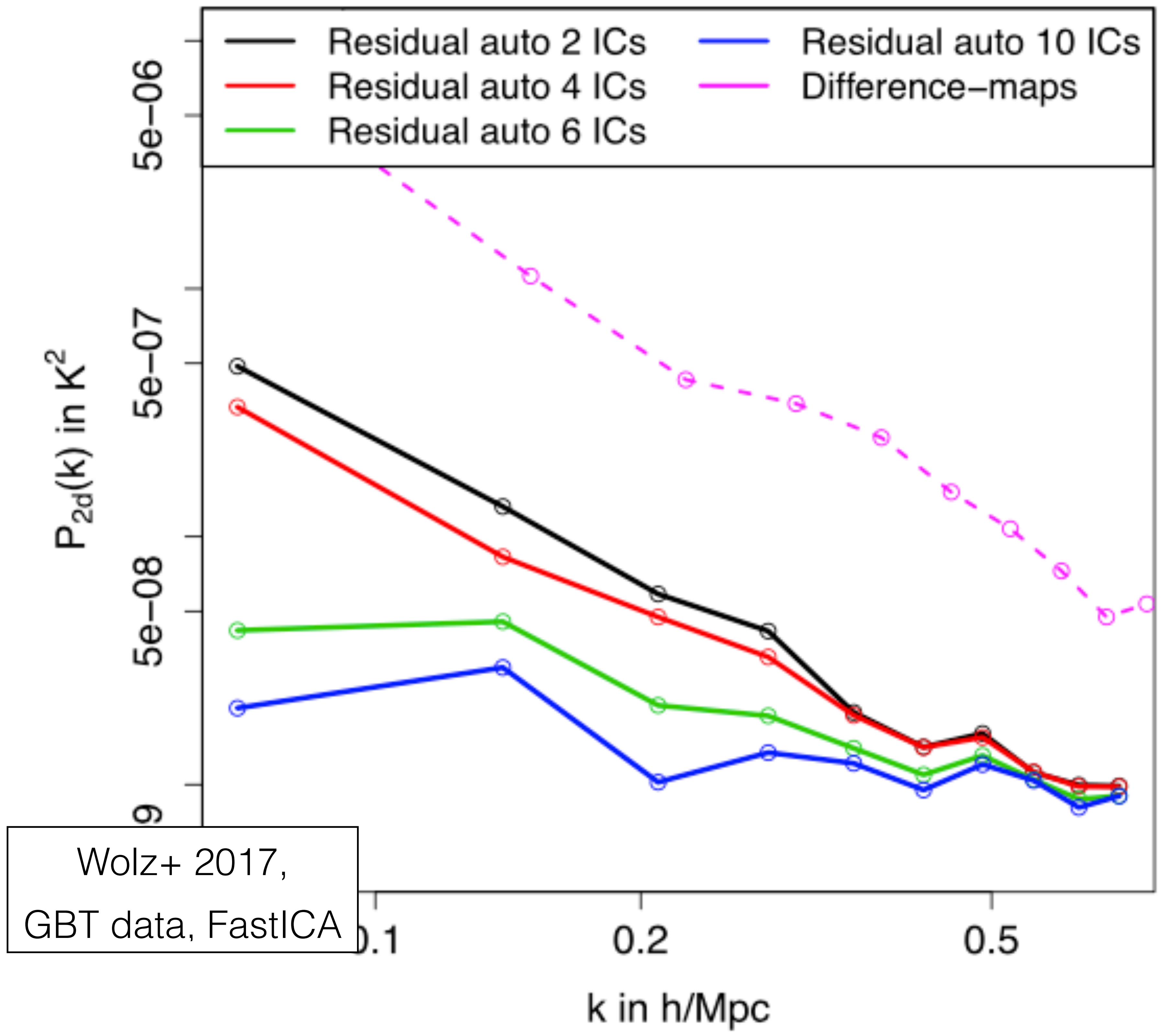

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how to subtract the contaminants?

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(Carucci+ 2020, Cunnington+ 2021, The SKAO Blind Challenge , work in progress…)

3. to test the BSS pipelines on the same set of sims

Started at the 2020 SKA Cosmology SWG meeting, as a collective project of the IM Focus Group

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First Blind Foreground Subtraction Challenge

if we were given SKA-mid IM data today,
what could we achieve in terms of
contaminants subtraction?

Simulating all we can (up to now)

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Sky components:

1. HI
2. Astrophysical Foregrounds
   - Galactic synchrotron
   - Galactic Free-Free
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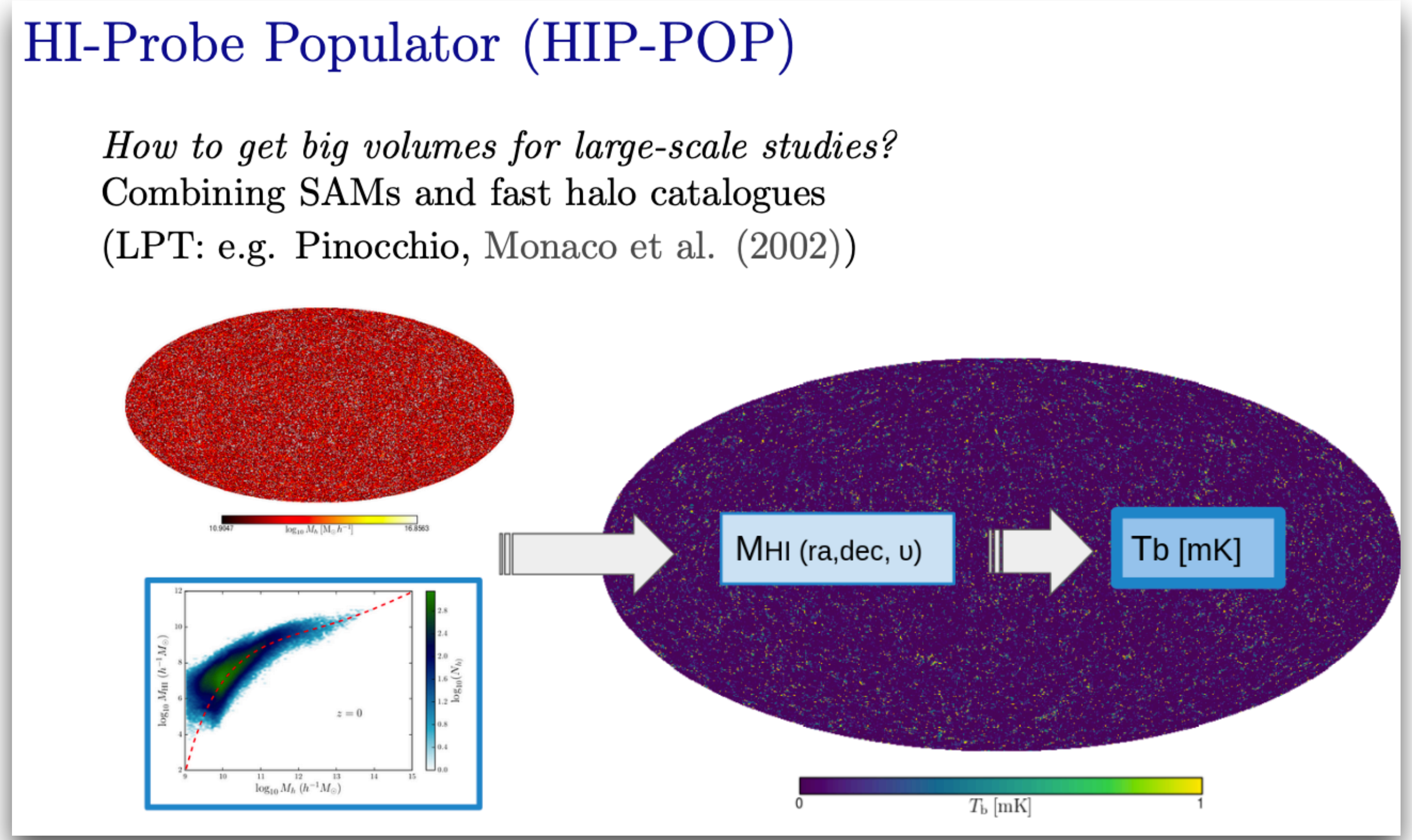

Slide: Marta Spinelli

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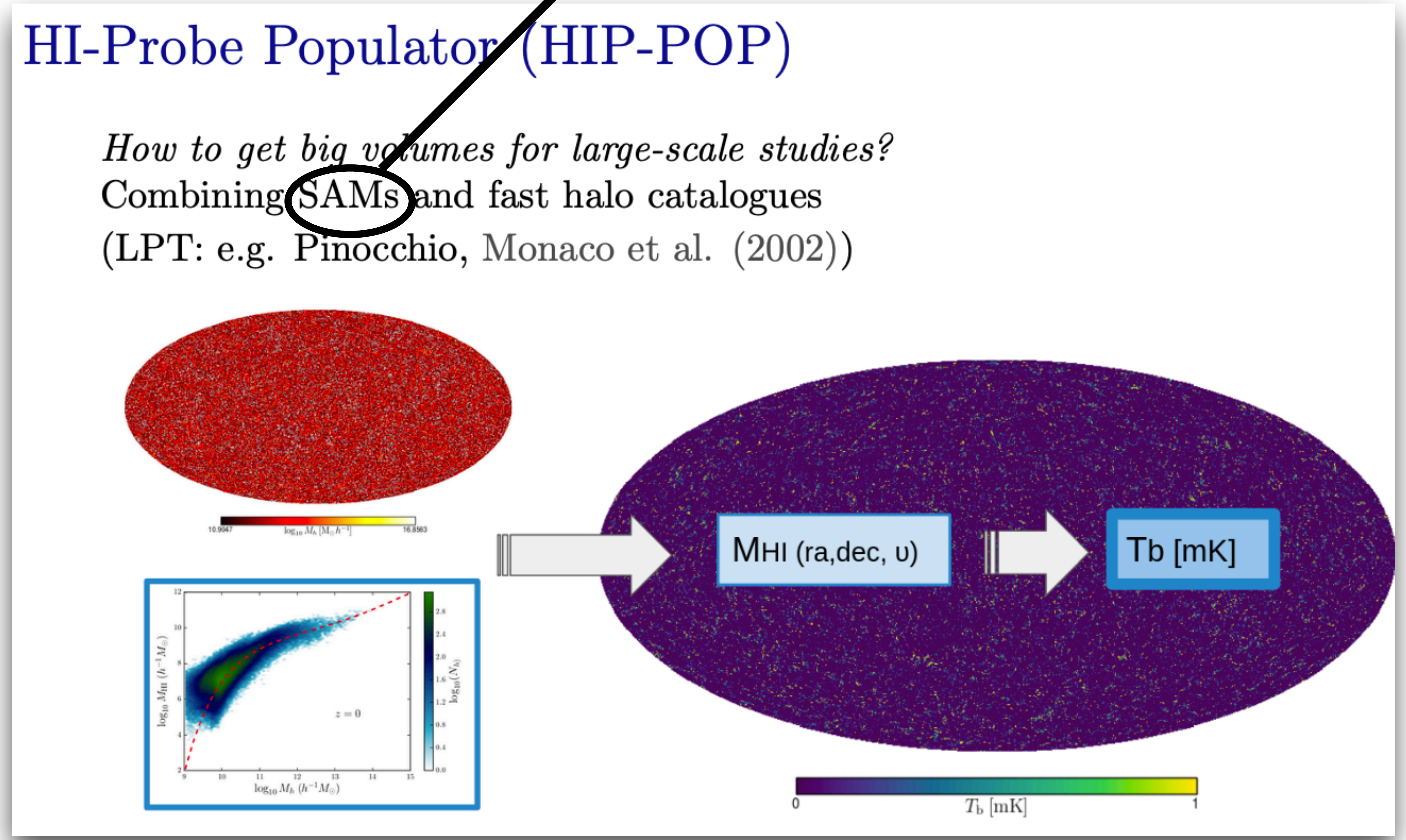
GAEA

(Gabriella De Lucia talking on Thursday)



Slide: Marta Spinelli

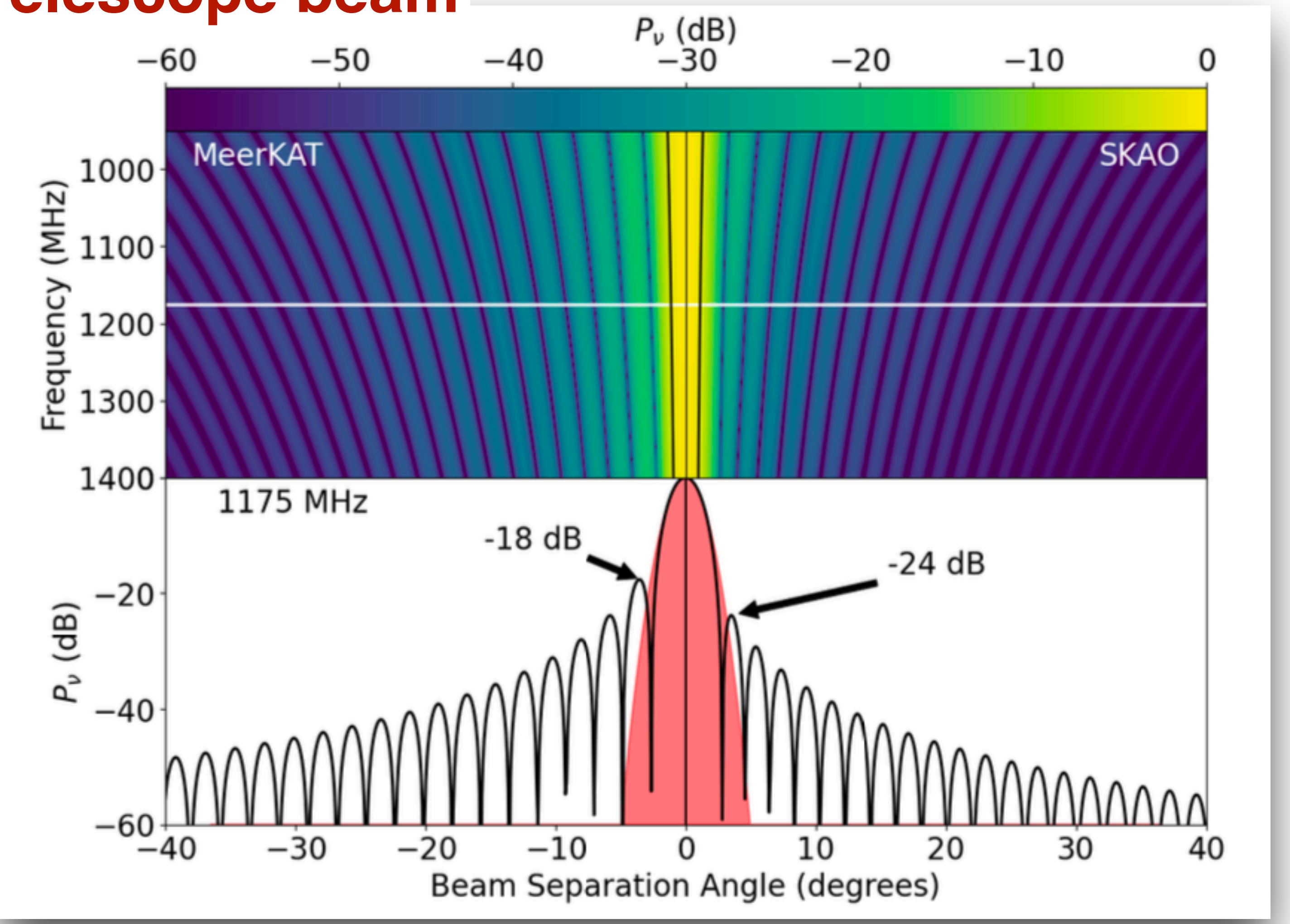
Simulating all we can (up to now)

Sky components:

1. HI
2. Astrophysical Foregrounds
   - Galactic synchrotron
   - Galactic Free-Free
   - Extragalactic background
   - Point Sources

+

Telescope beam



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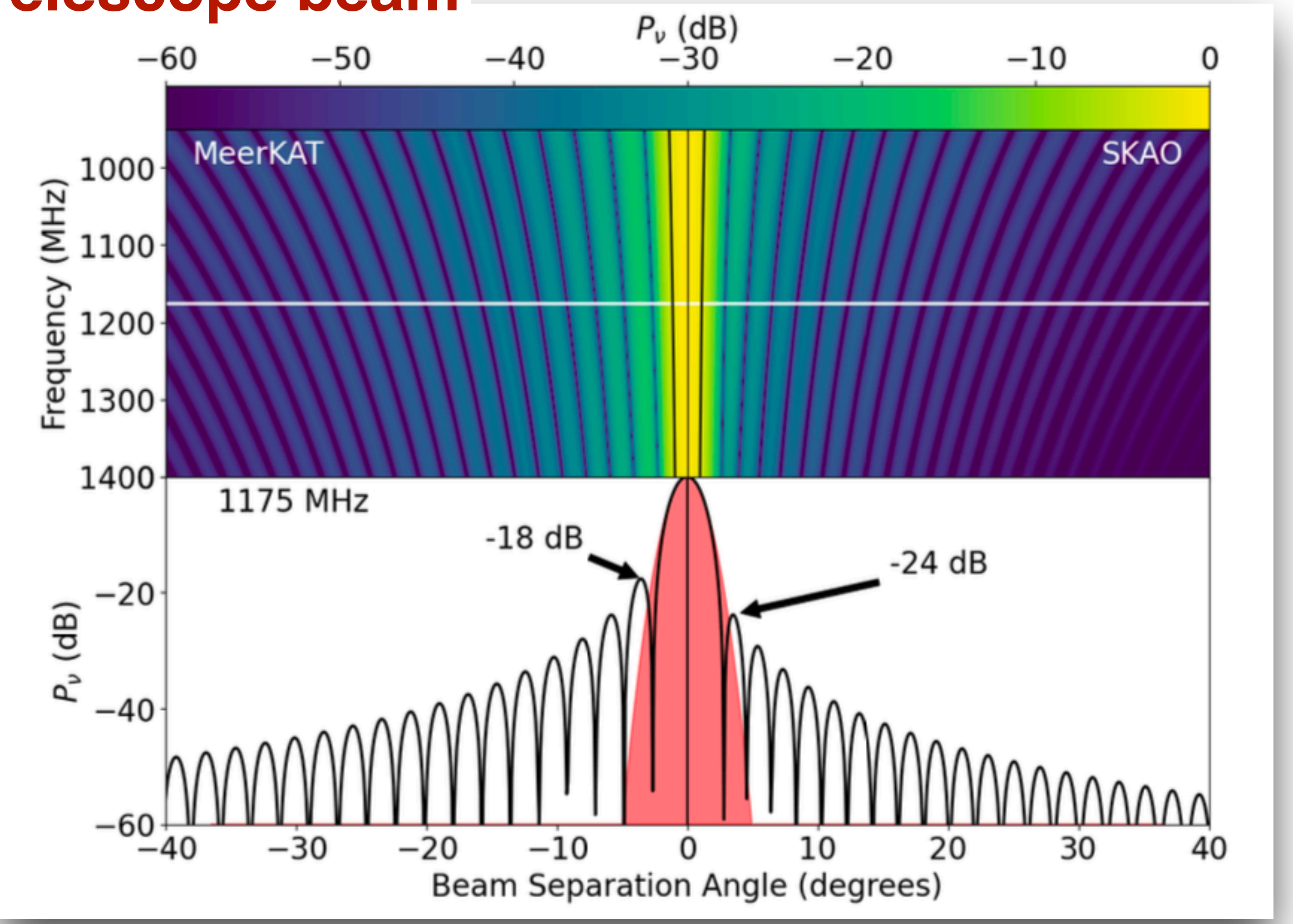

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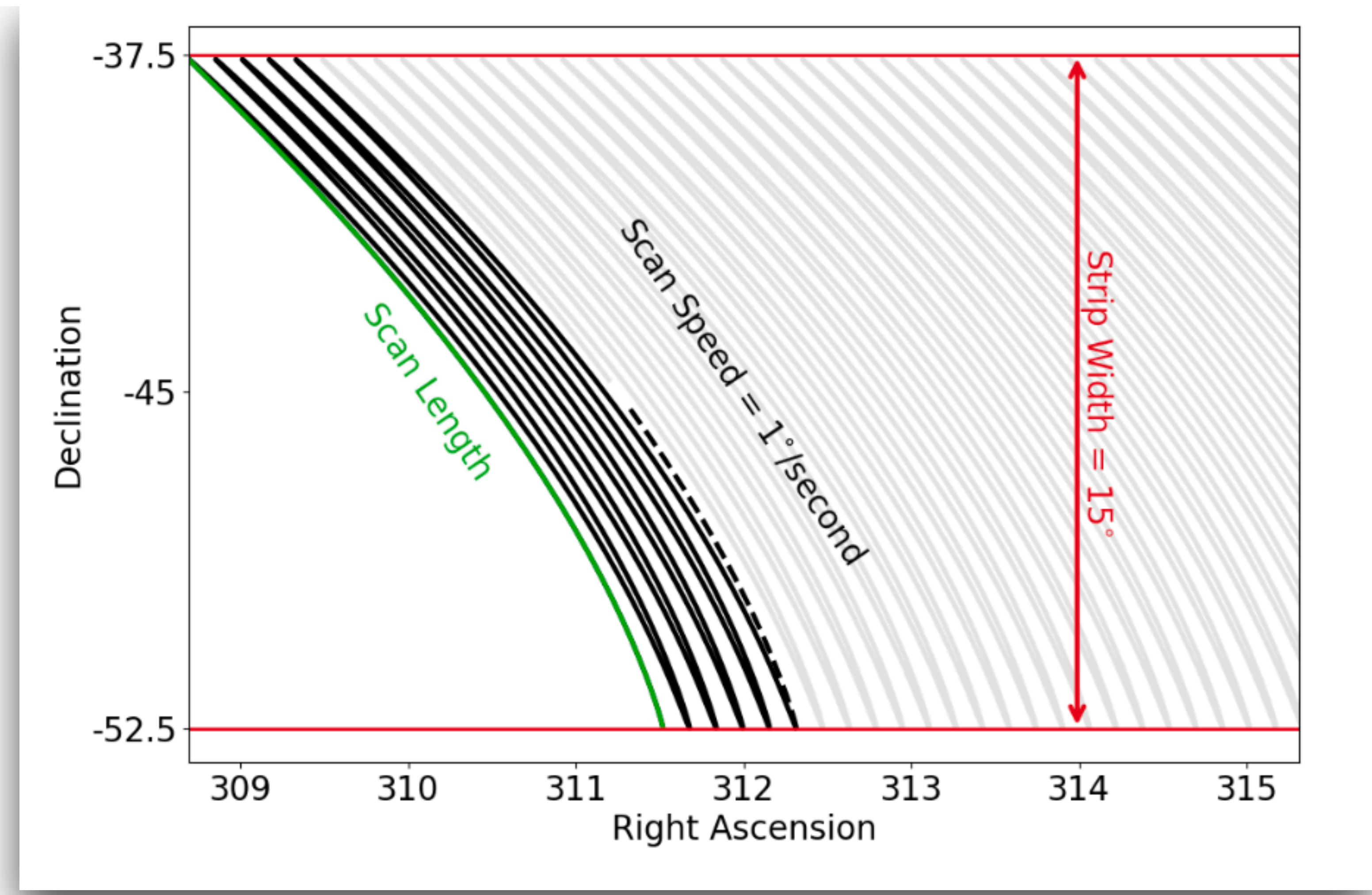
Scanning strategy (non-uniform noise)



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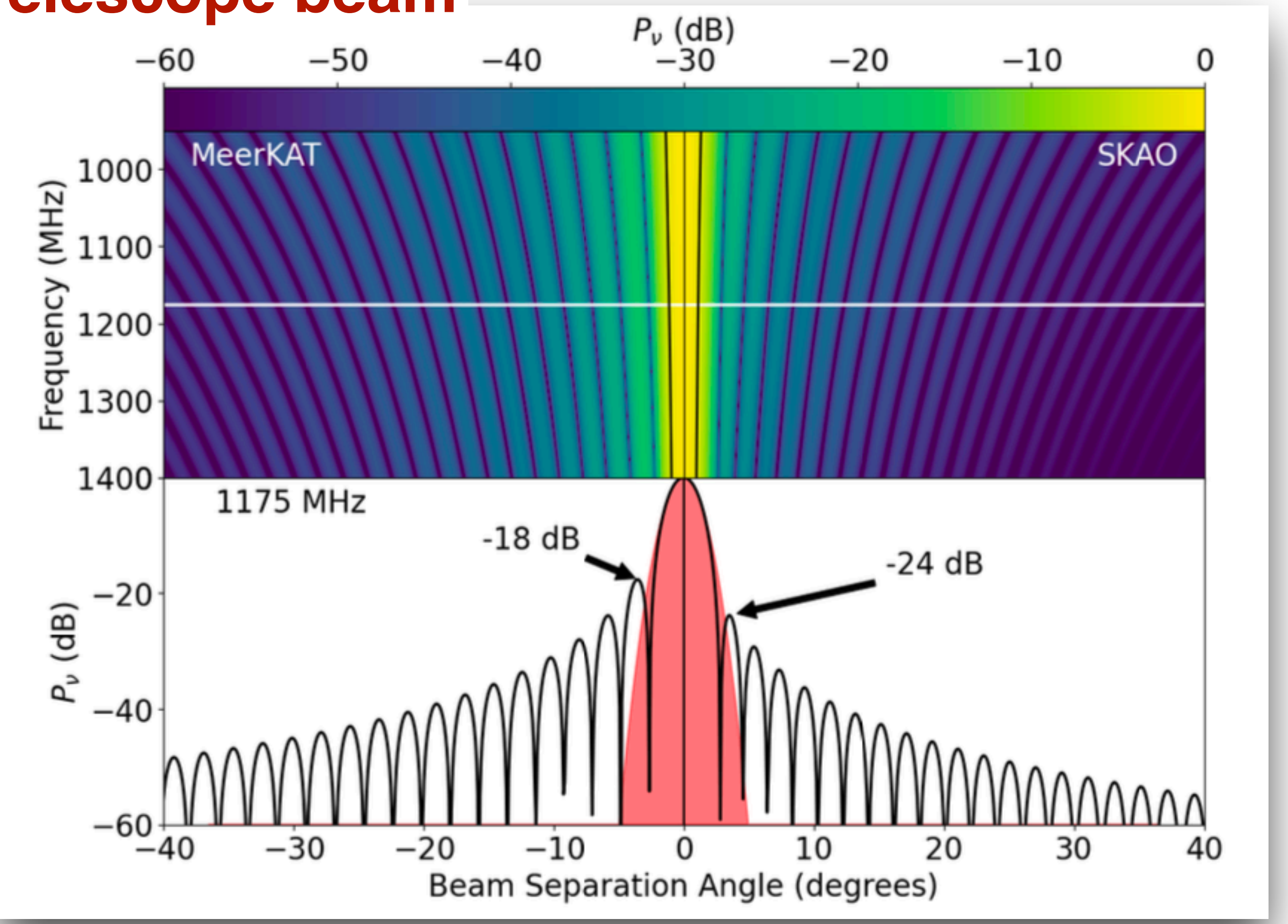

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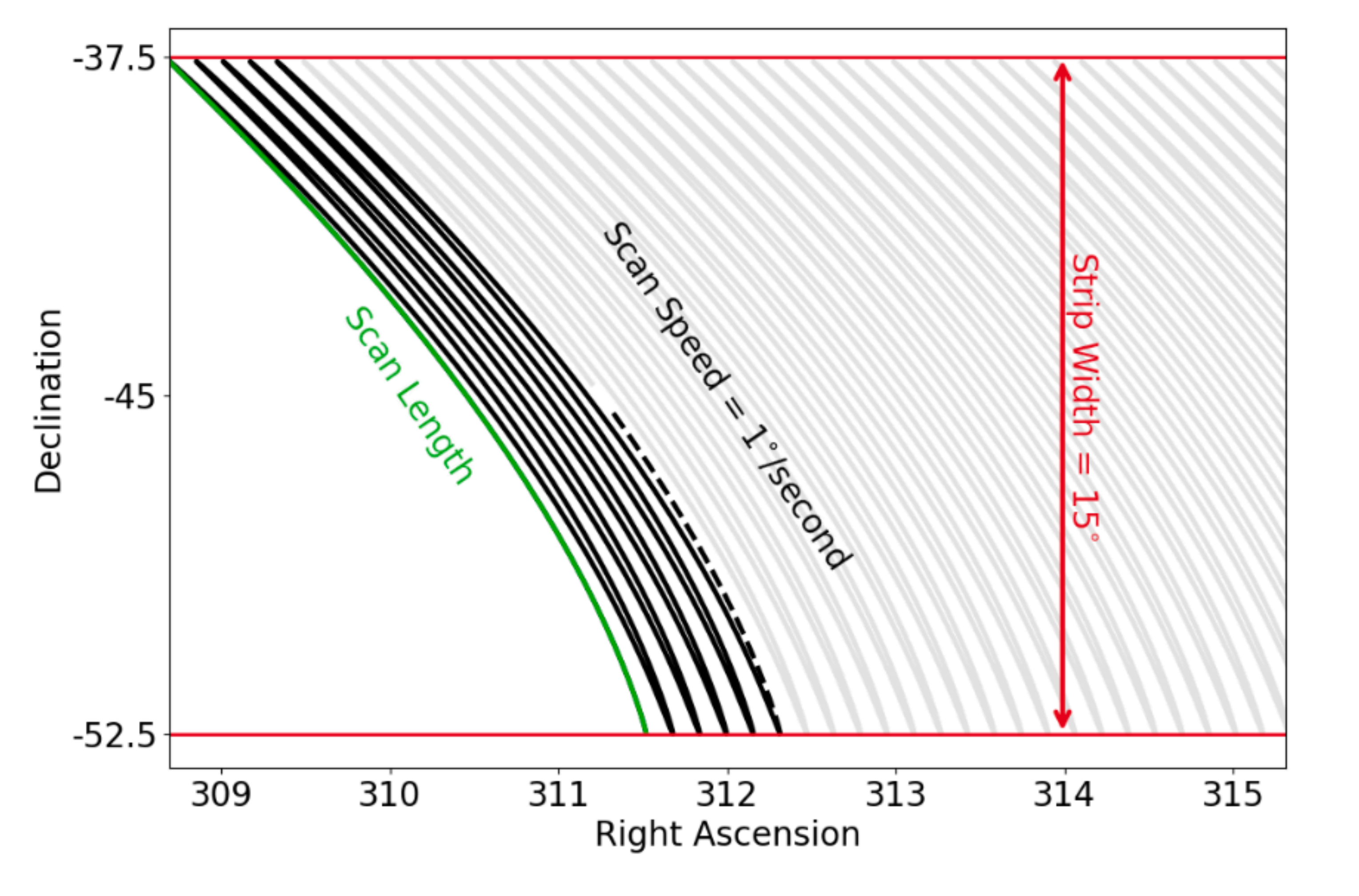
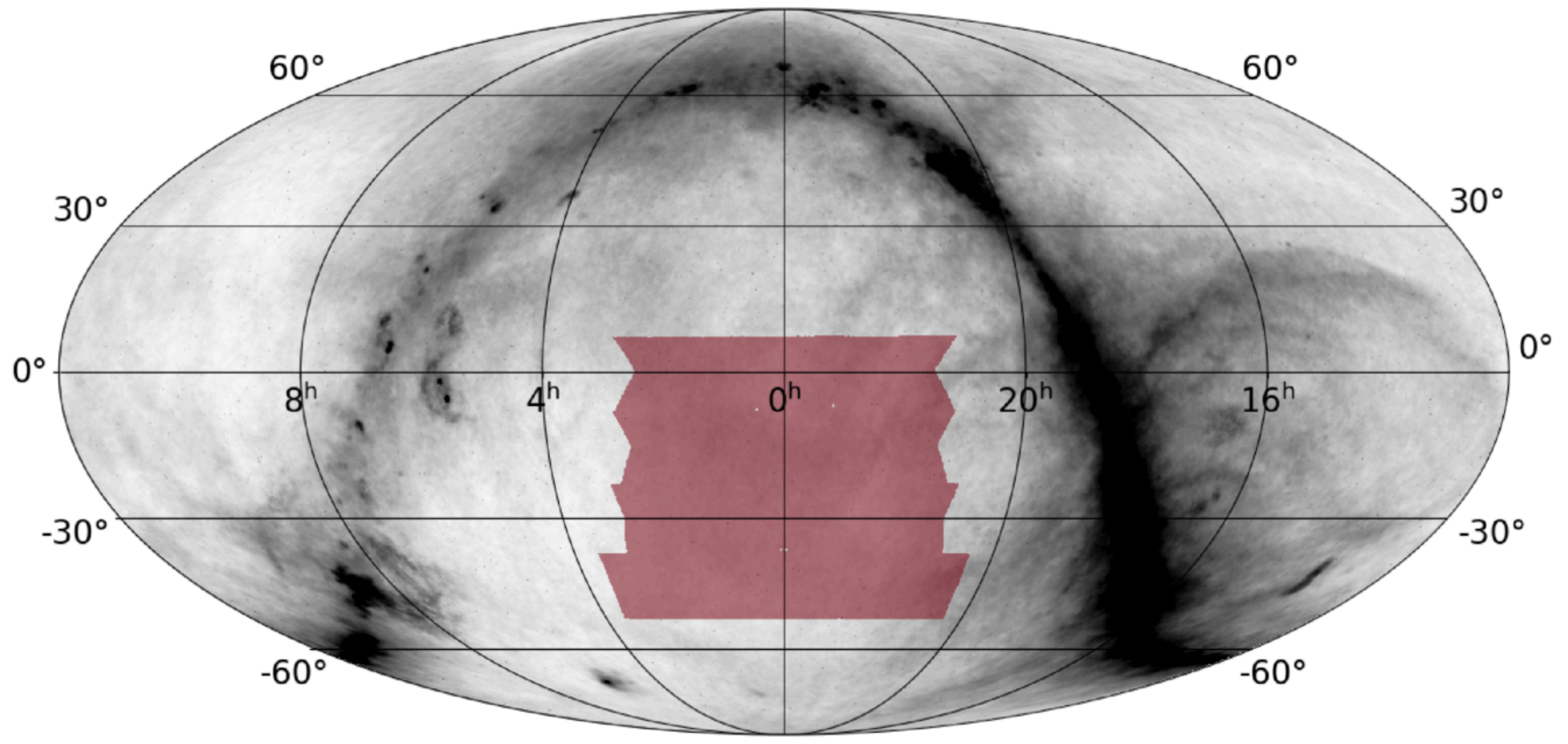
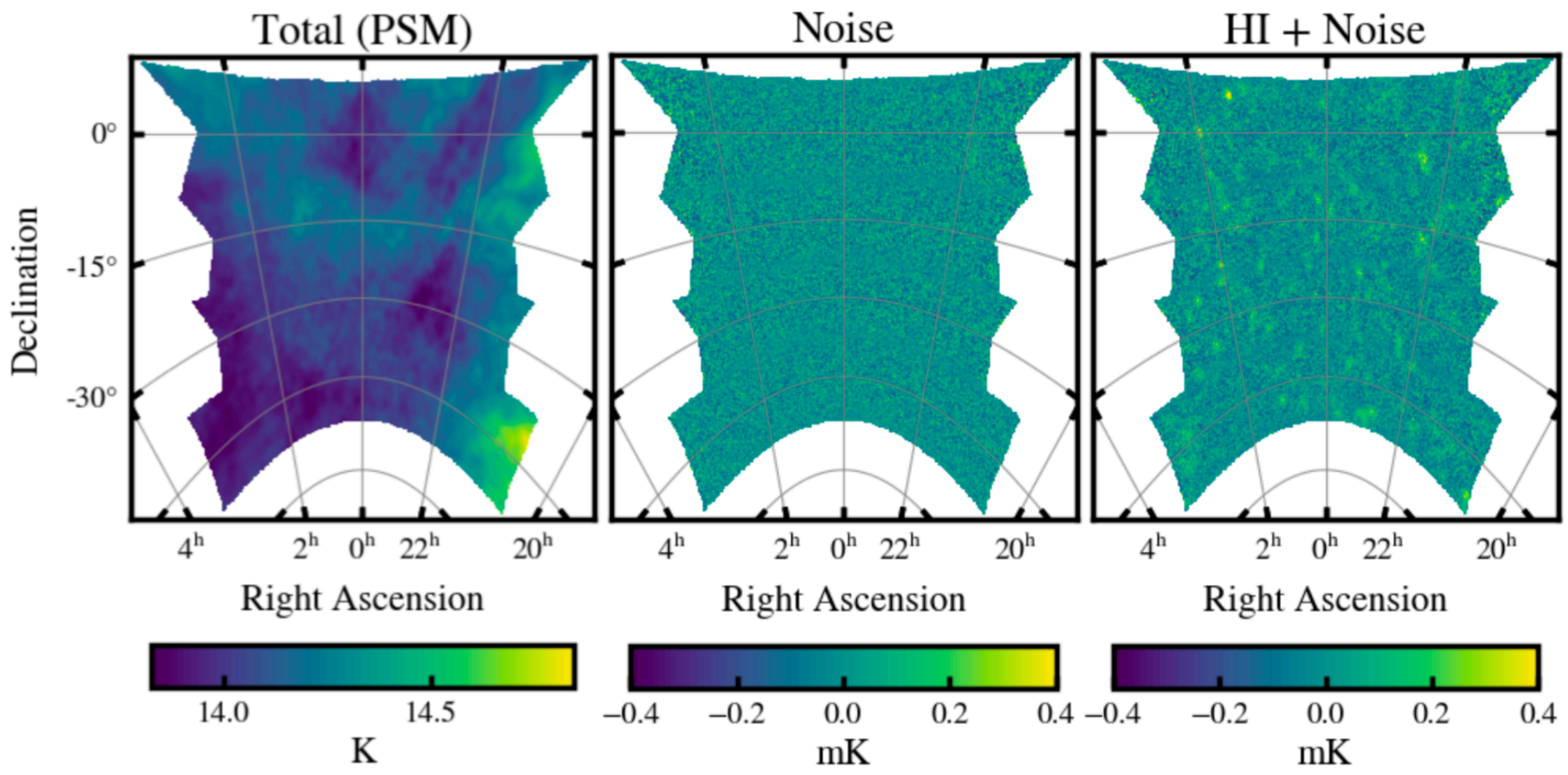


2 FGs models x 2 Beam Models
x 2 Instruments x 2 Deconvolution strategies
= 16 data cubes to clean

Simulating all we can (up to now)





L-band: 950-1400 MHz

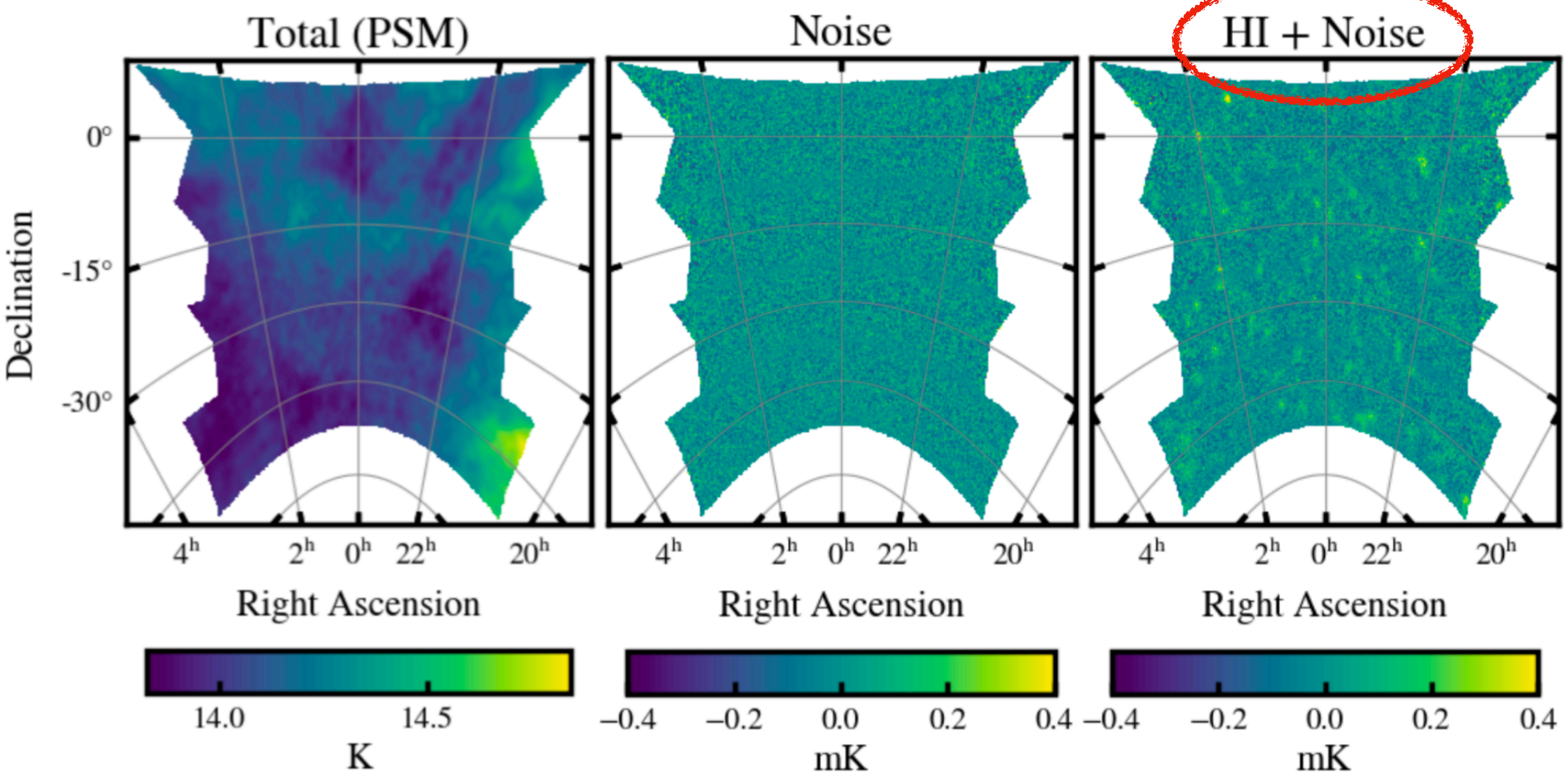
Single-dish mode

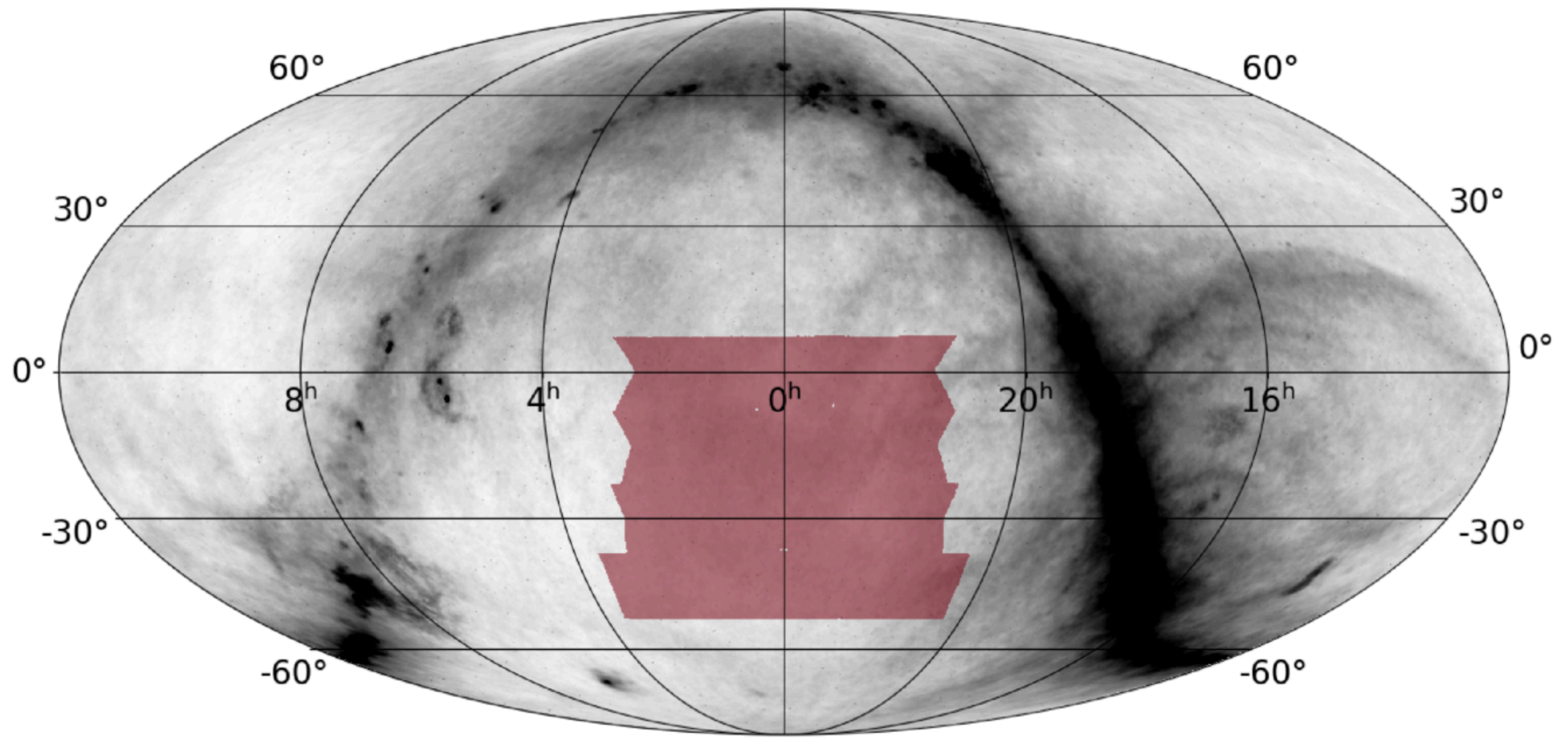
N_{dish}: 133 (SKAO) and 64 (MeerKAT)

x 512 channels

Simulating all we can (up to now)

Unknown to participants!





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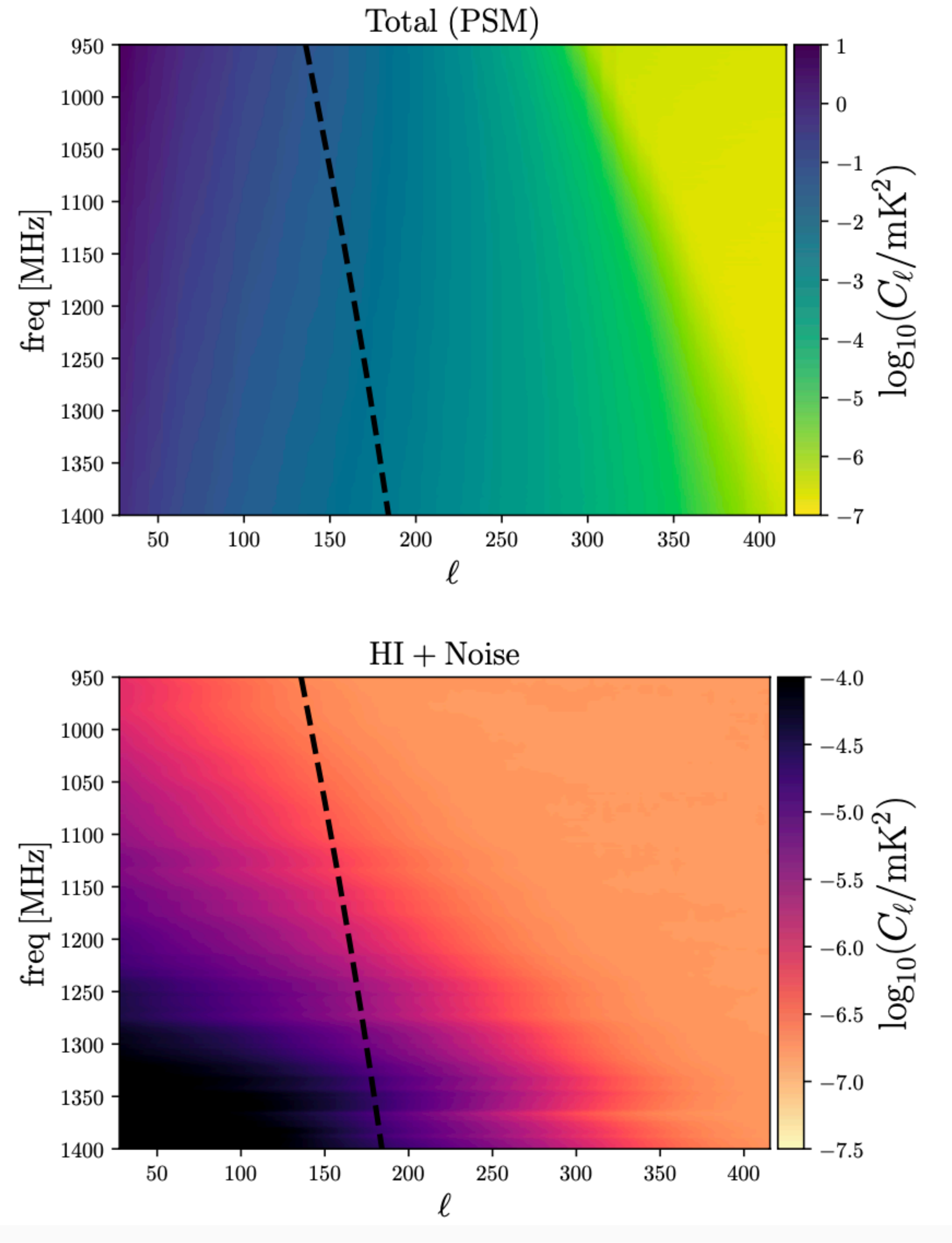
Pipelines that joined the Blind Challenge

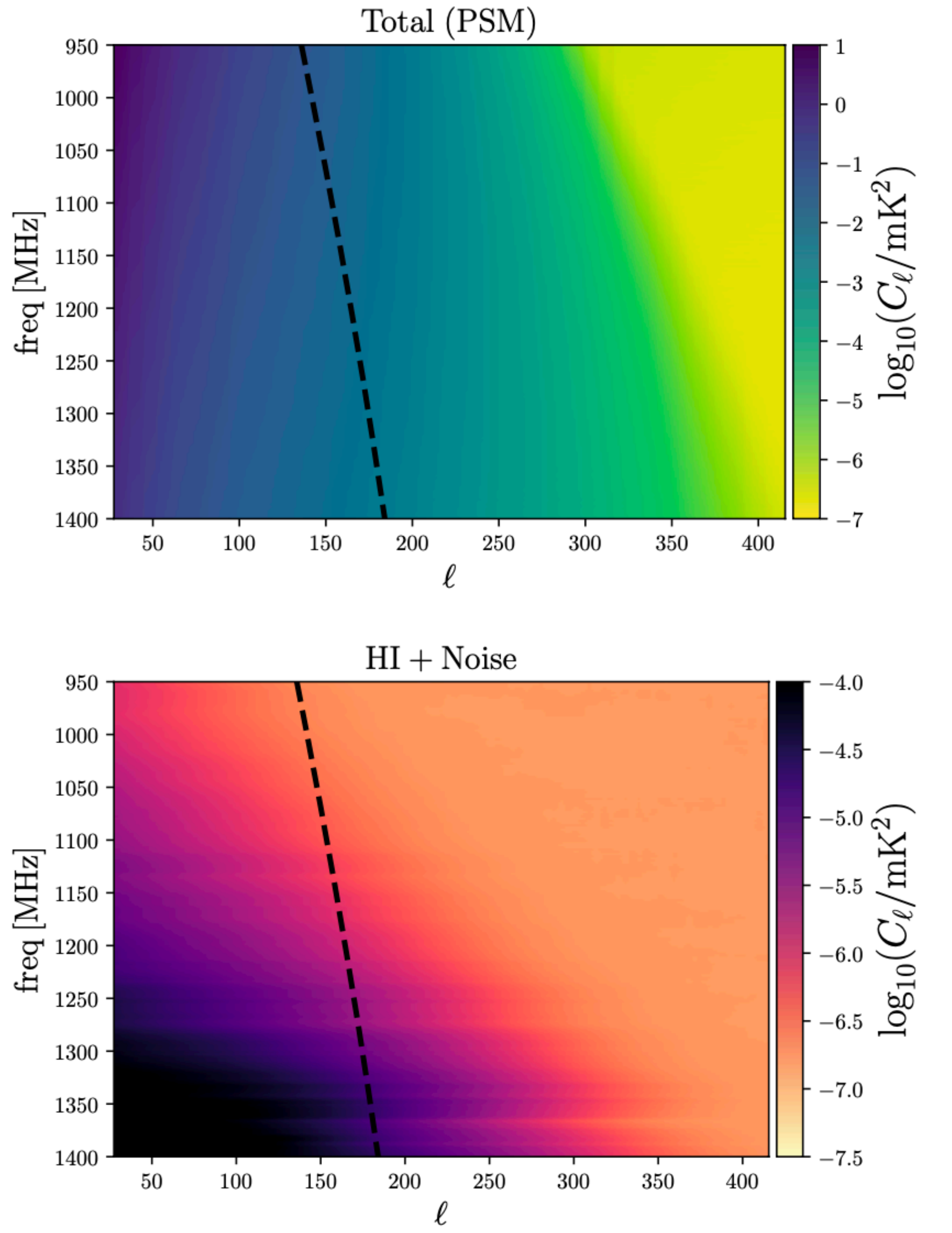
Method	Assumption on foreground components	Pipeline	Description
Principal Component Analysis	Statistically uncorrelated	PCA(a)	As in Cunnington et al. (2021b)
		PCA(b)	*fg_rm* code (Alonso et al. 2015), with rms weitghing
		PCAwls	PCA applied on the wavelet-transformed data
Independent Component Analysis	Non-Gaussian	FASTICA(a)	Based on `Scikit-learn` package
		FASTICA(b)	*fg_rm* code (Alonso et al. 2015)
Generalised Morphological Component Analysis	Sparse in a given domain and morphologically diverse	GMCA	As in Carucci et al. (2020)
		mixGMCA	PCA on the coarse scale + GMCA on small scales
Polynomial Fitting	Smooth in frequency	poLOG	In log-log space (Alonso et al. 2015, *fg_rm* code)
Parametric Fitting	Assumptions on spectral indices	LSQ	Fit to individual foregrounds

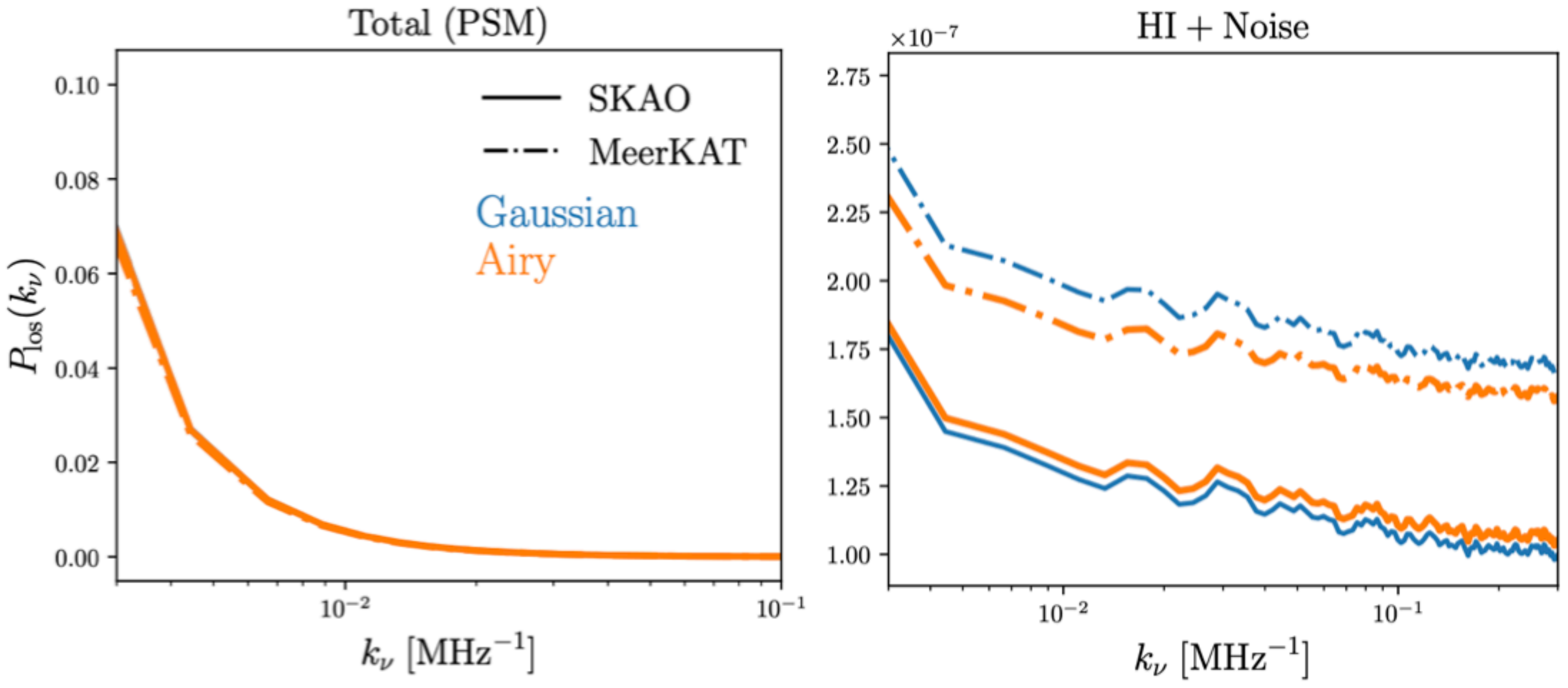
9 pipelines on 16 data cubes

Comparison at the map level: angular and radial power spectra

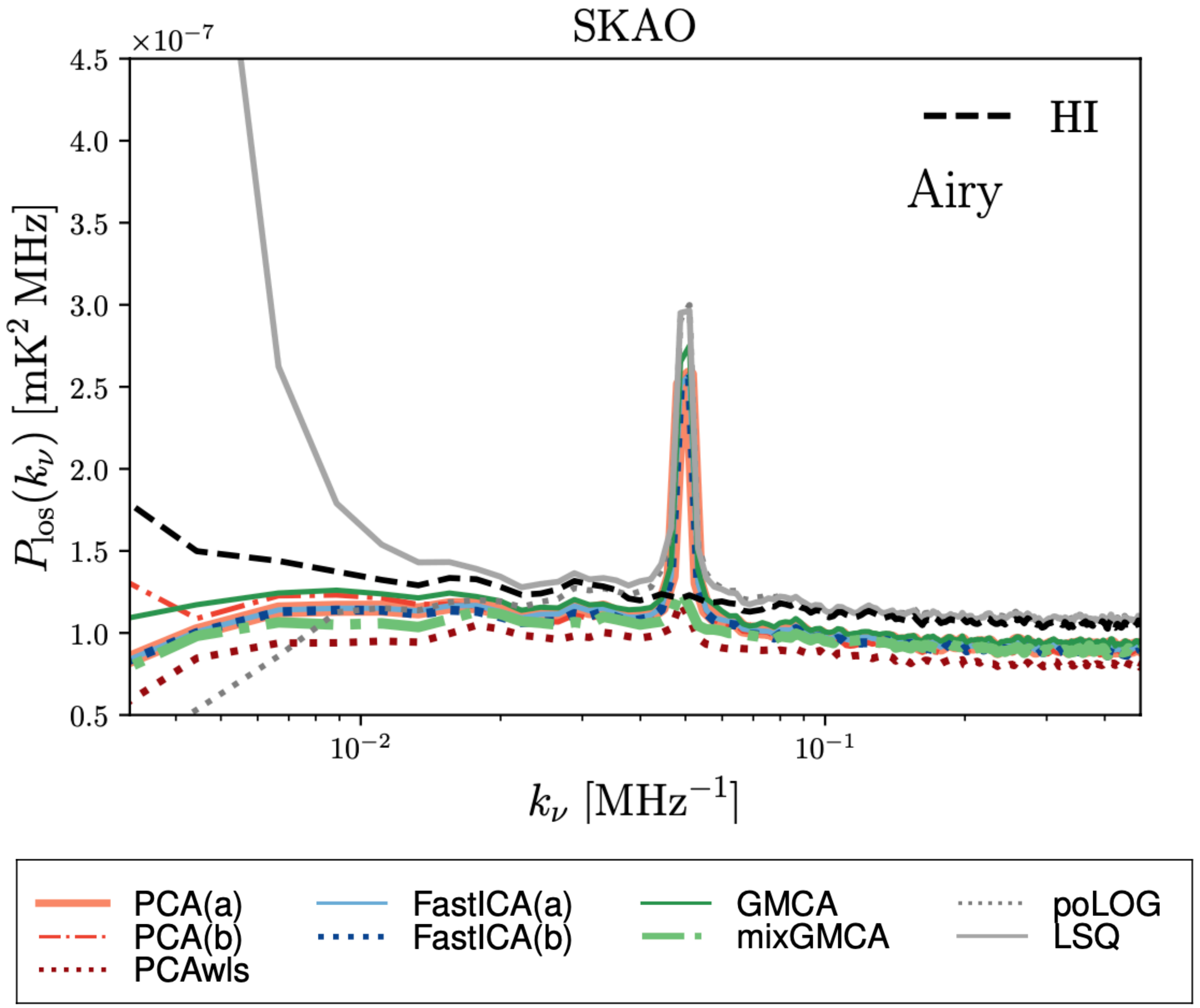


Comparison at the map level: angular and radial power spectra





Results: radial power spectra



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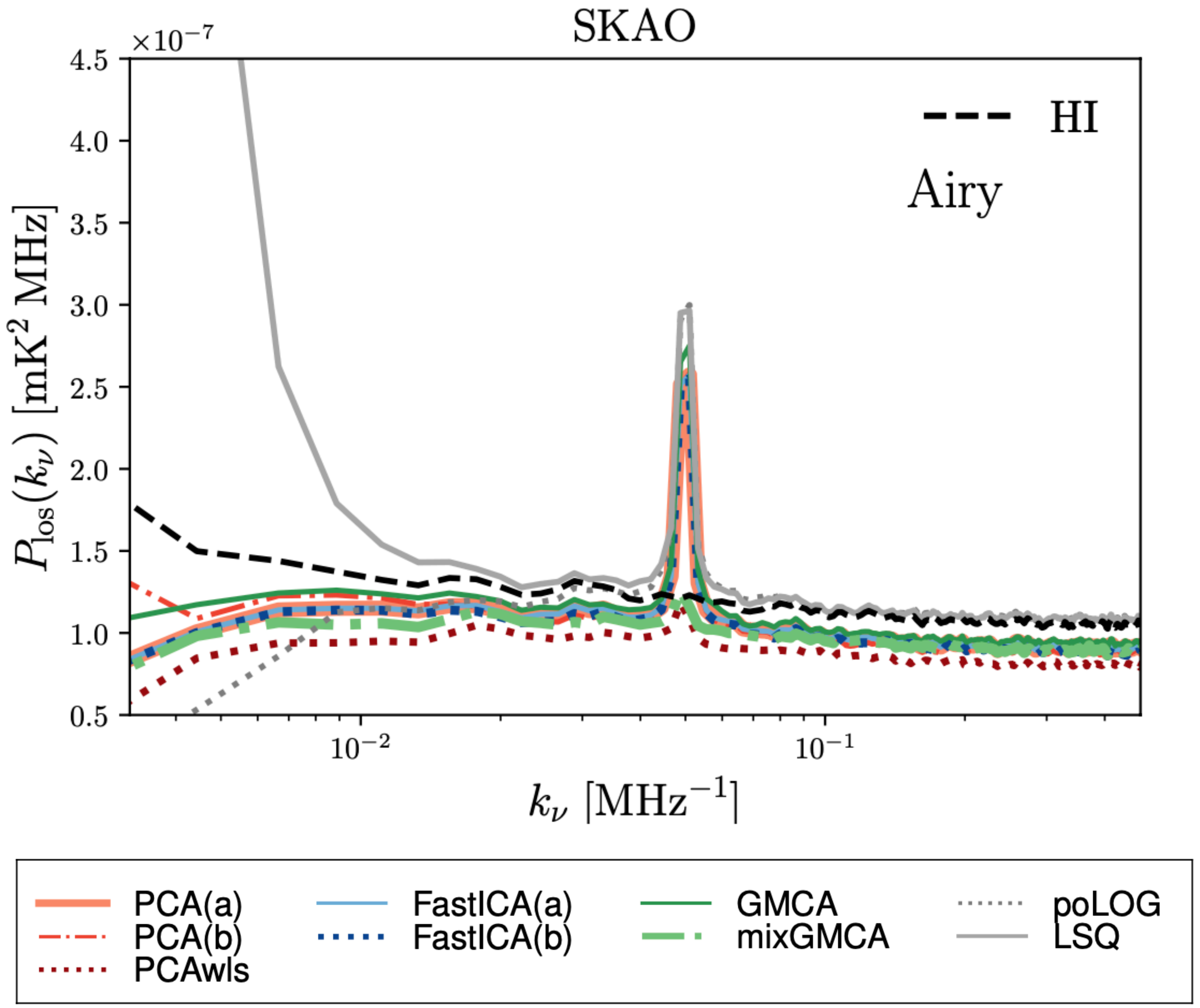
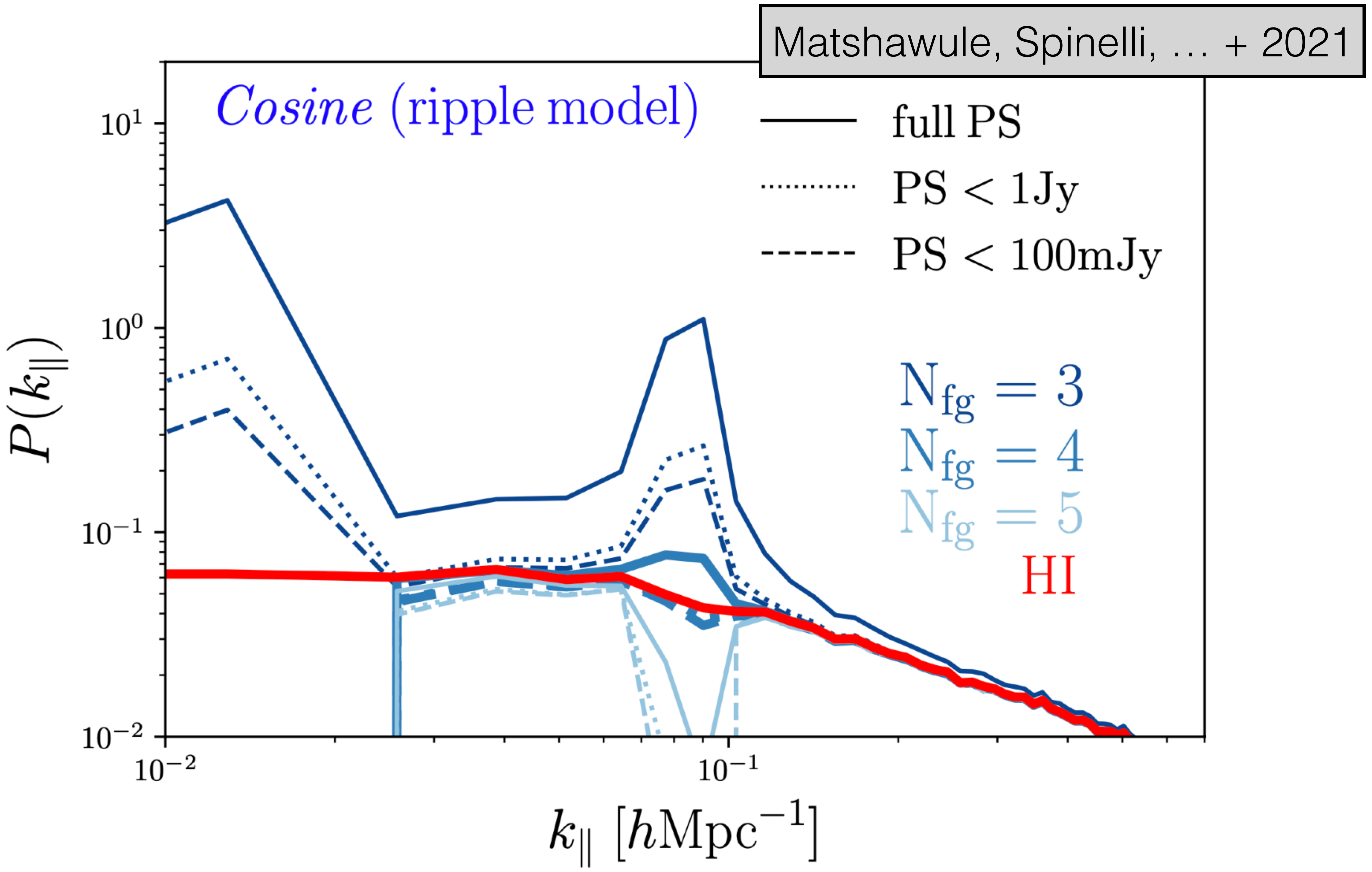
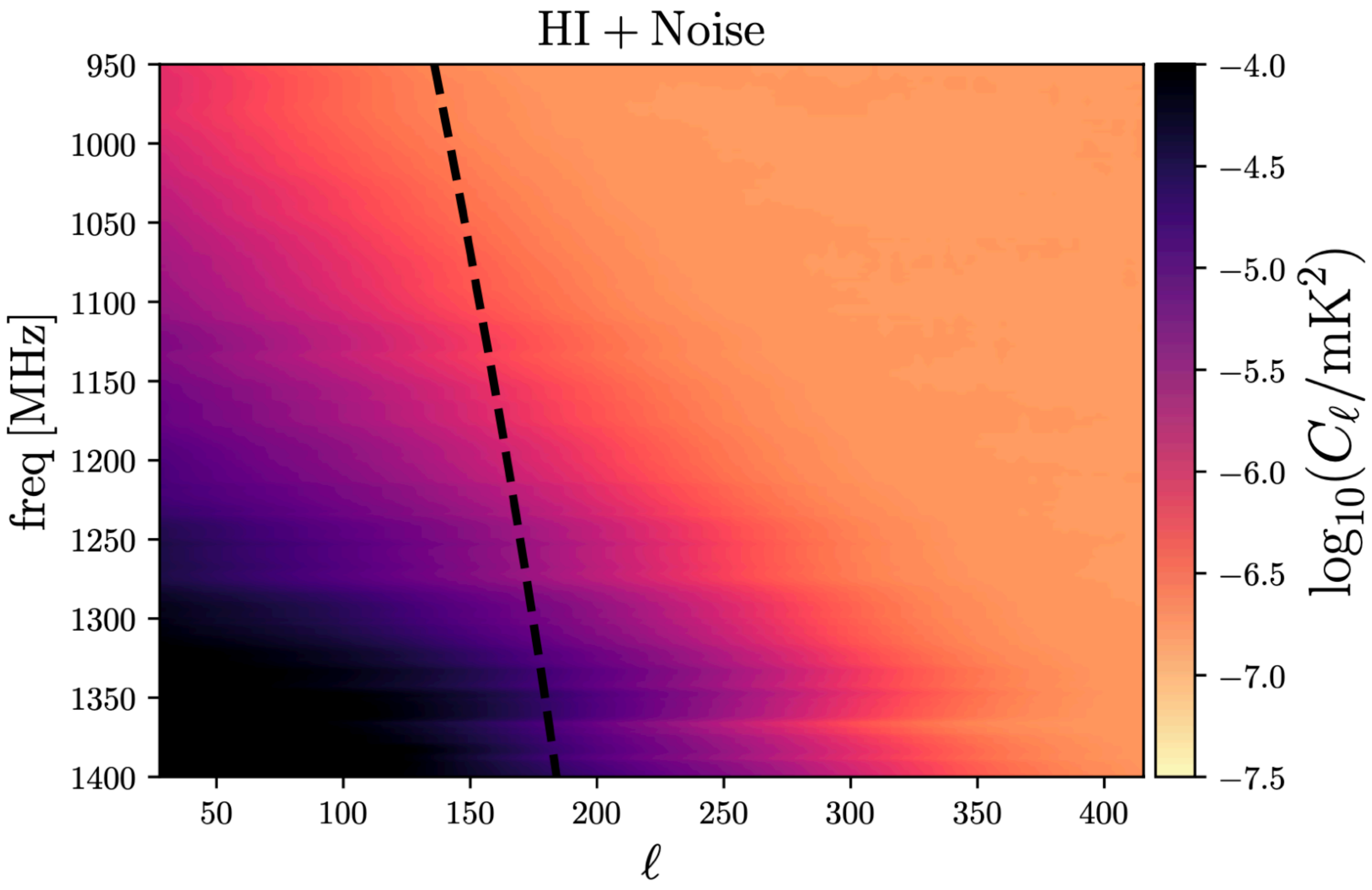
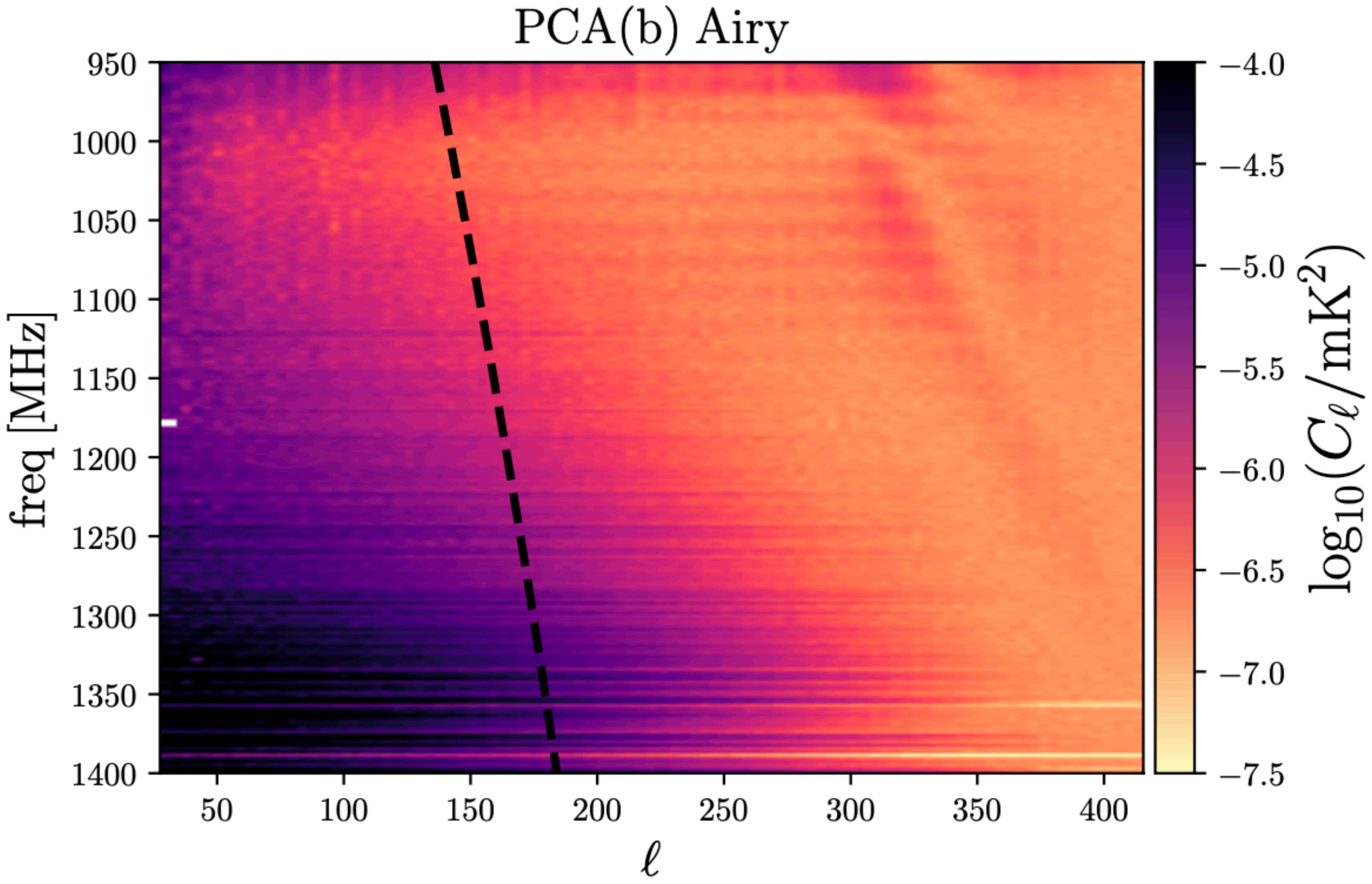




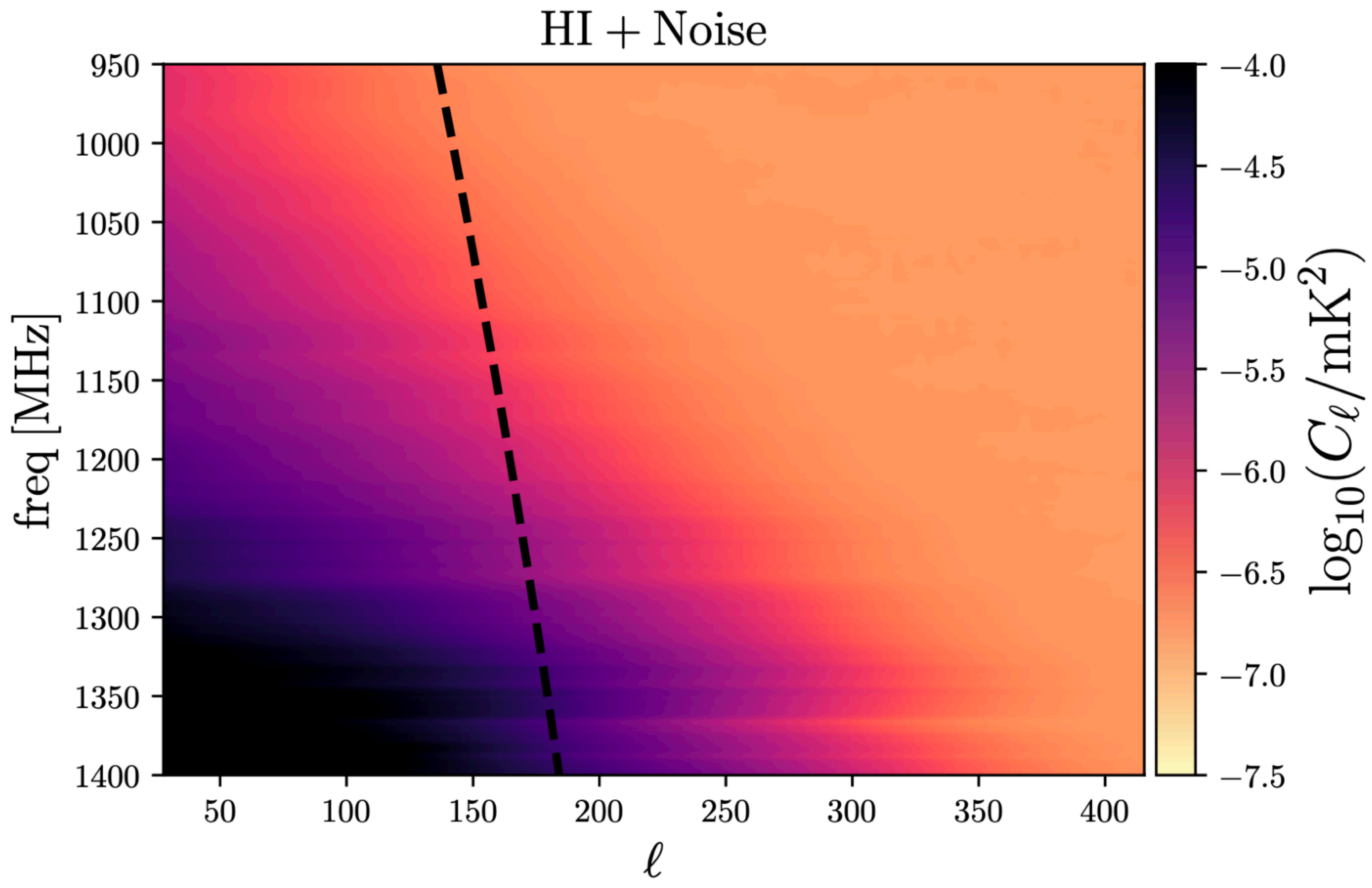
The *peak* feature in the recovered radial PS due to the interaction between the beam and the foregrounds

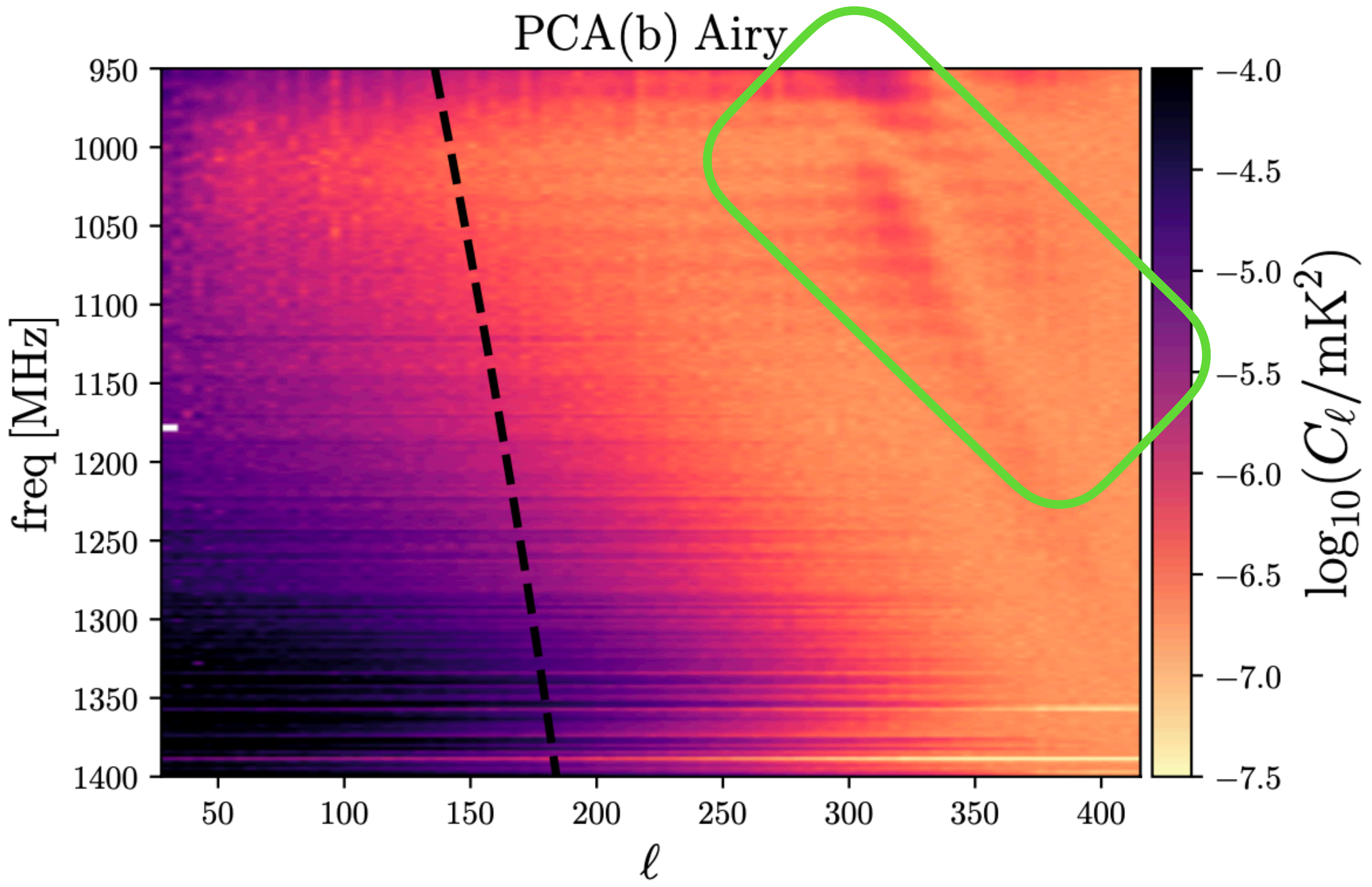
Results: angular power spectra





Results: angular power spectra





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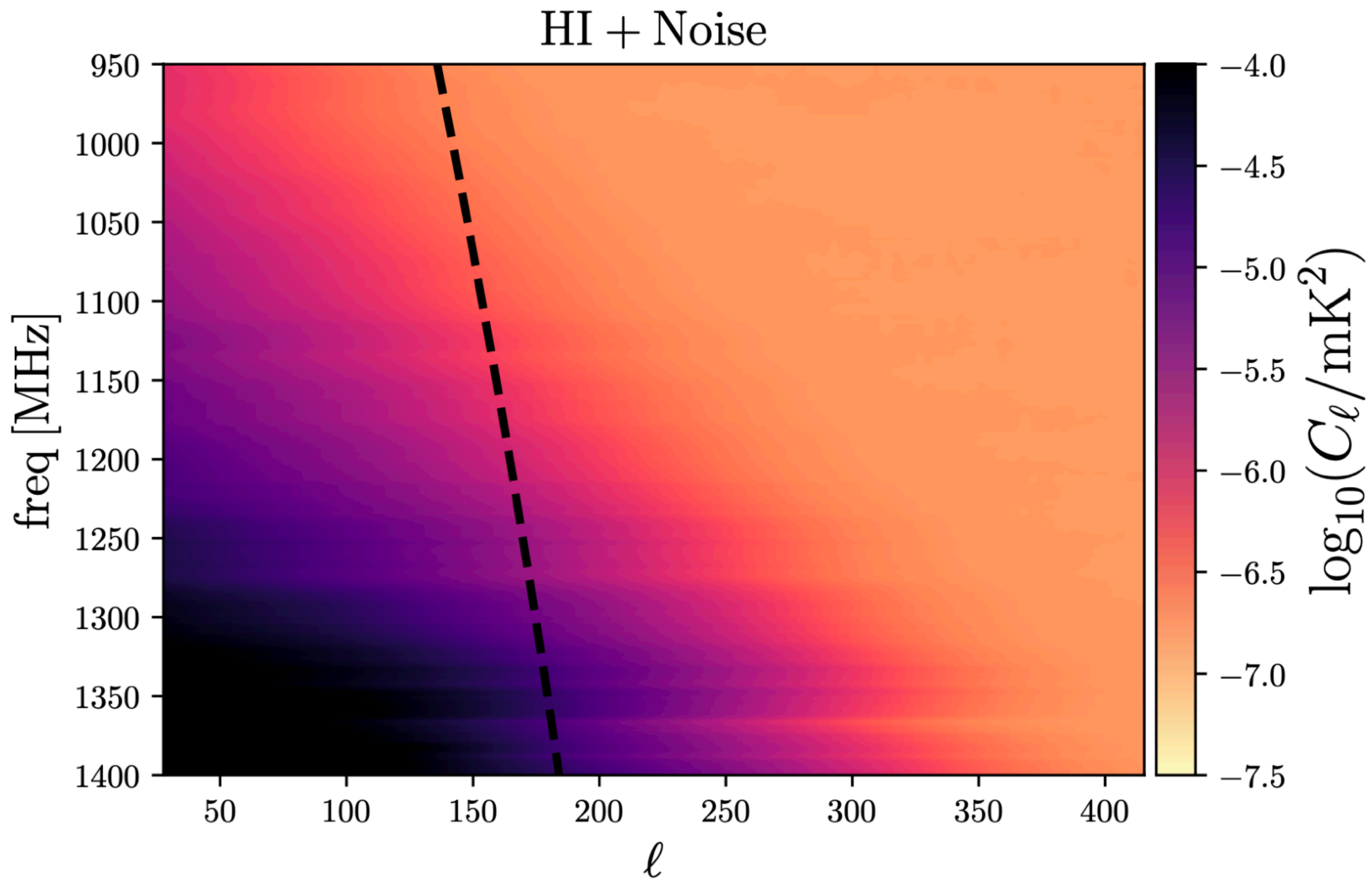

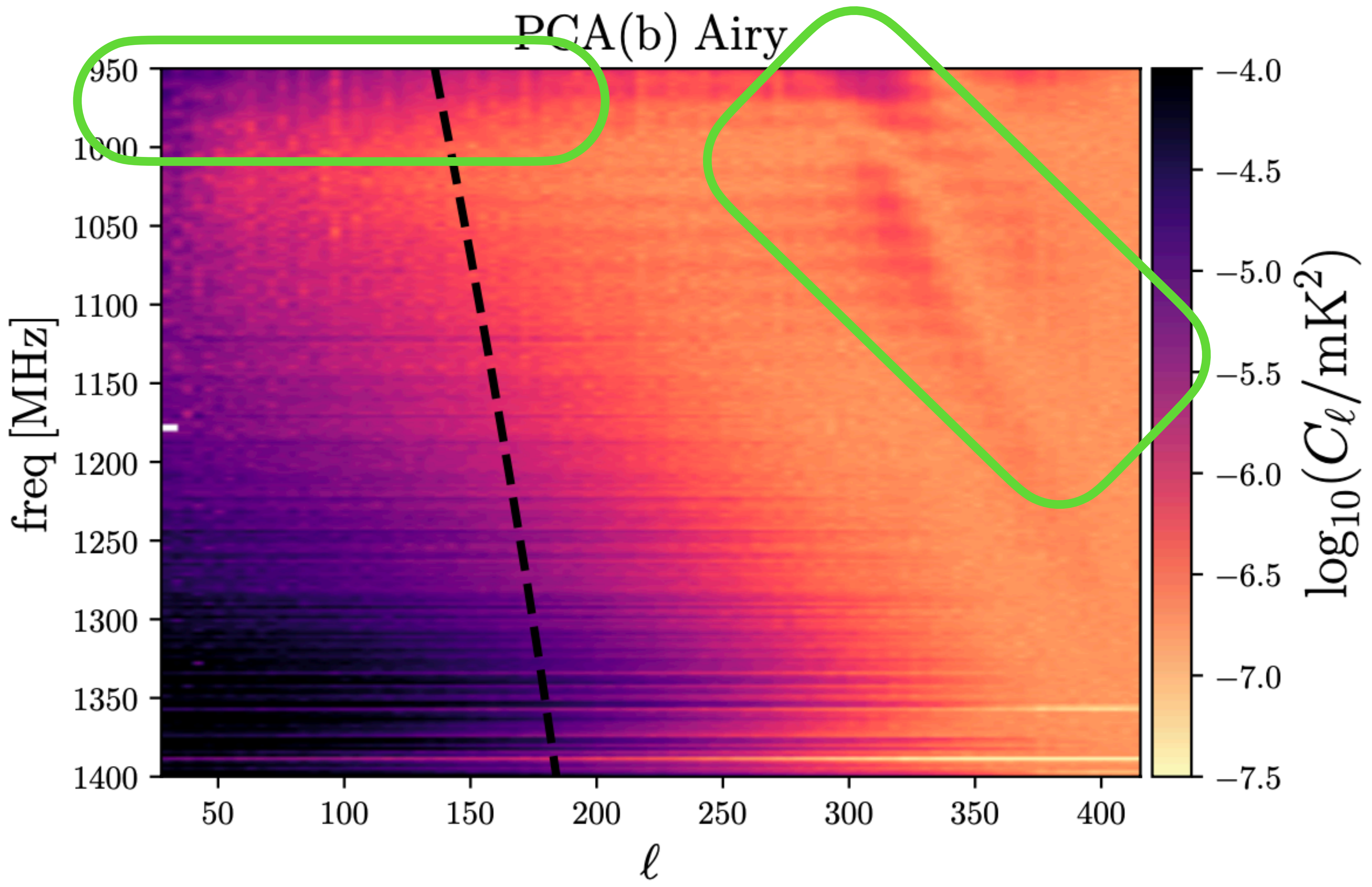

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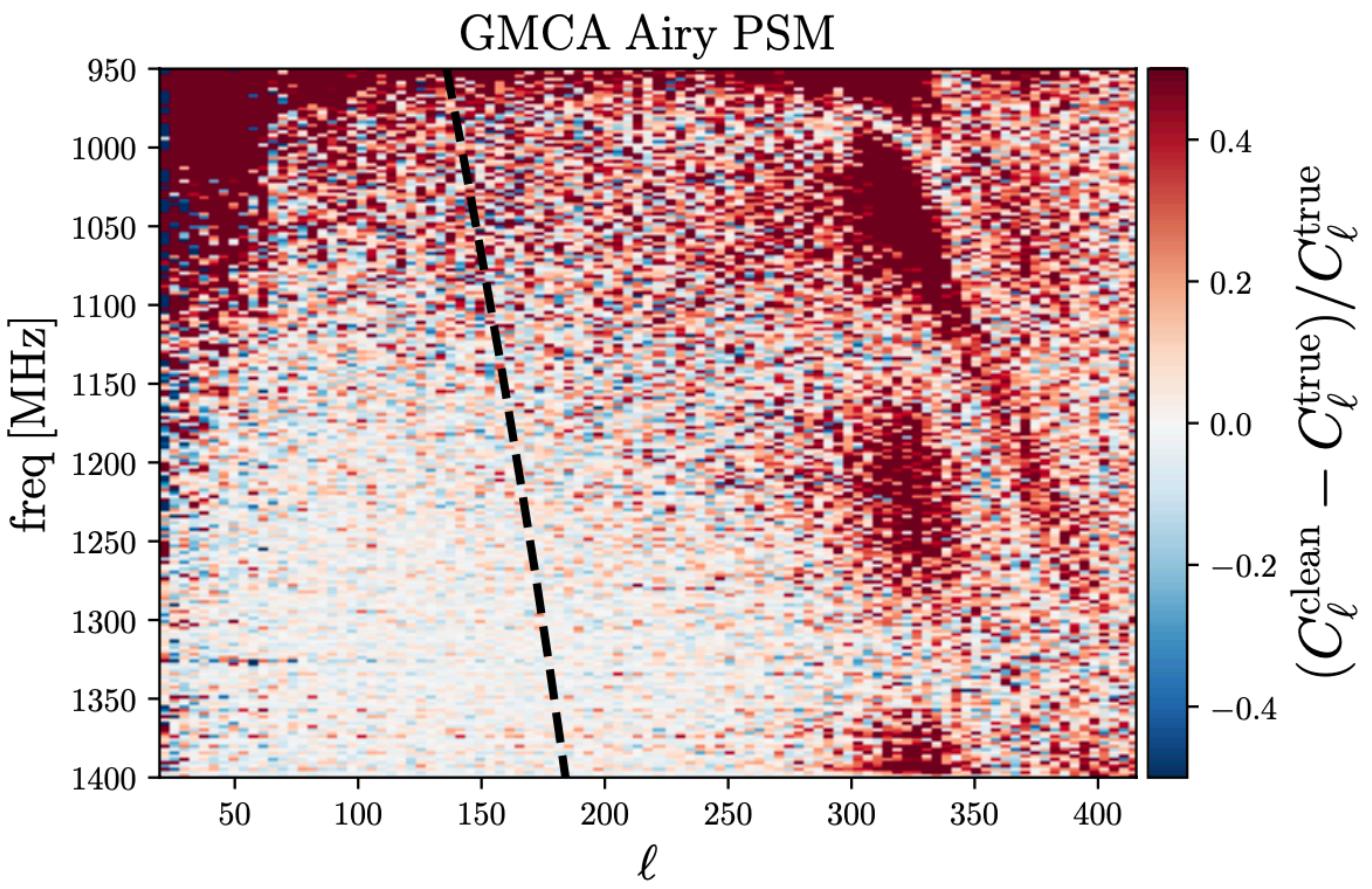
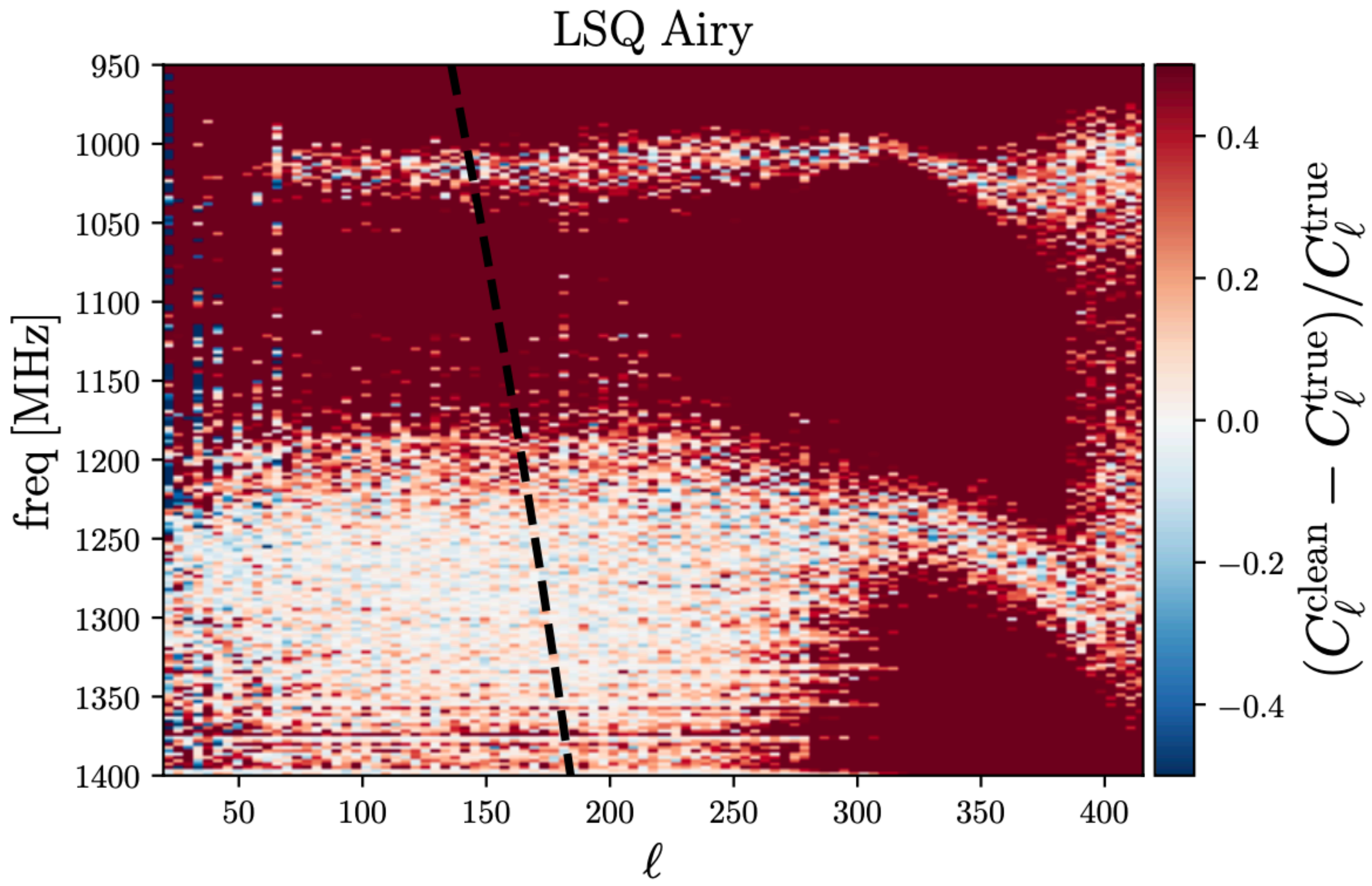
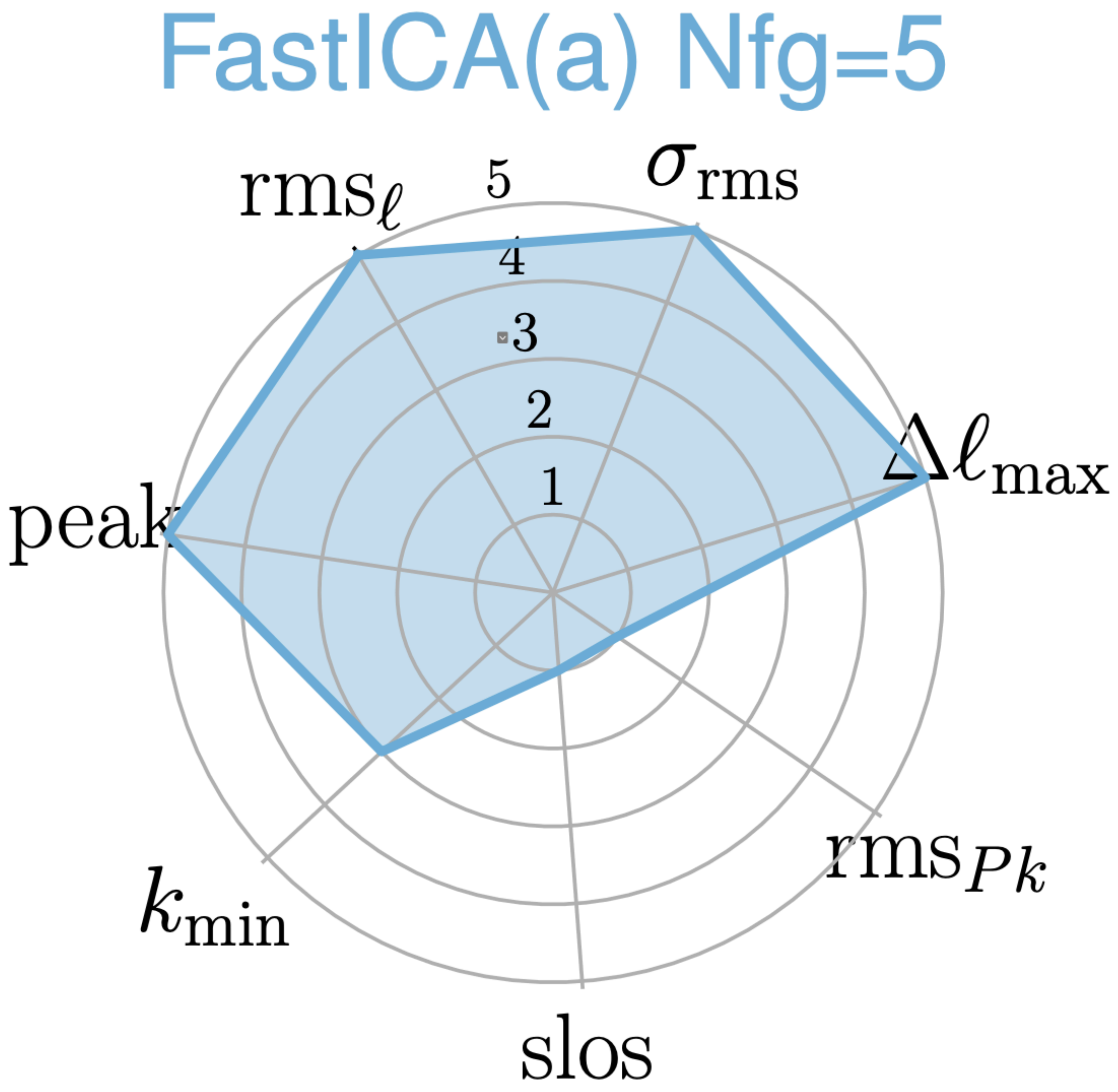




Results: compressed in radar charts, example



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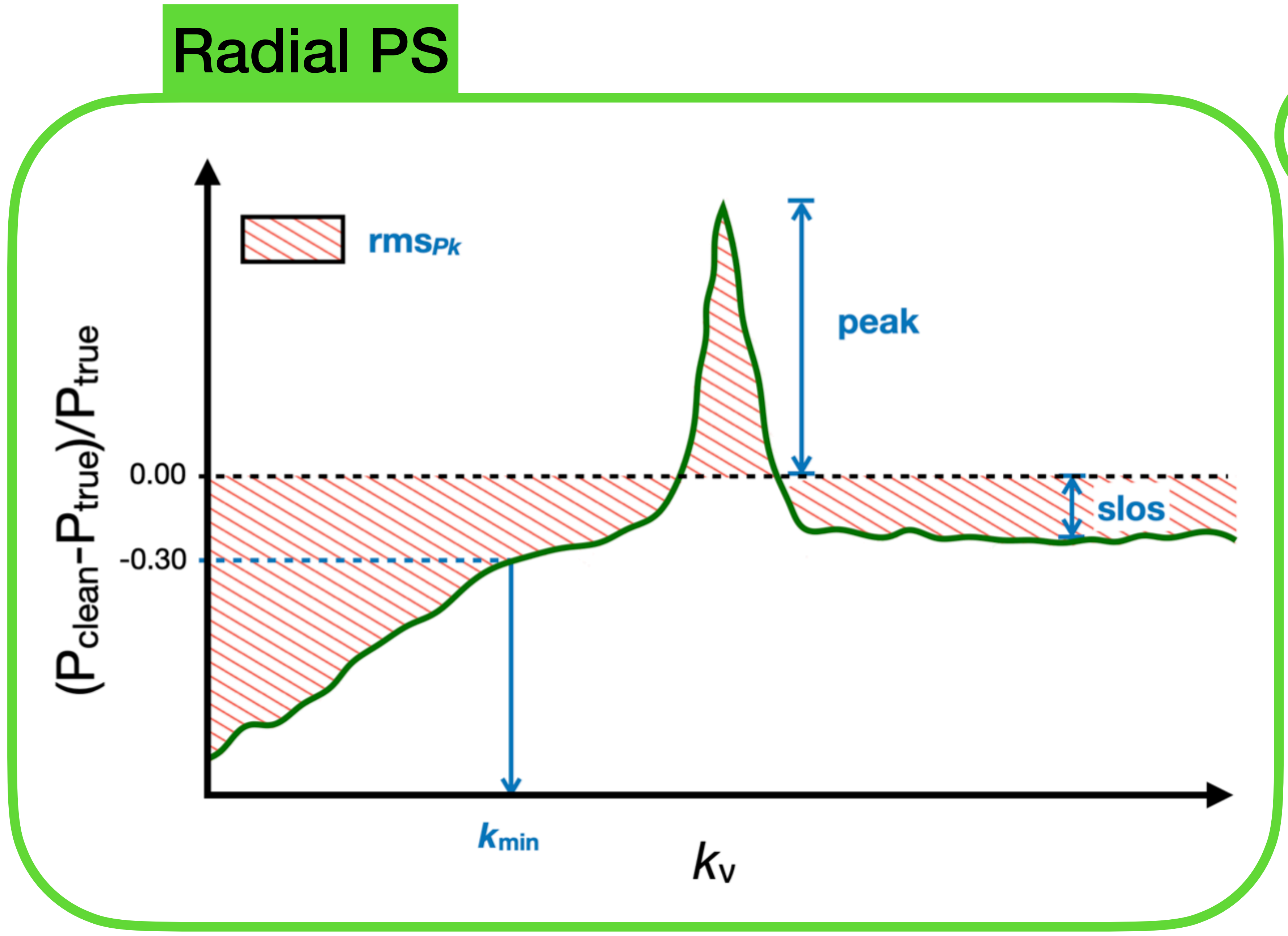

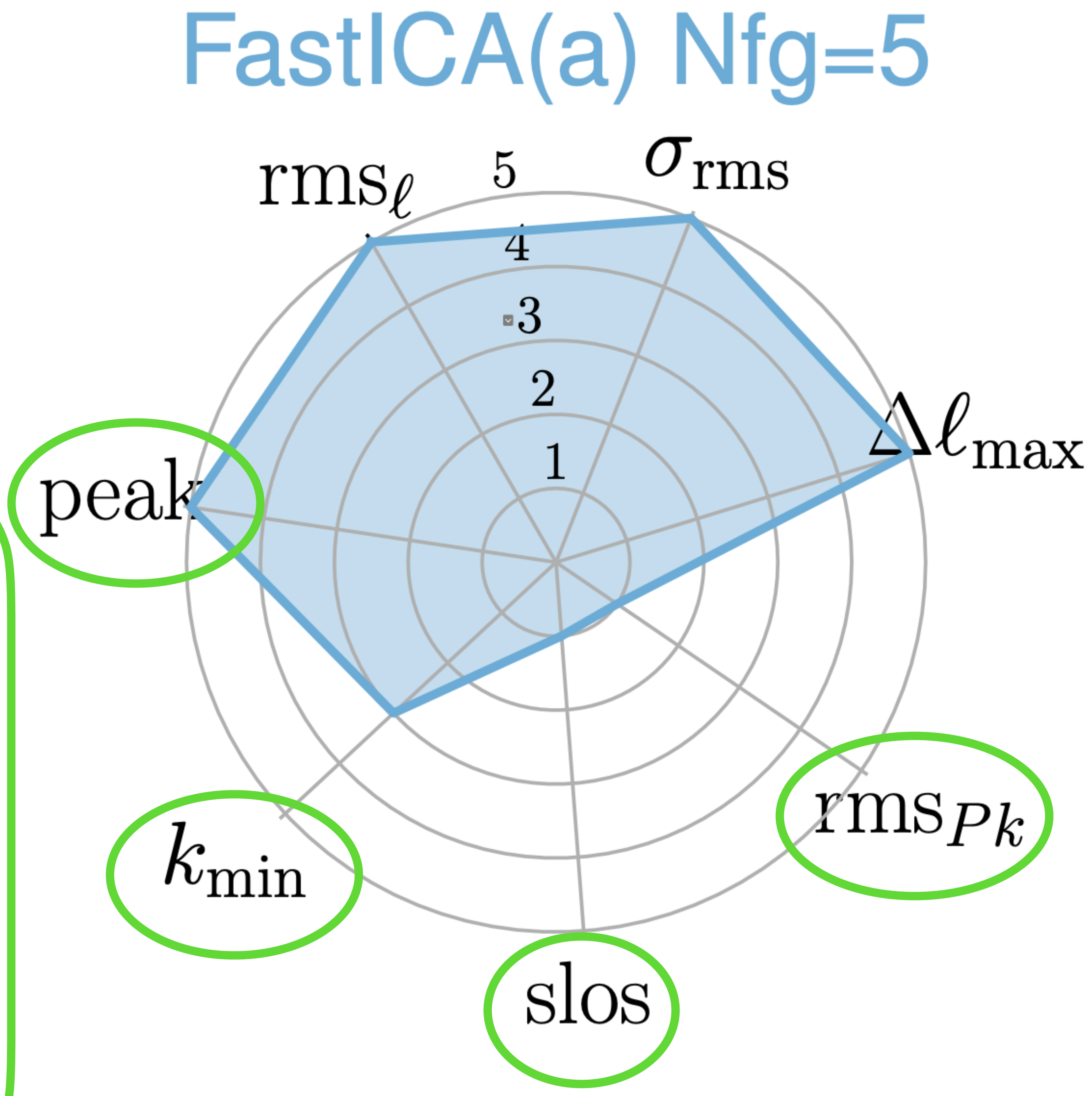

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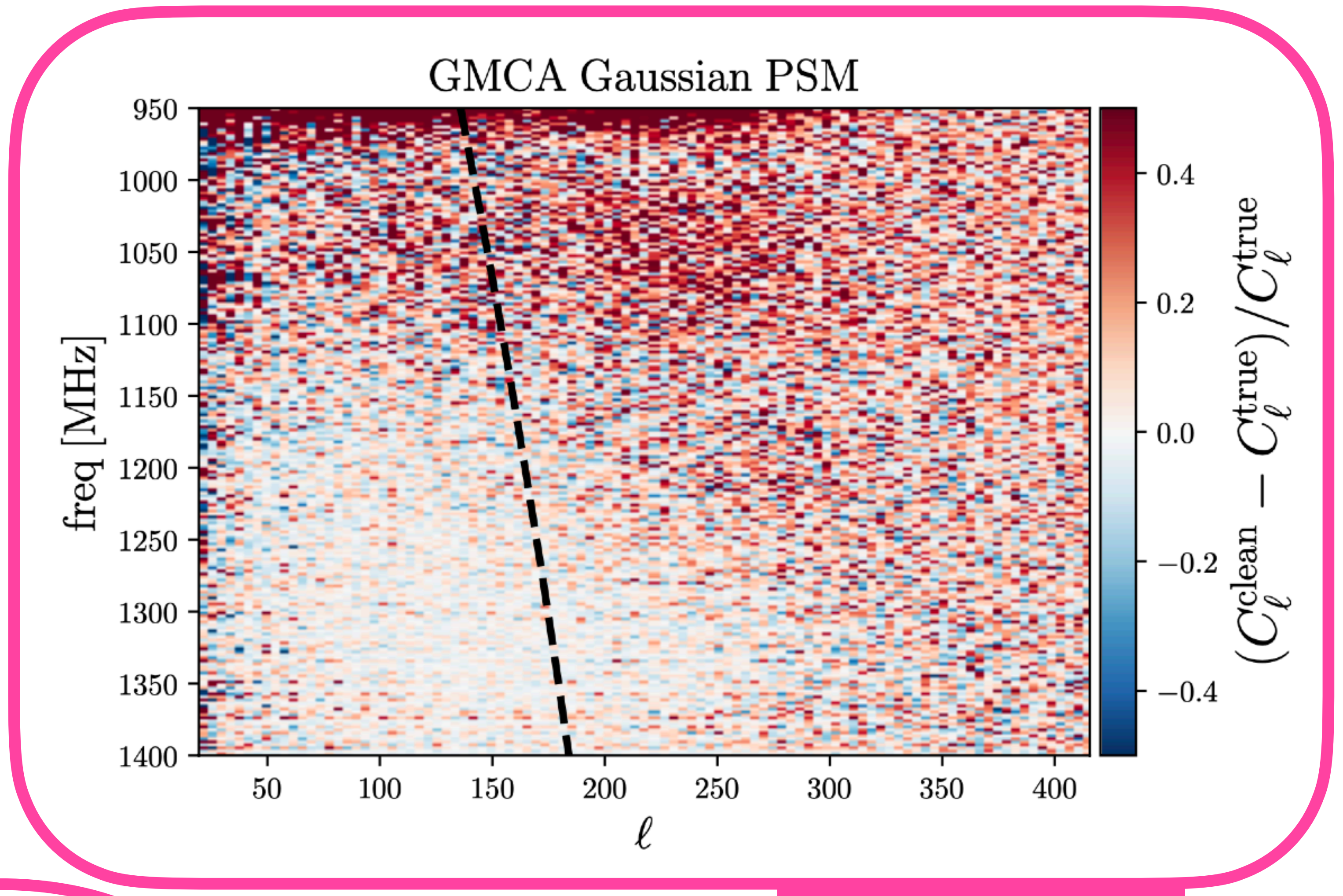
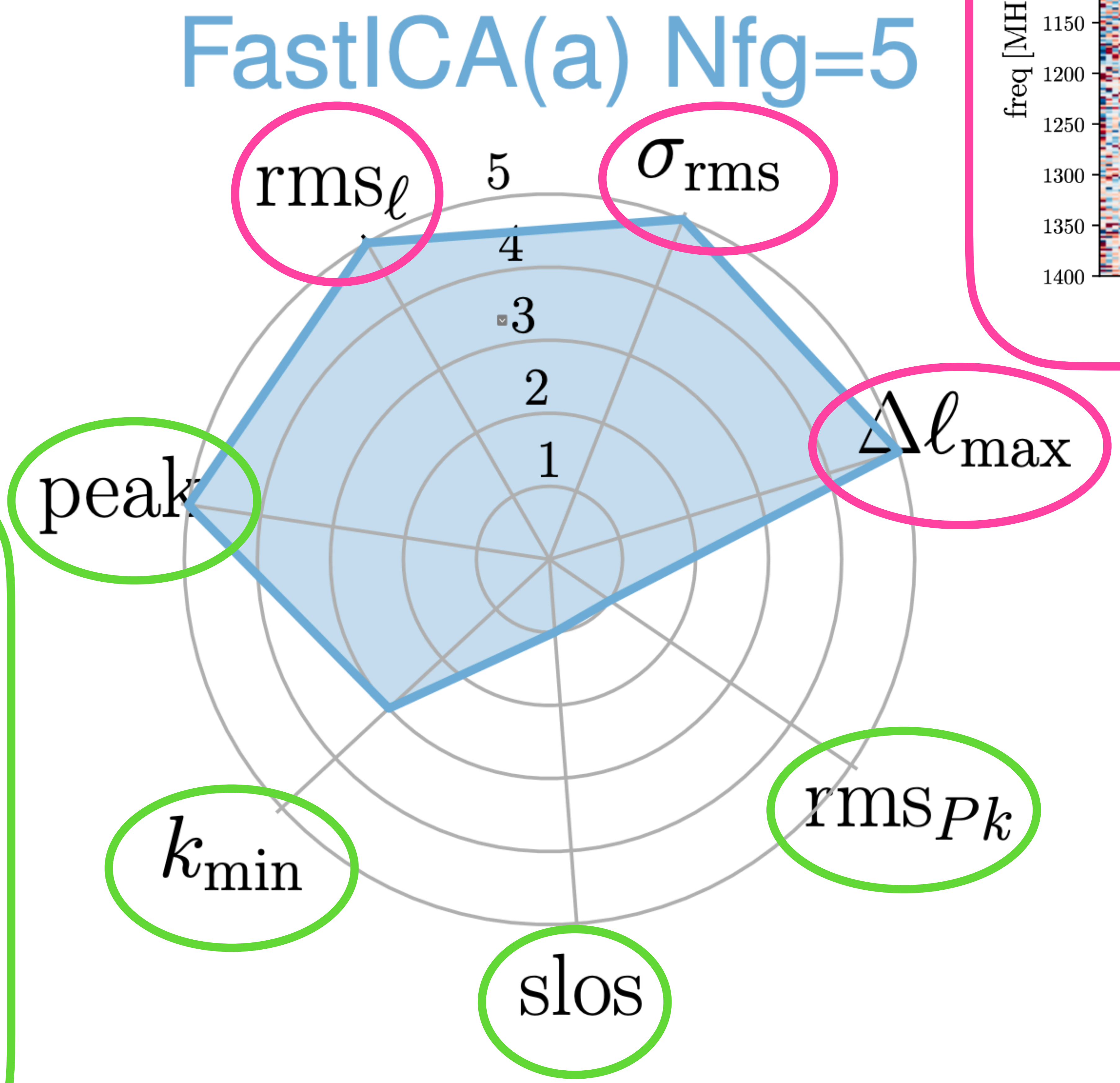
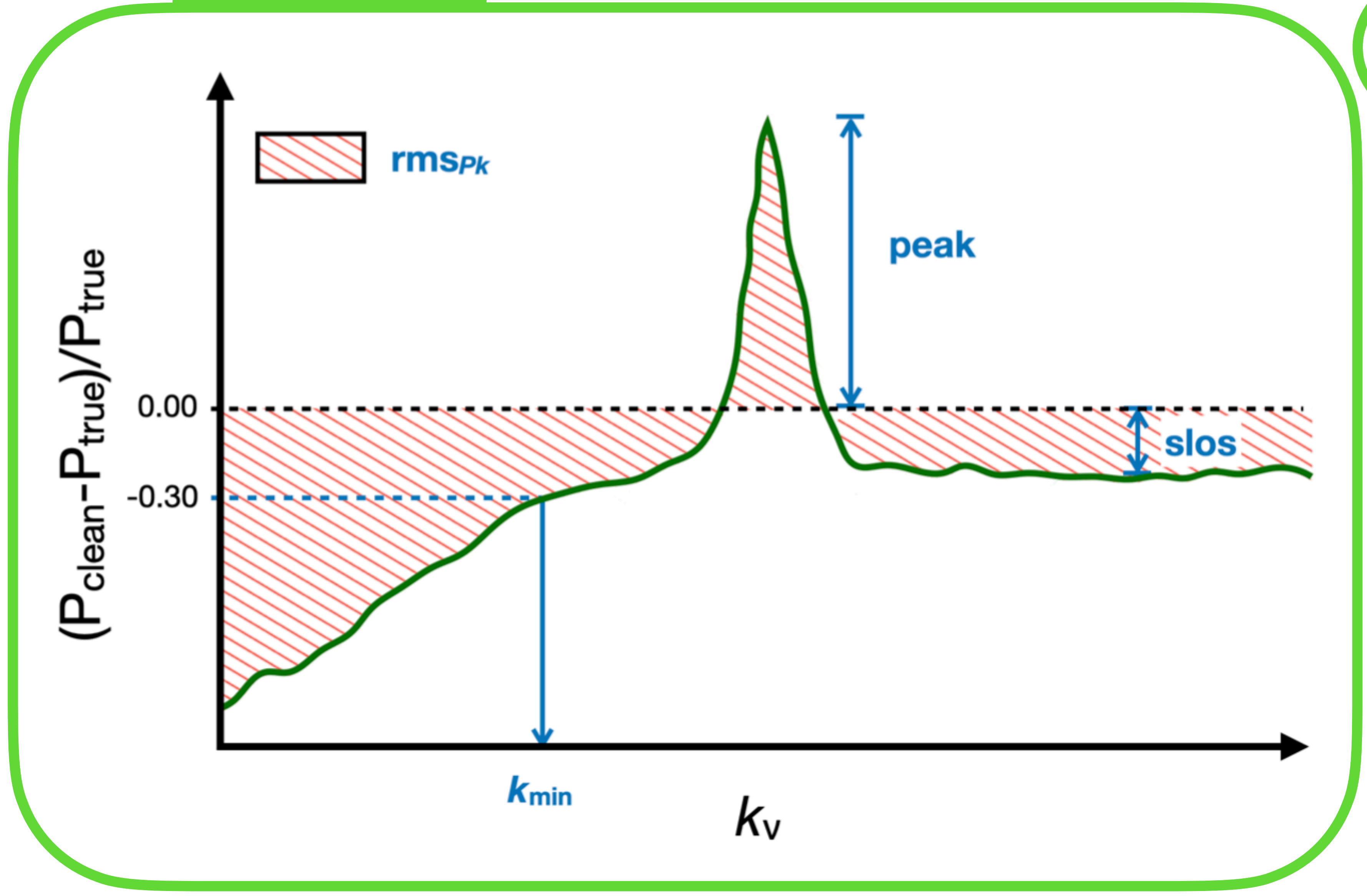


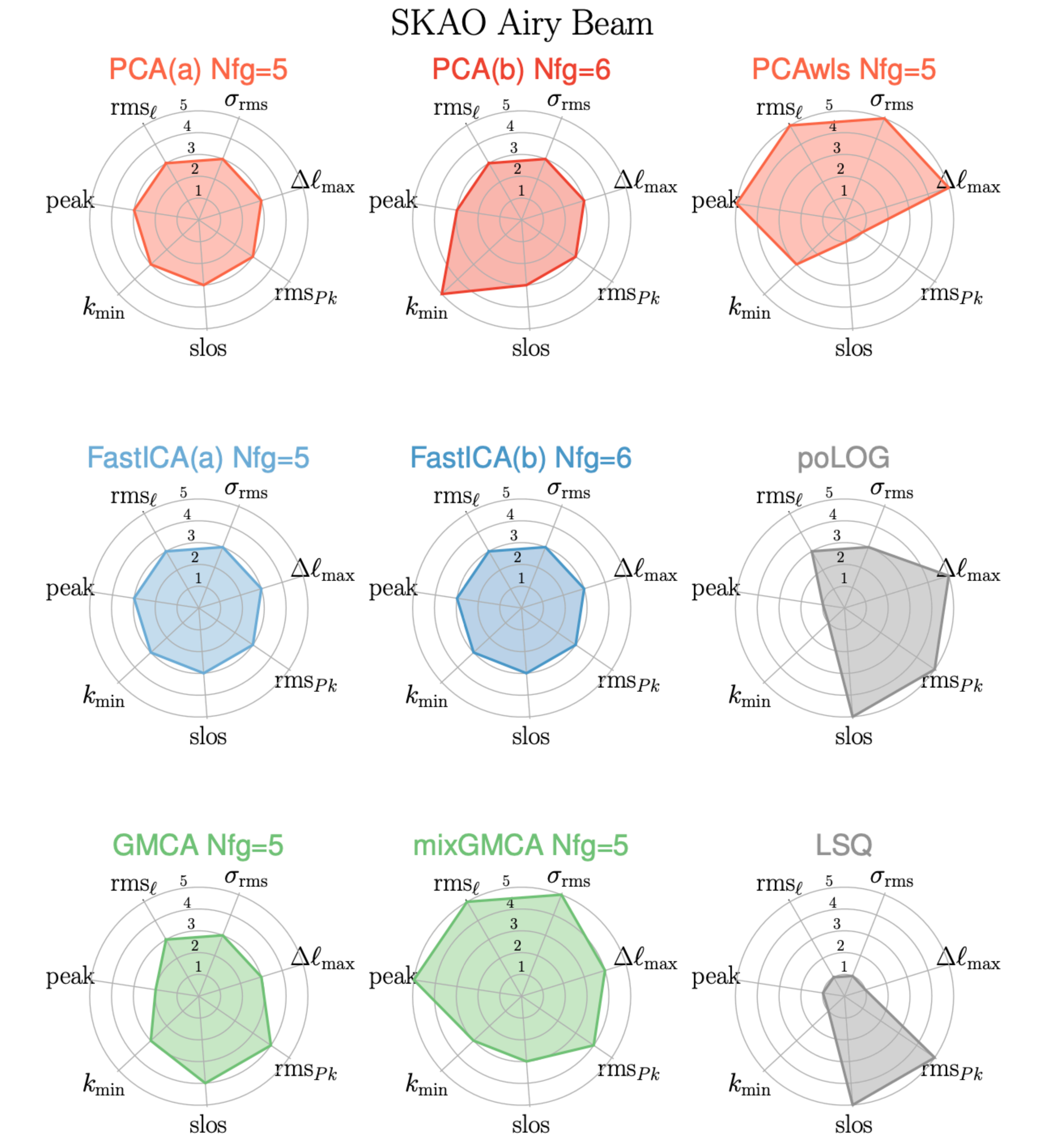
Angular PS

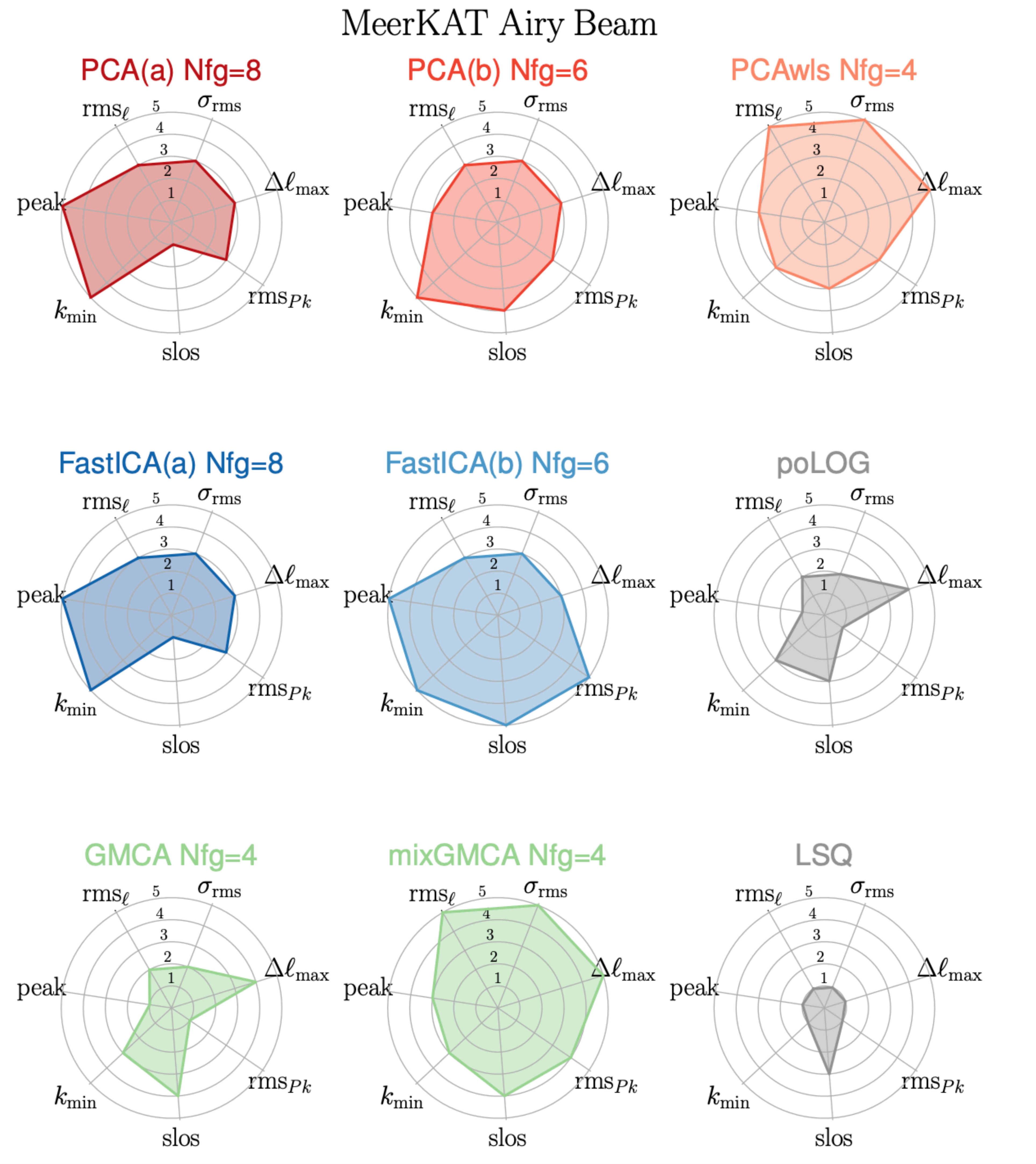


Radial PS



Results


SKAO Airy Beam
PCA(a) Nfg=5
PCA(b) Nfg=6
PCAwls Nfg=5
FastICA(a) Nfg=5
FastICA(b) Nfg=6
poLOG
GMCA Nfg=5
mixGMCA Nfg=5
LSQ
rms_ℓ
σ_{rms}
$\Delta\ell_{\mathrm{max}}$
rms_{Pk}
slos
k_{min}
peak


MeerKAT Airy Beam
PCA(a) Nfg=8
PCA(b) Nfg=6
PCAwls Nfg=4
FastICA(a) Nfg=8
FastICA(b) Nfg=6
poLOG
GMCA Nfg=4
mixGMCA Nfg=4
LSQ
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peak

Summary

- **The Blind Challenge is an excellent exercise**, both for the *simulations* and for the *methods*. It should be used also as a way to devise/ design optimal cleaning pipelines

- Beam + spatially structured FGs —> non-trivial artefacts in the maps. We need better deconvolution strategy

- Blind methods (i.e. based on statistical properties of data) should be preferred

- Small differences in the implementation —> quite different results. We opened a pandora box of things to be checked/ investigated

- **MeerKLASS** ongoing!

HI intensity mapping with the SKAO

Proposed SKA1 Cosmology Surveys

a) Medium–Deep Survey of 5,000 deg^2 at 0.95-1.4 GHz for
- HI galaxy redshift survey with 3.5 million objects
- Weak Lensing shape measurements with ~50 million objects
- Continuum galaxy survey with ~60 million objects

b) Wide Survey of 20,000 deg^2 at 0.35-1.05 GHz for
- Continuum galaxy survey with ~100 million objects
- HI intensity maps for $0.35<z<3$

c) Deep Survey 100 deg^2 at 200-350 MHz for
- HI intensity maps for $3<z<6$

Cosmology with Phase 1 of the Square Kilometre Array **Red Book** 2018: Technical specifications and performance forecasts

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