

UPDATES FROM THE **LOFAR-EOR PROJECT:** RESULTS FROM THE **NCP** AND THE **3C196 FIELDS**

Emilio Ceccotti (IRA-INAF, Bologna, Italy)

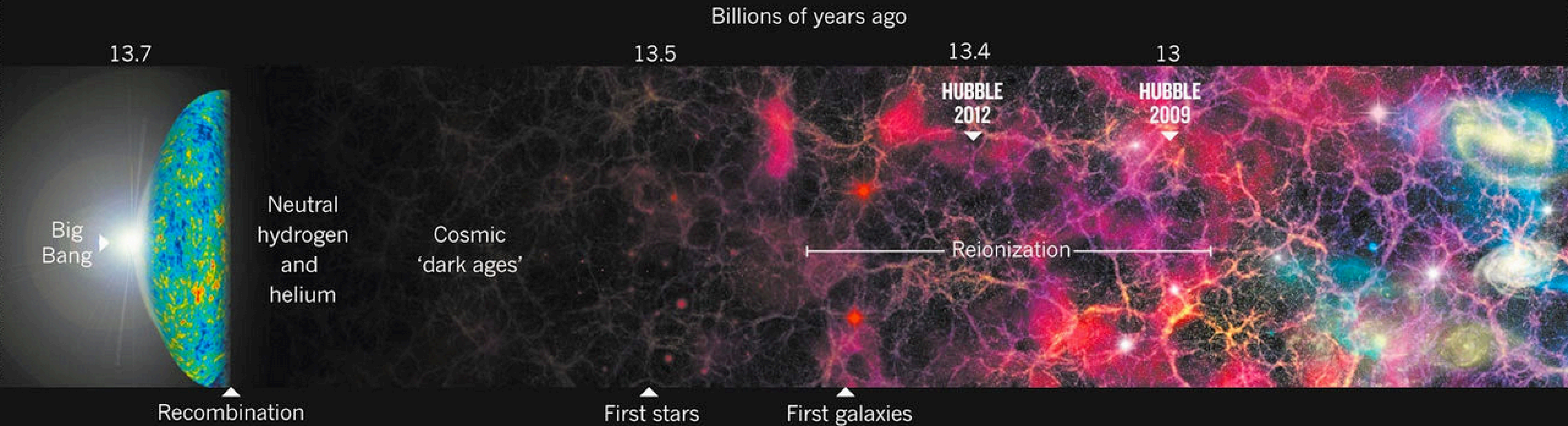
LOFAR Annual Meeting 2026, 8 June



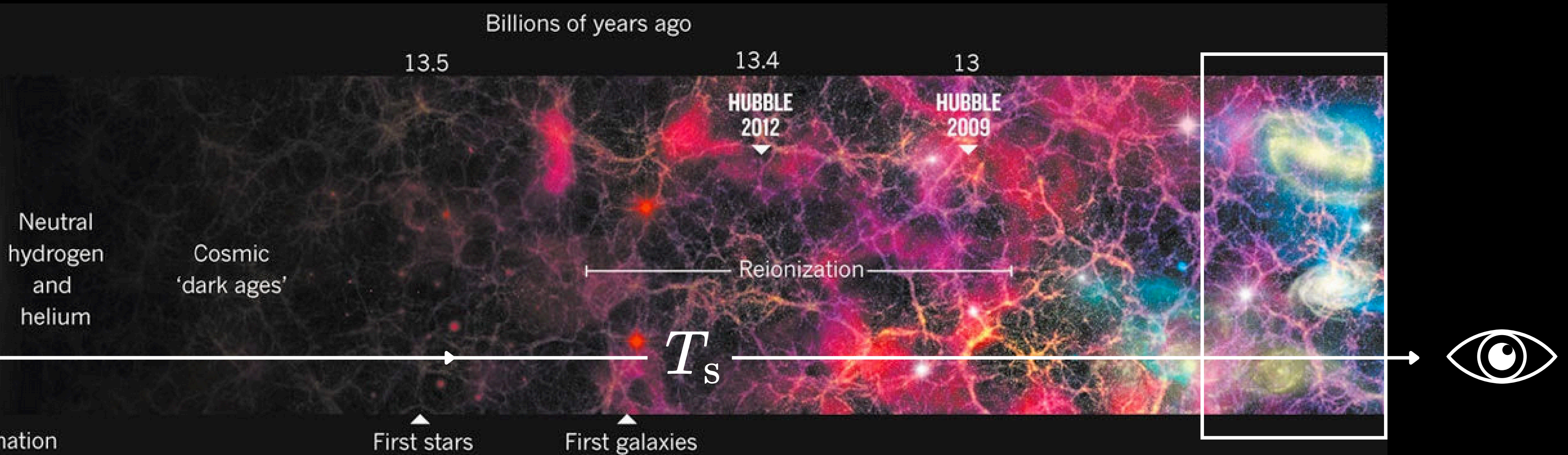
LOFAR EoR Collaboration
(PI: Koopmans, Offringa, Zaroubi)



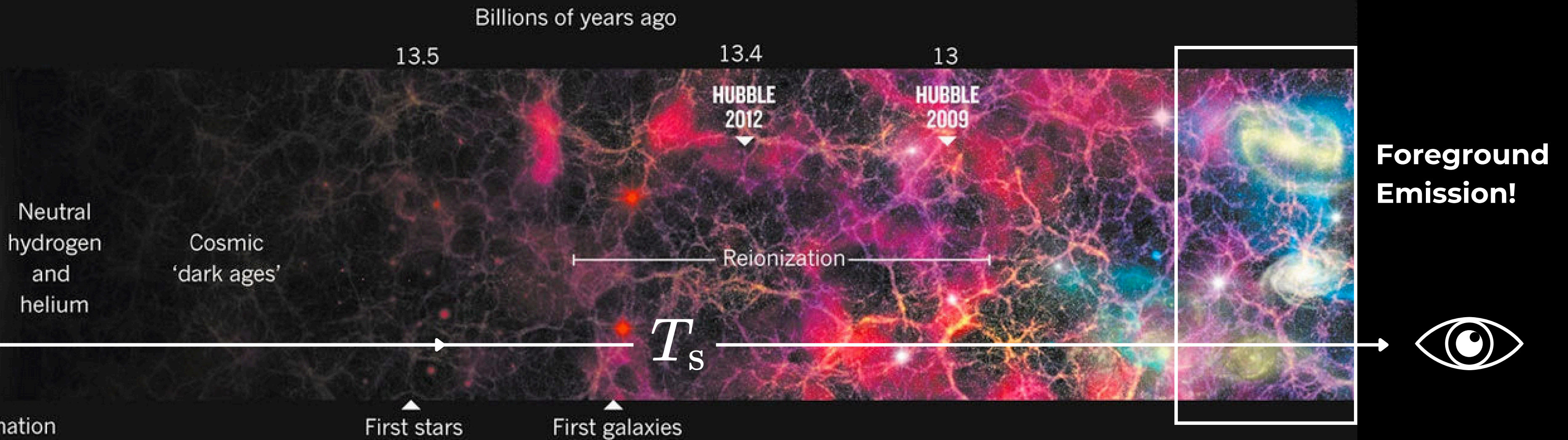
OBSERVING THE EOR WITH THE 21-CM SIGNAL



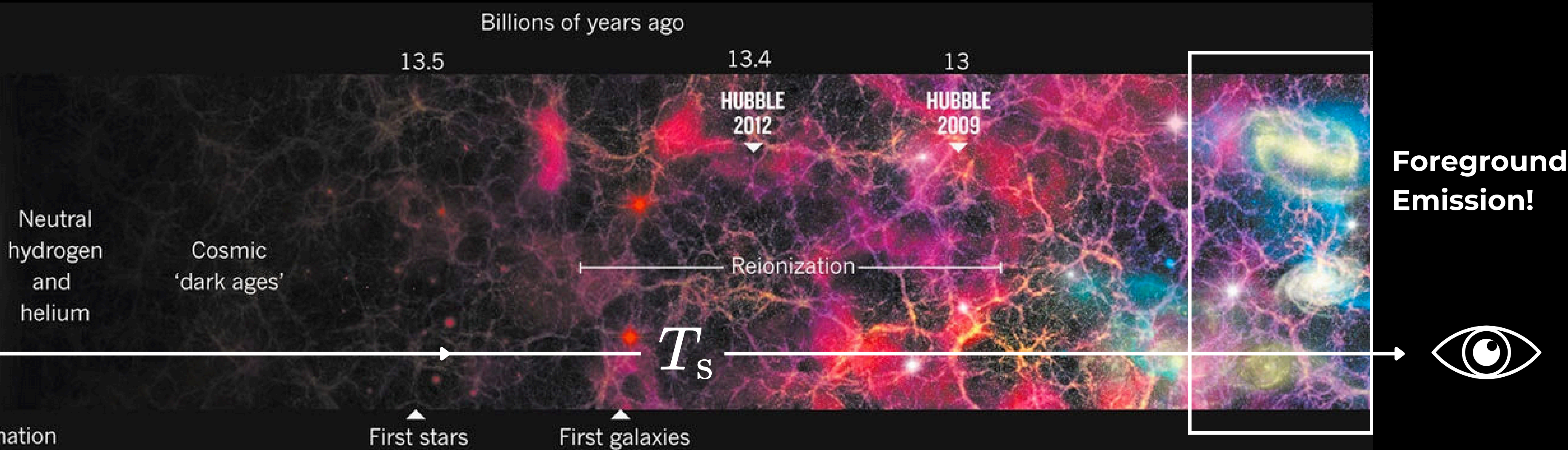
OBSERVING THE EOR WITH THE 21-CM SIGNAL



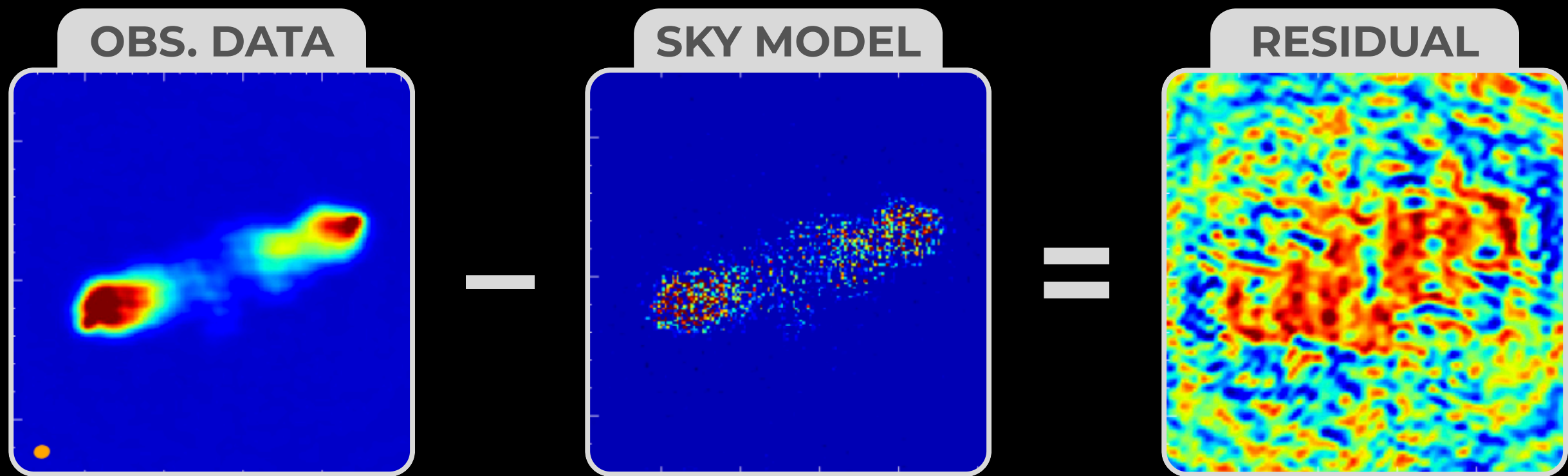
OBSERVING THE EOR WITH THE 21-CM SIGNAL



OBSERVING THE EOR WITH THE 21-CM SIGNAL

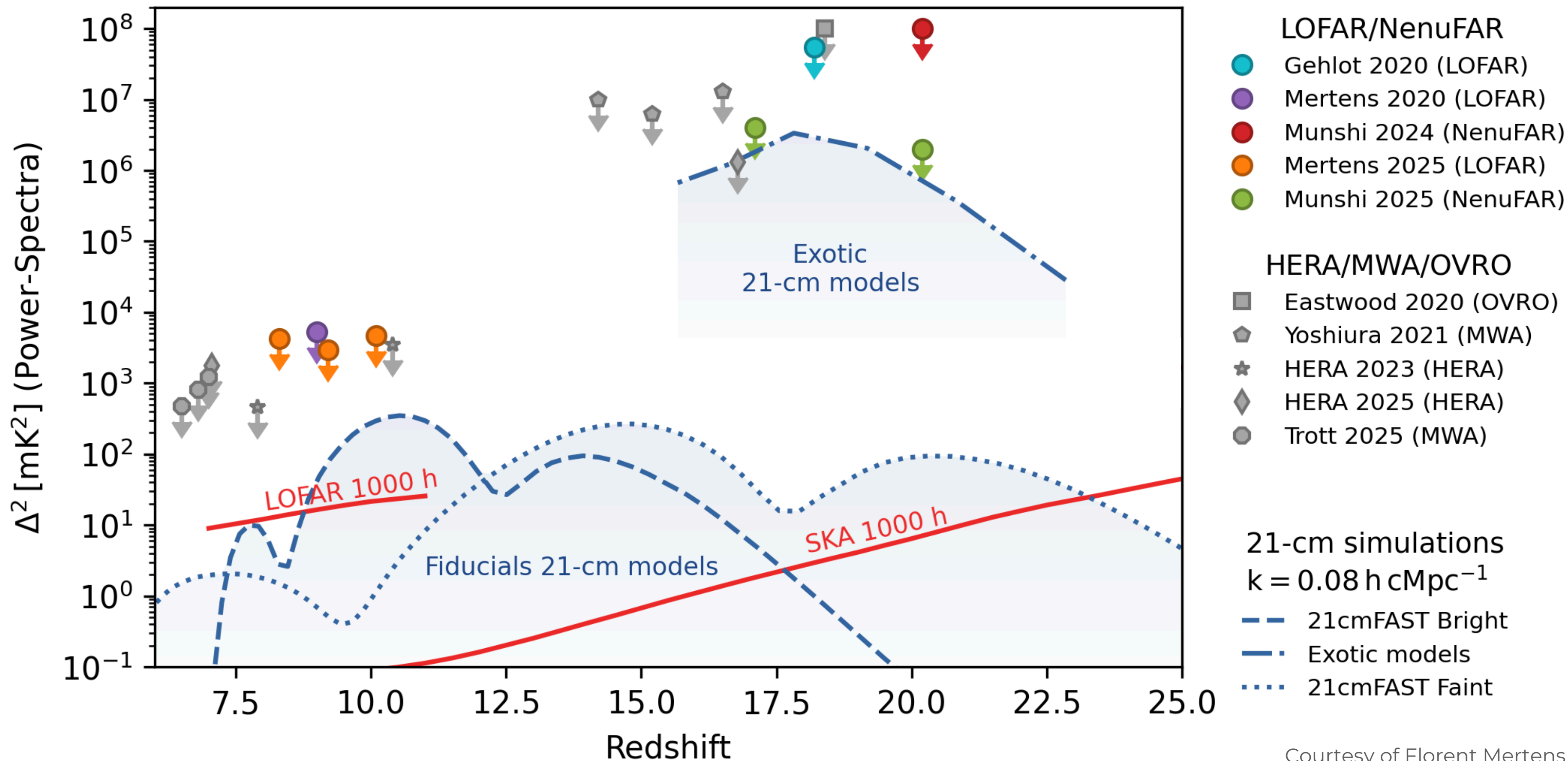


**FOREGROUND
SUBTRACTION**

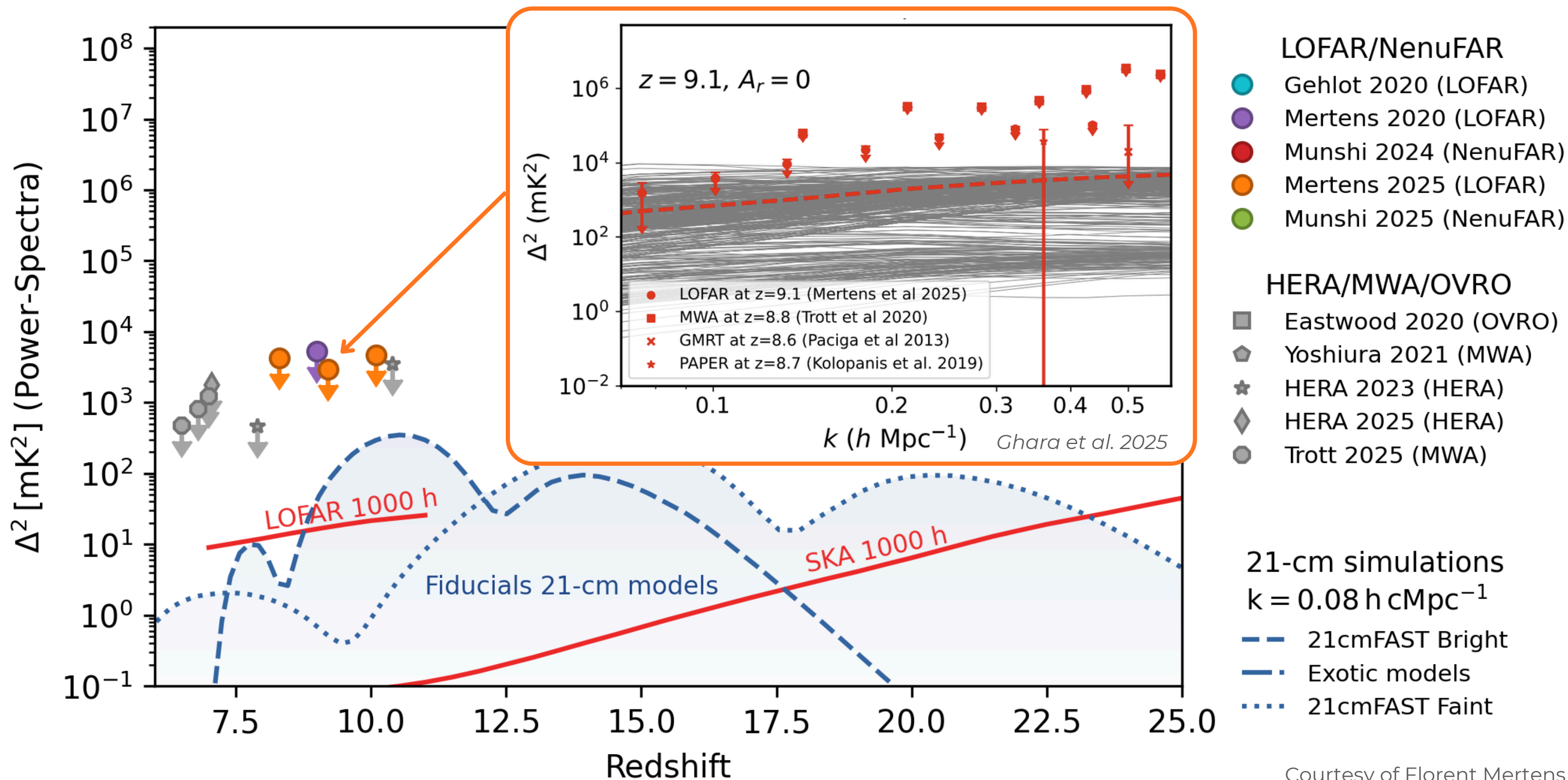


Adapted from
Gardsen et al. 2015

WHERE ARE WE TODAY?



WHERE ARE WE TODAY?



LOFAR-EOR PROJECT

Redshift range $z \sim 7-11$

3C196

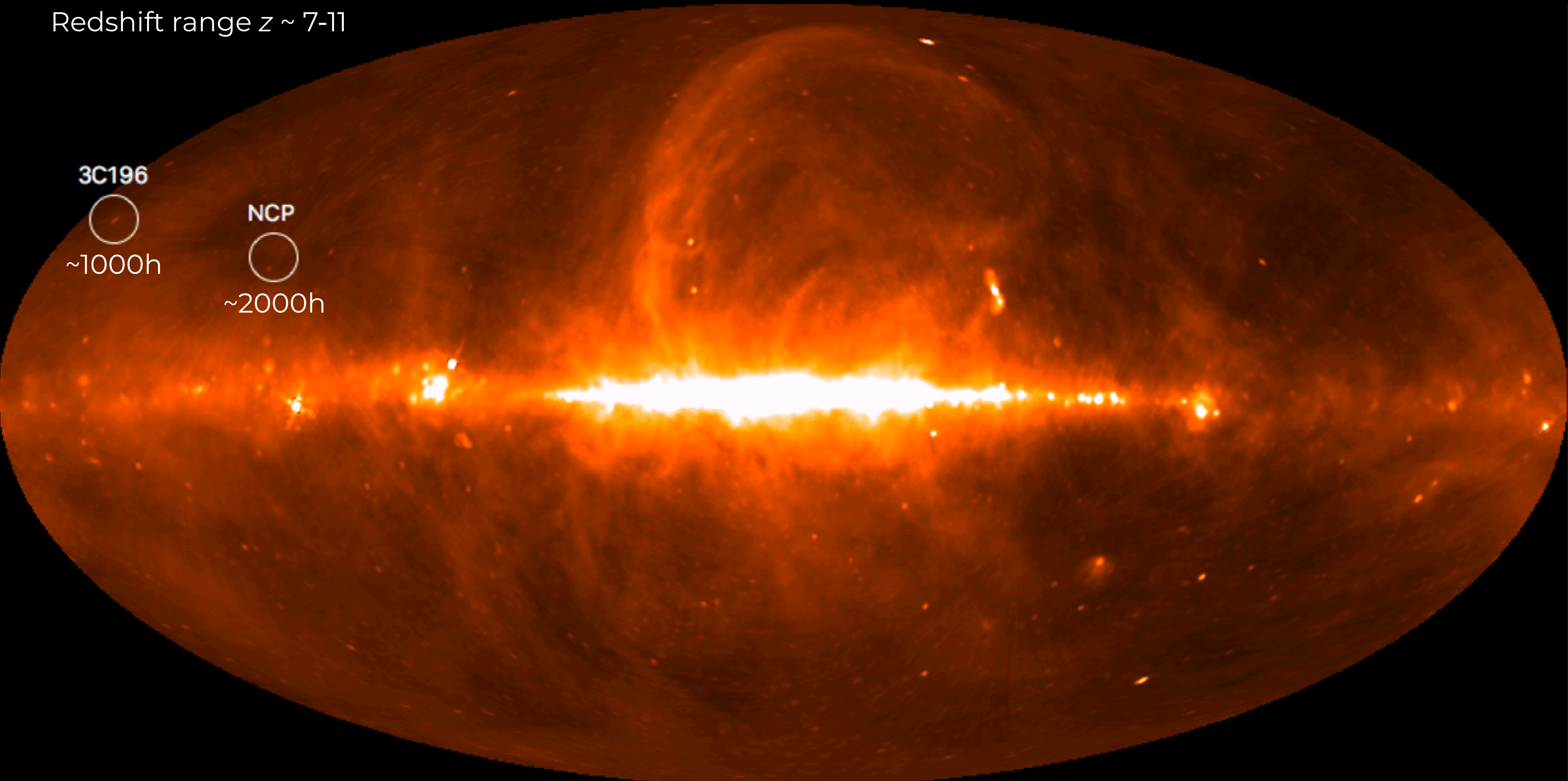


$\sim 1000h$

NCP



$\sim 2000h$



LOFAR-EOR PROJECT

Redshift range $z \sim 7-11$

3C196

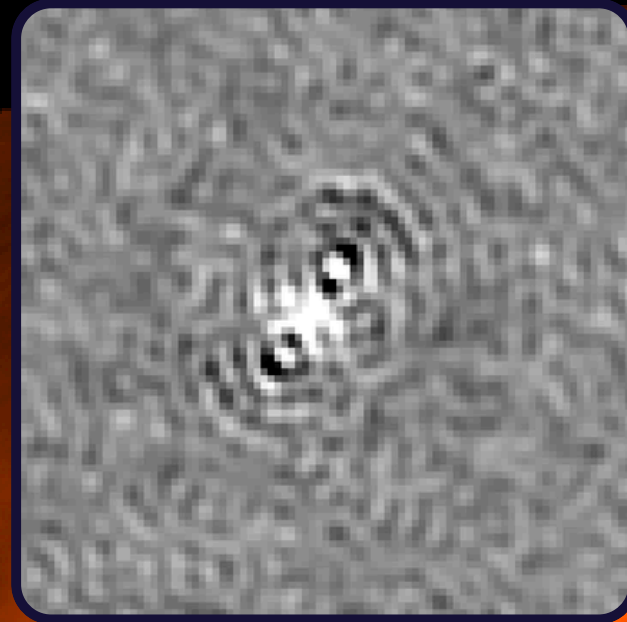


$\sim 1000h$

NCP



$\sim 2000h$



PROS:

- observable throughout the year
- circular uv-coverage

CONS:

- RFI adds up coherently
- 3C61.1 close to 1st primary beam null

LOFAR-EOR PROJECT

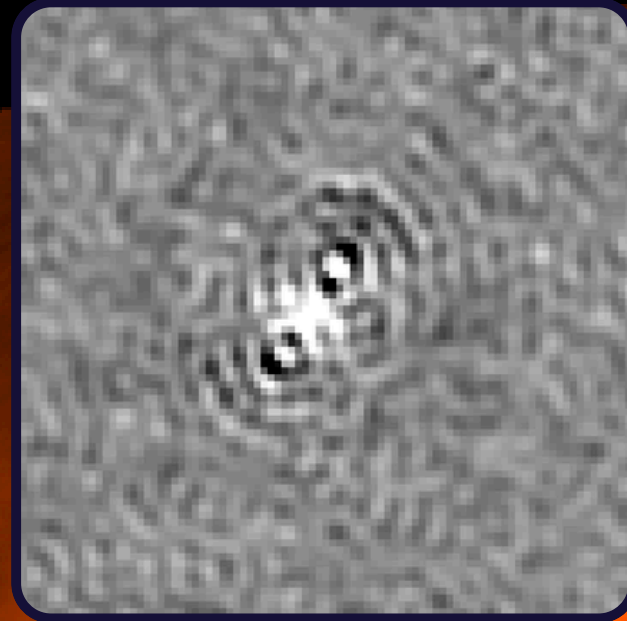
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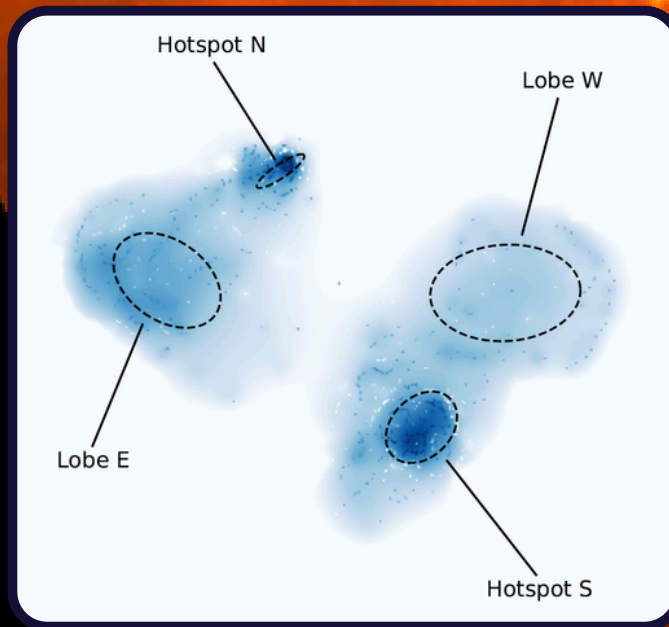


3C196

NCP

~1000h

~2000h



PROS:

- Sensitivity higher passing close to the zenith
- Strong source in the centre that helps DI calibration

CONS:

- Accurate subtraction of 3C196 required
- Bright linearly polarized structures

LOFAR-EOR PROJECT

Redshift range $z \sim 7-11$

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3C196

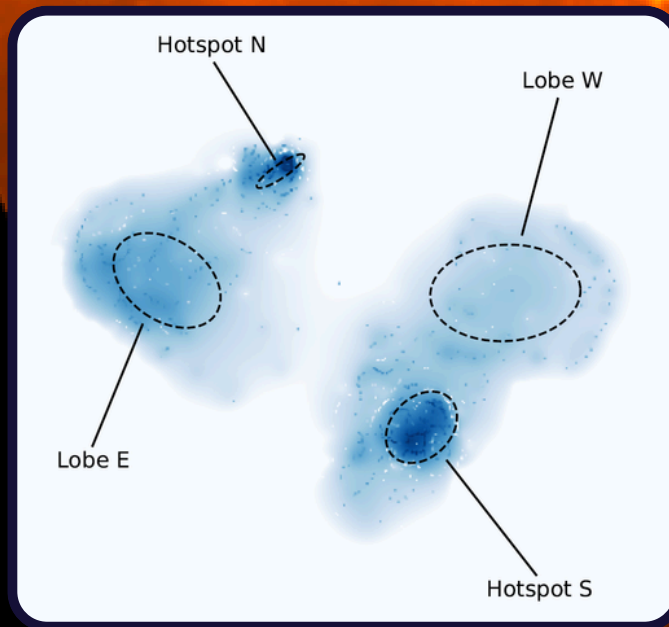
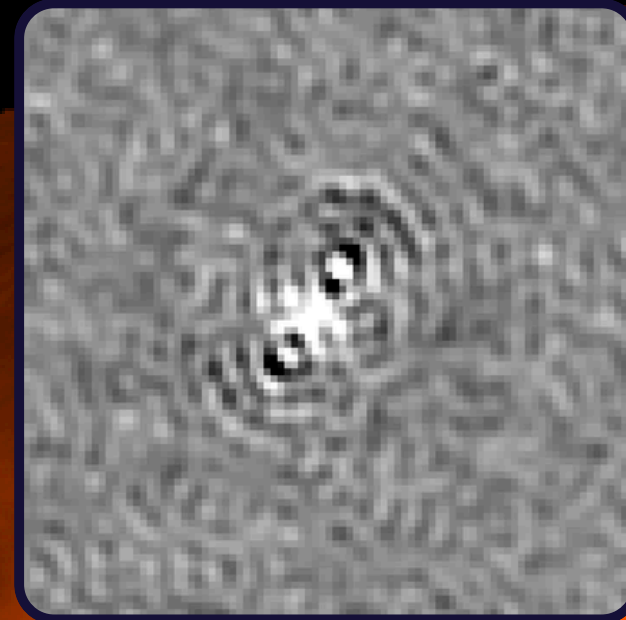


$\sim 1000h$

NCP



$\sim 2000h$

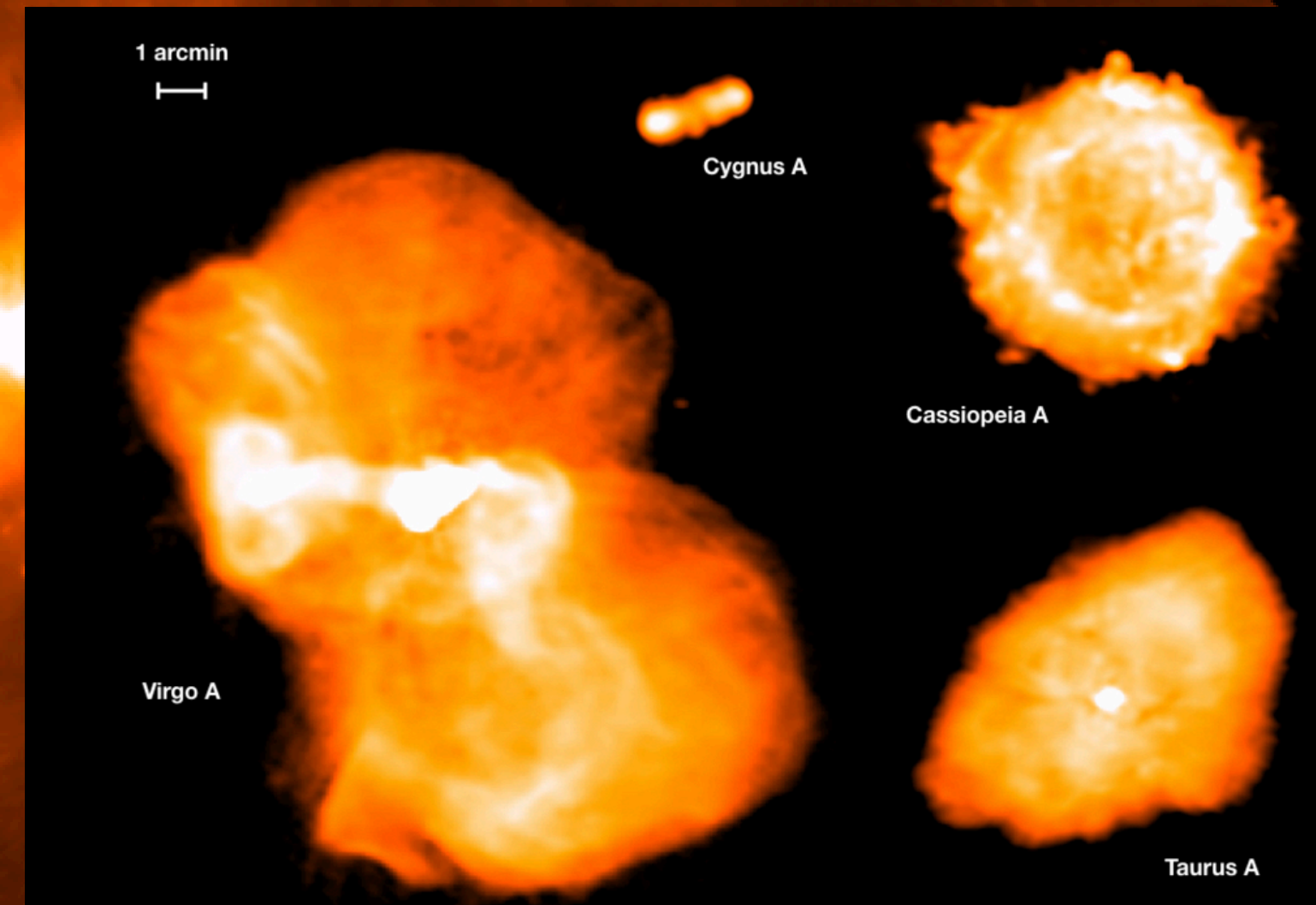


PROS:

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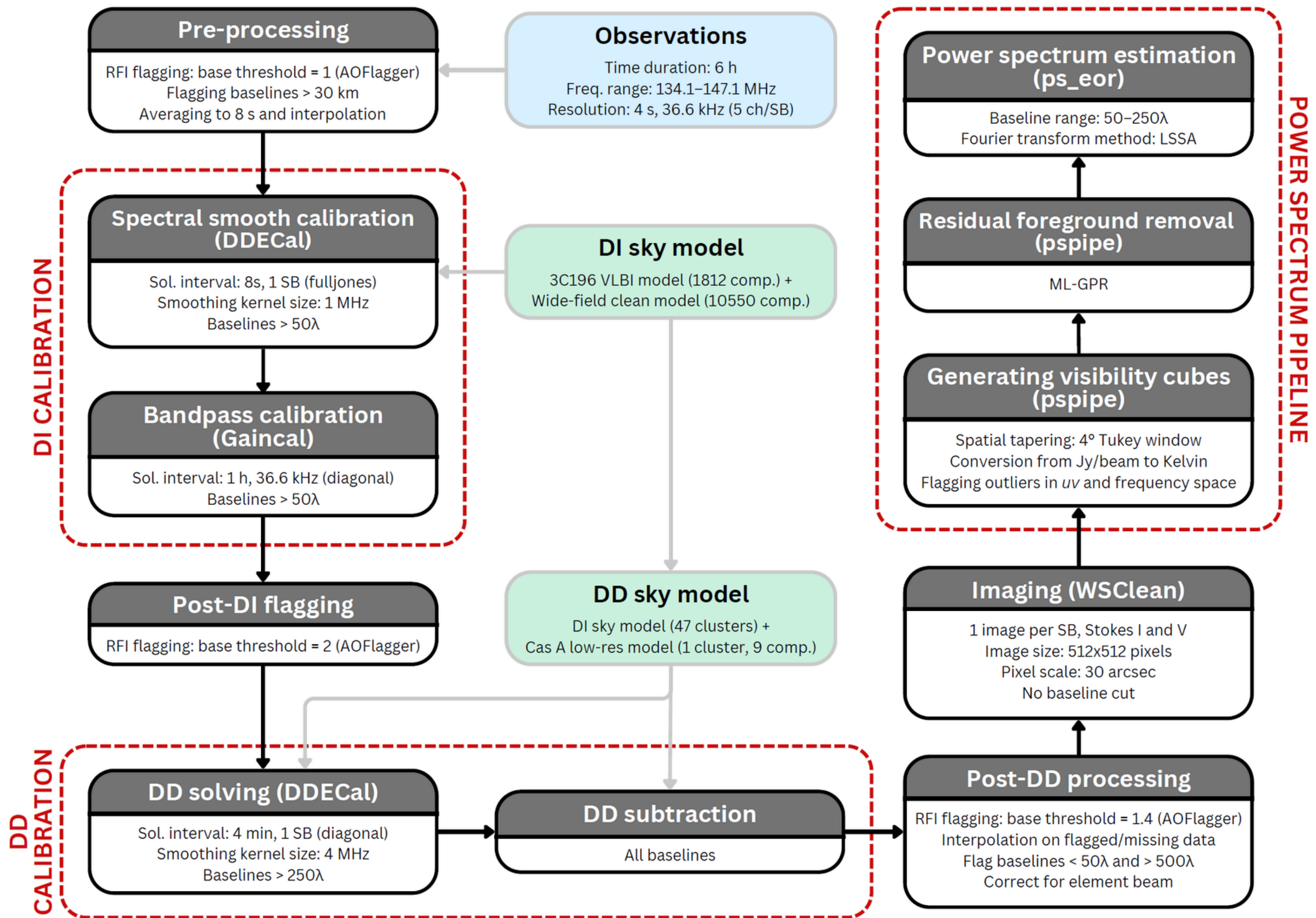
CONS:

- Accurate subtraction of 3C196 required
- Bright linearly polarized structures



Far A-team sources (from 1 to 10 kJy) may leave strong residuals through their sidelobes if not accurately subtracted

FOR PROCESSING PIPELINE (3C196)




```

graph TD
    Observations[Observations  
Time duration: 6 h  
Freq. range: 134.1–147.1 MHz  
Resolution: 4 s, 36.6 kHz (5 ch/SB)]
    PreProcessing[Pre-processing  
RFI flagging: base threshold = 1 (AOFlagger)  
Flagging baselines > 30 km  
Averaging to 8 s and interpolation]
    DI_Sky_Model[DI sky model  
3C196 VLBI model (1812 comp.) +  
Wide-field clean model (10550 comp.)]
    DD_Sky_Model[DD sky model  
DI sky model (47 clusters) +  
Cas A low-res model (1 cluster, 9 comp.)]
    DD_Subtraction[DD subtraction  
All baselines]
    Post_DD_Processing[Post-DD processing  
RFI flagging: base threshold = 1.4 (AOFlagger)  
Interpolation on flagged/missing data  
Flag baselines < 50λ and > 500λ  
Correct for element beam]
    Imaging[Imaging (WSClean)  
1 image per SB, Stokes I and V  
Image size: 512x512 pixels  
Pixel scale: 30 arcsec  
No baseline cut]
    Generating_Visibility_Cubes[Generating visibility cubes (pspipe)  
Spatial tapering: 4° Tukey window  
Conversion from Jy/beam to Kelvin  
Flagging outliers in uv and frequency space]
    Residual_Foreground_Removal[Residual foreground removal (pspipe)  
ML-GPR]
    Power_Spectrum_Estimation[Power spectrum estimation (ps_eor)  
Baseline range: 50–250λ  
Fourier transform method: LSSA]

    Observations --> PreProcessing
    PreProcessing --> Spectral_Smooth_Calibration
    Spectral_Smooth_Calibration --> Bandpass_Calibration
    Bandpass_Calibration --> Post_DI_Flagging
    Post_DI_Flagging --> DD_Solving
    DD_Solving --> DD_Subtraction
    DD_Subtraction --> Post_DD_Processing
    Post_DD_Processing --> Imaging
    Imaging --> Generating_Visibility_Cubes
    Generating_Visibility_Cubes --> Residual_Foreground_Removal
    Residual_Foreground_Removal --> Power_Spectrum_Estimation

    DI_Sky_Model --> Spectral_Smooth_Calibration
    DI_Sky_Model --> DD_Sky_Model
    DD_Sky_Model --> DD_Subtraction

    subgraph DI_CALIBRATION [DI CALIBRATION]
        Spectral_Smooth_Calibration
        Bandpass_Calibration
    end

    subgraph DD_CALIBRATION [DD CALIBRATION]
        DD_Solving
    end

    subgraph POWER_SPECTRUM_PIPELINE [POWER SPECTRUM PIPELINE]
        Generating_Visibility_Cubes
        Residual_Foreground_Removal
        Power_Spectrum_Estimation
    end
  
```

Observations
Time duration: 6 h
Freq. range: 134.1–147.1 MHz
Resolution: 4 s, 36.6 kHz (5 ch/SB)

Pre-processing
RFI flagging: base threshold = 1 (AOFlagger)
Flagging baselines > 30 km
Averaging to 8 s and interpolation

DI CALIBRATION

Spectral smooth calibration (DDECal)
Sol. interval: 8s, 1 SB (fulljones)
Smoothing kernel size: 1 MHz
Baselines > 50λ

Bandpass calibration (Gaincal)
Sol. interval: 1 h, 36.6 kHz (diagonal)
Baselines > 50λ

Post-DI flagging
RFI flagging: base threshold = 2 (AOFlagger)

DD CALIBRATION

DD solving (DDECal)
Sol. interval: 4 min, 1 SB (diagonal)
Smoothing kernel size: 4 MHz
Baselines > 250λ

DD subtraction
All baselines

DD sky model
DI sky model (47 clusters) +
Cas A low-res model (1 cluster, 9 comp.)

DI sky model
3C196 VLBI model (1812 comp.) +
Wide-field clean model (10550 comp.)

POWER SPECTRUM PIPELINE

Post-DD processing
RFI flagging: base threshold = 1.4 (AOFlagger)
Interpolation on flagged/missing data
Flag baselines < 50λ and > 500λ
Correct for element beam

Imaging (WSClean)
1 image per SB, Stokes I and V
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Residual foreground removal (pspipe)
ML-GPR

Power spectrum estimation (ps_eor)
Baseline range: 50–250λ
Fourier transform method: LSSA

LOFAR-EOR CALIBRATION STEPS

RIME:

$$\mathbf{V}_{pq} = \mathbf{G}_p \mathbf{M}_{pq} \mathbf{G}_q^H$$

gain matrices

observed visibility

model visibility

The diagram illustrates the RIME calibration equation: $\mathbf{V}_{pq} = \mathbf{G}_p \mathbf{M}_{pq} \mathbf{G}_q^H$. The term $\mathbf{V}_{pq}$ is labeled as 'observed visibility' with an arrow pointing to it. The term $\mathbf{M}_{pq}$ is labeled as '**model visibility**' with an arrow pointing to it. The terms $\mathbf{G}_p$ and $\mathbf{G}_q^H$ are collectively labeled as 'gain matrices' with arrows pointing to each. The word 'RIME:' is written in red to the left of the equation.

LOFAR-EOR CALIBRATION STEPS

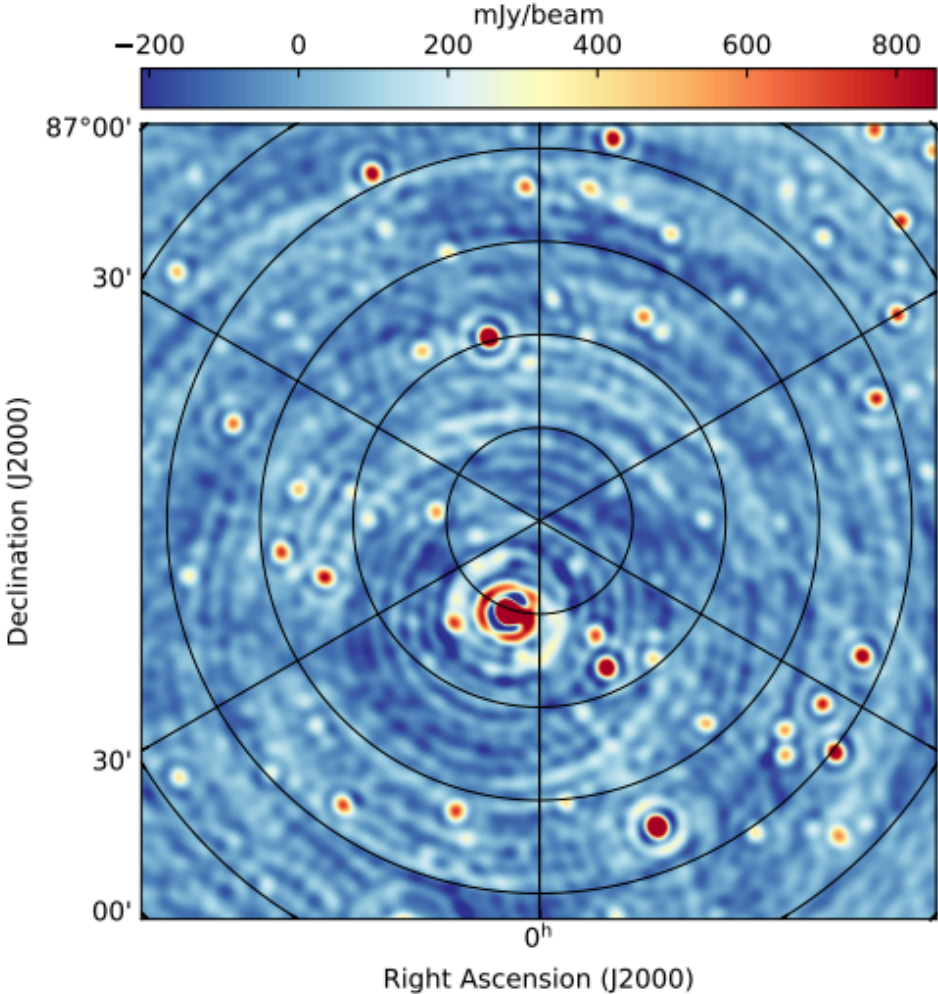
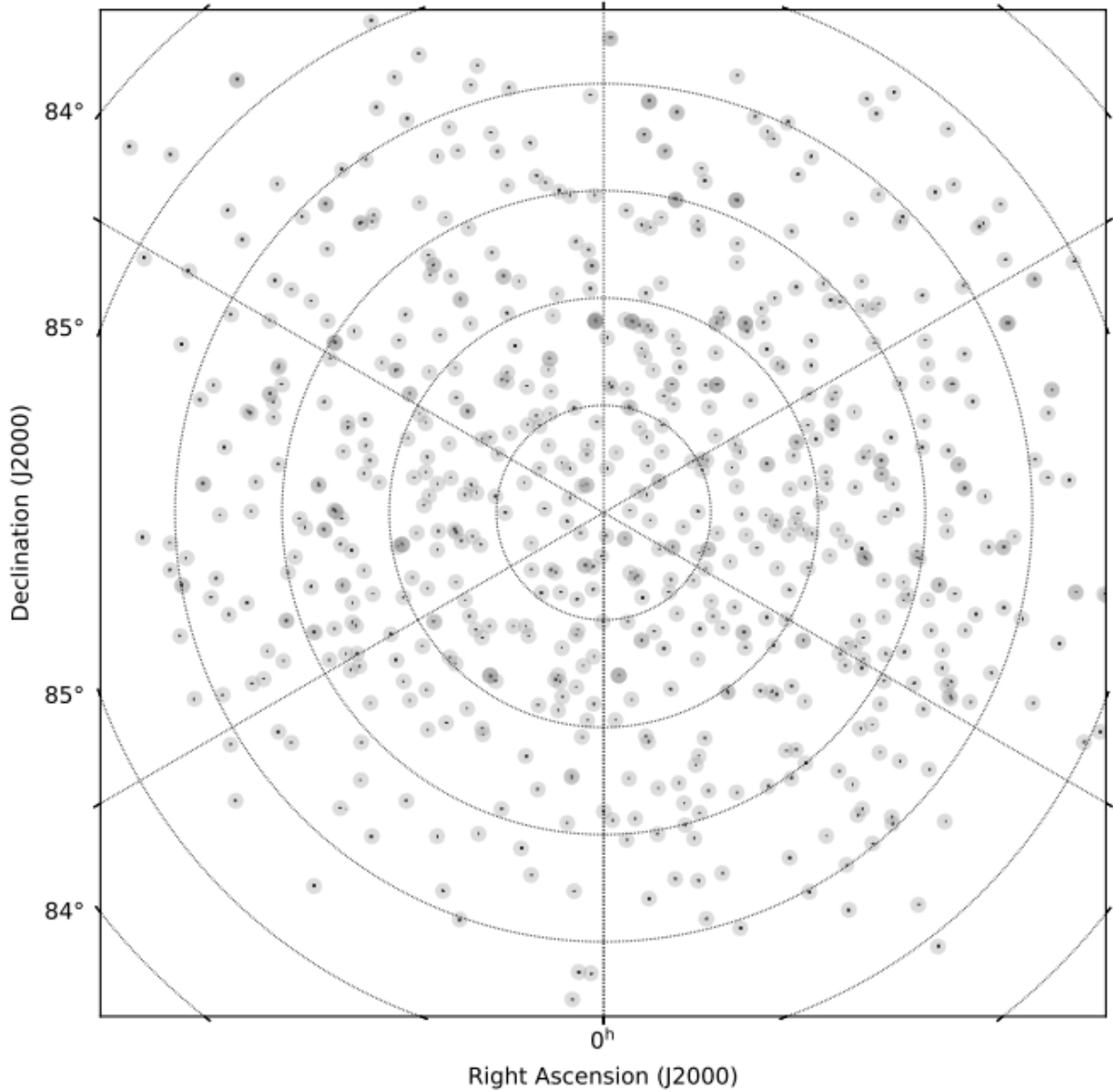
RIME:

$$\mathbf{V}_{pq} = \mathbf{G}_p \mathbf{M}_{pq} \mathbf{G}_q^H$$

observed visibility gain matrices model visibility

DI CALIBRATION

Main field model, solving for a **single direction** (no A-team)

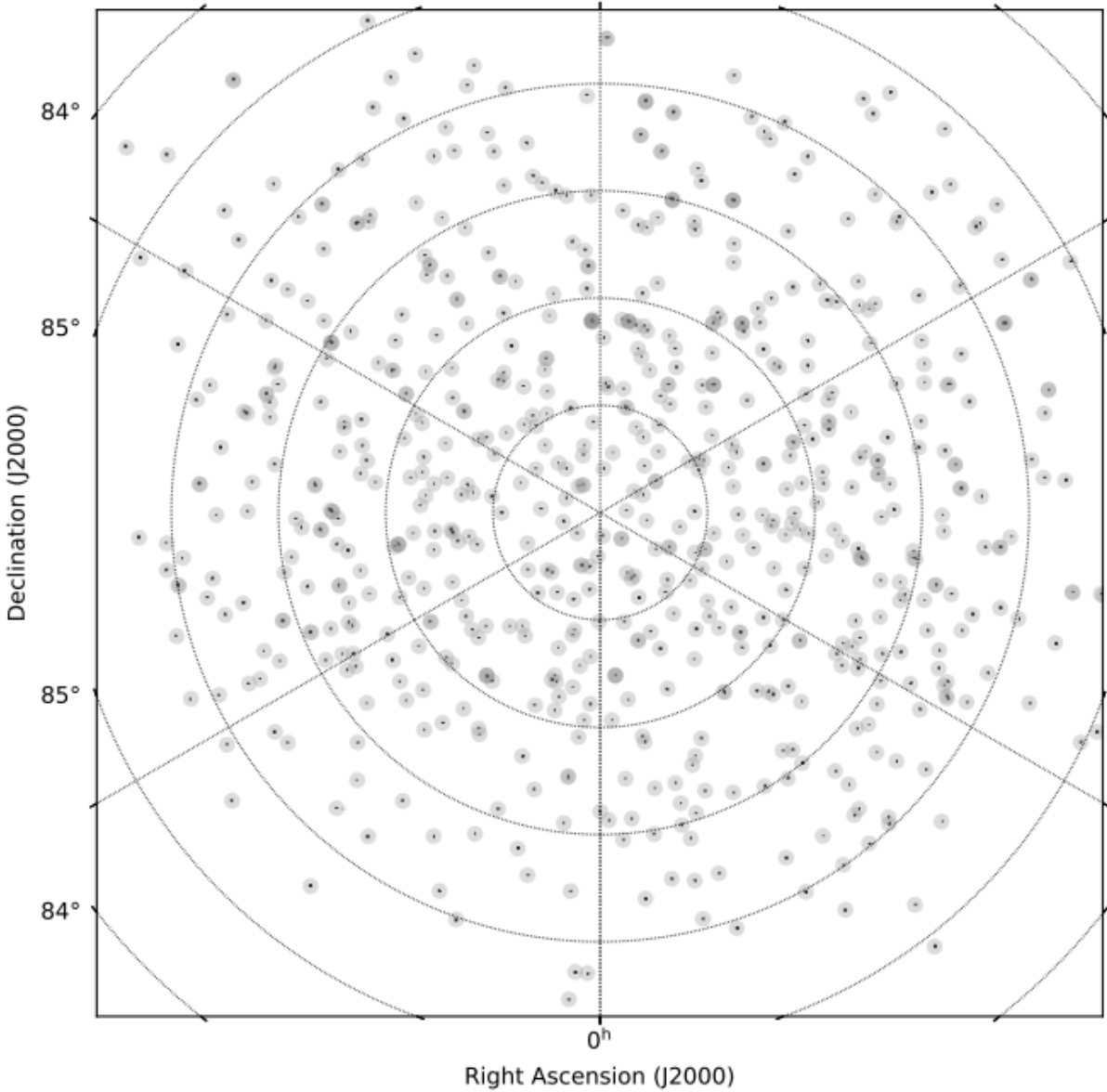


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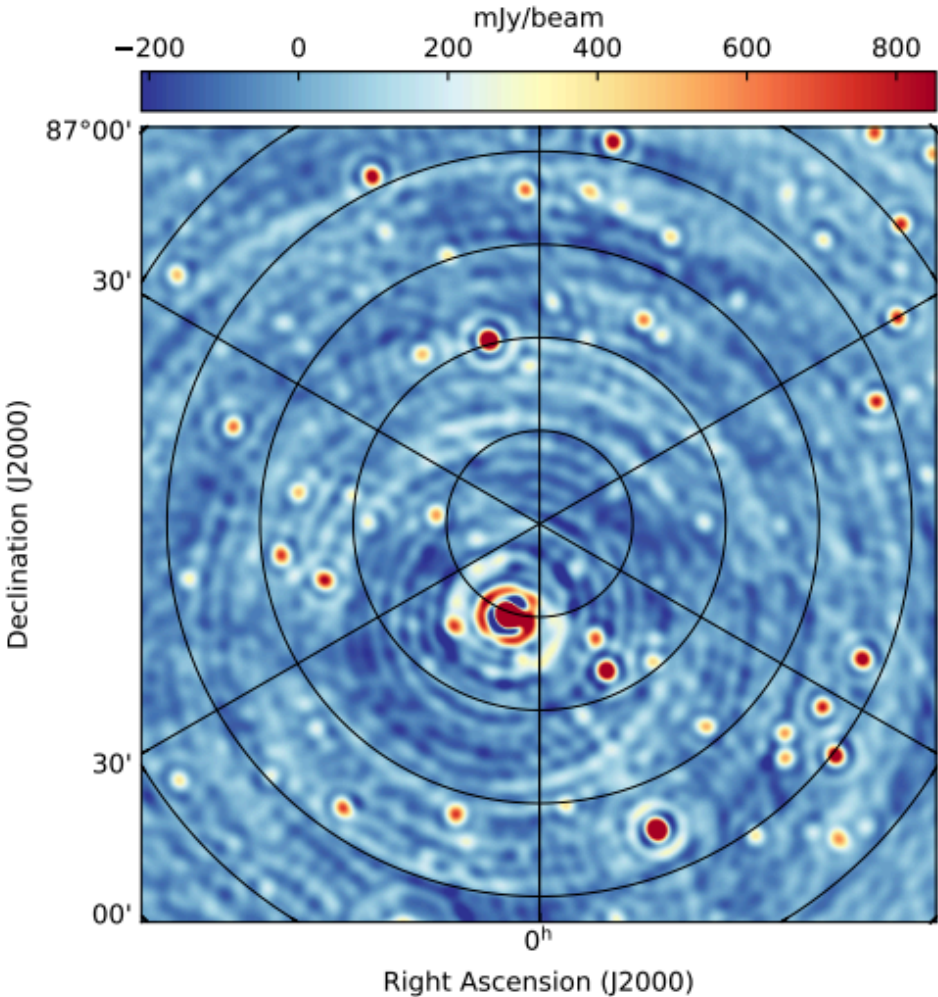
observed visibility gain matrices model visibility



DI CALIBRATION

Main field model, solving for a **single direction** (no A-team)

Solutions are **applied** to data



LOFAR-EOR CALIBRATION STEPS

RIME:

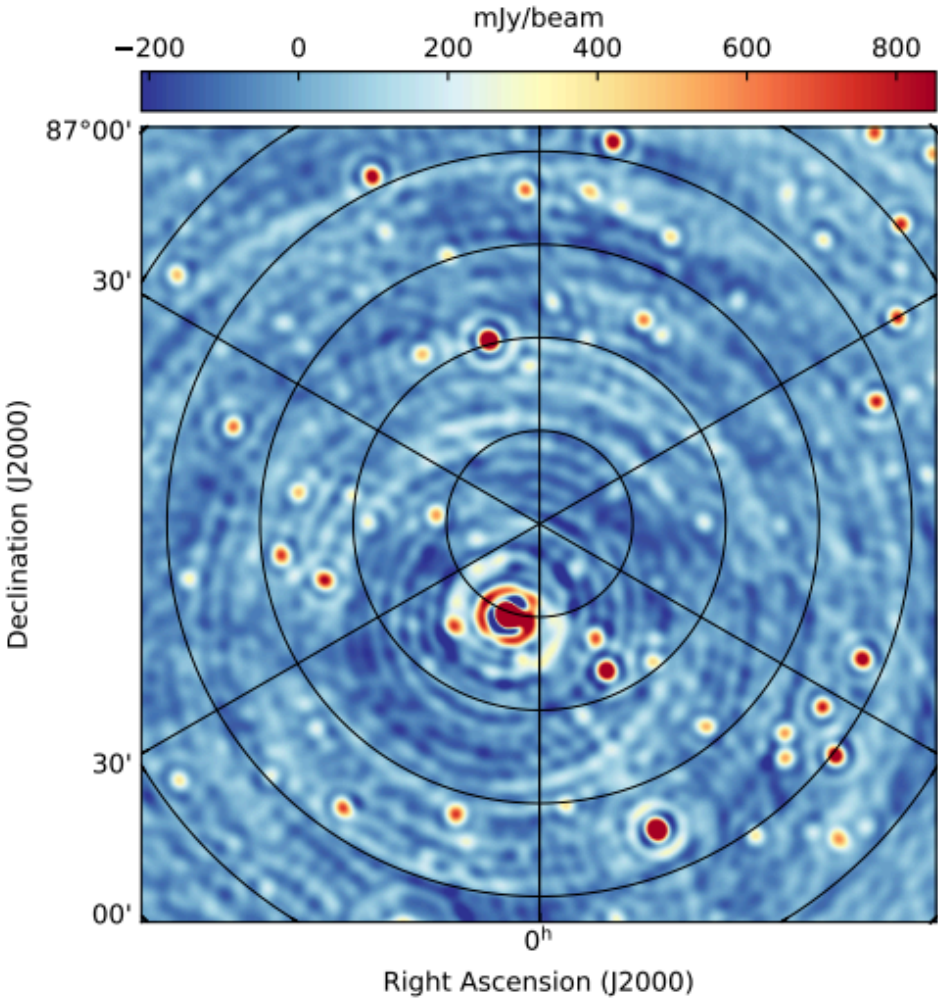
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observed visibility gain matrices model visibility

DI CALIBRATION

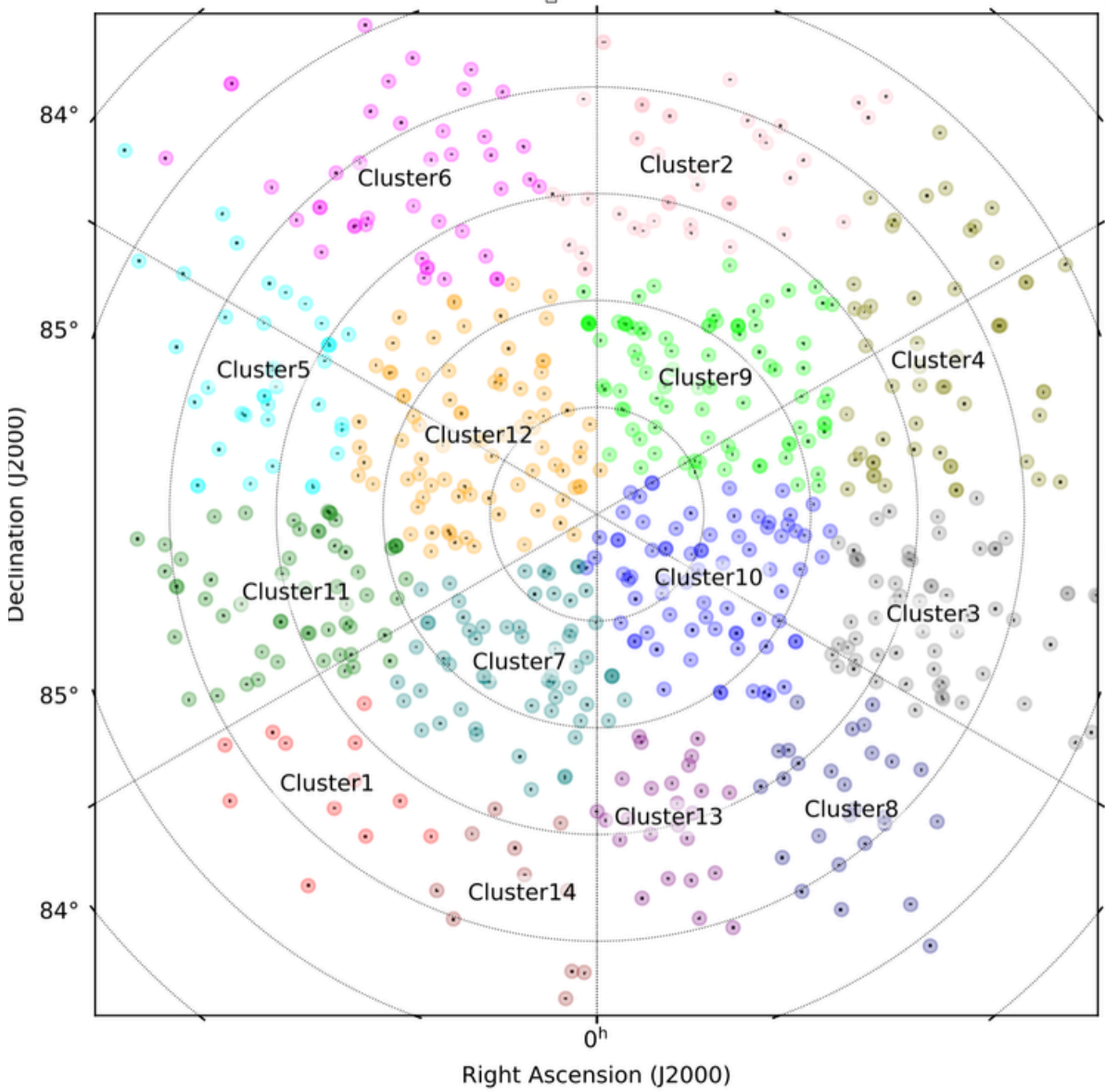
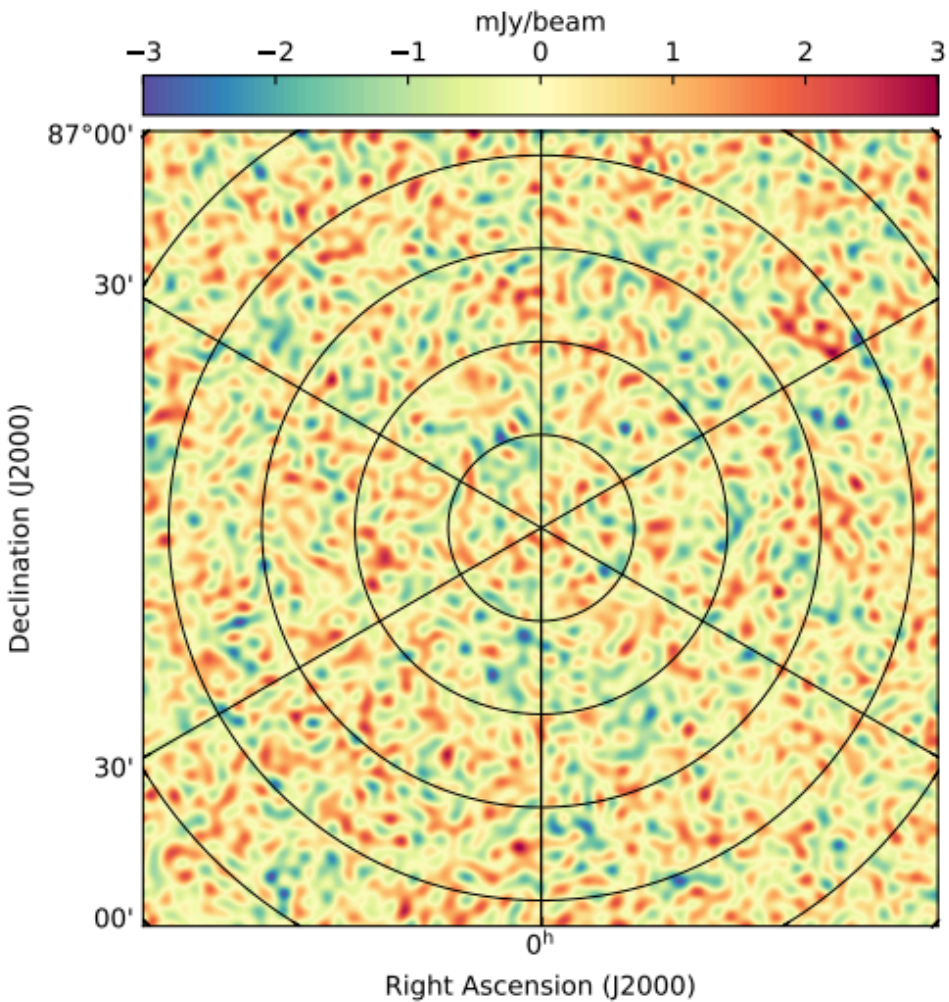
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DD CALIBRATION

Main field model & A-team sources, solving for **each cluster direction** simultaneously



LOFAR-EOR CALIBRATION STEPS

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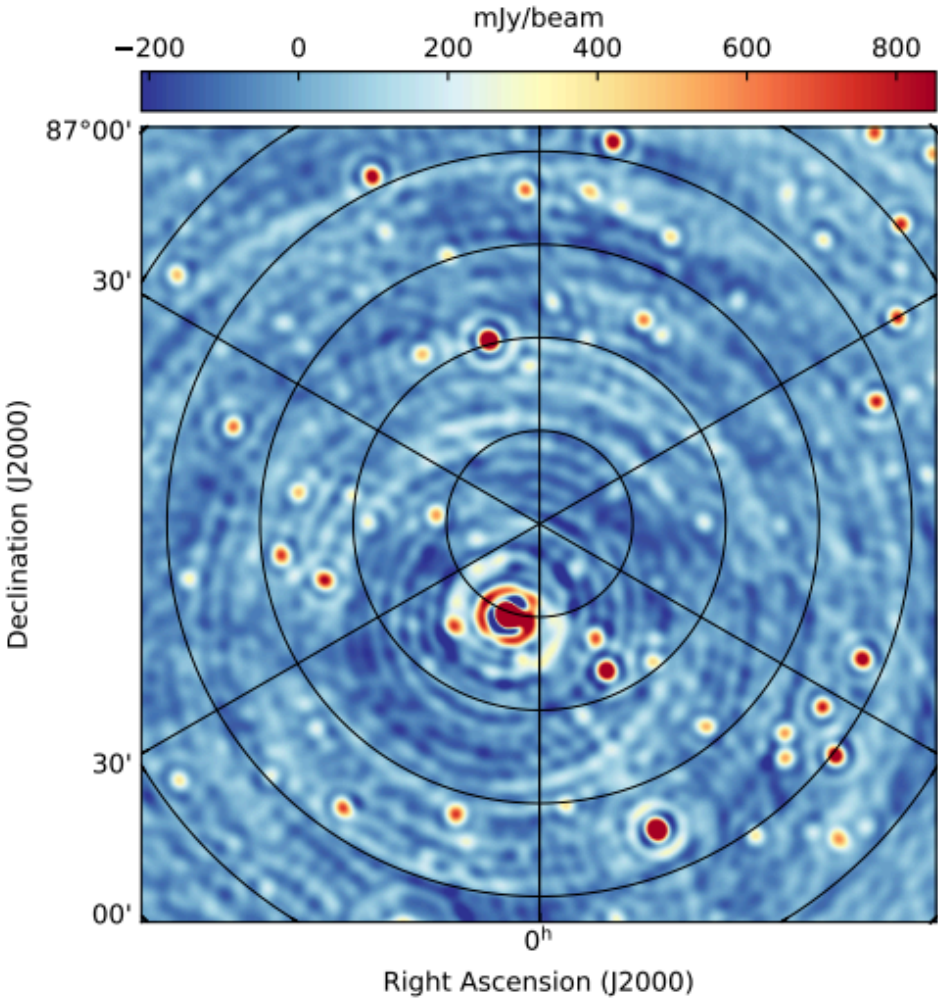
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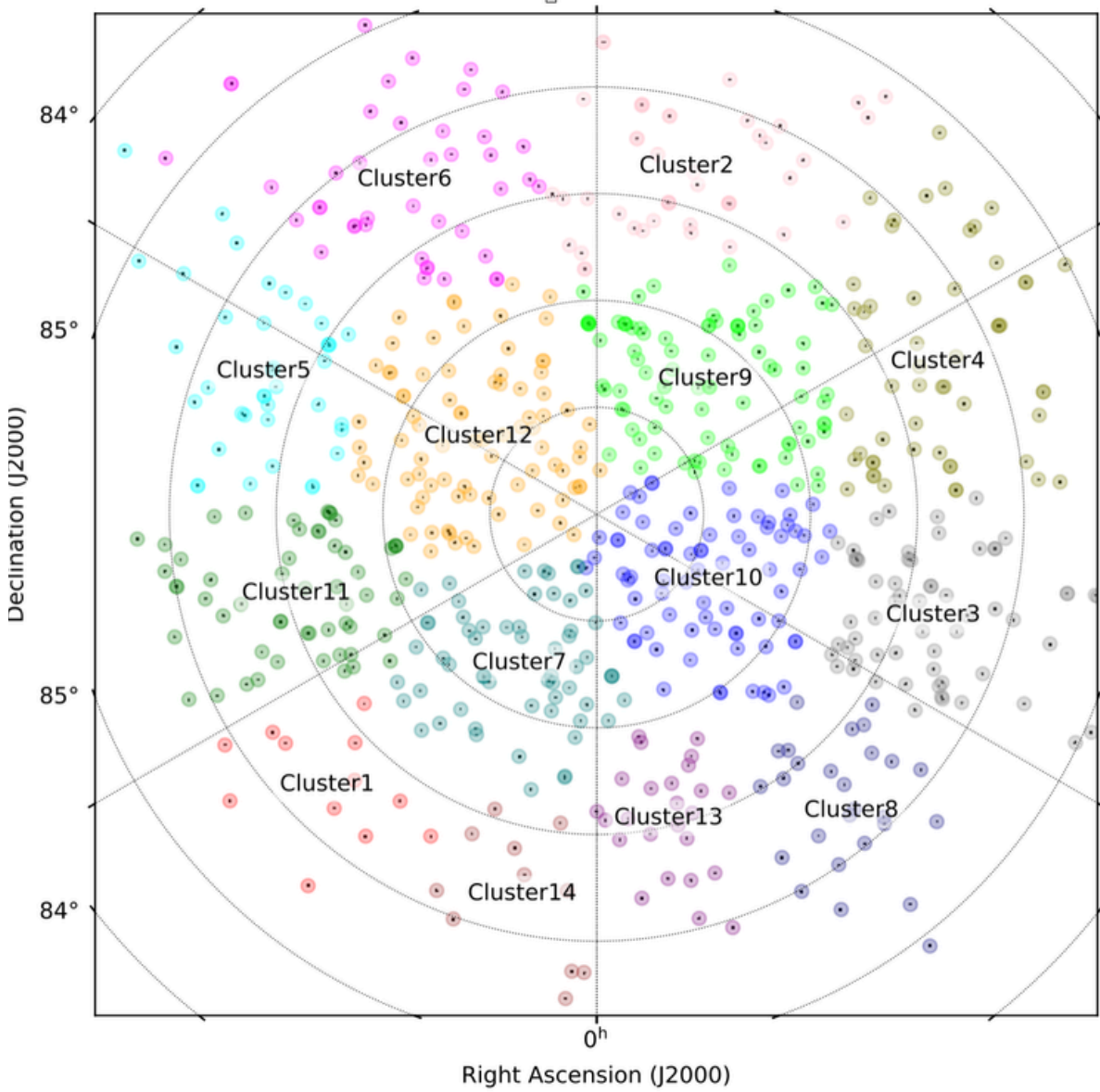
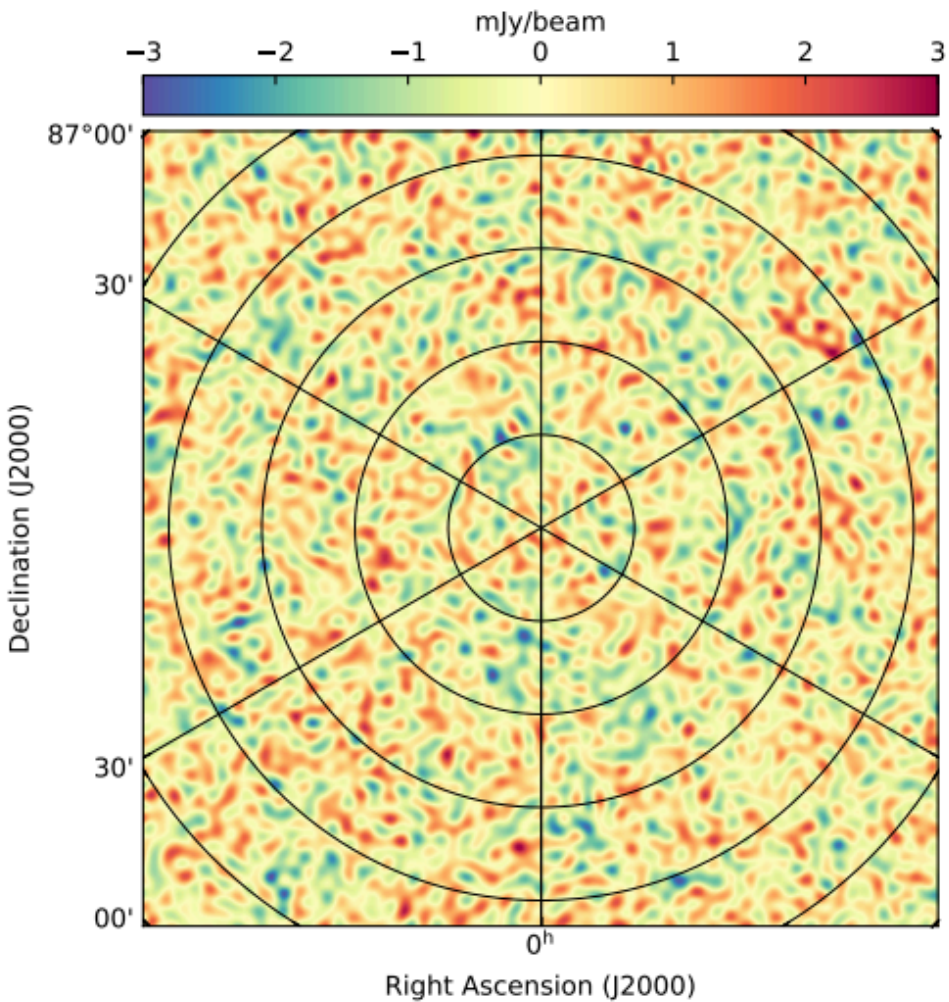
Solutions are **applied** to data



DD CALIBRATION

Main field model & A-team sources, solving for **each cluster direction** simultaneously

These solutions are **not** applied, but used to corrupt the data



LOFAR-EOR CALIBRATION STEPS

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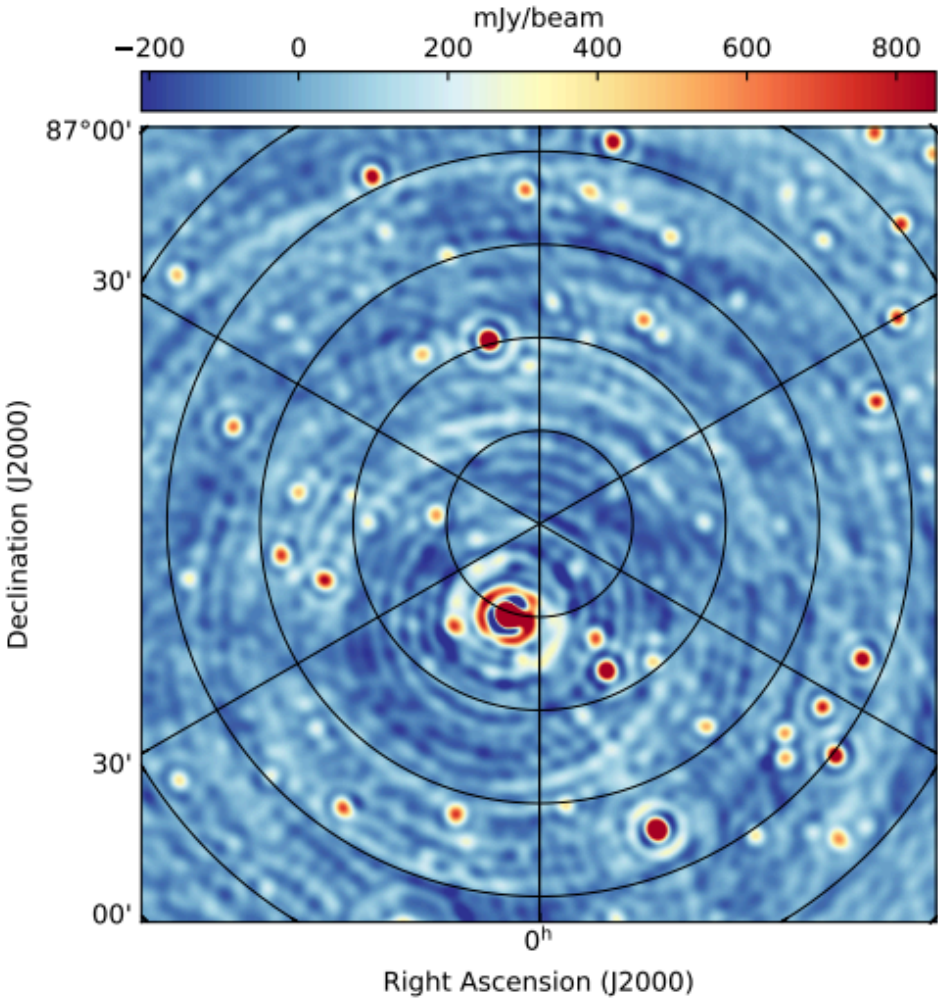
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observed visibility gain matrices model visibility

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Main field model, solving for a **single direction** (no A-team)

Solutions are **applied** to data

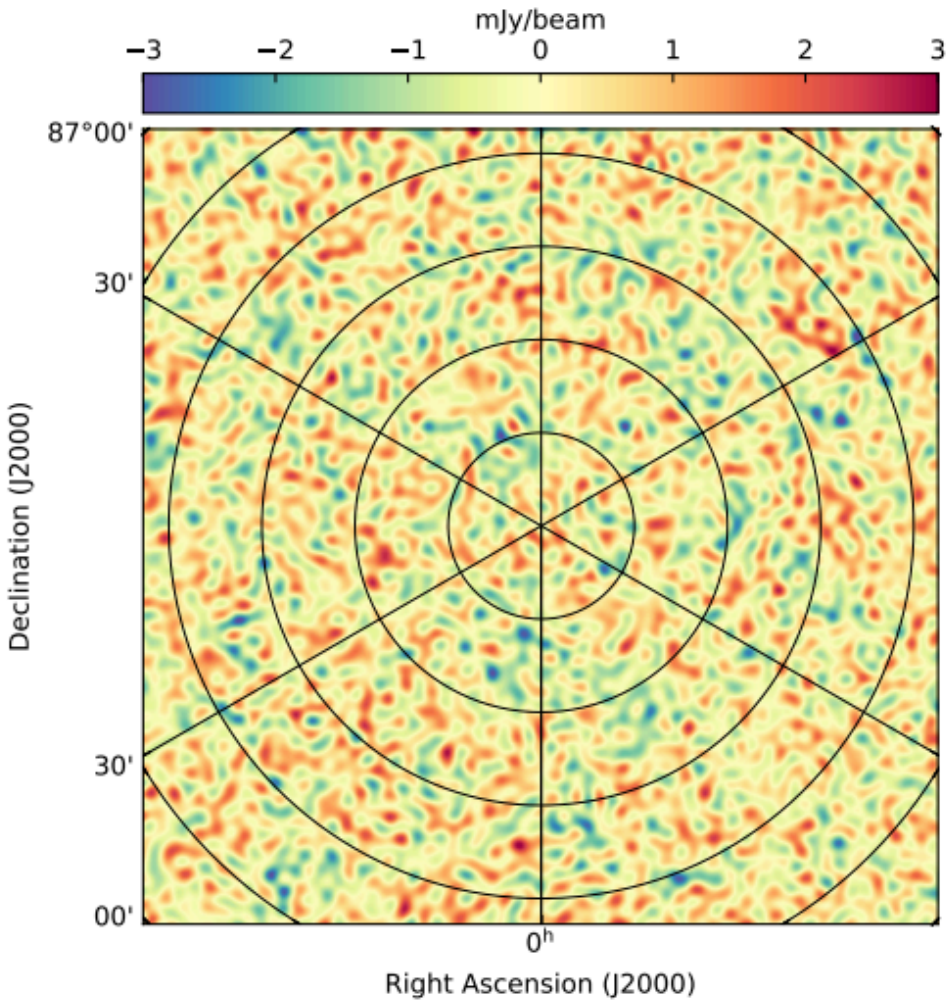
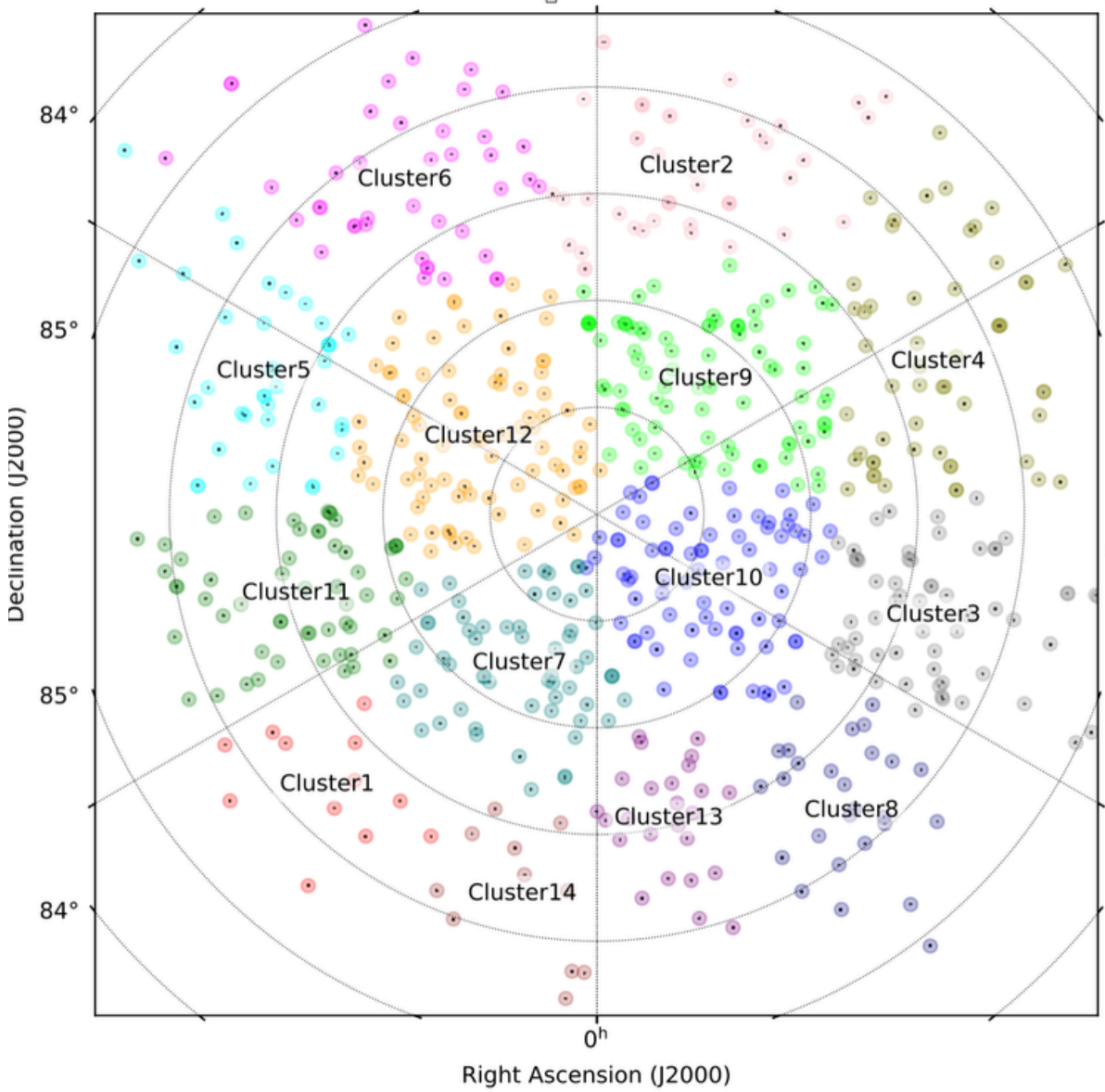


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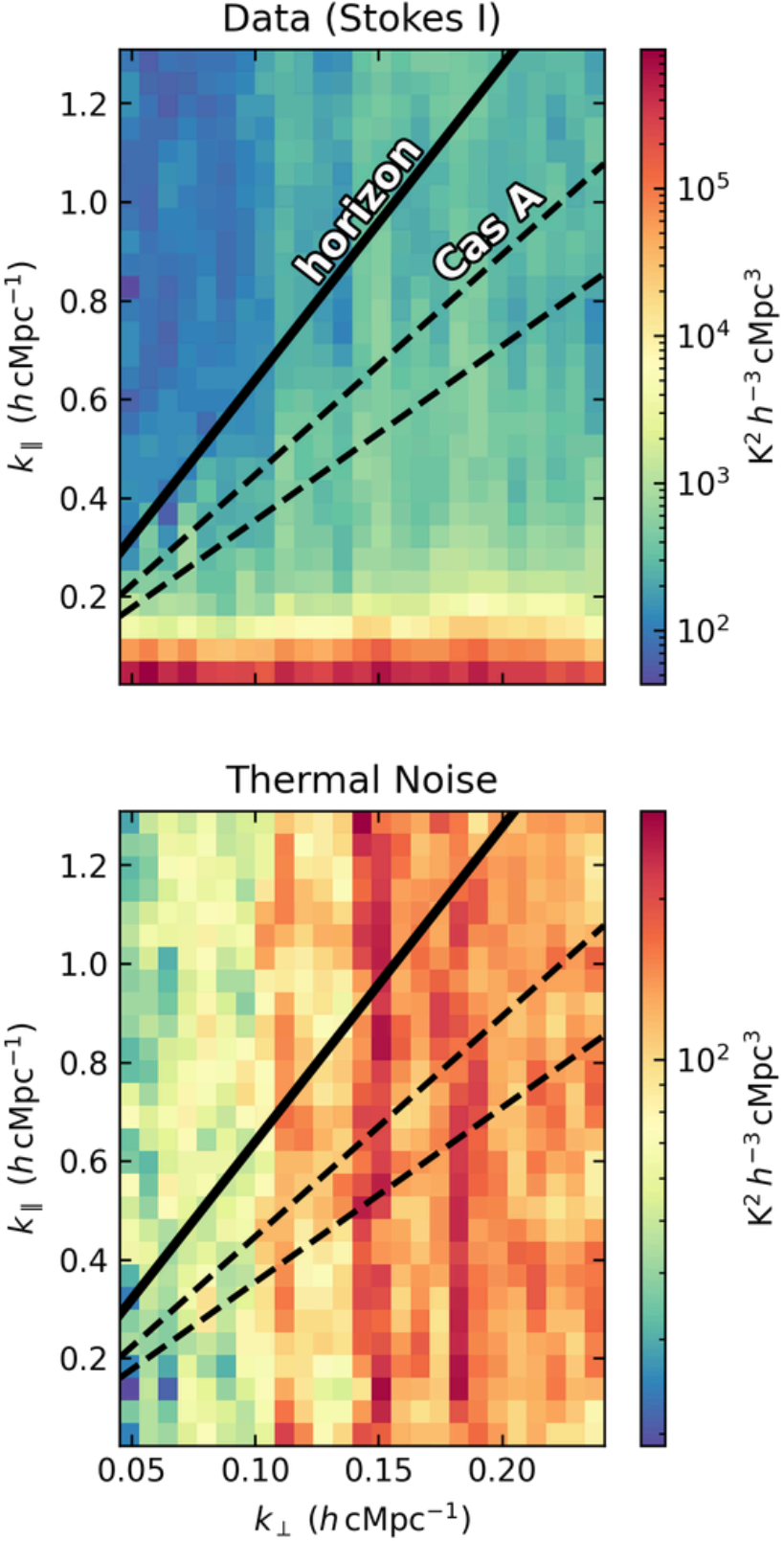
These solutions are **not** applied, but used to corrupt the data

FOREGROUND SUBTRACTION



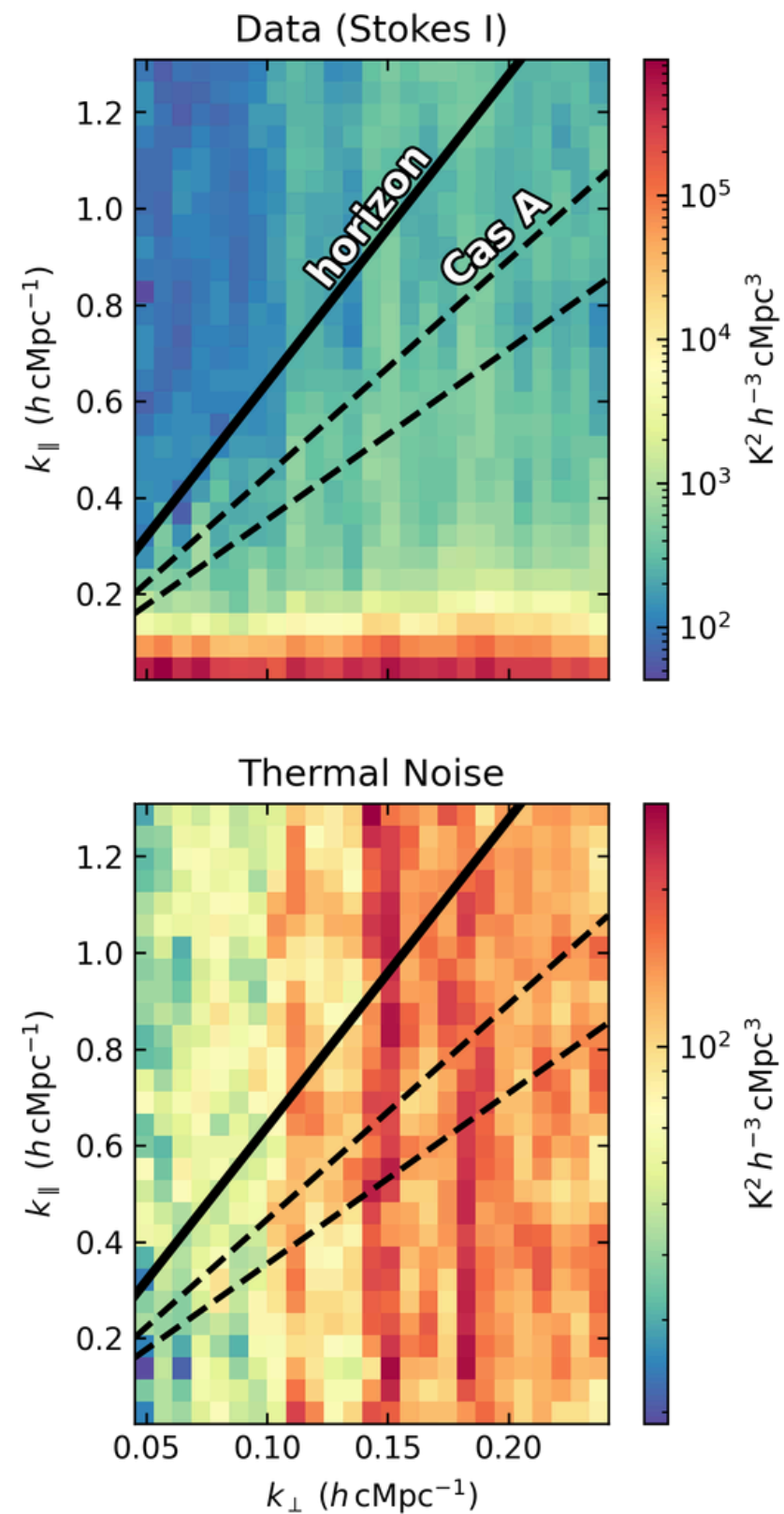
PS PIPELINE & GPR

INPUT DATA

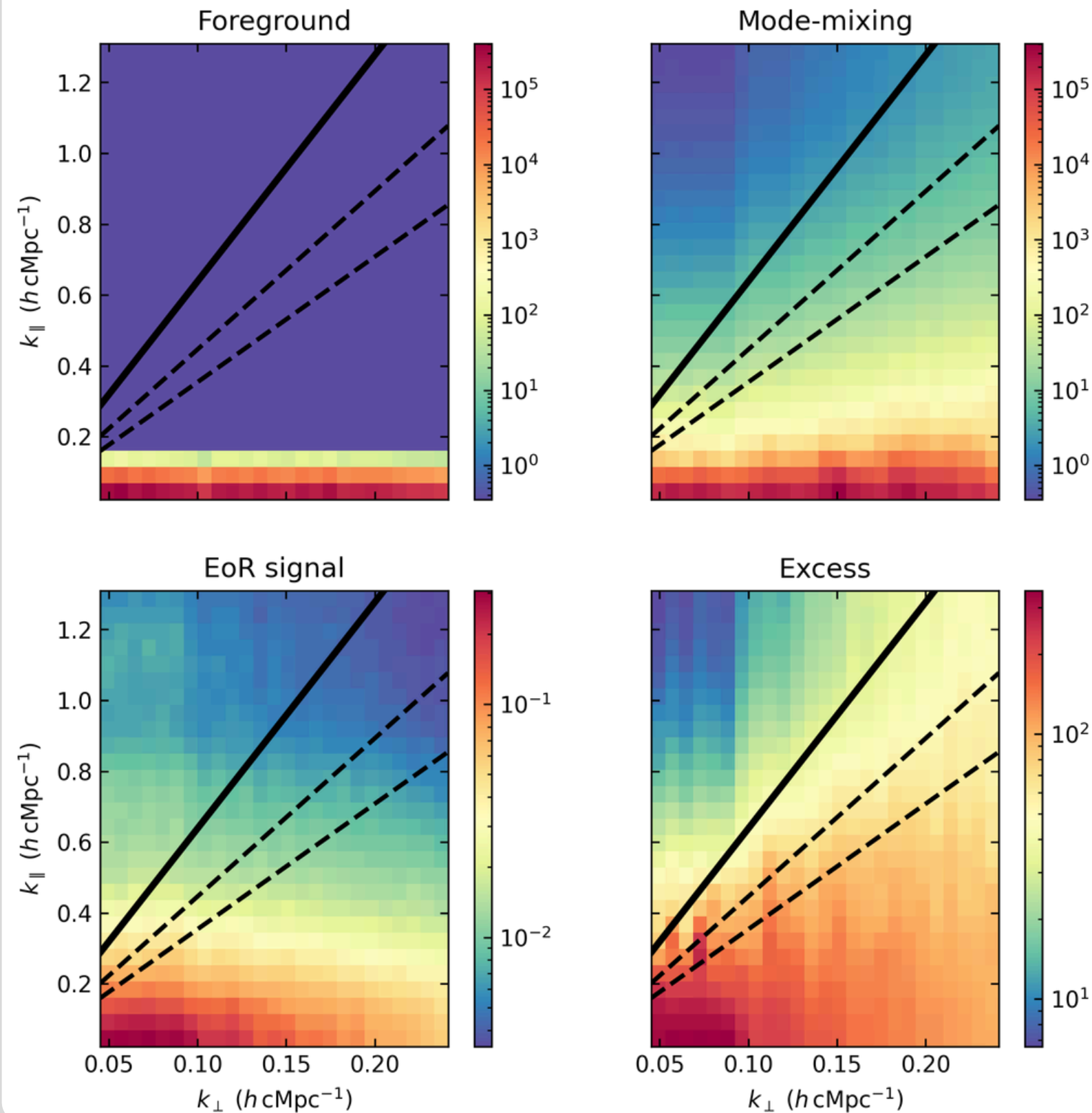


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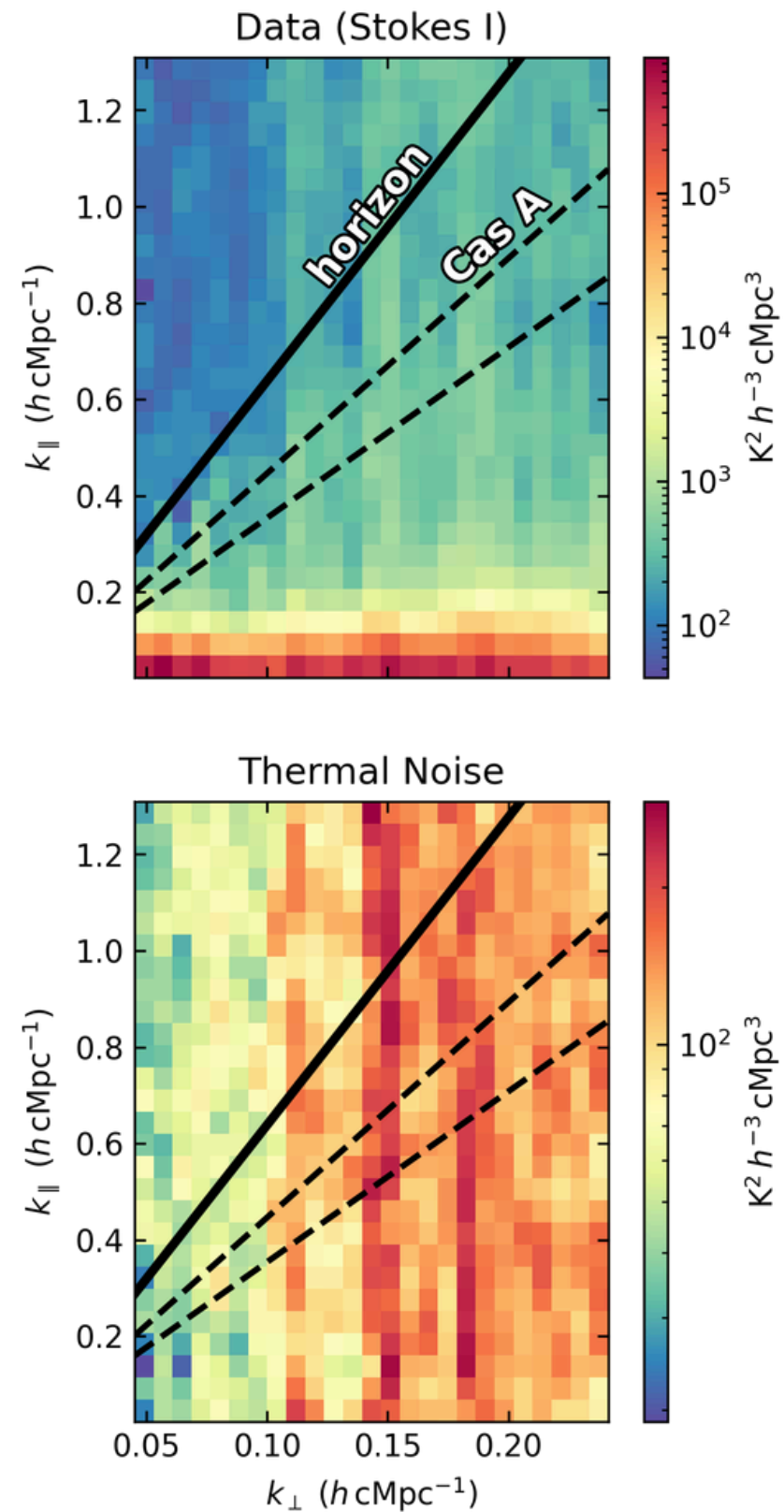
GAUSSIAN PROCESS REGRESSION



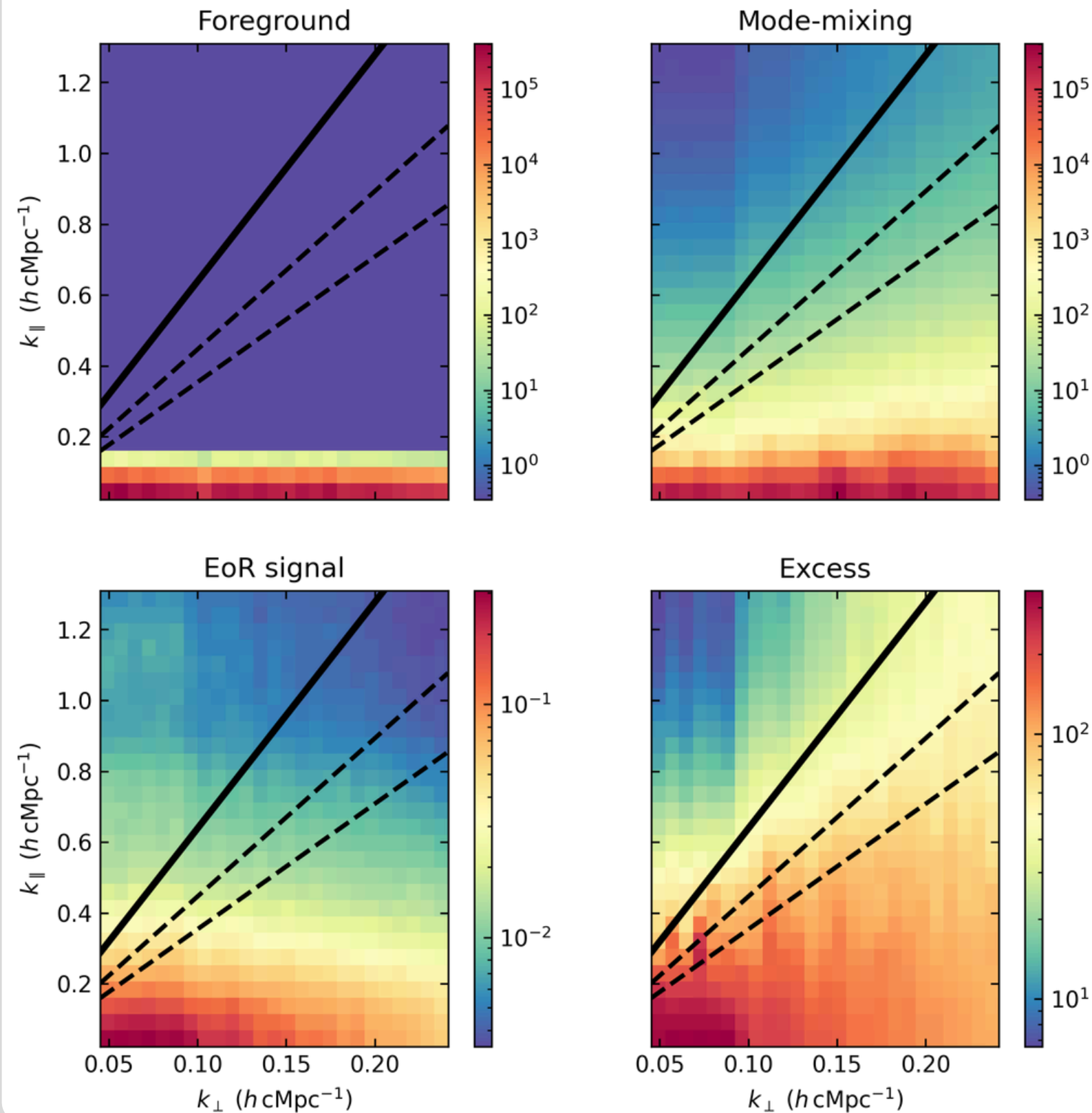
Matern covariance functions described by parameters that are optimised by maximising their posterior probability

PS PIPELINE & GPR

INPUT DATA



GAUSSIAN PROCESS REGRESSION

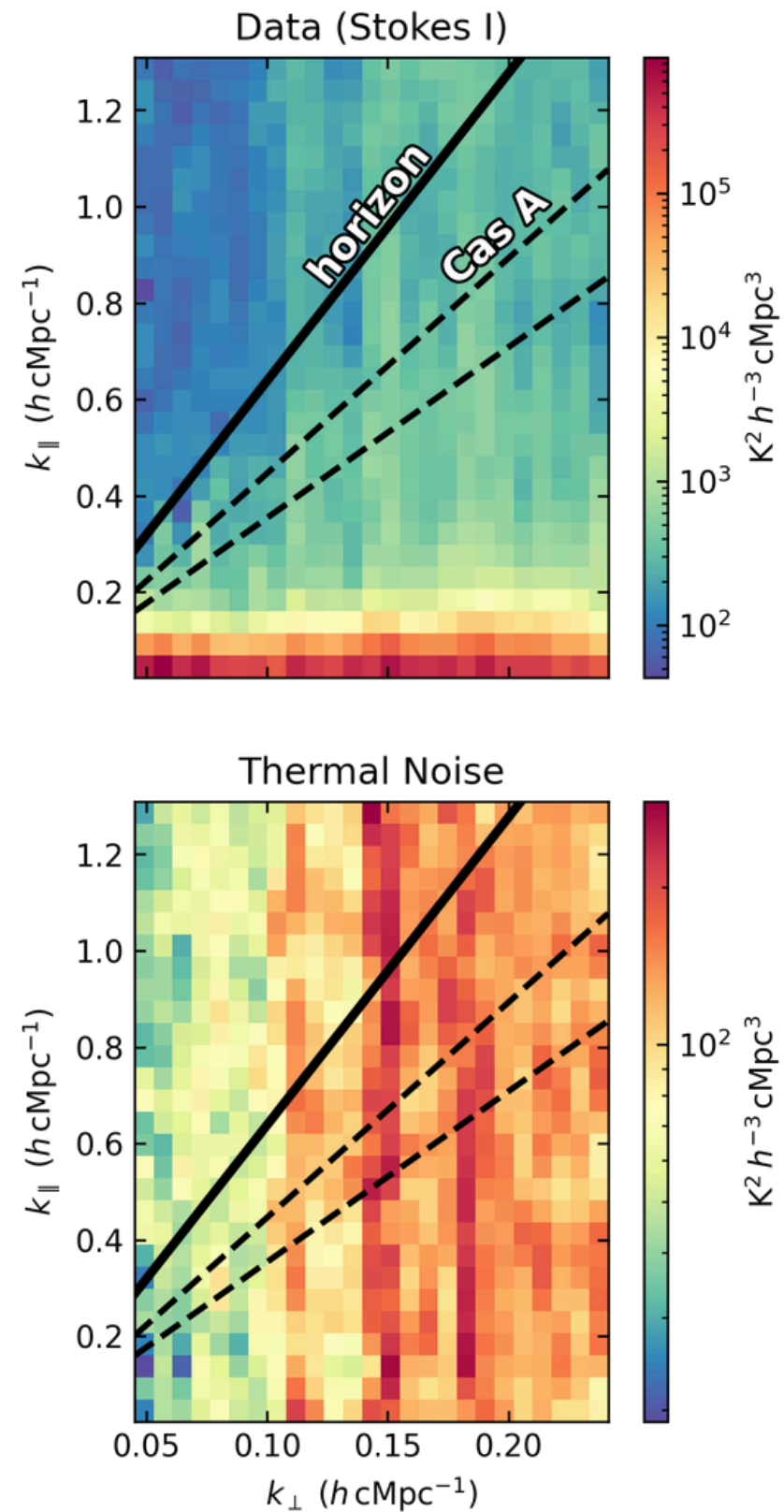


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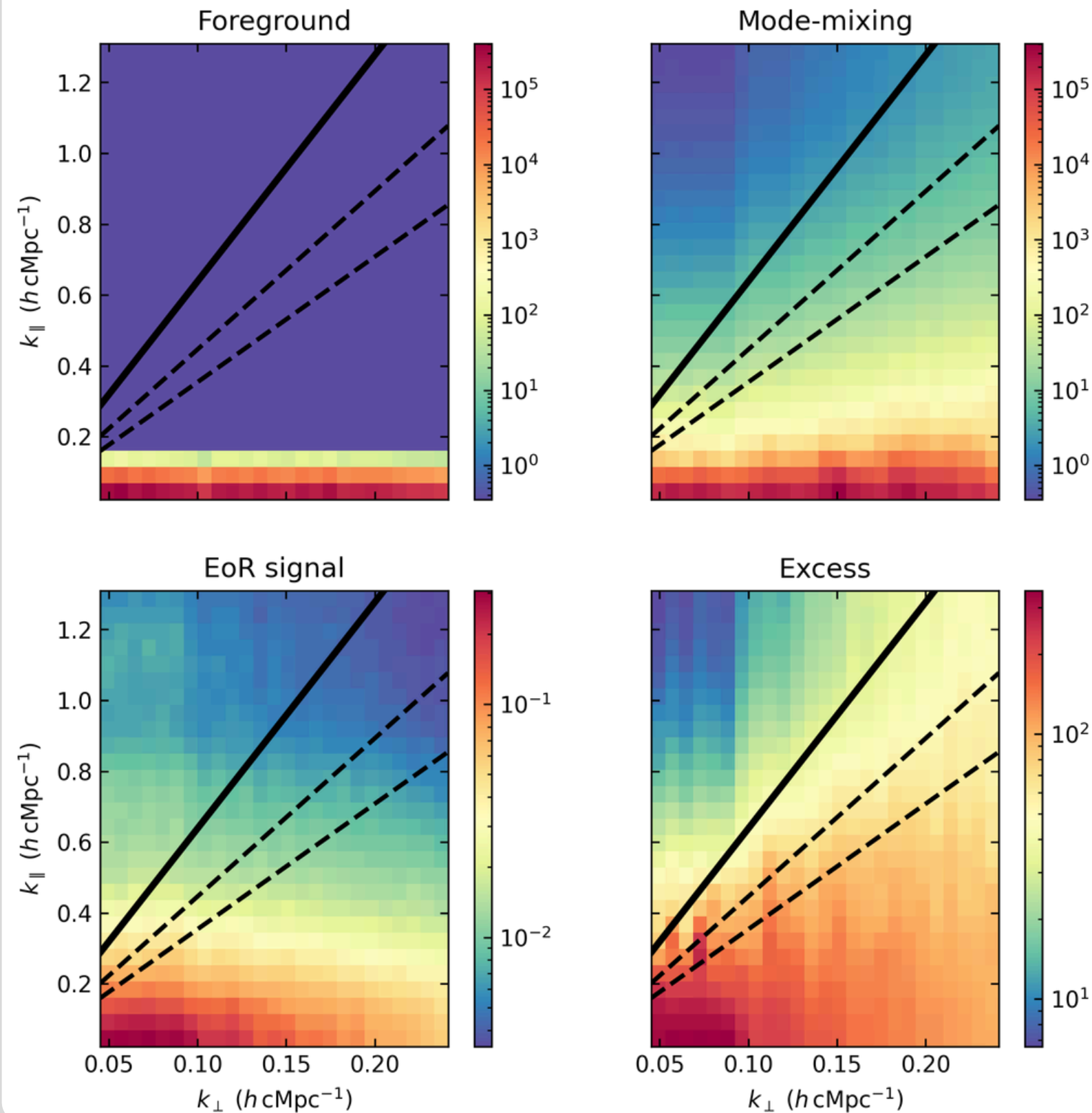
**DATA –
FOREGROUNDS =
RESIDUALS**

PS PIPELINE & GPR

INPUT DATA



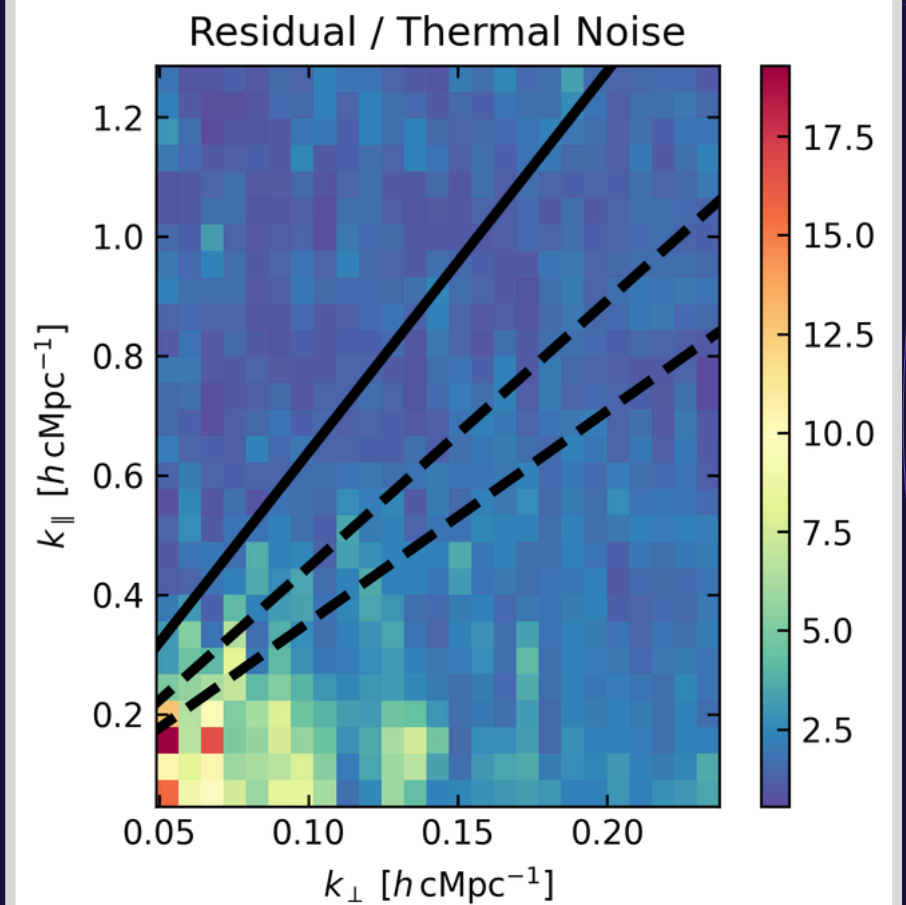
GAUSSIAN PROCESS REGRESSION



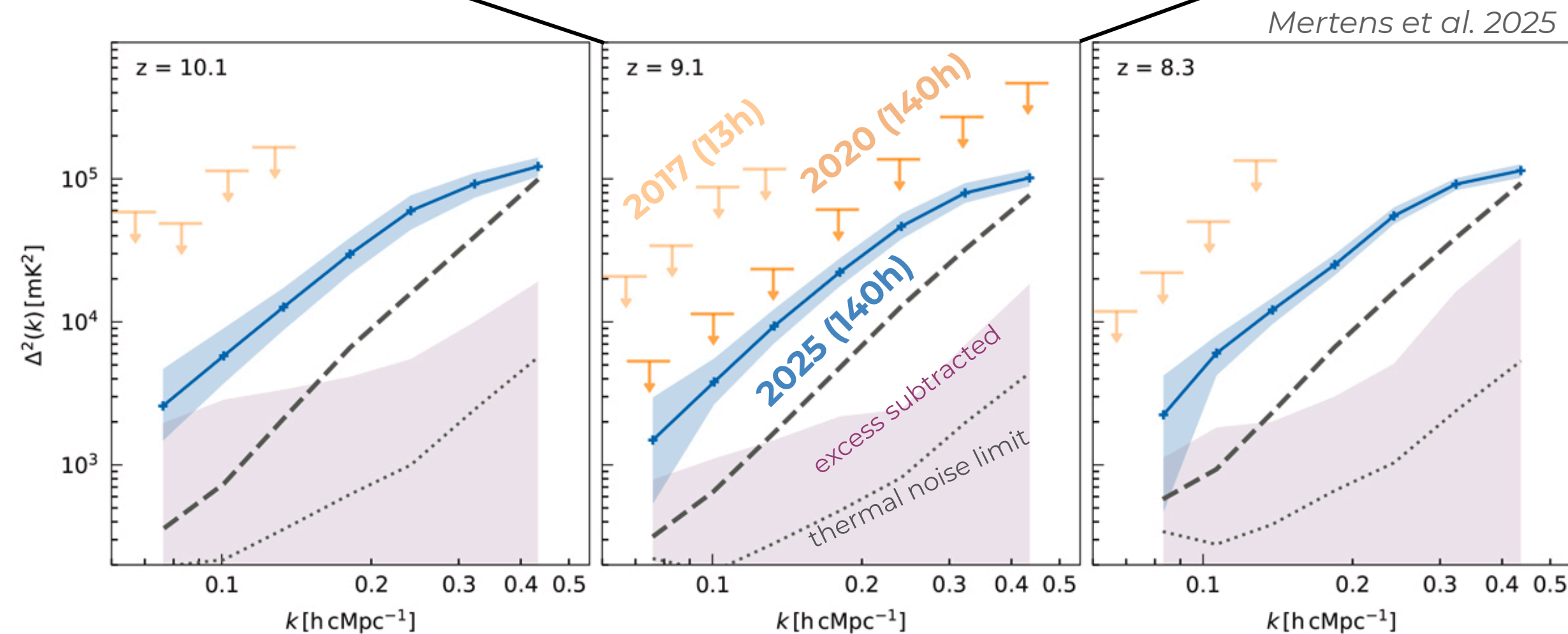
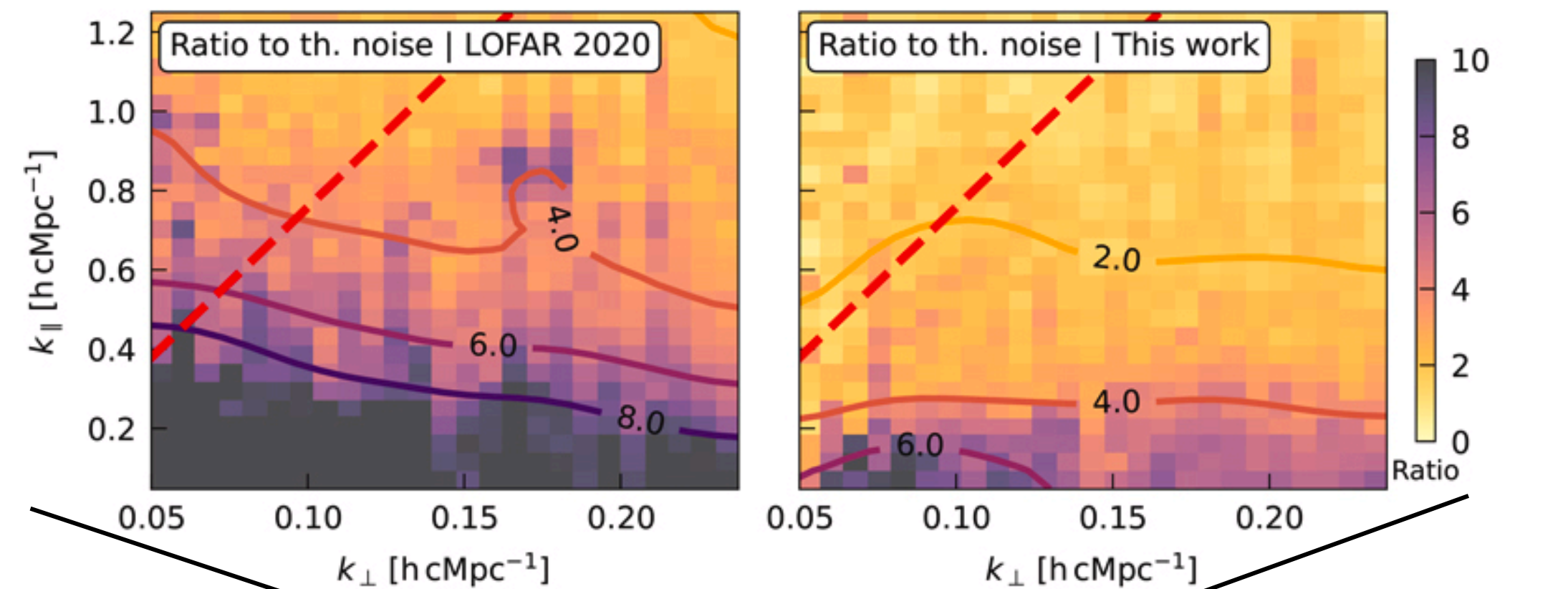
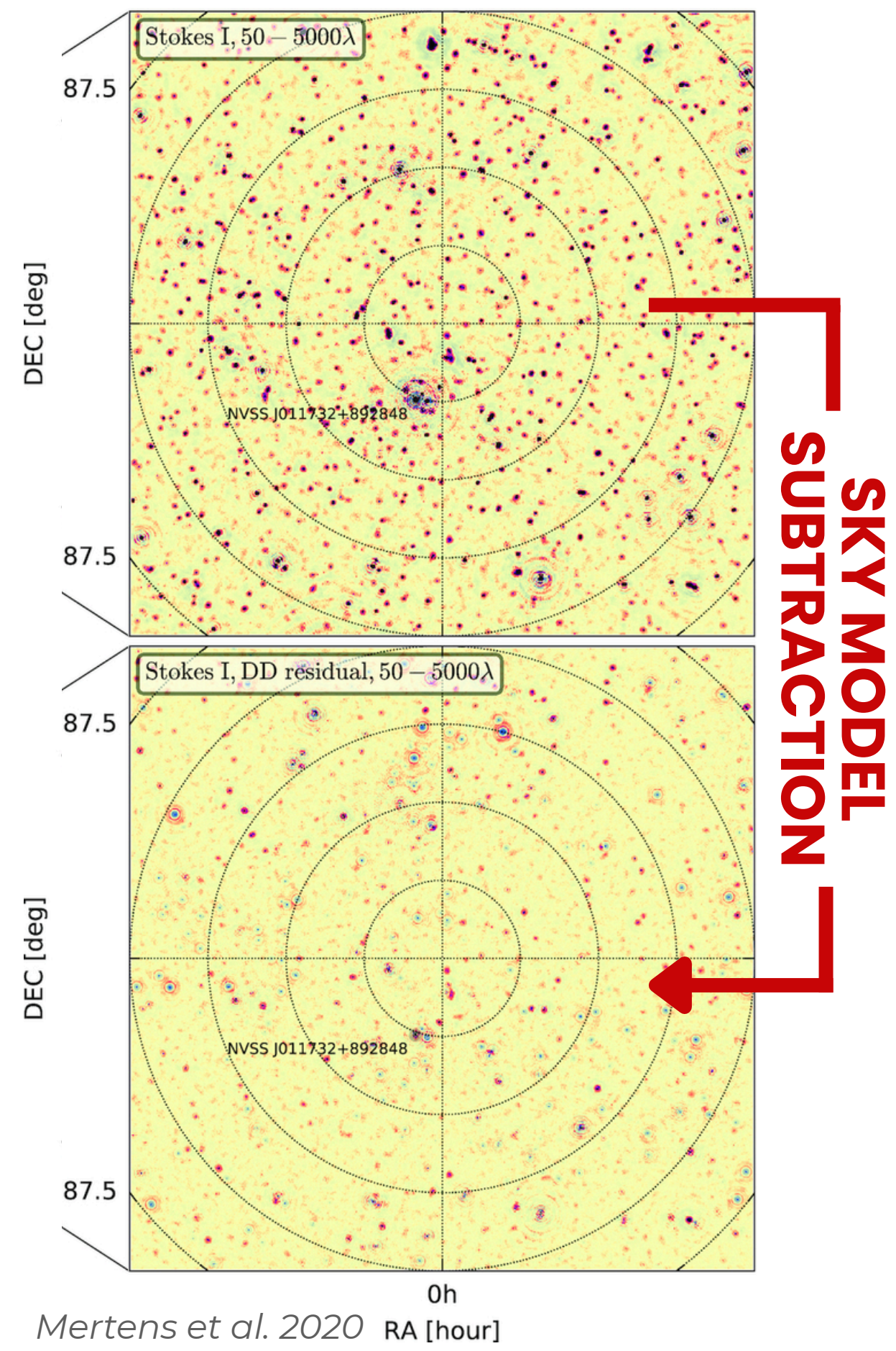
Matern covariance functions described by parameters that are optimised by maximising their posterior probability

DATA – FOREGROUNDS = RESIDUALS

RESULTS

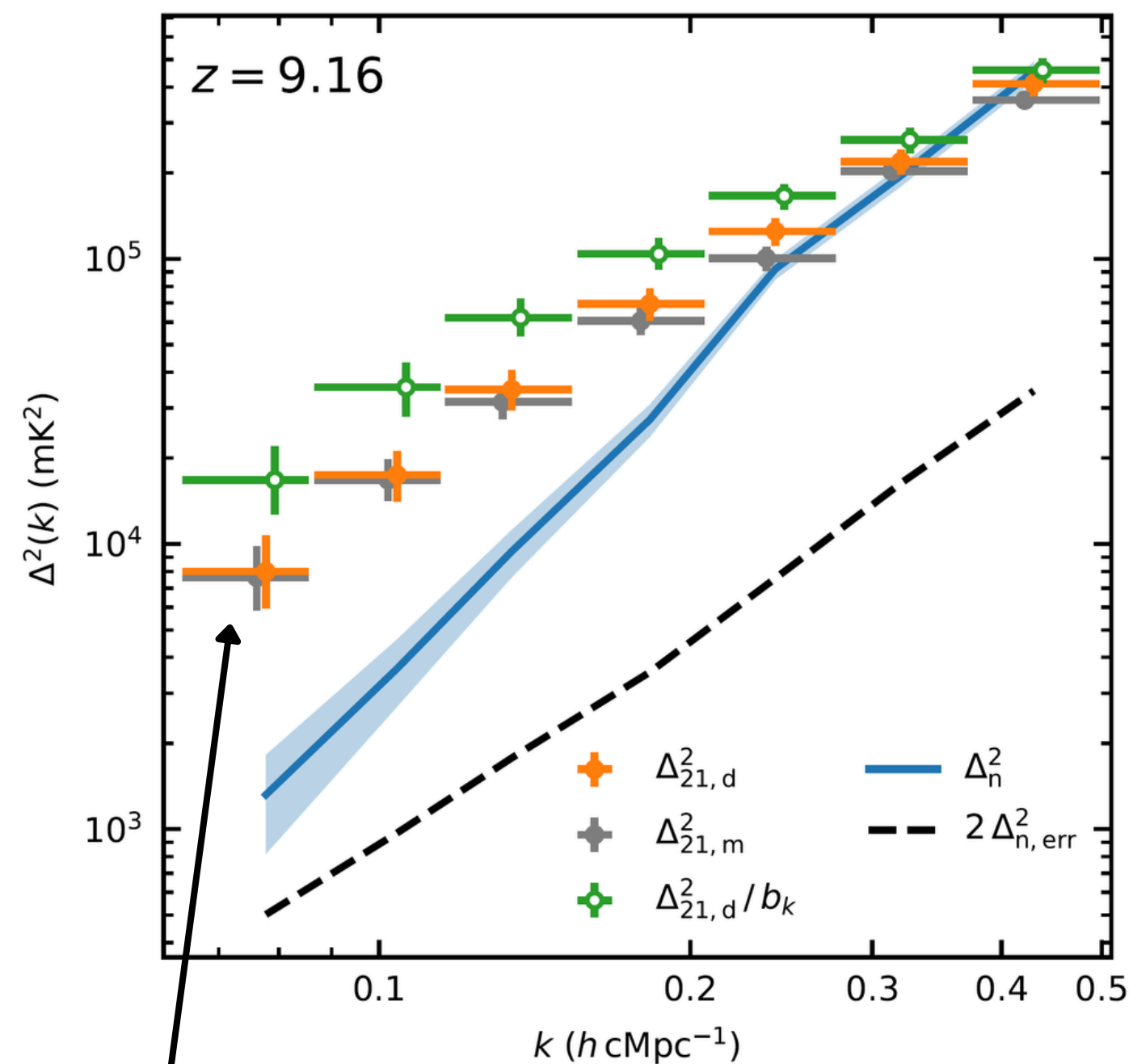


RESULTS FROM NCP FIELD

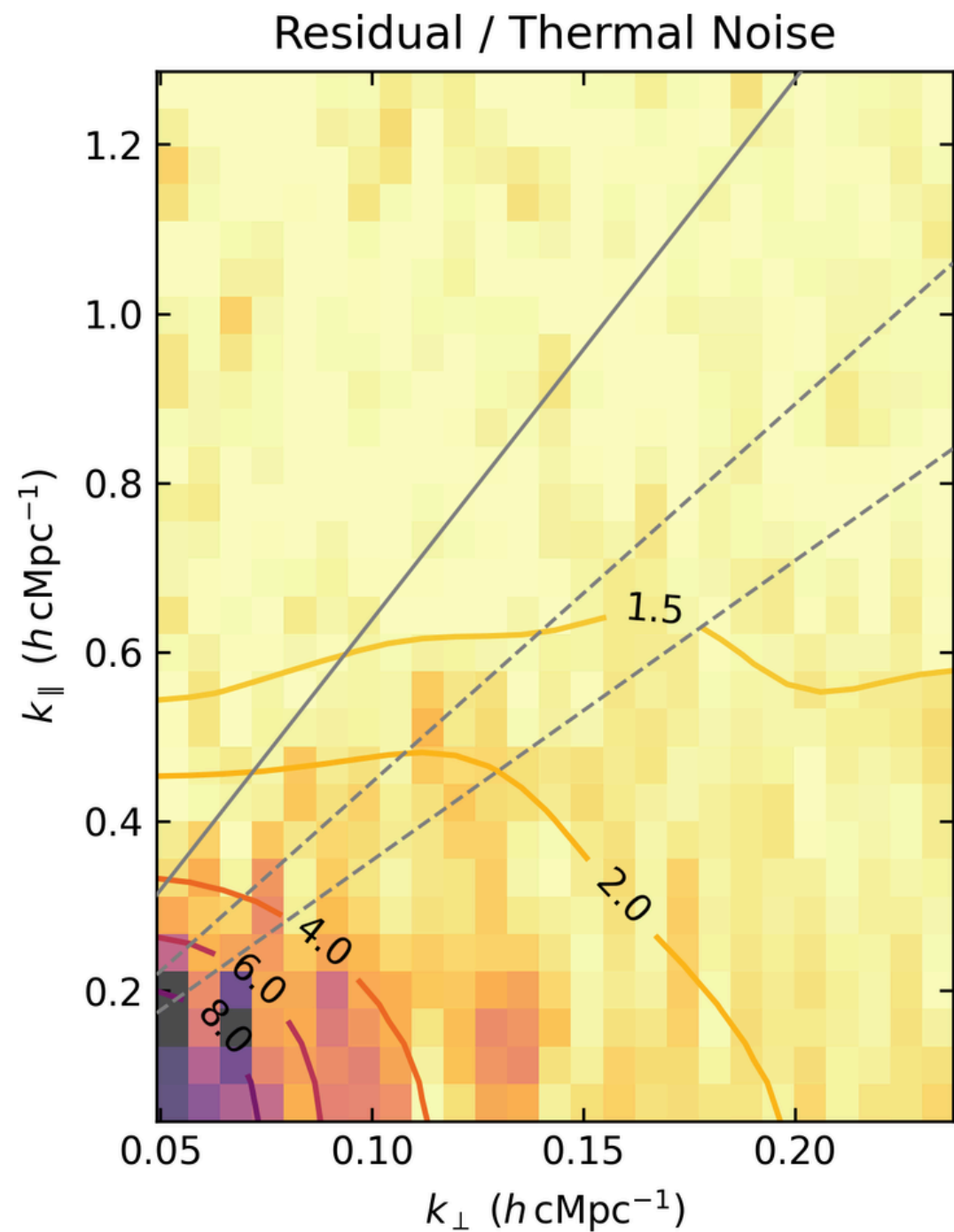


RESULTS FROM 3C196 FIELD

First upper limits from 1 night = 6h
(Ceccotti et al. 2025b)

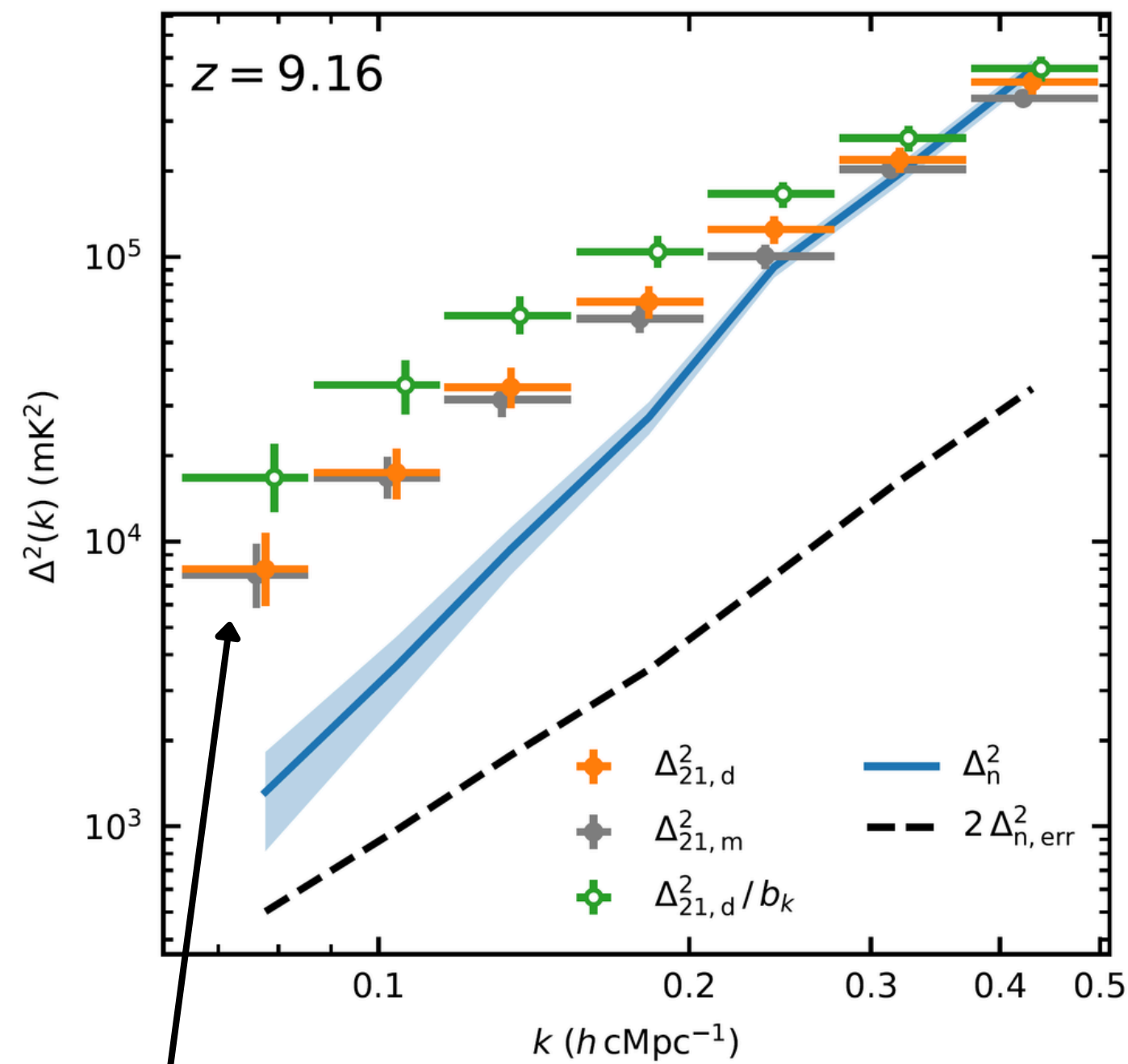


Possible **signal loss** during ML-GPR,
bias correction applied

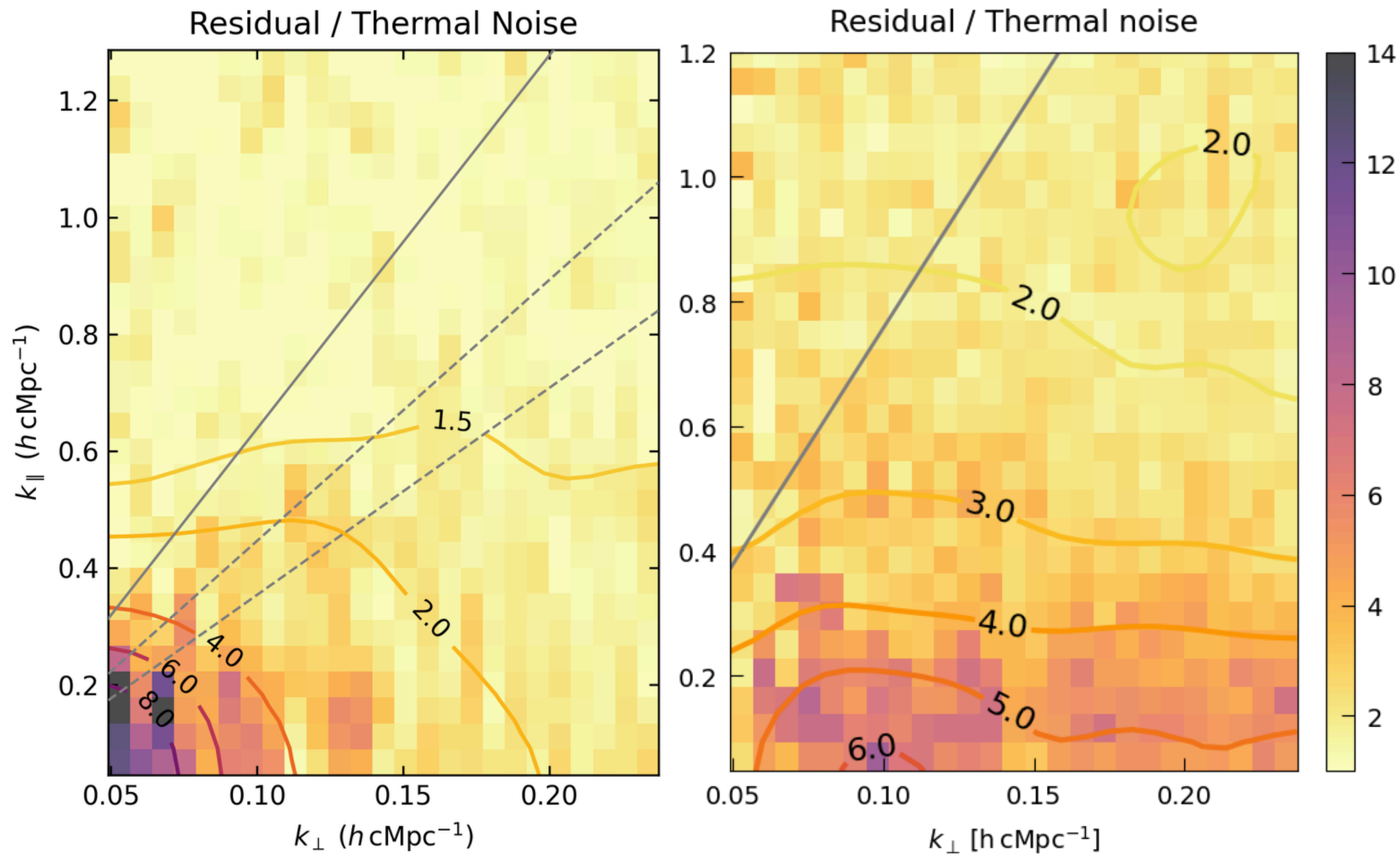


RESULTS FROM 3C196 FIELD

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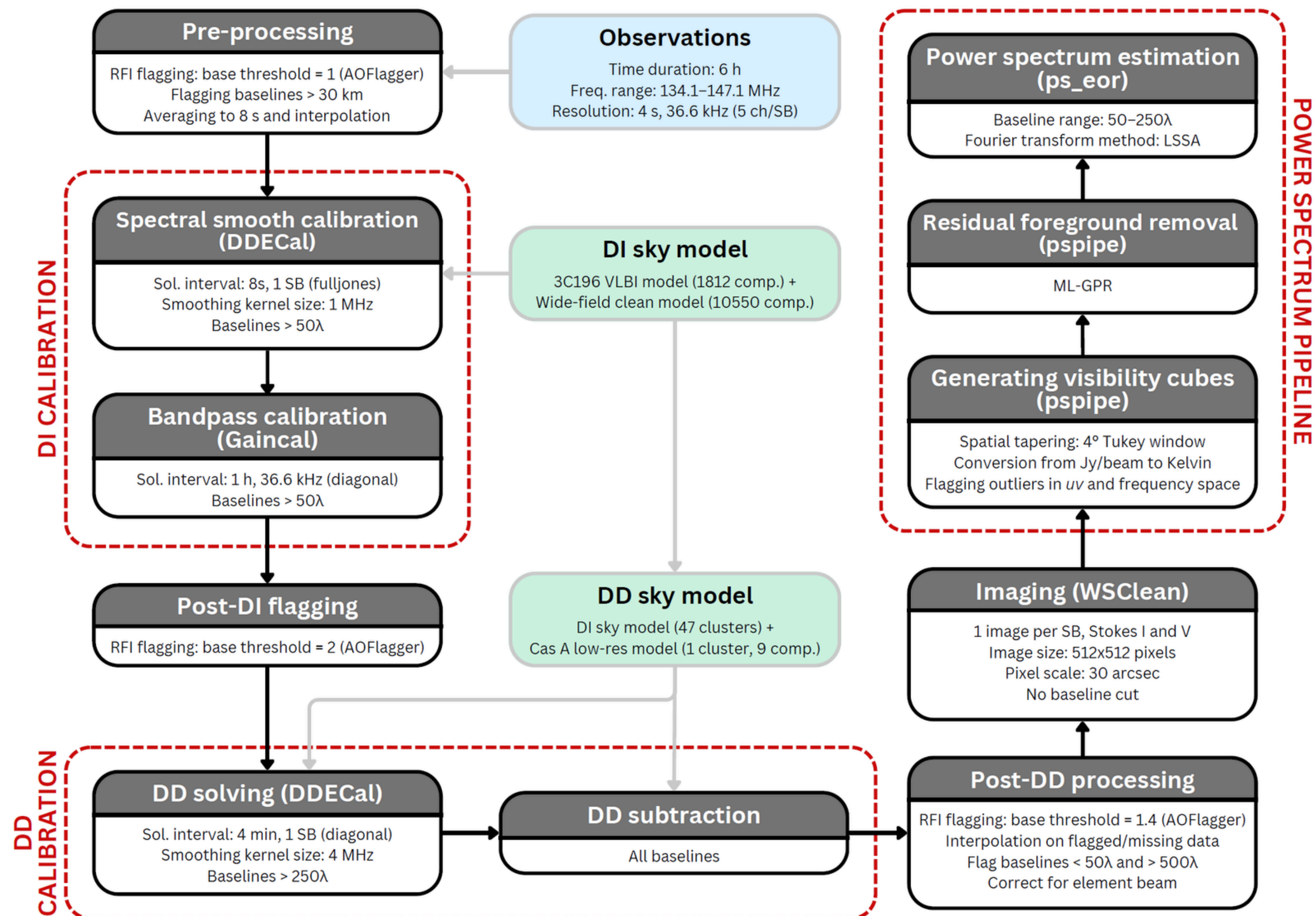


Comparison with NCP, 12
nights = 144h
(Mertens et al. 2025)

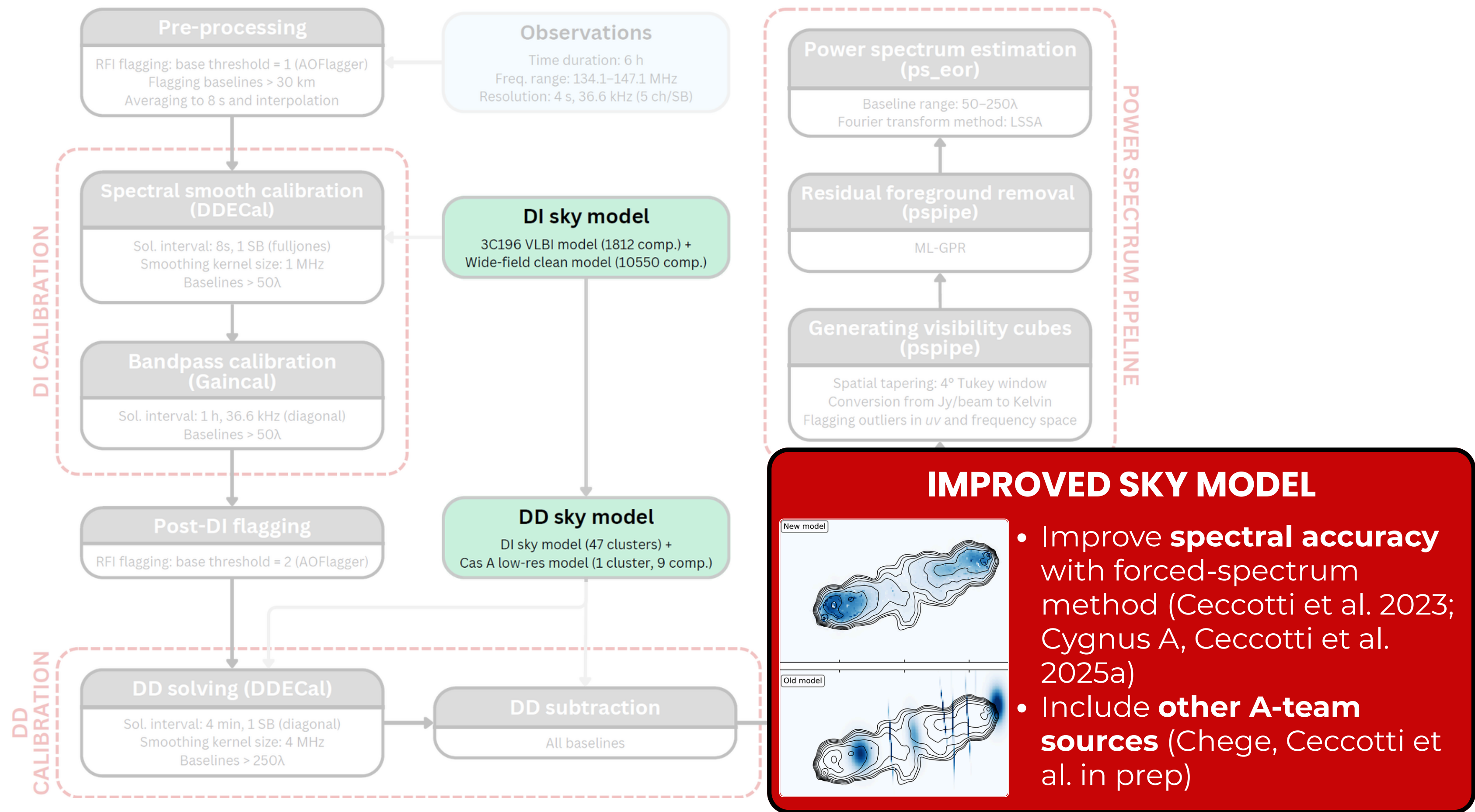


Residuals are **cleaner** than in the NCP field

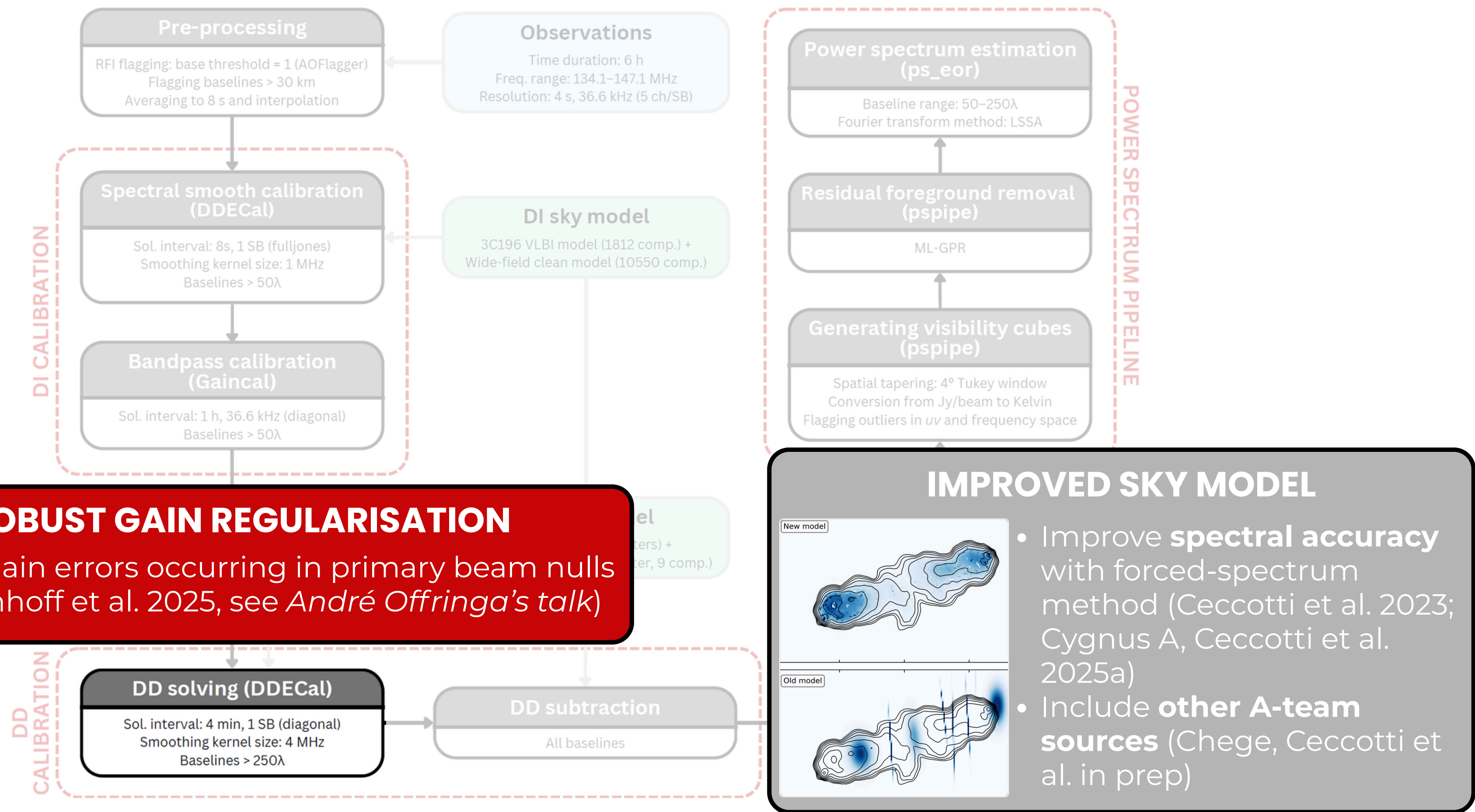
PIPELINE DEVELOPMENTS



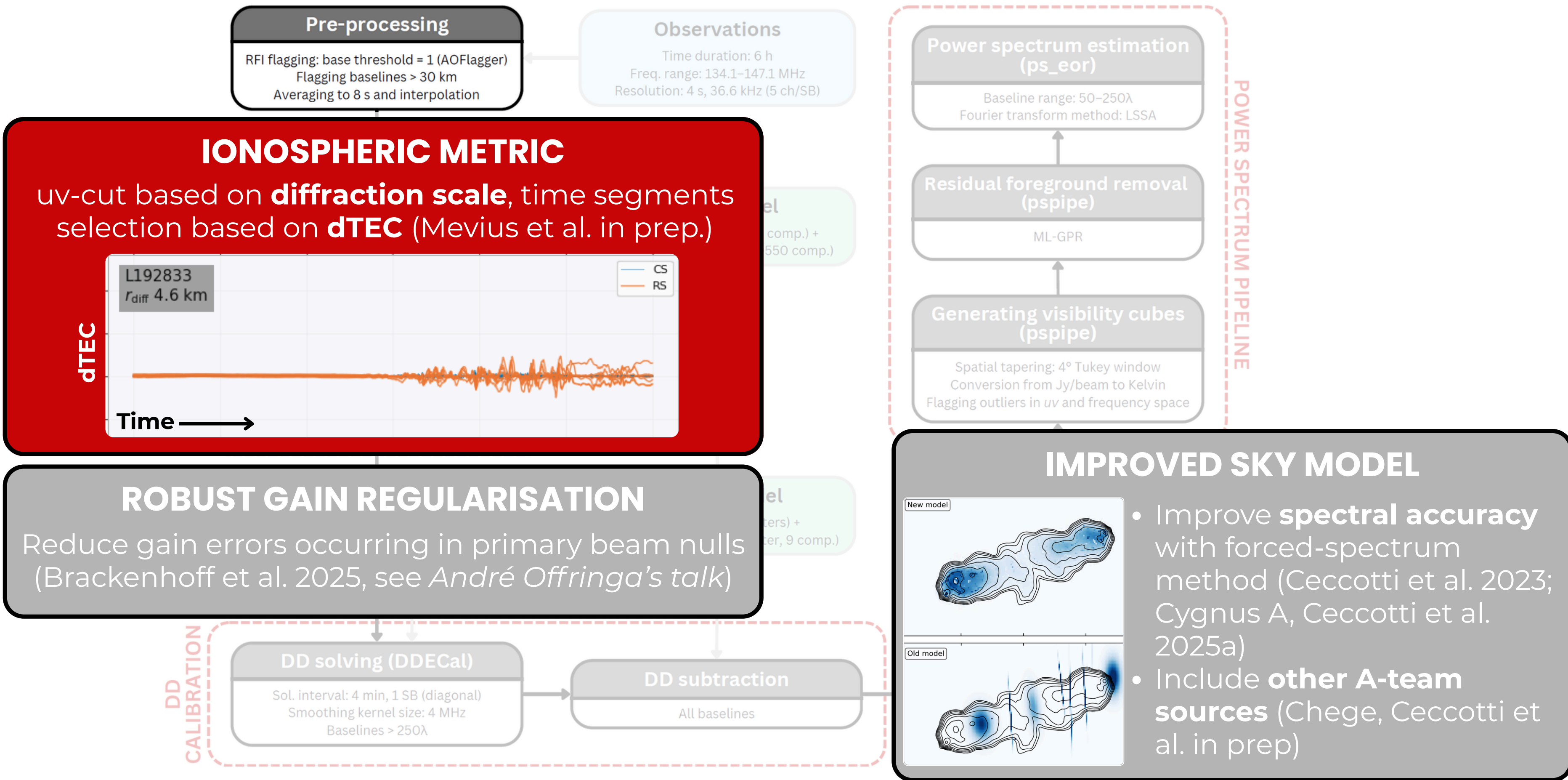
PIPELINE DEVELOPMENTS



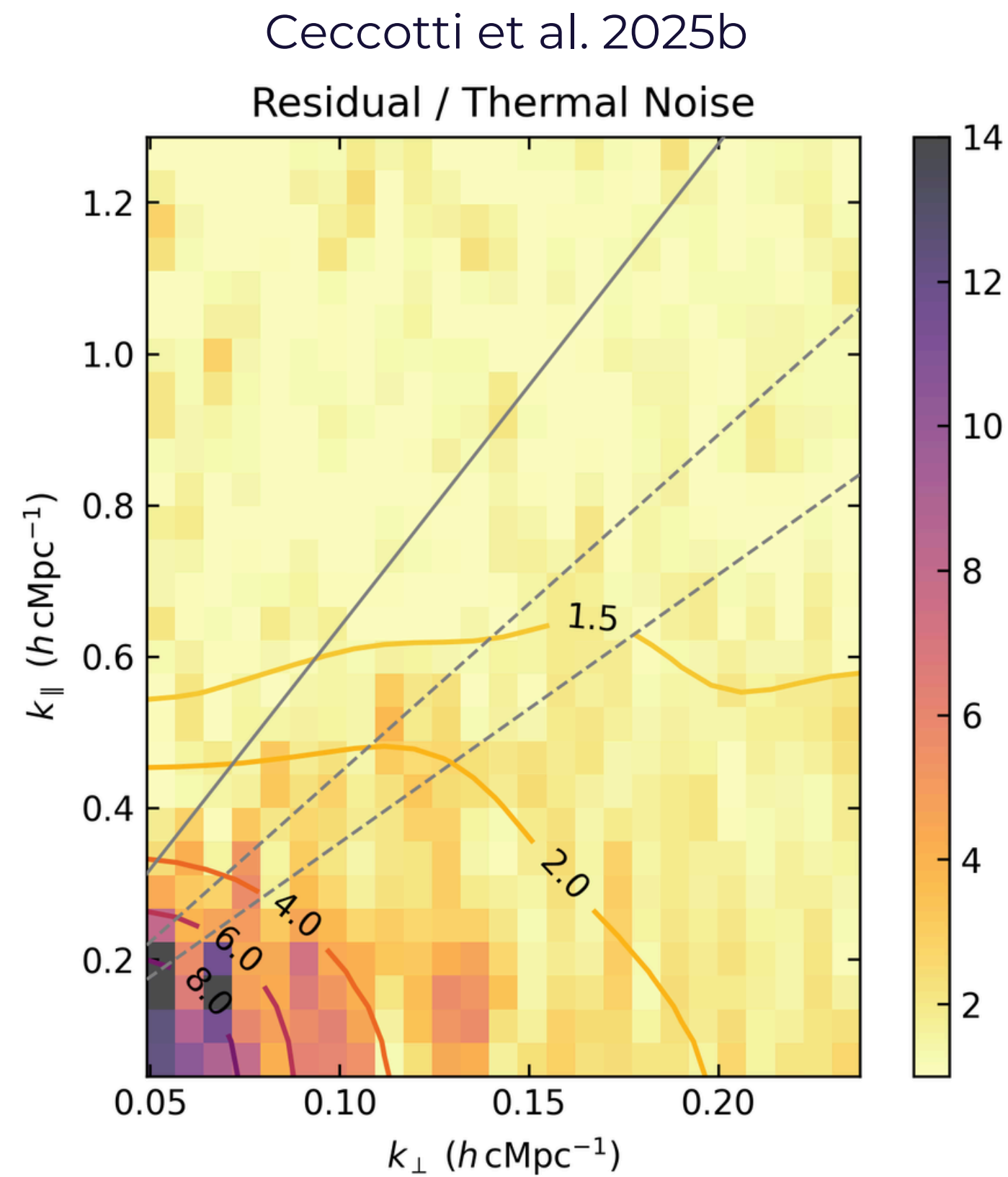
PIPELINE DEVELOPMENTS



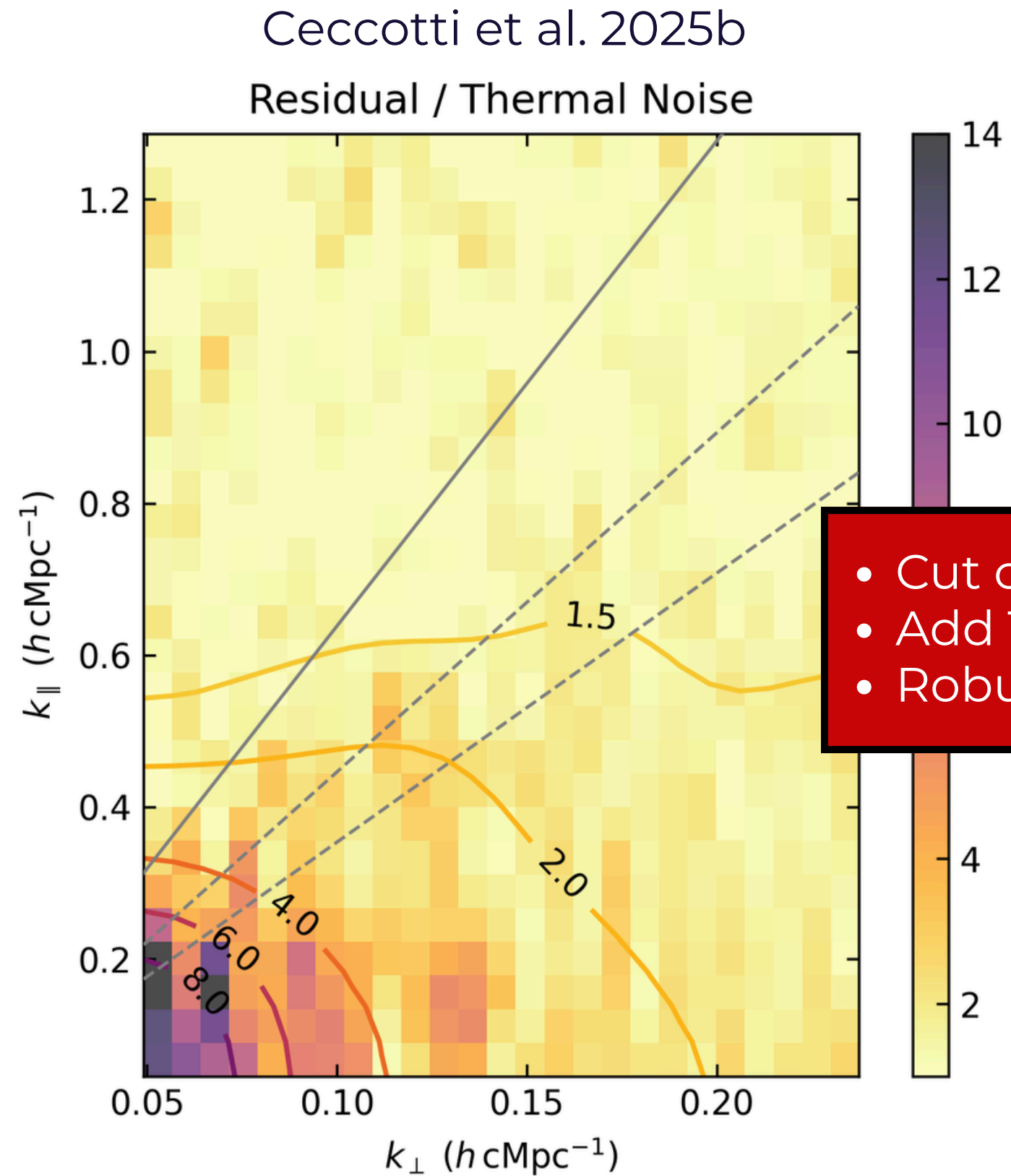
PIPELINE DEVELOPMENTS



PRELIMINARY RESULTS ON 1 NIGHT (3C196)



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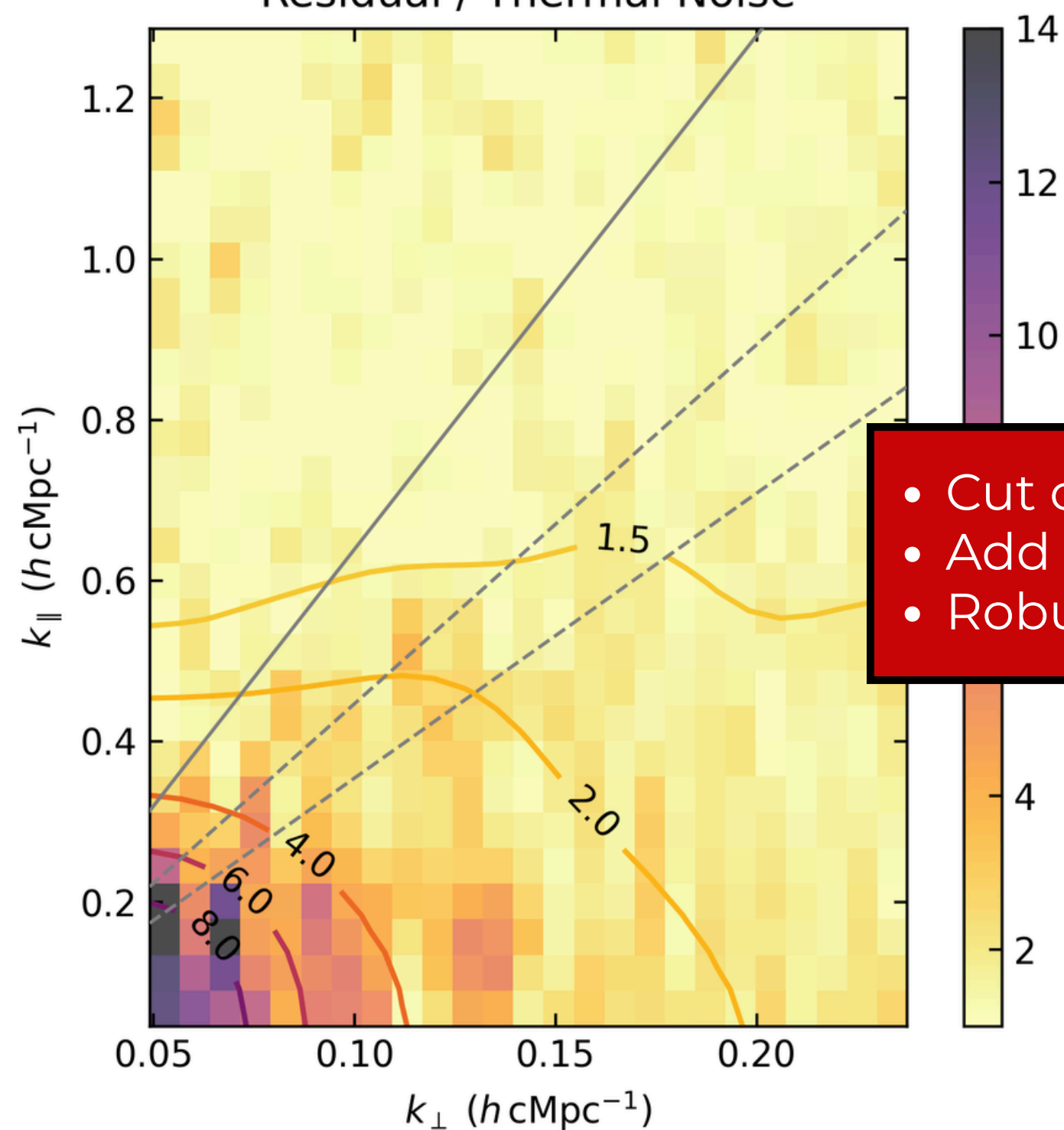


- Cut out last 1.5h (high dTEC)
- Add Taurus A in DD sky model
- Robust DD-gain regularisation

PRELIMINARY RESULTS ON 1 NIGHT (3C196)

Ceccotti et al. 2025b

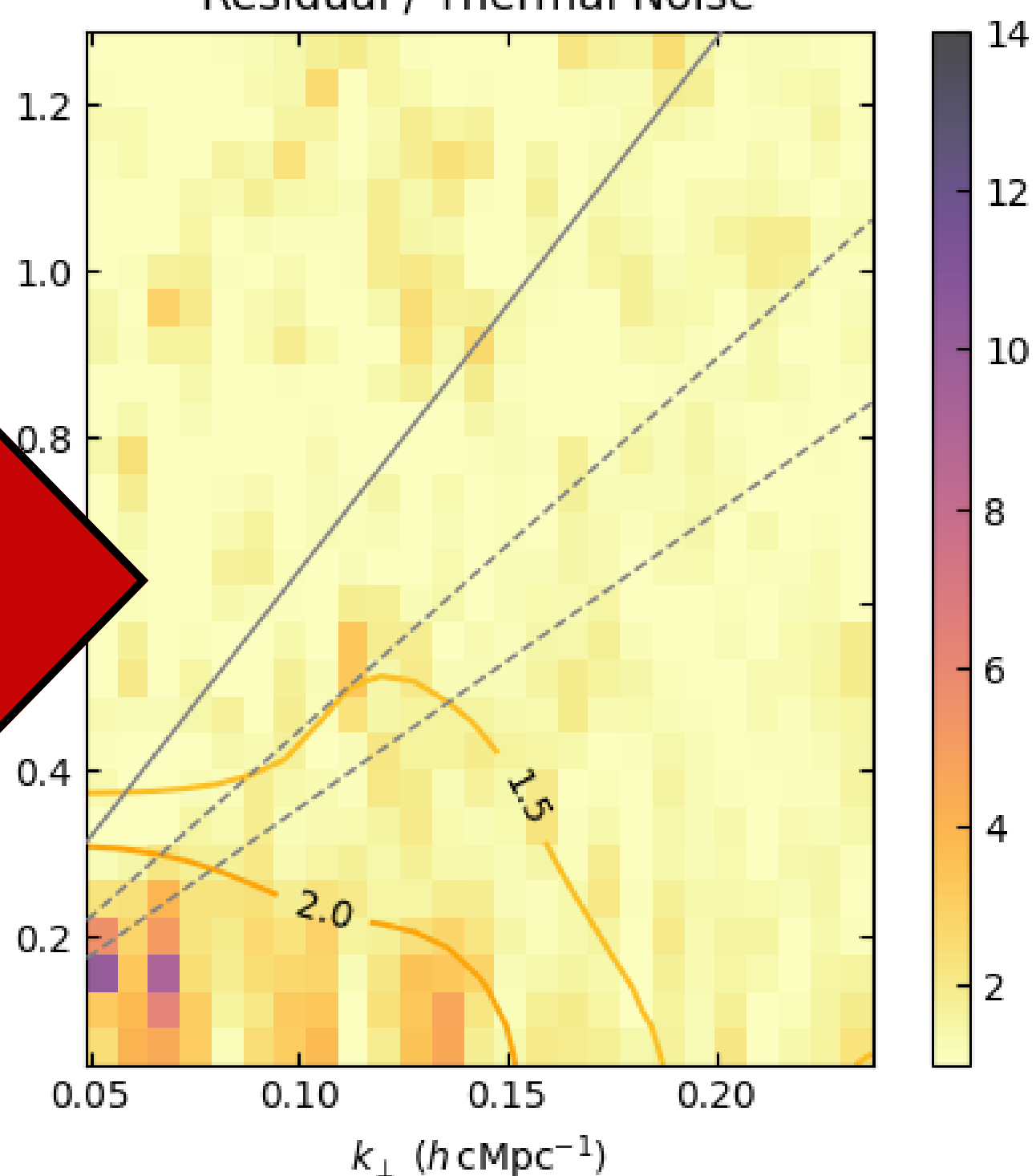
Residual / Thermal Noise



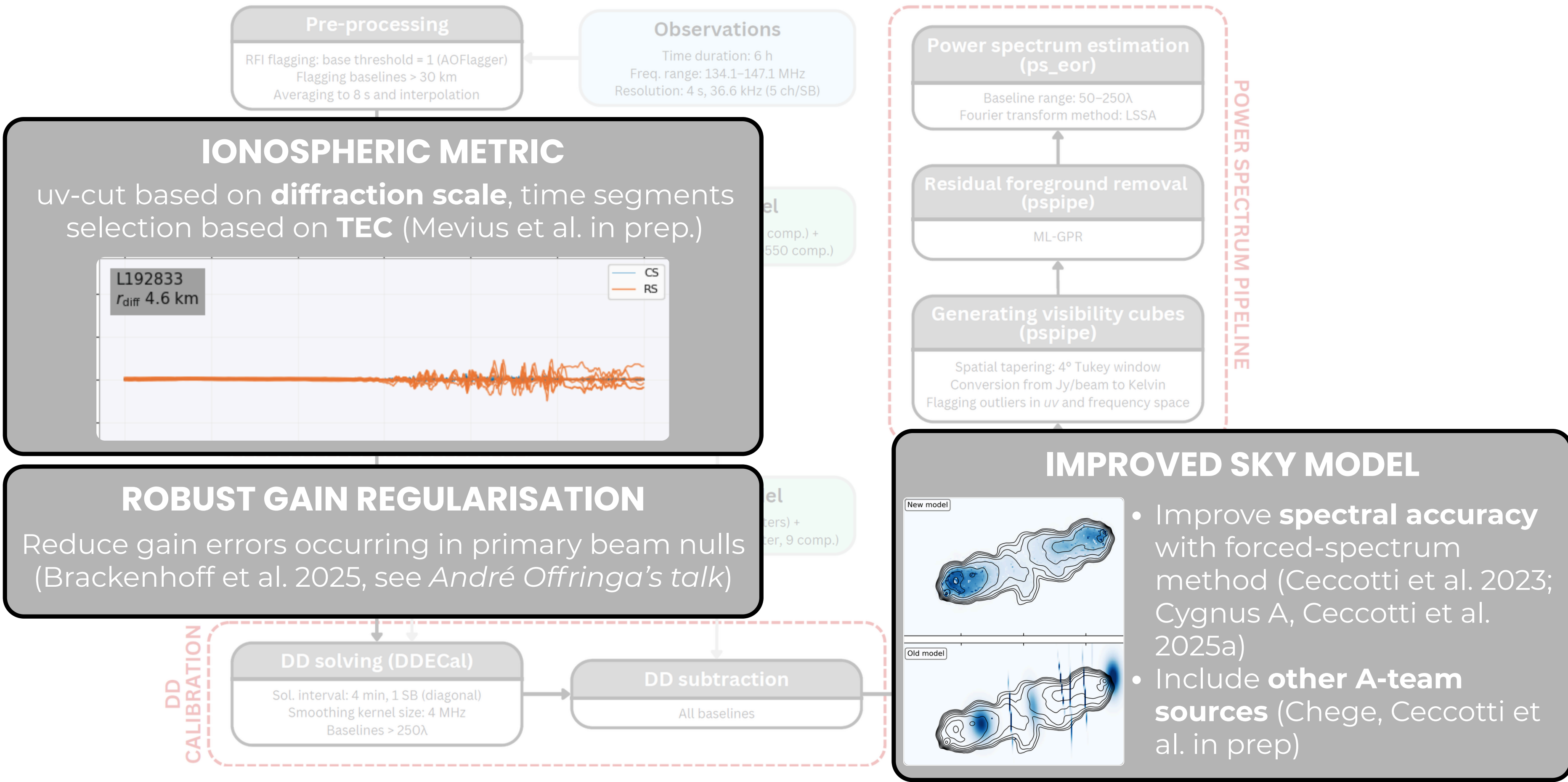
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Chege, Ceccotti et al. in prep.

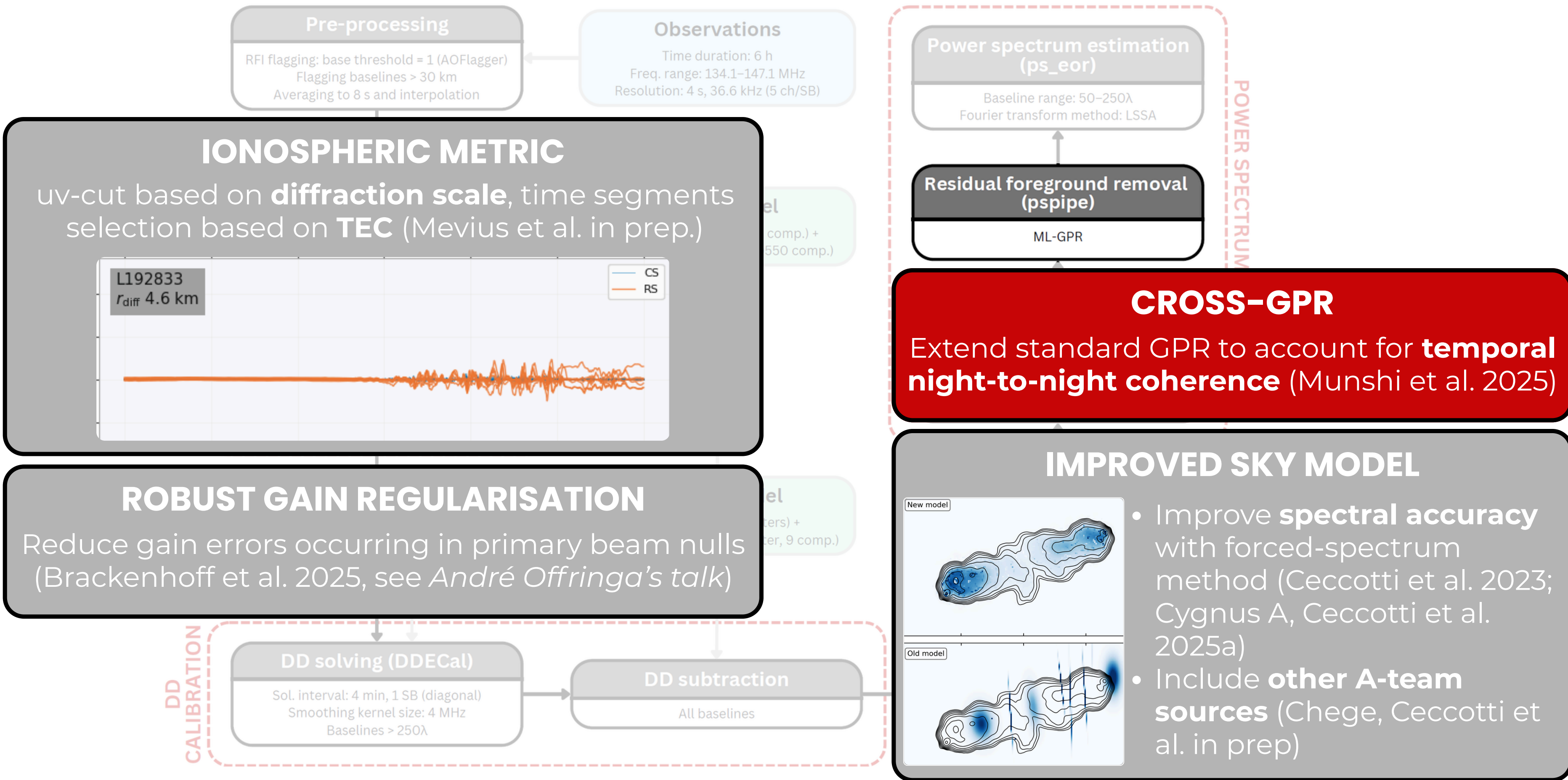
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PIPELINE DEVELOPMENTS



PIPELINE DEVELOPMENTS

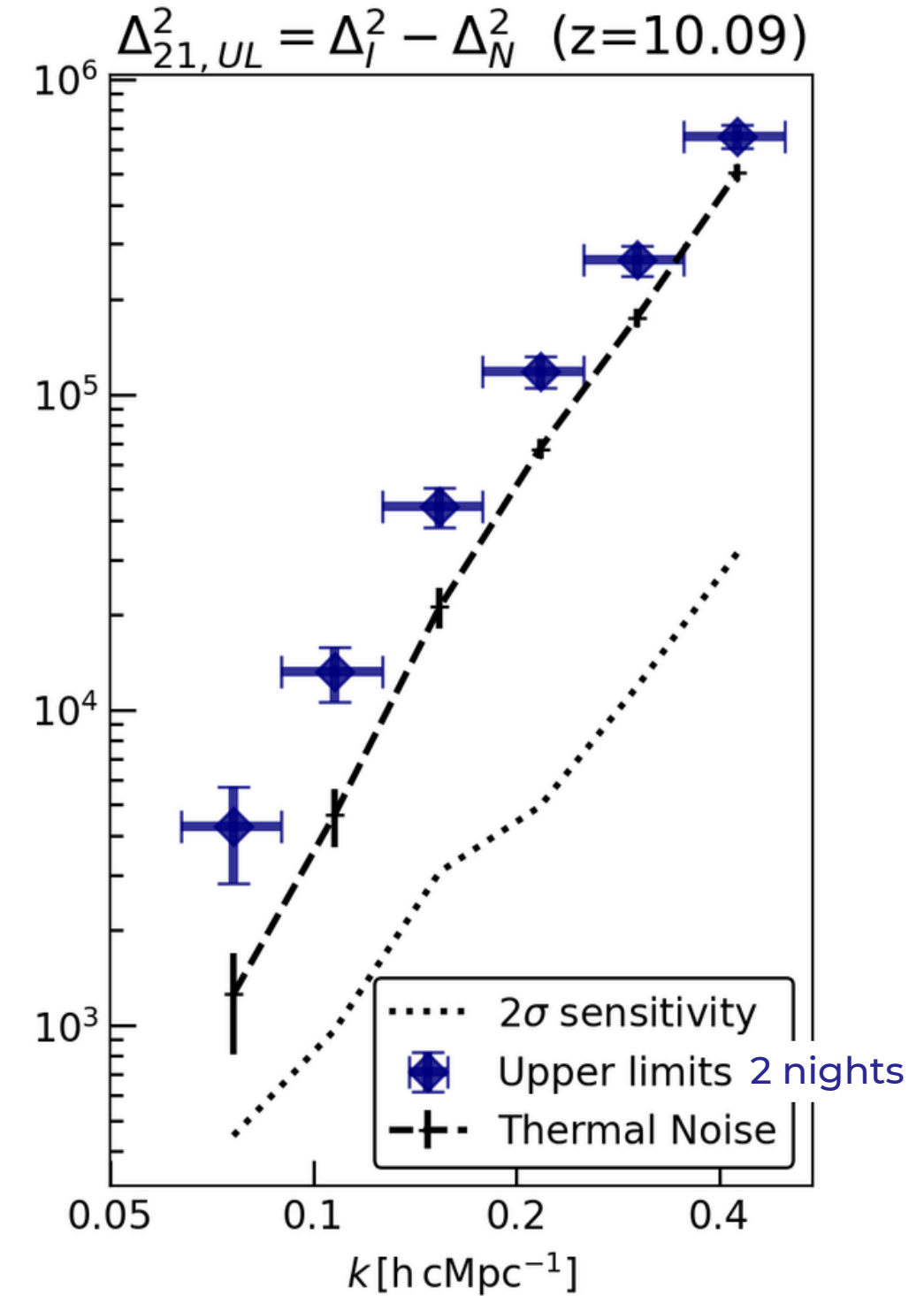
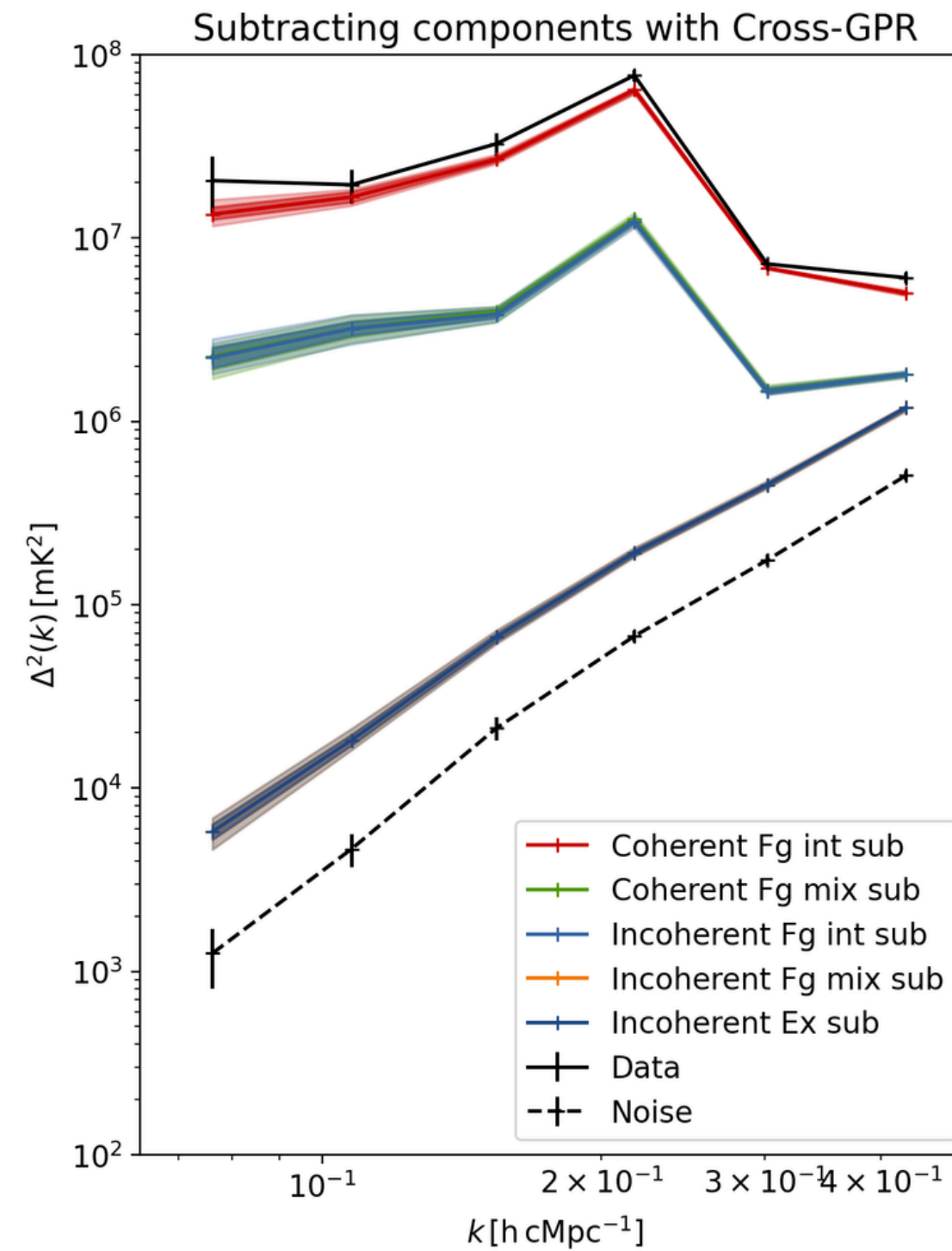


PRELIMINARY RESULTS WITH CROSS-GPR (3C196)

HOW DOES CROSS-GPR WORKS?

- The cross-GPR model captures the **cross-covariance between pairs of datasets**: it captures the (in)coherence of specific components across multiple datasets
- **Break degeneracy** when excess and 21-cm signal have similar spectral behavior
- The **incoherent excess can be subtracted from residual data**, resulting in lower upper limits

Munshi et al. 2025

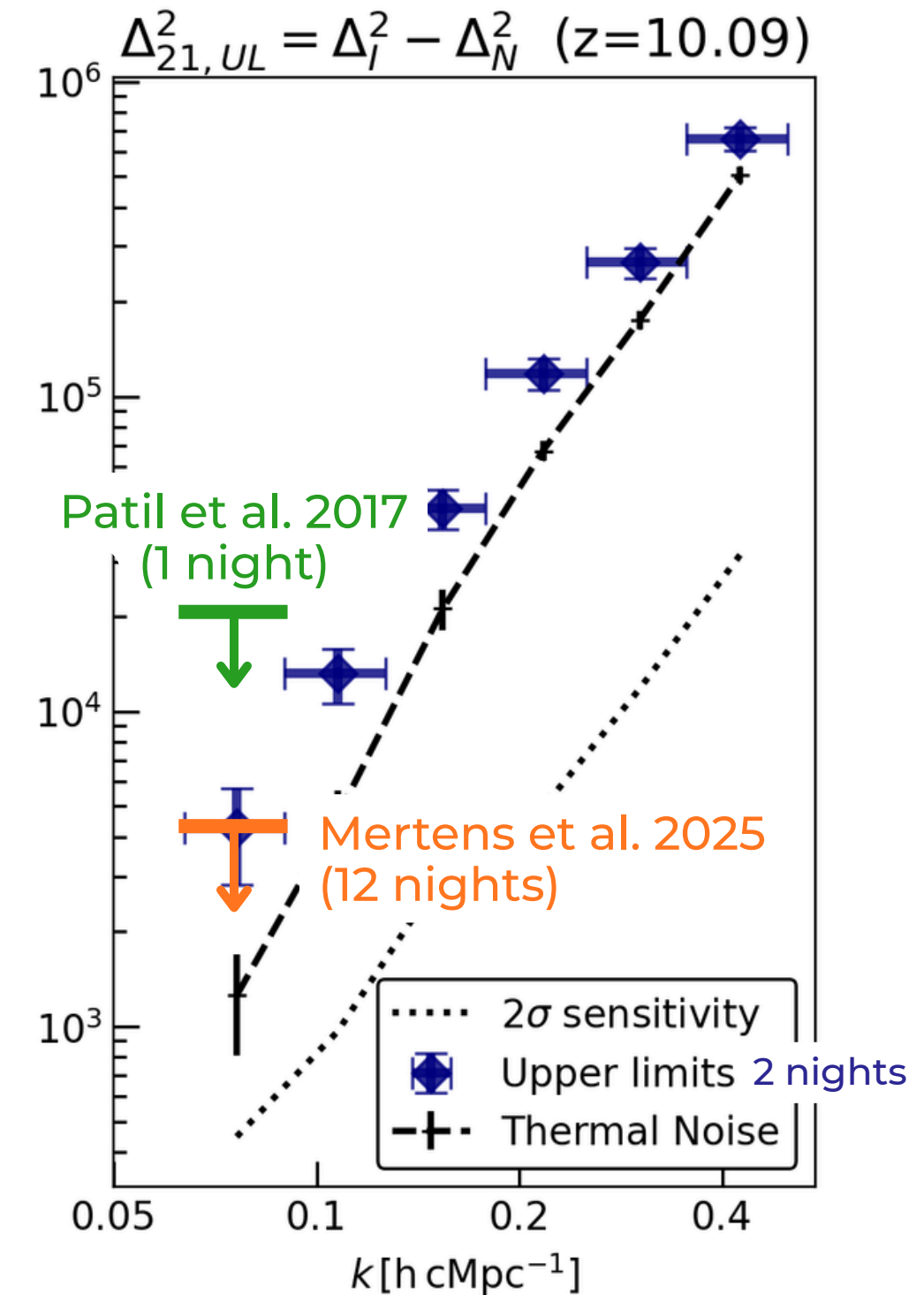
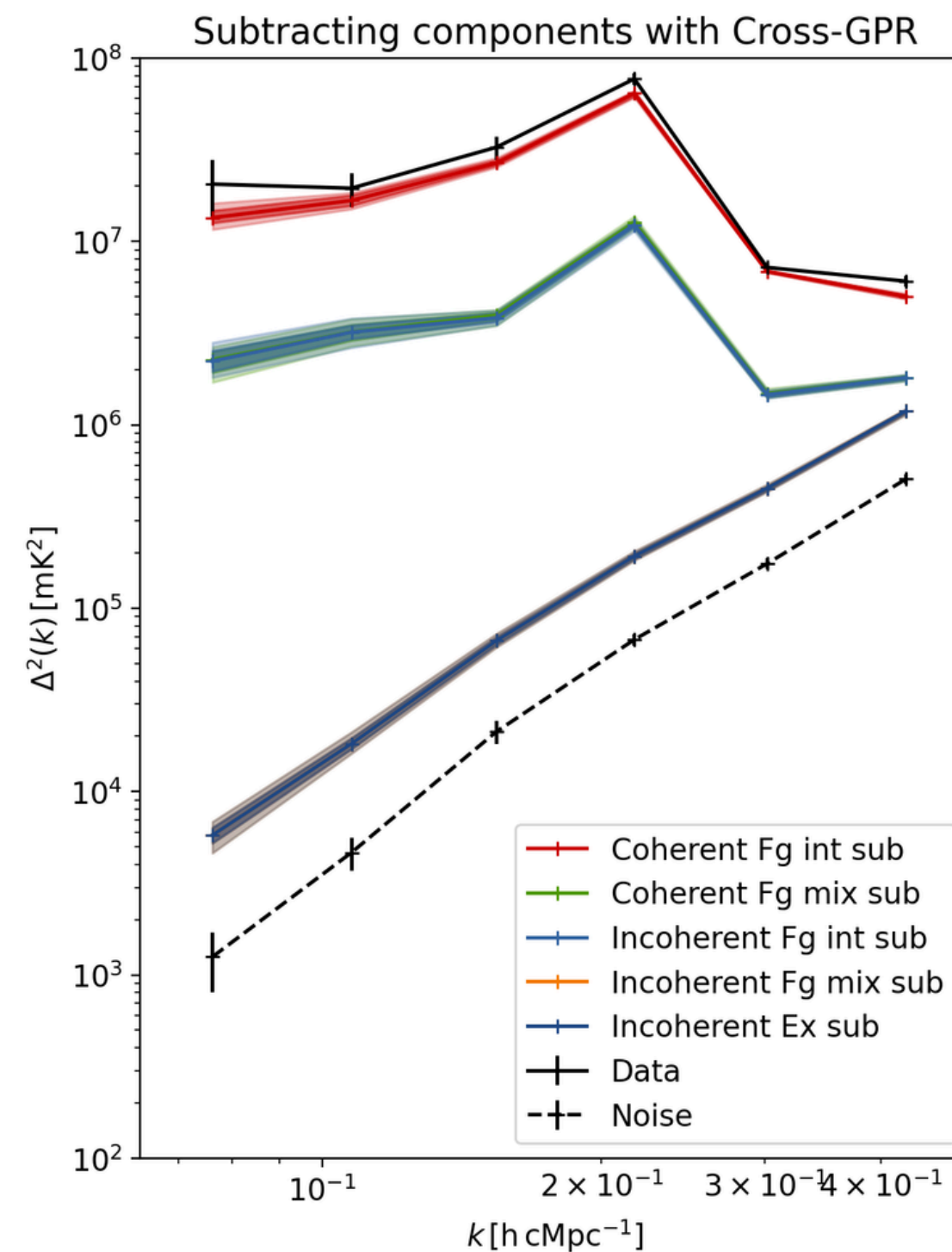


PRELIMINARY RESULTS WITH CROSS-GPR (3C196)

HOW DOES CROSS-GPR WORKS?

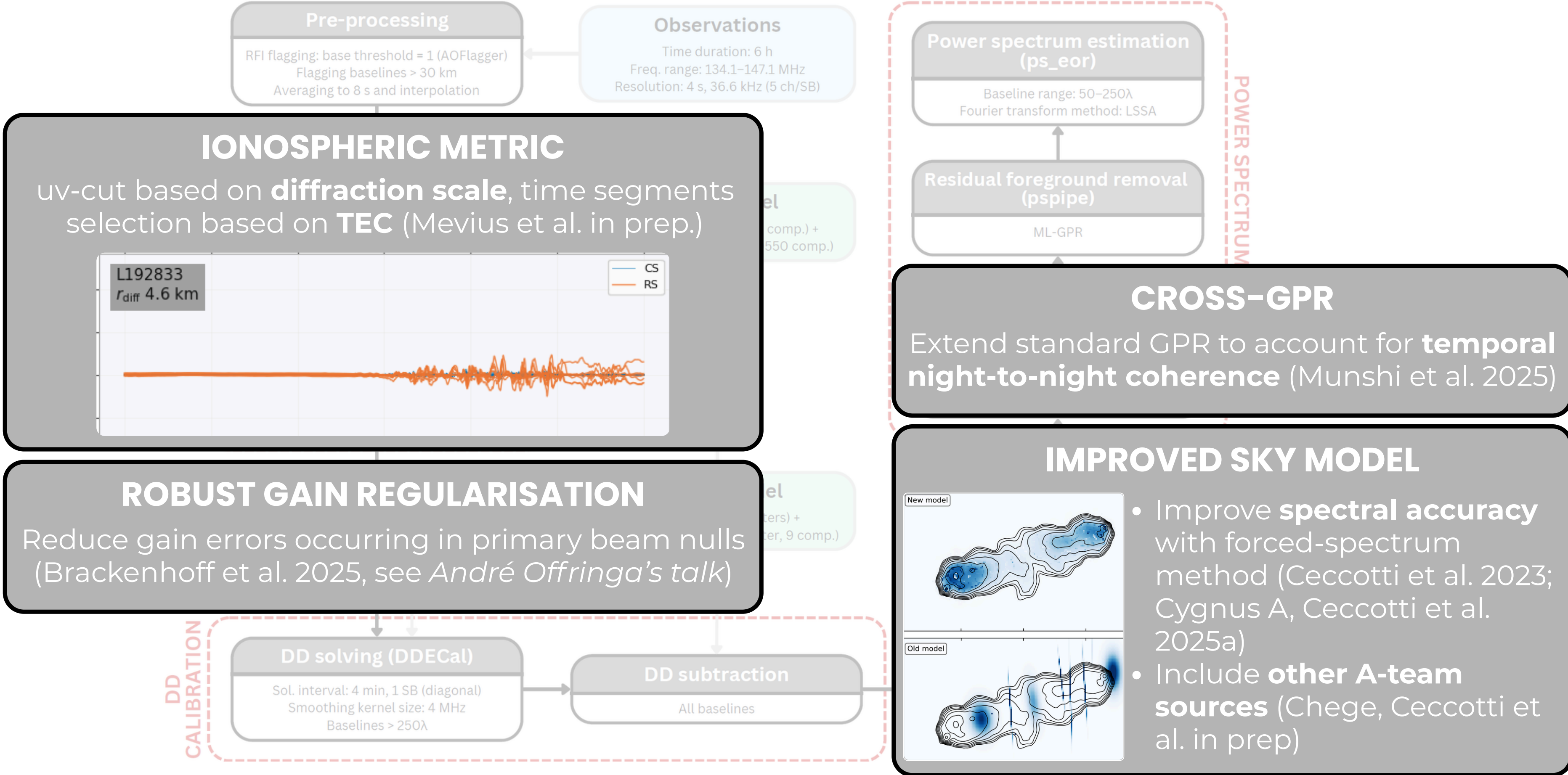
- The cross-GPR model captures the **cross-covariance between pairs of datasets**: it captures the (in)coherence of specific components across multiple datasets
- **Break degeneracy** when excess and 21-cm signal have similar spectral behavior
- The **incoherent excess can be subtracted from residual data**, resulting in lower upper limits

Munshi et al. 2025

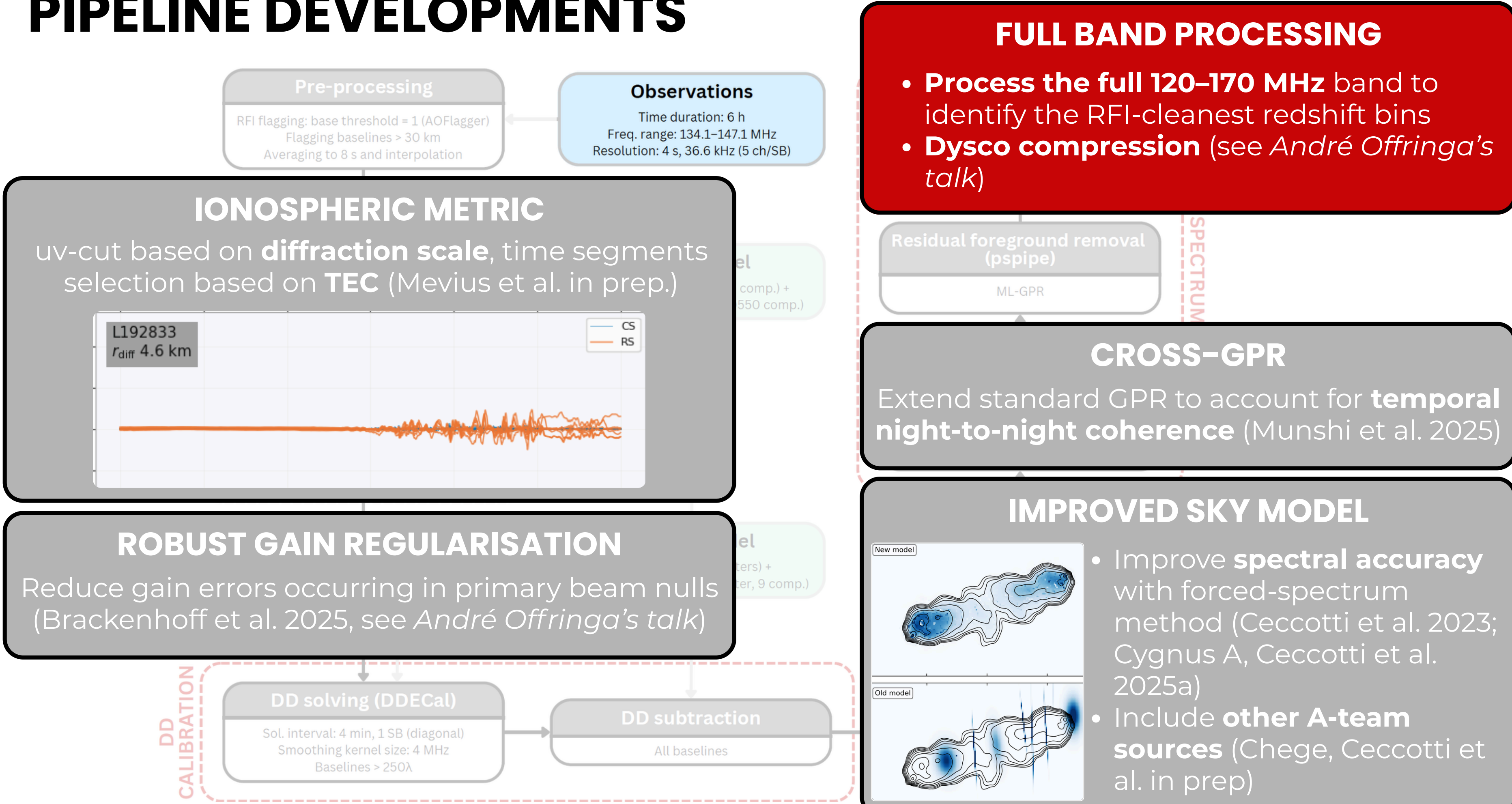


Results are promising, but **signal loss analysis is underway** to confirm these (Munshi, Chege, Ceccotti)

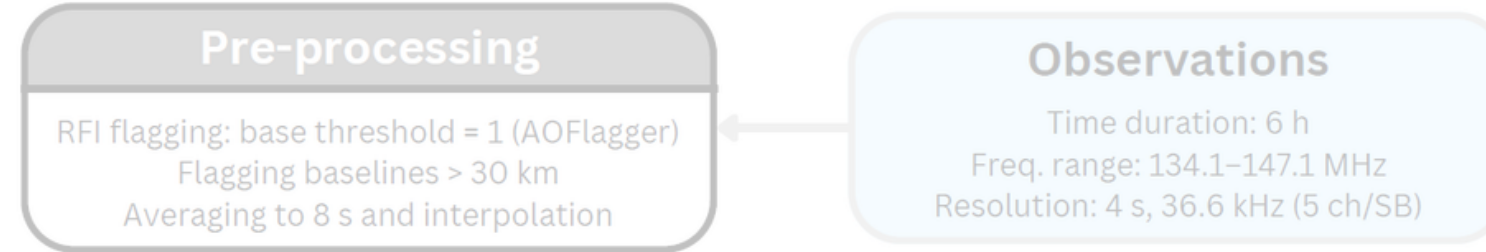
PIPELINE DEVELOPMENTS



PIPELINE DEVELOPMENTS

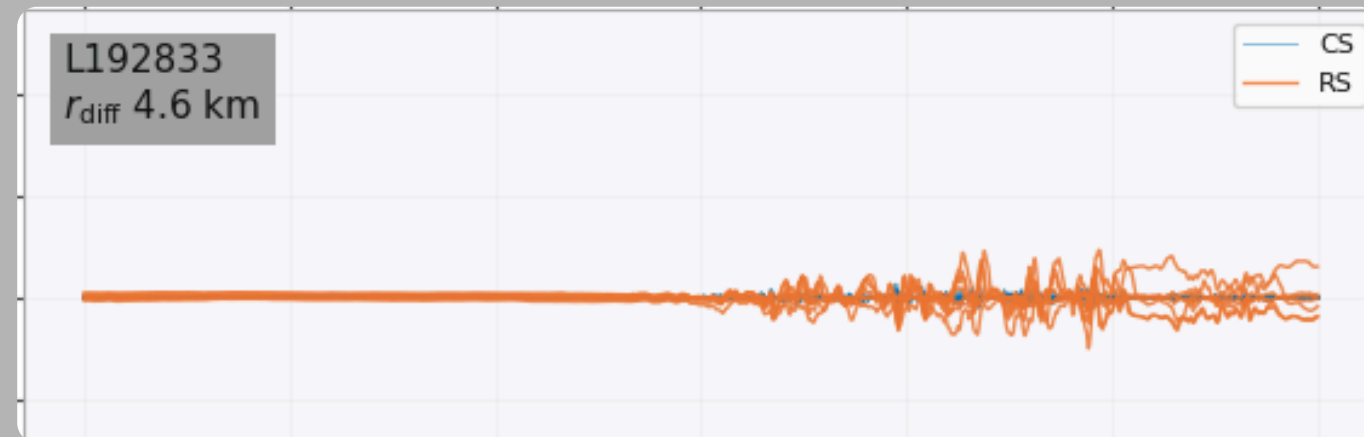


CONCLUSIONS



IONOSPHERIC METRIC

uv-cut based on **diffraction scale**, time segments selection based on **TEC** (Mevius et al. in prep.)



ROBUST GAIN REGULARISATION

Reduce gain errors occurring in primary beam nulls (Brackenhoff et al. 2025, see *André Offringa's talk*)

LOFAR2.0 PLANS?

Piggyback on **LUDO** (survey proposal of the Euclid Deep Field North) to process it as a deep EoR field

FULL BAND PROCESSING

- Process the full 120–170 MHz band to identify the RFI-cleanest redshift bins
- **Dysco compression** (see *André Offringa's talk*)

Residual foreground removal (pspipe)

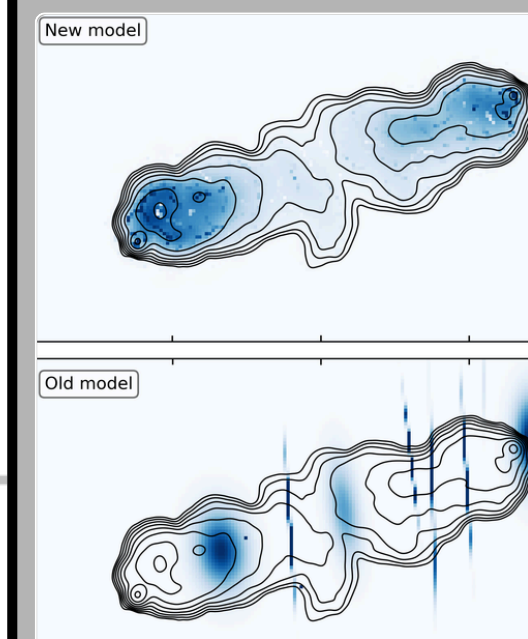
ML-GPR

SPECTRUM

CROSS-GPR

Extend standard GPR to account for **temporal night-to-night coherence** (Munshi et al. 2025)

IMPROVED SKY MODEL



- Improve **spectral accuracy** with forced-spectrum method (Ceccotti et al. 2023; Cygnus A, Ceccotti et al. 2025a)
- Include **other A-team sources** (Chege, Ceccotti et al. in prep)