INAF
ISTITUTO NAZIONALE DI ASTROFISICA

LOFAR

university of groningen

Epoch of Reionization observations with SKAO

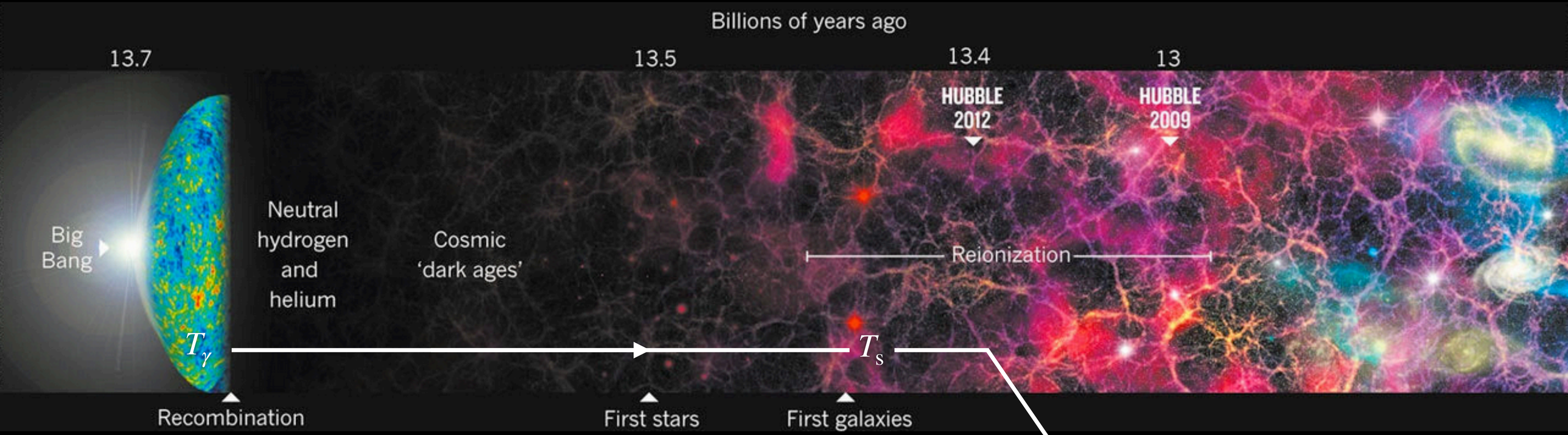
Lessons learnt from LOFAR and synergies with MeerKAT

Emilio Ceccotti

Collaborators: Gianni Bernardi, Chanasorn Kongprachaya, André Offringa, Florent Mertens, Léon Koopmans (and the LOFAR-EoR Team)

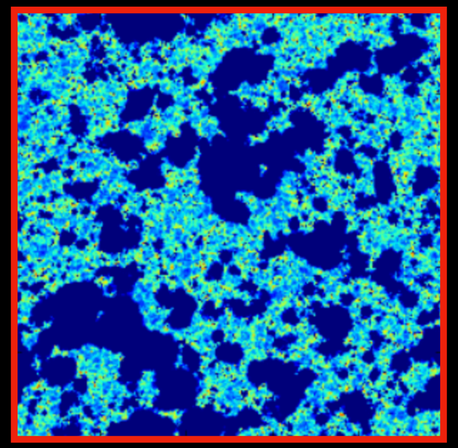
5th National Workshop on the SKA Project, Bologna, 2025/11/25

OBSERVING THE EOR WITH THE 21-CM SIGNAL



$$\delta T_b(z) \propto x_{\rm HI}(1+\delta)\left(1-\frac{T_\gamma}{T_s}\right)$$

BRIGHTNESS CONTRAST



$$\delta T_b = T_b - T_\gamma$$

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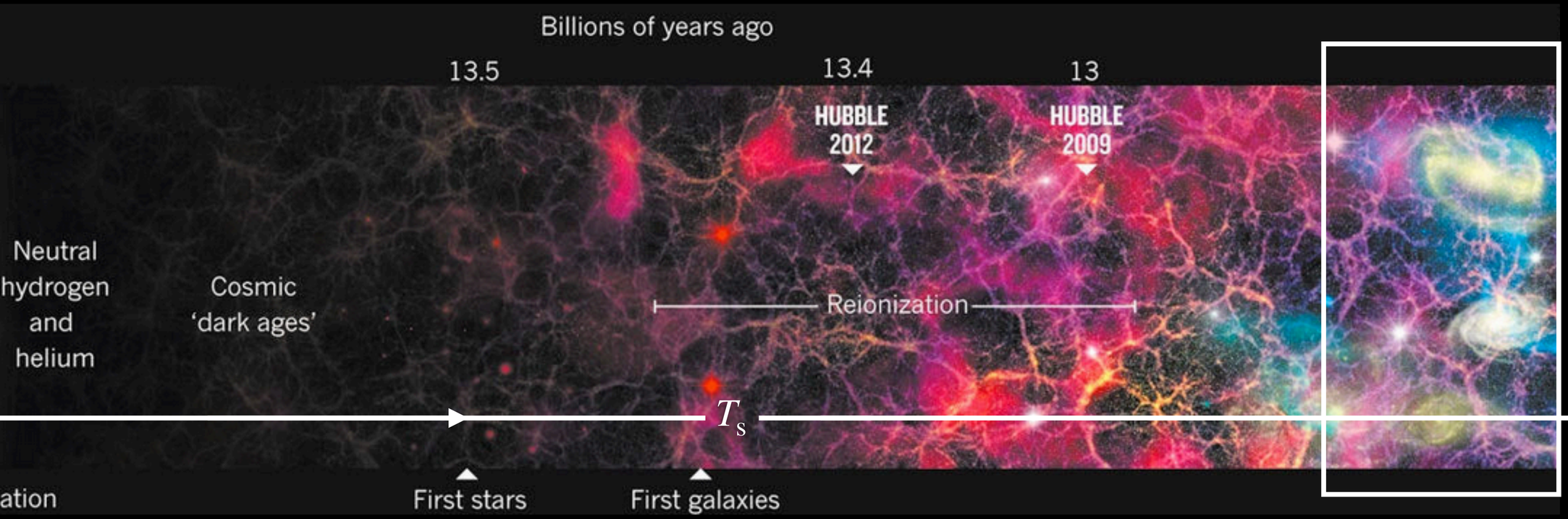
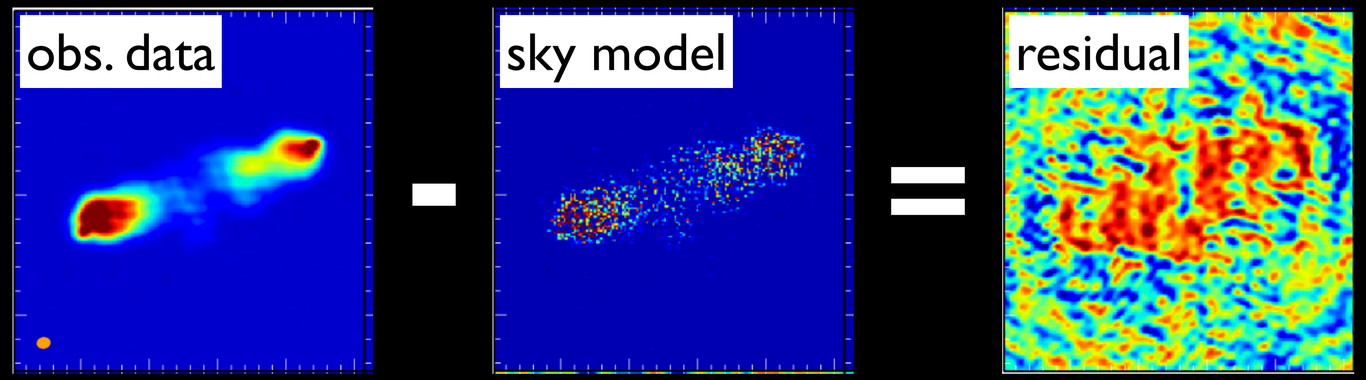


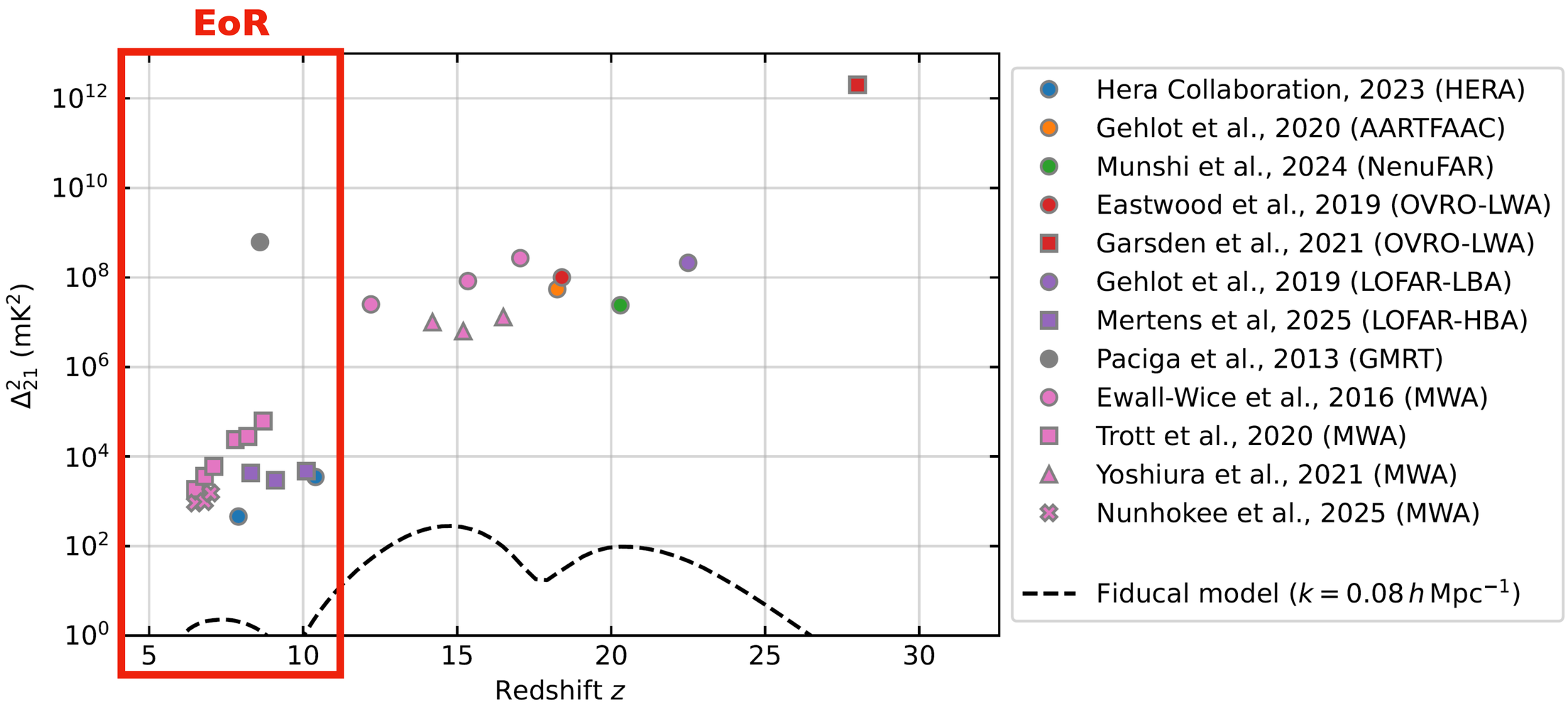
Foreground emission!

FOREGROUND SUBTRACTION



Adapted from Gardsen et al. 2015

WHERE ARE WE TODAY?



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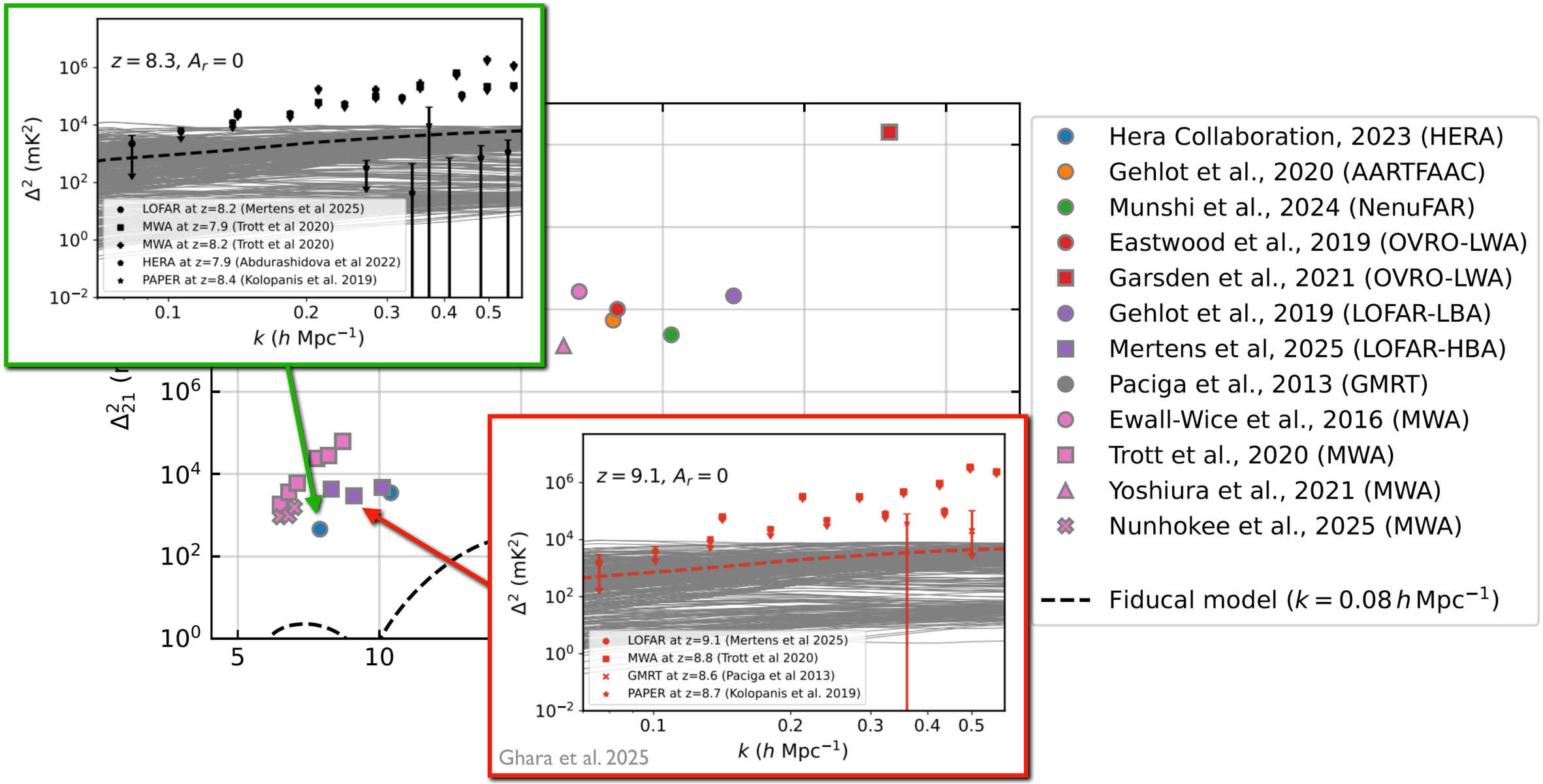
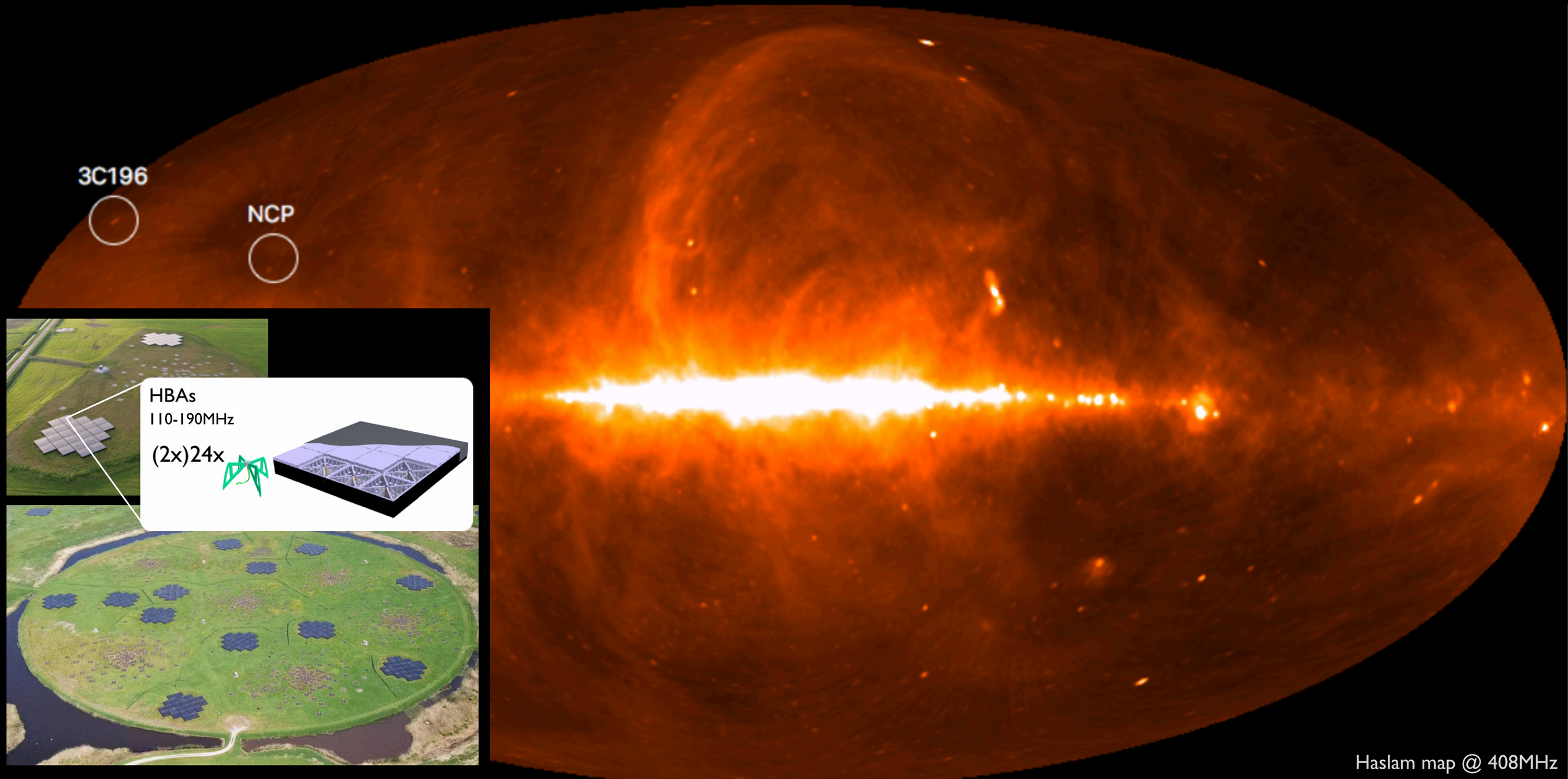


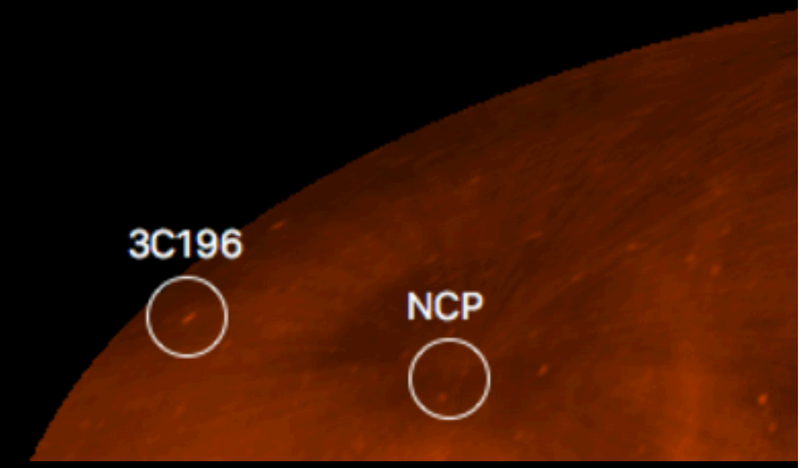
Ghara et al. 2025

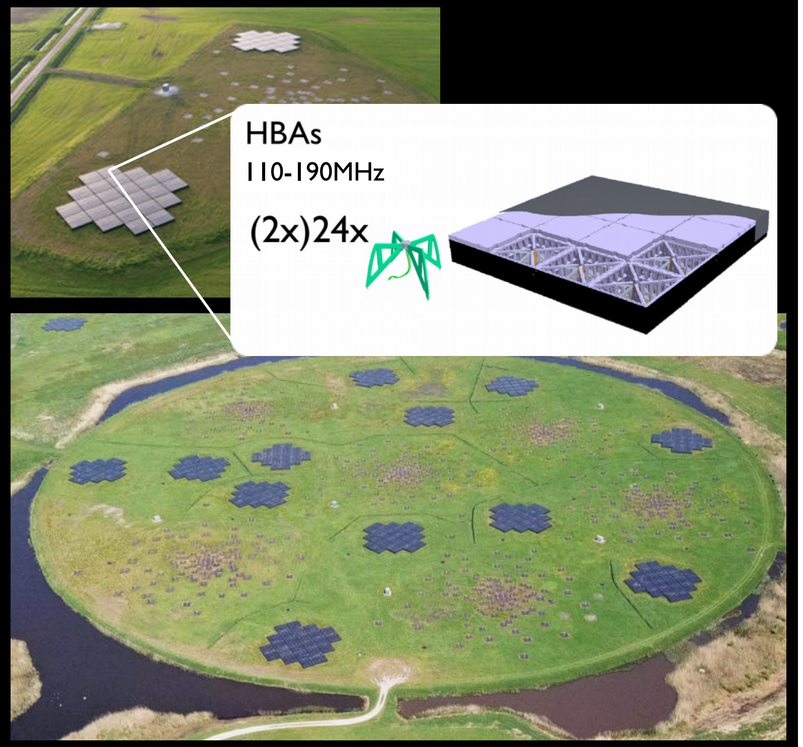
LOFAR-EOR PROJECT



Haslam map @ 408MHz

LOFAR-EOR PROJECT





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

DI CALIBRATION

Pre-processing
RFI flagging: base threshold = 1 (AOFlagger)
Flagging baselines > 25 km
Averaging to 8 s and interpolation

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)

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

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

DD CALIBRATION

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

DD subtraction
All baselines

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
Image size: 512x512 pixels
Pixel scale: 30 arcsec
No baseline cut

POWER SPECTRUM PIPELINE

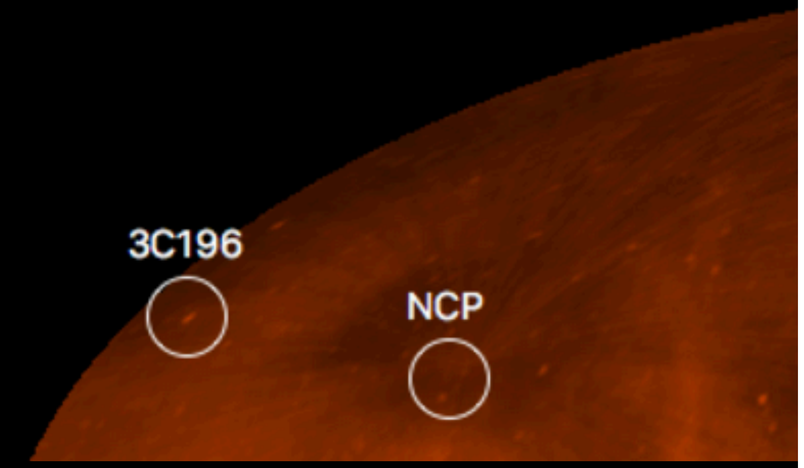
Generating visibility cubes (pspipe)
Spatial tapering: 4° Tukey window
Conversion from Jy/beam to Kelvin
Flagging outliers in *uv* and frequency space

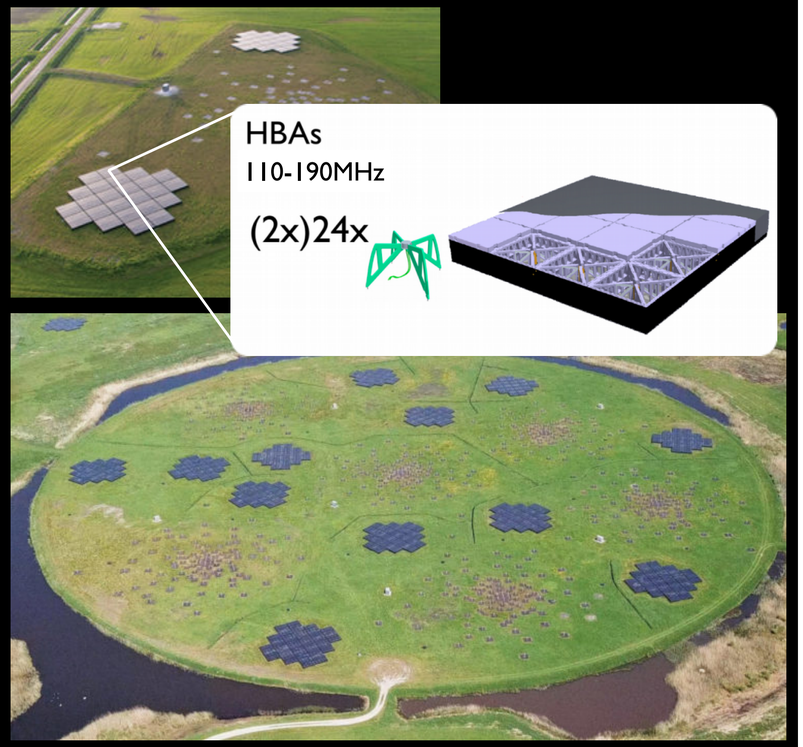
Residual foreground removal (pspipe)
ML-GPR

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

Ceccotti et al. 2025

LOFAR-EOR PROJECT





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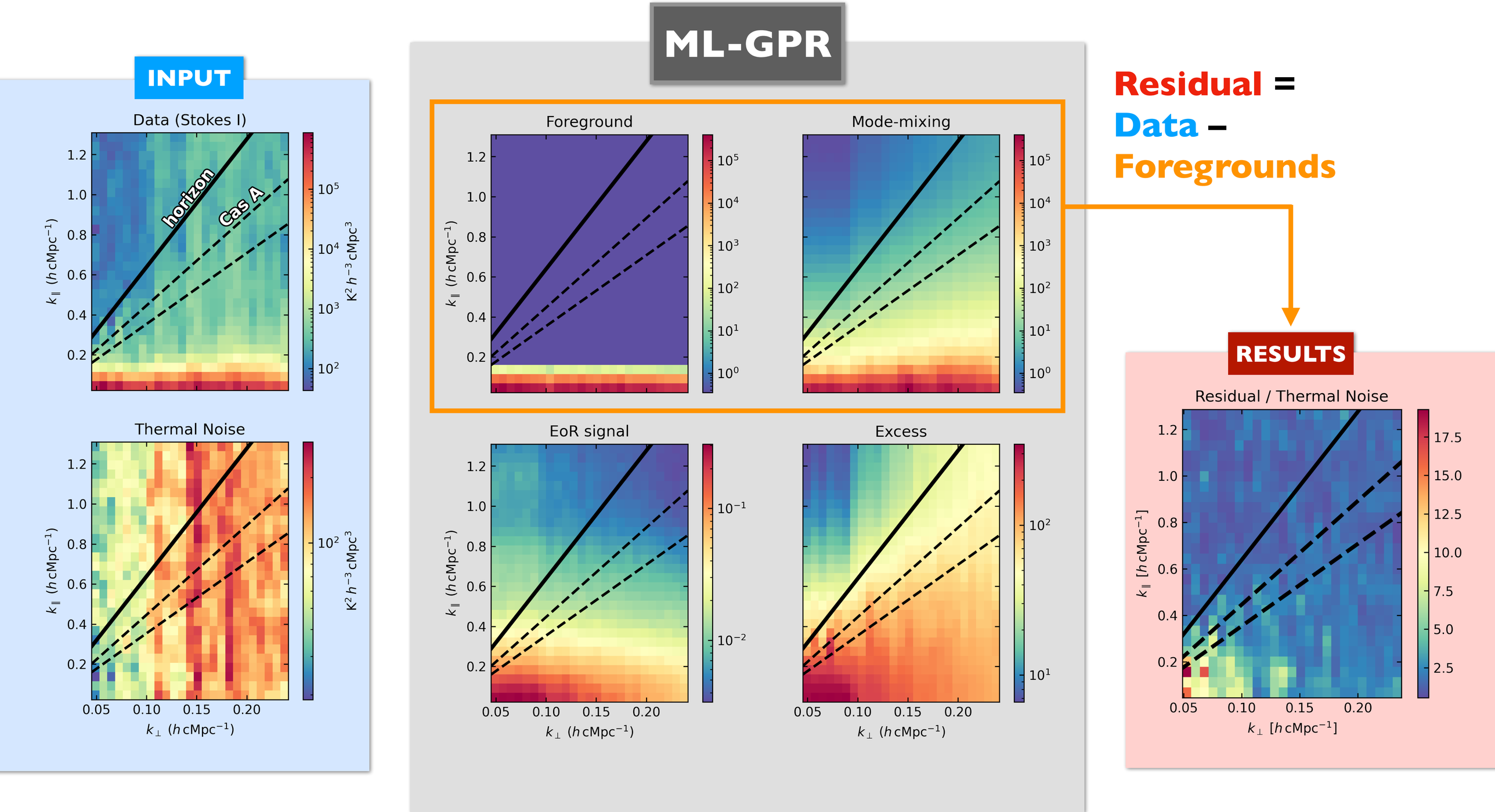
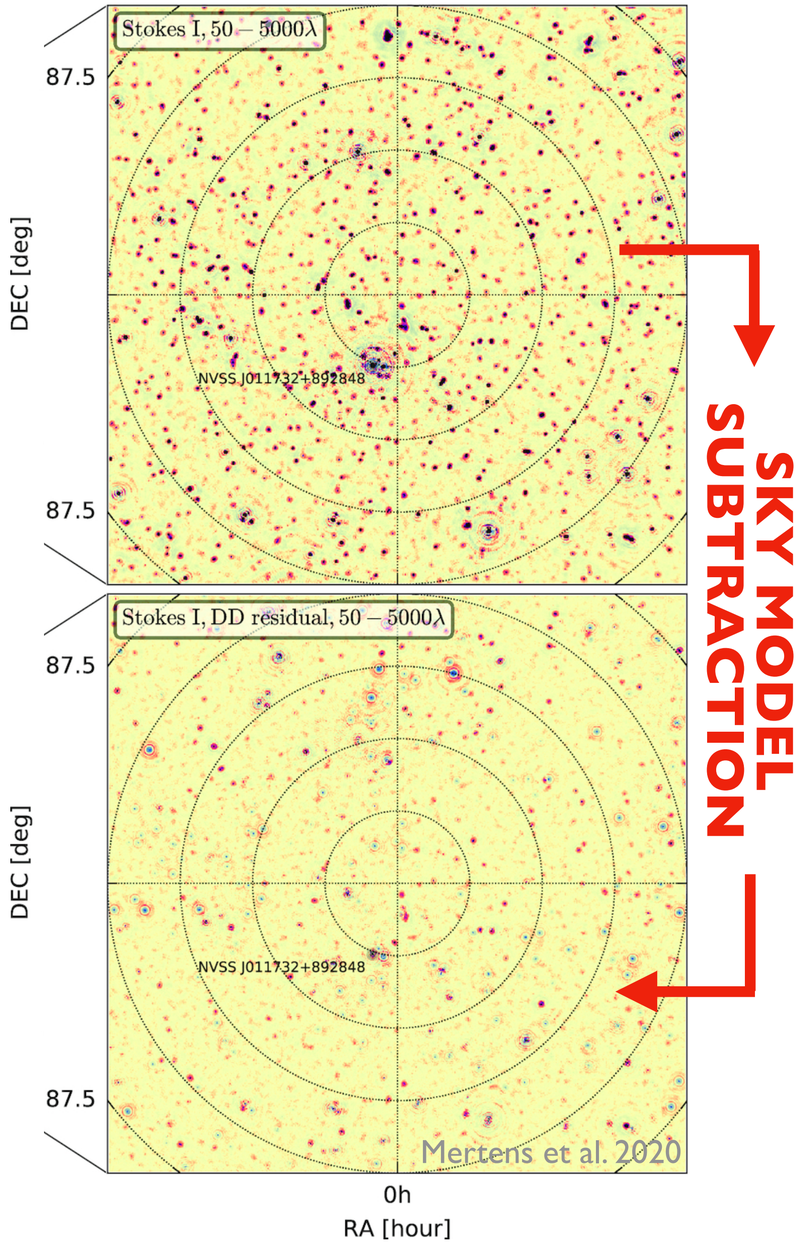
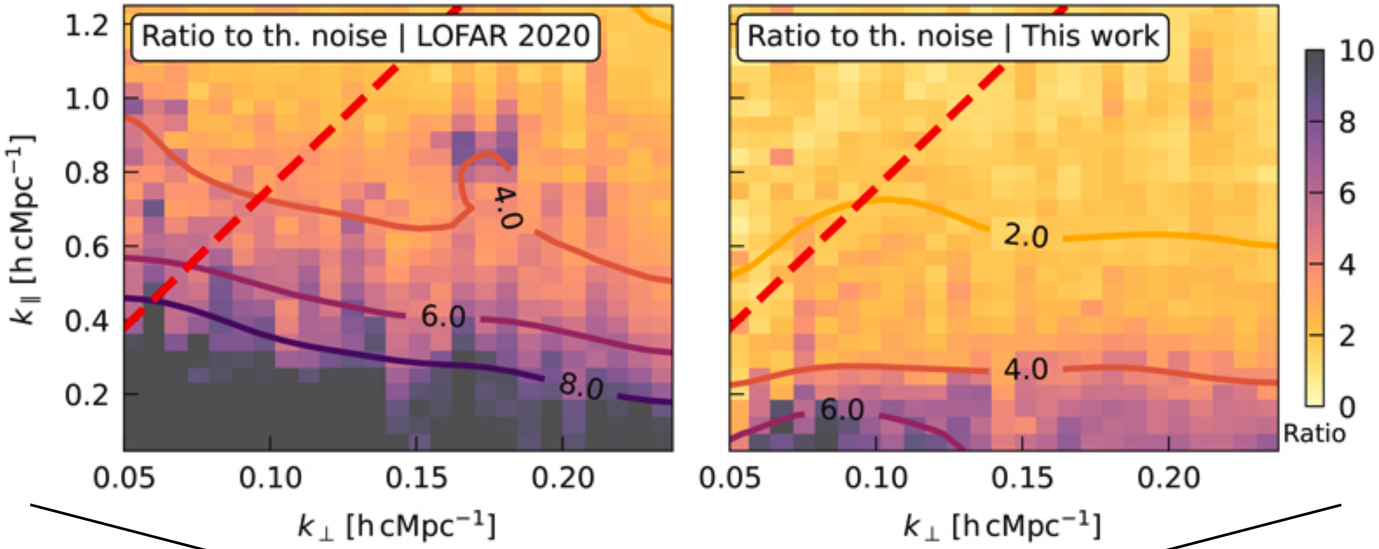
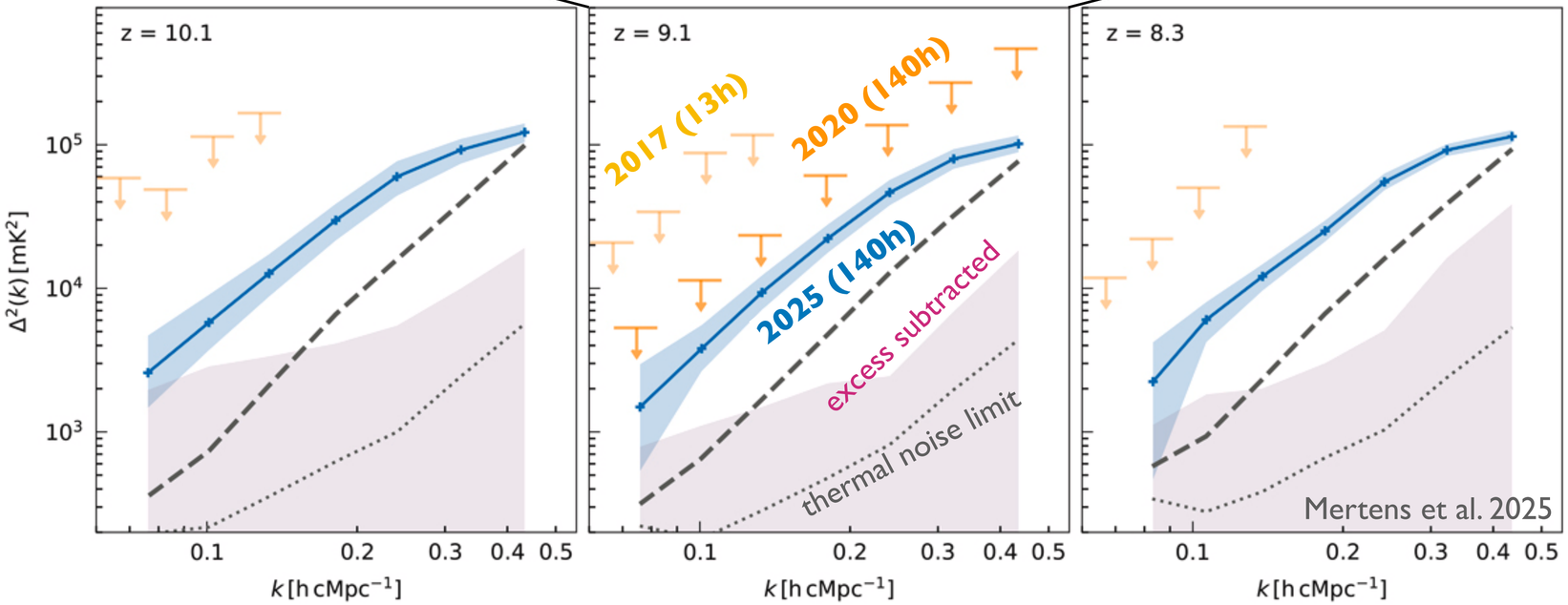

INPUT
Data (Stokes I)
horizon
Cas A
Thermal Noise
ML-GPR
Foreground
Mode-mixing
EoR signal
Excess
Residual = Data – Foregrounds
RESULTS
Residual / Thermal Noise
$k_\parallel$ (h cMpc^{-1})
$k_\perp$ (h cMpc^{-1})
K^2 h^{-3} cMpc^3

RESULTS FROM NCP FIELD



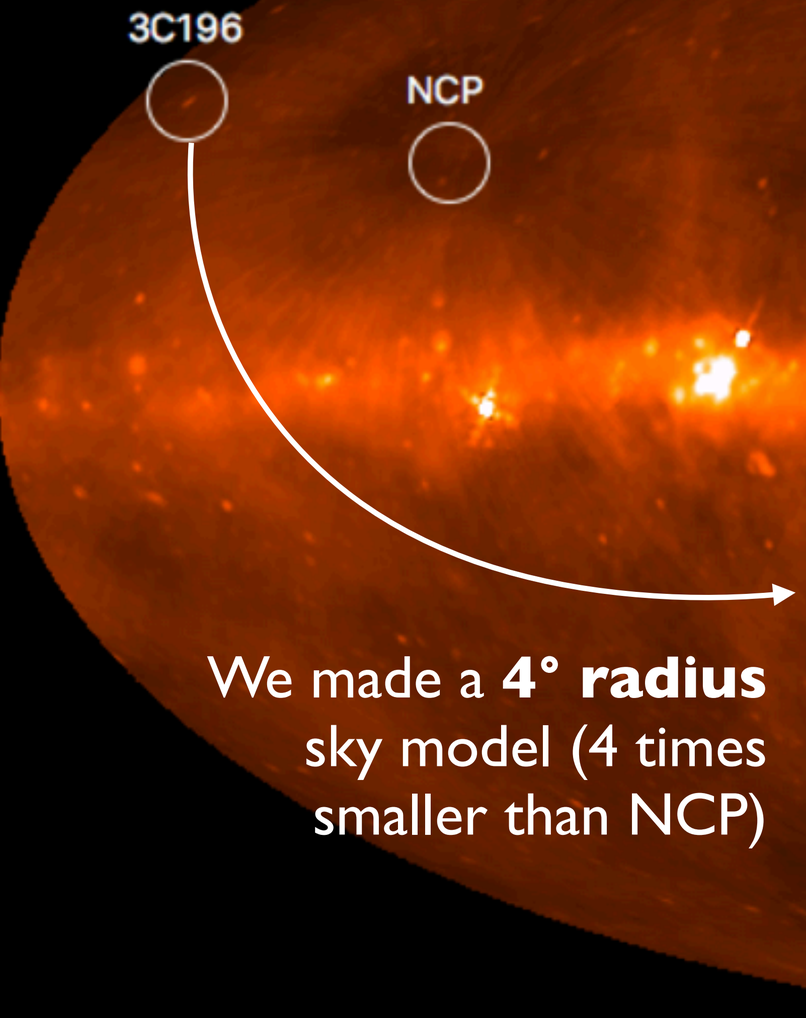
SKY MODEL SUBTRACTION



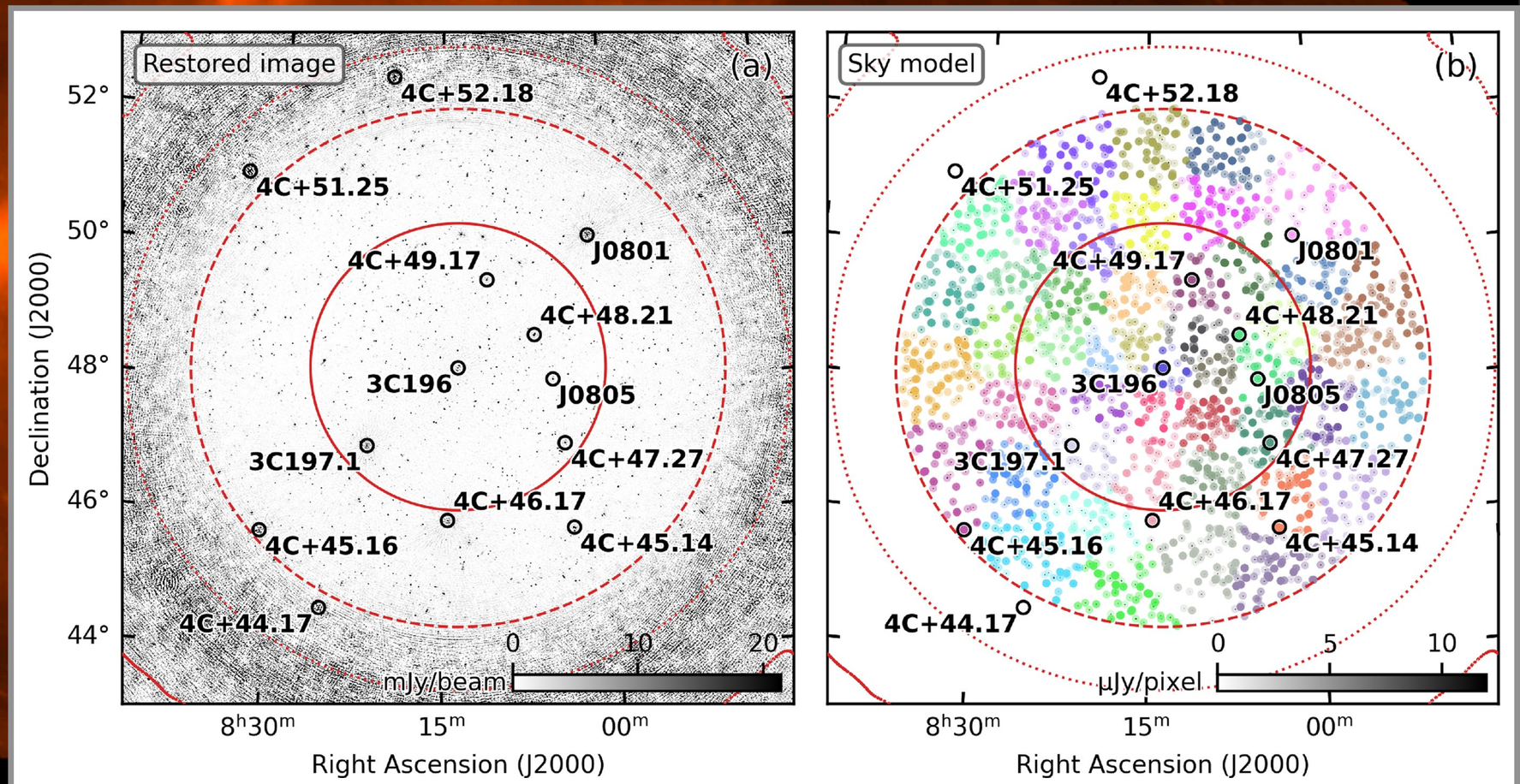


RESULTS FROM 3C196 AT z~9.2

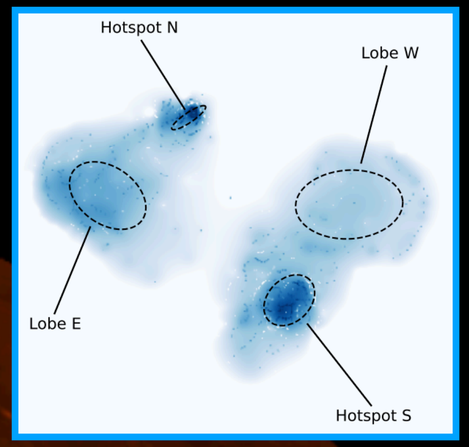
- Sensitivity **higher** than NCP (closer to zenith)
- **Strong source** in the centre that makes DI calibration easier
- Cas A & Cyg A more than 66° far from the centre



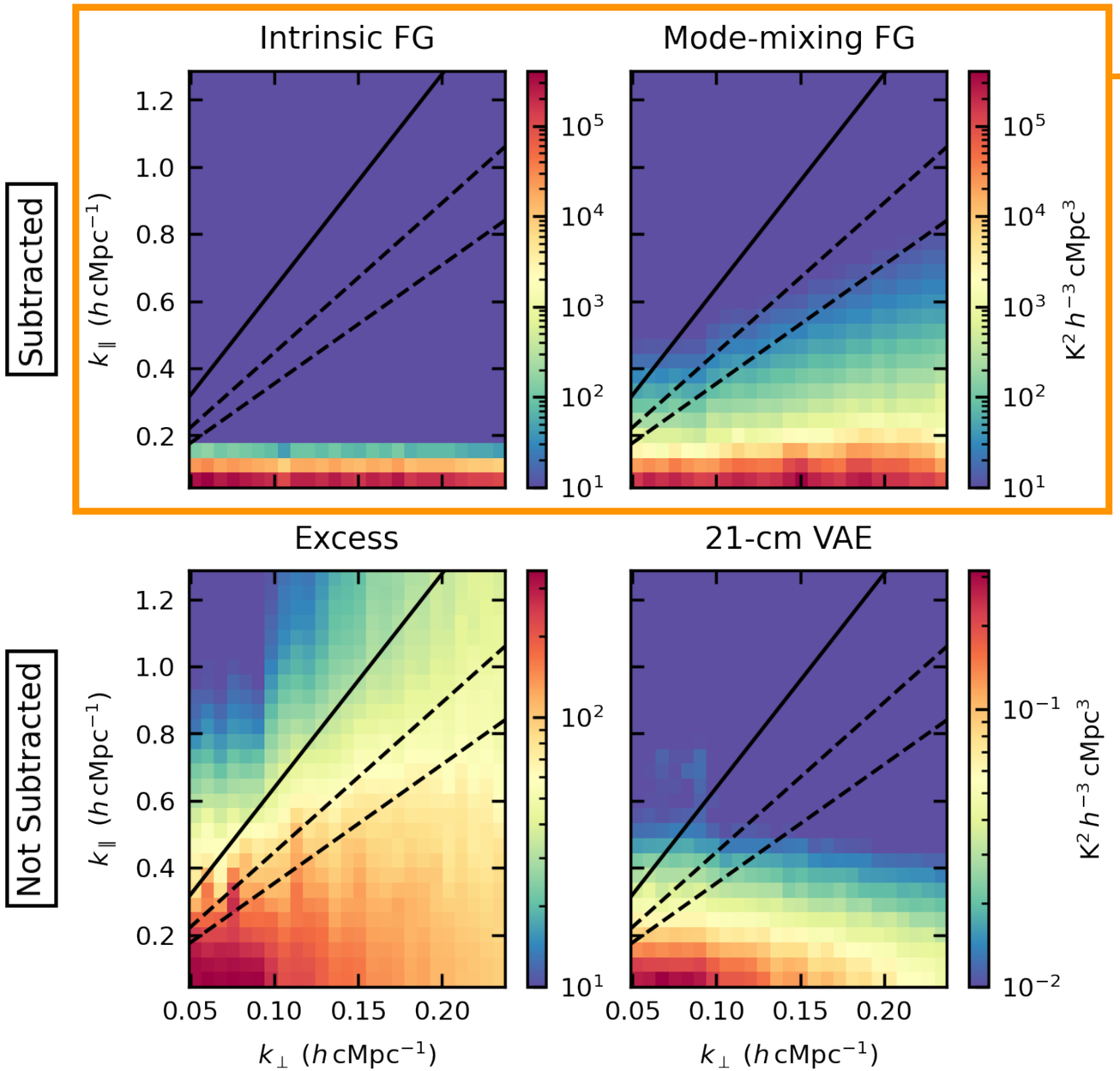
We made a **4° radius** sky model (4 times smaller than NCP)

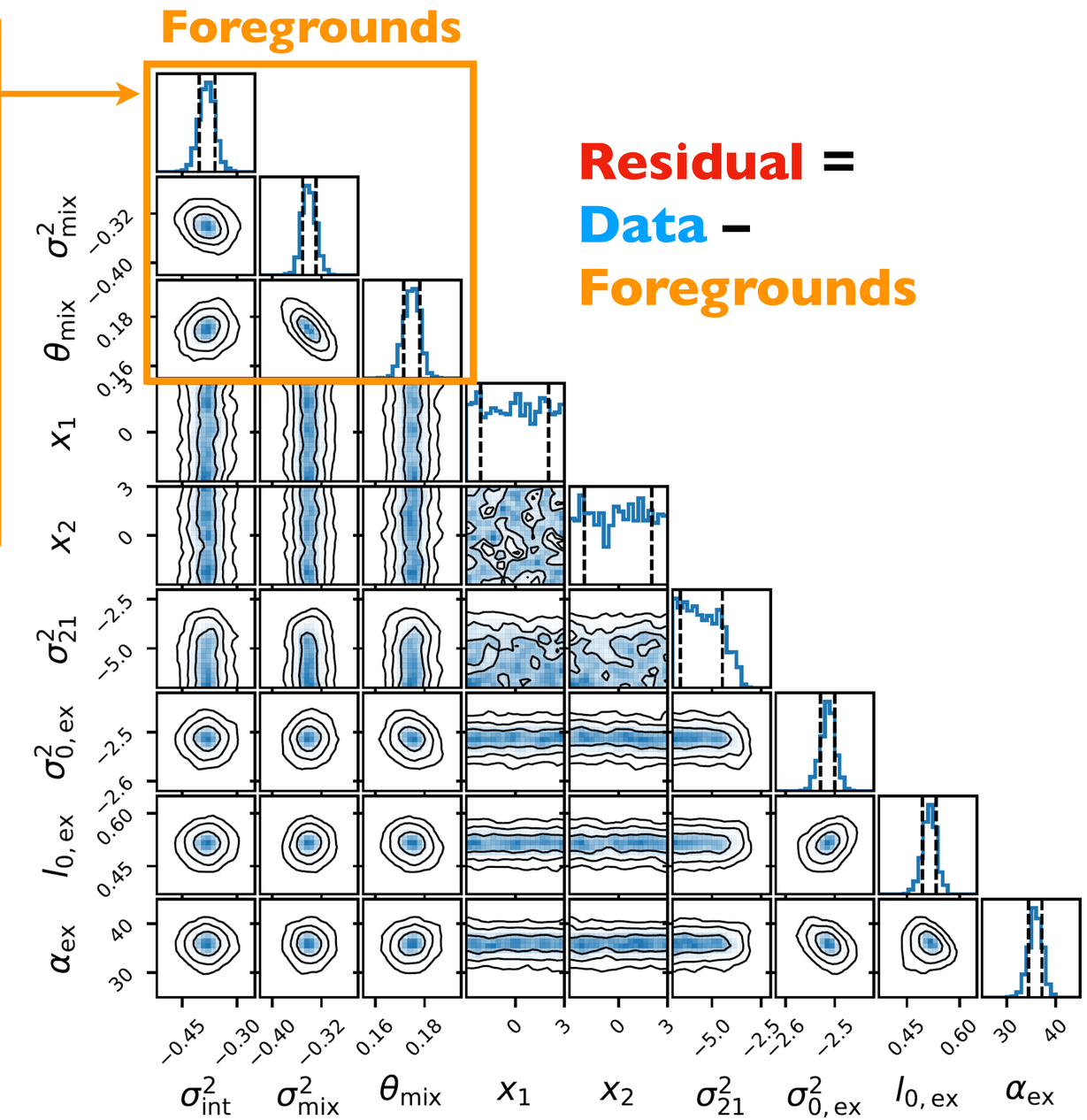


VLBI model of 3C196



RESULTS FROM 3C196: ML-GPR



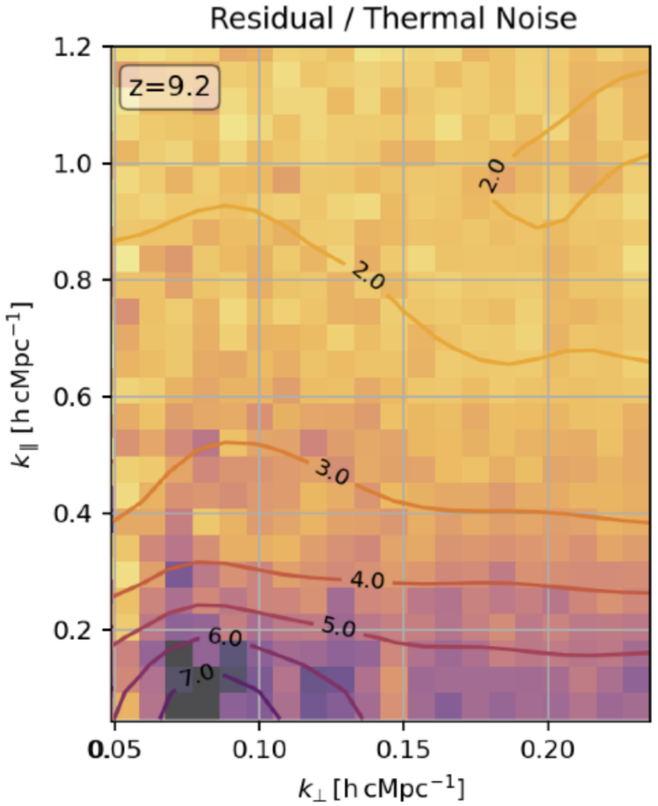


Residual = Data – Foregrounds

3C196 VS NCP

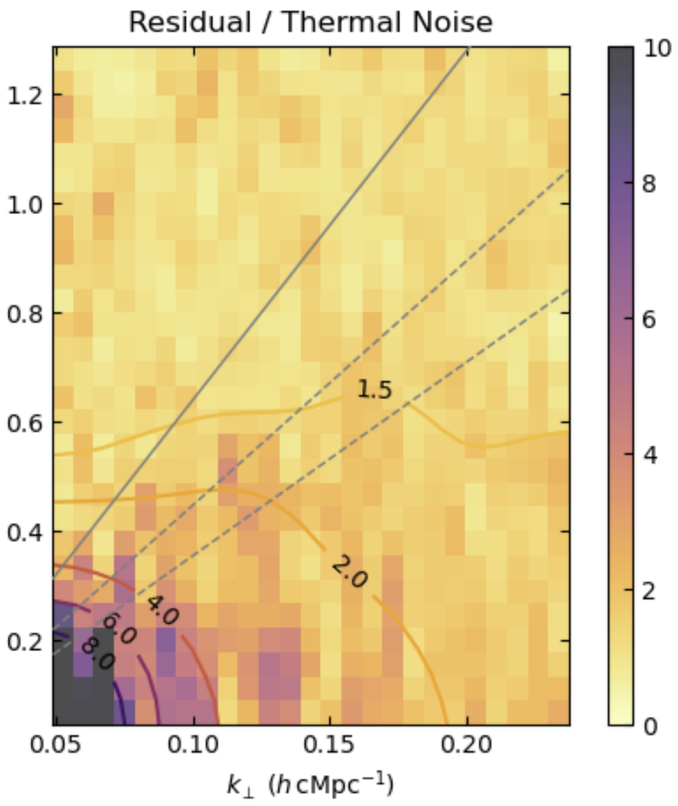
2D POWER SPECTRUM

NCP



Mertens et al. 2025

3C196

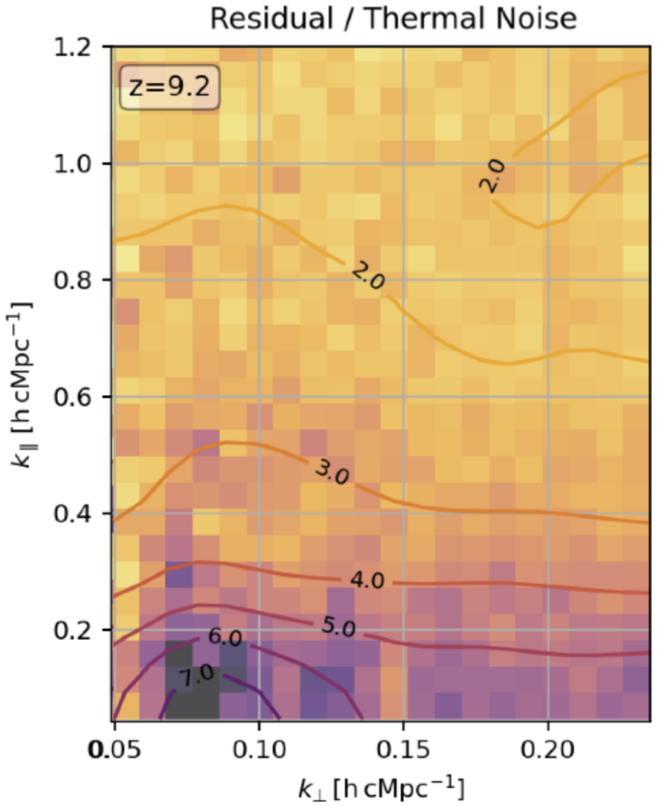


Ceccotti et al. 2025

3C196 VS NCP

2D POWER SPECTRUM

NCP



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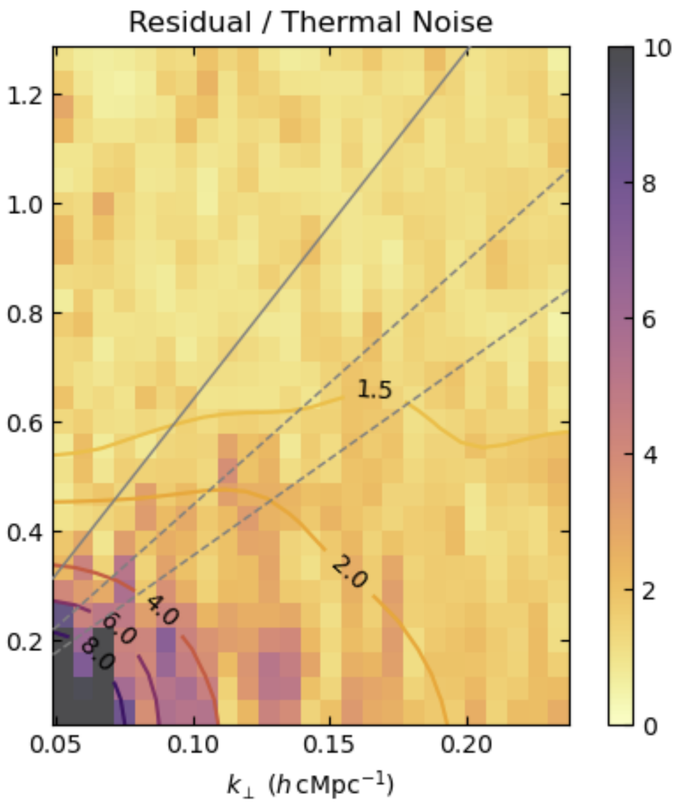
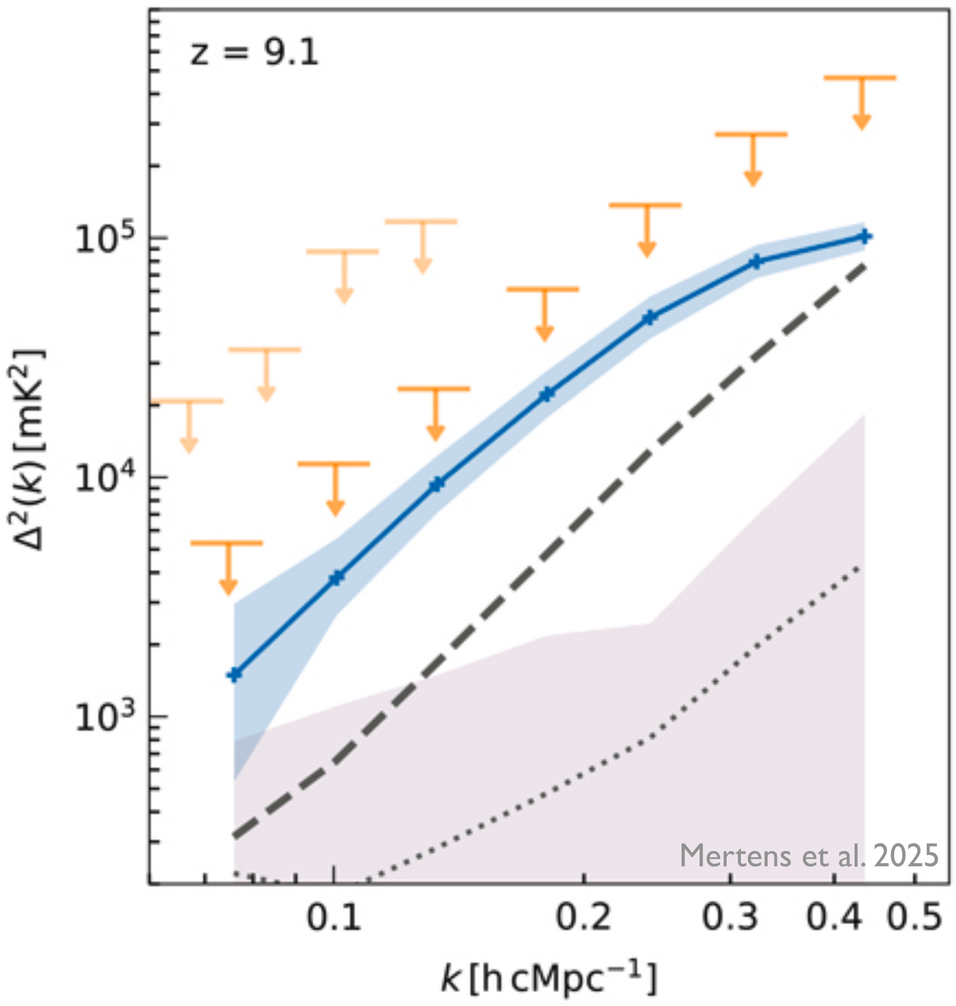


Ceccotti et al. 2025

2σ UPPER LIMITS

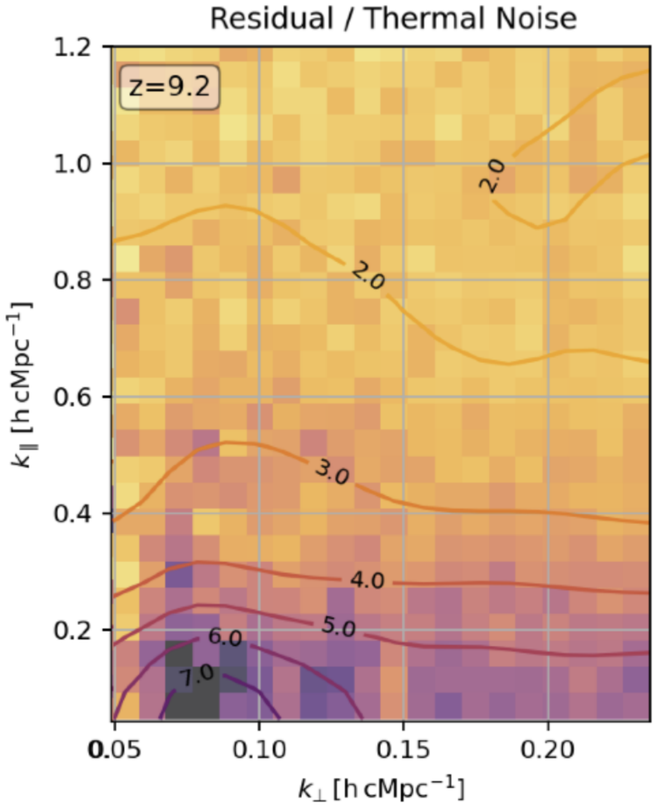


Mertens et al. 2025

3C196 VS NCP

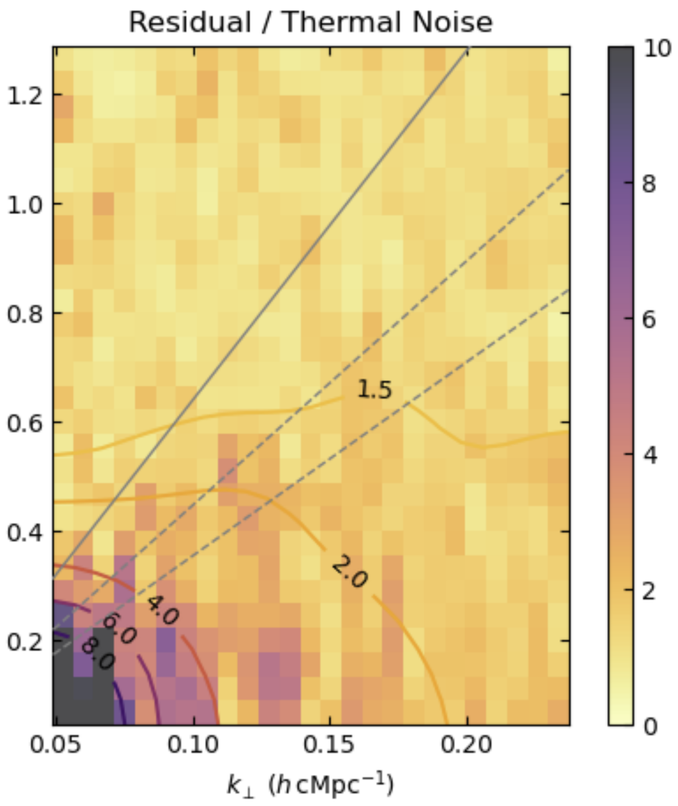
2D POWER SPECTRUM

NCP



Mertens et al. 2025

3C196



Ceccotti et al. 2025

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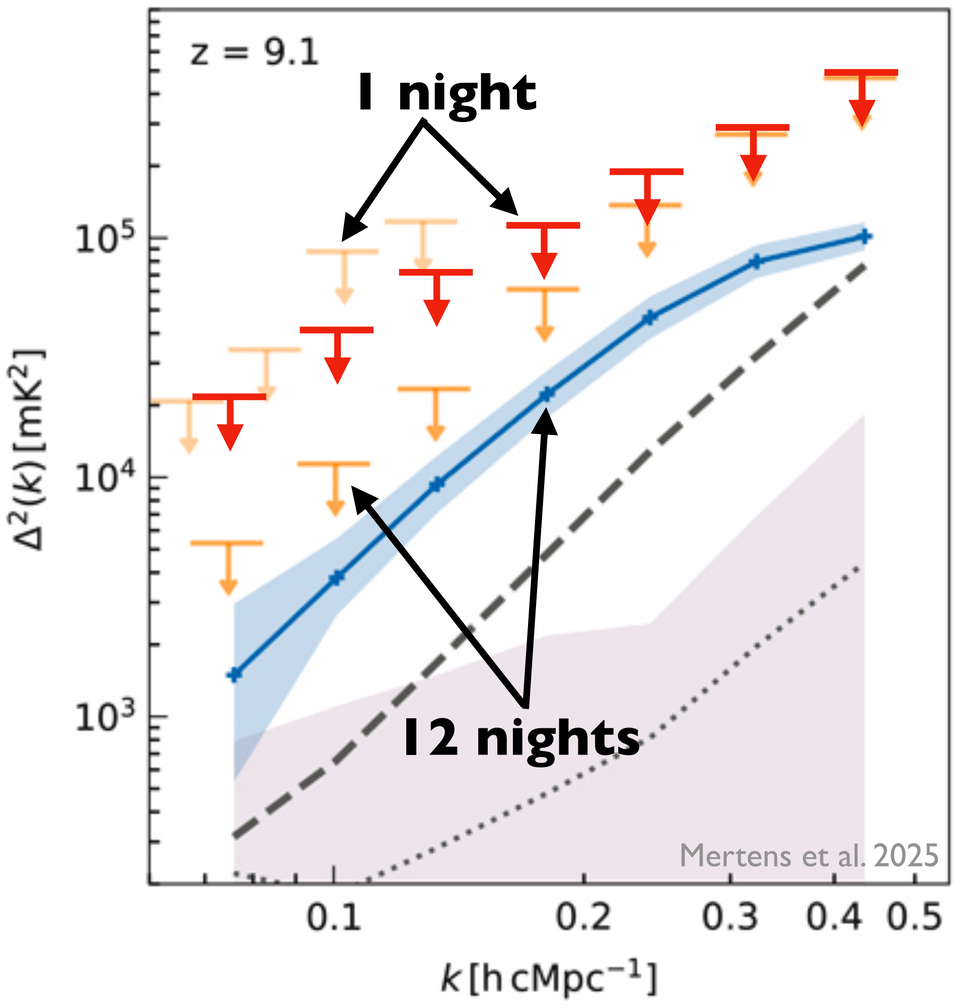
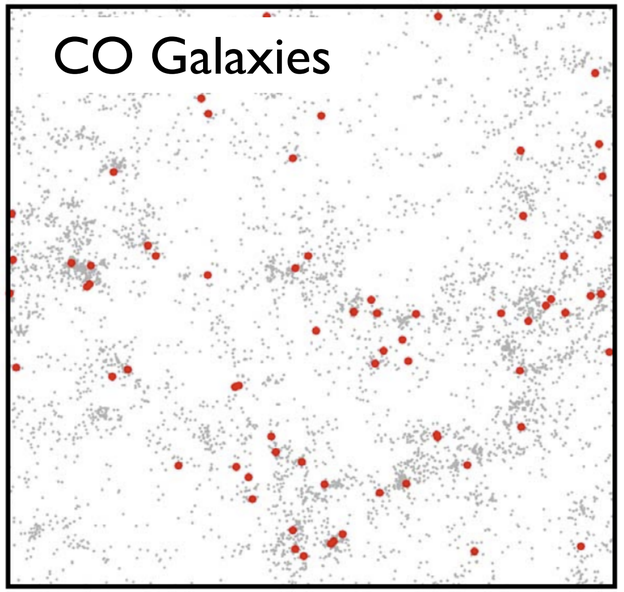
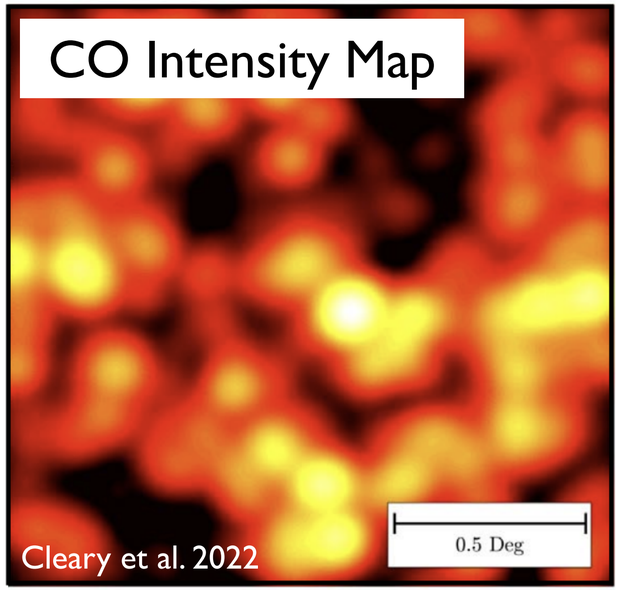
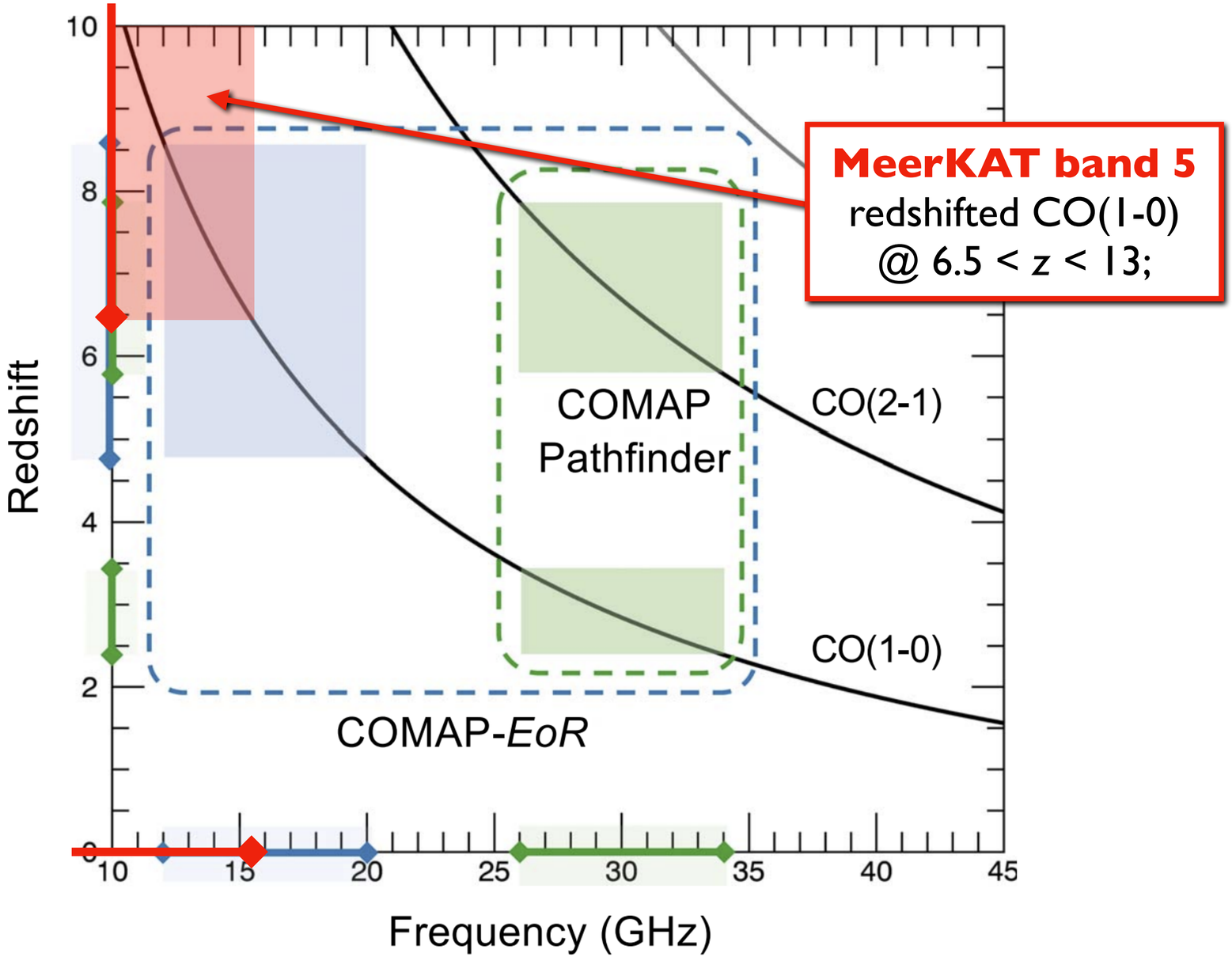


Mertens et al. 2025

MEERKAT SYNERGY: CO-21CM IM CORRELATION?



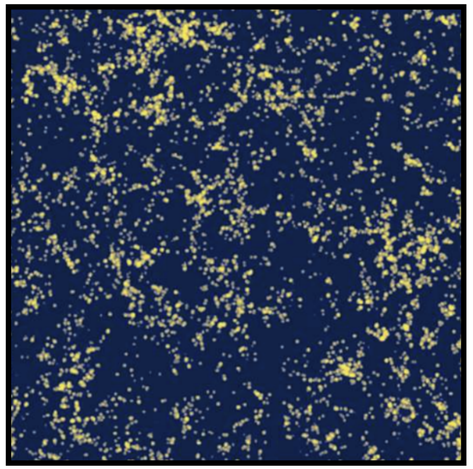




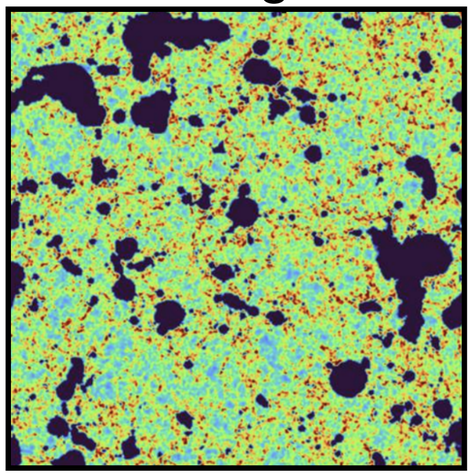
MEERKAT SYNERGY: CO-21CM IM CORRELATION?

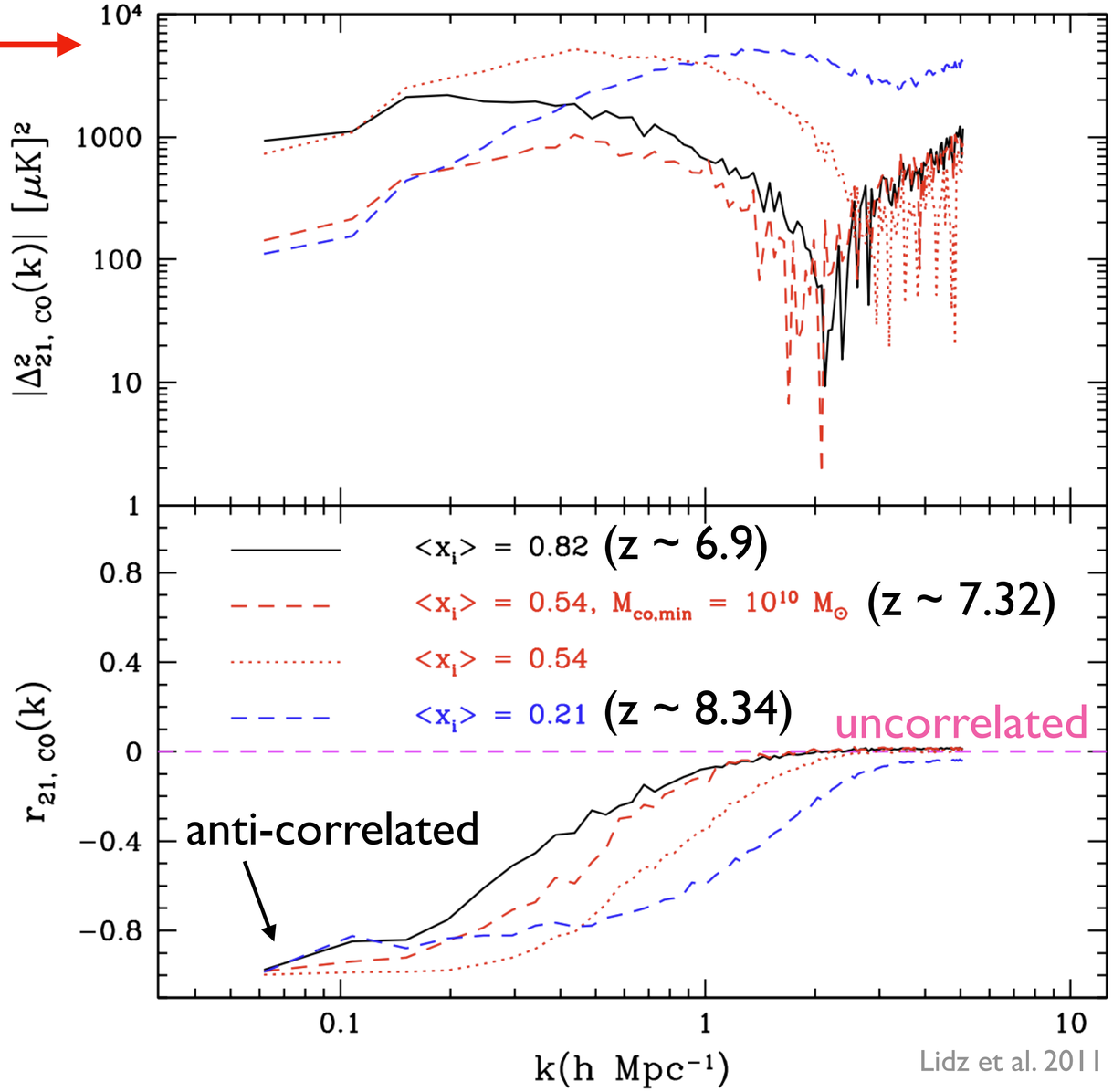
CROSS POWER SPECTRUM

CO Intensity Map



21-cm Brightness





Lidz et al. 2011

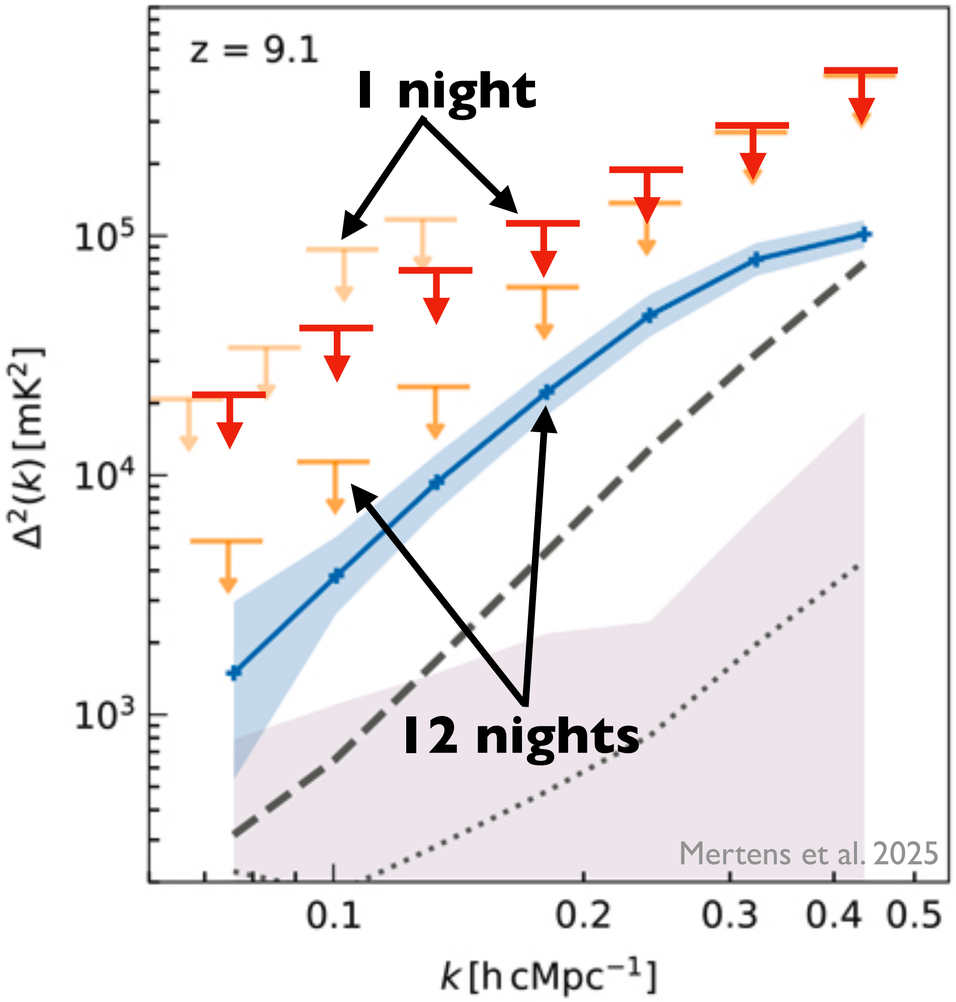
Scales > ionized bubbles = anti-correlated

Overdense regions host more CO-bright galaxies, but are mostly ionised

Scales << ionized bubbles = uncorrelated

Gas within an ionized region is fully ionized regardless of the local galaxy density

SUMMARY AND CONCLUSIONS



- LOFAR provides the current **most stringet 21-cm power spectrum upper limits limits at z~9.16** from 140h of observations of the NCP field, demonstrating the level of calibration and modelling requirements needed for SKA-Low

- We extracted the **first 21-cm upper limits at z~9.16 from the 3C196 field** using one night (13h) observed with LOFAR-HBA, showing that bright sources, if accurately modelled, could benefit the calibration

- Synergy between MeerKAT and SKAO-Low: **cross-correlation of CO(1-0) intensity mapping with 21-cm observations**

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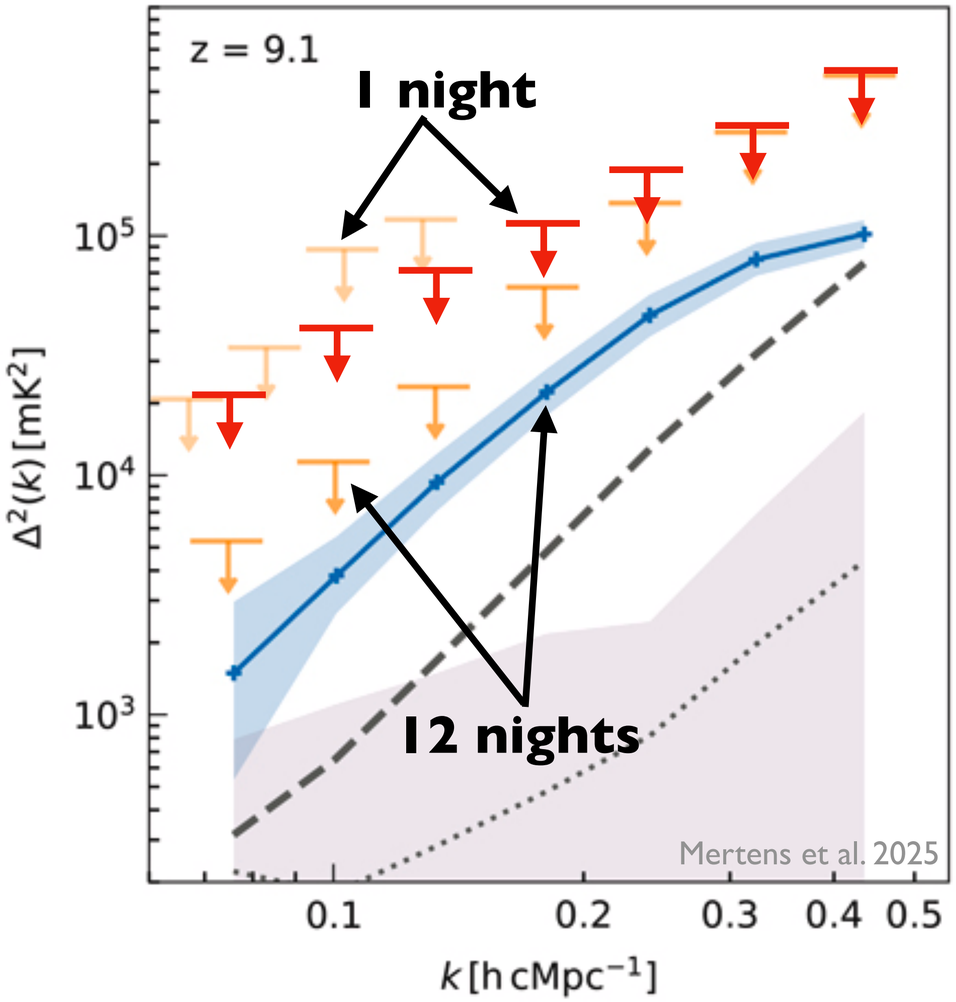

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