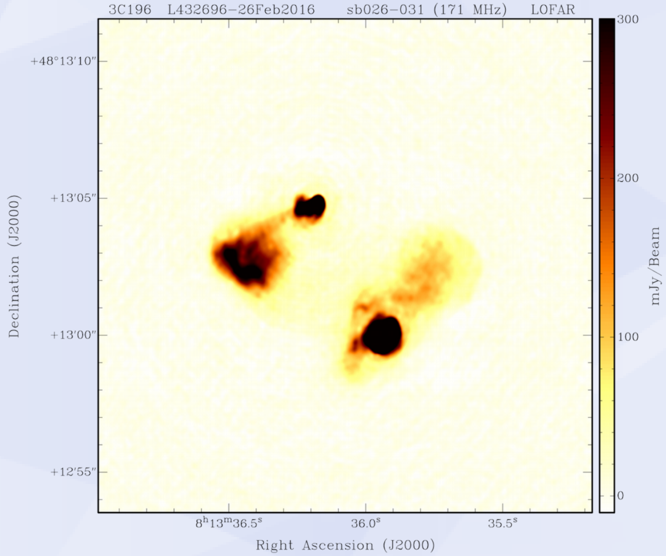
Upper limits on the 21-cm EoR power spectrum with LOFAR



Ger de Bruyn (Astron)
presented by **André Offringa** (Astron)
on behalf of the **LOFAR EoR group**

Bologna, 19 June 2017

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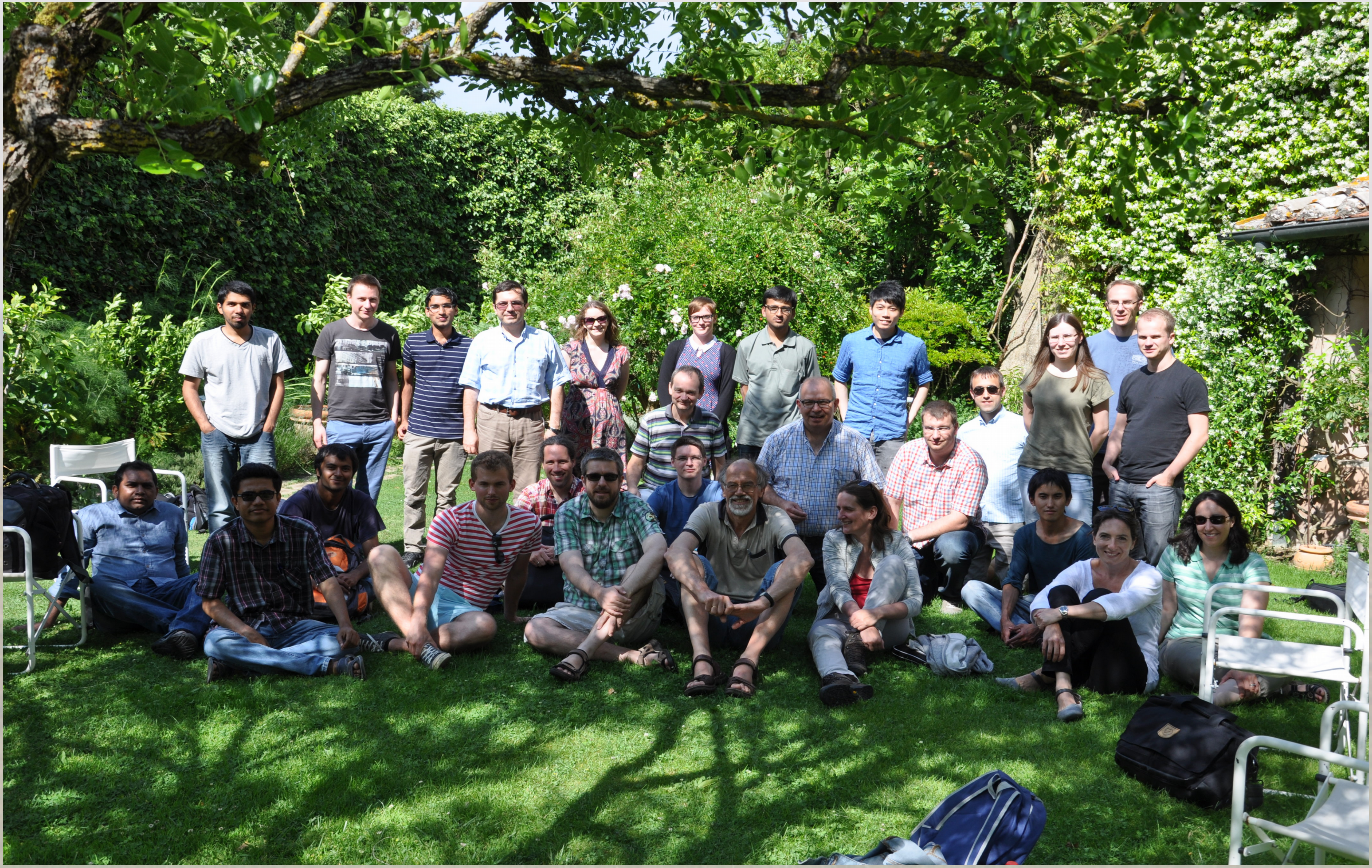
The LOFAR EoR team Spineto, Italy, June 2014

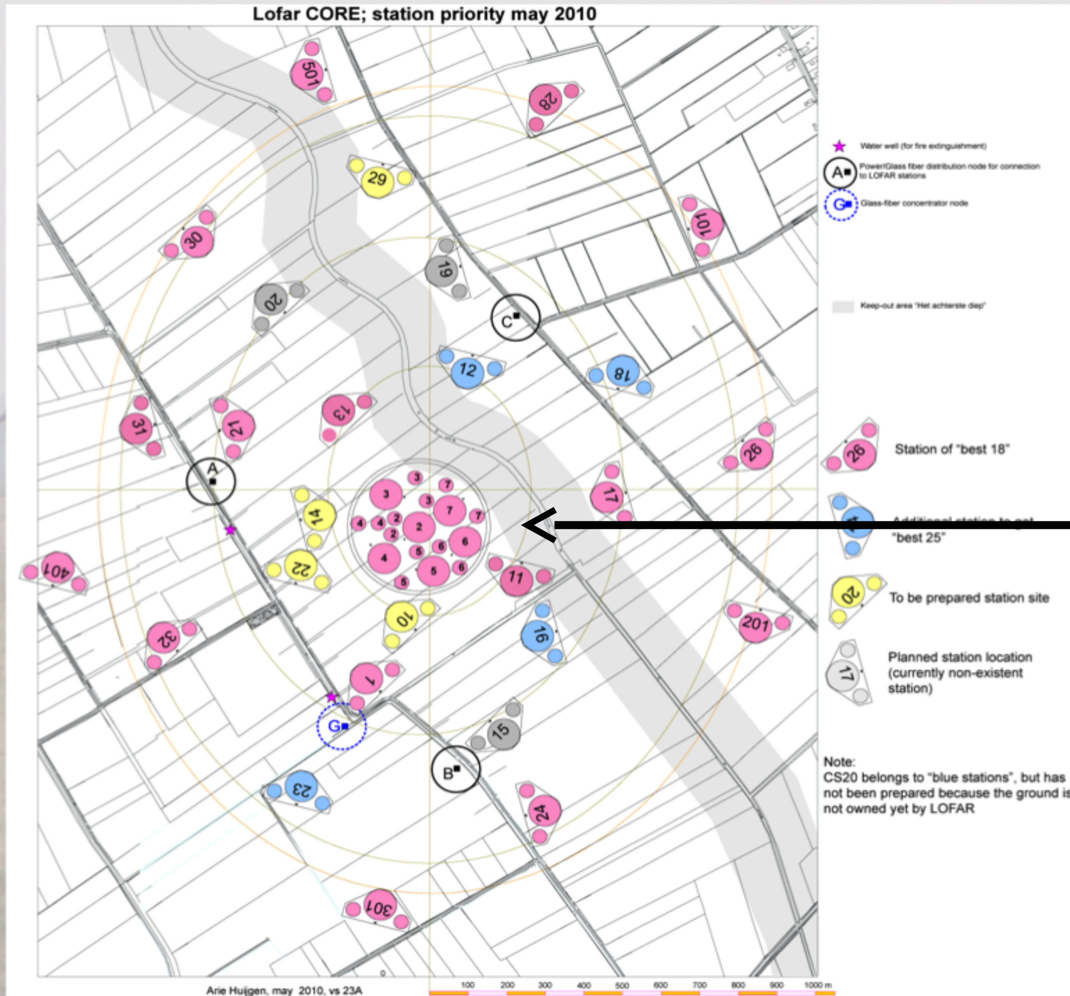


The LOFAR EoR team Spineto, Italy, June 2014

LOFAR EoR MT:
Ger de Bruyn, Leon Koopmans, André Offringa, Saleem Zaroubi, Michiel Brentjens

Working on power spectra:
Sarod Yatawatta, Maaijke Mevius, Florent Mertens,
André Offringa, Ger de Bruyn, Leon Koopmans (Ajinkya Patil)

LOFAR core configuration - ‘tailored’ to EoR project



1000 m

Core dimension
2 x 2.5 km

the iconic ‘superterp’
diameter ~ 350 m
(12 x 24-tile stations)

The Epoch of Reionization

- A key era in the evolution of our universe
- Many open questions, e.g.:
  - When and how quick?
  - What sources?
  - How did the ionization evolve?
- The EoR answers define the “initial conditions” for galaxy formation
  - Constrain cosmological parameters

UPPER LIMITS ON THE 21-CM EPOCH OF REIONIZATION POWER SPECTRUM FROM ONE NIGHT WITH LOFAR

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ABSTRACT

We present the first limits on the Epoch of Reionization (EoR) 21-cm HI power spectra, in the redshift range $z = 7.9 - 10.6$, using the Low-Frequency Array (LOFAR) High-Band Antenna (HBA). In total 13.0 h of data were used from observations centred on the North Celestial Pole (NCP). After subtraction of the sky model and the noise bias, we detect a non-zero $\Delta_{\mathrm{I}}^2 = (56 \pm 13\,\mathrm{mK})^2$ (1-σ) excess variance and a best 2-σ upper limit of $\Delta_{21}^2 < (79.6\,\mathrm{mK})^2$ at $k = 0.053\,h\,\mathrm{cMpc}^{-1}$ in the range $z = 9.6 - 10.6$. The excess variance decreases when optimizing the smoothness of the direction- and frequency-dependent gain calibration, and with increasing the completeness of the sky model. It is likely caused by (i) residual side-lobe noise on calibration baselines, (ii) *leverage* due to non-linear effects, (iii) noise and ionosphere-induced gain errors, or a combination thereof. Further analyses of the excess variance will be discussed in forthcoming publications.

Keywords: cosmology: theory - large-scale structure of Universe - observations - diffuse radiation - methods: statistical - radio lines: general - cosmology: dark ages, reionization, first stars

1. INTRODUCTION

During the Epoch of Reionization (EoR) hydrogen gas in the universe transitioned from neutral to ionized (Madau

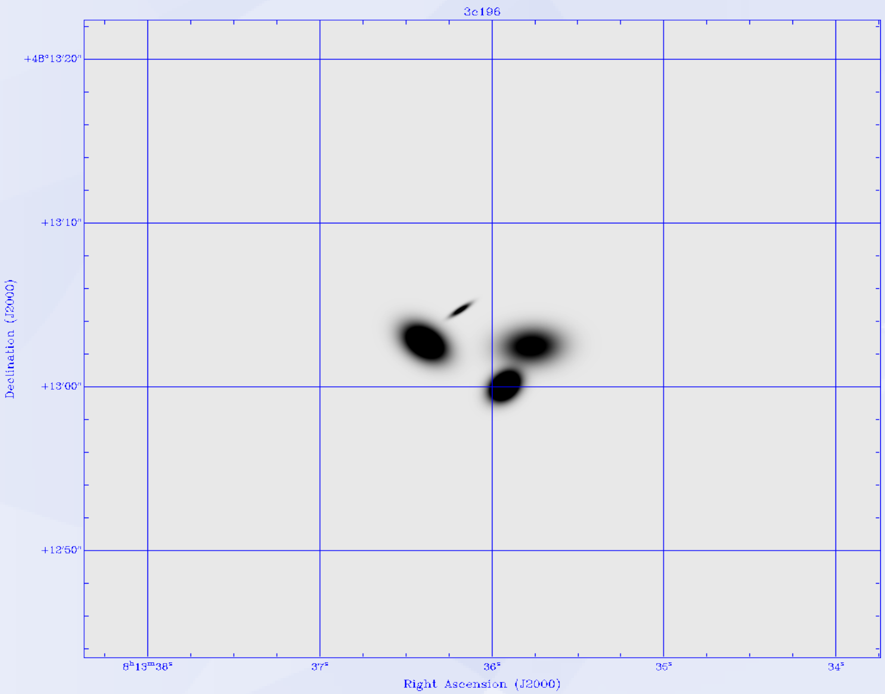
limit inferred from the Gunn-Peterson trough in high-redshift quasar spectra (Becker et al. 2001; Fan, *et al.* 2003, 2006), and the upper limit of the redshift range currently being set

LOFAR: Two main fields

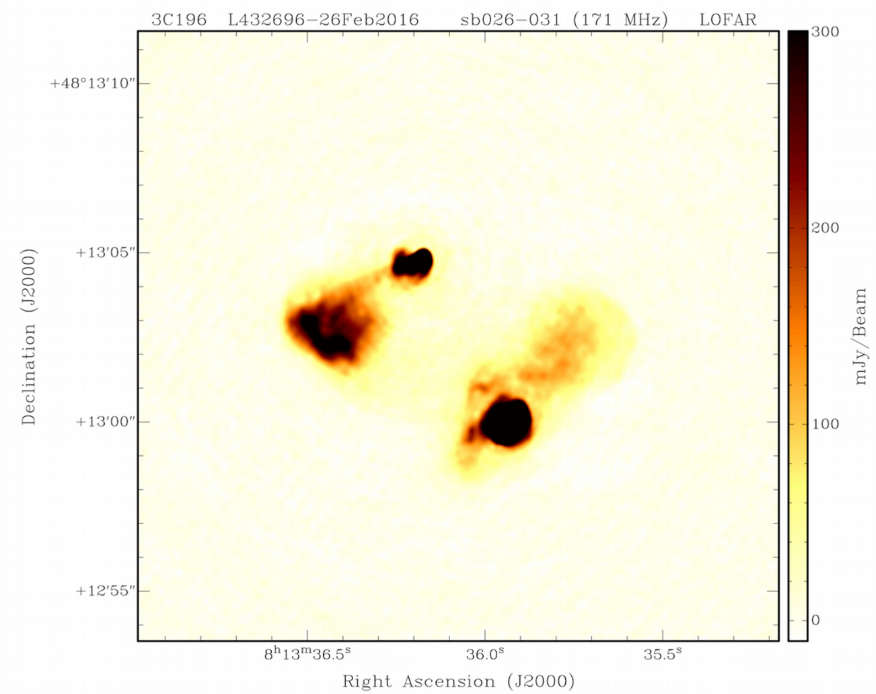
LOFAR observations are focused on 2 fields:

- **North Celestial Pole (NCP)**
  - Quiet field and always visible
  - Leaked RFI might be harder to handle.
  - 1,300 h observed, ~80% usable.
  - First 13-h upper limits published
- **3c196**
  - Not quiet, but high SNR and easier to handle RFI.
  - 1,000 h observed, ~80% usable.

VLBI 3c196 model



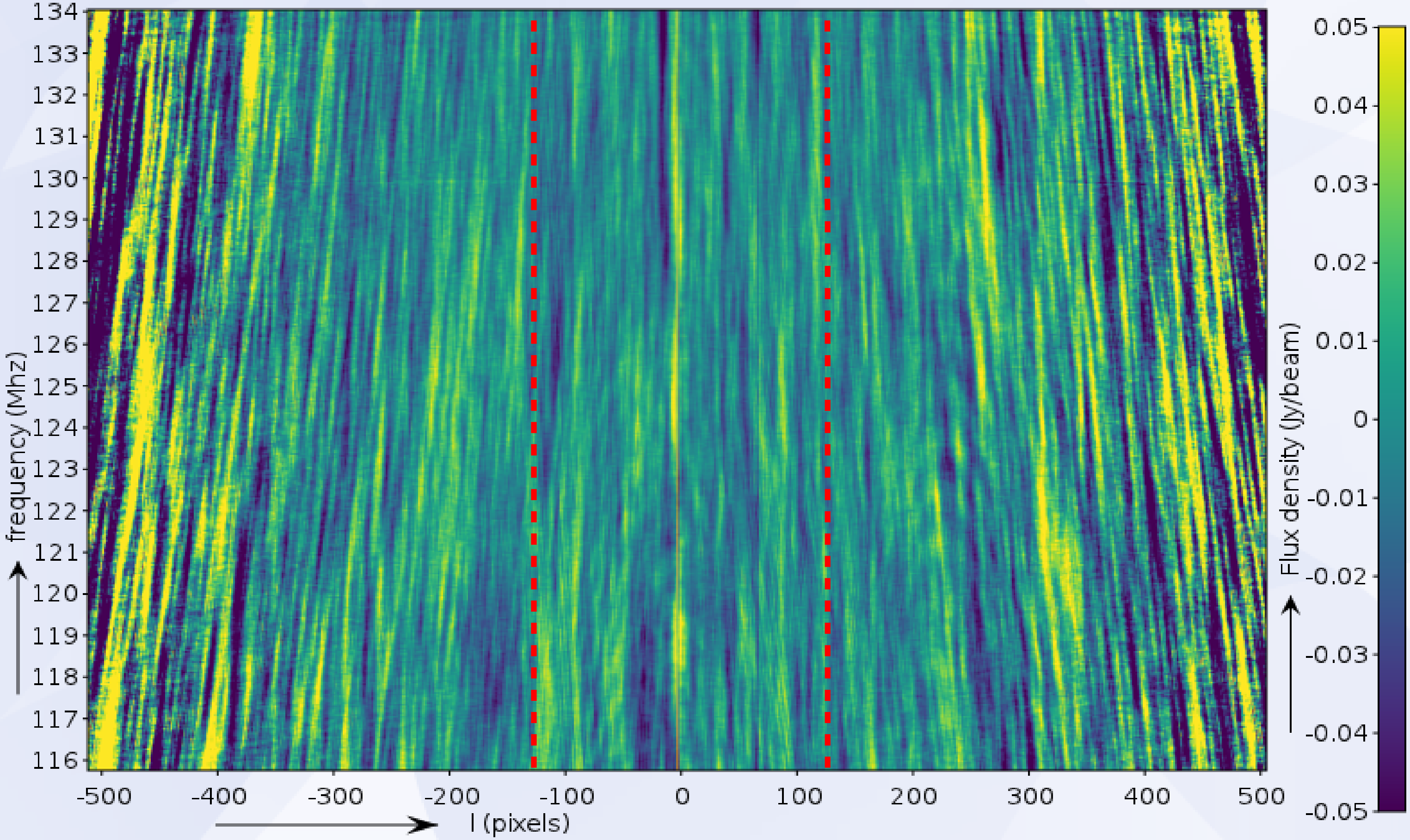
Current 3c196 model
(by P. Vishambhar)
Made from Dutch stations



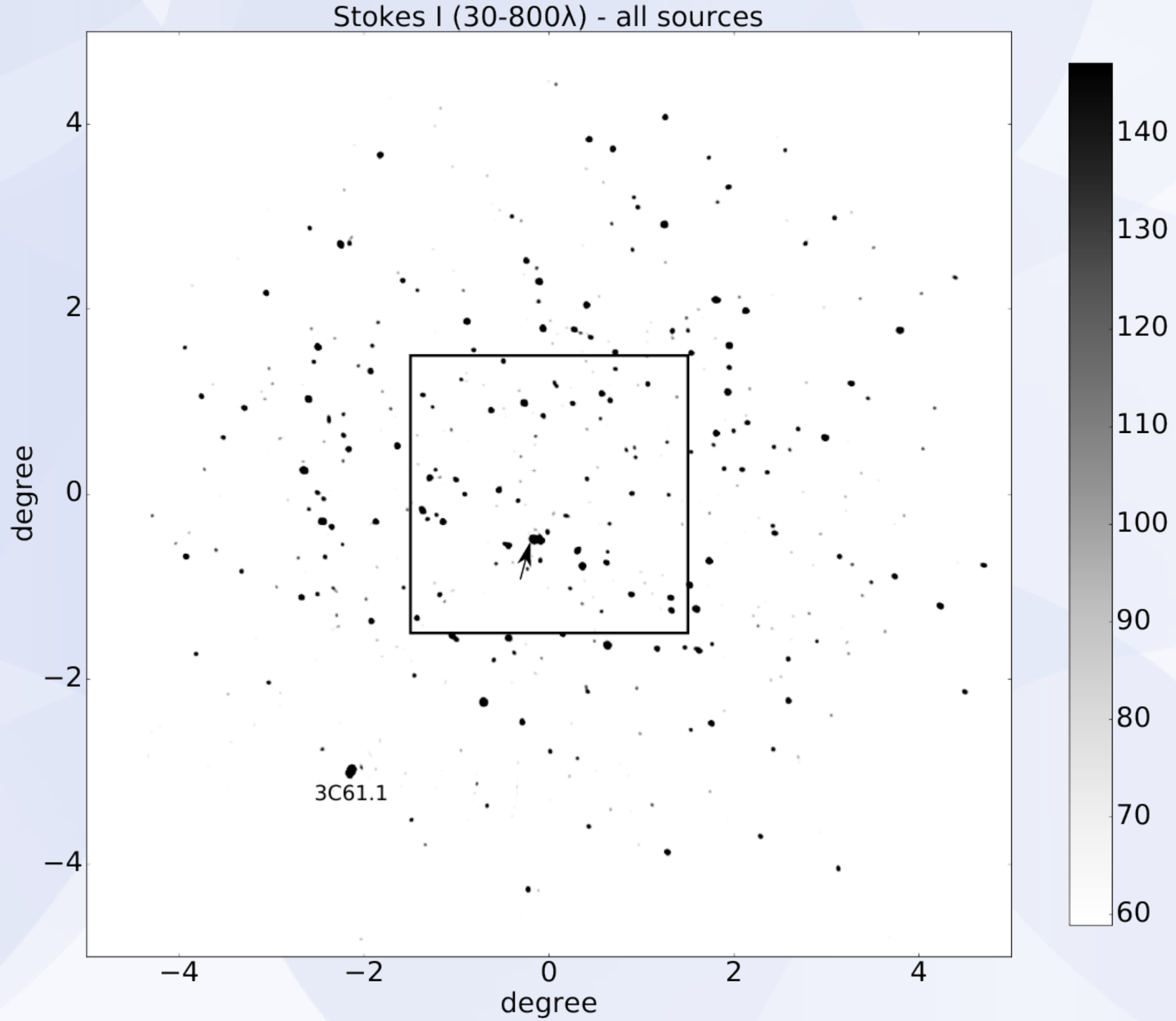
LOFAR VLBI model
(not yet used)

3c196 subtraction

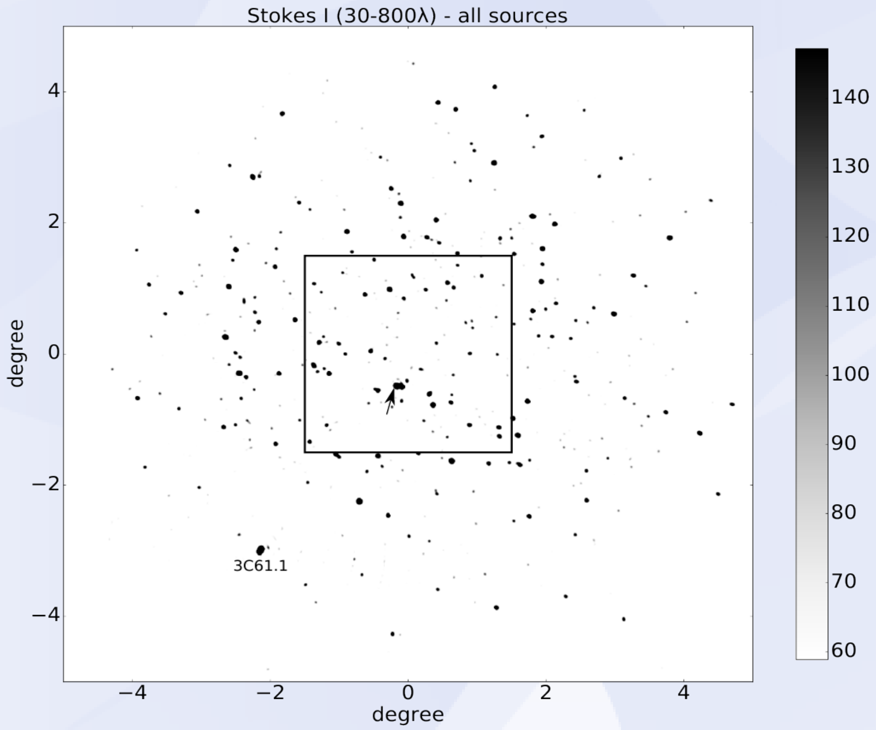
(old model)



The NCP field



Calibration strategy

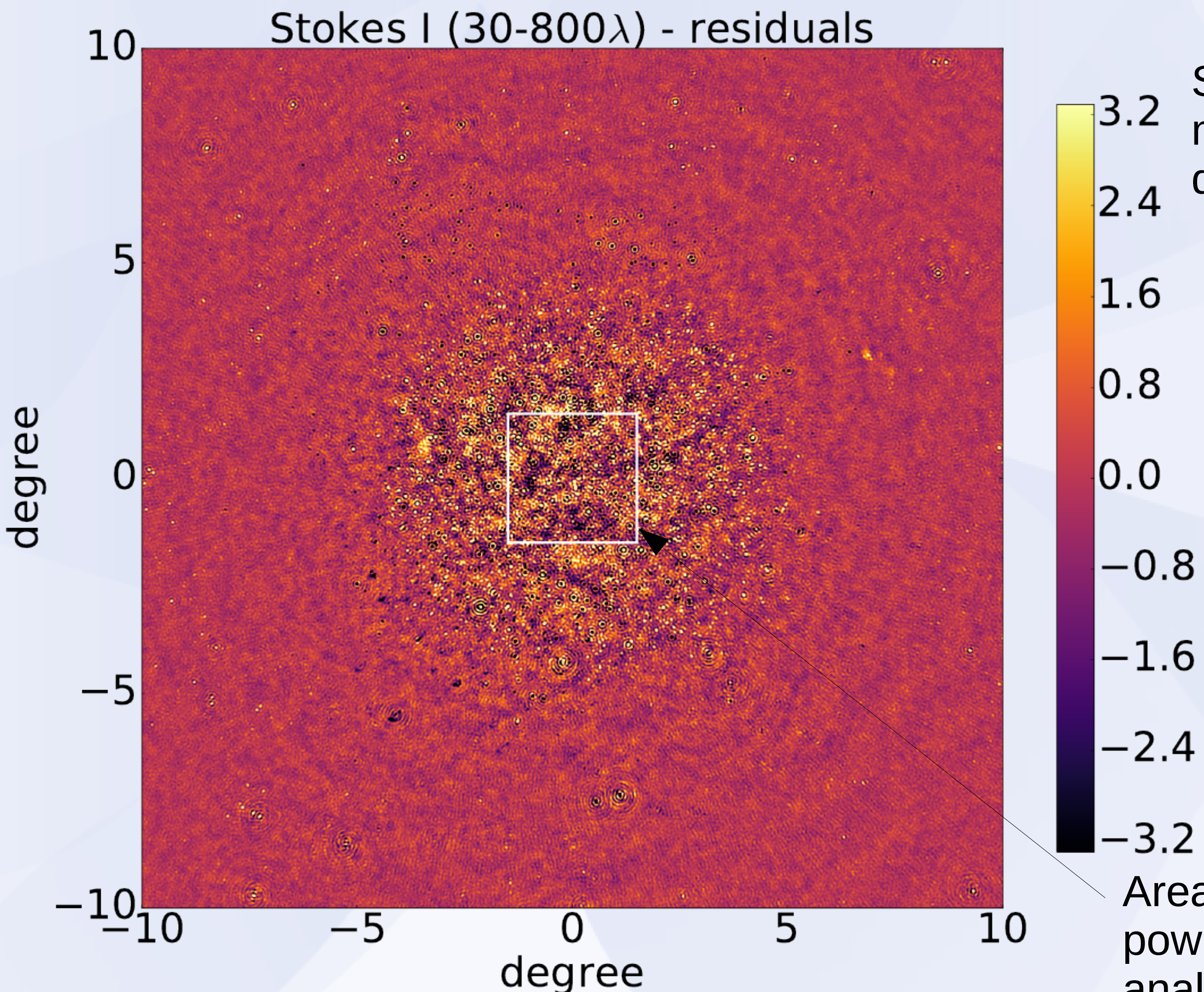


- Direction independent cal: global solution, but with separate solutions for 3c61.1
- Direction dependent cal: Subtract full model with solutions for 120 directions
- Both steps are performed with Sagecal Concensus (S. Yatawatta), using long baselines only.
- Sagecal uses regularization to penalize unsmooth solutions over frequency

Recent progress

- So far, we have **excluded 50-250λ data** in calibration to avoid **signal suppression**, but giving rise to statistical leverage (**excess noise**).
- Our model now includes **diffuse Stokes I, Q & U (RM=0) emission**. This avoids suppression and therefore allows **including 50-250λ data** in DD calibration.
- We switched from **GMCA** to **Gaussian Process Regression** (GPR, Mertens in prep.) for removing diffuse emission.
- We continue to improve our models:
  - Work on automated modelling pipeline, more sources
  - LOFAR VLBI measurements

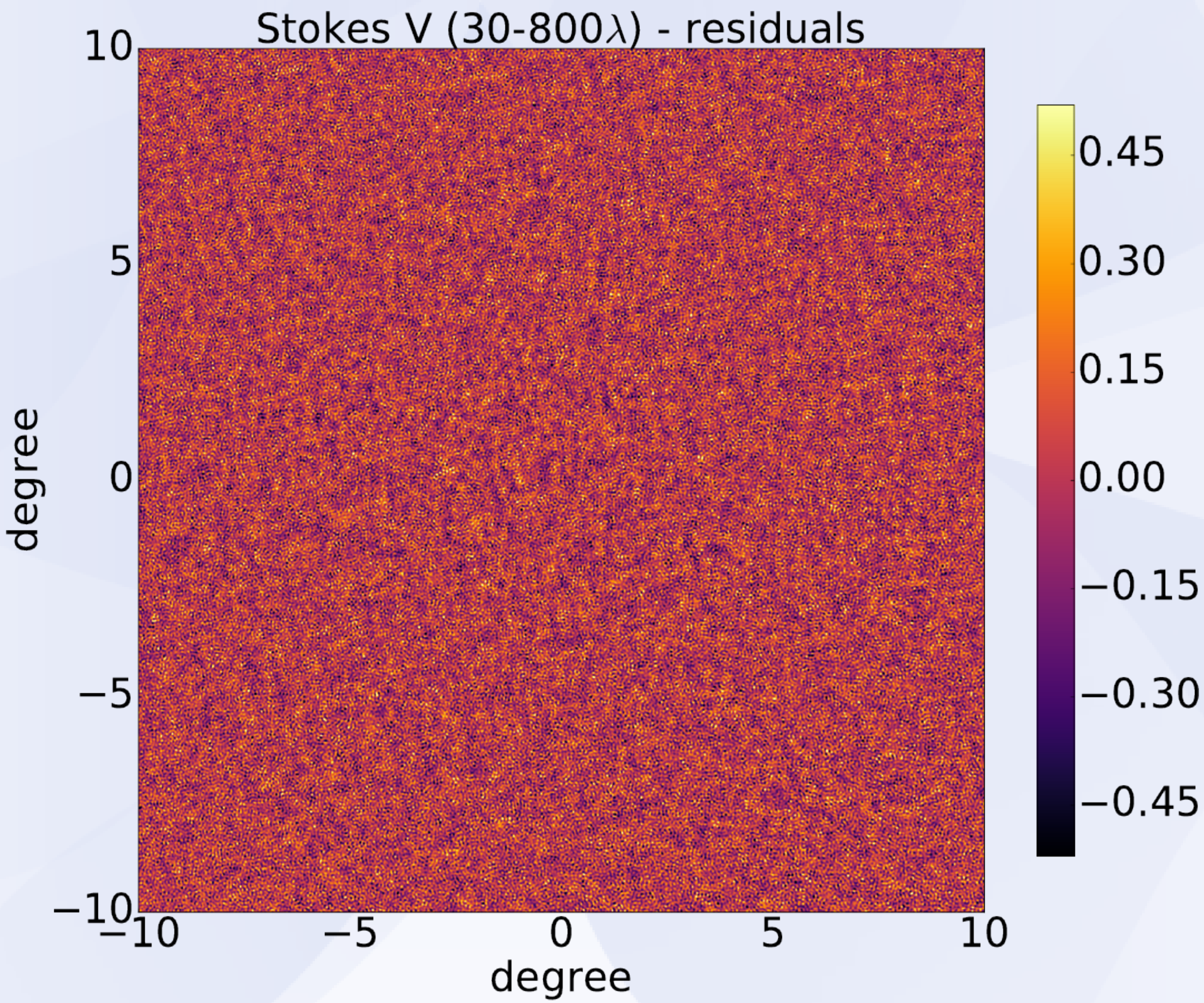
Stokes I, after running Sagecal



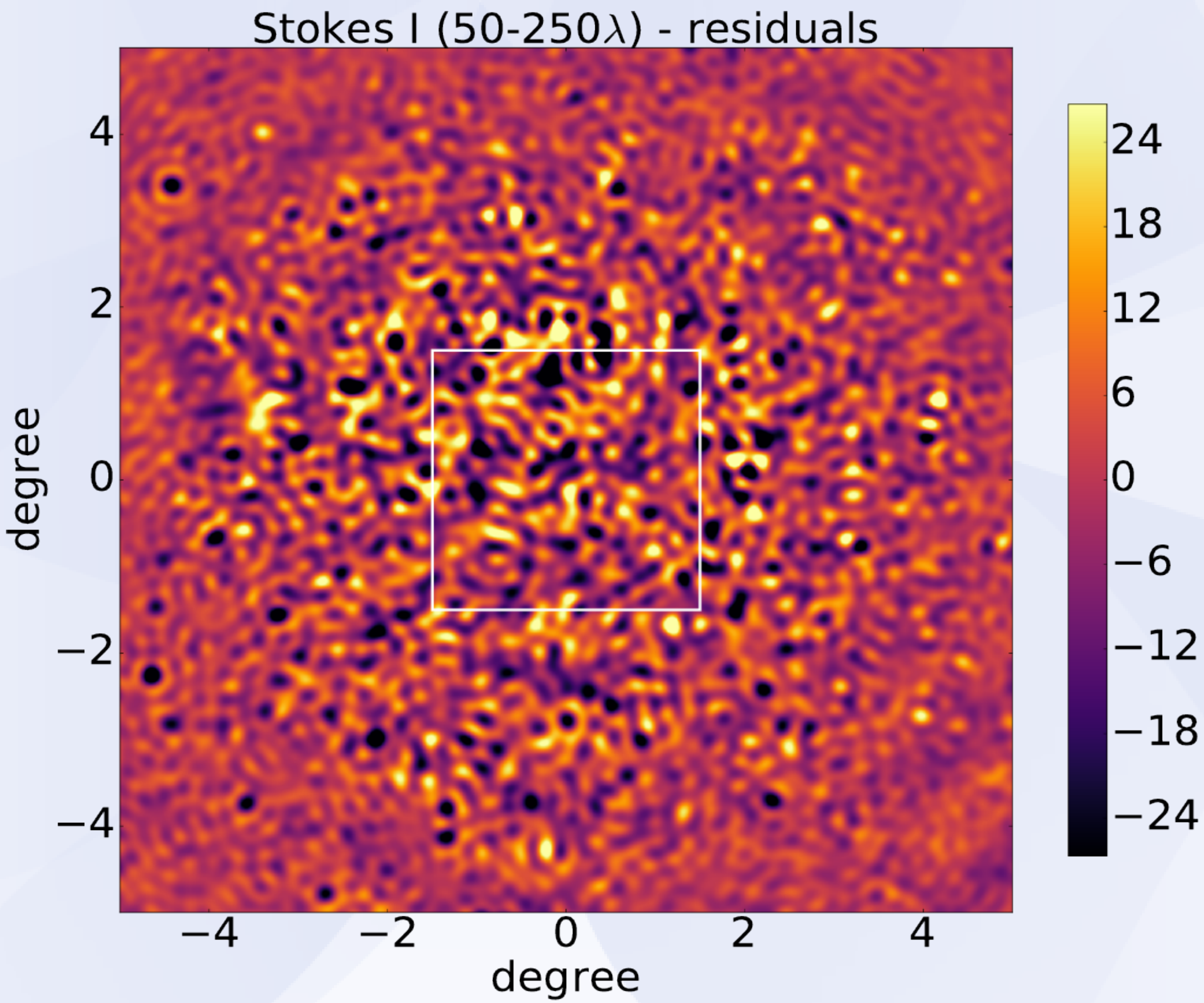
Sagecal subtracts the sky model with direction dependent solutions

Area used for the power spectrum analysis

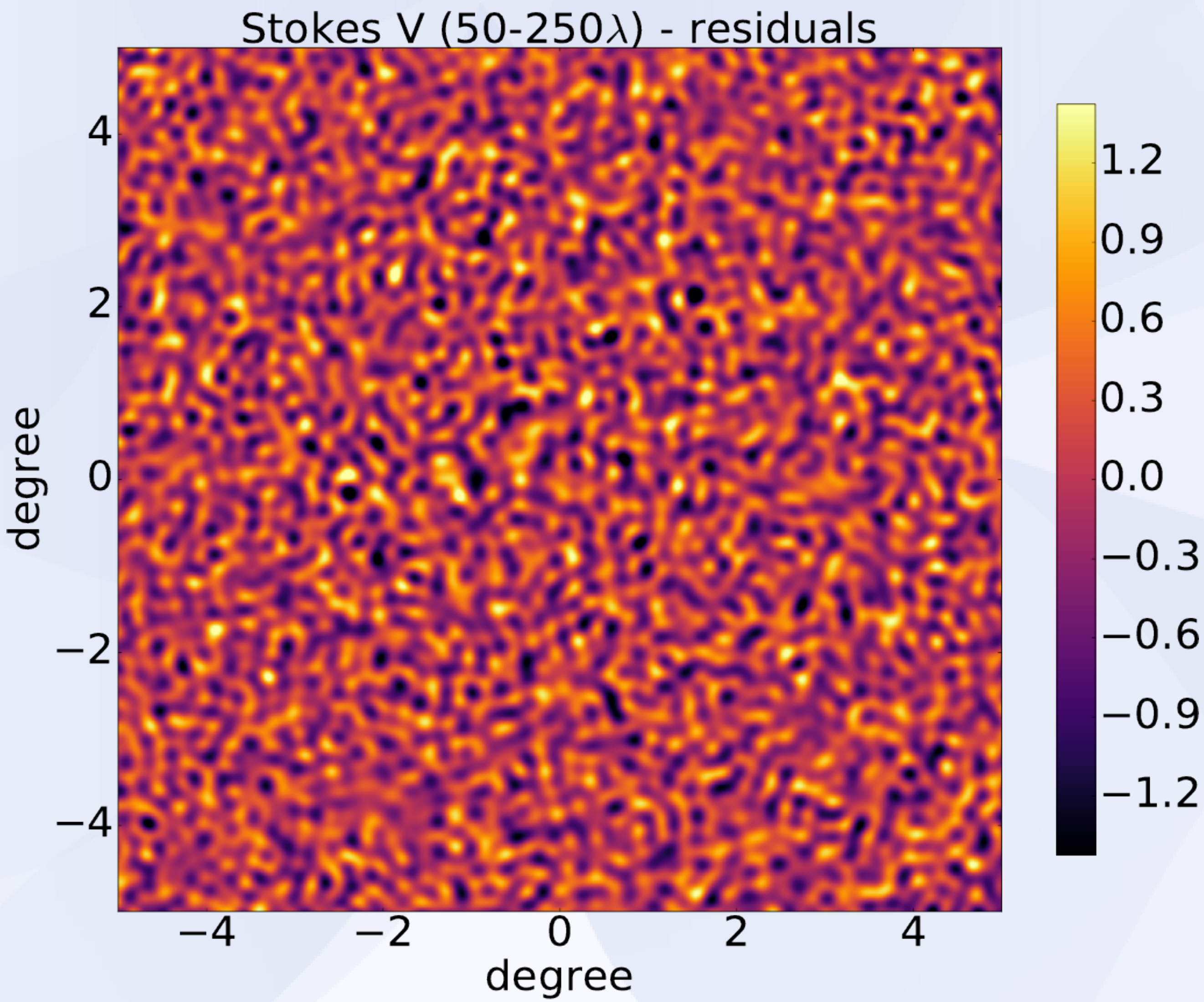
Stokes V, after running Sagecal



Stokes I at “PS resolution”



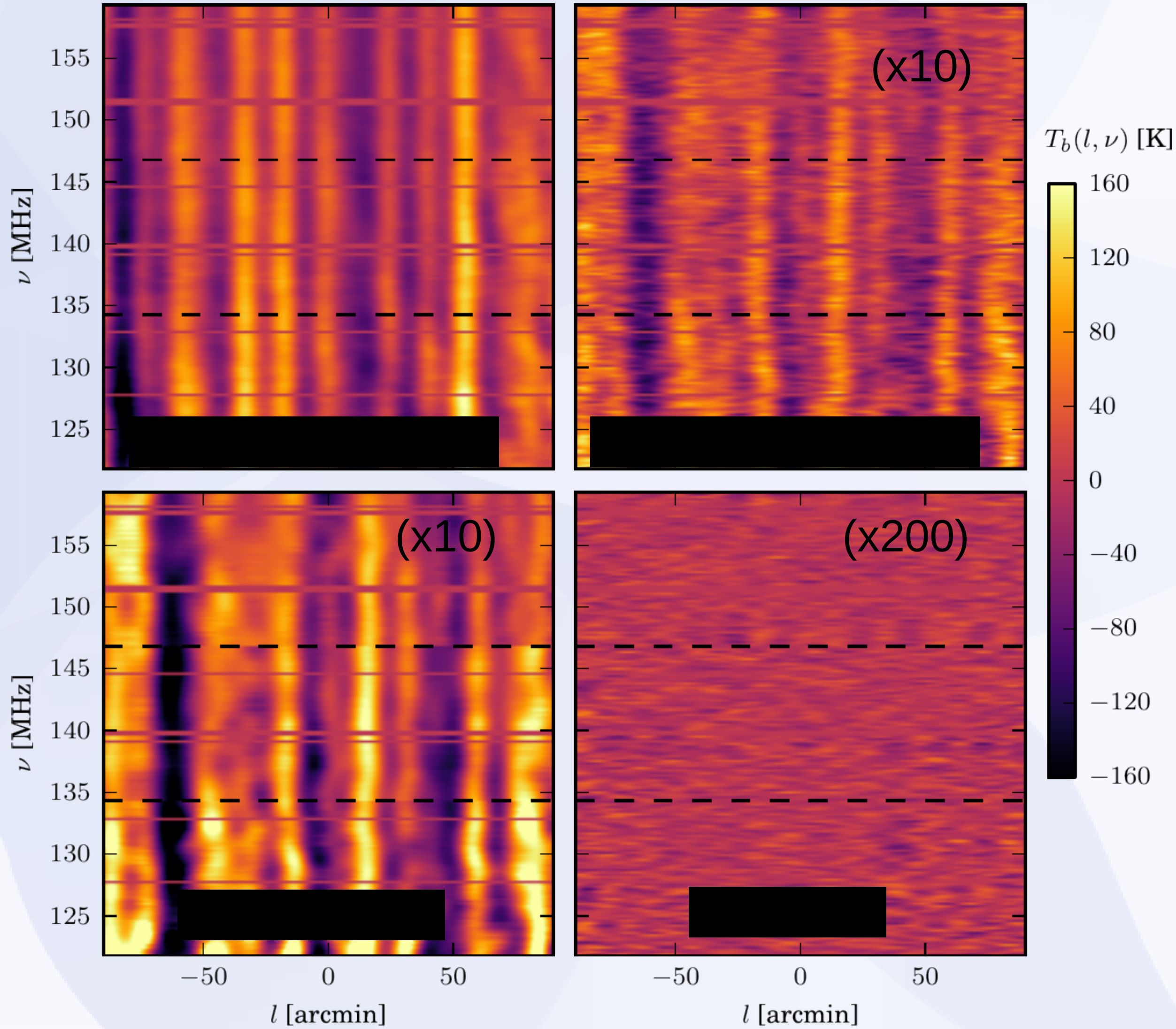
Stokes V at “PS resolution”



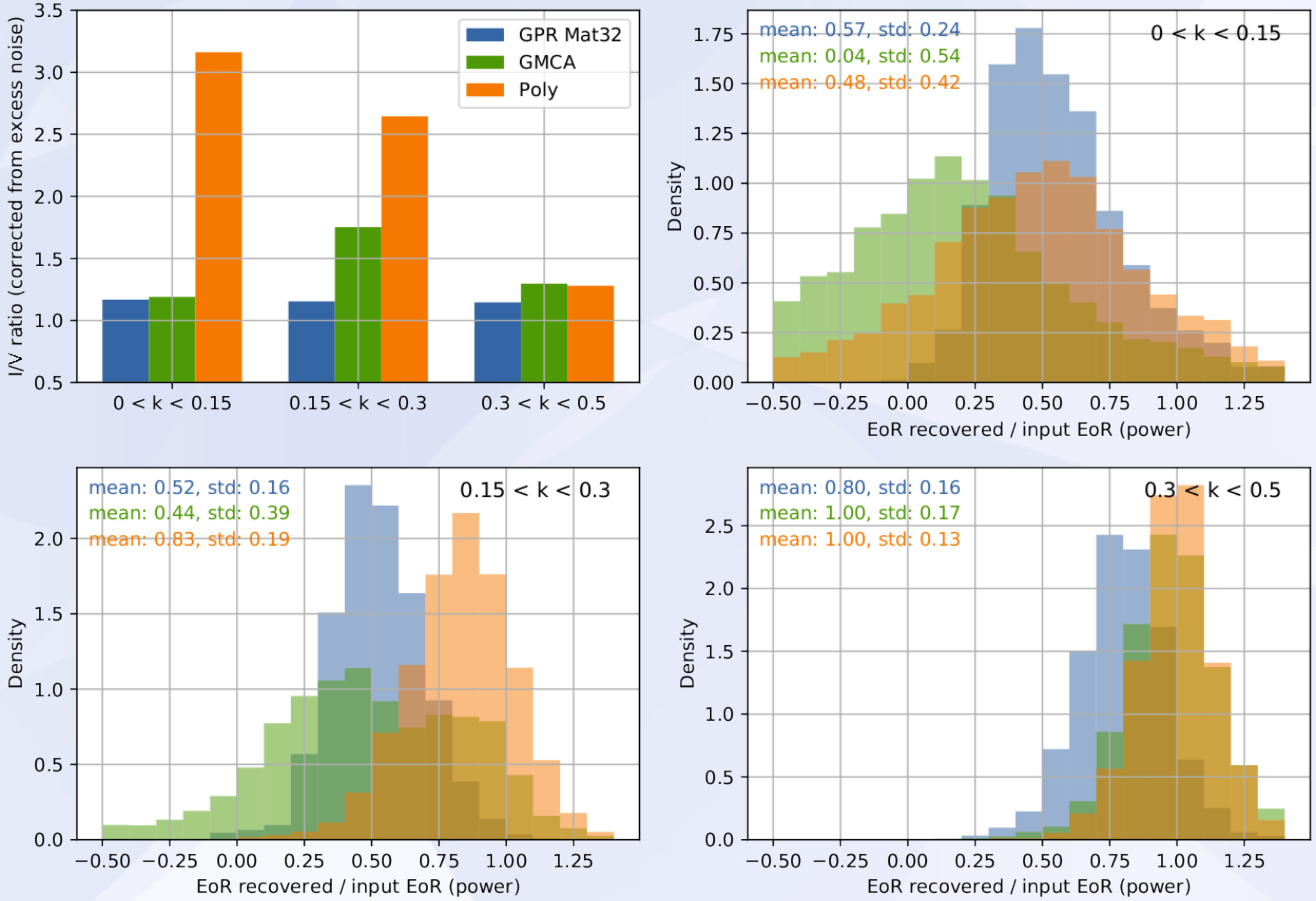
Diffuse foreground removal

After calibration, "GMCA" is used to remove diffuse, "non-EoR"-like signals.

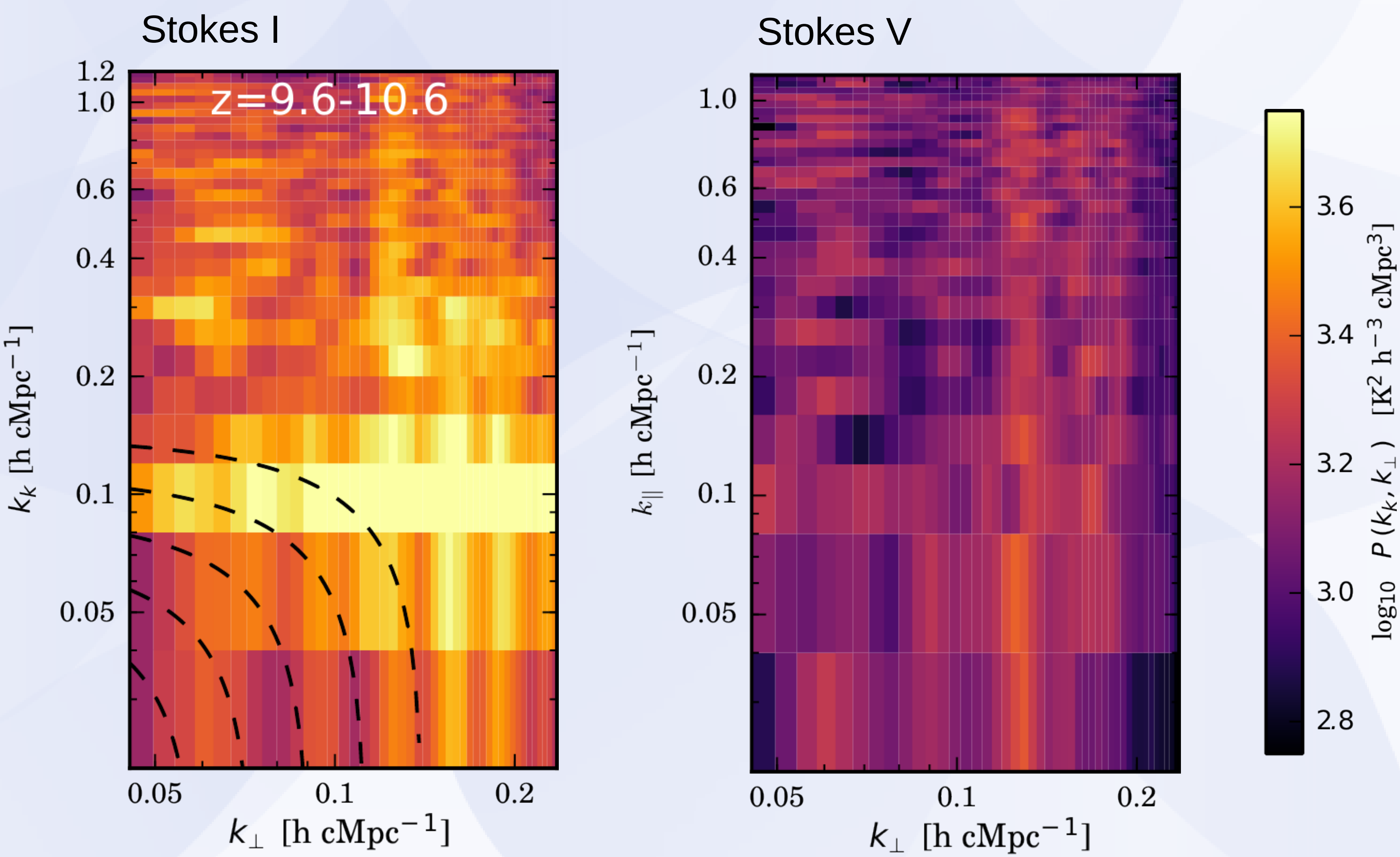
Figure to the right: Slices throught the image cube



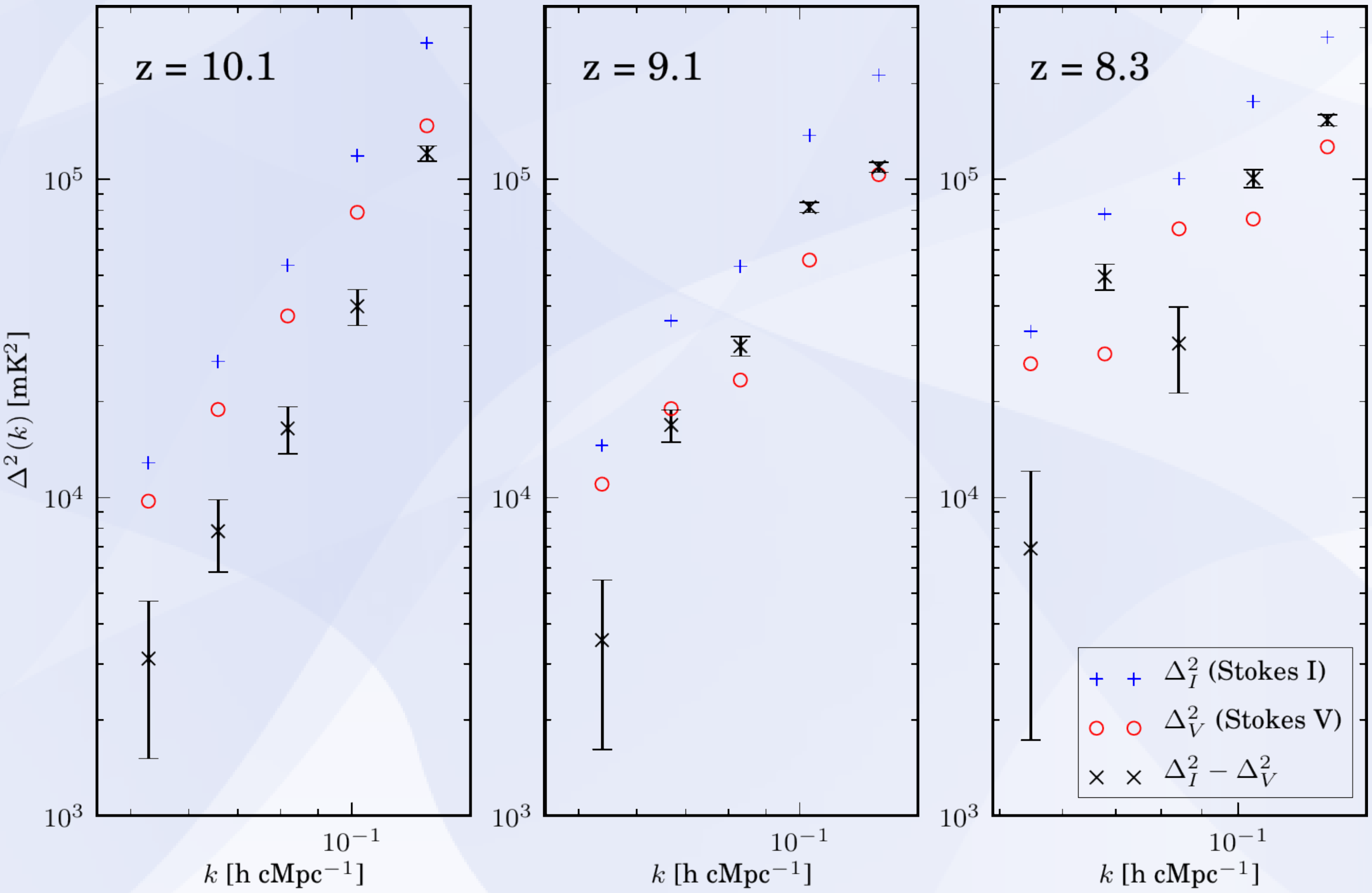
New diffuse subtraction method: GPR



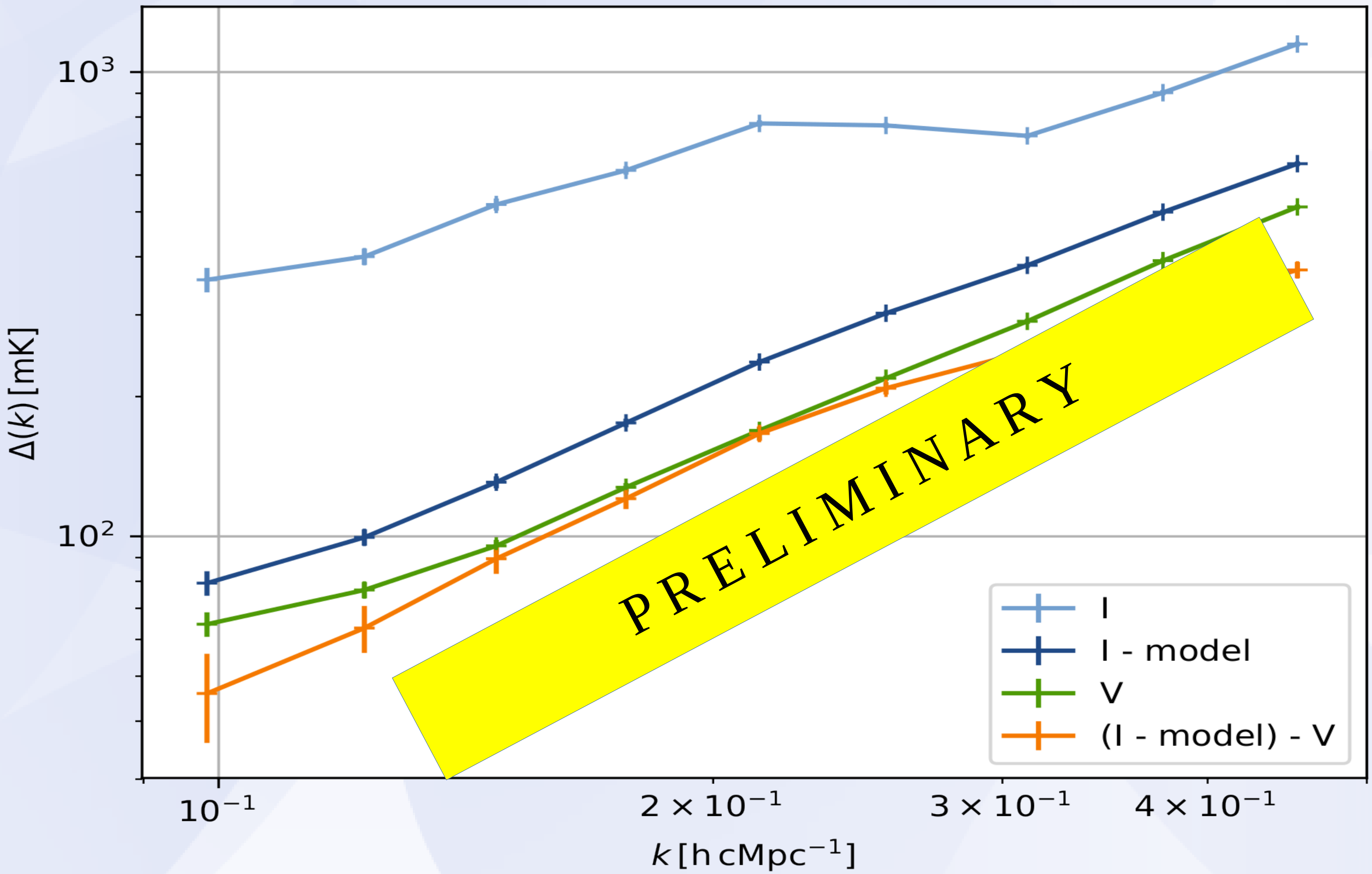
Cylindrical power spectra



Spherical power spectra



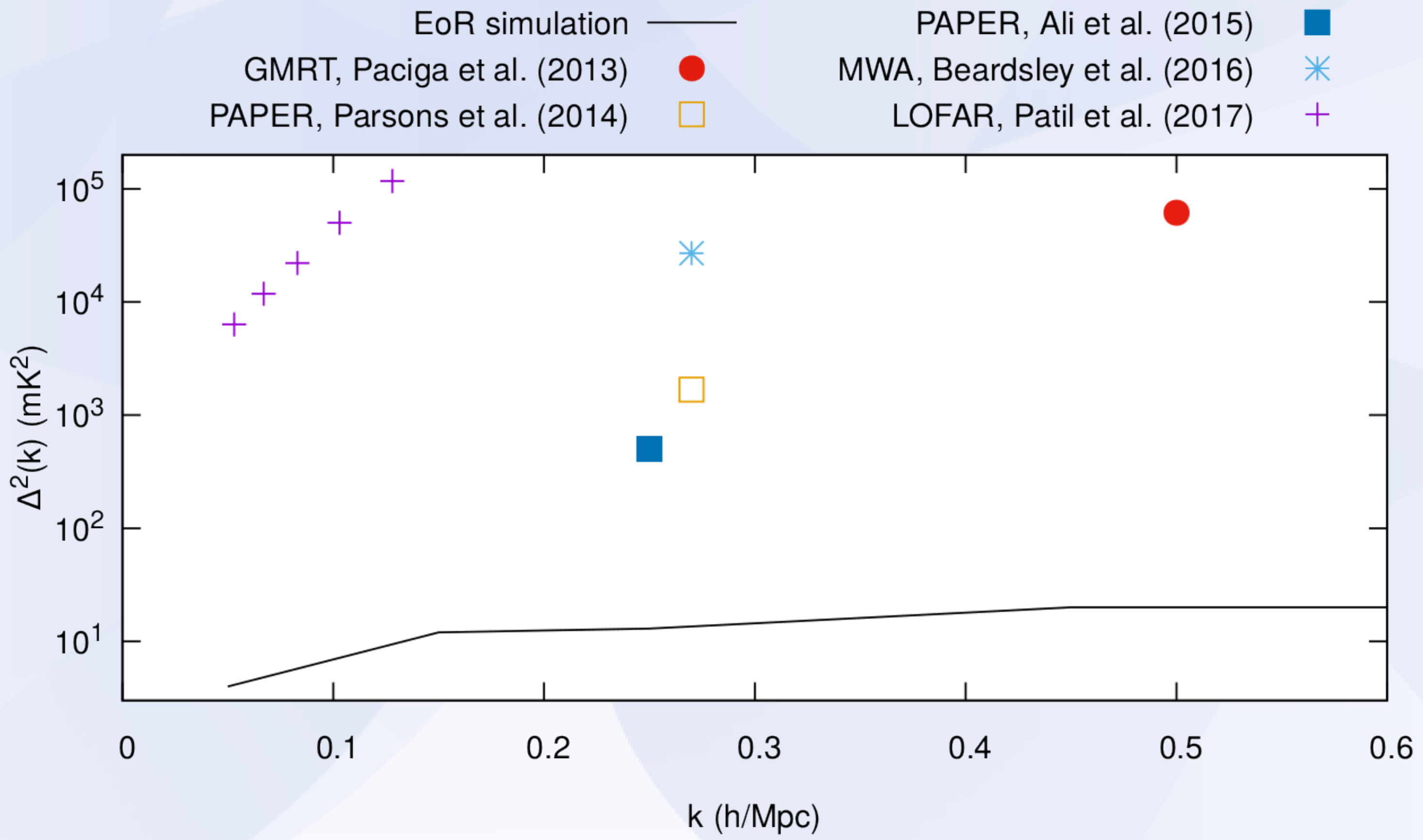
3-night spherical PS
(preliminary)



131-146 MHz (z=9.1), error bars at 1 sigma

Comparison of current progress

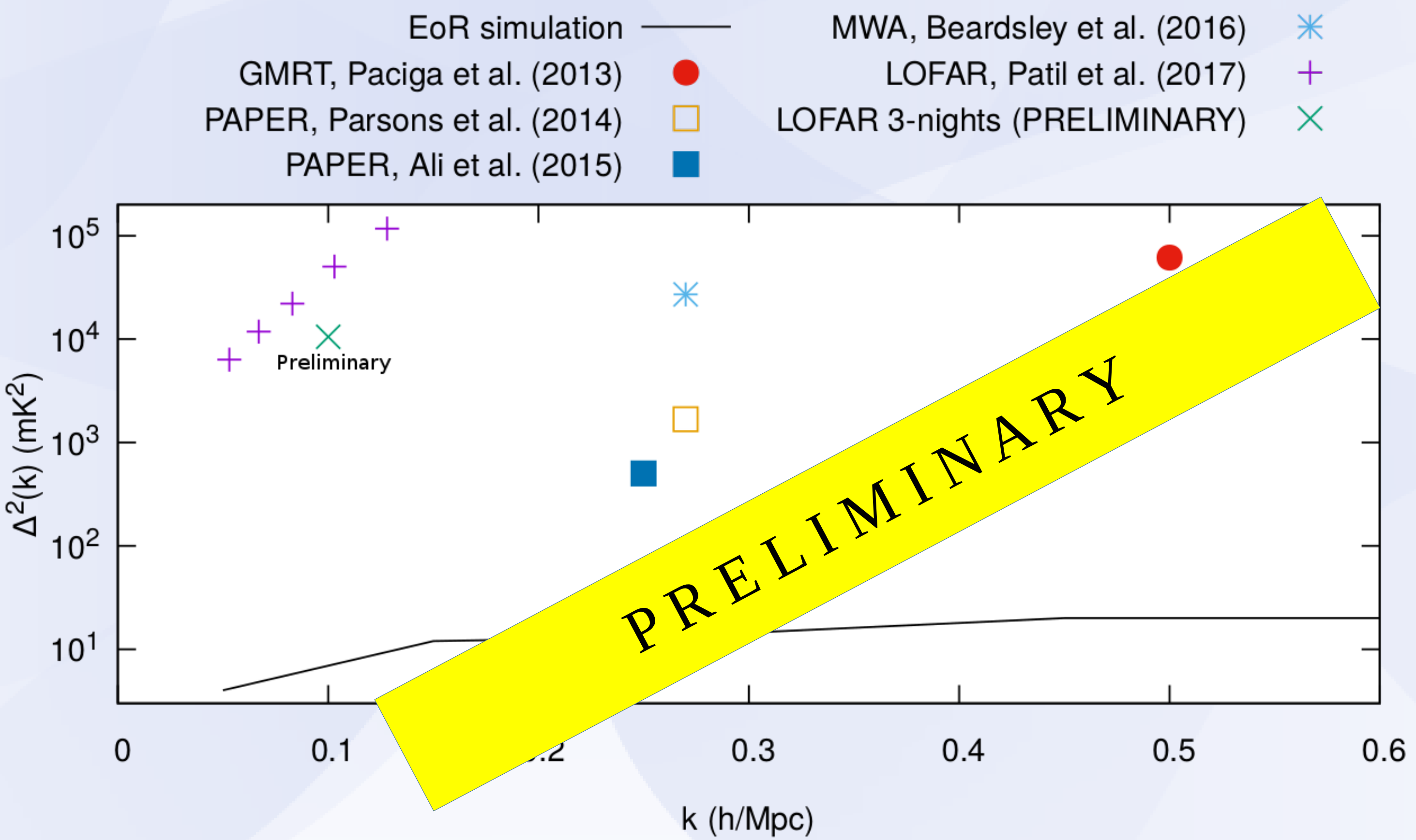
Current best 2-sigma upper limits
NB: Limits are at different redshifts



MWA results:
32 hours
GMRT results:
50 hours
PAPER'15 results:
135 days
LOFAR results:
13 hours

Comparison of current progress

Current best 2-sigma upper limits
NB: Limits are at different redshifts



MWA results:
32 hours
GMRT results:
50 hours
PAPER'15 results:
135 days
LOFAR results:
13 hours
Preliminary results:
3 nights

Next steps

- Process 10-20 nights of the NCP
  - Include 50-250 λ data in DD calibration
  - With GPR
- Improve model & strategy for deconvolution & calibration
- Use VLBI 3c196 model