Advanced modeling of bright radio sources for LOFAR 21-cm power spectrum analysis: the Cygnus A and 3C196 cases

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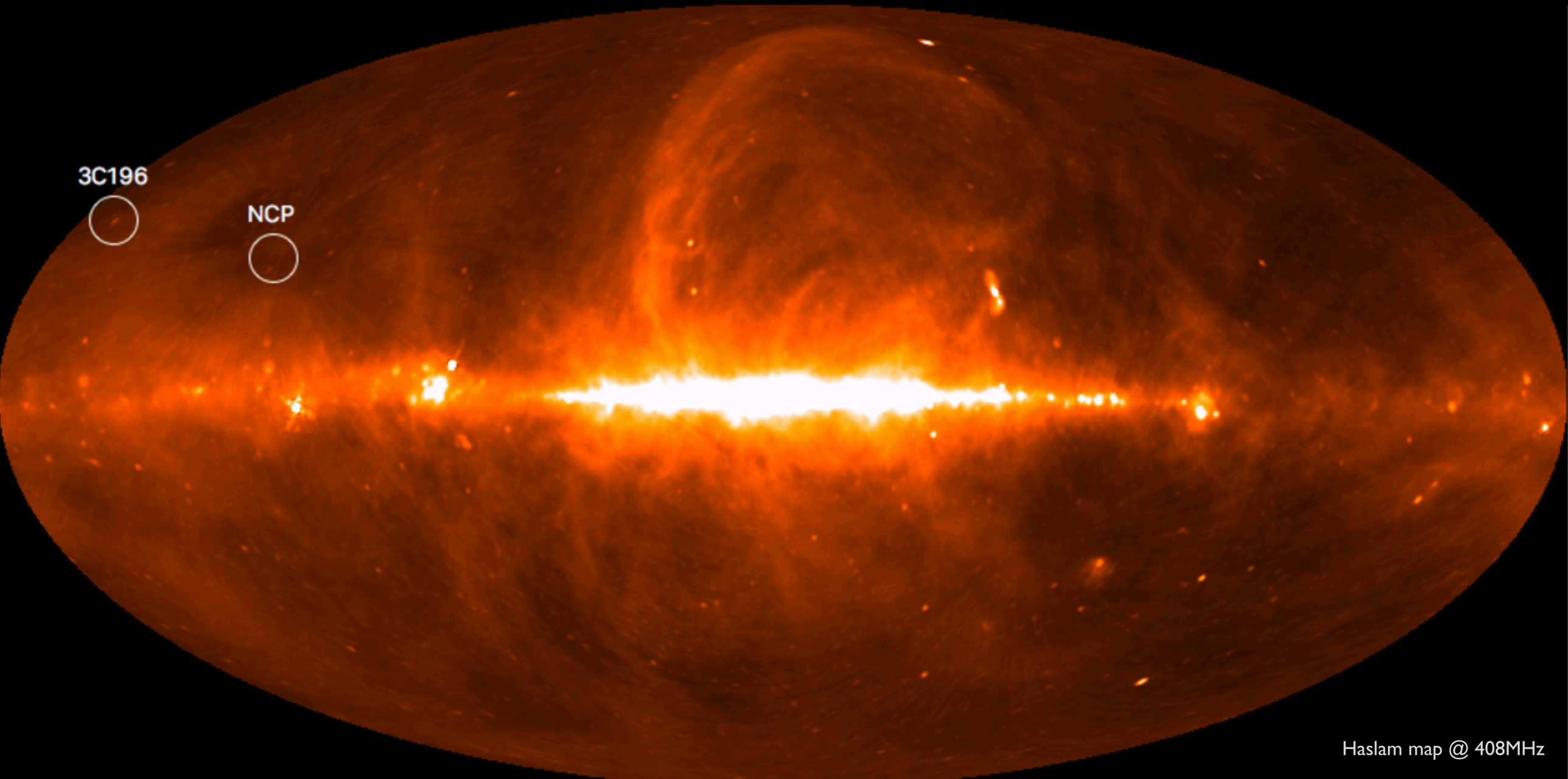
with the collaboration of the LOFAR-EoR team

LOFAR Family Meeting, 2024/06/06

LOFAR-EOR PROJECT



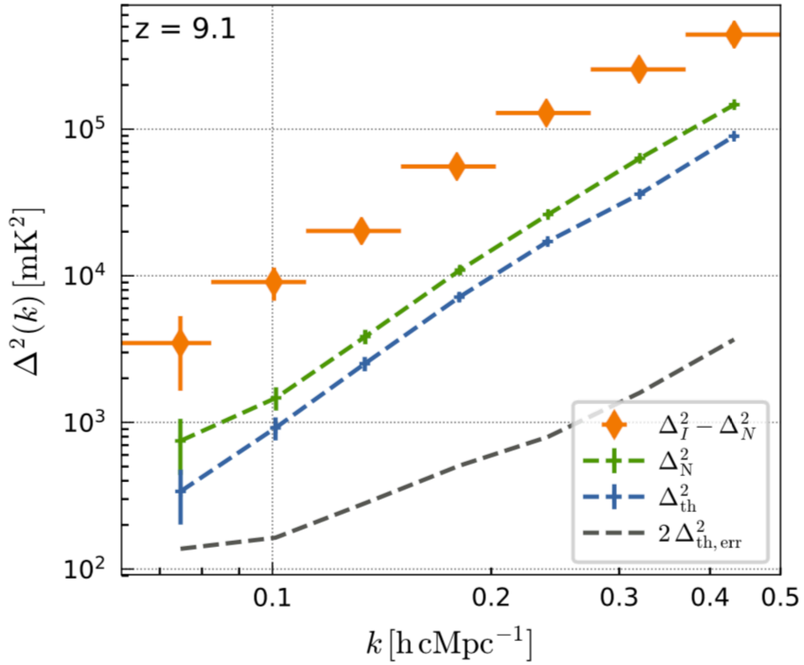
Haslam map @ 408MHz

LOFAR-EOR PROJECT

3C196

NCP

Latest upper limits from **NCP** (Mertens et al. 2020)

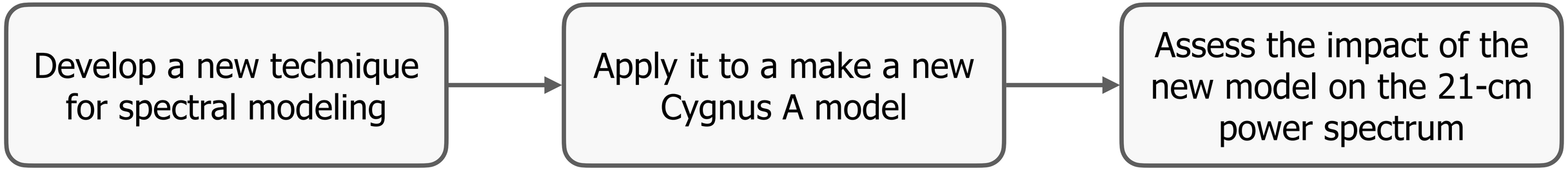


Excess power can be related to:

- *residuals from foreground subtraction*
- calibration errors
- ionospheric effects
- Radio-Frequency Interference
- …

Haslam map @ 408MHz

IS THE NCP EXCESS DUE TO FOREGROUND RESIDUALS?



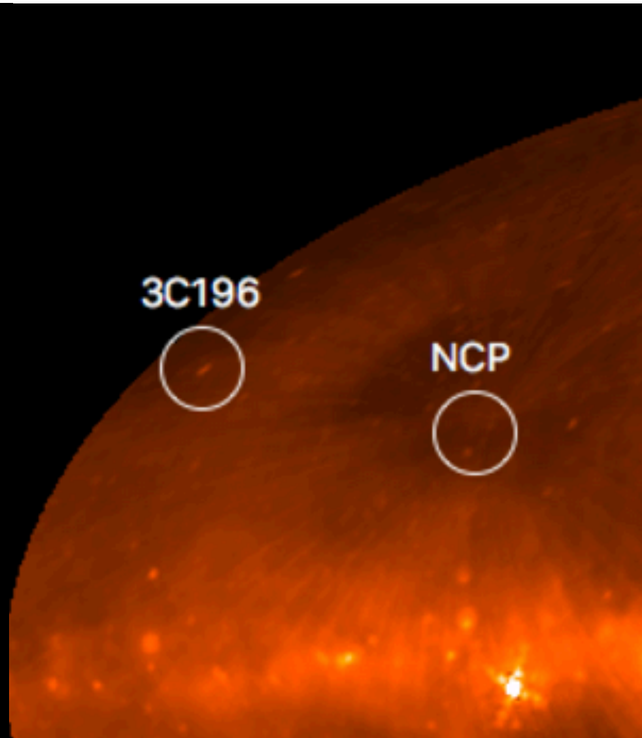
IS THE NCP EXCESS DUE TO FOREGROUND RESIDUALS?

Develop a new technique for spectral modeling → Apply it to a make a new Cygnus A model → Assess the impact of the new model on the 21-cm power spectrum

… BUT WHAT ABOUT THE 3C196 FIELD? IS THERE AN EXCESS THERE?

Make a sky model of the field taking advantage of the latest LOFAR software (DP3, WSClean)

Extract the first upper limits at z~9.16



FORCED-SPECTRUM FITTING (WSCLEAN)

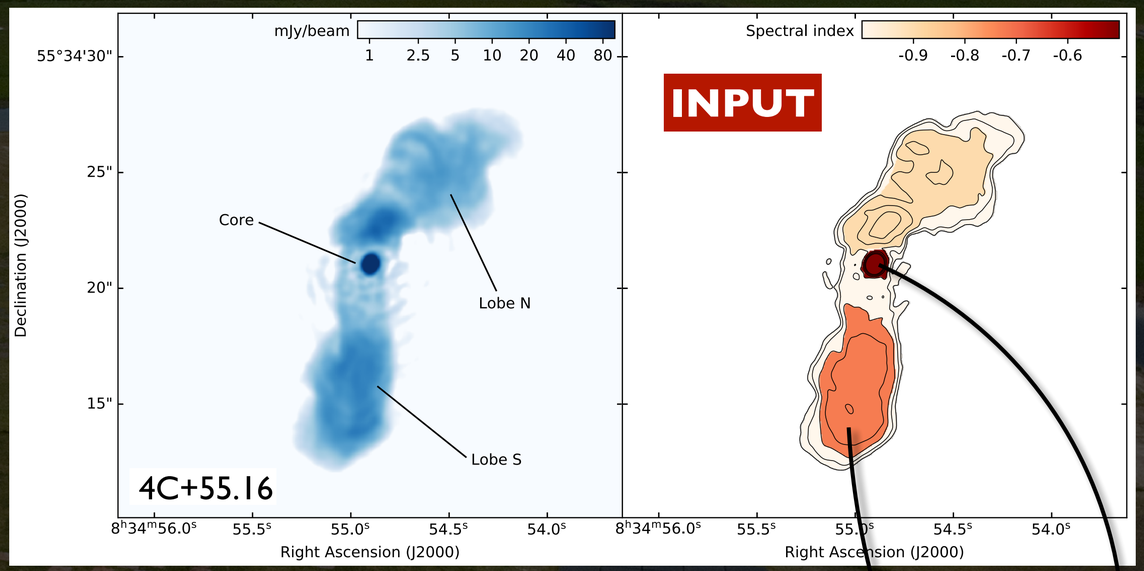
Use a **pre-existing spectral index map** to force spectral indices of each clean components during multi-frequency deconvolution, fitting a **logarithmic polynomial**

spectral index

$$S(\nu) = \exp\left[\log S_0 + \alpha \log \frac{\nu}{\nu_0} + \beta \left(\log \frac{\nu}{\nu_0}\right)^2\right]$$

flux normalisation (*weighted linear least-squares fitting*)

curvature



Name	Type	RA	Dec	I (Jy)	SpectralIndex
s0c1069	POINT	$08^h34^m54^s.906$	$55°34'20''.950$	0.293	1.738
s3c41	GAUSSIAN	$08^h34^m54^s.971$	$55°34'18''.750$	0.010	−0.724

OUTPUT

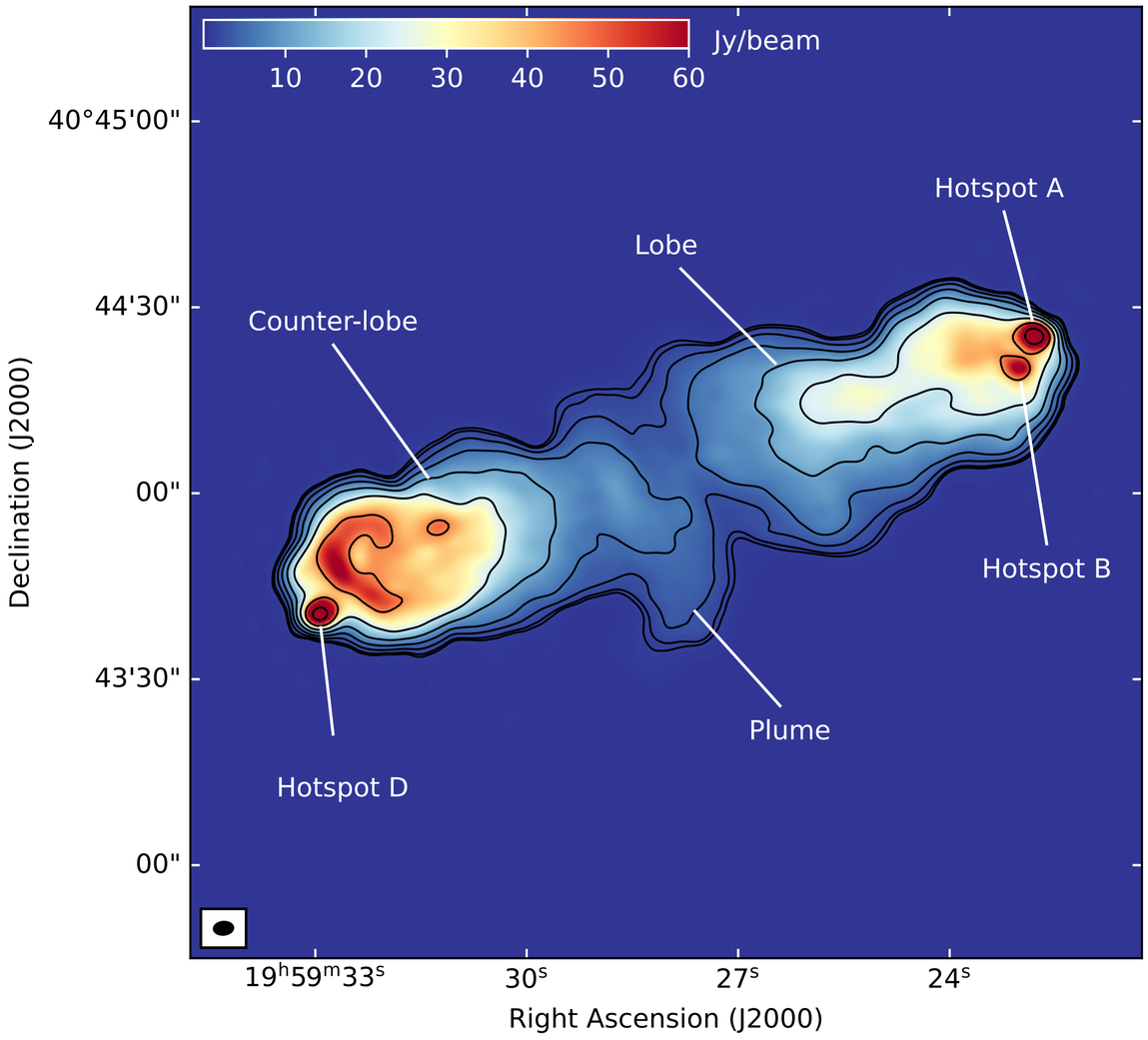
Text model file: each line is a cleaned component

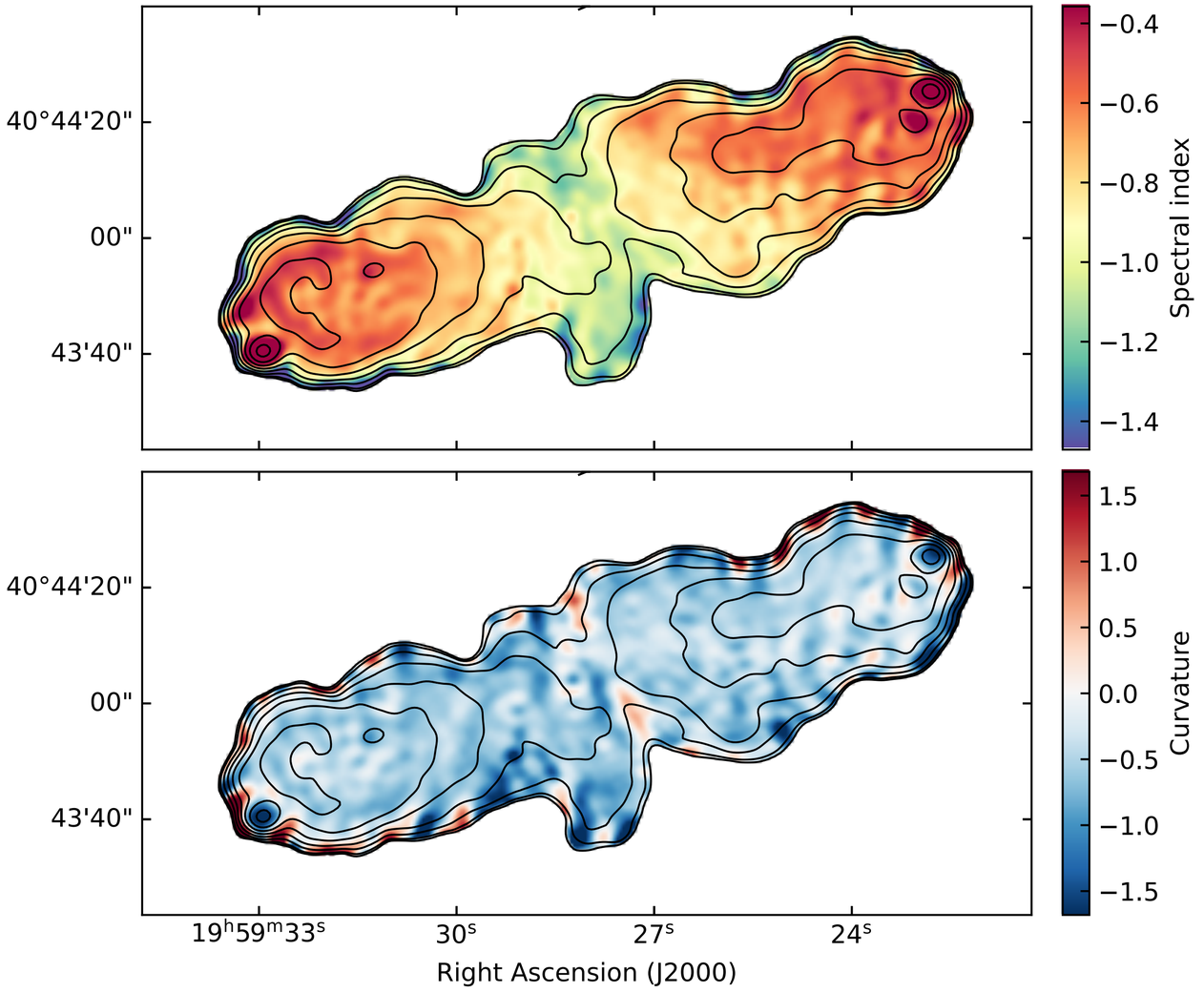
Any kind of spectral index map can be used:

- from **multi-instruments** data
- from **in-band** observations
- applying any **smoothing**

NEW CYGNUS A MODEL

12h of **LOFAR HBA-mid** (110-180 MHz) & **HBA-high** (210-250 MHz) observations





```
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s0c2057,POINT,-04:00:35.872,40.44.34.496,-0.1705819,[-0.8523039,-0.4598097],tru
s0c2058,POINT,-04:00:36.136,40.44.34.495,-0.004446548,[-1.227291,2.360613],true
s1c10,GAUSSIAN,-04:00:29.009,40.43.43.498,0.0368371,[-0.5594726,-0.8271046],tru
s1c11,GAUSSIAN,-04:00:29.053,40.43.43.498,0.02156431,[-0.5554785,-0.8329763],tr
s1c12,GAUSSIAN,-04:00:29.097,40.43.43.998,0.05520307,[-0.5635682,-0.8319924],tr
```
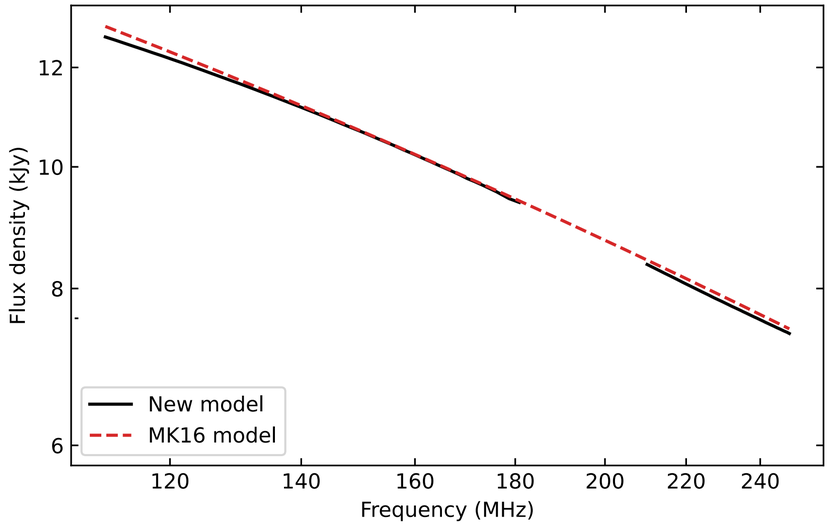
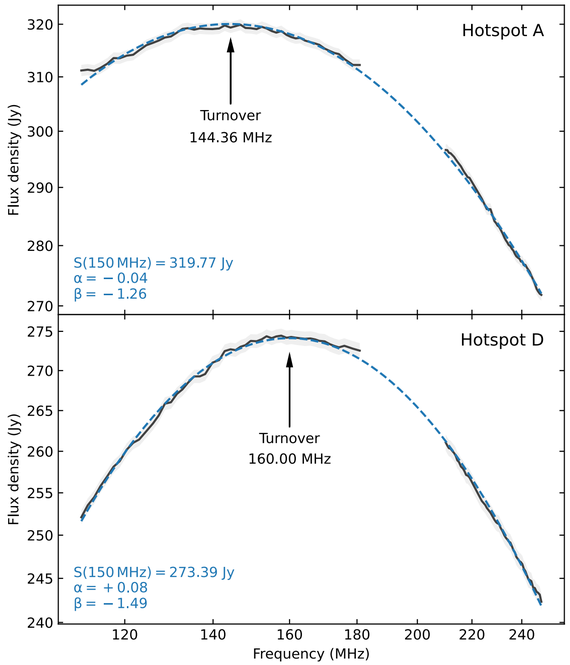
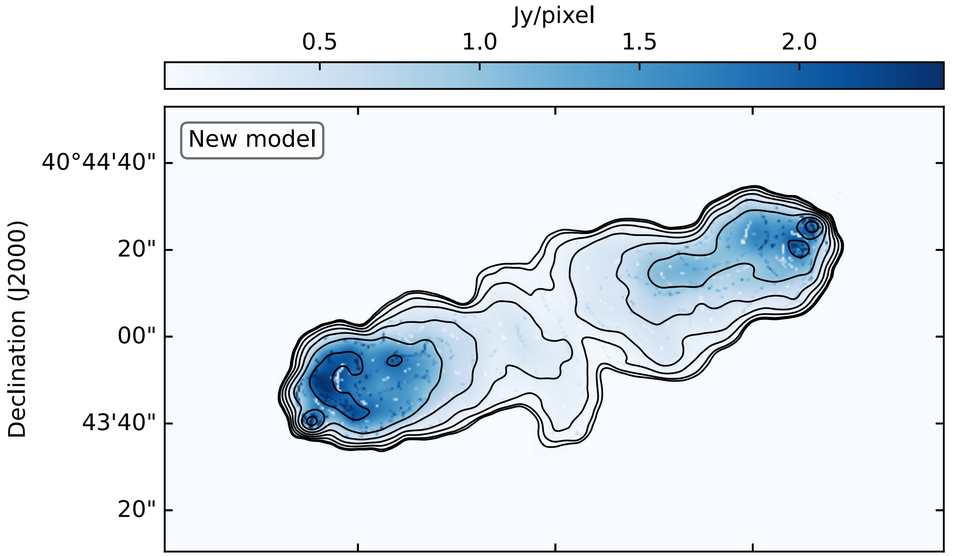
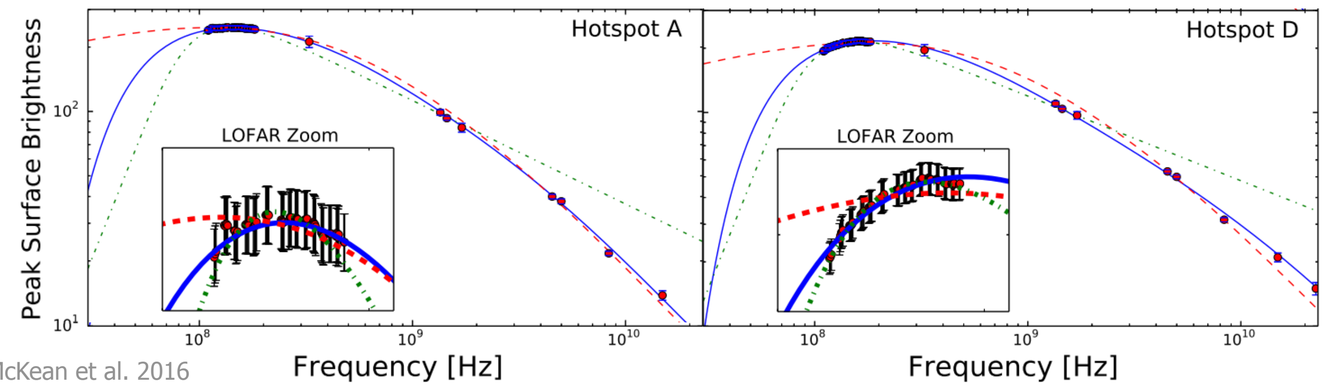

Each clean component has **spectral index and curvature** according to the input maps







Agree with literature!



McKean et al. 2016

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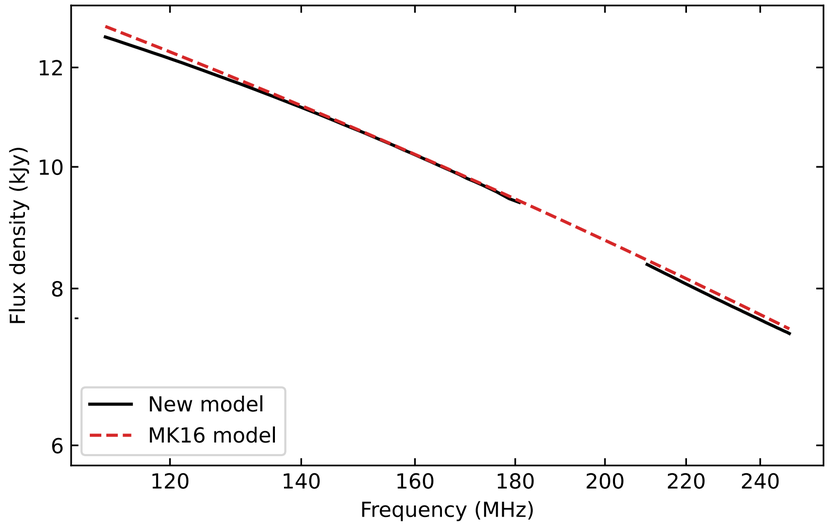

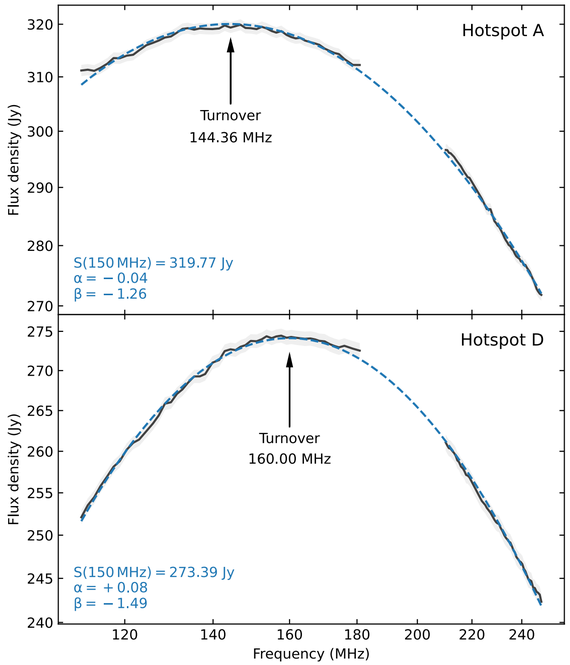

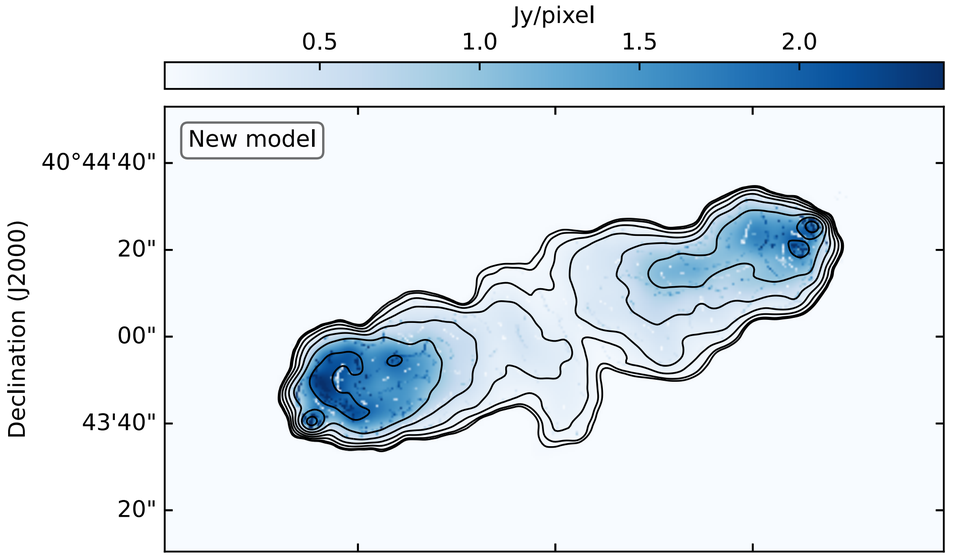

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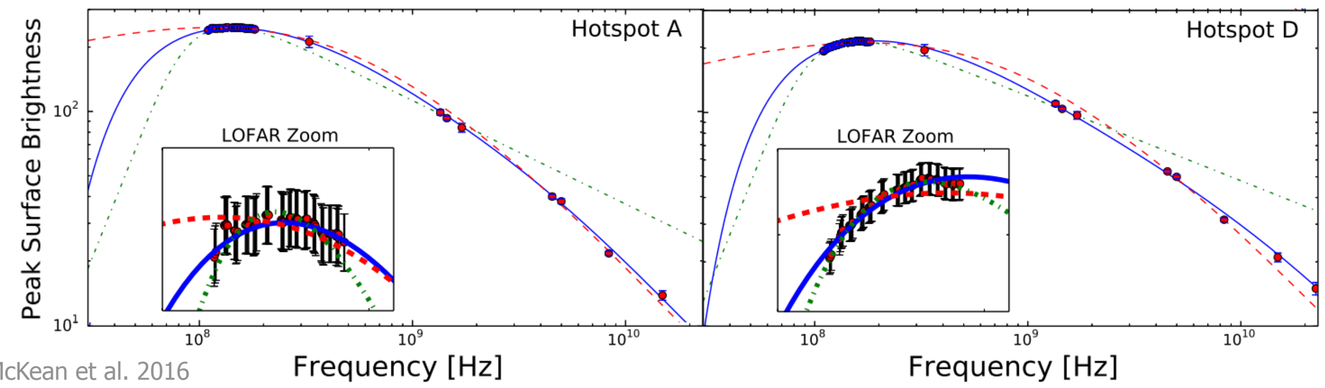

McKean et al. 2016

But why do we need a new model of Cygnus A?

OLD VS NEW CYGNUS A MODEL

Old model has three main issues:

(i) Fluxes given at **74 MHz**

(ii) Every components has **fixed** $\alpha = -0.8$

(iii) Very **low resolution**

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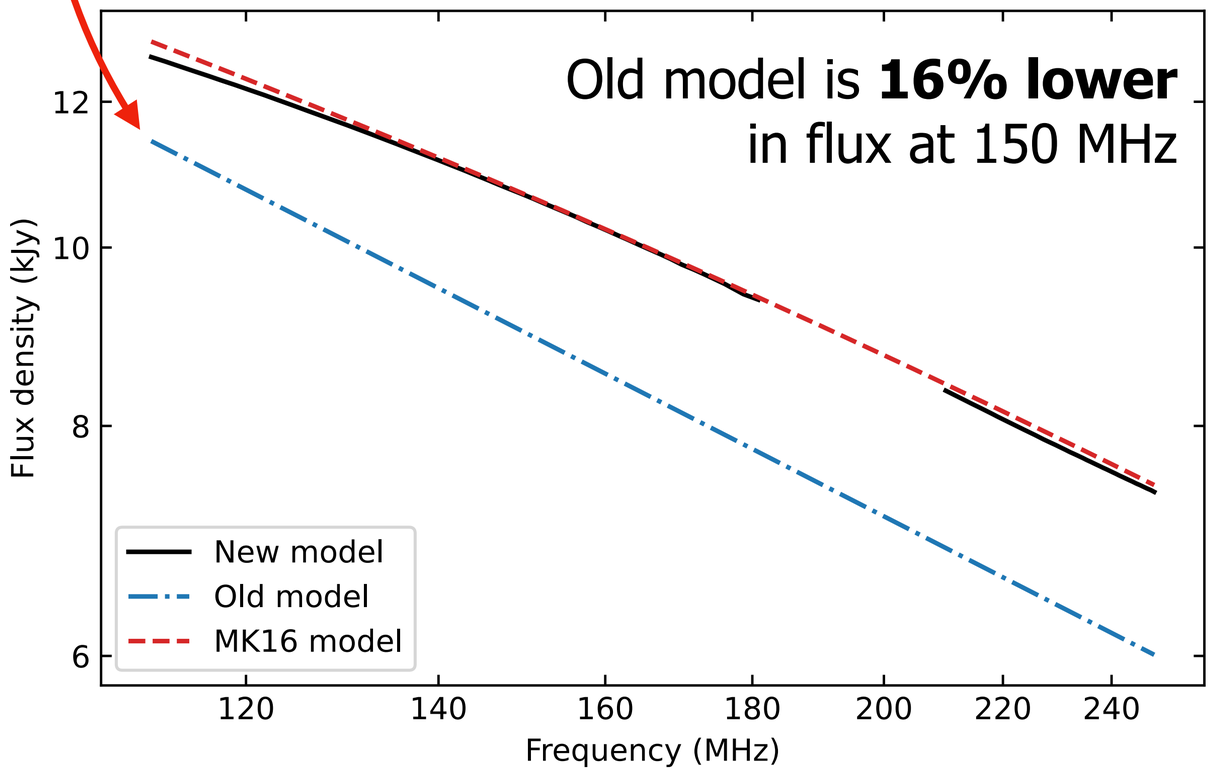

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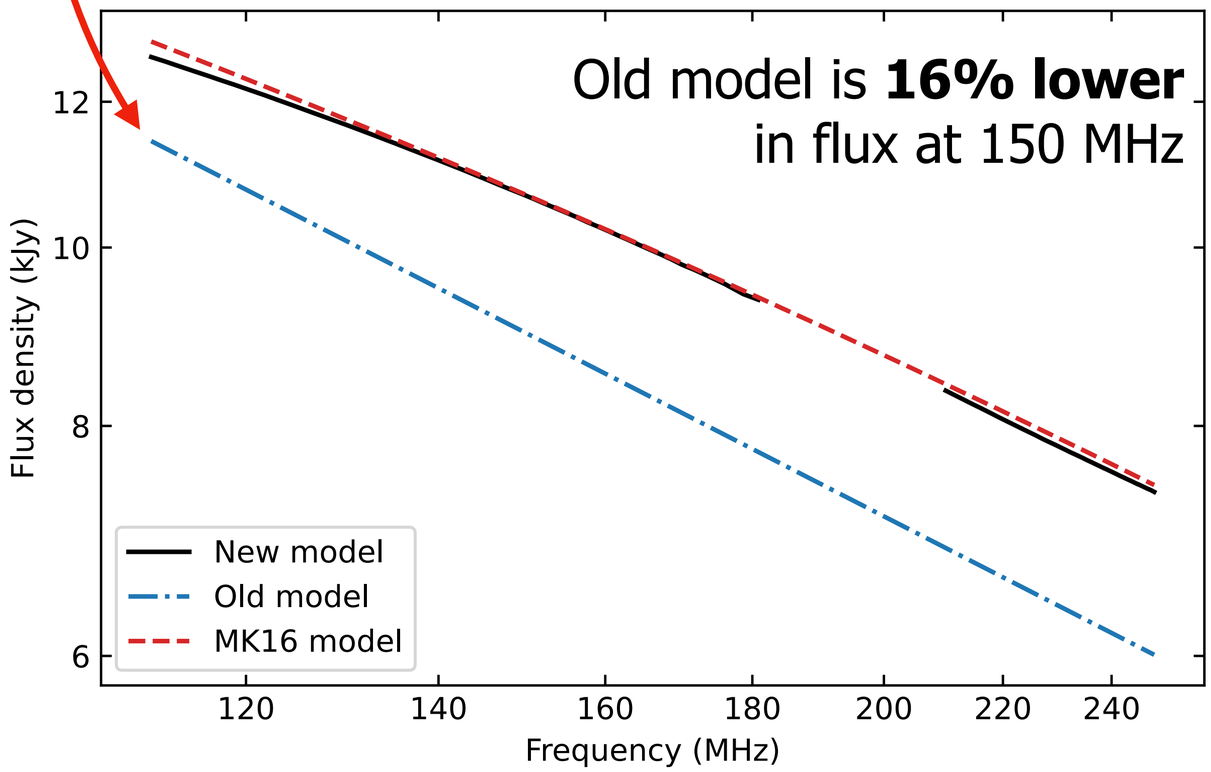
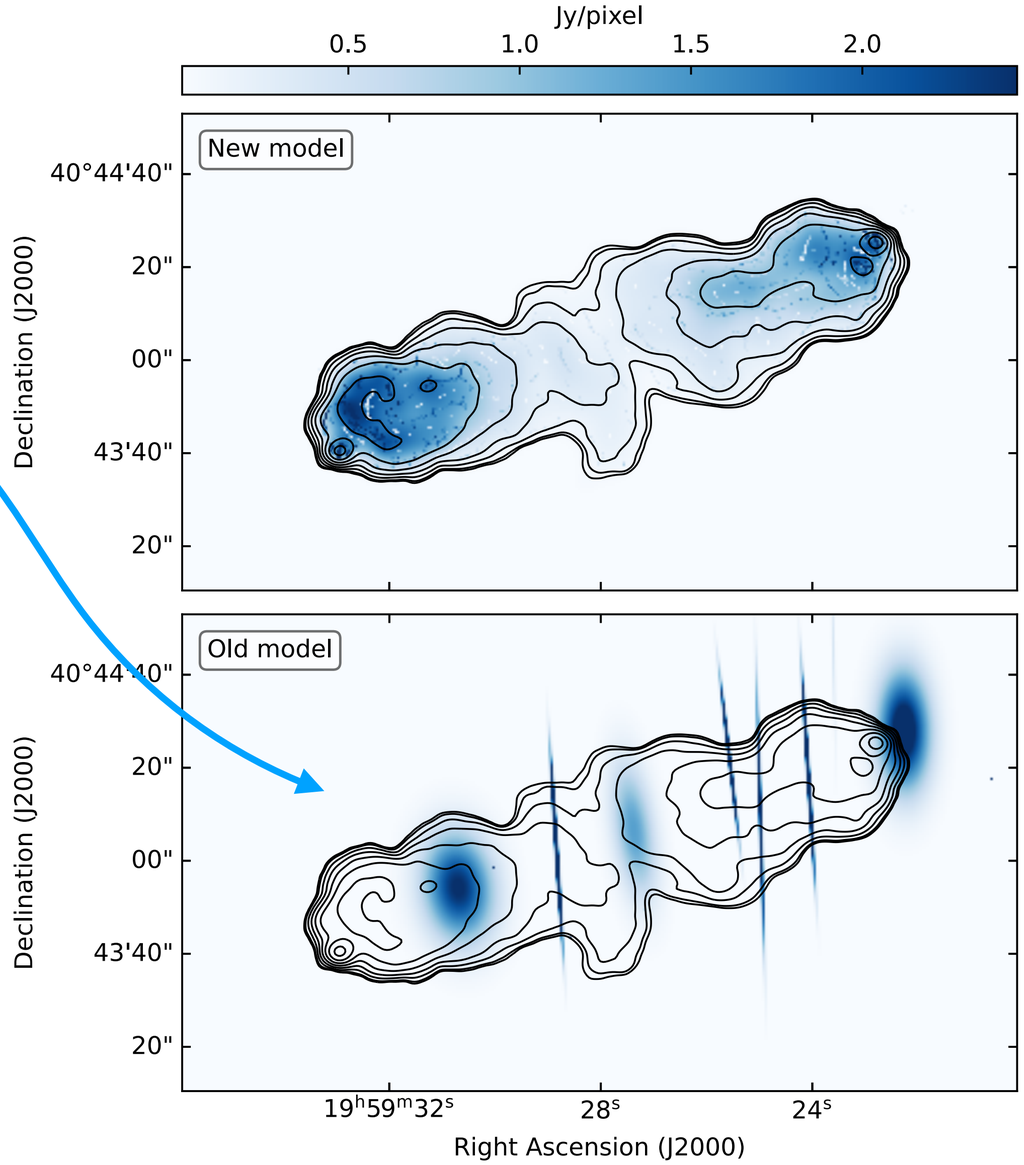
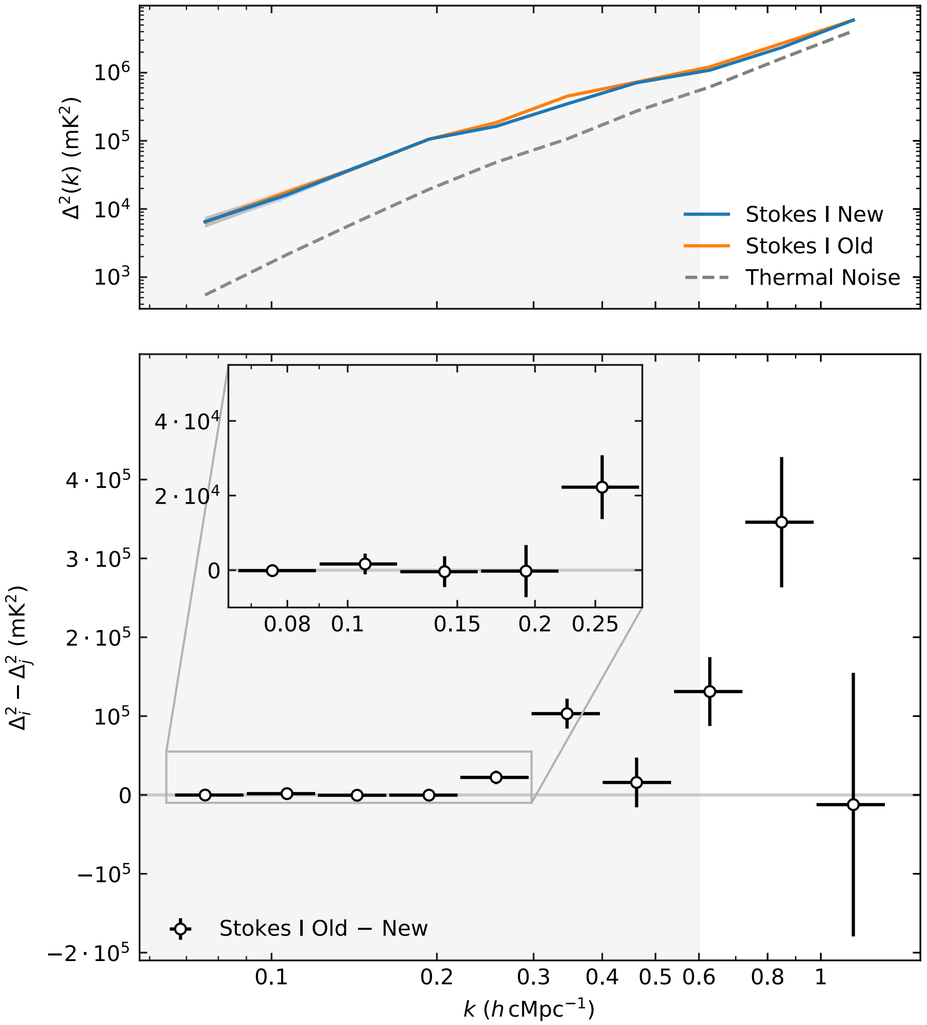




IMPACT ON THE NCP POWER SPECTRUM

SIMULATIONS



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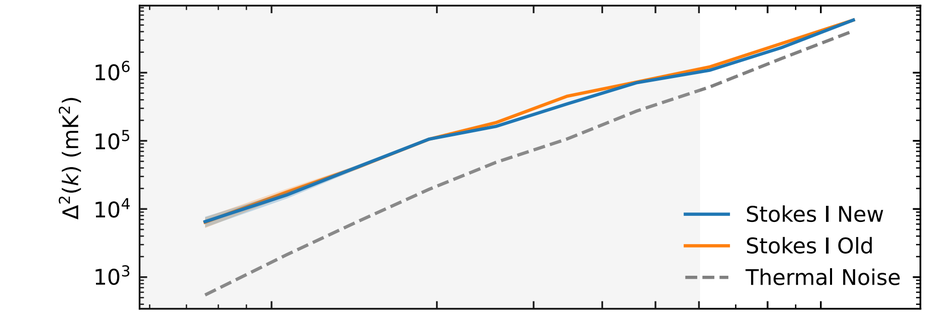
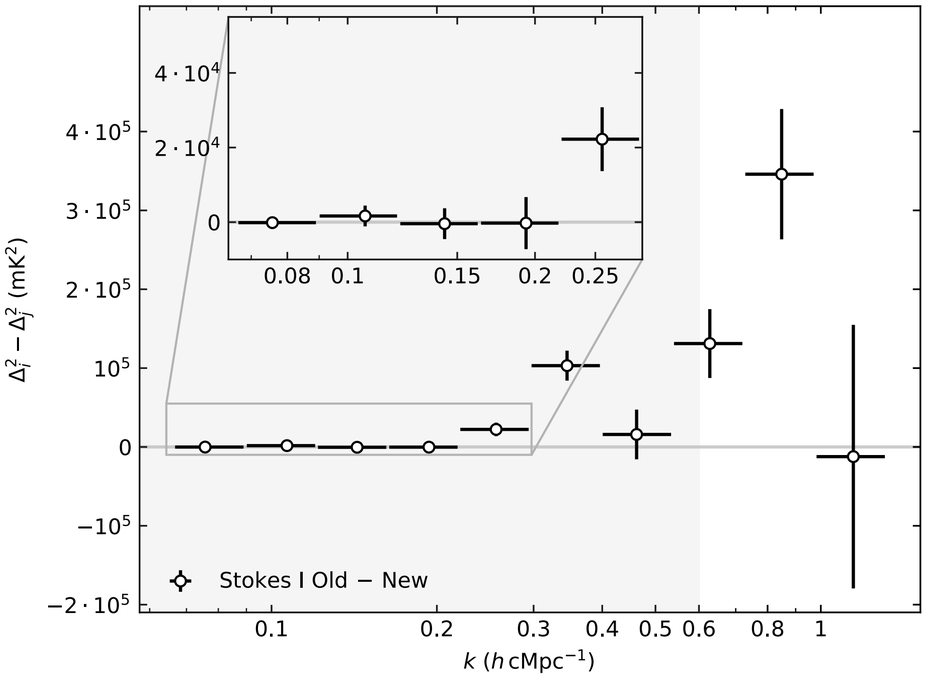
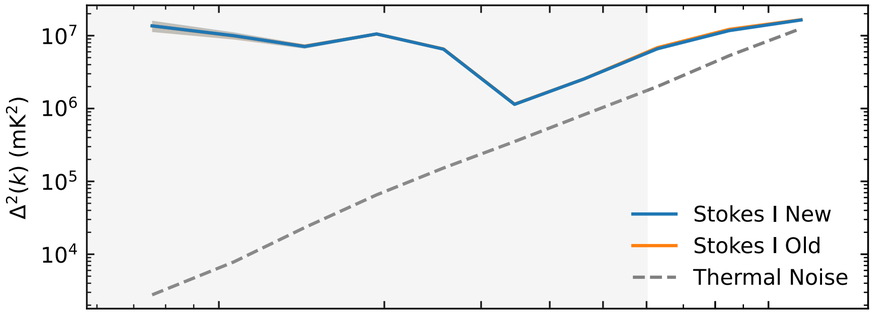
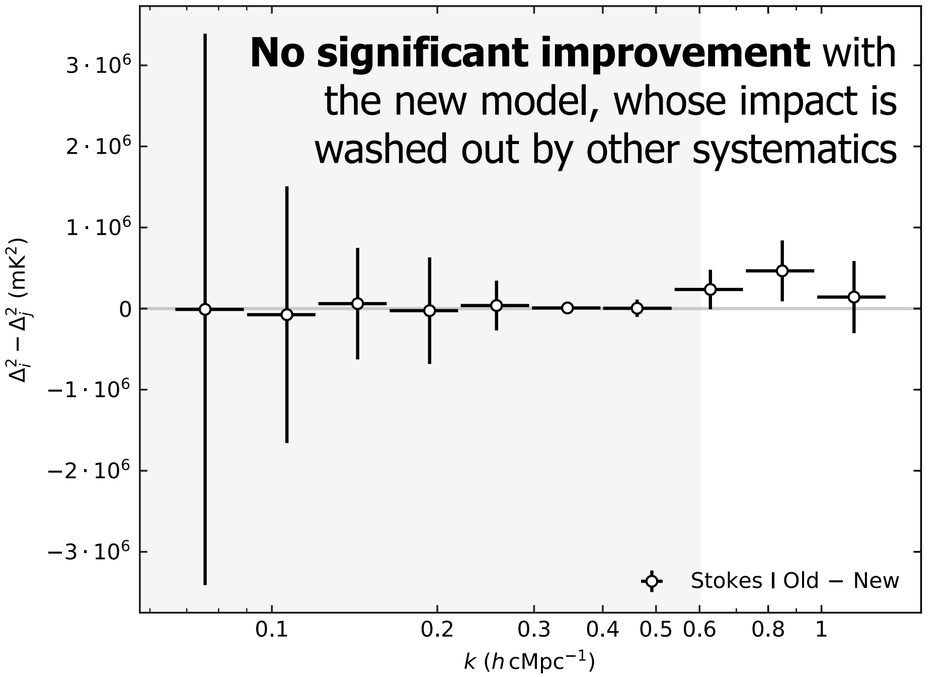




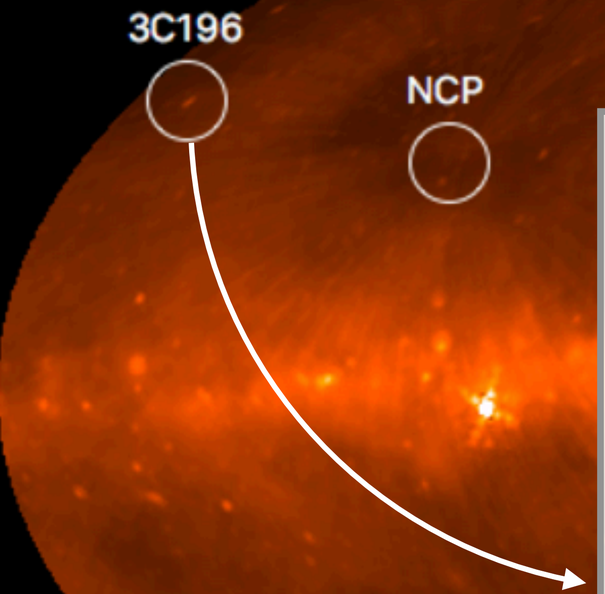
OBSERVATIONS



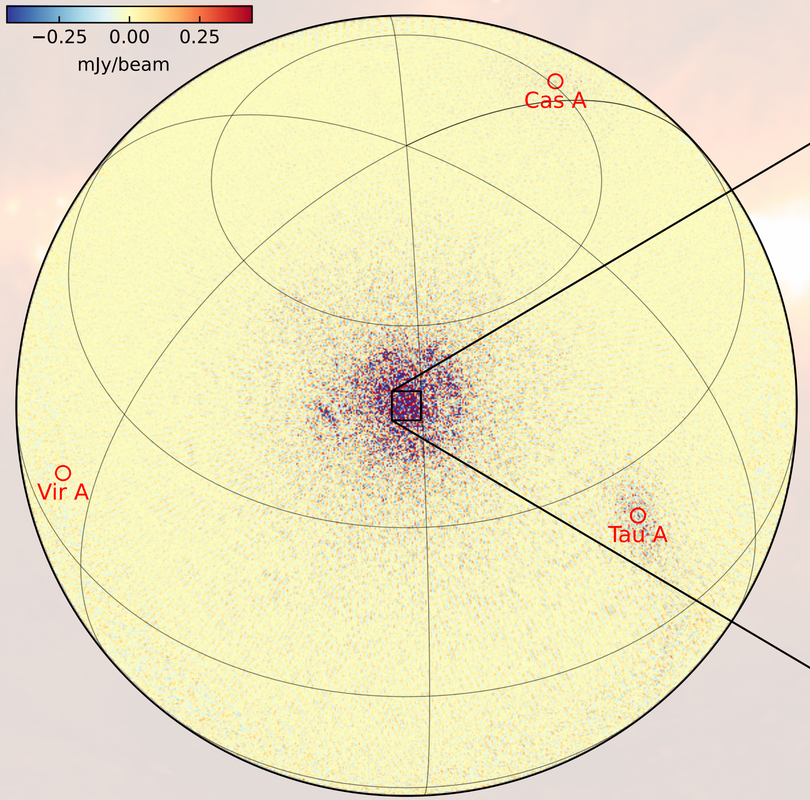


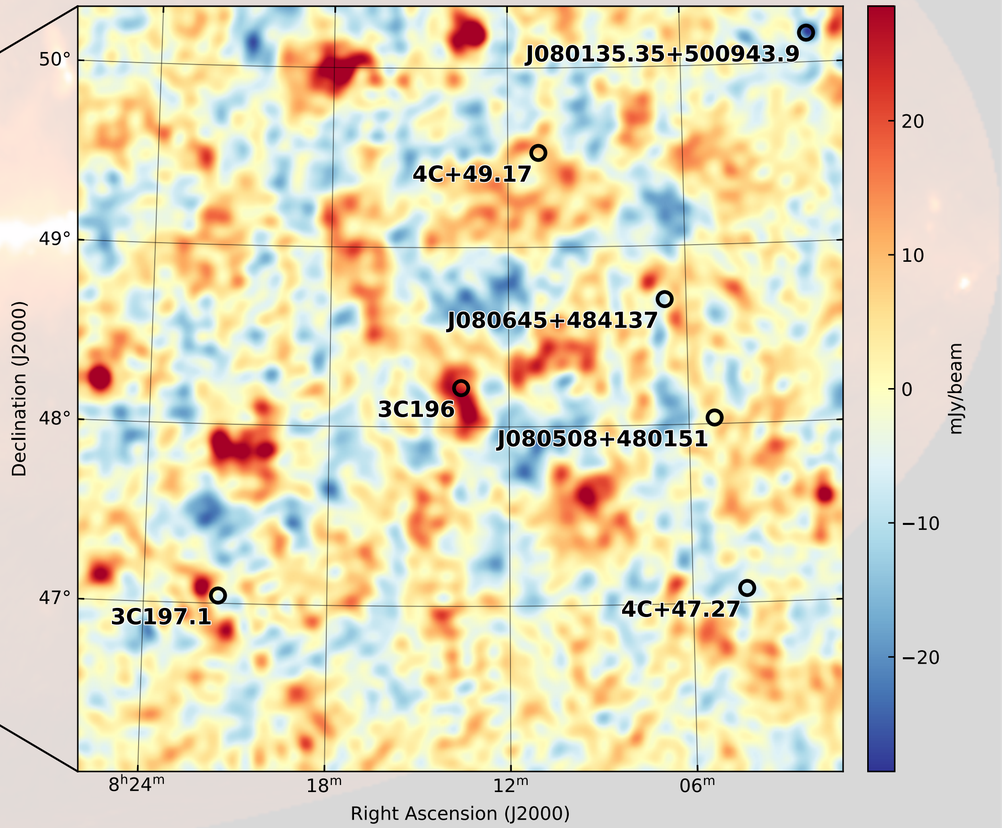
NEW (FIRST) RESULTS FROM 3C196 FIELD AT z~9.2

- 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

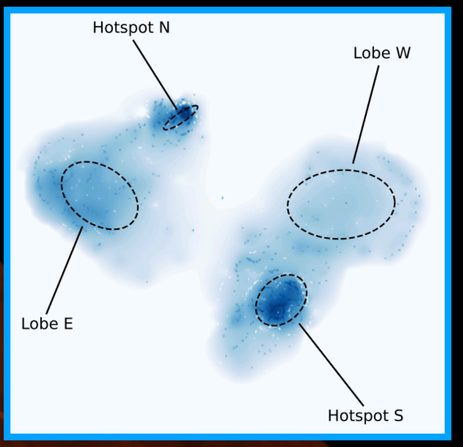


We made a **4° radius** sky model (4 times smaller than NCP)



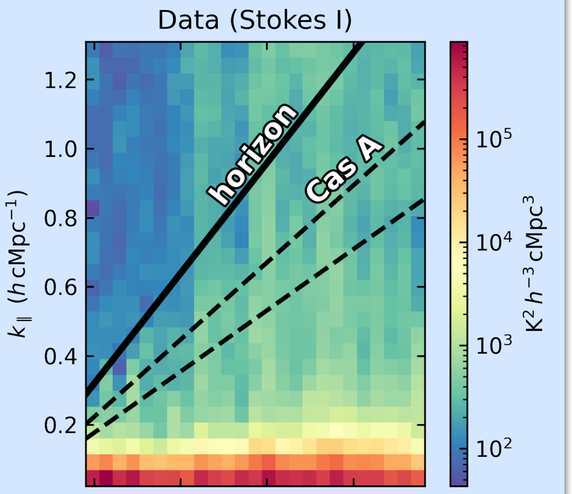


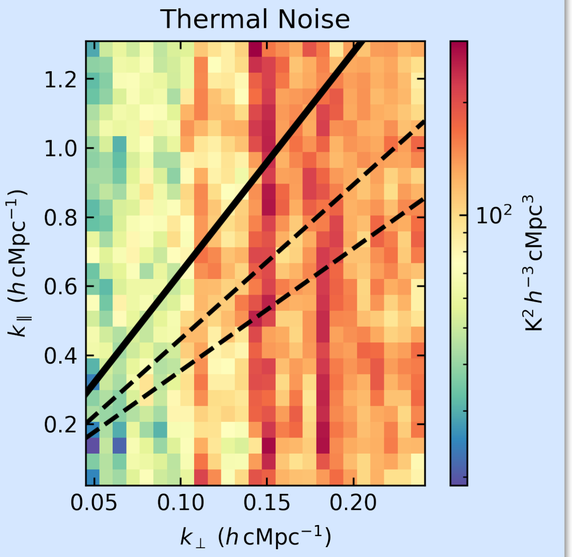
VLBI model of 3C196

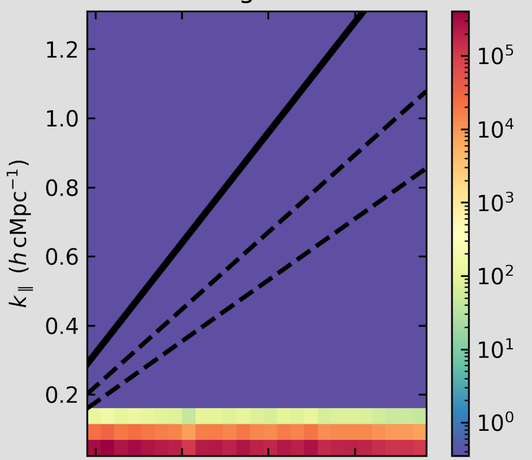


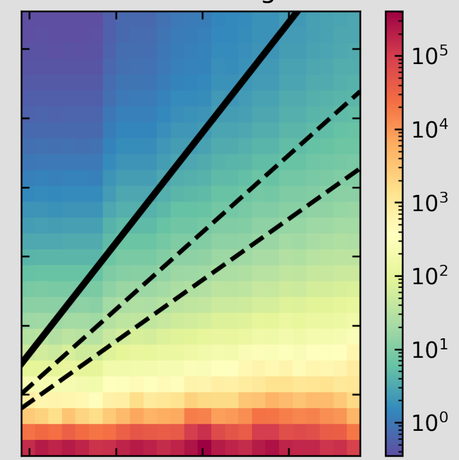
ML-GPR

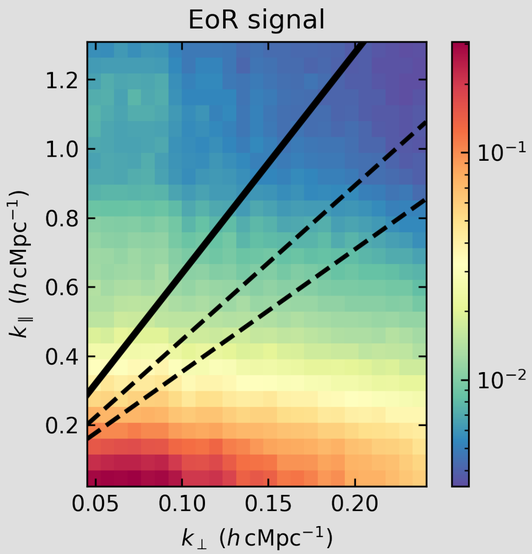
INPUT

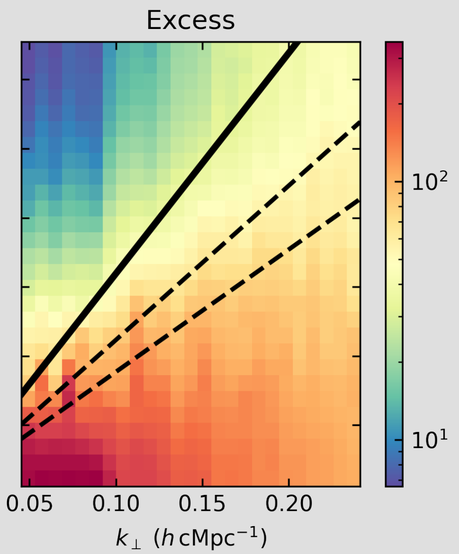






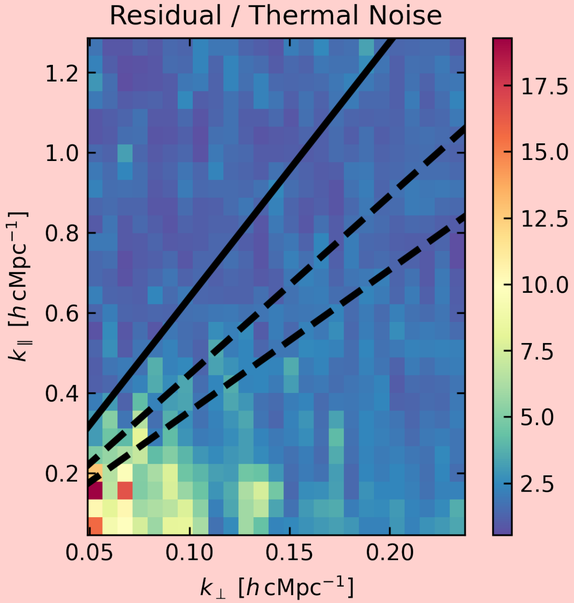






DATA
- FOREGROUNDS
= RESIDUALS

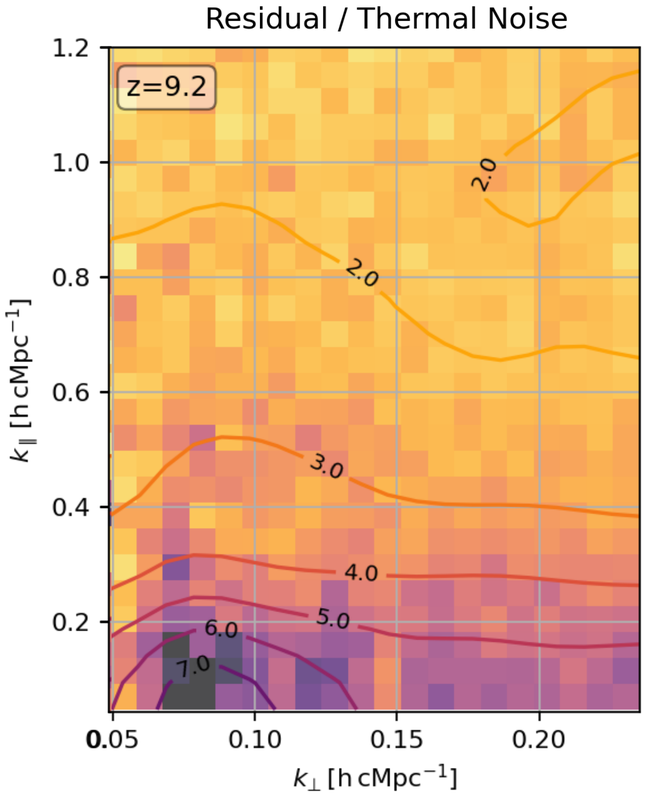
RESULTS



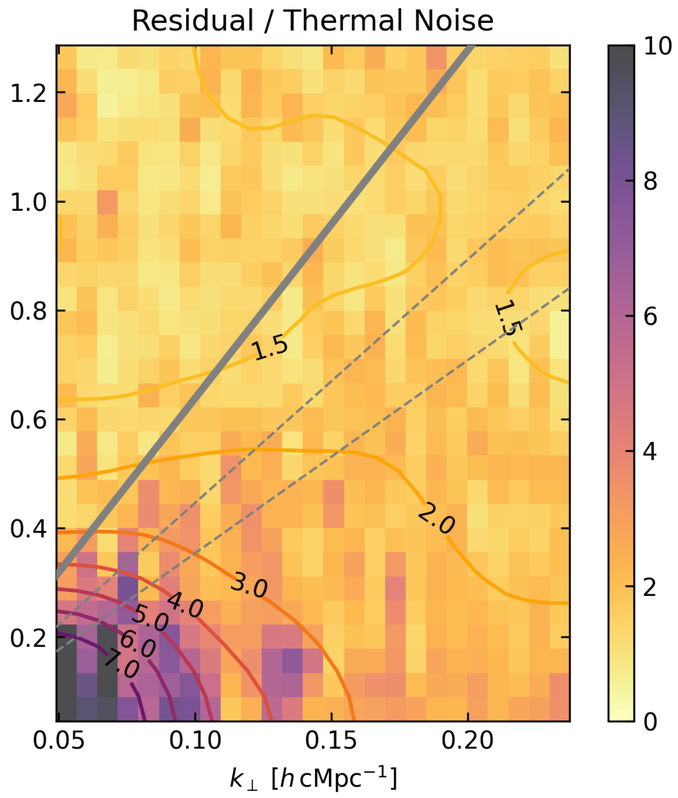
3C196 VS NCP

2D POWER SPECTRUM

NCP

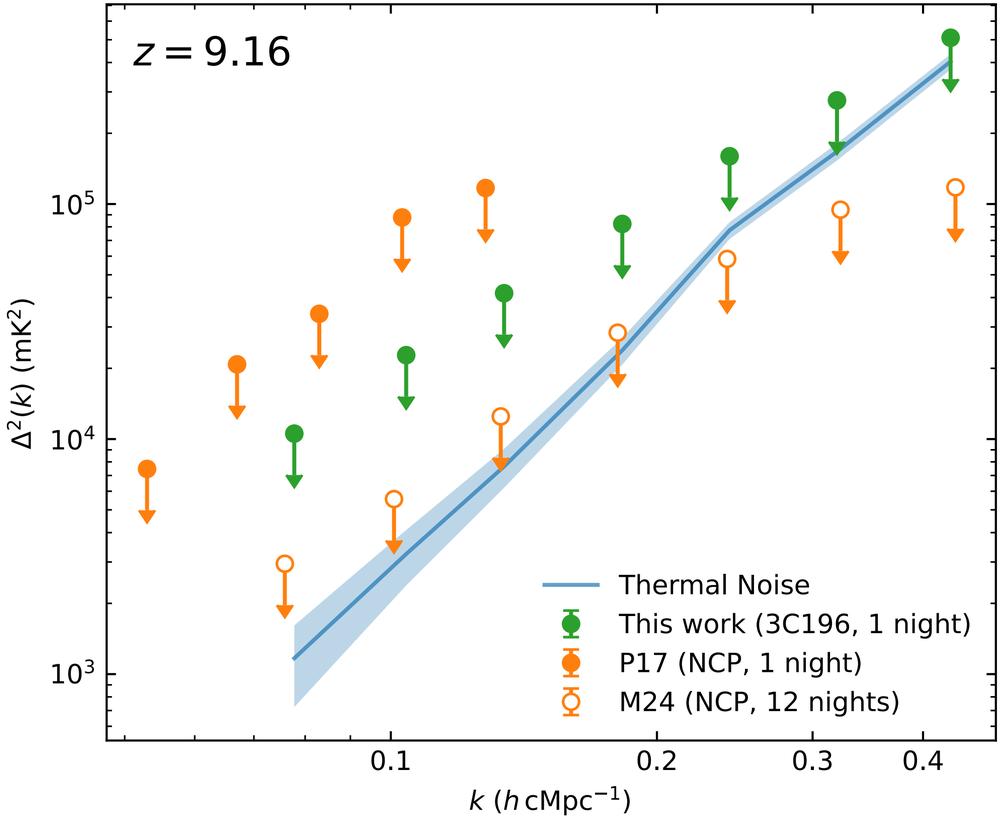


3C196



Mertens et al. 2024, in prep.

2σ UPPER LIMITS



SUMMARY AND CONCLUSIONS

- The new **forced-spectrum method** of WSClean, with the multi-scale and the multi-frequency deconvolution, allows the generation of **accurate sky models with physical spectral information**
- Using the forced-spectrum fitting, we made a **new high-resolution model of Cygnus A**, embedding physical spectral information
- We investigated the impact of the new Cyg A model against the old model on the **LOFAR-HBA 21-cm power spectrum**, finding that the effects of the improved modelling are washed out by **other systematics**
- We extracted the **first 21-cm upper limits at z~9.16 from the 3C196 field** using one night observed with LOFAR-HBA
- The **excess** of the 3C196 field seems being dominated by **distant foreground emission**
- The **EoR window is more clean than NCP**, and with a preliminary sky model and processing pipeline, we get **promising results**