Observing the Epoch of Reionization with LOFAR
Progress and challenges

CoDA II — Pierre Ocvirk

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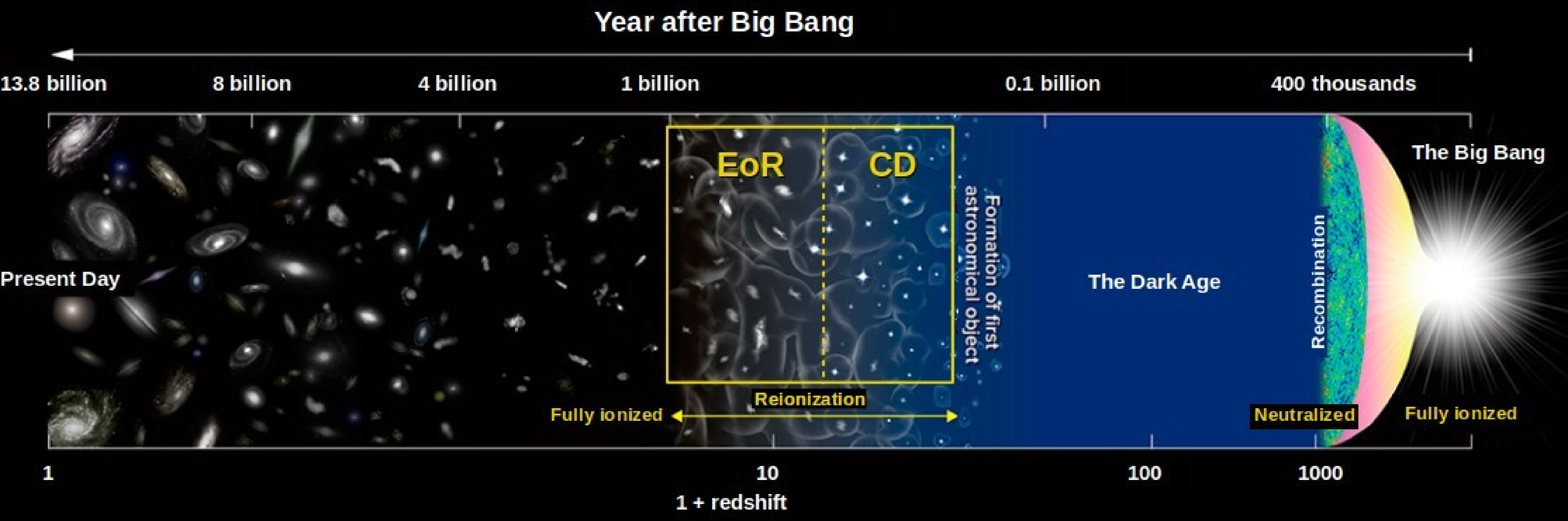
Sarod Yatawatta (ASTRON)
Saleem Zaroubi (K./Haifa)

Cosmic Dawn / Epoch of Reionization



Credit: NAOJ

Epoch of Reionization

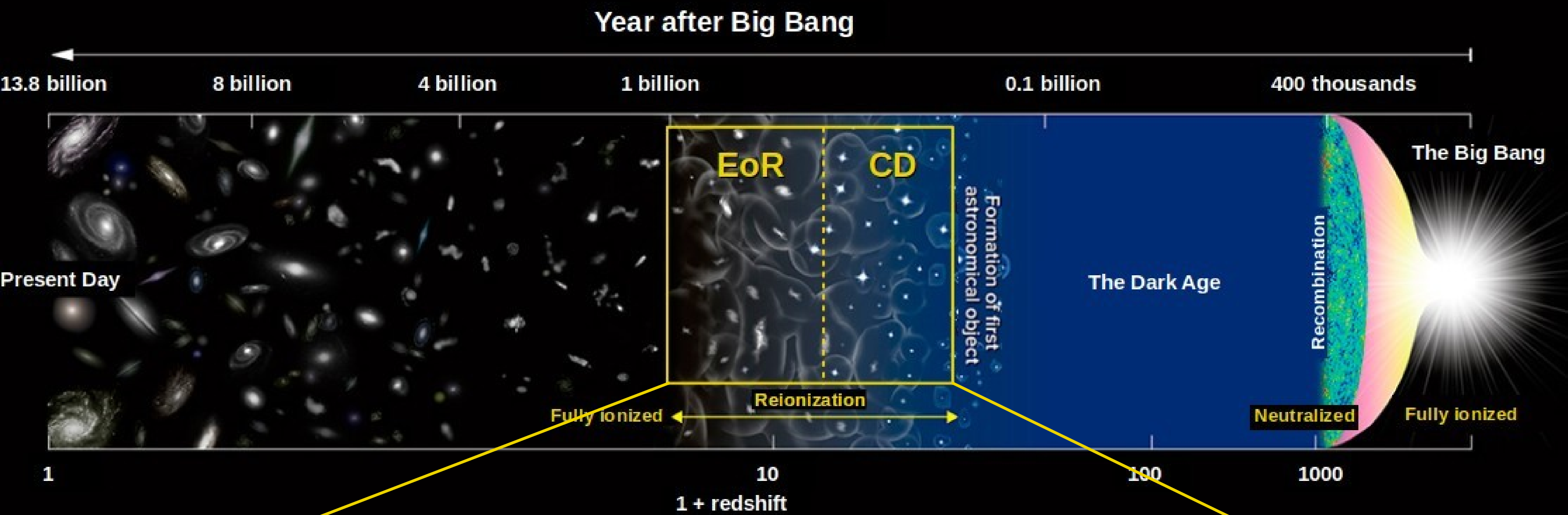
- Reionization by stars & mini-quasars
- IGM feedback (e.g. metals)
- PopIII - PopII transition
- Emergence of the visible universe

Cosmic Dawn

- Appearance of first stars/Bhs (PopIII?)
- Ly-α radiation field
- Impact of Baryonic Bulk Flows
- First X-ray heating sources

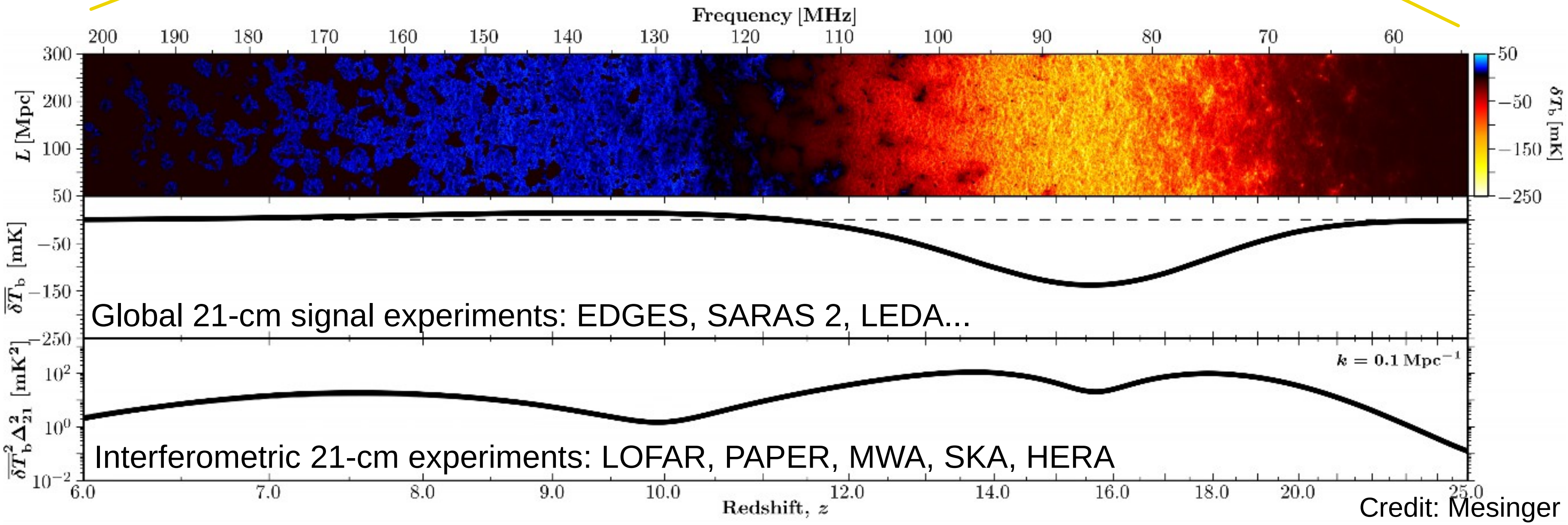
- When did the first galaxies/stars/black hole form?
- How did reionization proceed?
- How do galaxies form and evolve?

Cosmic Dawn / Epoch of Reionization



High-z HI 21-cm signal unique probe of the CD/EoR

Credit: NAOJ

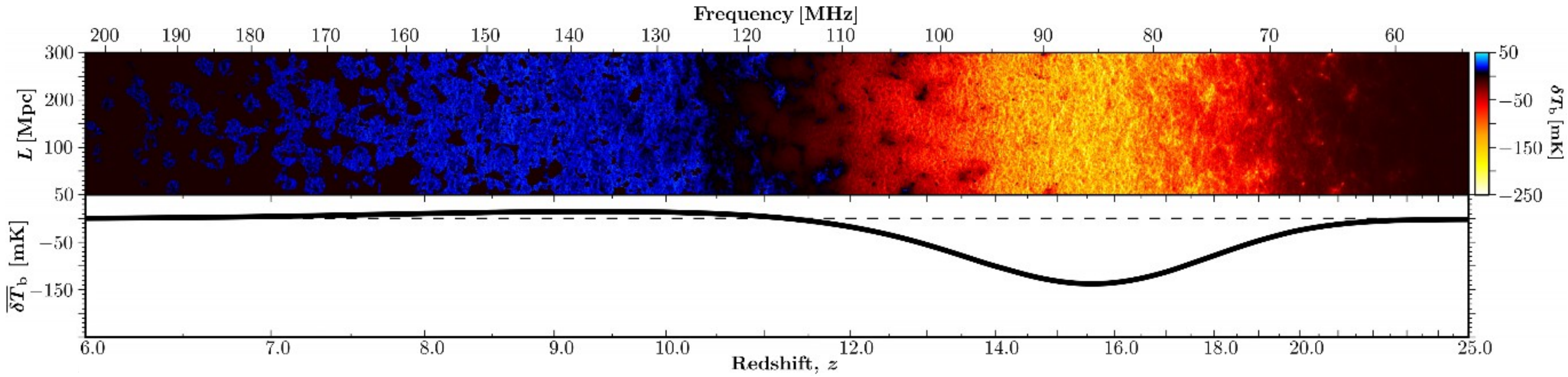


Global 21-cm signal experiments: EDGES, SARAS 2, LEDA...

Interferometric 21-cm experiments: LOFAR, PAPER, MWA, SKA, HERA

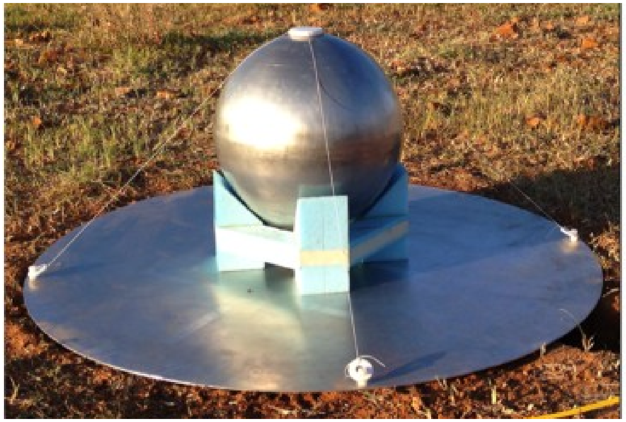
Credit: Mesinger & Greig

The Global experiments



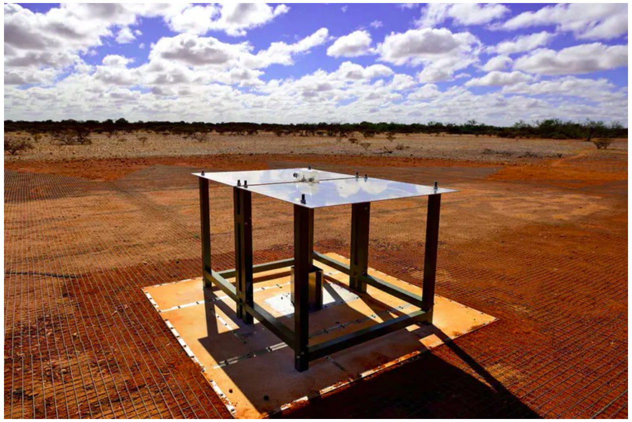
PRIZM
30-200 MHz
Marion Island

Peterson, Sievers, Chiang ++



SARAS
50-100, 100-200 MHz
India (Himalayas)

Singh et al. 2017

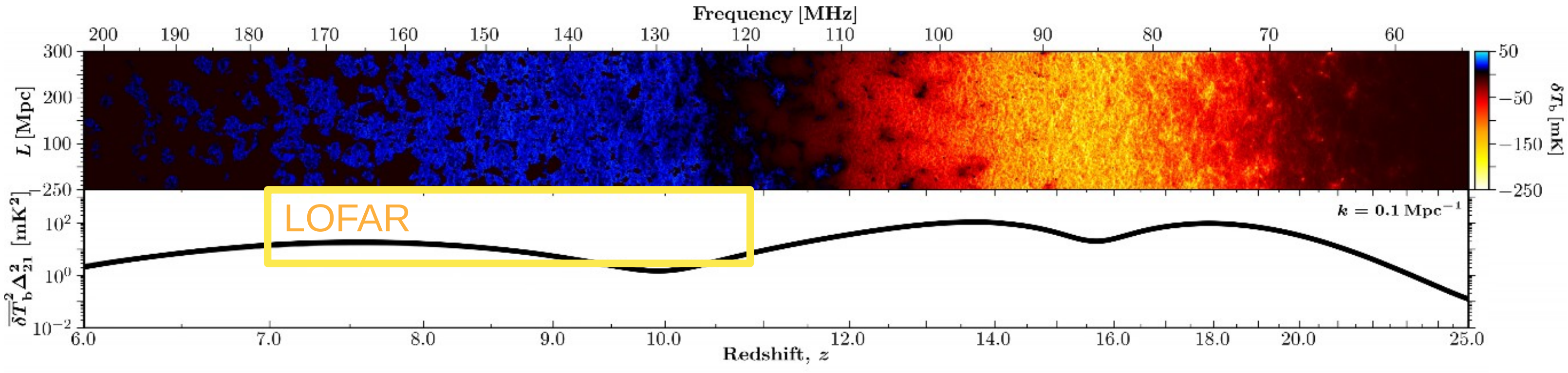


EDGES
50-100, 100-200 MHz
Western Australia

Rogers & Bowman 2008, 2012;
Bowman et al 2018

+ Many more

The Interferometric experiments

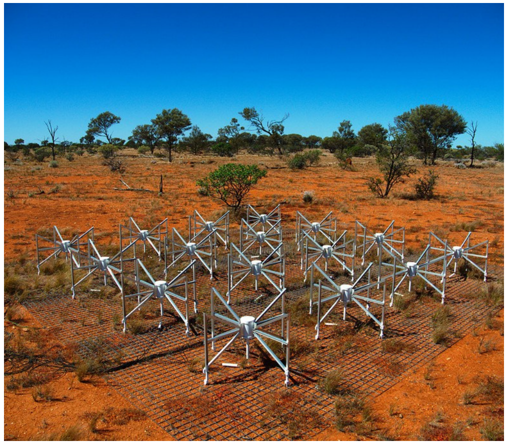


GMRT
India

40 h @ z ~ 8.5
Paciga et al. 2013

PAPER
South Africa

1148 h @ z=8.4
~~Ali et al. 2015~~
Kolopanis et al. 2019



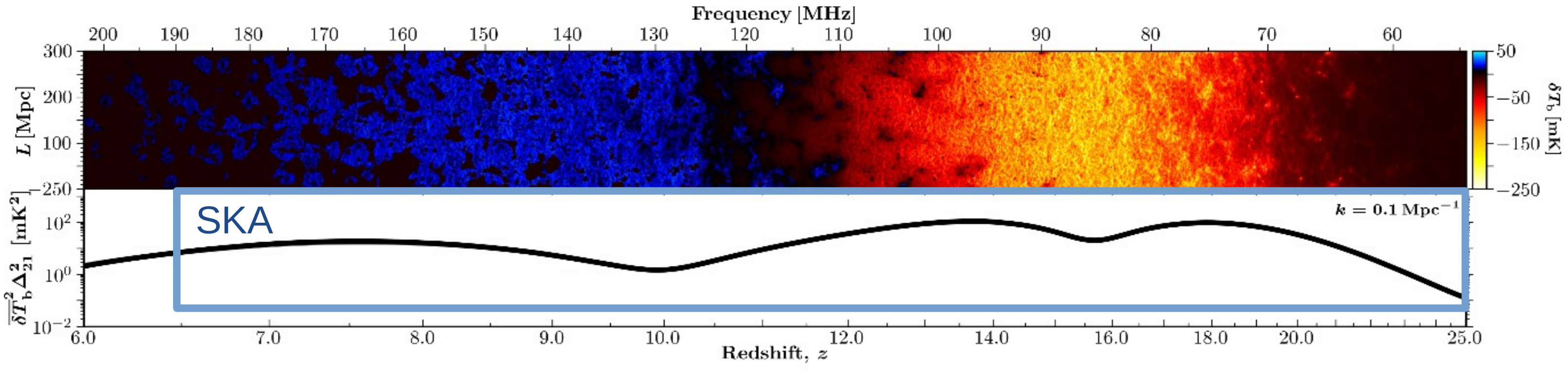
MWA
Western Australia

z ~ 6 – 10
~ 32 h published
Beardsley et al. 2016
Barry et al. 2019
MWA phase 2

LOFAR
The Netherlands

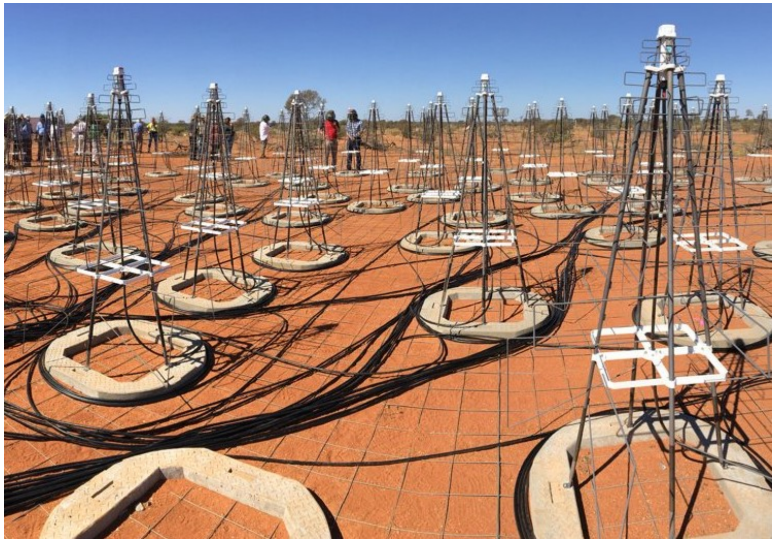
z ~ 7 – 11
+ 2000 h observed
13h published
Patil et al. 2017
140h in prep.

The Interferometric experiments



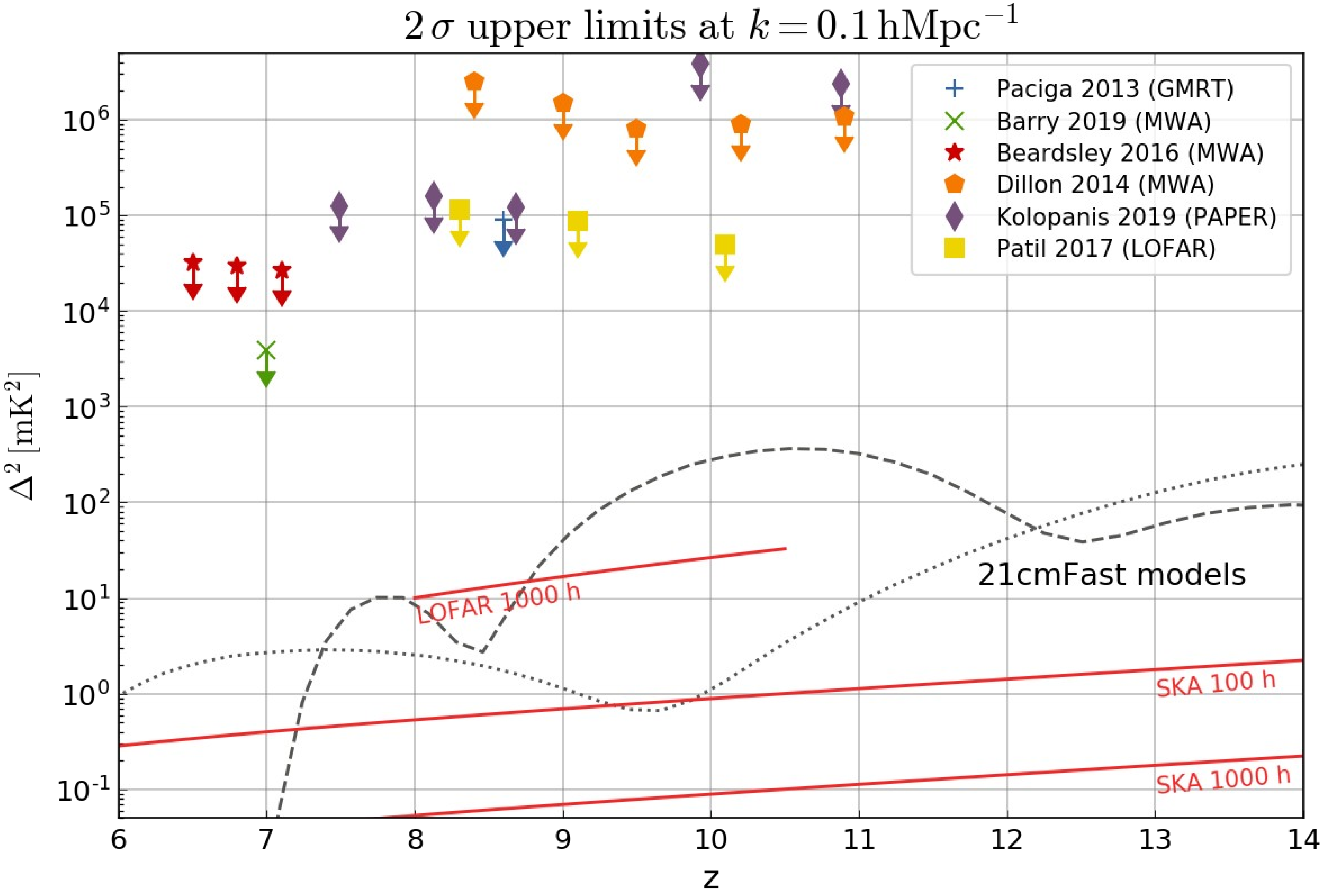
Second generation experiments in near and far future

HERA
South Africa
z ~ 6 – 25
240 dishes of 14 m (by ~ 2020)
In (partial) commissioning

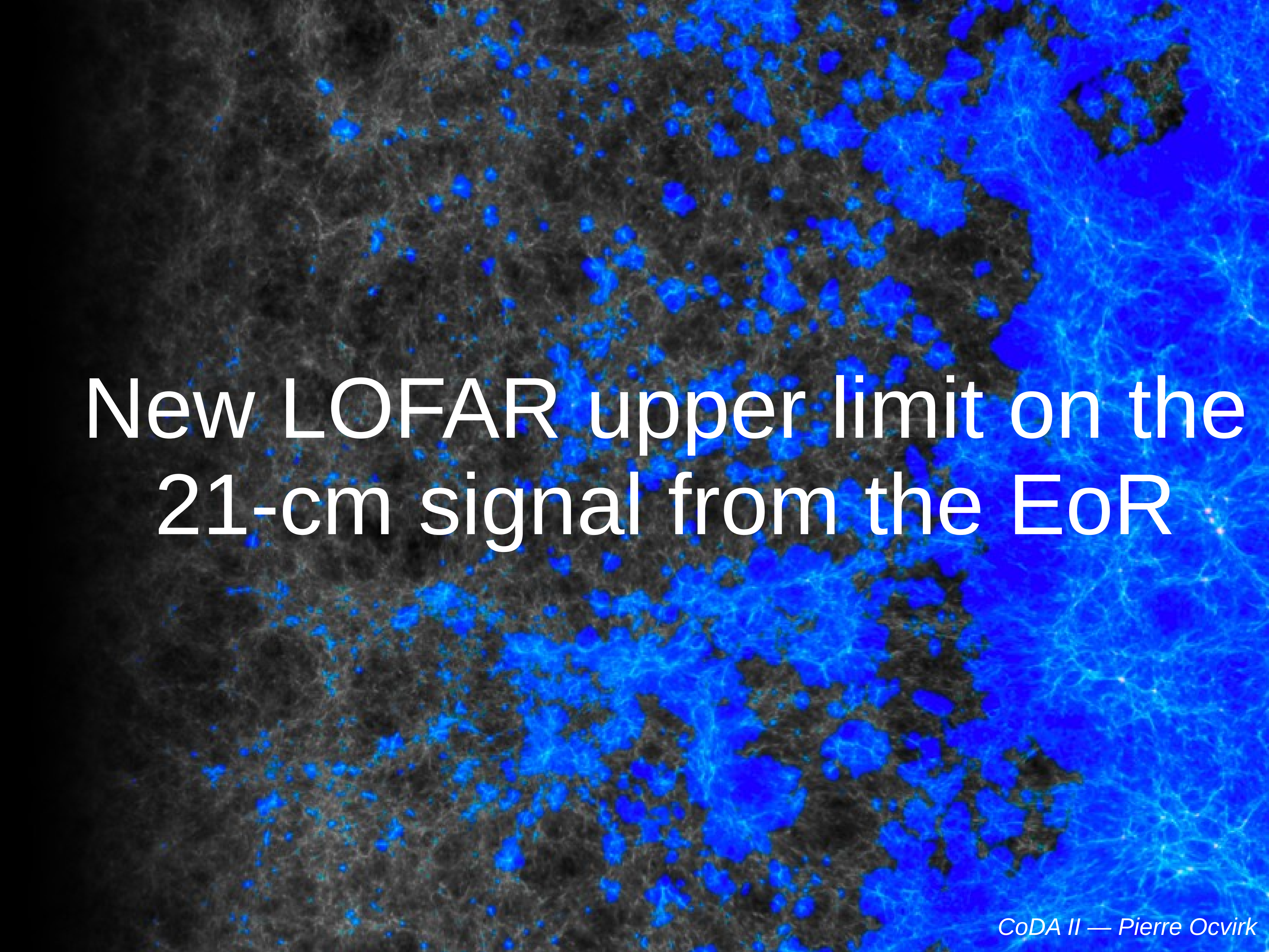


SKA
Western Australia
Low band (z ~ 6 – 25)
Construction 2020-2025

Where do we stand ?

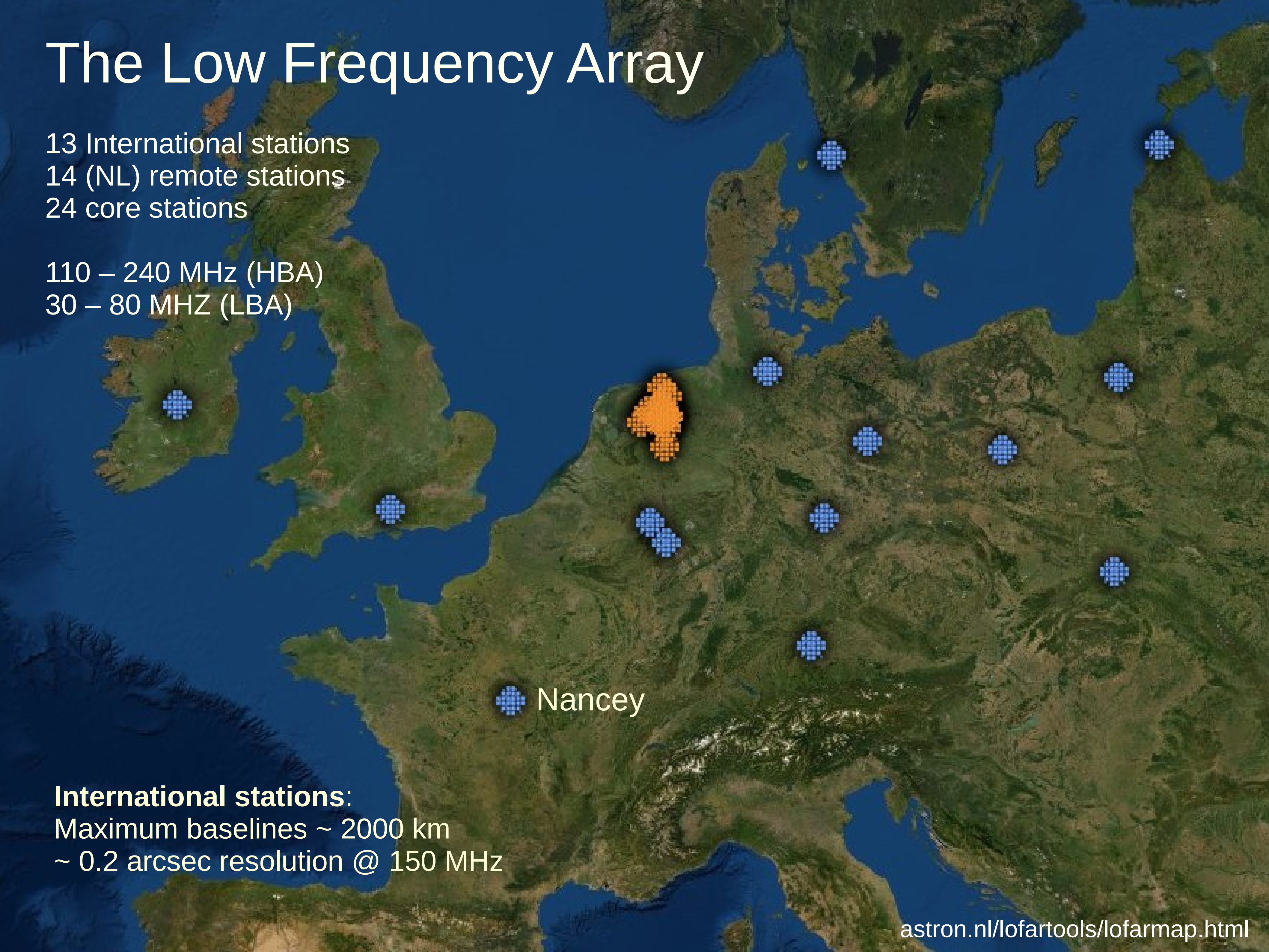


New LOFAR upper limit on the 21-cm signal from the EoR



CoDA II — Pierre Ocvirk

The Low Frequency Array



13 International stations
14 (NL) remote stations
24 core stations

110 – 240 MHz (HBA)
30 – 80 MHZ (LBA)

International stations:
Maximum baselines ~ 2000 km
~ 0.2 arcsec resolution @ 150 MHz

astron.nl/lofartools/lofarmap.html

The Low Frequency Array

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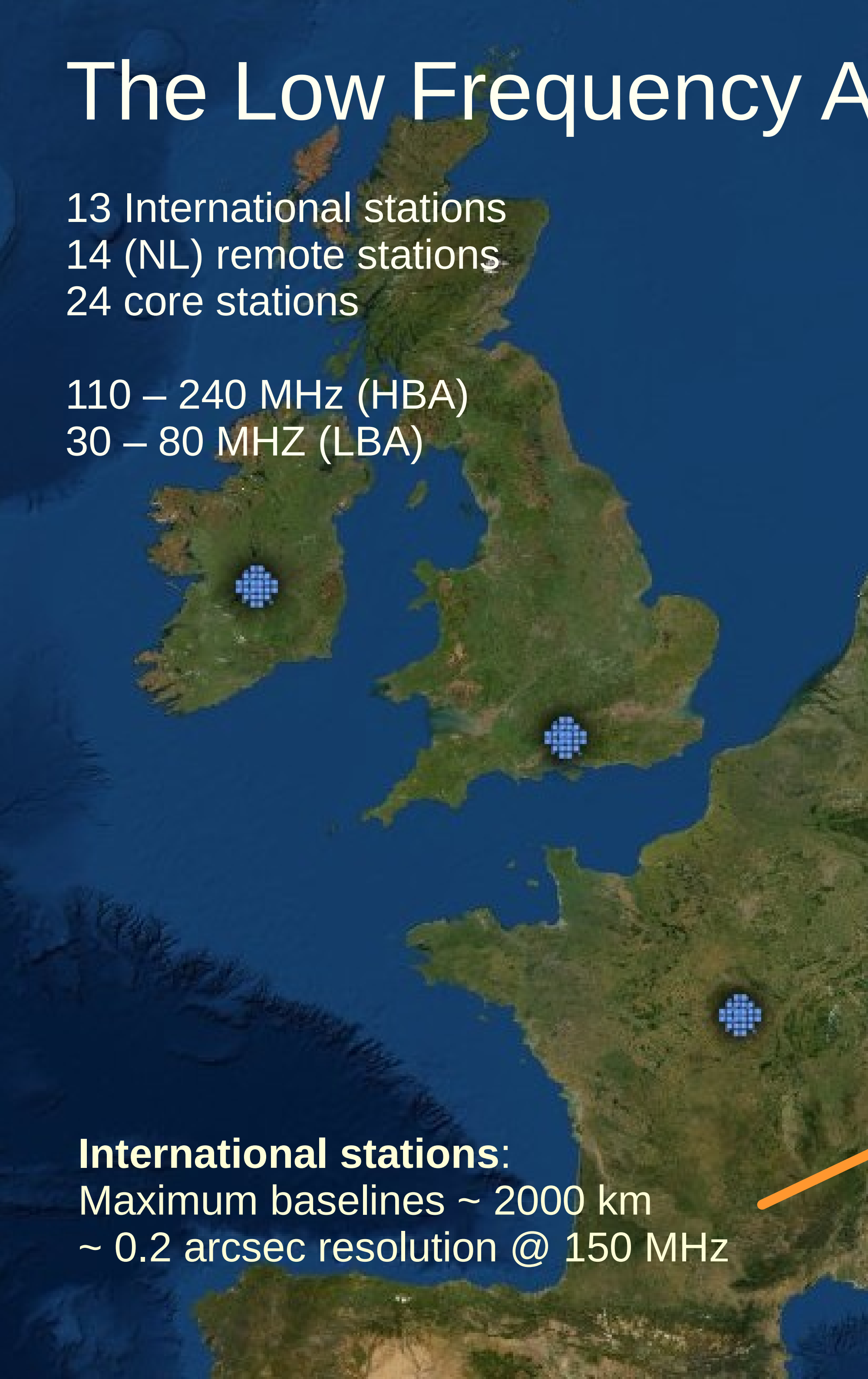
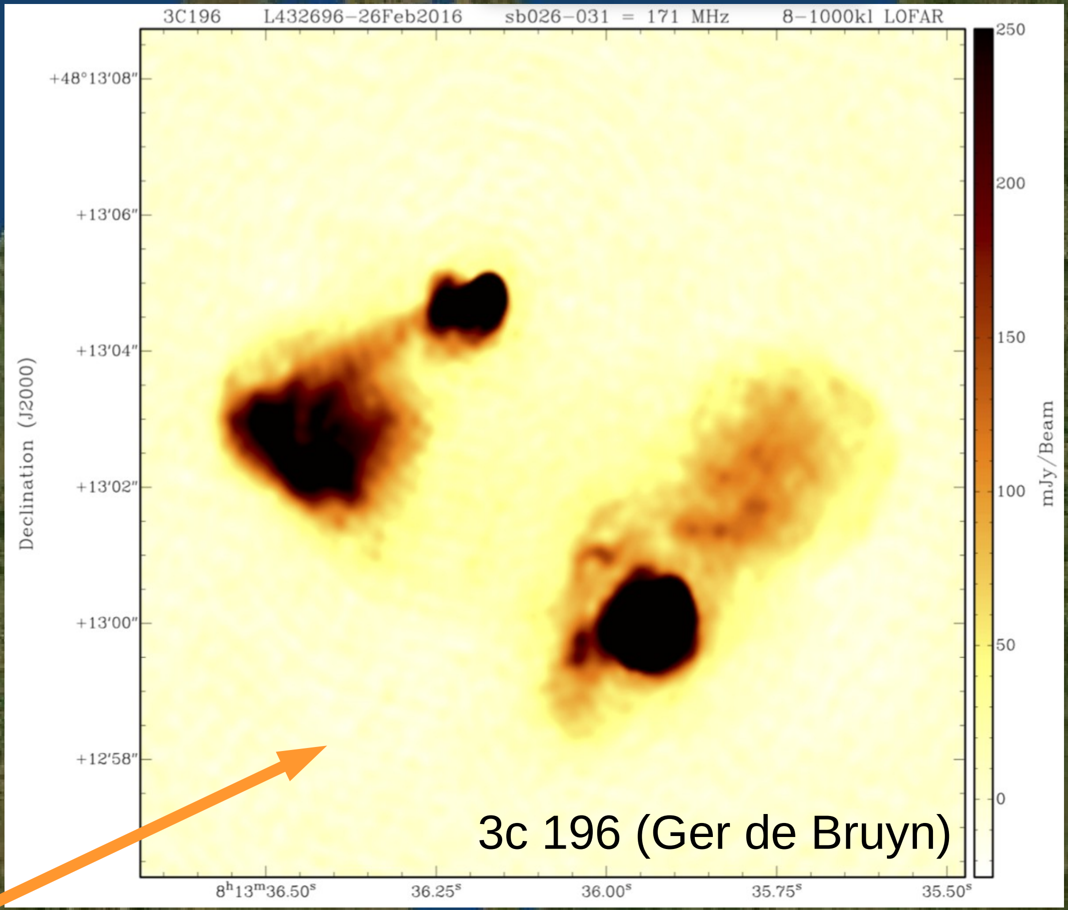


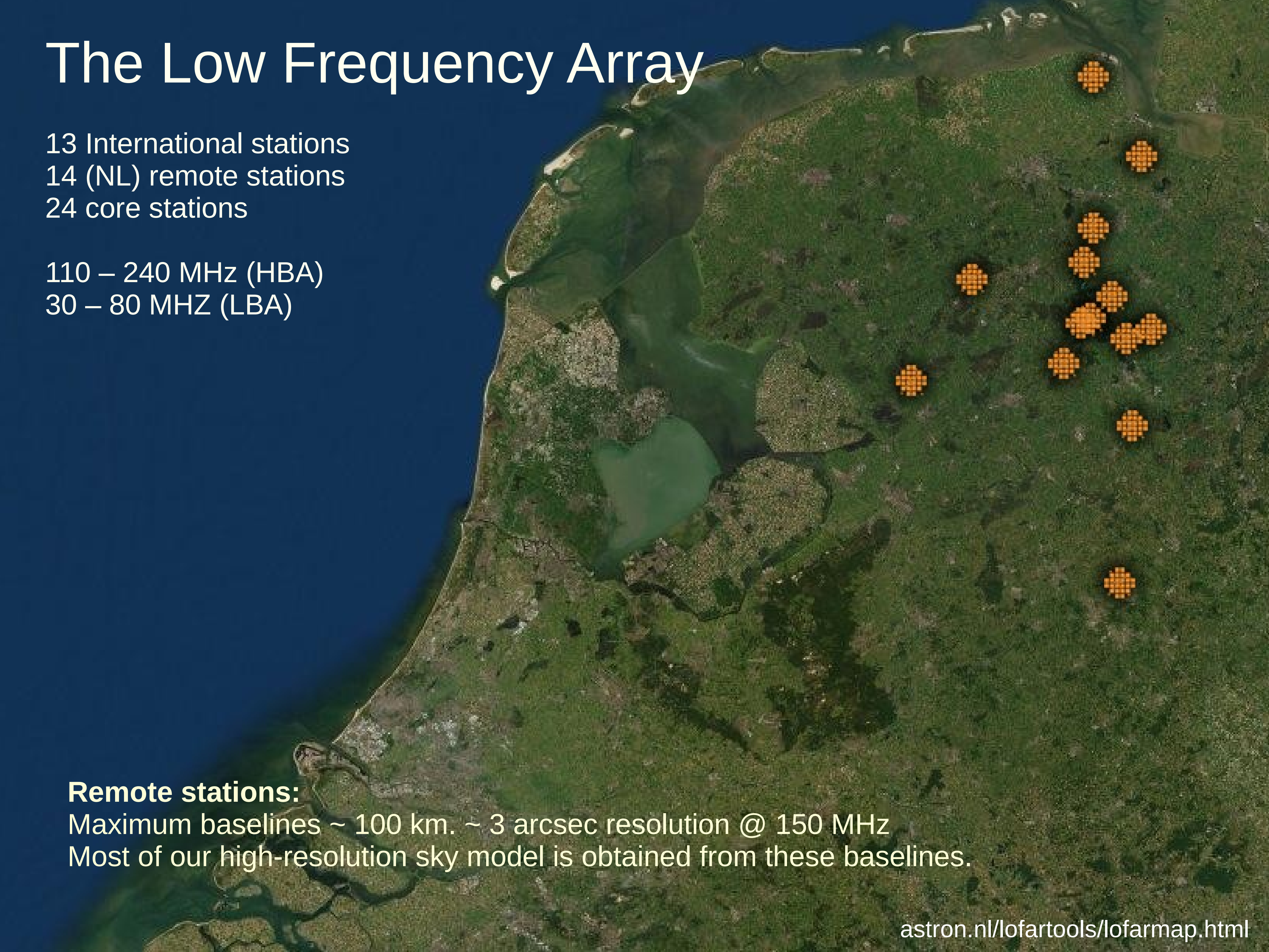


3c 196 (Ger de Bruyn)

International stations:
Maximum baselines ~ 2000 km
~ 0.2 arcsec resolution @ 150 MHz

astron.nl/lofartools/lofarmap.html

The Low Frequency Array



13 International stations
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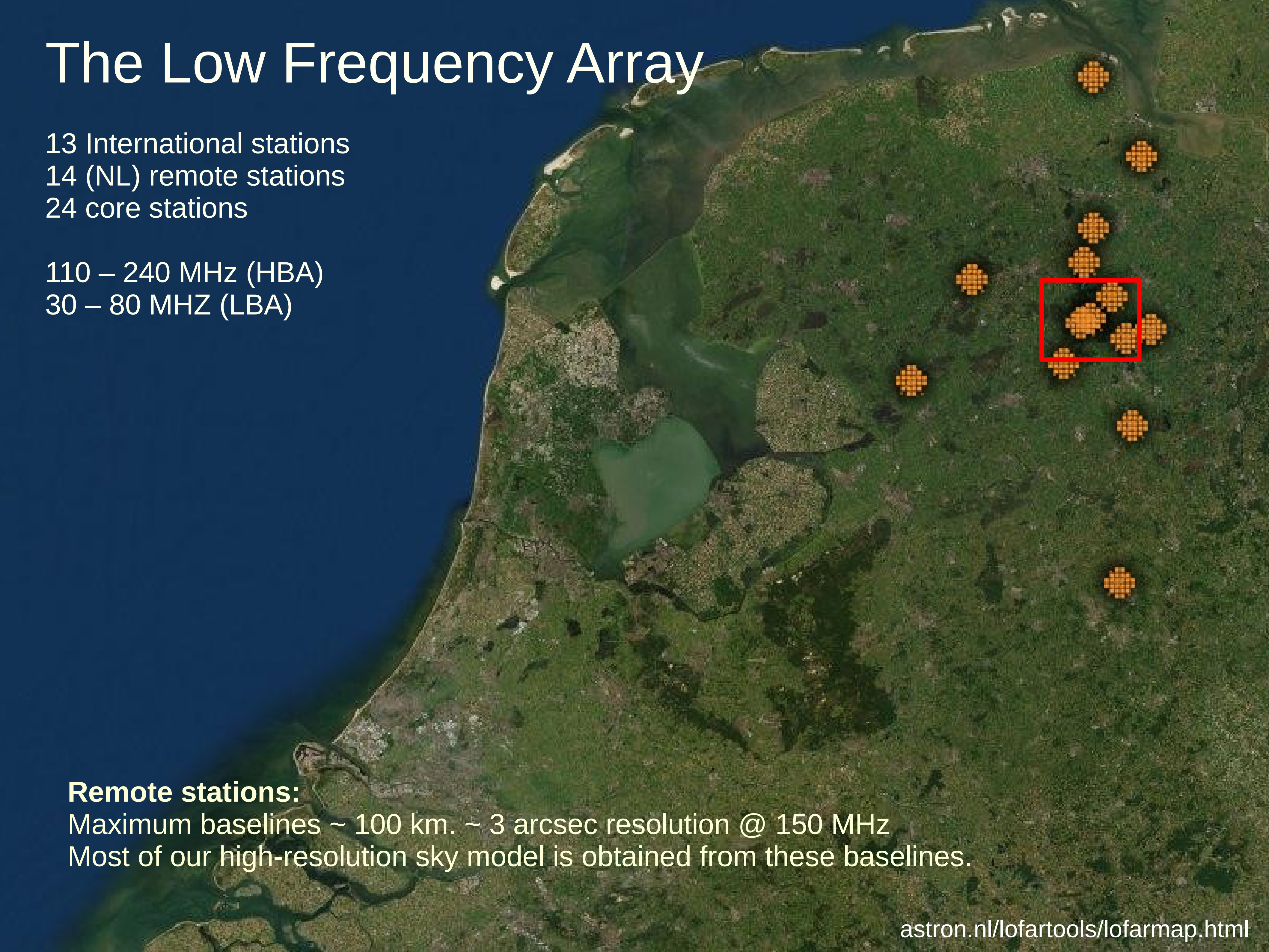
110 – 240 MHz (HBA)
30 – 80 MHZ (LBA)

Remote stations:
Maximum baselines ~ 100 km. ~ 3 arcsec resolution @ 150 MHz
Most of our high-resolution sky model is obtained from these baselines.

astron.nl/lofartools/lofarmap.html

The Low Frequency Array



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Maximum baselines ~ 100 km. ~ 3 arcsec resolution @ 150 MHz
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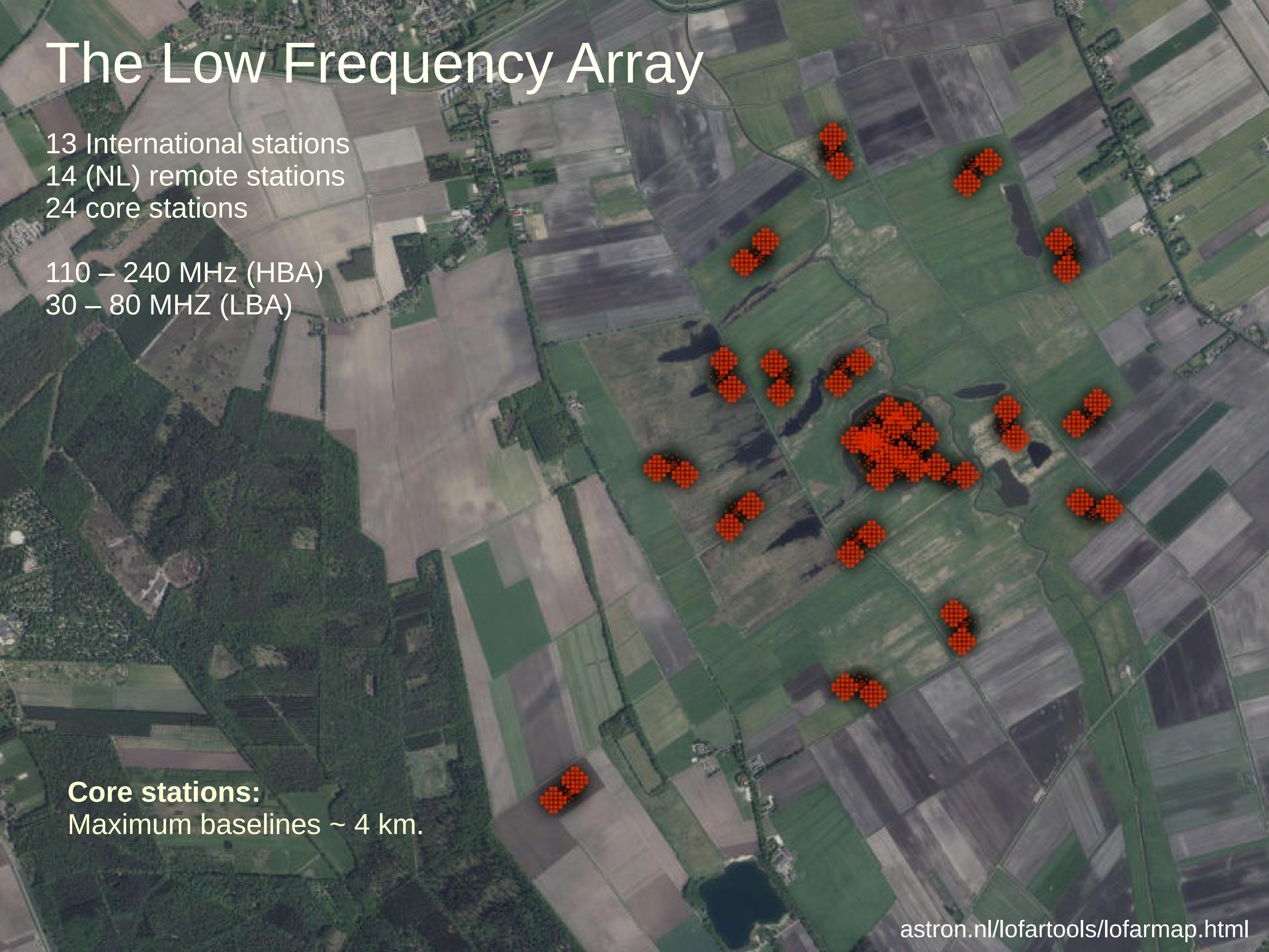
The Low Frequency Array



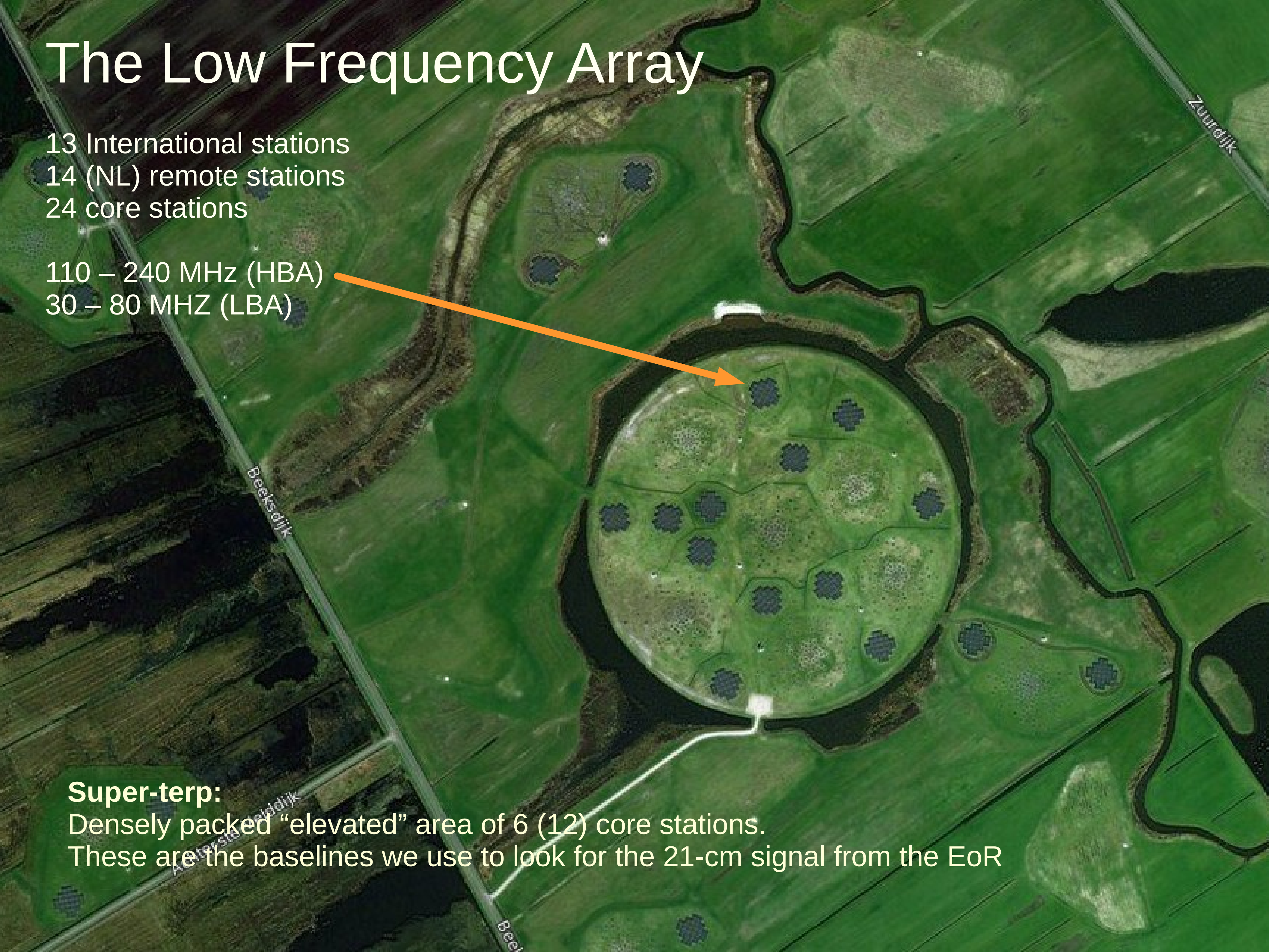
13 International stations
14 (NL) remote stations
24 core stations

110 – 240 MHz (HBA)
30 – 80 MHZ (LBA)

Core stations:
Maximum baselines ~ 4 km.

astron.nl/lofartools/lofarmap.html

The Low Frequency Array



13 International stations
14 (NL) remote stations
24 core stations

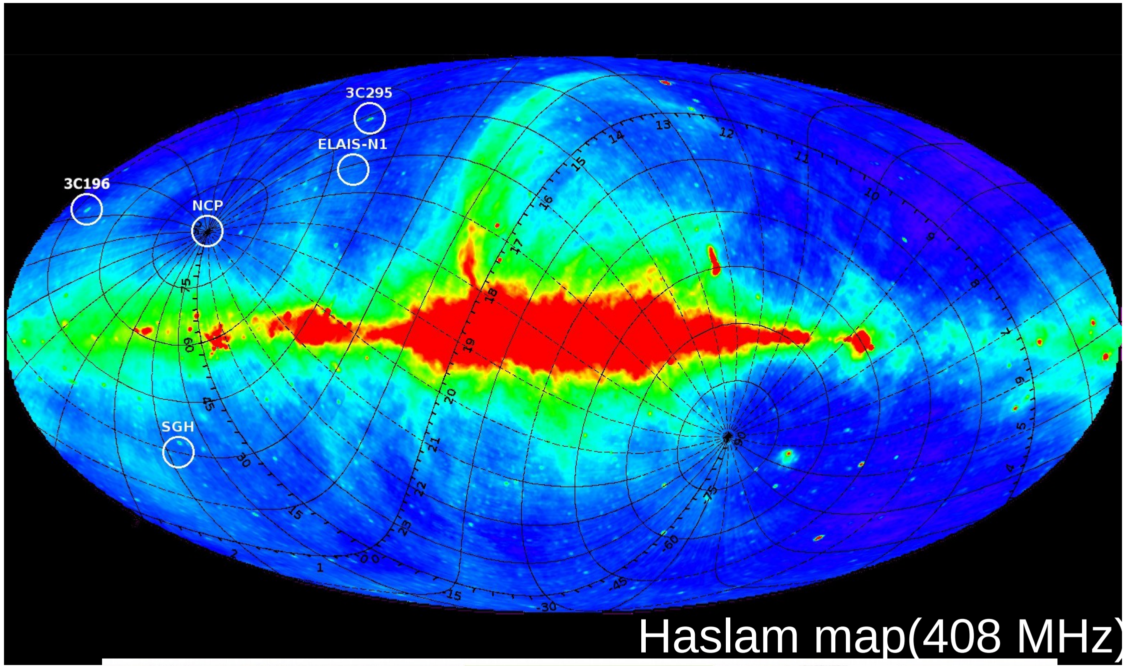
110 – 240 MHz (HBA)
30 – 80 MHZ (LBA)

Super-terp:
Densely packed “elevated” area of 6 (12) core stations.
These are the baselines we use to look for the 21-cm signal from the EoR

The LOFAR-EoR KSP

2 main targets

- North Celestial Pole
  - ✓ Constant Beam, all year observable
  - ✓ + 2200 hours observed
- 3C 196
  - ✓ Bright calibrator
  - ✓ + 1100 hours observed



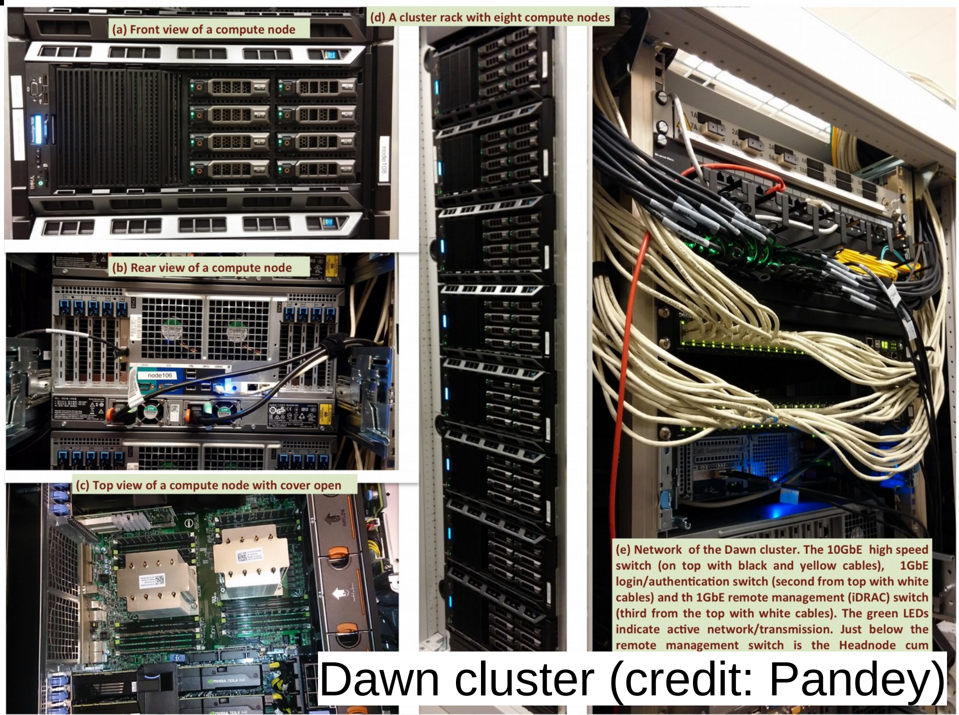
Haslam map(408 MHz)

2-3 other windows for various other projects

Raw data volume: 20-70 TB / night
Archived data: > 5 PB

Dawn cluster:

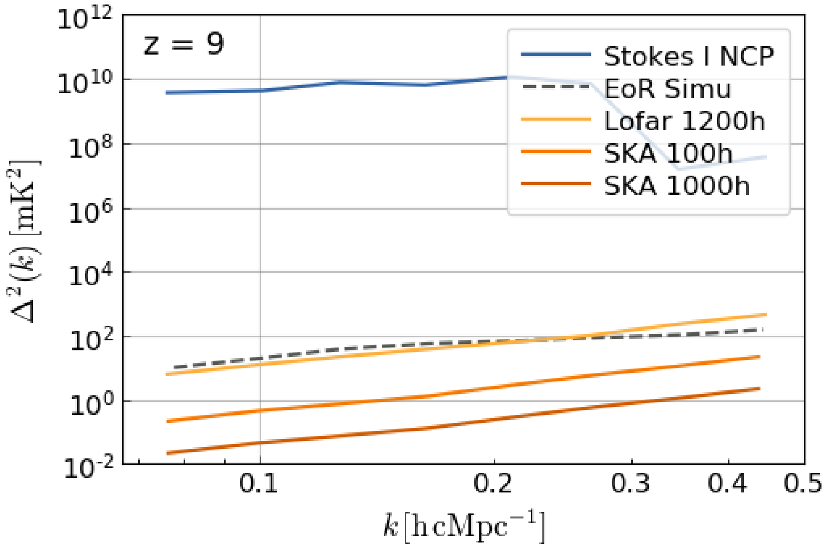
- ✓ 32 nodes
- ✓ each with 48 CPU cores + 4 GPU



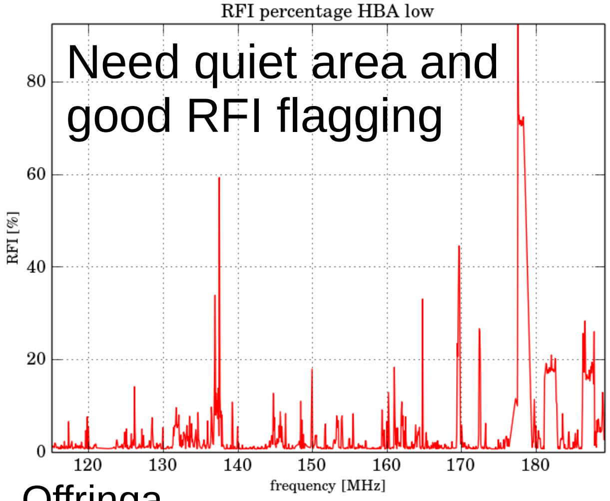
Dawn cluster (credit: Pandey)

What make this experiment so challenging ?

Foregrounds



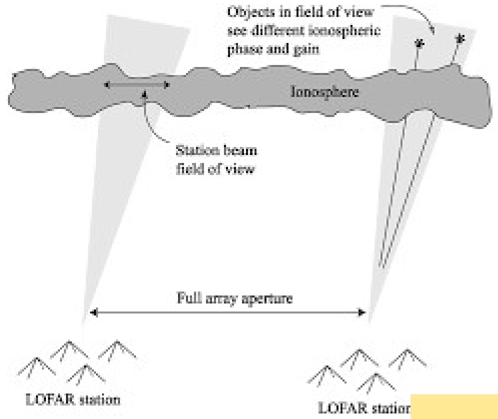
Radio Frequency Interferance (RFI)



Need quiet area and good RFI flagging

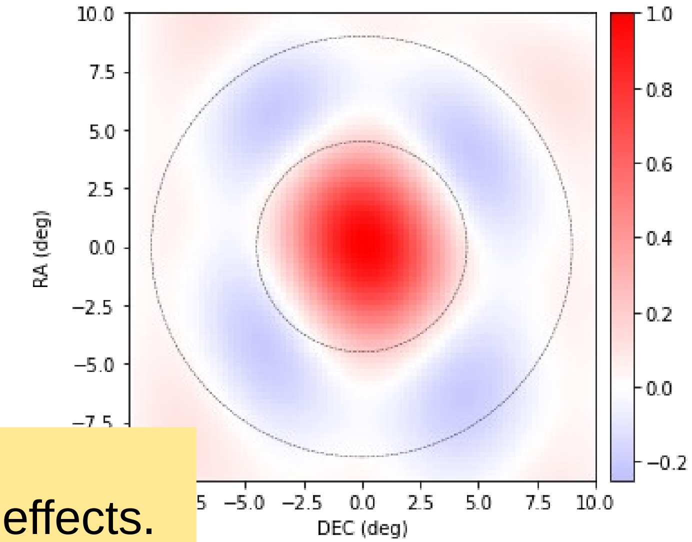
Credit: A. Offringa

Ionosphere



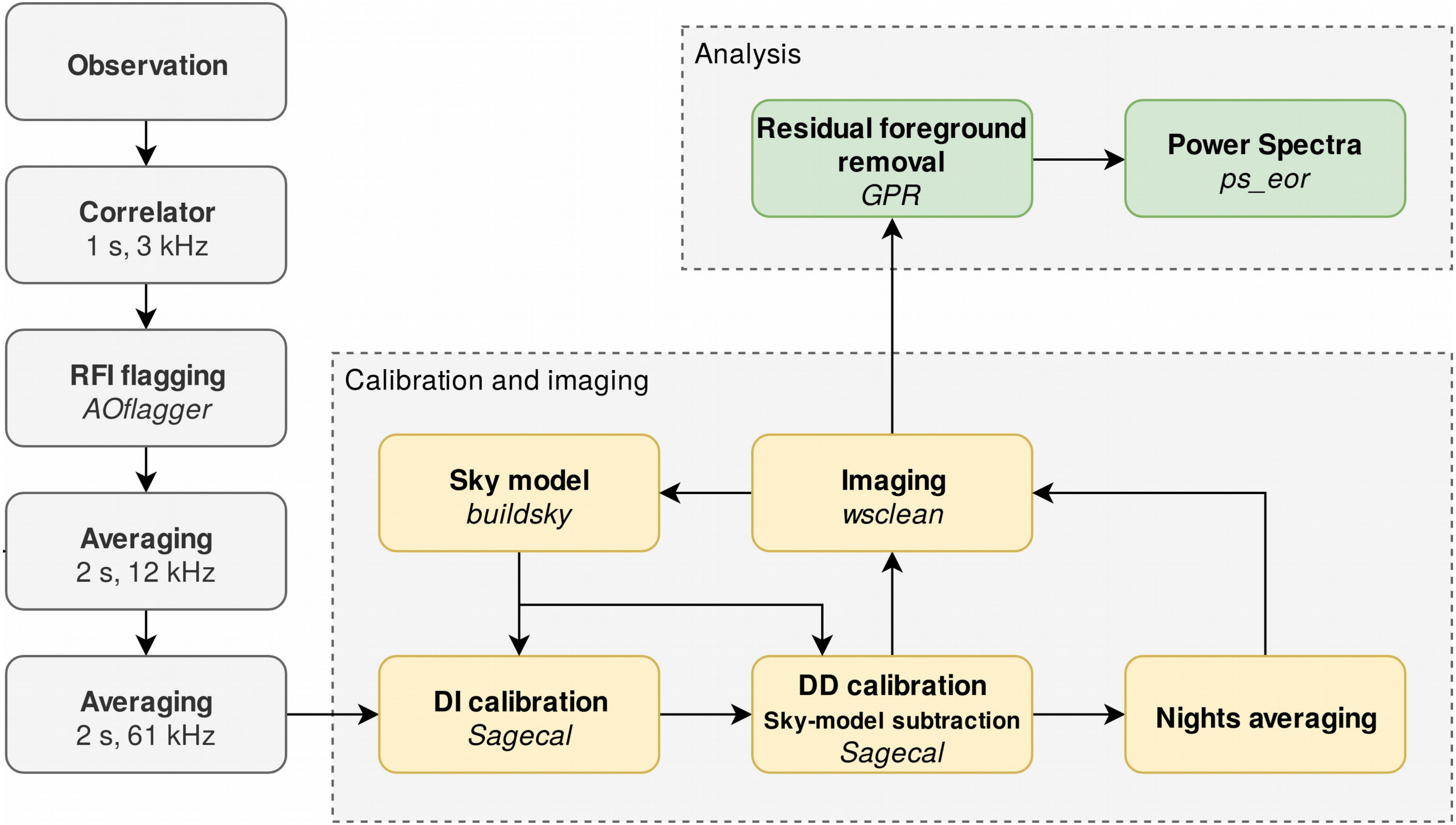
Credit: S. Van der Tol

Primary beam



+ polarization leakage.
All direction dependent effects.

(Simplified) Processing Pipeline

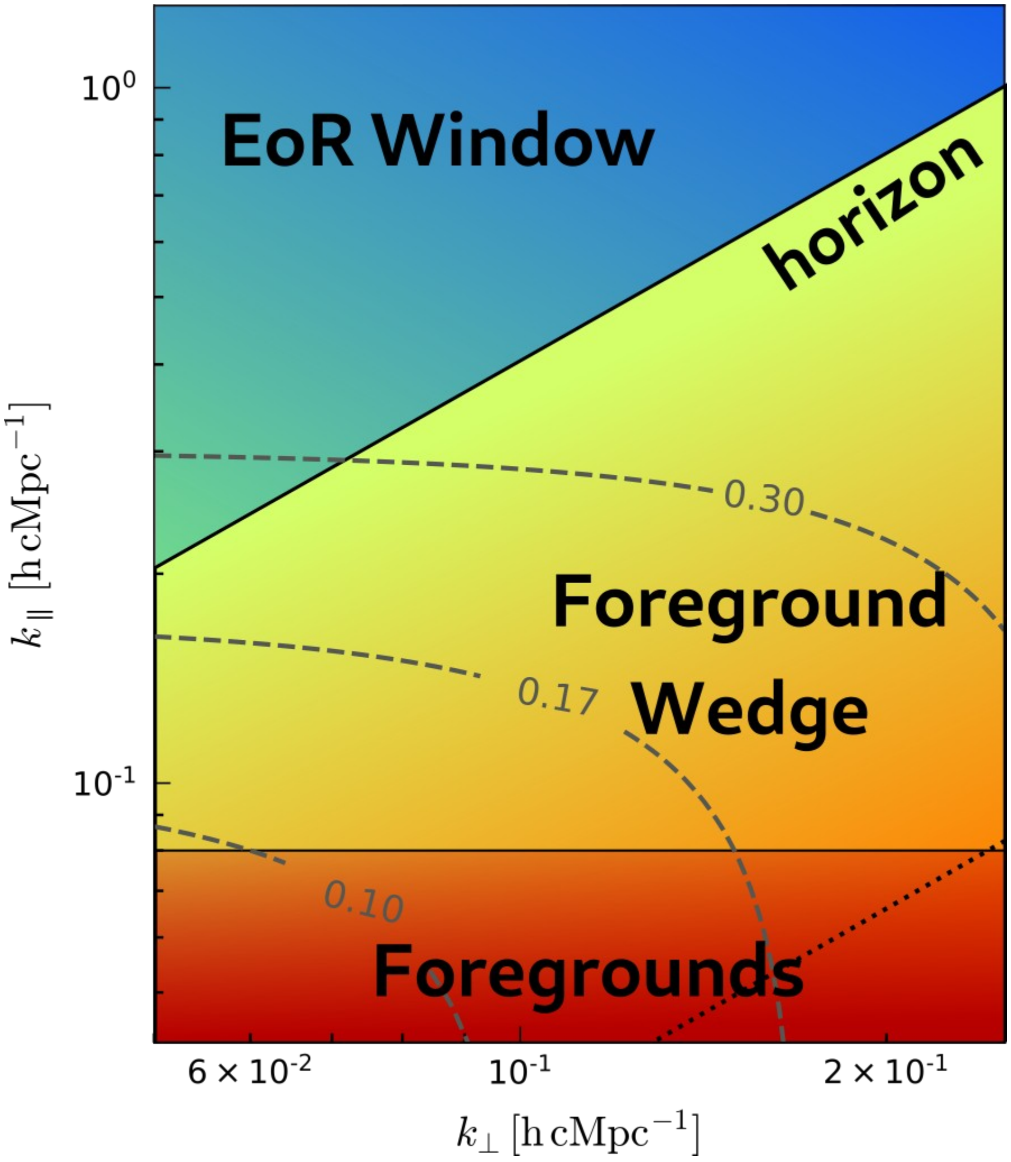


The challenge of the foregrounds

21-cm signal:
- Uncorrelated ~ MHz
- Isotropic

Foreground emission:
- Mainly synchrotron and free-free emission
- Smooth in frequency

Foreground Wedge:
- ➔ Chromatic instrument (beam/uv-coverage)
- ➔ Ionosphere
- ➔ Calibration error
- ➔ Polarization leakage



Spatial vs line-of-sight power-spectra

Removing the foregrounds

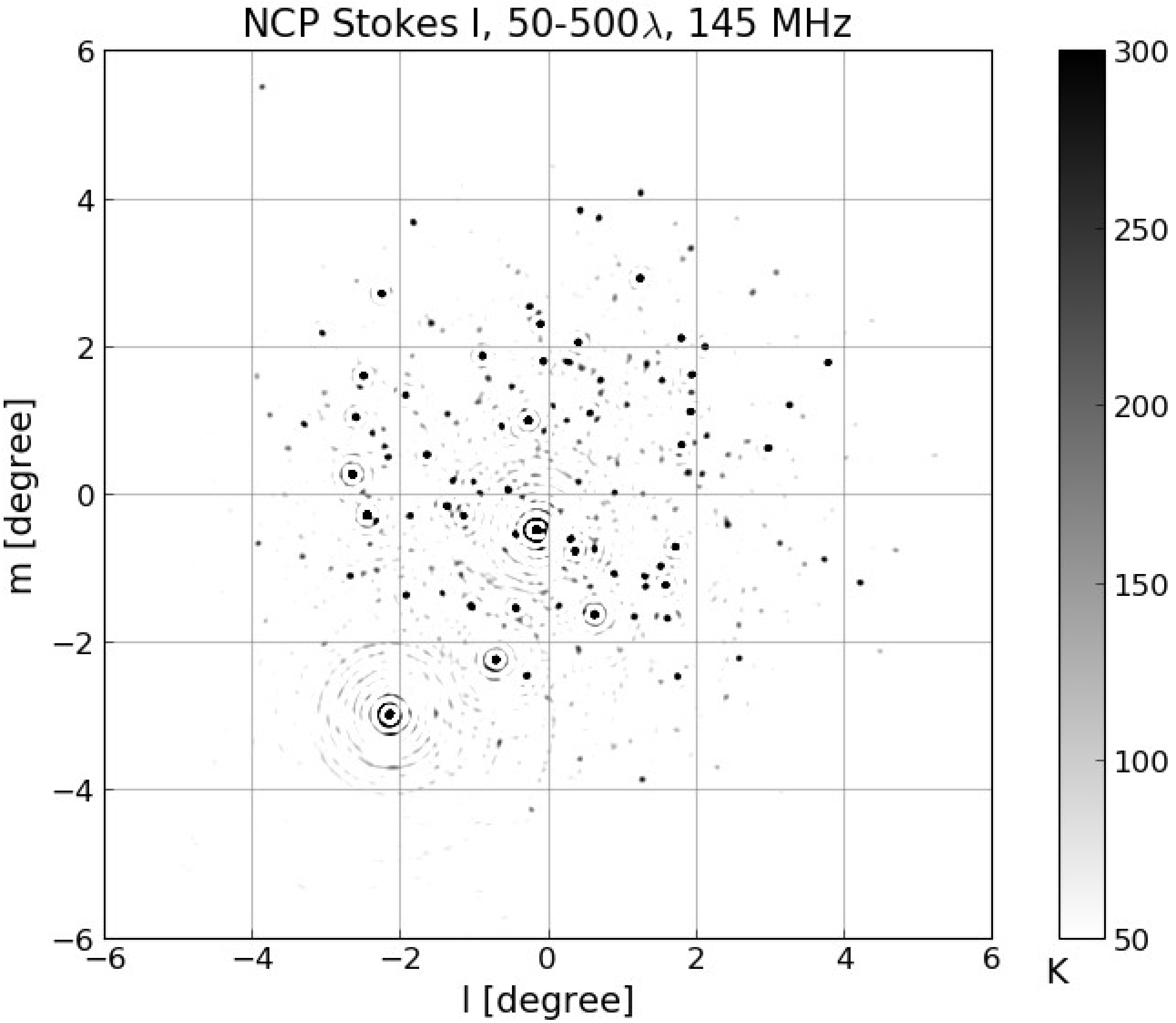
Step 1:
Point-sources subtraction

- ➔ Need accurate sky-model
- ➔ Solve for instruments gains in direction of sources

Direction Dependent (DD) calibration using Sagecal-CO (Yattawatta et al. 2013, 1015, ...)

Step 2:
Residual spectrally-smooth foregrounds subtraction

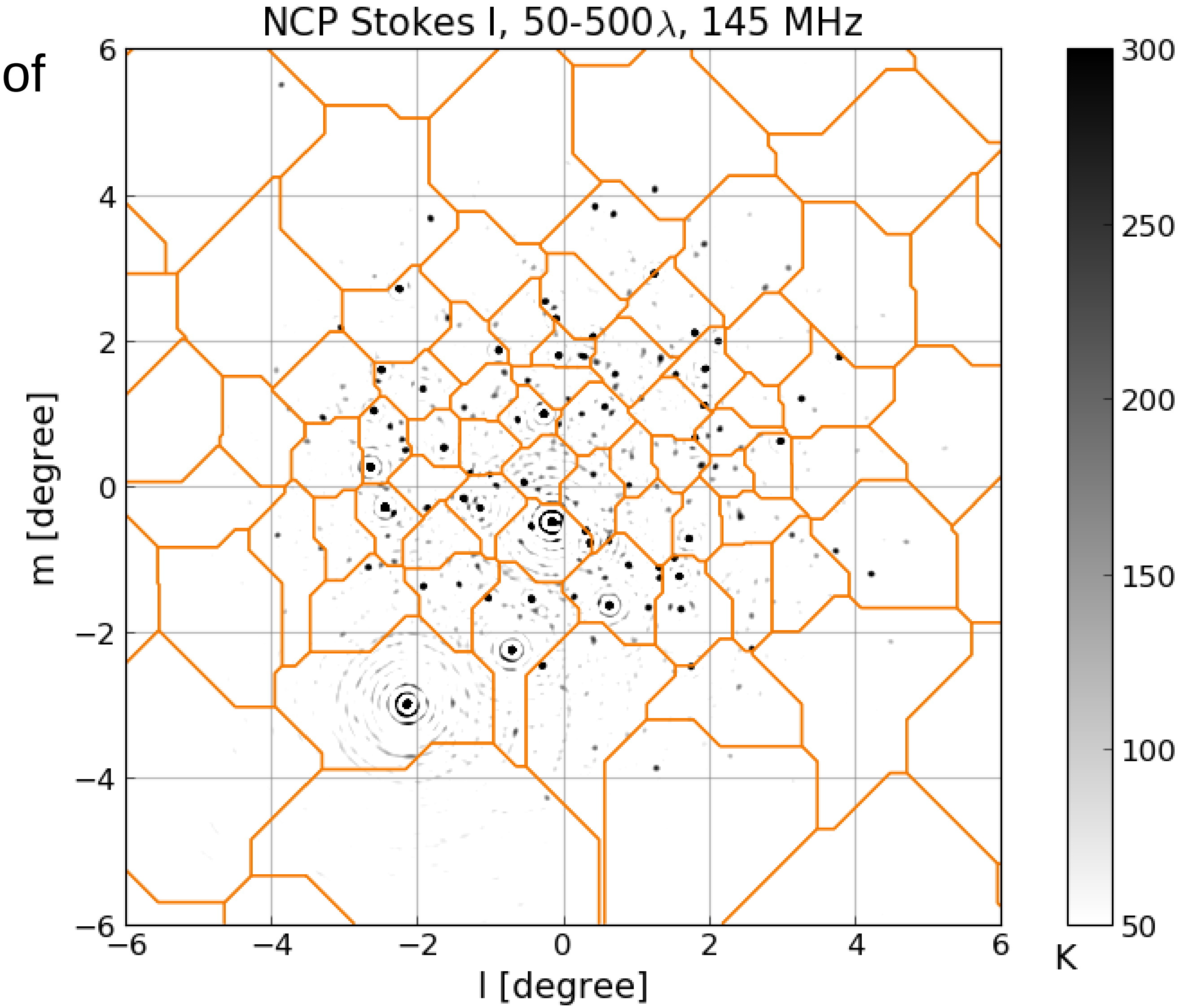
Using e.g. Gaussian Process Regression (GPR) (Mertens et al. 2018)



Direction Dependent calibration

Need to reduce the number of degree of freedom:

- ➔ Clustering (NCP ~ 120 clusters)



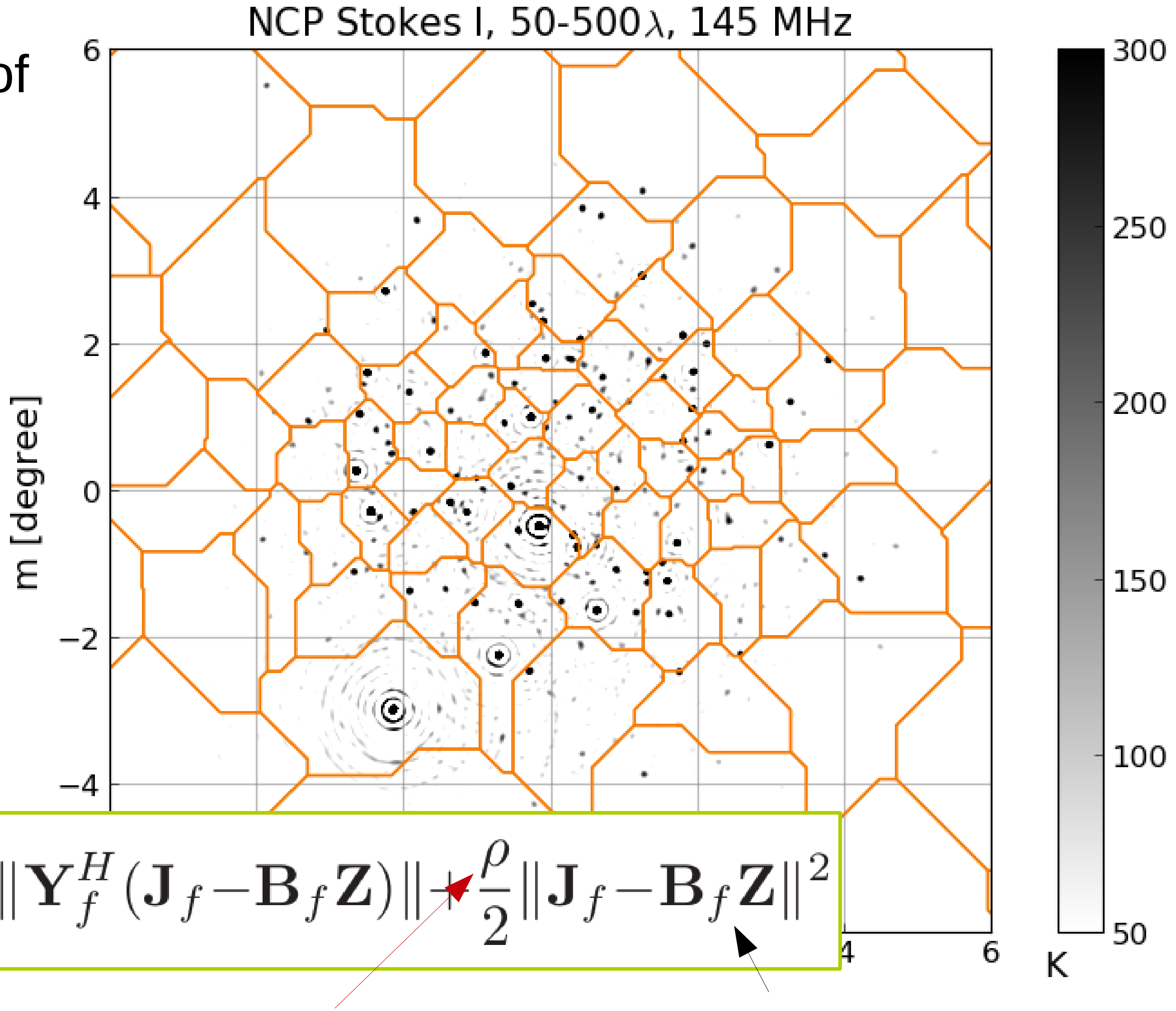
(Yatawatta et al. 2013, 2015)

Direction Dependent calibration

Need to reduce the number of degree of freedom:

- ➔ Clustering (NCP ~ 120 clusters)
- ➔ Force spectrally-smooth instrumental response

Sagecal-CO: distributed calibration, solve augmented Lagrangian:



$$L_f(\mathbf{J}_f,\mathbf{Z},\mathbf{Y}_f) = g_f(\mathbf{J}_f) + \|\mathbf{Y}_f^H(\mathbf{J}_f-\mathbf{B}_f\mathbf{Z})\| + \frac{\rho}{2}\|\mathbf{J}_f-\mathbf{B}_f\mathbf{Z}\|^2$$

Gains

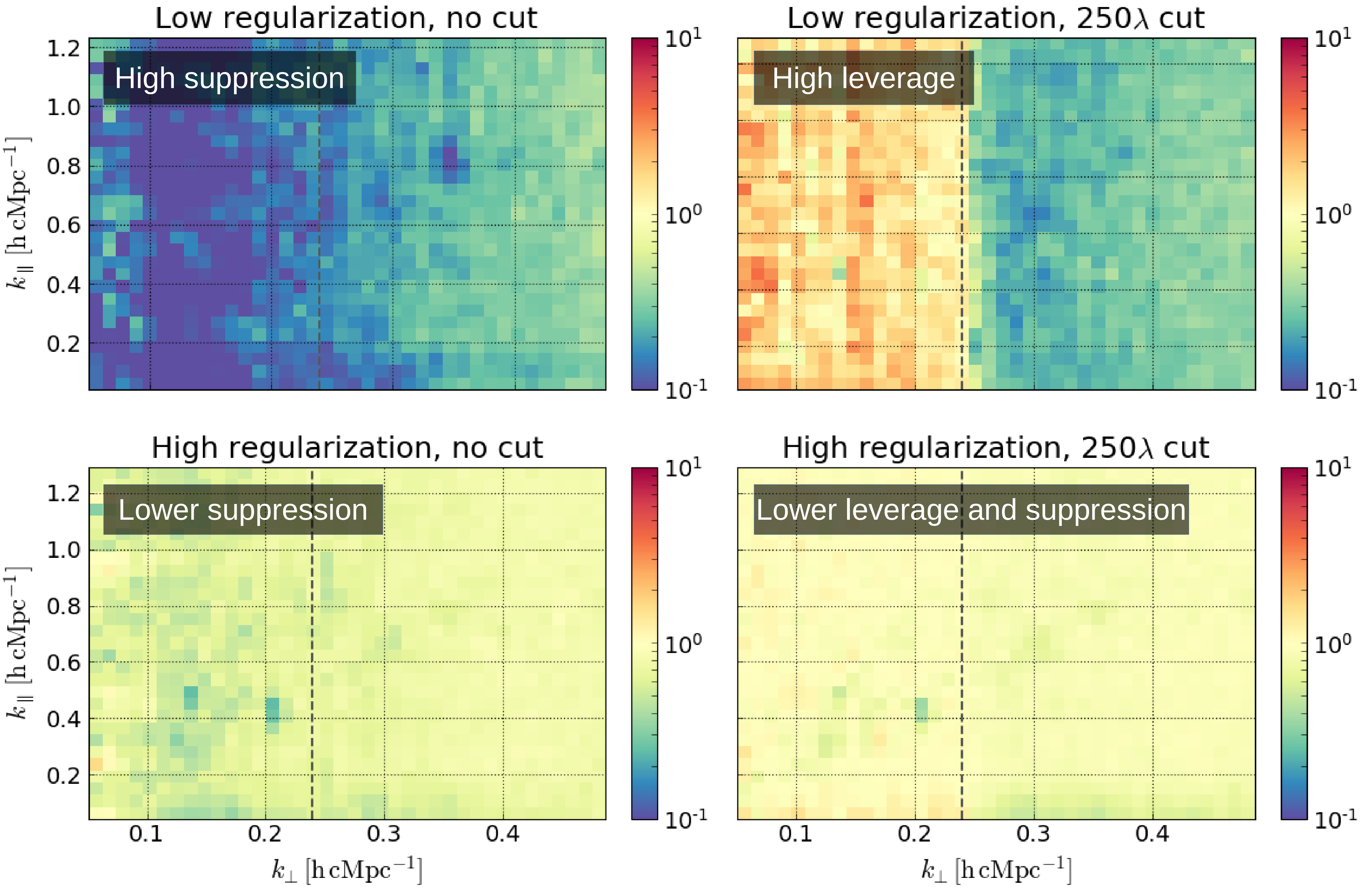
Original cost function

Regularization parameter

Spectrally-smooth constraint

(Yatawatta et al. 2013, 2015)

DD calibration: effect of enforcing smoothness

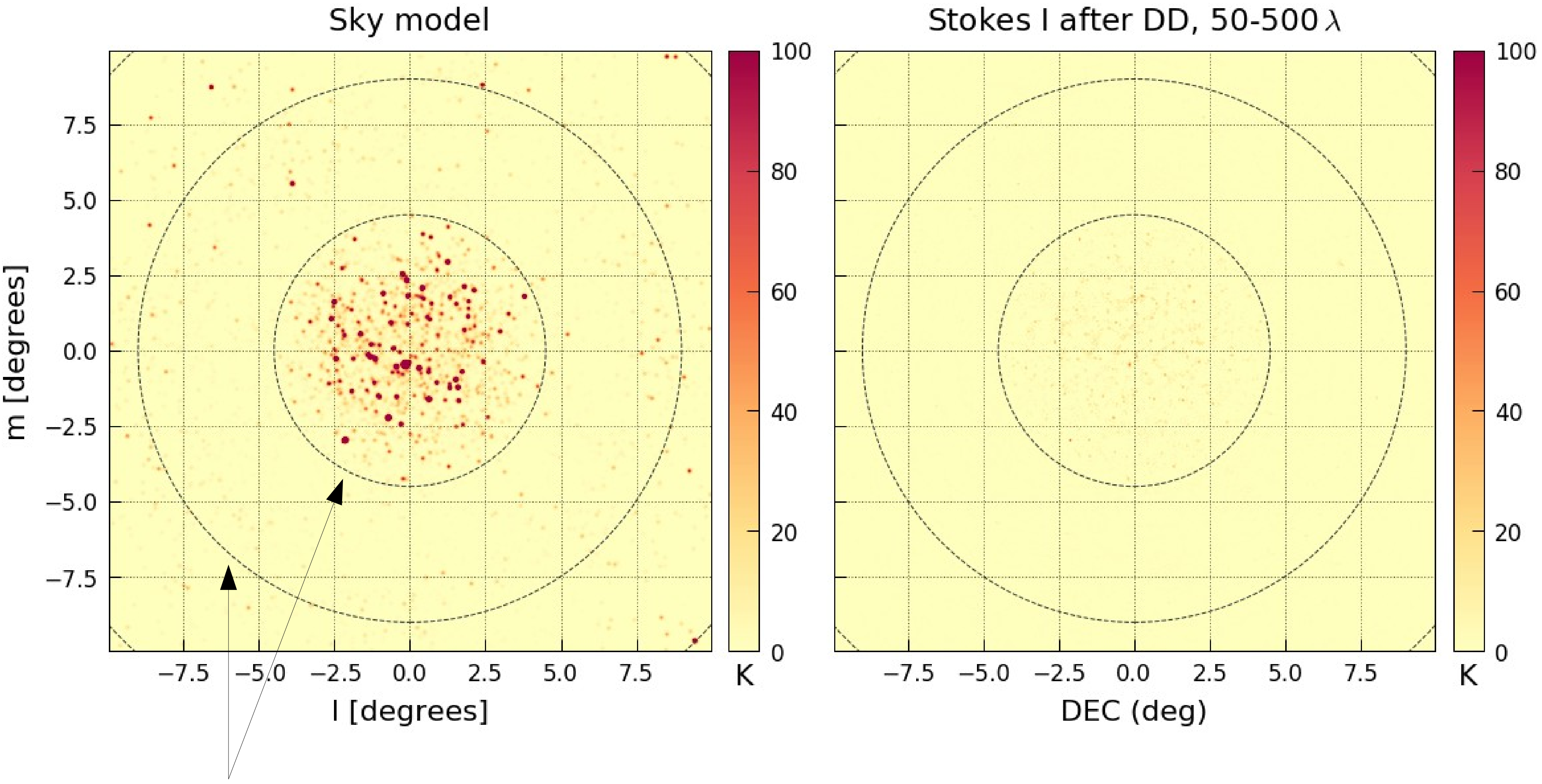


Ratio of Stokes V before/after DD show the effect of enforcing frequency-smoothness

(Mevius, Mertens, et al in prep.)
See also Sardarabadi et al. 2018

DD calibration results

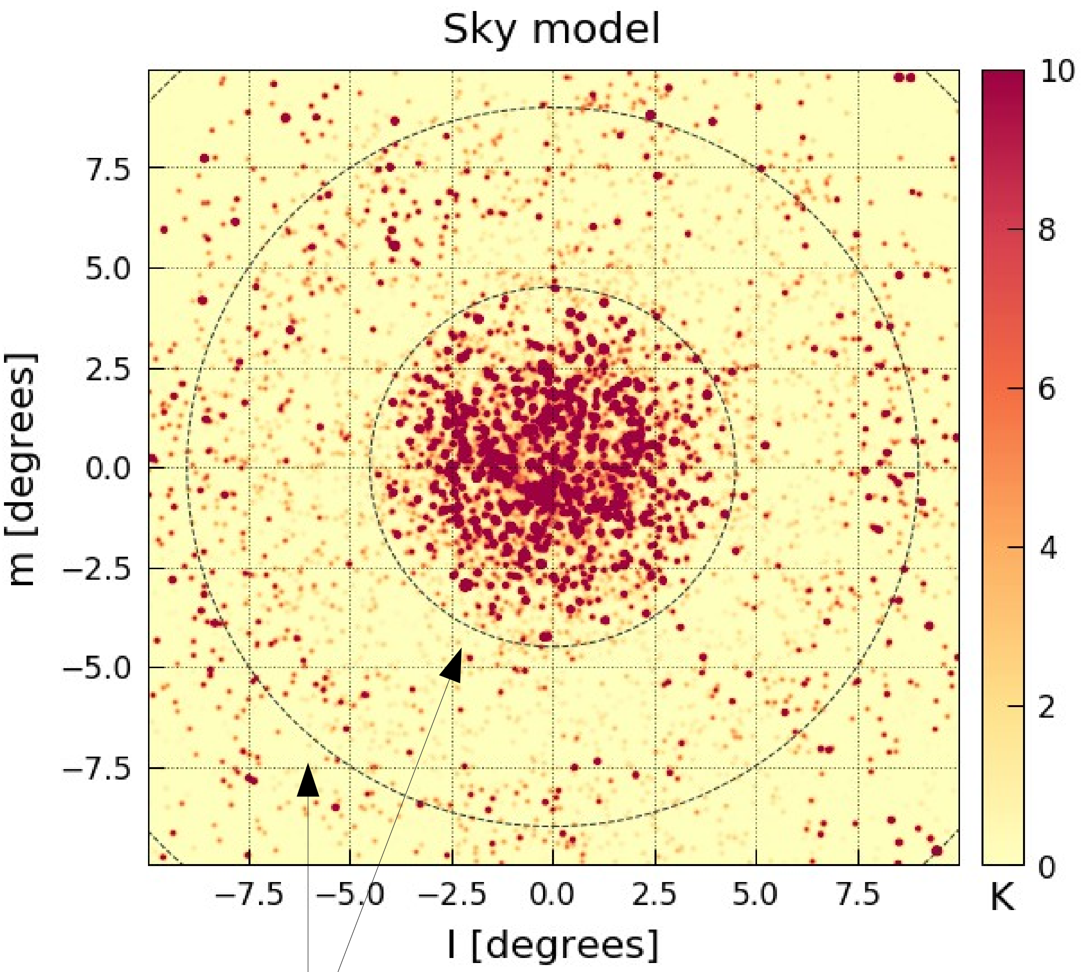
NCP field, 140 hours, 134-146 MHz, z ~ 9.1

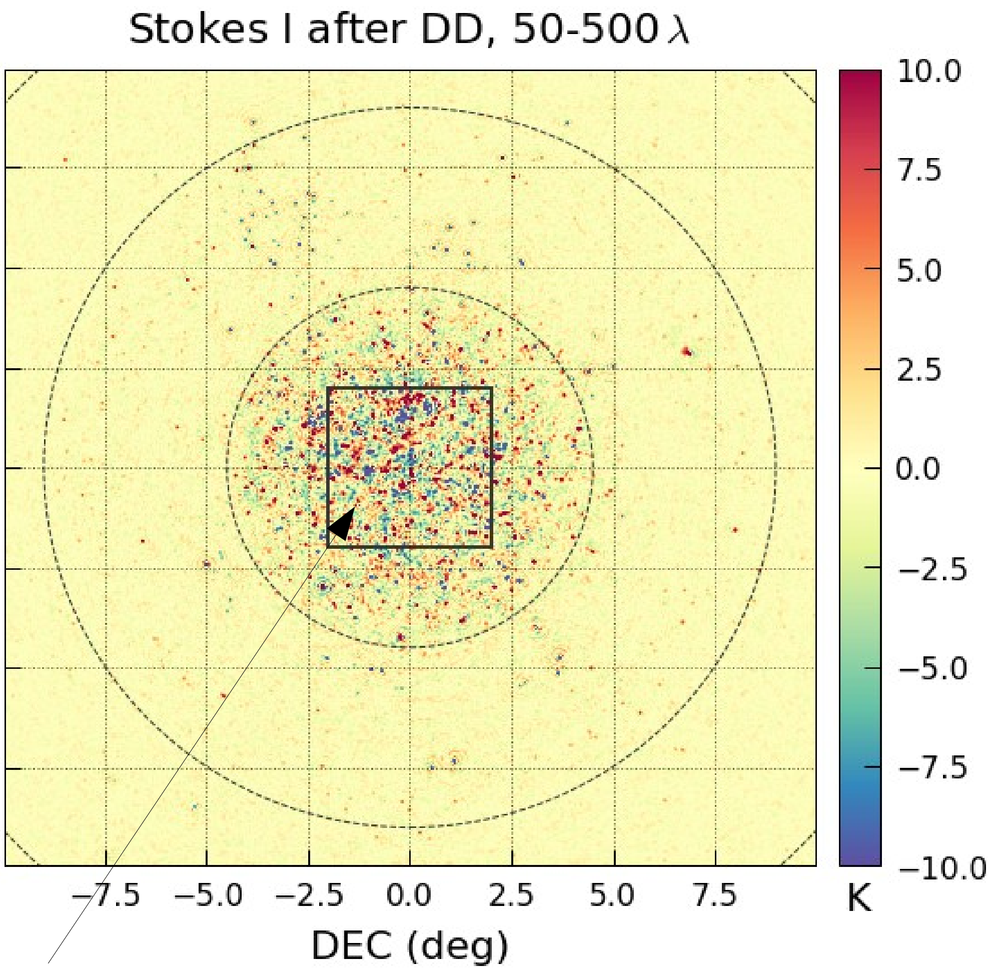


First and second null
of the Primary Beam

DD calibration results

NCP field, 140 hours, 134-146 MHz, z ~ 9.1





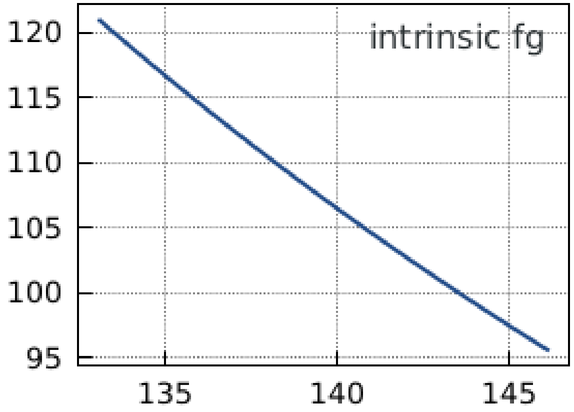
Inner 4x4 where we look for the signal

First and second null of the Primary Beam

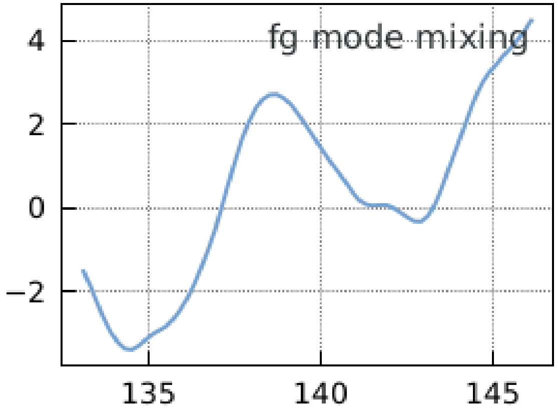
Next step: Remove confusion-limited foregrounds

GPR modeling for 21-cm experiments

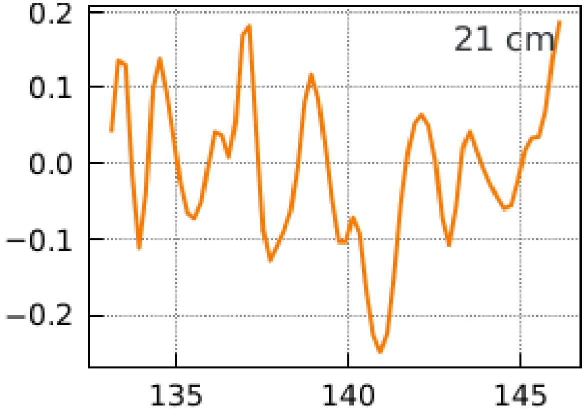
Residual data can be decomposed in three main components:



Residual astrophysical sources:
Smooth in frequency



Mode mixing:
Less frequency smooth



21-cm signal:
Uncorrelated ~ MHz

GPR: uses Gaussian Process (GP) as prior information $\mathbf{f} \sim \mathcal{N}(0, K)$

$$E(\mathbf{f}_{\mathrm{fg}}) = K_{\mathrm{fg}} \left[K_{\mathrm{fg}} + K_{21} + \sigma_n^2 I\right]^{-1} \mathbf{d}$$

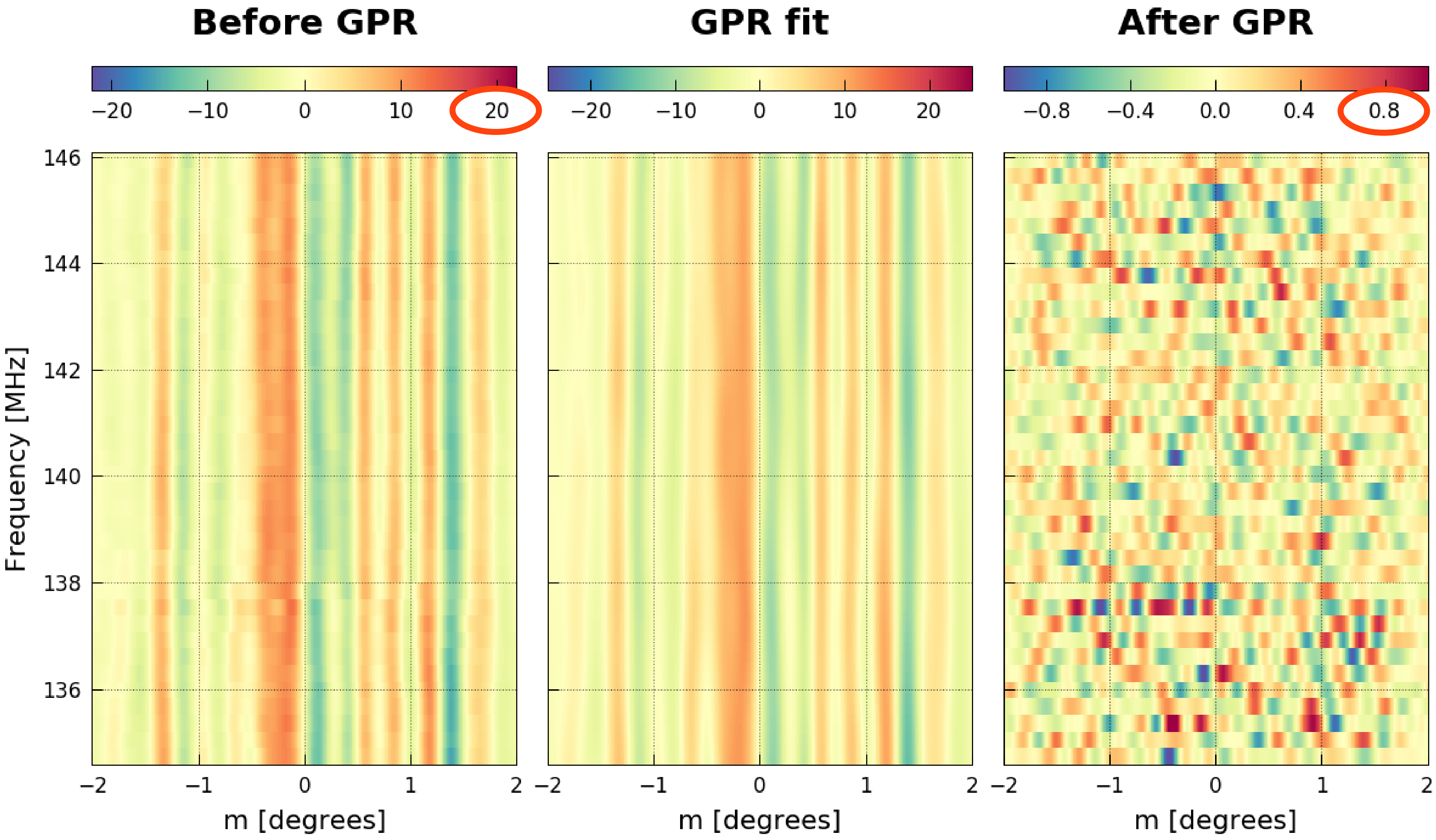
$$\mathrm{cov}(\mathbf{f}_{\mathrm{fg}}) = K_{\mathrm{fg}} - K_{\mathrm{fg}} \left[K_{\mathrm{fg}} + K_{21} + \sigma_n^2 I\right]^{-1} K_{\mathrm{fg}}$$

- ➔ Parametric Covariance optimized by maximizing the marginal likelihood (i.e. Bayesian evidence).
- ➔ Including prior information on the covariance contribution of the signal is key to avoid signal suppression!

(Mertens et al. 2018)

GPR on LOFAR data

NCP field, 140 hours, 134-146 MHz, z ~ 9.1

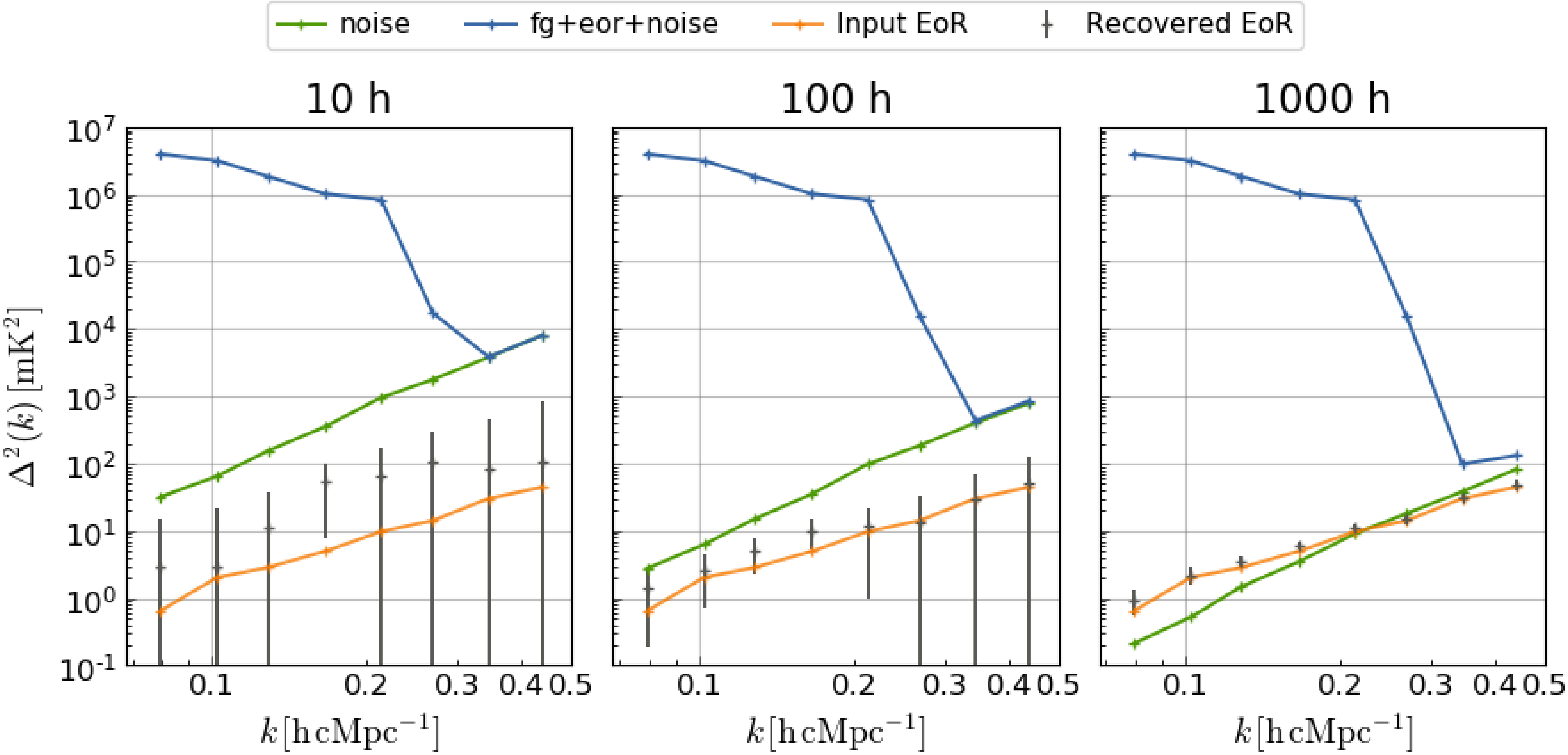


GPR remove frequency-coherent structure
Residual power level close to thermal noise

GPR on SKA simulation

Simulation (from Modhurita Mitra for the SKA CD/EoR blind challenge):

- Intrinsic foregrounds: galactic diffuse emission, 10 degree FoV
- 21-cm input signal: simulated from 21cmFast
- noise: equivalent to 10-100-1000 hours of SKA observation
- Visibility simulated using OSKAR



GPR on LOFAR data

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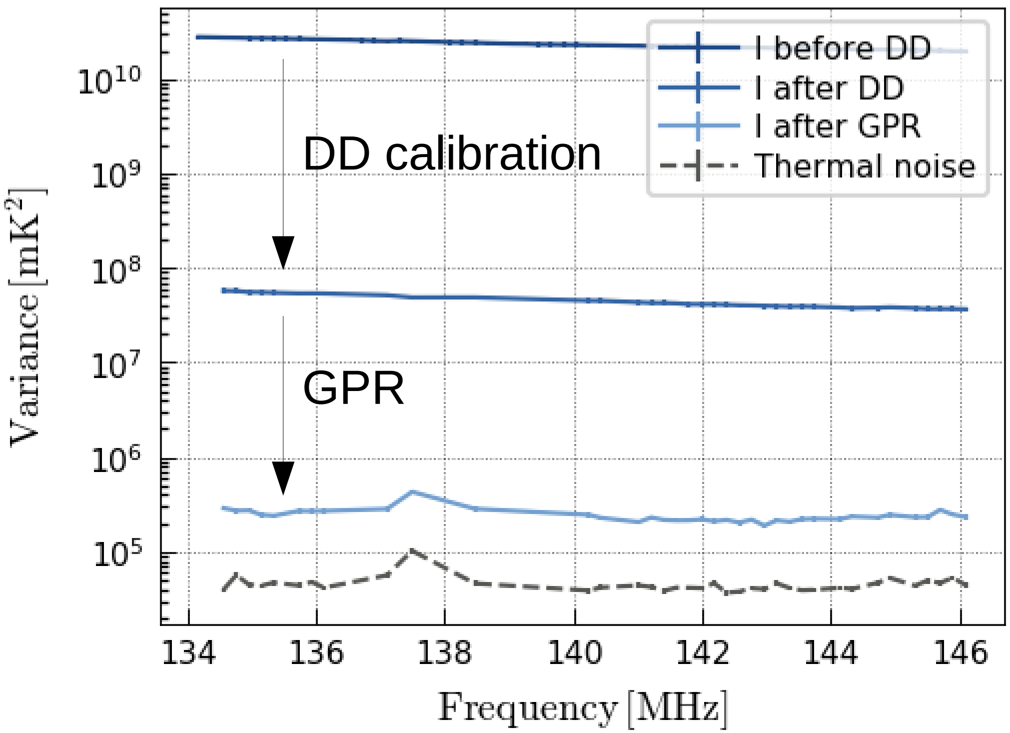
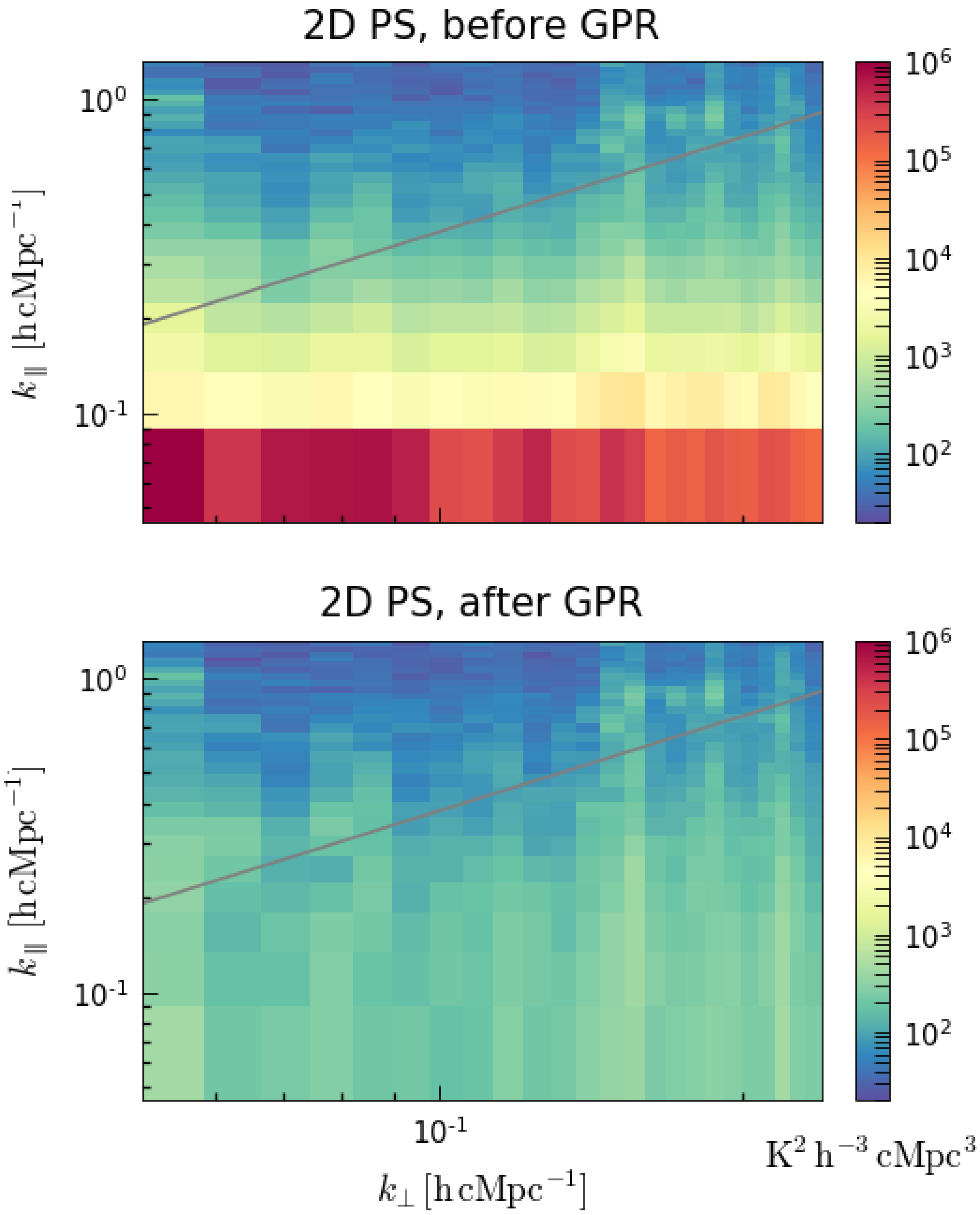
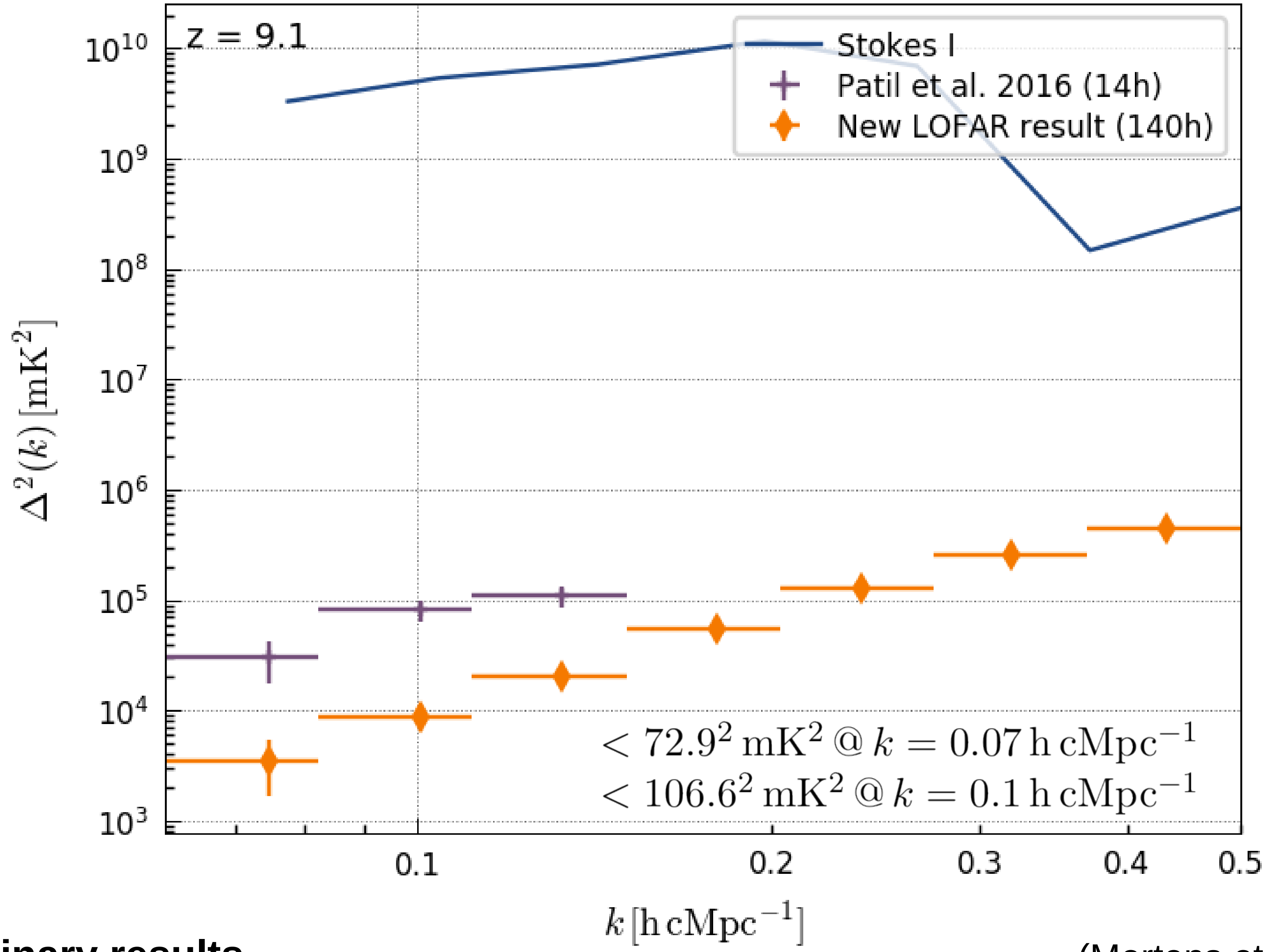




- DD calibration reduce foregrounds power by an order of magnitude down to confusion limit
- GPR remove residual foregrounds down to (very close to) noise level
- Residual power mostly incoherent between nights

New upper limit !

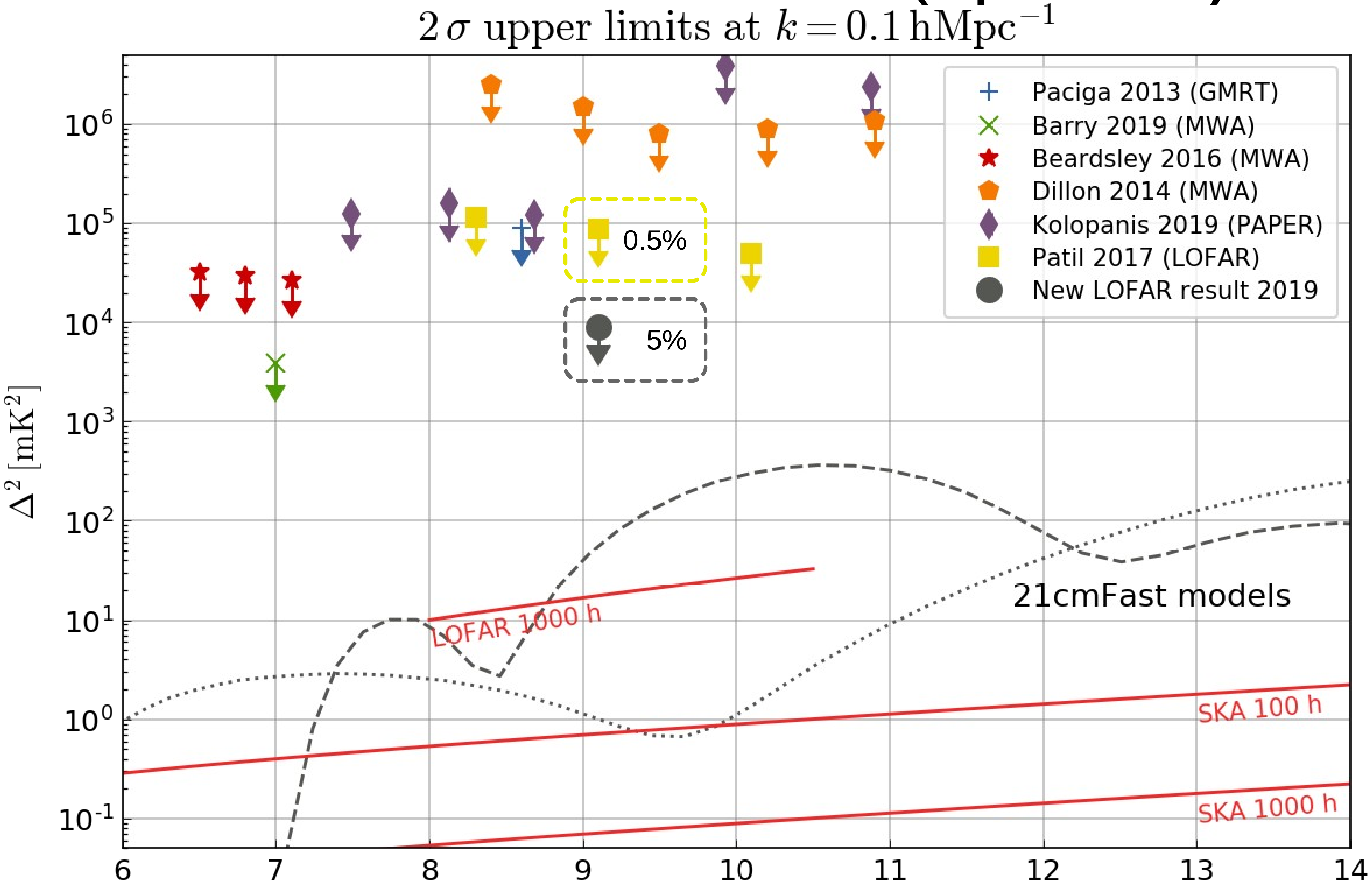
NCP field, 140 hours, 134-146 MHz, z ~ 9.1



Preliminary results

(Mertens et al. In prep.)

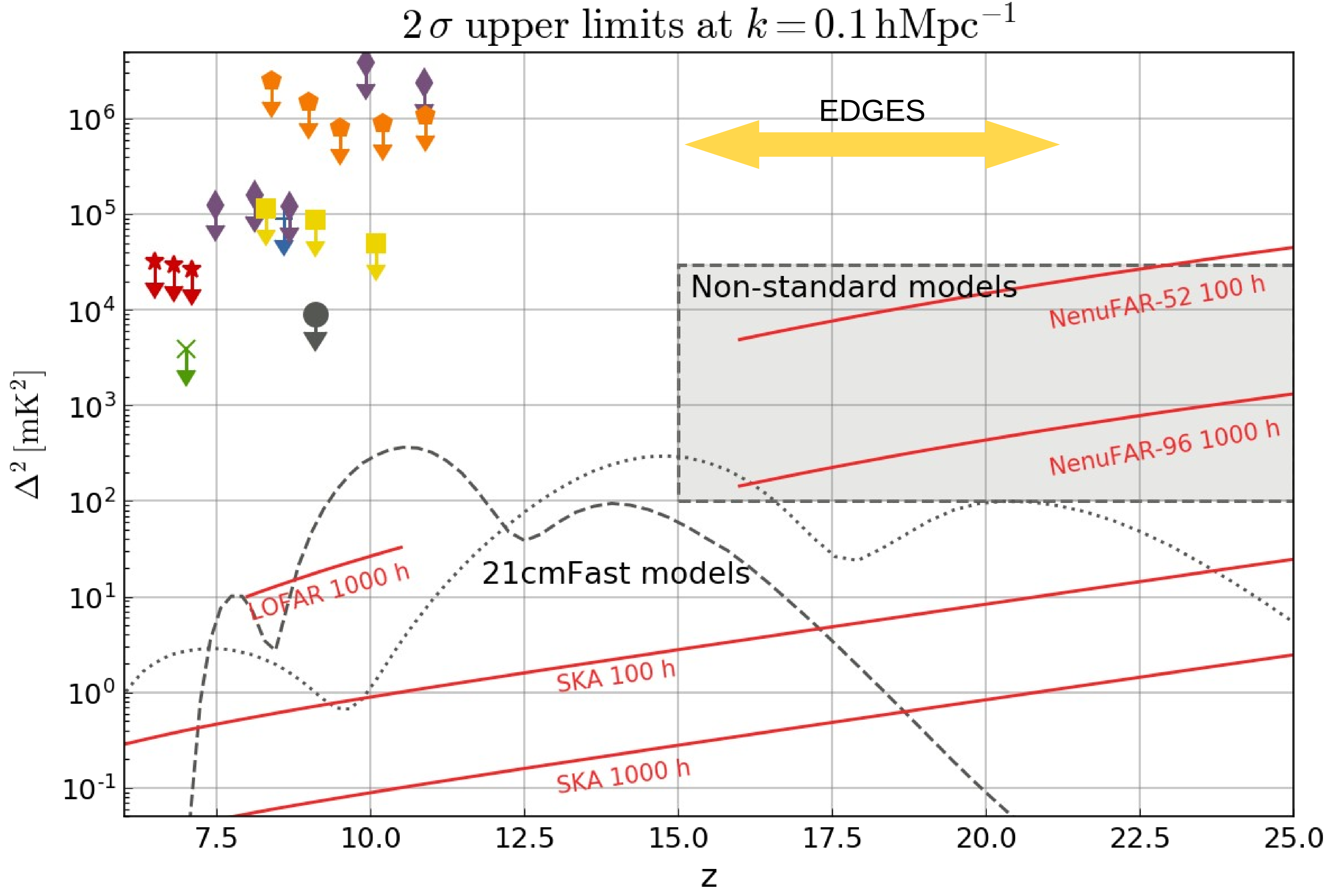
Where do we stand ? (updated)



Preliminary results

(Mertens et al. In prep.)

Perspective: NenuFAR, SKA

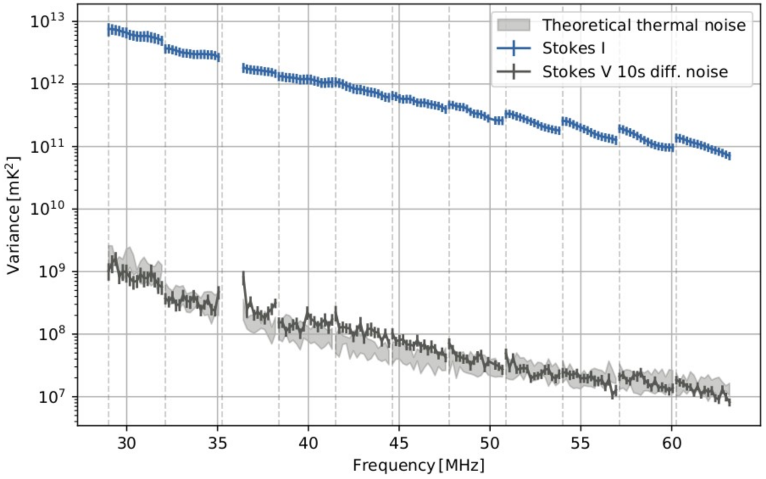


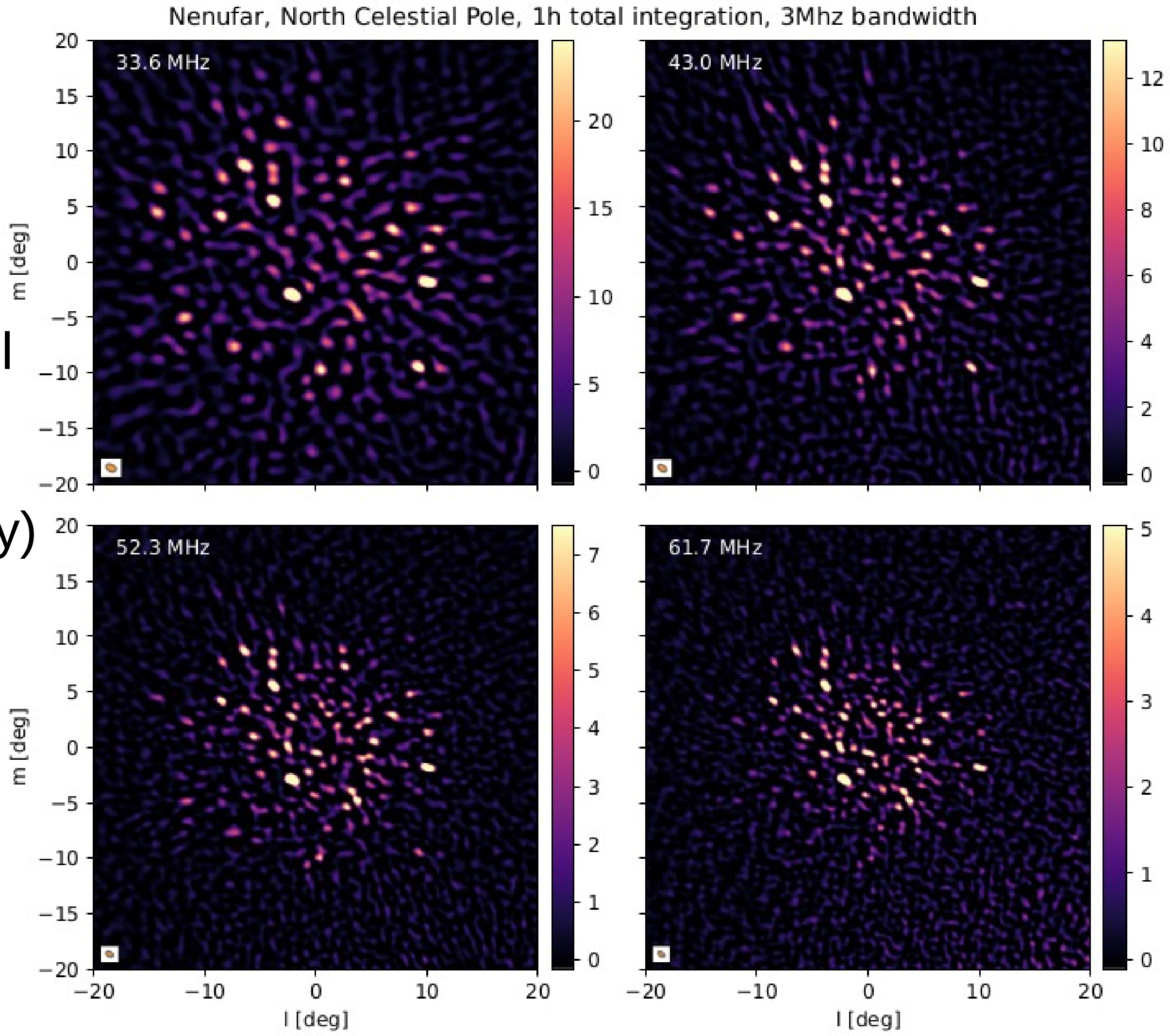
First NenuFAR results

Nenufar Cosmic Dawn KSP started observing 13/07/2019

- **First phase:**
  - Limited bandwidth and frequency/spatial resolution
  - ~ 170 / 330 hours observed
  - Goal 30-85 MHz NCP sky model

- **Second phase:**
  - Beginning 2020 (correlator ready)
  - + 1000 hours on NCP
  - 30 – 85 MHz (z ~ 46 – 15)





Summary

- The 21-cm signal from the Dark Ages, Cosmic Dawn and Reionization promises a new and unique probe of the first billion year of the Universe.

- Many ongoing/planned global and interferometric experiments, but very difficult experiments.

- Dealing with the foregrounds is one of the major challenges of CD/EoR experiments.

- **Current Status of the LOFAR-EoR project:**
  - ➔ Preliminary LOFAR deepest upper limits (based on ~5% of data): $\Delta^2 < (100\ \mathrm{mK})^2$ @ $k=0.1\ \mathrm{cMpc}^{-1}$, $z \sim 9$

- **Perspectives:**
  - ➔ Very interesting upper limit is still at reach with LOFAR.
  - ➔ Near future: NenuFAR exploring the Cosmic Dawn.
  - ➔ Far future: SKA promising tomography of the 21-cm signal.