Observing the Epoch of Reionization and Cosmic Dawn with LOFAR and NenuFAR

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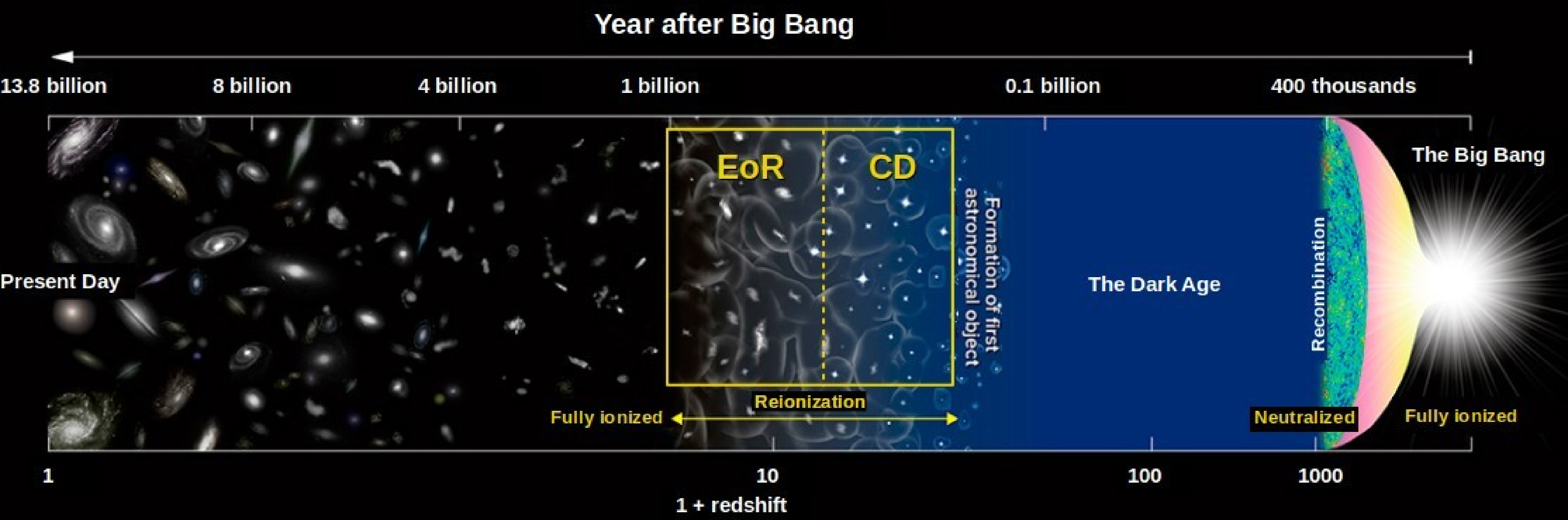
Saleem Zaroubi (K./Haifa)

+ The NenuFAR CD KP team

CoDA II — Pierre Ocvirk

Cosmic Dawn / Epoch of Reionization



Credit: NAOJ

Epoch of Reionization

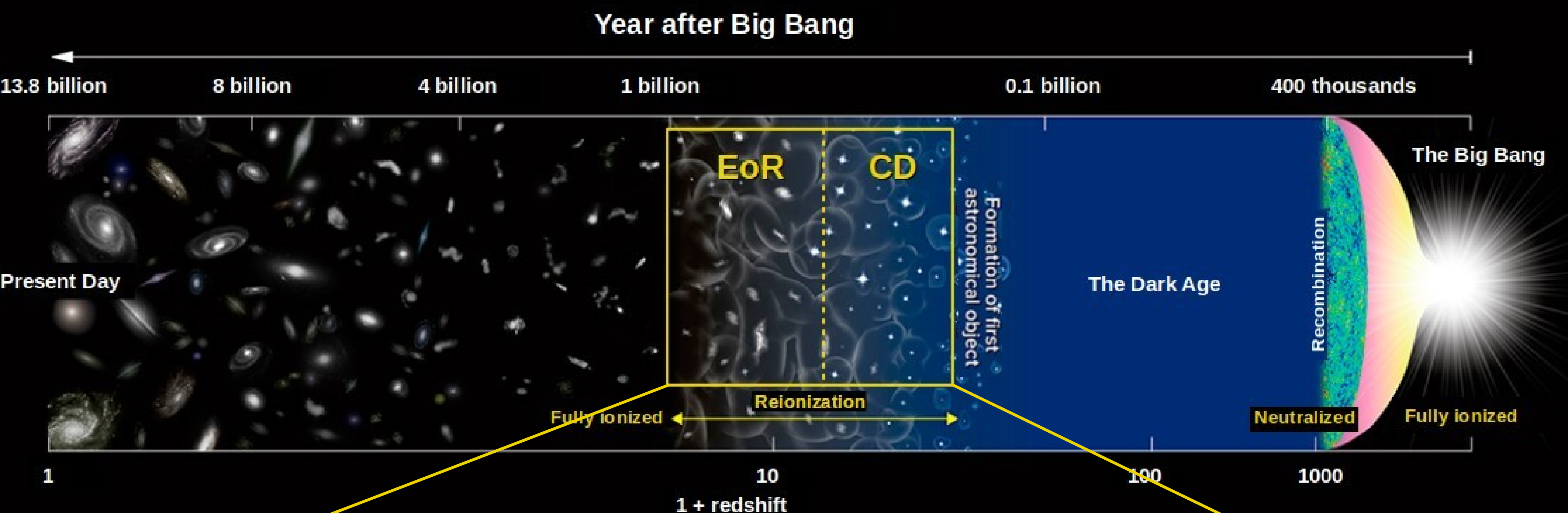
- Reionization by stars & mini-quasars
- IGM feedback (e.g. metals)
- PopIII - PopII transition
- Emergence of the visible universe

Cosmic Dawn

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

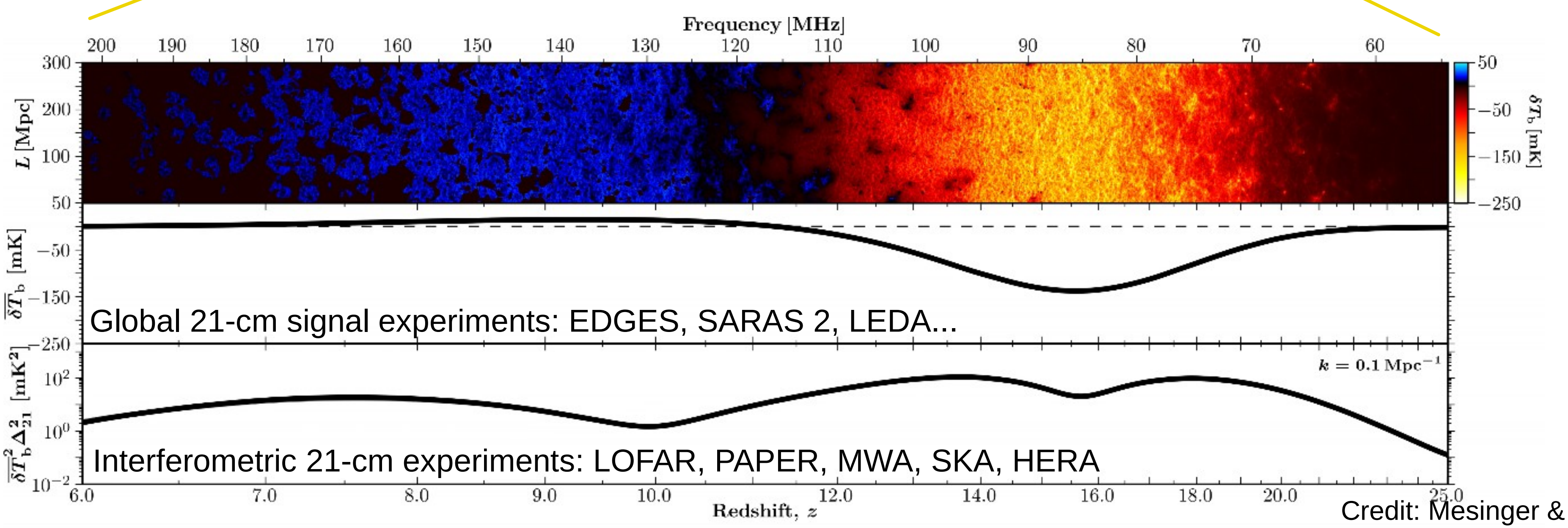
- When did the first galaxies/stars/black hole form?
- How did reionization proceed?
- How do galaxies form and evolve?

Cosmic Dawn / Epoch of Reionization



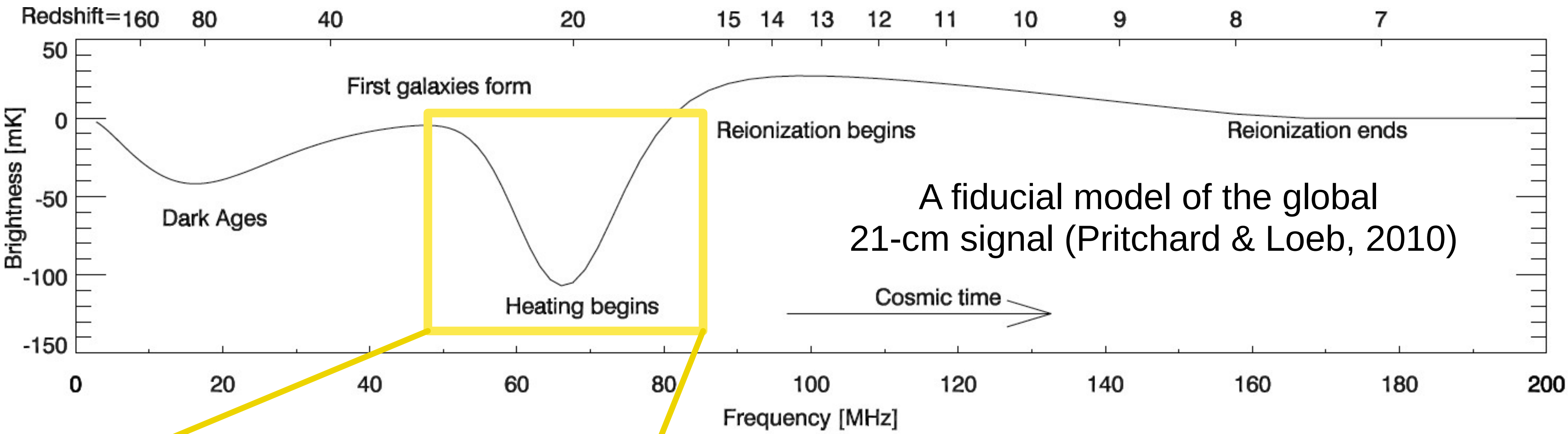
Credit: NAOJ

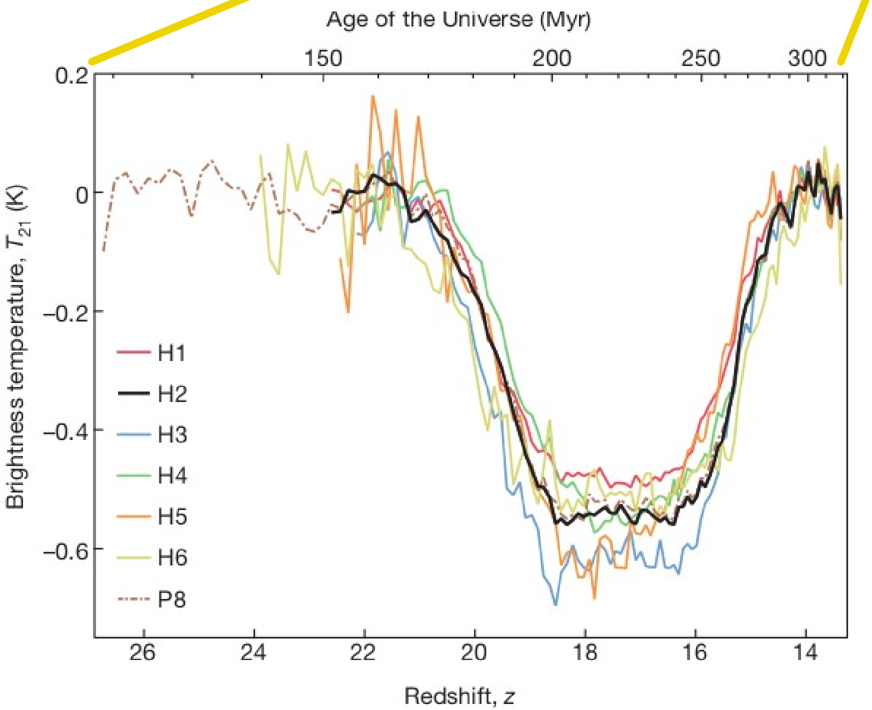
High-z HI 21-cm signal unique probe of the CD/EoR



Credit: Mesinger & Greig

First Detection of the Cosmic Dawn (?)





21-cm absorption profile observed by EDGES (Bowman et al., Nature, 2018)

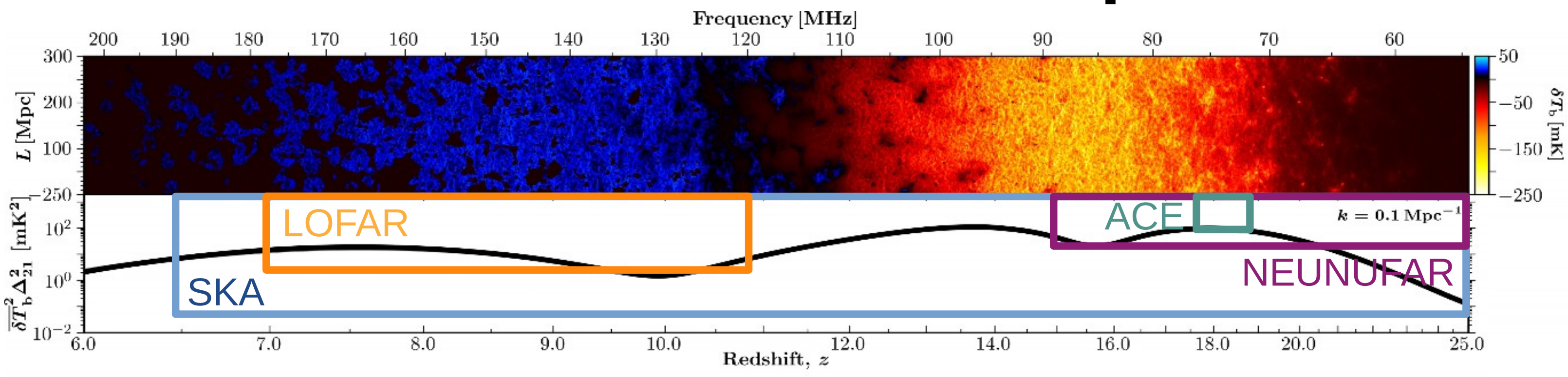
Detection passed through numerous hardware and processing tests: 2 independent antennas, different hardware configurations, calibrations, fitting methods...

Profile is largely consistent with expectations, however absorption about 2.5 x deeper than most extreme models!

→ new science ? (e.g. Barkana, Nature, 2018)

Need to be confirmed by other experiments !

The Interferometric experiments



LOFAR-HBA
The Netherlands

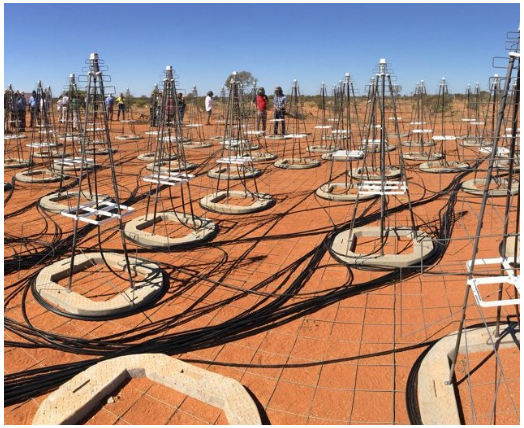
z ~ 7 – 11
+ 2000 h observed
13h published
Patil et al. 2017
140h in prep.

AARTFAAC (ACE)
The Netherlands

z ~ 18
Target: ~ 1000 h
Piggybacks on ongoing observations

NENUFAR
France

z ~ 15 - 46
Target: ~ 1000 h

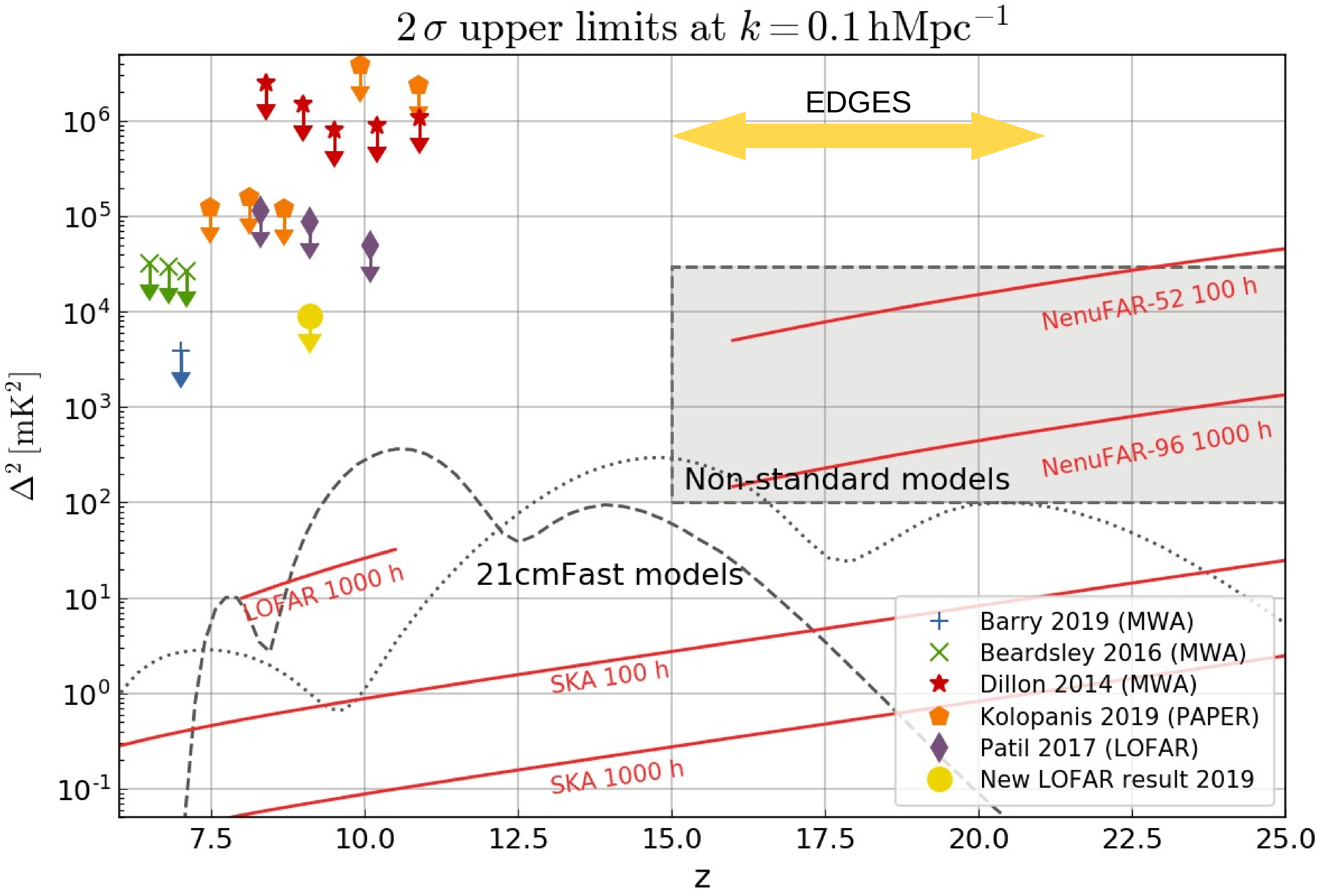


SKA
Western Australia

Low band (z ~ 6 – 25)
Constr.: 2020-2025

+ Many more

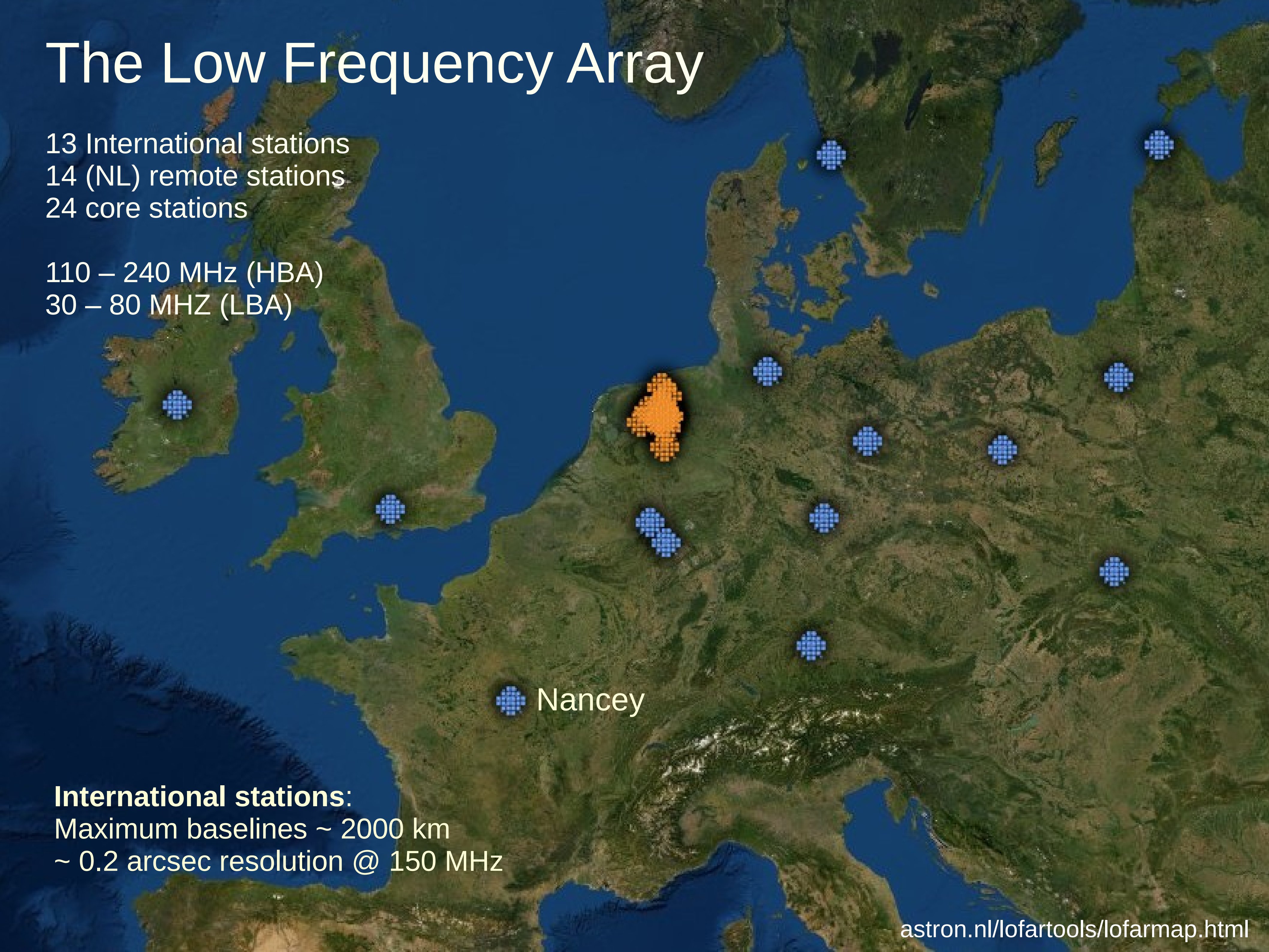
Where do we stand ?



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

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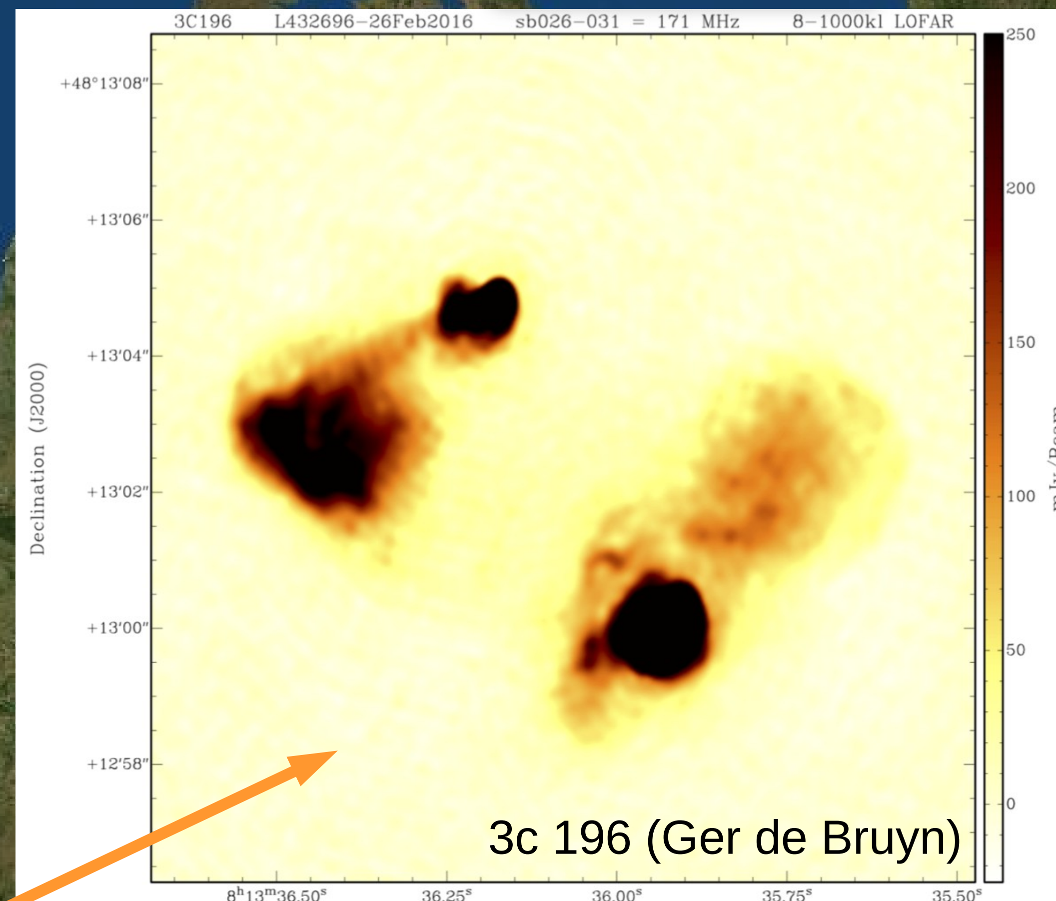

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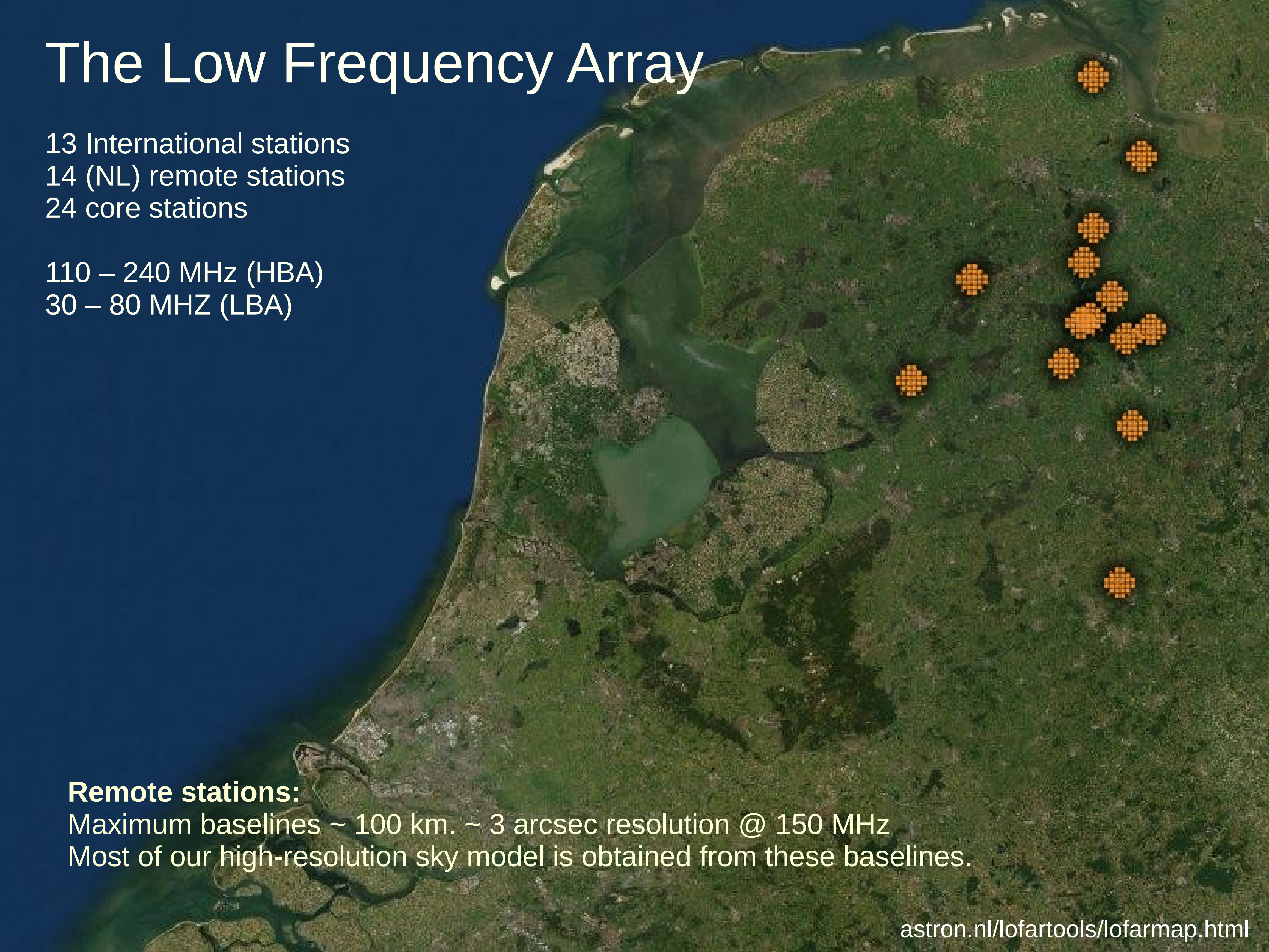

Remote stations:
Maximum baselines ~ 100 km. ~ 3 arcsec resolution @ 150 MHz
Most of our high-resolution sky model is obtained from these baselines.

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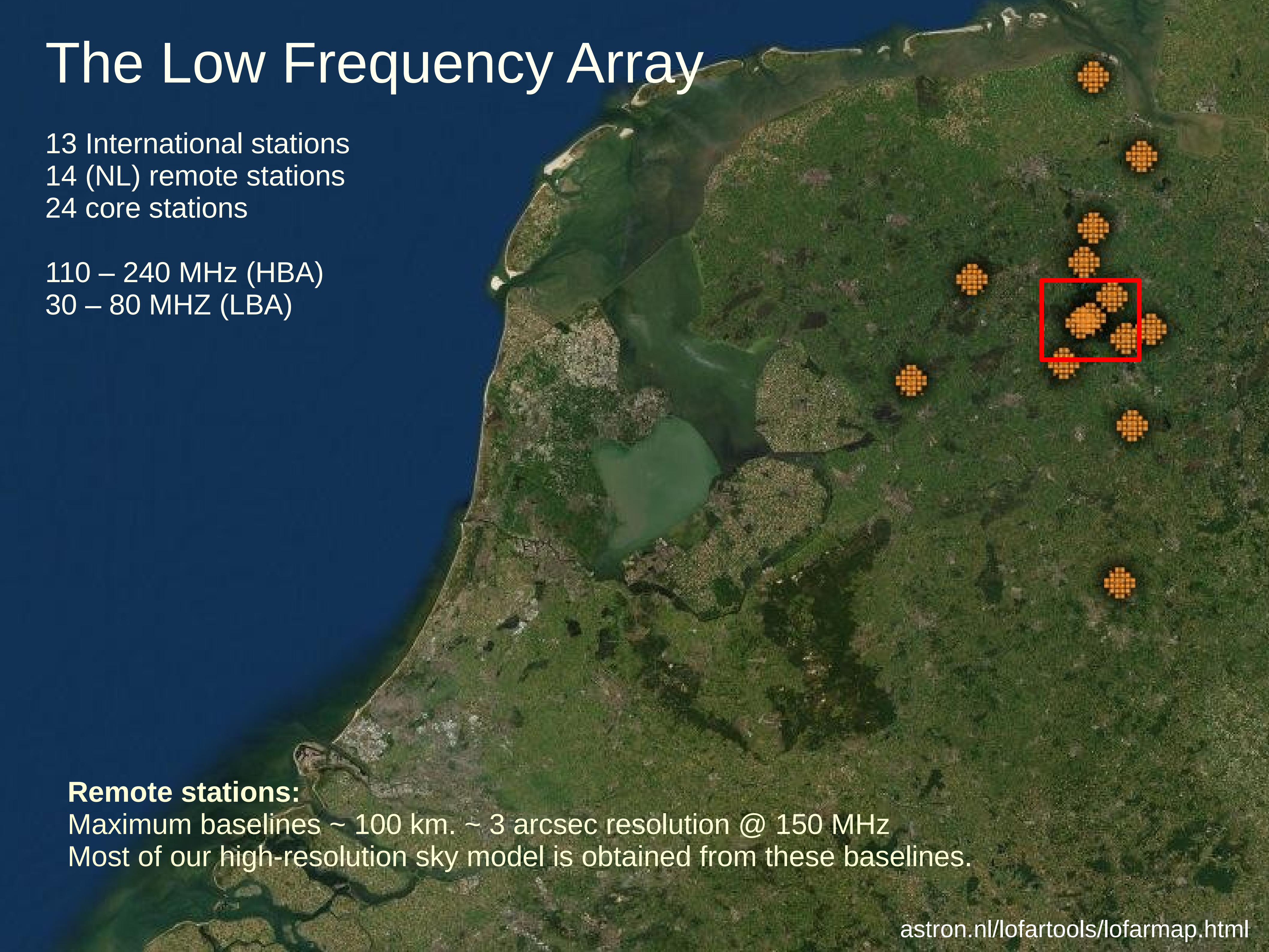

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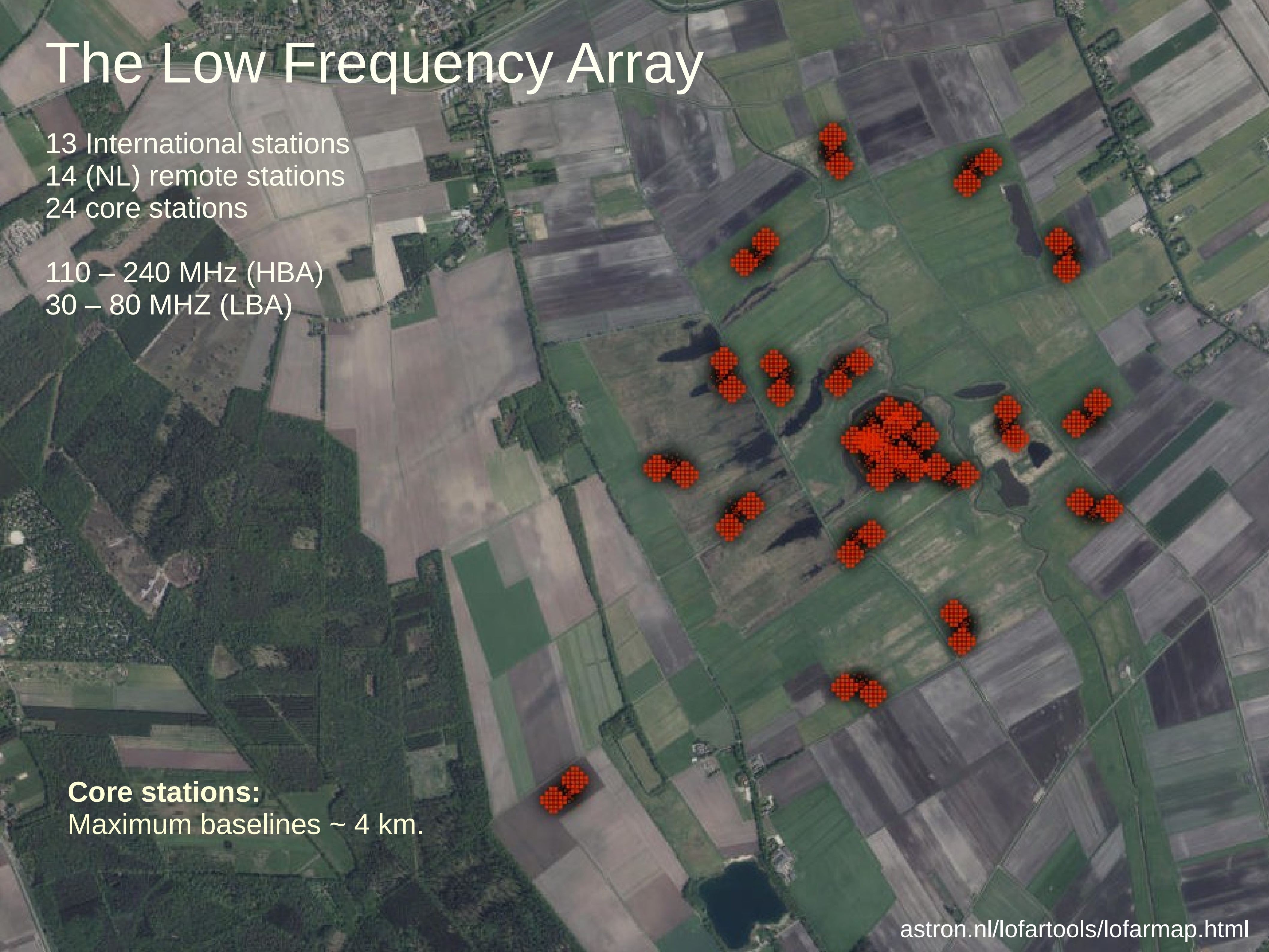

13 International stations
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24 core stations

110 – 240 MHz (HBA)
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Core stations:
Maximum baselines ~ 4 km.

astron.nl/lofartools/lofarmap.html

The Low Frequency Array

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110 – 240 MHz (HBA)
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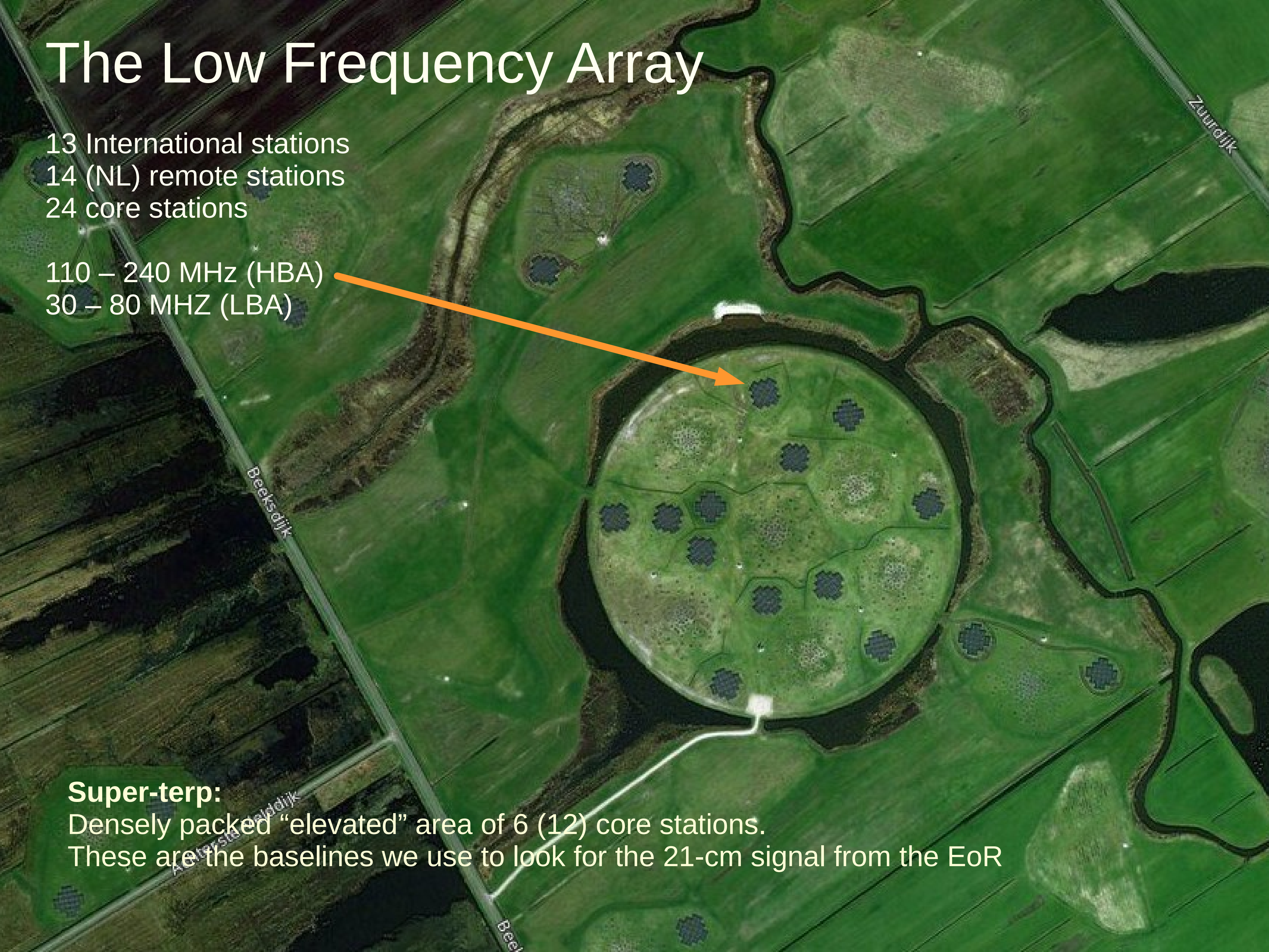
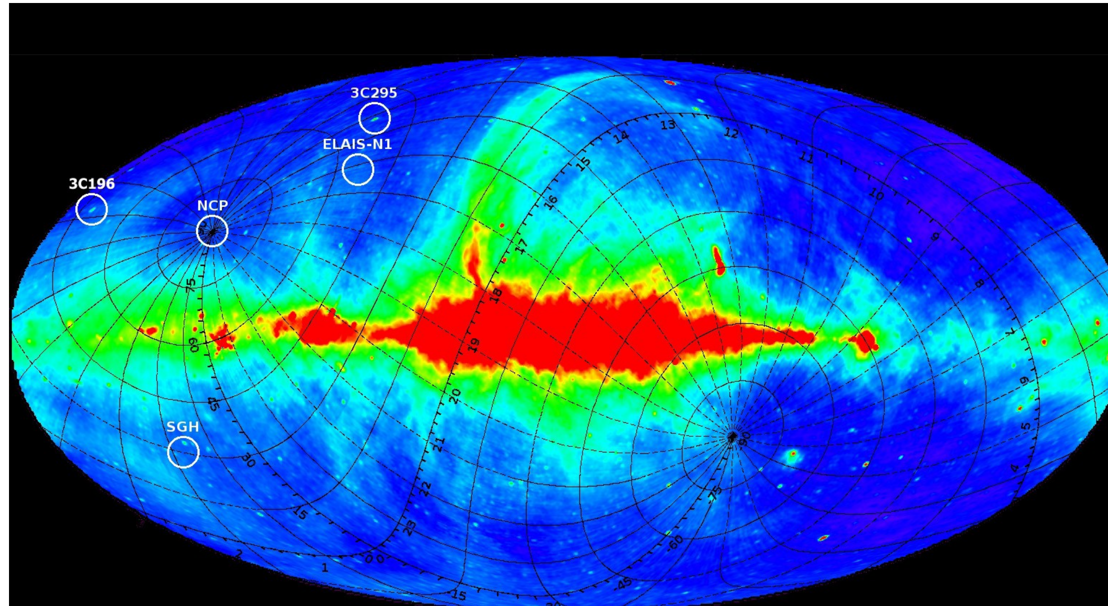
Super-terp:
Densely packed “elevated” area of 6 (12) core stations.
These are the baselines we use to look for the 21-cm signal from the EoR



The LOFAR-EoR KSP

2 main targets

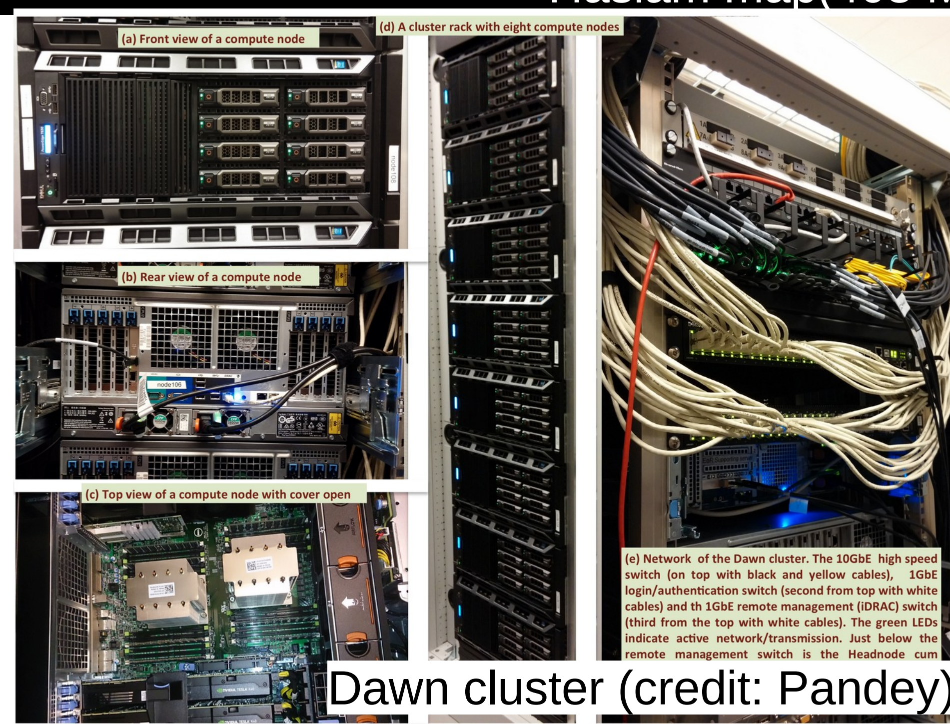
- North Celestial Pole
  - ✓ Constant Beam, all year observable
  - ✓ + 2200 hours observed
- 3C 196
  - ✓ Bright calibrator
  - ✓ + 1100 hours observed



Haslam map(408 MHz)

2-3 other windows for various other projects

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



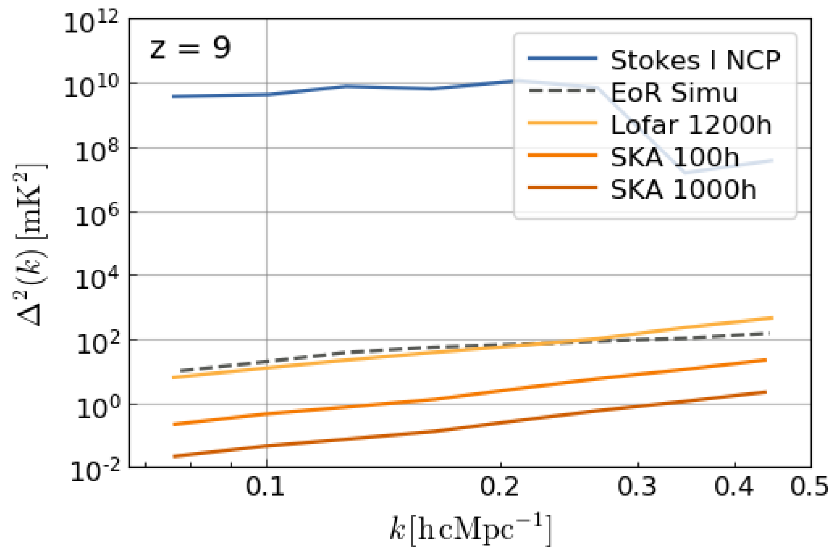
Dawn cluster (credit: Pandey)

Dawn cluster:

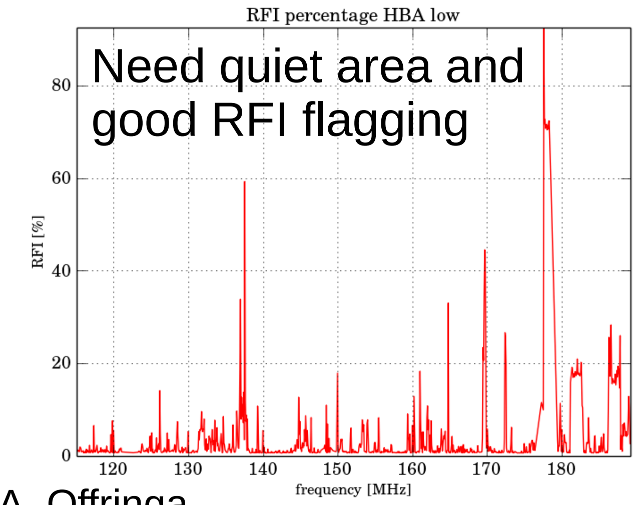
- ✓ 32 nodes
- ✓ each with 48 CPU cores + 4 GPU

What make this experiment so challenging ?

Foregrounds



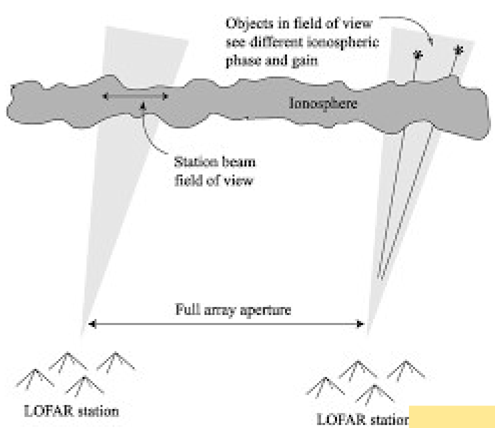
Radio Frequency Interferance (RFI)



Need quiet area and good RFI flagging

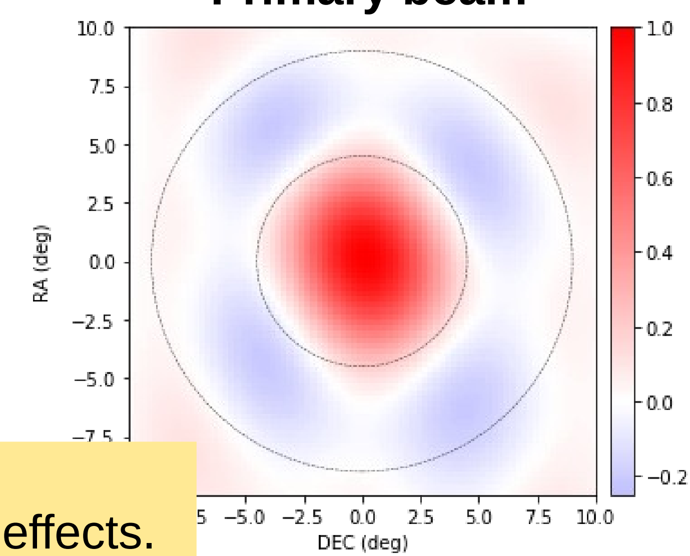
Credit: A. Offringa

Ionosphere



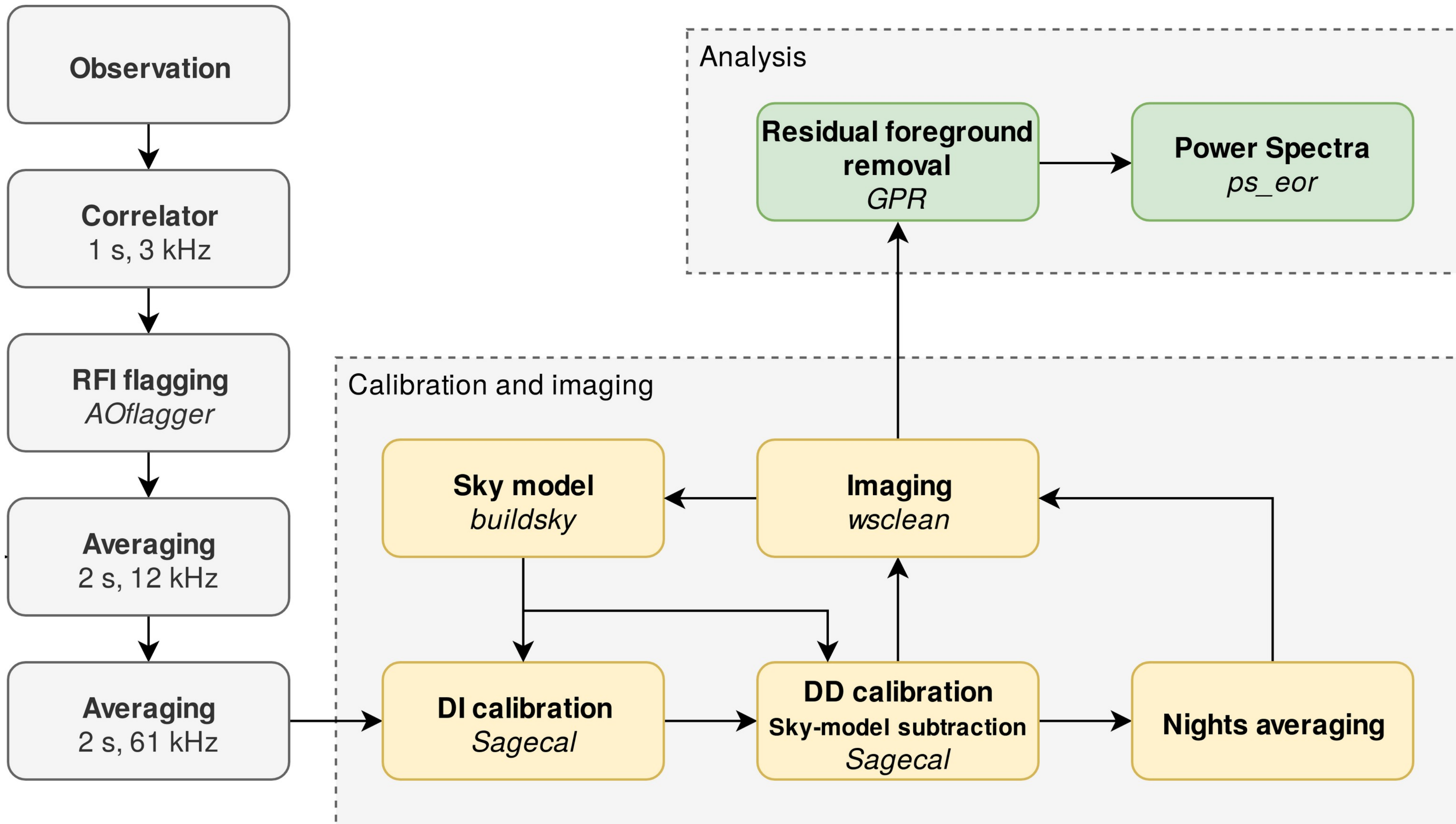
Credit: S. Van der Tol

Primary beam



+ polarization leakage.
All direction dependent effects.

(Simplified) Processing Pipeline



Removing the foregrounds

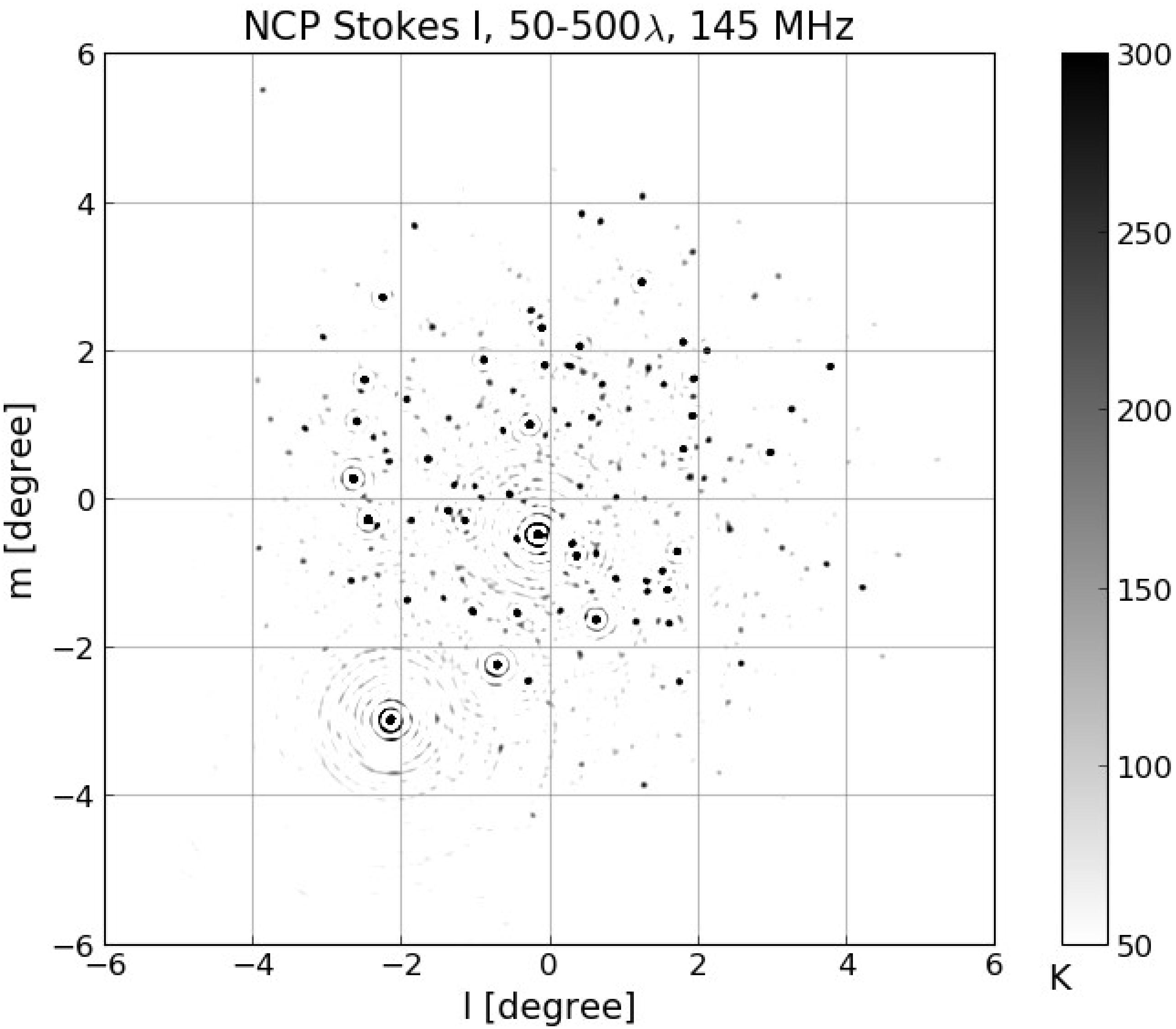
Step 1:
Point-sources subtraction

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

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

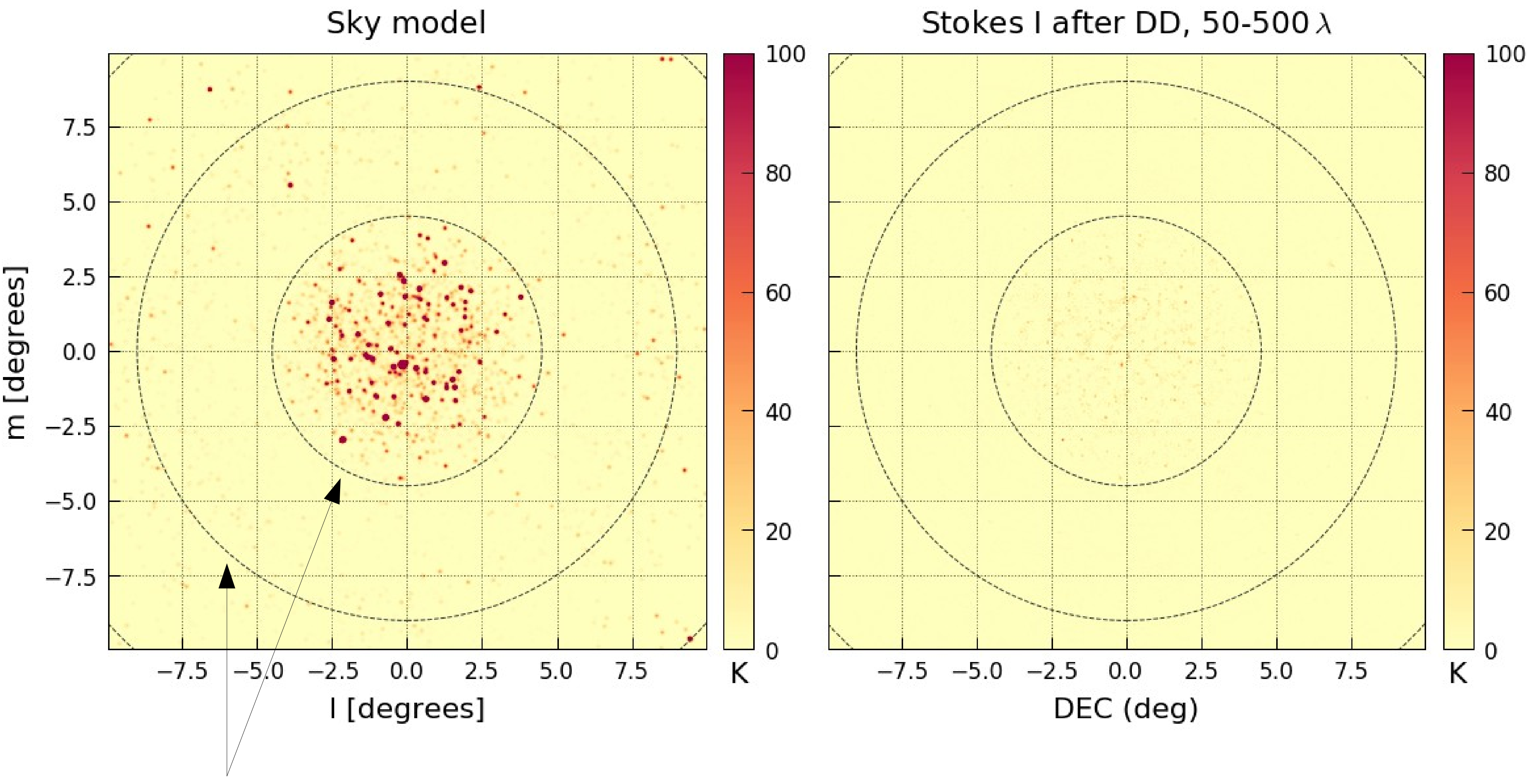
Step 2:
Residual spectrally-smooth foregrounds subtraction

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



DD calibration results

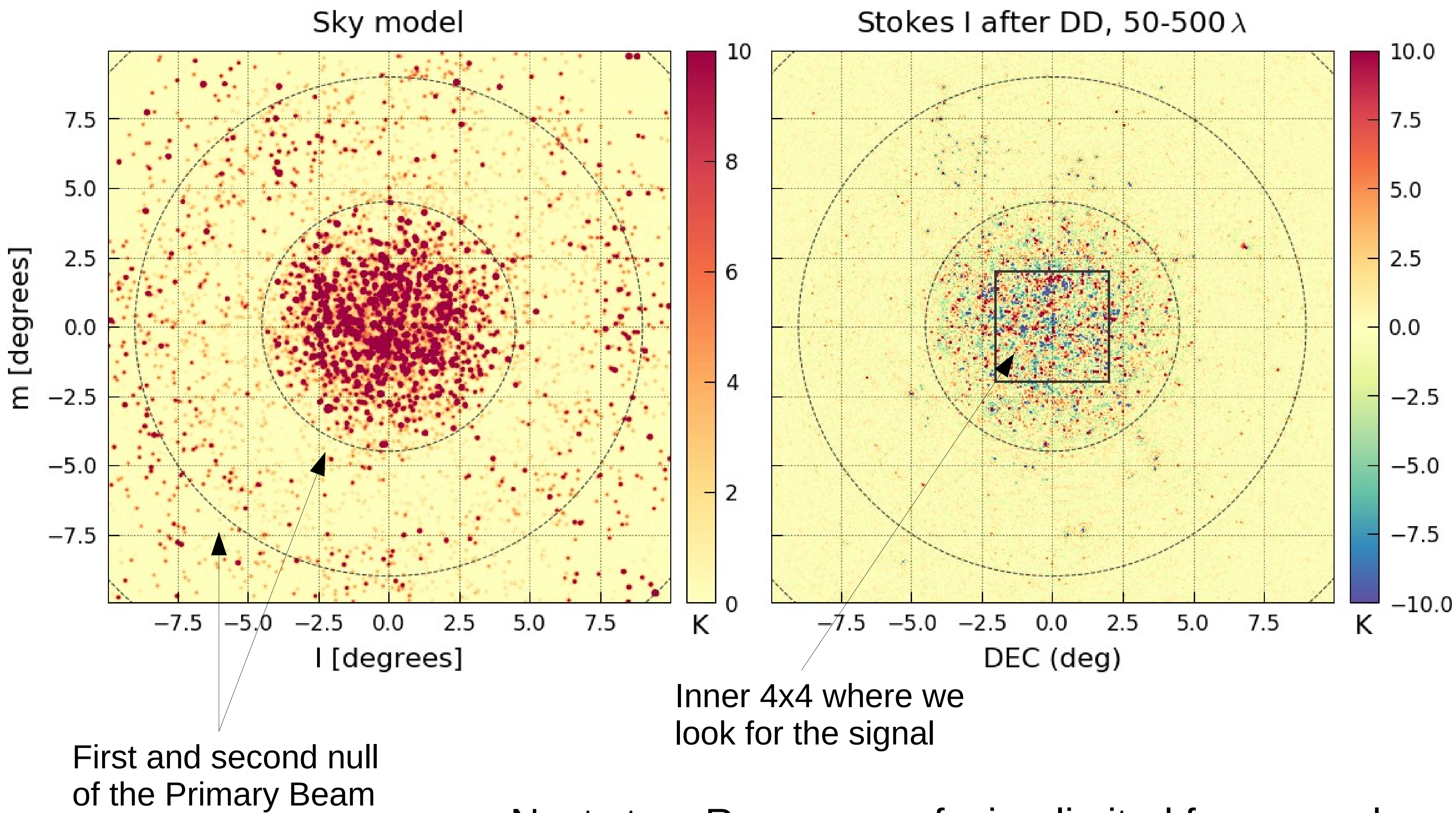
NCP field, 140 hours, 134-146 MHz, z ~ 9.1



First and second null
of the Primary Beam

DD calibration results

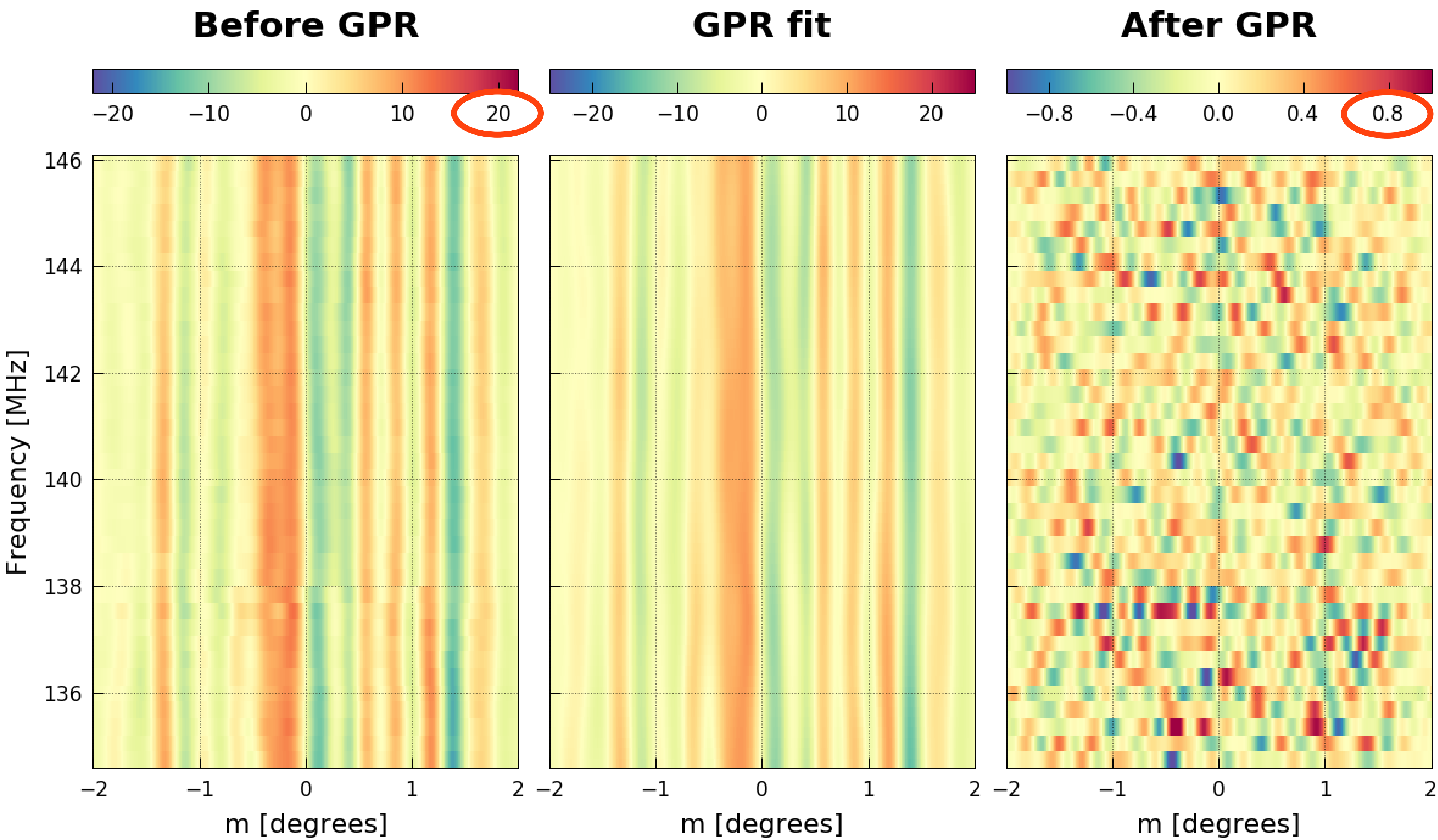
NCP field, 140 hours, 134-146 MHz, z ~ 9.1



Next step: Remove confusion-limited foregrounds

GPR on LOFAR data

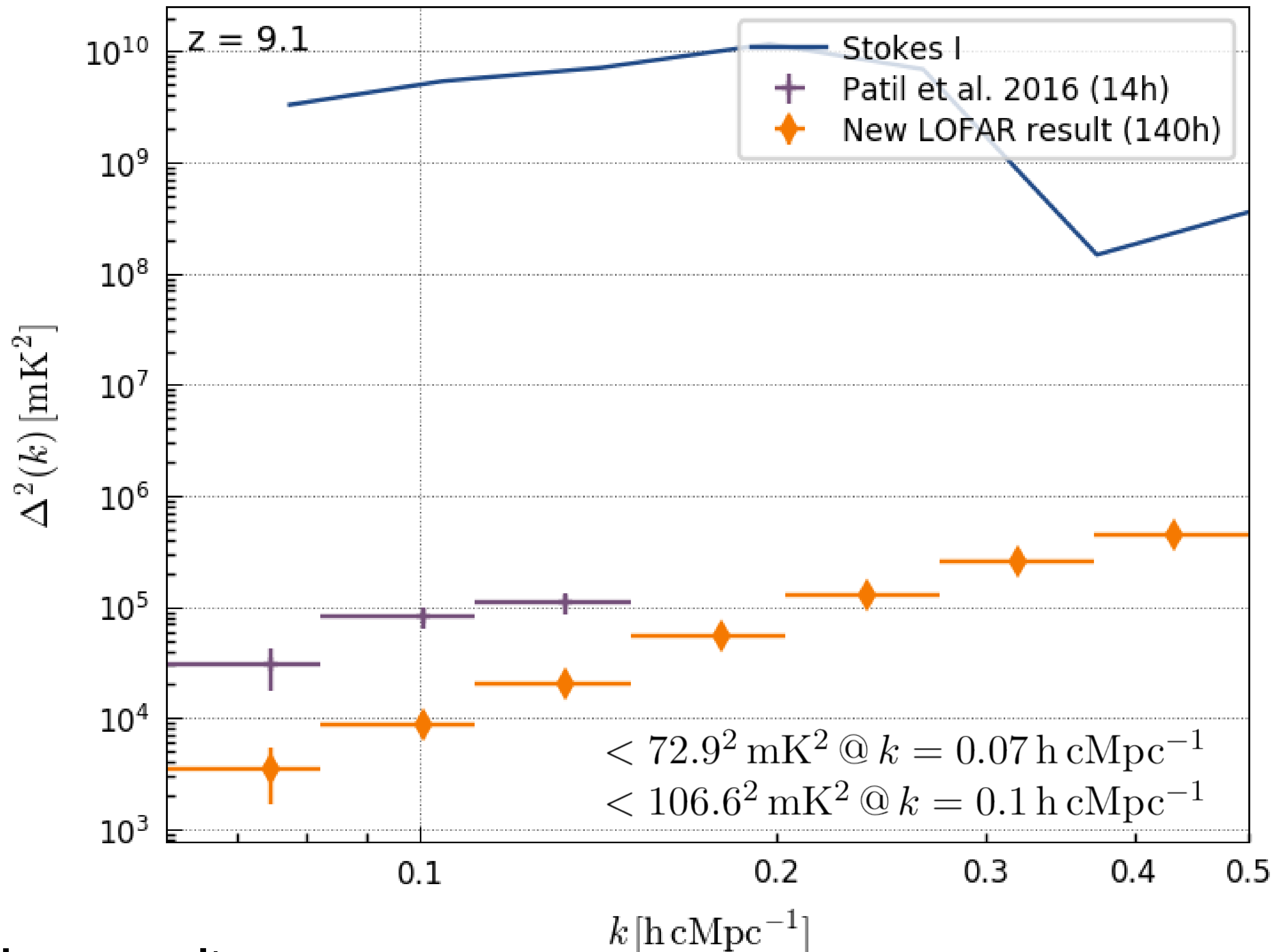
NCP field, 140 hours, 134-146 MHz, z ~ 9.1



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

New upper limit !

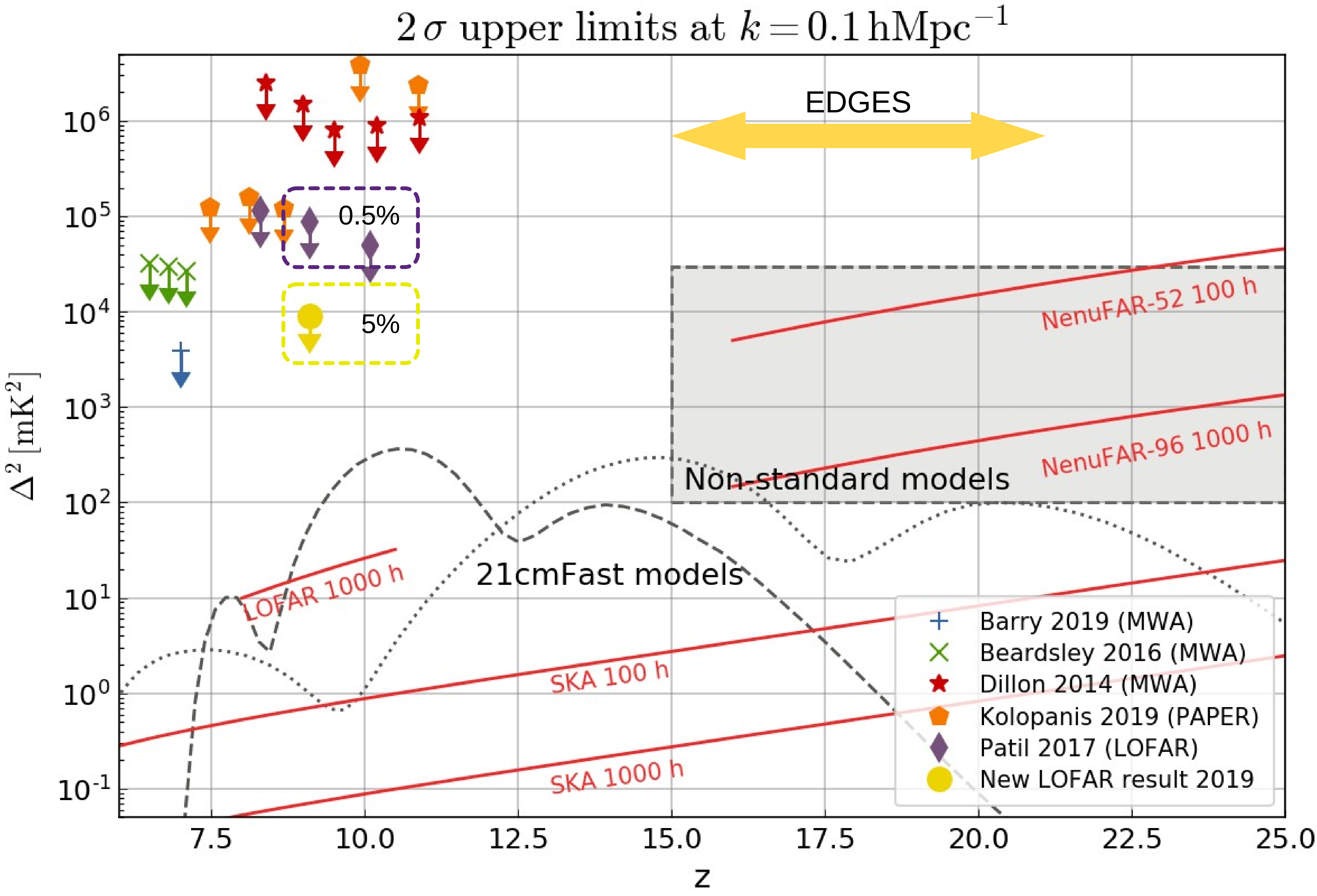
NCP field, 140 hours, 134-146 MHz, z ~ 9.1



Preliminary results

(Mertens et al. In prep.)

Where do we stand ?



NenuFAR Cosmic Dawn KP

Stage 1: Preparation phase (started July 19)

Limited bandwidth and frequency/spatial resolution.

Target	Total time	Frequency range	Total Bandwidth
NCP	18 x 18h	30-85 MHz	18 x 3.1 MHZ

Goals:

- Detailed spatial and spectral model of the NCP.
- Check systematic, adjust observation strategy if needed.
- Cross-validation with our AARTFAAC observation in the ACE program.

Stage 2: Deep integration (Beginning 2020)

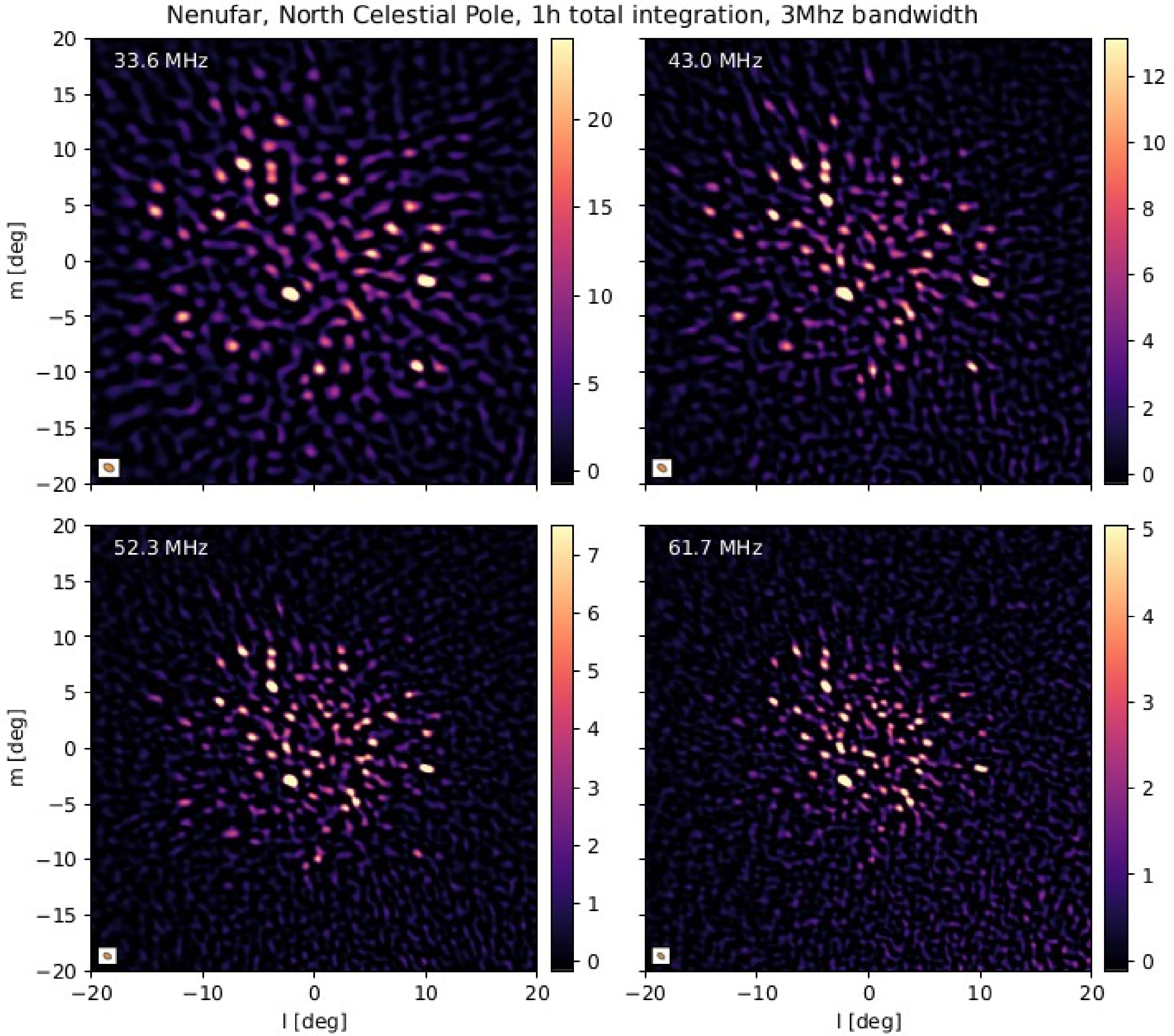
Correlator + Remote stations (increase max baseline)

Target	Total time	Frequency range	Total Bandwidth
NCP	1000 h (TBC)	30-85 MHz	55 MHZ

Goals:

- 21-cm signal power-spectra in several redshift bins in the range z ~ 14 – 46
- Many other science cases (diffuse galactic emission, variable source, transients ...)

First NenuFAR results



- Confusion noise limited 40x40 degrees image around the NCP between 30 and 70 MHz
- Thermal noise estimated (time difference rms) is at the expected level.
- RFI situation seams manageable (more tests to come)

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): $\Delta^2 < (100 \text{ mK})^2$ @ $k = 0.1 \text{ cMpc}^{-1}$, $z \sim 9$.
  - ➔ Very interesting upper limit is still at reach with LOFAR.
- **Current status of the NenuFAR CD project:**
  - ➔ Observations in phase 1 started in July 2019.
  - ➔ Initial 30-85 MHz sky model around the NCP.
  - ➔ We are preparing for phase 2: increased bandwidth, spectral resolution, and max baseline (higher resolution, lower confusion noise).