Observing the Epoch of Reionization with LOFAR Progress and challenges

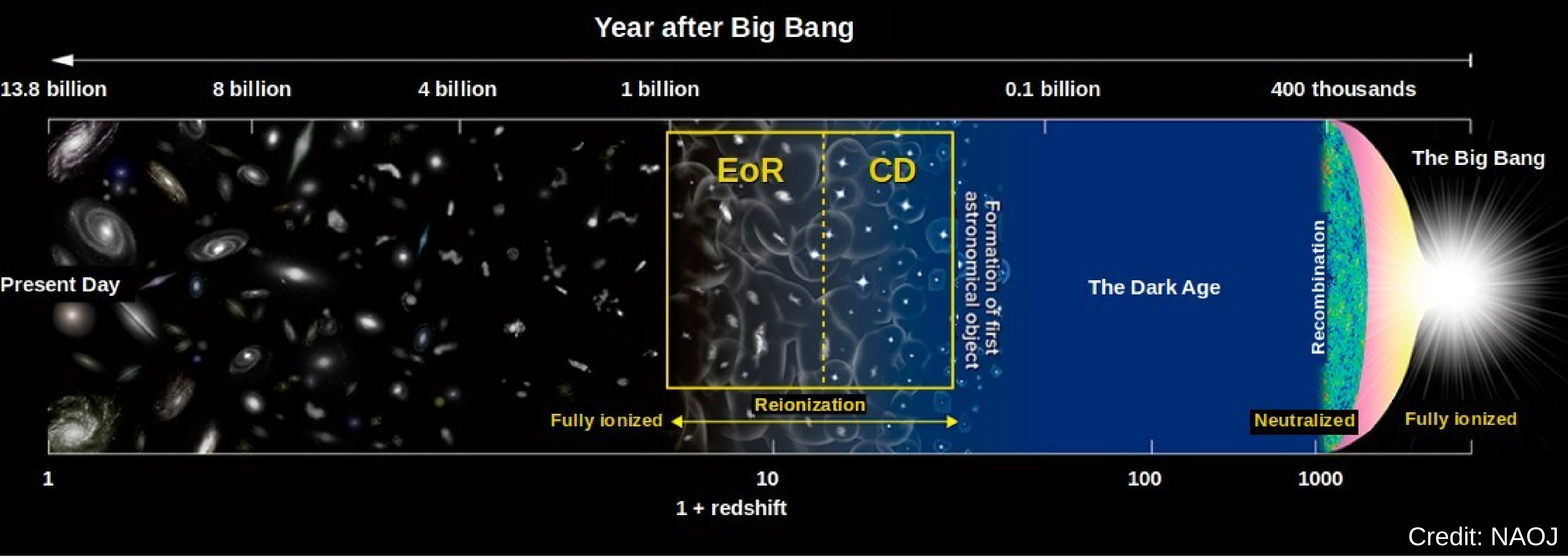
Florent Mertens (Kapteyn Astronomical Institute)

The LOFAR EoR KSP Team

Michiel Brentjens (ASTRON)
Wim Brouw (Kapteyn)
Emma Chapman (Imperial)
Benedetta Ciardi (MPA)
Keri Dixon (Sussex)
Simon Gazagnes (Kapteyn)
Hyoyin Gan (Kapteyn)
B.K. Geholot (ASU)
Abhik Ghosh (SKAO-SA)
Ilian Iliev (Sussex)
Vibor Jelic (IRB)
Hannes Jensen (Imperial)
Koki Kakiichi (MPG)
Robin Kooistra (Tokyo)
Léon Koopmans (Kapteyn)
F. Krause (Kapteyn/UCL)
Suman Majumdar (Imperial)
Garrelt Mellema (Stockholm)
Maaijke Mevius (ASTRON)
Florent Mertens (Kapteyn)
Modhurita Mitra (Kapteyn)
Rajesh Mondal (Sussex)
Kahn Asad (SKAO-SA)
André Offringa (ASTRON)
V.N Pandey (K./ASTRON)
Marta Silva (Oslo)
Joop Schaye (Leiden)
M. Sardarabadi (Kapteyn)
H. Vedantham (ASTRON)
Stefan Wijnholds (ASTRON)
Sarod Yatawatta (ASTRON)
Saleem Zaroubi (K./Haifa)

CoDA II — Pierre Ocvirk

Cosmic Dawn / Epoch of Reionization



Epoch of Reionization

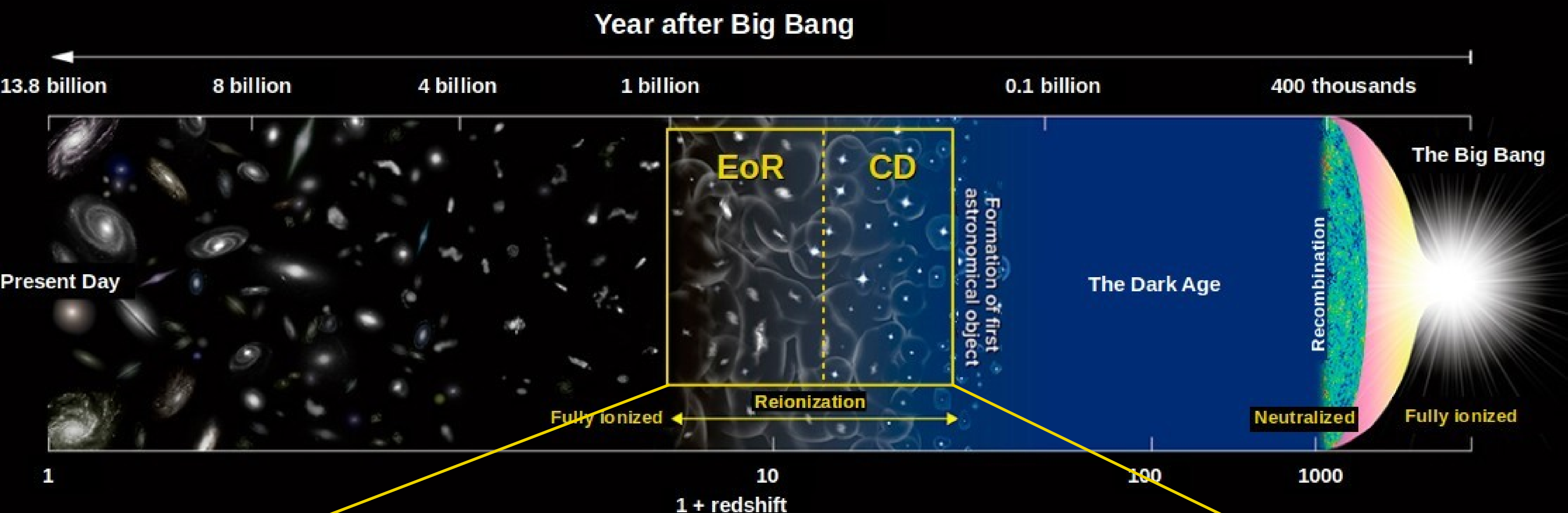
- Reionization by stars & mini-quasars
- IGM feedback (e.g. metals)
- PopIII - PopII transition
- Emergence of the visible universe

Cosmic Dawn

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

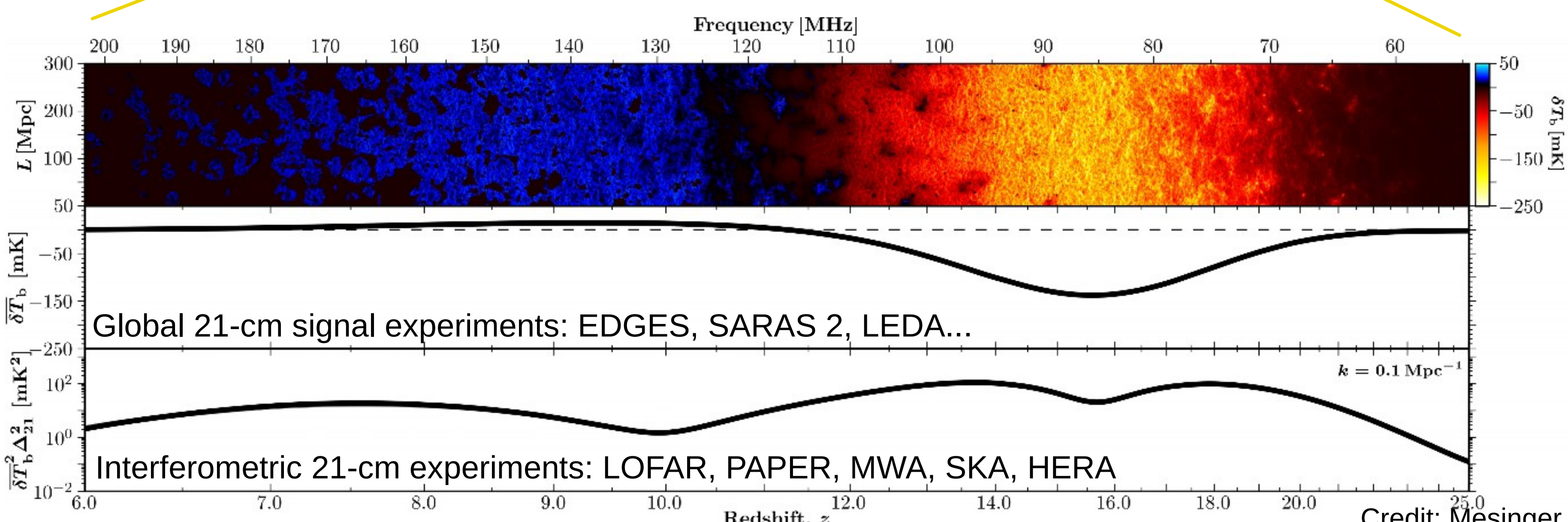
- When did the first galaxies/stars/black hole form?
- How did reionization proceed?
- How do galaxies form and evolve?

Cosmic Dawn / Epoch of Reionization



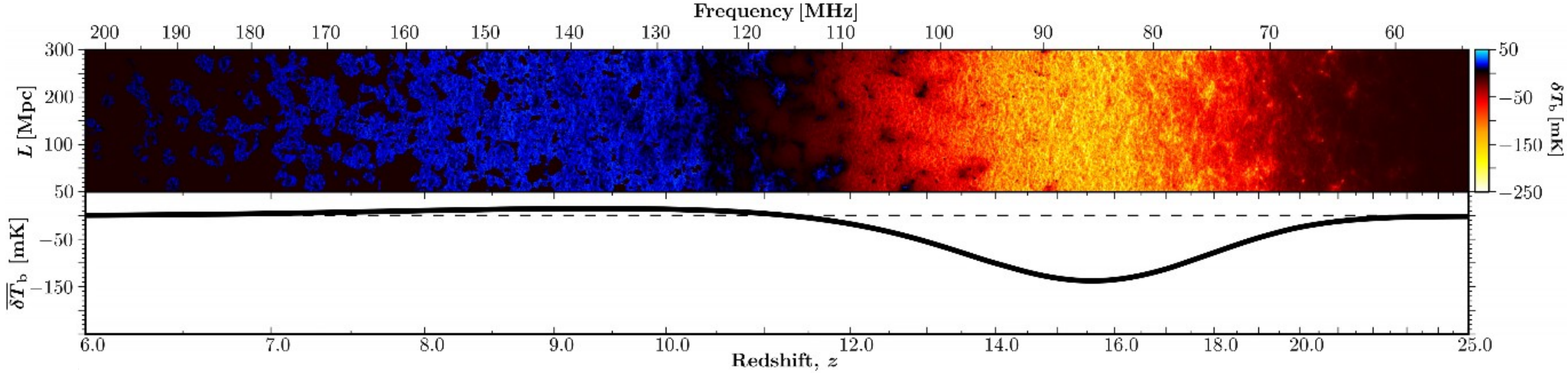
High-z HI 21-cm signal unique probe of the CD/EoR

Credit: NAOJ



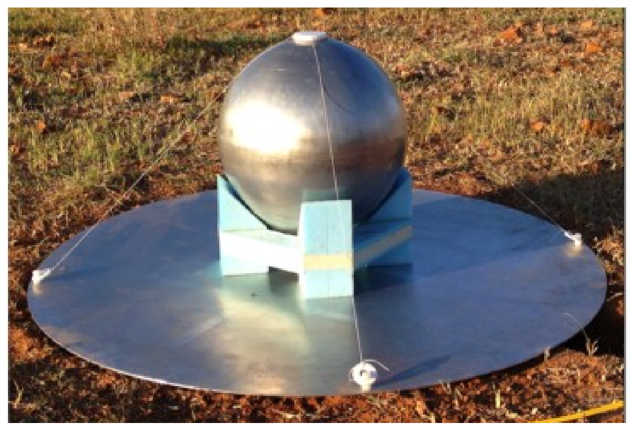
Credit: Mesinger & Greig

The Global experiments



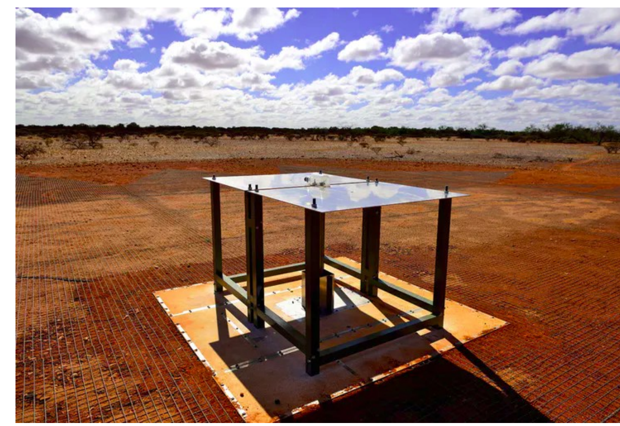
PRIZM
30-200 MHz
Marion Island

Peterson, Sievers, Chiang ++



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

Singh et al. 2017

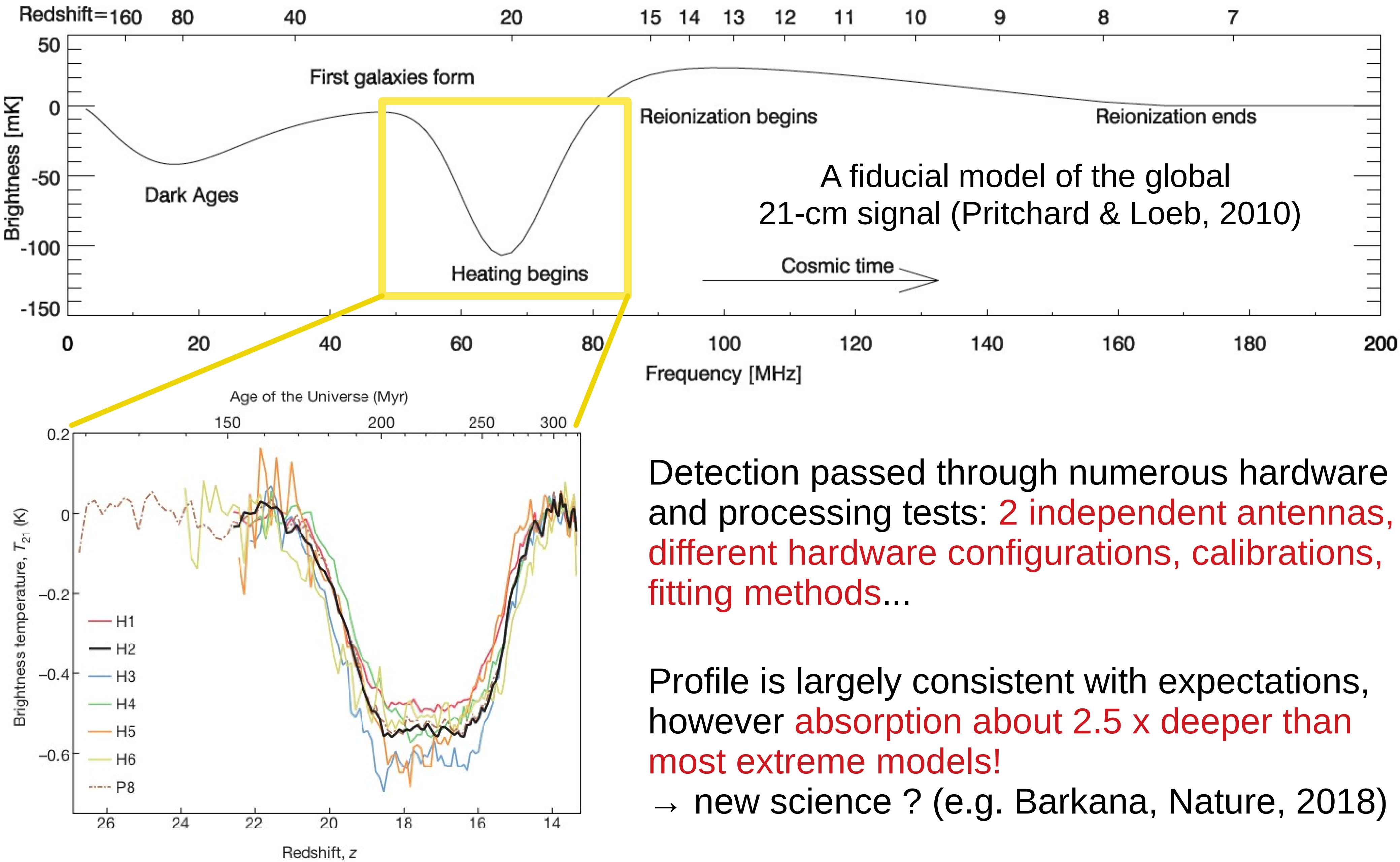


EDGES
50-100, 100-200 MHz
Western Australia

Rogers & Bowman 2008, 2012;
Bowman et al 2018

+ Many more

First Detection of the Cosmic Dawn (?)



A fiducial model of the global 21-cm signal (Pritchard & Loeb, 2010)

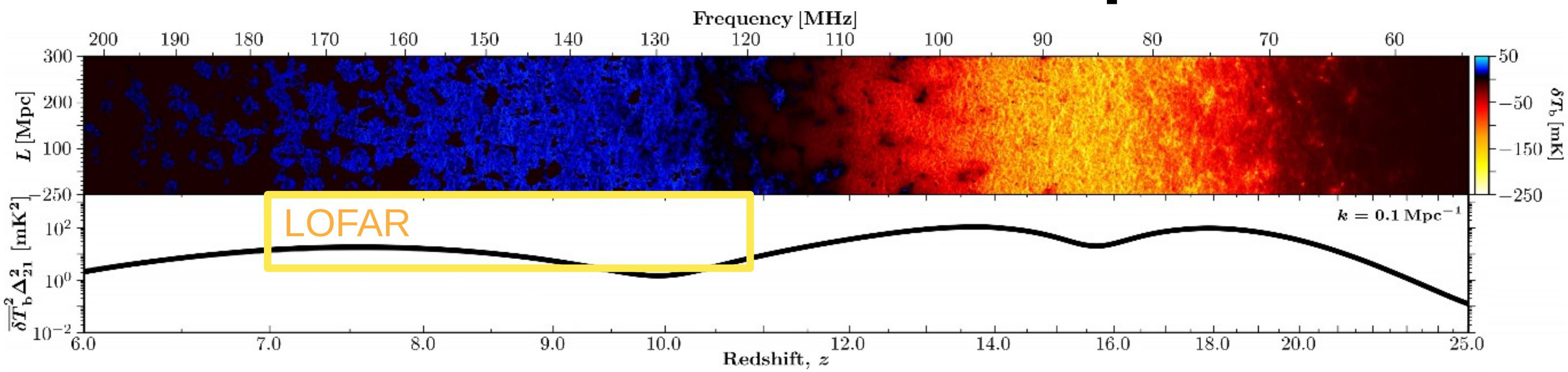
21-cm absorption profile observed by EDGES (Bowman et al., Nature, 2018)

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

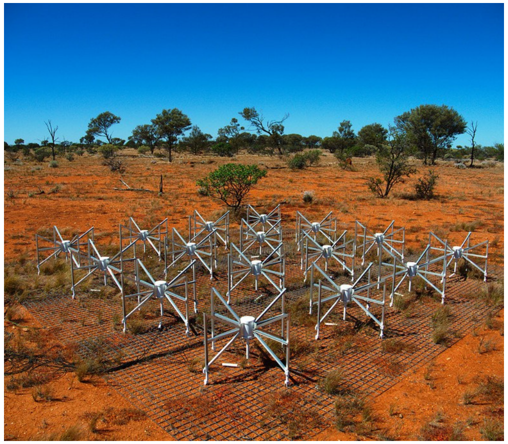


GMRT
India

40 h @ z ~ 8.5
Paciga et al. 2013

PAPER
South Africa

1148 h @ z=8.4
Ali et al. 2015
Retracted



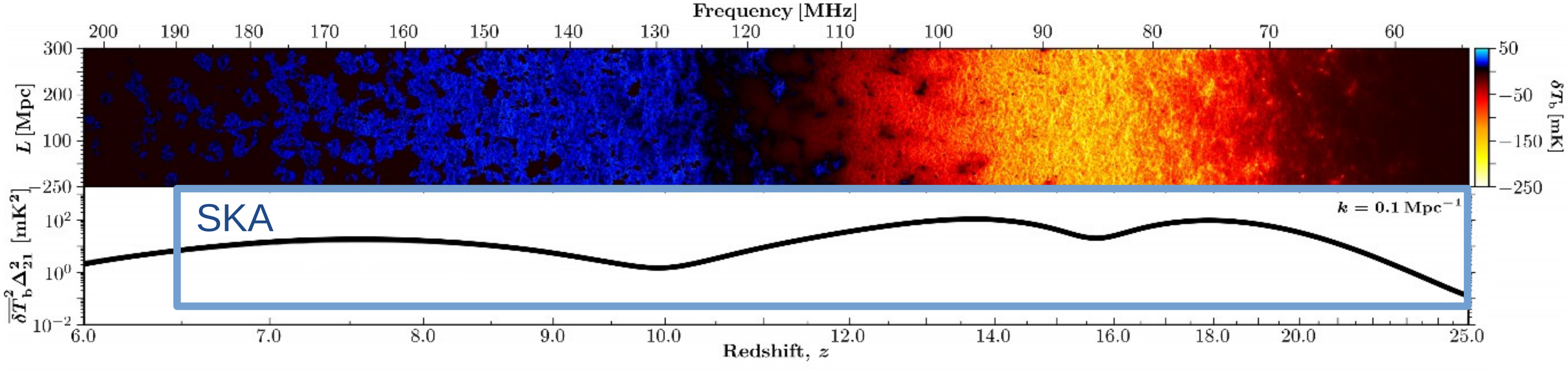
MWA
Western Australia

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

LOFAR
The Netherlands

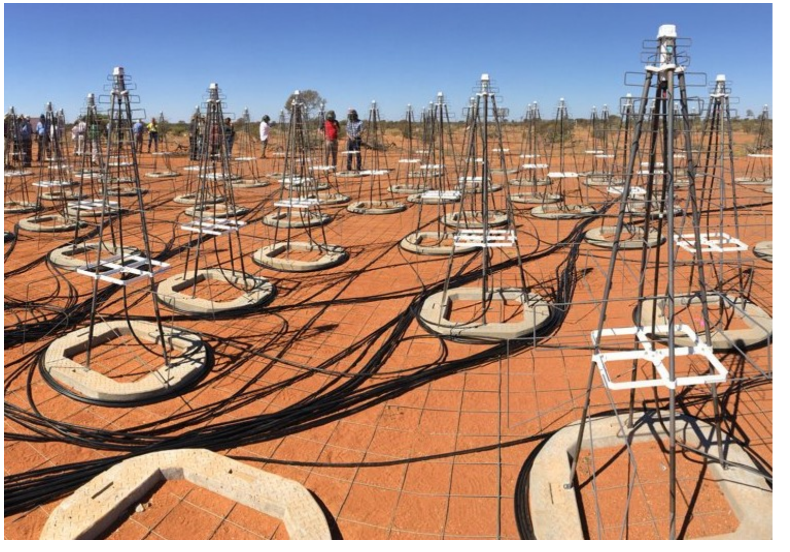
z ~ 7 – 11
+ 2000 h observed
13h published
Patil et al. 2017
140h in prep.

The Interferometric experiments



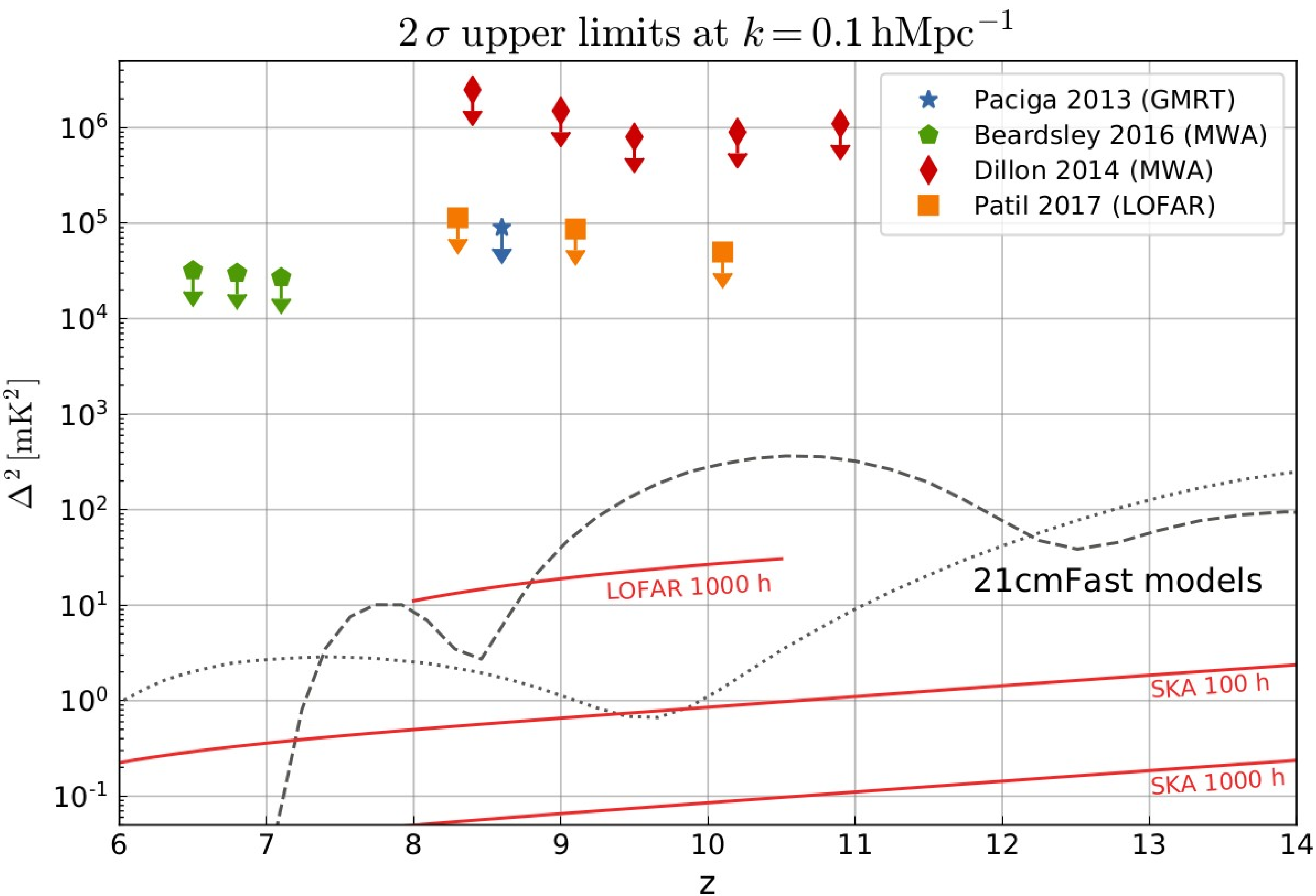
Second generation experiments in near and far future

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



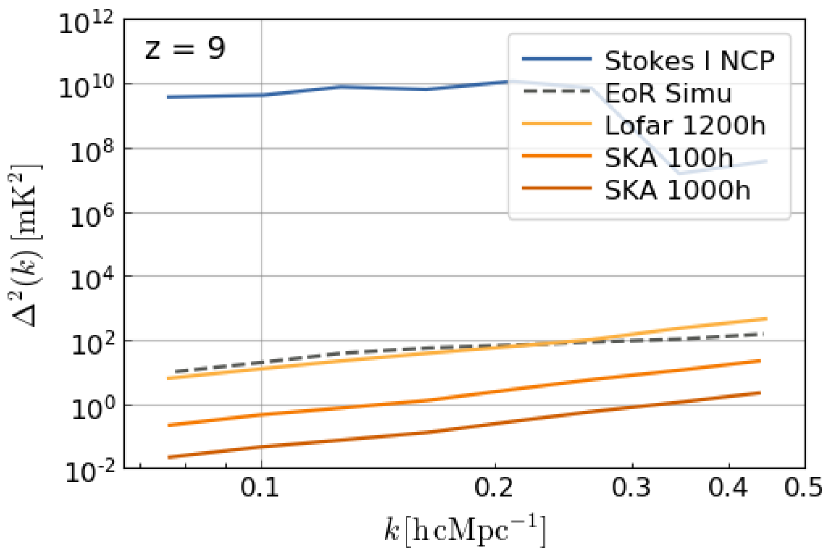
SKA
Western Australia
Low band (z ~ 6 – 25)
Construction 2020-2025

Where do we stand ?

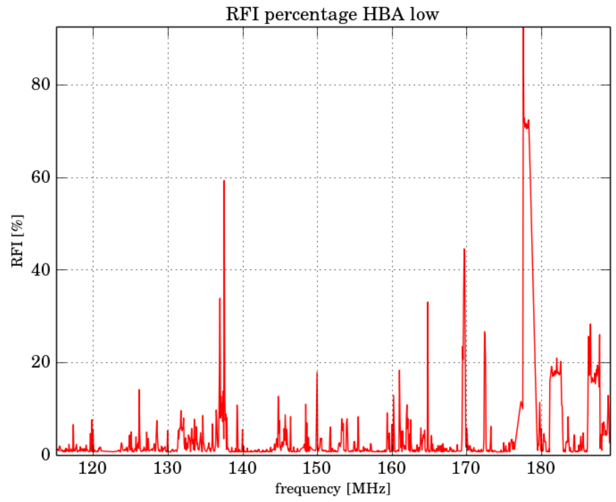


Why is it so challenging ?

Foregrounds

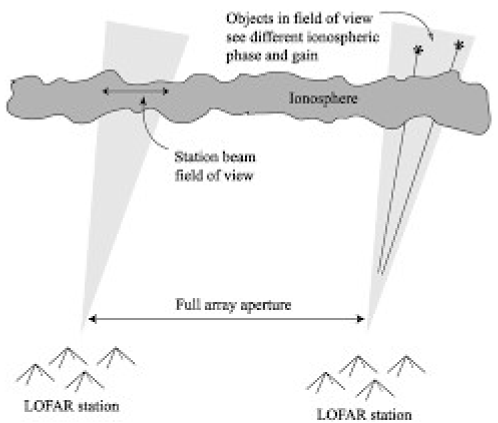


Radio Frequency Interferance (RFI)



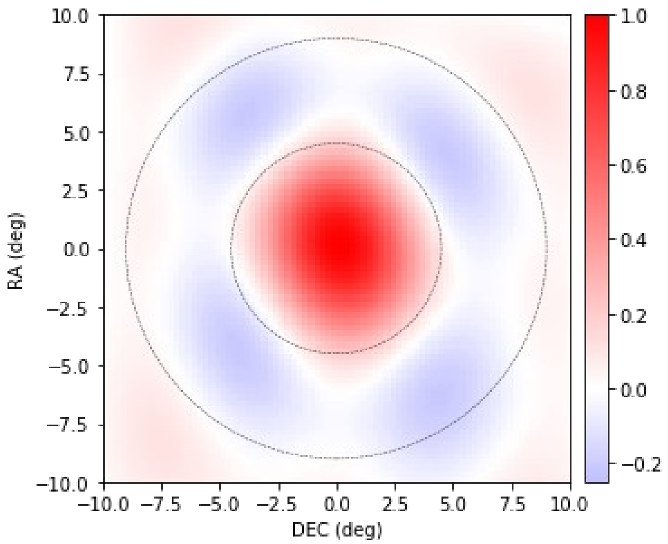
Credit: A. Offringa

Ionosphere



Credit: S. Van der Tol

Primary beam

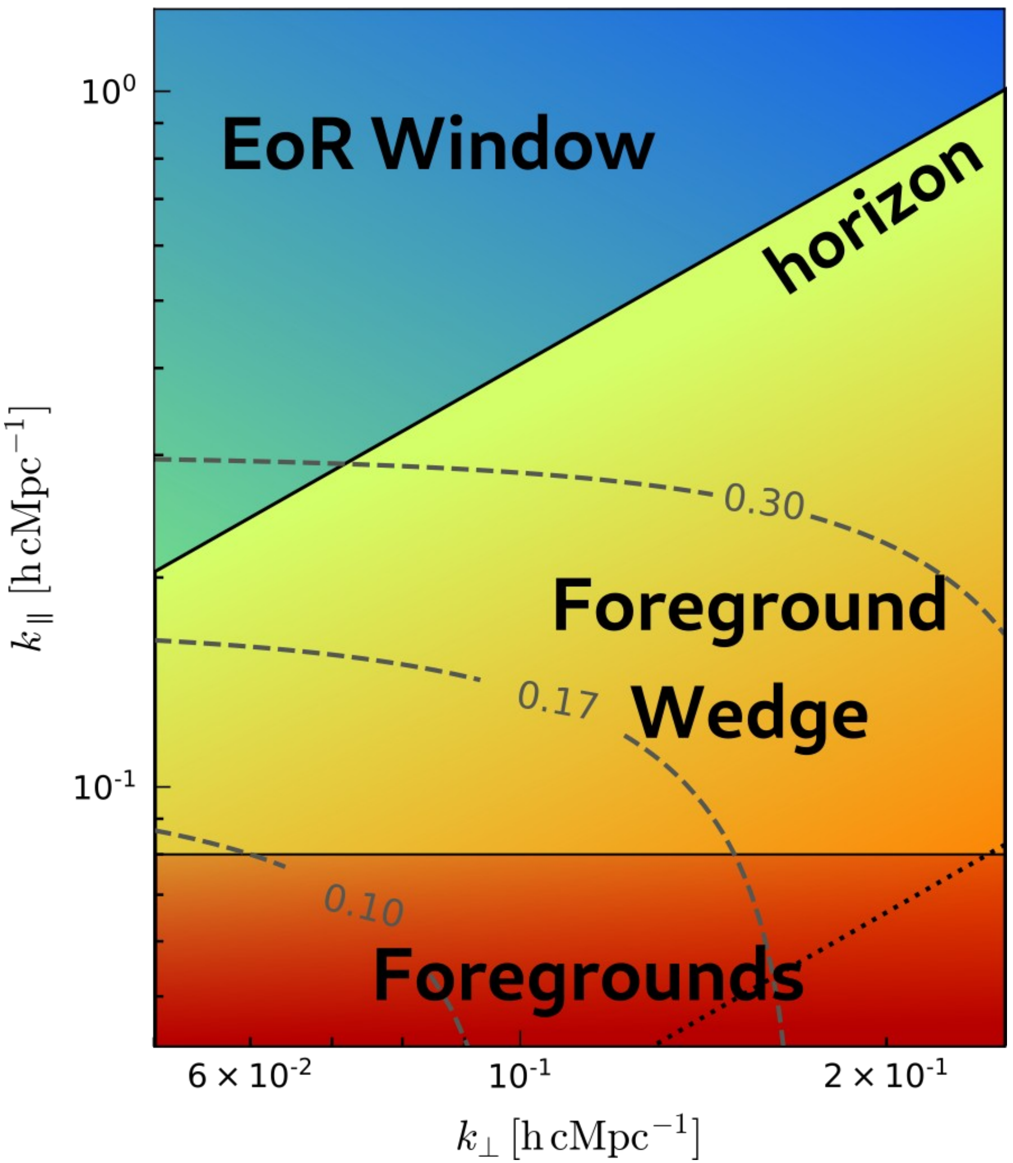


The challenge of the foregrounds

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

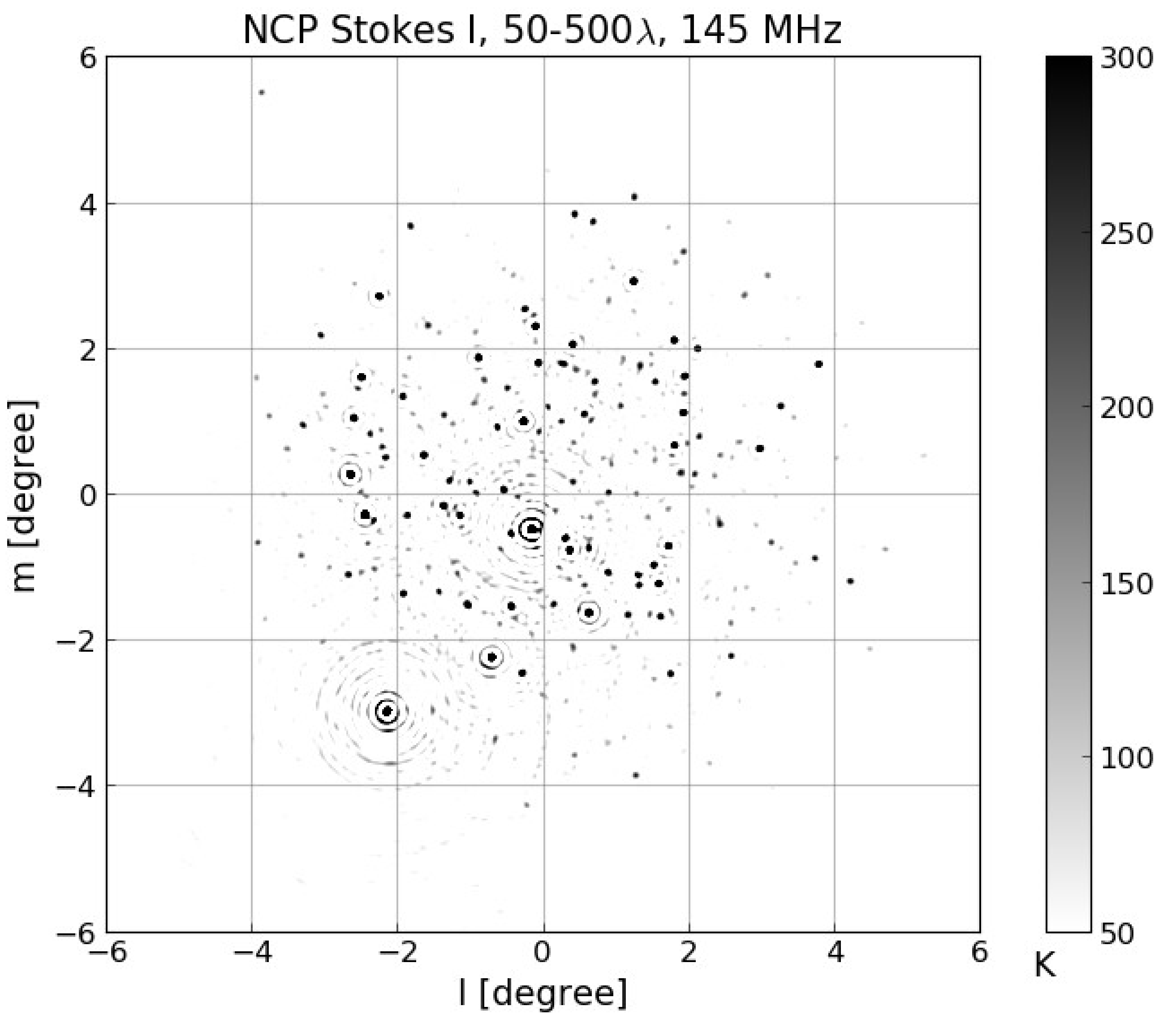
Step 1:
Point-sources subtraction

- ➔ 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

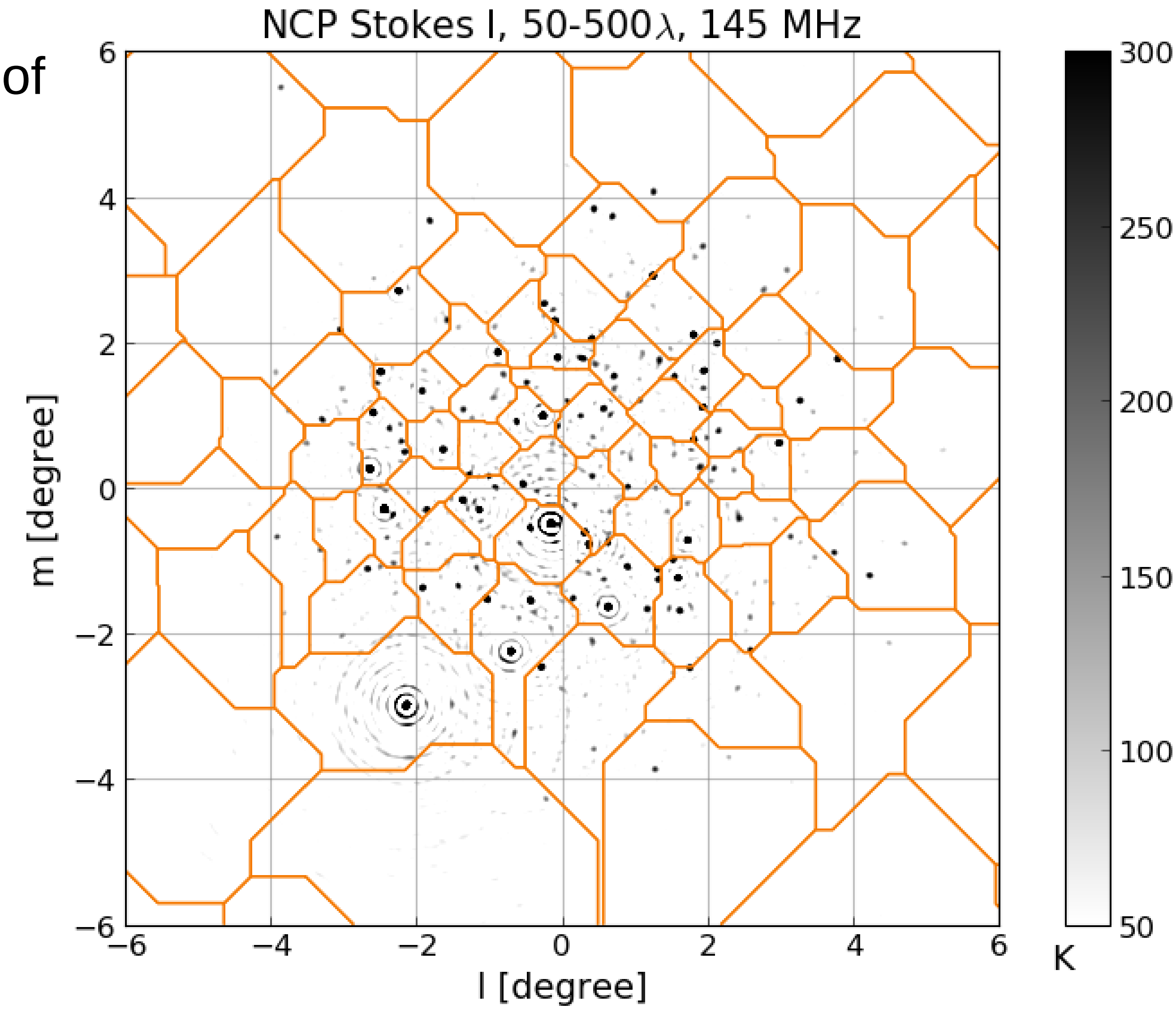
Using e.g. Gaussian Process Regression (GPR) (Mertens et al. 2018)



Direction Dependent calibration

Need to reduce the number of degree of freedom:

➔ Clustering (NCP ~ 120 clusters)

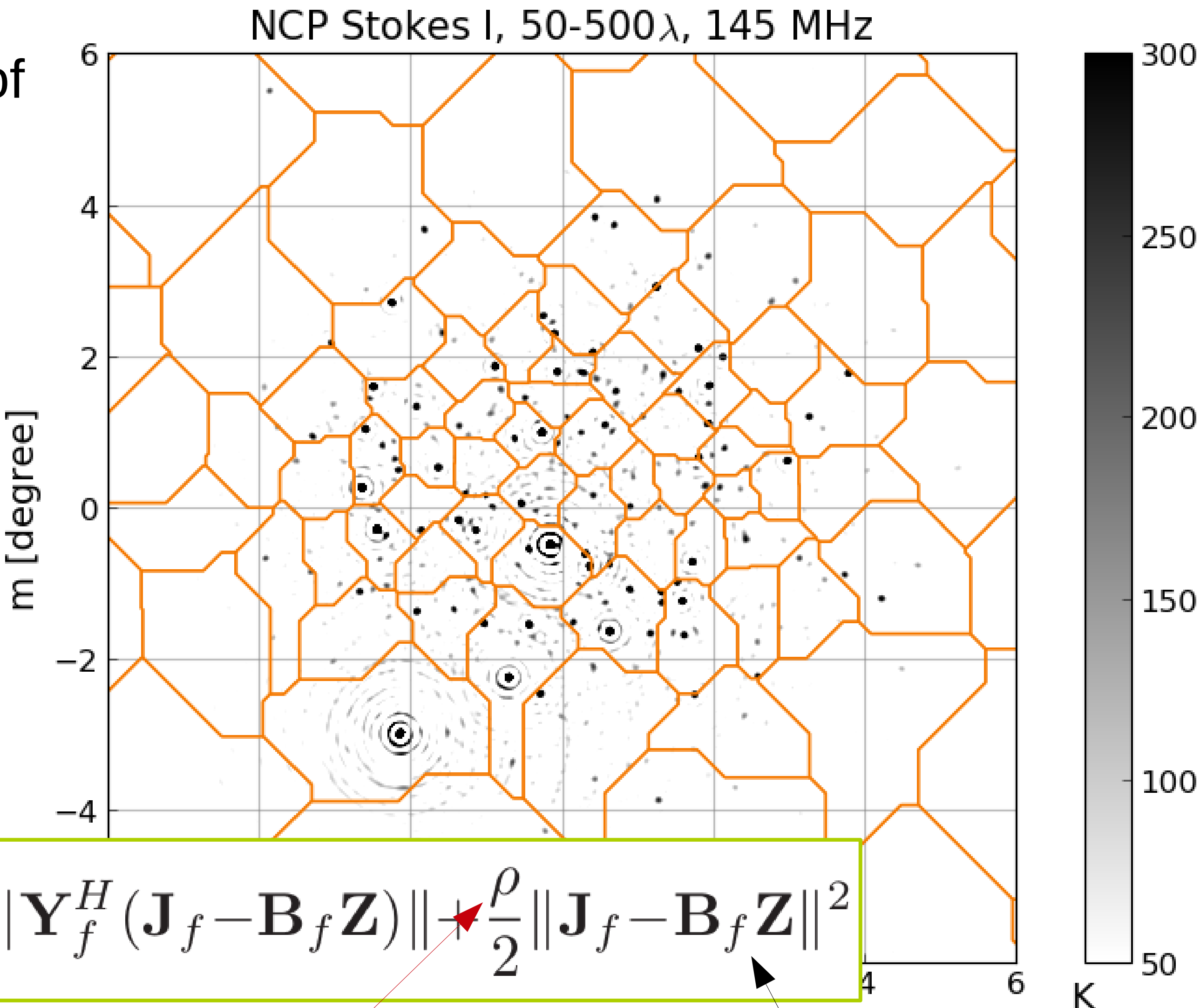


(Yatawatta et al. 2013, 2015)

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

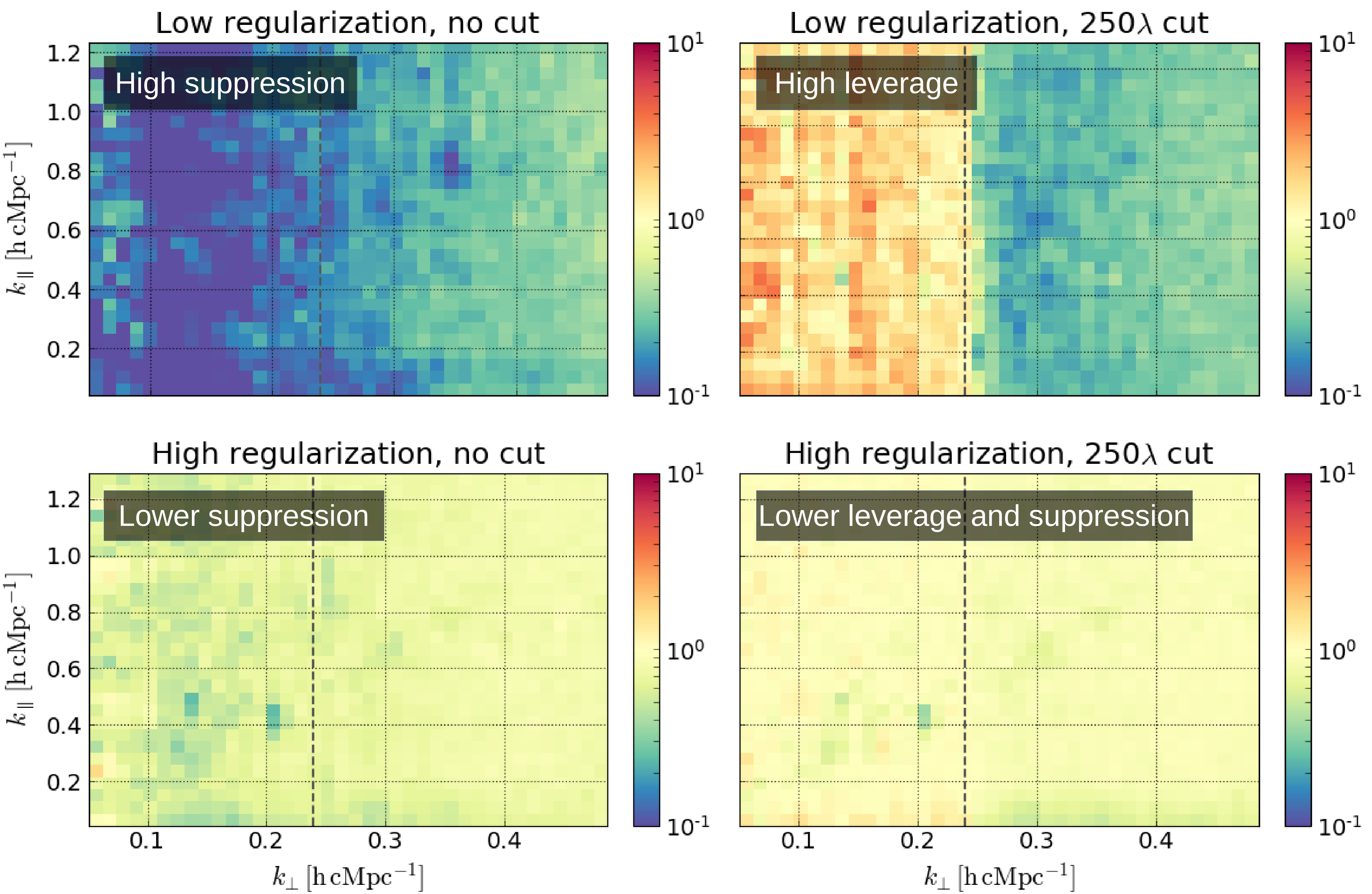
Original cost function

Regularization parameter

Spectrally-smooth constraint

(Yatawatta et al. 2013, 2015)

DD calibration: effect of enforcing smoothness

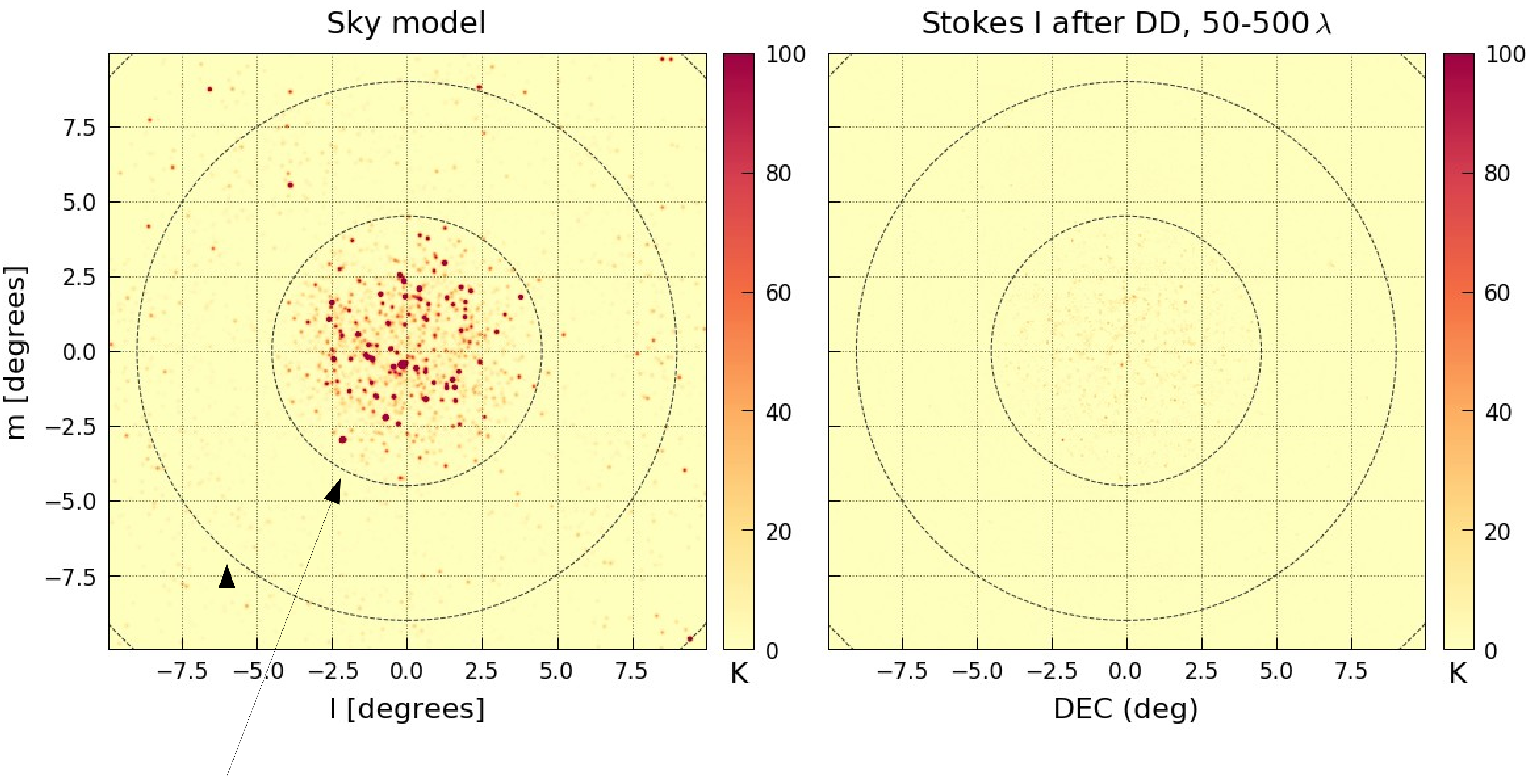


Ratio of Stokes V before/after DD show the effect of enforcing frequency-smoothness

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

DD calibration results

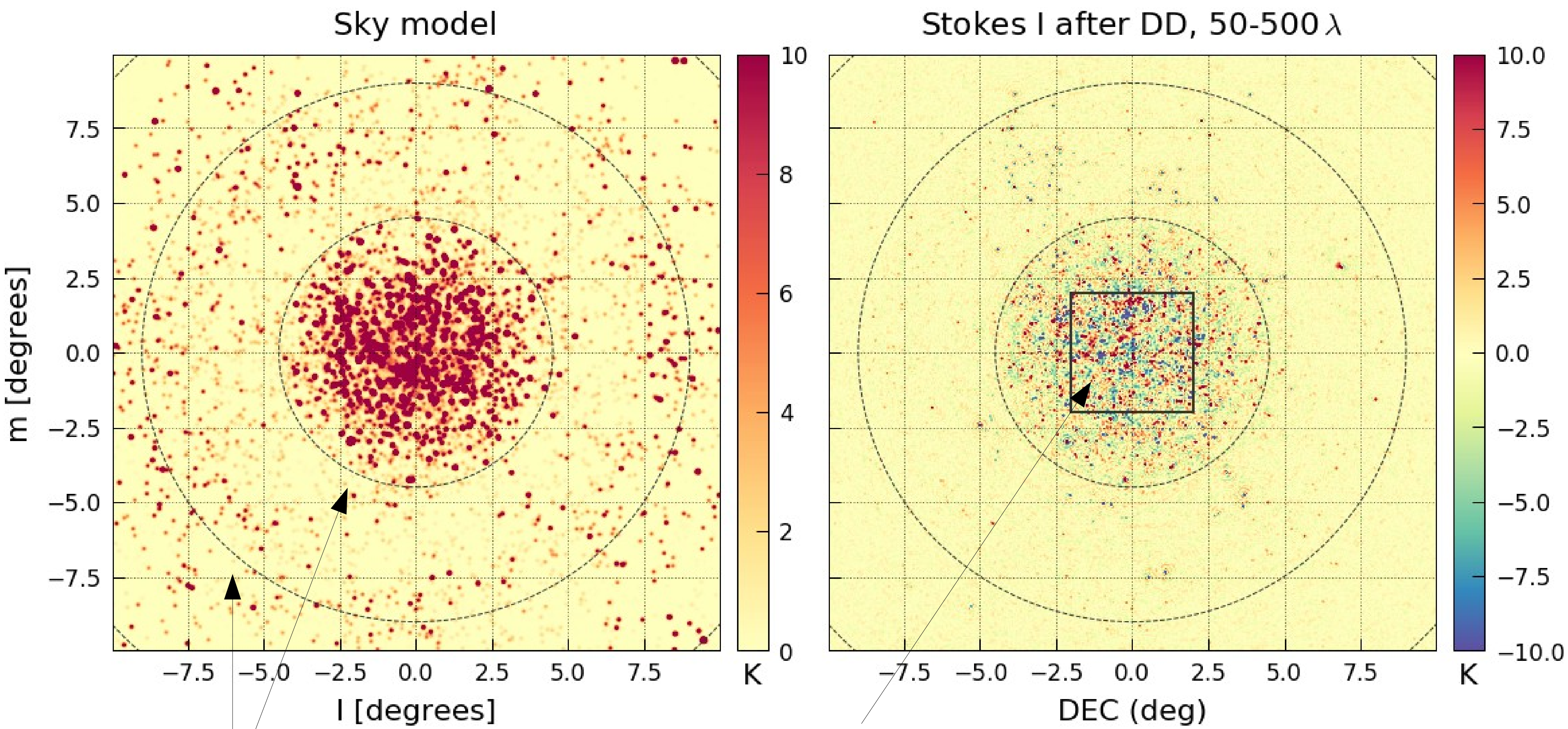
NCP field, 140 hours, 134-146 MHz, z ~ 9.1



First and second null
of the Primary Beam

DD calibration results

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



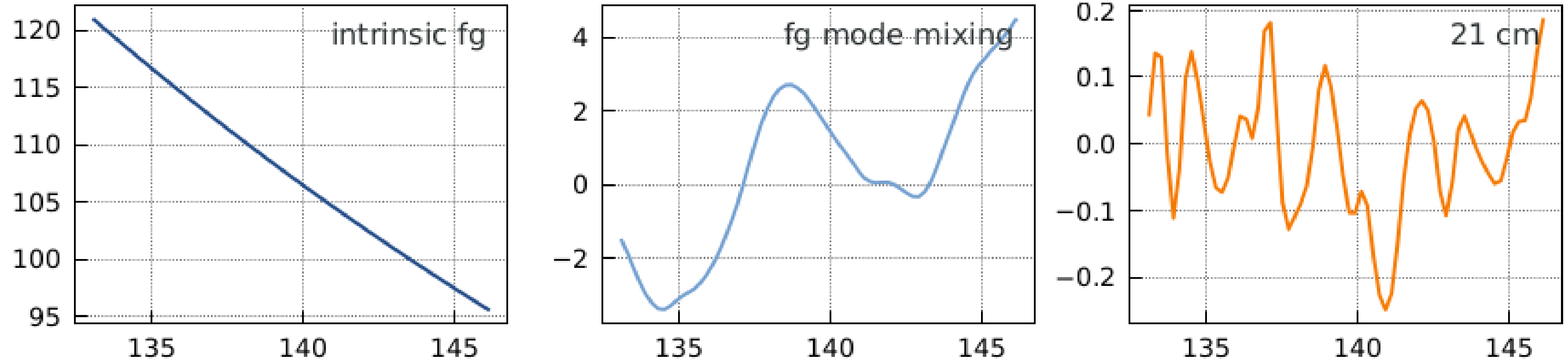
First and second null of the Primary Beam

Inner 4x4 where we look for the signal

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 $\mathbf{f} \sim \mathcal{N}(0, K)$

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

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

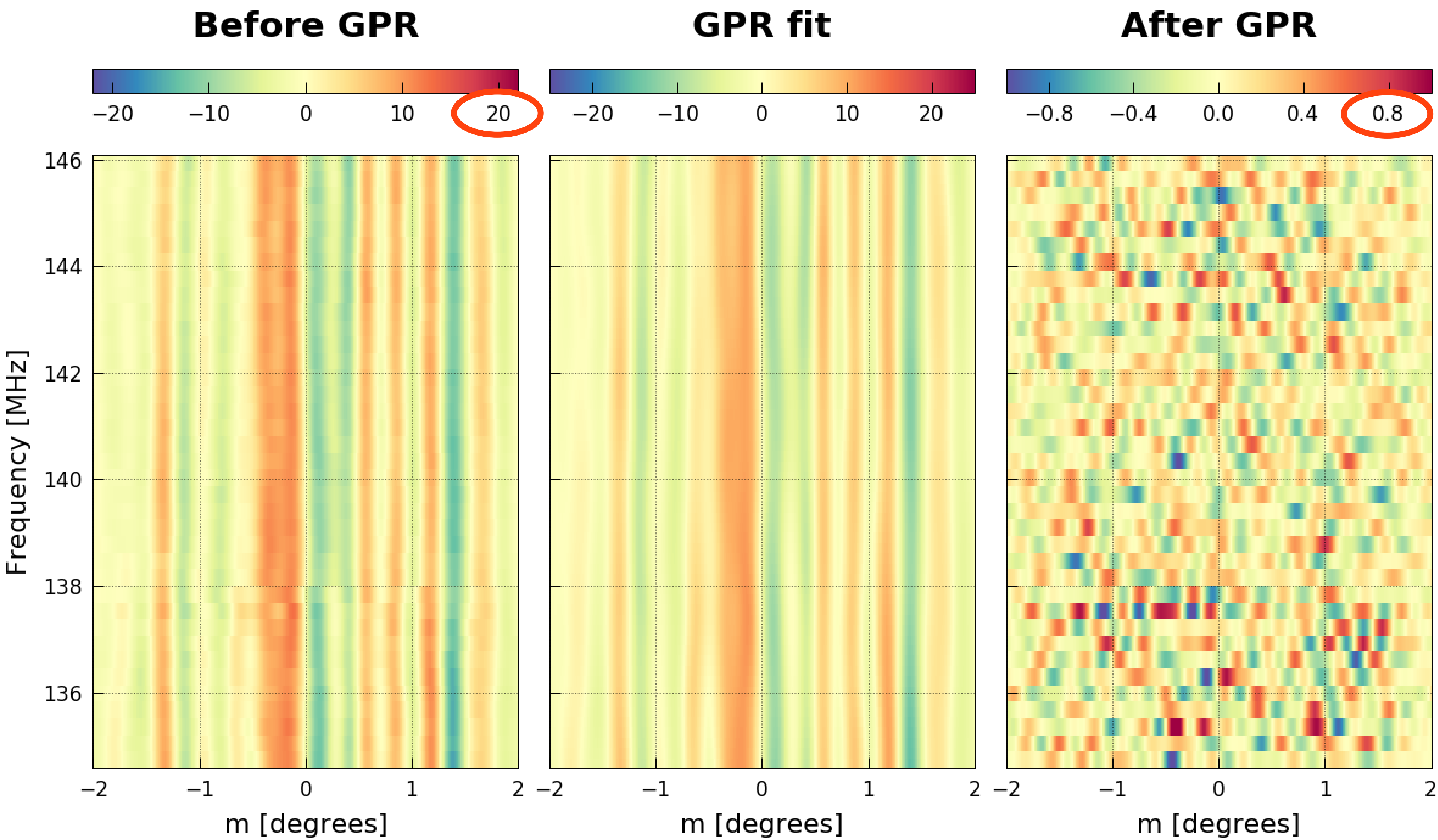
➔ Parametric Covariance optimized by maximizing the marginal likelihood (i.e. Bayesian evidence).

➔ 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

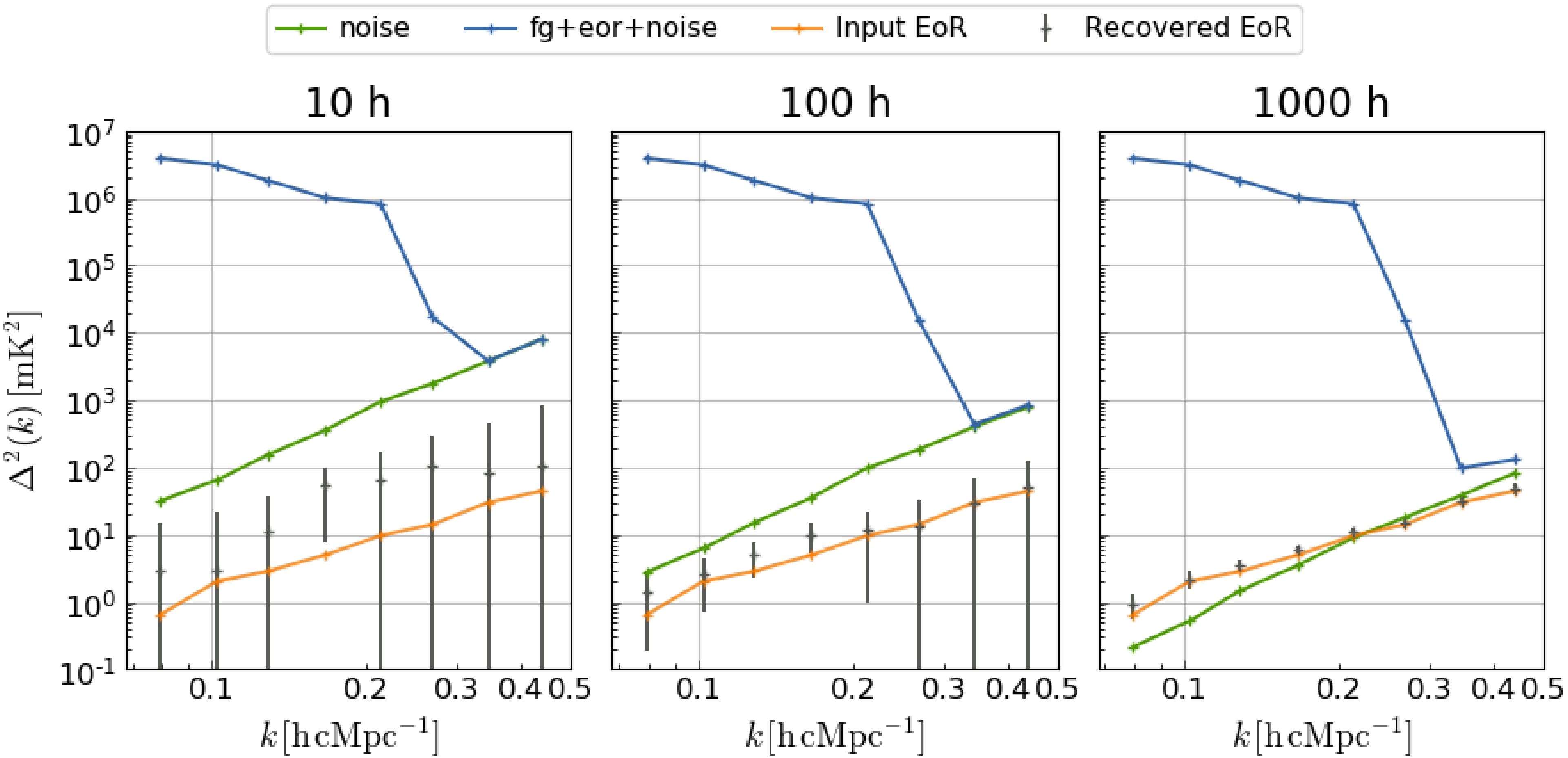


GPR remove frequency-coherent structure
Residual power level close to thermal noise

GPR on SKA simulation

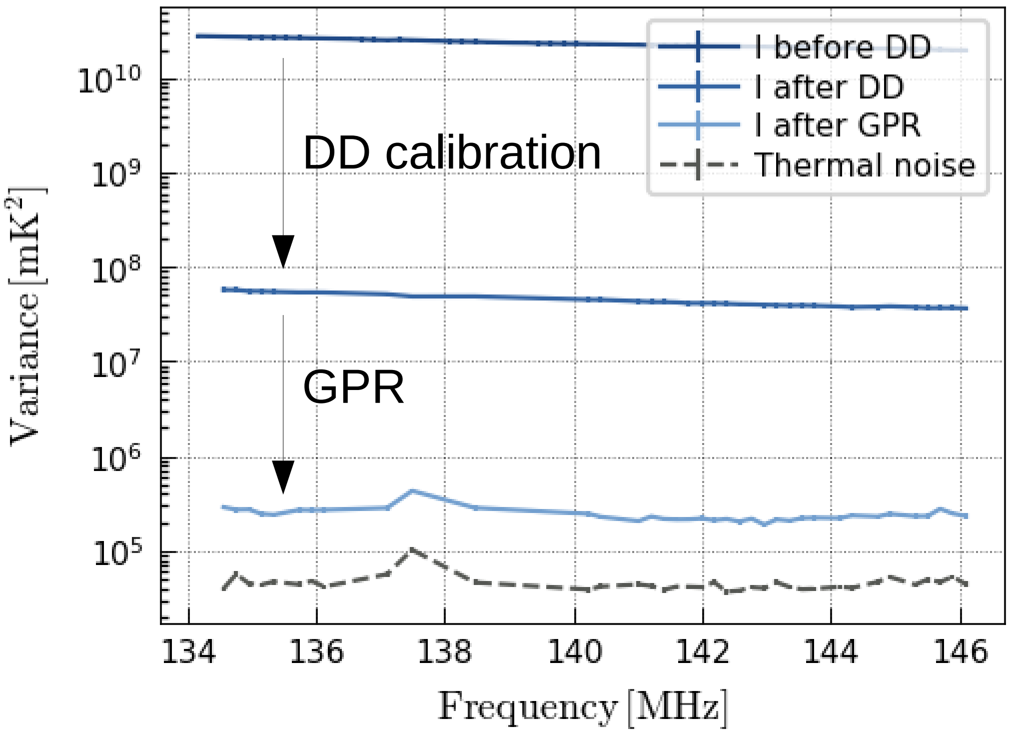
Simulation (from Modhurita Mitra for the SKA CD/EoR blind challenge):

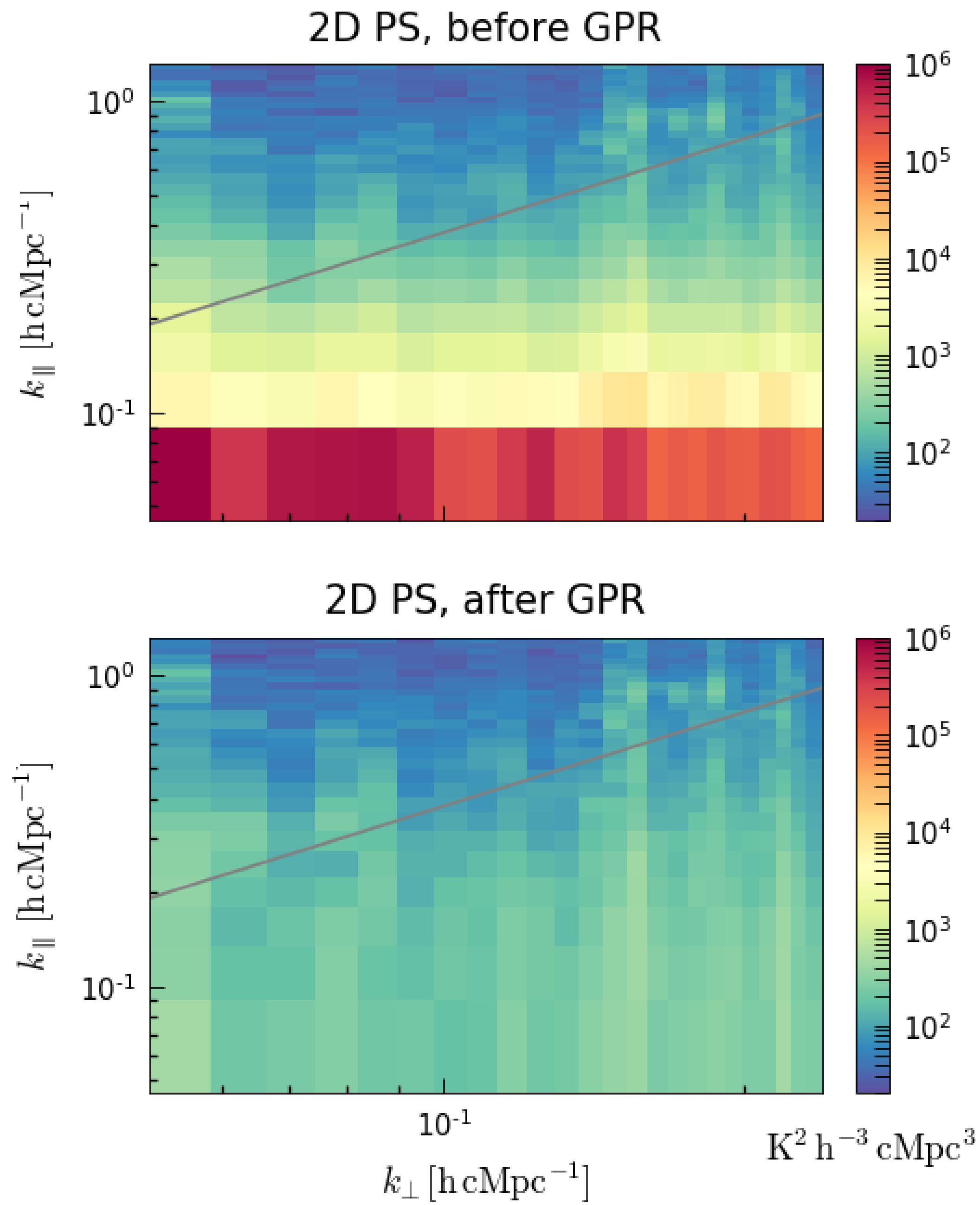
- Intrinsic foregrounds: galactic diffuse emission, 10 degree FoV
- 21-cm input signal: simulated from 21cmFast
- noise: equivalent to 10-100-1000 hours of SKA observation
- Visibility simulated using OSKAR



GPR on LOFAR data

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

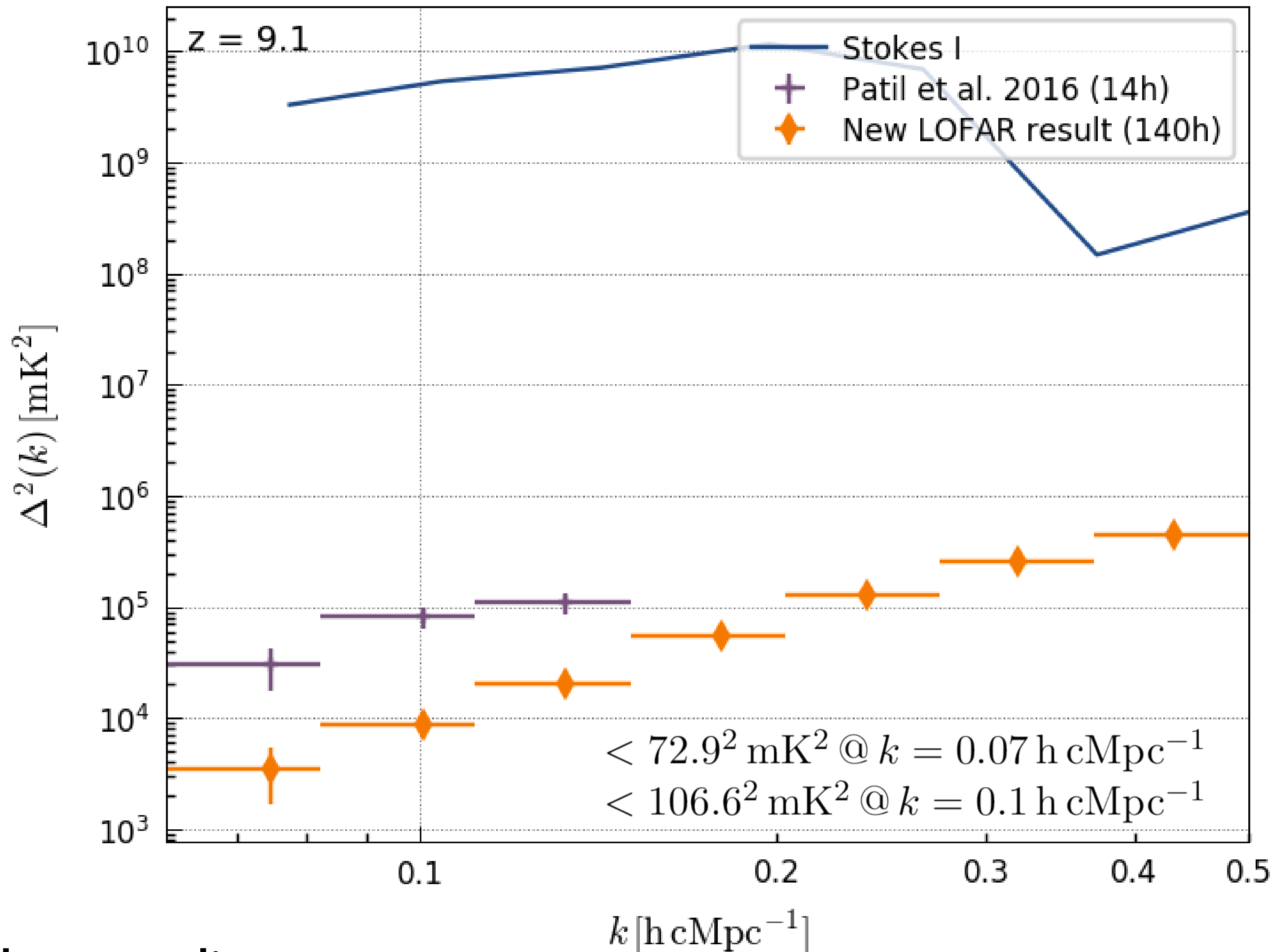




- ➔ DD calibration reduce foregrounds power by an order of magnitude down to confusion limit
- ➔ GPR remove residual foregrounds down to (very close to) noise level
- ➔ Residual power mostly incoherent between nights

New upper limit !

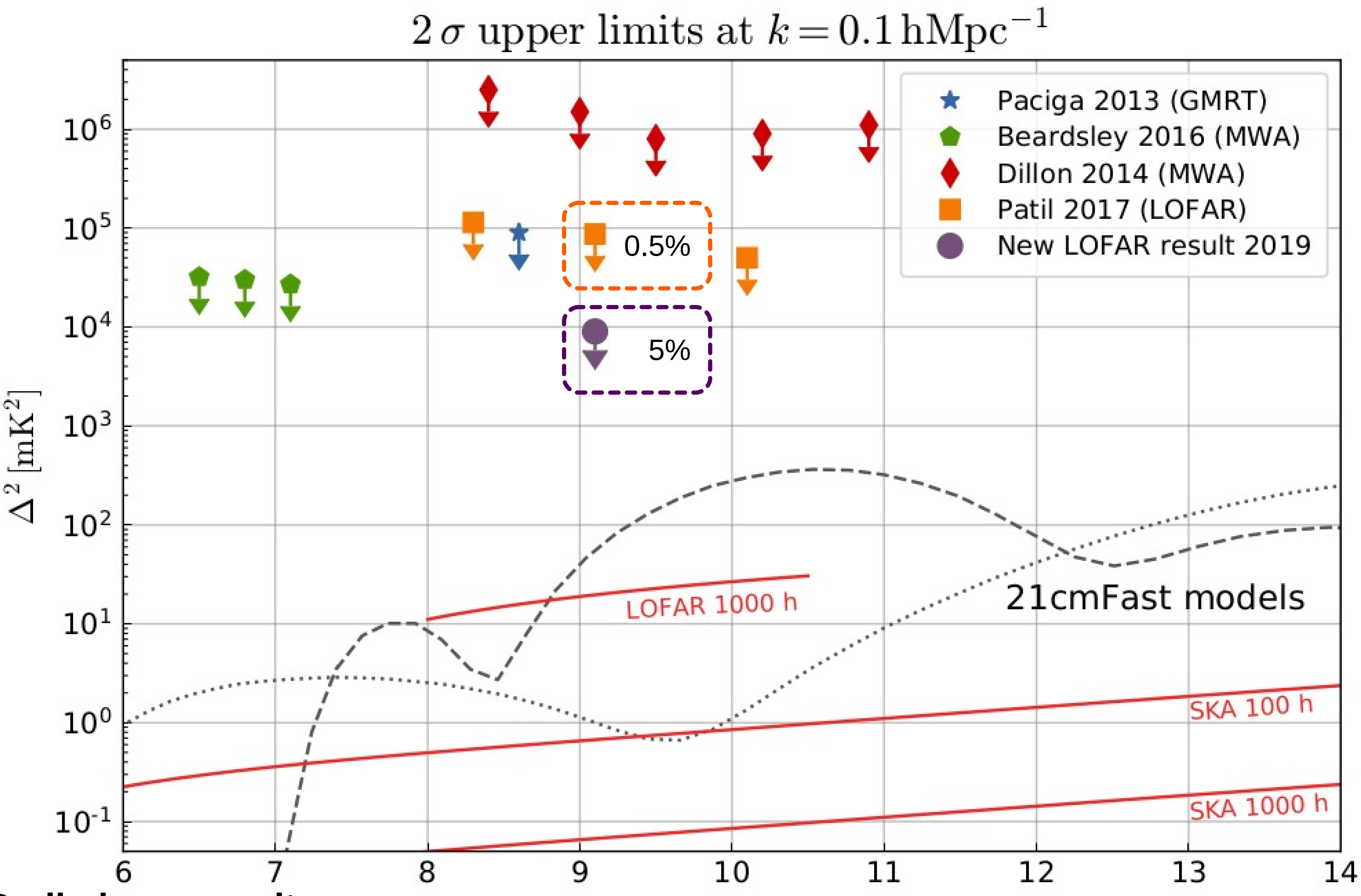
NCP field, 140 hours, 134-146 MHz, z ~ 9.1



Preliminary results

(Mertens et al. In prep.)

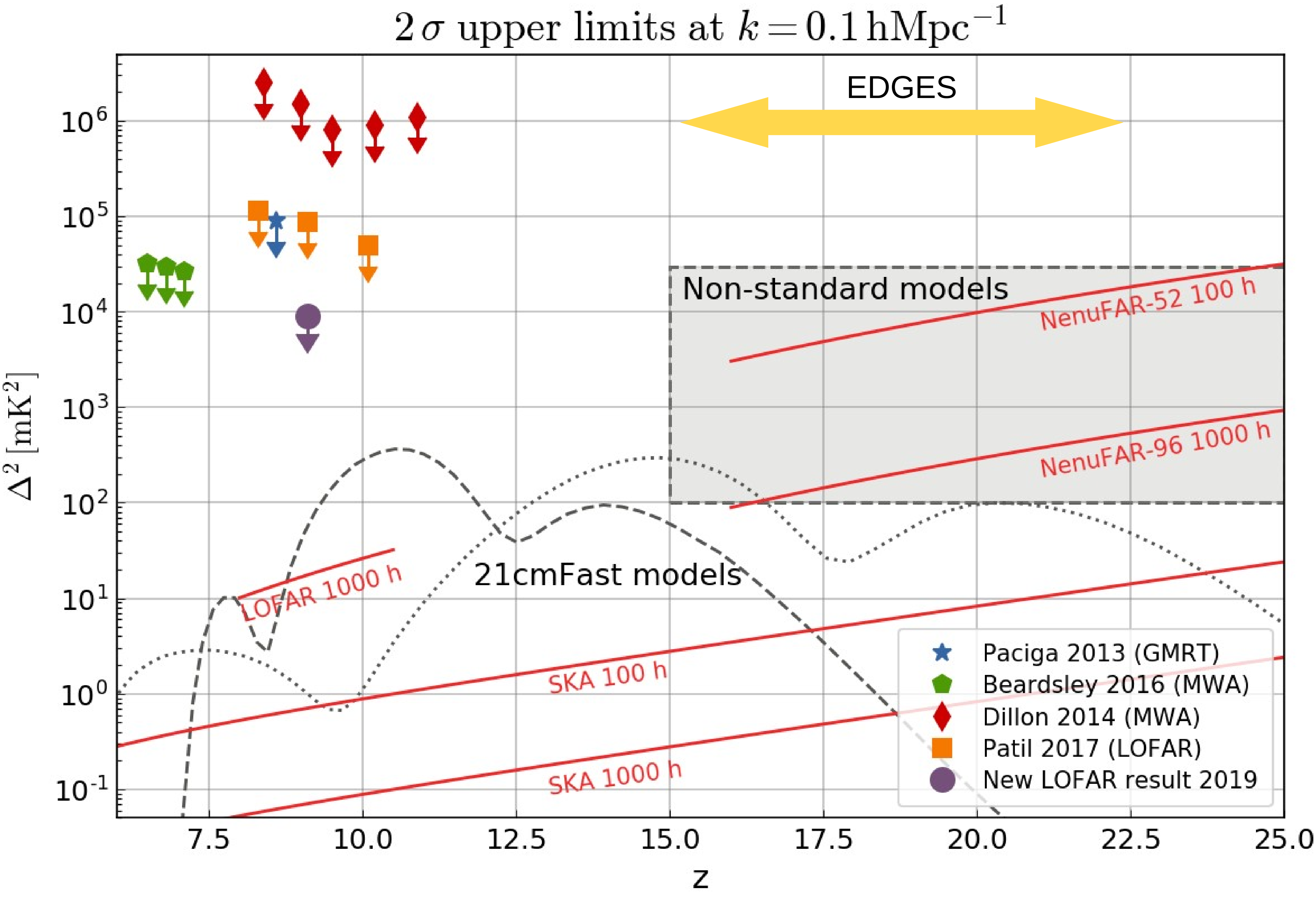
Where do we stand ? (updated)



Preliminary results

(Mertens et al. In prep.)

Perspective: ACE, NenuFAR, SKA



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:**
  - ➔ Claimed detection of the global signal (EDGES, -0.5K @ z ~ 17)
  - ➔ 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.
  - ➔ Confirm EDGES result with e.g. SARAS2 …
  - ➔ Near future: AARTFAAC and NenuFAR exploring the Cosmic Dawn.
  - ➔ Far future: SKA promising tomography of the 21-cm signal.