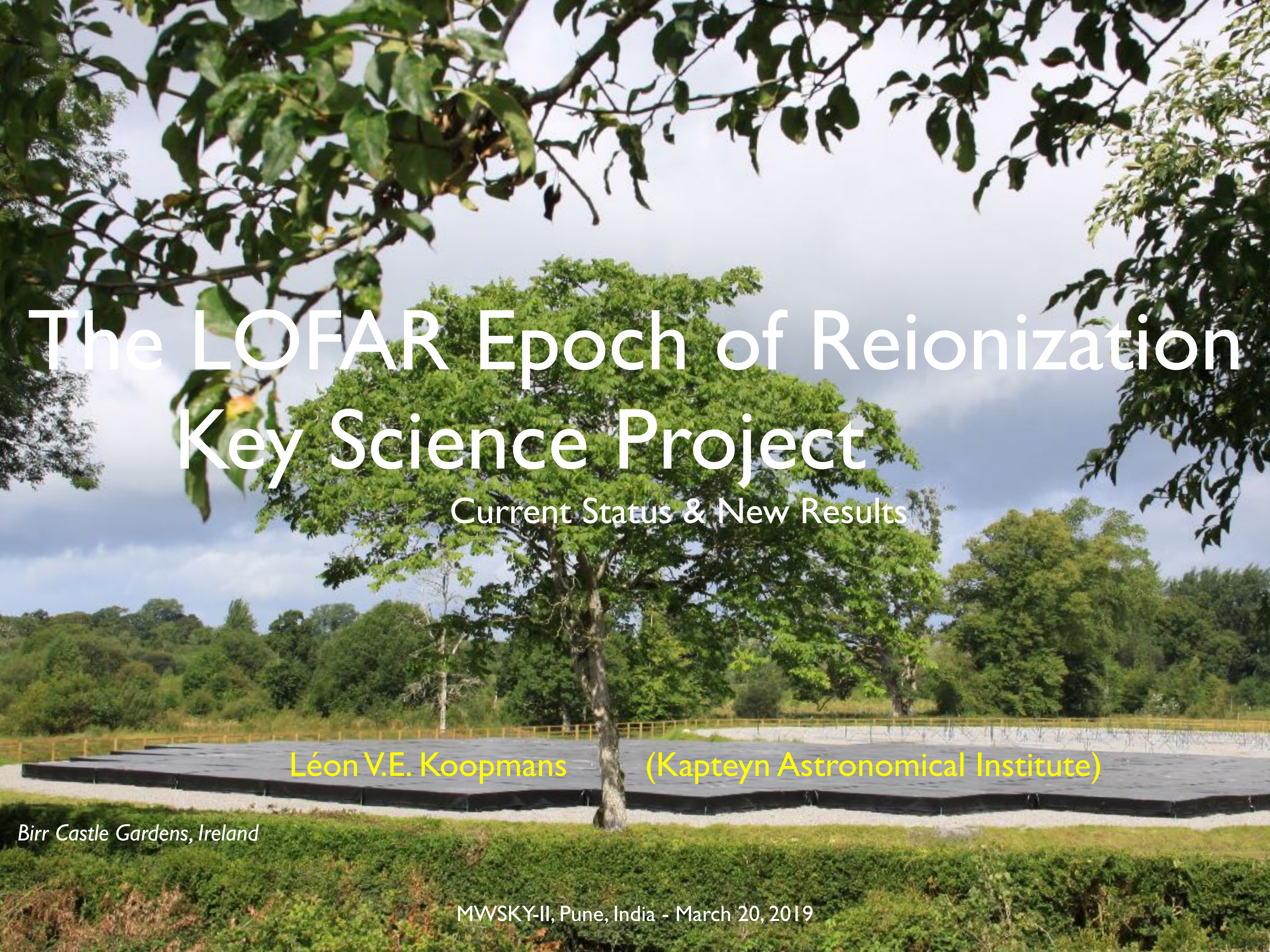
The LOFAR Epoch of Reionization Key Science Project

Current Status & New Results

Léon V.E. Koopmans (Kapteyn Astronomical Institute)



Birr Castle Gardens, Ireland

MWSKY-II, Pune, India - March 20, 2019

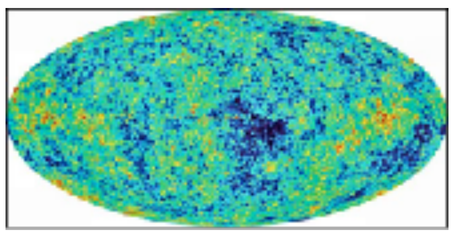
The LOFAR EoR KSP Team

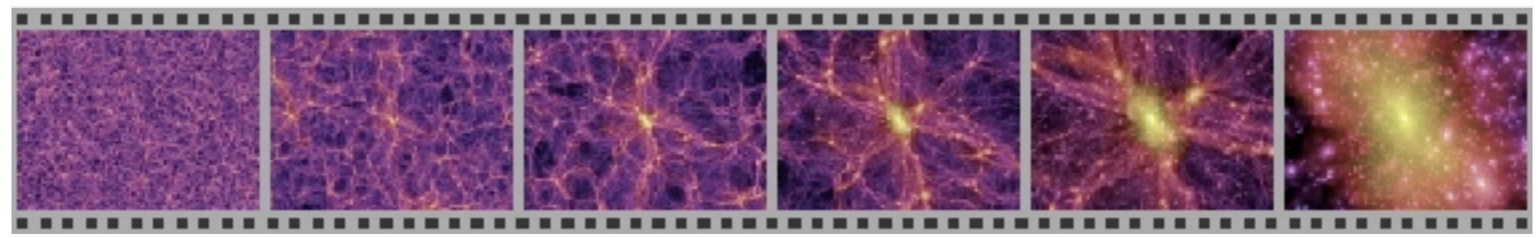
Michiel Brentjens (ASTRON)
Wim Brouw (Kapteyn)
Emma Chapman (Imperial)
Benedetta Ciardi (MPA)
Keri Dixon (Sussex)
Bharat Kumar Gehlot (ASU)
Abhik Ghosh (SKAO-SA)
Ilian Iliev (Sussex)
Vibor Jelic (IRB)
Hannes Jensen (Imperial)
Koki Kakiichi (MPG)
Robin Kooistra (Tokyo)
Léon Koopmans (Kapteyn)
Fabian Krause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

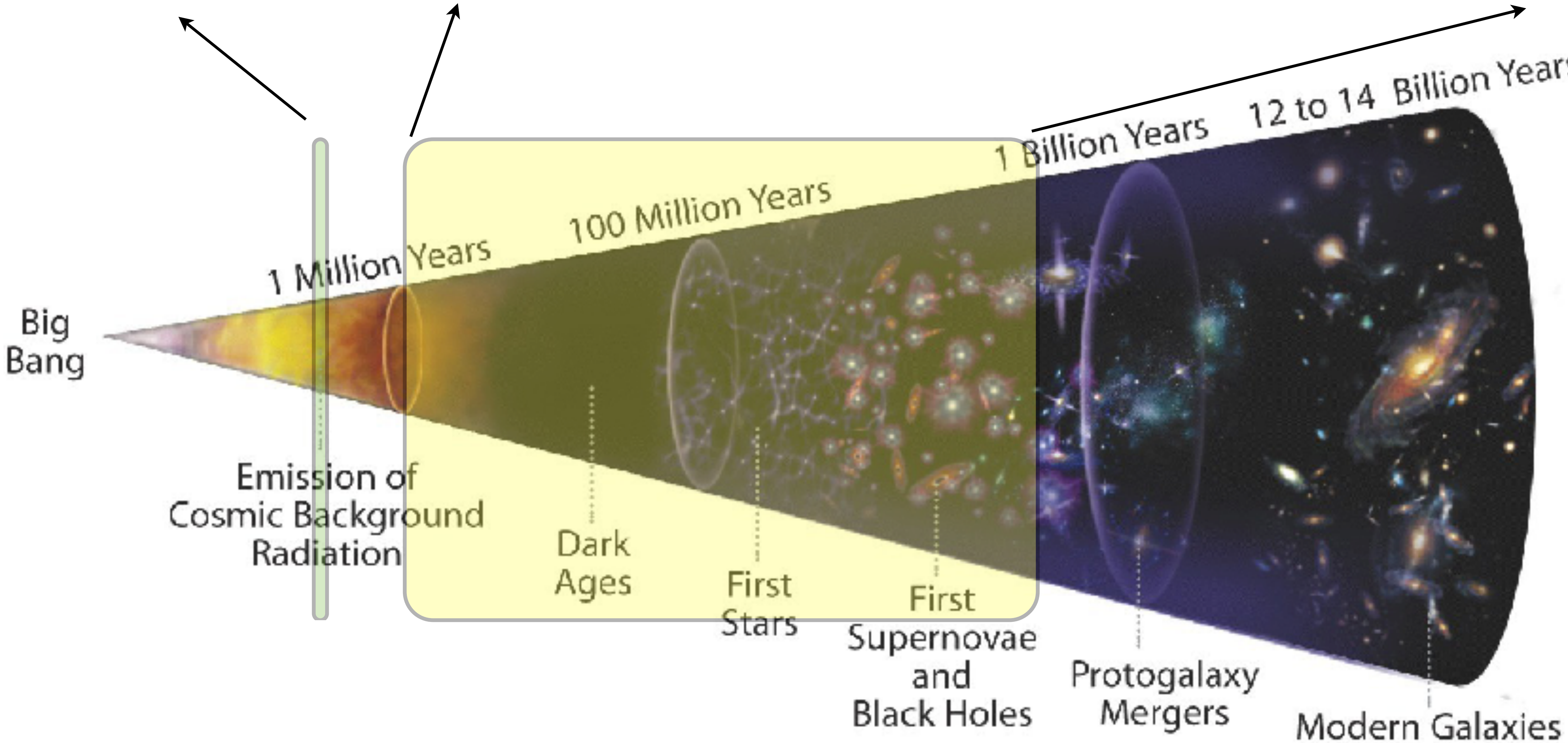
Dark Ages, Cosmic Dawn & EoR

CMB displays a single moment of the Universe. Its initial conditions at ~400,000 yrs

HI emission from the Dark Ages, Cosmic Dawn & Epoch of Reionization traces an evolving "movie" of baryonic and DM structure formation at $t_{univ}<10^9$ years.







"We know more about recombination than about reionization, even though it forms the foundation of the present-day Universe."

What will "21-cm Cosmology" tell us?

z

30-200 — Dark Ages

- DM power-spectrum evolution
- DM annihilation physics
- Baryonic Bulk Flows
- Physics of Gravity/GR

2030+ — Space/Lunar based Instruments

12-30 — Cosmic Dawn

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

2025+ — SKA/HERA/NenuFar/ LEDA/JWST/ALMA…

6-12 — Reionization

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

~2020 — LOFAR, MWA, PAPER, GMRT, HST, ALMA, VLT, Subaru, Keck, …

0-6 — Post-Reionization

- BAO - DE EoS/Gravity
- Intensity Mapping - DE EoS/Gravity
- Galaxy Counts - Mass function ++

Summary of Current Constraints on the EoR/CD

- Scattering optical depths from CMB observations
  Ionised medium causes CMB polarisation: z_{eor} ~ 8 (latest Planck results!)
- High-z galaxies/Ly-alpha emitters
  IR drop-outs give SFR/LF to z~10: SFR rises fast below z~10 but there are not enough UV photons to reionize the Universe

  Ly-alpha emitters seem to drop out already at z>7.
- High-z QSOs
  Gunn-Peterson troughs suggest >30% neutral HI at z~7.5, i.e. the end of reionization occurs close to the highest z QSO/galaxies that we observe
- High-z GRBs
  GRBs traces massive star formation. Currently rare events, but z~8.2 GRB has been seen and could be a direct tracer of the SFR.
- Temperature of the IGM
  Extrapolation of the high-z IGM temperature suggest late reionization
- NIR/X-ray backgrounds
  Detection of NIR fluctuations made, but far above predictions.
  X-rays limit AGN contribution to reionization to ~10% max.

- Discovery of the global 21-cm signal from Cosmic Dawn (EDGES2) in 2018 ?

Expectations of the 21-cm Signal of Neutral Hydrogen

Most evidence points at substantial reionization occurring at z<10, being halfway around z~8 and ending around z~6.

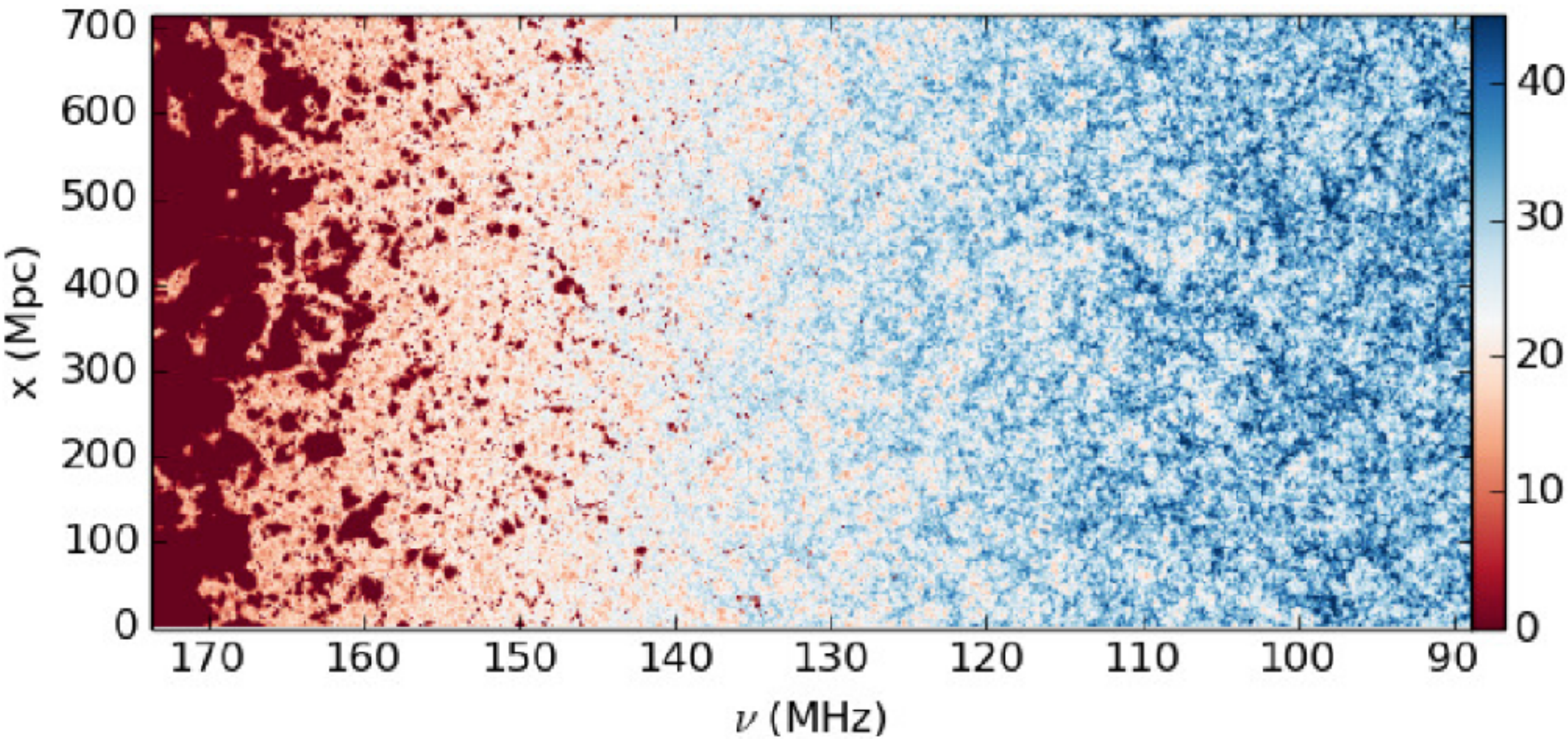
But the details are largely unknown: a complementary tracer is needed that is volume filling and actually traces what is being ionised and what forms stars/galaxies (i.e. hydrogen itself)

Hydrogen Brightness Temperature

The tomography of HI emission/absorption is a treasure trove of information for (astro)physics, cosmology & fundamental physics.

Post-Reionization | Dark Ages/Cosmic Dawn/Reionization

HI is found largely in galaxies ← HI has a filling factor of order unity



Credit: Dixon, Illiev et al.

Hydrogen Brightness Temperature

The brightness of the 21-cm signal (in Kelvin; Rayleigh-Jeans regime) that can be measured with radio telescopes is given by:

$$\delta T_b = \frac{T_S - T_R}{1+z}\left(1 - \mathrm{e}^{-\tau_\nu}\right)$$

$$\approx \frac{T_S - T_R}{1+z}\tau$$

$$\approx 27 x_{\rm HI}\,(1+\delta_b)\left(\frac{\Omega_b h^2}{0.023}\right)\left(\frac{0.15}{\Omega_m h^2}\,\frac{1+z}{10}\right)^{1/2}$$

$$\times\left(\frac{T_S - T_R}{T_S}\right)\left[\frac{\partial_r v_r}{(1+z)H(z)}\right]\,\mathrm{mK},$$

Cosmology

Ionization

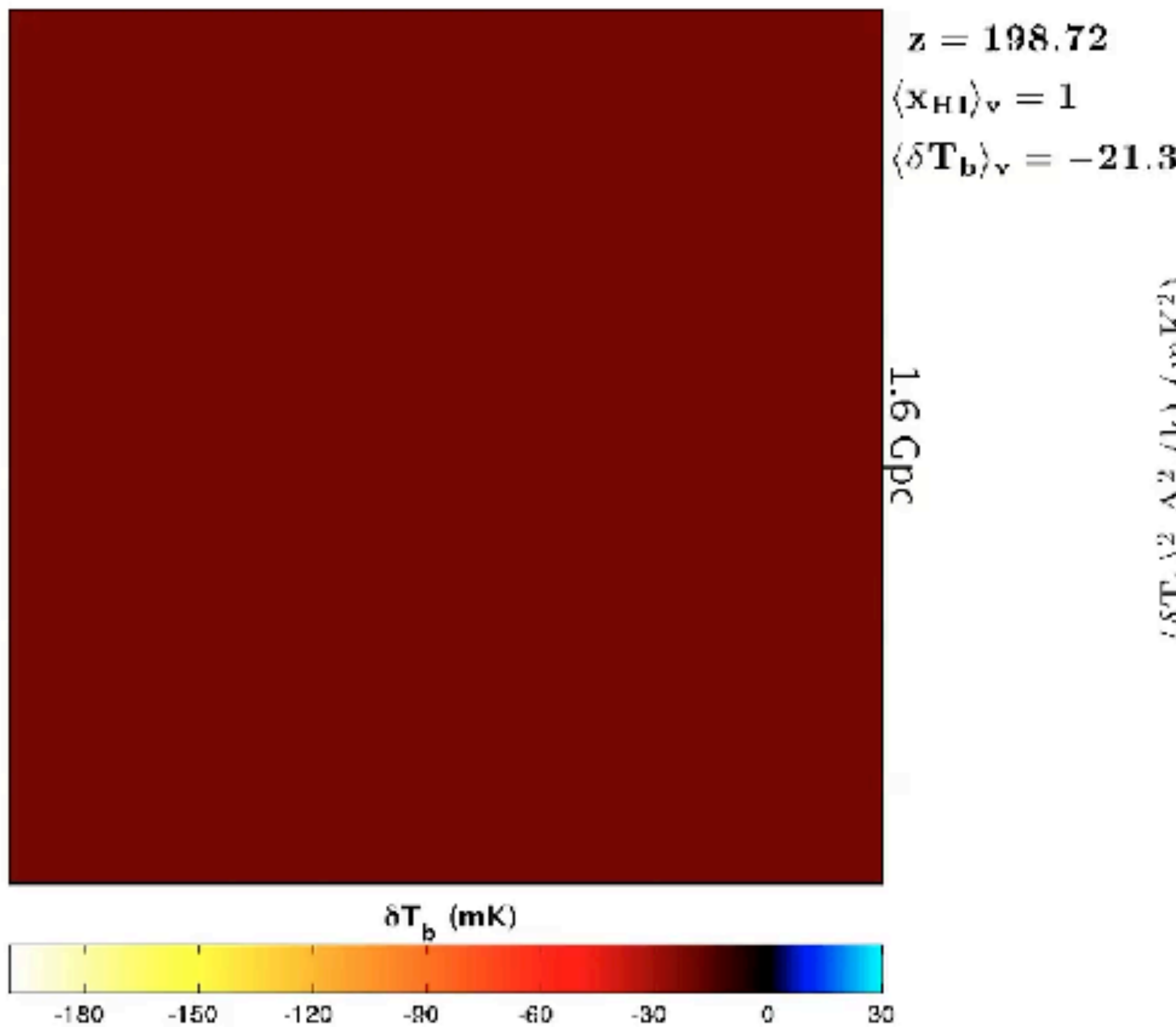
(G)astrophysics

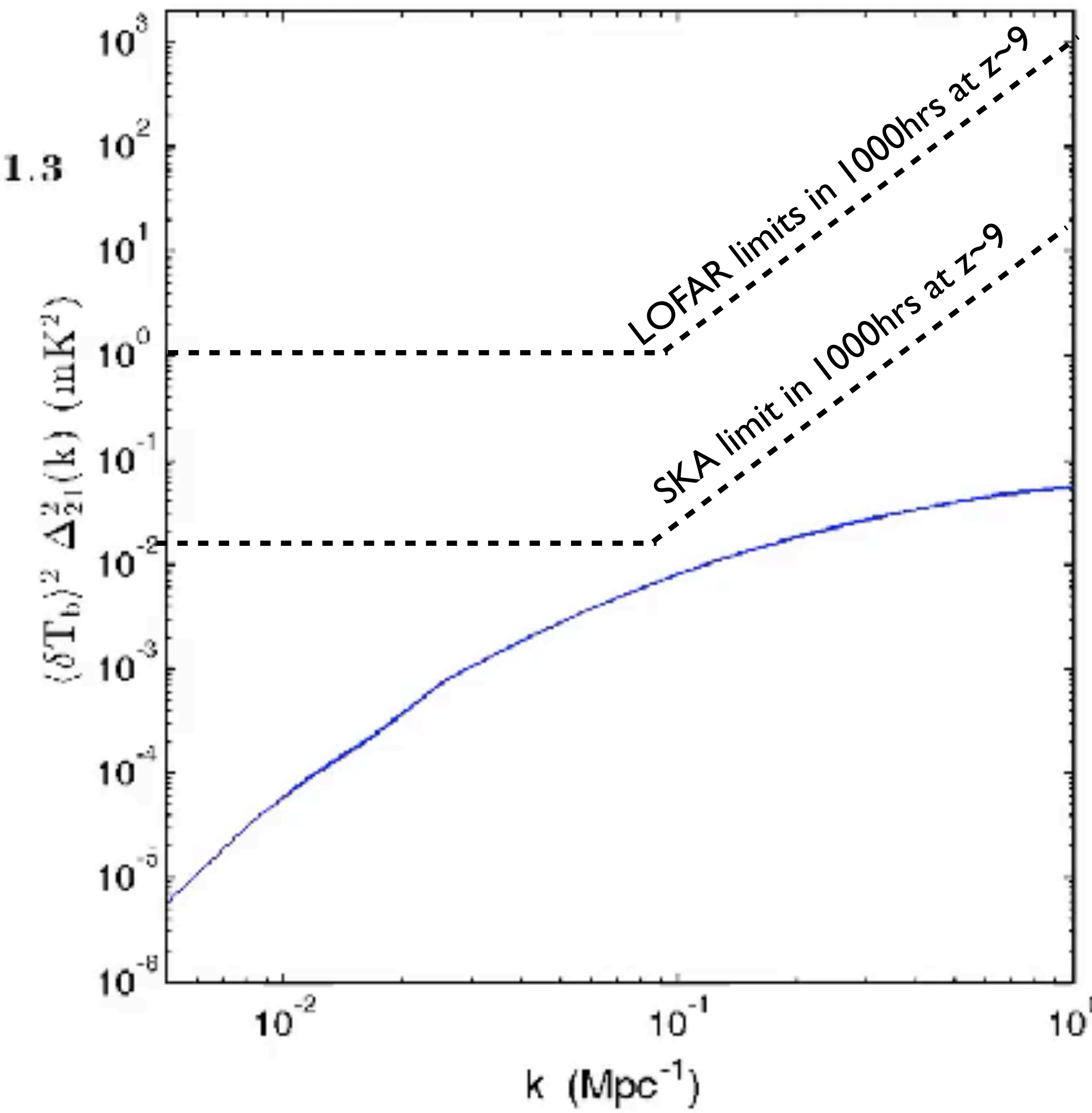
Peculiar velocities/Bulk-flows

The 21-cm signal is set by a complex interplay between cosmology and (g)astrophysics.

Hydrogen Brightness Temperature

Power-spectrum



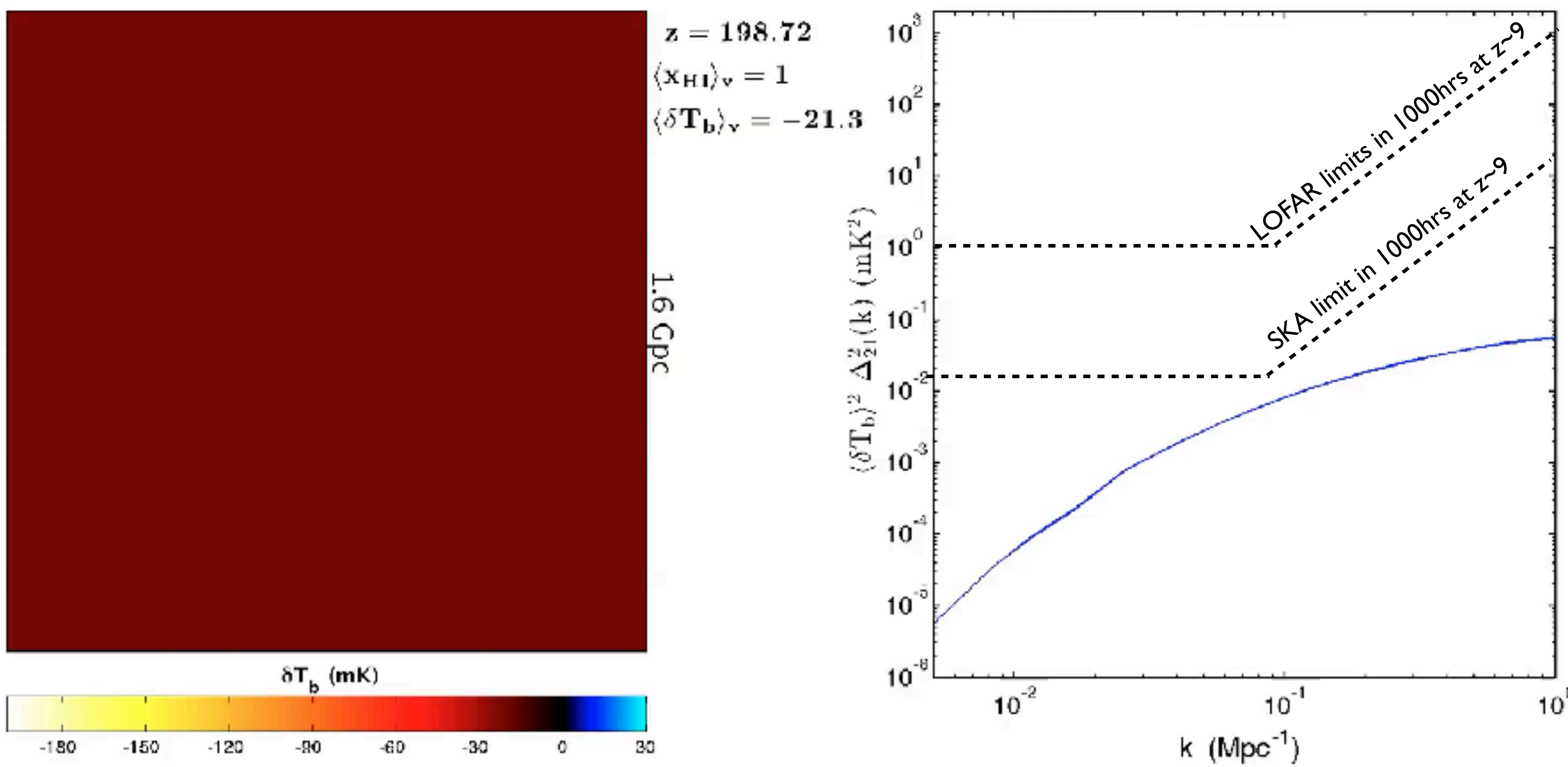


Signals are scale dependent: Δ^2_{21cm}~ few to a few hundred mK^2 at k~0.1 during the Epoch of Reionization and Cosmic Dawn, respectively.

Credit movie: Mesinger

Hydrogen Brightness Temperature

Power-spectrum

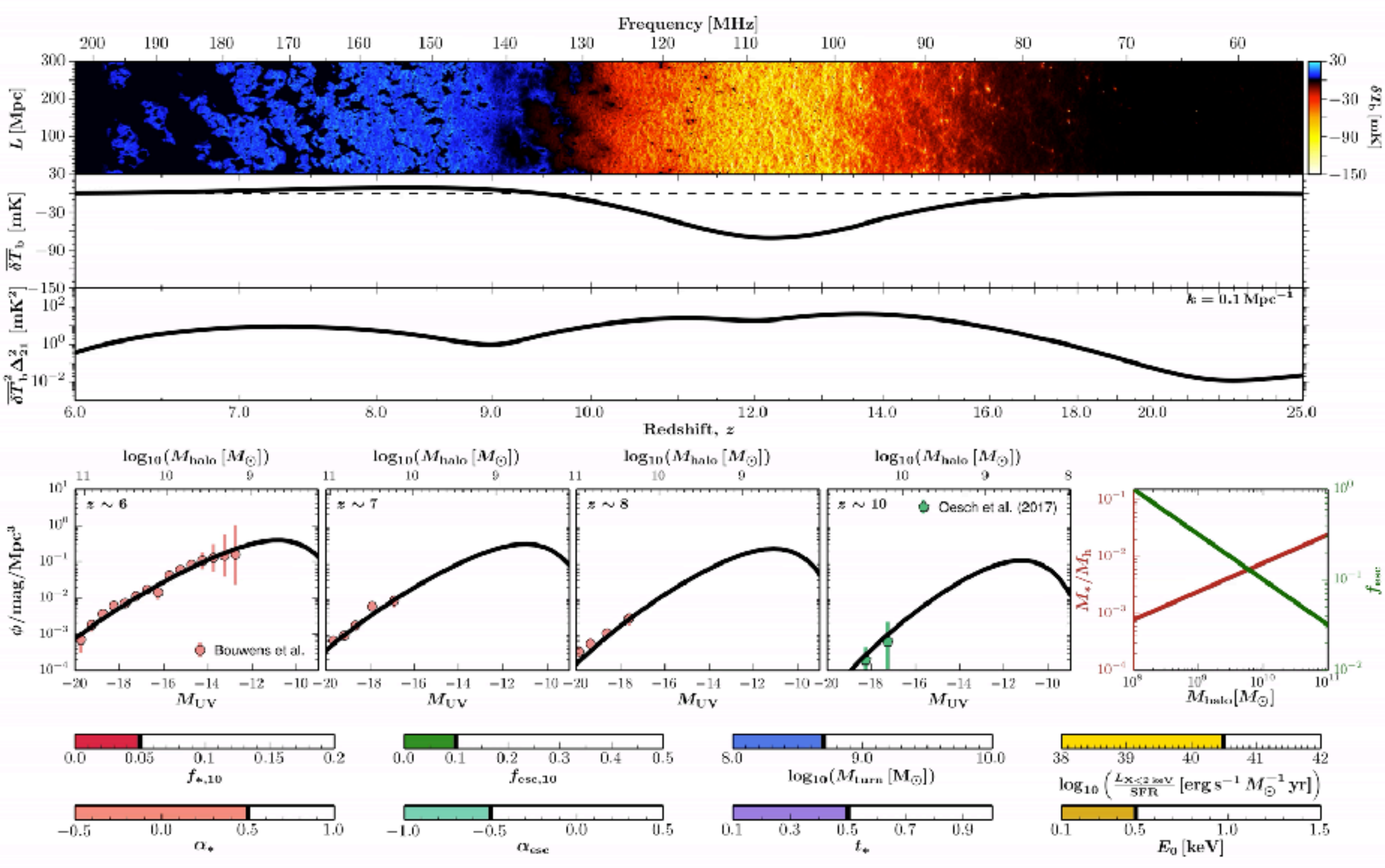


Signals are scale dependent: Δ^2_{21cm}~ few to a few hundred mK^2 at k~0.1 during the Epoch of Reionization and Cosmic Dawn, respectively.

Credit movie: Mesinger

Hydrogen Brightness Temperature

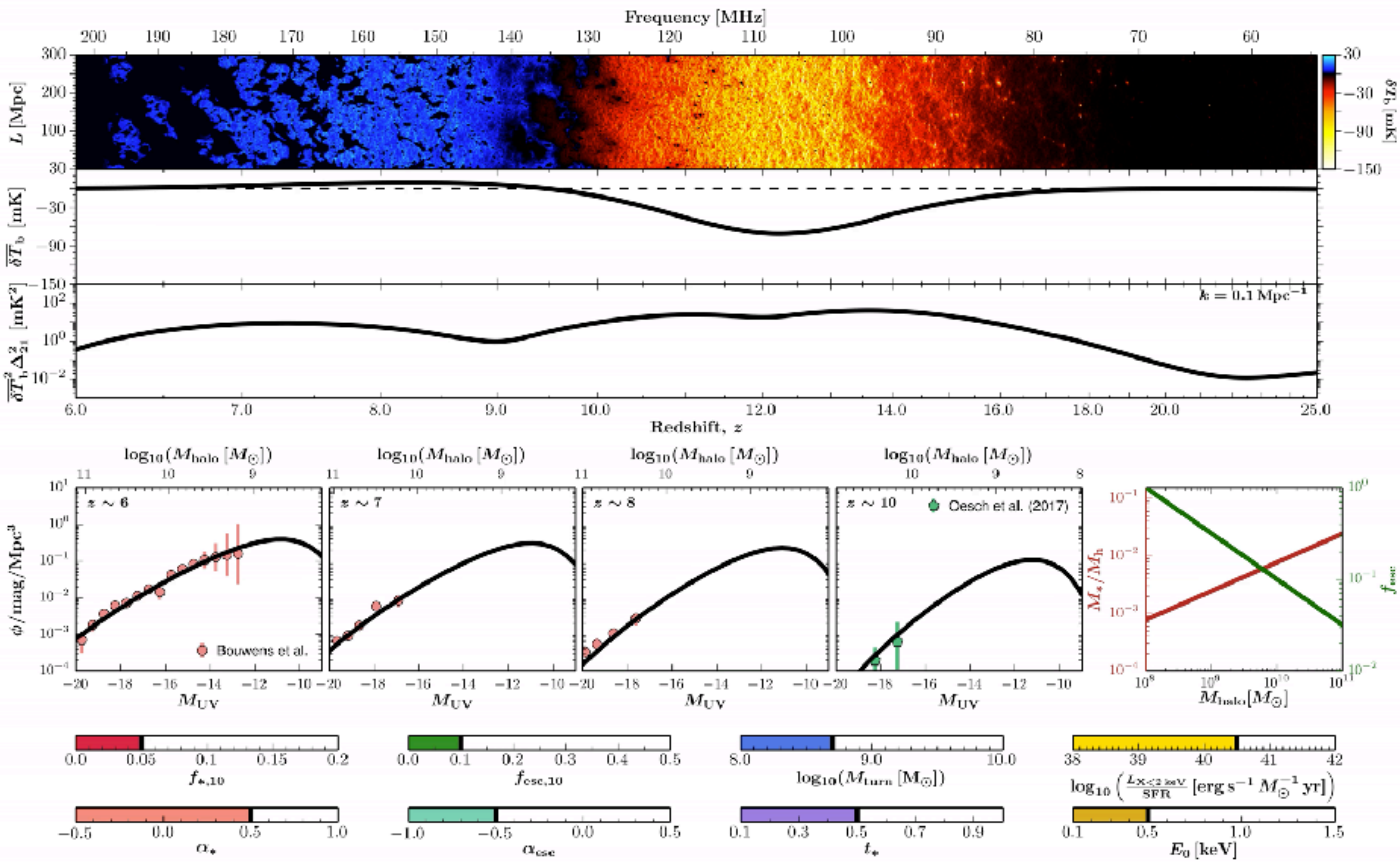
Inferring physical processes/ingredients from the data



21CMMC — Meisinger & Greig

Hydrogen Brightness Temperature

Inferring physical processes/ingredients from the data



21CMMC — Meisinger & Greig

rijksuniversiteit groningen
faculteit wiskunde en natuurwetenschappen
kapteyn instituut

The LOFAR Epoch of Reionization (EoR) Key Science Project

Where do we stand at the moment and what keeps us busy?

MWSKY-II, Pune, India - March 20, 2019

Current 21-cm Power-Spectrum Detection Experiments/Results

Specs
- 40 hrs data [12/2007] on PSRB0823+26
- FWHM = 3.1d primary beam
- Resolution 20 arcsec
- Freq = 139.3-156.0 MHz [64x0.25MHz]
- Time resolution = 64 sec
- z = 8.1-9.2

Paciga et al. 2013

Specs:
- 3 hrs of data; - August 23 2013
- R.A.(J2000) = 0h 0m 0s,
  Decl.(J2000) = $-30^\circ\ 0'\ 0''$
- high-band of 30.72 MHz, centered at
  182 MHz i.e. $6.2 < z < 7.5$

Dillon et al. 2015

Specs:
- 1148 hrs of data
  (8/11/2012 to 23/3/2013)
- 100 to 200 MHz, 1024 chan
- visibility integr.: 10.7 seconds

Retracted
Ali et al. 2015

Specs:
- 13 hrs of data; - Feb11/12 2013
- R.A.(J2000) = 0h 0m 0s,
  Decl.(J2000) = $90^\circ\ 0'\ 0''$
- high-band of 115-189 MHz

Patil et al. 2017

Current 21-cm Power-Spectrum Detection Experiments/Results

Specs
- 40 hrs data [12/2007] on PSRB0823+26
- FWHM = 3.1d primary beam
- Resolution 20 arcsec
- Freq = 139.3-156.0 MHz [64x0.25MHz]
- Time resolution = 64 sec
- z = 8.1-9.2

Paciga et al. 2013

Specs:
- 3 hrs of data; - August 23 2013
- R.A.(J2000) = 0h 0m 0s, Decl.(J2000) = $-30^\circ\ 0'\ 0''$
- high-band of 30.72 MHz, centered at 182 MHz i.e. $6.2 < z < 7.5$

Dillon et al. 2015

Specs:
- 1148 hrs of data (8/11/2012 to 23/3/2013)
- 100 to 200 MHz, 1024 chan
- visibility integr.: 10.7 seconds

Retracted
Ali et al. 2015

Specs:
- 13 hrs of data; - Feb11/12 2013
- R.A.(J2000) = 0h 0m 0s, Decl.(J2000) = $90^\circ\ 0'\ 0''$
- high-band of 115-189 MHz

Patil et al. 2017

The Low Frequency Array

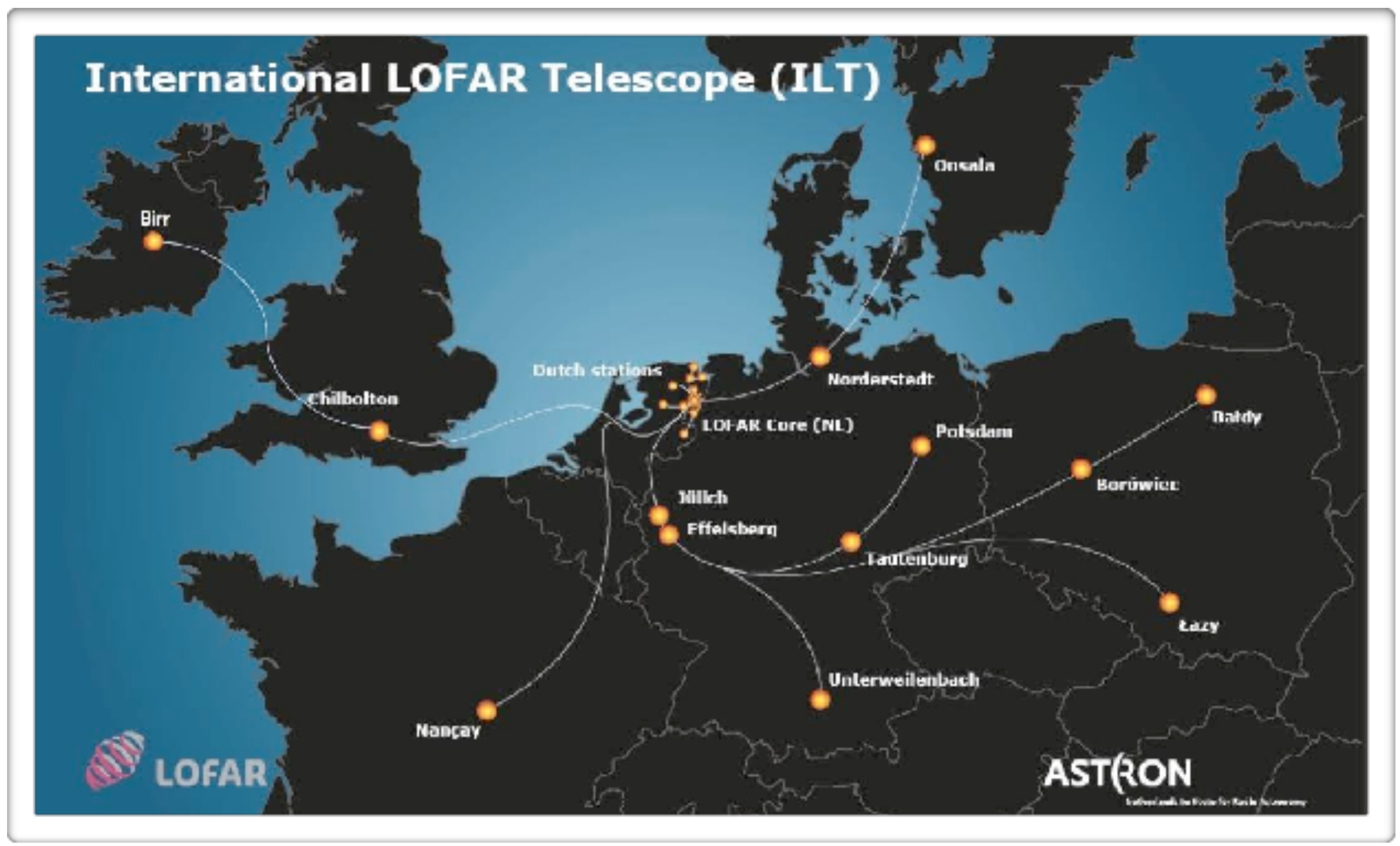
LOFAR is now a European telescope with its core in the Northern Netherlands, developed by ASTRON+Dutch Universities

(ILT Members: Netherlands, Germany, UK, France, Sweden, Poland, Ireland, Estonia, Italy*)*

Core
3 km — 48 stations
Netherlands
80 km — 14 stations
Europe
2000 km — 12 stations

Stations have 24 – 48 – 96 antennas/tiles, respectively.

van Haarlem et al. 2013



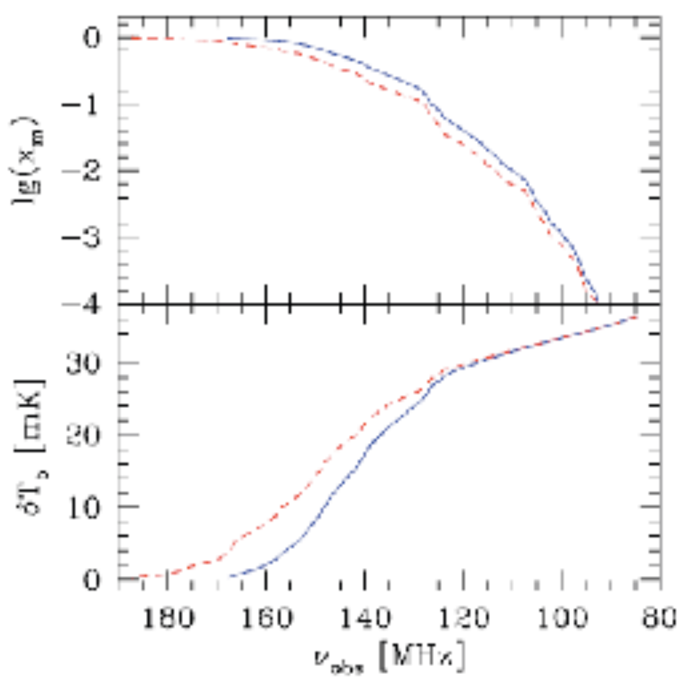
The Low Frequency Array

The Low Frequency Array

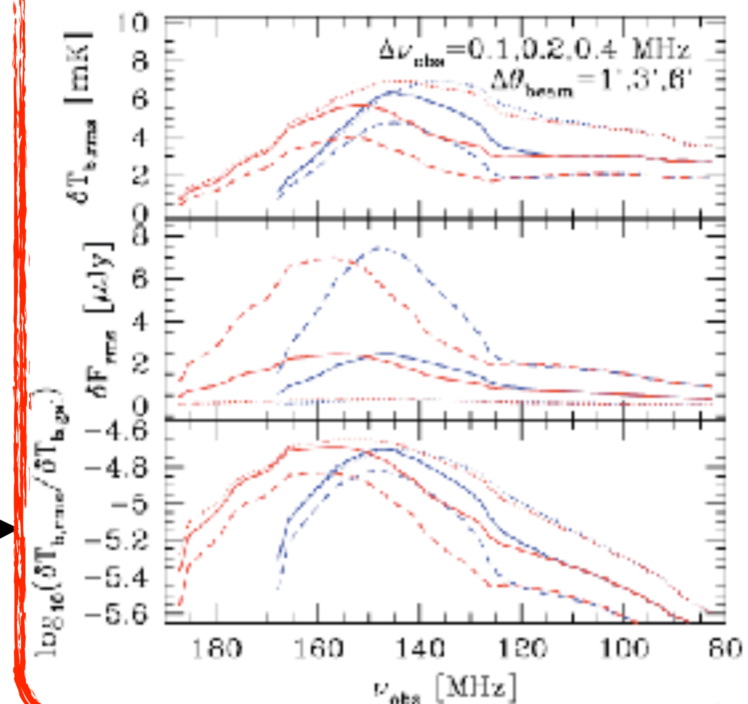
The Low Frequency Array

LOFAR EoR KSP: Goals

Signal Variance



Power-Spectra



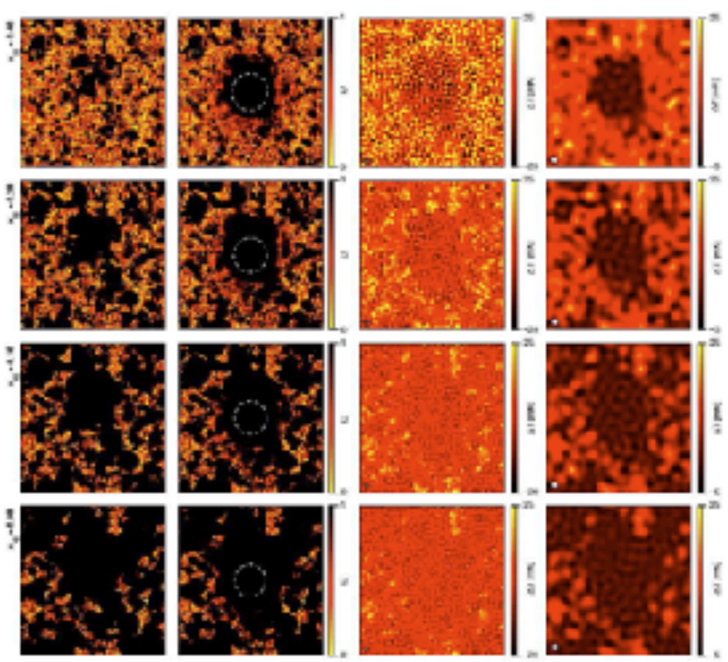
Key Questions versus Observations

When/how did reionization occur?

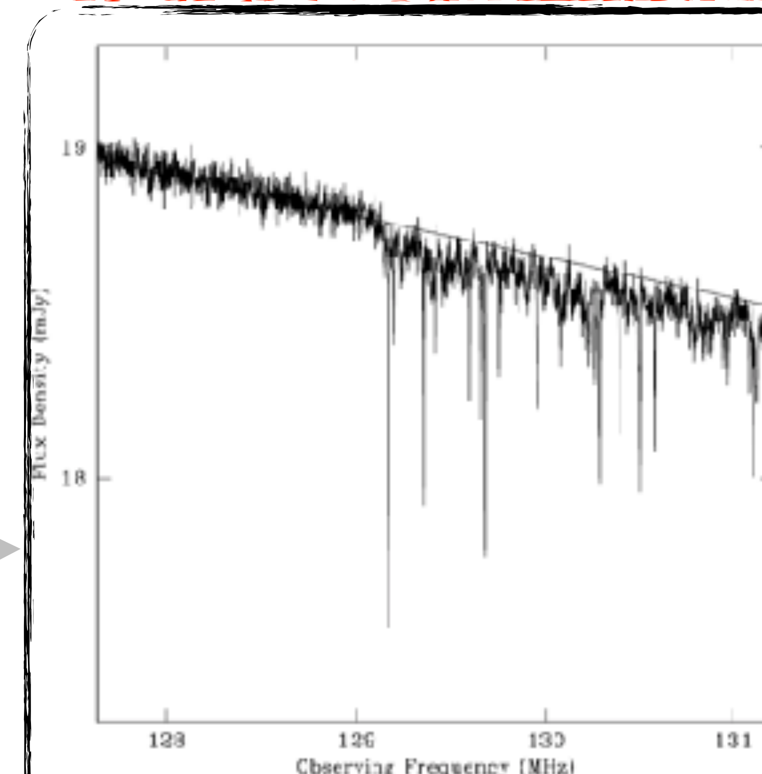
Which sources (Pop II/III stars or quasars/IMBHs) were responsible?

How did these first sources form?

What was their impact & feedback on the IGM/ISM?



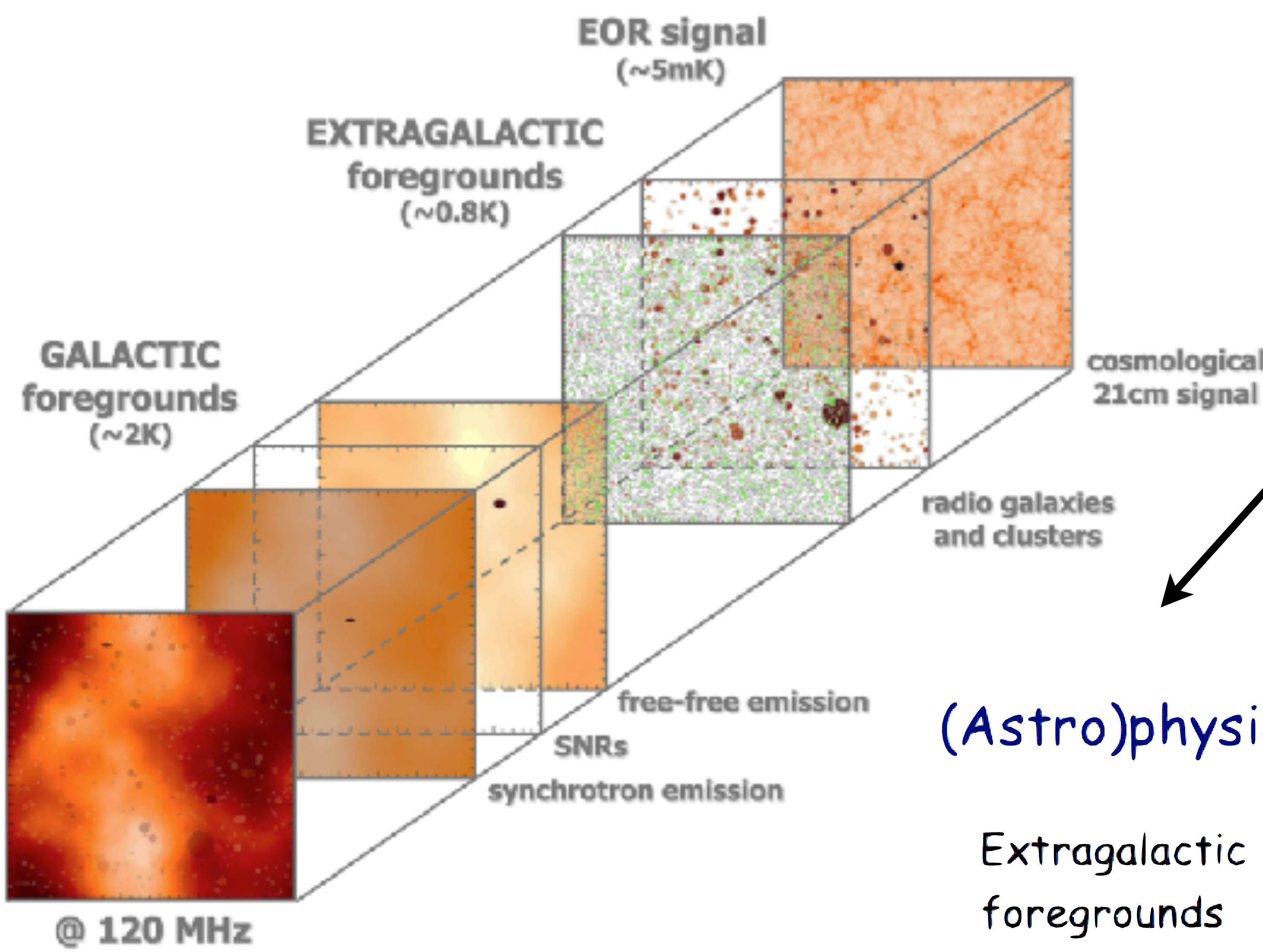
Strömgren Bubbles



HI Absorption

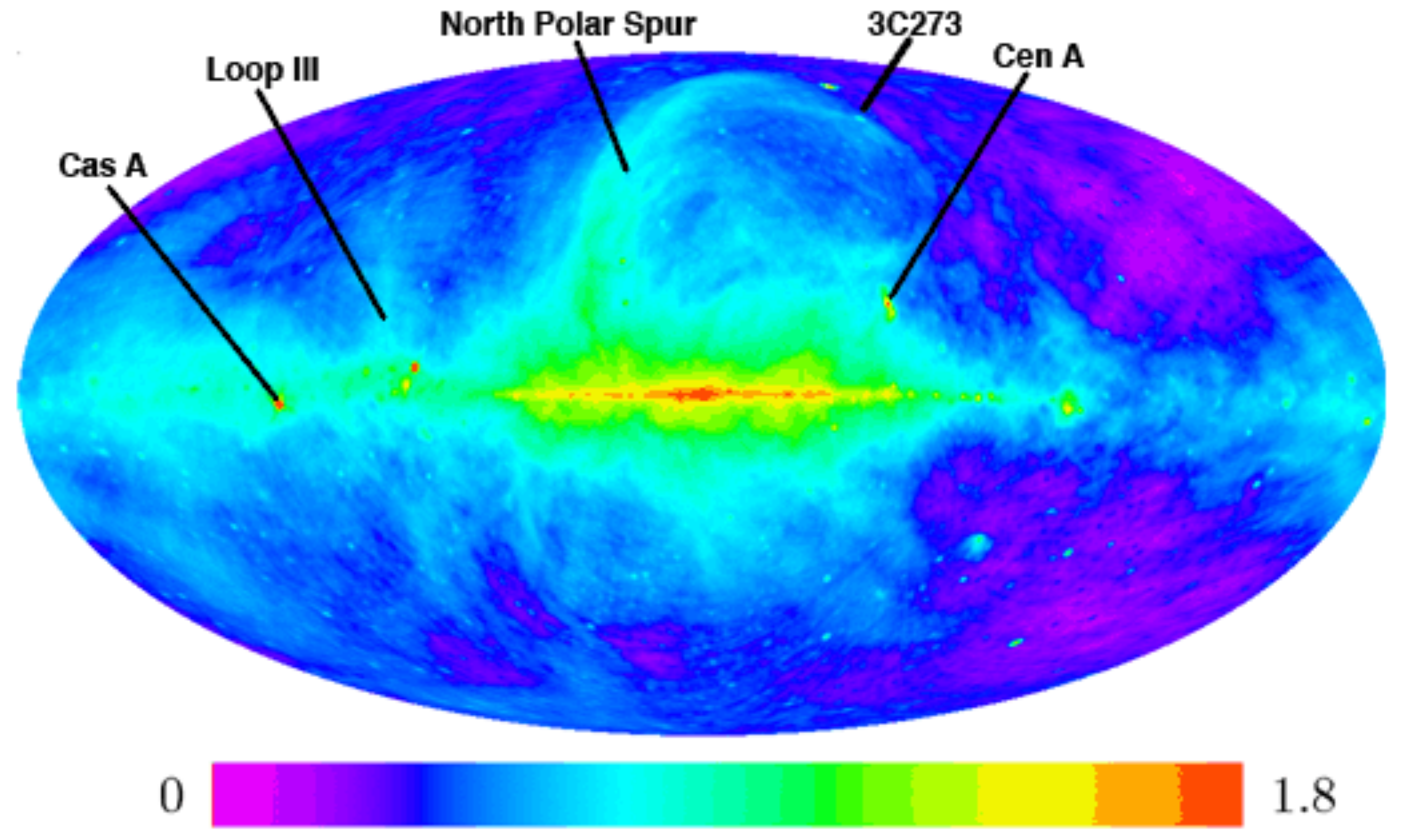
LOFAR 21-cm signal Detection Challenges

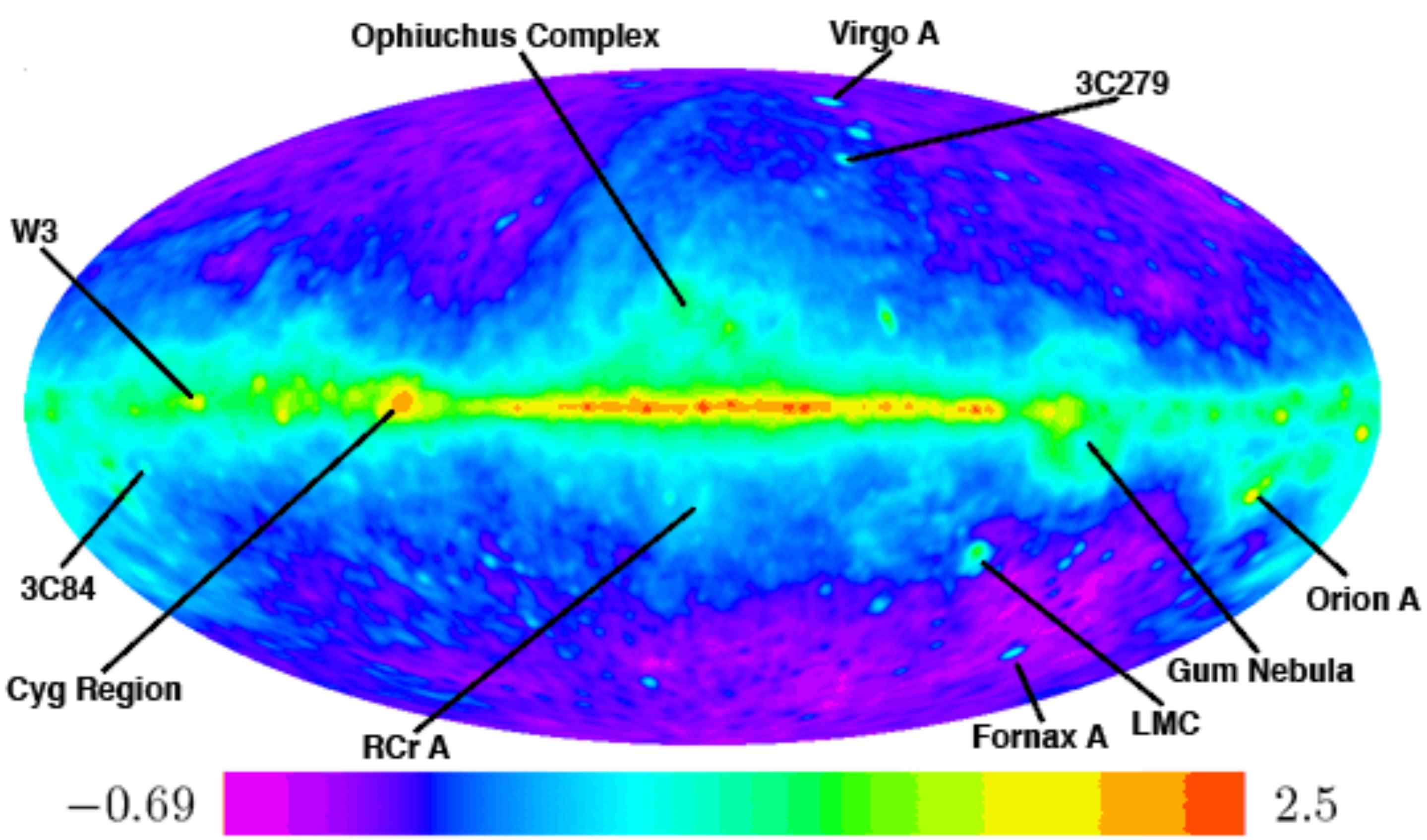
Detecting the CMB is hard, but detecting the 21-cm signal is even harder!!



Many Challenges

(Astro)physical	Instrumental	Computational
Extragalactic foregrounds	Beam stability	Large data rate
Galactic foregrounds	Sensitivity	~1 Pb raw data
Ionosphere	Dynamic Range	(Non)-linear optim. of coupled equations
Interference	UV Coverage	10s Tflop*year
Polarized emission	Calibratability	...
Variability	...	





Foregrounds

Main challenge

The radio sky is extremely bright (few x $10^{2\text{-}3}$ K):

- Diffuse (polarised) emission of the Milky Way
- Compact extra-galactic sources

The 21-cm signal is few x 10^{-3} K

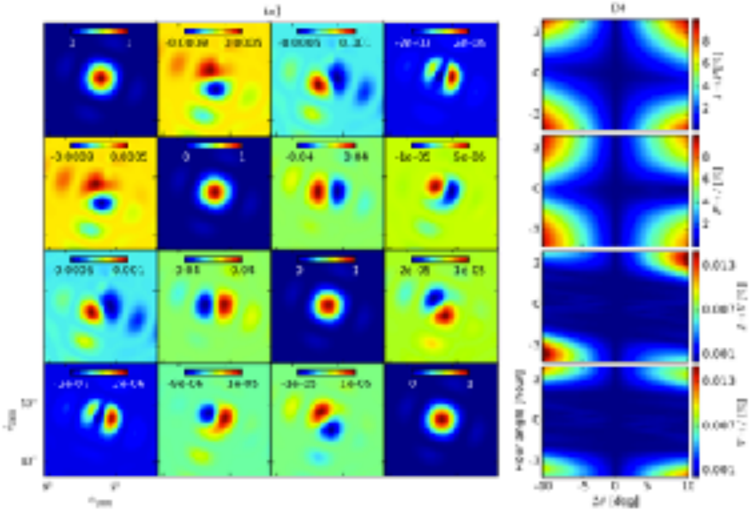
We need to remove the bright "foregrounds" from the 21-cm signal.

Luckily: Foreground are spectrally smooth, whereas the 21-cm signal fluctuates spectrally.

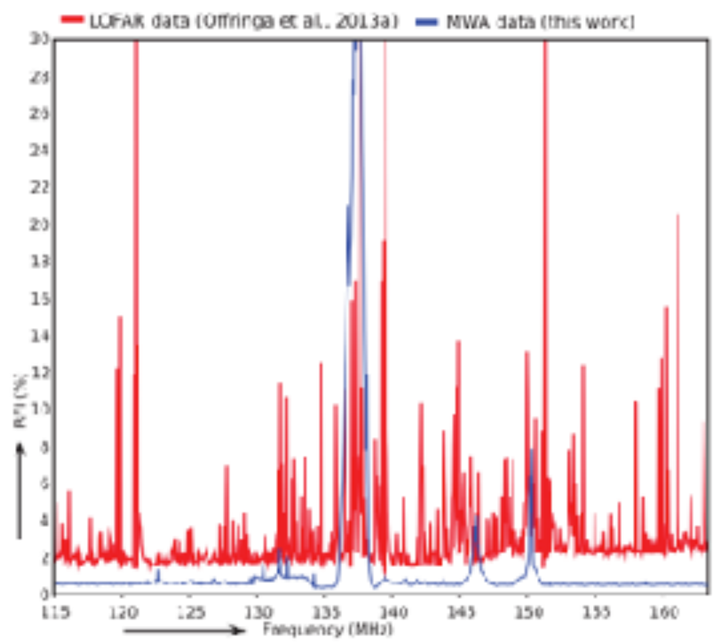
Many Other Challenges

- Ionospheric refraction/diffraction
- Radio Frequency Interference
- Beam/Band-pass calibration
- Polarisation leakage from Q/U <=> I

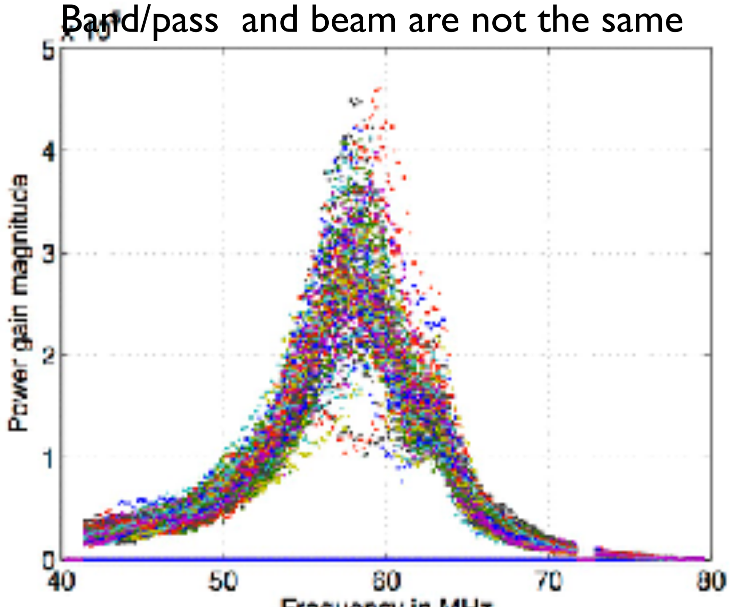
The instrument is polarised

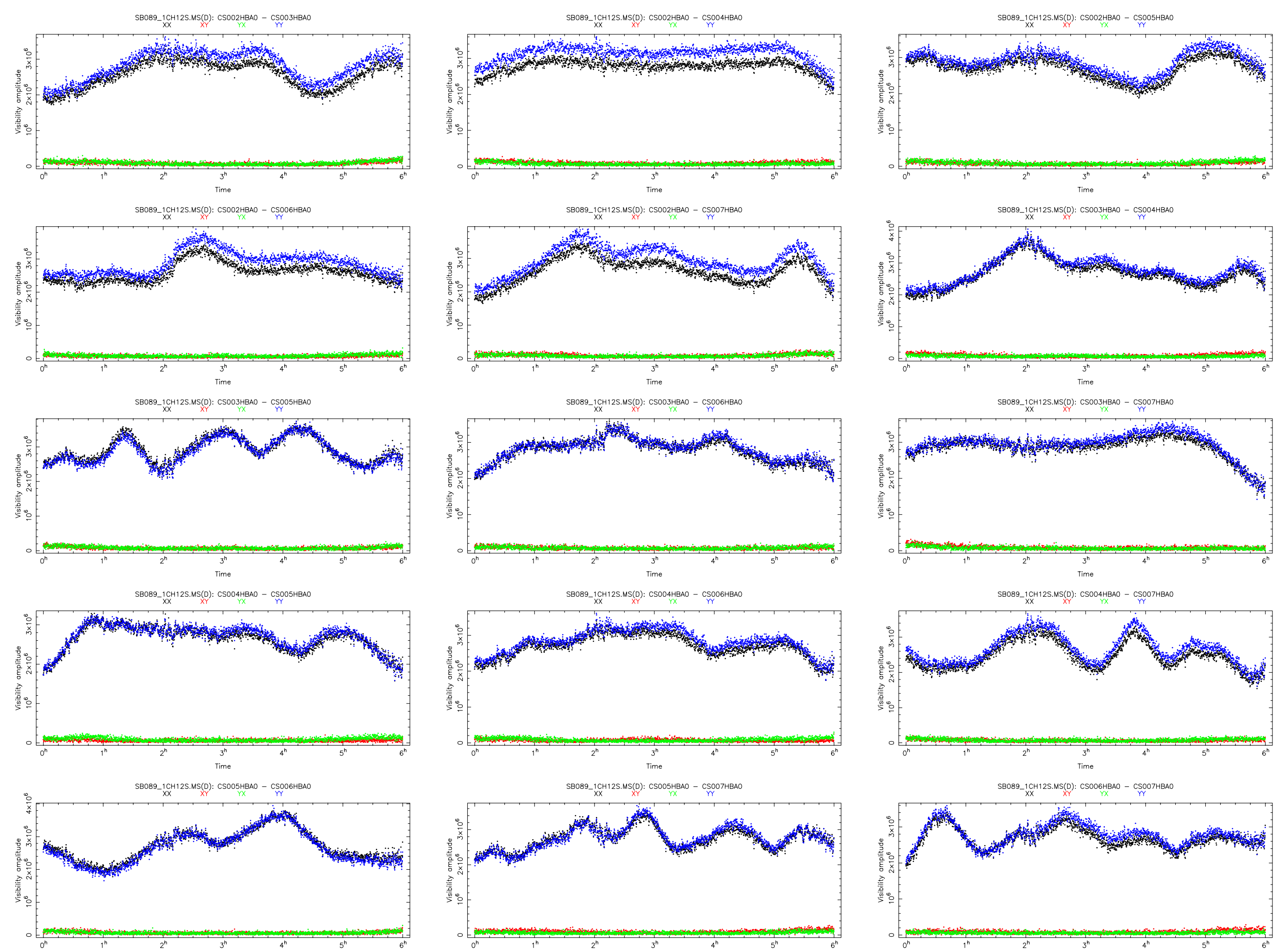


Even the best sites have RFI



Band/pass and beam are not the same

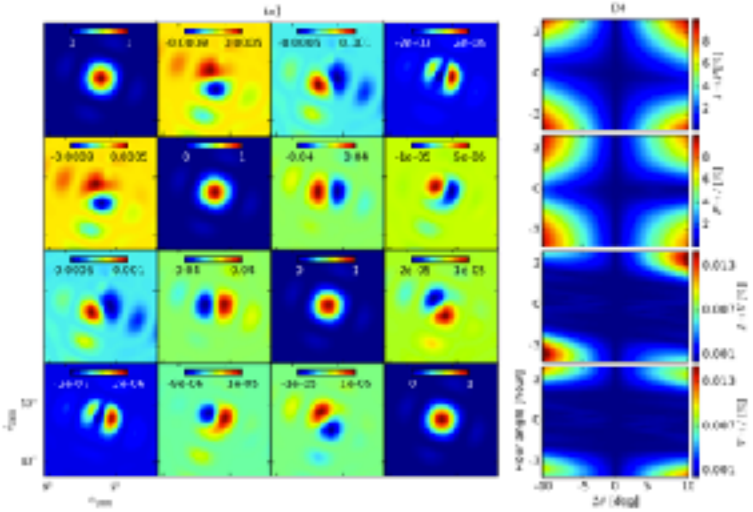




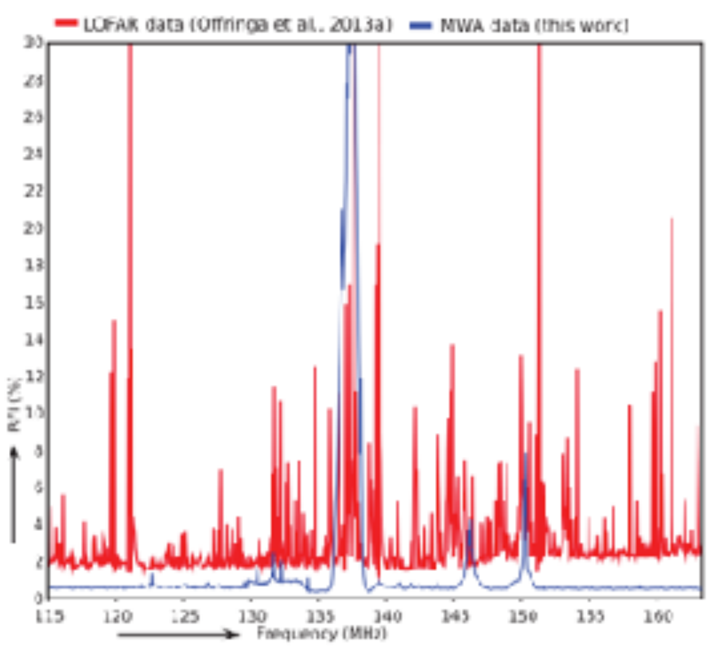
Many Other Challenges

- Ionospheric refraction/diffraction
- Radio Frequency Interference
- Beam/Band-pass calibration
- Polarisation leakage from Q/U <=> I

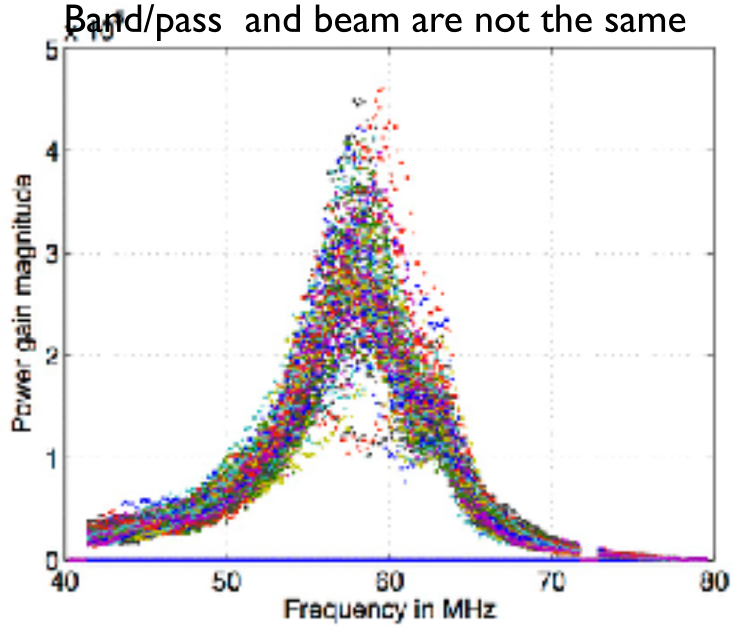
The instrument is polarised

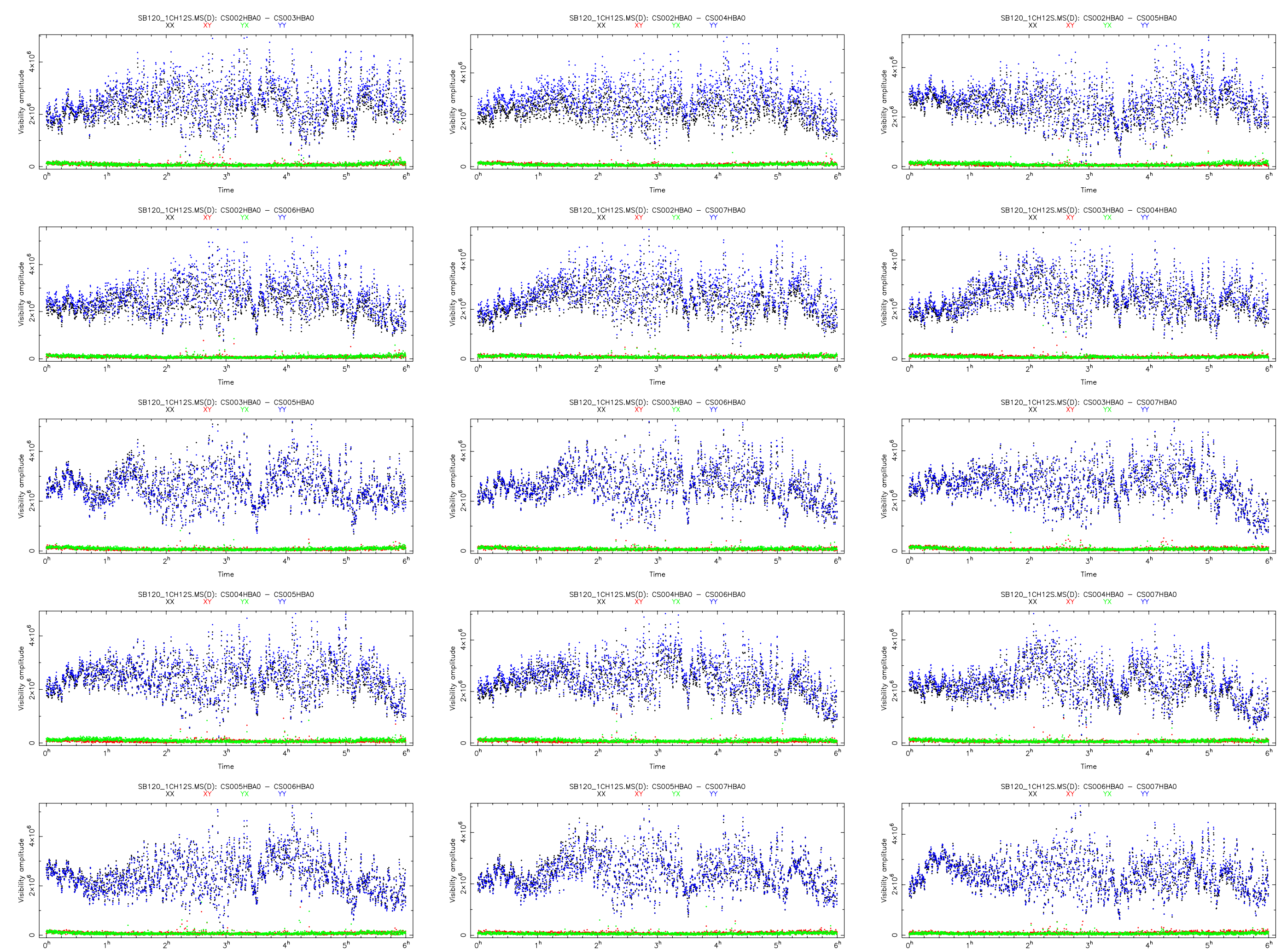


Even the best sites have RFI



Band/pass and beam are not the same

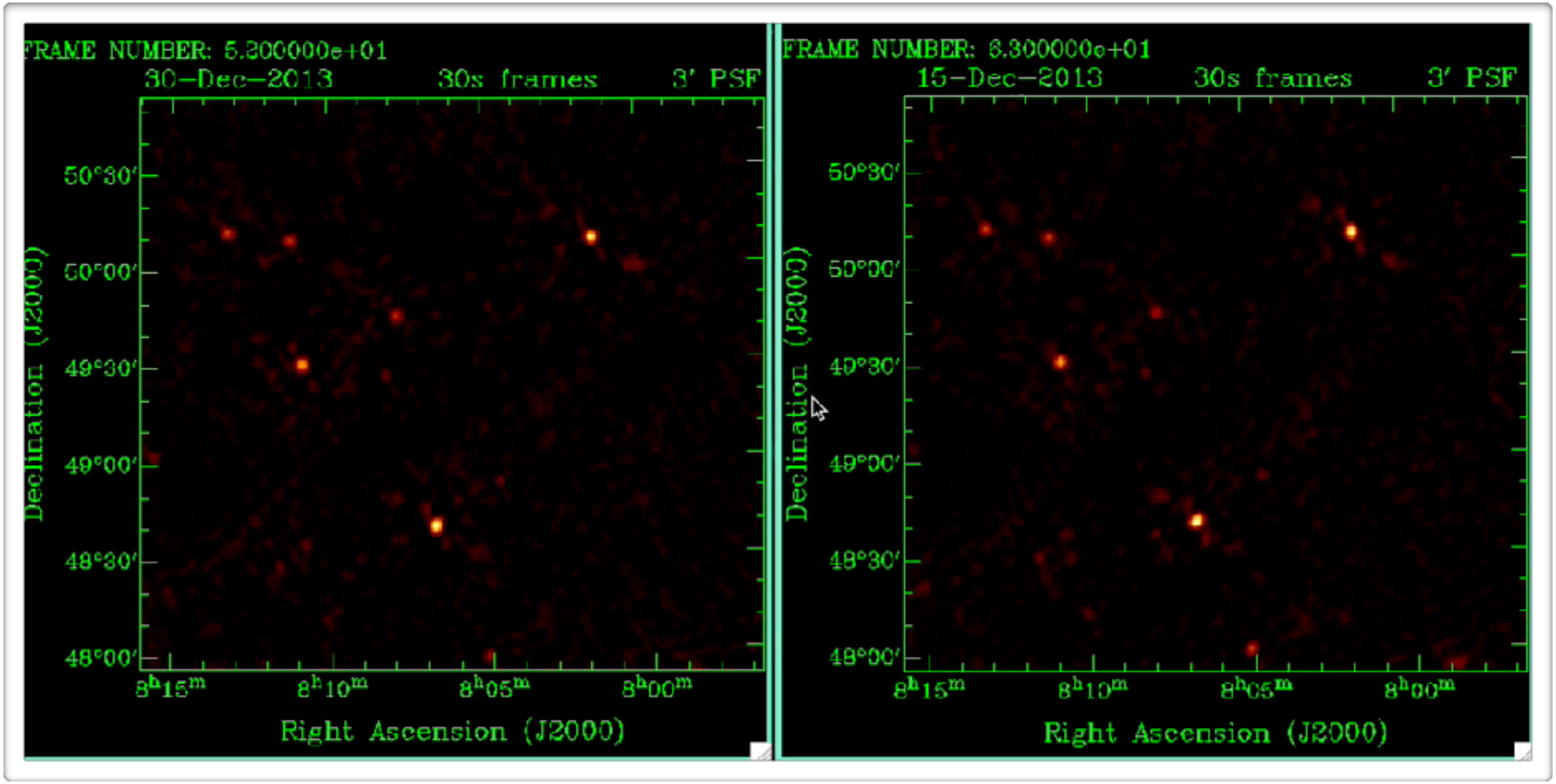




Ionospheric Effects: Refractive & Diffractive

The ionosphere causes direction-dependent distortions of the sky than need to be solved for on short timescales (DD-calibration)

Bad night 3x3 degrees Good night

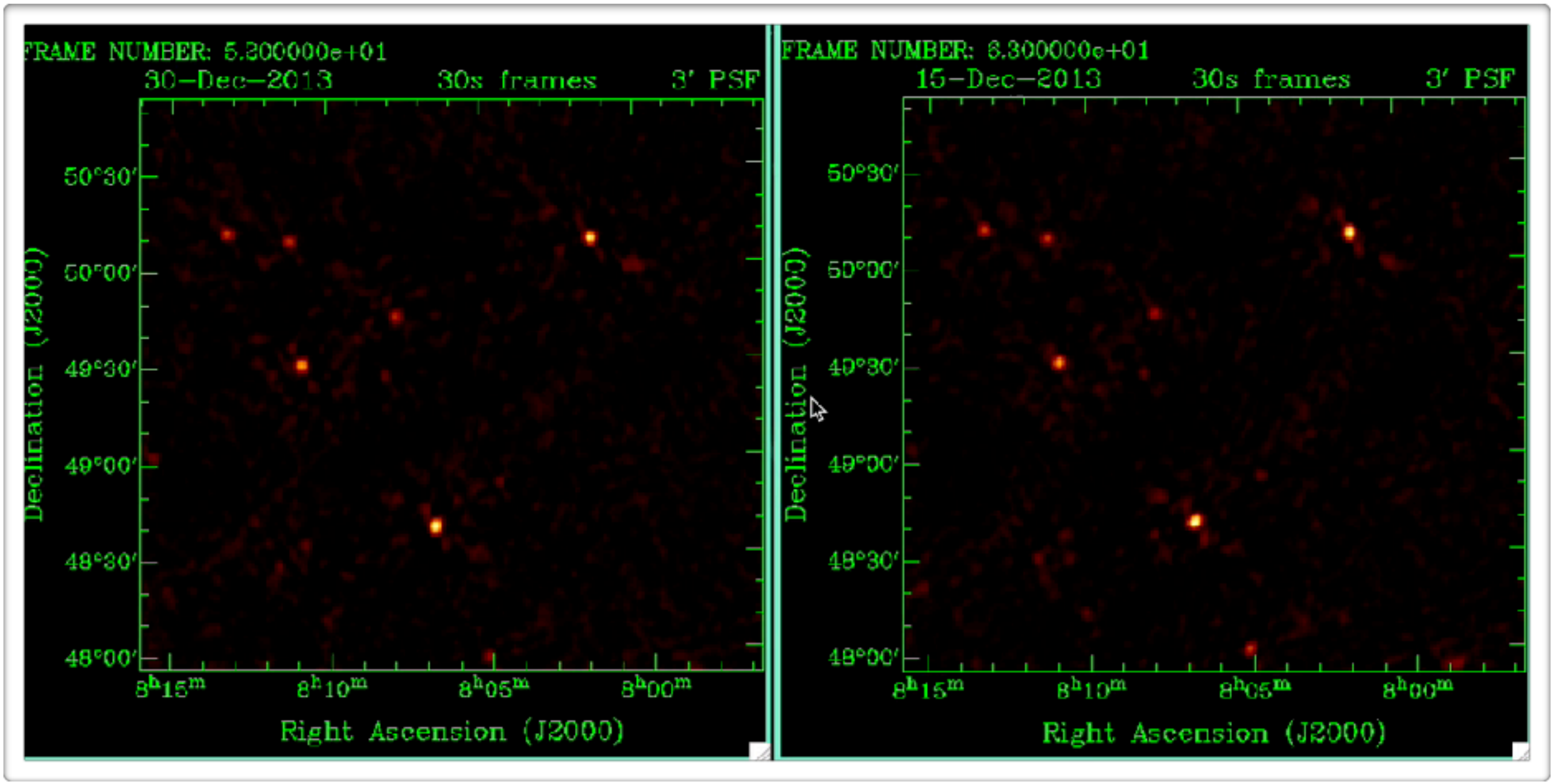


Credit: Ger de Bruyn

Ionospheric Effects: Refractive & Diffractive

The ionosphere causes direction-dependent distortions of the sky than need to be solved for on short timescales (DD-calibration)

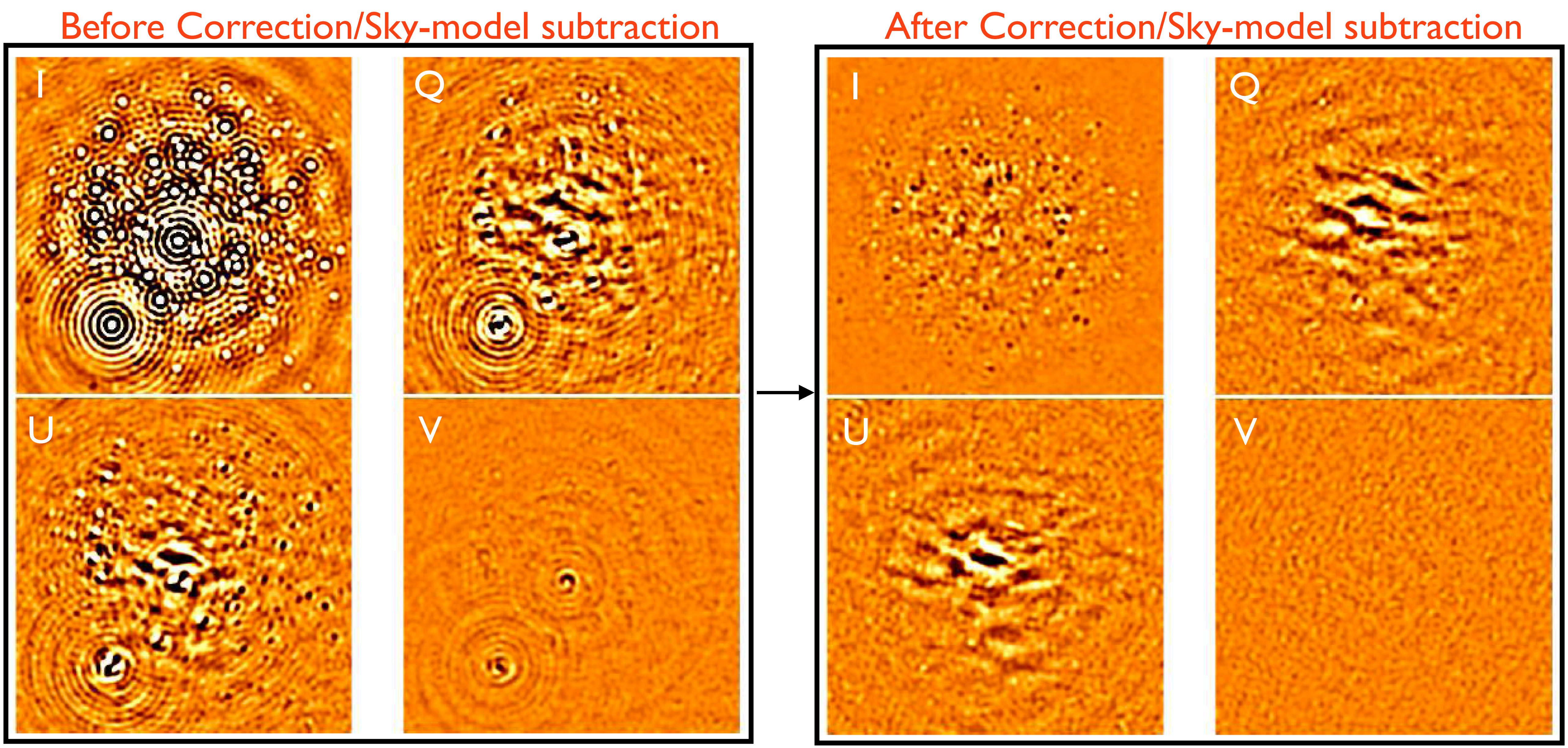
Bad night 3x3 degrees Good night



Credit: Ger de Bruyn

Correction for Image Distortions

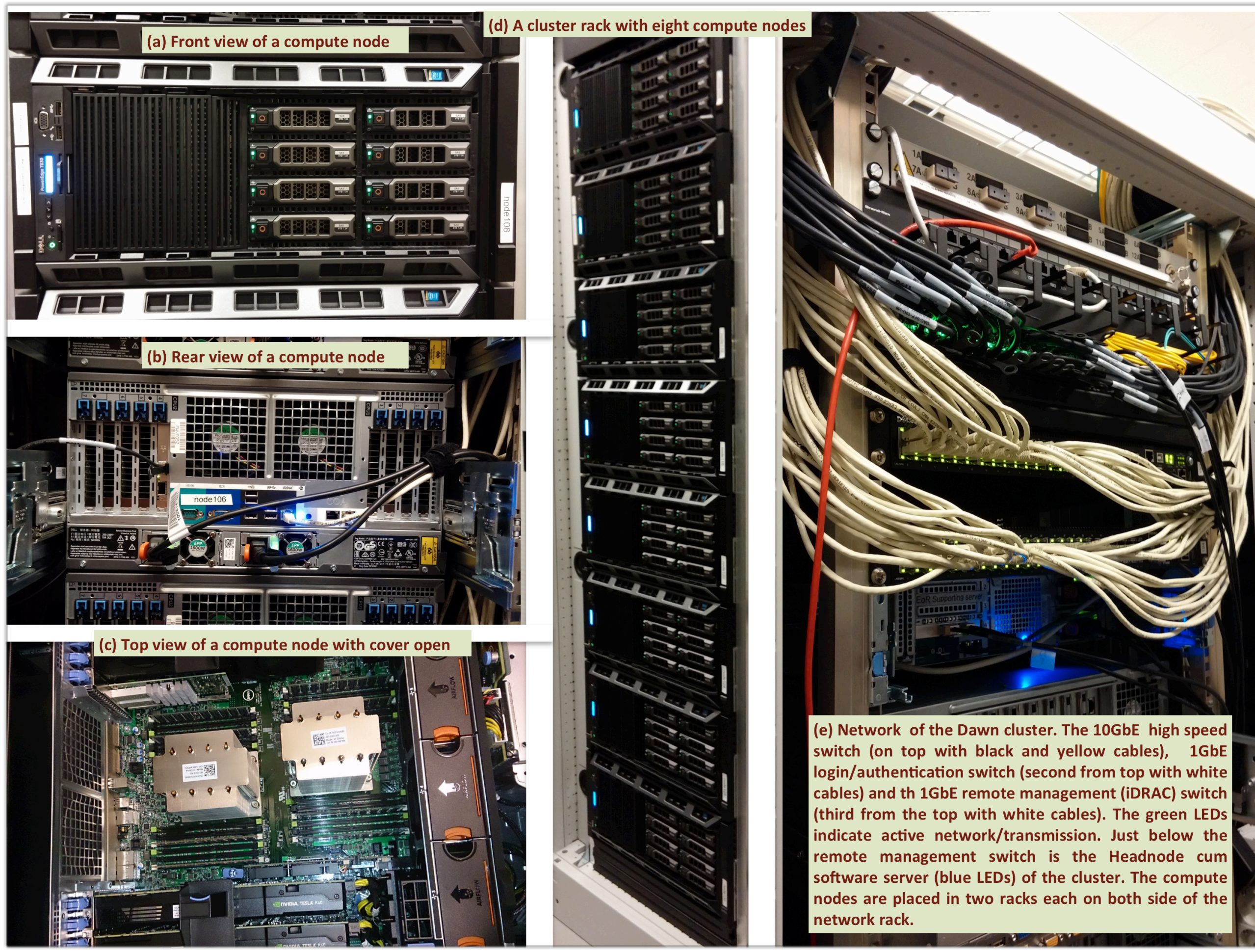
Telescope beam errors are also direction dependent (but vary slower in time) and need to be accounted for in the data calibration.



(Calibration/Imaging: >250λ/<250λ baselines)

Credit: Sarod Yatawatta

LOFAR EoR-KSP GPU HPC Cluster: *"Dawn"*

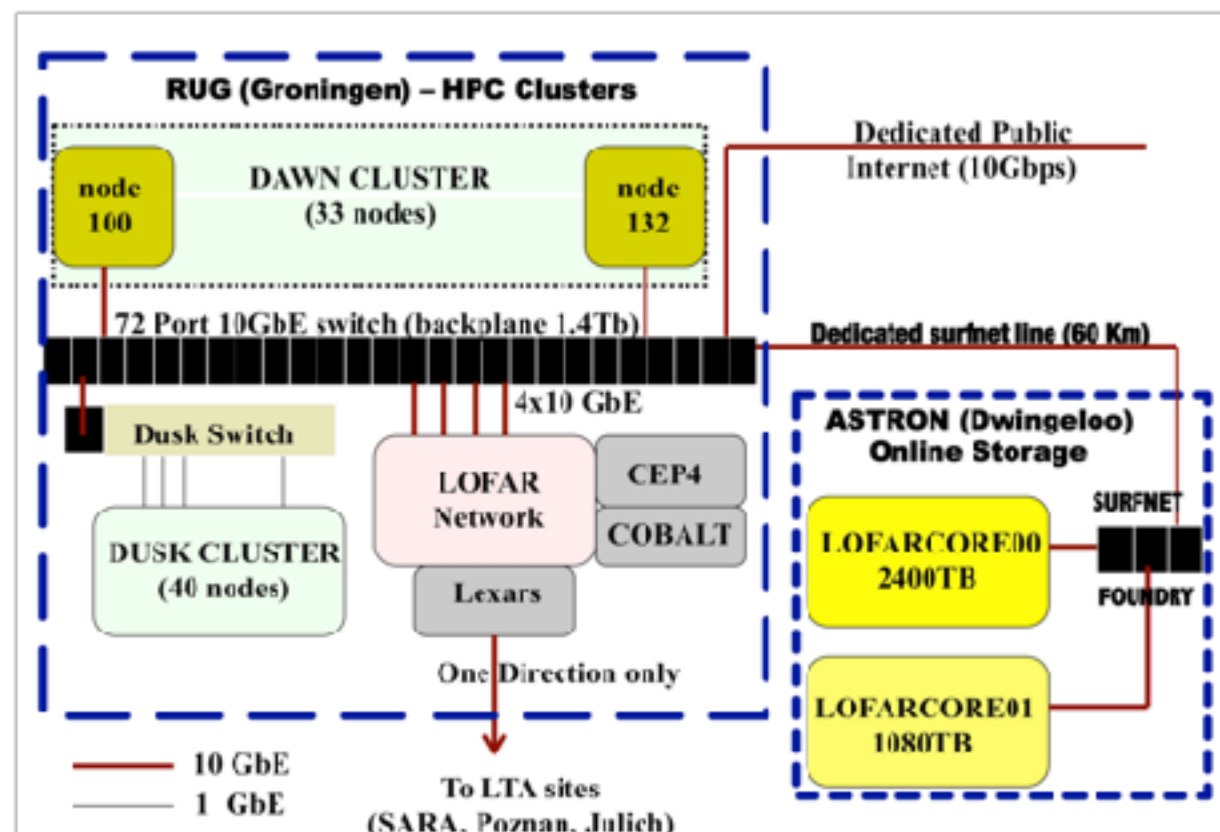


32 nodes in four 19" racks

32x4 GPU (K40)
32x48 (HT) cores

0.6/0.2 Petaflops in GPU power

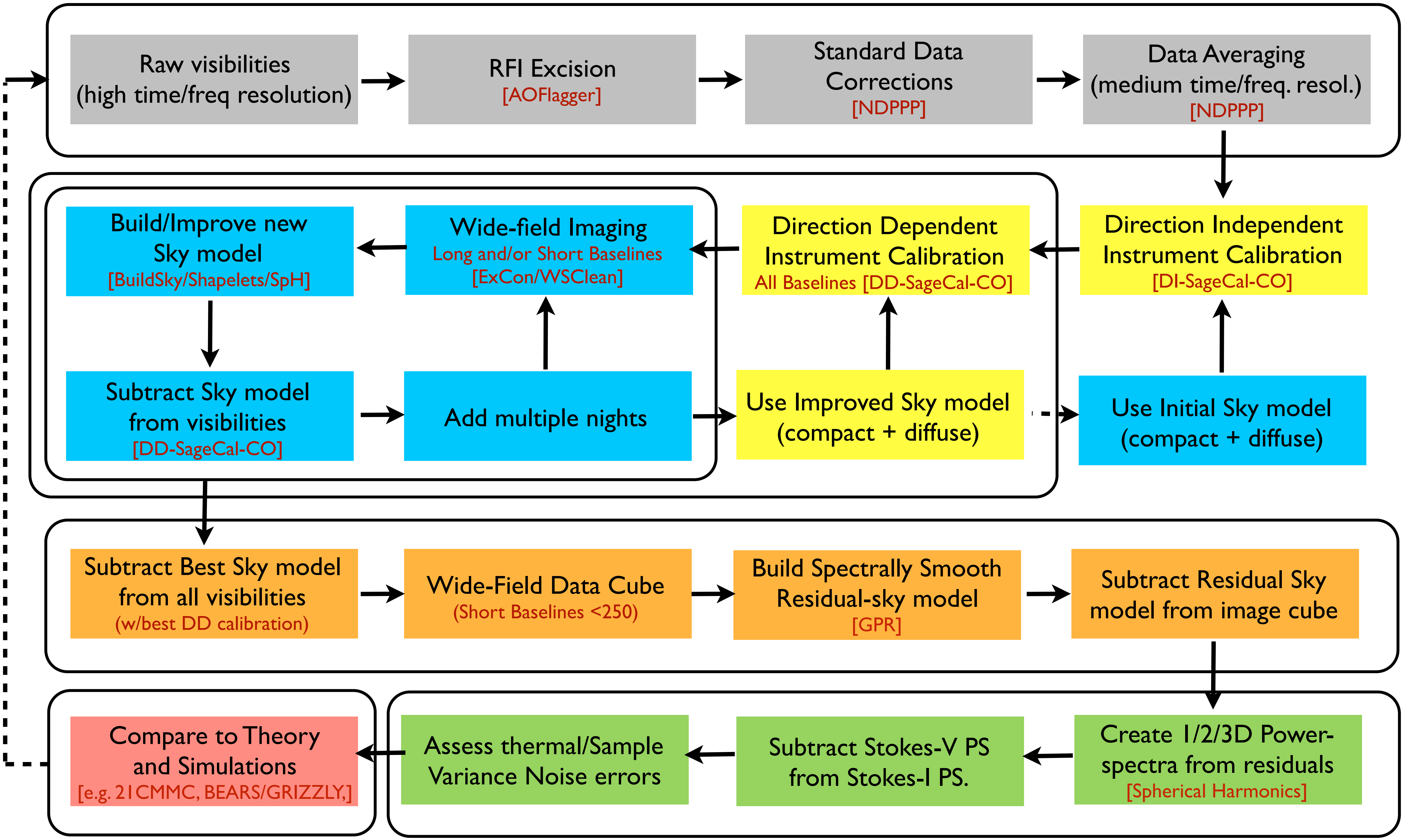
Hard-core number crunching on a dedicated GPU-based cluster in Groningen.



Cluster is connected to storage clusters and external world via 1-10Gb/s connections.

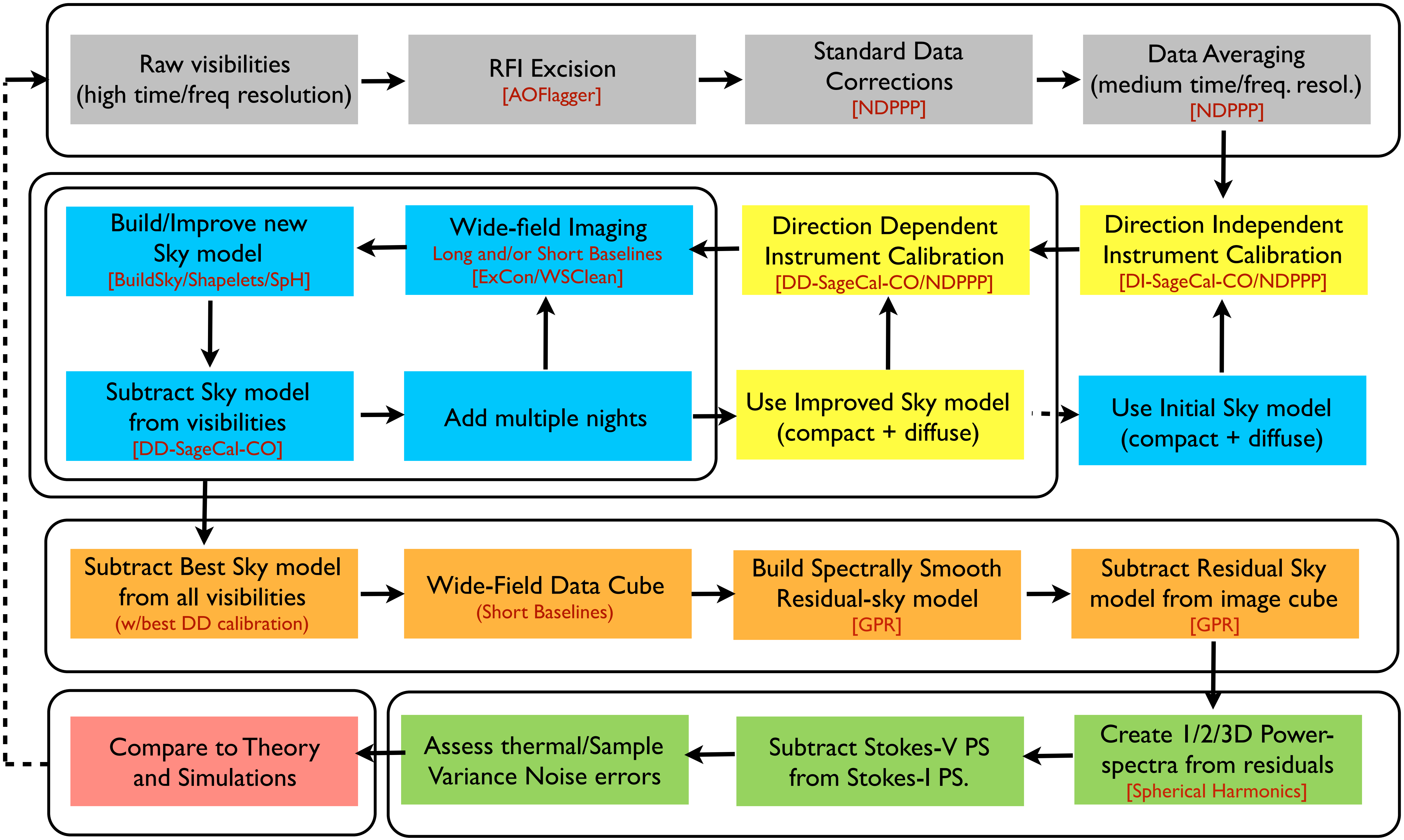
LOFAR EoR Data-Processing Flow Diagram

Nearly all processing software has been developed in house by our team.



LOFAR EoR Data-Processing Flow Diagram

Nearly all processing software has been developed in house by our team.



rijksuniversiteit groningen

faculteit wiskunde en natuurwetenschappen

kapteyn instituut

LOFAR EoR Upper Limits on the 21-cm Power-Spectrum during Reionization

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

A.H. Patil[1], S. Yatawatta[1,2], L.V.E. Koopmans[1], A.G. de Bruyn[2,1], M. A. Brentjens[2], S. Zaroubi[1,11], K. M. B. Asad[1], M. Hatef[1], V. Jelić[1,8,2], M. Mevius[1,2], A. R. Offringa[2], V.N. Pandey[1], H. Vedantham[9,1], F. B. Abdalla[7,13], W. N. Brouw[1], E. Chapman[7], B. Ciardi[4], B. K. Gehlot[1], A. Ghosh[1], G. Harker[3,7,1], I. T. Iliev[10], K. Kakiichi[4], S. Majumdar[12], M. B. Silva[1], G. Mellema[5], J. Schaye[6], D. Vrbanec[4], S. J. Wijnholds[2]

MWSKY-II, Pune, India - March 20, 2019

Primary EoR Window: North Celestial Pole

- Night-time observing, elevation > 50°
- Frequency range 115-190 MHz (Cycle 6: 2-3 beams x 32MHz; Cycle 8-9: 7 beams x 12 MHz on NCP→“Fast track”)
- Time/spectral resolution: 2s, 3.2kHz
- Raw data volume: 20 - 70 TB / night

Currently 1^{st} stage processing ongoing
(RFI flagging, averaging, initial calibration, imaging)

✓ ~2200 hrs on NCP
✓ ~1100 hrs on 3C196
✓ ~300+hrs out of 1000 hrs awarded on NCP with AARTFAAC/LBA

>5 PB on disk

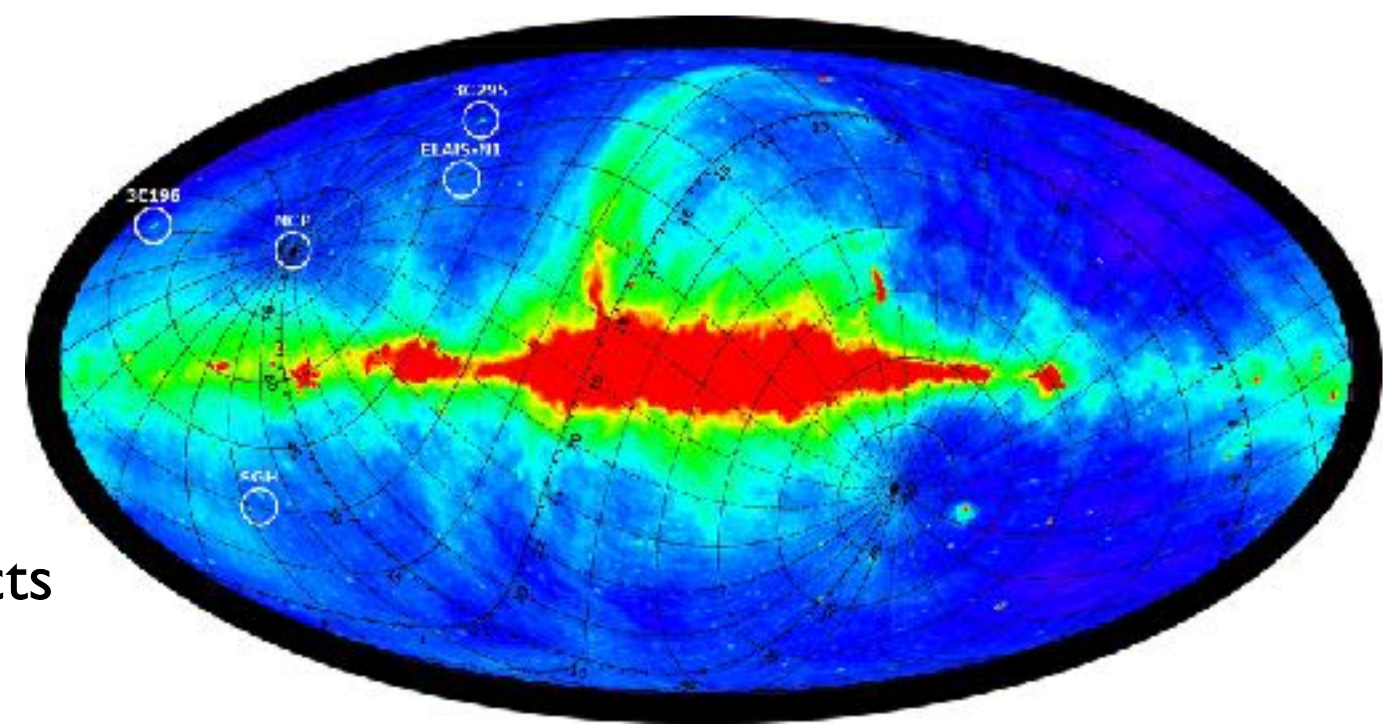
- NCP: constant beam, all-year observable
- 3C196: bright, compact, wintertime

- 2-3 other windows for various other projects

LOFAR spectral capabilities:

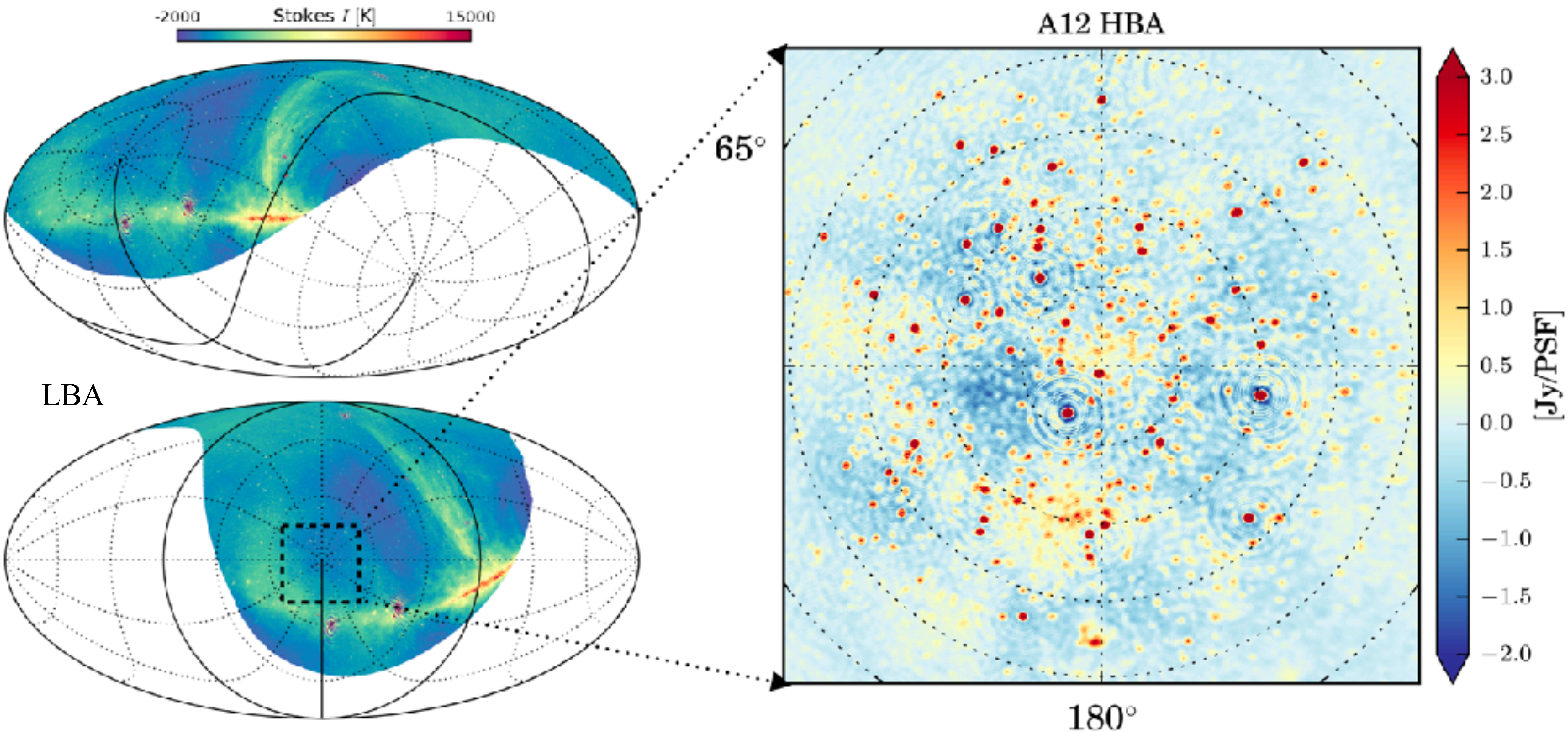
- 8-bit mode 488 sub-bands
- 1sub-band = 0.195 MHz
- 96 MHz total bandwidth

One sub-band can have up to 256 ch. We opted to store 64 ch. max. We analyse 3-ch. data (~60kHz).



Primary EoR Window: North Celestial Pole

A complex field made of compact & extended (extra-galactic) sources and diffuse emission from the Galaxy (in Stokes I, Q, U)



A recent wide-field view of the the NCP with LOFAR AARTFAAC-LBA- & HBA-12 system

Image credit: Bharat Gehlot & Florent Mertens

Primary EoR Window: North Celestial Pole

Diffuse Emission:

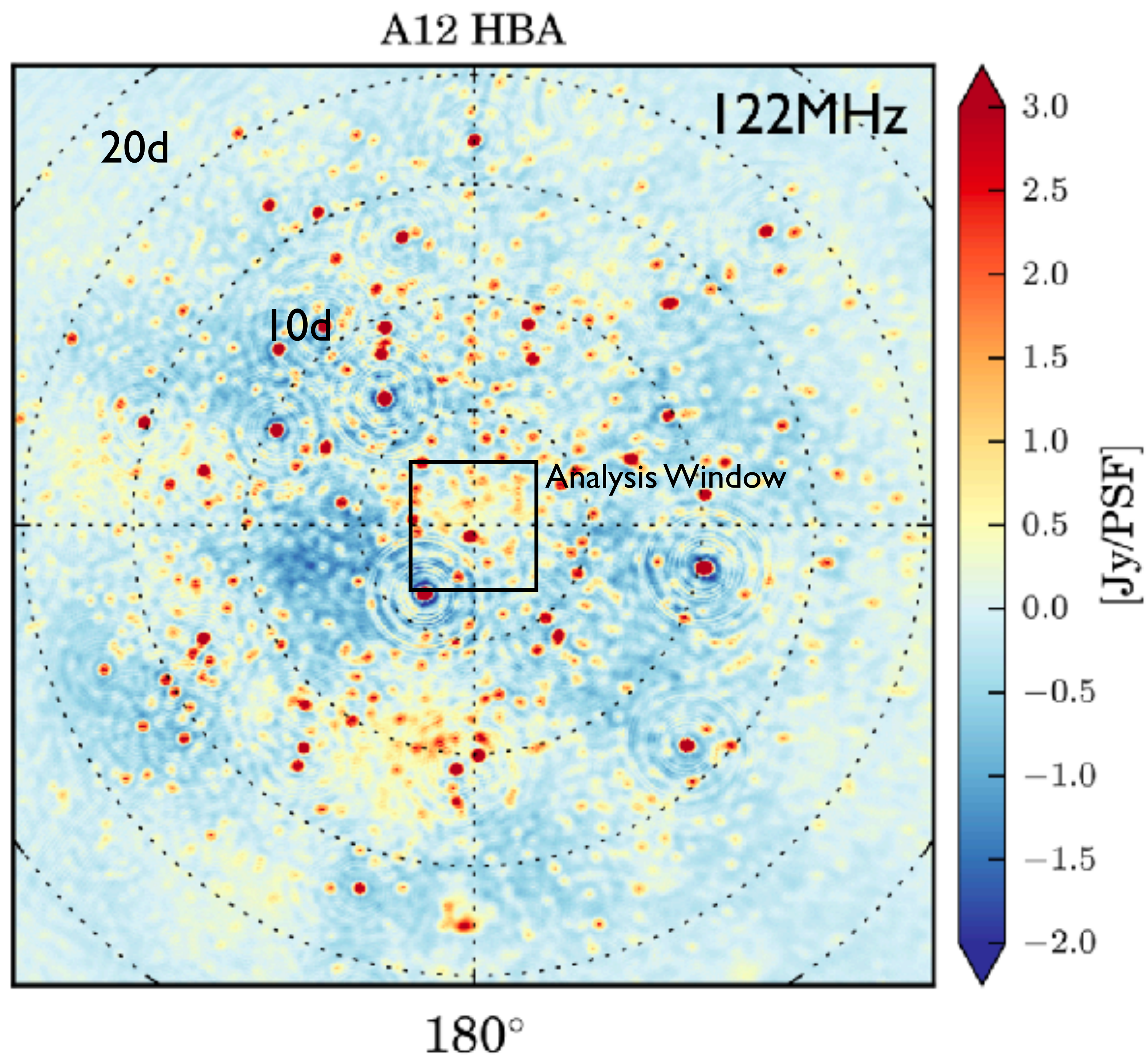
Observations with LOFAR-AARTFAAC-HBA-12 @ 122MHz.

Cross-correlating all 576 tiles. Baselines >5λ.

Only DI-calibration on CasA/CygA, which are subtracted, as are all compact sources (CLEAN).

This diffuse emission is why we calibrate on >250λ baselines. If not, calibration will be biased and signal will be subpressed.

Image credit: Bharat Gehlot



Primary EoR Window: North Celestial Pole

Diffuse Emission:

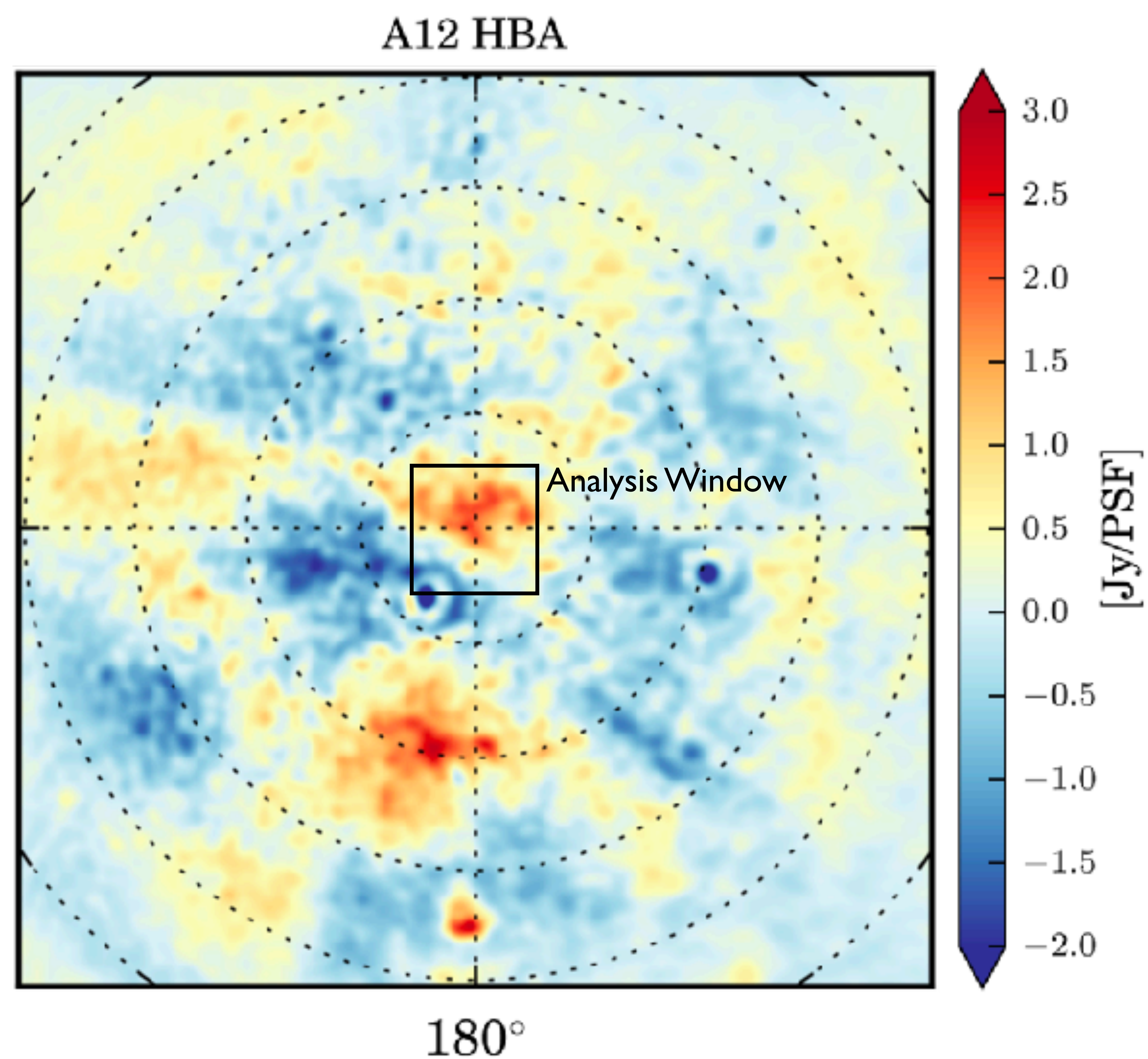
Observations with LOFAR-AARTFAAC-HBA-12 @ 122MHz.

Cross-correlating all 576 tiles. Baselines >5λ.

Only DI-calibration on CasA/CygA, which are subtracted, as are all compact sources (CLEAN).

This diffuse emission is why we calibrate on >250λ baselines. If not, calibration will be biased and signal will be subpressed.

Image credit: Bharat Gehlot



Primary EoR Window: North Celestial Pole

Compact Sources:

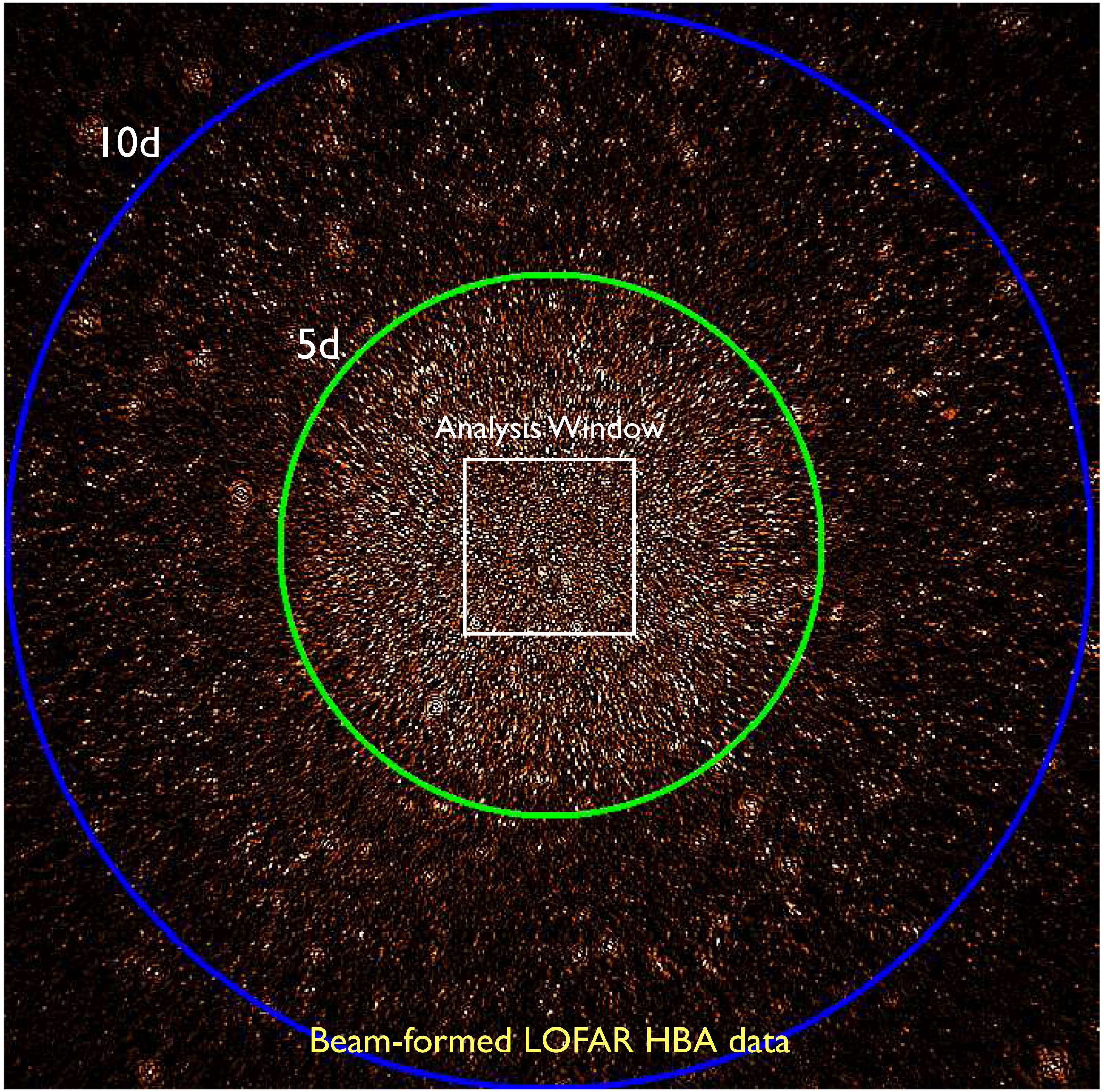
- BW=60 MHz
- 20° x 20° ; 3' FWHM PSF

Note that this image is the sky residual: 28,000 bright sources are removed after calibration in 122 directions for each station and frequency channel, for each ~20 min time interval.

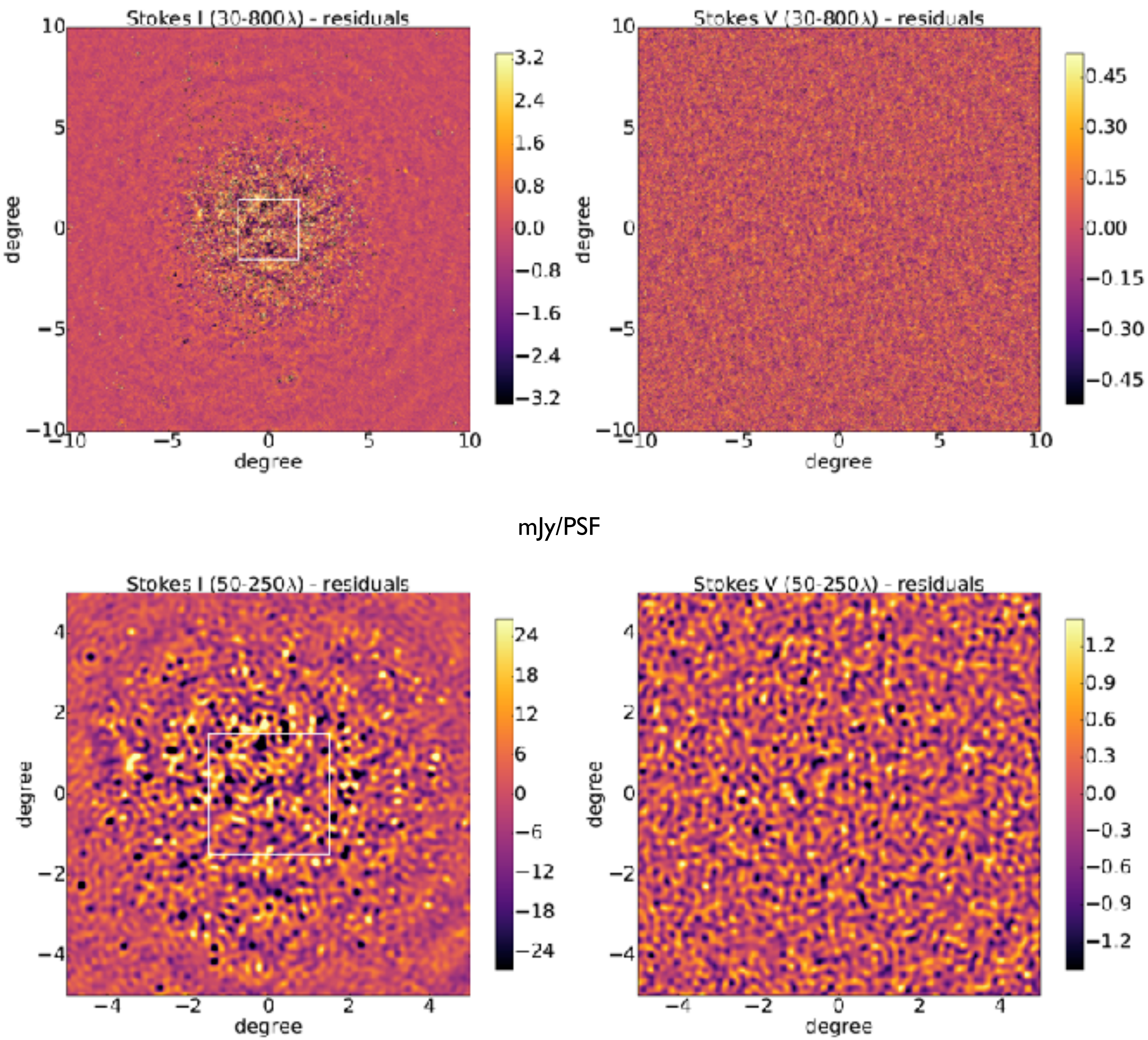
All of this emission, should be spectrally smooth, otherwise one would not be able to detect the EoR 21-cm signal.

Image credit: V. Pandey

Confusion limited image of the NCP



NCP — Residuals after Sky-Model Subtraction



Top images shows 20x20d FoV in Stokes I (left) and V (right) with 3’ resolution.

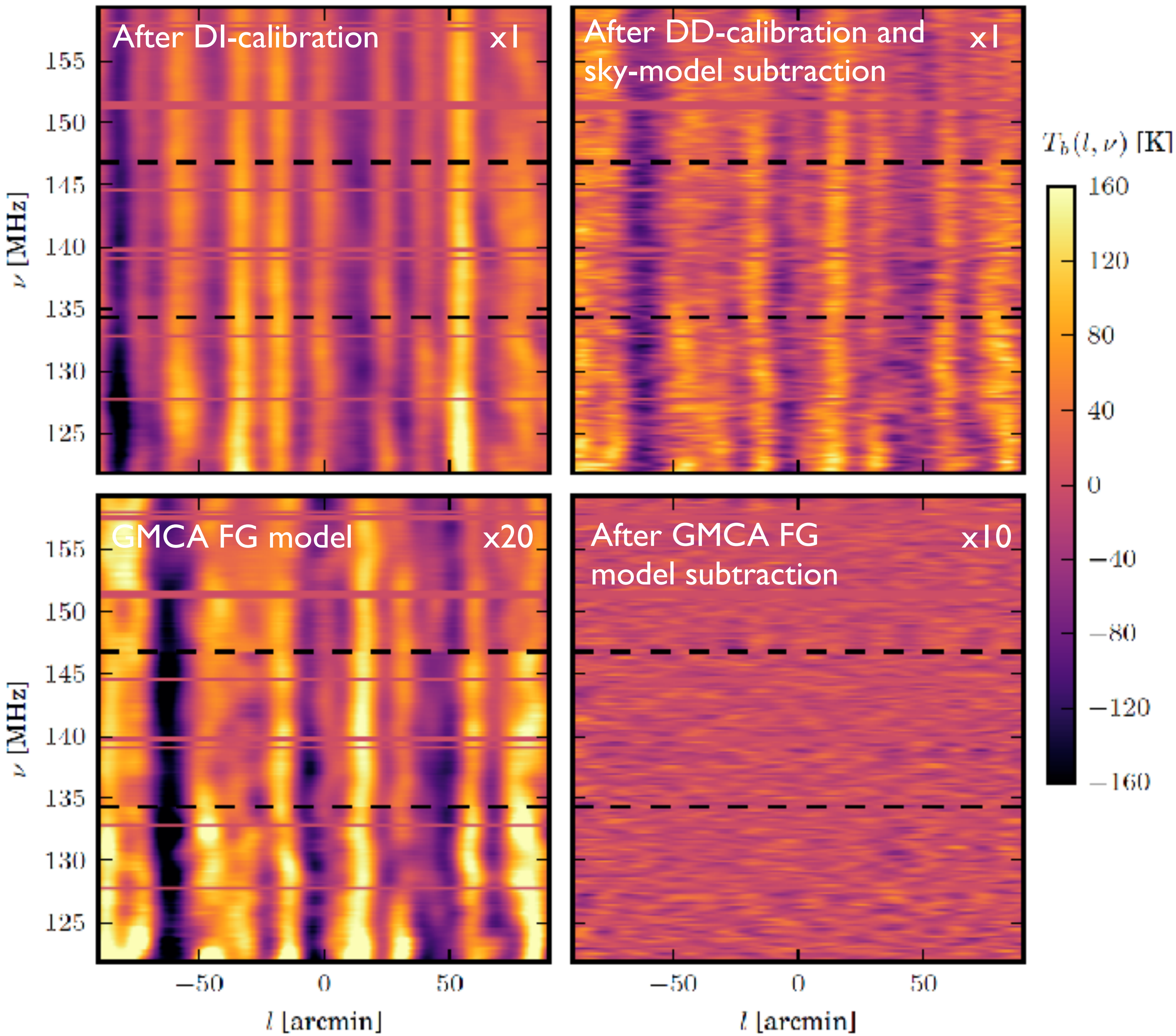
Stokes I shows the primary beam and is confusion limited; Stokes V is consistent with thermal noise to within ~5%.

White box in top of primary beam: region being analysed for power-spectrum

Bottom images shows 10x10d FoV in Stokes I (left) and V (right) with 10’ resolution.

Patil et al. (2017, ApJ)

NCP — Residuals after Sky-Model Subtraction



Slice (3°) trough the cube in one spatial direction and frequency (note scaling in brightness for some panels).

Note the resemblance between GMCA model (Chapman et al. 2013) and data after DD calibration.

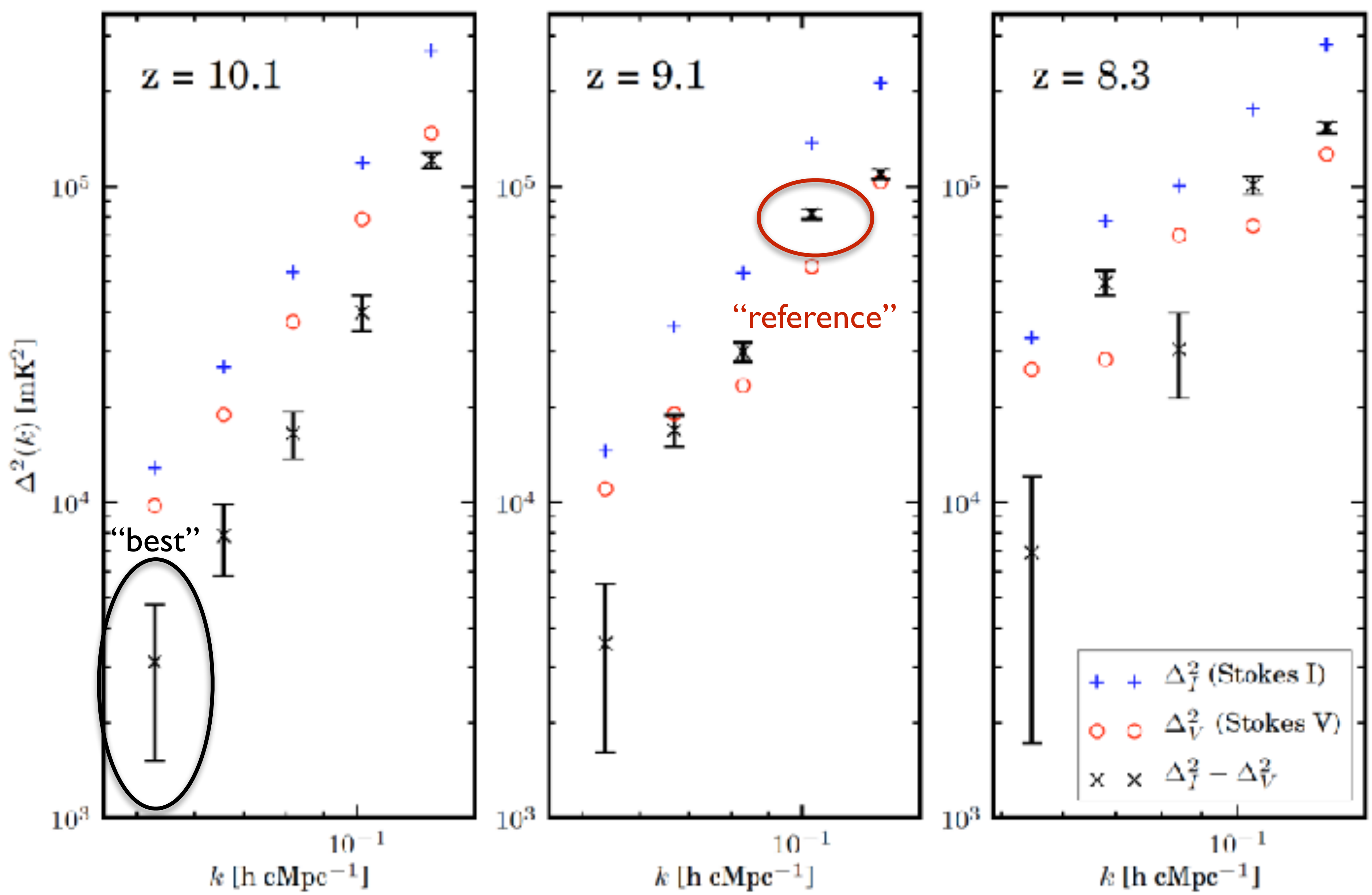
Dashed lines are the three redshift ranges: z=7.9-8.7, 8.7-9.6, 9.6-10.6

Patil et al. (2017, ApJ)

NCP — Power Spectra Results

Currently these are the deepest 21-cm power spectrum limits of all 21-cm signal experiments but still far away (factor ~$10^{3\text{-}4}$) from a detection of the signal.

Averaging spherically provides the lowest errors (maximum # of samples per shell).



Patil et al. (2017, ApJ)

rijksuniversiteit groningen / faculteit wiskunde en natuurwetenschappen / kapteyn instituut

LOFAR EoR — New Results from 10 Nights of Data

Where do we stand at the moment and what has kept us busy?

MWSKY-II, Pune, India - March 20, 2019

Our 2017-2018 Roadmap

Improve calibration

- Remove/reduce "excess variance" (3-4x thermal variance).
- Improve the sky/calibration model further reducing gain errors transferred to shorter baselines; Improve DD calibration; Improve beam-model
- Include diffuse emission from Stokes, Q, U and possible I to enable including short baselines in calibration (currently not possible)
- Improve diffuse FG subtraction via various methods (e.g. above).
- Use cross-variance methods to avoid the noise bias in PS analysis.
- Improve cross-correlation of gain solutions with various metrics to gain insight.

Improve sensitivity

- If OK, include previously flagged short (30-60 lambda) baselines that have very high PS sensitivity (~10x deeper at k~0.03, vs k~0.05 at the moment).
- Analyse and combine more of the data (1➟10➟100 nights, rather than ~1 night).

Second window/more data

- Add second field to the processing/results: 3C196
- Keep collecting data (~3000hr total)

Calibration — 21-cm Signal Suppression

The bias-variance trade-off in calibration and foreground removal is critical

Direction Dependent Calibration

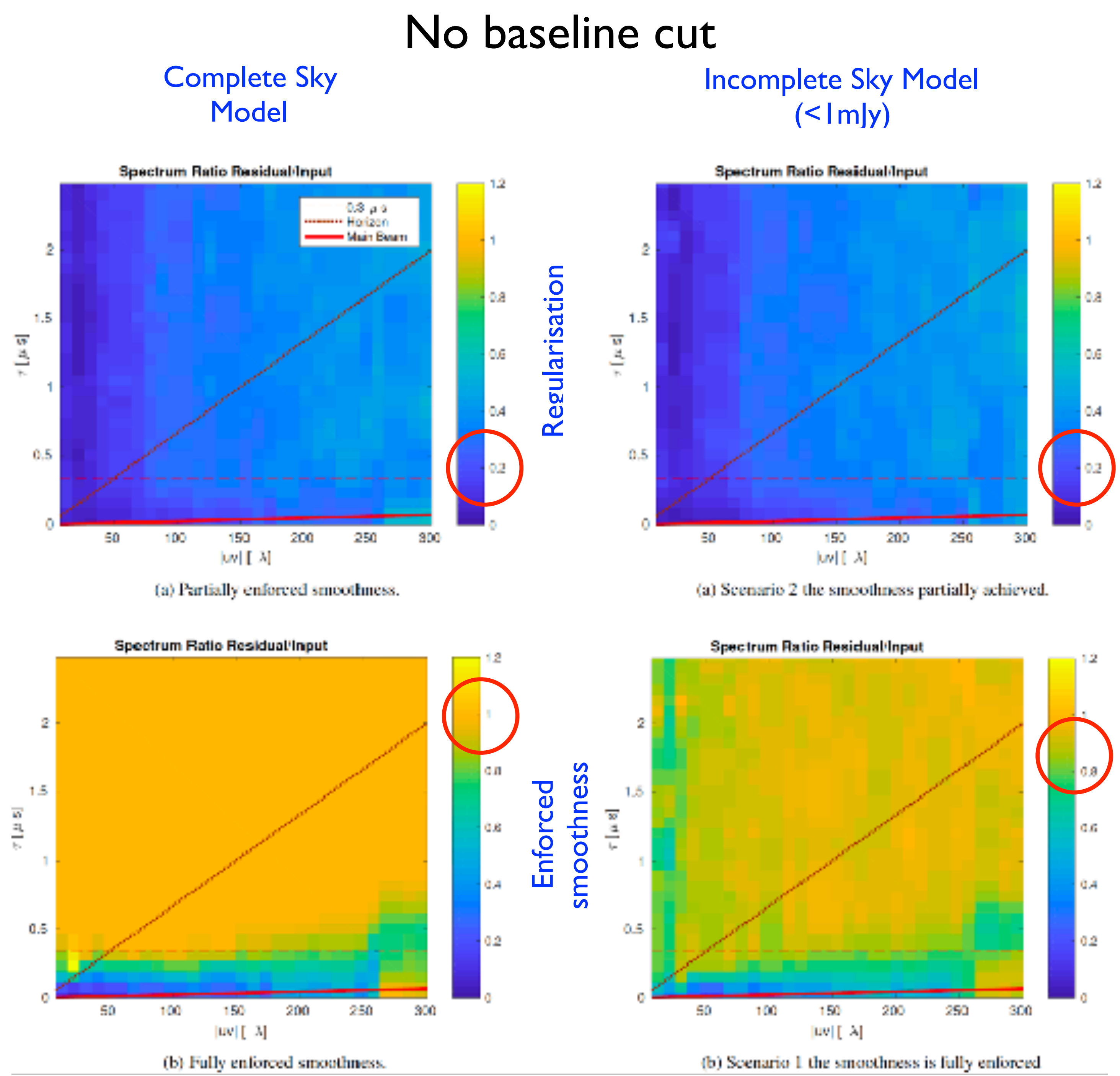
Gains can absorb diffuse emission including the 21-cm signal !!

This causes:

a. *Signal suppression* if the gain solutions are not spectrally smooth.
b. *Excess noise* if the sky model is incomplete.

Two solutions:

1. Optimal: Enforce spectrally smooth (>3MHz) gains.
2. Cheap: Introduce a baseline cut — no bias, but excess noise.



Sardarabadi & Koopmans, 2018; Mevius et al. in prep.

Calibration — 21-cm Signal Suppression

The bias-variance trade-off in calibration and foreground removal is critical

Direction Dependent Calibration

Gains can absorb diffuse emission including the 21-cm signal !!

This causes:

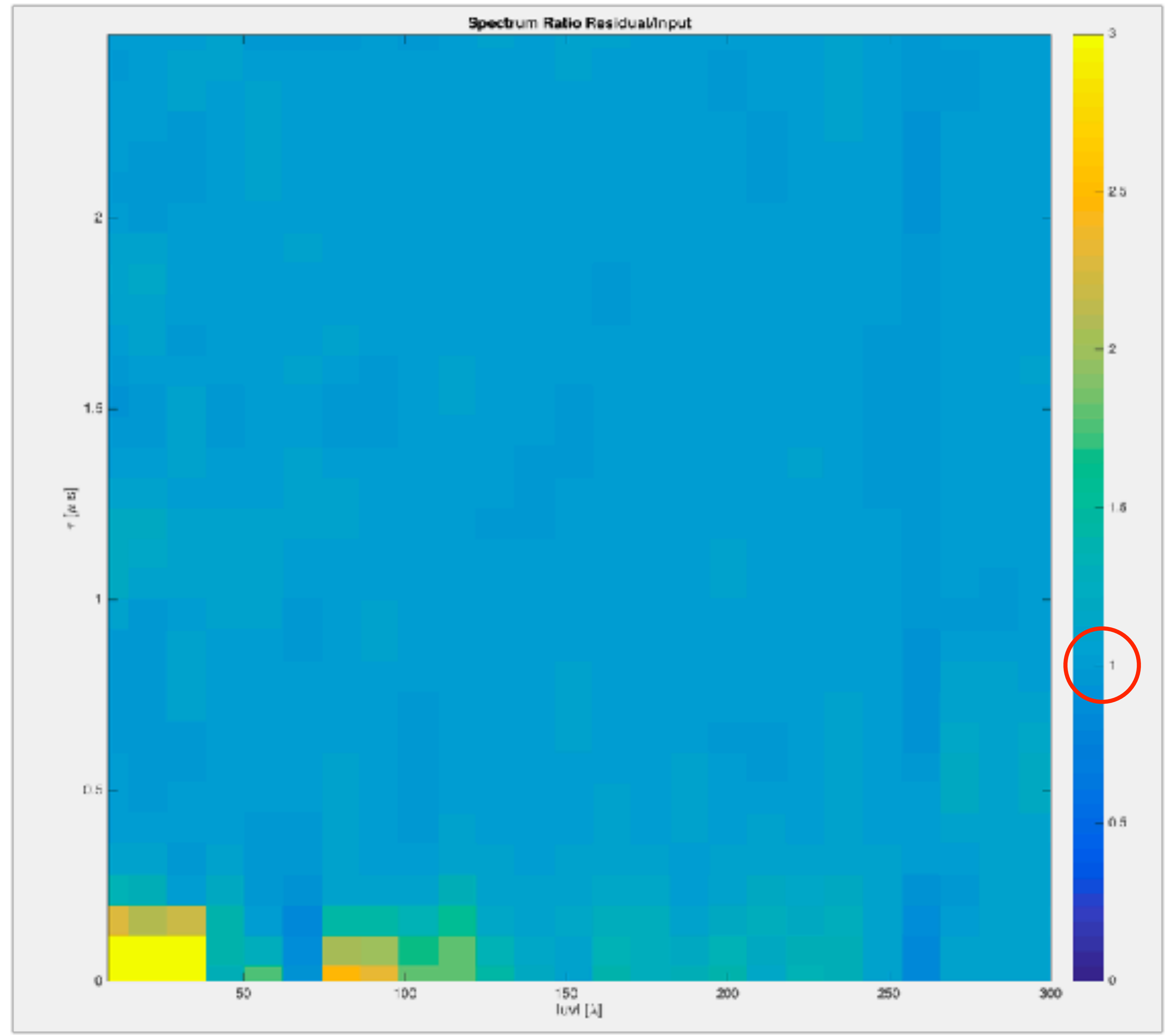
a. *Signal suppression* if the gain solutions are not spectrally smooth.
b. *Excess noise* if the sky model is incomplete.

Two solutions:

1. Optimal: Enforce spectrally smooth (>3MHz) gains.
2. Cheap: Introduce a baseline cut — no bias, but excess noise.

Sardarabadi & Koopmans, 2018; Mevius et al. in prep.

Regularisation but now with baseline cut & incomplete sky model.



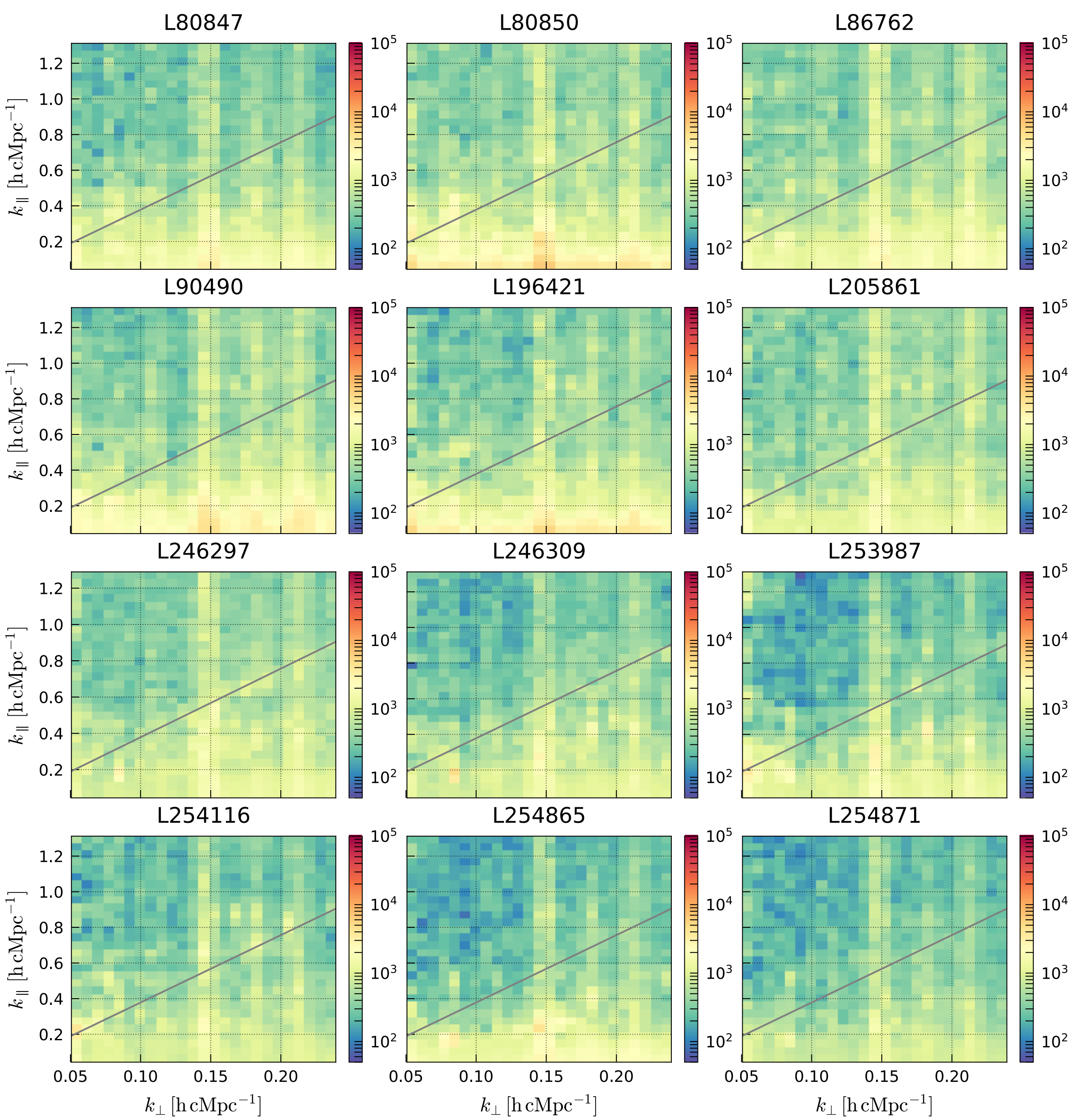
Foreground Removal — Gaussian Process Regression

Twelve nights of data have now been calibrated, sky-model subtracted, imaged, and cleaned of foreground emission. Ten ‘best’ nights are further analysed (140h).

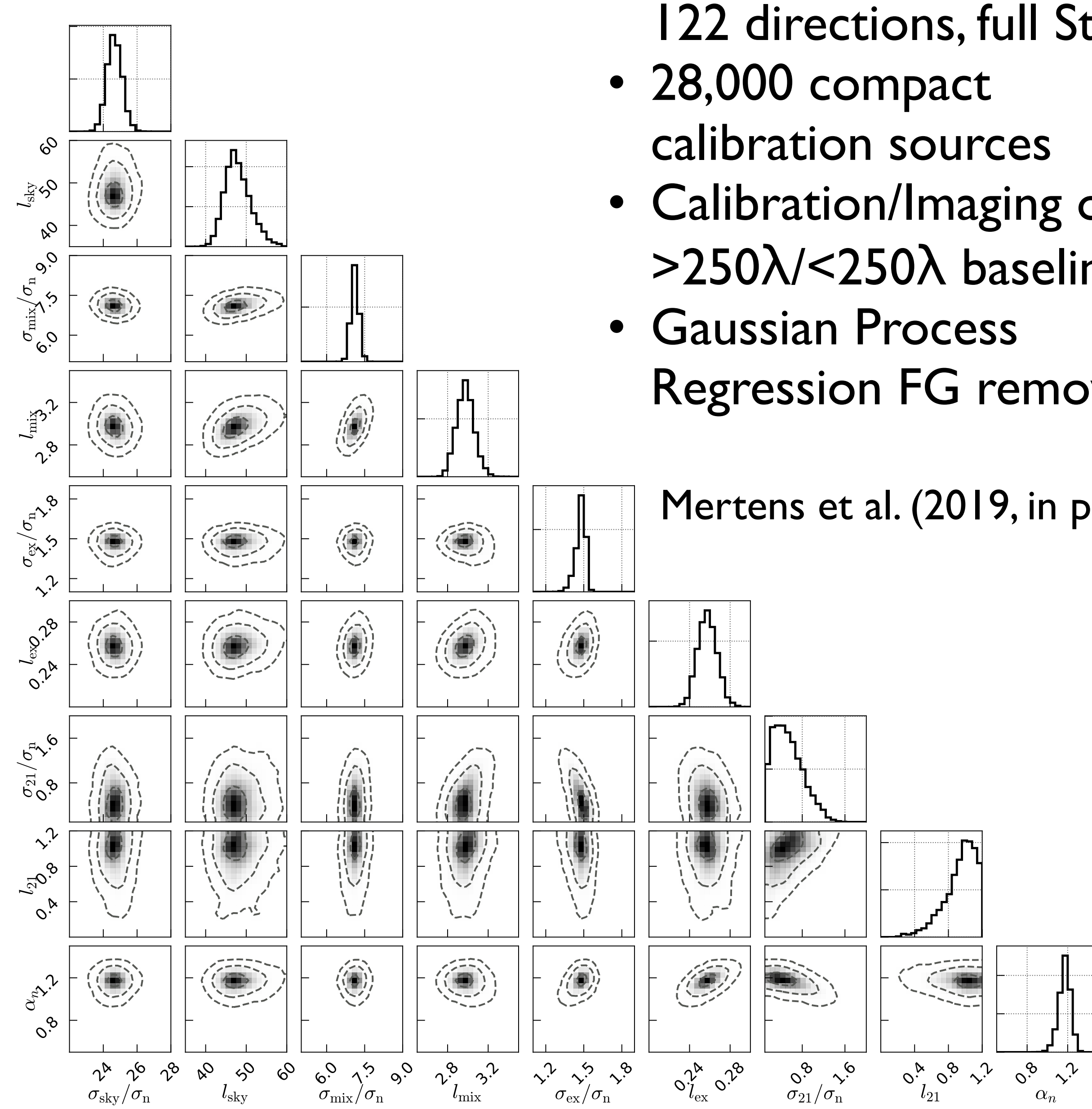
Processing:

- Enforcing more spectral smoothness over12 MHz.
- DI/DD-calibration in 122 directions, full Stokes
- 28,000 compact calibration sources
- Calibration/Imaging on >250λ/<250λ baselines
- Gaussian Process Regression FG removal.

Mertens et al. (2019, in prep.)



Power spectra after foreground removal via GPR



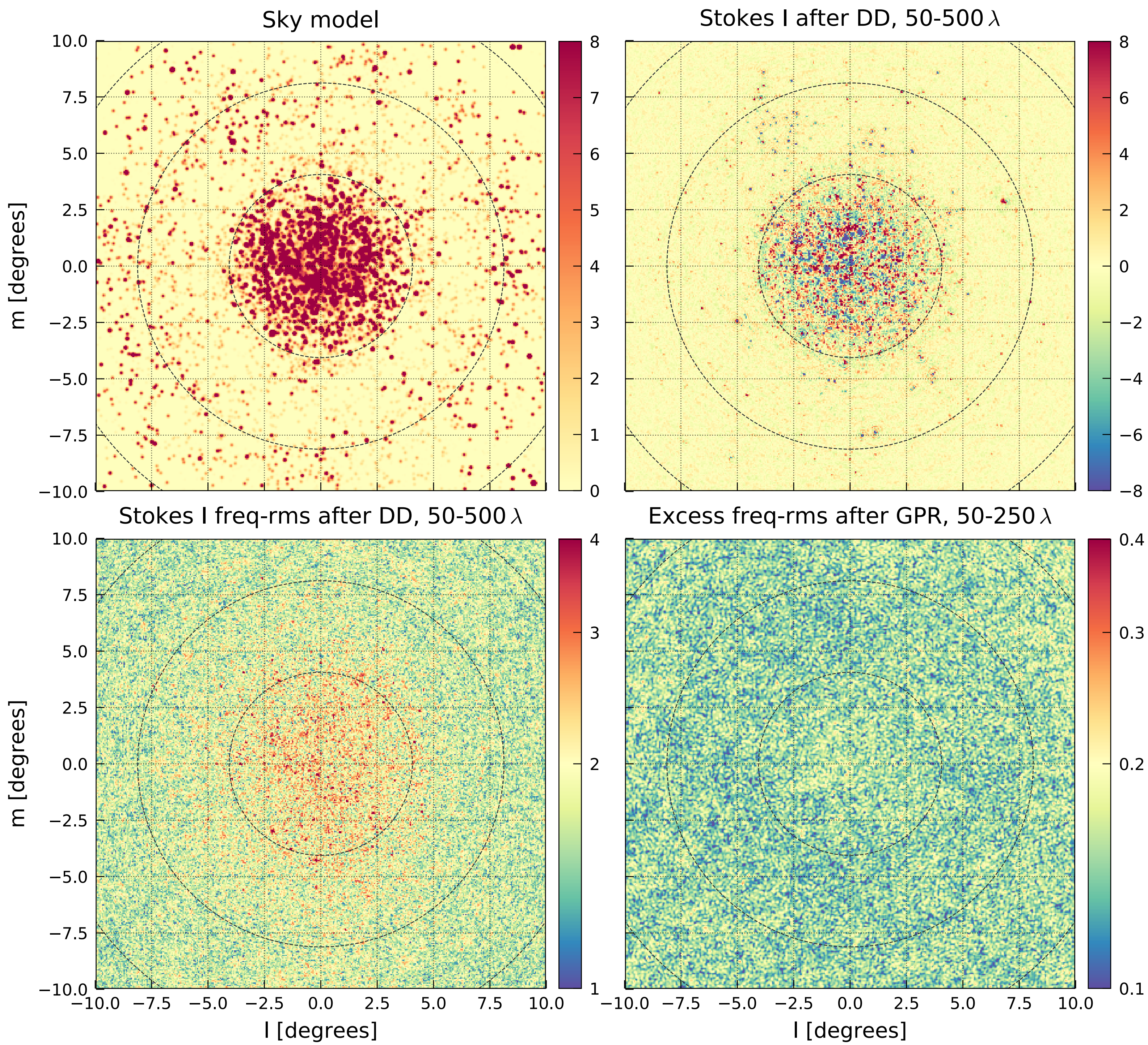
Foreground (GPR) model parameters

Foreground Removal — Gaussian Process Regression

Gaussian Process Regression (GPR) removes most remaining spectrally smooth emission, even below the noise level for a single night of data *(but not yet all)*.

Sky Model (28,000 compact sources out to 20°)

RMS in frequency direction after sky-model subtraction



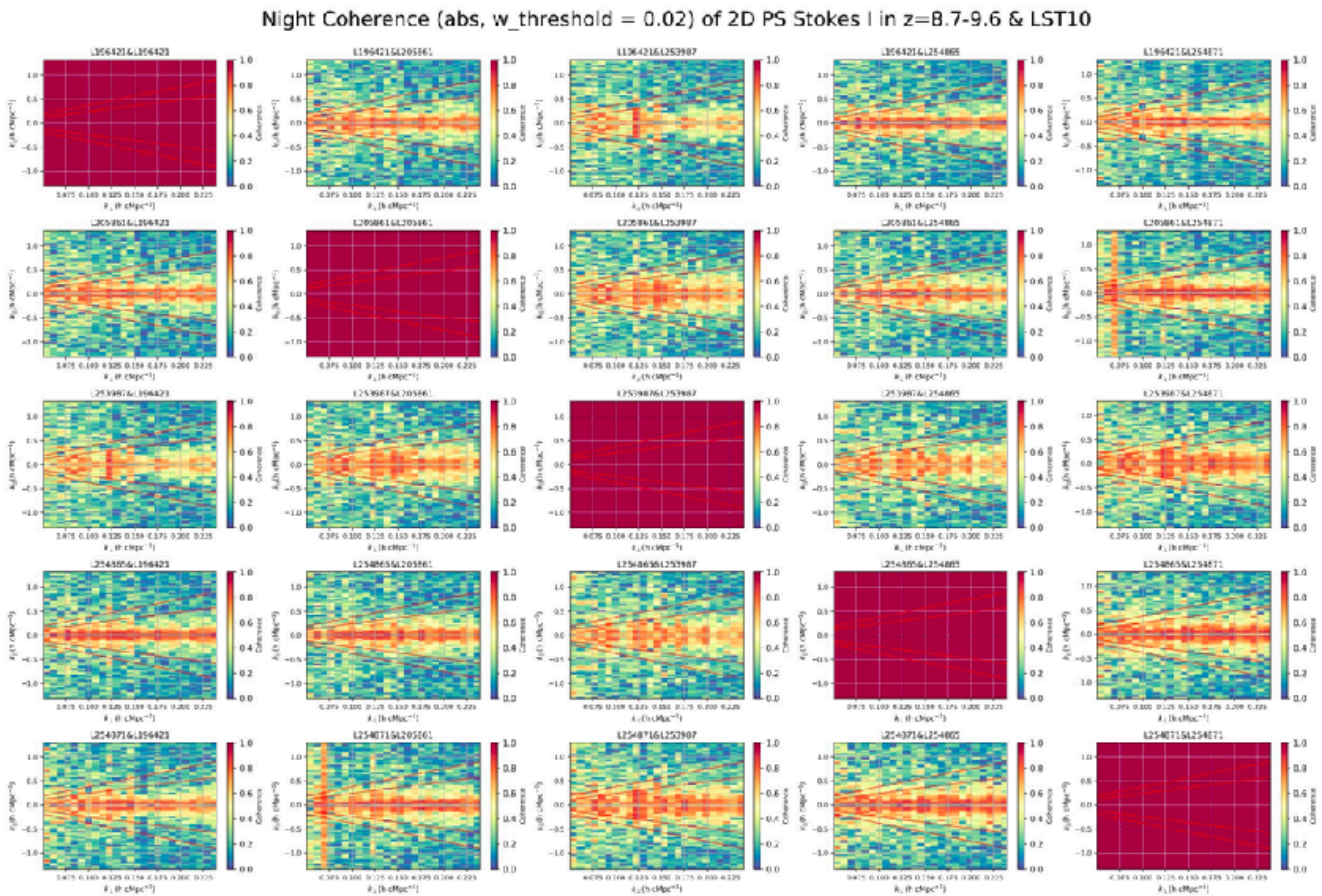
Residuals after Sky-model removal

RMS in frequency direction after GPR

Mertens et al. (2019, in prep.)

Foreground Removal — Gaussian Process Regression

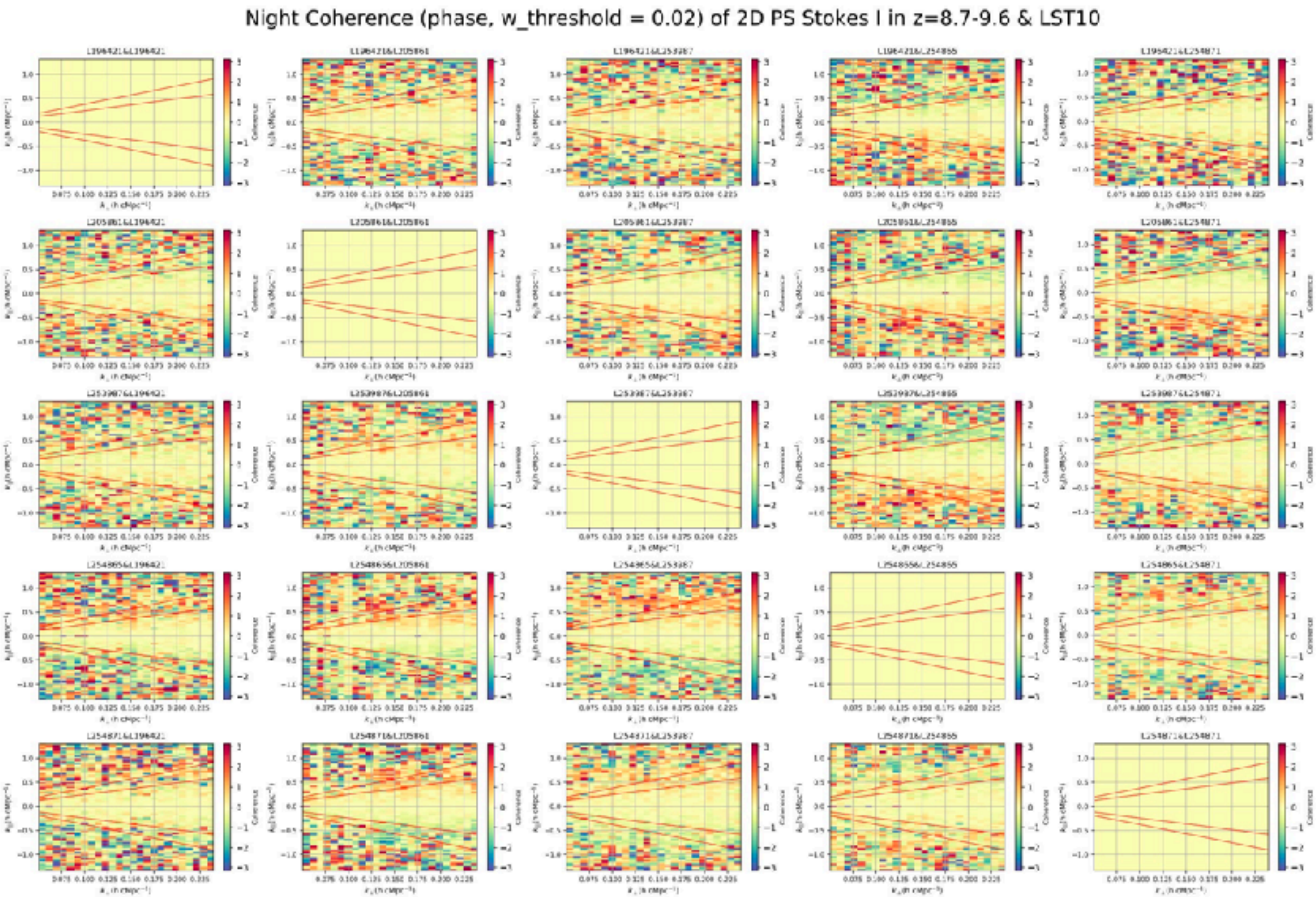
The effect of coherence is strong between 1h LST slices; less so for full 12h tracks.



Credit: Hyoyin Gan

Foreground Removal — Gaussian Process Regression

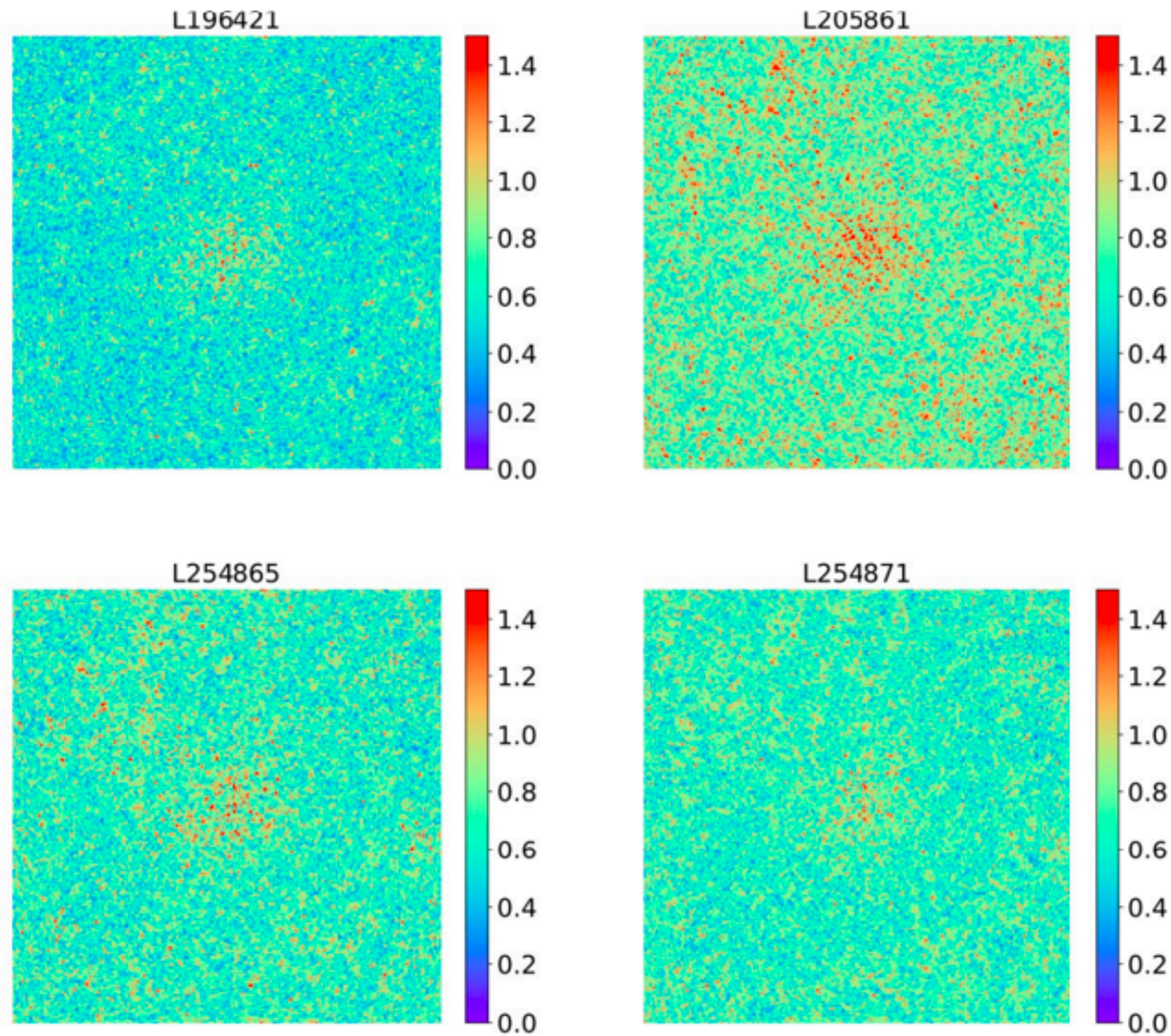
The effect of coherence is strong between 1h LST slices; less so for full 12h tracks.



Credit: Hyoyin Gan

Foreground Removal — Gaussian Process Regression

Variance in the frequency direction after applying a “wedge-filter” (inside 90° horizon) to the visibility cube and imaging. Coherence ~0.3MHz, excess shows the primary beam

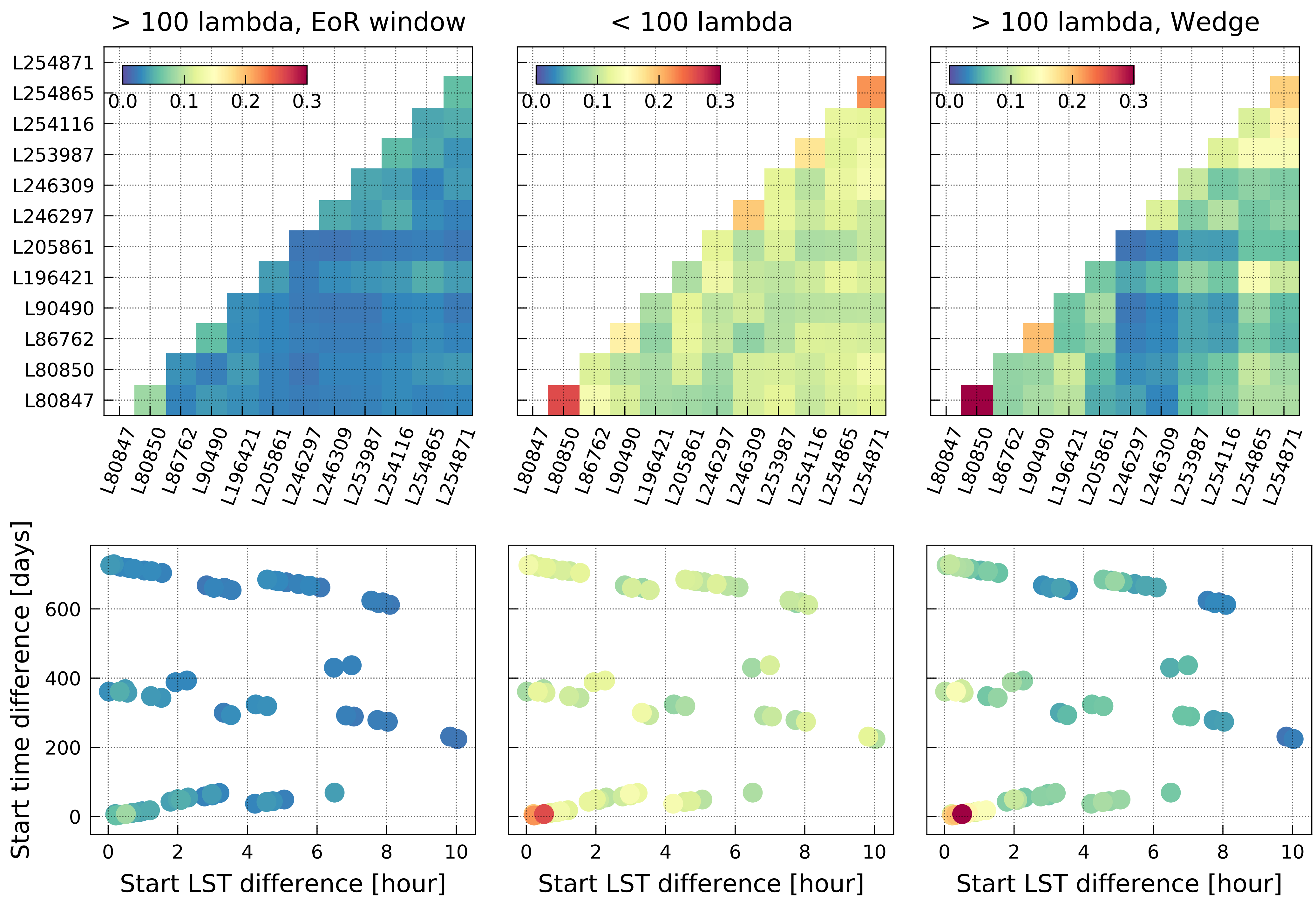


This is caused by residual gain errors due to an incomplete sky model and not fully enforced gain smoothness. Applied to the sky model this causes excess noise.

Credit: Hyoyin Gan

Power-Spectra — Night-to-night Correlations

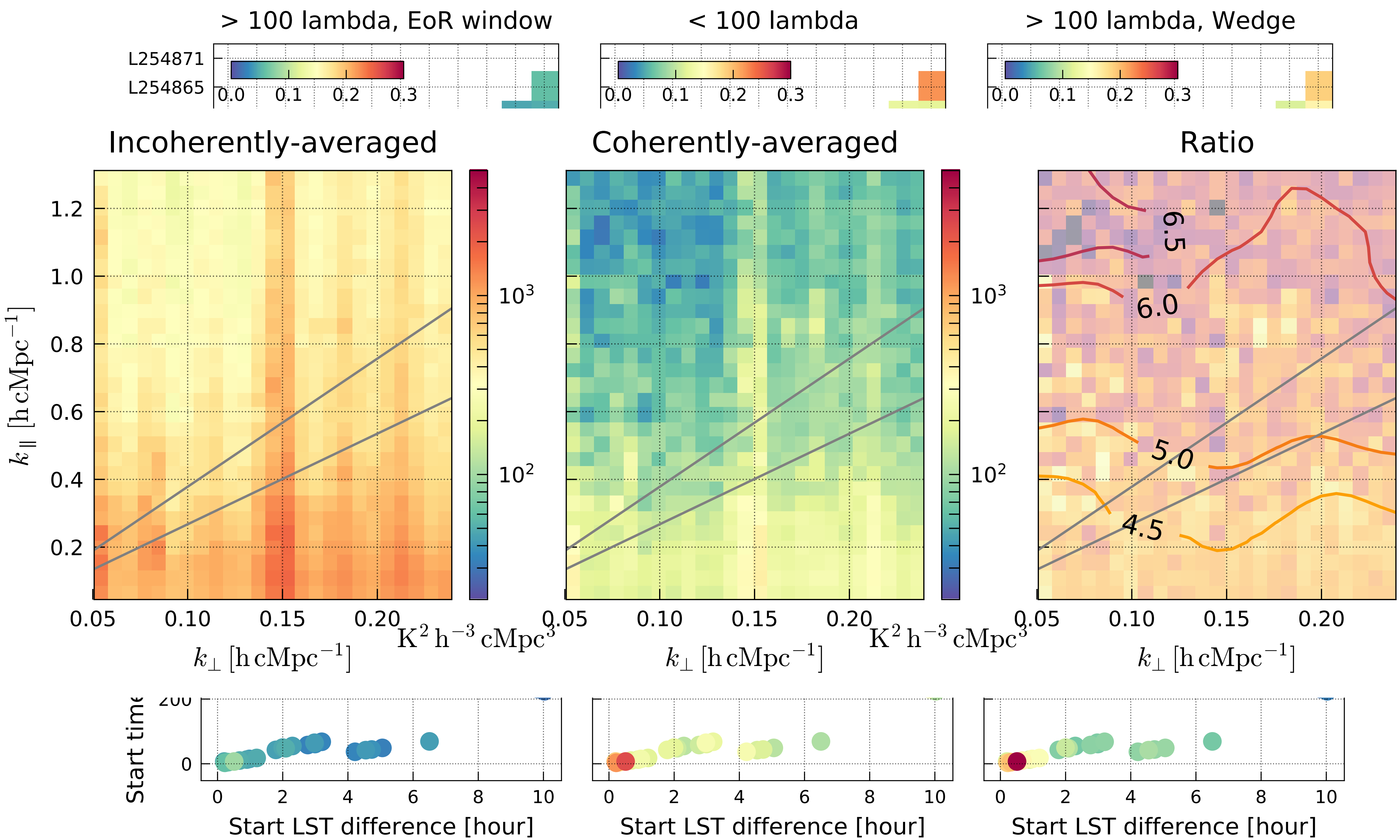
There are still correlations between nights. Closer correlation for nights starting at the same sidereal time: suggests that part of the sky still leaks through



Mertens et al. (2019, in prep.)

Power-Spectra — Night-to-night Correlations

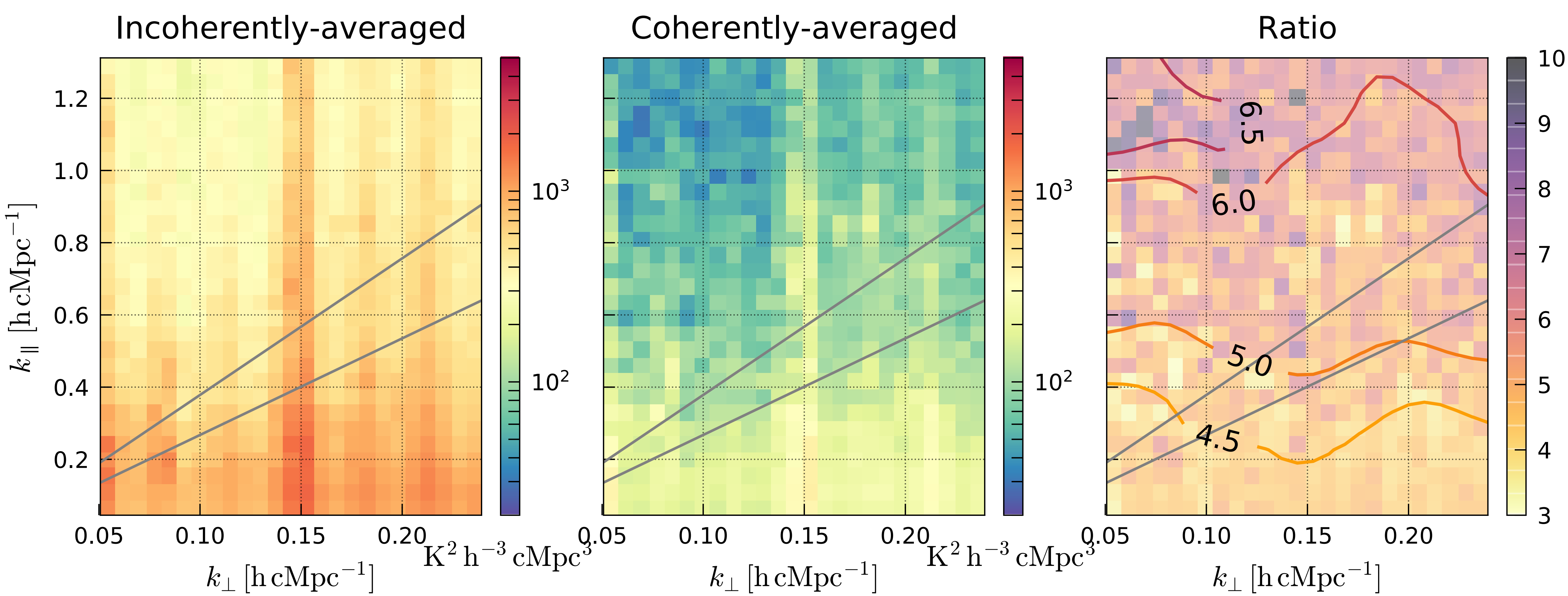
There are still correlations between nights. Closer correlation for nights starting at the same sidereal time: suggests that part of the sky still leaks through



Mertens et al. (2019, in prep.)

Power-Spectra — Night-to-night Correlations

There are still correlations between nights. Closer correlation for nights starting at the same sidereal time: suggests that part of the sky still leaks through



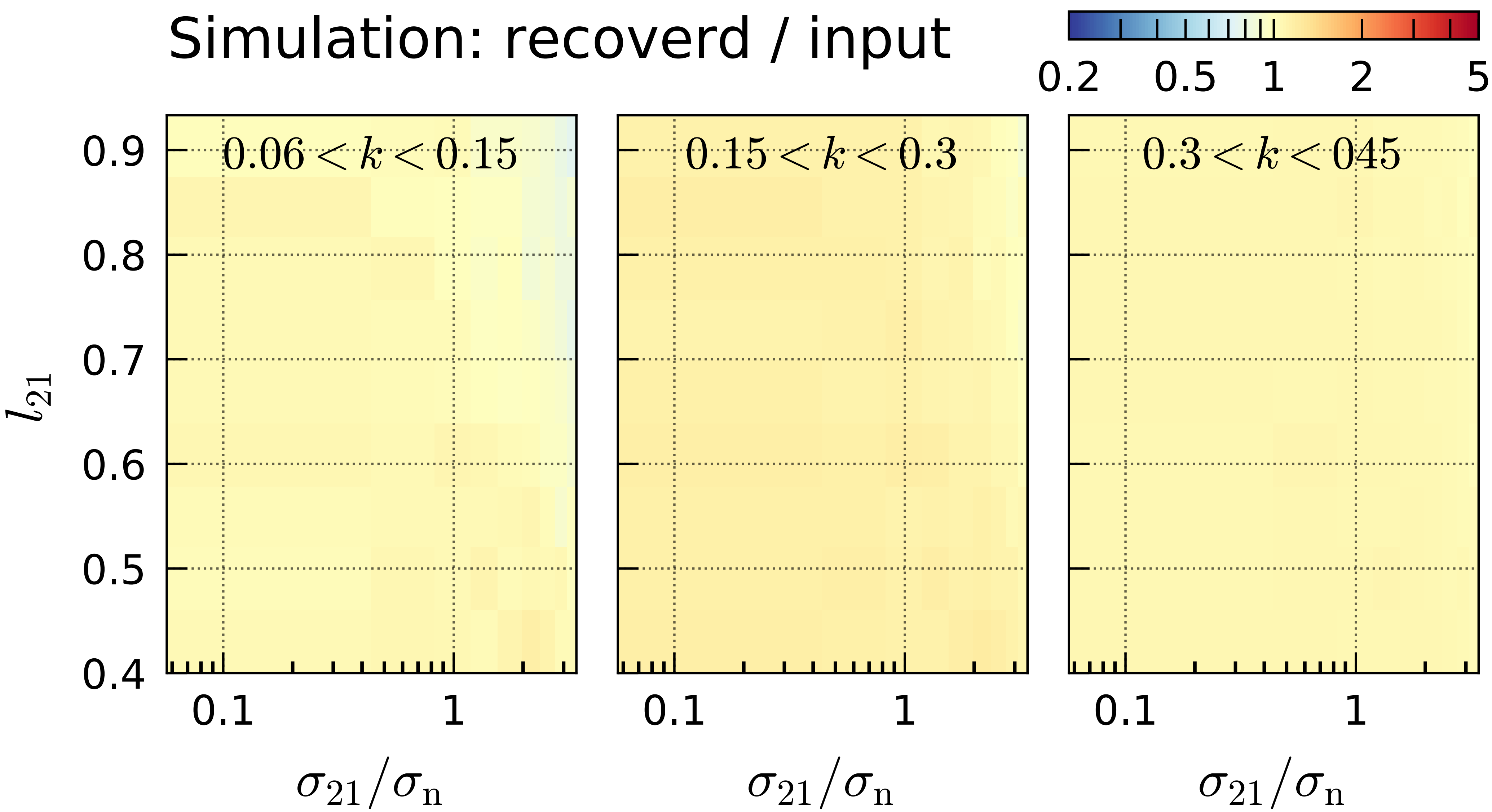
Mertens et al. (2019, in prep.)

Power-Spectra — No 21-cm Signal Suppression

The bias-variance trade-off in calibration *and* foreground removal is critical.

No 21-cm signal suppression in GPR is found in GPR:

We assess that GPR does not suppress the 21-cm signal via simulations and via signal injection in to the real data: Ratio recovered/input signals >= 1.0



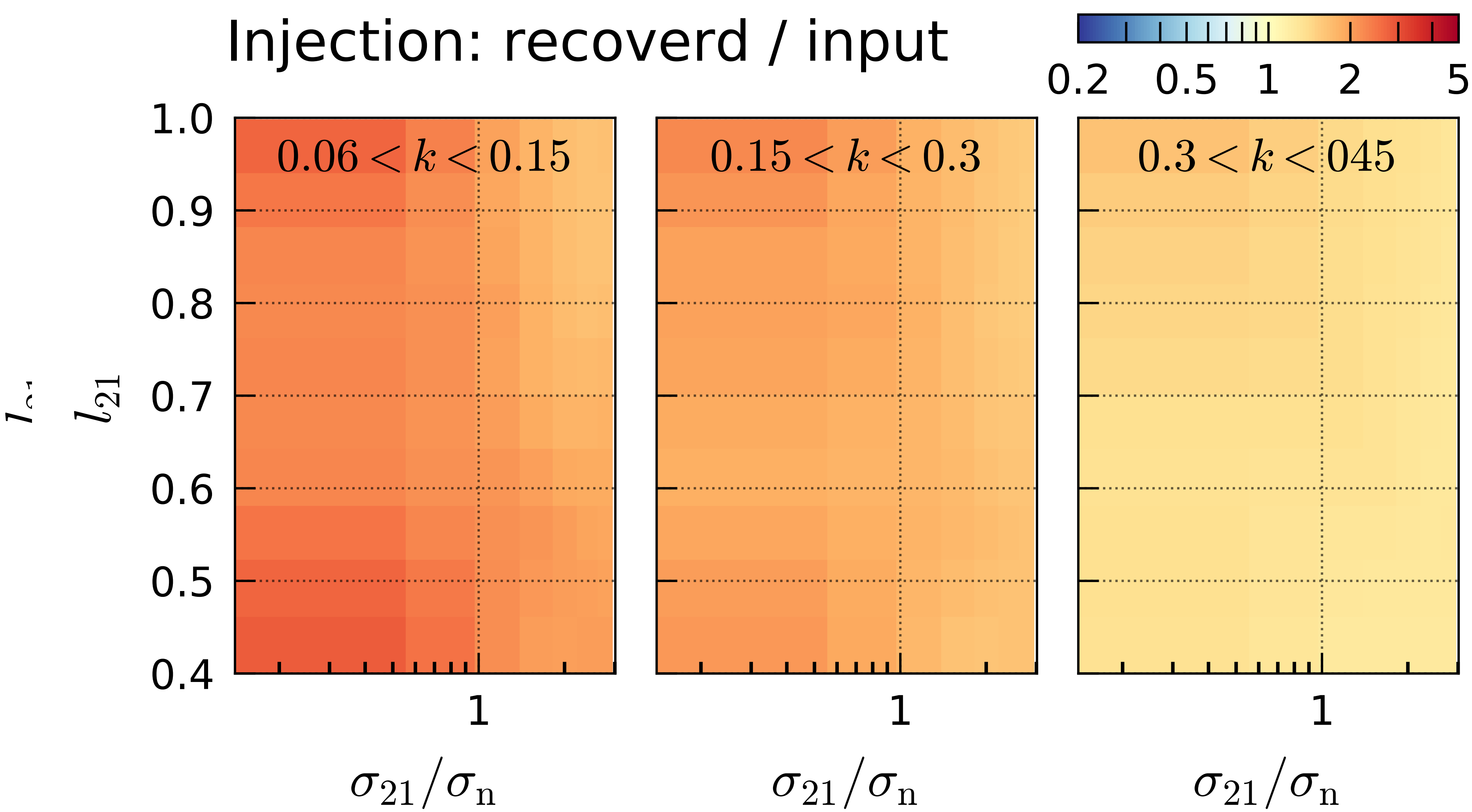
Mertens et al. (2019, in prep.)

Power-Spectra — No 21-cm Signal Suppression

The bias-variance trade-off in calibration *and* foreground removal is critical.

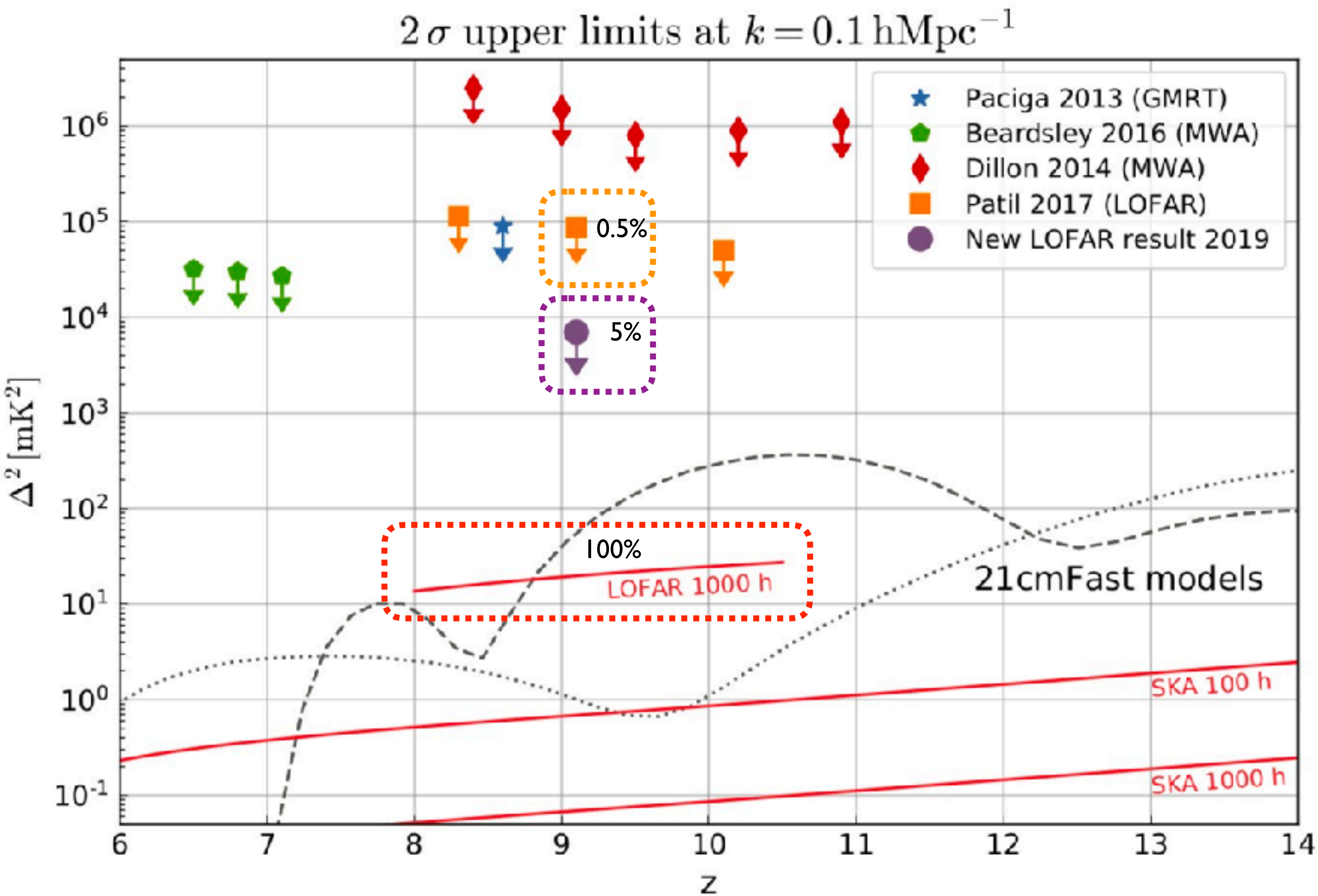
No 21-cm signal suppression in GPR is found in GPR:

We assess that GPR does not suppress the 21-cm signal via simulations and via signal injection in to the real data: Ratio recovered/input signals >= 1.0



Mertens et al. (2019, in prep.)

Power-Spectra — Forecast for >1000h



Mertens et al. 2019, in prep.

rijksuniversiteit groningen
faculteit wiskunde en natuurwetenschappen
kapteyn instituut

Some dessert after the main course…

AARTFAAC Cosmic Explorer 'ACE'

All-Sky Imaging in the EDGES band

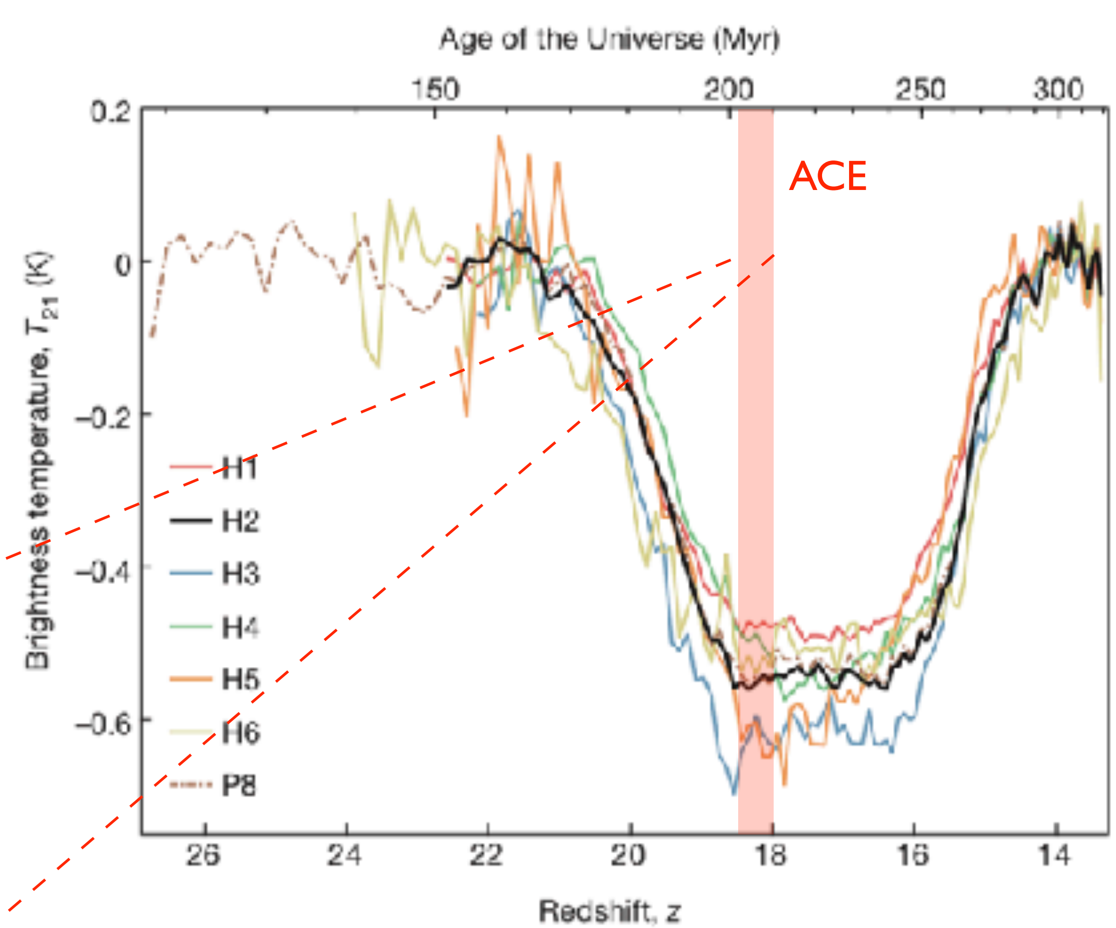
Probing the 21-cm signal during the Cosmic Dawn

MWSKY-II, Pune, India - March 20, 2019

AARTFAAC Cosmic Explorer (ACE) Program

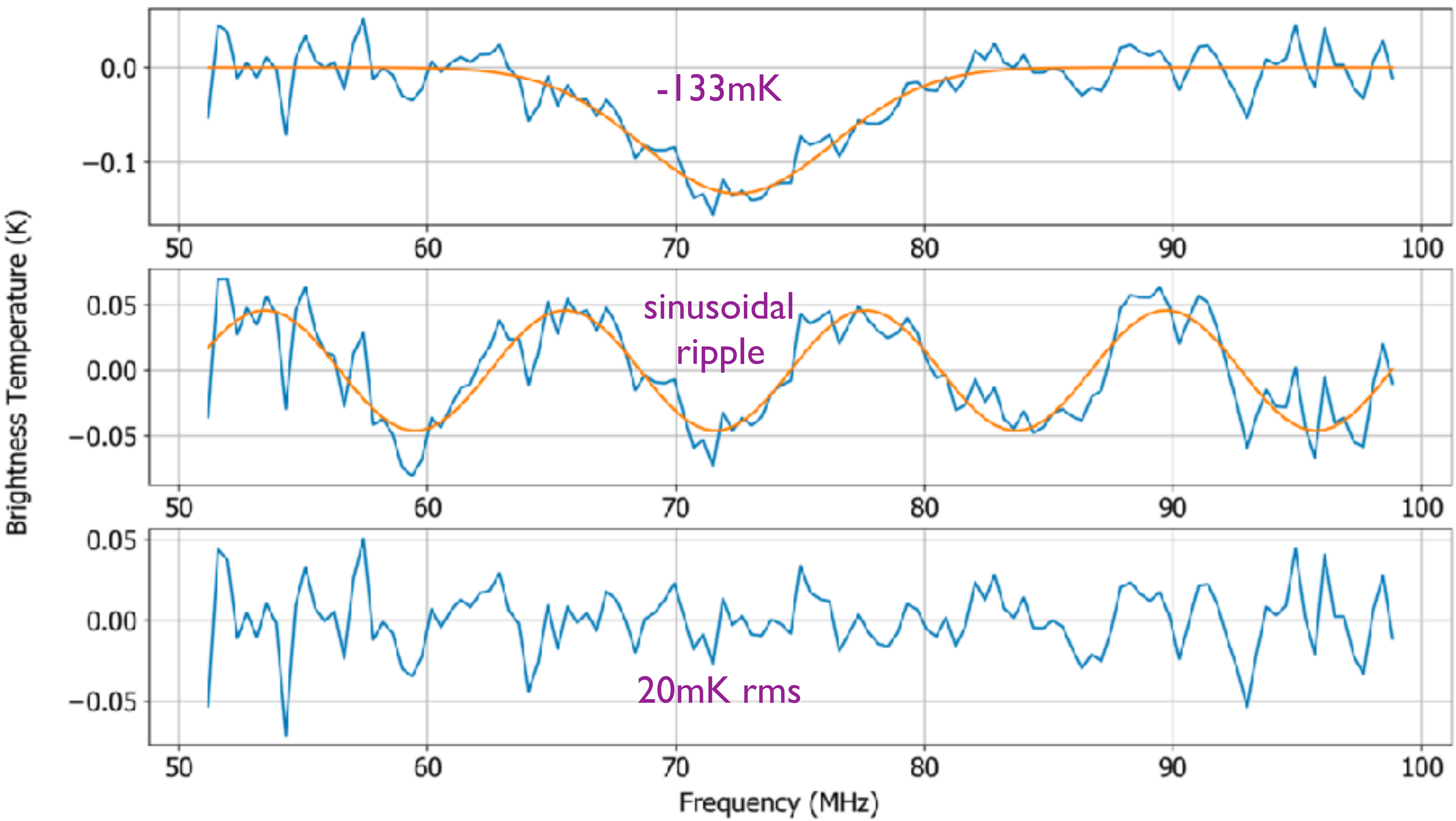
EDGES2 results motivated the 1000-hr 'ACE' multi-cycle program with LOFAR-LBA using the AARTFAAC system/correlator; ~300+h or data in hand.

Cross-correlate all 576 LOFAR LBA dipoles over ~2.5 MHz between 72.5-75MHz (z~18) using 42x61 kHz channels + two outrigger subbands.



AARTFAAC Cosmic Explorer (ACE) Program

But alternative, more plausible, models exist consistent with standard 21-cm signal models

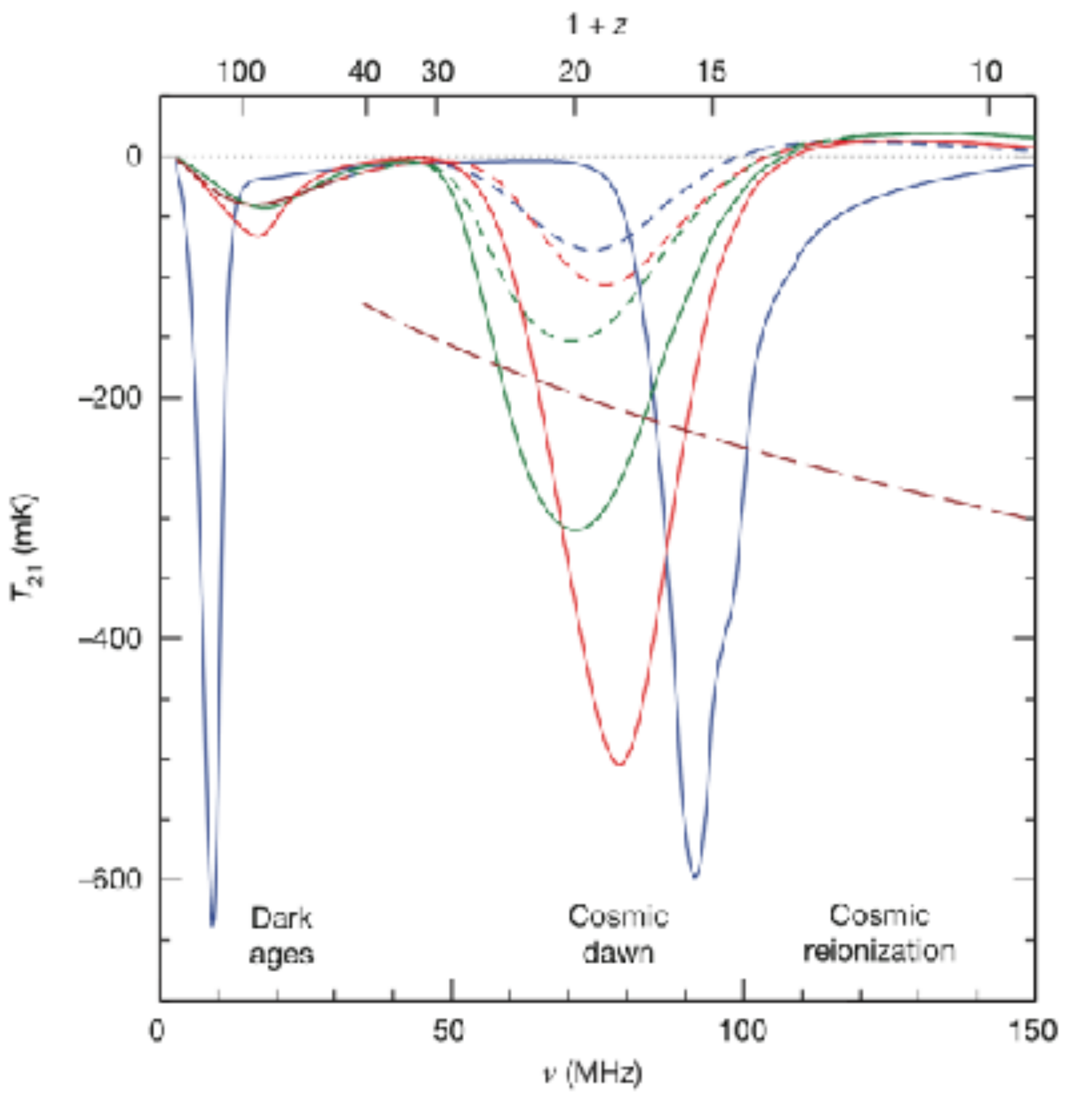


Singh & Subrahmanyan 2019

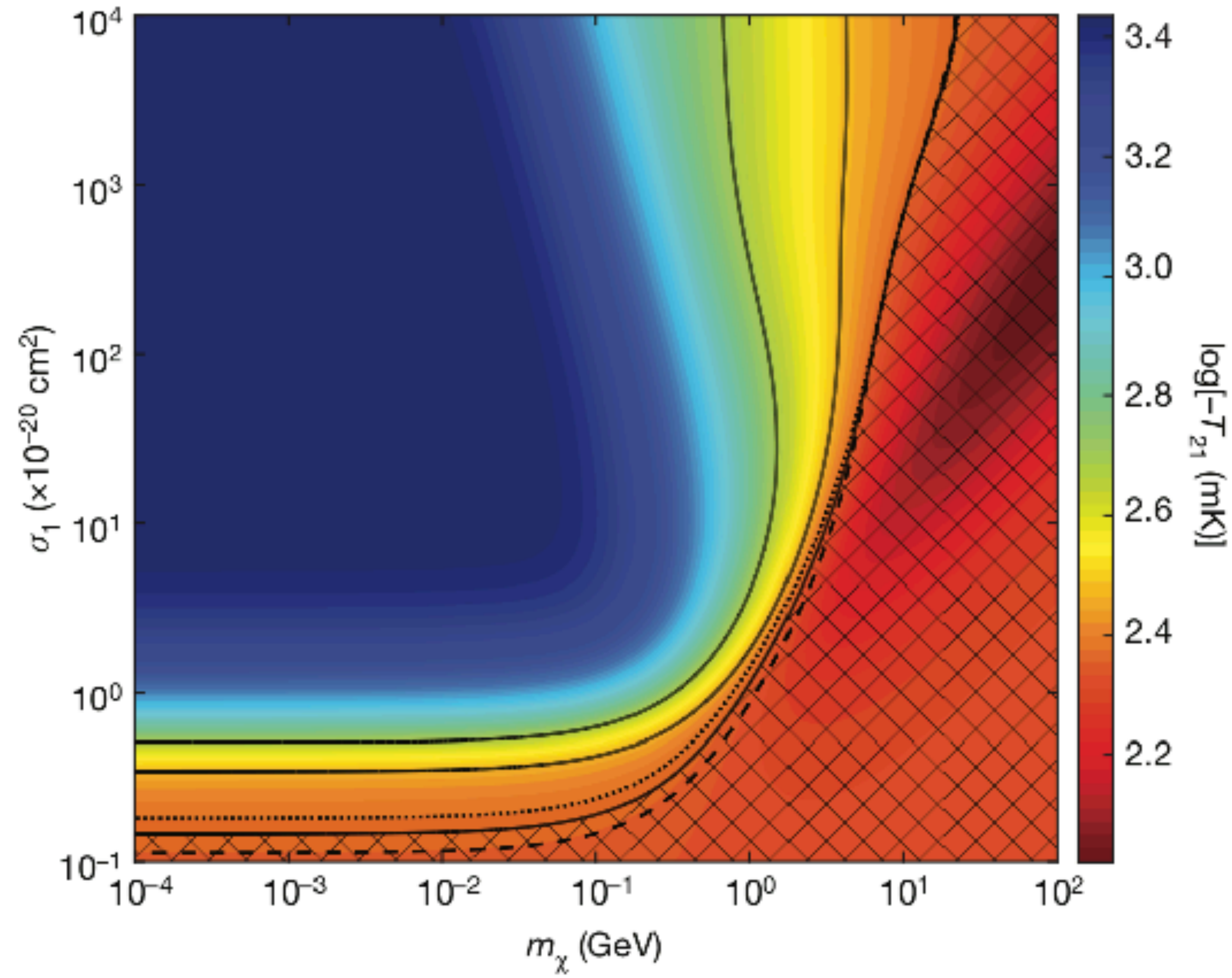
AARTFAAC Cosmic Explorer (ACE) Program

Regardless, the EDGES2 result has generated an enormous interest.
If genuine, it requires 'exotic physics', such as the cooling of baryons by scattering off dark matter, to explain the depth of the signal (-600mK).

Global-signal models; some affect the Dark Ages



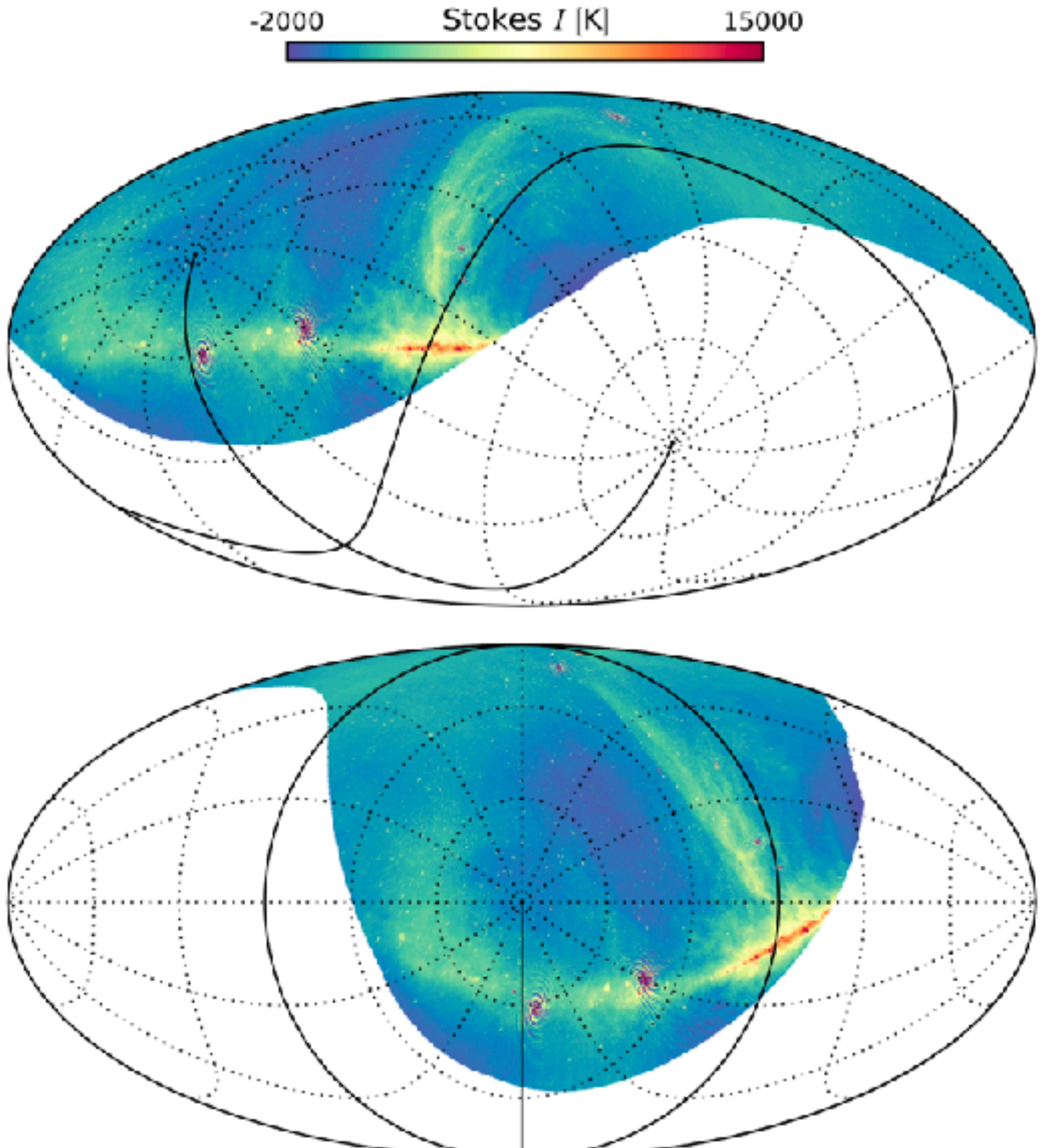
Constraint on DM particle mass and cross-section



Barkana 2018

AARTFAAC Cosmic Explorer (ACE) Program

Observations started in May 25 2018; continue for 4 Cycles until 2020.

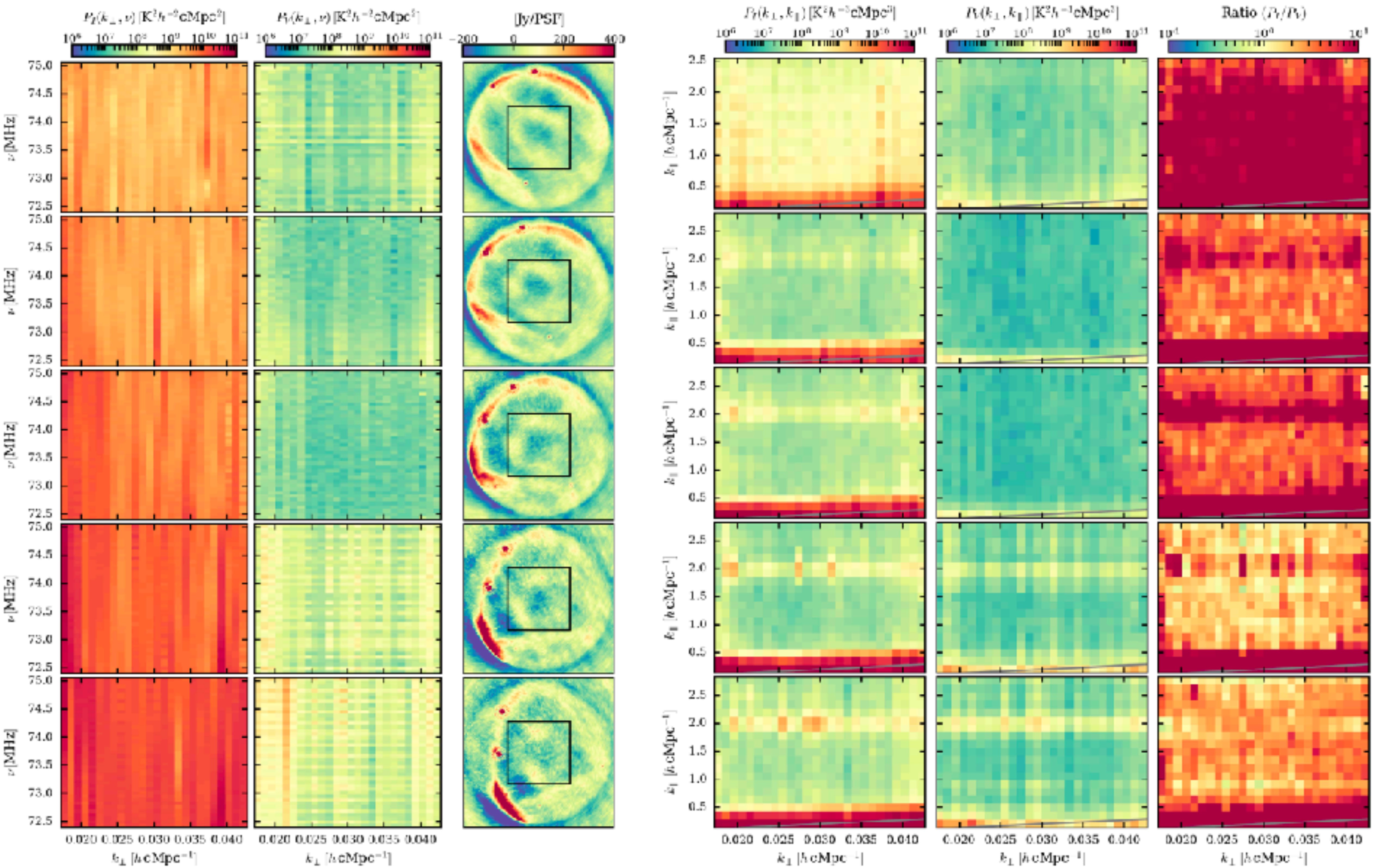


Single sub-band (@68MHz); 5.8hr integration; sliced and calibrated (NDPPP) per 10min with 20s/65kHz solution intervals). Sky model: Cas A, Cyg A, Vir A, 3C380, 3C196, 3C295

Gehlot et al. 2019

AARTFAAC Cosmic Explorer (ACE) Program

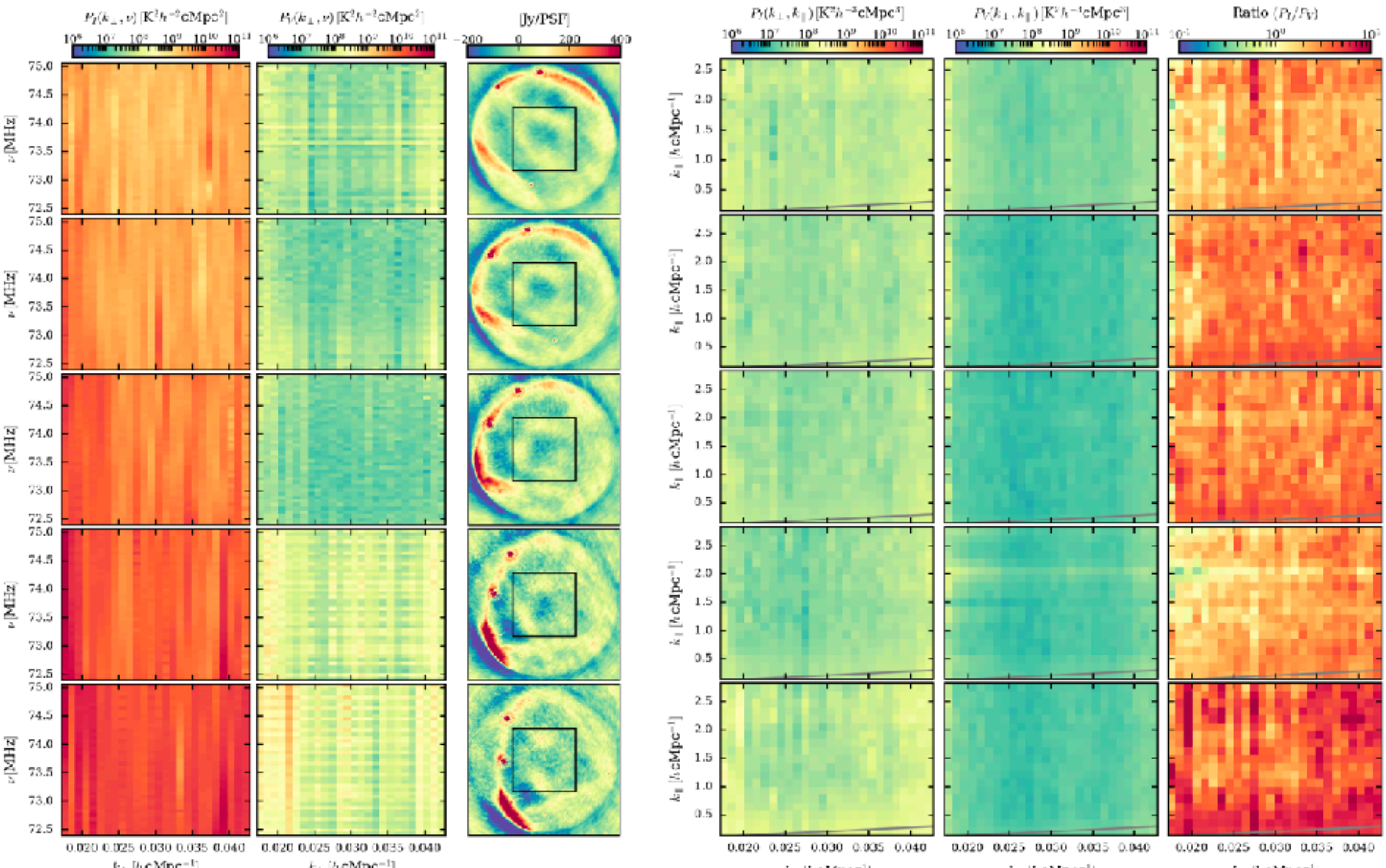
Cylindrical power spectra at z~18 before and after FG removal w/GPR



Gehlot et al. 2019

AARTFAAC Cosmic Explorer (ACE) Program

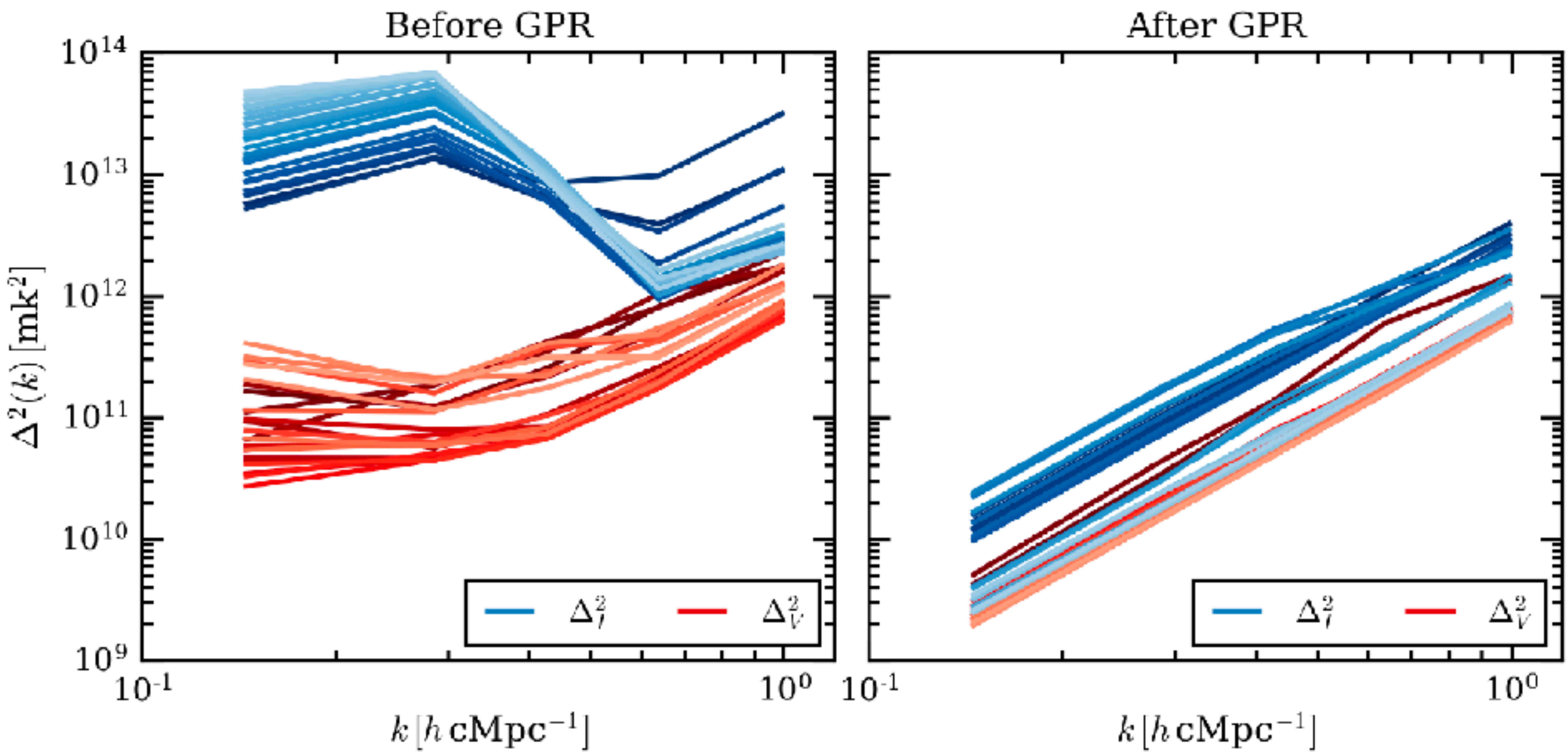
Cylindrical power spectra at z~18 before and after FG removal w/GPR



Gehlot et al. 2019

AARTFAAC Cosmic Explorer (ACE) Program

Spherical power spectra at z~18 before and after FG removal w/GPR

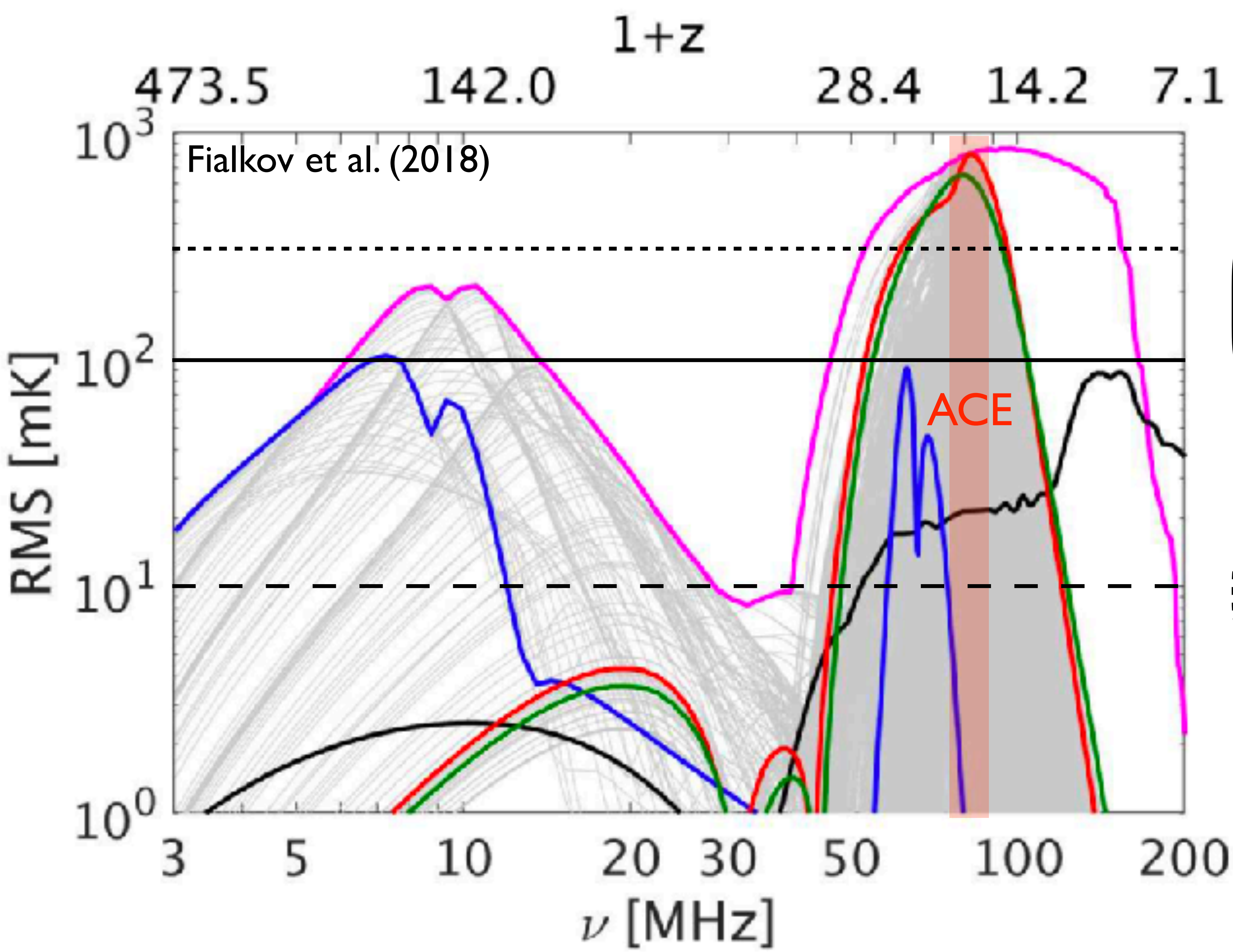


"Excess noise" remains and appears "white". It seems to have a constant scaling w.r.t the thermal noise — origin not yet known, but suspected to be related to gain calibration errors.

Gehlot et al. 2019

AARTFAAC Cosmic Explorer (ACE) Program

Sensitivity of AARTFAAC is sufficient in 1000h to exclude the most extreme models by Barkana (2018) & Fialkov et al. (2018, 2019)



Expected:

Excess noise of AARTFAAC.

Thermal noise of AARTFAAC

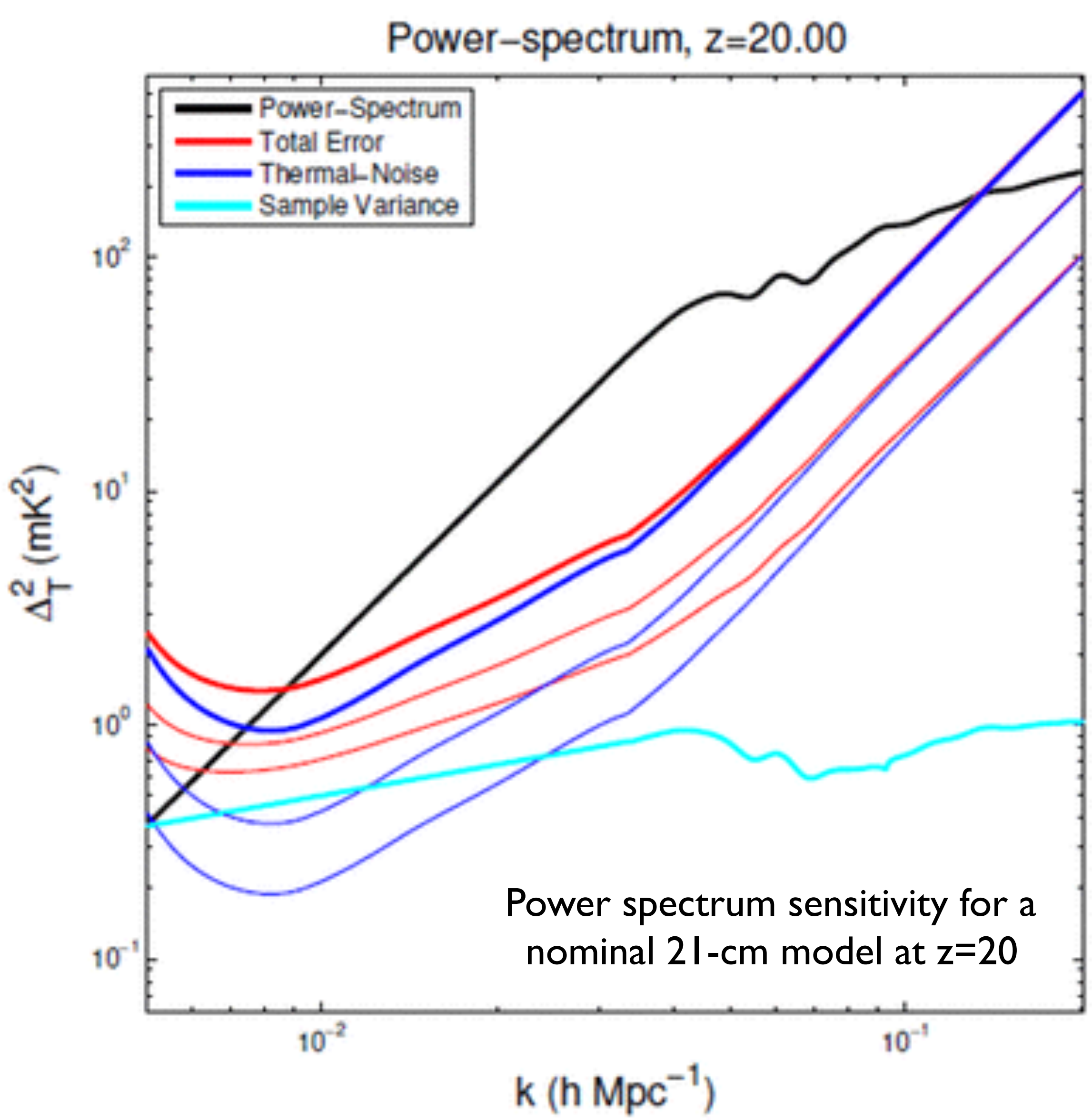
Thermal noise of NenuFar (planned programme).

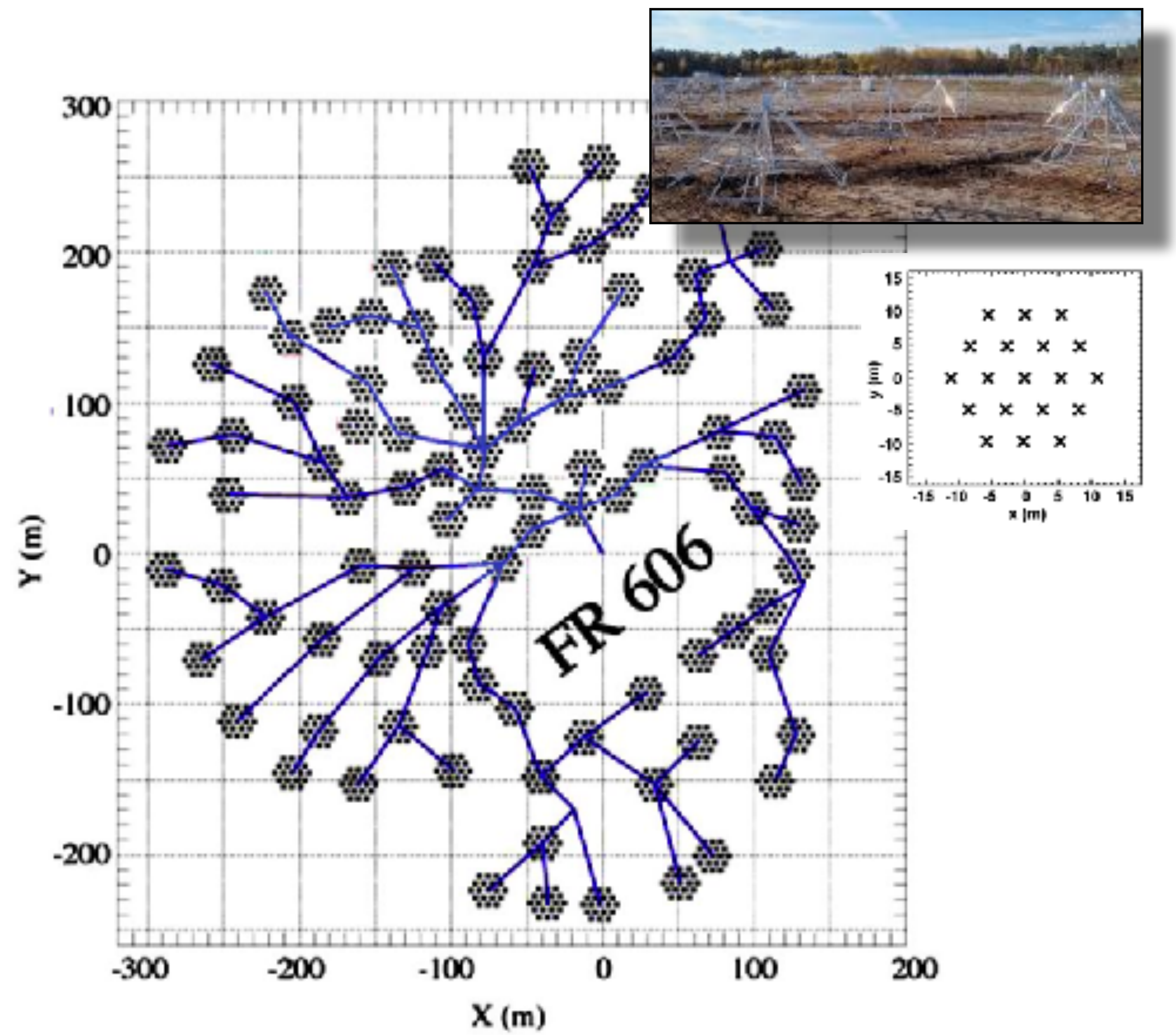
New Extension in Nançay Upgrading LOFAR: NenuFar

First data taken on NCP field in December 2018.
Cosmic Dawn Key Science Program starting ~2020.

New Extension in Nançay Upgrading LOFAR: NenuFar

Starting a new Key Science Project: 21-cm signal from the Cosmic Dawn!





Large number of dipole receivers (96x19 = 1824) leads to extremely high sensitivity at low frequencies (f~1 @ 30MHz); Nançay, France)

Zarka et al. 2015

General Summary

The 21-cm signal from the Dark Ages, Cosmic Dawn and Reionization promises a new and unique probe of the 1st billion year of the Universe.

- Current Status LOFAR EoR Key Science Project
  - Only upper limits on the 21-cm signal, but much better understanding of the entire signal processing chain (in particular calibration!)
  - LOFAR-HBA/LBA has obtained the deepest upper limits on PS @ k=0.1, z=8-10 (EoR), and at z=20-25 (CD; not presented here).
  - AARTFAAC-LBA-12 (‘ACE’ Programme) probes models the from Barkana (2018), Fialkov et al. (2018) based on the EDGES2 results.

- Next steps
  - Improve DD-gain solutions (enforce smoothness) to further reduce excess variance and bias in the 21-cm signal (on short baselines). Improve sky model by including diffuse emission from AARTFAAC-HBA-12. (lessons for SKA!)
  - Process *all* LOFAR-HBA NCP data (~2200hrs) at z=9 (going deep fast).
  - Idem for the other redshifts and 3C196 window (~1100h data in hand).