university of groningen / faculty of mathematics and natural sciences / kapteyn astronomical institute

Observing the Epoch of Reionisation and Cosmic Dawn with LOFAR and NenuFAR, and the upcoming SKA

Léon Koopmans, (Kapteyn Astronomical Institute, University of Groningen, NL)

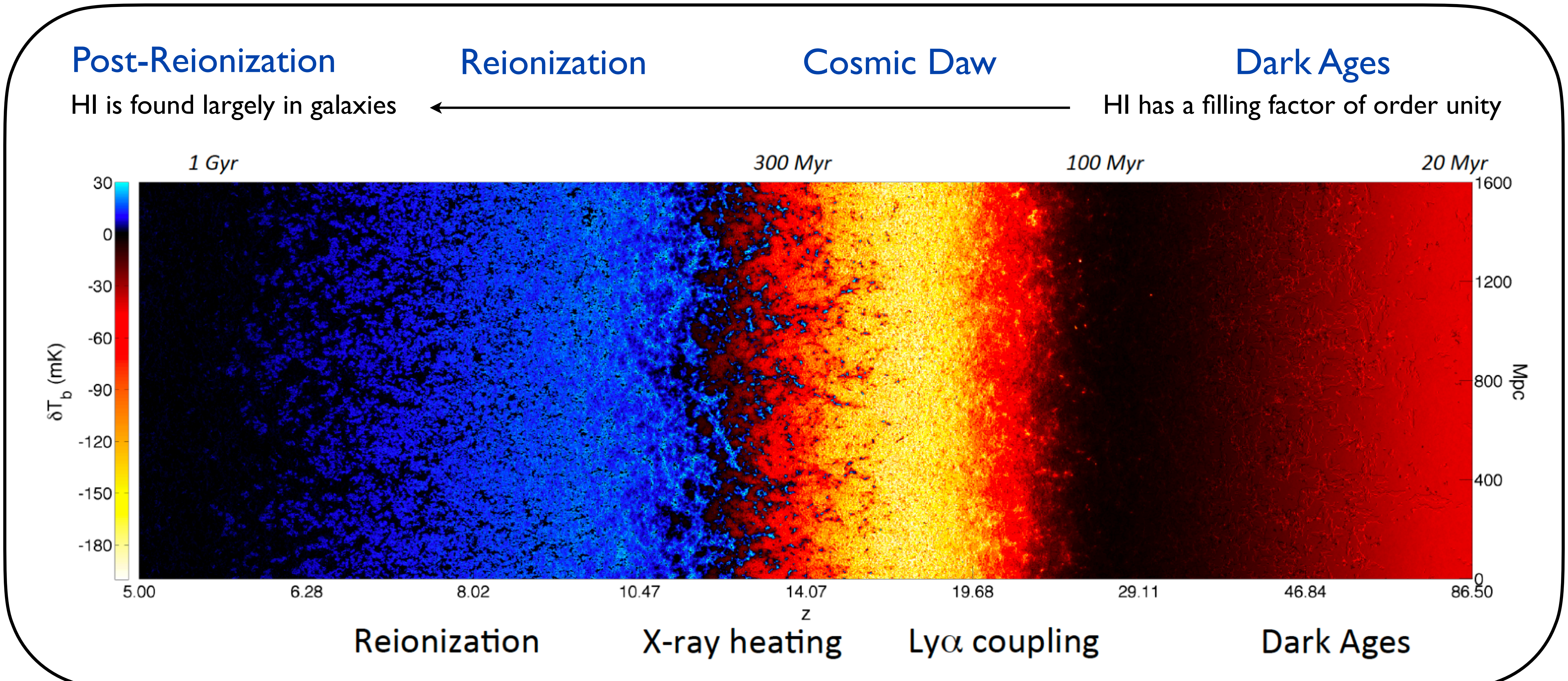
European Research Council
Established by the European Commission

Supported in part by
an ERC Advanced Grant "CoDEX"

Cosmology in the Alps, March 2024

What can “21-cm Cosmology” tell us?

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

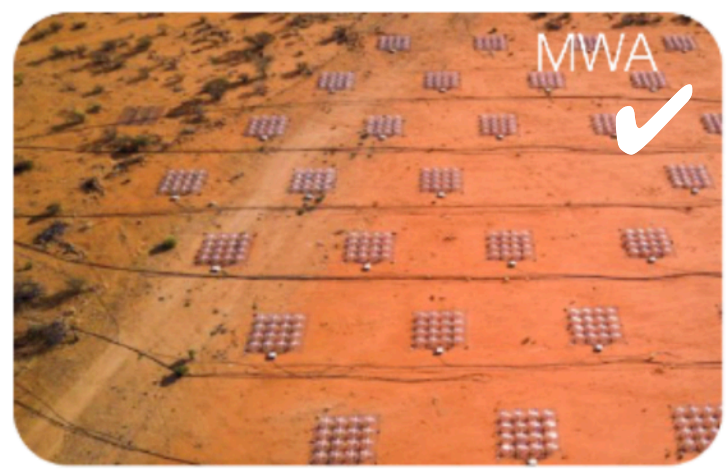


Credit figure: Mesinger

Ground-based interferometry experiments

Globally (China, India, South Africa, US, Australia, Netherlands, France, etc.) many efforts are underway to detect the 21-cm signal from z~6 to z~25 with ground-based interferometers — experiments are extremely hard!

Past/Current instruments focussing mostly on z<10



Upcoming instruments in coming decade focussing mostly on z~6-25

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CoDEX Program:

A broad-brush overview of our 21-cm Cosmology programs with LOFAR[1], AARTFAAC, NenuFAR and DEX

1 See also talks by Mellema & Mertens

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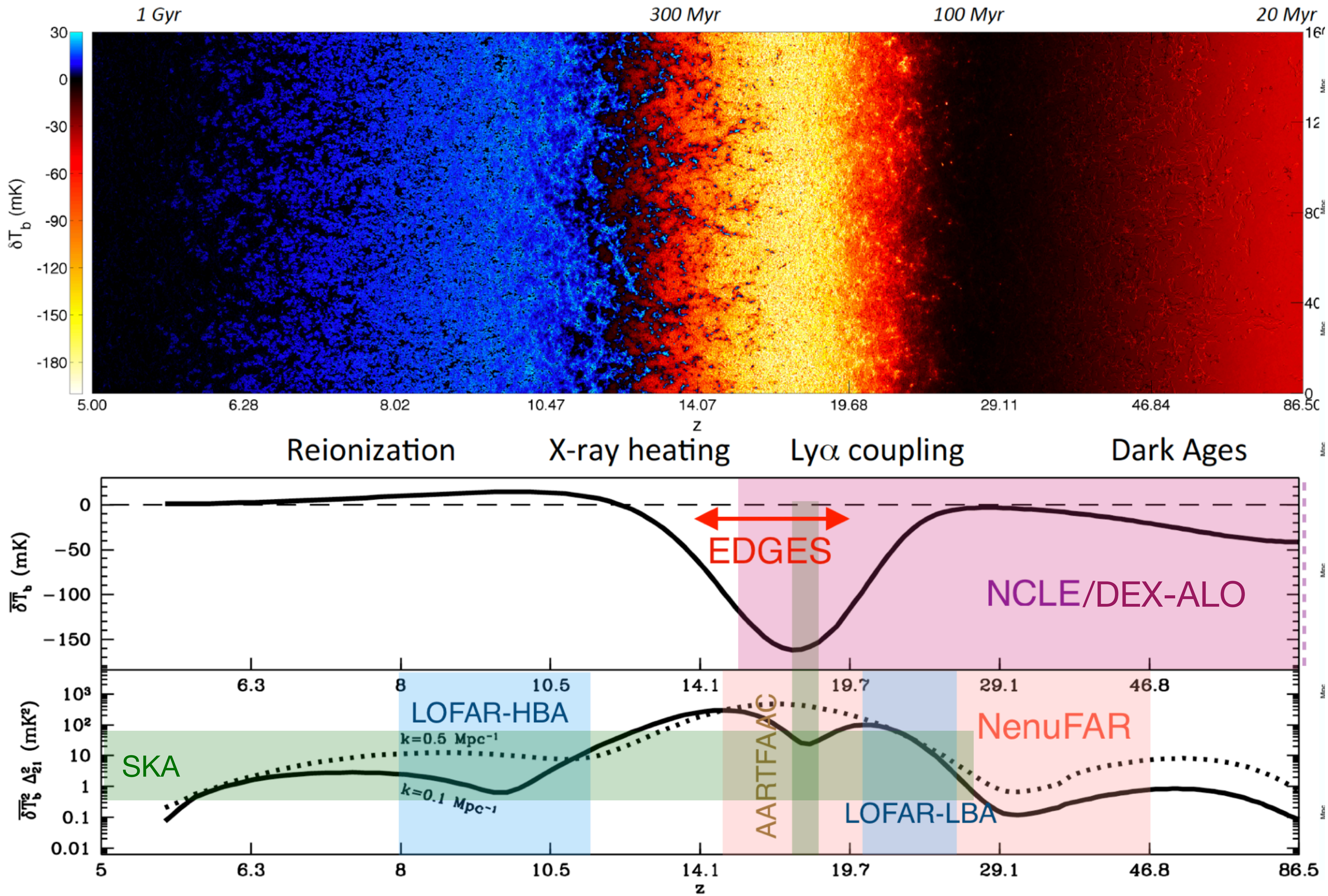
CoDEX — ERC-Advanced Program



CoDEX — ERC-Advanced Program

LOFAR EoR KSP

Power-spectra

~3500h

z~6-11 — Epoch of Reionization

AARTFAAC Cosmic Explorer

Power-spectra

~500h

z~18 — EDGES CD signal

NenuFAR CD KSP

Power-spectra

~1500h

z~12-30 — Cosmic Dawn

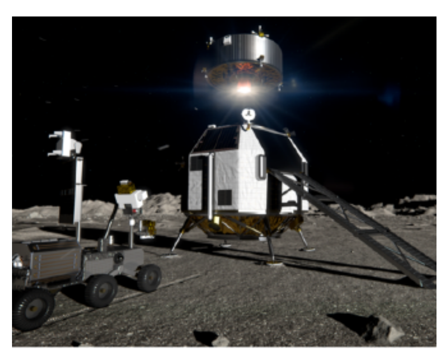
Netherlands China Low-frequency Explorer

Global Signal

Commissioning

z~12-200 — CD & Dark Ages

Dark-ages EXplorer - ALO



Global Signal/ Power-spectra/ Tomography

z~12-50 — CD & Dark Ages

SKA CD/EoR KSP

Power-spectra/ Tomography

z~3-27 — EoR & CD

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The Team ++

Groningen

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Florent Mertens
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Sambit Giri
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Ivelin Georgiev

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Saleem Zaroubi
Raghu Ghara
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Abinash Kumar Shaw

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Bene Ciardi
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Michele Bianco
Stefan Wijnholds
Simon Gazagnes
Hyoyin Gan
Rajaeh Mondal
Daan Meerburg
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Sussex

Ilian Iliev
Luke Conaboy

Nottingham

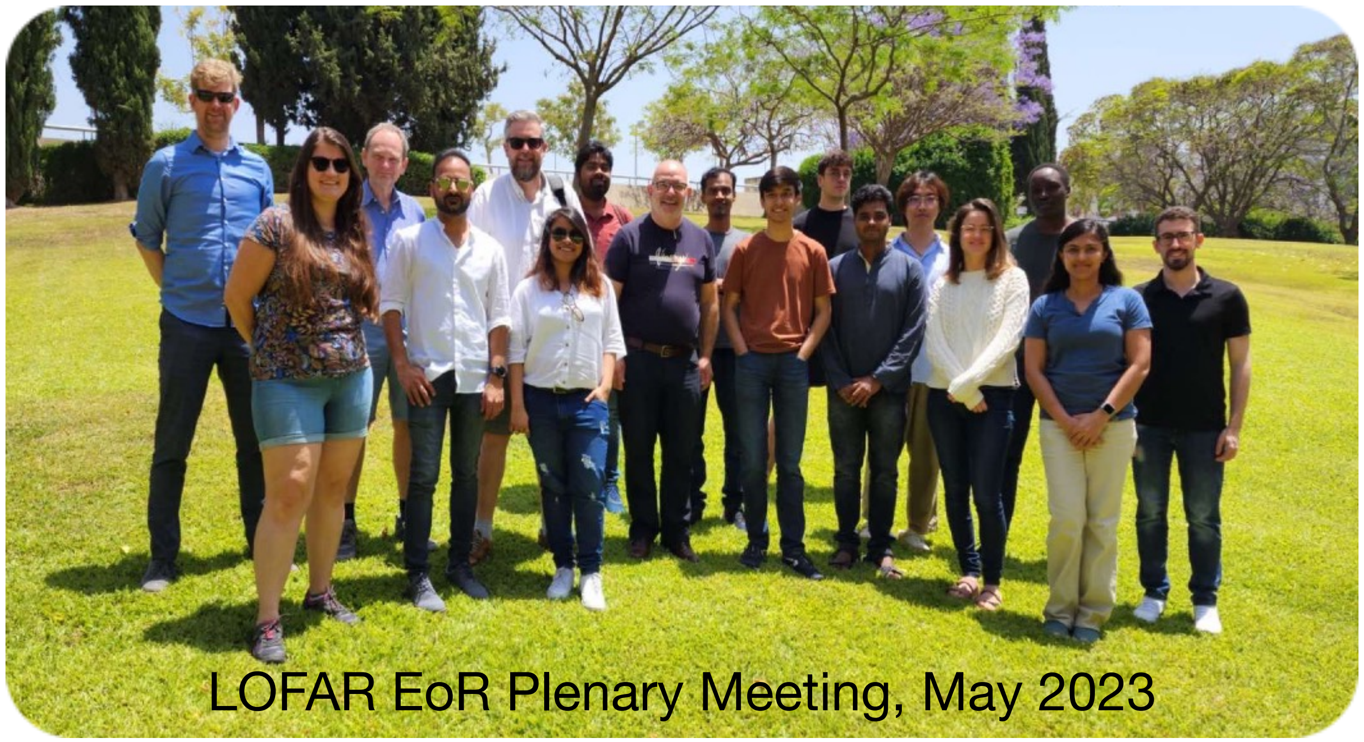
Emma Chapman
Luke Conaboy

ASTRON

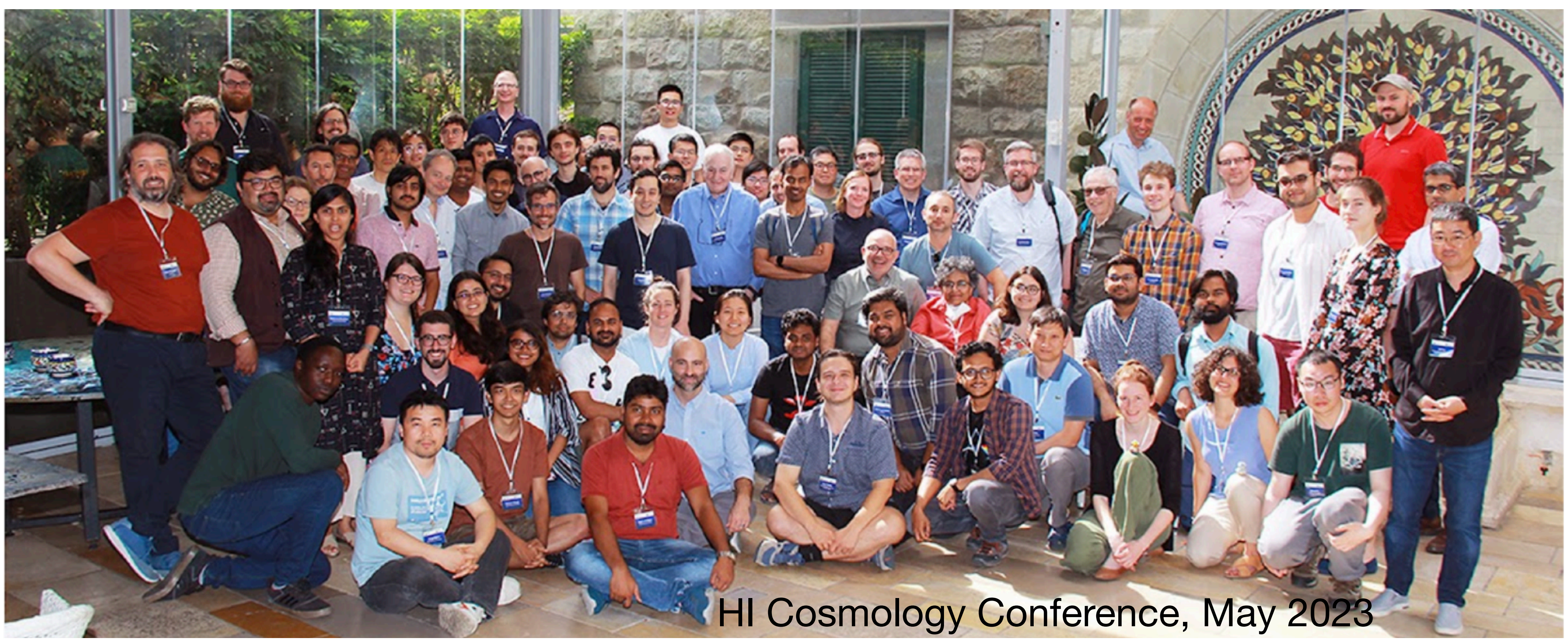
Andre Offringa
Maaijke Mevius
Sarod Yatawatta
Michiel Brentjens
V. Pandey
Harish Vedantham

Overlapping and additional members for the ACE, NCLE/ALO & NenuFAR programs.

The Team ++


LOFAR EoR Plenary Meeting, May 2023

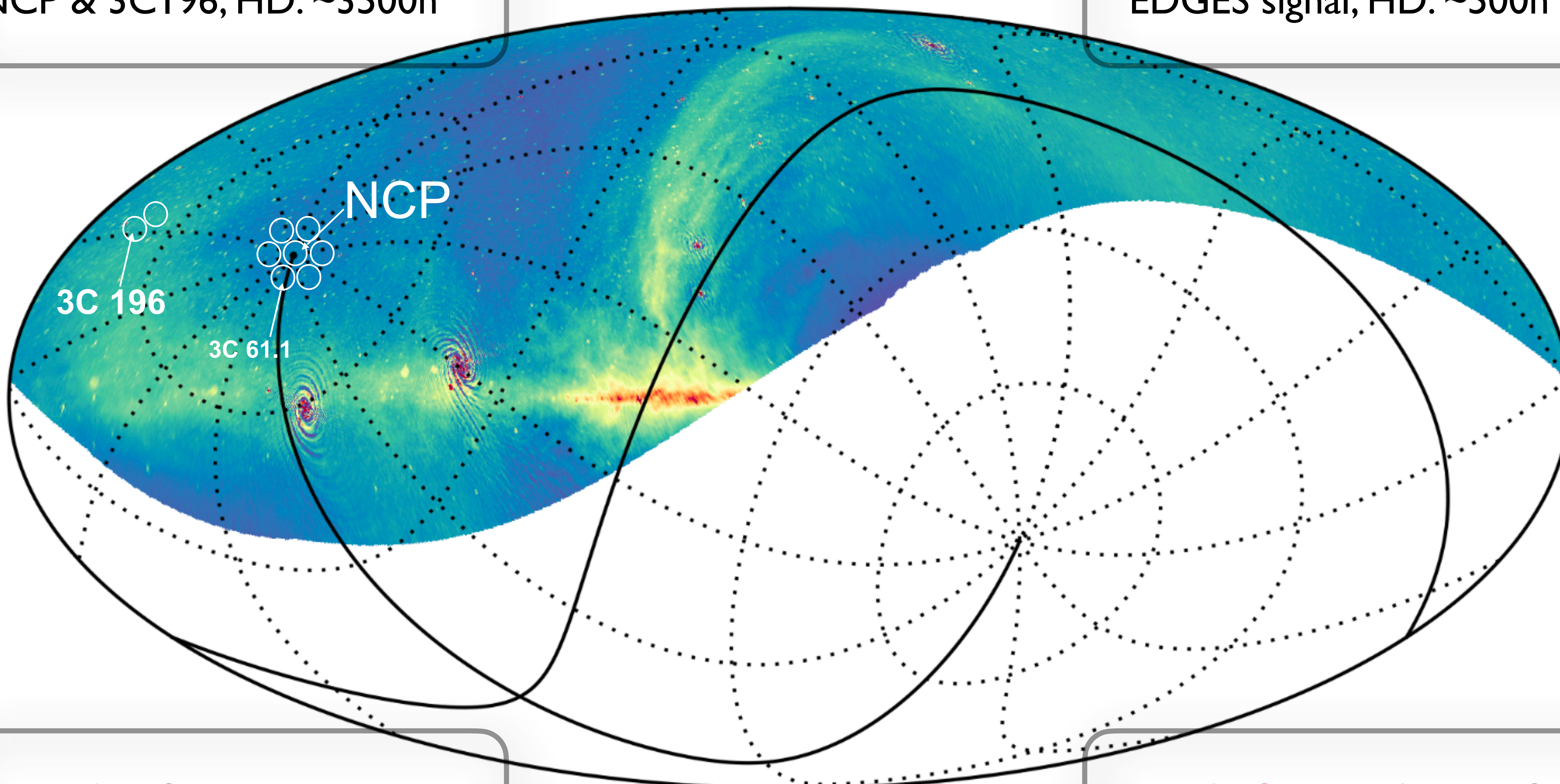

NenuFAR CD Plenary Meeting, May 2023


HI Cosmology Conference, May 2023

The Observational Windows

LOFAR: Epoch of Reionization; NCP & 3C196; HD: ~3500h

AARTFAAC: Cosmic Dawn EDGES signal; HD: ~500h



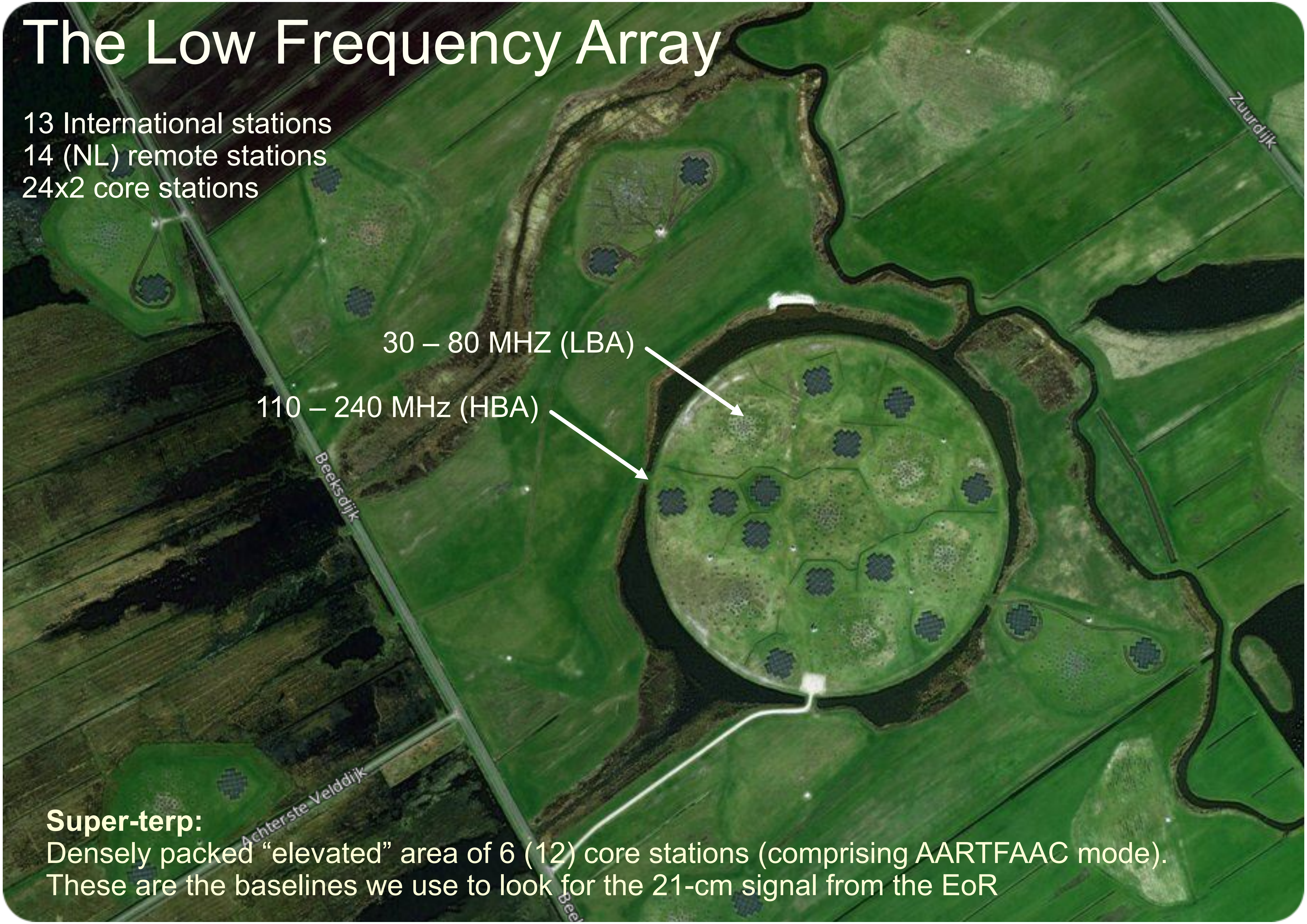
NenuFAR: Cosmic Dawn; NCP; pilot/KSP: 400/1500+h

DEX-ALO: Dark Ages & CD; all-sky; ~years

Image: AARTFAAC-LBA 70-73 MHz data (credit: Gehlot, Mertens)

The Low Frequency Array

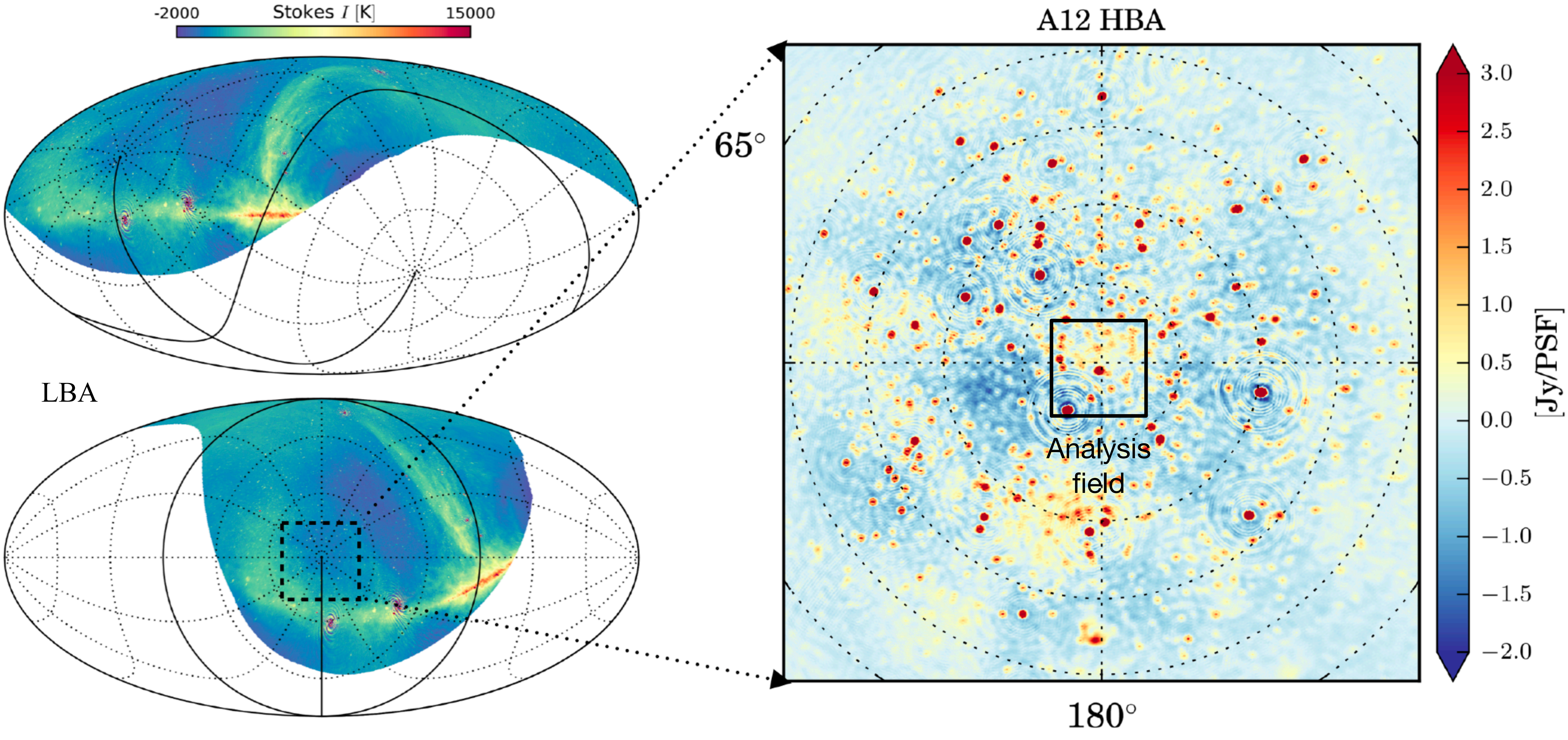
13 International stations
14 (NL) remote stations
24x2 core stations



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

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, but hardly any Stokes V)



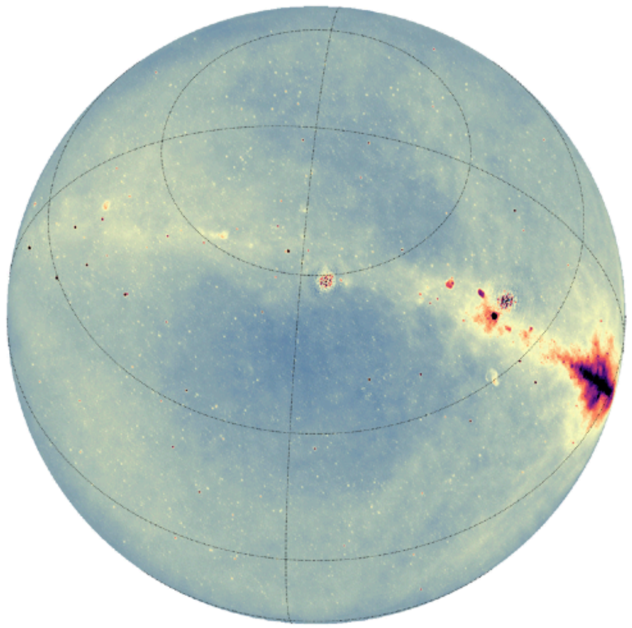
A recent wide-field view of the the NCP with LOFAR AARTFAAC-LBA- & HBA-12 system

Image credit: Bharat Gehlot & Florent Mertens

Signal Processing: Recent Advances

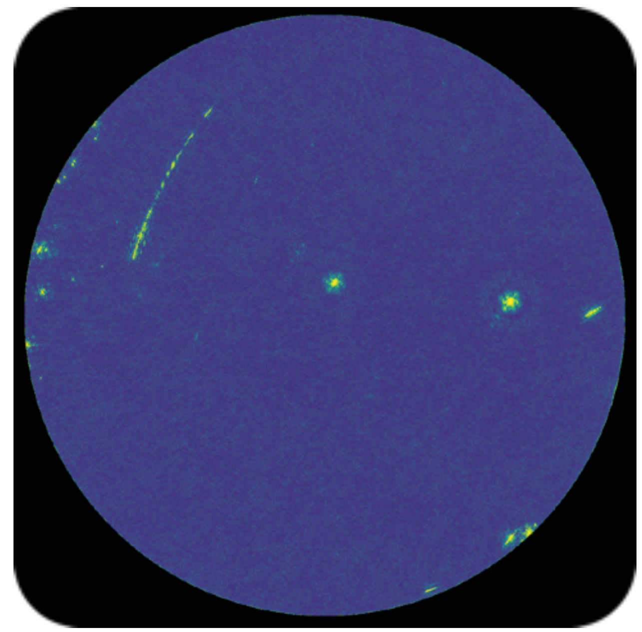
Bright Foregrounds/ Full-Stokes Sky Models

Gehlot et al. 2020



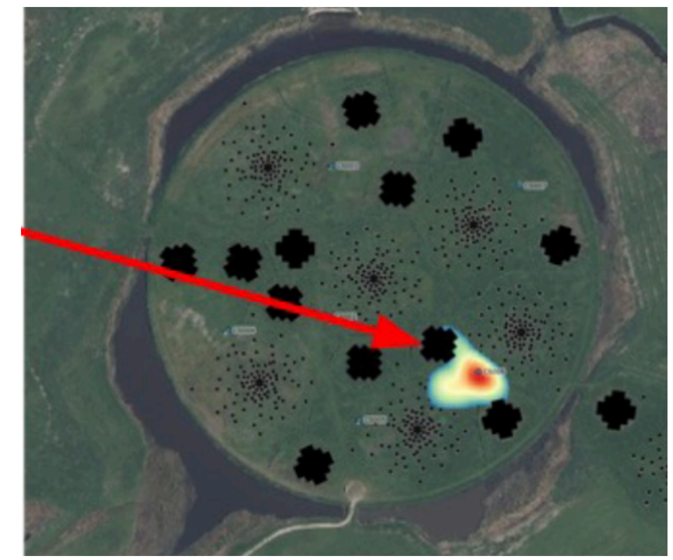
Radio Frequency Interference Mitigation

Gehlot et al. 2023



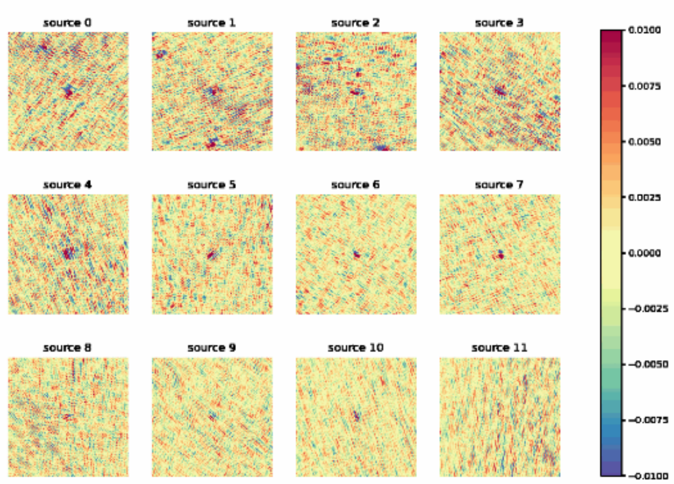
Near-Field RFI Imaging

Credit: Mevius & Mertens



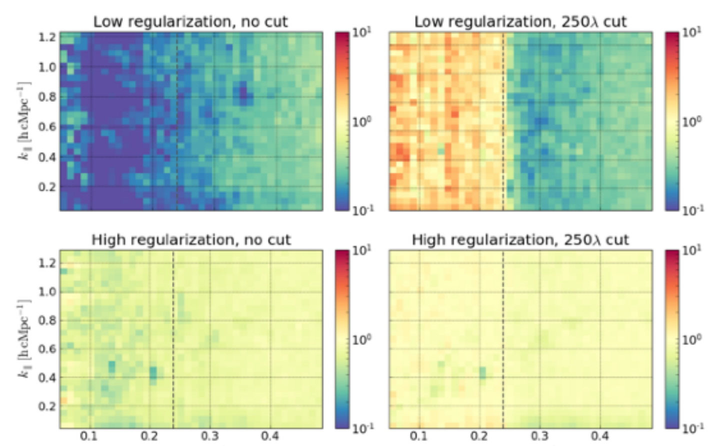
Ionospheric Refraction Diffraction

Credit: Brackenhoff



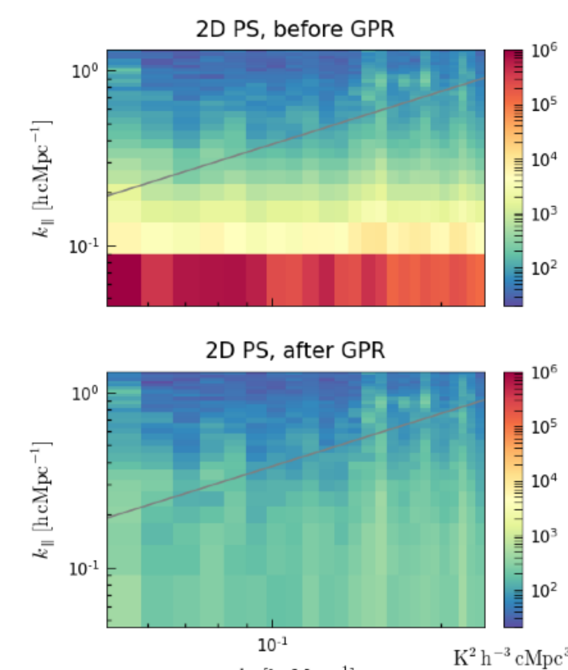
Frequency/Direction-Dependent Calibration

Mevius et al. 2022



GPR Data Modelling

Mertens et al.



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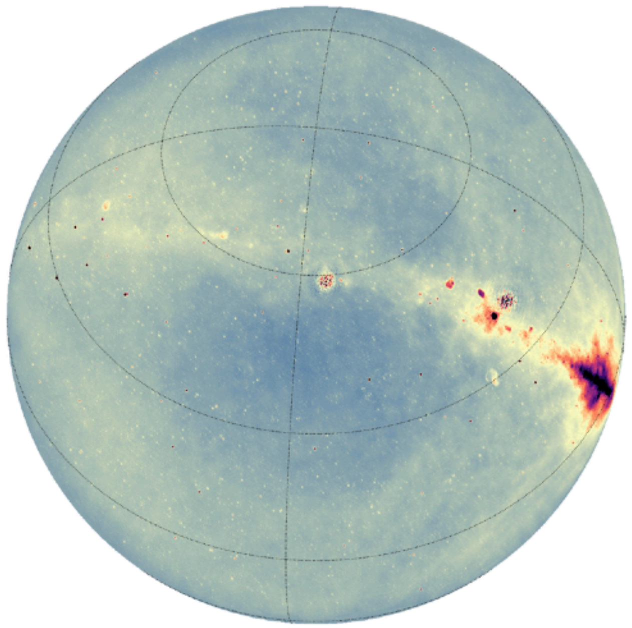
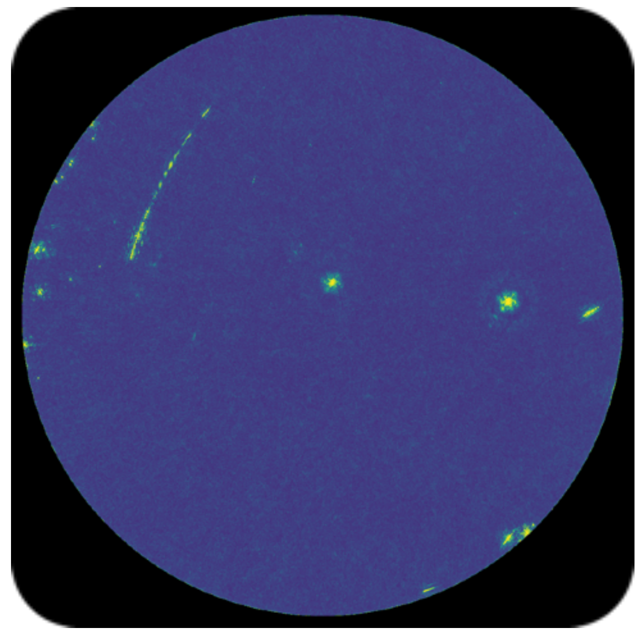
Gehlot et al. 2020



Radio Frequency Interference Mitigation

Gehlot et al. 2023



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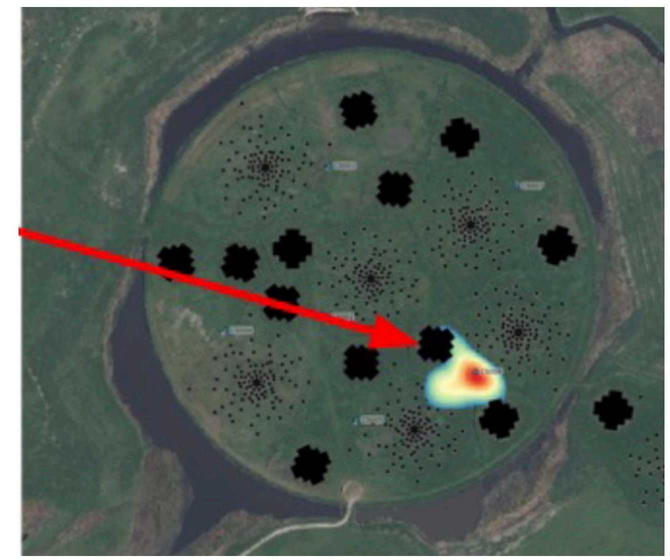

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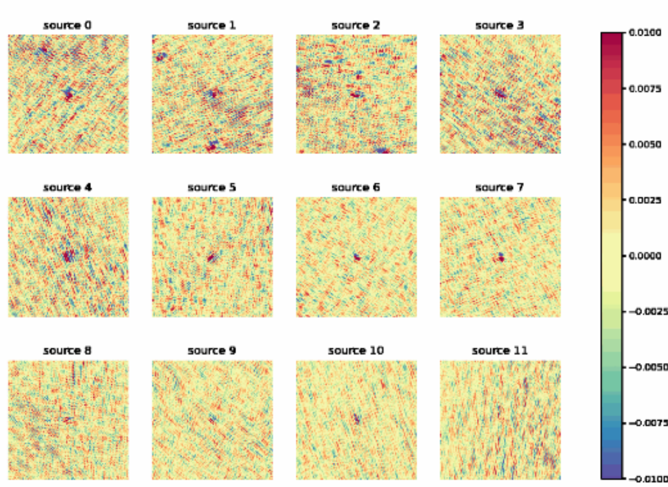
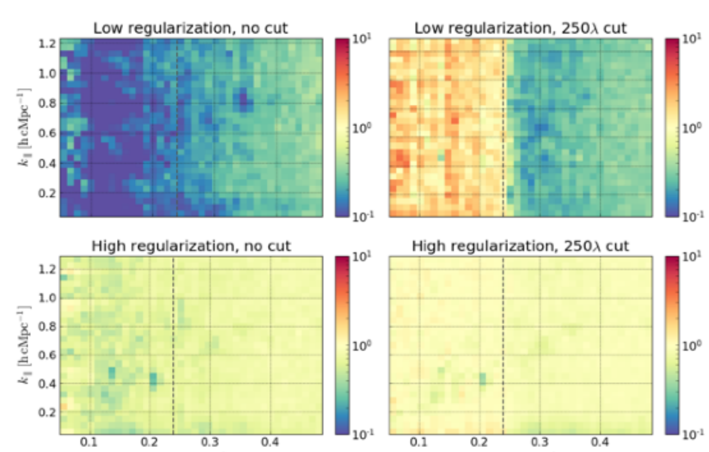


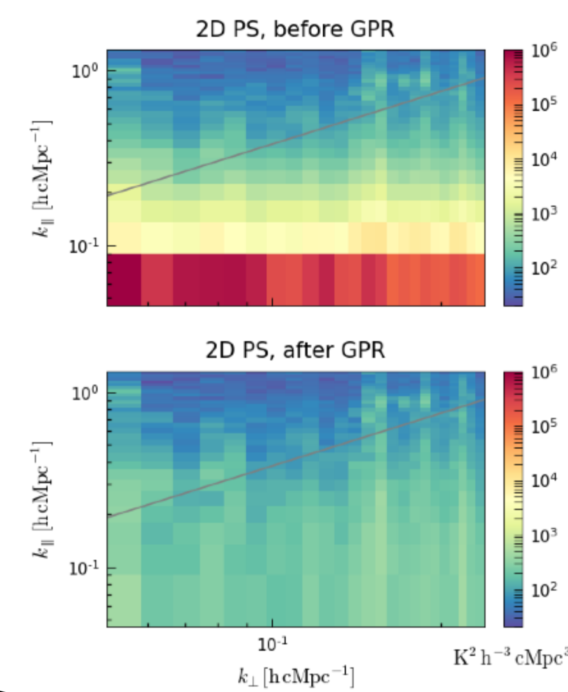
Frequency/Direction-Dependent Calibration

Mevius et al. 2022



GPR Data Modelling

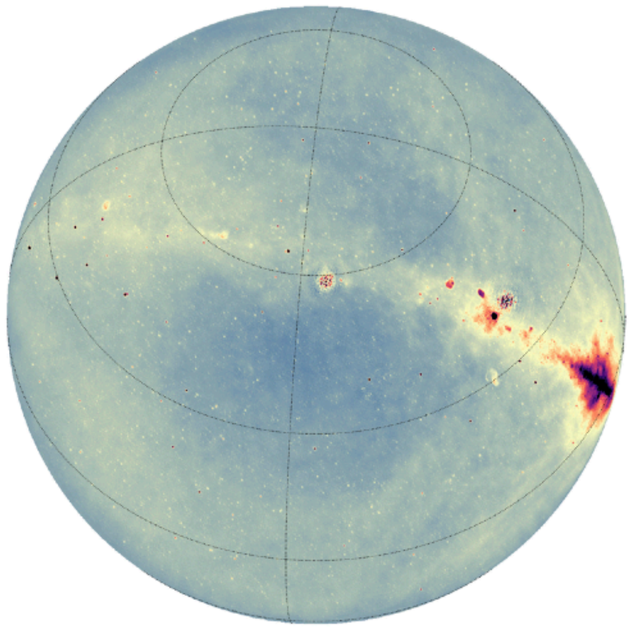
Mertens et al.



Signal Processing: Recent Advances

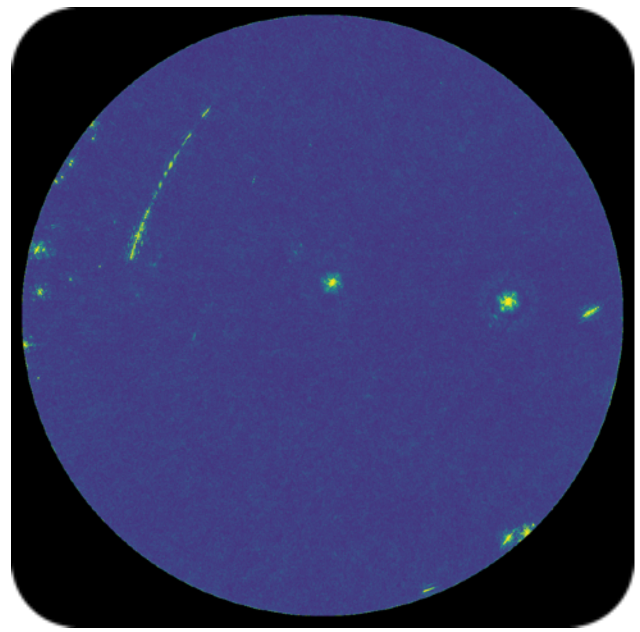
Bright Foregrounds/ Full-Stokes Sky Models

Gehlot et al. 2020



Radio Frequency Interference Mitigation

Gehlot et al. 2023



Near-Field RFI Imaging

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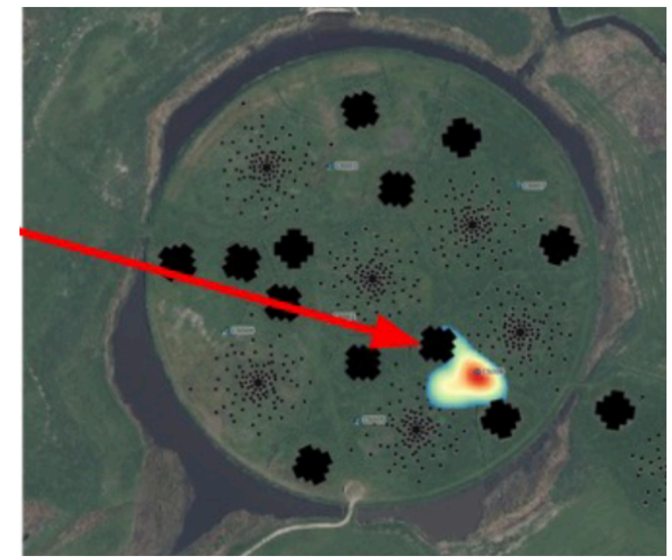

Ionospheric Refraction Diffraction

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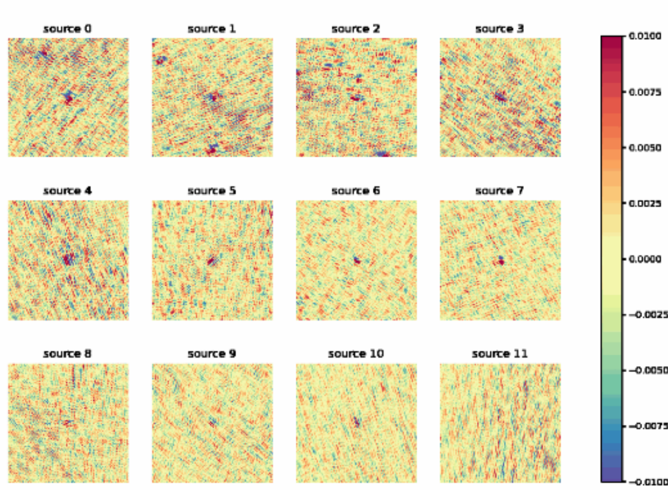

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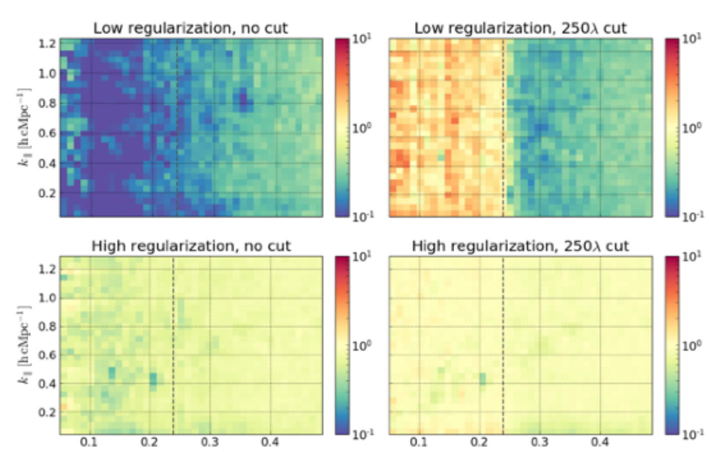
Mevius et al. 2022



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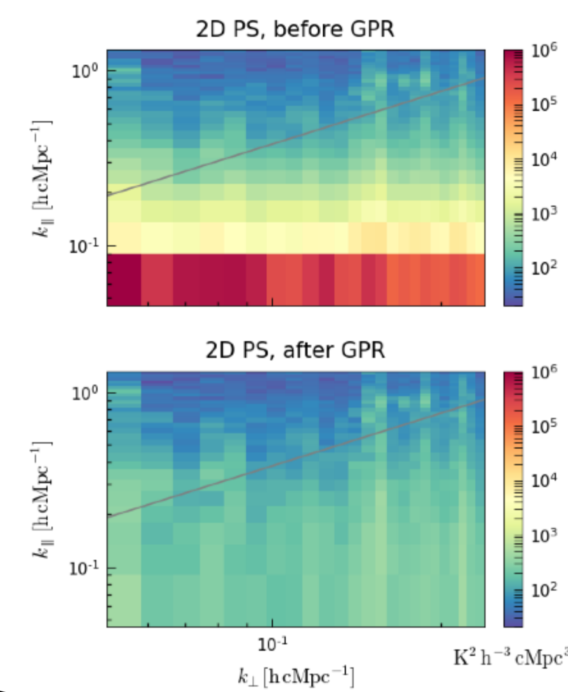
Mertens et al.



Signal Processing: Pipeline

All data processing codes have been developed in house and open source (many now in use by global community, e.g. AOFlagger, WSClean, etc) .

Processing pipeline

2019 – 2020

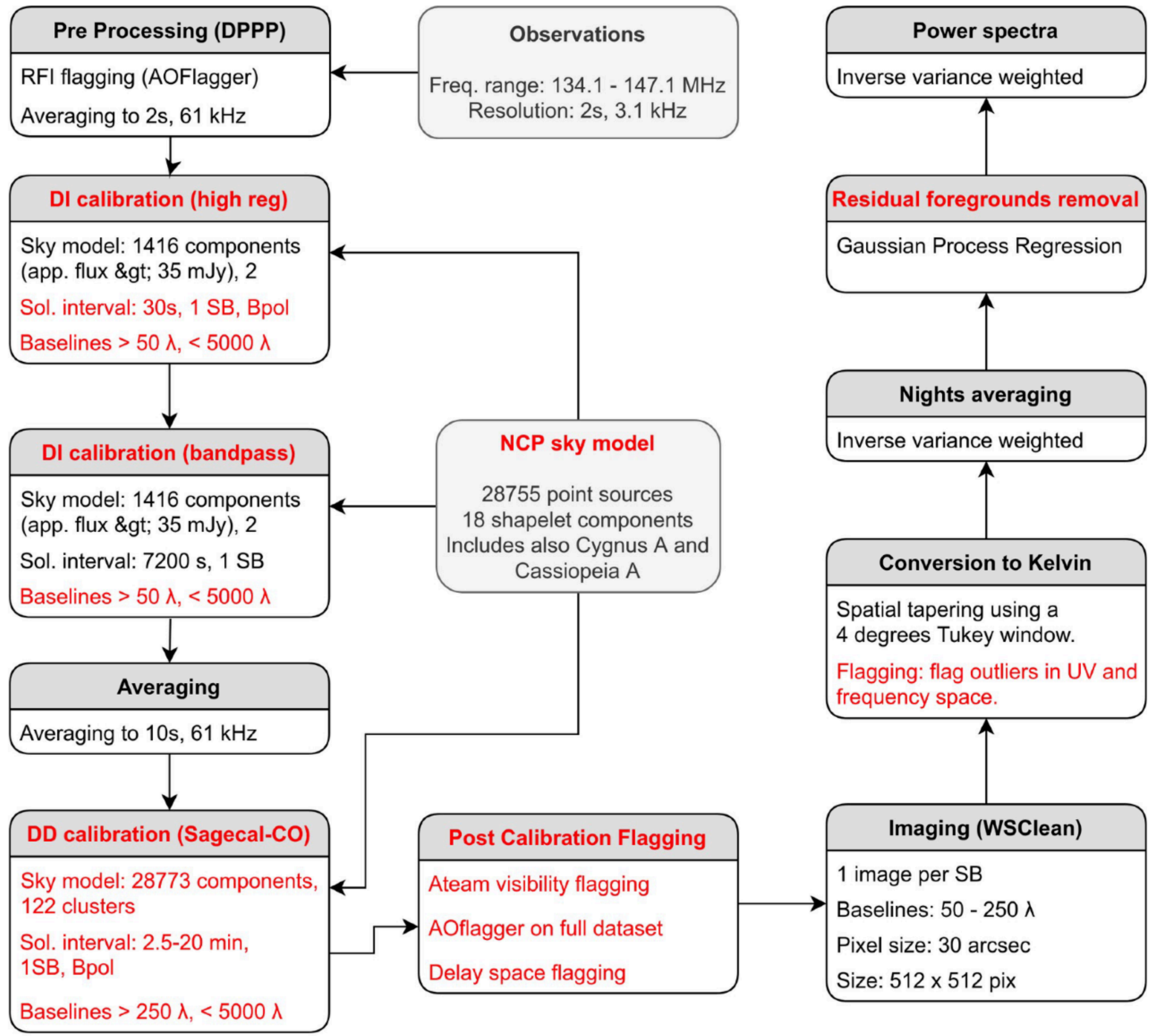
Improvements in DI calibration
- Separate Band-pass calibration
- Enforce smooth gain solutions

Improvements in RFI flagging
- Post calibration flagging
- Baseline flagging affected by local source of RFI

New improvements

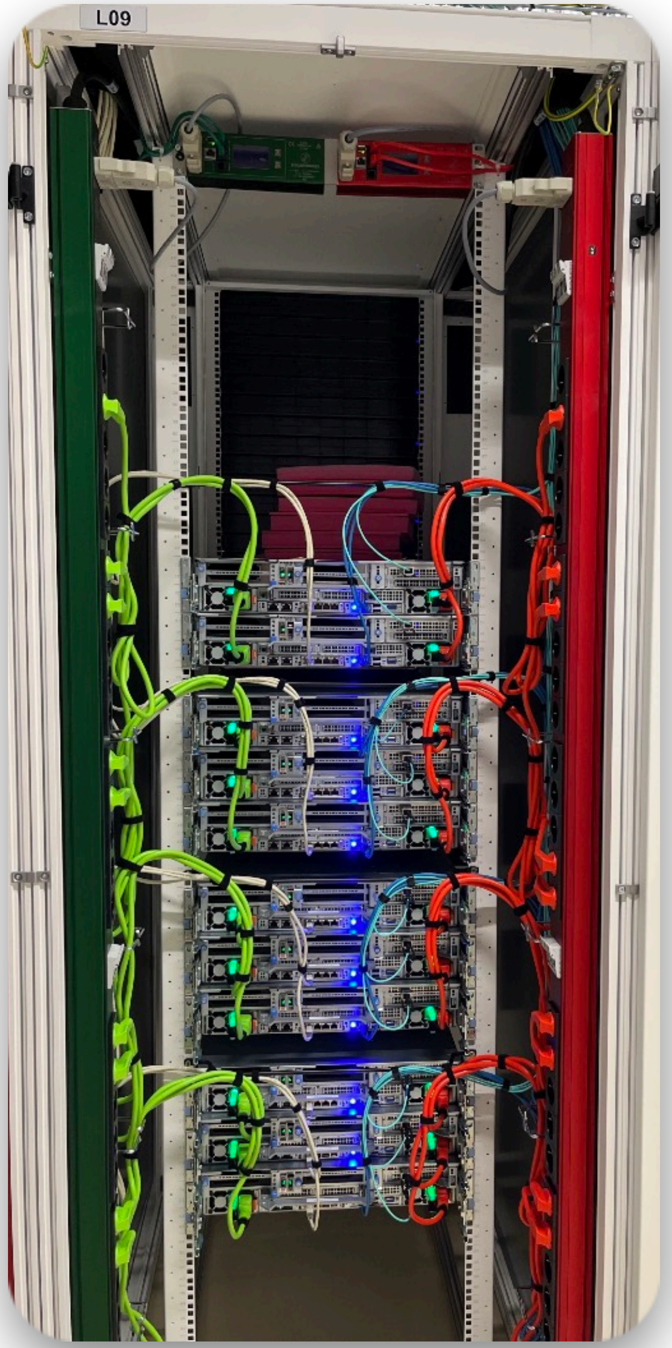
Improvements in DD calibration
- Enforce smooth gain solutions
- Discard outer clusters
- Simpler (better?) Cygnus A model

New ML-GPR
- Covariance from simulations
- Covariance depend on baseline
- Improved PS uncertainities

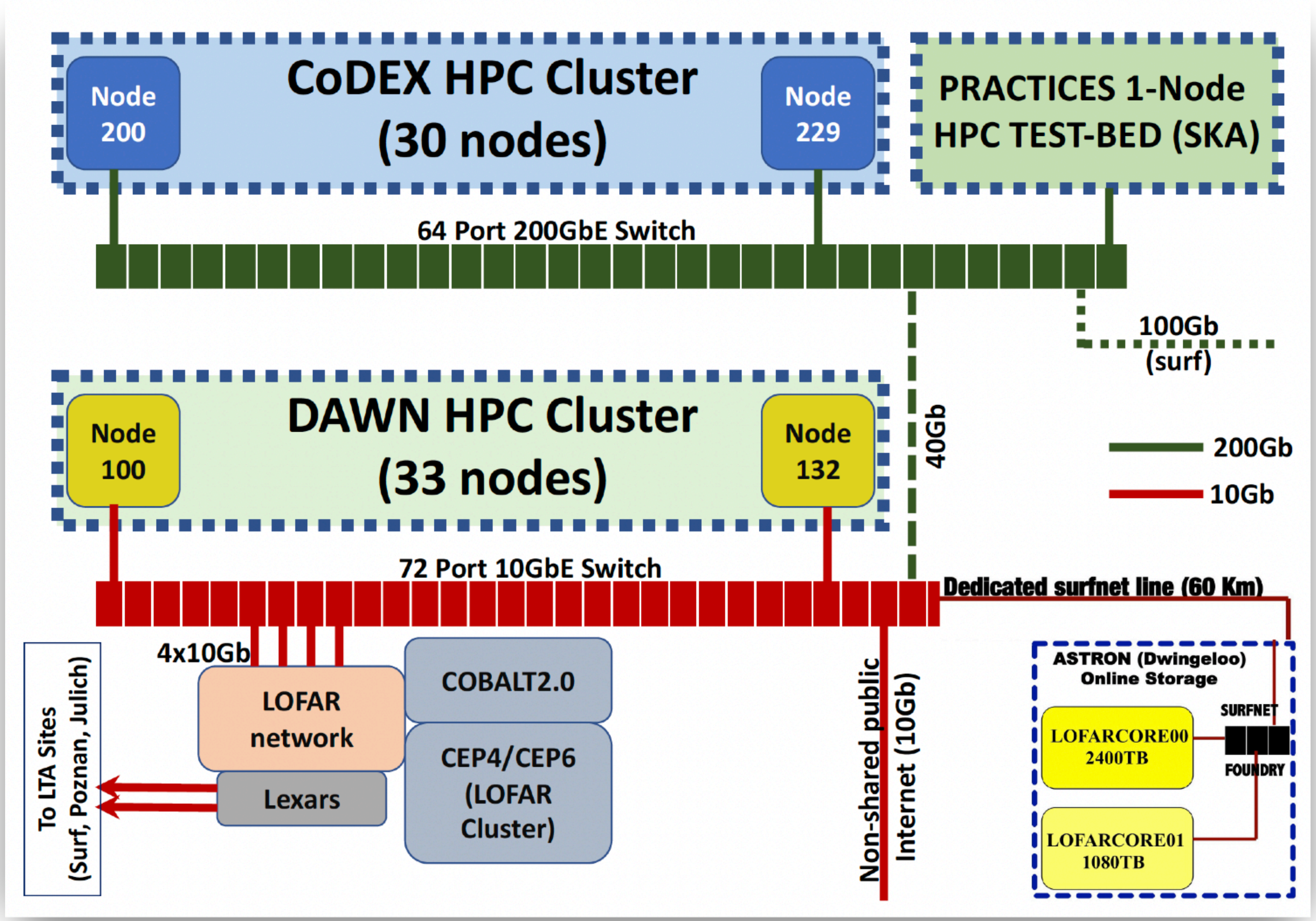


Signal Processing: HPC GPU computing

Data processing of ~5+ petabytes of data in hand requires dedicated peta-flops processing capacity: “Dawn” & “CoDEX” GPU clusters



Part of “CoDEX”
@ CIT-UG



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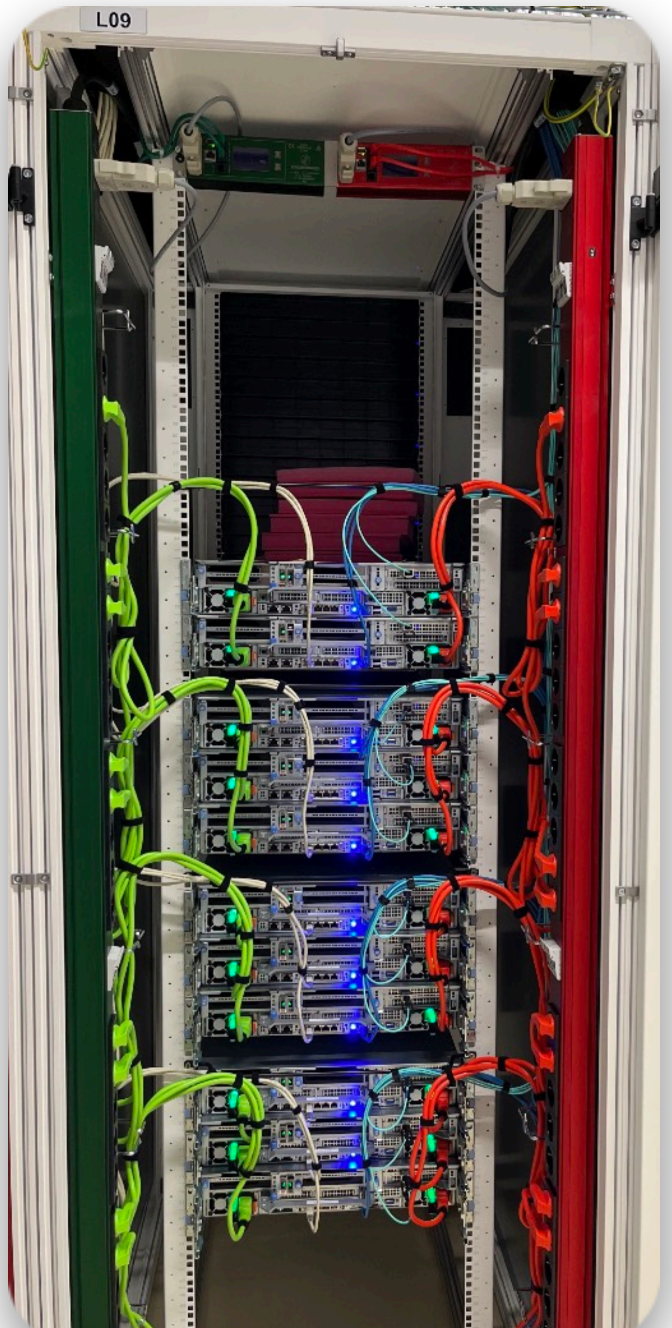


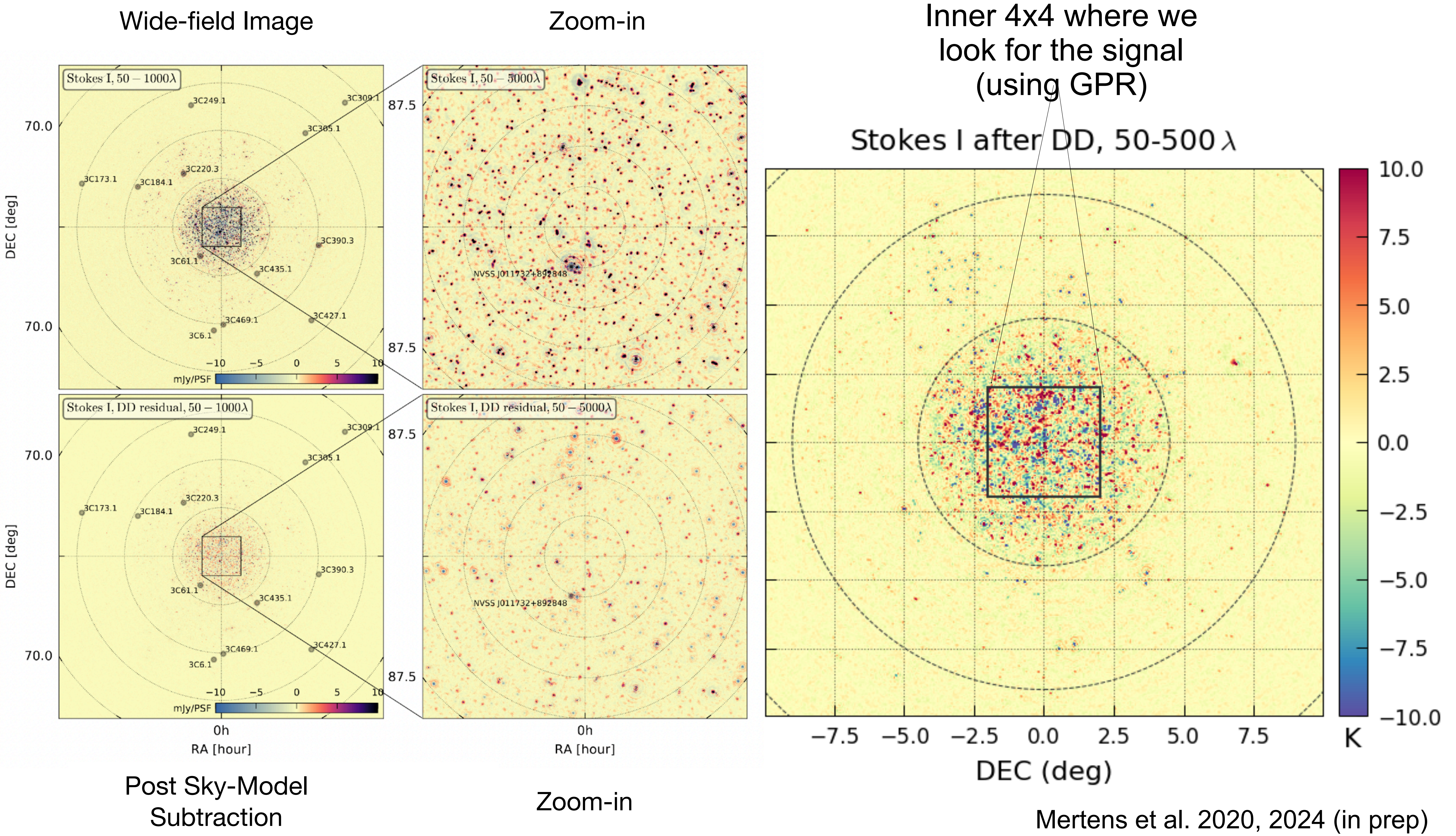
Part of “CoDEX”
@ CIT-UG

CoDEX HPC – Main Specs

- CPU (AMD Milan) - 3040 CPU cores – 350 TFLOPS
- GPU (A100 PCIe 40GB, Nvidia) – 1.2 PFLOPS
- 4608 TByte HDD data storage
- 200 GbE network
- ~16 TB SSD (separate disk for boot/OS)
- Connection to Dawn 40Gb
- Connection to Surf 100Gb (proposed)
- 29 production nodes (256GB, 2 x A100 40GB, 2 x 48 core CPU)
- One High memory Innovation node (1TB, 2 x A100 80GB, 2 x 64 core CPUs)

Signal Processing: DD-gain & Sky-Model Subtraction

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



Mertens et al. 2020, 2024 (in prep)

Signal Processing: GPR Signal Separation

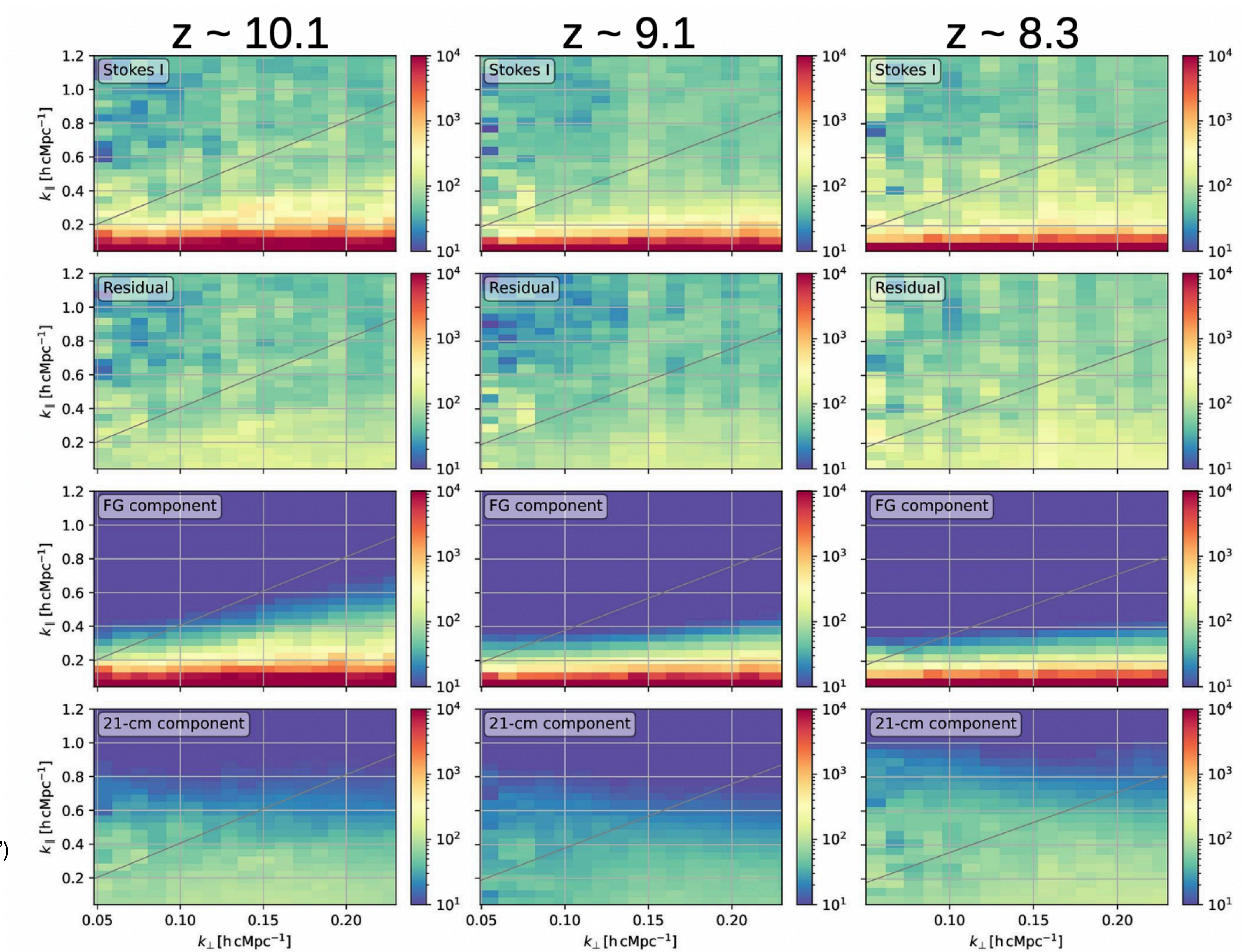
See talk of Florent Mertens

Data
(minus sky-model)

Residuals

Foregrounds

Rest
(incl. 21-cm signal
and “excess variance”)

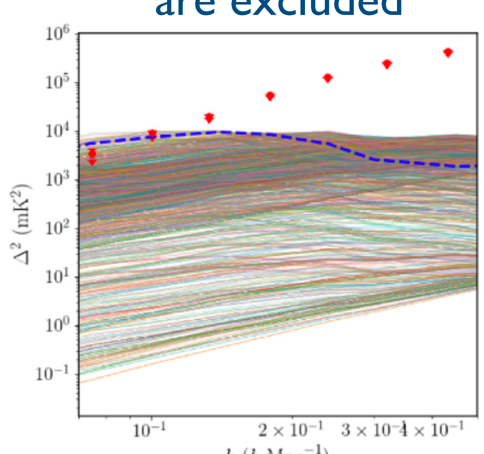


Mertens, Mevius et al. 2024, in prep.

Astrophysical Interpretations

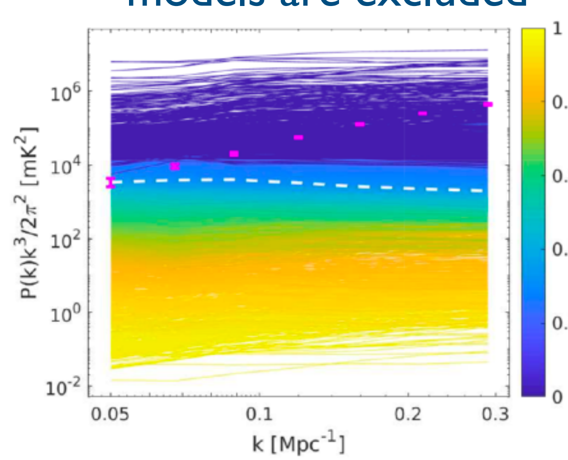
Theory and Simulations

Very cold IGM models are excluded



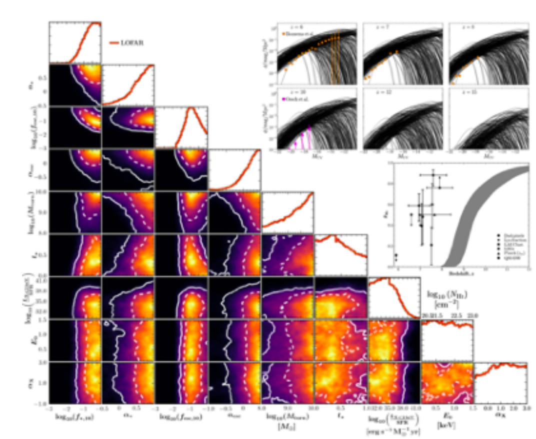
Ghara et al. 2020

Strong excess radio-background models are excluded



Mondal et al. 2020

Astrophysical models

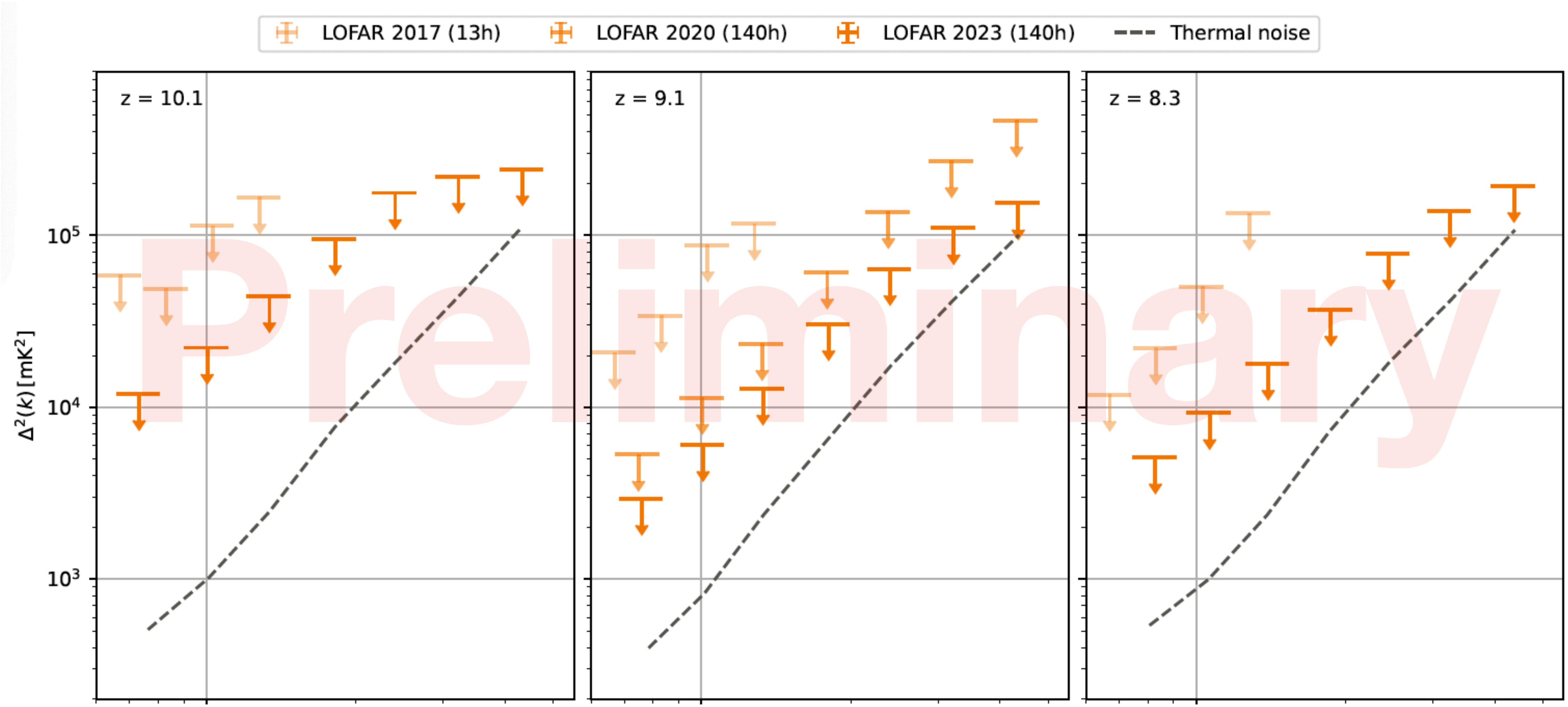


Greig et al. 2020

See talk of Garrelt Mellema

Where do we currently stand? (2024)

Based on all improvements, we reprocessed 140 hrs of data reaching 2x deeper levels with same data and expanded to 3 redshifts.



Next steps: with the new 1+ petaflop CoDEX GPU cluster, we plan to process ~10x data in the coming year.

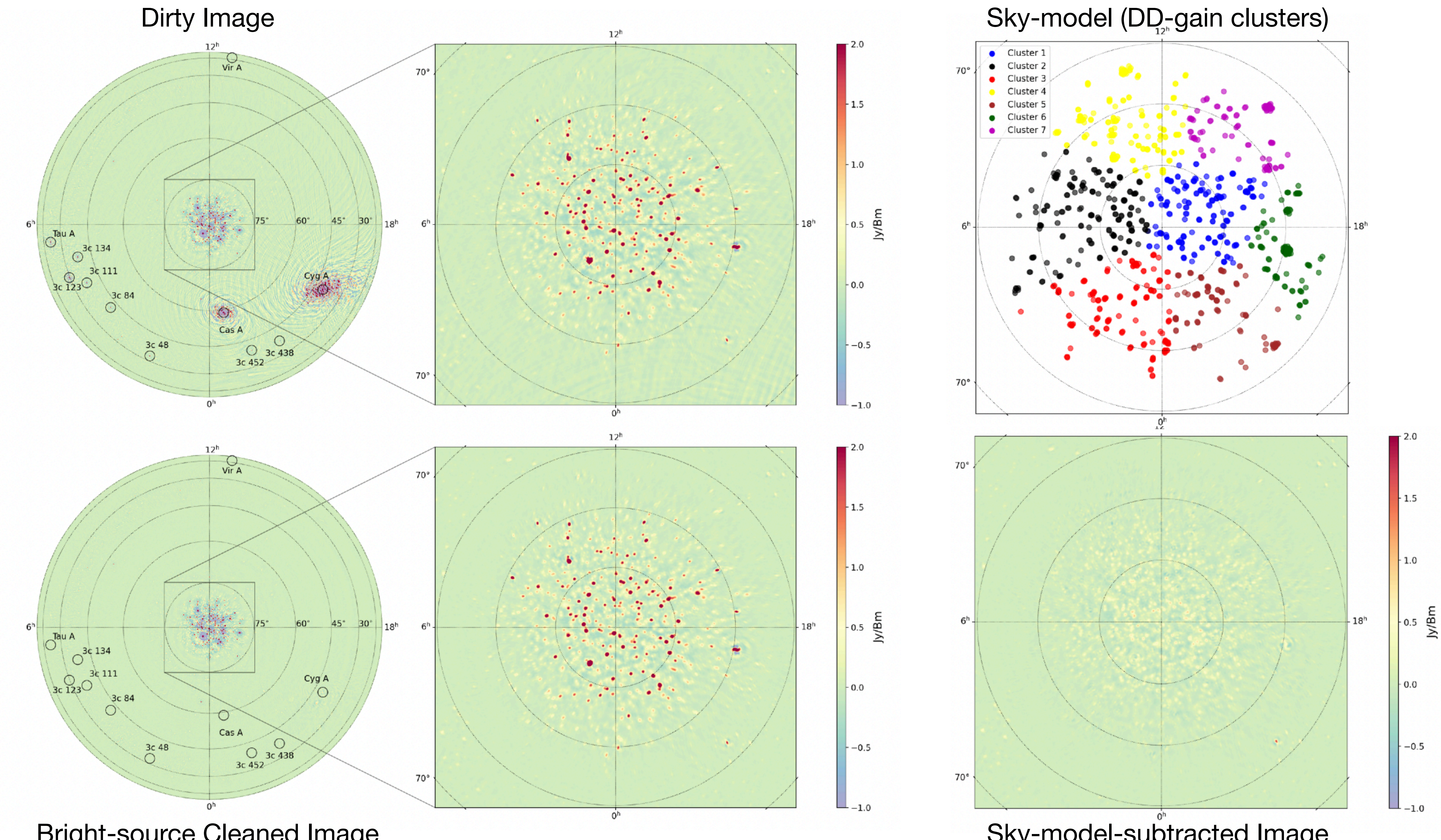
Image credit: Florent Mertens

New Extension in Nançay Upgrading LOFAR: NenuFar

Cosmic Dawn Key Science Program started in 2020 and continuing to collected data (over 1500 hours of data on NCP + other fields).

NenuFAR Cosmic Dawn Key Science Programme

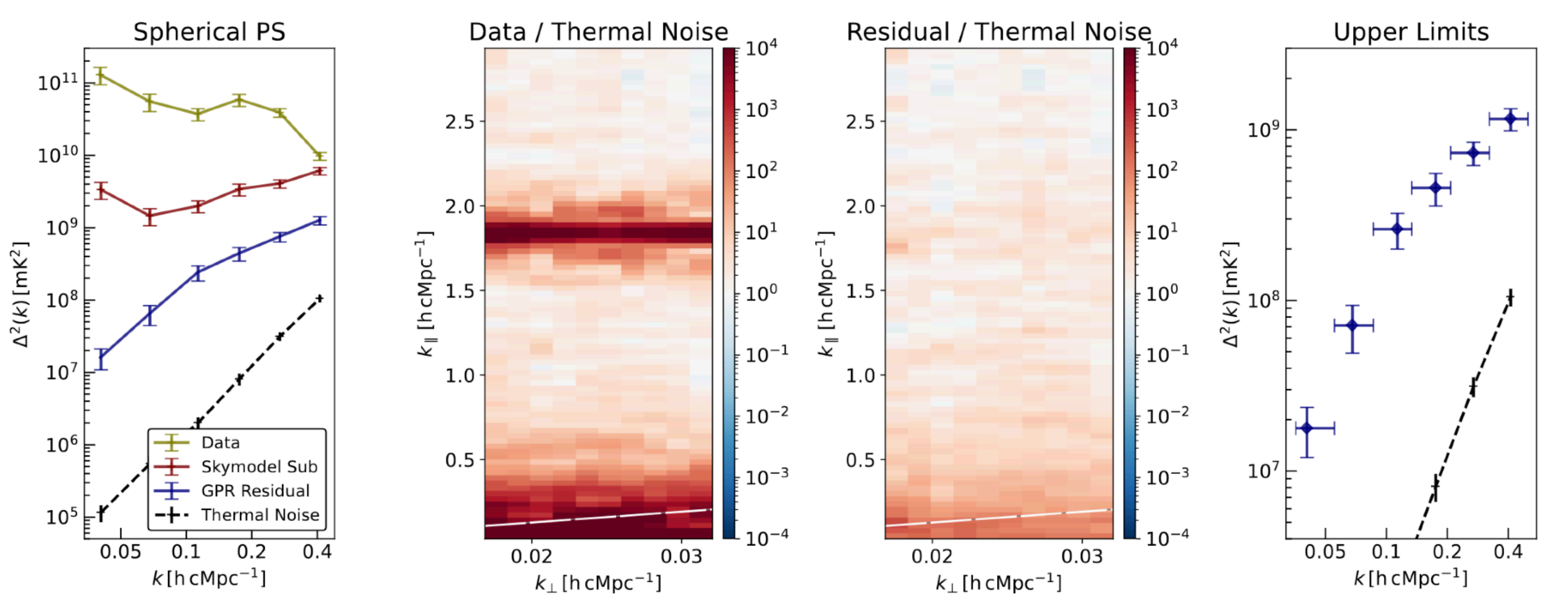
All-sky model, calibration and imaging is essential: Cas A & Cyg A are the “enemies”!



Munshi et al. 2024

NenuFAR Cosmic Dawn Key Science Programme

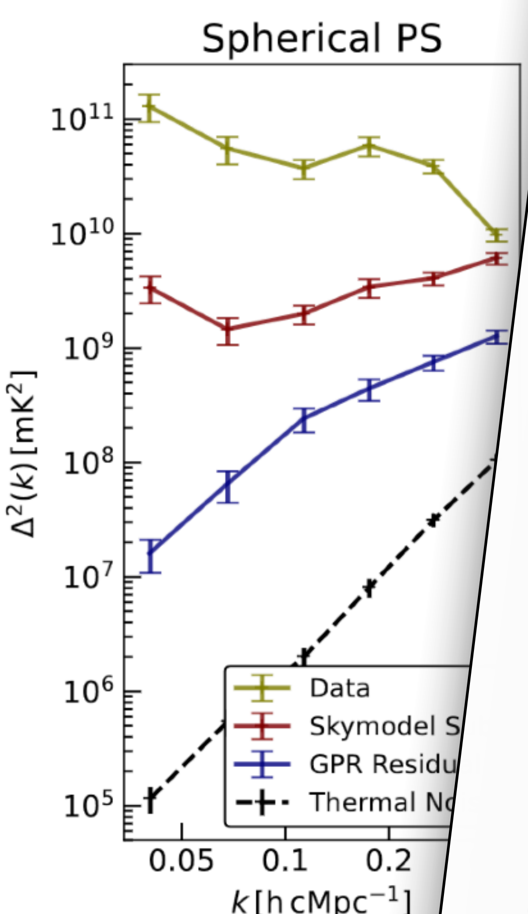
Applying ML Gaussian Process Regression models, directly connected to 21-cm models (e.g. 21cmfast, BEARS, GRIZZLY)



Munshi et al. 2024

NenuFAR C ... amme

Applying ML ... nected
to



A&A, 681, A62 (2024)
https://doi.org/10.1051/0004-6361/202348329

Astronomy & Astrophysics

First upper limits on the 21 cm signal power spectrum from cosmic dawn from one night of observations with NenuFAR

S. Munshi[1], F. G. Mertens[2,1], L. V. E. Koopmans[1], A. R. Offringa[3,1], B. Semelin[2], D. Aubert[4], R. Barkana[5,6,7], A. Bracco[8], S. A. Brackenhoff[1], B. Cecconi[9,10], E. Ceccotti[1], S. Corbel[10,14], A. Fialkov[11,12], B. K. Gehlot[1], R. Ghara[13], J. N. Girard[9], J. M. Grießmeier[15,10], C. Höfer[1], I. Hothi[2,8], R. Mériot[2], M. Mevius[3], P. Ocvirk[4], A. K. Shaw[13], G. Theureau[15,10,16], S. Yatawatta[3], P. Zarka[9,10], and S. Zaroubi[13,1]

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6 Institute for Advanced Study, 1 Einstein Drive, Princeton, New Jersey 08540, USA
7 Department of Astronomy and Astrophysics, University of California, Santa Cruz, CA 95064, USA
8 Laboratoire de Physique de l'Ecole Normale Supérieure, ENS, Université PSL, CNRS, Sorbonne Université, Université de Paris, 75005 Paris, France
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14 AIM, CEA, CNRS, Université Paris Cité, Université Paris-Saclay, 91191 Gif-sur-Yvette, France
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16 LUTh, Observatoire de Paris, Université PSL, Université de Paris Cité, CNRS, 92190 Meudon, France

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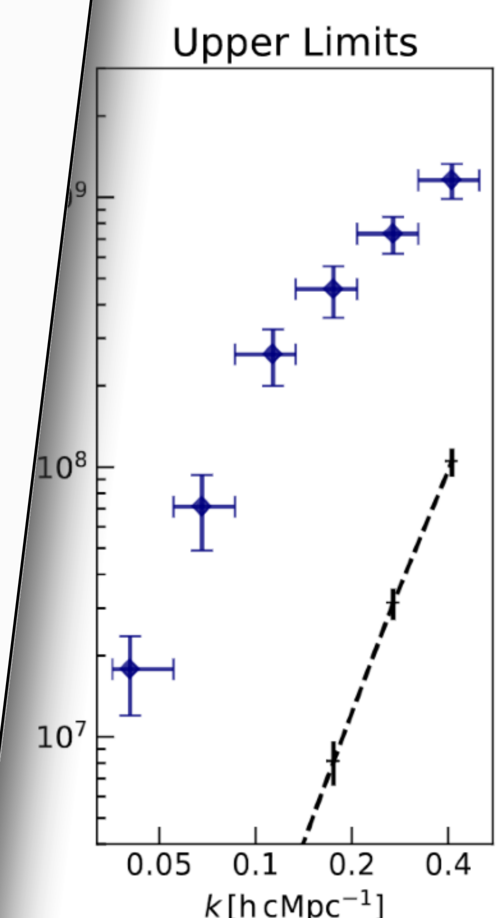
ABSTRACT

The redshifted 21 cm signal from neutral hydrogen is a direct probe of the physics of the early universe and has been an important science driver of many present and upcoming radio interferometers. In this study we use a single night of observations with the New Extension in Nançay Upgrading LOFAR (NenuFAR) to place upper limits on the 21 cm power spectrum from cosmic dawn at a redshift of $z = 20.3$. NenuFAR is a new low-frequency radio interferometer, operating in the 10–85 MHz frequency range, currently under construction at the Nançay Radio Observatory in France. It is a phased array instrument with a very dense uv coverage at short baselines, making it one of the most sensitive instruments for 21 cm cosmology analyses at these frequencies. Our analysis adopts the foreground subtraction approach, in which sky sources are modeled and subtracted through calibration and residual foregrounds are subsequently removed using Gaussian process regression. The final power spectra are constructed from the gridded residual data cubes in the uv plane. Signal injection tests are performed at each step of the analysis pipeline, the relevant pipeline settings are optimized to ensure minimal signal loss, and any signal suppression is accounted for through a bias correction on our final upper limits. We obtain a best 2σ upper limit of $2.4 \times 10^7\,\mathrm{mK}^2$ at $z = 20.3$ and $k = 0.041\,h\,\mathrm{cMpc}^{-1}$. We see a strong excess power in the data, making our upper limits two orders of magnitude higher than the thermal noise limit. We investigate the origin and nature of this excess power and discuss further improvements to the analysis pipeline that can potentially mitigate it and consequently allow us to reach thermal noise sensitivity when multiple nights of observations are processed in the future.

Key words. methods: data analysis – techniques: interferometric – dark ages, reionization, first stars

1. Introduction

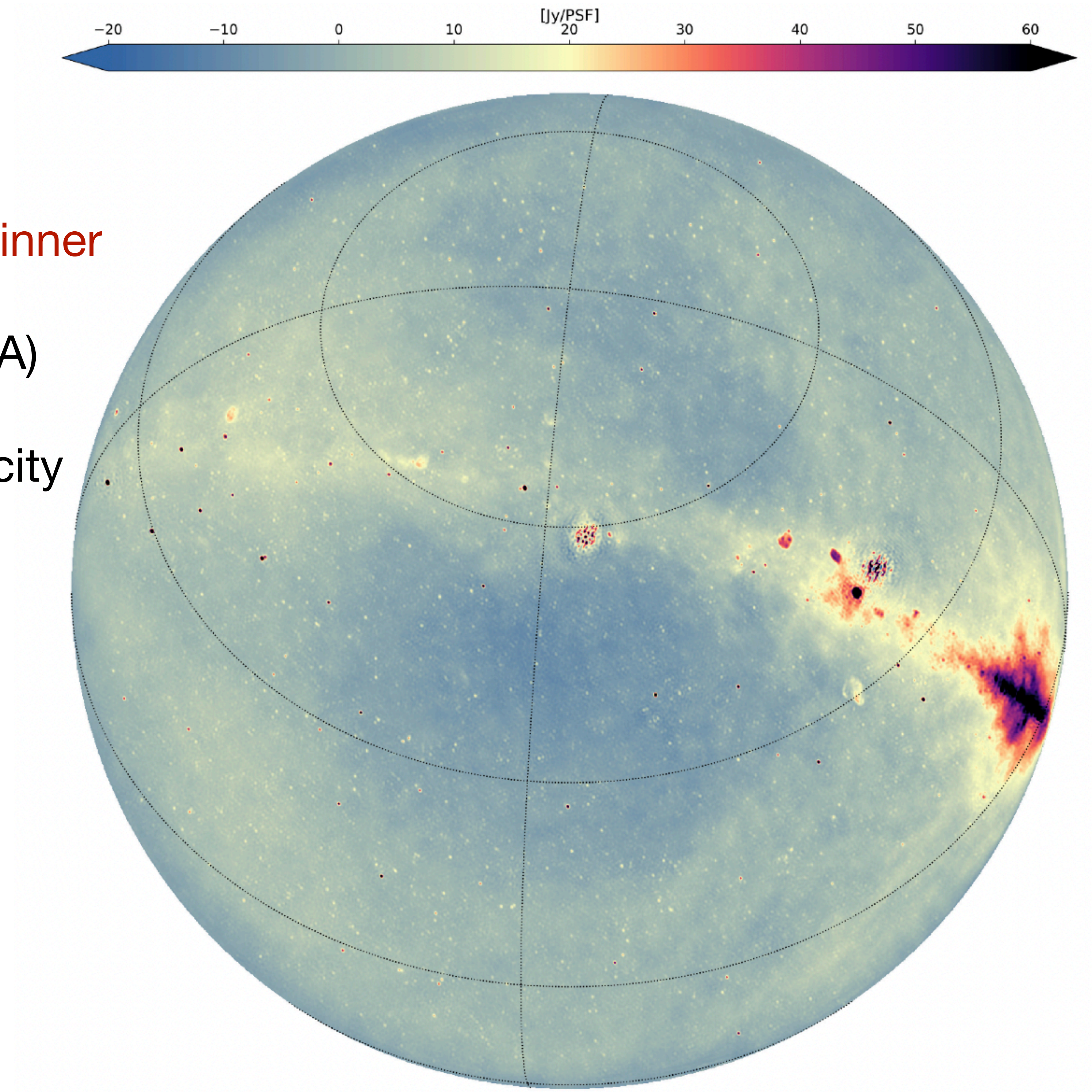
The redshifted 21 cm signal arising out of the hyperfine transition of neutral hydrogen (HI) is a very sensitive probe of the astrophysical processes active during the early stages of cosmic evolution (Madau et al. 1997; Shaver et al. 1999). Cosmic dawn is a particularly interesting epoch in the early universe for which the 21 cm signal can potentially give us rich insights. This is the period when the gas aggregated in dark-matter halos became dense enough to undergo gravitational collapse and form the first luminous objects in the universe. The two main processes believed to dominate during cosmic dawn are Lyman-α coupling and X-ray heating. The Lyman-α radiation emitted by the first sources couples the spin temperature of HI to the kinetic temperature of the intergalactic medium (IGM) through the Wouthuysen-Field effect (Wouthuysen 1952; Field 1958). Due to large spatial fluctuations in the distribution of early galaxies, this Lyman-α coupling is believed to have occurred



LOFAR-AARTFAAC Cosmic Explorer

AARTFAAC

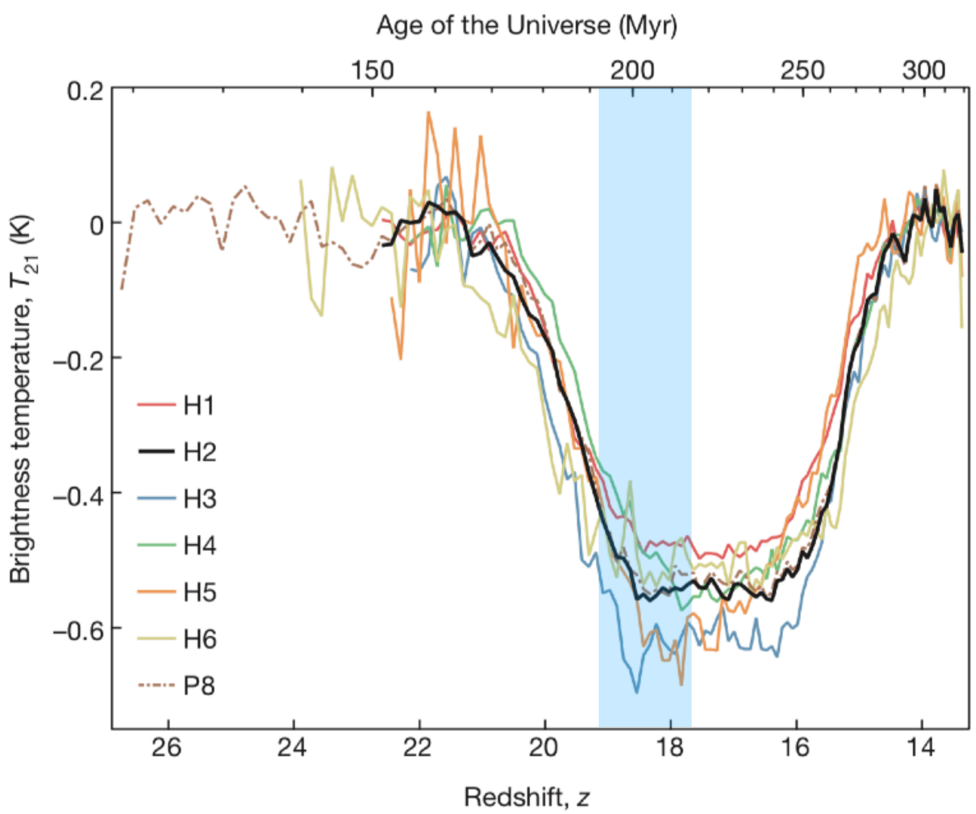
- Cross-correlation all dipoles/tiles of inner 6-12 stations (576 receivers)
- Full sky/beam field of view (LBA/HBA)
- Build originally for transients
- Limited BW due to correlators capacity



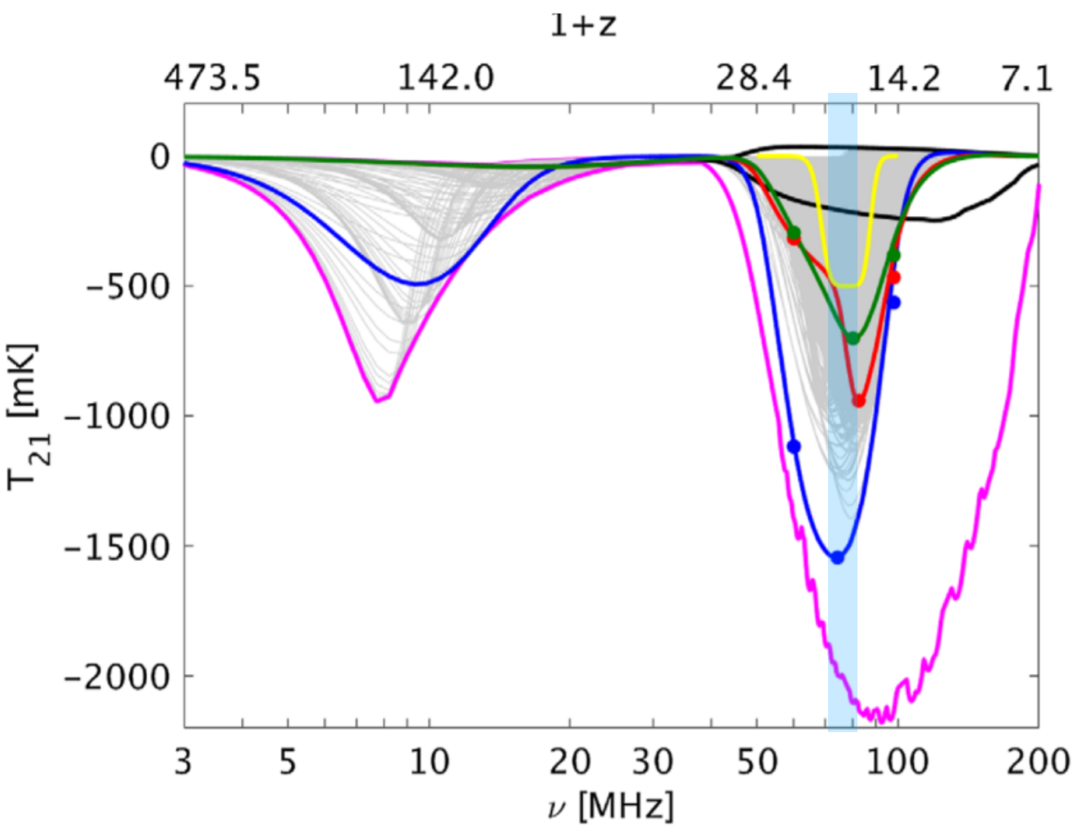
- PIs: Gehlot & Koopmans

LOFAR-AARTFAAC Cosmic Explorer

Bowman et al. 2018

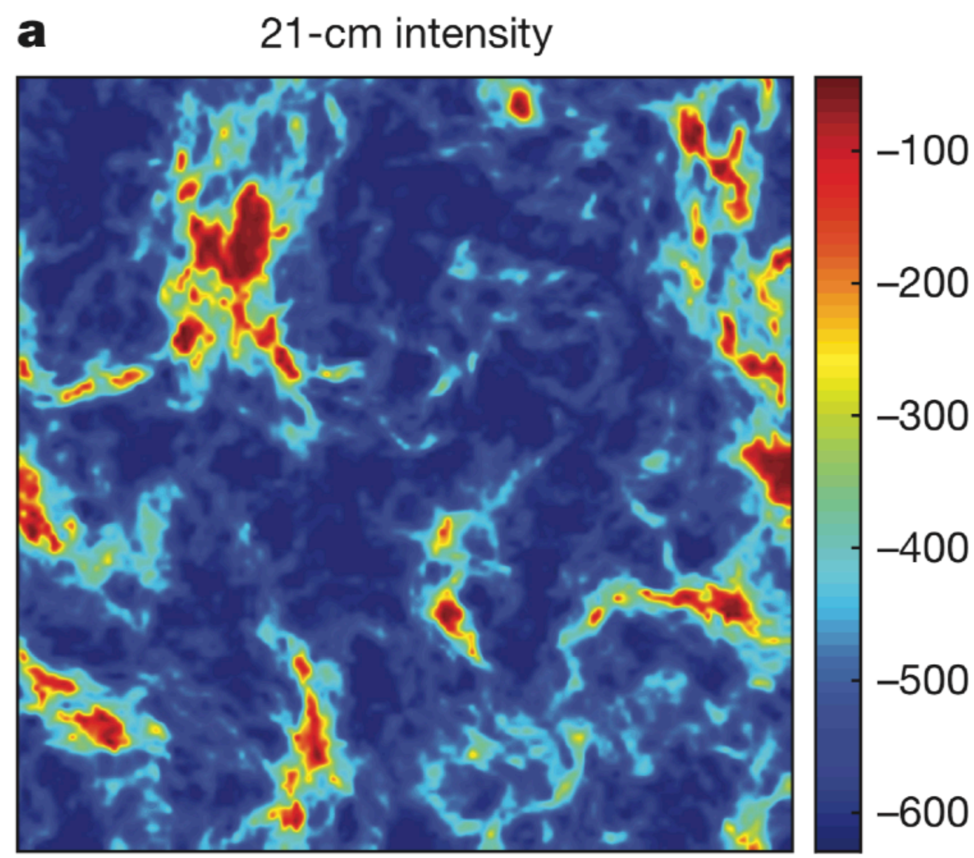


Fialkov et al. 2018



Aim: Exclude or detect power spectra Δ_{21}~0.1-1K @ k~0.1 cMpc^{-1} @ z~18

- In hand: 500 hrs of LOFAR-LBA data
- Cross-correlating 576 dipoles; all-sky FoV
- z~18 (72-75MHz; medium BW)
- Some signal strengths require 50x less integration time than standard models.



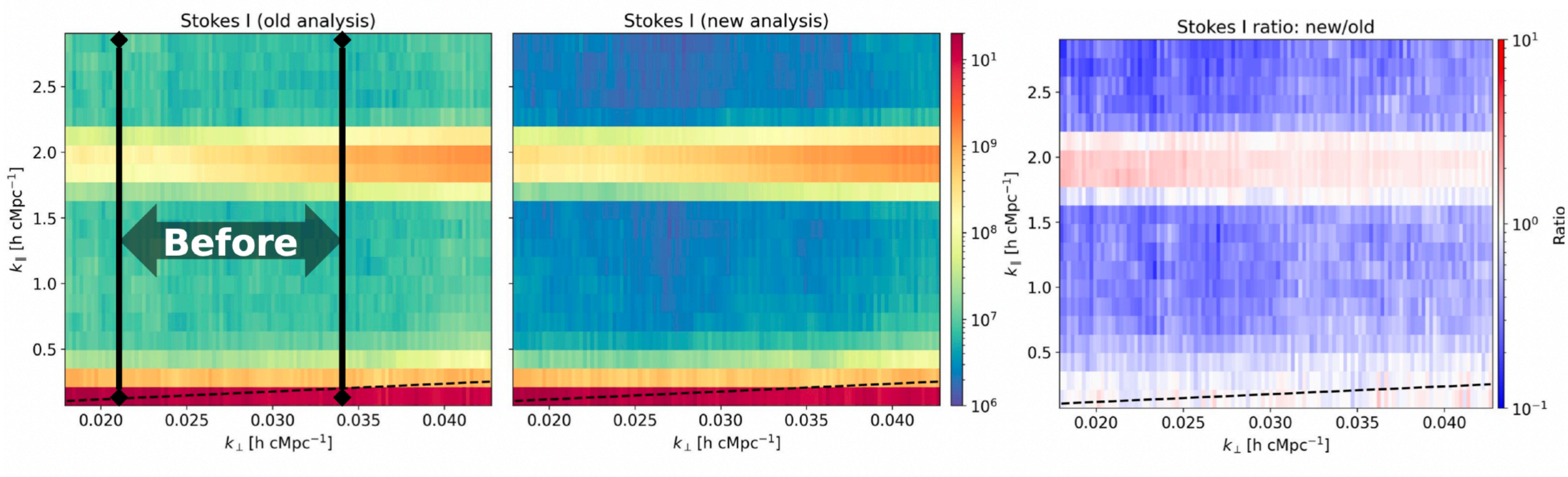
Barkanna et al. 2018

LOFAR-AARTFAAC Cosmic Explorer

In 2023, significant progress on the same 2 hours of data (of the current 500 hr in hand) as published first in 2020.

- Improved sky-model: 10,000 components rather than just 2 (Cas/Cyg)
- Improved RFI excision: several levels (pre-post calibration)
- Improved DI+DD cal. (DD-calibration instead of just DI calibration)
- etc.

OLD ANALYSIS | NEW ANALYSIS | RATIO



Gain by factor ~3 on same data

Gehlot et al. in prep

Where do we currently stand? (2024)

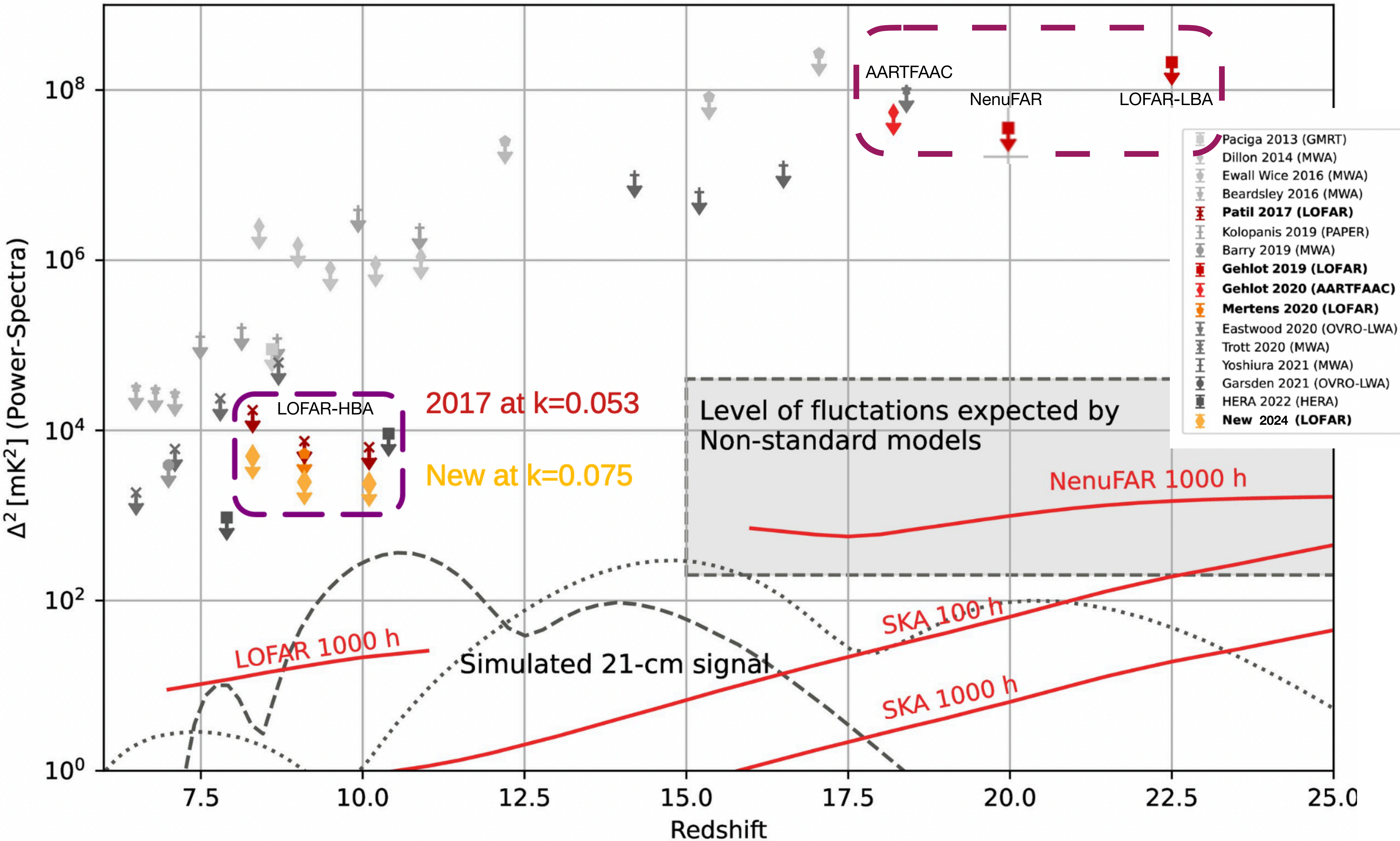


Image credit: Mertens

university of groningen
faculty of mathematics and natural sciences
kapteyn astronomical institute

The Next Frontiers: Tomography, Cosmic Dawn & Dark Ages

21-cm Cosmology with the SKA and from the Lunar Far-side, building on precursor and pathfinder results/techniques

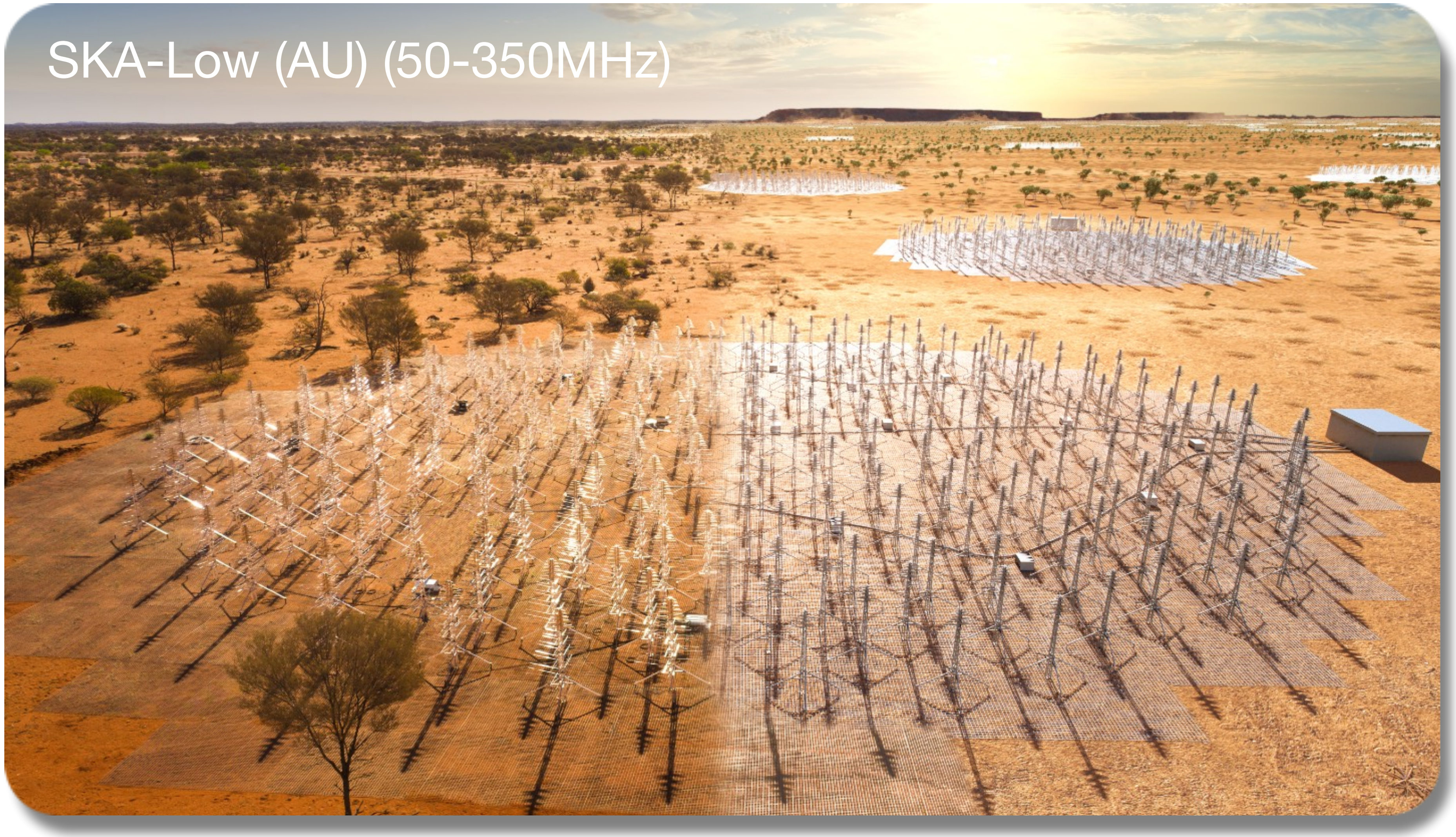
European Research Council
Established by the European Commission

Supported in part by
an ERC Advanced Grant "CoDEX"

The Square Kilometre Array: Tomography

Transformational Science:

- Tomography/Imaging during the Epoch of Reionization
- Power-spectra during the Cosmic Dawn (and EoR)
- HI absorption against high-z radio sources + IM z~3-6



The Square Kilometre Array: Power Spectra

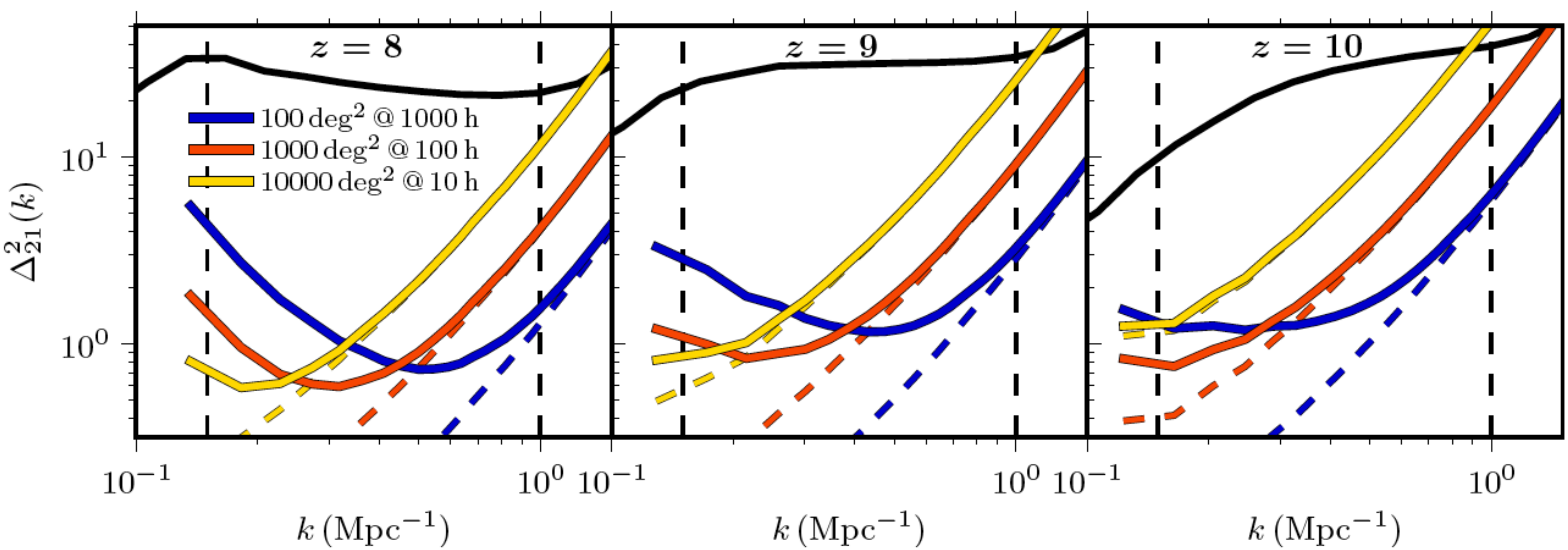
A three tiered-survey (3x5,000hrs):

- **DEEP**: 100sdq with 1000hr/pointing
- **MEDIUM**: 1000sqd with 100hr/pointing
- **SHALLOW**: 10000sqd with 10hr/pointing

Deeper is better for small scales (less thermal noise; bubbles)

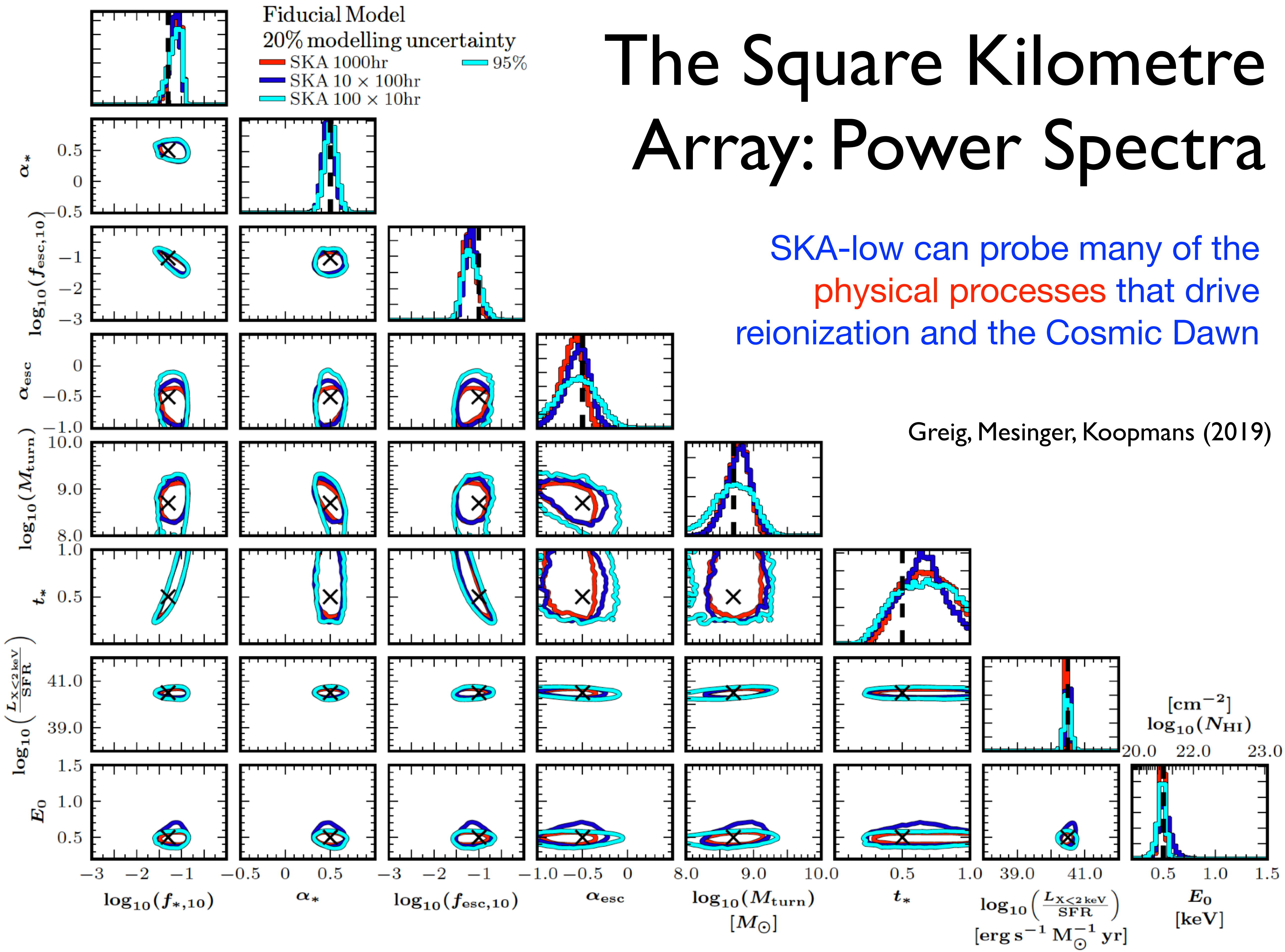
Wider is better on large scales (less sample variance)

Both are needed (PS+Tomography)



Greig, Mesinger & Koopmans (2015)

The Square Kilometre Array: Power Spectra

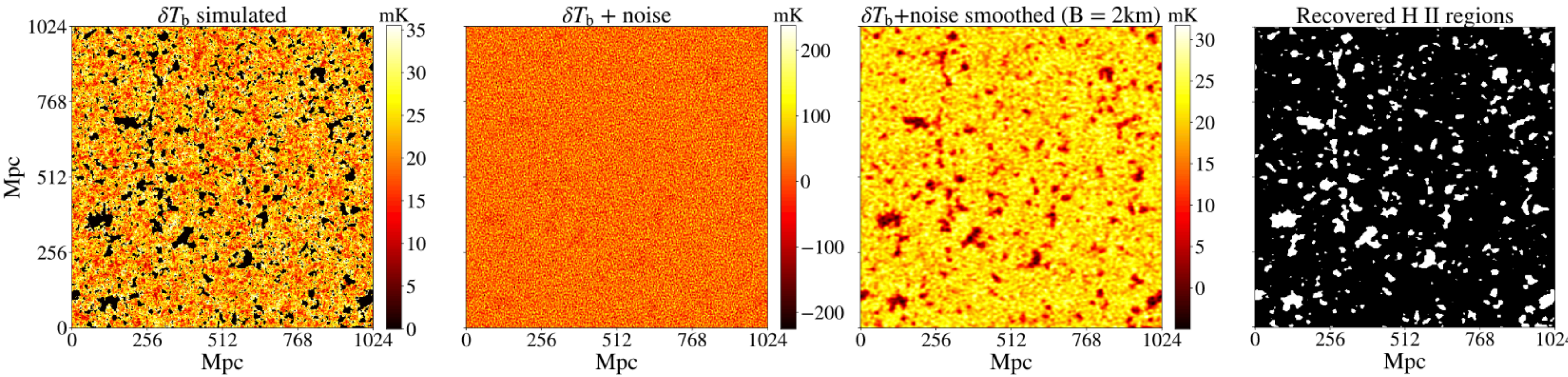


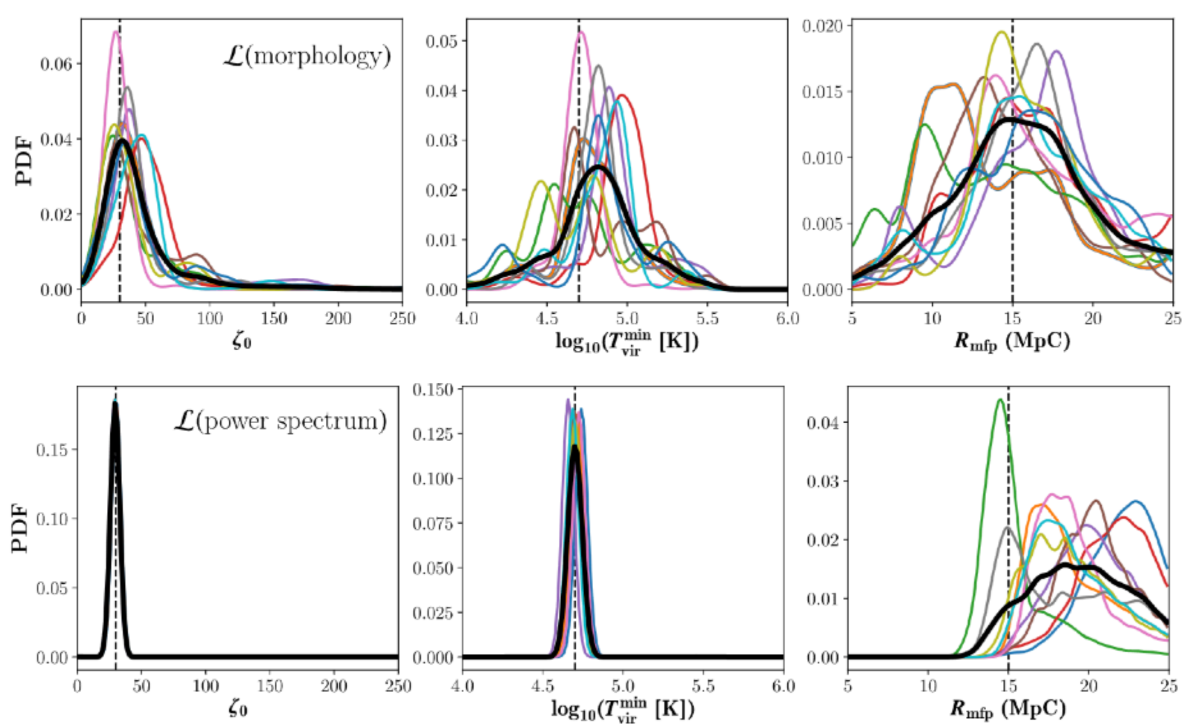
SKA-low can probe many of the physical processes that drive reionization and the Cosmic Dawn

Greig, Mesinger, Koopmans (2019)

The Square Kilometre Array: Tomography

SKA is sensitive enough to directly image the 21-cm signal (and bubbles) during the Epoch of Reionization





Bubble Analysis - for some parameters less accurate, but less biased

Power Spectrum - for some parameters more accurate, but sometime biased

Gazagnes et al. 2021

Dark-ages EXplorer (DEX) — ALO

ESA Explorer Mission Concept (Phase 0 study)

- Concept for a low-frequency radio telescope on the lunar surface (pole/far-side)
- Science payload on several of first EL3 landers
- Both global 21-cm signal receivers (pole/far-side) and array for 21-cm power-spectrum/ tomography observations (lunar far-side)
- Covering Cosmic Dawn and Dark Ages redshifts (z>~15), needing >10^4 hours of integration.

European Large Logistics Lander (concept)

Dark-ages EXplorer (DEX) — ALO

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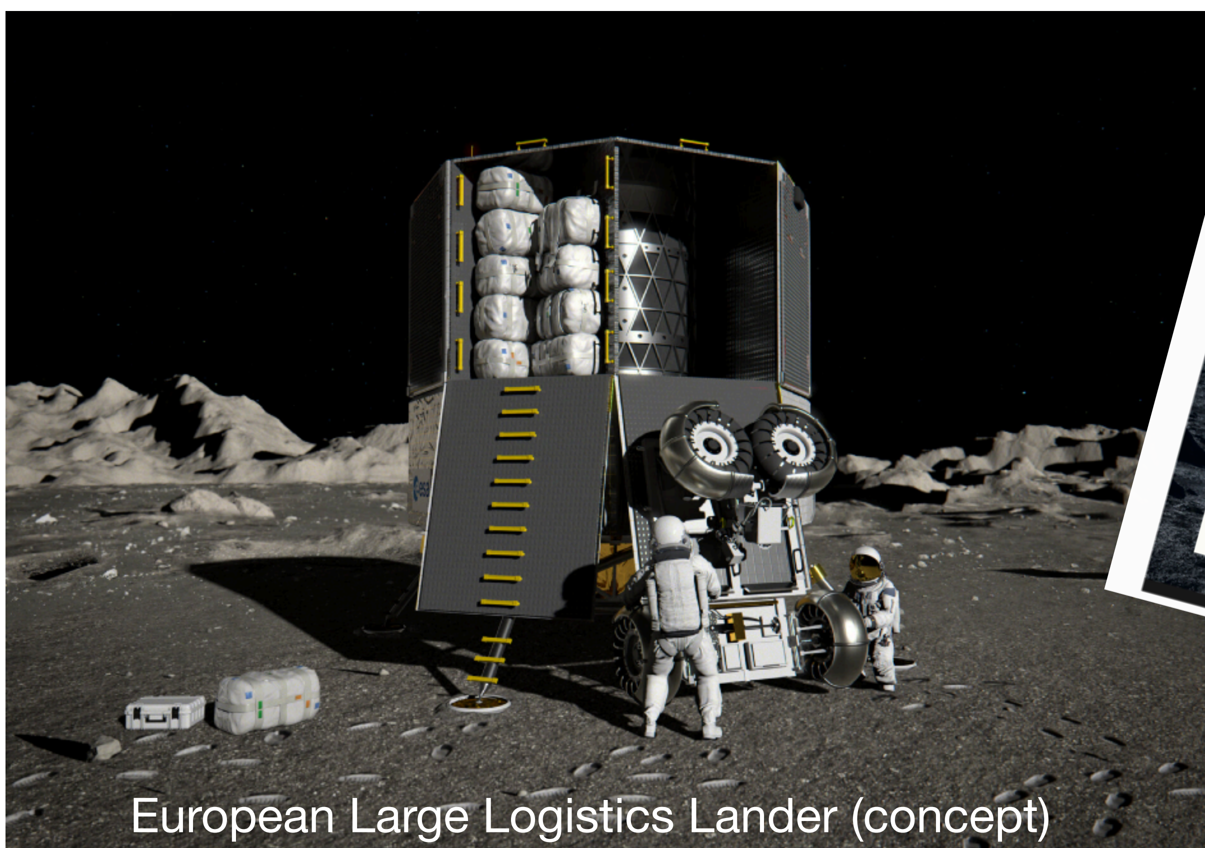

European Large Logistics Lander (concept)


10

WETENSCHAP

ZATERDAG 21 OKTOBER 2023

Radiotelescoop speurt naar oudste geluid

Luisteren op de achterkant van de maan

Een radiotelescoop op de achterzijde van de maan plaatsen om met metingen een eerste 'beeld' te krijgen van het heelal kort na de oerknal. Het is een immense opdracht waar astronoom Léon Koopmans zich in vastbijt.

HANS VAN ZON

'De telescoop moet groot worden, het liefst een kilometer bij een kilometer'

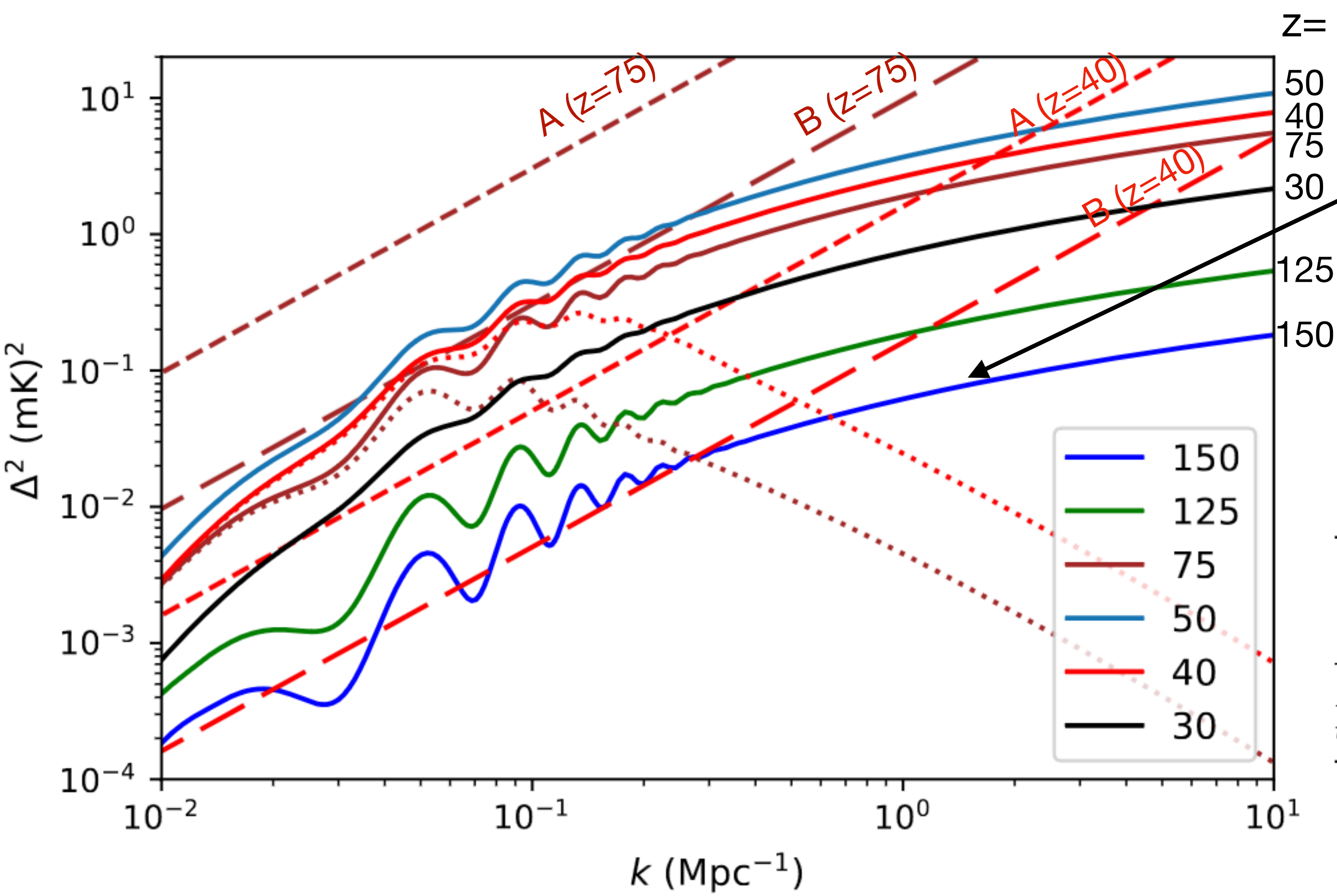
'We willen iets nieuws gaan doen'

Léon Koopmans is goed in de interpretatie.

Marc Klein Wolt is de technische man.

Dark-ages EXplorer (DEX) — ALO

Power-spectrum sensitivity for 16 (4x4), 1024 (32x32), 16384 (128x128) receivers:
Compact (f=1) array, 5m dipoles, BW=10MHz, 10^4h integration, half-sky



The (Cosmological) Standard models exactly predicts the signal

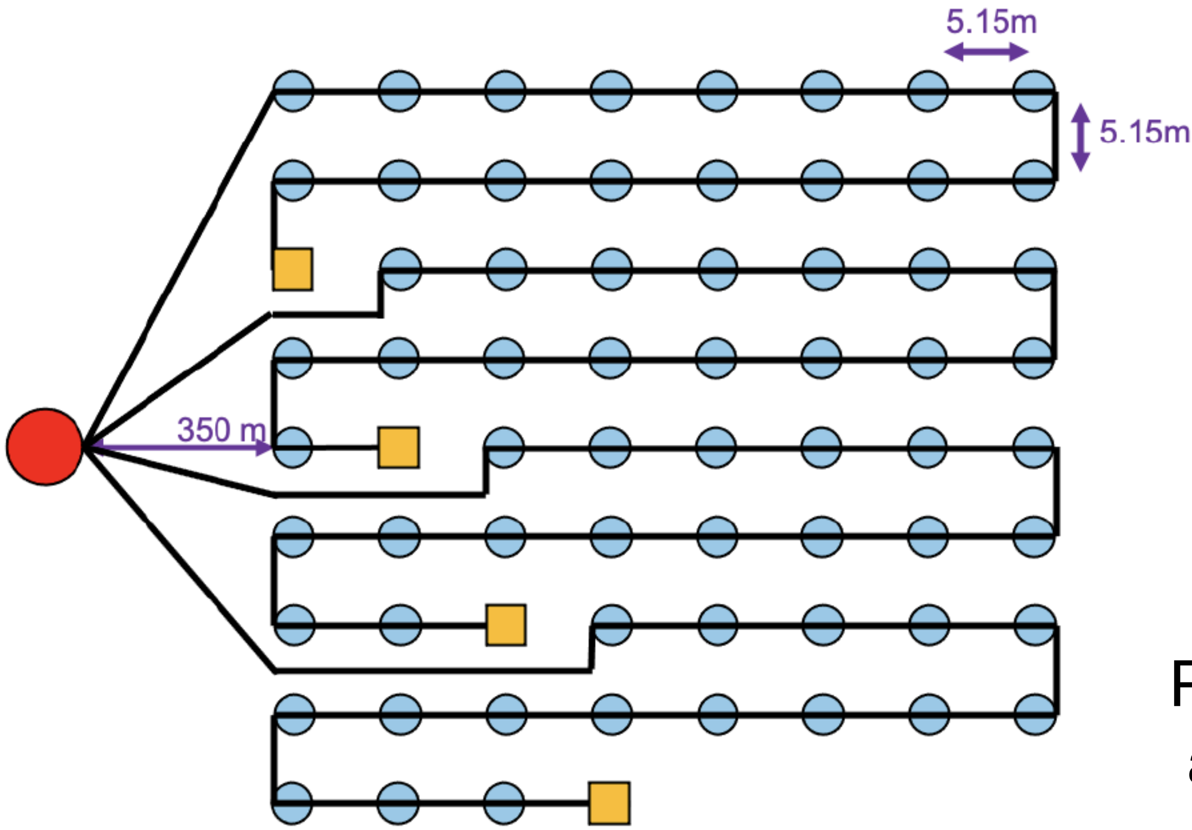
Mondal & Barkana 2023

	Configuration			
	D	C	B	A
$A_{\rm coll}$ [km^2]	100	100	10	10
$t_{\rm int}$ [hrs]	10,000	1,000	10,000	1,000

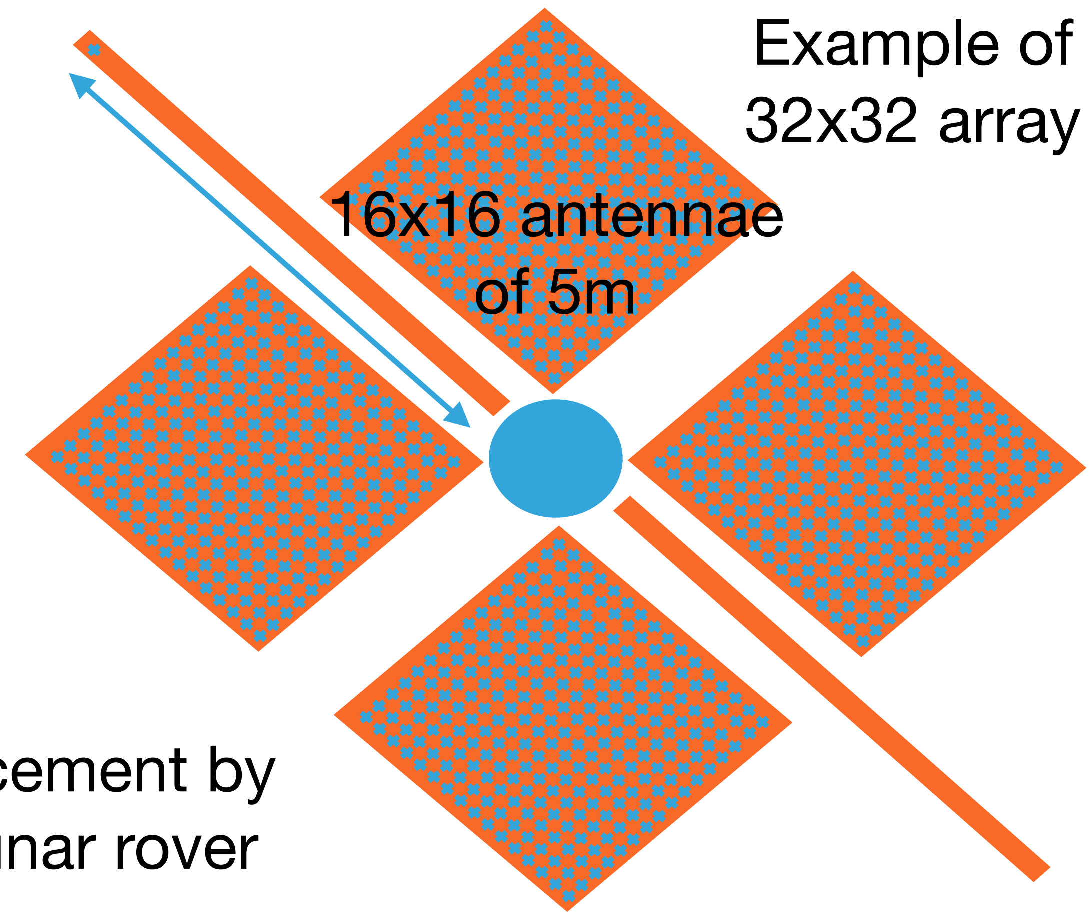
[Note an array of 128x128 5x5m dipoles has "only" $A_{\rm eff}$=0.4km^2 at 30MHz;
Larger $A_{\rm eff}$ than the SKA-low core and 100x SKA-low's FoV at 50MHz]

Dark-ages EXplorer (DEX) — ALO

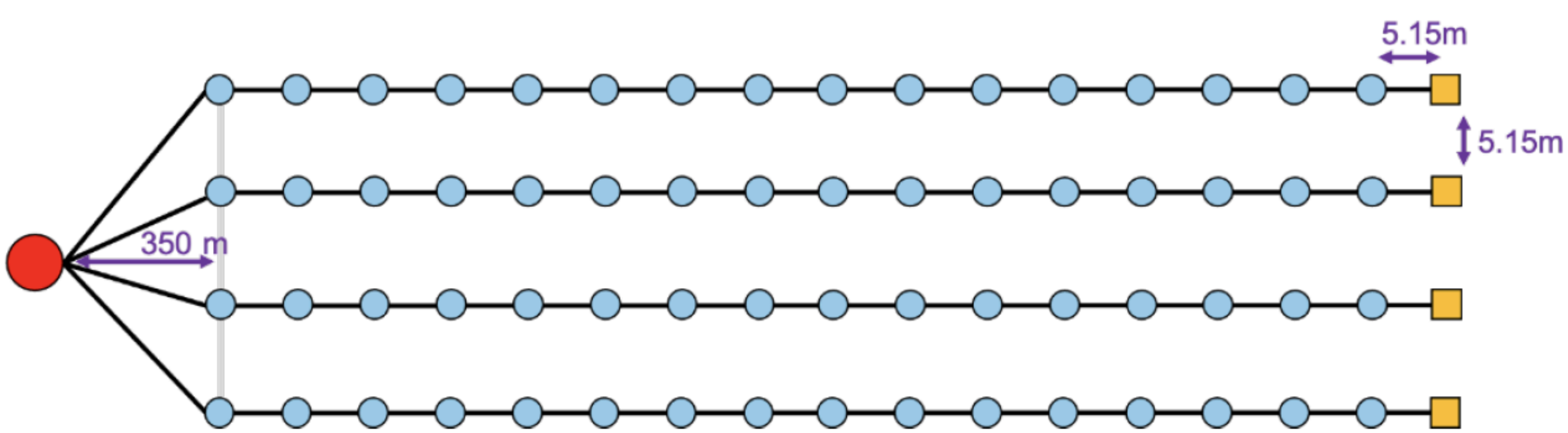
Basic concept of NxN array (power-spectrum) with 4 outriggers (global signal)



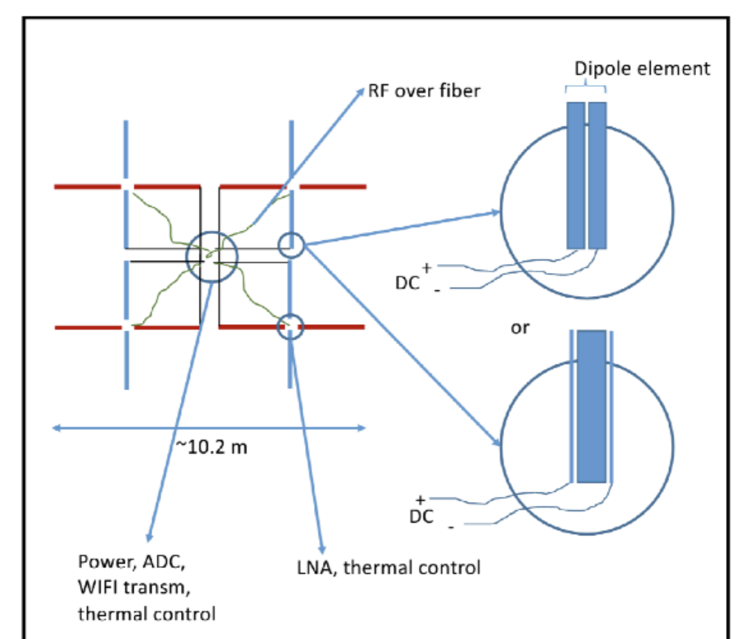
Example of 32x32 array



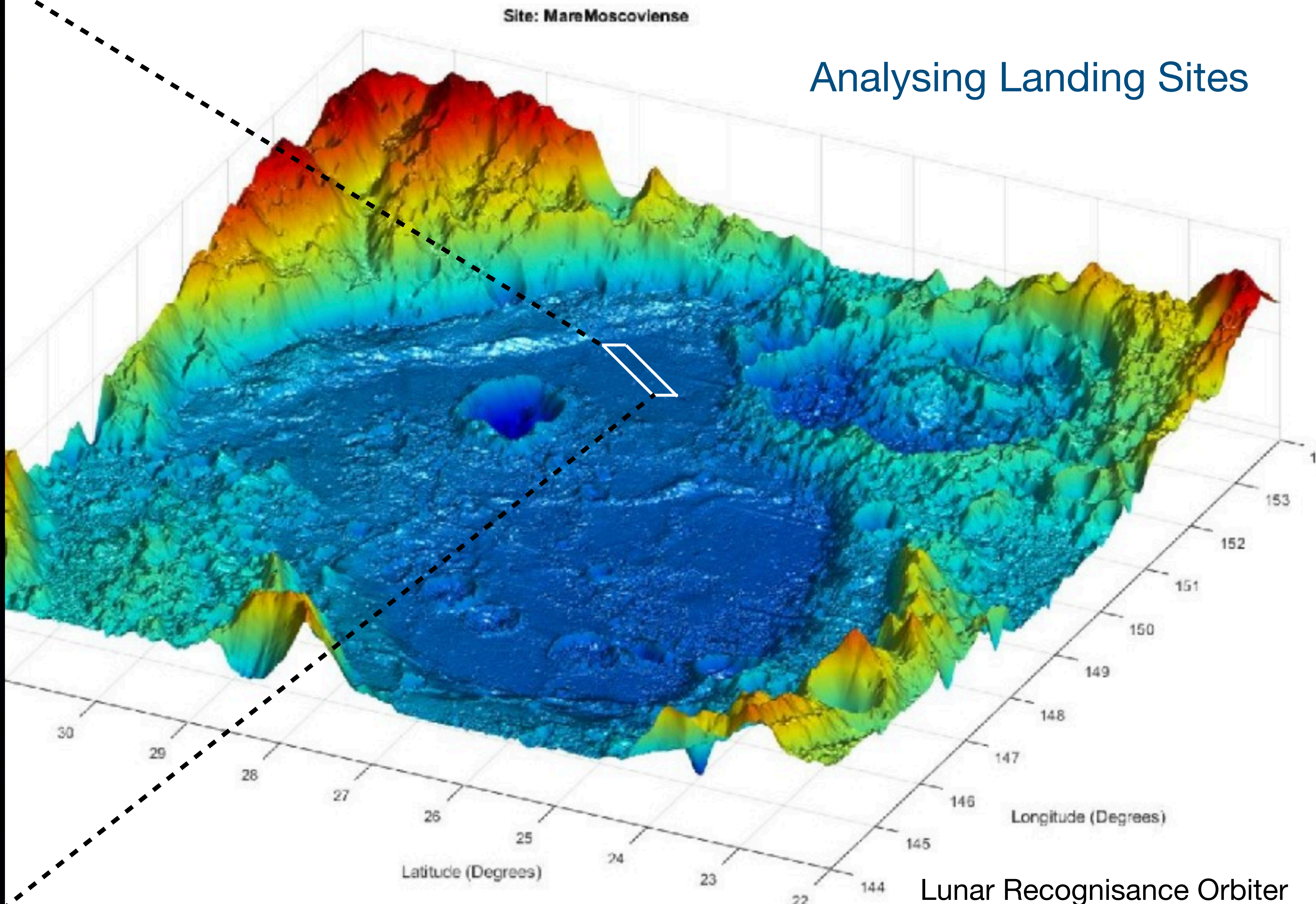
Placement by a lunar rover



(red: lander, blue: antennas, yellow: magazines)



Dark-ages EXplorer (DEX) — ALO

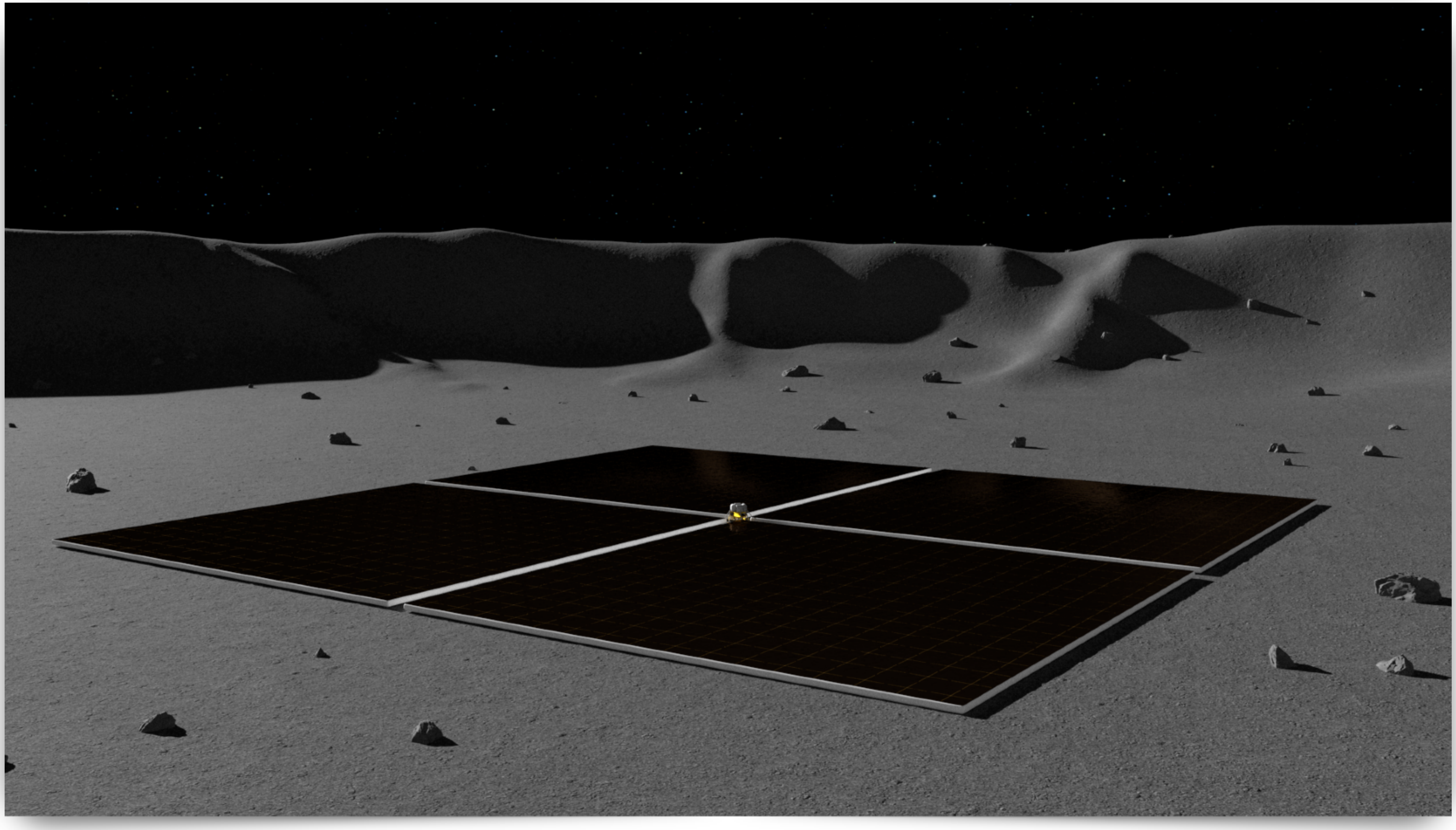


Analysing Landing Sites

Lunar Recognisance Orbiter

Dark-ages EXplorer (DEX) — ALO

A conformal grid-like array (allowing for a spatial FFT correlation), shielded from (other) activities on the lunar surface, with up to four outrigger global 21-cm receivers placed at a distance.



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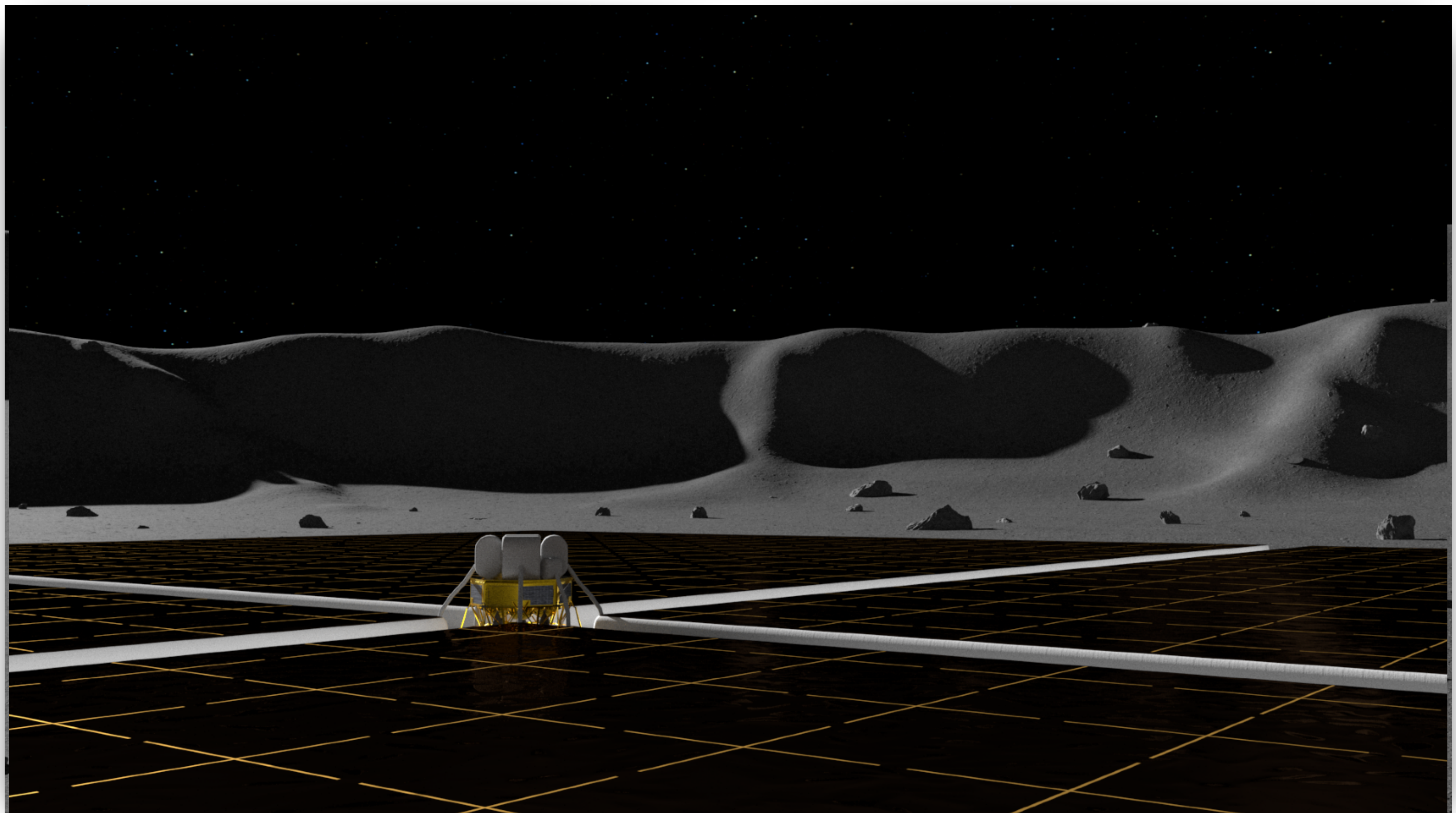

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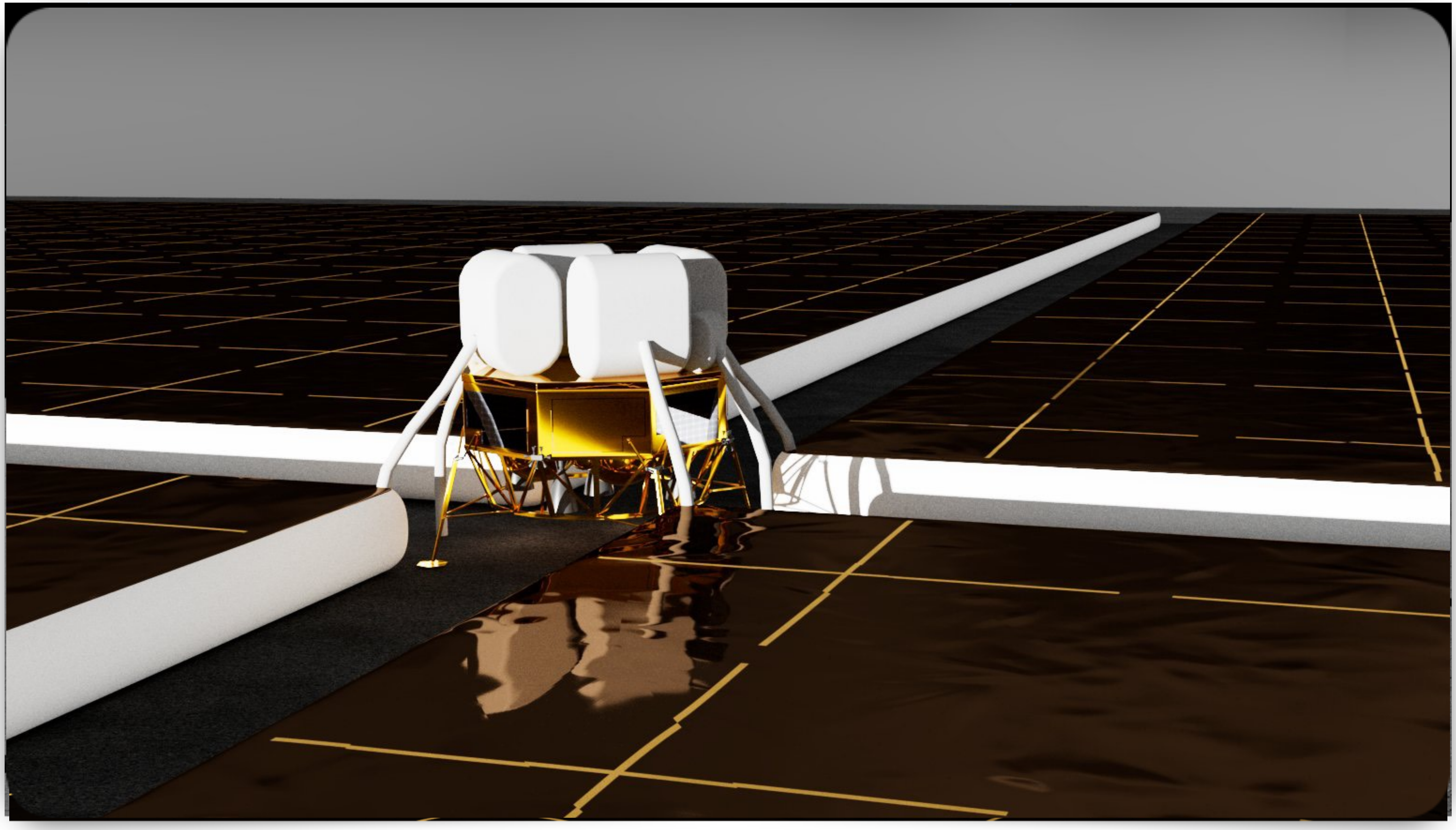
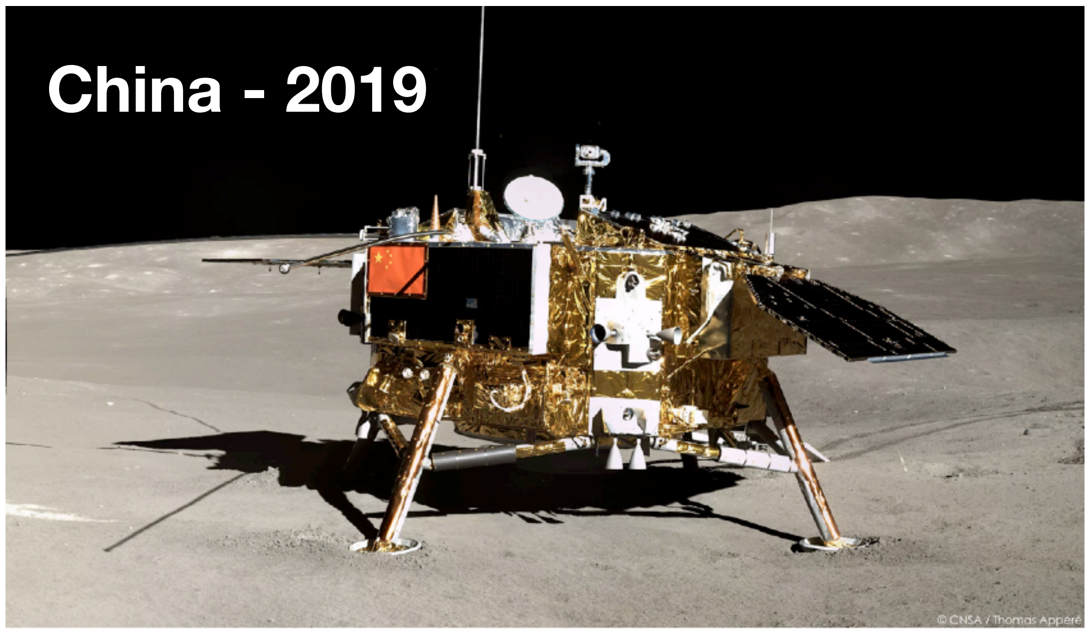
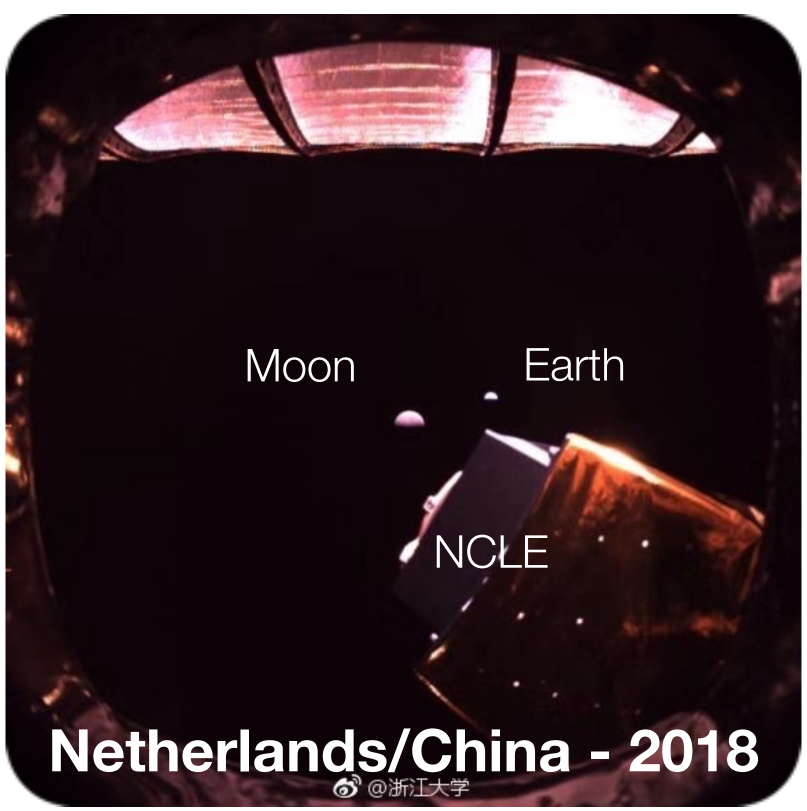
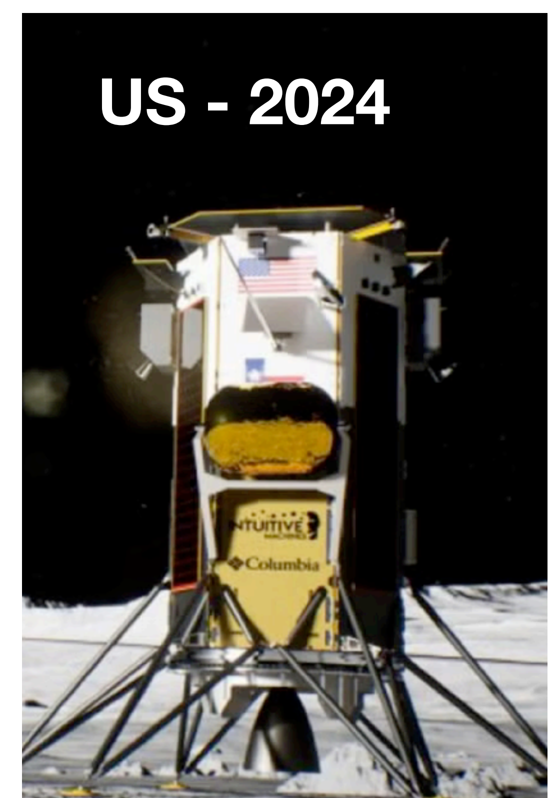


A “Race” to the Moon is on!







What is next?

LOFAR

- Automate data processing (NextLeap) on our new 1 peta-flop GPU cluster CODeX at RuG/CIT-HPC
- Analyse second field: 3C196
- Incorporate new calibration and GPR techniques.
- Process and analyse ~100 nights of data at multiple-redshifts

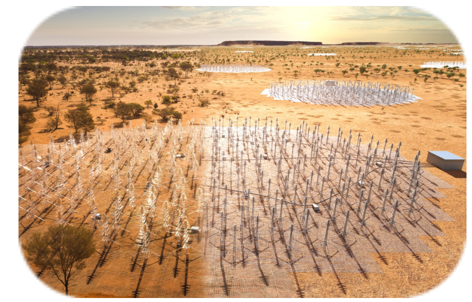
NenuFAR

- Automate data processing with NextLeap on Dawn GPU cluster.
- Improve RFI excision and cross-power spectra
- Process more NCP data and new NT04/05 fields (less excess noise)

AARTFAAC

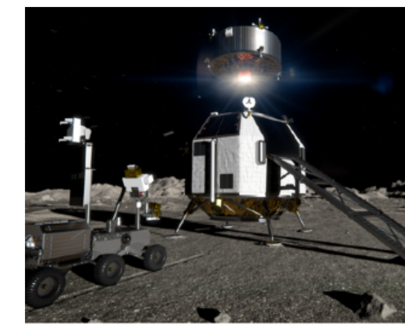
- Process all 500h of AARTFAAC data
- Obtained more data with LOFAR2.0 with HBA
- Planning for COxHI cross power-spectra analysis in the future (future)

SKA-Low



- Successful Data Challenges
- Preparing data proc. pipeline (NextFlow)
- Prepare for SKA AA0.5, 1, 2 data
- Tomography EoR
- Power spectra Cosmic Dawn

DEX - ALO



- Continue build team
- Doctoral network proposal submitted - 15 PhD students
- Science and instrument specifications
- Design full signal chain, receivers, electronics, data processing, etc.

Before wrapping up:

A new postdoc position will probably soon become available for to help process and analyse LOFAR-AARTFAAC and NenuFAR data.

If you know people that could be interested or you are interested, please contact me.

European Research Council
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Summary & Conclusions

- HI is the only tracer (21-cm line) that allows us to study many astrophysical processes **during the Dark Ages, Cosmic Dawn & EoR over wide range of angular scales.**
- Currently six **CD/EoR** detection experiments are ongoing: **LOFAR/AARTFAAC NenuFAR, LWA/LEDA, MWA, and HERA, [21CMA/PAPER]**. No detection yet, but increasingly stronger statistical (power-spectra) upper limits.
- Near Future: **SKA** will allow **tomography** (imaging!) to z=25.
- To detect the 21-cm signal from the **Dark Ages** we need to go to space or the moon: **DEX-ALO/NCLE, FAR-SIDE/VIEW, DSL, LUSEE, ROLSES, PRATUSH, …**
- **All these experiment are difficult**: a journey of discovery where tools are invented while doing the experiment - a long and rewarding voyage!

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Thanks!