Recent Advances in the LOFAR-EoR and NenuFAR Cosmic Dawn Projects

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LOFAR-EoR collaboration (PI: Koopmans, Offringa, Zaroubi)
NenuFAR Cosmic Dawn KP (PI: Mertens, Koopmans, Semelin)

The first billion years of the universe

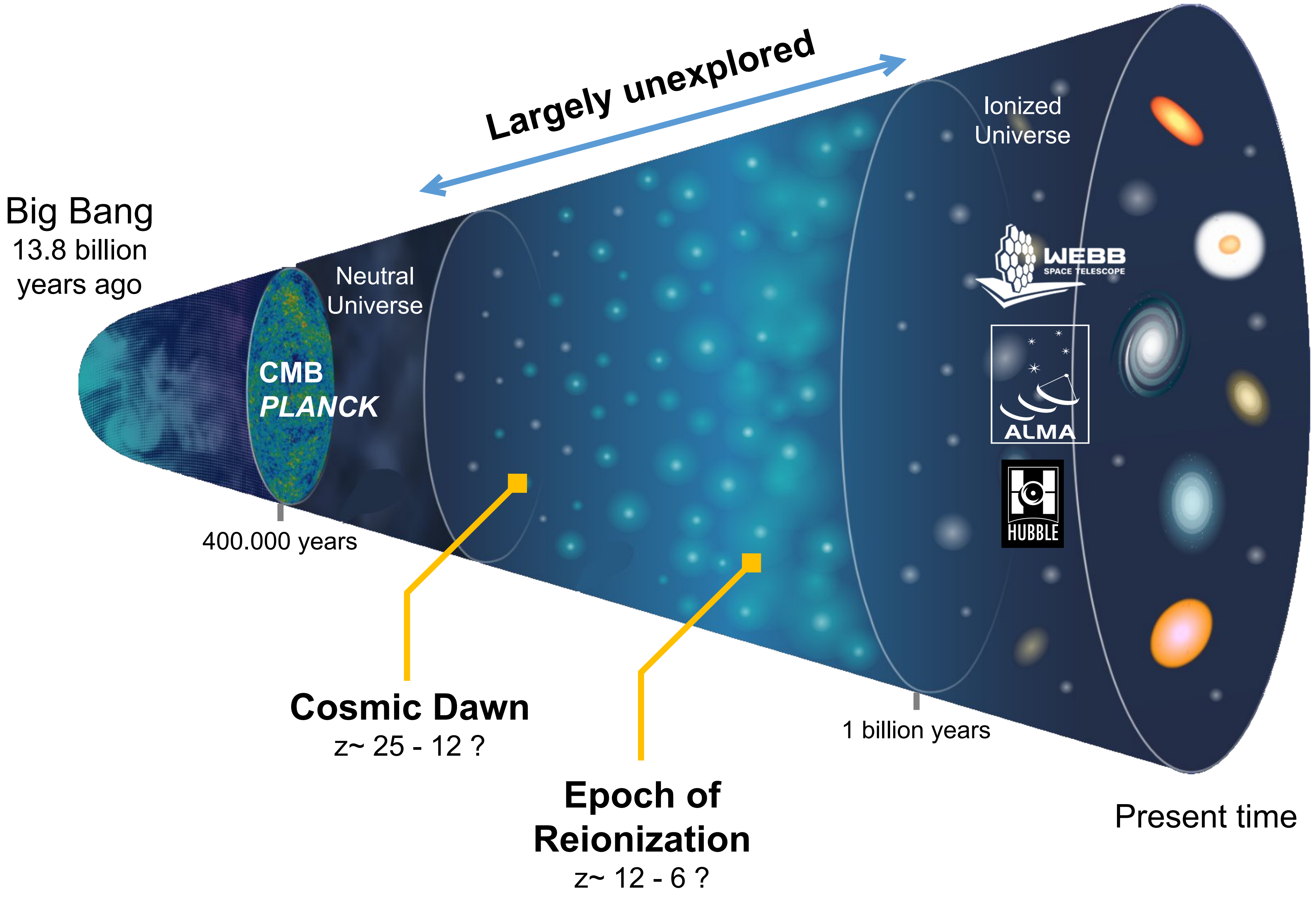
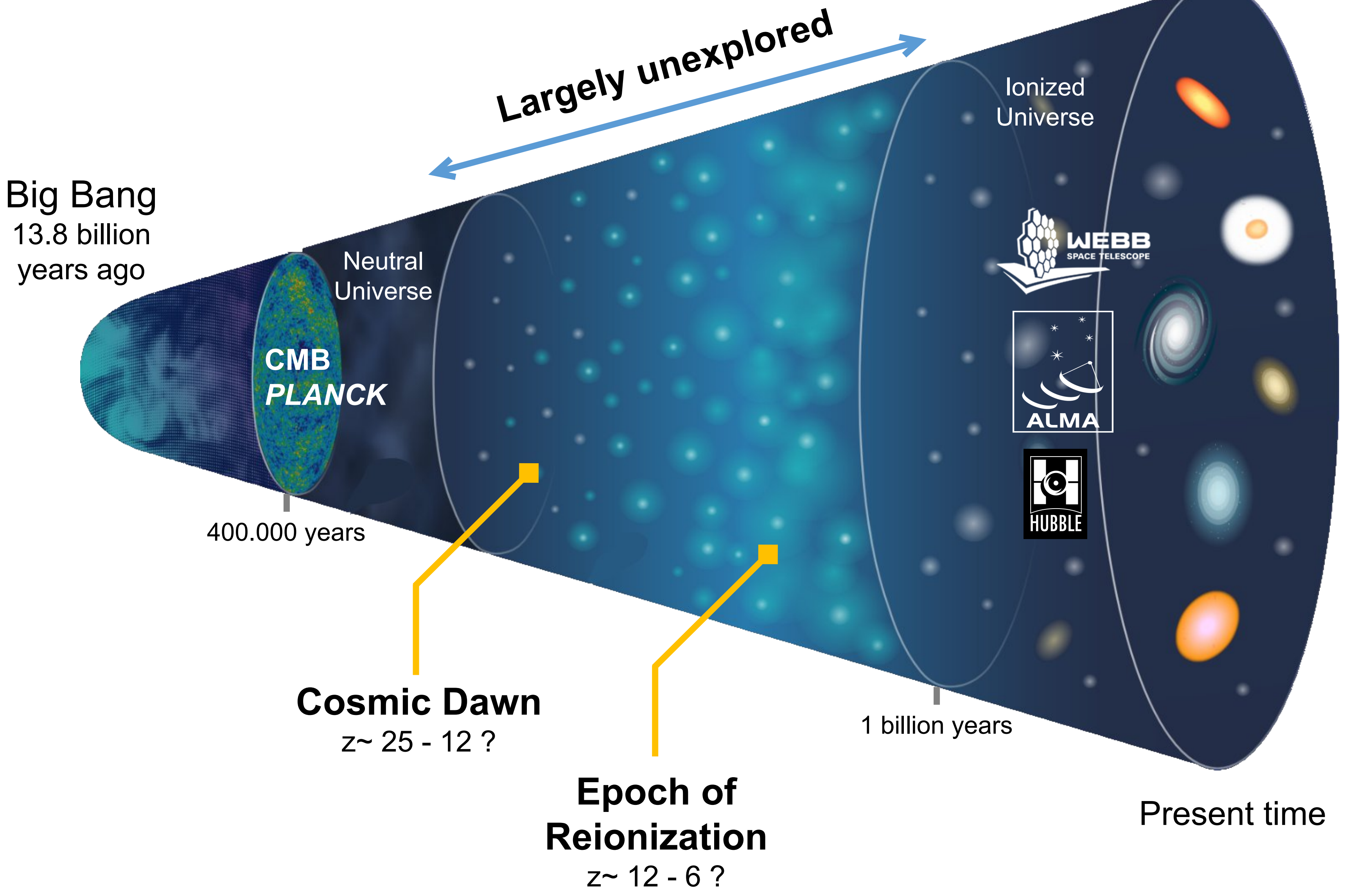
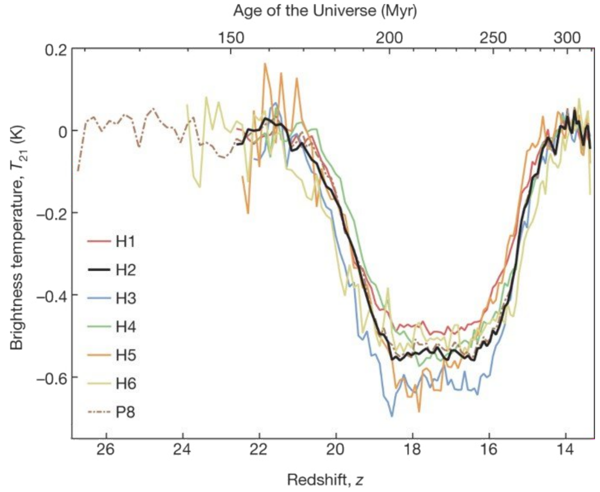


Image: NASA, ESA, CSA, Joyce Kang (STScI)

The first billion years of the universe



- What where the major stages of reionisation?
- When did the first luminous sources emerge?
- Do we need to invoke new physics to explain EDGES?

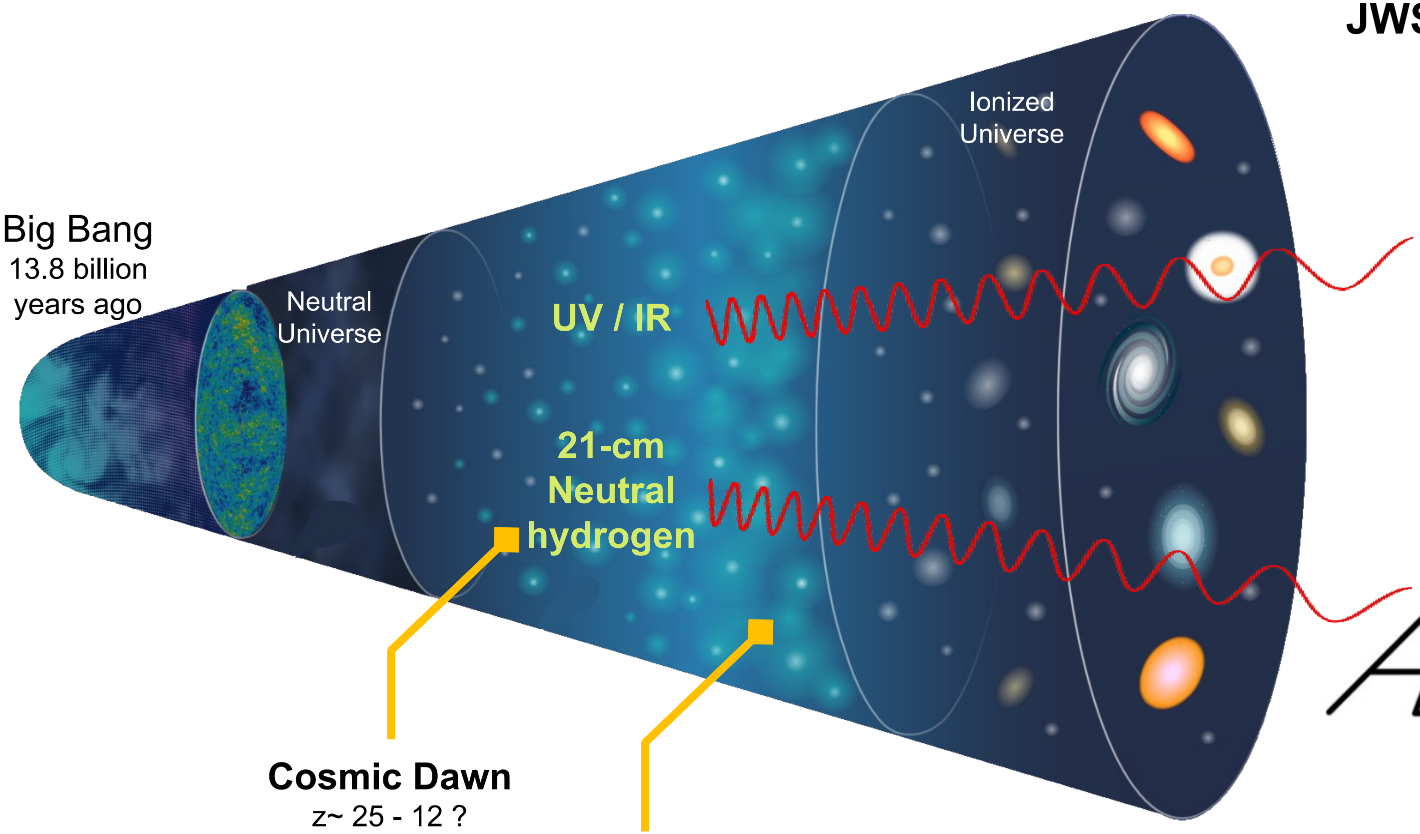


EDGES observation (Bowman et al. 2018)

Image: NASA, ESA, CSA, Joyce Kang (STScI)

The first billion years of the universe

Big Bang
13.8 billion years ago



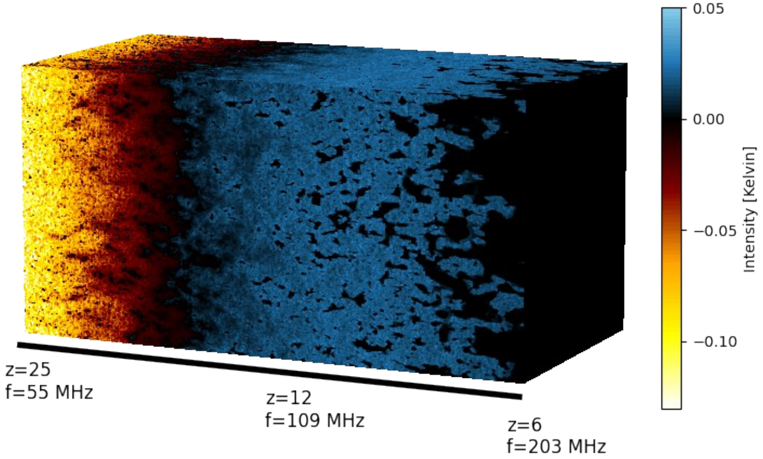
Cosmic Dawn
z~ 25 - 12 ?

Epoch of Reionization
z~ 12 - 6 ?

Present time

JWST: Only the **brightest** galaxies (<10% at z~10)

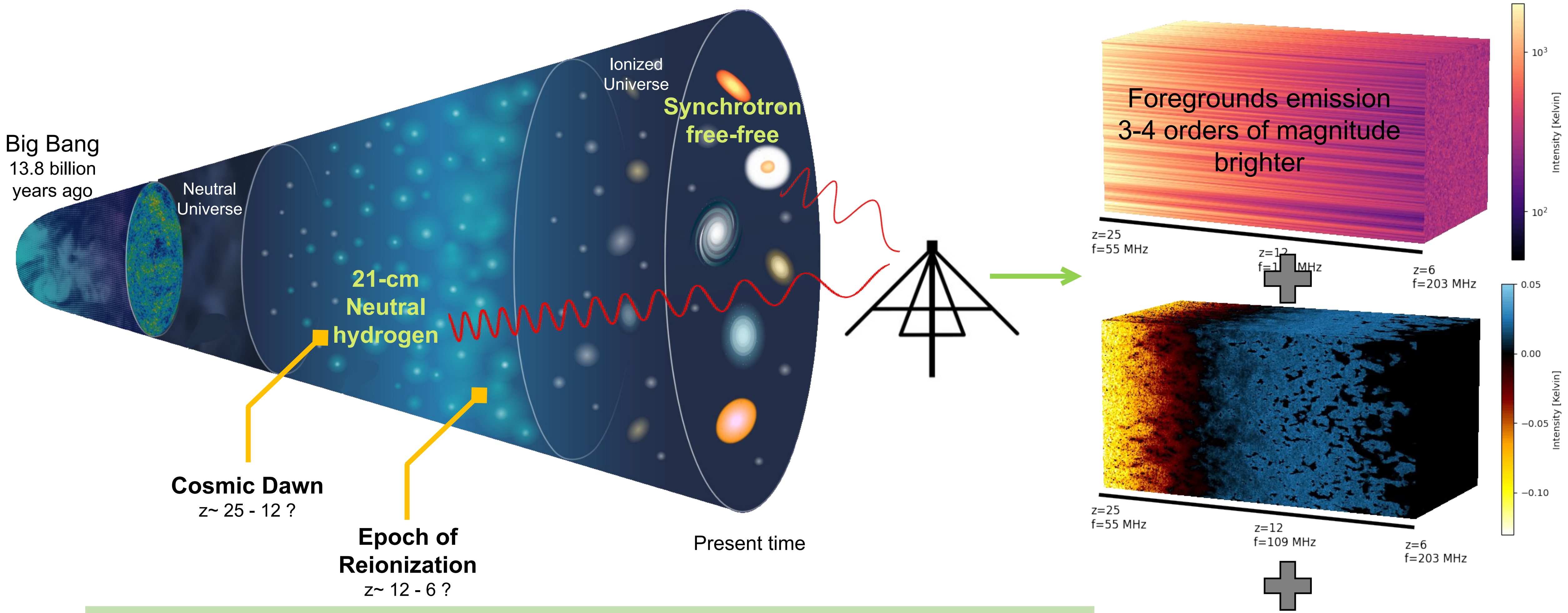
WEBB



21-cm over cosmic time

The 21-cm line reveals the chronology and the topology of the reionization, key to understanding the first stars, galaxies, and the reionization.

The first billion years of the universe



The 21-cm signal is dominated by astrophysical foregrounds and altered by instrumental and ionospheric effects, an unprecedented observational challenge.

Instrumental effects, ionosphere, RFI...

The Reionization with LOFAR

Redshift range: z~6–12
Observation started in 2012
+3000hrs observed

frequency range:
110 MHz to
190 MHz

Core collecting area:
0.02km²

18,432
antennas spread between
24 core stations

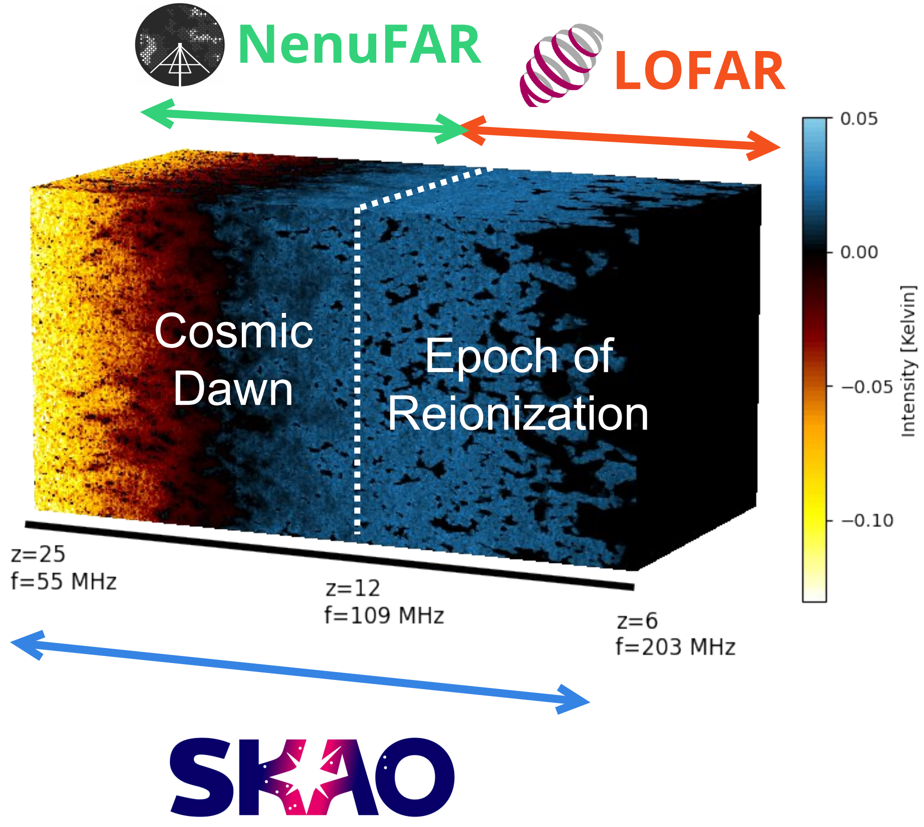
The Cosmic Dawn with NenuFAR

Redshift range: z~15–25
Observation started in 2019
+2000hrs observed

frequency range:
10 MHz to
85 MHz

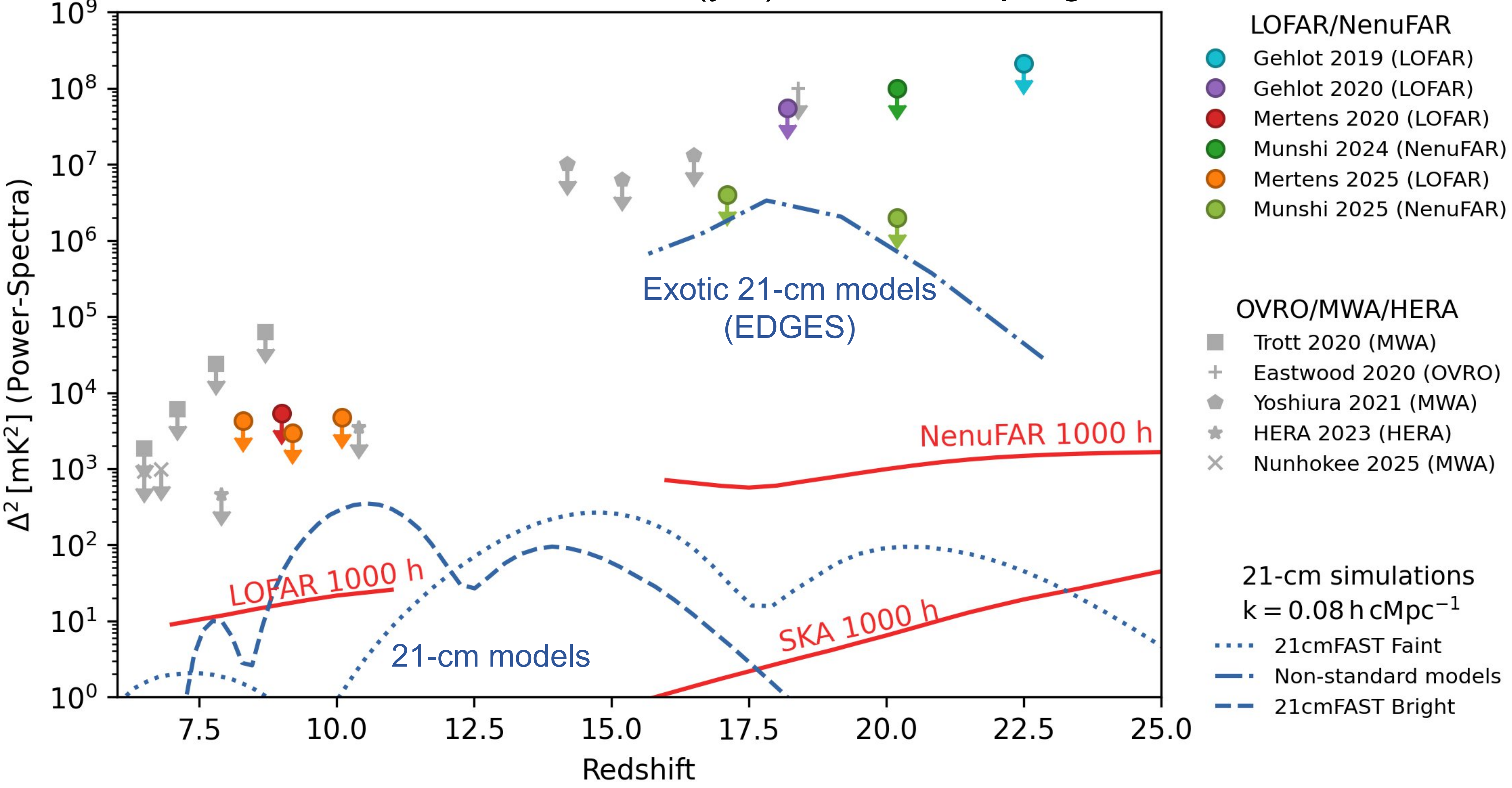
Core collecting area:
0.01km²

1,824
antennas spread between
96 core stations

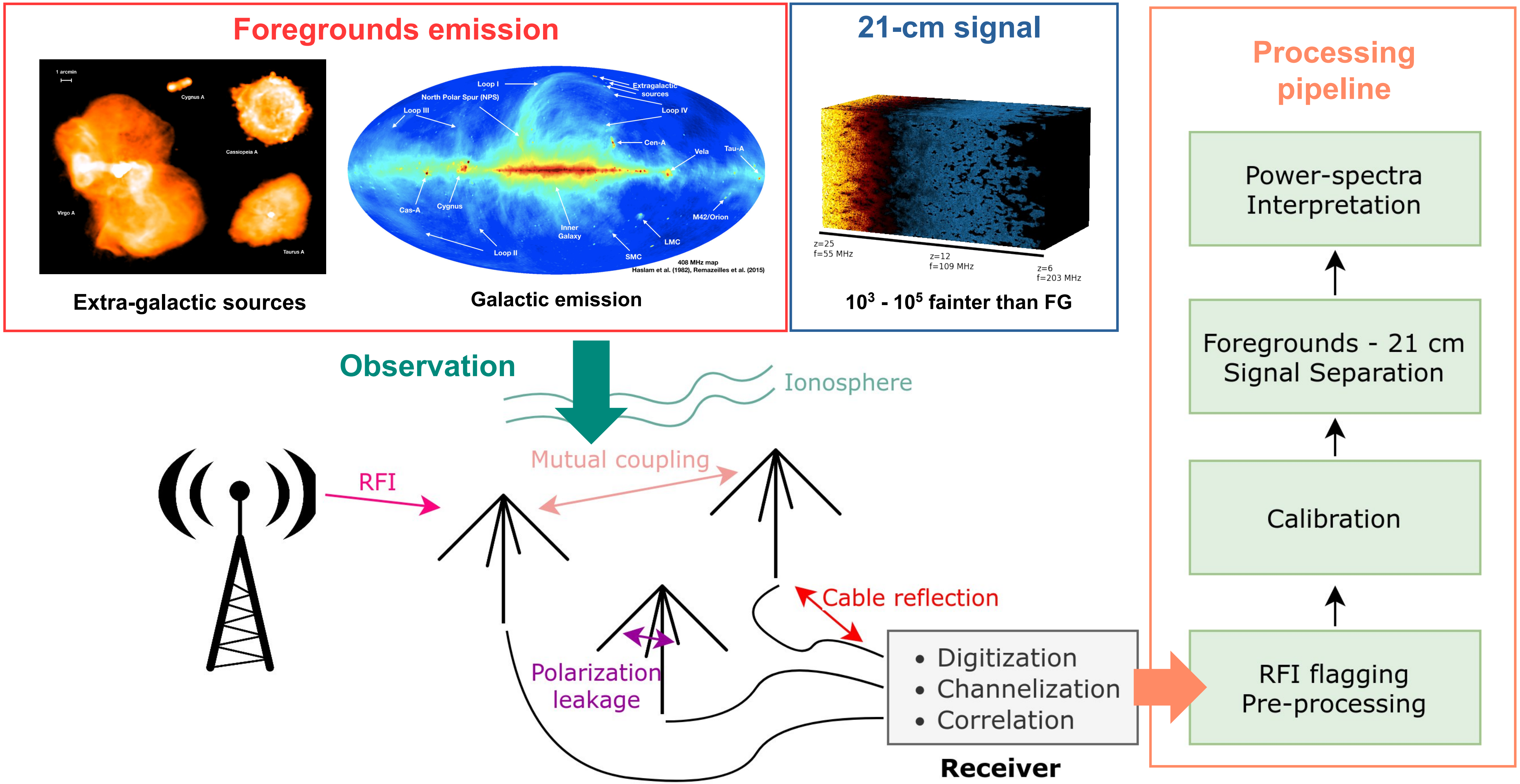


Where do we stand ?

No detection (yet) but a lot of progress

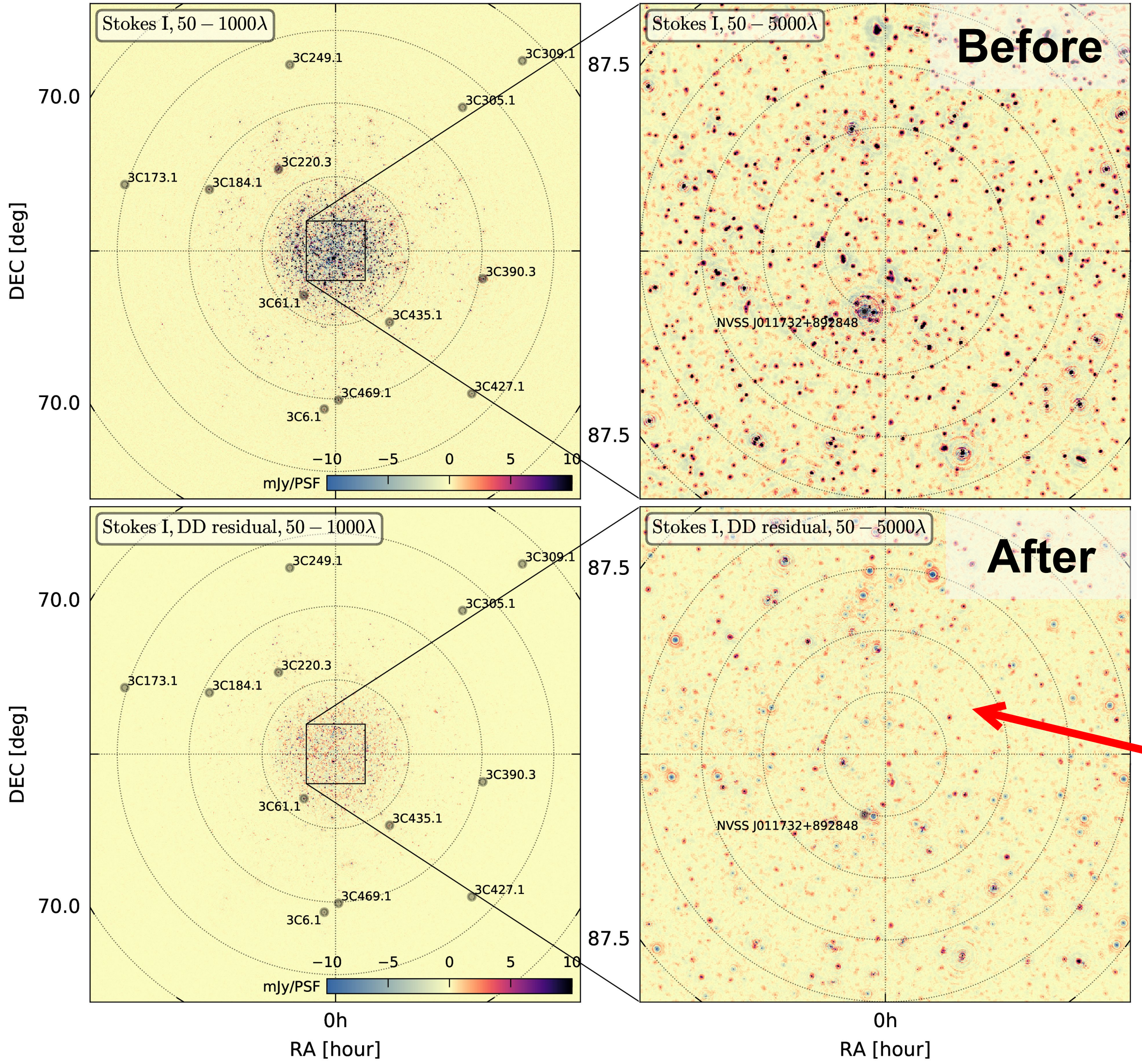


Major challenges: foregrounds sources & RFI



Foreground mitigation: subtracting point-sources

LOFAR | NCP | 140 hours | 134-146 MHz



➔Need accurate sky-model

➔Solve for instruments gains in direction of (cluster of) sources

Confusion limited foregrounds + low level residuals

Mertens et al. 2020
Mevius et al. 2022

Foreground mitigation: statistical separation

The ML-GPR method (Mertens et al. 2018, 2024)

- Non-parametric signal separation with Gaussian processes
- Exploiting spectral differences between signal and foregrounds
- 21-cm signature learned from simulations

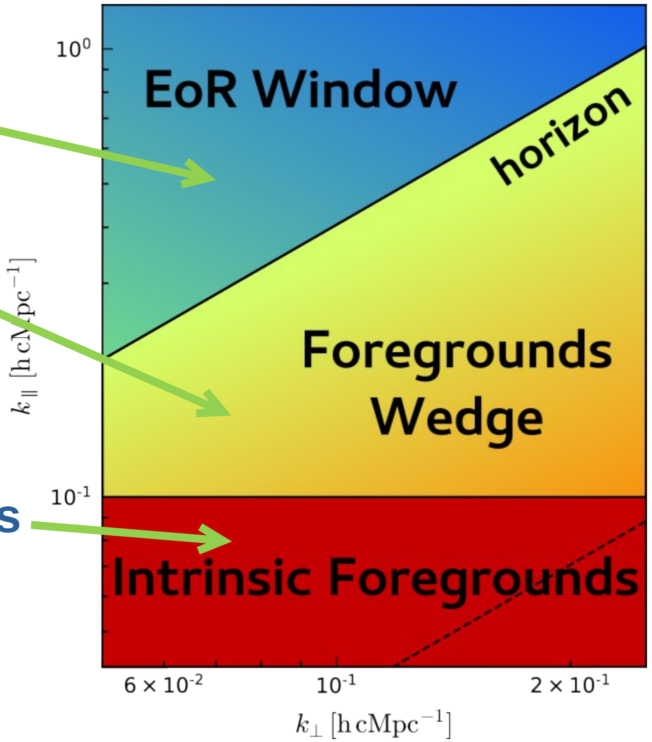
21-cm signal

Instrumental effects

- PSF/beam chromaticity
- Calibration errors

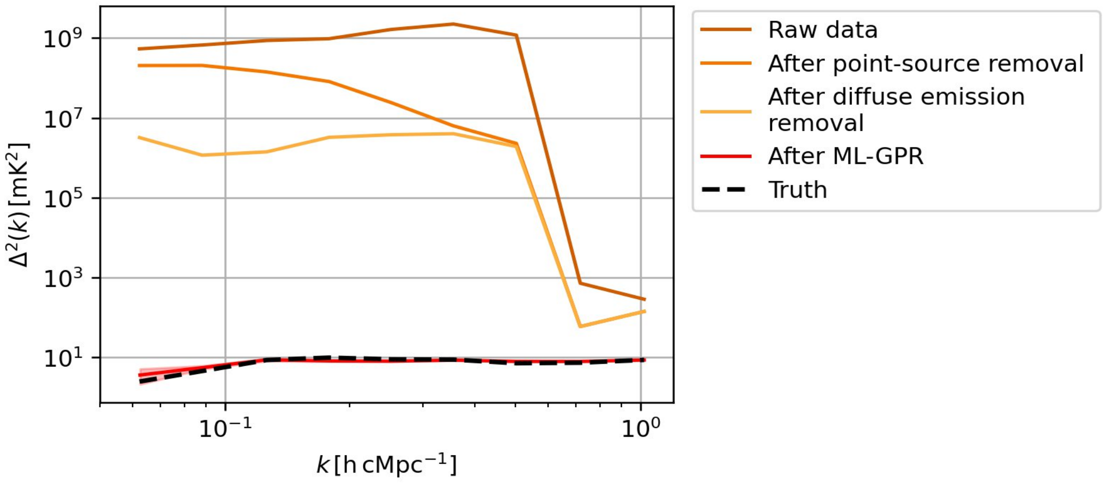
Astrophysical Foregrounds

- Extragalactic sources
- Galactic diffuse emission



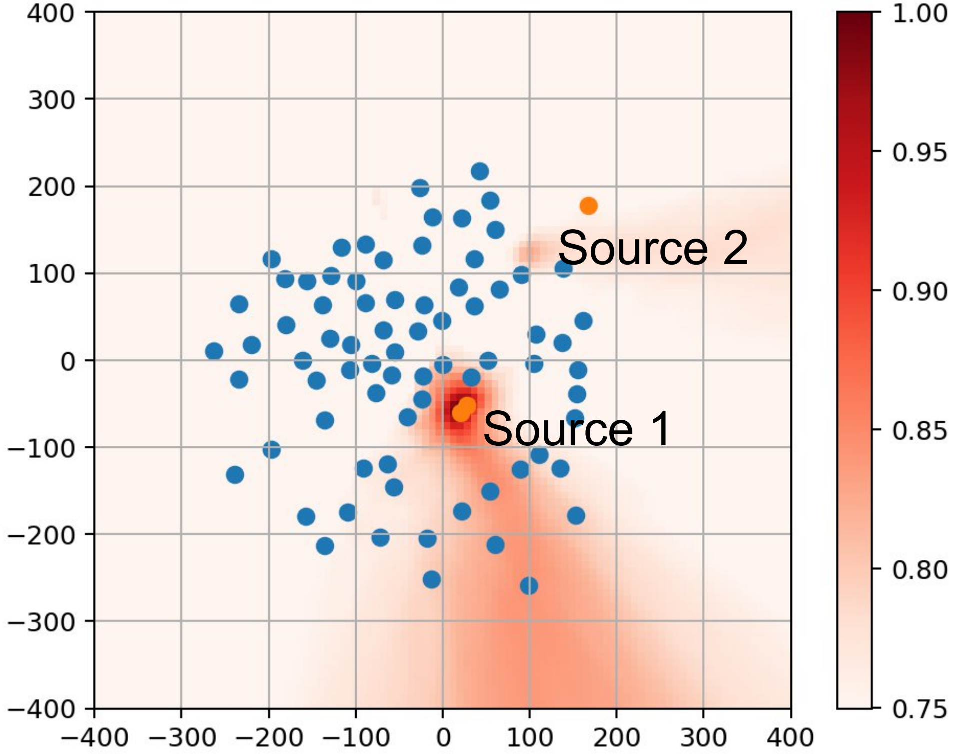
Application of ML-GPR to the SKA Data Challenge 3a

a simulated 21-cm extraction challenge organised by SKAO, that our team DOTSS-21 won

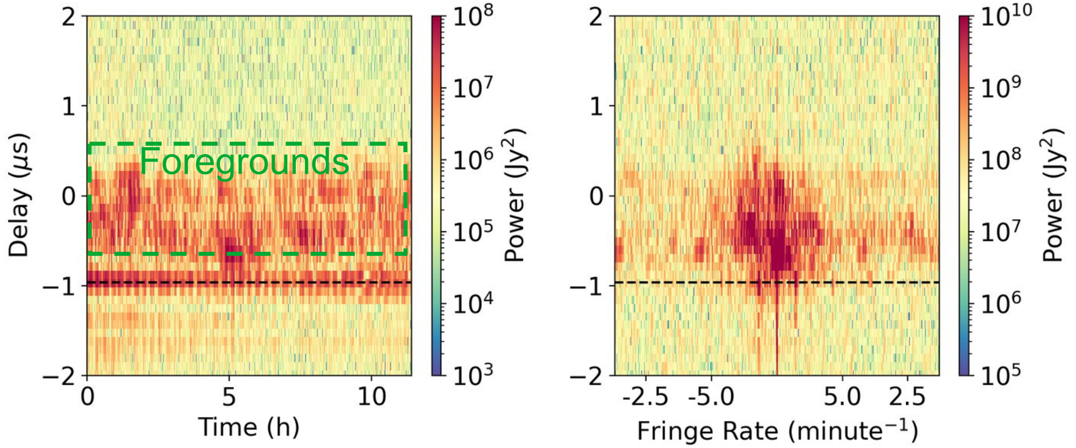


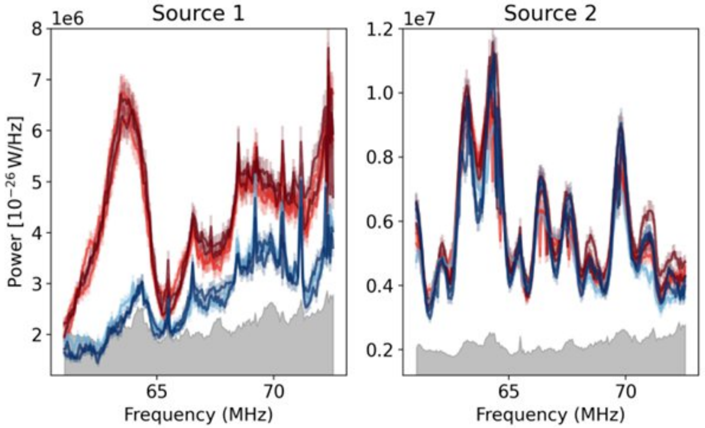
Mitigating faint & broadband RFI

Near-field image 12/12/2021
61 –72 MHz | NCP | A-team masked



Source 1: delay and Fringe Rate power spectra for an example baseline





Spectral characterization of the local sources of RFI

Current strategy: detect & flag affected baseline
In the future: model & subtract RFI source

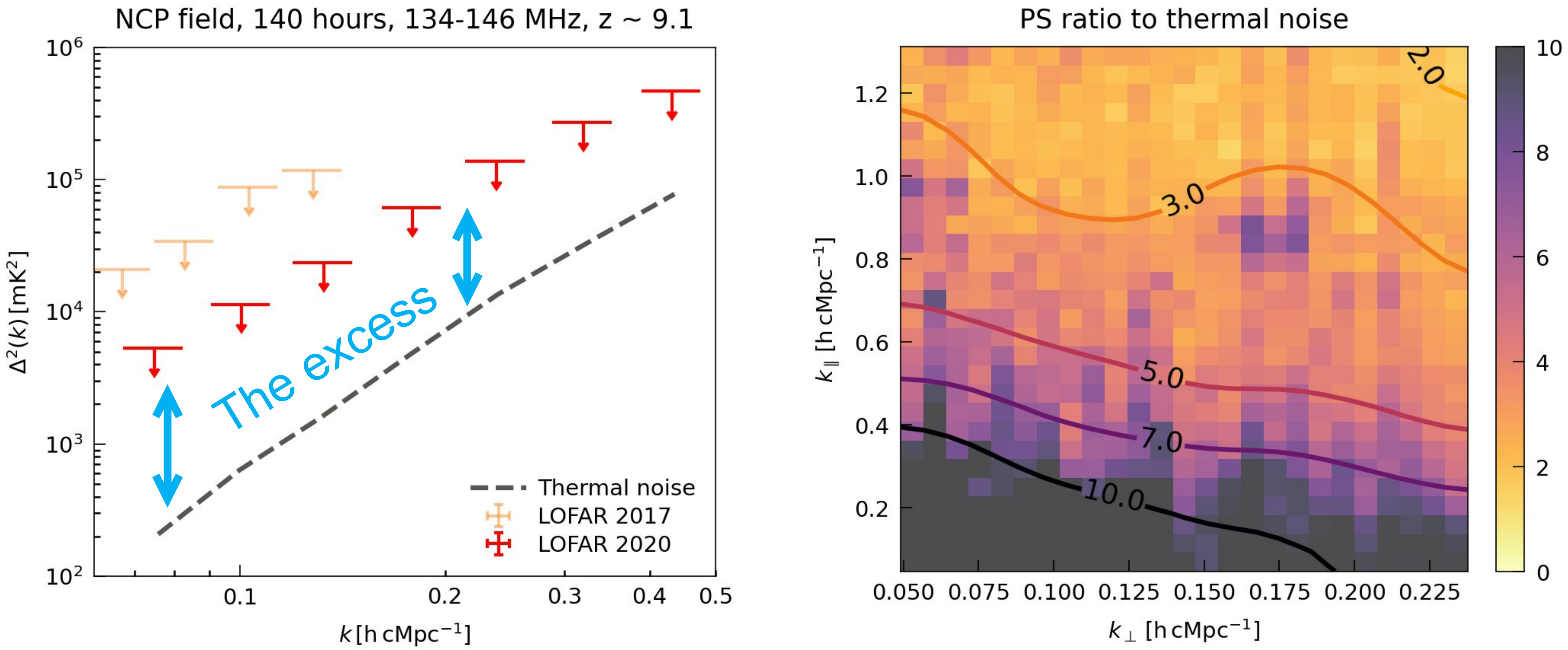
Munshi, Mertens et al 2025b

The Epoch of Reionization with LOFAR

The LOFAR-EoR team

The LOFAR telescope

LOFAR 2020 upper limit at z~9

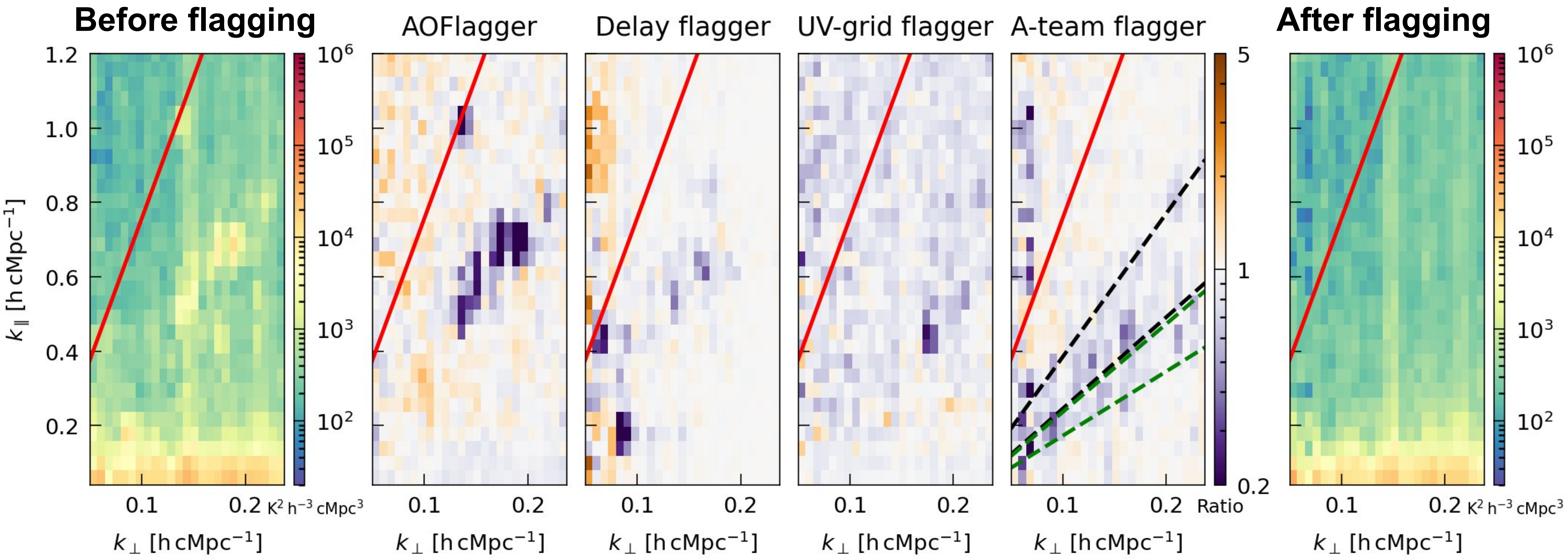


A reduction by a factor ~ 10 compared to our 2017 upper limit, the deepest at z ~ 9 (at that time) ...

… but affected by large **excess power**.

Mertens et al. 2020

Improved RFI flagging

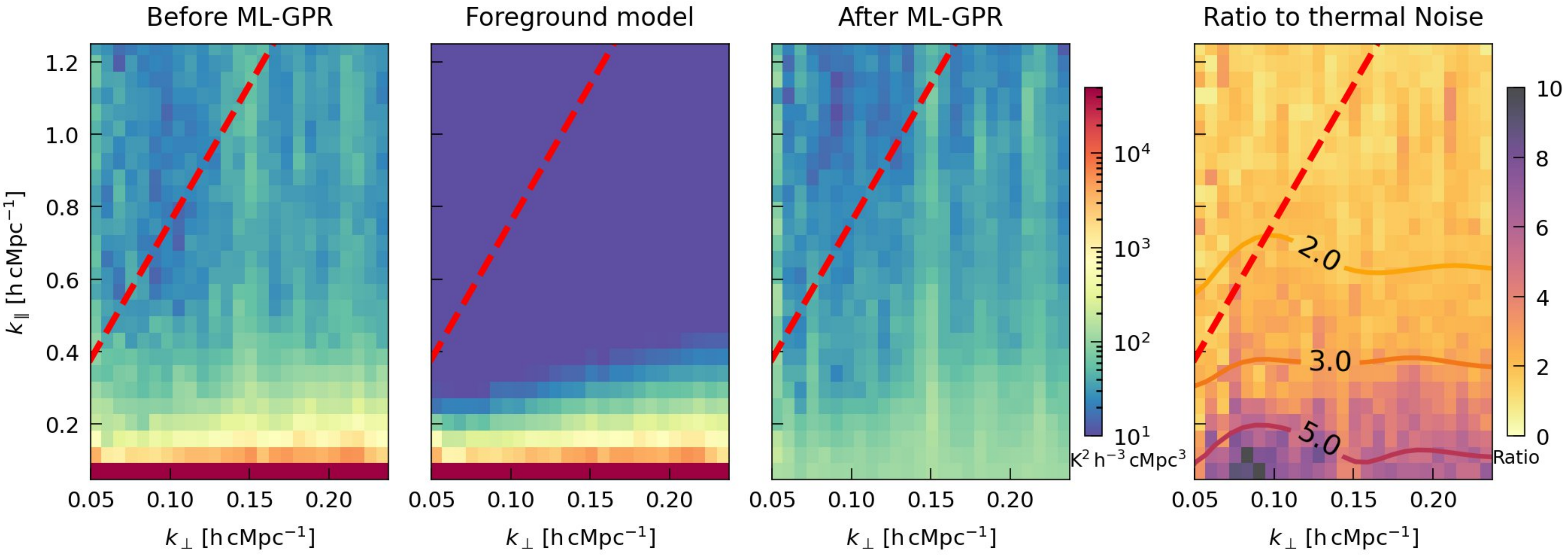


New and **improved RFI excision** steps
significantly **reduces contamination** across the power spectrum

Mertens et al. 2025

Improved foregrounds removal

Using ML-enhanced Gaussian Process Regression (Mertens et al. 2024)

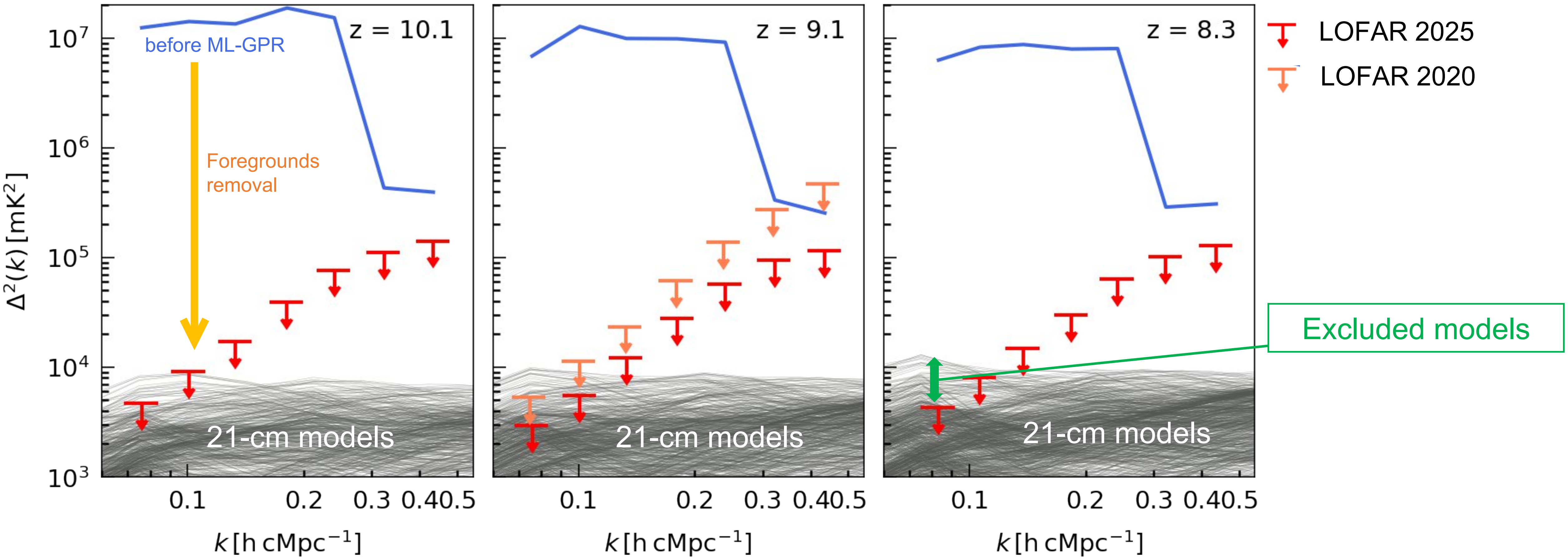


- 21-cm spectral signature **learned from simulations**
- Signal **preservation** validated through **injection tests**

Mertens et al. 2025

Deeper multi-redshift LOFAR upper limits

LOFAR, NCP field, 140 hours, 122 - 160 MHz



Best LOFAR **constraint** on the signal power spectra **at z~8-10**

➔ Several scenarios of cold IGM excluded

Mertens et al. 2025
Ghara et al. 2025

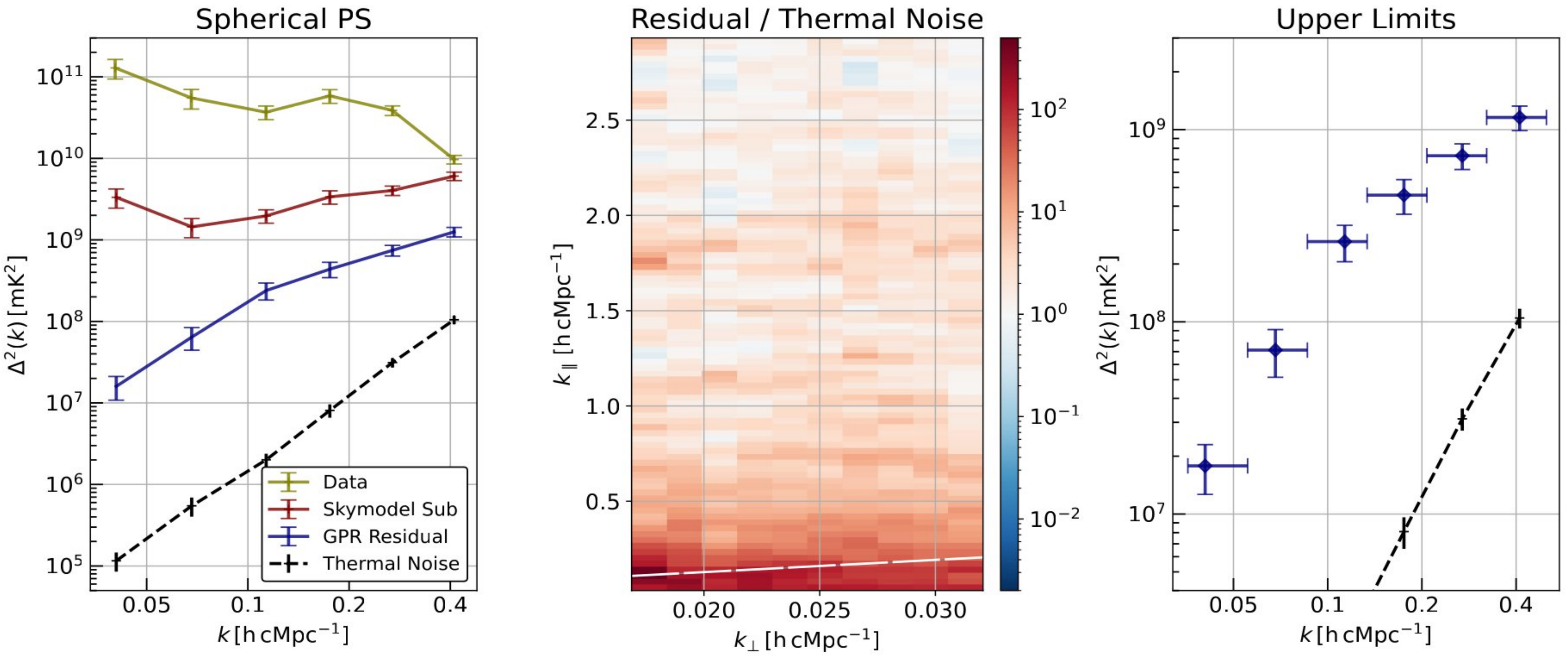
The Cosmic Dawn with NenuFAR

The NenuFAR
Cosmic Dawn team

The NenuFAR telescope

First NenuFAR upper limit

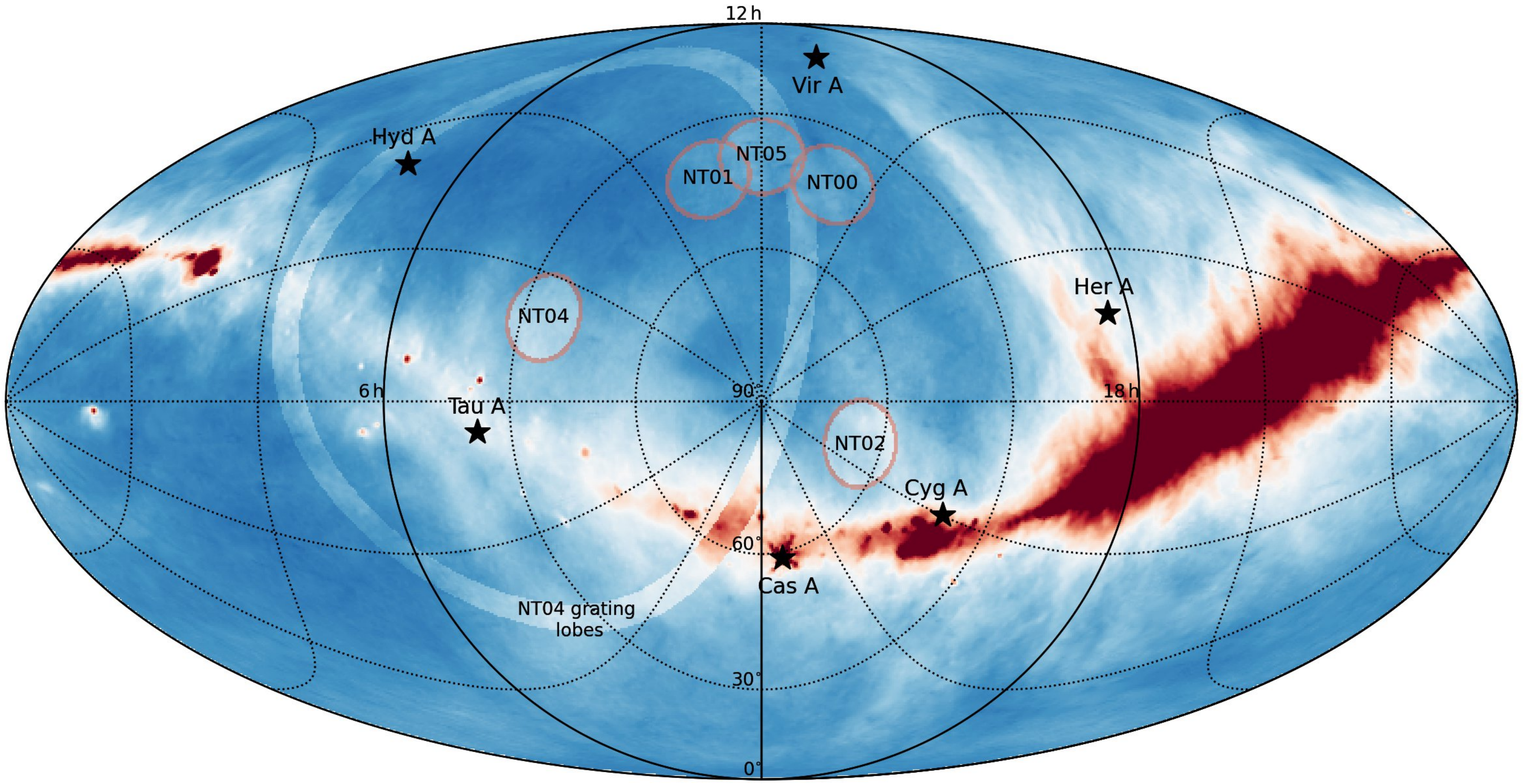
NCP field, 11.5 hours, 61-72.5 MHz, z ~ 20 (Munshi, Mertens et al. 2024)



The deepest upper limit on the 21-cm power-spectra at z~20
... but limited by bright source contamination and local RFI

NenuFAR search for a “darker” deep field

2022 – 2023 observation campaign on 5 candidates deep fields



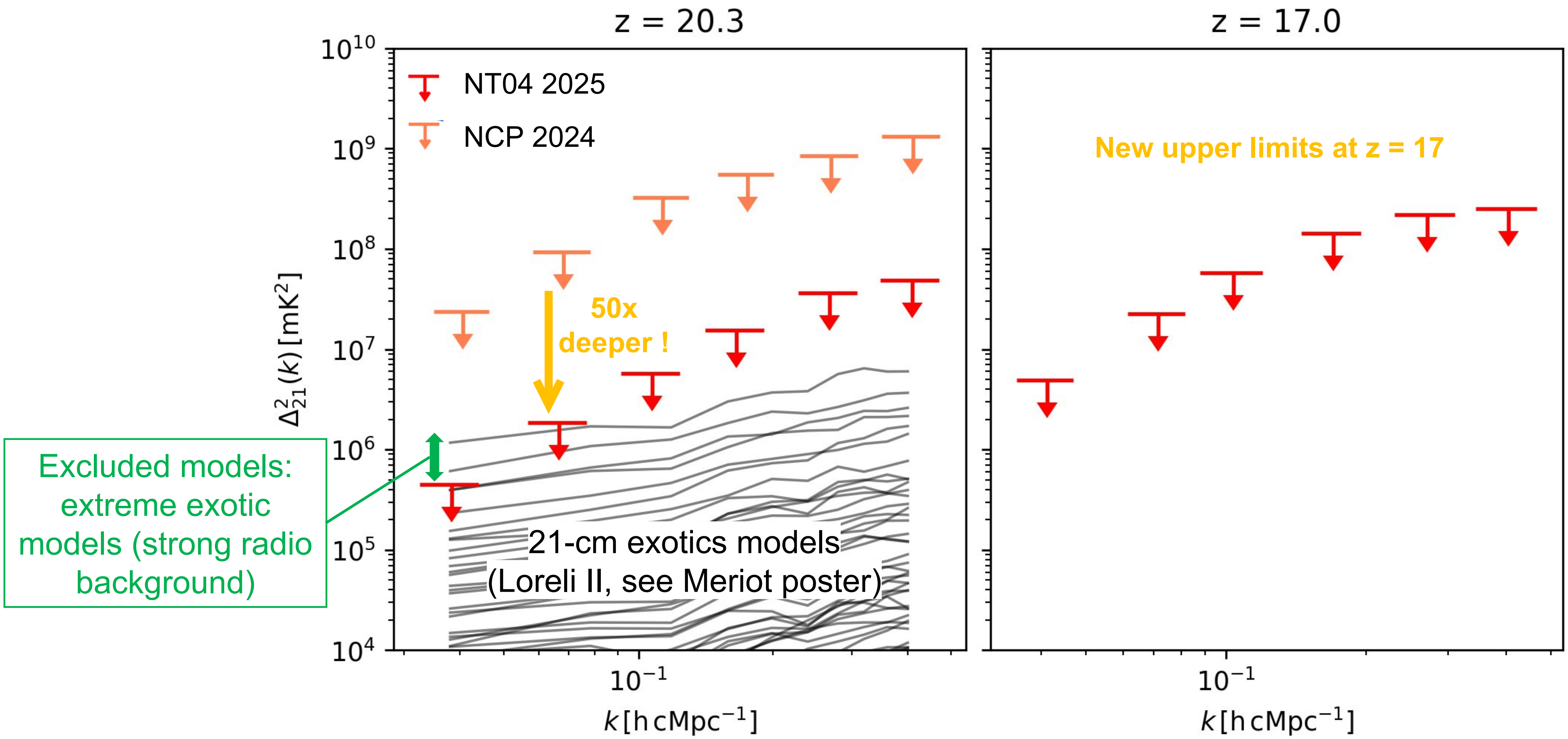
Selection strategy:

- ➔ Minimize apparent flux from Bright A-team sources.
- ➔ Transit close to zenith for maximum sensitivity.

Mertens et al. in prep.

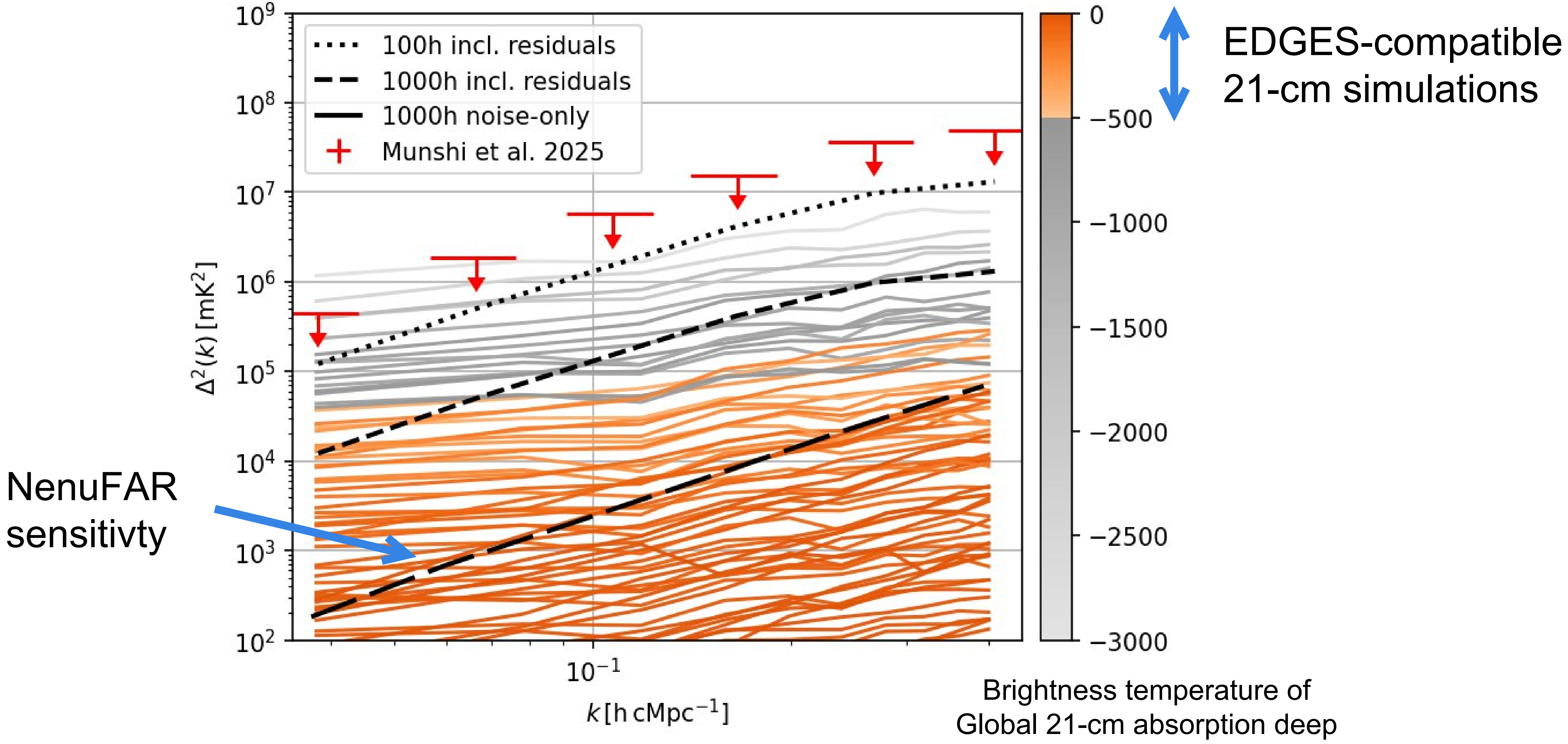
New NenuFAR upper limit

NT04 field, 26.1 hours, z ~ 20 & z~17



Munshi, Mertens et al. 2025

Next steps for NenuFAR: 1000hrs



Making a big leap towards a detection

Investigation and mitigation of the excess

➔ Ionosphere impact analysis (Brackenhoff et al. 2024)

➔ Improved bright source model (Cecconi et al. 2025a)

➔ New more robust DD-calibration (Brackenhoff et al. 2025)

➔ Filtering of local sources of RFI (Munshi et al. 2025)

New end-to-end automated pipelines

➔ LOFAR EoR: NextLEAP

➔ NenuFAR Cosmic Dawn: NenuFlow

Next step for LOFAR-EoR

➔ Analysis of the 3C196 field with LOFAR (Cecconi et al. 2025b)

➔ Next step: large batch of 3C196 (Chege et al. in prep)

Next step for NenuFAR Cosmic Dawn

➔ Analysis of ~1000hrs of the new deep field (120hrs already done)

Summary & perspective

- ➔ Deepest LOFAR upper-limits at z ~ 8 - 10, based on ~5% of LOFAR data
- ➔ New NenuFAR upper limits at z ~ 17 - 21 comparable to extreme exotic models
- ➔ **We are scaling up processing significantly**