Unveiling the Physics of the Cosmic Dawn and the Epoch of Reionisation in the SKA era

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LOFAR-EoR collaboration – NenuFAR-CD collaboration
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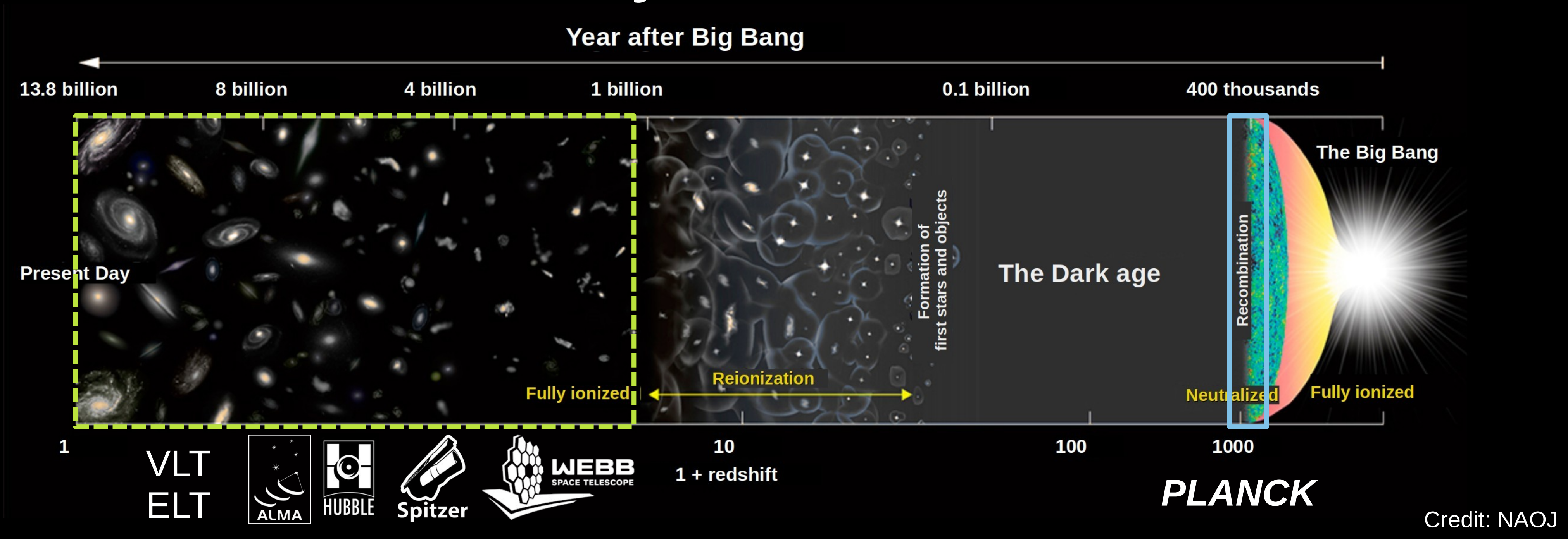
Image credit: Michale Goh/ICRAR-Curtin

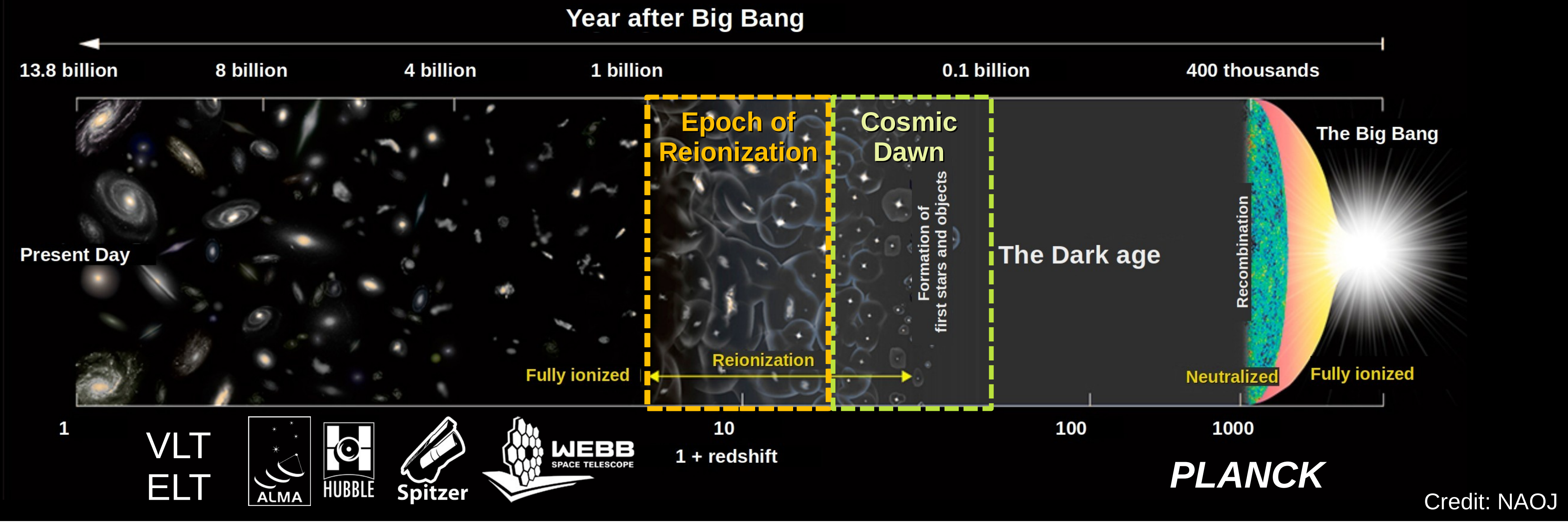
The history of our universe



Observations of galaxies and clusters of galaxies provide a detailed picture of the Universe at increasingly high redshifts.

The CMB: a snapshot of the Universe at z=1100

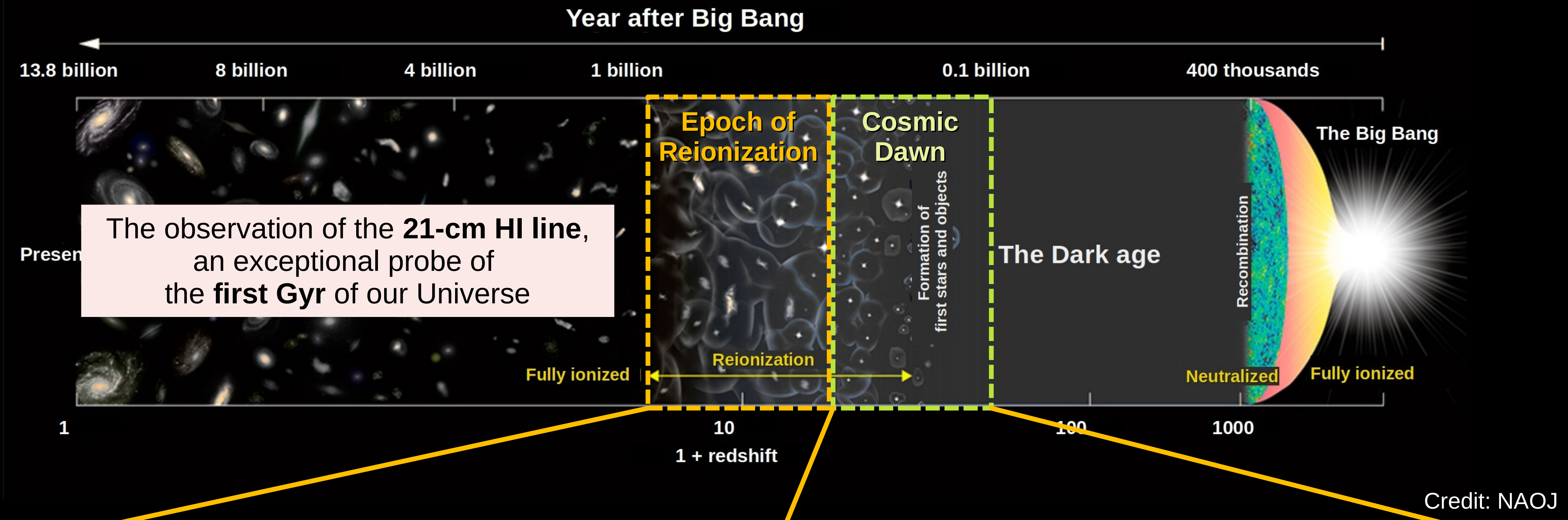
The history of our universe



Epoch of Reionization
➔ Reionization by stars & mini-quasars
➔ 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

The history of our universe

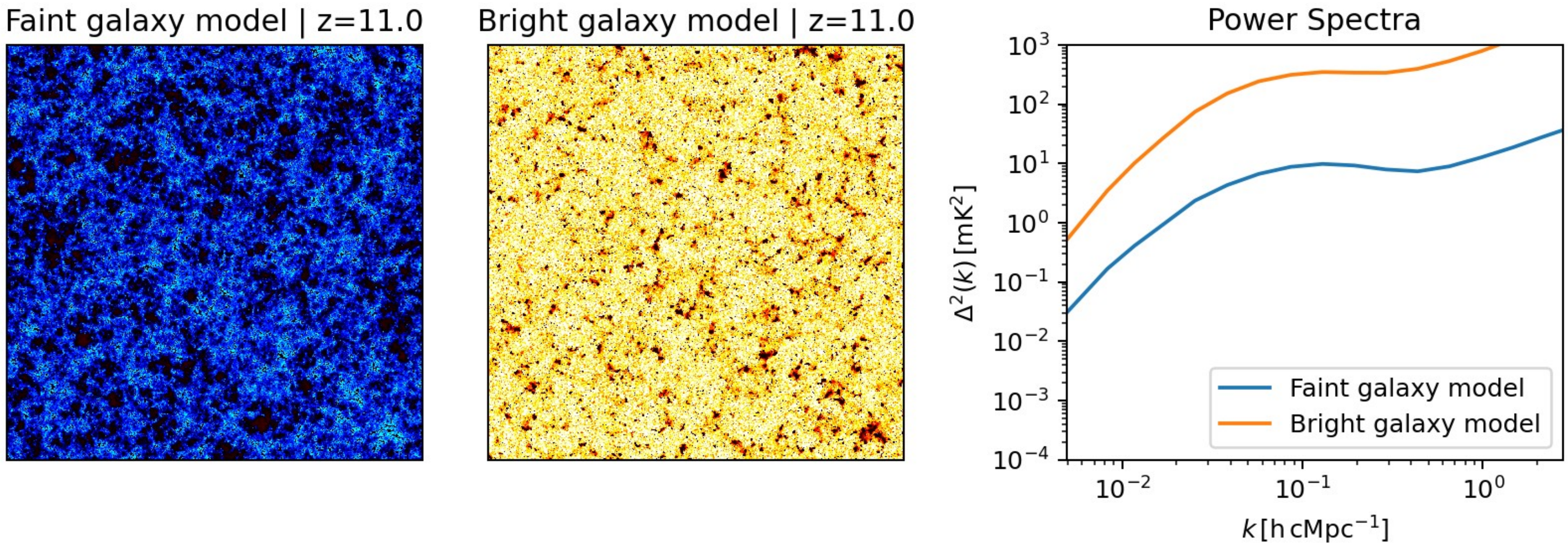


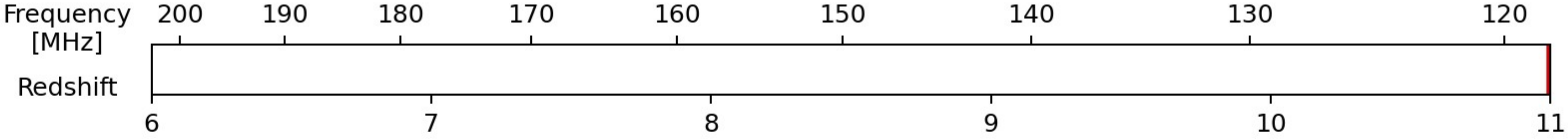
The observation of the **21-cm HI line**, an exceptional probe of the **first Gyr** of our Universe

The redshifted 21-cm Hydrogen line

An exceptional probe of the period of the first stars and reionization

Z = 11





Main ingredients of the 21-cm models:

➔ Star formation model

➔ X-ray production efficiency

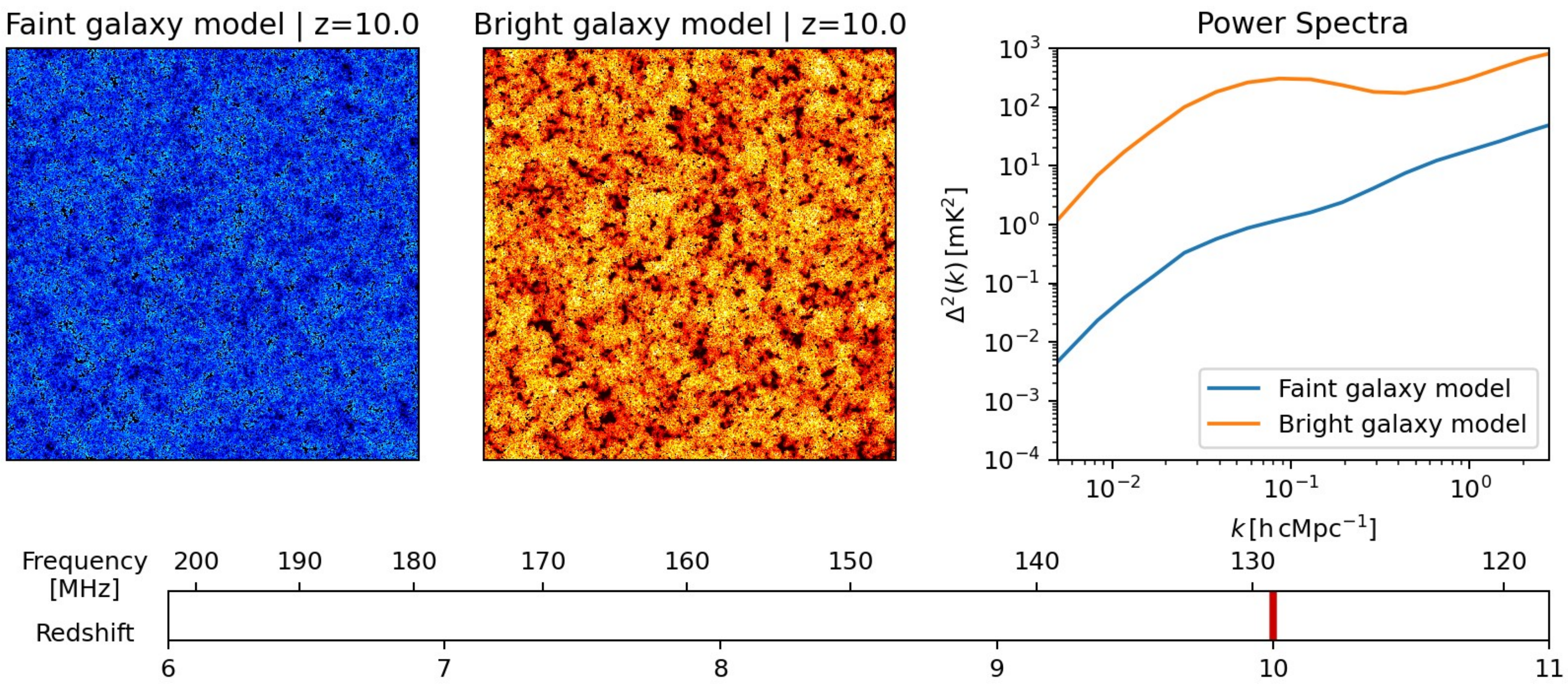
➔ Escape fraction of ionizing photon

Simulations :
Mesinger et al. 2016

The redshifted 21-cm Hydrogen line

An exceptional probe of the period of the first stars and reionization

Z = 10



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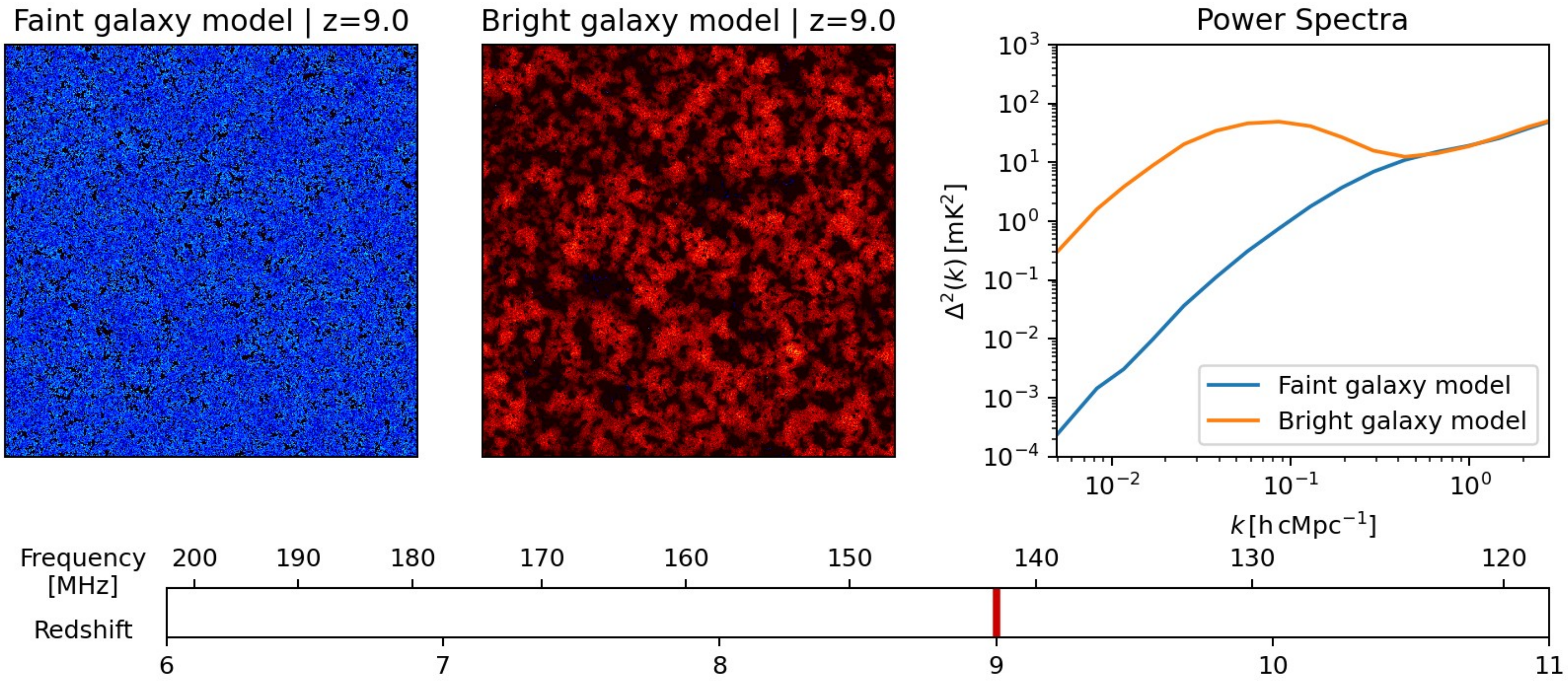
Mesinger et al. 2016

The redshifted 21-cm Hydrogen line

An exceptional probe of the period of the first stars and reionization

Z = 9



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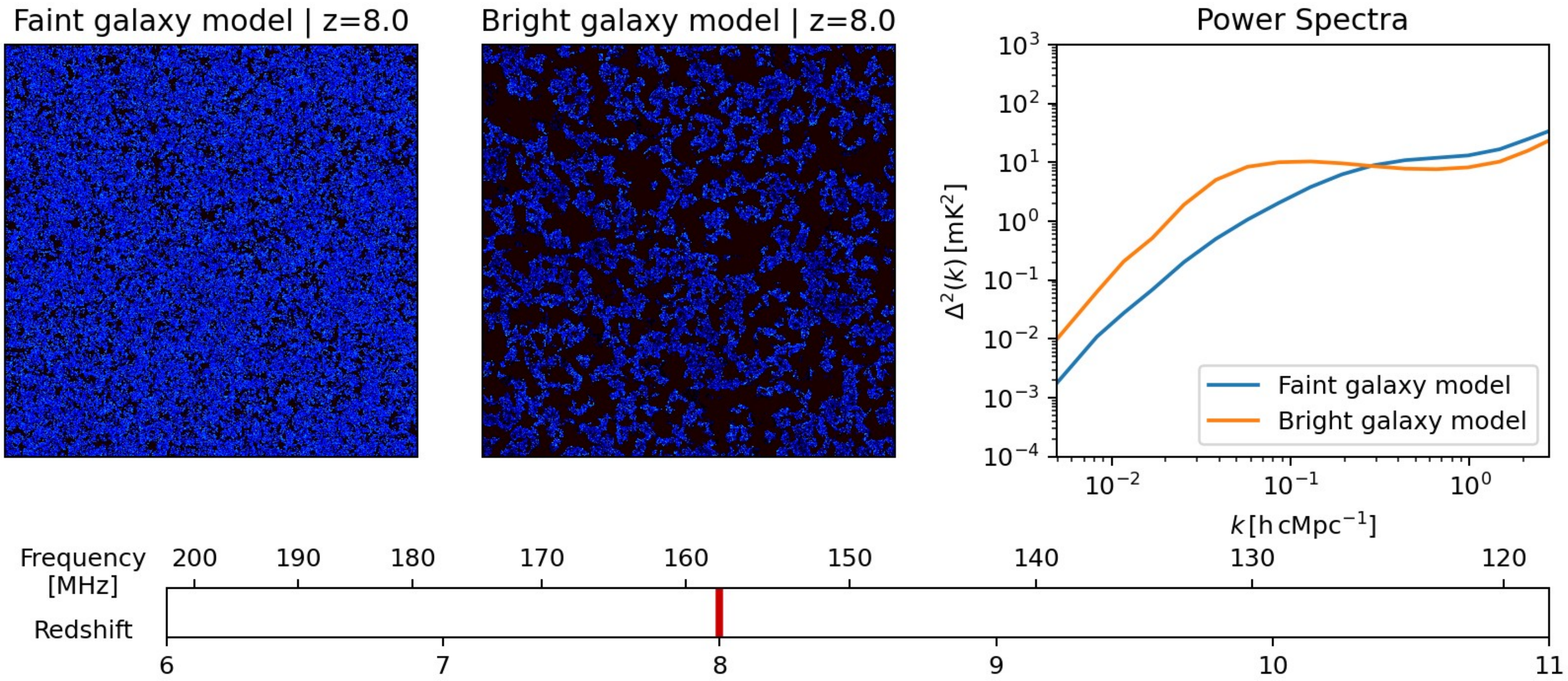
Mesinger et al. 2016

The redshifted 21-cm Hydrogen line

An exceptional probe of the period of the first stars and reionization

Z = 8



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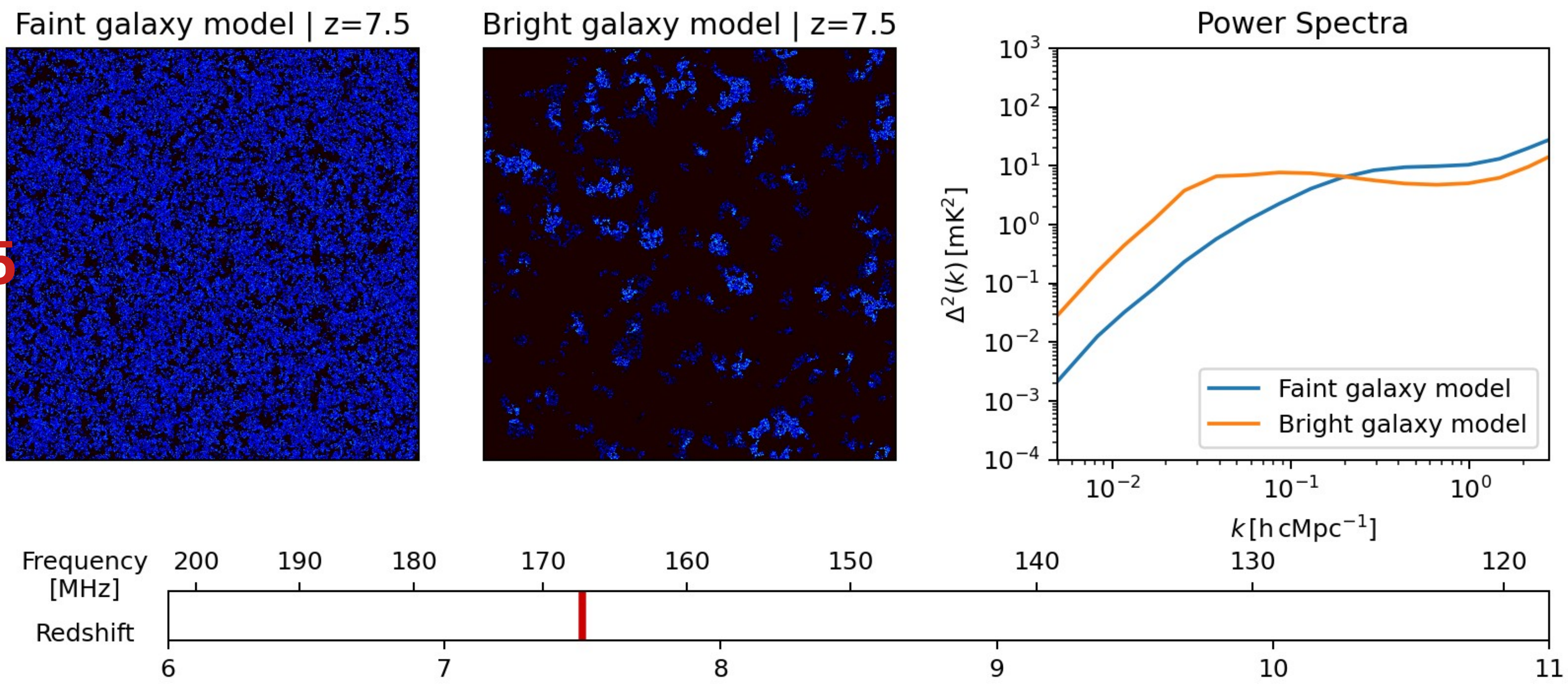
- ➔ Escape fraction of ionizing photon

Simulations :
Mesinger et al. 2016

The redshifted 21-cm Hydrogen line

An exceptional probe of the period of the first stars and reionization

Z = 7.5



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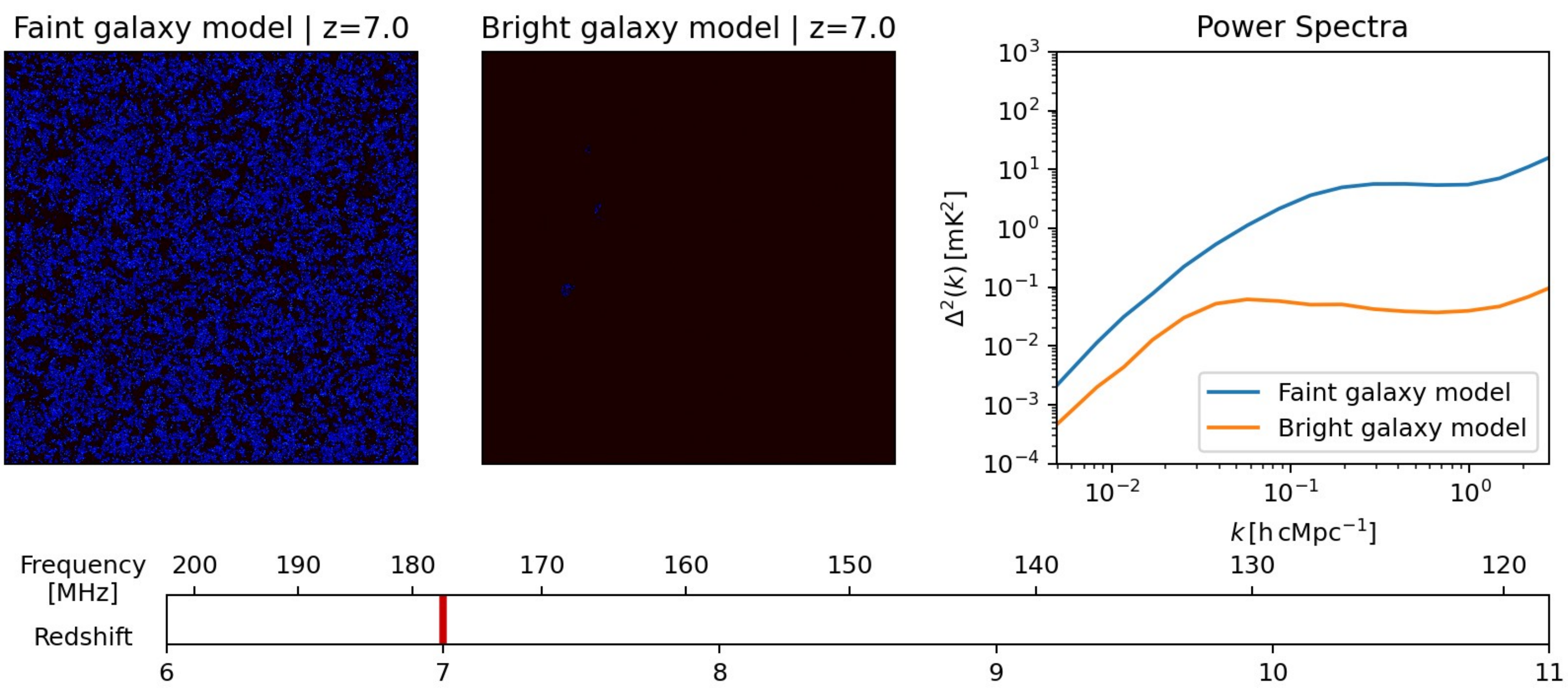
Simulations :
Mesinger et al. 2016

The redshifted 21-cm Hydrogen line

An exceptional probe of the period of the first stars and reionization

Z = 7



Main ingredients of the 21-cm models:
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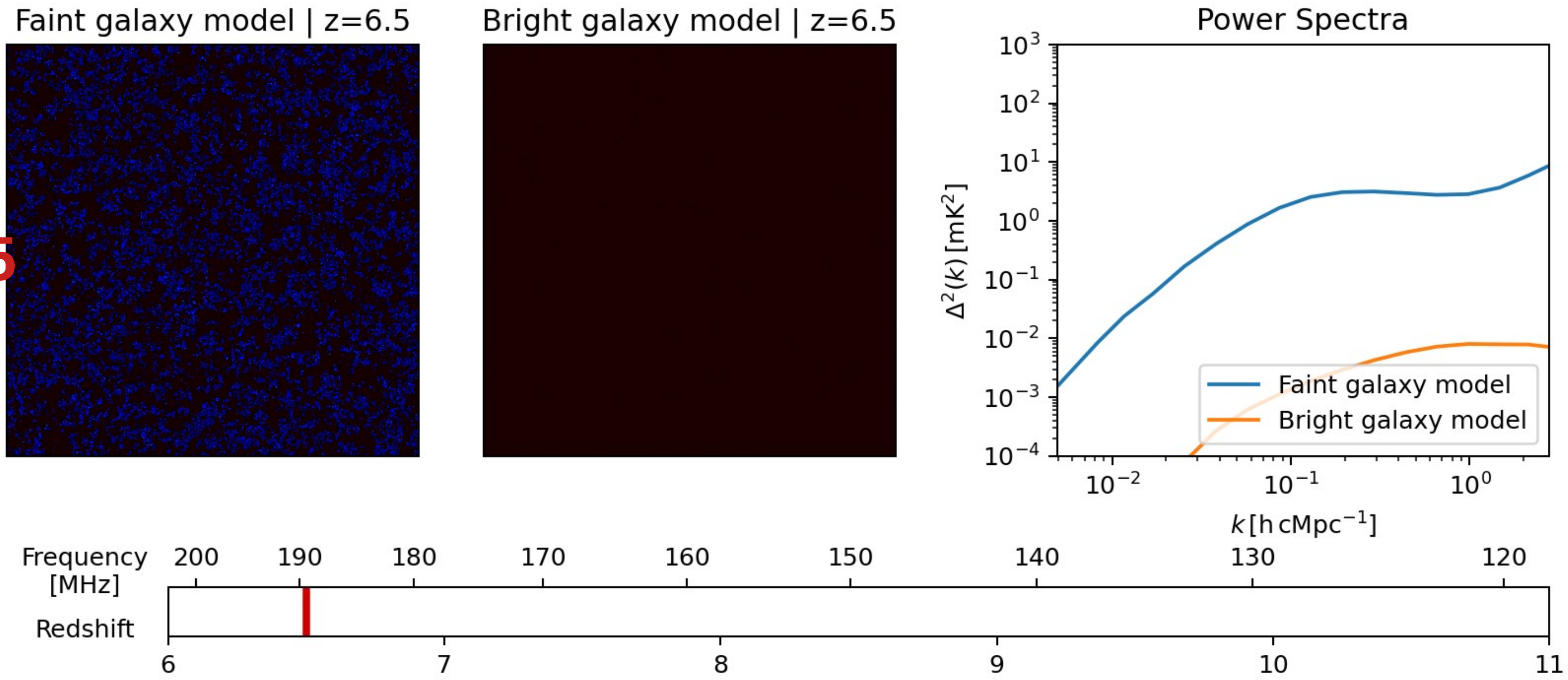
Simulations :
Mesinger et al. 2016

The redshifted 21-cm Hydrogen line

An exceptional probe of the period of the first stars and reionization

Z = 6.5



Main ingredients of the 21-cm models:
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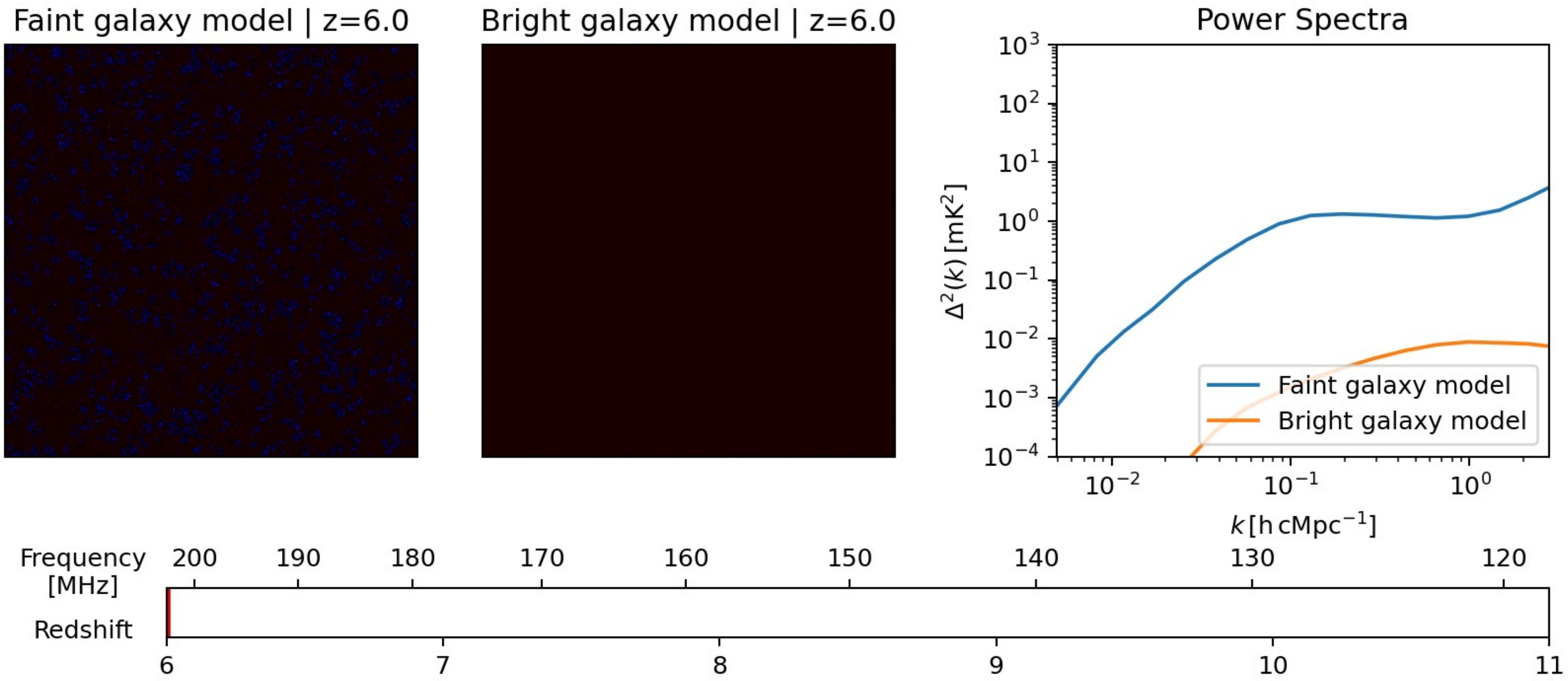
- ➔ Escape fraction of ionizing photon

Simulations :
Mesinger et al. 2016

The redshifted 21-cm Hydrogen line

An exceptional probe of the period of the first stars and reionization

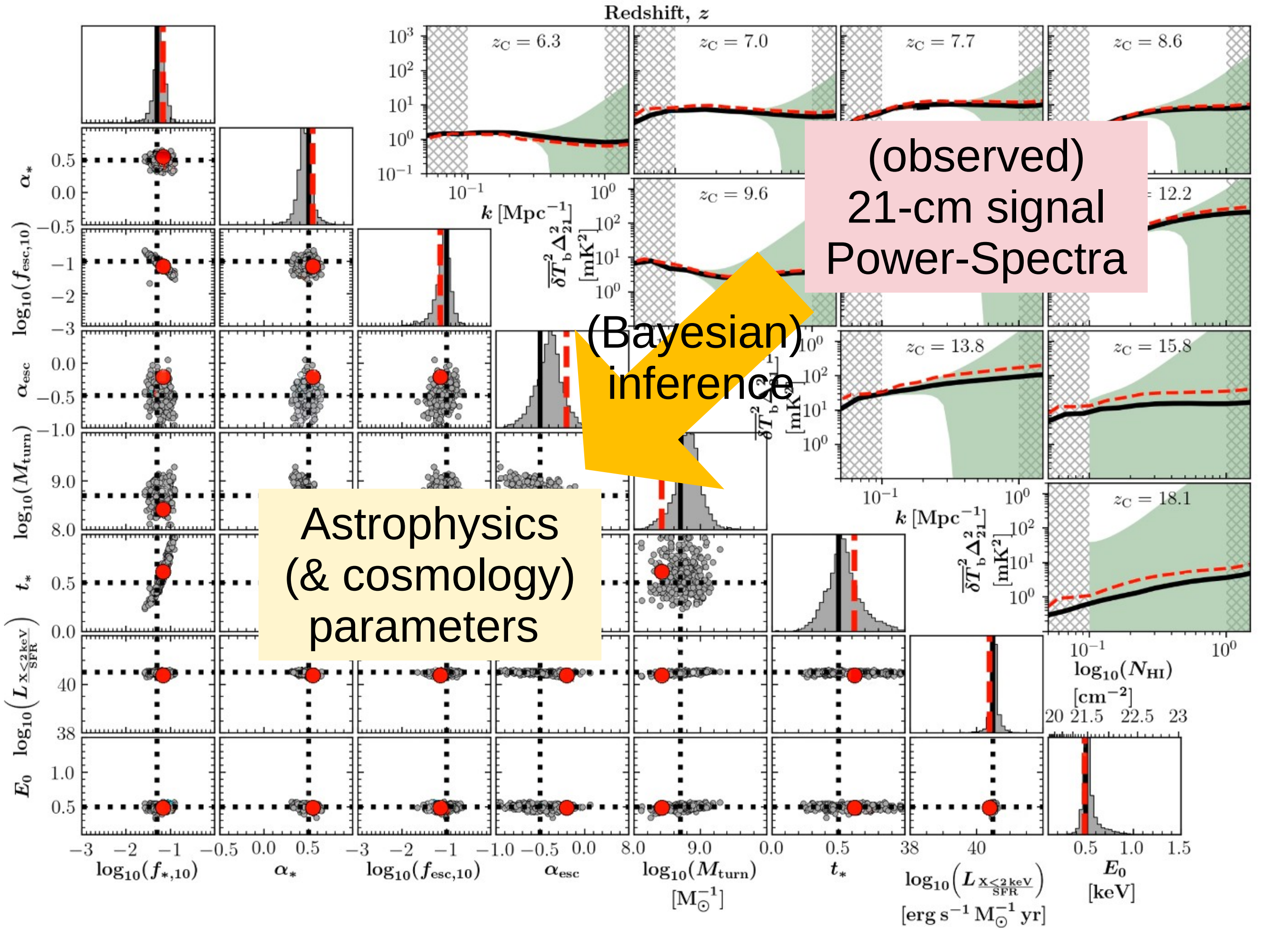
Z = 6



Main ingredients of the 21-cm models:
➔ Star formation model
➔ X-ray production efficiency
➔ Escape fraction of ionizing photon

Simulations :
Mesinger et al. 2016

Inferring the physics of the EoR / Cosmic Dawn with the 21-cm signal



Observable:
- ➔ 21-cm power-spectra
- ➔ 21-cm higher order statistics
- ➔ Other probes, e.g. luminosity function (JWST/Hubble), Planck, etc...

Astrophysics parameters :
- ➔ Star formation model
- ➔ X-ray production efficiency
- ➔ Escape fraction of ionizing photon

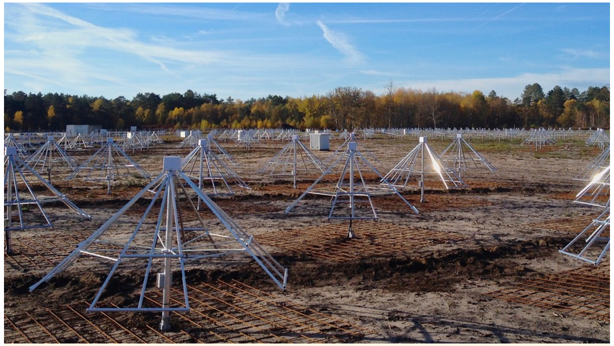
The interferometric 21-cm experiments

LOFAR-EoR

Observation started in 2012

➔ Properties of the IGM and ionising sources.

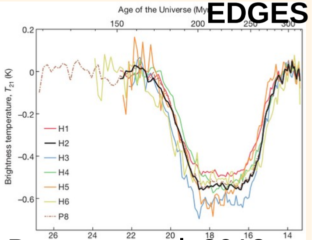
➔ History of reionization.



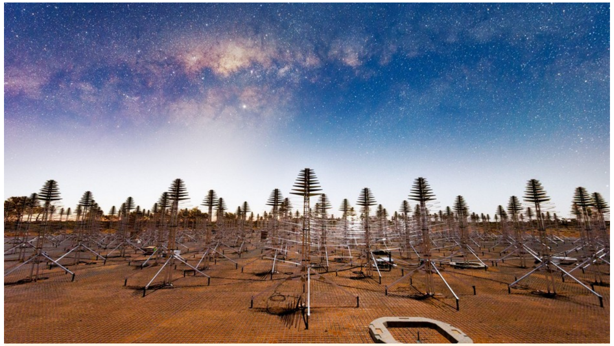
NenuFAR Cosmic Dawn

Observation started in 2019

➔ Testing of non-standard models.



Bowman et al. 2018

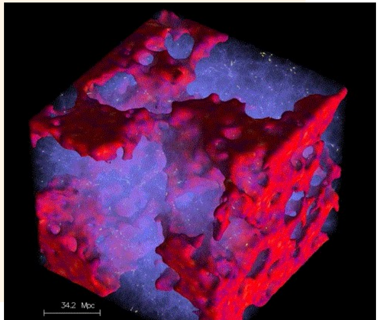


SKA CD/EoR

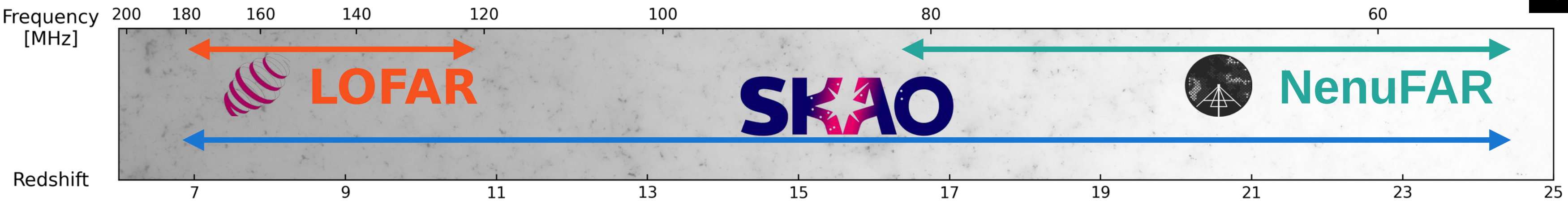
Completion ~2028

➔ Nature of the first stars.

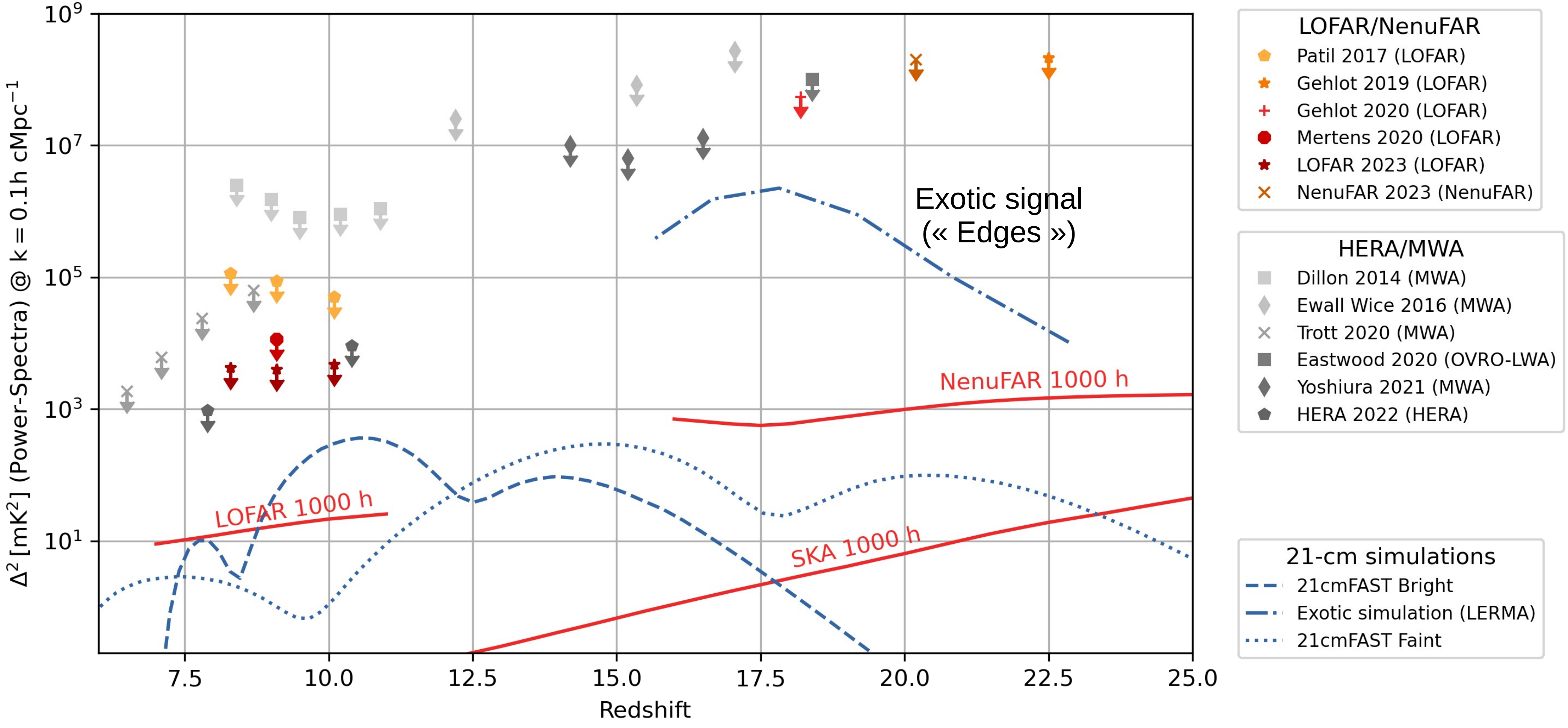
➔ Morphology of ionized regions.



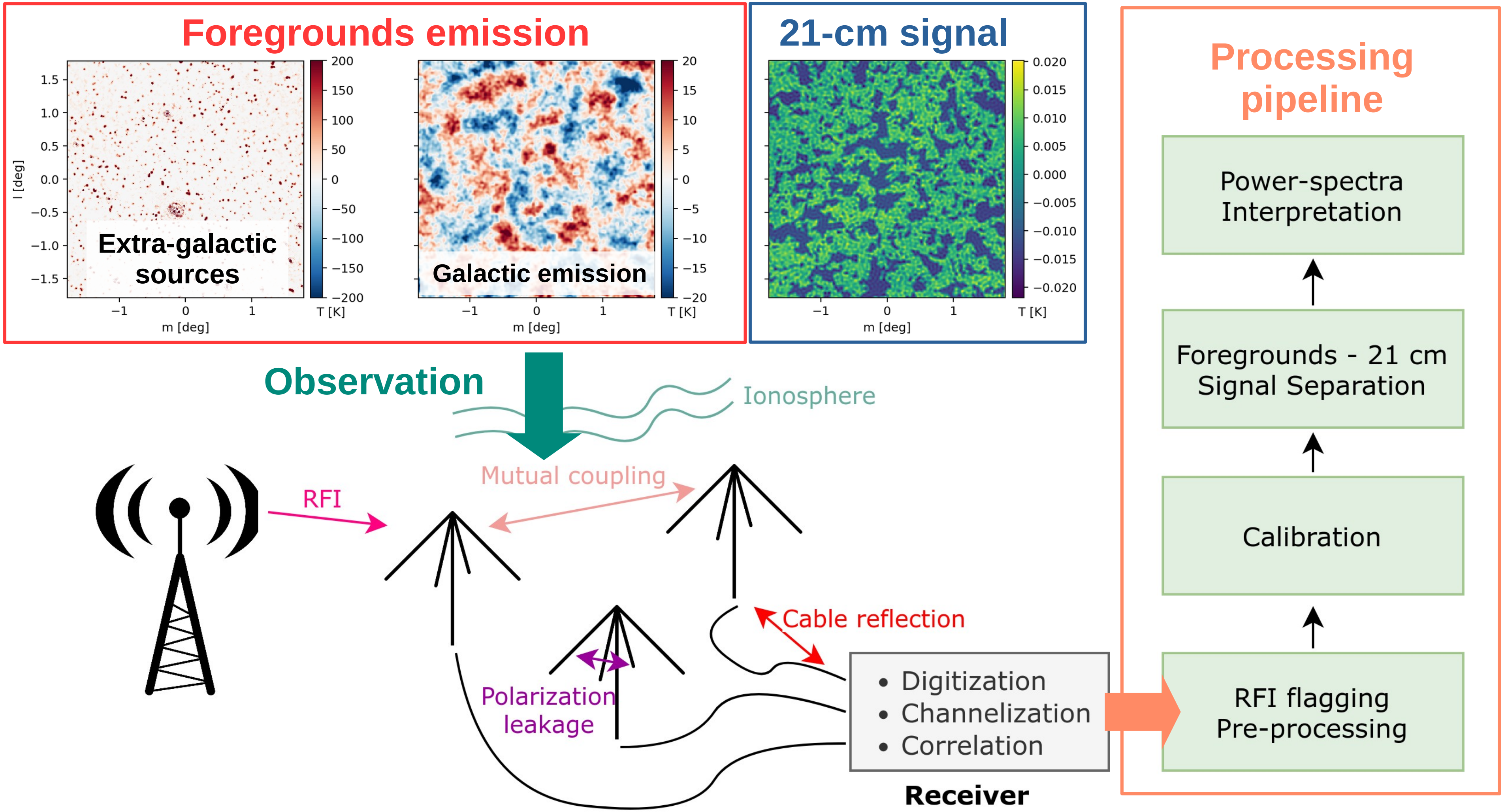
Simulation 21-cm du LERMA



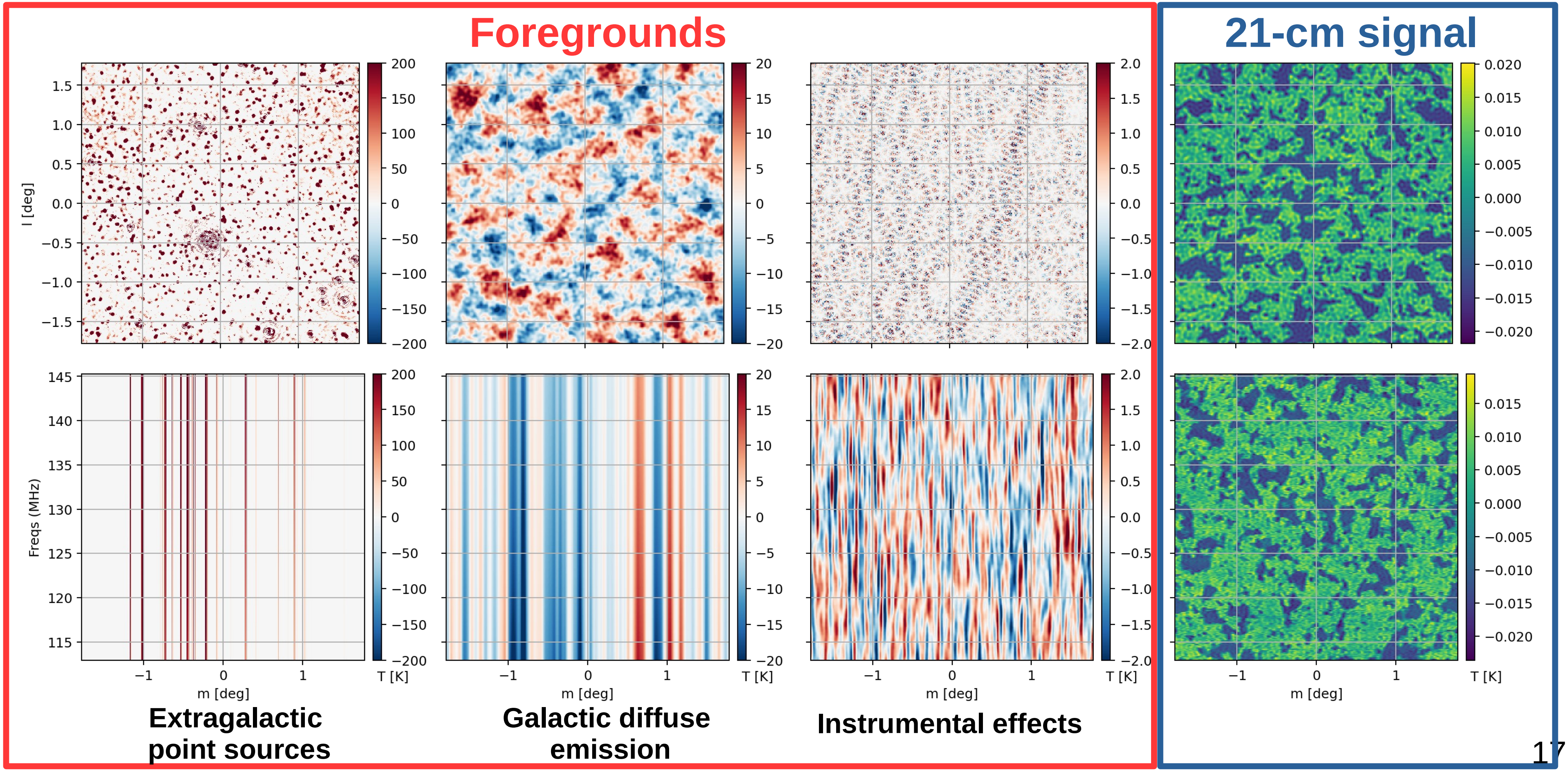
Progress toward a detection



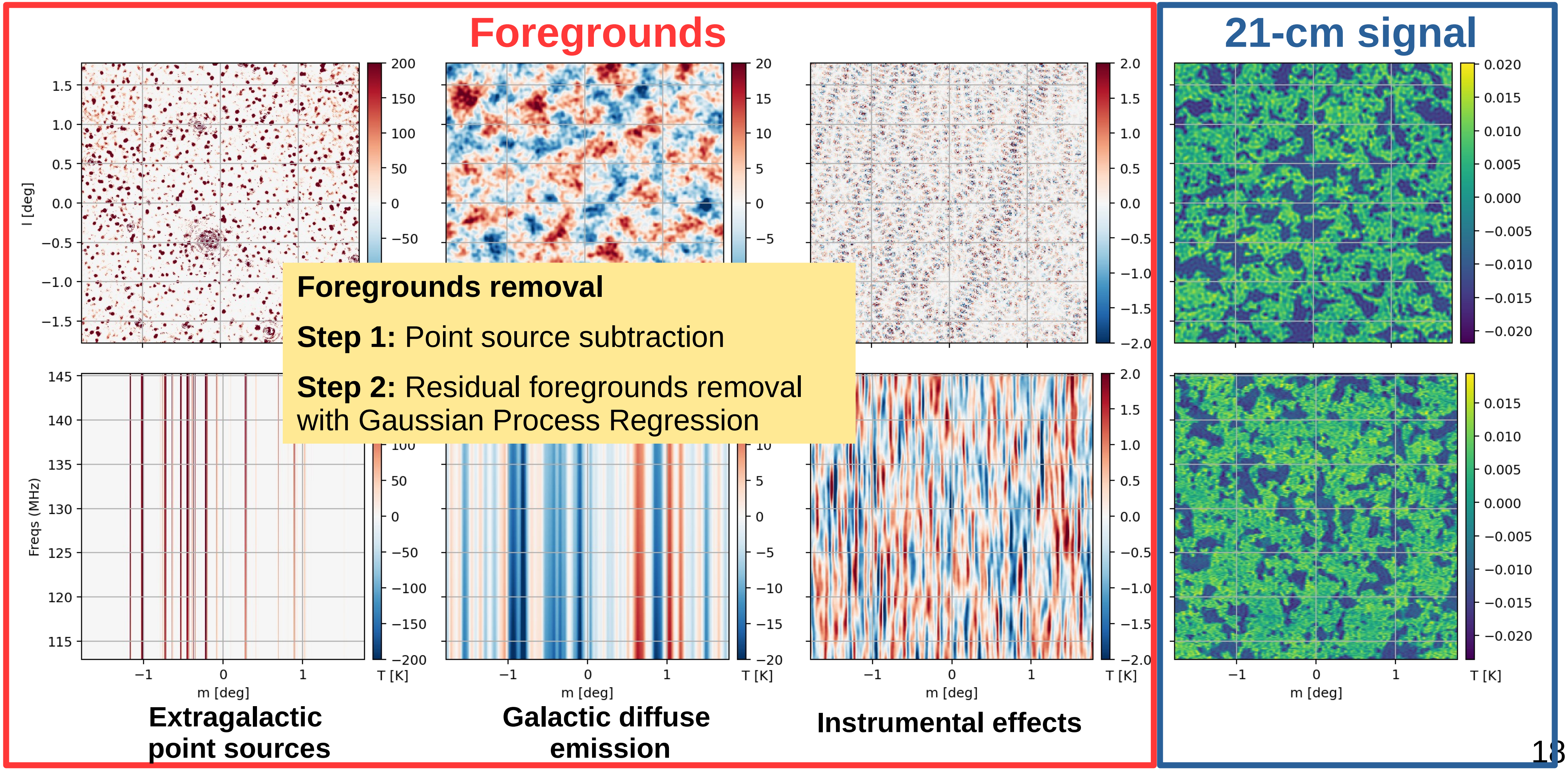
A challenging experiment



The challenge of the foregrounds



The challenge of the foregrounds



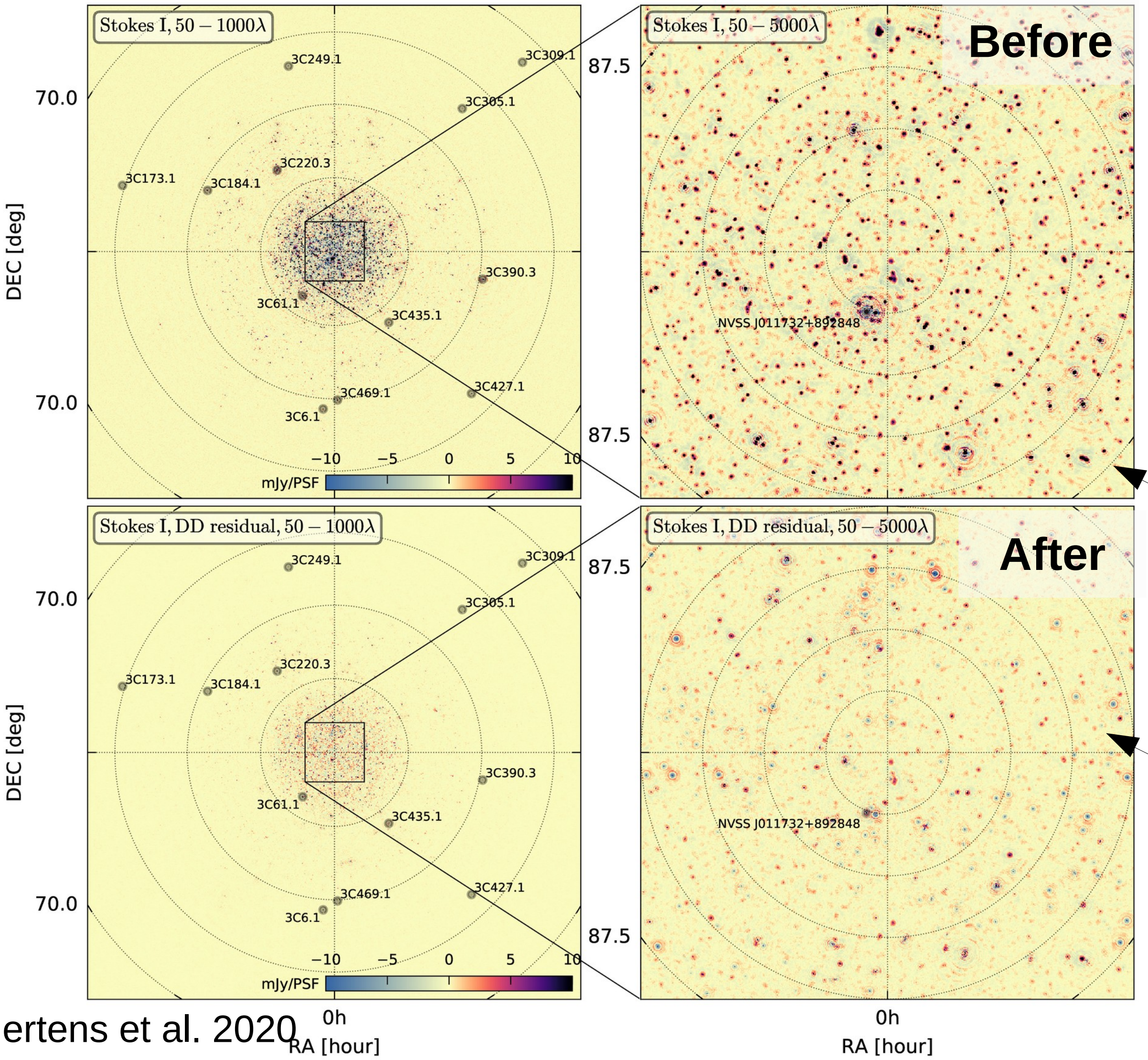
Foregrounds removal

Step 1: Point source subtraction

Step 2: Residual foregrounds removal with Gaussian Process Regression

LOFAR | NCP | 140 hours | 134-146 MHz

Point-source subtraction



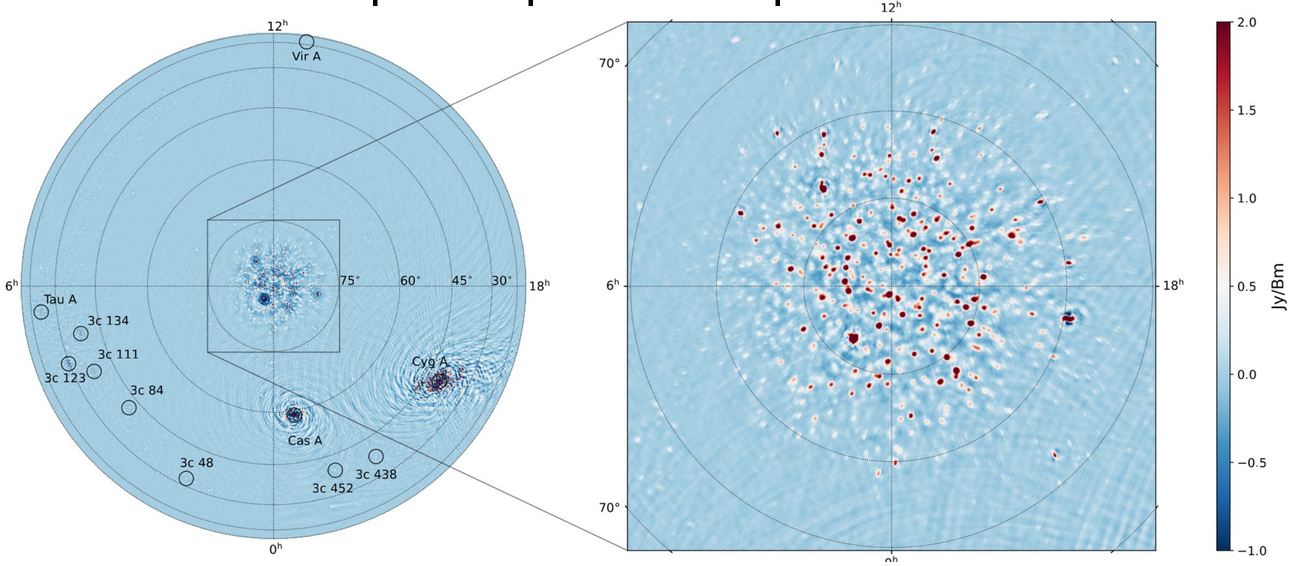
- ➔ Need accurate sky-model
- ➔ Solve for instruments gains in direction of sources

Inner 4° x 4° where we look for the signal

Confusion limited foregrounds + low level residuals

Mertens et al. 2020

NenuFAR | NCP | 11 hours | 61-72 MHz



Point-source subtraction

- ➔ Need accurate sky-model
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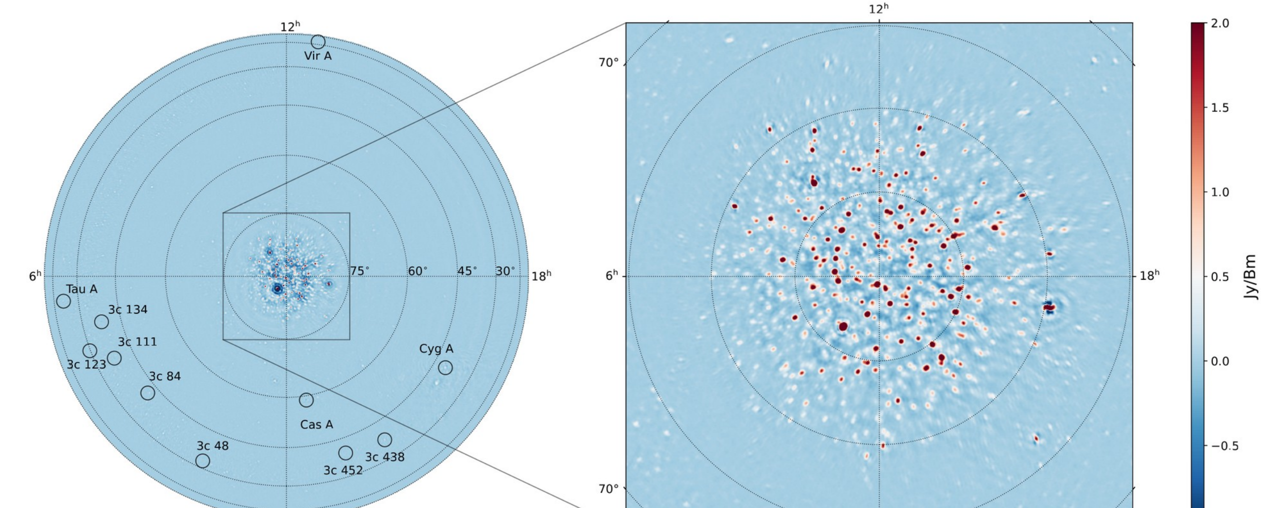
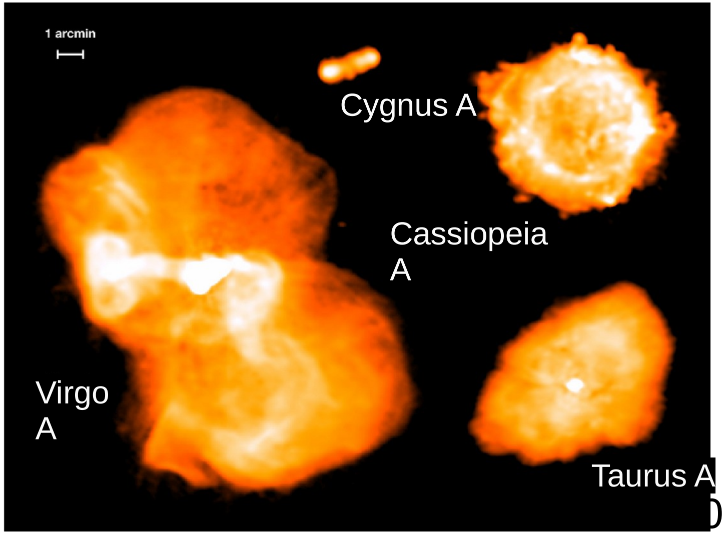


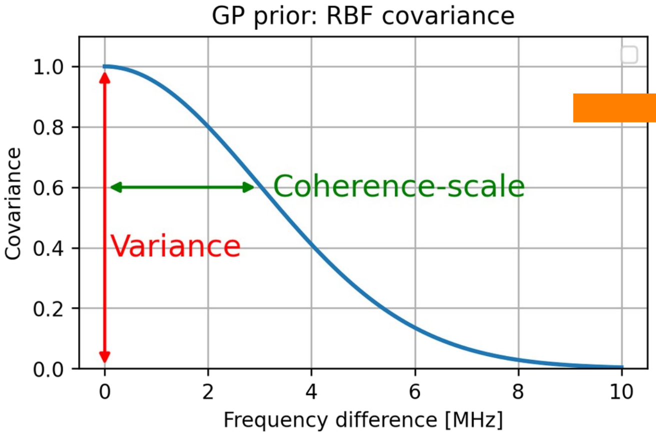


Munshi, Mertens et al. 2024

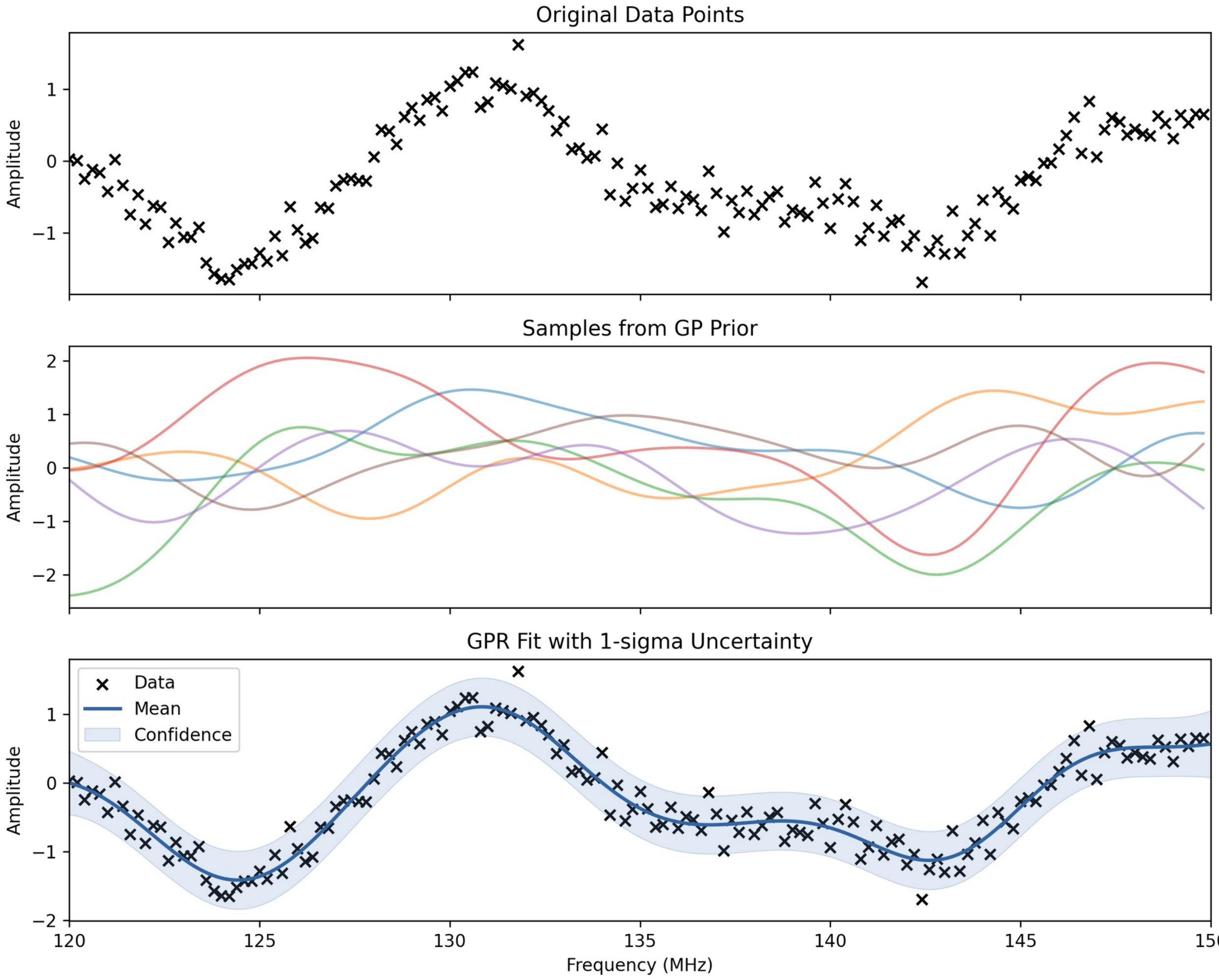
Gaussian Process Regression

After point-source subtraction, residual foregrounds still dominates

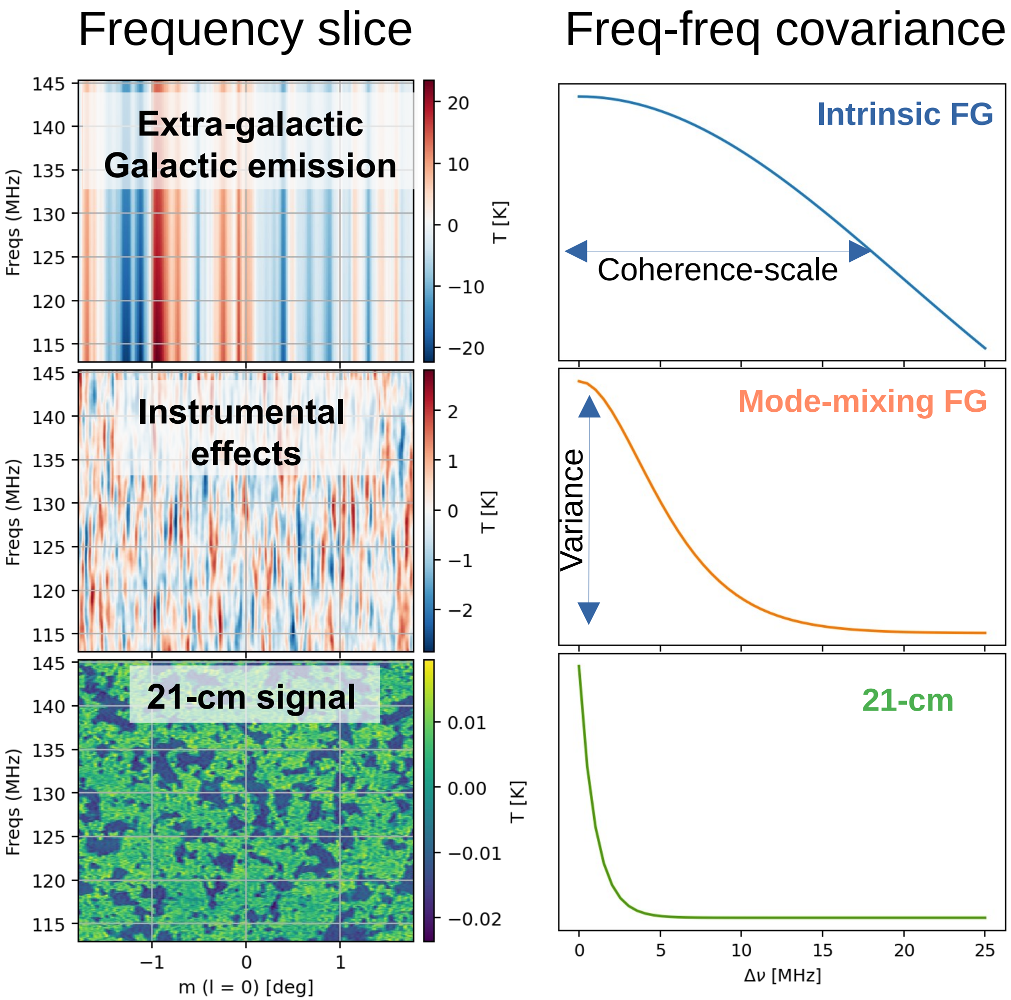
- **GPR:** Fits data without assuming a specific functional form.
- **Prior Information:** Encoded through a parametrized covariance function.



- **Parameters Optimization:** Covariance parameters are determined by maximizing the marginal likelihood.
- **Data fitting:** Conditioning the prior model to the data, we obtain fit + uncertainty.



GPR for 21-cm experiments



No functional forms but very different spectral characteristic

→ Statistical model prior made of Gaussian Process (GP).

→ Learnt kernel is used for the 21-cm prior covariance.

$$K = K_{\rm fg} + K_{21} + \mathrm{K}_{\rm noise} + \mathrm{K}_{\rm other}$$

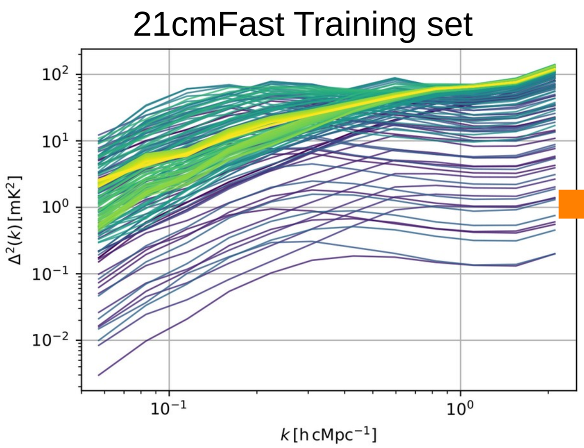
Hyper-parameters of the covariance prior to be optimized with the data

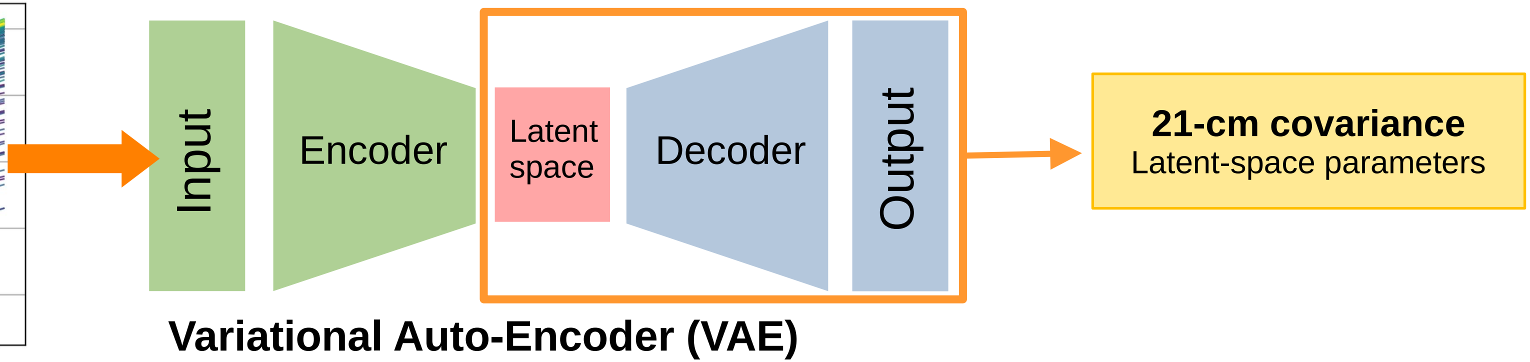
$$E(\mathbf{f}_{\rm fg}) = K_{\rm fg}\left[K_{\rm fg} + K_{21} + \sigma_n^2 I\right]^{-1}\mathbf{d}$$

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

Mertens et al. 2018
Mertens, Bobin, Carucci 2024

Learned covariance function





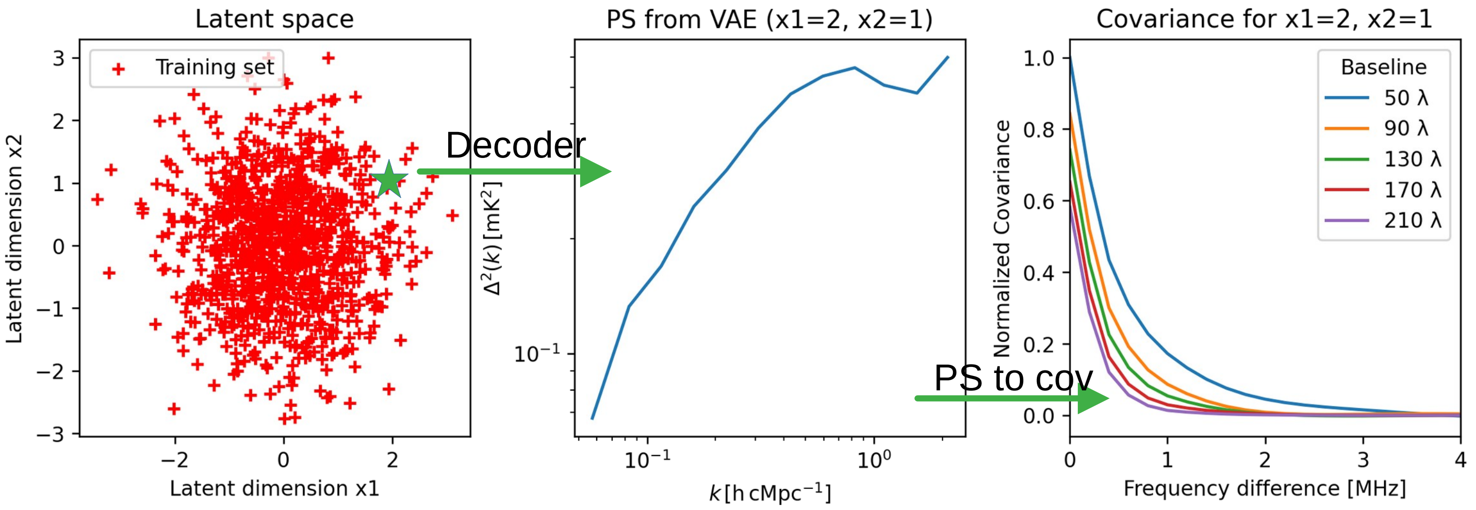
VAE: Trained to minimize:

➔ Reconstruction error.

➔ KL divergence to standard Gaussian in latent space.

✔ Compressed information (lower dimension latent space).

✔ Generative.



Mertens, Bobin, Carucci 2024

The Epoch of Reionization with LOFAR

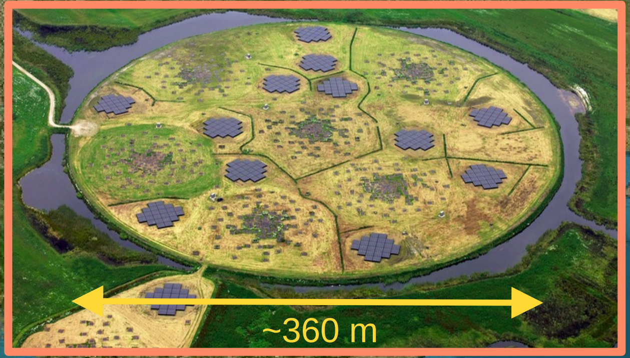
LOFAR-EoR plenary 2019 - Groningen

LOFAR-EoR plenary 2022 - Paris

The Low Frequency Array

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

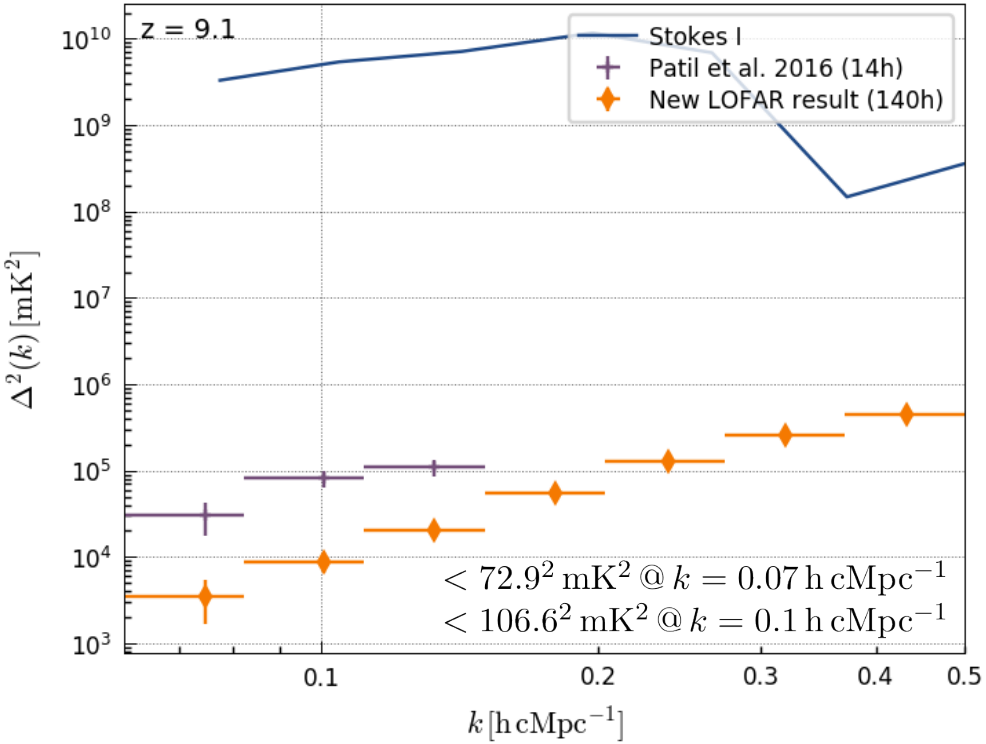
110 – 240 MHz (HBA)
30 – 80 MHZ (LBA)



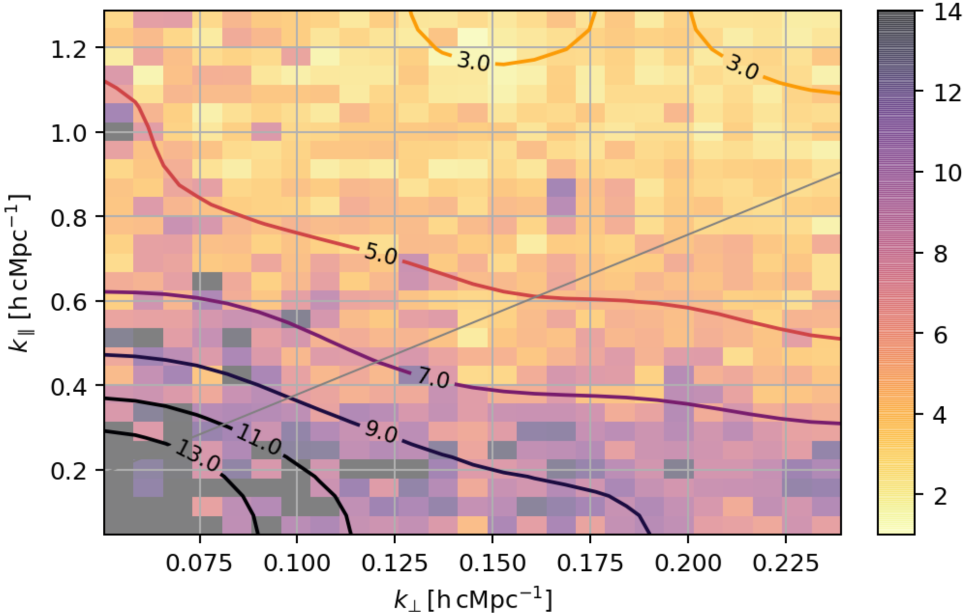
The « superterp »

Current LOFAR upper limit at z~9

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



PS ratio Stokes I residual / thermal noise



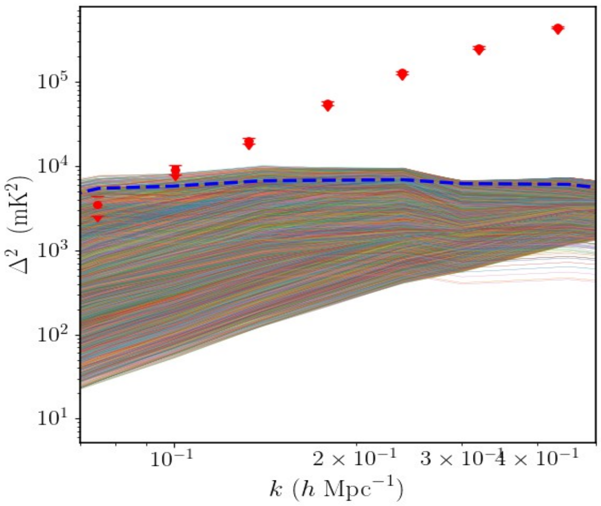
A reduction by a factor ~ 10 compared to our 2017 upper limit, the deepest at z ~ 9 ...

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

(Mertens et al. 2020)

Astrophysical interpretations of the upper limit

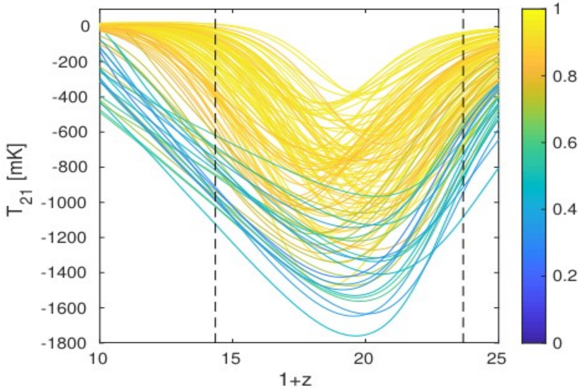
Constraining the IGM during the EoR (Ghara et al. 2020)



Discard several scenarii with **cold** IGM models (large emission regions, high UV photon emission rate).

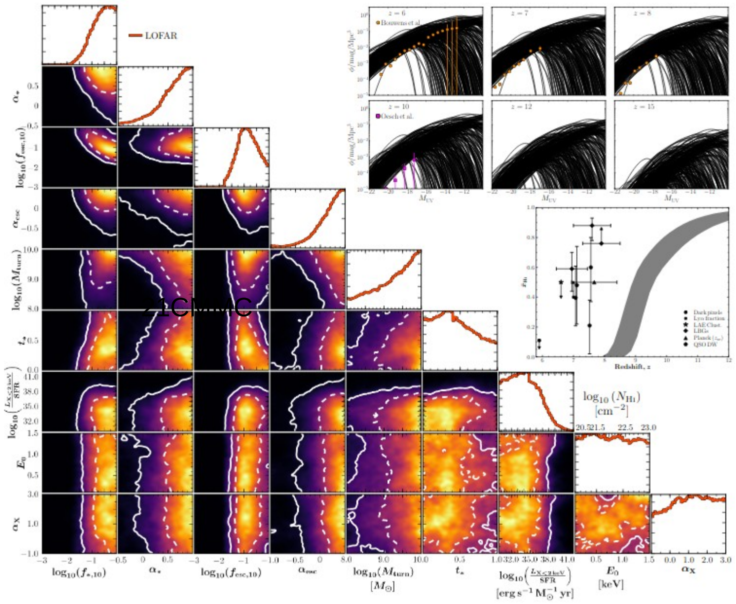
Constraint on the excess radio background (Mondal et al. 2020)

Global signal models.
Yellow to blue: likely to less likely model.



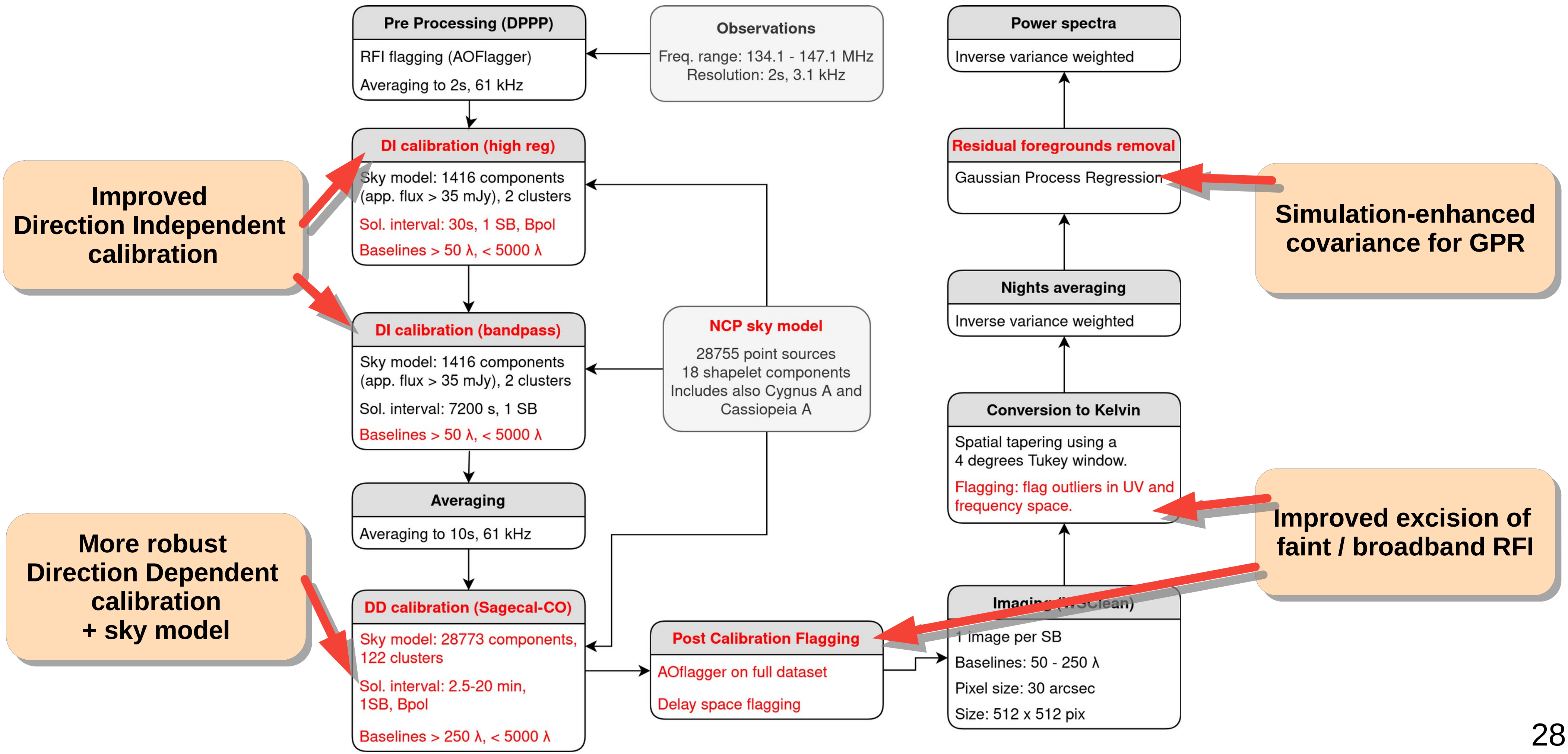
Discard excess radio background < 9.6 % CMB at 1.42 GHz but excess level could still explain the EDGES detection

Constraint on the properties of the high-z galaxies (Greig et al. 2021)

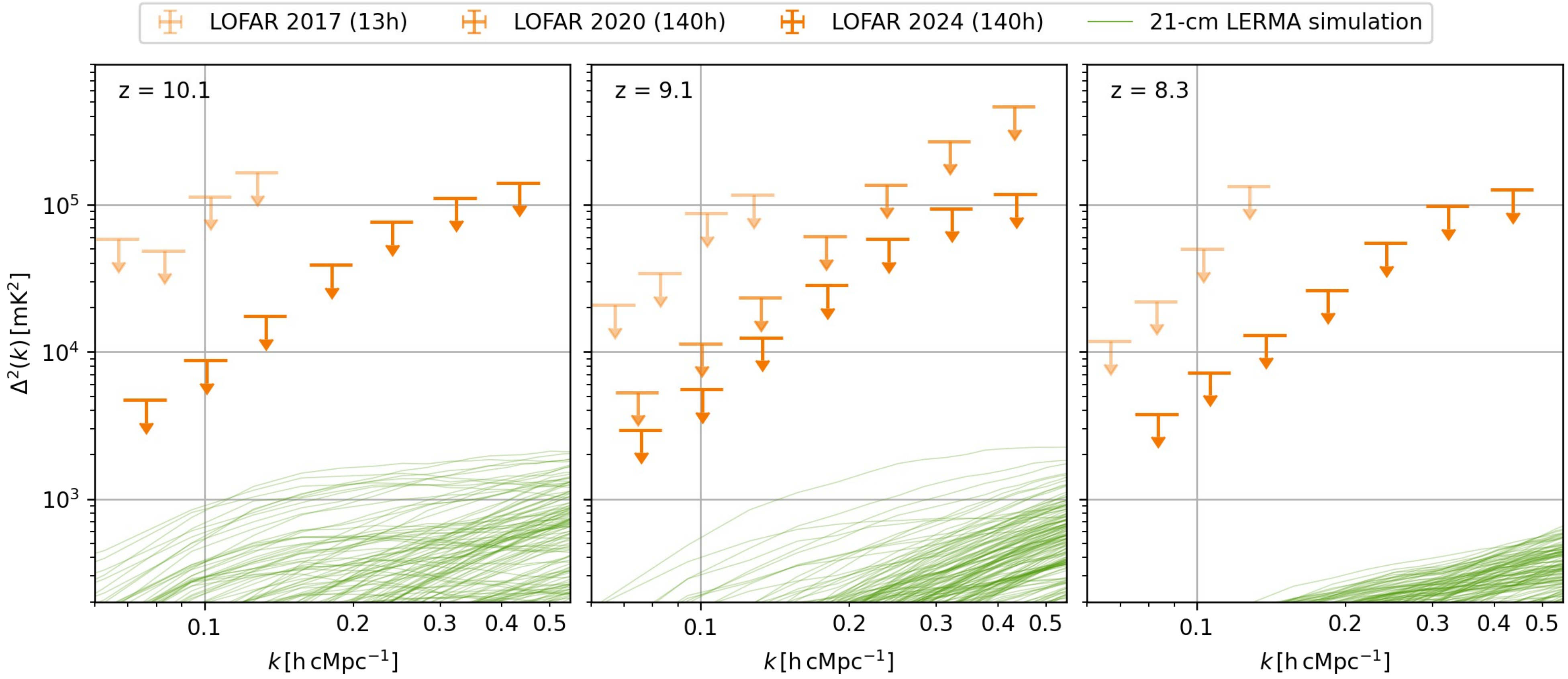


Use 21CMMC framework

Mitigating the excess



New LOFAR results



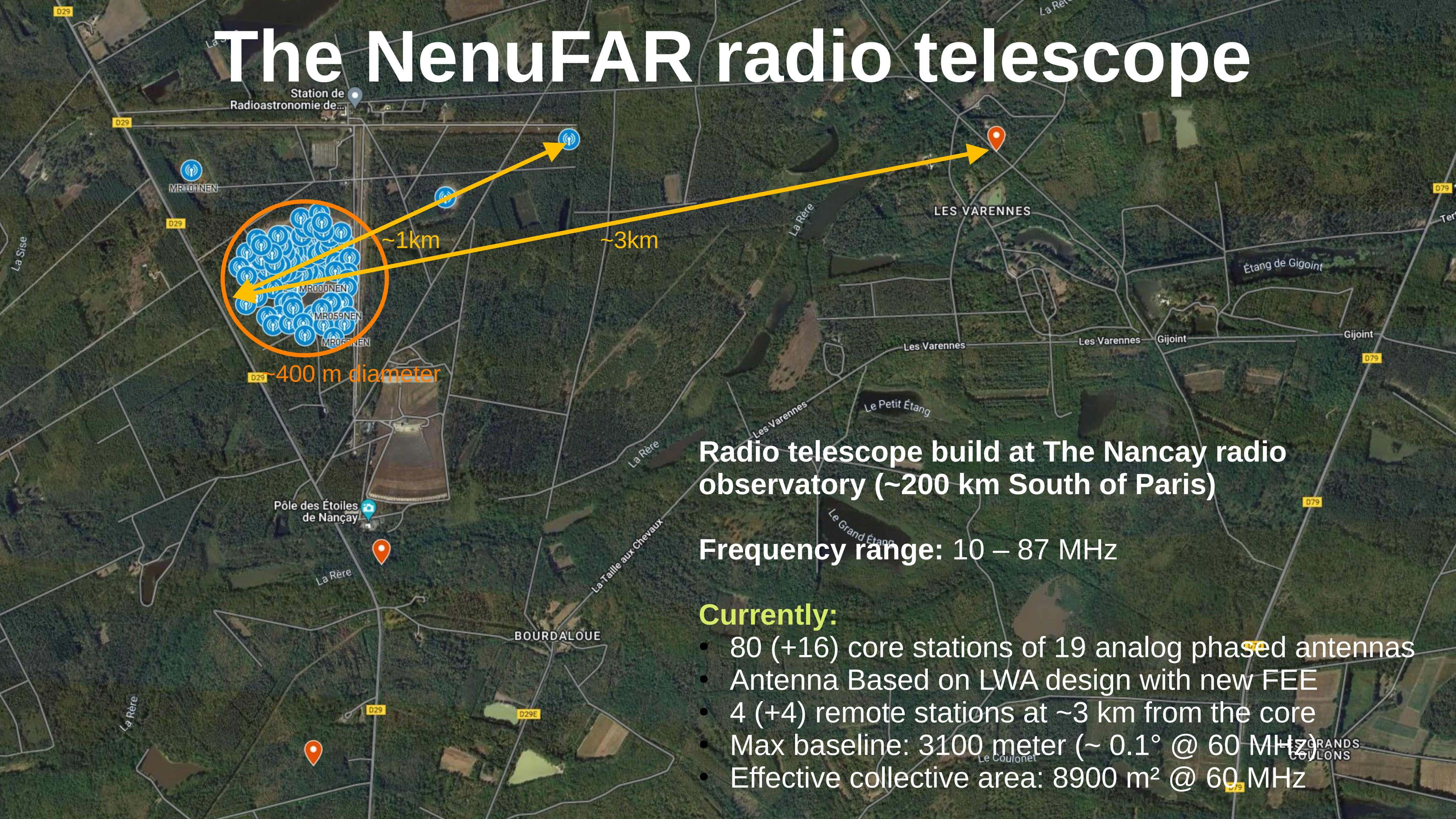
➔ A reduction in upper limits by a factor ~5 to 10 for the three LOFAR redshifts (Mertens, Mevius, et al. in prep.).

Probing the Cosmic Dawn with NenuFAR

NenuFAR CD plenary 2021 - Paris

NenuFAR CD plenary 2023 - Groningen

The NenuFAR radio telescope



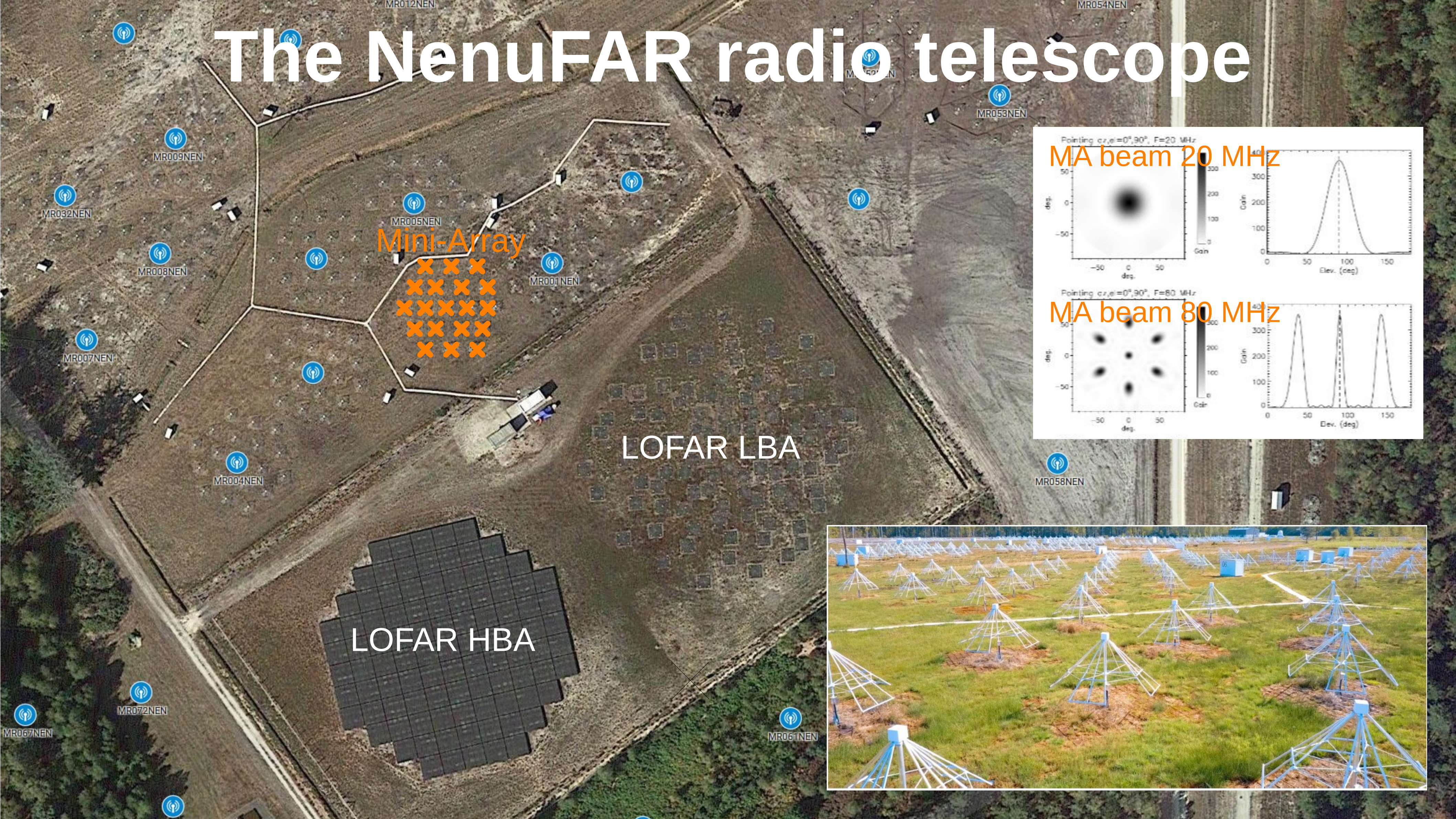
Radio telescope build at The Nancay radio observatory (~200 km South of Paris)

Frequency range: 10 – 87 MHz

Currently:

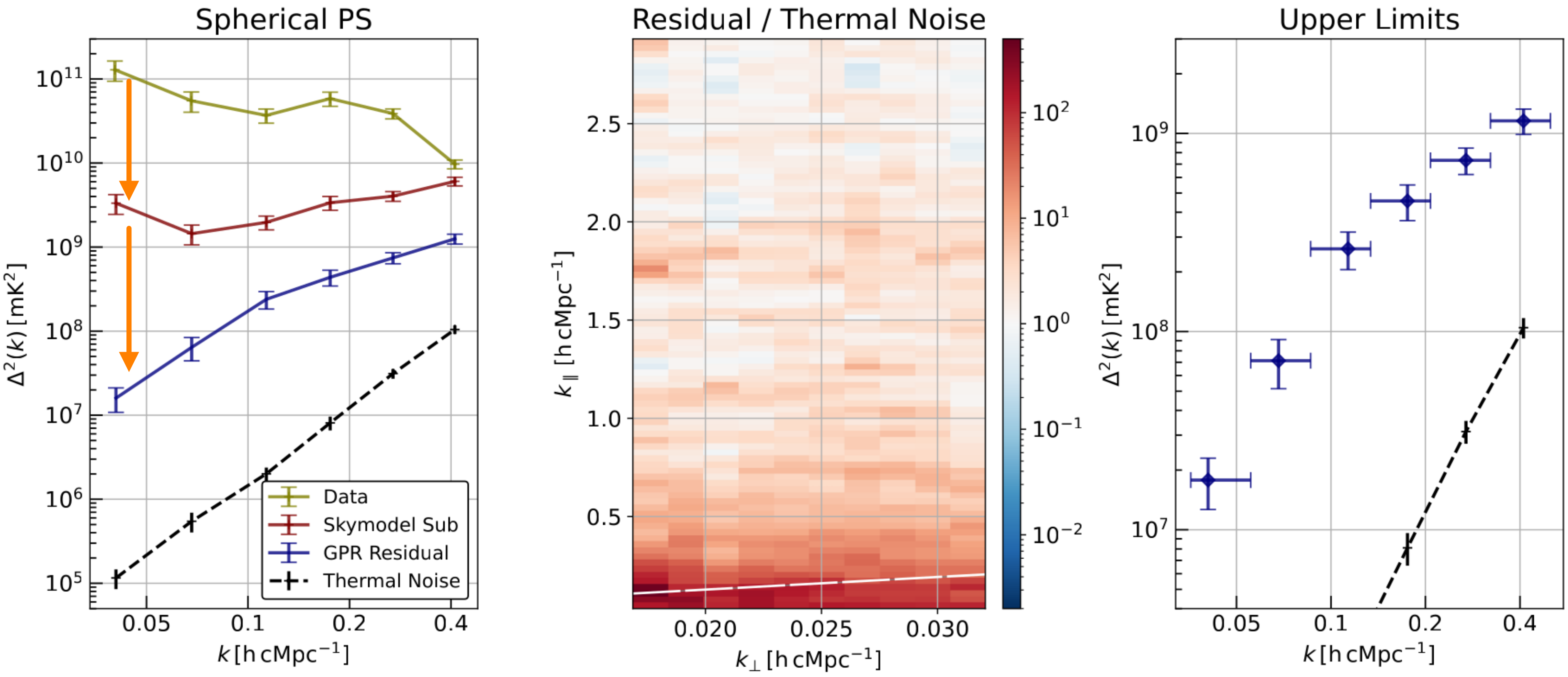
- 80 (+16) core stations of 19 analog phased antennas
- Antenna Based on LWA design with new FEE
- 4 (+4) remote stations at ~3 km from the core
- Max baseline: 3100 meter (~ 0.1° @ 60 MHz)
- Effective collective area: 8900 m² @ 60 MHz

The NenuFAR radio telescope



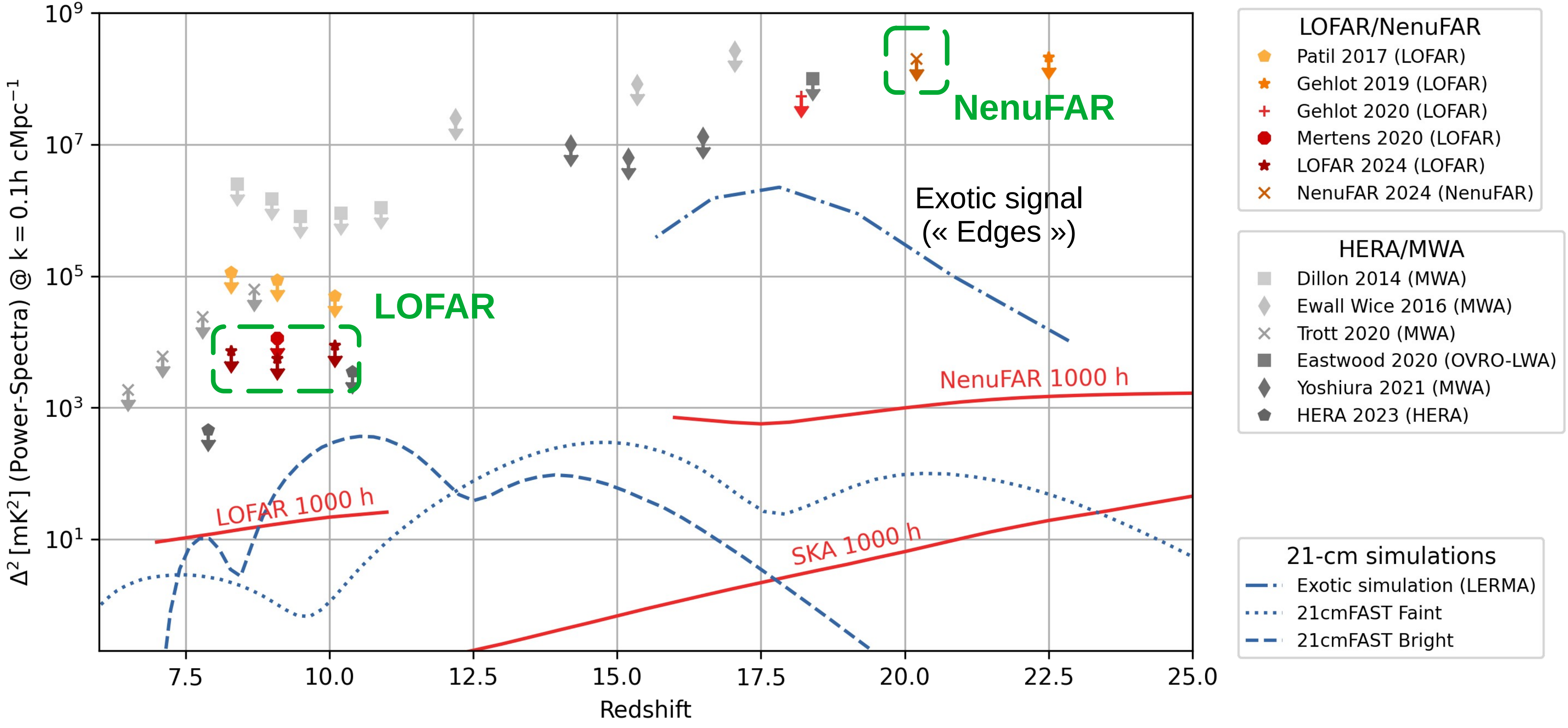
First NenuFAR upper limit

NCP field, 11.5 hours, 61-72.5 MHz, z ~ 20



Munshi, Mertens et al. 2024

Progress toward a detection



Summary

- ➔ The 21-cm signal from the Cosmic Dawn and Epoch of Reionization promises a new and unique probe of the first billion year of the Universe, **but very challenging experiment.**
- ➔ Many challenges: **Foregrounds, Calibration, RFI**

- ➔ **Status of the LOFAR-EoR project:**
  - The LOFAR-EoR project reported in 2020 its **deepest upper limit** at **z ~ 9:**

    $\Delta^2 < (100\ \mathrm{mK})^2$ @ $k=0.1\ \mathrm{cMpc}^{-1}$, z ~ 9 (based on ~5% of data)
  - New multi-redshift upper-limits !

- ➔ **Status of the NenuFAR Cosmic Dawn project:**
  - The NenuFAR Cosmic Dawn project aims at detecting the redshifted 21-cm signal from the Cosmic-Dawn in the redshift range **z ~ 15 – 31**.
  - **First upper limit at z ~ 20** published**.**

- ➔ **We are preparing for the first SKA observation**