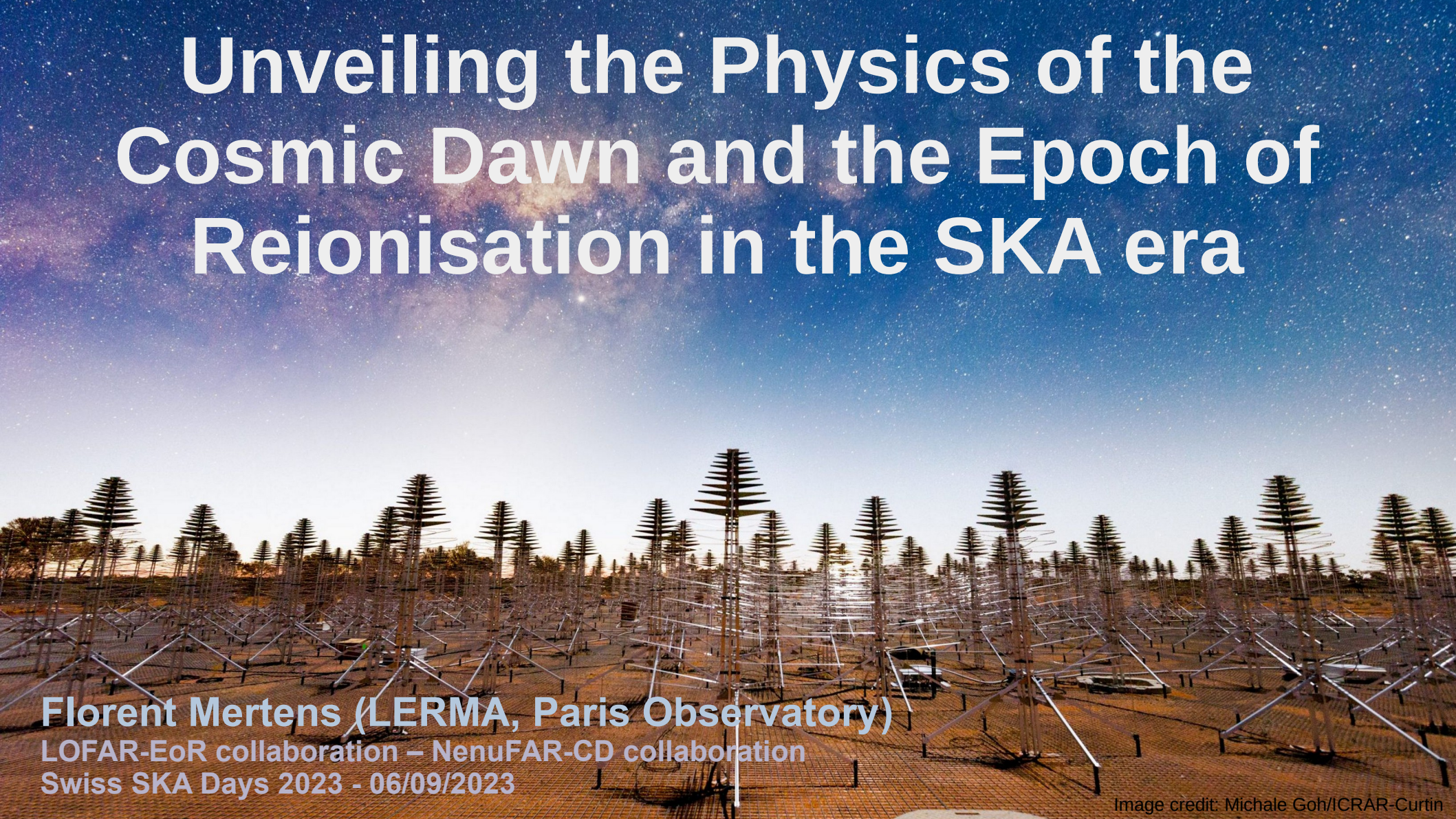
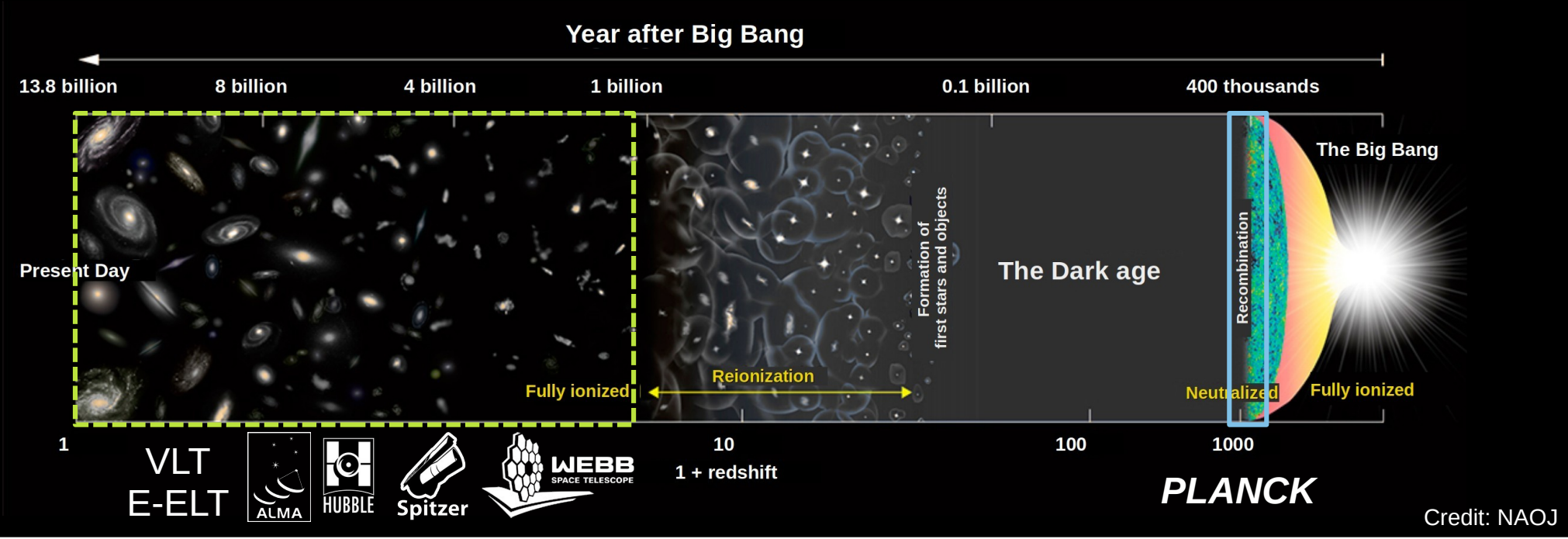
Unveiling the Physics of the Cosmic Dawn and the Epoch of Reionisation in the SKA era



Florent Mertens (LERMA, Paris Observatory)
LOFAR-EoR collaboration – NenuFAR-CD collaboration
Swiss SKA Days 2023 - 06/09/2023

Image credit: Michale Goh/ICRAR-Curtin

The history of our universe

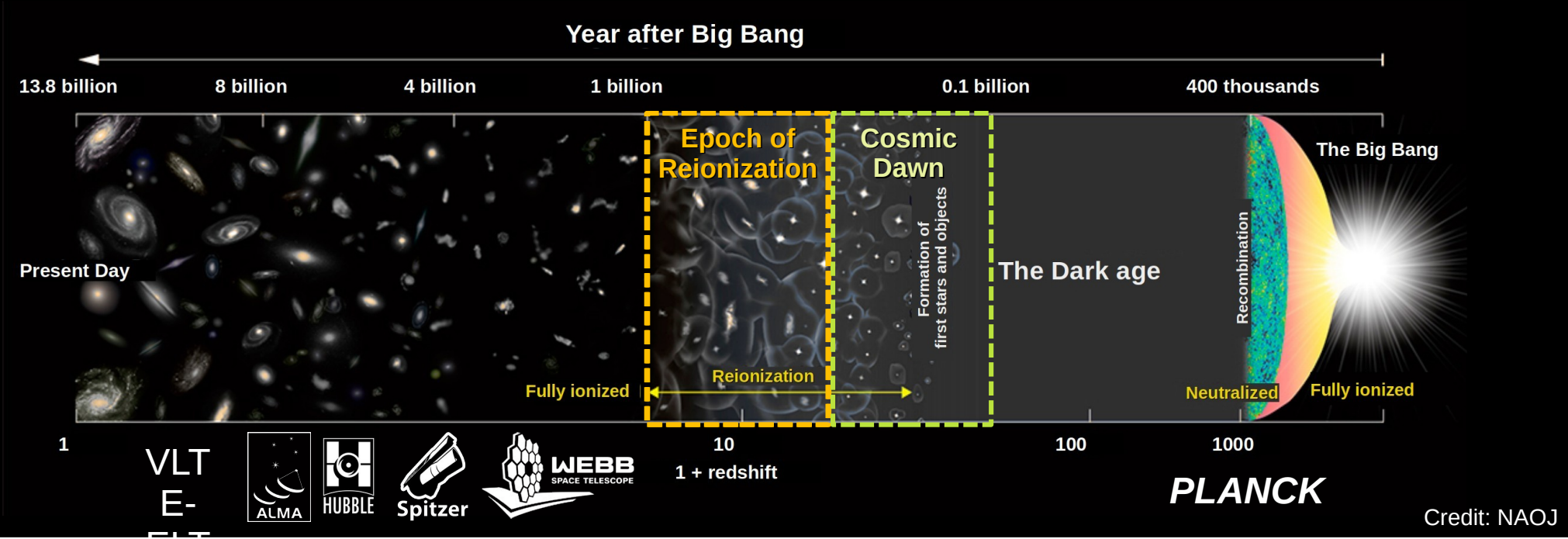


Credit: NAOJ

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

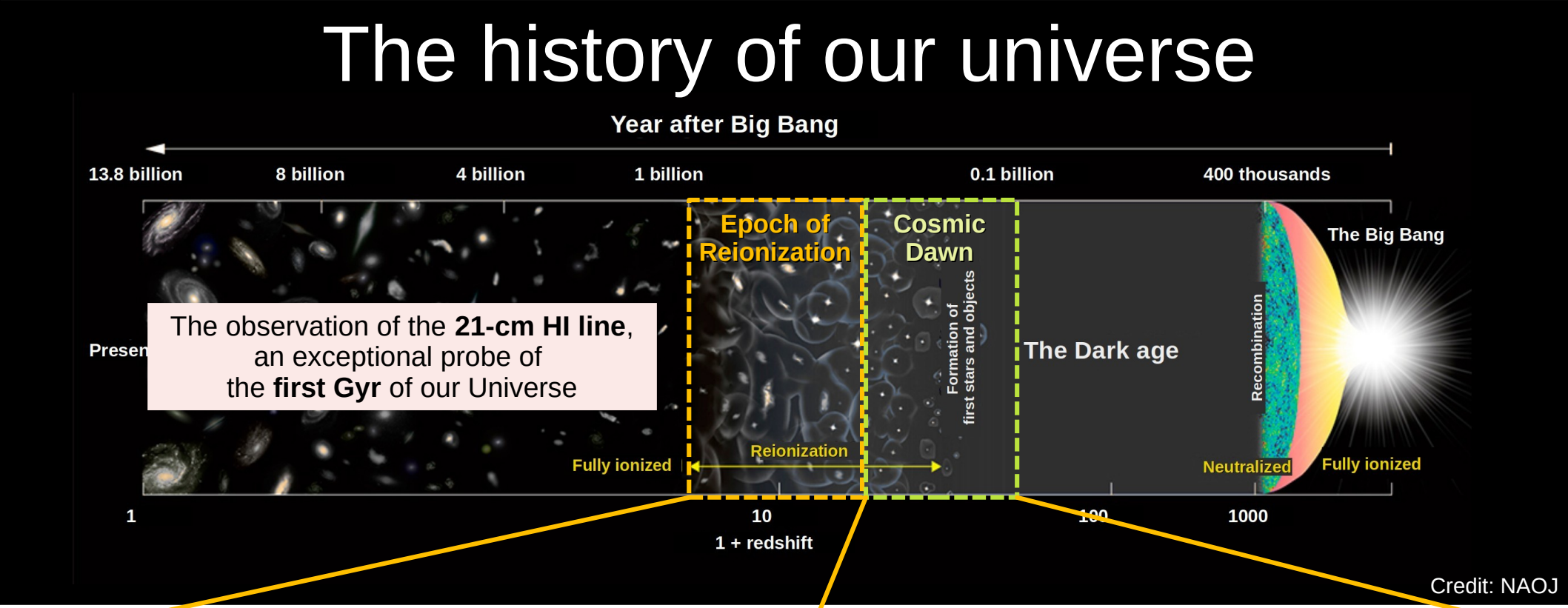


Credit: NAOJ

Epoch of Reionization
- ➔ Reionization by stars & mini-quasars
- ➔ PopIII - PopII transition
- ➔ Emergence of the visible universe

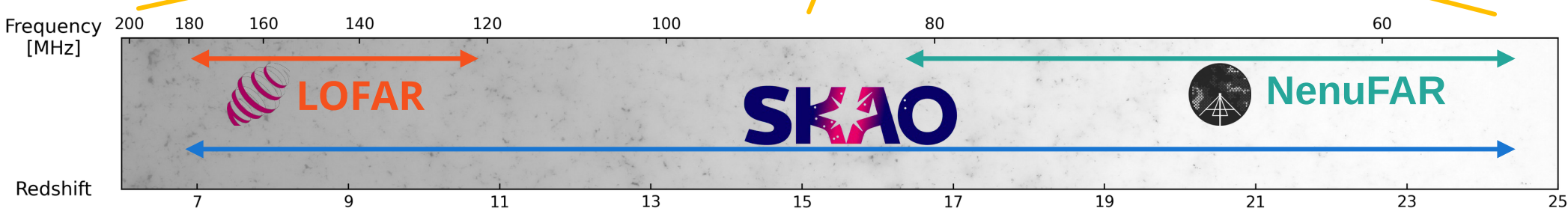
Cosmic Dawn
- ➔ Appearance of first stars/Bhs (PopIII?)
- ➔ Ly-α radiation field
- ➔ Impact of Baryonic Bulk Flows
- ➔ First X-ray heating sources

The history of our universe



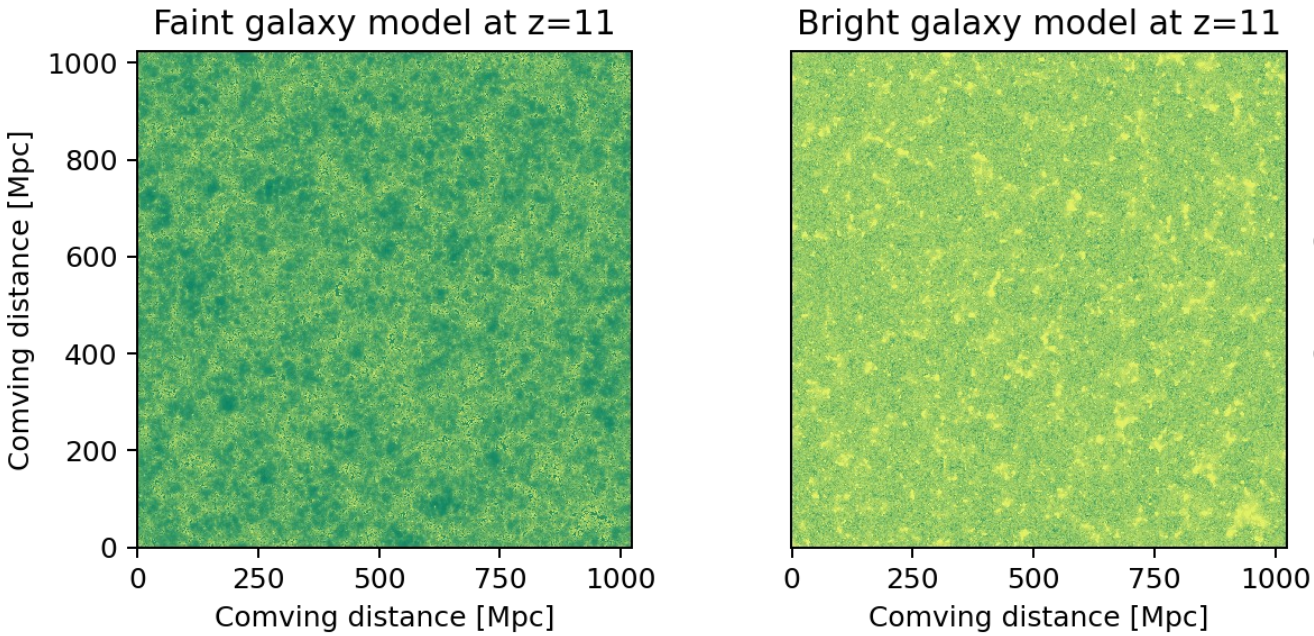
The observation of the **21-cm HI line**, an exceptional probe of the **first Gyr** of our Universe

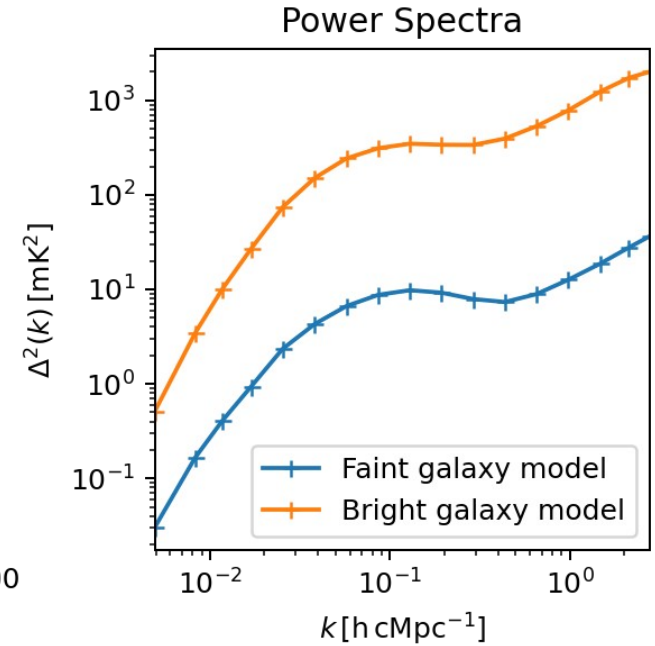
Credit: NAOJ

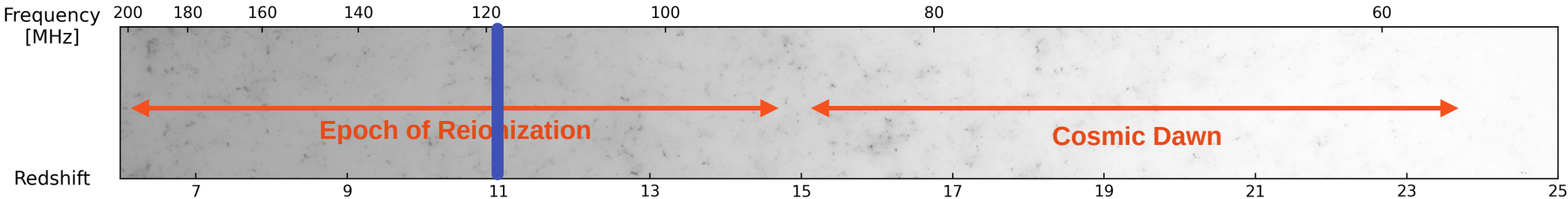


An exceptional probe of the EoR and CD

Exemple of 21-cm brightness temperature map from simulation (21cmFast)







An exceptional probe of the EoR and CD

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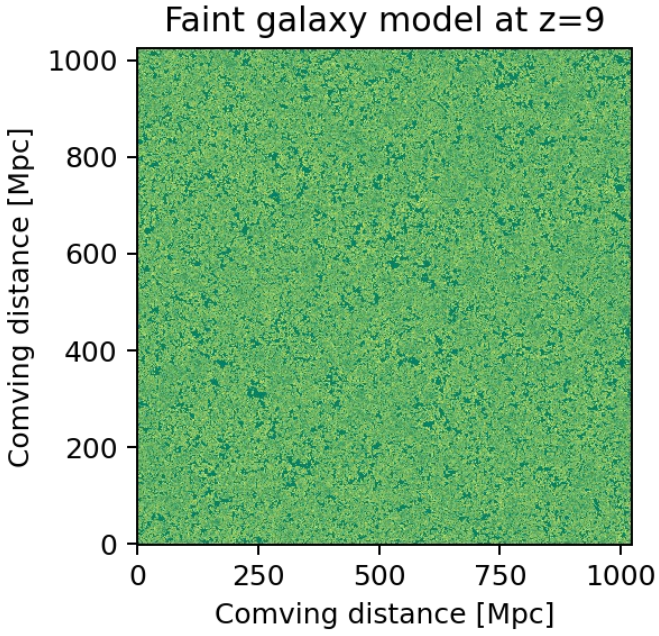

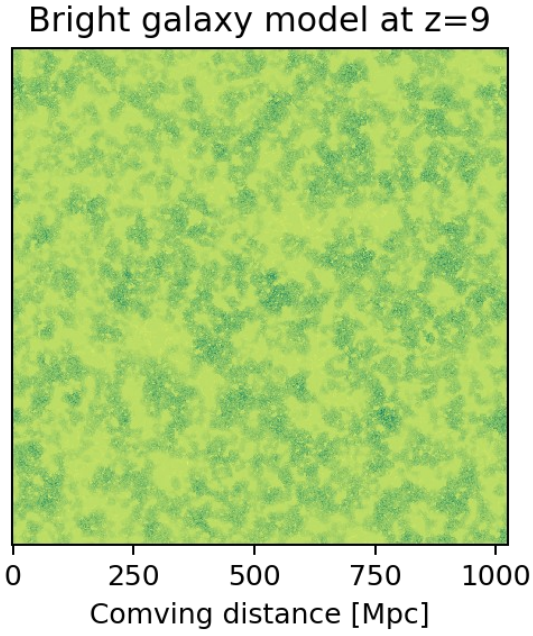

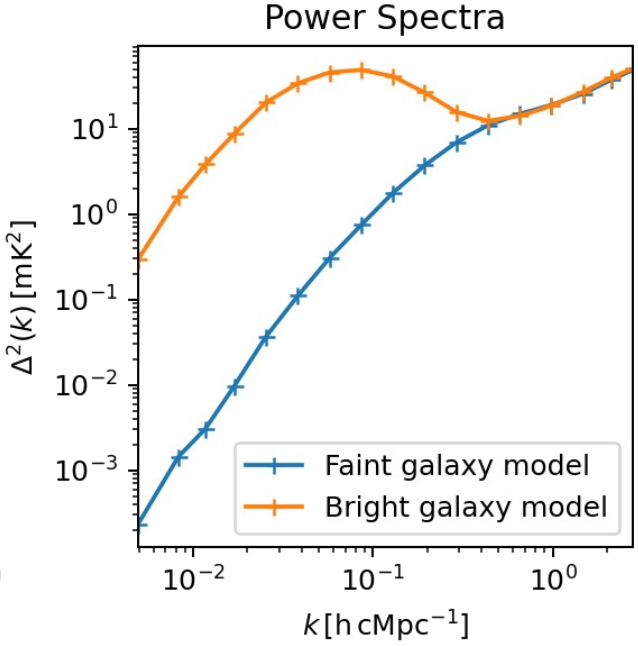

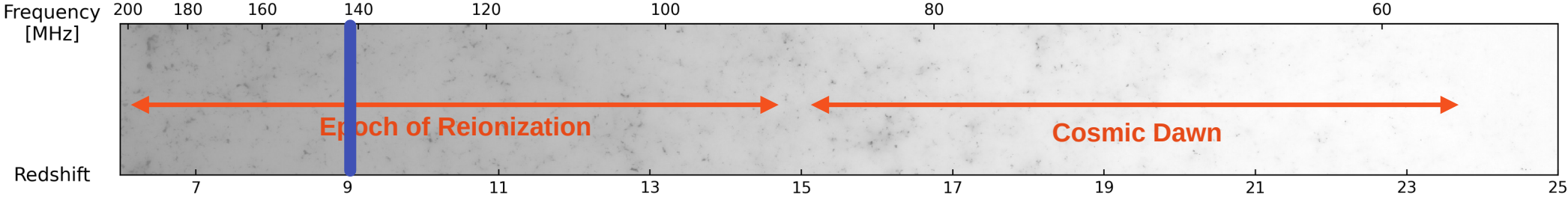

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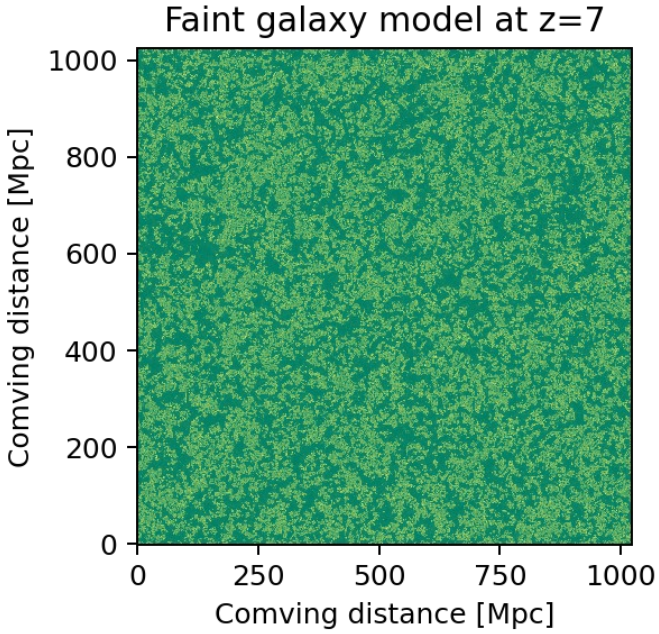
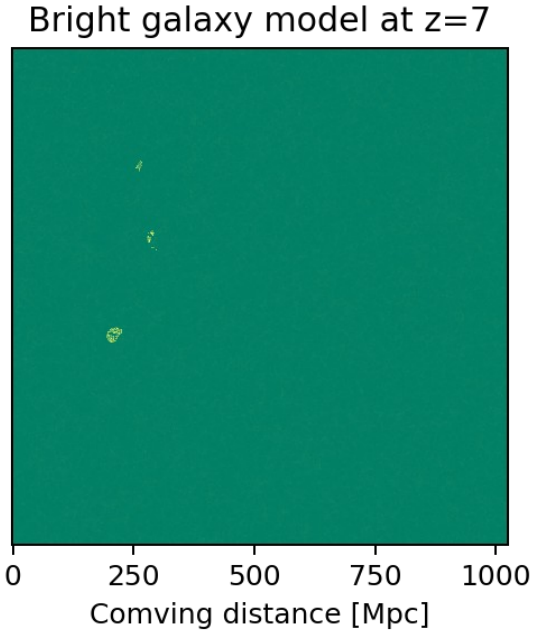
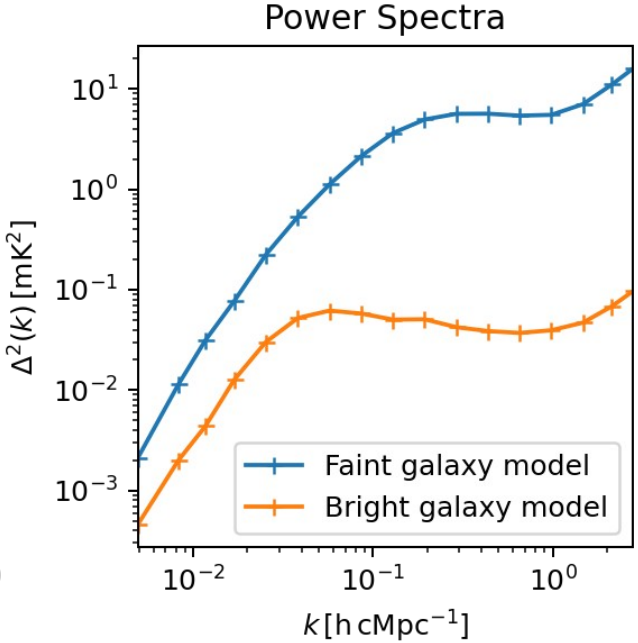
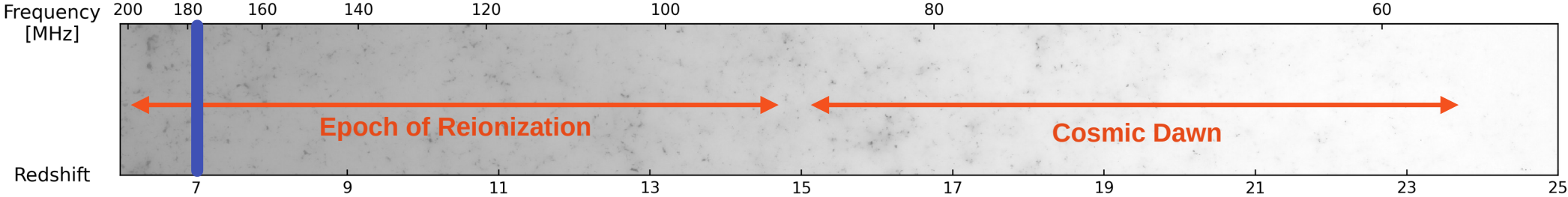




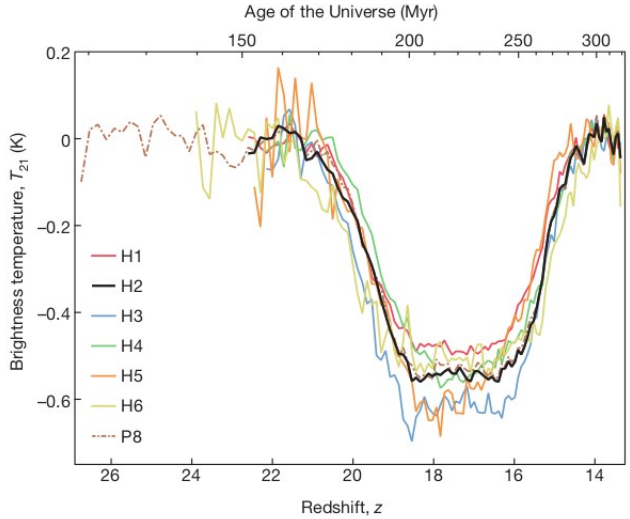




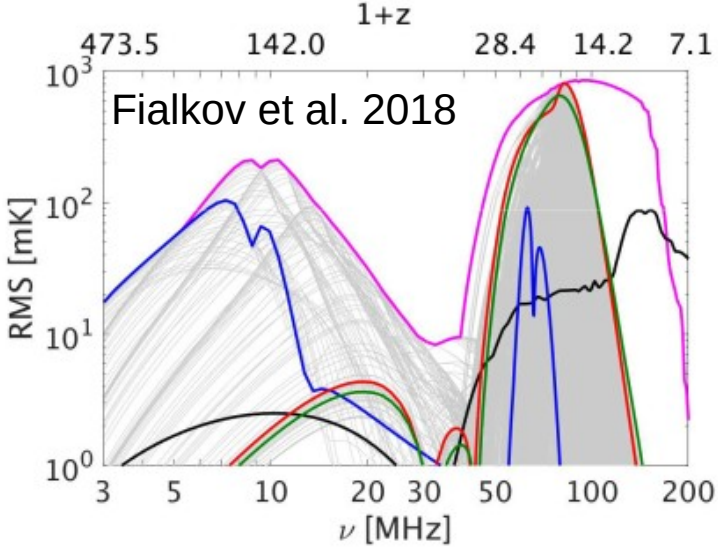
An exceptional probe of the EoR and CD

Explaining the EDGES observation of the global 21-cm signal at z~17 ?

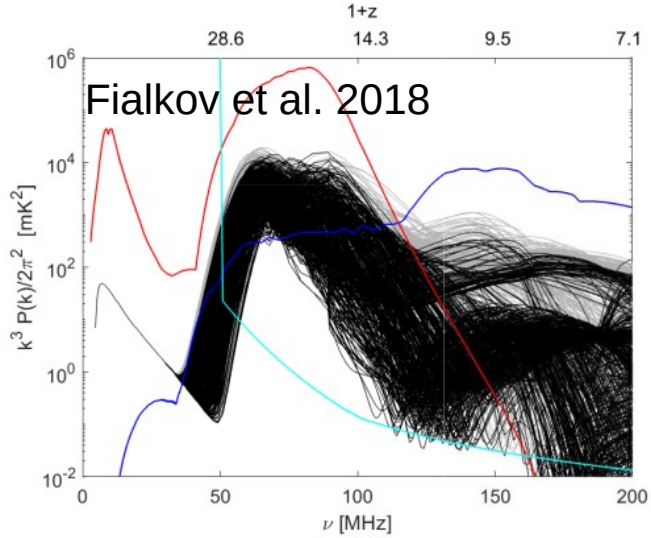
The EDGES Global 21-cm signal detection (Bowman et al. 2016)

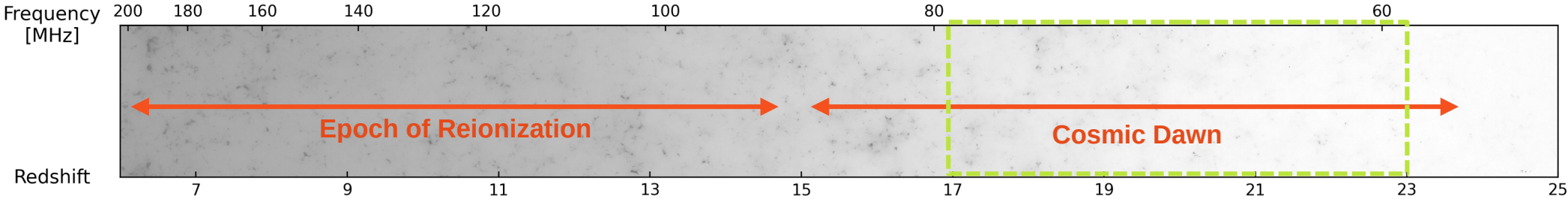


Additional cooling mechanism (e.g. baryons dark-matter scattering)



Excess radio background (e.g. SMBH, SNe, ...)





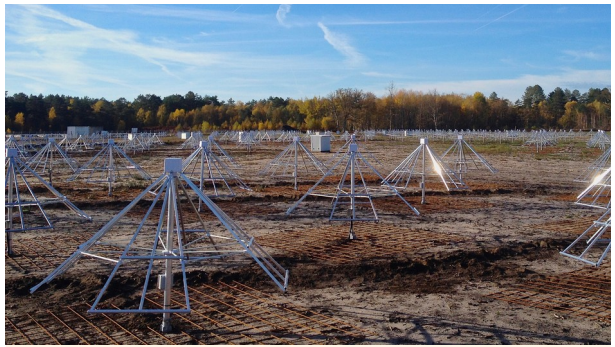
The 21-cm experiments

LOFAR-EoR

Observation started in 2012

+ 2000 h observed

- ➔ Properties of the IGM and ionising sources.
- ➔ History of reionization.

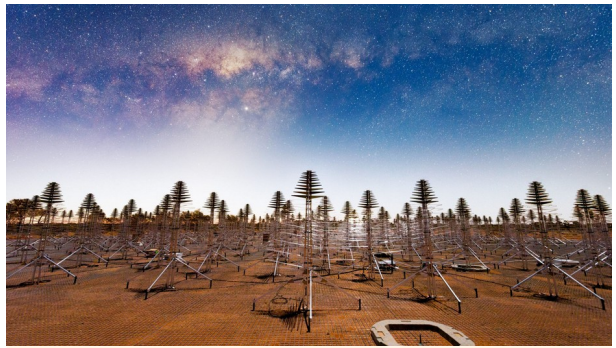


NenuFAR Cosmic Dawn

Observation started in 2019

+ 1000 h observed

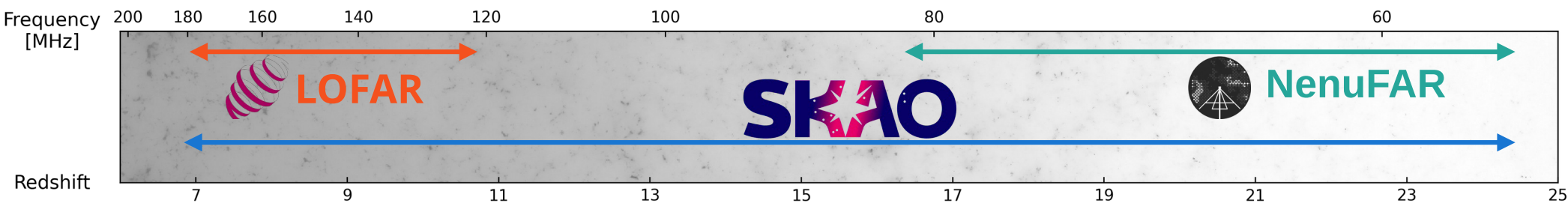
- ➔ Testing of non-standard models.
- ➔ First constraints on the properties of the first stars and on the physics at that time.



SKA CD/EoR

Completion ~2028

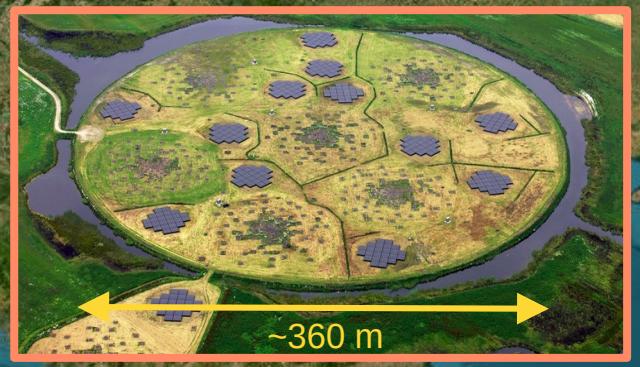
- ➔ Nature of the first stars.
- ➔ Morphology of ionized regions.



The Low Frequency Array

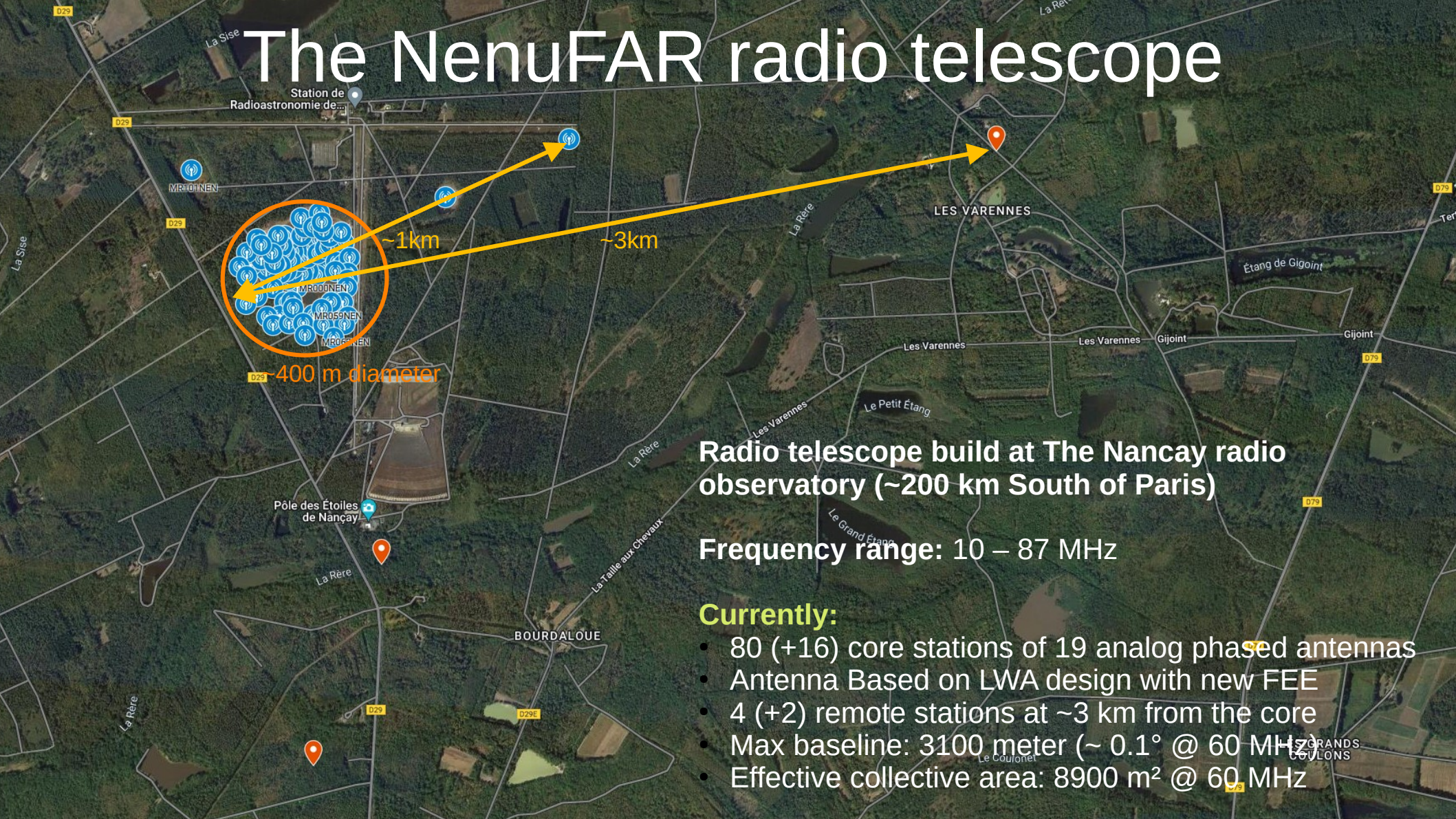
13 International stations
14 (NL) remote stations
24 core stations

110 – 240 MHz (HBA)
30 – 80 MHZ (LBA)



The « superterp »

The NenuFAR radio telescope



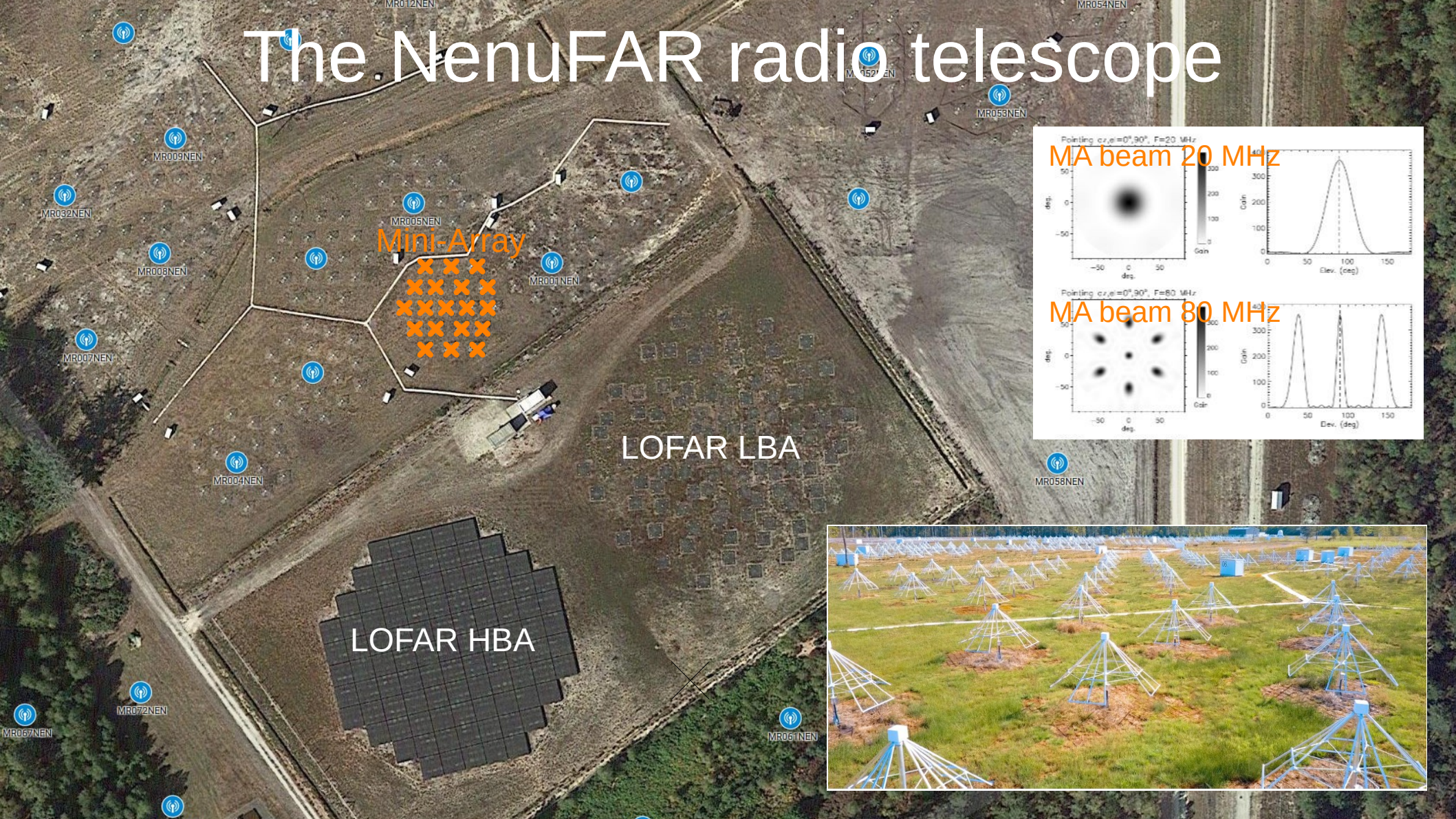
Radio telescope build at The Nancay radio observatory (~200 km South of Paris)

Frequency range: 10 – 87 MHz

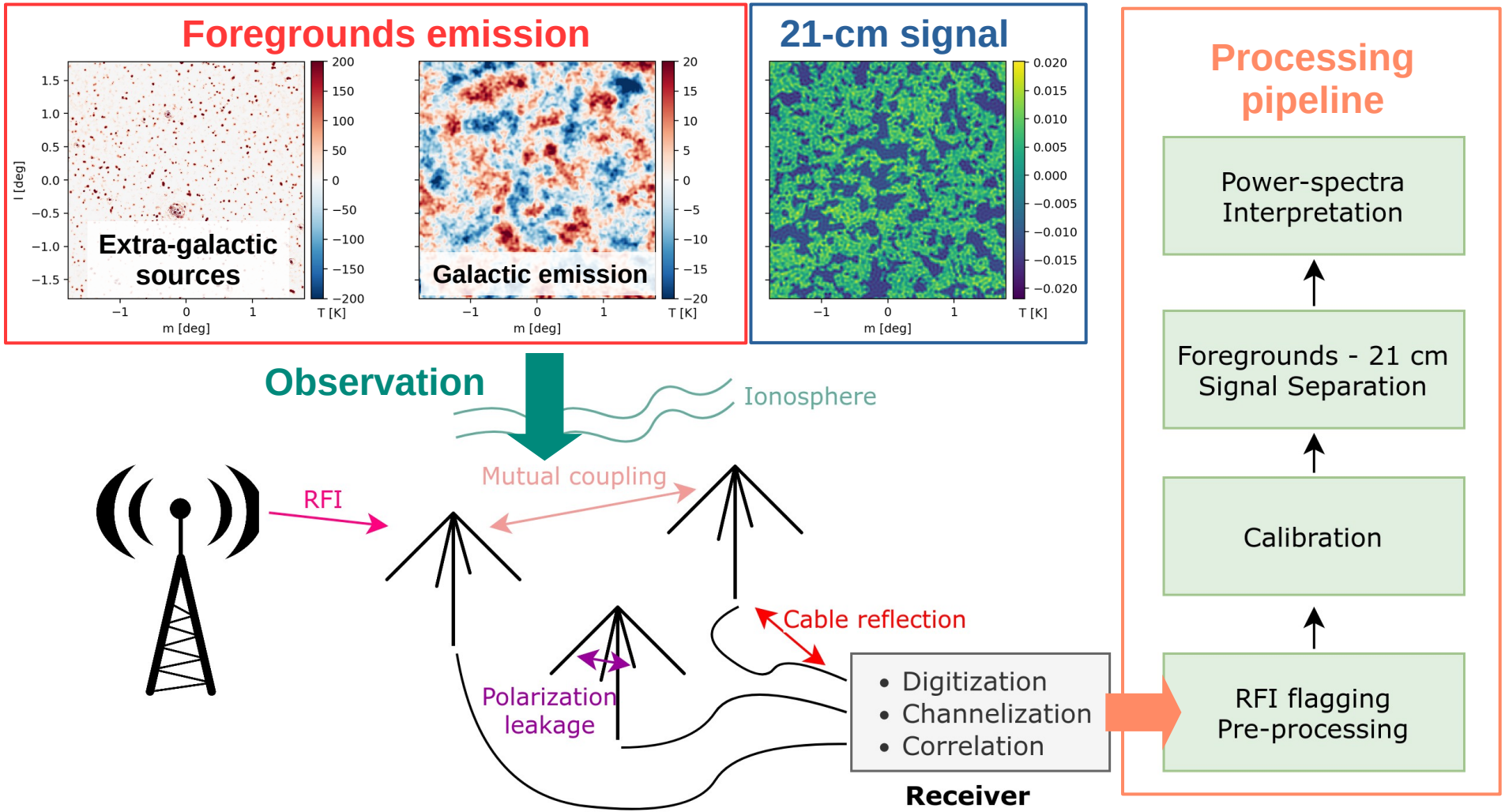
Currently:

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

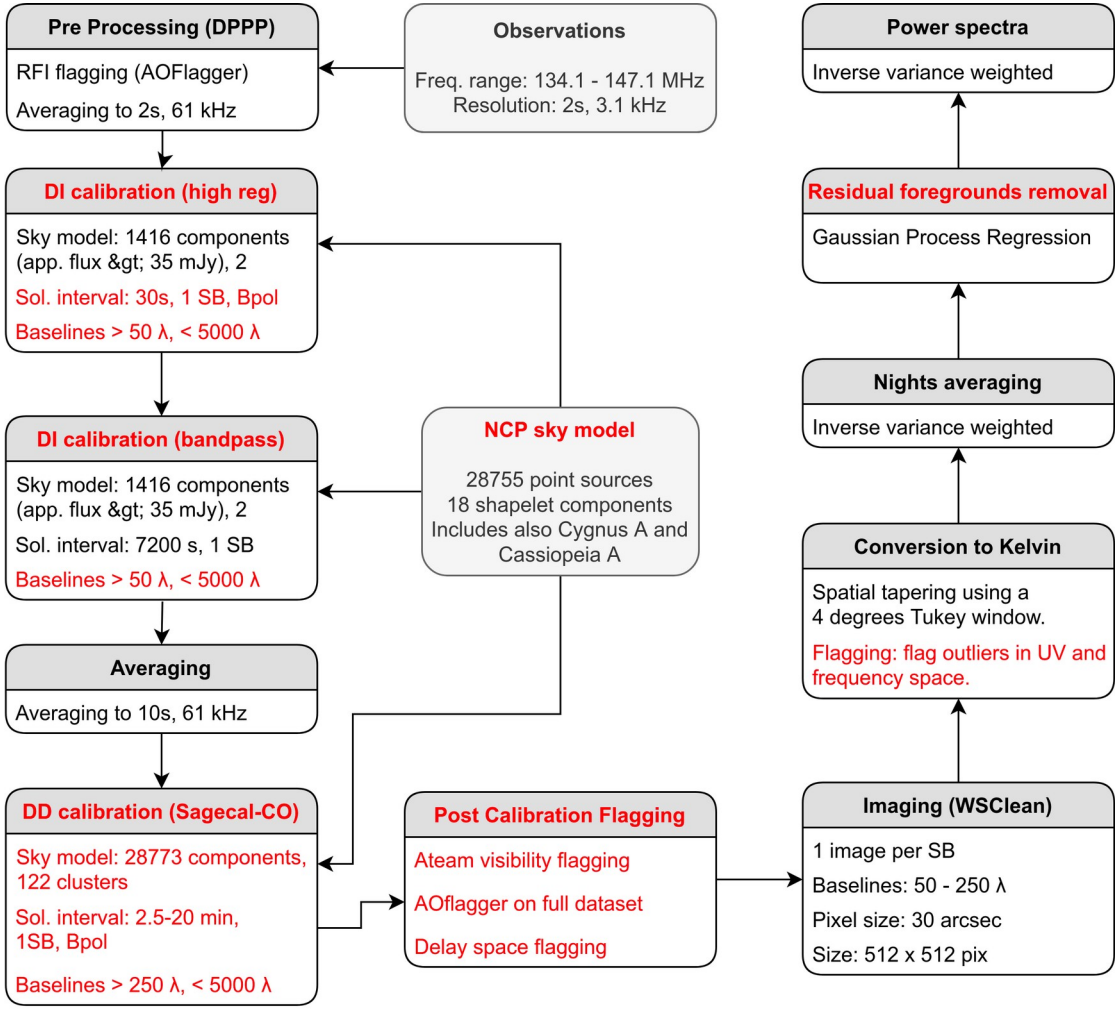
The NenuFAR radio telescope



A challenging experiment



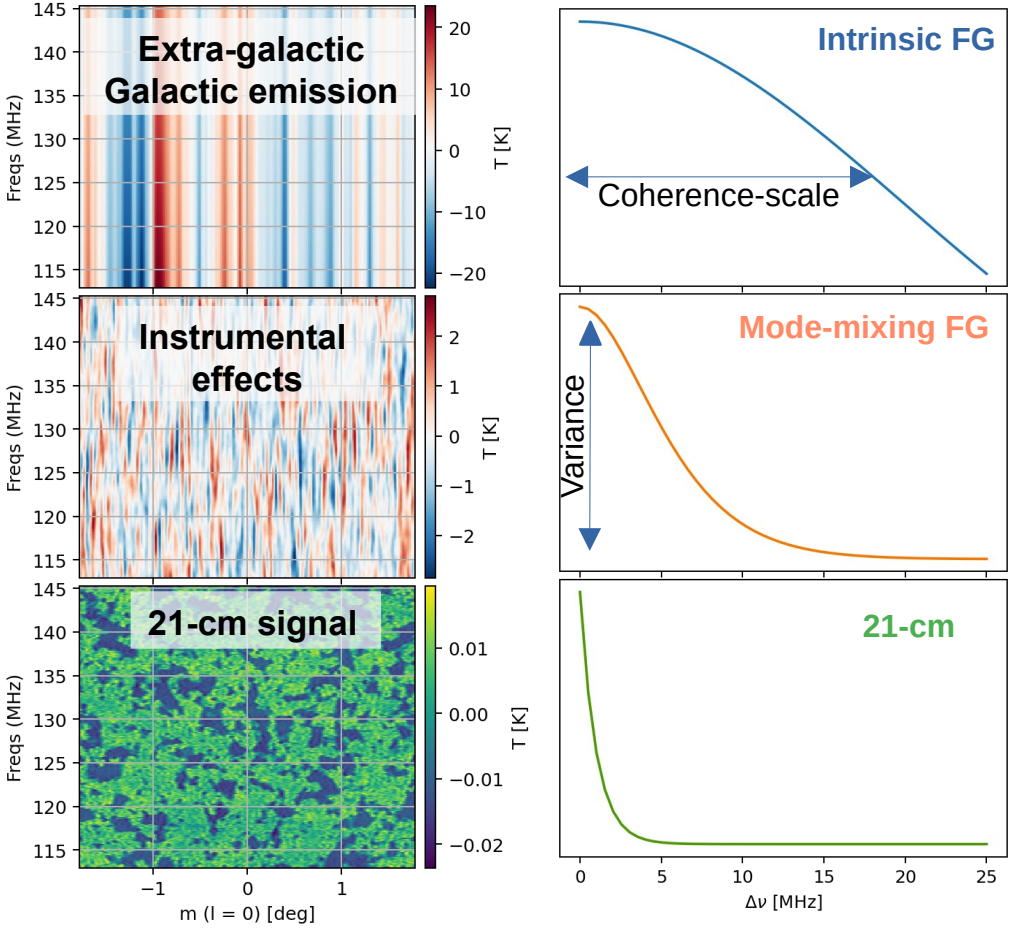
The “actual” processing pipeline



The GPR foregrounds / 21-cm seperation method

Frequency slice

Freq-freq covariance



No functional forms but very different spectral characteristic

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

→ In standard GPR, the covariance function are analytically defined. We use typically the Matern class covariance function.

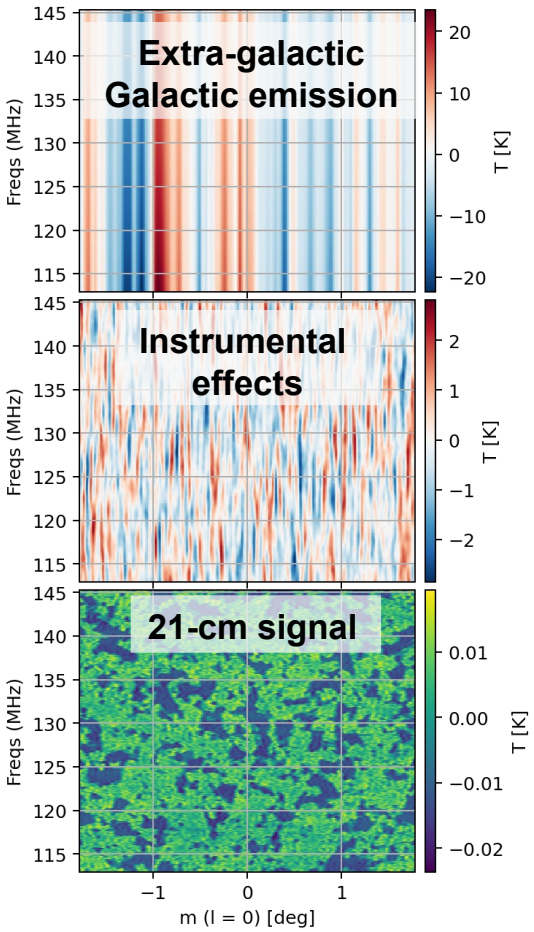
→ Learnt kernel is used for the 21-cm prior covariance.

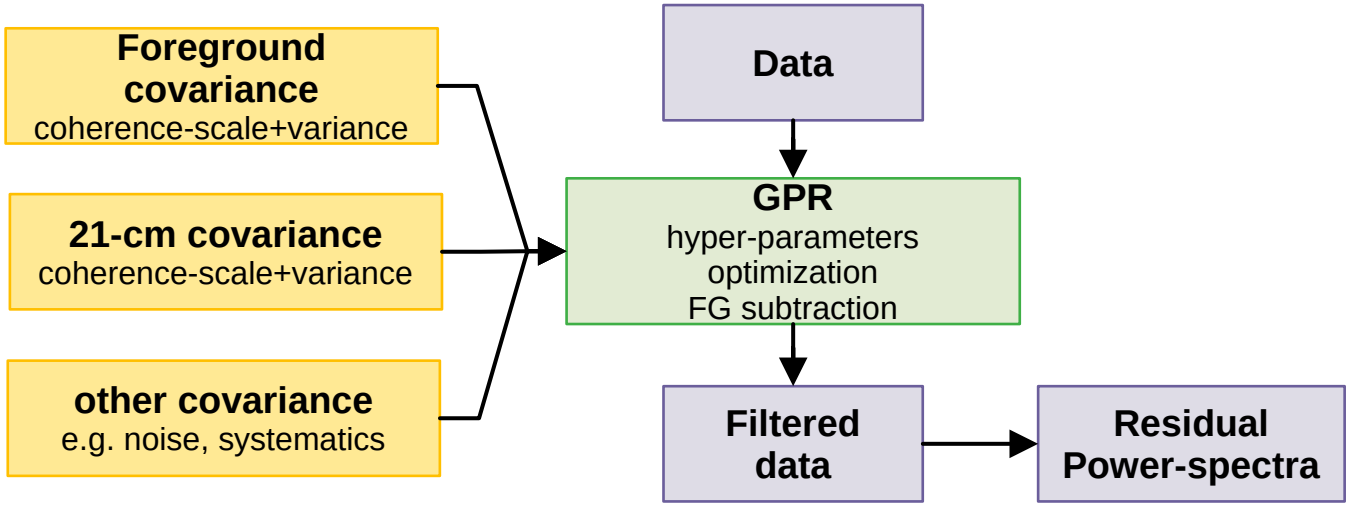
$$K = K_{\mathrm{fg}} + K_{21} + \mathrm{K}_{\mathrm{noise}} + \mathrm{K}_{\mathrm{other}}$$

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

Mertens et al. 2018
Mertens, Bobin, Carucci 2023

The GPR foregrounds / 21-cm seperation method





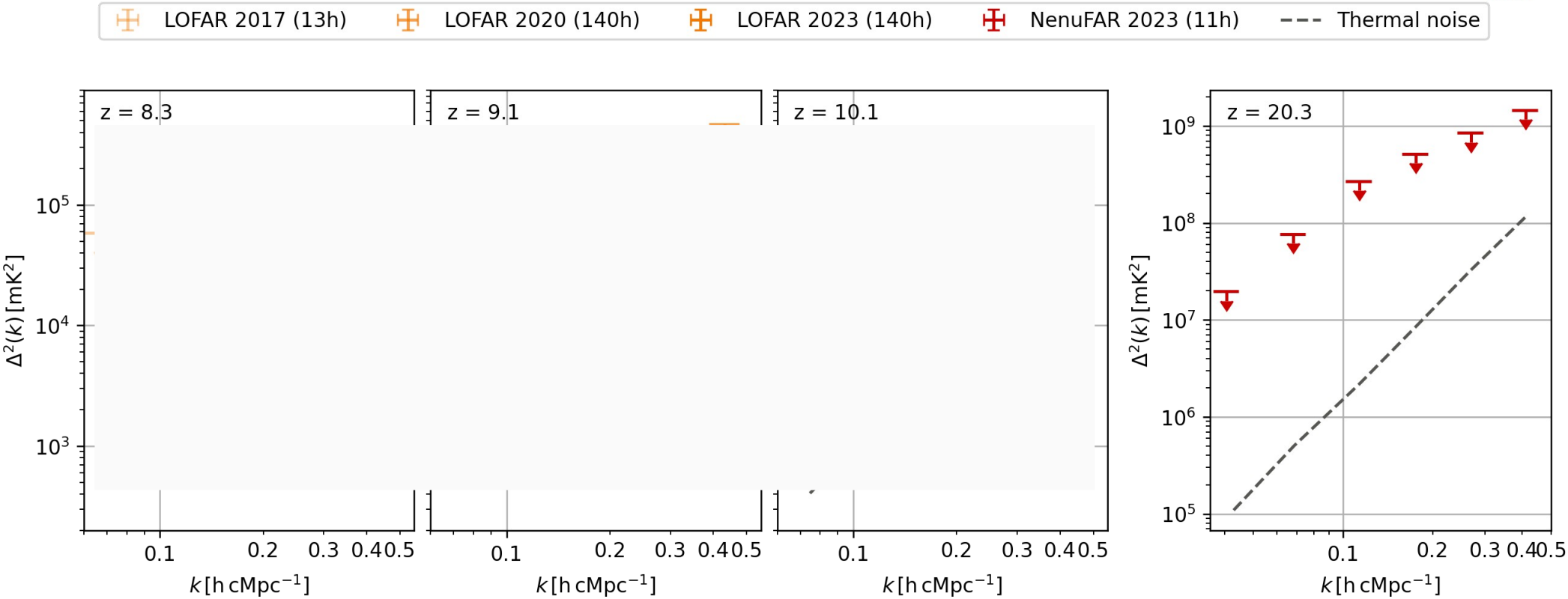
$$E(\mathbf{f}_{\rm fg}) = K_{\rm fg}\left[K_{\rm fg} + K_{21} + \sigma_n^2 I\right]^{-1}\mathbf{d}$$

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

Mertens et al. 2018
Mertens, Bobin, Carucci 2023

Preliminary results

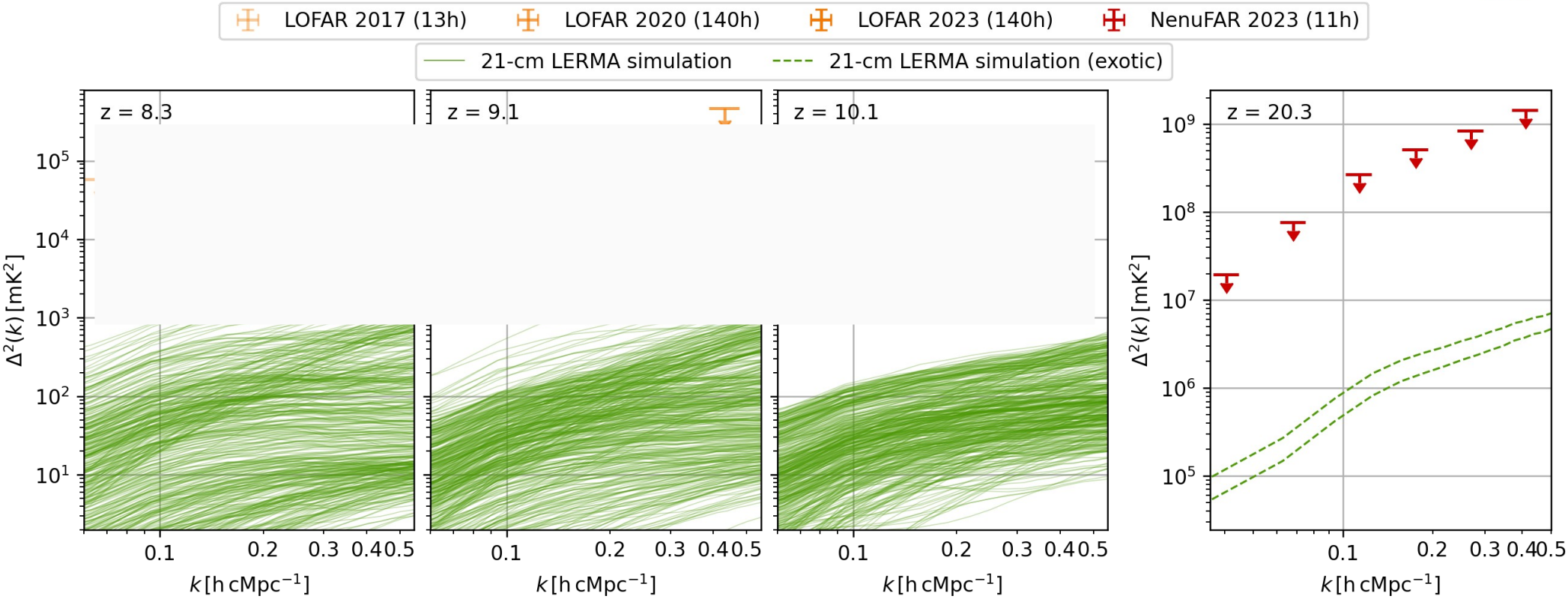
New LOFAR & NenuFAR results



- ➔ A reduction in upper limits by a factor of - to - for the three LOFAR redshifts (Mevius, Mertens et al. in prep.).
- ➔ New NenuFAR upper limit at z=20 (Munshi, Mertens et al. sub.)

Preliminary results

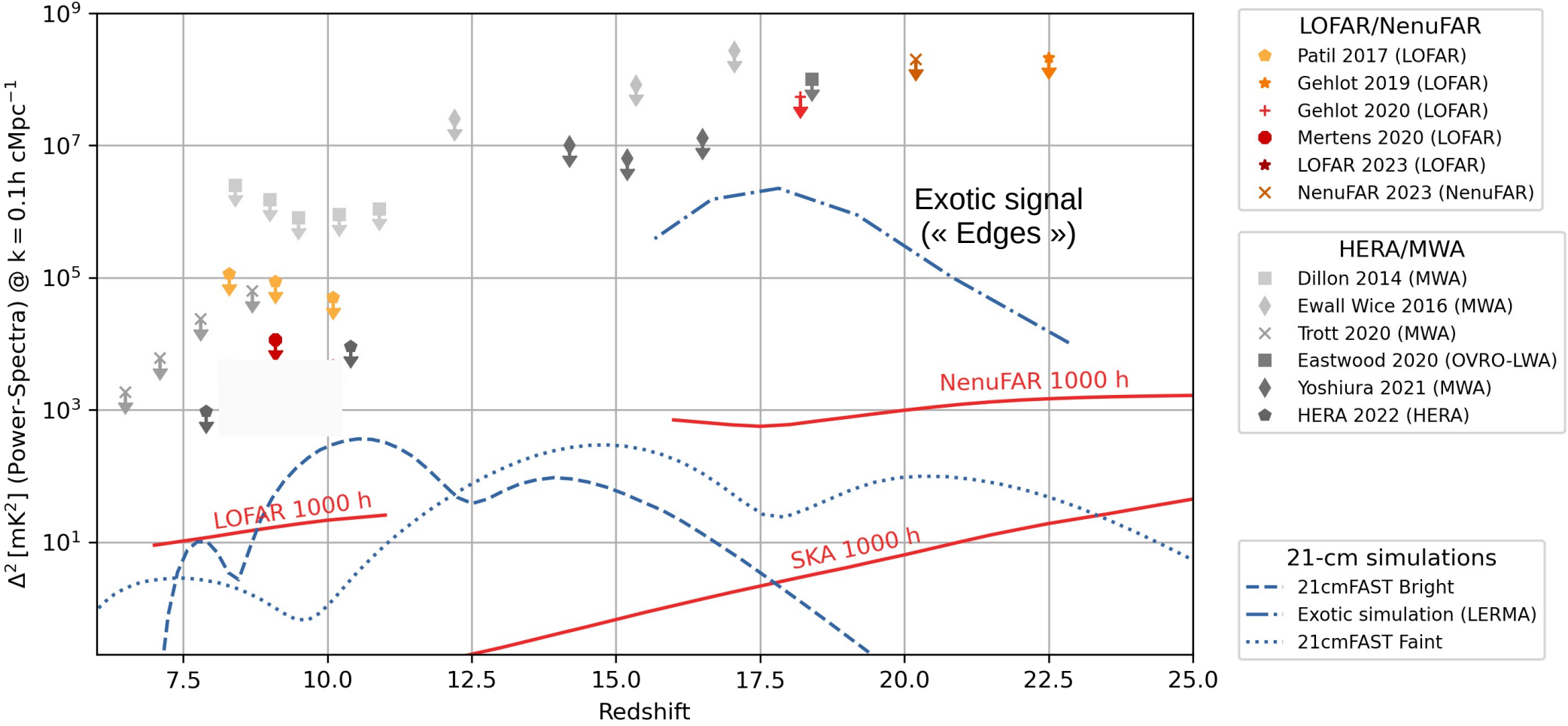
New LOFAR & NenuFAR results



➔ Upper limits approaching 21-cm signal simulations

Preliminary results

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.**
- Main challenge: **Foregrounds.** The **Gaussian Process Regression** method allows to make a statistical separation of the Foregrounds and the 21-cm signal.

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

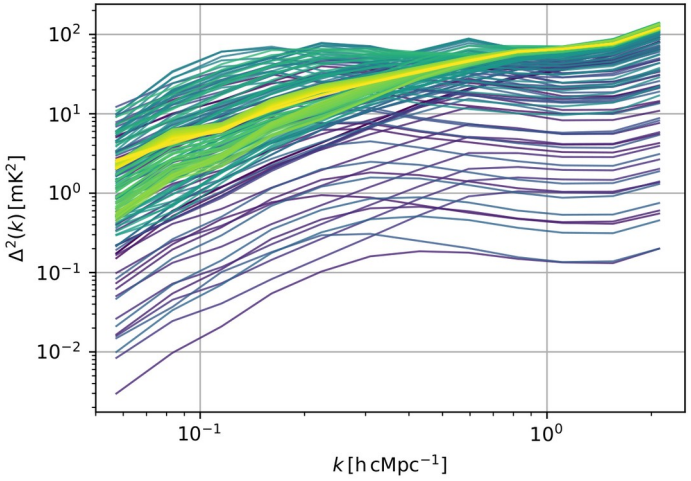
    $\Delta^2 < (100\ \mathrm{mK})^2$ @ k=0.1 cMpc^{-1}, z ~ 9 (based on ~5% of data)
  - New preliminary multi-redshift upper-limits !

- **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 in preparation at **z ~ 20**.

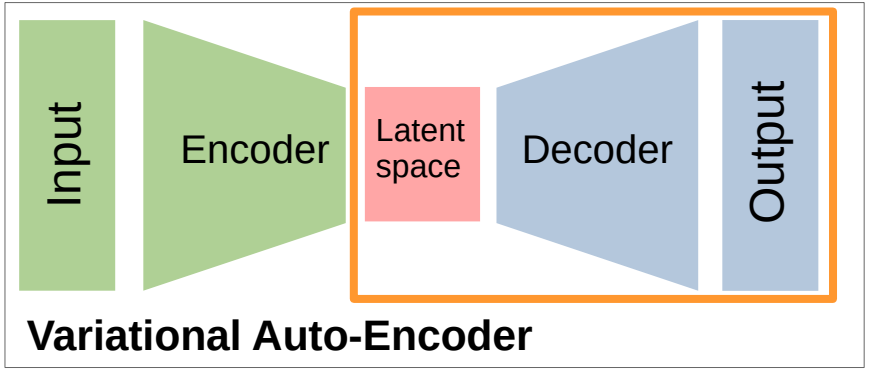
ML-GPR : Learnt covariance prior

21-cm signal simulations
e.g. 21cmFAST, Grizzly, LERMA, ...

Power-spectra



Training



21-cm covariance
Parameters : latent space

(Mertens, Bobin, Carucci 2023)