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

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

Epoch of Reionization
- Reionization by stars & mini-quasars
- PopIII - PopII transition
- Emergence of the visible universe
The observation of the 21-cm HI line, an exceptional probe of the first Gyr of our Universe.
An exceptional probe of the EoR and CD

Example of 21-cm brightness temperature map from simulation (21cmFast)
An exceptional probe of the EoR and CD

Example of 21-cm brightness temperature map from simulation (21cmFast)
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Example of 21-cm brightness temperature map from simulation (21cmFast)
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, ...)

Fialkov et al. 2018

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Fialkov et al. 2018
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 » ~360 m
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

LOFAR HBA

LOFAR LBA

Mini-Array

MA beam 20 MHz

MA beam 80 MHz
A challenging experiment

**Foregrounds emission**

**21-cm signal**

**Processing pipeline**

- Power-spectra Interpretation
- Foregrounds - 21 cm Signal Separation
- Calibration
- RFI flagging Pre-processing

**Observation**

- Ionosphere
- Mutual coupling
- RFI
- Cable reflection
- Polarization leakage

**Receiver**

- Digitization
- Channelization
- Correlation
The “actual” processing pipeline

Pre Processing (DPPP)
- RFI flagging (AOFlagger)
  - Averaging to 2s, 61 kHz

DI calibration (high reg)
- Sky model: 1416 components
  - (app. flux &gt; 35 mJy), 2
  - Sol. interval: 30s, 1 SB, Bpol
  - Baselines > 50 \(\lambda\), < 5000 \(\lambda\)

DI calibration (bandpass)
- Sky model: 1416 components
  - (app. flux &gt; 35 mJy), 2
  - Sol. interval: 7200 s, 1 SB
  - Baselines > 50 \(\lambda\), < 5000 \(\lambda\)

Averaging
- Averaging to 10s, 61 kHz

DD calibration (Sagecal-CO)
- Sky model: 28773 components, 122 clusters
  - Sol. interval: 2.5-20 min, 1SB, Bpol
  - Baselines > 250 \(\lambda\), < 5000 \(\lambda\)

Observations
- Freq. range: 134.1 - 147.1 MHz
- Resolution: 2s, 3.1 kHz

Post Calibration Flagging
- Ateam visibility flagging
  - AOFlagger on full dataset
- Delay space flagging

Power spectra
- Inverse variance weighted

Residual foregrounds removal
- Gaussian Process Regression

Nights averaging
- Inverse variance weighted

Conversion to Kelvin
- Spatial tapering using a 4 degrees Tukey window.
  - Flagging: flag outliers in UV and frequency space.

Imaging (WSClean)
- 1 image per SB
  - Baselines: 50 - 250 \(\lambda\)
  - Pixel size: 30 arcsec
  - Size: 512 x 512 pix
The GPR foregrounds / 21-cm separation method

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.

\[ K = K_{fg} + K_{21} + K_{\text{noise}} + K_{\text{other}} \]

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 separation method

- **Data**
- **GPR**
  - Hyper-parameters optimization
  - FG subtraction
- **Filtered data**
- **Residual Power-spectra**

**Mathematical Formulas**

\[
E(f_{fg}) = K_{fg} \left[ K_{fg} + K_{21} + \sigma_n^2 I \right]^{-1} d
\]

\[
\text{cov}(f_{fg}) = K_{fg} - K_{fg} \left[ K_{fg} + K_{21} + \sigma_n^2 I \right]^{-1} K_{fg}
\]

- **Foreground covariance**
  - Coherence-scale + variance
- **21-cm covariance**
  - Coherence-scale + variance
- **Other covariance**
  - E.g. noise, systematics

**Figures**

- **Extra-galactic Galactic emission**
- **Instrumental effects**
- **21-cm signal**

Source:

- Mertens et al. 2018
- Mertens, Bobin, Carucci 2023
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.)
Upper limits approaching 21-cm signal simulations
Progress toward a detection

\[ \Delta^2 [\text{mK}^2] \text{ (Power-Spectra) } @ k = 0.1h \text{ cMpc}^{-1} \]

- Preliminary results

Graph showing data points and lines for different telescopes and experiments:
- LOFAR/NenuFAR
- Patil 2017 (LOFAR)
- Gehlot 2019 (LOFAR)
- Gehlot 2020 (LOFAR)
- Mertens 2020 (LOFAR)
- LOFAR 2023 (LOFAR)
- NenuFAR 2023 (NenuFAR)

- HERA/MWA
  - Dillon 2014 (MWA)
  - Ewall Wice 2016 (MWA)
  - Trott 2020 (MWA)
  - Eastwood 2020 (OVRO-LWA)
  - Yoshiura 2021 (MWA)
  - HERA 2022 (HERA)

- 21-cm simulations
  - 21cmFAST Bright
  - Exotic simulation (LERMA)
  - 21cmFAST Faint

Exotic signal (« Edges »)
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 $z \sim 9$:
    $\Delta^2 < (100 \text{ mK})^2 @ k=0.1 \text{ cMpc}^{-1}, z \sim 9$ (based on $\sim$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 $z \sim 15 – 31$.
  ➔ First upper limit in preparation at $z \sim 20$. 
ML-GPR: Learnt covariance prior

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

Power-spectra

21-cm covariance
Parameters: latent space

Variational Auto-Encoder

(Mertens, Bobin, Carucci 2023)