Current constraints on cosmology is given by either large-scale or local cosmological observations.

1) Emission of first UV and X-ray
2) cold & neutral → hot & ionised
3) 21-cm signal direct observation
Final layout of the SKA-Low stations and start of the construction in the early months of 2023.

- **512 stations**, each with **128 antennas**
- Maximum baseline \(~65\ \text{km}\), station diameter \(35\ \text{m}\)
  - FoV of **10 deg** with **16 arcsec** resolution
- Frequency range between **50 to 350 MHz**
Global Evolution of the 21-cm Signal

\[ \delta T_b = 28 \text{mK} \left( 1 + \delta \right) x_{\text{HI}} \left( \frac{T_{\text{CMB}}}{T_{\text{spin}}} \right) \left( \frac{\Omega_b h^2}{0.0223} \right) \sqrt{\left( \frac{1 + z}{10} \right) \left( \frac{0.24}{\Omega_m} \right)} \left[ \frac{H(z)}{(1 + z)} \right] \]
Constrains on the 21-cm Power Spectrum

Power Spectrum 95% Confidence Upper Limits [0.03 < k < 0.4 Mpc\(^{-1}\)]

\[ \Delta^2_{21}(k) = T_0^2 \langle x_H \rangle^2 \left[ \Delta^2_{\delta\delta}(k) + 2 \Delta^2_{x\delta}(k) + \Delta^2_{xx}(k) \right] \]
Tomographic Imaging of the 21-cm signal

SKA1-Low tomographic images of redshifted 21-cm signal challenges:

- Instrumental noise (signal \(\sim 5\) K)
- Foreground emission (signal \(\sim 1 - 1000\) K)
- Antennas gain errors
- Ionospheric refraction effects
- Radio frequency interference
- And more ...

Jelic+ (2008)
Tomographic imaging of the 21-cm signal

Probe reionization process by observing the redshifted 21-cm signal

$$\delta T_b \propto (1 + \delta) x_{HI}$$

Square Kilometre Array (SKA1-Low):
Images sequence of redshifted 21-cm signal at different observed frequencies.

3D tomographic dataset or a.k.a. 21-cm lightcones
Tomographic imaging of the 21-cm signal

Probe reionization process by observing the redshifted 21-cm signal

\[ \delta T_b \propto \left(1 + \delta \right)x_{\text{HI}} \]

Square Kilometre Array (SKA1-Low):
Images sequence of redshifted 21-cm signal at different observed frequencies.

3D tomographic dataset or a.k.a. 21-cm lightcones

\[ z = 13.2 \]
\[ \nu_{\text{obs}} = 100 \text{ MHz} \]
Currently we can create EoR mock observation with a combination of numerical models for 21-cm, systematic noise and foregrounds.

Goal:
Recover 21-cm differential brightness and the distribution of neutral hydrogen from SKA-Low mock observations.
Combine the predicted binary maps of **SegU-Net** as additional input of **Rec-Unet** training step in order to include prior in the network training.

**SKACH 840k hybrid-h** allocation projects at Pitz Daint @ CSCS
Galactic and extra-galactic **foregrounds** have **frequency smooth flux** compared to the 21-cm signal.

From 2D power spectra, remove k-modes contaminated by foreground as:

- **avoidance** technique
- **model for substraction**
Pre-process: Foreground Mitigation & Avoidance

Residual image and 2D $P_k$ tomographic sub-volume centered at redshift $z = 8.25$ ($x_{\text{HI}} \sim 0.5$) and $\Delta v = 20$ MHz

$I_{\text{res}}$

$P(k_\perp, k_\parallel)$

Bianco+ (2023)
In SERENEt the SegU-Net binary map are employed as as a HI priors maps in Rec-Unet.
SegU-Net: Visual Comparison

$r_\phi = 0.70$

$r_\phi = 0.52$

$r_\phi = 0.84$

$r_\phi = 0.81$

Bianco+ (2023)
SegU-Net: Tomographic Data & Reionization History

<table>
<thead>
<tr>
<th>$z_c$</th>
<th>pre-process</th>
<th>$\bar{x}_{HI}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.24</td>
<td>Ground Truth</td>
<td>0.45</td>
</tr>
<tr>
<td></td>
<td>all z PCA</td>
<td>0.48 ± 0.07</td>
</tr>
<tr>
<td></td>
<td>PCA</td>
<td>0.49 ± 0.11</td>
</tr>
<tr>
<td></td>
<td>Wedge</td>
<td>0.16 ± 0.13</td>
</tr>
<tr>
<td></td>
<td>GPR</td>
<td>0.48 ± 0.09</td>
</tr>
<tr>
<td></td>
<td>Polynomial</td>
<td>0.49 ± 0.10</td>
</tr>
</tbody>
</table>
SegU-Net: HI size distribution

The Island Size Distribution (ISD): statistical distribution of HI regions during EoR (Giri+ 2018)

\[ \bar{R}_C(z) = \int_{R_{\text{min}}}^{\infty} R \frac{dP}{dR}(z) \, dR \]

SegU-Net results:

<table>
<thead>
<tr>
<th>$z_c$</th>
<th>pre-process</th>
<th>$\bar{R}_C$ [cMpc]</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.24</td>
<td>Ground Truth</td>
<td>29.54</td>
</tr>
<tr>
<td>all $z$ PCA</td>
<td>31.37$^{+3.09}_{-3.93}$</td>
<td></td>
</tr>
<tr>
<td>PCA</td>
<td>27.65$^{+9.13}_{-6.12}$</td>
<td></td>
</tr>
<tr>
<td>Wedge</td>
<td>15.20$^{+24.13}_{-6.18}$</td>
<td></td>
</tr>
<tr>
<td>GPR</td>
<td>29.14$^{+5.26}_{-4.89}$</td>
<td></td>
</tr>
<tr>
<td>Polynomial</td>
<td>29.21$^{+5.83}_{-5.21}$</td>
<td></td>
</tr>
</tbody>
</table>
RecU-Net: Recover 21-cm with U-Net
(Bianco+ in prep.)

U-Net architecture with intercepting convolution block to process the binary prior map from SegU-Net
SERENET: Recover of 21-cm Signal

Recovered 21-cm signal for EoR for lightcone subvolume centered at redshift \( z = 8.25 \) (\( x_{\text{HI}} \approx 0.5 \)) and \( \Delta \nu = 20 \) MHz on PCA pre-process images
SERENEt: Recover of 21-cm Signal

Ground Truth at $z = 7.27$

**RecU-Net** (no prior)
$R^2 = 64.2\%$

SERENEt($\text{GT}$) + $x_H^{\text{TRUE}}$
$R^2 = 92.9\%$

SERENEt($\text{GT}$) + $x_H^{\text{PRED}}$
$R^2 = 82.9\%$
SERENEt: Recover of 21-cm Signal

Coefficient of determination ($R^2$ score) redshift evolution to quantify the foreground mitigation:

- **SERENEt(GT) + $x_H^{TREU}$**
  upper limit based on best prior binary map (ground truth)

- **SERENEt(GT) + $x_H^{PRED}$**
  next best results when compared to RecU-Net
SERENET: Comparison with Current Data

Power Spectrum 95% Confidence Upper Limits \([0.03 < k < 0.4 \text{ Mpc}^{-1}]\)

- pathfinder upper limit
- Foreground contamination
- SKA expected sensitivity
- SERENET predictions

\[ \Delta^2 [\text{mK}^2] \]

- Barry+2019 (MWA)
- Li+2019 (MWA)
- Trott+2020 (MWA)
- Ewall-Wice+2016 (MWA)
- Yoshiura+2021 (MWA)
- Kolopanis+2019 (PAPER)
- Patil+2017 (LOFAR)
- Mertens+2020 (LOFAR)
- Gehlot+2020 (LOFAR)
- Mesinger+2016 (k = 0.03)
- Mesinger+2016 (k = 0.1)
- Mesinger+2016 (k = 0.4)
- SKA FG-Avoid 1000 hr
- SKA FG-Sub 100 hr
- SKA FG-Sub 1000 hr

Barry+ (2022)
Conclusion & Discussion

• U-Net have the potential to recover 21-cm signal with prior information
  - Need more realistic mock observation

• At SKACH, working on simulation pipeline for realistic mock observation
  - Interferometer systematic
  - DD & DI gain error
  - Update extra-galactic point sources foreground model
  - Machine learning implementation of SERENEt pipeline

• Participation at the SKA Data Challenge (SDC3) with SERENEt pipeline (deadline September 30th)