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Learning the Radio 21cm Signal – From Dawn till Dusk, from Tomography to Sources

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Abstract. Measurements of the 21cm signal are a key example of the data-driven era in astrophysics we are entering. Tomography of 21cm intensity maps targeted by SKA-LOW teaches about source properties, state of the intergalactic medium (IGM) and cosmology during the epoch of reionisation (EoR), while imaging with SKA-MID traces late-time structure formation via neutral hydrogen within sources. We showcase deep networks tailored for tomographic 21cm light-cones to firstly infer cosmological and astrophysical parameters, and to secondly detect and characterise HI sources, all in 3D. We highlight how comparably simple 3D network architectures are the best-performing models.

Key words. large-scale structure of Universe – dark ages, reionization, first stars – Methods: data analysis – Radio continuum: galaxies – Radio lines: general – cosmological parameters

1. Introduction

The first stars and galaxies illuminate the Universe at Cosmic Dawn, leading at first to an absorption signal in the forbidden spin-flip transition of neutral hydrogen, the so-called 21cm signal. With further heating the 21cm signal emits above the Cosmic microwave background (CMB). With more and more radiation pervading larger volumes, the before neutral hydrogen becomes ionised again during Reionisation. This signal of fluctuations in 21cm brightness is targeted by SKA-LOW, see 2.1 direct inference from 3D intensity maps. At later times, the 21cm signal and radio continuum trace neutral hydrogen in sources, allowing for large-scale mappings of the Universe e.g. with SKA-MID, see 2.2 21cm source detection in 3D. The Square Kilometre Array (SKA, https://www.skao.int/) will achieve this 3D tomography via 2D spatial maps combined with finely gridded frequency information. This produces up to TB/s of data for a highly non-Gaussian signal, thus making deep learning (DL) a suitable candidate to reduce and analyse. We highlight here our findings regarding optimal deep learning models to analyse 21cm tomography.

2. Learning from the 3D 21cm signal

2.1. Direct inference from 3D maps

The 3D-21cmPIE-Net Neutsch et al. (2022) performs direkt likelihood-free inference of astrophysical and cosmological parameters from 3D mappings during CD and EoR, as expected for SKA-LOW and at different noise levels, see fig. 1. The network was trained on a database of ~5000 lightcones of 140x140x2350 vox and 1.4 Mpc resolution. Different options were tested to treat 3D data optimally:

- Slicing for spatial images → 2D CNN (convolutional neural network), residual network with skip connections,
- Time series of co-eval images → LSTM (long-short-term memory) network,
- Full 3D convolution → 3D CNN.

The best-performing architecture, the 3D-21cmPIE-Net, can:

- **Directly constrain** cosmology and EoR astrophysics from 3D data,
- with **low scatter and bias**,
- **transfer learn** simulations and mocks, and
- is **robust** towards increased noise levels.

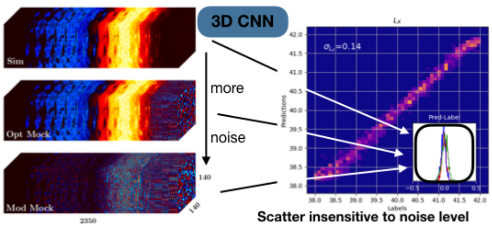

Fig. 1. 3D-21cm Parameter InfErence Net (3D-21cmPIE-Net) – A public architecture tailored for 3D-21cm lightcones.Neutsch et al. (2022)

2.2. 21cm source detection in 3D

A 3D data cube of 1TB as expected for the SKA-MID, together with a 1GB training cube with ground truth information, was presented for the second SKA science data challenge (SDC2, https://sdc2.astronomers.skatelescope.org). Goal was the detection and characterisation of >100.000 HI sources. Key findings, see also fig. 2, were:

- Direct 3D approaches perform best for **3D segmentation of sources**,
- where 3D U-Nets offer robust 3D reconstructions,

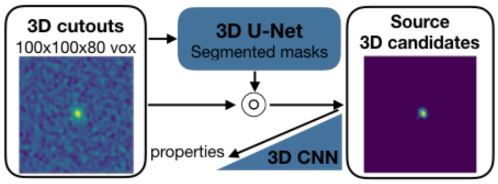

Fig. 2. Our source detection and characterisation pipeline for the SKA Science Data Challenge 2. Hartley et al. (2022)

- allowing for **high precision** estimate of flux & HI size,
- with properties **unbiased** almost independently of source brightness.

3. Conclusions

Why (3D) intensity mapping? As compared to the measurement of single galaxies, intensity mapping (IM) measures the sum of all radiation reaching us over larger sky areas. These intensity fluctuations tell us about properties of both galaxies and the gaseous medium between. As there is no need to resolve single objects, and as we pick up all radiation components (also diffuse radiation), the signal is enhanced and we detect fluctuations from higher redshifts. At the same time, we are not biased towards brightest sources. In addition, 3D information is derived via frequency-dependence for full tomography. Due to this variety and wealth of information encoded, as well as the signal being highly non-Gaussian, IM is prone to be explored with deep learning.

We highlight two successful DL applications to 21cm 3D mappings, direct inference of astrophysical and cosmological model parameters, and detection of HI sources.

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References

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