Exploring techniques to eliminate systematic errors in HERA data.

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Introduction

- The red-shifted 21 cm line is one of the most promising probes of the Epoch of Reionization (EoR), when the first galaxies were formed and emitted a background of ultraviolet radiation that ionised the Hydrogen in the intergalactic medium.
- The detection of the 21 cm emission from the EoR is challenged by the presence of foreground sources that are a few orders of magnitude brighter.
- The separation of 21 cm signal from foreground emission requires high precision calibration of radio interferometric data.
- The Hydrogen Epoch of Reionisation Array (HERA) is an instrument designed to measure the power spectrum of the 21 cm emission line, the HERA layout is a split core hexagonal grid (optimised for redundancy) with the smallest spacing between two antennas of 14.6 m (Figure 1).
- Due to the compact nature of the array it is prone to effects of *mutual coupling* (e.g., Fagnoni et al., 2020). Secondly, most of the baselines are sensitive to unmodelled diffuse emission, both effects inevitably introduce calibration errors.
- This work makes use of so-called *fringe rate filters* (Parsons et al., 2016) to mitigate the impact of mutual coupling effects and unmodelled diffuse emission in the calibration of radio data.

Calibration

- Signals from two radio antennas in a radio interferometer array, say antenna i and j, are cross-correlated and averaged in time to form a quantity known as *visibility*
- Antenna responses are typically well characterised and smooth, however, effects of mutual coupling complicate the response by introducing non-smooth structures in antenna response.
- Radio data needs to be calibrated to remove propagation and signal chain effects that corrupt the signal from the radio source.
- The corrupted visibilities are given by

$$V_{ij}^{c} = g_i \, V_{ij}^{m} \, g_j^{*} + n_{ij}, \tag{1}$$

  where g_i and g_j are the complex gain terms of antenna i and j, and n_{ij} is any complex thermal noise generated by the antenna.
- Calibration involves deriving the antenna gain response g_i through a χ^2-minisation, thus the entire process relies upon the accurate modelling of the sky emission and the array instrument response.
- Inaccurate modelling of the primary response leads to calibration errors, which inevitably introduce systematic errors in the data.
- The fringe-rate visibility is defined as the Fourier transform of the visibility along the time axis.

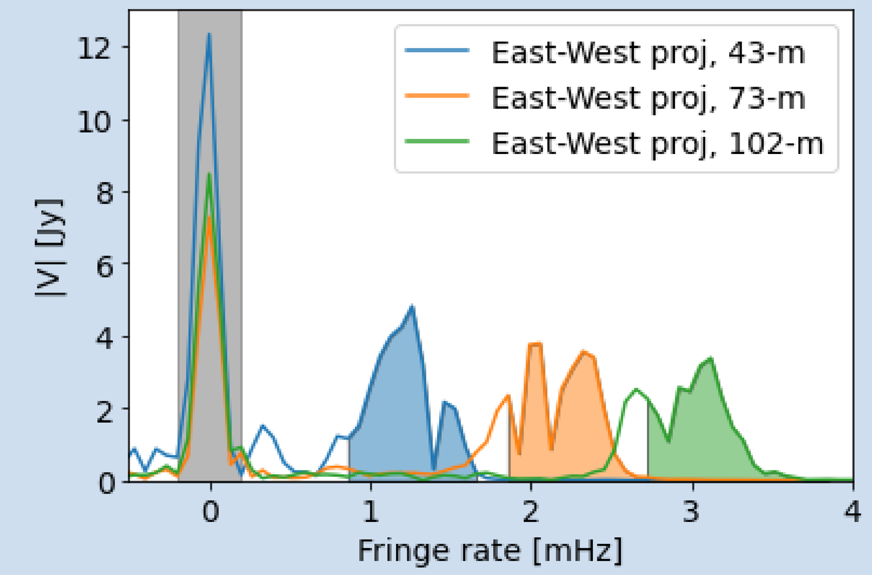

Figure 2. Visibility amplitude in fringe rate space for three baselines with an East-West projection of 43 m (blue), 73 m (orange) and 102 m (green). The colour field regions denote the sky emission in fringe rate space that is retained for calibration when the *main lobe filter* is used. Also shown in grey is the region around the fringe rate value of zero, where the sky emission is filtered upon application of the *notch filter*

Epoch of Reionization (EoR)

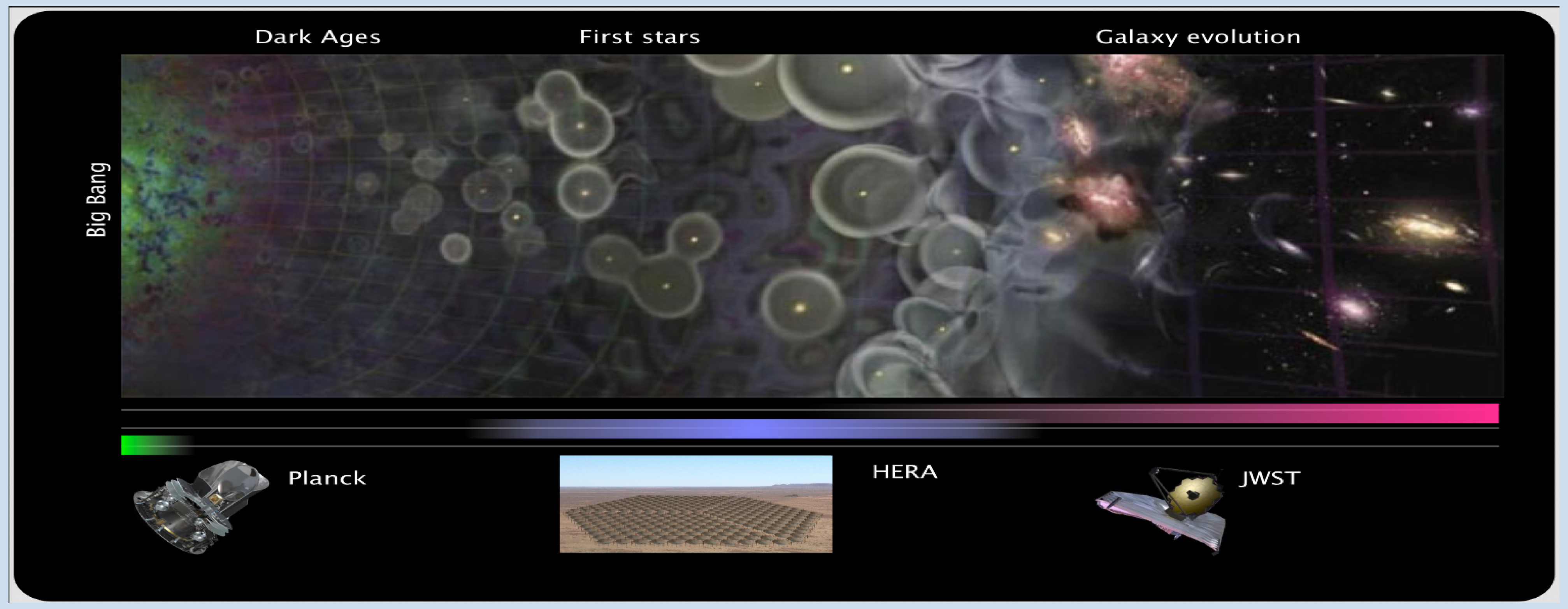

Figure 1. Schematic diagram depicting the evolution of the Universe according to the Hot Big Bang model from the Cosmic Microwave Background (CMB) to the current state. Image credit: *HERA collaboration*

Results: Application of Fringe Rate Filters

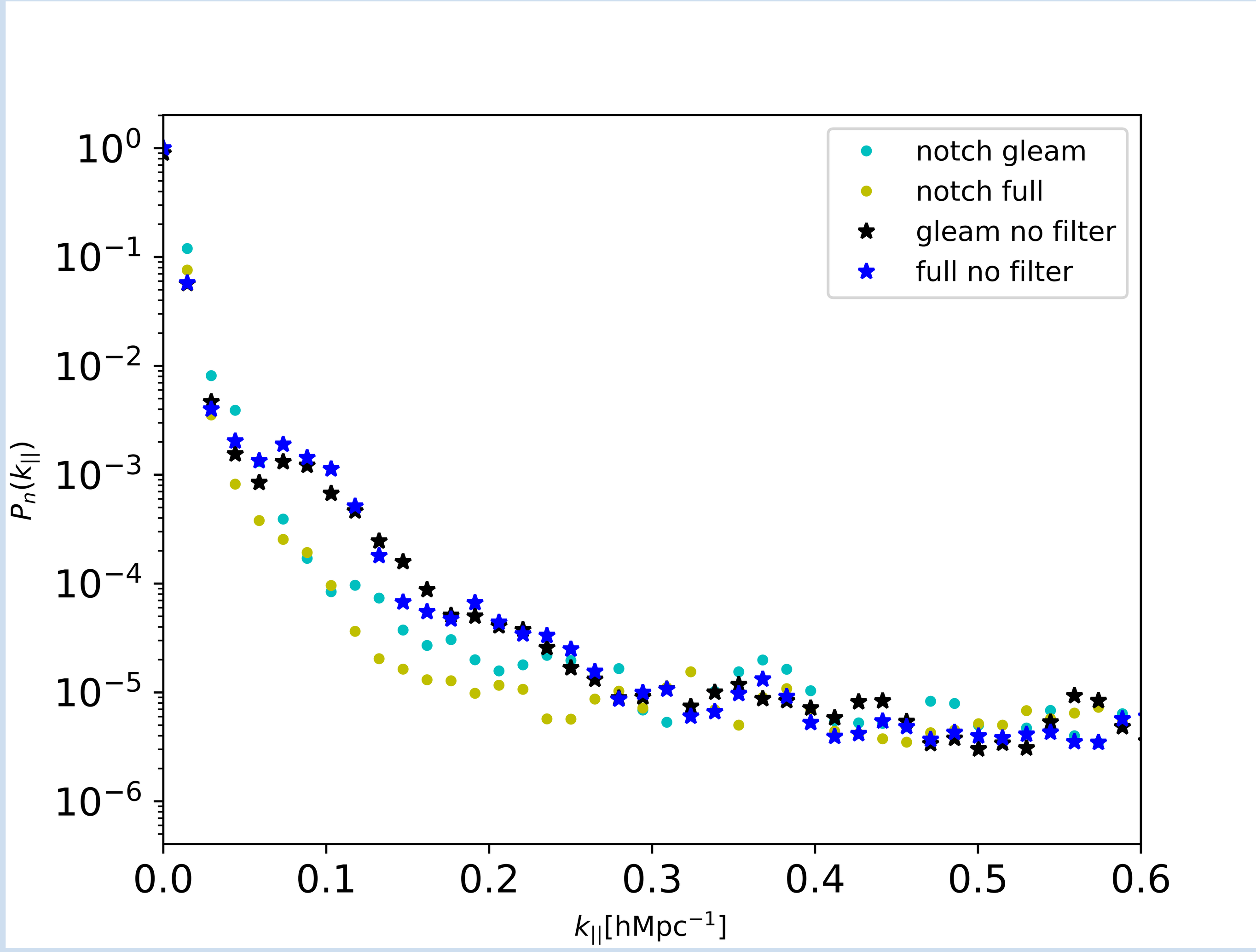

Figure 3. Normalised amplitude of Fourier transform of visibilities along the frequency axis (power spectra at $z \sim 23$) after calibration. Here, we plot the power spectra recovered from calibrating the data without the use of a filter (black and blue), and power spectra when we apply a simple notch filter (cyan and yellow). A significant amount of spectral structure is seen when calibrating the data without a filter; however, this is suppressed after applying the notch filter.

Conclusions

- Spectral unsmoothness of the instrument response introduced by effects of mutual coupling causes calibration errors that overall lead to excess foreground power on high $k-$modes.
- In this work, we demonstrate that the use of a simple notch fringe rate filter prior to calibration can significantly reduce calibration errors, thus mitigating excess foreground power at high $k-$modes.
- Future work will investigate the prospect of using the main lobe filter and incorporate this technique into the HERA data calibration pipeline.