Radio Cosmology Lab | *Exploring the Epoch of Reionization*

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Introduction

Following the recombination of hydrogen and release of the cosmic microwave background radiation, the baryonic matter of the universe consisted mostly of neutral hydrogen and helium. Gradually, small inhomogeneities collapsed and ignited into the first luminous structures. Energetic photons emitted from the first stars and quasars reionized the surrounding medium, producing ionized bubbles which grew and merged into the fully ionized intergalactic medium we see today. This *Epoch of Reionization* (EoR) remains a poorly-understood period of the universe's history which offers a wealth of cosmological and astrophysical information.

The Pober lab is part of an international effort to build instruments capable of studying the EoR. The neutral hydrogen (HI) of the EoR emits faintly at a wavelength of 21cm due to the hyperfine transition. This emission is unique to neutral hydrogen, and is anti-correlated with the ionized (HII) regions that fill the universe through the EoR. CMB constraints and quasar absorption spectra place the EoR within the redshift range $6 < z < 12$, which means 21cm emissions will reach us at meter scale wavelengths. This is accessible to modern radio interferometers, including the *Donald C. Backer Precision Array for Probing the Epoch of Reionization* (PAPER), the *Murchison Widefield Array* (MWA), and our newly observing *Hydrogen Epoch of Reionization Array* (HERA). Extracting this weak signal remains a challenge unprecedented in radio astronomy.

Differential Brightness Temperature

$$\delta T_b = 27(1+\delta)\, x_{\rm HI}\left(1-\frac{T_{\rm CMB}}{T_{\rm spin}}\right)\left(\frac{\Omega_b h^2}{0.0223}\right)\left(\frac{1+z}{10}\,\frac{0.15}{\Omega_m h^2}\right)^{1/2}\left[\frac{H(z)/(1+z)}{\partial_r v_r}\right]\ \mathrm{mK}$$

Density perturbation | Neutral fraction | Spin excitation | Baryon and matter mass fractions | Peculiar velocities

The differential brightness temperature δT_b is the contrast between the intensity of 21 cm emissions/absorptions against the Cosmic Microwave Background. Its full expression is related to cosmological (green) and astrophysical (red) parameters. Figure 1 shows the evolution of the spherically-averaged *global* 21 cm brightness temperature.

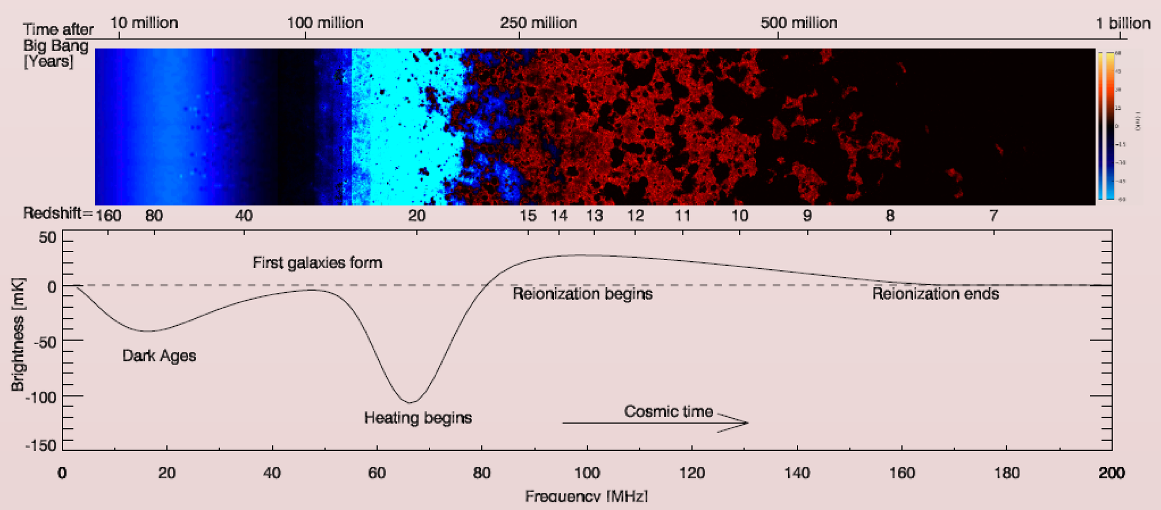

Figure 1: The global differential brightness temperature, δT_b, evolution over redshift $6 < z < 160$. δT_b becomes observable when the spin temperature T_S decouples from the CMB temperature, T_{CMB}. Source: Pritchard & Loeb. Nature 468.7325 (2010): 772-773.

The Foreground Problem

The expected EoR signal is ~ 5 orders of magnitude weaker than known foreground sources, such as diffuse emission from the Galaxy and extragalactic point sources. Removing these foregrounds, as well as instrumental noise, is a nontrivial problem. An example of the overlapping sources of power in our observations can be seen in Fig. 2.

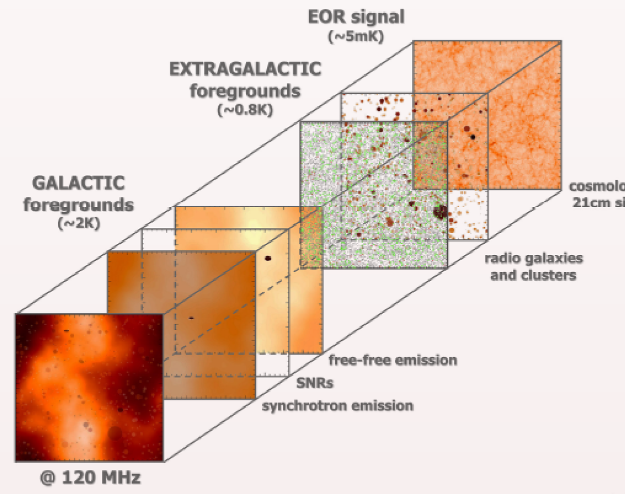

Figure 2: The various cosmological and galactic sources that contribute to the measured sky temperature, and their relative strengths.
Source: Zaroubi, Saleem. 'The First Galaxies. Springer Berlin Heidelberg, 2013. 45-101.

To overcome foreground dominance in our power spectrum analysis we can use a combination of foreground power mitigating techniques as outlined in the following sections.

Hydrid Foreground Subtraction and Avoidance

The need for managing foregrounds in 21cm EoR experiments has led to two distinct techniques: Avoidance and Subtraction. Avoidance is the practice of filtering out foregrounds in Fourier space. Subtraction requires a model of either extragalactic point sources or diffuse emission that can be precisely subtracted from observations. The hybrid approach attempts to use both techniques to further mitigate foreground contamination for the purpose of an EoR detection in the 21cm power spectrum.

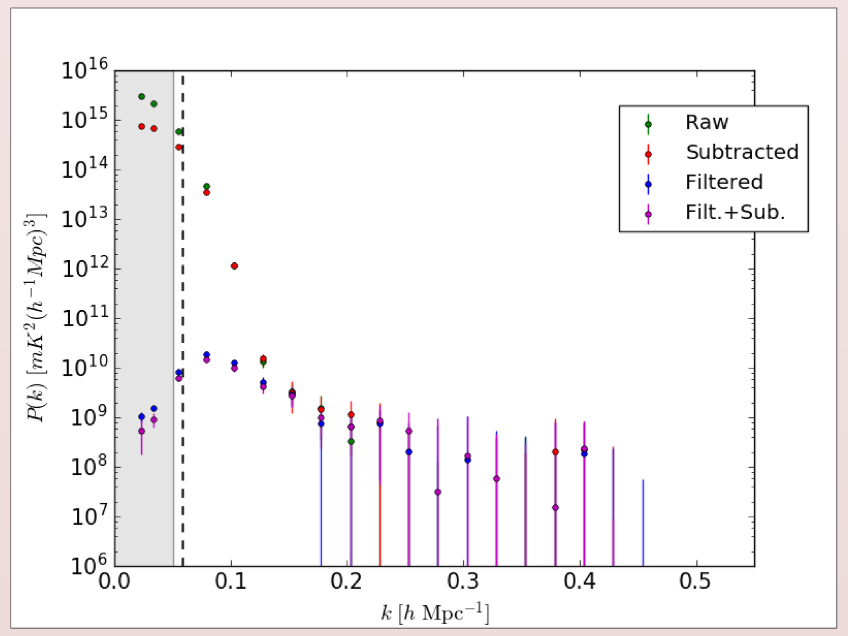

Figure 3: Power spectra from PAPER-64 which shows the effectiveness of filtering (blue), subtraction (red), and hybrid (purple) strategies for foreground subtraction and avoidance when compared with a raw (green) power spectrum.

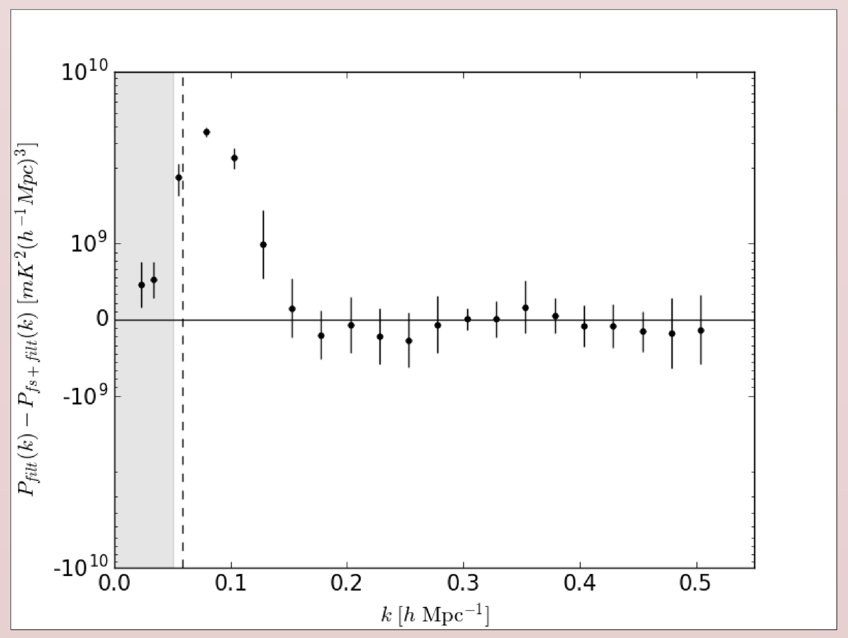

Figure 4: The differenced power spectrum of filtering (blue) and filtering + subtraction (purple) from Fig. 3. This demonstrates that the hybrid foreground subtraction and avoidance technique is able to remove additional contamination from foregrounds necessary for placing the tightest constraints on the EoR power spectrum.

Simulation

The particular characteristics of an array can introduce unexpected effects into the data. Understanding and mitigating instrumental effects is critical to making a confident detection of the EoR. For this reason, much effort has been put into simulating the full analysis pipeline – from the point and diffuse sources on the sky, to the raw visibilities that come out of the correlator, to the power spectrum estimations.

Fast Holographic Deconvolution (FHD) is a purpose-built software framework for analyzing MWA data. FHD does foreground subtraction by *forward modeling*, which builds a simulated data set, including instrumental effects, and subtracts it from the actual data. This forward modeling feature can also be used as a standalone simulation tool, to generate raw visibilities of foregrounds, noise, and EoR off of existing and future 21cm experiments.

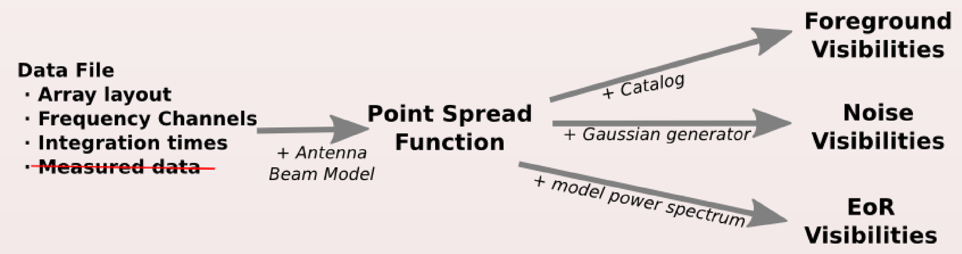

Figure 5: A sample data file (or generated data file) holds array coordinates over time and the frequency channels of the instrument. Given a beam model for the antenna, FHD calculates the full synthesized beam (or point-spread function) for a particular time and set of frequencies. The synthesized beam can then convert a sky catalog into a set of foreground visibilities for the instrument. External EoR simulations can also be fed in to test EoR sensitivity, or Gaussian noise can be injected to simulate noise.

Calibration

21 cm observations of the Epoch of Reionization (EoR) have the potential to reveal a wealth of information about the formation of the first stars and galaxies by measuring the three dimensional power spectrum and full tomographic maps of the neutral IGM. However, these observations are technically very challenging due to bright astrophysical foregrounds and the chromatic nature of radio interferometers. In the last two years it has become apparent that precision instrument calibration is crucial for disentangling the faint cosmological signal from the bright foregrounds. Current precision calibration efforts for EoR observations fall into two camps: sky based calibration using deep foreground catalogs and forward modelling of the instrument visibilities, and redundant calibration that foregoes a sky model but requires the tiles be placed on a precise grid.

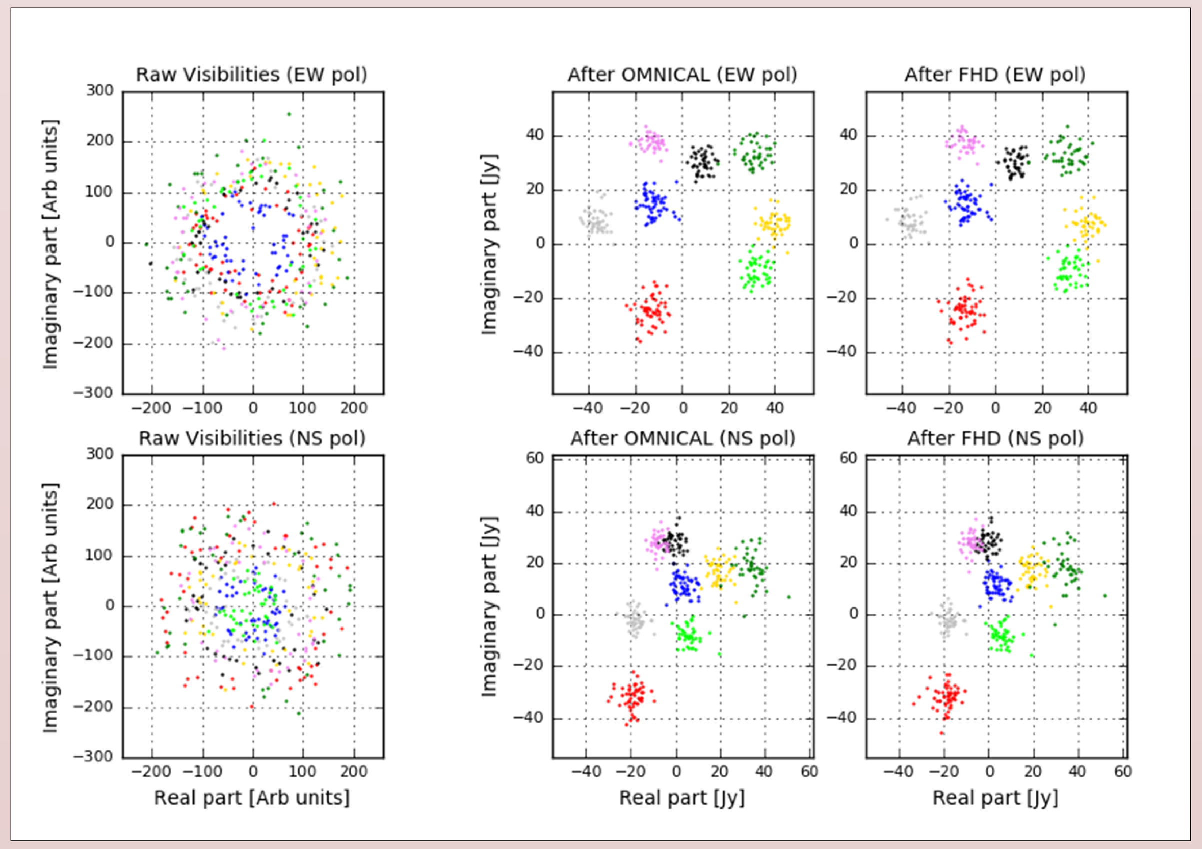

Figure 6: 2 min averaged complex visibilities of EoR0 observation by MWA II at 191MHz from 8 redundant baseline groups. Each color represents one baseline group. Left column: raw visibilities, with arbitrary units; Middle column: visibilities after `OMNICAL`, with degeneracy parameters projected (units: Jy); Right column: visibilities after FHD sky calibration (units: Jy). Top row: East-West polarization; Bottom row: North-South polarization.

Hydrogen Epoch of Reionization Array (HERA)

The Hydrogen Epoch of Reionization Array is a 2$^{\rm nd}$ generation radio interferometer observing the 21 cm emission from neutral hydrogen during the Epoch of Reionization (z = 6 - 12). The HERA instrument will eventually be an array with 350 14-meter parabolic dishes in South Africa. These elements will be divided into a 320-element hexagonal shaped core and 30 outriggers. The current stage of HERA has 37 dishes deployed and observing.

Although increasingly stringent upper limits of the 21 cm signal have been placed by the first generation experiments targeting the EoR such as the Precision Array for Probing the Epoch of Reionization array (PAPER), Murchison Widefield Array (MWA) and LOw Frequency ARray (LOFAR), they are not able to detect it due to their sensitivity limits (see Fig. 8). HERA is designed to bring both the sensitivity and precision required to directly constrain the topology and evolution of reionization. By understanding the evolution of reionization we can better comprehend the formation of the first stars and earliest galaxies.

Figure 7: HERA - Located in the Karoo desert in South Africa. The current phase of HERA consists of 37 14m parabolic dishes. In its final form, HERA will comprise 331 dishes in a closely-packed hexagonal grid. HERA is also a pathfinder project for the Square Kilometer Array (SKA).

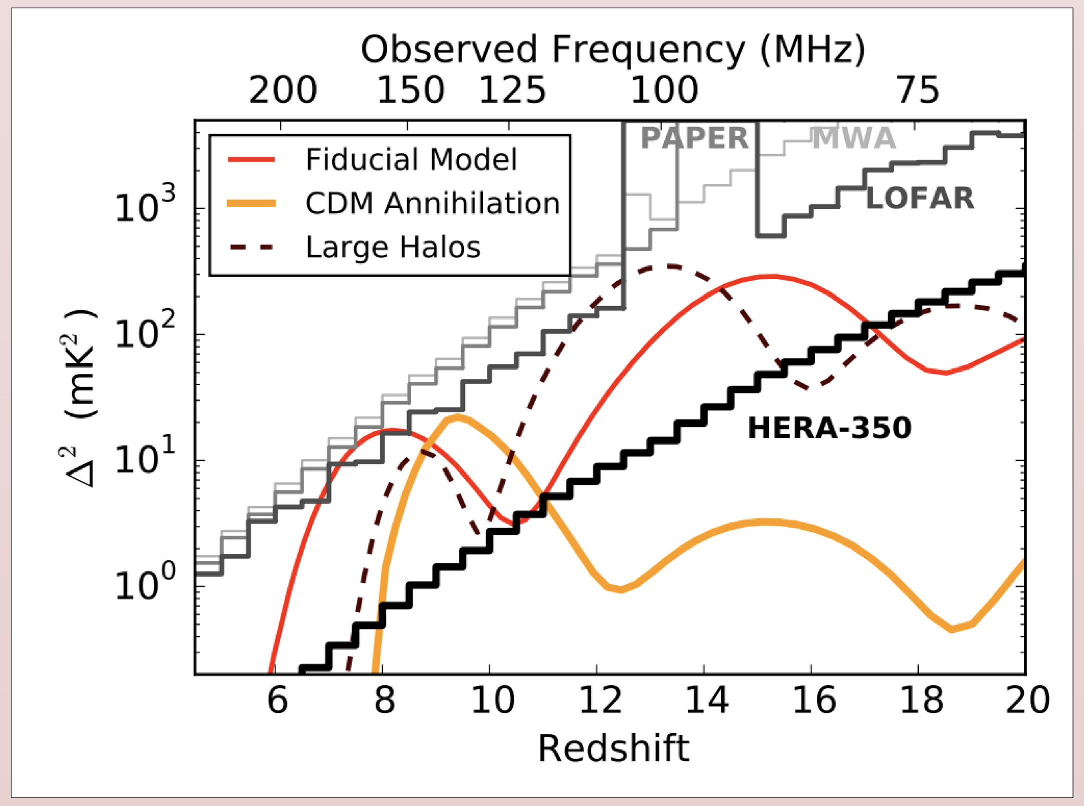

Figure 8: Projected SNR comparison of the 350 element phase of HERA (with 1080 hrs integration time) to other low frequency arrays. Relative to several reionization models (colored), HERA-350 should have the sensitivity to measure the 21cm EoR signal across multiple redshifts. Source: DeBoer & HERA Collaboration. PASP 2017.