Pushing the Scale and Redshift Frontiers: Next-Generation EoR Measurements

Adrian Liu, BCCP Fellow, UC Berkeley
Vision
CMB ~0.4 Myr

Today

neutral H

HII bubble

ionized HII

Loeb 06
21cm Cosmology

Emit radio wave with 21cm wavelength

Absorb radio wave with 21cm wavelength
21cm Cosmology

CMB

Hydrogen atom

CMB
Representative HI shells and HII holes detectable at SNR > 10 after 100 hours

$z = 8$
Foreground contamination is serious

Foregrounds $\sim O(100 \text{ K})$; Signal $\sim O(1 \text{ mK})$
Detection and characterization of the power spectrum
Take-home messages

• Existing techniques allow the Hydrogen Epoch of Reionization Array (HERA) to measure the power spectrum at high significance.

• Pushing the redshift frontier allows astrophysical parameter degeneracies to be broken.

• Pushing the scale frontier to lower $k$ may allow further increases in science payoff, although analysis becomes trickier.
What can HERA do “by default”?
Low k’s are Foreground-limited; High k’s are thermal noise-limited

$\Delta^2(k) \text{[mK}^2\text{]}$

$k \text{[hMpc}^{-1}\text{]}$
Low $k$'s are Foreground-limited; High $k$'s are thermal noise-limited

$\Delta^2(k) \text{ [mK}^2\text{]}$

Thermal noise ($\sim k^3$):
- $T_{\text{sys}} \sim T_{\text{sky}} \sim \nu^{-2.5}$
- Collecting Area
- Integration Time

Graph:
- HERA-127, foreground avoidance
- HERA-331, foreground avoidance
- Mesinger et al. 2011
HERA can detect the rise and fall of the Reionization 21cm Power Spectrum
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\[ \Delta^2(k) [\text{mK}^2] \]

\[ k [\text{hMpc}^{-1}] \]

From a detection to parameters

- $\zeta$: ionizing efficiency of first sources
- $T_{\text{vir}}$: minimum virial temperature (proxy for virial mass) of first ionizing galaxies
- $R_{\text{mfp}}$: mean free path of ionizing photons
With only $z=7$ and $z=8$, parameters are quite degenerate.
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Including $z=9$ helps to break degeneracies.
And going up to \( z=10 \) does even better.

\[ \sim 5\% \text{ constraints} \]

What needs to be done to push HERA to the next level?
Scale and Redshift Frontiers

- Scale Frontier: Noise ($\sim k^3$) vs. Foregds ($\sim k^{-\text{steep}}$)

- Redshift Frontier: $T_{\text{sys}} \sim T_{\text{sky}} \sim \nu^{-2.5}$

- Collecting Area

- Integration Time
Pushing the scale frontier to lower $k$ increases sensitivity, but foregrounds need to be dealt with
Why do foregrounds live at low $k$?
The cosmological signal is expected to be spectrally unsmooth.
Foregrounds are expected to be smooth functions of frequency.
Foregrounds and Fourier Transforms
Foregrounds and Fourier Transforms

\[ k_x \quad k_y \]

\[ \theta_x \quad \theta_y \]

image cube

3D power spectrum

(frequency)\(^{-1} \)
Foregrounds are probably localized in Fourier space…

Foregrounds here, perhaps?
…but aren’t that localized because of subtleties to do with interferometry…
An interferometer builds up a picture of the sky Fourier mode by Fourier mode
Foregrounds and Fourier Transforms

What an interferometer measures

Baseline \( y \)
\( k_y \)

Baseline \( x \)
\( k_x \)

imaging

\( \theta_y \)

3D power spectrum

\( \theta_x \)

Baseline \( y \)
\( k_y \)

Baseline \( x \)
\( k_x \)
$k_{||} \sim$ Baseline time delay
$k_\parallel \sim \text{Baseline time delay}$

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$k_{\parallel} \sim$ Baseline time delay

Foregrounds should appear in a “wedge”

AL et al. 2014
arxiv:1404.2596, 1404.4372
PAPER observations confirm the predicted “wedge” structure

Multi-frequency MWA data shows similar wedge behavior

Dillon, AL et al. 2014, PRD 89, 023002
The wedge can be thought of in terms of window functions

\[ \Delta^2(k) [\text{mK}^2] \]

\[ k [\text{hMpc}^{-1}] \]
The wedge can be thought of in terms of window functions

Sample galaxy survey window functions from SDSS
The “wedge” arises because of a coupling between spatial modes and spectral modes

\[ \int T(\theta) \exp \left( -i \frac{2\pi b \nu \theta}{c} \right) d\theta \]
The wedge can be thought of in terms of window functions.

\[ W(k_\perp, k_\parallel) \]

AL et al. 2014
arxiv:1404.2596, 1404.4372
Errors within the wedge are highly correlated.

**AL et al. 2014a,b arxiv:1404.nextweek**
Errors within the wedge are highly correlated

\[ \text{Error Correlation } \overline{\Sigma}_{\alpha\beta} = \Sigma_{\alpha\beta}/\sqrt{\Sigma_{\alpha\alpha} \Sigma_{\beta\beta}} \]

AL et al. 2014
arxiv:1404.2596, 1404.4372
Optimal power spectrum estimators can help alleviate the wedge

Optimal estimator

Basic estimator

AL et al. 2014
arxiv:1404.2596, 1404.4372
Pushing the scale frontier to lower $k$ increases sensitivity, but there are subtleties.

\[ \Delta^2(k) \, [\text{mK}^2] \]

\[ k \, [\text{hMpc}^{-1}] \]
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