Reionization constraints from HERA 21cm power spectrum limits

Based on work with the HERA Collaboration & Theory team

HERA Phase I Limits on the Cosmic 21-cm Signal: Constraints on Astrophysics and Cosmology During the Epoch of Reionization [arXiv 2108.07282]

Stefan Heimersheim

3rd year PhD student with Anastasia Fialkov (IoA)

Other research: Reionization constraints with Fast Radio Bursts
The HERA Telescope

39 antennas, 18 nights of observation, separated by LST (fields), drift scan

Figure from HERA papers (arXiv 2108.02263, 2108.07282)

HERA telescope in Karoo desert, South Africa
Image credit: HERA Partnership

Stefan Heimersheim
sh2061@cam.ac.uk
21cm power spectrum

\[ \Delta^2(k) = \frac{k^3 P(k)}{2\pi^2} \]

(Figure: HERA Collaboration 2021a)

Image adopted from Reis et al. 2021
The 21cm signal EoR window

Interferometer
→ Baseline \sim k_\perp
→ Frequency \sim k_\parallel

Graphics credit: Avison & George, arXiv 1211.0228

Power spectra and foreground wedge
(Figure adopted from HERA Collaboration 2021a)
What do we mean by an “upper limit”? 

<table>
<thead>
<tr>
<th>$k$</th>
<th>$\Delta^2$</th>
<th>$1\sigma$</th>
<th>$\Delta^2_{UL}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h$ Mpc$^{-1}$</td>
<td>(mK)$^2$</td>
<td>(mK)$^2$</td>
<td>(mK)$^2$</td>
</tr>
<tr>
<td>0.128</td>
<td>$(29.17)^2$</td>
<td>$(17.39)^2$</td>
<td>$(38.16)^2$</td>
</tr>
<tr>
<td>0.192</td>
<td>$(14.55)^2$</td>
<td>$(19.17)^2$</td>
<td>$(30.76)^2$</td>
</tr>
</tbody>
</table>

Measurement $(14^2 \pm 19^2 \text{ mK}^2) = \text{Cosmological + Systematics}$

$\rightarrow$ Cosmological signal anywhere between 0 and measurement
Seminumerical codes (see Thomas’ talk)

Numerical simulations (e.g. Fialkov et al.)

- Evolve density field & identify star-forming halos (parameterized by $M_{\text{min}}$ or $V_c$)
- Model emission of UV, X-Ray, Radio, LyA etc.
  - (parameterized by $\tau$, $f_X$, $f_r$, $f_*$)
- Compute 21cm brightnes temperature fields and derive power spectra

Parameters ($V_c$, $\tau$, $f_*$, $f_X$, $f_r$) → Power spectrum $\Delta^2_{21\text{cm}}(k,z)$

Image adopted from Reis et al. 2021

Stefan Heimersheim
sh2061@cam.ac.uk
Emulator for semi-numerical simulations

Neural network
• Use to “emulate” simulation. i.e. effectively interpolate between existing simulations
• 10,000 simulations in 5D parameter space
• Uncertainty ca. 20% of power spectrum

About 1ms

Stefan Heimersheim
sh2061@cam.ac.uk
21cm signal & extra radio background

- Extra background radiation in addition to CMB:
  - Homogeneous synchrotron background, strong at high $z$ (see also Shikhar’s PBH talk)
  - Radio emission from galaxies (inhomogeneous, scaling with SFR)

\[ T_{21} \propto \left( 1 - \frac{T_{\text{rad}}}{T_S} \right) \]
Extra Radio Background in 21cm Power Spectra

Figure from Reis et al. 2021
Intuitive interpretation of HERA limits
(lead by Julian B. Muñoz)

If 21cm PS traces matter power spectrum

\[ \Delta^2_{21}(k, z) = b^2_m(z) \Delta^2_m(k, z) \]

\[ b_m = T_0 x_{HI} \left\{ (1 + \mu) - \frac{T_{\text{rad}}}{T_S} [(1 + \mu) - C_T] \right\} \]

Positive: Emission, saturated at \( \sim 30\,\text{mK} \)

Negative: Absorption, up to 100% in principle

Emission not yet detectable:
Intuitive interpretation of HERA limits
(lead by Julian B. Muñoz)

If 21cm PS traces matter power spectrum (“bias approach”)

\[ \Delta_{21}^2(k, z) = b_m^2(z) \Delta_m^2(k, z) \]

\[ b_m = T_0 x_{\text{HI}} \left\{ (1 + \mu) - \frac{T_{\text{rad}}}{T_S}[(1 + \mu) - C_T] \right\} \]

Absorption:
Upper limit on \(|T_{21}| \rightarrow \) Lower limit on \(T_s/T_{\text{rad}}\)

[Diagram showing temperature evolution and absorption limits]

Stefan Heimersheim
sh2061@cam.ac.uk
Comparison to claimed EDGES detection

Density-driven

- Example heating
- CDM
- mQDM ($f_{dm} = 0.5\%$)

- Excess Radio ($f_r = 9000$)
- EDGES
- HERA ($\overline{x}_{HI} = 1$)
- HERA ($\overline{x}_{HI} = 0.5$)
- $\mu = 0.6$

Stefan Heimersheim
sh2061@cam.ac.uk
Constraints from HERA limits (alone) on models

Rule out cold IGM together with strong radio background

- Preference for high $f_X$ and low $f_r$, models with both, low $f_X$ and high $f_r$, are excluded ($f_X < 25\%$ today’s X-ray efficiency, $f_r > 400$ times today’s radio emissivity)

- Similar constraints: Low $f_X$ with synchrotron radio background $> 5 \times$ CMB (large, but lower than ARCADE 2 limits, $50 \times$ CMB, Fixsen et al. 2011) ruled out
Constraints on Extra Radio Background models

Complementary constraints to LWA/ARCADE2 & Chandra

Excluded models correspond to those with high radio background and relatively low gas temperature (T_{rad} / T_K > 10 excluded)

\[ T_{21} \propto \left( 1 - \frac{T_{rad}}{T_S} \right) \]

High contrast

Large Signal

\( \sim 4\sigma \)
Standard models, no additional radio background
(lead by Yuxiang Qin, with Andrei Mesinger and Bradley Greig)

- HERA constraints slightly improve constraints over other constraints (UV LVs, QSOs, CMB)
- Especially on the X-ray luminosity (heating)
  → Rule out too-cold IGM

Posterior

\[ z = 7.9 \]

\[ \log_{10}[L_X < 2\text{keV}/\text{SFR/erg s}^{-1} M_\odot^{-1} \text{yr}] \]

local HMXBs
- low-metallicity HMXBs
- with HERA
- without HERA

Stefan Heimersheim
sh2061@cam.ac.uk
Summary

- 21cm cosmology will probe a large part of the observable Universe
  - Power spectrum measurements by HERA
    - $(14.55\text{mK})^2 \pm (19.17\text{mK})^2$ at $z=7.93$, $k=0.2$ h/Mpc
  - Strongest upper limits on 21cm power spectrum

- Constrain IGM & radiation temperature
  - Require heating of IGM by redshift 8
  - Ratio $T_{\text{rad}}/T_{\text{gas}} < 10$

- Constrain astrophysical models
  - Rule out some parts of astrophysical parameter space
    (those leading to high radio / less heating)