A Bayesian approach to recovering the power spectrum of the Epoch of Reionization with HERA

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Motivation & Overview

- Astrophysical objects unique to the early universe
- Feedback and structure formation
- Sources of ionizing photons

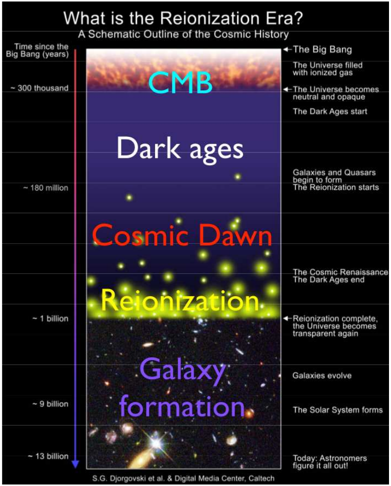


Figure: Schematic representation of cosmic history. Image credit, G. Djorgovski.

Motivation & Overview

- Redshifted 21-cm emission from neutral hydrogen provides a promising avenue for observations
- Direct multi-scale probe of the hydrogen gas
- $\nu_{\rm obs} = \dfrac{\nu_{21}}{1+z}$ MHz
  $\nu_{\rm obs}$ $\longleftrightarrow$ redshift $\longleftrightarrow$ line-of-sight distance
- Foreground emission presents a major challenge

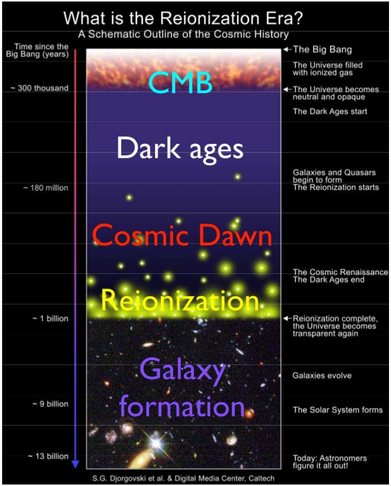


Figure: Schematic representation of cosmic history. Image credit, G. Djorgovski.

EoR signal and foreground emission

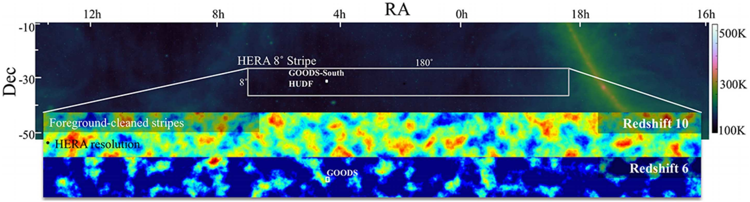
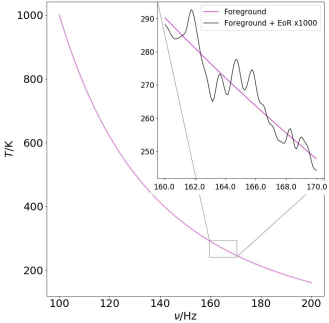
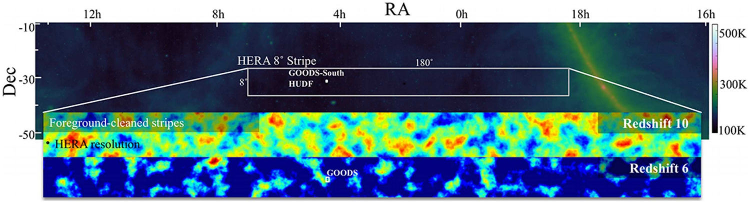


Figure: Mock HERA imaging stripe. Image credit, DeBoer et al. [2017]



- Galactic synchrotron emission and extragalactic sources are up to 5 orders of magnitude brighter than the EoR signal
- Relative spectral smoothness of the foregrounds provides the primary discriminant for isolating the EoR signal

EoR signal and foreground emission



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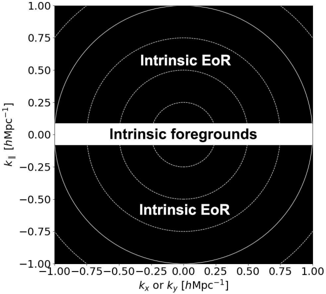
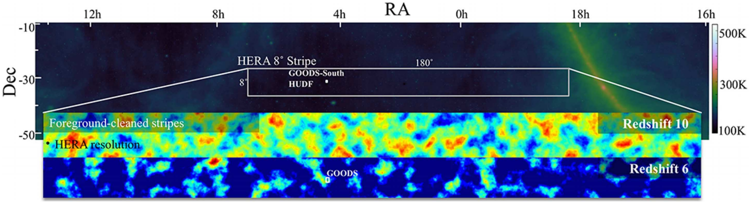


- In k-space, smooth spectrum foregrounds are intrinsically concentrated in a strip centered on $k_{\parallel} = 0$.
- EoR signal has power across a wide range of spatial scales

EoR signal and foreground emission



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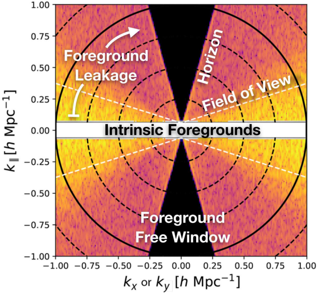
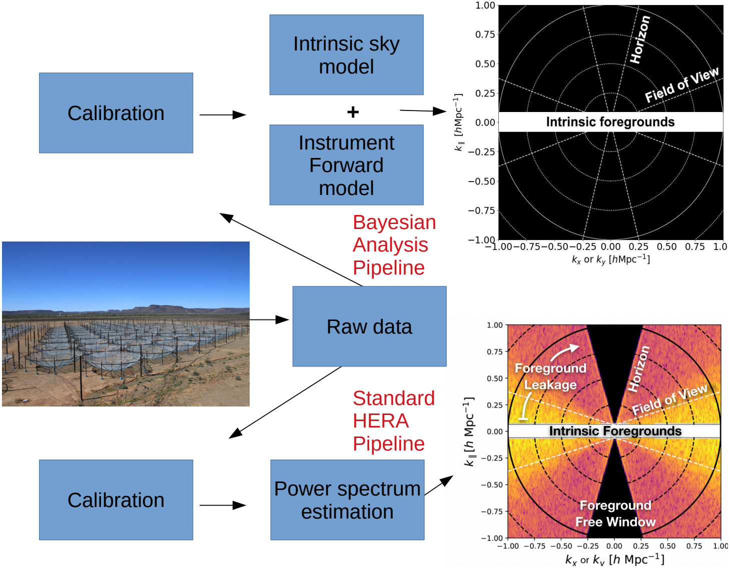
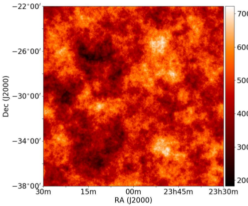


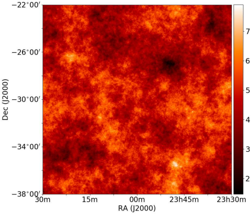
- Instrumental chromaticity, if unmodelled, spreads foreground contamination throughout a large region of k-space, restricting the spatial scales on which the EoR power spectrum can be estimated

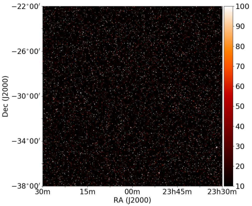
Approaches to power spectral estimation

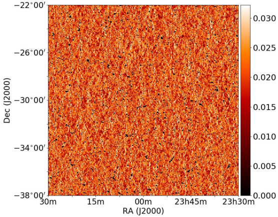


Foreground & EoR signal simulations









- 10 MHz spectral band
- Galactic diffuse synchrotron emission, Gaussian spectral index distribution, $\bar{\beta}_{\mathrm{g}} = 2.6$, $\sigma_{\mathrm{g}} = 0.02$ (Mozdzen et al. 2017)
- Diffuse free-free emission, $\bar{\beta}_{\mathrm{ff}} = 2.15$
- Extragalactic sources, $\bar{\beta}_{\mathrm{egs}} = 2.82$, $\sigma_{\mathrm{egs}} = 0.19$ (Lane et al. 2014)

Recovering the power spectrum of the EoR from simulated interferometric observations

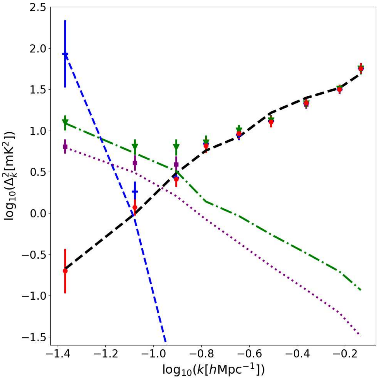


Figure: Input power spectrum of the simulated EoR signal (black dashed) and recovered estimates for four choices of spectral model (points with error bars) Sims and Pober [2019]

- Monopole plus double power law spectral model (mdpl) for the foregrounds enables recovery of the EoR power spectrum on all spatial scales accessible in the simulated data set (red points)
- Mpdl decisively preferred by Bayesian evidence relative to quadratic (blue) and single power law (green, purple) foreground parametrisations
- Idealised, zero uncertainty forward model of the instrument

HERA IDR2.2

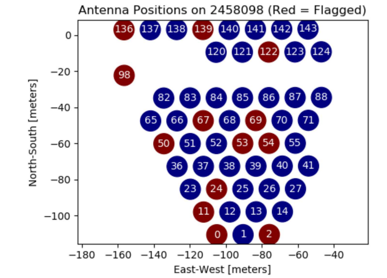


Figure: Top: Current HERA build-out. Image credit, Kathryn Rosie. Bottom: Antennas used in the current analysis. Image credit, Dillon et al. [2019].

- IDR2.2: 18 days of LST averaged data using 40 antennas
- Preliminary analysis with Bayesian pipeline: 3 h of data (10 min per day)
- Limits derived using all baselines with lengths ($b < 40$ m)
- Data coherently averaged over nominally redundant baselines

HERA IDR2.2 **preliminary** power spectrum limits demonstration with Bayesian pipeline

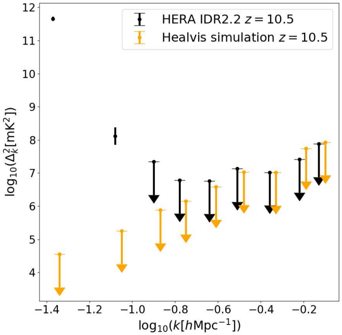


Figure: **Preliminary** 2-σ upper limits (arrows) on the power spectrum of the EoR at $z = 10.5$ recovered from 3 h of HERA 50 IDR2.2 data release (black) and from simulated observations with HERA 50 (orange)

- 3 h data; 120–128 MHz spectral band; central redshift, $z = 10.5$
- Noise dominated upper limits recovered at $\log_{10}(k[h\mathrm{Mpc}^{-1}]) > -1.0)$
- Best limit at $k = 0.2\ h\mathrm{Mpc}^{-1}$: $\log_{10}(\Delta_k^2[\mathrm{mK}^2]) < 6.8$
- Foreground contamination at low-k resulting from an imperfect calibration and instrument forward model

Summary

- A Bayesian power spectral analysis allows for a robust characterization of the errors and covariances of the measurements and provides a framework for including additional uncertainties (Sims et al. 2019, Sims and Pober 2019)
- Noise dominated upper limit at $k = 0.2\ h\mathrm{Mpc}^{-1}$ with 3 h of data: $\log_{10}(\Delta_k^2[\mathrm{mK}^2]) < 6.8$
- Upper limit of $\log_{10}(\Delta_k^2[\mathrm{mK}^2]) < 4.5$ feasible using the same data set with sufficiently accurate data calibration and instrument forward model
- Work is ongoing on covariant propagation of the uncertainties in data calibration through to the power spectrum and on characterising the instrumental forward model accuracy required to recover the EoR power spectrum on large spatial scales

Simulated observations - instrumental and observational parameters

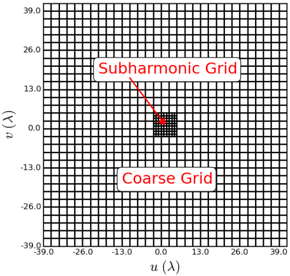
Table: Instrumental and observational parameters.

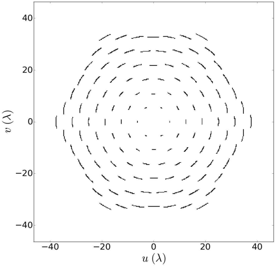
Parameter	Description	Value
η_s	System efficiency	1
$\Delta\nu$	Channel width	$200\ \mathrm{kHz}$
τ	Integration time	$30\ \mathrm{s}$
η_a	Antenna efficiency	1
A	Antenna area	$150\ \mathrm{m}^2$

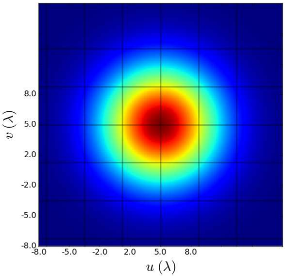
- $\sigma_V = \dfrac{1}{\eta_s}\dfrac{SEFD}{\sqrt{2\Delta\nu\tau}}$
- $SEFD = \dfrac{2k_B T_{\mathrm{sys}}}{\eta_a A}$

- Assuming $T_{\mathrm{sys}}(130\ \mathrm{MHz}) = 550\ \mathrm{K}$
- $\sigma_V(2000\ \mathrm{hrs}) \simeq 0.045\ \mathrm{Jy}$

Data Model - Spatial Model & Instrumental Forward Modelling

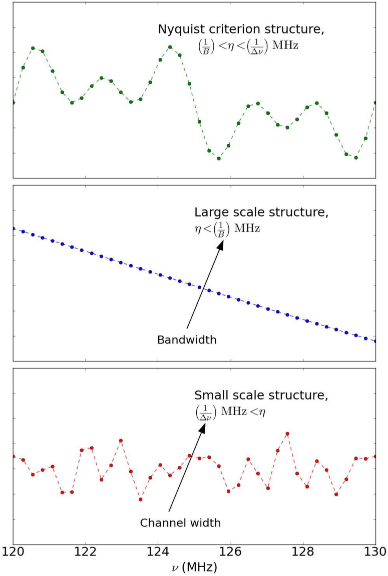






- De-grid the intrinsic model (t-l) onto the frequency-dependent instrumental sampling of the *uv*-plane (t-r) using the aperture function of the instrument (b-r)

Data Model - Multi-scale Spectral Model



- Estimate the power spectrum on scales fulfilling the Nyquist sampling criterion for the dataset
- Model structure on spectral scales longer than the bandwidth with quadratics (Sims et al. 2016) or power laws (Sims and Pober 2019)
- Model structure on spectral scales smaller than the channel width with a noise term that is estimated in the analysis