Simulations of the polarized Galactic sky for the Epoch of Reionization observations

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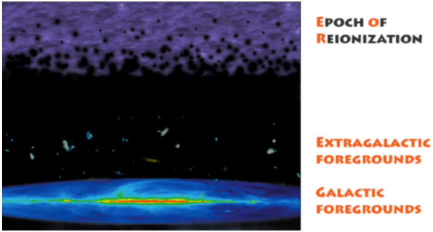
EoR with the 21 cm line: the challenge of foregrounds

- Extragalactic Point Sources (PS)
  radio galaxies, AGNs, ..
- Galactic and Extragalactic free-free
  bremsstrahlung radiation from electron-ion collisions
- Galactic synchrotron
  (dominant foreground) cosmic ray electrons interacting with the galactic magnetic field.

e.g. Santos et al 2005, Jelic et al 2008, Geil et al 2011



credit: LOFAR

Synchrotron is linearly polarised.

Foreground cleaning

Heritage form CMB analysis (more complex with the 3D 21 cm signal)

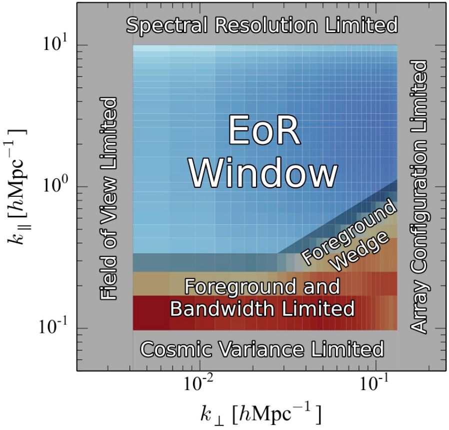
$$T(\nu, \hat{\mathbf{n}}) = \sum_{k=1}^{N_{\rm fg}} f_k(\nu) S_k(\hat{\mathbf{n}}) + T_{\rm cosmo}(\nu, \hat{\mathbf{n}}) + T_{\rm noise}(\nu, \hat{\mathbf{n}})$$

- *Blind subtraction*: spectral polynomial fitting (LOS), principal component analysis (PCA), ..
- model the foregrounds with a *physically motivated functions* (log-polynomial in Global signal analysis)

foreground sources are expected to be spectrally smooth, while the cosmological EoR signal is expected to fluctuate rapidly with frequency

Foreground Avoidance

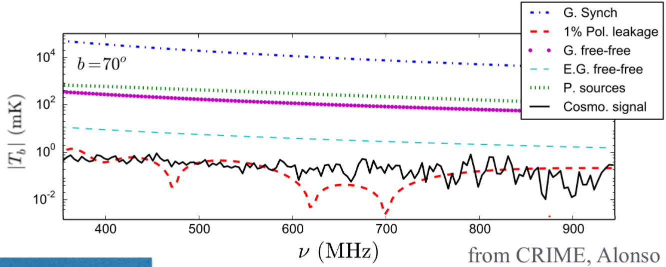
Alternative strategy: use data only from the EoR window (in the cylindrical $k_\perp$-$k_\parallel$ Fourier plane) that are not contaminated by foregrounds



Liu et al. (2014)

- Smooth foregrounds are expected at small $k_\parallel$
- going to higher $k_\perp$, due to the instrument response, foregrounds leak out to higher $k_\parallel$ (foreground wedge)

Polarised Synchrotron emission



from CRIME, Alonso et al 2014

Why is it important?

- non trivial frequency structure
- can leak into the unpolarized part
- can contaminate the 21cm analysis:
  1. preventing component separation to work properly
  2. mimic the high $k_{||}$ EoR emission, scattering power in otherwise clean EoR window Moore et al. (2013)

Synchrotron generalities

- Depends on $B_\perp$ to the LOS modulated by the density of *cosmic electrons*
- Diffuse polarised emission:

$P = \Pi_0 I e^{2i\phi}$ with $\phi = \phi_0 + \psi\lambda^2$ faraday rotation
given by $B_\parallel$ and the presence of *thermal electrons*
$$\psi \propto \int_{\mathrm{LOS}} n_e B_\parallel dr$$

At Eor frequencies P simulations are difficult:

- lack of correlation with total intensity
- not a lot of polarised data at low frequencies
- depolarisation effects prevent extrapolation from higher frequencies

Simulation strategy

Spinelli, Bernardi, Santos (2018)

Use RM-synthesis framework (ψ and λ^2 as a Fourier pair) Bretjens& Bruyn (2005) Heald, Brown & Edmonds (2009):

- full-sky gaussian Q,U maps in ψ space with specific power spectrum:

$$\tilde{Q}(\psi, \hat{\mathbf{n}}) = \sum_{\ell m} \tilde{q}_{\ell m}(\psi) Y_{\ell m}(\hat{\mathbf{n}})$$
$$\langle \tilde{q}_{\ell m}(\psi) \tilde{q}^*_{\ell' m'}(\psi) \rangle = (2\pi)^2 A(\psi) \ell^{-\alpha(\psi)}$$
$$\langle \tilde{q}_{\ell m}(\psi) \tilde{q}^*_{\ell m}(\psi') \rangle \propto \rho(\Delta\psi, \ell)$$

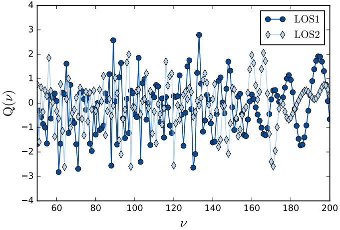
  We use MWA data to constrain free parameters (from Bernardi et al 2013 but we can use other data)

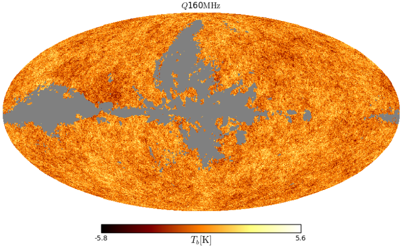
- transform back to frequency space using the Fourier relation between ψ and λ^2

$$Q(\lambda^2, \hat{\mathbf{n}}) = \int \tilde{Q}(\psi, \hat{\mathbf{n}}) e^{2\pi \lambda^2 \psi} d\psi$$

Full-sky polarized maps

- complex frequency structure
- a *worst case* scenario for depolarization (MWA @189 MHz)
- no ionosphere (yet)
- simulations in the range 50-200 MHz publicly available at UWC-CRC drive folder
- option to select frequency and spatial resolution



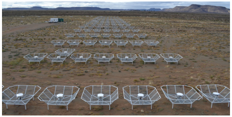


Some applications

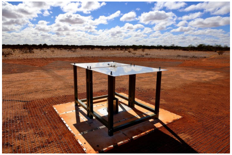
- foreground avoidance:
  an example from PAPER
  21-cm power spectrum
  polarization contamination
  EoR
  120-180 MHz

- foreground cleaning:
  (simulated) EDGES 21-cm
  Global signal analysis in
  presence of polarized
  foregrounds
  Cosmic Dawn
  50-100 MHz

PAPER: Karoo desert (South Africa)

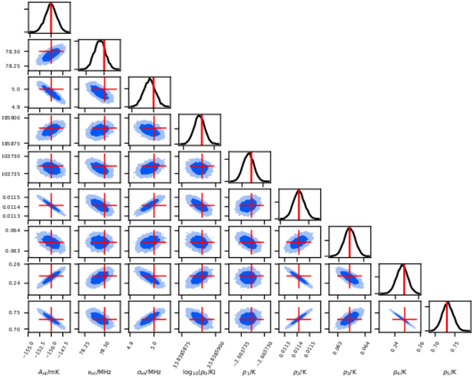


EDGES: Murchison Radio-astronomy Observatory (Western Australia)



"Cleaning" in Global-signal studies for Cosmic Dawn

$$T(t,\nu) \propto \int_{\Omega} T_{sky}(t,\nu,\hat{n}')A(\nu,\hat{n}')d\hat{n}' + T_N$$



Bernardi et al. (2016)

$$T(t,\nu) = T_f(t,\nu) + T_{\mathrm{HI}}(\nu)$$

Foregrounds:

$log_{10} T_f(\nu_j) = \sum_{n=0}^{N} p_n [log_{10}(\frac{\nu_j}{\nu_0})]^n$

Signal:

$T_{HI}(\nu_j) = A_{HI} e^{-\frac{(\nu_j - \nu_{HI})^2}{2\sigma_{HI}^2}}$

or the *flattened Gaussian*

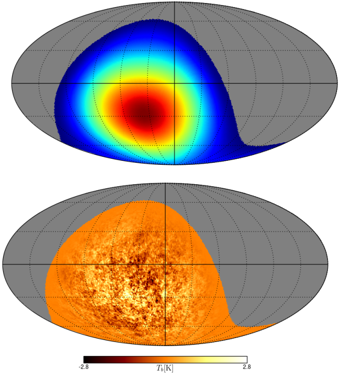
Bowman et al. (2018)

What if there is a polarized sky contamination?

A polarized signal can leak into the measurements but the analysis assumes it is weak.

Can EDGES absorption profile have local astrophysical origin?

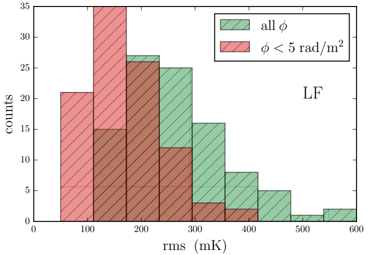
- observations every h from $lst = 0$ to $lst = 8$
- frequency range: 50-100 MHz
- beam model Dowell (2011)
- Bayesian pipeline for foreground removal: HIBayes Zwart et al. (2016) based on *MultiNest* Feroz et al. (2009)

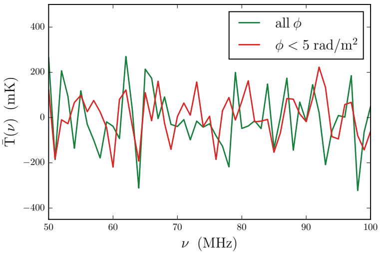


Spinelli, Bernardi, Santos *in prep*

Contamination

- Two types of simulations:
    1. all ϕ
    2. $\phi < 5$ rad/m^2
- 1000 sims for each case
- high contamination of the order of ~ 200 mK
- single dipole will measure $I + Q$ $(I - Q)$
- I: 5th degree log-polynomial
- Q: typical cases from our simulations





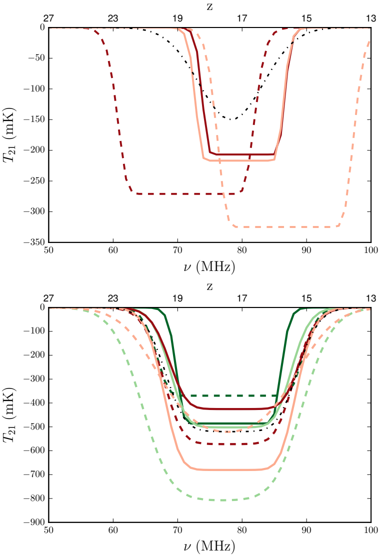
Possible scenarios

- *current simulation* typical Gaussian:

  the measured profile is unlikely to be due to (our) astrophysical foreground

- confirmed EDGES signal:

  $+Q$ (solid) and $-Q$ (dashed) contamination could bias the result and shift the deep up and *down*



Conclusions

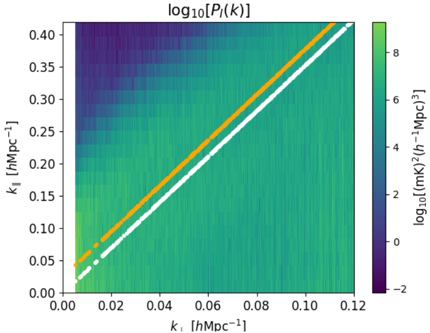
- polarized synchrotron can in principle be one of the main challenges to unveil the 21cm signal both for foreground avoidance and foreground cleaning
- we developed full-sky simulations based on MWA data in the range 50-200 MHz.
- we have investigated the impact of a (unaccounted for) polarized sky component in global-signal analysis for Cosmic Dawn:

  1. EDGES results are unlikely to have a local astrophysical origin (assuming our simulated sky)
  2. there is still a possible bias due to polarization in the extraction of the cosmic signal

Backup

Foreground avoidance with PAPER

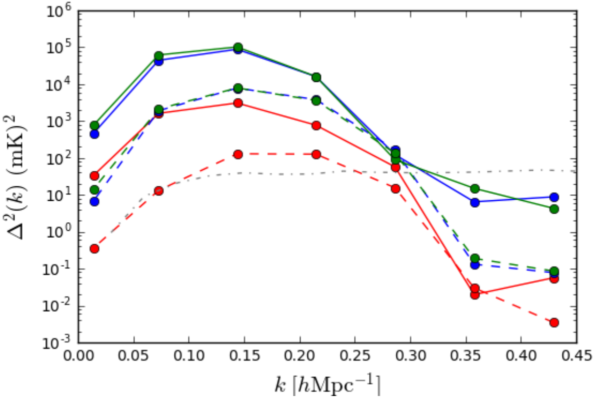
- *Sky brightness* I,Q,U,V through the telescope: $\mathbf{s}'(\hat{\mathbf{r}},\nu)) = \mathbf{A}(\hat{\mathbf{r}},\nu)s(\hat{\mathbf{r}},\nu)$ ($\mathbf{A}$ Mueller matrix)
- $\tau = \frac{\mathbf{b}\cdot\hat{\mathbf{r}}}{c}$ geometric delay between antenna pairs
- *delay-transform*: Parsons & Backer (2009) localizes foreground emission in "delay" space
- compute $P(k_\perp, k_\parallel)$



$k_\perp \propto |\mathbf{b}|$, $k_\parallel \propto \tau$

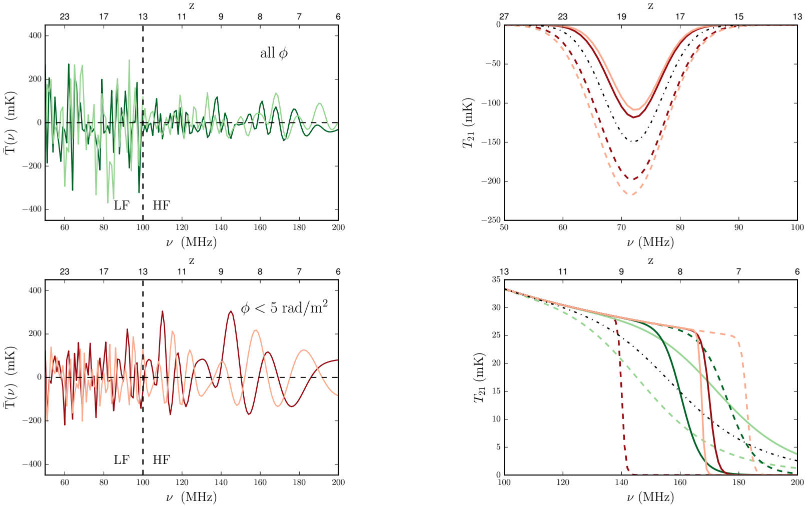
Formalism (and code) adapted from Nunhokee et al 2017

Looking for a clean window



Q,U and leaked I at $z = 8.5$ for a 30 m baseline

Polarization leakage in Global Signal Analysis



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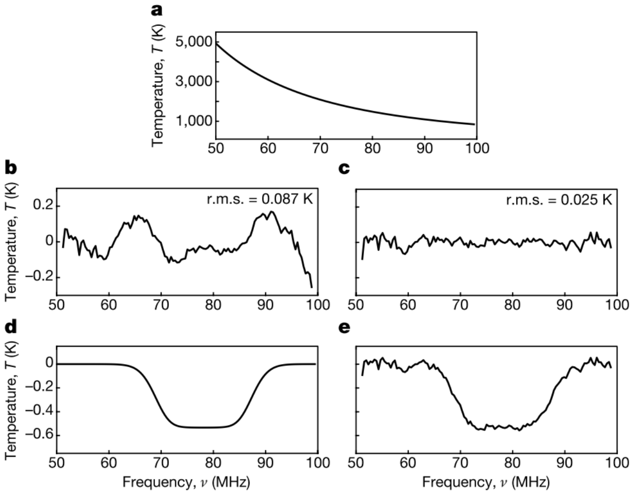
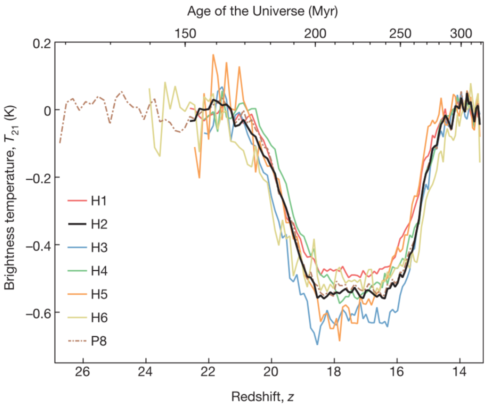
EDGES results I

Bowman et al. (2018)



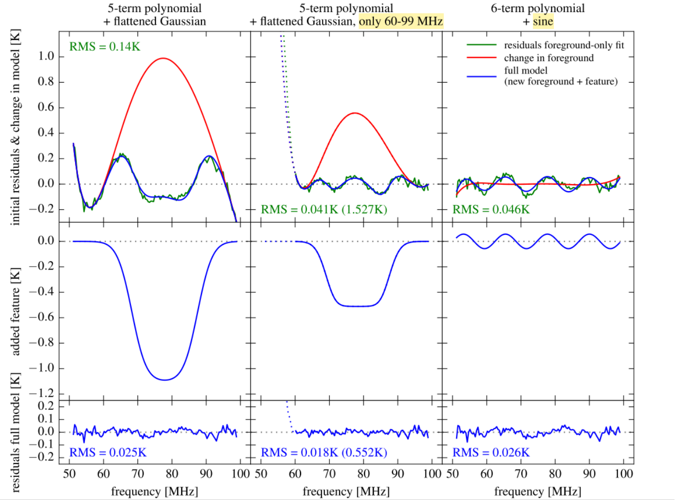
EDGES results II

Bowman et al. (2018)



(Some of the) EDGES criticism

Hills et al. (2018)



Rotation Measure (RM) synthesis

Bretjens& Bruyn (2005) Heald, Brown & Edmonds (2009)

Use Fourier relation between polarised surface brightness (P) and surface brightness per unit of Faraday depth (F)

$$P(\lambda^2) = \int_{-\infty}^{+\infty} F(\psi) e^{i2\psi\lambda^2} d\psi$$

Inverting this formula:

- only positive λ have physical meaning
- incomplete sampling in λ^2

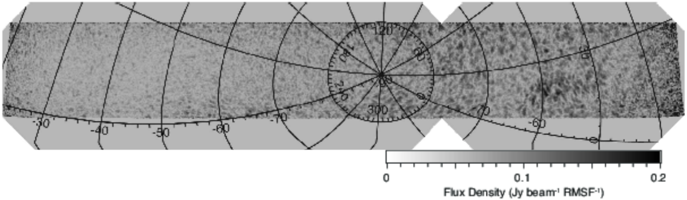
Need to define a RM transfer function (RMTF) that gives the resolution in Faraday depth:

$$\text{FWHM} \sim (\Delta\lambda^2)^{-1} \text{ total bandwidth}$$

lack of sensitivity to structures extended in Faraday depth

MWA data

G. Bernardi et al. 2013



- MWA 32 element 2400 degrees
- RM synthesis

cube of polarised images at selected faraday depth

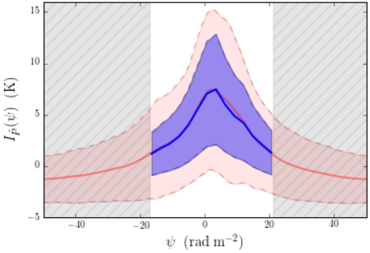
-50 < RM < +50 rad m^-2
in step of 1 rad m^-2
RMTF 4.3 rad m^-2

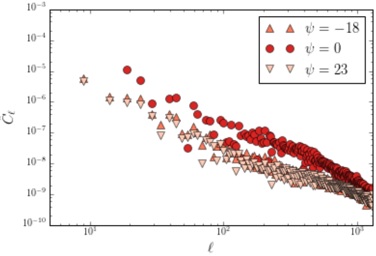
➡ describe MWA statistical behaviour and extend it to full-sky

- CONs: fine and local structures impossible to catch
- PROs: using genuine polarisation data instead of intensity

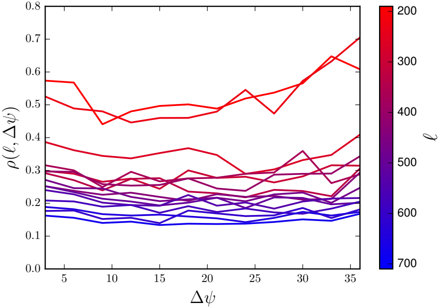
Characterization of MWA data

- At fixed ψ, the data can be approximated with a Rayleigh distribution $R(\sigma(\psi))$
- retain only maps with $S/N > 2$: the interval $-18 < \psi < +23$
- Power Spectrum reconstruction with HEALPIX (Gorski et al. 2005) and MASTER (Hivon et al. 2002)
- Fit a power law considering cosmic variance on large scale and noise on small scales (Tegmark 1997)





Mimicking the correlations



- Correlation decreses with ℓ
- No dependecy on $\Delta\psi$
- Residual correlation still present at high ℓ

In the simulations:

$$\vec{q}_{\ell m} = \frac{1}{\sqrt{2}} N(0, \Sigma_\ell) + \frac{i}{\sqrt{2}} N(0, \Sigma_\ell)$$

with

$$\Sigma_\ell^{ij} = \rho(\ell, \Delta\psi) (\ell^{\alpha(\psi_i) + \alpha(\psi_j)})^{1/2}$$

- $N_\psi \times N_\psi$ matrix $\forall \ell$
- the model reproduce the data well for $\ell > 200$.
- At lower ℓ more complex situation (demasking?)

A model for the beam

$$A(\nu,\theta,\phi) = \sqrt{[p_E(\nu,\theta)cos\phi]^2 + [p_H(\nu,\theta)sin\phi]^2}$$

Taylor et al. (2012), Ellingson et al. (2013), Dowell (2011)

$$p_i(\nu,\theta) = [1-(\frac{\theta}{\pi/2})^{\alpha_i(\nu)}](cos\theta)^{\beta_i(\nu)} + \gamma_i(\nu)(\frac{\theta}{\pi/2})(cos\theta)^{\gamma_i(\nu)}$$