On the contamination of the global 21 cm signal from polarized foregrounds

Marta Spinelli
in collaboration with G. Bernardi and M.G Santos

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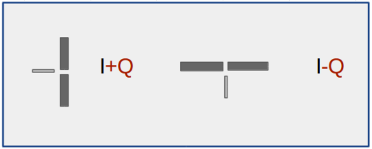
Prelude

Single-polarization antenna: inevitably measures polarized emission from the sky



- Q maps: diffuse polarized synchrotron
  Spinelli, Bernardi, Santos MNRAS 479, 275–283 (2018)

Study the bias in the analysis that could come from this contamination in two bands:

- Low Frequency (LF): 50-100 MHz
- High Frequency (HF): 100-200 MHz

Spinelli, Bernardi, Santos MNRAS 489,(2019)

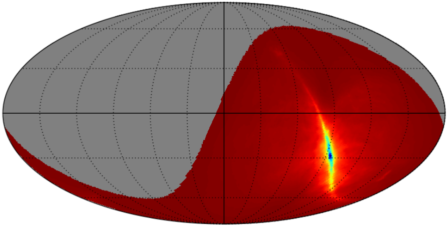
Caveat:

limited validity of the assumptions of our model

Mimicking global signal observations

$$T(\hat{\boldsymbol{r}}_0,\nu,t) = \frac{\int_\Omega A(\hat{\boldsymbol{r}}',\nu)\,T_{\text{sky}}(\hat{\boldsymbol{r}}',\nu,t)\,d\hat{\boldsymbol{r}}'}{\int_\Omega A(\hat{\boldsymbol{r}}',\nu)\,d\hat{\boldsymbol{r}}'} + T_N(\nu,t)$$

- $\hat{\boldsymbol{r}}_0$: EDGES location
- Frequency resolution: 1 MHz
- Data taking: $0 < \text{LST} < 8$ every 10 mins
- Gaussian noise with *std* considering 400 h integration time
- Need a beam model $A(\hat{\boldsymbol{r}},\nu)$



$$T_{\text{sky}} = T_{\text{foregrounds}} + T_{\text{signal}}$$

Mimicking global signal observations

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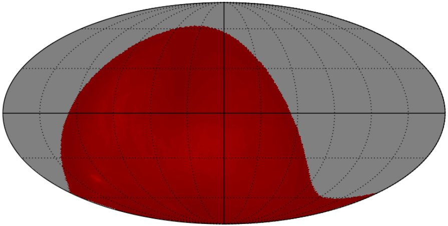


$$T_{\rm sky} = T_{\rm foregrounds} + T_{\rm signal}$$

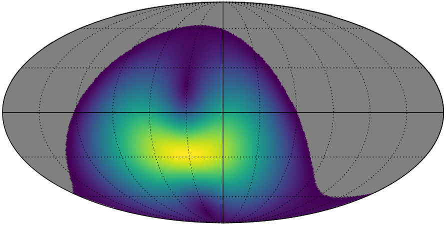
A model for the beam

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

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

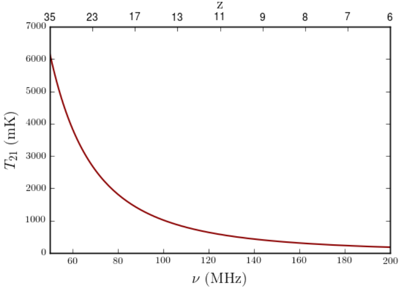
$$p_i(\nu,\theta) = [1-(\frac{\theta}{\pi/2})^{\alpha_i(\nu)}](cos\theta)^{\beta_i(\nu)} + \gamma_i(\nu)(\frac{\theta}{\pi/2})(cos\theta)^{\gamma_i(\nu)}$$

- α, β, γ, δ interpolated from Dowell (2011) measurements and extrapolated up to 100 MHz
- From 100 MHz to 200 MHz we use a simple scaling of the 100 MHz beam



A simple sky model

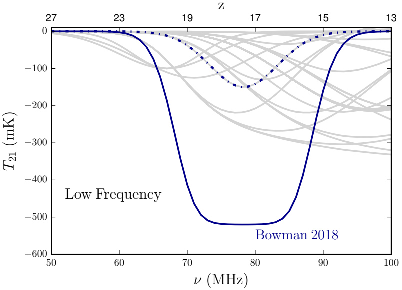
$$T_{\text{sky}} = T_{\text{foregrounds}} + T_{\text{21signal}}$$

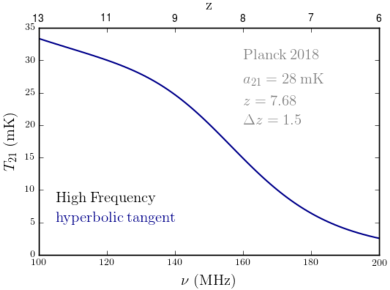


The **unpolarized** foreground contamination is modeled with a 5-term log polynomial

Bernardi et al. 2015

Main component: synchrotron





Synchrotron generalities

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

$$P = \Pi_0 I e^{2i\phi} \text{ with } \phi = \phi_0 + \psi\lambda^2 \text{ faraday rotation}$$

given by $B_\parallel$ and the presence of *thermal electrons*

$$\psi \propto \int_{\mathrm{LOS}} n_e B_\parallel dr$$

At low frequencies P simulations are difficult:

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

Polarization simulations

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)

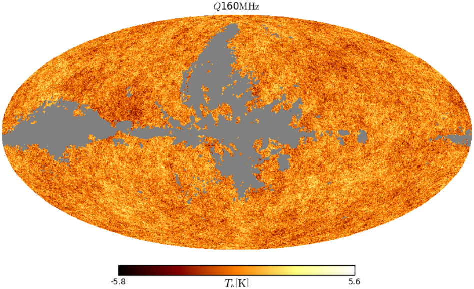
- transform back to frequency space using the Fourier relation between ψ and λ^2

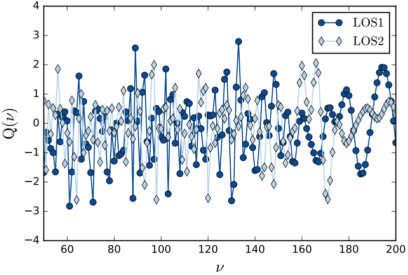
$$Q(\lambda^2, \hat{\mathbf{n}}) = \int \tilde{Q}(\psi, \hat{\mathbf{n}}) e^{2\pi \lambda^2 \psi} d\psi$$

Polarization simulations

- code on GitHub: CRCosmo/PolSynch
- spatial structure statistically reproducing the data (extrapolated to larger scales)
- no ionosphere
- a *worst case* scenario for depolarization (MWA @189 MHz)

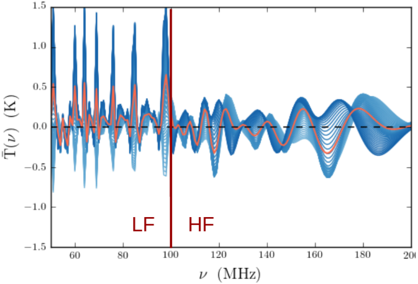
Faraday structure
⇒ Complex frequency behavior



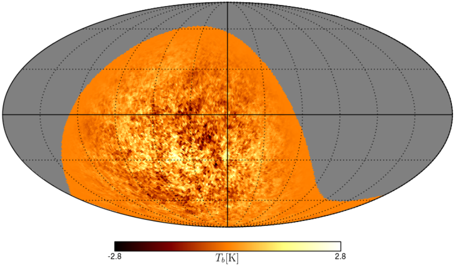


Polarization spectra: $T_Q(\nu)$

$\forall f$, $\forall t$ we integrate the visible polarized sky seen through the beam



Average over time get a mean polarized spectra

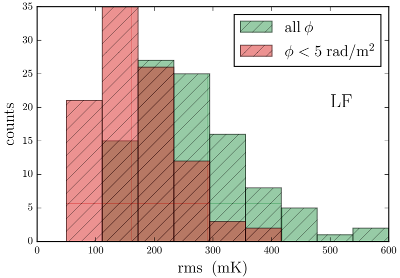


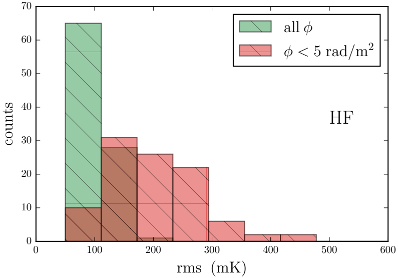
2 sets of 100 simulations:

- the full Faraday structure (all-ϕ)
- only small ϕ values ($\phi < 5\mathrm{rad/m^2}$)

Contamination

∀ realization of the simulations we evaluate the *rms* of the resulting polarized spectrum

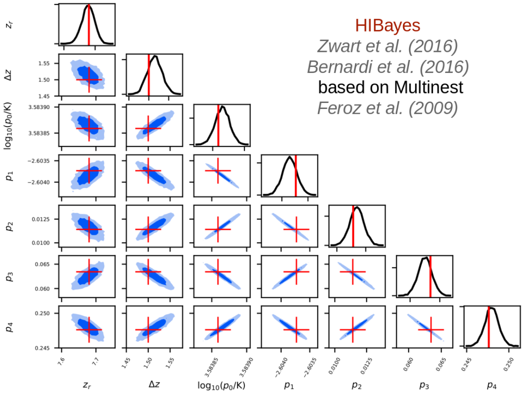




- all-ϕ peaks at 250 mK with a long tail to higher values
- less contamination for the case $\phi < 5\text{rad/m}^2$

- opposite situation for the high frequency case

Extracting the signal



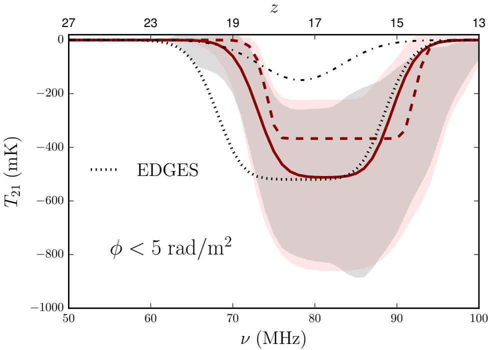
HIBayes
Zwart et al. (2016)
Bernardi et al. (2016)
based on Multinest
Feroz et al. (2009)

- Gaussian likelihood with flat priors
- Consistency check: no contamination case is unbiased (for both LF and HF case)
- Foreground fitting model: 5-term log polynomial
- Signal fitting model as in input (LF: Gaussian, EDGES HF: hyperbolic tangent)

What is the impact on the reconstructed signal if there is a polarized component that is not modeled?

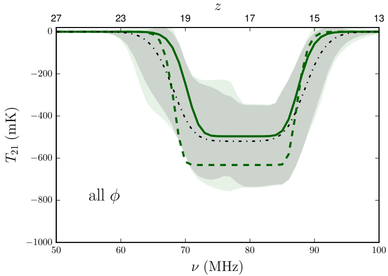
Low frequency: Gaussian-like case

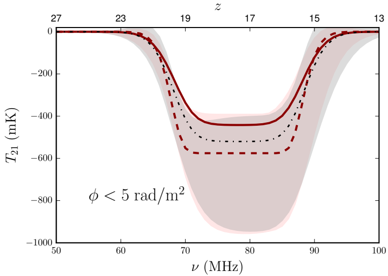
- all-ϕ contamination prevents proper reconstruction of fiducial signal
- extraction possible for the $\phi < 5\text{rad/m}^2$ case
- polarization contamination introduce a bias
- tension at the $\sim 1.5\sigma$ level only



Low frequency: EDGES-like case

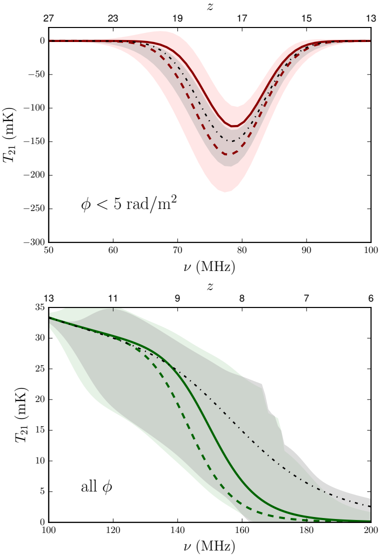
- **flattened Gaussian** profile as both input and output
- amplitude bias at the $\sim 20 - 30\%$ level that changes with the polarization orientation (qualitatively comparable with Fig. 2 of Bowman et al. 2018)
- enhanced signal may mitigate the need for exotic physics





Reducing the contamination

- full contamination prevents the extraction of the 21 cm *standard* signal both in HF and LF band.
- 10% **Q** (rms $\lesssim$ EDGES and mimic subtraction of the two orthogonal polarizations)
- LF band: amplitude bias
- HF band: z_r biased up to the 10%, Δz underestimated



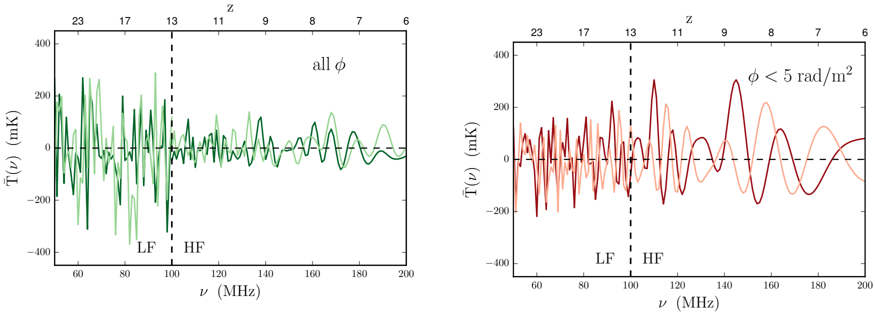
Conclusions

- we have investigated the impact of a (unaccounted for) polarized sky component in global-signal analysis for EoR and Cosmic Dawn
- we used full-sky polarized synchrotron simulations based on MWA data covering the $50 - 200$ MHz band
- we tested different scenarios:

  1. our contamination is too pessimistic to reconstruct *standard* models (for both LF and HF). Reduced to 10% still gives biased results
  2. an enhanced absorption signal could appear if fitting a flattened Gaussian in presence of polarization (only weak tension)
  3. assuming the EDGES signal, polarization can still bias the reconstruction

Backup

Spectra


z
23
17
13
11
9
8
7
6
400
200
0
−200
−400
$\bar{T}(\nu)$ (mK)
all ϕ
LF
HF
60
80
100
120
140
160
180
200
ν (MHz)
$\phi < 5$ rad/m^2

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

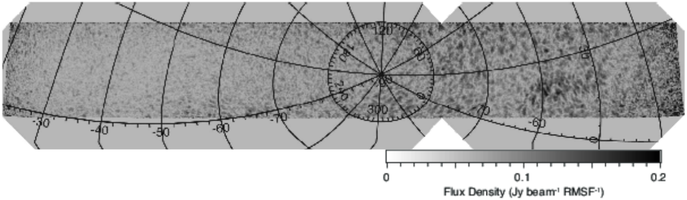
Need to define a RM transfer function (RMTF) that gives the resolution in Faraday depth:

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

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

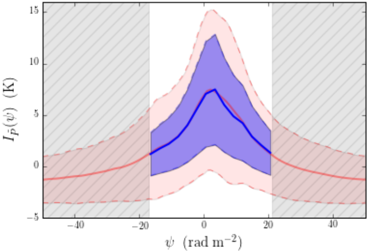
-50 < RM < +50 rad m^-2
in step of 1 rad m^-2
RMTF 4.3 rad m^-2

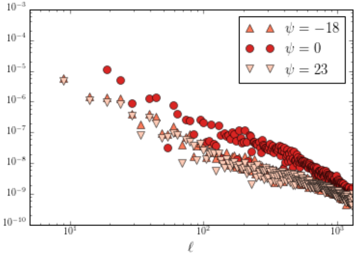
→ describe MWA statistical behaviour and extend it to full-sky

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

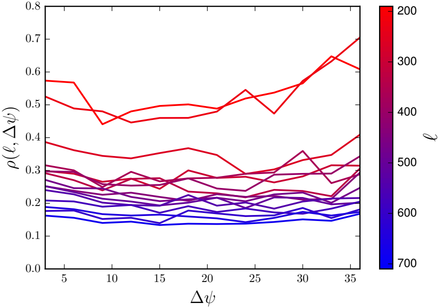
Characterization of MWA data

- 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

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

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