Using Dynamic Polarization as Leverage to Extract the Global Signal

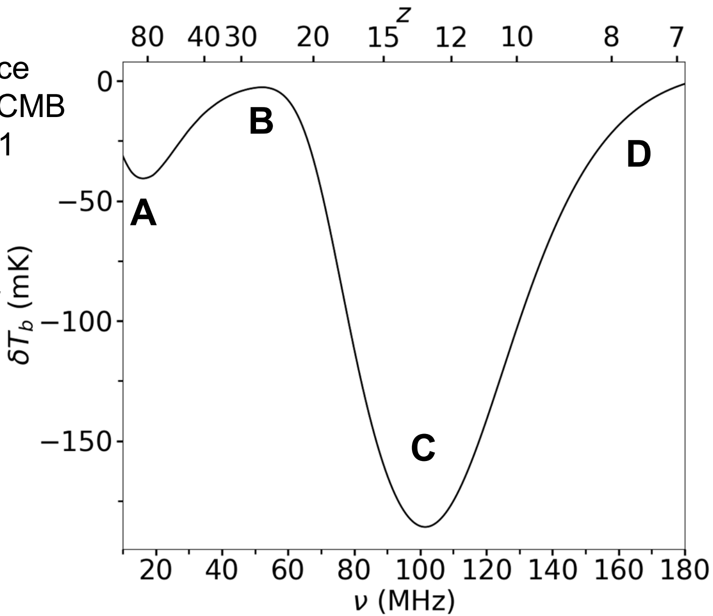
Keith Tauscher

University of Colorado Boulder

Why do we pursue the global 21-cm signal?

- Interaction of excitation temperature, TS, of HI's 21-cm transition with radiation fields produces signal which opens up the first billion years after recombination to new inquiry

Difference between TCMB and T21



A: Collisions between H atoms no longer relevant to TS because CMB temperature exceeds kinetic temperature of H gas

B: First stars ignite, coupling TS to the strength of their Lyman-α radiation

C: First black holes begin accretion, heating gas to warmer than the CMB

D: Reionization drives signal to zero since only neutral hydrogen emits 21-cm radiation

Signals generated with Jordan Mirocha's Accelerated Reionization Era Simulations (ares) code available at https://bitbucket.org/mirochaj/ares

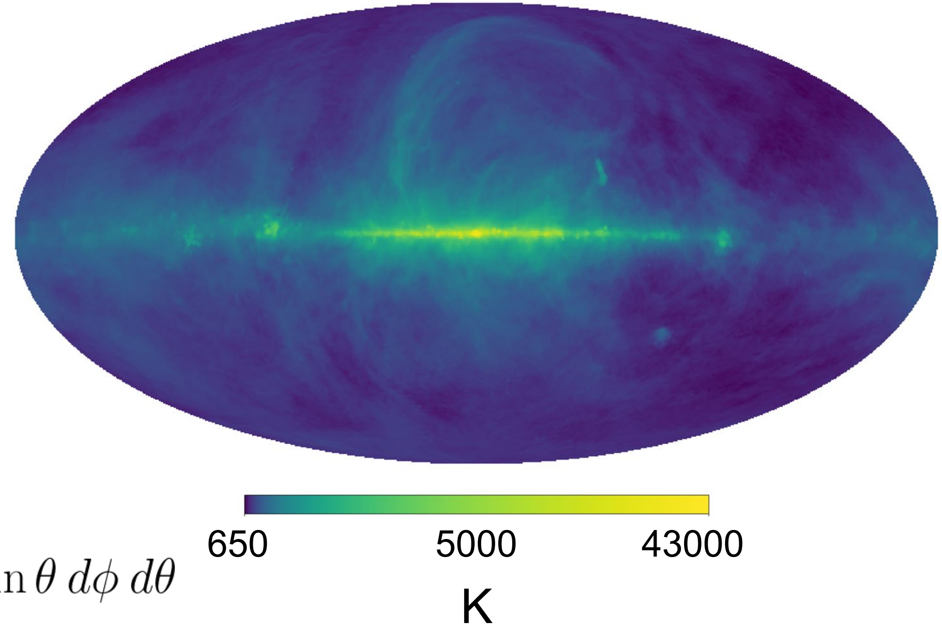
Difficulty of measuring 21-cm signal

- Strong galactic foregrounds combine with antenna beam chromaticity to produce complicated spectral structure.
- Foregrounds have steep spectra with spectral index of -2.5, i.e.

$$T_{\rm FG}(\nu,\theta,\phi) \approx A(\theta,\phi) \times \nu^{-2.5}$$

$$T_{\rm BWFG}(\nu) = \int_0^{\pi}\int_0^{2\pi} B(\nu,\theta,\phi)\, T_{\rm FG}(\nu,\theta,\phi)\, \sin\theta\, d\phi\, d\theta$$

Galaxy map from Haslam et al. (1982) scaled to 80 MHz



Haslam, C. G. T., Salter, C. J., Stoffel, H., & Wilson, W. E. 1982, A&AS, 47, 1

Traditional approach to measurement

- Experiments such as EDGES attempt to calibrate out beam chromaticity from single spectra and then fitting a polynomial or polynomial-like model simultaneously with a chosen signal model.
- The beam corrections rely on the temperature of the sky model and the simulation of the beam model being correct.

$$BCF(\nu) = \frac{\int_0^{\pi} \int_0^{2\pi} B(\nu, \theta, \phi)\; T_{\rm FG}(\nu, \theta, \phi)\; \sin\theta\; d\phi\; d\theta}{\int_0^{\pi} \int_0^{2\pi} B(\nu_n, \theta, \phi)\; T_{\rm FG}(\nu, \theta, \phi)\; \sin\theta\; d\phi\; d\theta}$$

Beam chromaticity factor

Model of beam weighted foreground

$$M_{\rm BWFG}(\nu) = \sum_{k=0}^{N-1} a_k\; \nu^{-2.5+k}$$

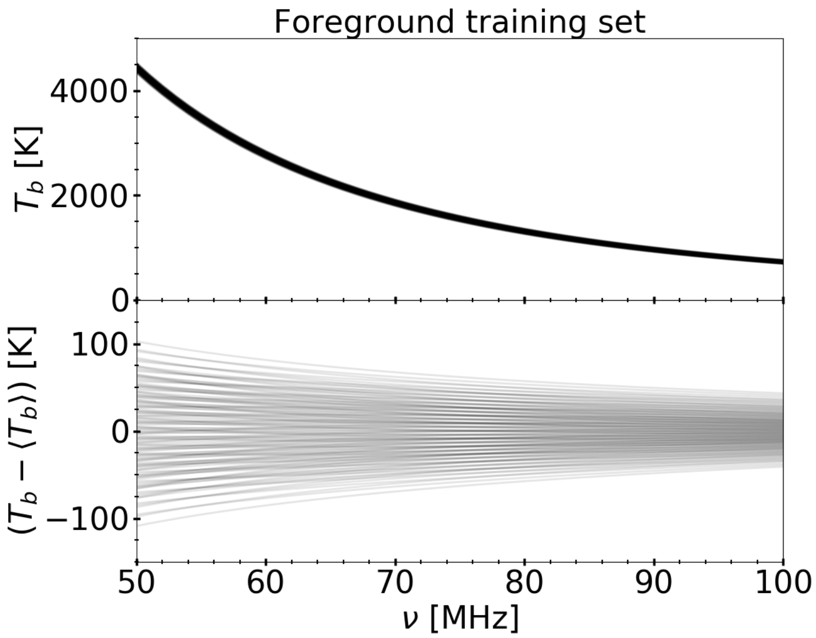
Monsalve, R.A., Rogers, A.E.E., Bowman, J.D., Mozdzen, T.J., 2017, ApJ, 847, 64

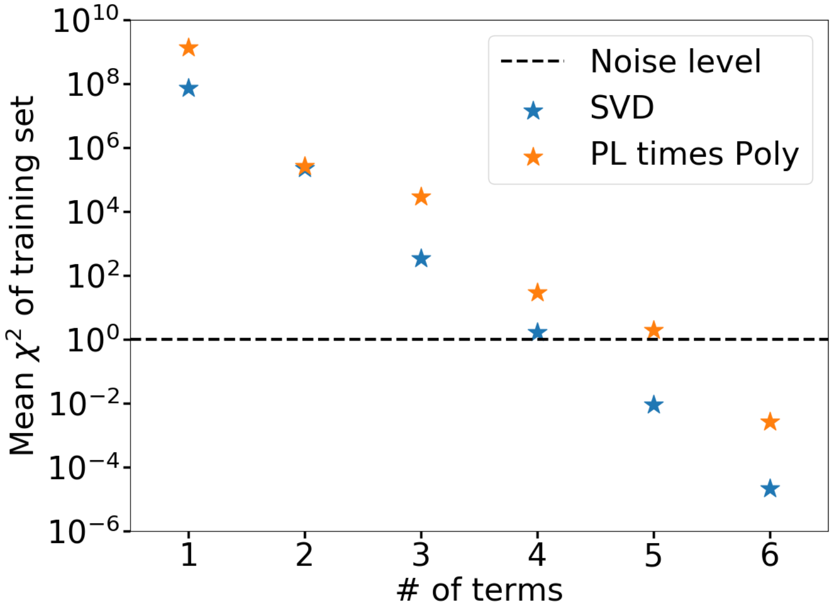
Our new method, SVD/MCMC

- We have developed a technique to analyze many spectra at once.
  - The information relating different spectra (such as different foregrounds caused by looking in a different direction) can help extract the signal, which doesn't change from spectrum to spectrum, more rigorously.
- By simulating training sets for these sets of spectra, we can create models specifically suited for that dataset, instead of relying on an a priori model.
- We also use training sets of the signal derived from physical simulations.

Using SVD to generate optimal basis vectors

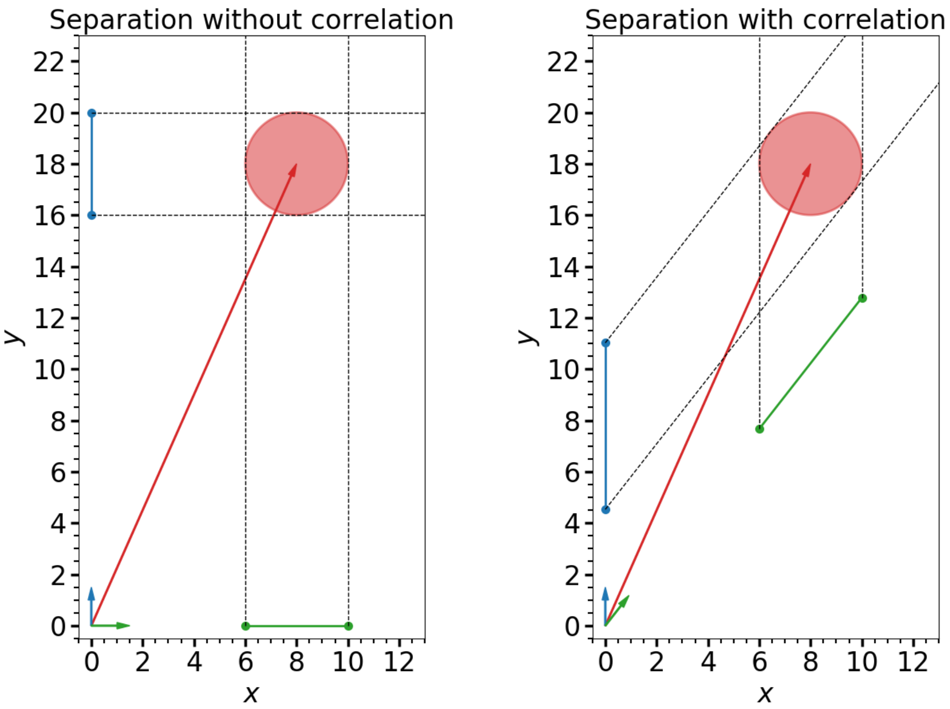
- Singular Value Decomposition (SVD) is a factorization of the training set that provides the optimal basis vectors with which to fit that training set.





Simultaneously fitting foreground and signal

- Once we have SVD models for both foreground and signal, we fit them simultaneously to the data.
- The uncertainties in this separation of the two components depend on how similar their models are.
    - **If the foreground and signal training sets are different enough and the experiment is designed well enough, then the signal can be constrained rigorously.**



Drift-scan measurements

- One example of experimental design that can lower the overlap/similarity between foreground and signal is drift-scan.

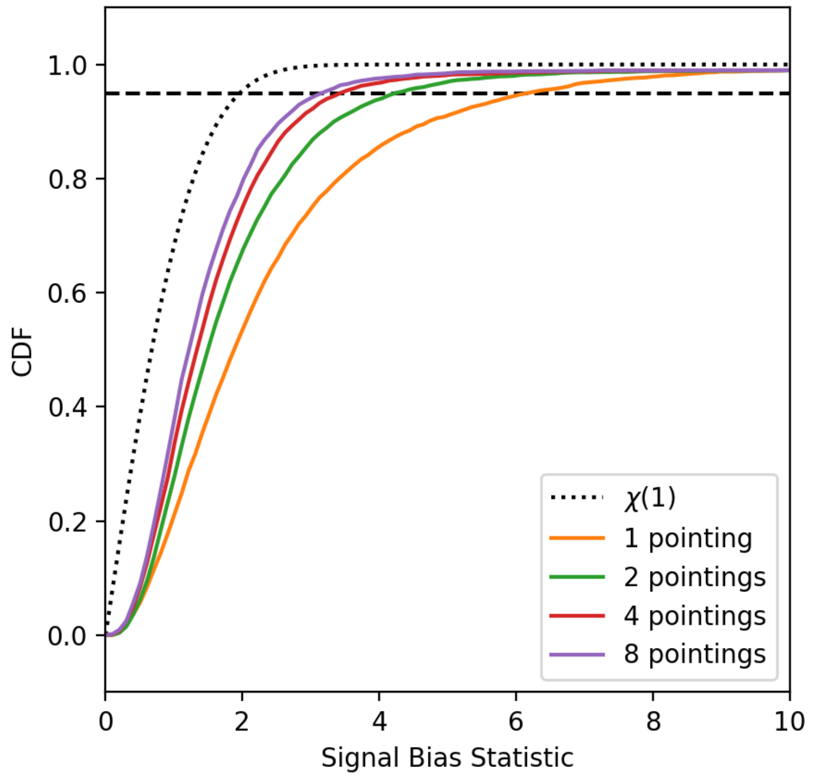
- Time introduces valuable structure into sky-averaged data because the antenna beam points at different points in the sky at different times.

- This leads to multiple spectra with the same signal but different foregrounds.

Effect of multiple pointings

- Looking at multiple independent directions is a discrete form of drift-scan.

- The forecasted errors are smaller and the signals are less biased when simulating data with multiple antenna pointings instead of one.



Other benefits of SVD/MCMC generalization

- Since our pipeline does not require a foreground model to be given beforehand (only training sets), data aspects with no obvious extension in the polynomial-like approach can be utilized.
- One of these effects is polarization, which is measured in terms of the Stokes parameters I, Q, U, and V.

Single antenna experiments (e.g. EDGES, SARAS)

$$I = \langle |E_X|^2 + |E_Y|^2 \rangle$$

$$Q = \langle |E_X|^2 - |E_Y|^2 \rangle$$

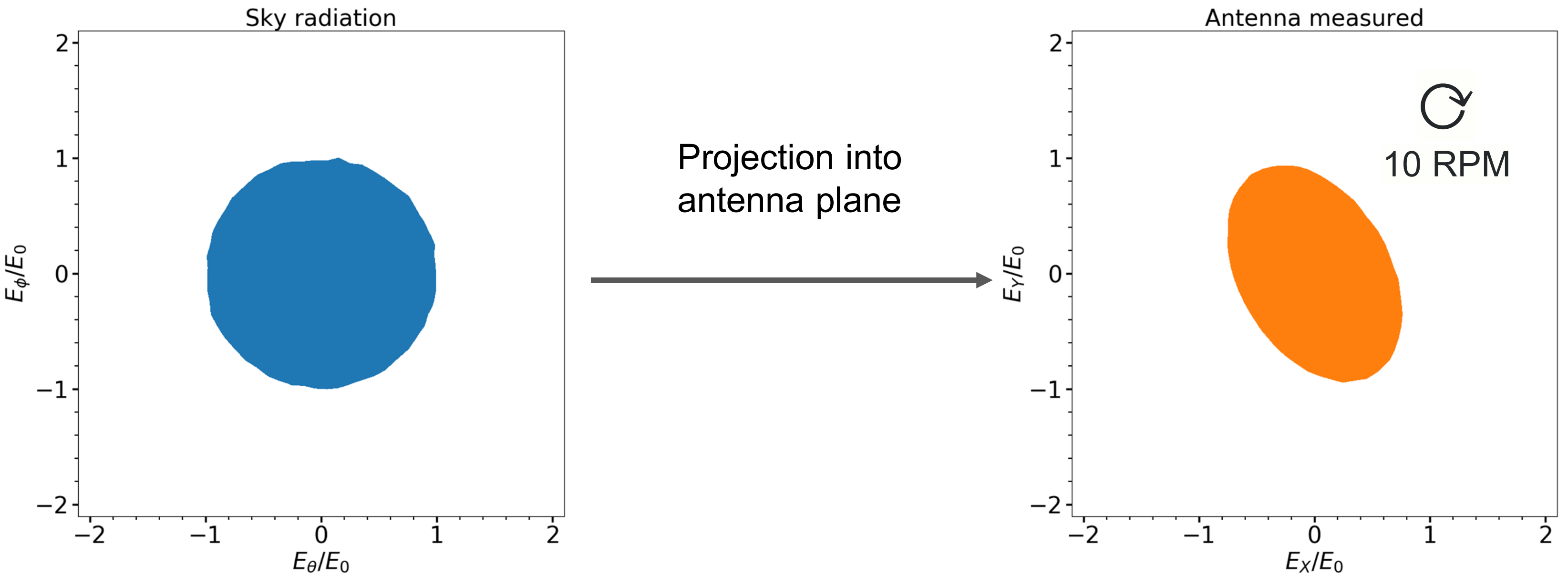
$$U = 2\,\mathrm{Re}(E_X^* E_Y)$$

$$V = 2\,\mathrm{Im}(E_X^* E_Y)$$

Dual antenna experiments (e.g. DAPPER, CTP)

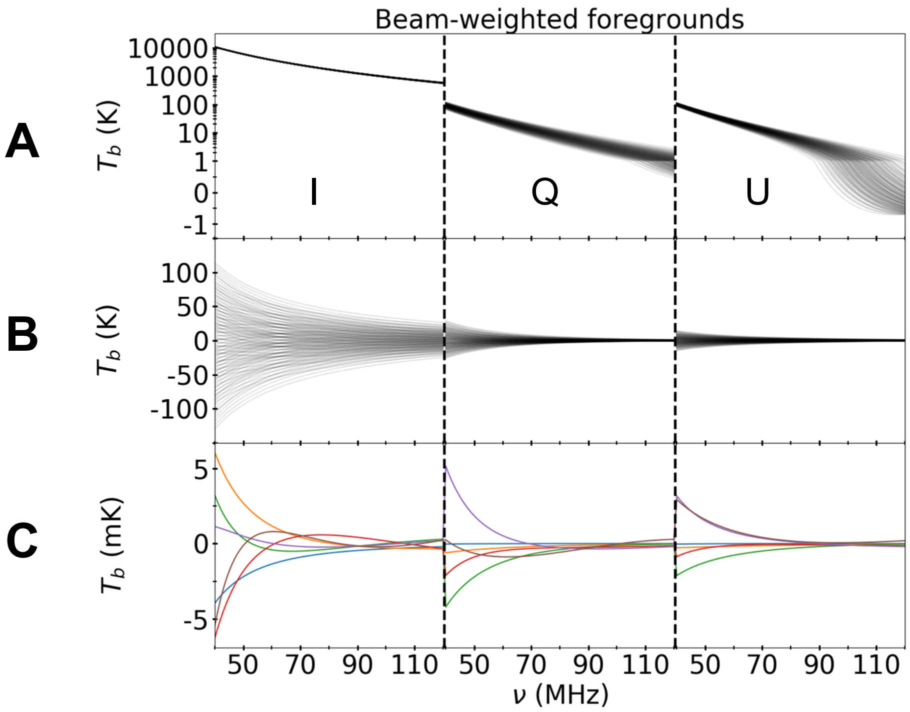
Induced polarization

- Projection onto the instrument's antennas induces a polarization signal measured by dual antenna instruments, which can help constrain foreground.



SVD takes advantage of structure

- SVD naturally provides a model which accounts for connections between Stokes parameters

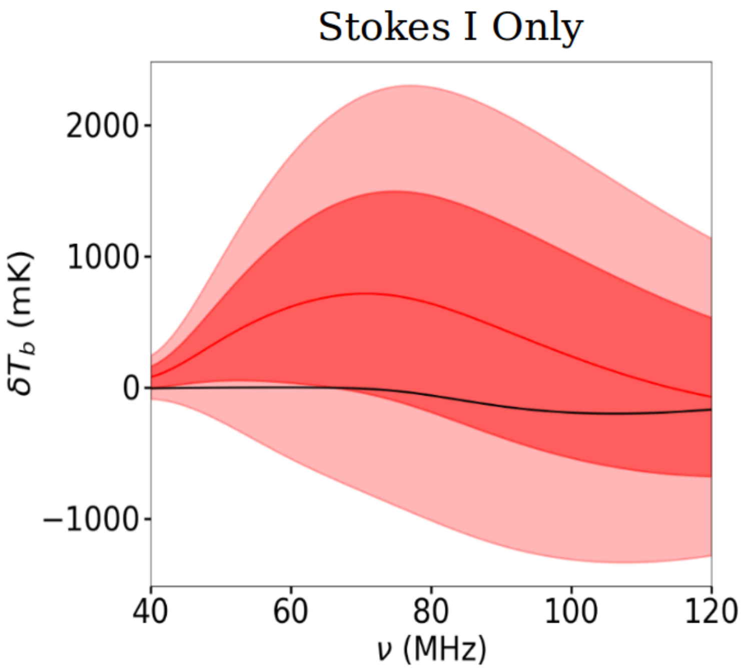


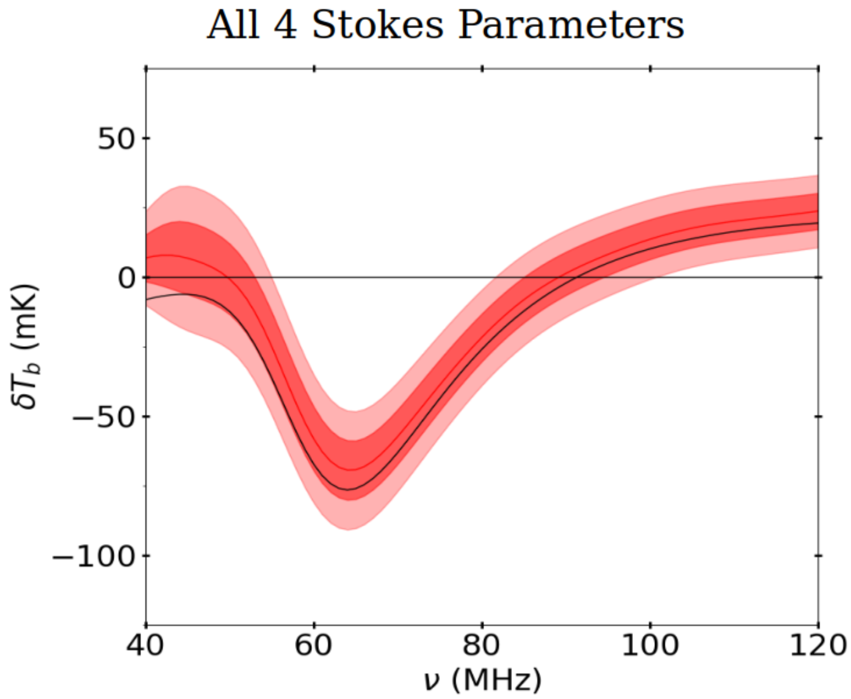
A: Training set of Stokes parameters accounting for induced polarization.

B: Training set with average subtracted

C: Optimal basis vectors to fit training set, provided SVD

Effects of induced polarization data on constraints

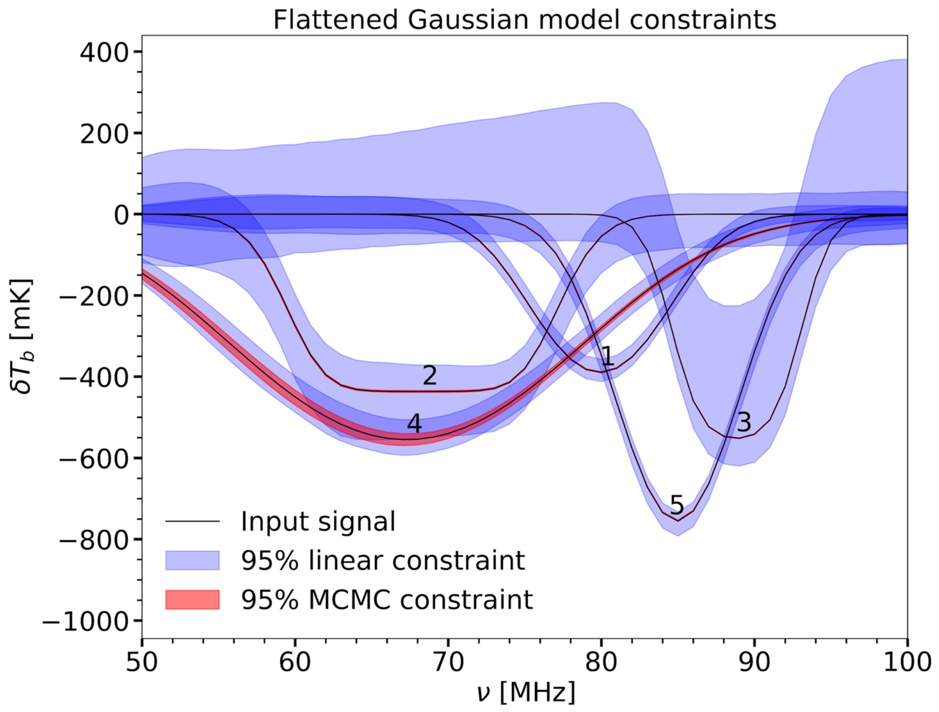




Note the large scale difference between the plots.

Results with signal model from EDGES paper

- When using a training set of flattened Gaussian models defined as in EDGES Nature paper (Bowman et al. 2018), we obtain the confidence intervals on the right.
- These simulations include both induced polarization and multiple antenna pointings.



Summary and ongoing work

- We have been developing a pipeline for extracting the 21-cm global signal from sky-averaged spectral data.
- Our training set based pipeline allows any effect that can be simulated to be included in the analysis.
- In our simulations, we include multiple antenna pointing directions (precursor to drift-scan measurements) and Stokes parameters because they lower the overlap between foreground and signal, decreasing uncertainties.
- In the past year, we have for the first time completed the pipeline to extract physical parameters from our 21-cm signal constraints in frequency space (see David R.'s talk)