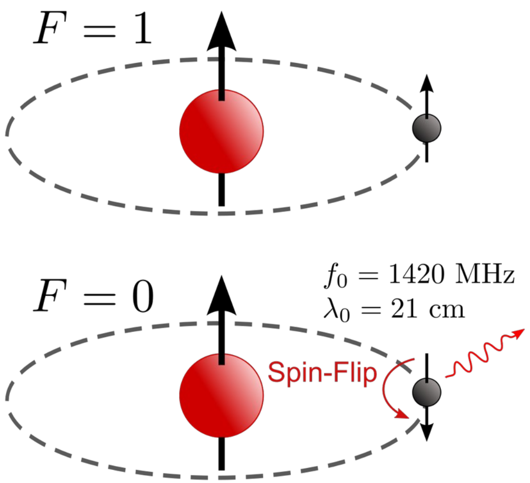
Using Bayesian data analysis to model systematics and inform experiment design in Global 21cm experiments

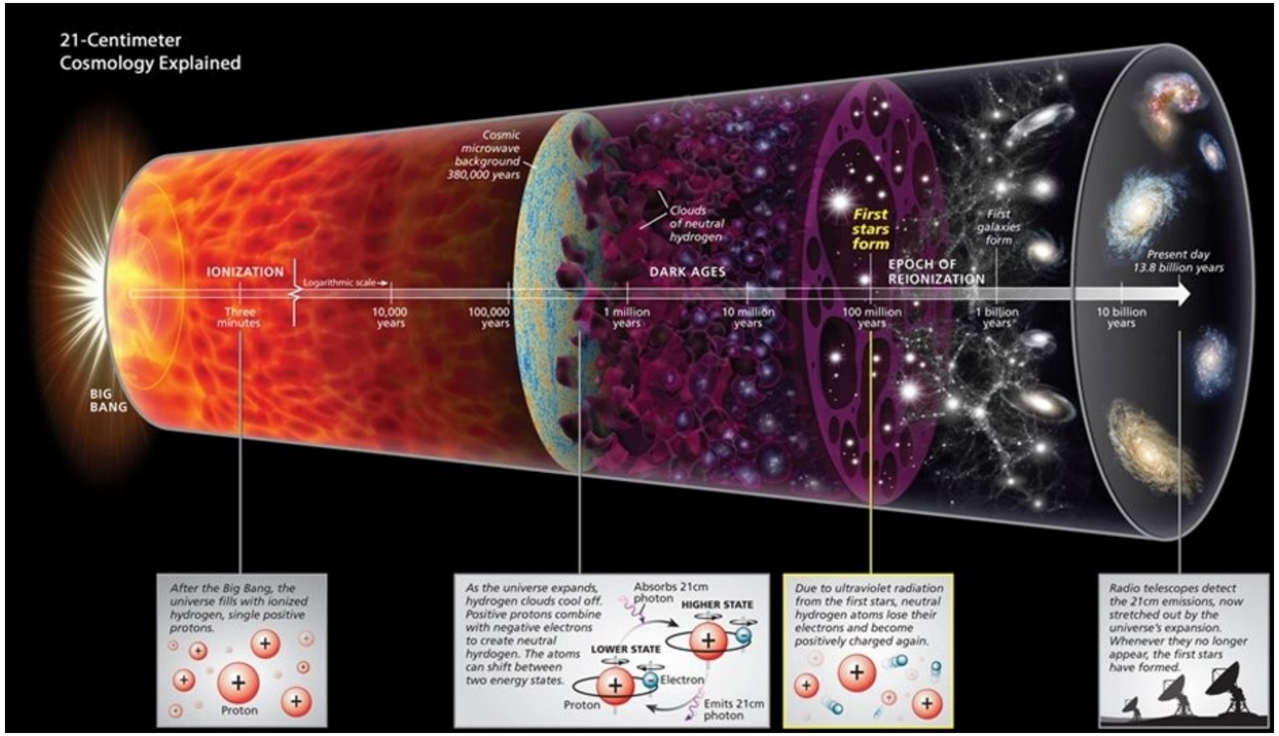
Dominic Anstey

On behalf of the REACH collaboration

Global 21cm Experiments



https://en.wikipedia.org/wiki/Hydrogen_line



Roen Kelly, Discover Magazine

Bayesian Data Analysis

$$\mathrm{P}\left(A|B\right) = \frac{\mathrm{P}\left(B|A\right)\mathrm{P}\left(A\right)}{\mathrm{P}\left(B\right)}$$

$$\mathrm{P}\left(\theta_{\mathcal{M}}|\mathcal{D},\mathcal{M}\right) = \frac{\mathrm{P}\left(\mathcal{D}|\theta_{\mathcal{M}},\mathcal{M}\right)\mathrm{P}\left(\theta_{\mathcal{M}}|\mathcal{M}\right)}{\mathrm{P}\left(\mathcal{D}|\mathcal{M}\right)}$$

$$\mathcal{P} = \frac{\mathcal{L}\pi}{\mathcal{Z}}$$

$$\mathrm{P}\left(\mathcal{M}|\mathcal{D}\right) = \frac{\mathrm{P}\left(\mathcal{D}|\mathcal{M}\right)\mathrm{P}\left(\mathcal{M}\right)}{\mathrm{P}\left(\mathcal{D}\right)} = \mathcal{Z}\frac{\mathrm{P}\left(\mathcal{M}\right)}{\mathrm{P}\left(\mathcal{D}\right)}$$

REACH

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Kavli Institute for Cosmology in Cambridge

The Kavli Foundation

Cavendish Astrophysics

Stellenbosch University

National Research Foundation South African Radio Astronomy Observatory

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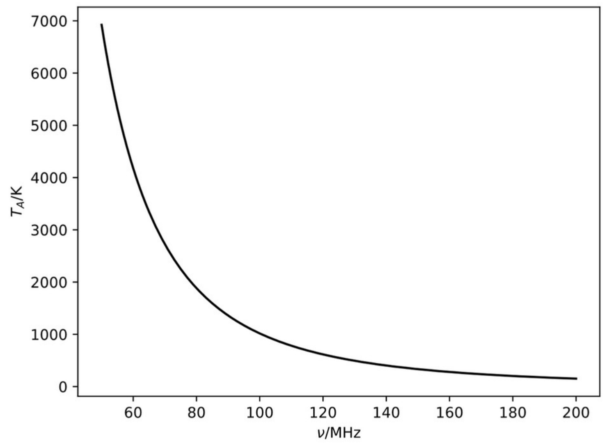
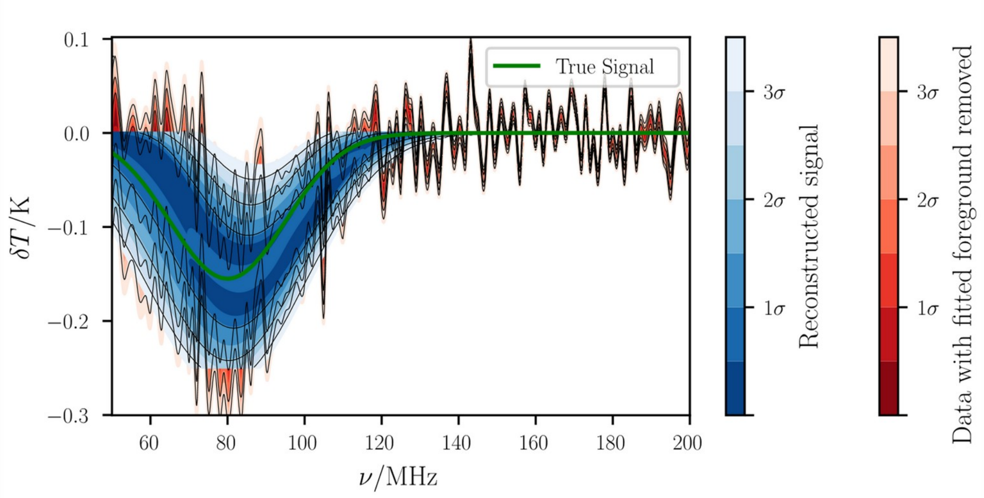
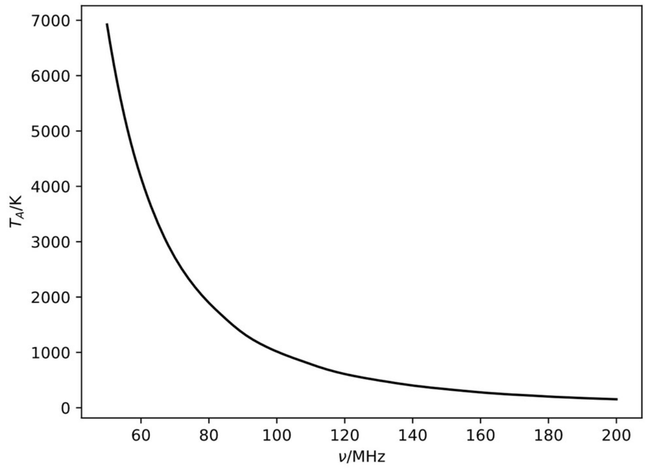
Radio Foregrounds and Chromaticity

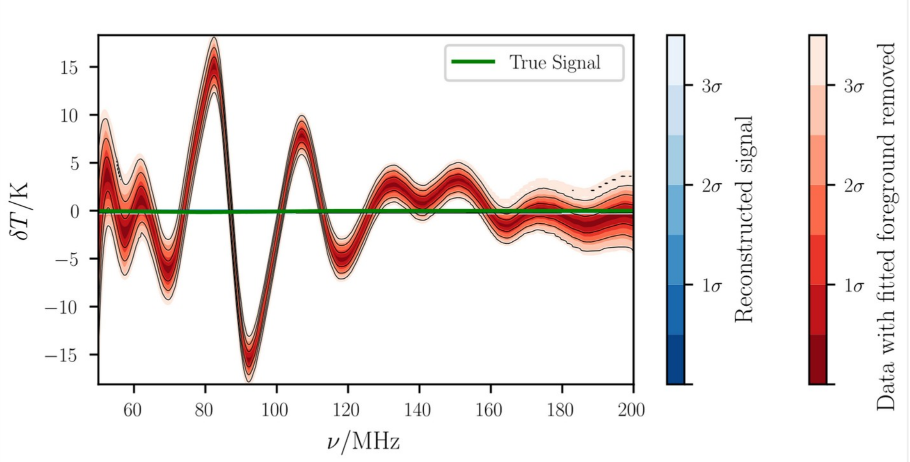
Achromatic antenna





Chromatic antenna





REACH Data Analysis Pipeline

- Generate a model of the sky radio emission based on physical parameters

$$T_{\mathrm{sky}}\left(\Omega, \nu, \theta_{\mathrm{F}}\right)$$

- Convolve this with a model of the antenna beam to produce a parameterised foreground model that includes chromatic distortions

$$T_{\mathrm{F}}\left(\nu, \theta_{\mathrm{F}}\right) = \frac{1}{4\pi} \int_0^{4\pi} D\left(\Omega, \nu\right) T_{\mathrm{sky}}\left(\Omega, \nu, \theta_{\mathrm{F}}\right) d\Omega$$

- Use this model in a Nested Sampling fit

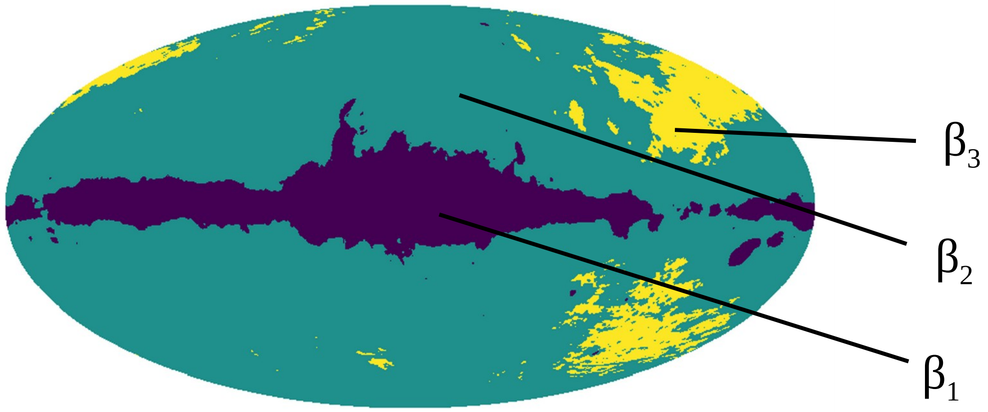
$$\log \mathcal{L} = \sum_i \left[-\frac{1}{2} \log\left(2\pi\theta_\sigma\right) - \frac{1}{2} \left(\frac{T_{\mathrm{data}}\left(\nu_i\right) - T_{\mathrm{F}}\left(\nu_i, \theta_{\mathrm{F}}\right) - T_{\mathrm{S}}\left(\nu_i, \theta_{\mathrm{S}}\right)}{\theta_\sigma} \right)^2 \right]$$

Anstey et al. 2021 (a), arXiv:2010.09644

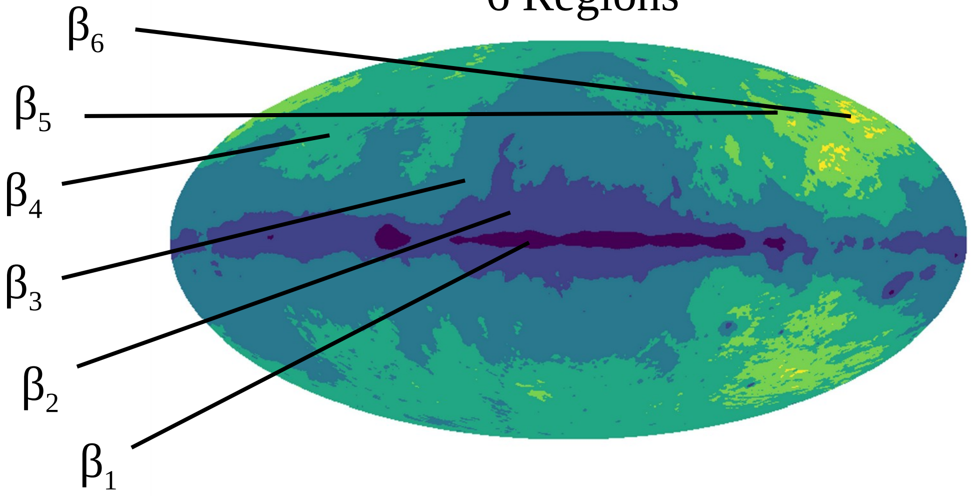
Parameterised Sky Modelling

Parameterise by spectral index

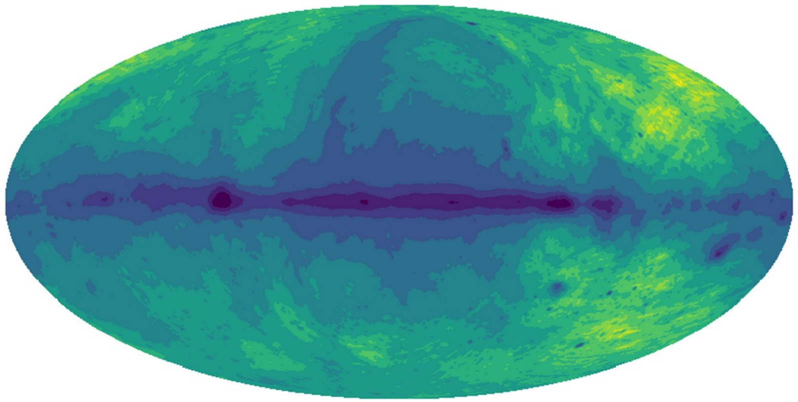
3 Regions



6 Regions



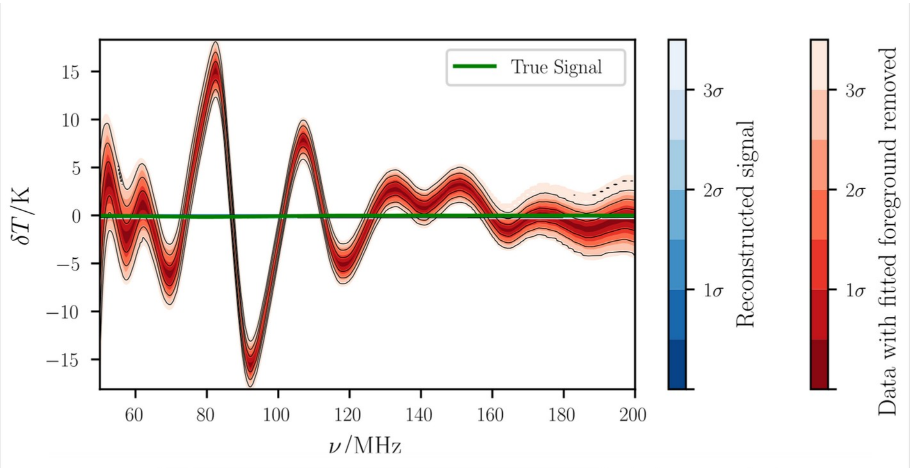
12 Regions

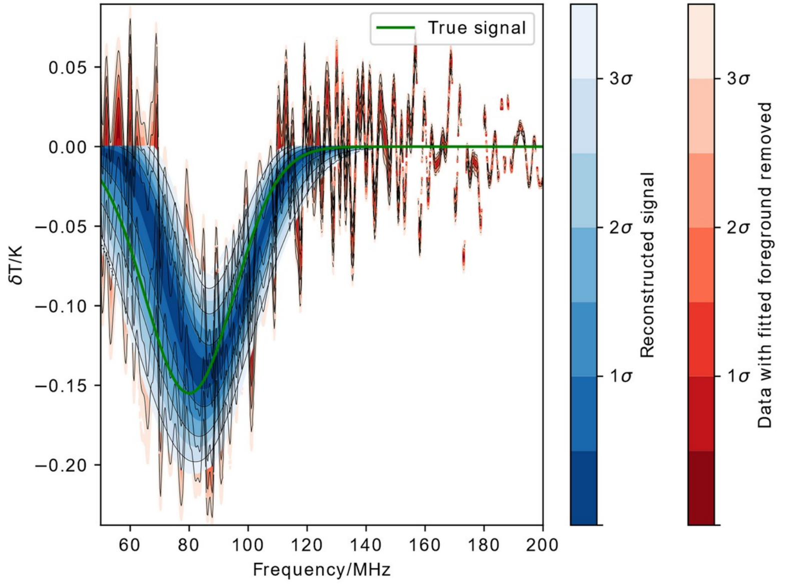


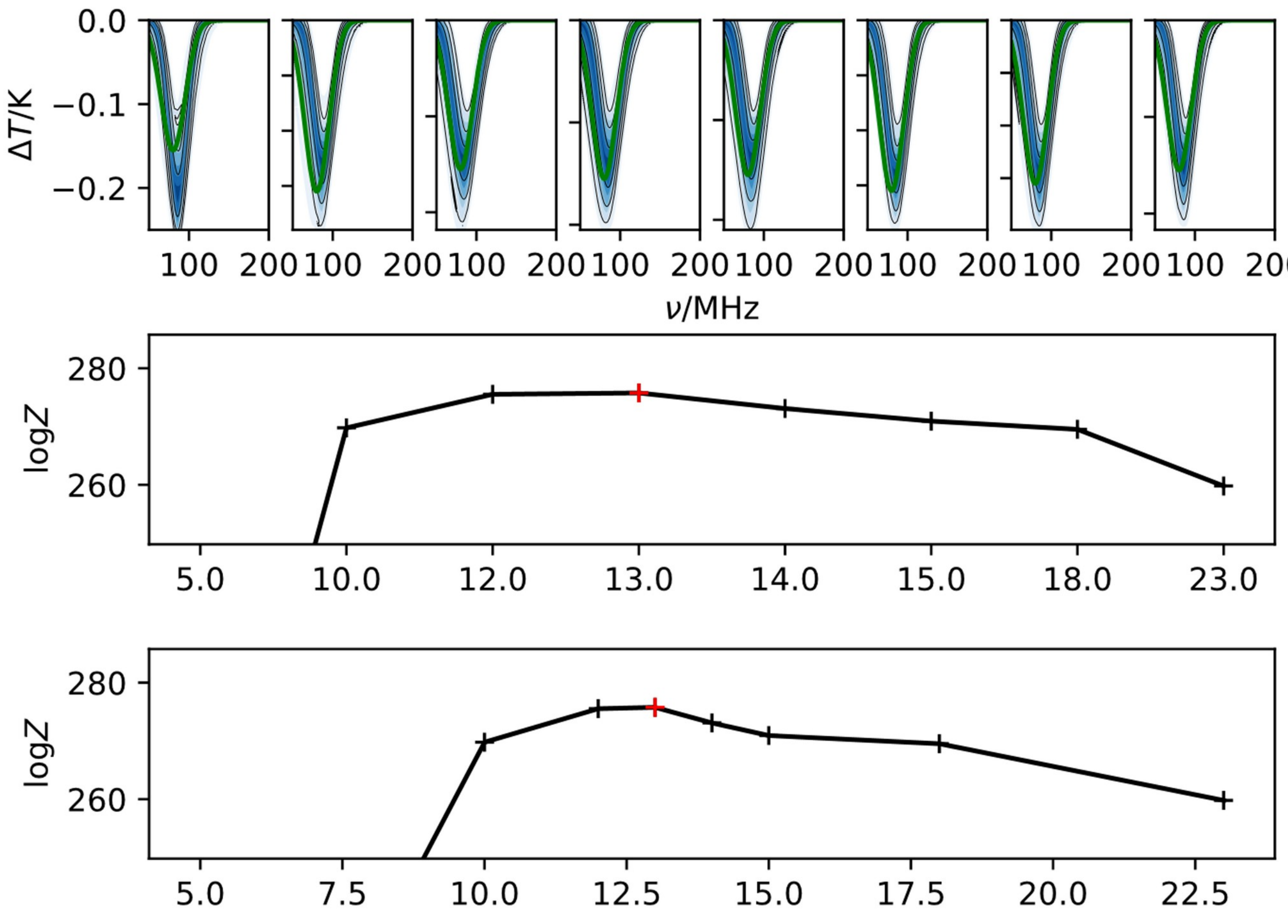
$$T_{\text{sky}}\left(\Omega,\nu\right)=\left[\sum_{n=1}^{N}M_{n}\left(\Omega\right)\left(T_{\text{base}}\left(\Omega\right)-T_{\text{CMB}}\right)\left(\frac{\nu}{\nu_{\text{base}}}\right)^{-\beta_{n}}\right]+T_{\text{CMB}}$$

Anstey et al. 2021 (a), arXiv:2010.09644

Performance



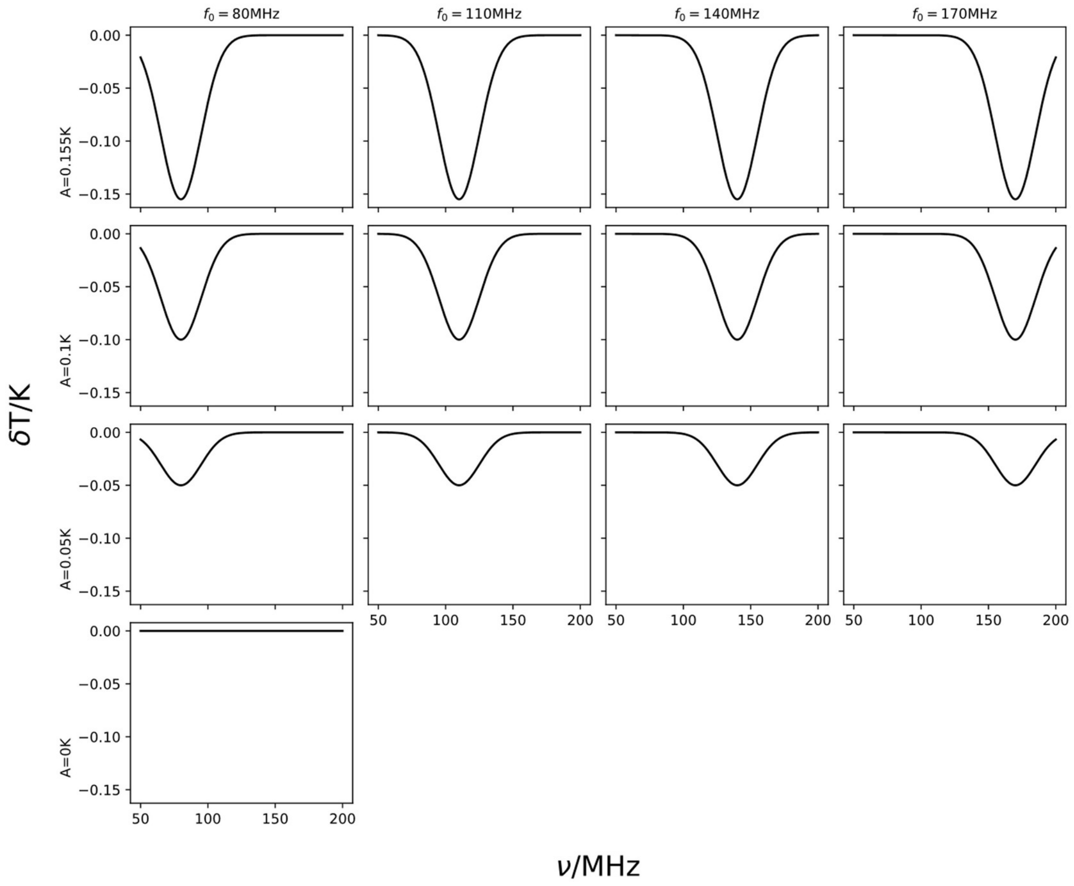




Informing Experiment Design

- Simulate observation data for a range of potential antenna designs
- Insert a range of mock 21cm signals into the data
- Attempt to recover each signal using the described pipeline

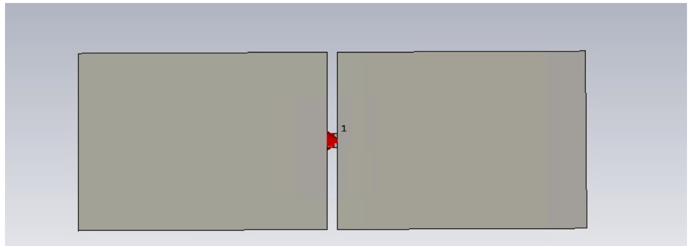
This allows the accuracy of each recovered signal to be quantified relative to the true signal. We can also quantify the statistical confidence with which the signal is detected.



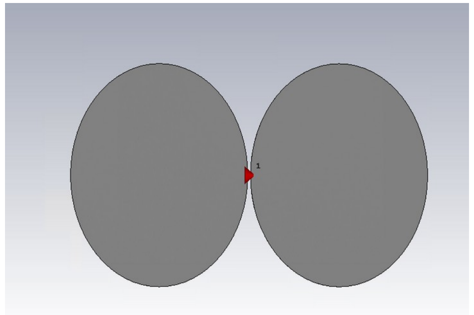
Anstey et al. 2021 (b), arXiv:2106.10193 (preprint)

Tested Antennae

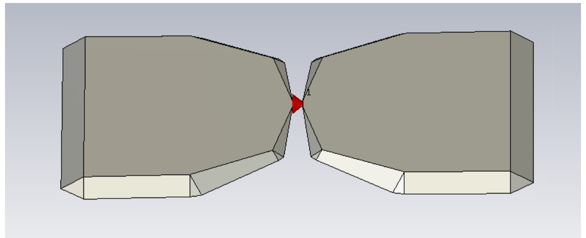
Dipoles:



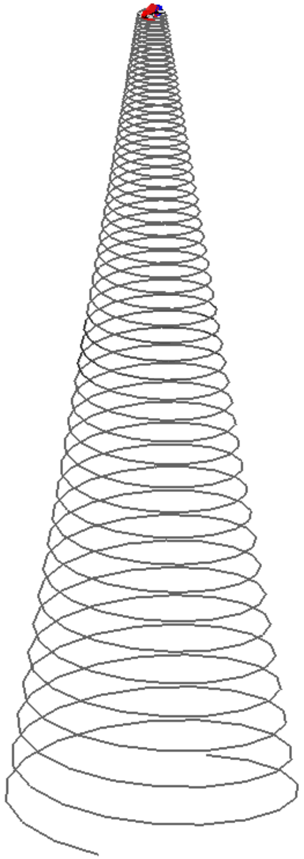
Rectangular



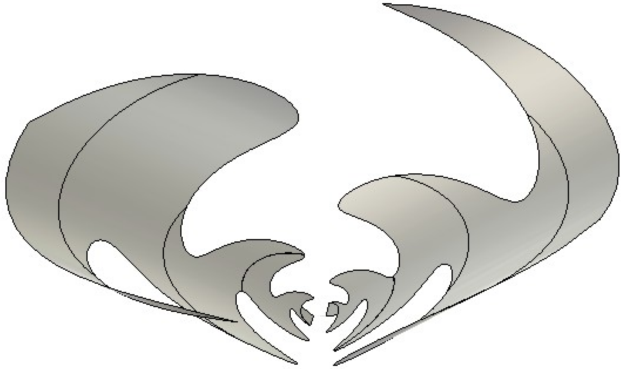
Elliptical



Polygonal



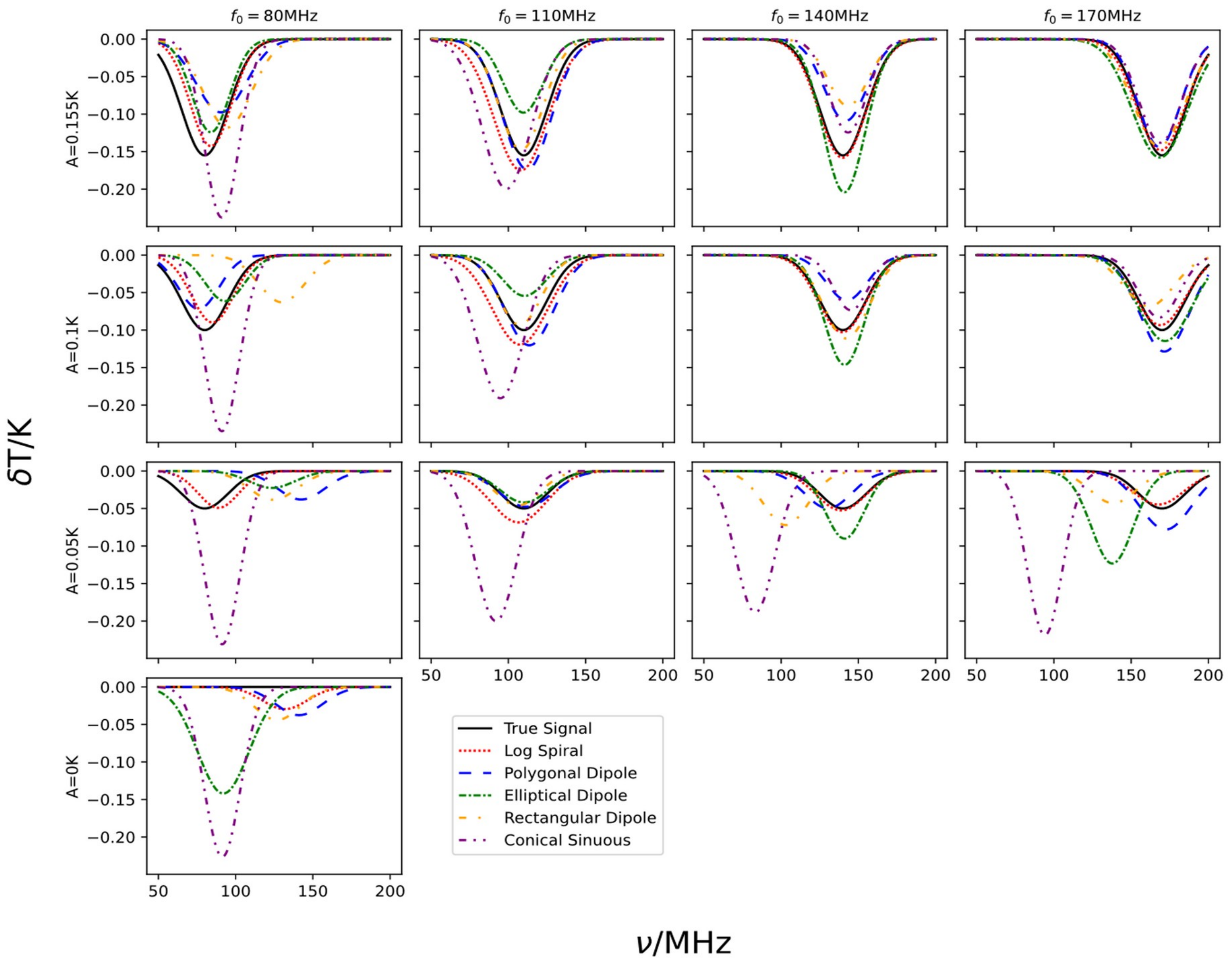
Conical
Logarithmic Spiral

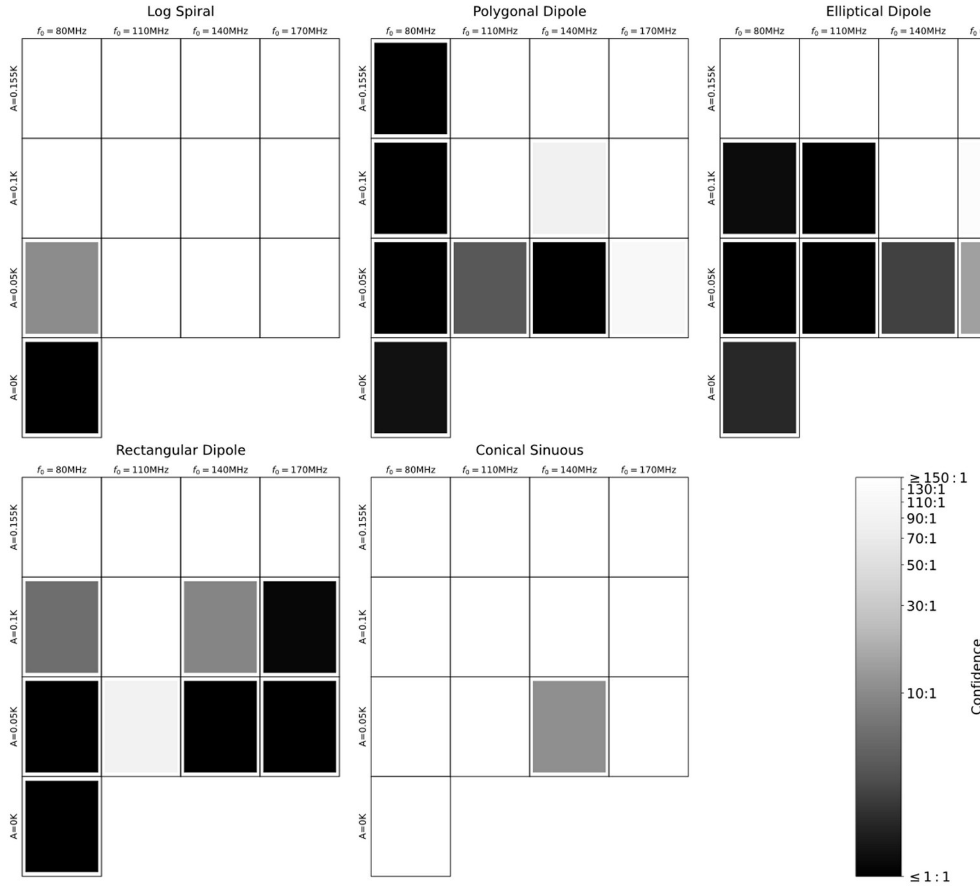


Inverse Conical
Sinuous

Antenna patterns and images provied by John Cumner and Quentin Guerring

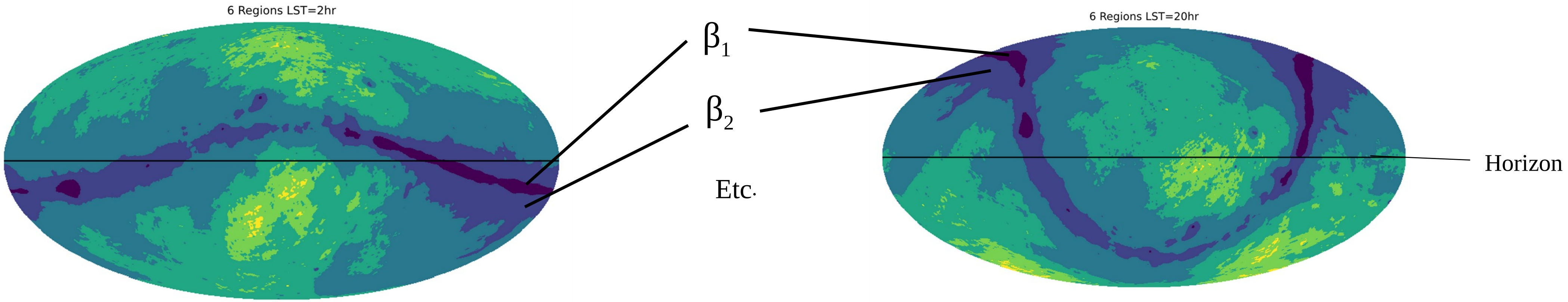
Results





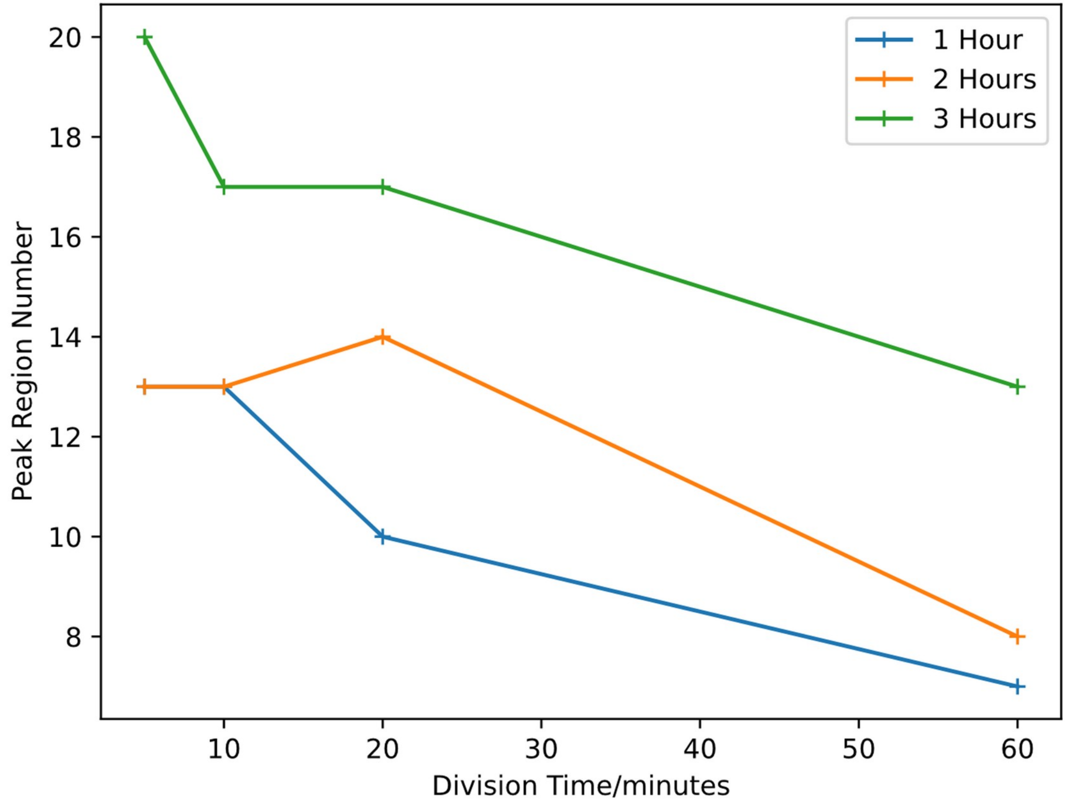
Anstey et al. 2021 (b), arXiv:2106.10193 (preprint)

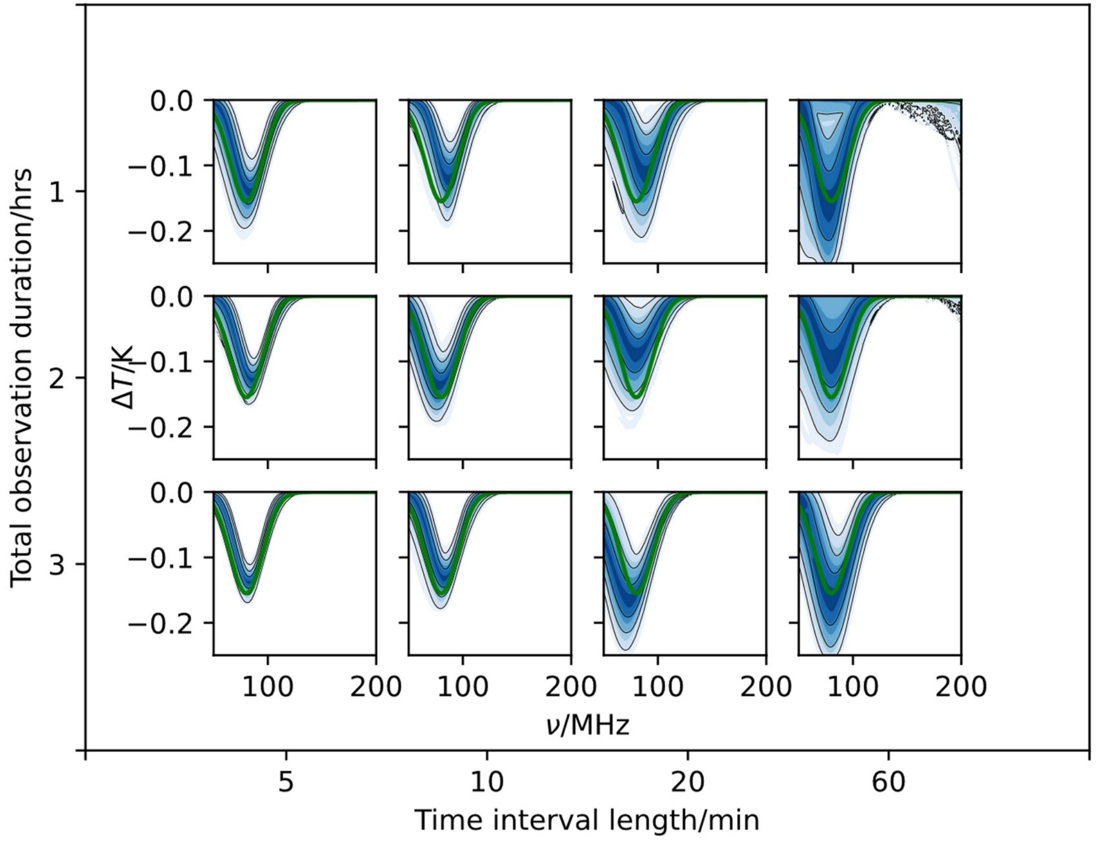
Improving Fit Accuracy



$$\log \mathcal{L} = \sum_i \sum_j \left[-\frac{1}{2} \log\left(2\pi\theta_\sigma\right) - \frac{1}{2}\left(\frac{T_{\mathrm{data}}\left(\nu_i, t_j\right) - T_{\mathrm{F}}\left(\nu_i, t_j, \theta_{\mathrm{F}}\right) - T_{\mathrm{S}}\left(\nu_i, \theta_{\mathrm{S}}\right)}{\theta_\sigma}\right)^2 \right]$$

Improving Fit Accuracy





Conclusions

- The REACH pipeline uses physical models of foregrounds to correct for chromatic distortions
- Analysing simulated data with this pipeline can indicate efficacy of a given antenna in a Global 21cm experiment
- Demonstrated this process with 5 example antennae.
- Physically motivated parameters allow multiple time-dependent data sets to be fit simultaneously
- Demonstrated the improvement in foreground modelling and signal fitting that this provides.

Antenna EM simulations provided by John Cumner and Quentin Gueuning

Plots produced using fgivenx tool: Handley, 2018

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