Global 21cm signal extraction using a Pattern Recognition Framework for REACH

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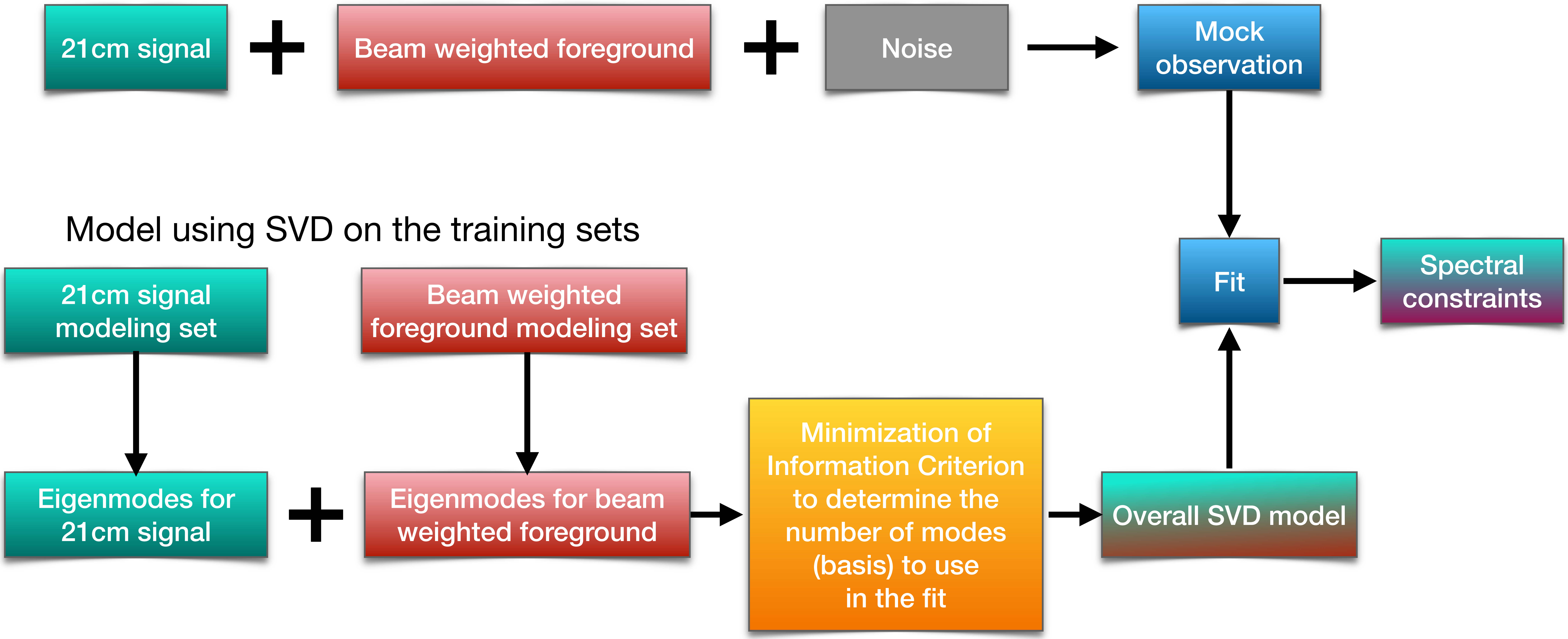
Challenges

- Extracting and constraining the small 21cm signal from the forergrounds which are 4-6 orders of magnitude brighter than the signal.
- Chromaticity of the antenna: Potential overlap between the spectral shapes of the 21cm signal and systematics.
- Ionospheric distortions and RFI

Previous works

- A pattern recognition framework for extracting the 21cm signal from the data.
- The formalism works for a simple simulated experiment (Tauscher et al. 2017, 2020; Rapetti et al. 2019)
  - Smooth Gaussian beams
  - Gaussian distribution of spectral index
  - Used polarization channels and time dependence to improve the fit
- Test the framework for REACH:
  - Simulated beams for different antennas
  - Distribution of spectral index over the sky

Schematic view of pattern recognition setup

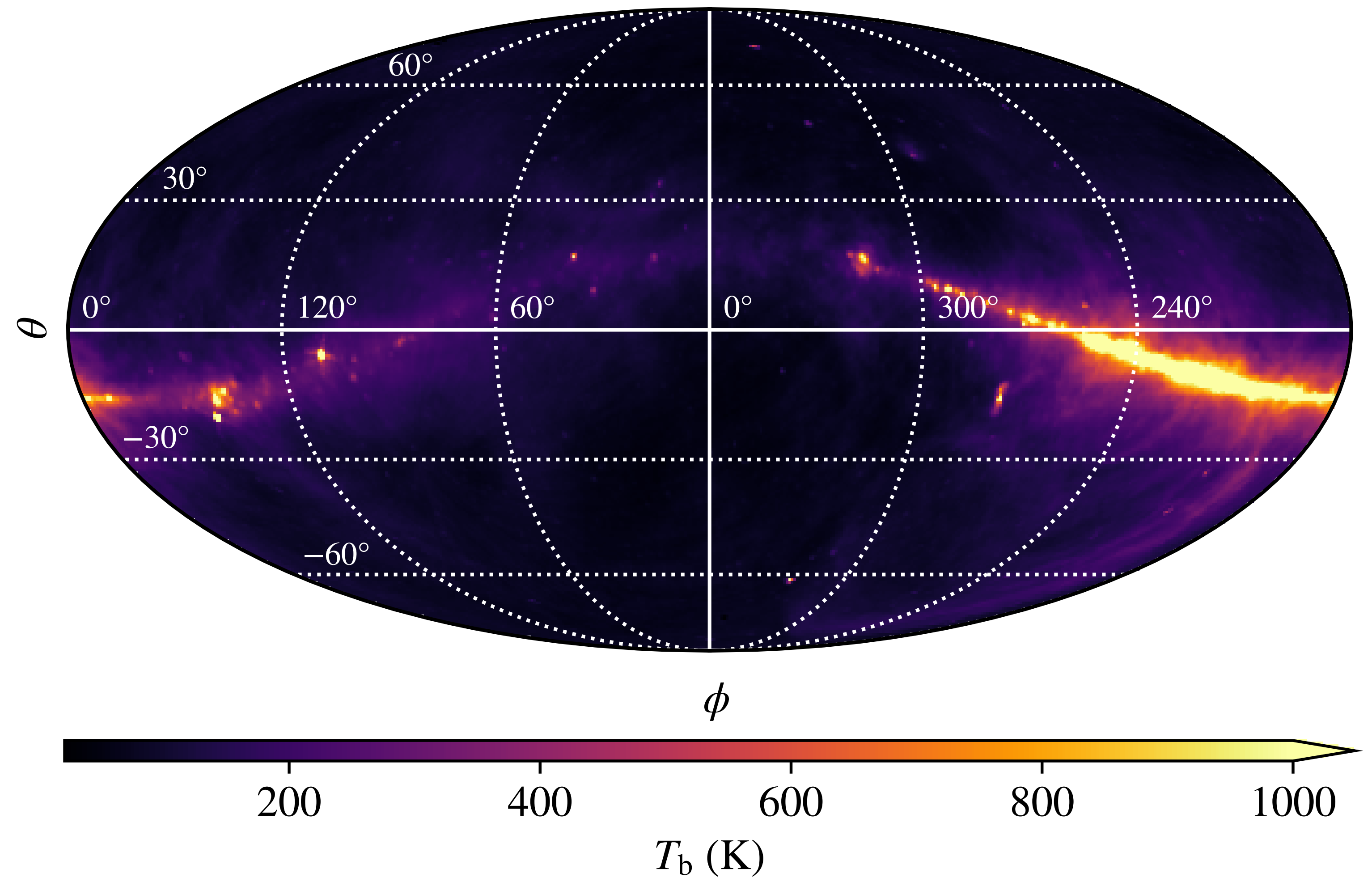


A simple model for foregrounds ($N_{\rm reg}^{\beta} = 1$) + Physical 21cm signals

Beam-weighted foregrounds modeling set

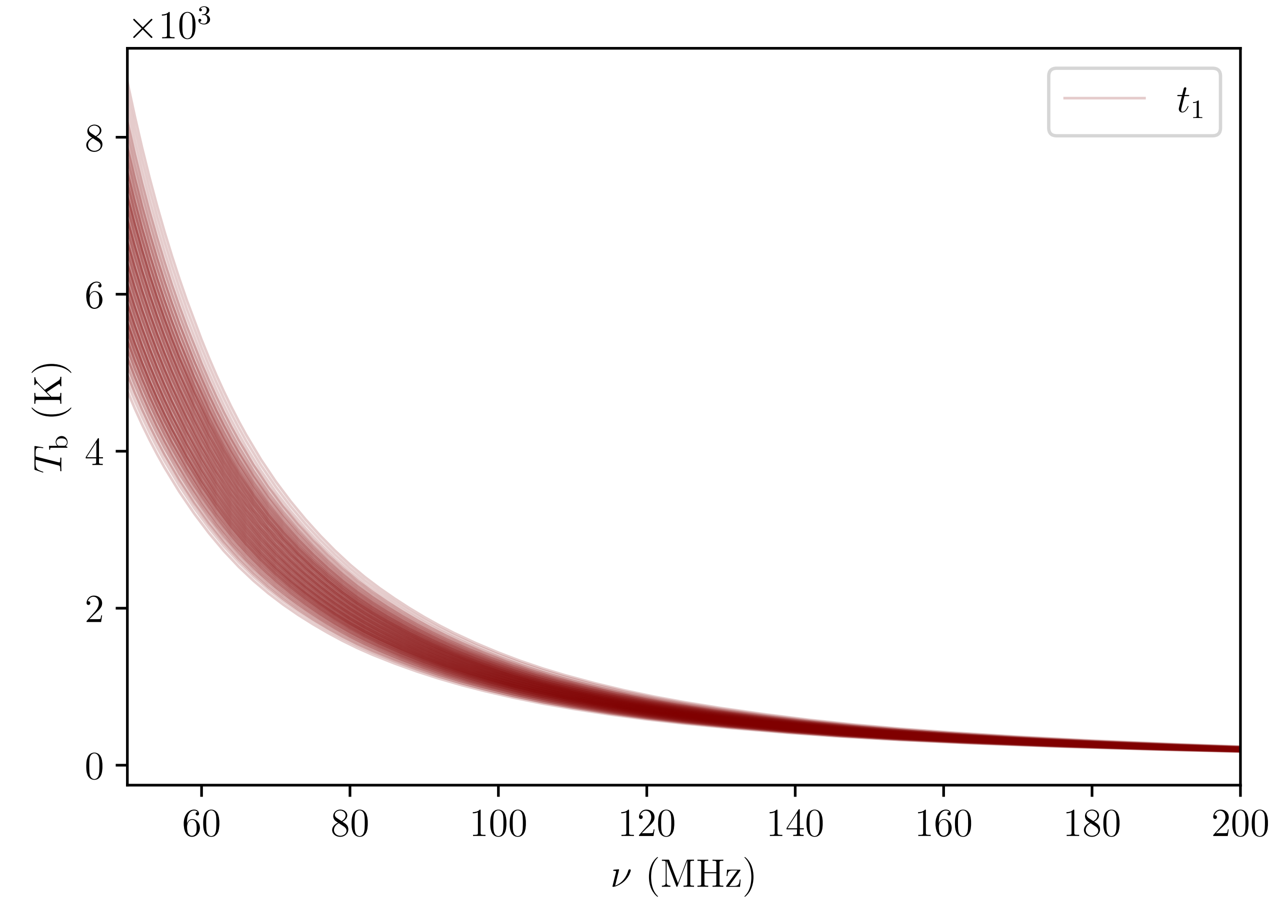
$$T_{\rm sky}(\theta, \phi, \nu, t) = \left(T_{\rm GSM}(\theta, \phi, t) - T_{\rm CMB}\right) \left(\frac{\nu}{230}\right)^{-\beta} + T_{\rm CMB}\,,$$

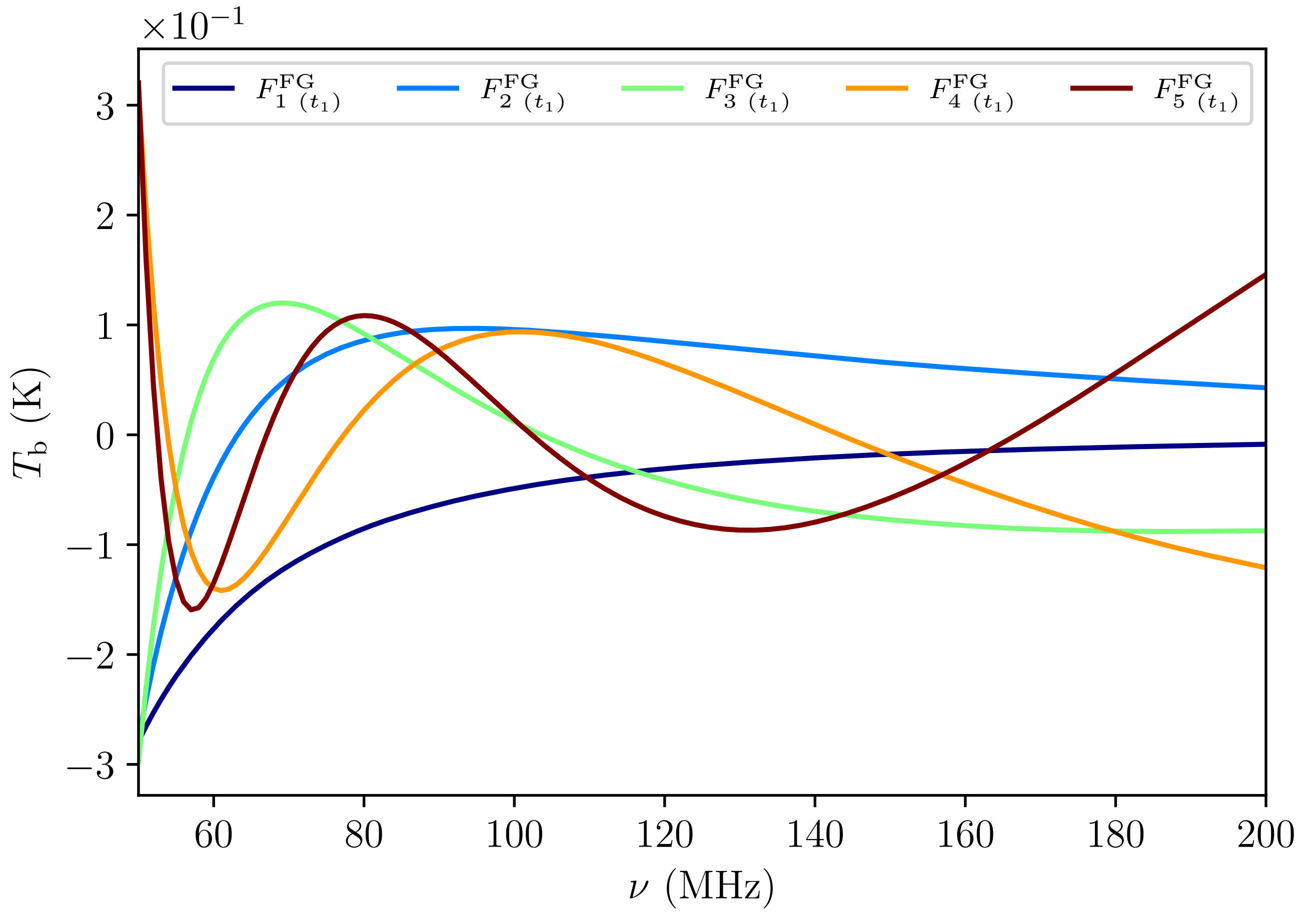
Throughout the modeling set, $\beta \in (2.45, 3.15)$



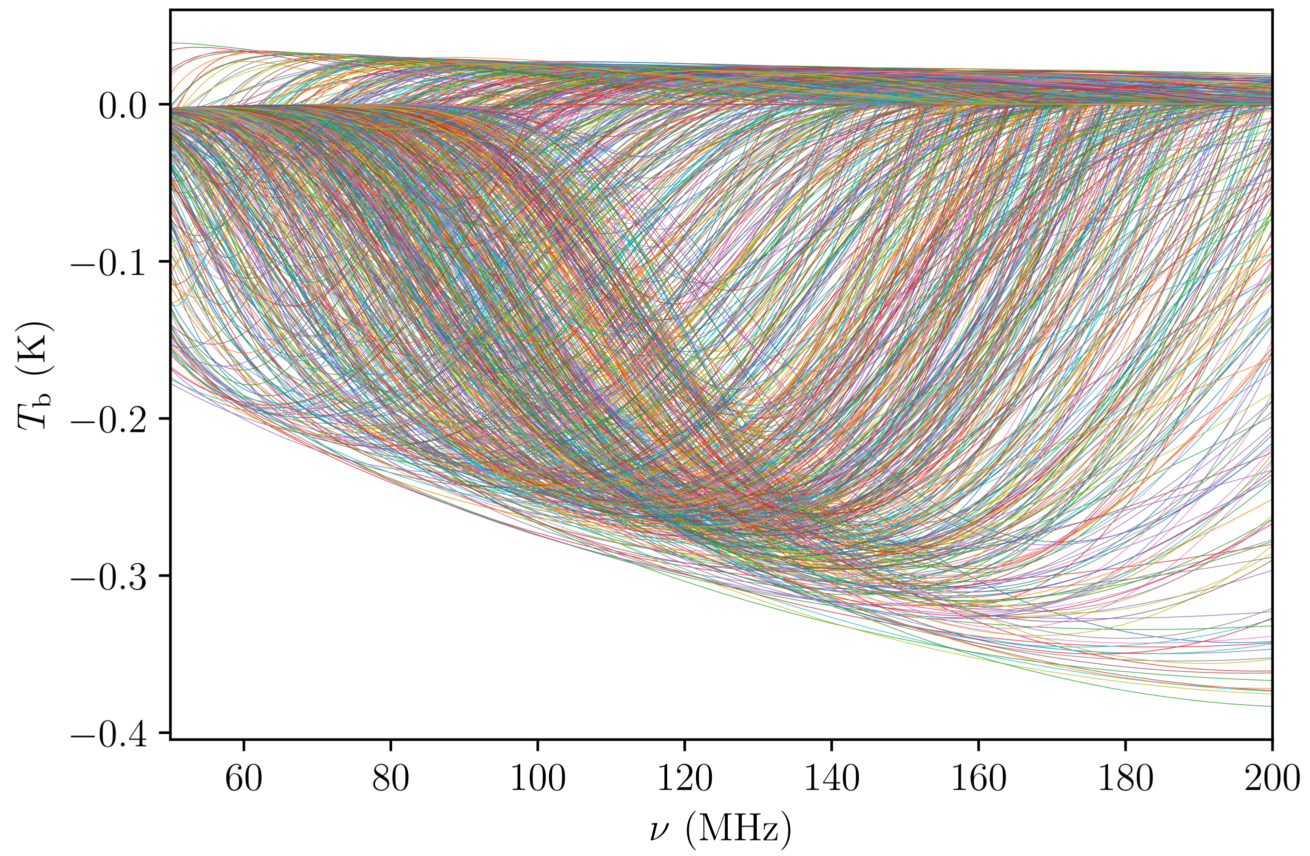
Obervations on 2019-10-01, 00:00:00 - 06:00:00

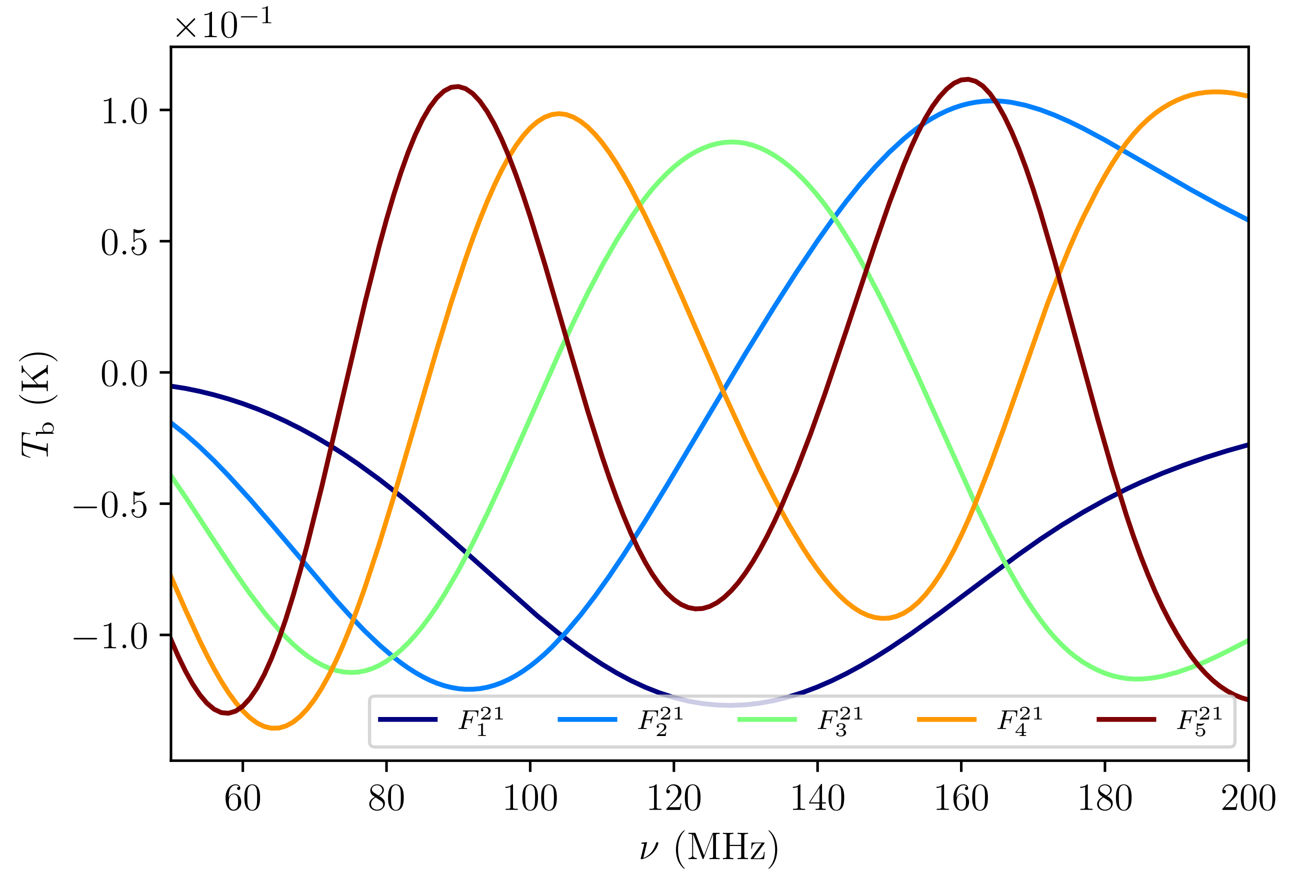
$$T_{\rm BW-FG}(\nu, t) = \frac{1}{4\pi}\int_0^{4\pi} D(\theta, \phi, \nu)\; T_{\rm sky}(\theta, \phi, \nu, t)\,{\rm d}\Omega\,,$$





21cm modeling set: ARES simulation

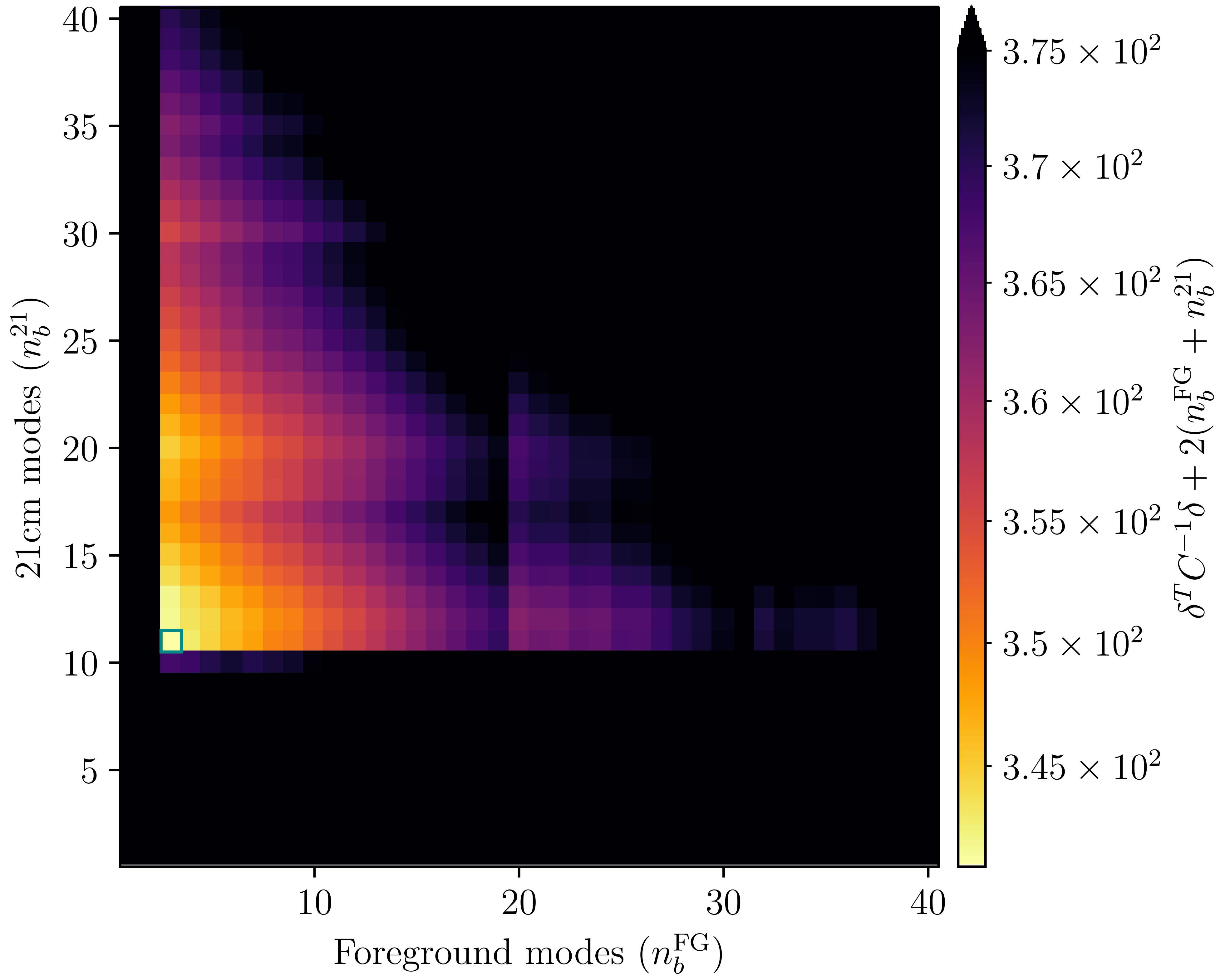




A simple model for foregrounds ($N^{\beta}_{\text{reg}} = 1$) + Physical 21cm signals

Minimization of Information Criterion

$$\text{DIC} = \delta^T C^{-1} \delta + 2(n_b^{21} + n_b^{\text{FG}})$$



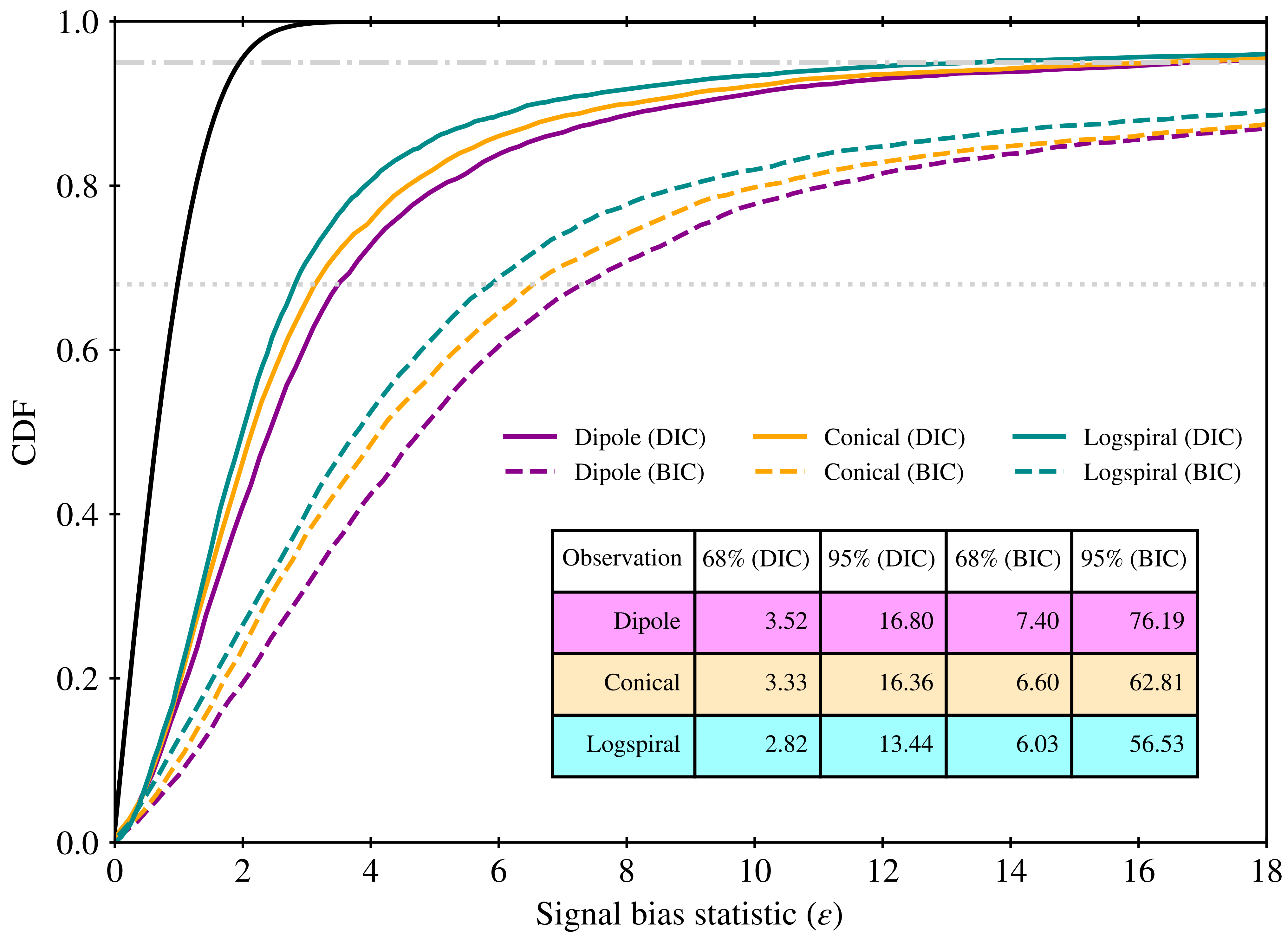
Deviance Information Criterion estimated over a grid of number of modes $(n_b^{21}, n_b^{\text{FG}})$ used while reconstructing the data vector

Choice of Information Criterion

$$\varepsilon = \sqrt{\frac{1}{n_\nu} \sum_{i=1}^{n_\nu} \frac{(\gamma_{21} - y_{21})^2}{(\Delta_{21})_{ii}}}$$

$$\text{DIC} = \delta^T C^{-1} \delta + 2(n_b^{21} + n_b^{\text{FG}})$$

$$\text{BIC} = \delta^T C^{-1} \delta + (n_b^{21} + n_b^{\text{FG}})\ \ln(n_c)$$



Observation	68% (DIC)	95% (DIC)	68% (BIC)	95% (BIC)
Dipole	3.52	16.80	7.40	76.19
Conical	3.33	16.36	6.60	62.81
Logspiral	2.82	13.44	6.03	56.53

Consistent with Tauscher et al. 2017

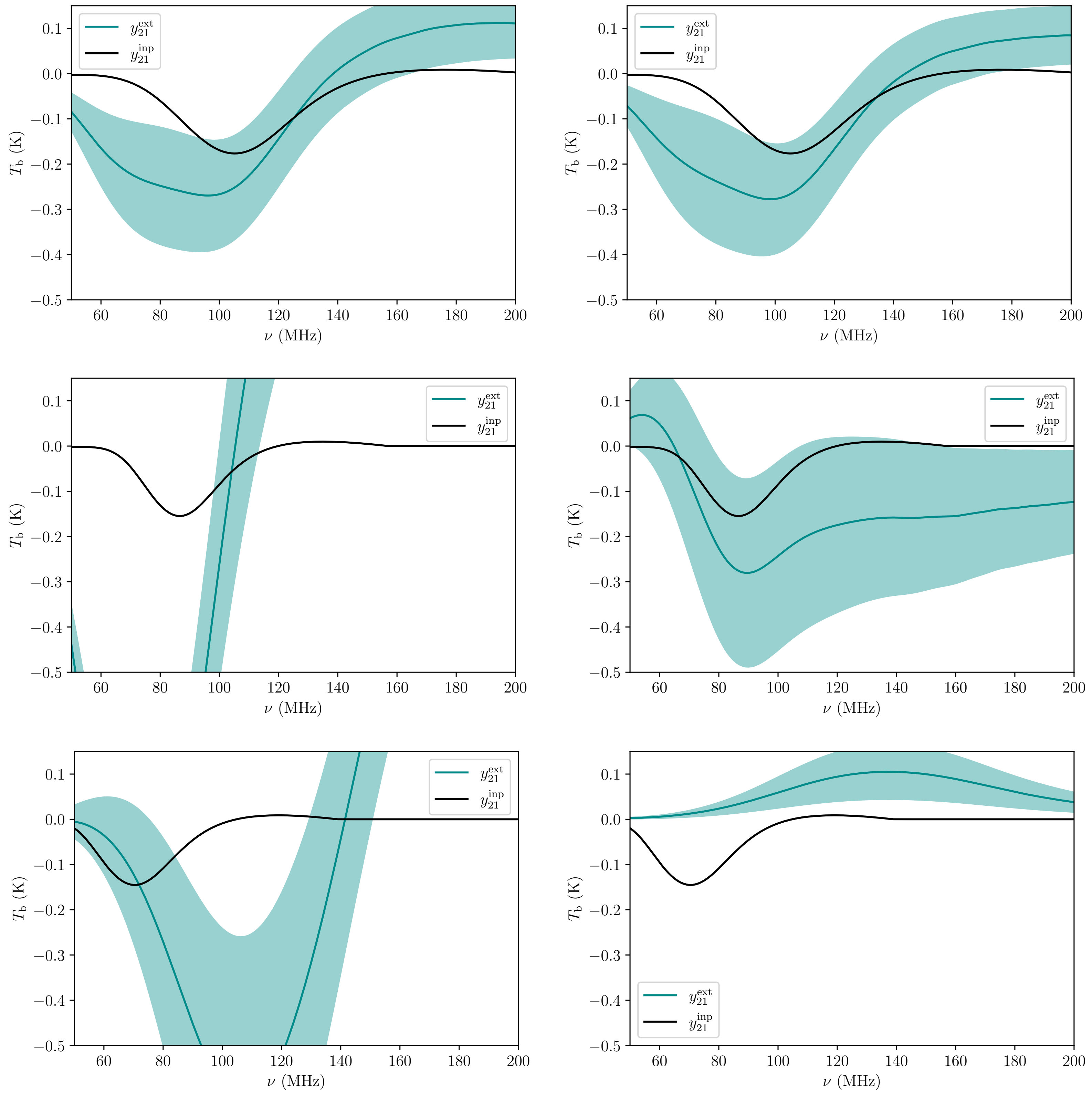
A simple model for foregrounds ($N^{\beta}_{\text{reg}} = 1$) + Physical 21cm signals

Extracted 21cm signals

21cm signal and foregrounds are taken from their respective modeling sets.

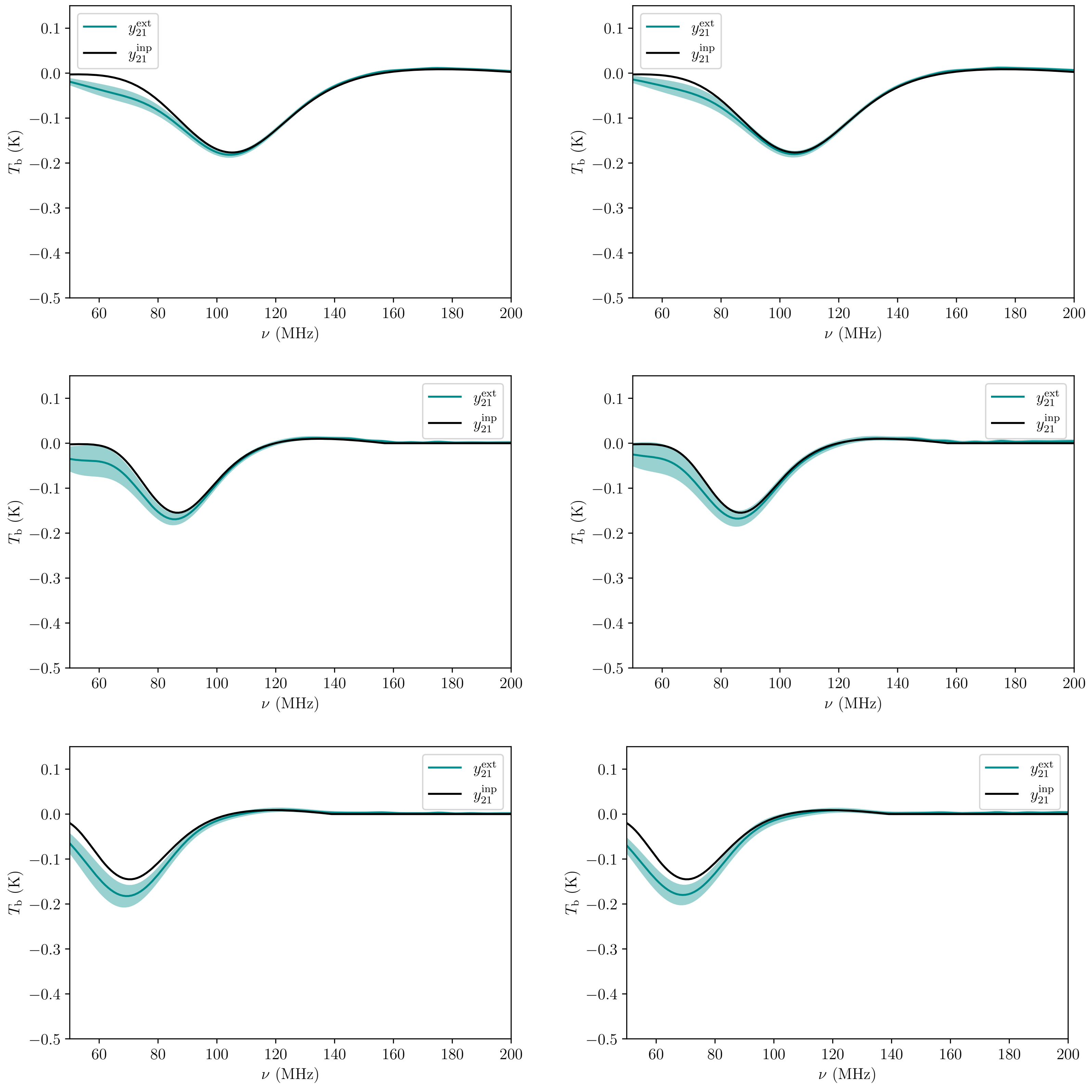
$\chi^2 = 1.04$ $t_{\text{BINS}} = 1$ RMS ~ 130 mK

Conical Sinuous Conical Logspiral



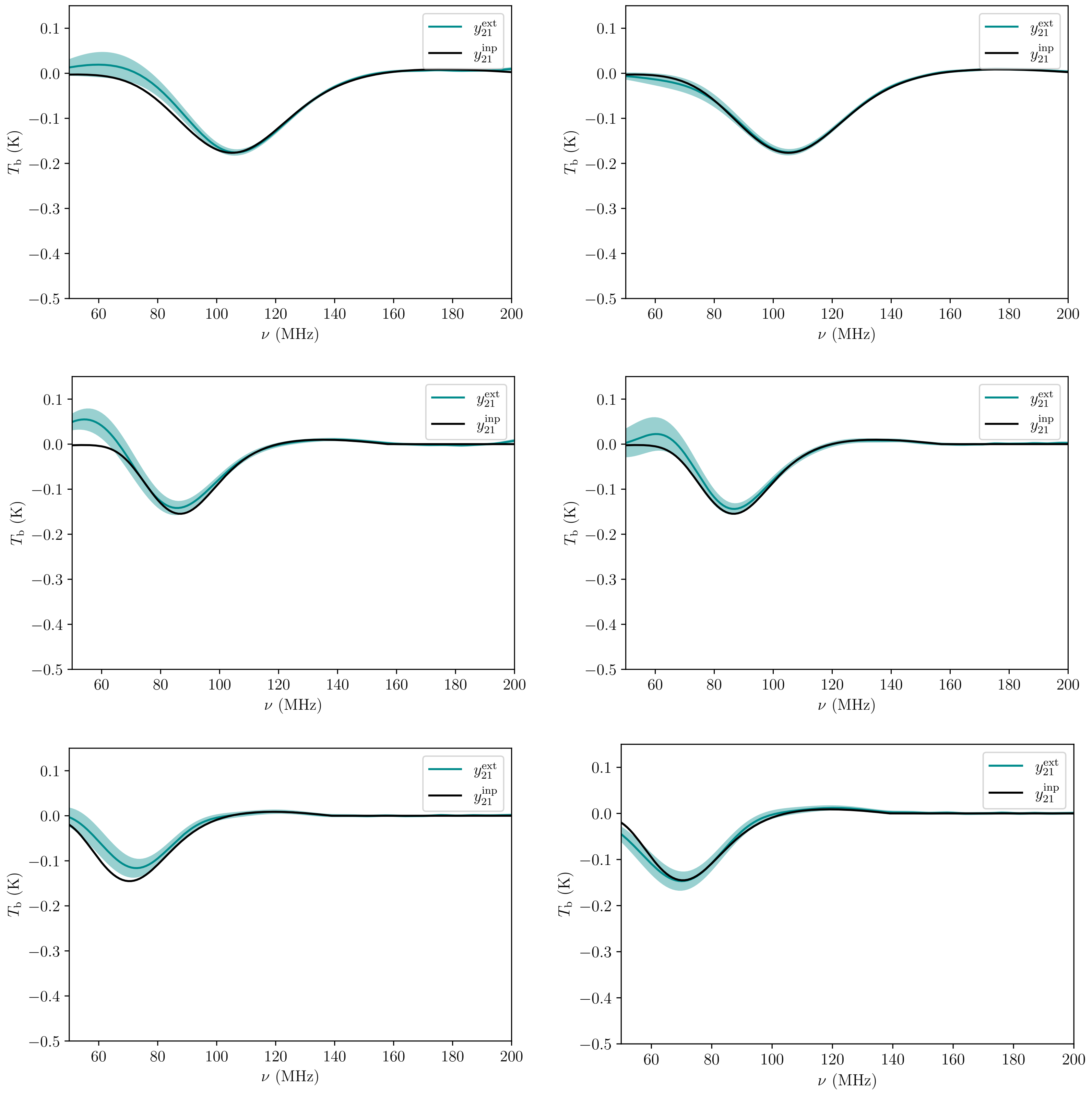
$\chi^2 = 1.02$ $t_{\text{BINS}} = 2$ RMS ~ 11 mK

Conical Sinuous Conical Logspiral



$\chi^2 = 0.99$ $t_{\text{BINS}} = 4$ RMS ~ 6 mK

Conical Sinuous Conical Logspiral

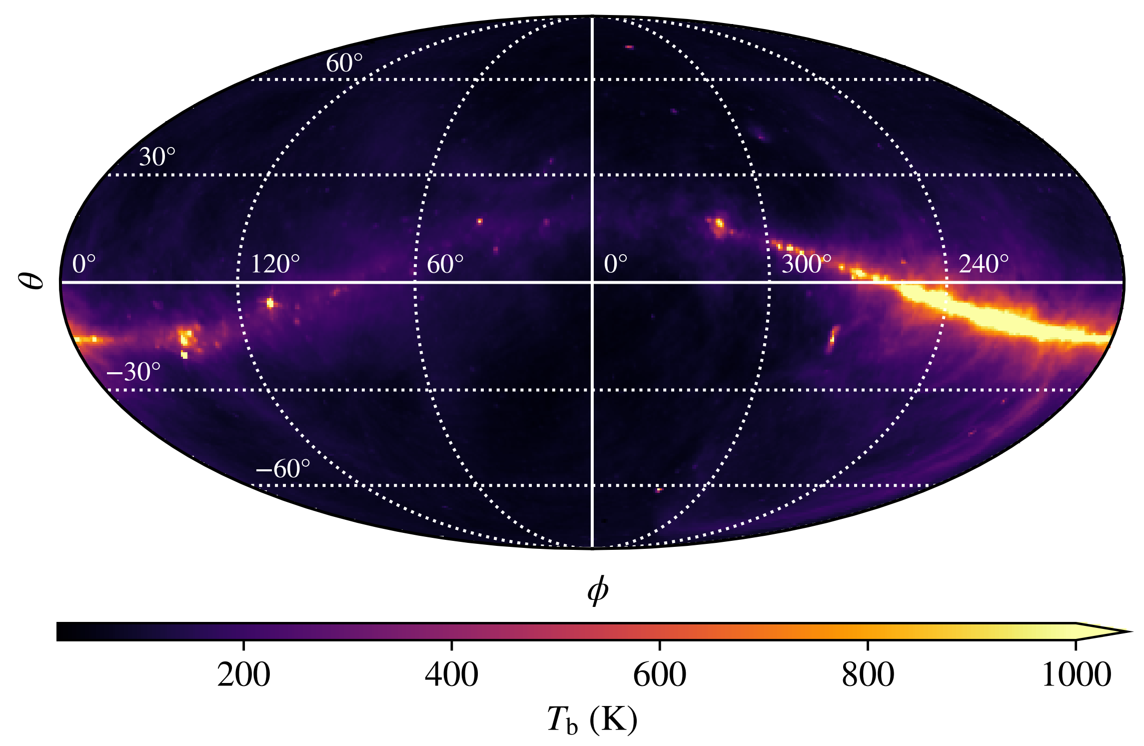


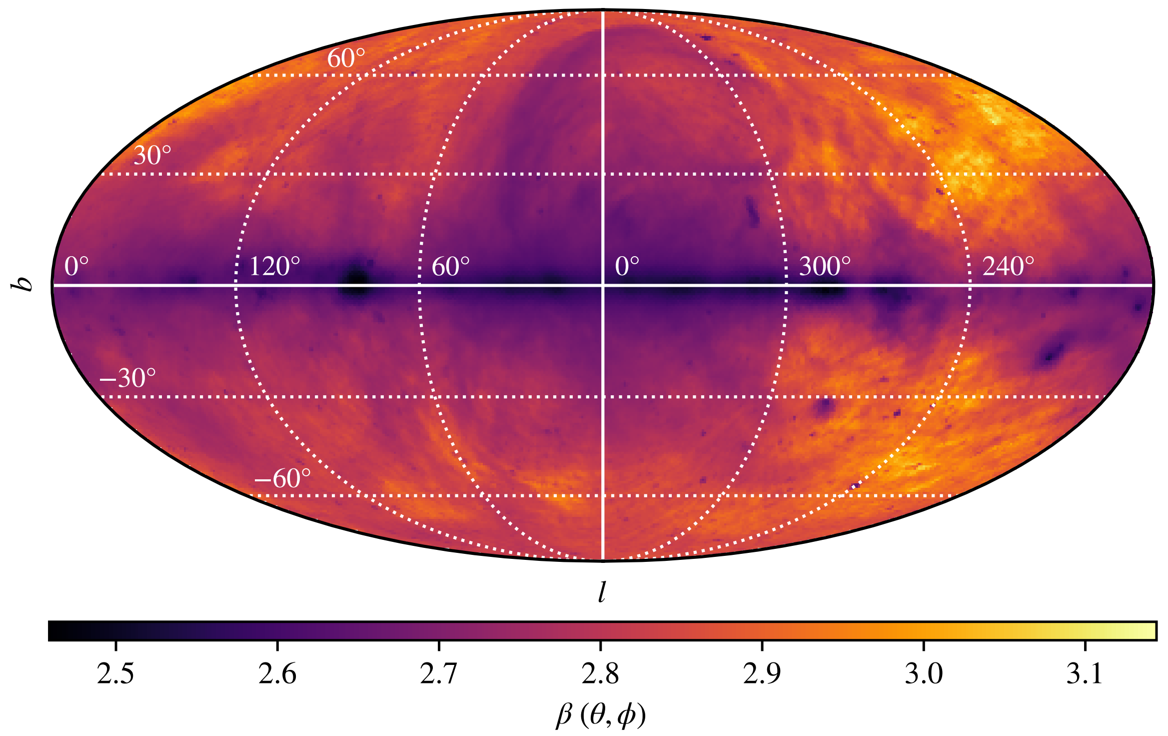
Including time dependence reduces the overlap between the foreground and 21cm signal modes.

Detailed foregrounds in observation fitted with $N_{\rm reg}^{\beta} = 1$ modeling set

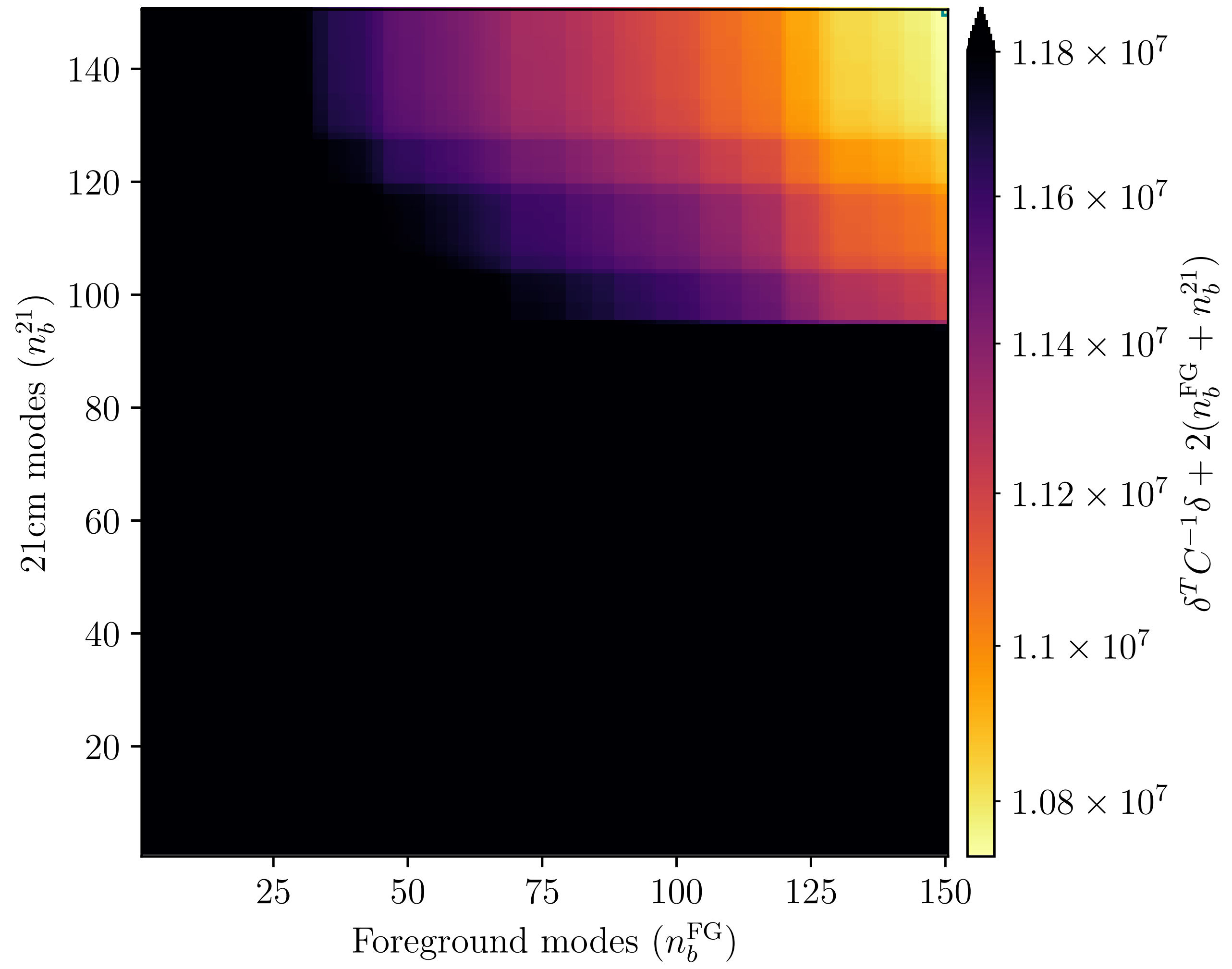
Foregrounds used in mock observation

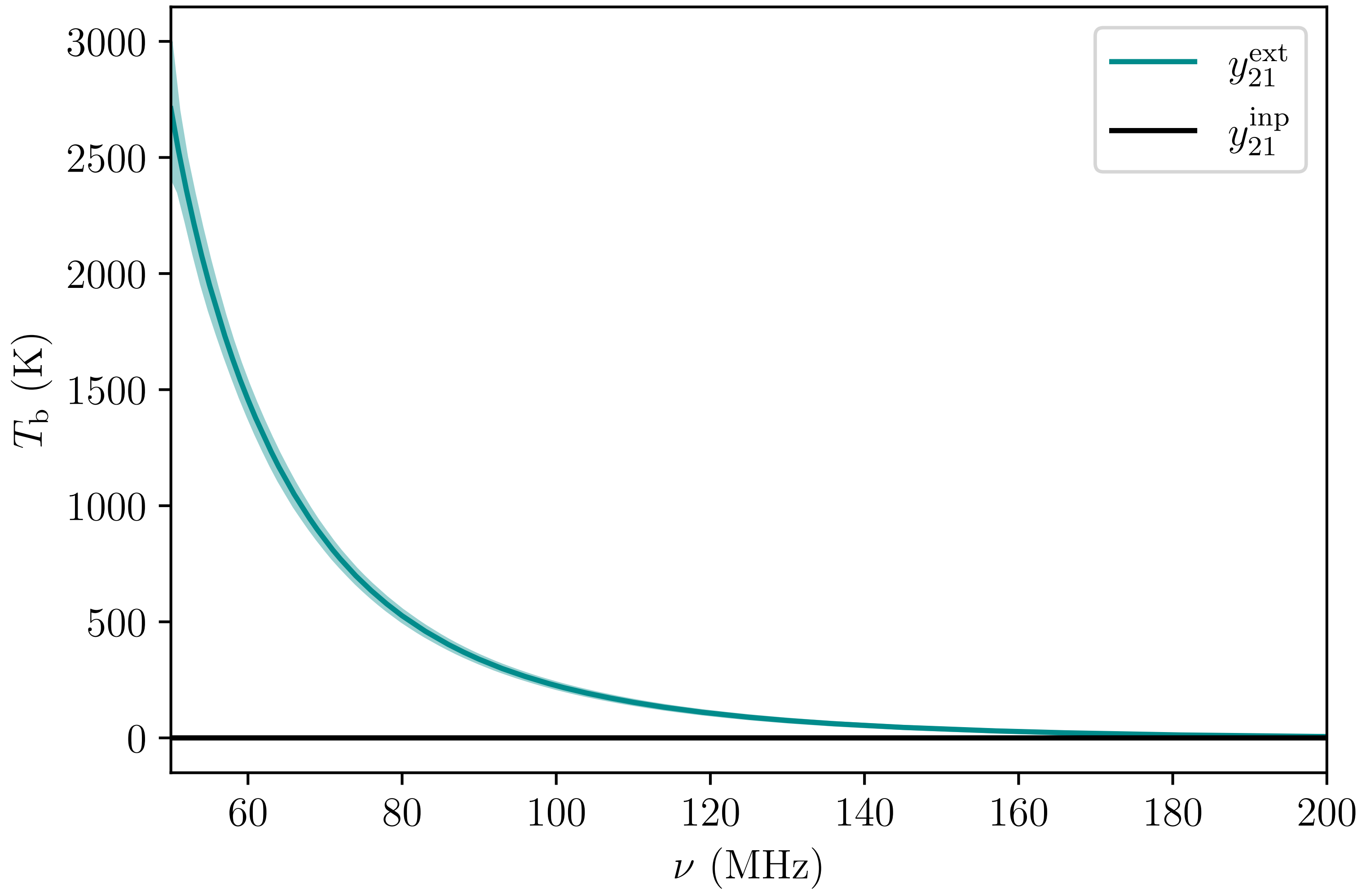
$$T_{\rm sky}(\theta, \phi, \nu, t) = \left(T_{\rm GSM}(\theta, \phi, t) - T_{\rm CMB}\right) \left(\frac{\nu}{230}\right)^{-\beta(\theta, \phi, t)} + T_{\rm CMB}\,,$$





$$T_{\rm BW-FG}(\nu, t) = \frac{1}{4\pi} \int_0^{4\pi} D(\theta, \phi, \nu)\; T_{\rm sky}(\theta, \phi, \nu, t)\, {\rm d}\Omega\,,$$



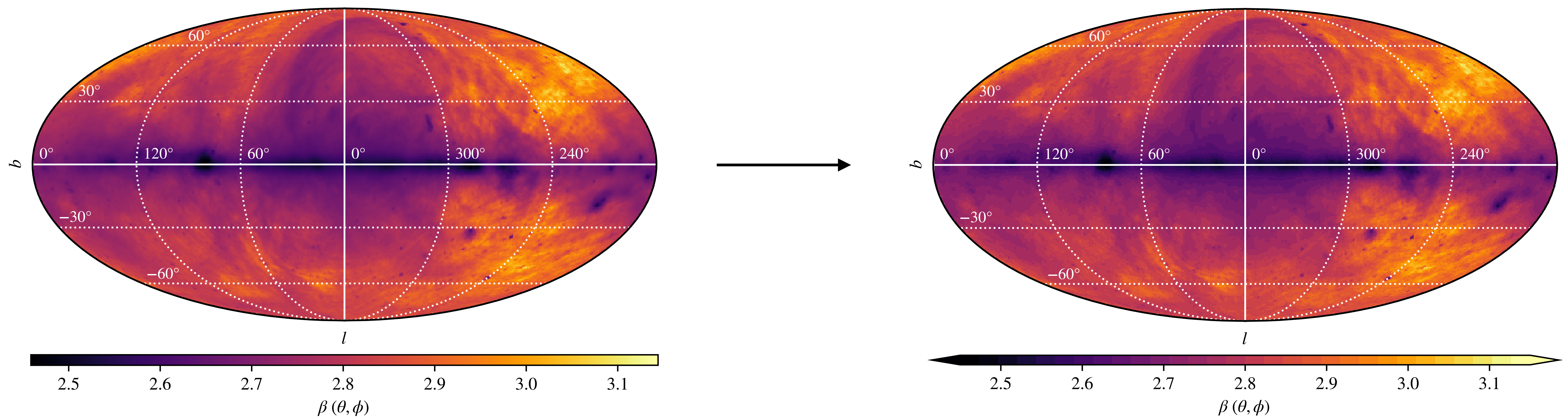


We can't extract the 21cm signal from these foregrounds using the foreground basis from $N_{\rm reg}^{\beta} = 1$ modeling set.

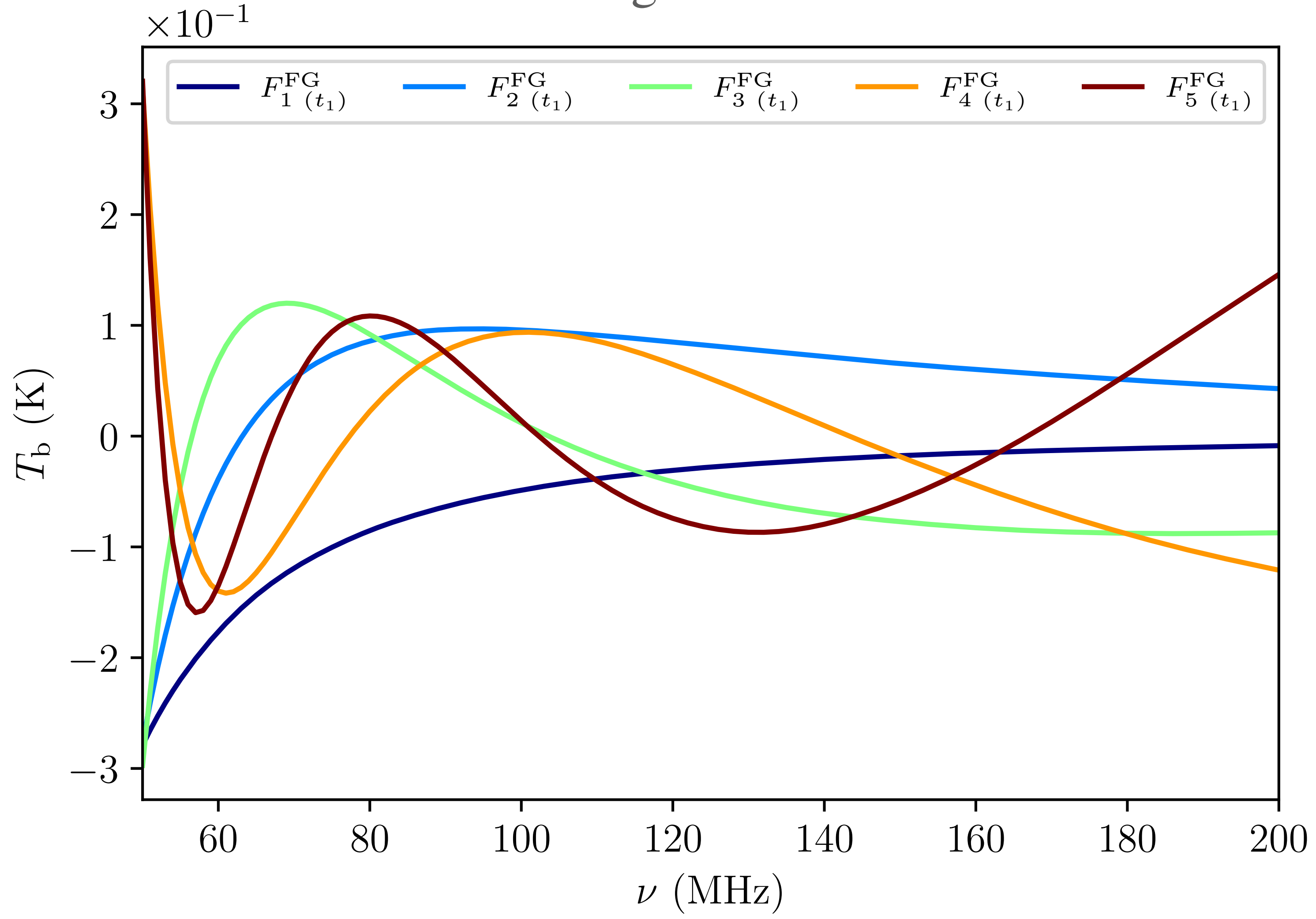
Detailed foreground modeling set with $N_{\text{reg}}^{\beta} = 30$

Divide the sky into 30 regions and assign a constant spectral index to each region for the modeling set.

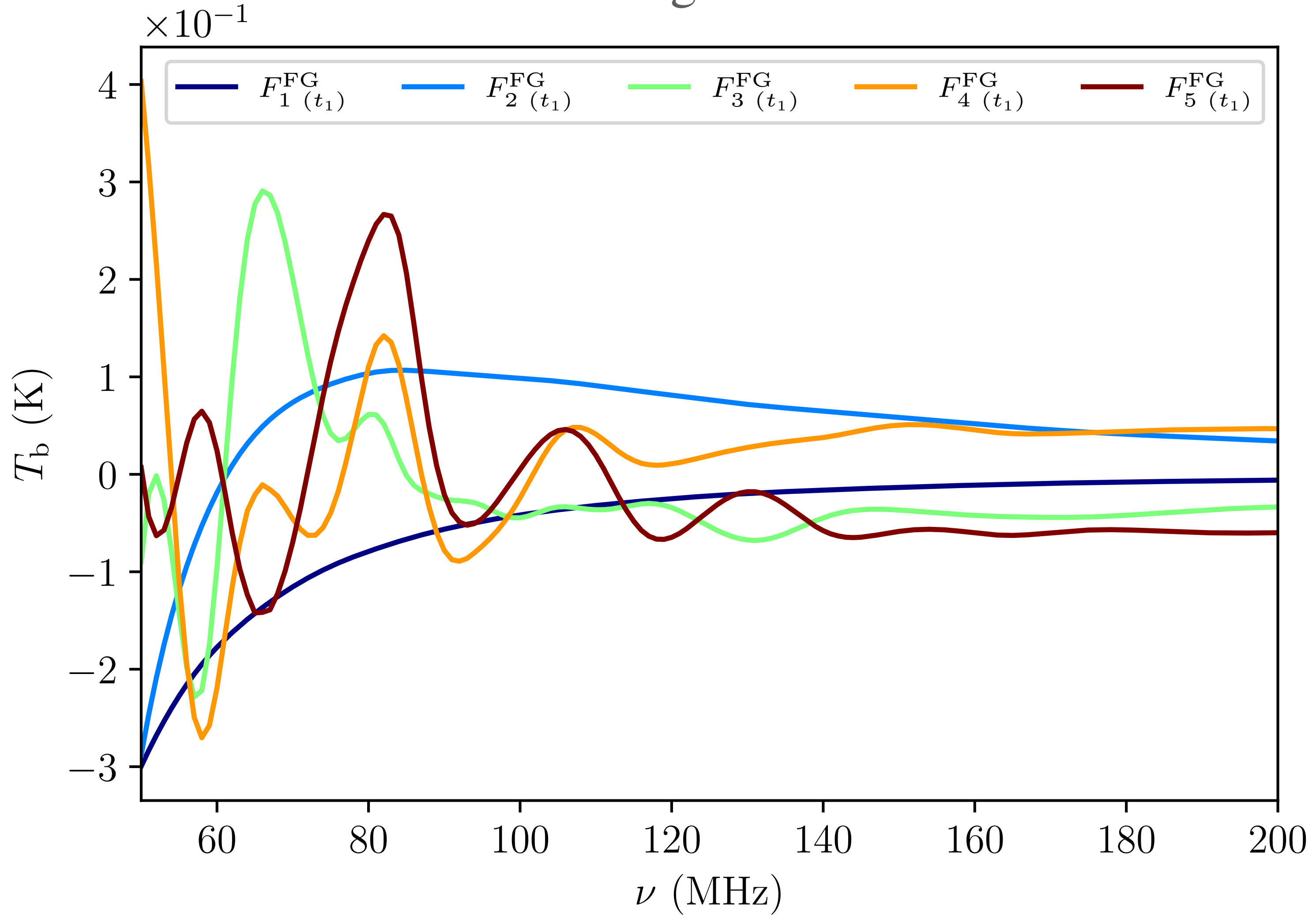
$\beta_i \in (2.45, 3.15)$ for $1 \leq i \leq 30$



$N_{\text{reg}}^{\beta} = 1$



$N_{\text{reg}}^{\beta} = 30$



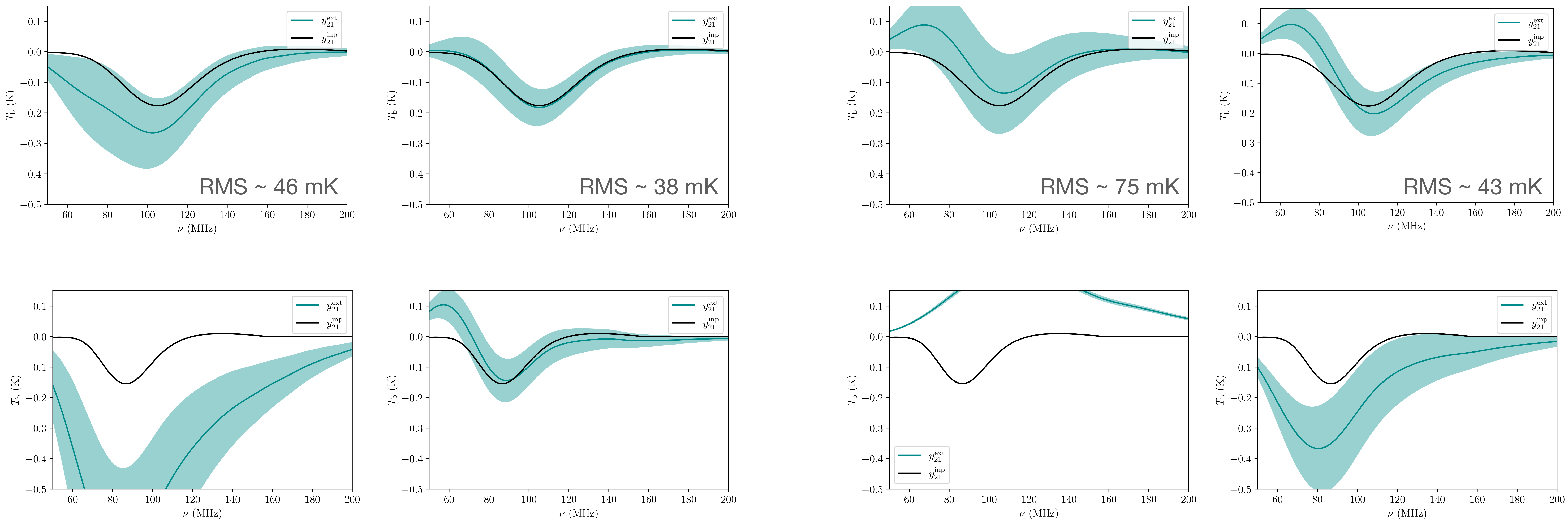
Adding more details to the foreground modeling set introduces structures in the beam weighted foreground basis.

Extracted 21cm signals

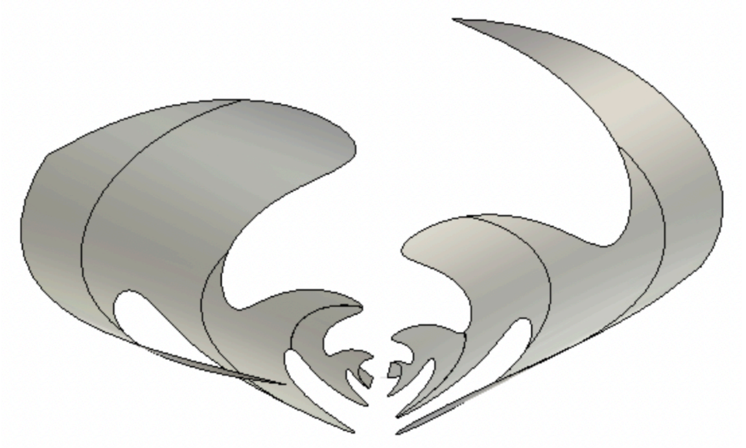
Conical Logspiral

Conical Sinuous

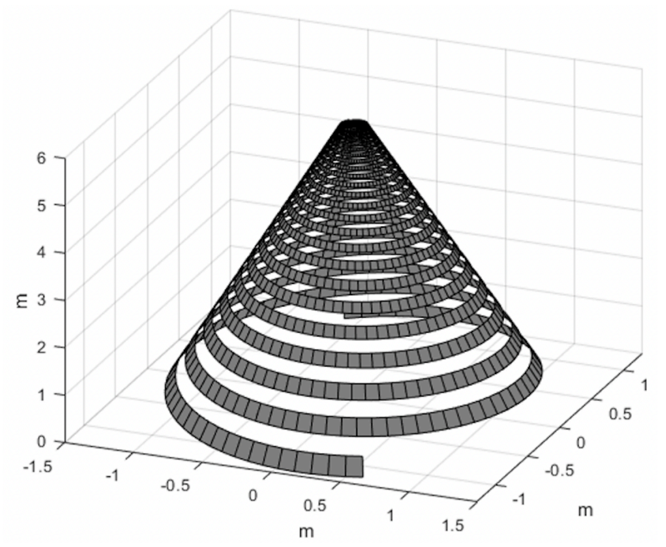
$t_{\mathrm{BINS}} = 4$ $t_{\mathrm{BINS}} = 12$ $t_{\mathrm{BINS}} = 4$ $t_{\mathrm{BINS}} = 12$



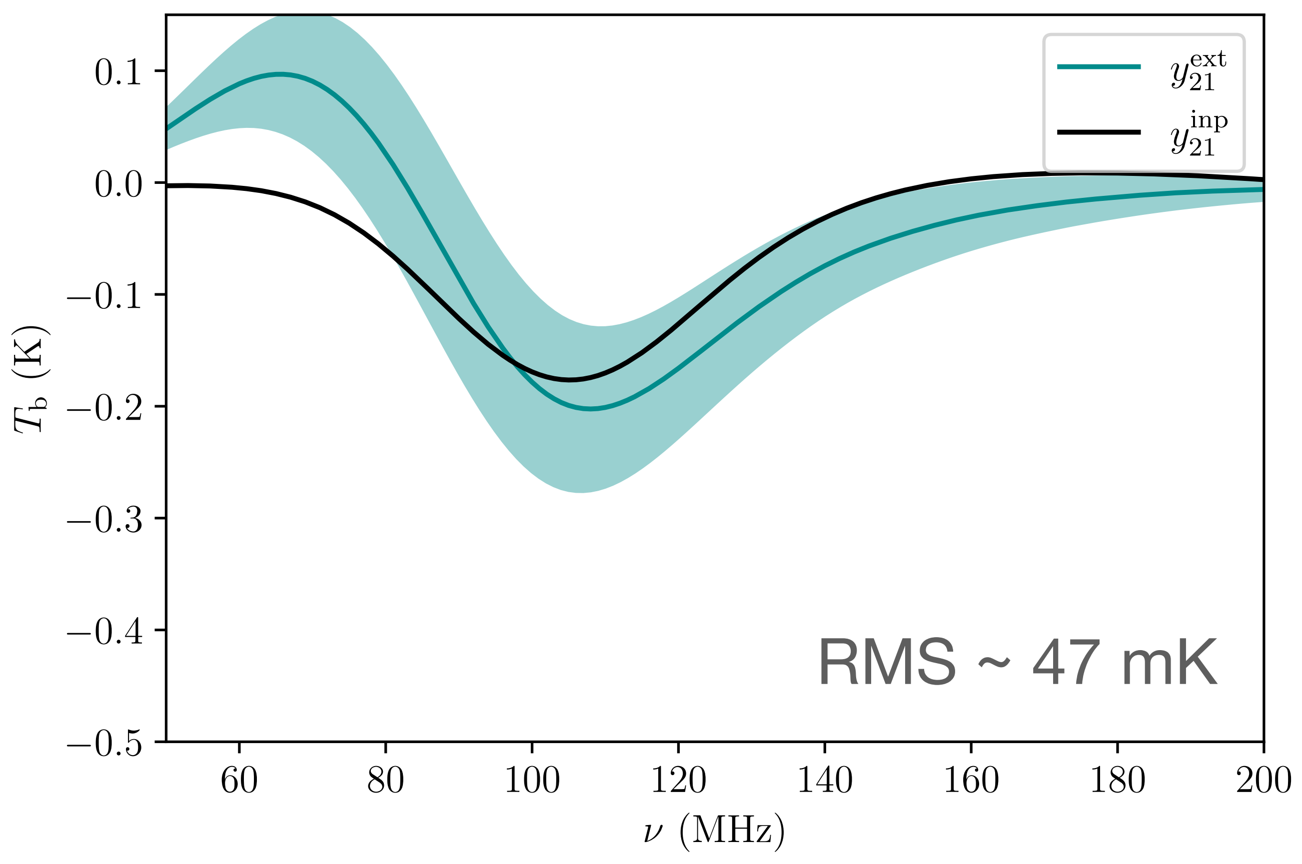
Simultaneously fitting the data from multiple antennas



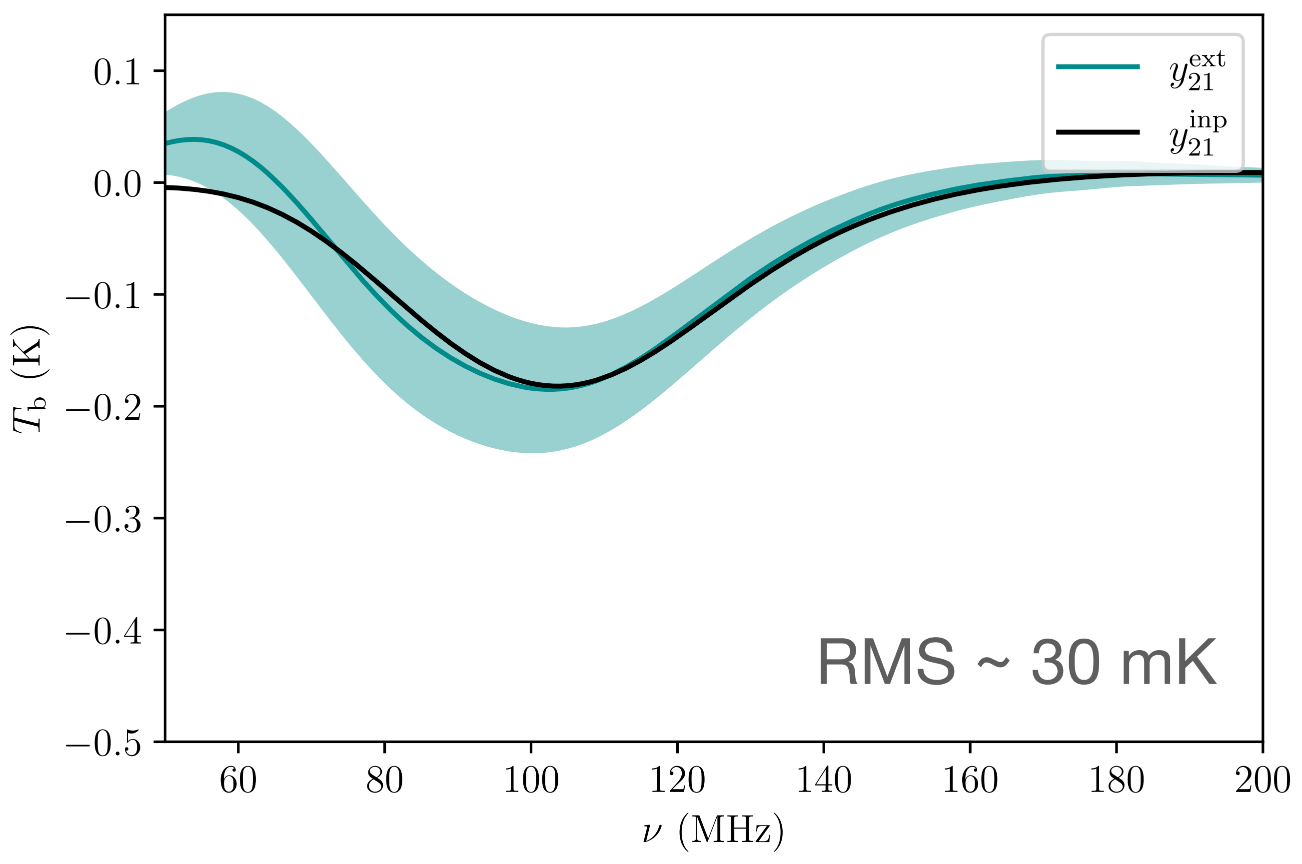
Conical Sinuous
2019-10-01, 00:00:00 - 03:00:00



Conical Logspiral
2019-10-01, 03:00:00 - 06:00:00



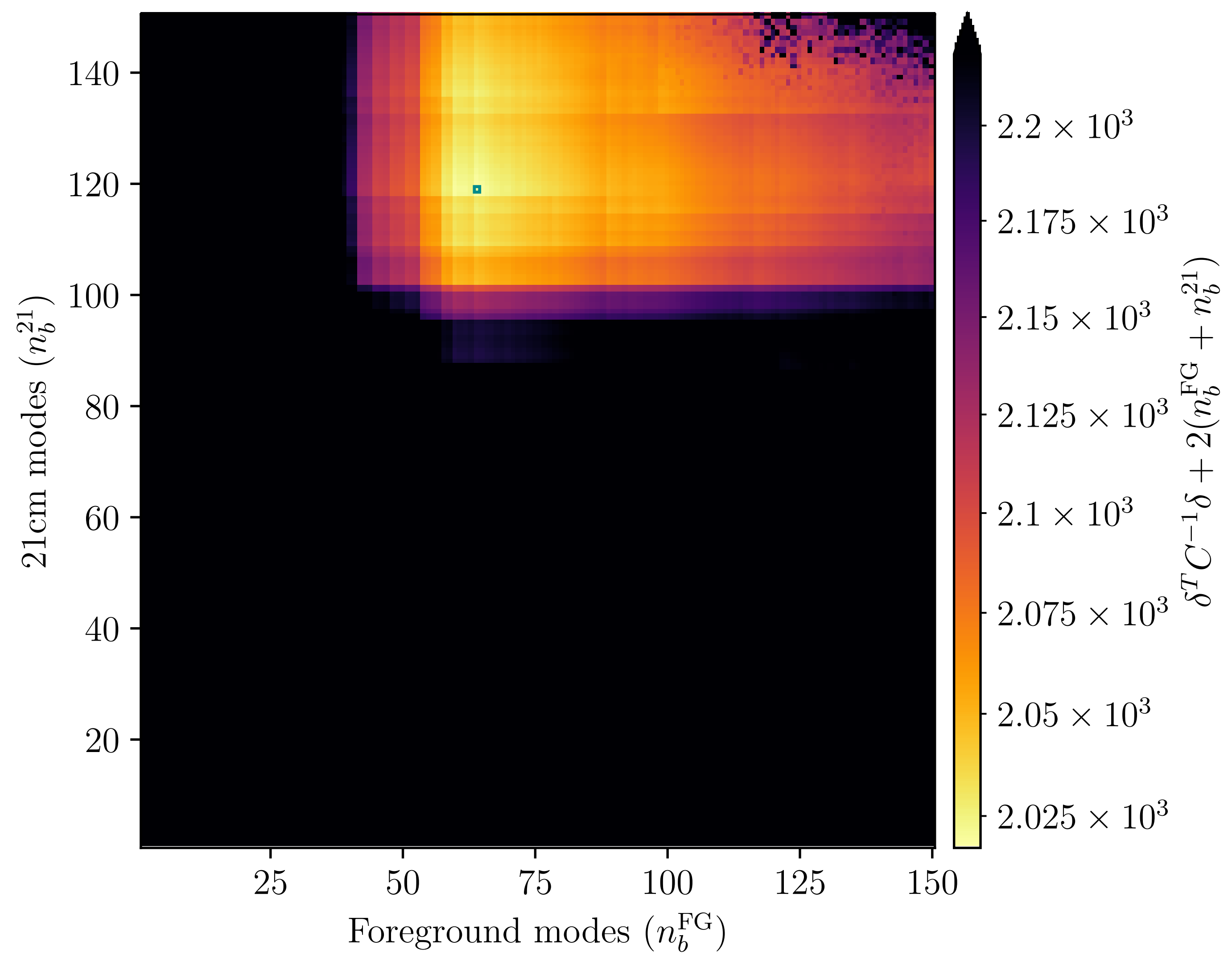
Single Antenna

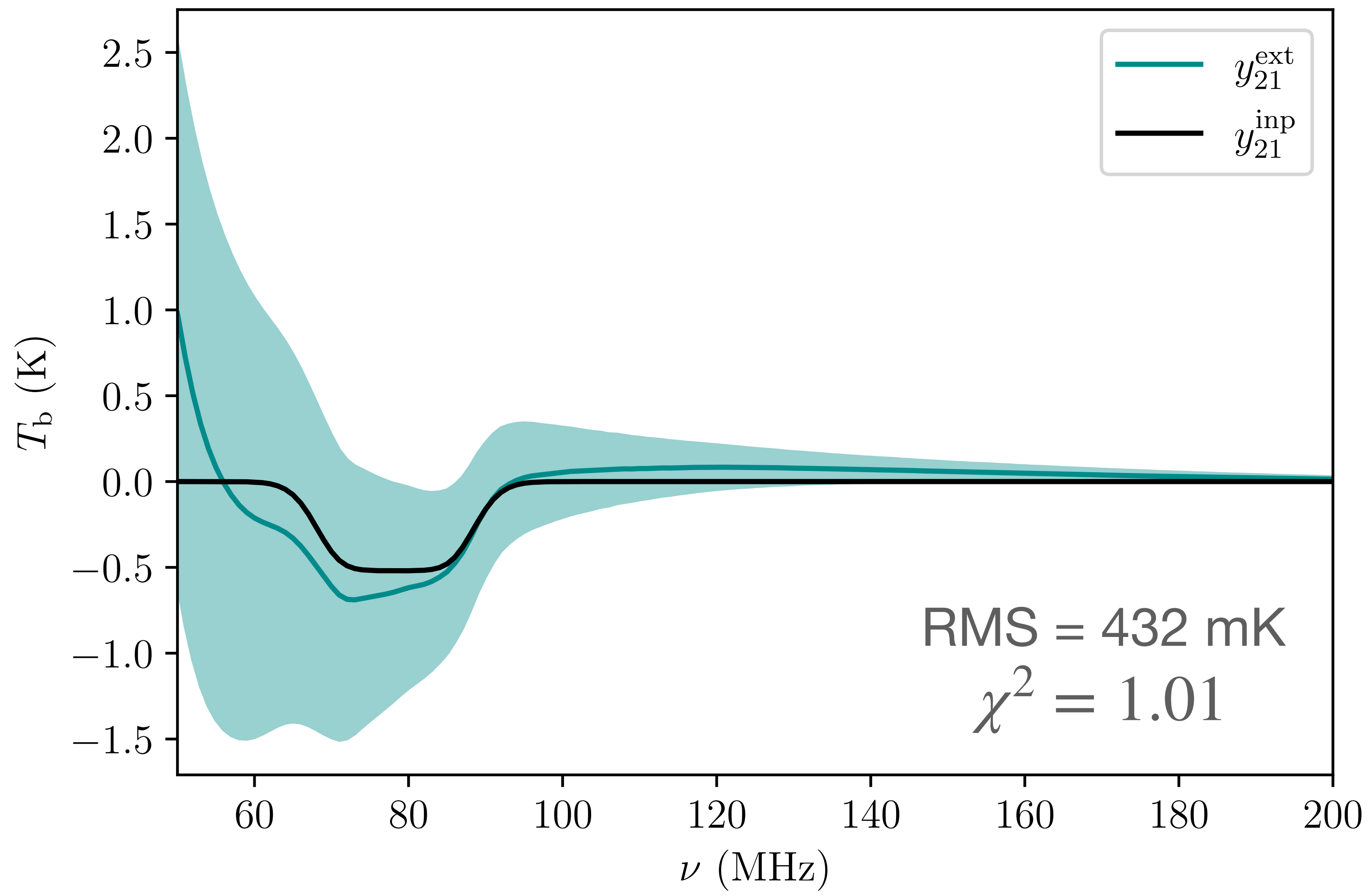


Multiple Antennas

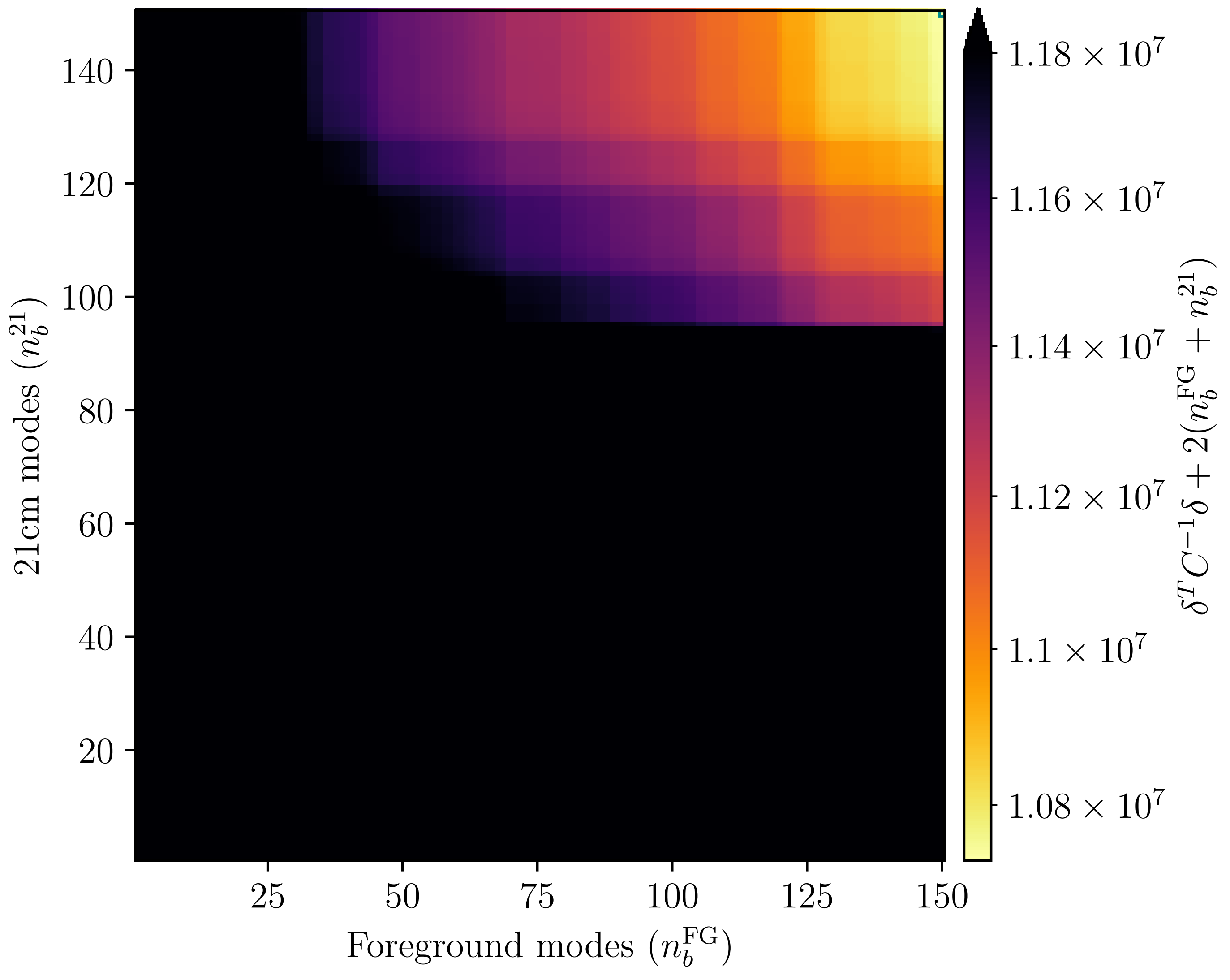
Limitations

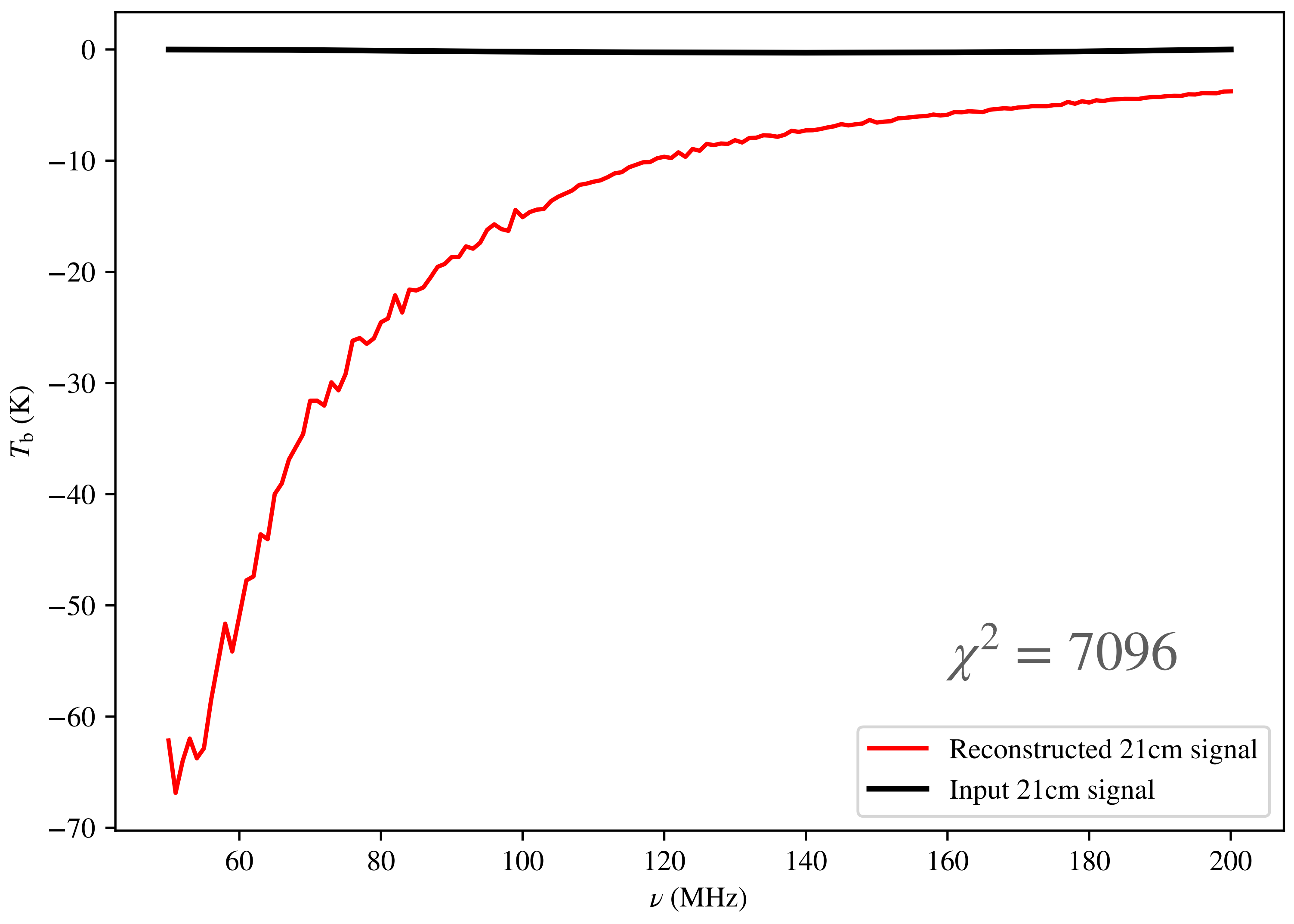
Fitting the EDGES like signal using the modes derived from the physical 21cm signals.





Fitting the beam-weighted Haslam foregrounds using the modes derived from the beam-weighted GSM foregrounds modeling set





Summary

- Given the simulated beam of both the antenna, the 21cm signal can be extracted from the data while simultaneously fitting multiple time bins.
- The foreground modes derived from a constant spectral index ($N^{\beta}_{\rm reg} = 1$) modeling set along with the 21cm modes can model any data randomly sampled from their modeling sets. However, these modes can't recover the signal if the input foregrounds are generated using the full sky distribution of spectral index.
- To model such foregrounds, we need a more detailed modeling set ($N^{\beta}_{\rm reg} = 30$), which adds the relevant structure to the foreground modes, which can then model the foregrounds, and extract the 21cm signal.
- To better constrain the 21cm signal, we can simultaneously fit the data from two different antennas, at two different time bins.