Foreground removal for 21-cm experiments*

*(especially sky-averaged 21-cm measurements)

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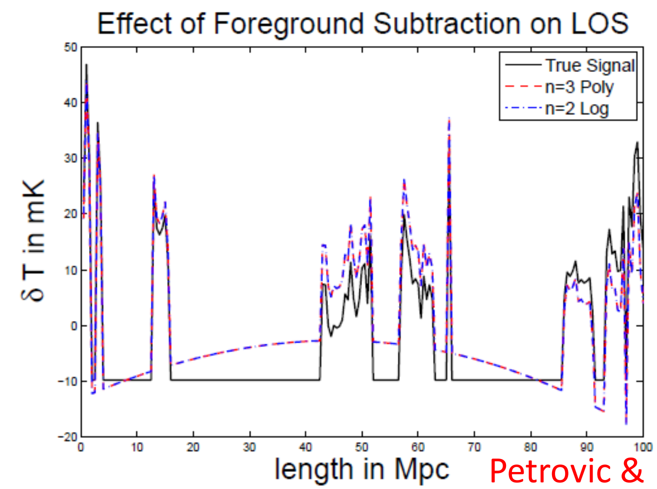
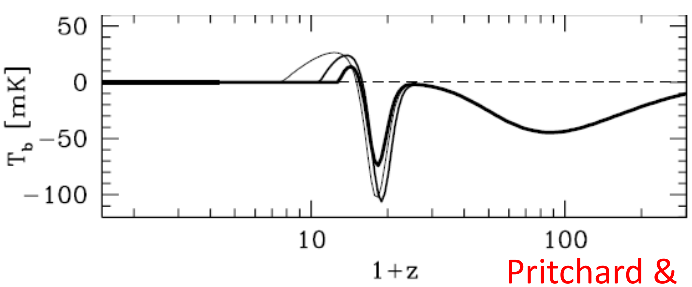
Interferometric and sky-averaged 21-cm foregrounds: similarities

- Foregrounds dominate over signal by orders of magnitude, wherever you look in the sky.
- Use the different spectral structure of the foregrounds and 21-cm signal to distinguish them: there are good reasons to think that many of the foregrounds are spectrally smooth.
- The spatial correlation of signal and foregrounds are also different, though this is less often exploited.
- The foregrounds and the instrument are coupled together strongly: can't remove the foregrounds without understanding both.



Petrovic & Oh (2011)

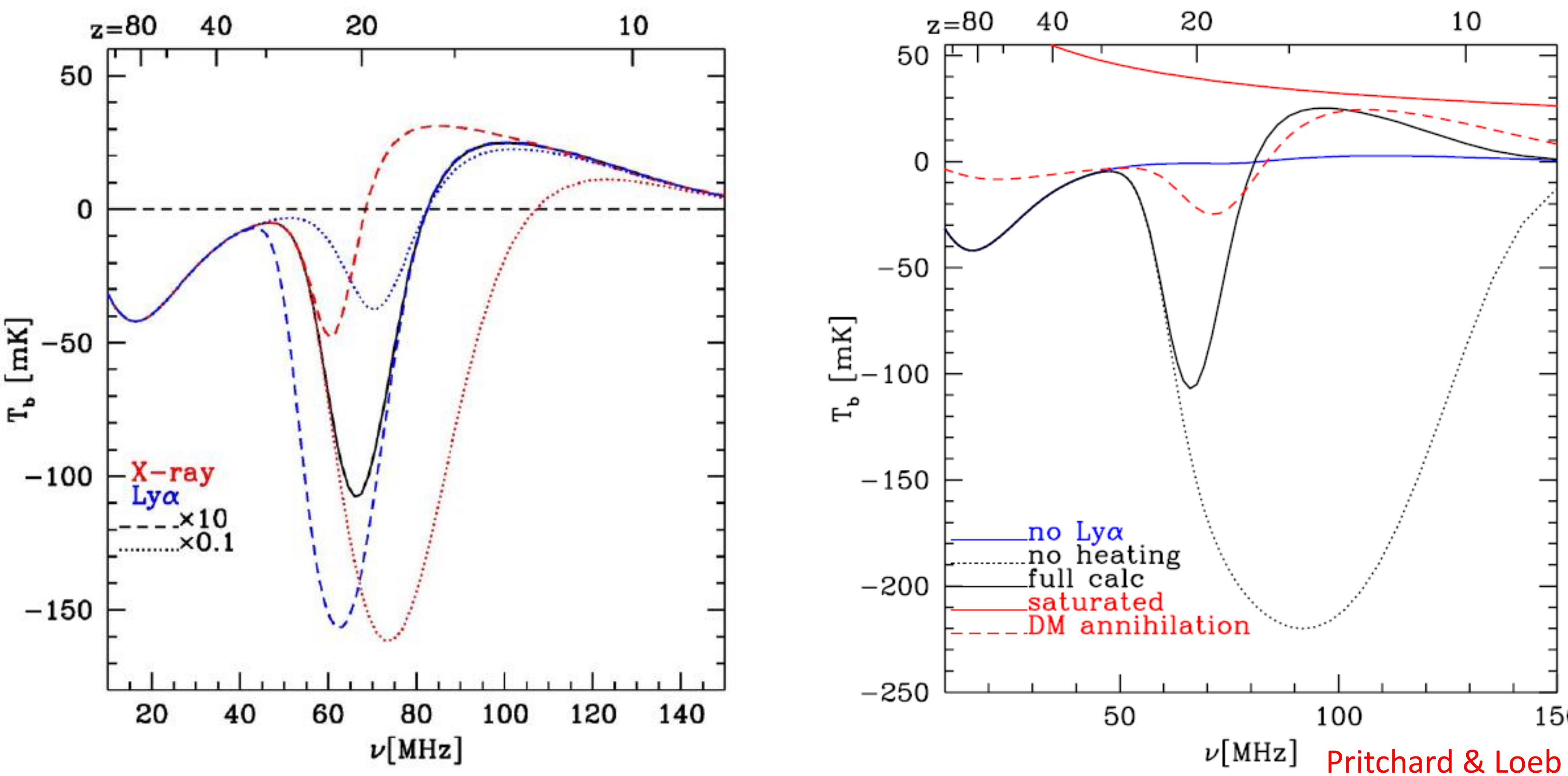


Pritchard & Loeb (2008)

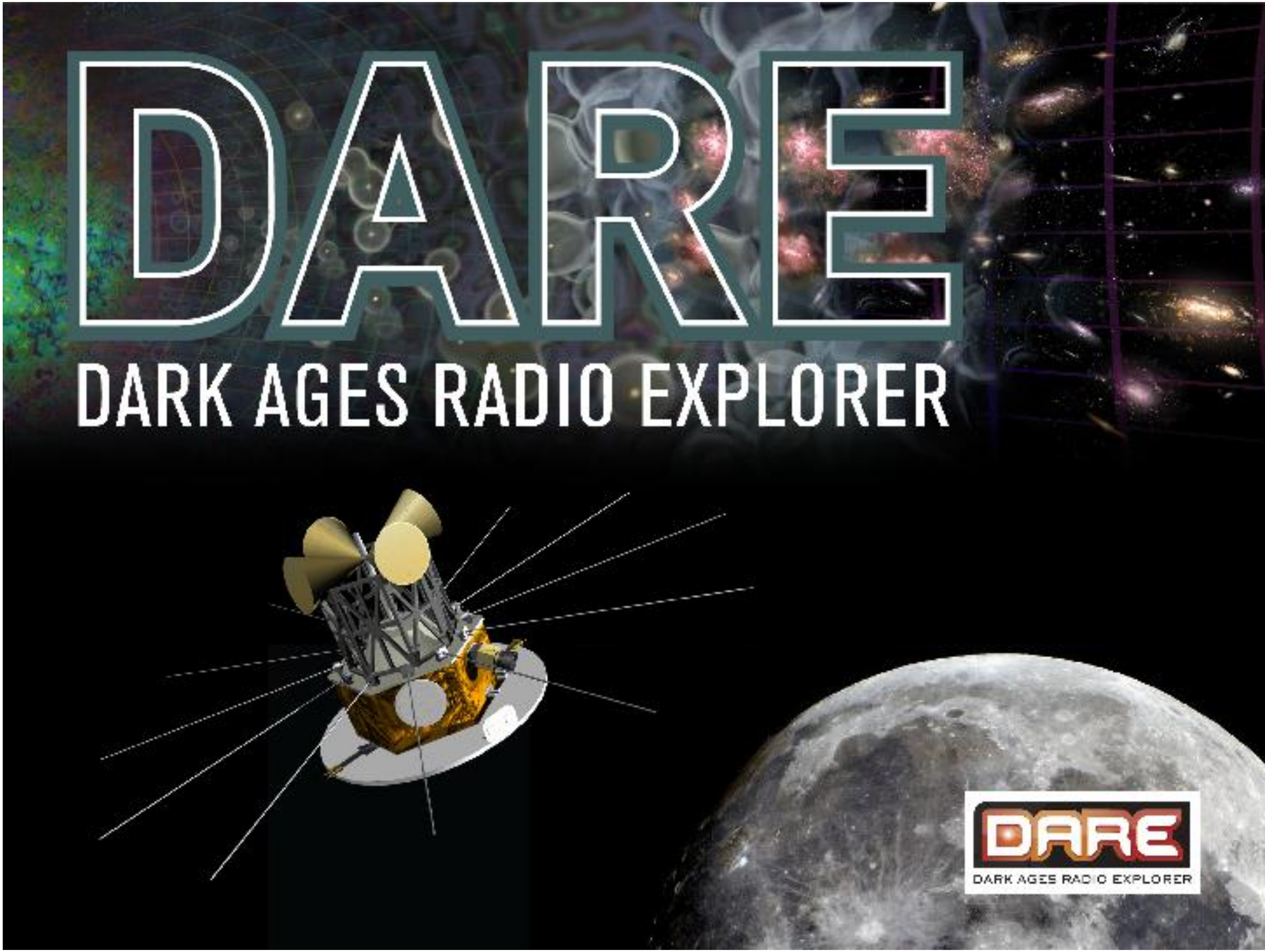
Interferometric and sky-averaged 21-cm foregrounds: differences

- Averaged over a big enough area of sky, the global signal is the same wherever you look whereas the foregrounds vary (could help with subtraction, as suggested by Shaver et al. 1999).
- Point sources are dealt with very differently
  - Carefully subtracted for interferometer experiments
  - Averaged over and treated as a diffuse foreground for global signal experiments
- The signal is a lot smoother in the sky-averaged case, and the foregrounds are effectively much larger (especially for ‘cosmic dawn’ / ‘dark ages’ work), so stronger assumptions need to be made about the foregrounds (and calibration of the frequency response becomes even more crucial: we want a stable environment!).
- Easier to beat down the noise below the level of the signal for the global signal.
- Nothing to cross-correlate the global signal with?
- RFI for the global signal could be even more awkward: can’t be localised, may require a more complicated receiver design, etc., though a single antenna experiment could in principle be much simpler and cheaper.

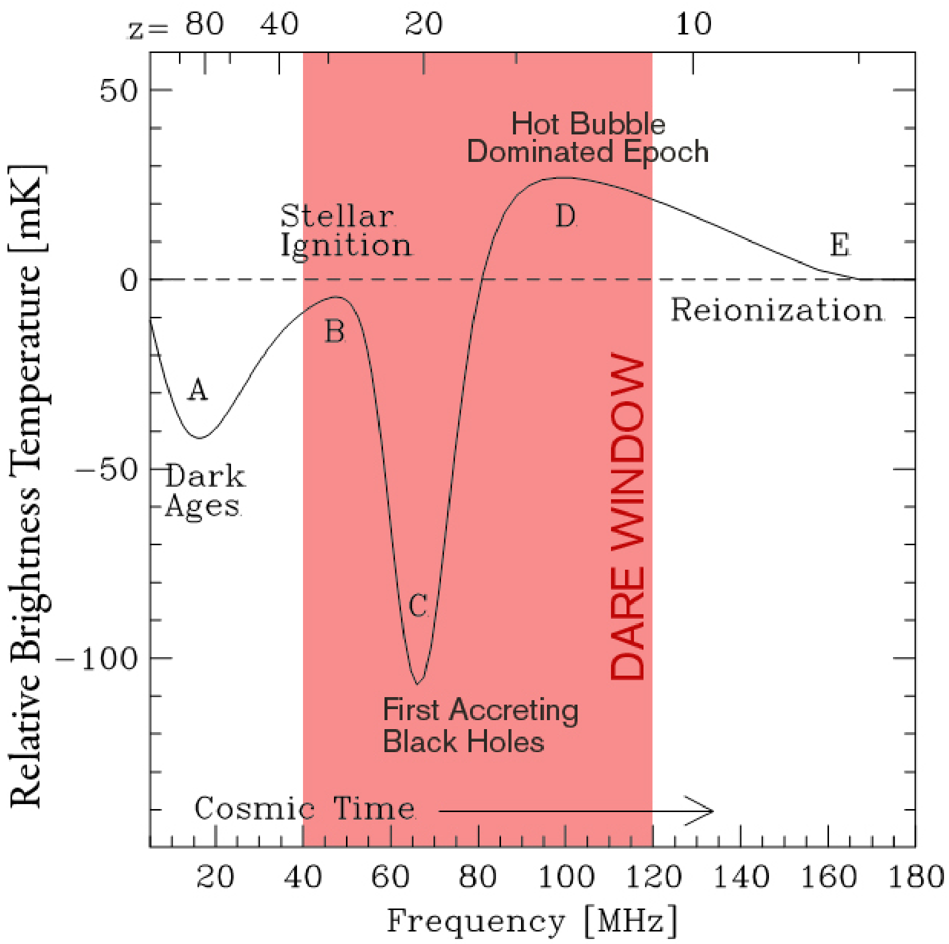
The global 21-cm signal



Pritchard & Loeb (2010)


DARE
DARK AGES RADIO EXPLORER
DARE
DARK AGES RADIO EXPLORER

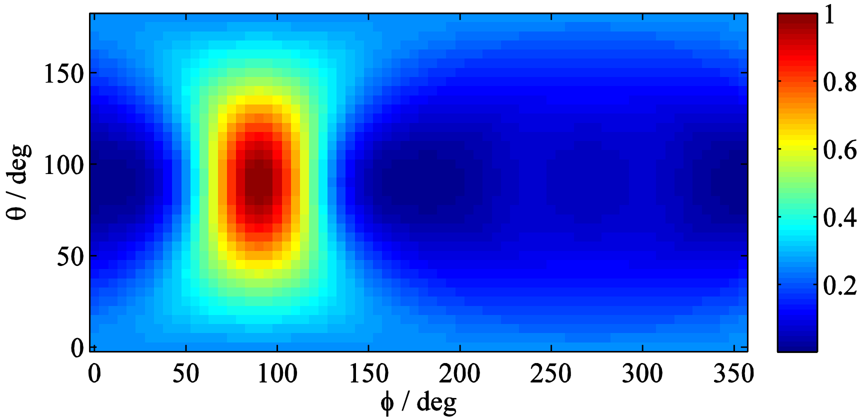
The DARE band



- The antenna is designed to cover a large range in frequency.
- A band of 40-120 MHz gives a good chance of finding both turning point B and turning point D within the band…
- …but a great variety of different models are plausible.
- Extending to even lower frequencies is difficult because of the limited size of a non-deployable antenna on a spacecraft.

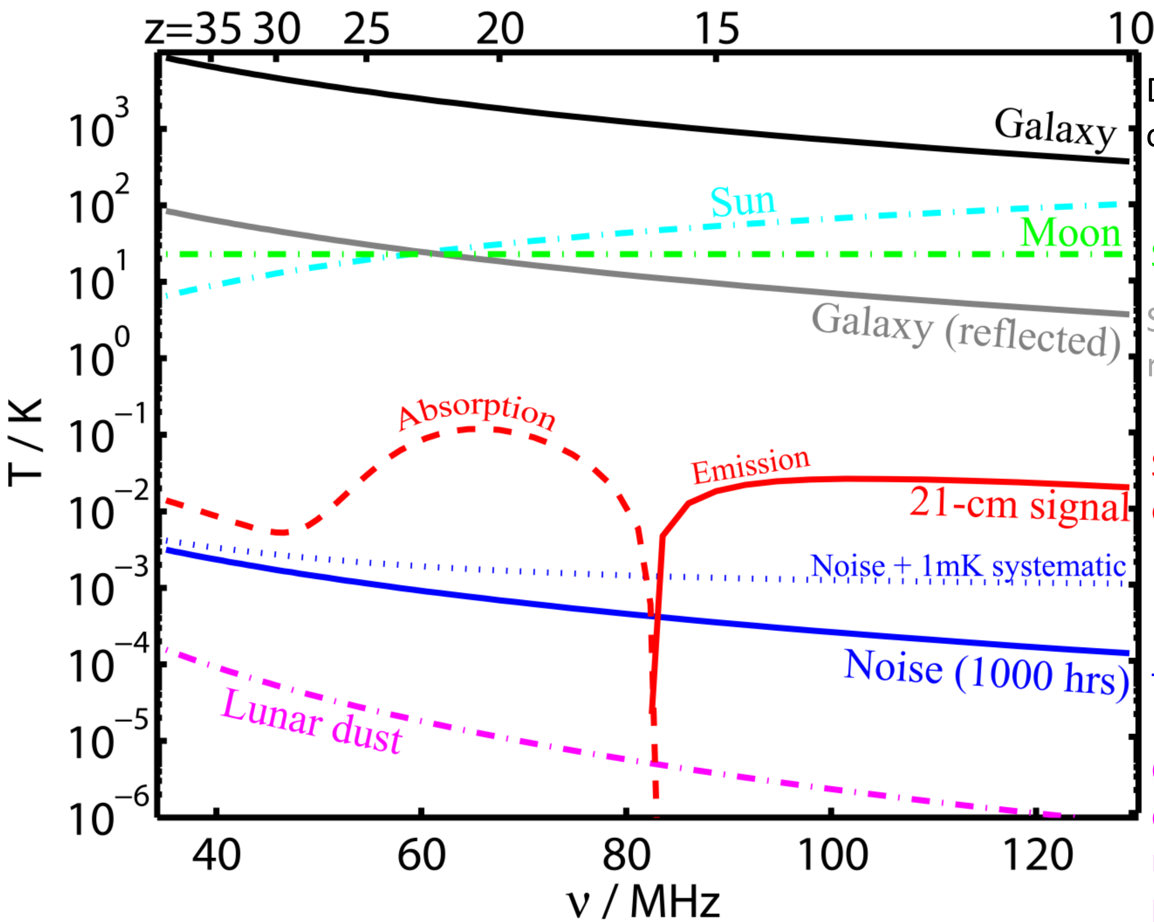
Antenna power pattern

DARE antenna power pattern at 75 MHz



- Radials provide an imperfect ground plane: backlobe is suppressed by only 9-15 dB.
- Effective beam solid angle approx. 1-2 sr depending on frequency.
- At 75 MHz:
  - FWHM≈57°
  - Effective solid angle corresponds to around 1/8 of the sky

Foreground and noise levels



Diffuse foregrounds: log T is a third-order polynomial in log(frequency)

Log T a 3[rd] order polynomial in log(ν)

Single parameter giving the temperature

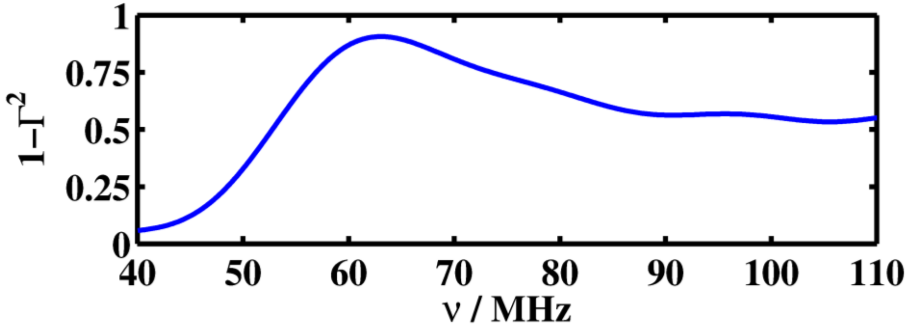
Single parameter for the reflectivity of the Moon

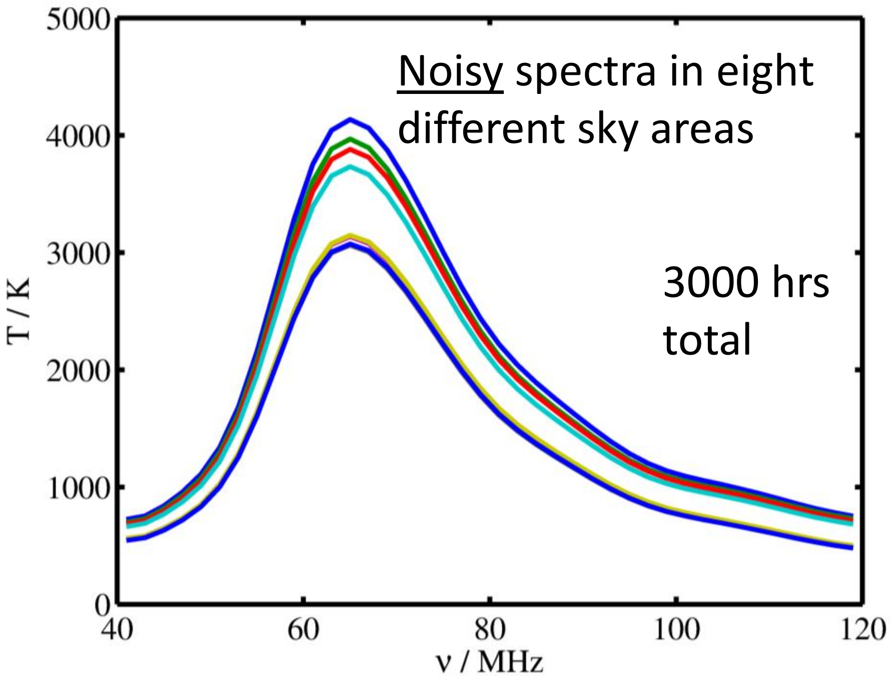
Six parameters: the positions of the turning points

Noise is determined from the antenna temperature by the radiometer equation

Considered negligible; we do not model dust impacts here (likewise radio recombination lines, other spacecraft, planets…)

Instrument frequency response and simulated spectra

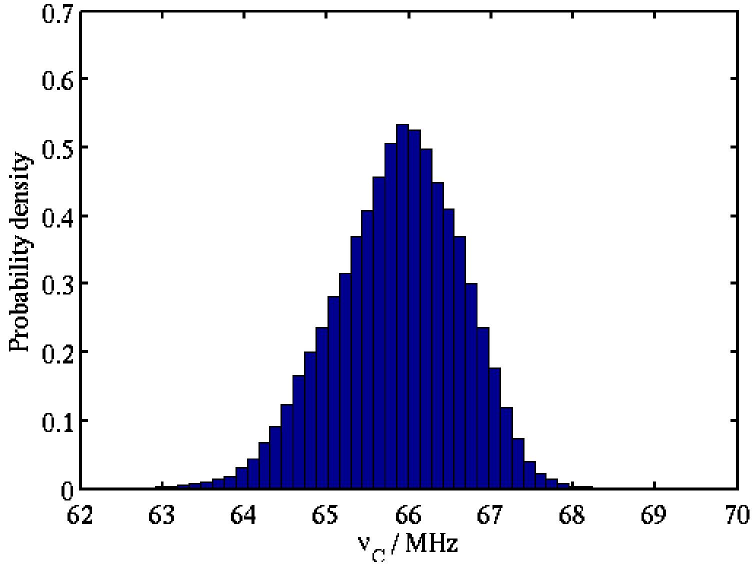




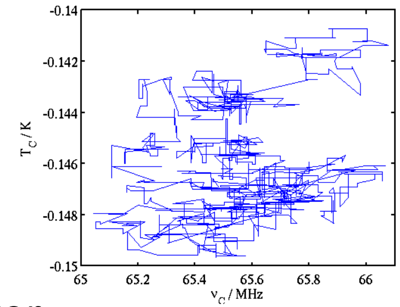
$$
\begin{aligned}
T_{\rm ant}(\nu) = & \left[1 - |\Gamma(\nu)|^2\right] T_{\rm sky}(\nu) \\
& + \left[2\epsilon|\Gamma(\nu)|\cos(\beta) + \epsilon^2|\Gamma(\nu)|^2\cos^2(\beta)\right. \\
& \left. + (1-\epsilon)^2|\Gamma(\nu)|^2\right] T_{\rm rcv}(\nu) + \ldots\,,
\end{aligned}
$$

- Reflection coefficient, Γ(ν), modeled using its ten lowest-frequency discrete cosine transform coefficients.
- ε, cos(β) and the receiver temperature are parameters in our model; the latter is constrained by the magnitude of the thermal noise, as well as the spectrum itself

The Markov Chain Monte Carlo technique



The path taken by part of the Markov Chain through a two-dimensional slice of parameter space. The parameter space has 64 dimensions in our model.

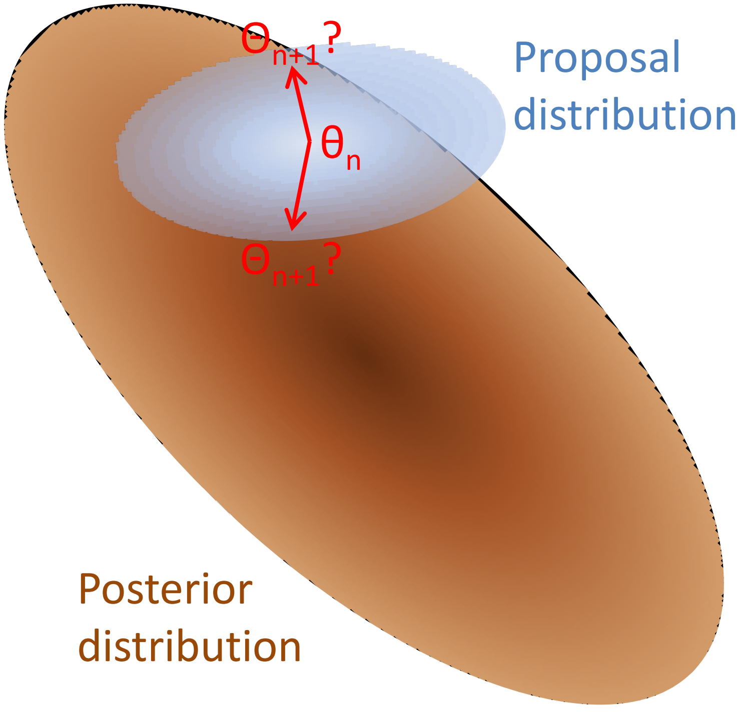


A Markov Chain Monte Carlo simulation allows us to draw unbiased, random samples from the posterior probability distribution of the parameters we're trying to find.

Parameter group	No. of parameters
21-cm signal	3x2 = 6
Diffuse foregrounds	4x8 = 32
Sun	8 + 3 = 11
Moon	2
Instrument	13
Total	**64**

Efficiently exploring parameter space

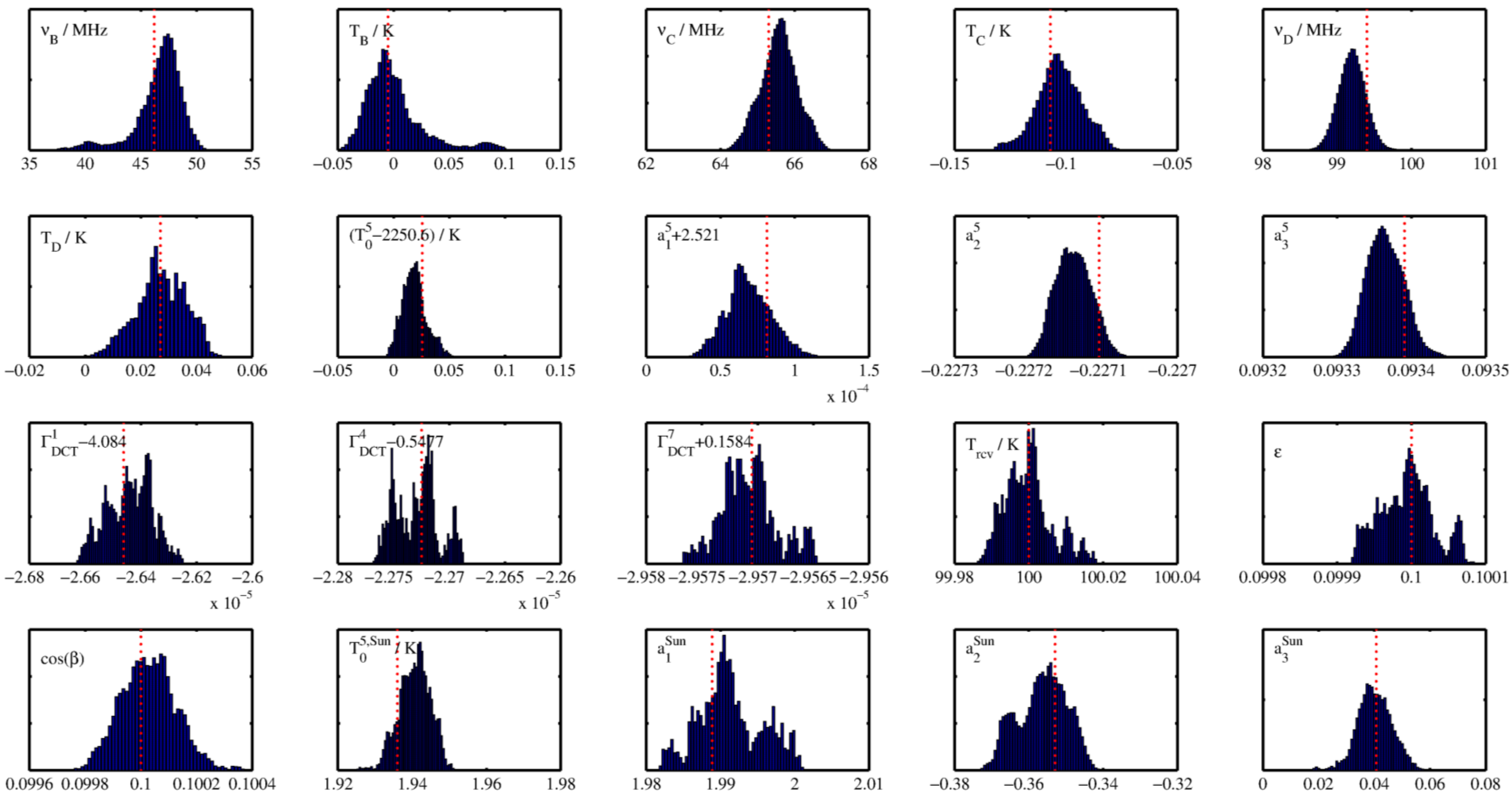
- Suppose we have just drawn a sample at position θ_n.
- We propose a subsequent link in the chain according to the proposal distribution.
- If this point is at a higher likelihood (a better fit to the data) it is accepted as the next point in the chain.
- If the point is at a lower likelihood, it is still accepted with some probability, allowing the chain to move round in parameter space.
- The form of the proposal distribution is crucial to the efficiency of the algorithm.



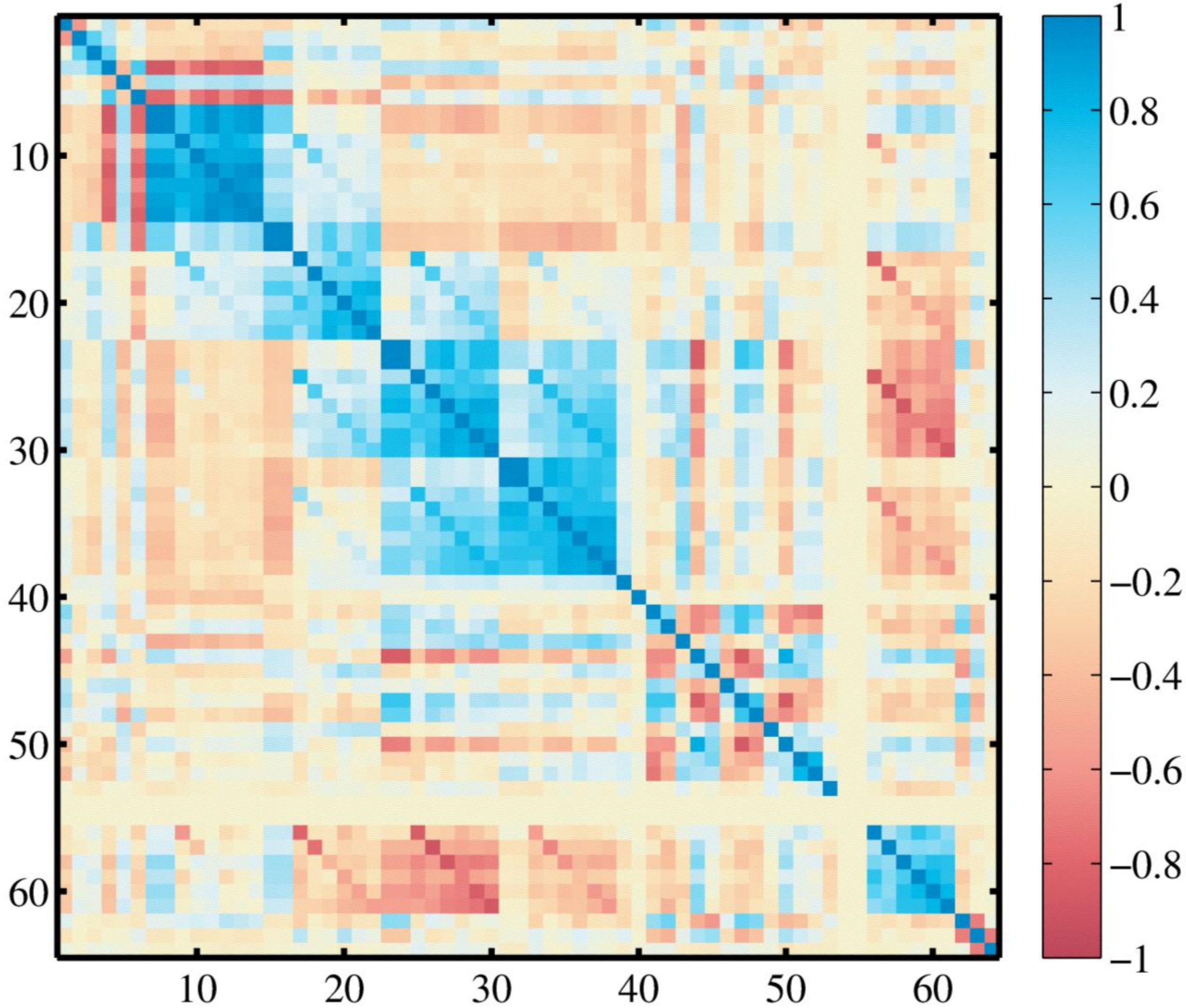
More details of the MCMC implementation

- Proposal distributions of similar size and shape to the posterior distribution improve efficiency by increasing the probability that new points are accepted (have to evaluate the likelihood fewer times).
- We estimate the posterior distribution as we go along to improve the proposal distribution.
- Typical acceptance rates of around 70% by automating the choice of proposal distribution.
- We must also know when we have enough samples: we've tested this is the case using a Gelman-Rubin test (running several chains in parallels and comparing the variance between chains to the variance within chains).

Results: 1-dimensional marginalized posterior distributions

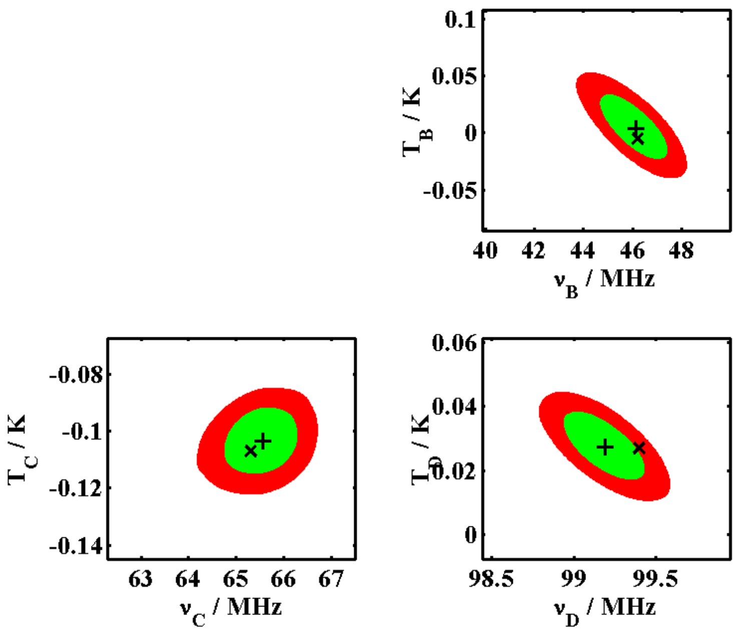


Correlation matrix of the parameters

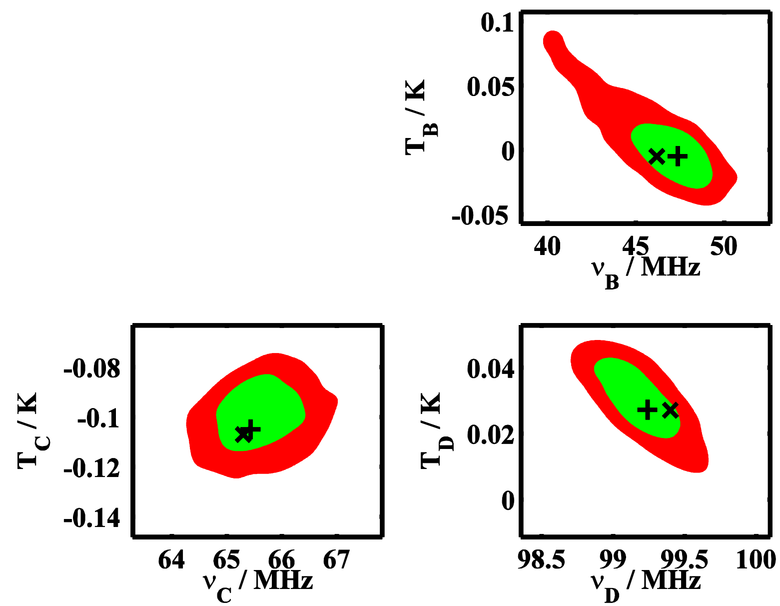


Results: position of the turning points

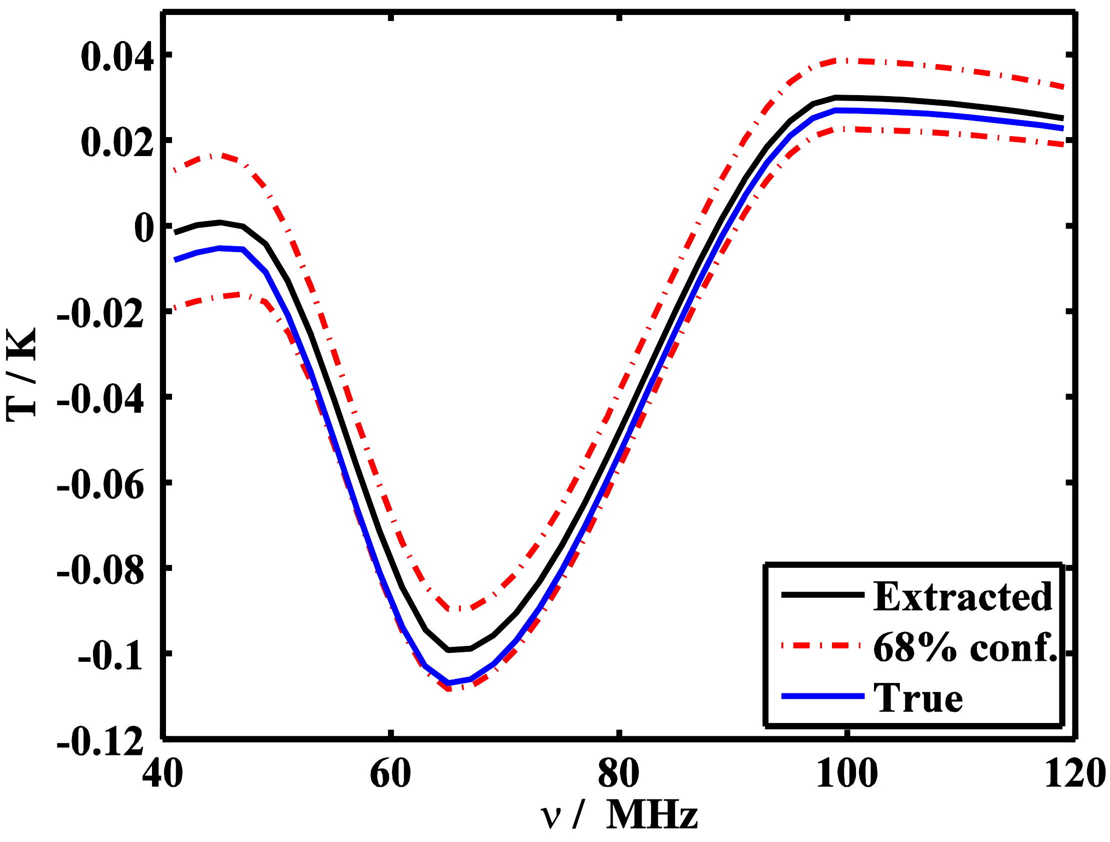
3000 hours, perfect instrument



3000 hours, tight priors

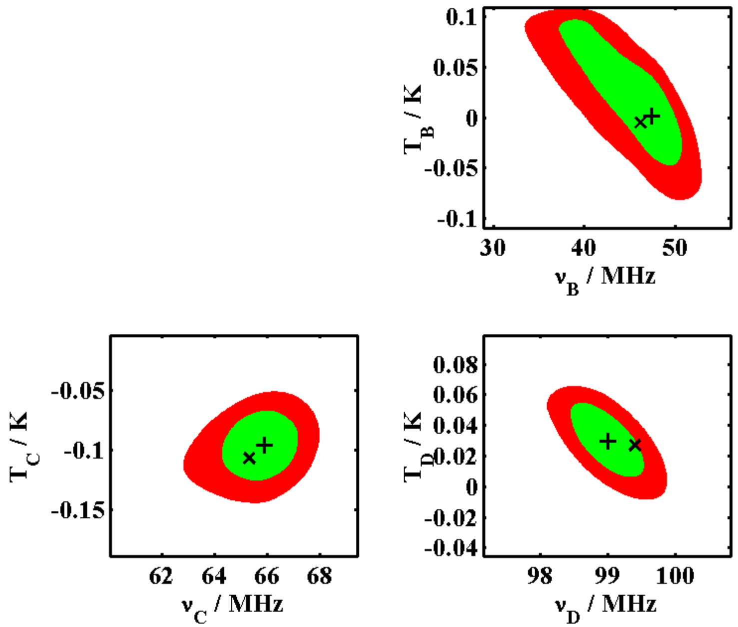


Signal derived from the position of the turning points

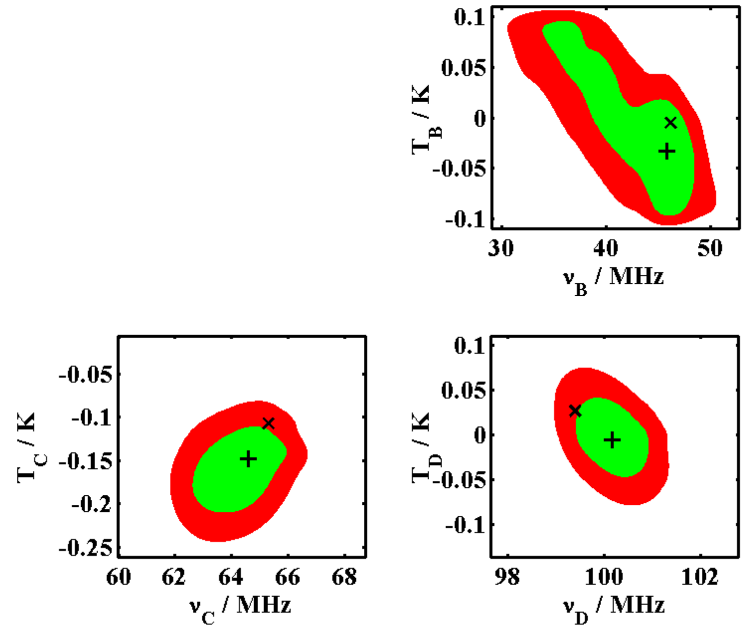


Less optimistic assumptions

1000 hours



No prior information about the parameters



Conclusions

- The 21-cm signal is dominated by foregrounds from various sources.
- We have developed a model for the spectra measured by DARE using parametrized models for these foregrounds, the redshifted 21-cm signal and the instrumental response.
- We fit the parameters from this model, and find confidence regions on those parameters, using an MCMC code developed for the purpose.
- A fiducial, 3000 hr dataset gives tight constraints on the 21-cm signal.
- For a 1000 hr data set, turning points C and D may still be recovered well.
- Further work is required to study:
  - A wider range of 21-cm histories and parametrizations
  - More sophisticated models of some of the foregrounds
  - Dealing with a situation where we have less prior information
  - The validity of our assumptions about the smoothness of the foregrounds
  - Constructing the spectra in the eight sky regions given the 1 s, 10 kHz data DARE is expected to produce.

Questions?