Extracting the 21-cm signal* from the cosmic dawn

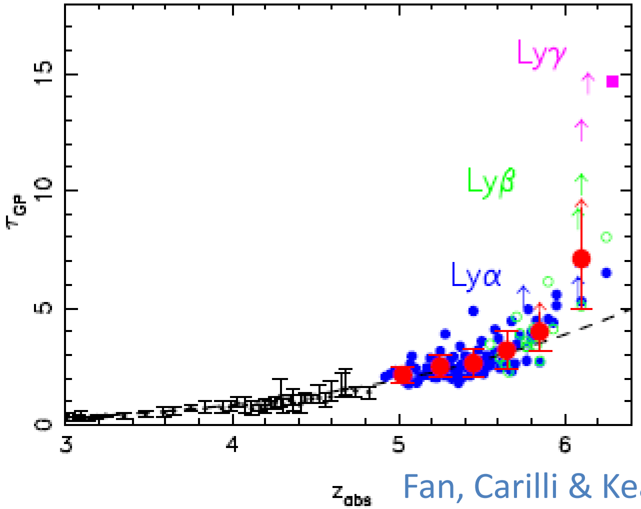
*(especially the sky-averaged 21-cm signal)

Geraint Harker

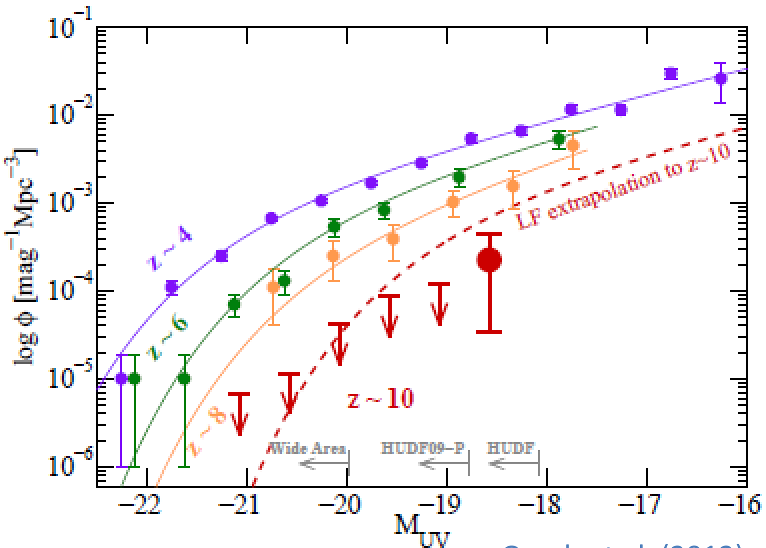
Stages in the evolution of the Universe, from redshift 1100 to 6

DARE proposal; graphics adapted from A. Loeb, 2006, *Scientific American*, 295, 46

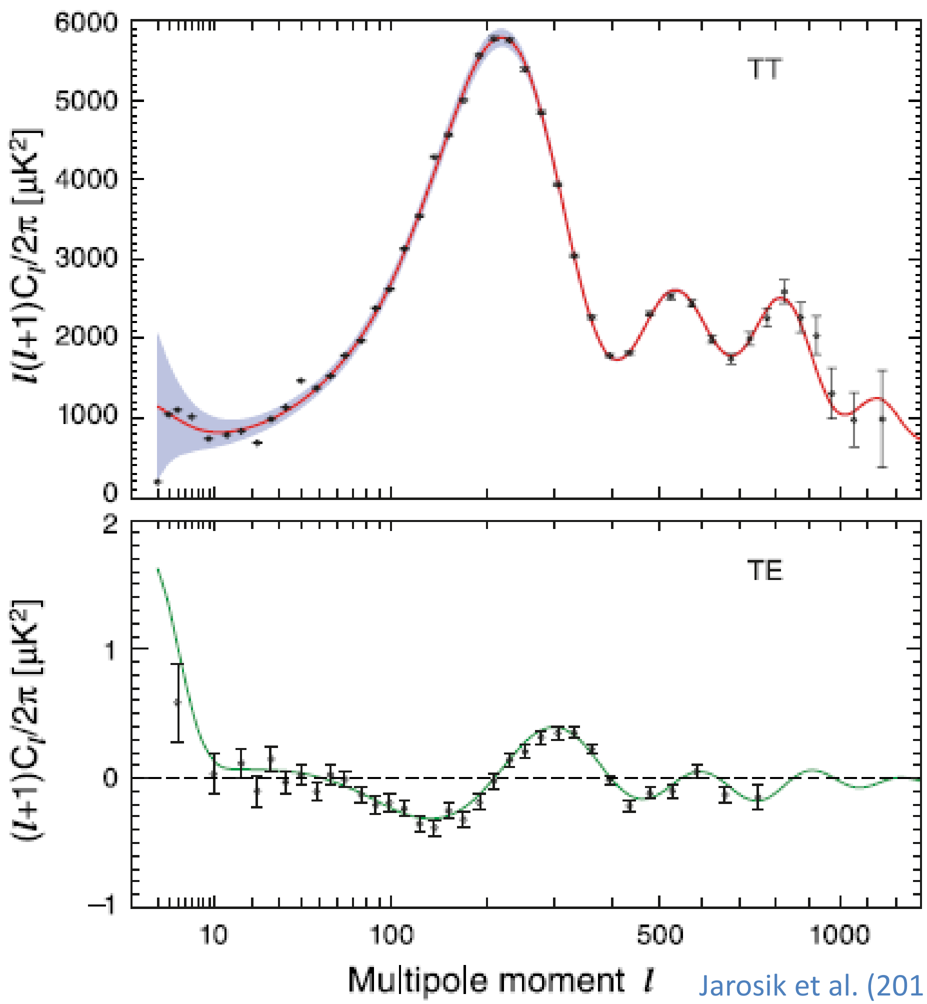
Observational constraints on the z>6 Universe



Fan, Carilli & Keating (2006)



Oesch et al. (2012)

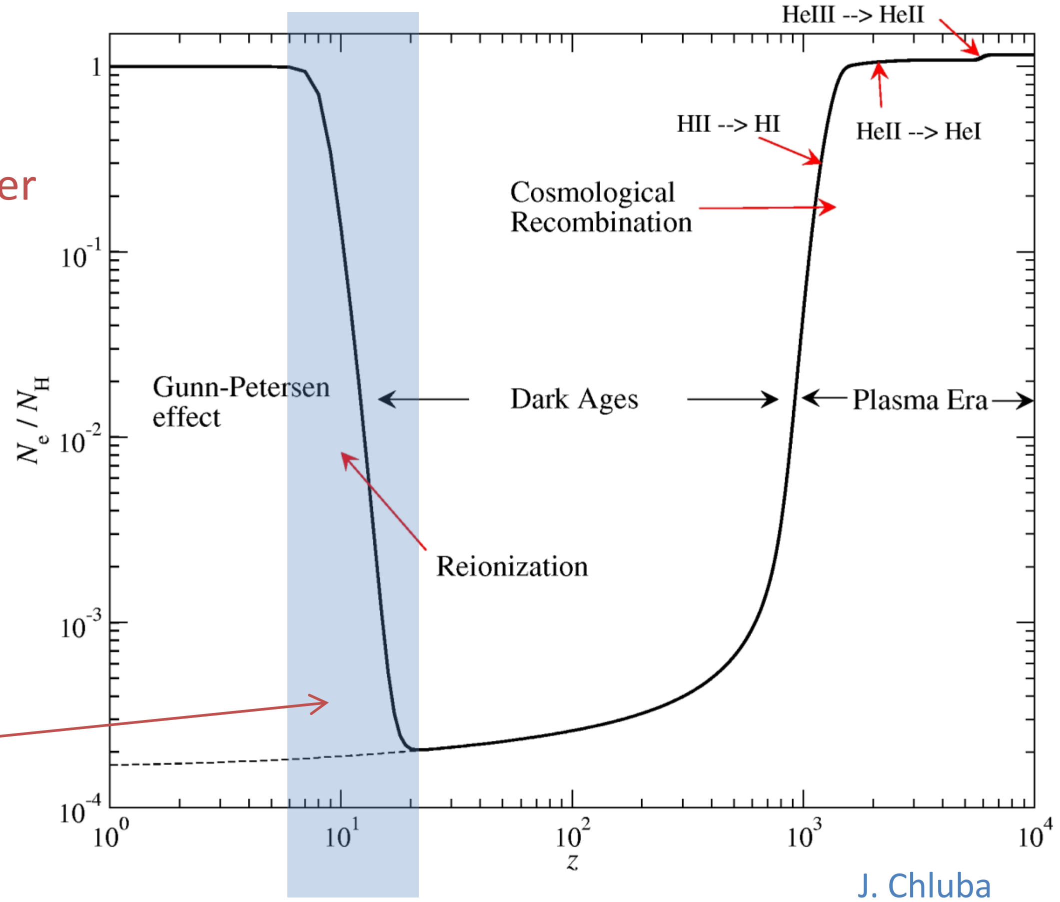


Jarosik et al. (2011)

Ionization fraction

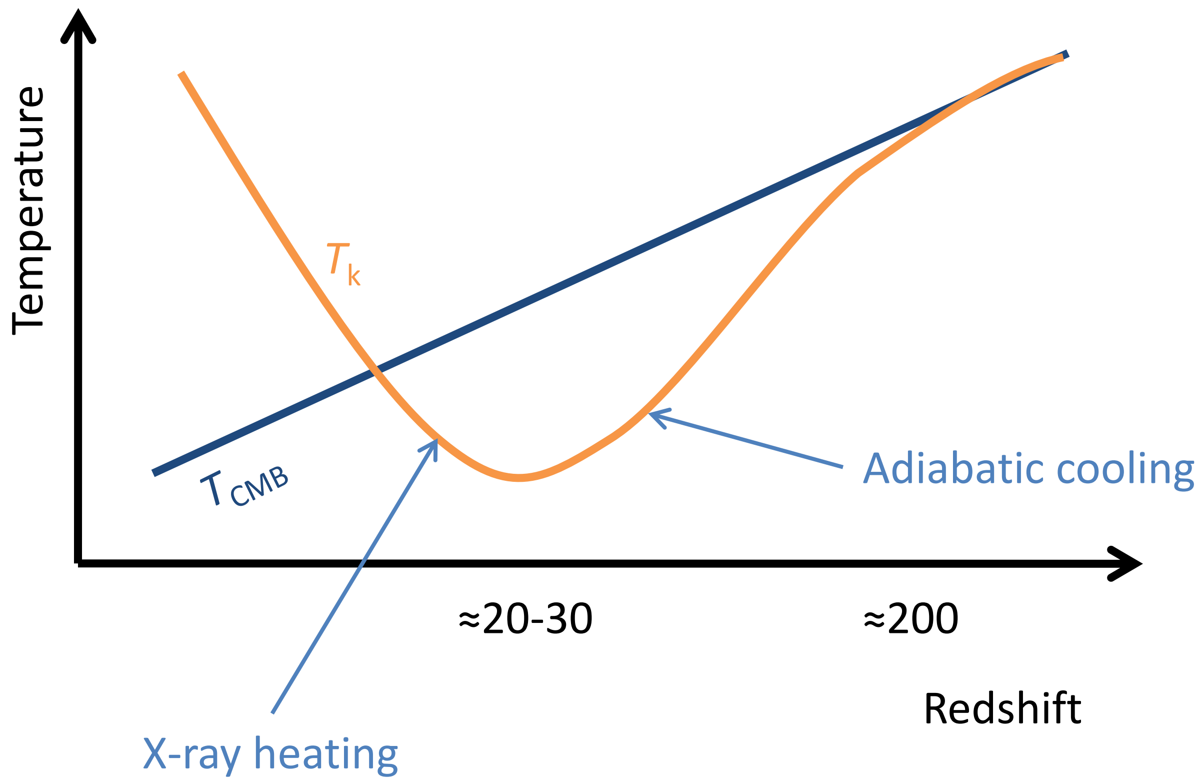
Number density of free electrons divided by number density of hydrogen atoms

Epoch of reionization (EoR)



J. Chluba

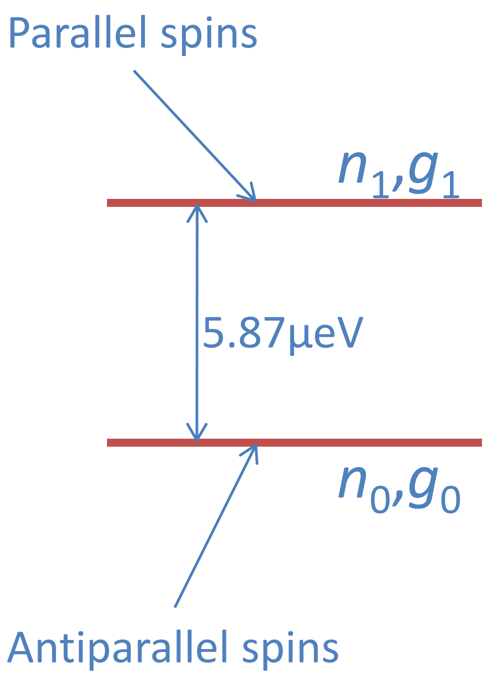
Temperature evolution



The hydrogen 21-cm line

$$\frac{n_1}{n_0} = \frac{g_1}{g_0} \mathrm{e}^{-T_*/T_\mathrm{spin}} \qquad (T_* = 0.068\mathrm{K})$$

Hydrogen 1s ground state



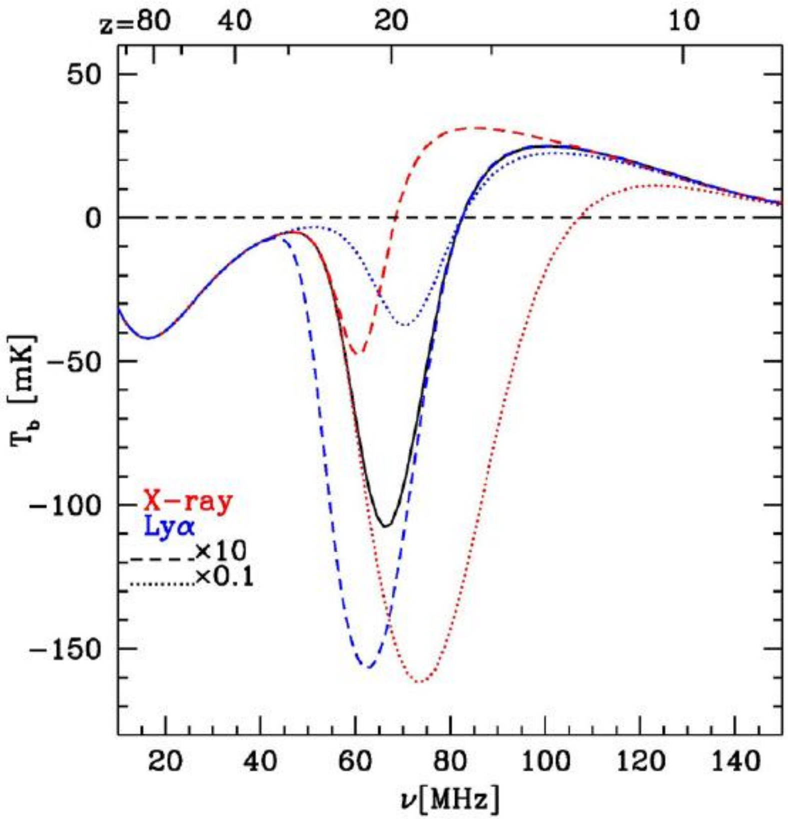
'Colour temperature', shown to be equal to T_k for the situation studied here

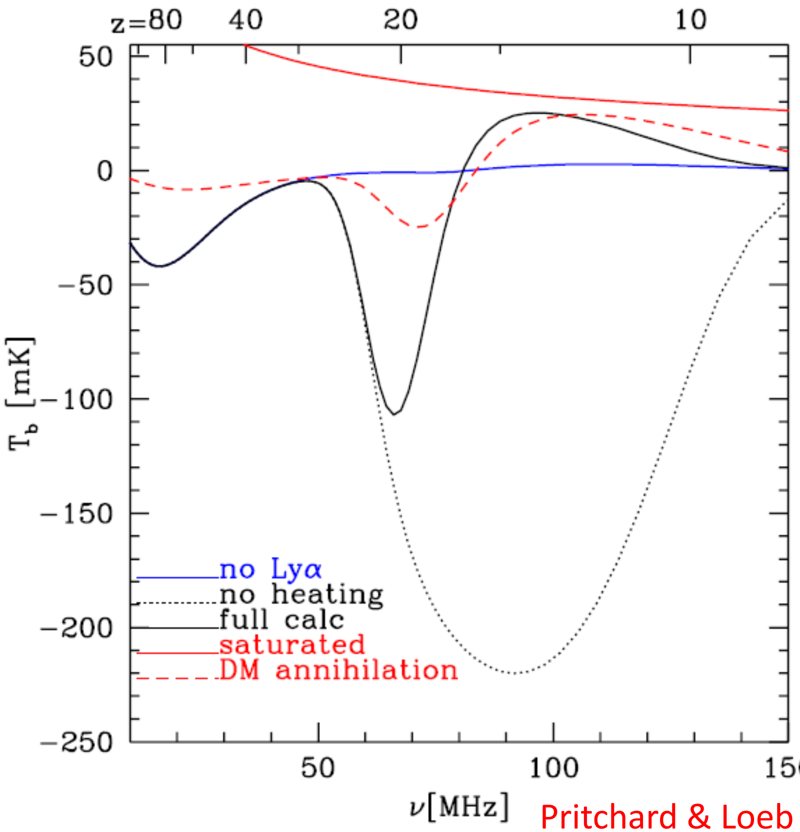
$$T_\mathrm{spin} = \frac{T_\mathrm{CMB} + y_\alpha T_\alpha + y_\mathrm{c} T_\mathrm{k}}{1 + y_\alpha + y_\mathrm{c}}$$

Field, 1958, Proc. IRE

$$\delta T_\mathrm{b} = \frac{T_\mathrm{spin} - T_\mathrm{CMB}}{1+z} \overbrace{(1 - \mathrm{e}^{-\tau_{\nu_0}})}^{\approx\, \tau_{\nu_0} \propto 1/T_{spin}}$$

The global 21-cm signal

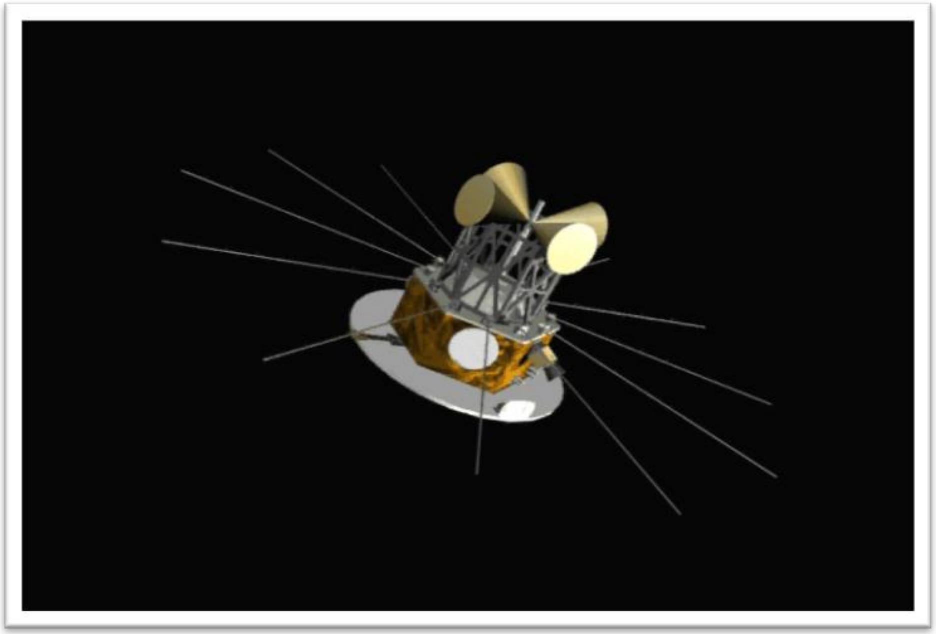




Pritchard & Loeb (2010)

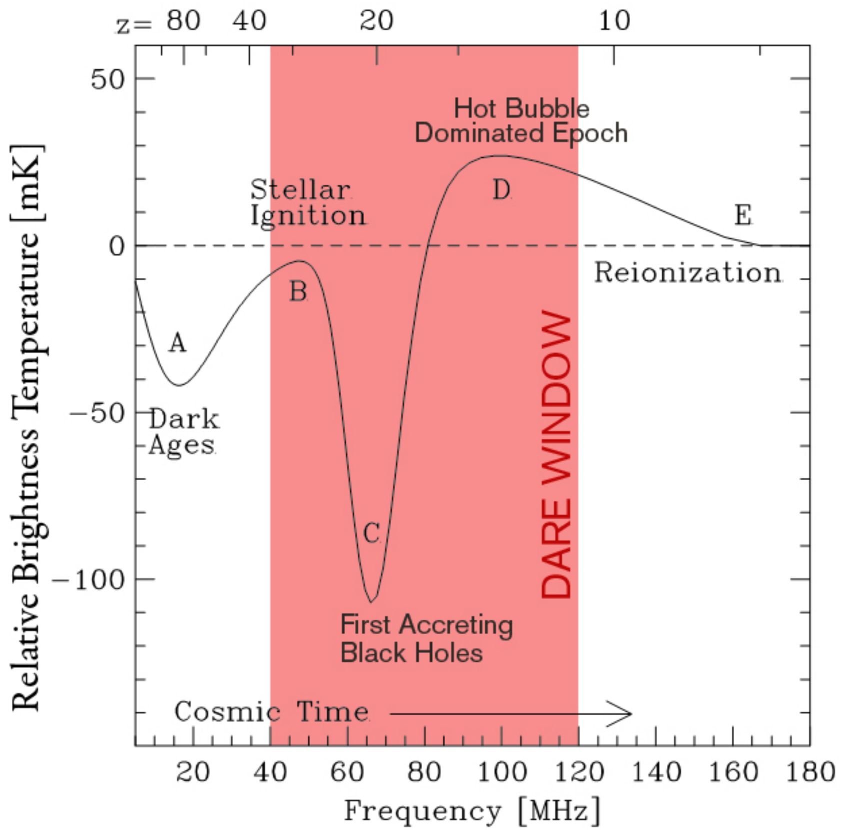
Global 21-cm experiments

- DARE
- EDGES
- CoRE/CoRE2
- BIGHORNS
- LEDA (LWA)

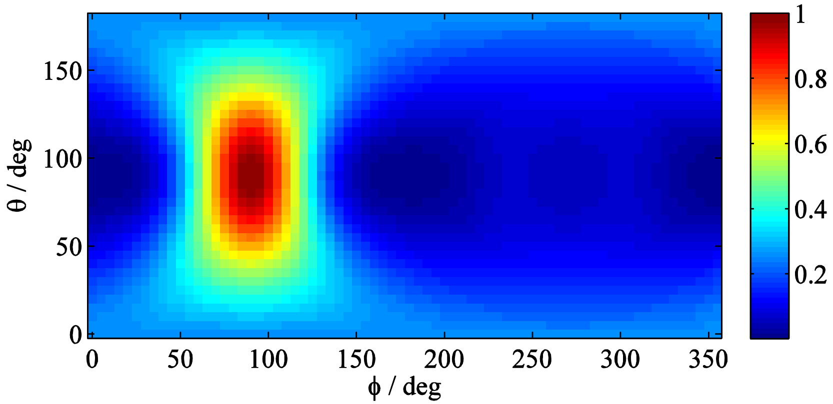


- Operates over the lunar farside
- Escapes RFI
- Whole sky available; beam covers ≈1/8 of the sky
- No ionospheric distortion or contribution to the spectrum.

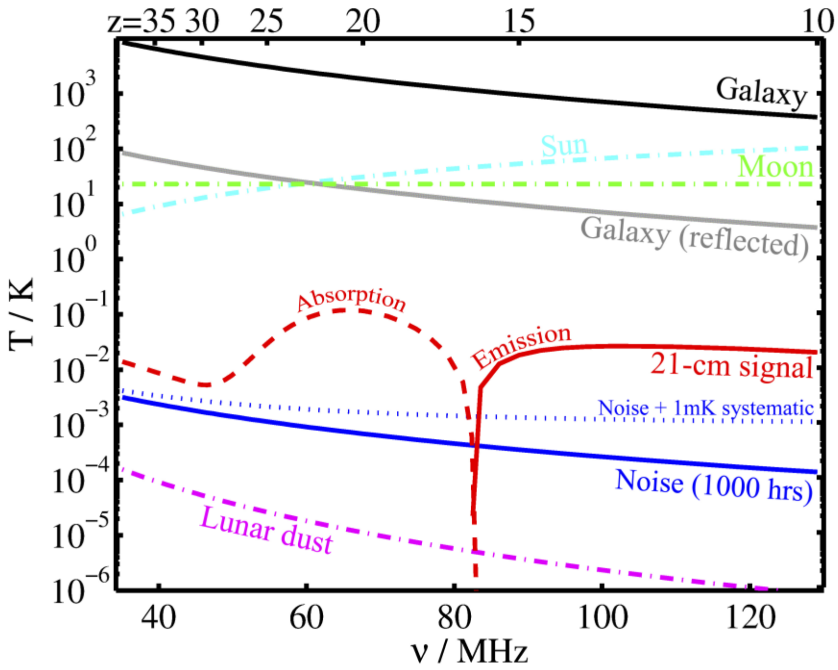
Basic parameters of the DARE experiment

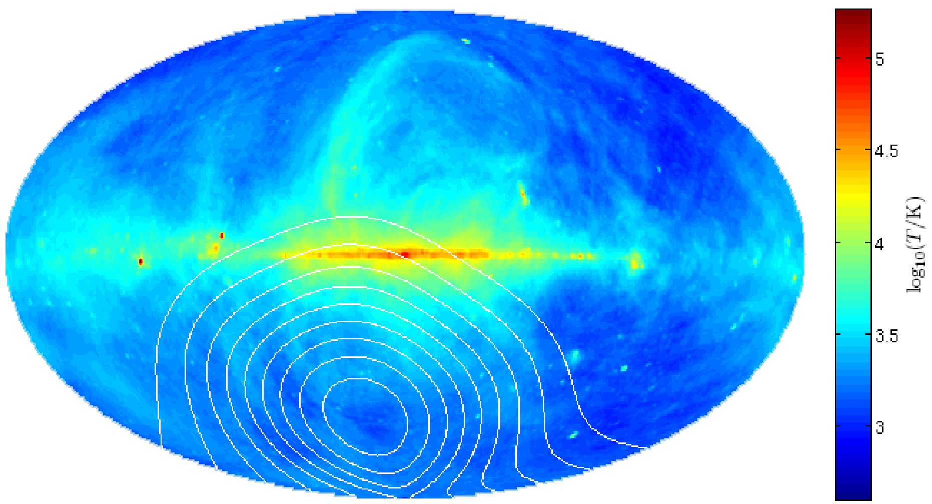


DARE antenna power pattern at 75 MHz



Foregrounds



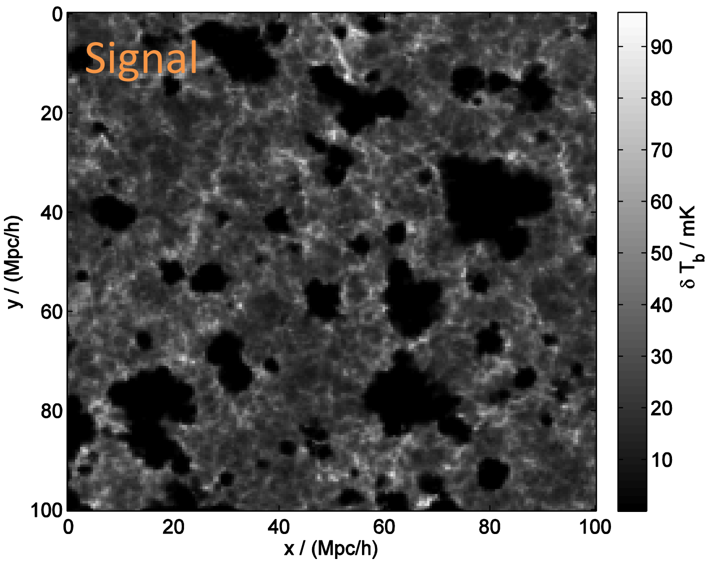


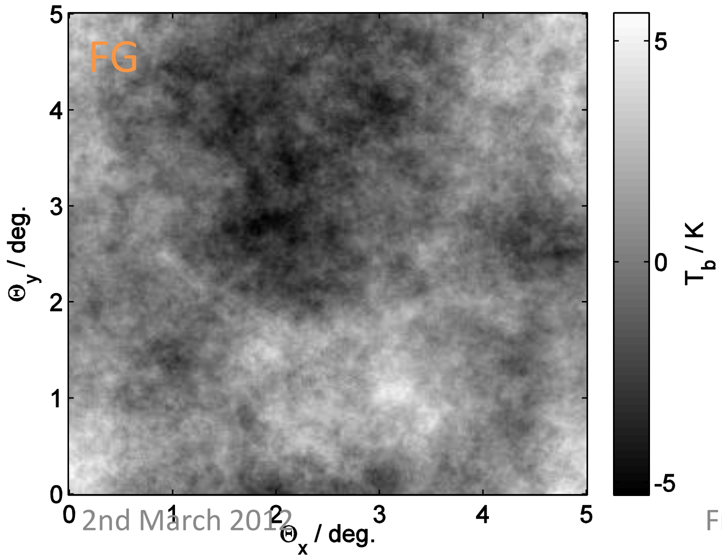
de Oliveira-Costa et al. (2008)

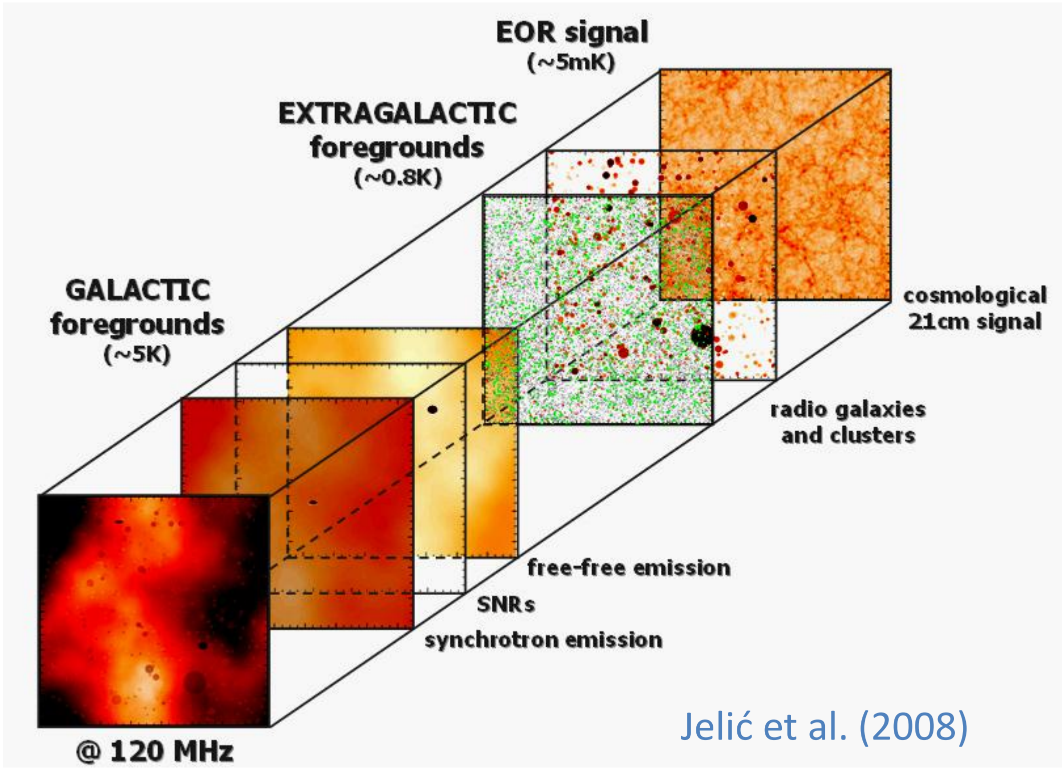
Spectrally smooth…

… but spatially variable

Similar-looking problem for experiments going after spatial information



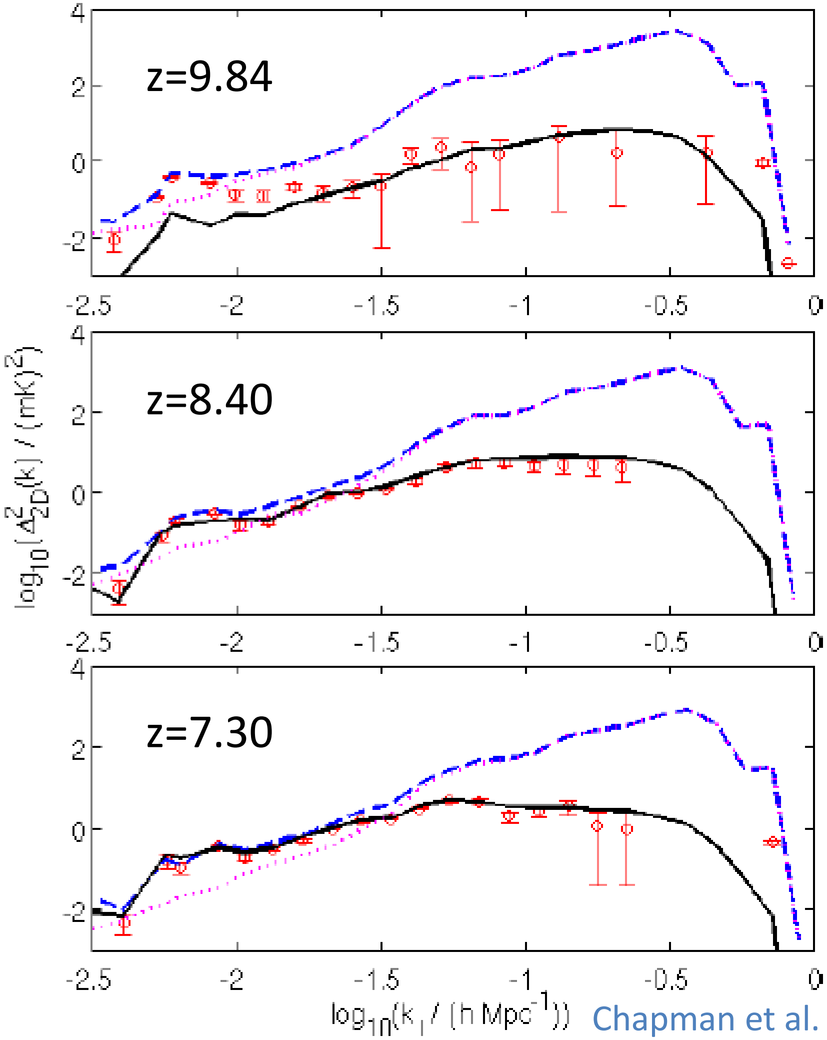




Jelić et al. (2008)

Independent component analysis

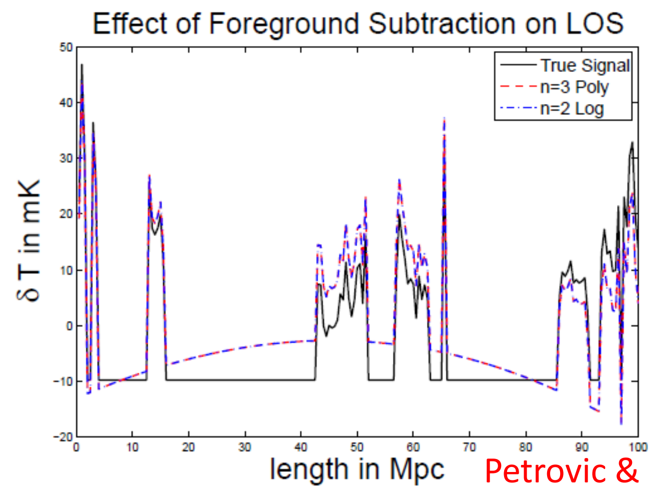
- Sophisticated foreground removal tools have been developed for the CMB and for interferometric 21-cm experiments.
- ICA uses the statistical independence of the foregrounds and signal to separate the two with minimal assumptions.
- Uses the fact that we have many different samples of the signal and foreground from the many pixels of the interferometric map.
- Other approaches:
  - Wp smoothing: uses smoothness of foregrounds directly
  - Even fitting simple parametric models seems to work OK.



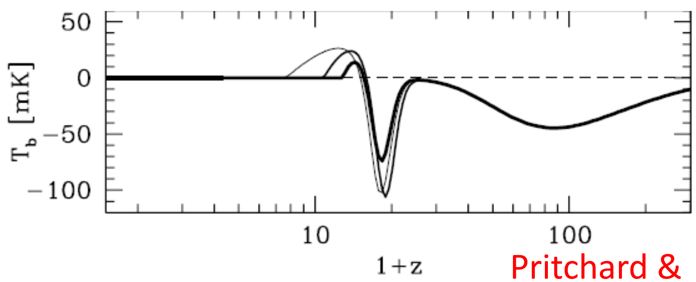
Chapman et al. (2012)

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 (c.f. simultaneous fitting of signal and instrument in e.g. FIRAS analysis).



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, but see e.g. Datta, Bowman & Carilli (2010) or Morales et al. (2012).
  - 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.

Recovering the shape of the global 21-cm signal from simulated DARE data

Developed parametrized models of the signal and foregrounds in eight directions:

- Galaxy and diffuse extragalactic sources
- Sun
- Moon (emission and reflections)
- Instrument

- Simulate data
- Fit the parameters and derive errors with a Markov Chain Monte Carlo code

Bayesian inference

Parameters

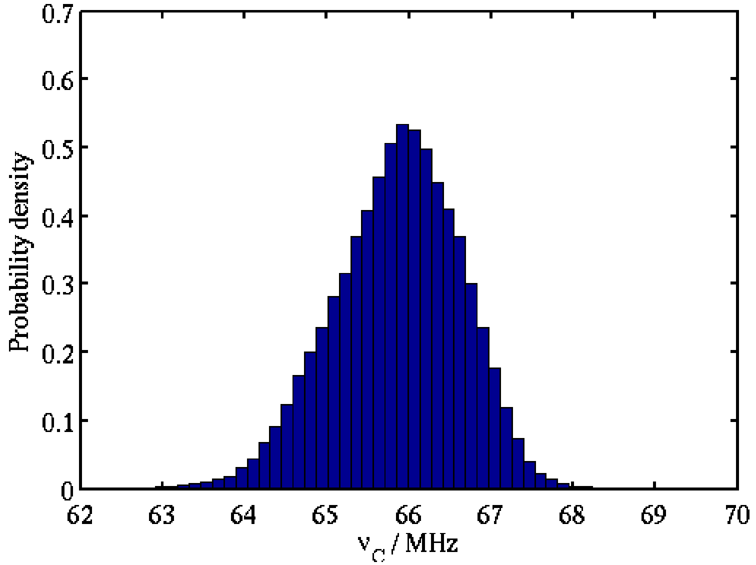
Data

$$\underbrace{\boxed{\Pr(\boldsymbol{\Theta}|\mathbf{D},H)}}_{\text{Posterior}} = \frac{\overbrace{\boxed{\Pr(\mathbf{D}|\,\boldsymbol{\Theta},H)}}^{\text{Likelihood, }\mathcal{L}(\Theta)}\overbrace{\boxed{\Pr(\boldsymbol{\Theta}|H)}}^{\text{Prior, }\pi(\Theta)}}{\underbrace{\boxed{\Pr(\mathbf{D}|H)}}_{\text{Evidence, }\mathcal{Z}}}$$

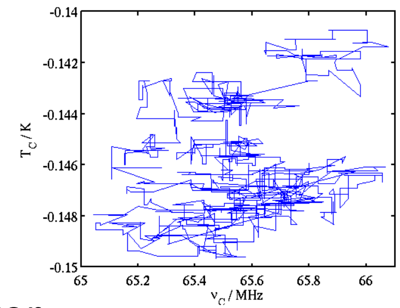
Hypothesis or model

$$\mathcal{Z} = \int \pi(\Theta)\mathcal{L}(\Theta)d^N\Theta$$

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 73 dimensions in our model.



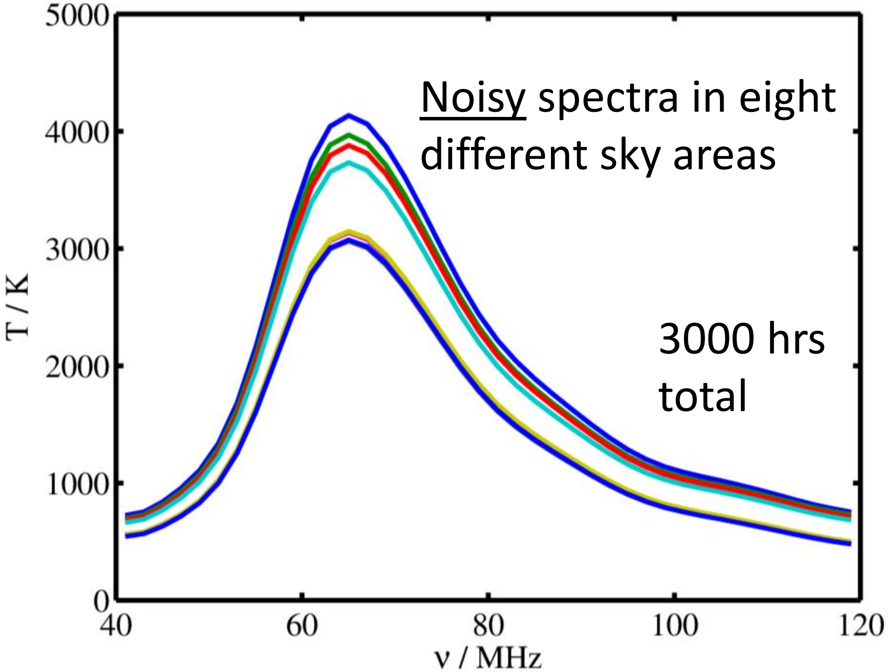
A Markov Chain Monte Carlo simulation allows us to draw unbiased, random samples from the posterior probability distribution of the parameters we're trying to find.

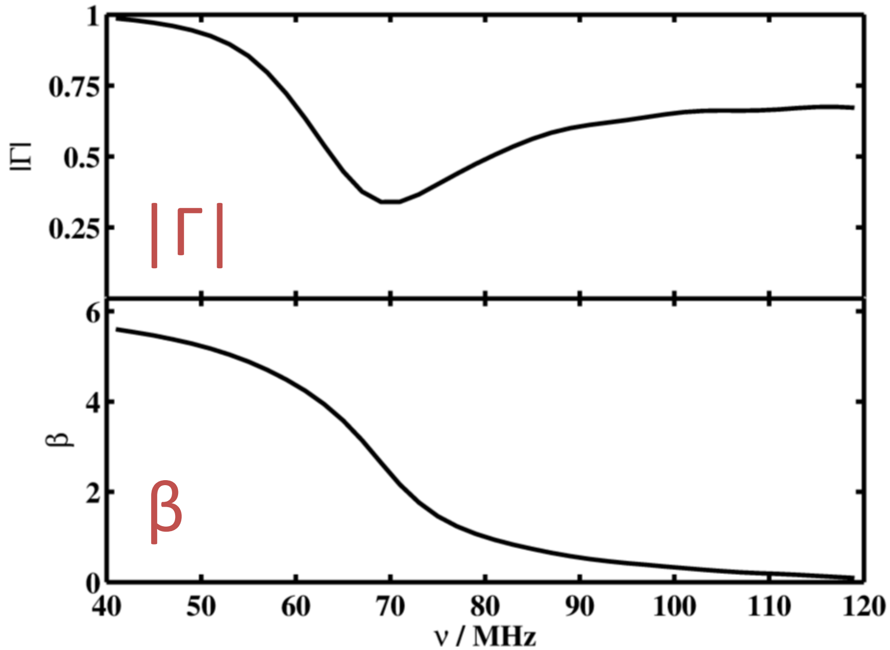
Parameter group	No. of parameters
21-cm signal	3x2 = 6
Diffuse foregrounds	4x8 = 32
Sun	8 + 3 = 11
Moon	2
Instrument	22
Total	**73**

Instrument frequency response and simulated spectra

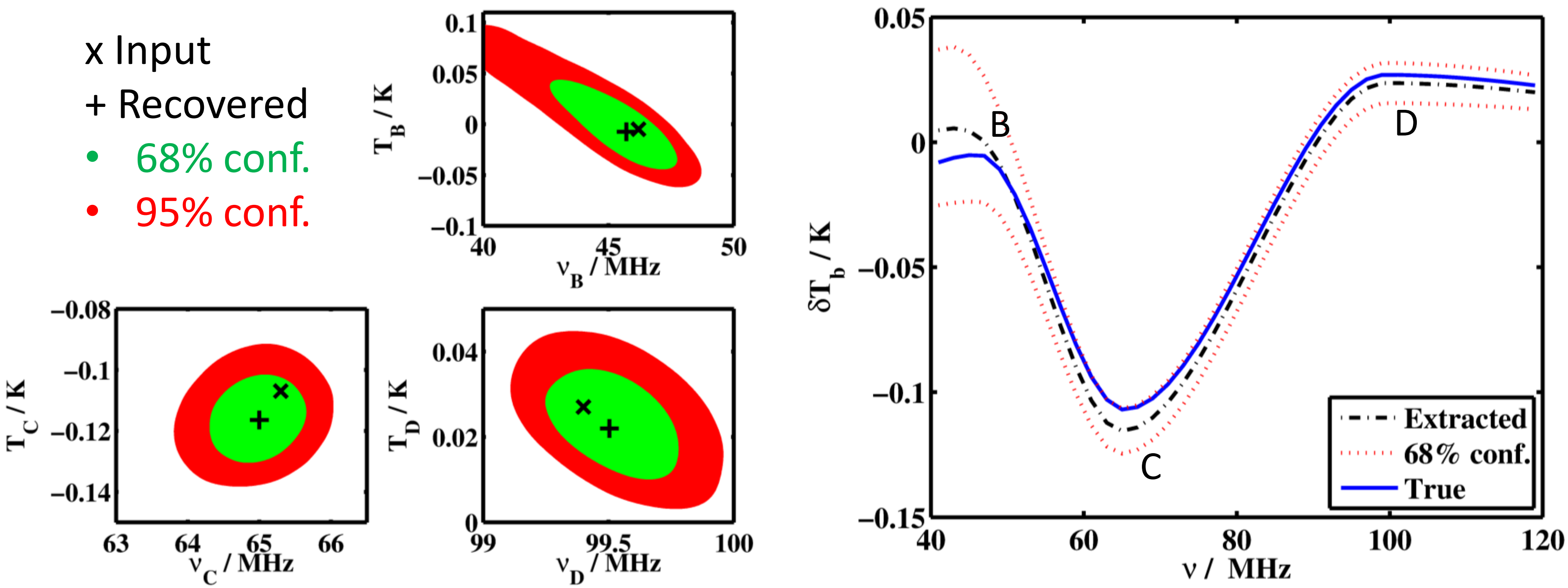
$$T_{\rm ant}(\nu) = T_{\rm a} + |\Gamma(\nu)|^2 T_{\rm b} + 2T_{\rm c}|\Gamma(\nu)|\cos\left[\beta(\nu) + \phi_{\rm c}\right] + T_{\rm sky}(\nu)\left[1 - |\Gamma(\nu)|^2\right]$$

Take $T_c = \varepsilon T_b = \varepsilon T_a$

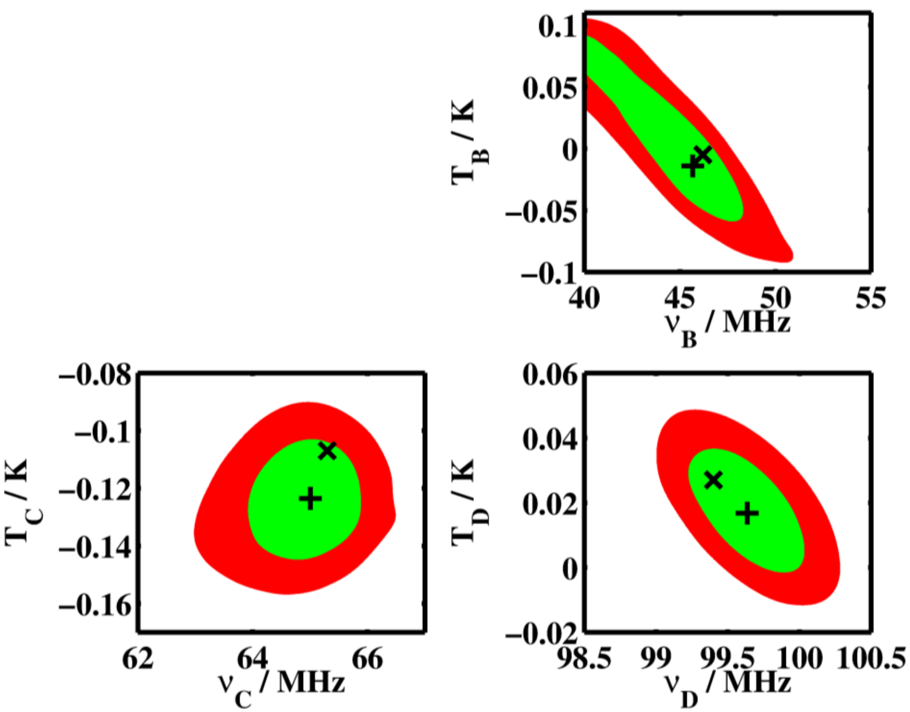


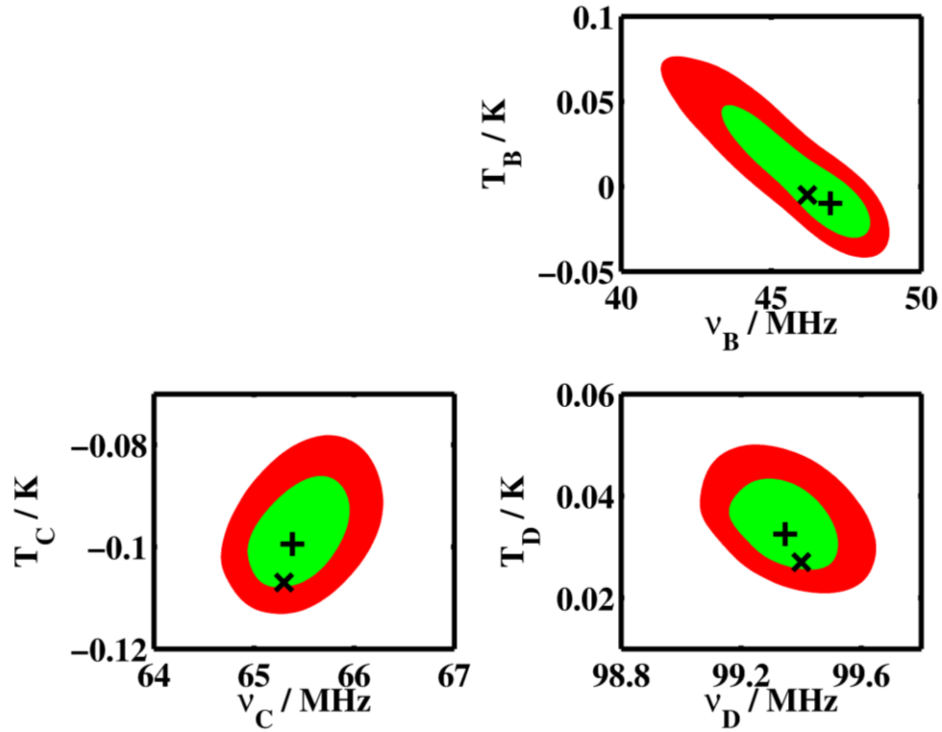


MCMC results: positions of turning points and shape of signal (3000 hrs)



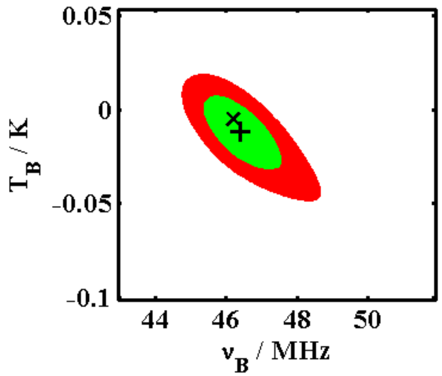
MCMC results: 1000 and 10000 hours



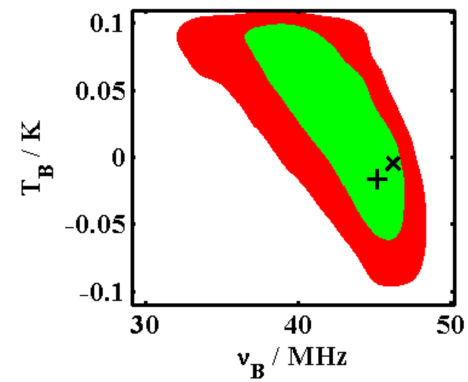


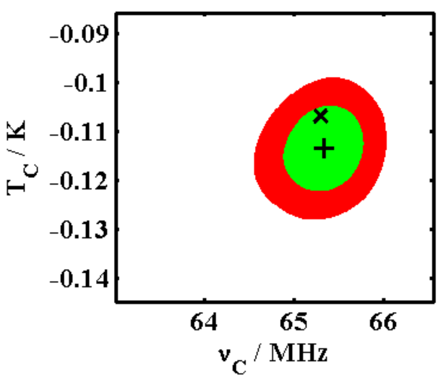
Varying the assumptions

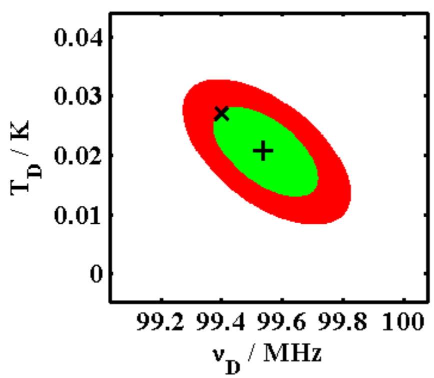
Redesigned antenna (wider cone opening angle)

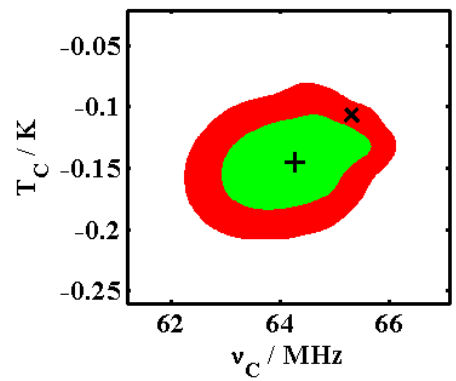


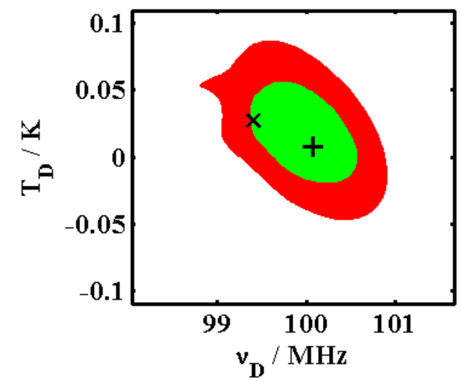
Looser priors on instrument response





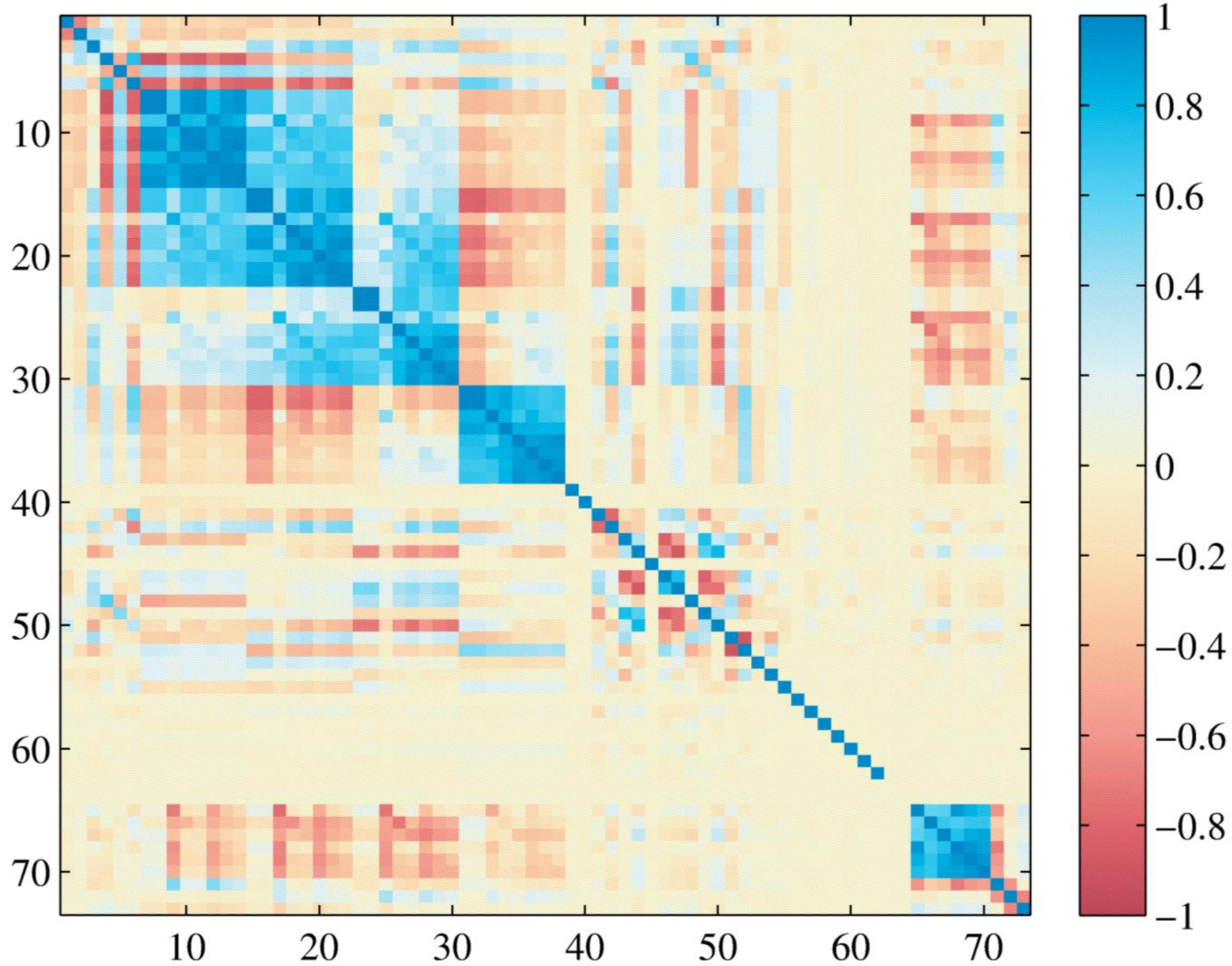






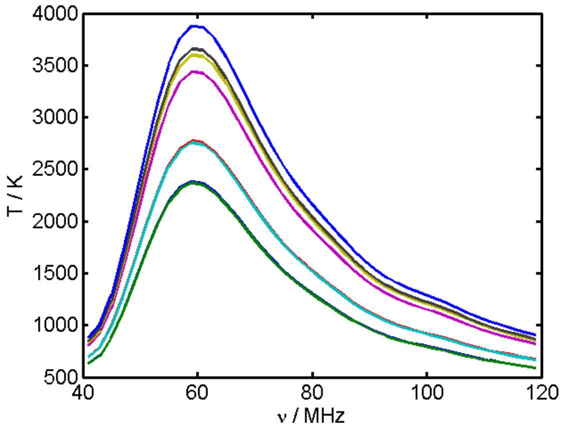
Constraints have actually been improved a little with a slightly modified antenna design!
But accurate modelling of the instrument remains the crucial ingredient.

Correlation matrix

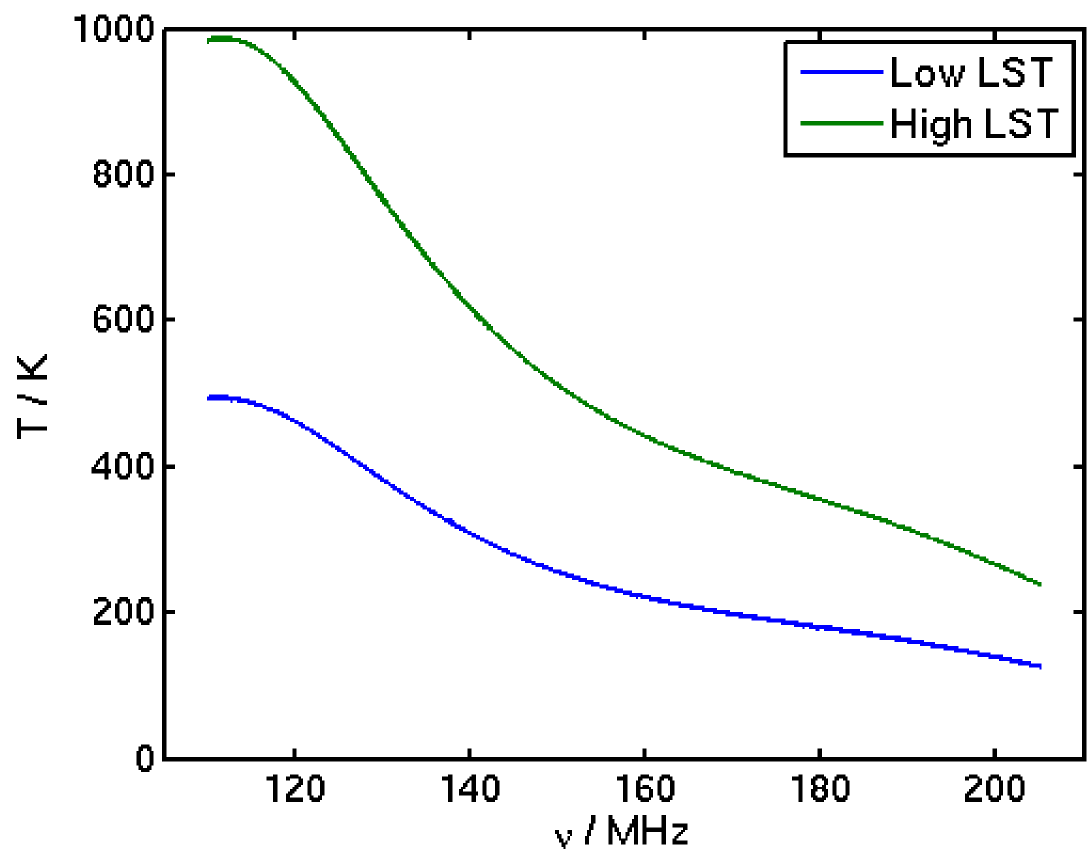


Applying MCMC to EDGES data

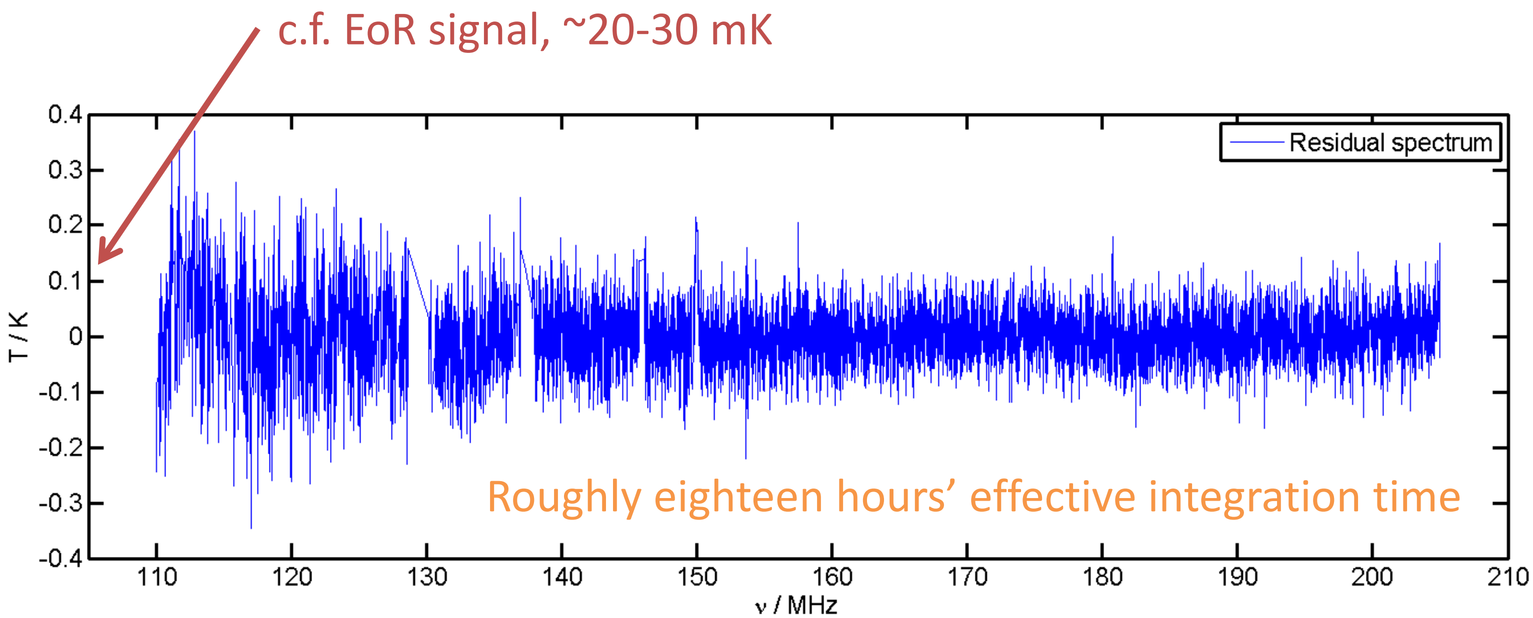
How does this analysis pipeline work with real data? Can we improve constraints on the epoch of reionization data?



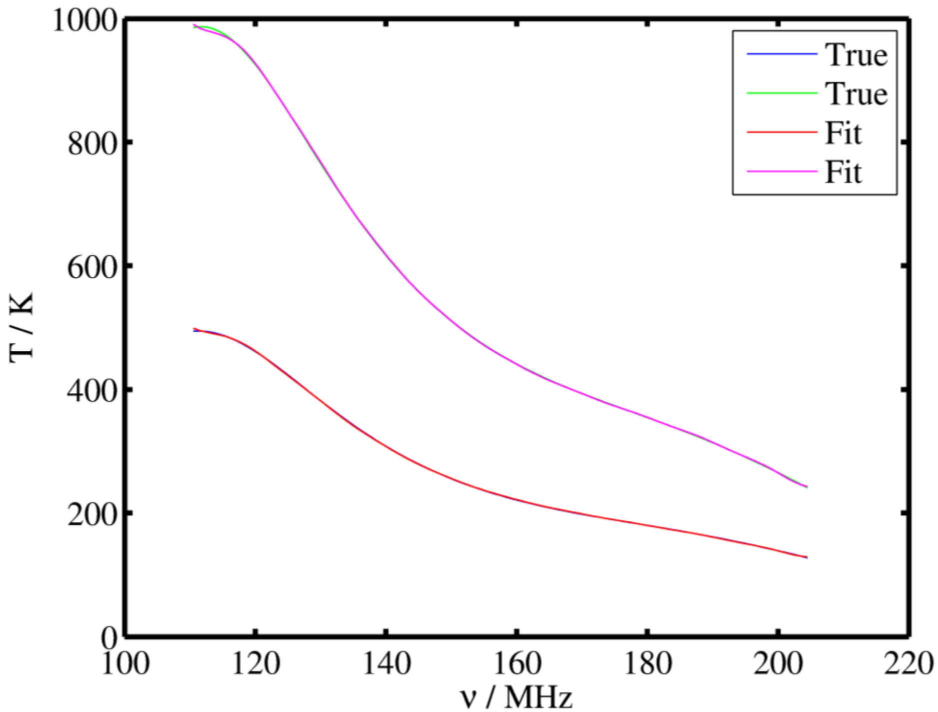
c.f. simulated DARE data

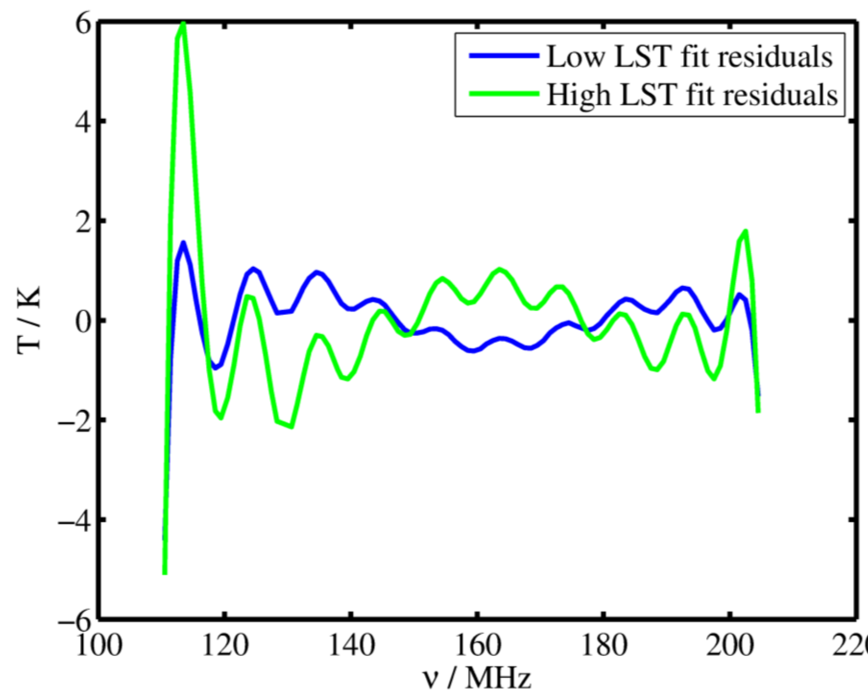


Applying MCMC to EDGES data

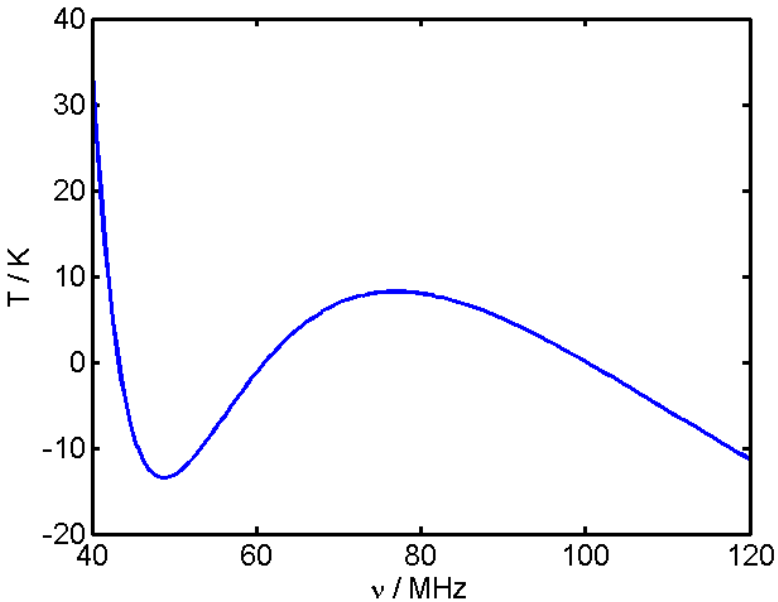


Applying MCMC to EDGES data





The ionosphere in global signal experiments



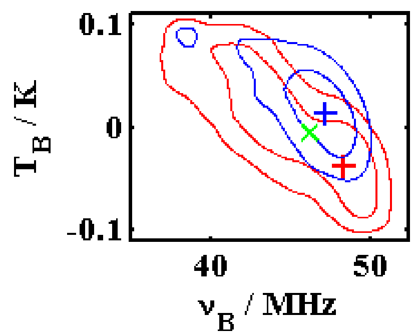
Fitting residuals for a power-law galaxy spectrum and an unmodelled ionospheric contribution

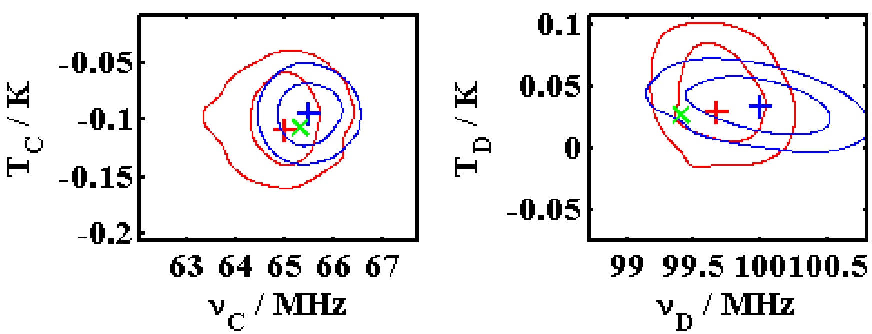
- The ionosphere absorbs low-frequency radio, and contains a population of ~1000 K electrons which also radiate at low frequencies.
- Importance of these effects goes like (frequency)$^{-2}$
- Absorbs ~1% of radiation at these frequencies.
- Simple error analysis (A.E.E. Rogers, EDGES memo 79) finds that reionization parameter errors are roughly doubled.
- Adds another 2 parameters per sky region to our model.

$$T_{with} = T_{without} - T_{without}(1-L)\left(\frac{\nu}{\nu_0}\right)^{-2} + T_{electrons}(1-L)\left(\frac{\nu}{\nu_0}\right)^{-2}$$

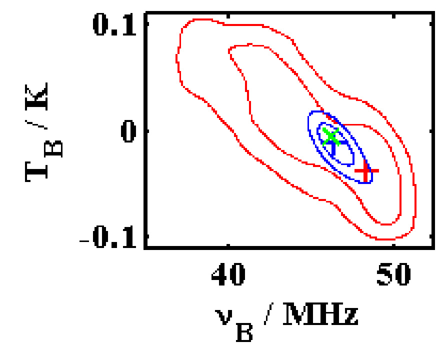
(Fundamental?) limits to a ground-based experiment

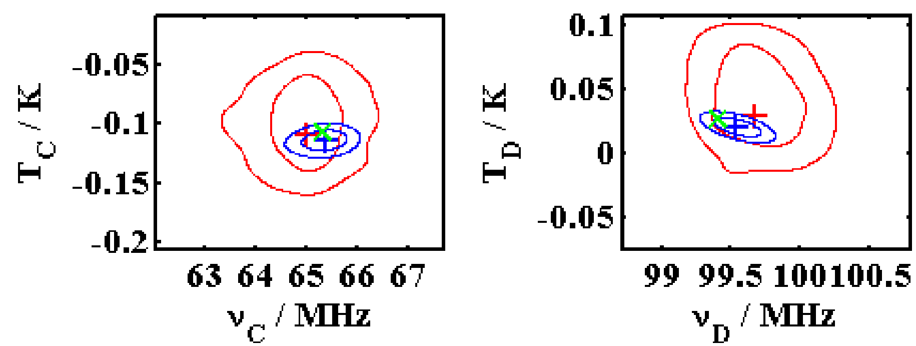
Loose priors on space-based instrument





Tight priors on space-based instrument



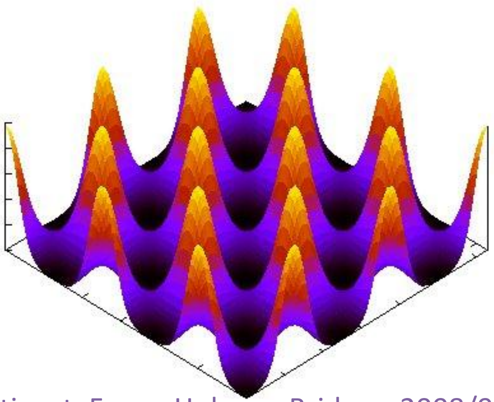


Blue = space measurement, 8 sky regions, 3000 hours

Red = ground-based measurement, 2 sky regions, 10000 hours

Coming up: code development and the DARE prototype system

- Increase the power and flexibility of the MCMC code:
  - Incorporate existing code base developed by other groups.



Multinest: Feroz, Hobson, Bridges, 2008/9

  - Find a way to start from high-resolution, time-ordered satellite data rather than assuming we begin with preprocessed data.
  - Include a wider range of 21-cm models: do *model selection* rather than simply parameter estimation.

Bayesian inference

Parameters

Data

Likelihood, $\mathcal{L}(\Theta)$

Prior, $\pi(\Theta)$

$$\boxed{\Pr(\boldsymbol{\Theta}|\mathbf{D},H)} = \frac{\boxed{\Pr(\mathbf{D}|\boldsymbol{\Theta},H)}\,\boxed{\Pr(\boldsymbol{\Theta}|H)}}{\boxed{\Pr(\mathbf{D}|H)}}$$

Posterior

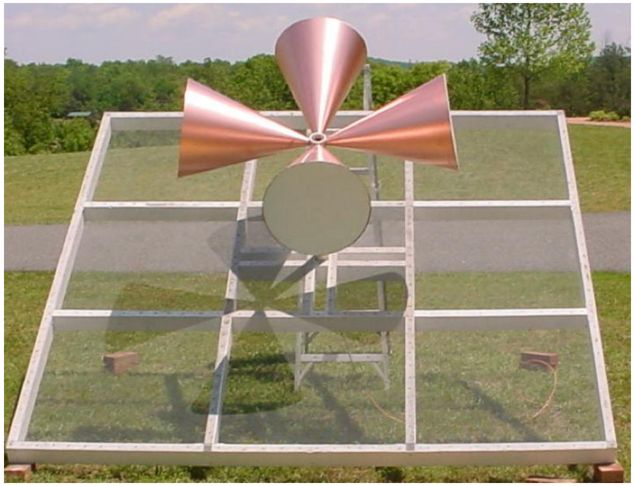
Evidence, $\mathcal{Z}$

Hypothesis or model

$$\mathcal{Z} = \int \pi(\Theta)\mathcal{L}(\Theta)d^N\Theta$$

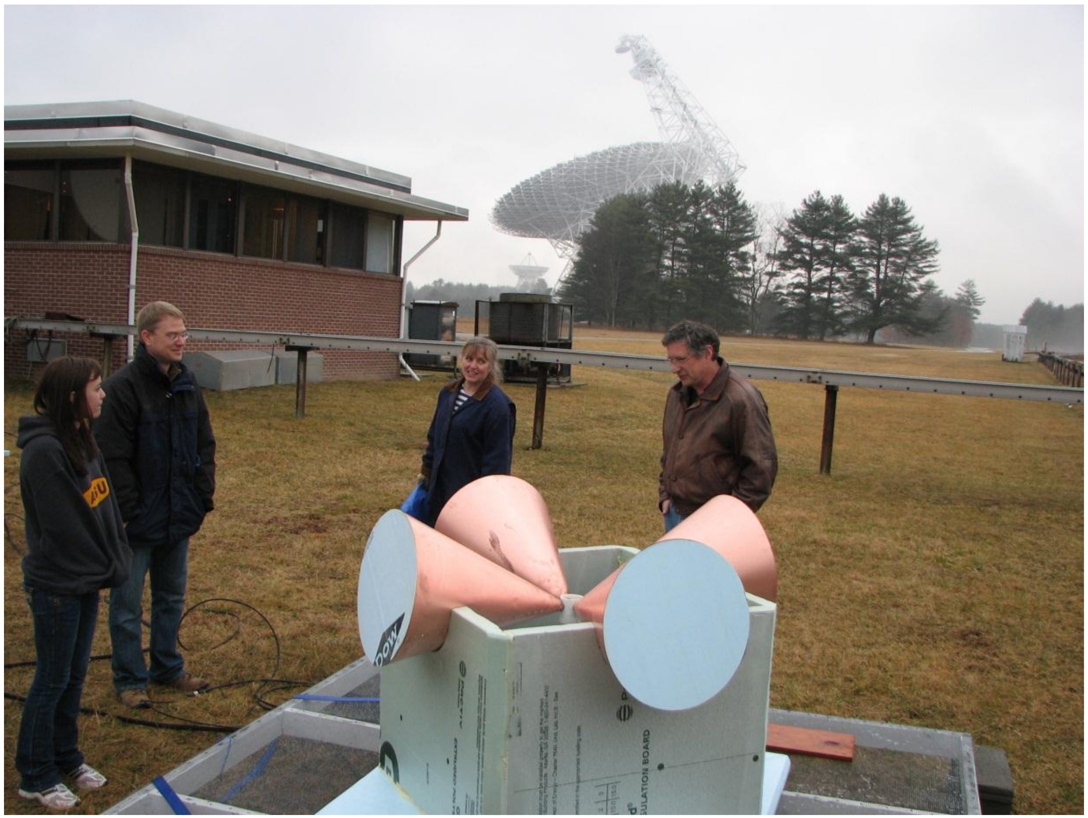
Coming up: code development and the DARE prototype system

- Applying the MCMC code to data from the DARE prototype system will be a good test of the code and will also require further development:

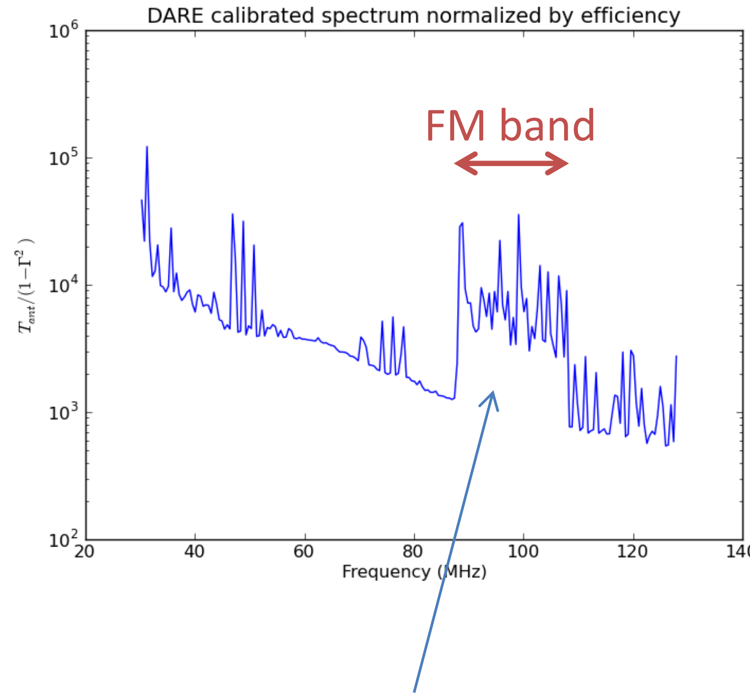


  - Incorporating the effects of environmental changes, solar bursts etc. will require the use of the time-ordered data
  - Does the ionospheric modelling in the current version of the MCMC code hold up?
  - Are tight constraints on the 21-cm signal possible using this or EDGES? Can we prove it?

The DARE prototype is up and running!



Some telescopes at Green Bank (pic and spectrum courtesy Abhi Datta)



Hopefully looks nicer from Western Australia (where the prototype gets shipped this month)

Summary

- Although foreground subtraction for sky-averaged experiments shares some features with interferometric experiments, it is different enough that we need different techniques.
- The foregrounds, signal and instrumental properties probably need to be measured simultaneously from the science data.
- Different spectral and spatial properties of the foregrounds must be used: to exploit this, DARE will be able to gather data from 8 independent regions on the sky.
- Promising results for DARE with 3000 hours of data, but we get useful constraints with 1000 hours or less.
- The MCMC method presented here is applicable (with some modifications) to ground-based experiments, which if nothing else provide useful and stringent tests on the performance of the foreground fitting.