Update on power spectra

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Summary of goals

- Find out what sorts of constraints on the 21cm power spectrum are possible in the best case.
- Study the effect of foreground subtraction on the recovered power spectrum.
- Find workable algorithms for power spectrum subtraction.
- Do these results have an impact on possible observing plans and strategies?
- Look at how the information we get from measuring the power spectrum compares to other statistics.

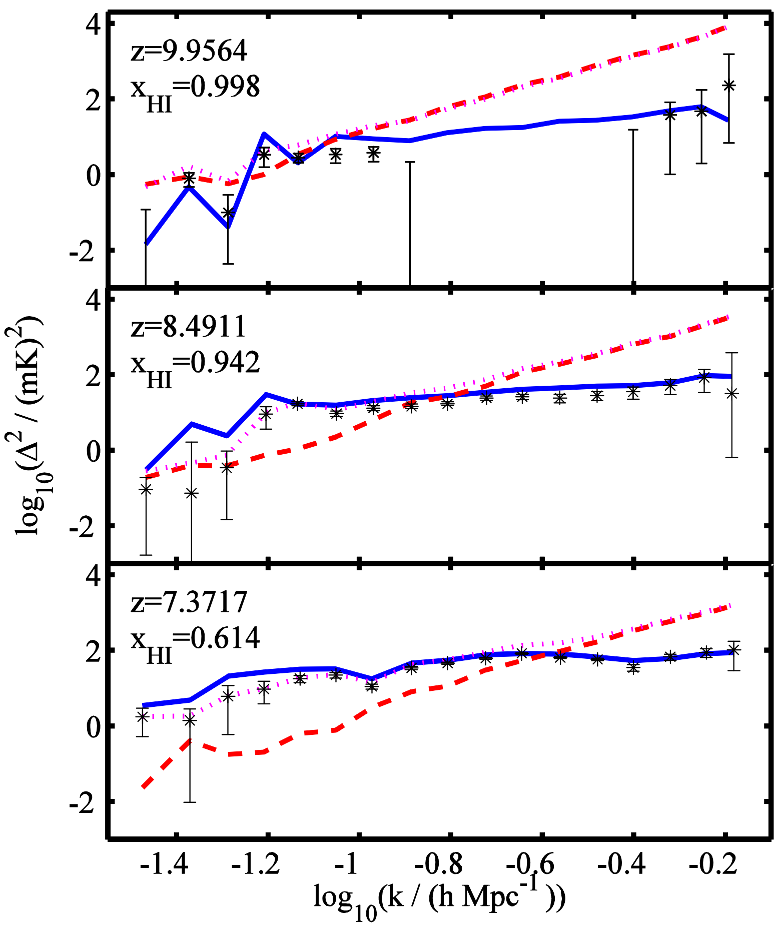
Methodology

- Simulate 21cm signal using Rajat's code.
- Foregrounds using Vibor's model.
- Add and Fourier transform these, implement instrumental response, and add noise proportional to 1/sqrt(S(u,v)).
- Fit (and subtract) the foregrounds assuming they're smooth in the frequency direction.
  - Can be done in image space or Fourier space.
- Estimate power spectra.

Paper status

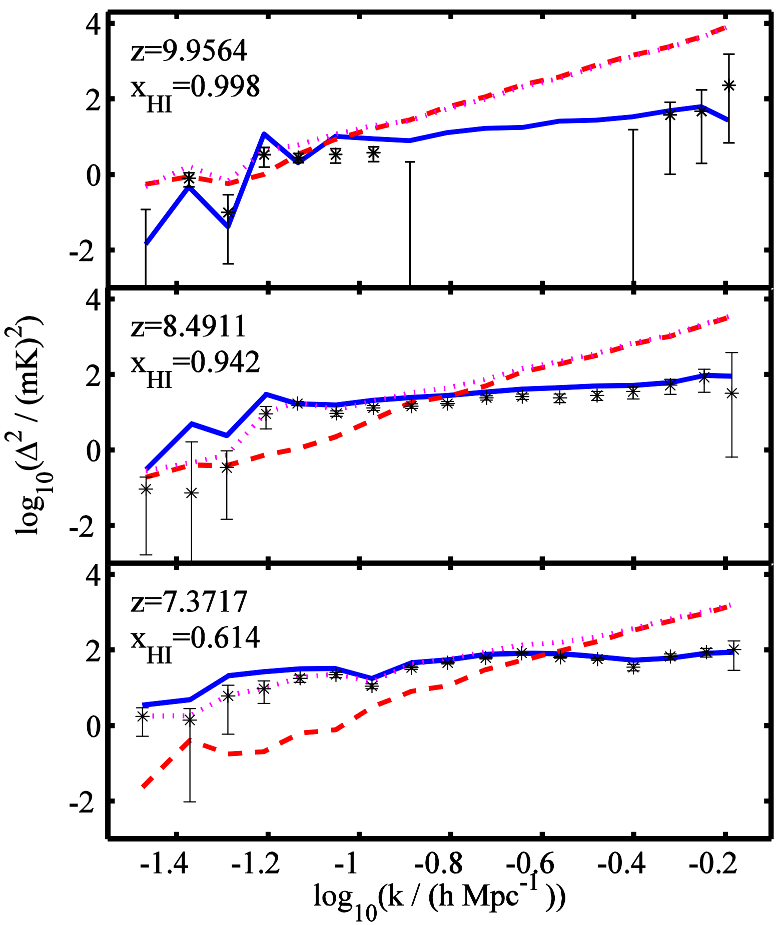
- MNRAS, in press.
- arXiv: 1003.0965.
- Difference between early draft and submitted version is mainly an extra emphasis on the difference between line-of-sight and angular power spectra.
- The only substantial modification between the accepted and submitted versions was the addition of a section on estimating the power spectrum using cross-correlation rather than autocorrelation.

Example power spectra and errors



- Points with (noise + sample variance) error bars: recovered power.
- Blue: input power spectrum (200 Mpc/h simulation with QSOs).
- Red: noise.
- Magenta: residuals after foreground fitting.
- 'Upper limits' are plotted, but in many cases they drop off the bottom of the plot.

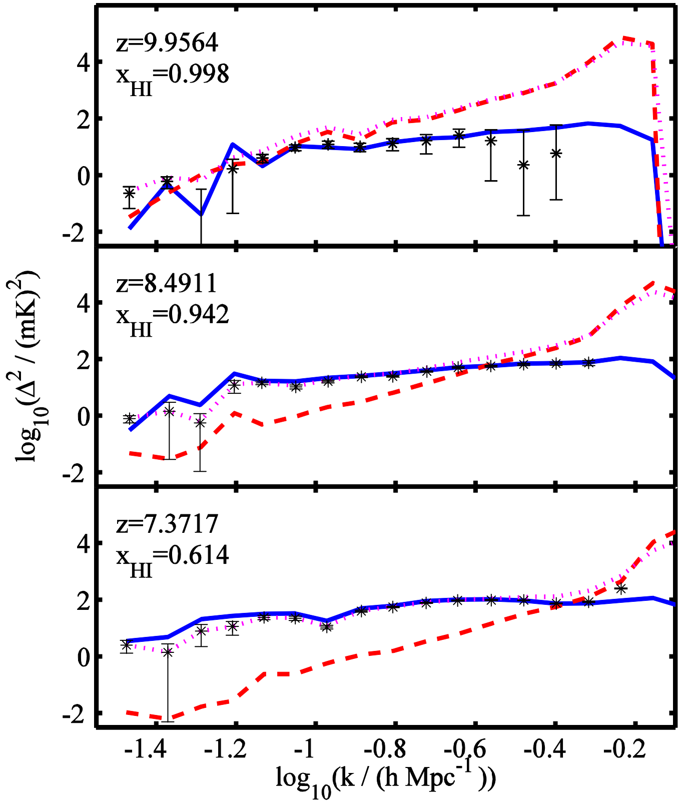
Example power spectra and errors



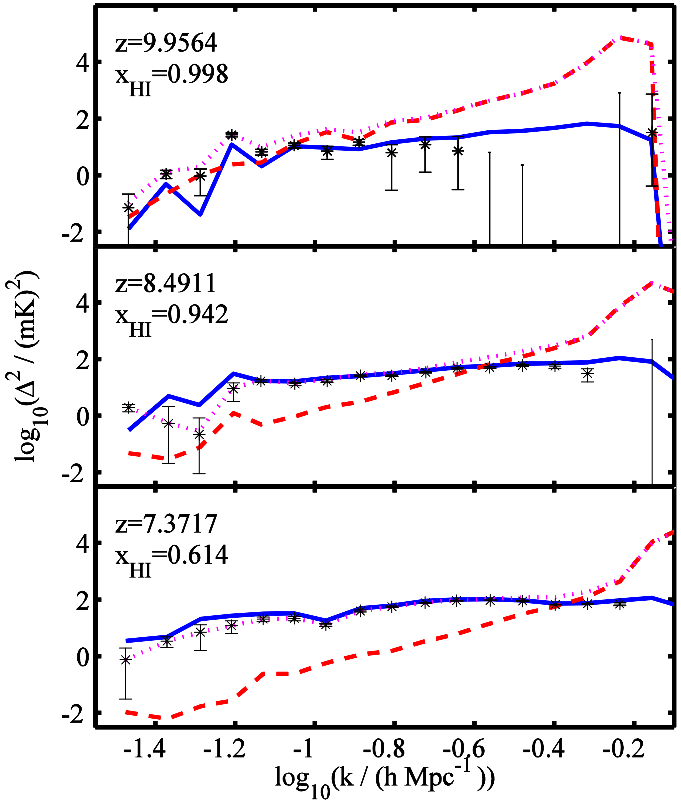
- Estimate the power spectrum by computing the autocorrelation of the foreground fitting residuals and subtracting a noise power spectrum
- 300 hrs, 1 beam, 1 window.
- Recover the power spectrum reasonably well at low redshift, but lose intermediate scales at high redshift.
- Some bias at large scales.

Fitting in the (*u*,*v*,ν) cube

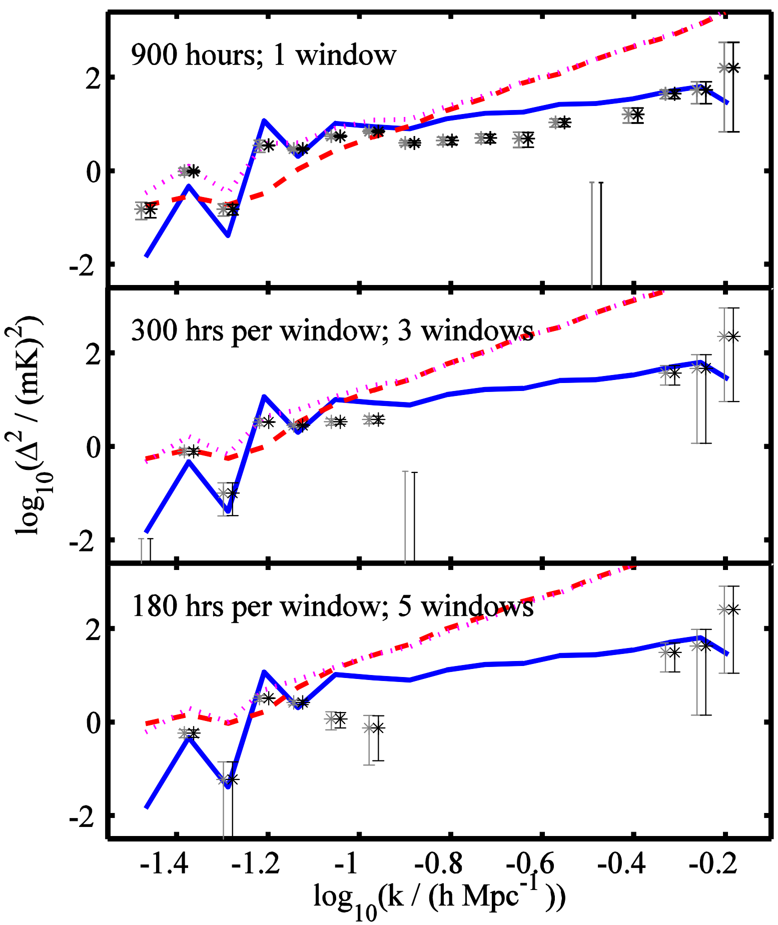
Wp smoothing



Polynomial fit



Different observing strategies



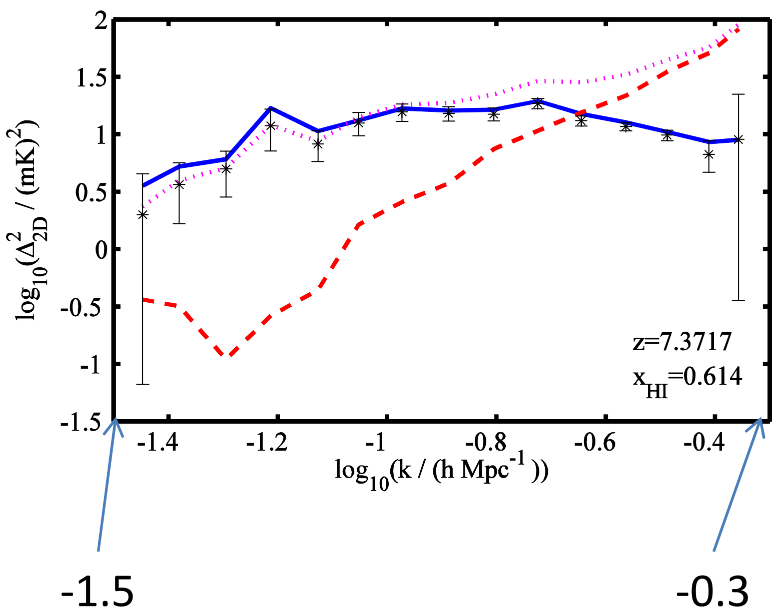
- z=9.96
- Smaller error bars exclude sample variance.
- For these high redshifts, it seems clearly beneficial to look at fewer windows for longer, to improve the foreground fitting.
- Balance is different at low redshift where foregrounds and noise are lower.
- Suggests different integration time at lo/hi *z* (no prob. from fitting POV).

Angular and line-of-sight power spectra

Angular power spectrum

•Large-scale bias as for 3D power

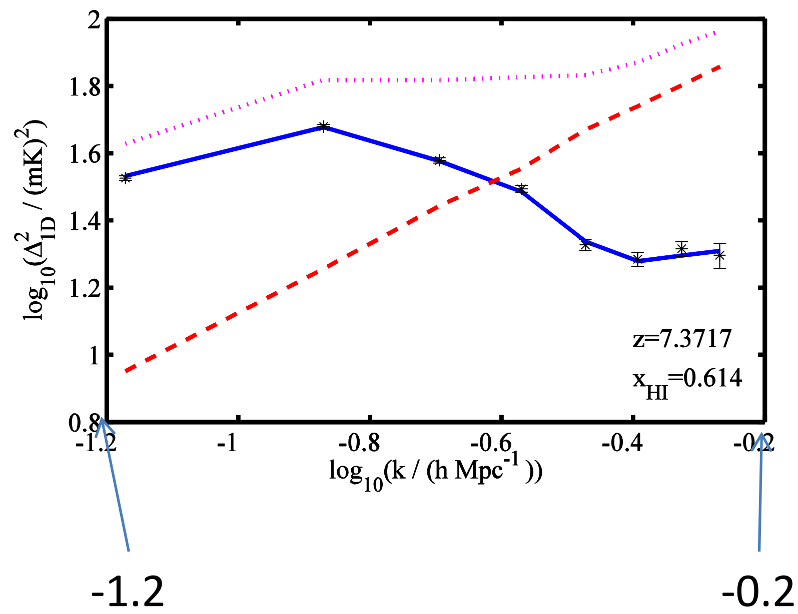
•Goes to larger scales without risking evolution effects



Line-of-sight power spectrum

•Can reach smaller scales (depending on frequency resolution)

•No large-scale bias



Why does the bias show up in the angular power spectrum?

- We assume smoothness in the frequency direction, but the fitting leads to loss of power in angular modes.
- Along one line of sight, for a narrow frequency range, we are likely to make an error estimating the foregrounds which is roughly constant with frequency.
  - No change in the one-dimensional power spectrum over this frequency range.
  - For the angular power spectrum, this constant offset is likely to be different between different lines of sight, leading to bias in the power spectrum.
  - A similar offset between nearby lines of sight (because of large-scale correlation in the foregrounds) would lead to the offset being roughly constant within small regions, so the small-scale power would be small.

Autocorrelation vs. cross-correlation

- Autocorrelation

$$P^r(k) = P^s(k) + P^n(k) + P^\epsilon(k) + \langle \epsilon(\boldsymbol{k})[s(\boldsymbol{k}) + n(\boldsymbol{k})]^* + [s(\boldsymbol{k}) + n(\boldsymbol{k})]\epsilon(\boldsymbol{k})^* \rangle_{|\boldsymbol{k}|=k}$$

Residual power

Signal power

Noise power (estimate and subtract)

Fitting errors and cross terms (simulate?)

- Cross-correlation

$$\langle r_1 r_2^* \rangle = P^s + \langle s\epsilon_2^* \rangle + \langle \epsilon_1 s^* \rangle + \langle \epsilon_1 \epsilon_2^* \rangle$$

Cross-correlation of two epochs

Signal power

Cross terms (no noise)

Comparison

Autocorrelation

- Requires an accurate estimate of the thermal noise power spectrum.
- Foreground fitting can always be done using the whole dataset.
- Overfitting the noise can produce systematic underestimates of the power, even yielding negative power

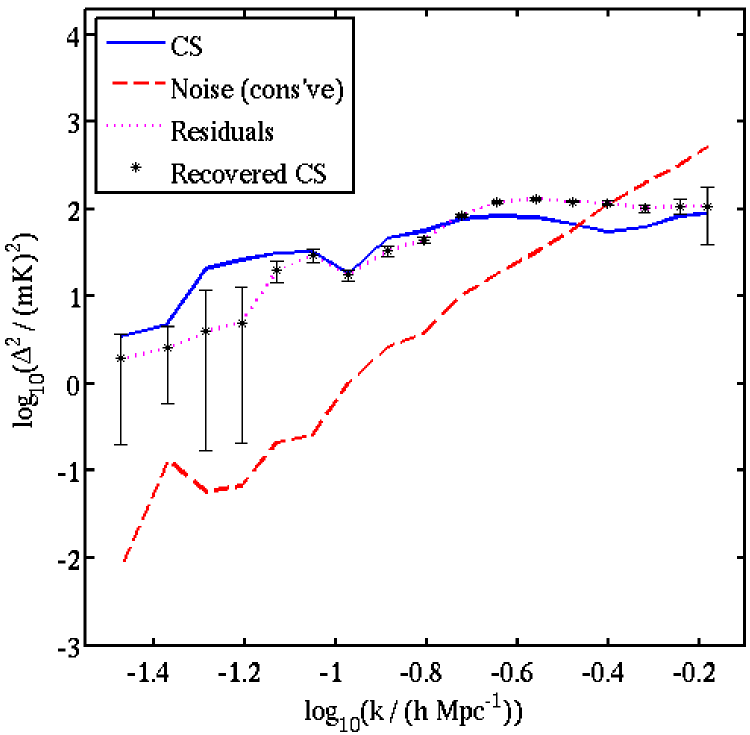
Cross-correlation

- Only need to be able to simulate the noise well enough to estimate errors.
- Separate foreground fitting for each epoch, or introduce correlated noise-induced fitting errors.
- Unless fitting errors are very large, should always yield a positive estimate for the signal power.

Cross-correlation: 900 hrs, 1 beam.

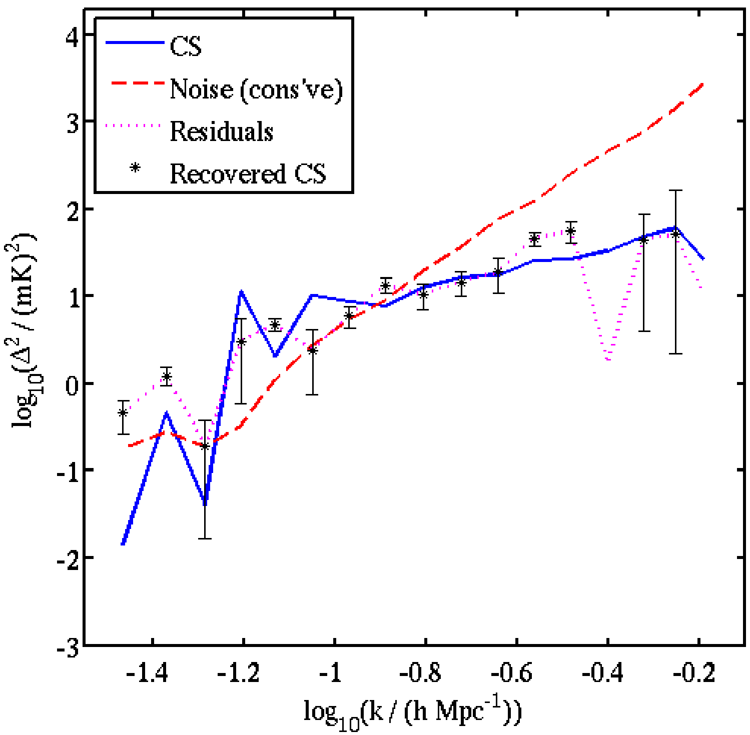
Low redshift

Power spectra in a slice 76.2377 h^{-1} Mpc deep centred at z=7.3717; 900 hrs, 1 beam, 1 window; 4-pixel bins.



High redshift

Power spectra in a slice 90.9198 h^{-1} Mpc deep centred at z=9.9564; 900 hrs, 1 beam, 1 window; 4-pixel bins.



Future work

- More realistic treatment of instrumental effects in general, and noise in particular (first-principles calculation). Do codes/data exist for this?
  - Is it possible to observe for longer at lower frequencies? If so then this may be the scenario to pursue.
- Estimate of parameter constraints given different scenarios.
- Further investigation of cross-correlation and estimates of the noise power spectrum.
- Speed up *uv*-plane fitting, which seems to be the most promising approach to foreground fitting at the moment.

Conclusions

- Foreground fitting seems to work well, especially in (u,v,ν) space, as will probably be required in practice.
- Fitting has a different effect on angular and line-of-sight power spectra so this should be considered in the data analysis.
- Cross-correlation is a promising approach, but since we would like an estimate of the noise power spectrum in any case it's probably best to look at this in parallel with estimates using autocorrelation.
- Splitting observing time equally between windows probably isn't the most efficient way to go, especially if we hope to go to high redshift.