EoR signal extraction using skewness

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Geraint Harker

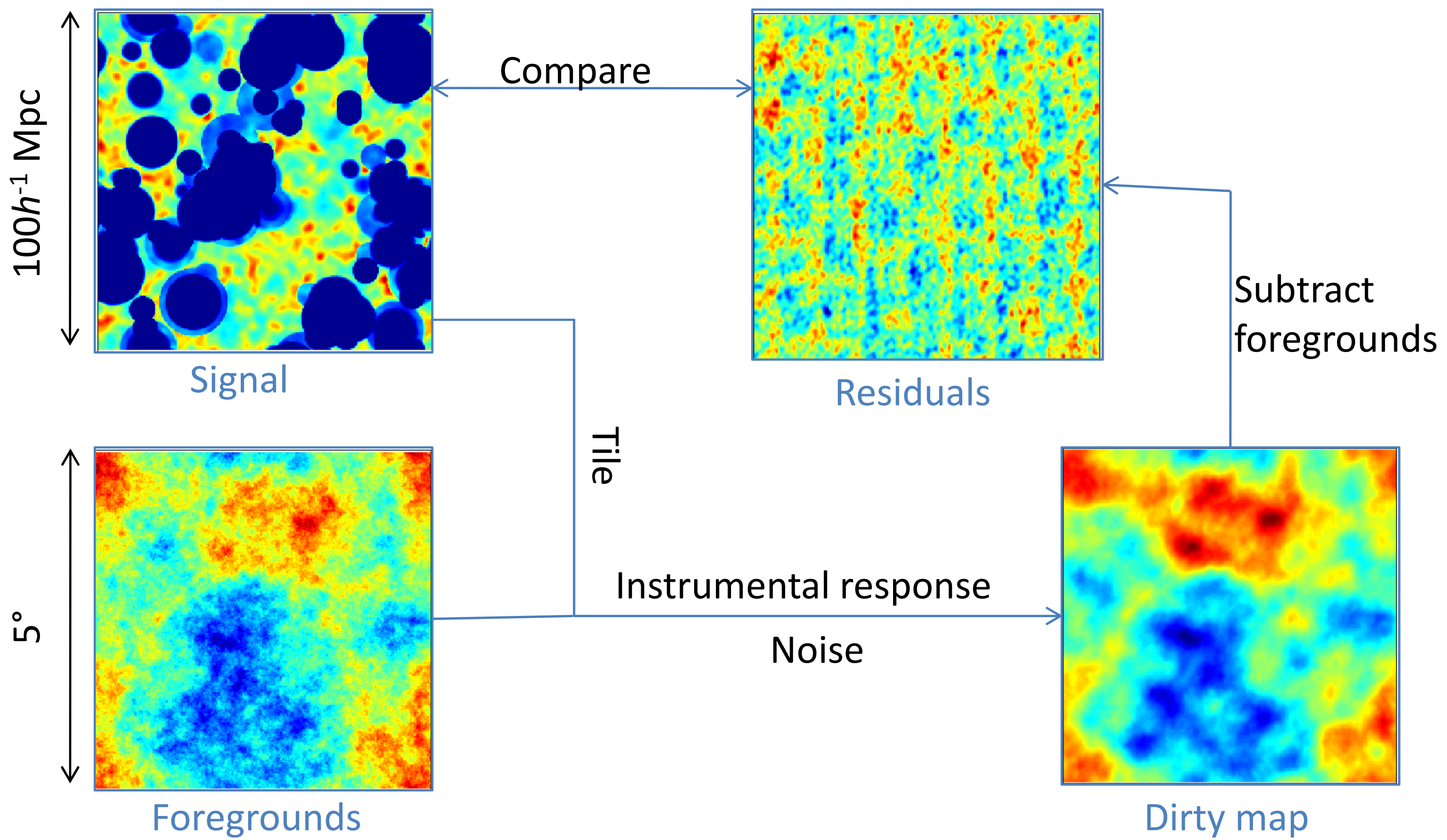
LOFAR EoR project

- Aim to detect redshifted 21cm emission from neutral hydrogen at high redshift.
- Observe using the LOFAR high band antennas at 115-200MHz.
- This corresponds to redshifts between approximately 6 and 11.5.
- In this redshift range we expect the hydrogen in the Universe to go from being mostly neutral to mostly ionized (‘reionization’).
- The cosmological signal contains information about cosmology, the first sources of ionizing photons, and the astrophysics of the high-redshift intergalactic medium.
- But there are many challenges along the way…

The problem

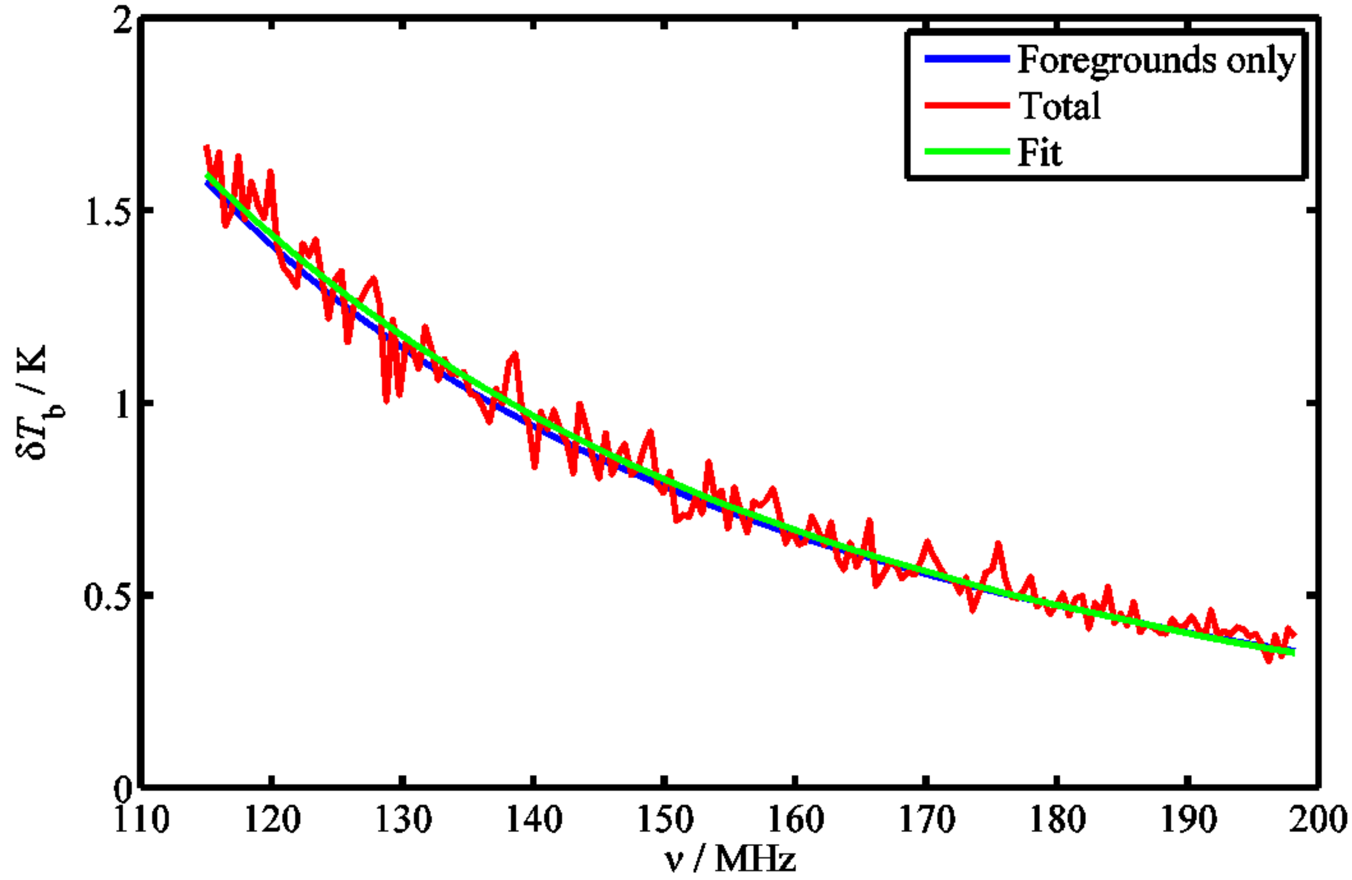
- Extract a cosmological signal from a datacube of brightness temperatures, the three axes of which are x and y positions, and frequency.
- To develop the extraction pipeline, we model the datacube with three components:
  - The cosmological signal itself;
    - Iliev et al. (2008)
    - Thomas et al. (2008)
  - Astrophysical foregrounds;
    - Jelić et al. (2008)
  - Noise.
- The foregrounds are expected to be smooth in frequency, which allows them to be fitted out.
- Does the signal also have any special properties which should enable us to tease it out?

Pipeline

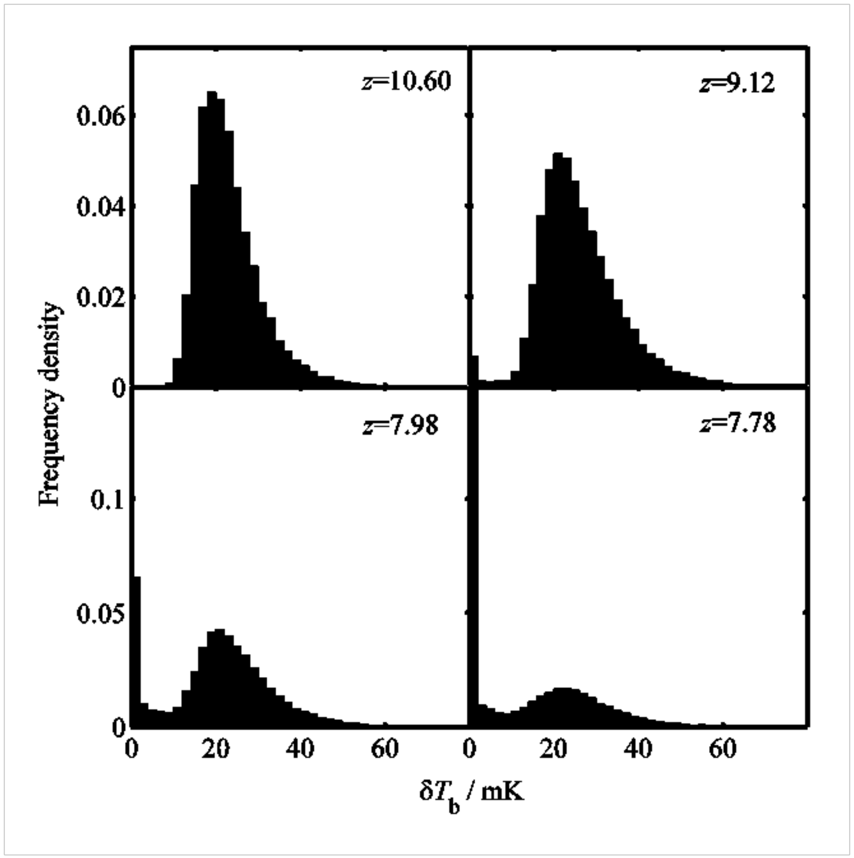


100h^{-1} Mpc
Compare
Signal
Residuals
Subtract foregrounds
Tile
5°
Instrumental response
Noise
Foregrounds
Dirty map

Fitting a line of sight

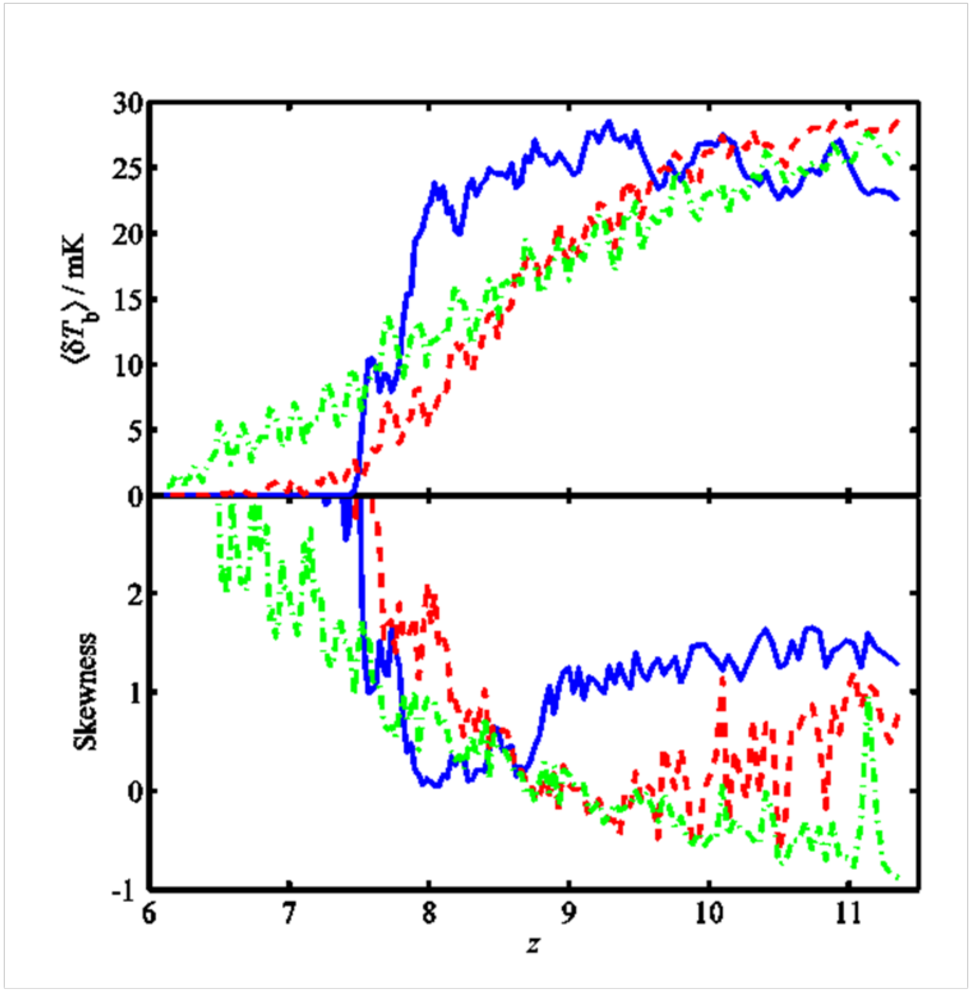


One-point distribution from simulations



- δT_b = (stuff)·x_{HI} ·(1+ δ)
- Skewness=μ_3/σ^3
- At early times, the brightness temperature follows the cosmological density field which is positively skewed.
- Reionization generates ionized bubbles, which show up as a peak at zero emission in the one-point distribution, reducing the skewness.
- At the late stages of reionization, the few remaining areas with emission form a high-δT_b tail.

Evolution of skewness in the cosmological signal



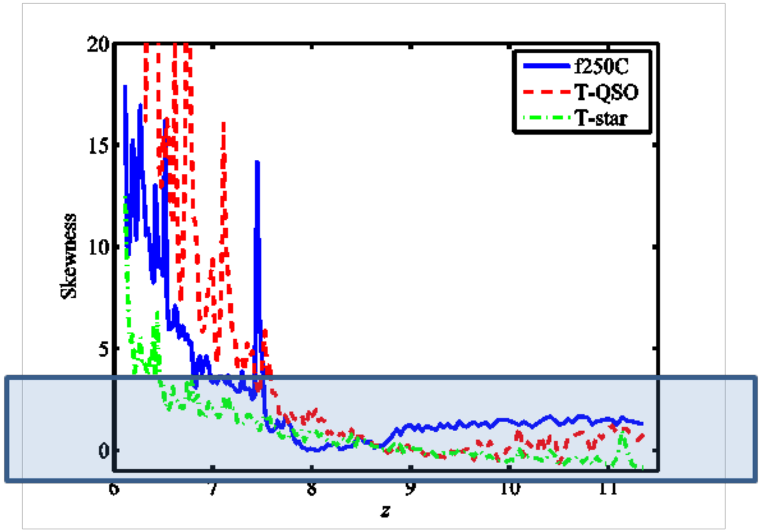
Three simulations:

f250C - Iliev et al. (2008)

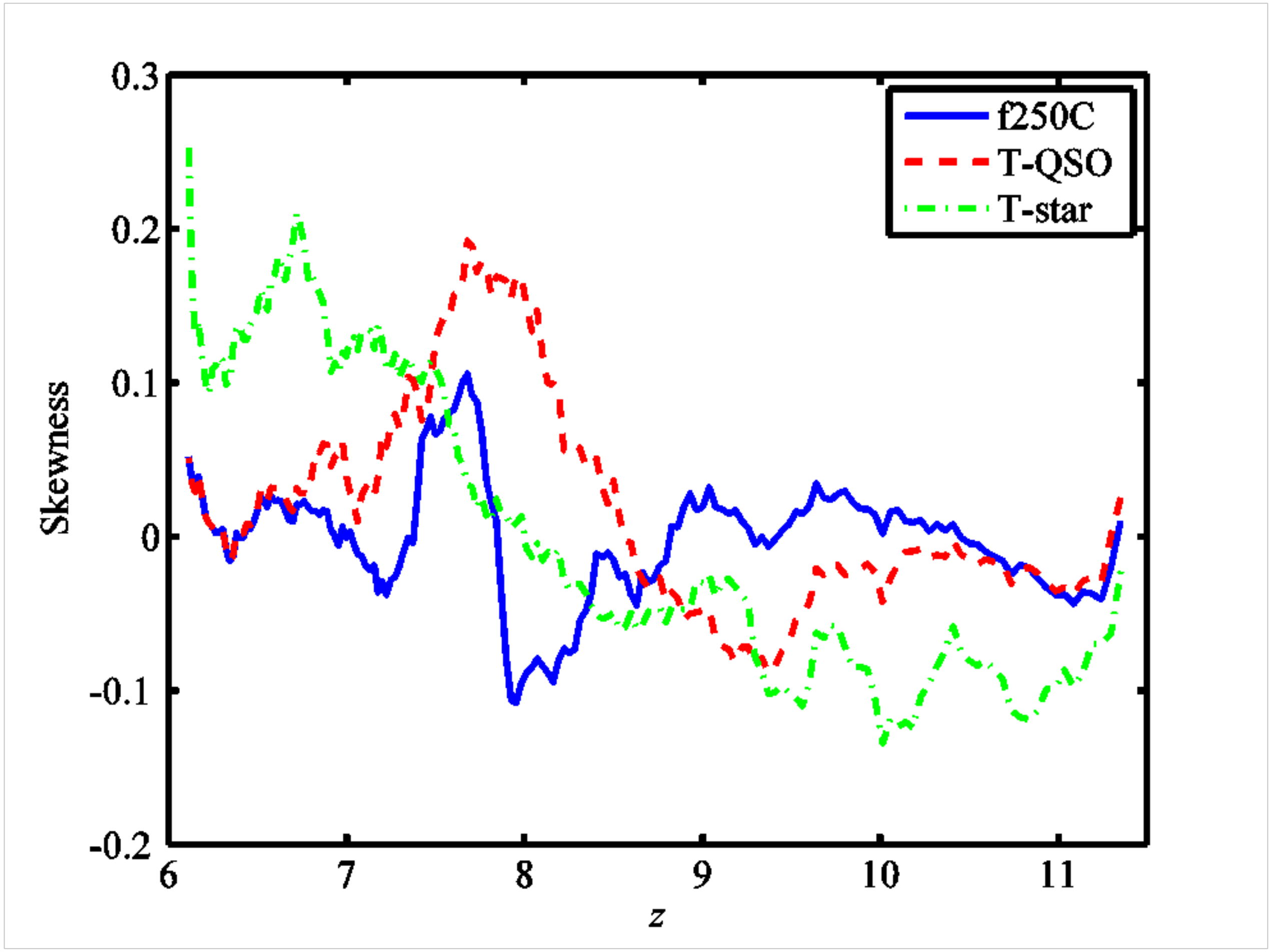
T-QSO

T-star

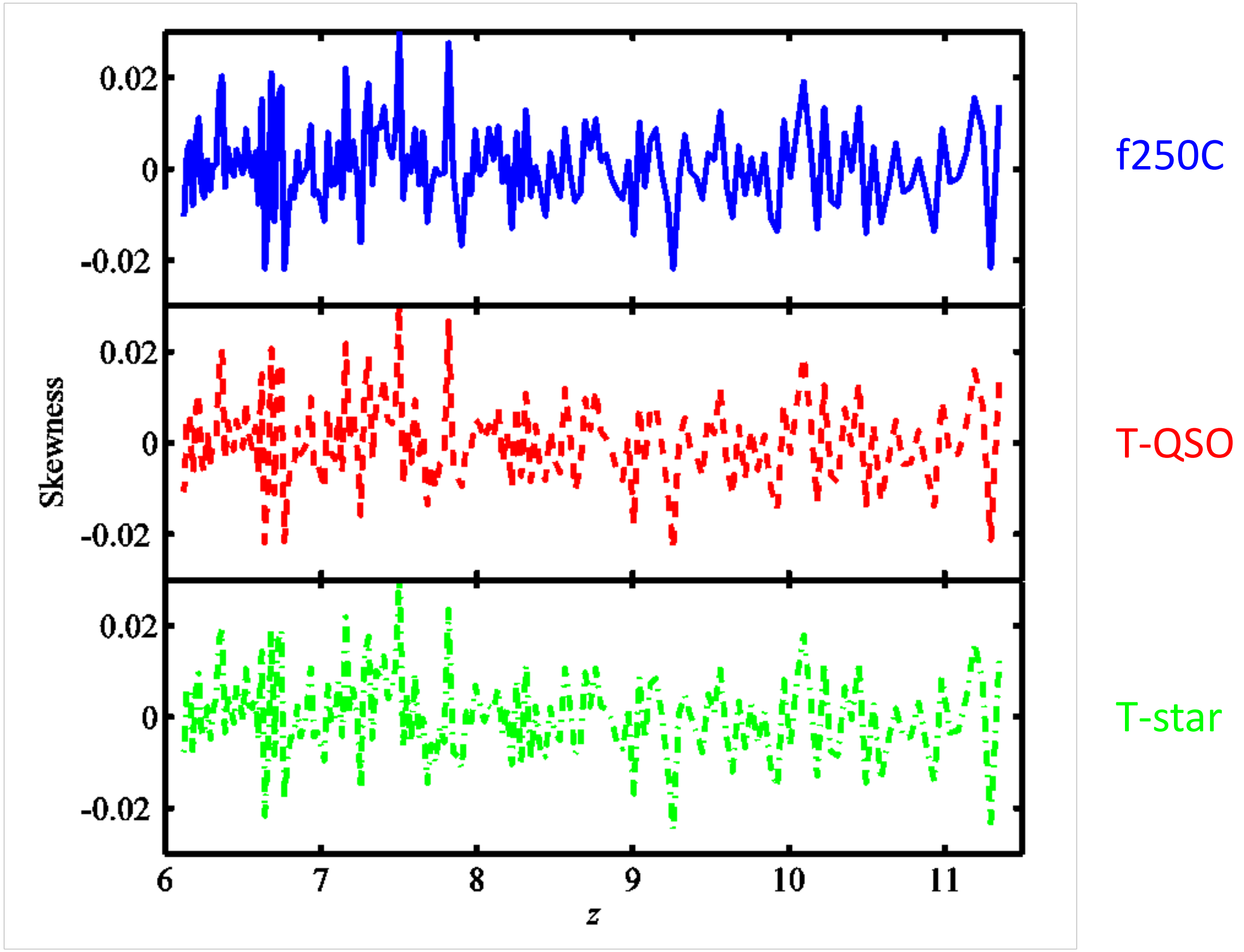
Thomas et al. (2008)



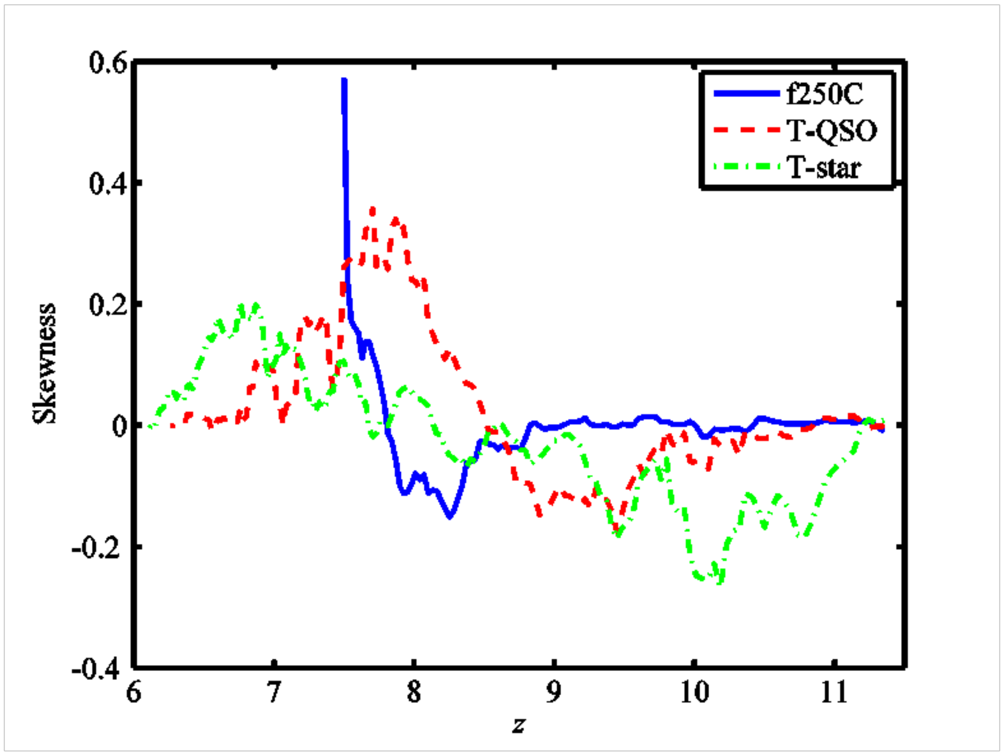
Skewness from dirty maps with no foregrounds



Evolution of skewness in residual maps



Deconvolved maps



- For the residual map at each frequency, attempt to reconstruct the cosmological signal with a Wiener deconvolution.
  - Optimal in a least-squares sense, BUT...
  - Requires knowledge of the correlation properties of the signal and noise, though in fact we ignore the contribution from the fitting errors.
- Recovers the main features of the evolution of the skewness in the cosmological signal simulations.

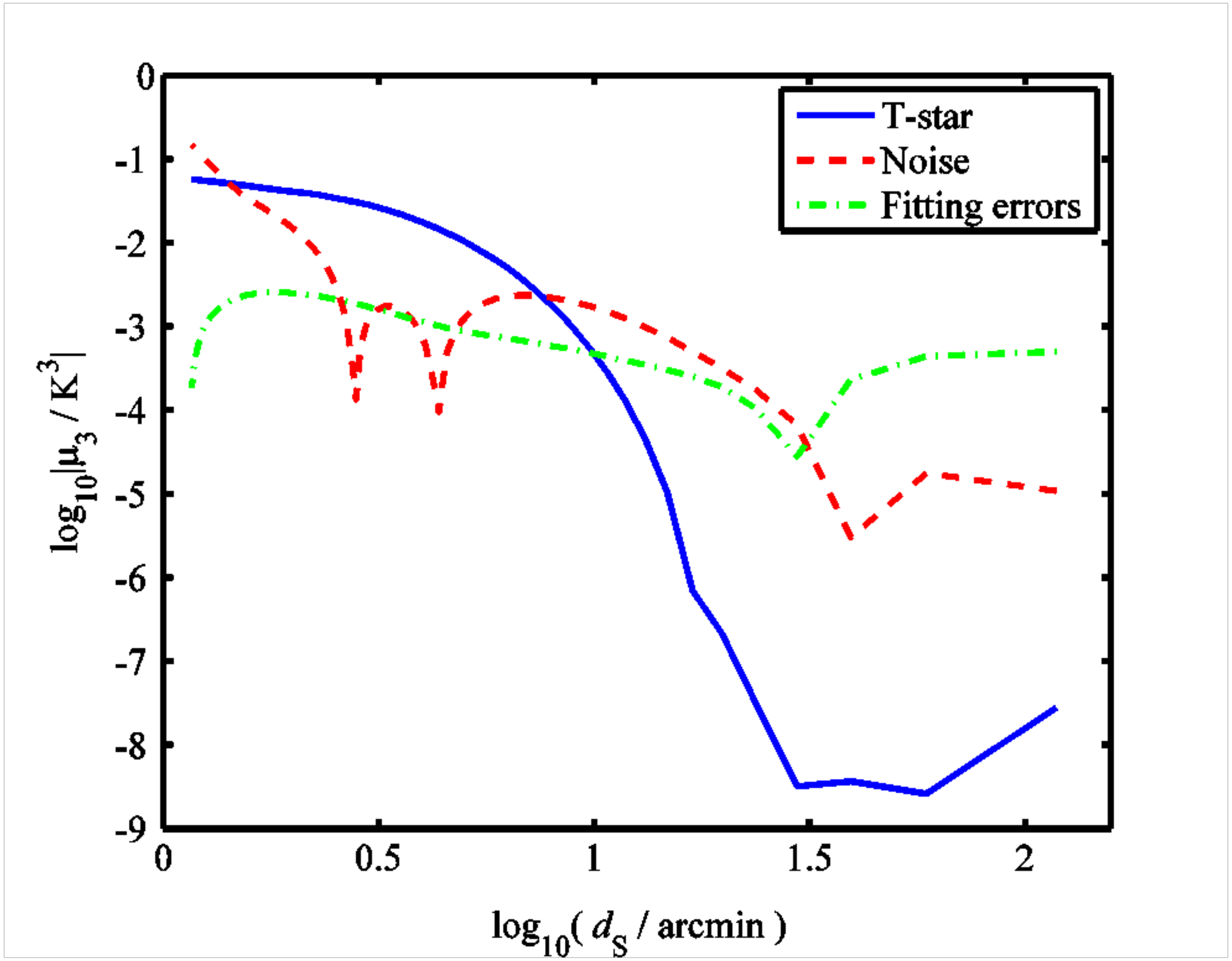
Further work

- Might the real foregrounds be more skewed and will this require a more sophisticated foreground subtraction algorithm?
- Test the level to which the correlation properties of the cosmological signal must be estimated to make the Wiener deconvolution feasible.
- Can the whole process be carried out in the uv-plane?
- Generate larger simulations of the signal which don’t require tiling.
- Effect of exotic reionization scenarios.
- Other statistics.

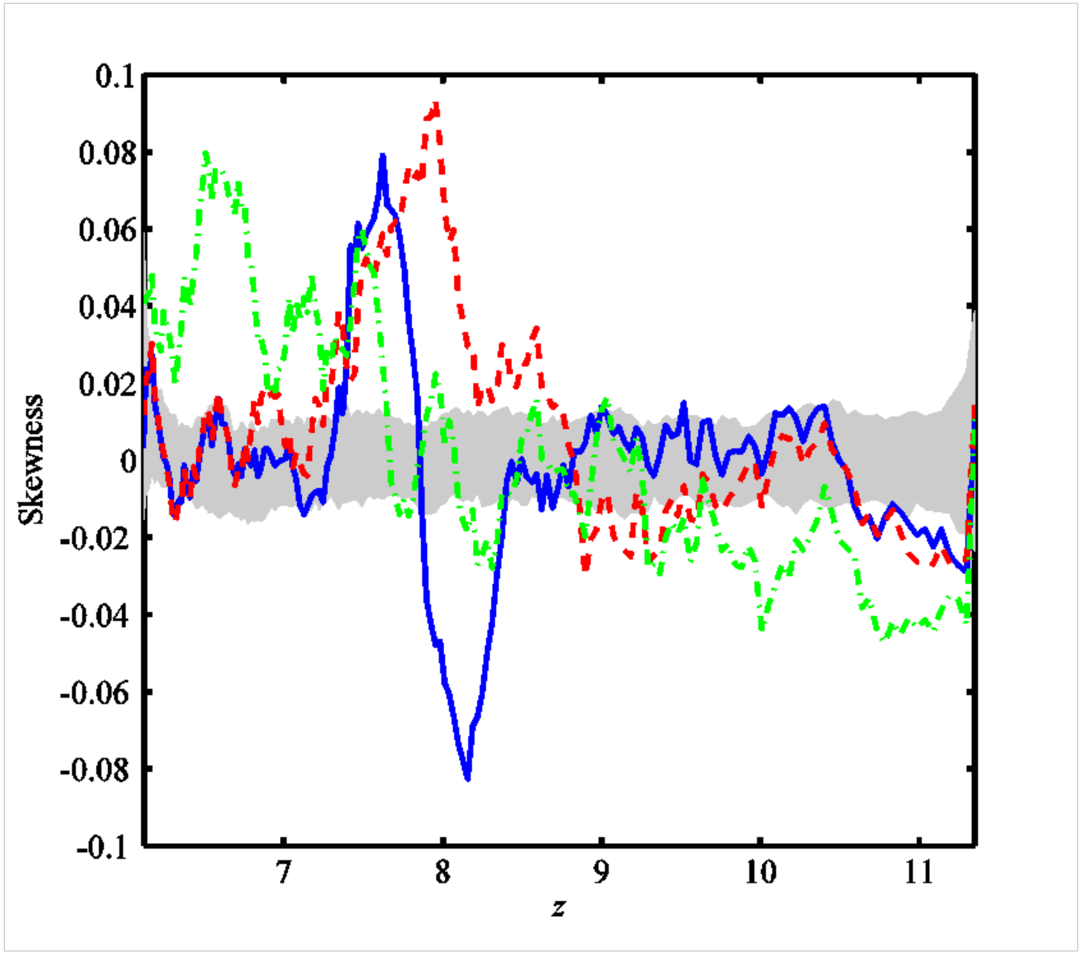
Summary

- We test the LOFAR EoR signal extraction algorithms using datacubes including the cosmological signal, foregrounds , noise and instrumental effects.
- Subtracting foregrounds which are smooth in frequency leaves a cube with three components: cosmological signal, noise and fitting errors, which have different correlation properties.
- We exploit these properties to differentiate the cosmological signal from the fitting errors and noise.
- The skewness of residual maps 'denoised' in this way shows similar (generic) features as a function of redshift as in the cosmological signal simulations.
- The difficulty comes from a combination of having to accurately subtract foregrounds and deal with structured noise.

Scale-dependence of components of residual maps



Skewness of smoothed maps for the uncorrelated noise case



Definitions

$$\frac{\delta T_{\rm b}}{\rm mK} = 39h(1+\delta)x_{\rm HI}\left(\frac{\Omega_{\rm b}}{0.042}\right)\left[\left(\frac{0.24}{\Omega_{\rm m}}\right)\left(\frac{1+z}{10}\right)\right]^{\frac{1}{2}}$$

Differential brightness temperature

Density field

Neutral fraction

Skewness

$$\gamma_1 \equiv \frac{\mu_3}{\sigma^3} \equiv \frac{\int_{-\infty}^{\infty}(x-\mu)^3 f(x)\mathrm{d}x}{\left(\int_{-\infty}^{\infty}(x-\mu)^2 f(x)\mathrm{d}x\right)^{\frac{3}{2}}}$$

Third moment

$(\text{Variance})^{3/2}$