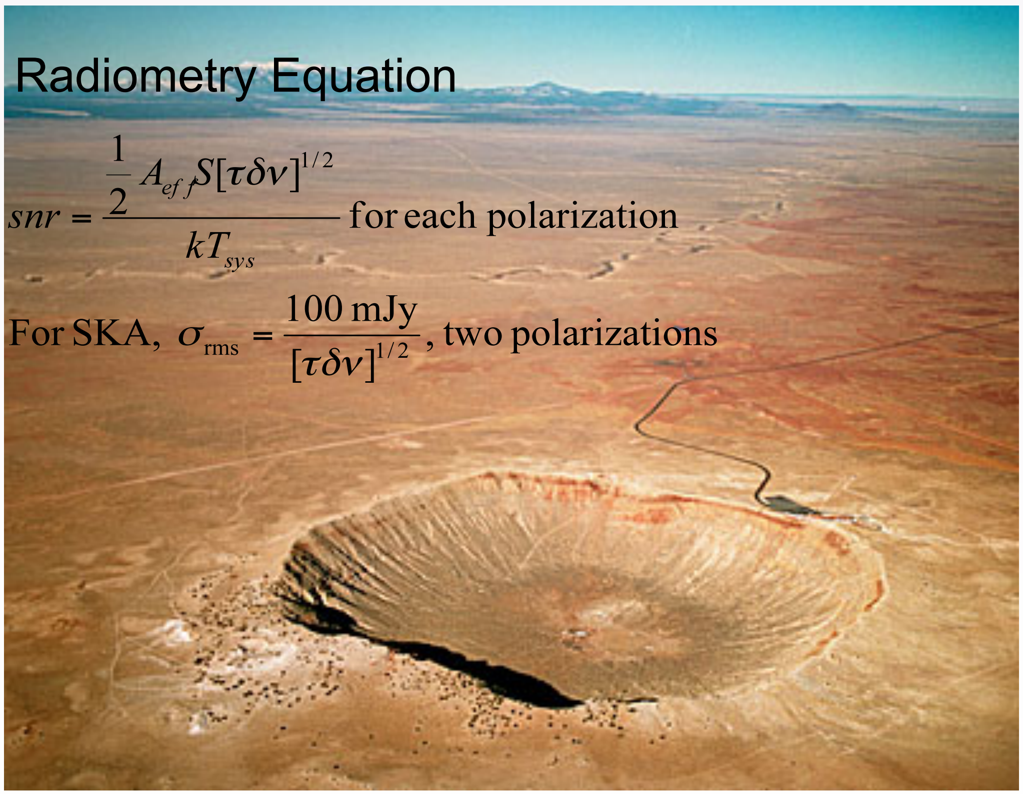
Foregrounds and Foreground Removal: Discussions/Issues for SKA-low.



Filipe B. Abdalla

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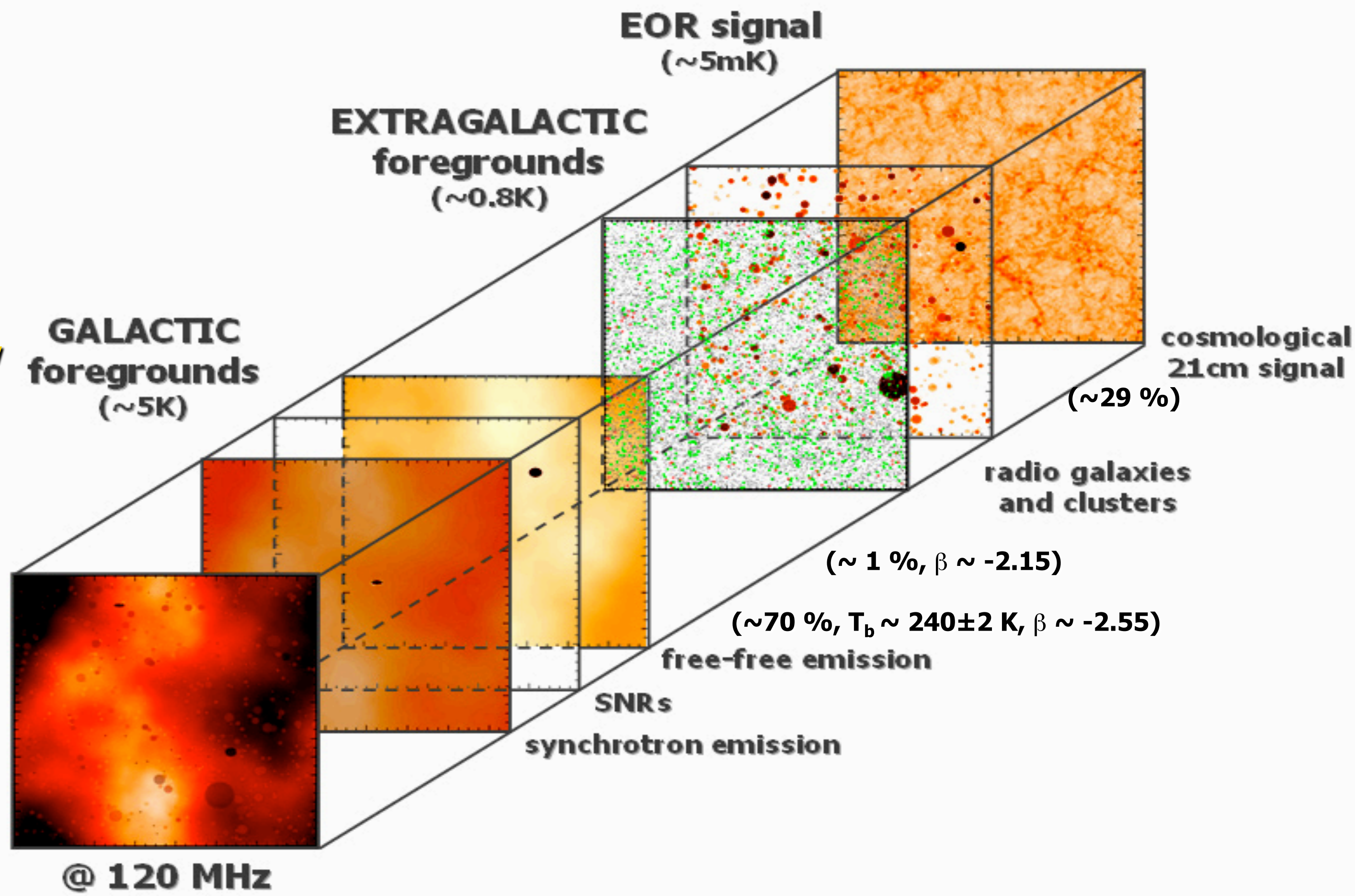
Outline:

- Foreground properties: what we know!
- Foreground removal: how we deal with it!
- Foregrounds for SKA_Low: a list of issues!

FG simulations

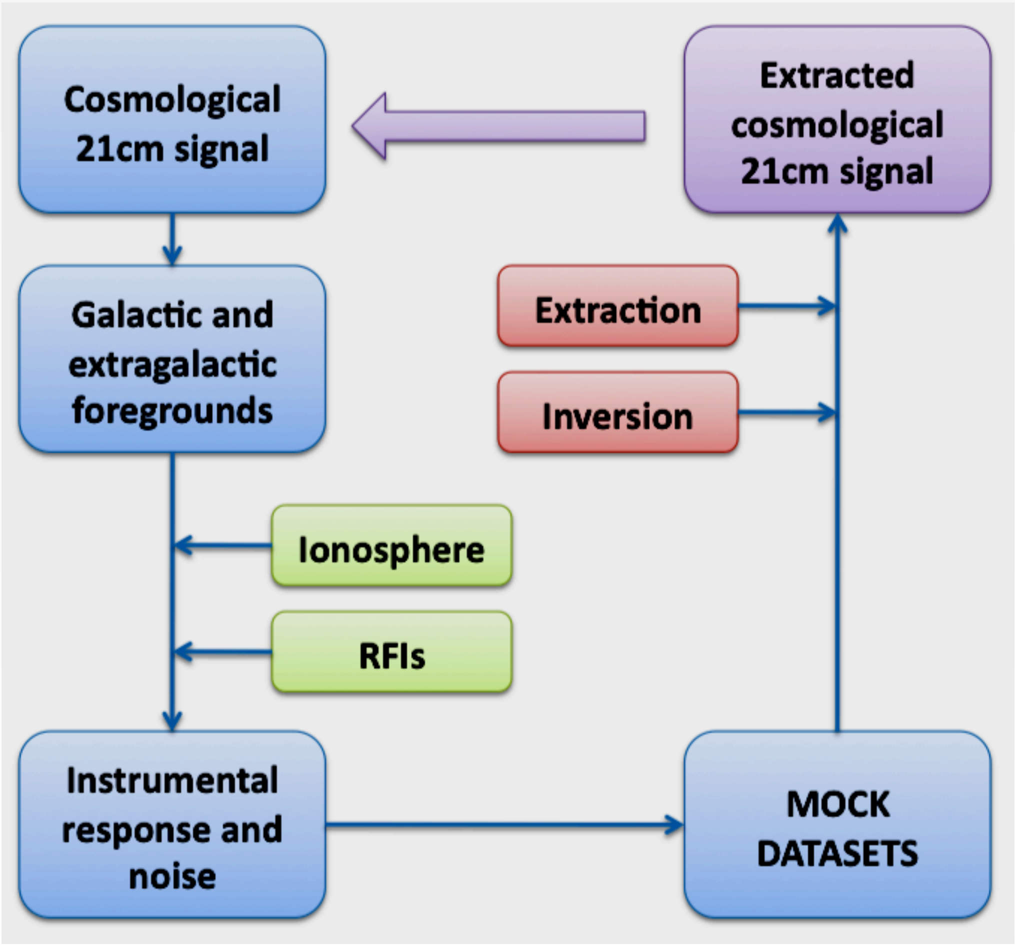
- featureless power law
- variation in spectral index with position on the sky and with frequency



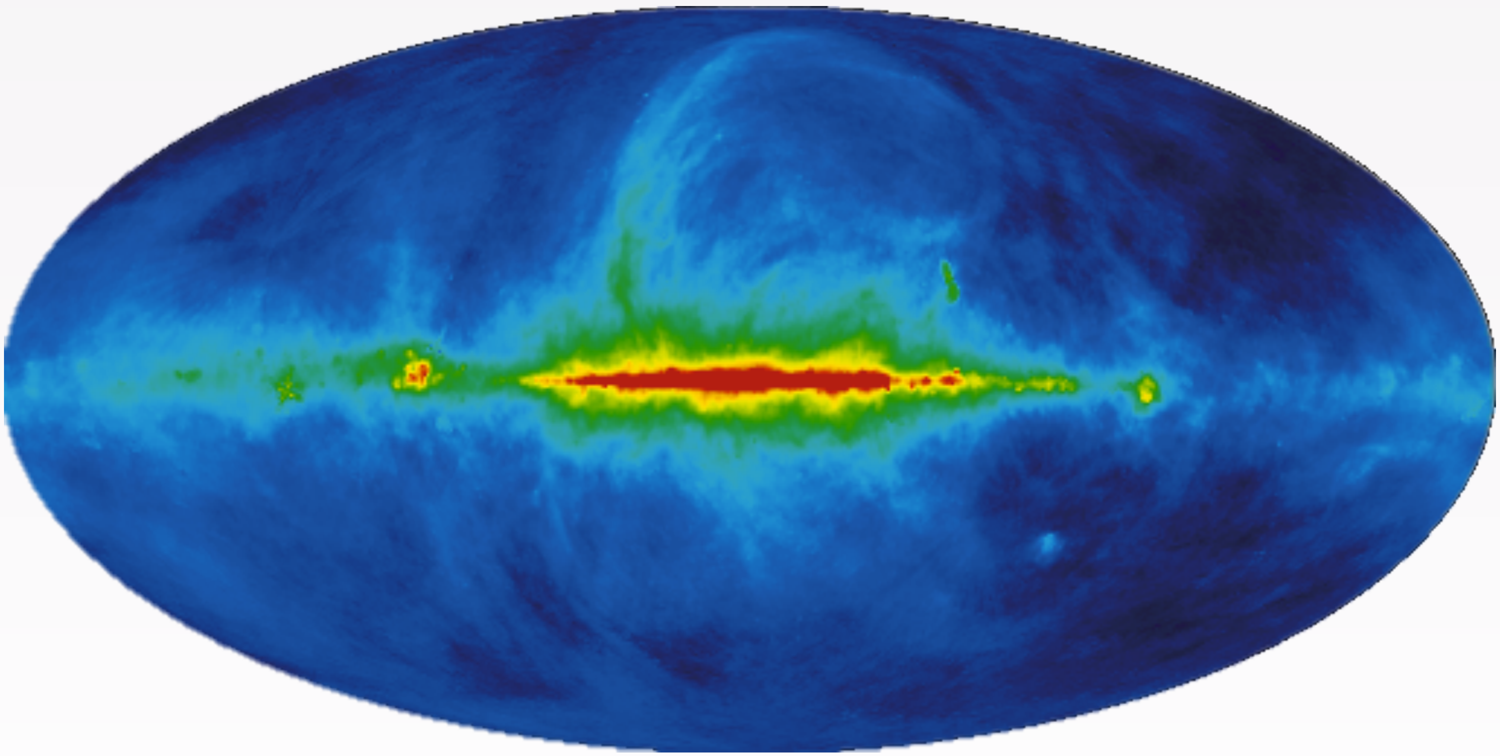
SIMULATIONS: 5° x 5° filed of view, ~ 0.6 arcmin resolution and freq. range: 115-180 MHz LOFAR 50-370 SKA-low

Jelic et al., 2008, MNRAS

The problem outline:



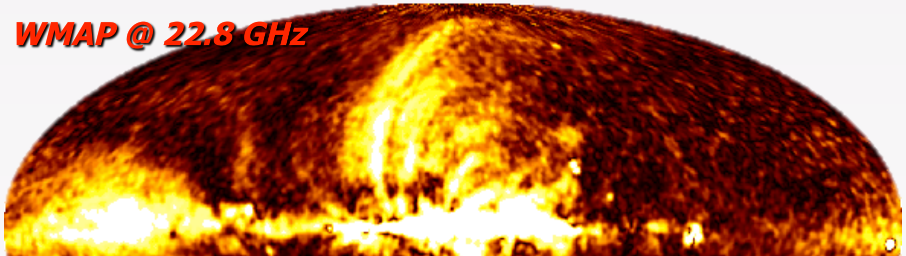
Galactic foreground emission



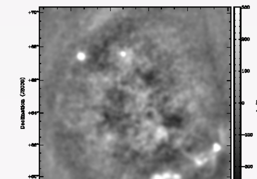
0.85^0 resolution
Galactic map @ 408 MHz
Haslam et al. 1982

5^0 resolution
Galactic map @ 150 MHz
Landecker & Wielebinski et al. 1982

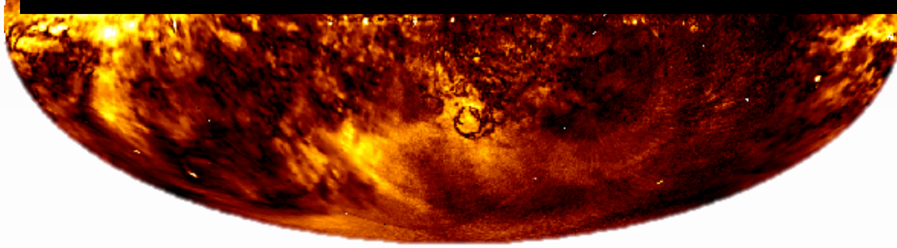
Polarized Galactic foreground emission



Fan region in total intensity @ 150 MHz



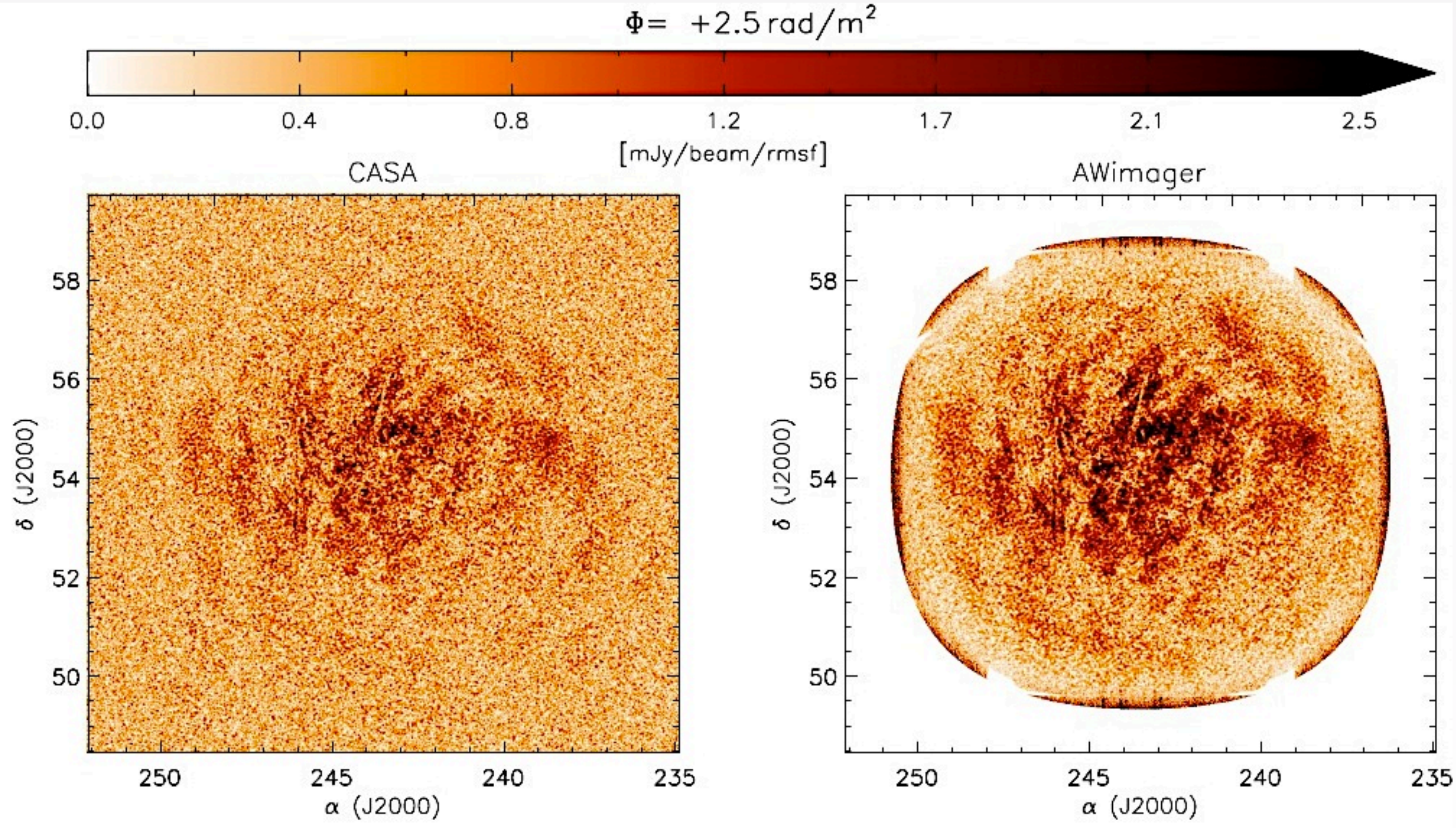
- spatially more smooth in total than in polarized intensity !
- polarized structures are not correlated with structures seen in total intensity, due to strong depolarization effects !
- in the Galactic halo fluctuations are of a few Kelvin in total intensity and a few 100 mK in polarized intensity !



Sun et al. 2008

Bernardi et al. 2009

LOFAR commissioning: Elais N1 field



From V. Jelic

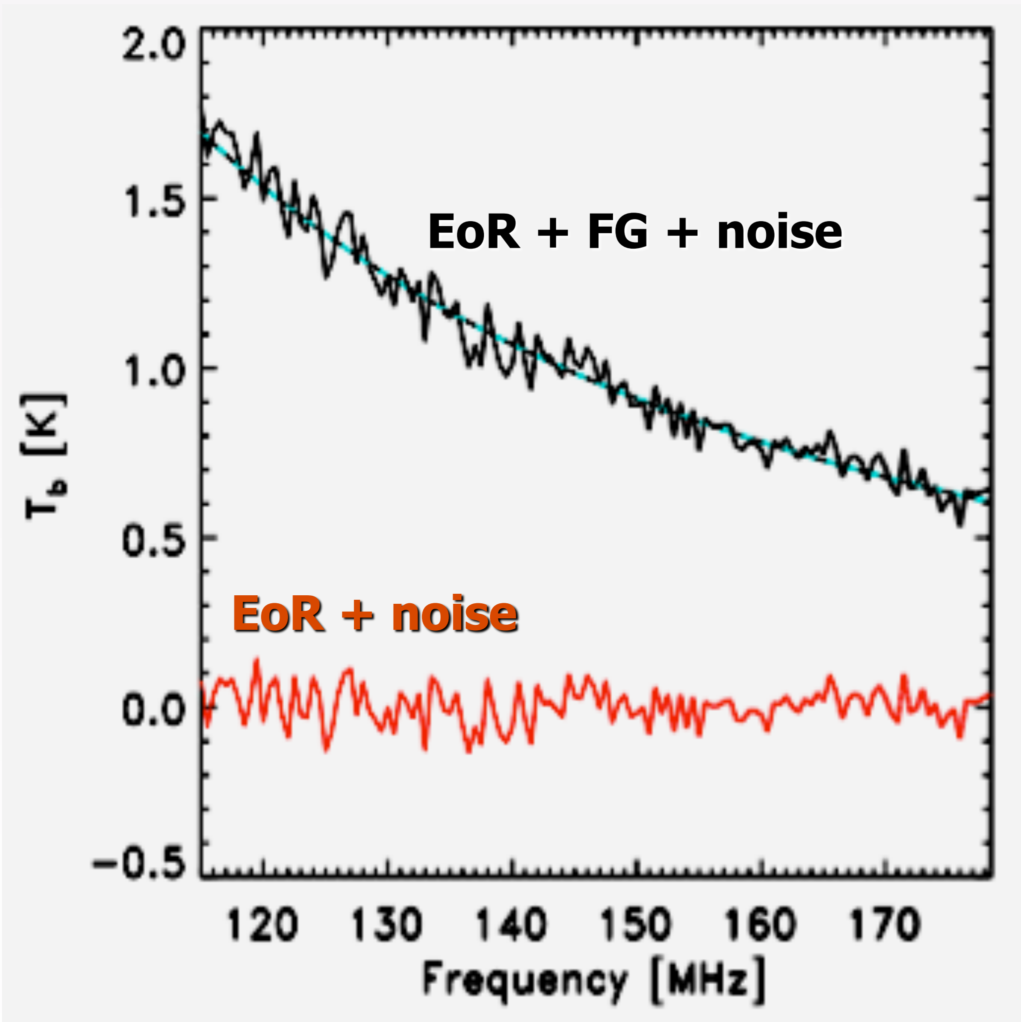
Outline:

- Foreground properties: what we know!
- Foreground removal: how we deal with it!
- Foregrounds for SKA-low: a list of issues!

Extraction of the EoR signal

@150 MHz

T_{EoR} ~ 5 mK
T_{FG} ~ 2 K
T_{noise} ~ 78 mK



Parametric fitting
(polynomial fitting)
Jelic et al. 2008

Non-parametric fitting
(Wp smoothing, ICA,..)
Harker et al. 2009
Chapman et al. 2012a,2012b

Problem Outline:

Spectral smoothness allows separation of 21cm. Options:

1 Fit power law to maps
2 Remove low order polynomials or some constraint fit (Harker et al.)
3 Measure components and model (Liu and Tegmark)
4 Measure modes of the foregrounds from a given FG model (Shaw not published yet)
5. Model independent methods (Chapman et al 2012a,2012b)
Issues:

- Mode mixing of angular and frequency fluctuations by frequency-dependent beams (esp. interferometers) [1, 2] method [2] does better in fourrier space.
- Robustness Biasing introduced if foreground model poorly understood (esp. non-gaussianities). [1, 3]
- Statistical Optimality Need to keep track of transformations on statistics, for optimal PS estimation [1, 2]
- Model Dependent [4] although excellent results.

How does it work, ICA +GMCA

- Find X where

$$\forall i = 1, \cdots, m; \quad x_i = \sum_{j=1}^{n} a_{ij} s_j \ ,$$

$$\mathbf{X} = \mathbf{AS} + \mathbf{N}$$

Information maximisation:

$$x = \sum_{i=1}^{D} \varphi_i = \sum_{i=1}^{D} \alpha_i \Phi_i \ ,$$

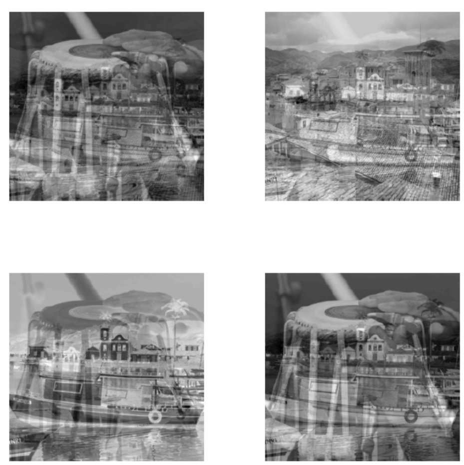
Wavelet decomposition in multi-scales

Sparsity -> solve:

$$\min_{\alpha} \|\alpha\|_0 \ \text{s.t} \ \mathbf{X} = \Xi \alpha \Phi \ ,$$

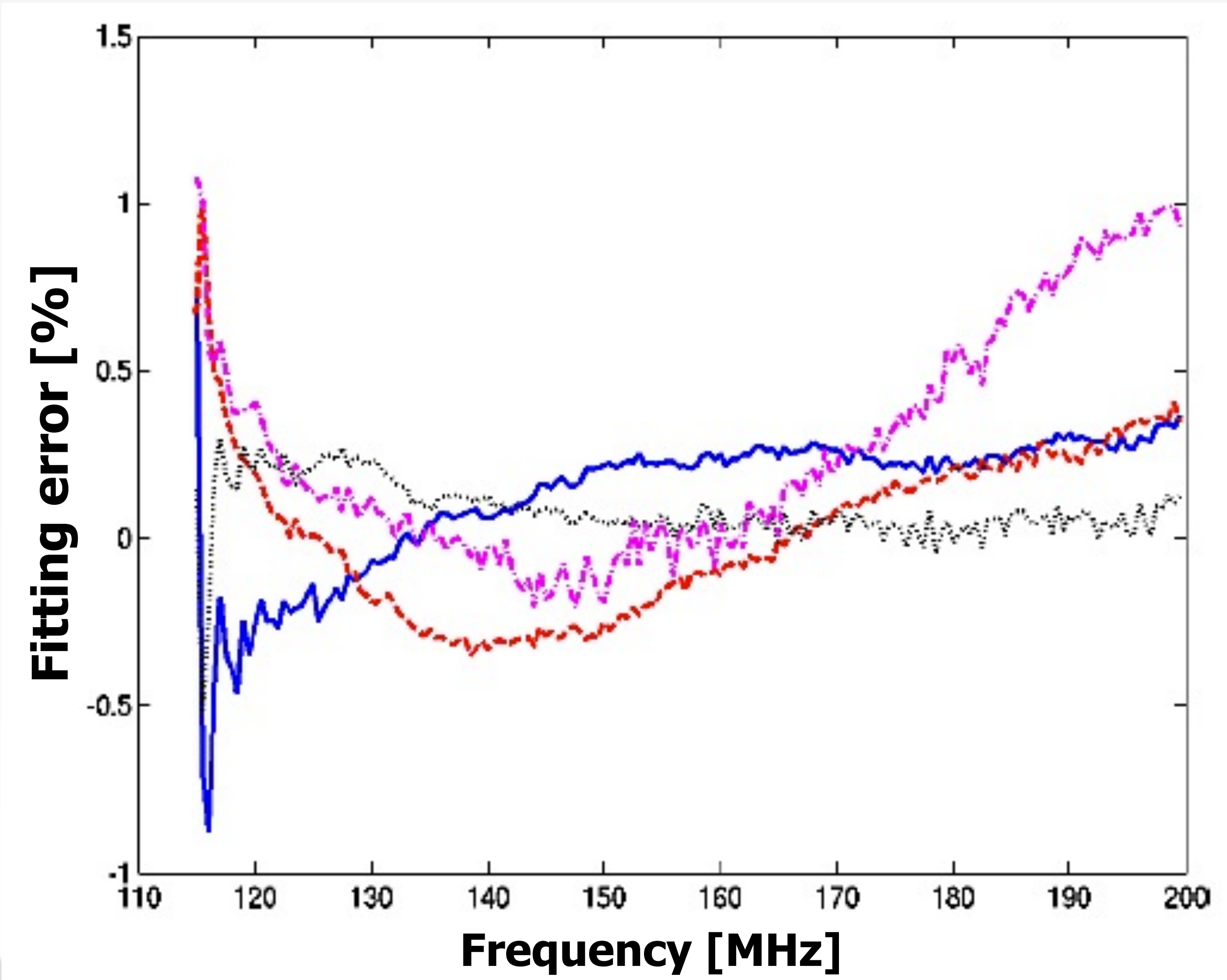
$$\min_{\alpha} \|\alpha\|_1 \ \text{s.t} \ \mathbf{X} = \Xi \alpha \Phi \ ,$$

- FastICA -> Remember the central limit theorem:
  - If you keep adding non-Gaussian signals they tend to a Gaussian component.



to

Extraction of the 21cm signal: simulations

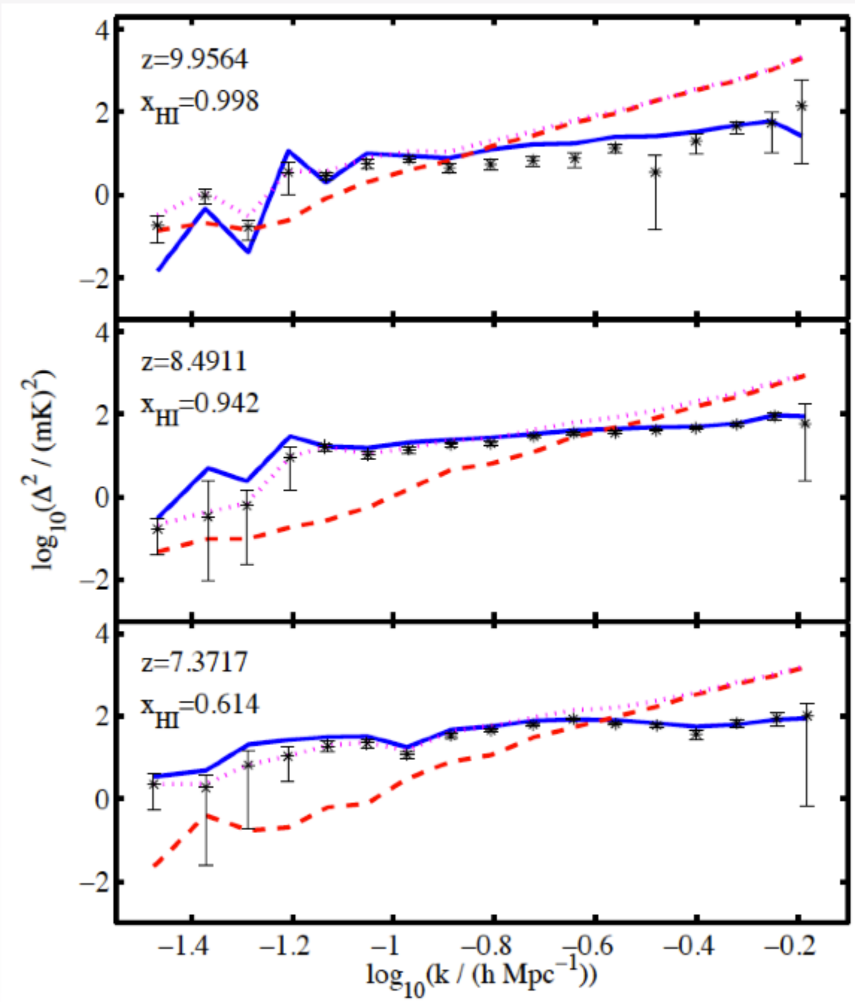


Chapman et al. 2012

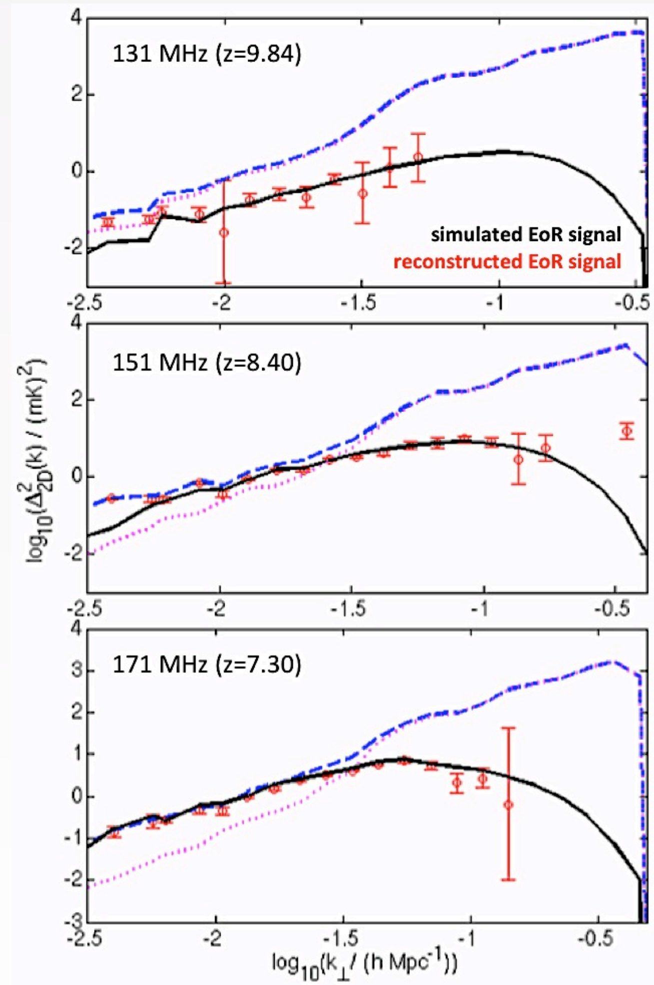
Method:

- We assume that we know the noise power spectrum.
- We assume that the point bright sources are removed in this process. All faint sources are included in the process.
- We calculate the total power spectrum of signal plus noise and remove the power spectrum of the noise. (warning -> this is why some plots will have negative variances!!! Not a mistake...)
- The excess variance is assigned to be from the cosmological signal and can calculate a power spectrum from that.

Extraction of the 21cm signal: simulations

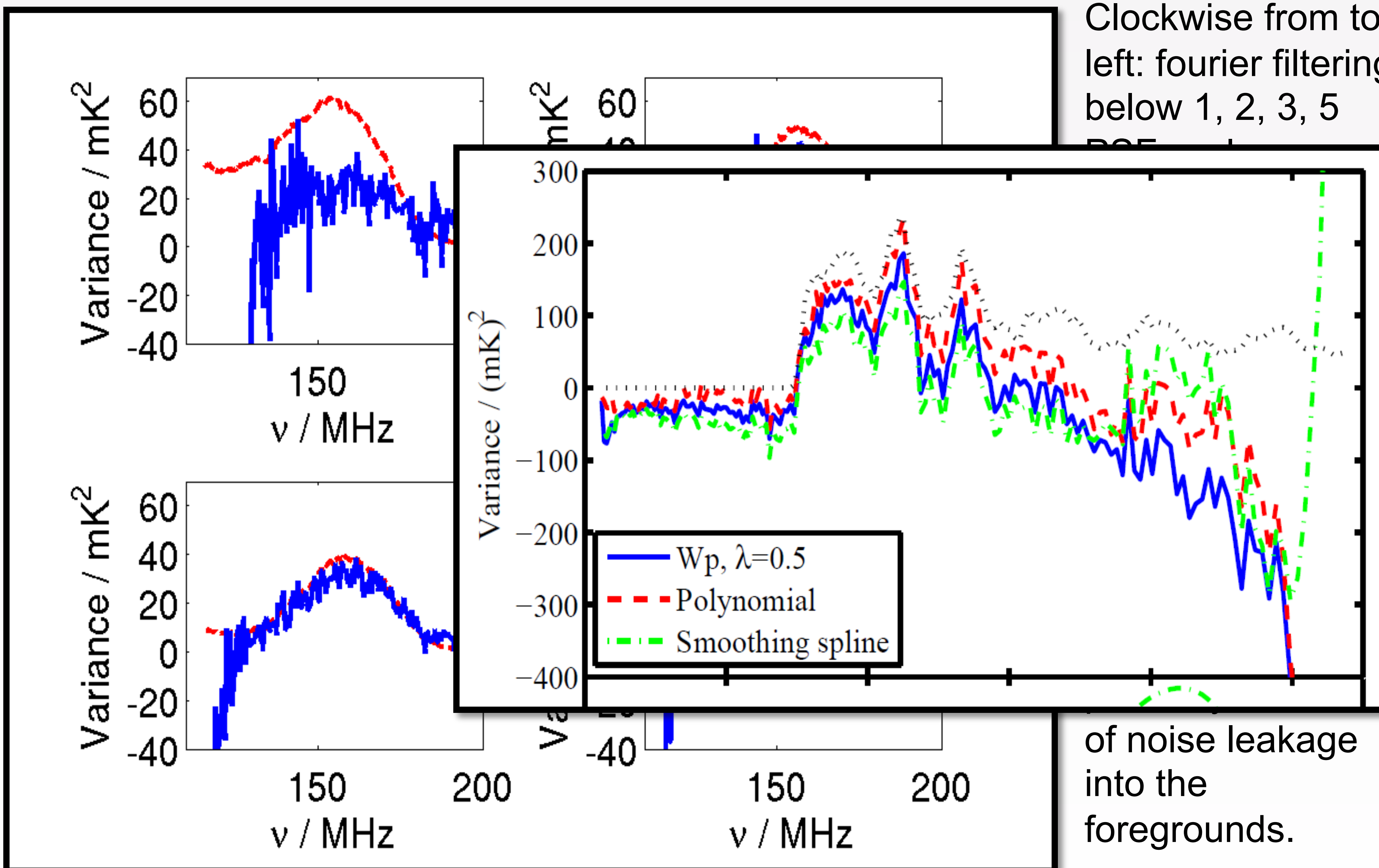


Harker et al. 2010



Chapman et al. 2012

Results: 21cm variance recovery – 1,2,3 and 5PSF Fourier filtered

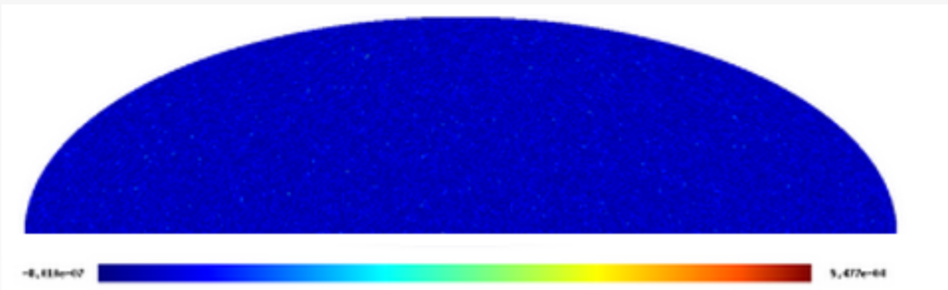


Clockwise from top left: fourier filtering below 1, 2, 3, 5

…

of noise leakage into the foregrounds.

Intensity mapping can be done at higher frequencies maybe!



Project galaxies in a bin onto the plane in the sky

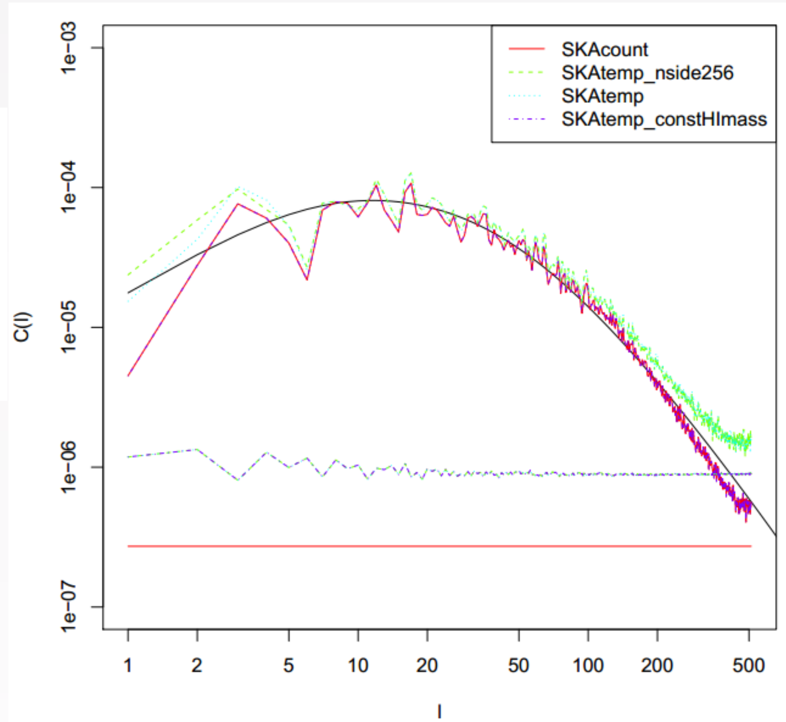
$$\sigma(\theta,\phi) = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell,m} Y_{\ell,m}(\theta,\phi)$$

Partial sky - correction to coefficients

$$C_{\ell,m}^{psky} = \frac{\left| a_{\ell,m} - \left(N/\Delta\Omega \right) i_{\ell,m} \right|^2}{J_{\ell,m}} - \frac{\Delta\Omega}{N}$$

$$J_{\ell,m} = \int_{\Delta\Omega} \left| Y_{\ell,m} \right|^2 d\Omega$$

$$i_{\ell,m} = \int_{\Delta\Omega} Y_{\ell,m}^{*} d\Omega$$



$$C_\ell \equiv < \delta^{2D} \delta^{*2D} > = 4\pi \int \Delta^2(k) W_i(k) W_j \frac{\mathrm{d}k}{k}$$

$$W_\ell(k) = \int f(z) j_\ell(kz) \mathrm{d}z$$

$$f(z) = n(z) D(z) \frac{\mathrm{d}z}{\mathrm{d}x}$$

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- Foreground properties: what we know!
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- Foregrounds for SKA-low: a list of issues!

Issues regarding foregrounds and foreground subtraction:

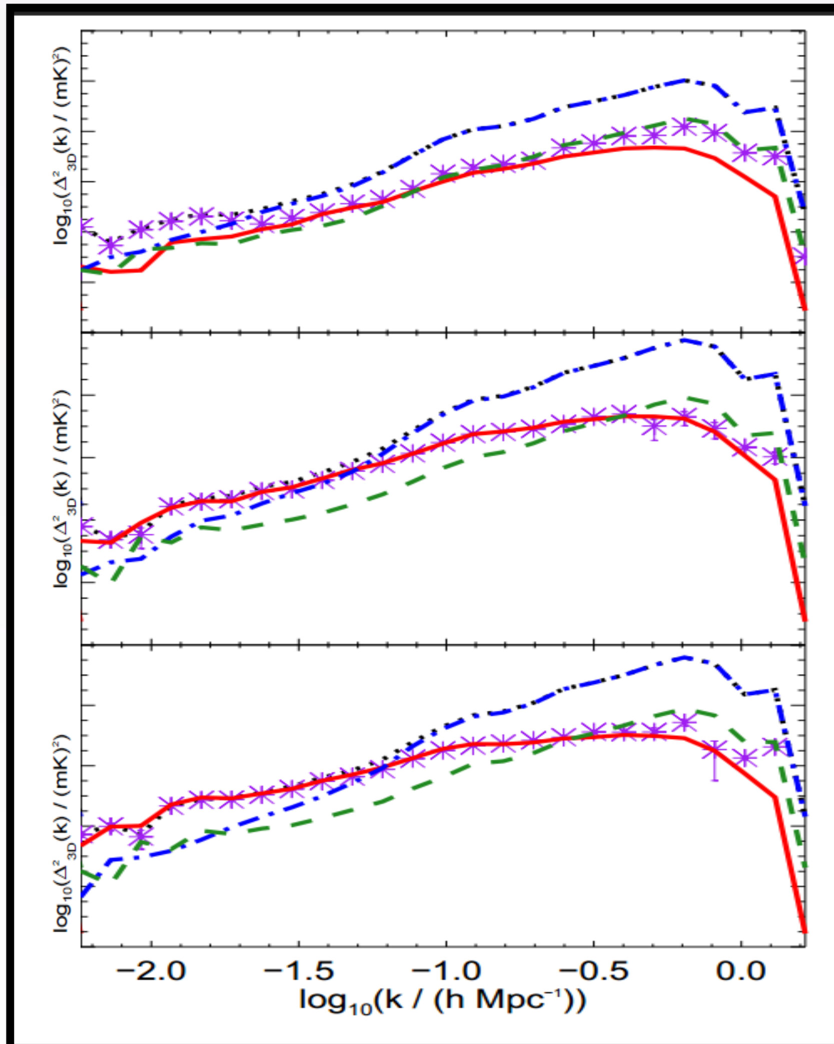
- UV coverage.
- Area to be covered in the sky.
- Polarisation.
- Frequency coverage.
- Band pass
- Imaging/Power spectra issues
- Sensitivity.

UV coverage:

- The core needs to be UV filled. No gaps for the Fg subtraction of the smooth galactic component.
- Need to remove point sources.
- Some long baselines are needed. No filled UV plane is needed beyond a few kms.
- Unsure if there is a requirement on the level of longer baselines (experience form LOFAR...)
- This is related to calibration!
- Can compressive sensing methods relax this?

Area coverage in the sky: station size and beams.

- Foreground subtraction at the larger scales are affected by the size of the field.
- Residuals can be significant but only at frequencies where teh foregrounds are large, at low nu.
- Question is how is this a function of FOV?
- How can we get the largest scale modes reliably or what are the largest scale modes available in these experiments? -> requirements.



Residual Projection

- We can project different signal elements onto the source space using the mixing matrix (A) calculated by GMCA in order to understand the amount of leakage.

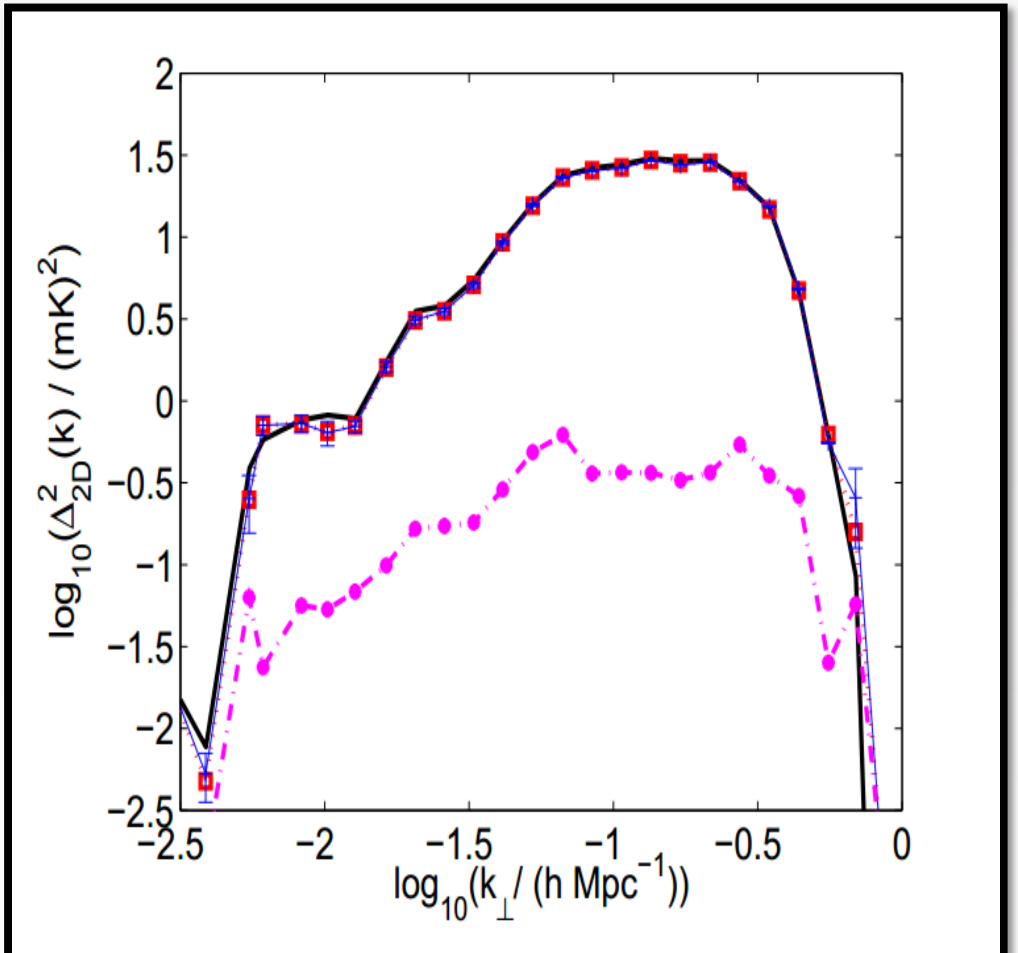
- $R_{fg} = fg - (A (A^T A)^{-1} A^T) fg$

  Amount of foreground leakage into reconstructed nocs
- $C_{nocs} = (A (A^T A)^{-1} A^T) (no+cs)$

  Amount of simulated no+cs leakage into the reconstructed foregrounds.
- $N_{nocs} = (A (A^T A)^{-1} A^T) (no)$ ->

  could try to correct for that!

Area covered in the sky: Residual Projection



fg: blue,dash

reconstructed fg: red, solid

simulated noise + cs: yellow,solid

C_{nocs}: green,dashdotdotdot

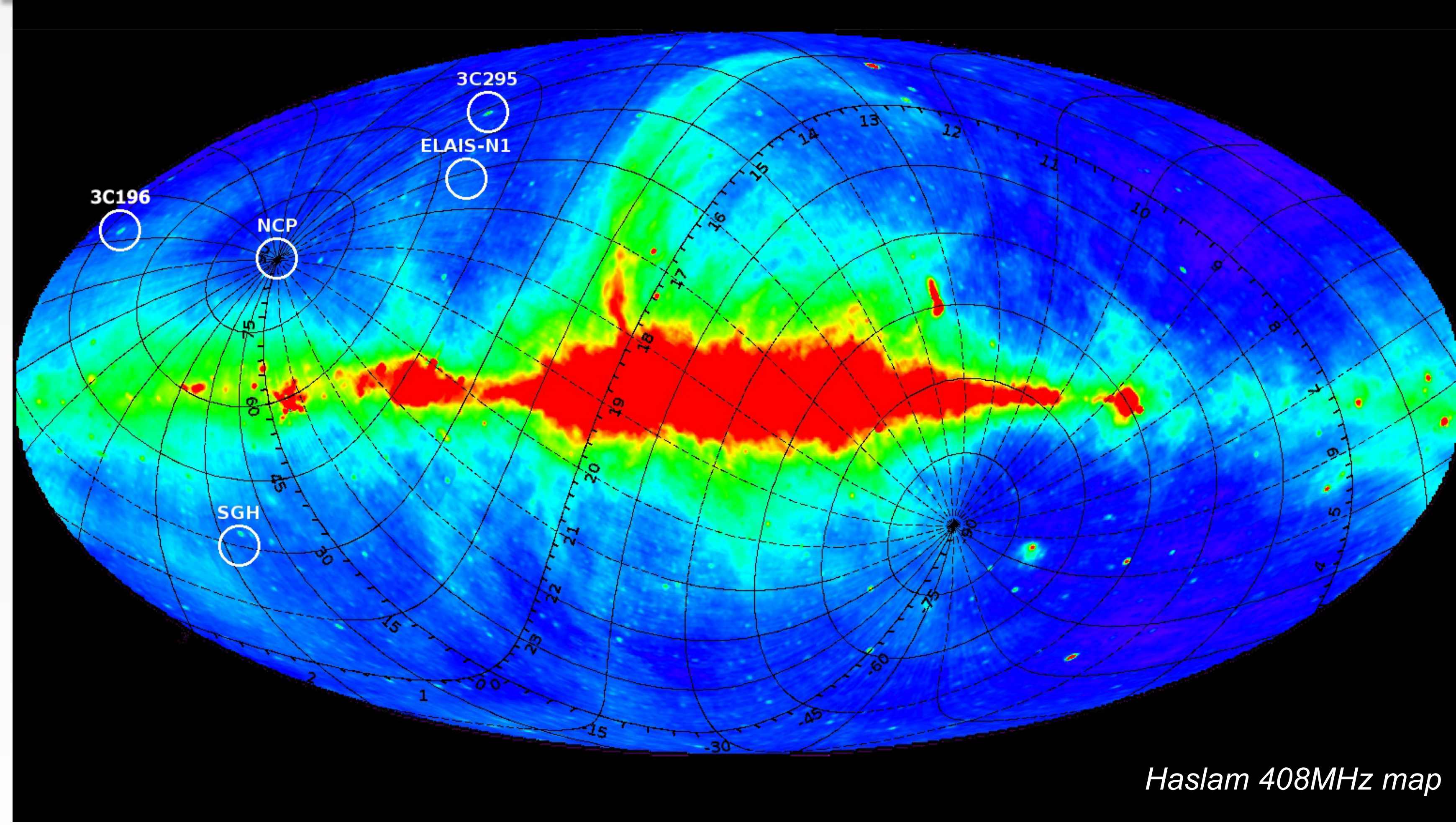
simulated cs: red,dashdot

reconstructed no+cs: black,dotted

R_{fg}: purple,dotted

Last plot: different wavelets

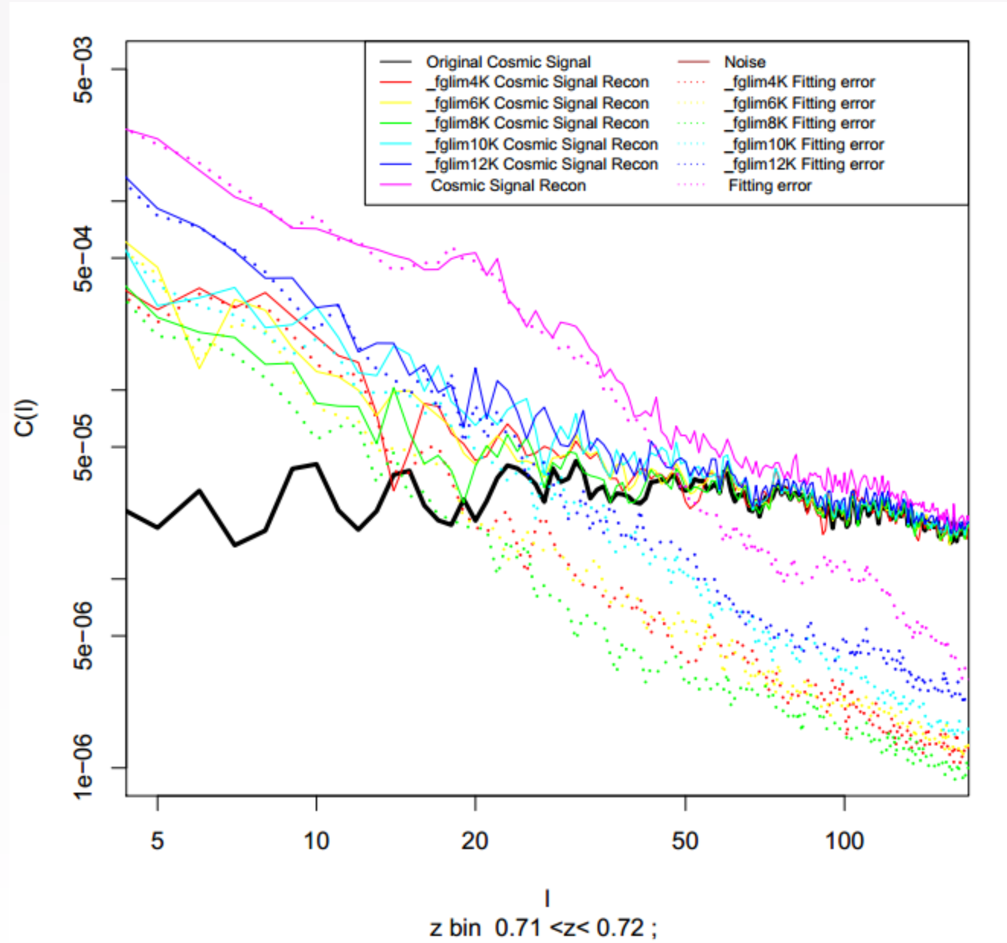
[redacted]



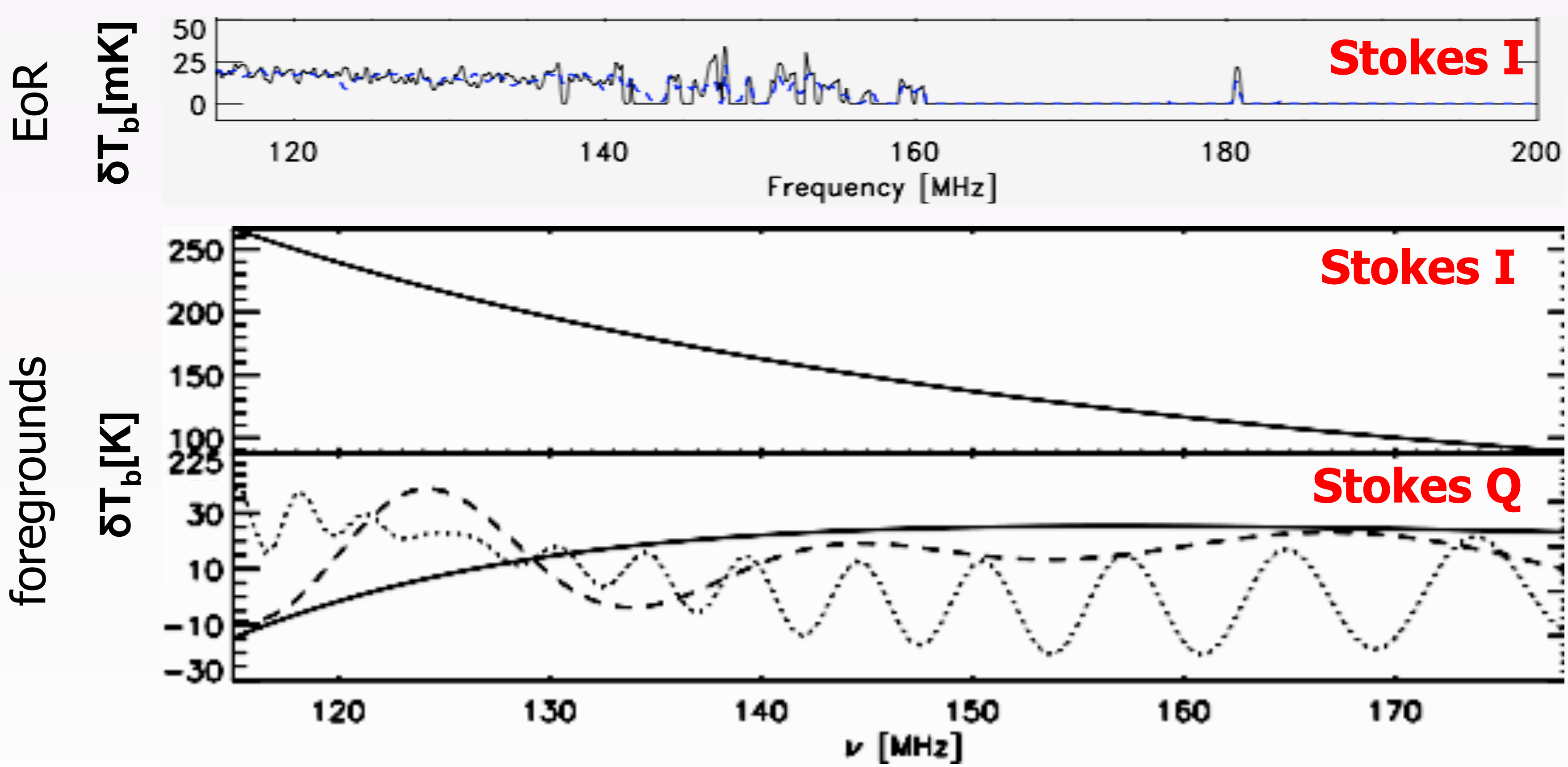
[redacted]

Area coverage in the sky: station size and beams.

- Foreground subtraction if all sky were available!
- Residuals are of the order of 0.1mK even in the center.
- This is a strong function of the area covered as the previous results for the LOFAR-EoR show bias at large scales.
- If all sky available sims, with proper masks, show biases at scales of l~20, which means ~ 10 degs scales. -> implications on science



Problem of the polarized foregrounds



➢ the leaked polarized emission can mimic the cosmological signal: extraction much more difficult

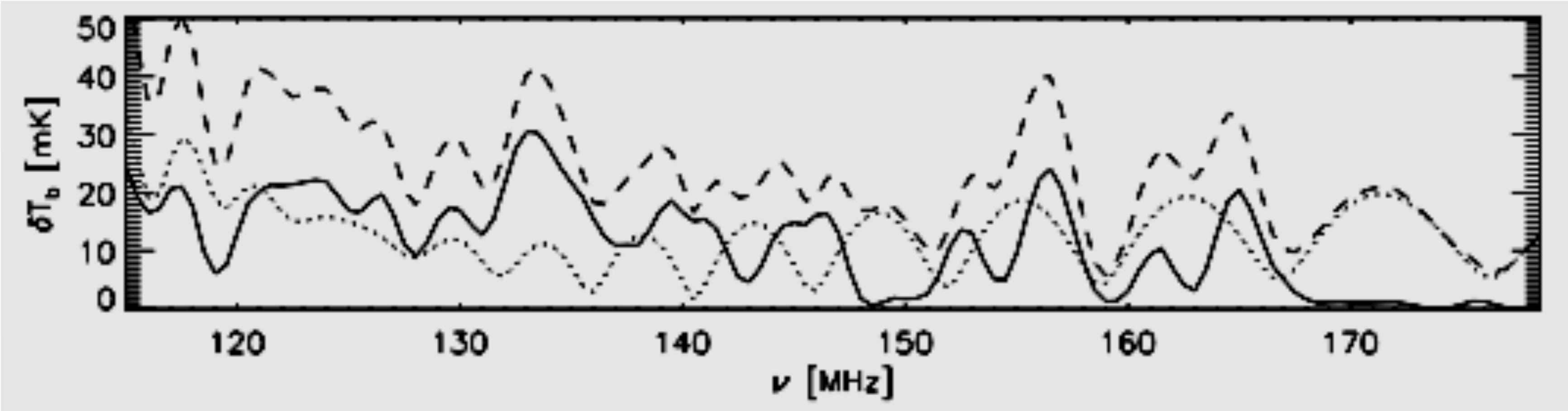
➢Leakage has to be controlled on a calibration level! Currently no FG separation method which deals with polarisation leakage. Leakage calibratable.

Problem of the polarized foregrounds

EoR ~ 25 mK

FG ~ 2 K

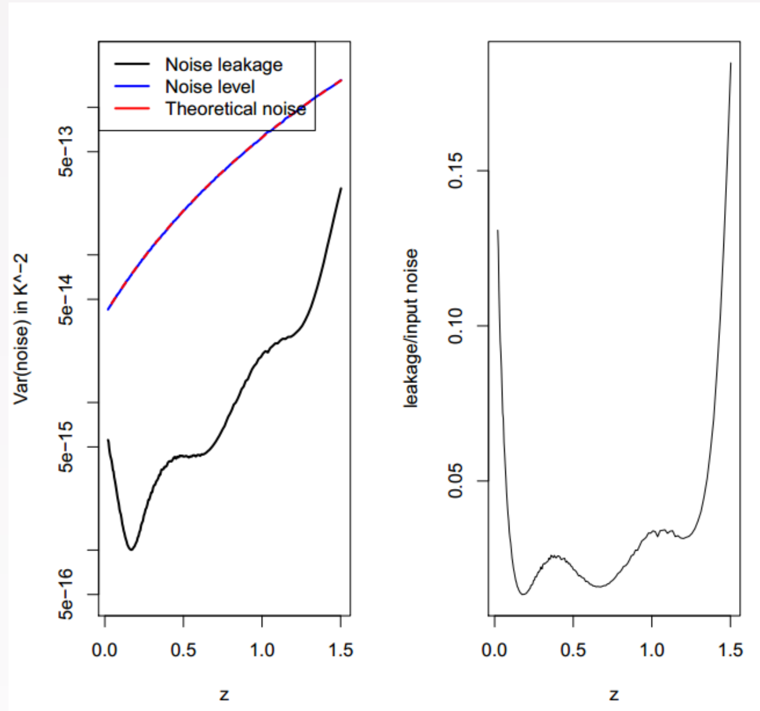
residual leakage ~ 1.5 % (30mK)

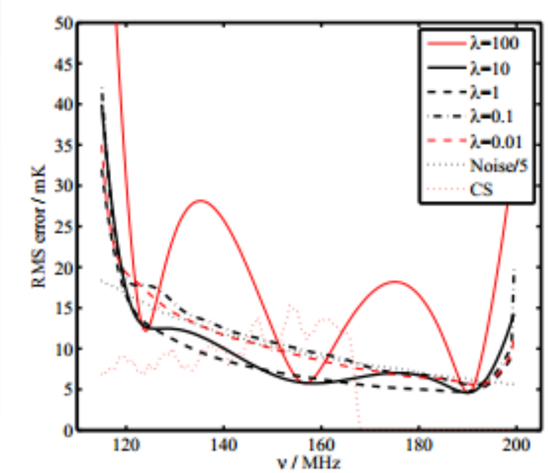


Jelic et al. 2010
Geil et al. 2011

Frequency coverage!

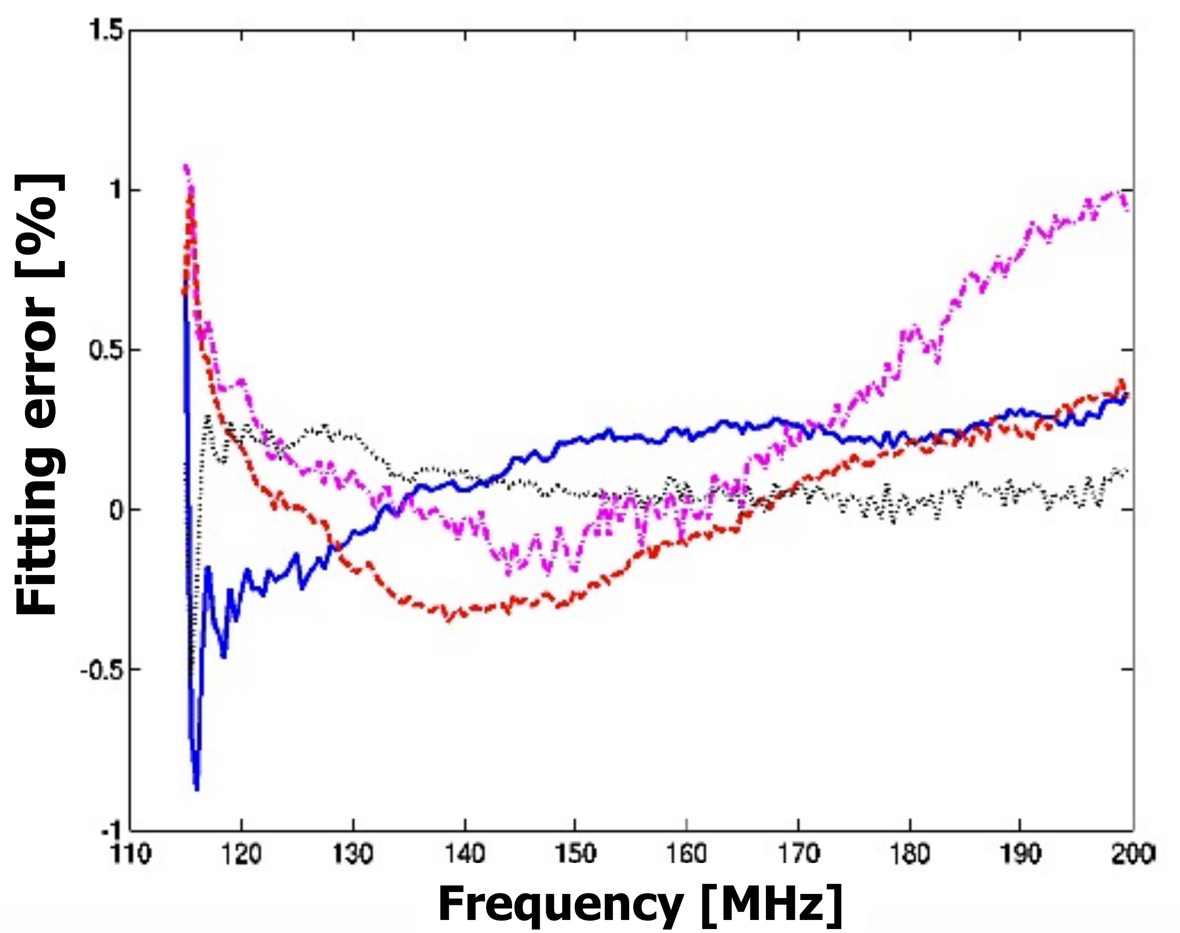
- Generic feature that we need a few MHz aside the central frequencies in order to obtain best foreground subtraction -> If band pass stops at 50Mhz, likely to not be able to remove foregrounds down to 60MHz...
- Frequency: EoR absorbtion signal & EoR heating period & 21cm Intensity mapping at high redshift < EoR?





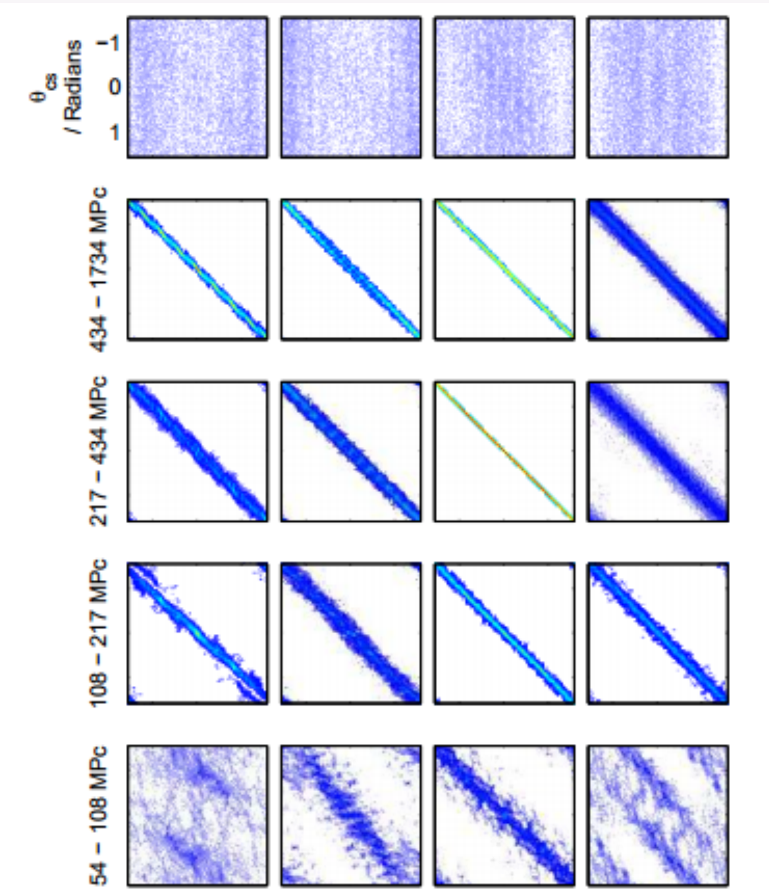
Band pass:

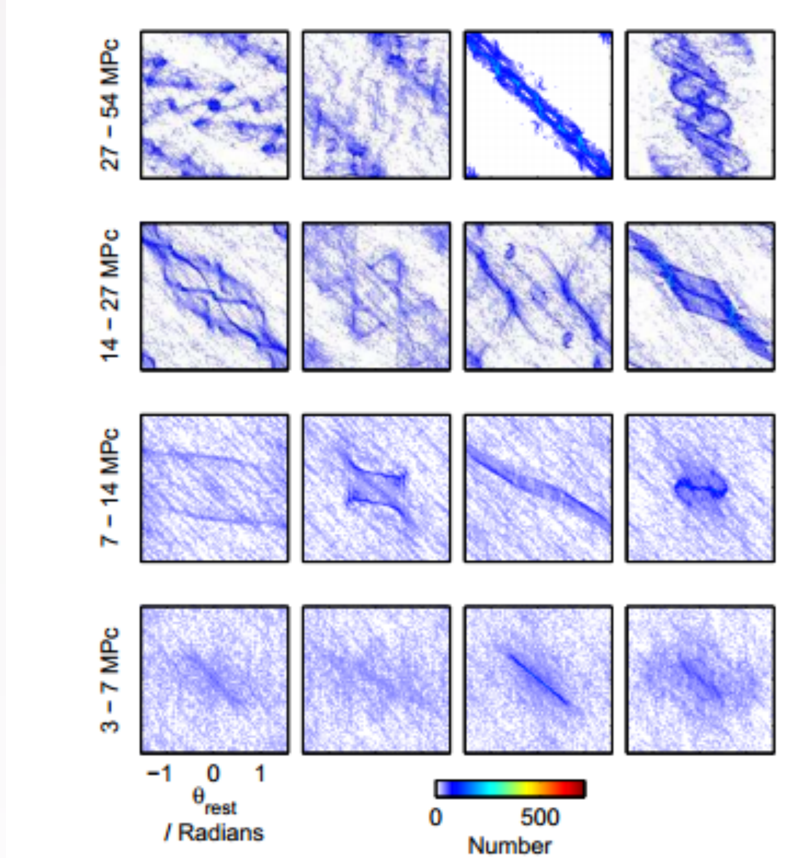
- Needs to be calibratable over the frequency range of the foregrounds
- Antenna gains may vary on many seconds timescale, direction dependent effects.



Chapman et al. 2012

Phase Conservation & imaging



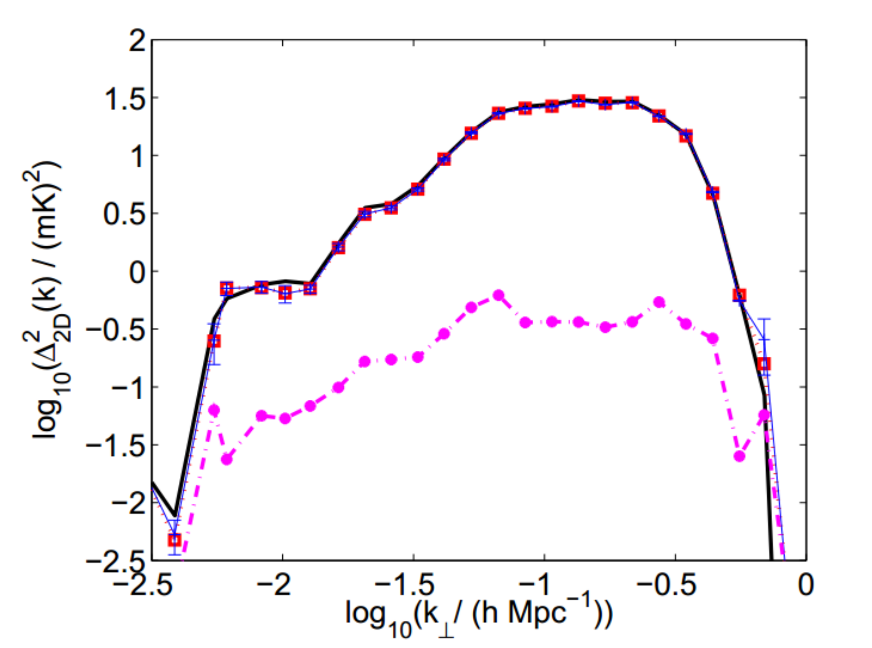


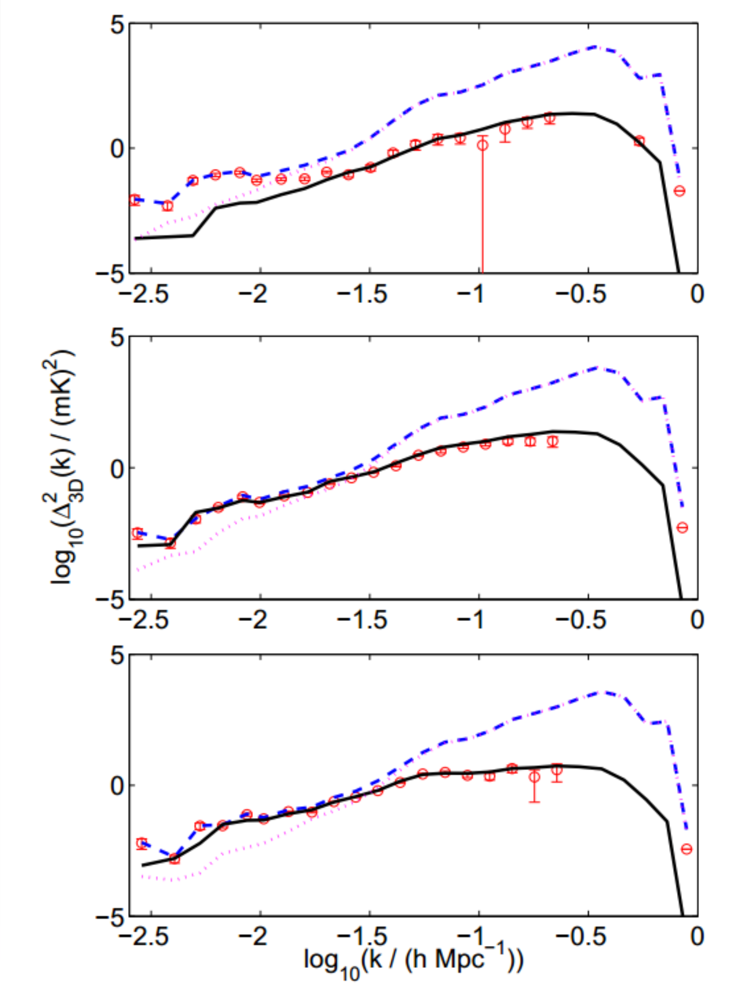
If image phase conserved throughout fg removal process, imaging may be possible with LOFAR.

Original image, Scales 1,2.....

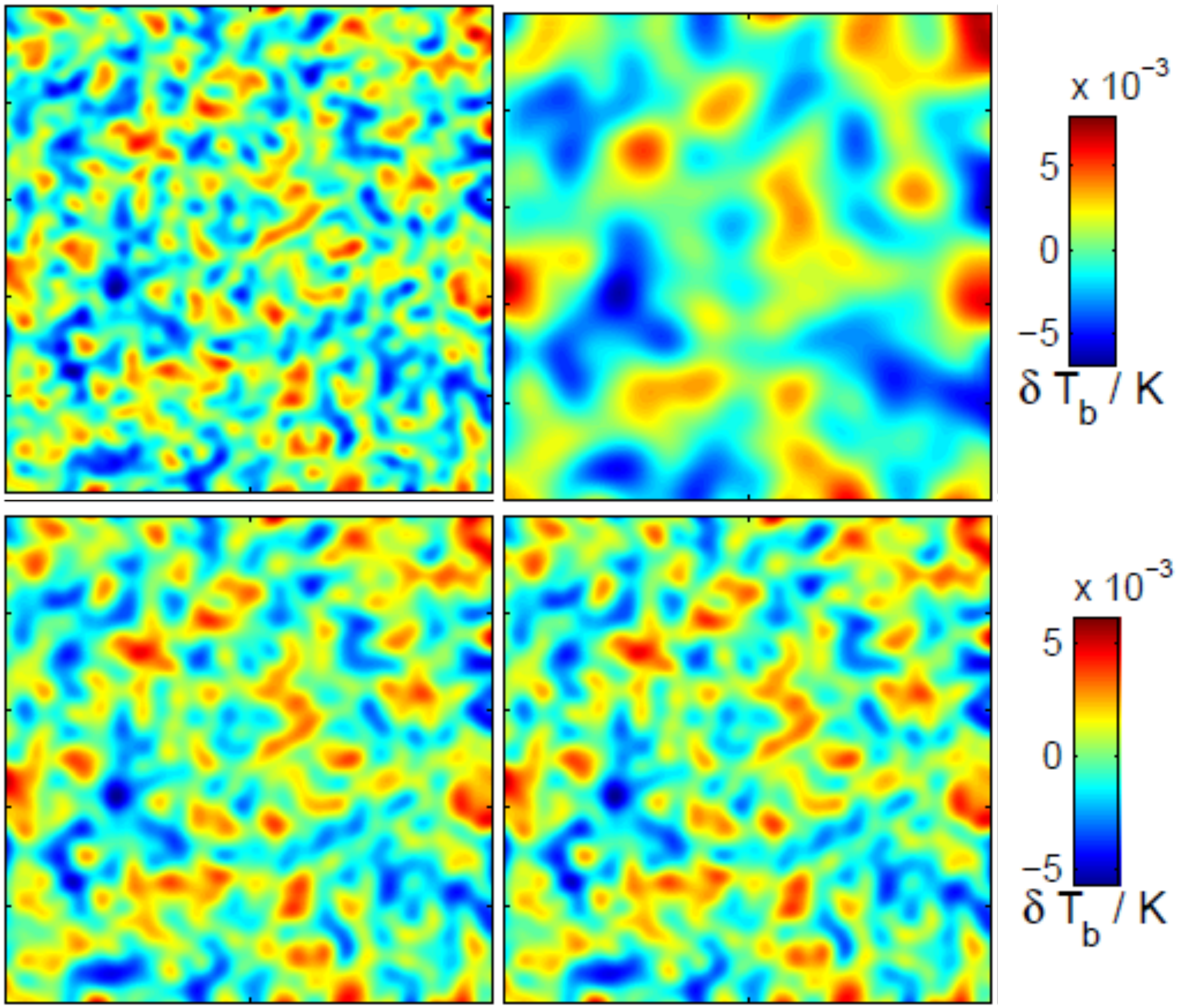
Phase Conservation & imaging

Foreground removal with different signals to noise, not only the foreground removal is better as the S/N changes, we are also able to perform imaging where the power spectrum of the signal is larger than the noise.





Phase Conservation & imaging



Correlation coeffs:

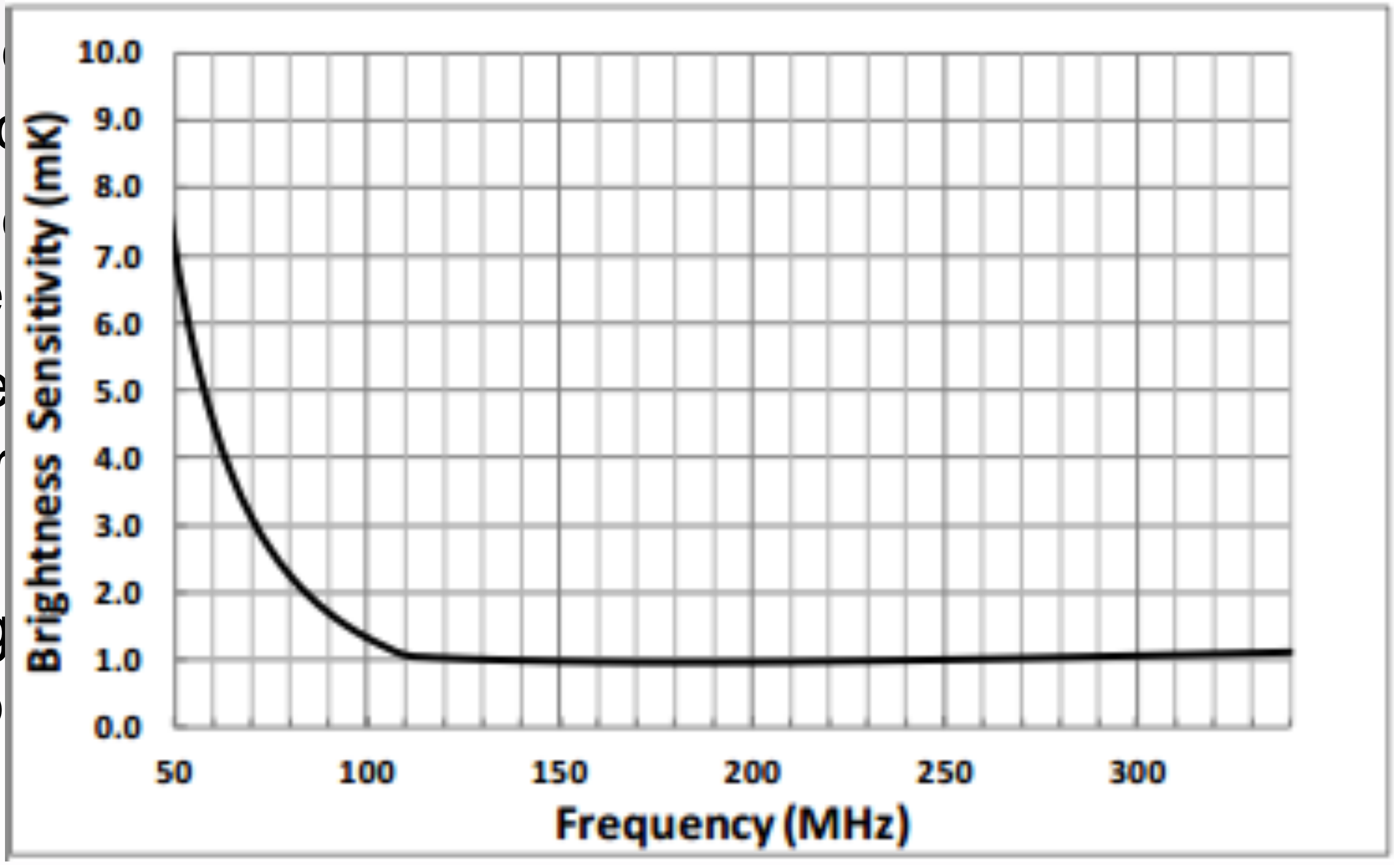
Smooth noise out:
0.588 and 0.605 in the middle half

Scales 2Gpc -> 50Mpc
0.687 and 0.788 inside

Scales 2Gpc -> 100Mpc
0.689 and 0.905 inside

Sensitivities:

- No ... led for ...
- No ... inte... ns.
- The ... uld be r... sen...
- Tog... is an imp...



Conclusions

- Properties and simulations of foregrounds briefly reviewed
- Some foreground separation methods outlined
- List of issues/non-issues:
  - UV coverage.
  - Area to be covered in the sky.
  - Polarisation.
  - Frequency coverage.
  - Band pass
  - Imaging/Power spectra issues
  - Sensitivity.