Cosmic Dawn & EoR Observational Challenges

Saleem Zaroubi, on behalf of the LOFAR EoR team

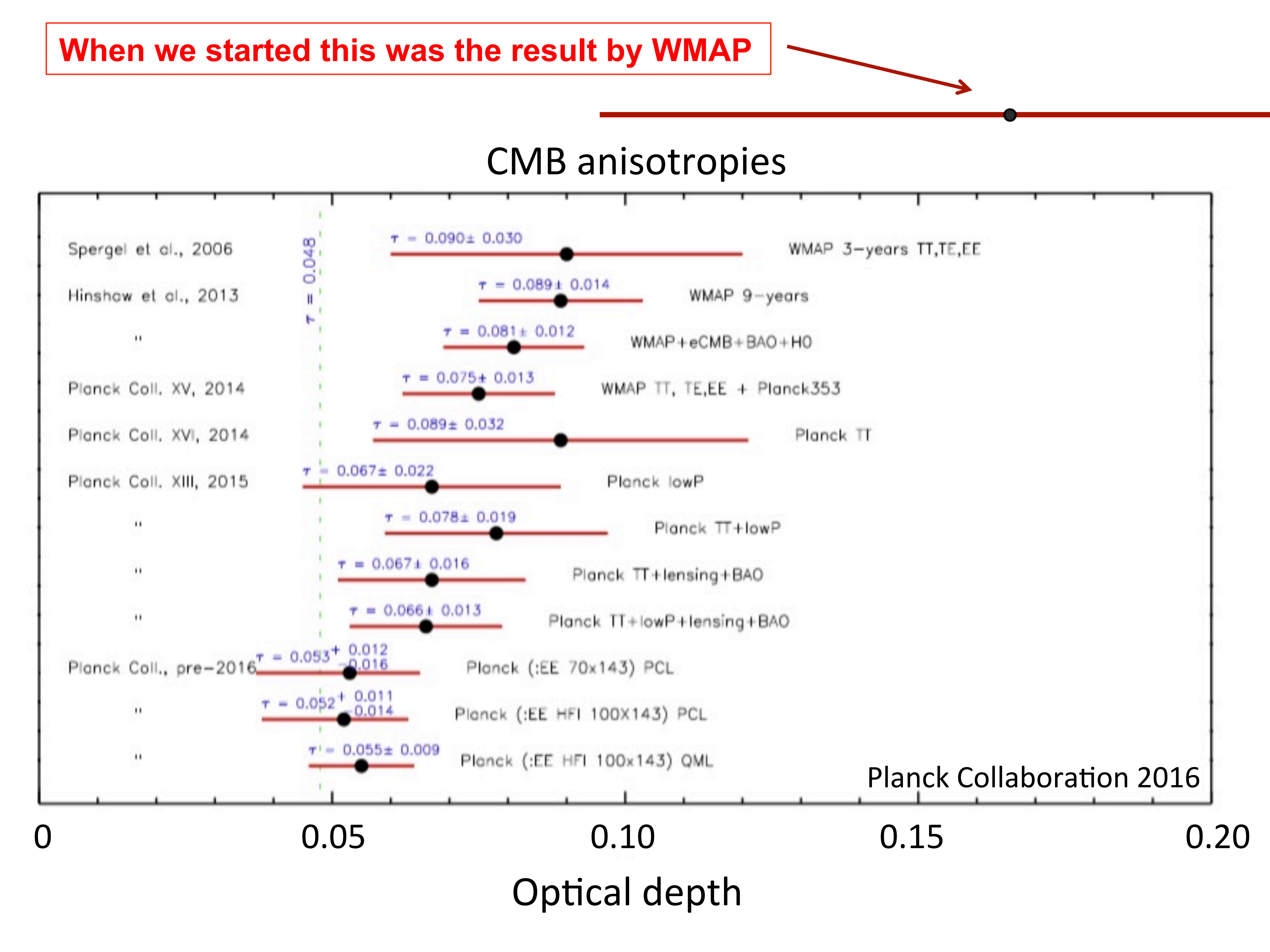
Ger de Bruyn, R.I.P.

Ger played a major role the proposal and preparatory phases of LOFAR.

Ger was the founding father of the LOFAR EoR Project, which started officially in 2004.

He played a major role in LOFAR in general and before that in WSRT.

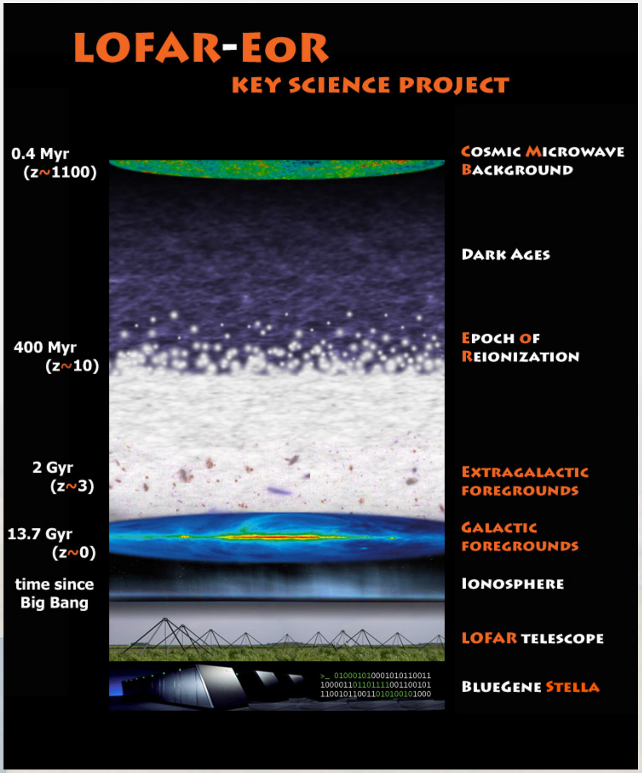


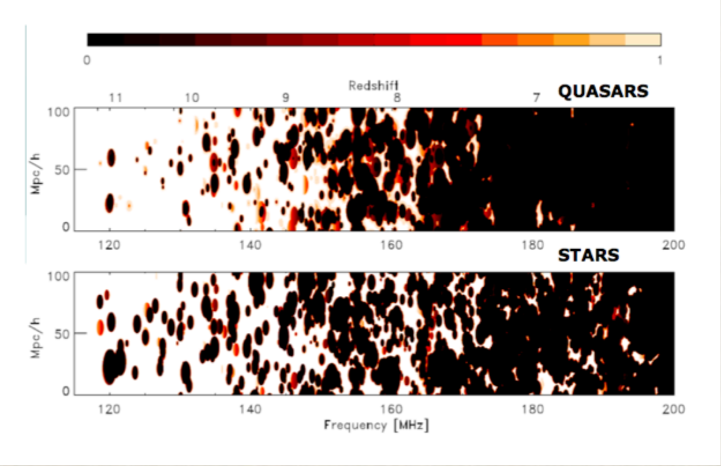
When we started this was the result by WMAP
CMB anisotropies
Spergel et al., 2006
τ = 0.090± 0.030
WMAP 3-years TT,TE,EE
Hinshaw et al., 2013
τ = 0.089± 0.014
WMAP 9-years
"
τ = 0.081± 0.012
WMAP+eCMB+BAO+H0
Planck Coll. XV, 2014
τ = 0.075± 0.013
WMAP TT, TE,EE + Planck353
Planck Coll. XVI, 2014
τ = 0.089± 0.032
Planck TT
Planck Coll. XIII, 2015
τ = 0.067± 0.022
Planck lowP
"
τ = 0.078± 0.019
Planck TT+lowP
"
τ = 0.067± 0.016
Planck TT+lensing+BAO
"
τ = 0.066± 0.013
Planck TT+lowP+lensing+BAO
Planck Coll., pre-2016
τ = 0.053 +0.012 -0.016
Planck (:EE 70x143) PCL
"
τ = 0.052 +0.011 -0.014
Planck (:EE HFI 100X143) PCL
"
τ = 0.055± 0.009
Planck (:EE HFI 100x143) QML
τ = 0.048
Planck Collaboration 2016
0
0.05
0.10
0.15
0.20
Optical depth

Main science goals of the LOFAR EoR project

- — Statistical detection of global signal; z-evolution
- — Constrain the sources: stars, QSOs or …
- — The environment of high z QSOs / SMBH
- — Measure underlying dark matter density spectrum
- — Statistical characterization of ionization bubbles
- — Study 21cm forest to high z radio sources (if any)
- — Cross correlation with other probes: Ly-α, NIRB, CMB,..



Vibor Jelic (2010)

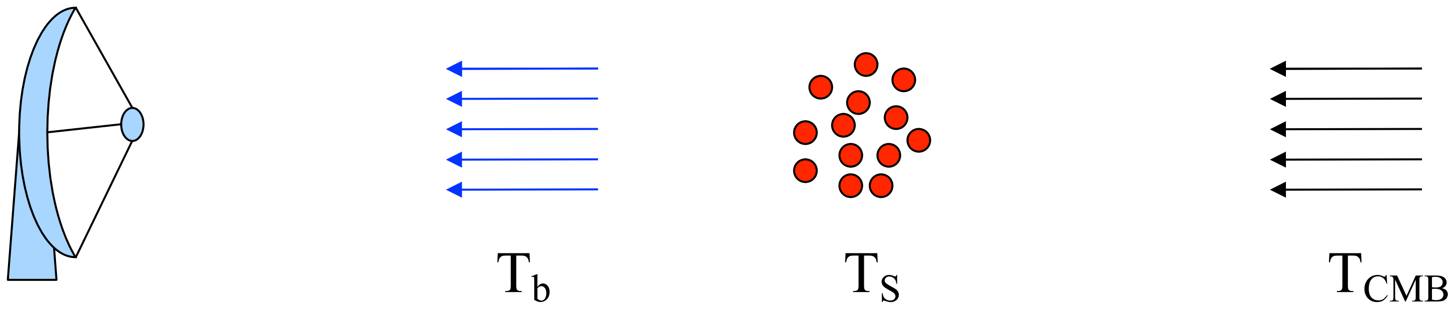


Rajat Thomas (2009)

115 - 177 MHz
z = 11.4 – 7.0

This will take 600 - 3000h of LOFAR HBA observing (2-3 windows)

δT_b, The Brightness Temperature



$$\delta T_b = 28\mathrm{mK}\,(1+\delta)\,x_{\rm HI}\left(1-\frac{T_{CMB}}{T_{spin}}\right)\left(\frac{\Omega_b h^2}{0.0223}\right)\sqrt{\left(\frac{1+z}{10}\right)\left(\frac{0.24}{\Omega_m}\right)}\left[\frac{H(z)/(1+z)}{\mathrm{d}v_{\parallel}/\mathrm{d}r_{\parallel}}\right],$$

Astrophysics

Cosmology

Field 1958, Madau, Meiksin & Rees 1997,
Ciardi & Madau 2003, ...

The rms and Cross-rms statistic

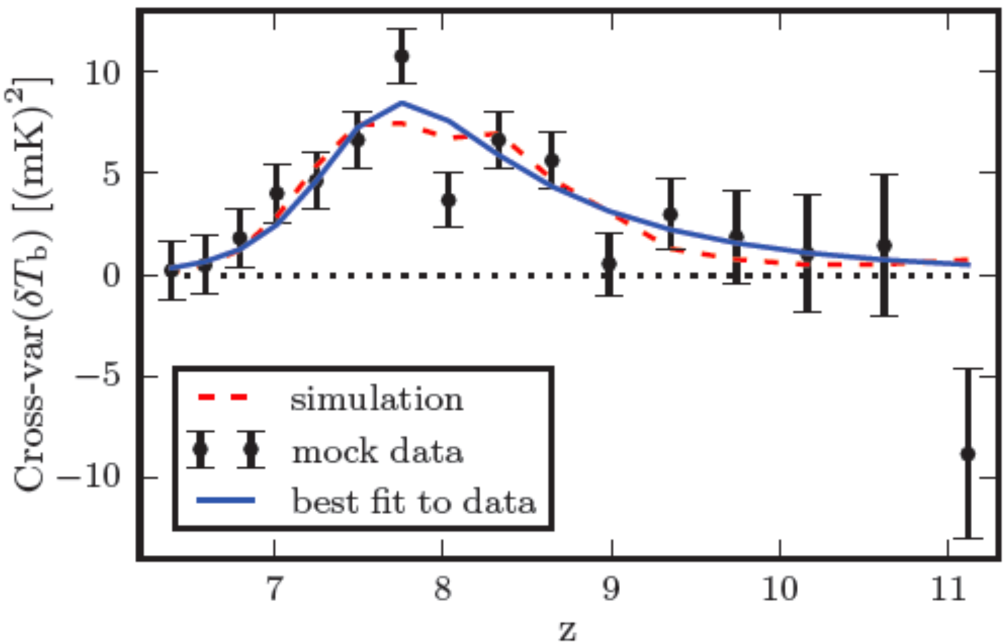
- Smooth the images with a Gaussian kernel

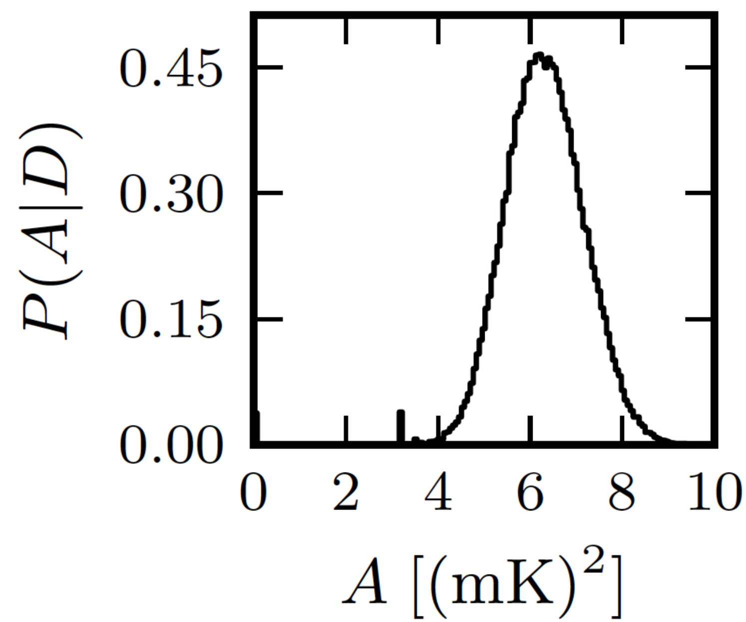
$$RMS(\nu) = \sqrt{\left\langle \left(I_{i,j}(\nu) I_{i,j}(\nu) \right) - \left\langle I_{i,j}(\nu) \right\rangle \left\langle I_{i,j}(\nu) \right\rangle \right\rangle_{i,j}}$$

$$CRMS(\nu) = \sqrt{\left\langle \left(I_{i,j}(\nu) I_{i,j}(\nu') \right) - \left\langle I_{i,j}(\nu) \right\rangle \left\langle I_{i,j}(\nu') \right\rangle \right\rangle_{i,j}}$$

$$\nu' = \nu + \Delta\nu$$

- Calculate the rms statistic and the Cross-rms:





$$Var(\delta T_b) = A \left(\frac{z}{z_0} \right)^{\beta} \left(1 + \tanh\left(\frac{z - z_0}{\Delta z} \right) \right)$$

Patil et al. 2014

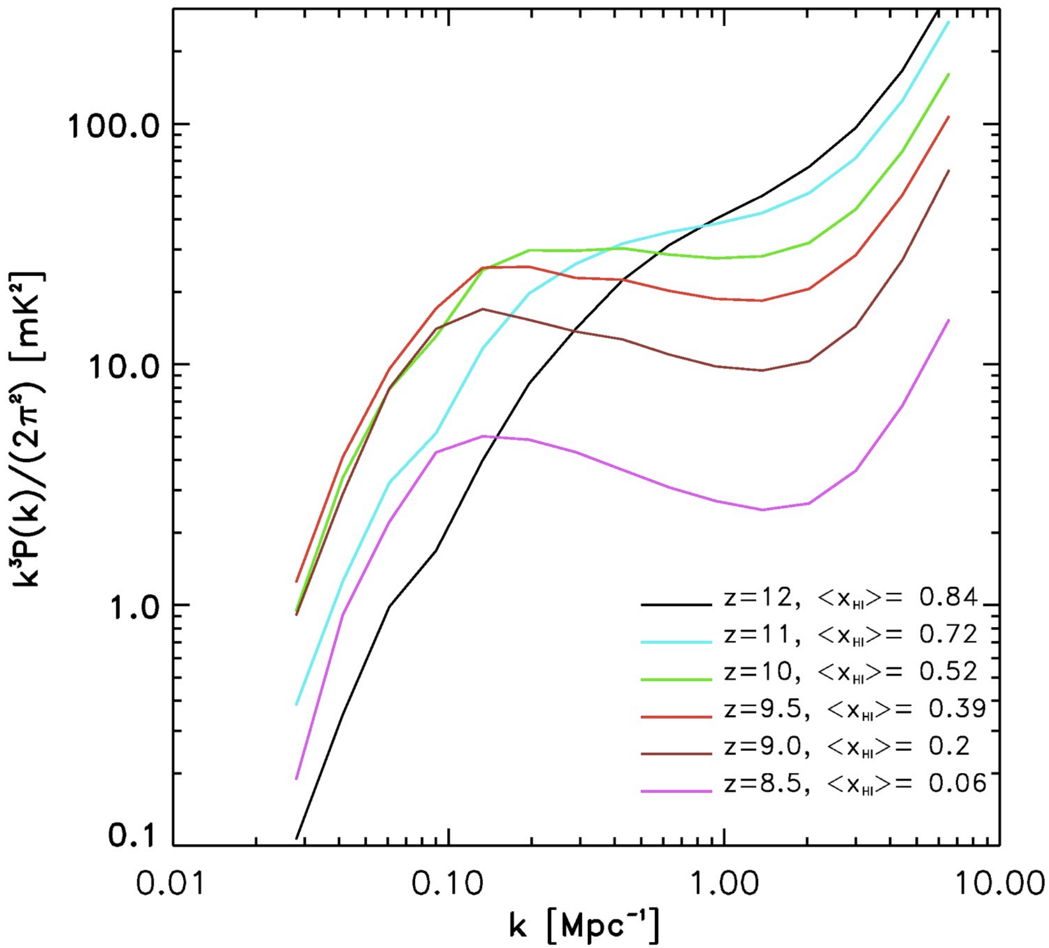
‘Dimensionless’ Power Spectra

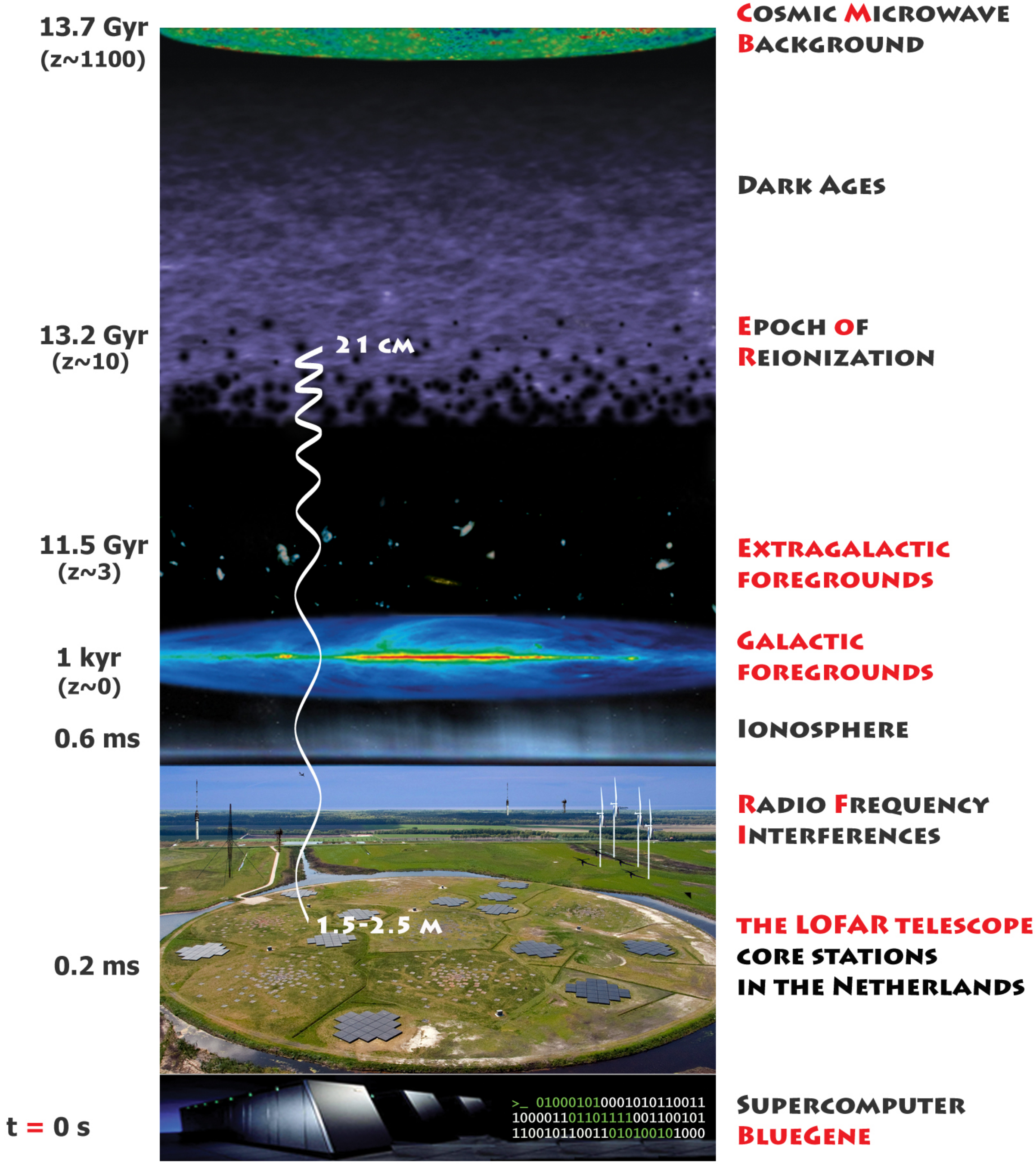
- The ‘Dimensionless’ spherically averaged power spectrum is defined as:

$$\Delta^2(k) = \frac{k^3 P(k)}{2\pi^2}$$

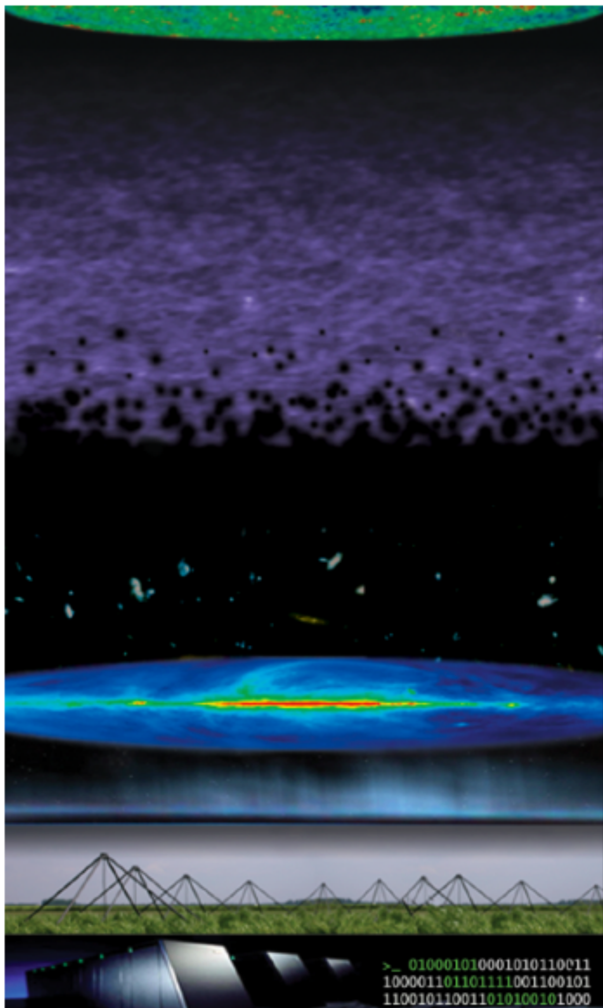
- The $(k_{\|}, k_{\perp})$ PS,

$$\Delta^2(k_{\|}, k_{\perp}) = \frac{(k_{\|}^2 + k_{\perp}^2)^{3/2}}{2\pi^2} P(k_{\|}, k_{\perp})$$



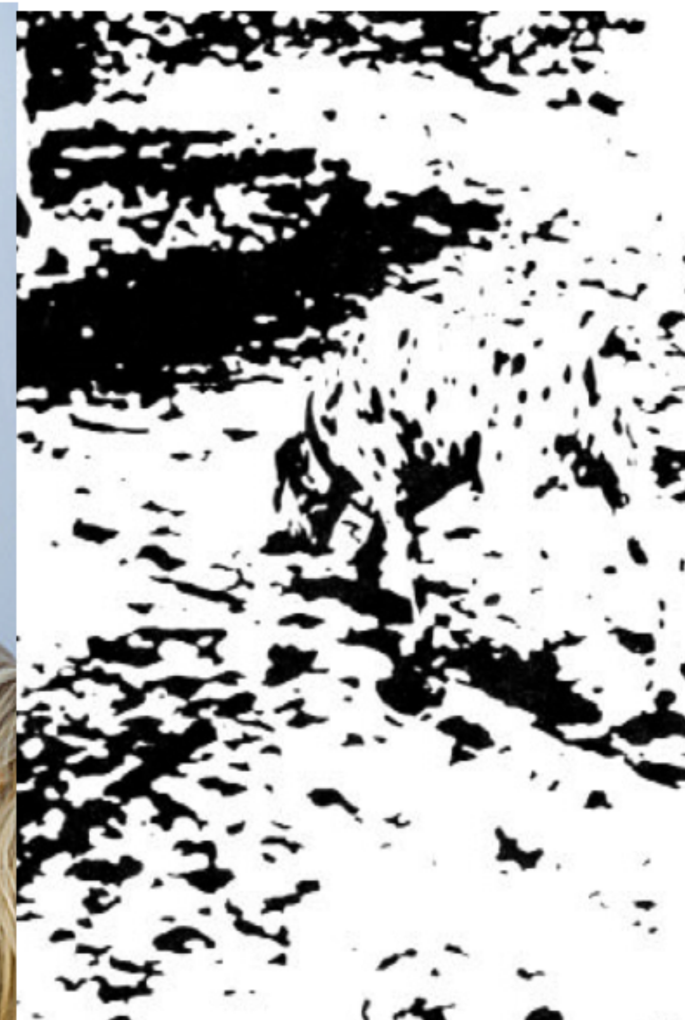

13.7 Gyr
(z~1100)
13.2 Gyr
(z~10)
11.5 Gyr
(z~3)
1 kyr
(z~0)
0.6 ms
0.2 ms
t = 0 s
21 cm
1.5-2.5 m
>_ 010001010001010110011
100001101101111001100101
110010110011010100101000
Cosmic Microwave Background
Dark Ages
Epoch of Reionization
Extragalactic foregrounds
Galactic foregrounds
Ionosphere
Radio Frequency Interferences
the LOFAR telescope
core stations
in the Netherlands
Supercomputer BlueGene

Observation



Extraction/ detection

Interpretation

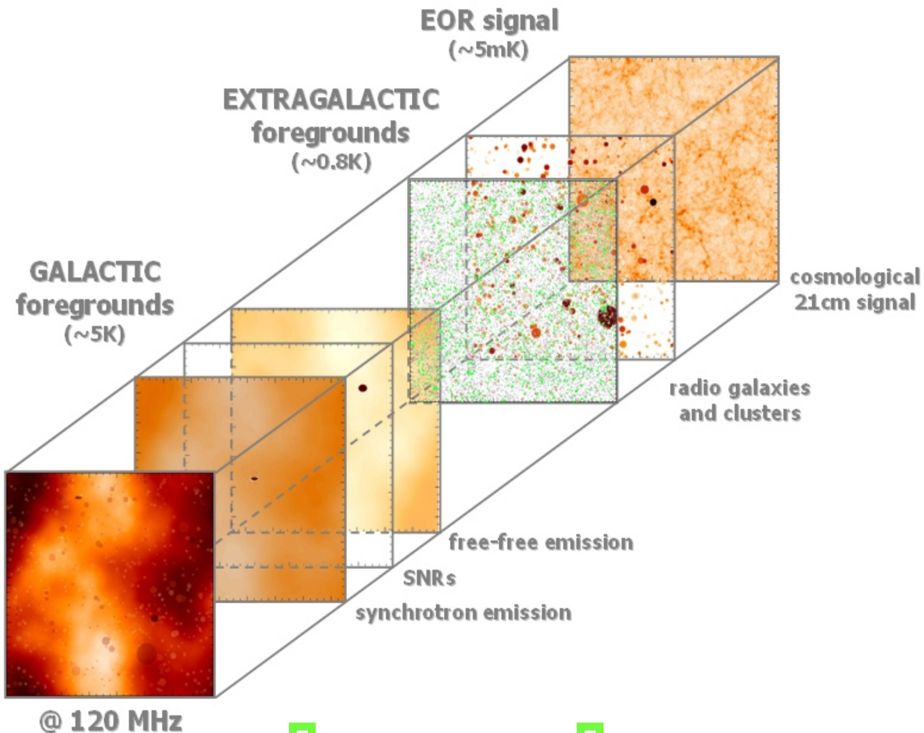


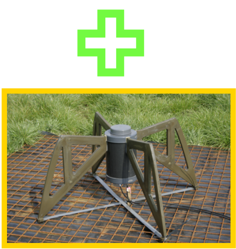
Low frequency radio astronomy is hard!

Things become much more difficult

at lower frequencies ~ $\nu^{-2.6\pm}$

Measuring Redshifted HI: Challenges





1. Astrophysical Challenges
   1. Weak unpolarized signal
   2. Foregrounds: total intensity
   3. Foregrounds: polarized
   4. Ionosphere
2. Instrumental challenges
   1. Beam stability
   2. Calibration
   3. Resolution
   4. uv coverage
3. Computational challenges
   1. Multi petabyte data set
   2. Calibration
   3. inversion

How to check reliability of results

Internal consistency checks

- Avoid problematic data, e.g., high RFI, very active ionosphere, etc.
- Observing multiple fields and obtain consistent results.
- Different times
- Frequencies
- Etc.

End to end pipeline

- Test observational strategy
- Performance of calibration methods
- Test various extraction techniques.
- Realistic estimates of errors of various statistics.
- What to expect from the results.

LOFAR

MWA

PAPER

GMRT

SKA

EDGES

Radio Frequency Interference

RFI can be a major problem, so good RFI excision at high temporal/frequency resolution is a must: SA/AU are good sites.

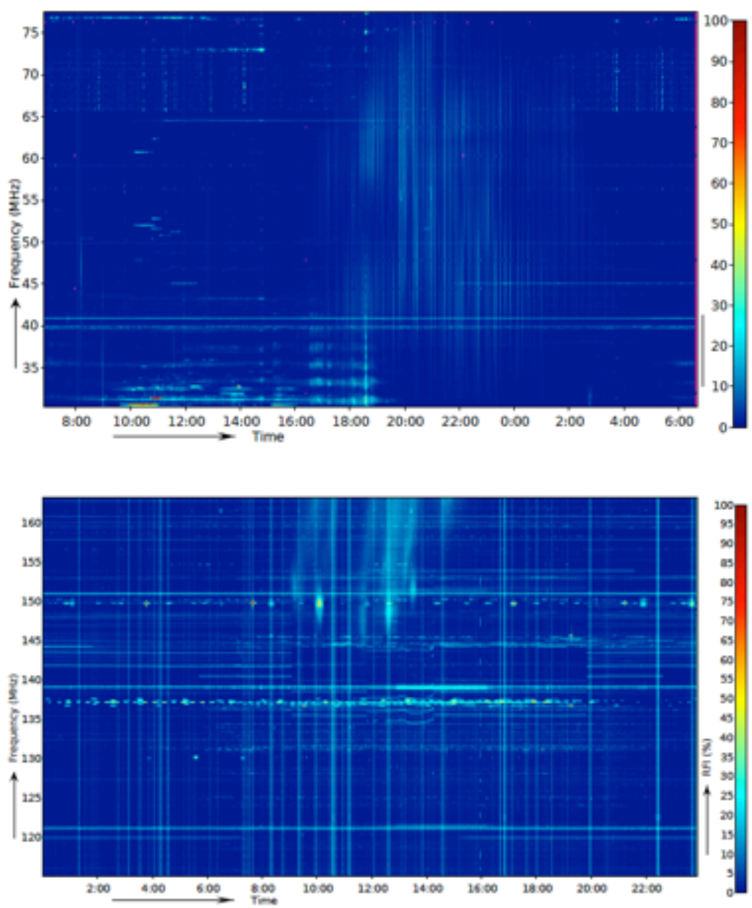
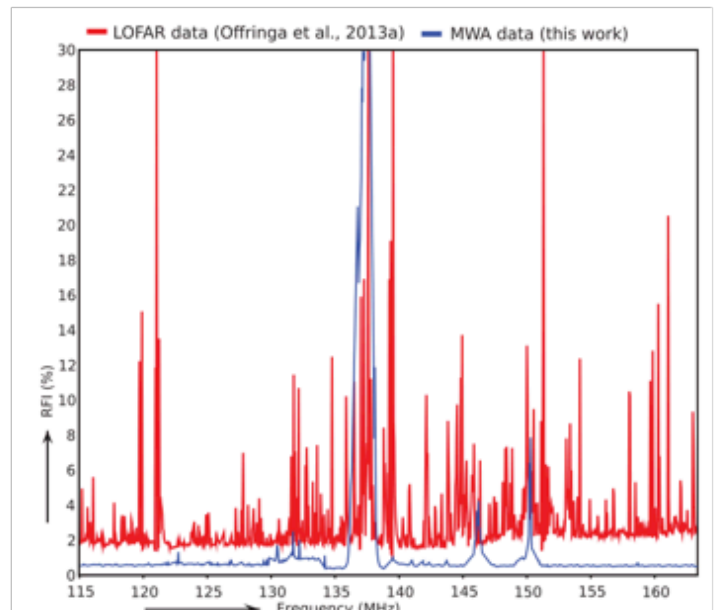


Fig. 10: The dynamic spectra of RFI occupancy during the surveys. Top: LBA, bottom: HBA.

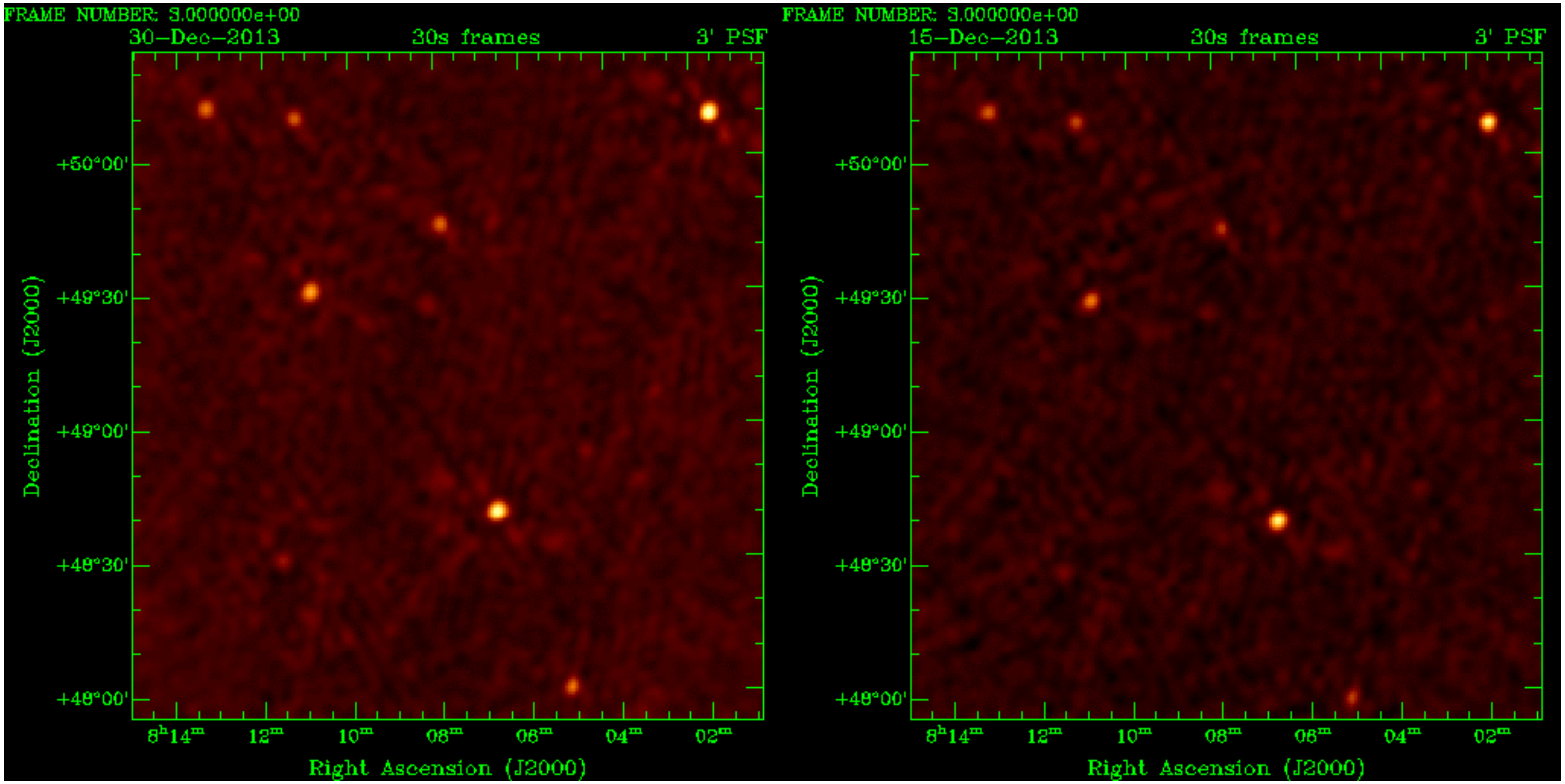
Offringa et al. 2012

Despite being in Western Europe LOFAR has a rather low occupancy of RFI (few % data loss) . LOFAR is close to the ground. Also high temporal/frequency resolution is critical. But of course being isolated makes a lot of difference

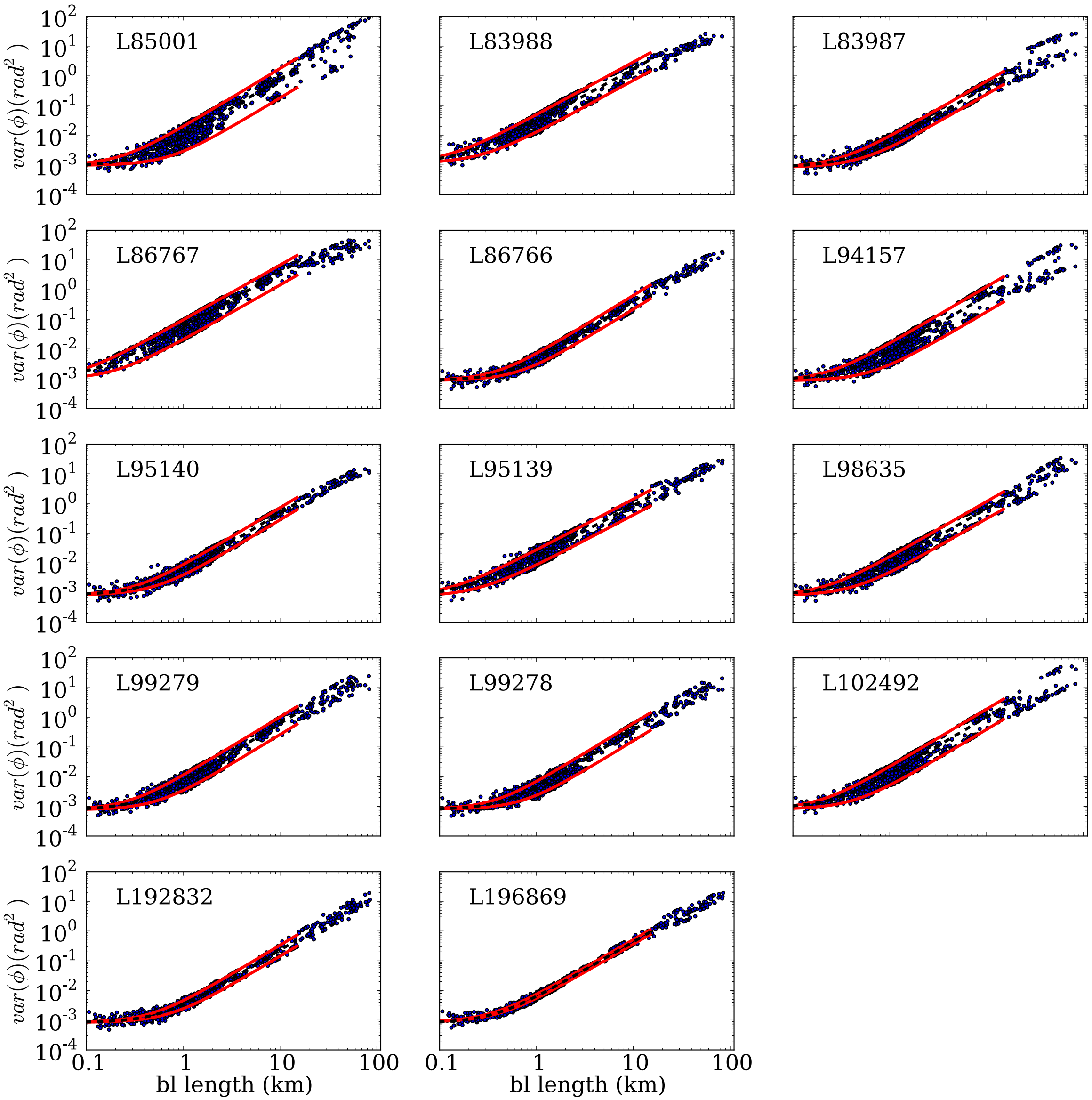


Offringa et al. 2015

Ionospheric effects: the good and the ugly

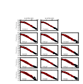


Ionospheric structure function

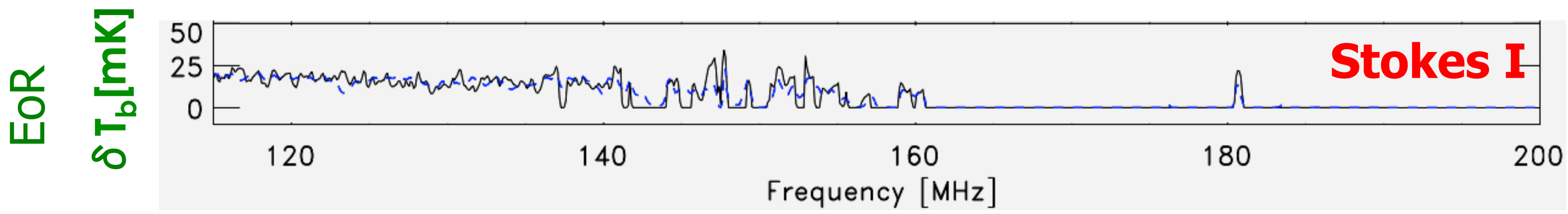


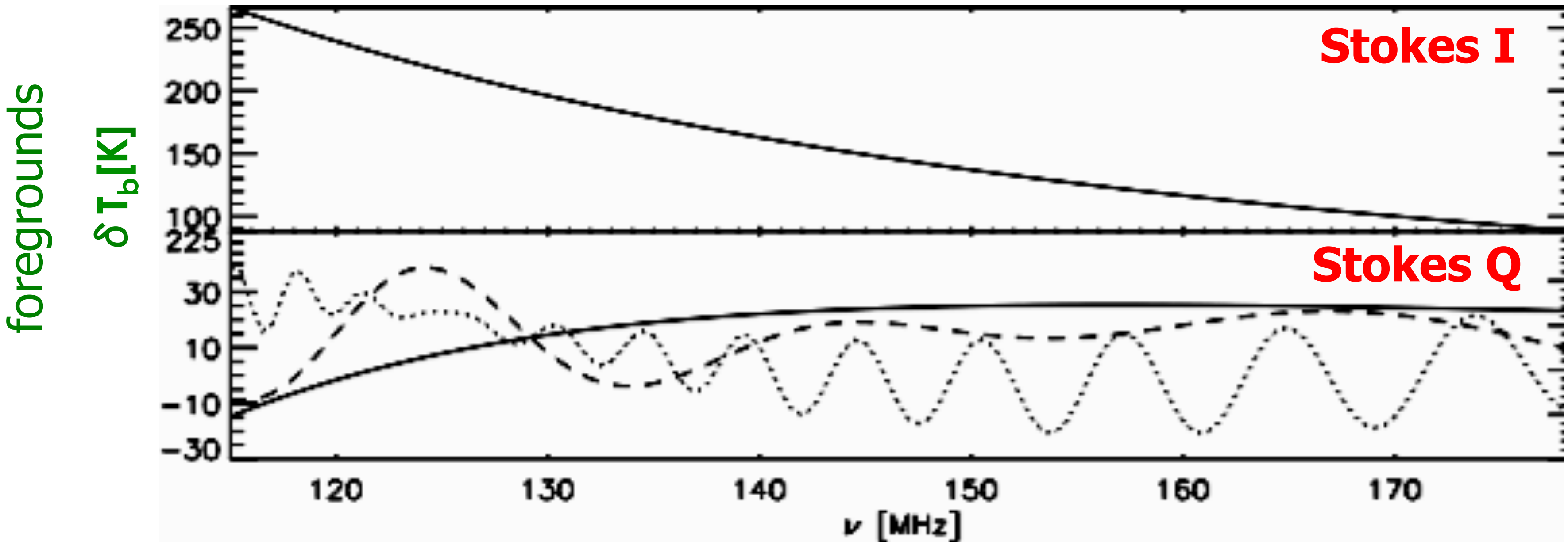
Slightly steeper than Kolmogorov

Mevius et al. 2016



The leakage problem





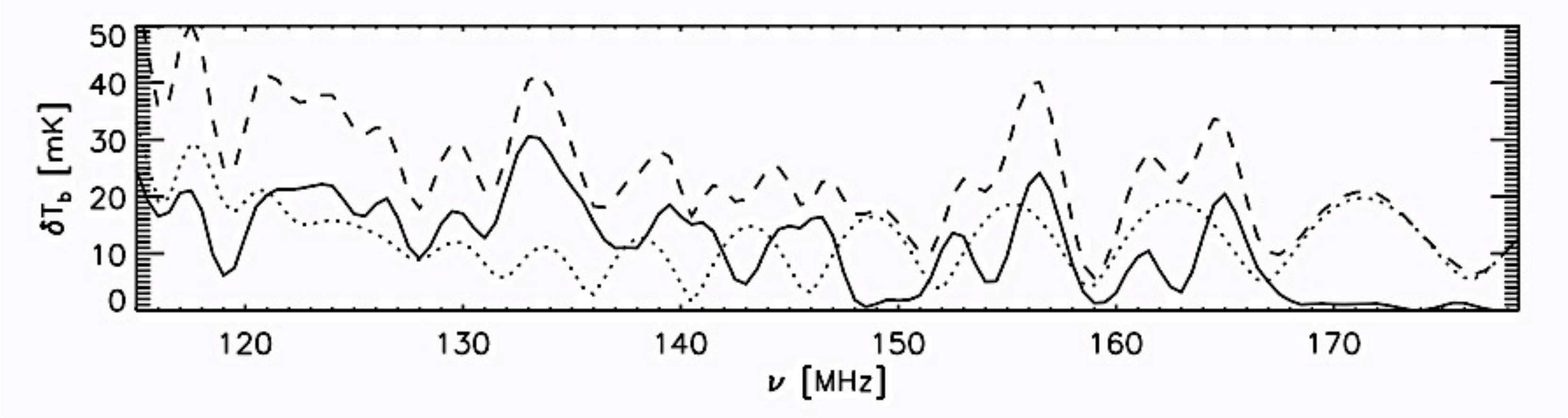
- **extraction is based on smoothness of the foregrounds in total intensity**

The problem of polarized foregrounds

EoR ~ 5 mK

FG ~ 2 K

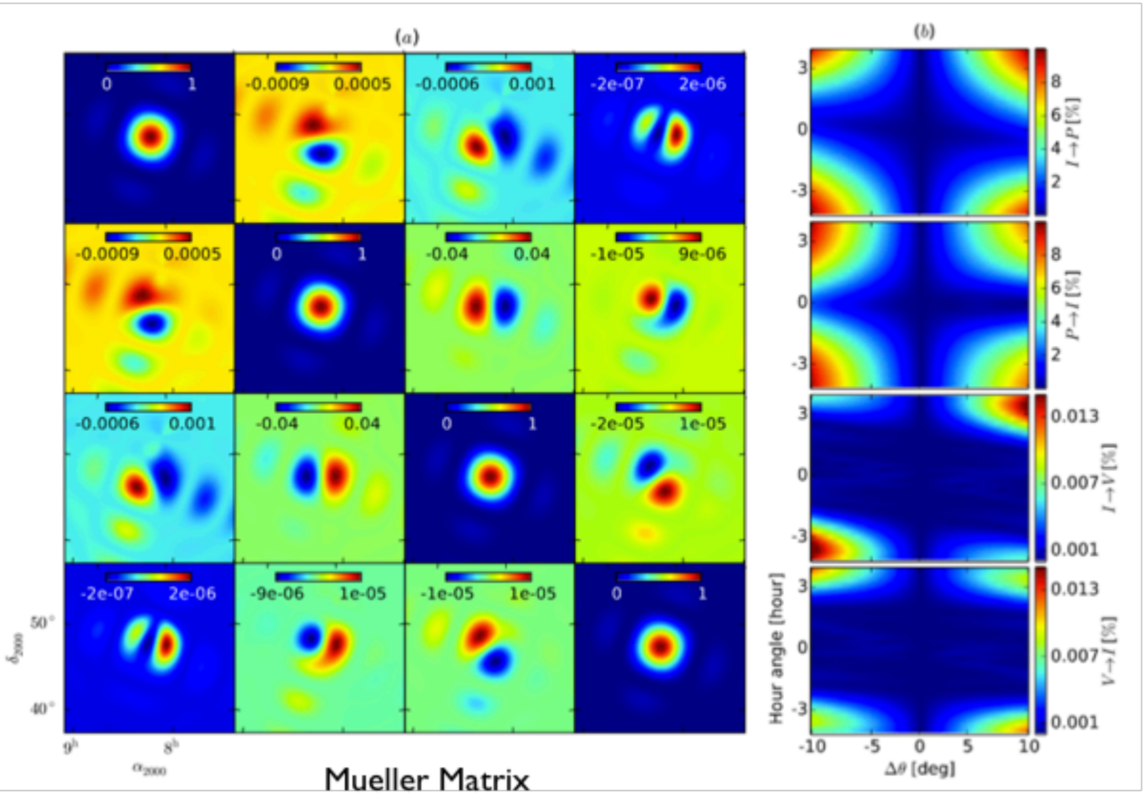
residual leakage ~ 1.5 %



Jelic et al. 2010
Geil et al. 2011

Polarisation Leakage

The polarised sky will leak from Q & U to Stokes I.



- Dipoles only project orthogonal on the sky at zenith
- The beam is instrumentally polarised away from the zenith

Stokes I leaks for Q & U and visa versa

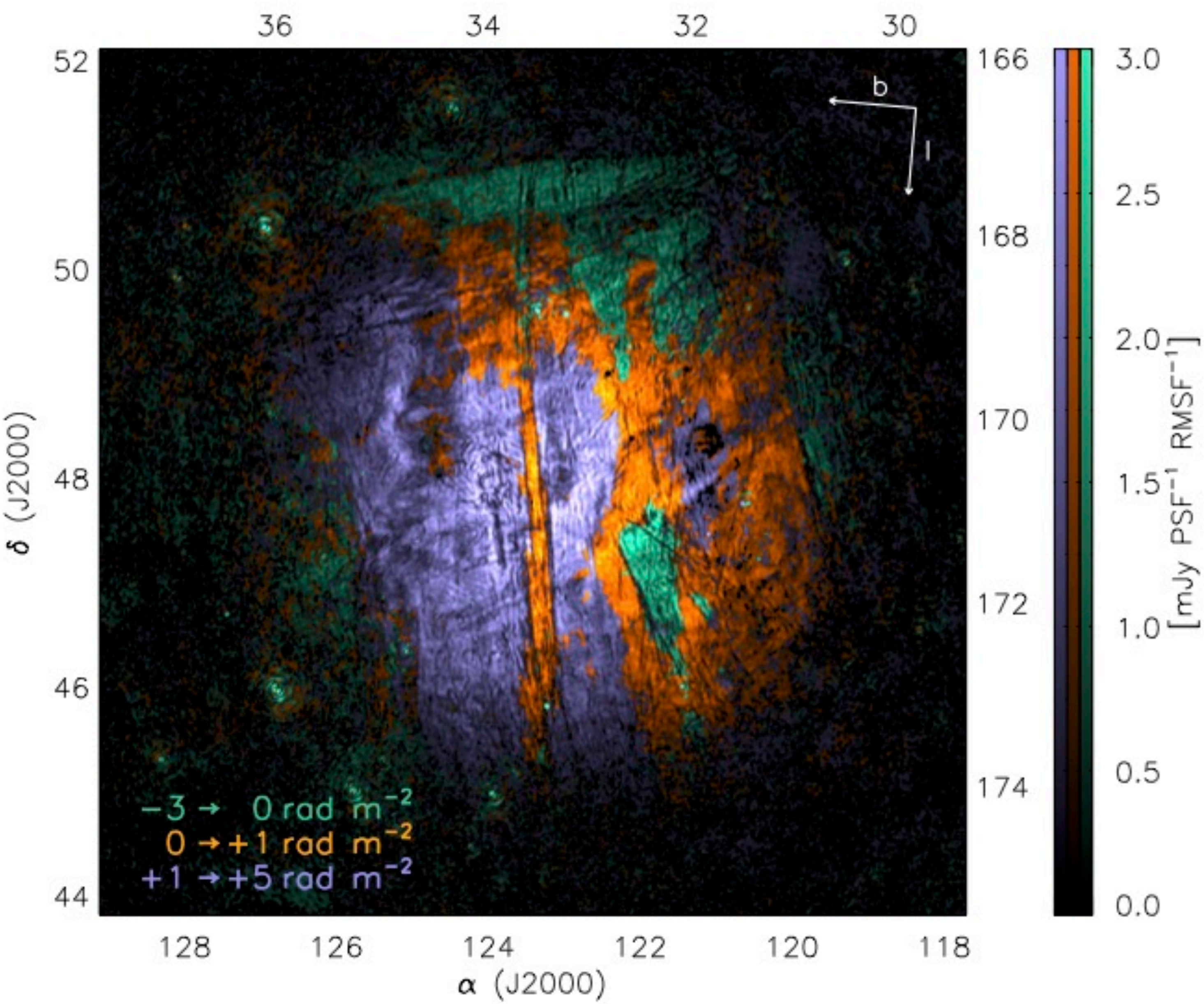
This is at the level of ~0.3% over 5d (LOFAR/SKA) and >10% over >25d FoV or ~1/2 θ^2 (MWA/PAPER/HERA).

This is a pure geometric effect and wider FoV leads to more leakage.

Asad et al. 2015, 2016

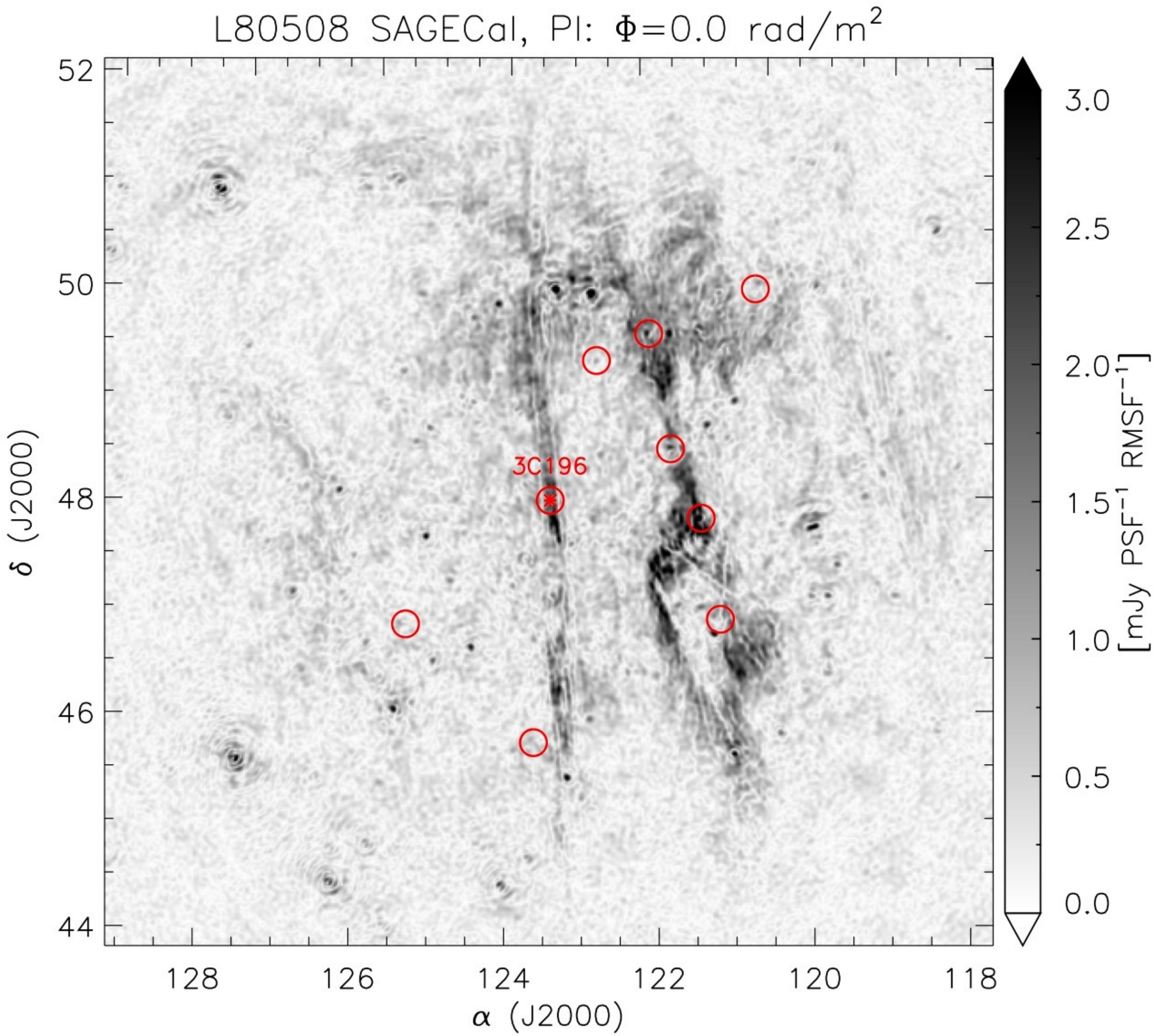
Curtsey L. Koopmans

3C196 polarization structures

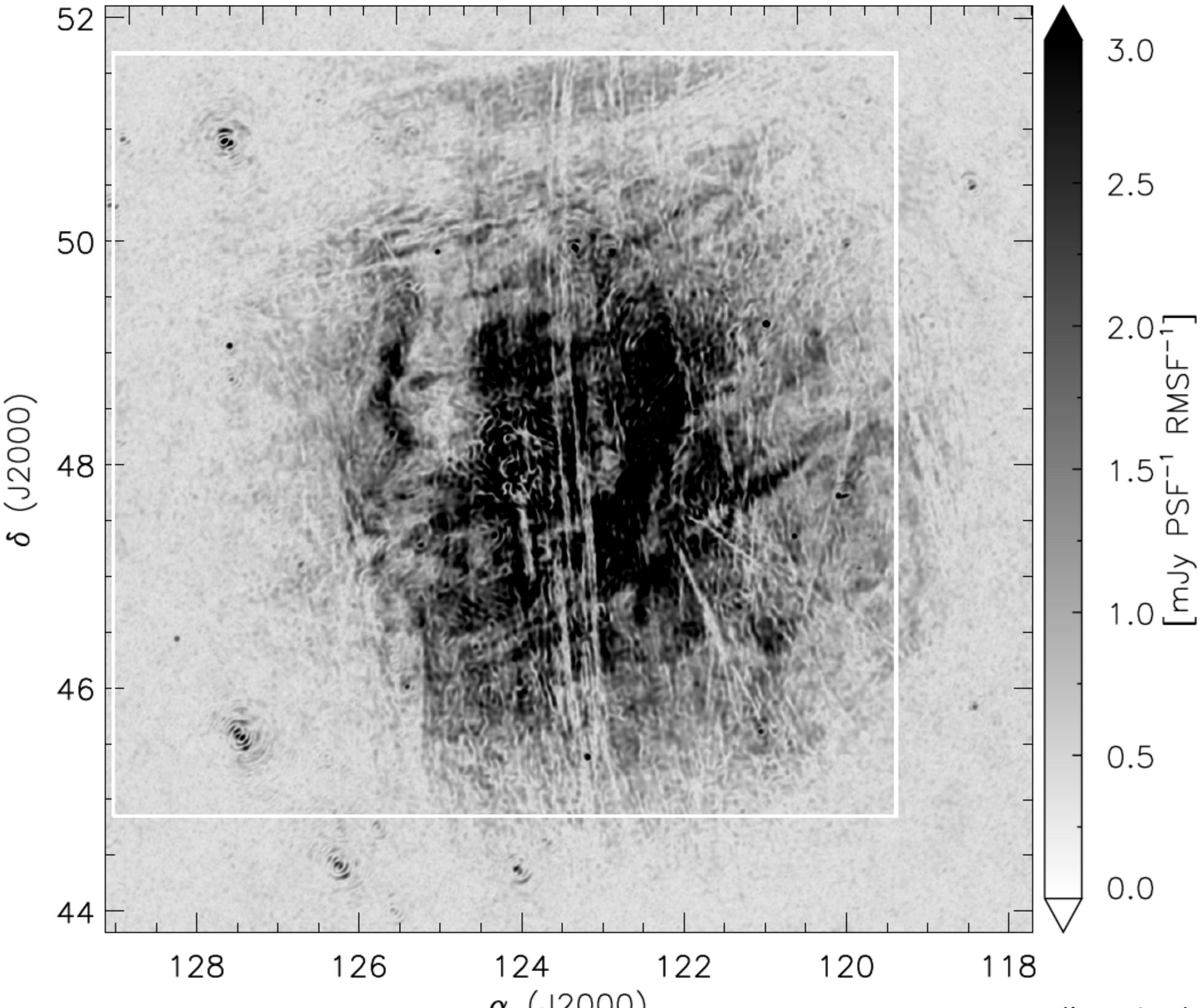


Jelic et al, 2015

LOFAR-EoR observations

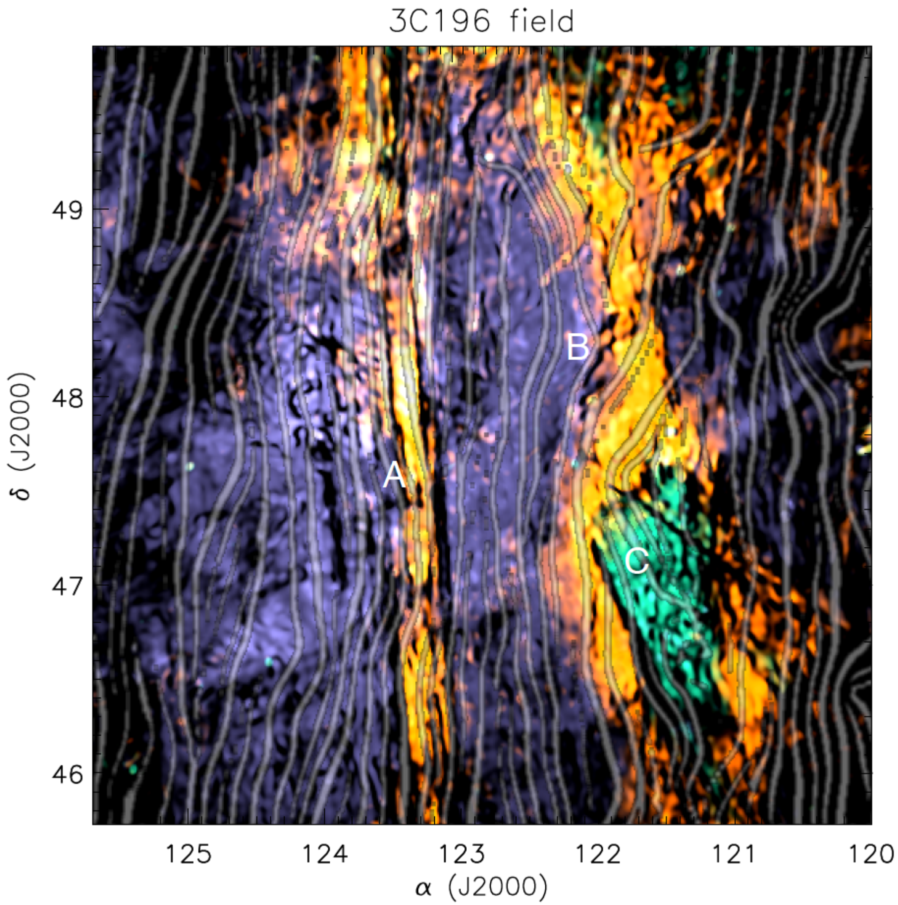


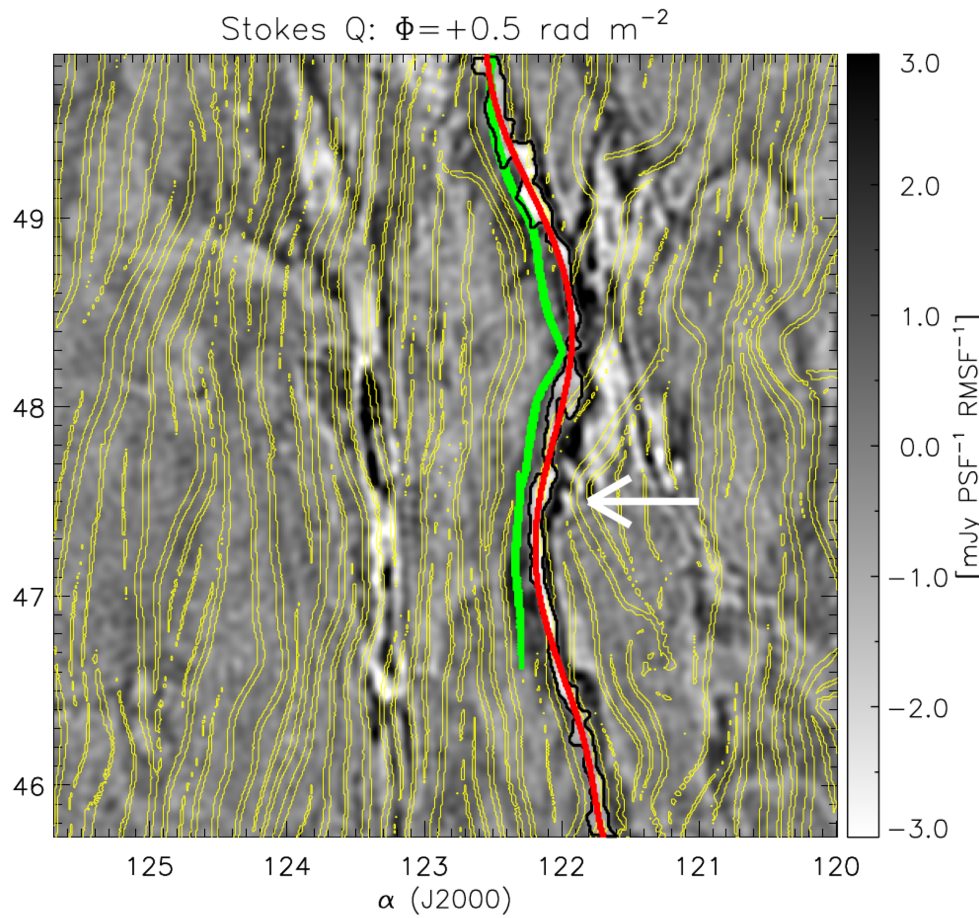
Jelic et al 2015



Jelic et al 2015

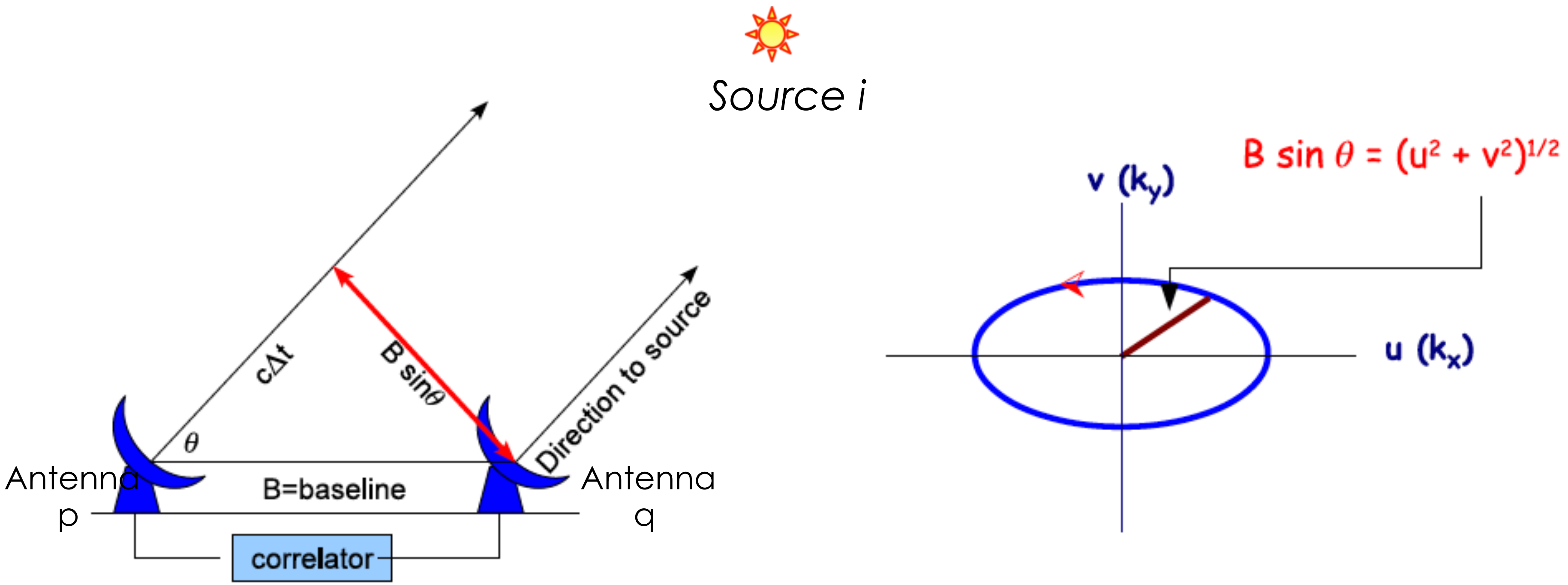
ISM magnetic/Faraday depth correlation (LOFAR vs. Planck)





Zaroubi et al 2015, MNRAS

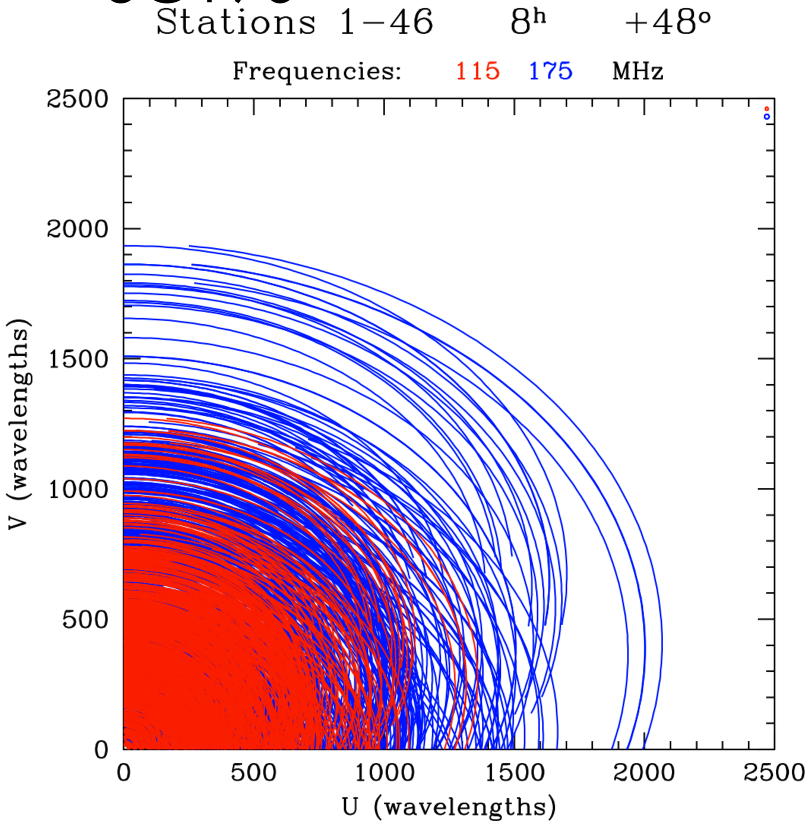
The calibration problem



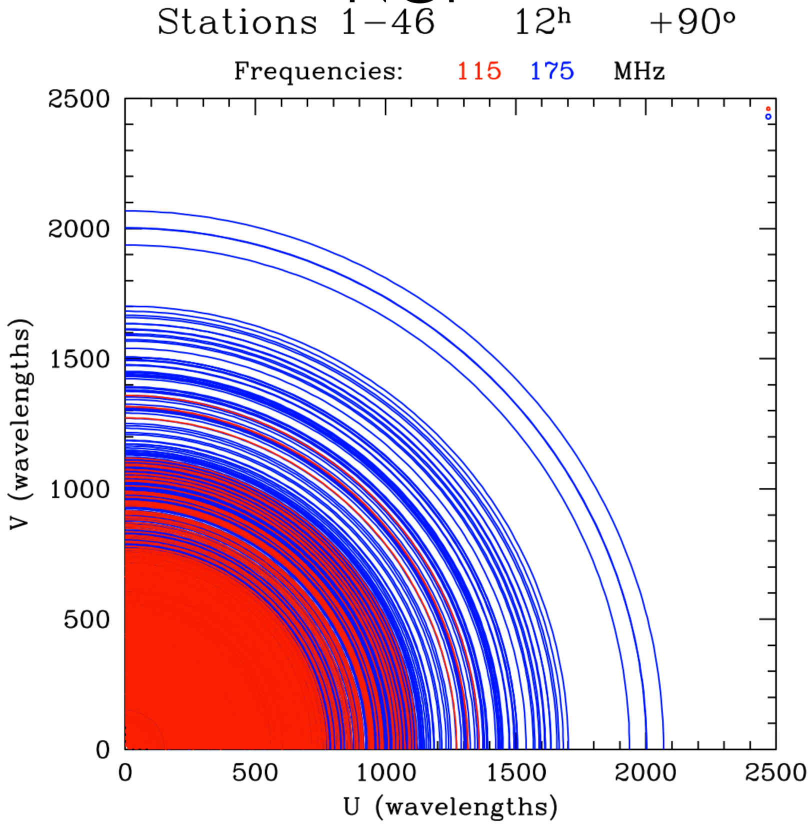
$$\mathbf{V}_{pq} = \sum_{i=1} \mathbf{J}_{pi}(\boldsymbol{\theta})\mathbf{C}_i\mathbf{J}_{qi}^H(\boldsymbol{\theta}) + \mathbf{N}_{pq}, \quad p,q \in \{1,2,\ldots,N\}$$

Inner uv-coverages for the two EoR windows

3C196



NCP



Complete uv-coverage in 2 km core (~800 λ) at all frequencies → 'perfect' 3' PSF imaging after 8-12h. Important for full-field EoR imaging !!

A flowchart of our calibration and analysis

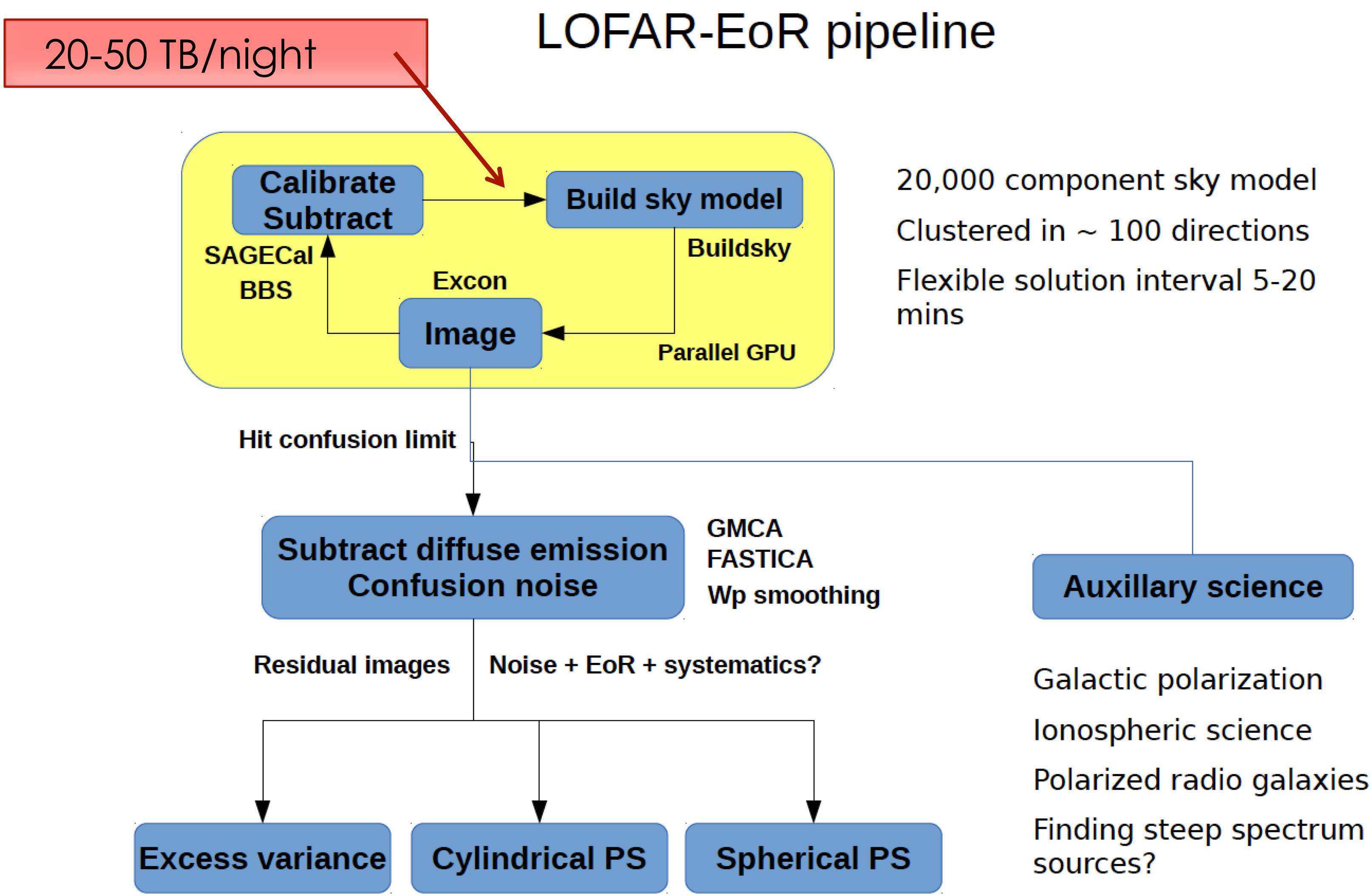
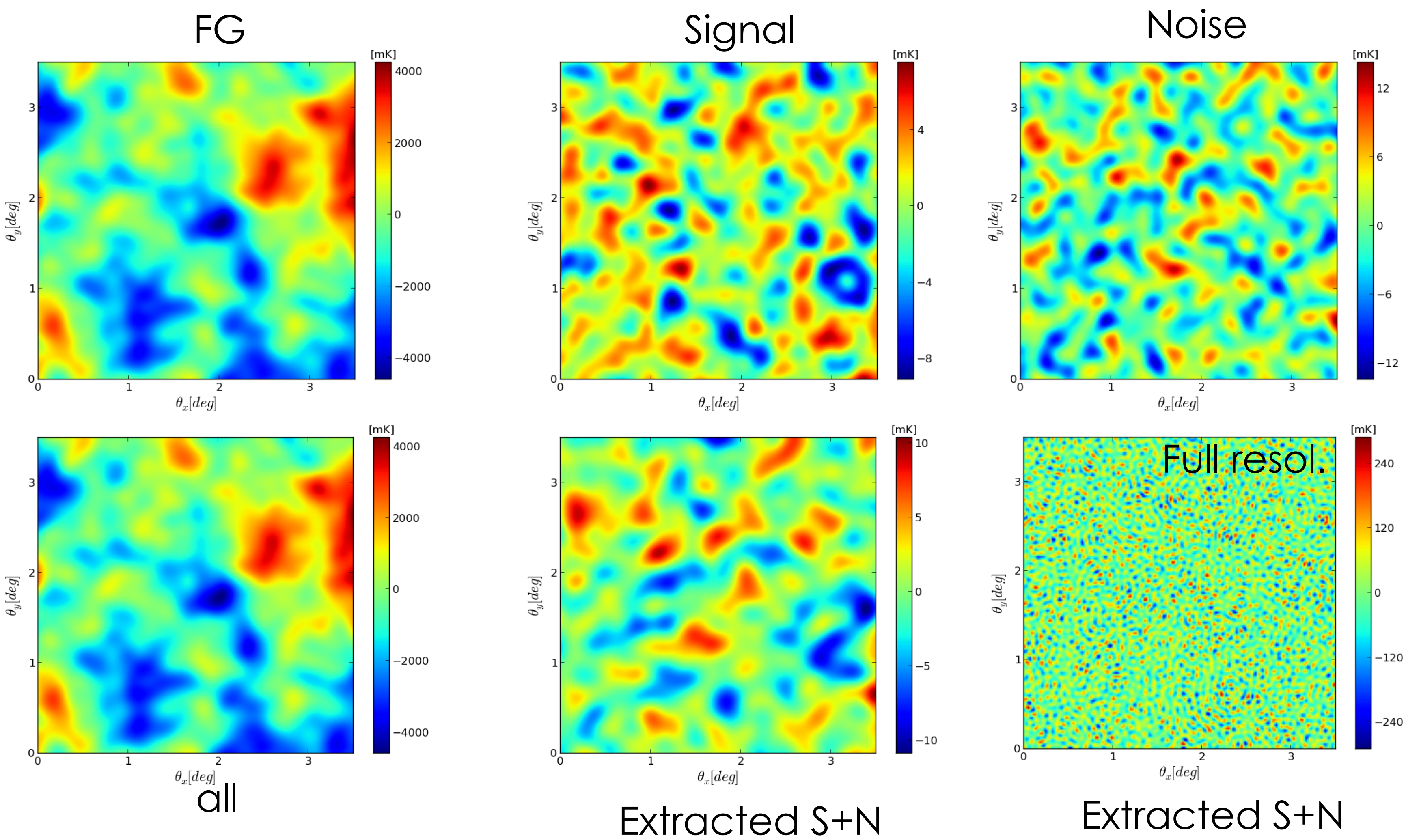


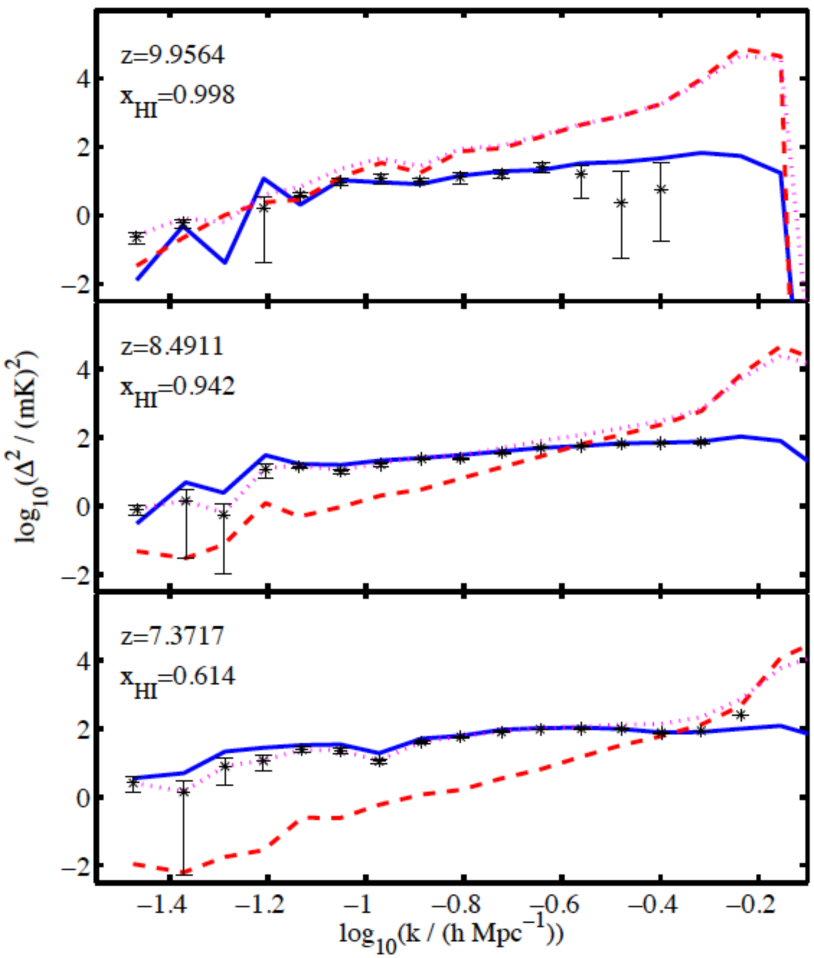
Fig. Harish Vedantham

Example of extraction @ 150MHz 5' (σ) smoothed

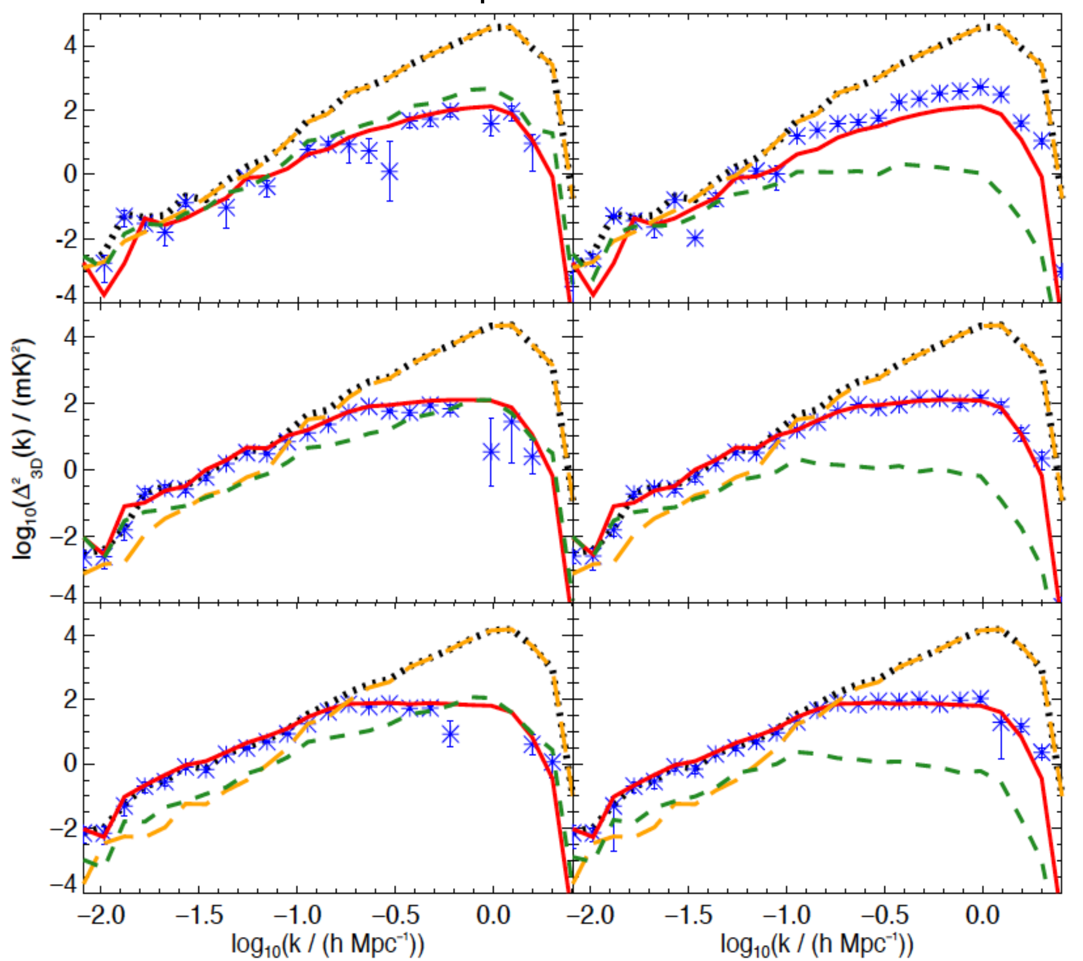


Power Spectrum Measurements

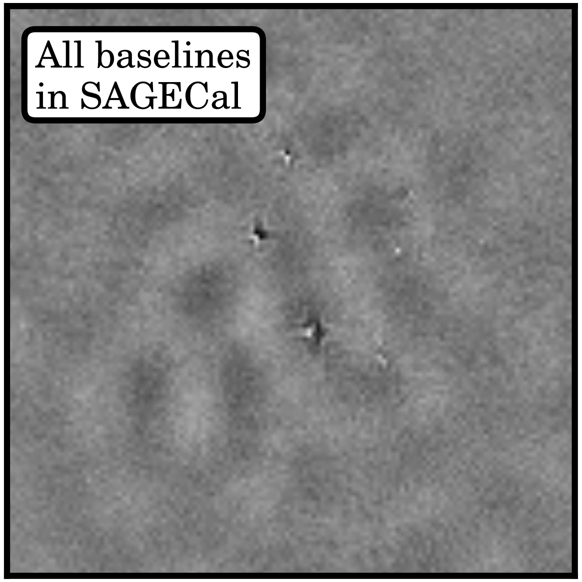
Harker et al 2010

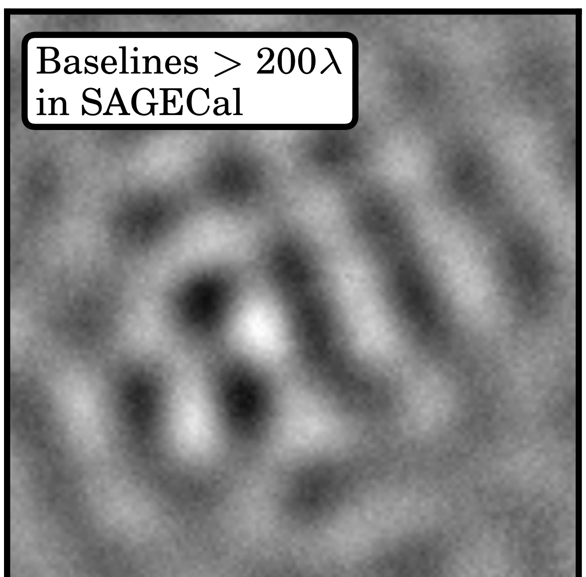


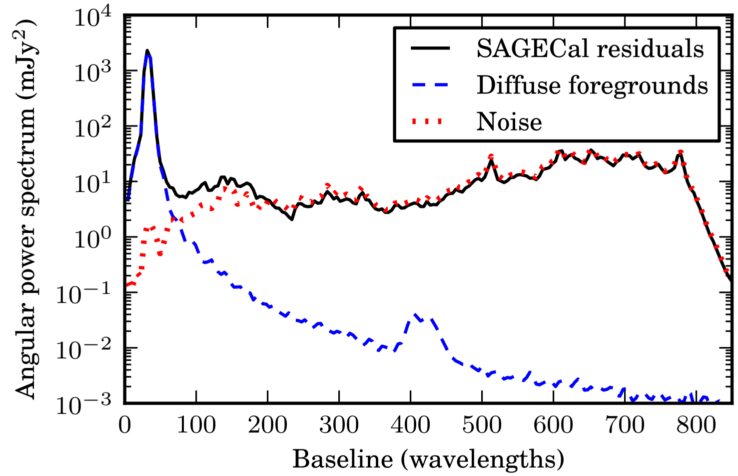
Chapman et al 2013

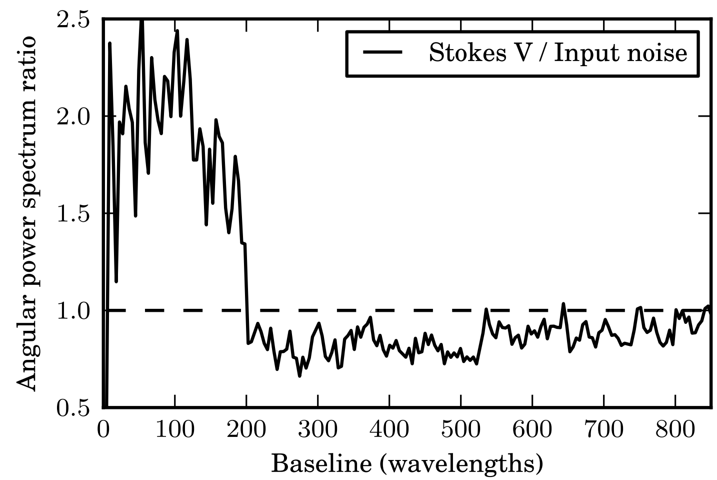


Calibration, suppression, leverage and excess noise









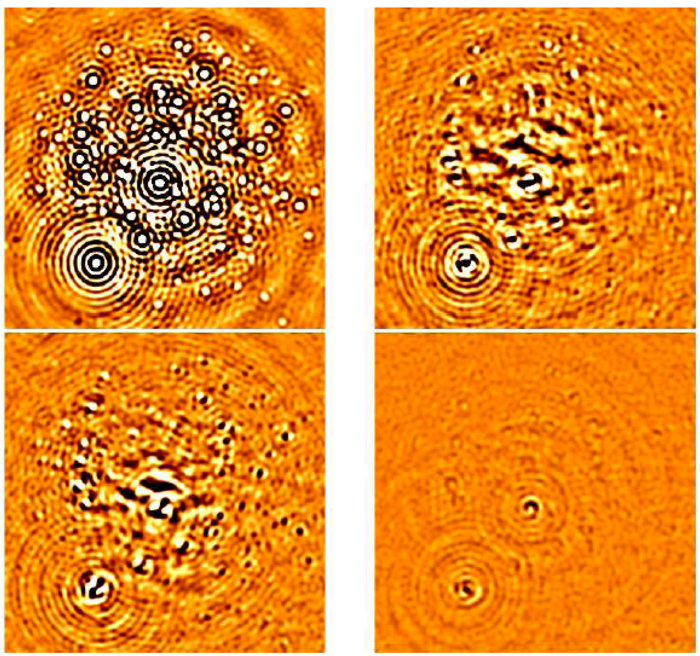
Patil et al. 2016

SAGEcal: robust and broad-band processing

Yatawatta, 2015

Calibration solves for a very large number of unknowns → dangerous
Adopted approach: exclude short baselines (< 250 λ) in SAGEcal and only image those !

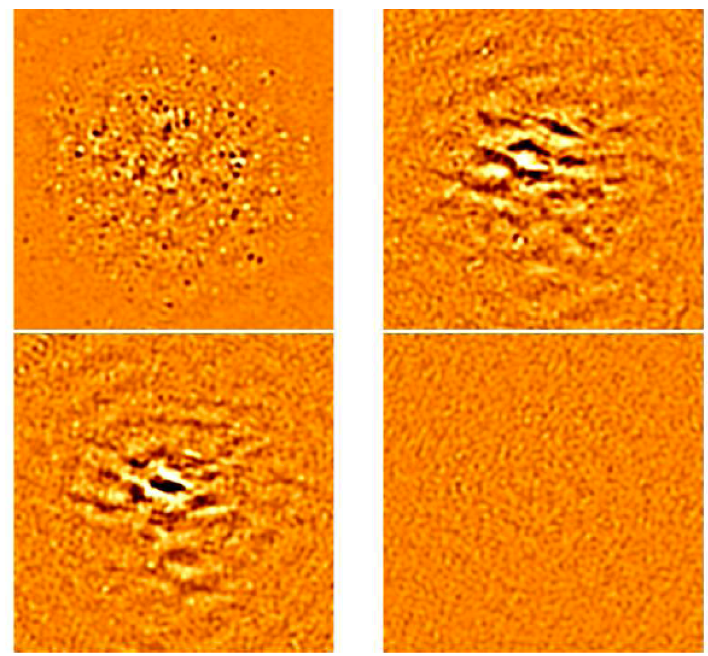
Diffuse polarization then preserved in calibration → EoR signal will be preserved too !



I,Q,U,V images baselines <= 250 wavelengths

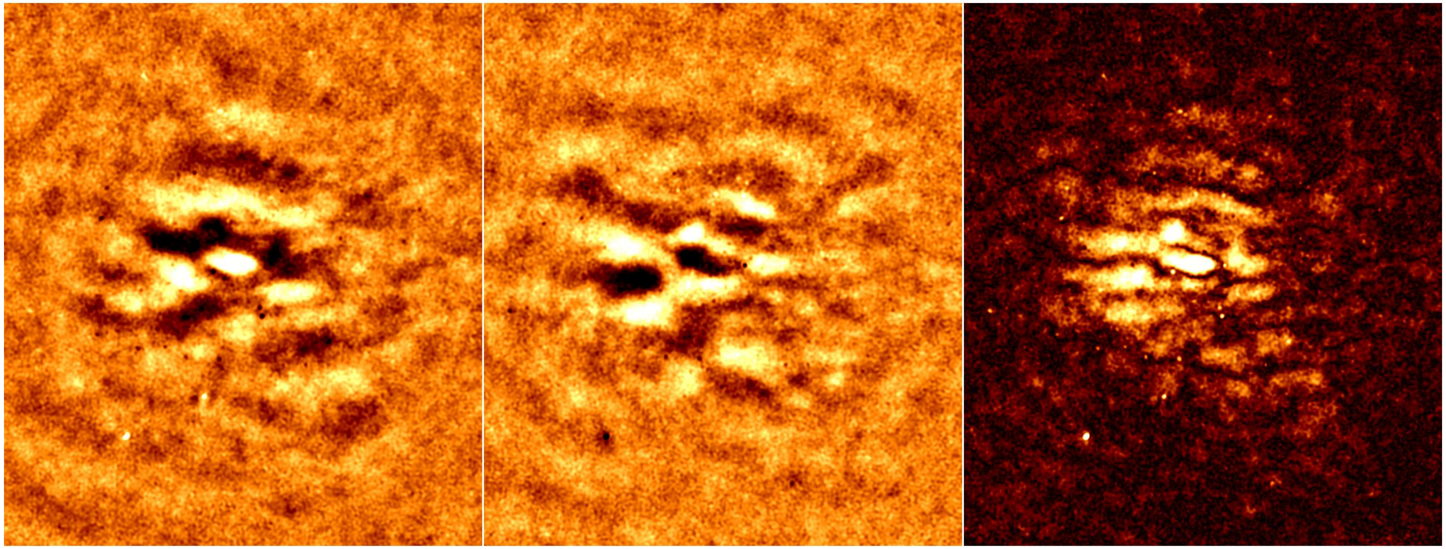
One
night
60 MHz

10' PSF



I,Q,U,V calibration using baselines > 250 wavelengths

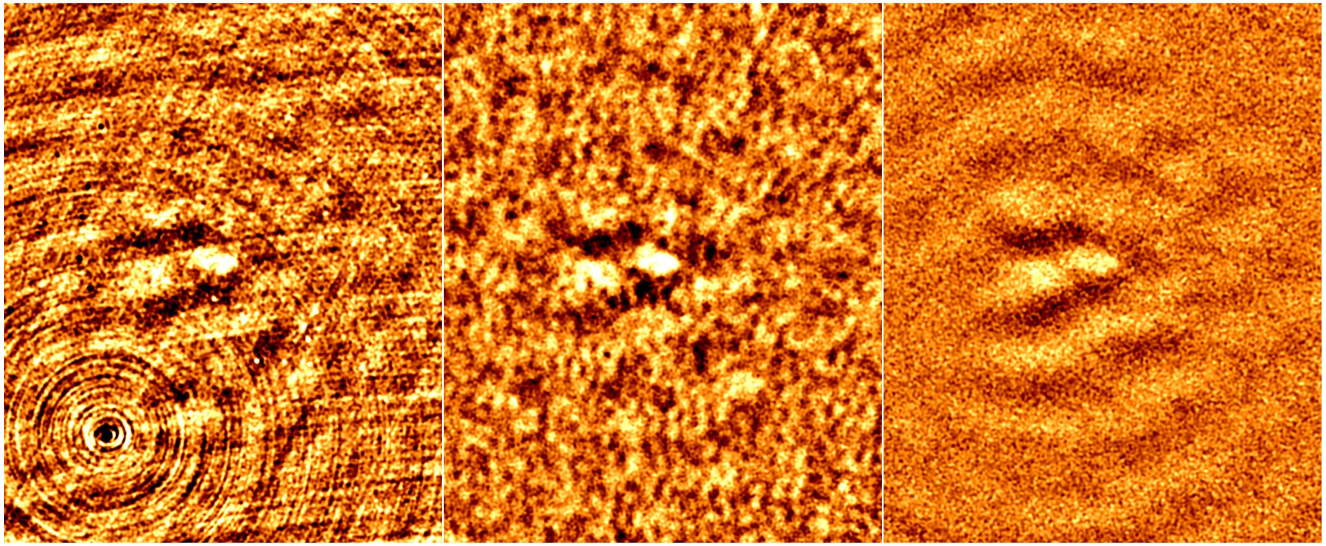
Include diffuse model for Q & U to calibrate the data



(left) Q (mid) U (right) P, 8×8 deg.

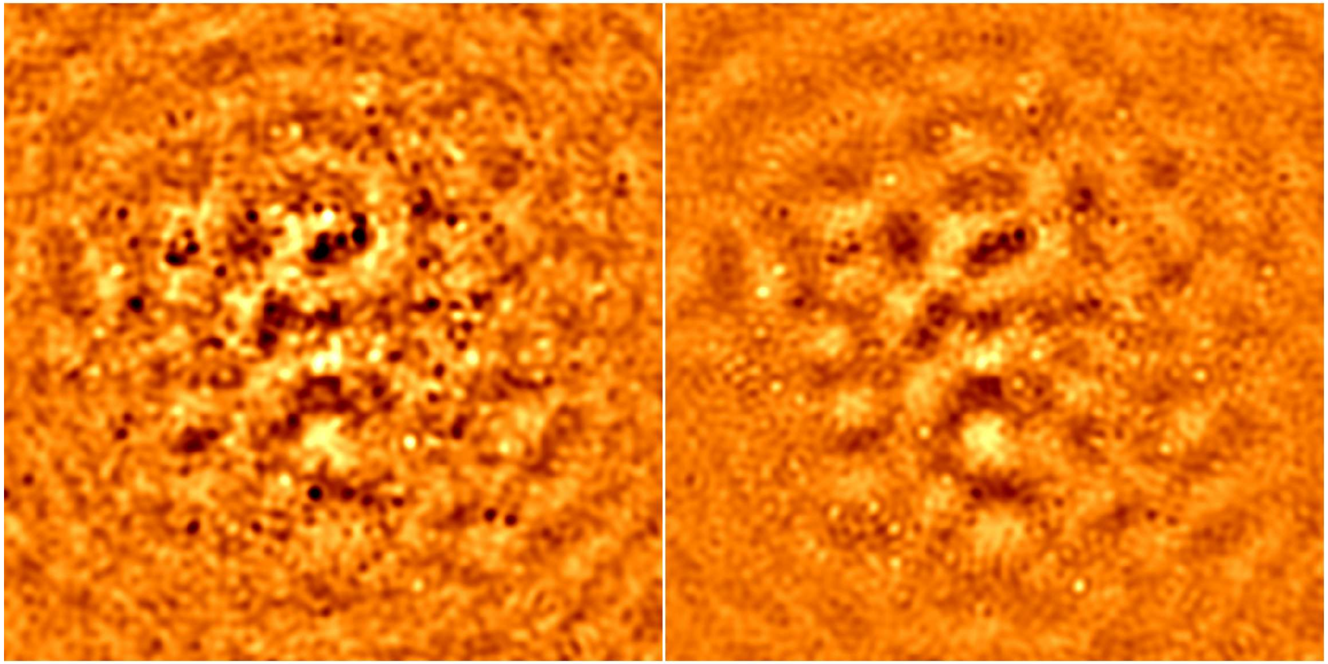
Yatawatta 2017

Stokes Q



(left) before SAGECal (mid) with 250λ cut (right) no cut

Stokes I



(left) SAGECal without foreground (right) with foreground, no cut

Yatawatta 17

Cross correlation with other data set

- EoR with CMB. That should be done but not as promising as initially thought.
- EoR with Galaxy surveys
- EoR with other line intensity mapping
- 21 cm forest

Cross Correlation 21cm-LAE surveys

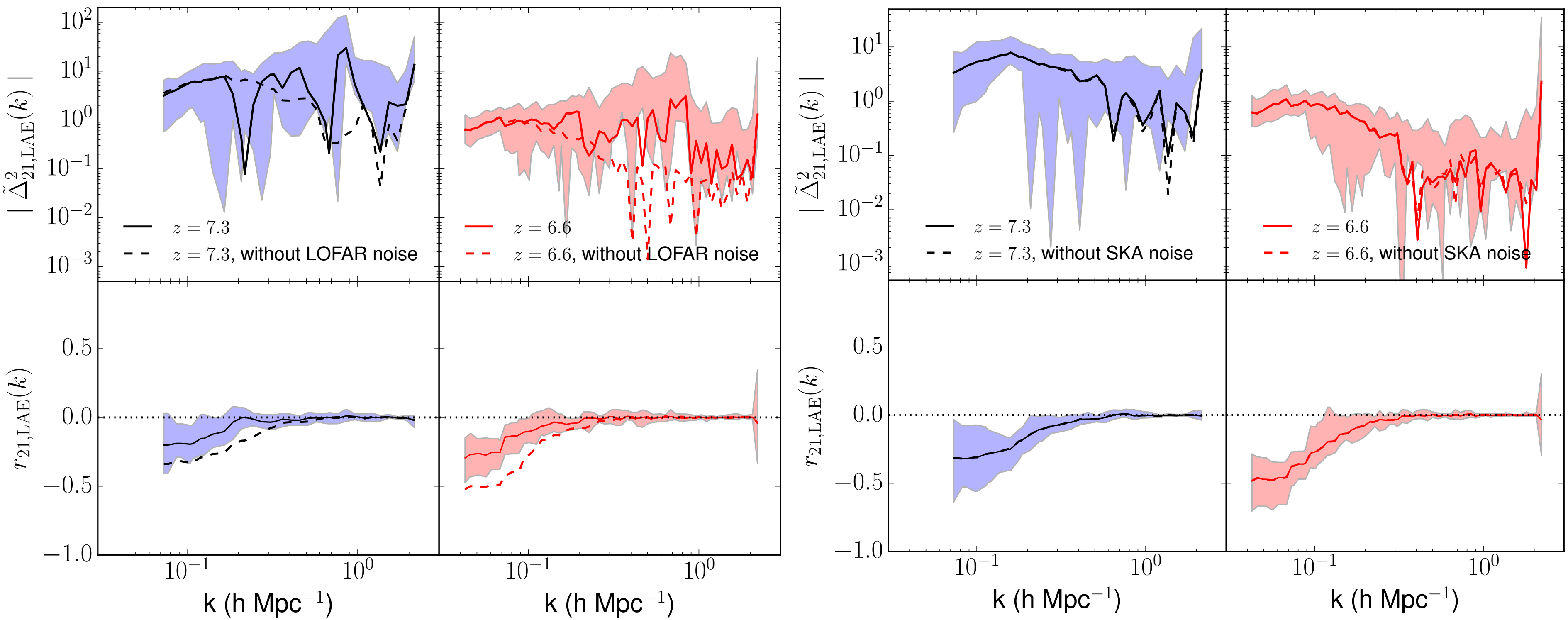
Lidz + 2009, Wiersma+ 2013, Vrbanec+ 2016

LOFAR with Subaru

2D circularly averaged cross power spectrum

SKA with Subaru

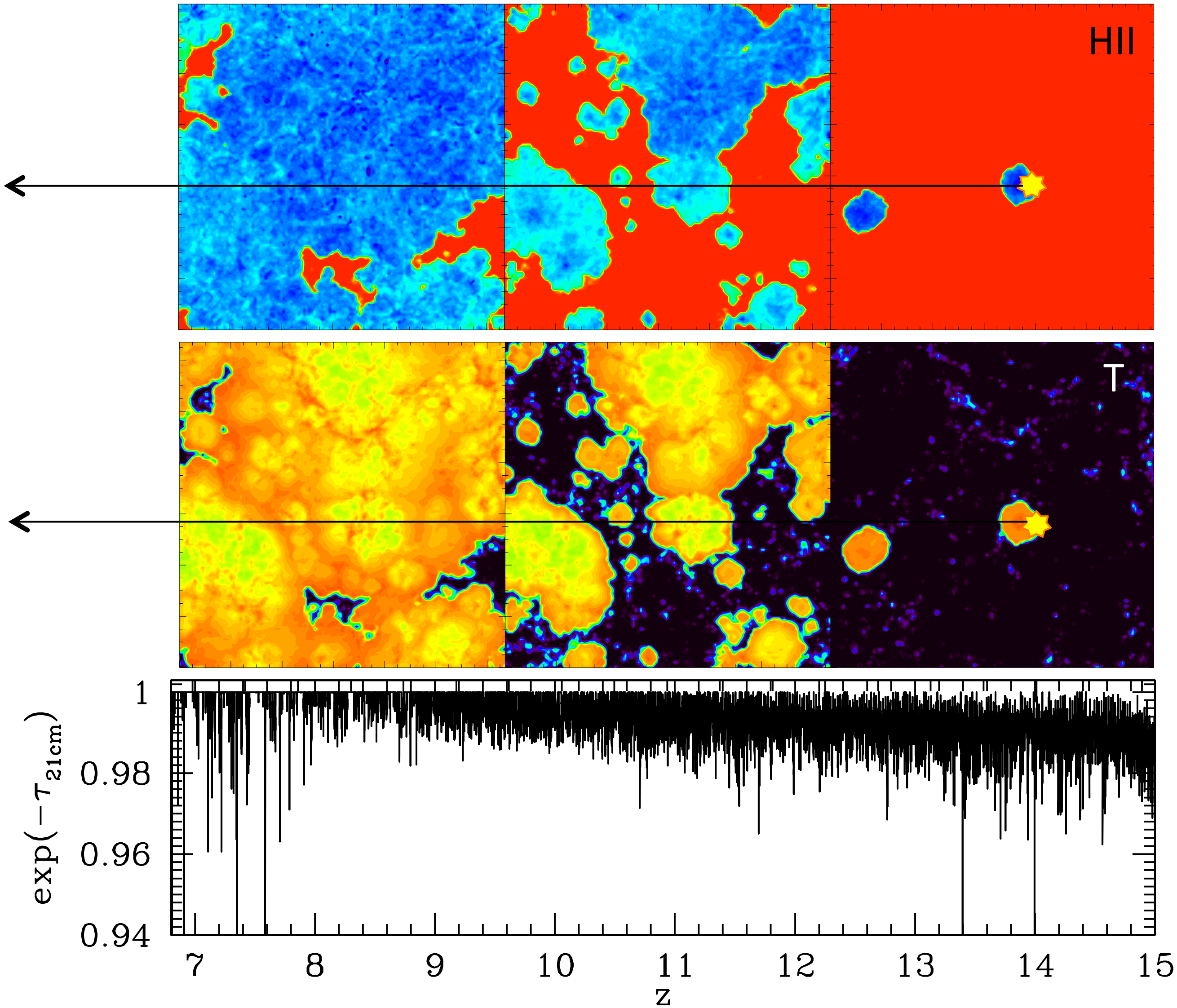
2D circularly averaged cross power spectrum



- ✧ Intensity of the power spectrum → volume average HI
- ✧ Correlation coefficient → typical dimension of the HII regions

21 cm forest

$$\tau_{21cm} \propto x_{HI}(1+\delta)\frac{1}{T_s}$$

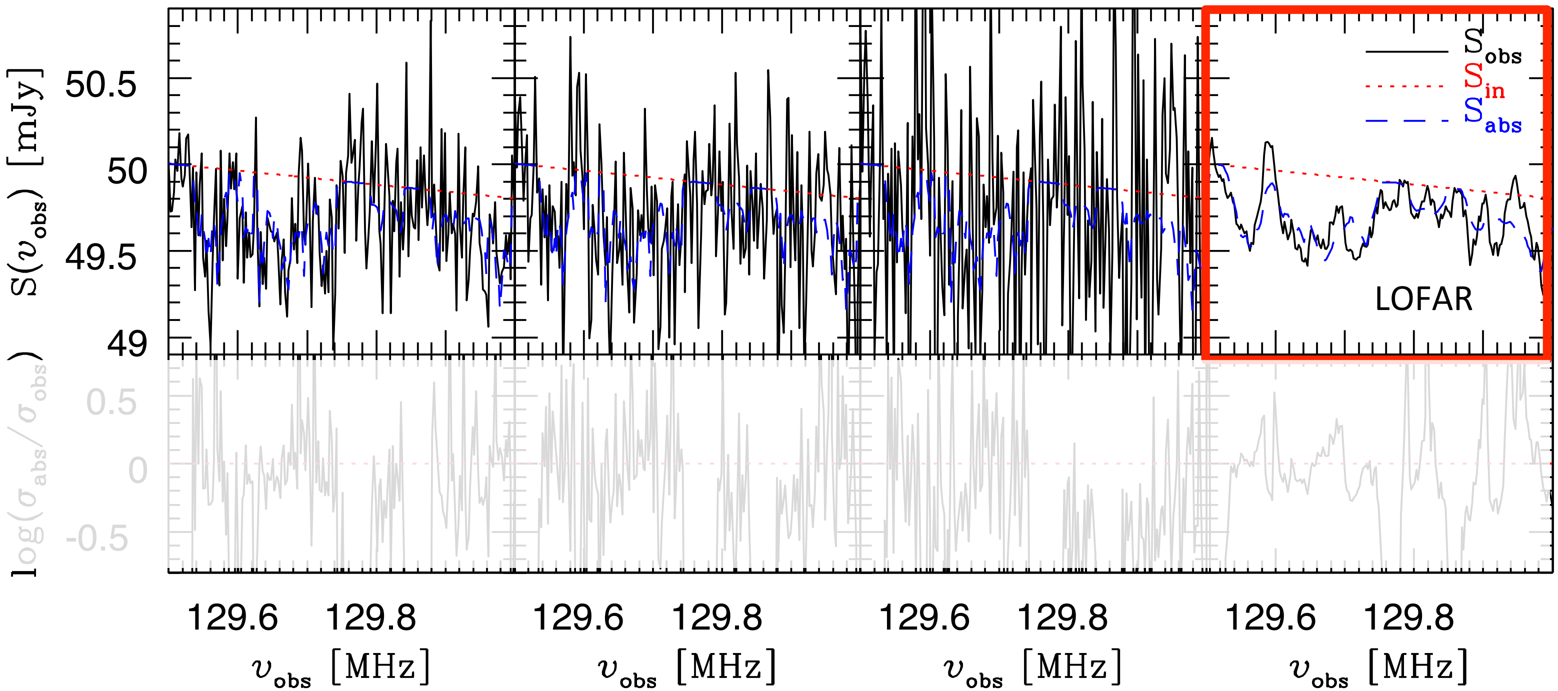


Curtsey B. Ciardi

21 cm forest

z=10, S=50 mJy, α=1.05

BW=10 kHz, t=1000 h



QSO spectrum

QSO spectrum
+
IGM absorption

Observed
spectrum

Curtsey B. Ciardi

Summary

Most effort so far is spent on ‘Discovery of Systematics”:
→ improved wide-field broad-band calibration (SAGEcal CO):
→ working on sky models, polarization calibration and ionospheric effects
→ Check how the noise behaves as a function of the amount of analyzed data.

A lot of progress us achieved in the last few years

We are still in the “detection” mode and far from the analysis and interpretation mode.

The evolution in redshift will be the most convincing evidence for the detection of the reionization.

We are looking forward for results in the near future!