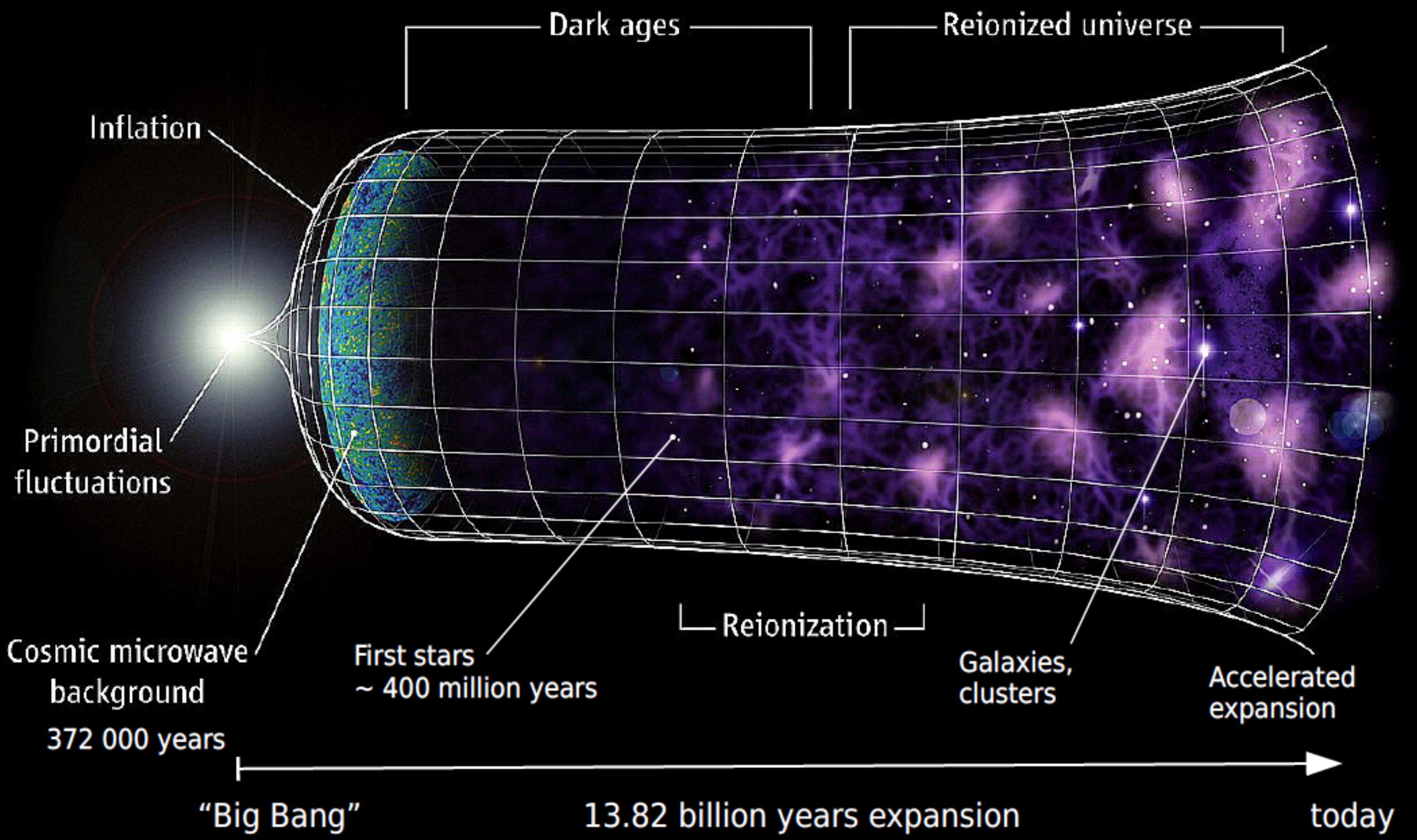
Cosmological 21 cm Experiments: The Current status

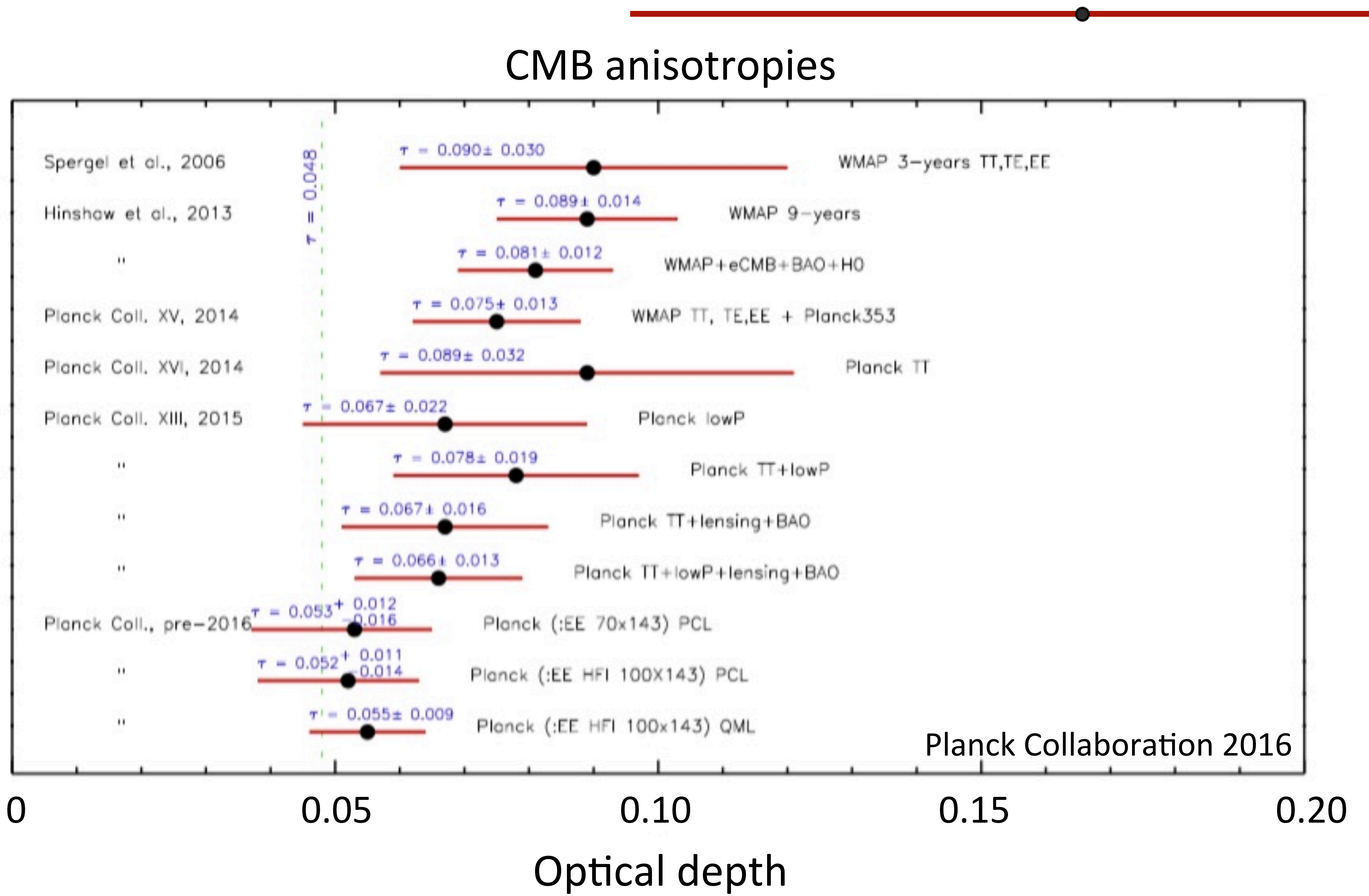
Saleem Zaroubi

The History

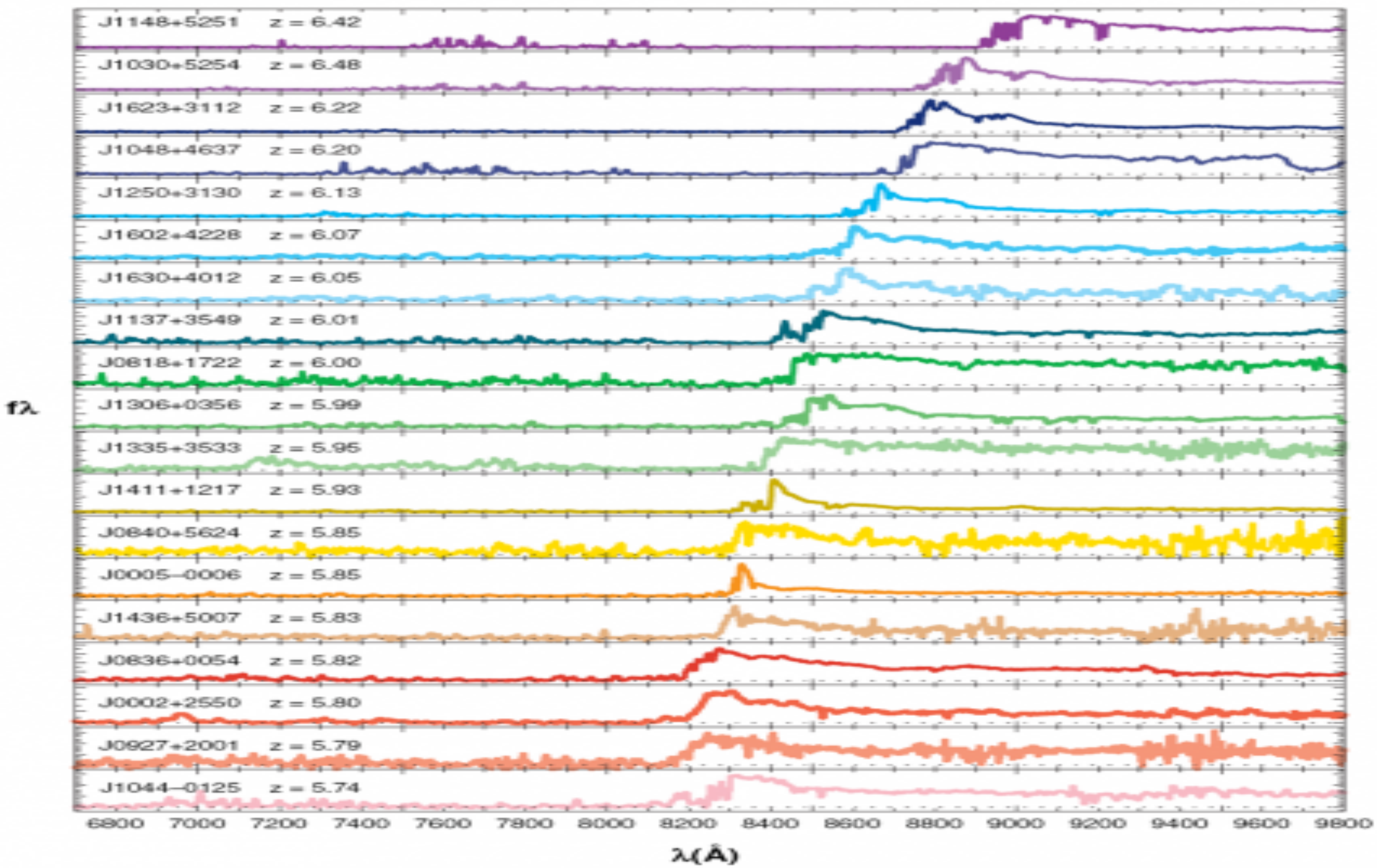
Credit: Science magazine



When we started this was the result by WWMAP

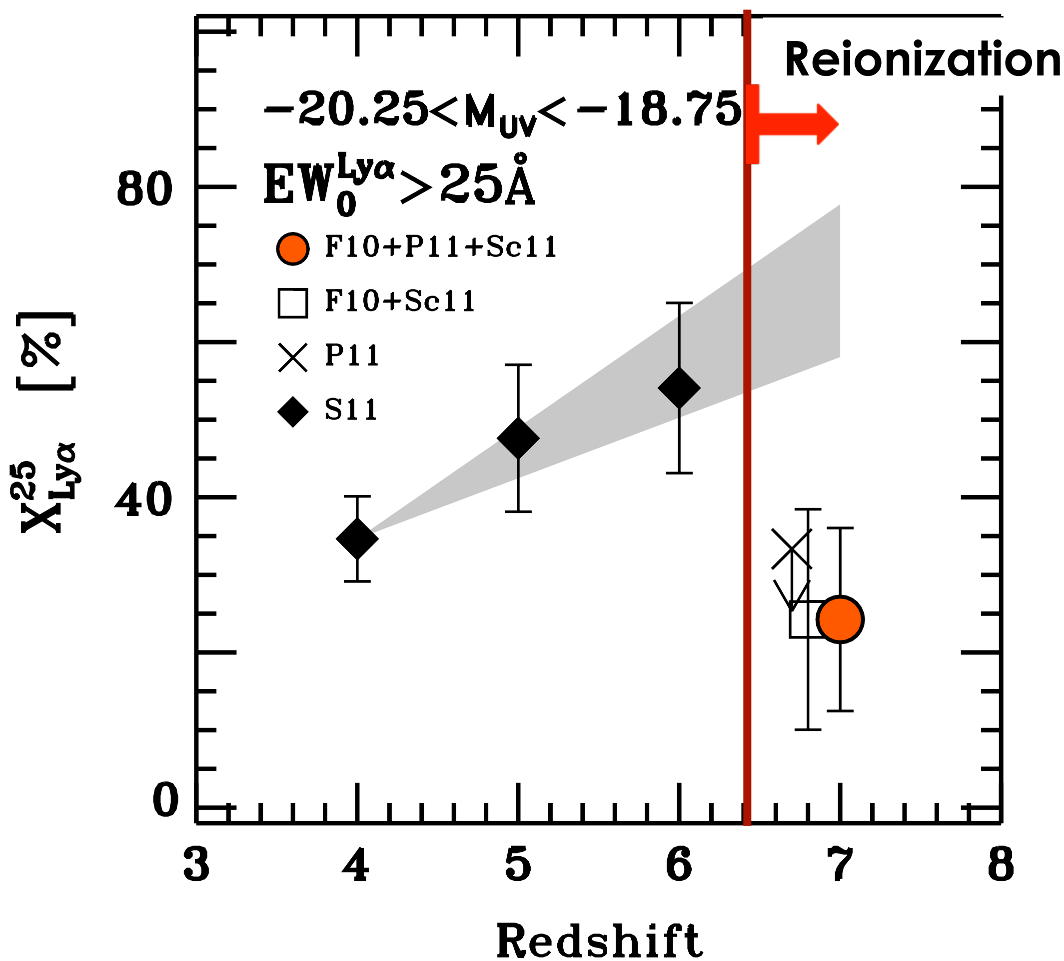


The Lyman-α forest optical depth at z about 6



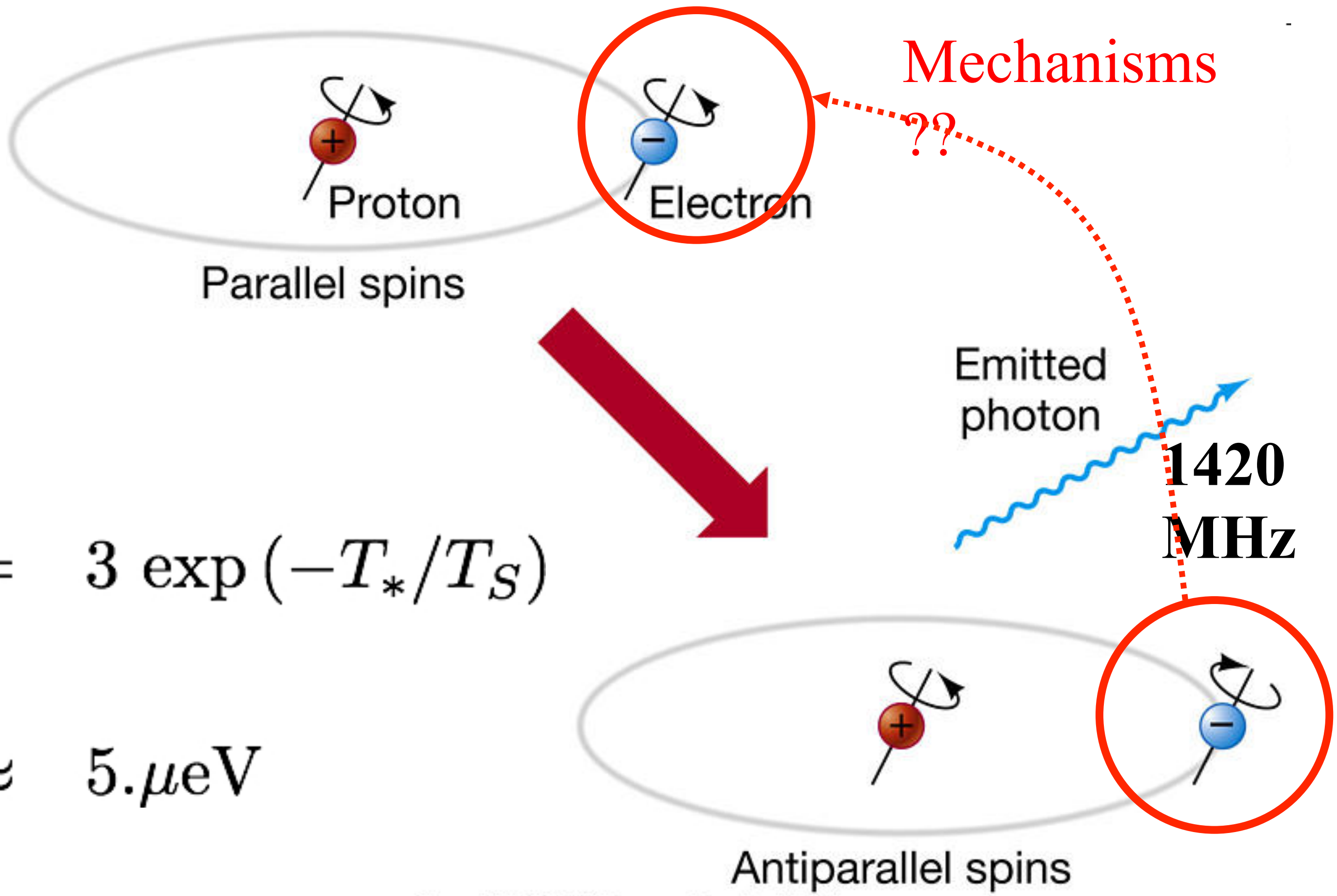
Fan et al. 2003, 2006

Lyman alpha emitters fraction in LBEs



Ono et al 2012

21-cm Physics

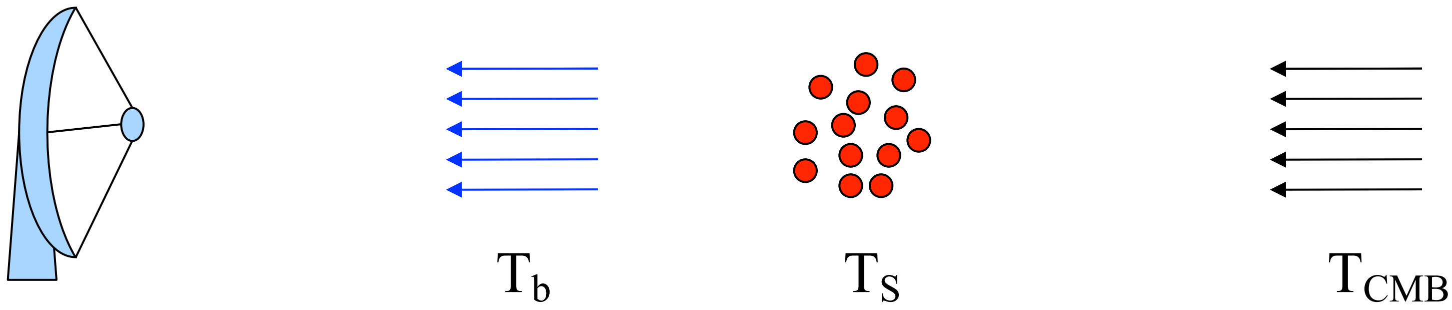


$$\frac{n_1}{n_0} = 3\exp\left(-T_*/T_S\right)$$

$$T_* \approx 5.\mu\mathrm{eV}$$

Lifetime of ~10 Myrs

δT_b, The Brightness Temperature

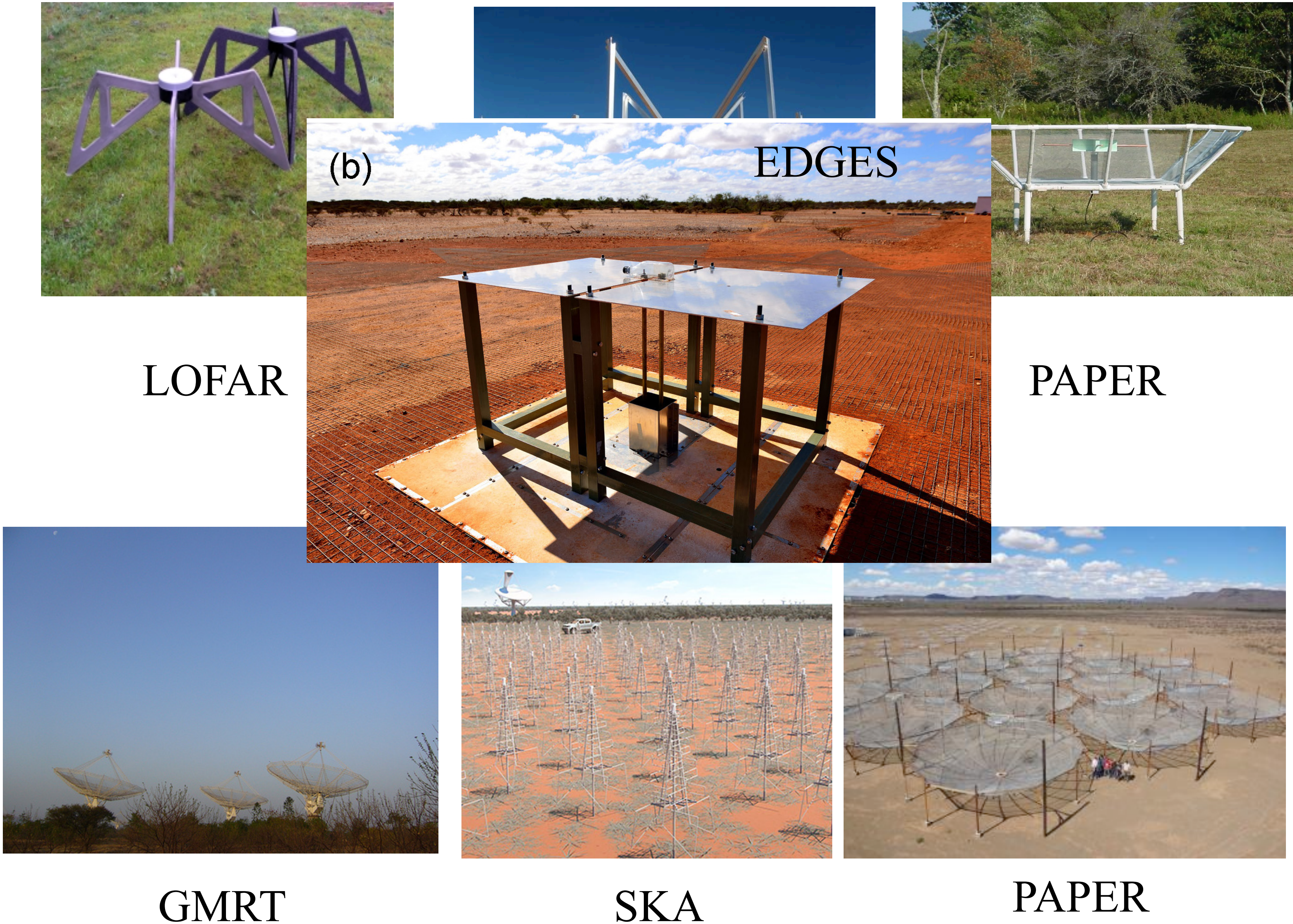


$$\delta T_b = 28\mathrm{mK}\,(1+\delta)\,x_{\mathrm{HI}}\left(1-\frac{T_{CMB}}{T_{spin}}\right)\left(\frac{\Omega_b h^2}{0.0223}\right)\sqrt{\left(\frac{1+z}{10}\right)\left(\frac{0.24}{\Omega_m}\right)}\left[\frac{H(z)/(1+z)}{\mathrm{d}v_{\|}/\mathrm{d}r_{\|}}\right],$$

Astrophysics

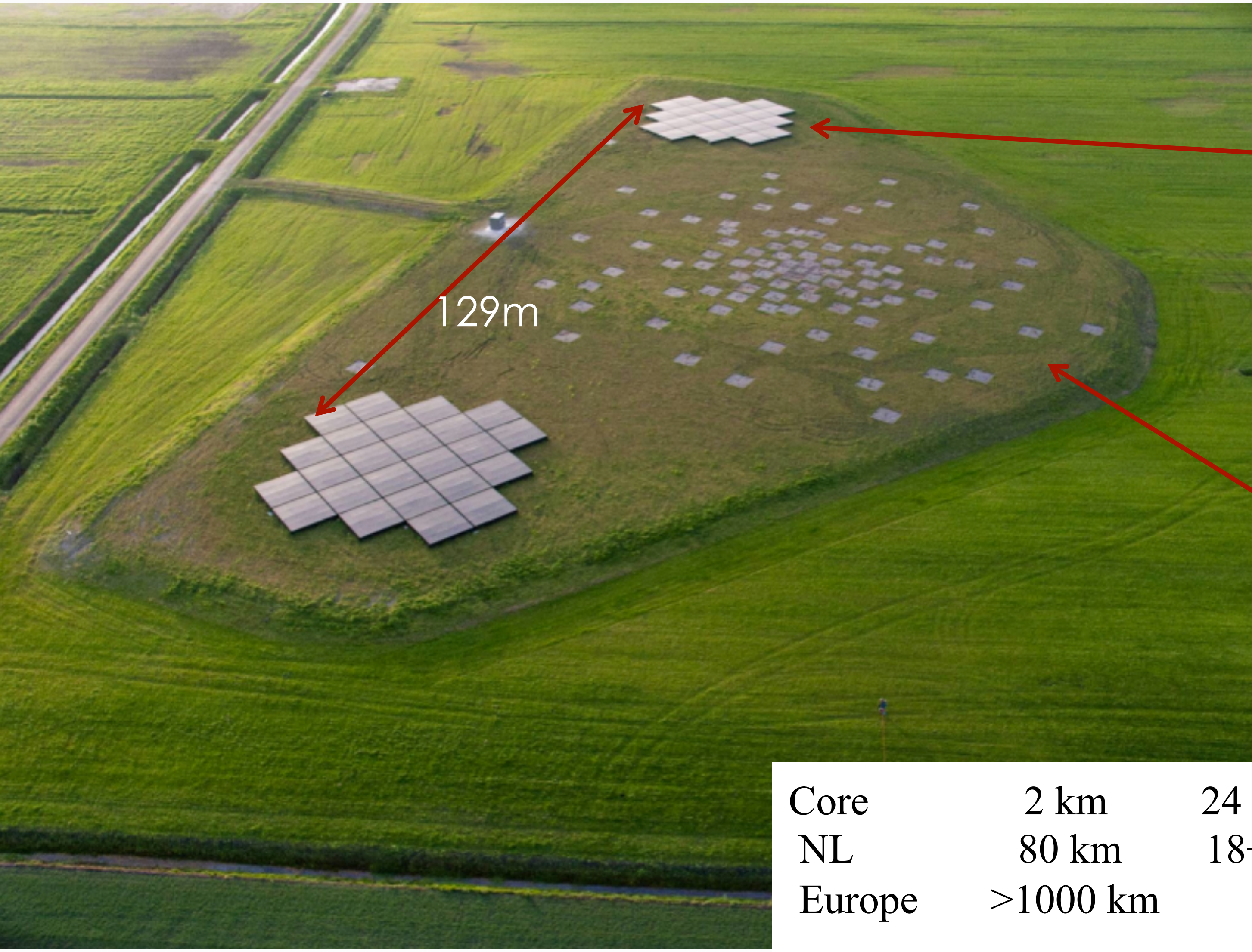
Cosmology

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


(b)
EDGES
LOFAR
PAPER
GMRT
SKA
PAPER

International LOFAR Telescope (ILT)

Core Station



HBA:
High frequency
Tiles
115 - 240 MHz

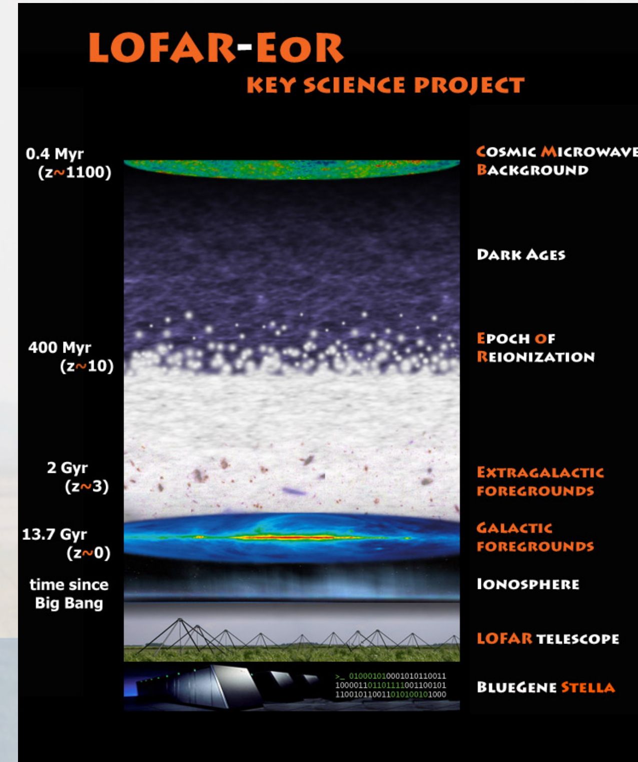
LBA:
Low frequency
dipoles
30 - 90 MHz

Core	2 km	24 (x2) stations
NL	80 km	18+ stations
Europe	>1000 km	12+ stations

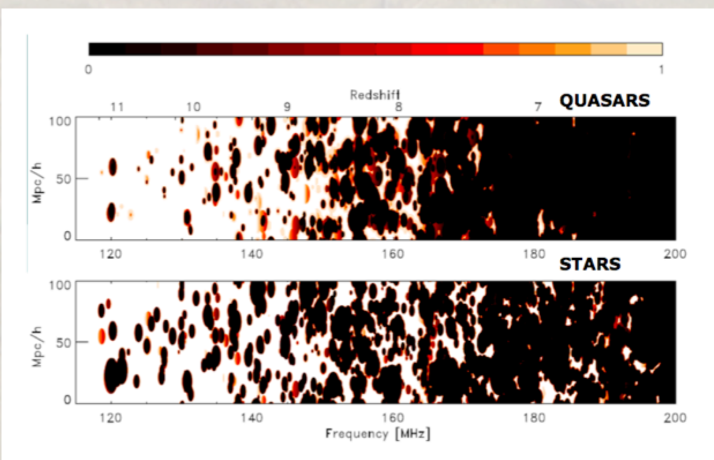
Total # of HBA dipoles: ~ 50000.

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)

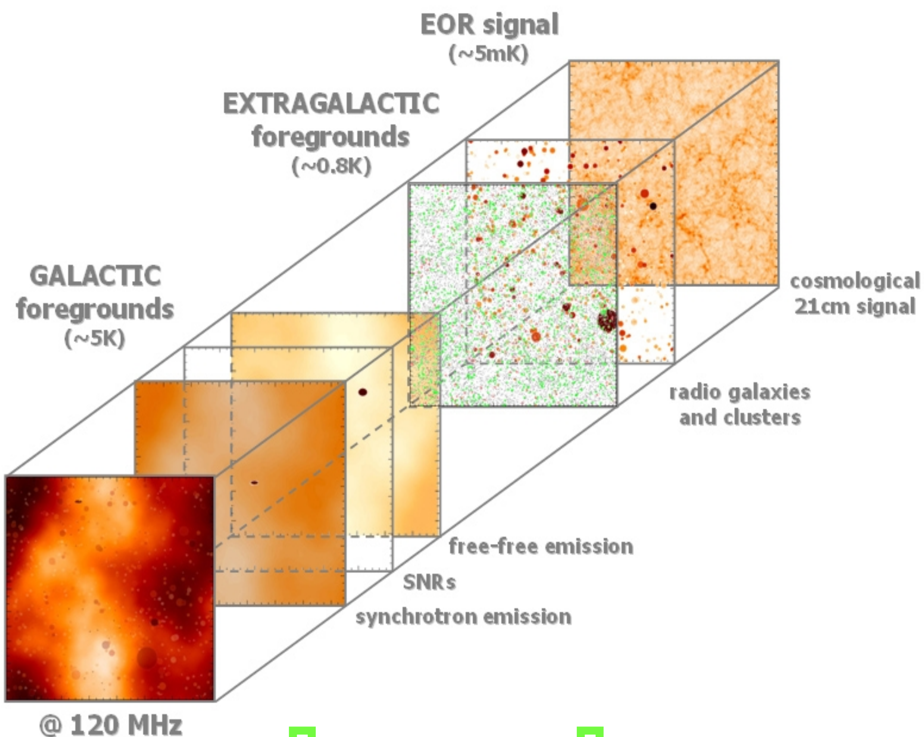


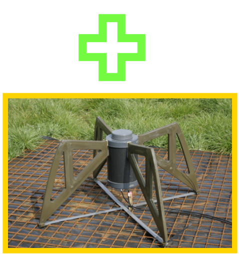
Rajat Thomas (2009)

115 - 177 MHz
z = 11.4 – 7.0

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

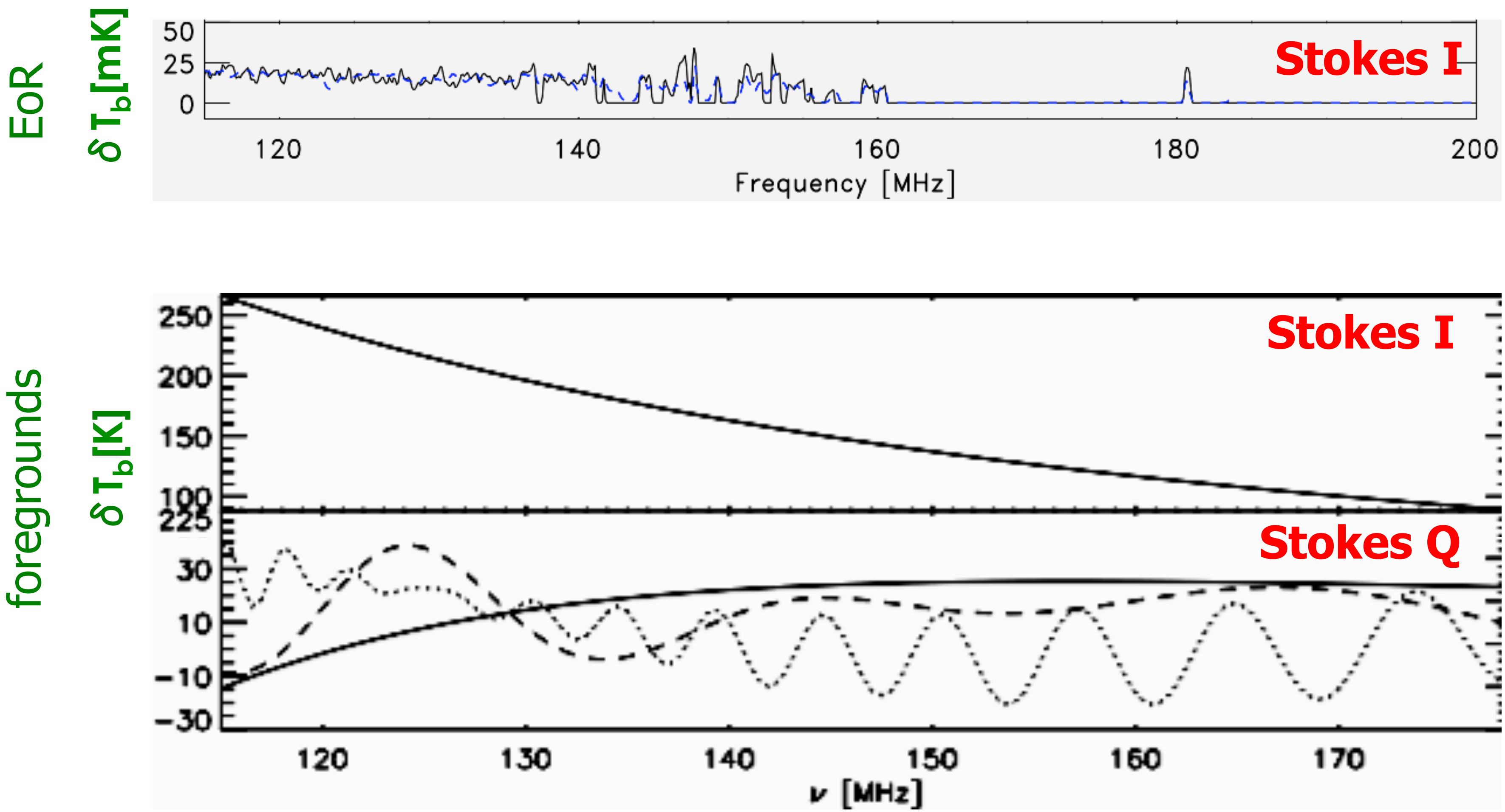
Measuring Redshifted HI: Challenges





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

The leakage problem



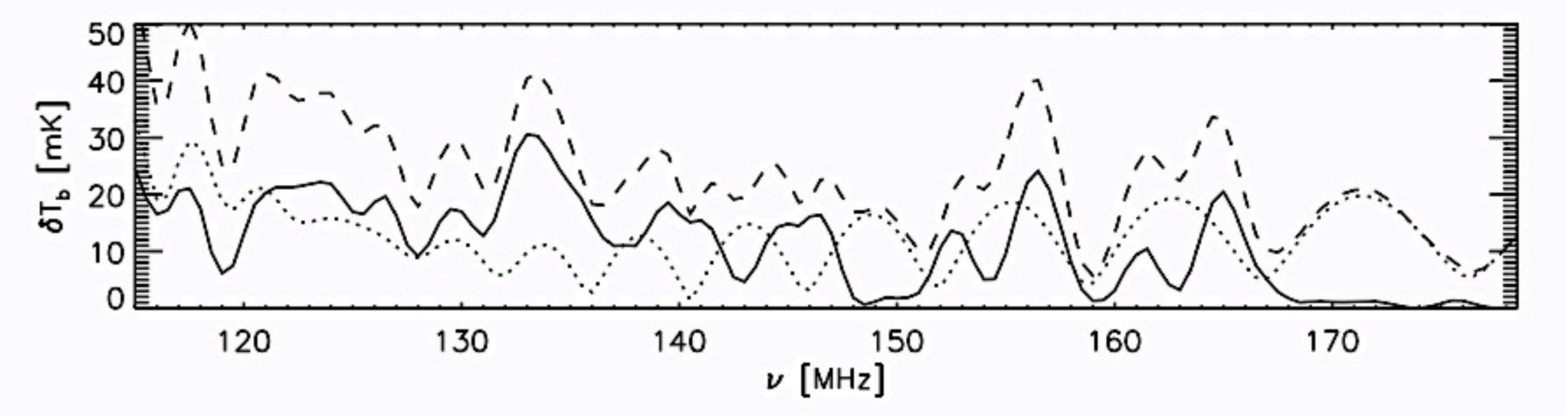
- **extraction is based on smoothness of the foregrounds in total intensity**

The problem of polarized foregrounds

EoR ~ 5 mK

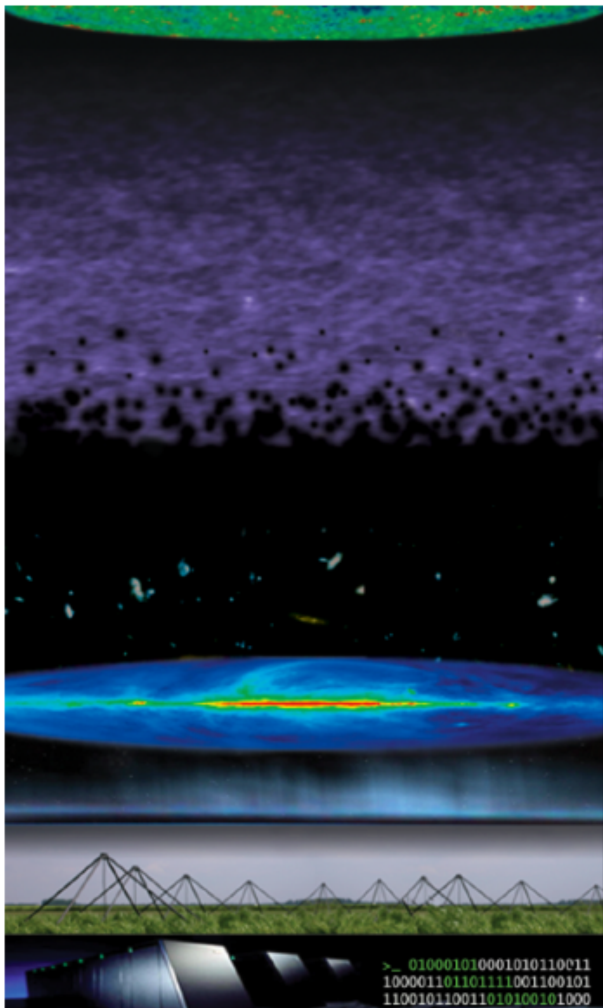
FG ~ 2 K

residual leakage ~ 1.5 %



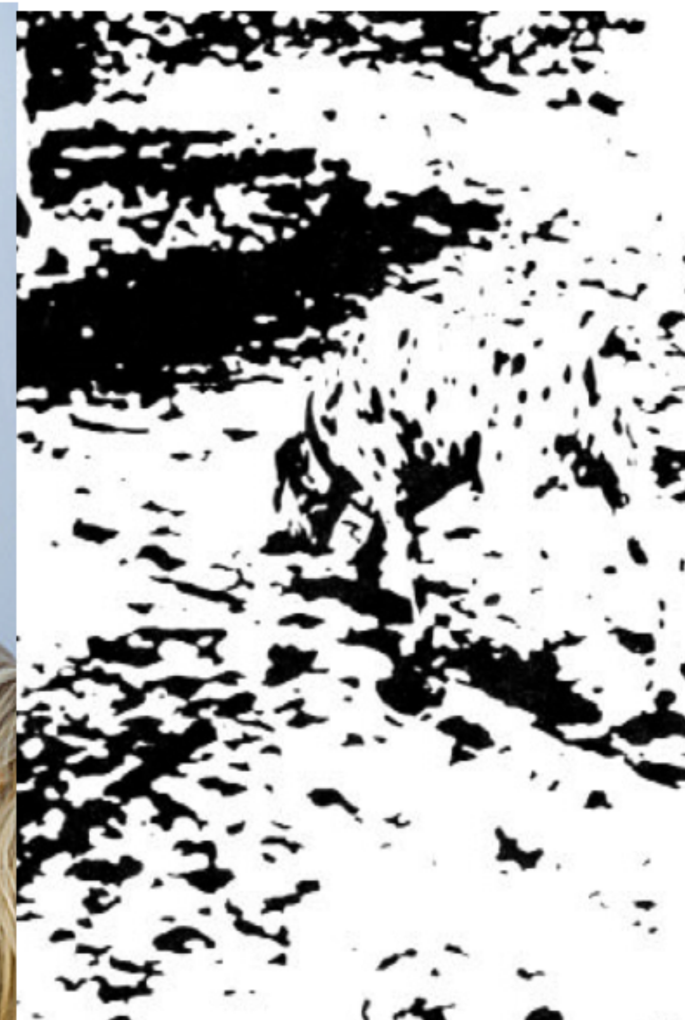
Jelic et al. 2010
Geil et al. 2011

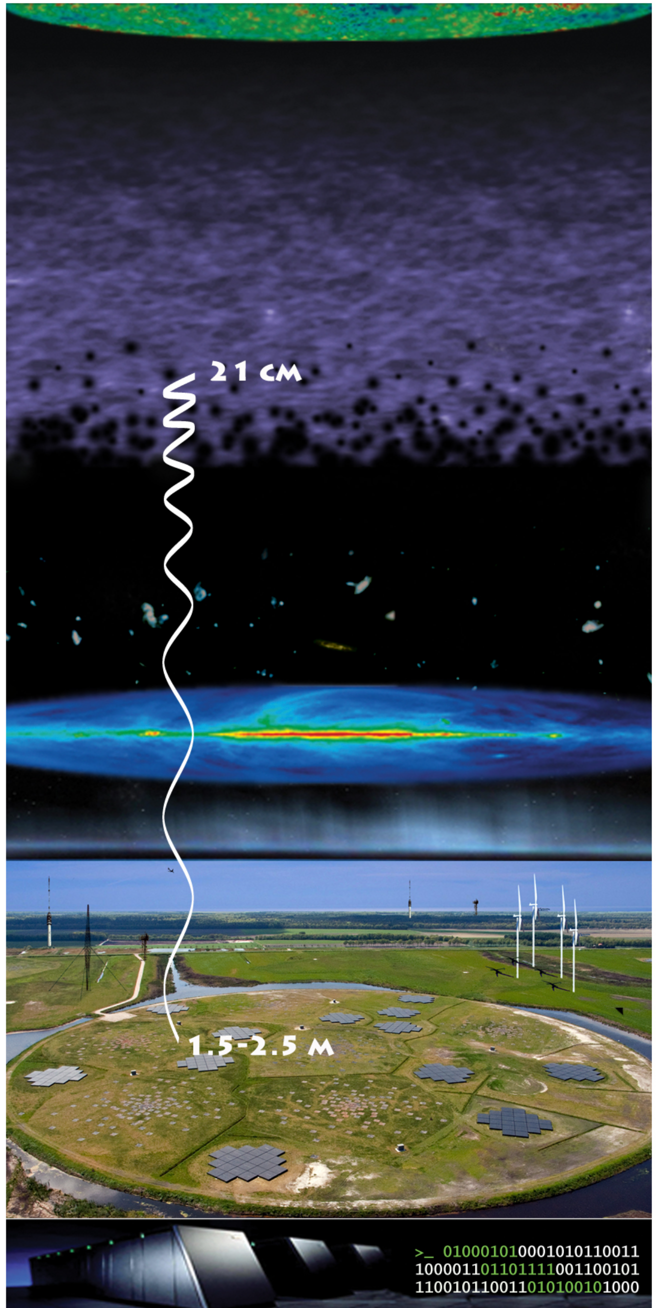
Observation



Extraction/ detection

Interpretation





13.7 Gyr (z~1100) — Cosmic Microwave Background

Dark Ages

13.2 Gyr (z~10) — Epoch of Reionization

11.5 Gyr (z~3) — Extragalactic foregrounds

1 kyr (z~0) — Galactic foregrounds

0.6 ms — Ionosphere

Radio Frequency Interferences

0.2 ms — the LOFAR telescope core stations in the Netherlands

t = 0 s — Supercomputer BlueGene

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.

The rms and Cross-rms statistic

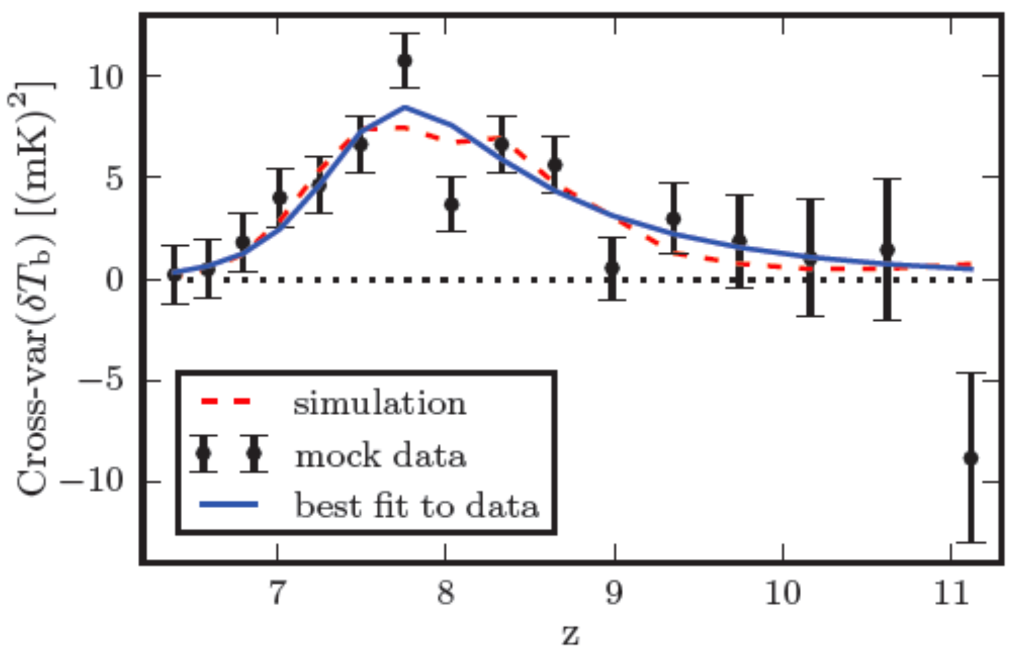
- Smooth the images with a Gaussian kernel

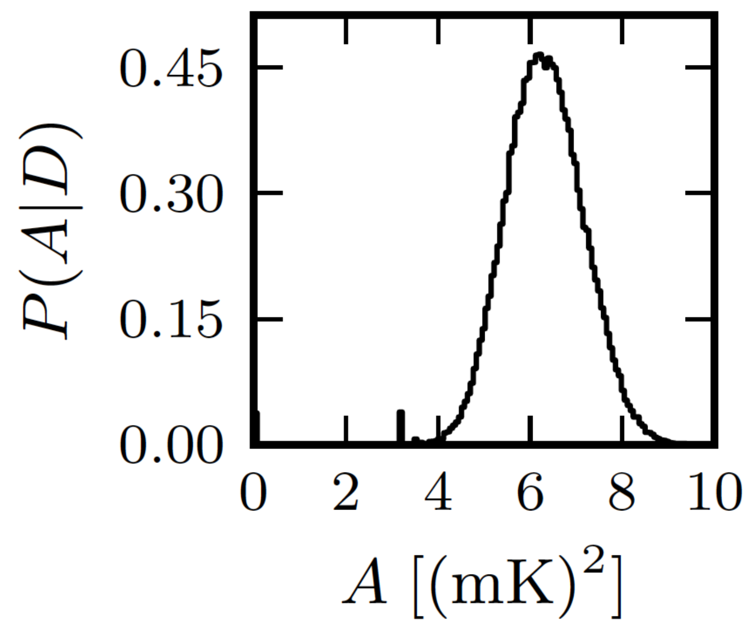
$$RMS(\nu) = \sqrt{\left\langle \left(I_{i,j}(\nu) I_{i,j}(\nu) \right) - \left\langle I_{i,j}(\nu) \right\rangle \left\langle I_{i,j}(\nu) \right\rangle \right\rangle_{i,j}}$$

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

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

- 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

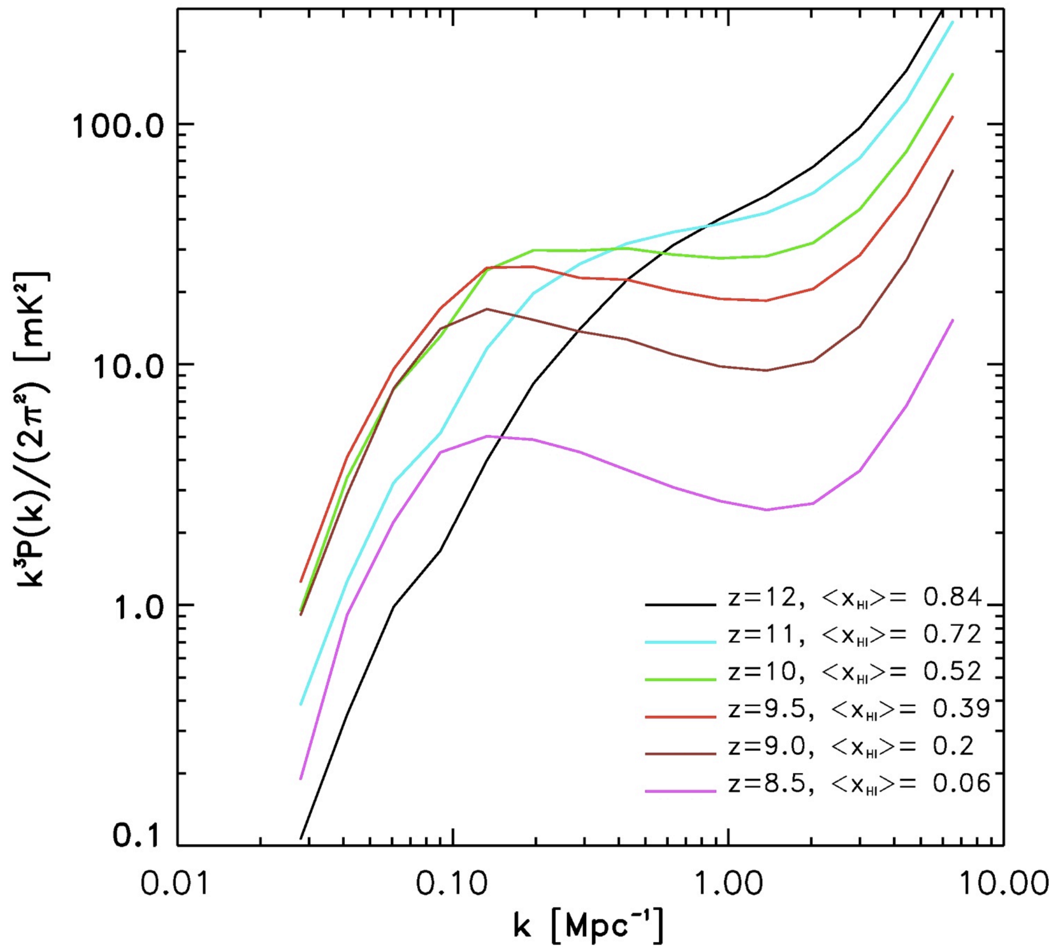
‘Dimensionless’ Power Spectra

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

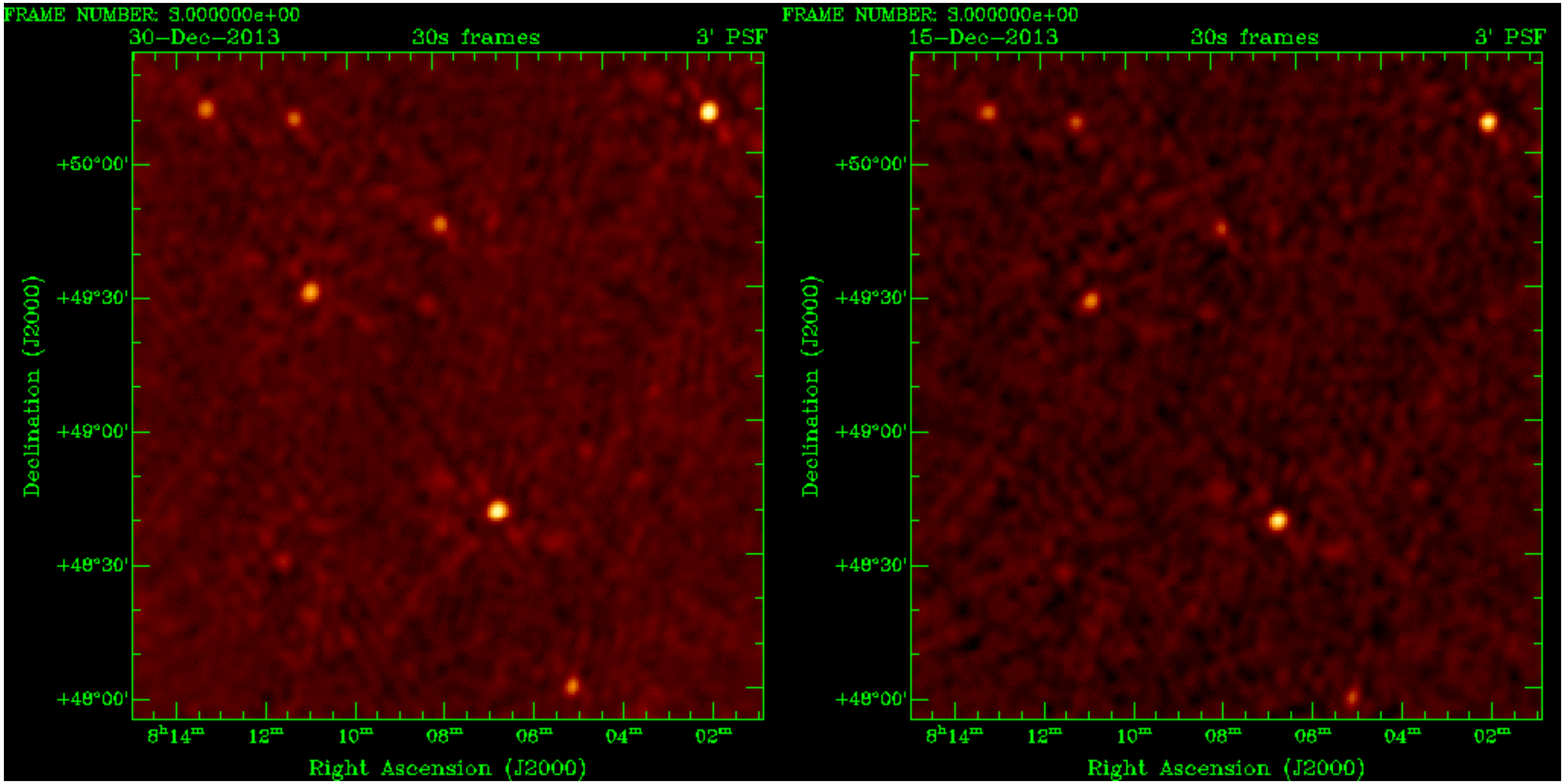
$$\Delta^2(k) = \frac{k^3 P(k)}{2\pi^2}$$

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

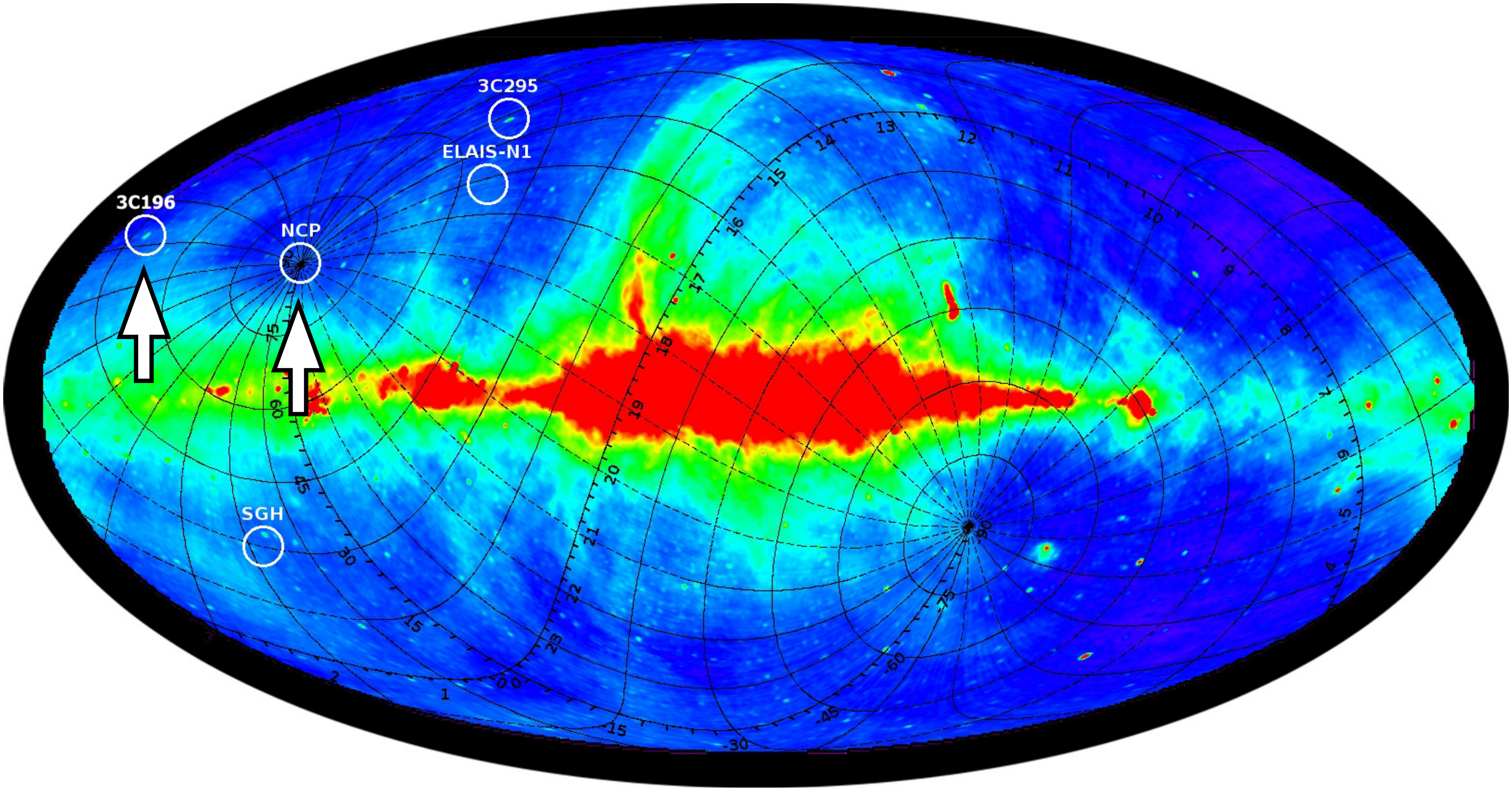
$$\Delta^2(k_{||}, k_{\perp}) = \frac{(k_{||}^2 + k_{\perp}^2)^{3/2}}{2\pi^2} P(k_{||}, k_{\perp})$$



Ionospheric effects: the good and the ugly

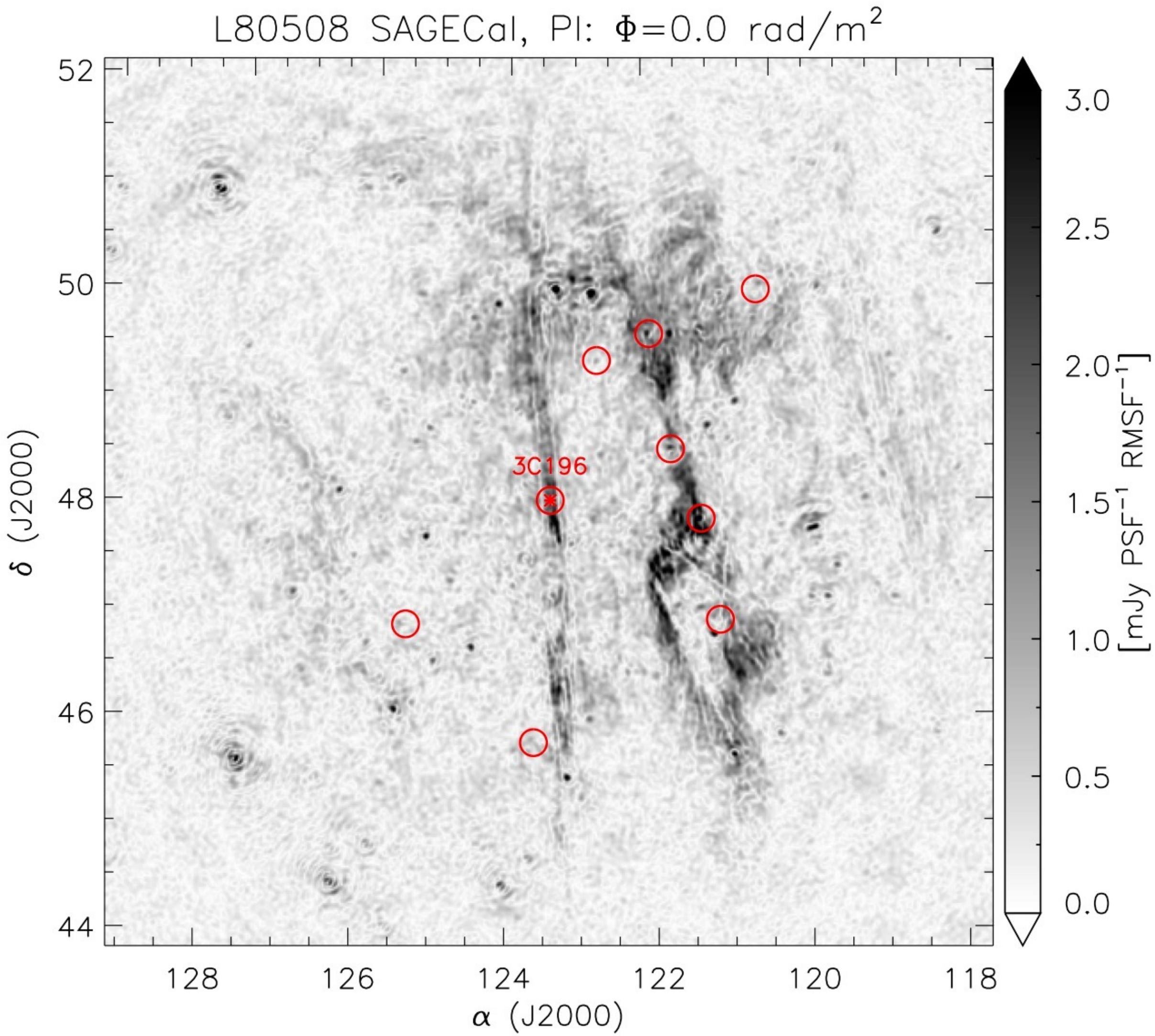


LOFAR EoR Deep Fields

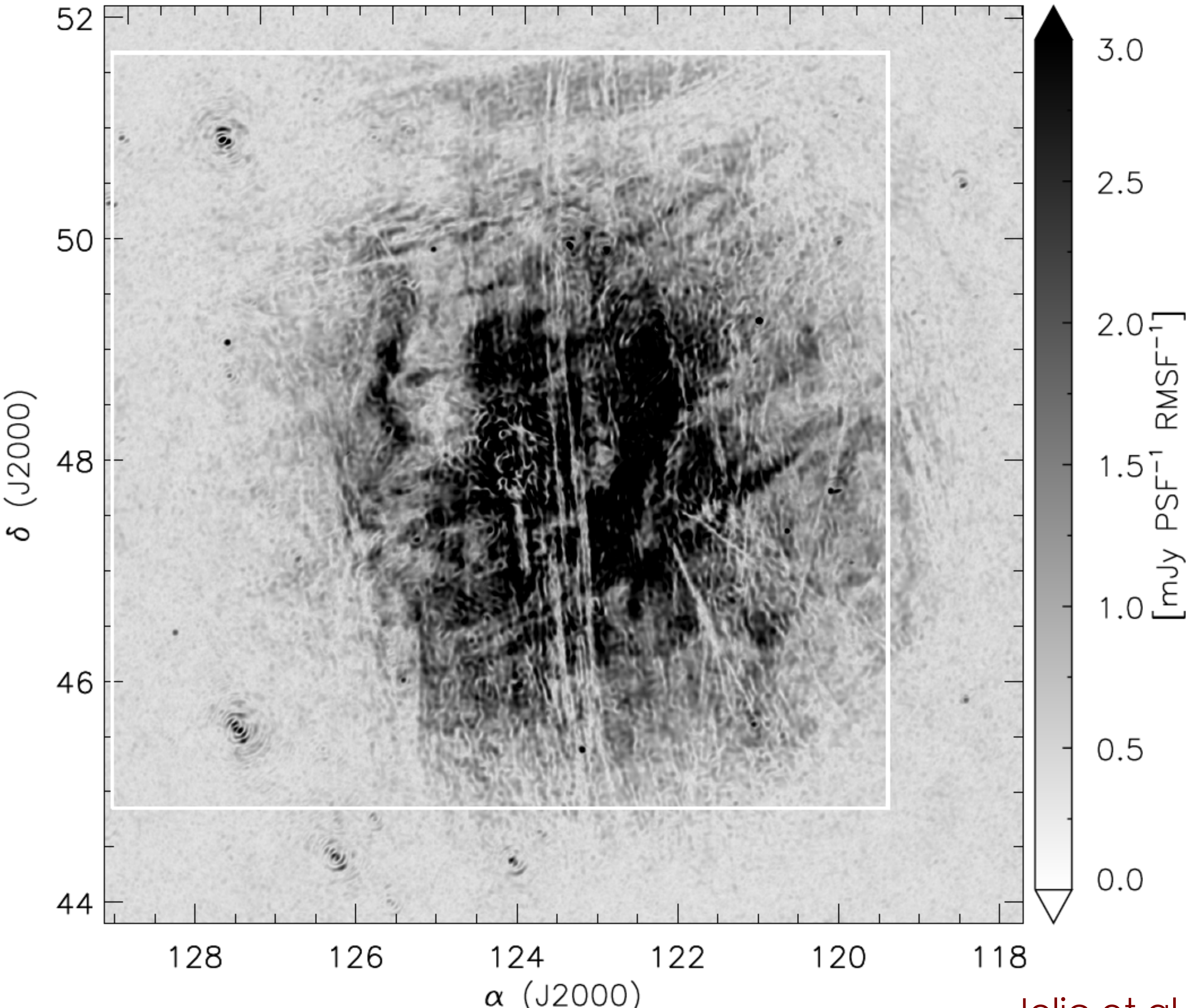


We currently focus on two deep windows: NCP and 3C196

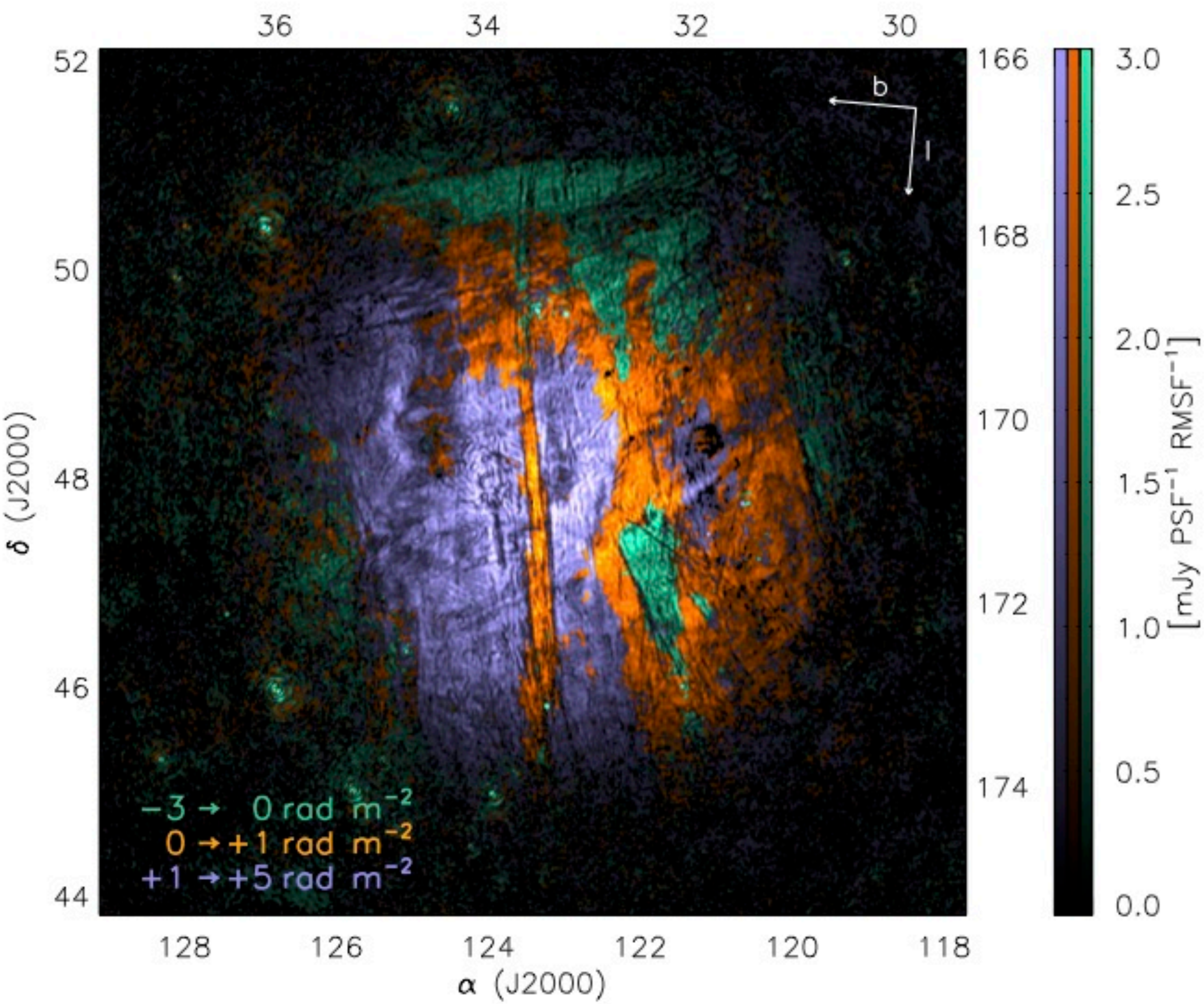
LOFAR-EoR observations



Jelic et al 2015

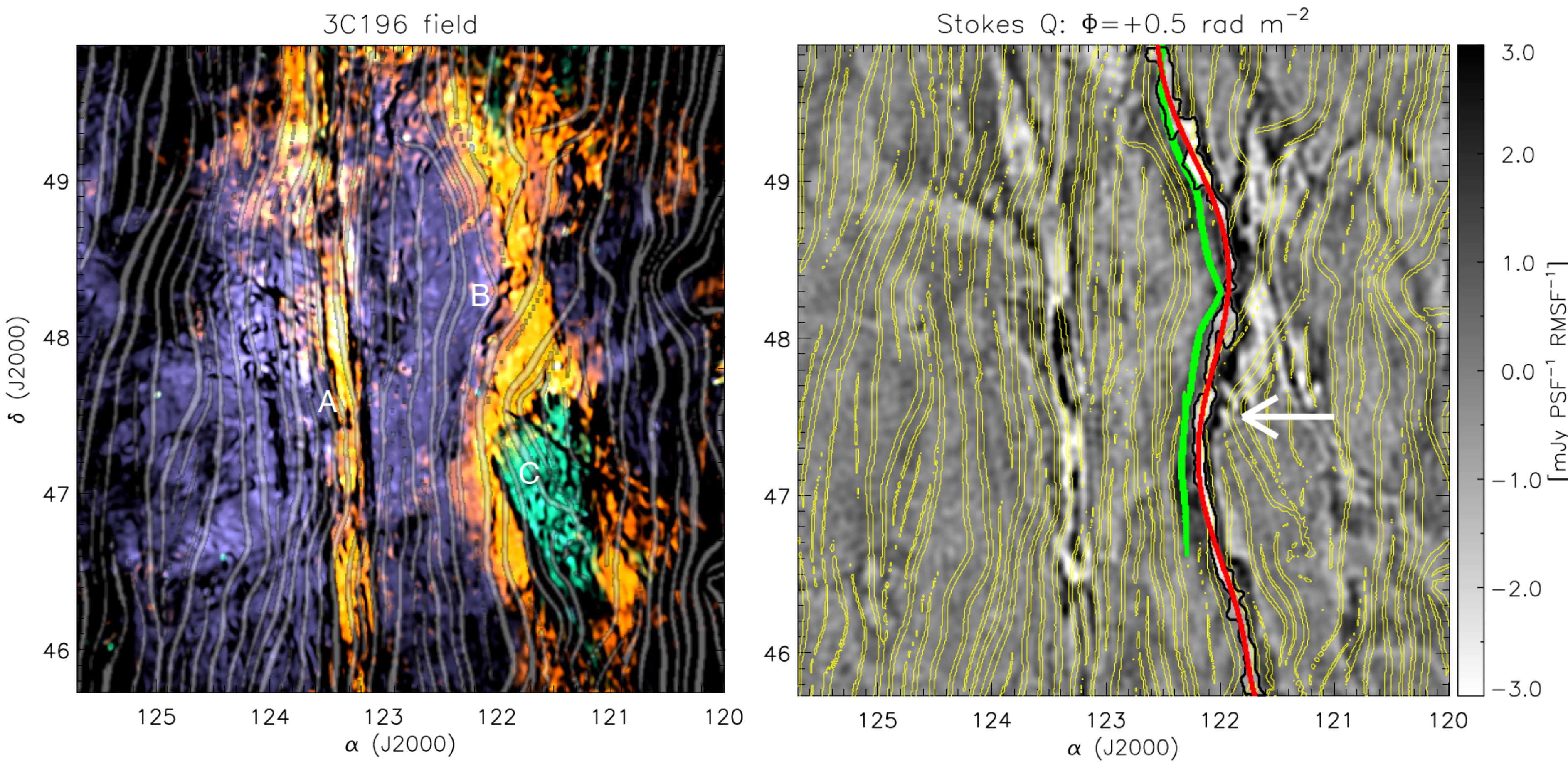


Jelic et al 2015



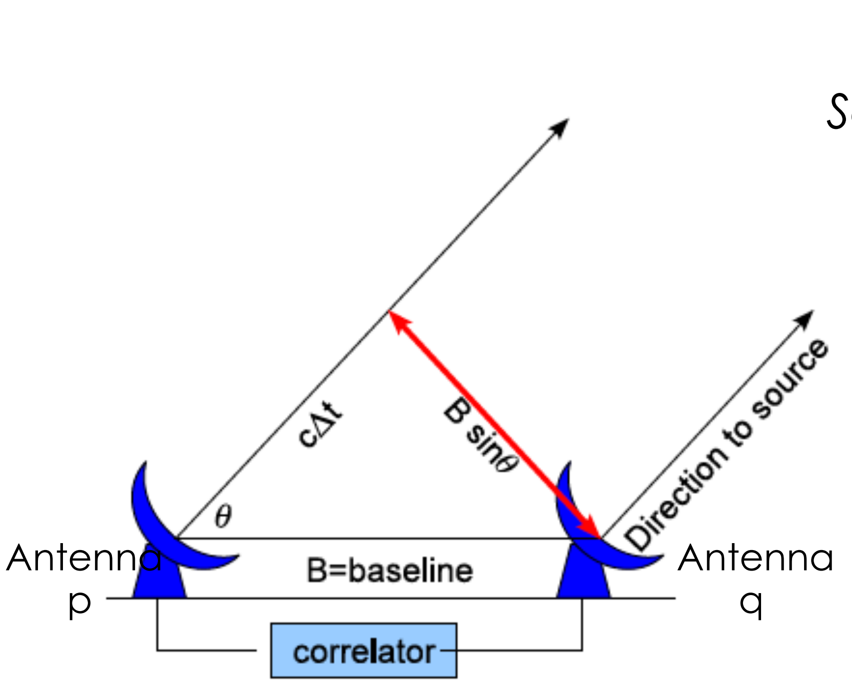
Jelic et al, 2015

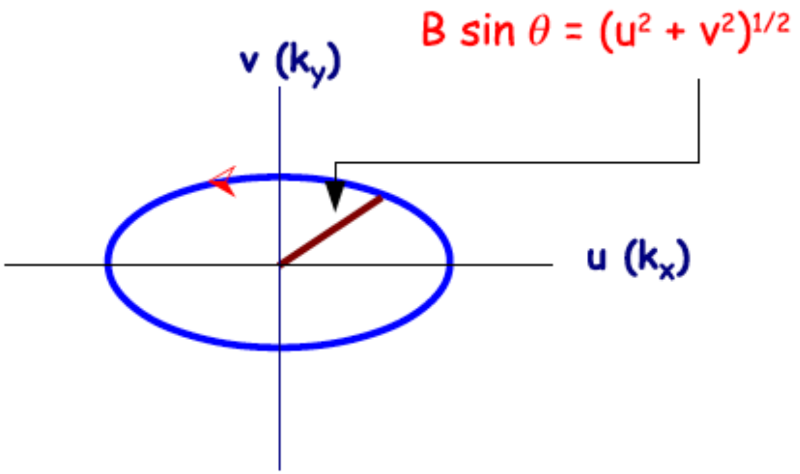
ISM magnetic/Faraday depth correlation (LOFAR vs. Planck)



Zaroubi et al 2015, MNRAS

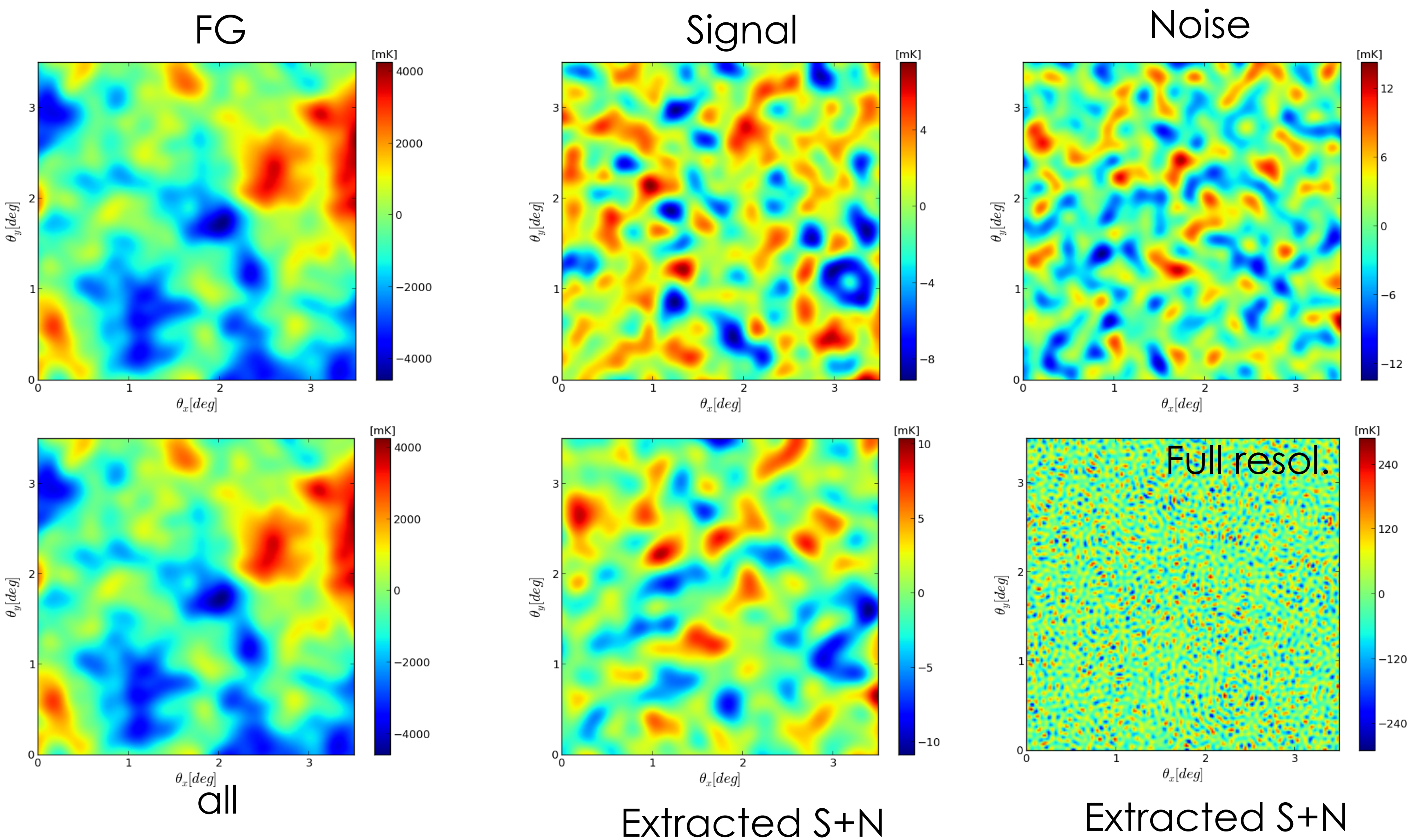
The calibration problem





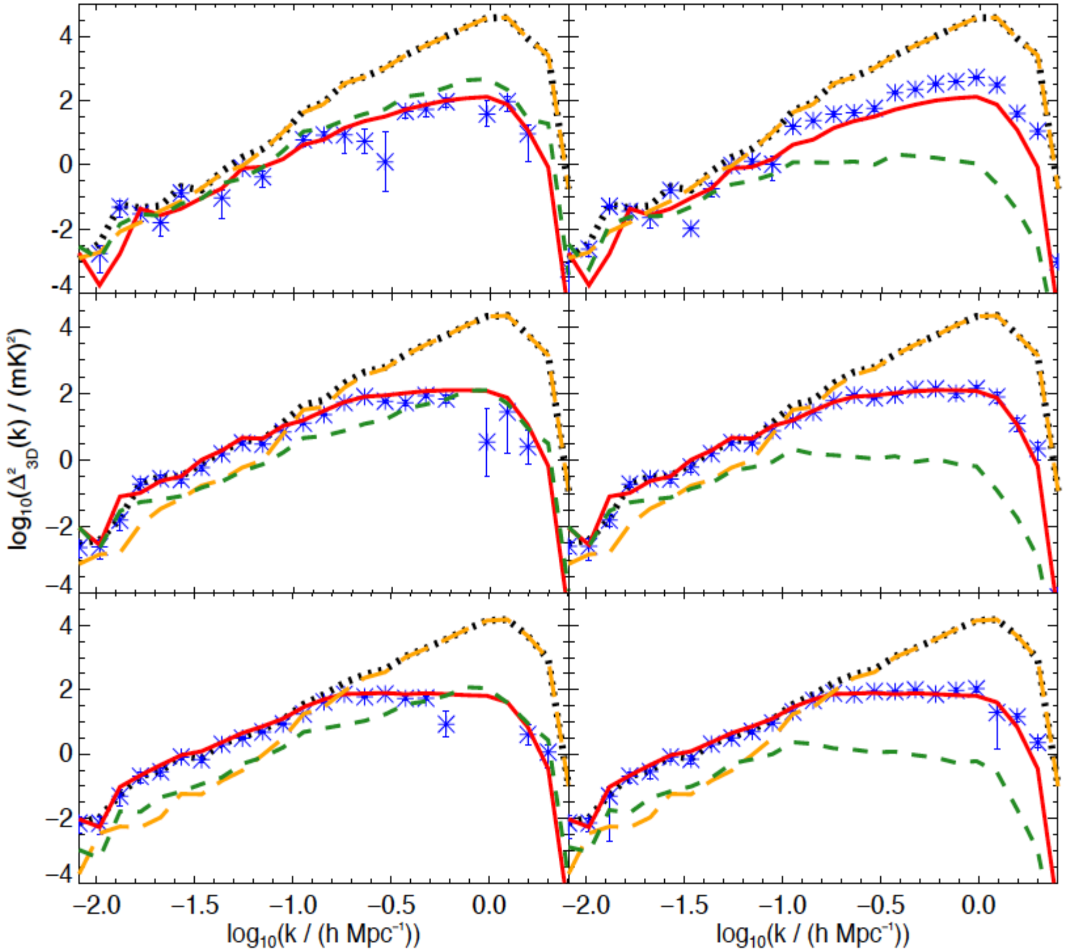
$$\mathbf{V}_{pq} = \sum_{i=1} \mathbf{J}_{pi}(\boldsymbol{\theta})\mathbf{C}_i\mathbf{J}_{qi}^H(\boldsymbol{\theta}) + \mathbf{N}_{pq}, \quad p, q \in \{1, 2, \ldots, N\}$$

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

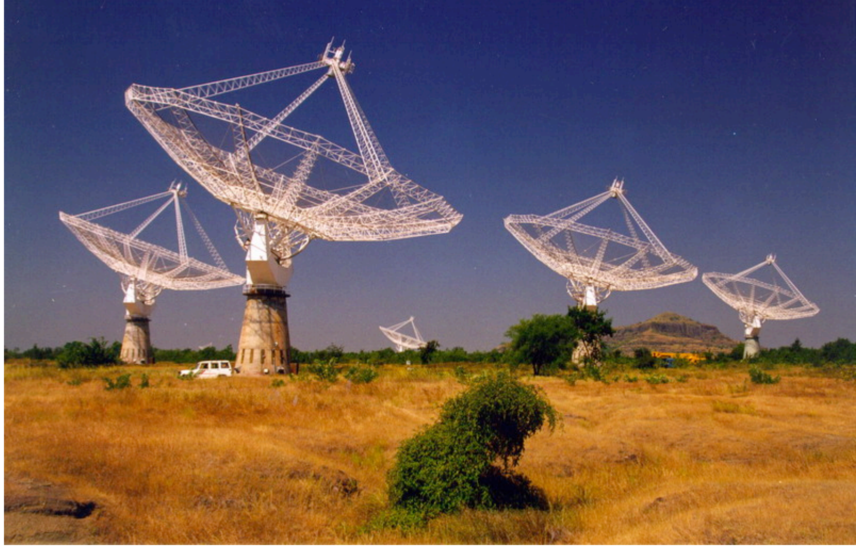


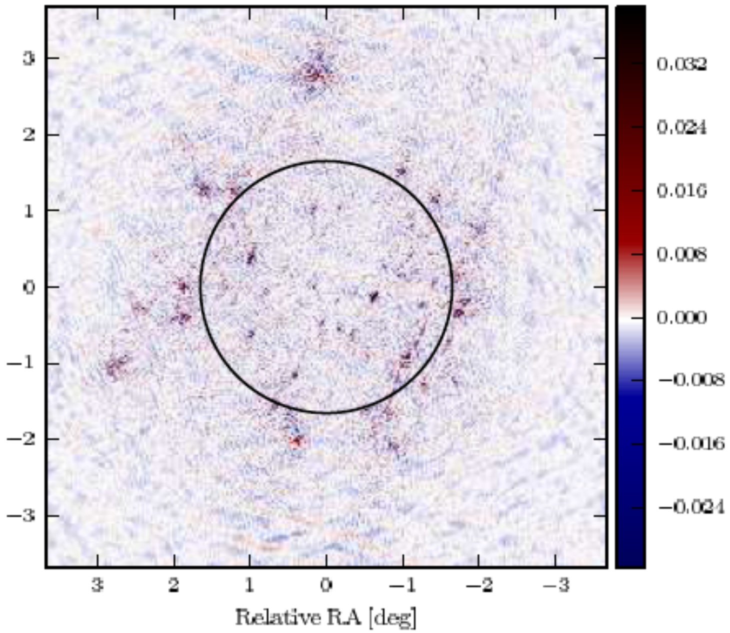
Power Spectrum Measurements

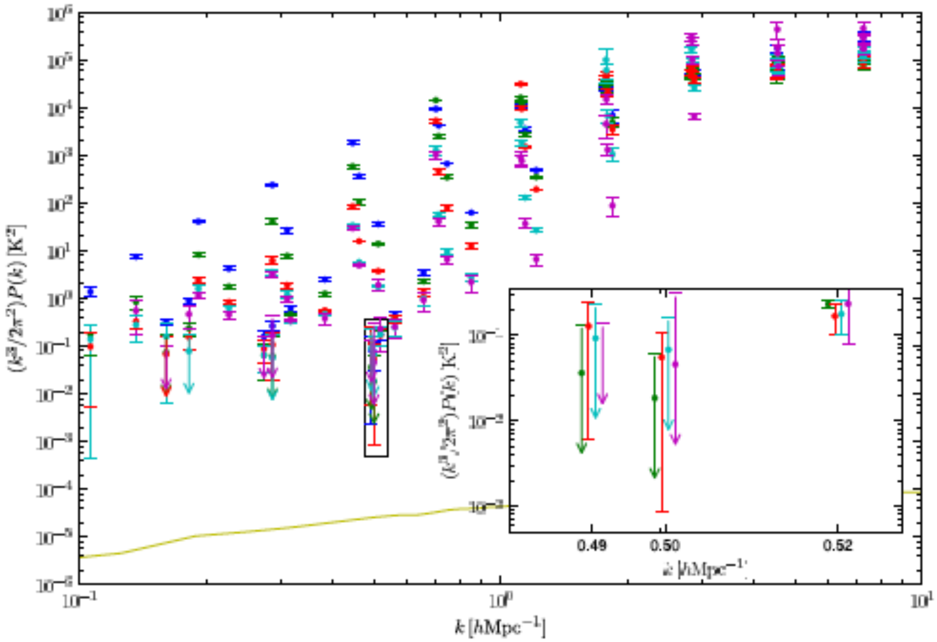
Chapman et al 2013



GMRT results

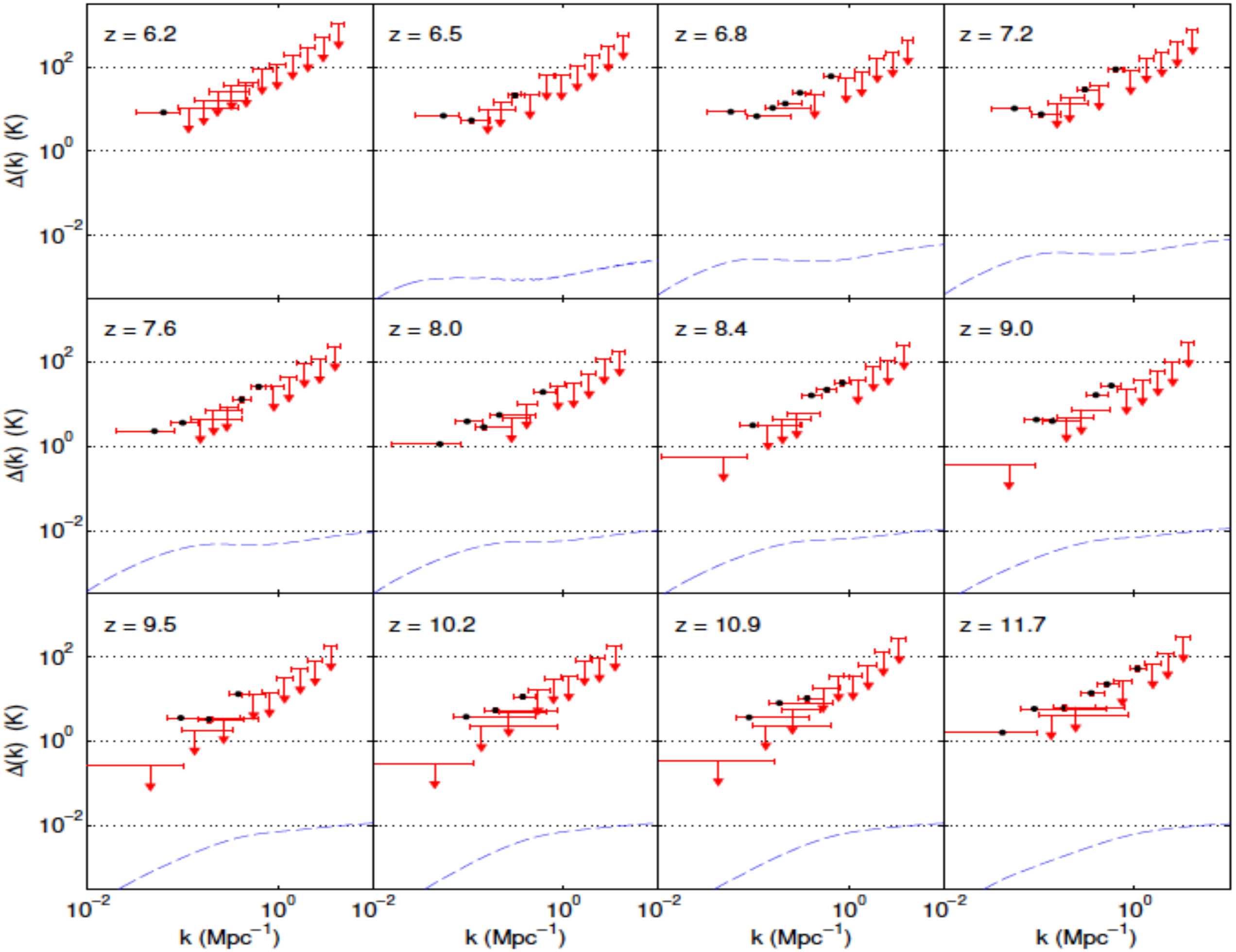




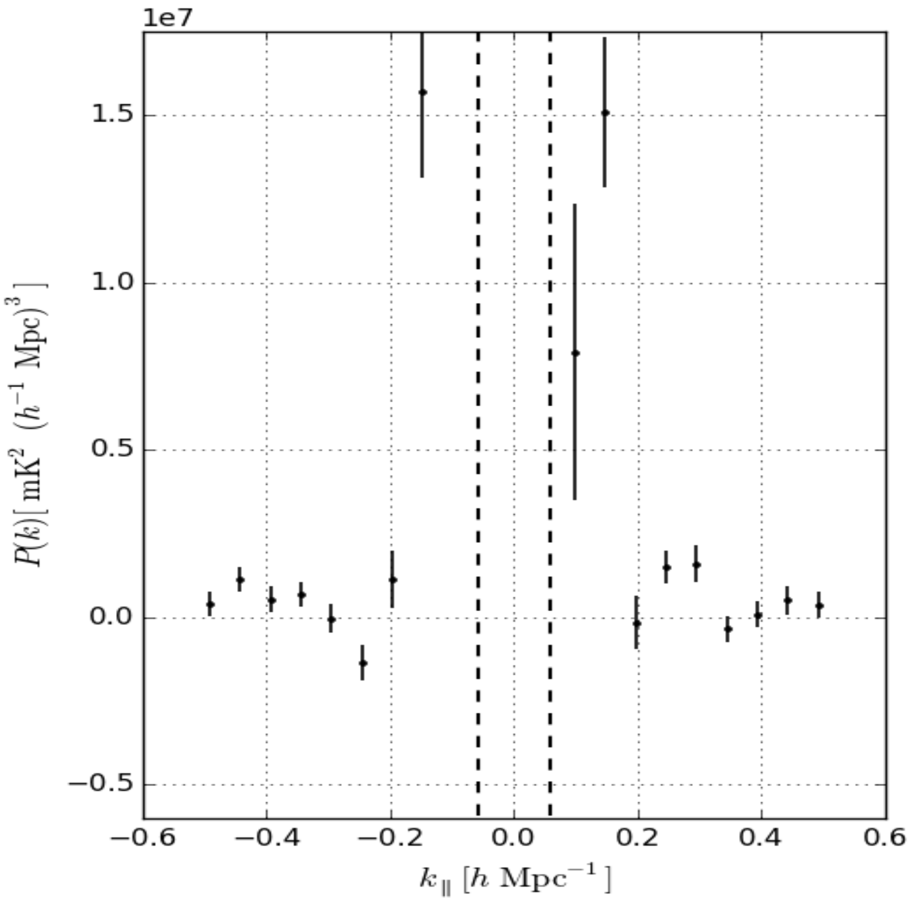


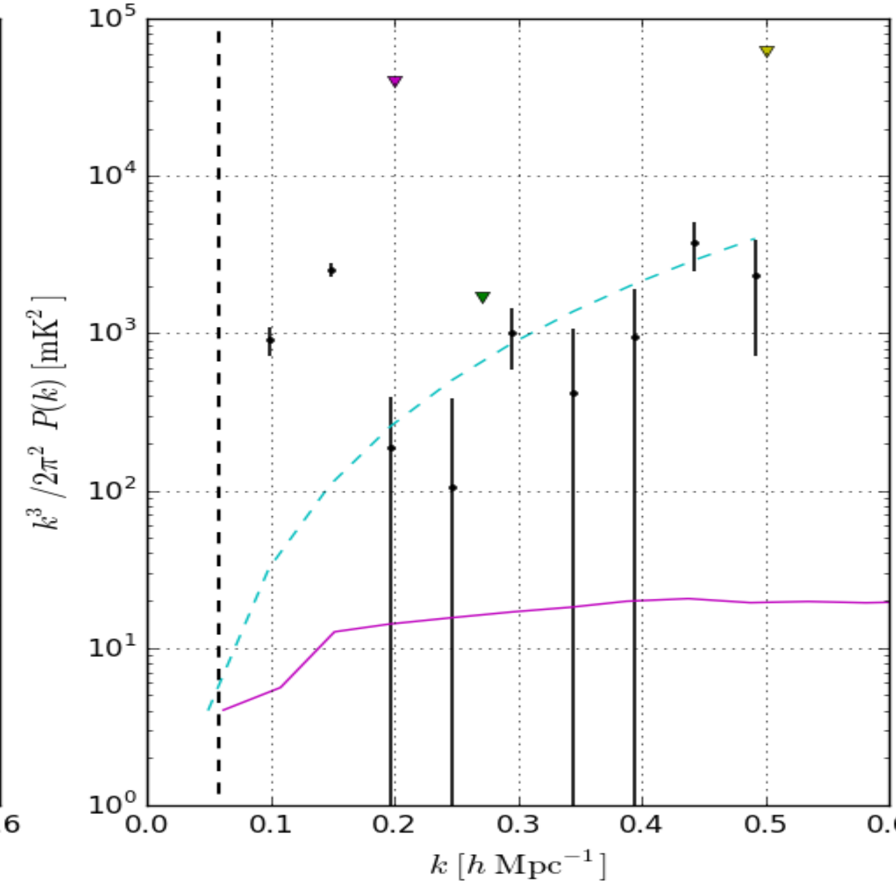
Paciga et al 2011

MWA current results



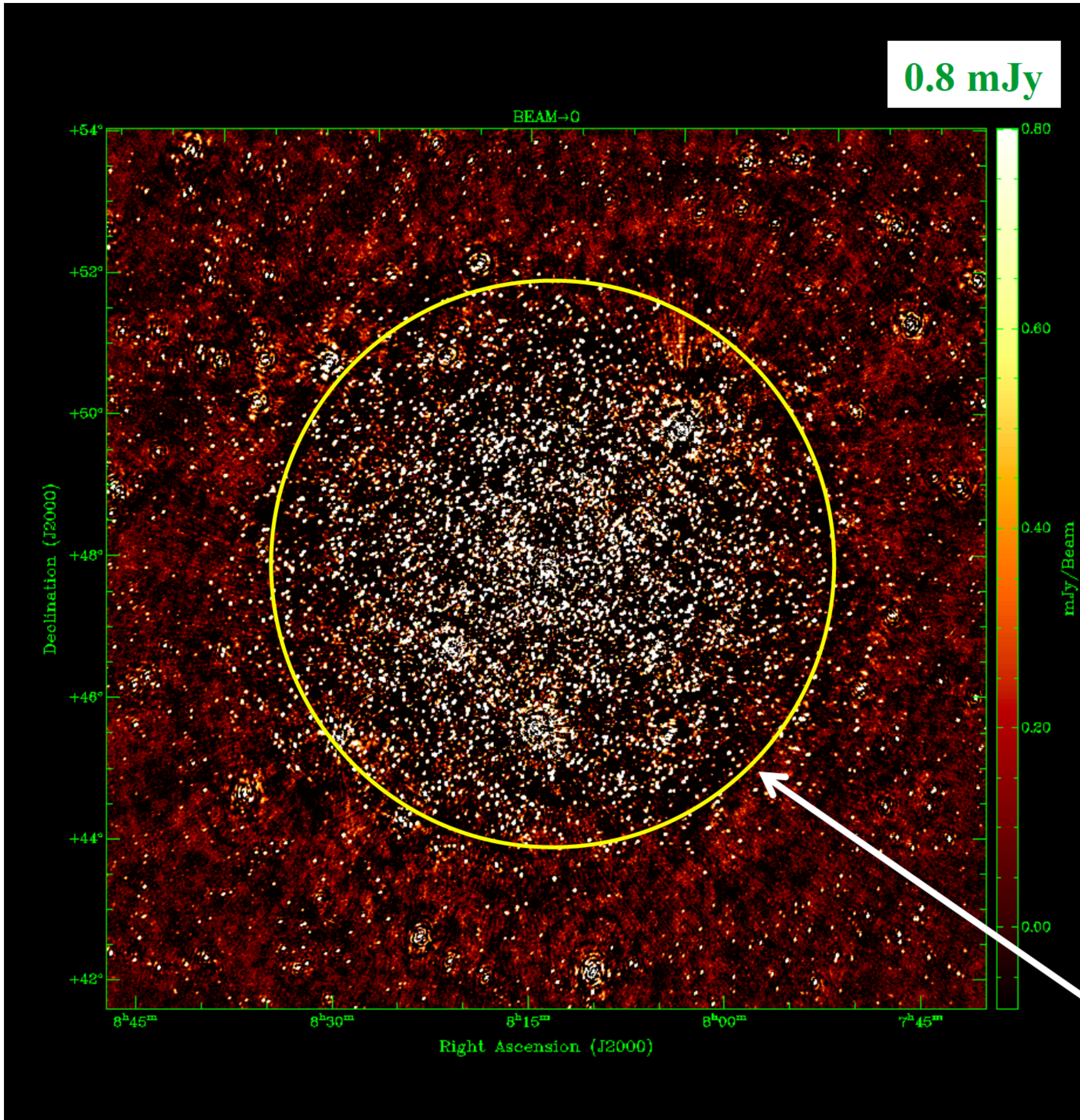
Dillon et al 2014





Ali et al 2015

NCP field



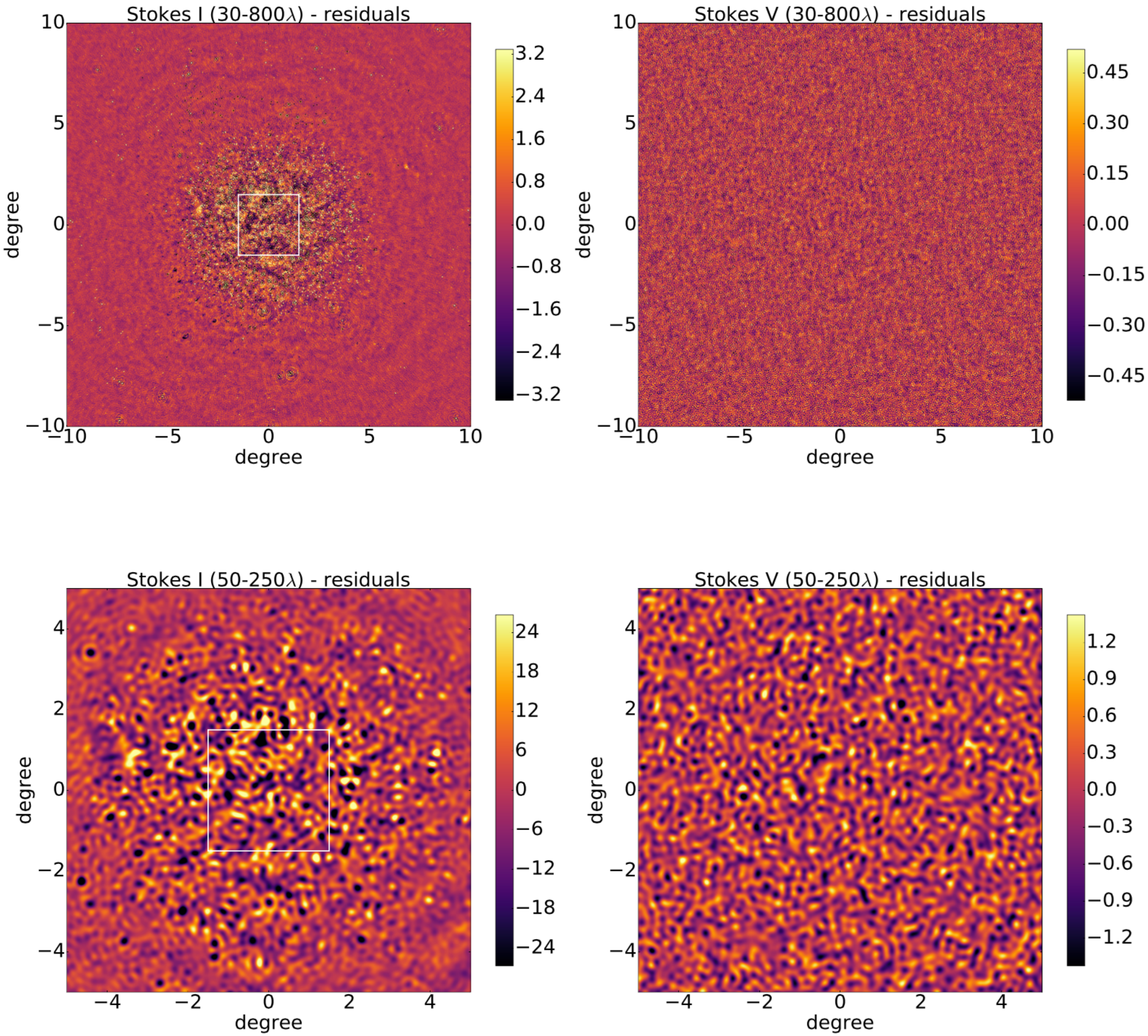
near the NCP is indicated by an arrow. The intensity units are mJy/PSF (see text). Right Ascension increases clockwise; RA=00h is towards the bottom.

L90490

13-hr integration over ~74 MHz with all LOFAR HBA stations (Feb 11/12, 2013)

Phase Centre ($\alpha, \delta; J2000$)	0^h, +90°	
Minimum frequency	115.039	MHz
Maximum frequency	189.062	MHz
Target bandwidth	74.249	MHz
Stations (core/remote)	48 / 13	
Raw data volume L90490	61	Tbyte
Sub-band (SB) width	195.3125	kHz
Correlator channels per SB	64	
Correlator integration time	2	s
Channels per SB after averaging	15, 3, 3, 1	
Integration time after averaging	2, 2, 10, 10	s
Data size (488 sub-bands)	50	Tbyte

Table 1. Observational and correlator set up of LOFAR-HBA observations of the North Celestial Pole (NCP).



Stokes I (left)
Stokes V (right)
@ 2 resolutions
(~12, 4 arcmin)

After SageCal-CO and removal sky-model.
Stokes I is confusion limited/Stokes V is thermal-noise limited.

Diffuse emission is hard to see

Figure 2. Stokes I and Stokes V images after sky-model subtraction for the baseline ranges 30-800λ (top panels) and 50–250λ (bottom panels). Sub-bands with frequencies between 121 and 134 MHz went into these images. Note the reduction in the displayed field-of-view from 20×20° to 10×10°. Intensity units are in mJy/PSF and the scale range is set by plus and minus three times the standard deviation over the full field in all images. Note the noise-like structure in the two Stokes V images. i.e. a lack of any features. The Stokes I images, on the other hand, clearly show the LOFAR-HBA primary beam attenuation effects on the remaining diffuse emission. The level of this emission is limited by the classical confusion noise within the primary beam. The 3° × 3° box delineates the area where we measure the power spectra.

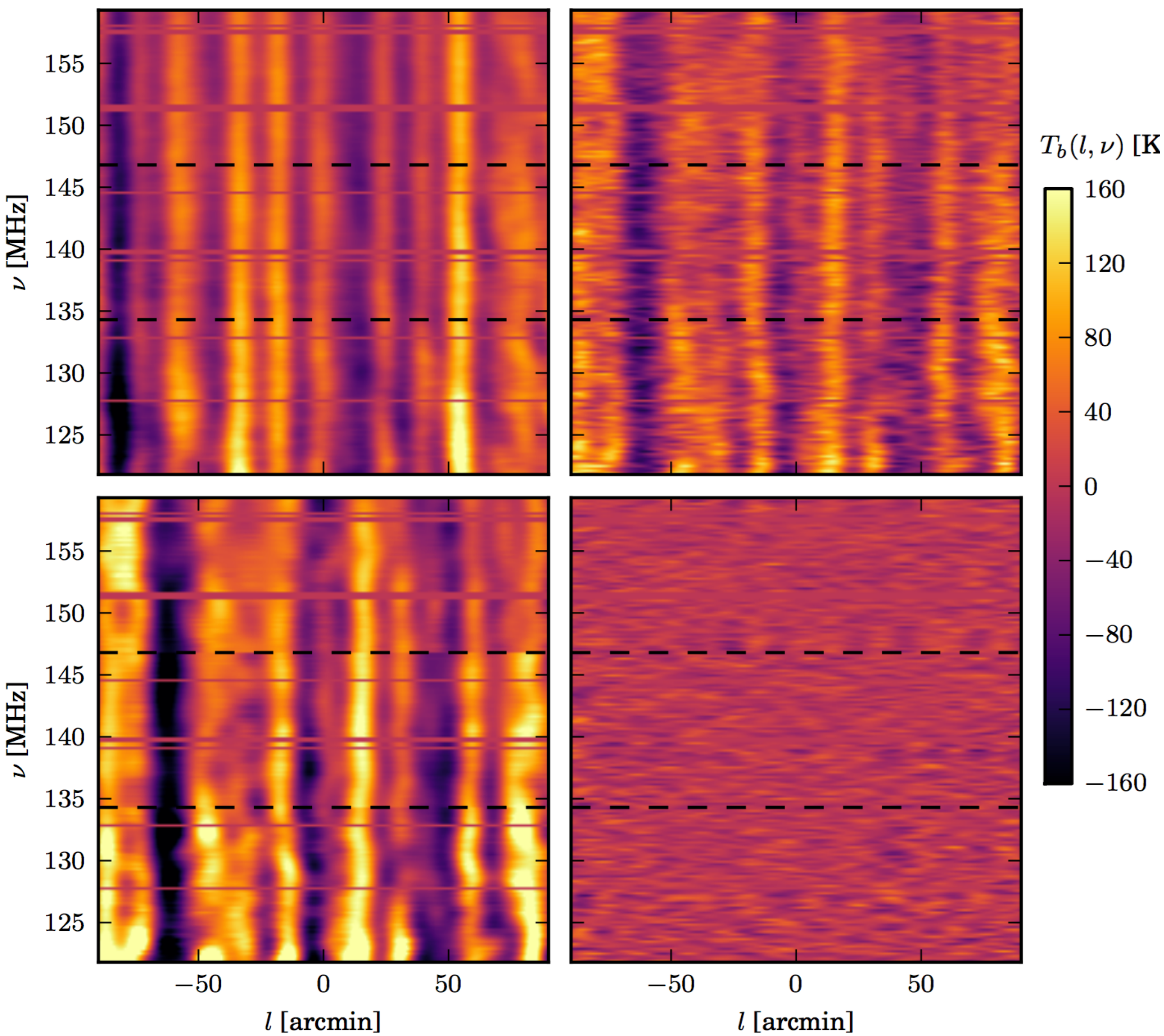


Figure 3. A slice across the centre of the 50–250λ Stokes-I data cube along the frequency direction. Top left: slice after *DI*-calibration with only 3C61.1 subtracted; the intensity scale, converted to brightness temperature, refers to this panel. Top right: after *DD*-calibration where the calibration sky model, consisting of compact sources, is subtracted with their respective direction-dependent gain solutions. The intensity scale is now multiplied by 10 for improved visualization; Bottom left: GMCA model (scale also multiplied by 10); Bottom right: GMCA residuals (scale multiplied by another factor of 20). The red horizontal bands are due to data lost due to RFI-flagging. The black dashed lines border the three redshift ranges. Note the factor ~200 reduction in intensity after GMCA.

A spatial-frequency slice:

(1) strong spectrally smooth sources before sky-model subtraction (upper left)

(2) Confusion noise of fainter source and diffuse emission (upper right)

(3) GMCA model of remaining FGs (lower left)

(4) Residuals after GMCA model subtraction (lower right)

Residuals look like noise, but they are not (there is excess variance beyond Stokes V).

Cylindrical Power-Spectra

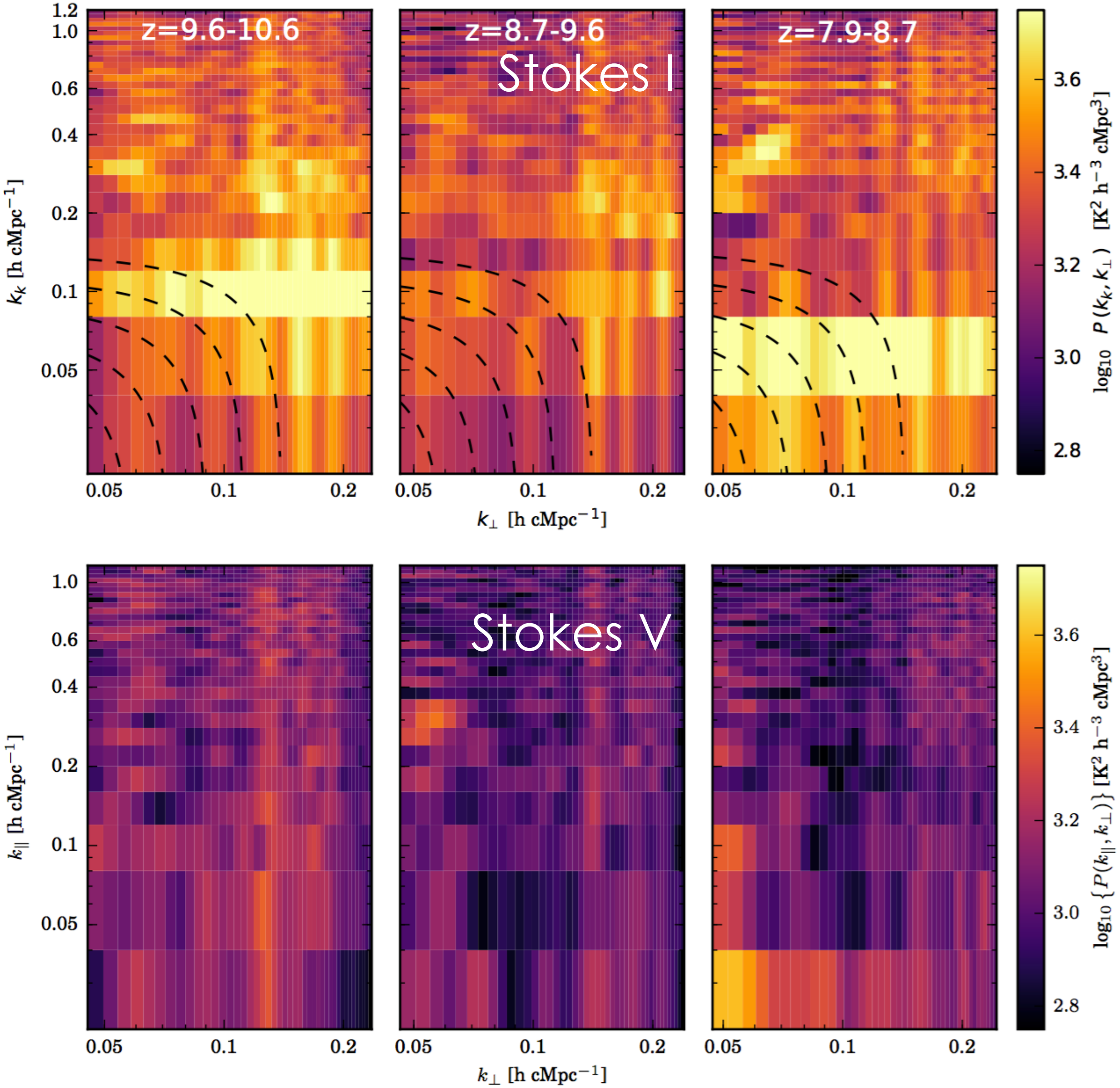


Figure 4. Stokes I (top) and V (bottom) cylindrical power spectra after sky model and GMCA-model subtraction, for L90490. From left to right are shown the redshift ranges $z = 9.6 - 10.6$, $z = 8.7 - 9.6$ and $z = 7.9 - 8.7$, respectively. The dashed curved lines in the Stokes I spectra refer to k values of 0.054, 0.067, 0.083, 0.103 and 0.128 for $z = 8.7 - 9.6$ and only slightly different values for the other redshift bins. It is along these lines that we form the spherically averaged power spectra.

(1) Removal of FG
(2) residuals are left around $k_{||}$ ~0.05-0.1
(3) Stokes I show "excess variance" on all scale by about factor ~2.
(4) Stokes V is relatively clean and close to thermal (but not fully, about

Residuals look like noise, but they are not (there is excess variance beyond Stokes V).

Causes could be:

(1) Leverage
(2) Gain errors on long baselines due to:
  a. Ionospheric errors
  b. Residual sources and their side-lobes

Spherical Power Spectra

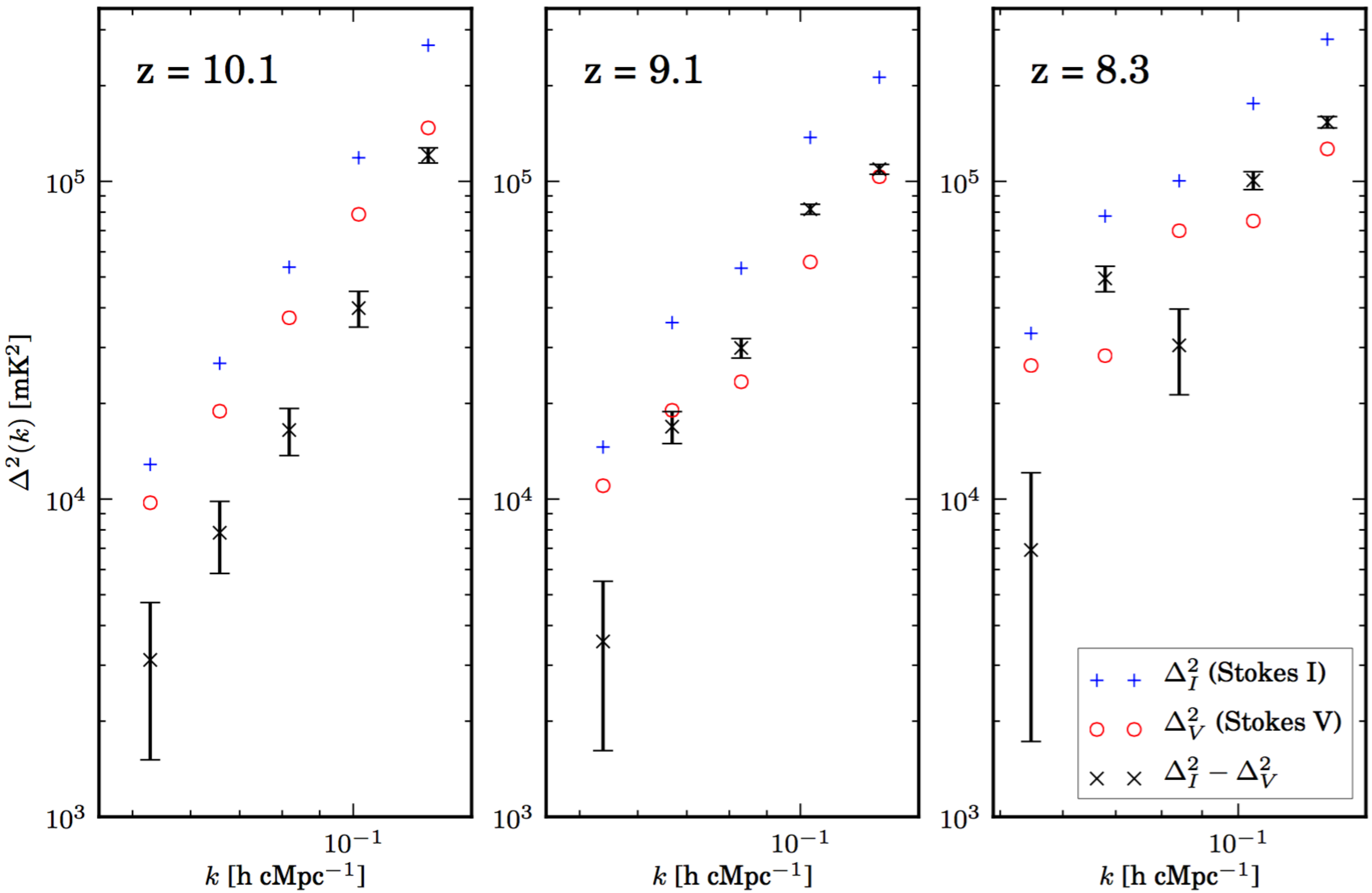


Figure 8. The spherically averaged Stokes I and V power spectra after GMCA for L90490; From left to right are shown the redshift ranges $z = 9.6 - 10.6$, $z = 8.7 - 9.6$ and $z = 7.9 - 8.7$ from left to right, respectively. The mean redshifts are indicated in the panels.

Spherical Power Spectra

- Although we have excess variance, we only give 2-sigma upper limits (incl. excess)
- Without excess variance we would have reached ~(57mK)^2 at z~10 and k~0.05
- We go less deep at higher-frequencies (issues with FG removal ?).

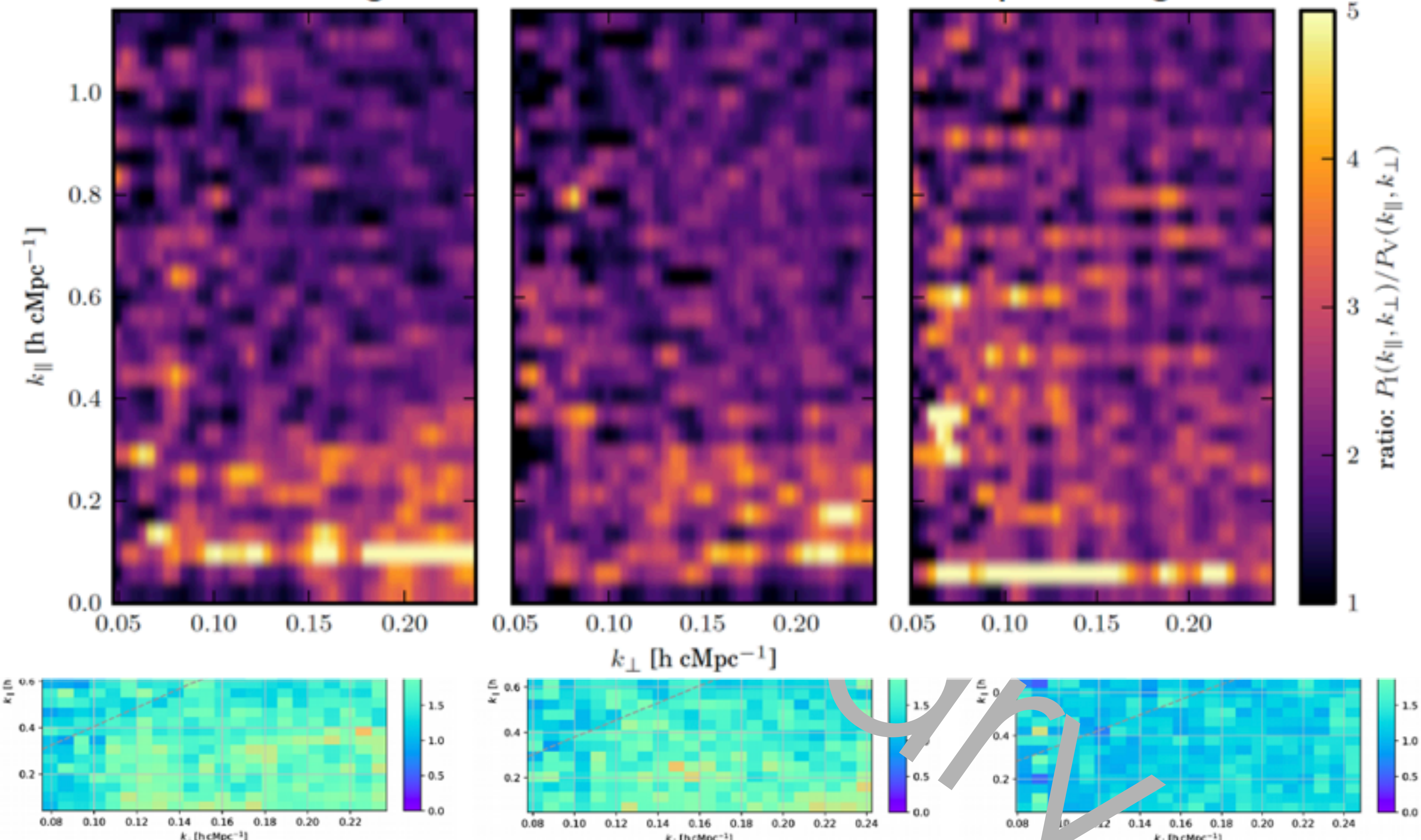
k h cMpc^{-1}	$z=7.9-8.7$ mK^2	$z=8.7-9.6$ mK^2	$z=9.6-10.6$ mK^2
0.053	$(131.5)^2$	$(86.4)^2$	$(79.6)^2$
0.067	$(242.1)^2$	$(144.2)^2$	$(108.8)^2$
0.083	$(220.9)^2$	$(184.7)^2$	$(148.6)^2$
0.103	$(337.4)^2$	$(296.1)^2$	$(224.0)^2$
0.128	$(407.7)^2$	$(342.0)^2$	$(366.1)^2$

Table 3. Δ^2_{21} upper limits at the 2-σ level.

Current power-spectrum results In April 2018

Going ~30-40x deeper…

Same night as in Patil et al. 2017, but with new processing



- Ratio I/V is quite flat; clear of obvious structure.
- Stokes I has r.m.s. ~ 10-20% higher than Stokes V (~thermal noise).
- In some cases RFI or residual (A-team) sources are seen

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!

Cross correlation with other data set

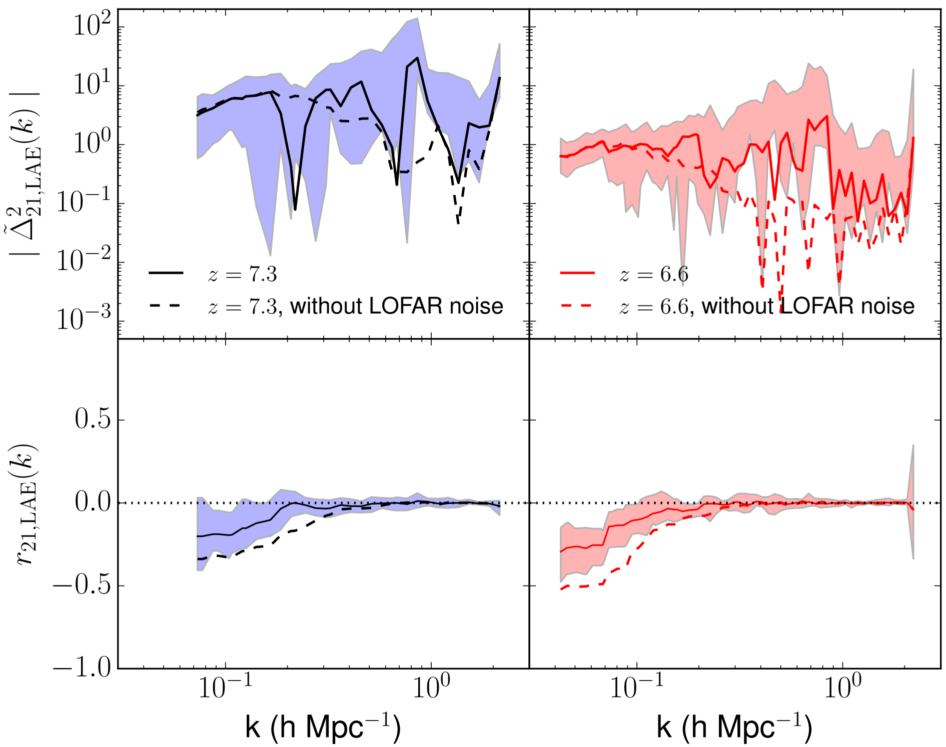
- EoR with CMB. That should be done but not as promising as initially thought.
- EoR with Galaxy surveys
- EoR with other line intensity mapping
- 21 cm forest

Cross Correlation 21cm-LAE surveys

Lidz + 2009, Wiersma+ 2013, Vrbanec+ 2016

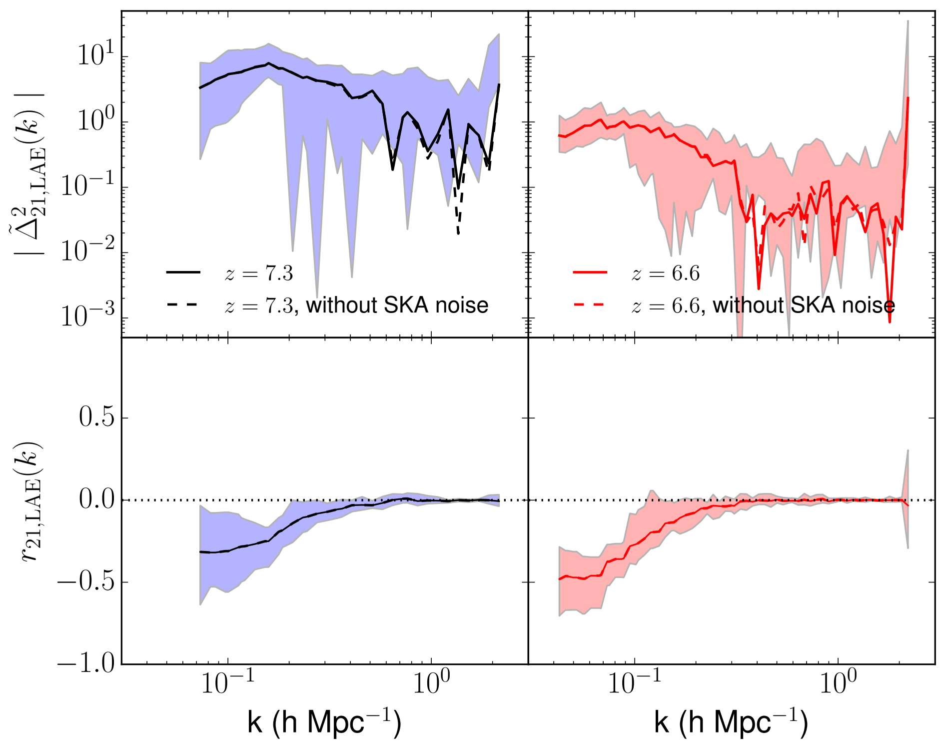
LOFAR with Subaru

2D circularly averaged cross power spectrum



SKA with Subaru

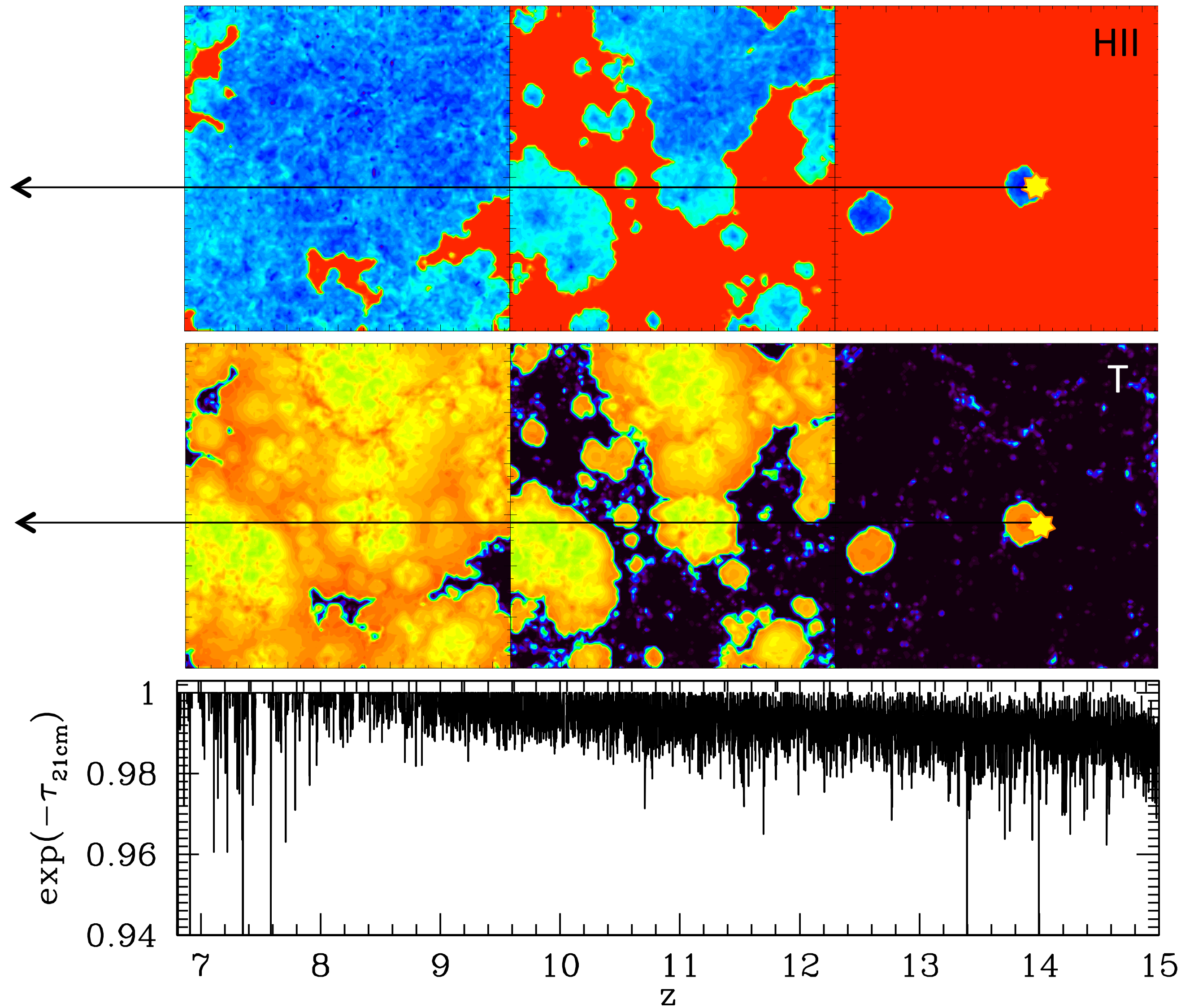
2D circularly averaged cross power spectrum



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

21 cm forest

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

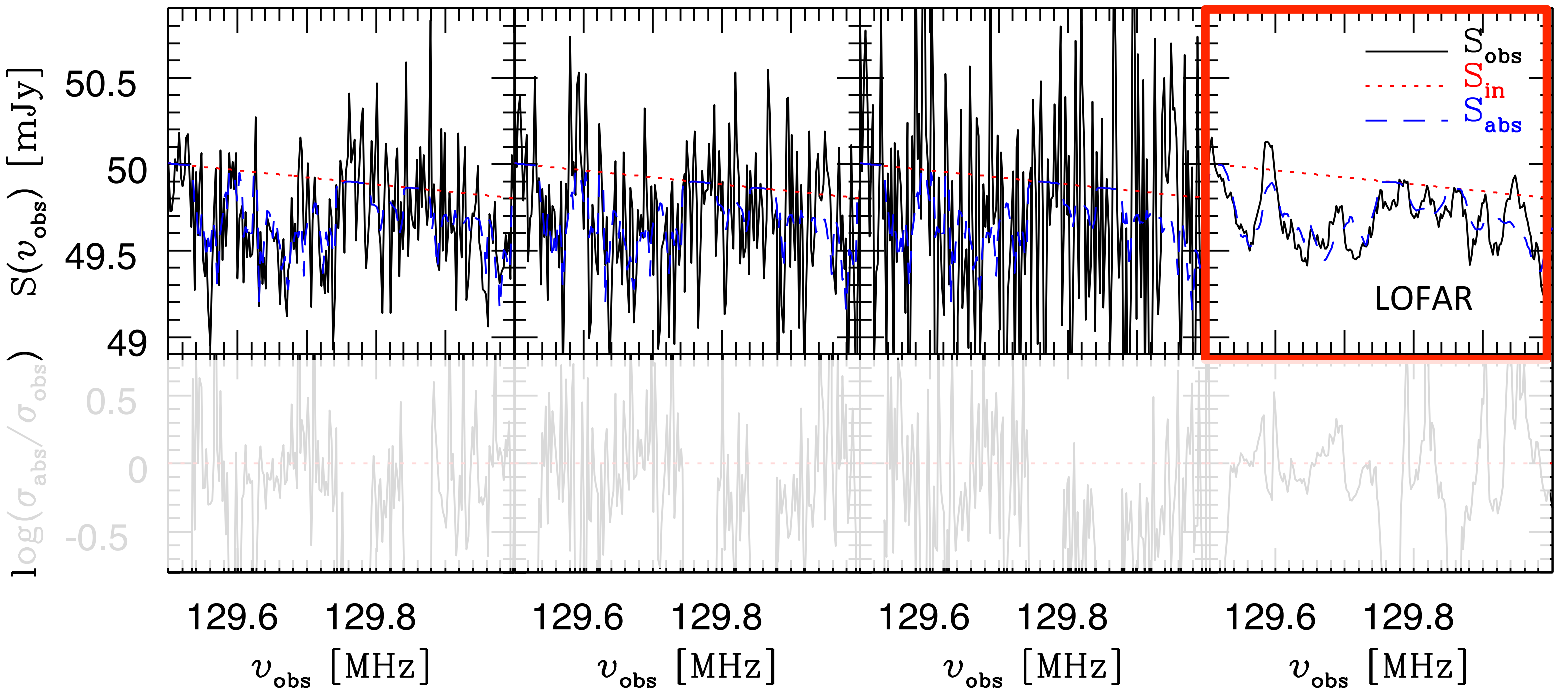


Curtsey B. Ciardi

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

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.

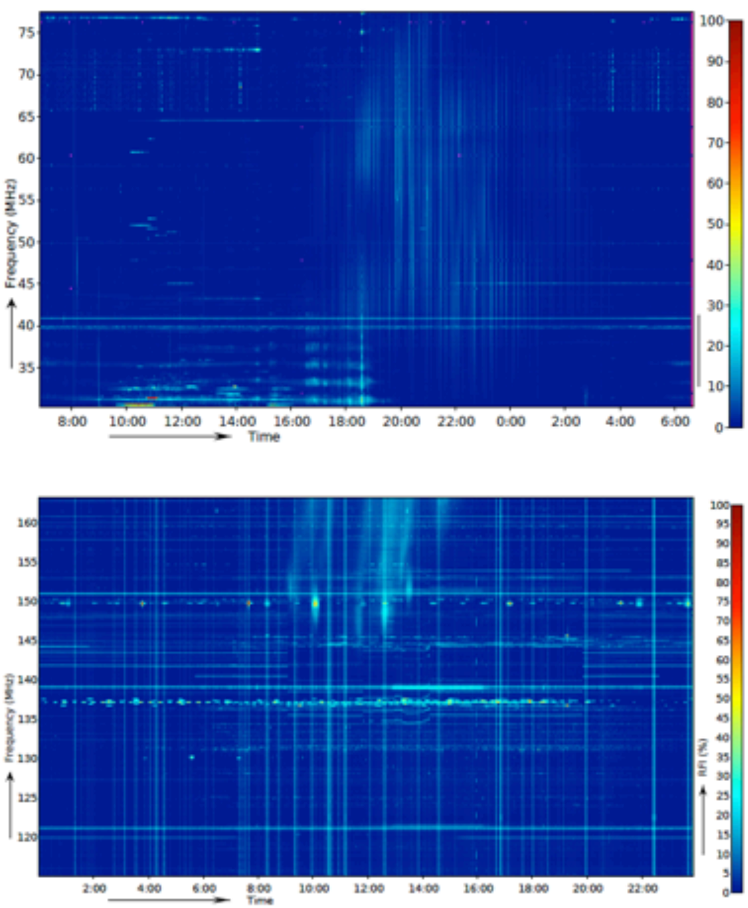
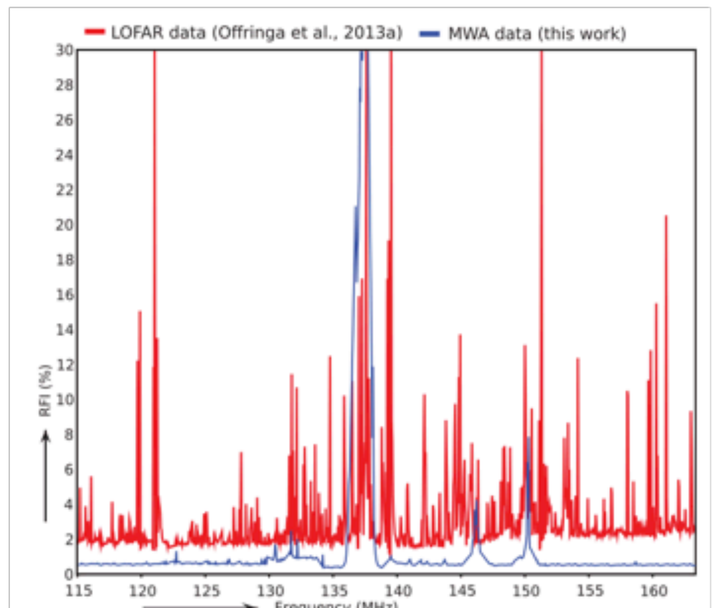


Fig. 10: The dynamic spectra of RFI occupancy during the surveys. Top: LBA, bottom: HBA.

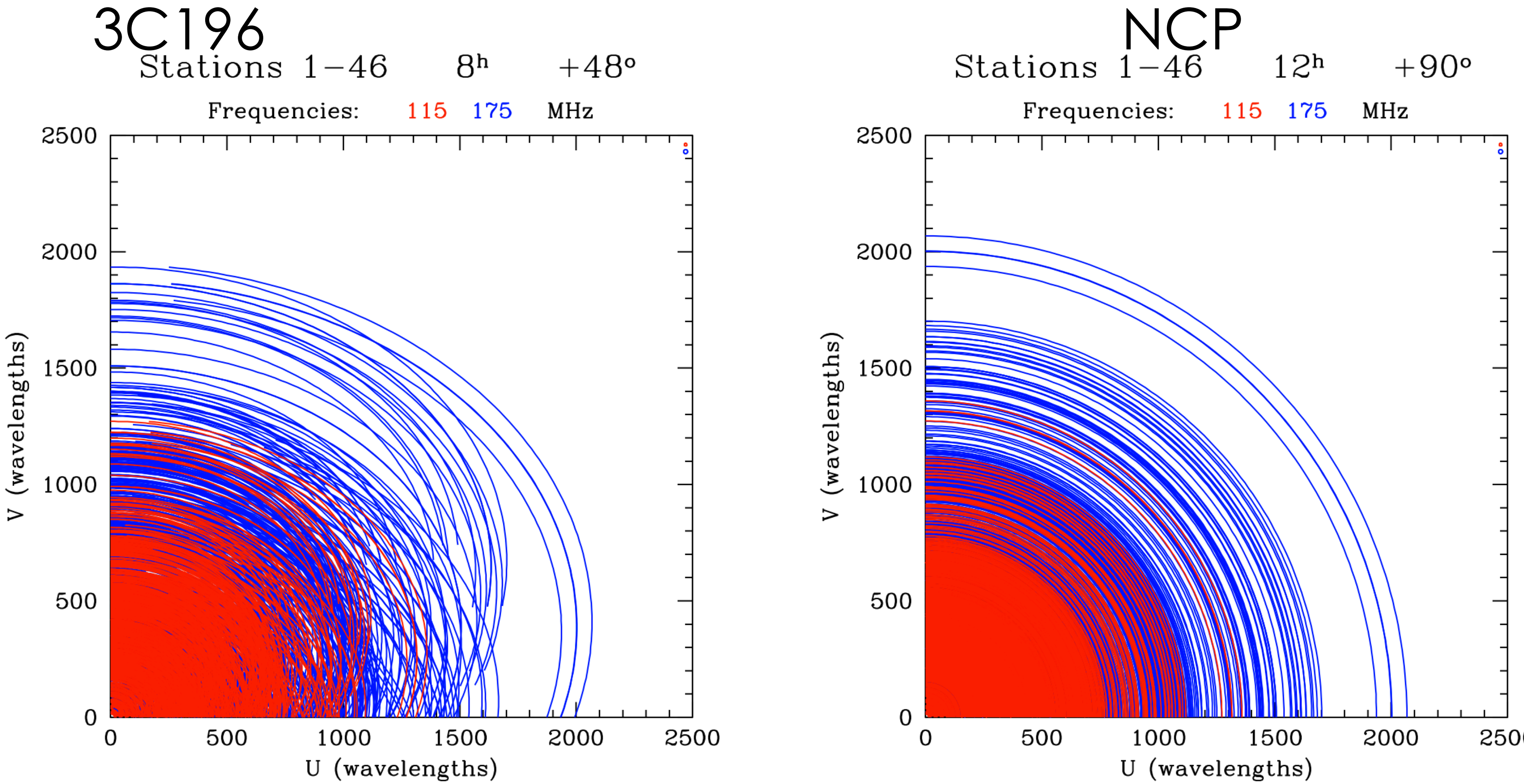
Offringa et al. 2012

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



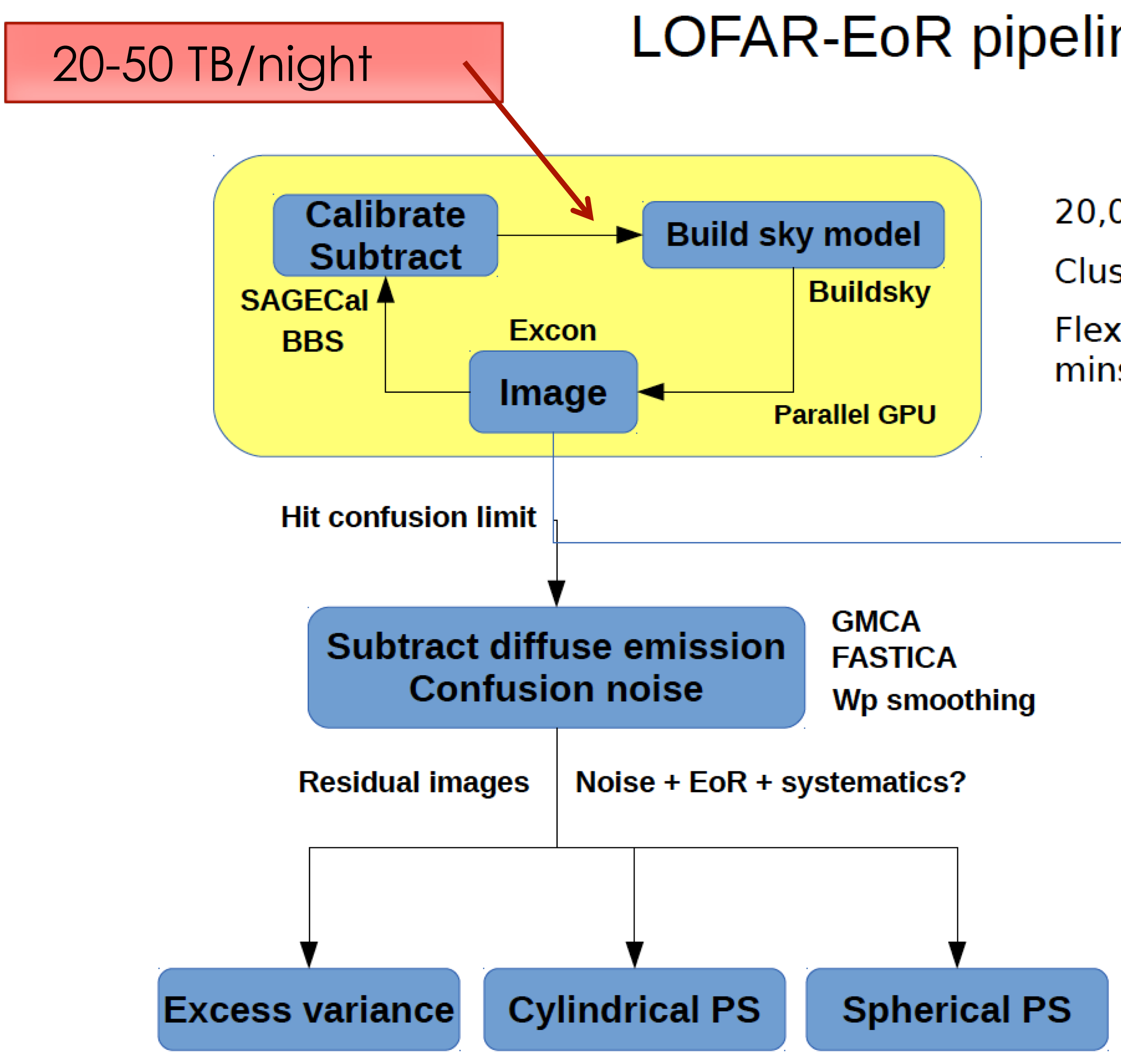
Offringa et al. 2015

Inner uv-coverages for the two EoR windows



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



20,000 component sky model

Clustered in ~ 100 directions

Flexible solution interval 5-20 mins

Galactic polarization

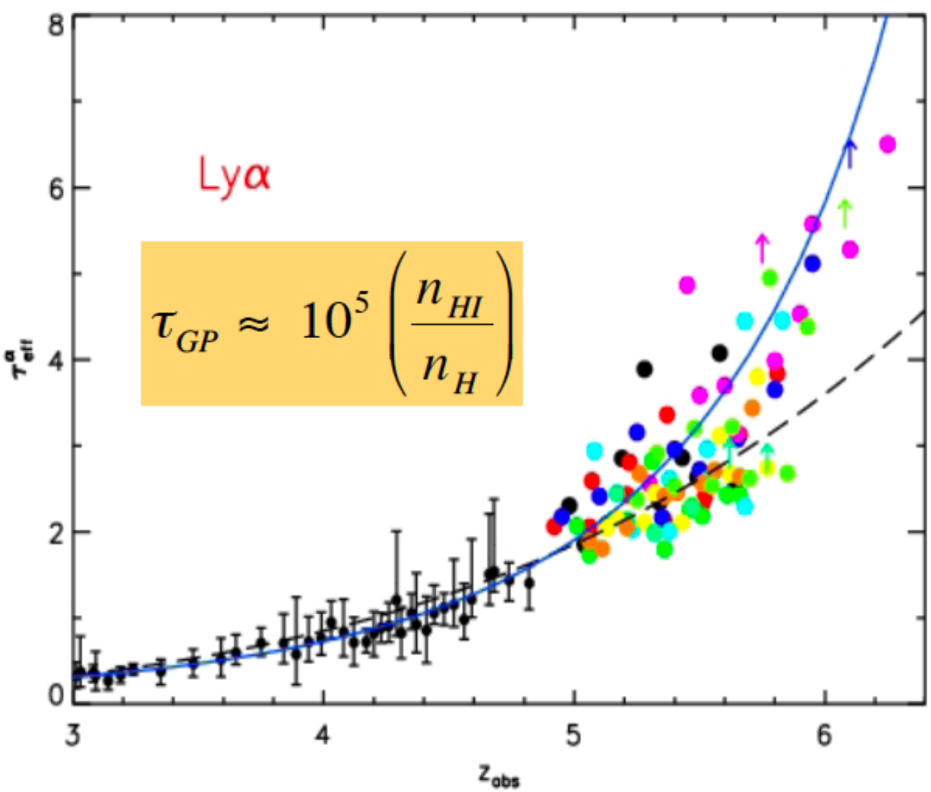
Ionospheric science

Polarized radio galaxies

Finding steep spectrum sources?

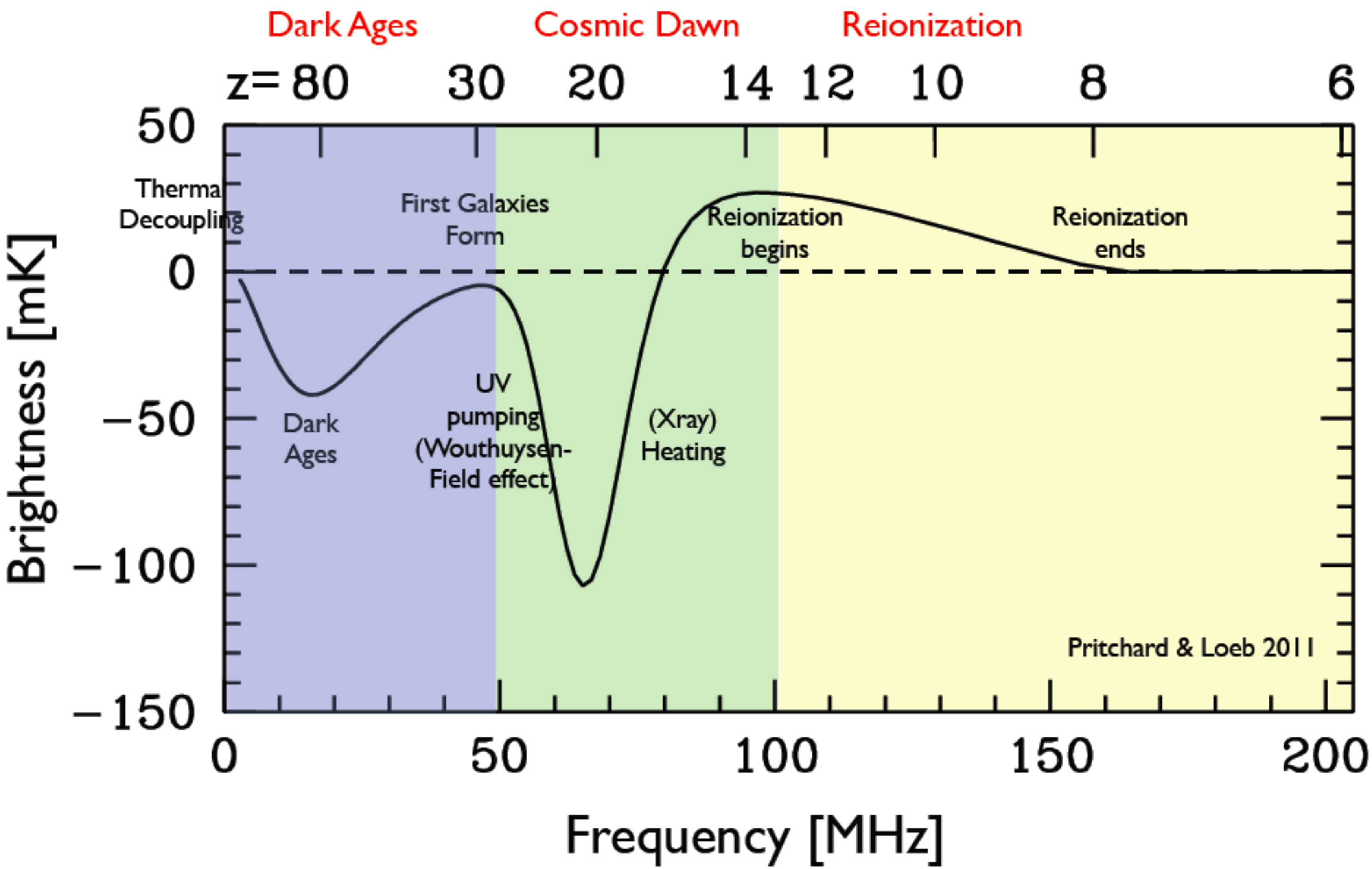
Fig. Harish Vedantham

The end of the reionization process



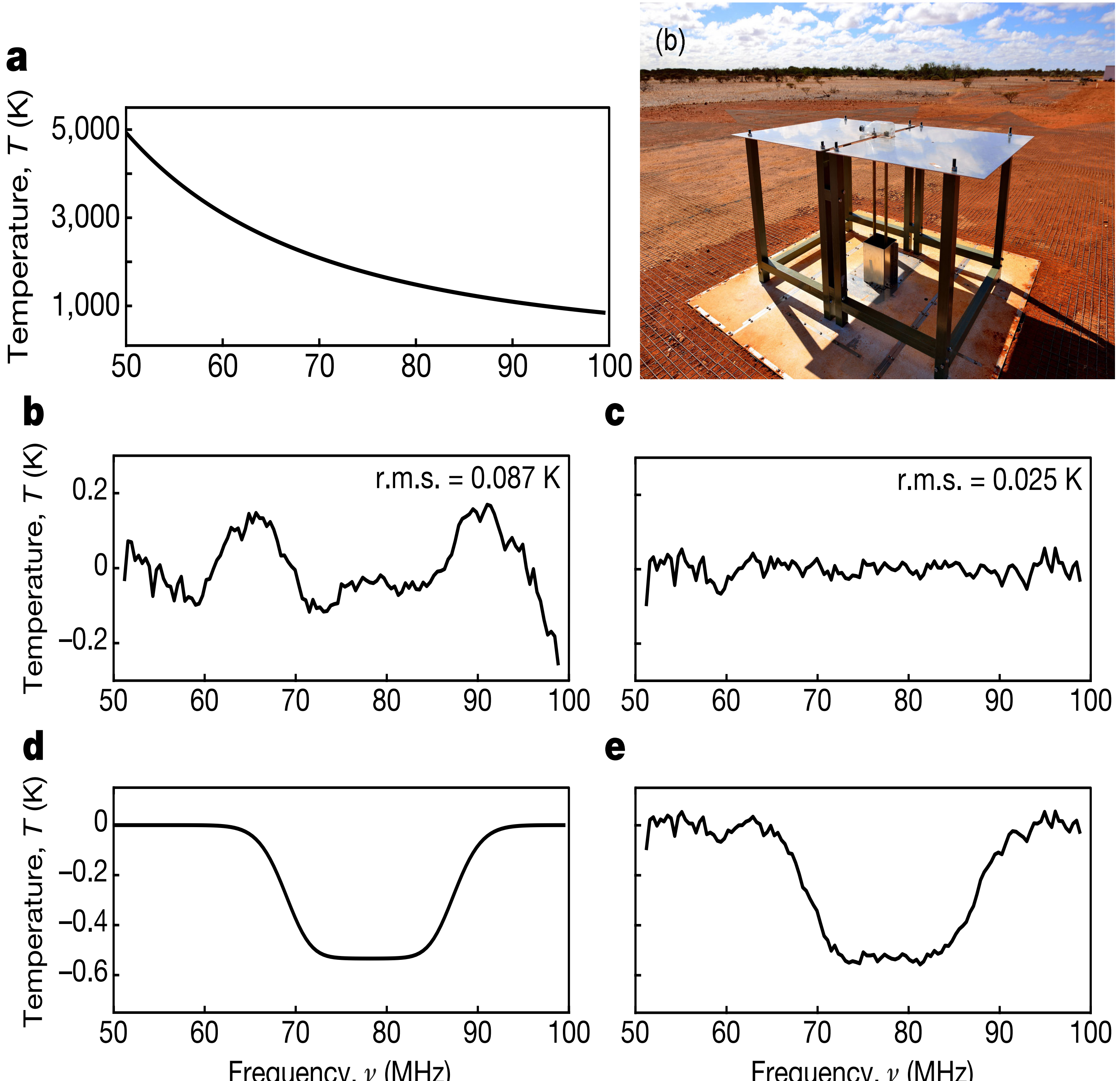
- The Lyman-alpha forest: At z<6 he Universe is completely ionized
- The Universe has completed its ionization by redshift 6: SSDS quasars (however, some, e.g., Mesinger 2009, still claim it is still about 10% neutral)

The Global evolution of T_s



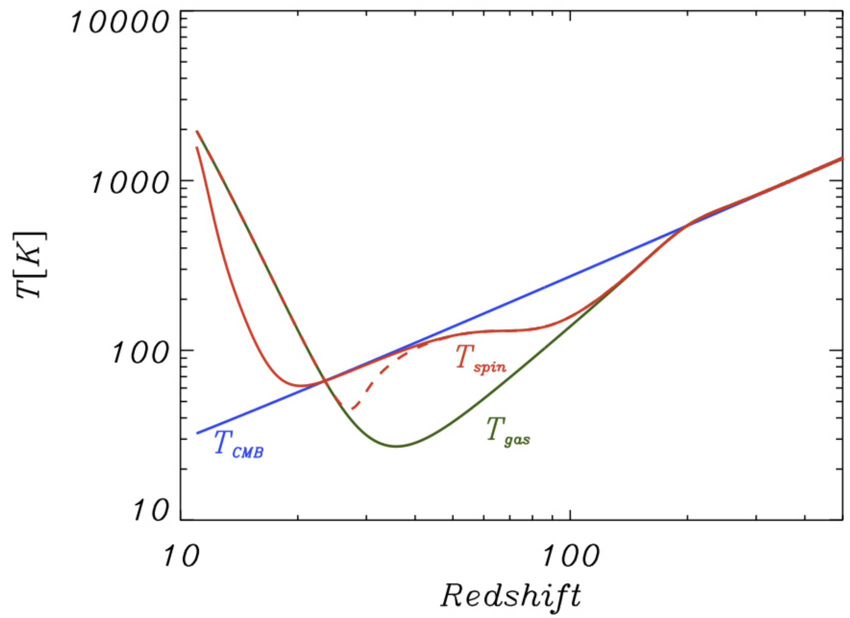
The EDGES result

Bowman+ 2018



How to explain this?

$$1-\frac{T_{CMB}}{T_{spin}}$$

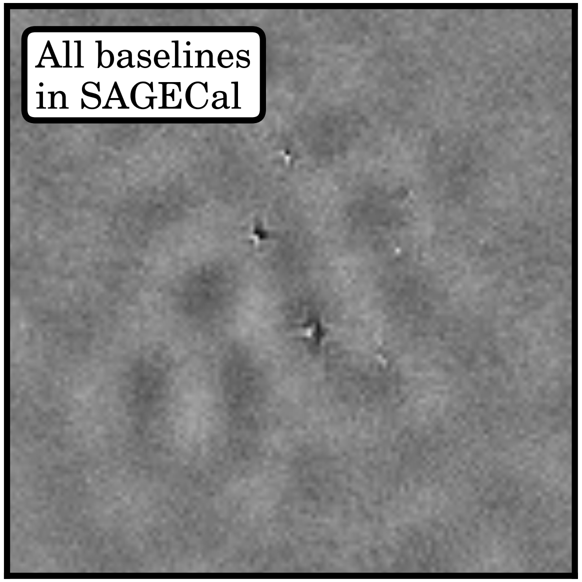


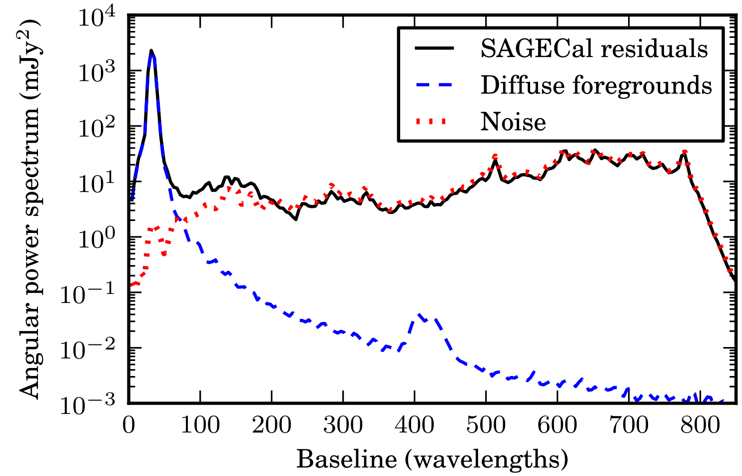
- Interacting dark matter! (Barkana 2018) lowers the gas and spin temps.
- Earlier decoupling of the gas temp from the CMB.
- Higher T_{γ} from radio sources.

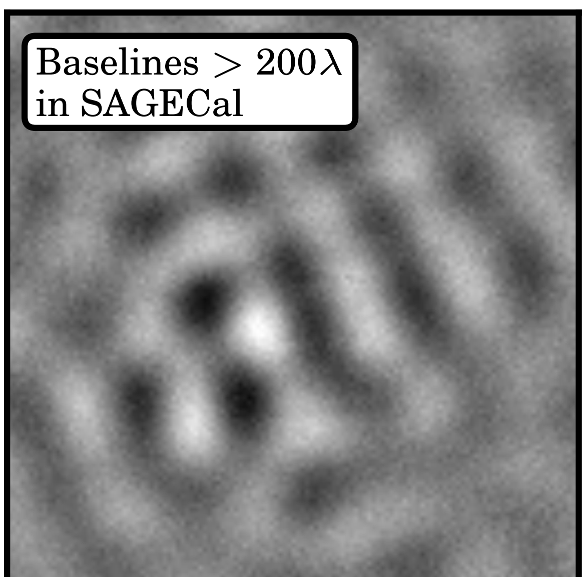
All of these models are very problematic.

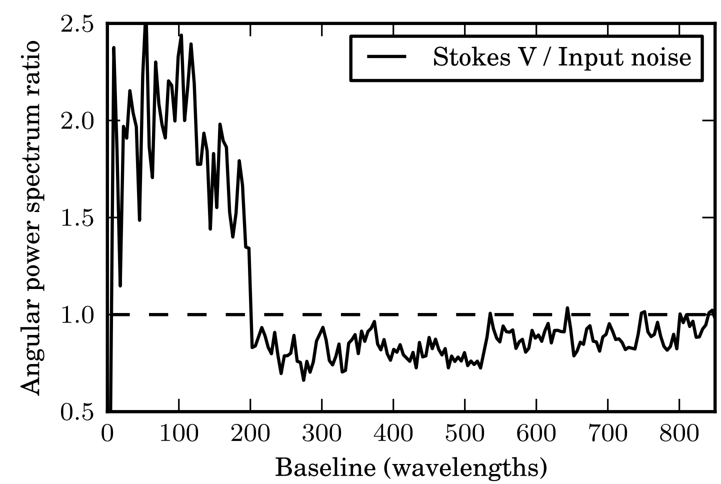
Or yet unknown systematic.

Calibration, suppression, leverage and excess noise









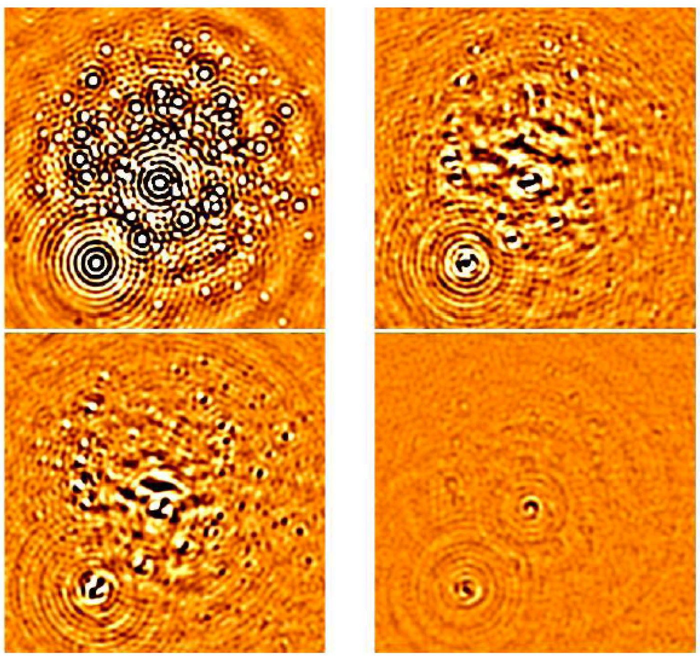
Patil et al. 2016

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 !

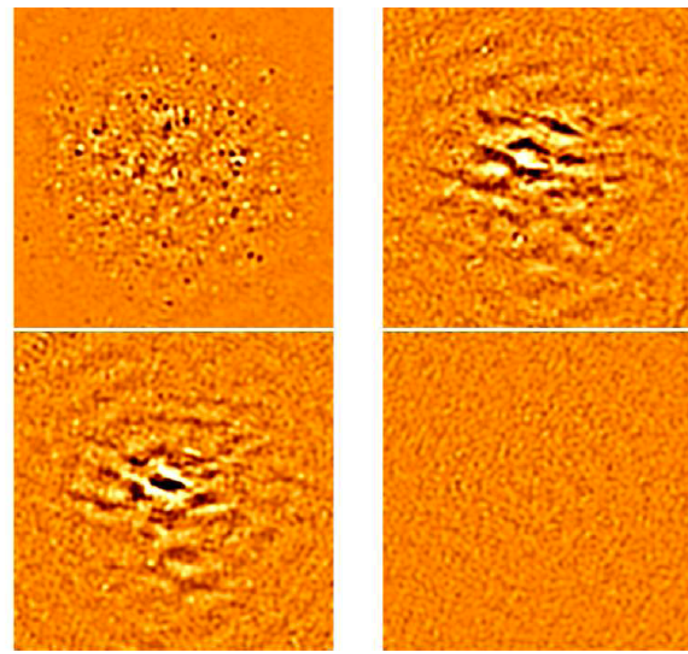
Diffuse polarization then preserved in calibration → EoR signal will be preserved too !



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

One night
60 MHz

10' PSF

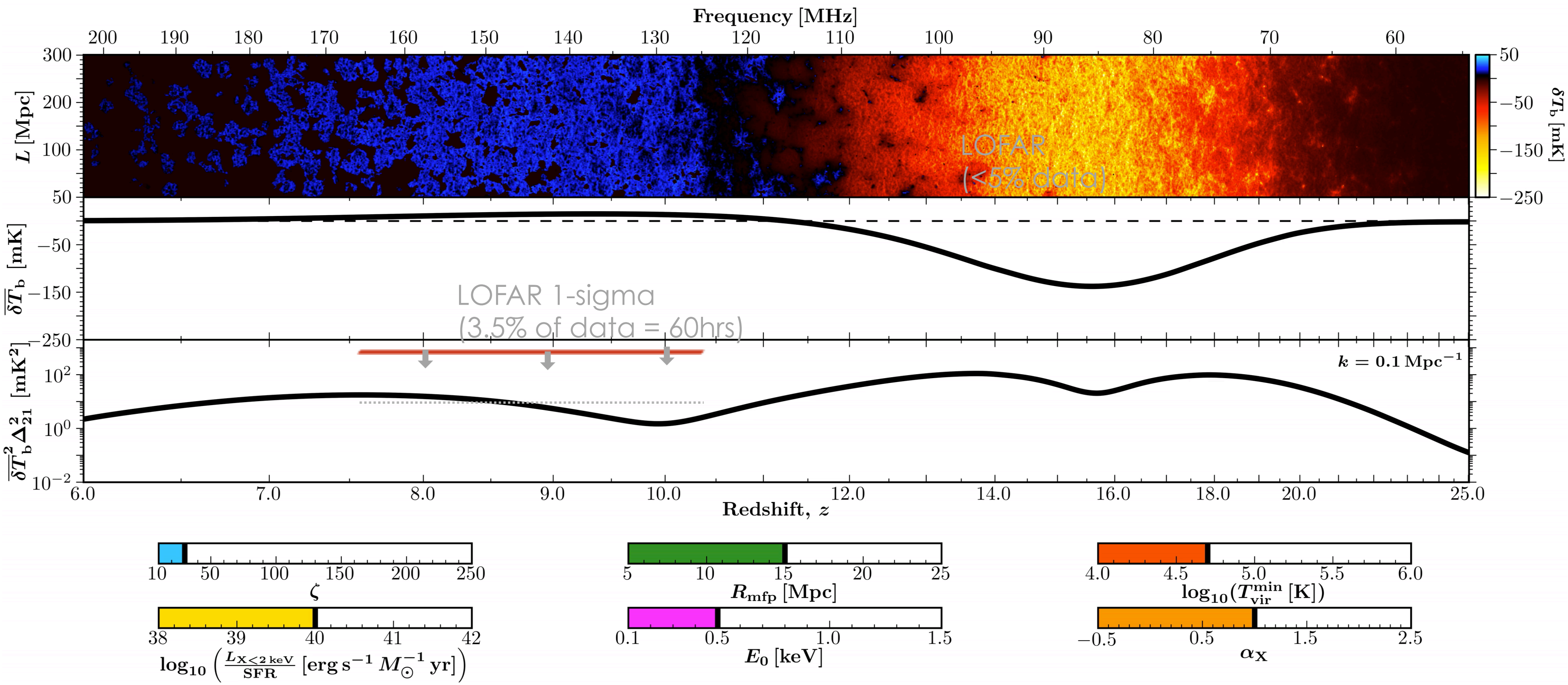


I,Q,U,V calibration using baselines > 250 wavelengths

Limits on the Cosmic Dawn

21CMFAST - varying the X-ray heating luminosity.

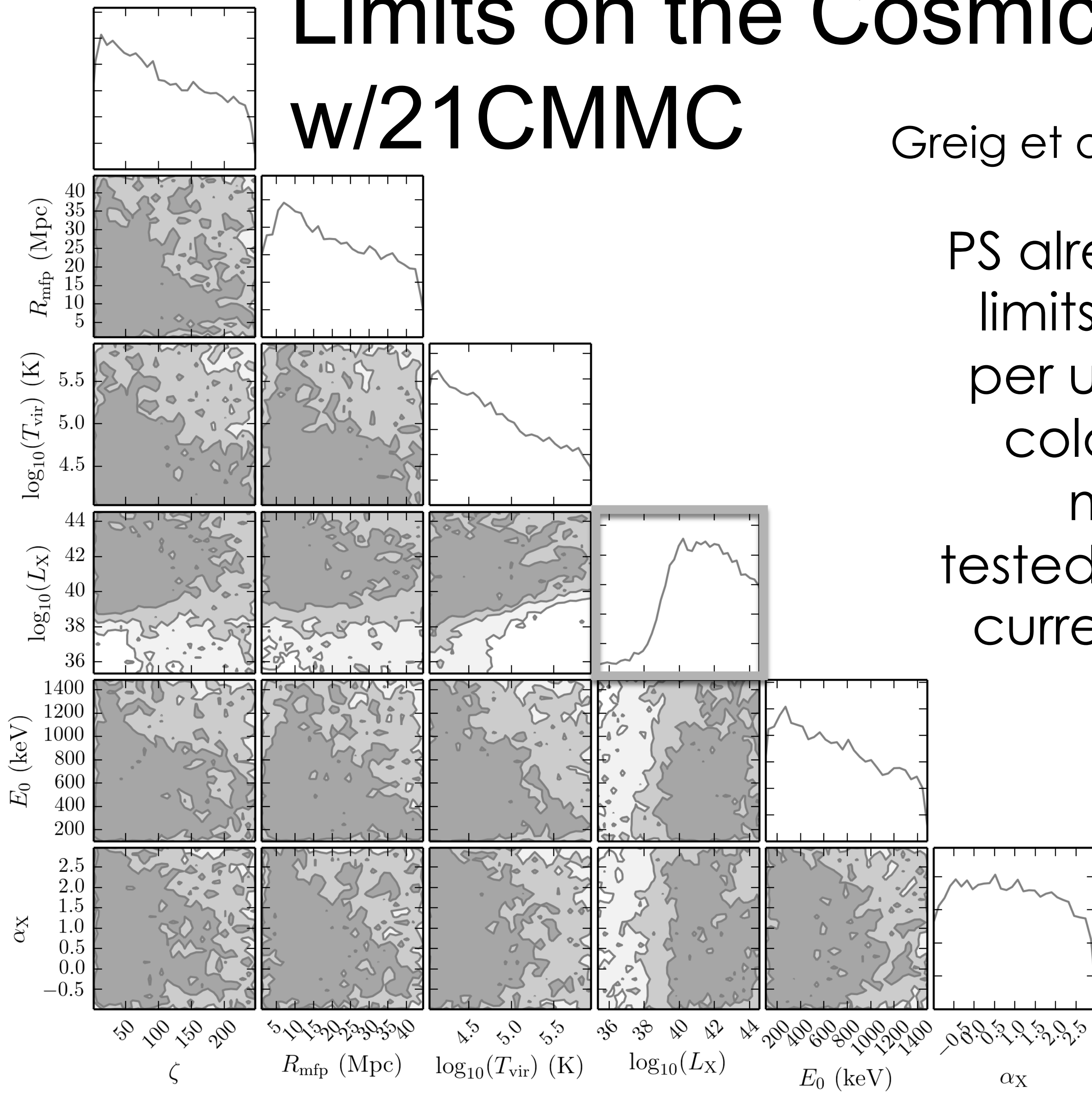
Credit: Mesinger & Greig



Note: Excess noise (I over V) is incoherent (averages away): we assume it drops in the cross-variance and plot the 1-sigma upper limits (in 21CMMC, we double the errors)

Limits on the Cosmic Dawn w/21CMMC

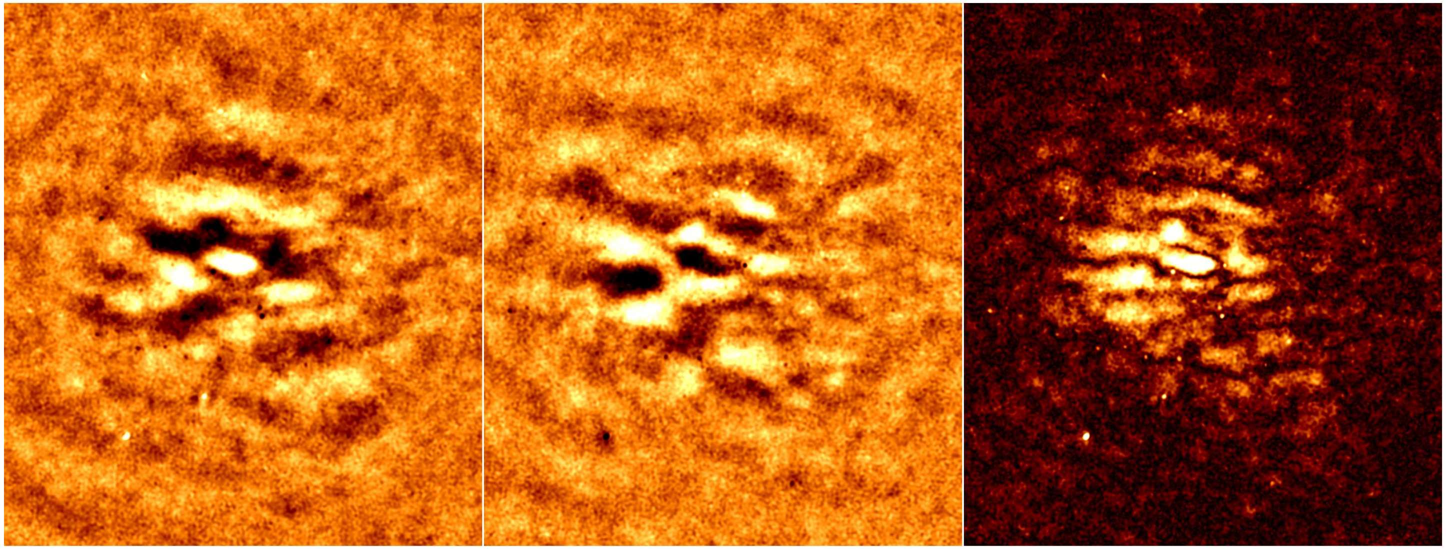
Greig et al. 2015, 2017



PS already seems to limits X-ray heating per unit SFR; hence cold IGM and CD models can be tested based on our current z=8, 9,10 PS limits.

(w/help of Brad Greig)
(1) no tau constraint,
(2) co-eval, no light cone

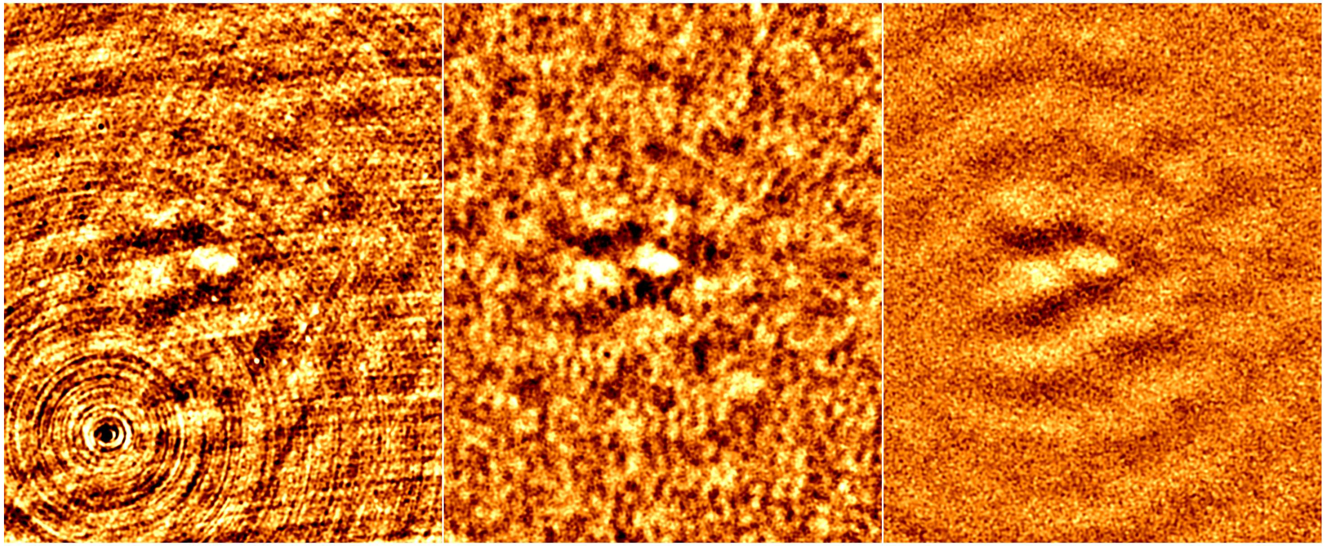
Include diffuse model for Q & U to calibrate the data



(left) Q (mid) U (right) P, 8×8 deg.

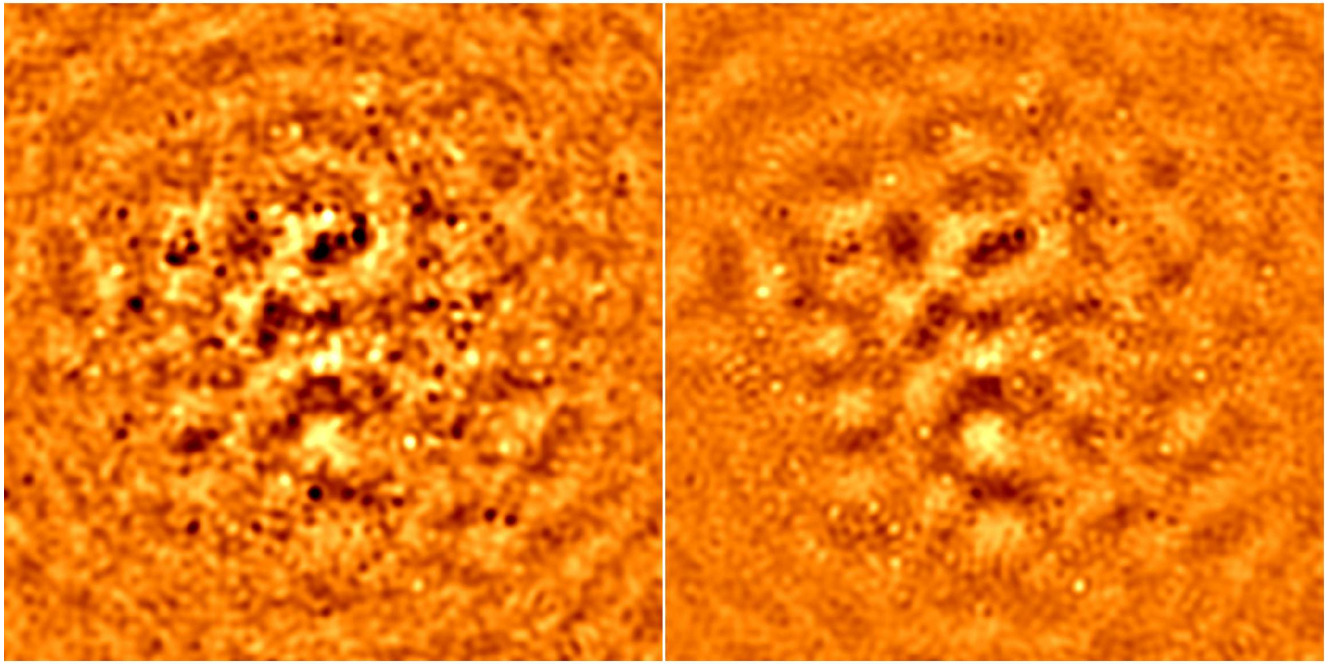
Yatawatta 2017

Stokes Q



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

Stokes I



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

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