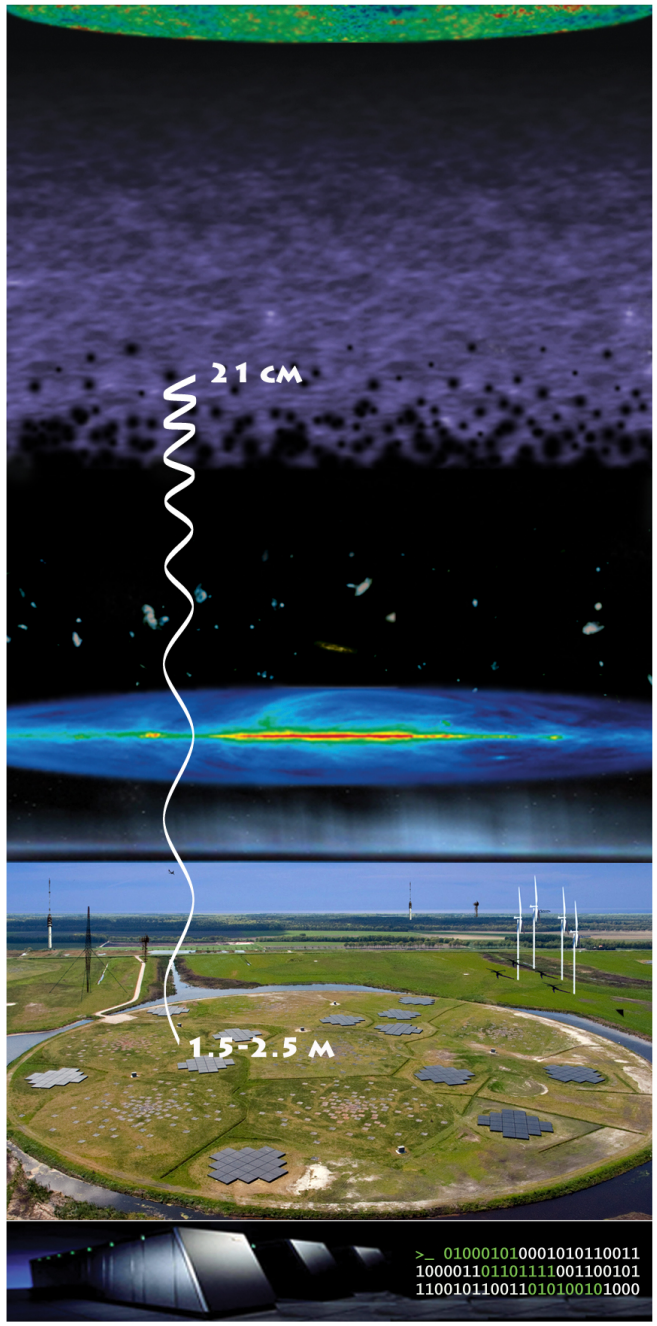
The LOFAR-EoR project: Analysis of the NCP data

Saleem Zaroubi, on behalf of the EoR team
Kapteyn Astronomical Institute
University of Groningen

Projects

- Simulations:
  - PPACE4LOFAR
  - TRAPHIC
  - CRASH
  - BEARS
    - Simulations …. Models and comparisons.
- Analysis pipeline
  - Library of simulations
  - Develop models based on these Libraries for various statistics.
- Other probes
  - Forest
  - Cross-correlations



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

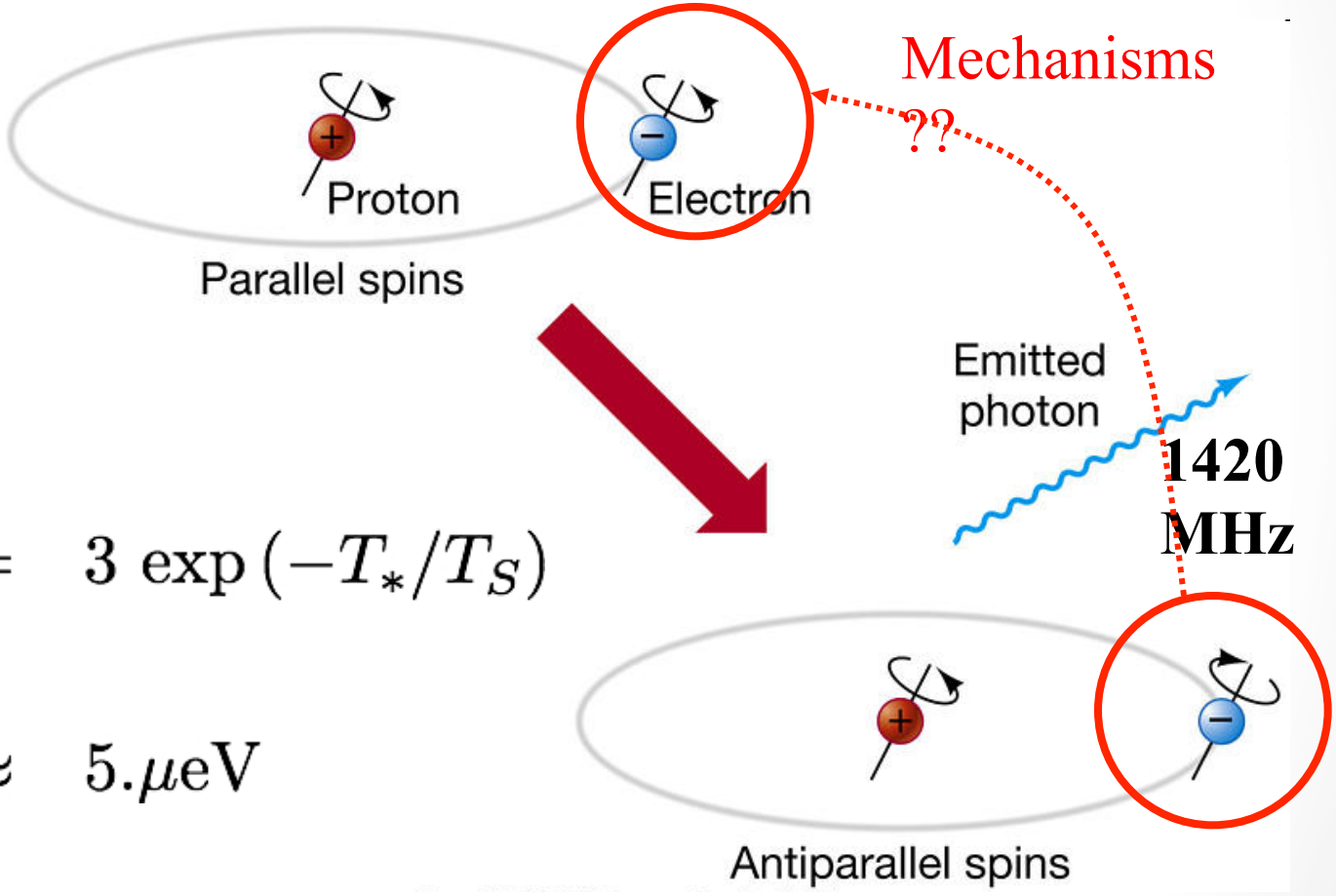
0.2 ms

The LOFAR telescope core stations in the Netherlands

t = 0 s

Supercomputer BlueGene

21-cm Physics

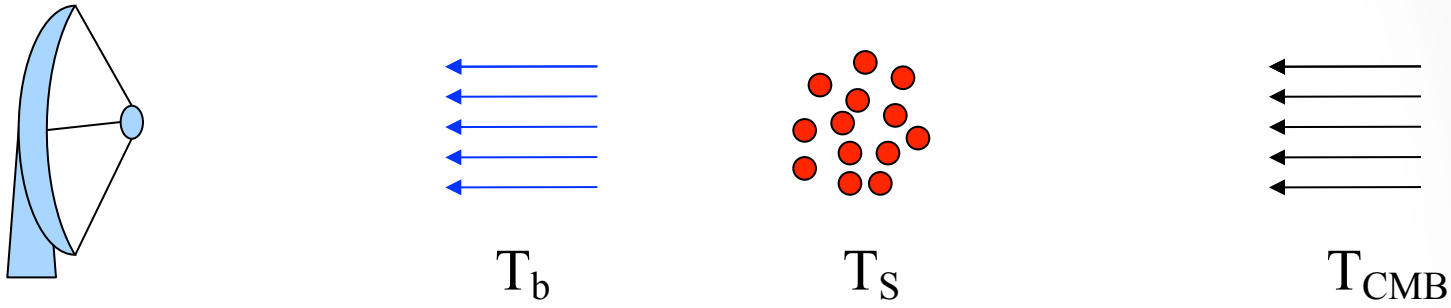


$$\frac{n_1}{n_0} = 3 \exp\left(-T_*/T_S\right)$$

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

Lifetime of ~10 Myrs

δT_b, The Brightness Temperature



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

Astrophysics

Cosmology

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

LOFAR

MWA

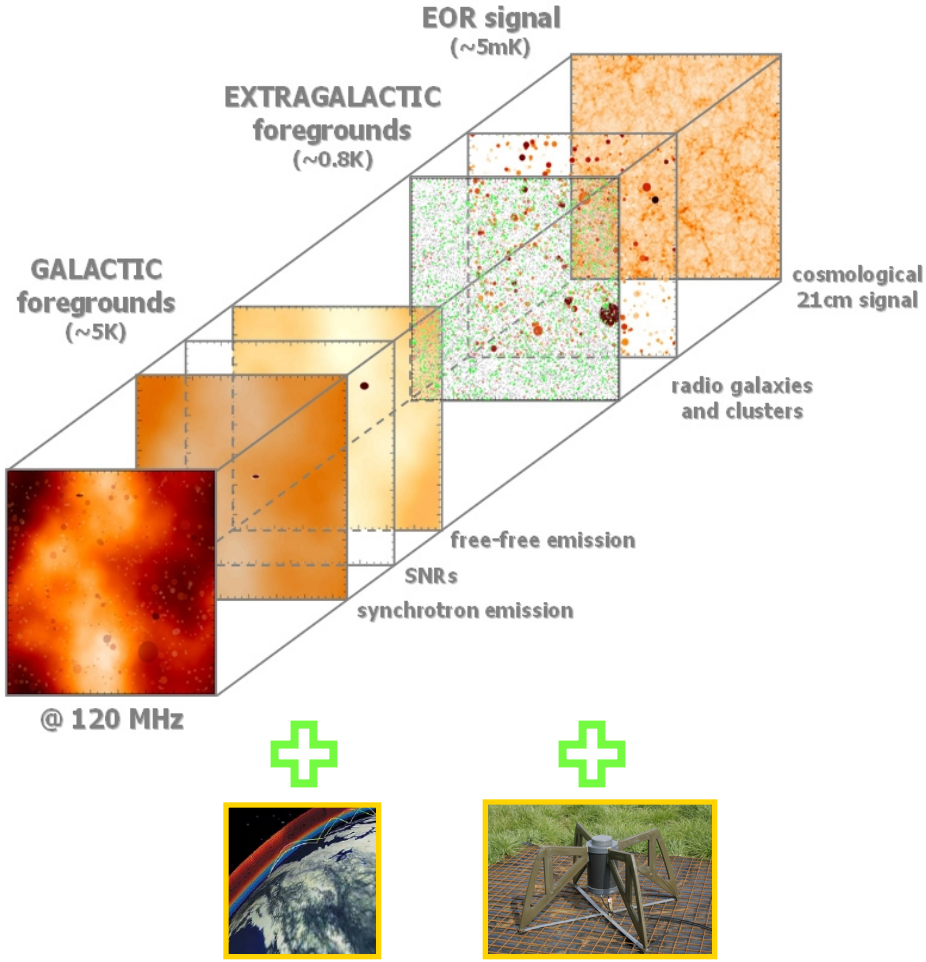
PAPER

GMRT

SKA

21CMA

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

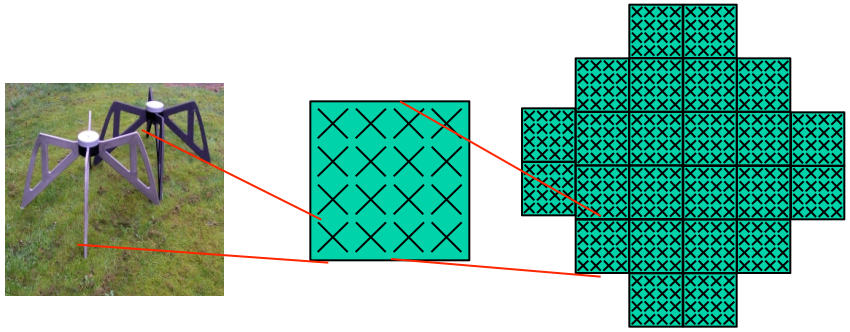
The LOFAR case

The LOFAR observatory

- **LBA** (10) 30 - 90 MHz
- isolated dipoles

HBA 115 - 240 MHz

tiles (4x4 dipoles)



Core	2 km	23+ stations
NL	80 km	18+ stations
Europe	>1000 km	8+ stations

Total # of HBA dipoles: ~ 50000.

Timeline:

1. Official opening: June 2010
2. Data for our project starts: Dec. 2012
3. First results (hopefully) 2014

Main Science targets

1. ‘Global’ evolution of the EoR: Variance as a function of redshift.
2. Power spectrum at various redshifts
3. High order statistics
4. Imaging!!

5. Cross-correlation with other probes
6. The 21 cm forest

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.
- Etc.

LOFAR EoR Windows

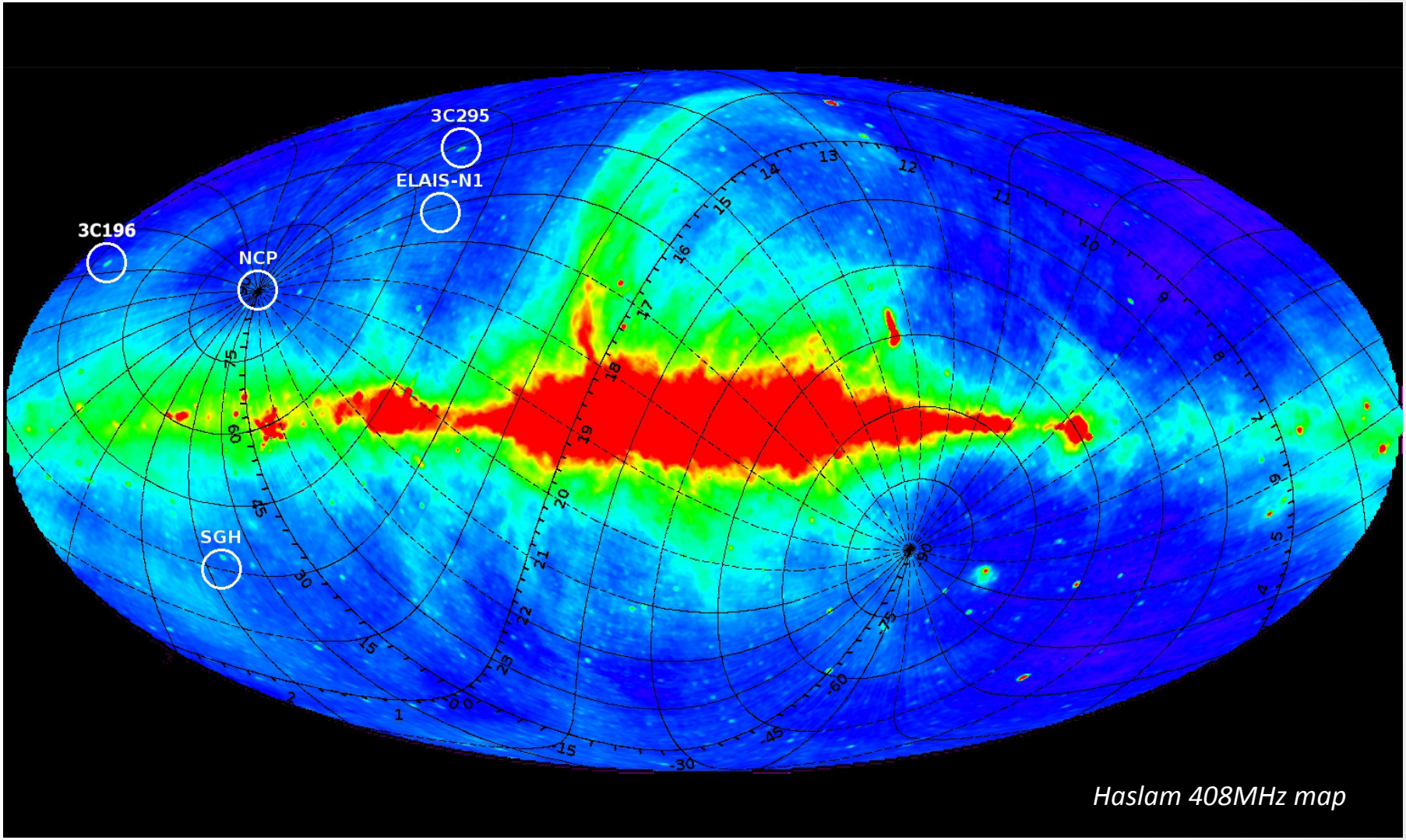
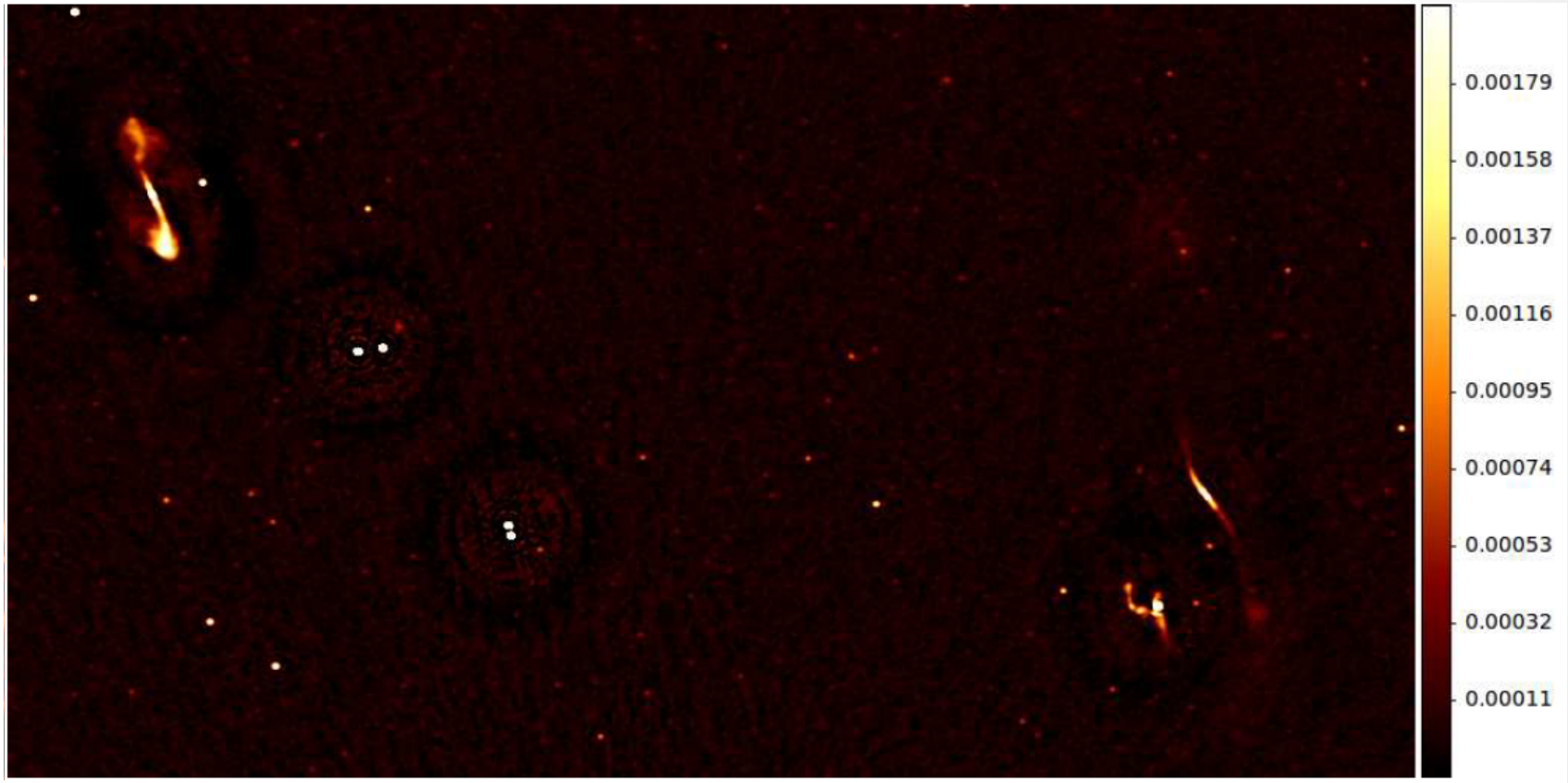


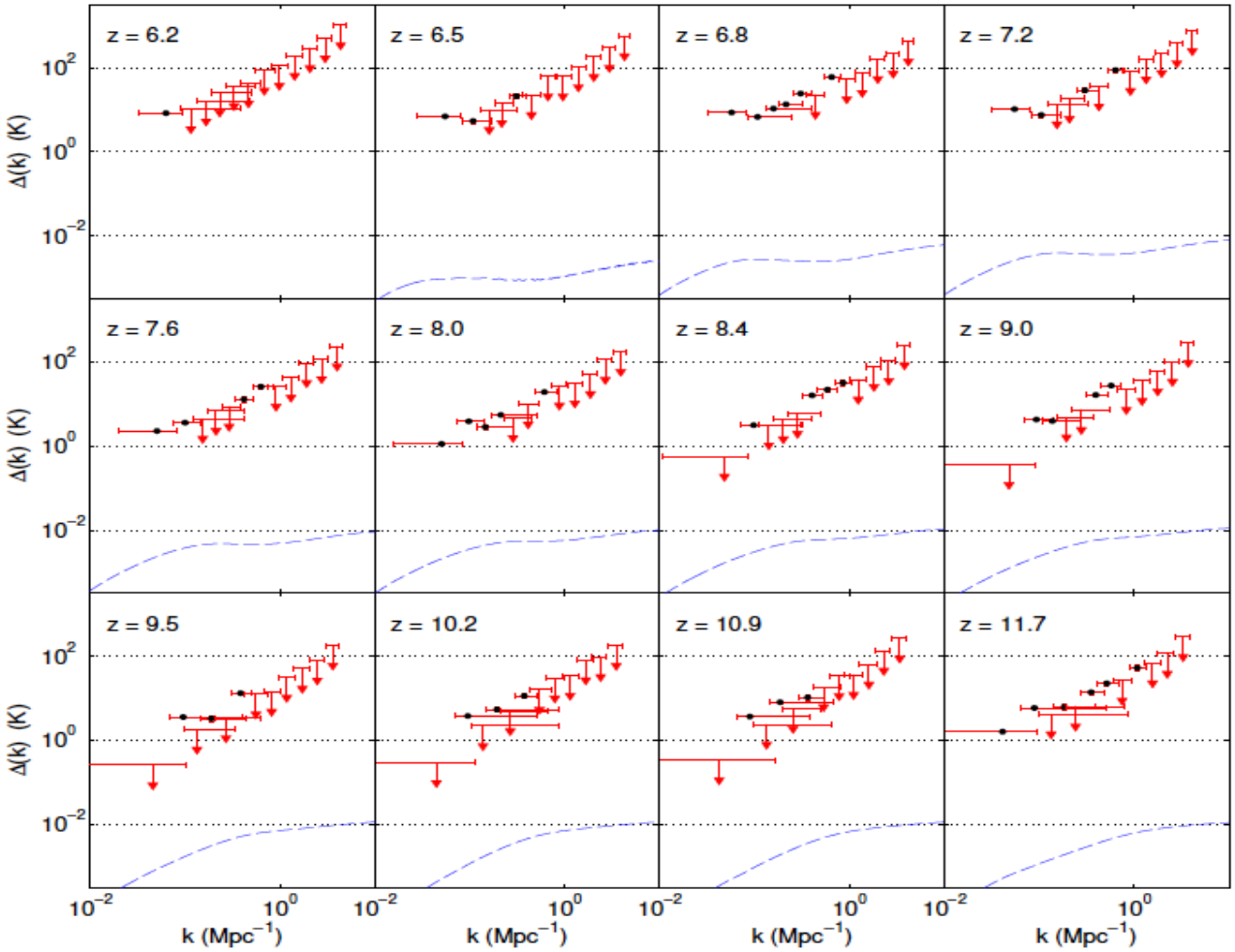
Image quality: NCP

SAGECAL



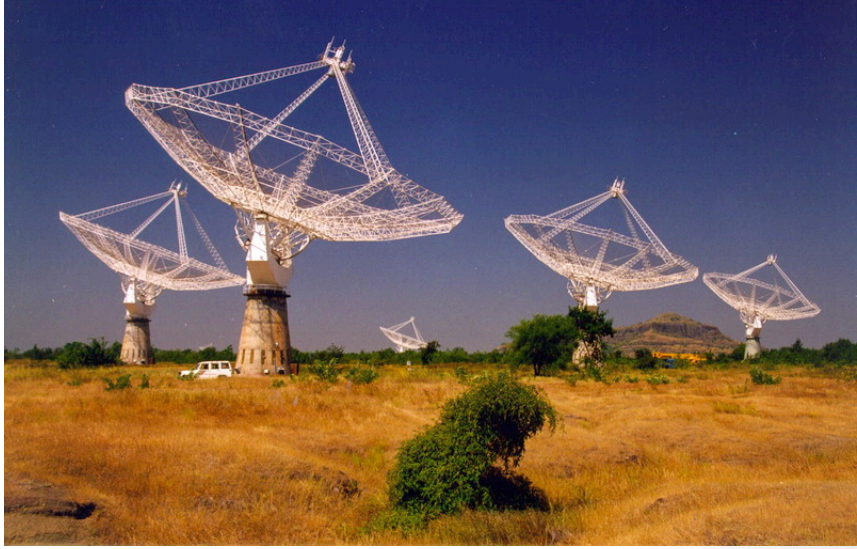
25-30 μJy, 6″ PSF, Dec 2012-Feb 2013, 80 km array, 0.5×0.25 degrees

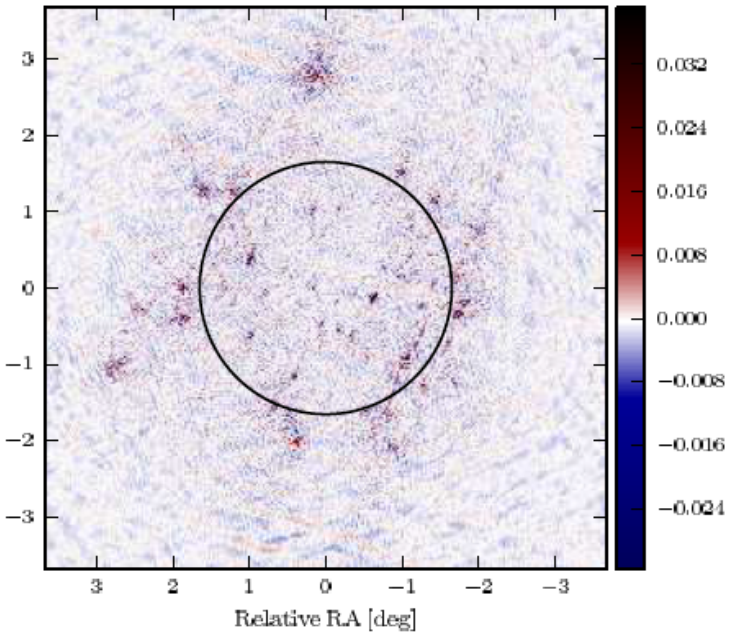
MWA current results

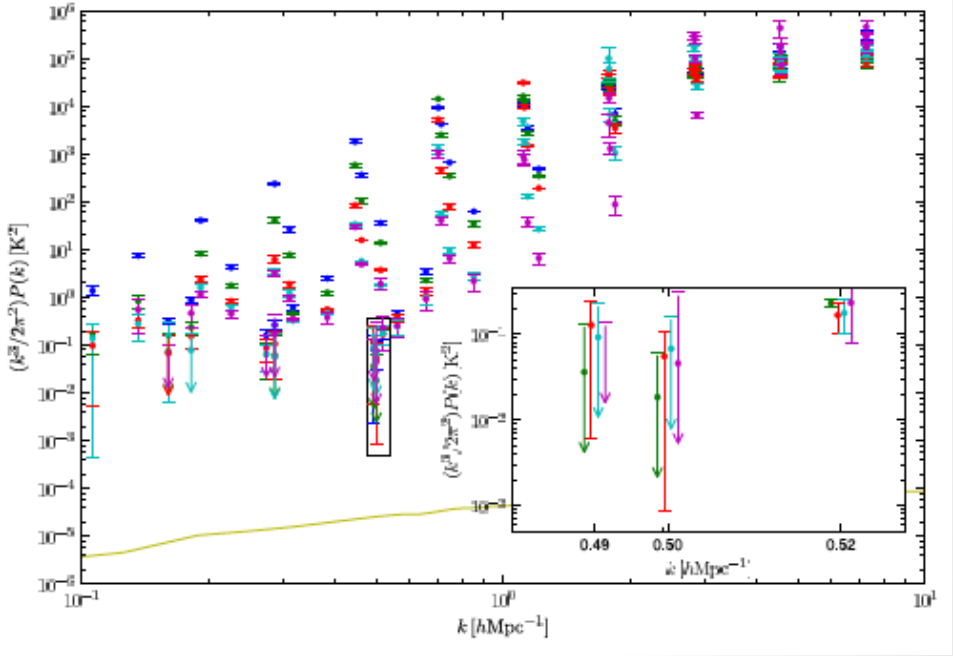


Dillon et al 2013

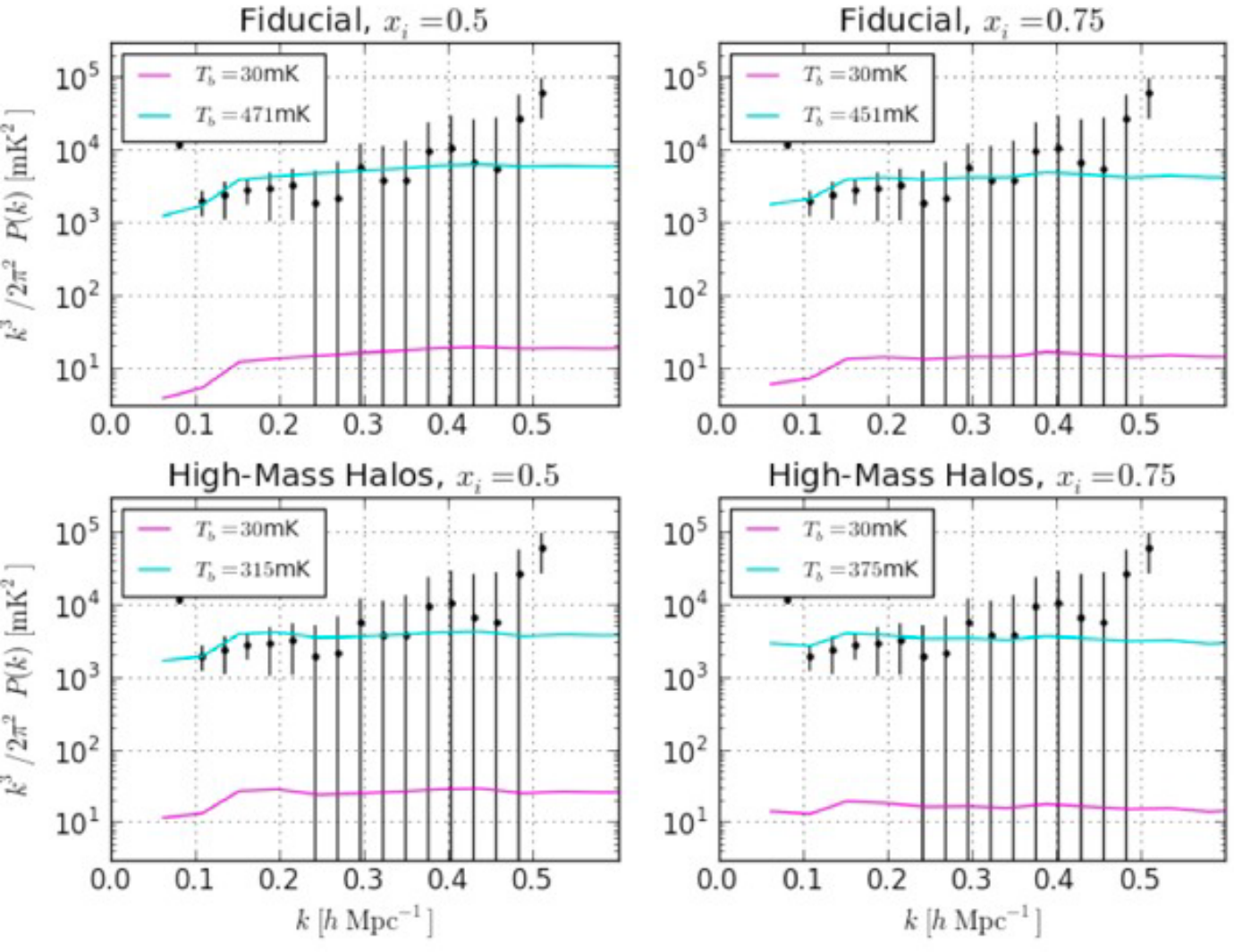
GMRT results



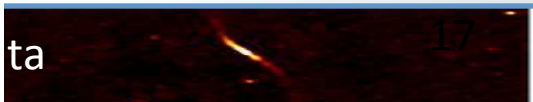




Current Results

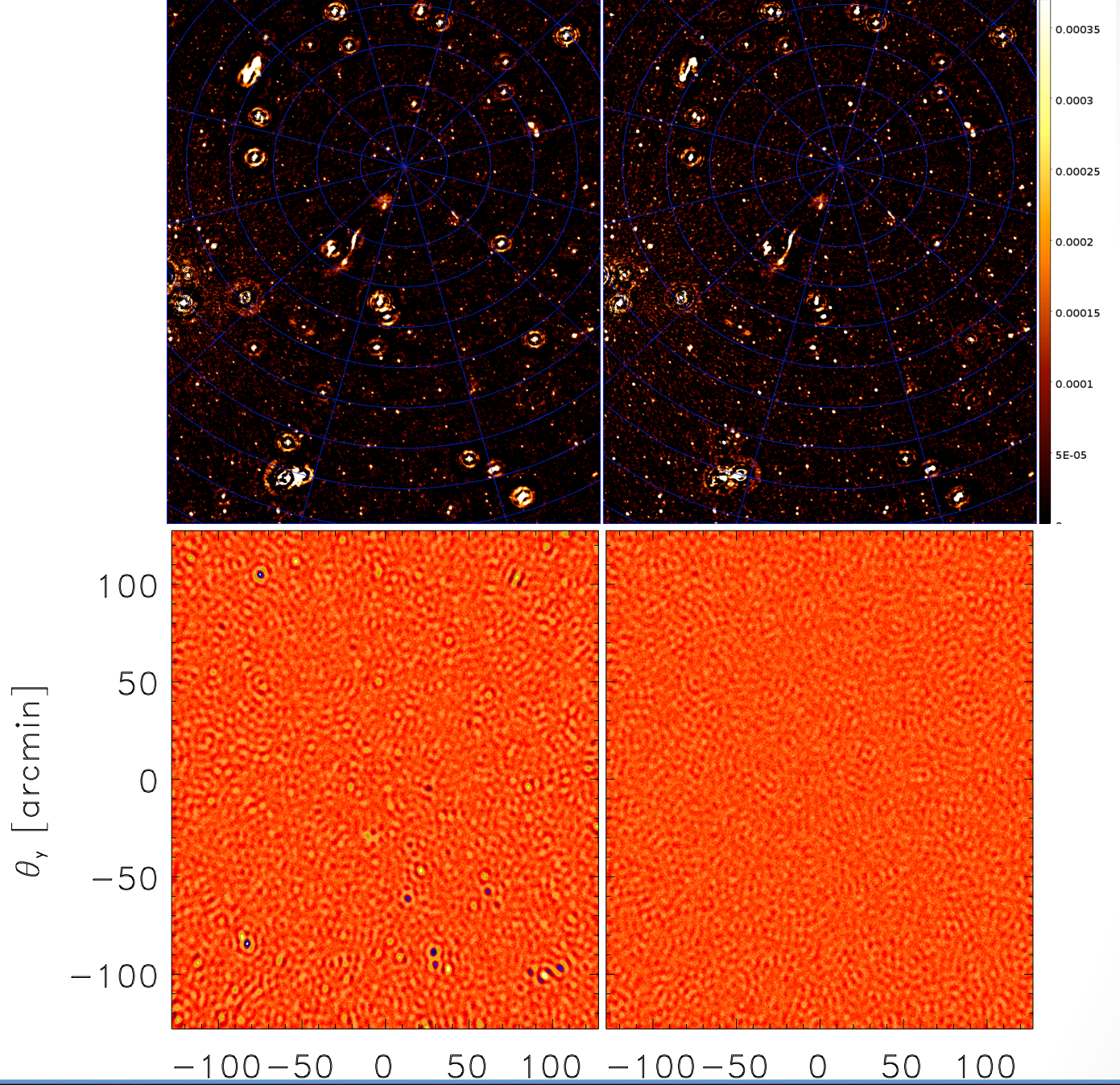


Parsons et al 2013



The NCP data

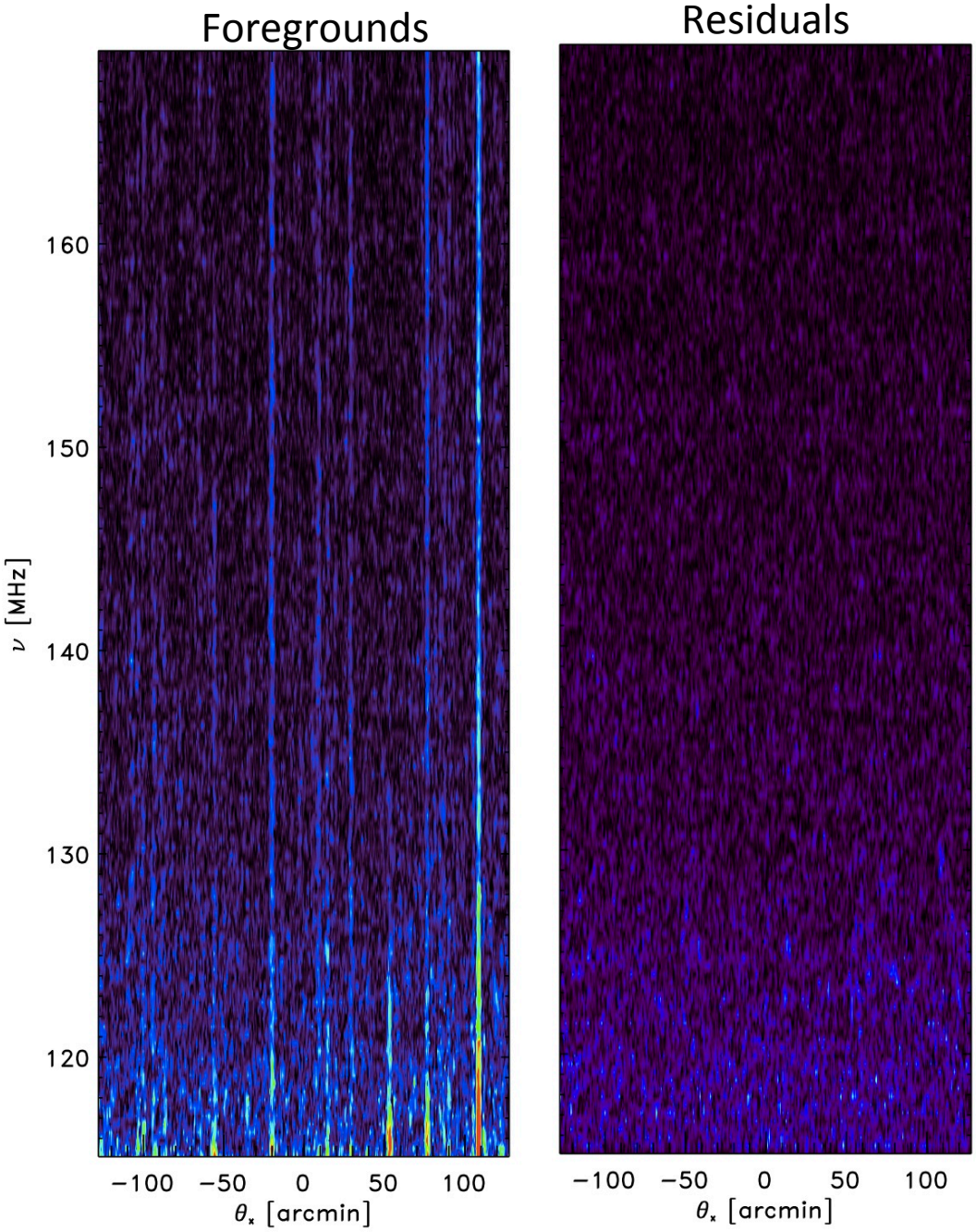
- Total 169 hours of observations (we have 450 hours)
- 114 hours were calibrated using 11k sources sky model.
- 55 hours were calibrated using 15k sources sky model.
- The images have 0.5 arcmin pixles and 0.4 MHz subbands.
- The analysis where made on 3deg.x3deg area at the field center.


0.00035
0.0003
0.00025
0.0002
0.00015
0.0001
5E-05
100
50
0
−50
−100
θ_y [arcmin]
−100 −50 0 50 100
−100 −50 0 50 100

Foreground extraction

Procedure

- Calibrate
- Subtract sky model
- Make the uv uniform (
- Apply a FG extraction method (preferably nc parametric).
- Analyze The residual map



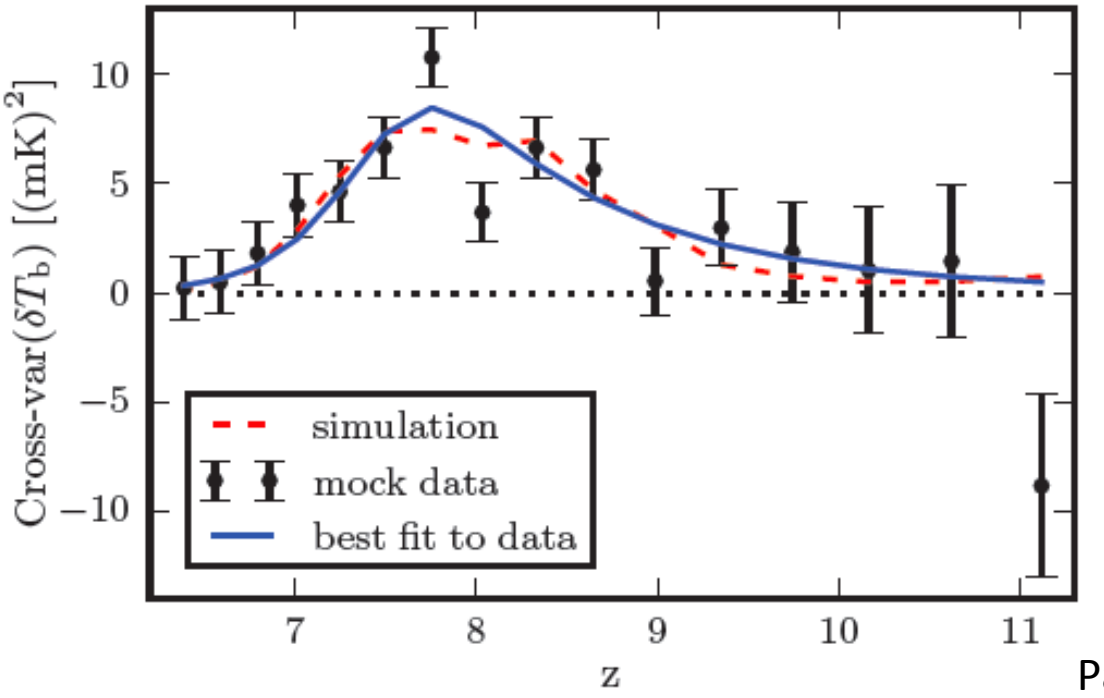
The rms and Cross-rms statistic

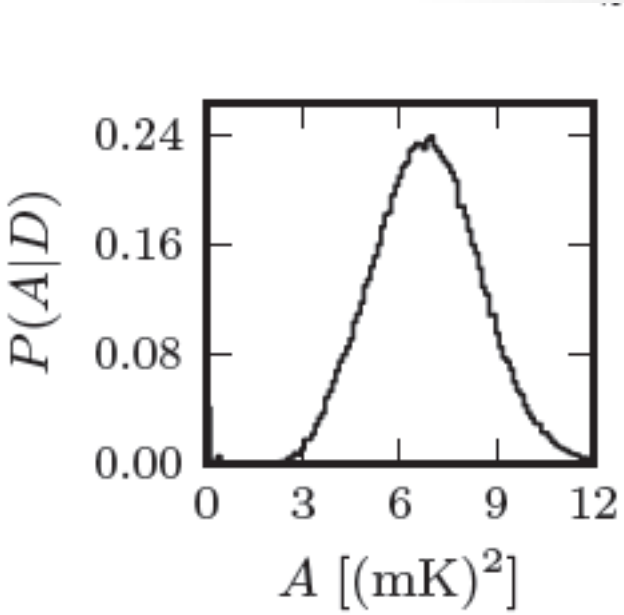
- Smooth the images with a Gaussian kernel
- Calculate the rms statistic and the Cross-rms:

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

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

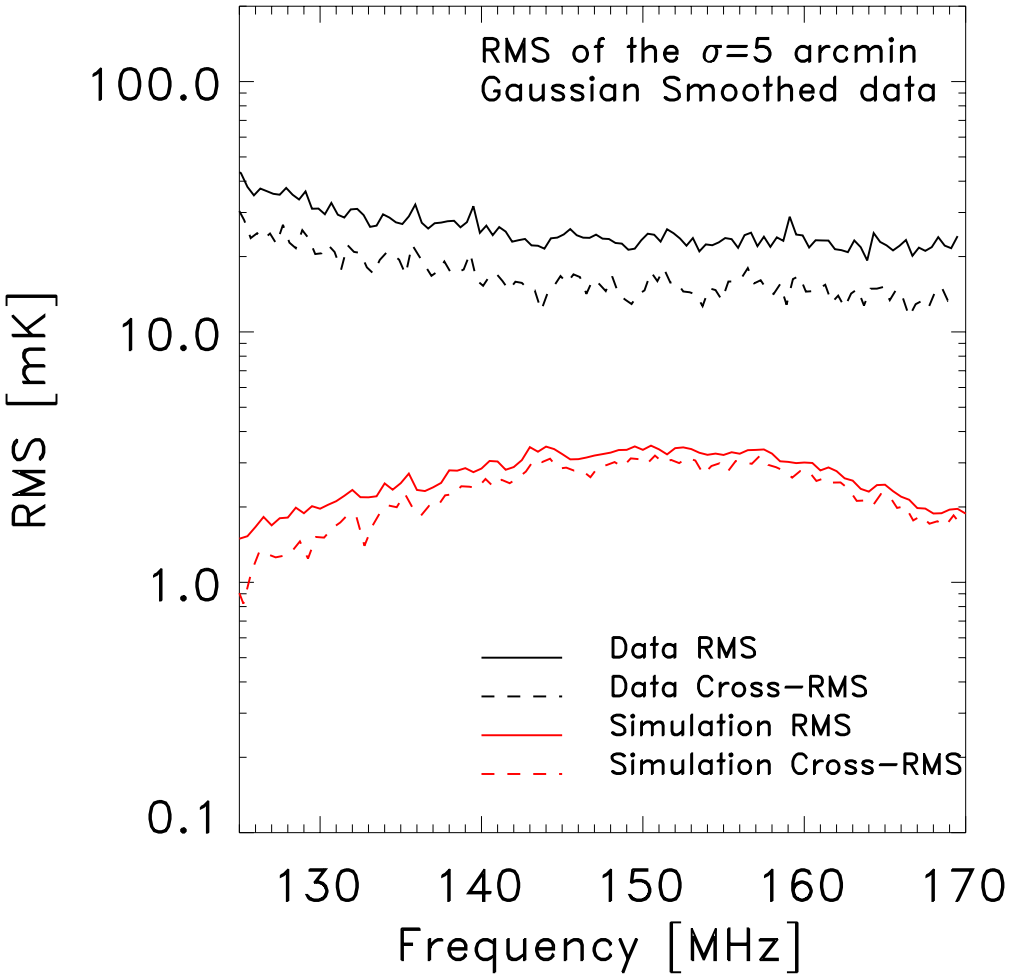
$$\nu' = \nu + \Delta\nu$$





Patil et al. 2014

The measured rms and cross-rms



The measured data is composed of: Cosmological signal, foregrounds subtraction errors, noise, systematics (stochastic and coherent).

All these effects have to be taken to account. The systematic effects are still dominating the signal.

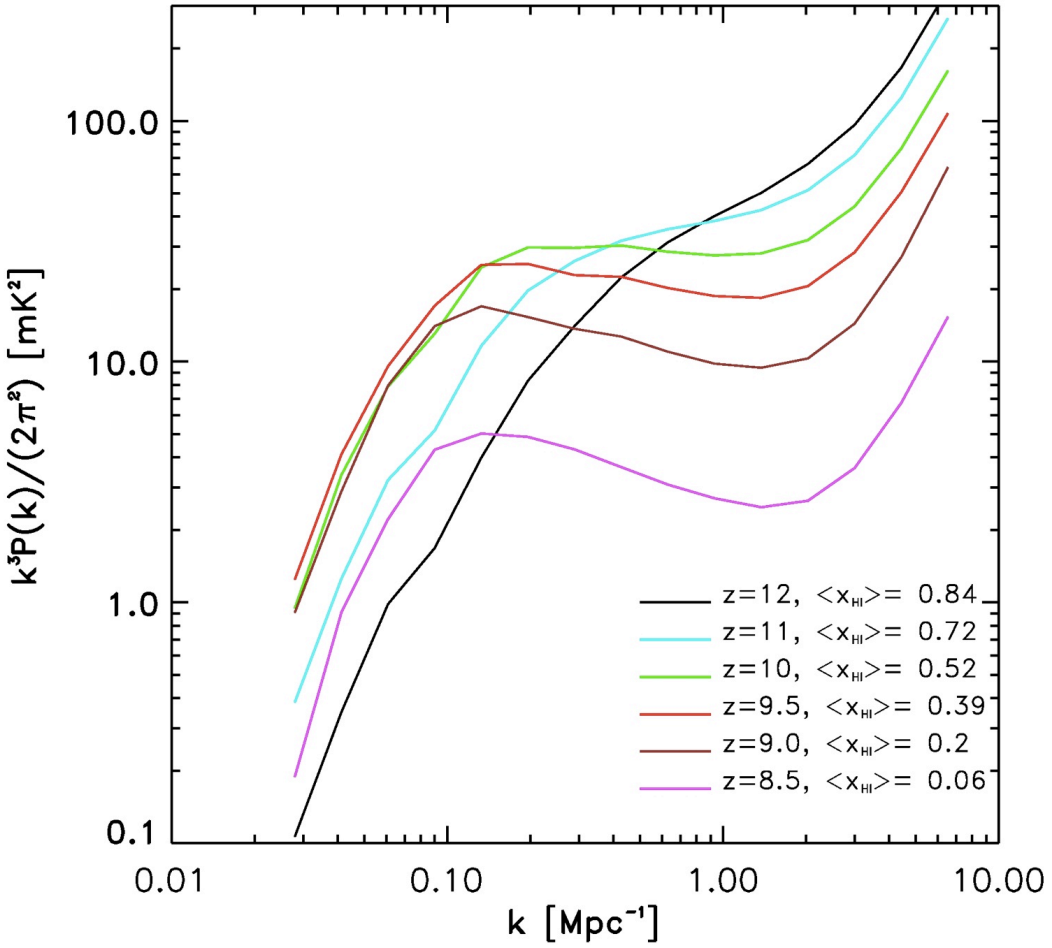
Dimensionless Power Spectra

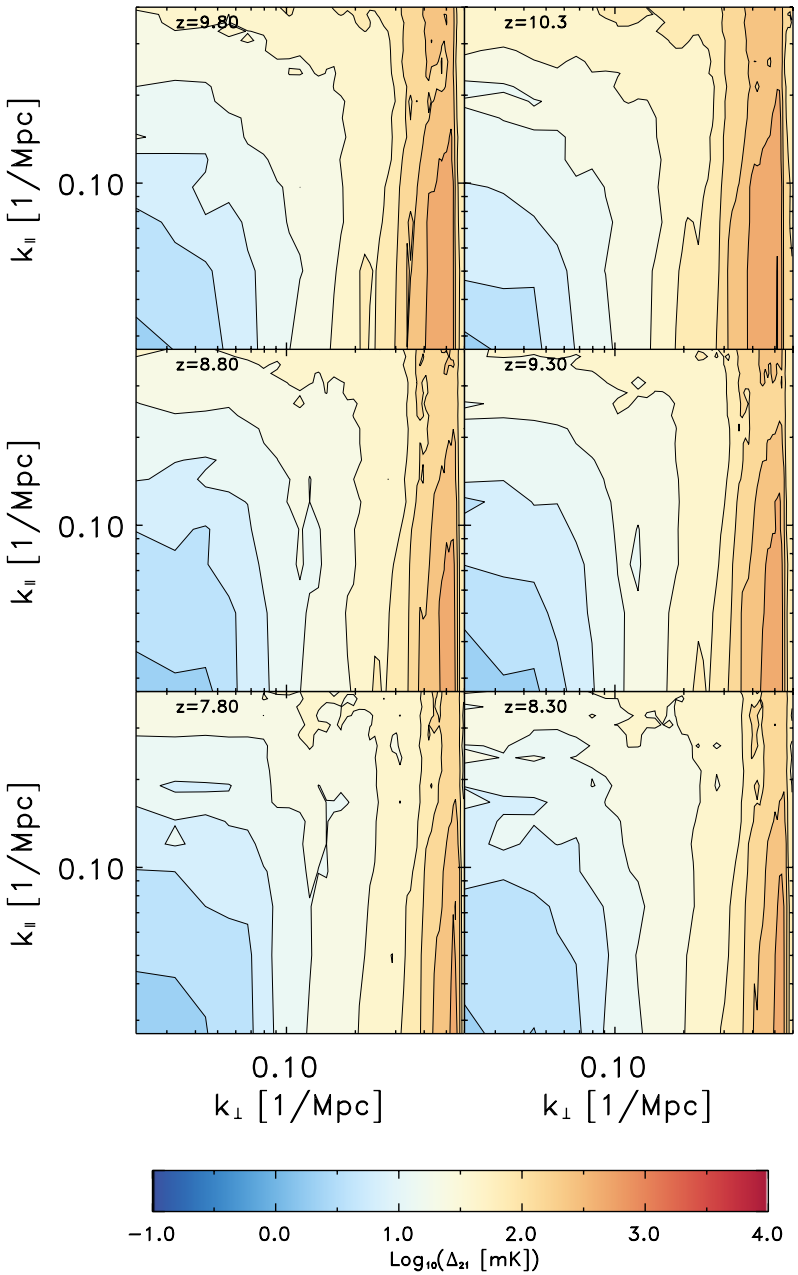
- The Dimensionless spherically averaged power spectrum is defined as:

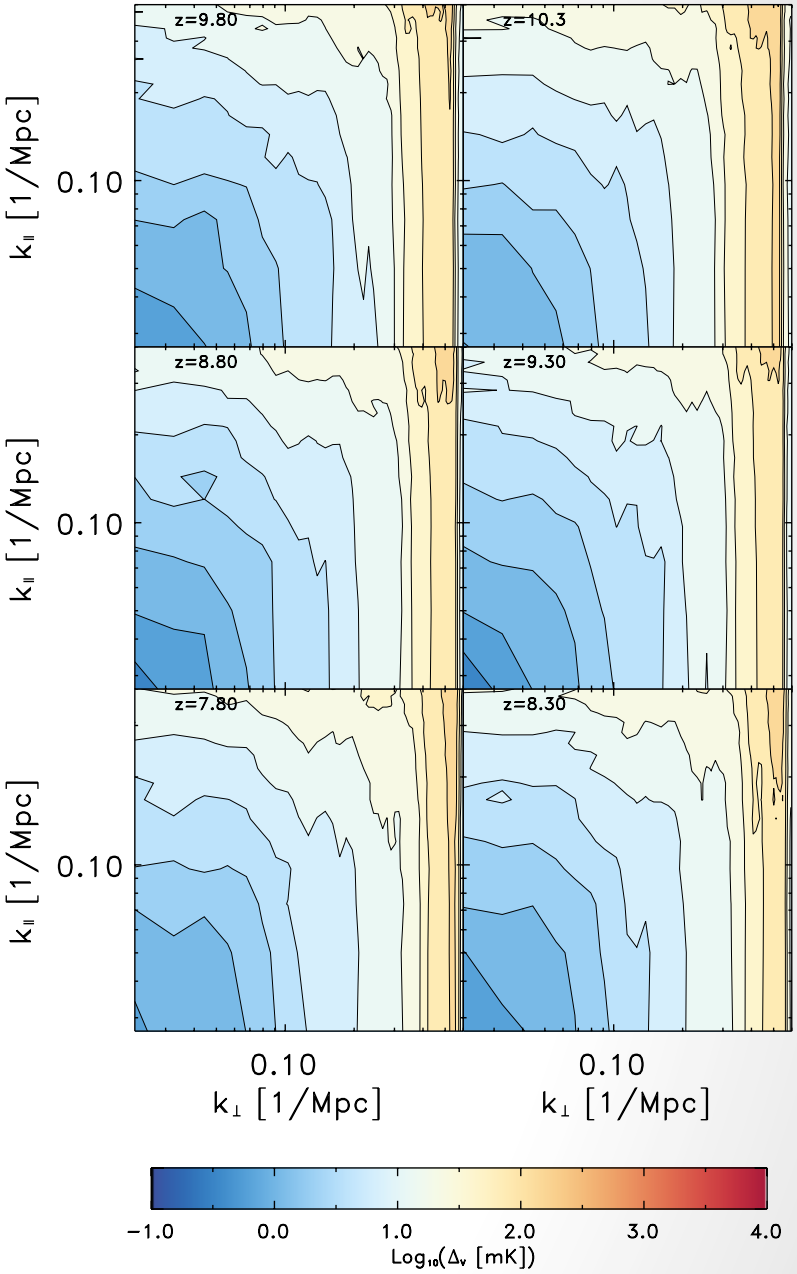
$$\Delta^2(k) = \frac{k^3 P(k)}{2\pi^2}$$

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

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



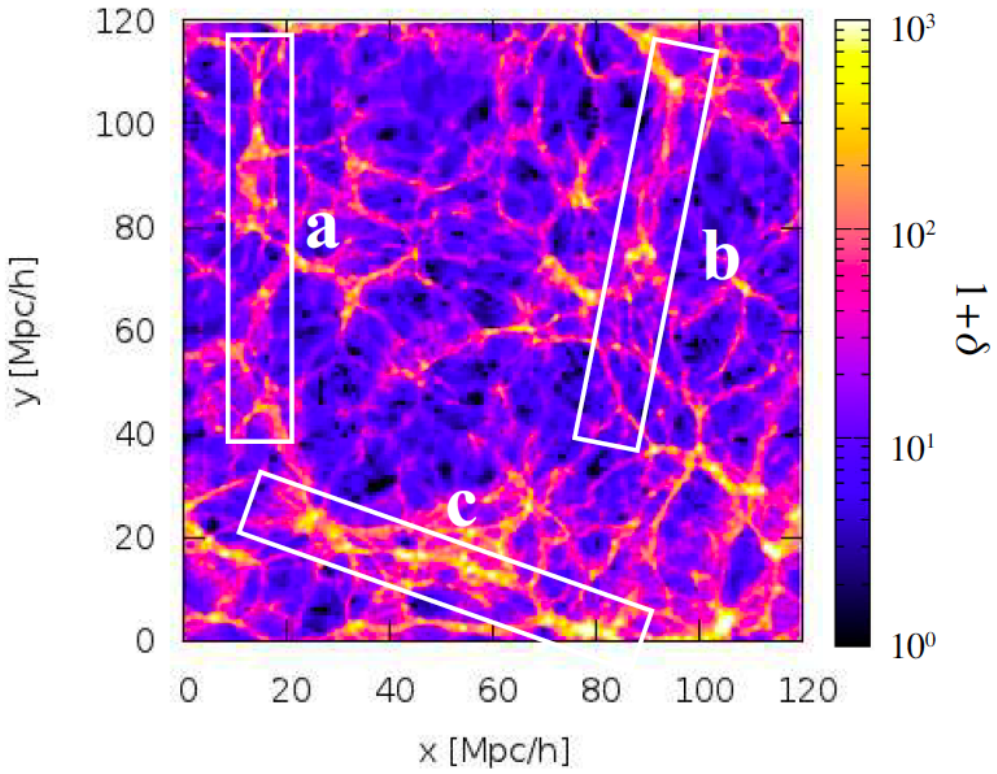

z=9.80
z=10.3
z=8.80
z=9.30
z=7.80
z=8.30
0.10
k⊥ [1/Mpc]
k∥ [1/Mpc]
−1.0
0.0
1.0
2.0
3.0
4.0
Log10(Δ21 [mK])


z=9.80
z=10.3
z=8.80
z=9.30
z=7.80
z=8.30
0.10
k⊥ [1/Mpc]
k∥ [1/Mpc]
−1.0
0.0
1.0
2.0
3.0
4.0
Log10(Δv [mK])

Next steps

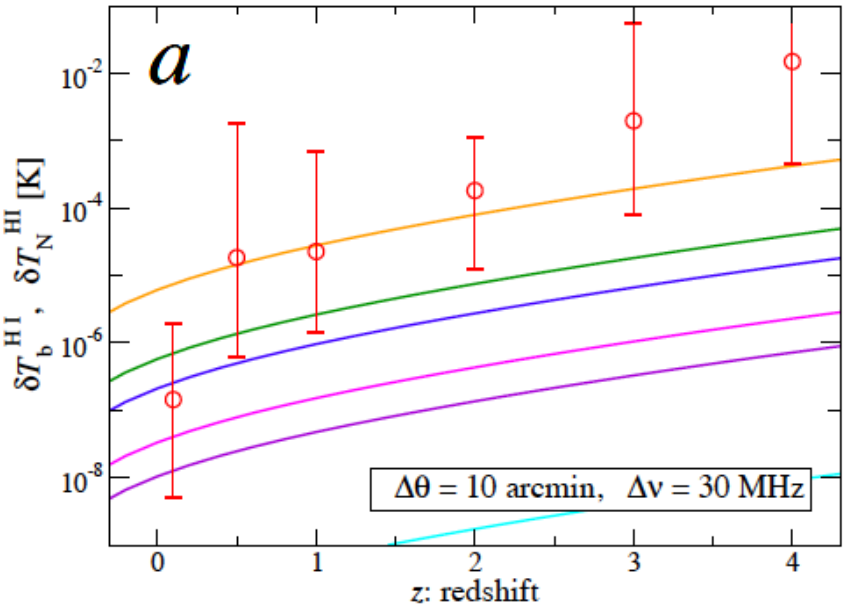
- Understand systematics better!!!!
- Add more calibration sources (current data 11000 and 15000).
- Improve the sky model.
- Calibrate on even higher frequency resolution (12 kHz)
- More data … More data …. More data
- We are slowly getting there

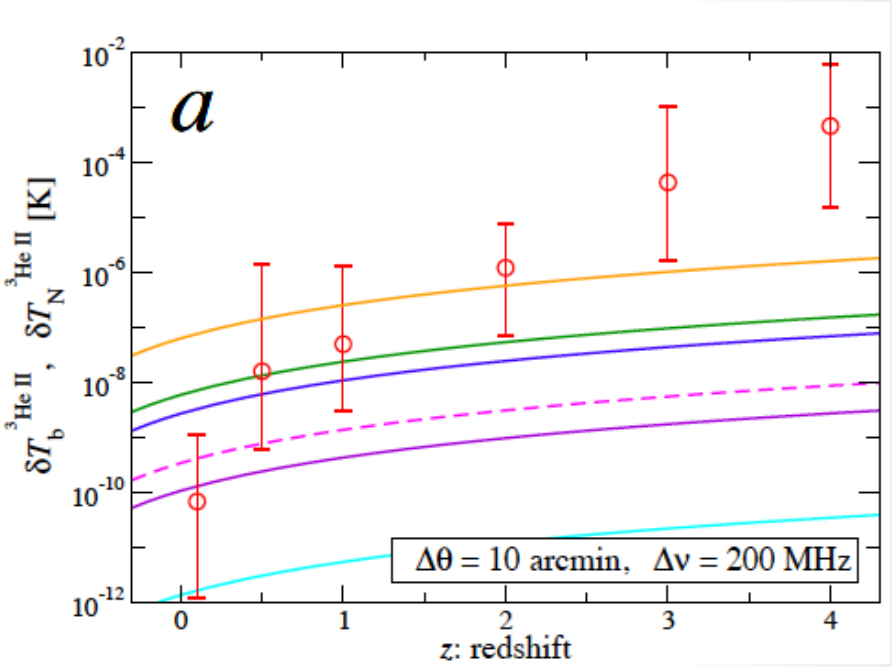
HI and HeII filaments mapping

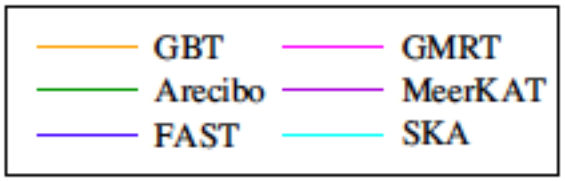


Takeuchi, Zaroubi, Sugiyama 2014

HI and HeII filament mapping







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Summary

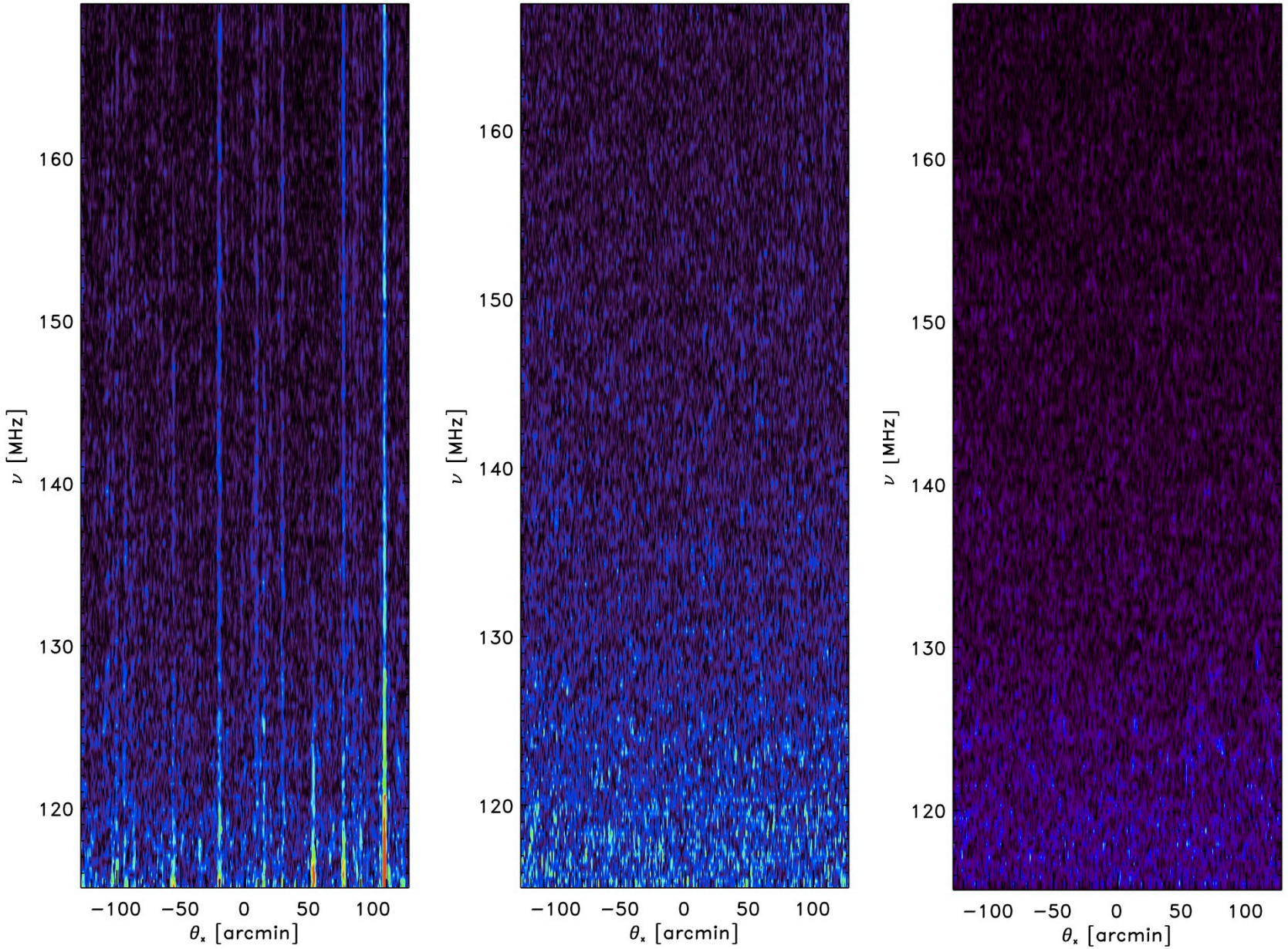
- Currently, we are still dominated by systematic effects that are dominated by the imperfect sky model we use. This is improving rapidly as we analyze more and more data.

- Crucially, the detection has to be made in multiple fields.

- Our current focus is on detection. Once a detection is made more data is needed to allow placing strong constraint on reionization models.

- In the future we will be able to even image the EoR on large scales with LOFAR

End of talk


160
150
140
130
120
ν [MHz]
−100 −50 0 50 100
θx [arcmin]