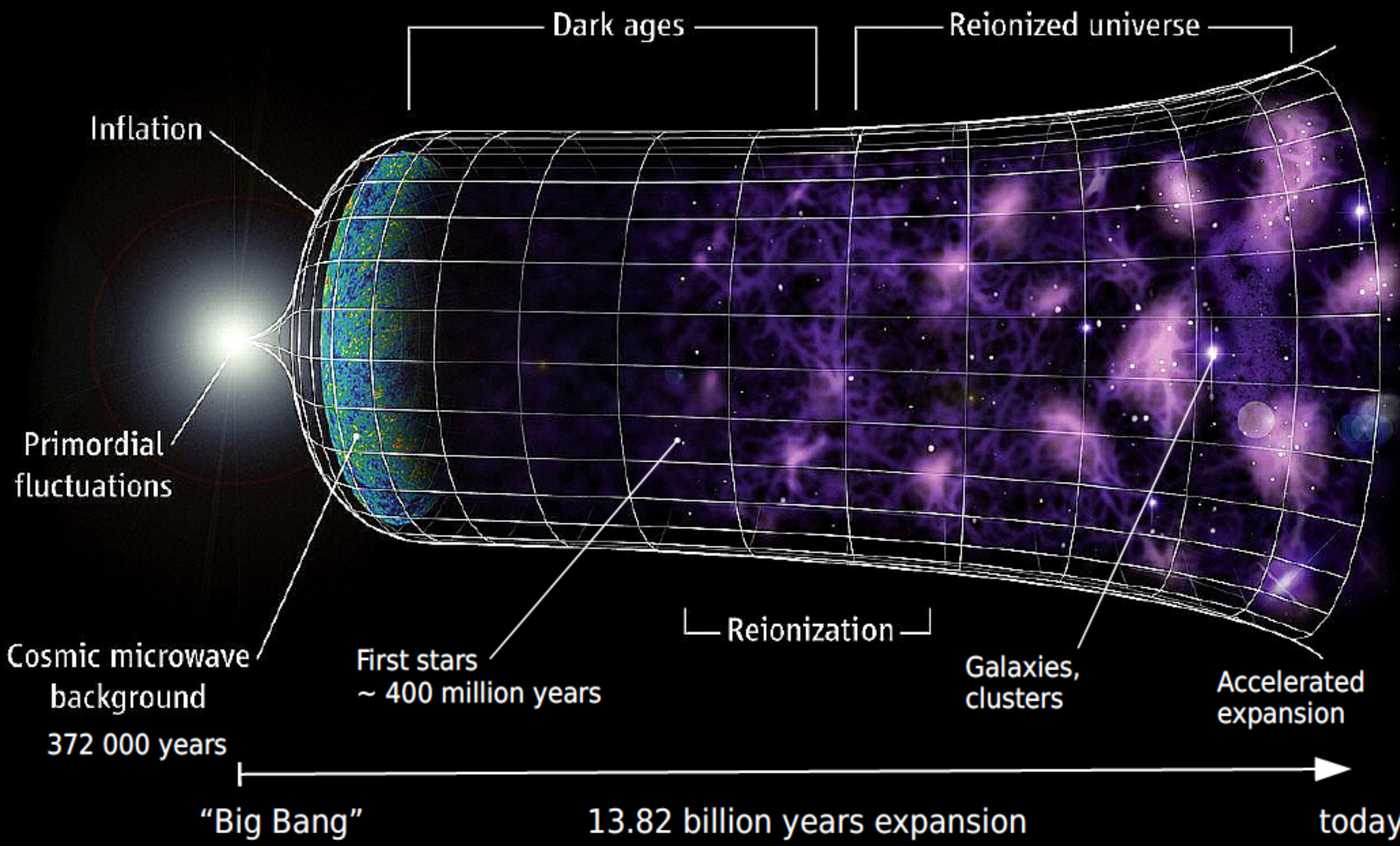
21cm cosmology with current and future radio telescopes

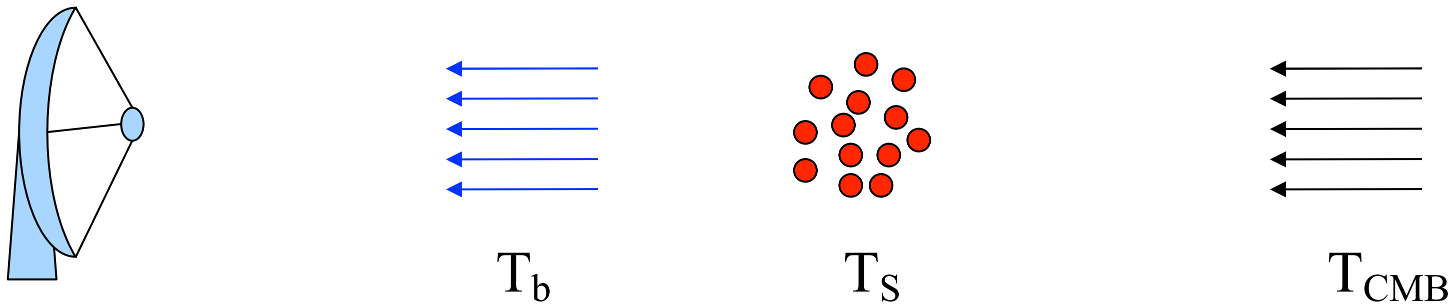
Saleem Zaroubi

The History

Credit: Science magazine



δT_b, The Brightness Temperature

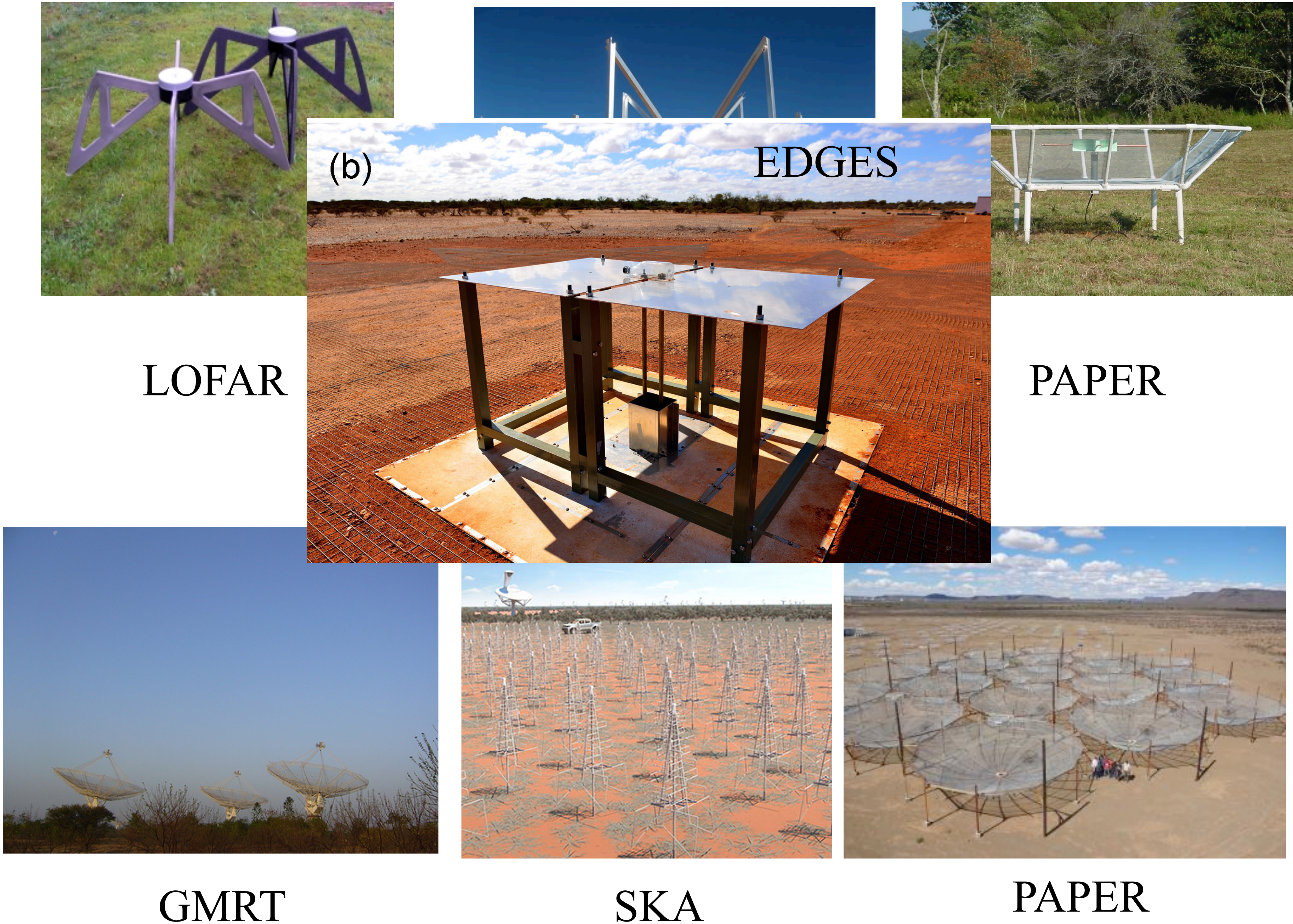


$$\delta T_b = 28\mathrm{mK}\,(1+\delta)\,x_{\mathrm{HI}}\left(1-\frac{T_{CMB}}{T_{spin}}\right)\left(\frac{\Omega_b h^2}{0.0223}\right)\sqrt{\left(\frac{1+z}{10}\right)\left(\frac{0.24}{\Omega_m}\right)}\left[\frac{H(z)/(1+z)}{\mathrm{d}v_{\|}/\mathrm{d}r_{\|}}\right],$$

Astrophysics

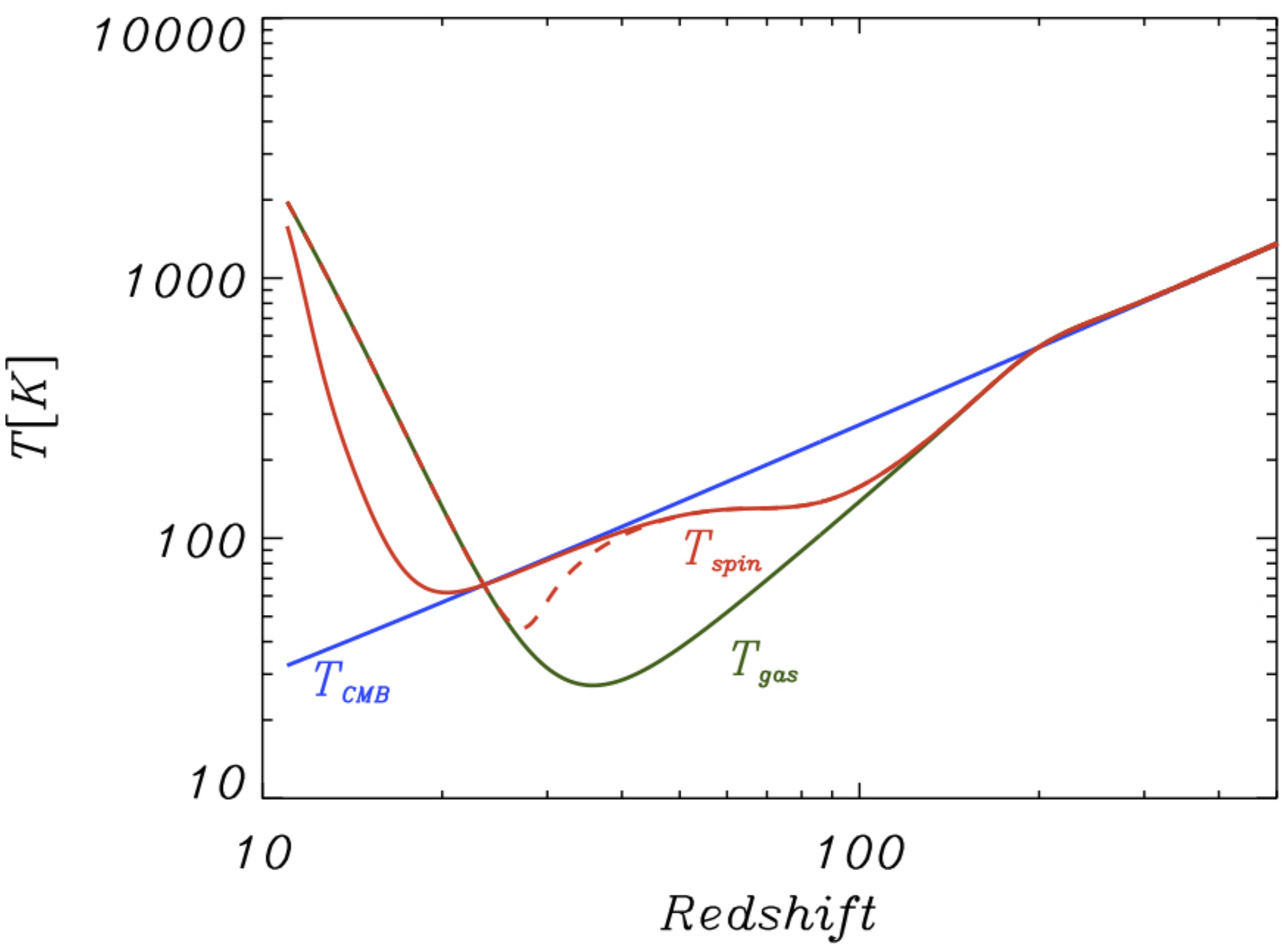
Cosmology

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



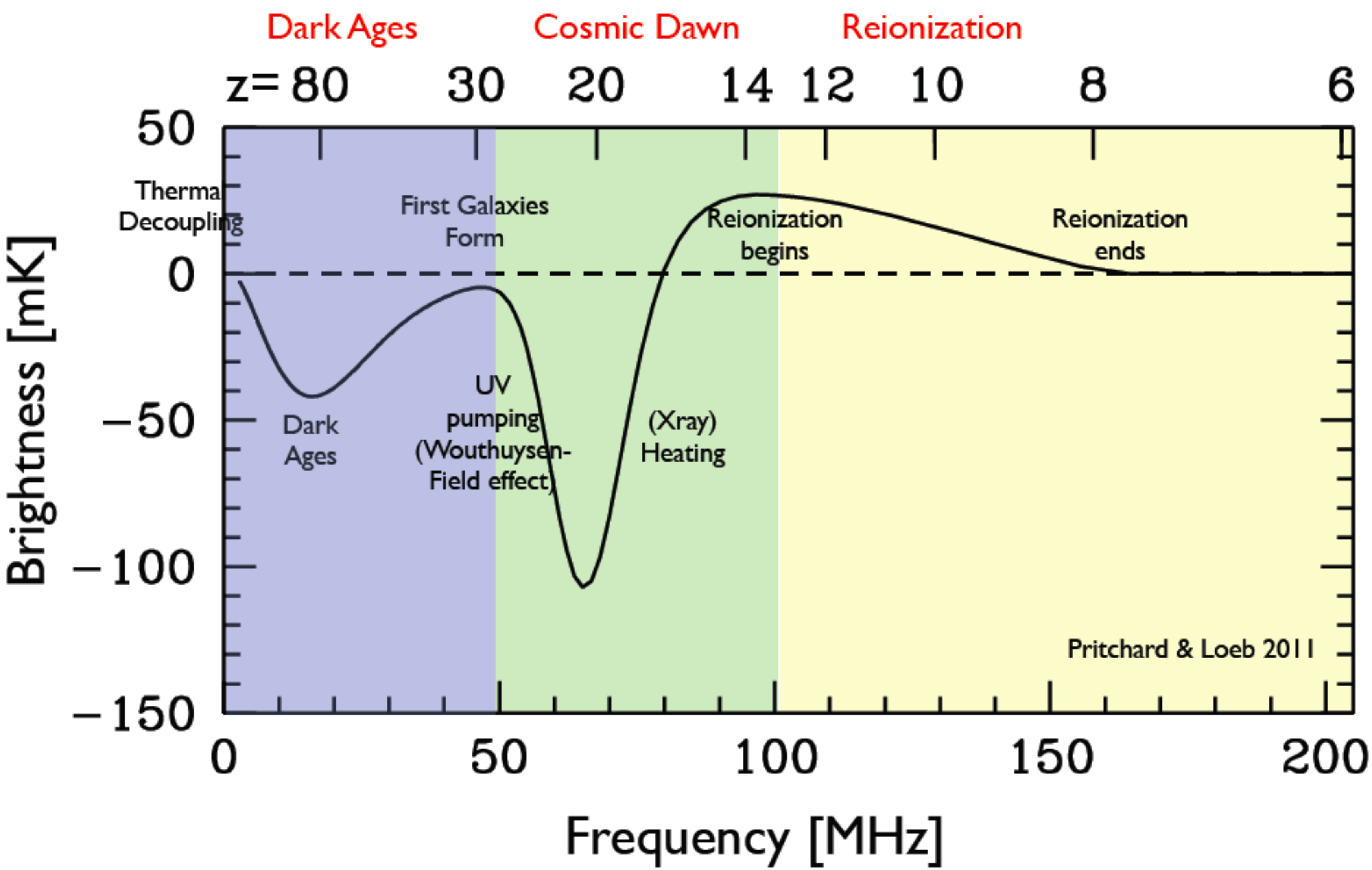
(b)
EDGES
LOFAR
PAPER
GMRT
SKA
PAPER

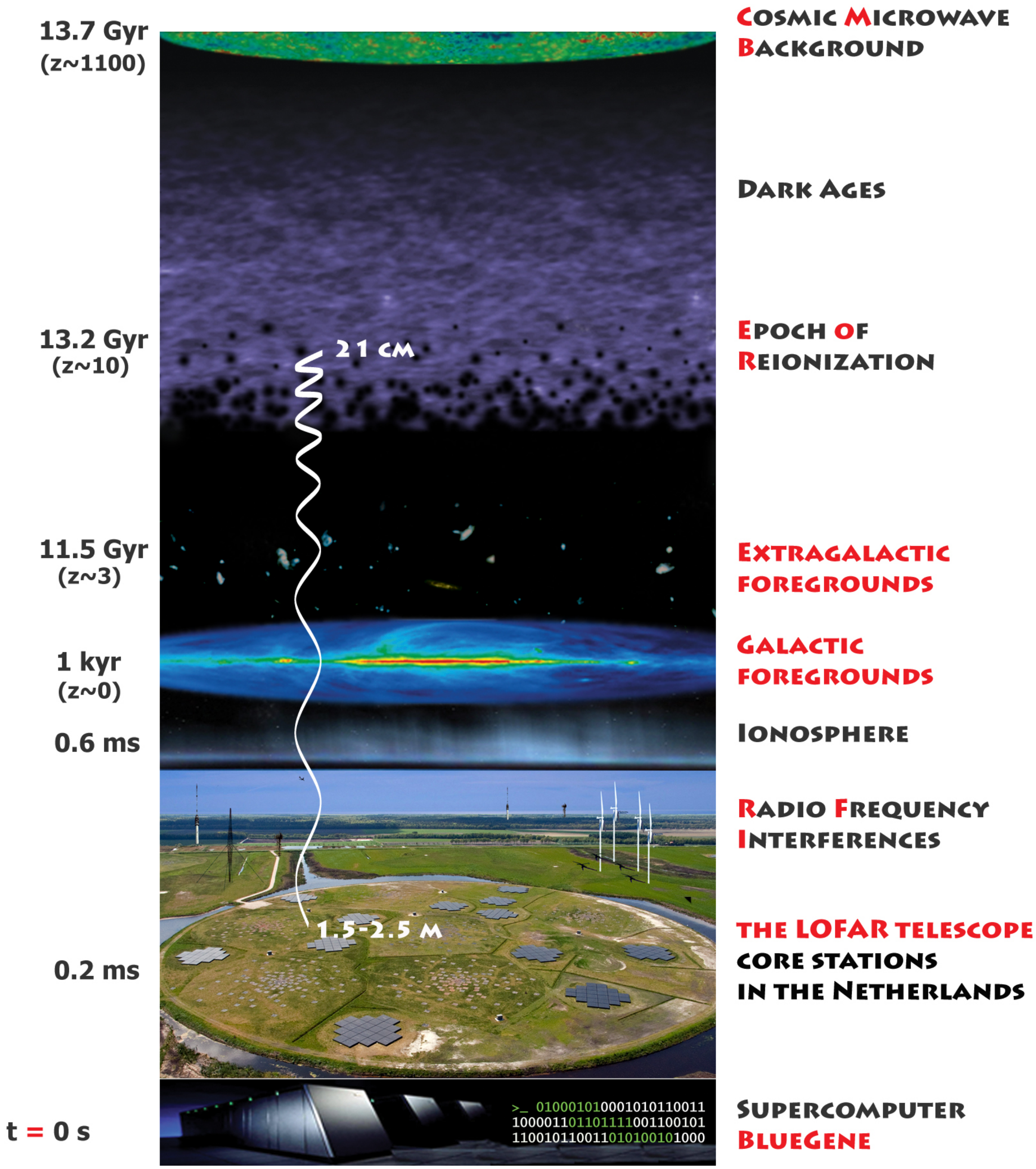
The Global evolution of T_s



Loeb & Zaldarriaga 2004, Pritchard & Loeb 2008, Baek et al. 2010, Thomas & Zaroubi 2010

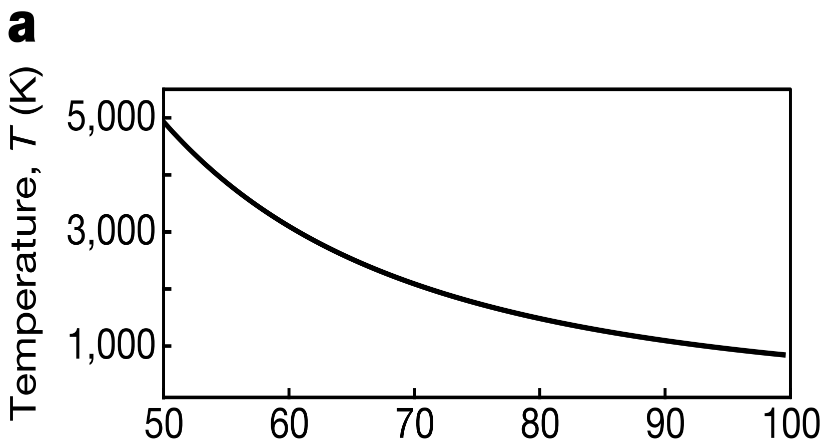
The Global evolution of T_s

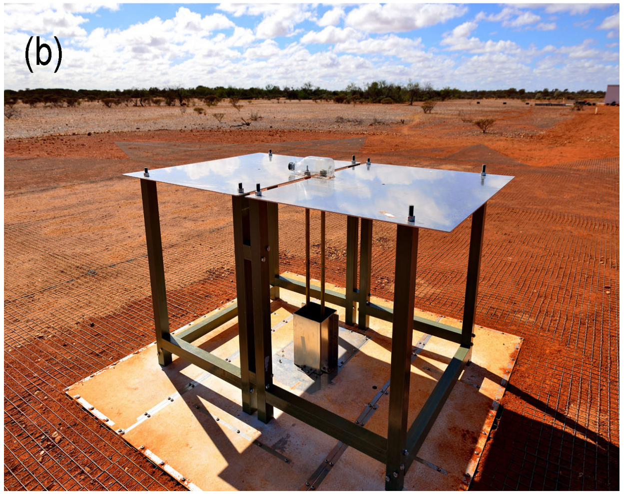


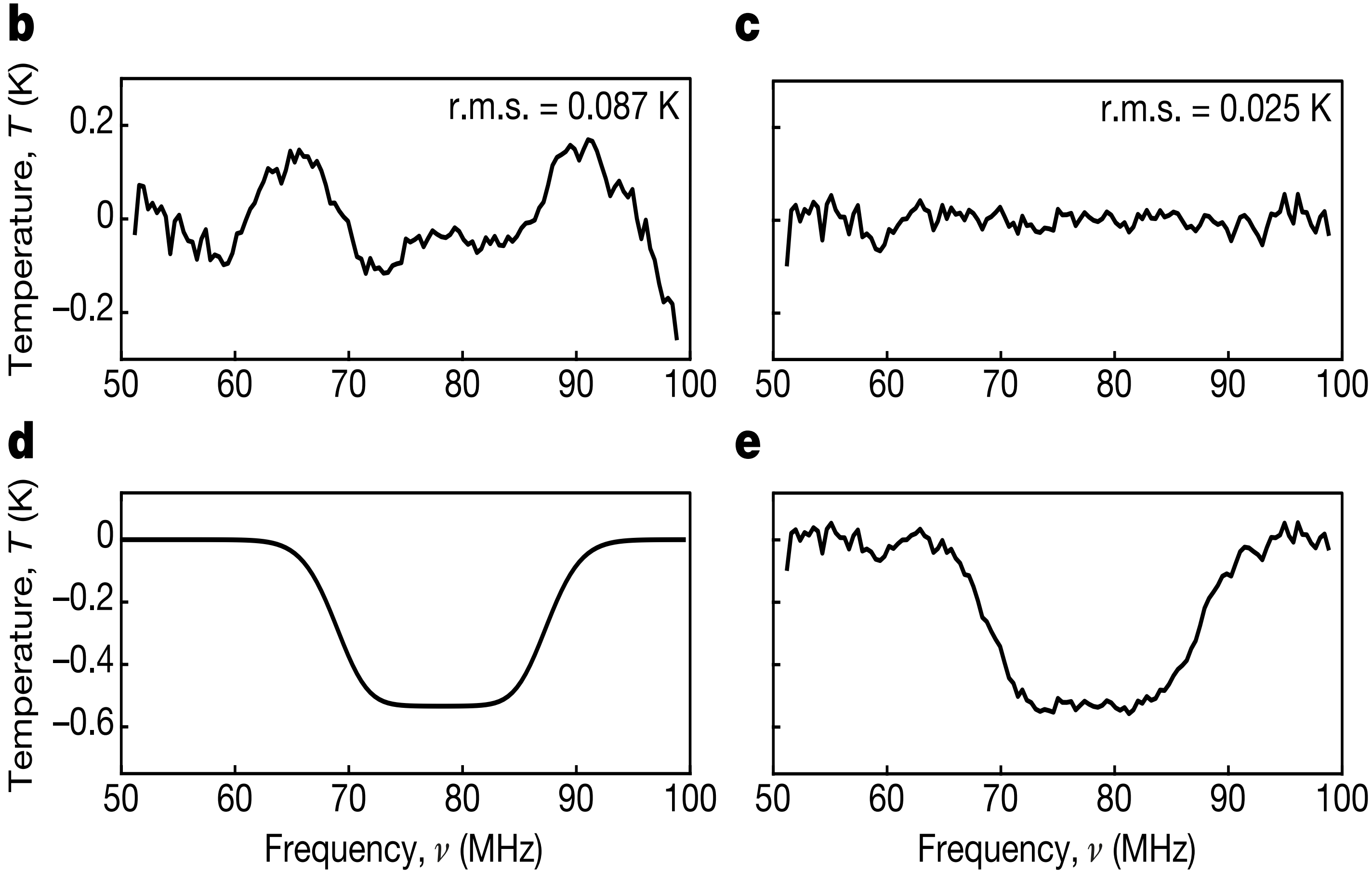

13.7 Gyr
(z~1100)
Cosmic Microwave Background
Dark Ages
13.2 Gyr
(z~10)
21 cm
Epoch of Reionization
11.5 Gyr
(z~3)
Extragalactic foregrounds
1 kyr
(z~0)
Galactic foregrounds
0.6 ms
Ionosphere
Radio Frequency Interferences
1.5-2.5 m
0.2 ms
the LOFAR telescope
core stations
in the Netherlands
t = 0 s
>_ 01000101000101010110011
1000011011011110011001 01
110010110011010100101000
Supercomputer
BlueGene

The EDGES result

Bowman+ 2018



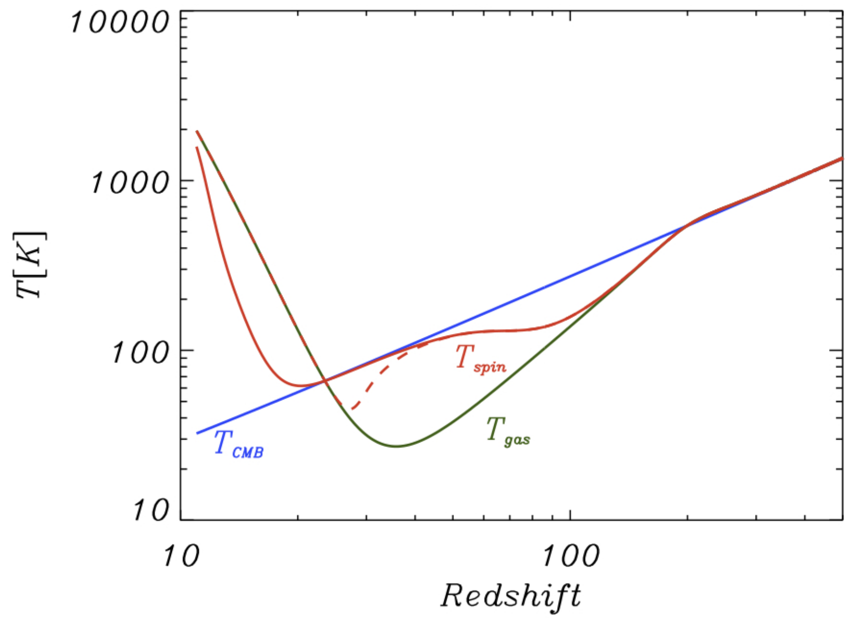




The EDGES paper

- Discussing the observations
- Proposing interpretations!!
  - Data analysis
  - Astrophysics
  - Fundamental physics
  - ETC.

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.

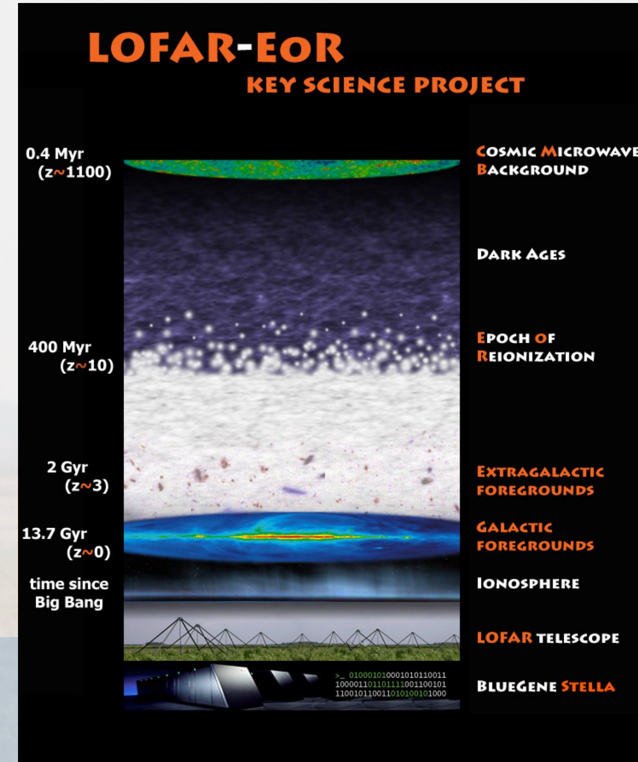
All of these models are very problematic.

Or maybe the explanation is a yet unknown systematic or feature in the galaxy, etc.

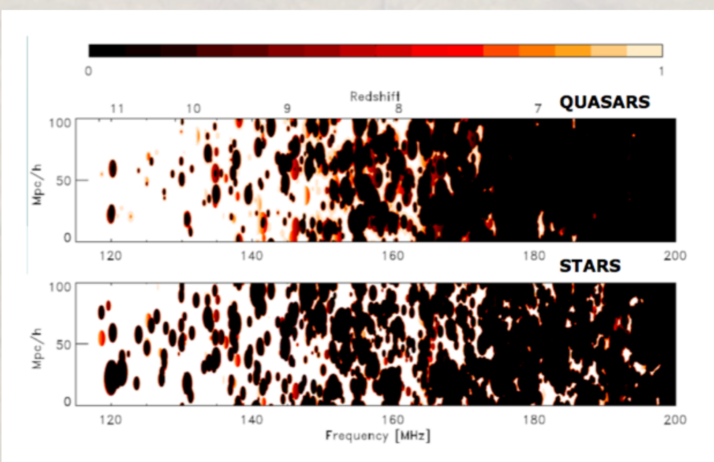
International LOFAR Telescope (ILT)

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)

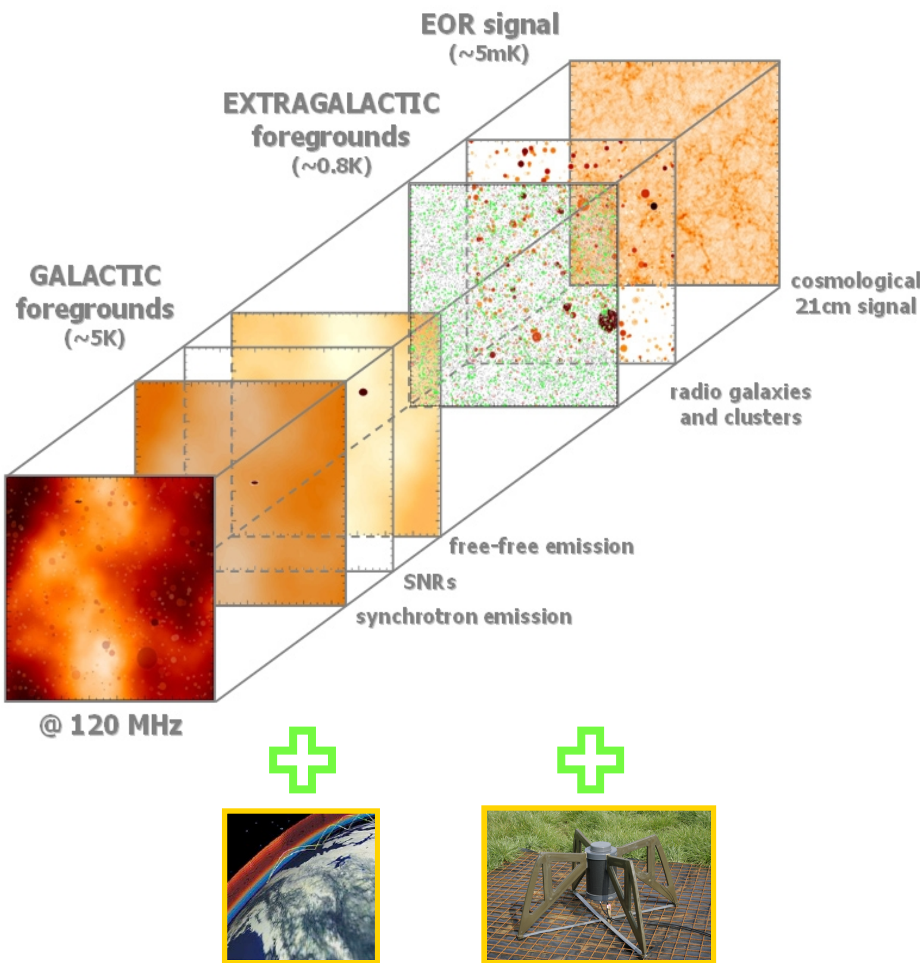


Rajat Thomas (2009)

115 - 177 MHz
$z = 11.4 – 7.0$

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

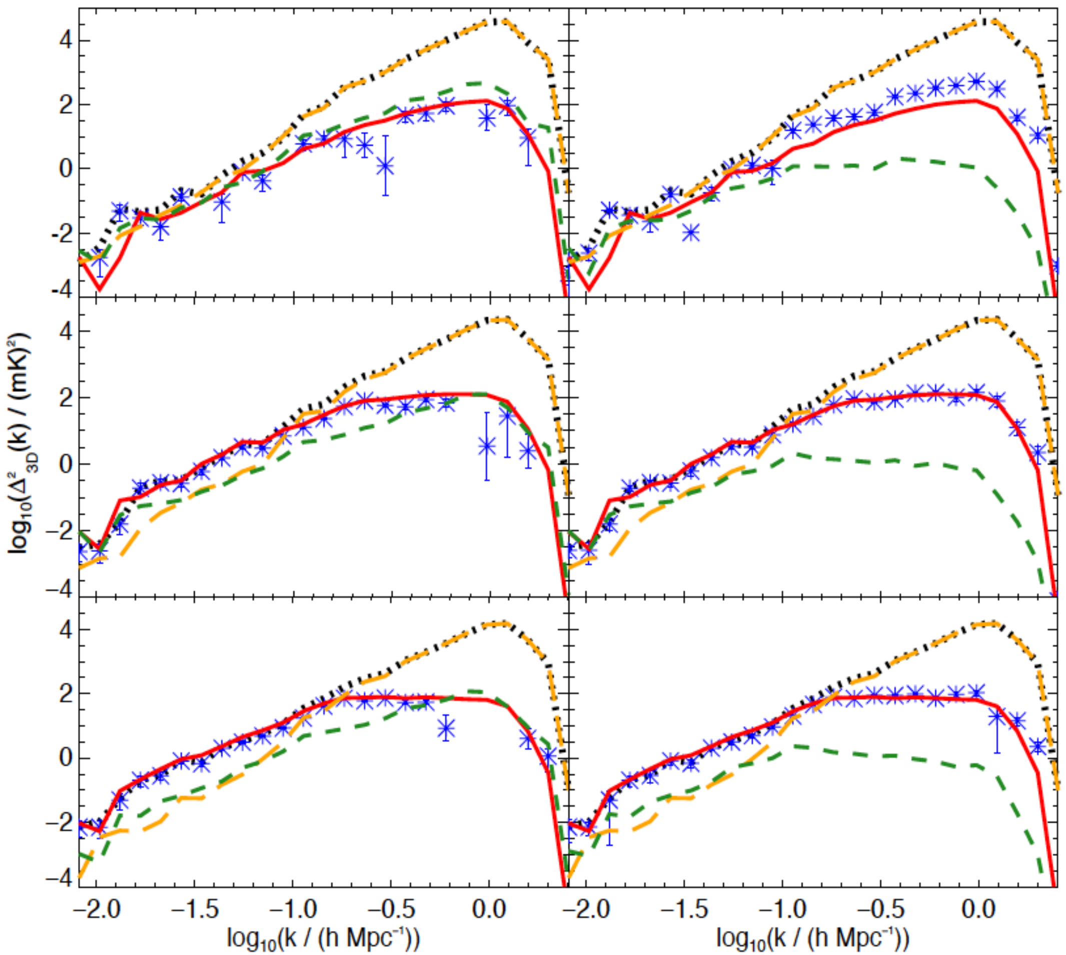
Measuring Redshifted HI: Challenges



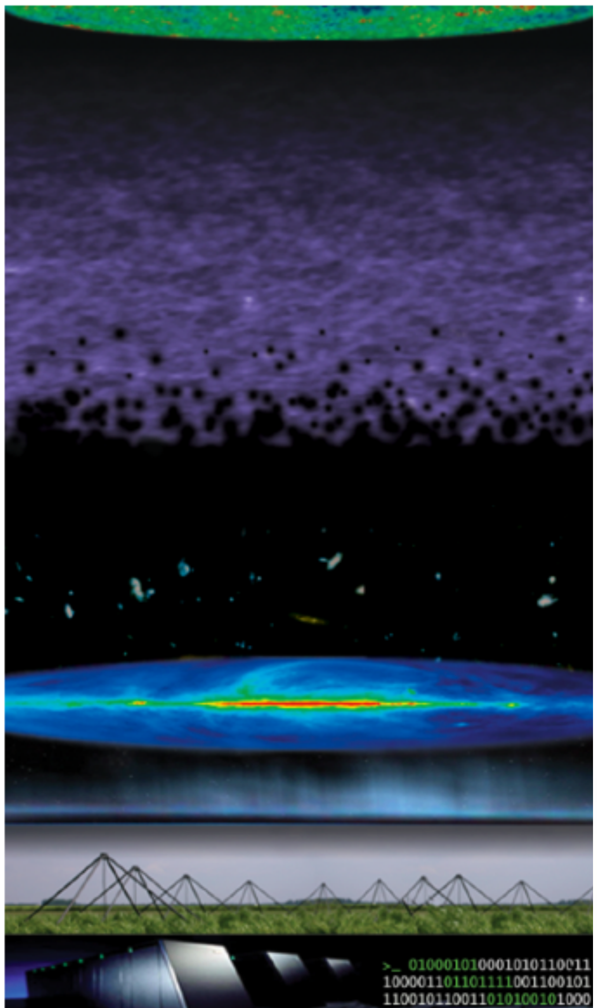
1. Astrophysical Challenges
    1. Foregrounds: total intensity
    2. Foregrounds: polarized
    3. Ionosphere
    4. Etc.
2. Instrumental challenges
    1. Beam stability
    2. Calibration
    3. Resolution
    4. uv coverage
    5. Etc.
3. Computational challenges
    1. Multi petabyte data set
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

Power Spectrum Measurements

Chapman et al 2013



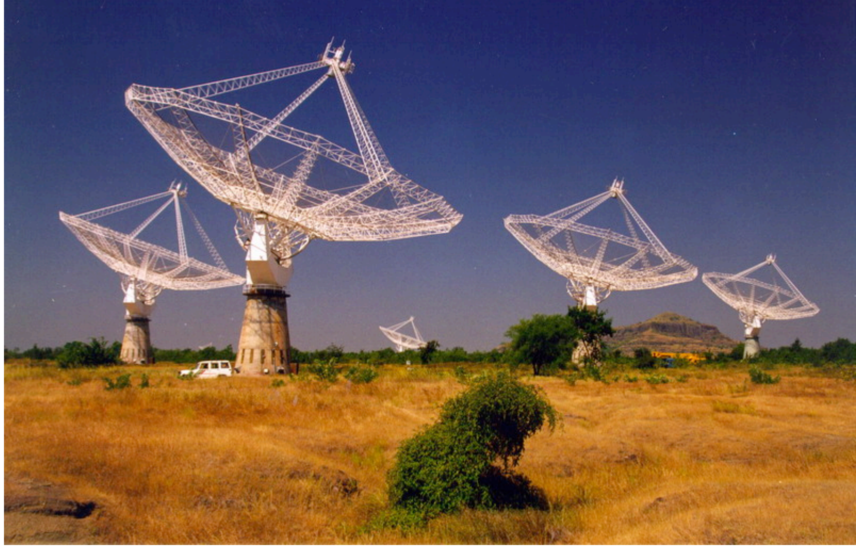
Observation

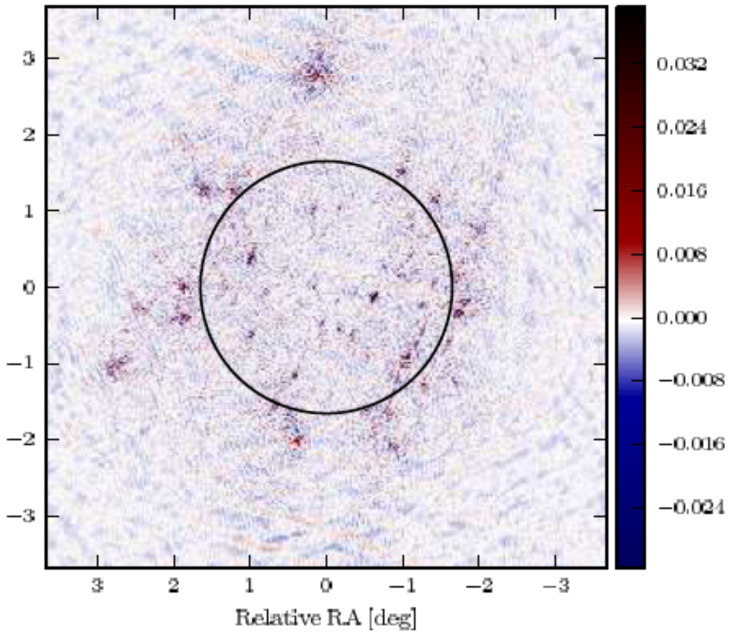


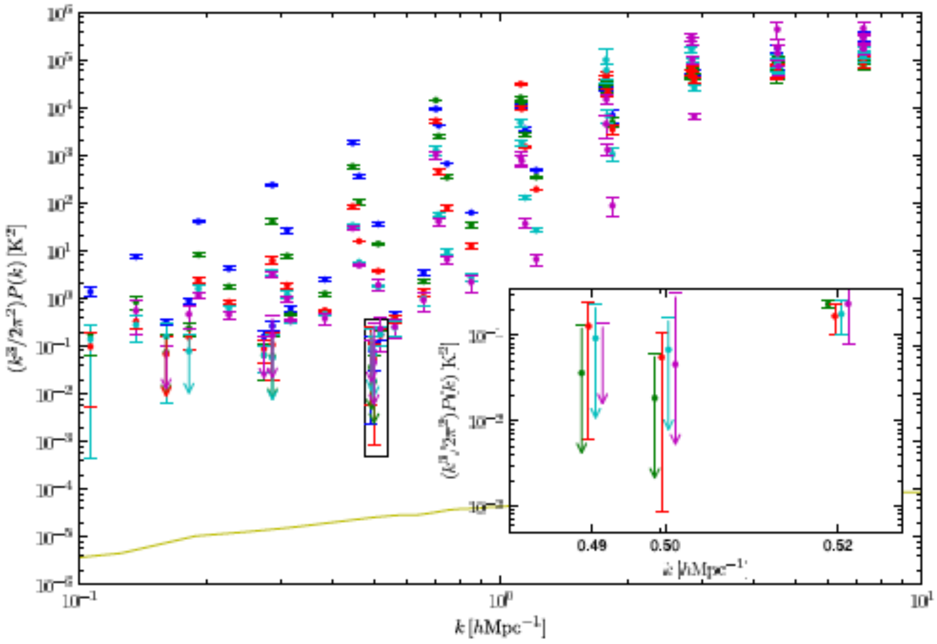
Extraction/ detection

Interpretation

GMRT results

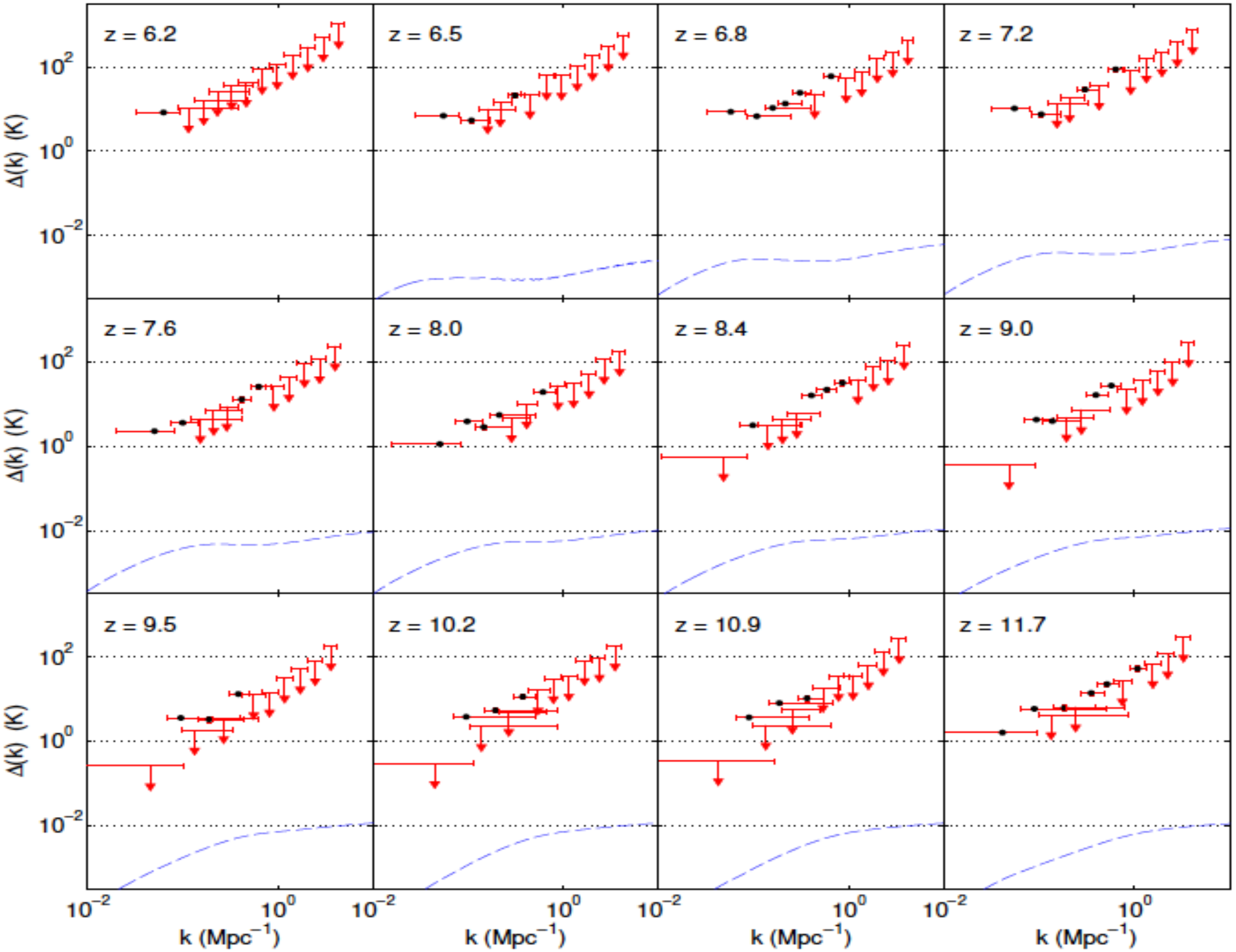




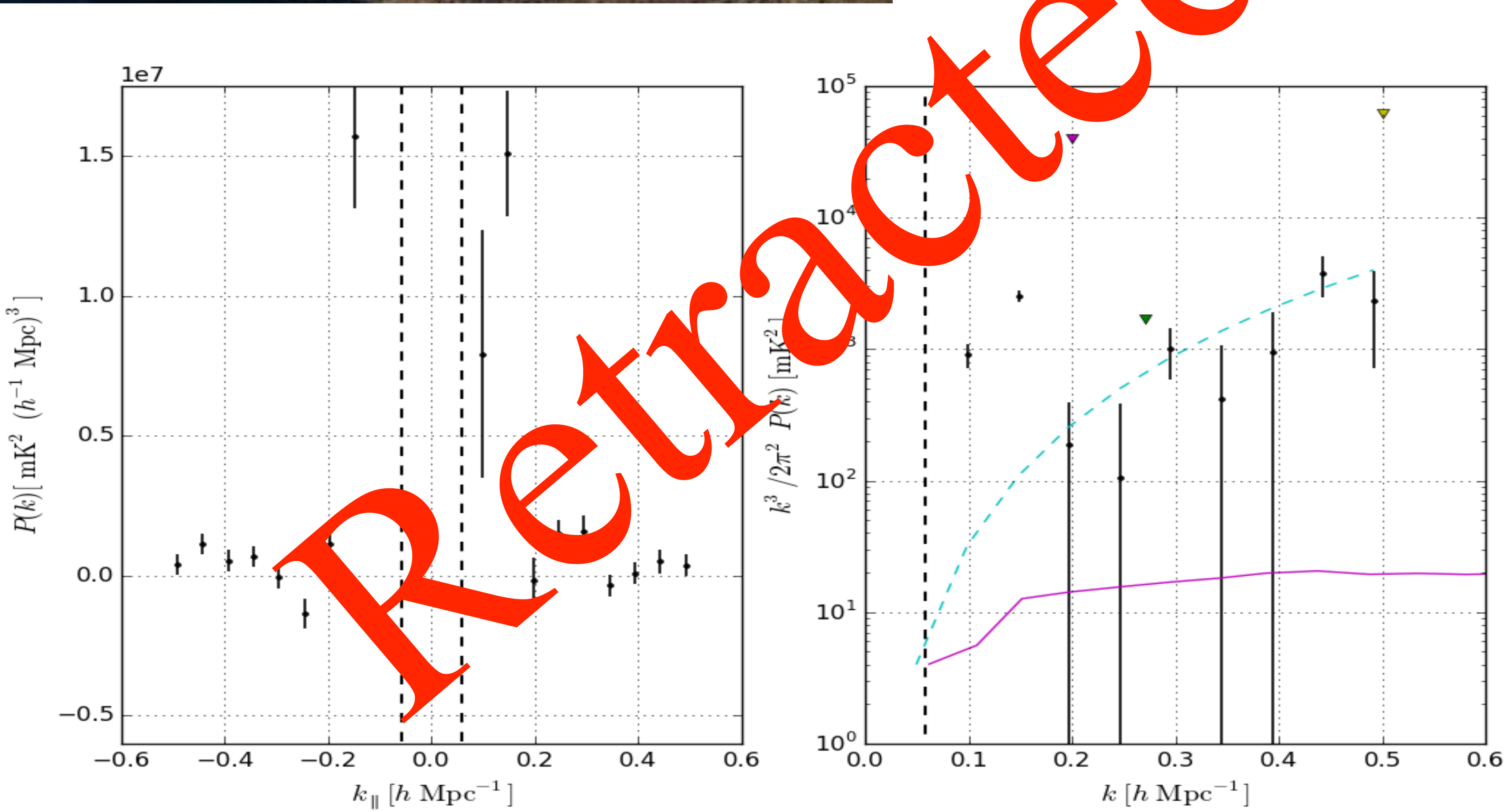


Paciga et al 2011

MWA current results



Dillon et al 2014



Ali et al 2015

Spherical Power Spectra

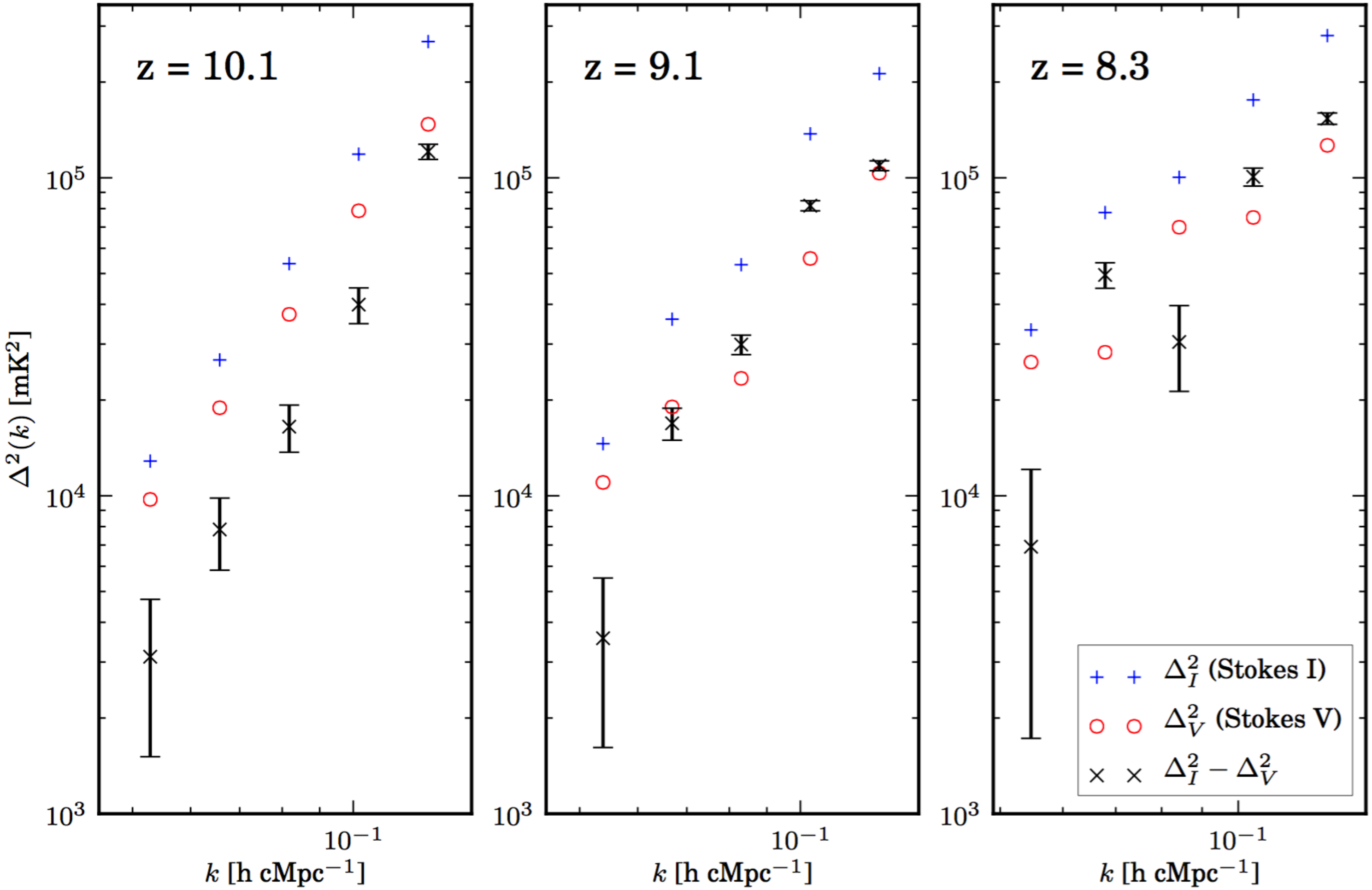


Figure 8. The spherically averaged Stokes I and V power spectra after GMCA for L90490; From left to right are shown the redshift ranges $z = 9.6 - 10.6$, $z = 8.7 - 9.6$ and $z = 7.9 - 8.7$ from left to right, respectively. The mean redshifts are indicated in the panels.

Patil et al. (2017, ApJ)

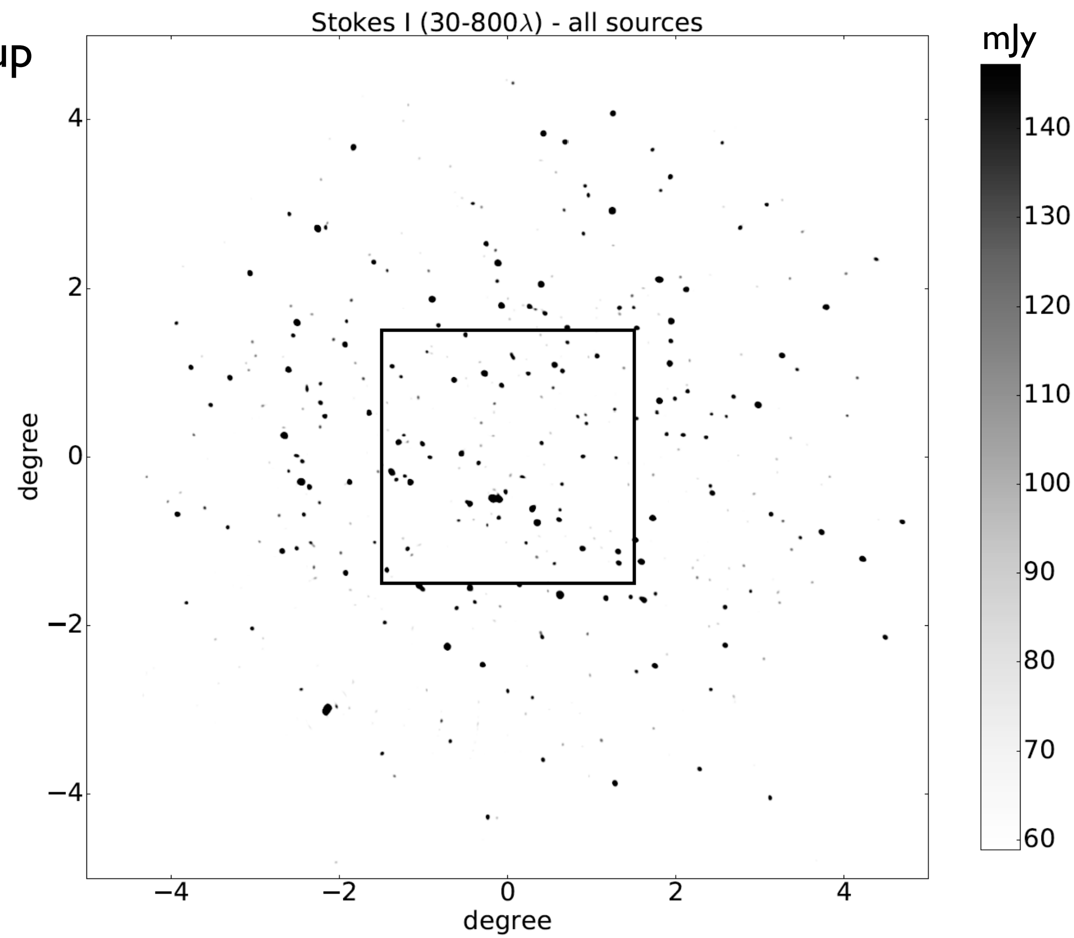
Patil et al. (2017, ApJ)

LOFAR-NCP Observations

Results presented today are based on a single 13-hr run taken 2nd Nov. 2013 @ 17:20:01 (UTC)

Observational and correlator set-up

Phase Centre α, δ	$0^h, +90°$	J2000
Minimum frequency	115.039	MHz
Maximum frequency	189.062	MHz
Target bandwidth	74.249	MHz
Antenna fields	48 / 13	CS / RS
Data size (488 channels)	50	Tbyte
Sub-band (SB) width	195.3125	kHz
Correlator channels per SB	64	
Correlator integration time	2	s
Channels per SB after averaging	1, 3, 3, 15	
Integration time after averaging	10, 10, 2, 2	s
Raw data volume L90490	61	Tbyte



A continuum (134.5-137.5 MHz) LOFAR-HBA image of 10x10 deg2 centred on the North Celestial Pole (NCP) field. Baselines between 30-800 were included. No sources have been subtracted and the image is partially cleaned. The 3x3d box delineates the area where we measure the power spectra. The bright source to the lower-left of the box is 3C61.1. The units are mJy/PSF. Right Ascension (RA) 00h is towards the bottom and increases clockwise.

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
As of March 2019

Going ~30-40x deeper…

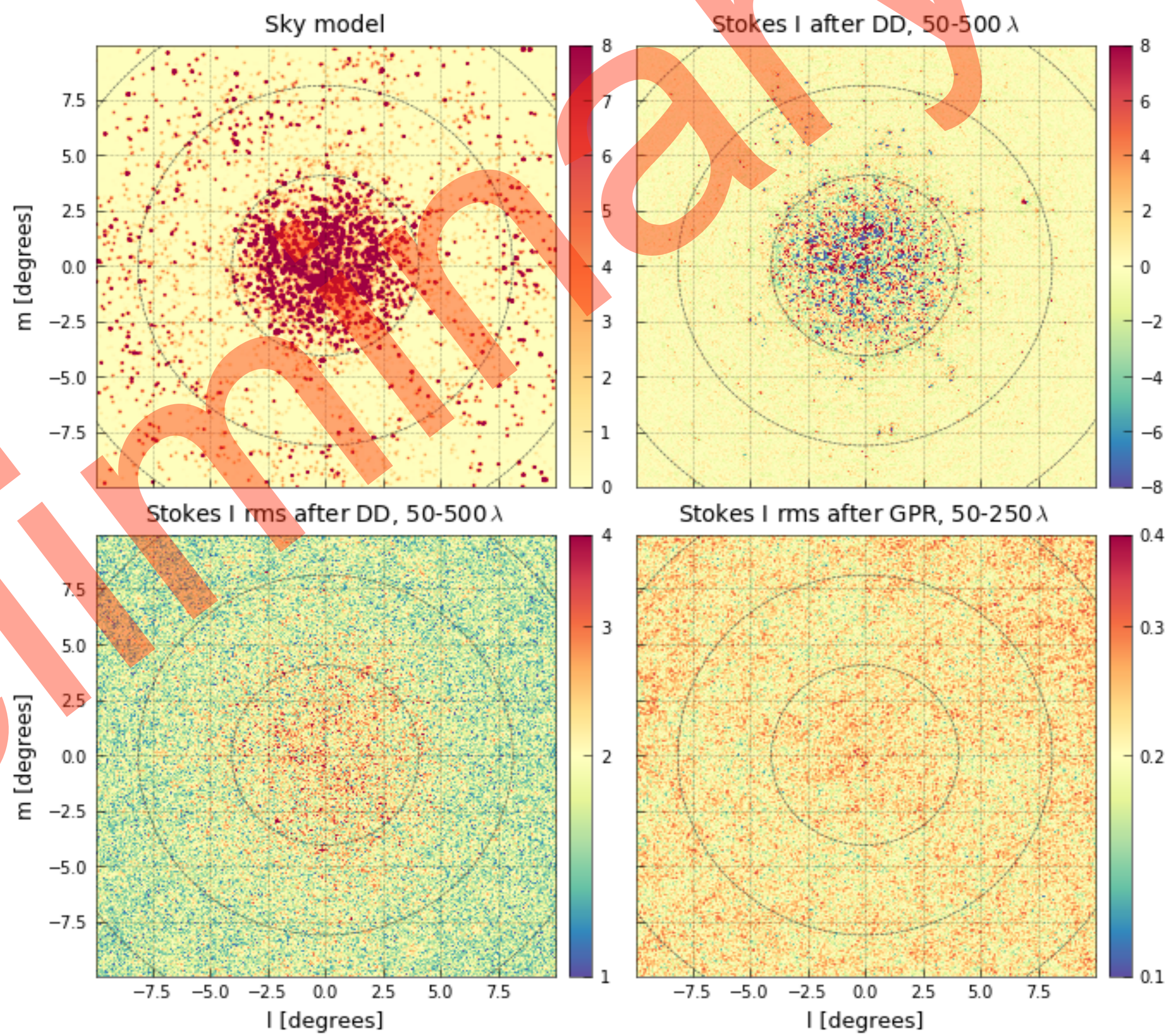
Image of the NCP field

From top-left to bottom-right

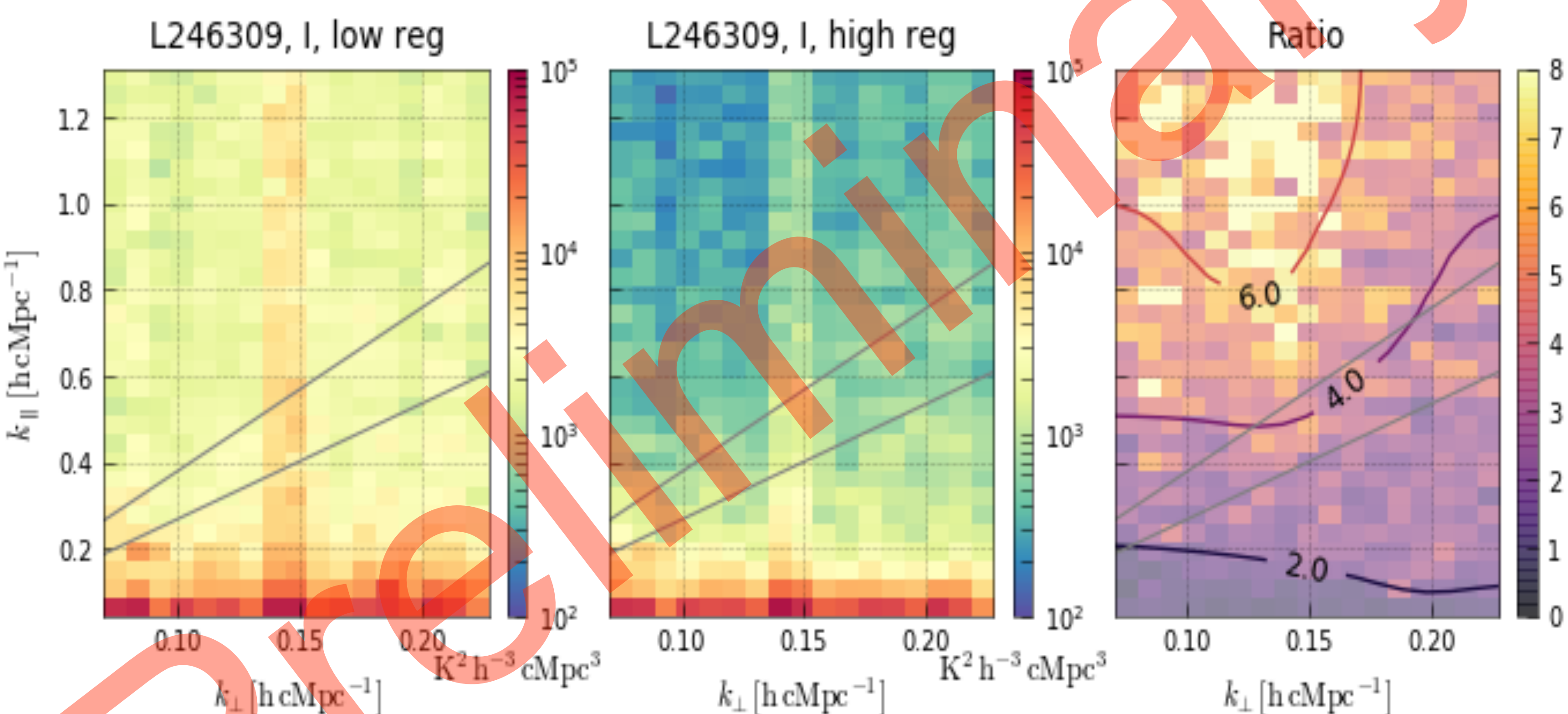
1- the sky-model restored with 6.8 arcmin gaussian beam, the mean over frequencies residual
2- Stokes I after DD
3- the Stokes I frequency-rms after DD
4-the Stokes I frequency-rms after GPR.

All units are Kelvin

The three circles have diameter of 2, 4 and 8 time the primary beam FWHM (~4 deg)

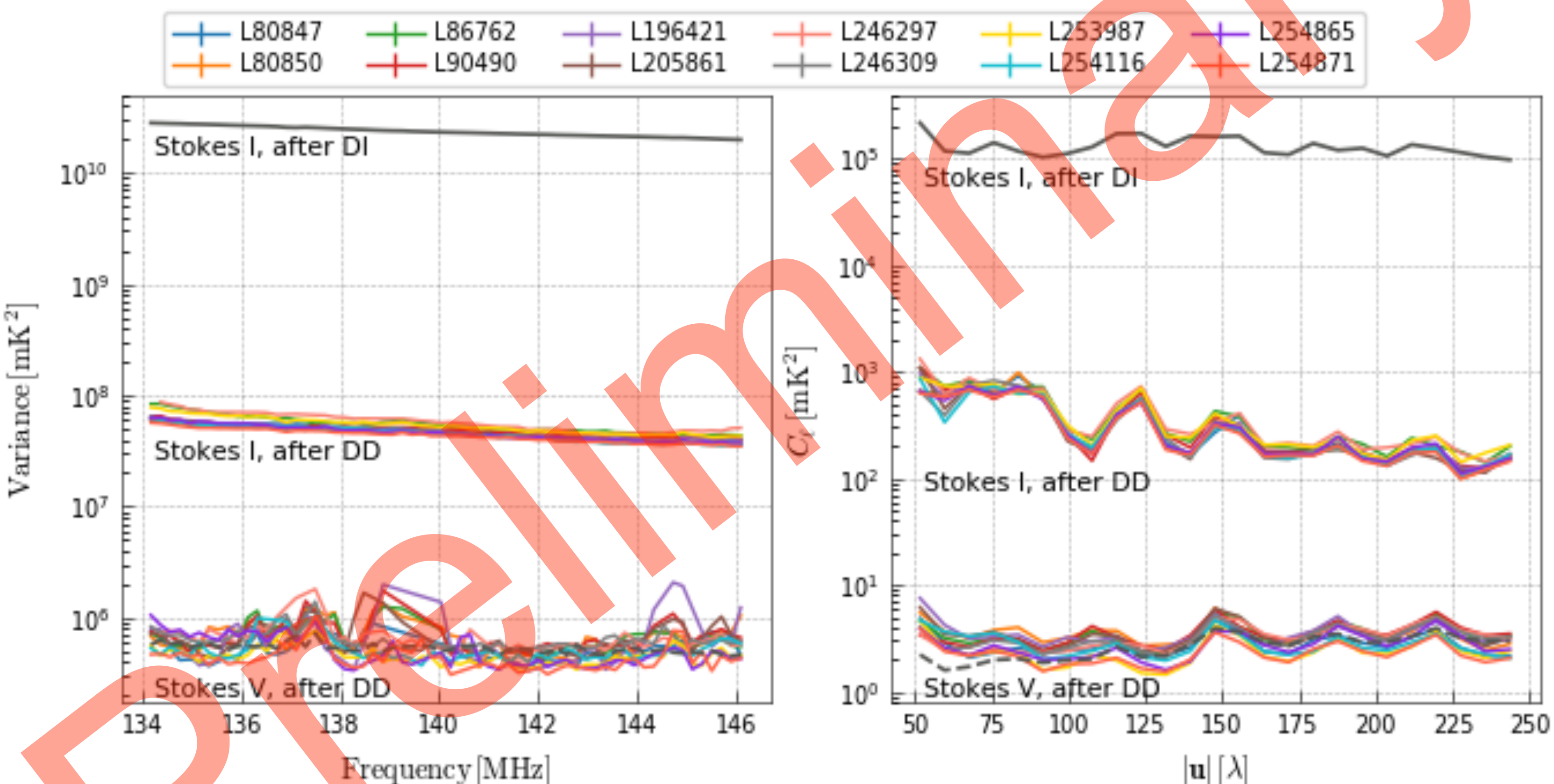


Improvement in calibration:



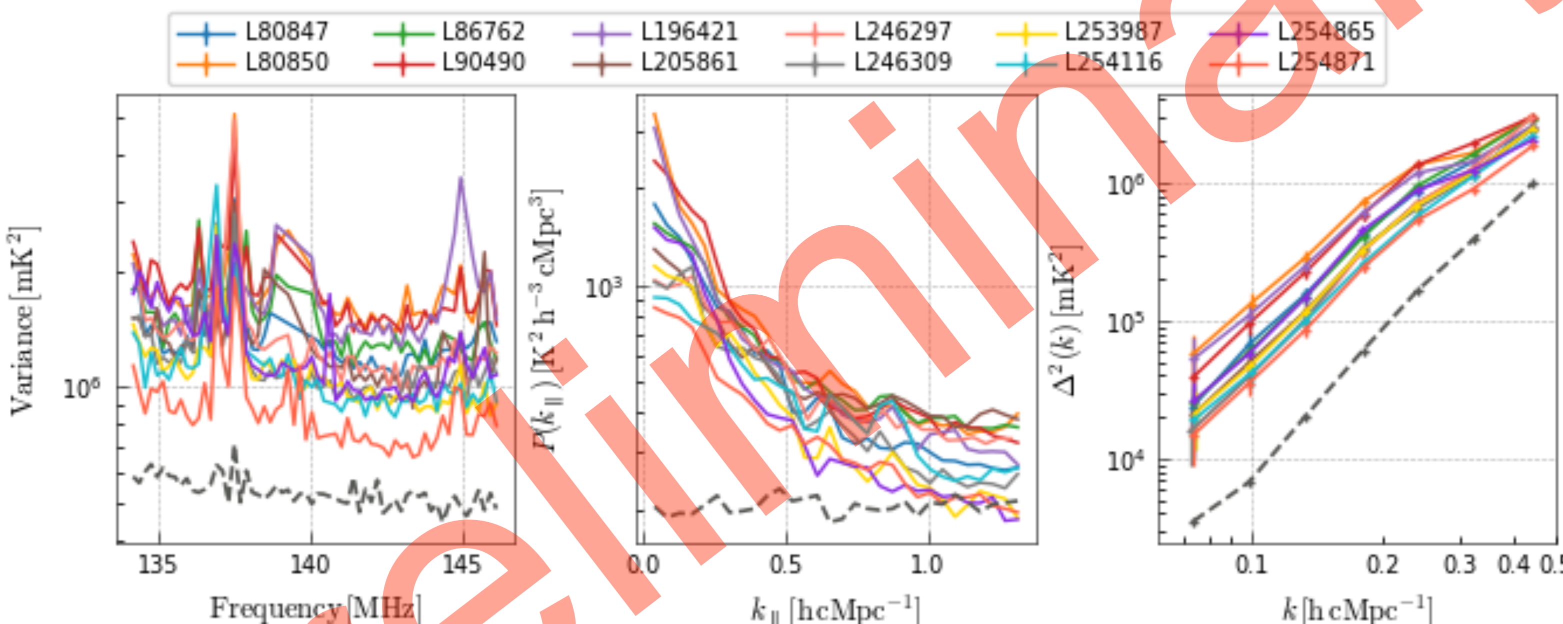
Illustrated by the reduction in power in the 2D power-spectra mainly above the wedge:

The 10 nights



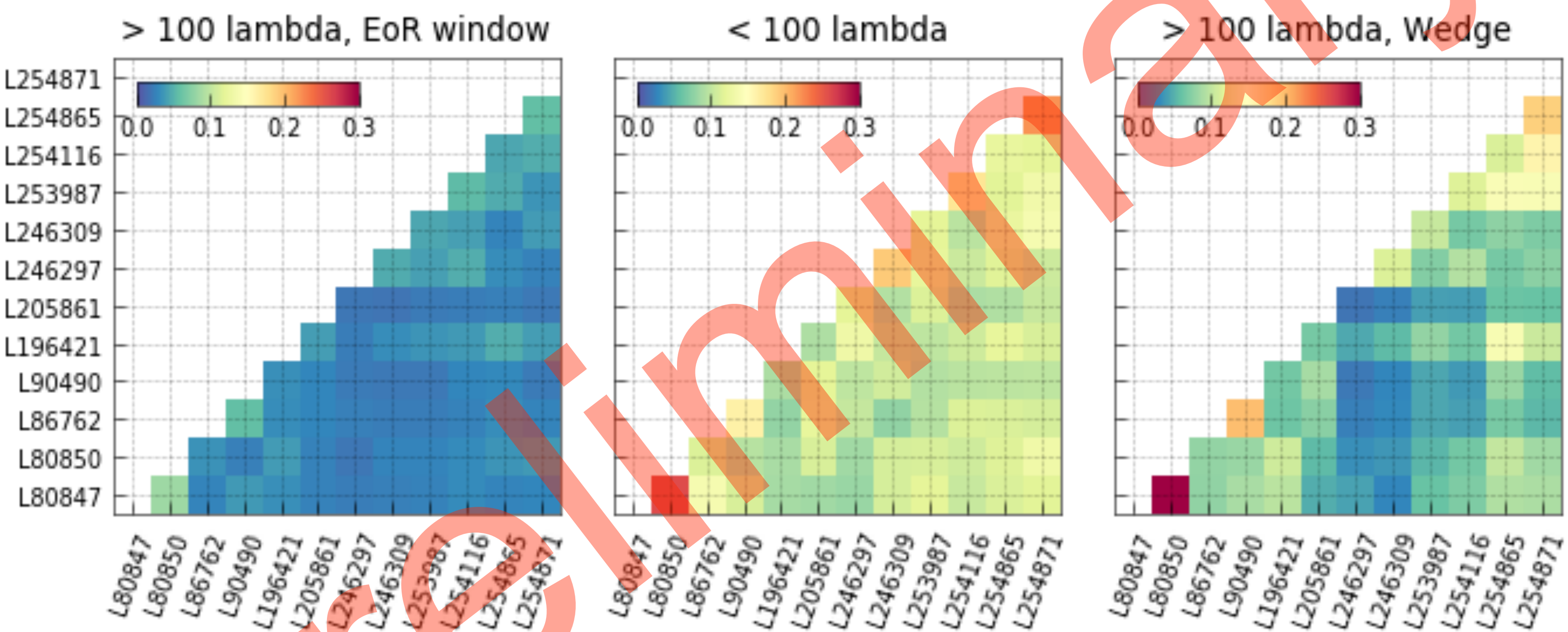
Variance and angular power spectra of all nights Stokes I DI, Stokes I DD and Stokes V + simulated Thermal noise of mean observing time (14h) and mean SEFD (4158 Jy)

Night by night analysis after FG (GPR) fitting

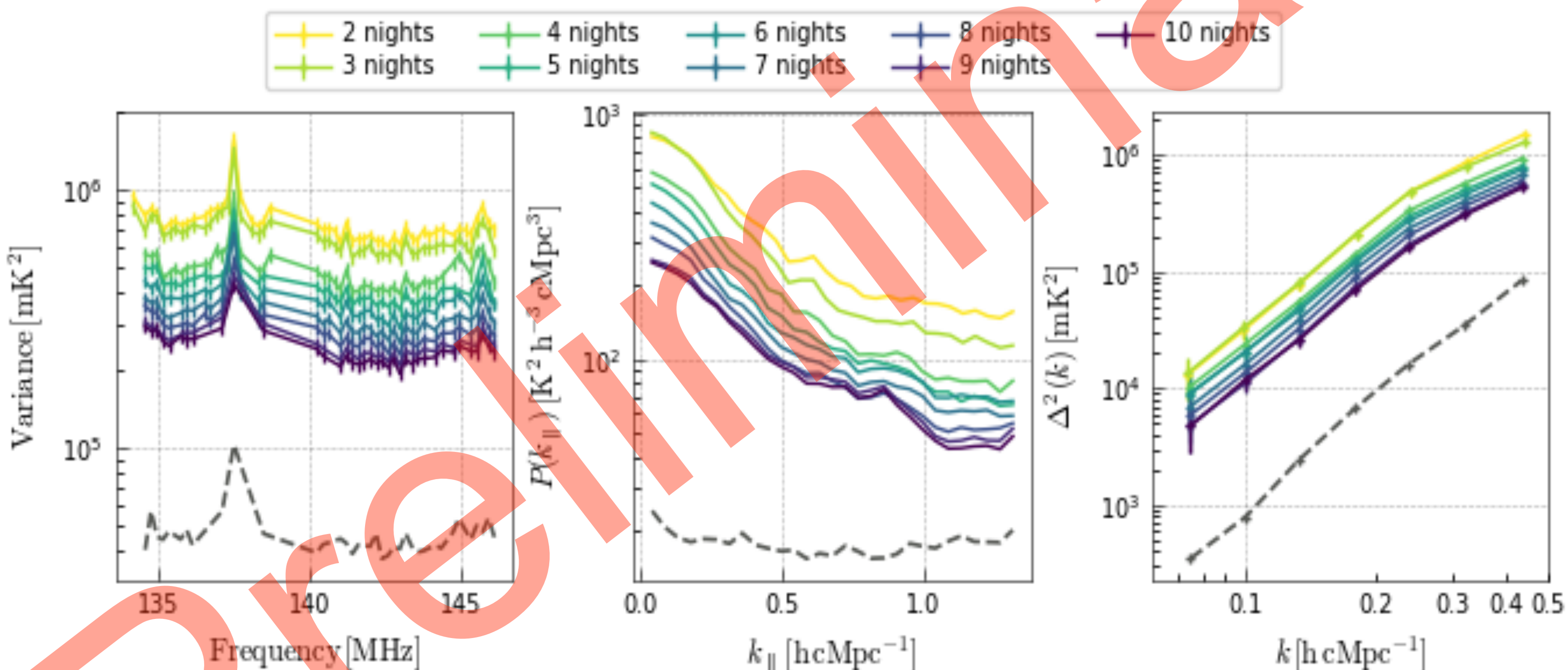


- Residual power after GPR differ from night to night
- At large k_par, residual power is very close to thermal noise level
- There is an excess power with coherence-scale ~ 0.3 MHz which is not removed by GPR. This might be due to calibration errors at DI or DD step.

Correlations between nights

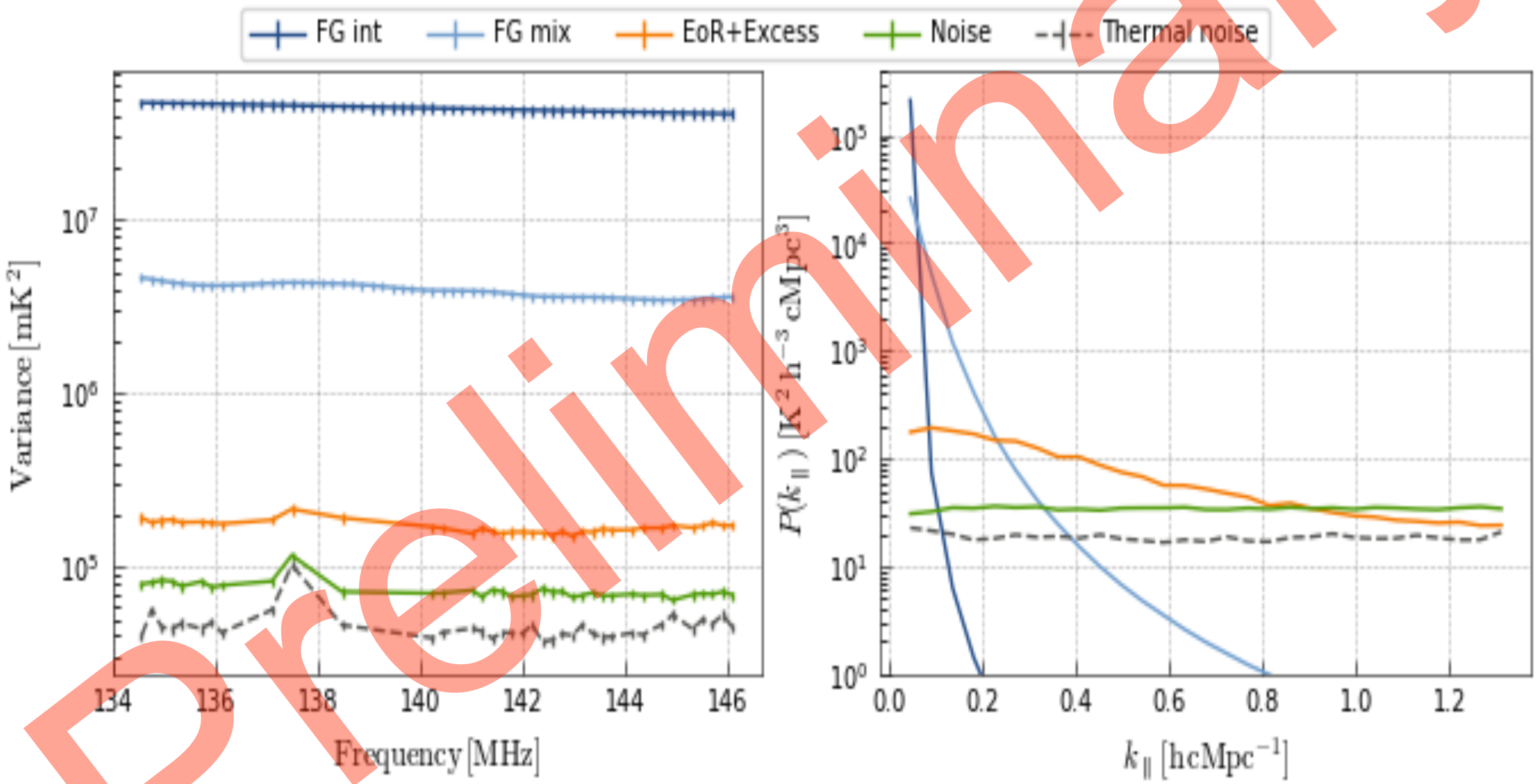


Residual power after FG fitting as we combined the 10 nights



Variance, P(k) as function of k_par and spherically averaged PS of the residual after GPR as we combine the 10 nights

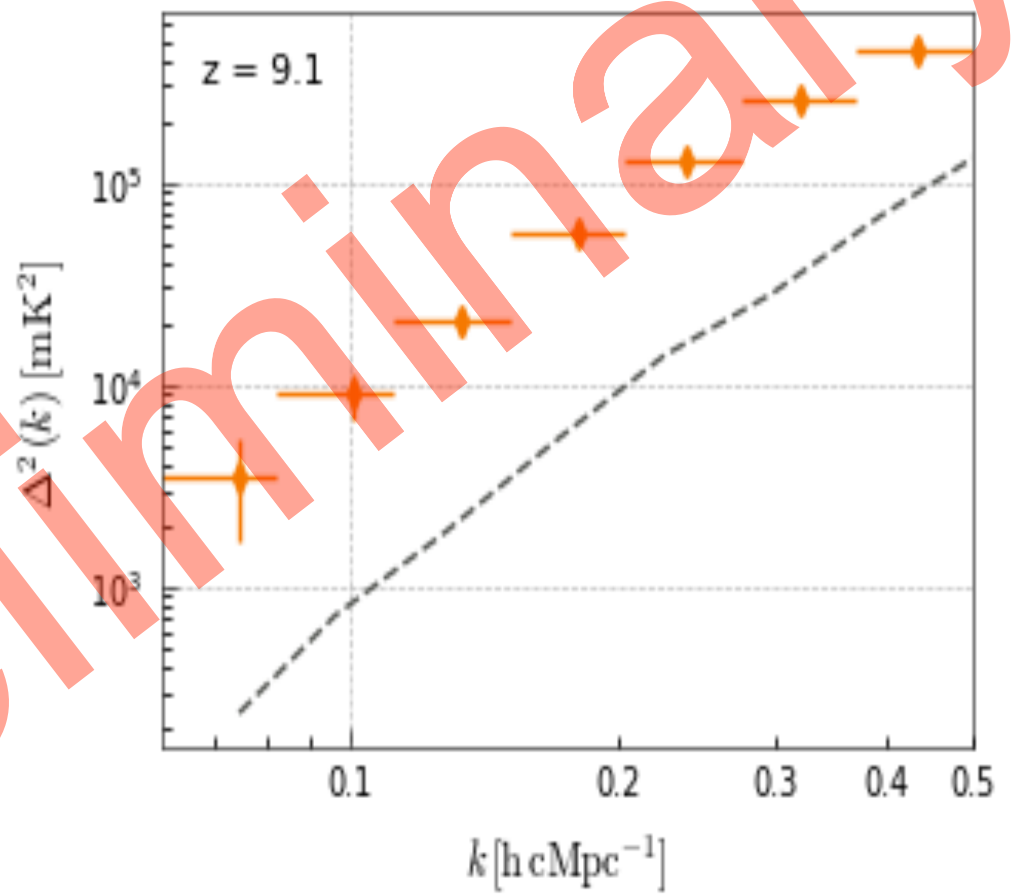
GPR detail results on the 10 nights



Variance and P(k) as function of k_par of the different GPR components

Spherical power spectra for 10 nights

Upper limits (2 sigma) are:
At k ~ 0.075: $\Delta^2 < 72.4^2$ mK^2
At k ~ 0.1: $\Delta^2 < 105.4^2$ mK^2



The 1-sigma uncertainty is 2 time the sampling variance of the noise-power + 1 time sampling variance of the noise-unbiased residual power (cosmic variance).

Forecast for 1500 hours.

Detection levels of ~few mK can be reached with the data in hand (on NCP alone) in a dk~k (1 dex) range for k~0.1).

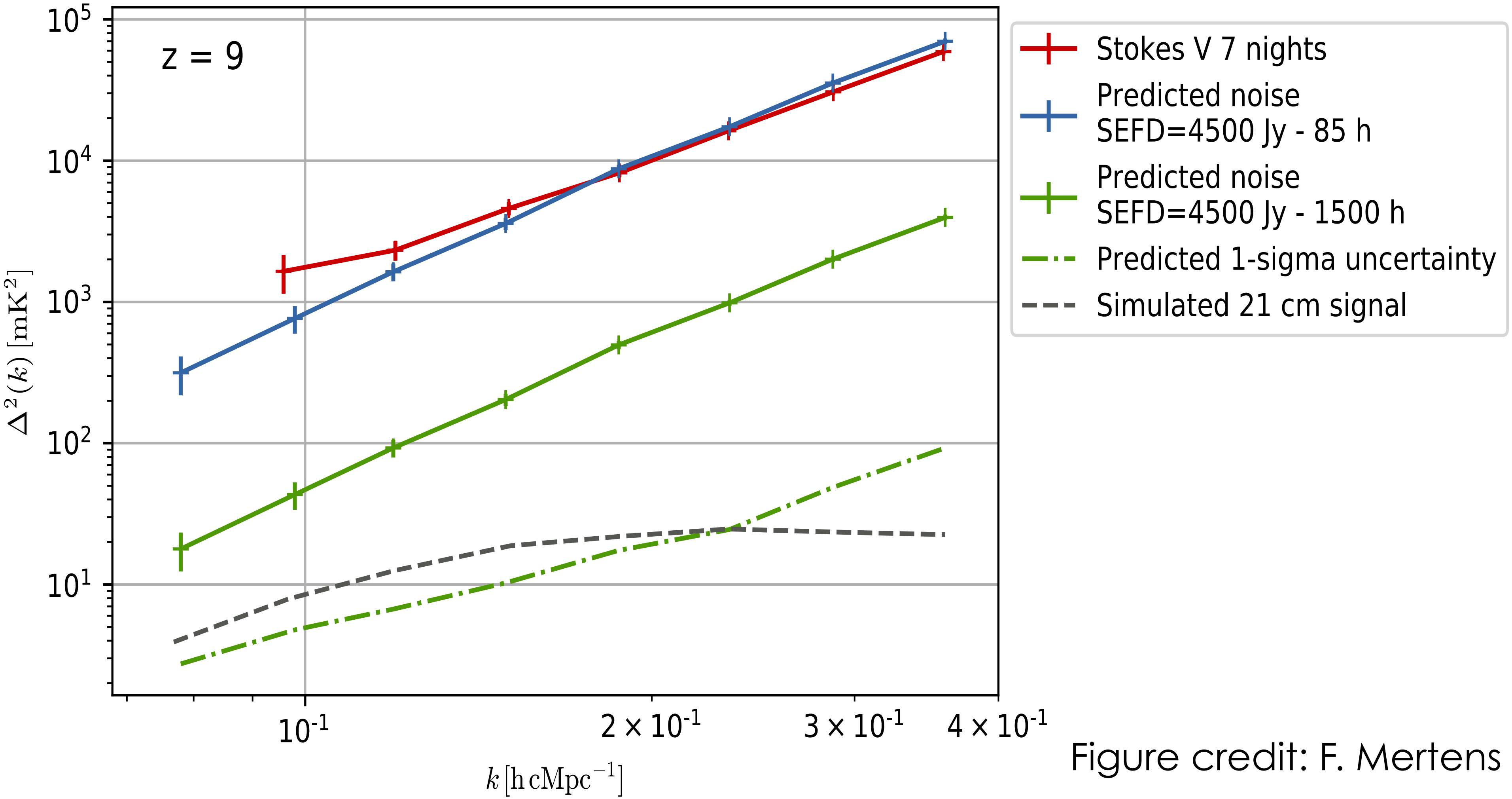


Figure credit: F. Mertens

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 and we can finally show 10 nights power spectrum.

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.