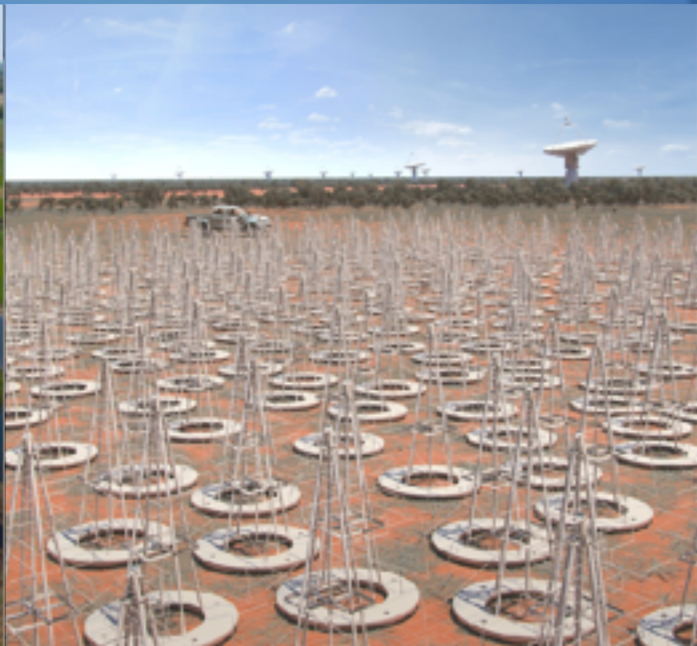
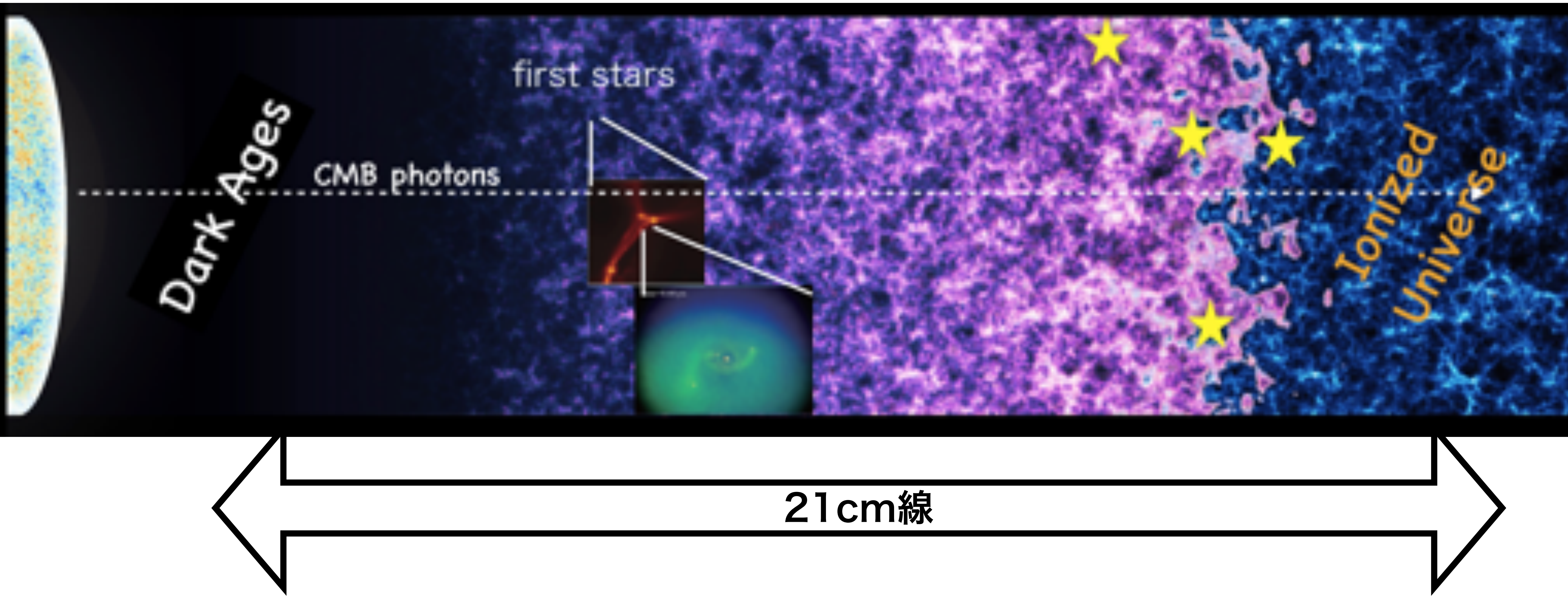
電波干渉計による 21cm線観測の困難

吉浦 伸太郎 (熊本大学)



21cm line as a probe of high-z

Credit : K Hasegawa

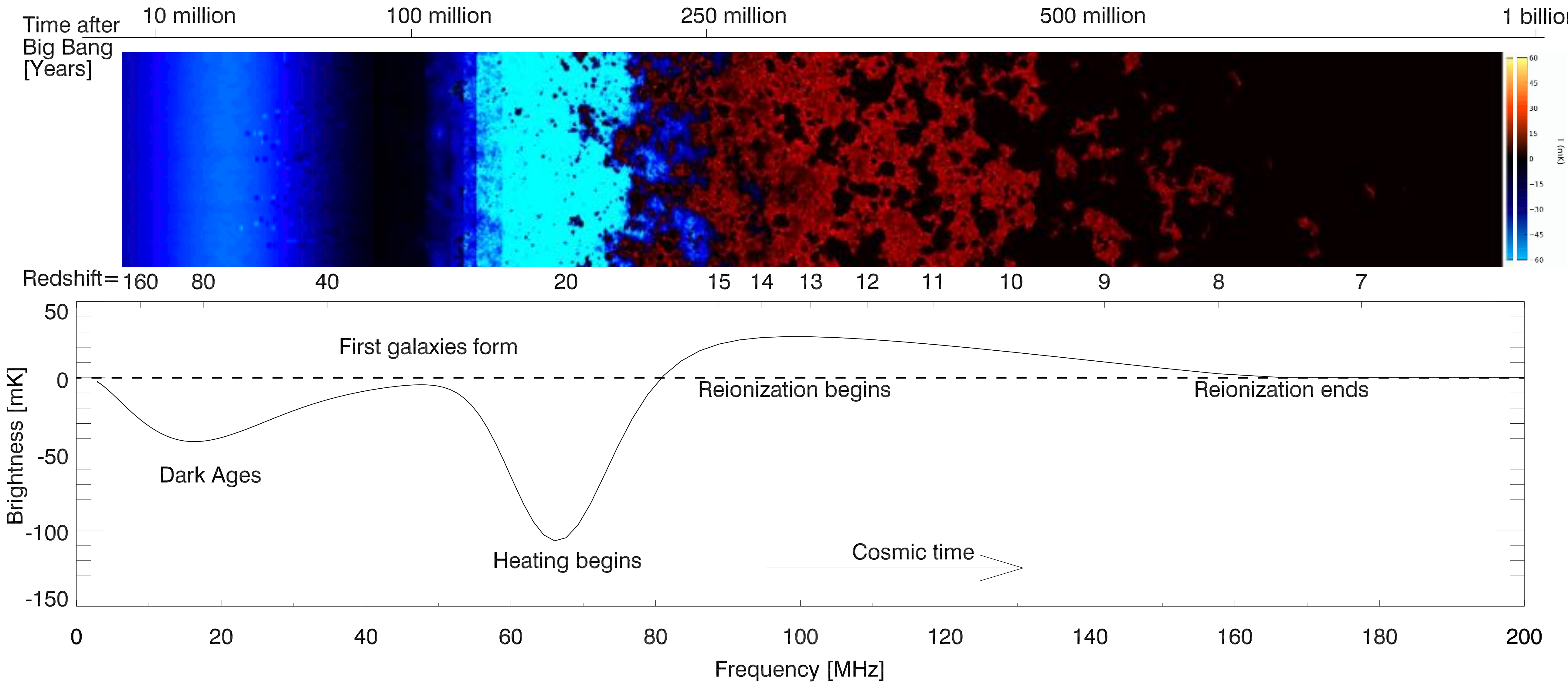


・21cm line is a powerful tool to study the Epoch of Reionization and the Cosmic Dawn.

・Topic of this talk is the observation of the 21cm line using the radio interferometer.

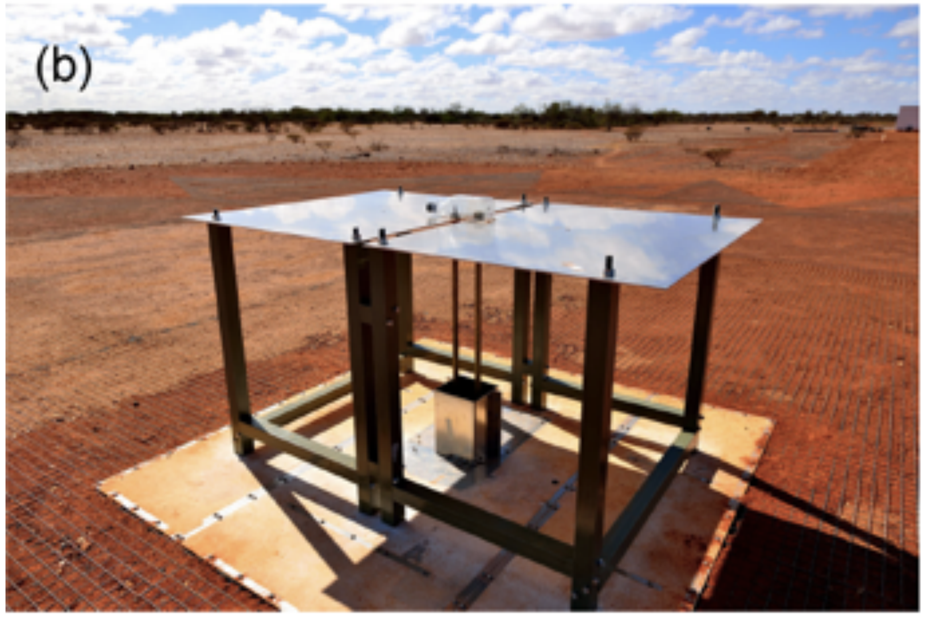
① : 21cm global signal

Global signal is averaged spectrum in wide field of view.
Instruments should detect the 21cm emission and absorption in the spectrum.



Credit : Pritchard & Loeb 2012

Radio instruments for GS

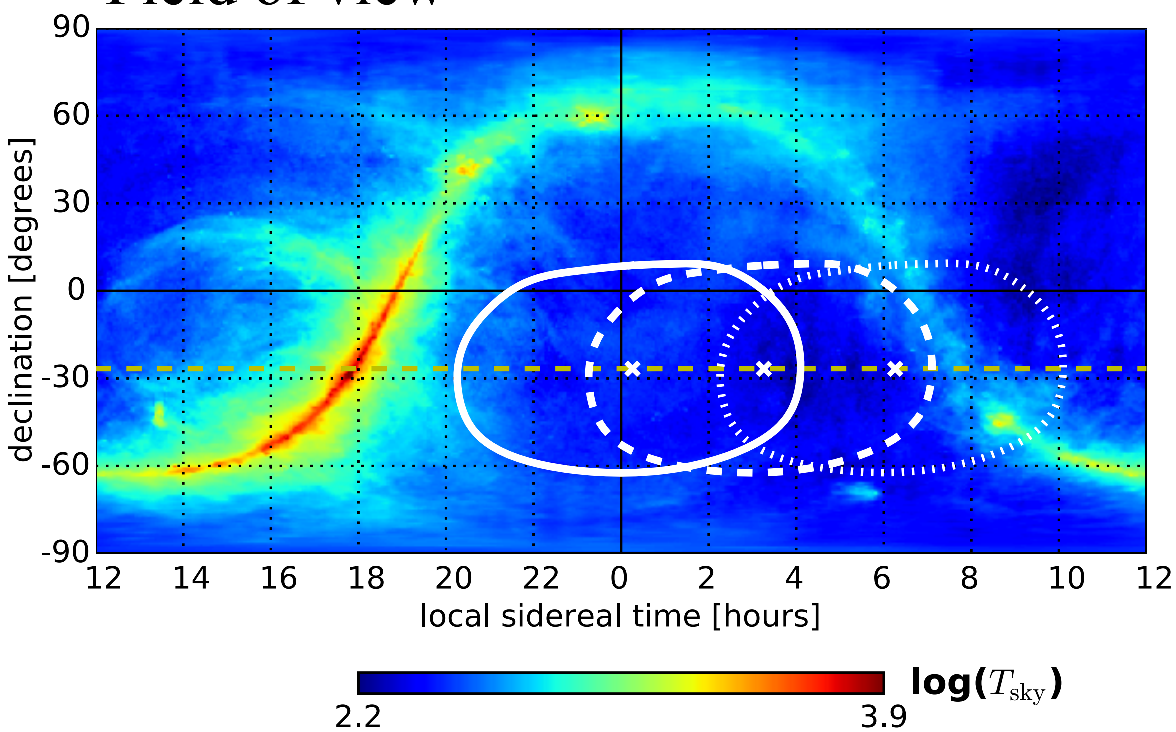


Credit : Bowman+2018

EDGES

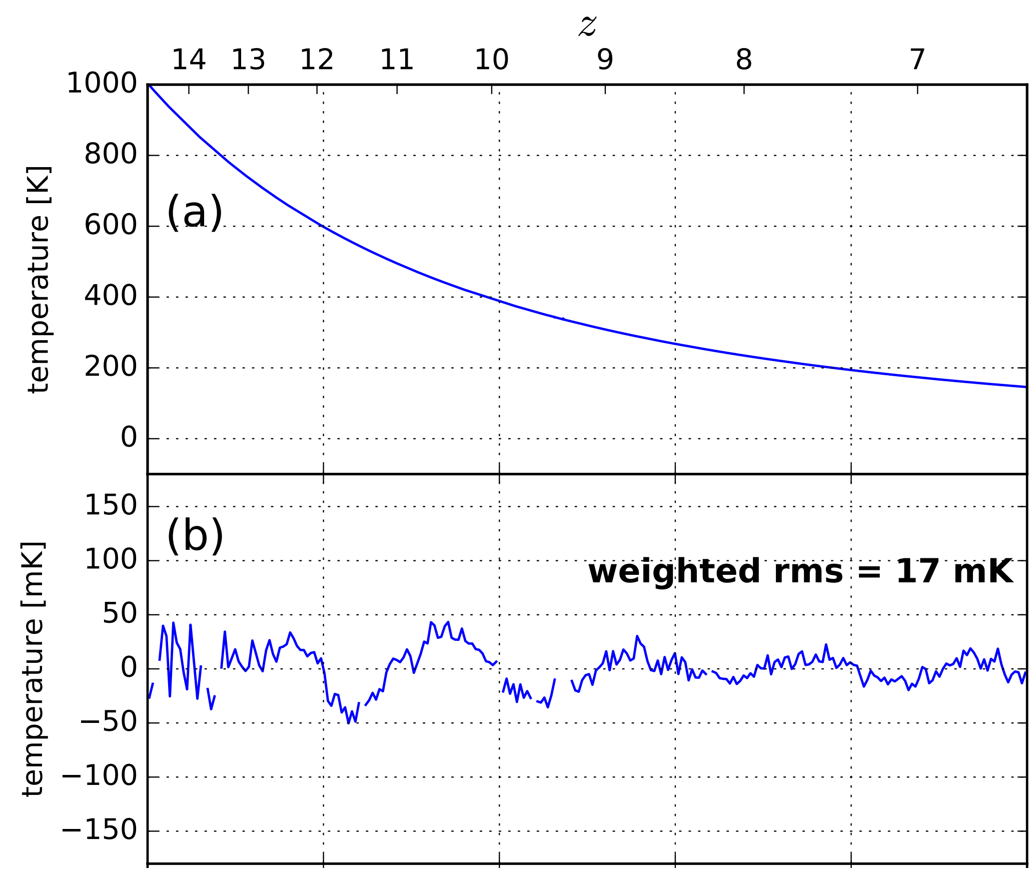
One of instruments which measures the global signal.

Field of view



Credit : MONSALVE+2018

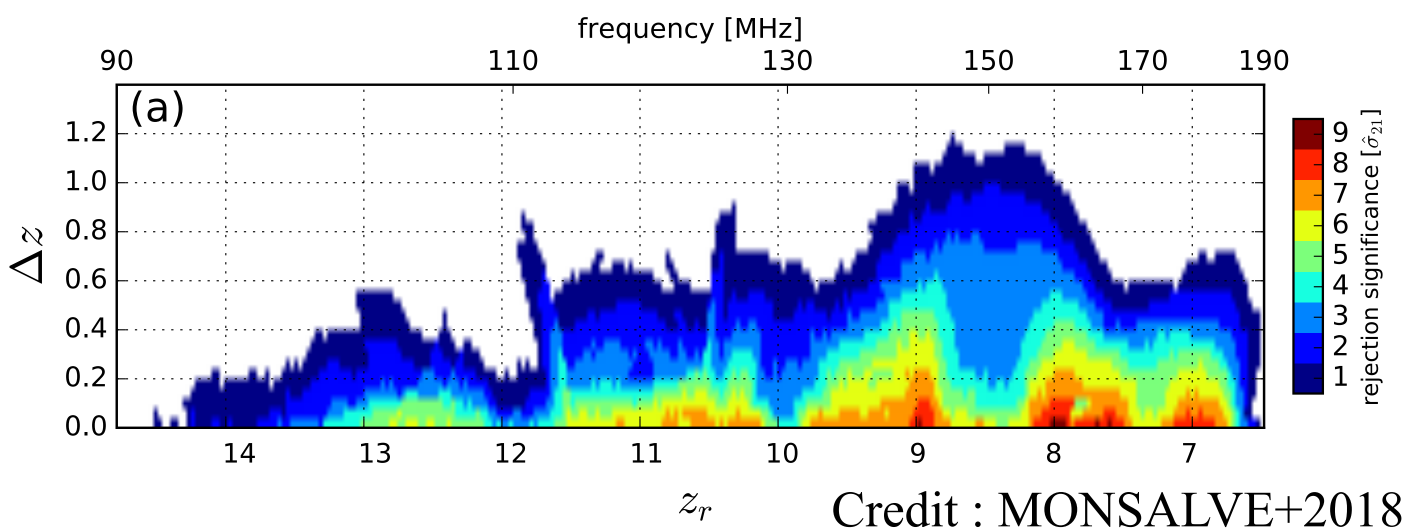
An example of actual data



Credit : Bowman+2018

Global Signal : constraints

- EDGES high band : constraints on reionization models



Credit : MONSALVE+2018

- EDGES low band : detection a powerful absorption

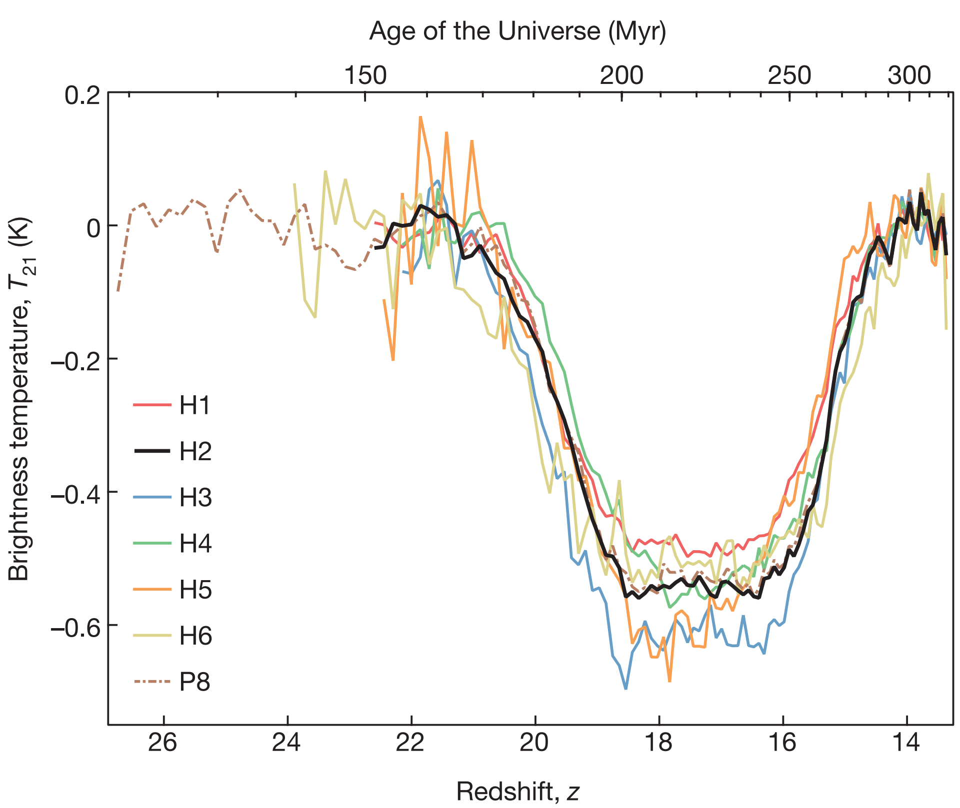
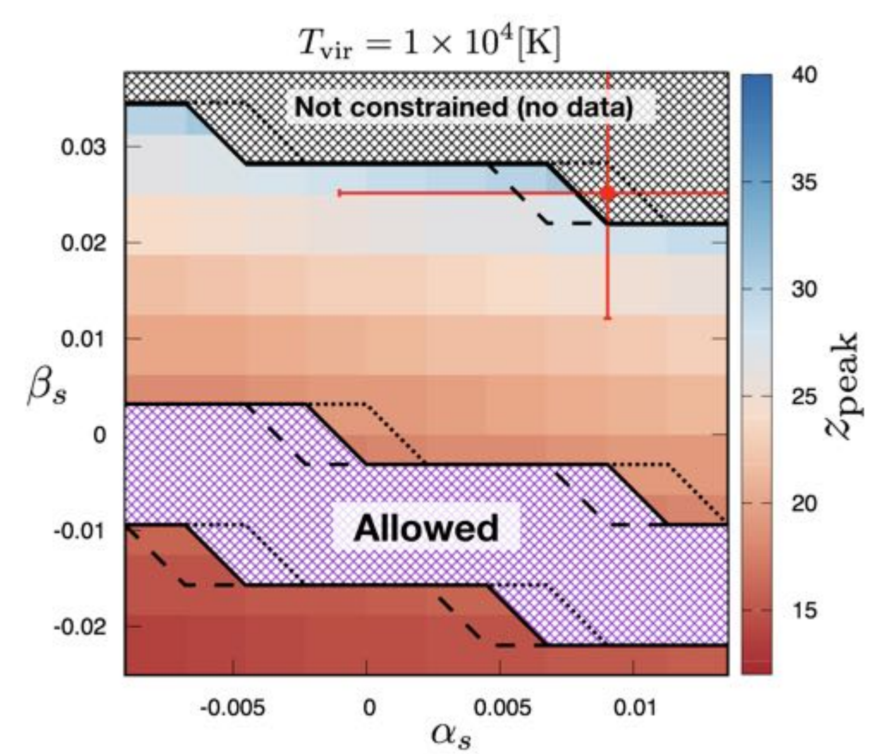


Figure 2 | Best-fitting 21-cm absorption profiles for each hardware case.

Credit : Bowman+2018

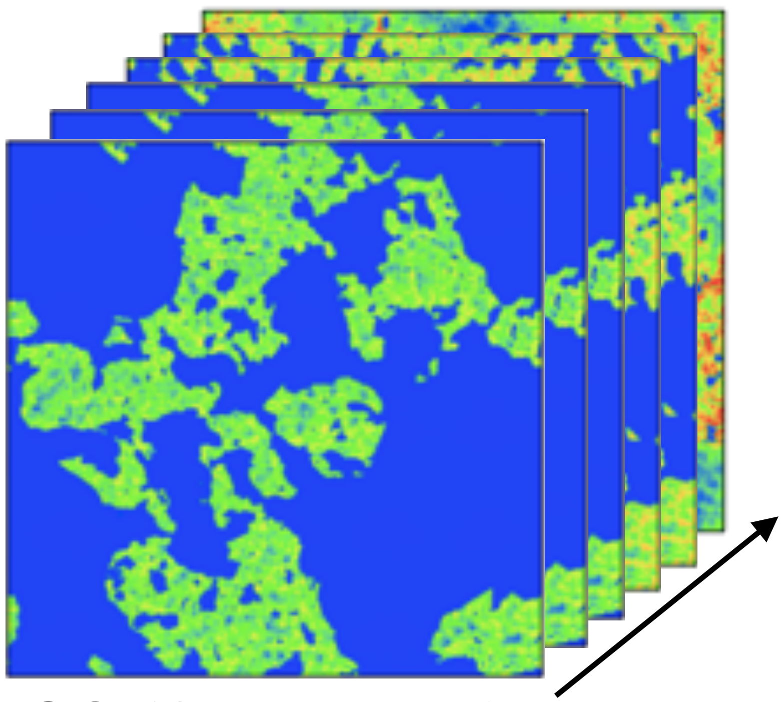
Inspired papers :
Barkana 2018, Fialkov+2018,
Berlin+2018, Fraser+2018,
Hirano&Bromm 2018, etc



SY +2018

② : fluctuation

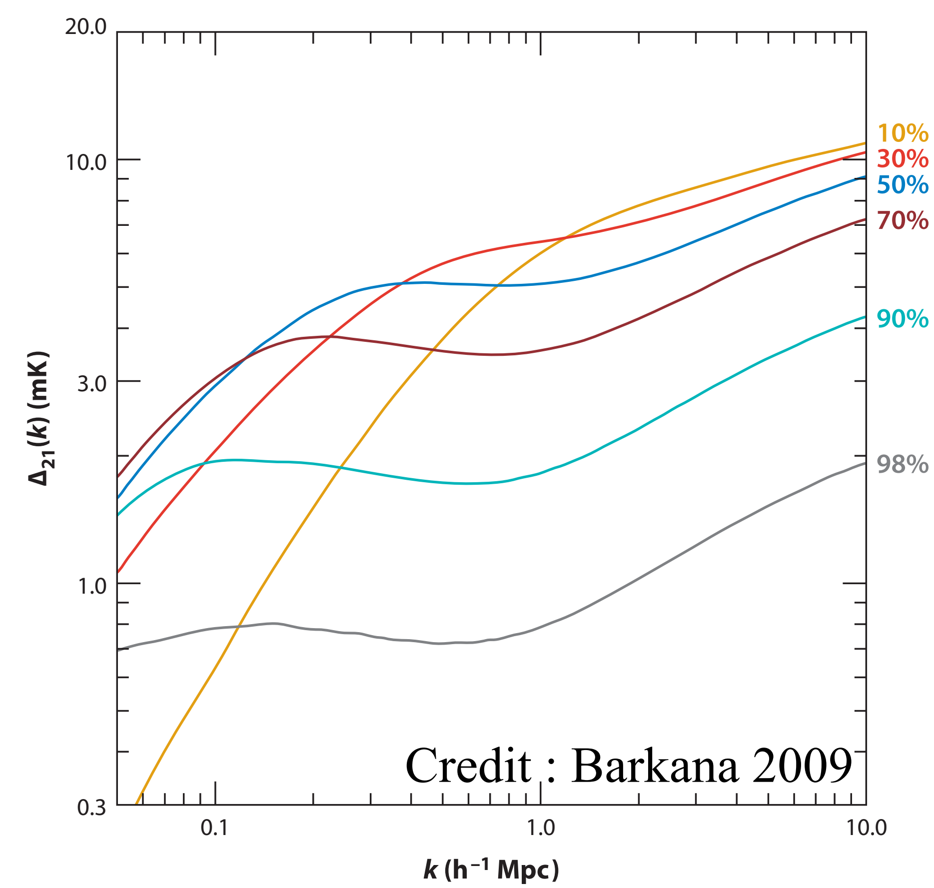
- Ideally, 21cm line will be imaged.
- Statistical analysis is required to increase sensitivity for ongoing telescopes.

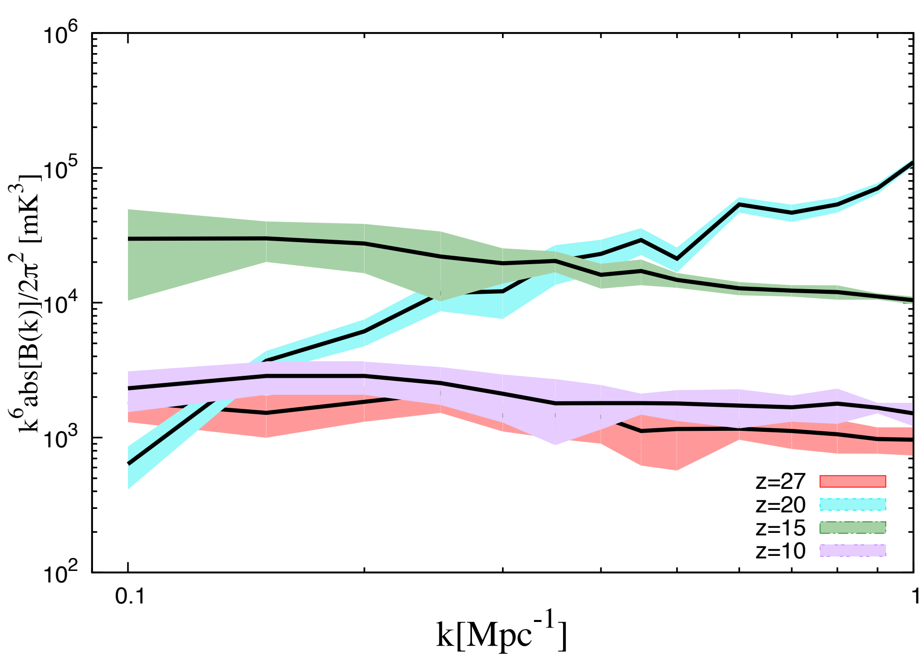


LOS (frequency) $\propto 1 + z$

Power spectrum

$$\langle \delta_{21}(\mathbf{k})\delta_{21}(\mathbf{k}^{'})\rangle = (2\pi)^3\delta(\mathbf{k}+\mathbf{k}^{'})P_{21}(\mathbf{k})$$





Bispectrum

$$\langle \delta_{21}(\mathbf{k}_1)\delta_{21}(\mathbf{k}_2)\delta_{21}(\mathbf{k}_3)\rangle = (2\pi)^3\delta(\mathbf{k}_1+\mathbf{k}_2+\mathbf{k}_3)B(\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3)$$

Credit : Shimabukuro,SY+ 2016

Radio Interferometers

- Output : visibility

$$V_{m,n}(\nu) = \int I_\nu(\boldsymbol{s}) \exp\left[2\pi i \left(\frac{\boldsymbol{D}\cdot\boldsymbol{s}}{\lambda}\right)\right] d\Omega$$

I_ν : intensity

$\mathbf{D}$: baseline of a pair antennae

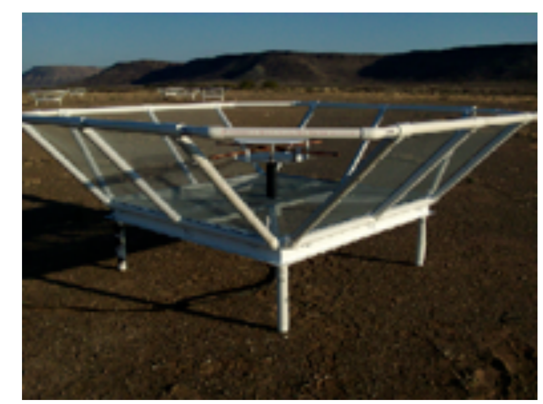
- Primary purpose : measurement of the 21cm power spectrum.
- Japan is the member of the MWA.

MWA

Credit : Natasha Hurley-Walker

LOFAR

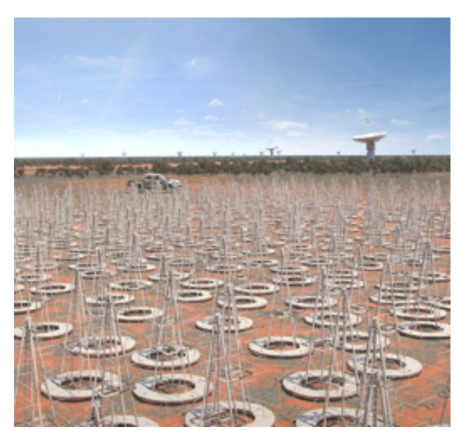
Credit : LOFAR/Astron



PAPER

http://eor.berkeley.edu

HERA Debore+2016

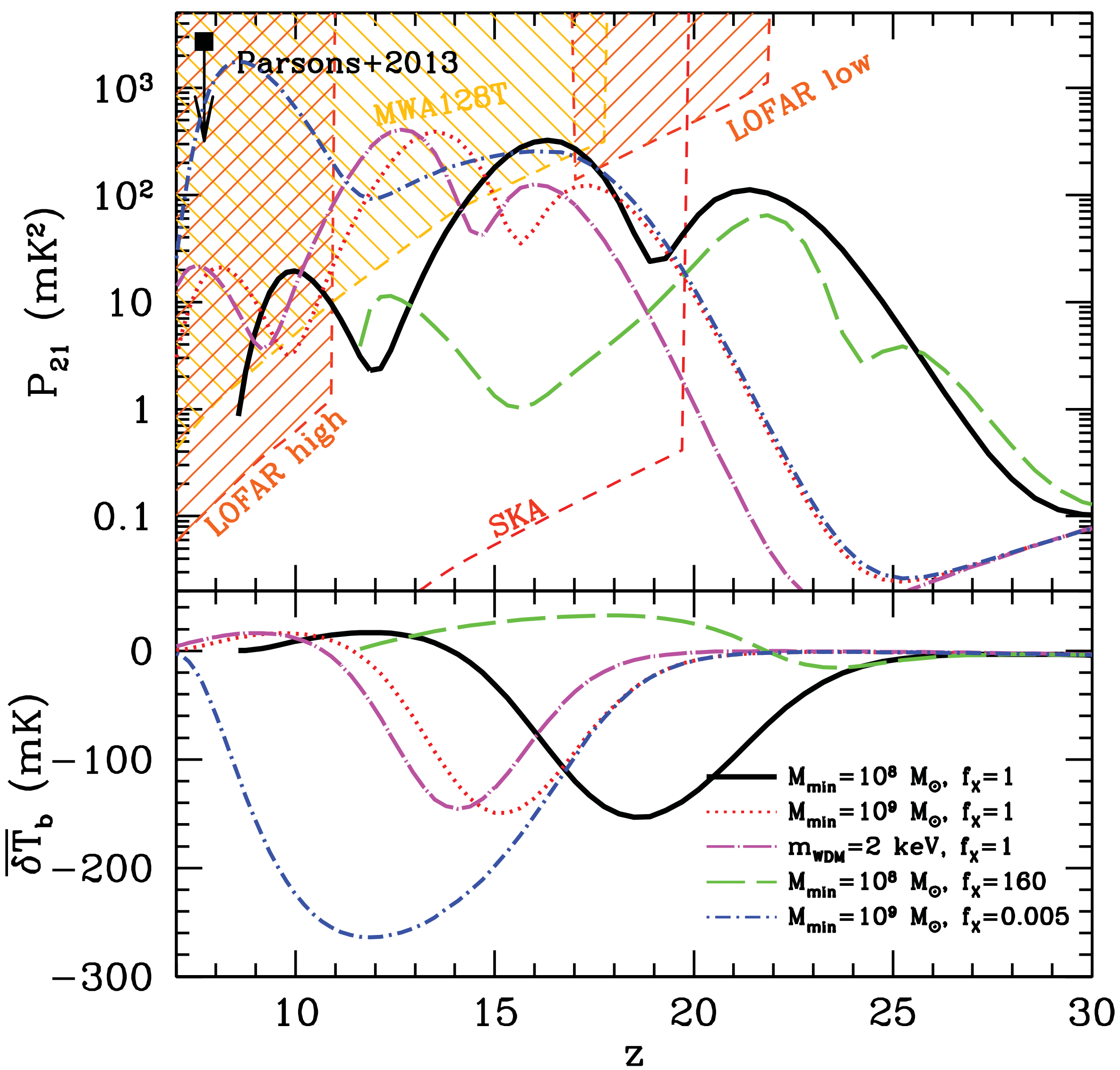


SKA low Credit : SKAO

Sensitivity

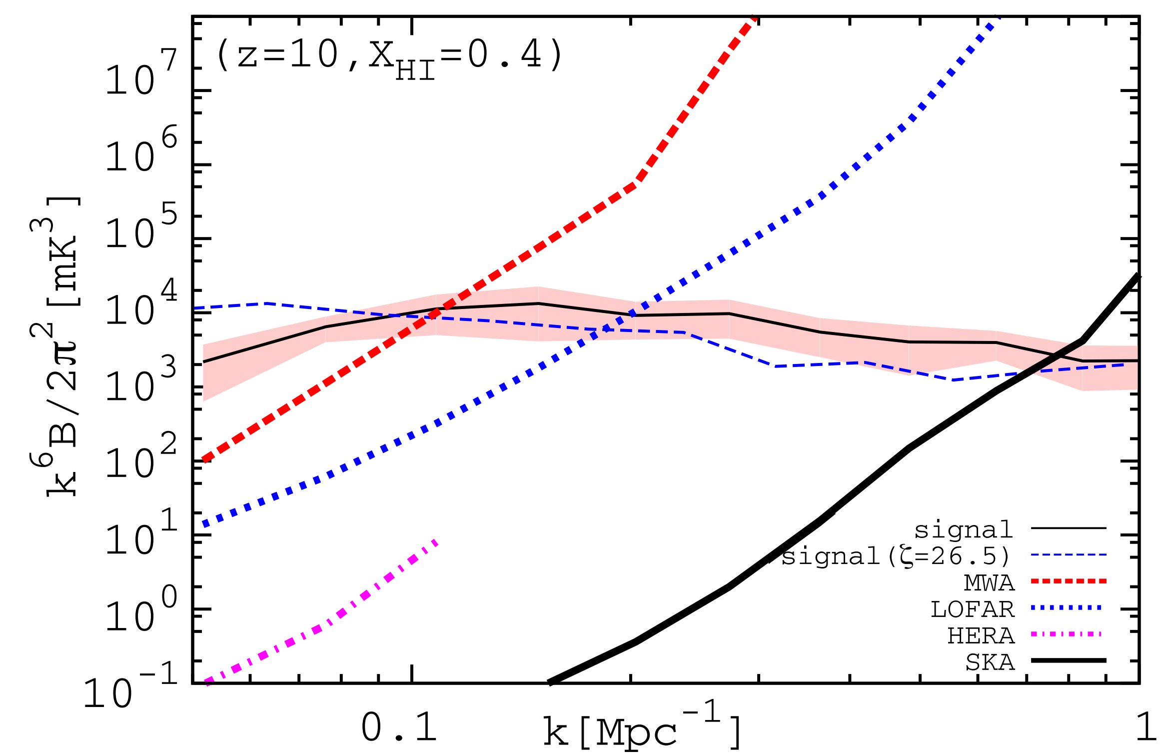
- Ongoing telescopes can detect the 21cm signal with 100-1000 hours of observation.

Power spectrum



Credit : Mesinger+2014

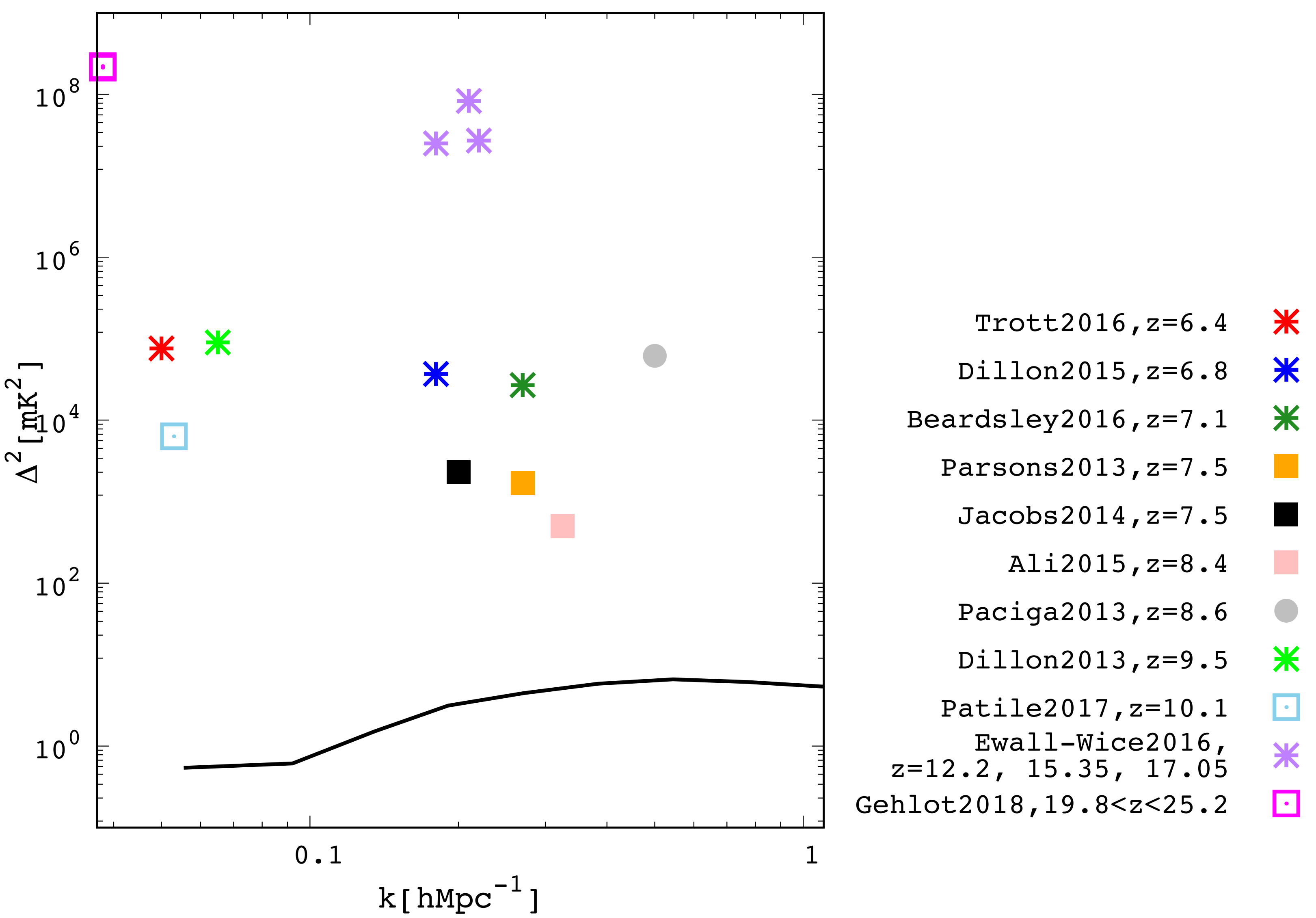
Bispectrum



Credit : SY+2015

Upper limit

- Ongoing telescopes have reported upper limits on the power spectrum.

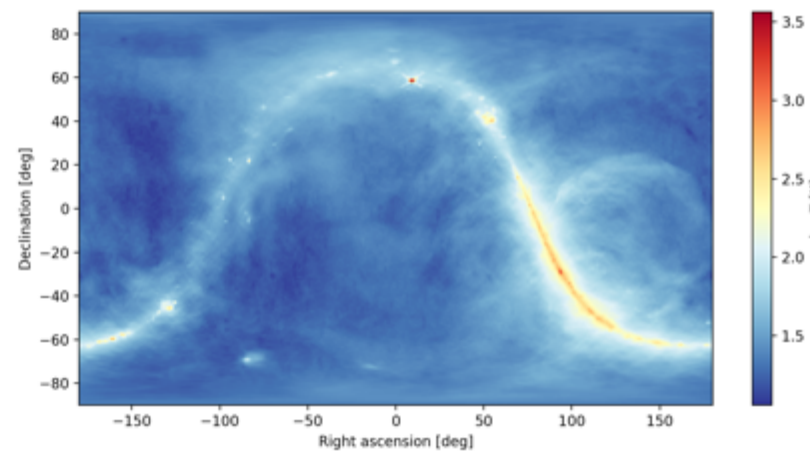


- However, the 21cm PS has not detected yet. This is due to some difficulties.

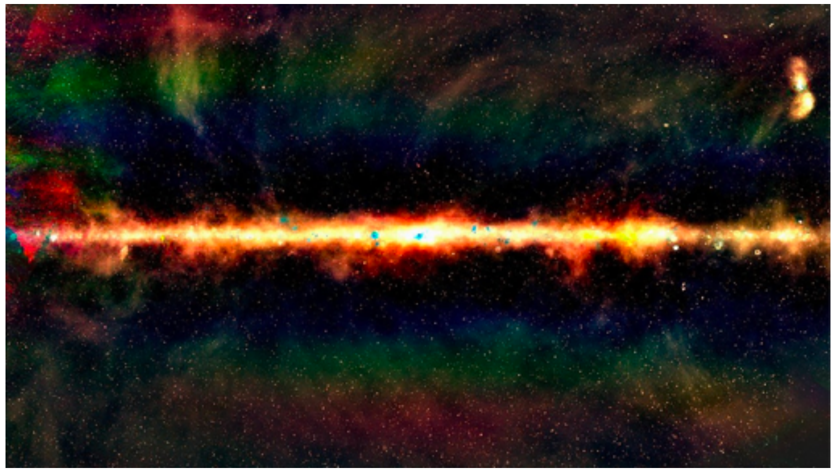
Difficulties

- Galactic foreground
- Extragalactic foreground
- Earth ionosphere
- RFI
- instruments

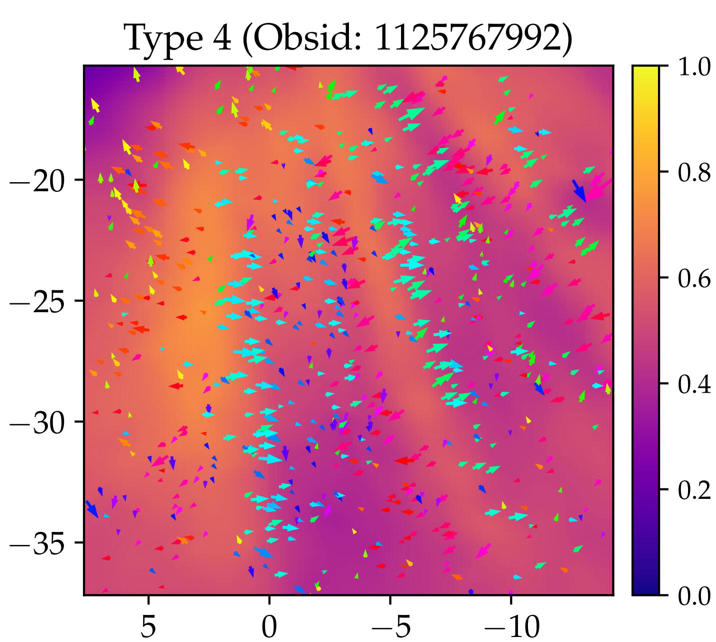
  -Beam
  -Calibration



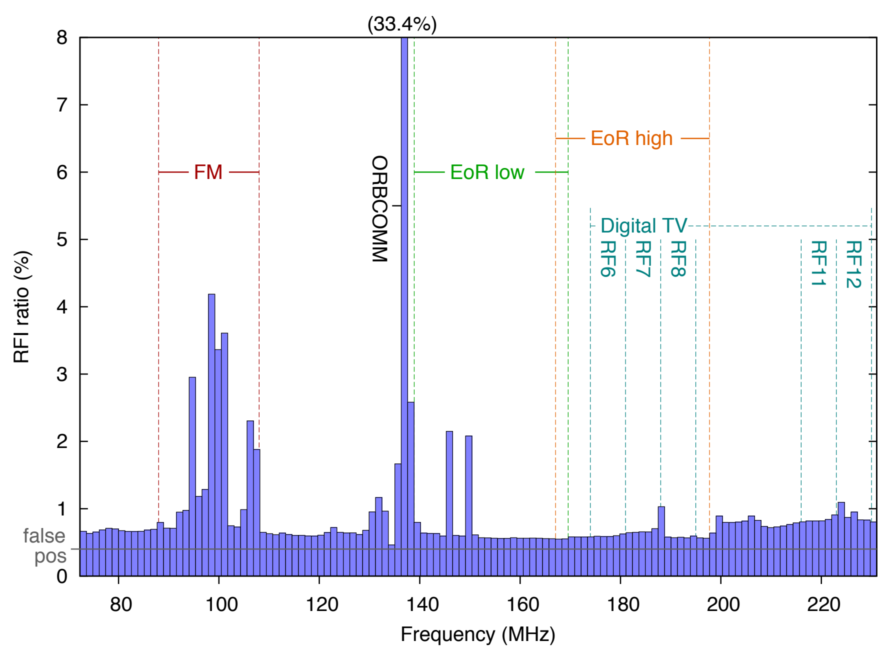
Data credit : Remazeilles+2015



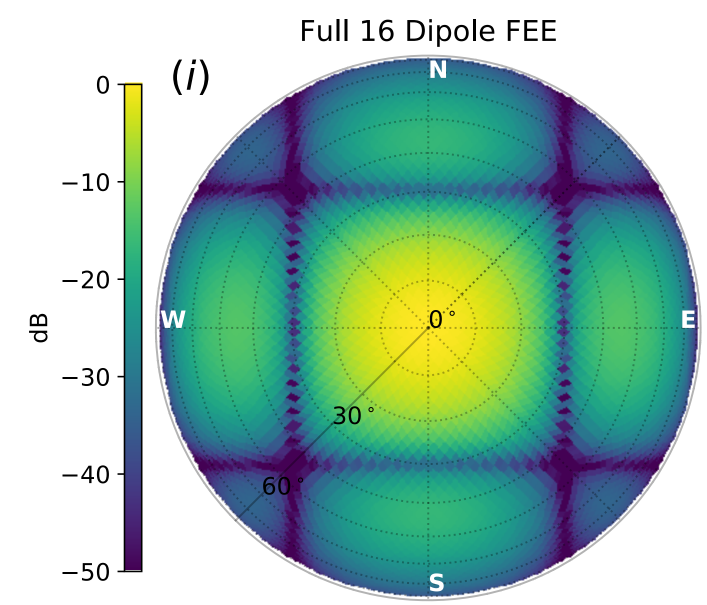
Credit : ICRAR/Curtin



Jordan+2017



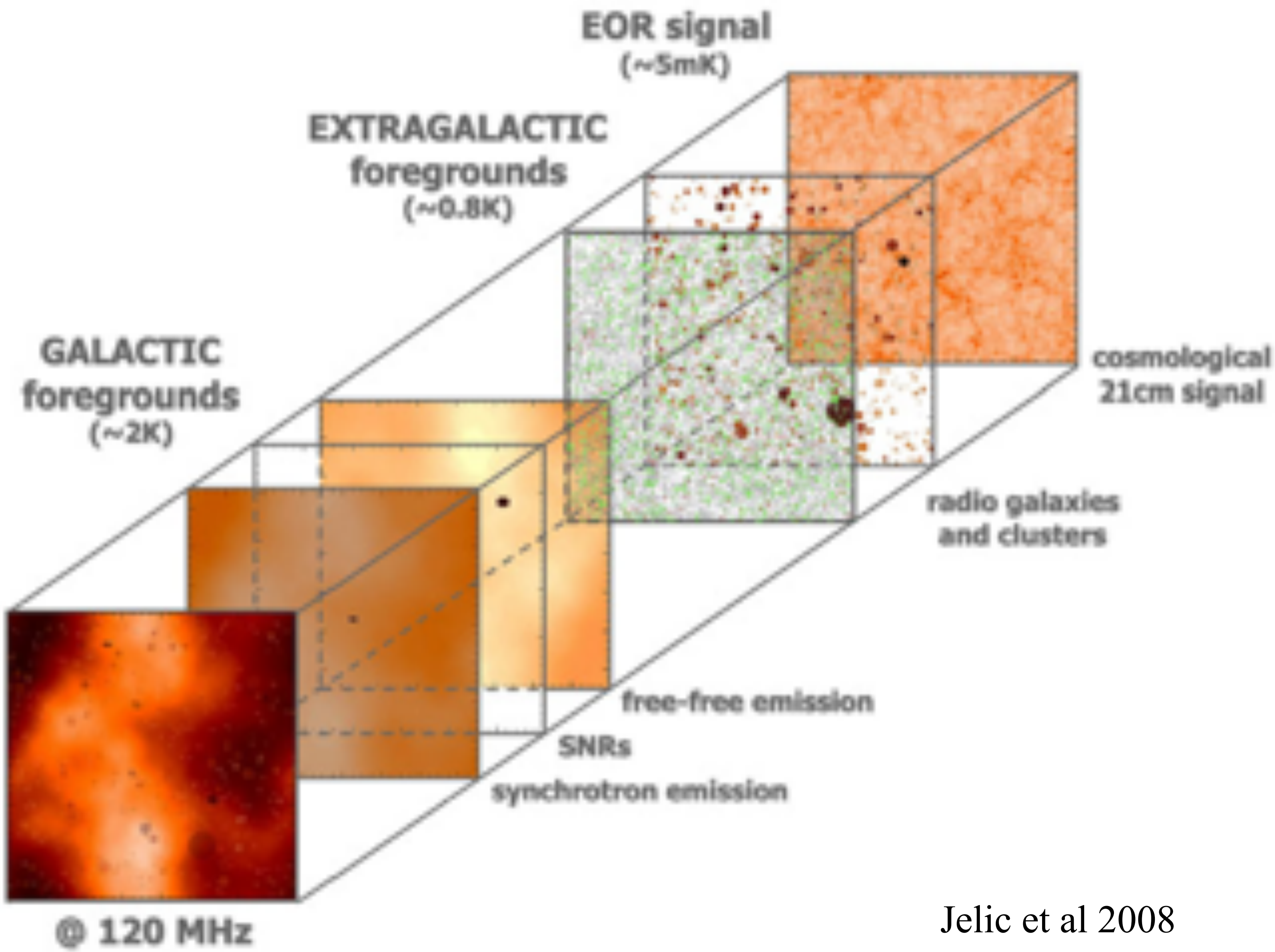
Offringa+2015



Line+2018

Foregrounds

- Foregrounds are 2~4 orders of magnitudes brighter than the expected 21cm line.
- Spectrally smooth emission.

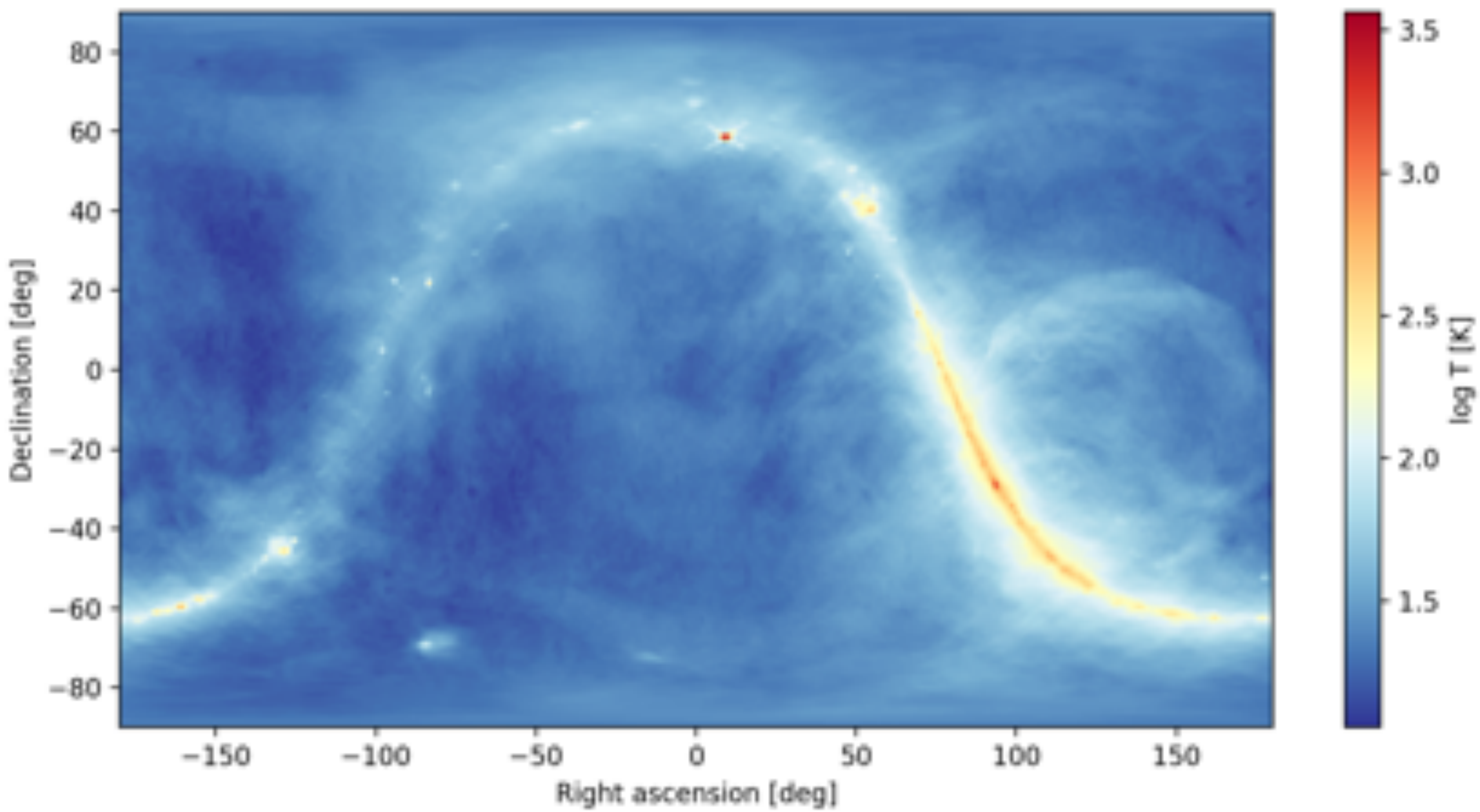


Jelic et al 2008

Galactic emission

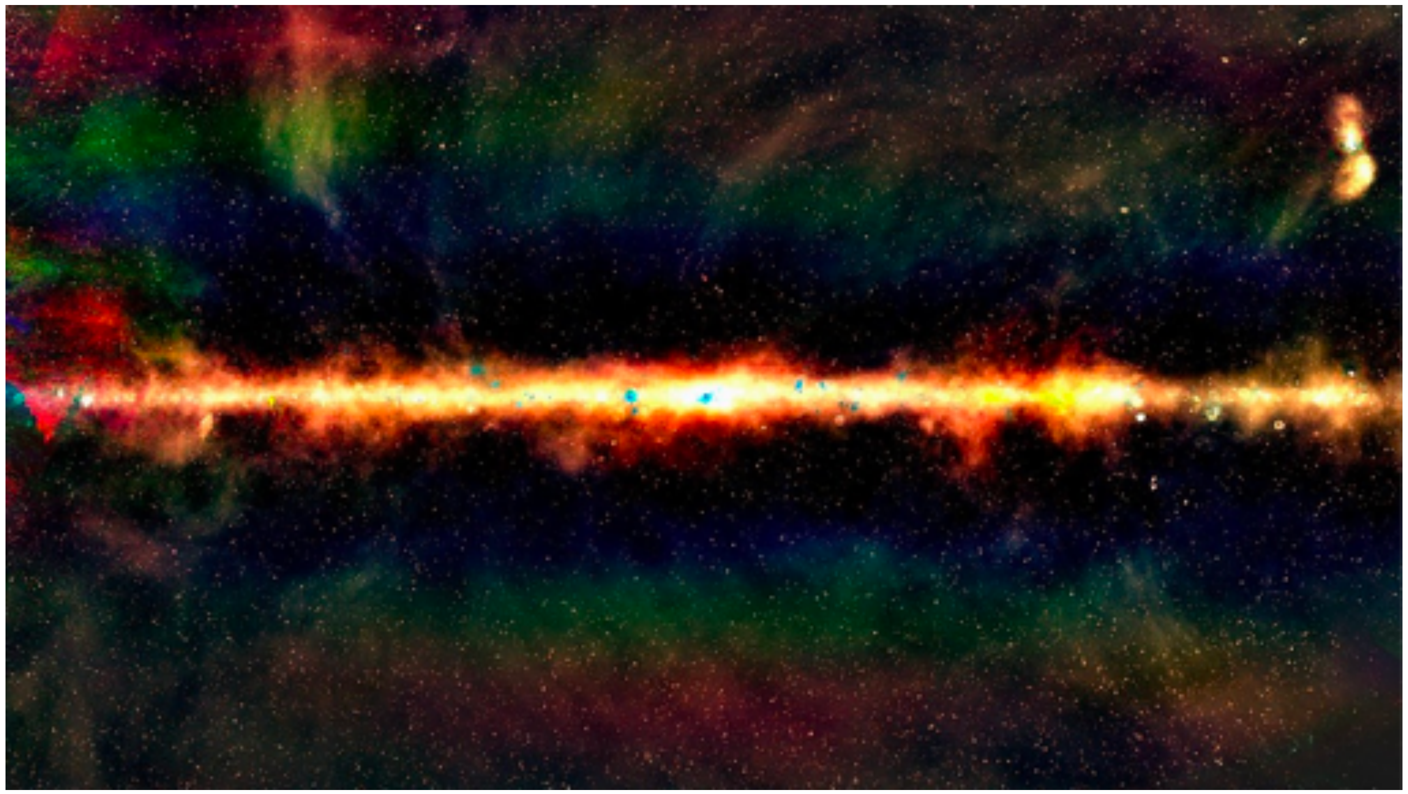
- Synchrotron emission
- Large scale fluctuation
- Modeling the emission using Haslam map

Reanalyzed Haslam map (Remazeilles+2015).
Original data is observed during 1965-1978.



Extra galactic emission

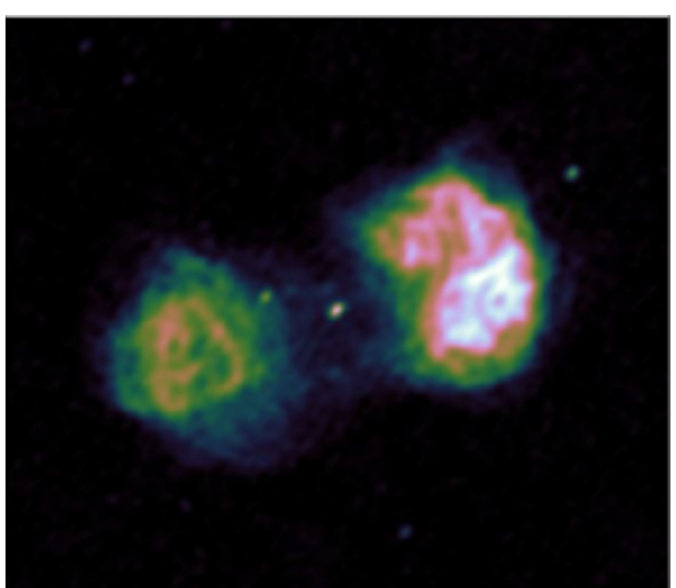
- In order to remove point like sources, a massive radio catalogue is required.



Credit : ICRAR/Curtin

- GLEAM survey by the MWA.

Catalogue contains 307,455 point sources. (Hurley-Walker+2016)

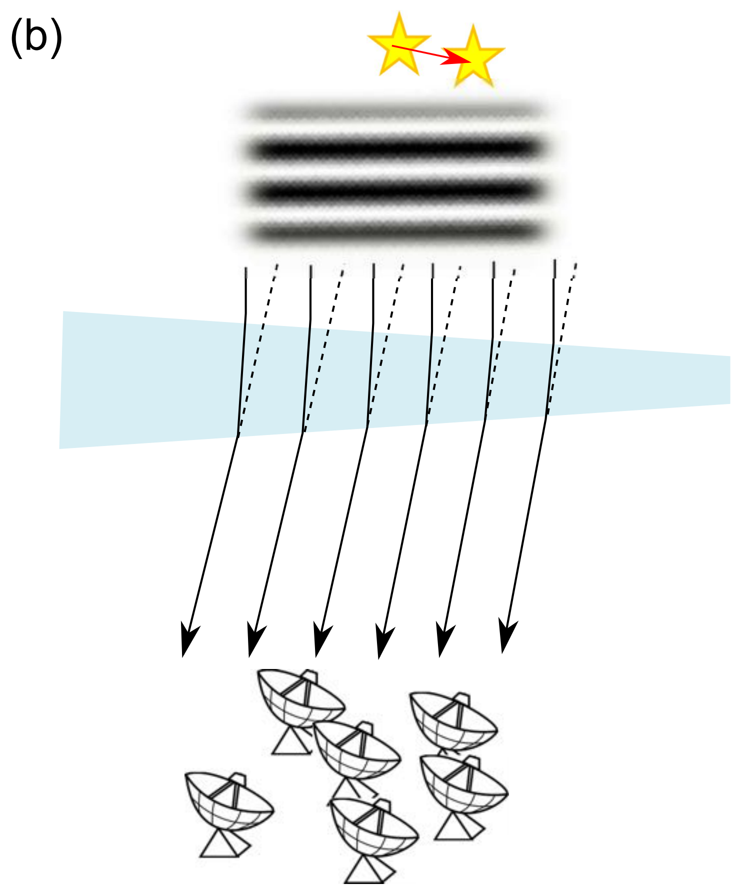


Credit : Curtin University

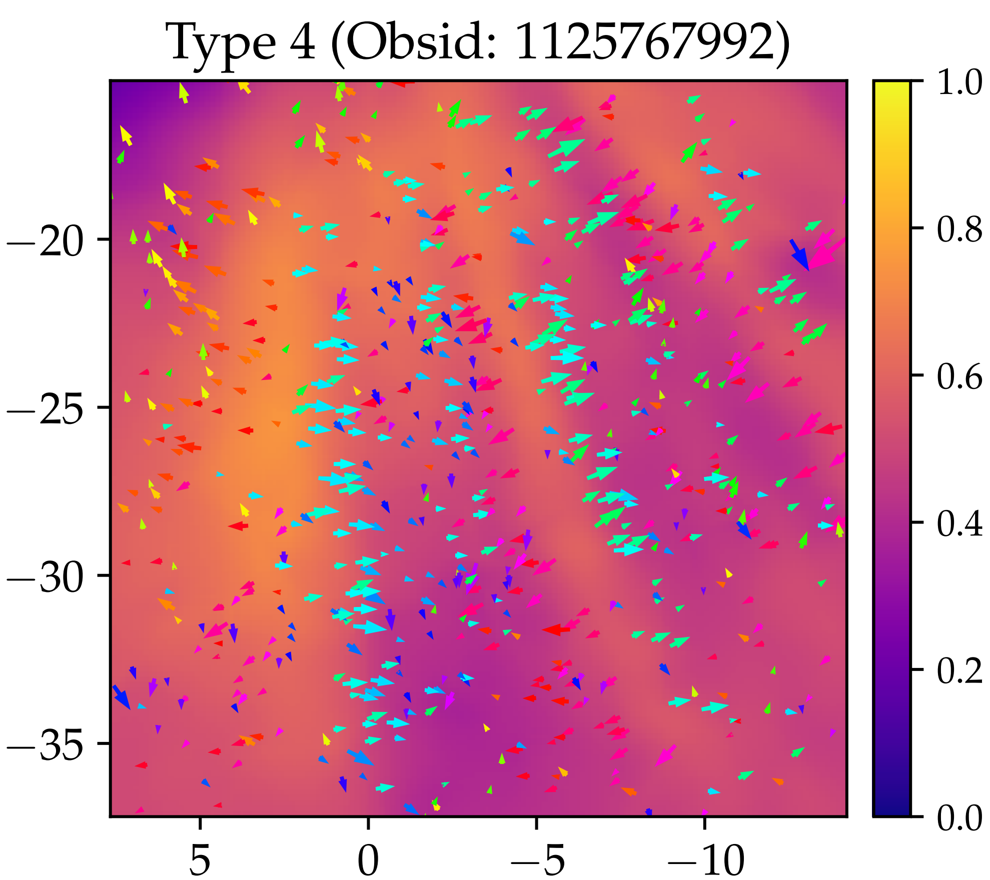
- Need to remove complicated shape.
- Left panel : Fornax A (MWA PhaseII)
- Modeling is ongoing. (gaussian, shapelet)

Ionosphere

- Earth Ionosphere (100-1000km) refracts astronomical signal.
- Position of point sources shifts slightly (0.2 arcmin).
- Need an accurate catalogue for correction.
- Choose quiet ionosphere data.
- Ionosphere contaminates at small scale($k \sim 10$ Mpc^{-1}), and the effects on the 21cm signal is ignored.



Loi+2016

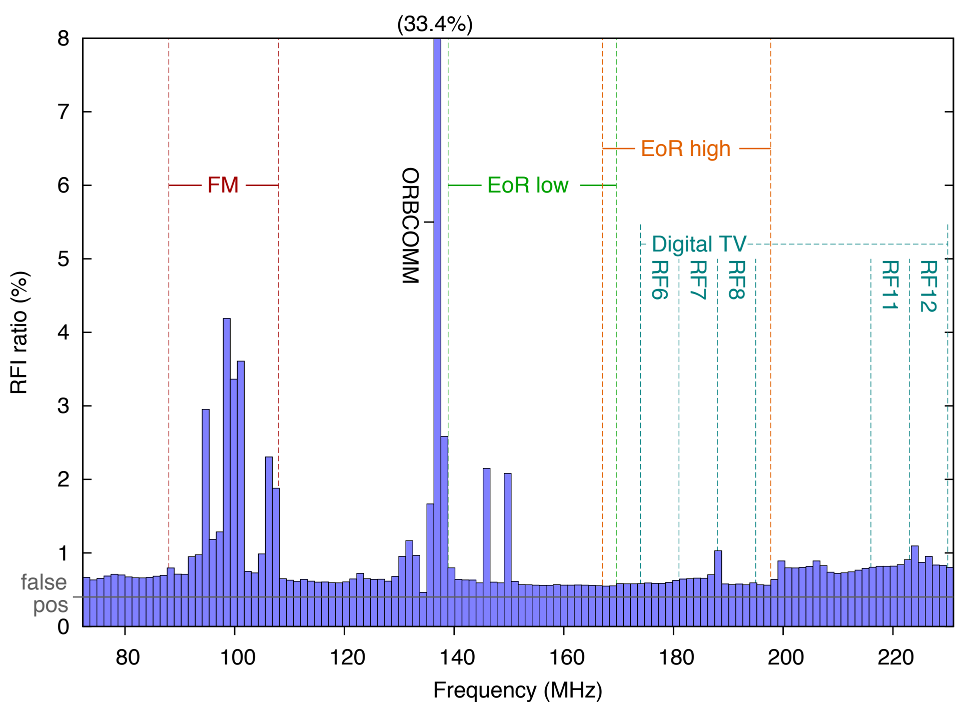


Jordan+2017

RFI

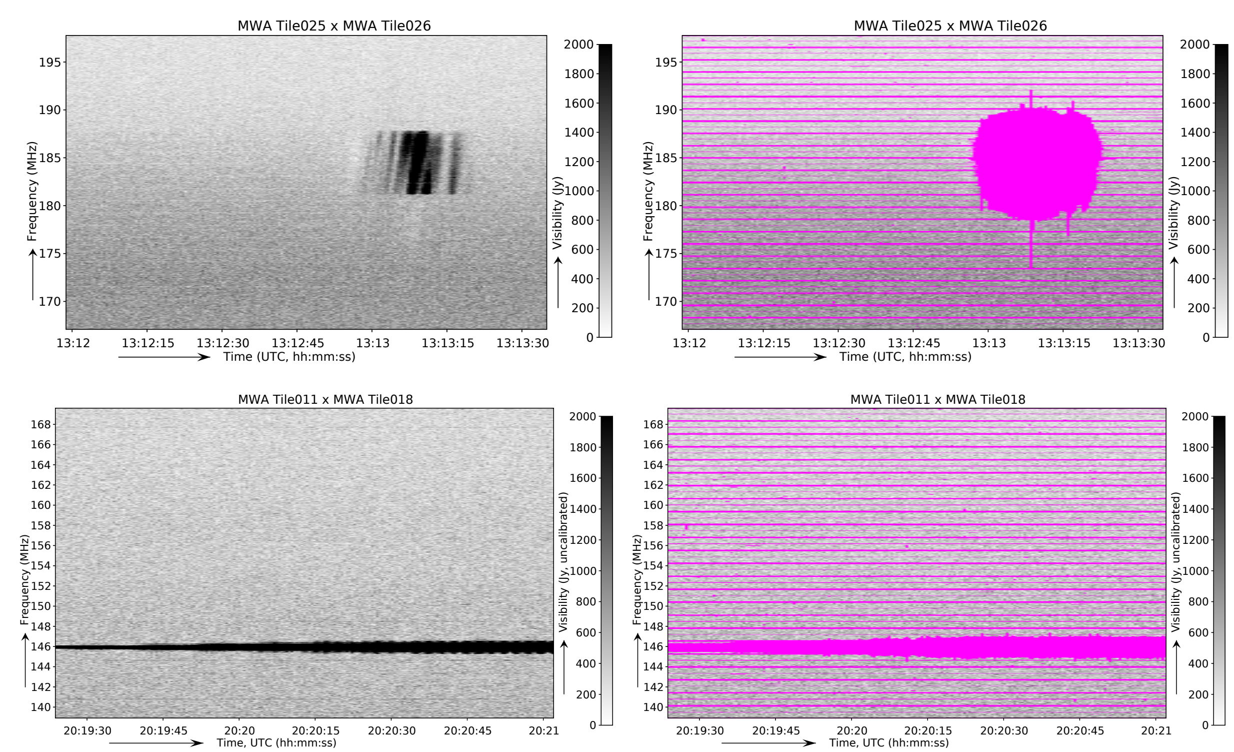
- Removal radio frequency interference (e.g. FM radio).
- MRO is RFI quiet, but RFI contaminates a few % of the data.
- AOFRAGGER is a RFI removal software.

— RFI at MRO

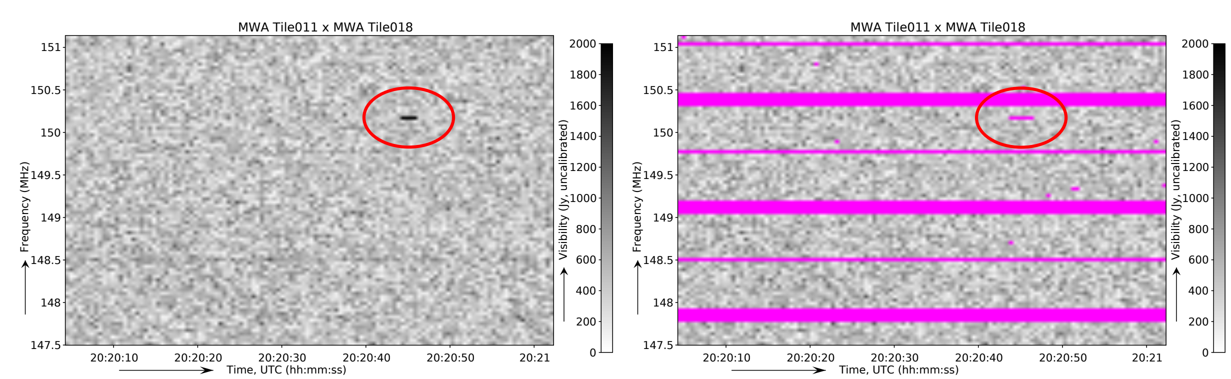


Offringa+2015

— RFI flagging : MWA, visibility



(a) RFI contamination found in the 2 m amateur band (146 MHz).



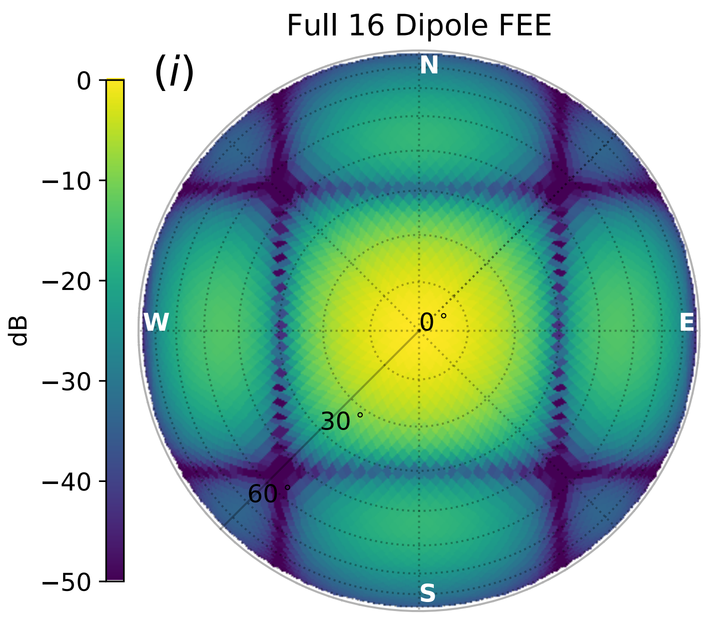
Offringa+2015

Beam

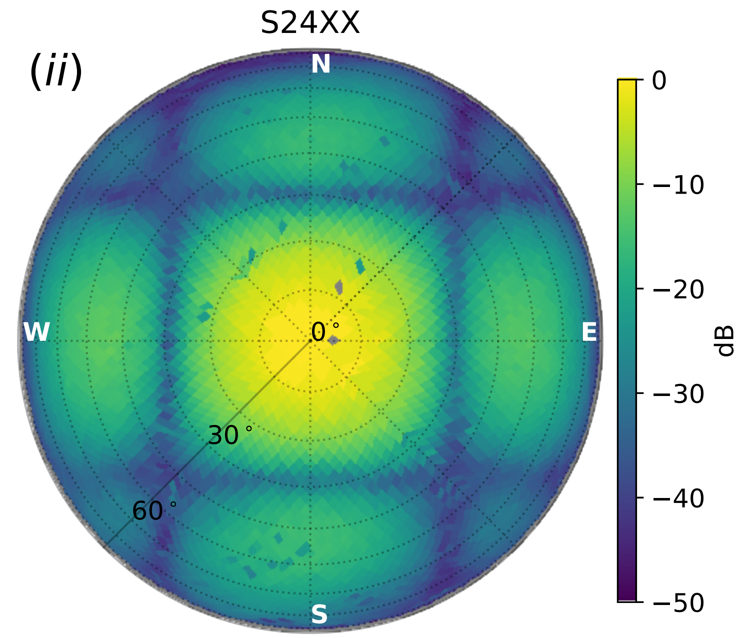
- Error on beam model provides the foreground residual.
- Need an accurate model for both the primary beam and side lobes.
- Random dipole position may mitigate the side lobe contamination.

e.g. : MWA(Line+2015)

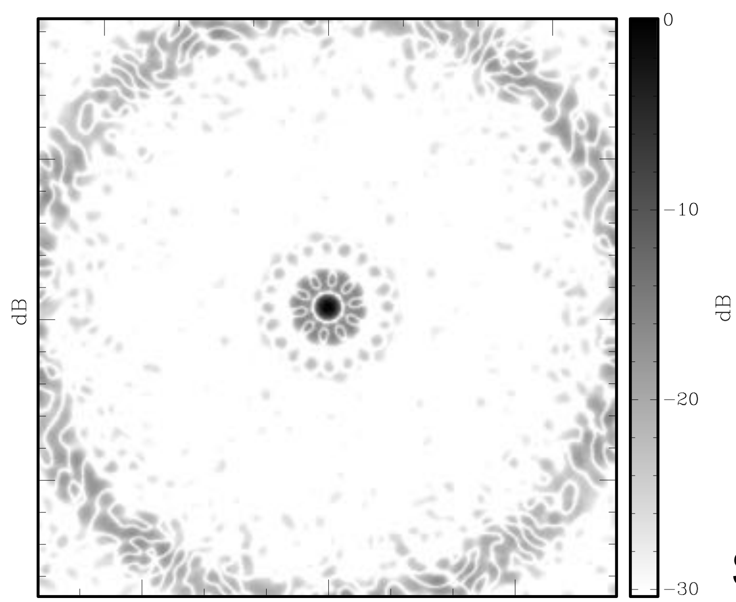
Model



Measured beam



e.g. : SKA low



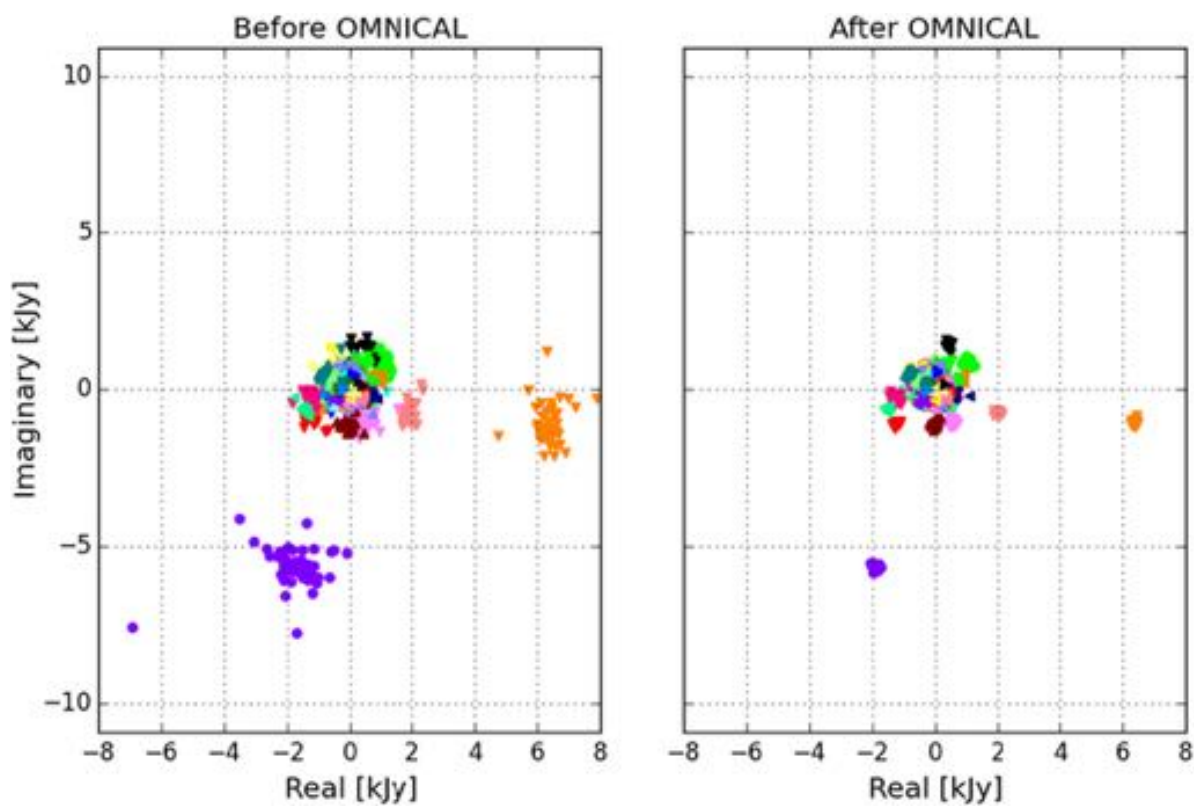
SKA1-Low-Configuration V4a

Calibration

- Need to correct instrumental (complex) gain and bandpass.
- Calibration pipelines :

  SAGECAL (e.g. Yatawatta 2016), RTS (Mitchell+2008),
  FHD (Jacobs+2016), OMNICAL (Zheng+2014)

- Basically, the calibration is performed using known intensity and position of bright sources.



Visibility example
PAPER (Ali+2015), OMNICAL.
Same color points should have same value.

- Other problems : cable reflection, mutual coupling, polarization

Foreground mitigation strategies

1 : Foreground removal
2 : EoR window
3 : Cross correlation

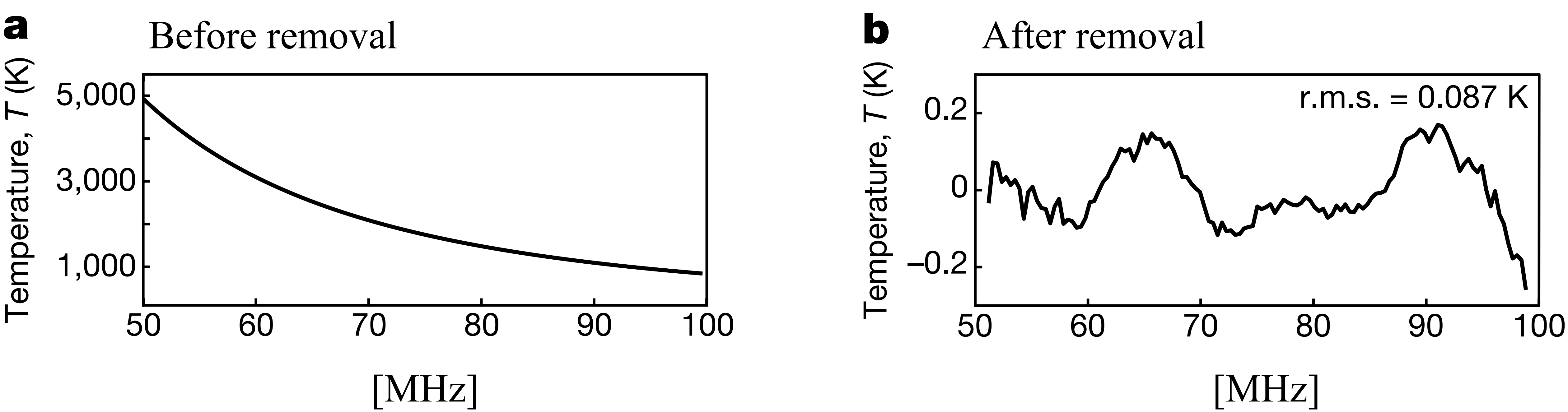
Foreground removal

・Polynomial fitting

- Foreground emission should be spectrally smooth.

EDGES (Bowman+2018)

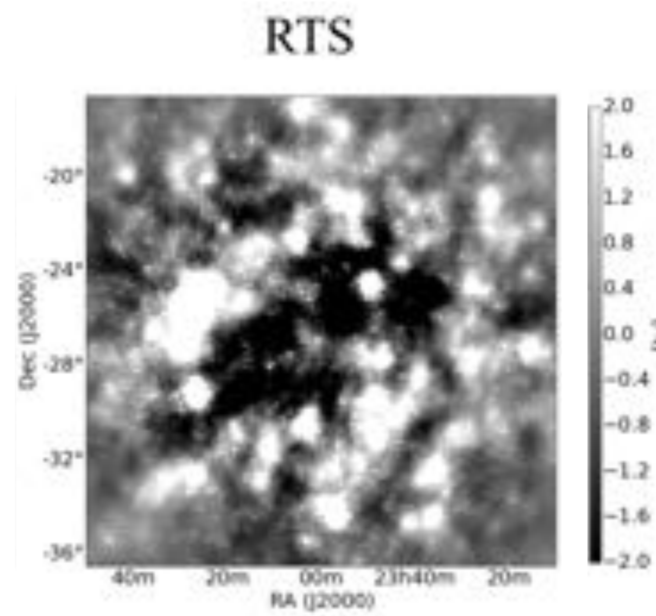
$$T_{\mathrm{F}}(\nu) = b_0 \left(\frac{\nu}{\nu_{\mathrm{c}}}\right)^{-2.5 + b_1 + b_2 \log(\nu/\nu_{\mathrm{c}})} \mathrm{e}^{-b_3(\nu/\nu_{\mathrm{c}})^{-2}} + b_4 \left(\frac{\nu}{\nu_{\mathrm{c}}}\right)^{-2}$$



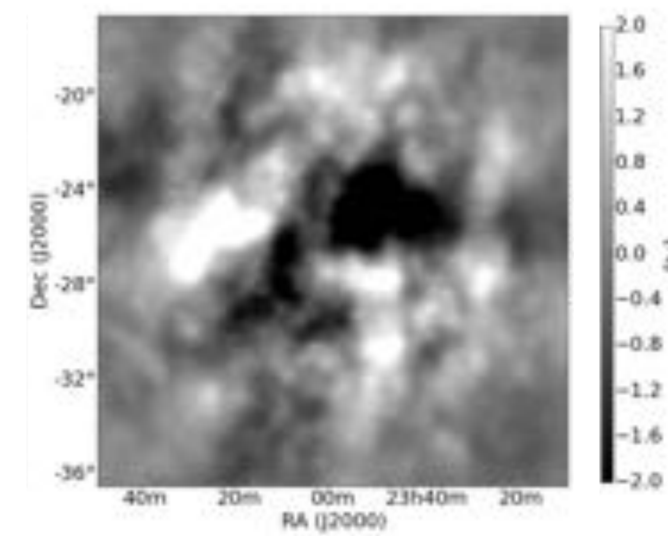
Foreground removal

- Building foreground model
  - Galaxy (Haslam map, new model)
  - Extra galaxies (e.g. PUMA, GLEAM)
- Statistical methods
  - (e.g. GMCA, GPR)

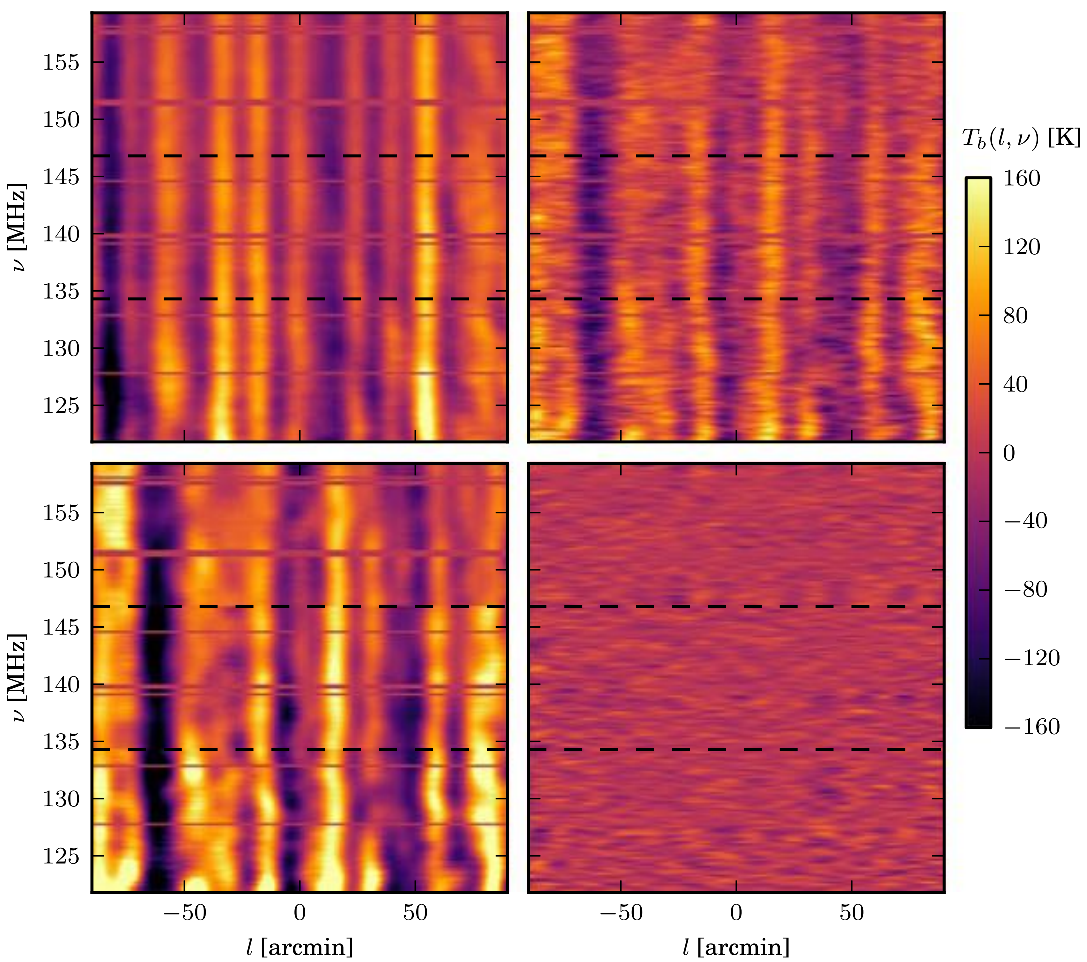
Jacob+2016



Before point source removal



After point source removal



Patil+2017 (GMCA)

Problems

- Signal loss
- Model error.
- We cannot tell 21cm signal and foreground residual.

EoR window

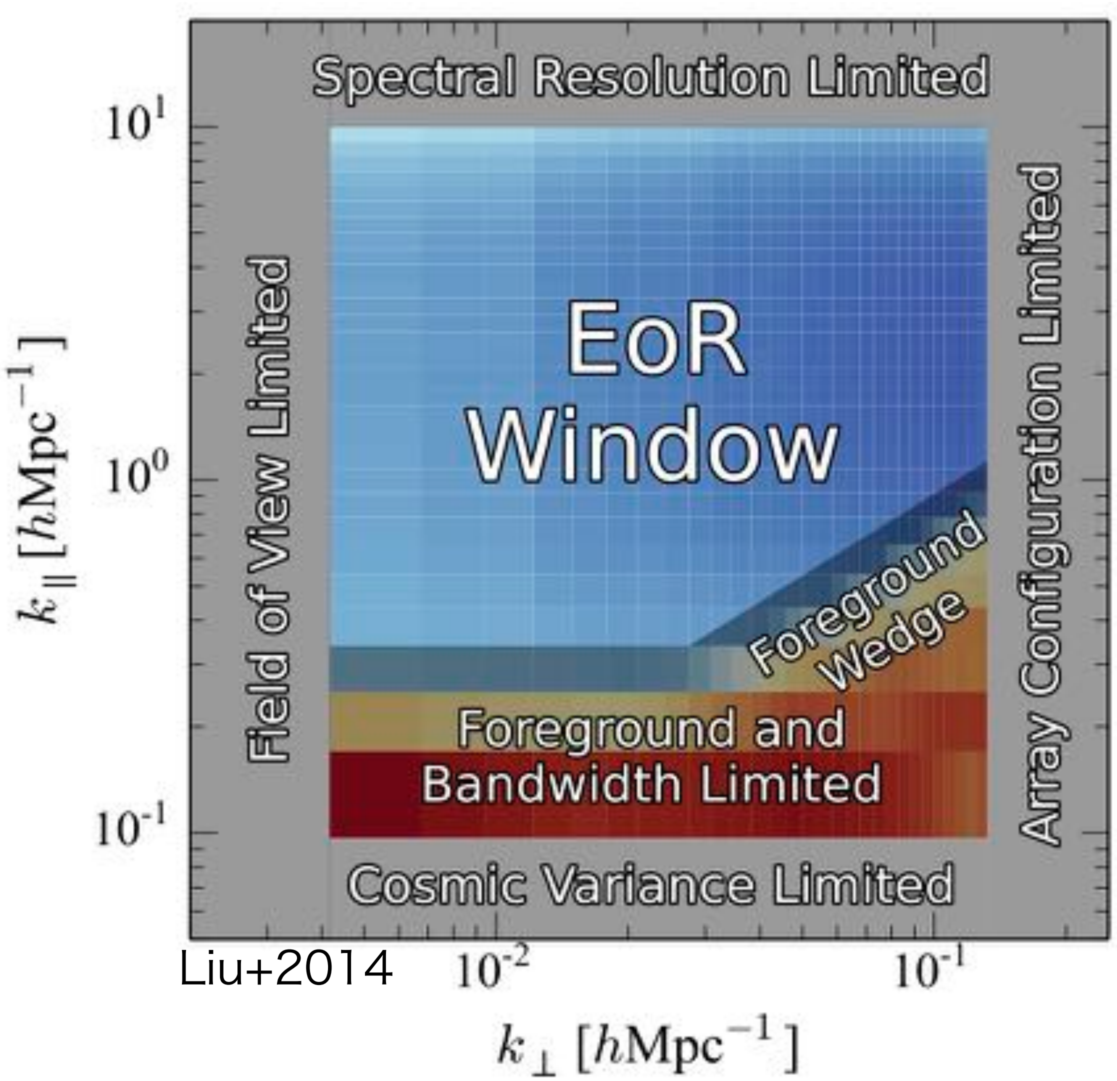
・Fourier transform along the line of sight (frequency).

Foreground emission is spectrally smooth and weak at small scale.
— EoR window

・Spectral structure of point sources due to chromaticity of an interferometer.

— Foreground Wedge

・Instrumental error propagates the foreground contamination to the EoR window.



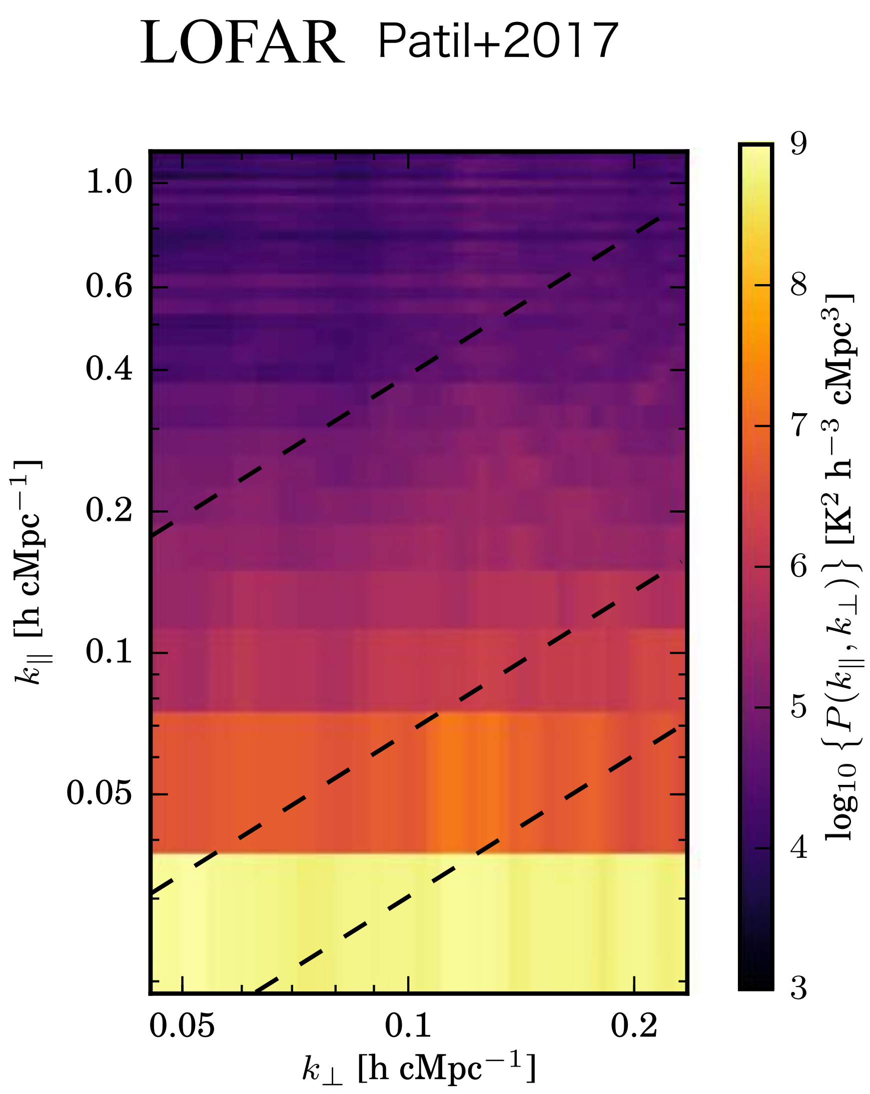
Liu+2014

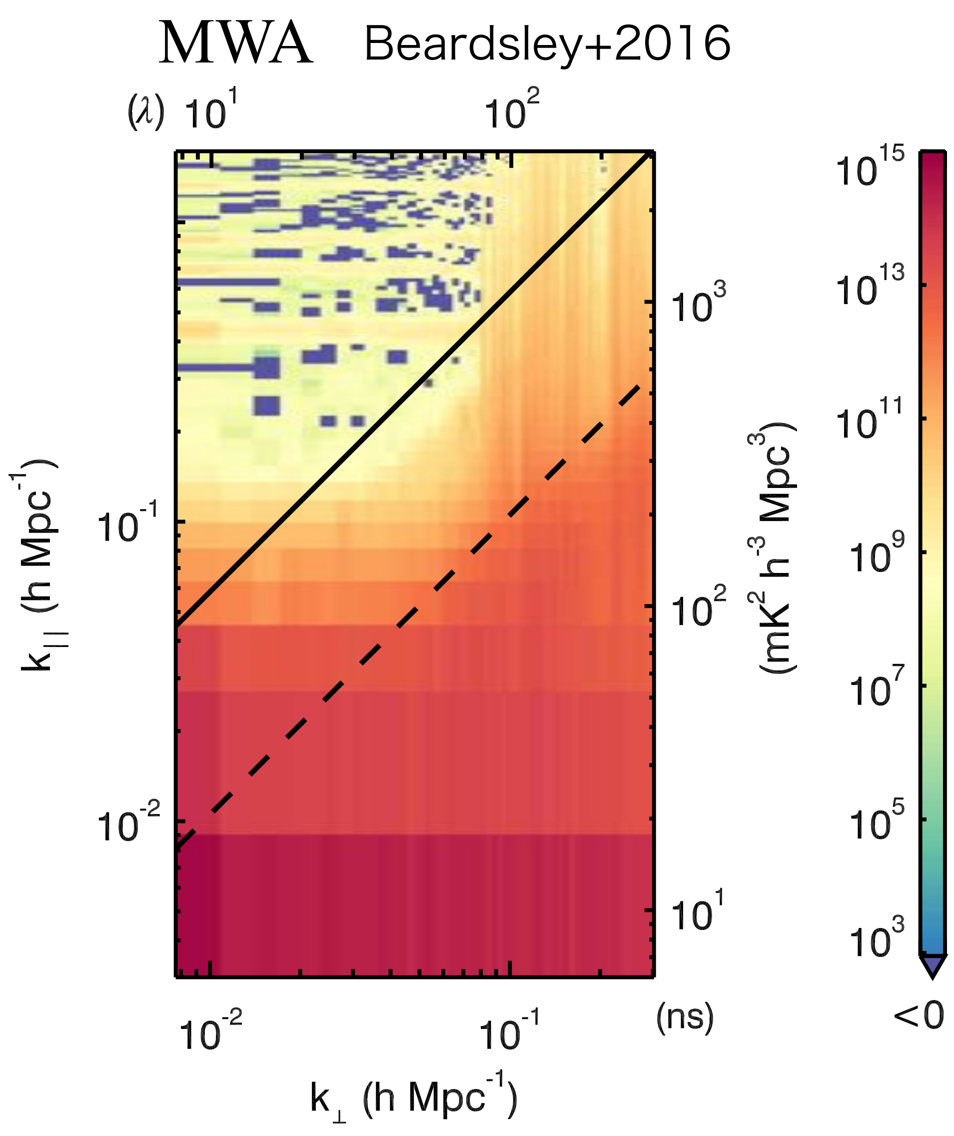
$\mathbf{k}_{\perp}$: corresponds to sky plane

$\mathrm{k}_{||}$: corresponds to LoS (frequency)

Measured EoR window

- In the EoR window, measured signal is consistent with the thermal noise.
- FG wedge structure.
- FG pollutes the window due to calibration error and instrumental error.





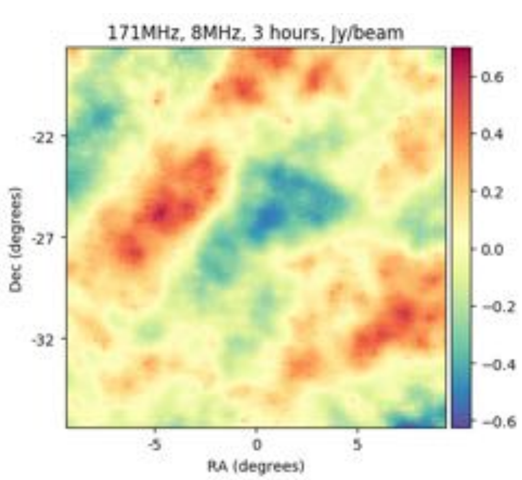
Cross correlation

For example, 21cm line and
— High-z galaxys (LAE) (Lidz+2008, Hutter+2017, Kubota, SY+2018, SY+2018)
— CMB (Alvarez+2006, Tashiro+2010, SY+2018)

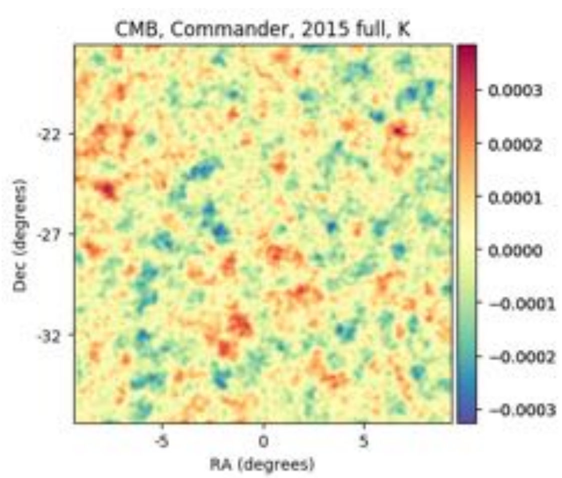
- High-z Galaxies do not correlate with foreground,
  and therefore CC mitigates the foreground contamination.
- Foreground contaminates to the error.
- CC is useful to distinguish the 21cm signal and foreground residuals.

21cm-CMB cross correlation (SY+2018)

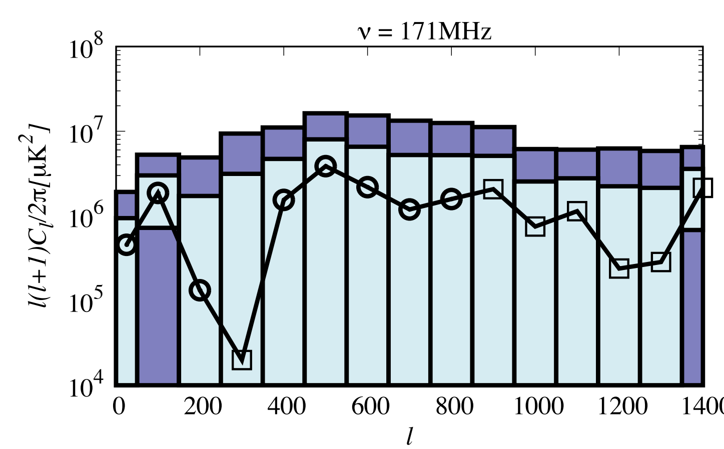
Radio (MWA)



CMB (Planck)

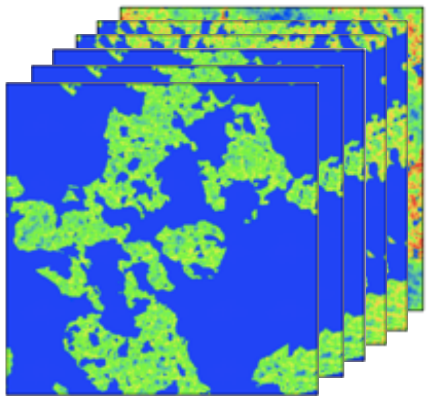


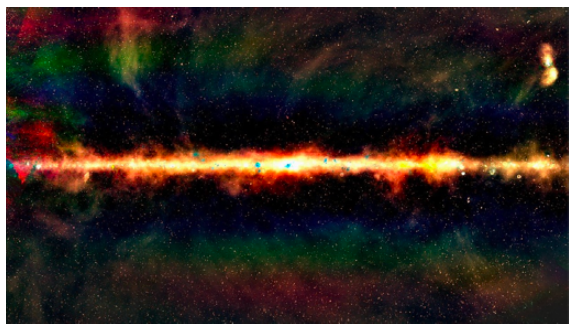
Cross power spectrum

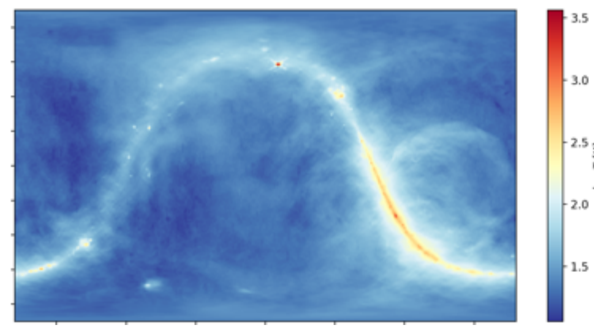


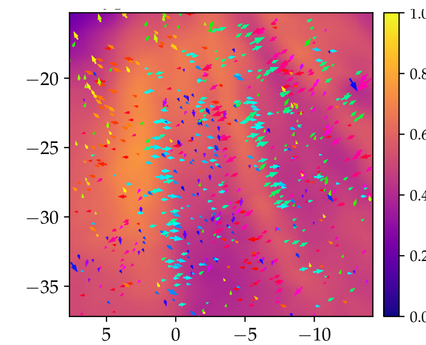
Summary

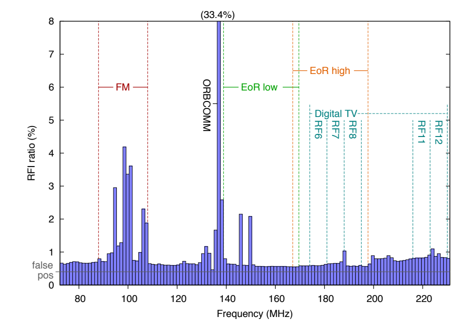
- 21cm line is powerful tool to study the EoR and CD, but the observation is complicated.
- The analysis is now in progress.



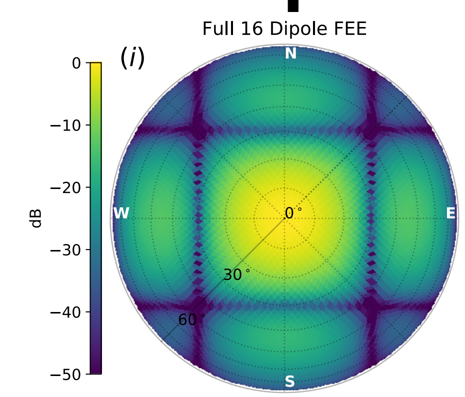








21cm line — Extragalactic foregrund — Galactic foregrund — Ionosphere refraction — RFI



Beam — Observation / Instrumental error — Calibration — Foreground removal & mitigation → Power spectrum / Bi-spectrum / Cross correlation

- Construction of SKA low and mid will take place from 2018 to 2023.