How far are we from detecting the 21 cm line from the Epoch of Reionization?

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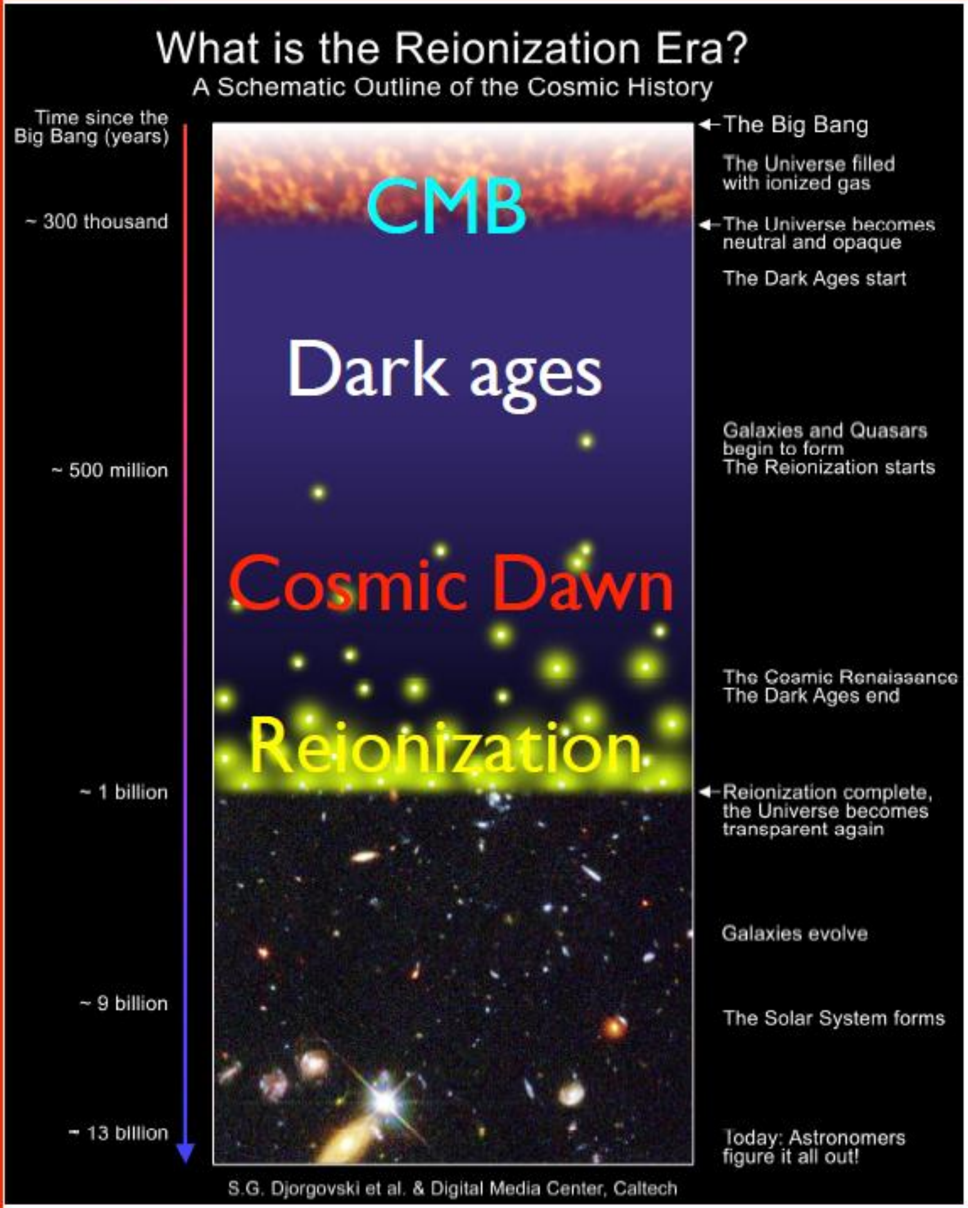
The 21cm line is ideal to study the first billion years



Dark Ages: no structures were formed, primordial fluctuations are imprinted in the HI gas

Cosmic Dawn: first luminous structures (Pop III stars? Micro quasars?) are formed in the dark matter halos

Reionization (EoR): luminous structures (galaxies, AGNs) re-ionize the IGM

21 cm line cosmology

T_γ $\quad$ T_S $\quad$ T_b

$z = 13$

$\nu = 1.4\,\mathrm{GHz}$

$z = 0$

$\nu = 100\,\mathrm{MHz}$

CMB acts as back light

Neutral gas imprints signal

Redshifted signal detected

brightness temperature

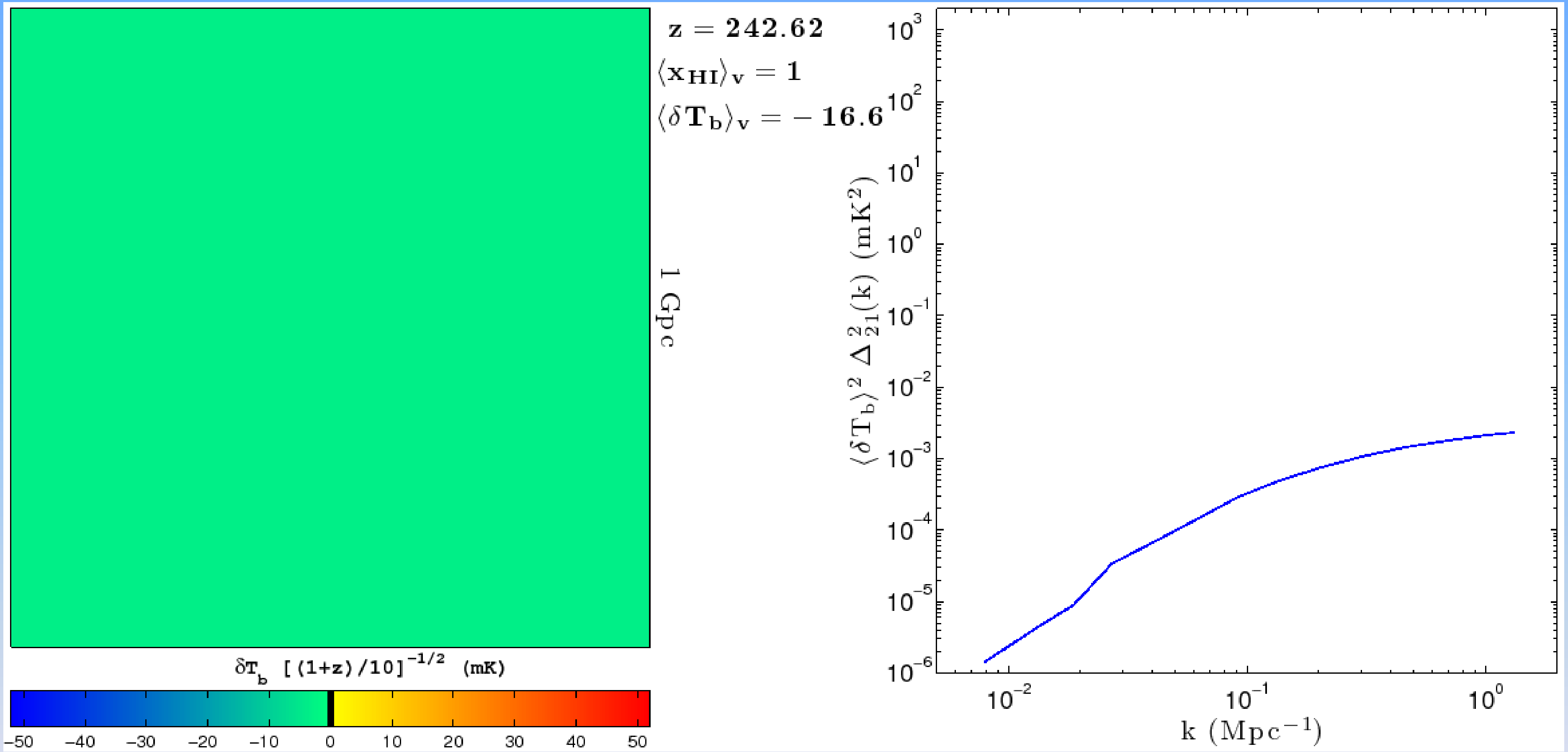
$$T_b = 27 x_{\mathrm{HI}} (1+\delta_b) \left(\frac{T_S - T_\gamma}{T_S}\right) \left(\frac{1+z}{10}\right)^{1/2} \left[\frac{\partial_r v_r}{(1+z)H(z)}\right]^{-1} \mathrm{mK}$$

spin temperature

$$T_S^{-1} = \frac{T_\gamma^{-1} + x_\alpha T_\alpha^{-1} + x_c T_K^{-1}}{1 + x_\alpha + x_c}$$

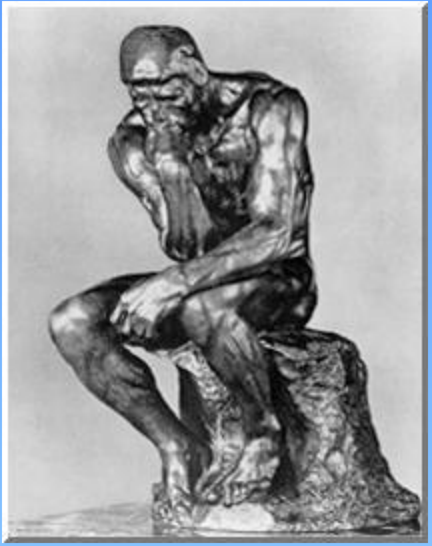
Coupling mechanisms:
Radiative transitions (CMB)
Collisions
Wouthysen-Field effect

Evolution of fluctuations



Courtesy A. Meisinger

Observational specs
for 21cm line experiments:



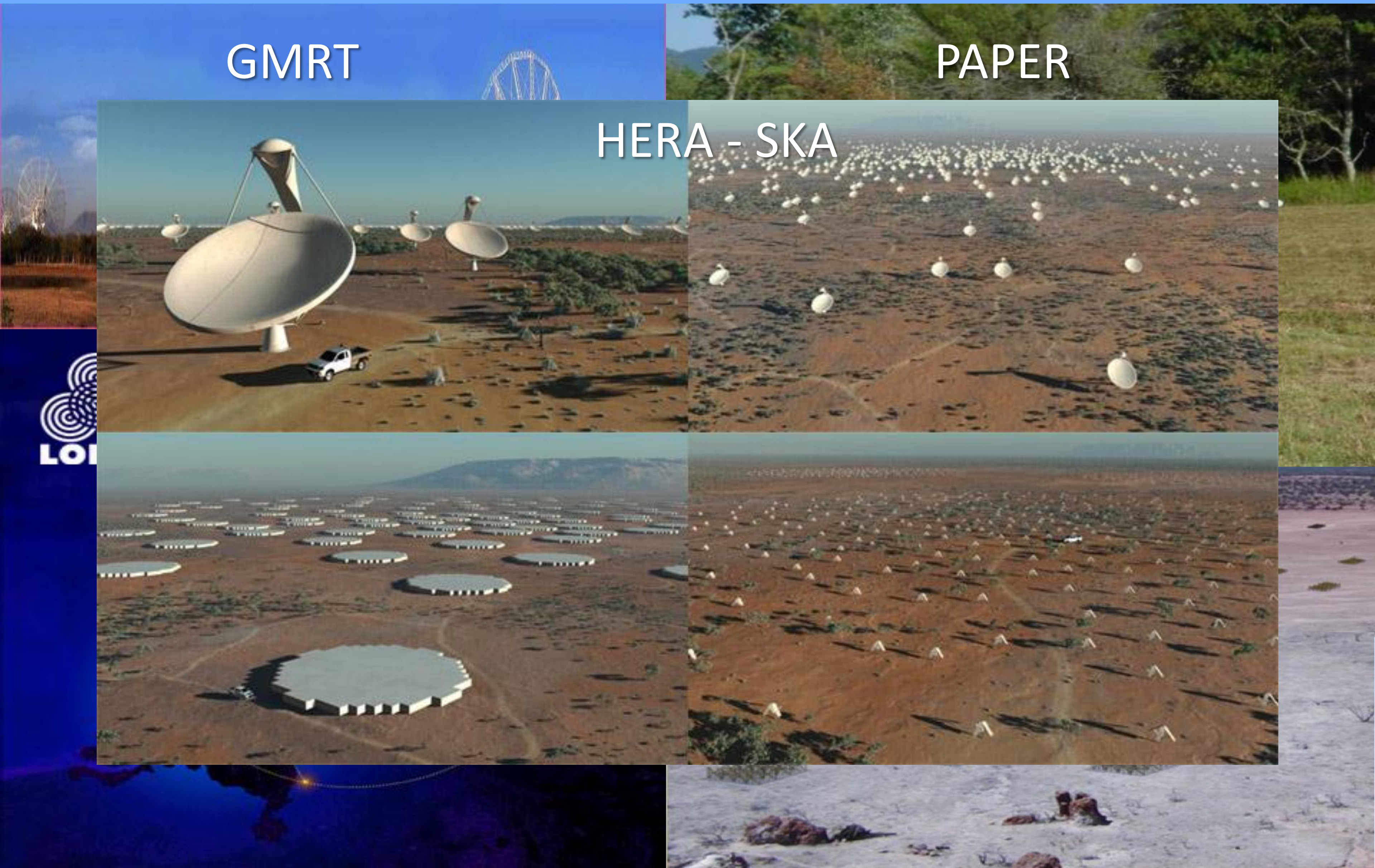
Frequency coverage:
30-200 MHz ($6 < z < 35$)

Angular resolution:
fluctuations → $5 < \theta < 30$ arcmin
imaging → up to < 1 arcmin

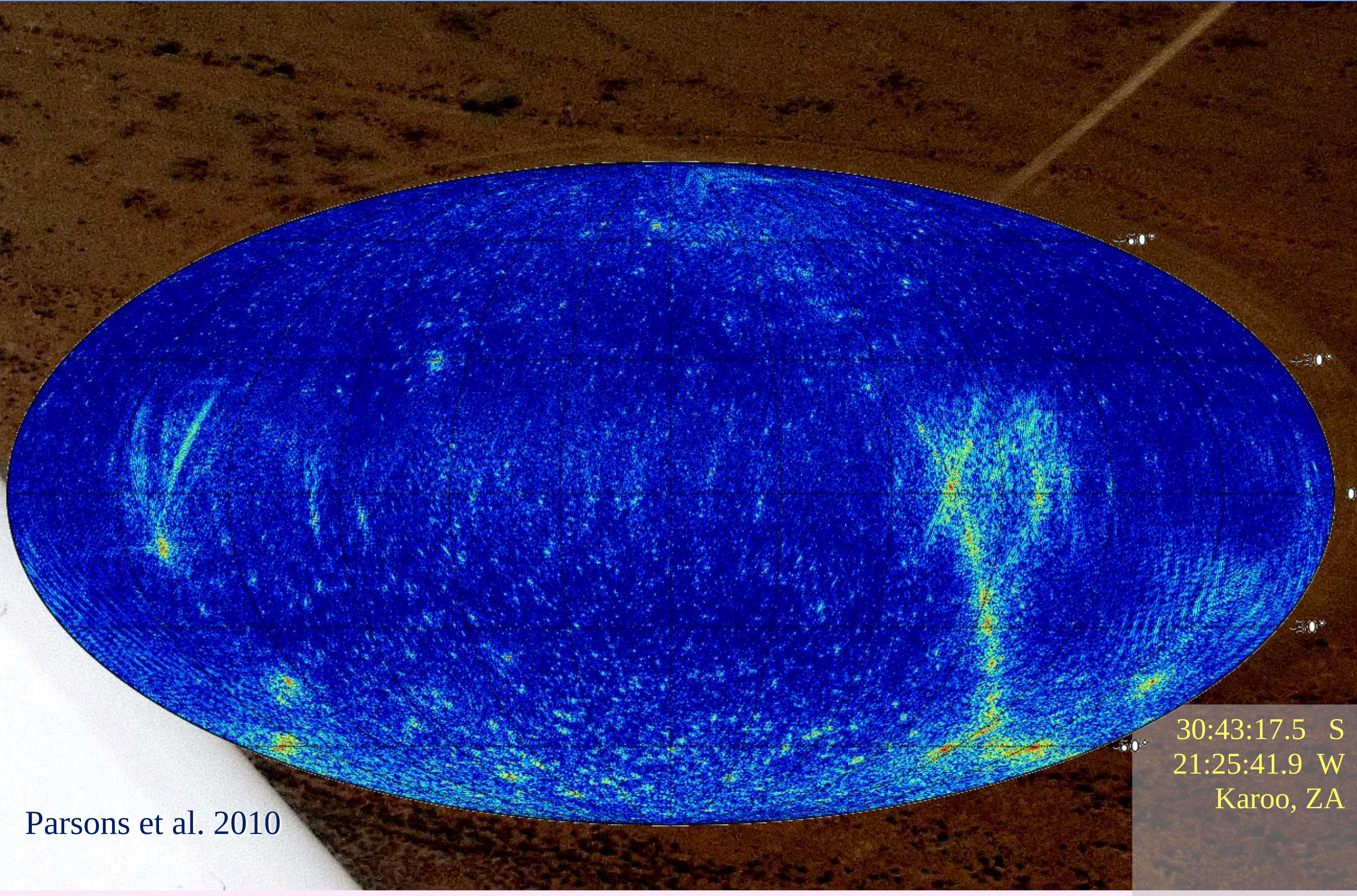
Sensitivity:
mK sensitivity is required to constrain most of the HI models
(The VLA @ 74 MHz has an rms sensitivity of 26 K (1 hour))

Challenges:
- correction of ionospheric distortions
- calibration of time and frequency variable telescope response (beam)
- subtraction of bright foregrounds (and their coupling with the instrumental response)

We live in the era of exploration: current and future 21 cm experiments



PAPER in South Africa: PSA-32



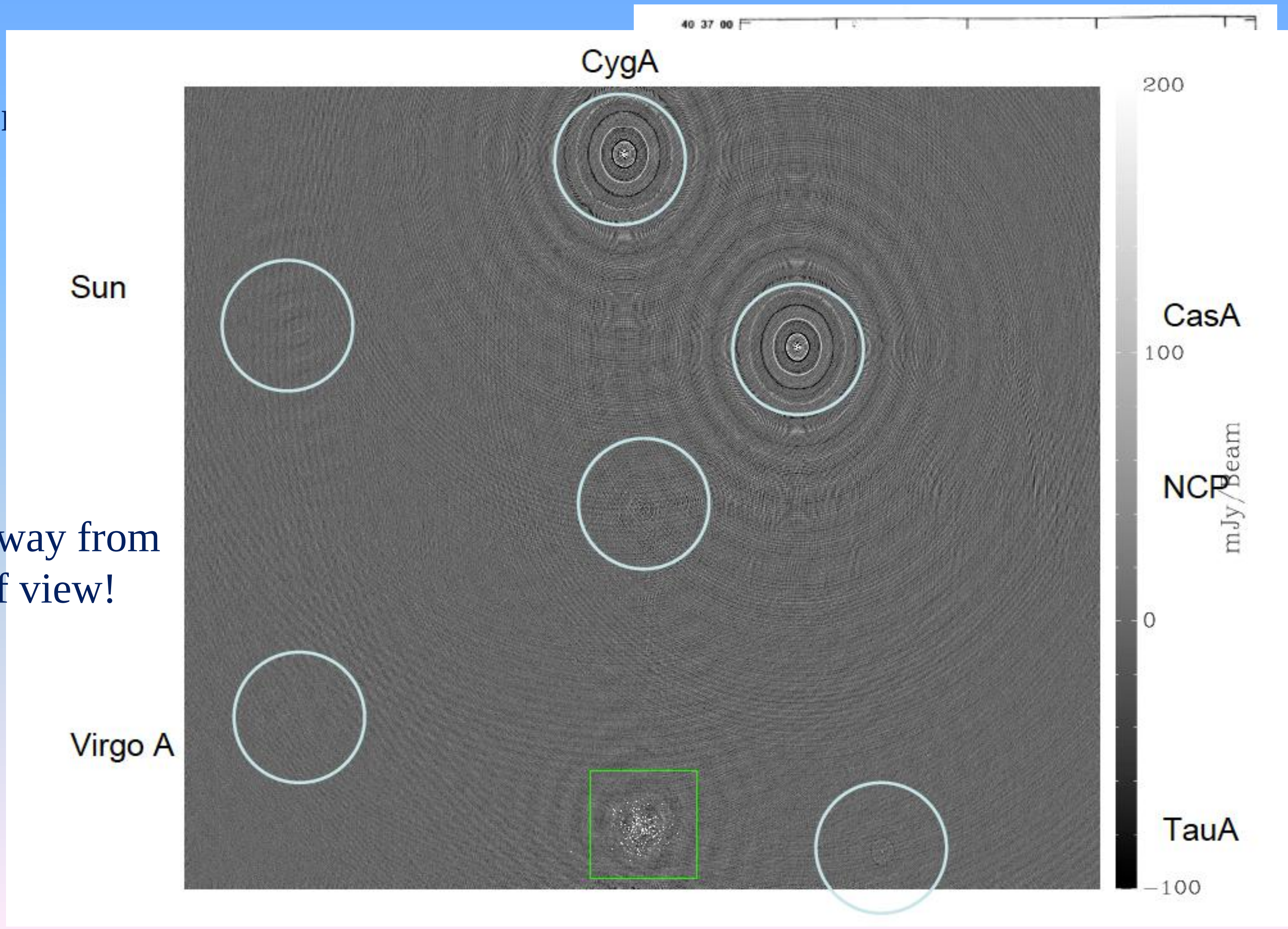
Parsons et al. 2010

30:43:17.5 S
21:25:41.9 W
Karoo, ZA

The key point to detect the high redshift 21cm signal is how well foregrounds can be removed!

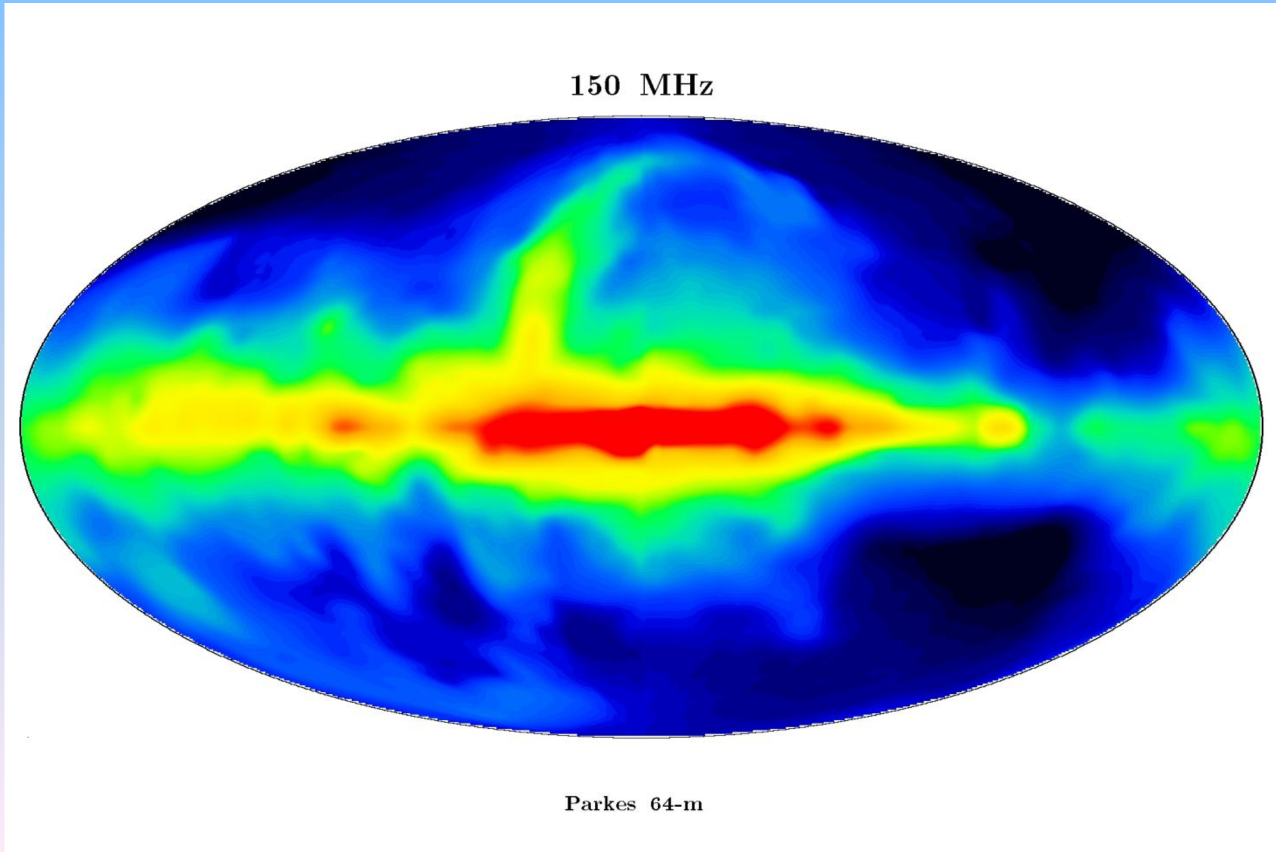
- Subtractio

- even far away from the field of view!



The key point to detect the high redshift 21cm signal is how well foregrounds can be removed!

- Subtraction of bright sources (S > 0.1-1 Jy);
- Subtraction of Galactic diffuse emission and extragalactic unresolved sources;

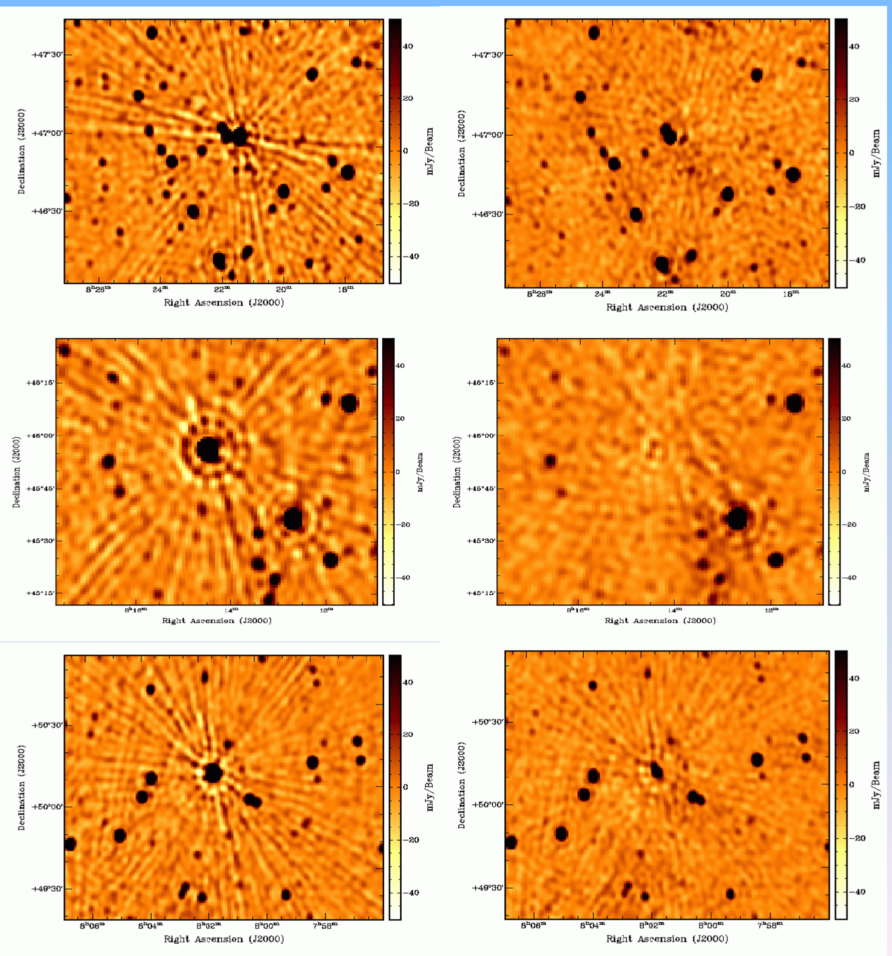


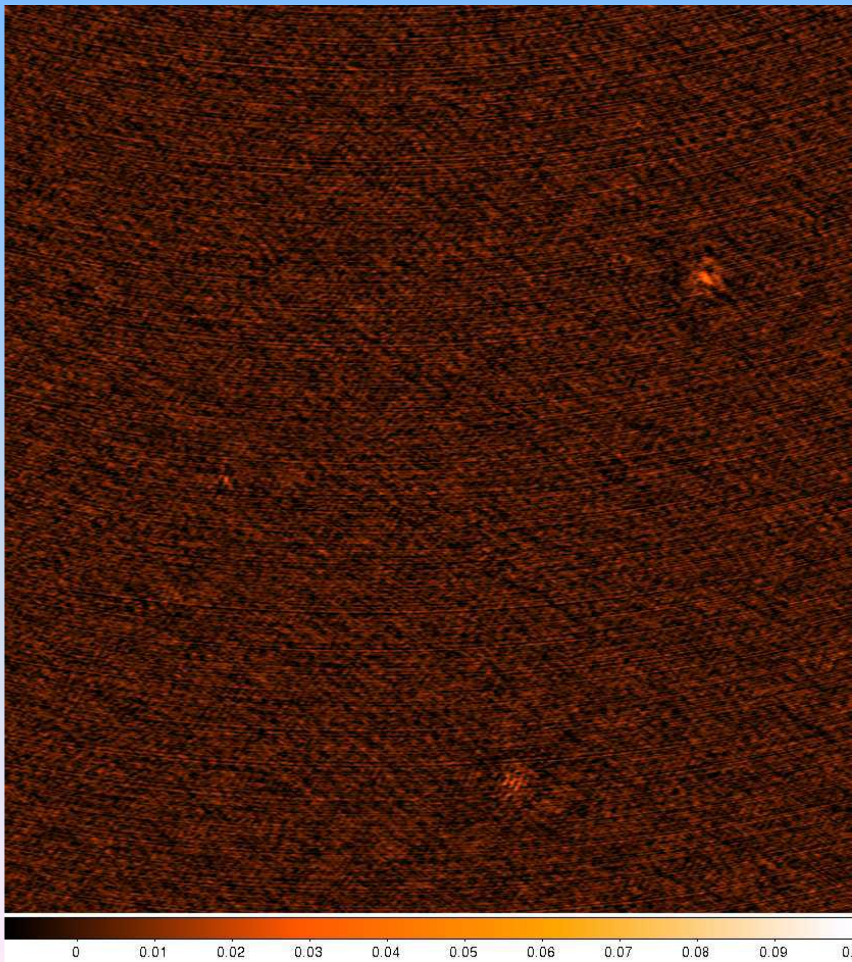
150 MHz all sky map

Do we know how to subtract foregrounds? How well?

- Subtraction of bright sources in the real world (correcting for ionosphere): direct evaluation of sky + instrument response ("peeling", Noordam 2004):

$$\left\| P - J^{-1}\, V\, J^{\dagger\, -1} \right\|$$

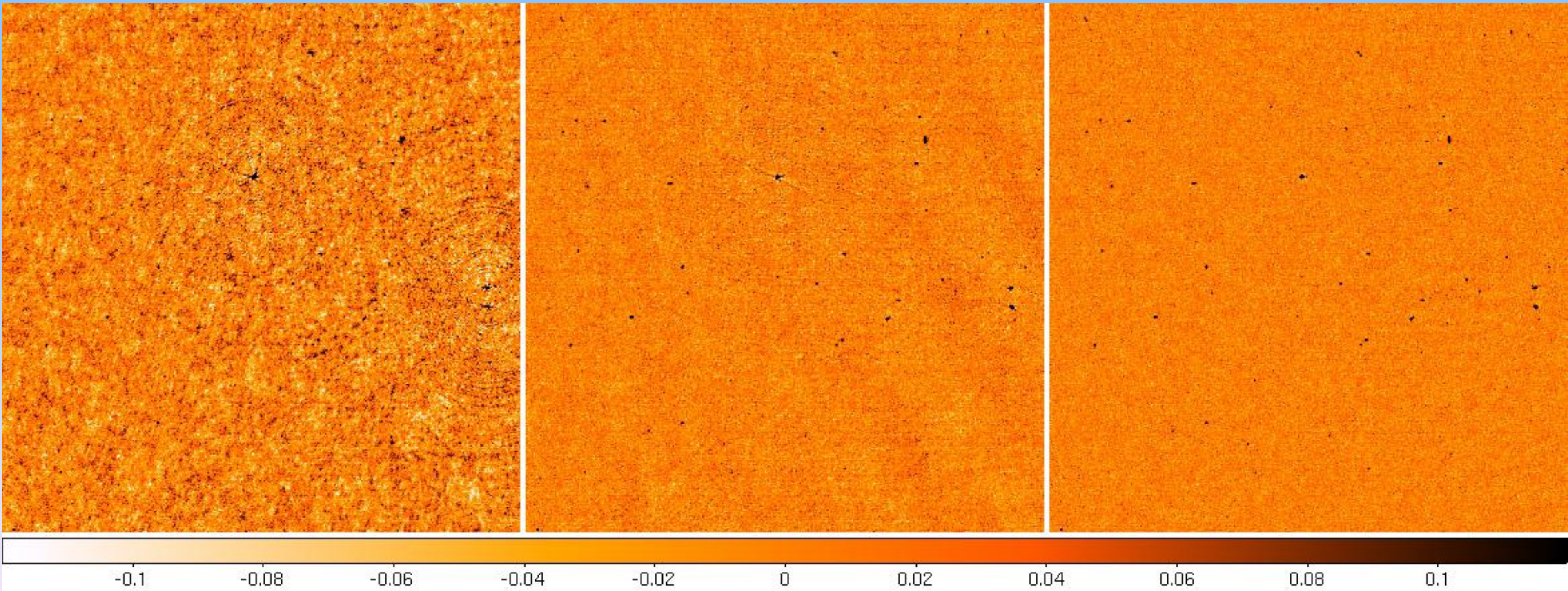




Do we know how to subtract foregrounds? How well?

- Subtraction of bright sources in the real world (correcting for ionosphere);

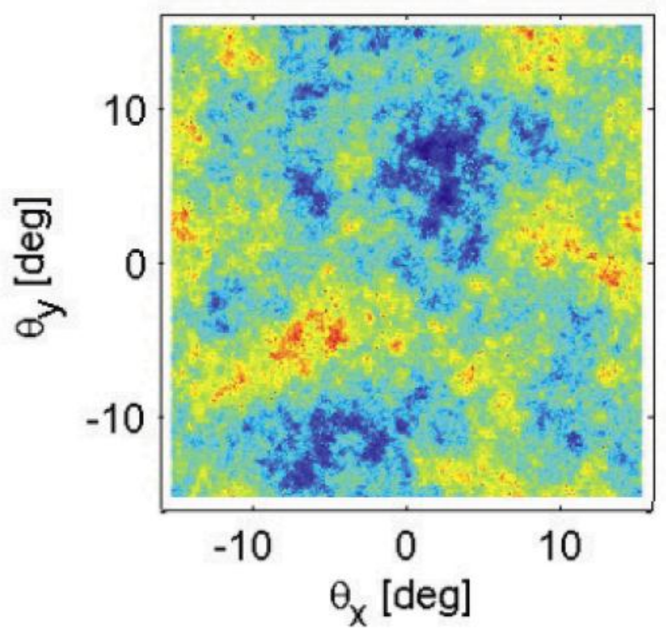
Direction evaluation of sky brightness and instrumental response + ionospheric modeling + direction dependent data correction

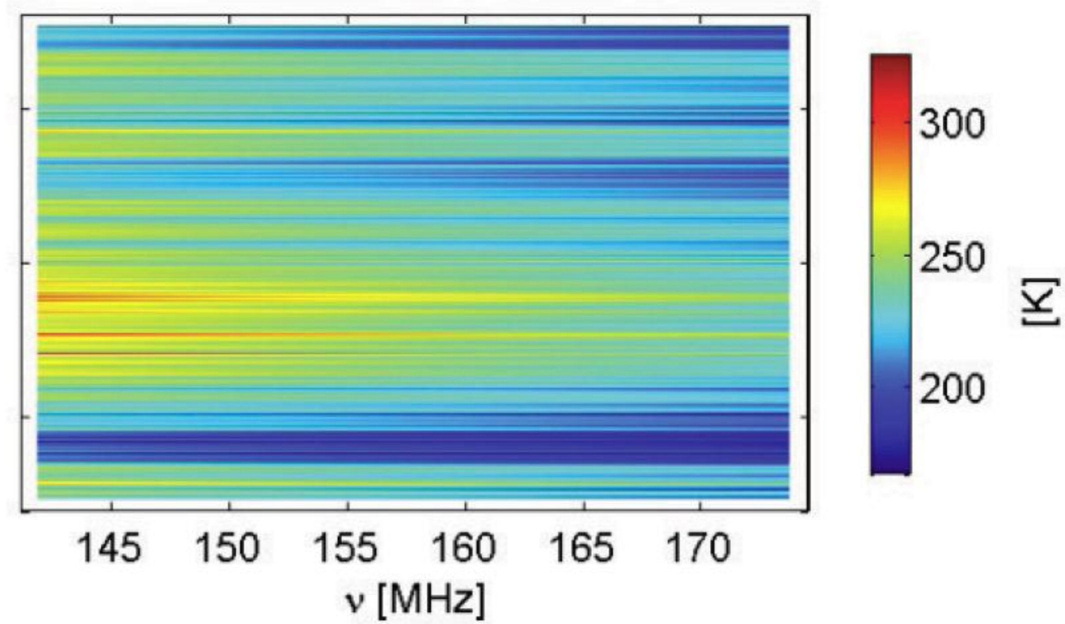


Intema et al. 2007

Do we know how to subtract foregrounds? How well?

- Subtraction of Galactic diffuse emission and extragalactic radio sources:
  they are supposed to have smooth spectra compared to the 21 cm signal;





Bowman, Morales & Hewitt, 2009

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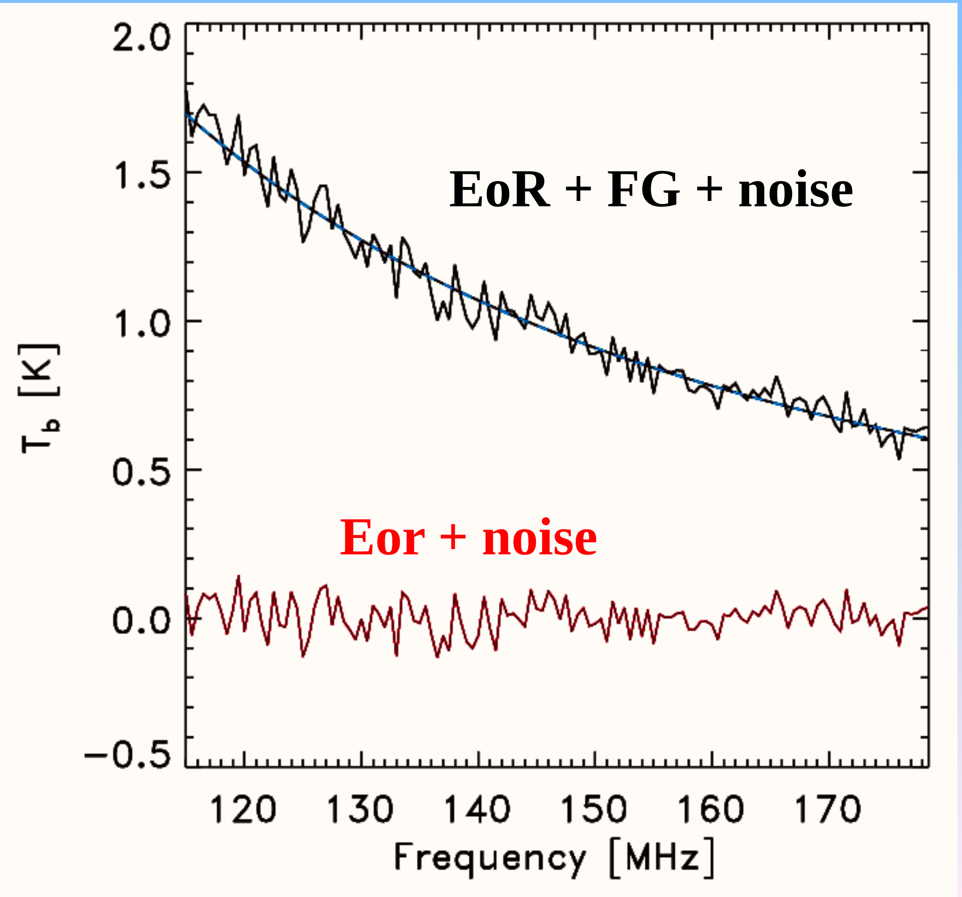


EoR ~ 5 mK
FG ~ 2 K
noise ~ 50 mK

How well does it work on data?
How is frequency filtering affected by ionosphere?

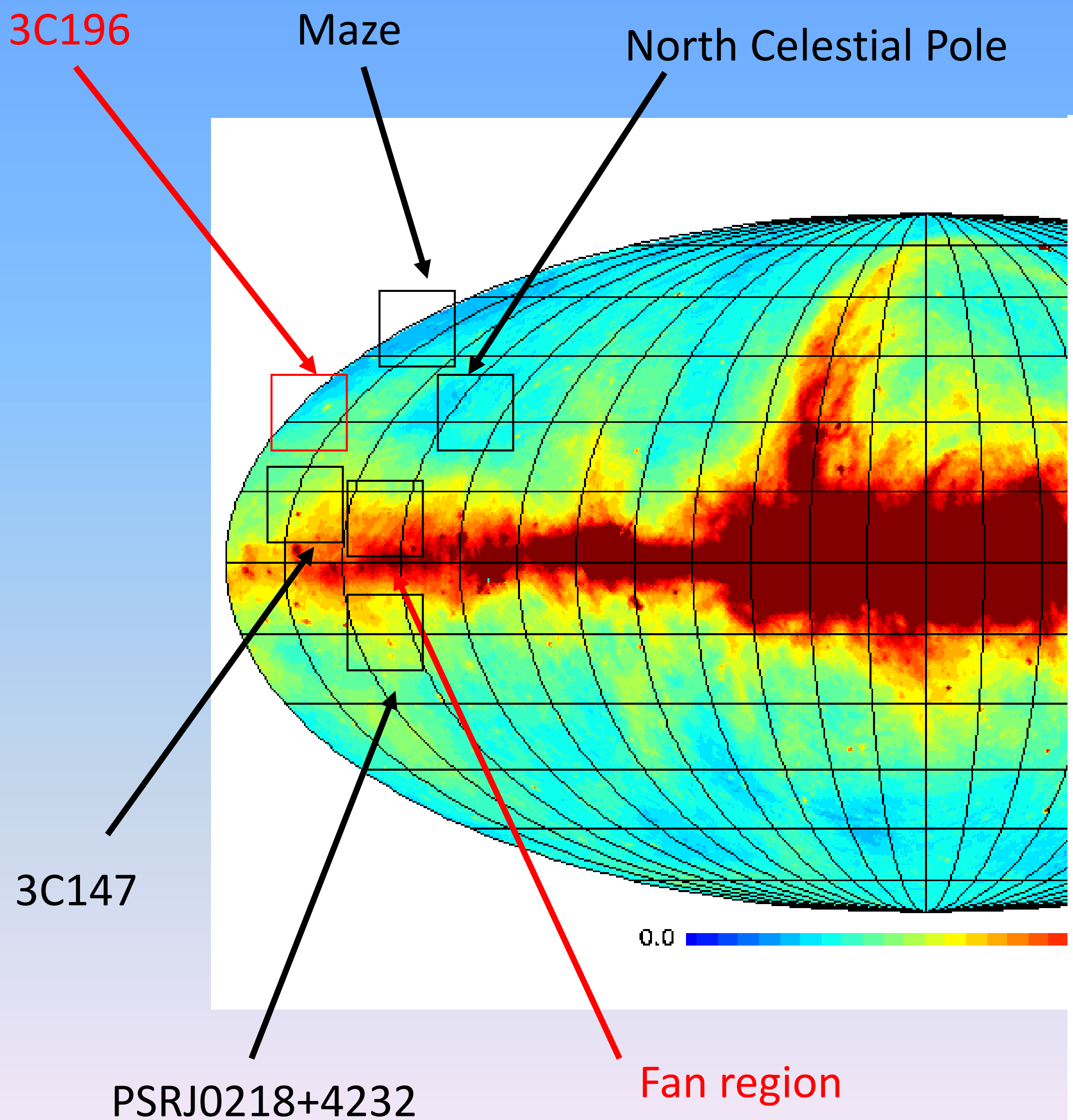
Jelic et al. 2008

Moving to the world of observations:

Westerbork ***LOFAR***

Survey purpose: understanding foreground emission and setting up the data analysis pipeline for LOFAR-EoR observations

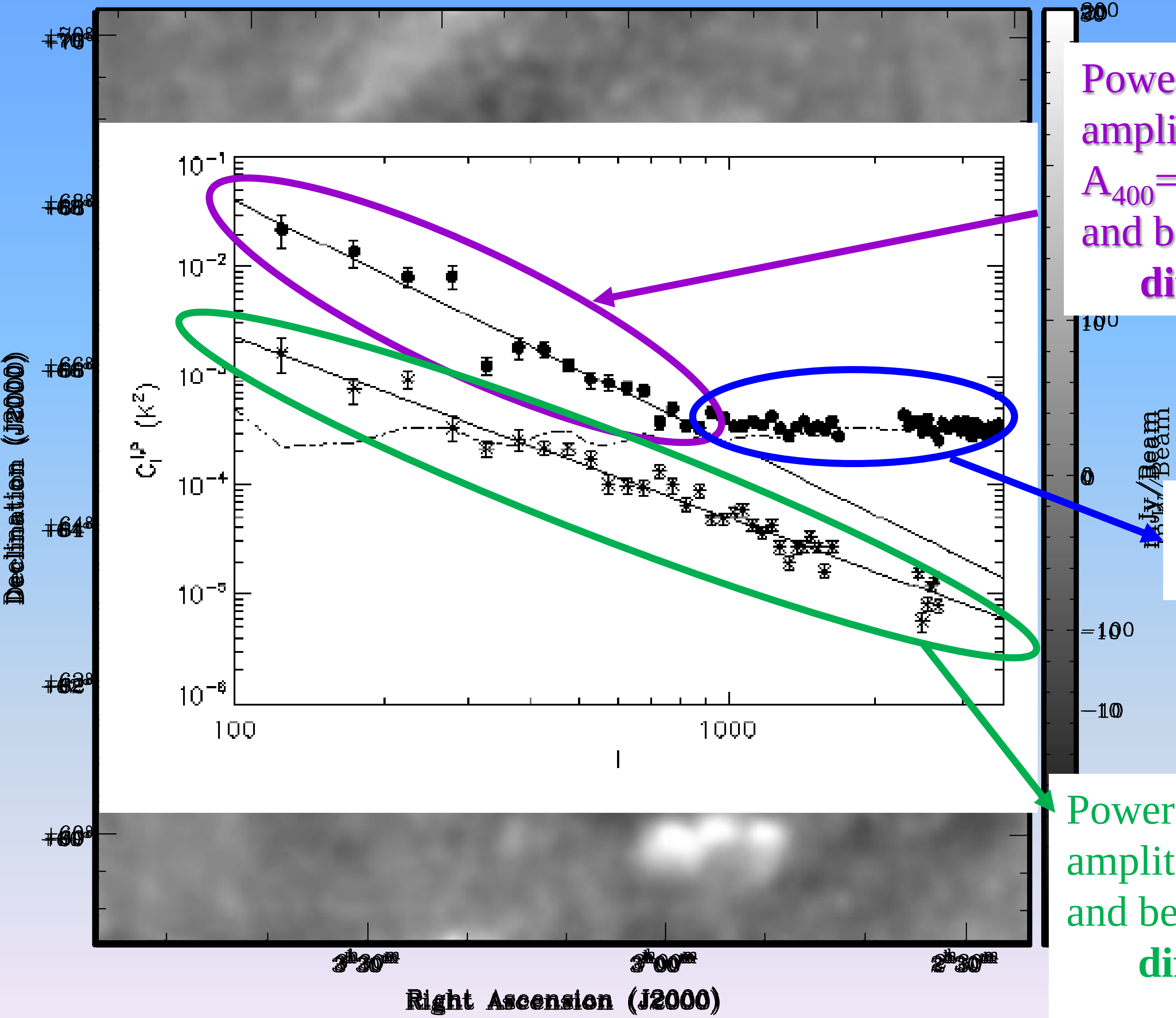
(Bernardi et al. 2009, Bernardi et al. 2010, Jelic et al. in prep)



Highlights from the survey:

- **first sub-mJy images at 115-170 MHz;**
- **first detection of Galactic (total intensity and polarized) foreground emission at sub-degree angular scales at low frequencies;**
- **characterization of foreground statistics through power spectra;**
- **first upper limits on 21cm signal at z~8.5;**

A field at Galactic latitude b~4°



Power law behavior with best fit amplitude
A_{400}= (0.0019 ± 0.0003) K^2,
and best fit slope β_I = -2.2 ± 0.3:
diffuse Galactic emission

frequency: ~150 MHz

peak flux ~ 2.8 Jy

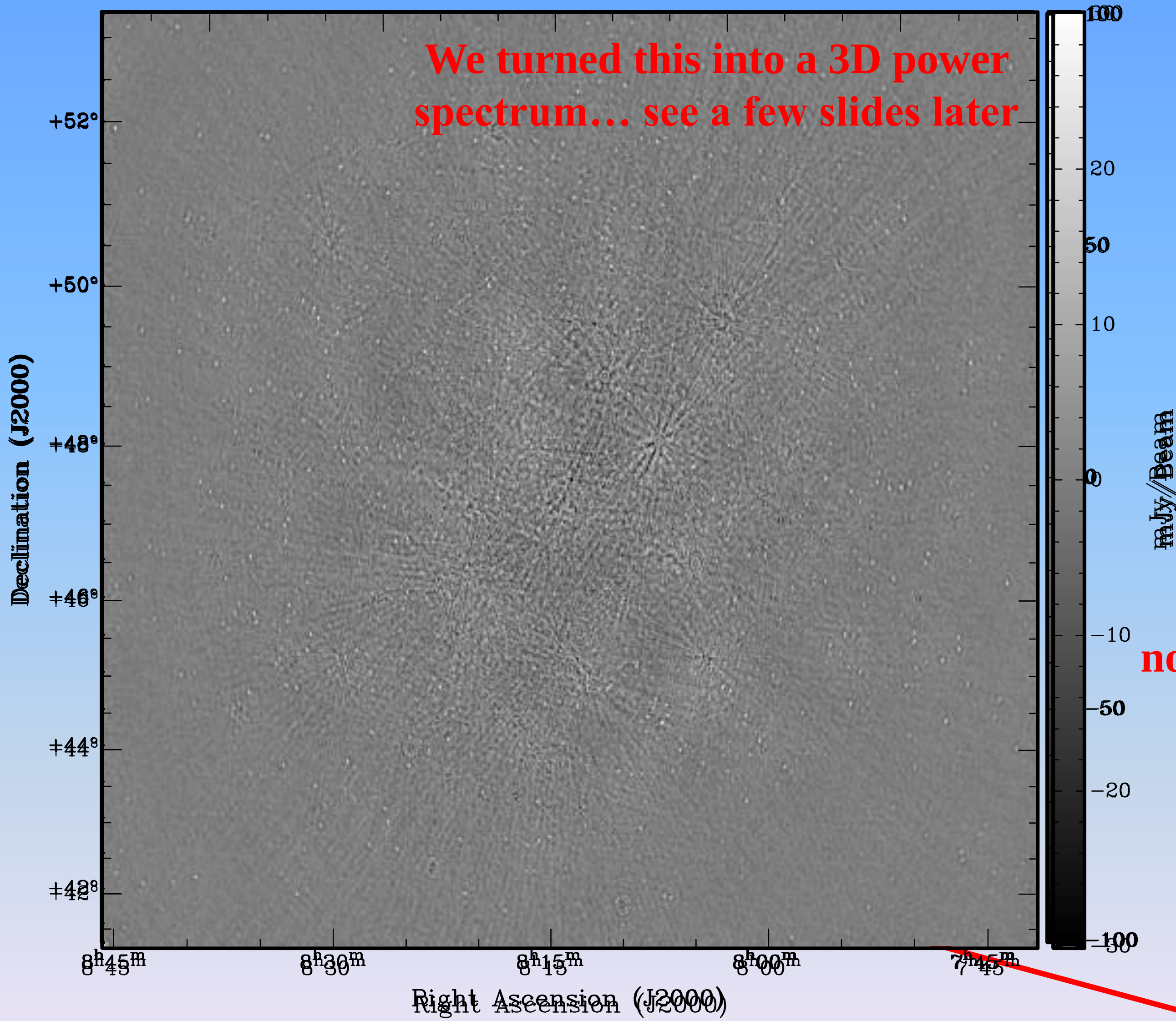
Flat power spectrum:
residual point sources

noise: 0.75 mJy/beam

Power law behavior with best fit amplitude A_{700}= (90 ± 7) $(mK)^2$
and best fit slope β_{Ip} = -1.52 ± 0.16:
diffuse polarized Galactic emission

Bernardi et al. 2009

A candidate LOFAR-EoR field: the 3C196 field



We turned this into a 3D power spectrum… see a few slides later

Bernardi et al. 2010

~2 arcmin resolution

peak flux ~ 77.4 Jy

frequency: ~ 150 MHz

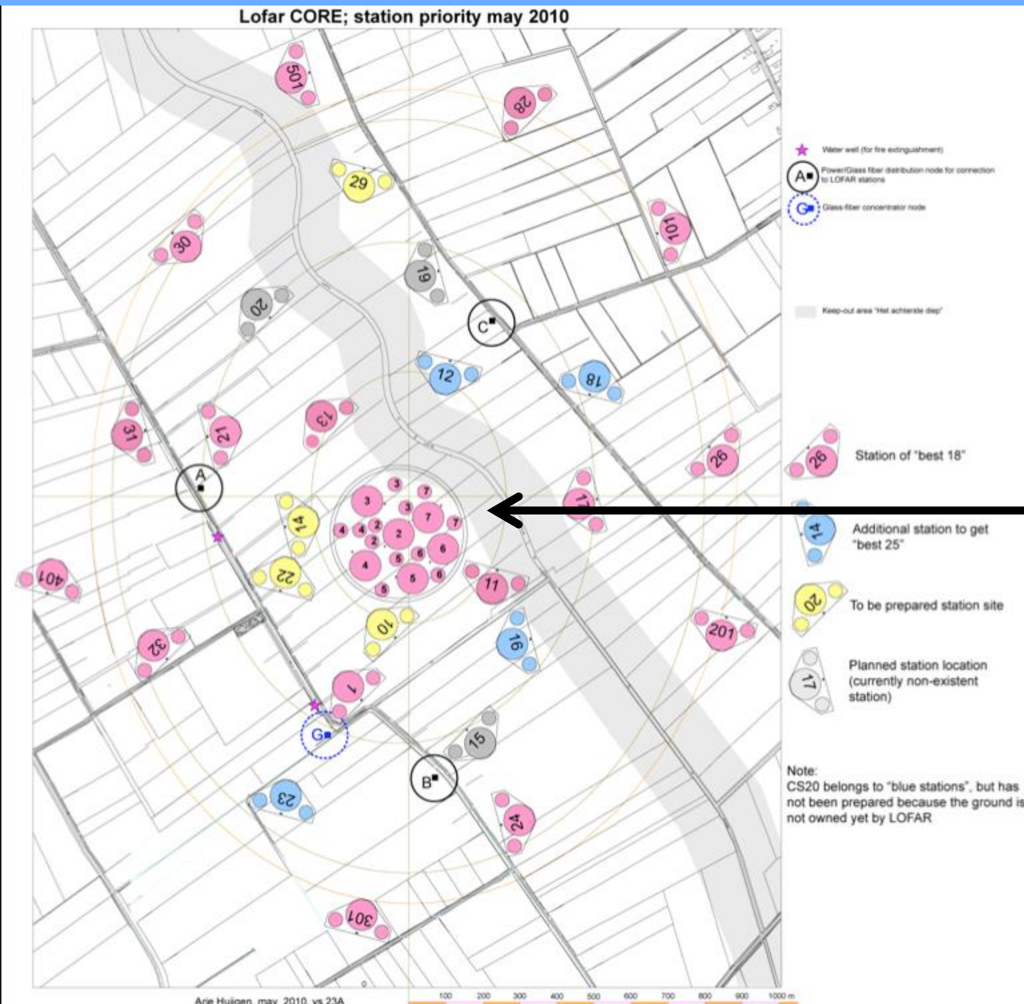
conversion factor: 1mJy/beam=3.3 K

noise: 0.5 mJy/beam (72 h, 16 MHz banwidth)

DR ~ 150000:1

chromatic phase errors due to ionospheric distortions are spread over a wide area

Deep observations with LOFAR



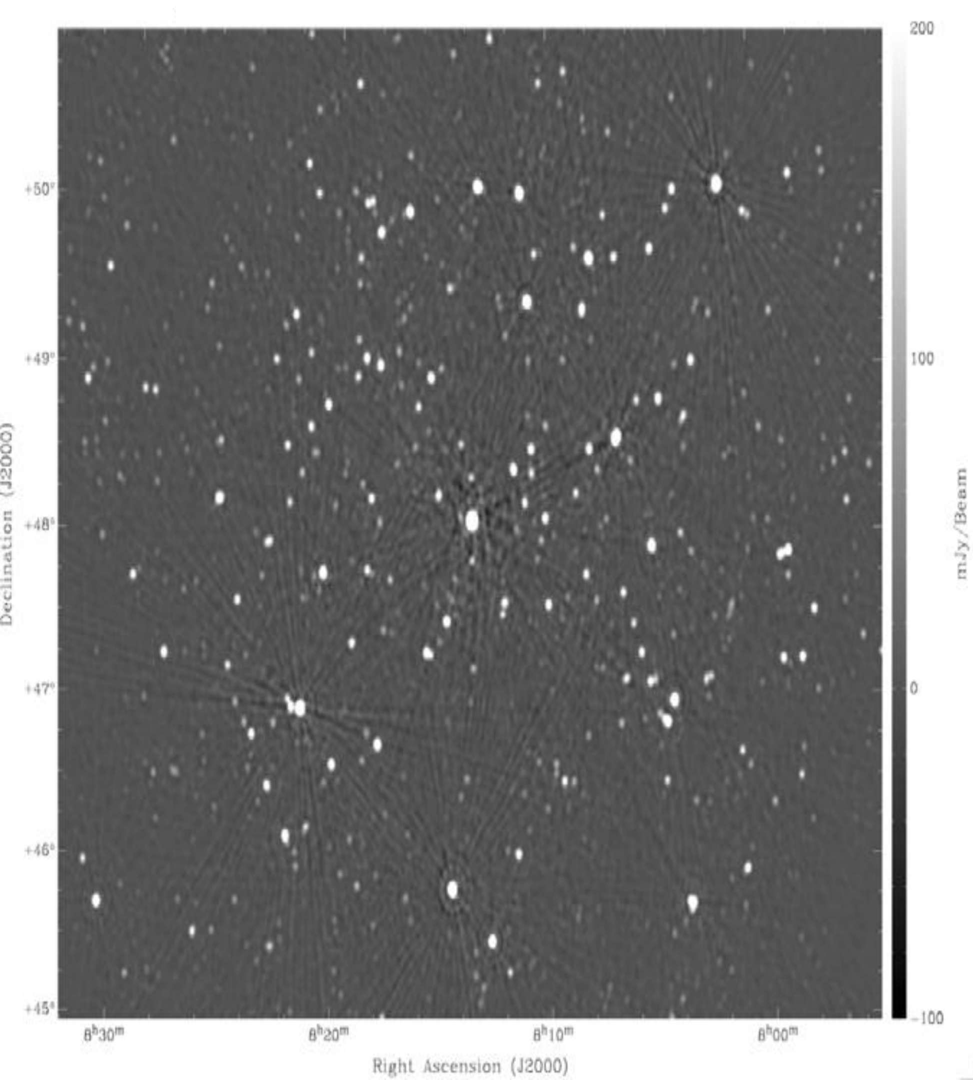
2.5 km

LOFAR core

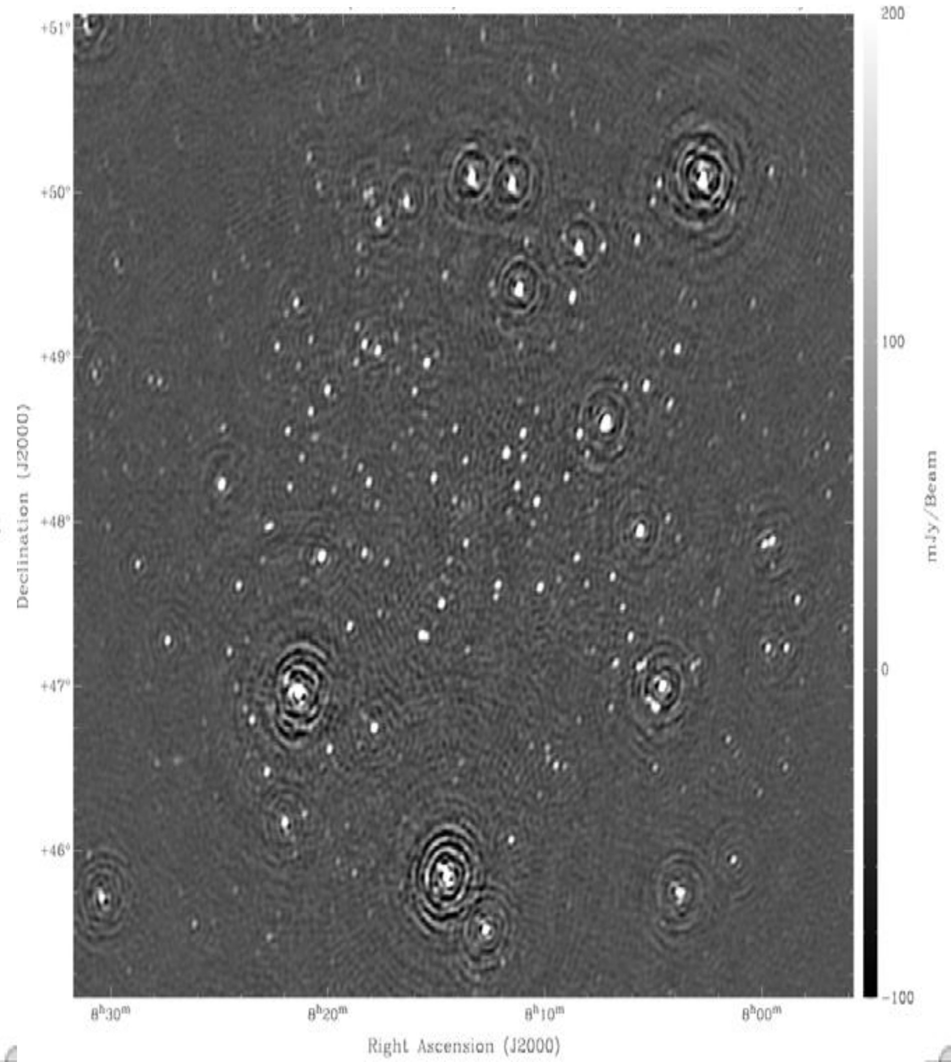
Super 'terp' – 350 m diameter

LOFAR deep integrations of the 3C196 field

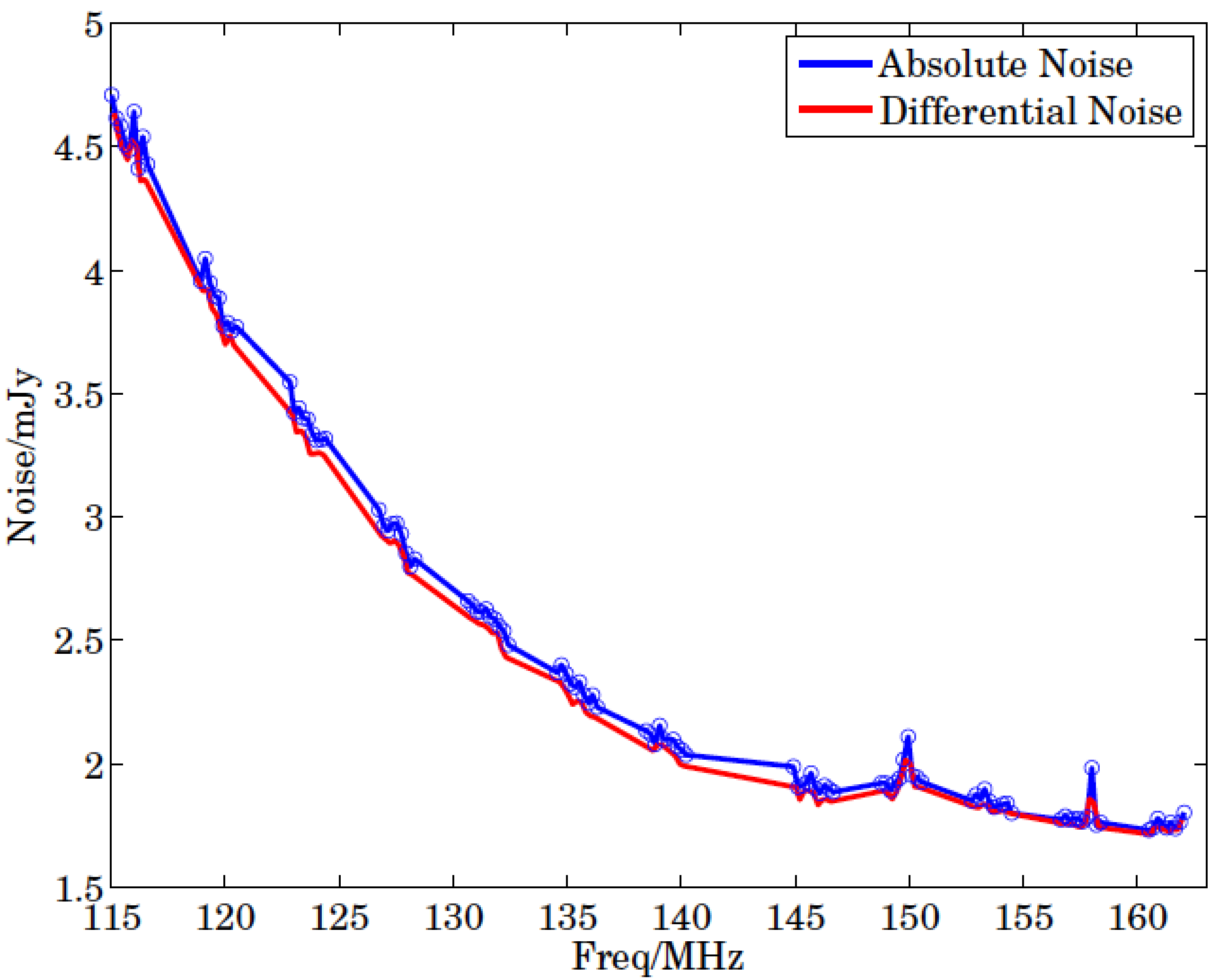
WSRT, 14 MHz bandwidth, 72 h,
0.5 mJy/beam sensitivity



LOFAR HBA, core stations, 36 MHz
bandwidth, 6 h, 0.3 mJy/beam sensitivity



Noise behavior as a function of frequency



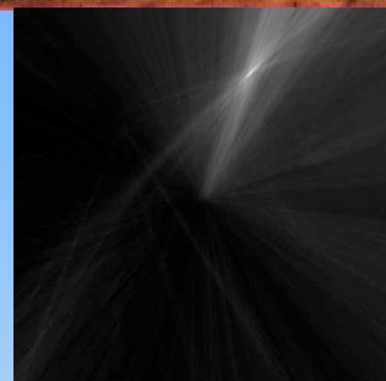
Differential and absolute noise

Near future:

- **400h observations in autumn/winter 2012-2013 should approach a continuum sensitivity of ~70 mK (getting close to EoR noise levels)?**
- **precise beam characterization needed**
- **ionospheric correction;**

Results from the GMRT

Severe RFI environment



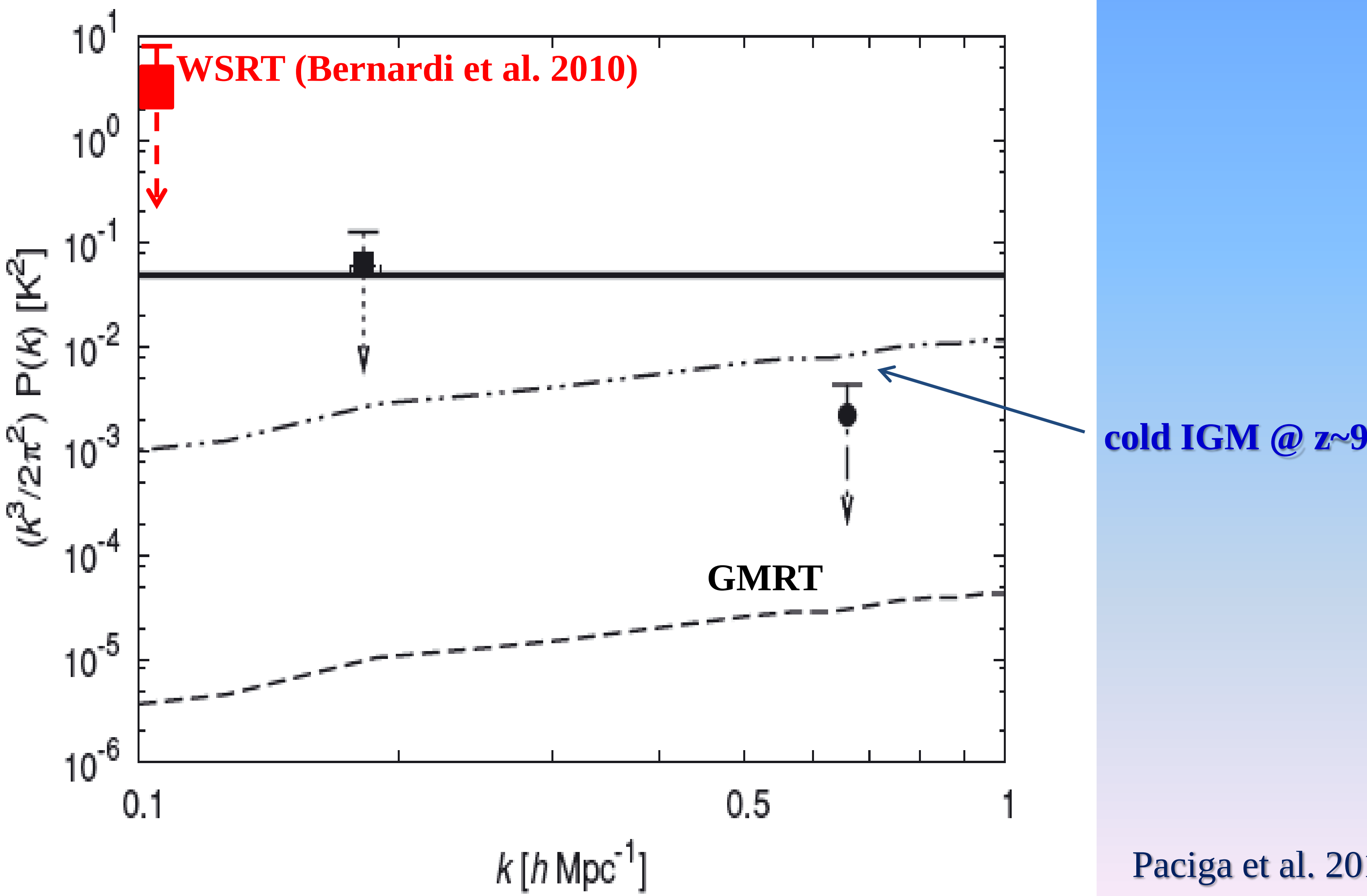
Clever calibration strategy: pulsar on – pulsar off provides the calibration for the 3 deg FoV

Foreground subtraction through a linear filter of the visibilities over 8, 5 and 0.5 MHz

Sky map | **Sky map - foregrounds** | **Sky map – foregrounds zoom**

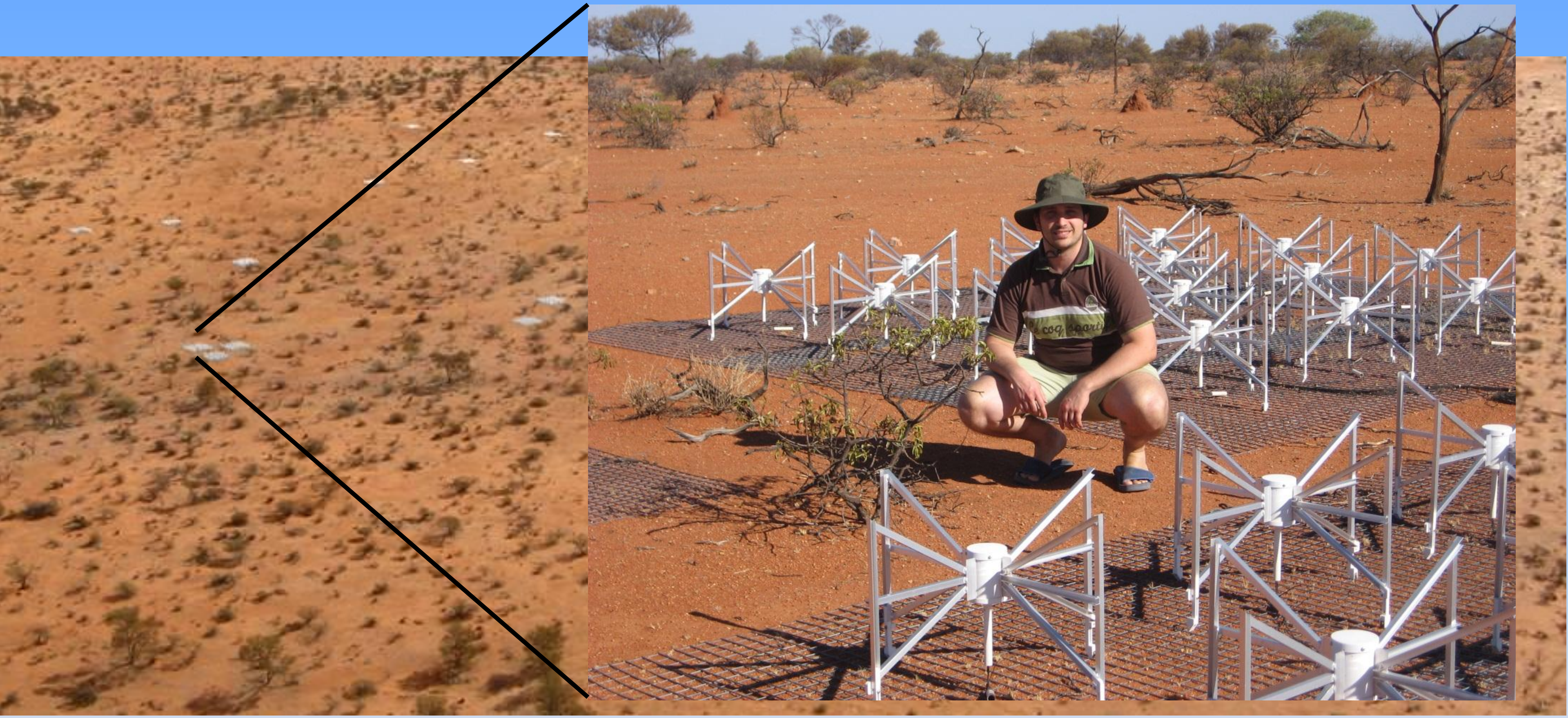
Pen et al. 2009, Paciga et al. 2011

Current state of the art: upper limits on HI at z ~ 8.5-9



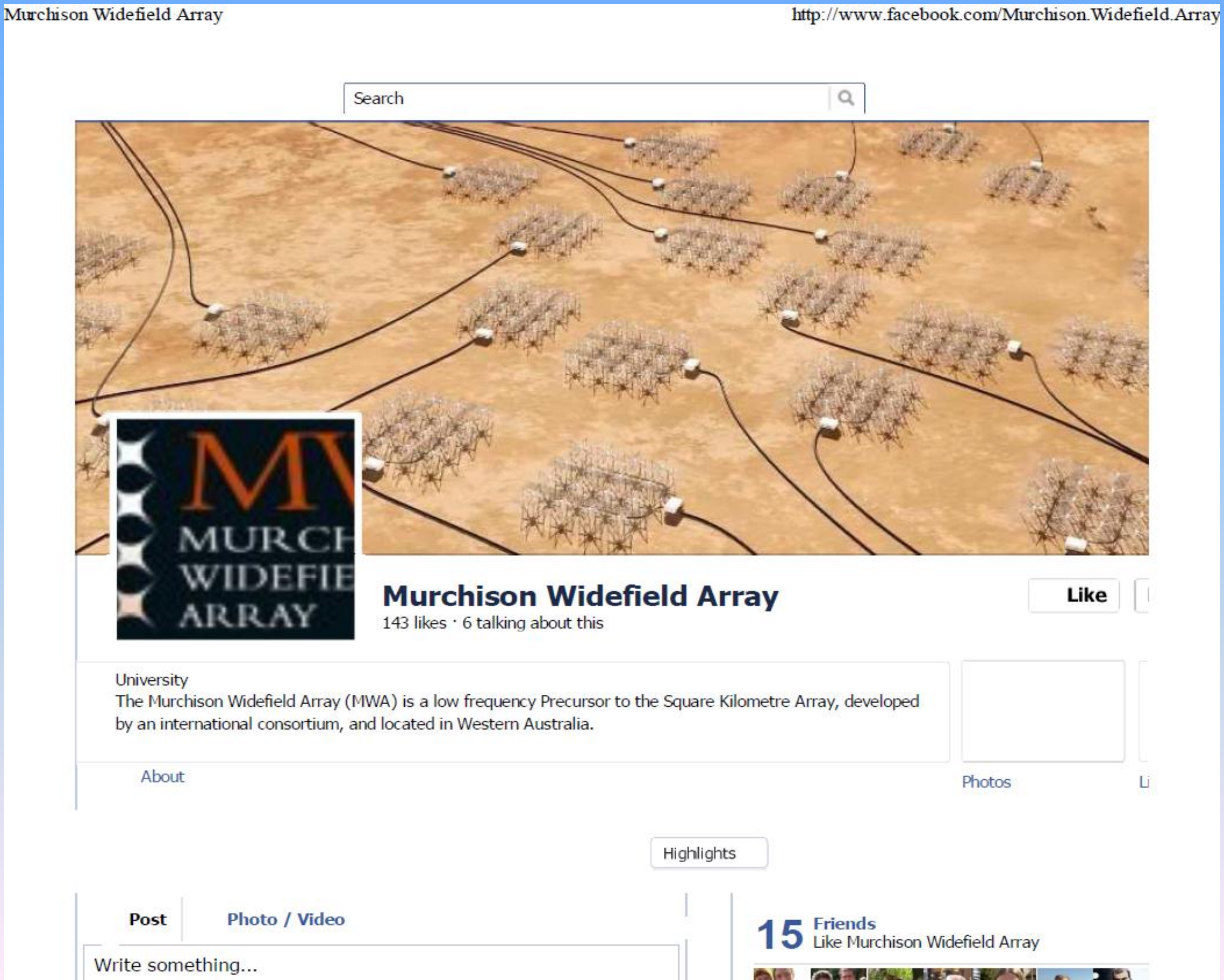
Paciga et al. 2011

Results from the Murchison Widefield Array



32 stations now (128 stations by the end of the year)
80-200 MHz coverage
1.5 km maximum baseline

Science 2.0: MWA on facebook (http://www.facebook.com/Murchison.Widefield.Array)

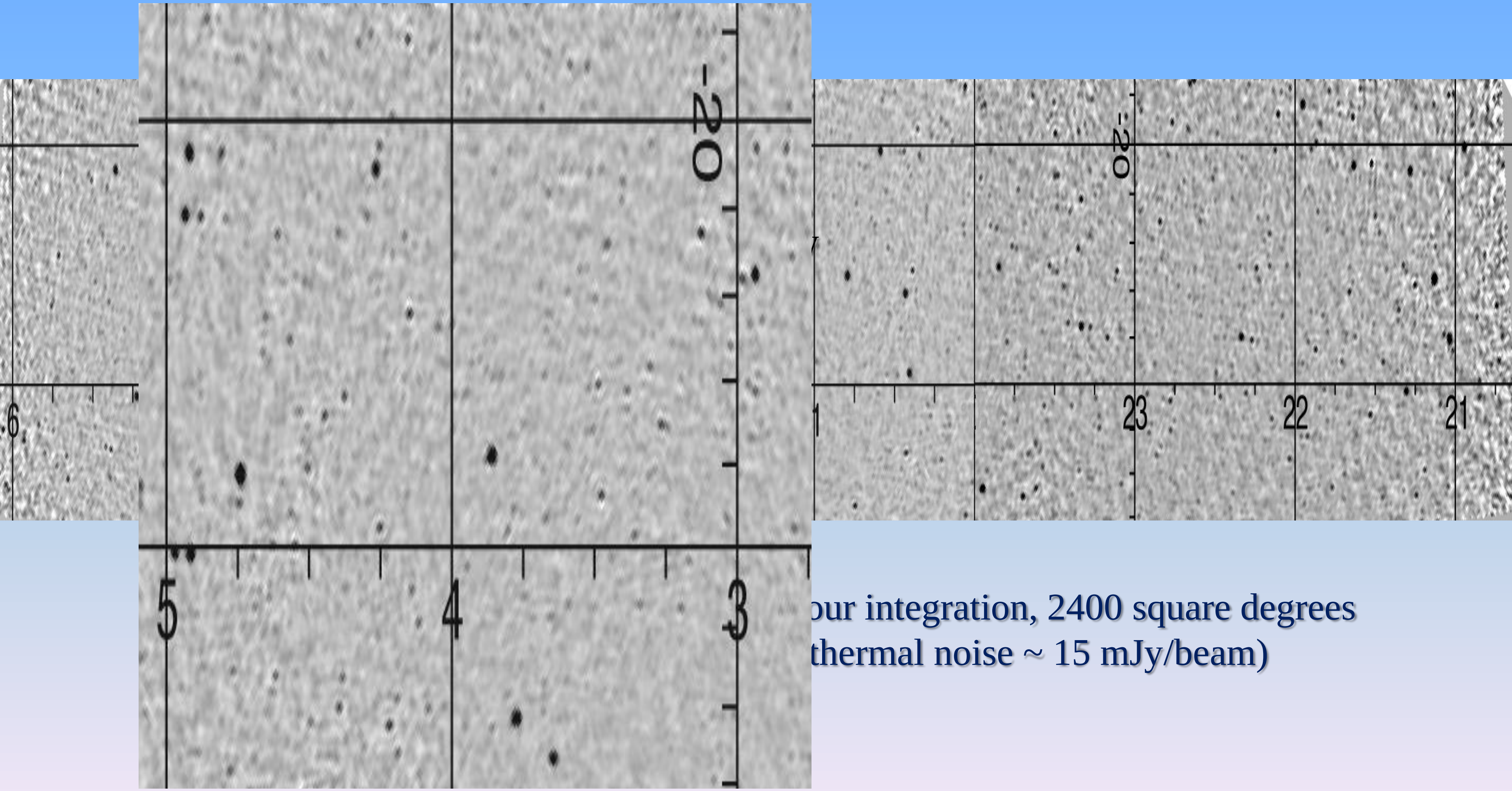


A 188.8 MHz drift scan survey with the 32T array

Calibration: Mitchell et al. 2008

Imaging: Ord et al. 2010

Deconvolution: Bernardi et al. 2011

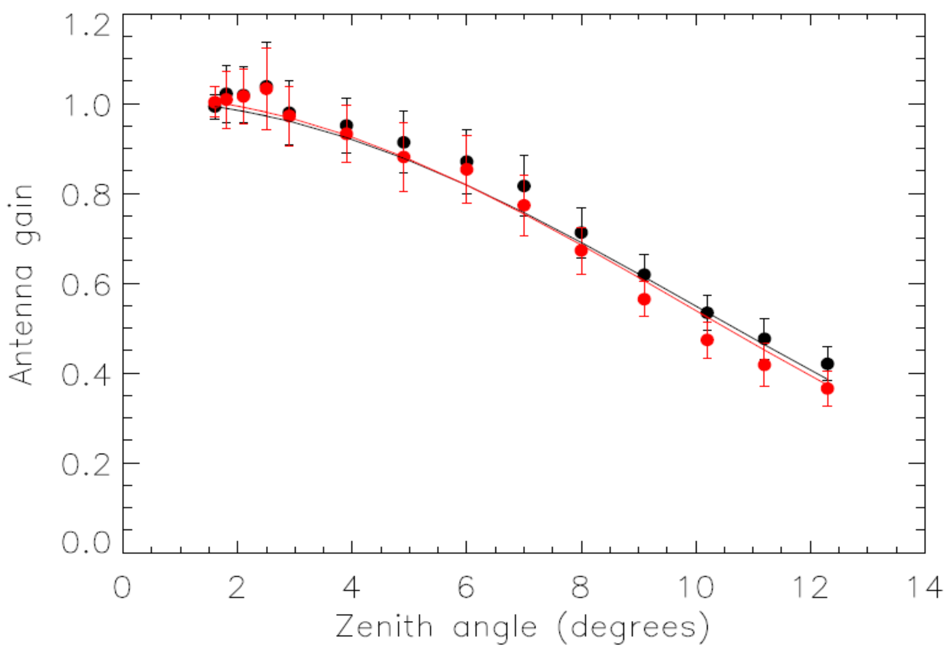


our integration, 2400 square degrees

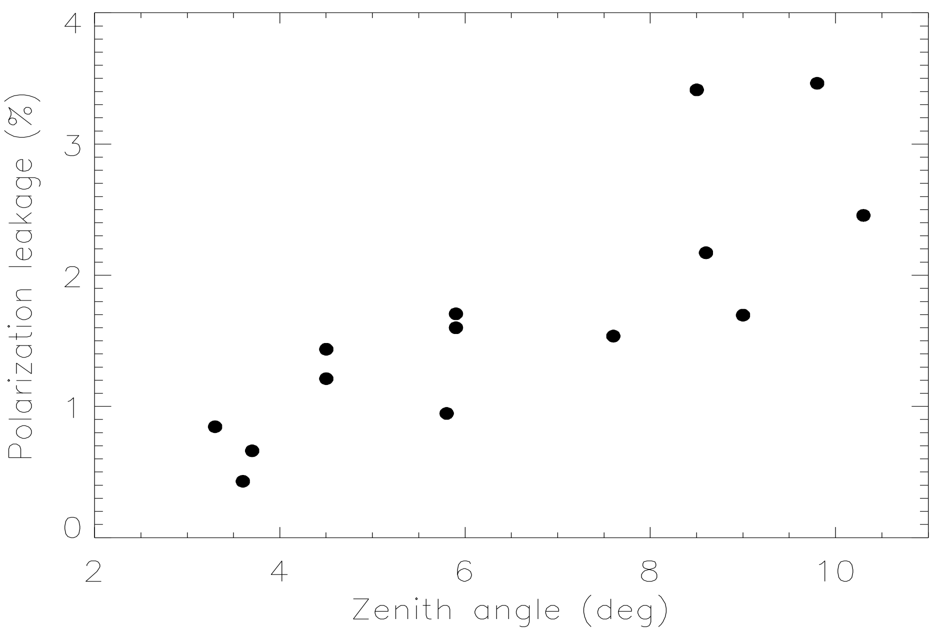
thermal noise ~ 15 mJy/beam)

Bernardi et al. 2012 in prep.

Calibration accuracy

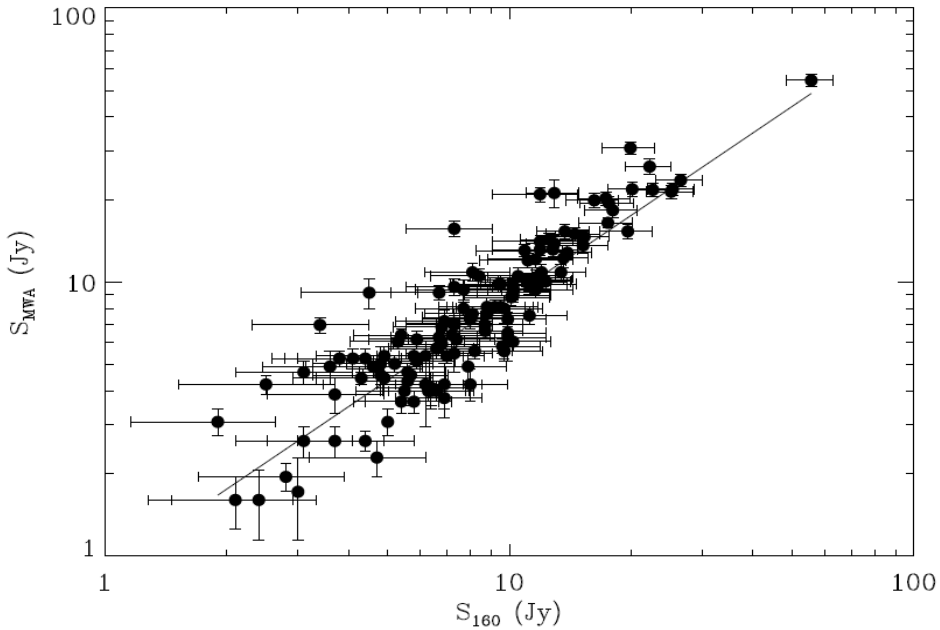


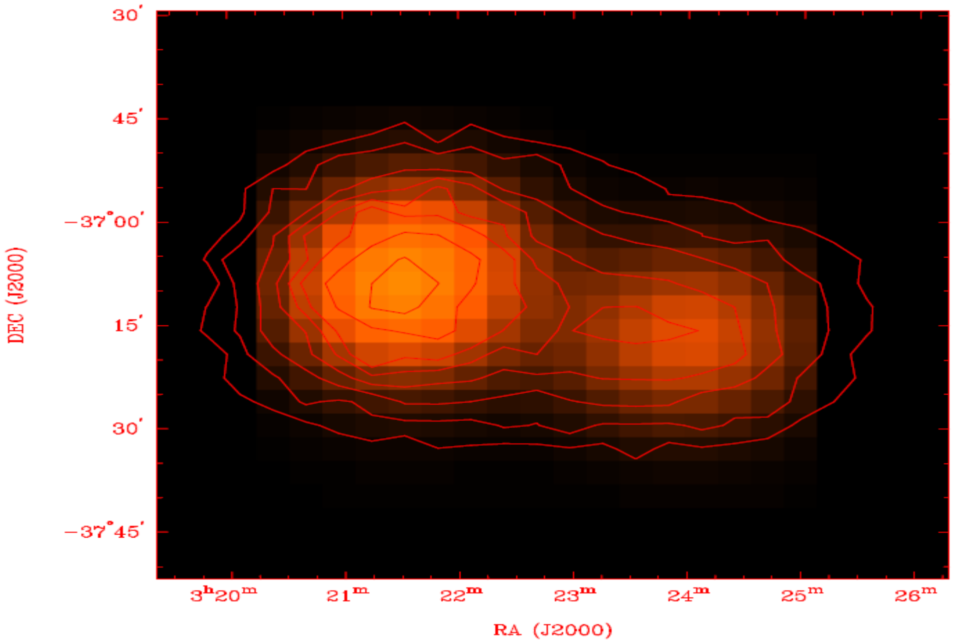
The primary beam model fitted to the data is good at the 2% level over 30.72 MHz



Polarization leakage is less than 5% over 20º, in average 1.8%

Calibration accuracy + science

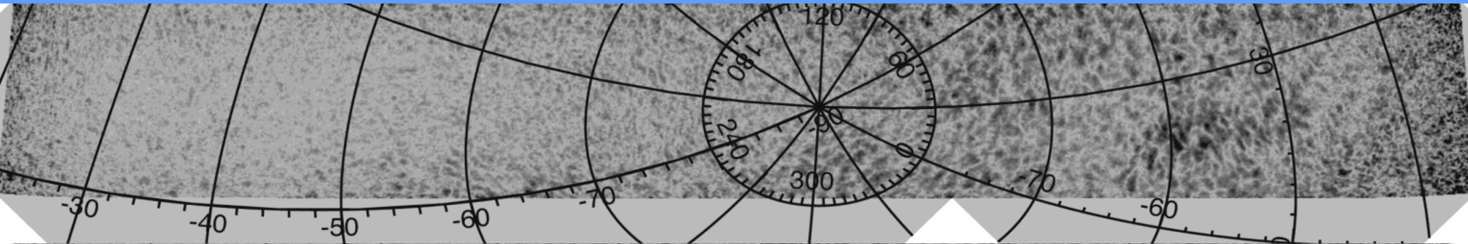




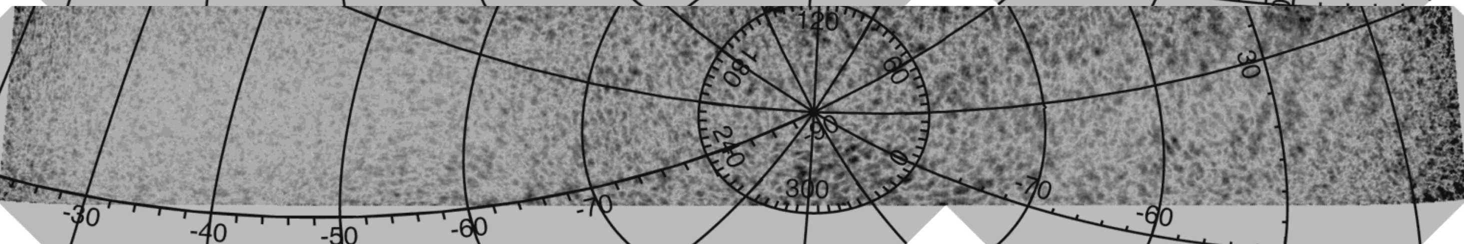
A catalogue of 137 sources greater than 4 Jy (29 sources measured for the first time below 200 MHz)

Comparison with 160 MHz measurement from the literature: 98% of sources matched, 19% rms difference above 4 Jy

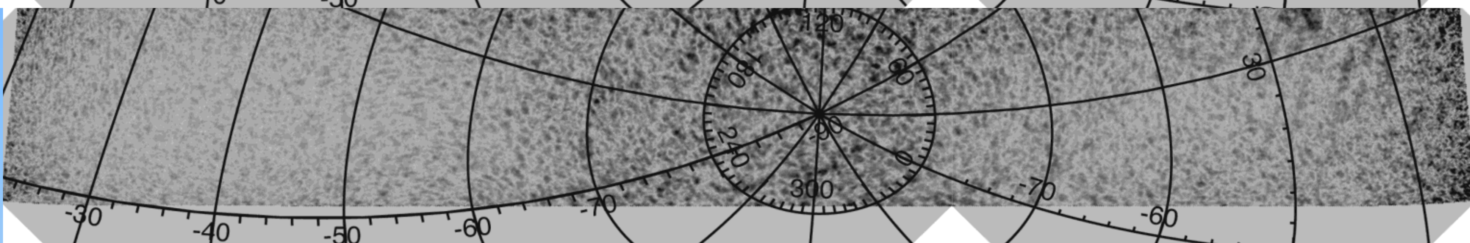
First Fornax A image below 200 MHz: integrated flux @ 188.8 MHz ~ 519 ± 26 Jy
$\alpha_{1421\text{-}188.8} = 0.71 \pm 0.02$



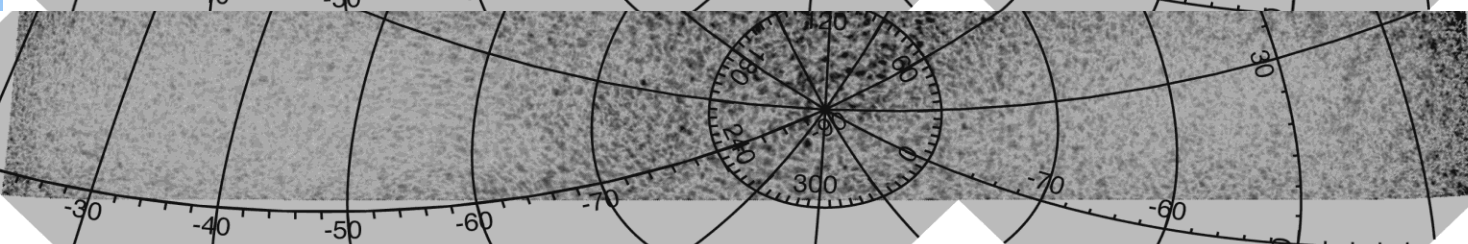
RM = 0



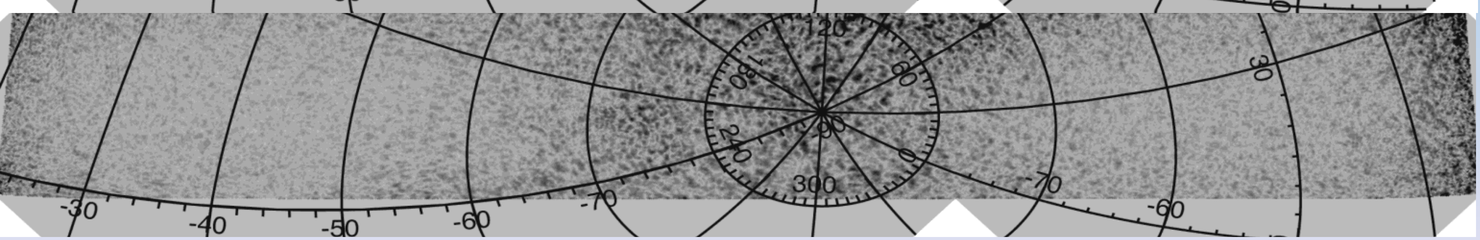
RM = 2



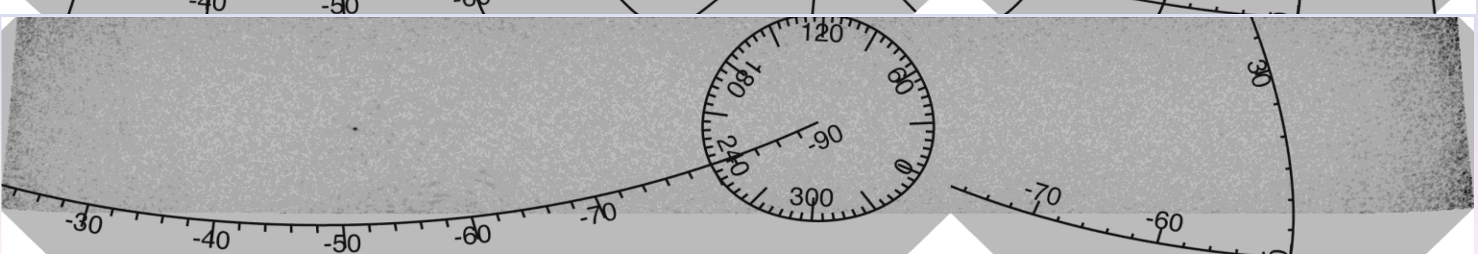
RM = 4



RM = 6



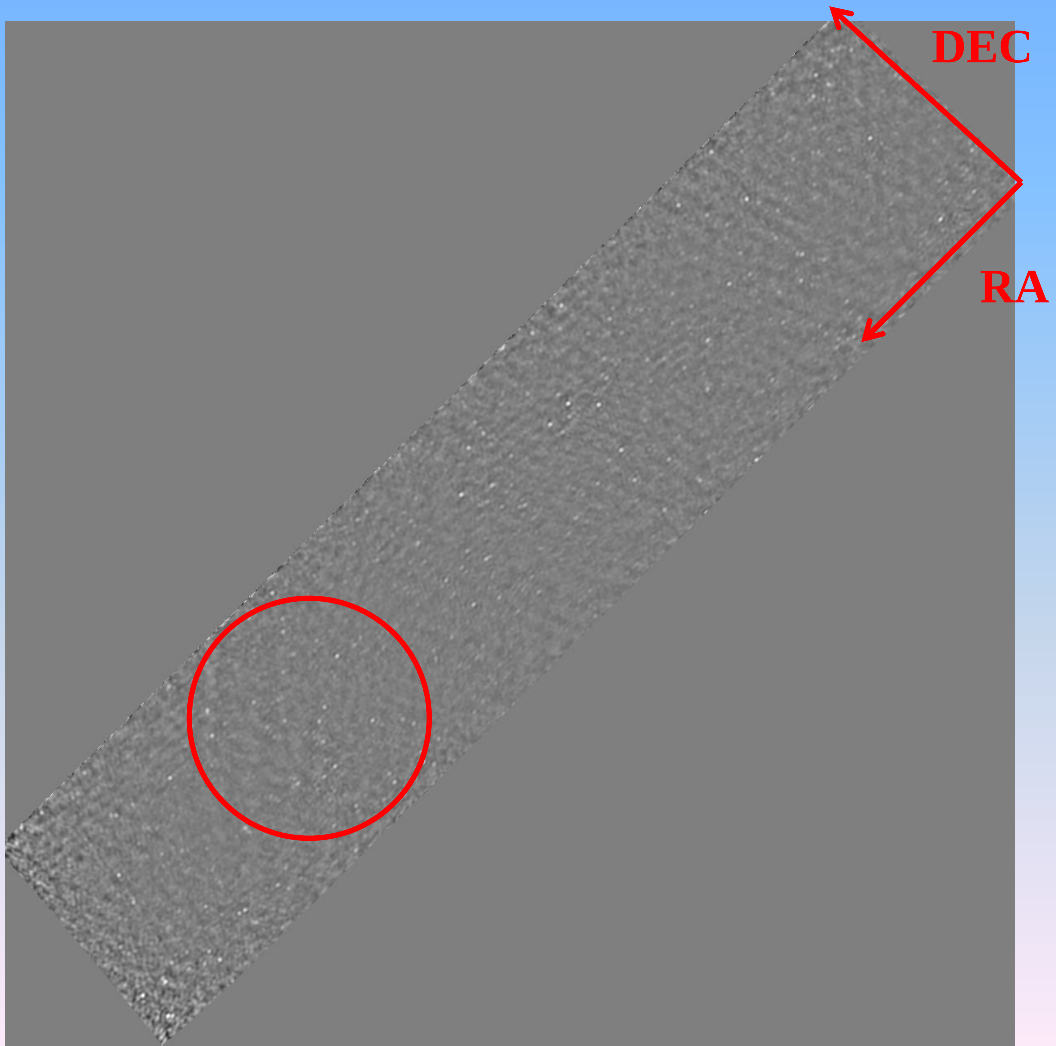
RM = 8



RM = 34

A (shallow) EoR like experiment at $\alpha = 4^h$

- Subtraction of bright sources through "peeling";



A (shallow) EoR like experiment at $\alpha = 4^h$

- Subtraction of bright sources through "peeling";
- Subtraction of extragalactic unresolved sources from the image cube at 0.6 MHz resolution through a principal component analysis (PCA, de Oliveira-Costa 2008):

$$C = P \Lambda P^T \qquad r_i = x_i - m_i = x_i - P P^T x_i$$

N_f x N_f covariance matrix

eigenvector matrix

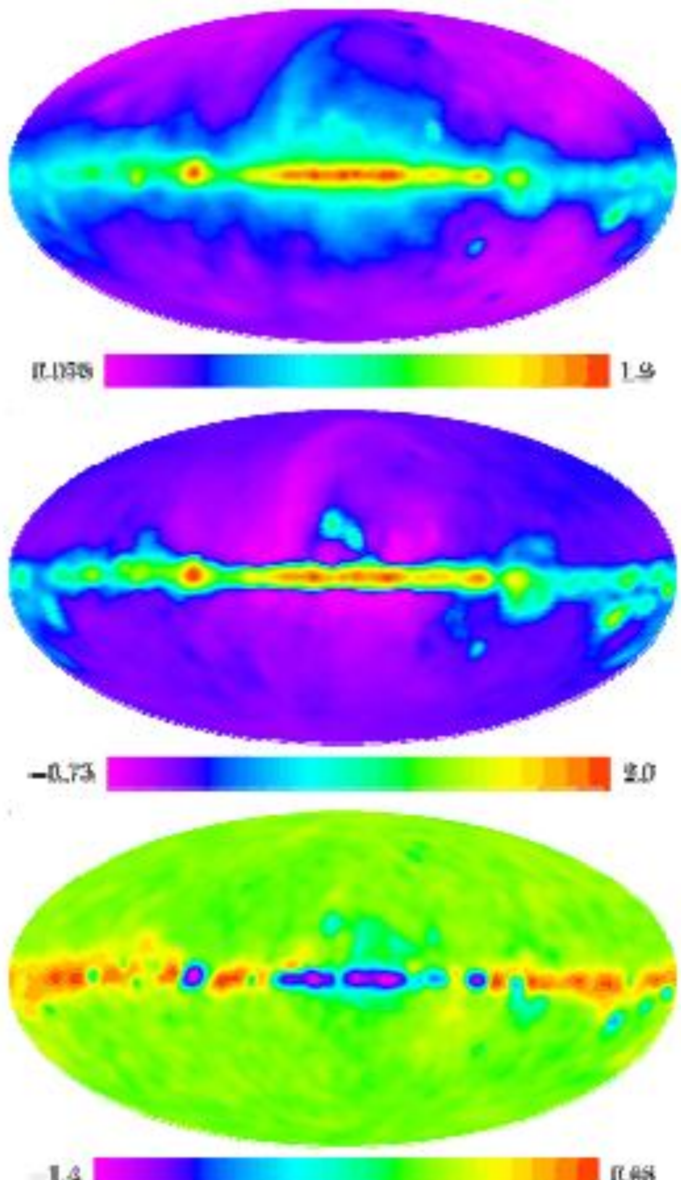
eigenvalue matrix

residual image at frequency ν

data at frequency ν

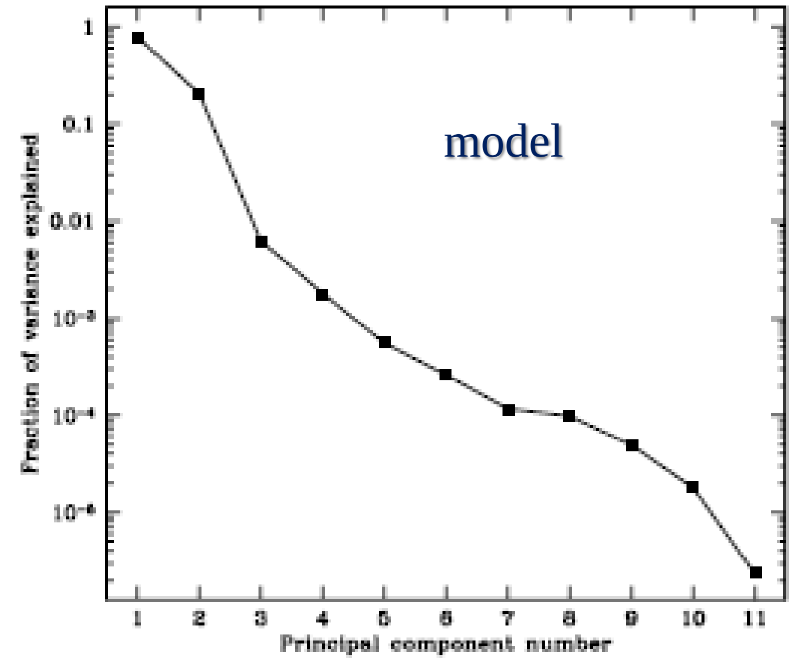
PCA model at frequency ν

A (shallow) EoR like experiment at $\alpha = 4^h$

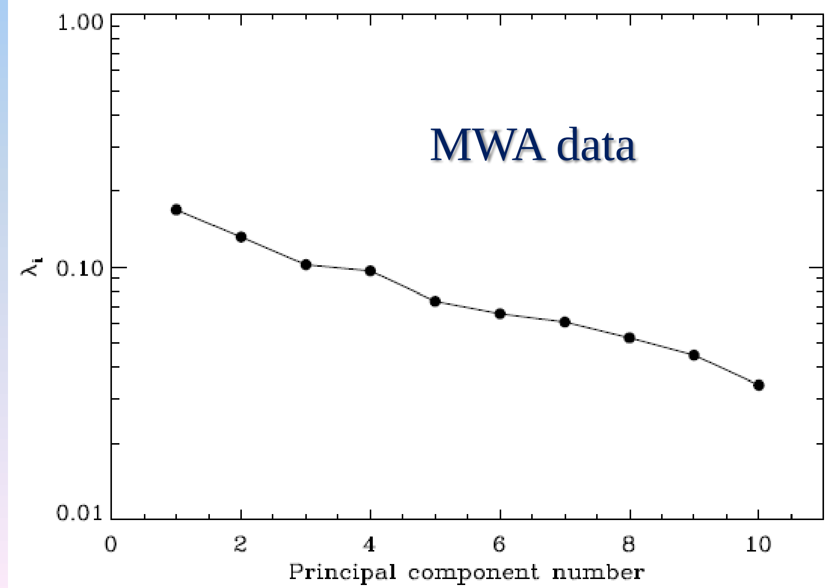


de Oliveira-Costa 2008

~99% of the power is the in first three components

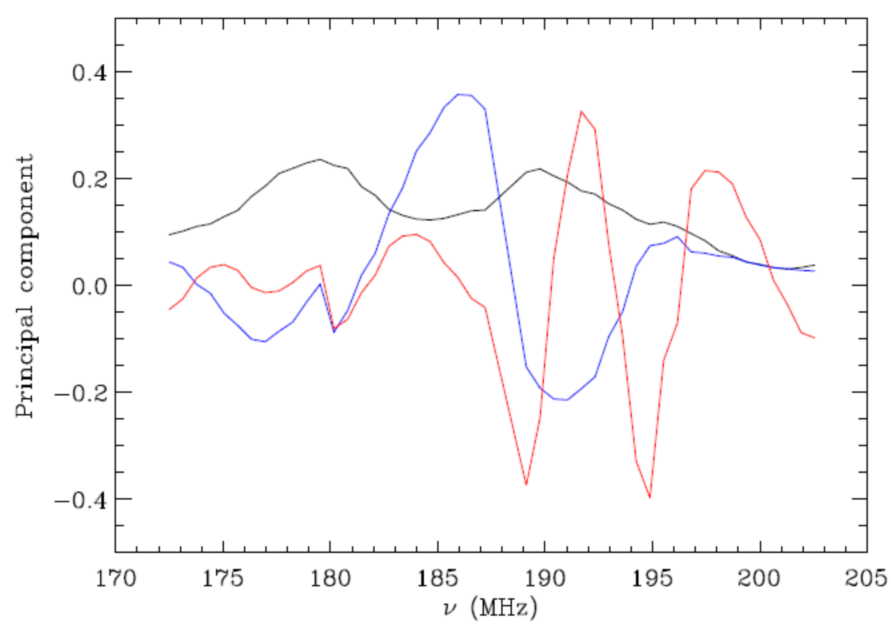


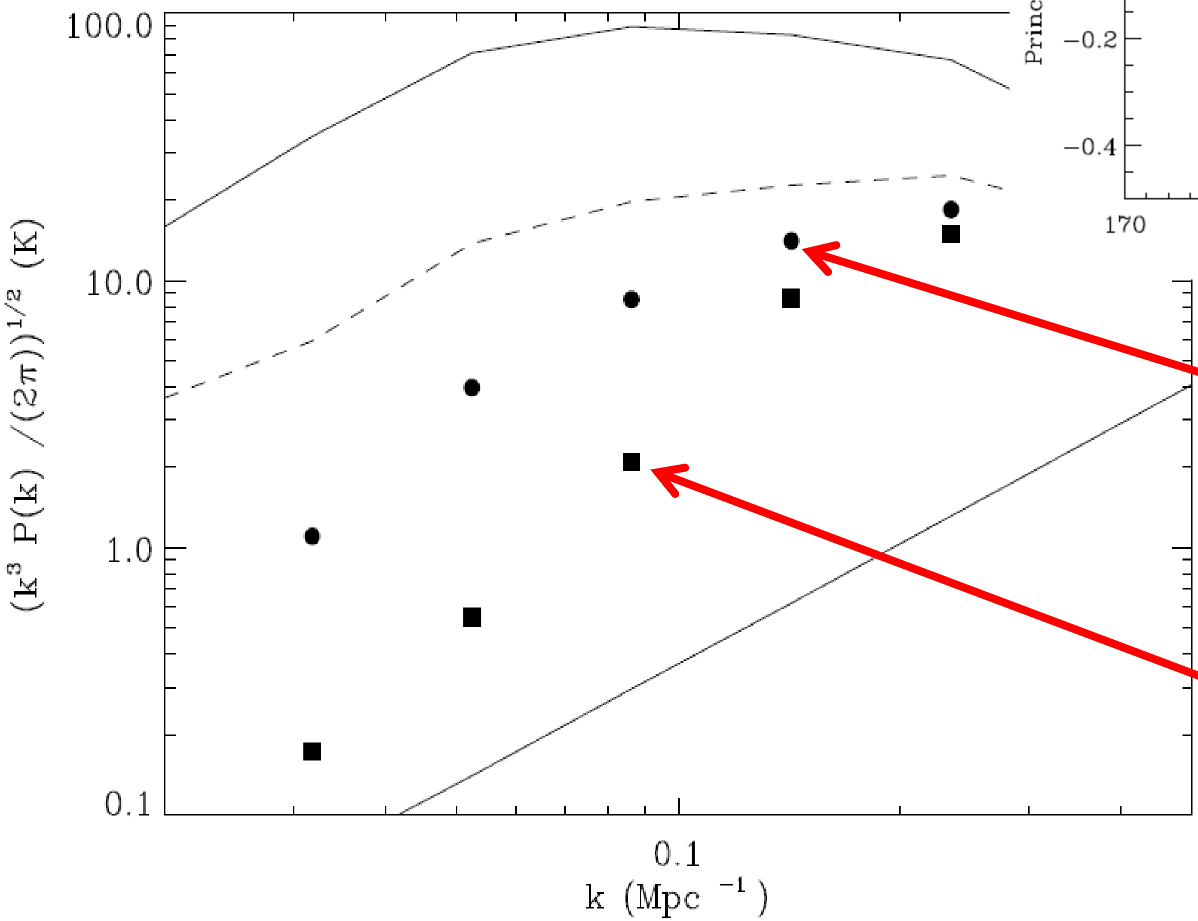
~40% of the power is the in first three components



A (shallow) EoR like experiment at $\alpha = 4^h$

near future work: improvement of the frequency calibration of the array



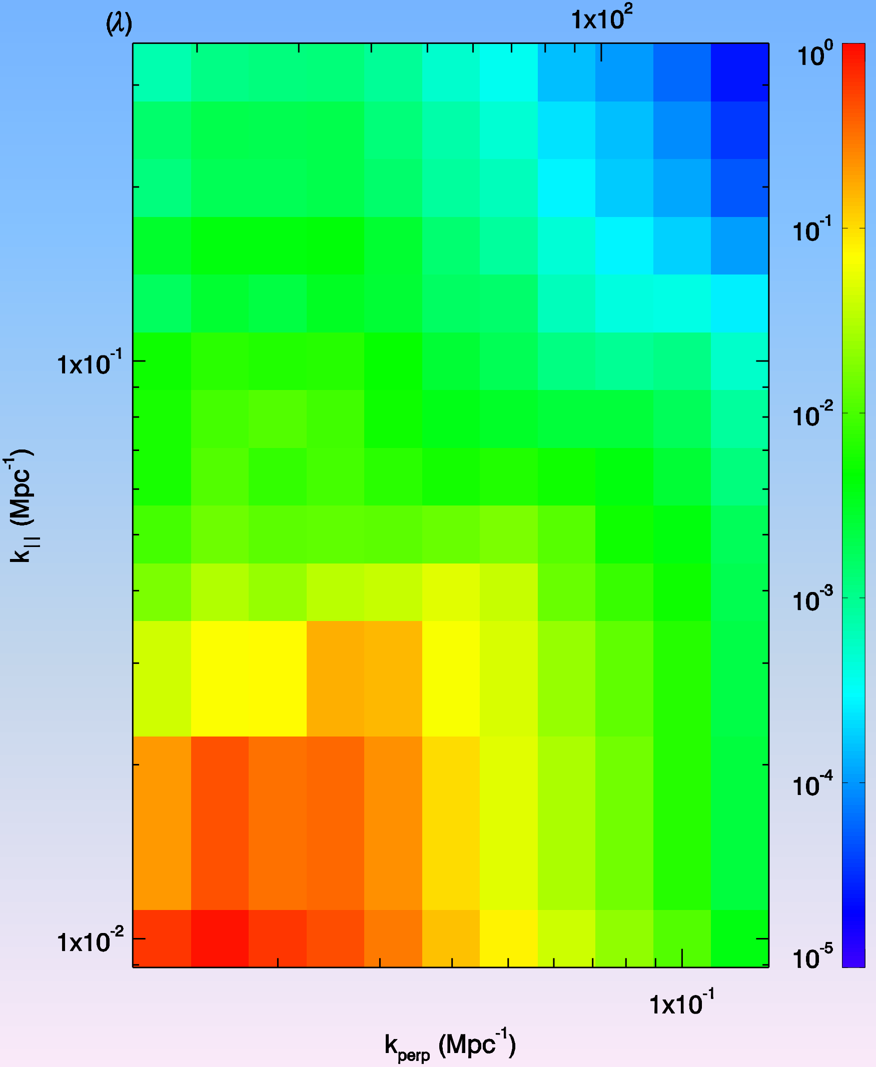


filtering the confusion level sources (first 5 PCA components)

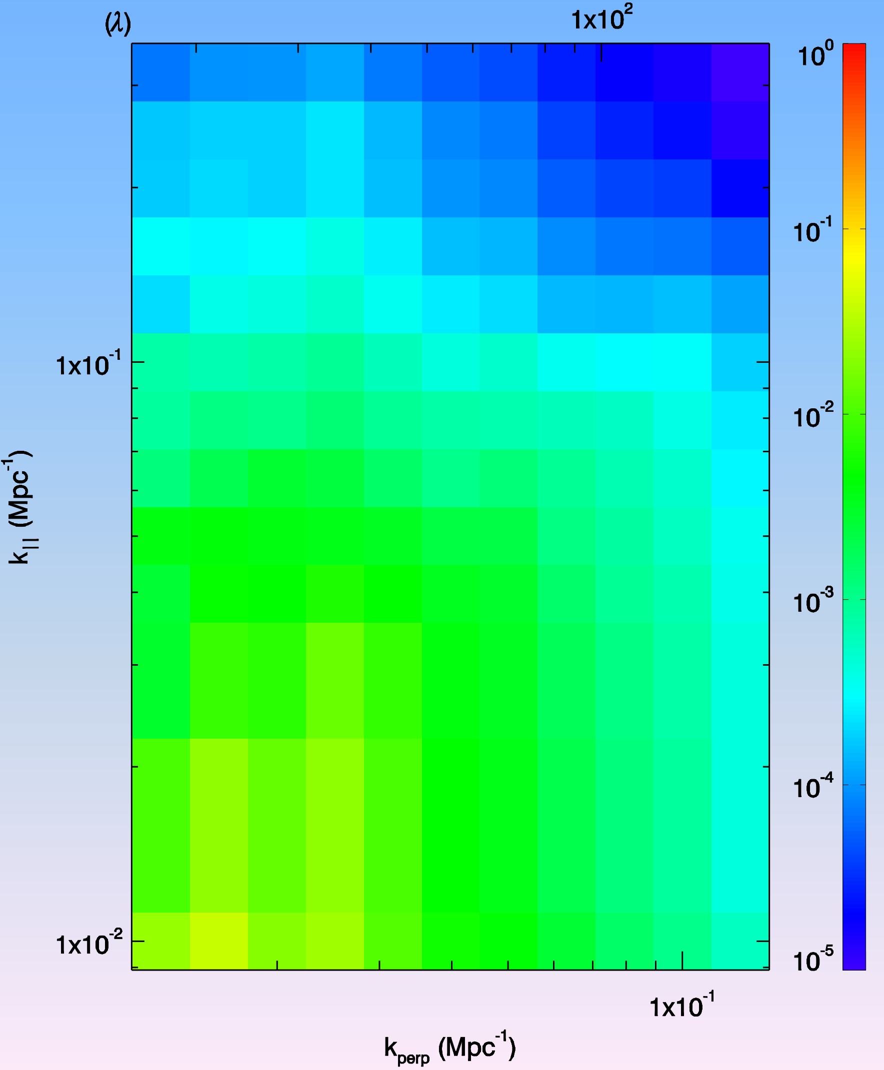
filtering the confusion level sources (first 10 PCA components)

A (shallow) EoR like experiment at $\alpha = 4^h$

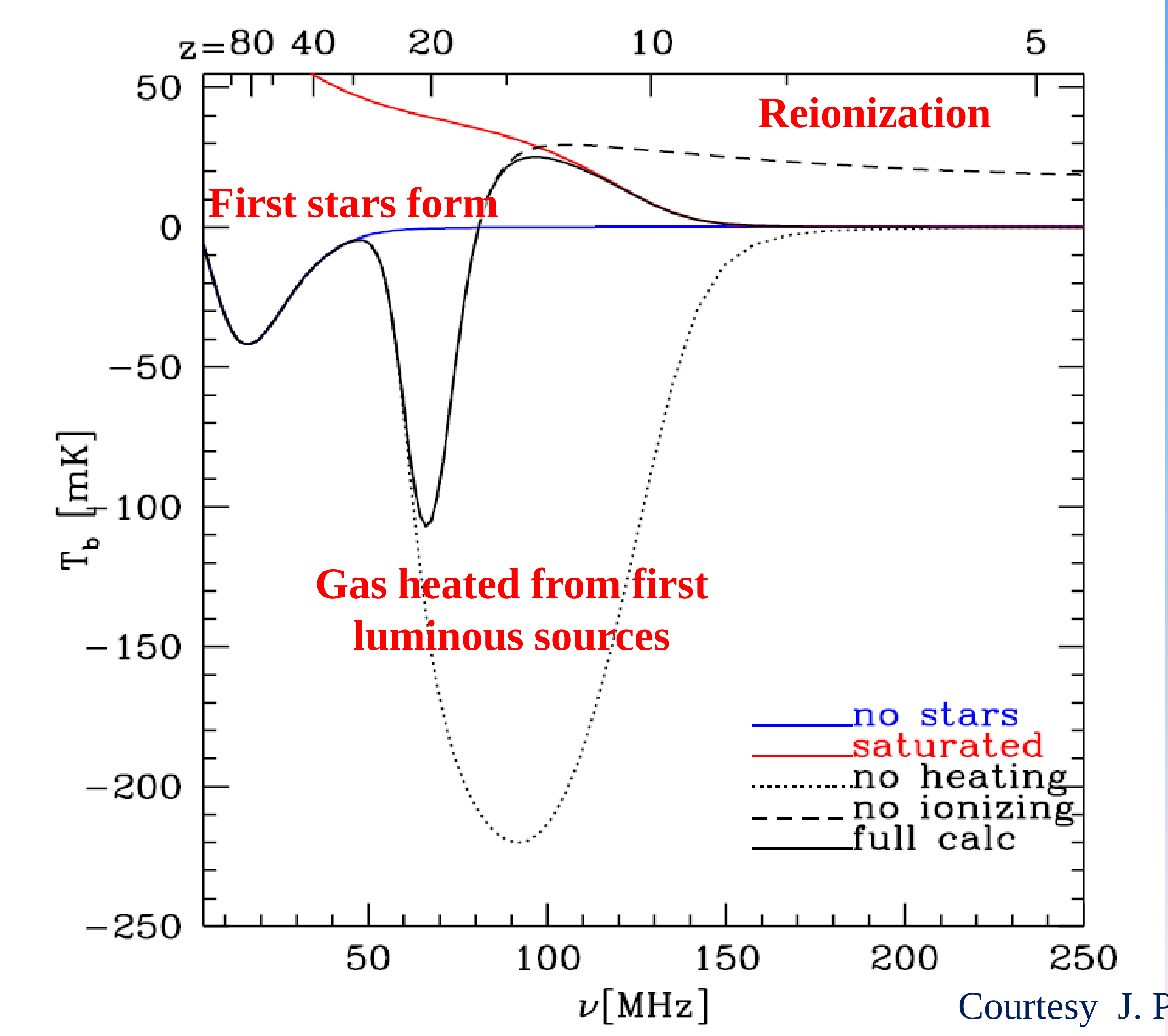
no subtraction



point sources subtracted

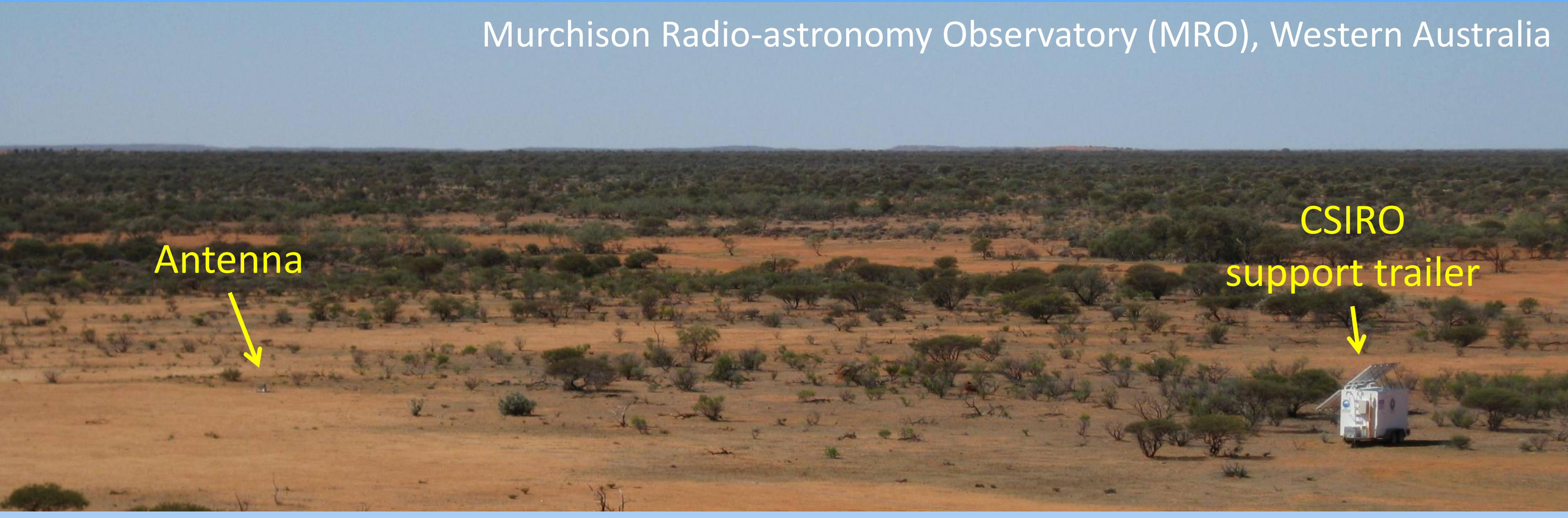


The evolution of the global HI signal



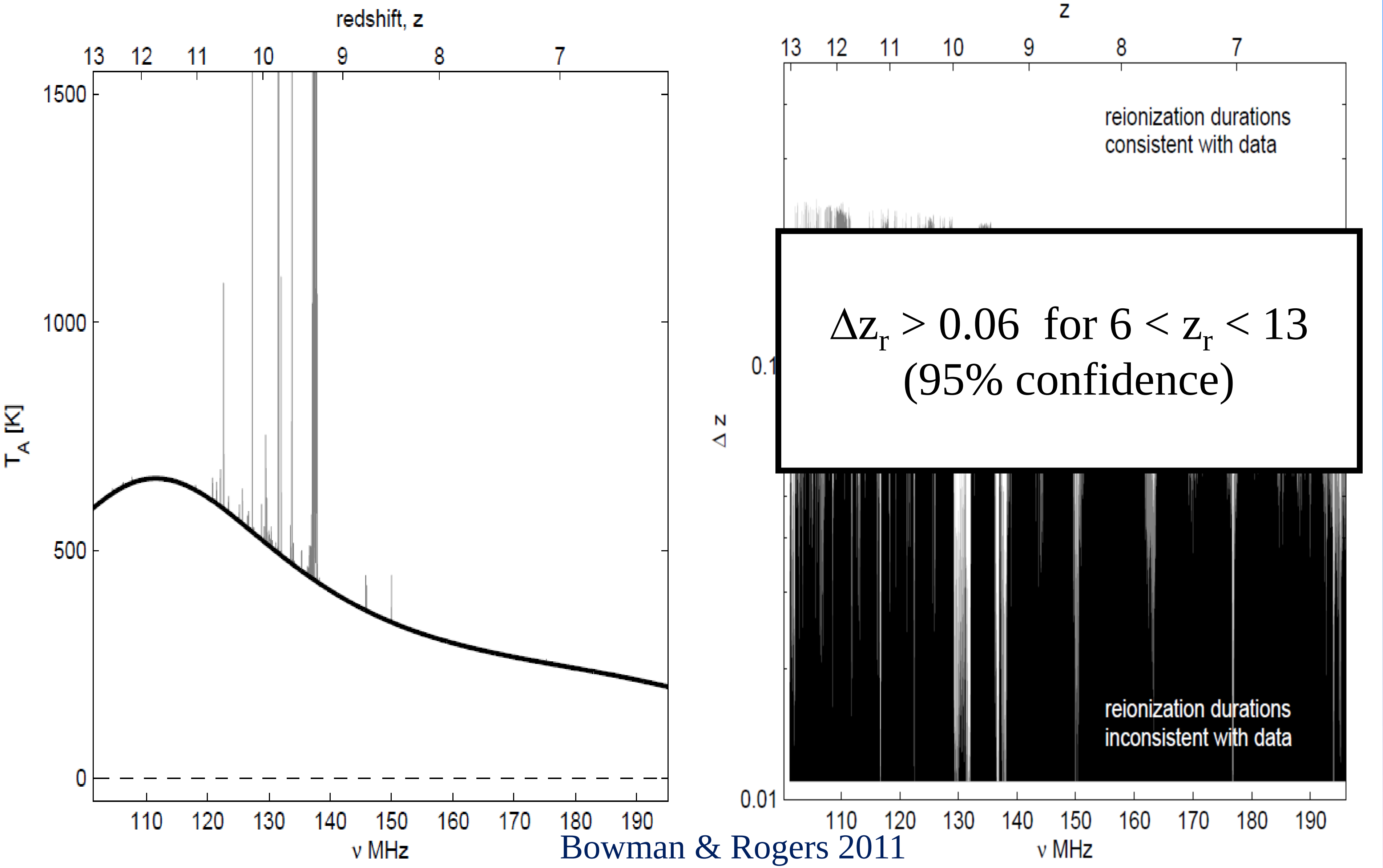
Courtesy J. Pritchard

The experiment to Detect the global EoR signature - EDGES



Courtesy J. Bowman

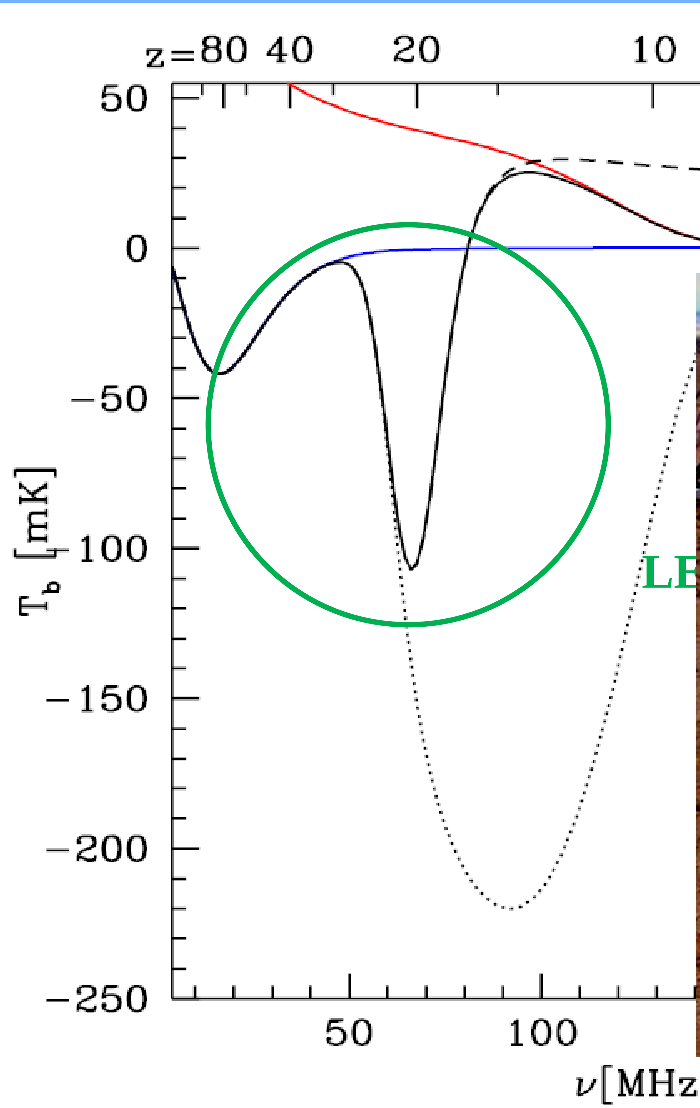
An upper limit on the duration of reionization from the sky-averaged frequency spectrum

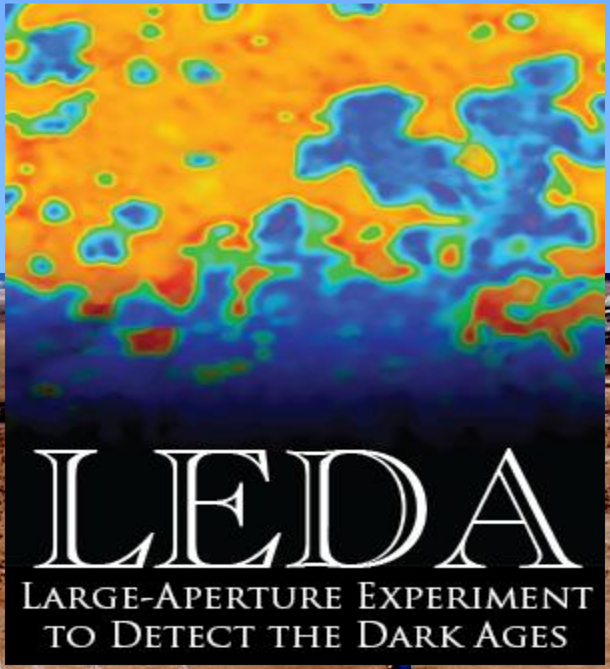


$\Delta z_r > 0.06$ for $6 < z_r < 13$
(95% confidence)

Bowman & Rogers 2011

The Large-aperture Experiment to detect the Dark Ages (LEDA, PI: L.J. Greenhill, collaboration between Harvard, Berkeley, UNM, VT, http://www.cfa.harvard.edu/LEDA/index.html)





Courtesy J. Pritchard

The present and future of LEDA

- ➢ constrain HI absorption at z ~ 25-30 through sky--averaged (DC) signature in ~100h;
- ➢ demonstrate correlator technology relevant to HERA scales;

- import full correlation back-end to LWA (Ø~100m/300m):
- ➢ 256x2 pol. (array + total---power dipoles);
- ➢ FPGA---GPU hybrid correlator: CASPER F-engine (Parsons, Backer & Werthimer) + Harvard X-engine (Clark, LaPlante & Greenhill 2012);
- ➢ GPU cal/im systems;
- ➢ leverage array cal. techniques to enable total---power measurement from four outriggers equipped with ad-hoc front end electronics;

- Excellent all-sky real-time monitor for transient events;

- first 32 input prototype deployment May 2012: first all sky maps?
- first deployment of a new front end electronics on the existing outrigger August 2012: first global sky spectrum?

Conclusions

- The redshifted 21cm line promises to be a fantastic probe of the high-z Universe;
- We have not achieved a detection yet but we have made steady progresses;
- Different/complementary experimental approac[illegible]s;
- Solid techniques developed to subtract poi[illegible] (“peeling”) that can also be used to map the beam response;
- New imaging and deconvolution [illegible] be further tested;
- Ionospheric correction;
- Calibration of the array f[illegible]sponse and beam and coupling with diffuse foreground emissio[illegible]
- Deep integrations c[illegible] in the next 1-2 years (GMRT, LOFAR, MWA, PAPER)… possible de[illegible]ction?

- Observations of the global sky signal represent a way to probe the cosmic dawn at z ~ 25-30;
- Will an array + total power measurement (LEDA) help beating systematics? We will know it in the next year;

THANK YOU