The LOFAR EoR project:

challenges, progress and status

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The LOFAR EoR team Spineto, Italy, June 2014

Outline

Science goals

Our EoR ‘windows’ on NCP & 3C196: observations

Calibration challenges:
- Sky modelling (at 5” resolution)
- Station beam (predictability)
- Ionosphere (scintillation)
- Polarization (sky, instrument)

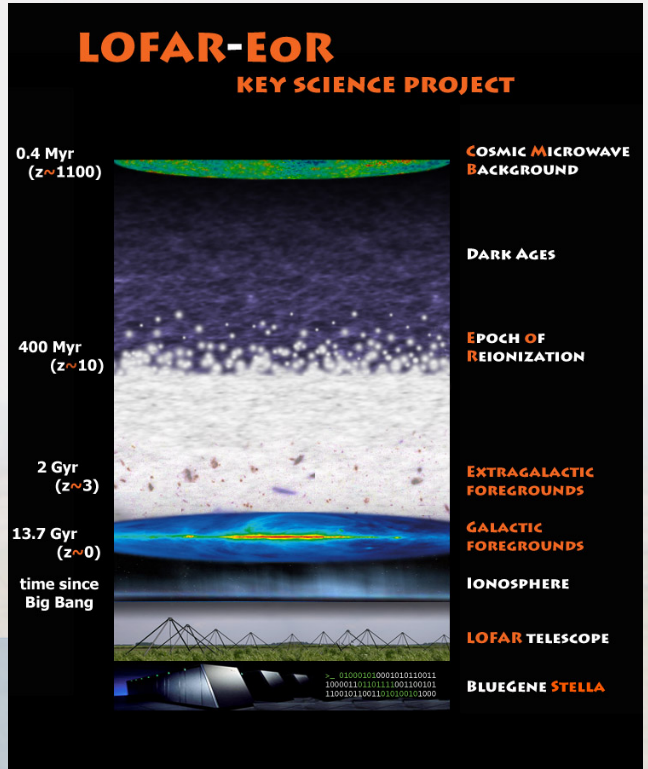
Foregrounds: polarization/ancillary science

Results on the Power Spectrum

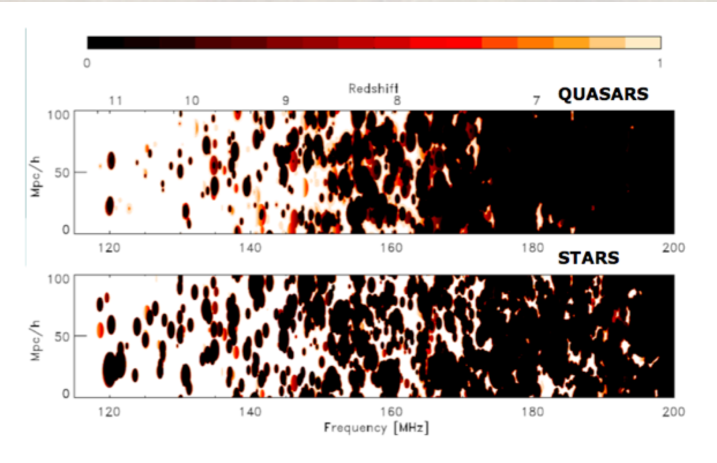
Summary & forward look

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)

When was the Epoch of Reionization ?

Lack of 'Gunn-Peterson' (Ly-α abs) trough in high z objects:

~ 10 QSO's at z = 6.0 - 6.4 and one at z = 7.1 *(Fan etal, 2006; Mortlock etal,2011)*

→ very little neutral hydrogen present → $z_{EoR} > 6.0$

WMAP/Planck CMB polarization data set limits on Thomson optical depth of free electrons (integral): WMAP $\tau \approx 0.088 \pm 0.015$ → Planck $\tau \approx 0.066 \pm 0.012$

→ EoR 'median' redshift (50% neutral) may be around $< z_{EoR} > \approx 8 - 9$

good match to LOFAR frequency range !!

Several ionizing sources have now been detected in the relevant redshift range:

GRBs at z = 8.2 and 9.4 *(Tanvir etal, 2009; Cucchiara etal, 2011)*
Ly-α emitter at z=8.68 (*Zitrin etal, 2015)*
'dropouts' out to z ≈ *12* *(Bouwens etal, 2010; Ellis etal, 2013*)

Intensity of 21cm / H I signals from the diffuse IGM

Single dipole experiments aim to measure Global Signal (e.g. Shaver etal, 1999)
Interferometers measure the spatial structure (emission and/or absorption !),
in fact, they directly measure the Angular Power Spectrum

Brightness temperature fluctuations are expected at 1-10 mK levels

$$\delta T_b = \frac{T_S - T_R}{1+z}(1 - e^{-\tau_\nu})$$
$$\approx \frac{T_S - T_R}{1+z}\tau$$
$$\approx 27 x_{\rm HI}(1+\delta_b)\left(\frac{\Omega_b h^2}{0.023}\right)\left(\frac{0.15}{\Omega_m h^2}\frac{1+z}{10}\right)^{1/2} \times \left(\frac{T_S - T_R}{T_S}\right)\left[\frac{\partial_r v_r}{(1+z)H(z)}\right] \mathrm{mK},$$

Cosmology

Ionization

(G)astrophysics

Peculiar velocities/Bulk-flows

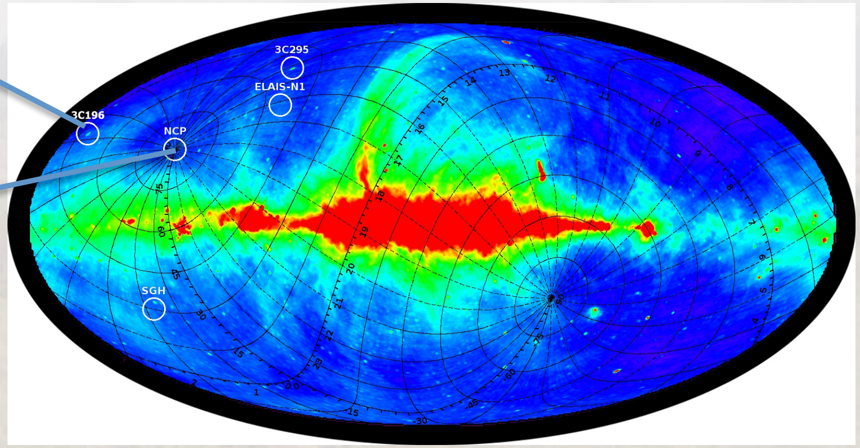
$T_R = T_{CMB} = 2.73 * (1+z)$ K

T_s = spin temperature

Salient characteristics of our two main EoR windows

3C196 (0813+48)

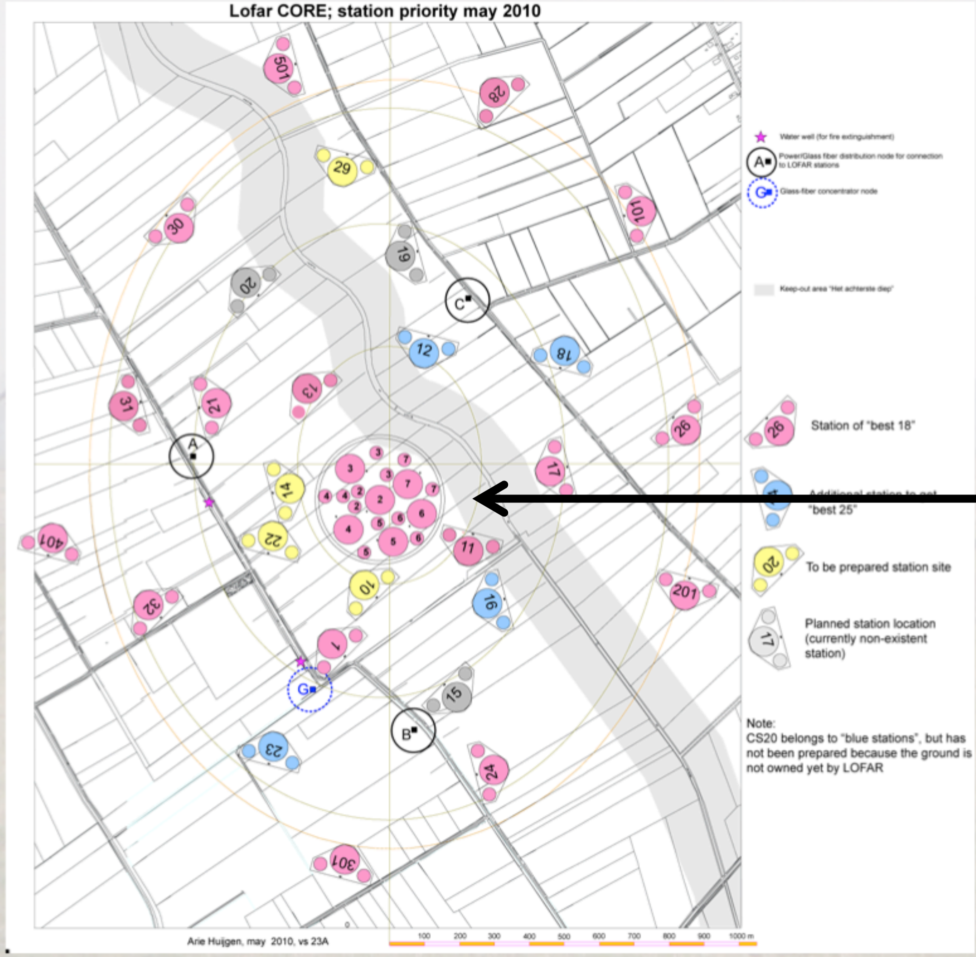
- Compact, bright (80 Jy) source → excellent calibrator inside
- Observable at night for 4 months (N. Winter: Nov → Mar)
- In Galactic halo



NCP (0000+90)

- Excellent uv-coverage
- Very long syntheses possible (up to 16h in winternights)
- Little variation in station beam (65% efficiency, at elev=53°)
- Cold halo location (at Galactic latitude=30°)
- Observable all year (at night) → potentially ~ 4000h/year !

LOFAR core configuration - ‘tailored’ to EoR project



1000 m

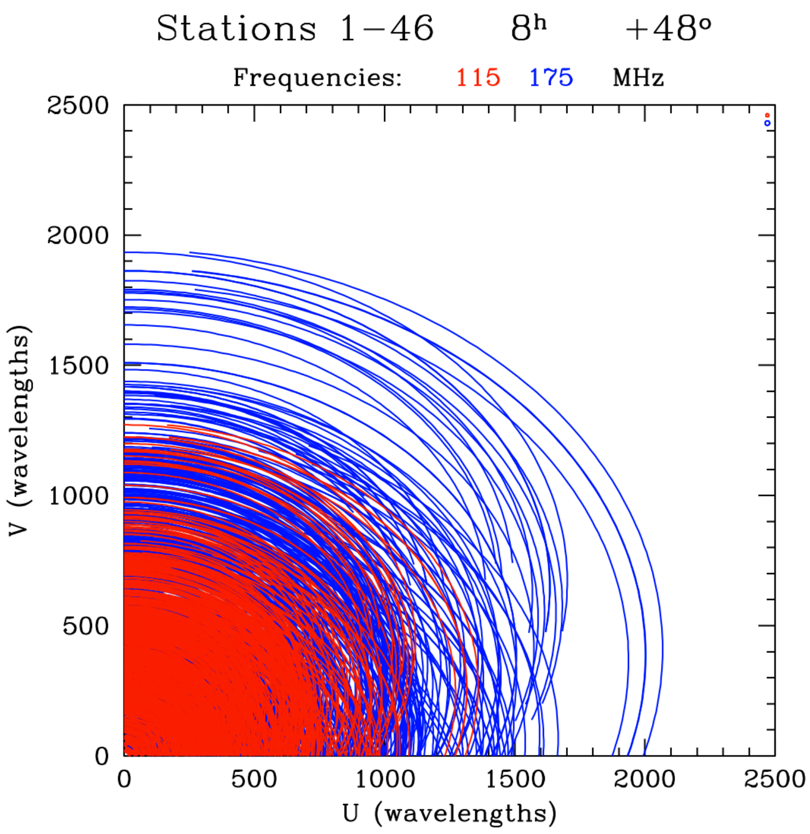
Core dimension
2 x 2.5 km

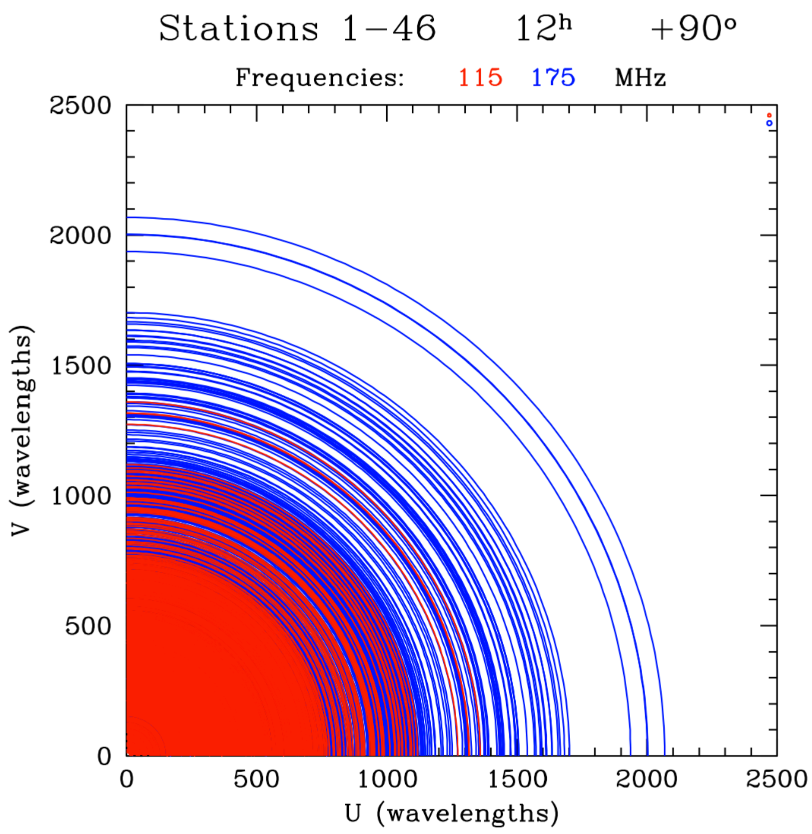
the iconic ‘superterp’
diameter ~ 350 m
(12 x 24-tile stations)

LOFAR inner uv-coverages for the two EoR windows

3C196

NCP





Complete uv-coverage in 2 km core (~ 800 λλ) at all frequencies
→ 'perfect' 3' PSF imaging after 8-12h. Important for full-field EoR imaging !!

LOFAR EoR project allocations status Nov 2015:

Cycle	NCP	3C196	Elais-N1	3C295	Usable*
LC0_019	300	200	100	50h	90%
LC1_039	300	200	-	-	70%
LC2_019	200	-	100	-	80%
LC3_028	200	300	-	-	80%
LT5_009	300	230	-	-	?

* Net useful time based on the quality of ionospheric phase fluctuations.

Cycle 0 started on 1 Dec 2012
Cycle 5 runs from 15 Nov 2015 – 15 May 2016

Calibration

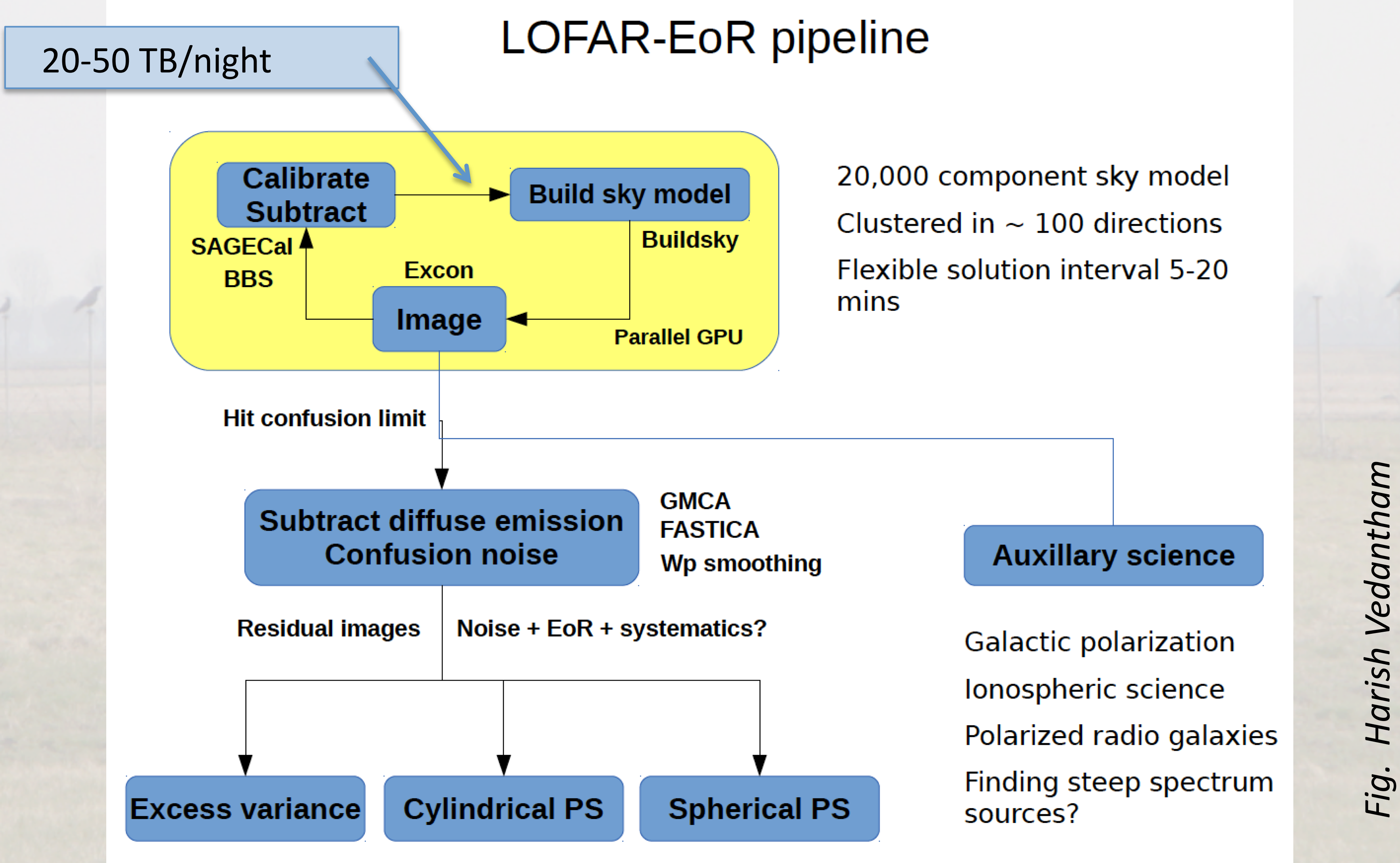
Solving for the three types of unknowns:

- Sky
- Ionosphere
- Station beams

All vary with time, direction and frequency

+ the sky is also highly polarized (talk Jelič, + poster Asad)

A flowchart of our calibration and analysis



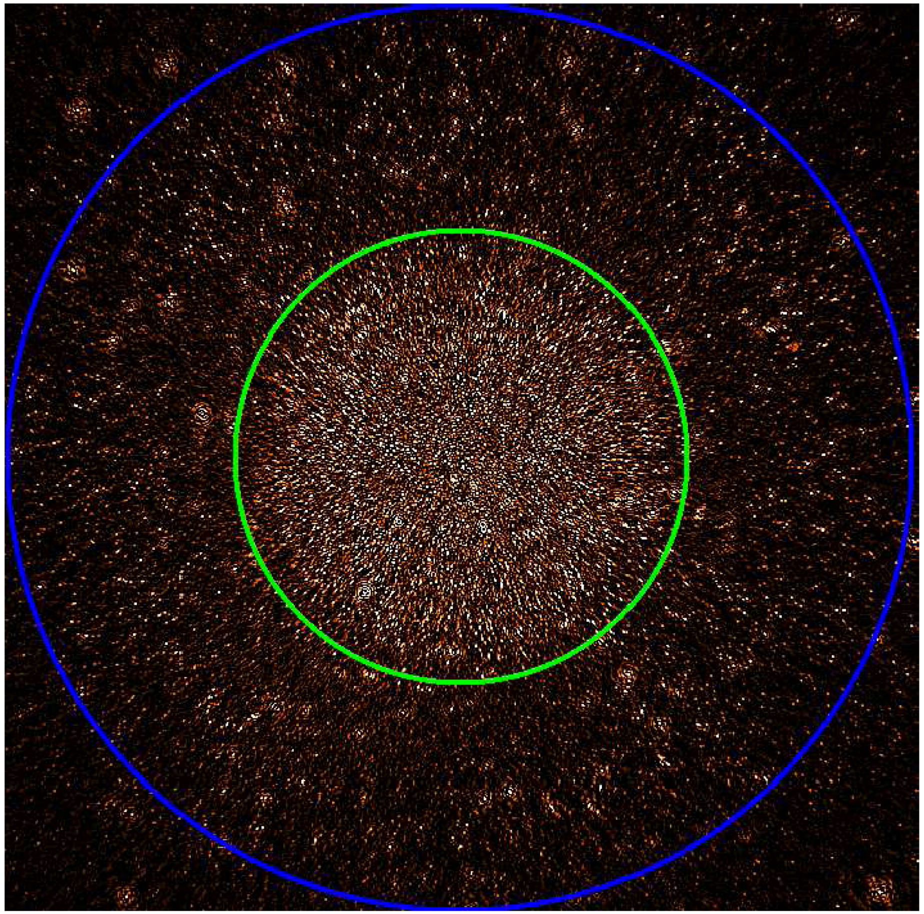
NCP deep low resolution continuum image

114h 60 MHz
$20^o \times 20^o$
3’ PSF

7.2 Jy peak
~ 30 µJy noise

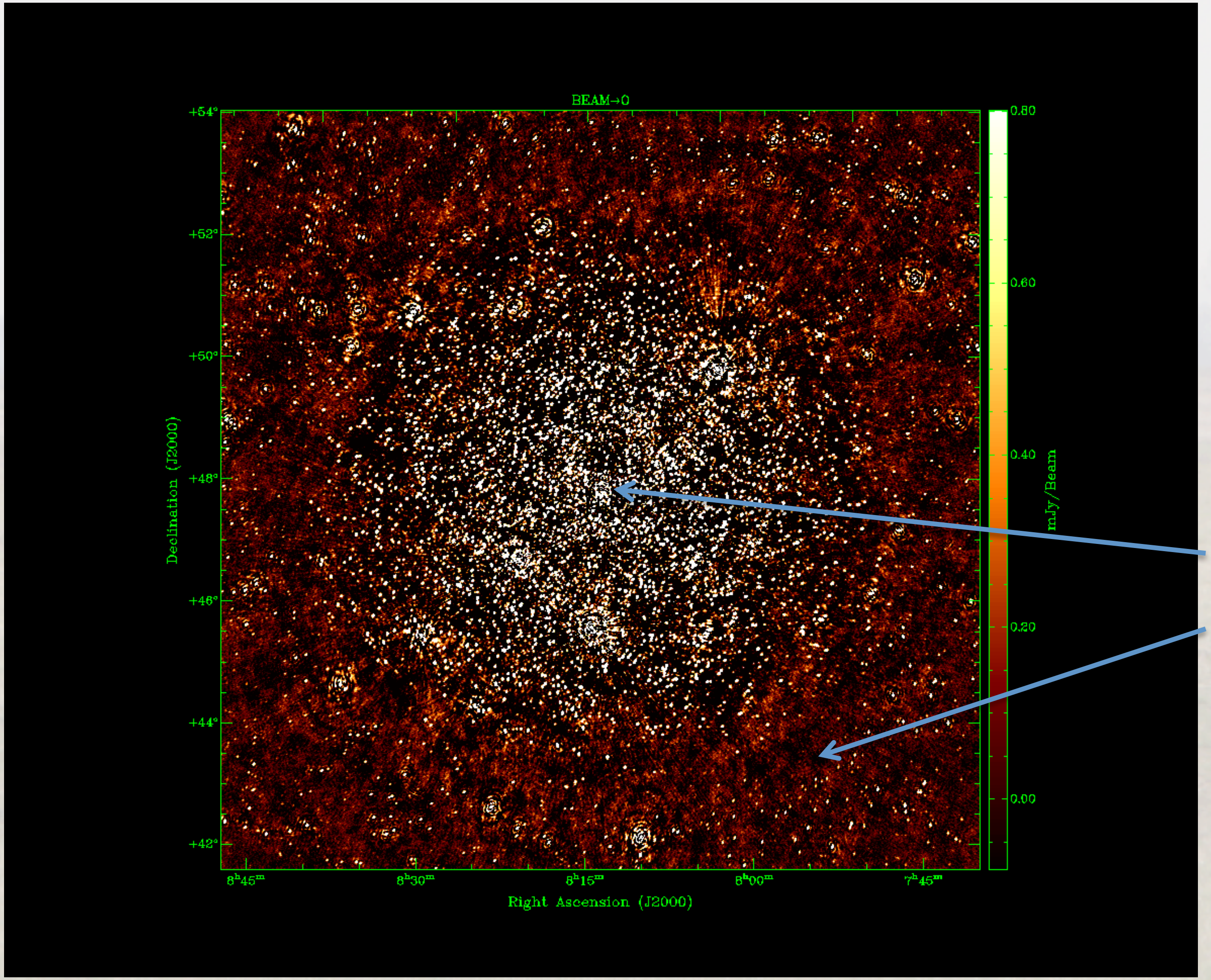
Note that this is the residual, i.e. not subtracted, emission !

All of this emission must be spectrally smooth ! Otherwise we would have no chance of ever detecting the EoR !



First null 10 deg. diameter, second null 20 deg. diameter

3C196 deep low resolution continuum image



115-175 MHz

4 x 8 hours

12^o x 12^o Image

3C196 - 80 Jy
'Noise' < 75 μJy

→ DR ~ 10^6: 1

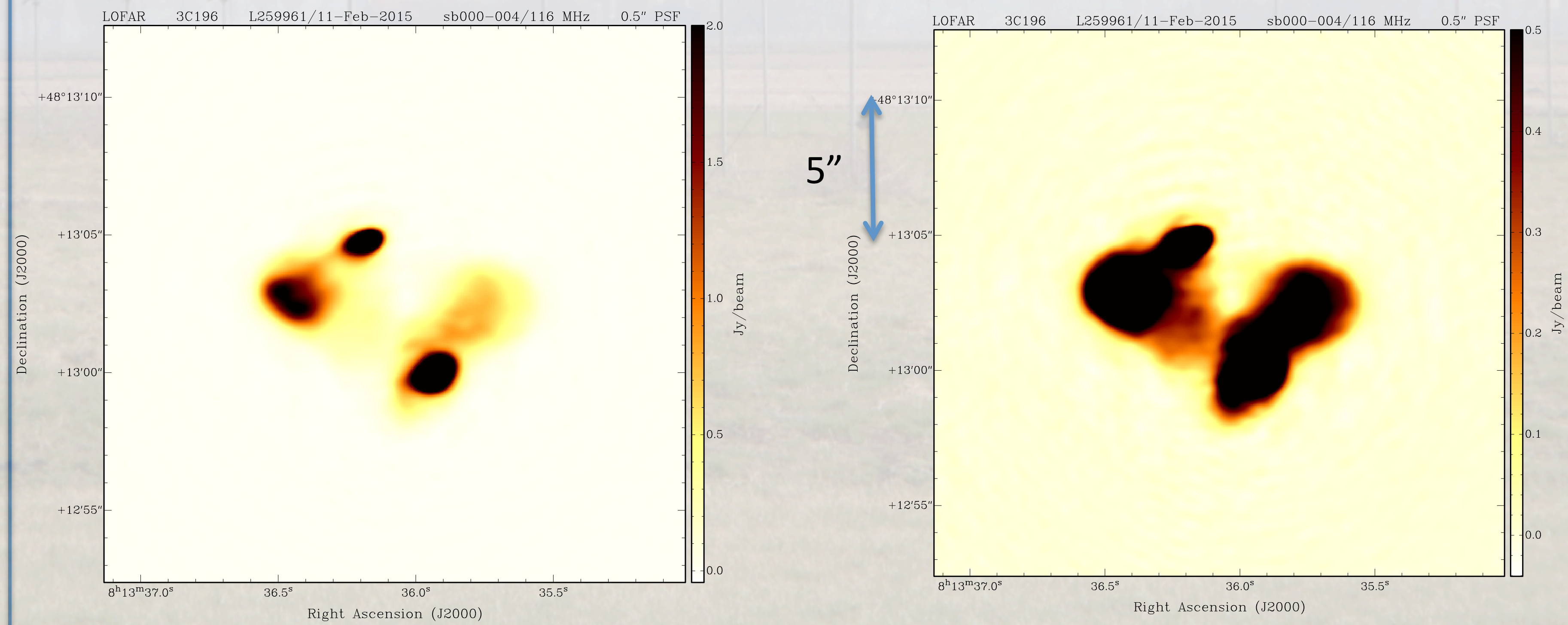
at a PSF of 50"

Pandey etal, 2016

3C 196 at 0.5” resolution !

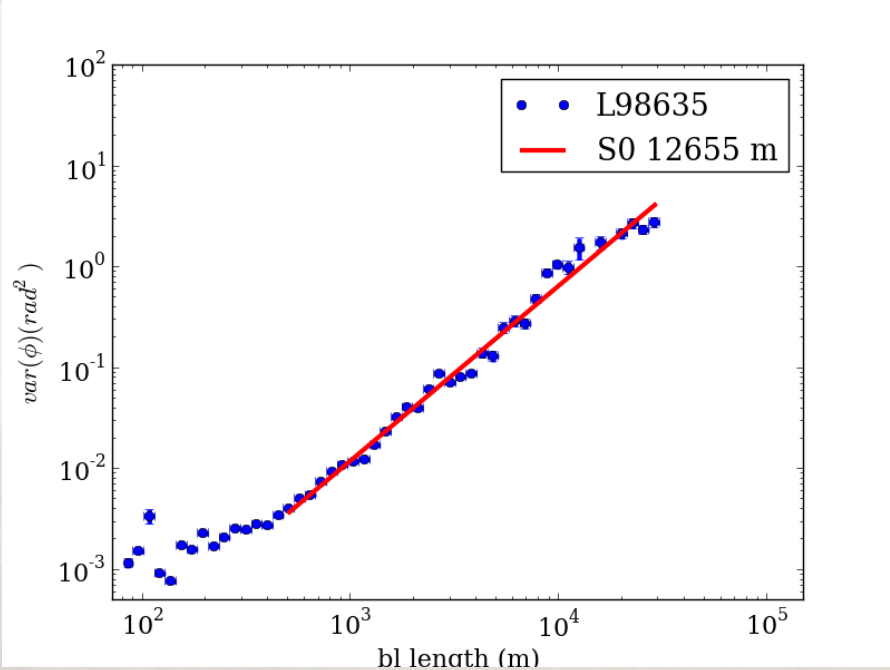
3C196 is aboiut 1 PSF of 6” on NL LOFAR baselines → very hard to subtract.

Because our calibration strategy utilizes baselines up to 100 km to calibrate the core stations we need a better 3C196 model → use baselines up to 1000 km !!



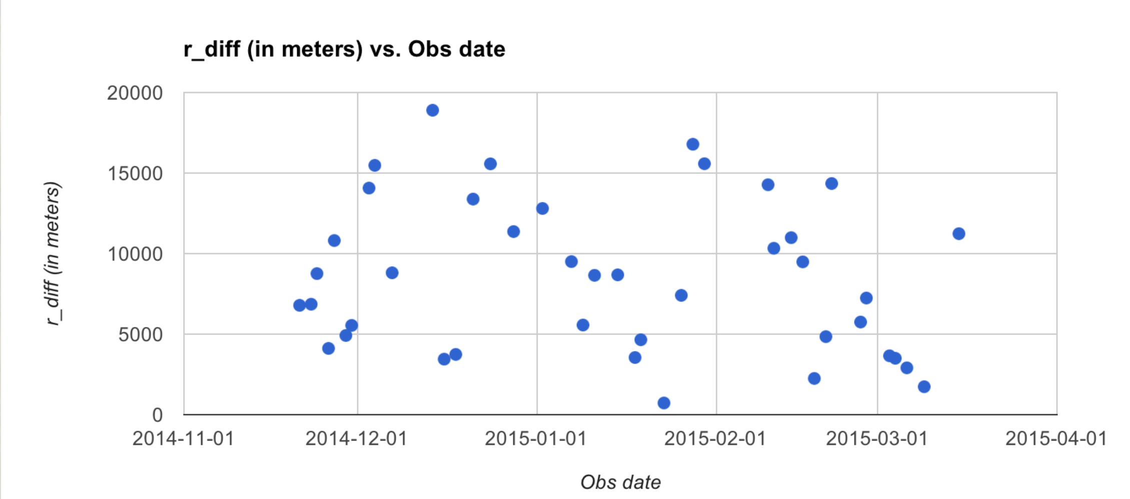
The ionospheric phase structure function

S_0 or r_{diff} is known as the diffractive scale, the baseline length over which we have 1 radian rms phase fluctuation.



r_{diff} statistics for 3C196

Cycle 3: 42 nights of 6h
>6 show scintillation



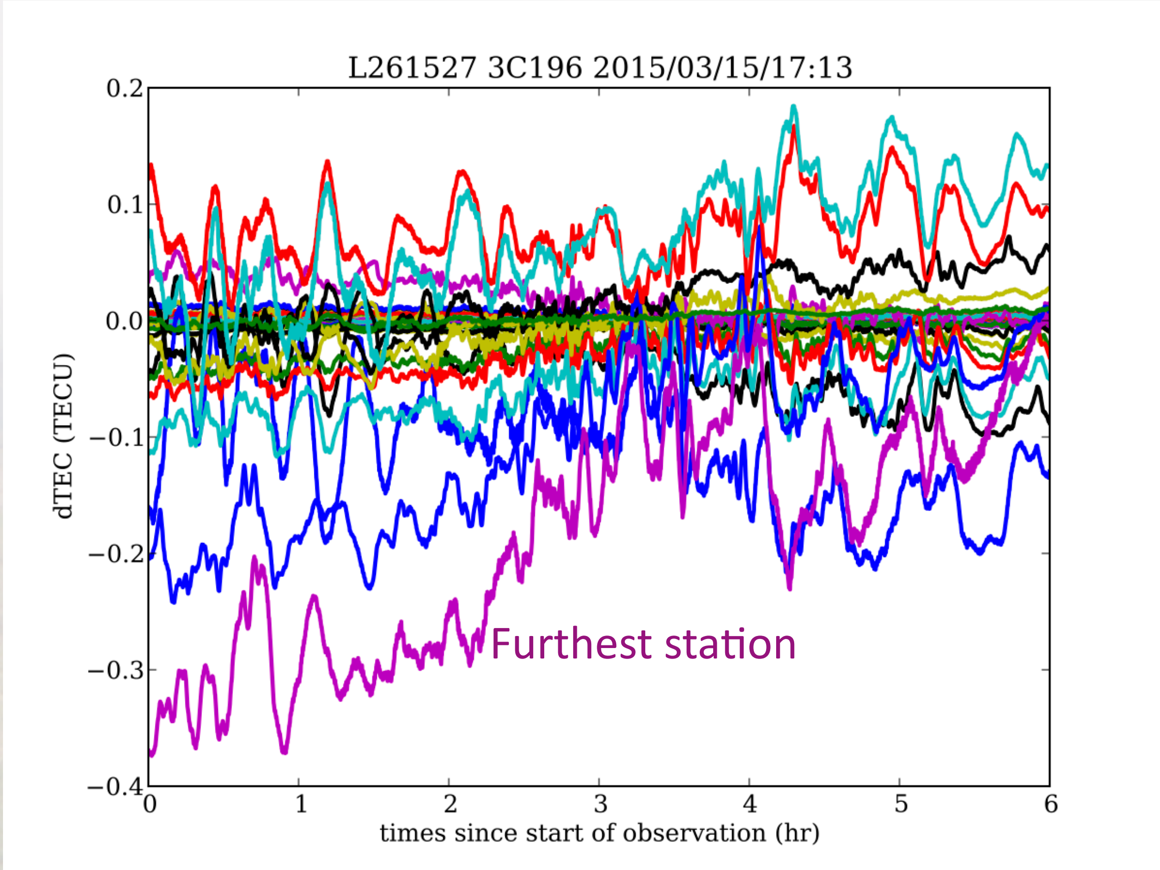
‘Typical’ night-time ionospheric TEC gradients

TEC
= Total Electron Content

1 TECU
= 10^{16} cm^{-2}

0.2 TECU → 10 radians phase at 150 MHz

Too rapid fluctuations result in poor calibration solutions on the longest baselines



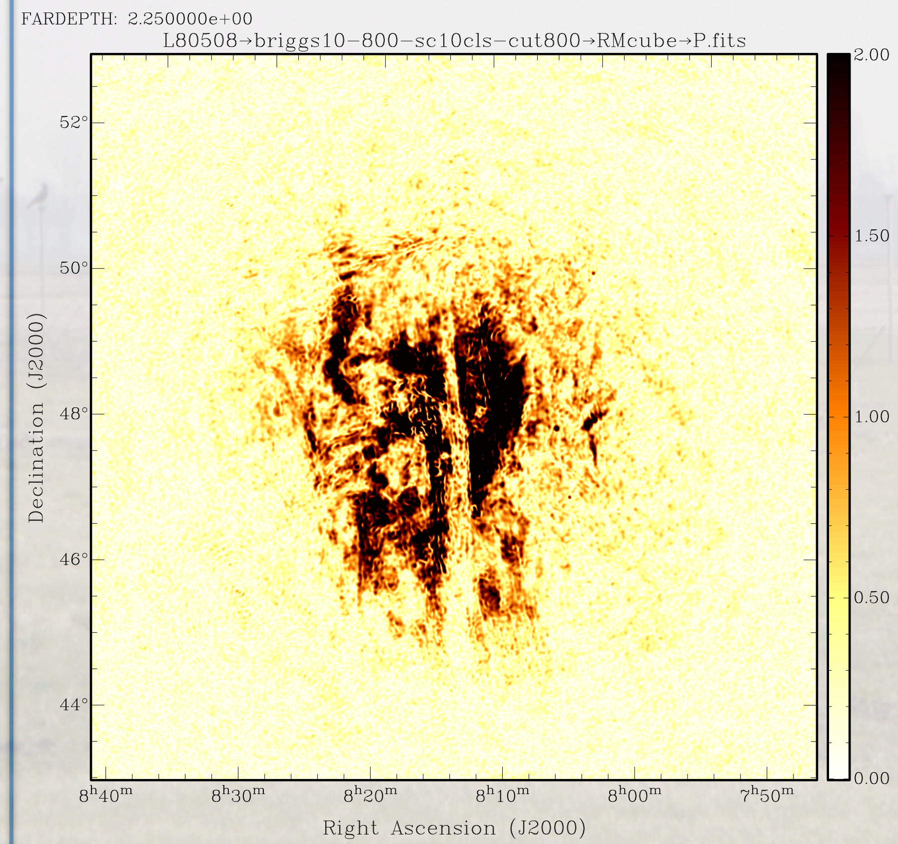
Clock-TEC separation: *Mevius etal, 2016*

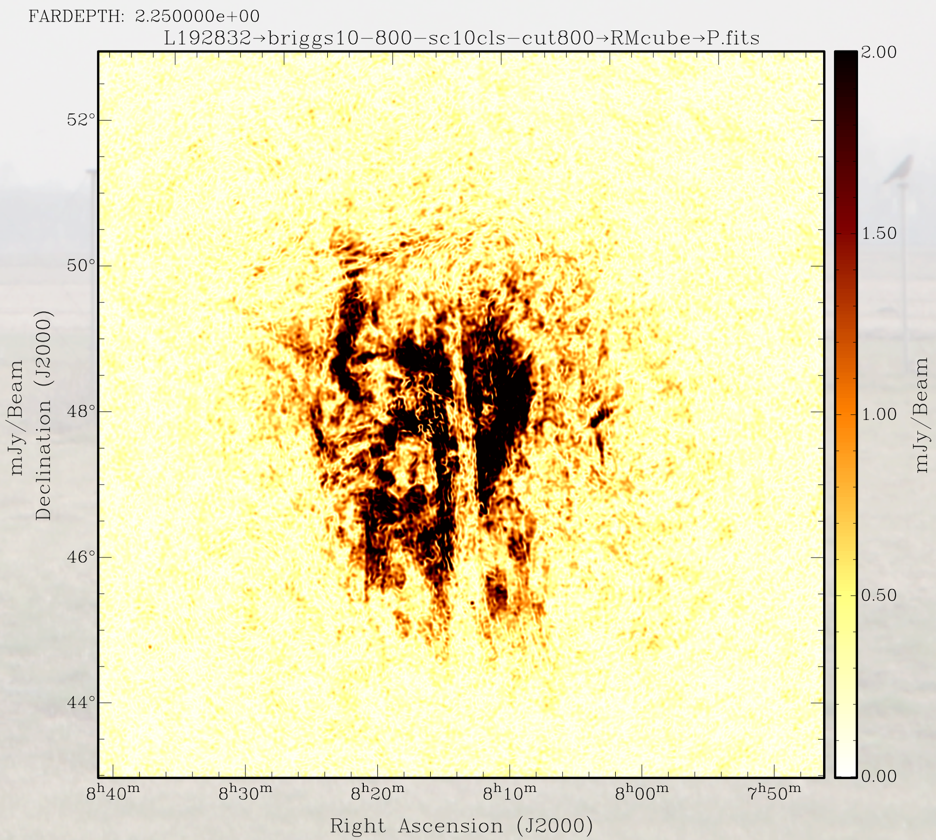
Polarization (many K !!) image quality is great !

Two 3C196 observations exactly 1 year apart.

(1 frame from RM cube at RM = +2.25 rad/m^2)

See Vibor Jelič talk





To trust polarization: primary beam attenuation should be clearly visible !

Foregrounds: remove or ‘avoid’ ?

see Chapman et al, 2014

We have three types of (more or less smooth) foregrounds:

- Galactic (synchrotron)
- Extragalactic discrete sources (synchrotron)
- Calibration artifacts

Two approaches:

- Subtract them, as much as possible, and fit (GMCA) rest → LOFAR, MWA (?)
- Filter them (delay,fringe rate) → PAPER

Wide field of view requires direction-dependent calibration:

- Up to 100 directions (?) for 62 LOFAR stations (48 in core, 14 remote)
- Worries about removing EoR signal → check Q,U signals
- Simulations using fake (=injected) structures

- Robust ‘broad-band’ calibration (Yatawatta, 2015)

SAGEcal: robust and broad-band processing

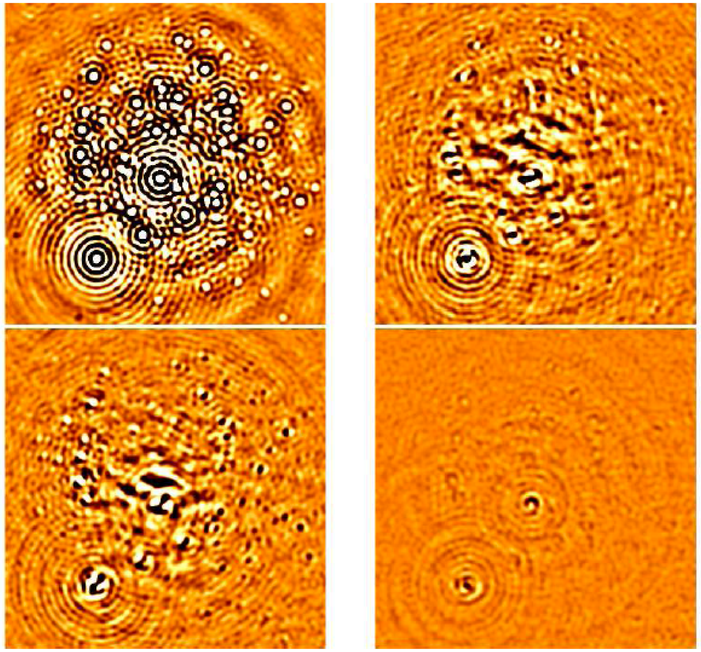
Yatawatta, 2015

Calibration solves for a very large number of unknowns → dangerous

Adopted approach: exclude short baselines (< 250λ) in SAGEcal and only image those !

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

Image before calibration

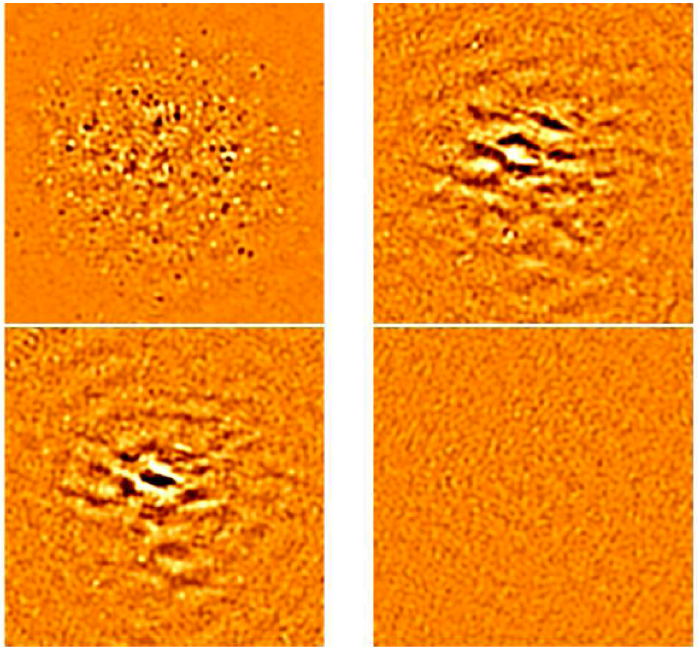


I,Q,U,V images baselines <= 250 wavelengths

One night
60 MHz

10' PSF

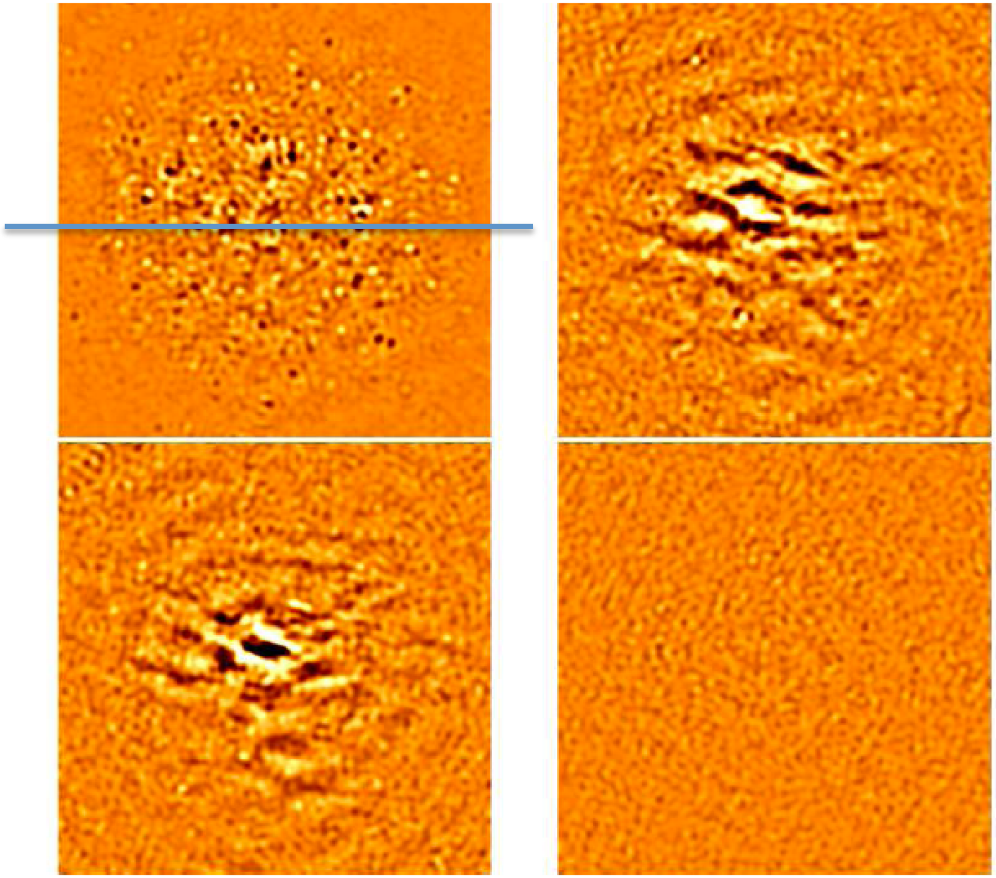
Image after calibration



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

Input cubes for GMCA foreground-fitting and removal

Image after calibration

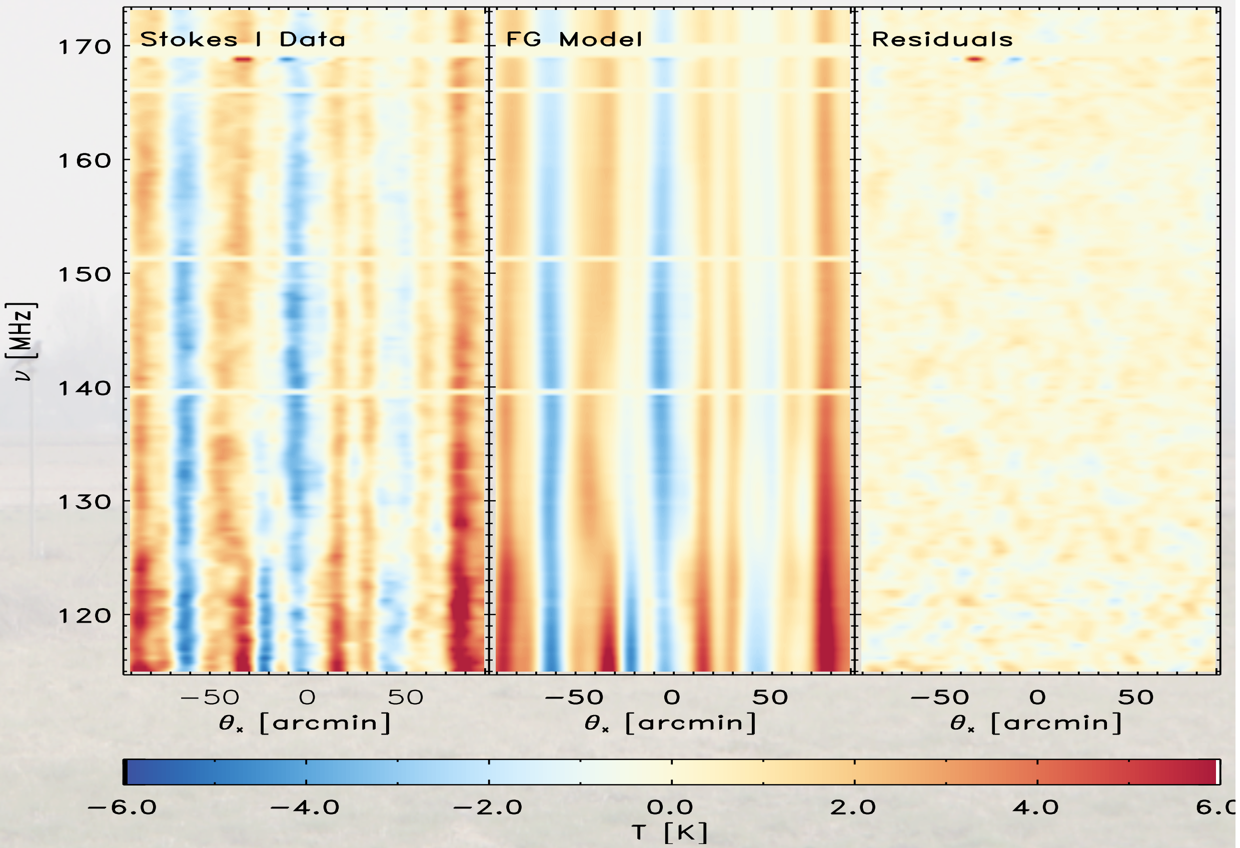


I,Q,U,V calibration using baselines > 250 wavelengths

GMCA fitting to remove foregrounds *see Chapman etal 2013*

3 panels show:

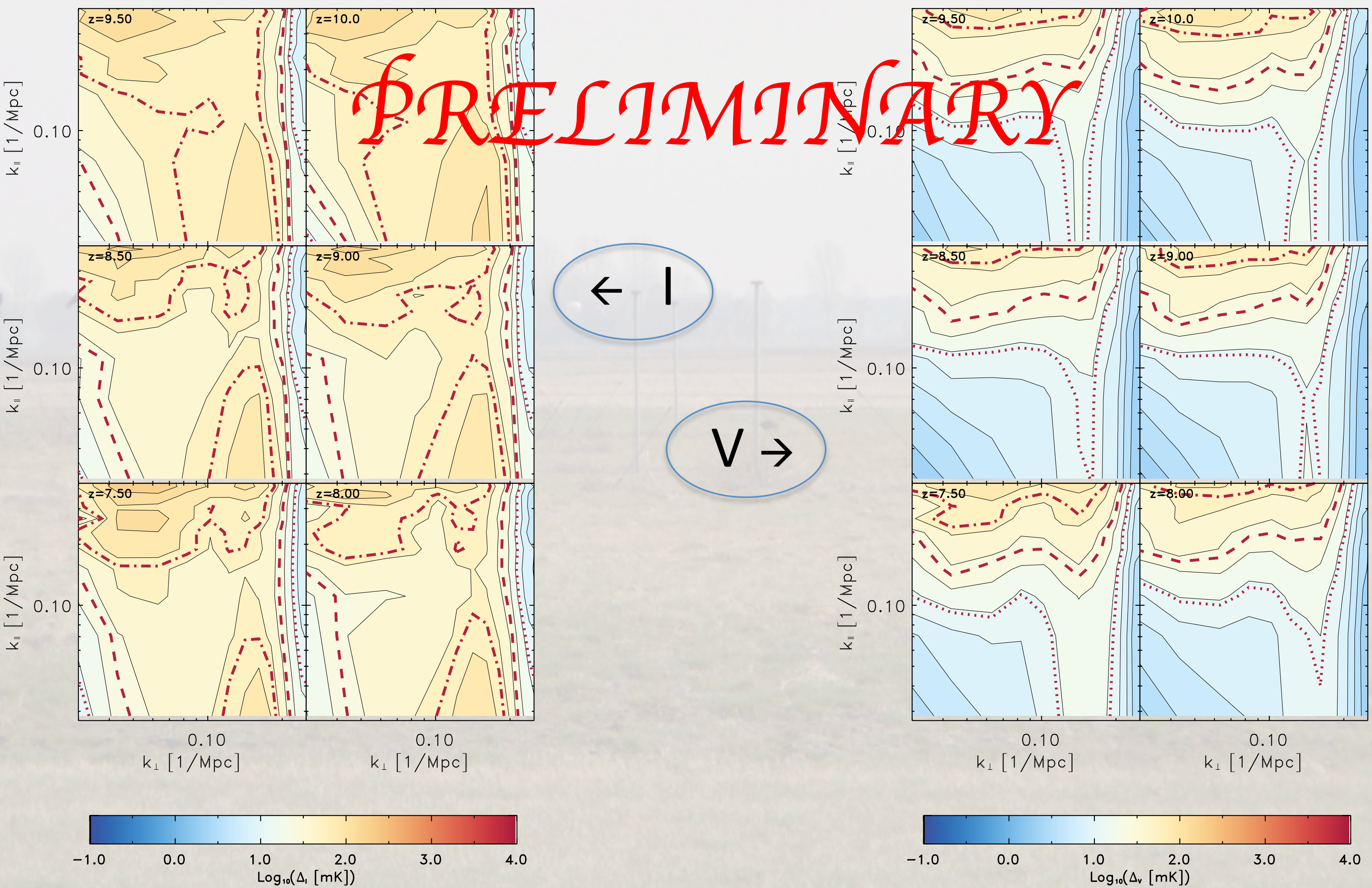
- 3^o cut across NCP
- the GMCA fit
- residuals



FWHM PSF = 10' scale; t_{int}=155hrs; HBA 115-173 MHz (1 MHz res.)

2-D Power Spectra for 6 redshift bins

Zaroubi etal, 2016

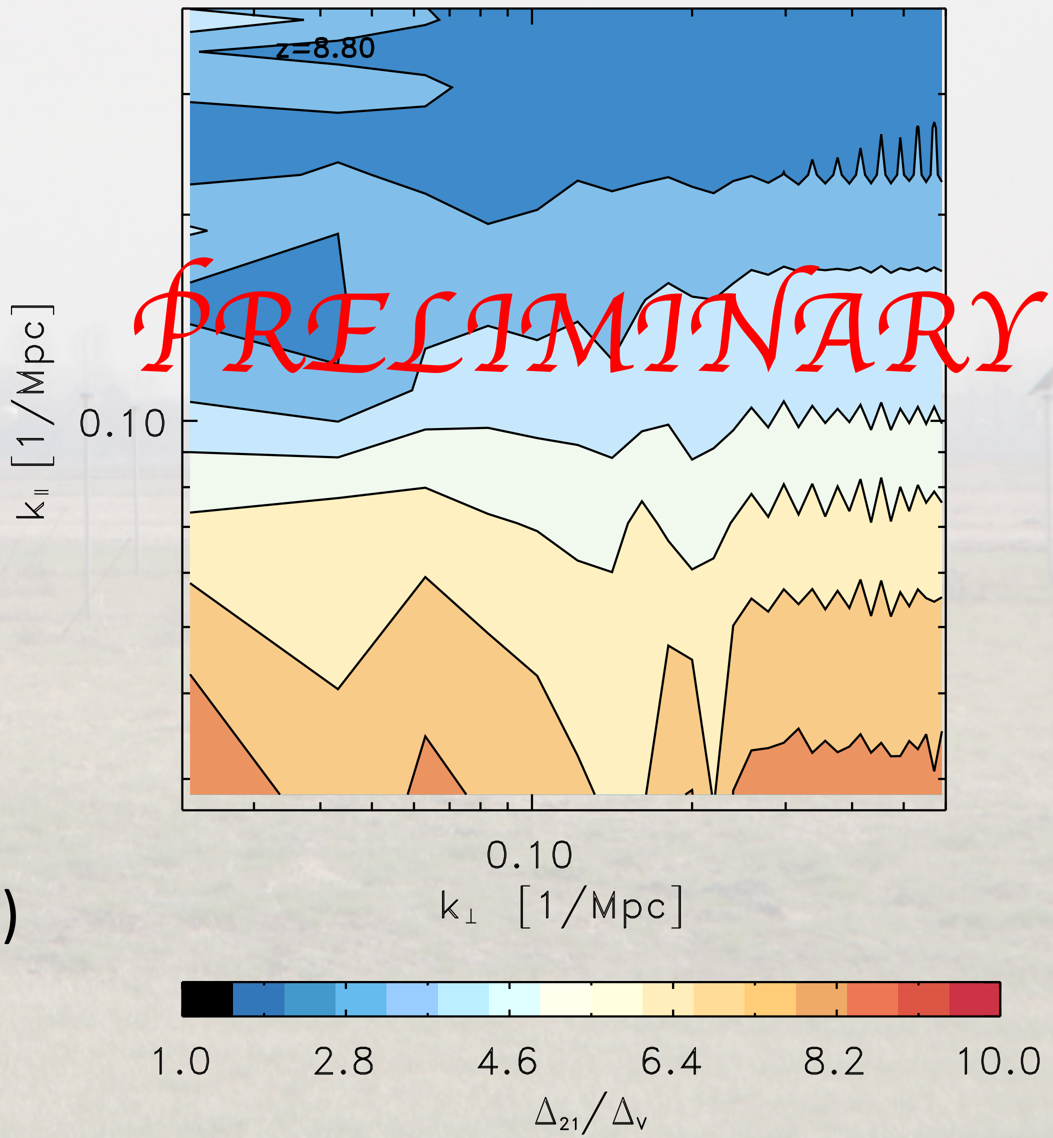


2-D power spectrum: ratio of Stokes I / V

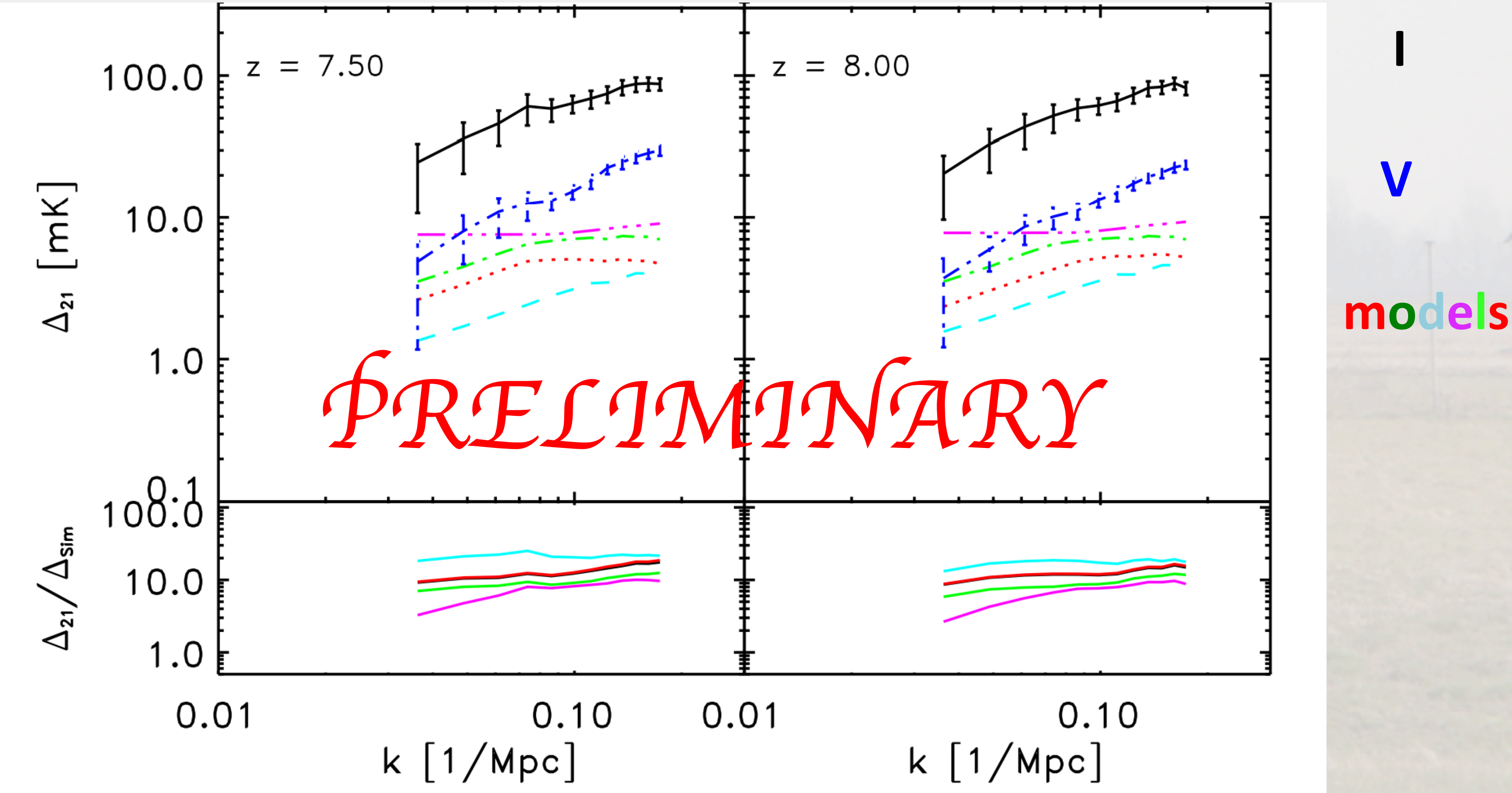
Stokes V is close to the thermal noise level

Stokes I noise higher depending on frequency scale

Possible sources of excess noise in Stokes I:
- miriad of faint sources
- imperfect subtractions
- foreground fitting (GMCA)
- ??



Upper limits on the 3-D power spectrum



Zaroubi etal, 2016

Summary and Forward look

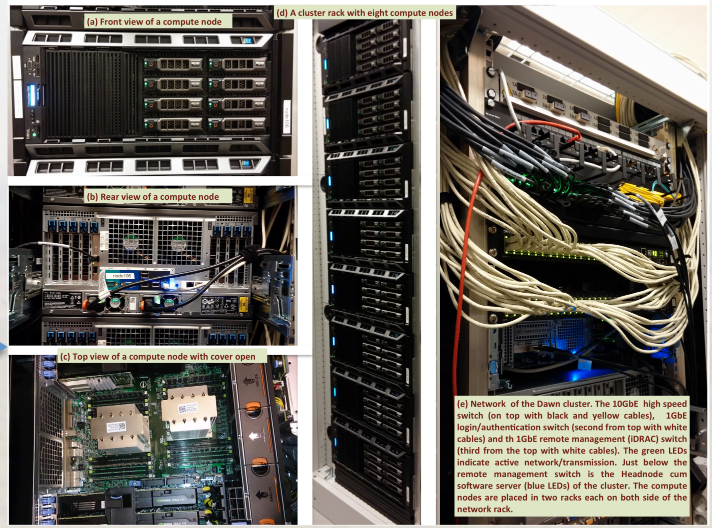
Soon 2000 hours of data (NCP, 3C196) : of which ~ 900 + 700 = 1600 h of good quality

Challenges and ancillary science at scales from 0.5” - 5” - 50” - 500”

Very ‘rich and bright’ polarized Galactic foreground

Ionospheric scintillation → 20% data ‘loss’

Now processing about one NCP-night / week
1 Dec 2015: new ERC-funded cluster operational
(32x4GPU, 32x48 (HT) CPU, 1 PB storage)



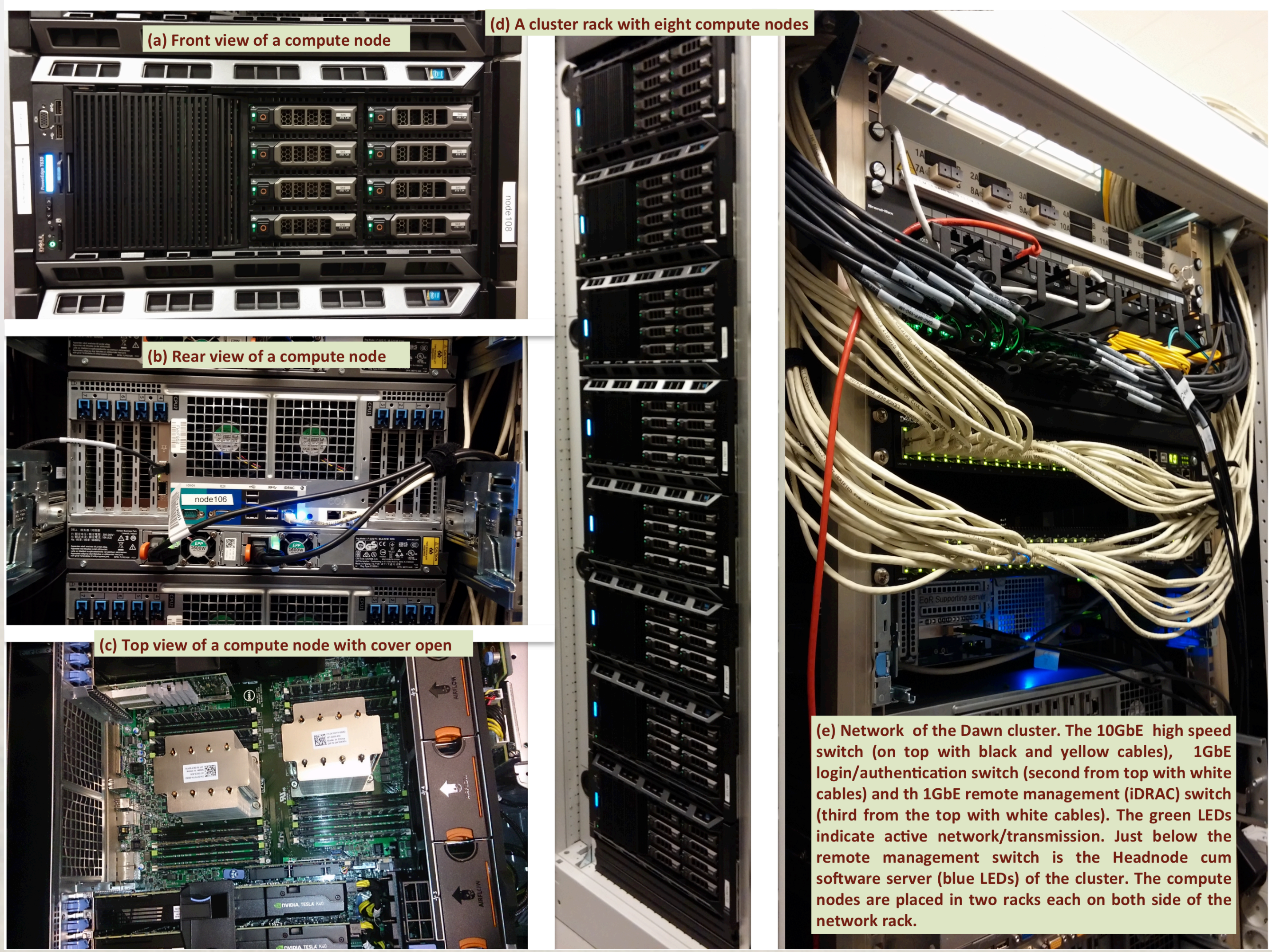
Pandey etal

2014/15: learning years: discovering ‘systematics’ :
→ improved wide-field broad-band calibration (SAGEcal CO):
→ working on sky models, polarization calibration and ionospheric effects

Current limits (155h) at z=7.5 to z=10 are at ~ 20 mK levels at k ~ 0.05 Mpc^{-1}

In 2016 and 2017 we hope to harvest

The new LOFAR EoR cluster: DAWN



32 nodes in four 19" racks

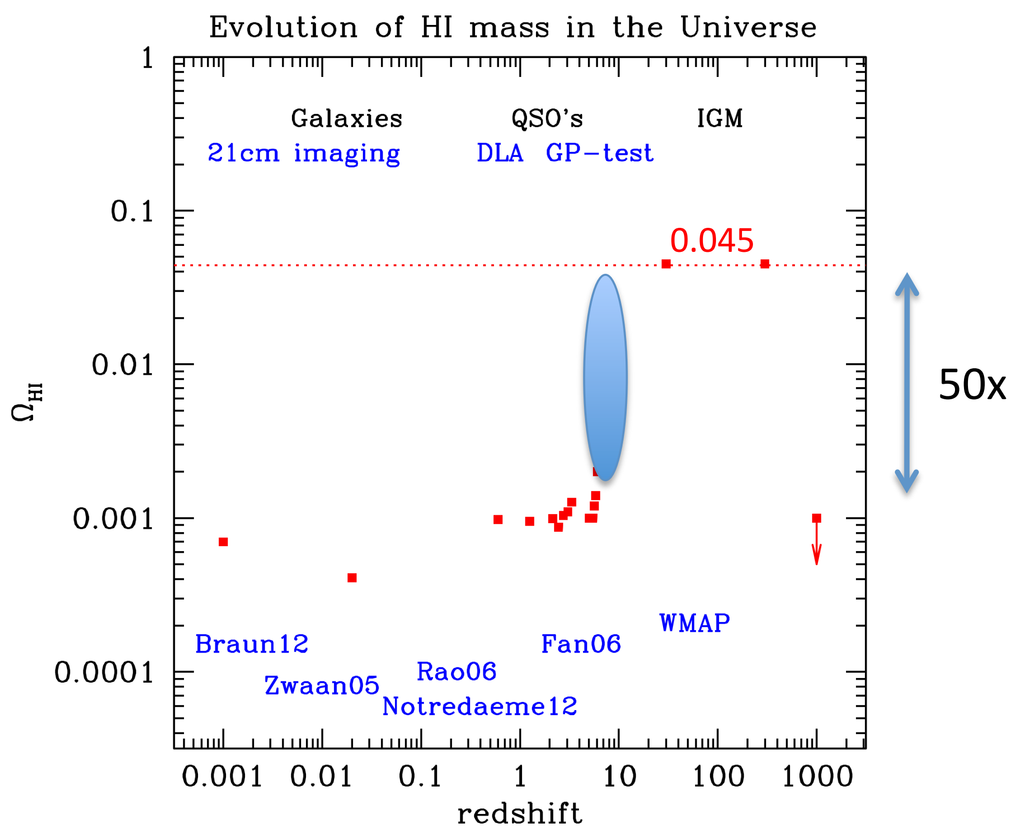
32x4 GPU
32x48 (HT) cores

0.6/0.2 Petaflops in GPU power

For details:

Pandey etal, ASTRON Newsletter Dec 2015

Evolution of cosmic neutral hydrogen density (H I)



WSRT, VLA and GMRT have detected H I in emission out to 'only' z ≈ 0.25

So how we can go out to z = 10 (~ 130 MHz) ??

Four reasons:

- signals are everywhere,
- there is 50x more H I,
- it will take ~ 1000 h,
- and it will 'only' be a statistical detection