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COSMIC DAWN ON LARGE ANGULAR SCALES WITH LOFAR AND AARTFAAC.

B. K. Gehlot, L.V.E. Koopmans
& LOFAR-EoR Team

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Introduction & Motivation

- LOFAR-EoR KSP: Current 1-night upper limit on EoR power spectrum using LOFAR is $\Delta_{21}^2 \sim (80\, mK)^2$ at $k = 0.053\, h\, Mpc^{-1}$ in the range $z = 9.6 - 10.6$ (Patil et al. 2017).

- LOFAR Low Band Antenna (LBA) system operates at 30-80 MHz frequency band (van Haarlem et al. 2013) which correspond to a part of the redshift range of Cosmic Dawn ($45 \geq z \geq 15$).

- Use LOFAR-LBA to study contamination effects such as (polarized) foregrounds, ionospheric propagation effects and systematic biases (e.g. station beam errors) in upcoming CD experiments (e.g. SKA-low, NENUFAR, LEDA etc.).

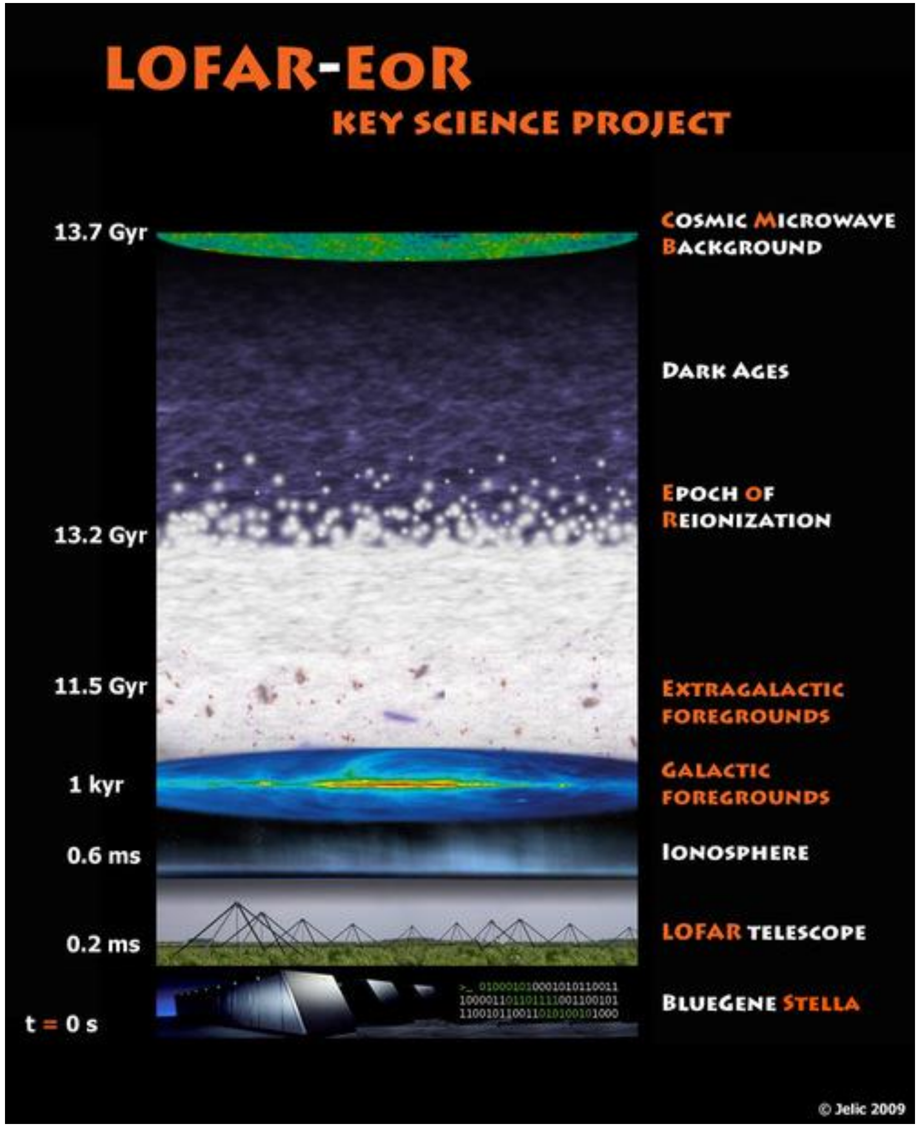
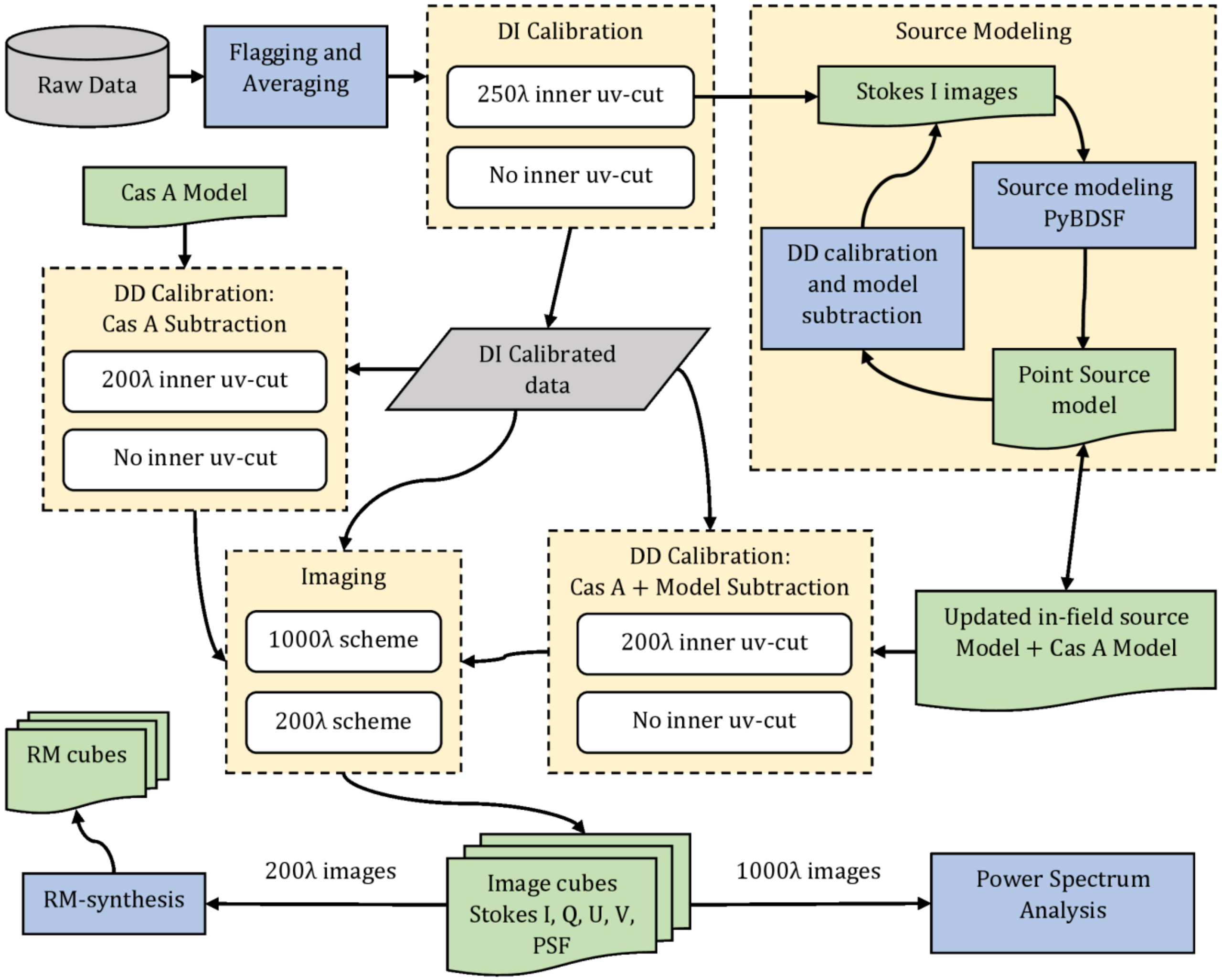


Image Credits: Vibor Jelic

Observations & Data Processing

Parameter	value
Telescope	LOFAR LBA
Observation cycle and ID	Cycle 0, L99269
Antenna configuration	LBA_INNER
Number of stations	37 (NL stations)
Observation start time (UTC)	March 2, 2013;17:02:52
Phase center (α, δ; J2000)	08h13m36s, +48°13′03″
Duration of observation	8 hours
Frequency range	30-78 MHz
Primary beam FWHM (at 60 MHz)	9.77°
Field of View (at 60 MHz)	74.99 $\deg^2$
SEFD (at 60 MHz)	~ 26 kJy
Polarization	Linear X-Y
Time, frequency resolution:	
Raw Data	1 s, 3 kHz
After flagging and averaging	5 s, 183.1 kHz

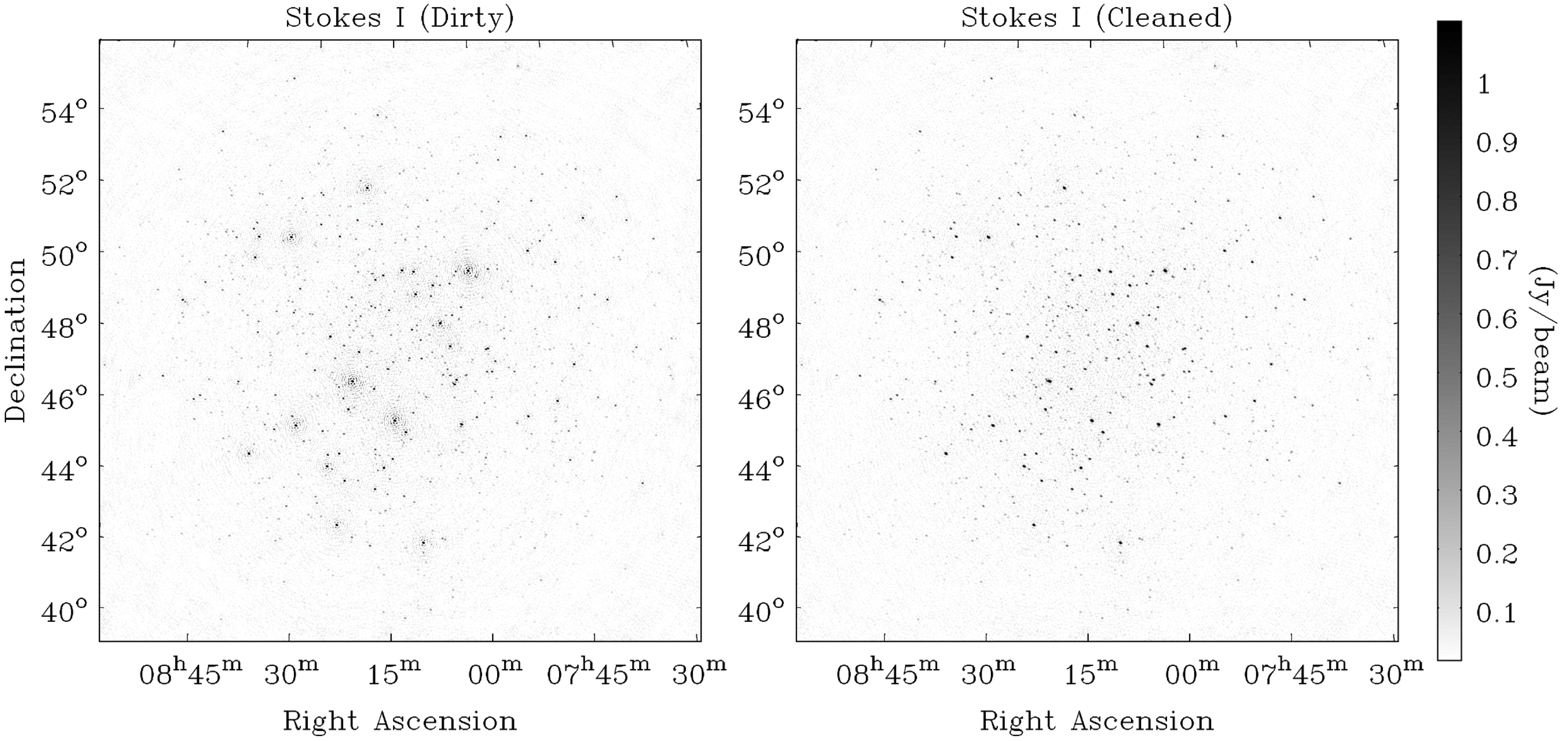


Four out of eight observation hours are used in our analysis and discard the visibilities affected by the strong ionospheric scintillation within the primary beam.

Two strategies for calibration (No Sagecal-CO):

- Using a baseline cut: $|\mathbf{b}| > 250\lambda$ (DI Cal), $|\mathbf{b}| > 200\lambda$ (DD Cal).
- Using all baselines.

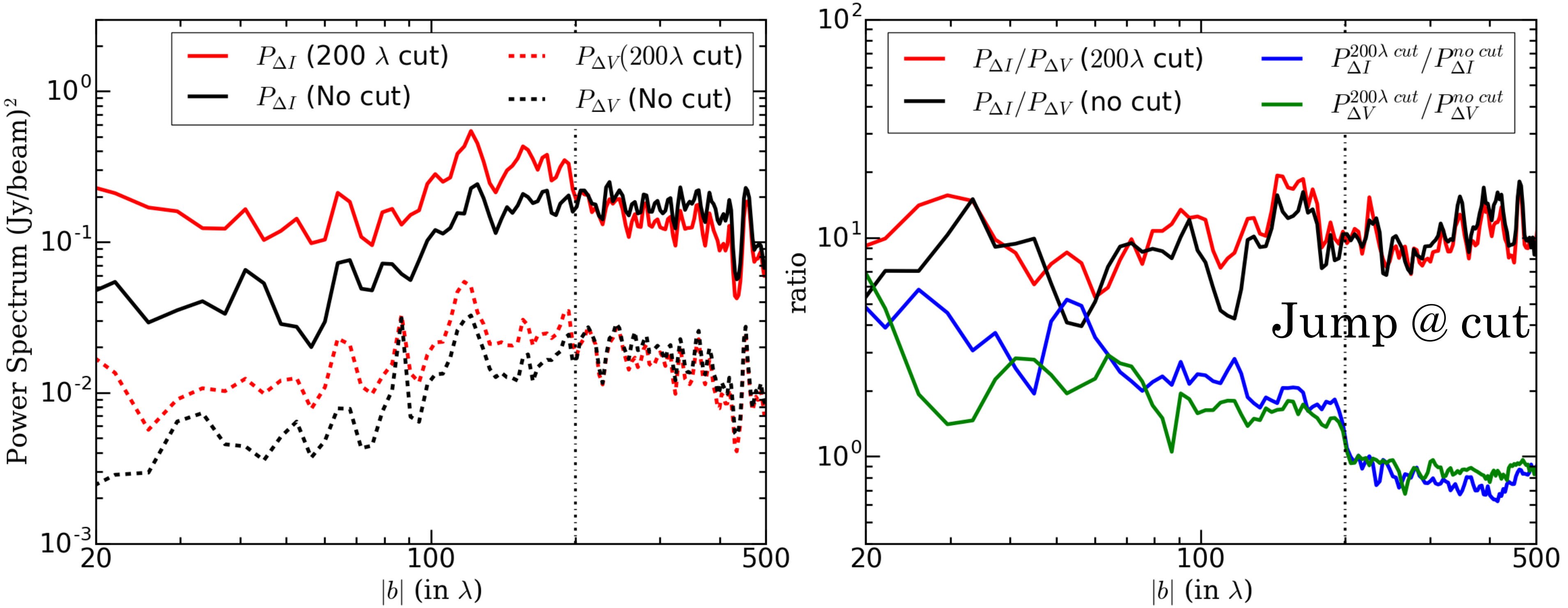
Stokes I images: Dirty and Cleaned



Stokes Q, U and V look like noise (no structure is visually seen on any spatial scale) but the rms is ~6-7x higher than thermal noise.

Excess variance between 195 kHz sub-bands

Power spectra of differential Stokes images.



- Excess variance present with/without cut; $P_{\Delta I}/P_{\Delta V} \sim 10$ for both cases.
- A baseline cut: 1. Enhances power below the cut and decreases power above the cut.
  2. 'Tilts' both stokes I and V ratios on $\lesssim 200\lambda$ baselines in an identical way.
- The ratio $P_{\Delta I}(200\lambda)/P_{\Delta I}(no\ cut) \gtrsim 2$ for $|\mathbf{b}| < 200\lambda$. Could be due to amplification of random errors introduced (on the longer baselines) in the Jones matrices during the calibration process. E.g. due to sky model incompleteness, ionosphere or imperfect calibration (Patil et al. 2016; Barry et al 2016).

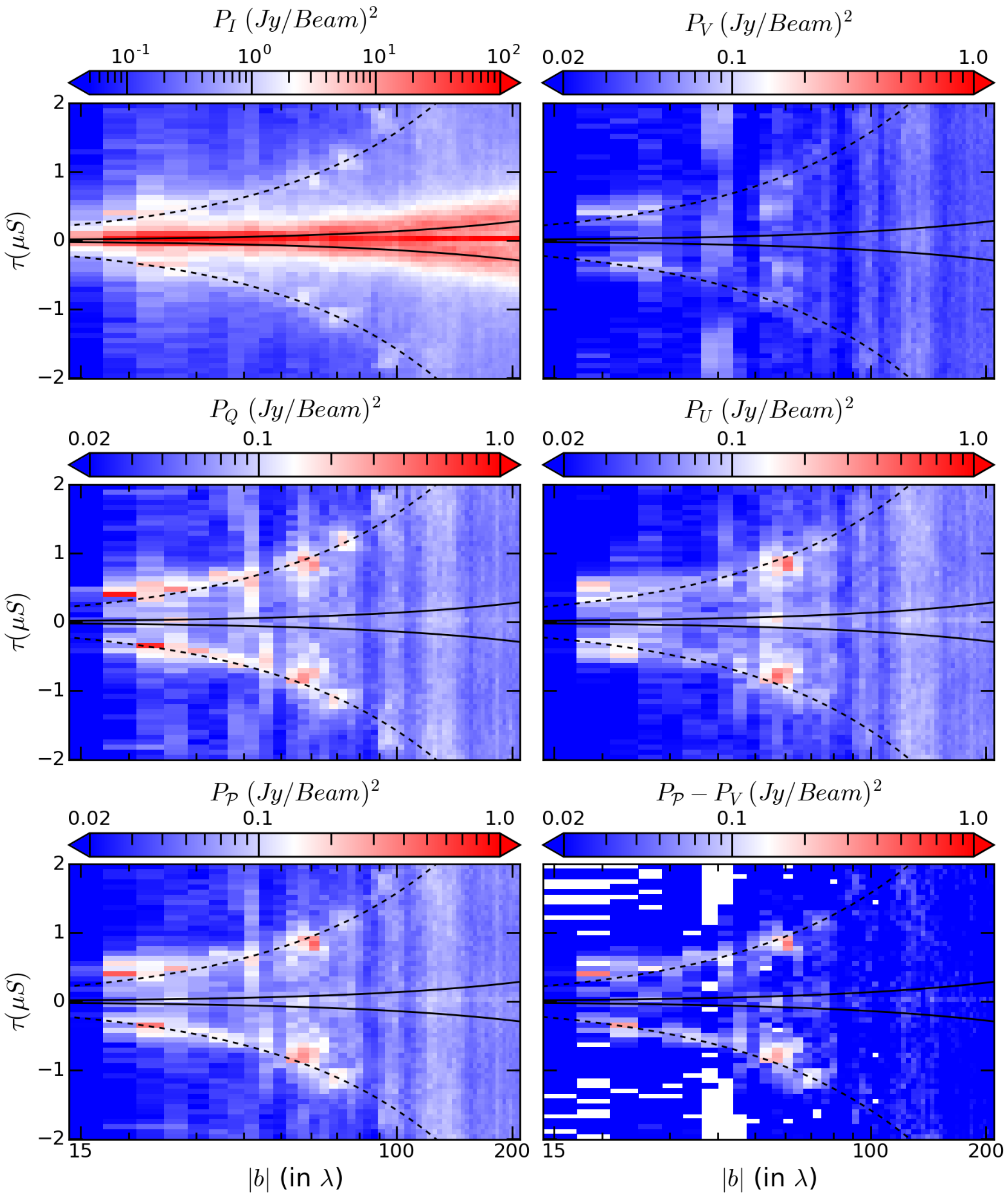
'Pitchfork' structure

Delay spectrum of Stokes I, Q, U, V and $\mathcal{P} = Q + iU$ (Polarized intensity).

$$\tilde{\mathcal{V}}_S(u, v; \tau) = \int_{-\infty}^{\infty} \mathcal{V}_S(u, v; \nu) e^{-2\pi i \nu \tau} d\nu$$

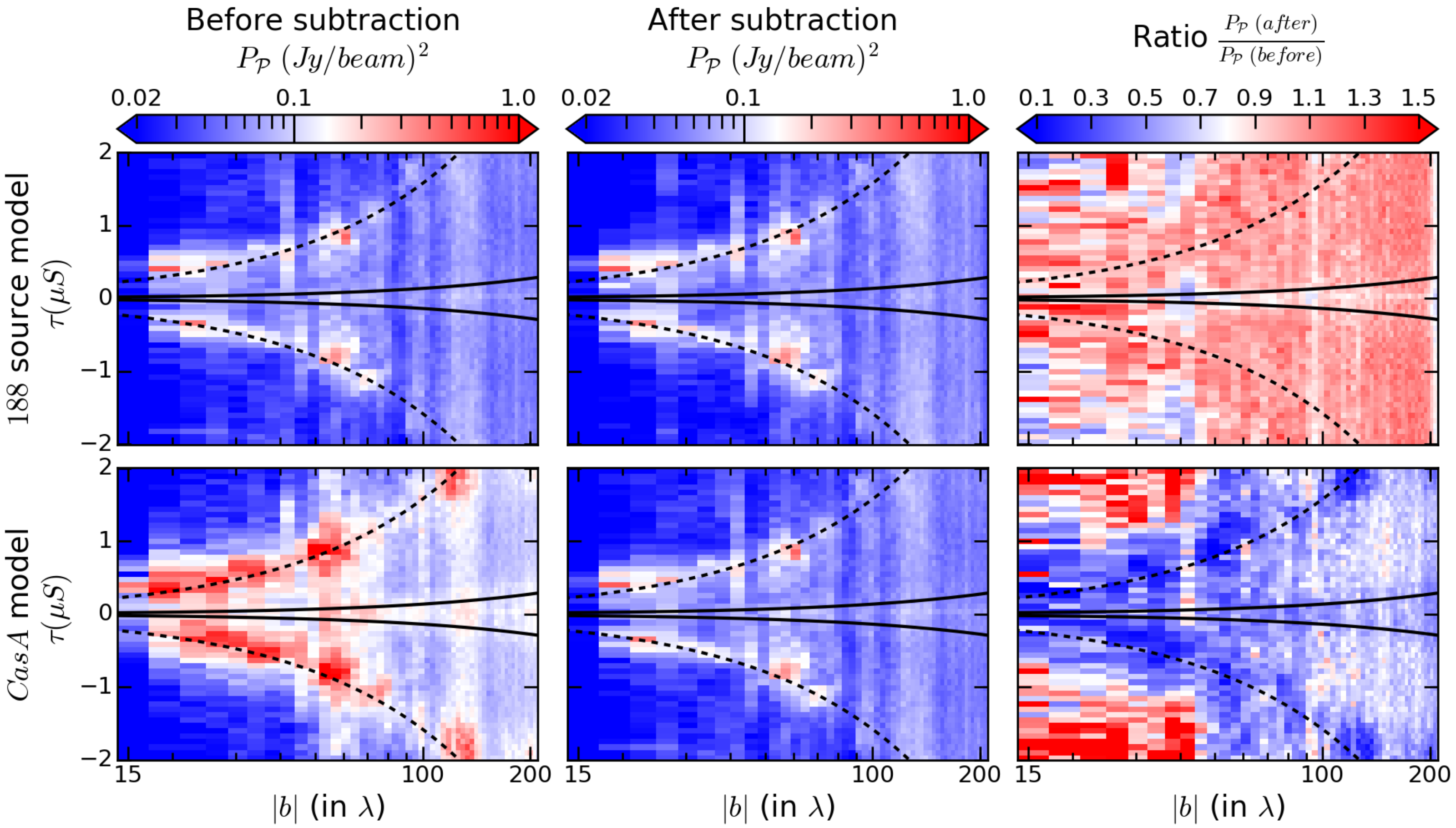
$$P_S(u, v; \tau) = |\tilde{\mathcal{V}}_S(u, v; \tau)|^2 \qquad \text{Where} \quad \tau = \frac{\mathbf{b} \cdot \hat{\mathbf{s}}}{c}$$

- 'Pitchfork' structure in Stokes I (Thyagarajan et al. 2015a,b; Kohn et al. 2016).
- 'Pitchfork' structure in Stokes Q, U and $\mathcal{P}$; Most power is localized on smaller baselines ($|\mathbf{b}| \lesssim 80\lambda$) and around delays close to instrumental horizon.
- Emission originates from far outside the primary beam and is extended in nature. Possibly due to genuine diffuse polarized emission or instrumental polarization leakage from Stokes I to Q and U.

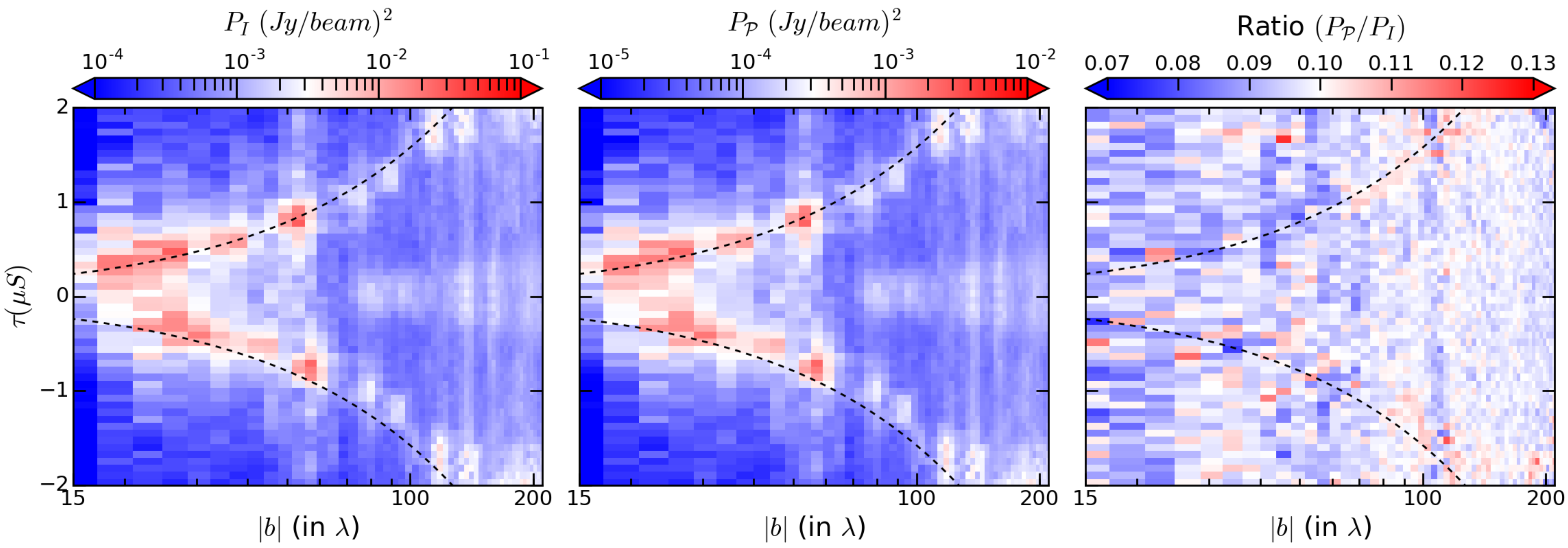


‘Pitchfork’: with and without sky-model

- Subtracting in-field sources largely within the primary beam does not affect the ‘pitchfork’.
- Subtraction of CasA has a significant impact on $P_{\mathcal{P}}$ around the horizon delay line as well as within the horizon lines.
- Residuals after subtracting CasA correlate strongly with the power before CasA subtraction.



‘Pitchfork’: comparison with simulations



Predicted visibilities using Stokes-I only CasA model, with the phase center at 3C196.

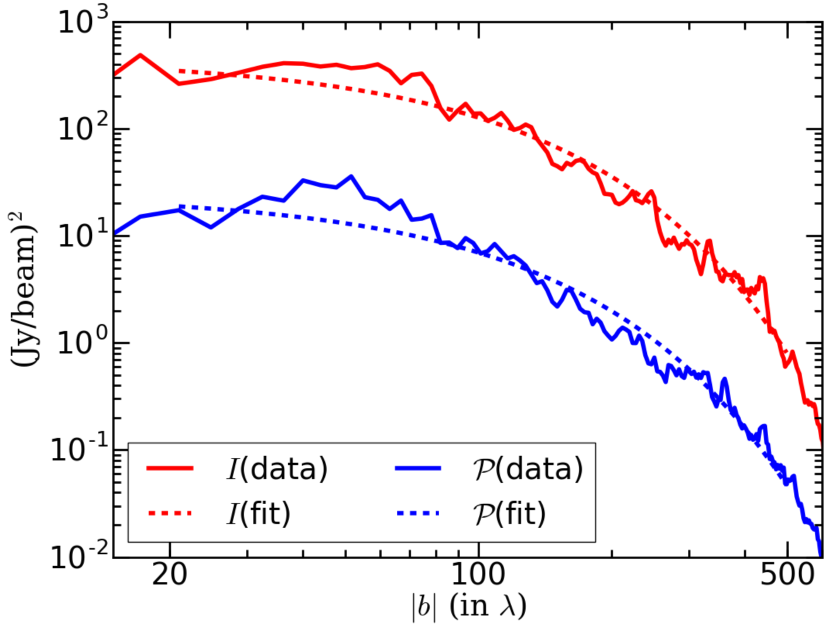
- \`Pitchfork' structure in $\mathcal{P}$: Polarised beam effect, arising from CasA leaking from Stokes I to $\mathcal{P}$ due to instrumental polarization leakage.
- $P_\mathcal{P}/P_I$ ~0.1 which corresponds to ~30% leakage from Stokes I to $\mathcal{P}$ compares well with the observation.

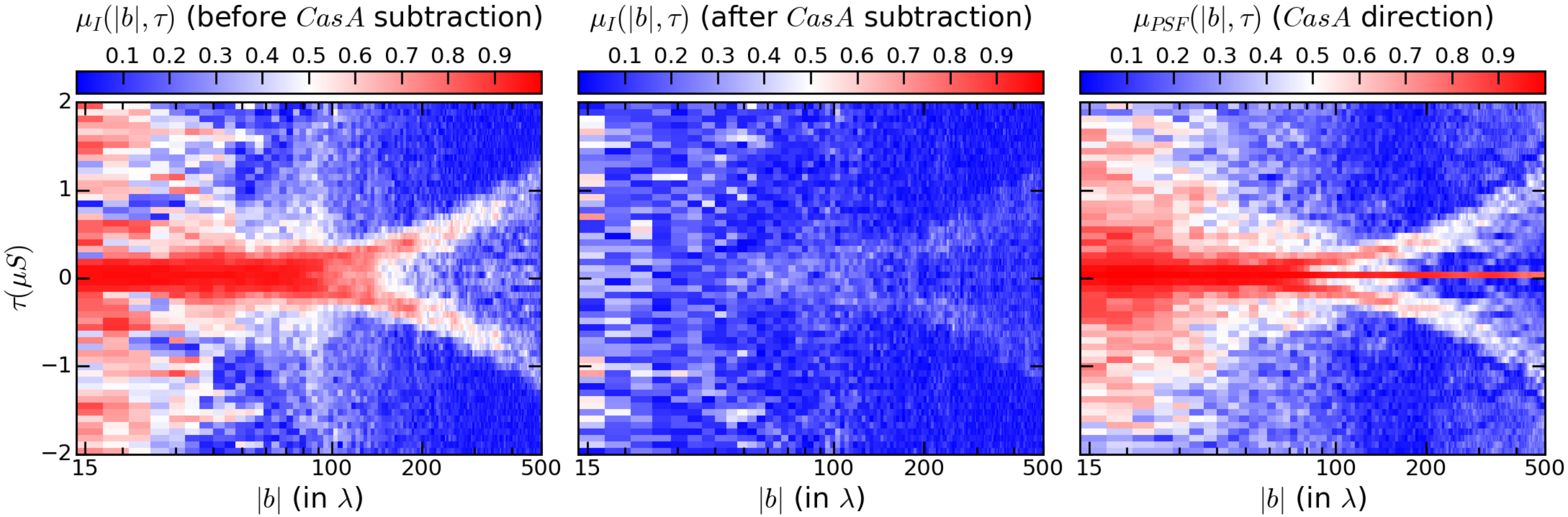
Ionospheric Scintillation

$$P_C(b) = |\mathcal{V}_S(\mathbf{b})|^2\ e^{-\mathcal{D}(b)} = P_S\ \exp\left[-\left(\frac{b}{r_{\rm diff}}\right)^{5/3}\right]$$

Fit parameters	$P_I(\lvert b\rvert, \tau = 0)$ slice	$P_{\mathcal{P}}(\lvert b\rvert, \tau = 0)$ slice
P_S (Jy/Beam)	450.2 ± 28.9	24.4 ± 1.6
$r_{\rm diff}$ (in λ)	78.8 ± 1.3	79.6 ± 1.4

$$\mu(|b|, \tau) = \frac{|\mathcal{V}_{\rm even}\mathcal{V}^*_{\rm odd}|}{\sqrt{|\mathcal{V}_{\rm even}|^2|\mathcal{V}_{\rm odd}|^2}}$$





Conclusions:

- ~10x higher excess variance in differential Stokes I than V with/without calibration cut compared to 10-50% level in HBA (Patil et al. 2016). This excess power might be due to incomplete sky-model and/or ionospheric effects.
- Discontinuity in differential Stokes I&V ratio between with and without cut. Baseline cut tilts both ratios in identical way. This effect is purely an artifact of the calibration cut.
- 'Pitchfork' structure in polarized intensity associated with Cas A leaking from Stokes I to V. The residual power in $\mathcal{P}$ delay spectrum after CasA subtraction correlates strongly with the power before CasA subtraction suggesting inaccurate CasA model and/or imperfect source subtraction during DD calibration.
- Polarization leakage towards at ~30% level in observations compares well with the simulations. Cas A is **'responsible'** for the 'pitchfork' structure in $\mathcal{P}$ delay spectrum.
- $r_{\mathrm{diff}} \sim 80\lambda \sim 400\mathrm{m}$ towards CasA, smallest diffractive scales ever measured. Cas A residuals decorrelate over 5 min timescales as shown in cross-coherence. Ionospheric scintillation causes imperfect subtraction of Cas A and leaving residuals which are incoherent in time.

Take home message: **The contamination effects appear much stronger in LOFAR LBA data, these and other far-field effects (such as scintillation of CasA) need to be accounted for before the thermal noise (or Stokes V rms) level can be reached.**

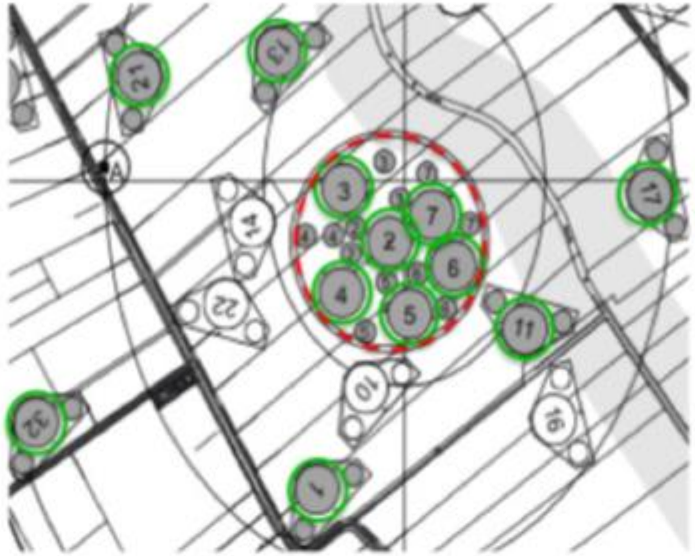
AARTFAAC: Imaging large-scale diffuse emission

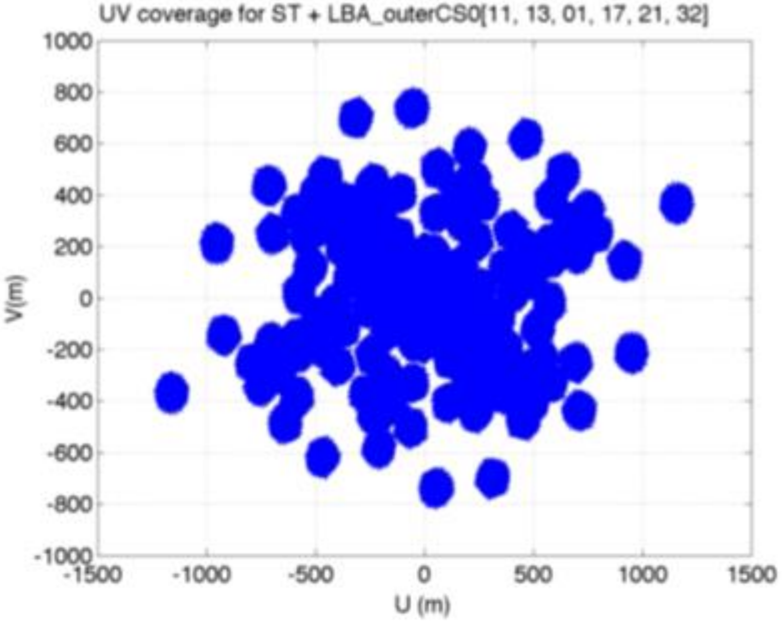
- Correlates signal from HBA-tiles/LBA-dipoles instead of beam- formed stations. Piggybacks on ongoing LOFAR observation.

- 166,176 baselines ($2.5\lambda - 600\lambda$ @ 150 MHz) in a single uv-snapshot, but limited instantaneous bandwidth.

- Use AARTFAAC to study and build full sky broadband diffuse foreground models (30-180 MHz) in Stokes I, Q and U.

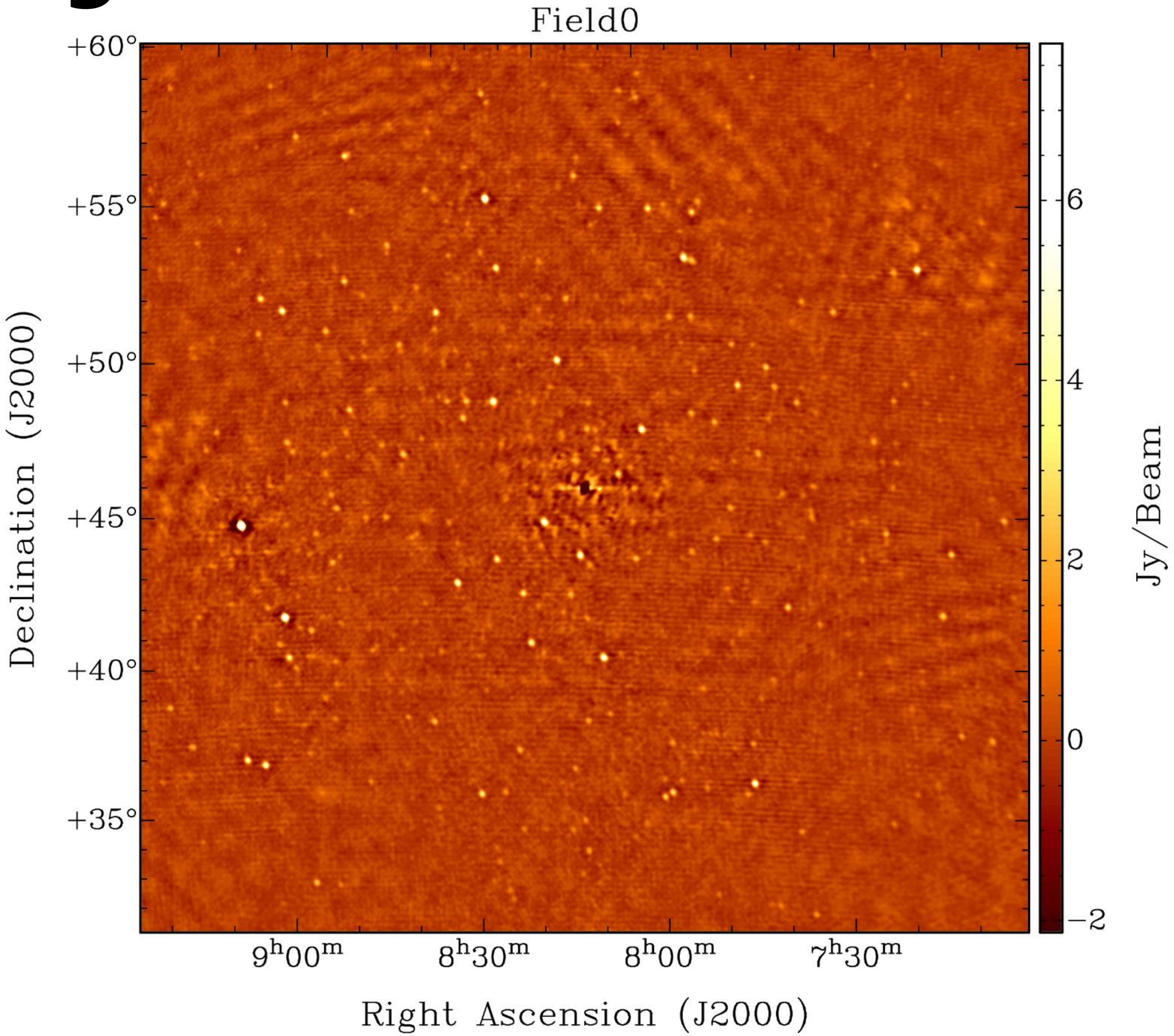
- Data acquisition in parallel to LOFAR-EoR observations starts in the next current and upcoming LOFAR observation cycle.





AARTFAAC: First image

- $30° \times 30°$ image of 3C196 field after 3C196 subtraction.
- Created using AARTFAAC HBA with 576 tiles with baseline range ~ 5 m – 1.2 km ($2\lambda - 550\lambda$).
- Using 8 minutes single sub-band ($\nu_c = 123$ MHz, $\Delta\nu = 195$ kHz) test dataset.
- DI calibration (using 3C196 model) using Sagecal.
- Imaging and cleaning using WSClean.



“Let the data tell us what it is”

- Ger de Bruyn