LOFAR Ultra Deep Imaging

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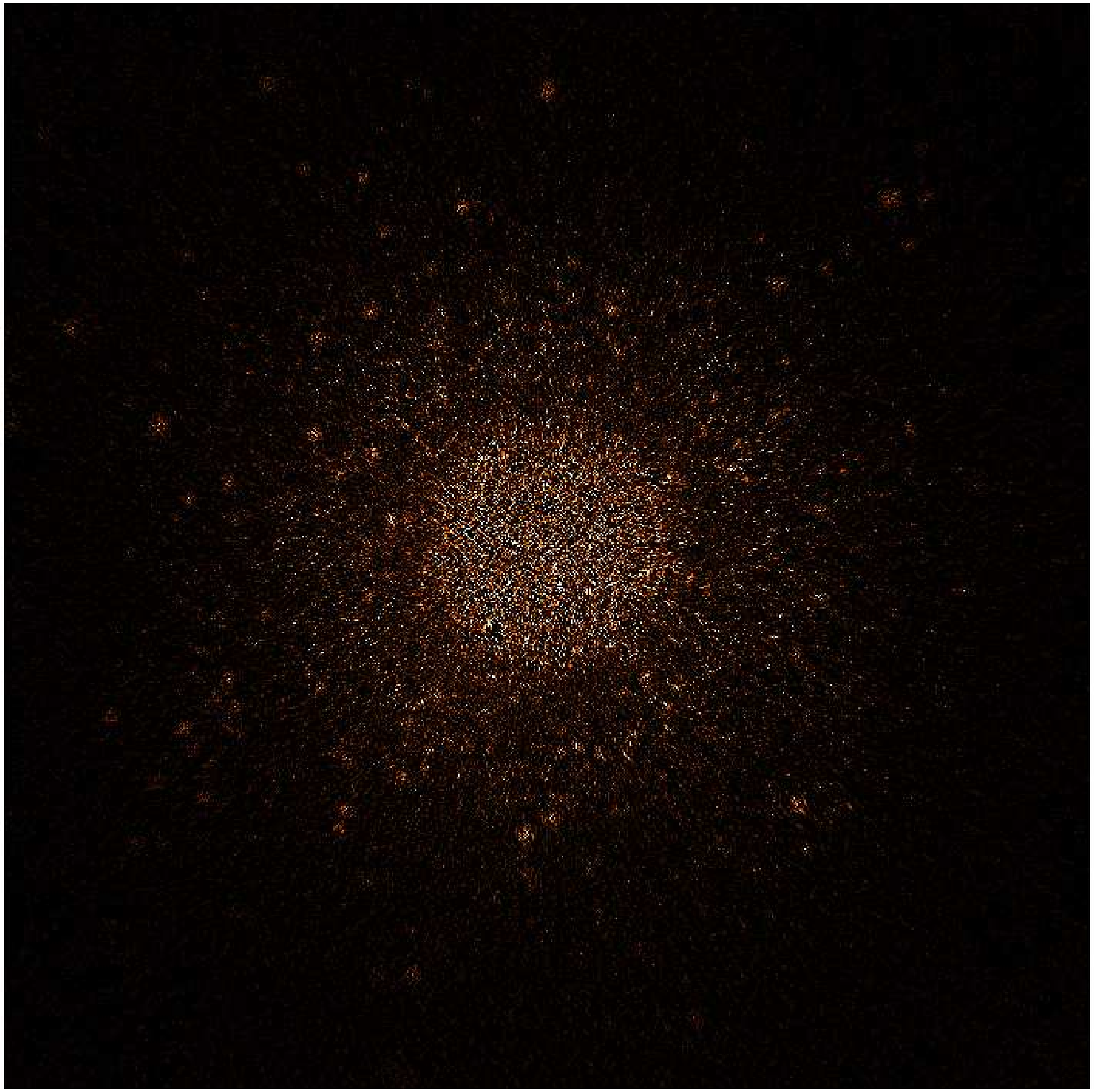
Deep to Ultra Deep

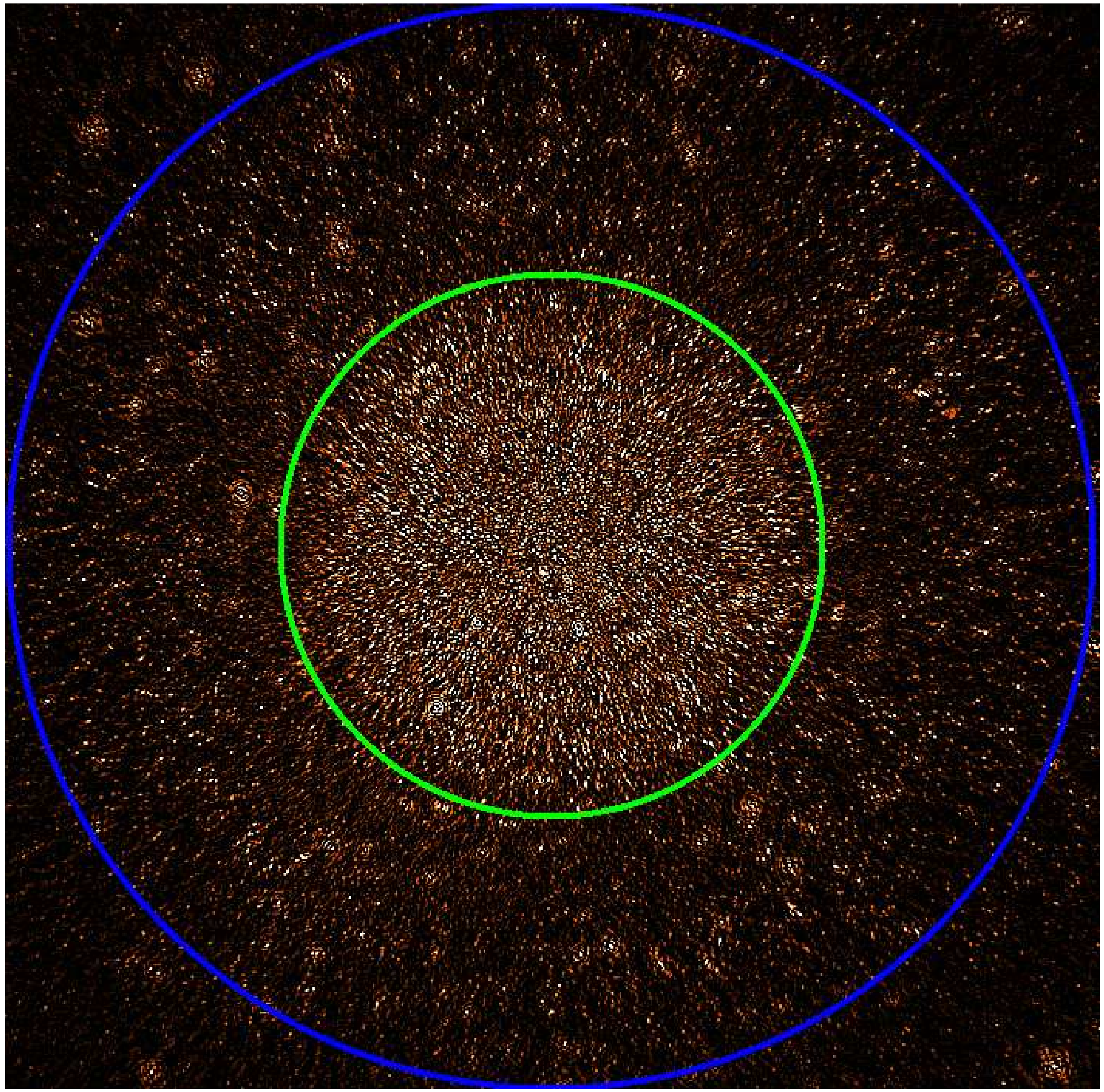
- LOFAR is producing good data (HBA), getting to $\approx$ 100 μJy noise in a single night is not difficult.
- Ultra deep imaging: going from single night to many nights, $>$ 100 hours and reaching noise limit (Ultra deep for LOFAR should be routine for SKA).
- Getting down to noise, what we can do:
  - Accurate and Robust calibration: Beam, Ionosphere, Receiver: many directions.
  - Suppression of deterministic signals that act as noise (outlier sources).
  - Optimal imaging: minimize artefacts, maximize signal/noise.
- What we cannot have influence on: RFI, closure errors, hardware sensitivity,. . . . . .
- Key requirement is a good sky model (full sky) and Key constraint is computational cost: need to cut down processing time.

NCP FOV



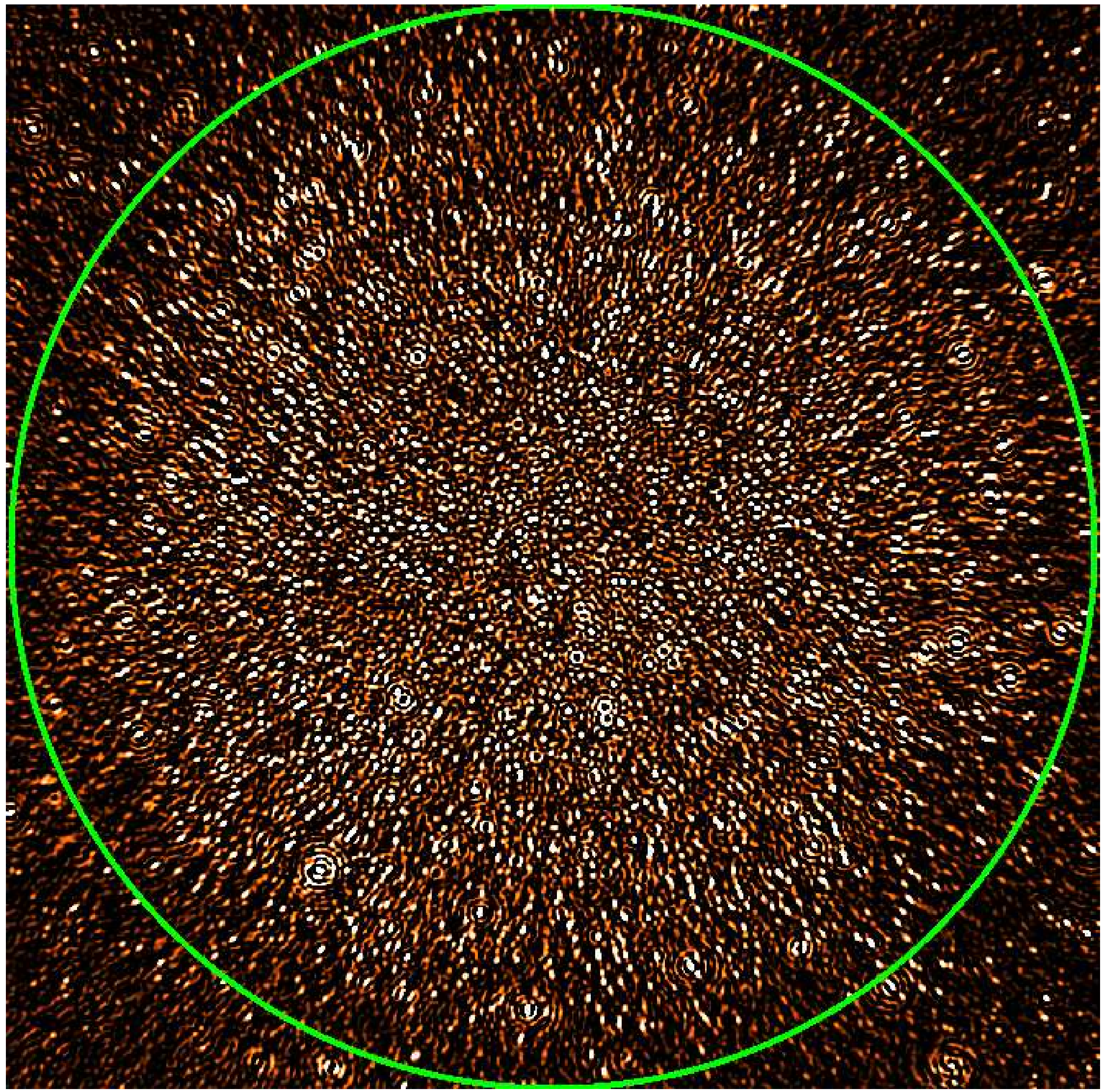
NCP 40×40 sq. deg., 150 MHz, $30 - 1000\lambda$, $3'$ PSF

Main FOV



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

Confusion

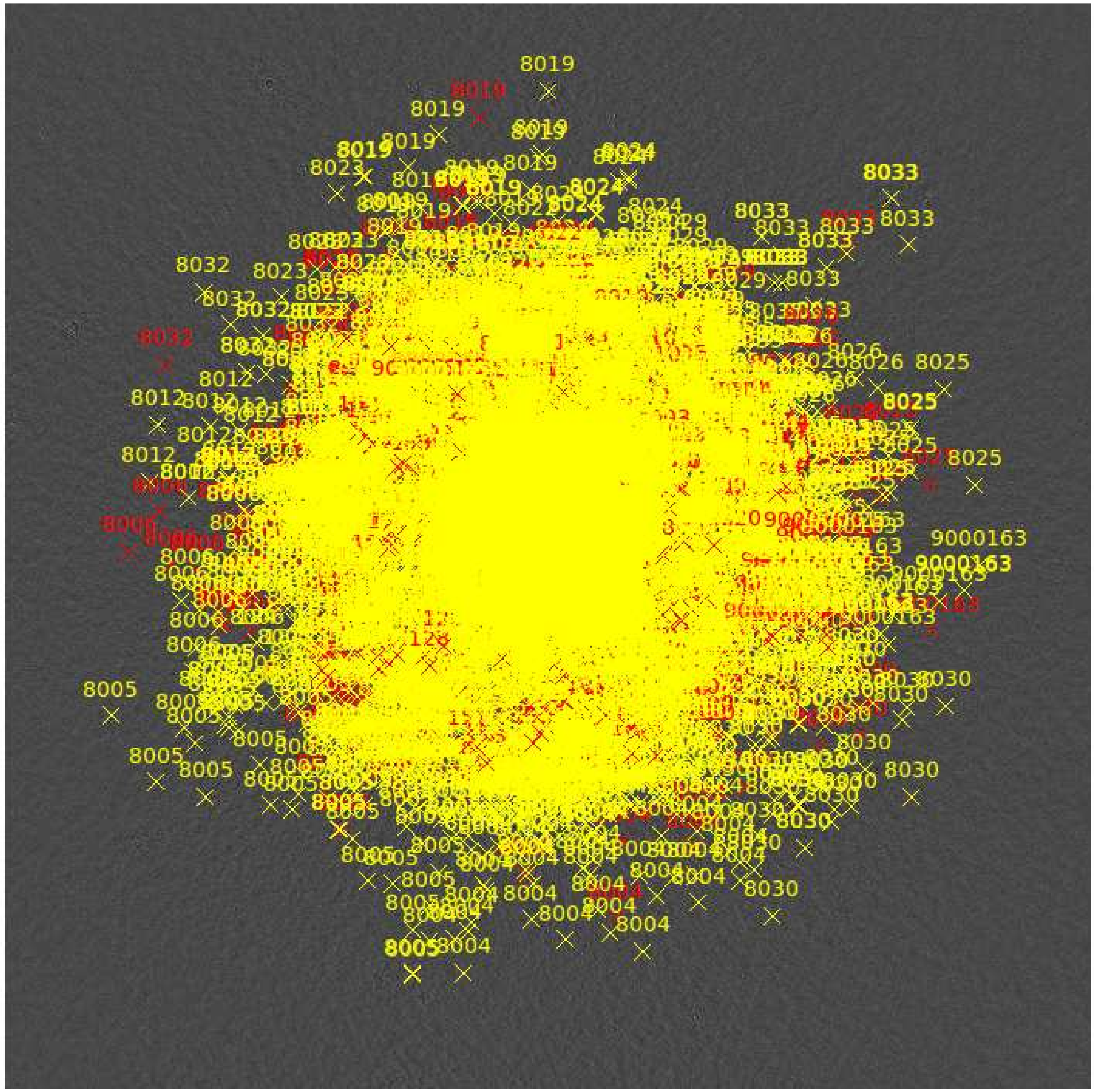


confusion limit, $3'$ PSF, peak 300 μJy, noise 60 μJy

Effects of Sources

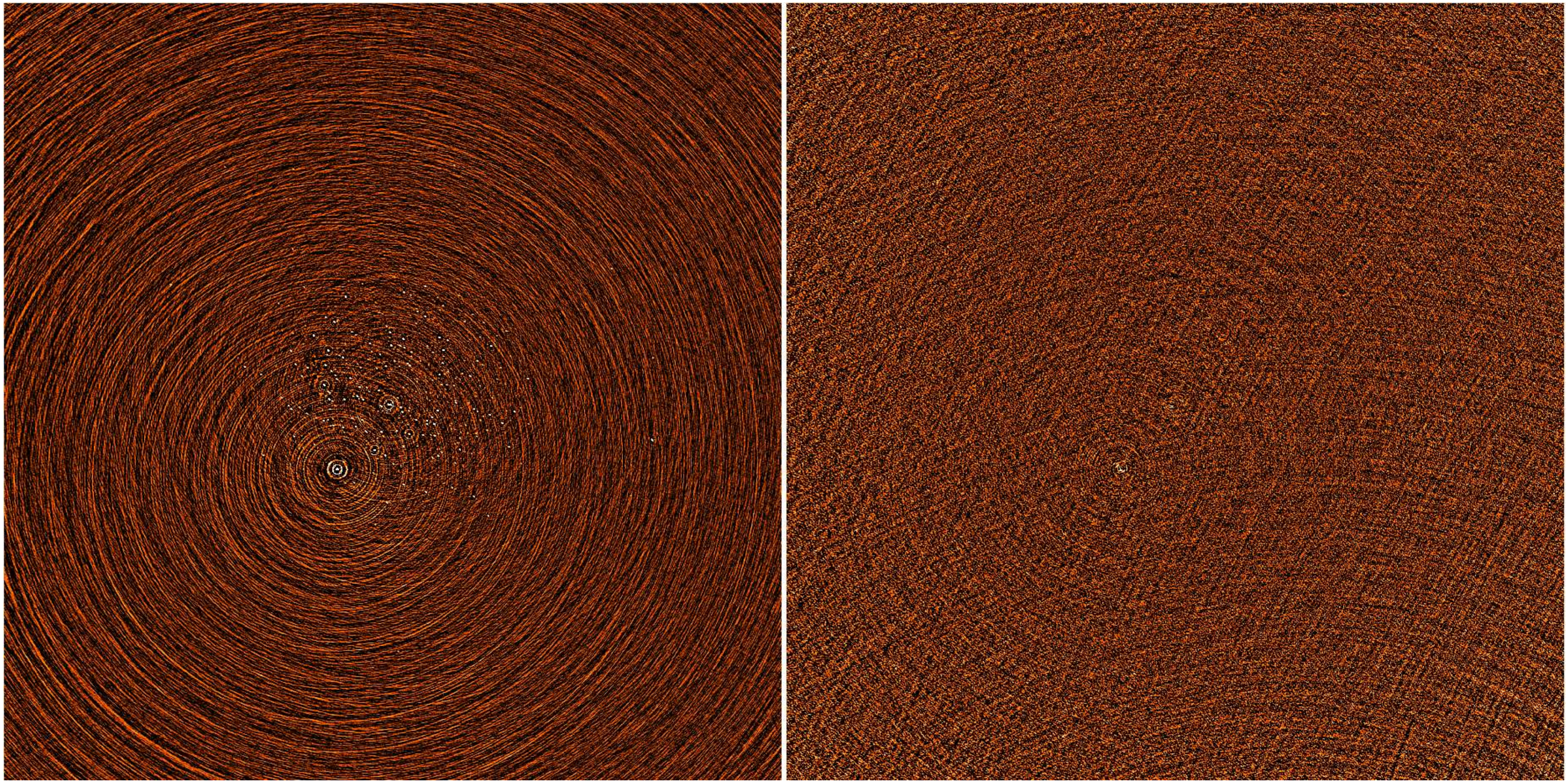
- No sources in the sky $\Rightarrow$ No problem regardless of errors due to ionosphere/beam: Root of all evil.
- Unsubtracted sources increase noise/confusion in residual images.
- Unmodeled sources change the noise statistics during calibration. Noise is not Gaussian anymore [Kazemi & Yatawatta, 2013].
- Non-Gaussianity $\Rightarrow$ spikes in data after calibration, calibration artefacts in images, suppression of flux of weak sources.
- Will need to model about 10 000 sources for a typical LOFAR HBA observation to go ultra deep.
- Increasing the number of sources $\neq$ Increasing number of degrees of freedom.
- Calibration satisfying all the above: SAGECal. Non-Gaussianity $\Rightarrow$ Robust calibration, Computational cost $\Rightarrow$ Clustering.
- 20×20 deg. FOV at $2''$ pixel size, need to make $>$ billion pixel images. ExCon makes billion pixel images using a normal computer $<$ 10GB memory.

NCP Sky Model



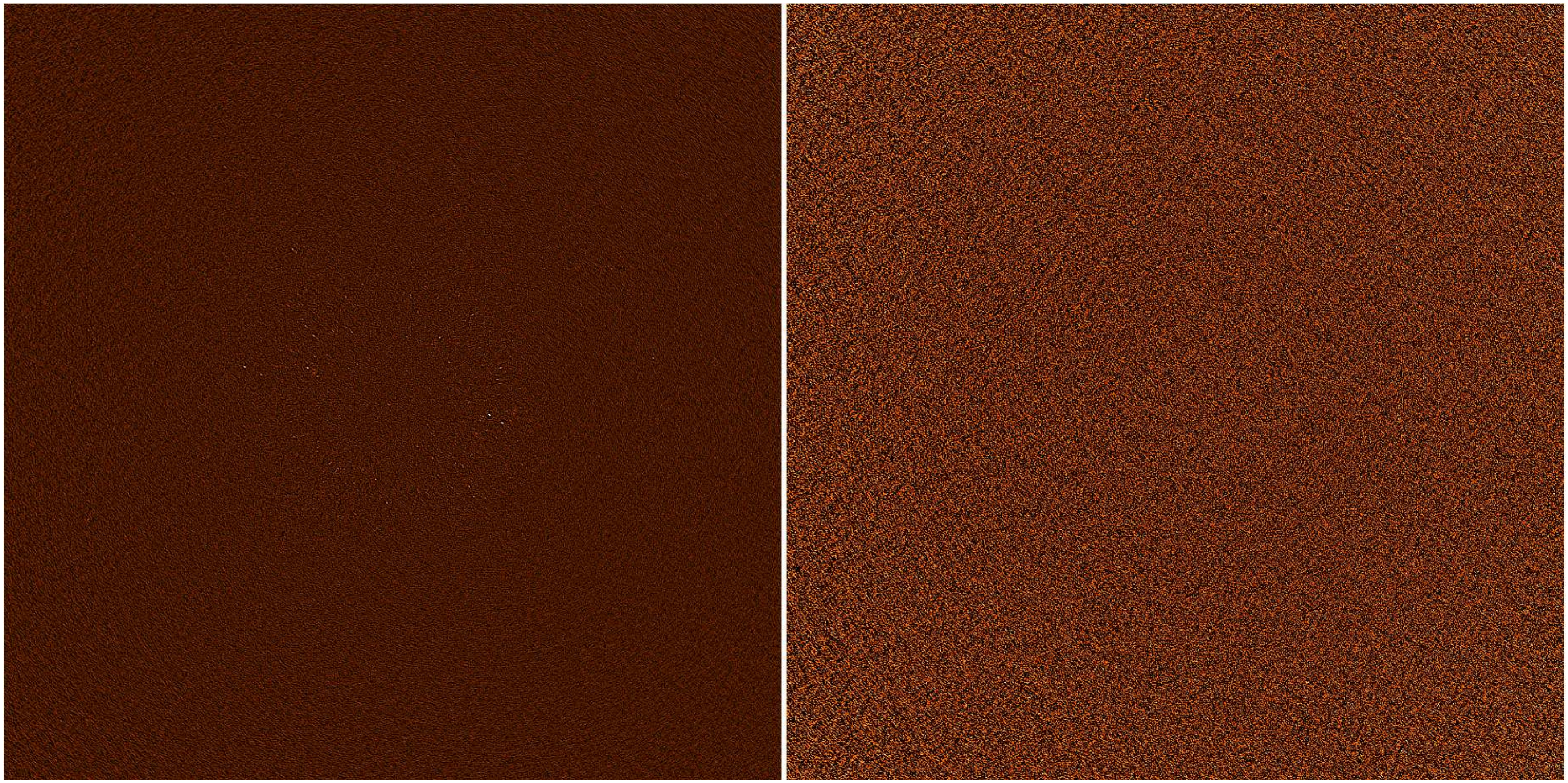
Sky model with $>$ 20 000 components, 40$\times$40 sq. deg. area

Before SAGECal



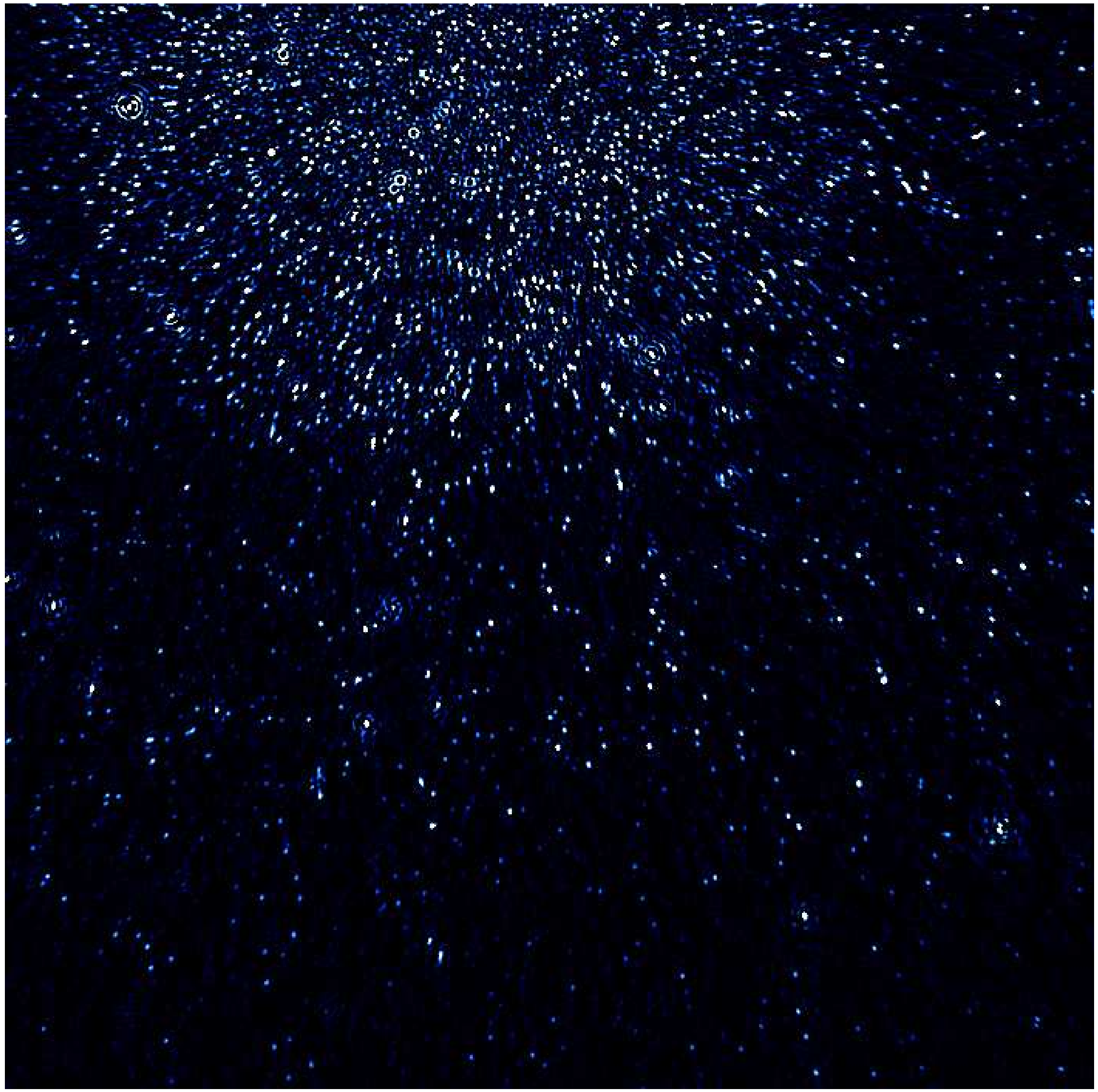
Stokes I (left) Stokes Q (right) showing sidelobes from CasA and CygA

After SAGECal



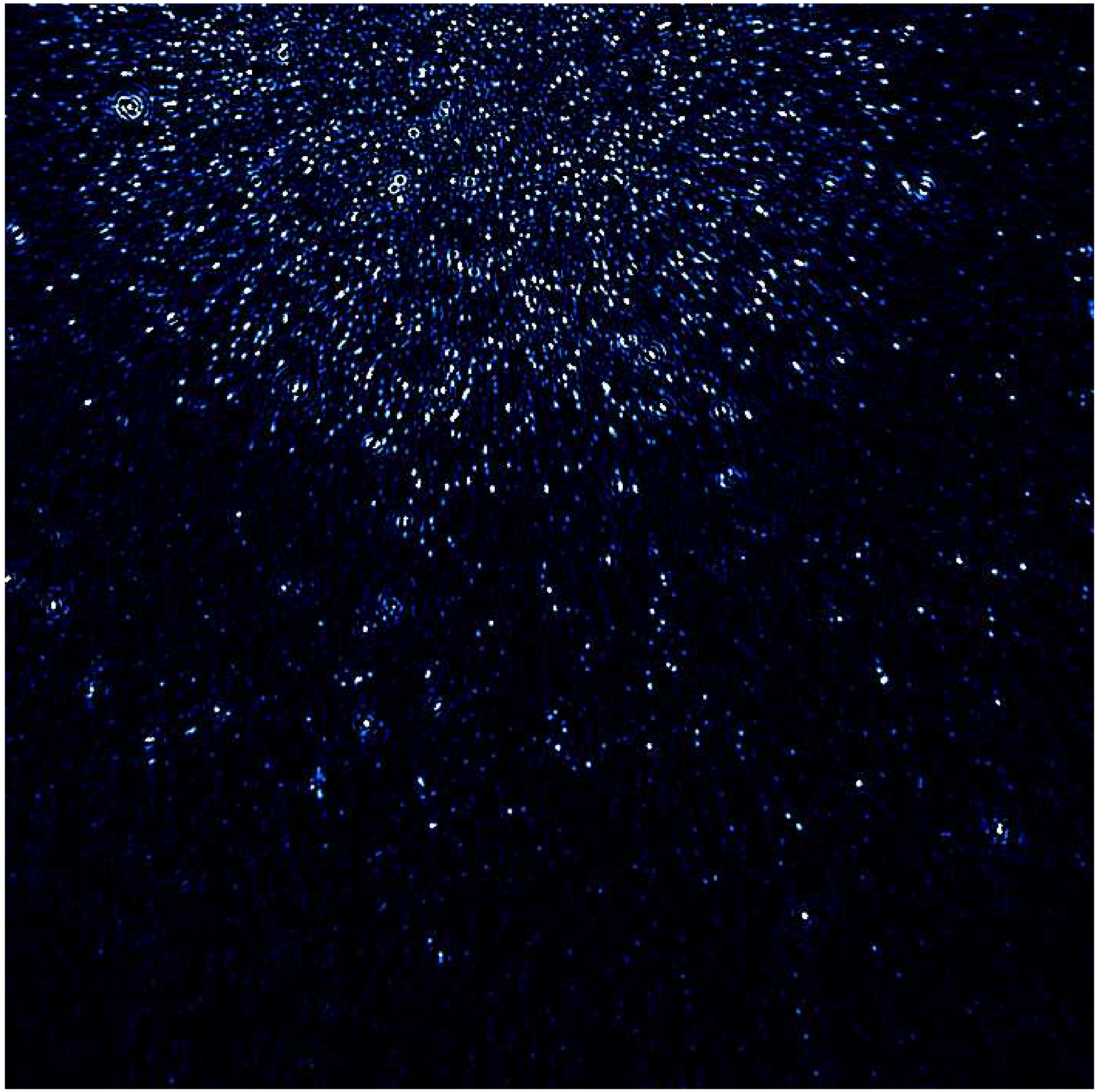
Stokes I (left) Stokes Q (right), after subtraction of 11,000 sources

Sources Outside the FOV



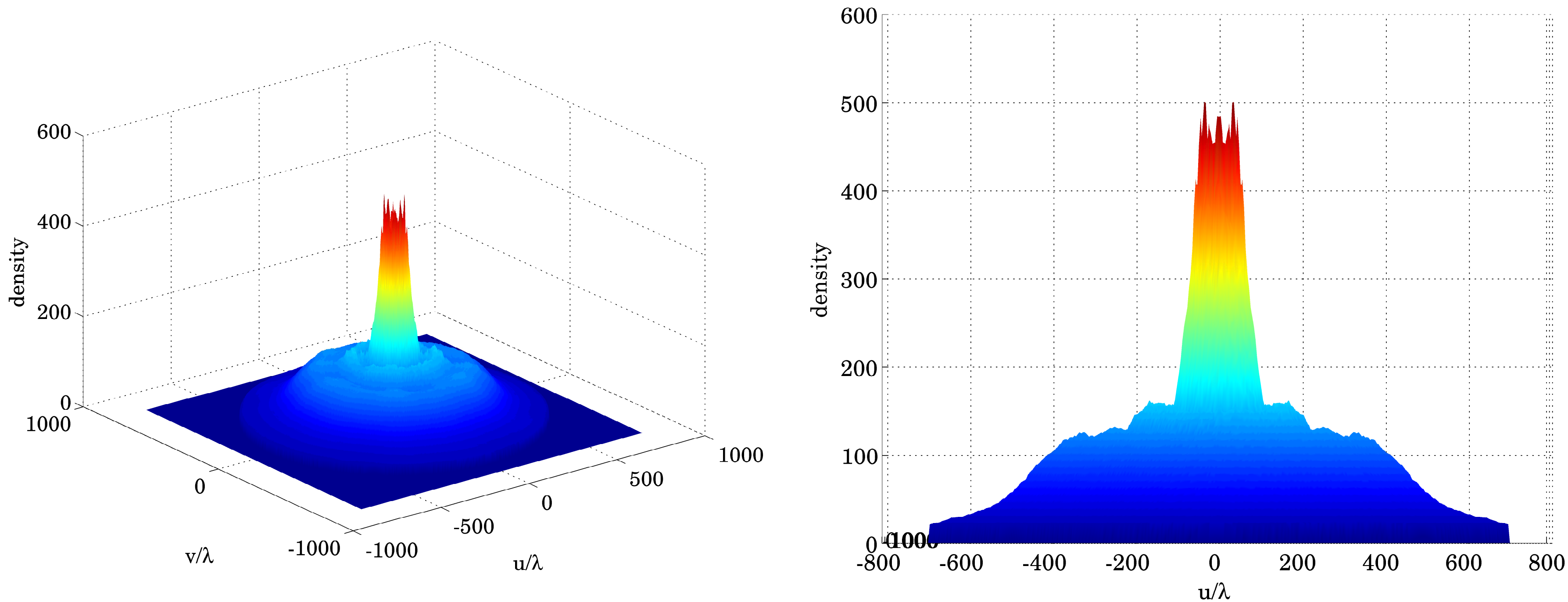
15×15 sq. deg., 11 000 sources subtracted using SAGECal

Sources Outside the FOV



15×15 sq. deg., 15 000 sources subtracted using SAGECal, same unknowns as before.

Optimal Imaging



Average uv sampling density for full bandwidth 115-185 MHz

Optimal imaging: enhancing weak signals, minimizing PSF variation. Key elements: image weighting, data gridding.

Image Weighting

- Natural weights: high SNR, high sidelobes; Uniform weights: low SNR, low sidelobes; Briggs weights: between uniform and natural weights.
- What we want: high SNR, low sidelobe variation over all frequencies and all epochs.
- Iterative weighting: [Pipe & Menon, 1999],[Yatawatta, 2014].
- $W(k)$: weights, $C(k)$: convolution kernel, $w(x)$ and $c(x)$ their FT. Gridded weights are $W(k) \otimes C(k)$, and FT of this is similar to the PSF. Given an a priori function $g(x)$ we want $w(x)c(x) \approx g(x)$. Convolve both sides with $w(x)$

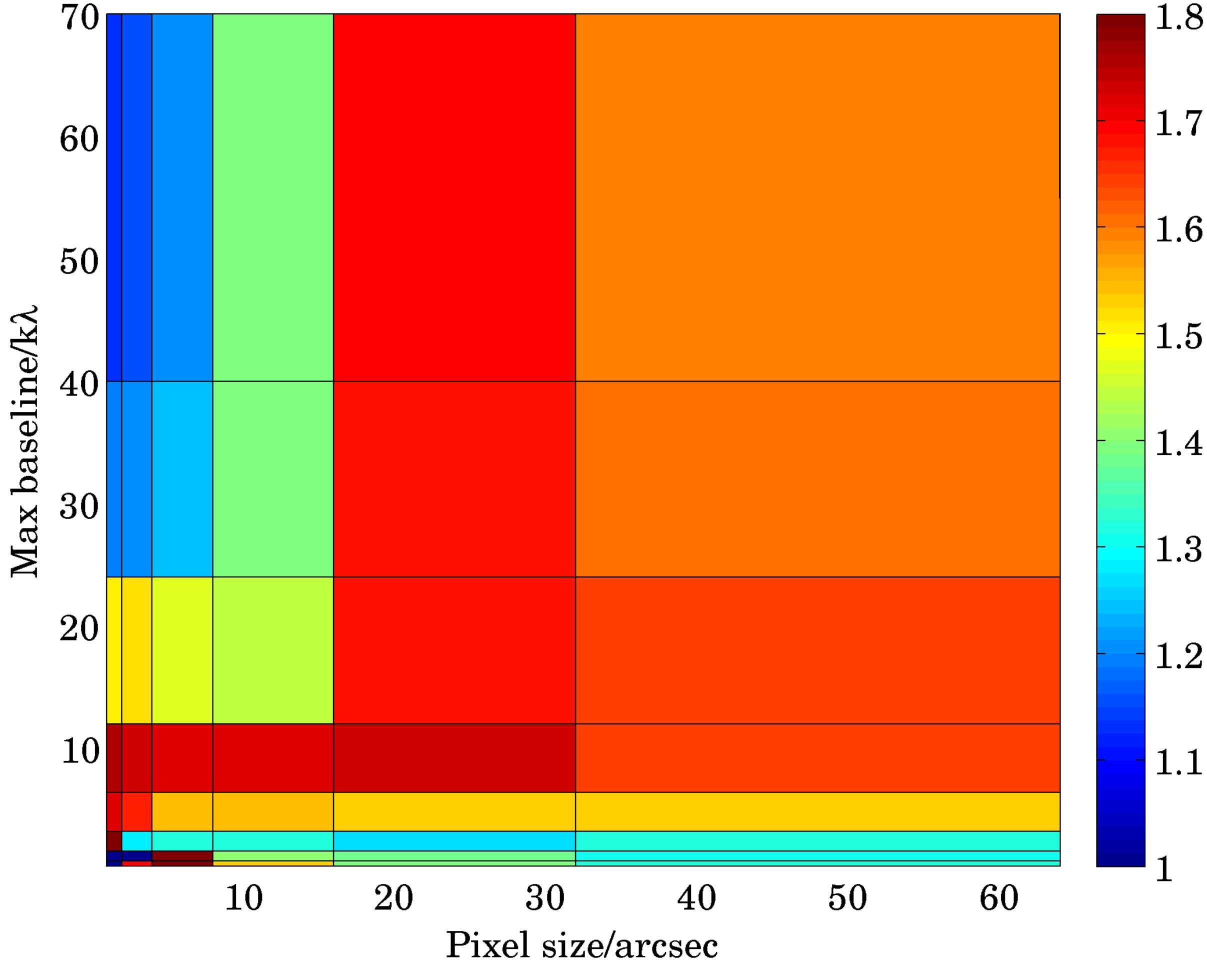
  $$w(x) \otimes (w(x)c(x)) \approx w(x) \otimes g(x) \;\; W(k)(W(k) \otimes C(k)) \approx W(k)G(k)$$

  Both $W(k), C(k)$ positive real,

  $$W^{i+1}(k) \leftarrow \frac{W^i(k)G(k)}{(W^i(k) \otimes C(k))}$$

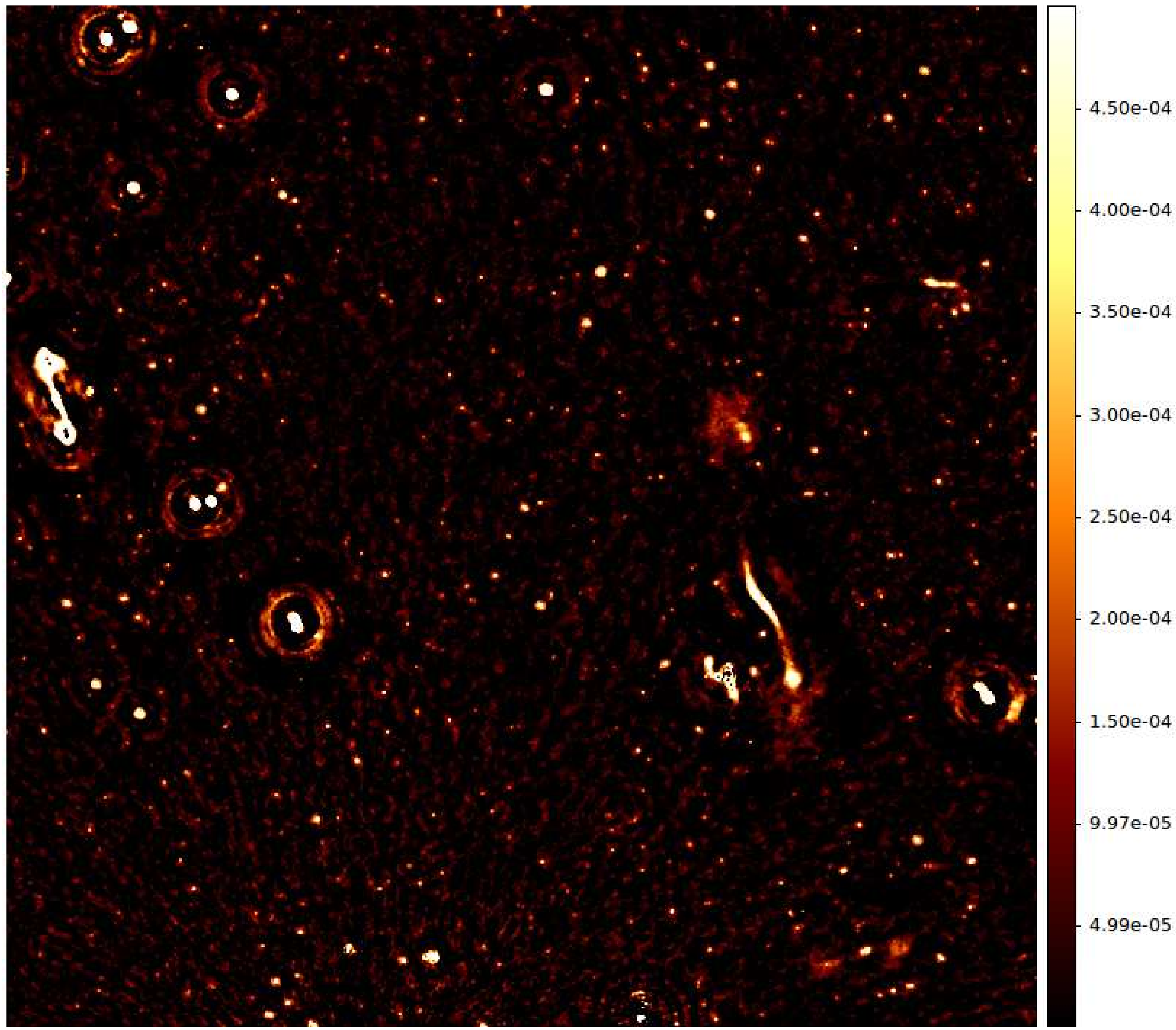
  which gives $W(k)$ to make the PSF as much as close to $g(x)$.

Optimal Imaging Parameters



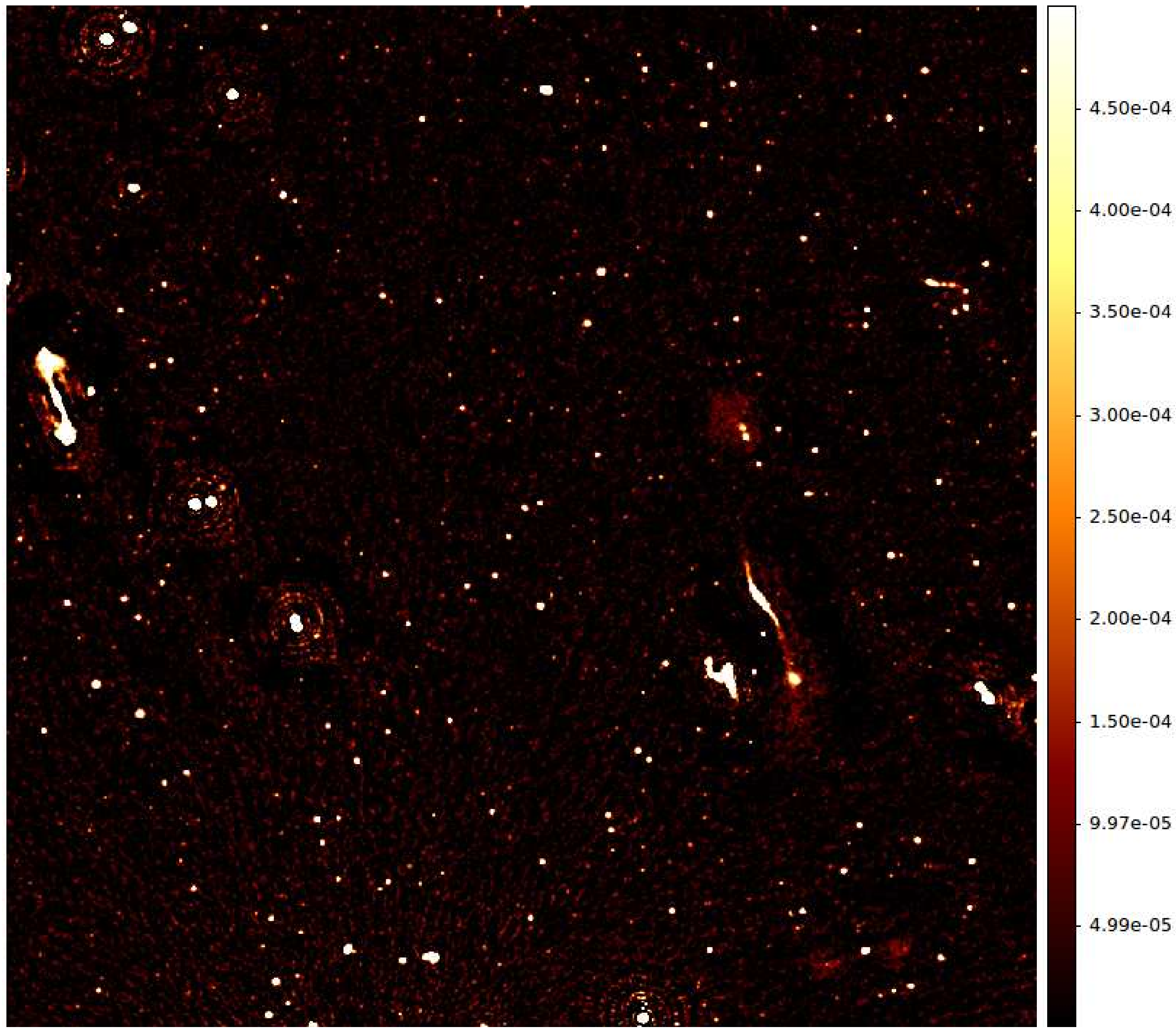
σ_I^2/σ_V^2 Variance of noise in I as a fraction of noise in V

Deepest LOFAR Image



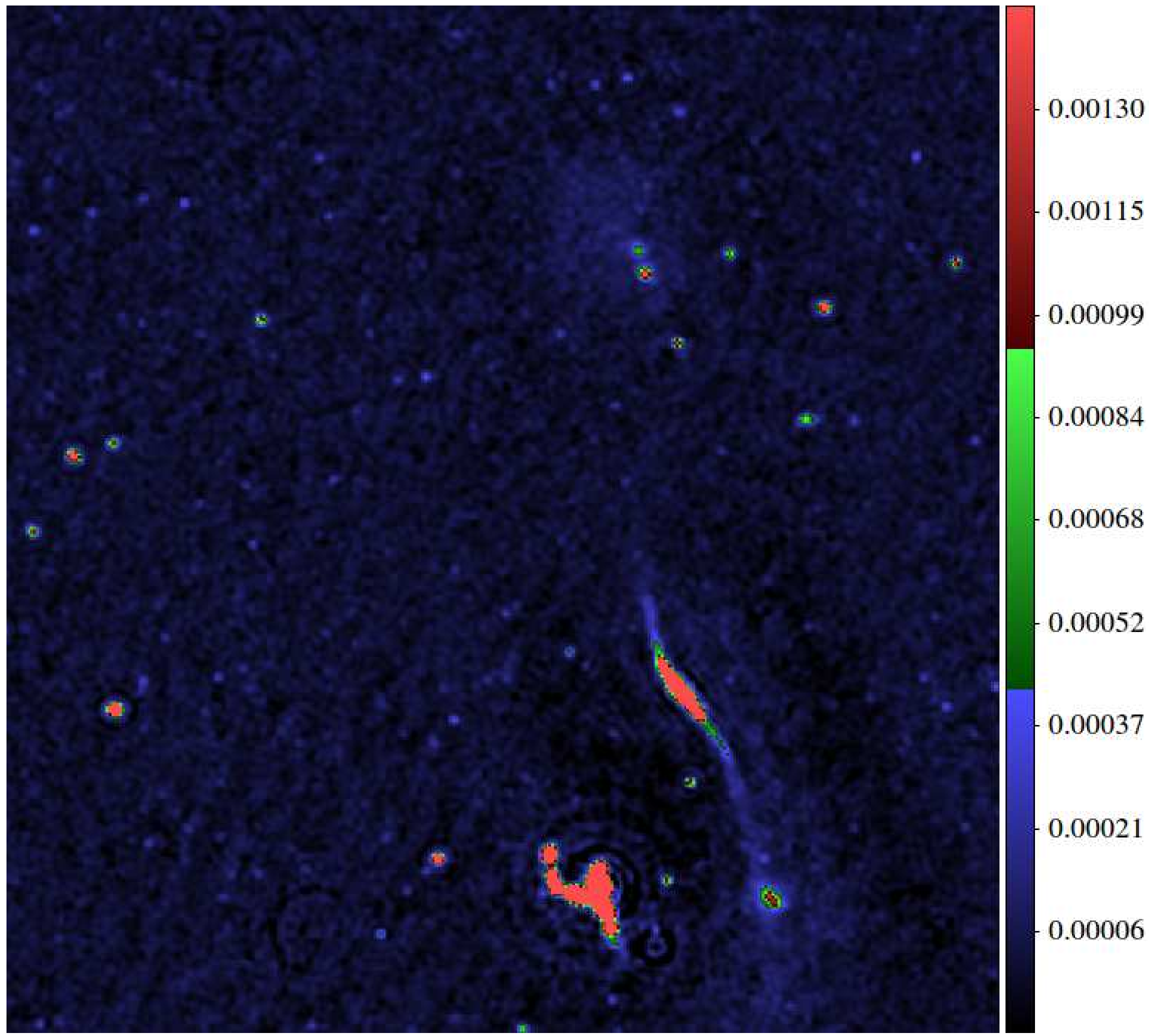
Small area at NCP at 150 MHz, 2″ pixels, 25 μJy noise, 200 hrs data, dynamic range $>$ 150 000 (ExCon imager)

Deconvolved/Restored Image



Deconvolution removes residual PSF, enhances resolution

Detecting 100 μJy Sources



Many $\sim$ 100 μJy sources visible