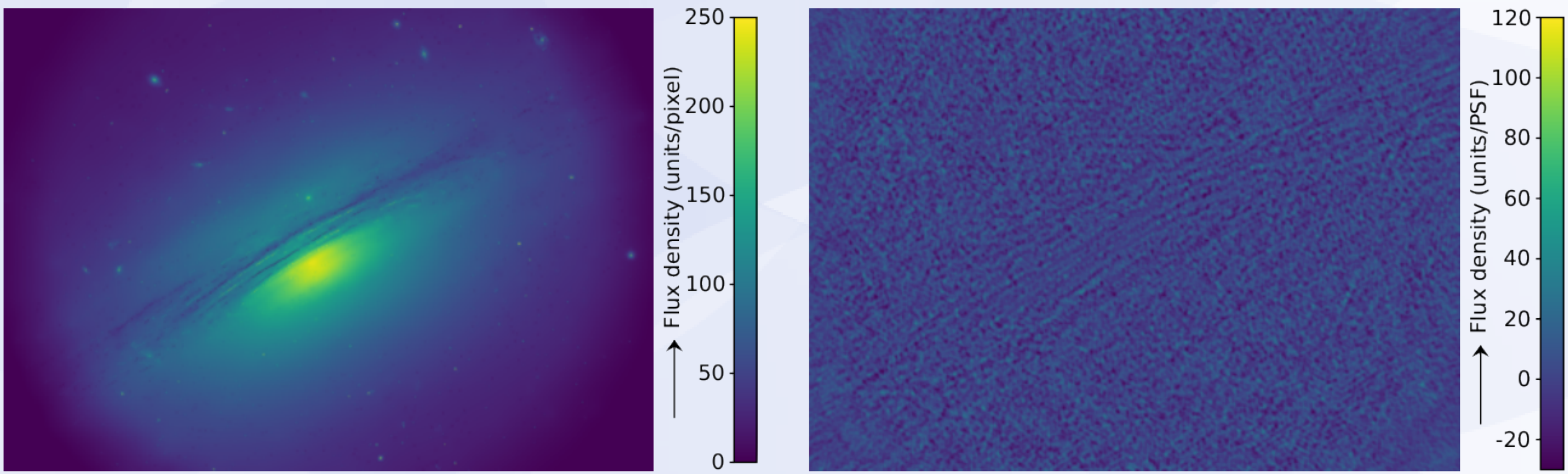
Imaging at low frequencies

André Offringa (ASTRON)

Bologna, Italy, 2017-06-20



(a) Reconstructed model image

(b) Residual image (σ=8.6 units/PSF)

Automatic scale-dependent masking applied on the UGC12591 test-set.

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Challenges in low-frequency imaging

- Large FOV
  - Large w-values
  - Harder to deconvolve
- Large fractional bandwidth
  - Requires multi-frequency deconvolution
- Large data volumes
- Robustness to calibration errors
- Connection to direction-dependent cal.

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An optimized algorithm for multi-scale wideband deconvolution of radio astronomical images

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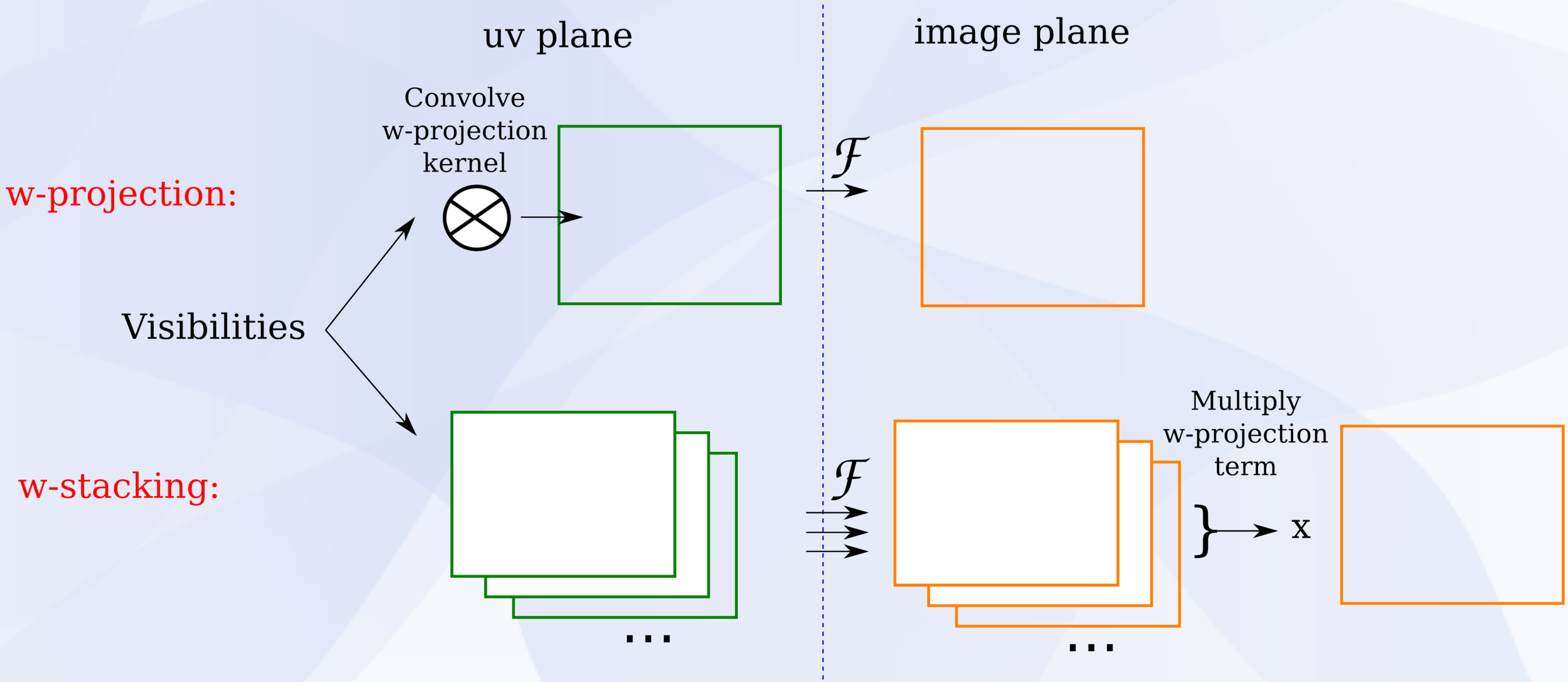
Accepted yesterday!

ABSTRACT

We describe a new multi-scale deconvolution algorithm that can also be used in multi-frequency mode. The algorithm only affects the minor clean loop. In single-frequency mode, the minor loop of our improved multi-scale algorithm is over an order of magnitude faster than the CASA multi-scale algorithm, and produces results of similar quality. For multi-frequency deconvolution, a technique named joined-channel cleaning is used. In this mode, the minor loop of our algorithm is 2-3 orders of magnitude faster than CASA MSMFS. We extend the multi-scale mode with automated scale-dependent masking, which allows structures to be cleaned below the noise. We describe a new scale-bias function for use in multi-scale cleaning. We test a second deconvolution method that is a variant of the MORESANE deconvolution technique, and uses a convex optimisation technique with isotropic undecimated wavelets as dictionary. On simple, well calibrated data the convex optimisation algorithm produces visually more representative models. On complex or imperfect data, the convex optimisation algorithm has stability issues.

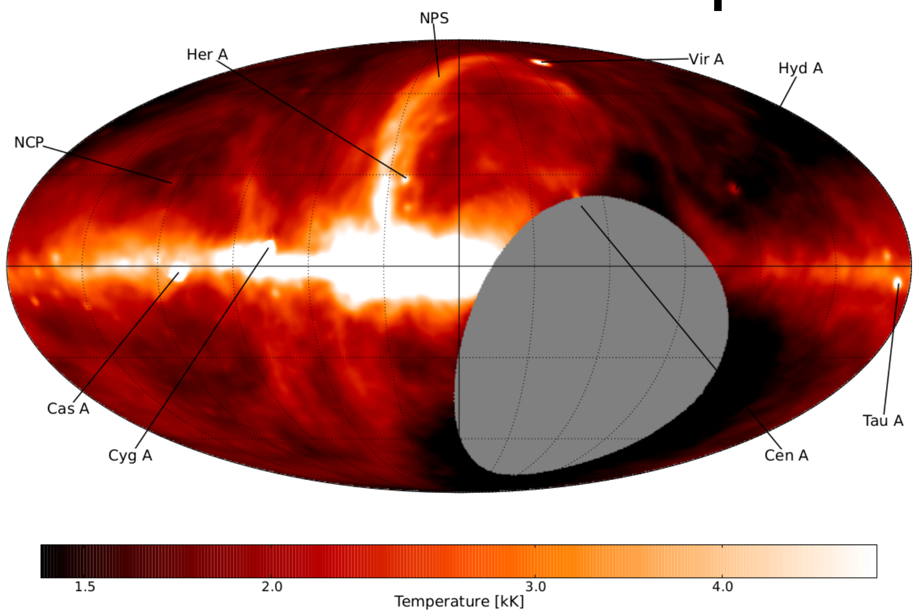
WSClean: *w*-stacking

$$V(u,v,w) = \iint \frac{I(l,m)}{\sqrt{1-l^2-m^2}} e^{-2\pi i \left(ul+vm+w(\sqrt{1-l^2-m^2}-1)\right)} dl dm$$

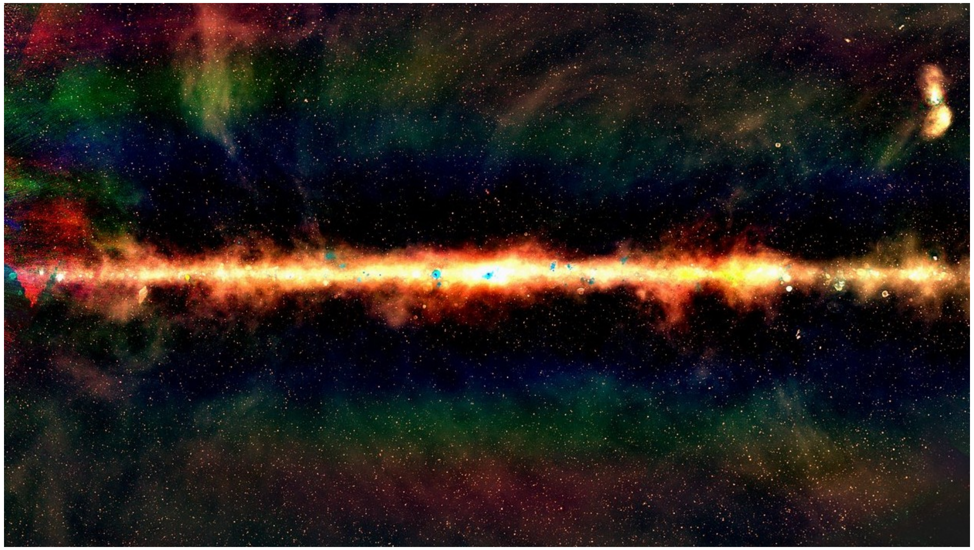


Offringa et al. (2014)

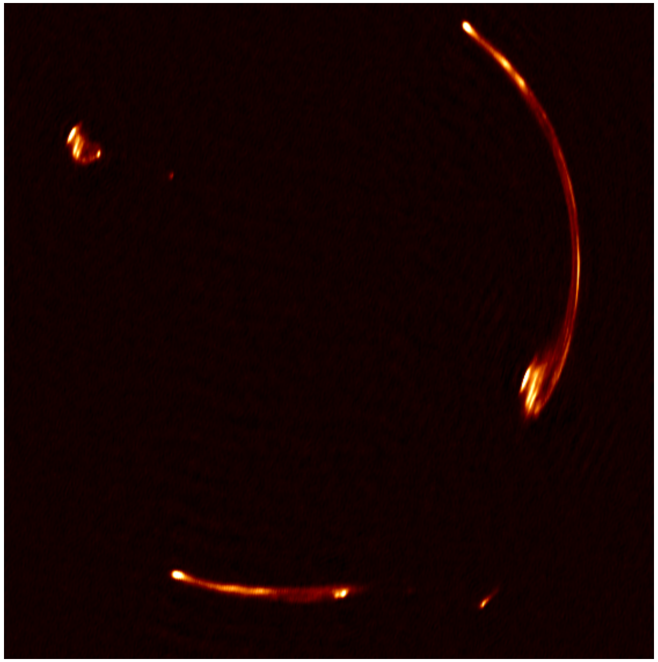
A few examples of WSClean results...



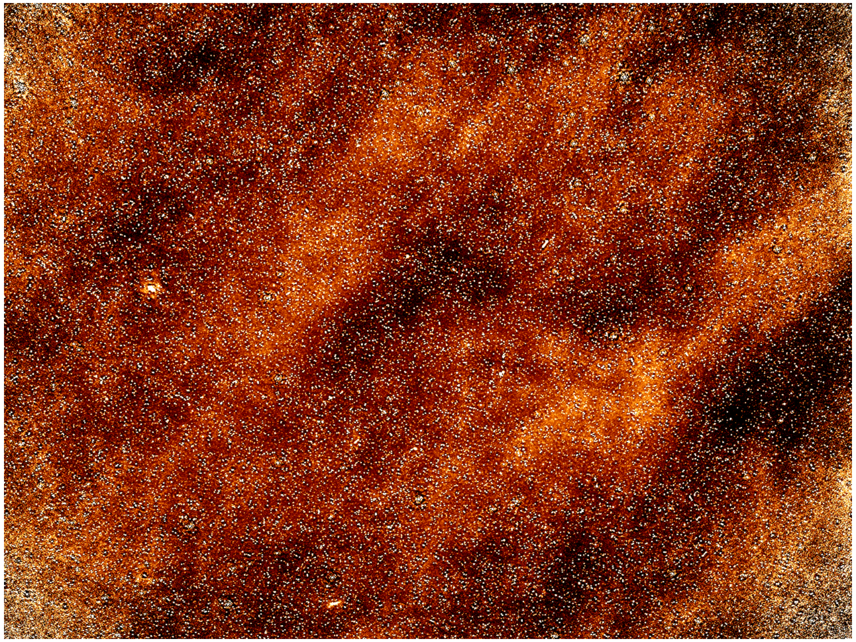
"The LWA1 Low Frequency Sky Survey", Jayce Dowell et al. (2017)



GLEAM, N. Hurley-Walker et al. (2017)



Gravitational Lense **(VLBI** data by J. P. McKean and C. Spingola)

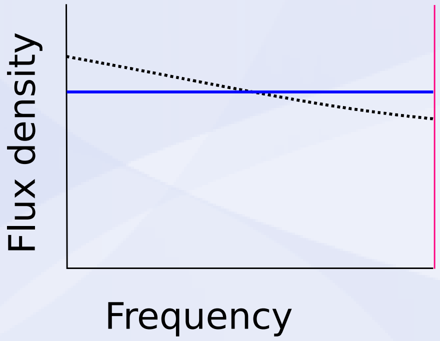


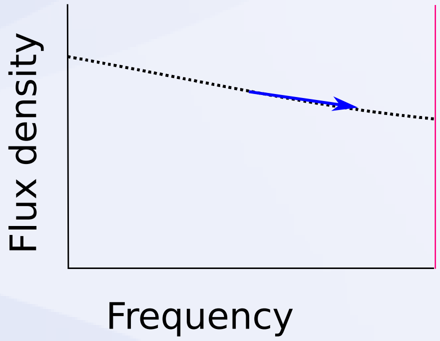
MWA EoR0, Offringa et al. (2016). **Deepest MWA image.**

Multi-frequency deconvolution

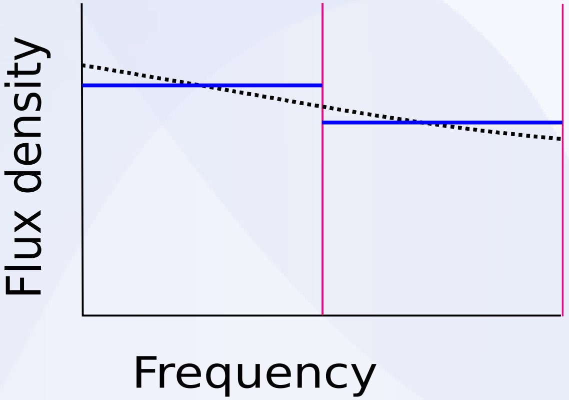
- Common approach in MF deconvolution is imaging / predicting “frequency derivative” images (“nterms>1”, the Sault & Wieringa (1994) method).

That results in:





Instead, WSClean splits the bandwidth and creates separate images for each part:



(Similar strategy is used by B. Cotton’s OBIT)

Multi-frequency deconvolution

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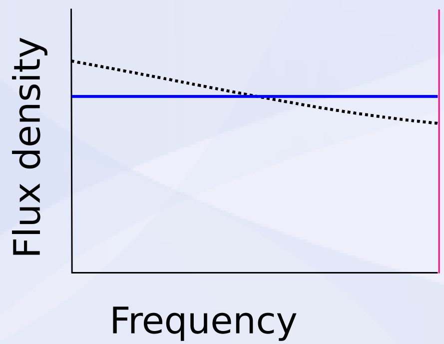
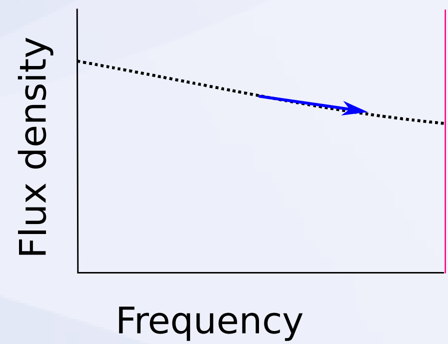
  derivative” images (“nterms>1”, the Sault &





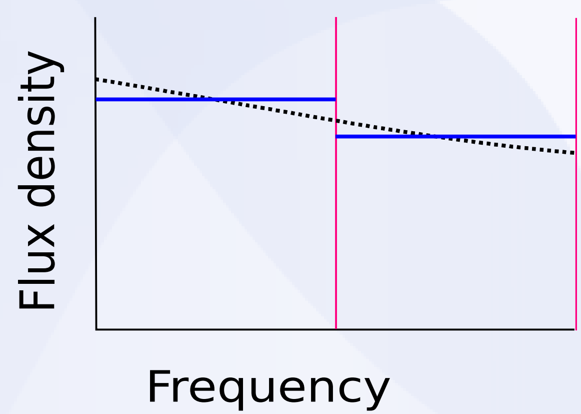
- Of course, these contain the same information

  (they can be converted from one to the other)

- But the second option is easier/more intuitive to clean...

an splits the
and creates
r each part:

(S
on’s OBIT)



Multi-frequency deconvolution

WSClean’s Multi-frequency clean algorithm: (1 maj iter)

- Make residual images at different frequencies
- Start cleaning:
  - Find a peak in the **integrated** image
  - Measure the flux at this position in the subband images
  - Subtracted the correct PSF from each subband image.
- ...Until major iteration threshold is reached
- (Optionally) convert to Taylor-term images and predict

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This is called
"joined-channel cleaning"
in WSClean

(Offringa and Smirnov. 2017)

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- ...U
- (Op edict

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in WSClean

(Offringa and Smirnov. 2017)

This is **not** the same as "MFS"
or "MSMFS" imaging.

Multi-scale kernel

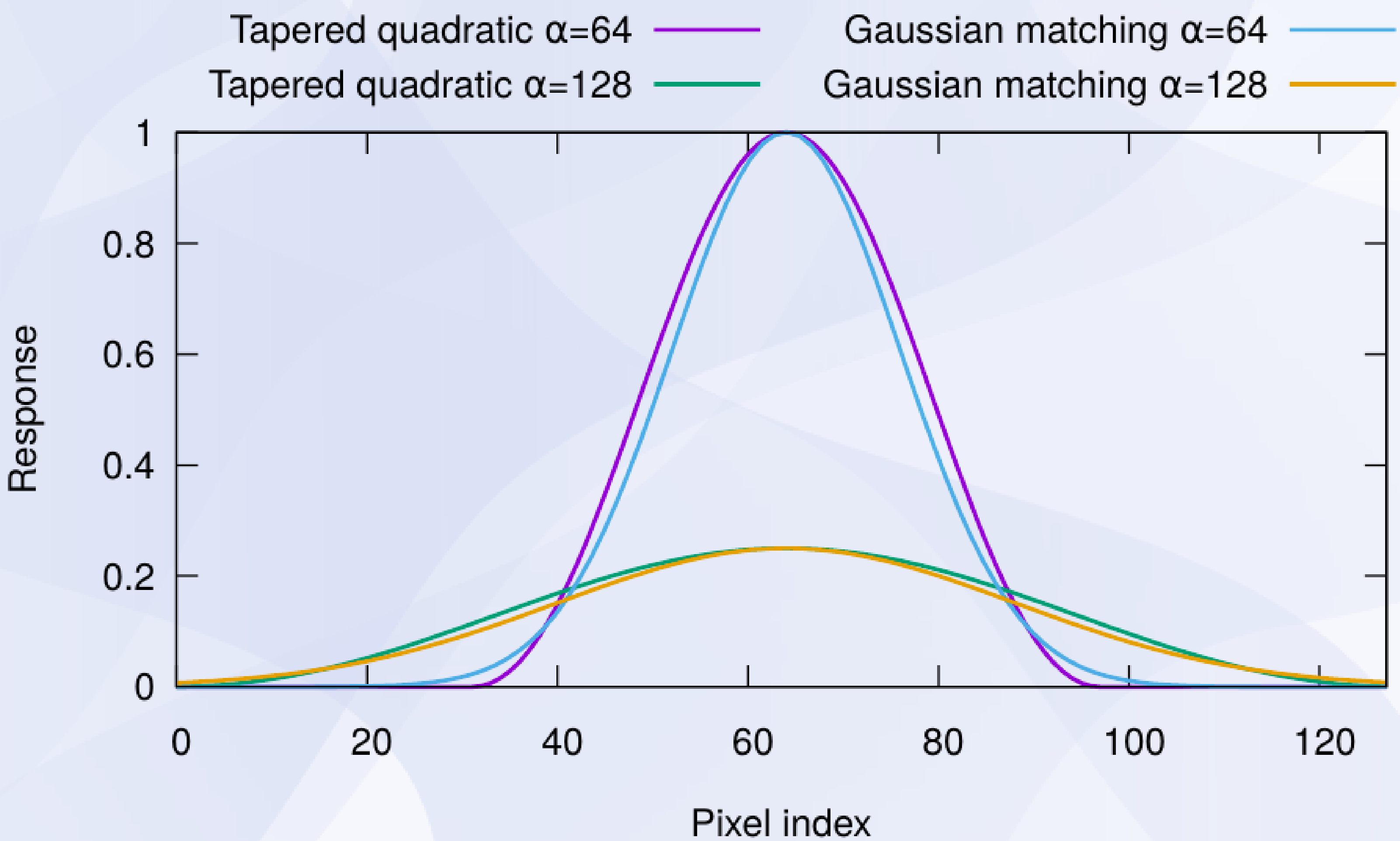
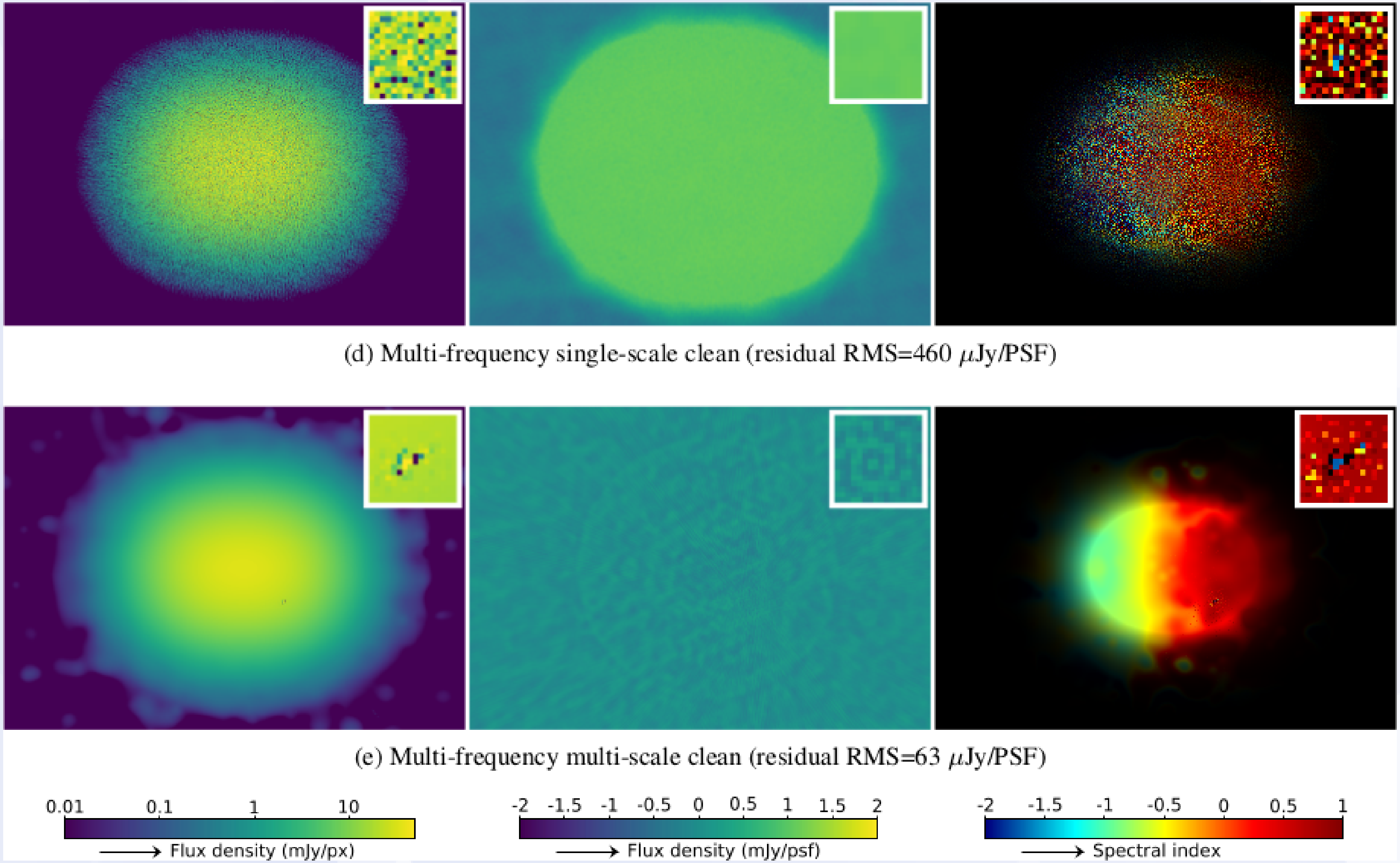


Figure 1. Shape functions for scales $\alpha = 64$ pixels and $\alpha = 128$ pixels.

Fast multi-scale deconvolution

- In Cornwell’s (2008) multi-scale method, the appropriate scale is determined every minor iteration
- Cornwell’s algorithm can be sped up by keeping the scale fixed “for a while”
- This is the algorithm implemented in WSClean



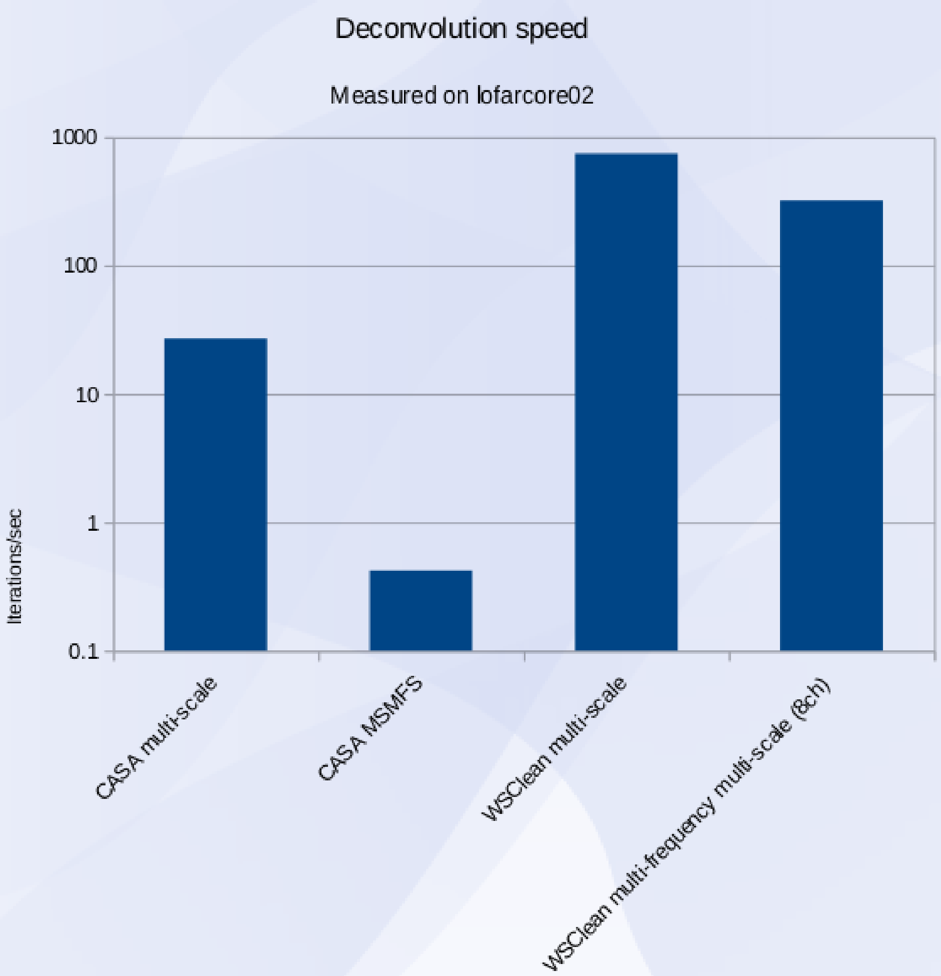
(d) Multi-frequency single-scale clean (residual RMS=460 μJy/PSF)

(e) Multi-frequency multi-scale clean (residual RMS=63 μJy/PSF)

- Comparison of WSClean MF single scale and multi-scale cleaning
- Simulated bandwidth of 30 MHz at 150 MHz.
- MWA layout, 2 min snapshot

Offringa and Smirnov (2017)

Deconvolution performance



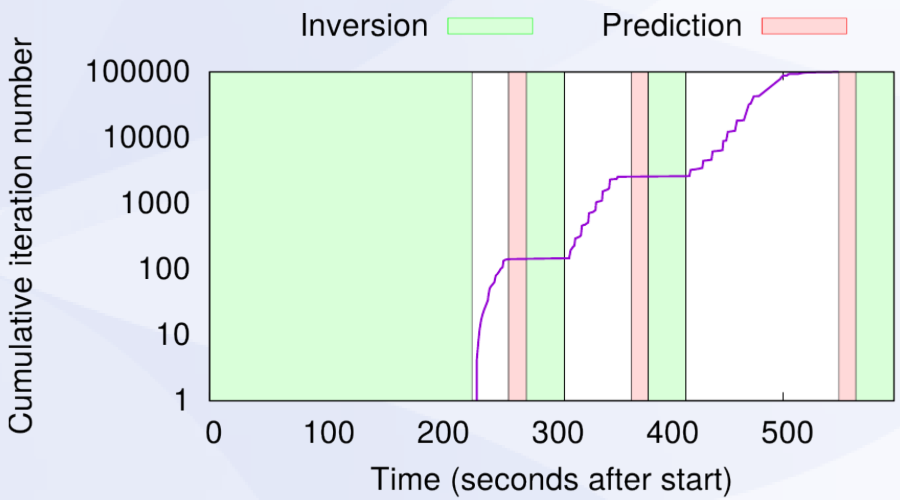
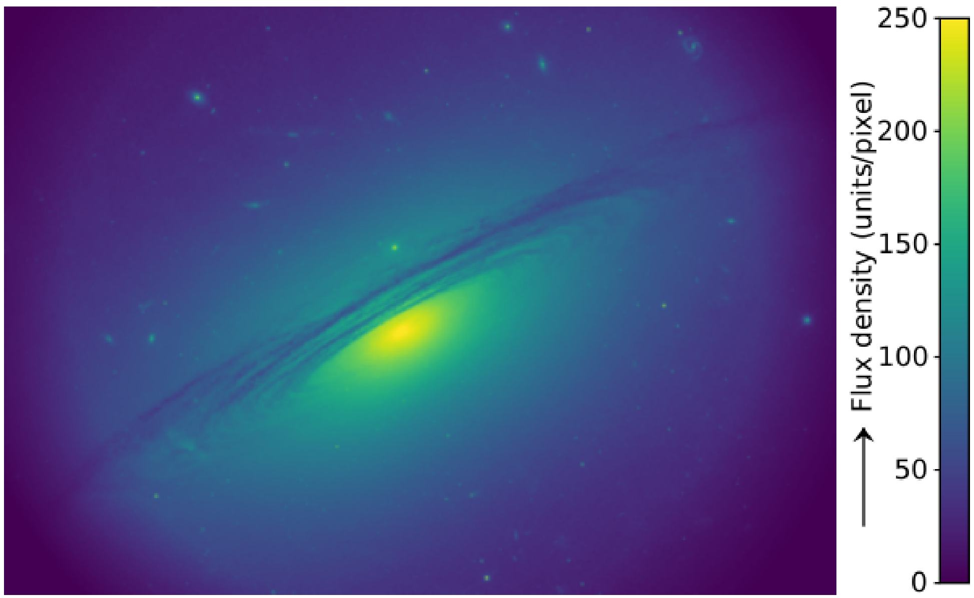
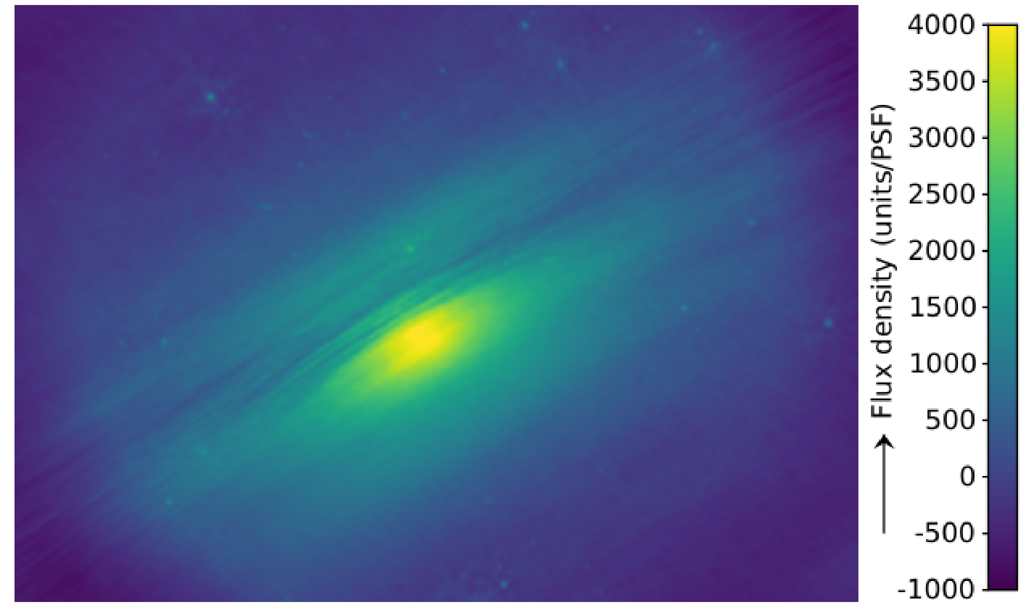


Figure 12. Example of the progression over time when using the new multi-scale clean algorithm on a 2048×2048 image.

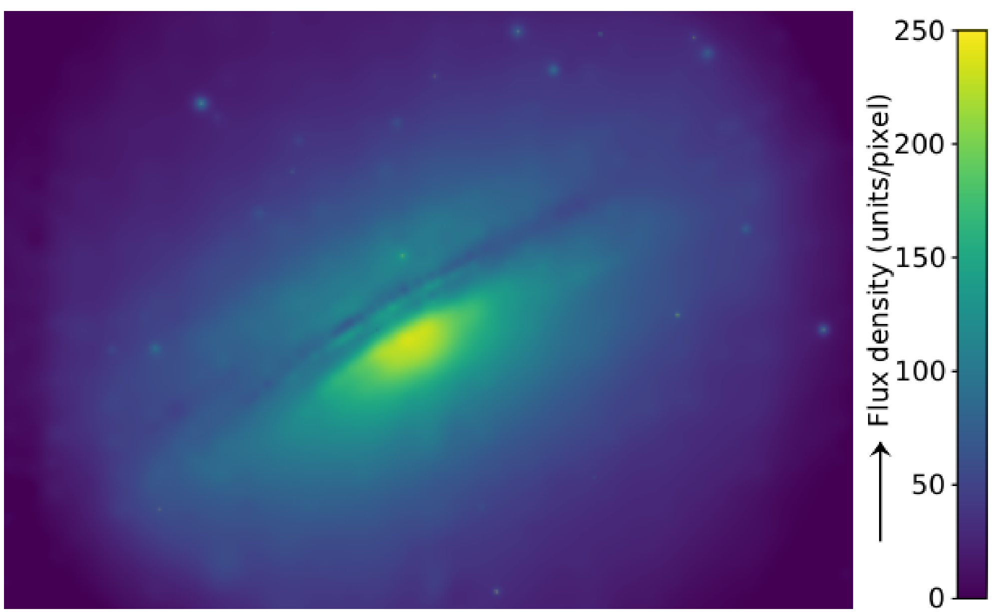
Offringa and Smirnov (2017)



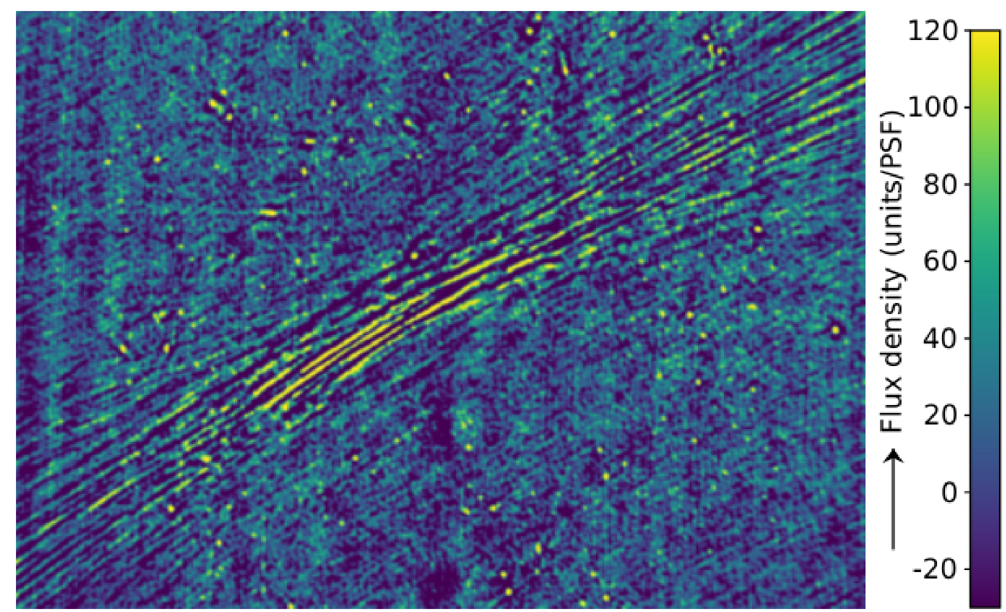
(a) Original



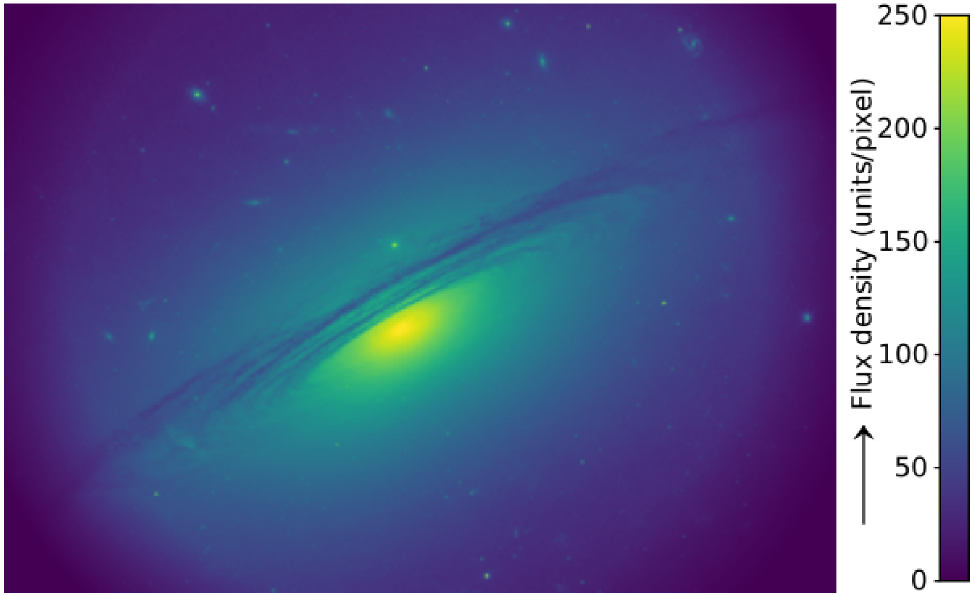
(b) Convolved image (σ=640,000 units/PSF)



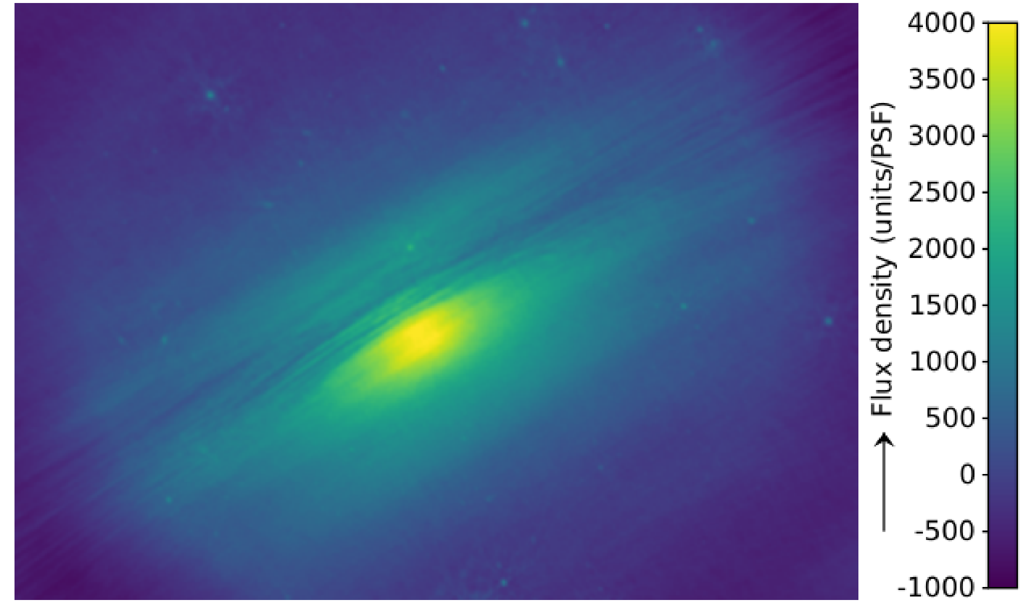
(c) CASA model



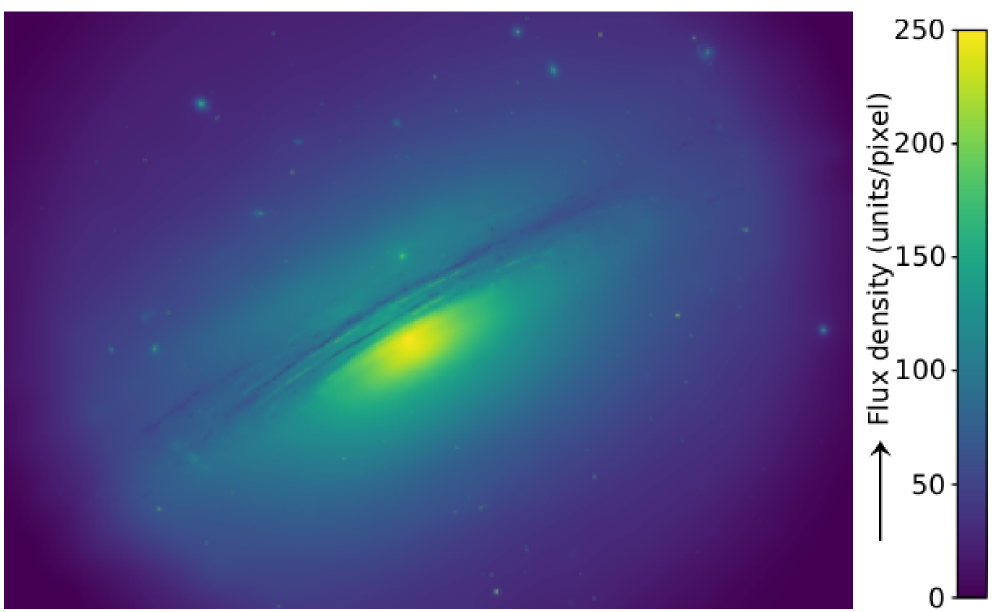
(d) CASA residual (σ=37 units/PSF)



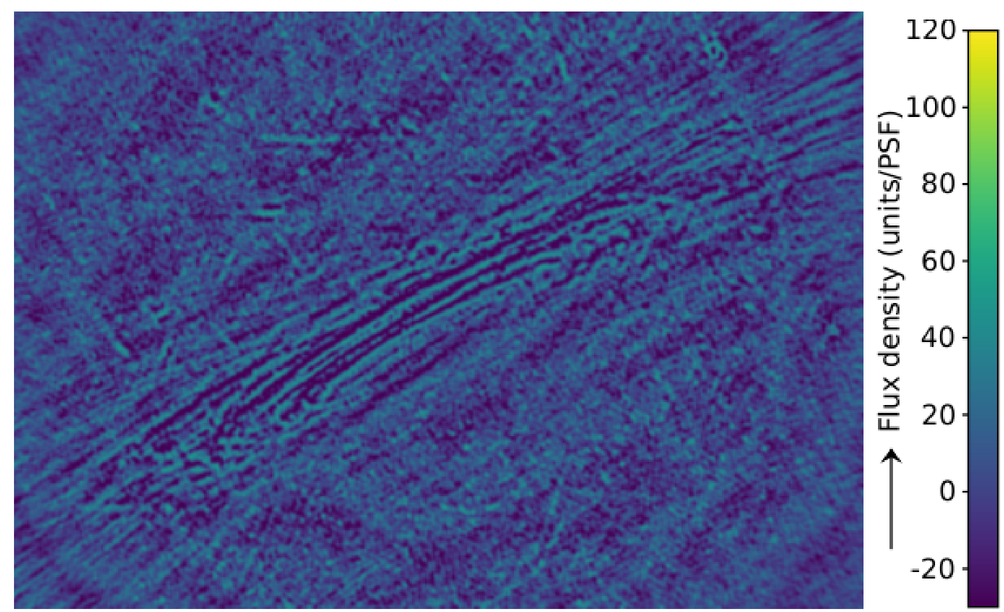
(a) Original



(b) Convolved image (σ=640,000 units/PSF)

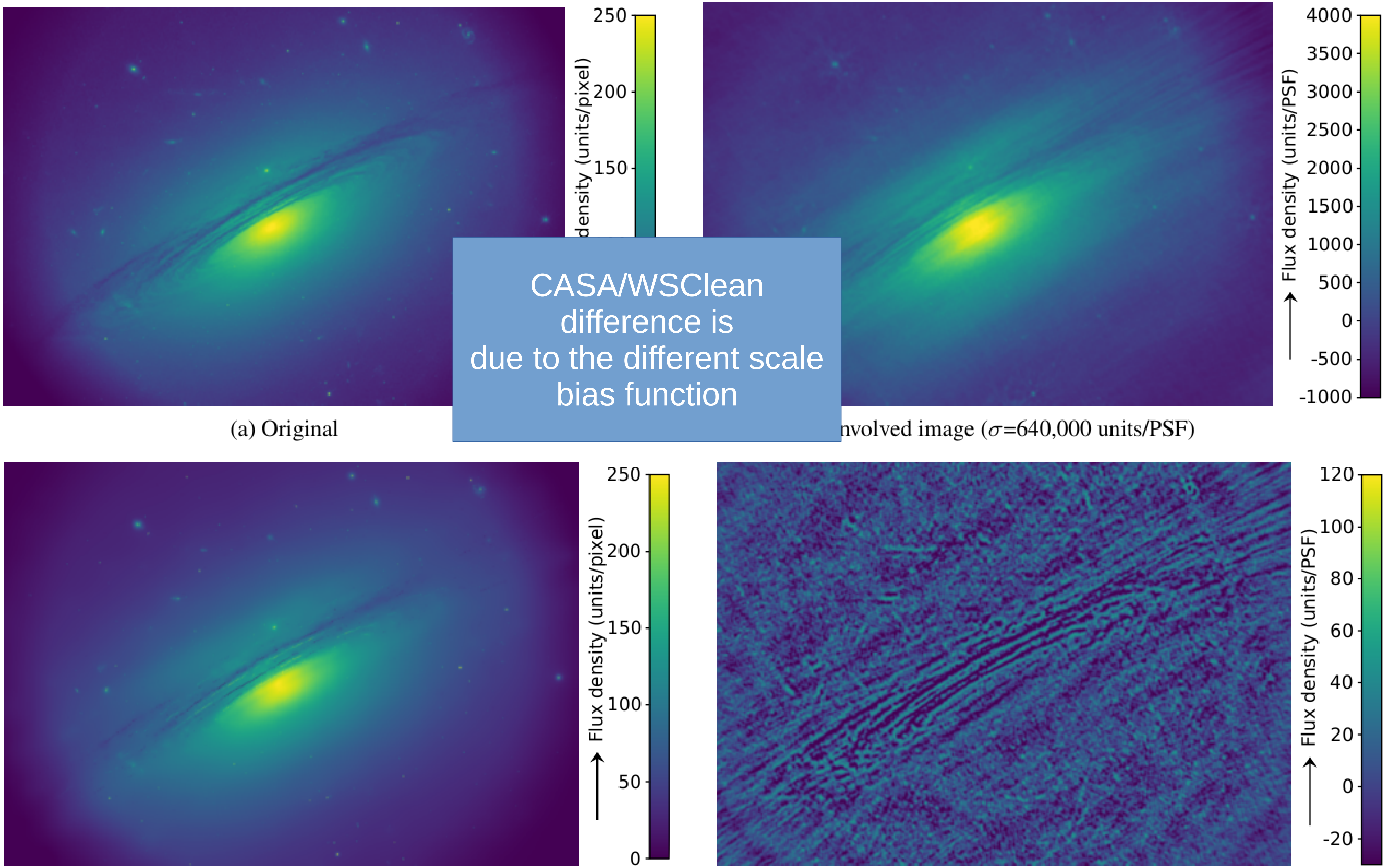


(e) WSCLEAN model



(f) WSCLEAN residual (σ=15 units/PSF)

CASA/WSClean difference is
due to the different scale bias function



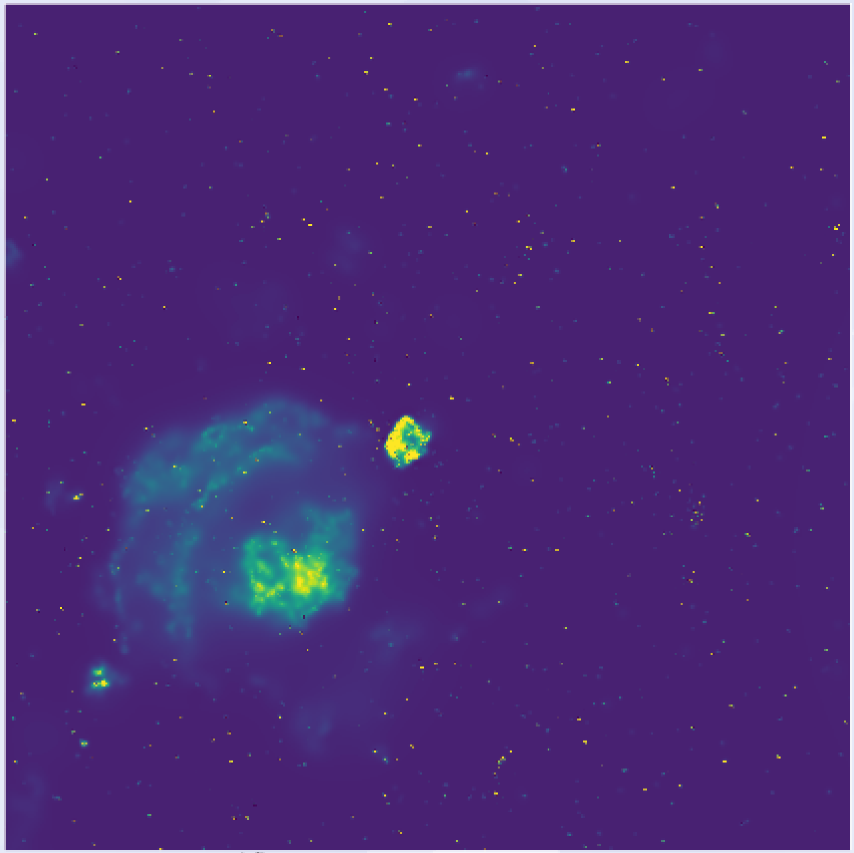
(a) Original

...nvolved image (σ=640,000 units/PSF)

(e) WSCLEAN model

(f) WSCLEAN residual (σ=15 units/PSF)

Compressed sensing results



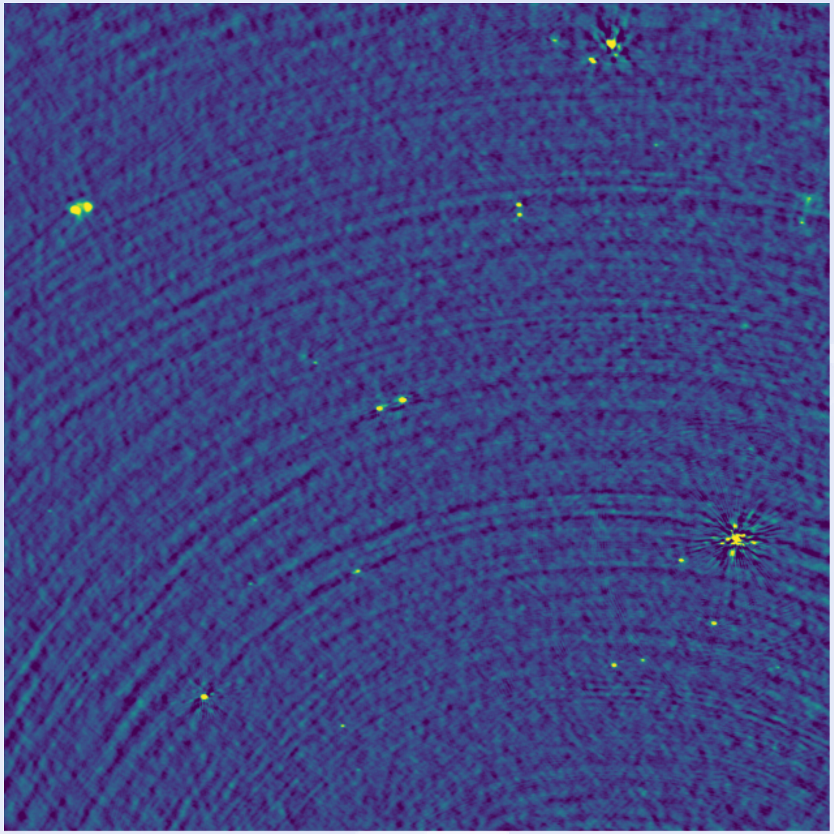
(d) WSCLEAN + MORESANE

- "Moresane" compressed sensing deconvolution (A. Dabbech et al. 2014)
- Multi-frequency implementation in WSClean
- Produces **sometimes** very good-looking models

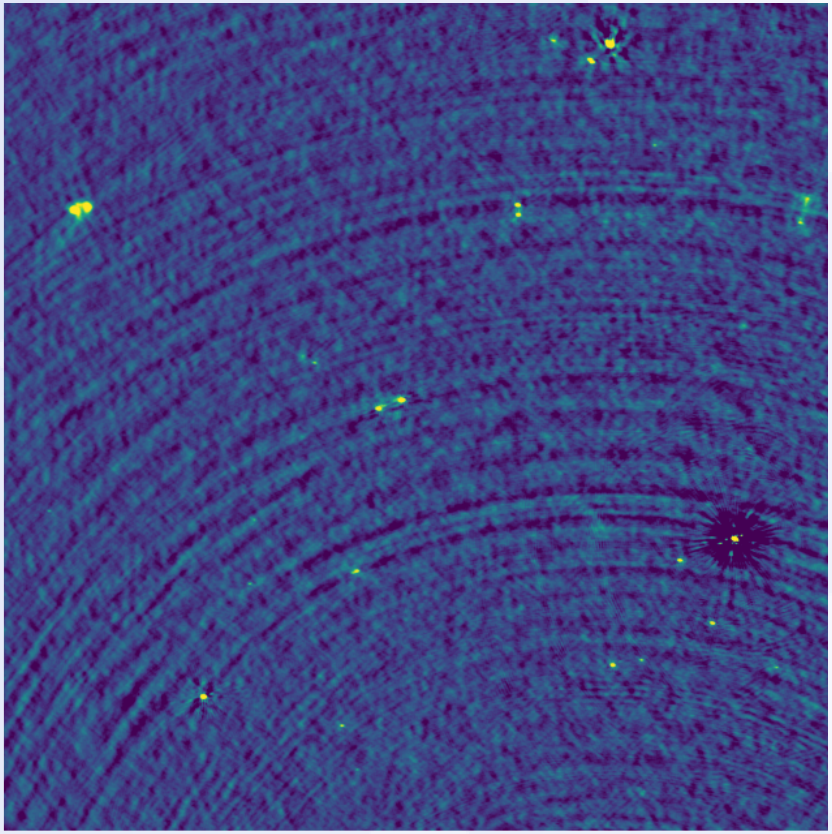
Model(!) image made with WSClean + Moresane

Offringa and Smirnov (2017)

An issue with IUWT / Moresane...



(a) WSCLEAN multi-frequency, multi-scale with β=0.6 (rms=1.4 mJy)



(b) WSCLEAN multi-frequency, iuwt (rms=2,7 mJy)

Offringa and Smirnov (2017)

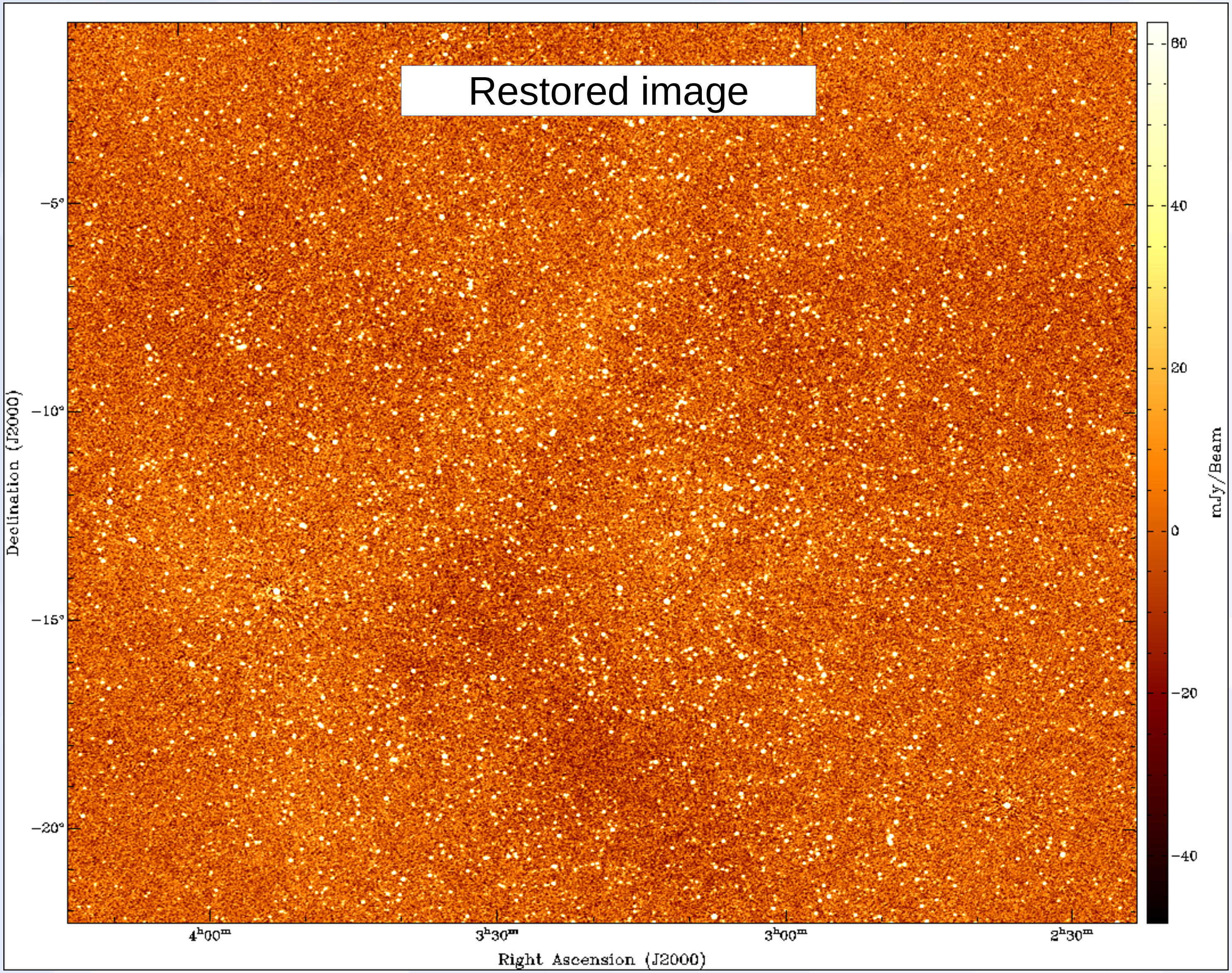
Automatic scale-dependent masking

- Normal cleaning requires manual threshold tweaking, manual masking, etc…
- Masking is hard when structures are diffuse
- Move towards non-interactive, fully automatic cleaning
- “Automatic scale-dependent masking” :
  - For each scale, a mask is accumulated
  - Clean normal to 3-5σ, continue to 0.5σ with a scale-dependent mask. In one run.

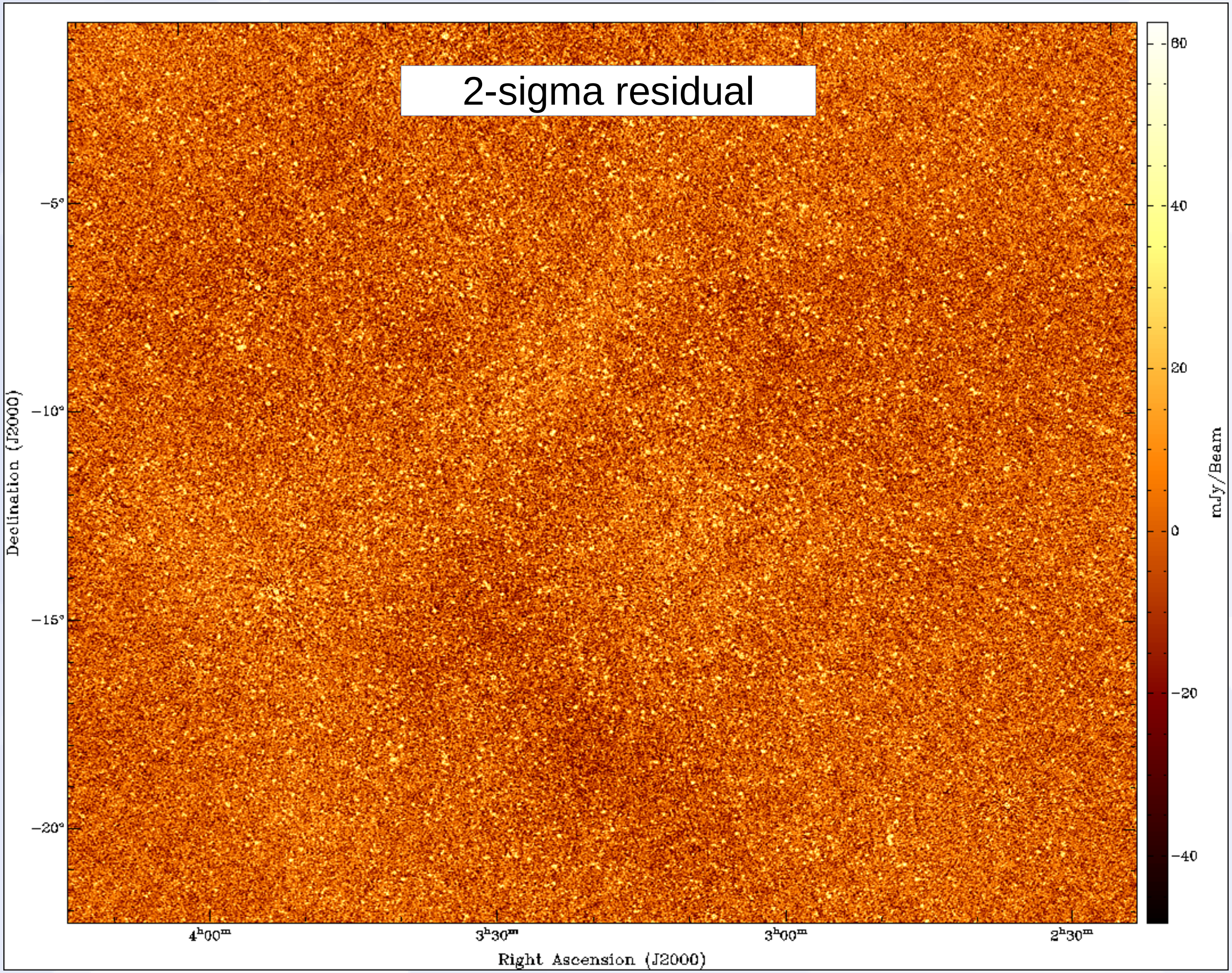
Automatic masking

- Threshold is relative to RMS estimate
- RMS estimate can be “local” when RMS is expected to change over the image
  (avoids picking up calibration errors)
- Avoids interaction & somewhat-arbitrary selection of features, etc.
- Allows deeper & more stable cleaning of complex structures. Limits clean bias.
- Can be done in multi-frequency mode

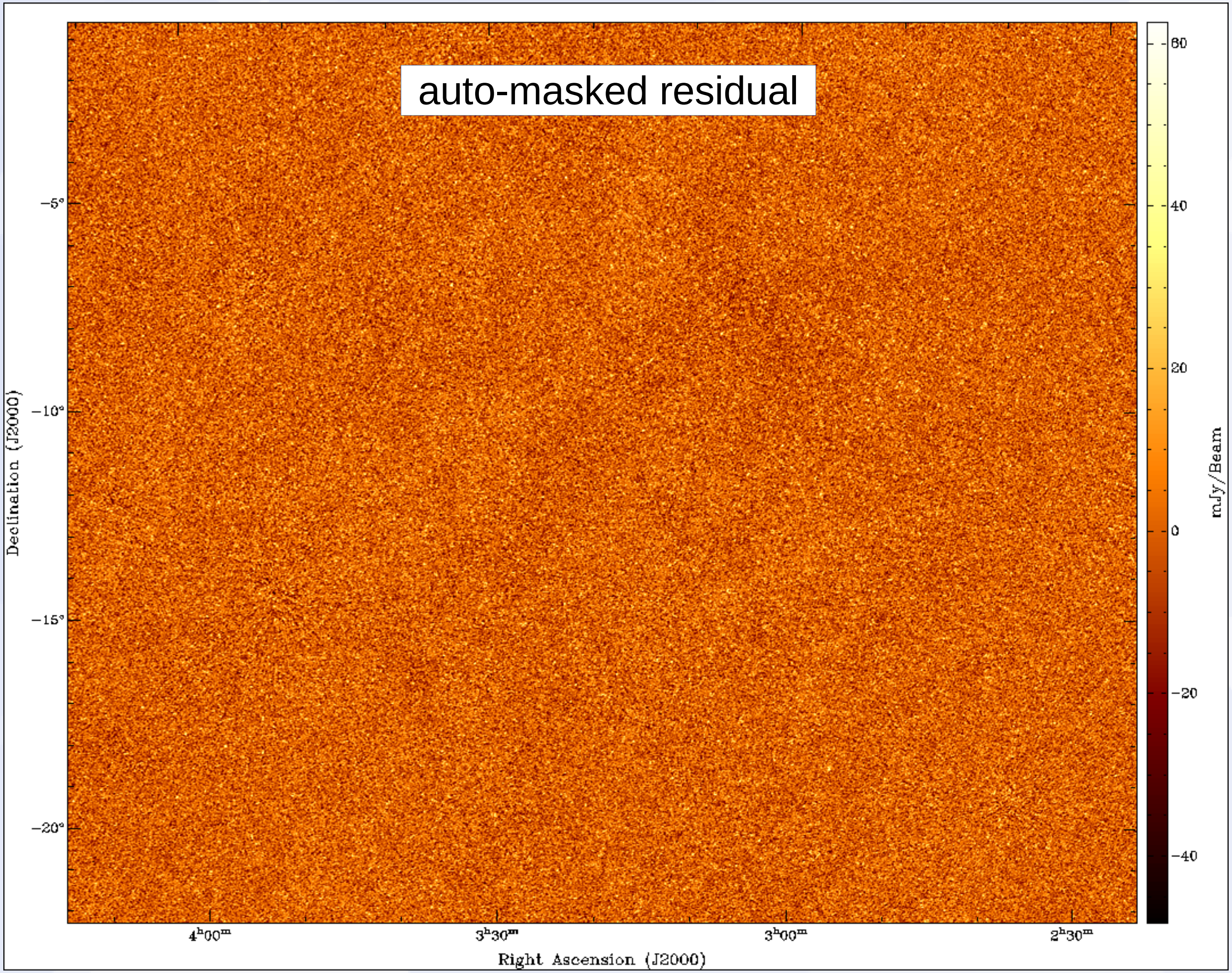
Auto-masking on point sources



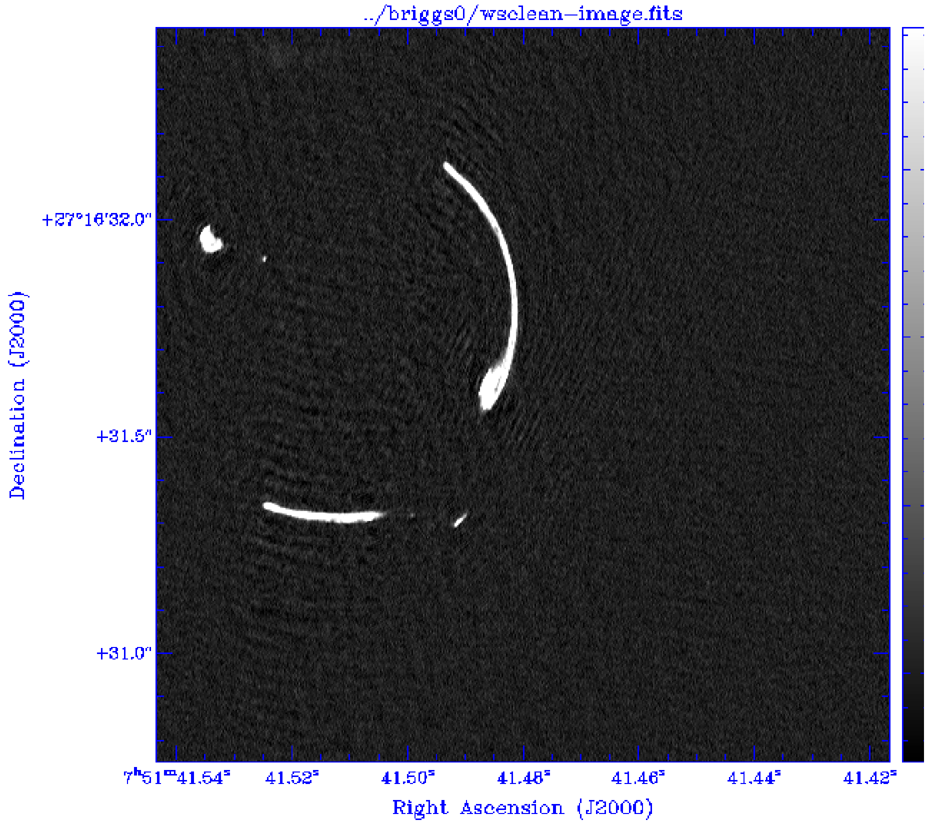
Auto-masking on point sources



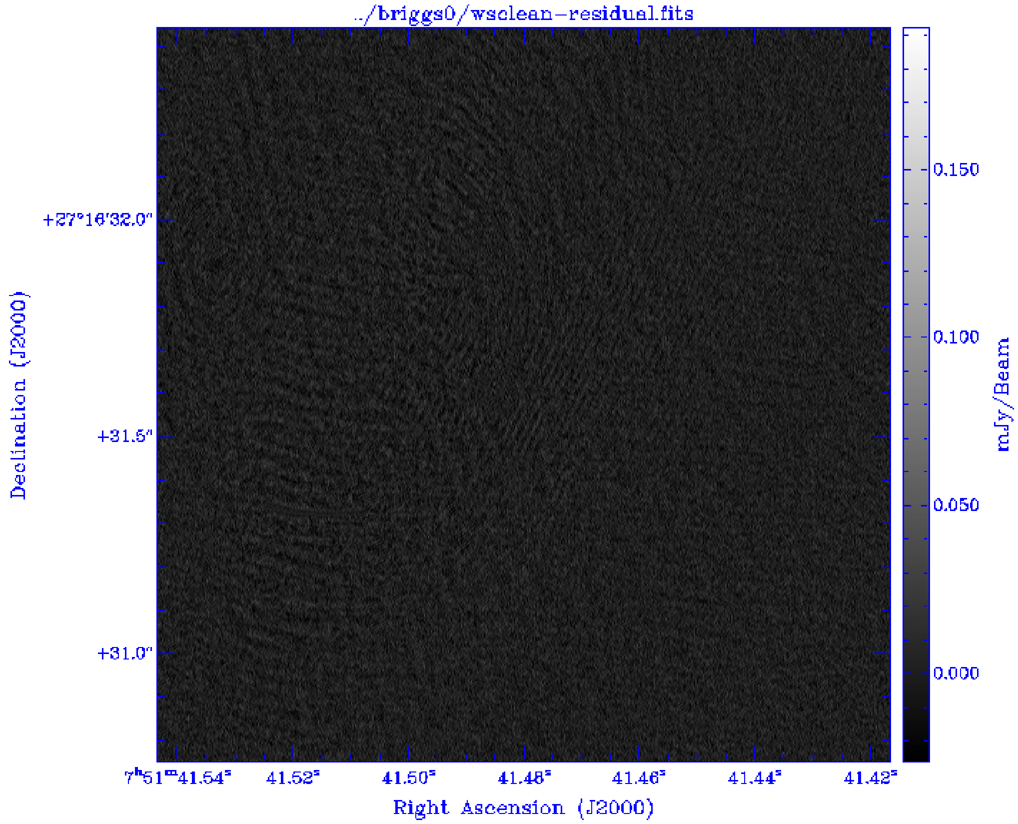
Auto-masking on point sources



Automasking VLBI example

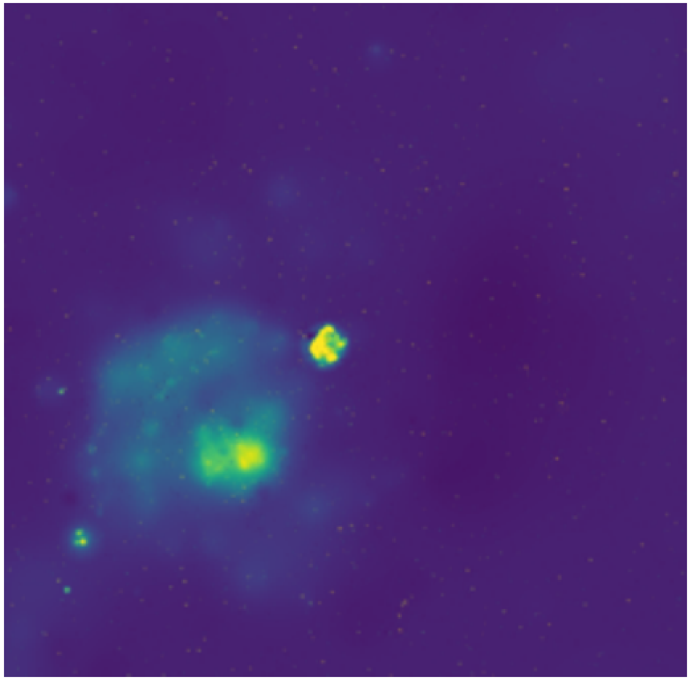


Restored

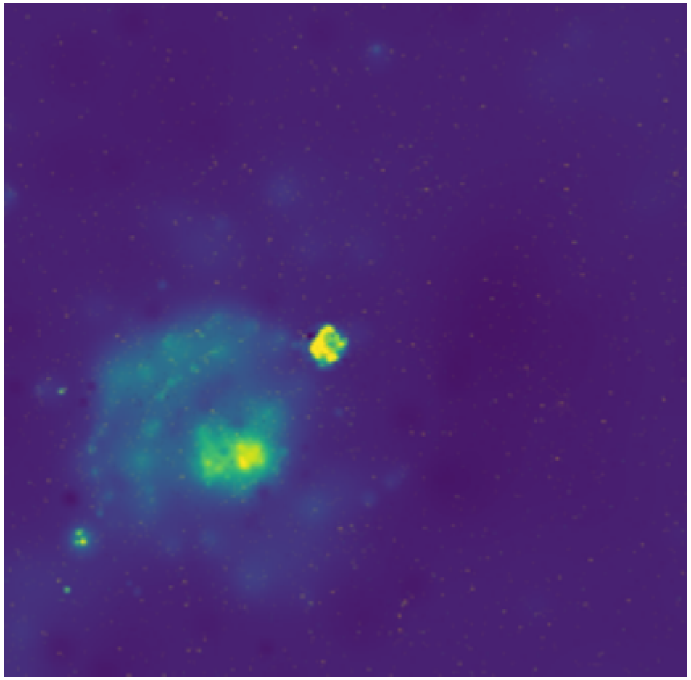


Residual

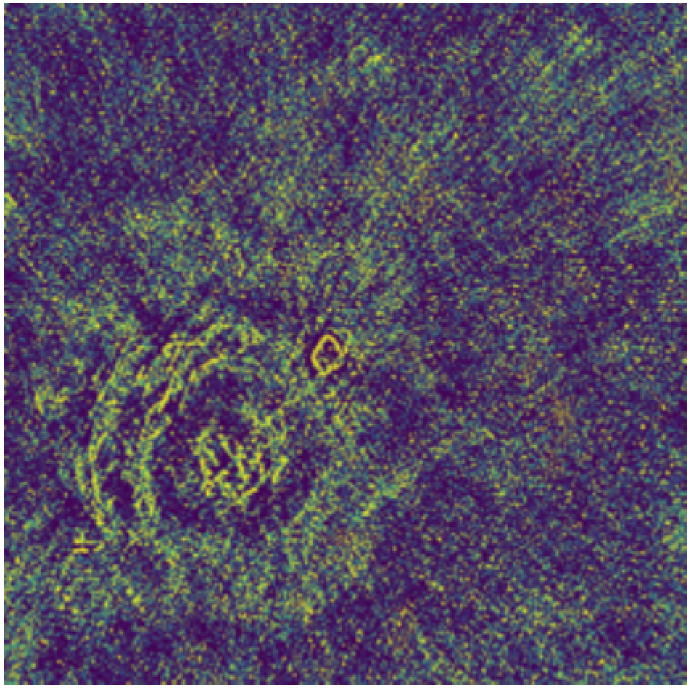
Data by J. P. McKean
and C. Spingola



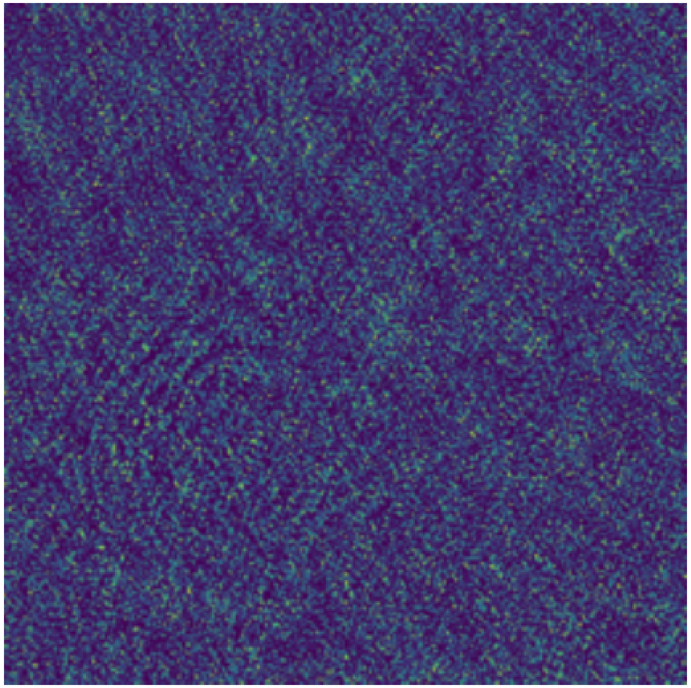
(a) Multi-scale model image without masking



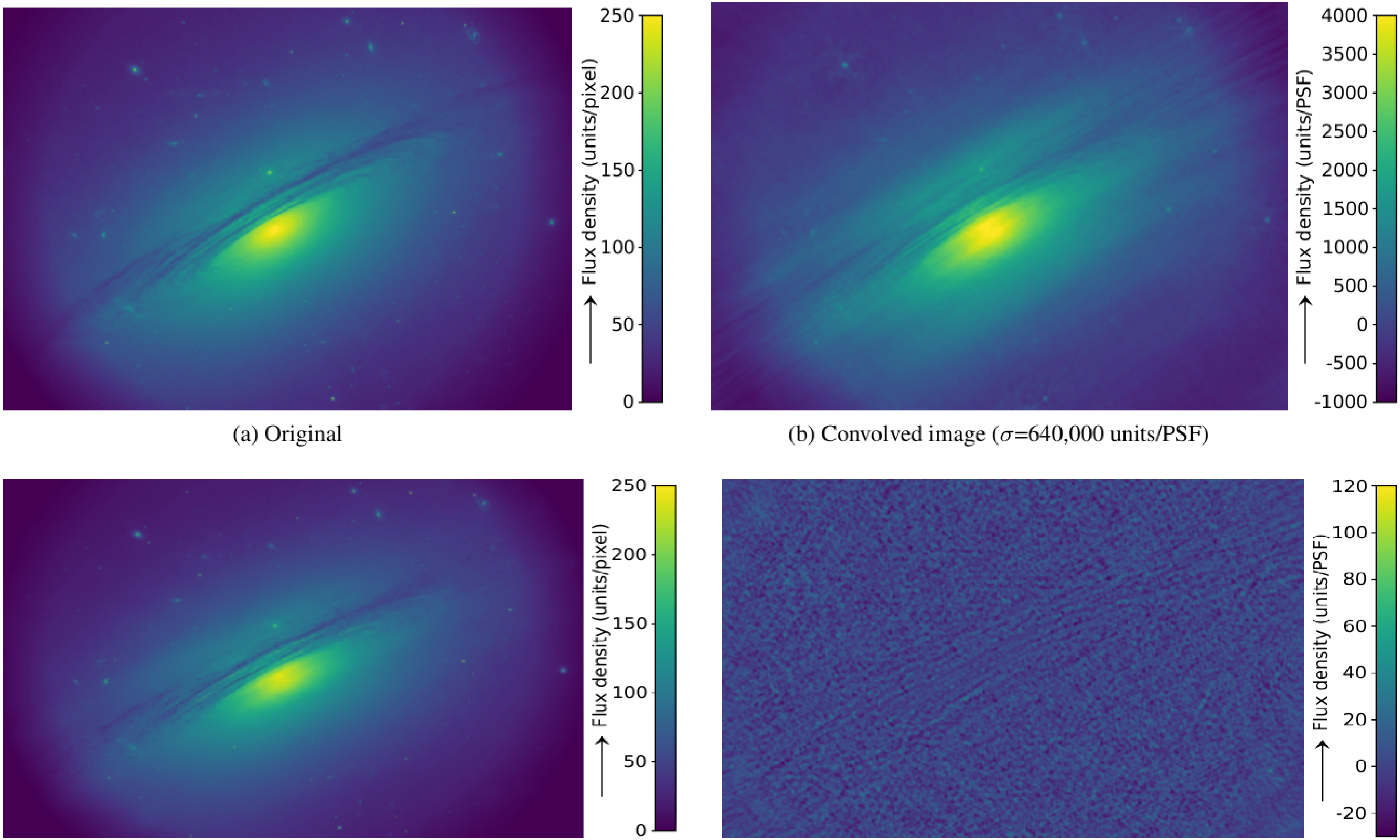
(b) Multi-scale model image with automatic masking



(c) Multi-scale residual without masking (rms=50 mJy/B)



(d) Multi-scale residual with automatic masking (rms=38 mJy/B)



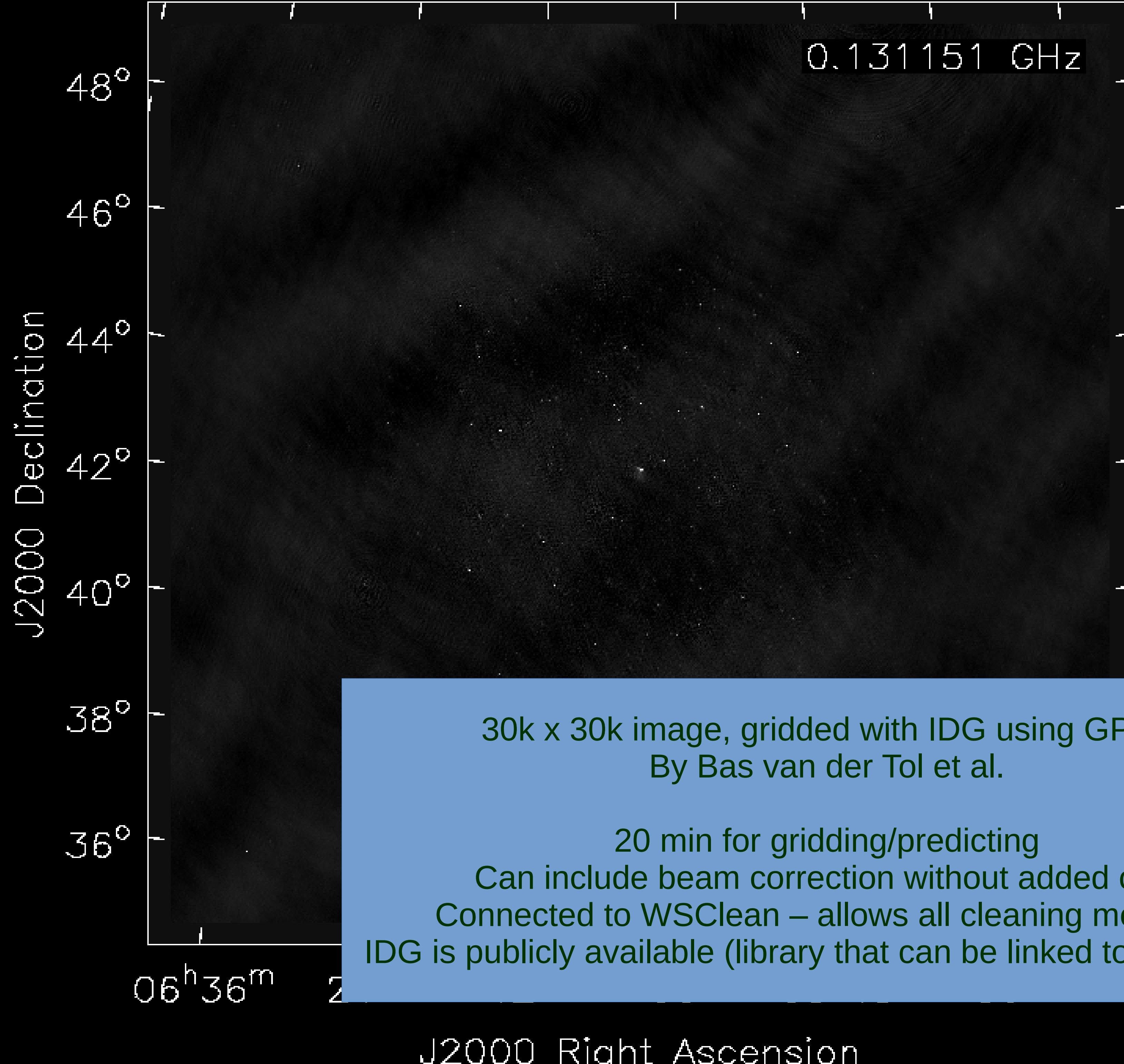
(a) Original

(b) Convolved image (σ=640,000 units/PSF)

(a) Reconstructed model image

(b) Residual image (σ=8.6 units/PSF)

Figure 9. Automatic scale-dependent masking applied on the UGC12591 test-set.



30k x 30k image, gridded with IDG using GPUs
By Bas van der Tol et al.

20 min for gridding/predicting
Can include beam correction without added cost
Connected to WSClean – allows all cleaning methods
IDG is publicly available (library that can be linked to WSClean)

Reasons for adding more constraints in DD calibration

- LBA calibration
  - See talk by Francesco later today
  - No current pipeline can produce (good) DD solutions
- HBA diffuse imaging
  - Current pipelines calibrate diffuse structures out
- EoR imaging
  - Constraints important to avoid reducing EoR signals
- “Normal” deep HBA imaging
  - Interpolated TEC screens to get solutions with more accurate solutions

Solve directions simultaneously (like Sagecal)

ionospheric smoothness constraint (like Ionpeel /SPAM)

Temporal constraints

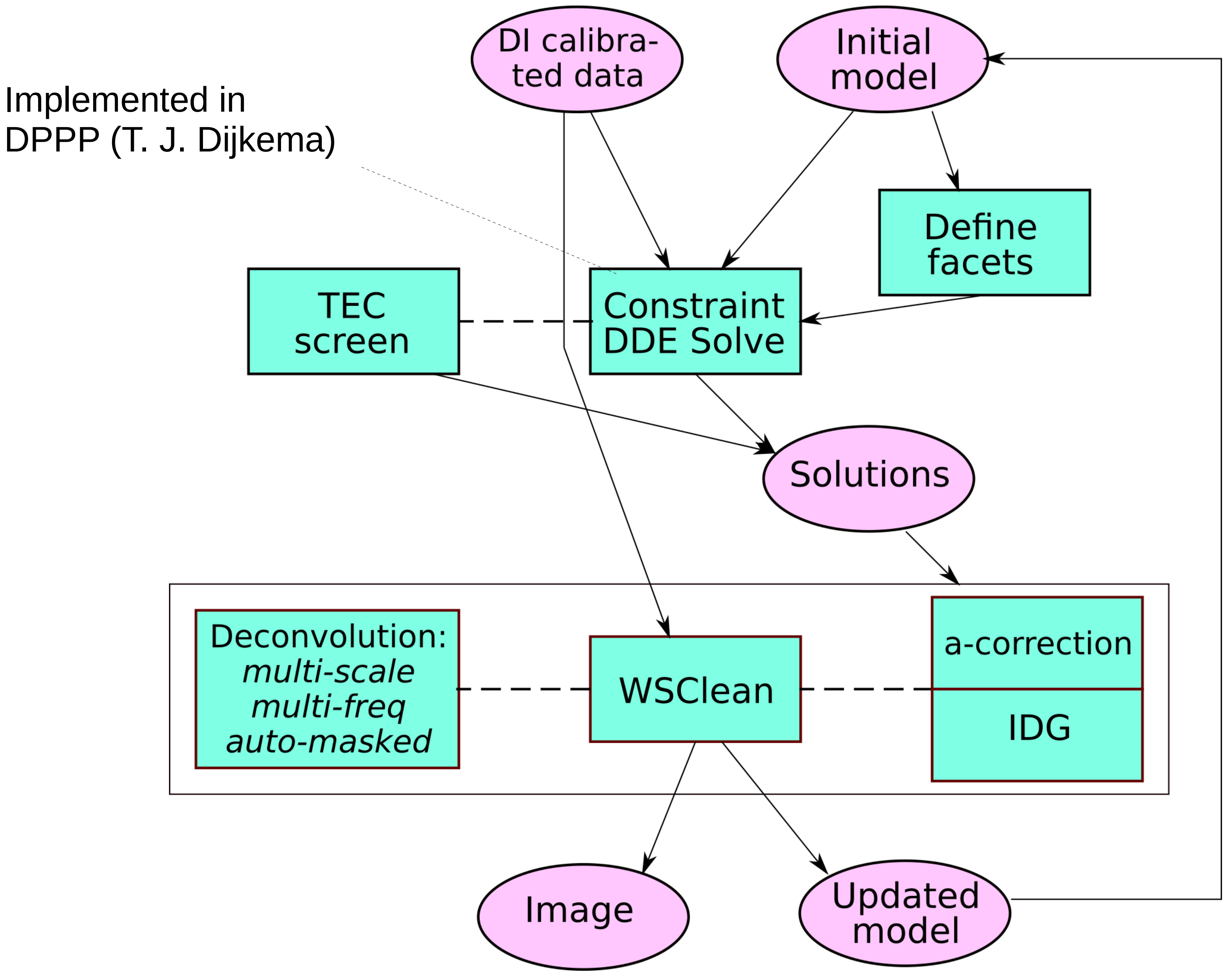
Fast (like Sagecal)

λ^2 constraint (like Factor)

Self-calibration loop (like Factor)

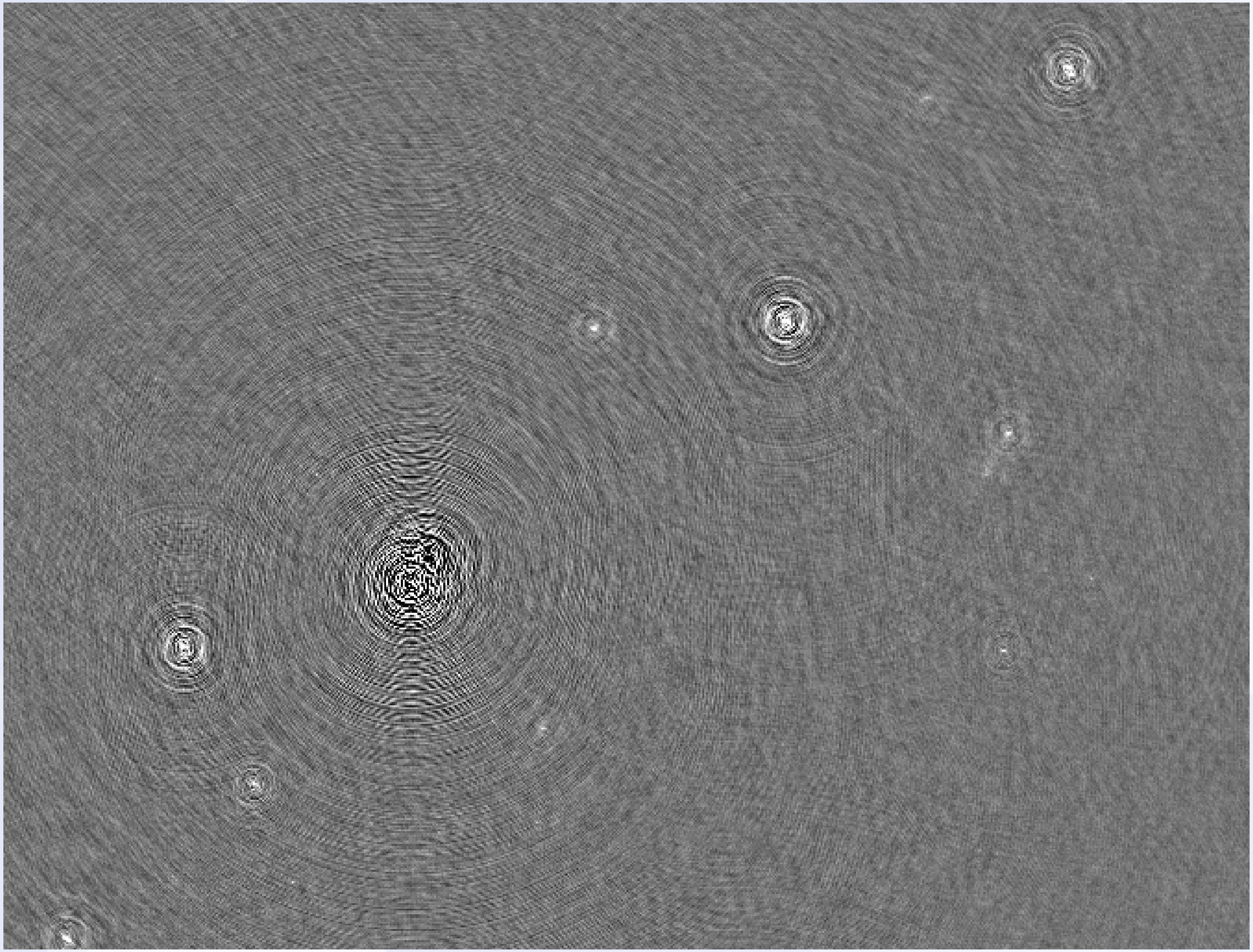
Other constraints? (e.g. redundancy, spectral smoothness)

Constraint DD solver pipeline
Implemented in DPPP (T. J. Dijkema)
See poster

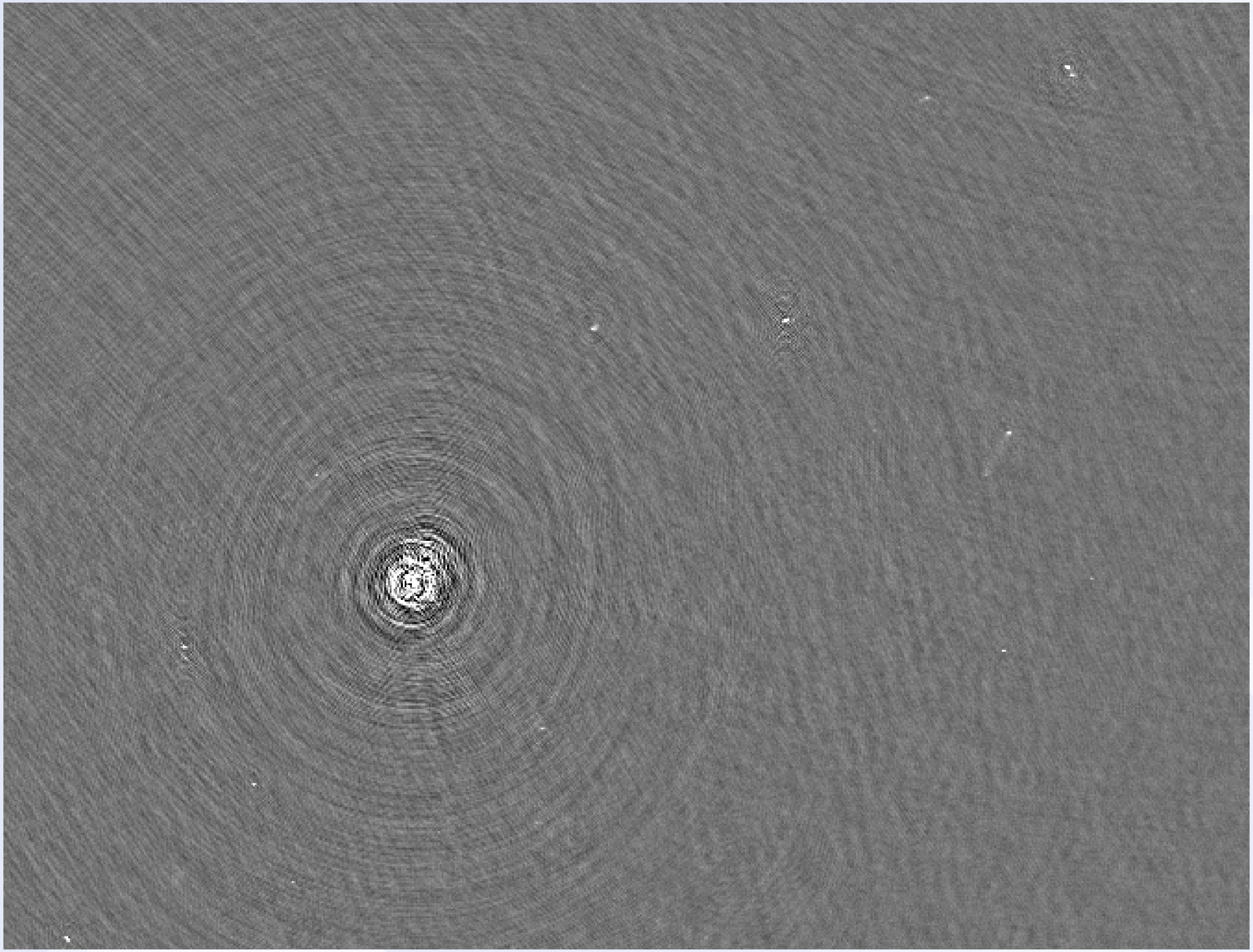


Collaboration with Dijkema, Offringa, Gasperin, Mevius, van Weeren, et al.

Local RMS cleaning



Local RMS cleaning



Modeling with WSClean

- WSClean (since 2.4) can directly output a beam corrected calibration model
- Consists of point sources, Gaussians and spectral information
- Directly readable by DPPP (T.J. Dijkema)
  - Allows DD calibration with WSClean + DPPP
- Local RMS method reduces false components

Summary

- WSClean provides fast gridding & deconvolution
  - WSClean multi-scale with joined channels
    >2 order of magnitude faster than CASA MSMFS mode.
- Fully automated cleaning
  - Thresholds given in sigma’s, not in Jy.
- Auto-masking improves accuracy / clean bias
- Can directly output point-source & Gaussian model including frequency information
- Next upgrade: WSClean + IDG + A-term correction

Download WSClean incl. manual from: http://wsclean.sourceforge.net/