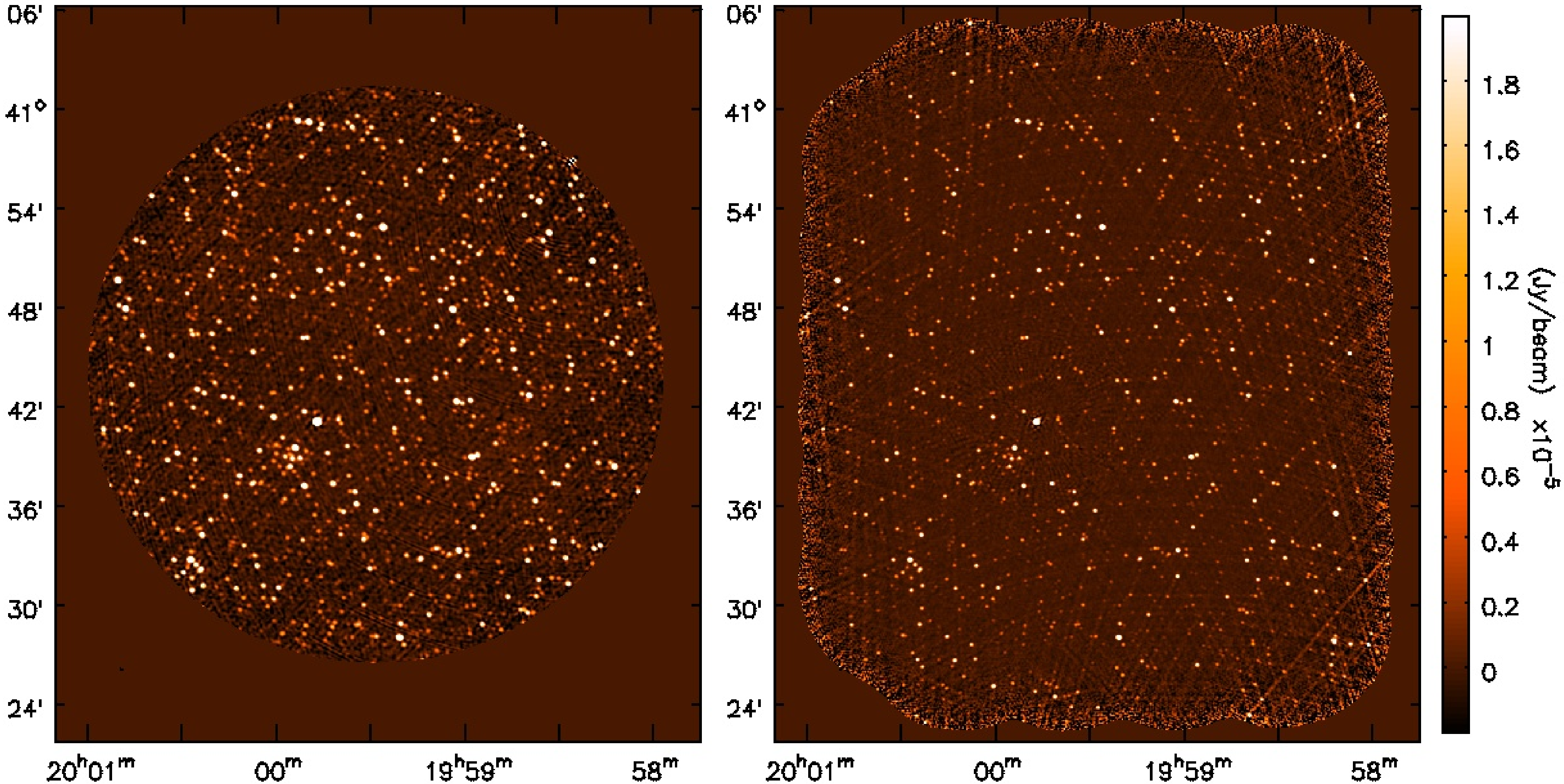
How accurately do our imaging algorithms reconstruct intensities and spectral indices of weak sources ?

Urvashi Rau, Sanjay Bhatnagar, Frazer Owen (NRAO, USA)

23 August 2016, NRAO Charlottesville, USA.



VLA Wide-band wide-field simulations : (LEFT) L-Band, C-config, 1-pointing , (RIGHT) C-band, D-config, 46 pointings

Simulation Parameters : One Pointing, L-Band (1-2 GHz), C-config

Sky : ~8000 point sources within one deg^2 (SCube)

Sources at pixel centers (+ compared with not)

Intensity : between 1 micro Jy and 7 mJy.

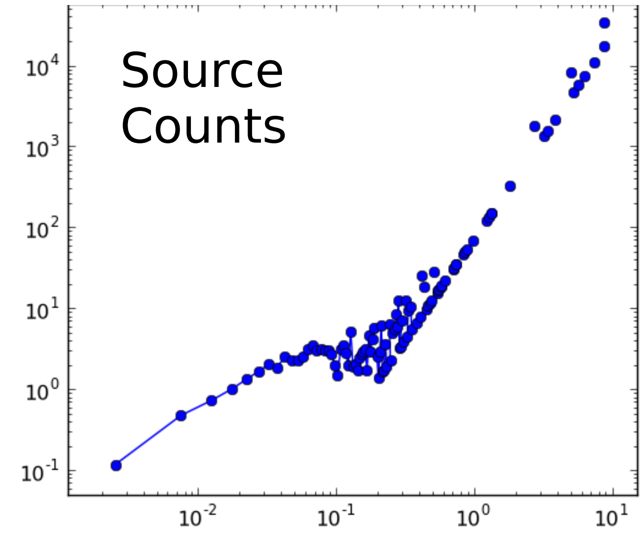
(+ one 100 mJy source for HDR test)

Spectral indices : between 0.0 and -0.8.

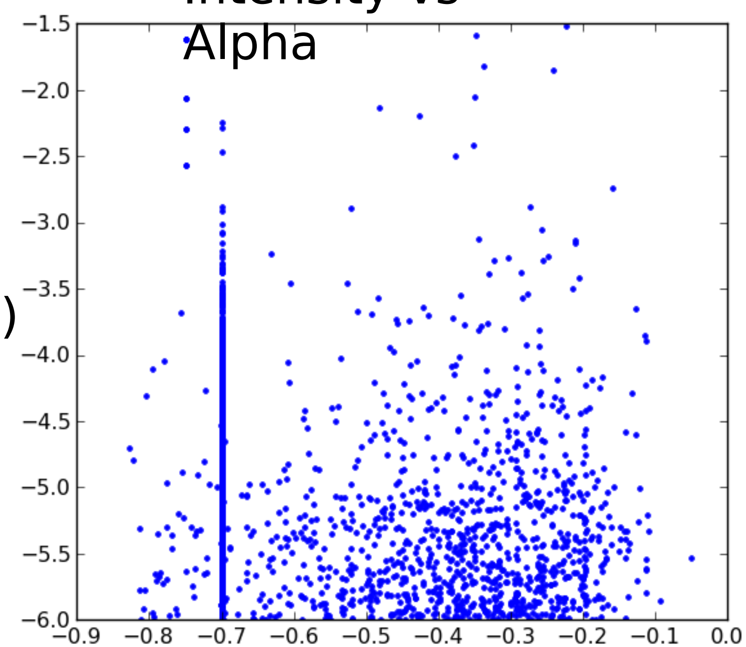
Observation : 16 channels/spws across 1-2 GHz

One snapshot every 20 minutes, for 4 hrs

(compare with one snapshot every 2 minutes, for 4 hrs)



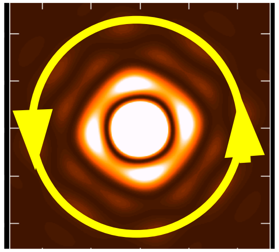
Intensity vs Alpha



log(I)

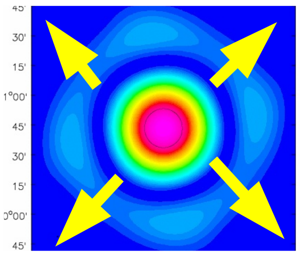
Alpha

Data Prediction : Visibilities were calculated using the Wideband A-Projection de-gridder. No noise.



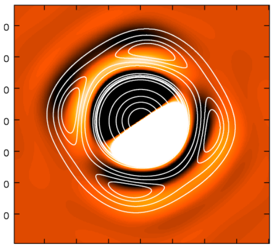
PB (time)

+



PB (freq)

+



PB (pol)

Imaging Options : Wideband MFS [yes/no], A-Projection [yes/no]

MT-MFS (nterms>1)

Multi-term MFS (wideband) Imaging
+
Absorb PB spectrum into sky model
+
Post-deconvolution Wideband PBcor
for intensity and alpha

Rau & Cornwell, 2011, Sault &Wieringa 1994

MT-MFS + WB-A-Projection

Multi-term MFS with wideband A-Projection
to remove PB spectrum during gridding
+
Minor cycle sees only sky spectrum
+
Post-deconvolution PBcor of intensity only.

Bhatnagar, Rau, Golap, 2013

Cube

Per channel Hogbom/Clark/CS Clean
+
Per channel post-deconvolution Pbcor
+
Smooth to lowest resolution
+
Fit spectrum per pixel, Collapse channels

Hogbom 1974, Clark 1980, Schwab & Cotton 1983,
Schwarz, 1978

Cube + A-Projection

Same as Cube,
- with narrow-band A-Projection per channel

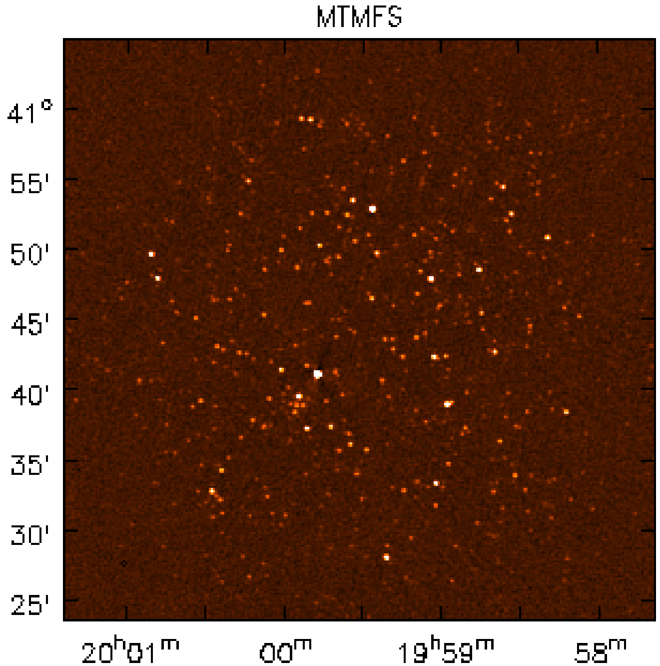
(A-Projection : Construct gridding convolution operators from antenna aperture illumination models. Removes beam squint and accounts for aperture rotation)

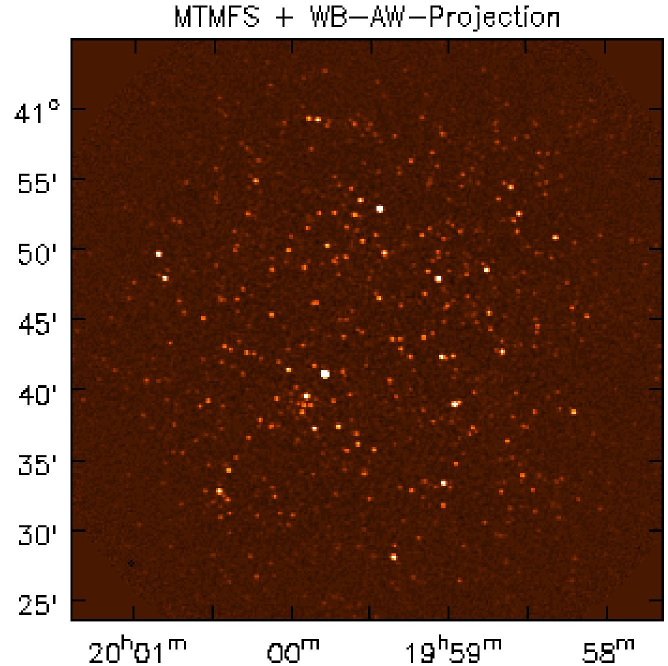
Bhatnagar, Cornwell, Golap, Uson, 2004

Low dynamic range test (< 10^4) – compare four methods

MT-MFS

2 uJy rms





MT-MFS
+
WB-AWP

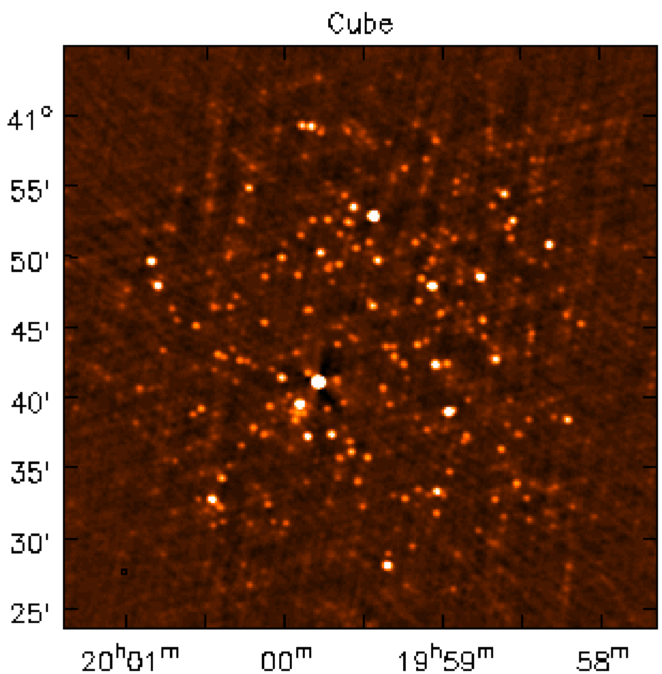
2 uJy rms

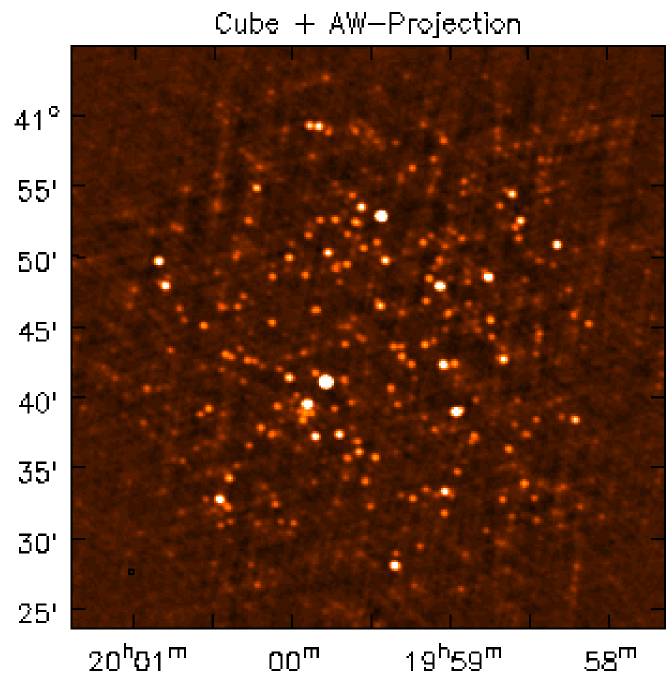
Brightest Source : 7 mJy

Cube

3 uJy rms

peak res : 9 uJy



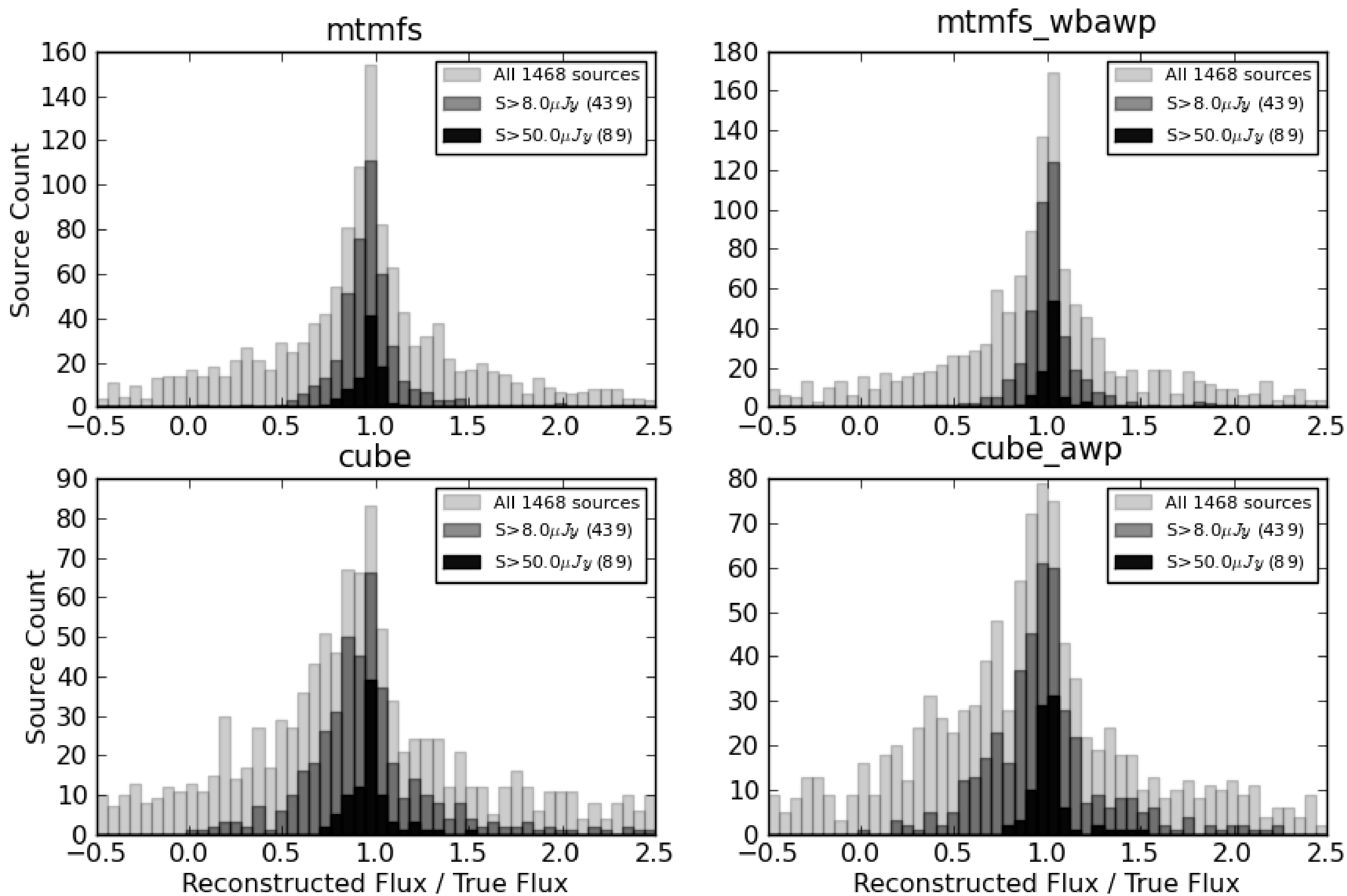


Cube
+
AWP

3 u Jy rms

(Reconstructed / True) Intensity for different intensity ranges

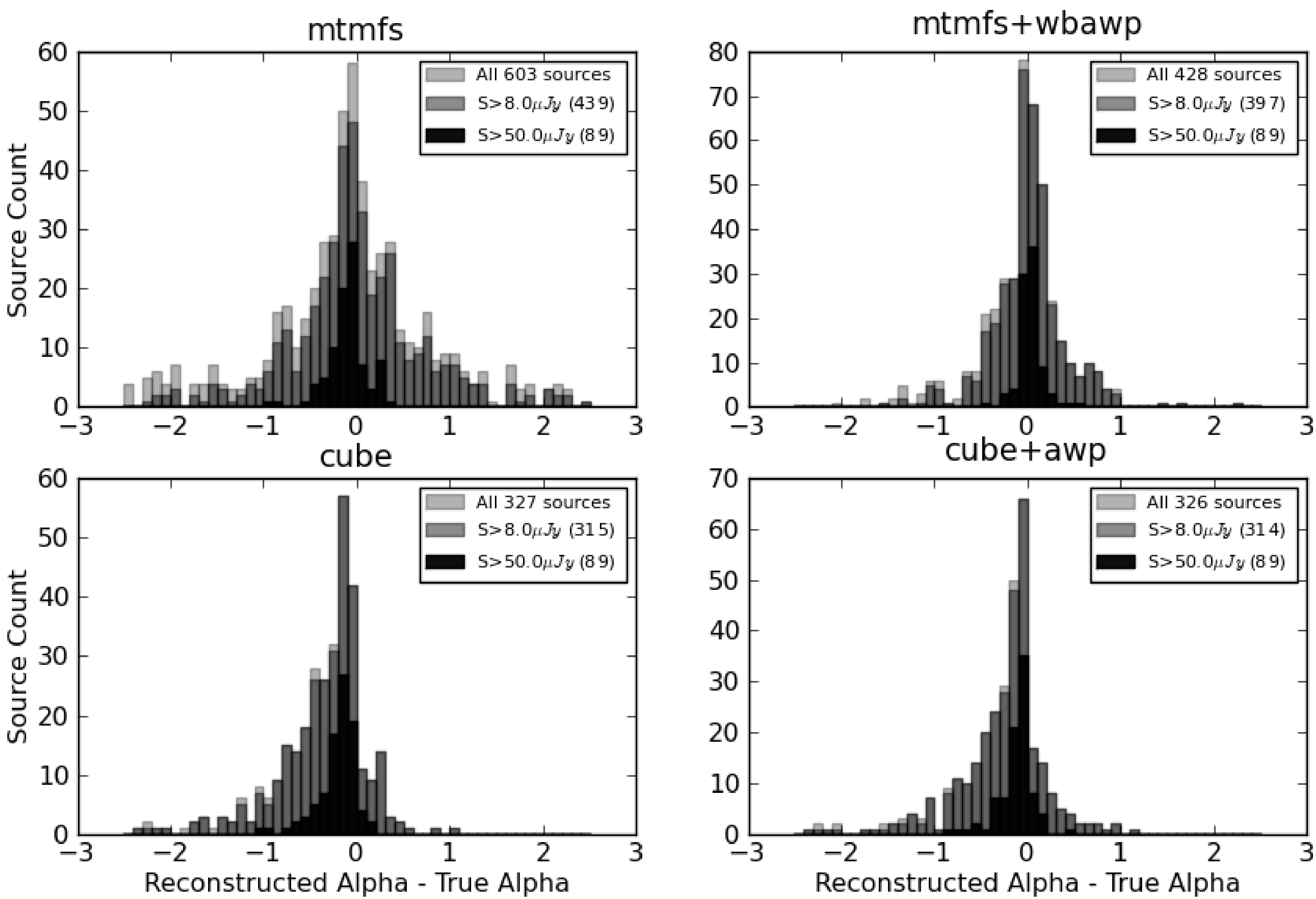
Locate sources in true image. Plot all sources >1 micro Jy. (Brighter sources are more accurate)
No source-finding uncertainty.



Single spw PSF sidelobe : 0.13 / Wide-band PSF sidelobe : 0.05

(Reconstructed – True) Alpha for different intensity ranges

Spectral index for brighter sources are more accurate. Degrades quickly with lower intensity.
(note different numbers of sources with alpha detections)



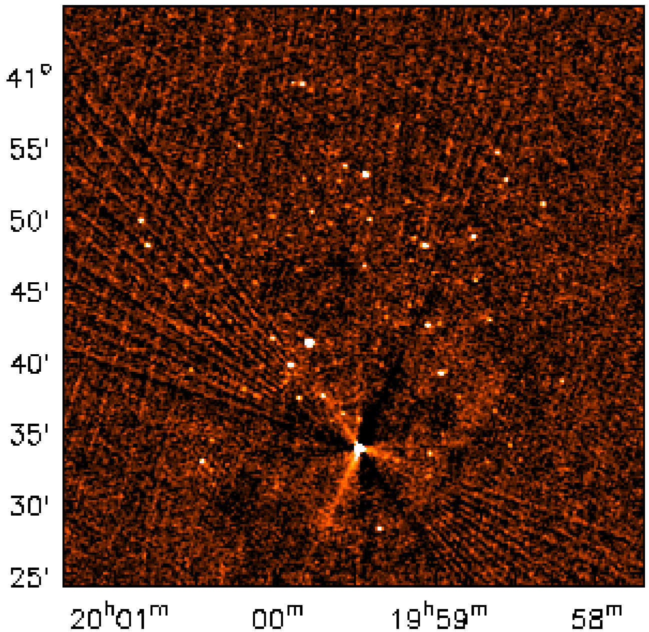
High dynamic range test (>10^4) - compare four methods

MT-MFS

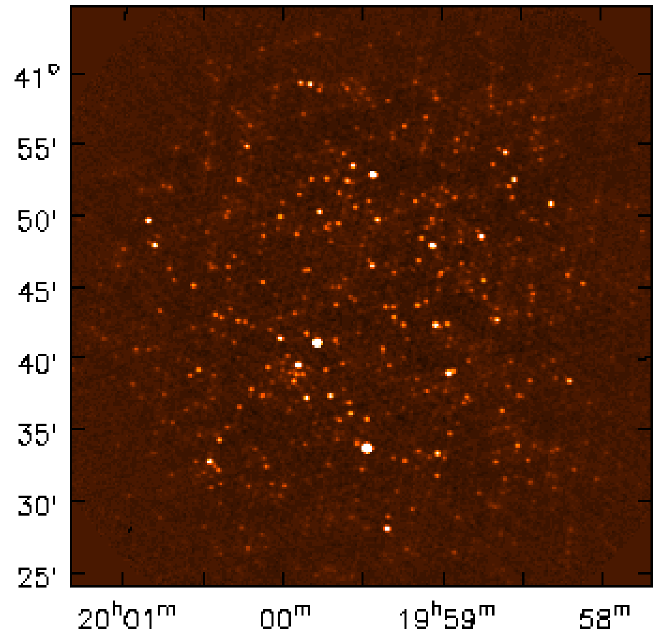
6 uJy rms*

peak res :
15 uJy

MTMFS



MTMFS + WB–AW–Projection



MT-MFS
+
WB-AWP

2 uJy rms

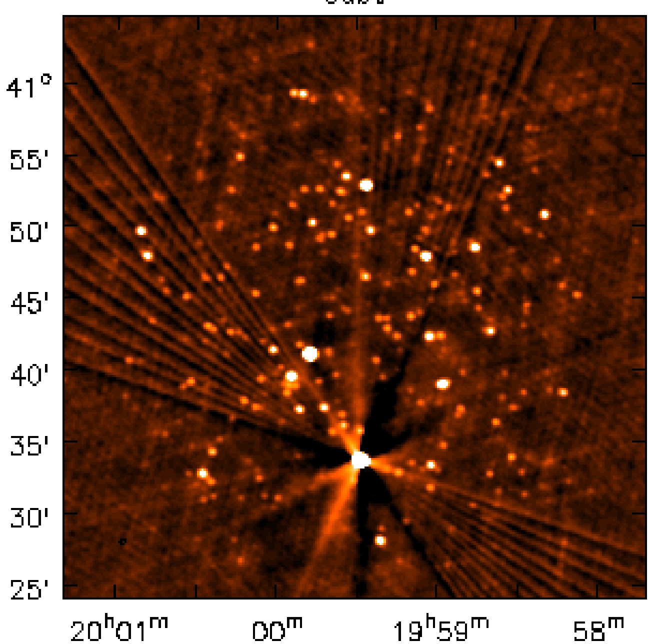
Brightest
Source :
100 mJy

Cube

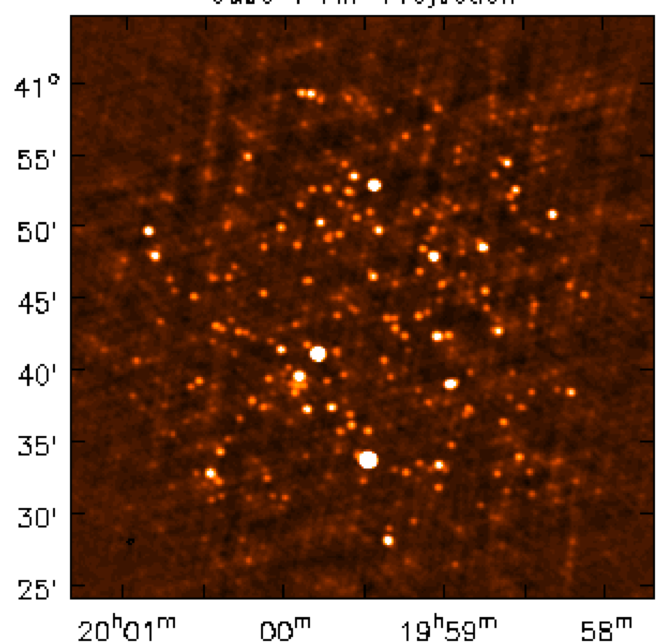
4 uJy rms

peak res :
20 uJy

Cube



Cube + AW–Projection



Cube
+
AW-Proj

3 uJy rms

Details : validating simulations and testing algorithm limits

– Clean bias and the role of masks : Need masks with PSFs from sparse coverage

– Effect of PSF quality : Side-lobe confusion and weak source accuracy

– Un-deconvolved weak sources with Cube CLEAN : A hybrid of Cube and MFS on residuals

– Instrumental polarization correction : Stokes V residuals with/without WB-A-Projection

– Effect of sources not at pixel centers : Nothing significant upto dynamic ranges of 10^4

– Effect of baseline based averaging : No noticeable effect with A-Projection (2xPB fov).

– Numerical / implementation details :

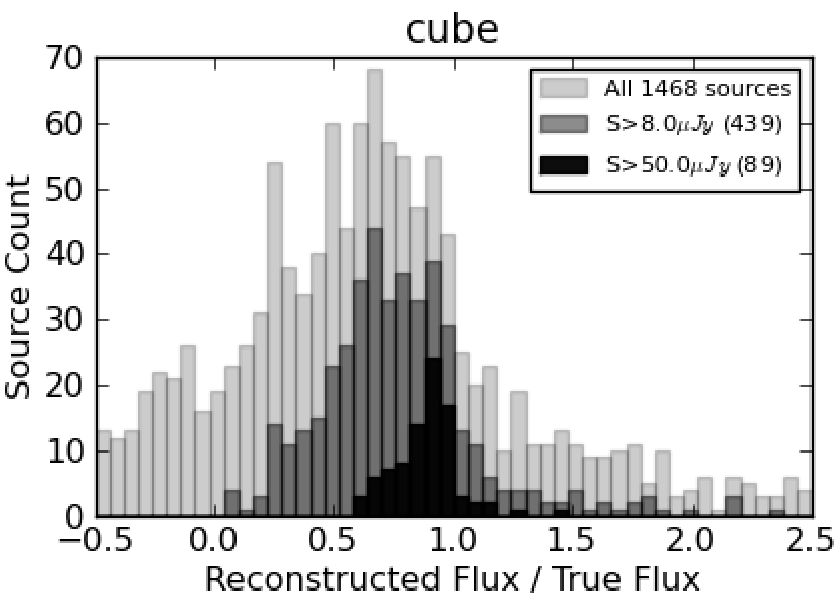
  – Differences due to choices of oversampling of gridding convolution functions.
  – Some uv-coverage patterns leave artifacts for MTMFS runs beyond 10^5 dynamic range.
  – Different algorithms react differently to bright outlier sources.
  – Different achieved noise levels with MosaicFT / FT / A-Projection for single pointings.
  – Non identical results between different implementations of the same algorithms.

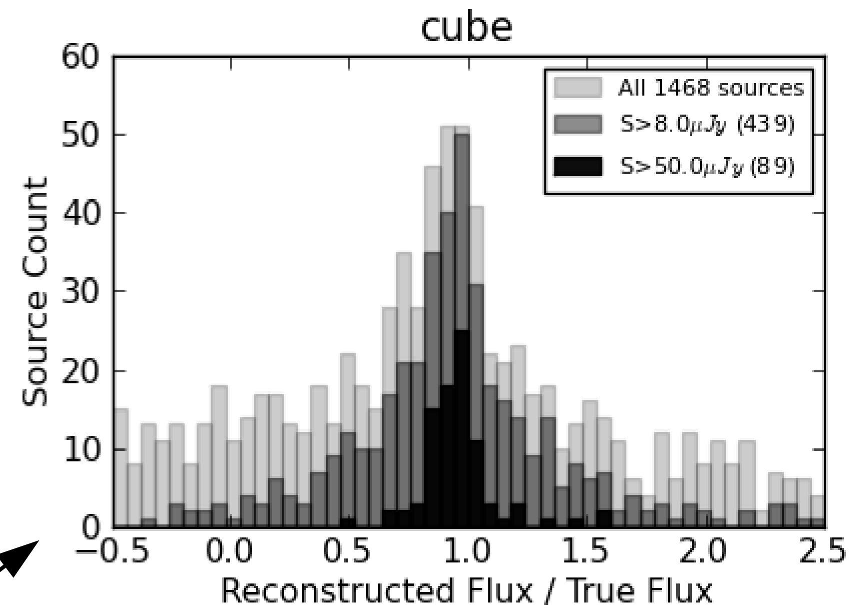
– Other tests : diffuse emission, visibility noise, calibration error, etc...

==> Provide guidelines for astronomers who want automation via advanced algorithms and processing heuristics, plus the ability to analyse their data in ways they are used to.

Details : validating simulations and testing algorithm limits

– Clean bias and the role of masks : Need masks with PSFs from sparse coverage

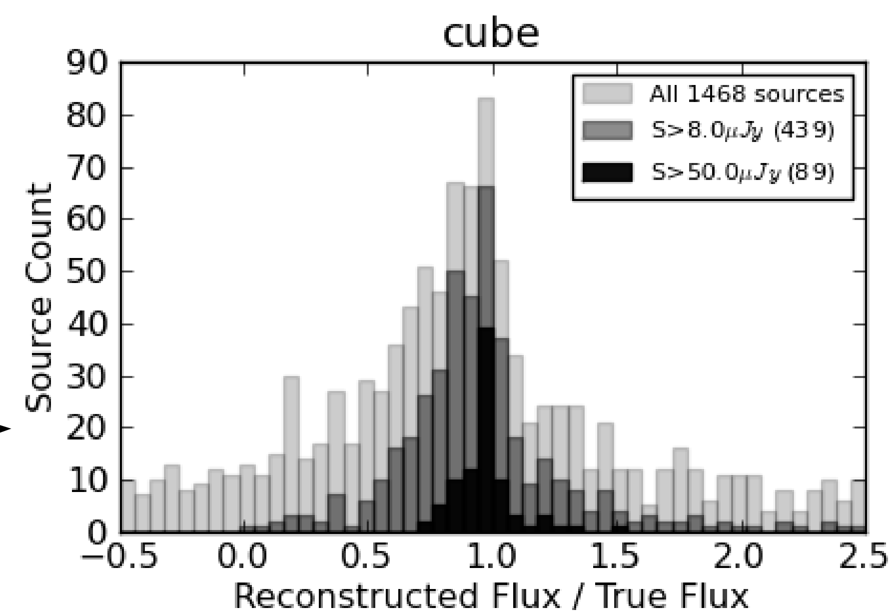




- Un-assisted CLEAN

- CLEAN with boxes around brightest sources (~ 5)

- CLEAN with boxes around many sources (~100s)

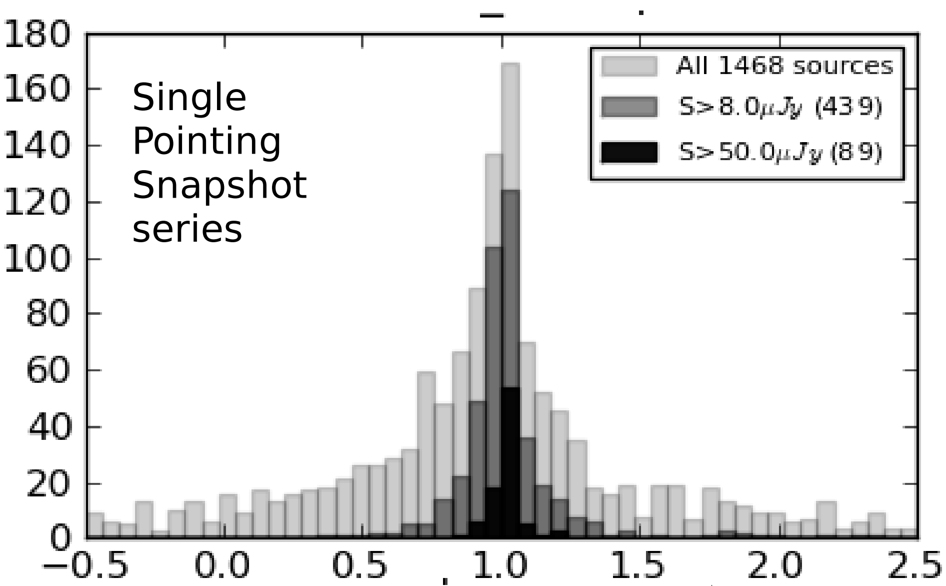


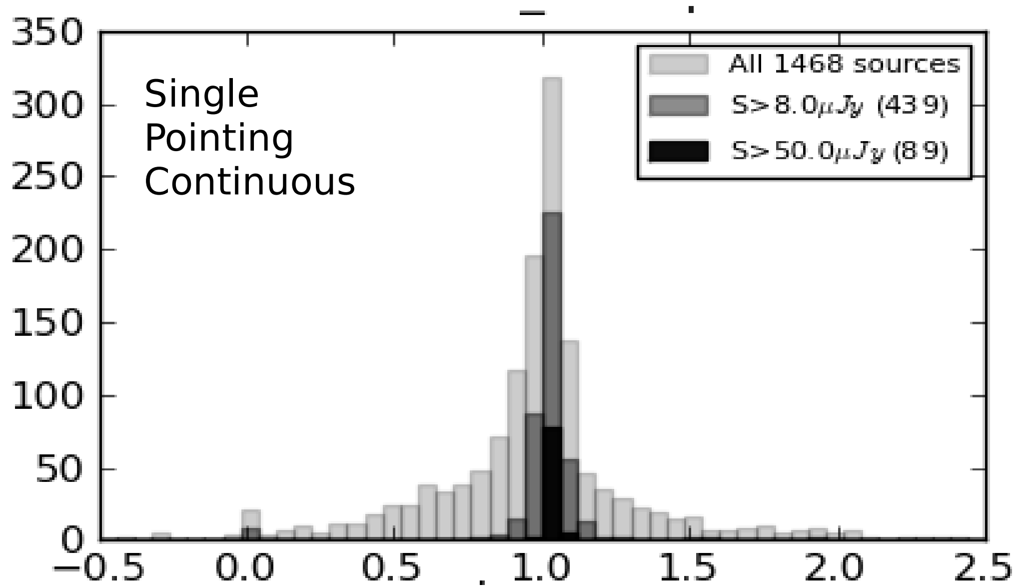
Single spw PSF sidelobe level : 0.13
Wide-band PSF sidelobe level : 0.05

Details : validating simulations and testing algorithm limits

– Clean bias and the role of masks : Need masks with PSFs from sparse coverage

– Effect of PSF quality : Side-lobe confusion and weak source accuracy

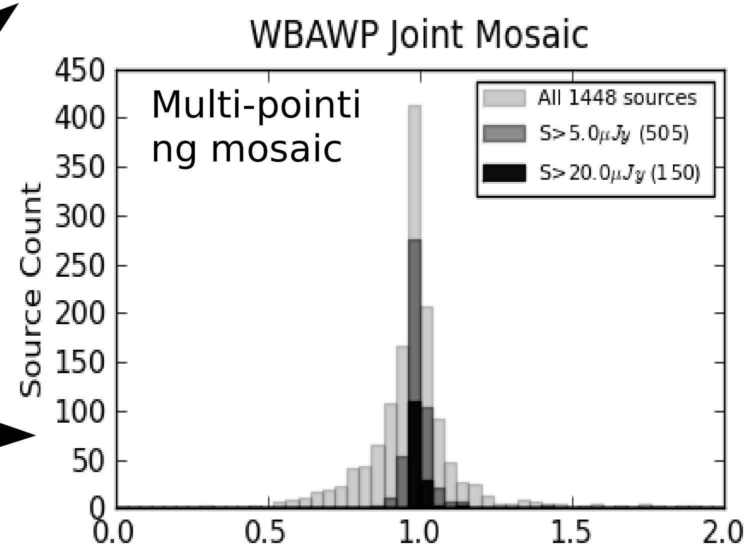




Wide-band PSF sidelobe : 0.05

Wide-band PSF sidelobe : 0.02

Wide-band PSF sidelobe (avg) : 0.008



Details : validating simulations and testing algorithm limits

– Clean bias and the role of masks : Need masks with PSFs from sparse coverage

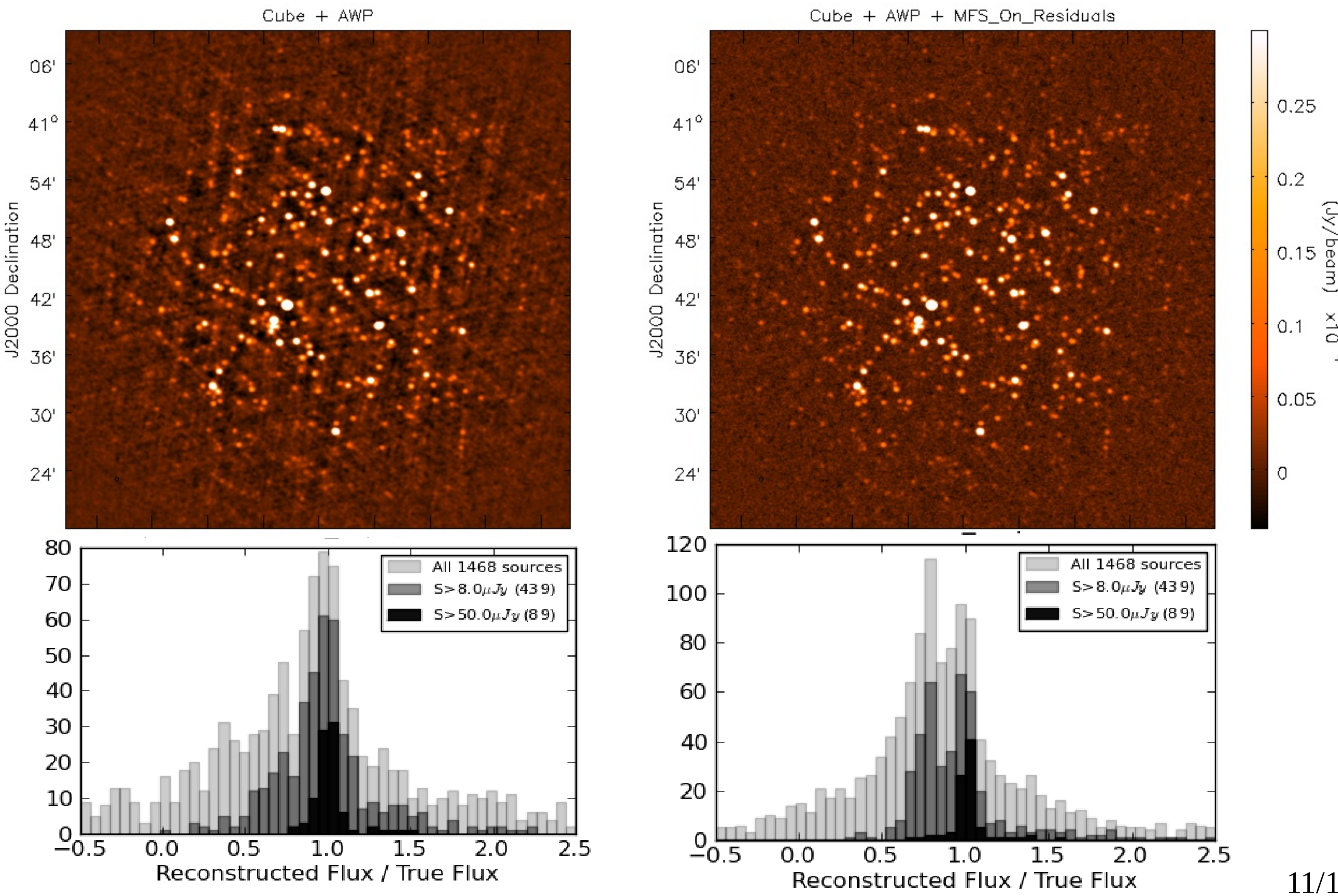
– Effect of PSF quality : Side-lobe confusion and weak source accuracy

– Un-deconvolved weak sources with Cube CLEAN : A hybrid of Cube and MFS on residuals

LEFT :
Cube Imaging + Channel collapse

RIGHT :
Cube + MFS on residuals

Image RMS improves, but flux accuracy does not.

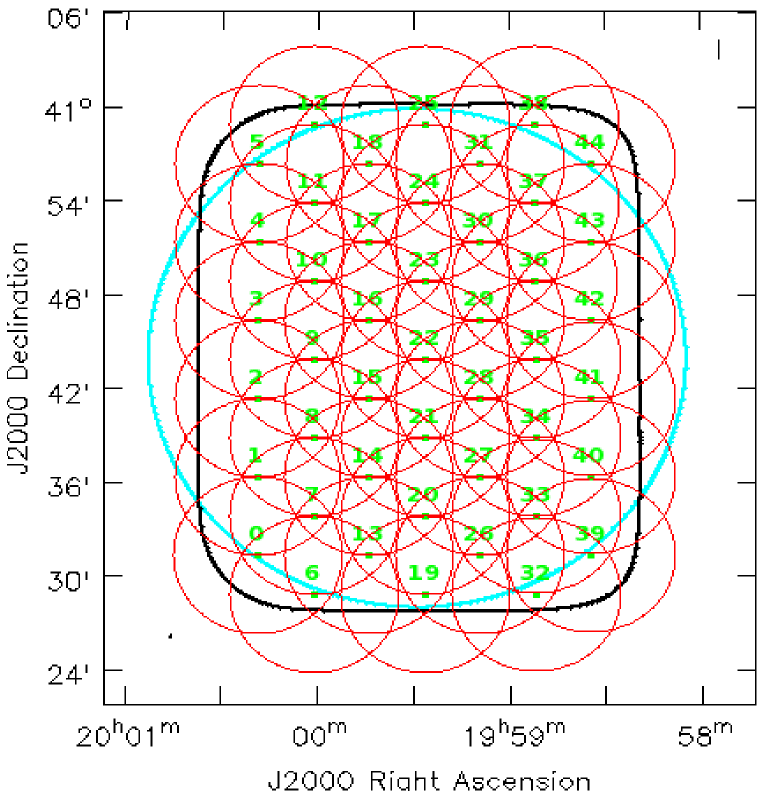


Wideband Mosaics – Simulation and Algorithms

EVLA D-config, C-band (4-8 GHz), 16 spws/chans

[Same field as with C-config L-band single pointing]

– 46 pointings at 5 arcmin spacing, 2 loops
– One snapshot every 6 min => 8.8 hr synthesis



Algorithms :

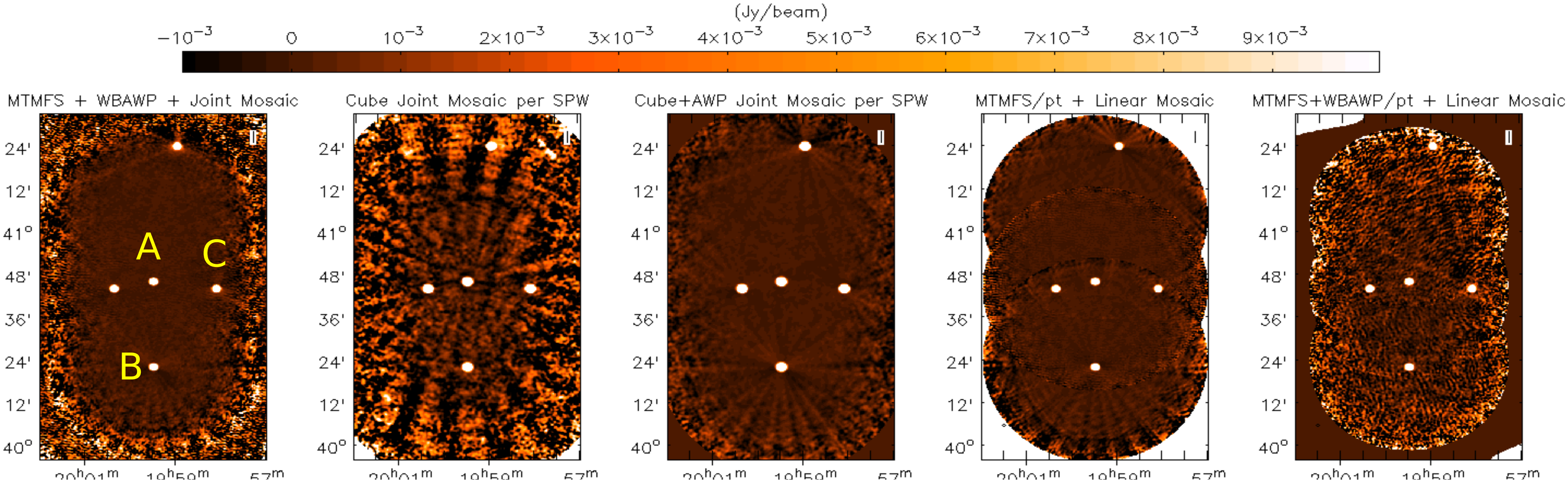
- Deconvolve Pointings separately or together
- Deconvolve Channels separately or together
- Use A-Projection or not

(1) Joint Mosaic with Wideband AW-Projection with MT-MFS (nterms=2)

(2,3) Cube Imaging with Joint Mosaic per SPW – With/Without rotating,squinted PBs

(4,5) MT-MFS per pointing with wideband PBCOR and post-deconvolution linear mosaic.
– With/Without rotating,squinted PBs.

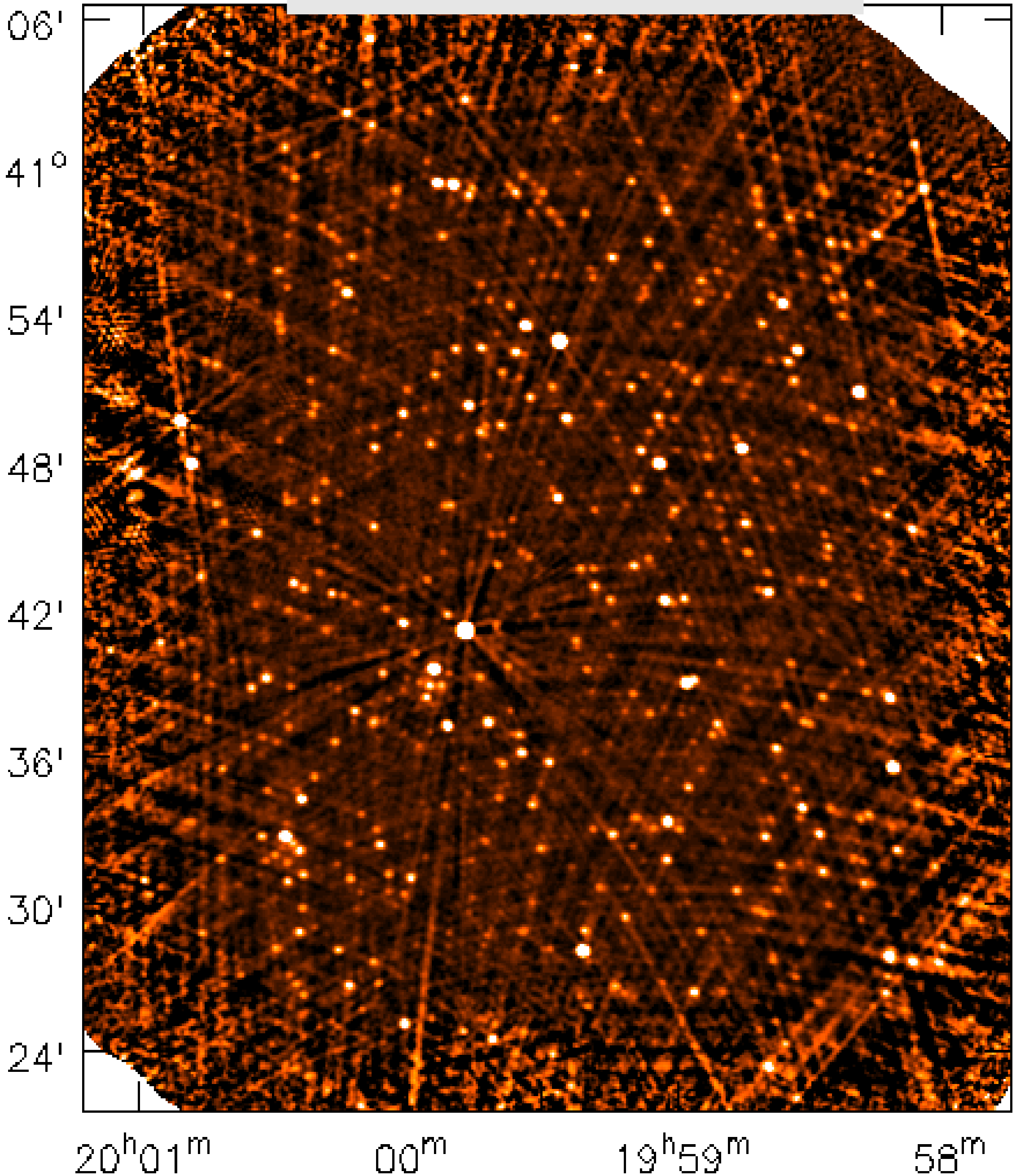
Dataset : L-Band D-config, 3 pointings, 5 sources (intensity = 1 Jy, alpha= -0.5)



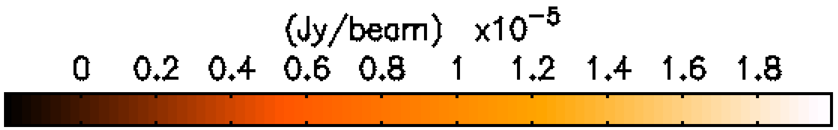
	Joint Mosaic Wideband-AP	Joint Mosaic Cube	Joint Mosaic Cube-AP	Linear Mosaic Wideband	Linear Mosaic Wideband-AP
A	1.0002	0.98	1.011	0.88	1.01
	-0.508	-0.52	-0.51	-0.87	-0.48
B	1.0004	0.99	1.012	0.90	0.99
	-0.502	-0.47	-0.48	-0.80	-0.50
C	1.0005	0.887	1.04	0.73	1.007
	-0.507	-0.62	-0.53	-1.6	-0.7

Cube Imaging with a Joint Mosaic (Ap=F) and PBCOR per SPW

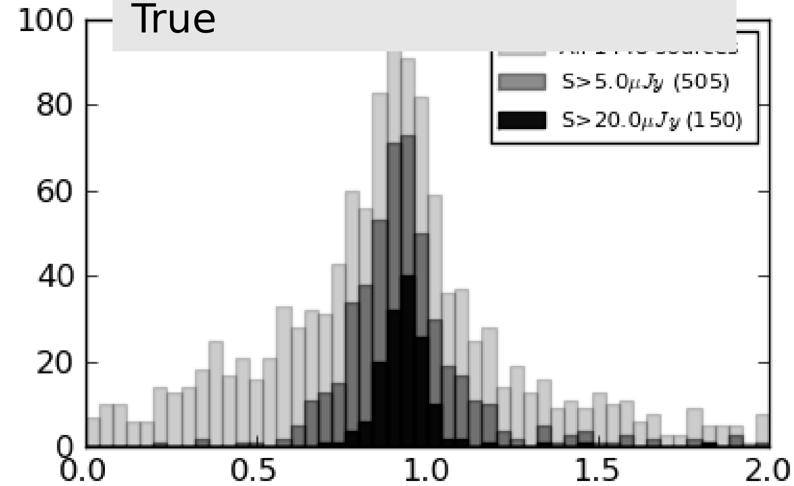
RMS : 1.1 microJy



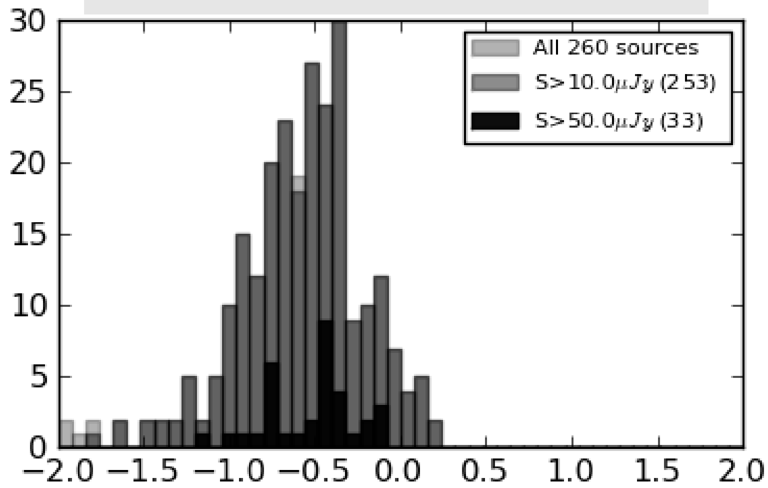
PSF sidelobe level :



Intensity : Reconstructed / True



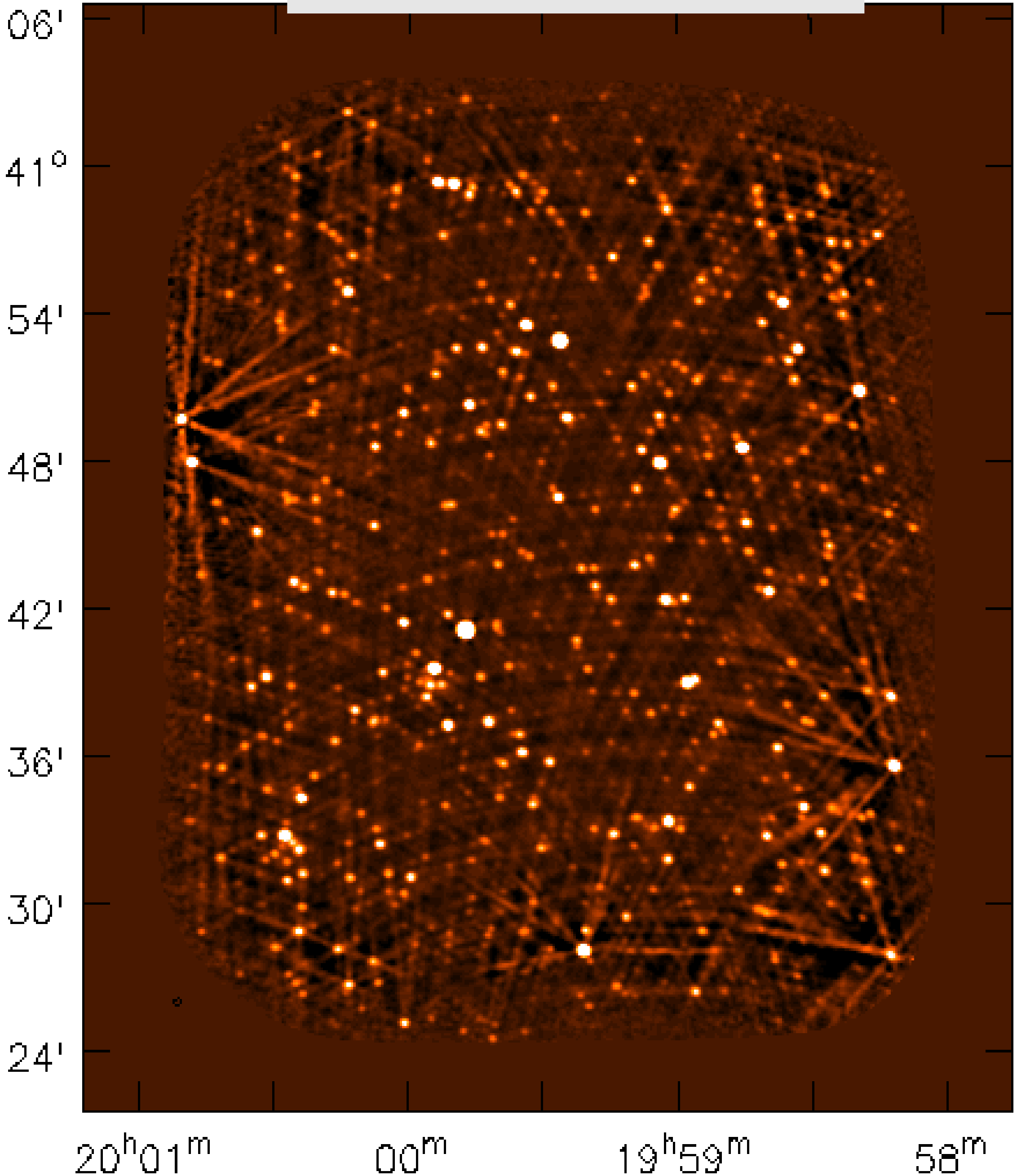
Alpha : Reconstructed - True



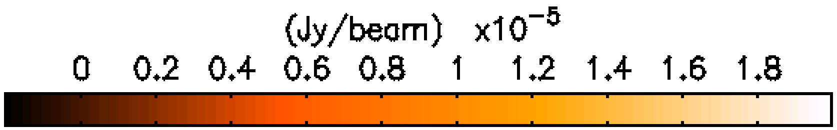
Spectra are too steep => WB PBcor error

Cube Imaging with a Joint Mosaic (Ap=T) and PBCOR per SPW

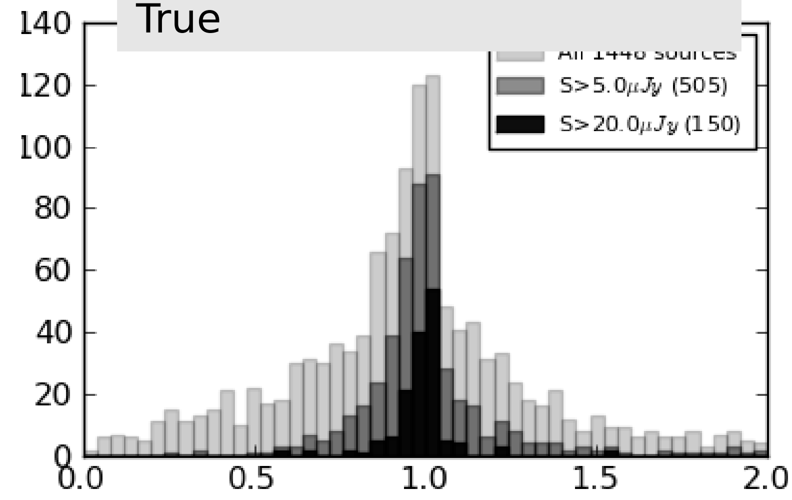
RMS : 0.7 microJy



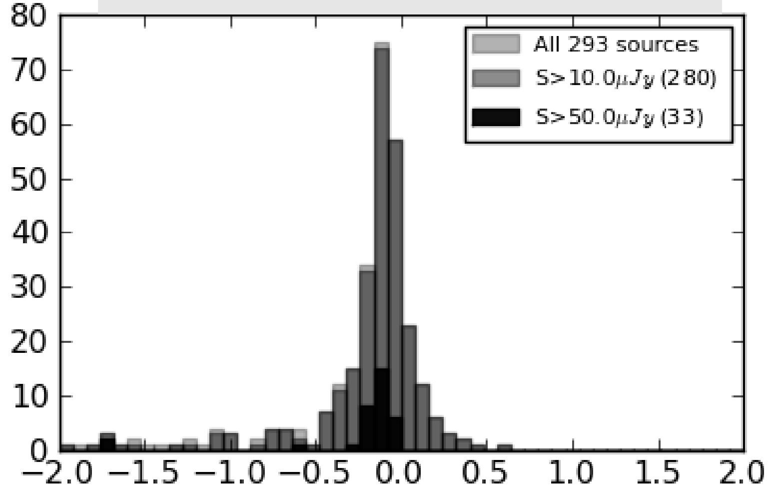
PSF sidelobe level : 0.07



Intensity : Reconstructed / True



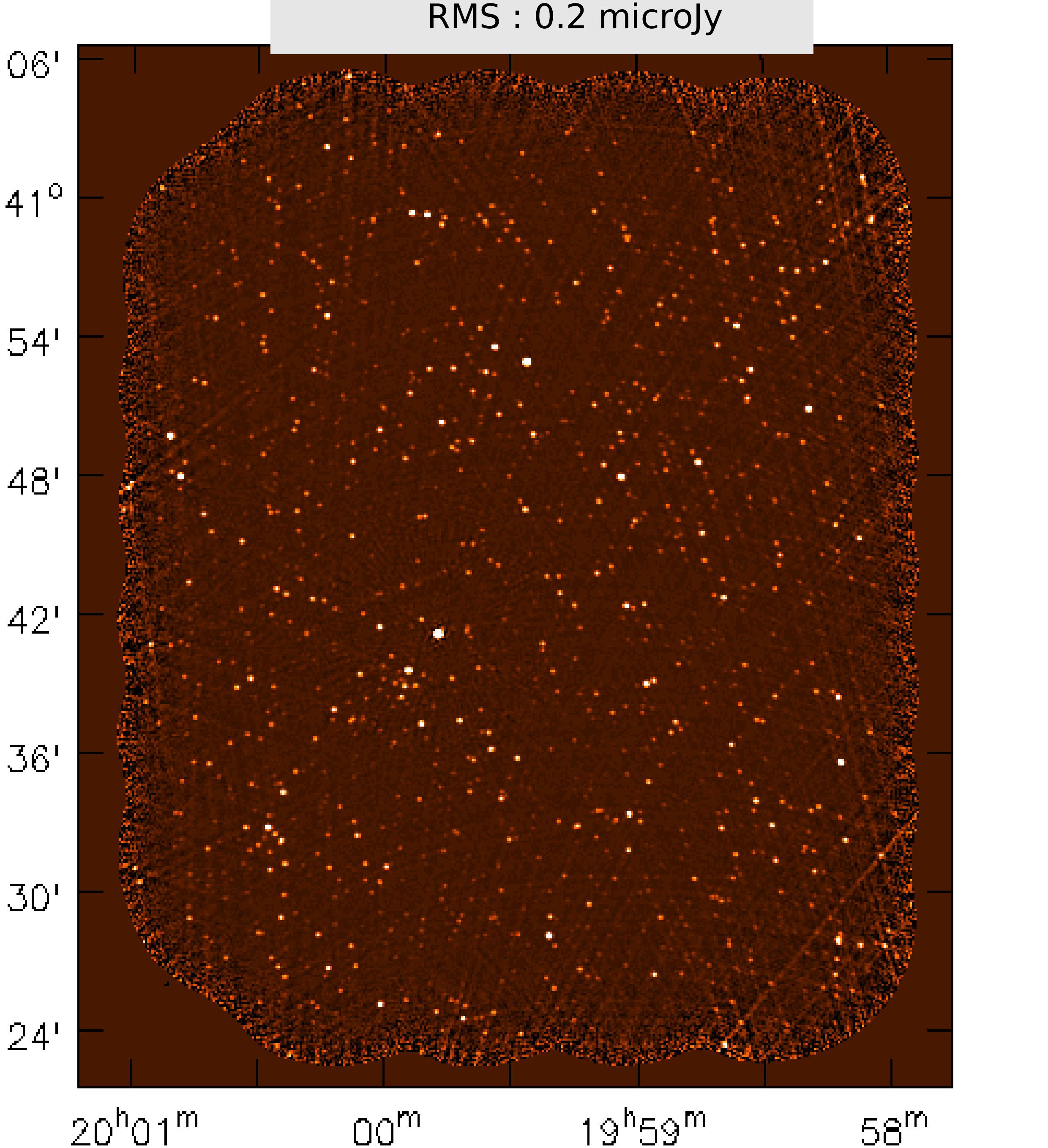
Alpha : Reconstructed - True



=> Better PB-correction

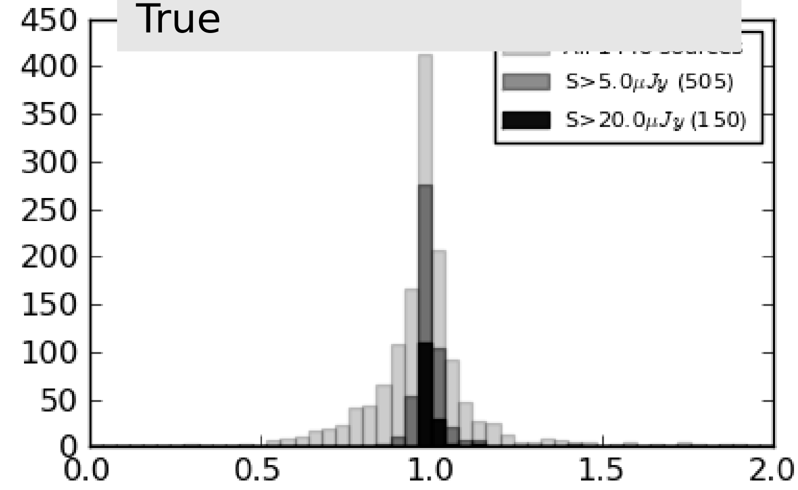
Joint Mosaic with Wideband AW-Projection and MT-MFS (nt=2)

RMS : 0.2 microJy

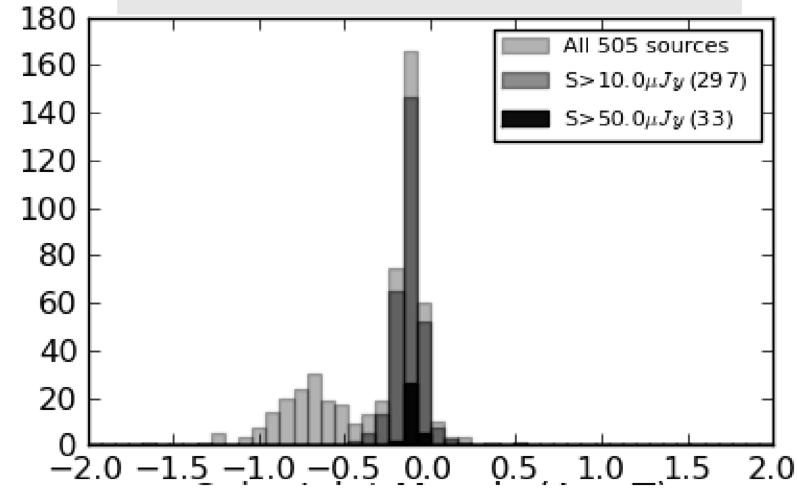


PSF sidelobe level : 0.01

Intensity : Reconstructed / True



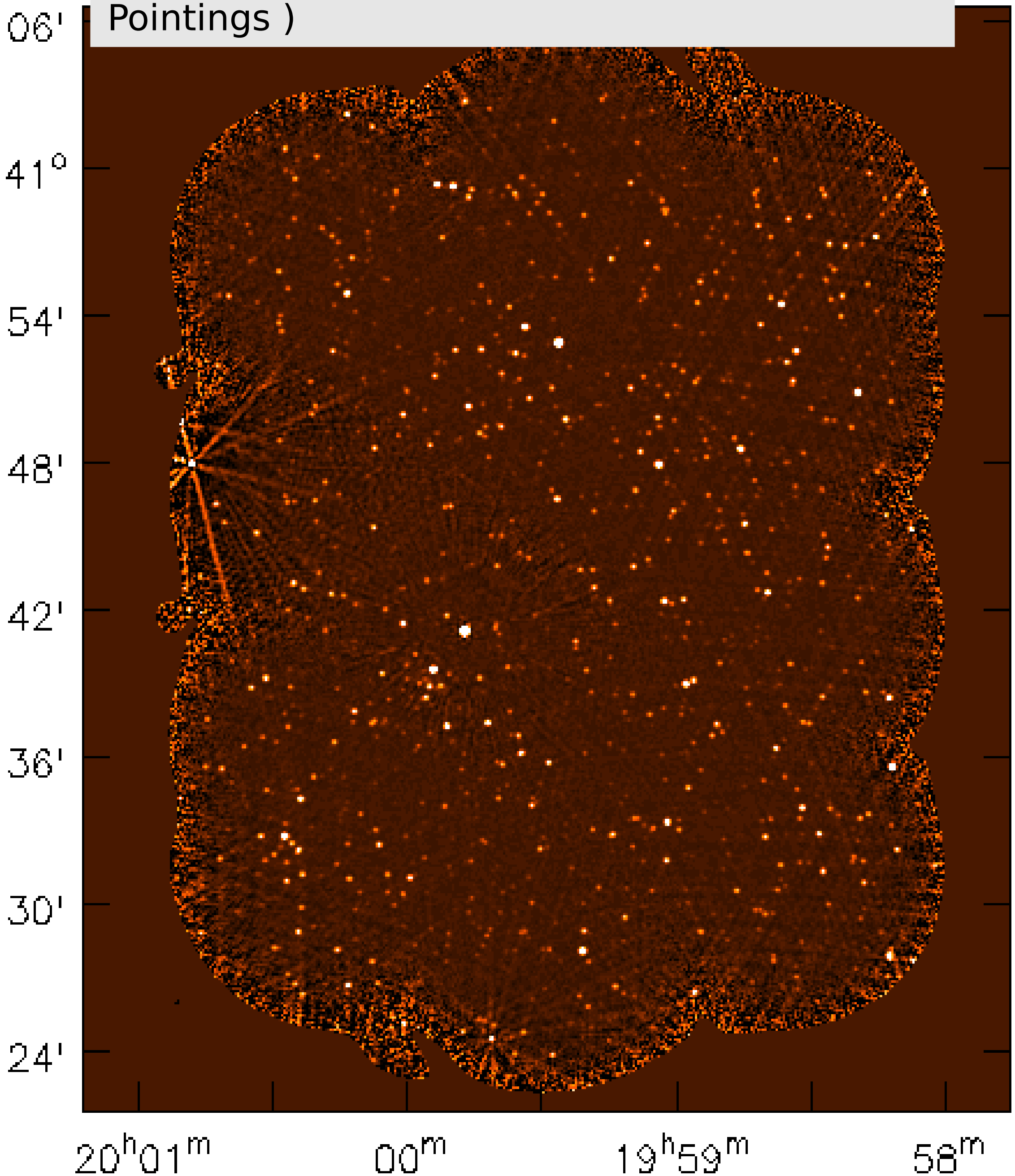
Alpha : Reconstructed - True



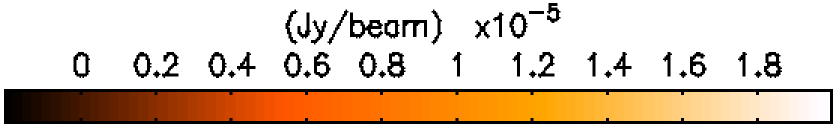
=> Fake steep-spectrum population !

Joint Mosaic with Wideband AW-Projection and MT-MFS (nt=2)

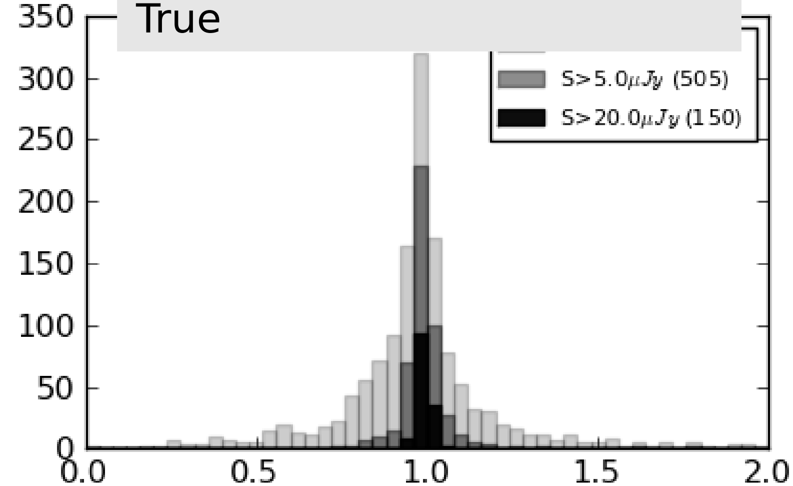
RMS : 0.3 microJy (Alternate Pointings)



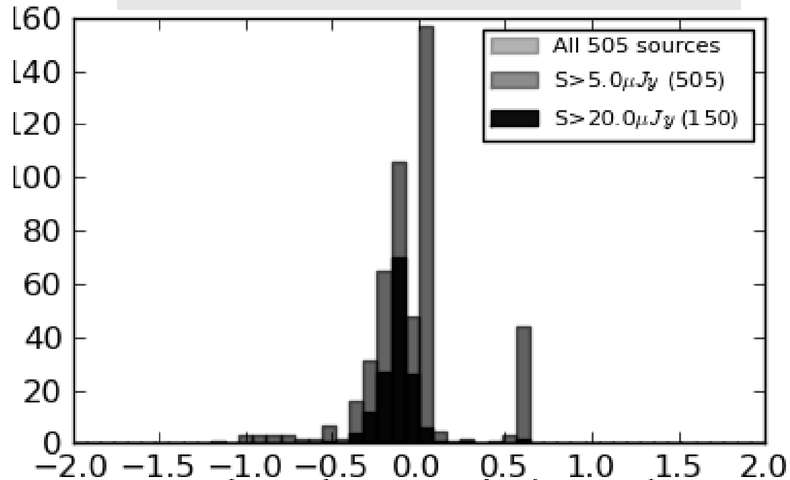
PSF sidelobe level : 0.01



Intensity : Reconstructed / True



Alpha : Reconstructed - True



=> Still far from perfect....

Summary

– Commissioning wideband mosaic algorithms and understanding analysis strategy

– Even in perfectly controlled conditions, a number of numerical effects can affect the astrophysical interpretation – need to be aware of and avoid them

– Demonstrations on wideband VLA data

(Rau et al (in prep))

– Single pointings : A225,3C465 at L-Band, IC10 at C-Band, G55 at L-Band, M87 at L-Band, Plaeides at C-Band, SWIRE deep field, ELIAS N1, Cosmos (Chiles)

– Mosaics : CTB80 field at L-Band, Centaurus-A at C-band, M31 at C-band, ELIAS N1 (GMRT,VLA)

– More simulations

– Add calibration errors and antenna-dependent PB perturbations

(Kara Kundert / undergrad intern from U.Michigan : ALMA single pointing, narrow-band)

– Add source polarization and test wideband IQUV and rotation-measure recovery

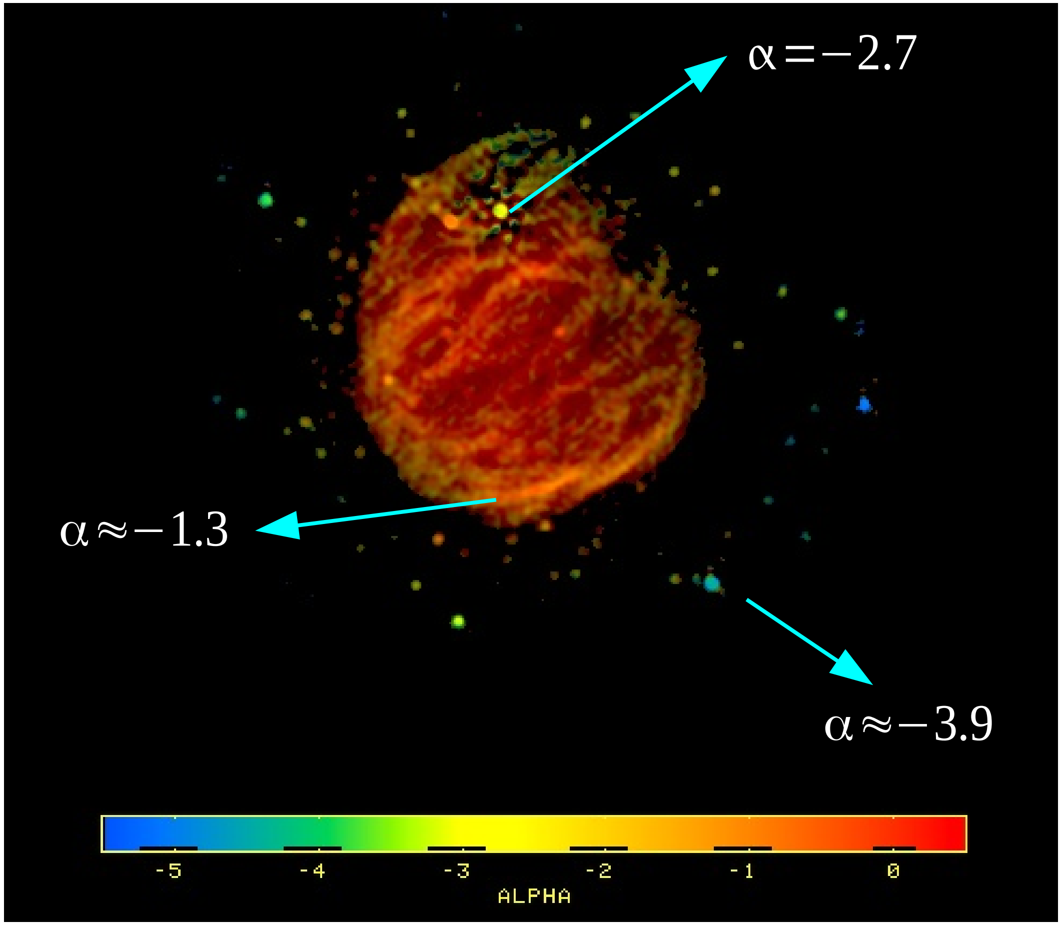
(Preshanth Jagannathan / U.Calgary : part of PhD thesis project + RSRO project (R.Taylor et.al.))

– Image the same wideband mosaic dataset with other algorithms and implementations

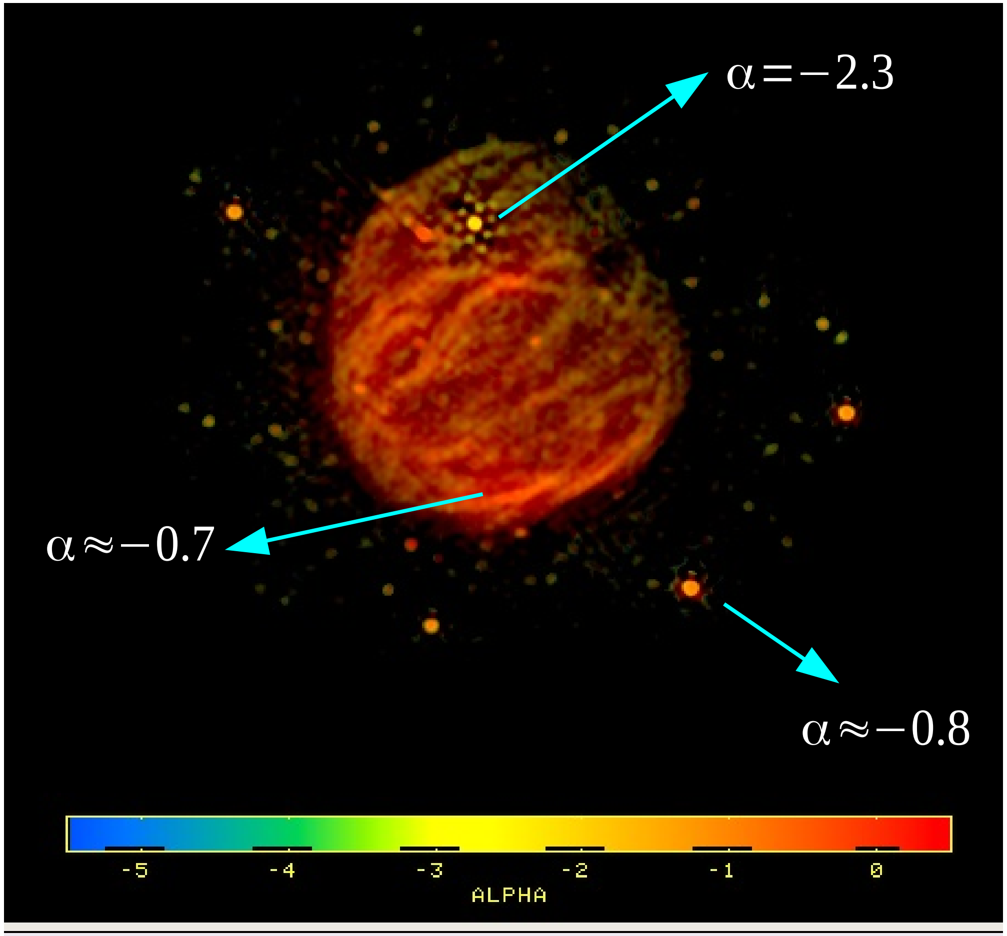
(CS-deconvolution, Peeling, DD-cal, new Imager software, ...)

Spectral indices before/after WB-AWP

Without PB correction
Outer sources are artificially steep



With PB correction (via WB-AWP)
Outer sources have correct spectra



Intensity-weighted spectral index maps (color = spectral index from -5.0 to +0.2)

Wide-field sensitivity because of wide-bandwidths

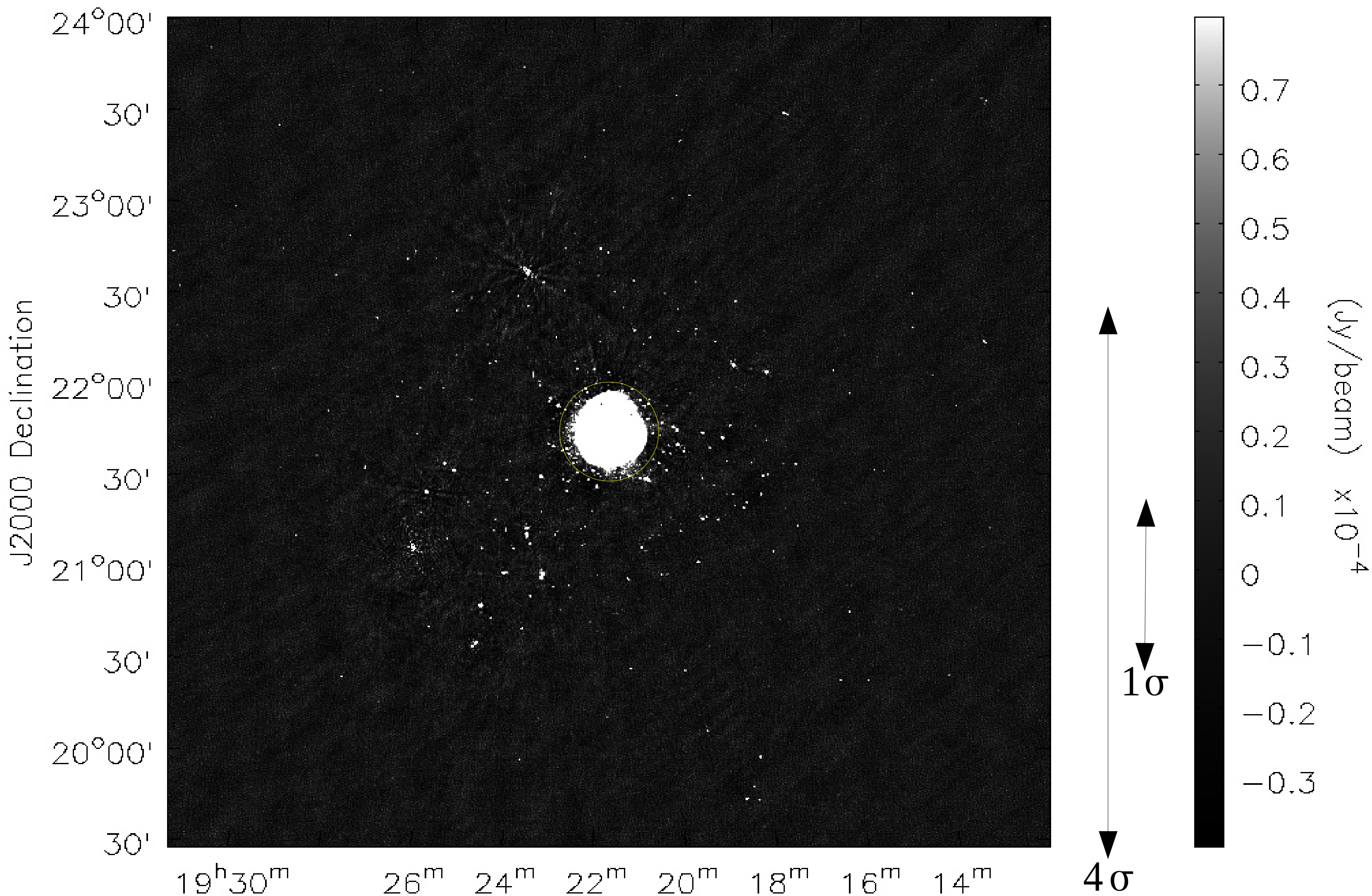
G55.7+3.4 : Field-of-view of 4x4 degrees from one EVLA pointing at 1-2 GHz

1 Jy total flux

24 arcmin

(PB: 30 arcmin)

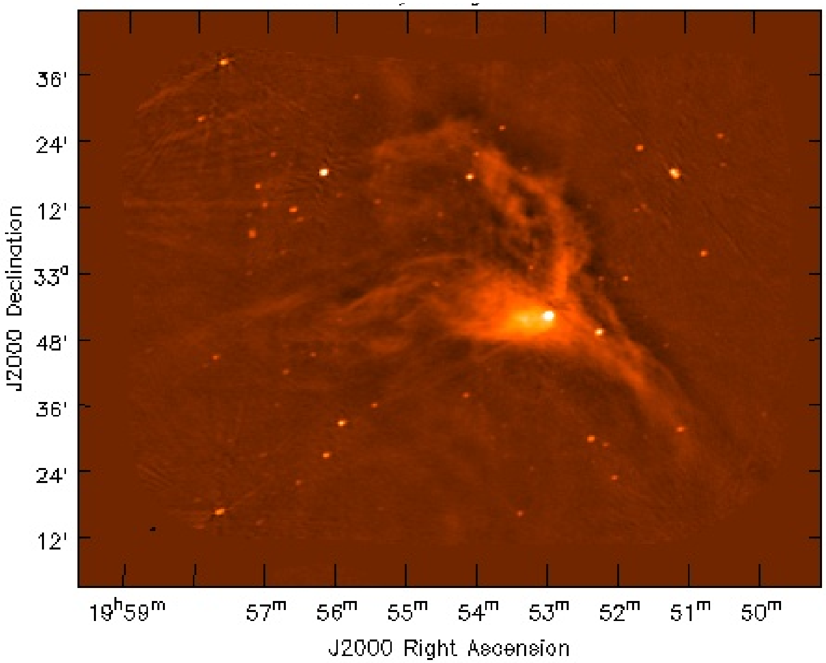
10 micro Jy RMS



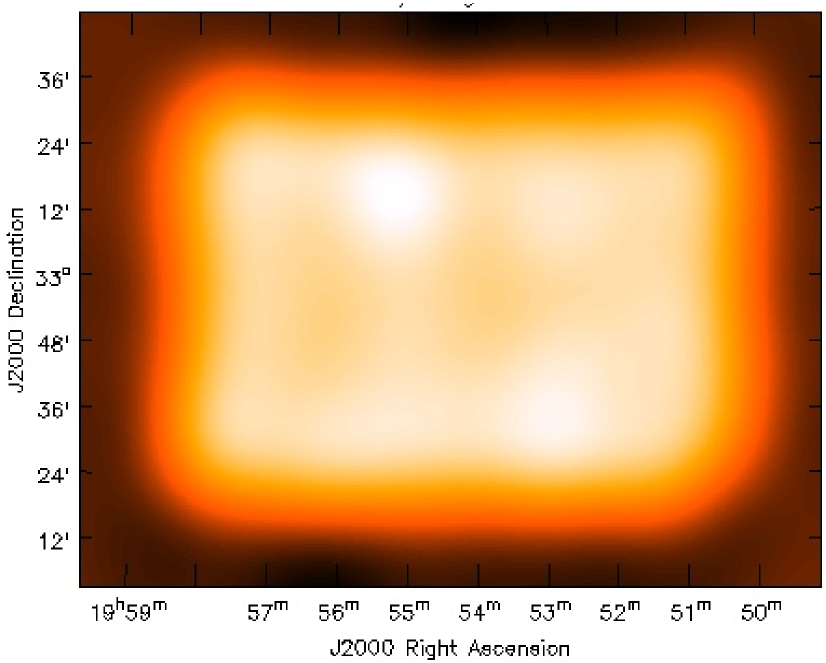
=> Wideband Imaging implies wide-field imaging

Wideband Mosaic of CTB80 (1-2 GHz, VLA-D config)

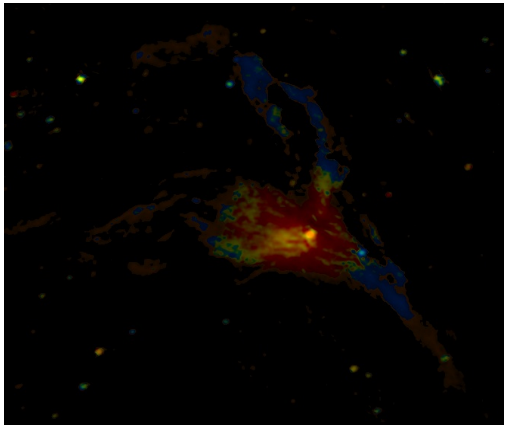
Intensity



Mosaic Primary Beam



Intensity-weighted
Spectral Index

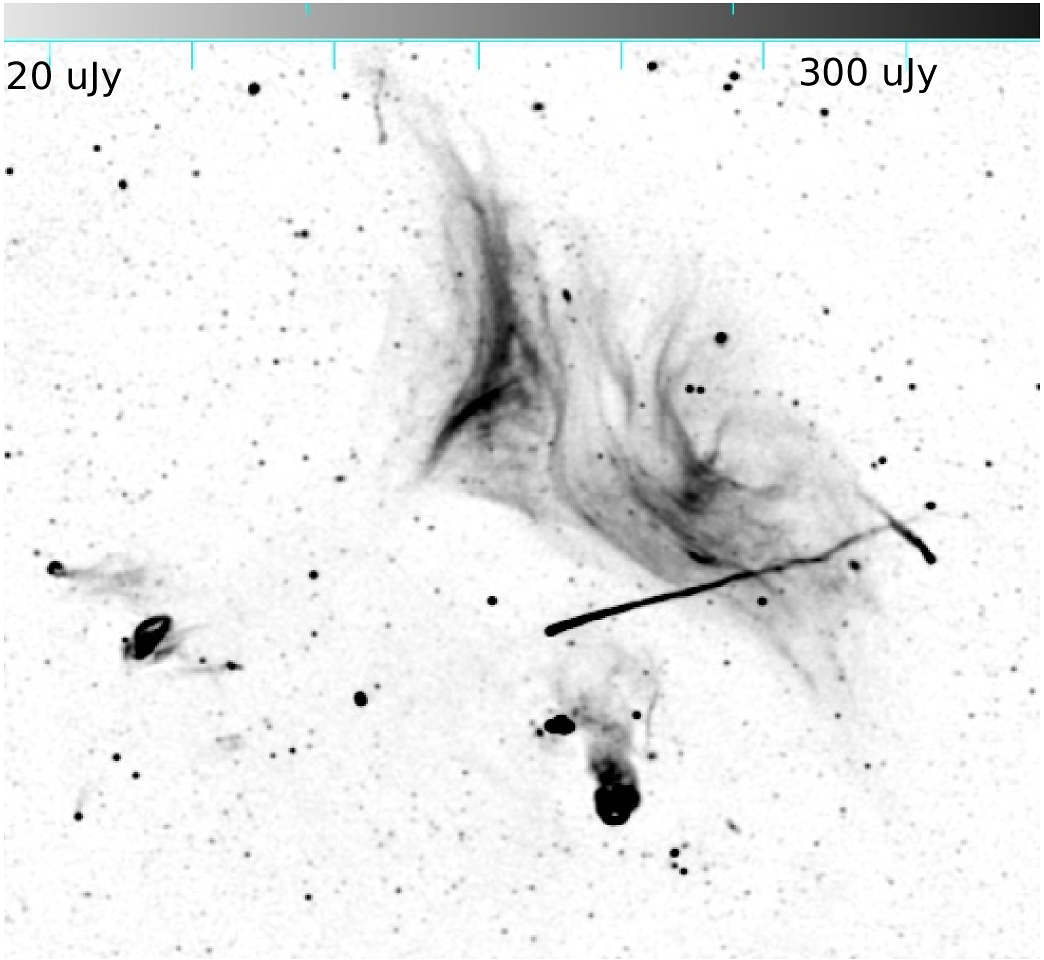


300GB calibrated dataset, 106 pointings over 1.5x2 deg, imaged with MT-MFS (NT=2) and WB-A-Projection.

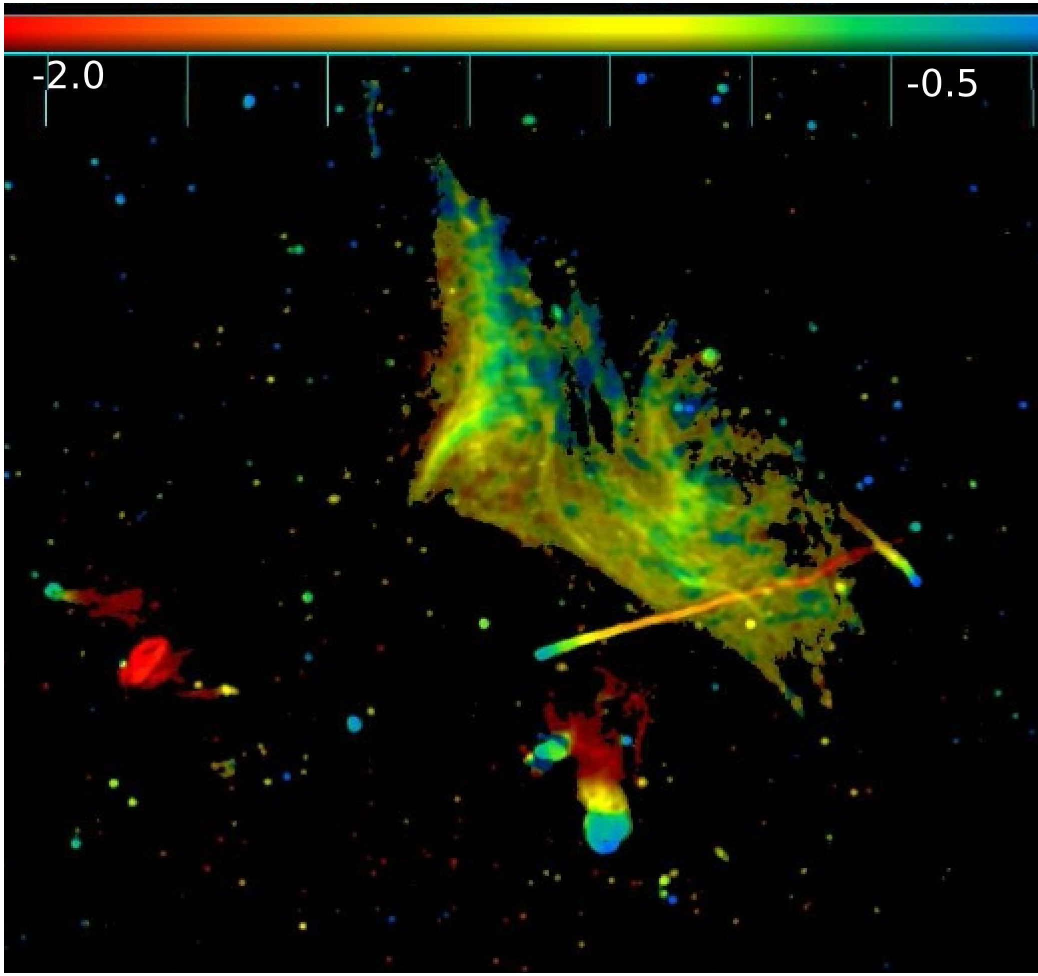
Major cycle runtime without parallelization : ~10 days.
With 40 processes : 5 hrs (CASA)

Example : Abell 2256 *[Owen et al, 2014]*

Intensity



Intensity weighted Spectral Index



VLA A,B,C,D at L-Band (1-2 GHz), VLA A at S&C bands(2-4, 4-6, 6-8 GHz)

Calibration and Auto-flagging in AIPS. Intensity/Spectral index Imaging in CASA.