Recent imaging results with wide-band EVLA data, and lessons learnt so far

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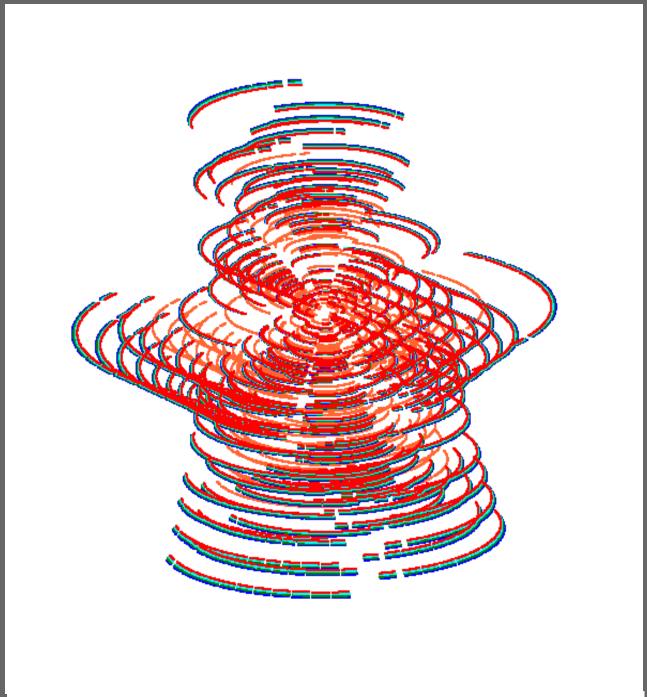
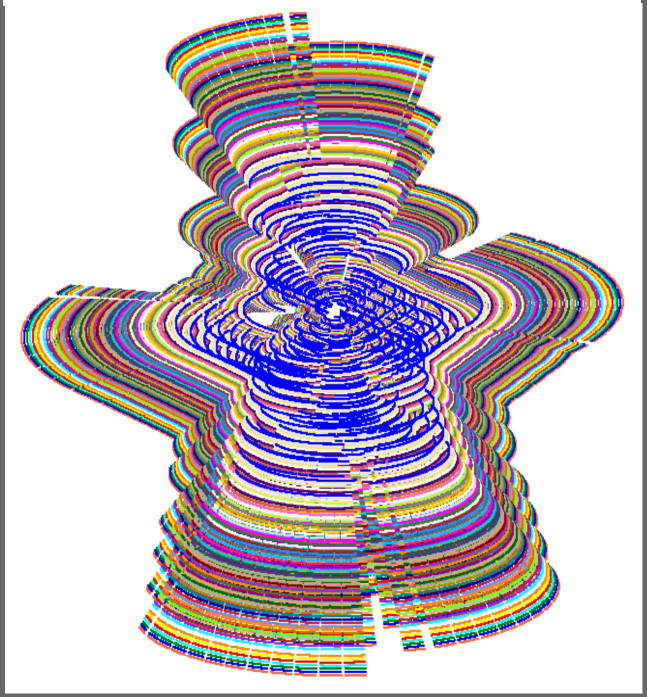




(1) Introduction : Imaging wideband data

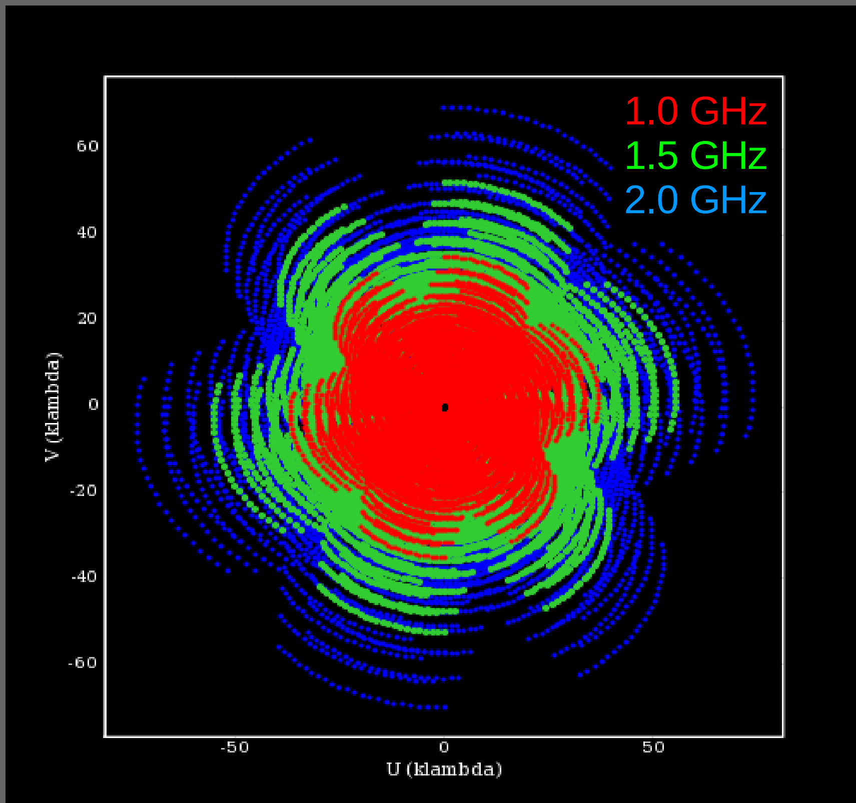
(2) Wideband Imaging fidelity on point sources and extended emission

(3) Wide fields-of-view + wideband primary-beam

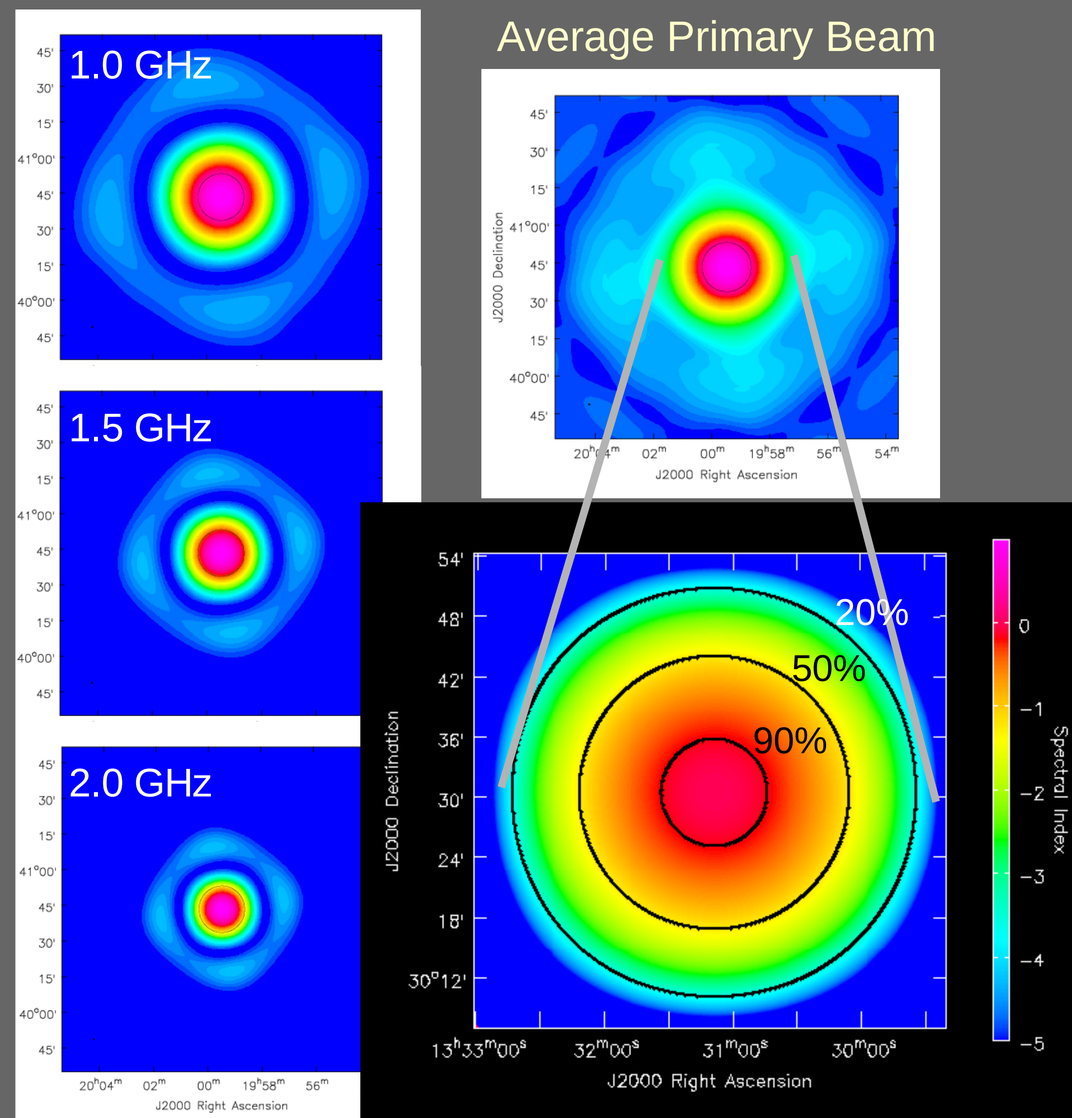
(4) Using MS-MFS (errors and performance), wide-band calibration, RFI...

Wide-band wide-field imaging

EVLA C configuration UV-coverage



Multi-Frequency Primary Beams



Spectral Index of PB

MFS : Combine all channels during imaging

- Better imaging fidelity
- Increased signal-to-noise ratio
- Higher angular resolution

Sky brightness changes with frequency

MS-MFS : as implemented in CASA

Sky Model : Collection of multi-scale flux components whose amplitudes follow a polynomial in frequency

$$I_\nu^{sky} = \sum_t I_t \left(\frac{\nu - \nu_0}{\nu_0} \right)^t \quad \text{where} \quad I_t = \sum_s [I_s^{shp} * I_{s,t}]$$

User Parameters : - Set of spatial scales (in units of pixels) : multiscale=[0,6,10]
- Order of Taylor polynomial : mode='mfs', nterms=3
- Reference frequency : reffreq = '1.5GHz'

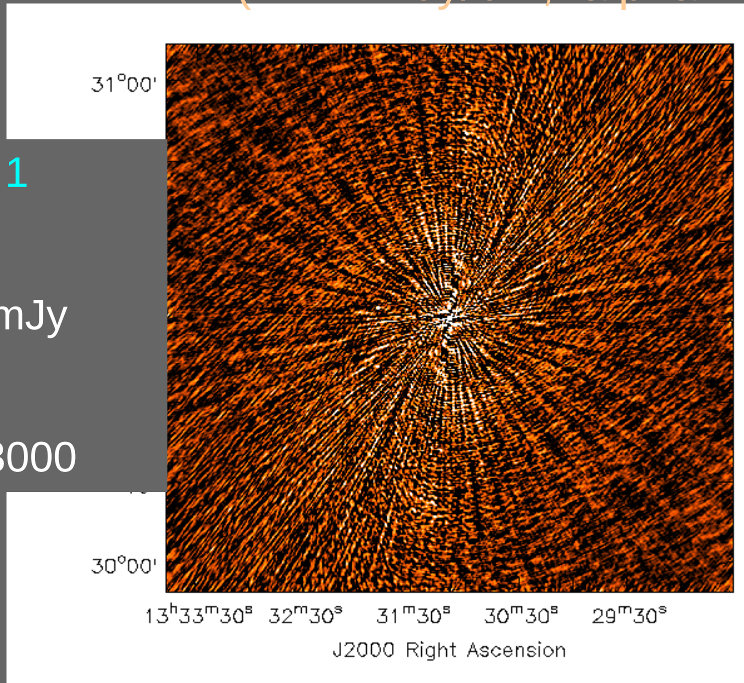
Image Reconstruction : Linear least squares + Deconvolution (+ W-Projection)
U.Rau & T.J.Cornwell, 2011 ArXiv:1106.2745 , DOI 10.1051/0004-6361/201117104

Data Products : Taylor-Coefficient images

- Interpret in terms of a power-law : spectral index and curvature
- Evaluate the spectral cube (for non power-law spectra)

3C286 field : Dynamic Range (vs) NTERMS

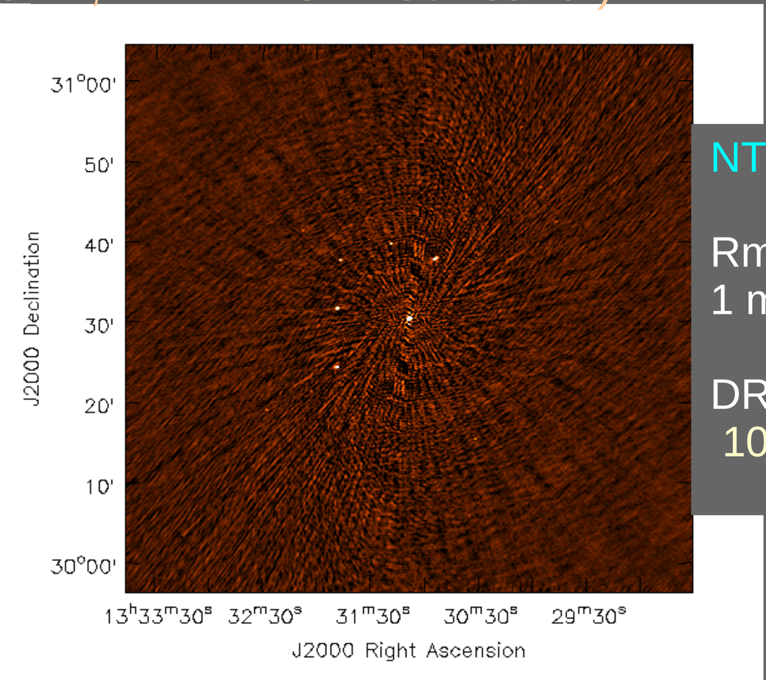
(I=14.4 Jy/bm, alpha = -0.47, BW=1.1GHz at Lband)



NTERMS = 1

Rms :
9 mJy -- 1 mJy

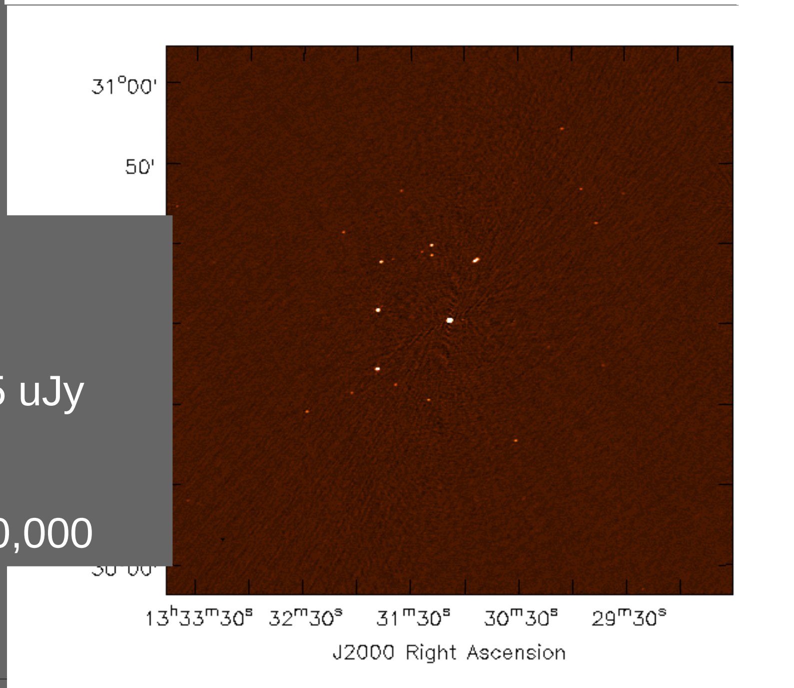
DR :
1600 -- 13000



NTERMS = 2

Rms :
1 mJy -- 0.2 mJy

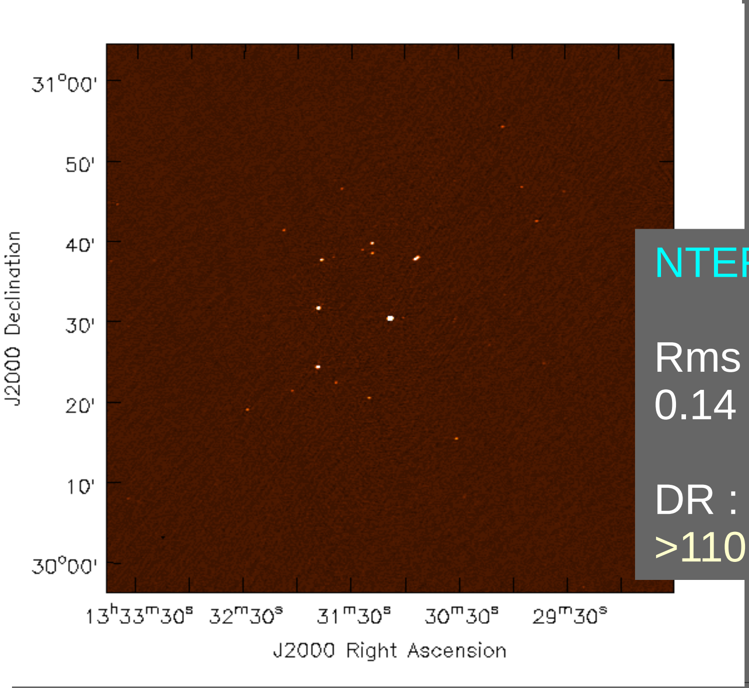
DR :
10,000 -- 17,000



NTERMS = 3

Rms :
0.2 mJy -- 85 uJy

DR :
65,000 -- 170,000

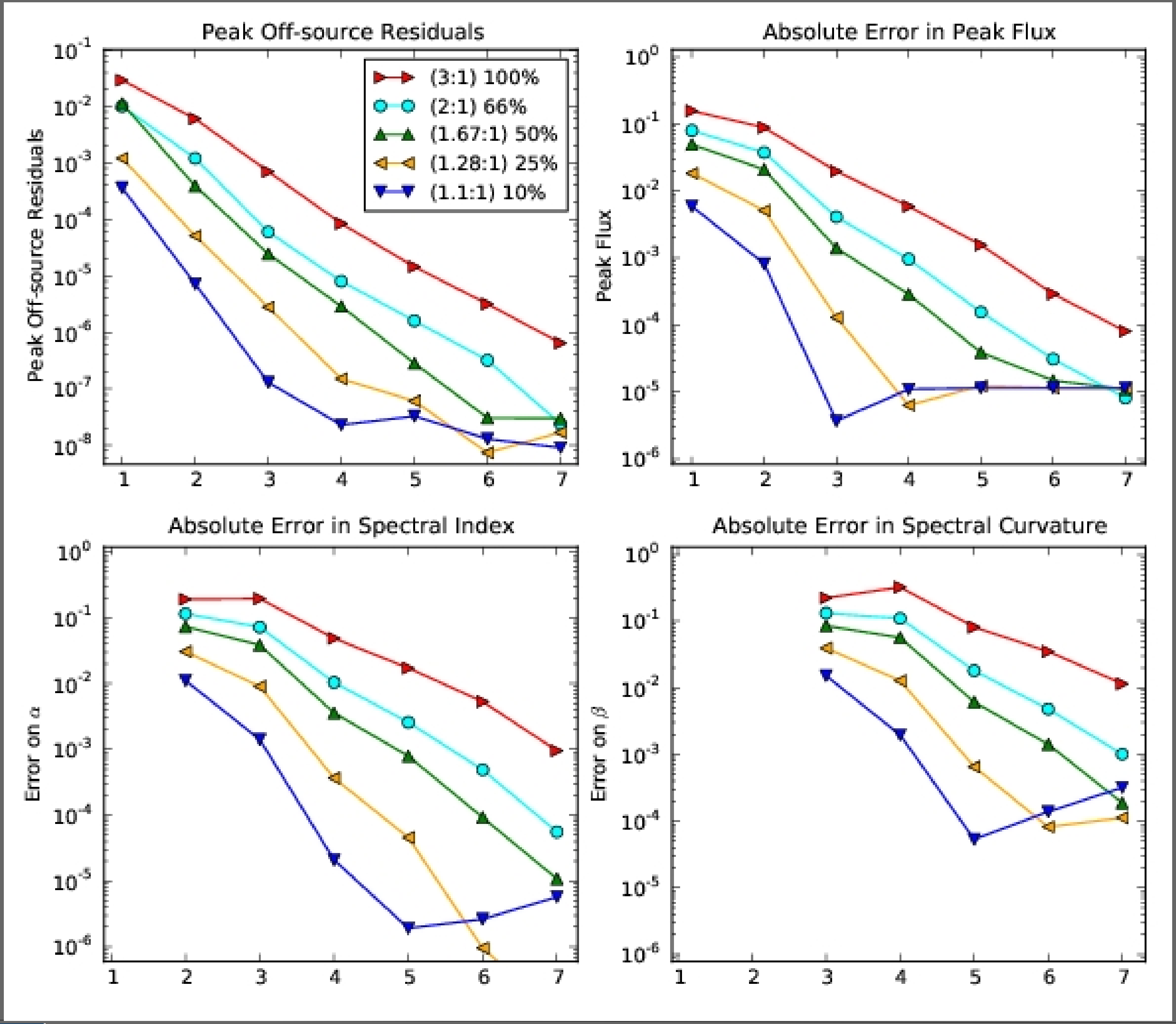


NTERMS = 4

Rms
0.14 mJy -- 80 uJy

DR :
>110,000 -- 180,000

High Signal-to-noise : Approximating a power-law with a Taylor-polynomial – error : O(n+1)



Errors for a simulated 1Jy point source with spectral index -1.0 located at the phase center, for different bandwidth-ratios.

In general, errors depend on

(a) Usual polynomial-fitting errors (Nterms vs SNR)

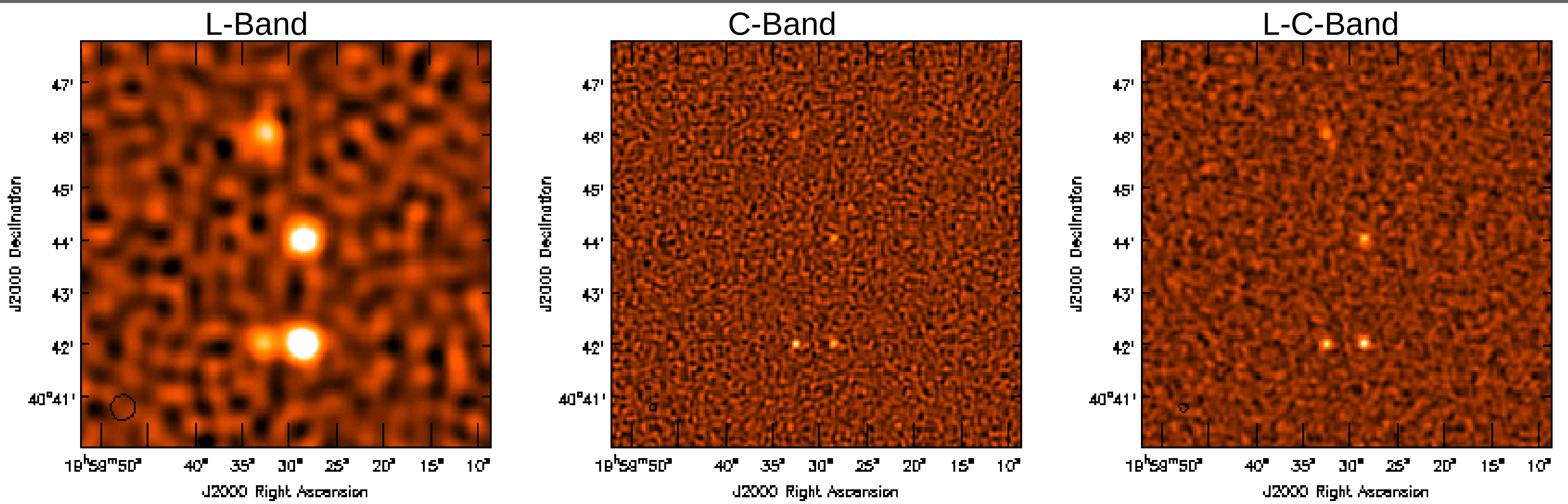
(b) Propagation of multi-scale deconvolution errors

(c) Condition-number of MS-MFS Hessian (depends on UV-coverage, frequency-sampling, and basis fns)

Low Signal-to-noise : Accuracy of spectral-index vs frequency-range

(simulated data : 16 chans/spws between 1-2 GHz and 4-8 GHz)

Source	Peak Flux	L alpha	C alpha	LC alpha	True	Wideband RMS
Bottom right	100 uJy	-0.89	-1.18	-0.75	-0.7	
Bottom left	100 uJy	+0.11	+0.06	+0.34	+0.3	
Mid	75 uJy	-0.86	-1.48	-0.75	-0.7	5 uJy
Top	50 uJy	-1.1	0	-0.82	-0.7	

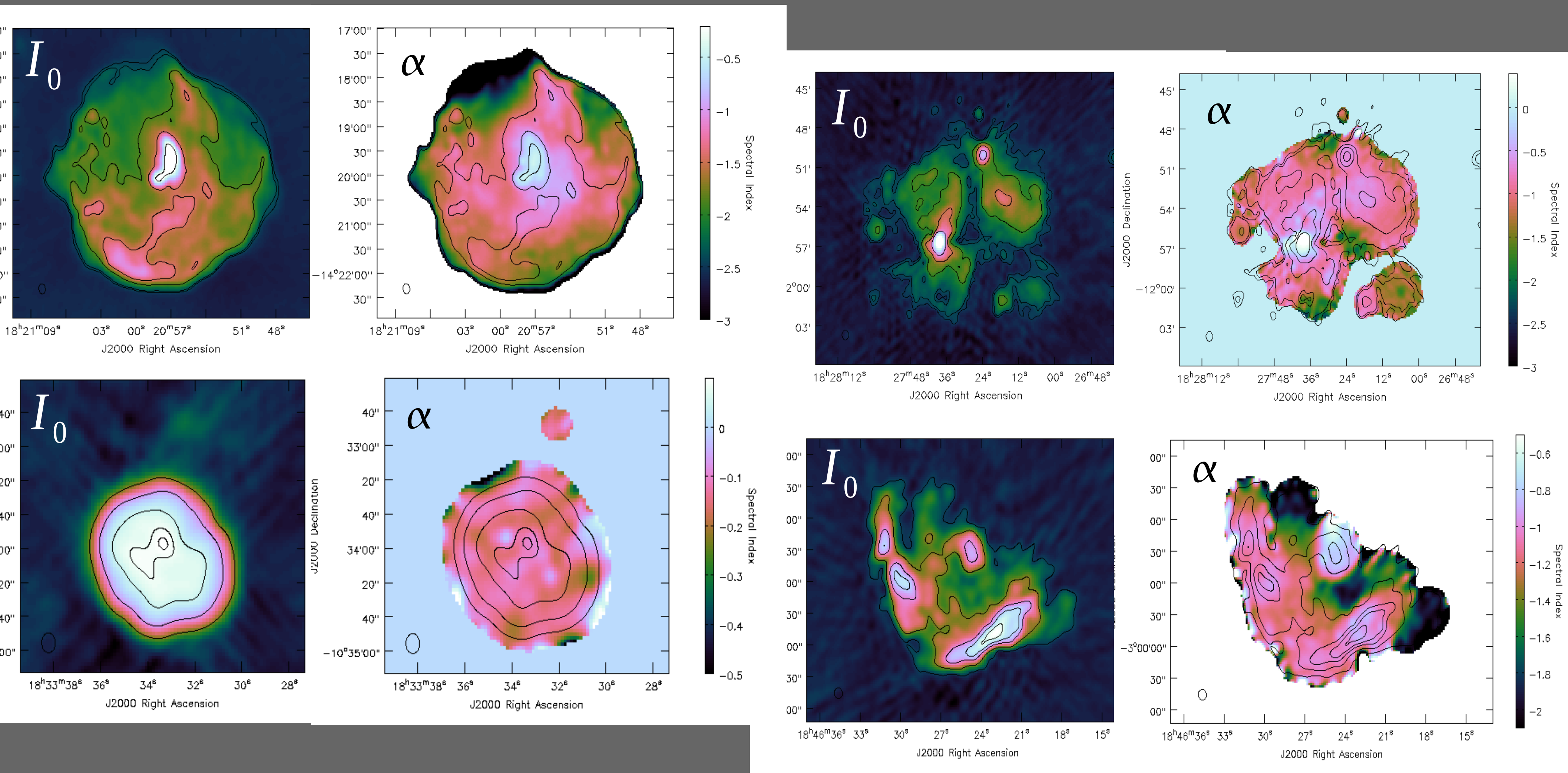


=> To trust spectral-index values, need SNR > 50 (within one band), or SNR > 10 (across bands)

=> Error-bars follow standard polynomial-fitting rules.

Extended Emission : Imaging Stokes-I and Spectral-Index

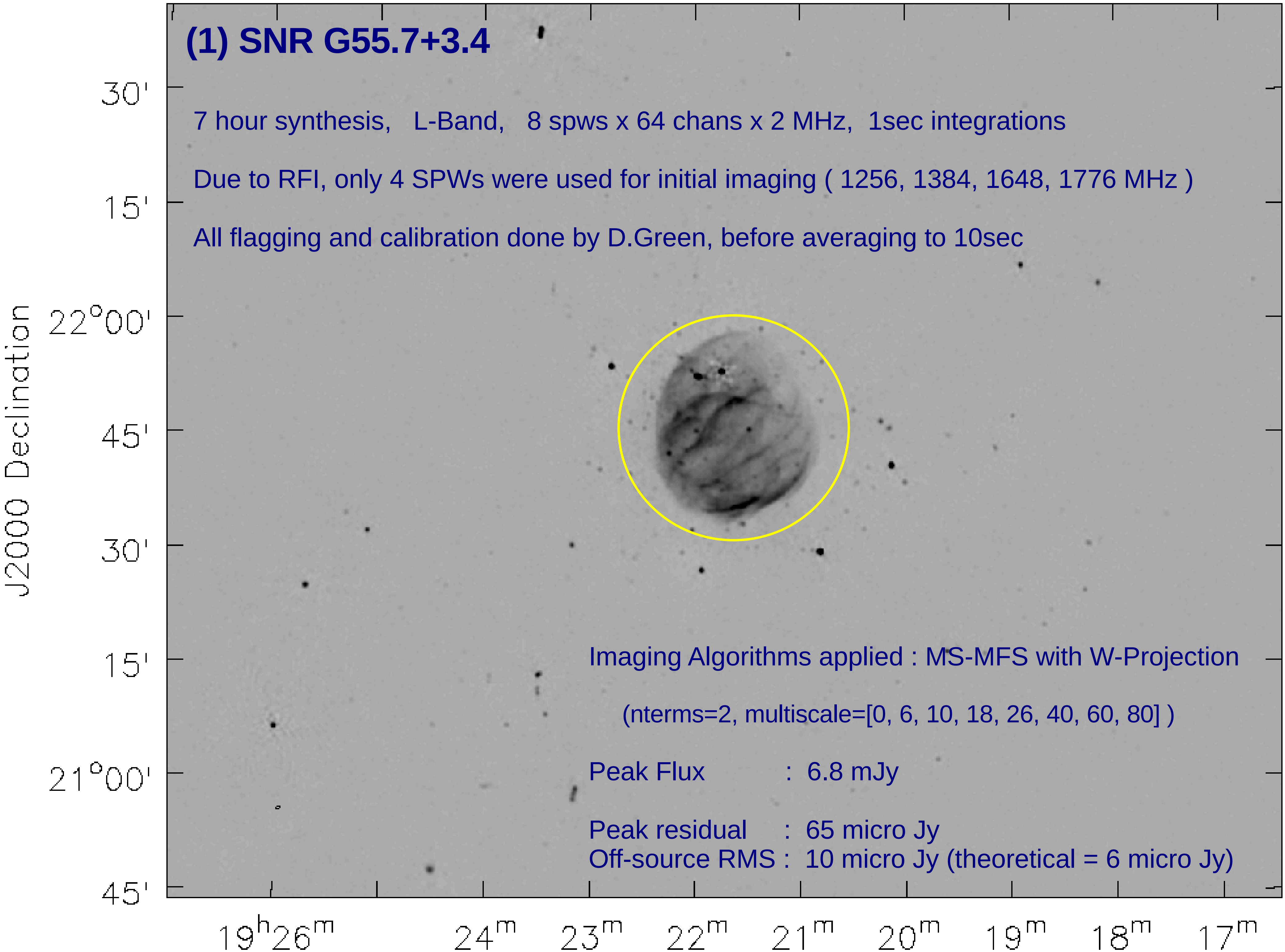
Separating regions/sources based on spectral index structure



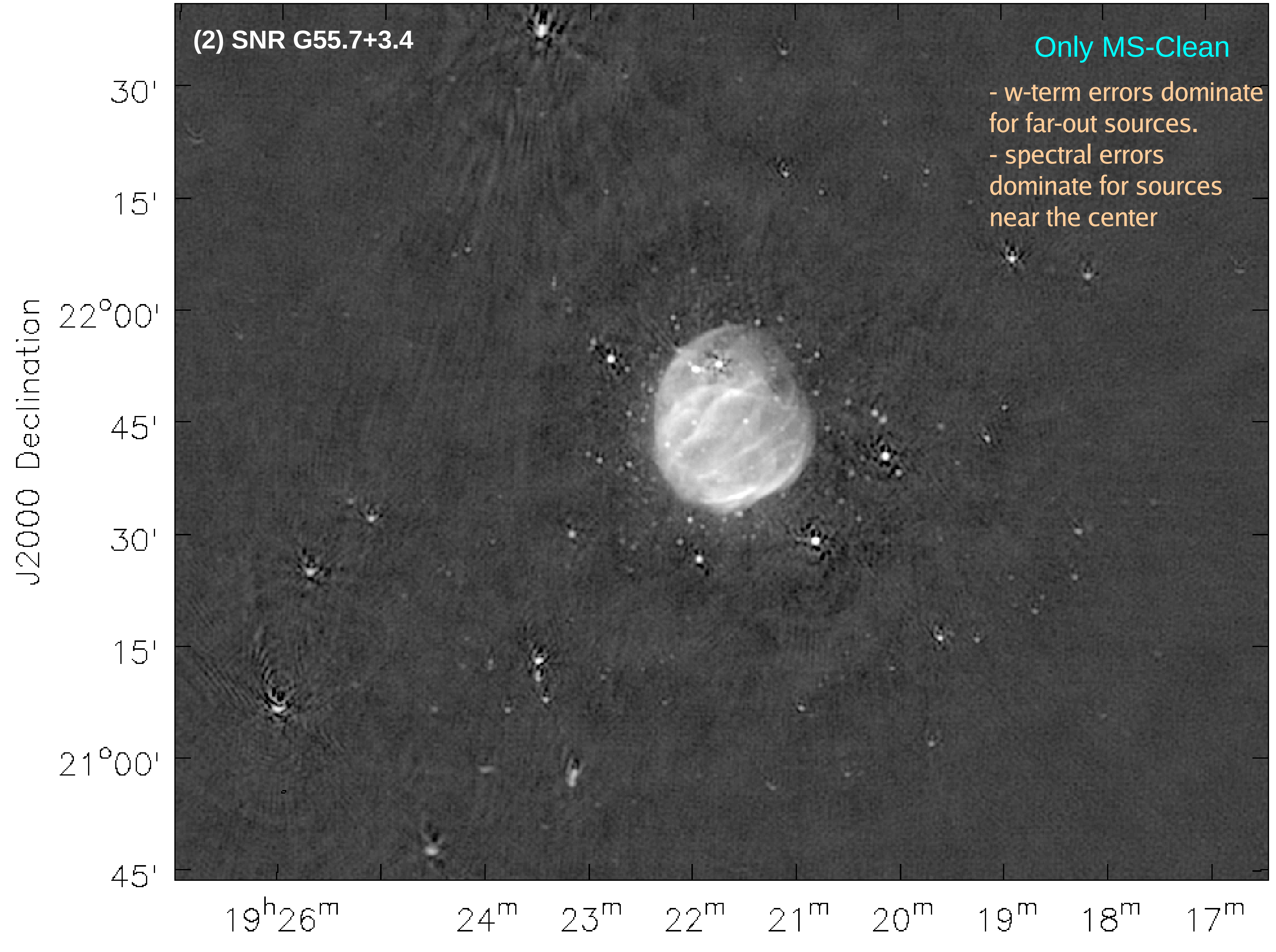
Initial results of a pilot survey (SNRs in the Galactic Plane).

(See ApJL EVLA special issue : S.Bhatnagar, D.Green, R.Perley, U.Rau, K.Golap , “EVLA Observations of Galactic Supernova Remnants – wide-field continuum and spectral-index imaging” – arXiv:1106.2796)

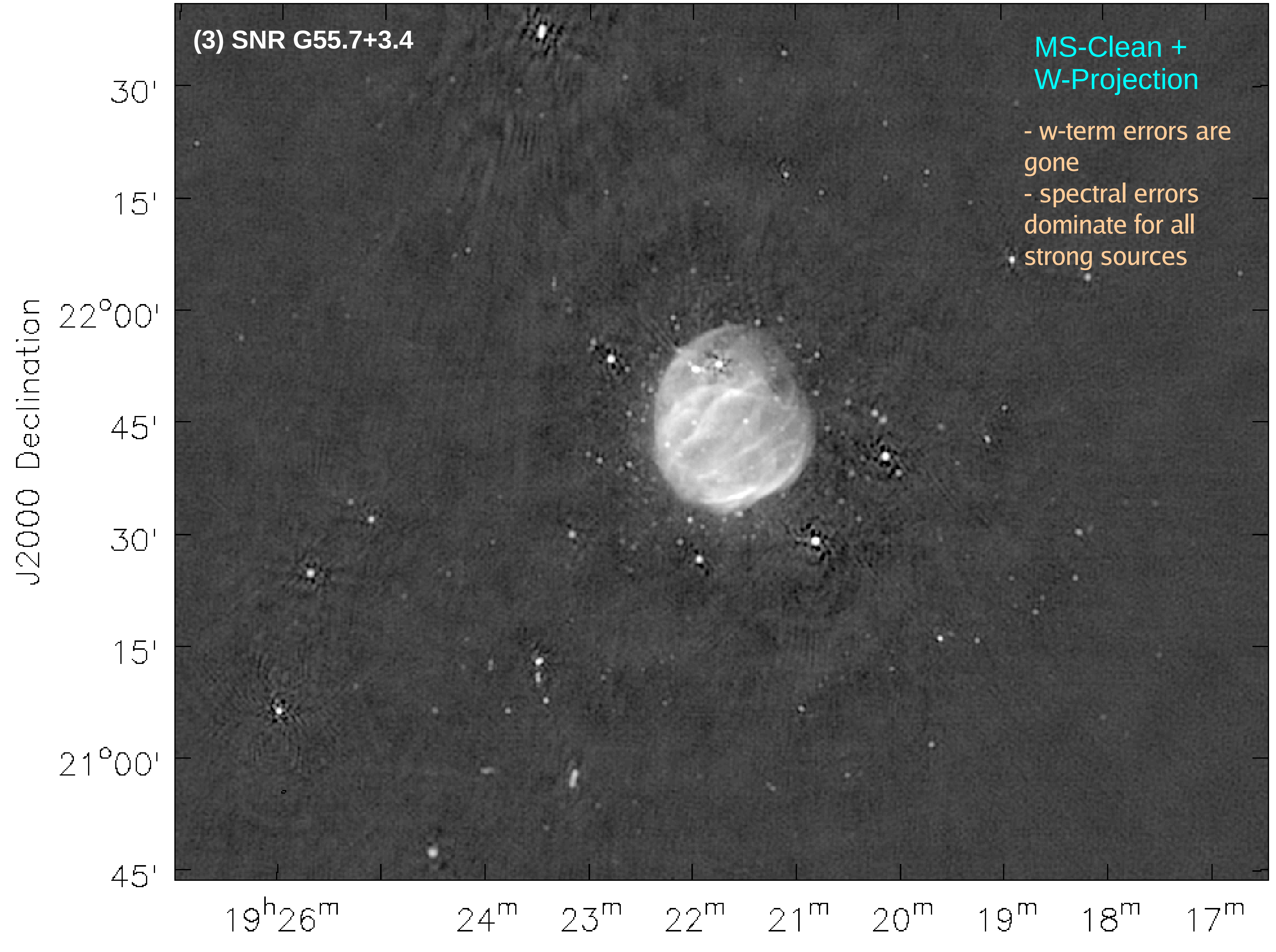
=> Within L-band and C-band, can tell-apart regions by their spectral-index (+/- 0.2) if snr>100

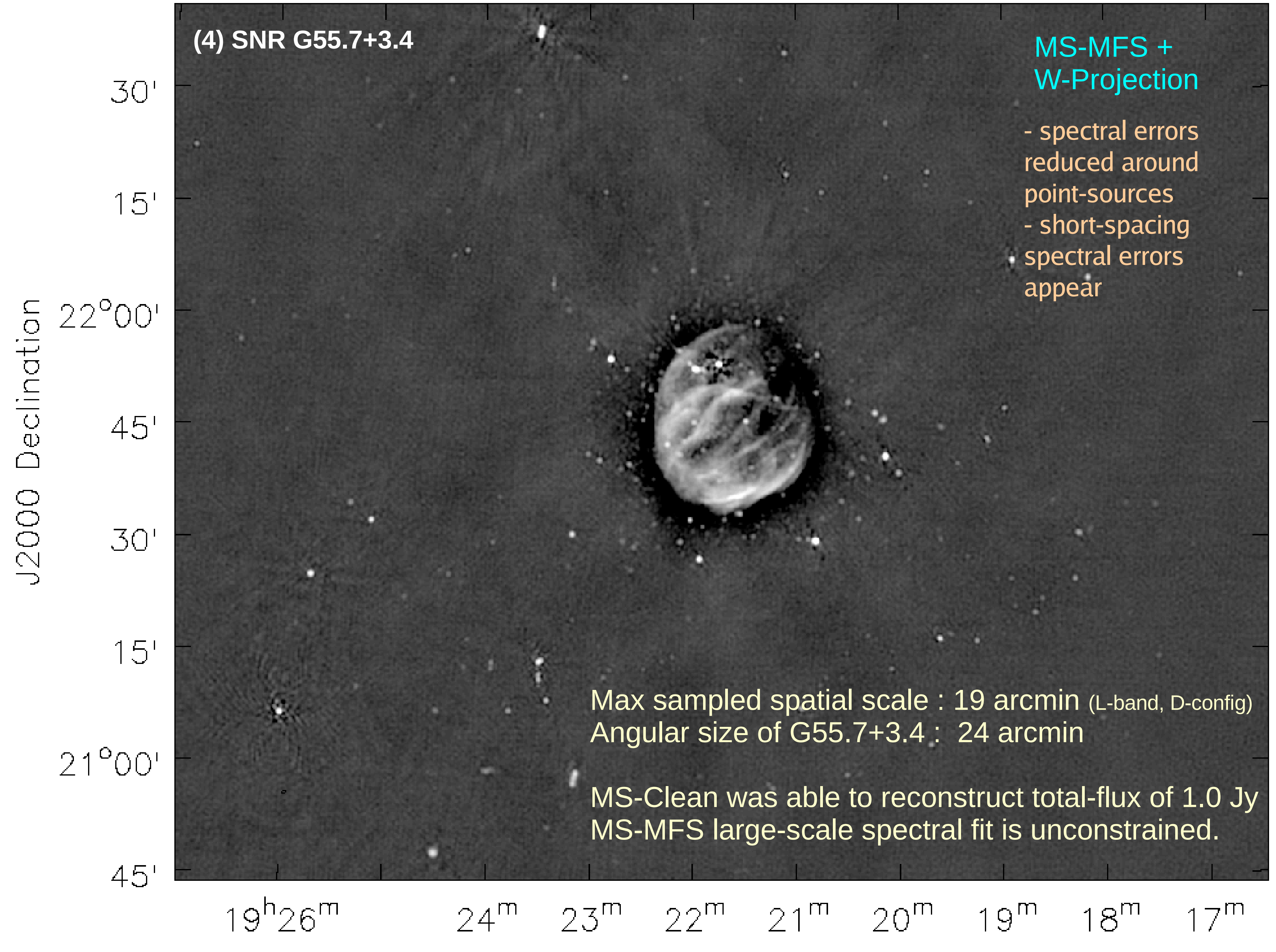


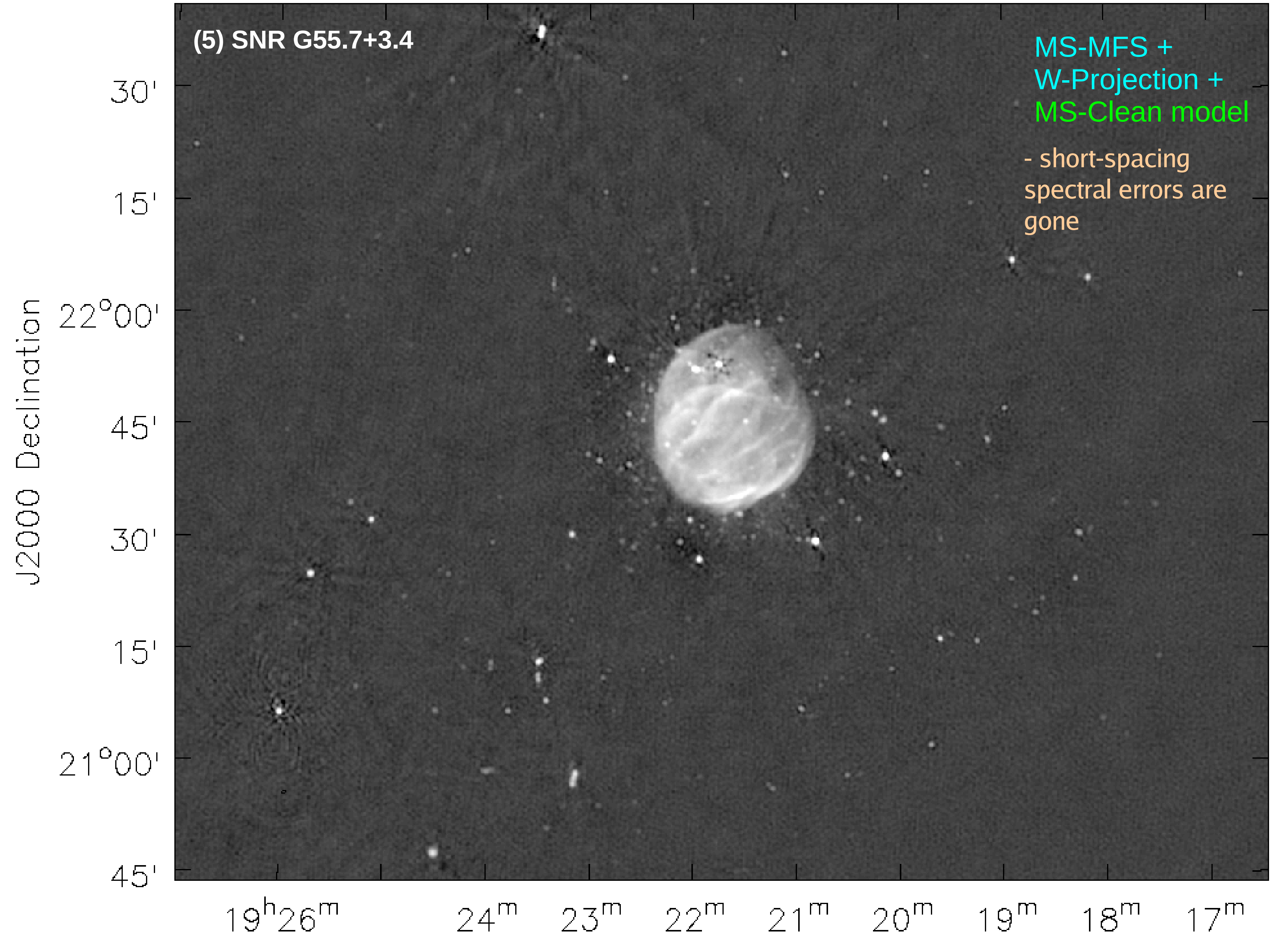
(1) SNR G55.7+3.4
7 hour synthesis, L-Band, 8 spws x 64 chans x 2 MHz, 1sec integrations
Due to RFI, only 4 SPWs were used for initial imaging (1256, 1384, 1648, 1776 MHz)
All flagging and calibration done by D.Green, before averaging to 10sec
Imaging Algorithms applied : MS-MFS with W-Projection
(nterms=2, multiscale=[0, 6, 10, 18, 26, 40, 60, 80])
Peak Flux : 6.8 mJy
Peak residual : 65 micro Jy
Off-source RMS : 10 micro Jy (theoretical = 6 micro Jy)
J2000 Declination
30'
15'
22°00'
45'
30'
15'
21°00'
45'
19h26m
24m
23m
22m
21m
20m
19m
18m
17m



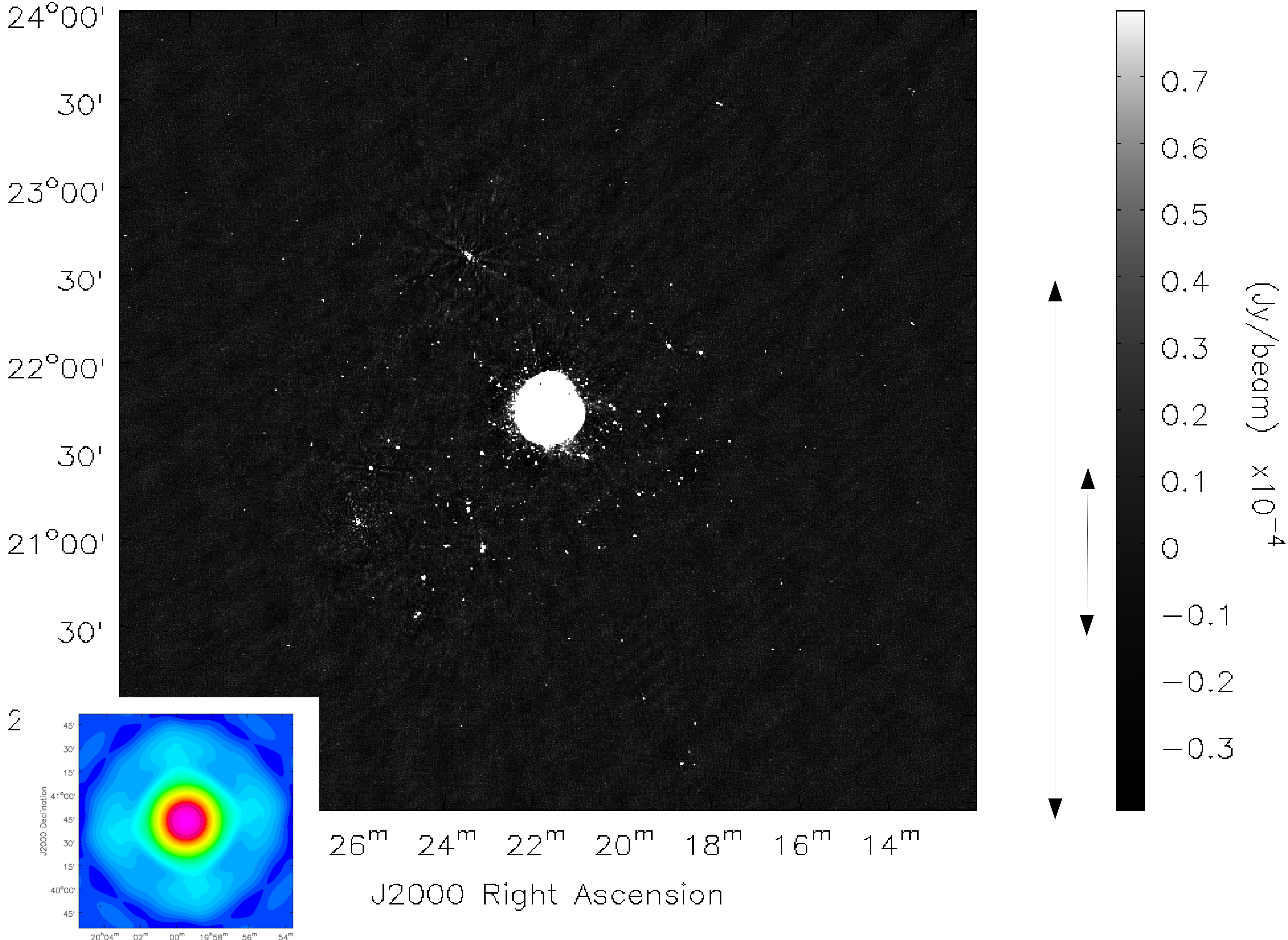
(2) SNR G55.7+3.4
Only MS-Clean
- w-term errors dominate for far-out sources.
- spectral errors dominate for sources near the center
J2000 Declination
30'
15'
22°00'
45'
30'
15'
21°00'
45'
19h26m
24m
23m
22m
21m
20m
19m
18m
17m


(3) SNR G55.7+3.4
MS-Clean +
W-Projection
- w-term errors are gone
- spectral errors dominate for all strong sources
J2000 Declination
30'
15'
22°00'
45'
30'
15'
21°00'
45'
19h26m
24m
23m
22m
21m
20m
19m
18m
17m

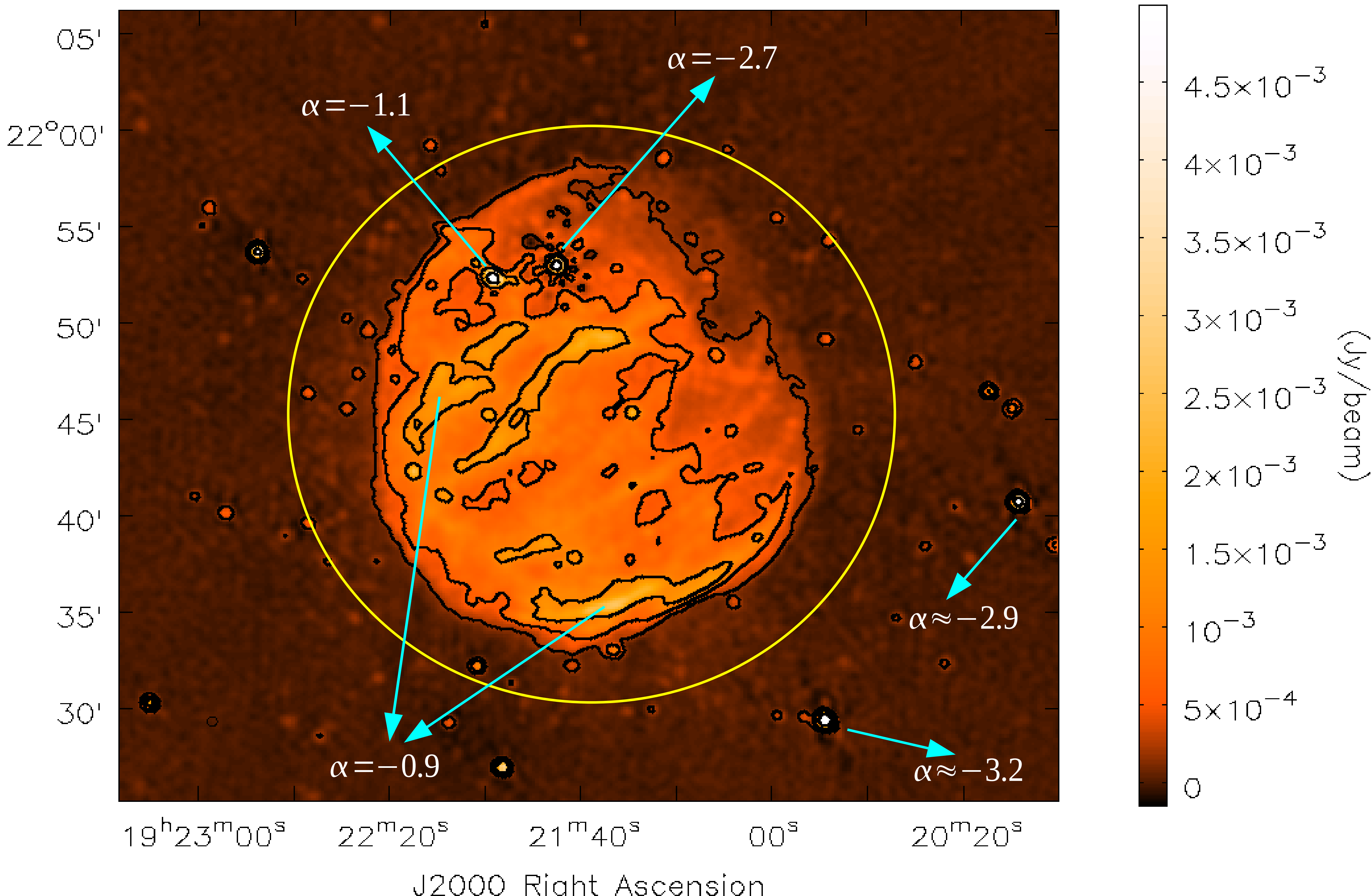

(4) SNR G55.7+3.4
MS-MFS +
W-Projection
- spectral errors reduced around point-sources
- short-spacing spectral errors appear
Max sampled spatial scale : 19 arcmin (L-band, D-config)
Angular size of G55.7+3.4 : 24 arcmin
MS-Clean was able to reconstruct total-flux of 1.0 Jy
MS-MFS large-scale spectral fit is unconstrained.
J2000 Declination
30'
15'
22°00'
45'
30'
15'
21°00'
45'
19h26m
24m
23m
22m
21m
20m
19m
18m
17m


(5) SNR G55.7+3.4
MS-MFS +
W-Projection +
MS-Clean model
- short-spacing spectral errors are gone
J2000 Declination
30'
15'
22°00'
45'
30'
15'
21°00'
45'
19h26m
24m
23m
22m
21m
20m
19m
18m
17m

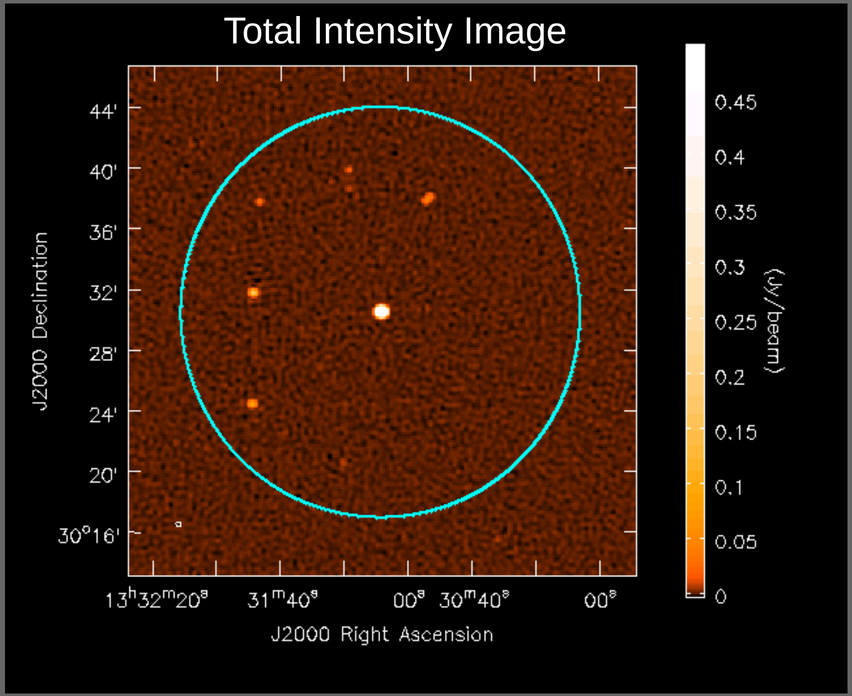
NR G55.7+3.4 : 4 deg x 4 deg FOV : ONE pointing : EVLA L-Band (~ 450 MHz bandwidth

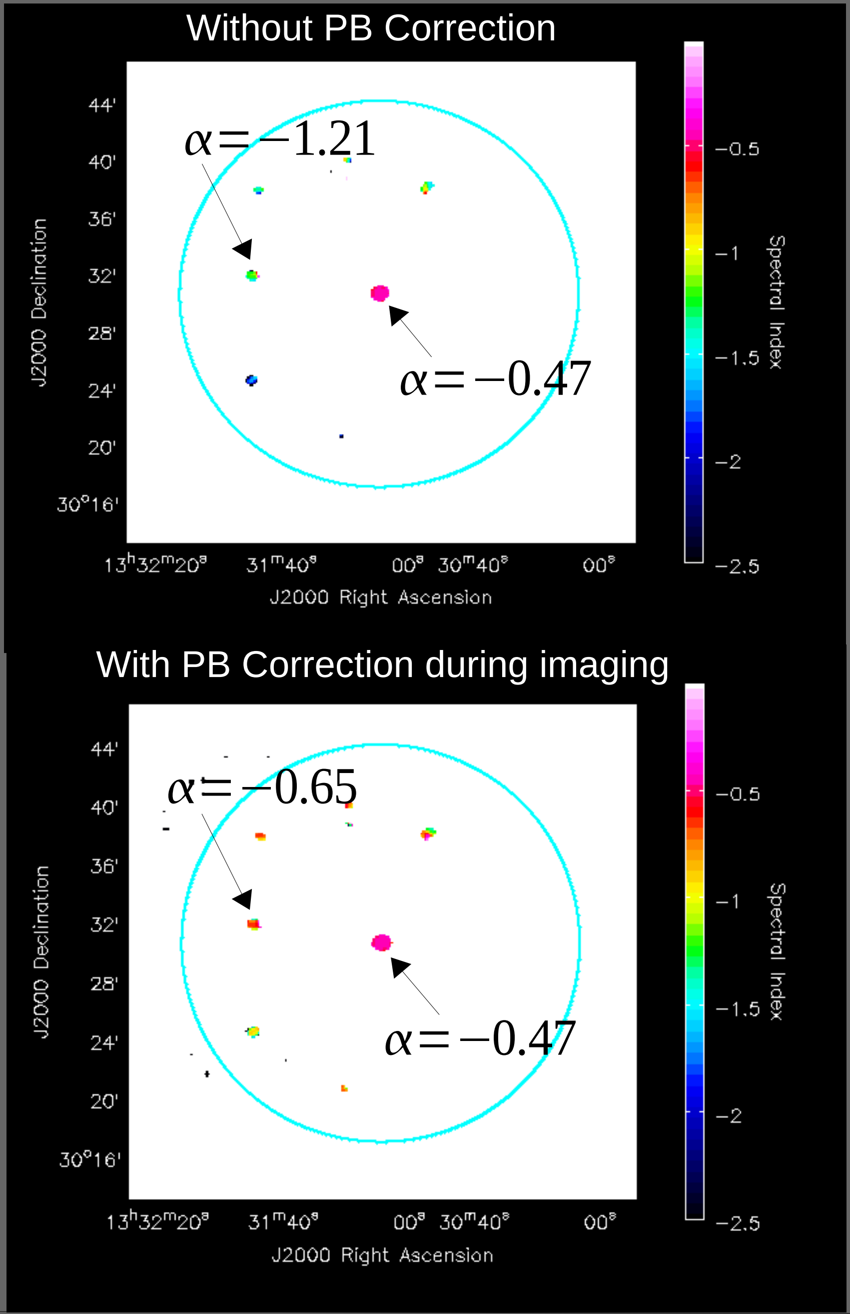


G55.7+3.4 : within the main lobe of the PB



Example : 3C286 field – wide-band PB correction





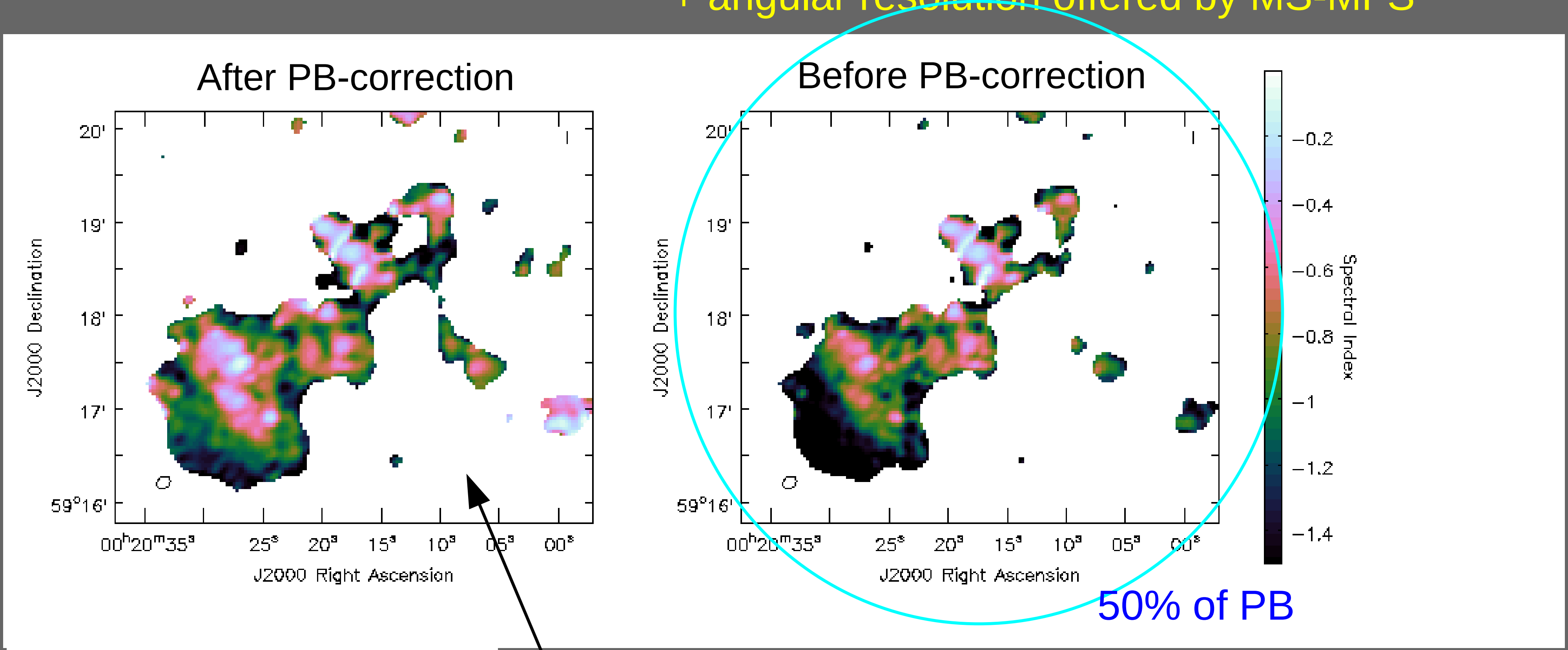
Verified spectral-indices by pointing directly at one background source.

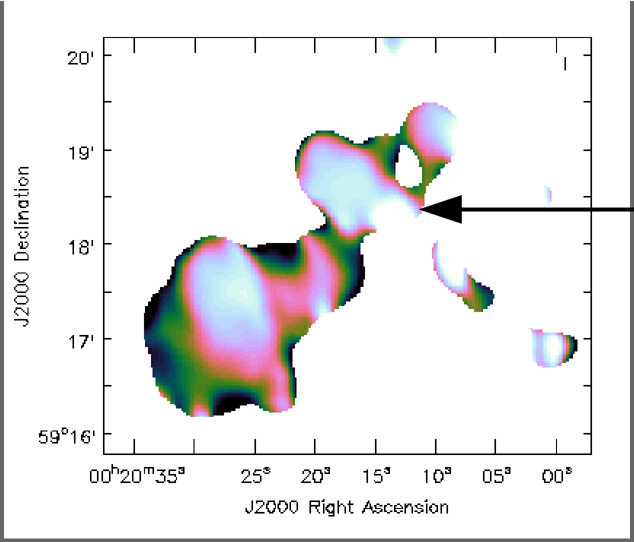
→ compared α_{center} with 'corrected' $\alpha_{off.center}$

Obtained $\delta\alpha$ = 0.05 to 0.1 for SNR or 1000 to 20

Also verified via holography observations at two frequencies

IC10 dwarf-galaxy : spectral-index : Wideband PB correction + angular resolution offered by MS-MFS

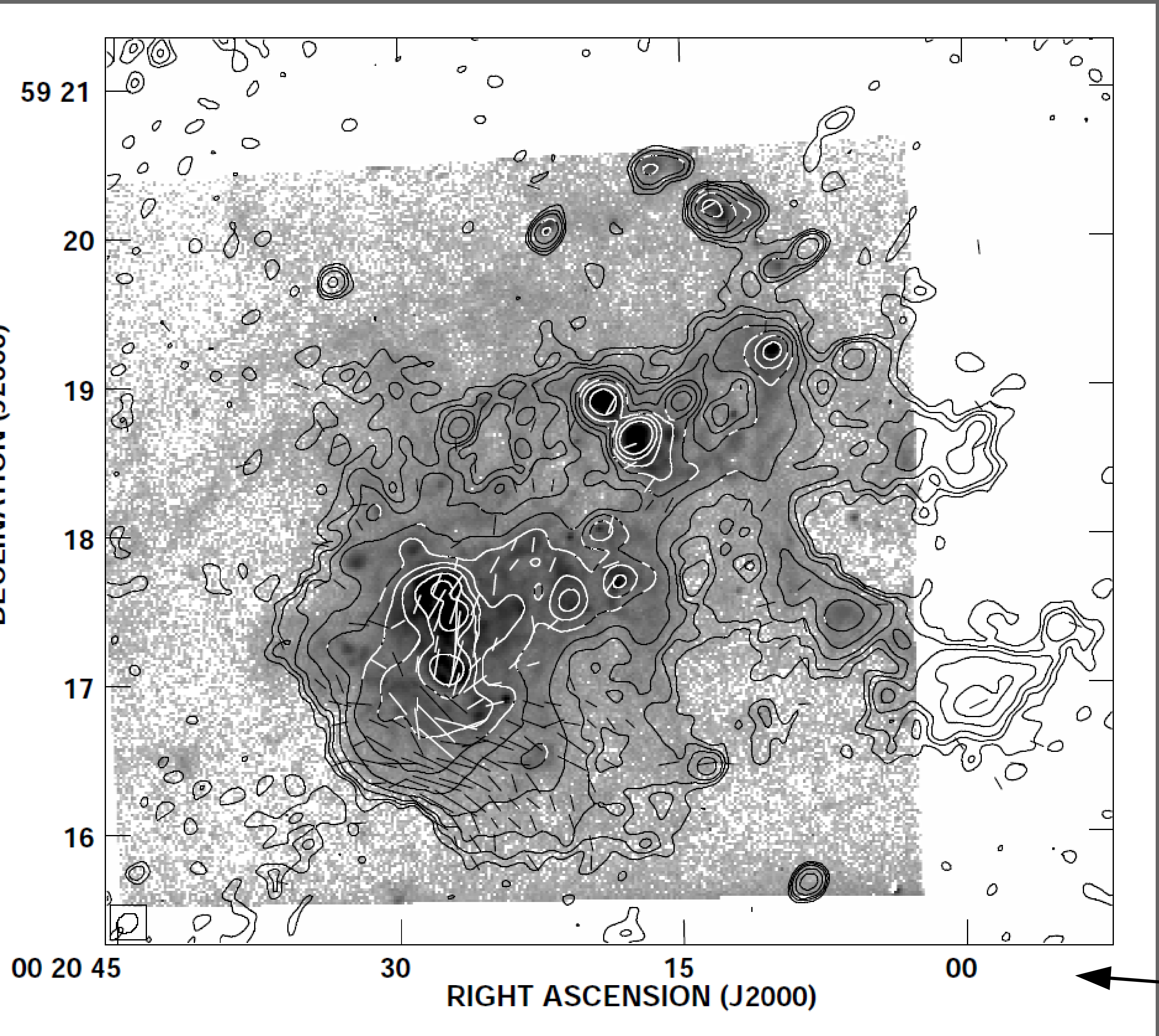




Result of post-MS-MFS wide-band PB-correction (CASA)

For comparison, spectral-index map made by PB-correcting single-SPW images smoothed to the lowest resolution (AIPS).

IC10 Dwarf Galaxy – Stokes IQUV, B-fields



Contours : Radio (5.0 GHz)
Grey : H-Alpha
Lines : B-field vectors

RMS (I,Q,U,V) : 4.6 micro Jy

Data : 3 hours of C-band data,
Theoretical rms : 3 micro Jy

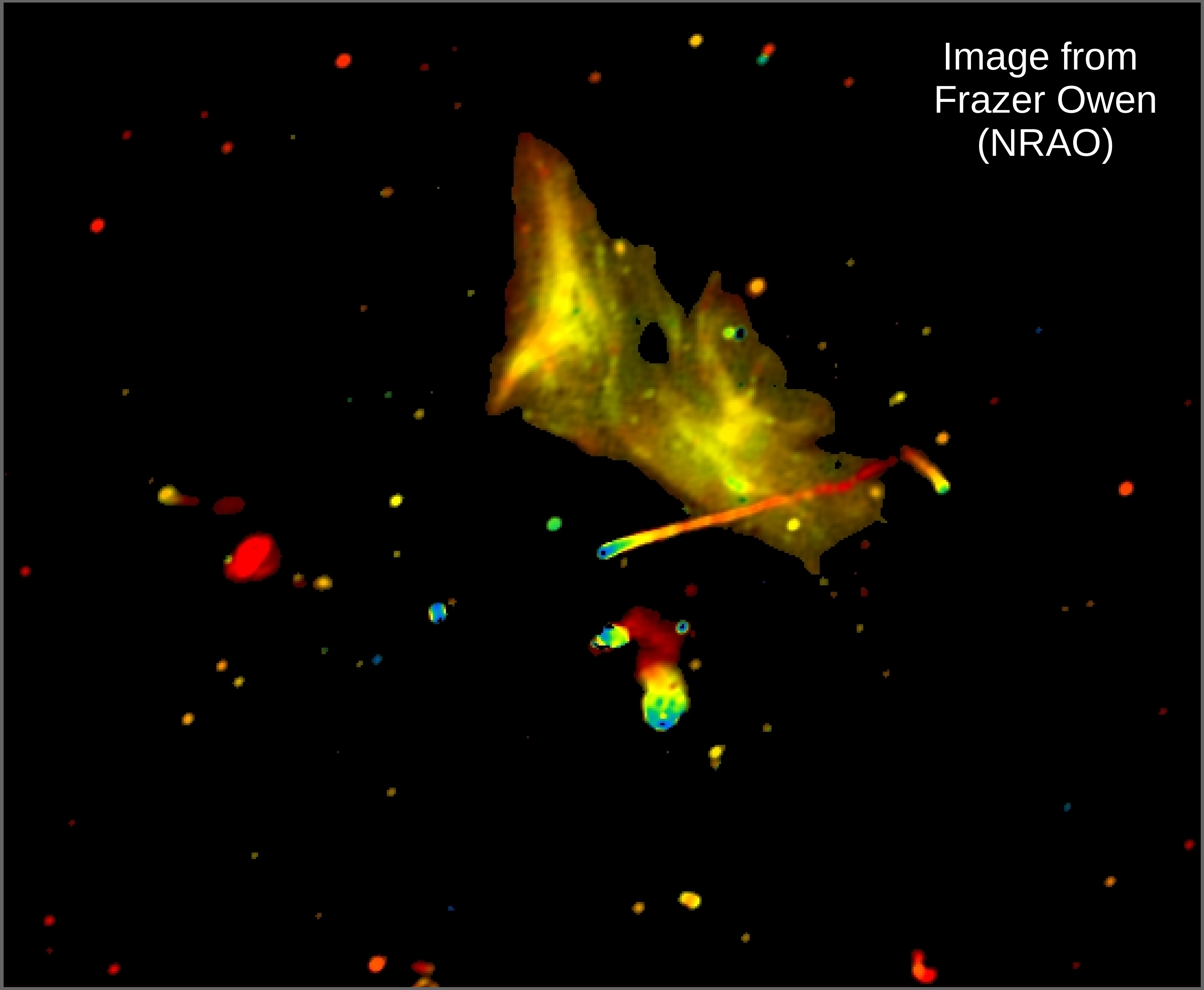
Peak flux : I : 11 mJy
Peak pol intensity : 50 micro Jy
(5 times the instrumental polarization – verified via test 3C84 observations)

"Deep Radio Continuum Imaging of the Dwarf Irregular Galaxy IC 10: Tracing Star Formation and Magnetic Fields" – Volker Heesen, Urvashi Rau, Michael P. Rupen, Elias Brinks, and Deidre Hunter

(submitted to ApJL EVLA spl issue)

Figure from Volker Heesen

Abell-2256 : L-Band (1-2 GHz) : intensity-weighted spectral-index



Choices that effect errors

- Artifacts in the continuum image due to too few Taylor-terms.

High signal-to-noise point sources : use a higher-order polynomial.   Otherwise N=2 or 3.
N=1 gives a dyn-range limit < 1000 for 2:1 bw, and spectral-index=-1.0

- Error in spectral index/curvature due to low SNR (over-fitting)

Low signal-to-noise : use a linear approximation.

- Error propagation during the division of one noisy image by another.

Extended emission : use multiple spatial scales to minimize error in alpha (0.05 up to 0.5)

- Flux-models that are ill-constrained by the measurements

Choose scales/nterms appropriately. For very large scales, add short-spacing information.

- Wide-field errors : Time and Frequency-variability of the Primary Beam

Use W-projection, A-projection along with MS-MFS (software in progress)

Choices that effect performance (MS-MFS implementation)

- Major Cycle runtime x N_{taylor} (and size of dataset)

  – N_Taylor residual images are gridded separately; N_Taylor model images are 'predicted'.
  – Wide-field corrections are applied during gridding (A-W-Projection, mosaicing).

- Minor Cycle runtime x $N_{taylor} N_{scales} N_{pixels}$

- Minor Cycle memory x $\left[0.5\left(N_{taylor} N_{scales}\right)^2 + N_{taylor} + N_{taylor} N_{scales}\right] N_{pixels}$

- Rate of convergence : Typical of steepest-descent-style optimization algorithms - logarithmic.

  Some source structures will handle loop-gains of 0.3 to 0.5 or more.

Runtimes reported by different people have ranged from 1 hr to several days.

=> Mostly due to differences in goals (reconstruct source-structure vs eliminate off-source artifacts, or both), point-sources vs large objects, and usage habits of people ; data size is secondary !

Wide-band (self) calibration

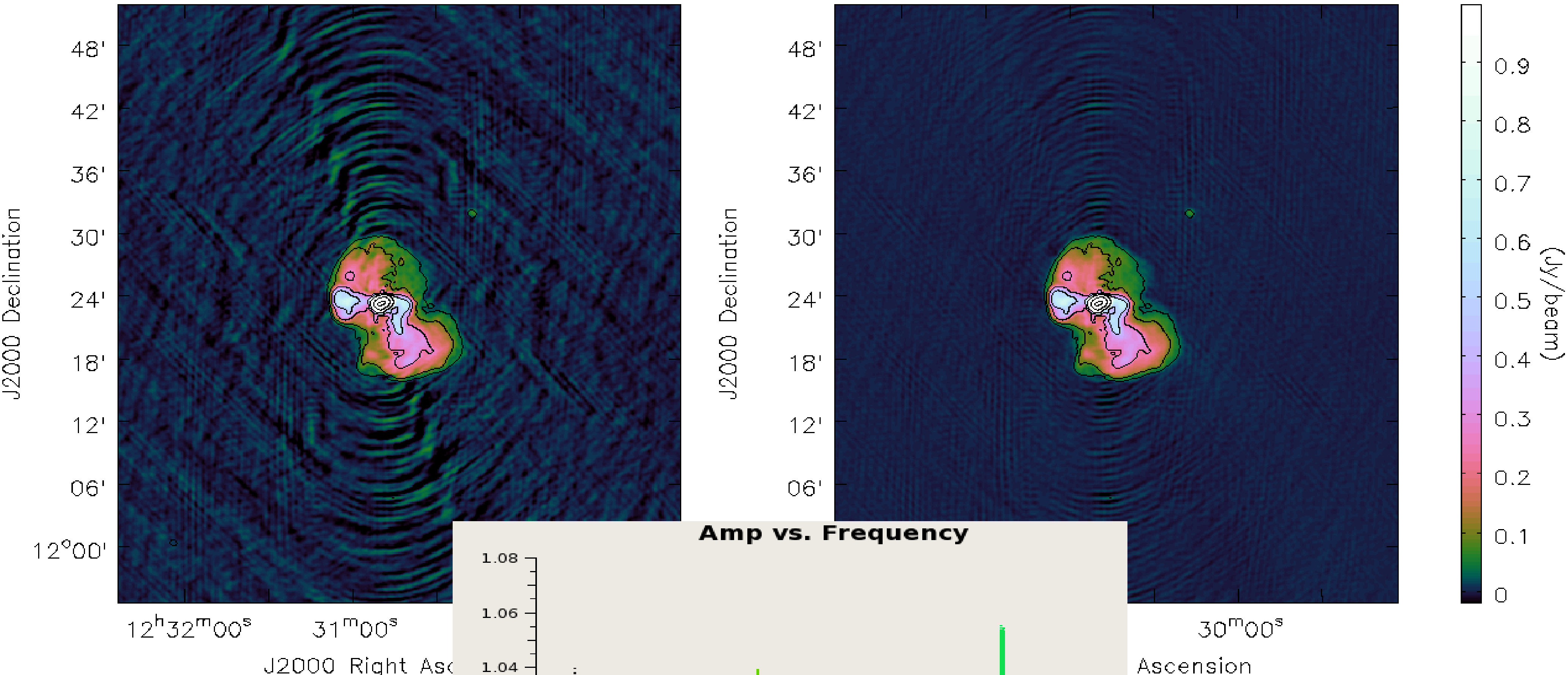
Goal : Maintain continuity of gain solutions across subbands.

- Flux/Bandpass calibration with an a-priori wide-band model
  - Perley-Taylor 1999 / Perley-Butler 2010 (evaluate spectrum)
  - Calibrator model images (fit and evaluate a spectrum - ms-mfs)
  - Note : due to increased sensitivity - need wide-field model images

- Use single-subband solutions to fit for polynomial bandpass solutions
  - simpler, doesn't require wide-band imaging, better for low snr...

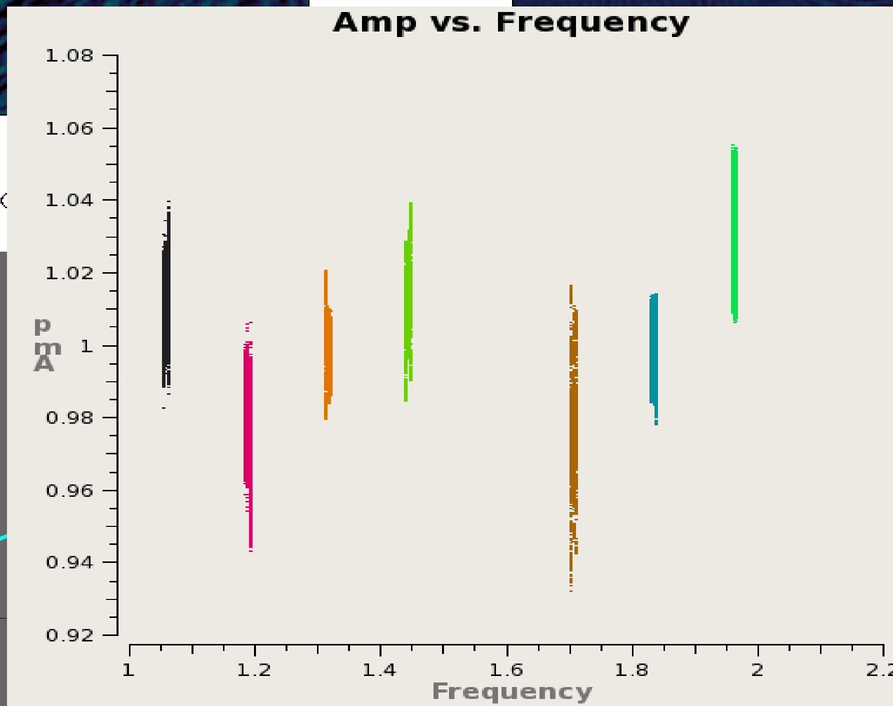
- Self-Calibration with the result of MS-MFS
  - In CASA, 'clean' writes wide-band model visibilities to disk
  - Use this model for continuum-subtraction (for spectral-line work)

Wide-Band Self-Calibration : M87



Peak residual = 65 mJy/bm
Off-source rms = 18 mJy/bm

Amplitudes of bandpass gain solutions......

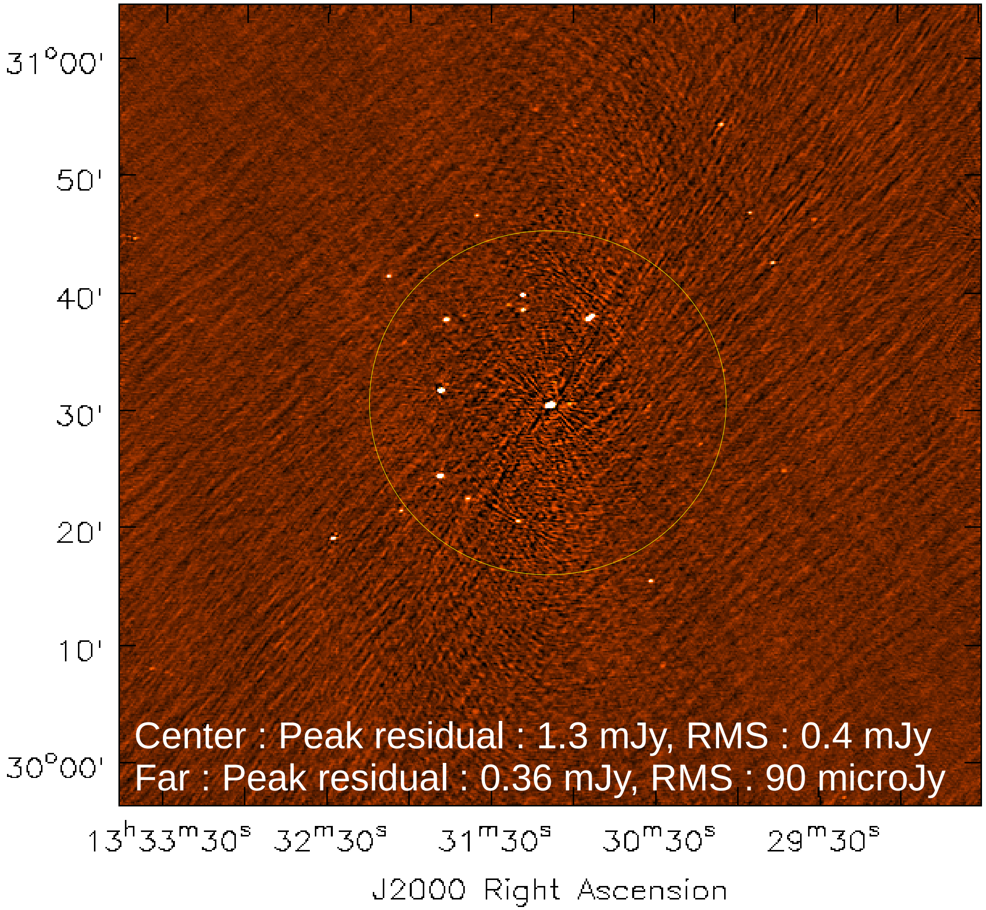


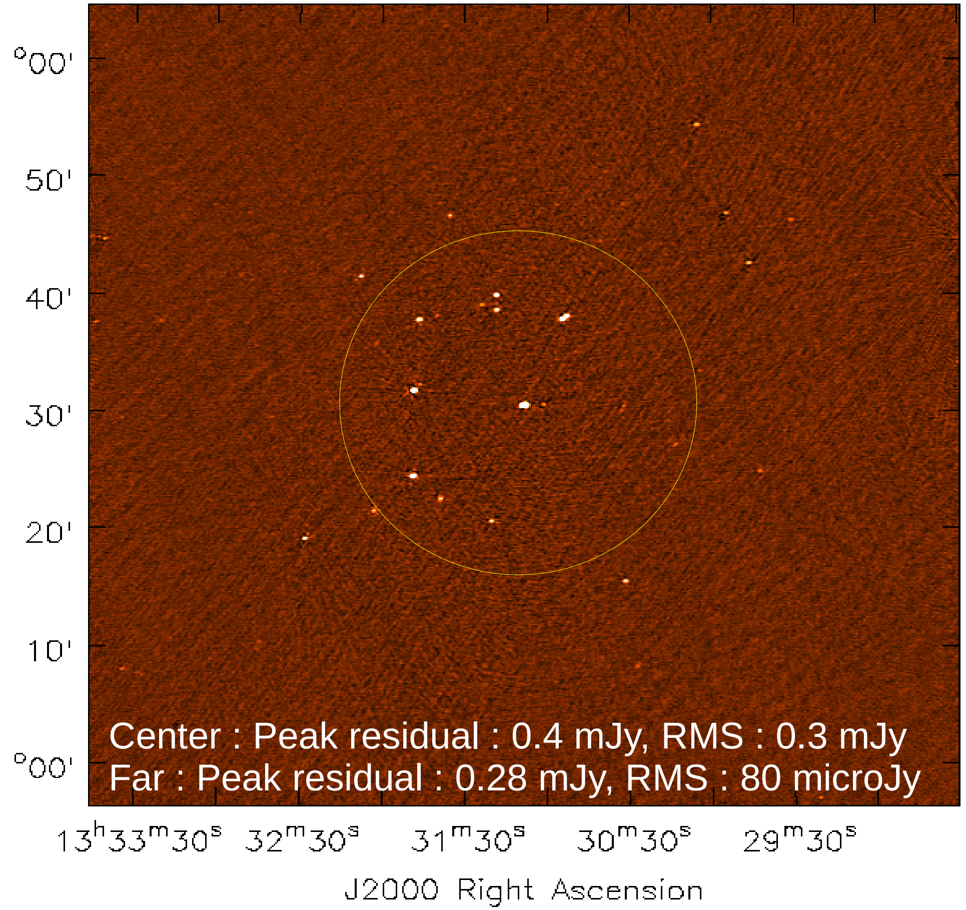
Peak residual = 32 mJy/bm
Off-source rms = 5 mJy/bm

Off-source dyn range = 50000

5 chans x 7 spectral-windows

3C286 field (one pointing – without and with 'baseline' self-calibration)





16 SPW x 64 chans x 1 MHz

1 sec integrations

30 mins of data

Theoretical rms : 30 micro-Jy

Obtained rms (off source)
: 85 micro Jy

Dynamic Range : 170,000

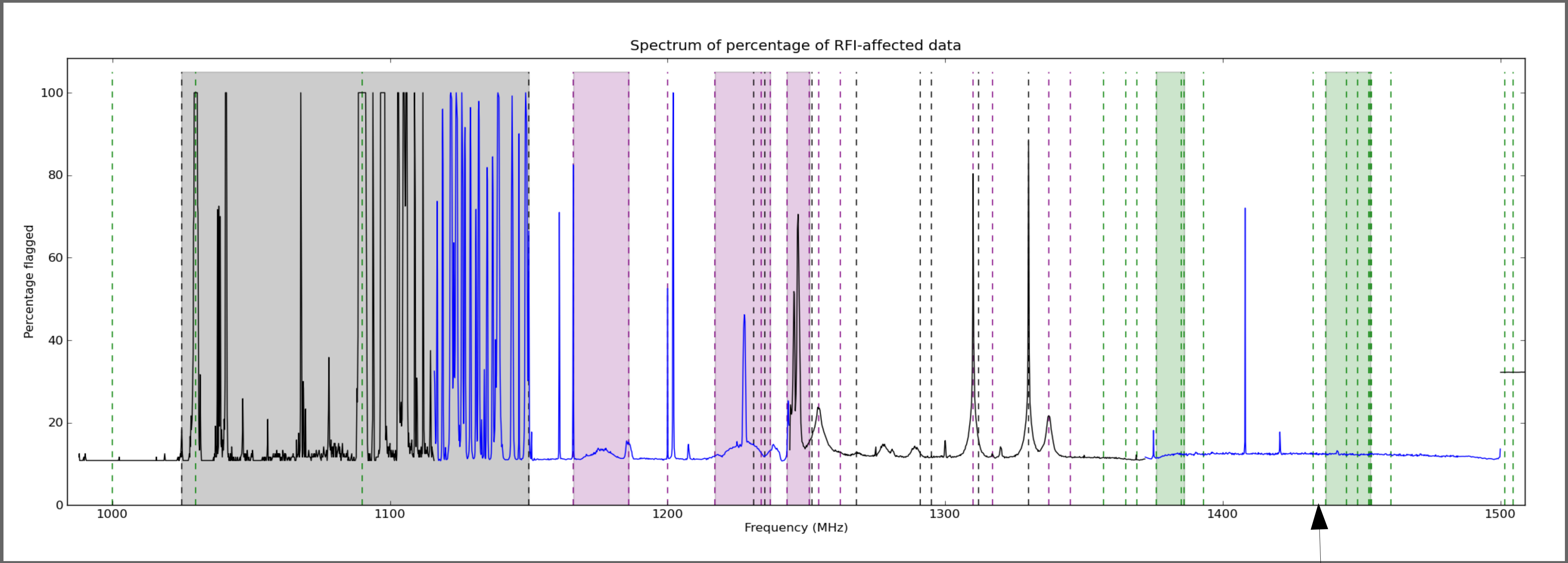
- Two rounds of bandpass calibration (30s intervals)
- Two rounds of auto-flagging (corrected, residuals)
- One “baseline-calibration”
  ---- (Pointing / Squint / etc....)
- MS-MFS with nterms=4

RFI and automatic flagging

At L-Band, can use ~500 MHz with very rough flagging, ~800 MHz if done carefully.

Tools for automatic flagging exist in CASA and AIPS; people are beginning to use/trust them.

CASA : TFCrop (fit a smooth function to the time-freq plane, and find outliers)
AIPS : RFLAG (statistics-based flagger with automatic threshold-calculation)



Plots of RFI at the EVLA between 1 GHz and 50 GHz :
http://www.aoc.nrao.edu/~mrupen/EVLA_RFI

Example summary-plot from CASA/TFCrop - % of data flagged + known RFI (vs frequency)

Summary

EVLA has been producing wide-band data for RSRO science since Fall 2010.

From Fall 2011, wide-band modes, and software to analyse these data, will be available to everyone.

From this one year of data,

- Large data sizes : ~300GB per observation (on average)
  - Progress on data-parallelization (CASA)
- A lot of RFI at the lower bands
  - Autoflagging tools have been made available (CASA/AIPS/LOFAR)
- Achieving wide-band sensitivity, and spectral-reconstructions
  - MS-MFS algorithm in CASA; Obtaining science-results from it.

    (For other types of science-results from the EVLA, see ApJL Special-Issue)
- Wide-band and wide-field imaging
  - Promising initial results; work in progress on software.