Wide-band imaging with the EVLA

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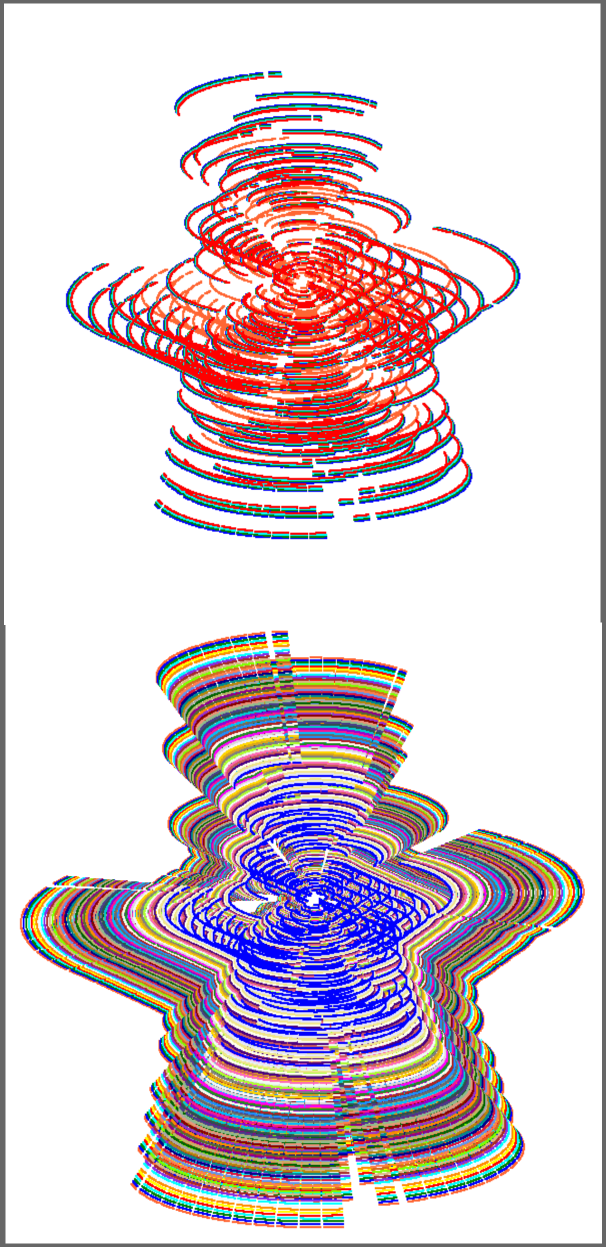
(2) MS-MFS details - 6

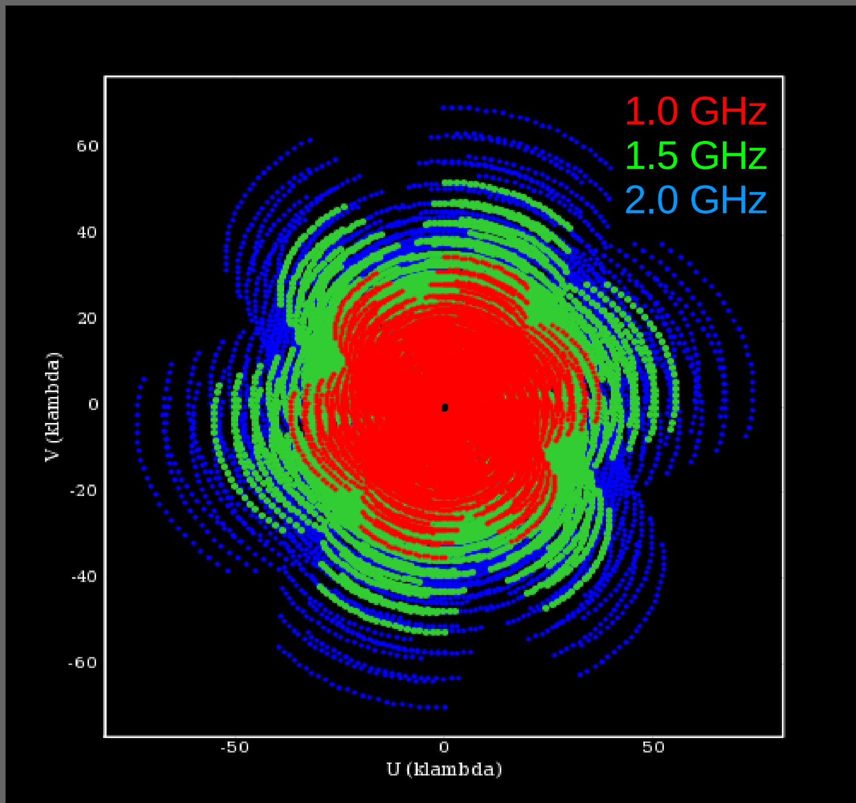
(3) Examples on EVLA data - 11

(4) Self-calibration and continuum subtraction - 3



Multi-Frequency Synthesis (MFS)

VLA C configuration UV-coverage

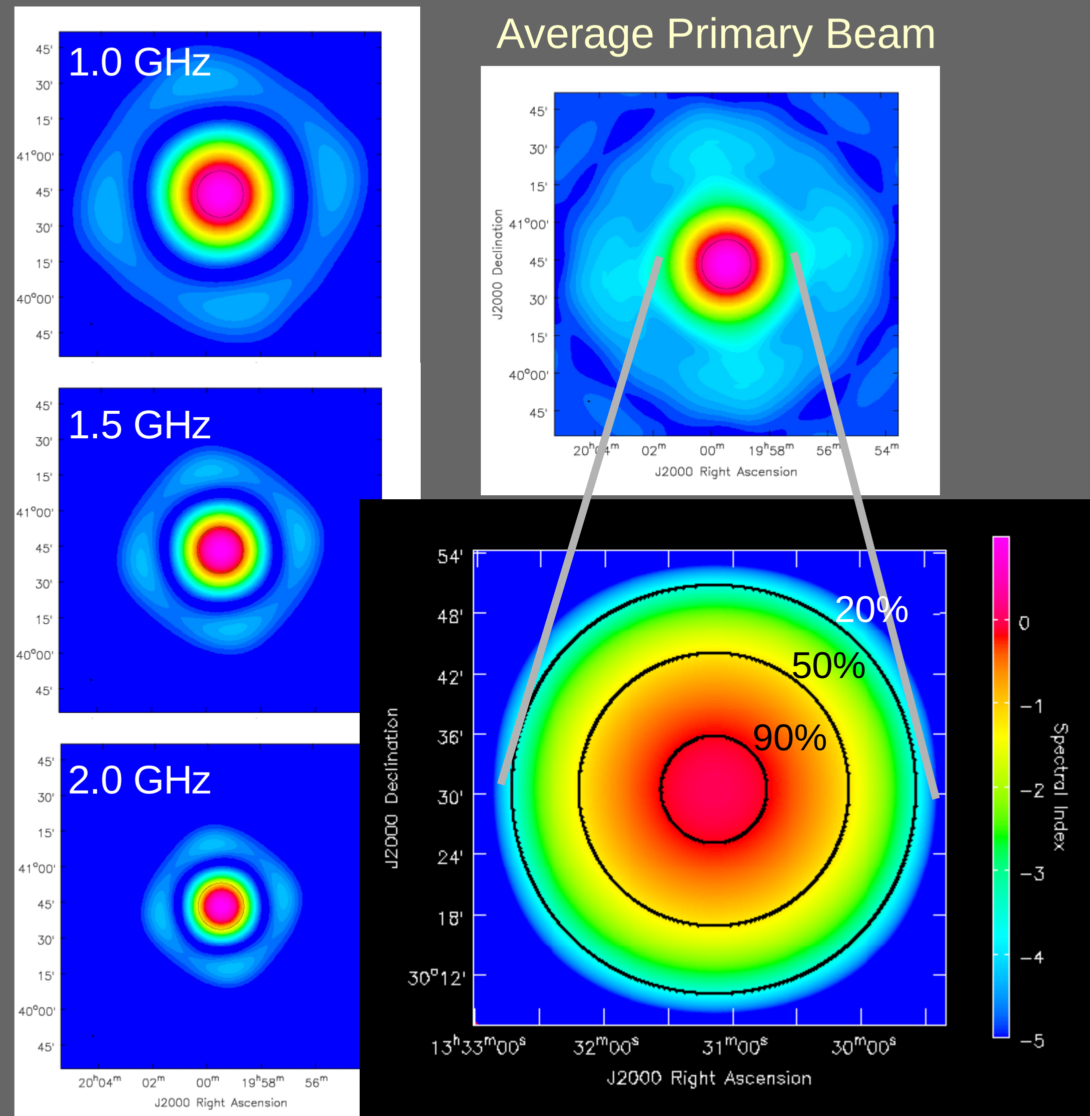


MFS : Combine all channels during imaging

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

- Sky brightness changes with frequency

Multi-Frequency Primary Beams



Spectral Index of PB

MS-MFS : as implemented in CASA

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

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

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'

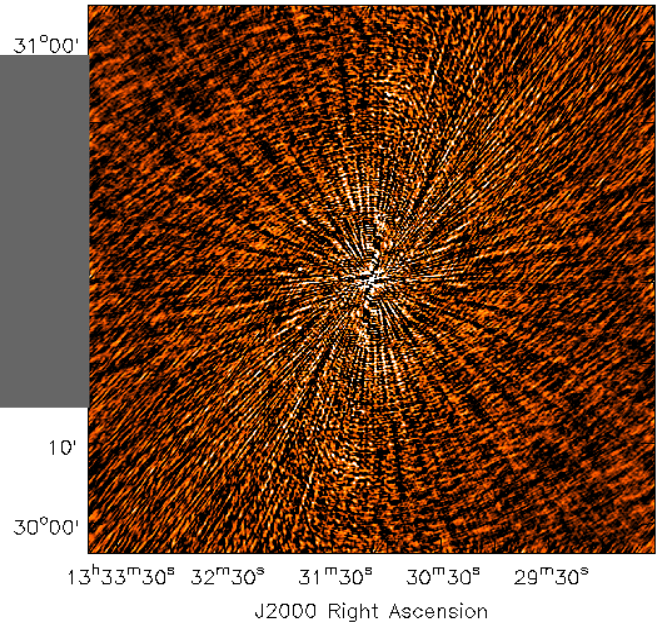
Image Reconstruction : Linear least squares + Deconvolution (+ W-Projection)

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)

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

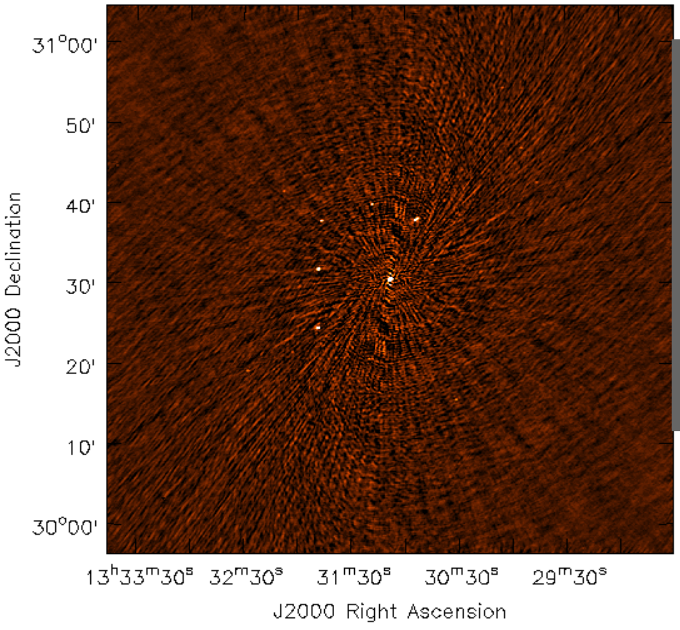
Dynamic Range (vs) NTERMS (I=14.4 Jy/bm, alpha = -0.47, BW=1.1GHz at Lband)



NTERMS = 1

Rms :
9 mJy -- 1 mJy

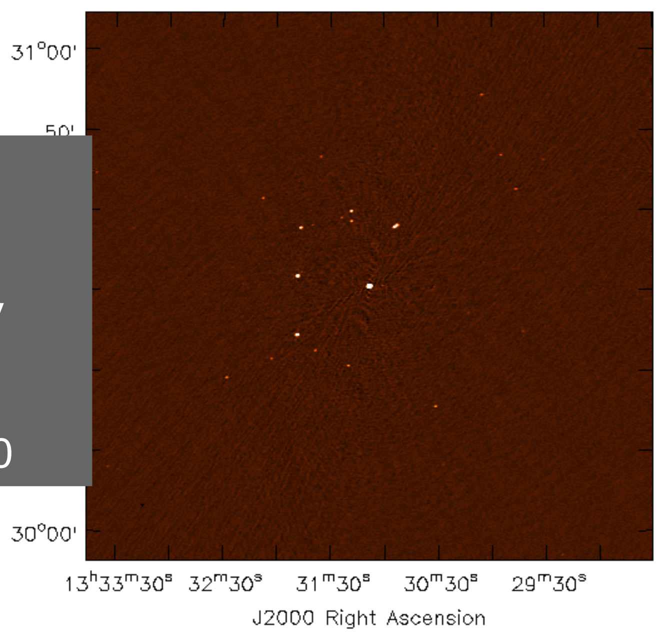
DR :
1600 -- 13000



NTERMS = 2

Rms :
1 mJy -- 0.2 mJy

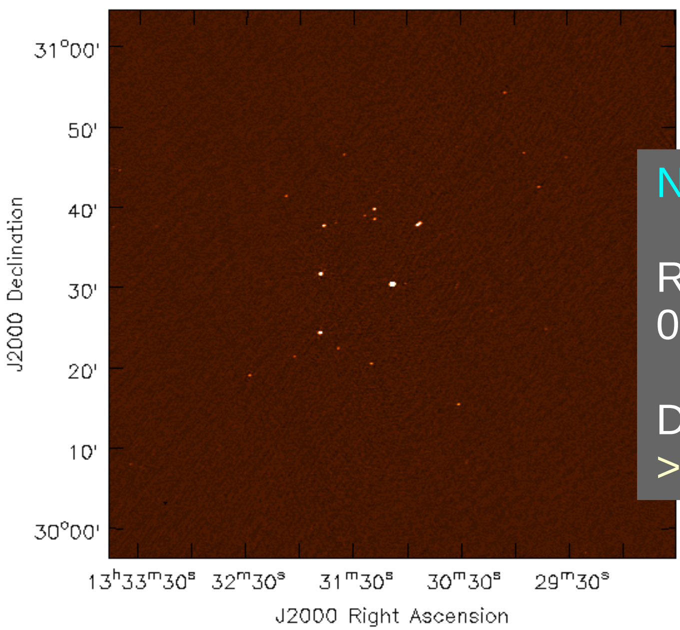
DR :
10,000 -- 17,000



NTERMS = 3

Rms :
0.2 mJy -- 85 uJy

DR :
65,000 -- 170,000

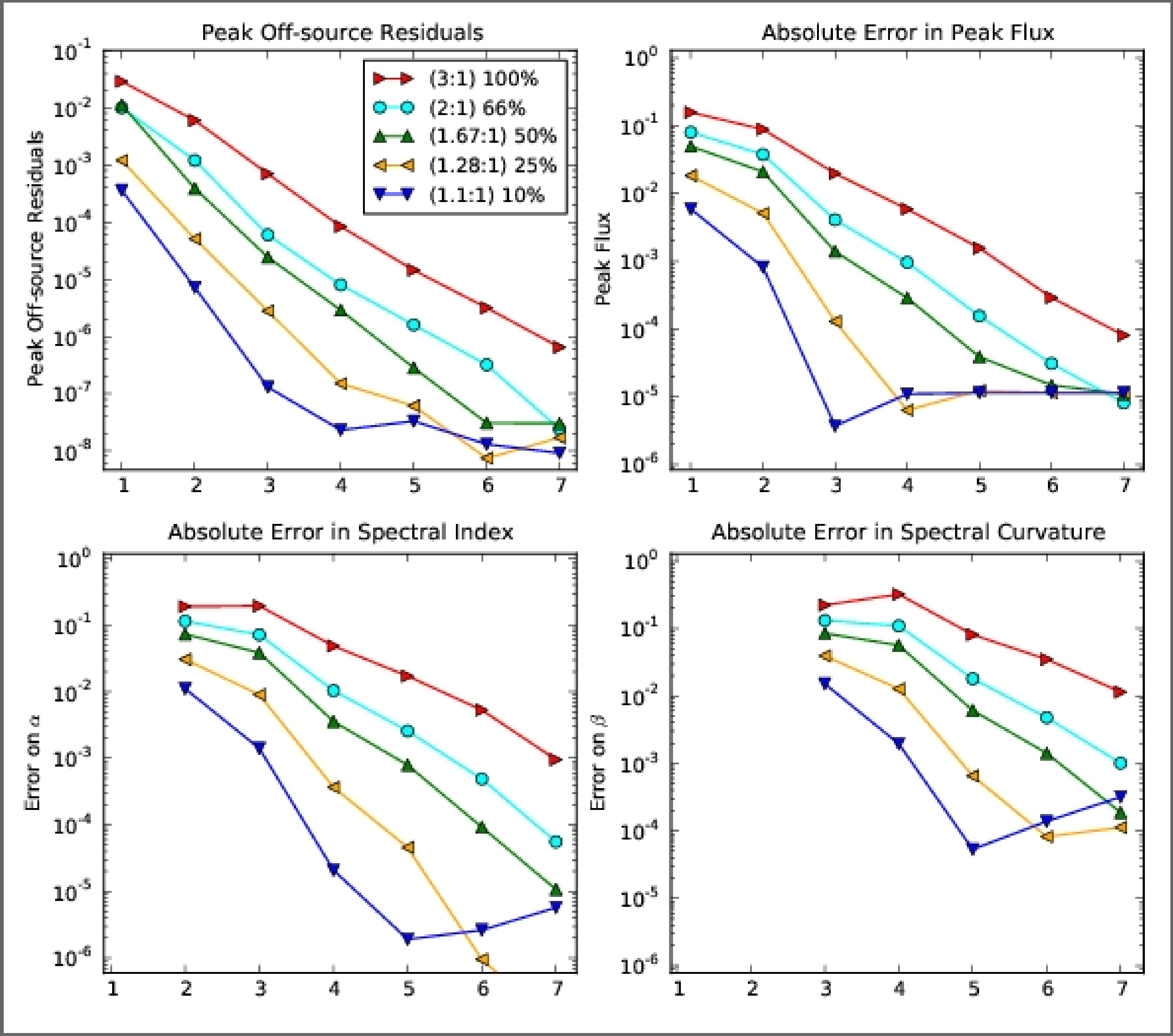


NTERMS = 4

Rms
0.14 mJy -- 80 uJy

DR :
>110,000 -- 180,000

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

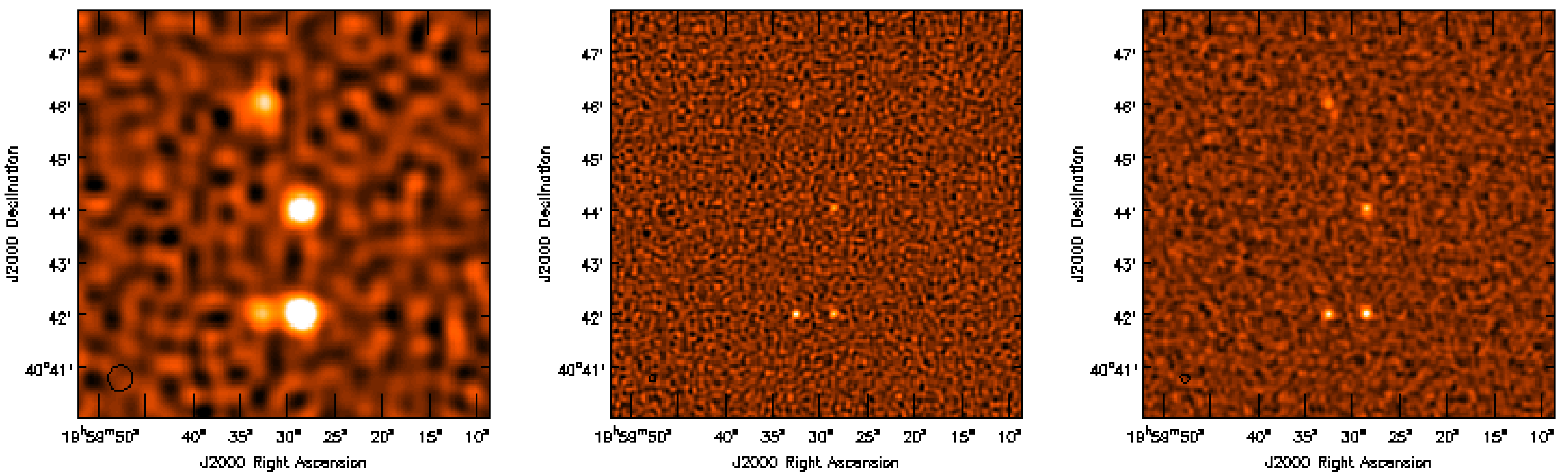


These plots are for a single point-source at the phase center, with very high signal-to-noise levels.

In practice, use more than nterms=2 or 3 only if there is sufficient signal-to-noise, and if you can see spectral artifacts in the image with nterms=2 or 3.

Accuracy of spectral-index vs frequency-range (and SNR)

Source	Peak Flux	L alpha	C alpha	LC alpha	True	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	

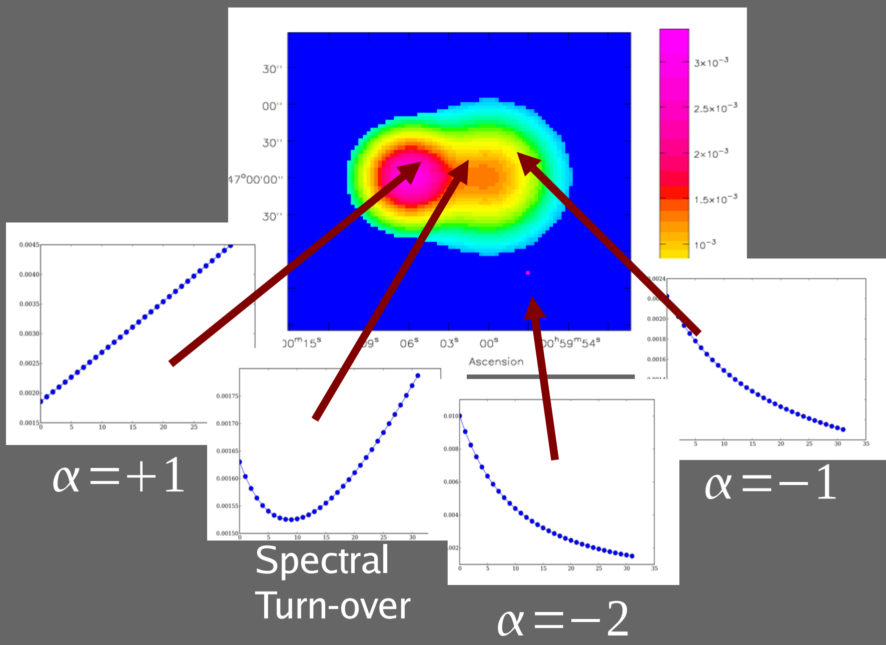


=> To trust spectral-index values, need SNR > 50 (within one band), or SNR > 10 (across bands)

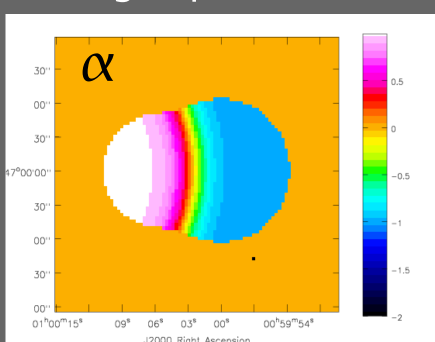
=> Error-bars follow standard polynomial-fitting rules.

Multi-Scale vs Point-Source model for wideband imaging

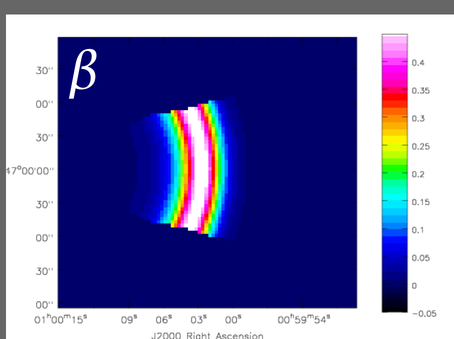
Intensity Image

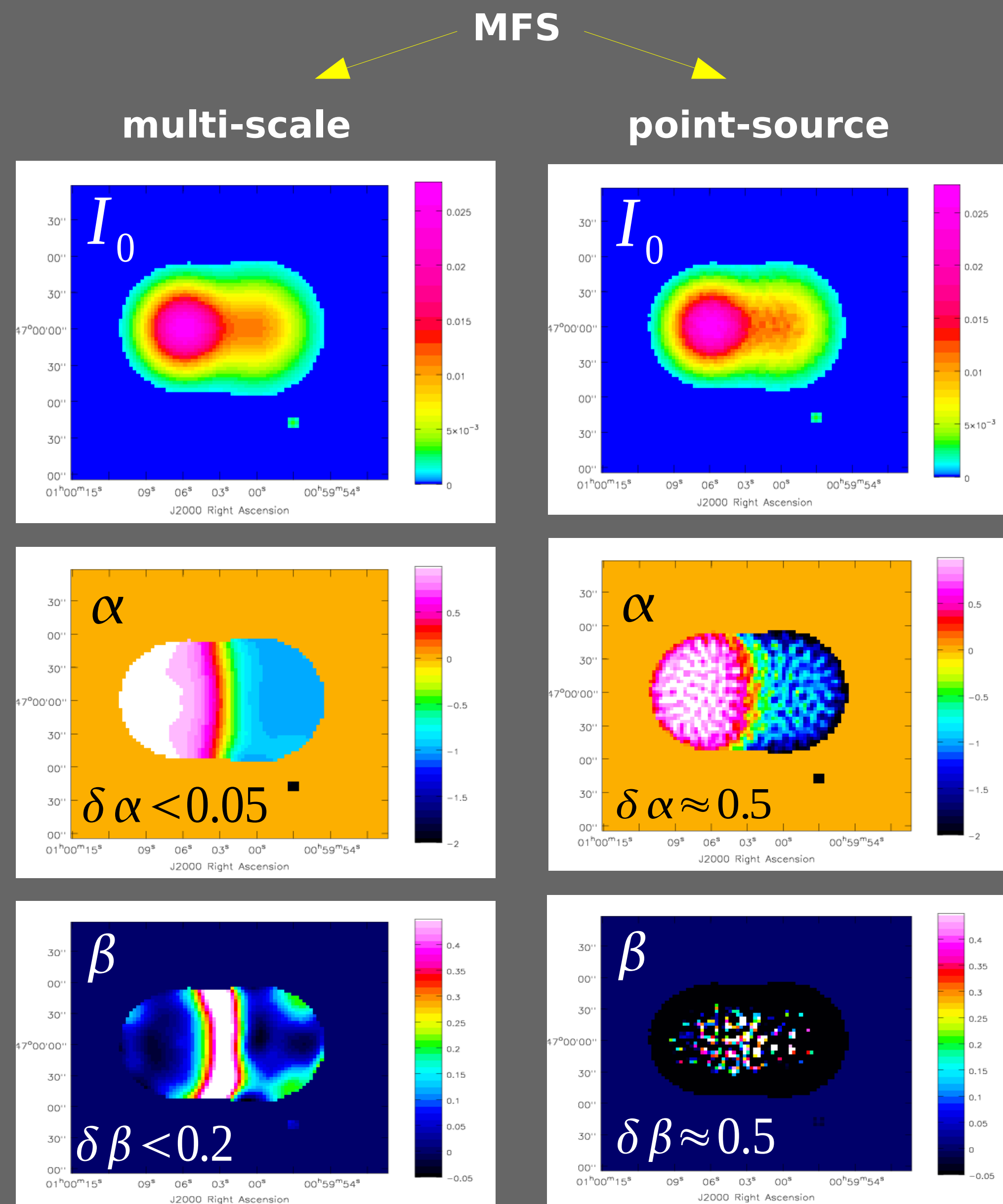


Average Spectral Index



Gradient in Spectral Index

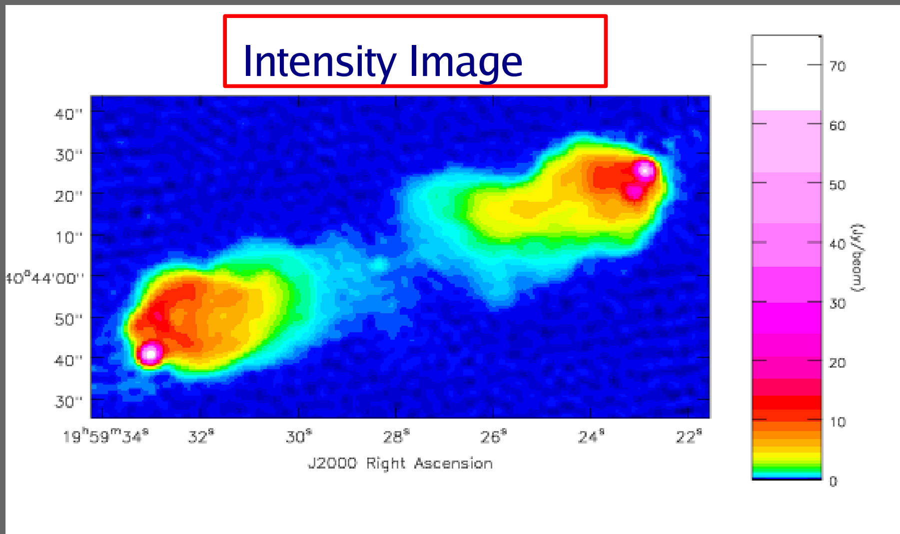


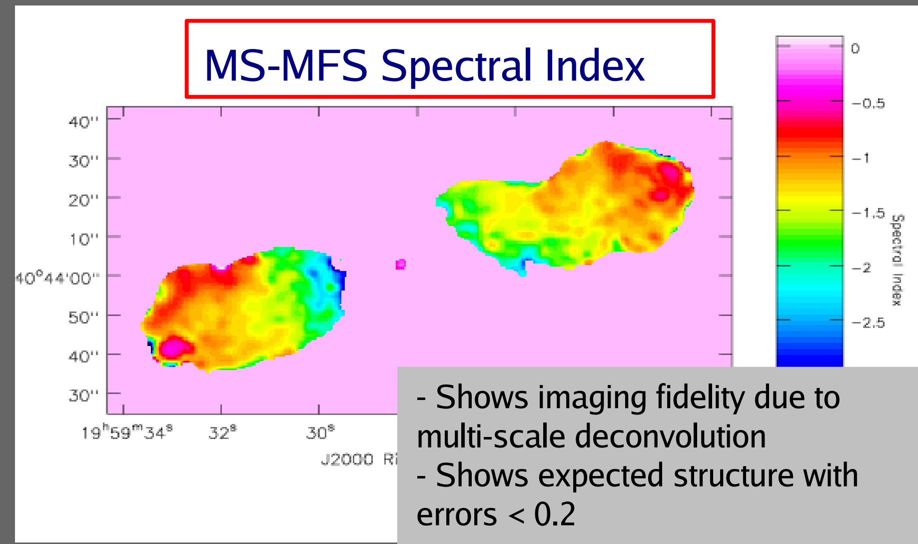


=> For extended emission, a multi-scale model gives a better spectral index maps

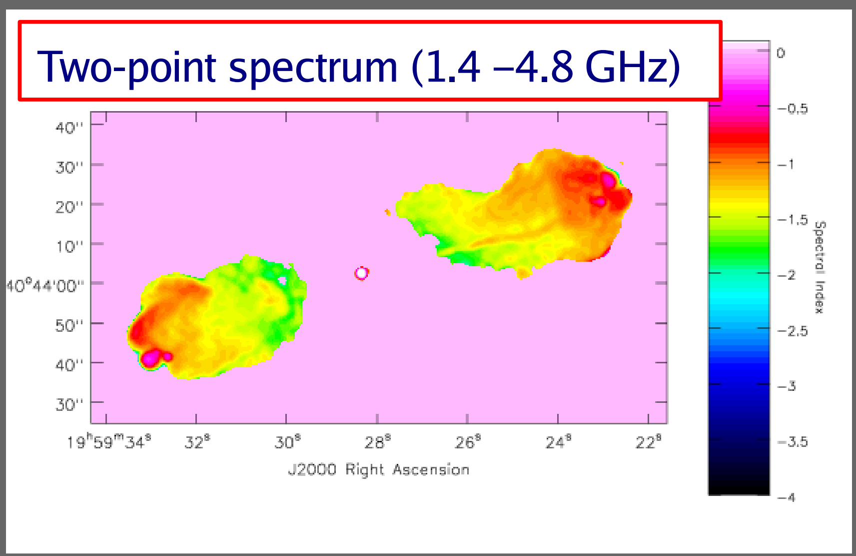
Comparison of MS-MFS with Single-SPW imaging

Data : 20 VLA snapshots at 9 frequencies across L-band + wide-band self-calibration

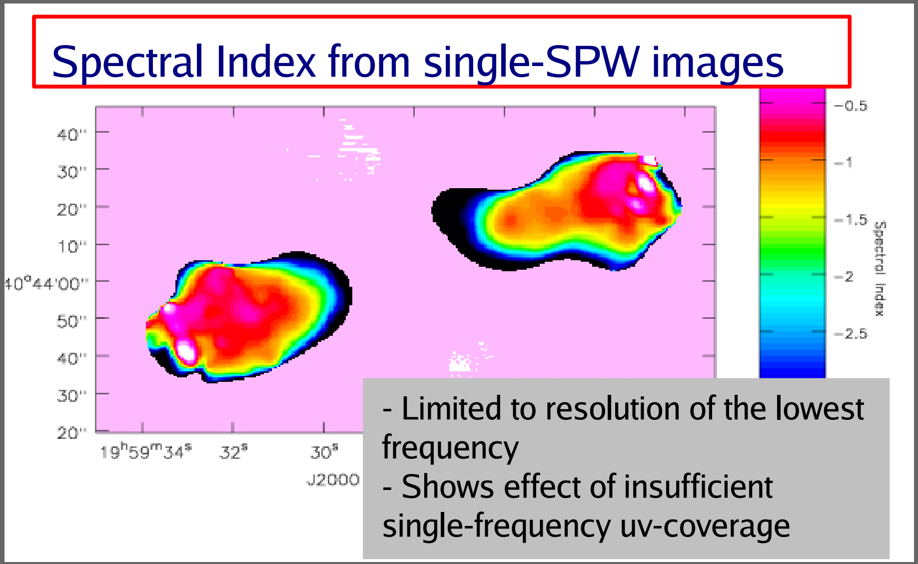




- Shows imaging fidelity due to multi-scale deconvolution
- Shows expected structure with errors < 0.2



C.Carilli et al, Ap.J. 1991.
(VLA A,B,C,D Array at L and C band)

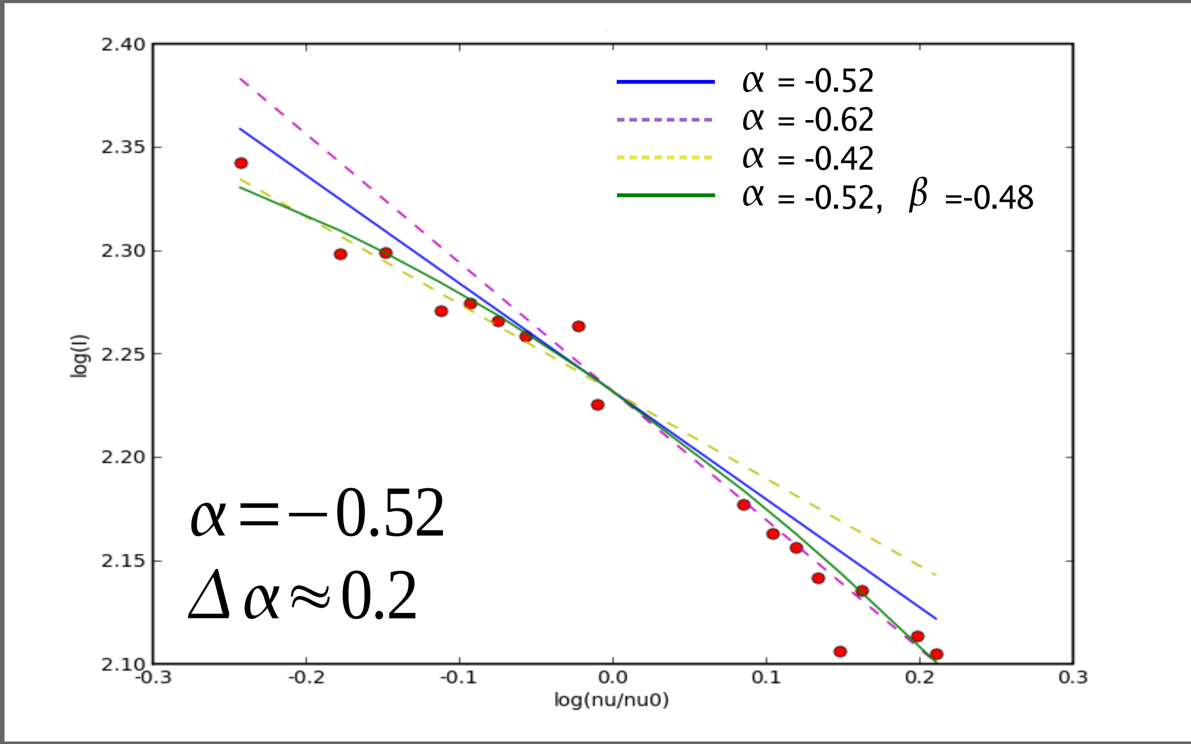


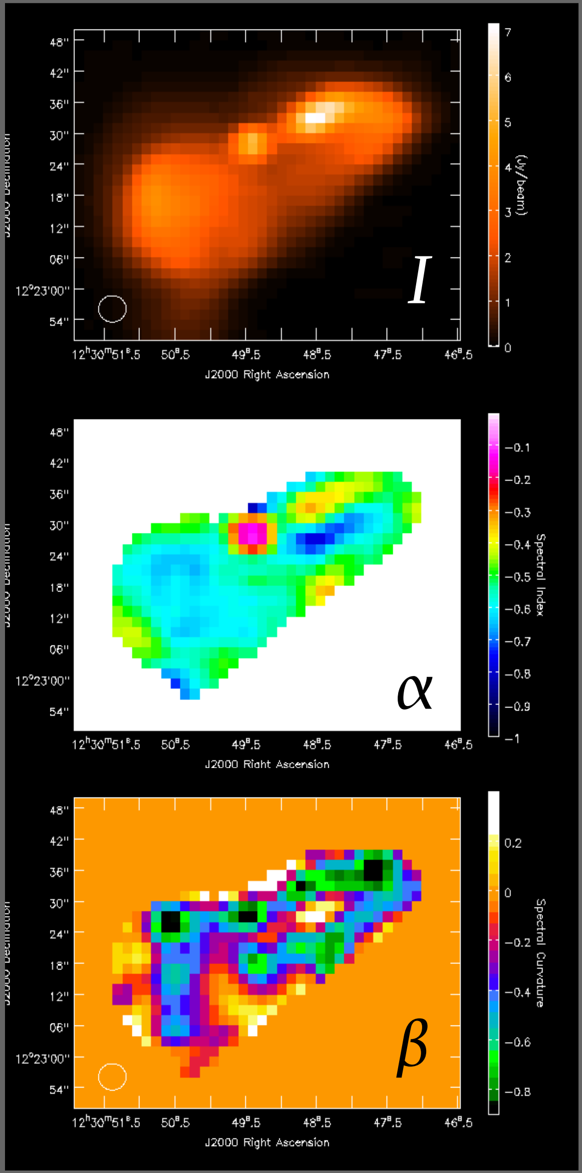
- Limited to resolution of the lowest frequency
- Shows effect of insufficient single-frequency uv-coverage

=> It helps to use the extra uv-coverage

VLA : M87 1.1-1.8 GHz spectral curvature

Data : 10 VLA snapshots at 16 frequencies across L-band





From existing P-band (327 MHz), L-band(1.42 GHz) and C-band (5.0 GHz) images of the core/jet

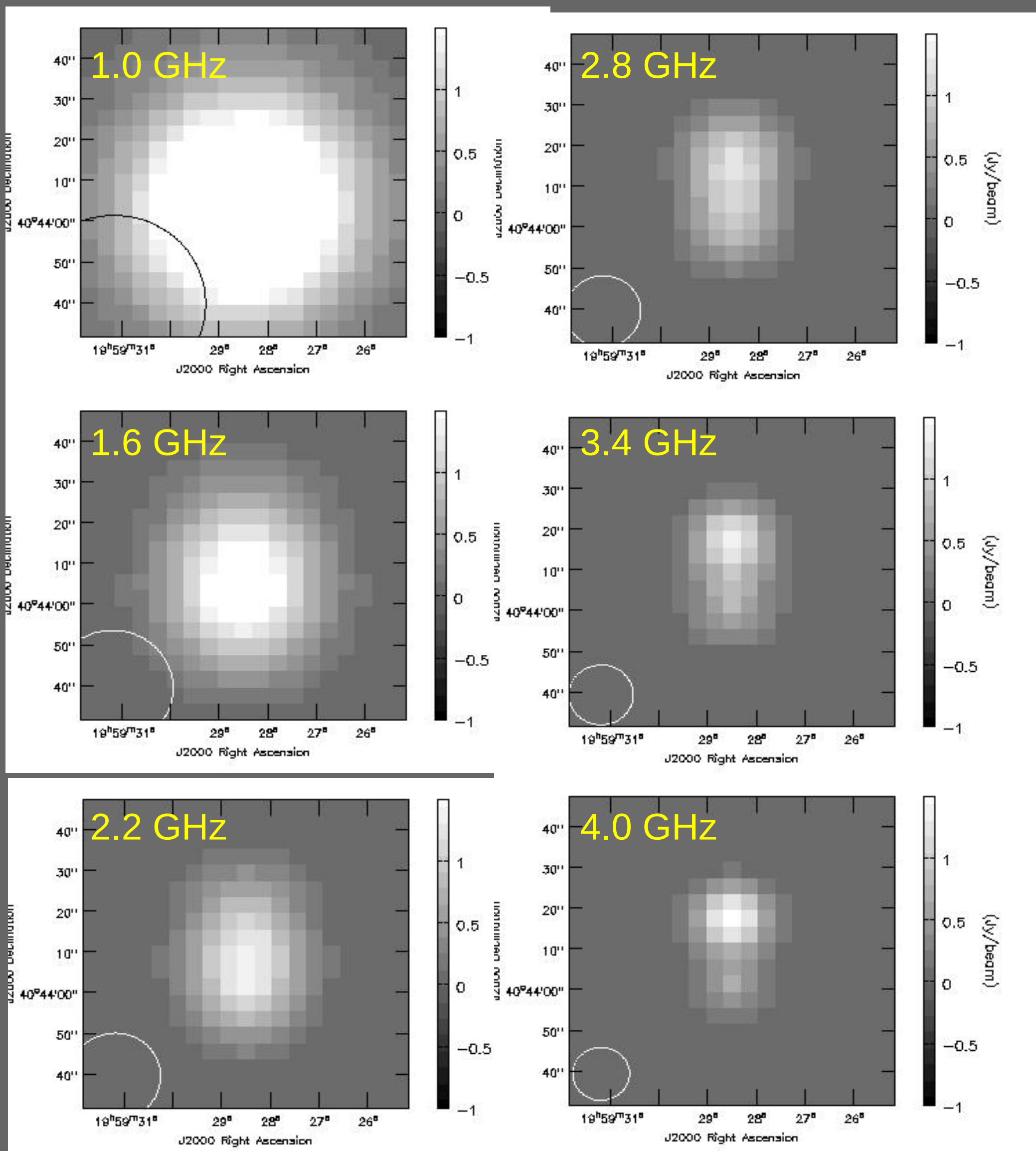
P-L spectral index : -0.36 ~ -0.45

L-C spectral index : -0.5 ~ -0.7

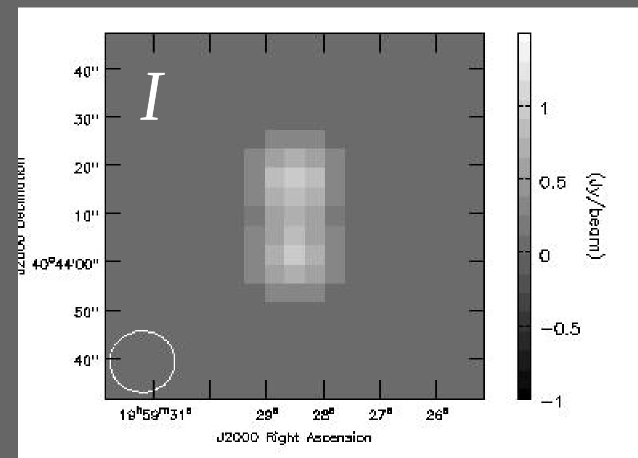
=> Need SNR > 100 to fit spectral index variation ~ 0.2 => Be careful about interpreting β

Moderately Resolved Sources

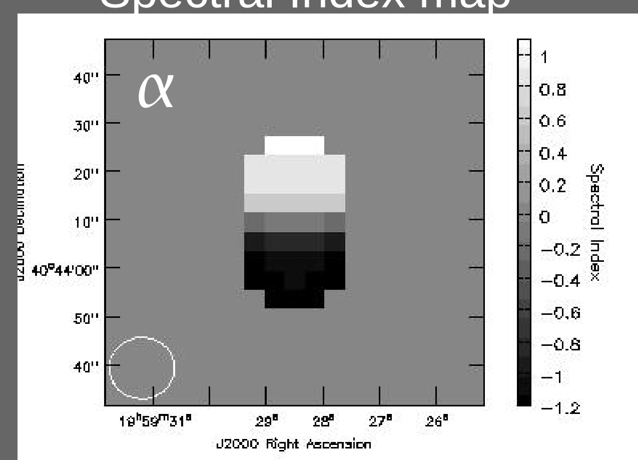
Can reconstruct the spectrum at the angular resolution of the highest frequency



Restored Intensity image



Spectral Index map

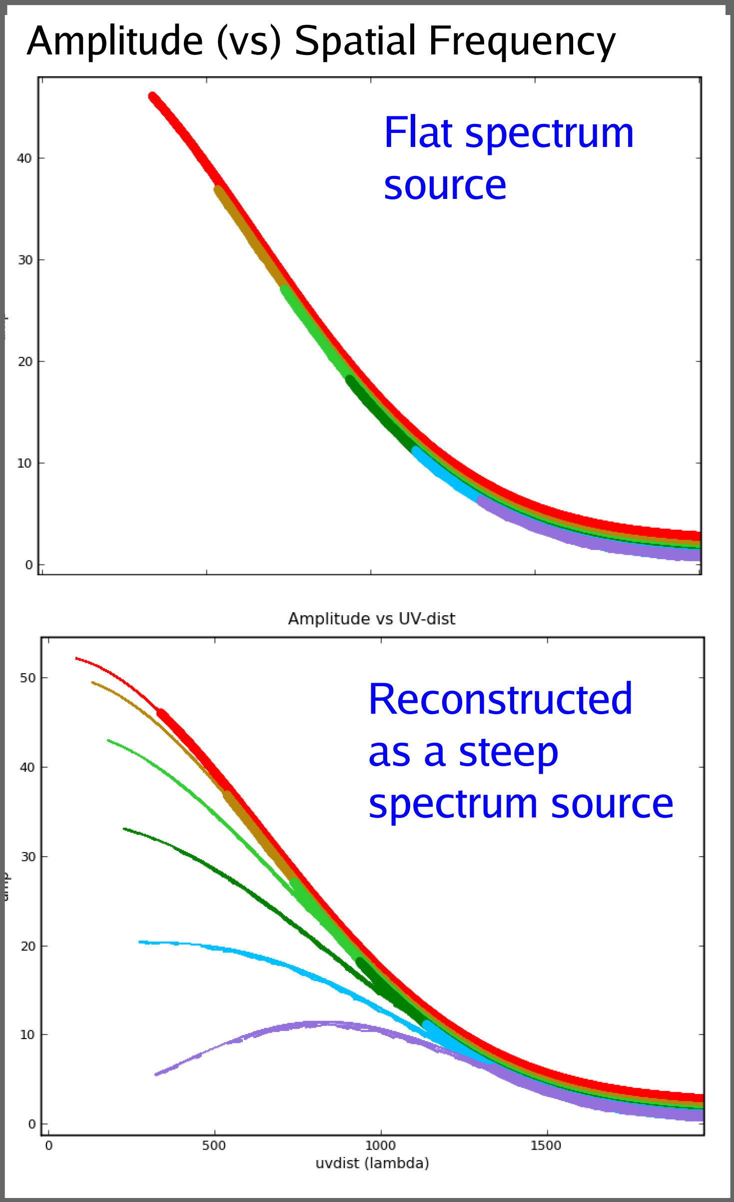


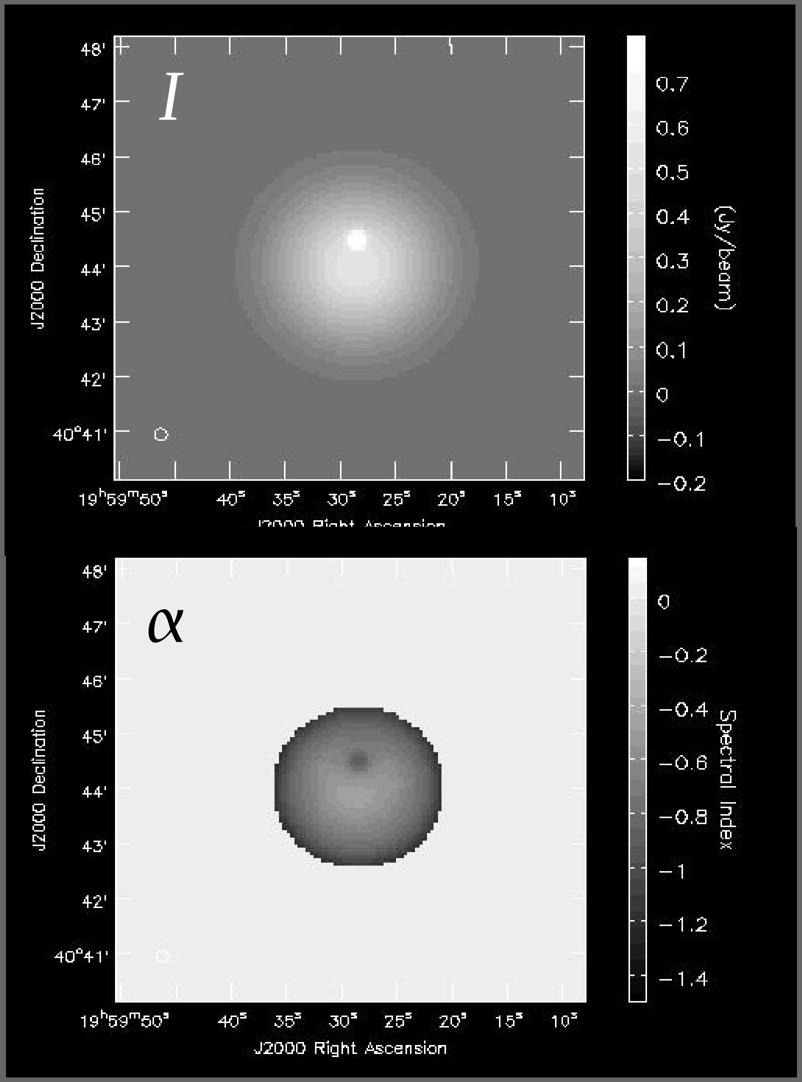
Very large spatial scales – without short-spacing data

The multi-frequency data do not constrain the spectrum at large scales

Data

Data
+
Model





750 lambda at the middle frequency
=
4.5 arcmin

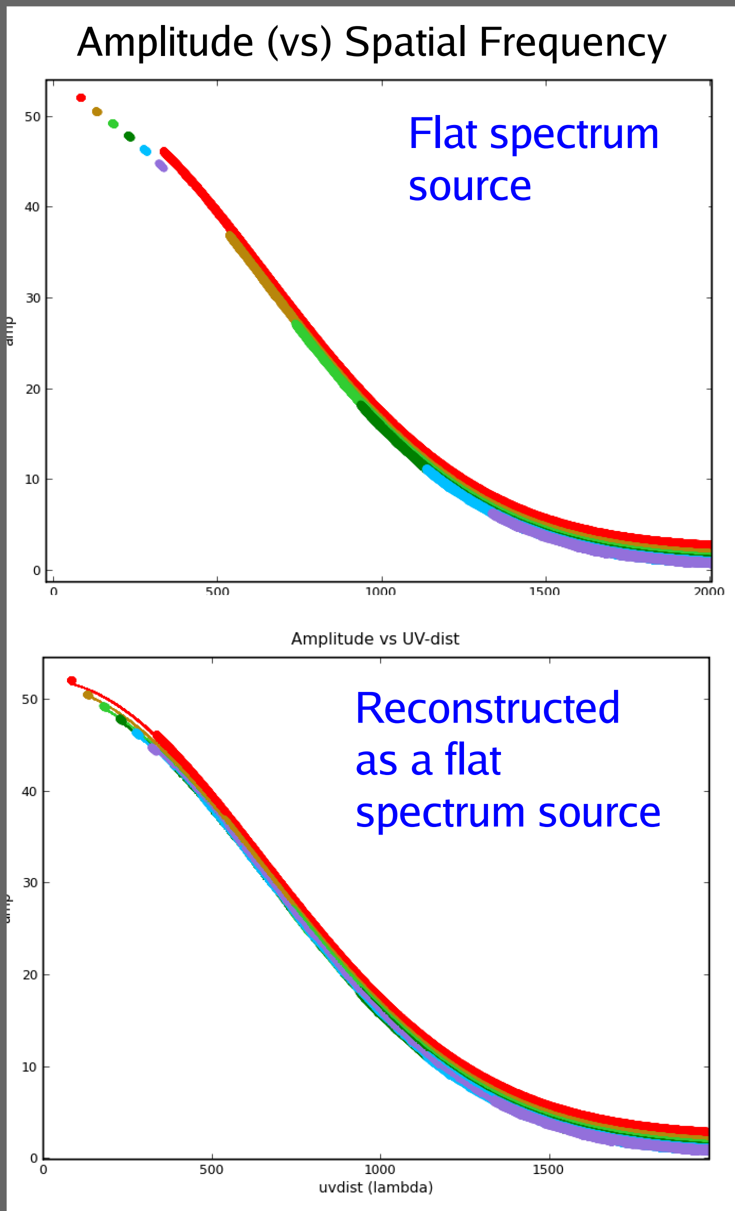
Artificially Steep Spectrum

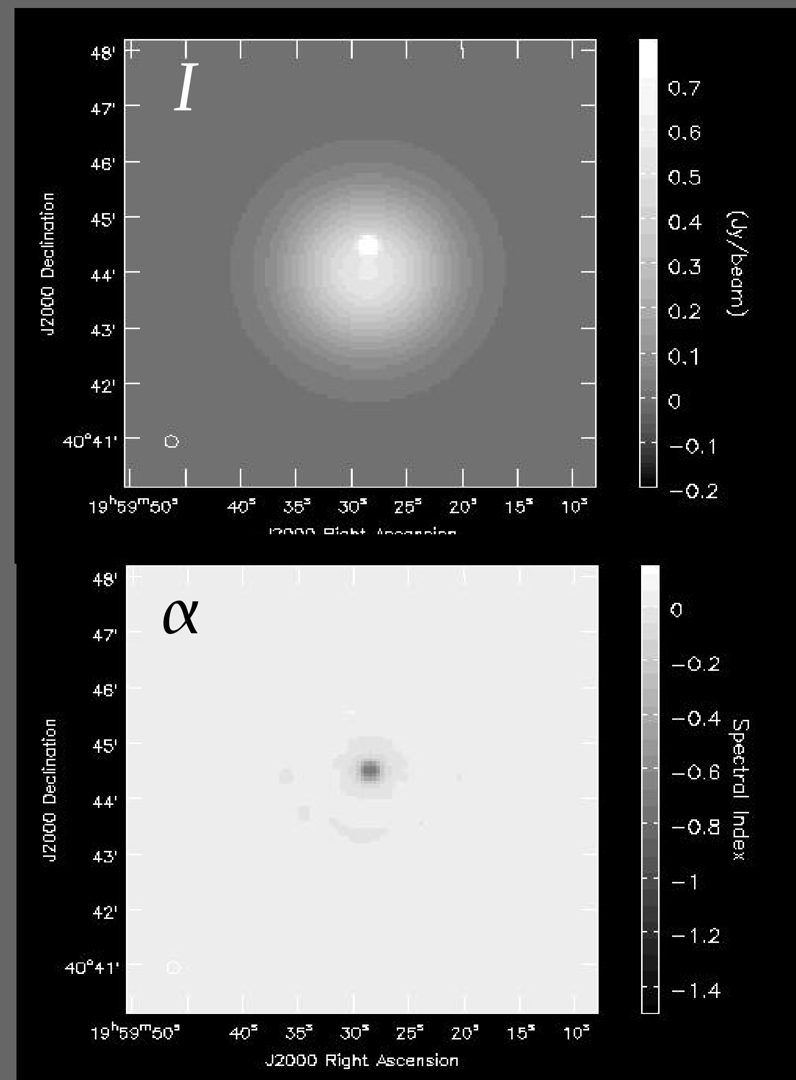
Very large spatial scales – with short-spacing data

Extra short-spacing information can help constrain the spectrum

Data

Data + Model





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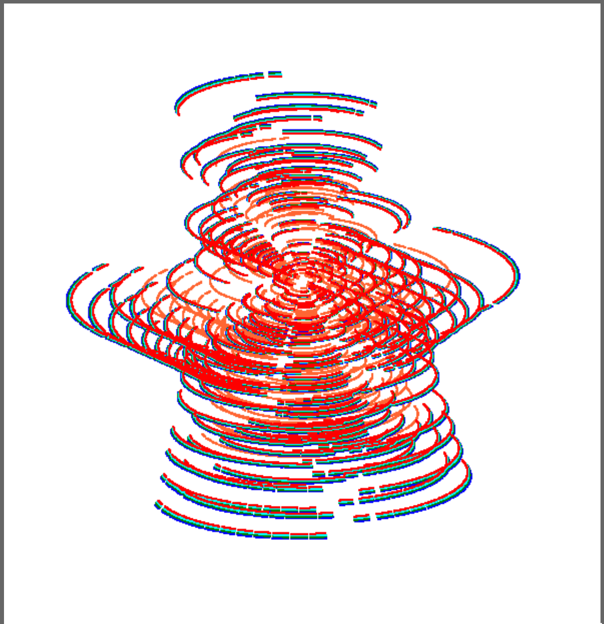
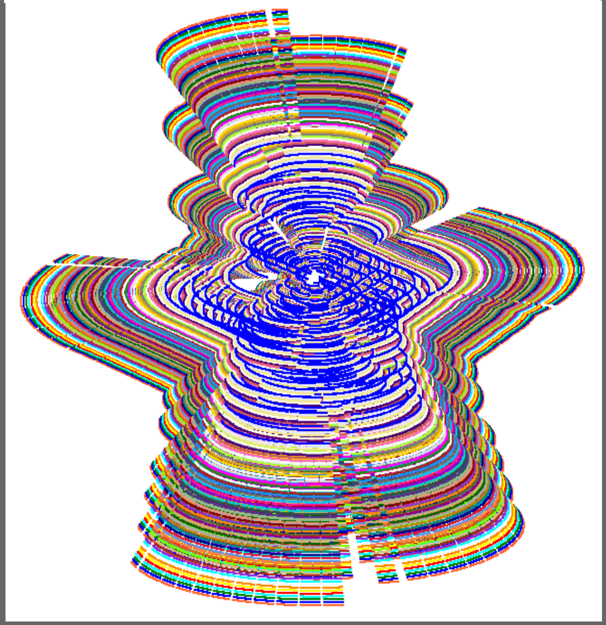




MFS with a spectral model

Taylor Polynomial in frequency

$$I_\nu^{sky} = \sum_t I_t^m \left(\frac{\nu - \nu_0}{\nu_0} \right)^t$$

Power Law with varying index

$$I_\nu^{sky} = I_{\nu_0}^{sky} \left(\frac{\nu}{\nu_0} \right)^{\alpha + \beta \log(\nu/\nu_0)}$$

Solve...

$$\begin{bmatrix} H_{00} & H_{01} & H_{02} \\ H_{10} & H_{11} & H_{12} \\ H_{20} & H_{21} & H_{22} \end{bmatrix} \begin{bmatrix} I_0^m \\ I_1^m \\ I_2^m \end{bmatrix} = \begin{bmatrix} I_0^{dirty} \\ I_1^{dirty} \\ I_2^{dirty} \end{bmatrix}$$

$$H_{ij} \rightarrow I_{ij}^{psf} = \sum_\nu \left(\frac{\nu - \nu_0}{\nu_0} \right)^{i+j} I_\nu^{psf}$$

$$I_i^{dirty} = \sum_\nu \left(\frac{\nu - \nu_0}{\nu_0} \right)^i I_\nu^{dirty}$$

Relate Taylor-coefficients and power-law parameters

$$I_0^{sky} = I_{\nu_0}^{sky} \qquad I_1^{sky} = I_{\nu_0}^{sky} \alpha \qquad I_2^{sky} = I_{\nu_0}^{sky} \left(\frac{\alpha(\alpha - 1)}{2} + \beta \right)$$

Repeat for multiple spatial scales, using cross-terms during peak-finding and updates

'CLEAN' Minor cycle – solves the convolution equation

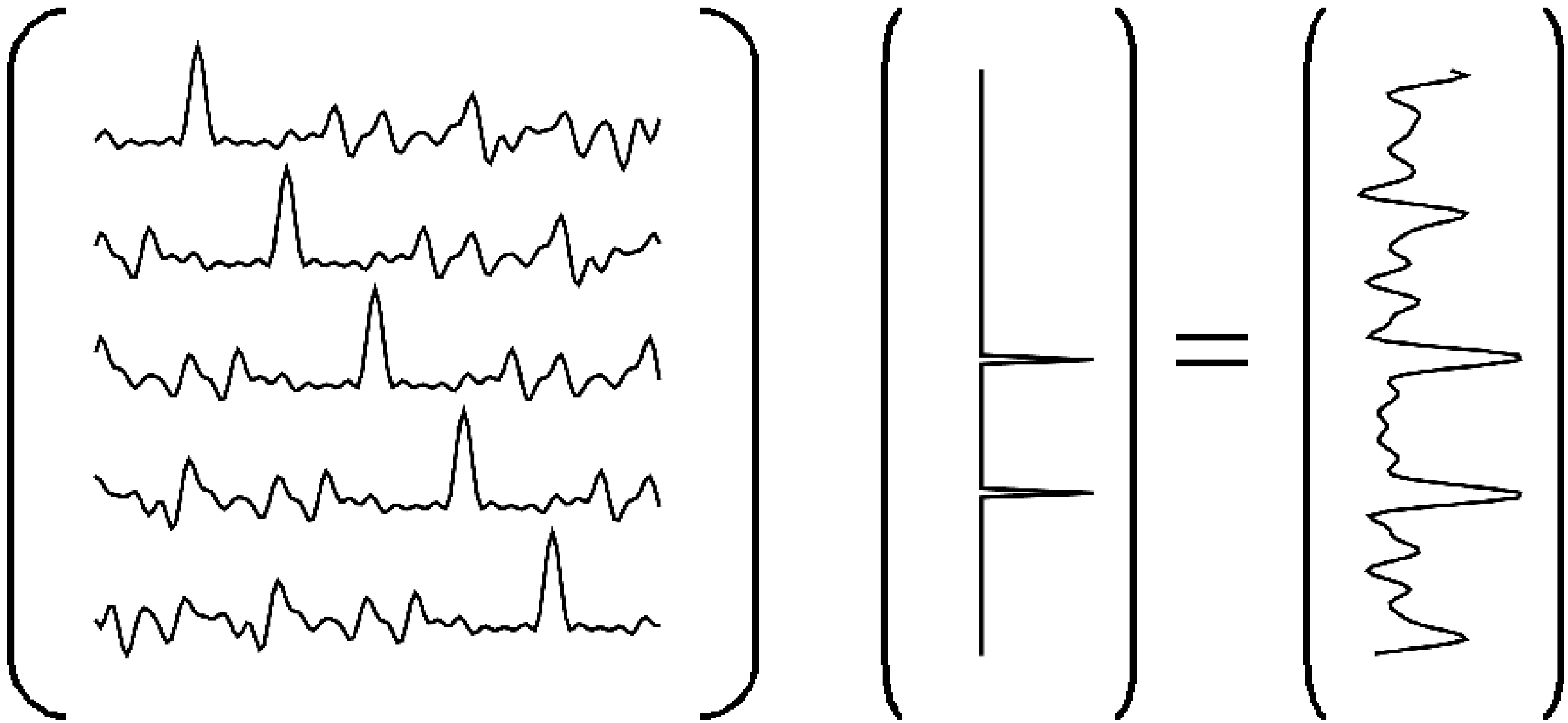
Measurement Eqns : $V = [S][F] I^{sky}$

$$[H] = [F^T][S^T][W][S][F]$$

Normal Eqns : $[H] I^{sky} = I^{dirty}$

$$I^{dirty} = [F^T][S^T][W] V$$

$$[B_{m\times m}] \; \vec{I}^{sky}_{m\times 1} \; \vec{I}^{dirty}_{m\times 1}$$

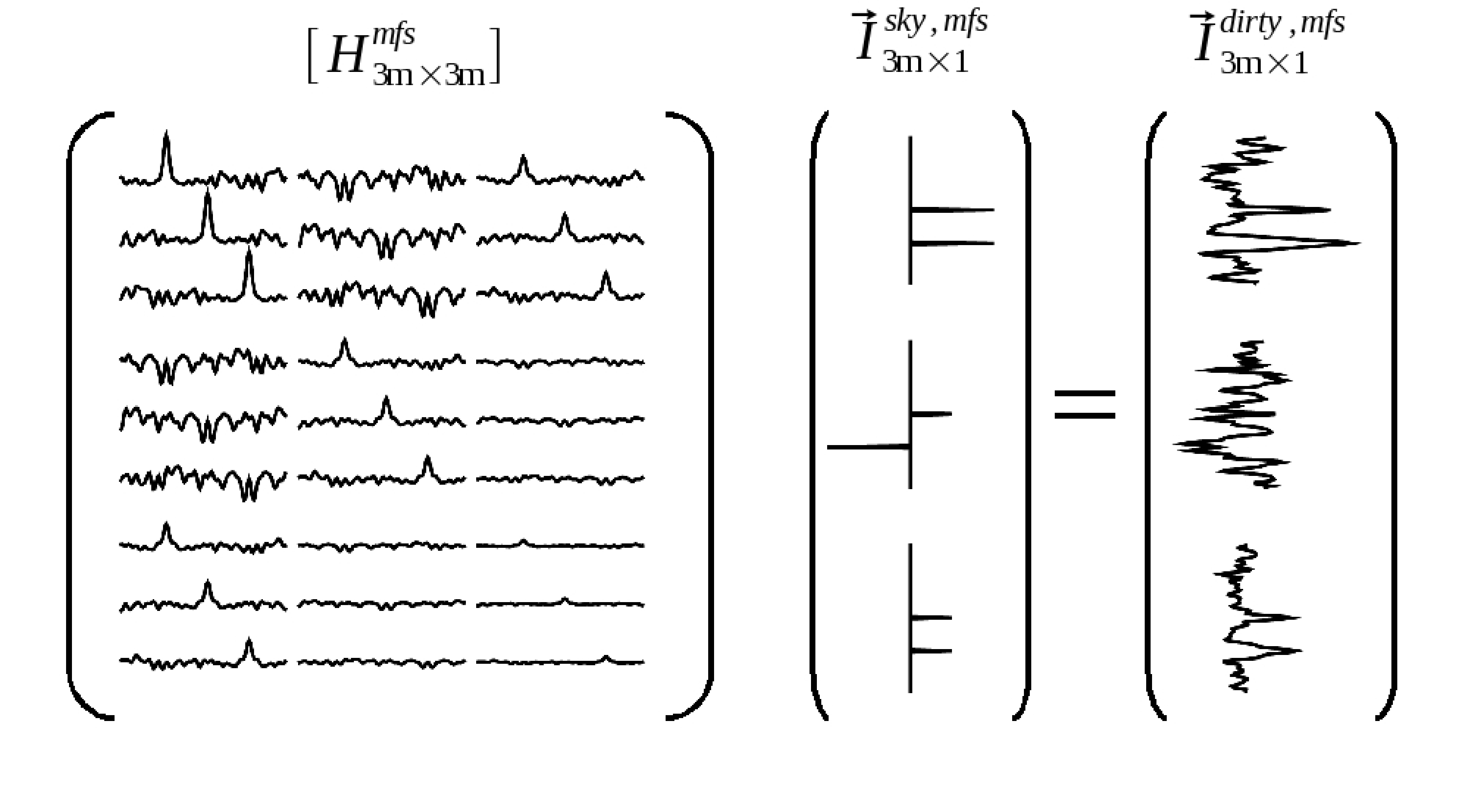


'Multi-Frequency Minor Cycle

$$I_{\nu}^{sky} = \sum_t I_t^{sky} \left(\frac{\nu - \nu_0}{\nu_0} \right)^t$$

A linear-combination of convolutions......

Joint deconvolution....



Choices that effect errors

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

  Very high signal-to-noise,point-sources : use a higher-order polynomial.
  Otherwise, use 2 or 3 terms to prevent over-fitting.

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

  Low signal-to-noise : use a linear approximation.
  Again, nterms=2 or 3 is safer for low signal-to-noise extended emission.

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

  Extended emission : use multiple spatial scales to minimize this error
  Choice of scale sizes : by eye, and verifying that the total-flux converges (i.e. increasing the largest scale size no longer increases the total flux in the reconstruction).

- 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)

Positive things : Increased imaging sensitivity (over wide fields), high-fidelity high dynamic-range reconstructions of both spatial and spectral structure.

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 $\left[0.5\left(N_{taylor} N_{scales}\right)^2 + N_{taylor} + N_{taylor} N_{scales}\right] N_{pixels}$

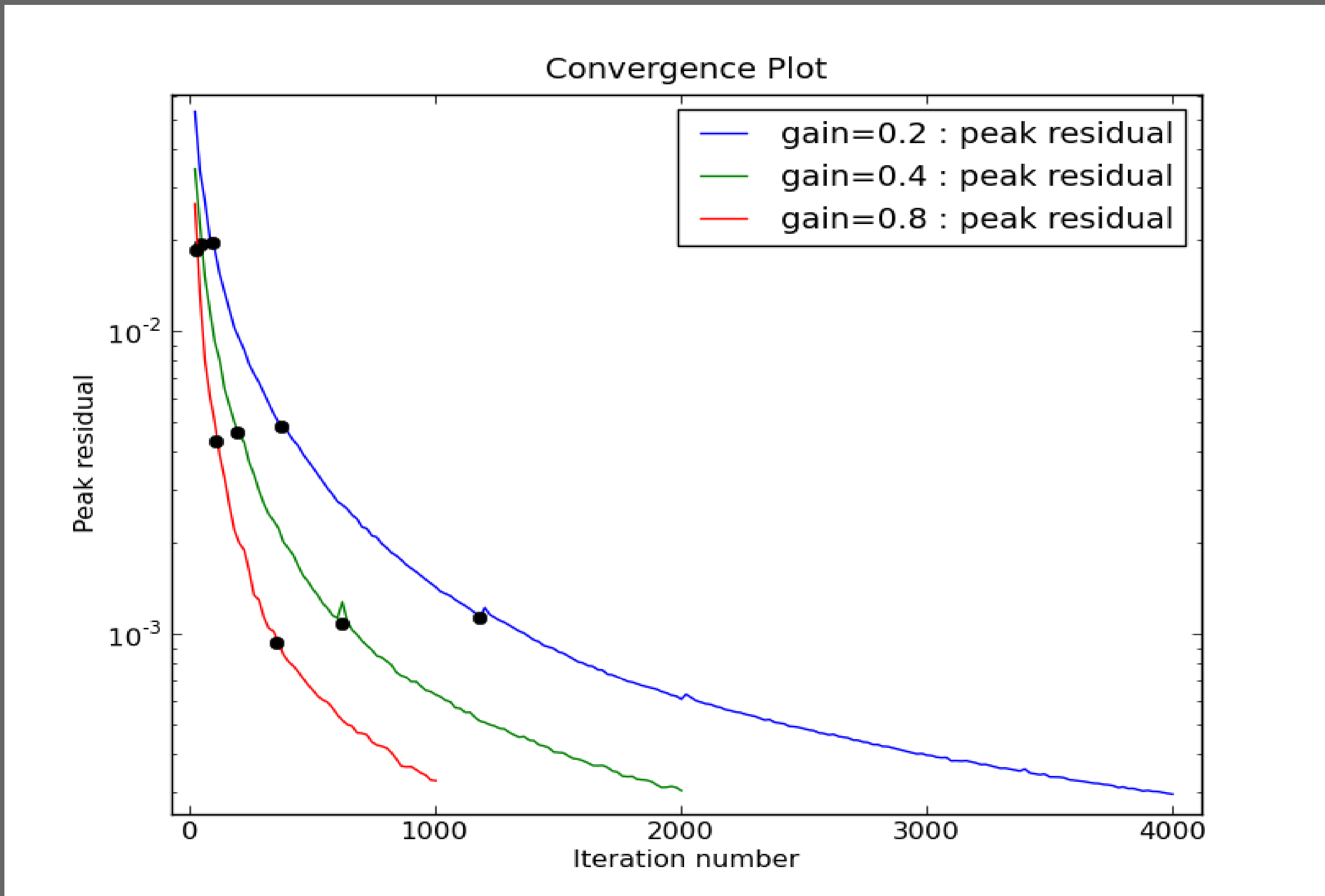
- Rate of convergence : Typical of steepest-descent-style optimization algorithms : exponential. Can control 'loop gain', 'cleaning depth'

  Some source structures will handle loop-gains of 0.3 to 0.5 or more (0.3 is safe).

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

Positive things : Increased imaging sensitivity (over wide fields), high-fidelity high dynamic-range reconstructions of both spatial and spectral structure.

Effect of loop gain



An example with loop gains of 0.2, 0.4 and 0.8 with ms-mfs on Hercules-A X-band EVLA data (11% bandwidth)

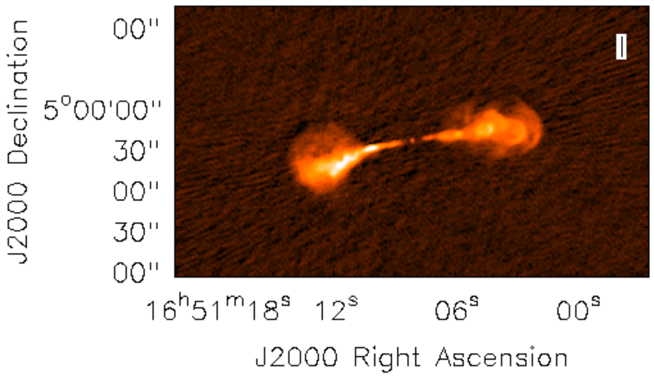
The peak residual decreases logarithmically, as is typical of a steepest-descent algorithm.

Number of iterations to reach the same residual scales inversely with loop-gain.

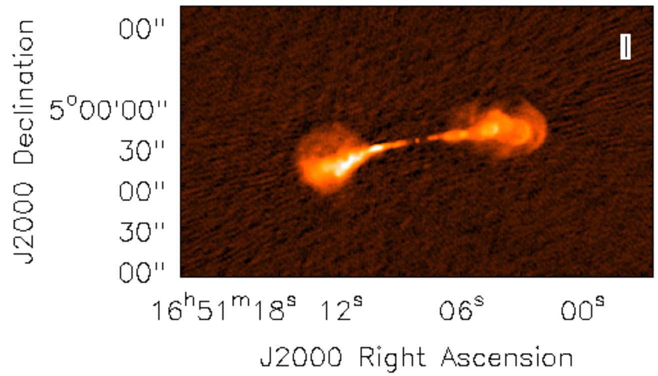
For this image with complex multiscale structure, slight errors are visible only for the very high loop gain of 0.8.

Again – use with caution. This is only one example.

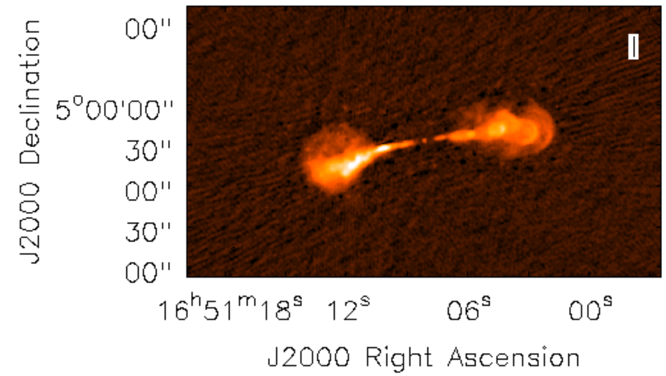
gain=0.2



gain=0.4



gain=0.8



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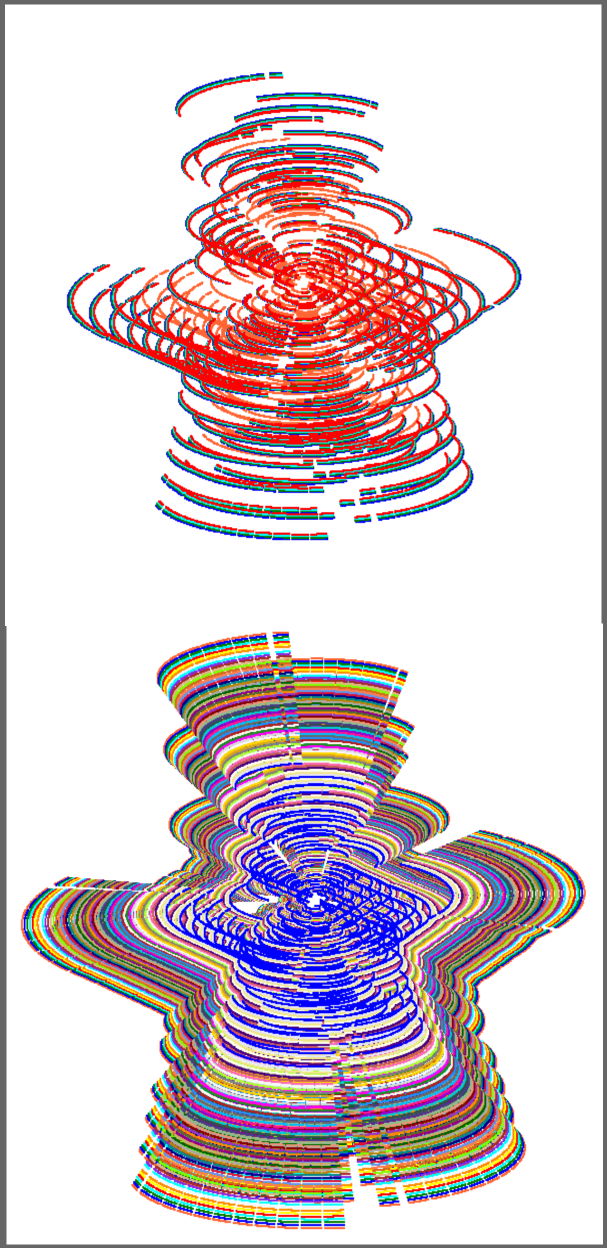
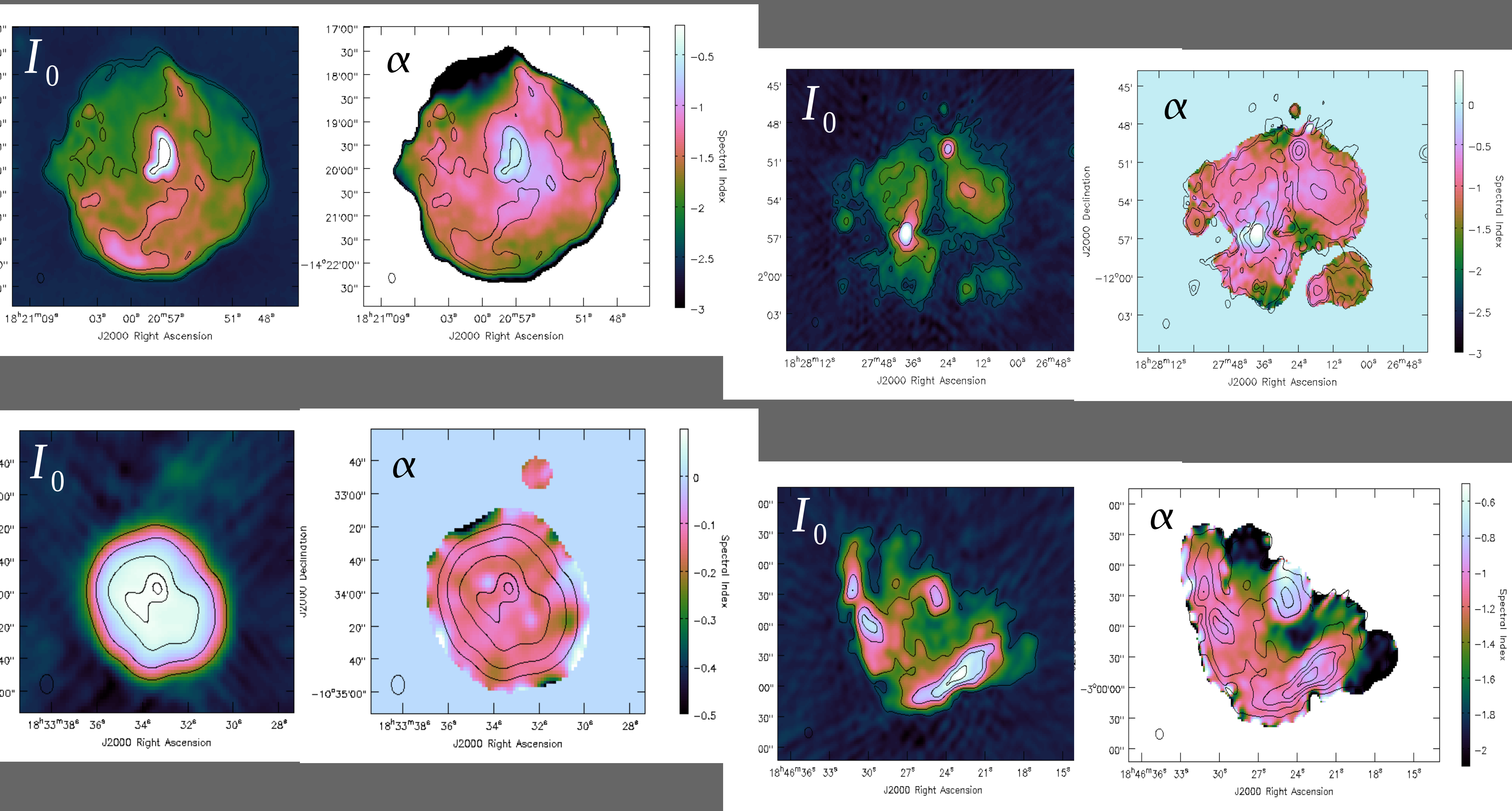
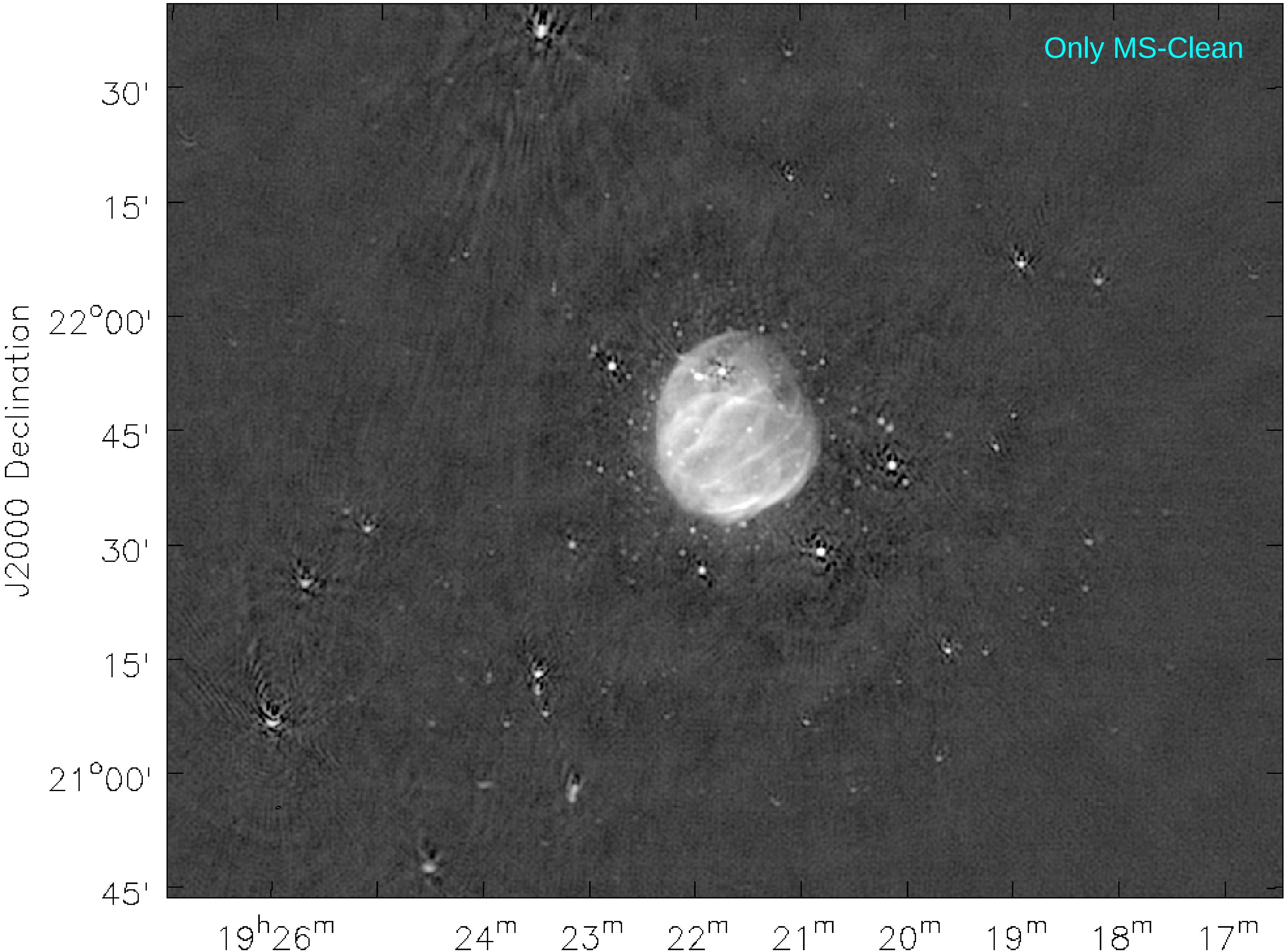


Separating regions/sources based on spectral index structure

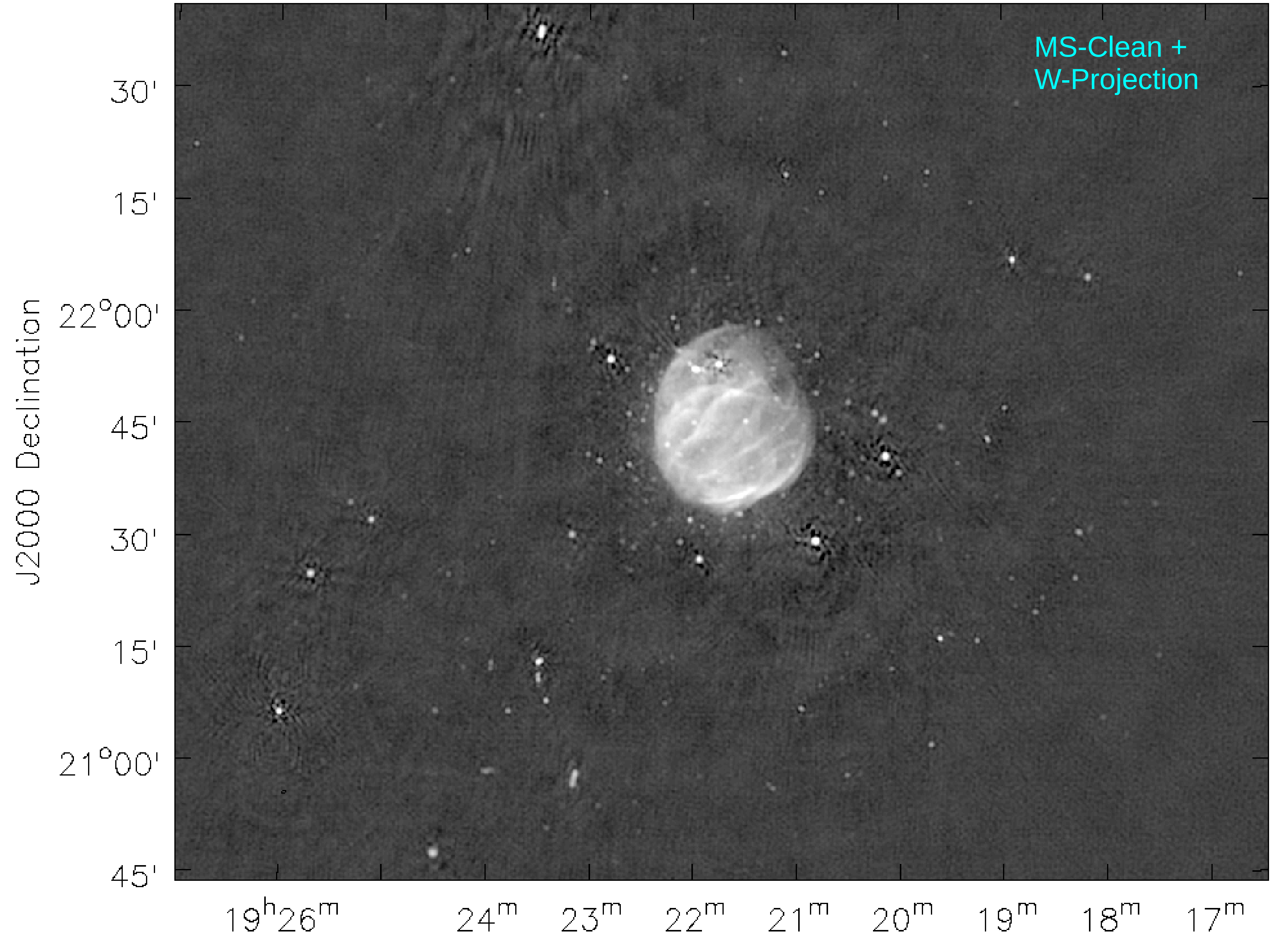


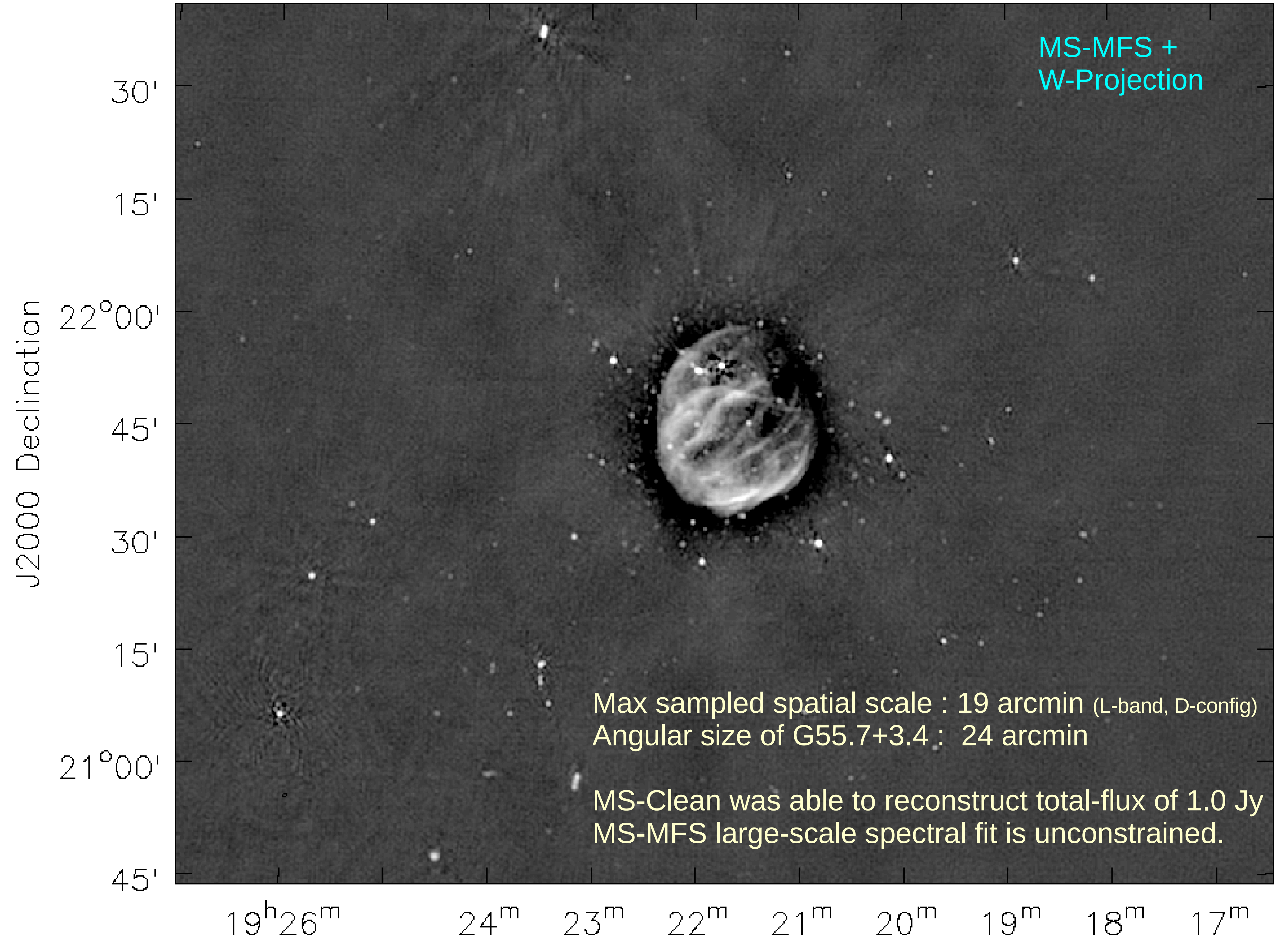
Initial results of a pilot survey (EVLA RSRO AB1345 : S.Bhatnagar, D.Green, R.Perley, Urvashi R.V., K.Golap)

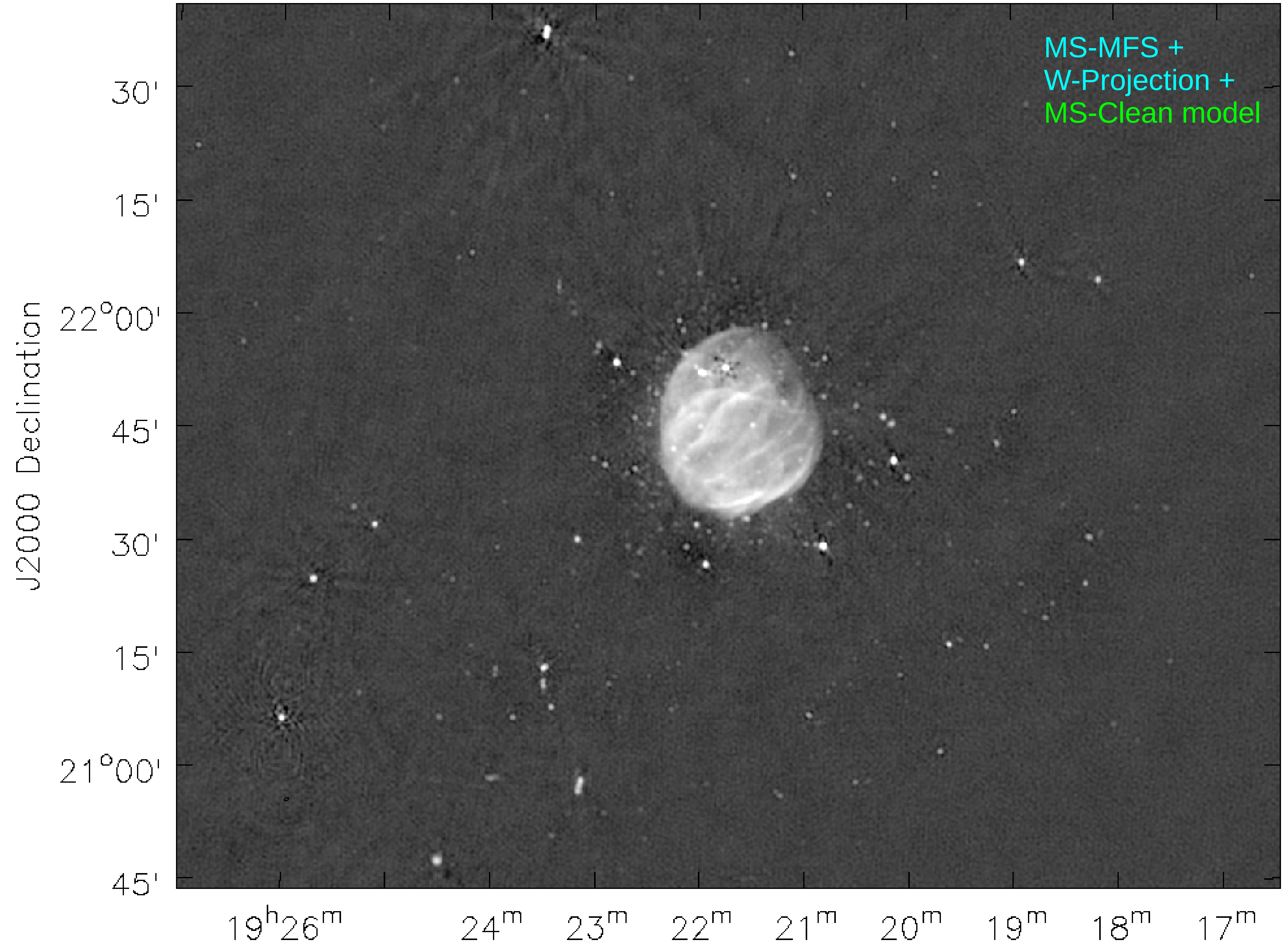
=> Within L-band and C-band, can tell-apart regions by their spectral-index (+/- 0.2) if snr>100

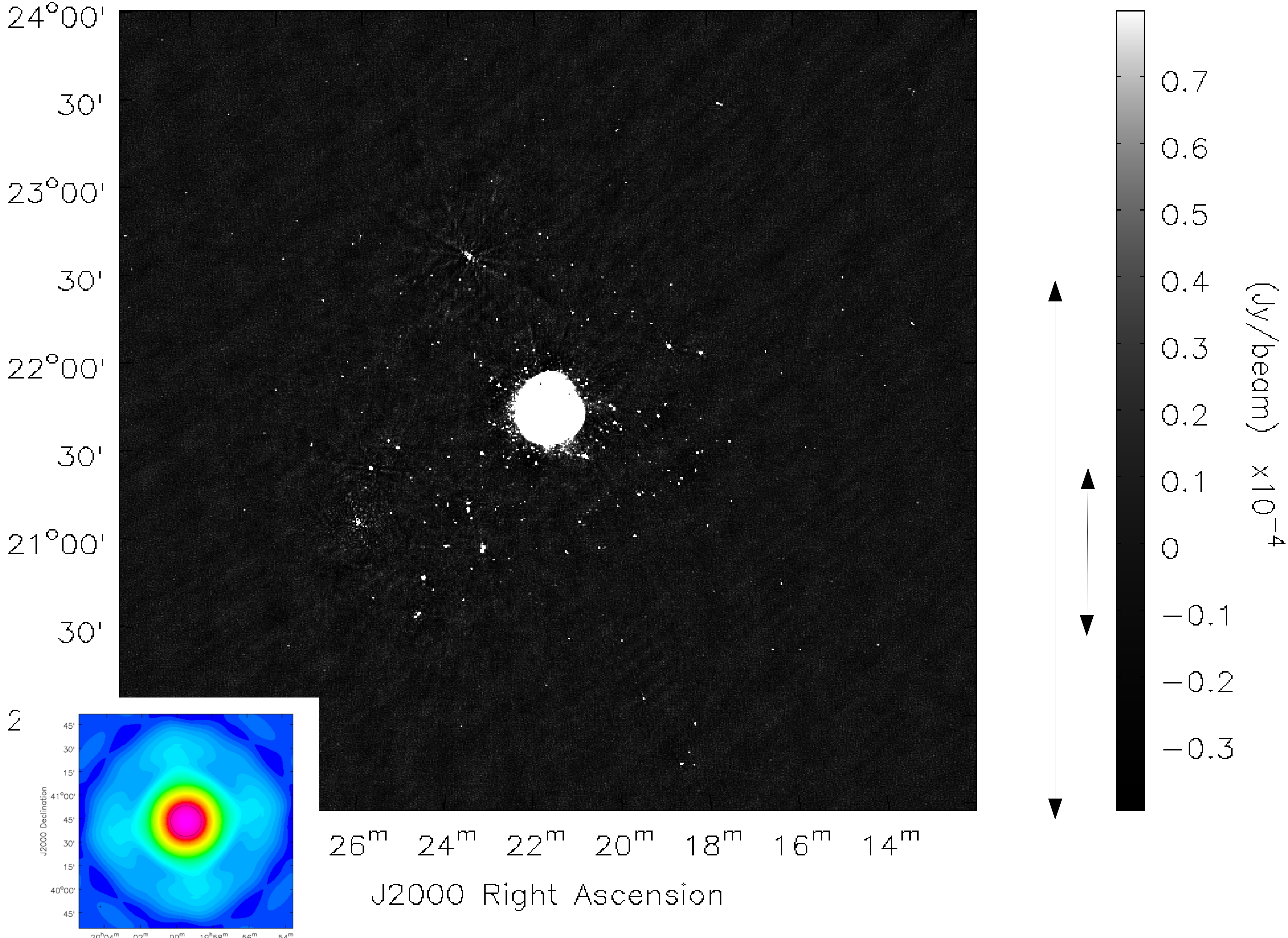


Only MS-Clean
J2000 Declination
30'
15'
22°00'
45'
30'
15'
21°00'
45'
19h26m
24m
23m
22m
21m
20m
19m
18m
17m

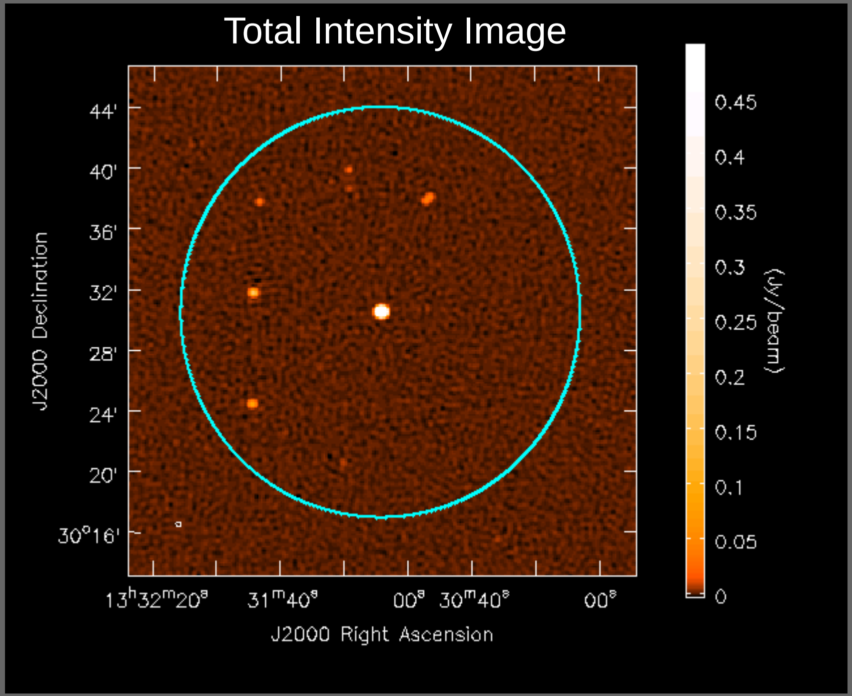

MS-Clean +
W-Projection
30'
15'
22°00'
45'
30'
15'
21°00'
45'
J2000 Declination
19h26m
24m
23m
22m
21m
20m
19m
18m
17m

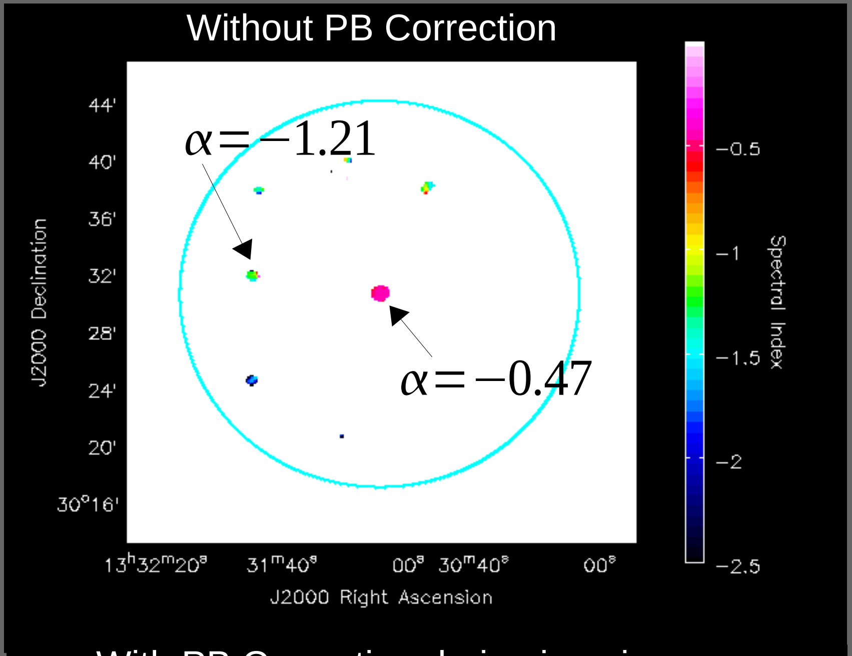

MS-MFS +
W-Projection
Max sampled spatial scale : 19 arcmin (L-band, D-config)
Angular size of G55.7+3.4 : 24 arcmin
MS-Clean was able to reconstruct total-flux of 1.0 Jy
MS-MFS large-scale spectral fit is unconstrained.
J2000 Declination
30'
15'
22°00'
45'
30'
15'
21°00'
45'
19h26m
24m
23m
22m
21m
20m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

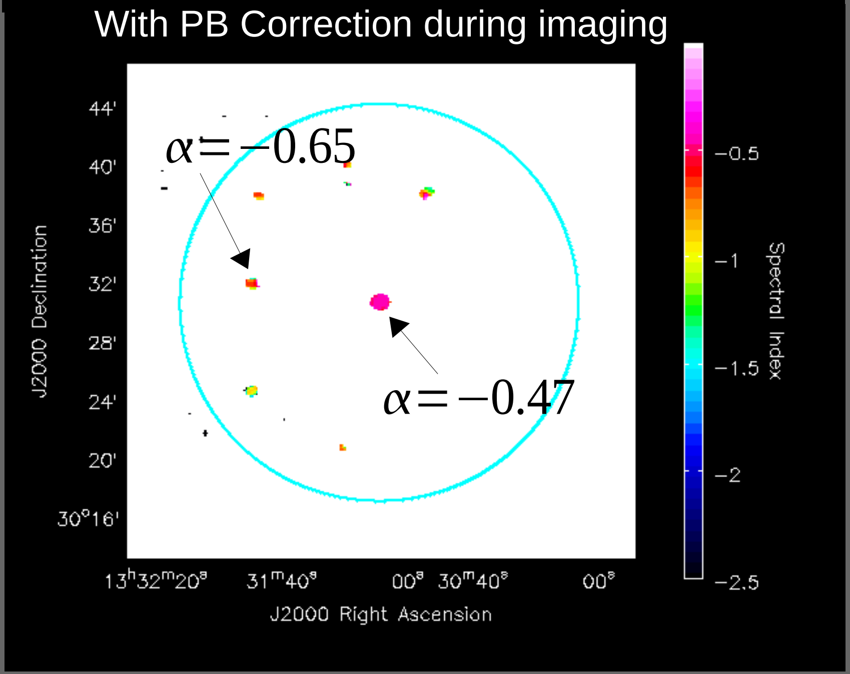

MS-MFS +
W-Projection +
MS-Clean model
J2000 Declination
30'
15'
22°00'
45'
30'
15'
21°00'
45'
19h26m
24m
23m
22m
21m
20m
19m
18m
17m


24°00'
30'
23°00'
30'
22°00'
30'
21°00'
30'
2
26m
24m
22m
20m
18m
16m
14m
J2000 Right Ascension
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
−0.1
−0.2
−0.3
(Jy/beam) x10−4
45'
30'
15'
41°00'
45'
30'
15'
40°00'
45'
J2000 Declination
20h04m
02m
00m
19h58m
56m
54m

Example : 3C286 field – wide-band PB correction







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

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

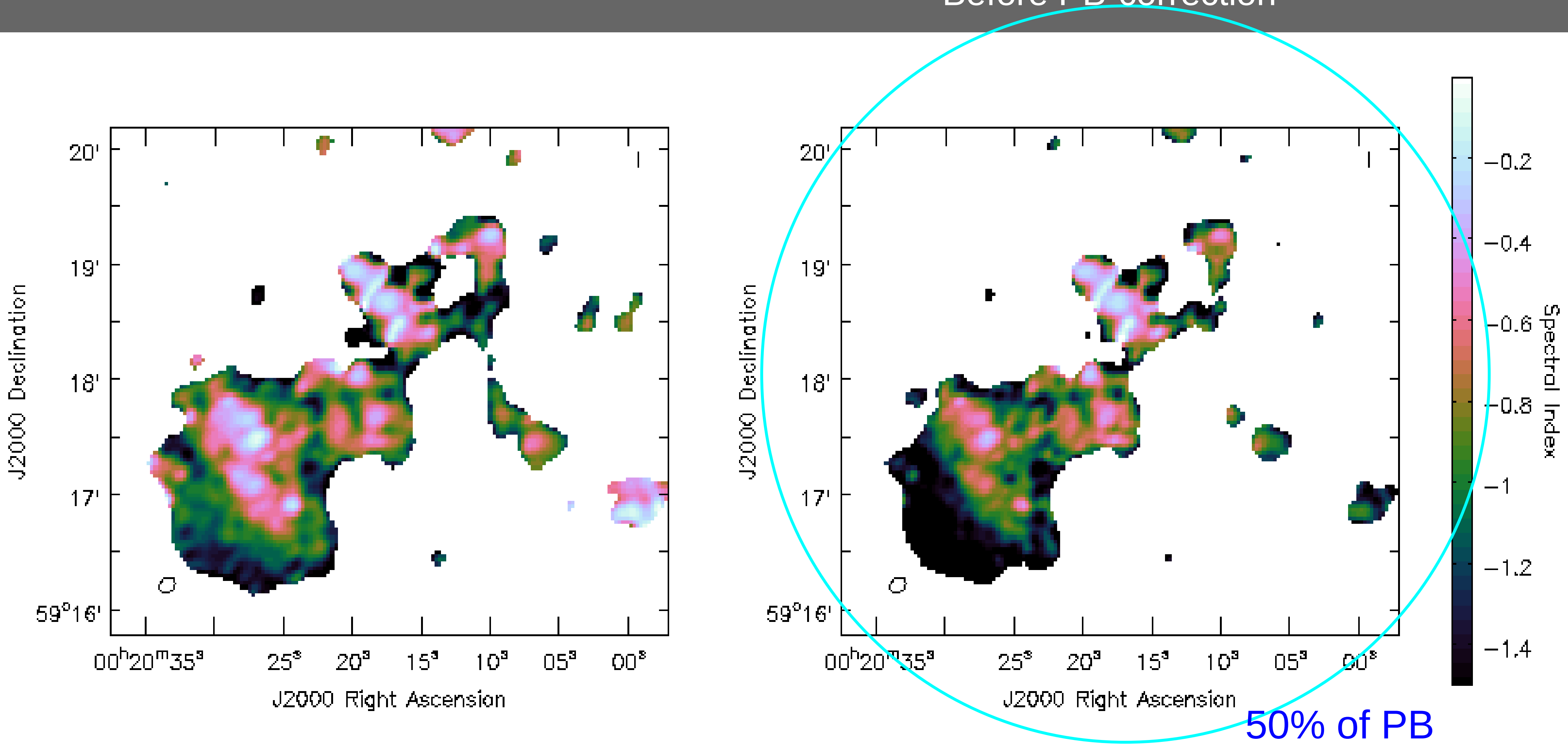
Obtained $\delta\alpha$ = 0.05 to 0.1 for SNR or 1000 to 20

Also verified via holography observations at two frequencies

IC10 spectral-index : post-deconvolution wide-band PB-correction

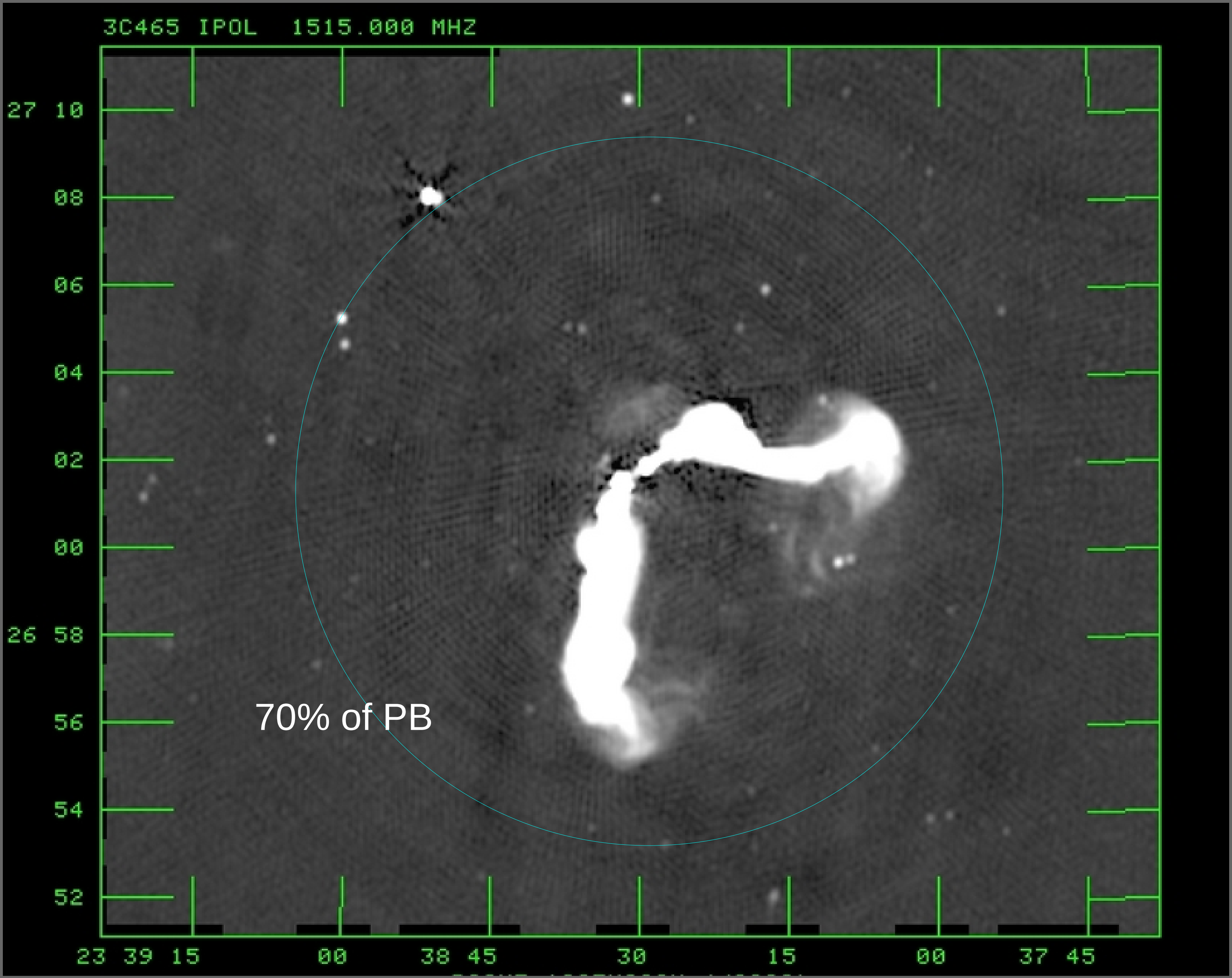
After PB-correction

Before PB-correction

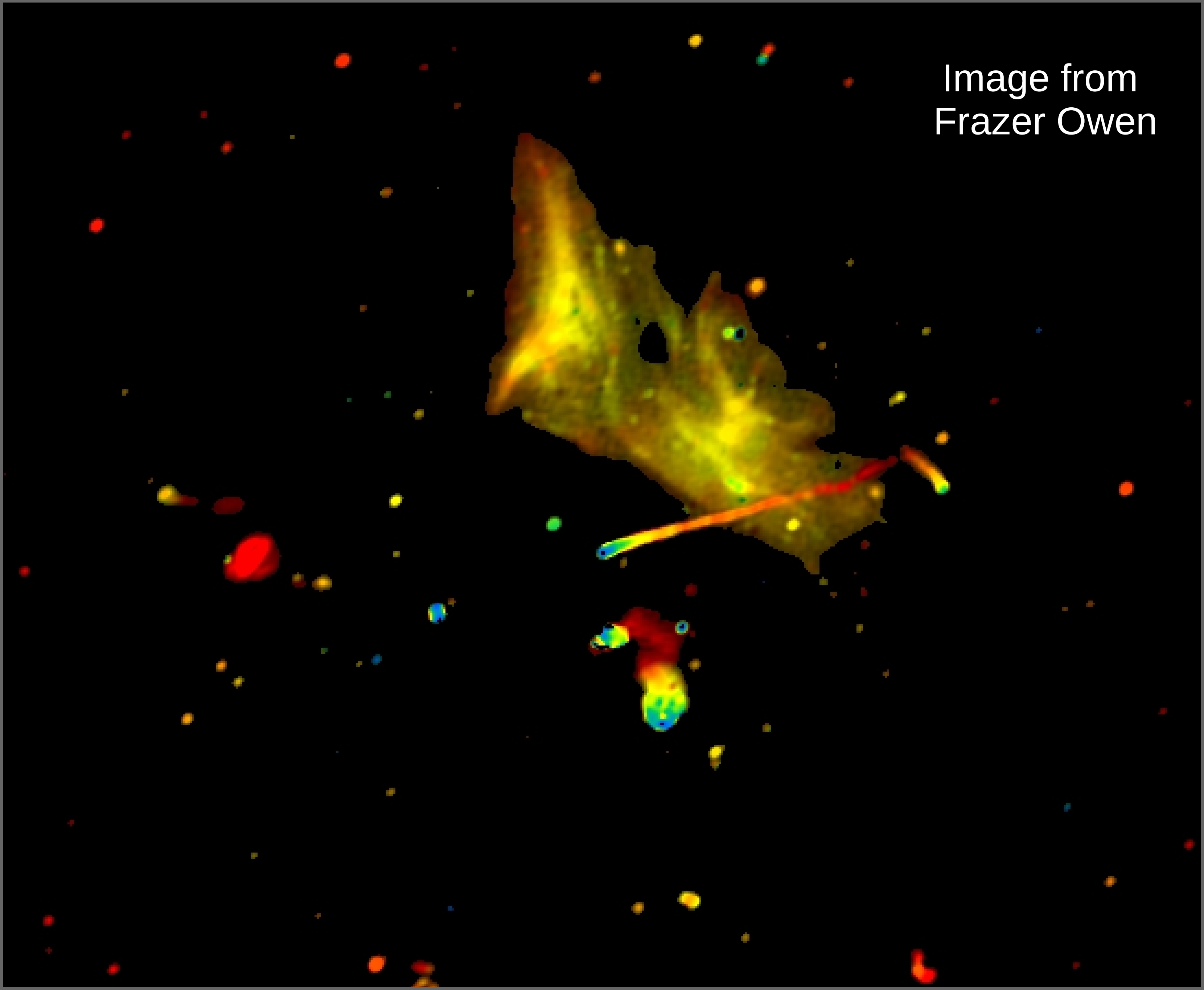


Difference between spectral structure of a VLA-model beam and a Gaussian < 0.2 at HPBW.

3C465 wide-band wide-field image



Abell-2256 : wide-field issues + a way to display wideband images



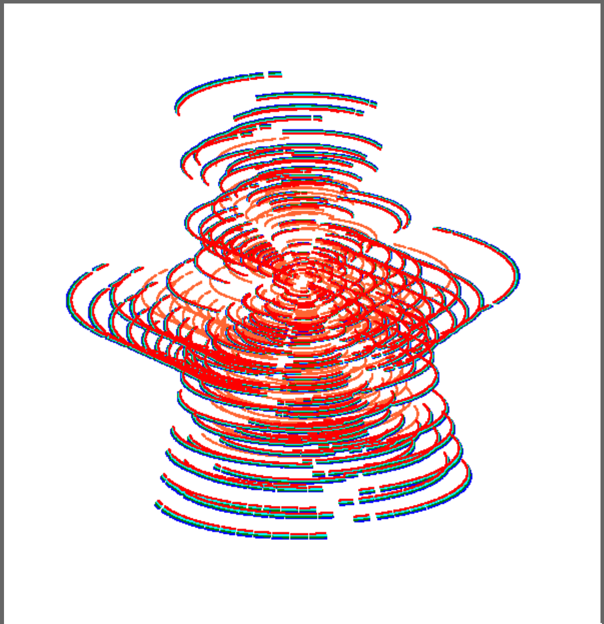
Wide-band imaging with the EVLA

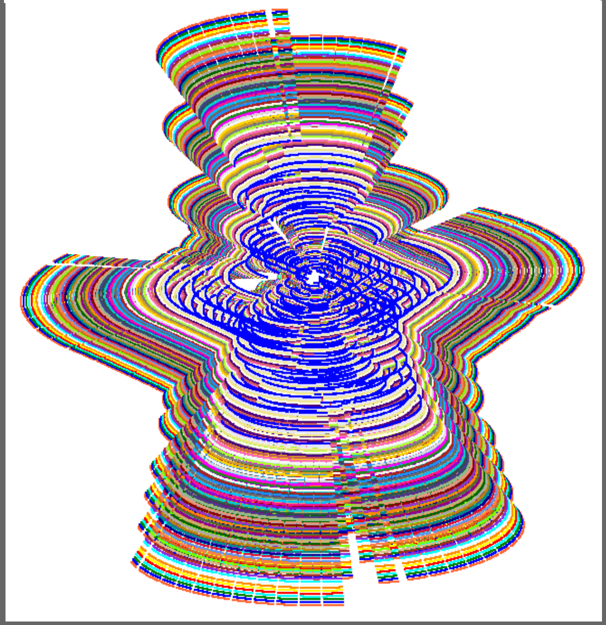
(1) Wide-band data and imaging - 11

(2) MS-MFS details - 6

(3) Examples on EVLA data - 11

(4) Self-calibration and continuum subtraction - 3





Wide-band (self) calibration

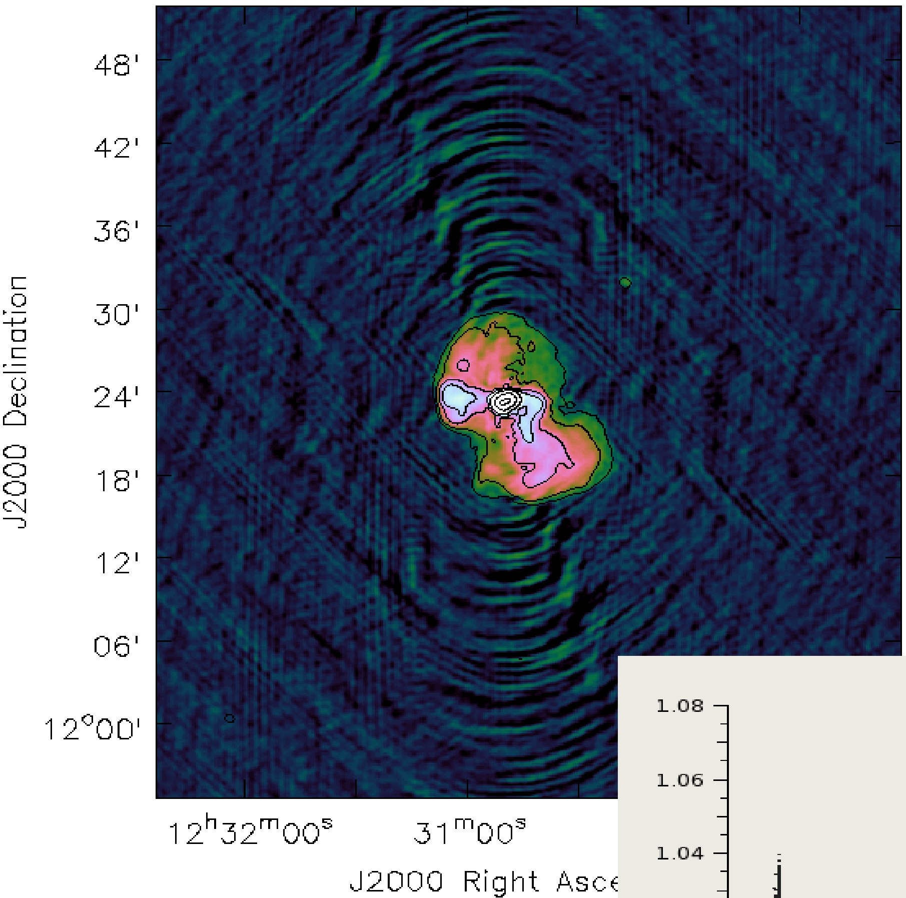
Goal : Maintain continuity of gain solutions across subbands.

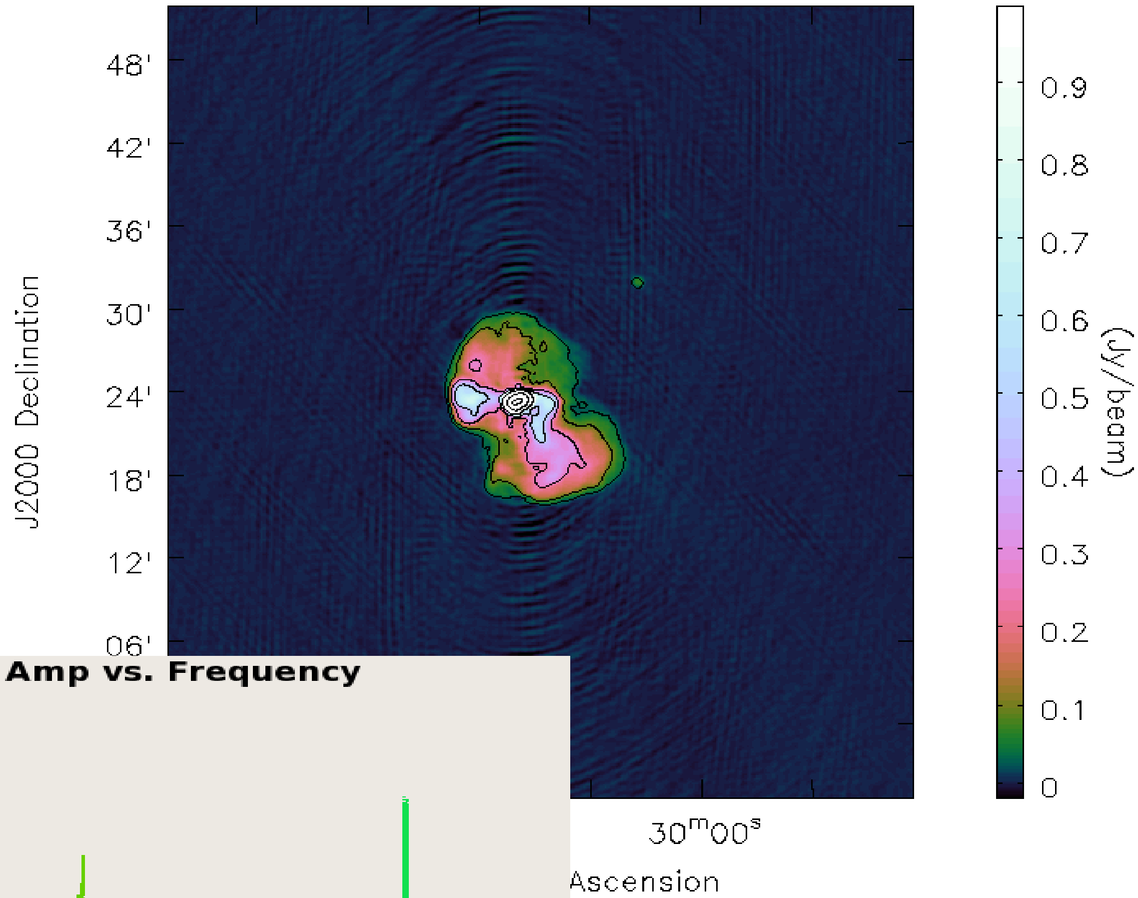
- Flux/Bandpass calibration with an a-priori wide-band model
    - Perley-Taylor 1999 / Perley-Butler 2010 (evaluate spectrum)
    - Calibrator model images (fit and evaluate a spectrum - ms-mfs)
        - Note : due to increased sensitivity - need wide-field model images

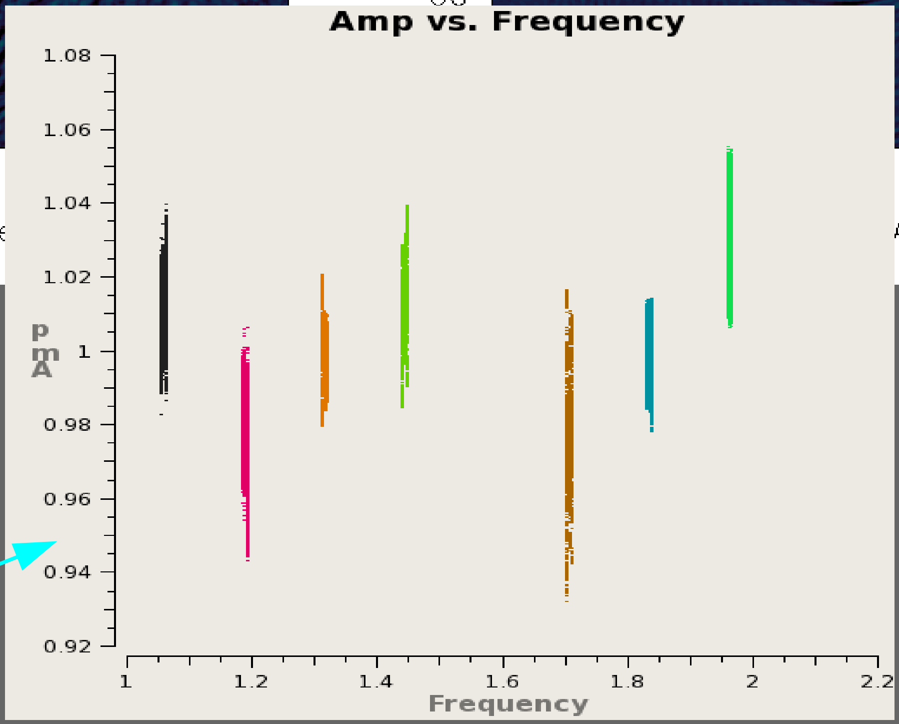
- Use single-subband solutions to fit for polynomial bandpass solutions
    - simpler, doesn't require wide-band imaging, better for low snr ?

- Self-Calibration with the result of MS-MFS
    - In CASA, 'clean' writes wide-band model visibilities to disk

Wide-Band Self-Calibration : M87







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

Peak residual = 32 mJy/bm
Off-source rms = 6 mJy/bm

Amplitudes of bandpass gain solutions......

5 chans x 7 spectral-windows

Continuum Subtraction

Goal : To separate narrow-band spectral lines from the underlying broad-band emission

Method :

--- Do wide-band imaging (MS-MFS) on line-free channels
--- Predict model visibilities for all channels (from Taylor coefficients)
--- Subtract model visibilities from corrected-data

Old/current methods :

' imcontsub ' – single-channel imaging, image-domain subtraction

' uvcontsub ' – fits polynomials to the spectrum from each baseline separately, and subtracts these polynomials on a per-baseline basis.

Summary

Wide-band Data : more sensitivity => need to use all data together.

– Single channel/SPW vs MFS (polynomial spectrum) +/-

– Nterms vs residual artifacts / on-source errors (poly-fit) / SNR

– Use of multi-scale to minimize deconvolution error

– Use wide-band image model for self-cal and continuum subtraction.

MS-MFS : Newest algo that does wideband image-reconstruction along with wide-field corrections (A-W-Projection)

– Point sources -- OK.
– Extended emission – OK upto a dynamic-range of few-1000
– Wide-band PB-correction – OK upto ~50% of reference beam
– Time-varying wide-band PB-corrections (work in progress)
– Several performance bottlenecks (work in progress)