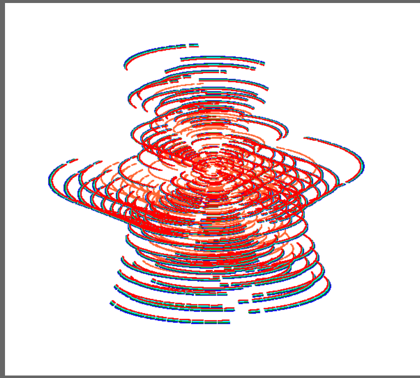
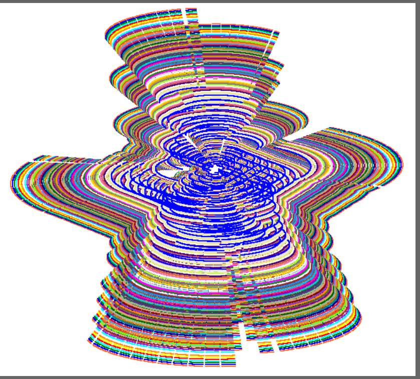
Wide-band (wide-field) imaging



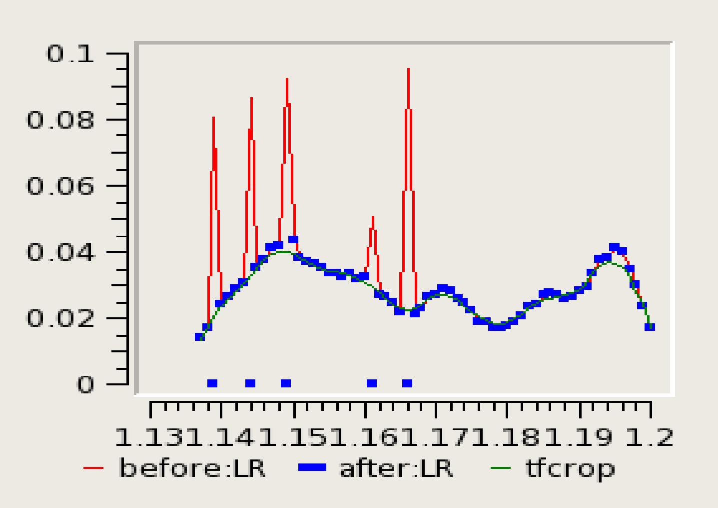


Goal : Make images at the wide-band sensitivity level

Outline :

- Bandwidth and bandwidth-ratio
- Frequency-dependent sky and instrument
- Methods to reconstruct intensity and spectra
- Wide-field effects of wide-band imaging
- Wide-band self-calibration

Flagging + RFI



Goal : Discard data unusable for imaging

Outline :

- Flagging based on data-selection
- Automatic RFI identification and flagging

Bandwidth and bandwidth-ratio

Instantaneous bandwidth : $\nu_{max} - \nu_{min}$

VLA = 50 MHz
EVLA = 1 GHz at L-Band, 4 GHz at C-band, upto 8 GHz at higher bands.

Currently, maximum bandwidth is 2 GHz => (x 6)

Broad-band receivers => Higher 'instantaneous' continuum sensitivity

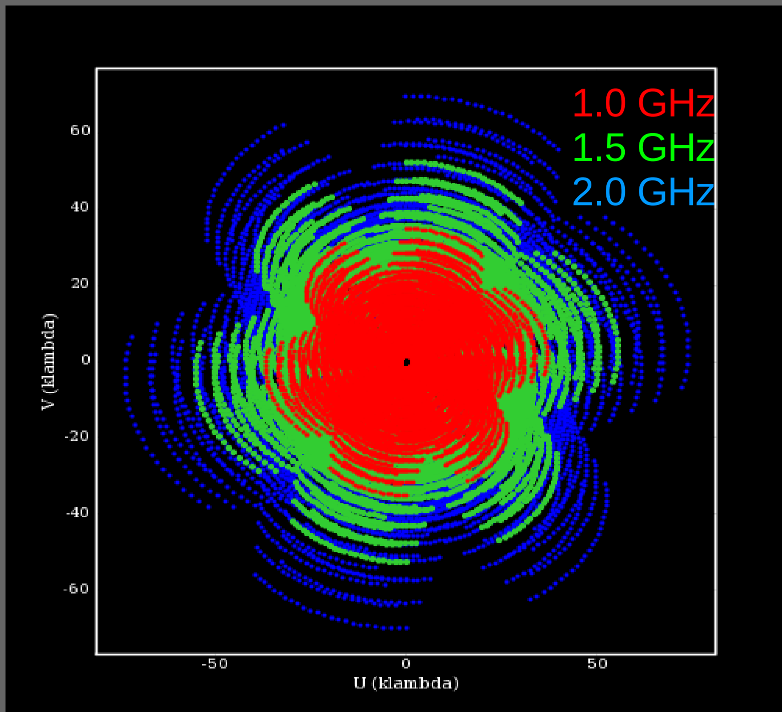
$$\sigma_{continuum} = \frac{\sigma_{\delta\nu}}{\sqrt{(\nu_{max} - \nu_{min})/\delta\nu}} = \frac{\sigma_{chan}}{\sqrt{N_{chan}}}$$

Bandwidth Ratio ($\nu_{max} : \nu_{min}$) or Fractional Bandwidth $\frac{\nu_{max} - \nu_{min}}{\nu_{mid}}$

Higher BWR (2:1 at L,S, C bands) => Stronger frequency-dependent effects within the band (sky and instrument)

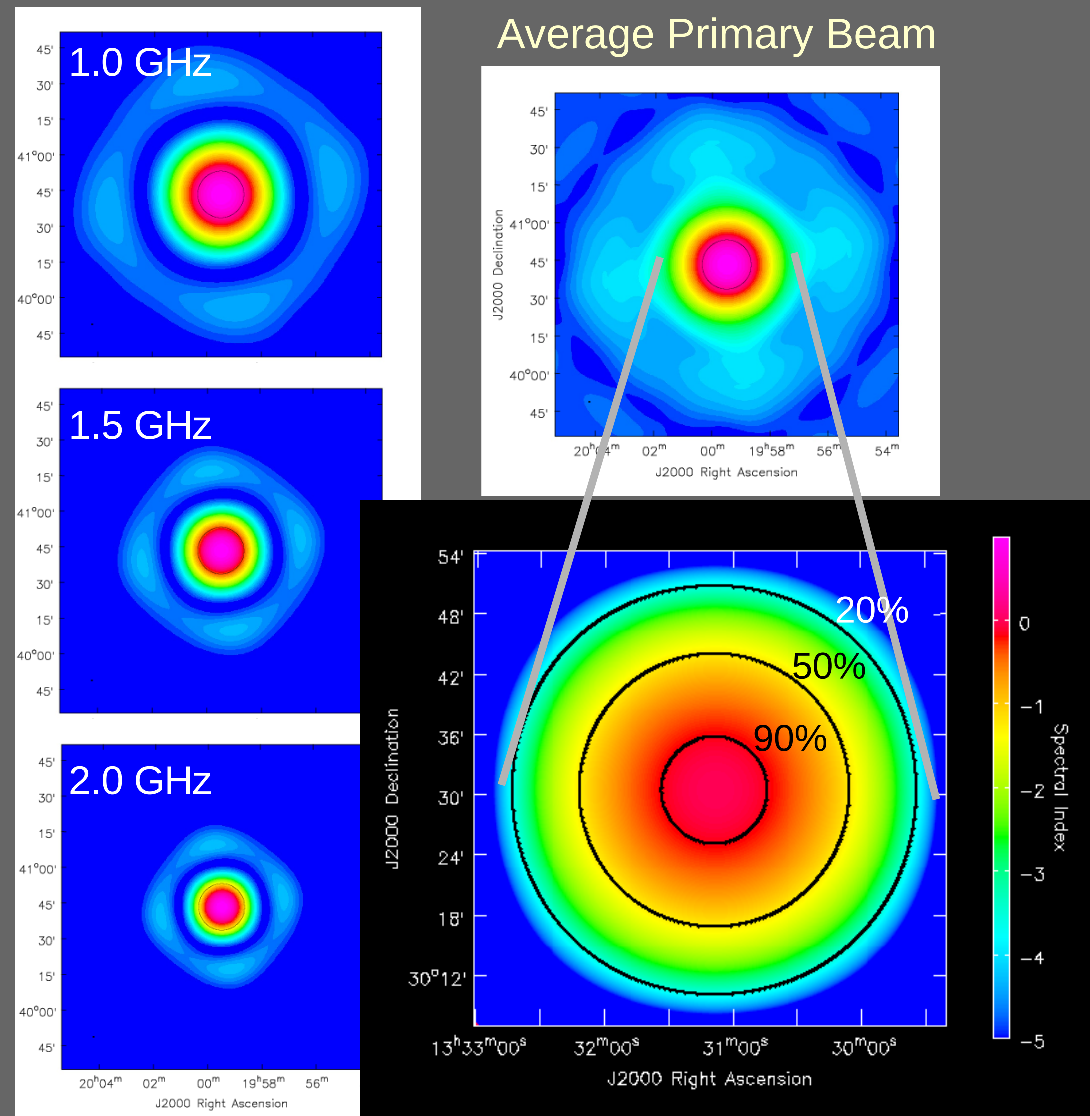
Frequency-dependence of the instrument and sky

Multi-Frequency UV-coverage



Multi-Frequency Primary Beams

Average Primary Beam



'Spectral Index' of PB

- UV-coverage (angular resolution)
- Primary-beam (field-of-view)
- Sky-brightness distribution

..... all change with frequency

Wideband Imaging Options

(1) Make images for each channel / SPW separately.

- Signal-to-noise ratio : one SPW
- Angular resolution varies with SPW (smooth to lowest)
- Imaging fidelity may change across SPWs

When will this suffice ?

- Sources have sufficient SNR in a single channel / SPW
- UV-coverage per SPW gives un-ambiguous reconstructions
- You don't need the highest-possible angular resolution for spectra

(2) Combine all frequencies during imaging
(MFS : multi-frequency synthesis)

- Signal-to-noise ratio : all SPWs
- Angular resolution is given by the highest frequency
- Imaging fidelity is given by the combined uv-coverage

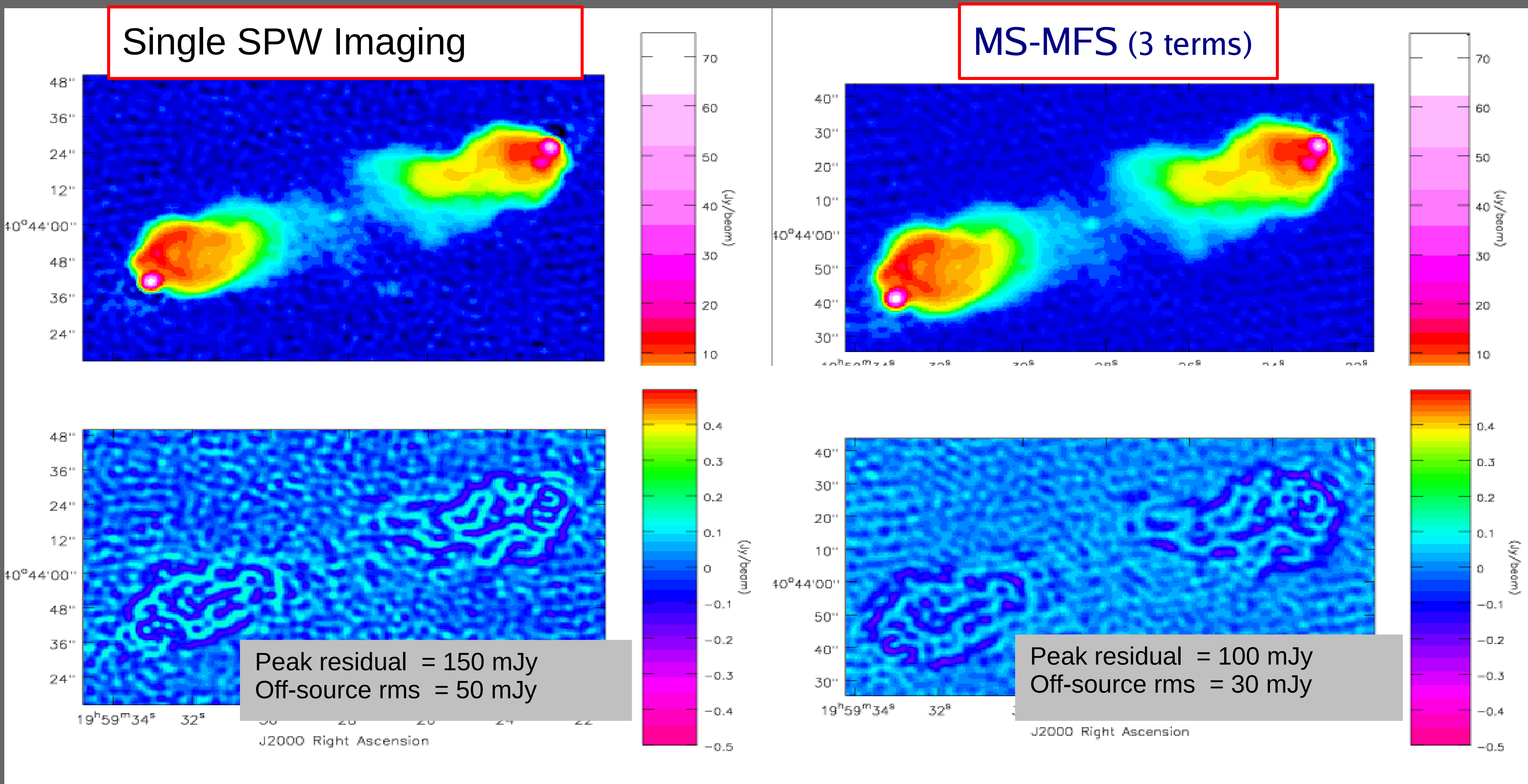
When do you need MFS ?

- Single channel / SPW sensitivity is too low
- Complicated fields where single-SPW uv-coverage gives non-unique solutions
- Need high angular-resolution images (intensity and spectral index)

(But, need to model / reconstruct spectra too...)

Comparison of single-SPW imaging with MFS - Intensity

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



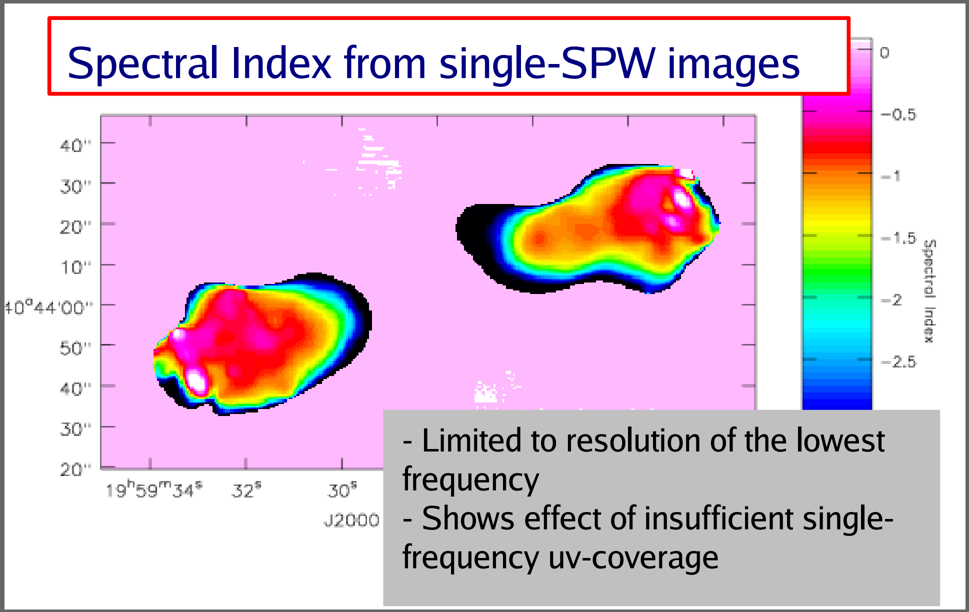
=> Similar results

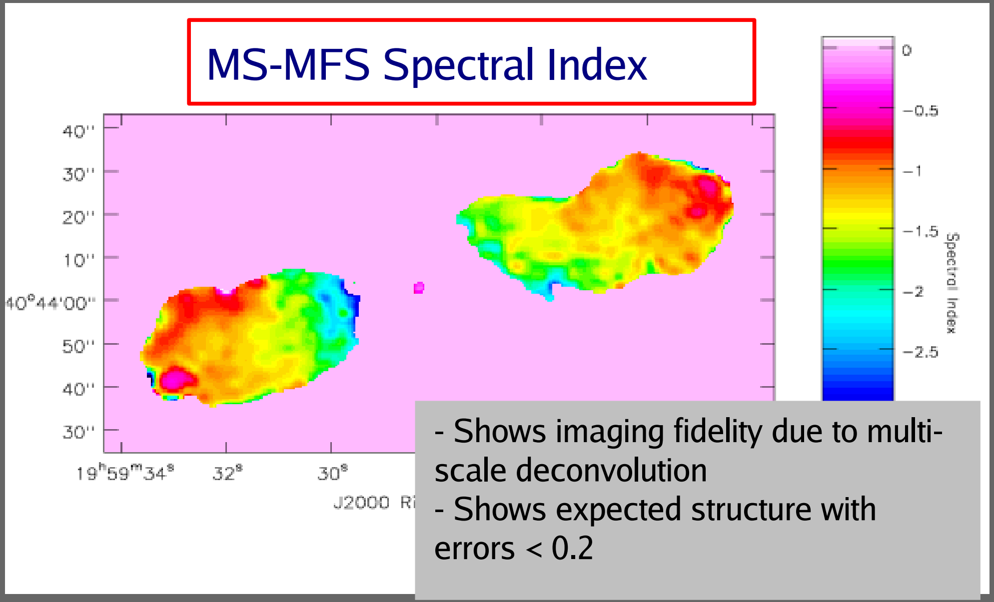
- both methods reconstruct plausible intensity images.
- both have similar residual errors due to deconvolution.

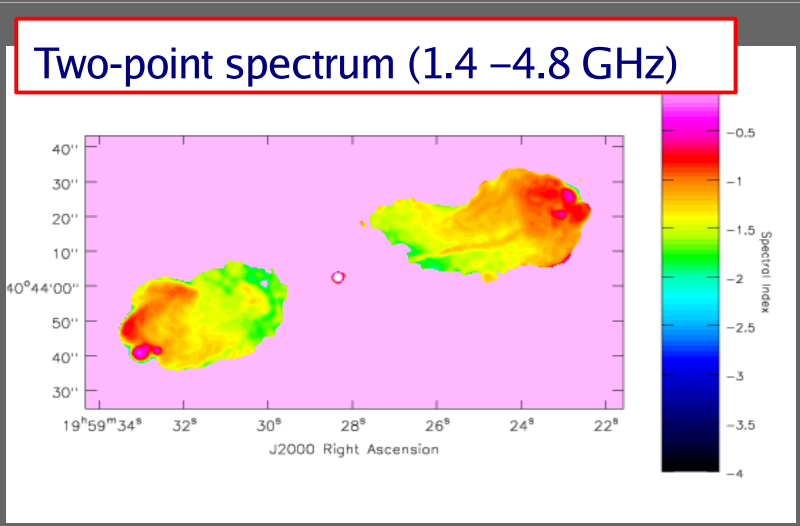
(MS-MFS : Multi-Scale Multi-Frequency Synthesis : models intensity and spectrum (Taylor polynomial))

Comparison of single-SPW imaging with MFS – Spectral Index

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







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

=> It helps to use the combined uv-coverage and solve for sky spectra.

Can often extract more information from your data, compared to traditional methods, but not always.

“Multi-Scale Multi-Frequency Synthesis”

Multi-Scale MFS : as implemented in CASA

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

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

Image Reconstruction : Linear least squares + Deconvolution (2011A&A...532A..71R , arXiv:1106.2745)

User Parameters : Imaging mode : mode='mfs'
Number of Taylor-polynomial coeffs. : nterms=2
Reference frequency : reffreq = '1.5GHz'
Set of spatial scales (in units of pixels) : multiscale=[0,6,10]

Data Products : Taylor-Coefficient images $I_0, I_1, I_2, \ldots$

- Interpret in terms of a power-law : spectral index and curvature

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

(Or, evaluate the spectral cube (for non power-law spectra))

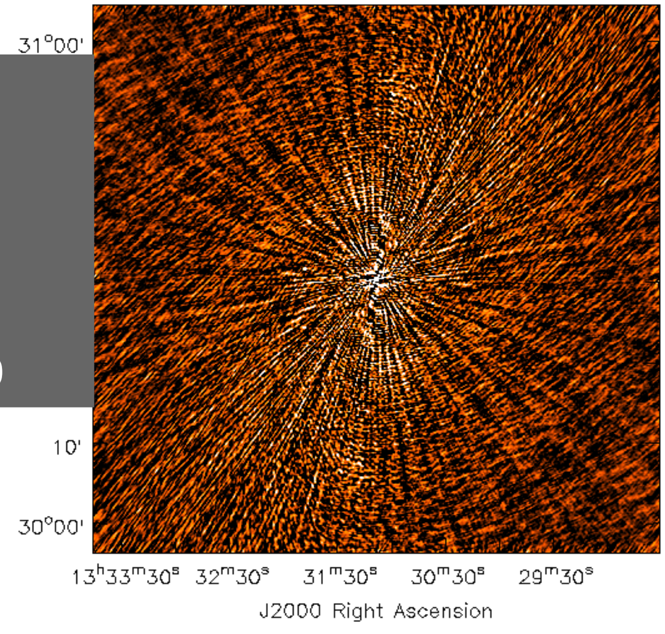
Dynamic Range (vs) NTERMS – 3C286 field (point sources)

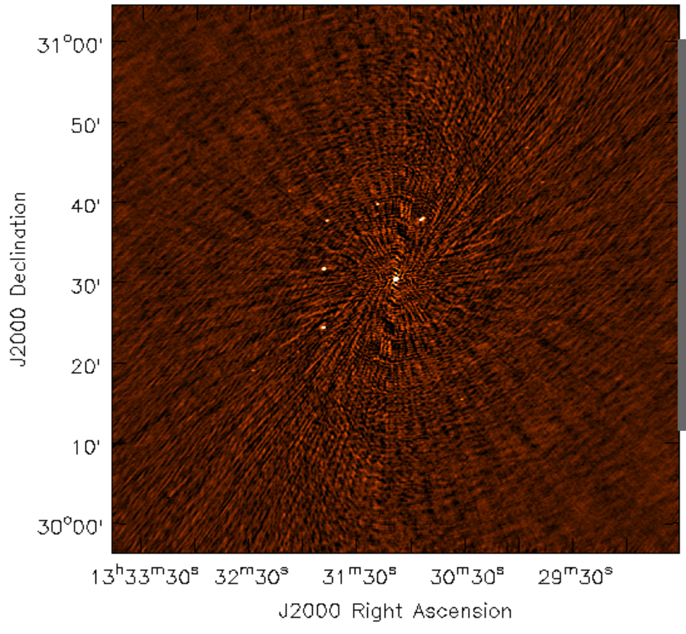
(I=14.4 Jy/bm, alpha = -0.47, BW=1.1GHz at Lband)

NTERMS = 1

Rms :
9 mJy -- 1 mJy

DR :
1600 -- 13000





NTERMS = 2

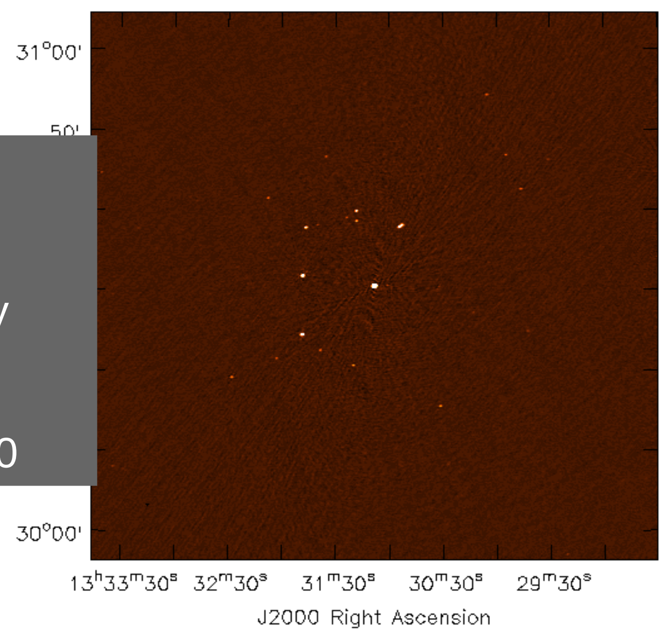
Rms :
1 mJy -- 0.2 mJy

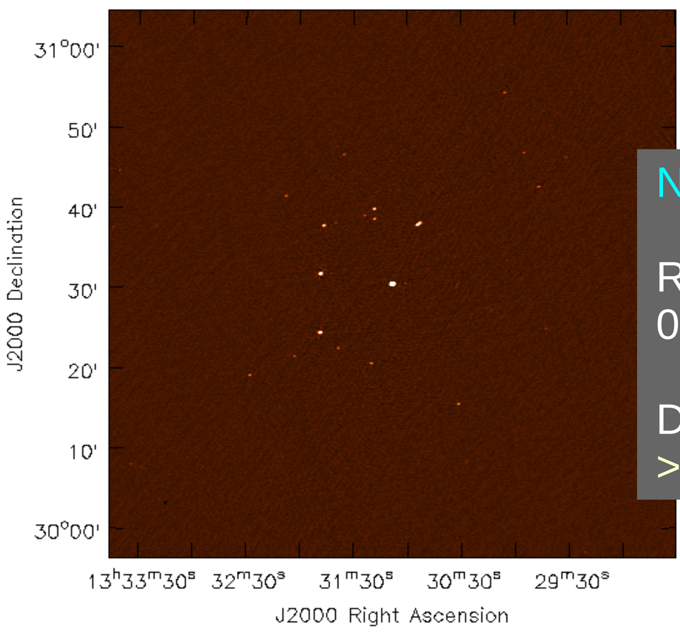
DR :
10,000 -- 17,000

NTERMS = 3

Rms :
0.2 mJy -- 85 uJy

DR :
65,000 -- 170,000



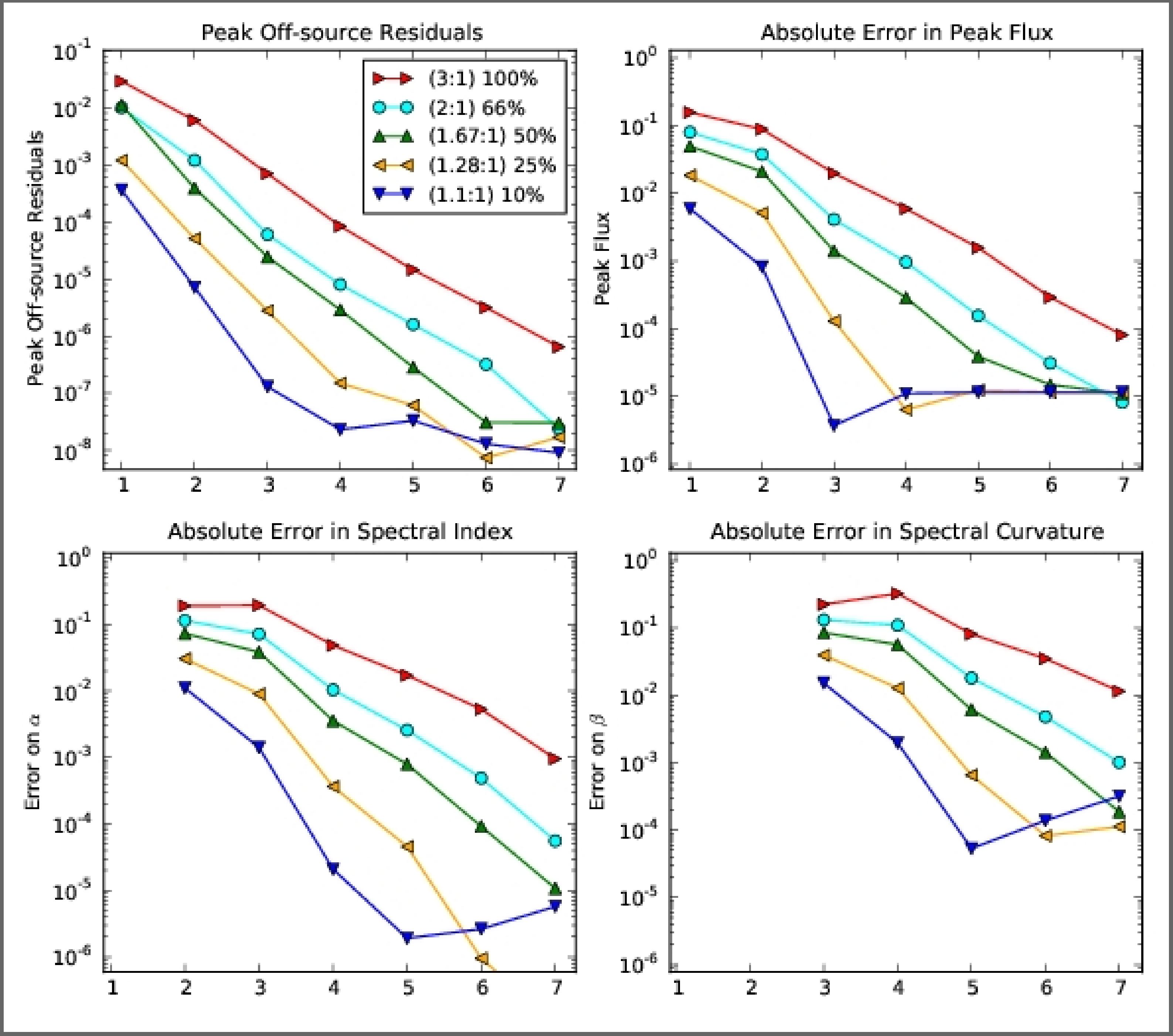


NTERMS = 4

Rms :
0.14 mJy -- 80 uJy

DR :
>110,000 -- 180,000

Error estimates : Bandwidth-ratio vs 'nterms' (high SNR)



If spectra are ignored

=> larger BWR gives larger errors

If there is high SNR,

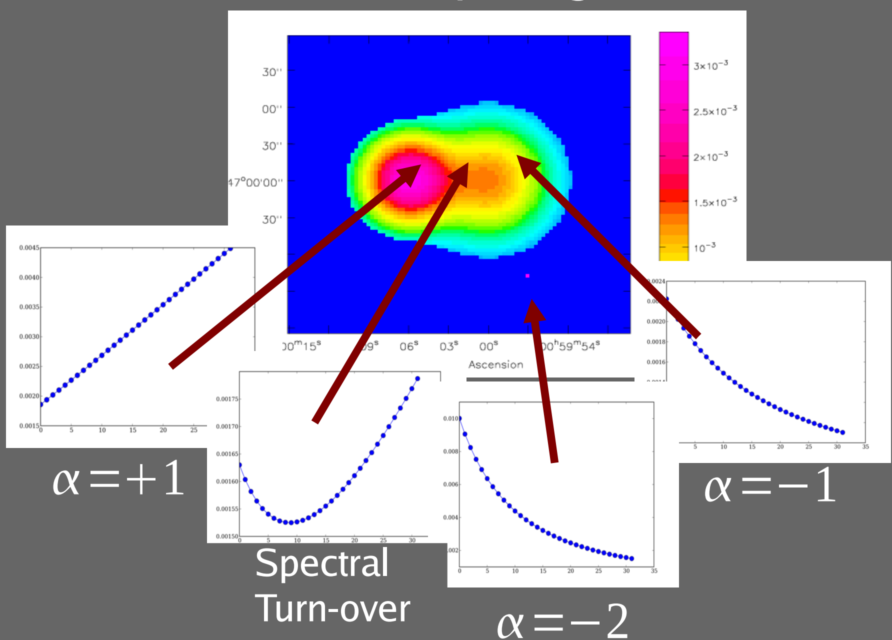
=> more terms gives smaller errors

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

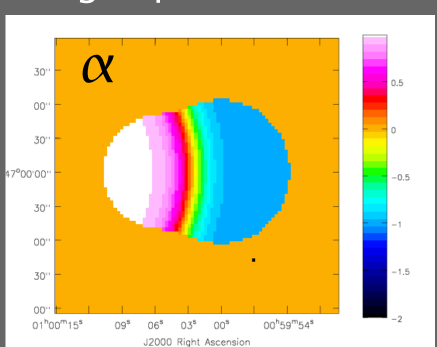
In practice, use nterms>2 only if there is high SNR (>100), and if you can see spectral artifacts in the image with nterms=2

Multi-Scale vs Point-Source model for wideband imaging

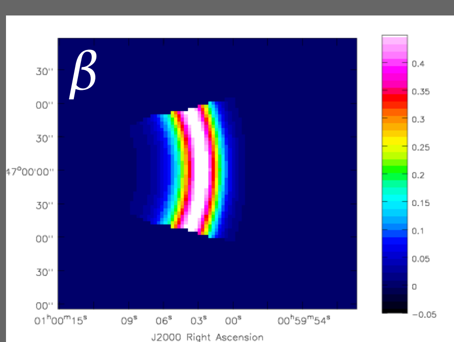
Intensity Image

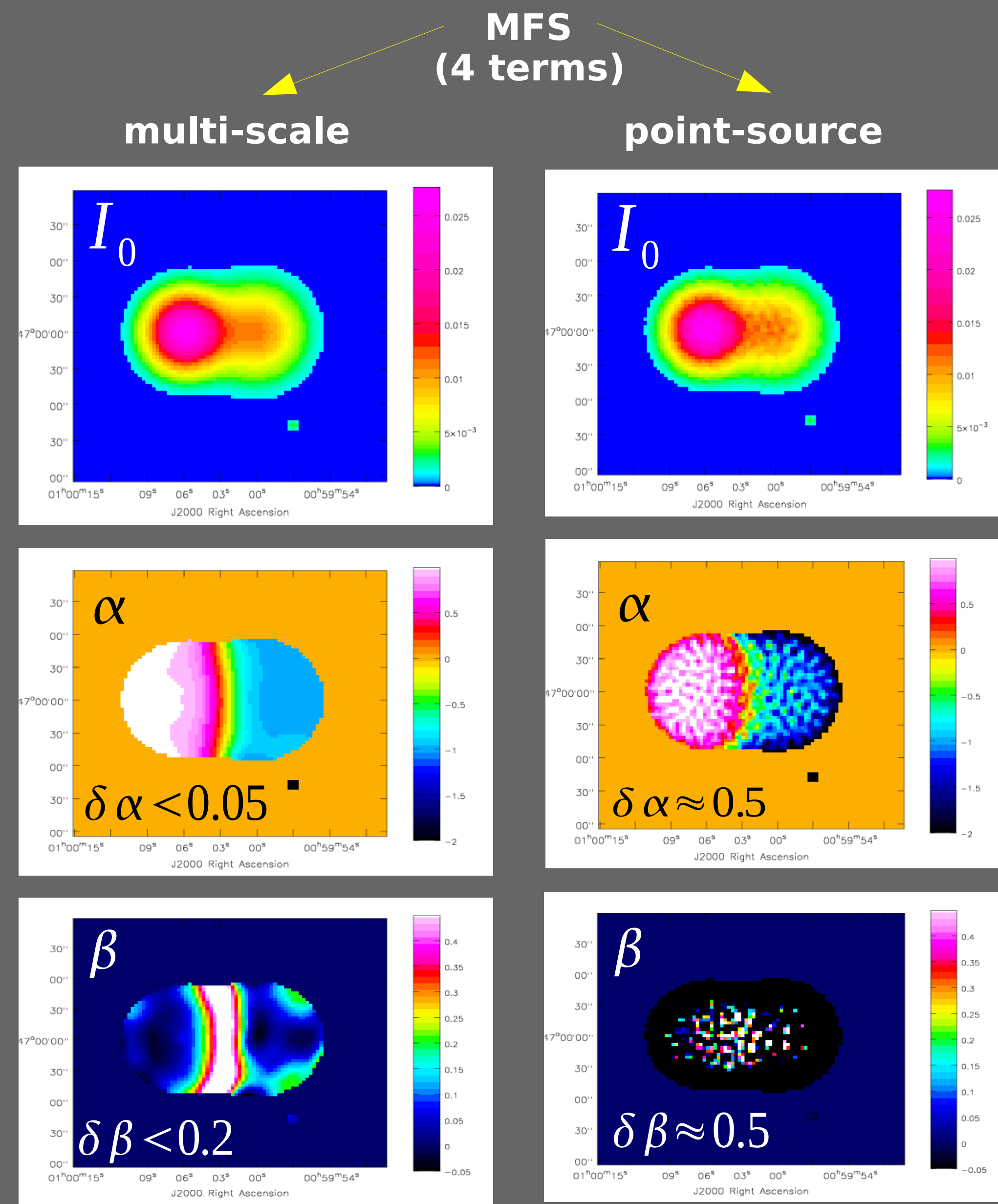


Average Spectral Index



Gradient in Spectral Index



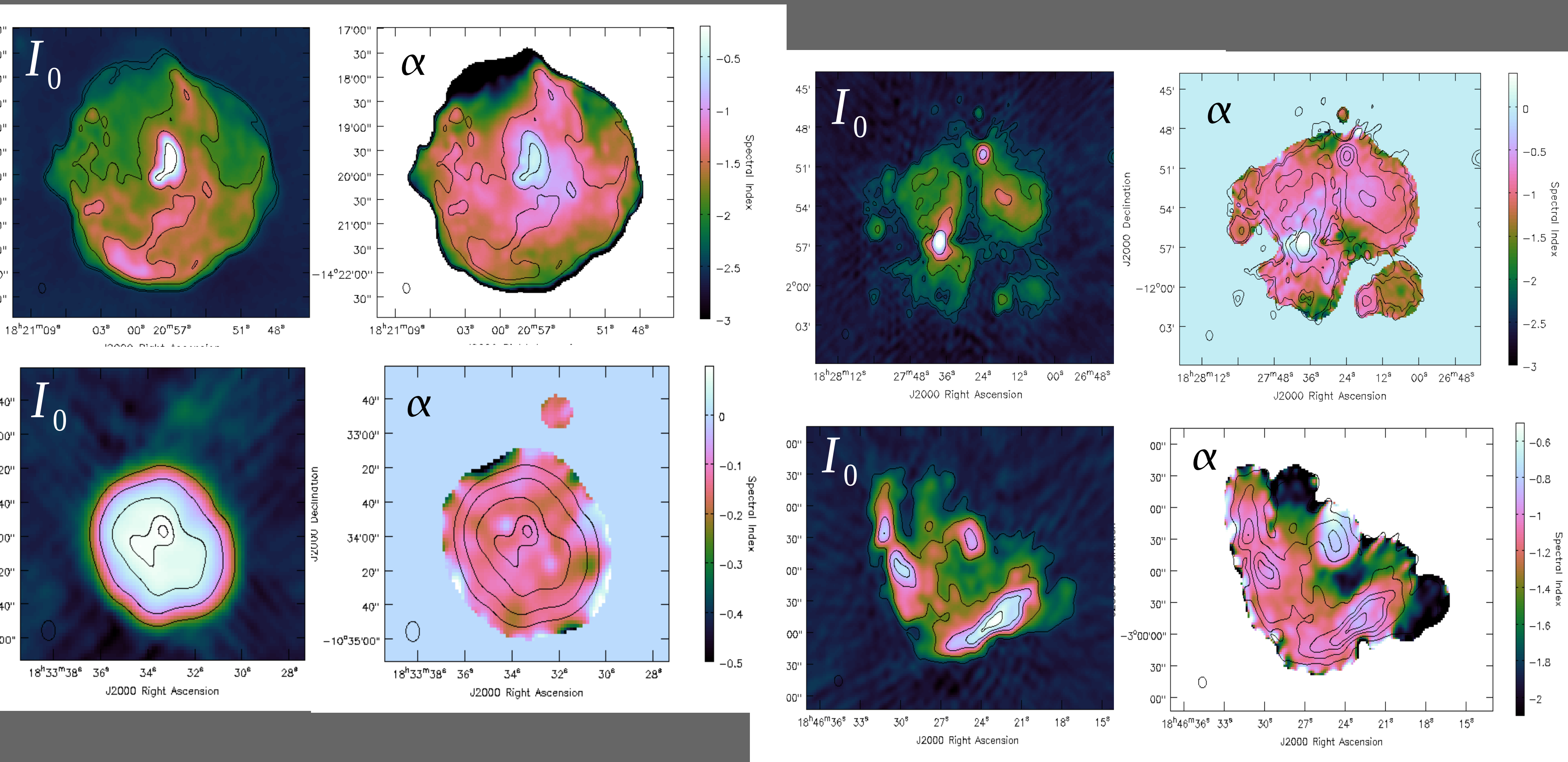


=> For extended emission,

-> a multi-scale model gives better spectral index and curvature maps

Separating regions/sources based on spectral index structure

(2011ApJ...739L..20B , arXiv:1106.2796)



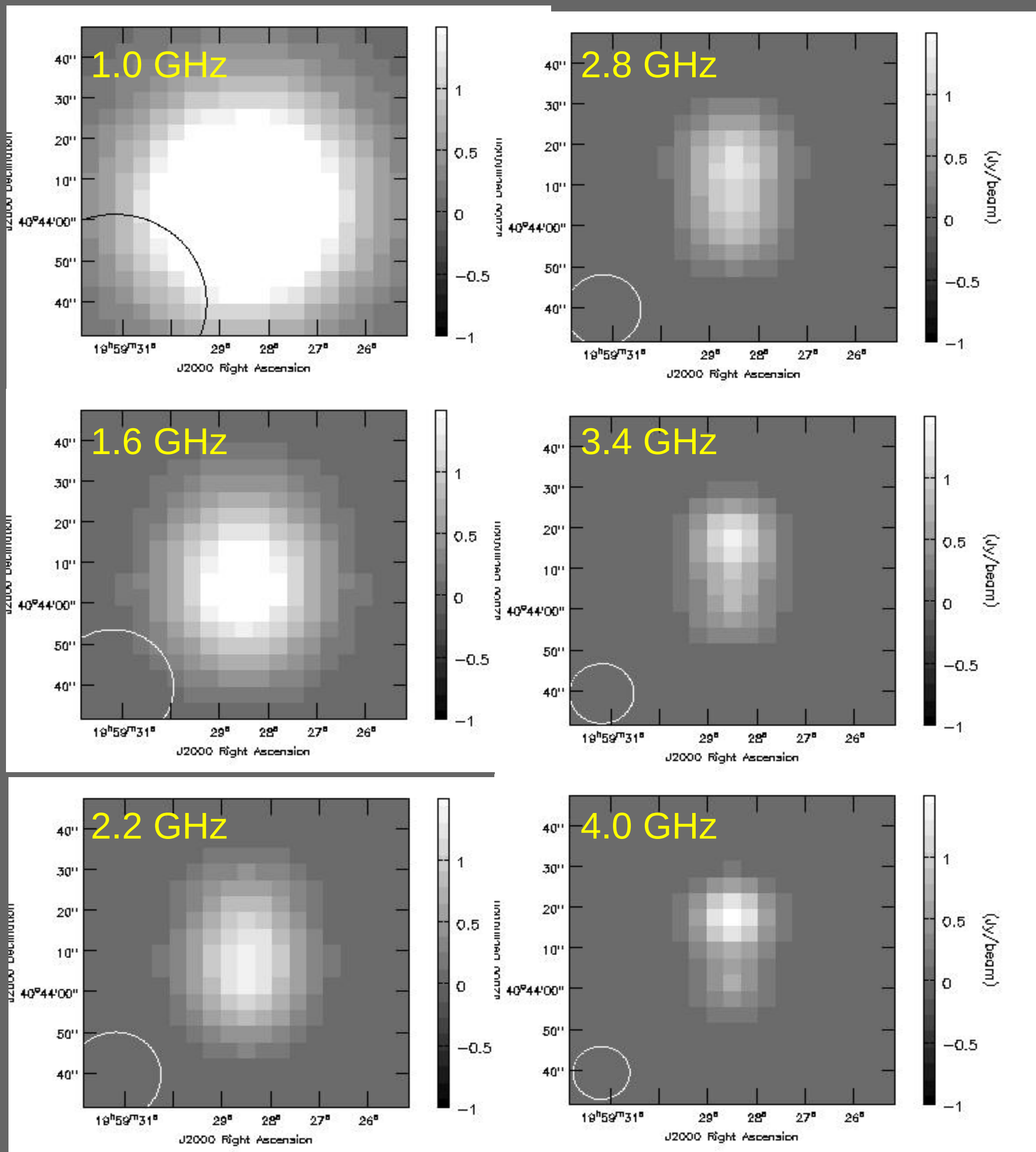
Initial results of a pilot survey (EVLA RSRO AB1345). These examples used nterms=2, and about 5 scales.

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

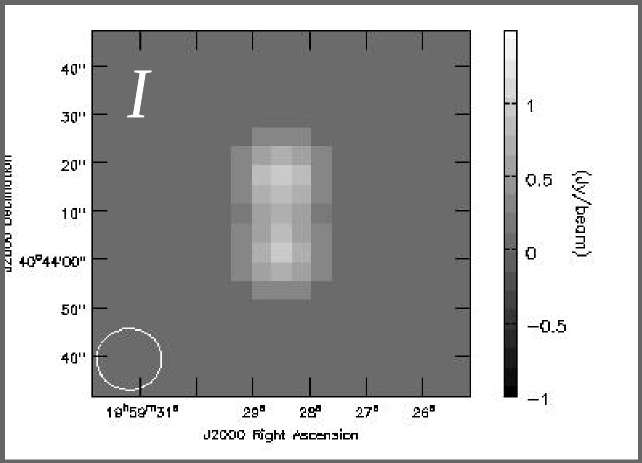
=> These images have a dynamic-range limit of few x 1000

Small spatial-scales - moderately-resolved sources

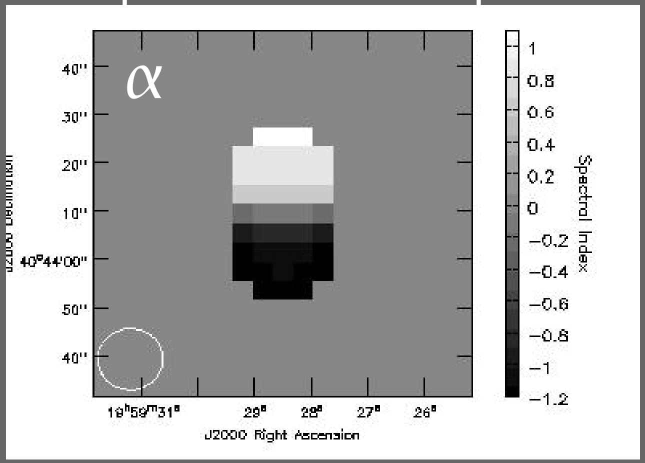
Can reconstruct the spectrum at the angular resolution of the highest frequency (only high SNR)



Restored Intensity image

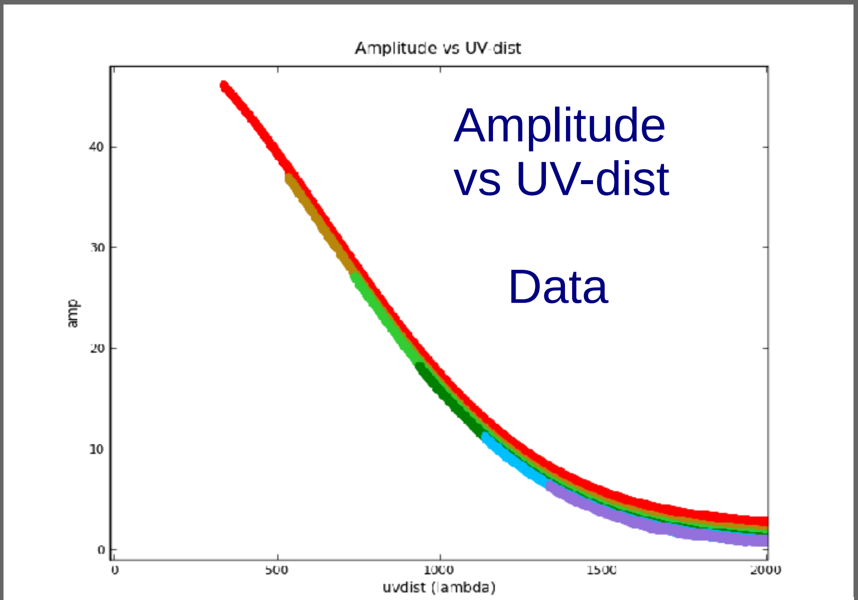


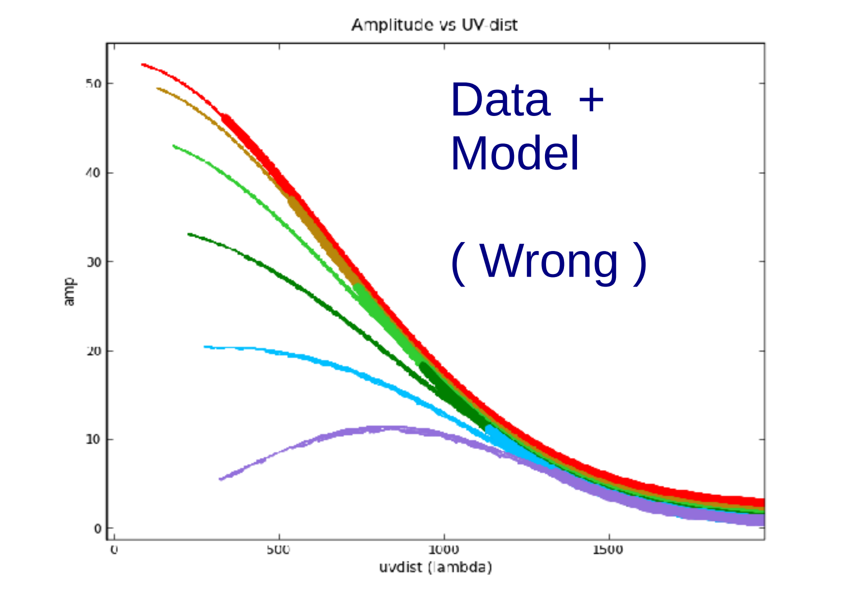
Spectral Index map

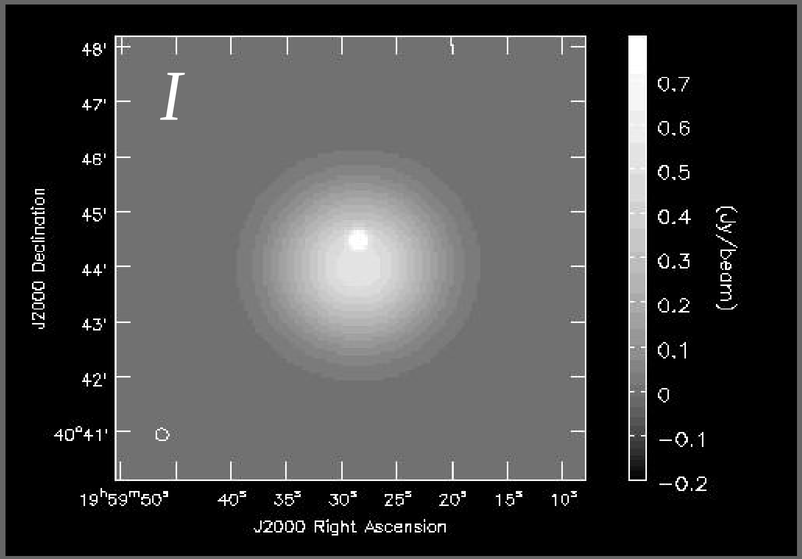


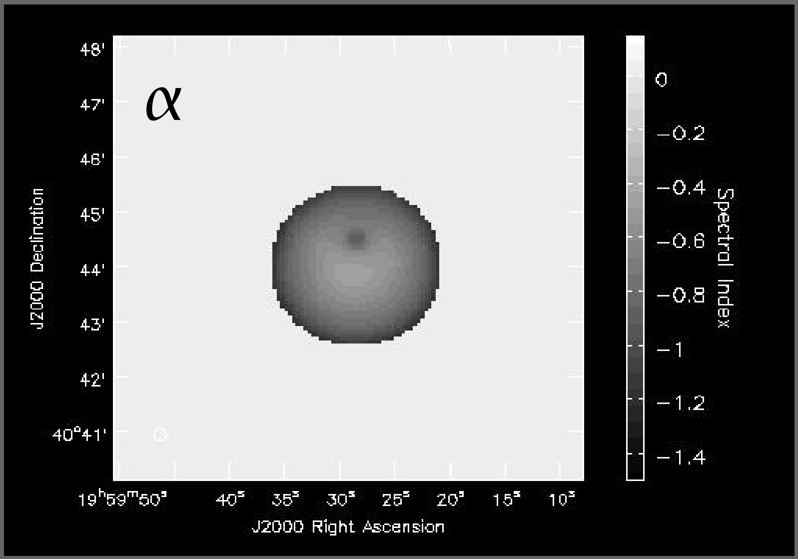
Very large spatial scales - without short-spacing data

The spectrum at the largest spatial scales is NOT constrained by the data



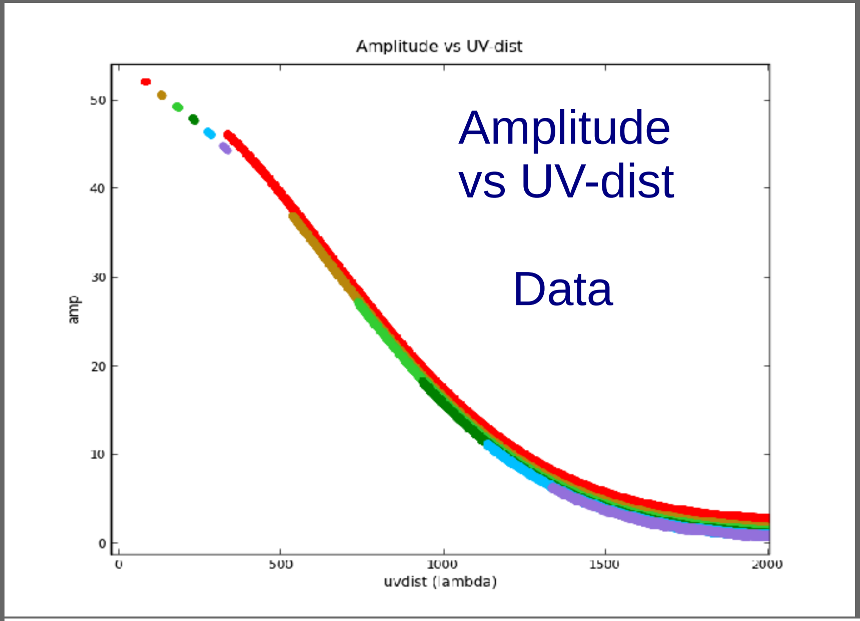


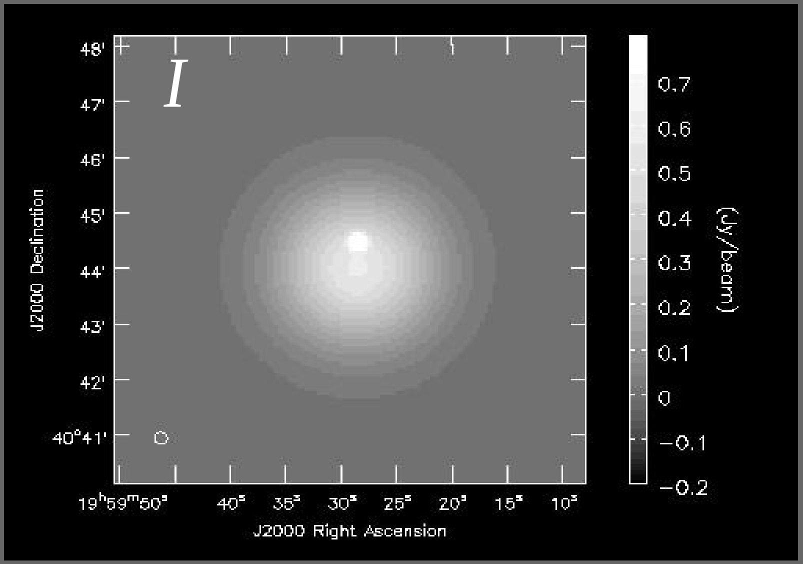


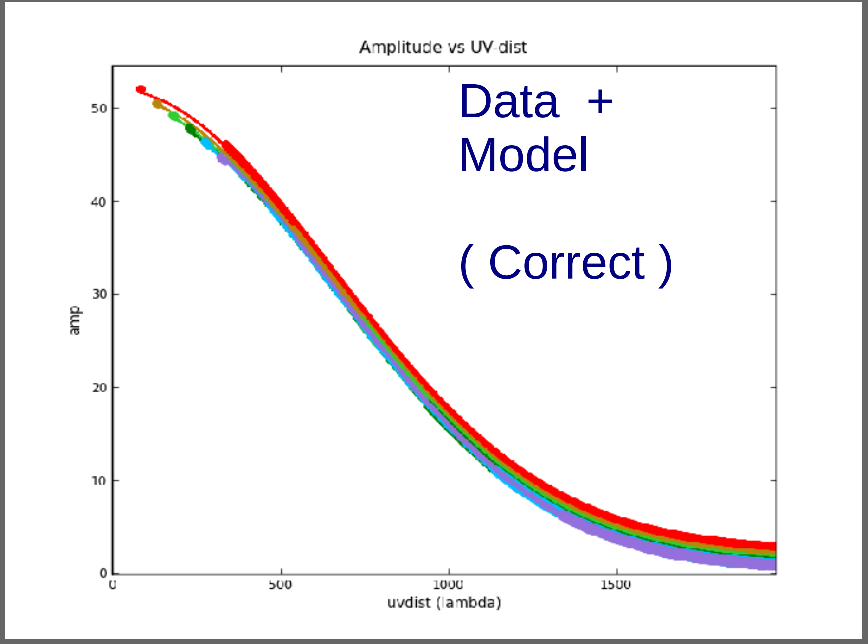


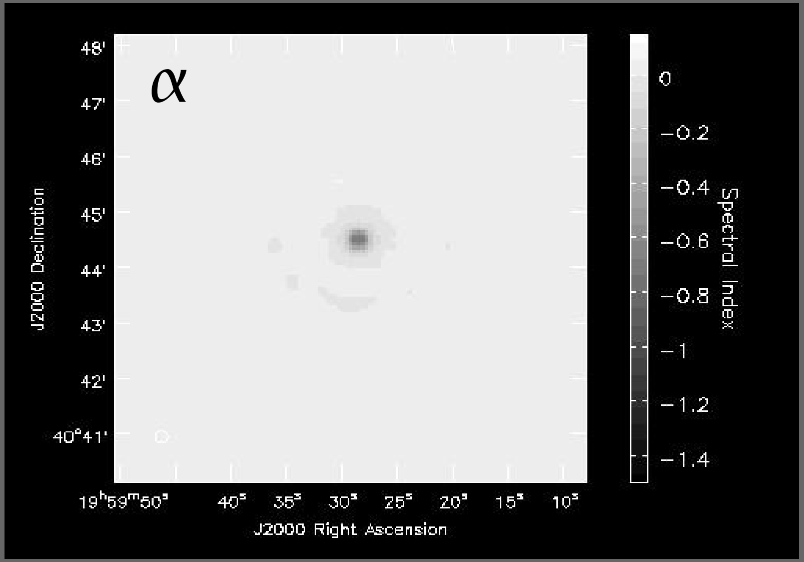
Very large spatial scales – with short-spacing data

External short-spacing constraints help (visibility data, or starting image model)



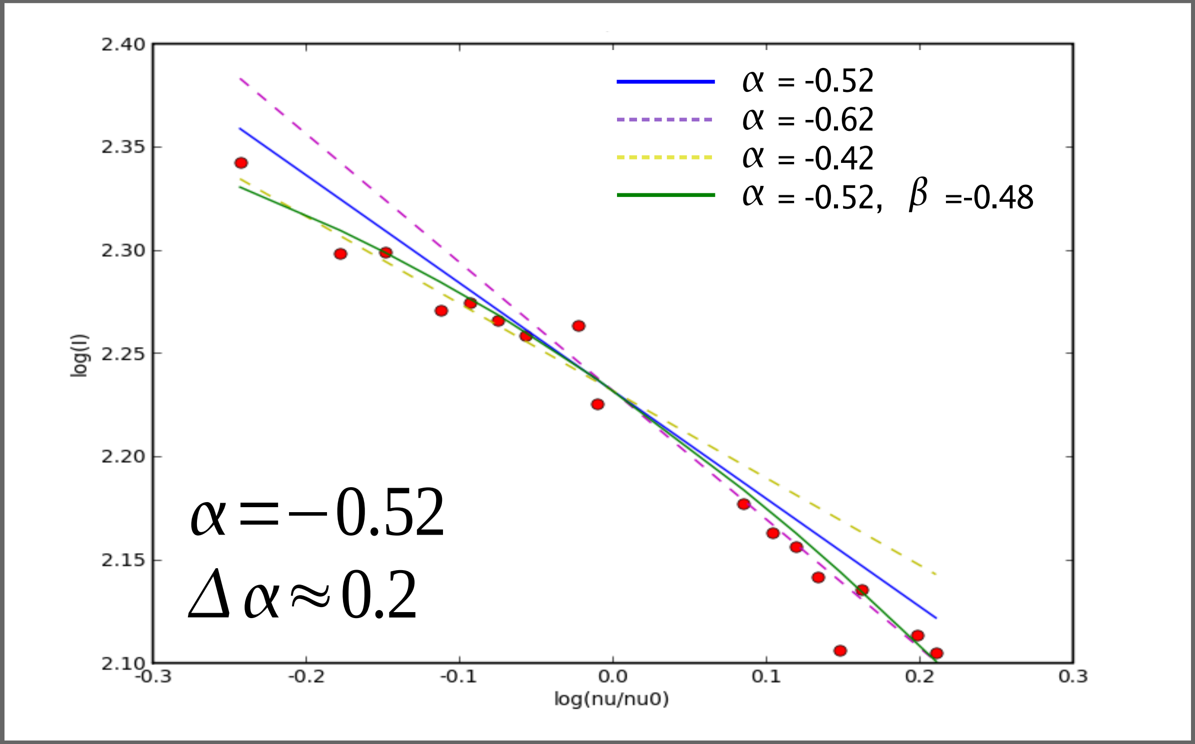


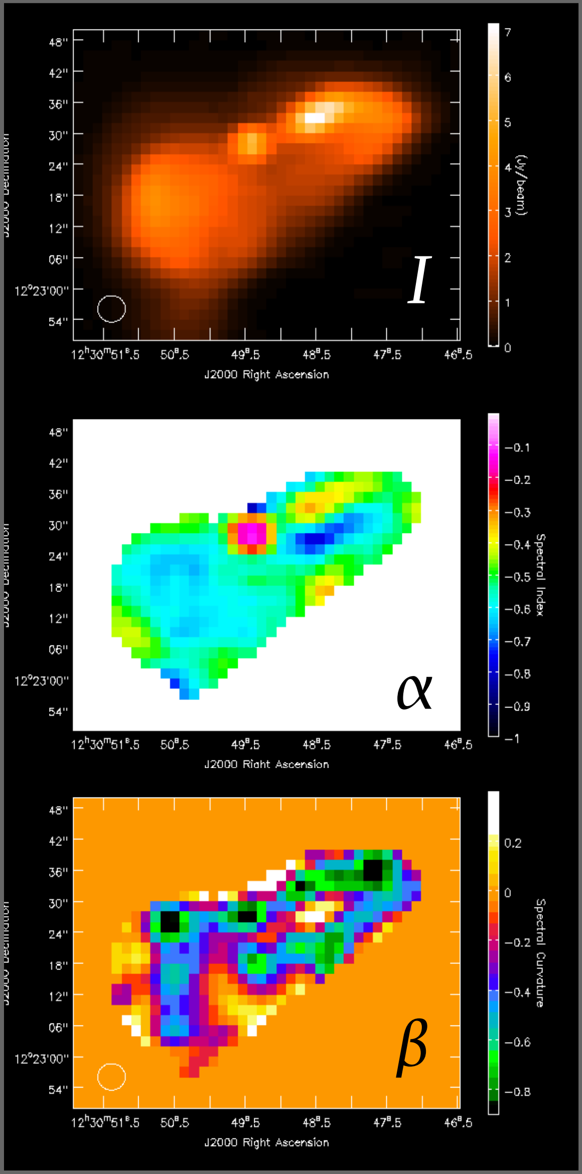




Spectral Curvature : VLA data : M87 1.1-1.8 GHz

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

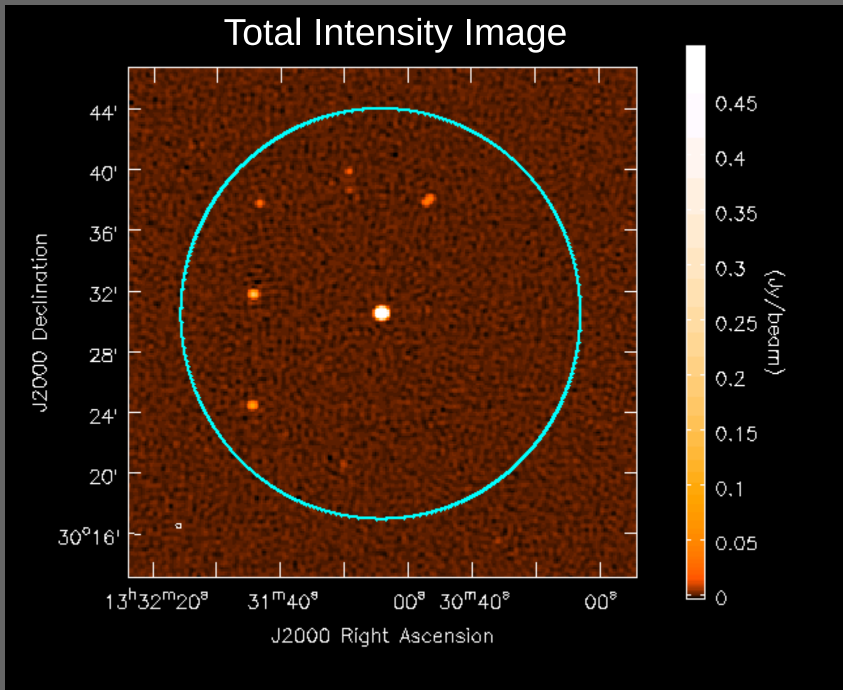
P-L spectral index : -0.36 ~ -0.45
L-C spectral index : -0.5 ~ -0.7

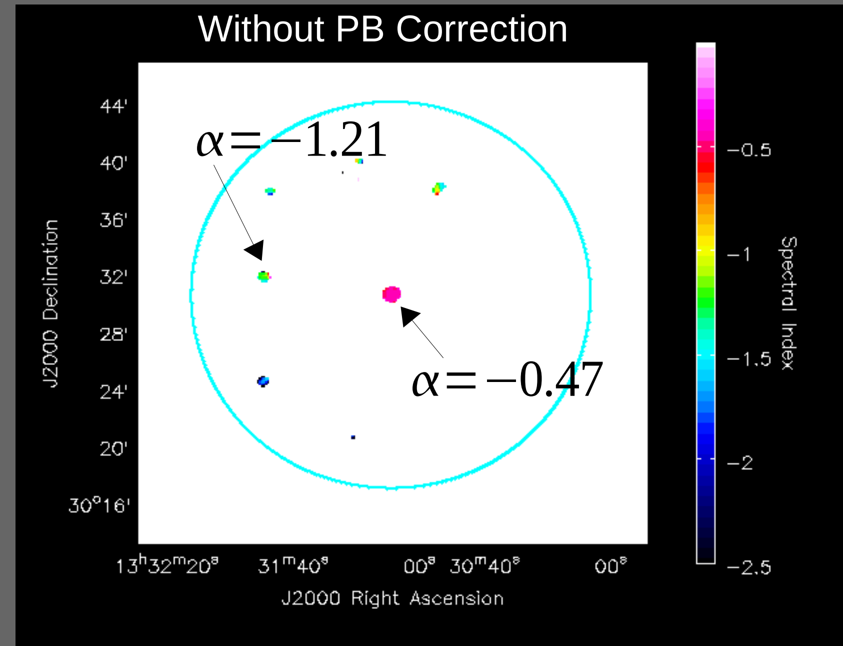
=> Need SNR > 100 to fit spectral index variation ~ 0.2 (at the 1-sigma level ...)

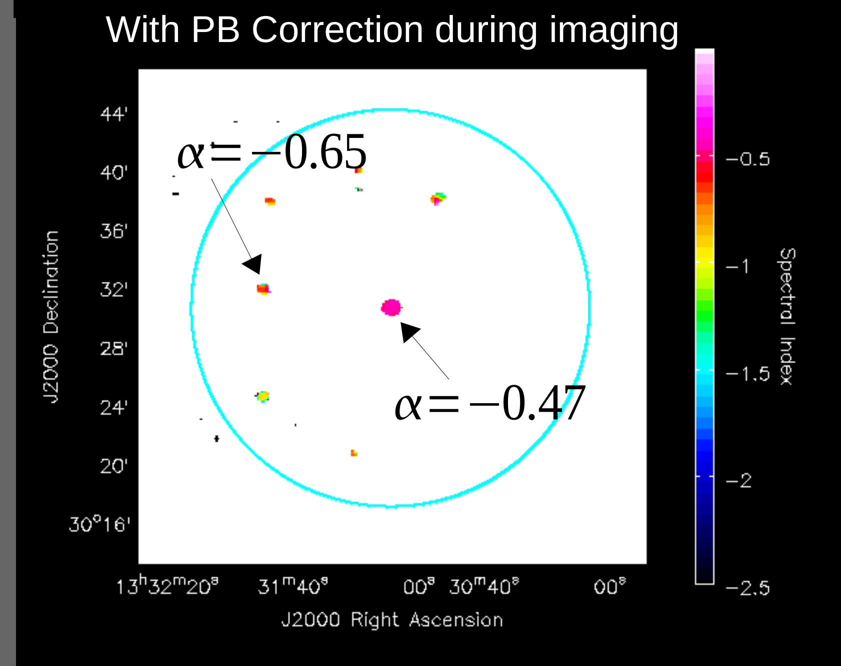
=> Be very careful about interpreting β

Wide-Field issues : Wide-band Primary-Beam

3C286 field , C-config , L-band







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

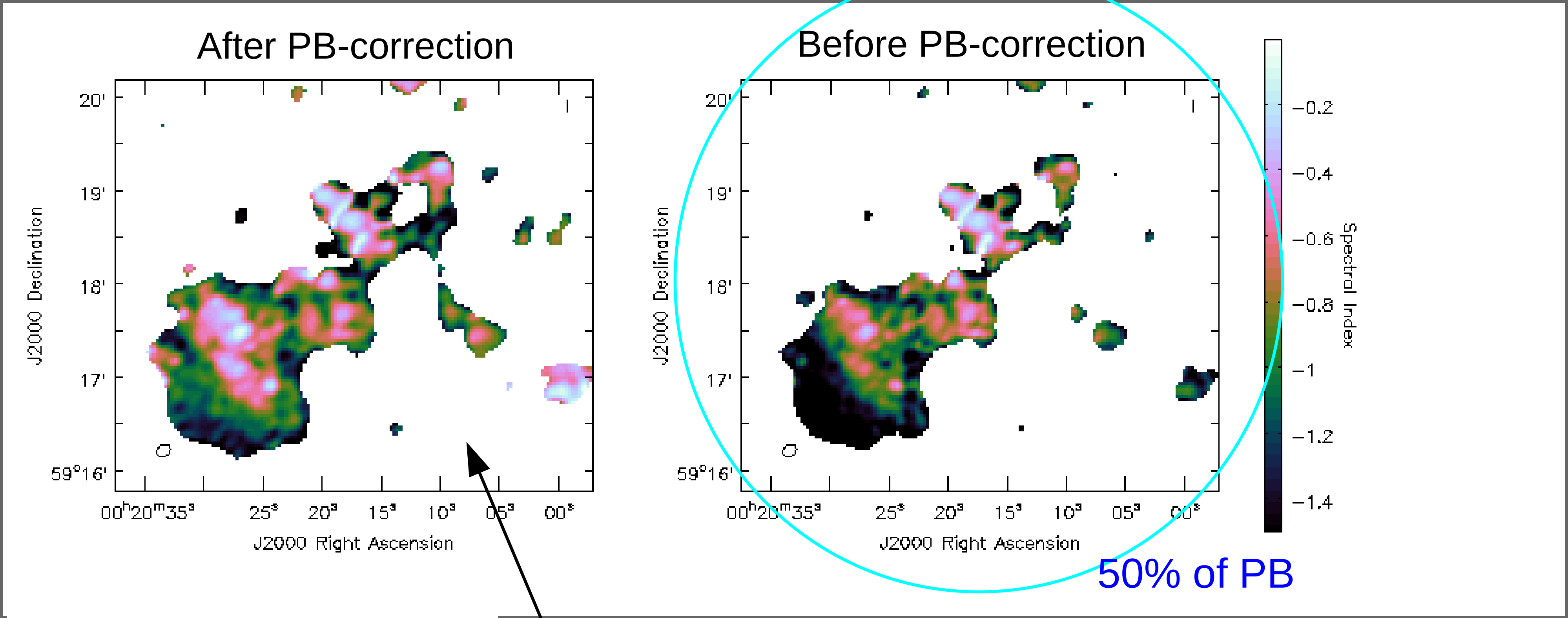
→ compared α_{center} with 'corrected' $\alpha_{off.center}$

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

Also verified via holography observations at two frequencies

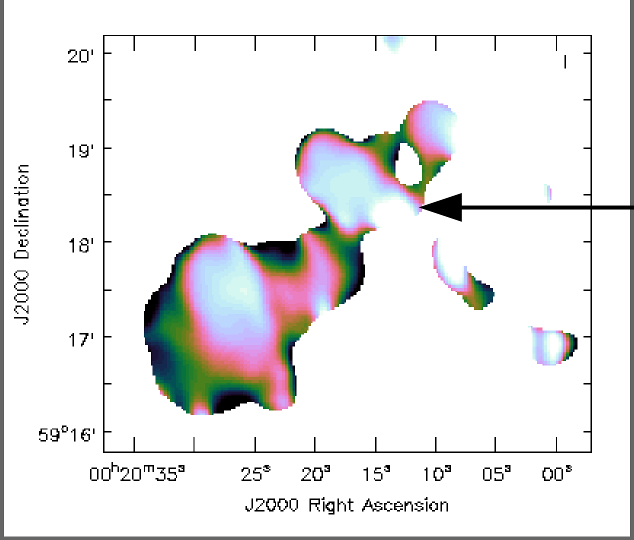
PB-correction + MS-MFS not yet available in 'clean', but approximate correction is possible with a python script.

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



(2011ApJ...739L..23H , arXiv:1108.0401)

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).

This post-deconvolution correction assumes that the primary-beam does not vary / rotate during the observation, and that all points are weighted equally....

Choices that effect errors during wide-band imaging

- 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 too many Taylor-terms.

  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 (see output error map)
  Choice of scale sizes : by eye, and verifying that the total-flux converges

- 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)

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

Choices that effect performance (current 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).

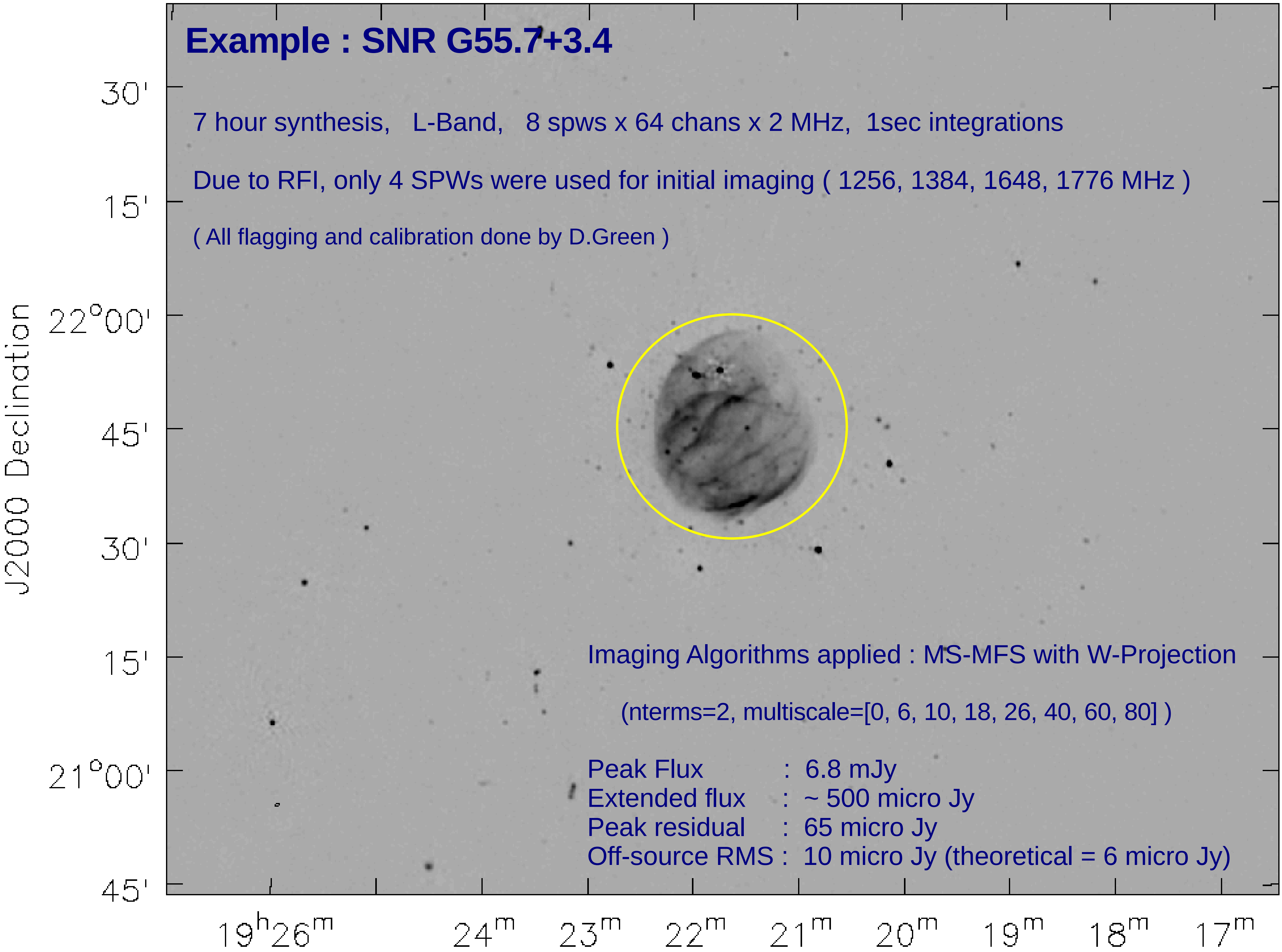
- Minor Cycle runtime x $N_{taylor} N_{scales} N_{pixels}$
- Minor Cycle memory x $\left[0.5\left(N_{taylor} N_{scales}\right)^2 + N_{taylor} + N_{taylor} N_{scales}\right] N_{pixels}$

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

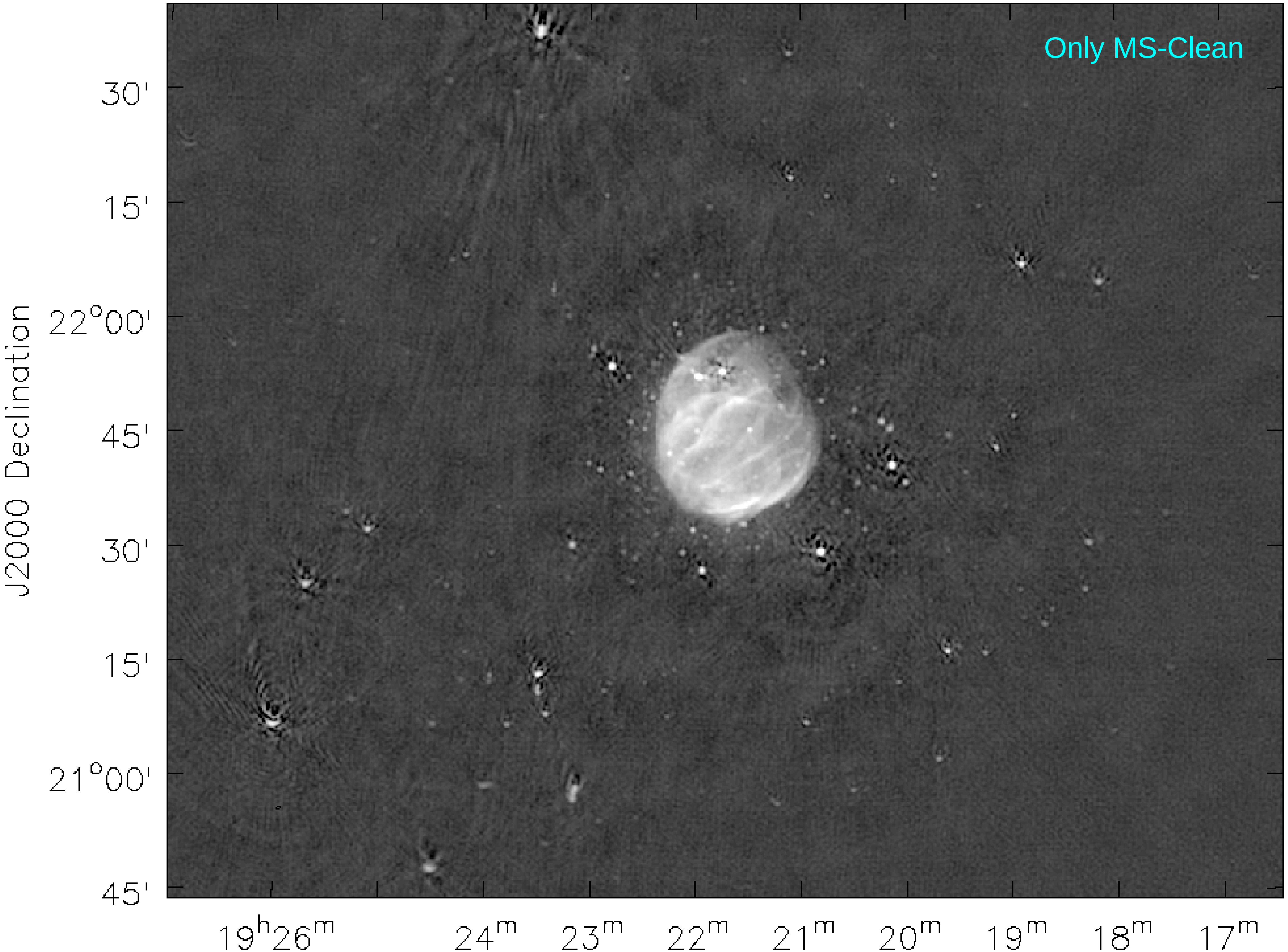
Some source structures will handle loop-gains of 0.3 to 0.5 or more (0.3 is safe).

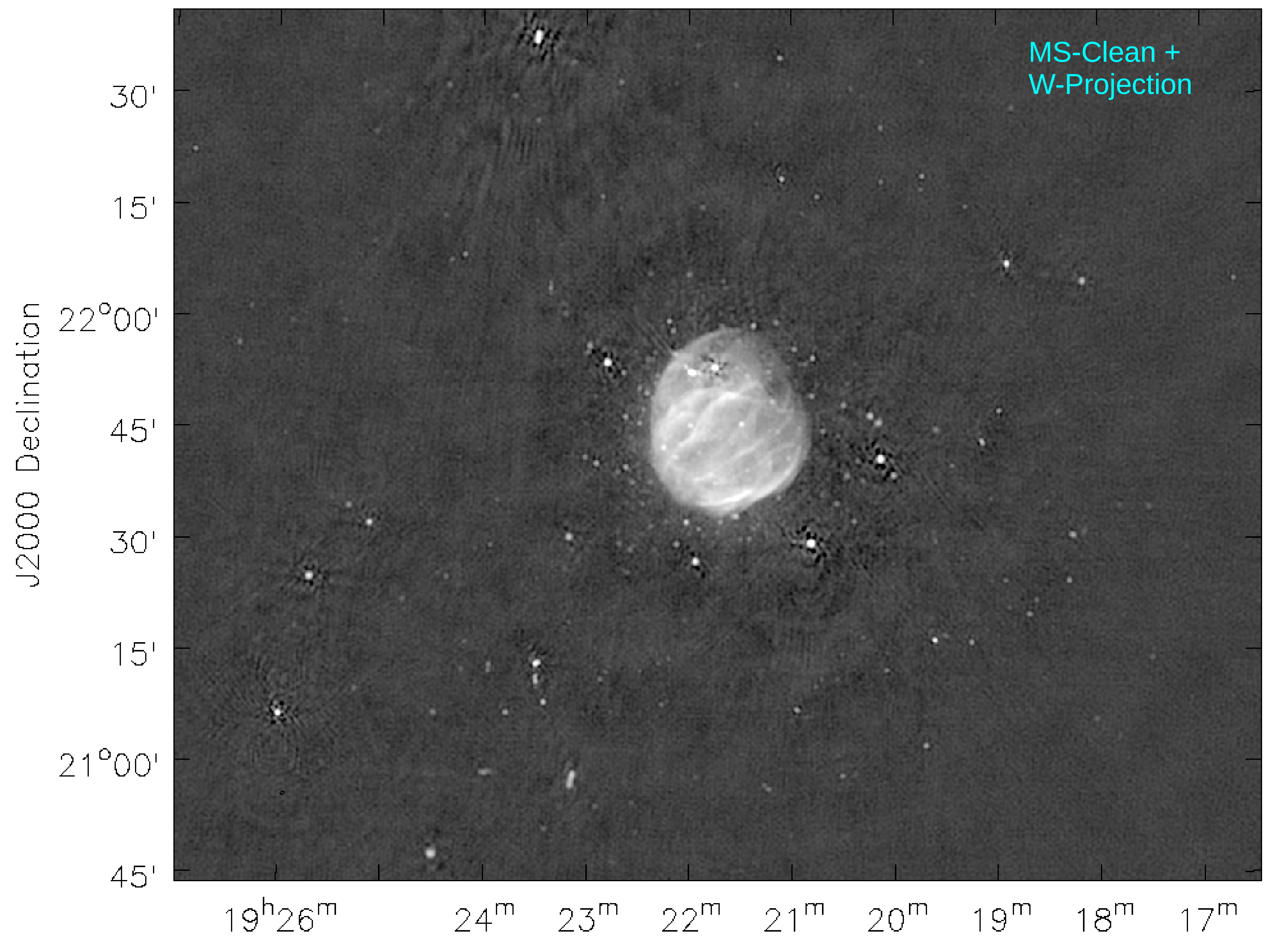
Runtimes reported by different people have ranged from 1 hr to several days.

=> Different choices of parameters => Choose only what you really need.

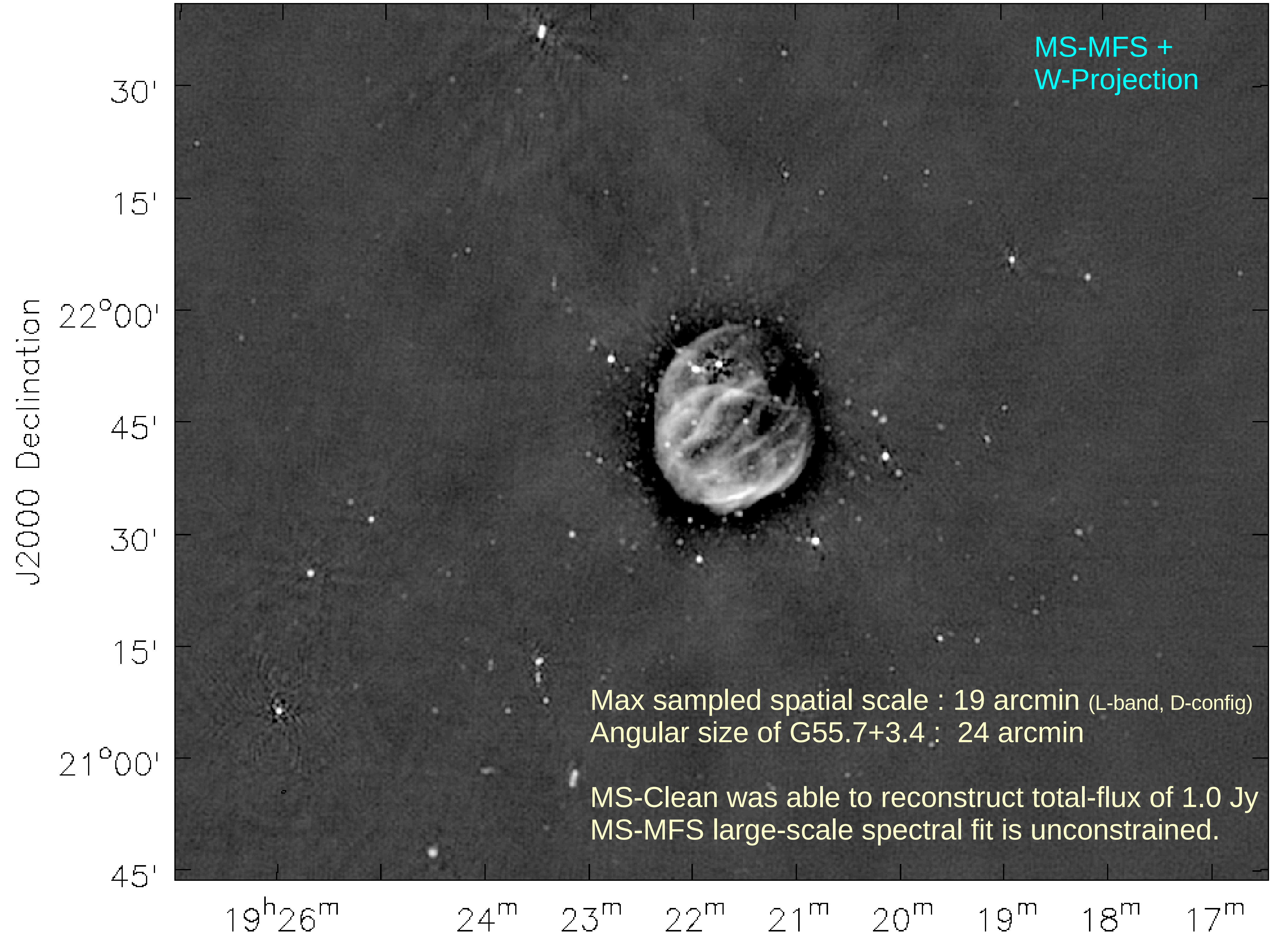


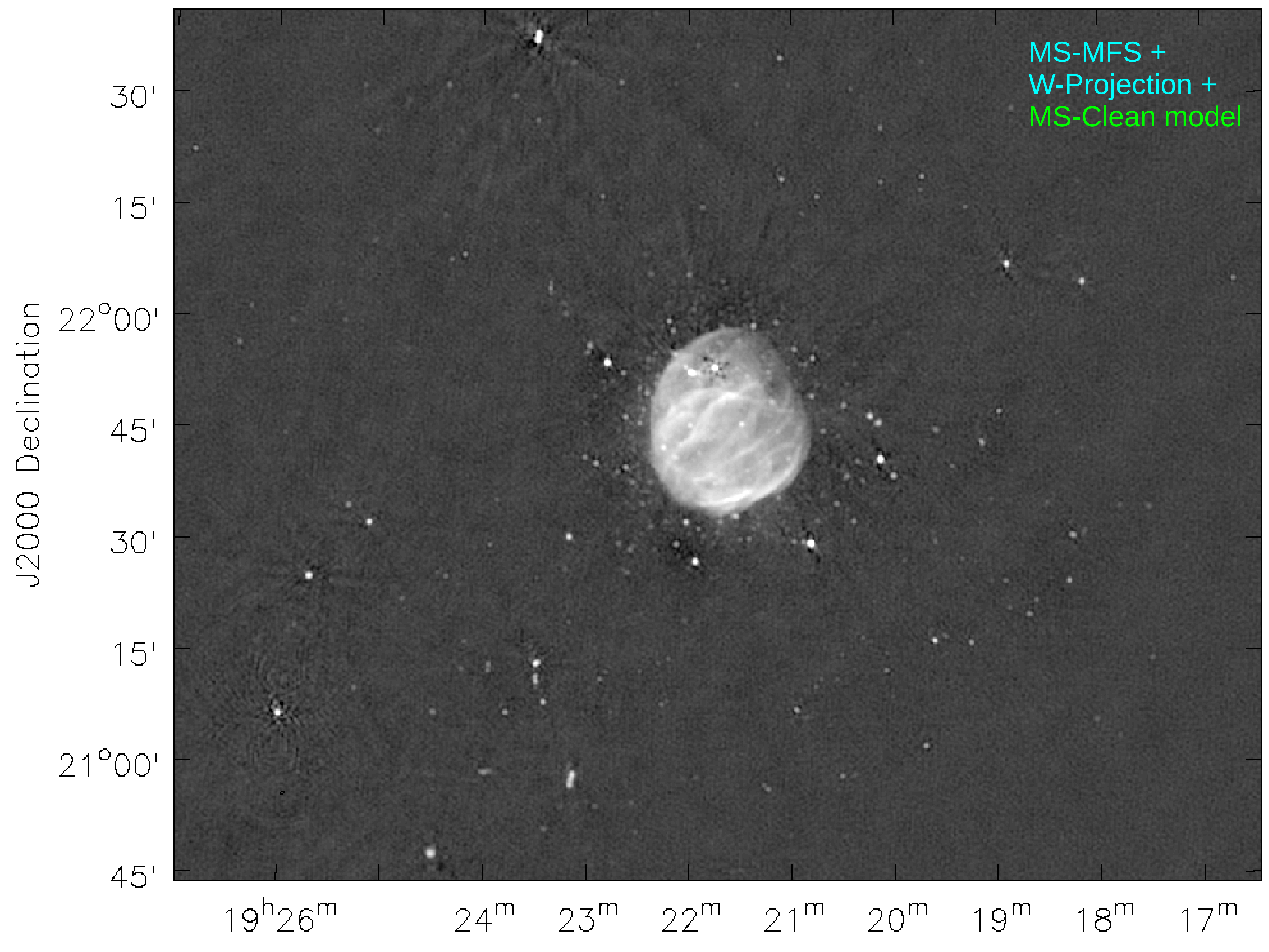
Example : SNR G55.7+3.4
7 hour synthesis, L-Band, 8 spws x 64 chans x 2 MHz, 1sec integrations
Due to RFI, only 4 SPWs were used for initial imaging (1256, 1384, 1648, 1776 MHz)
(All flagging and calibration done by D.Green)
Imaging Algorithms applied : MS-MFS with W-Projection
(nterms=2, multiscale=[0, 6, 10, 18, 26, 40, 60, 80])
Peak Flux : 6.8 mJy
Extended flux : ~ 500 micro Jy
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


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

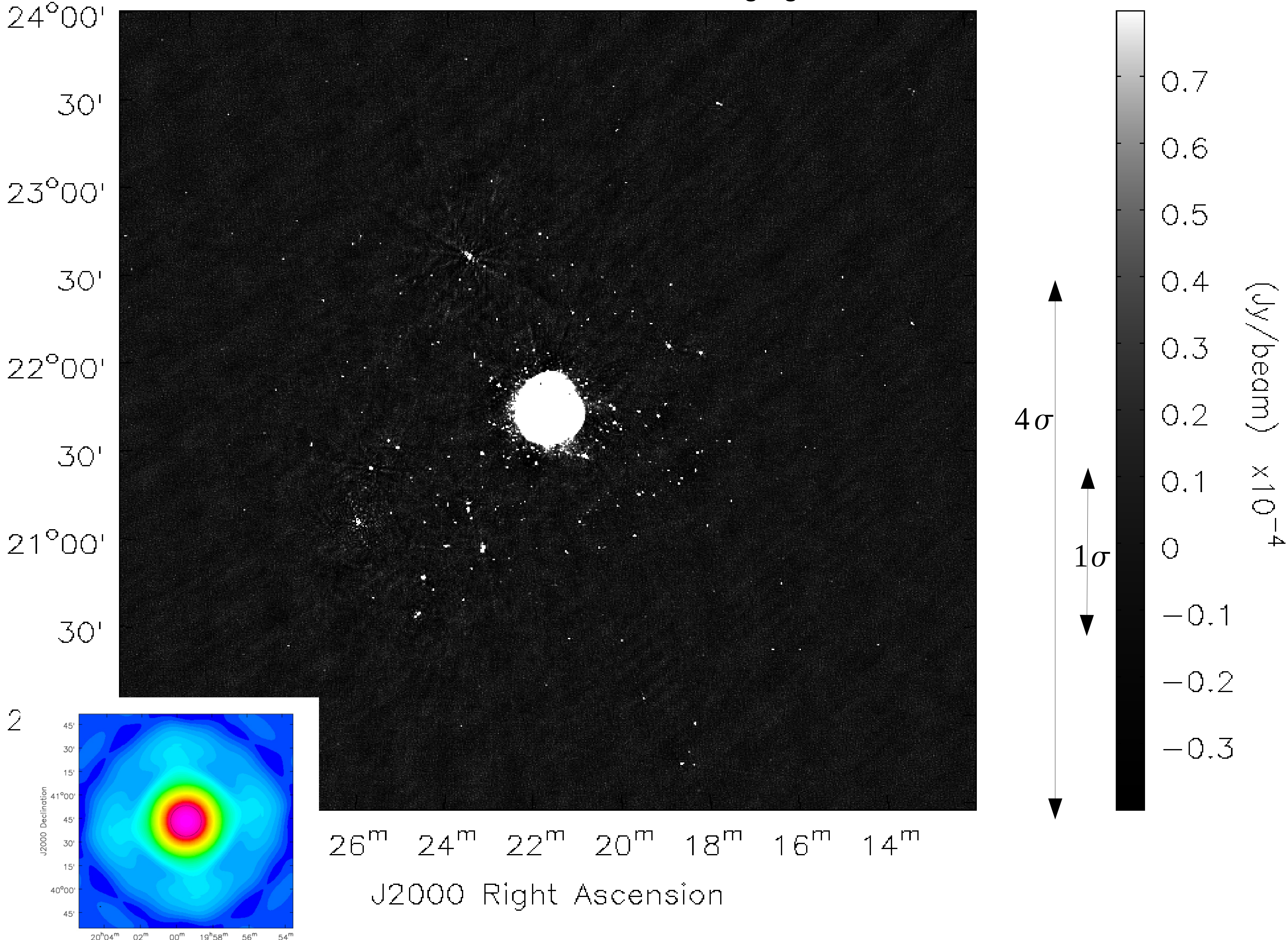


MS-Clean +
W-Projection
J2000 Declination
30'
15'
22°00'
45'
30'
15'
21°00'
45'
19h26m
24m
23m
22m
21m
20m
19m
18m
17m

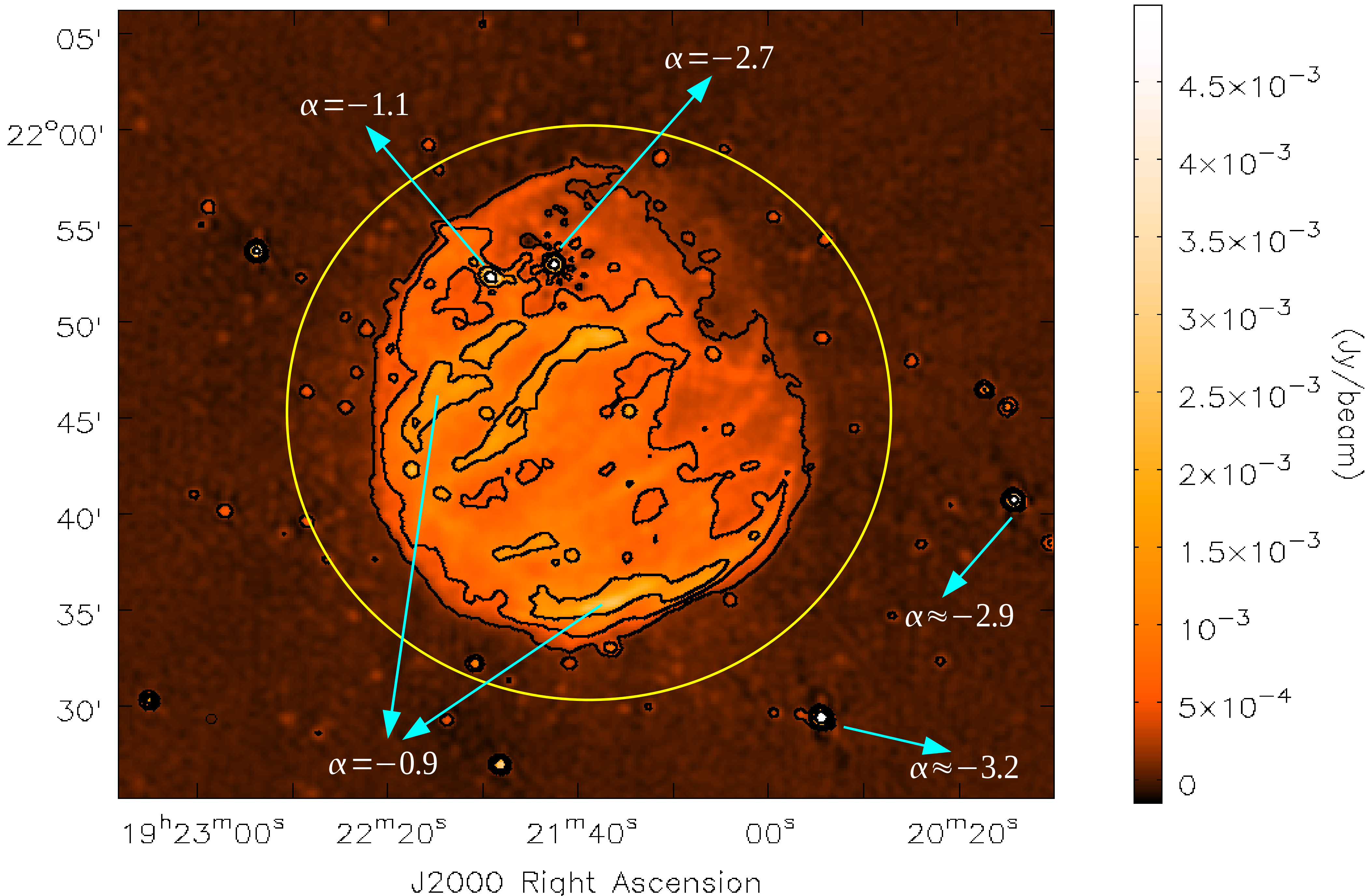

MS-MFS +
W-Projection
Max sampled spatial scale : 19 arcmin (L-band, D-config)
Angular size of G55.7+3.4 : 24 arcmin
MS-Clean was able to reconstruct total-flux of 1.0 Jy
MS-MFS large-scale spectral fit is unconstrained.
J2000 Declination
30'
15'
22°00'
45'
30'
15'
21°00'
45'
19h26m
24m
23m
22m
21m
20m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


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

Wide-field effects of wide-band imaging

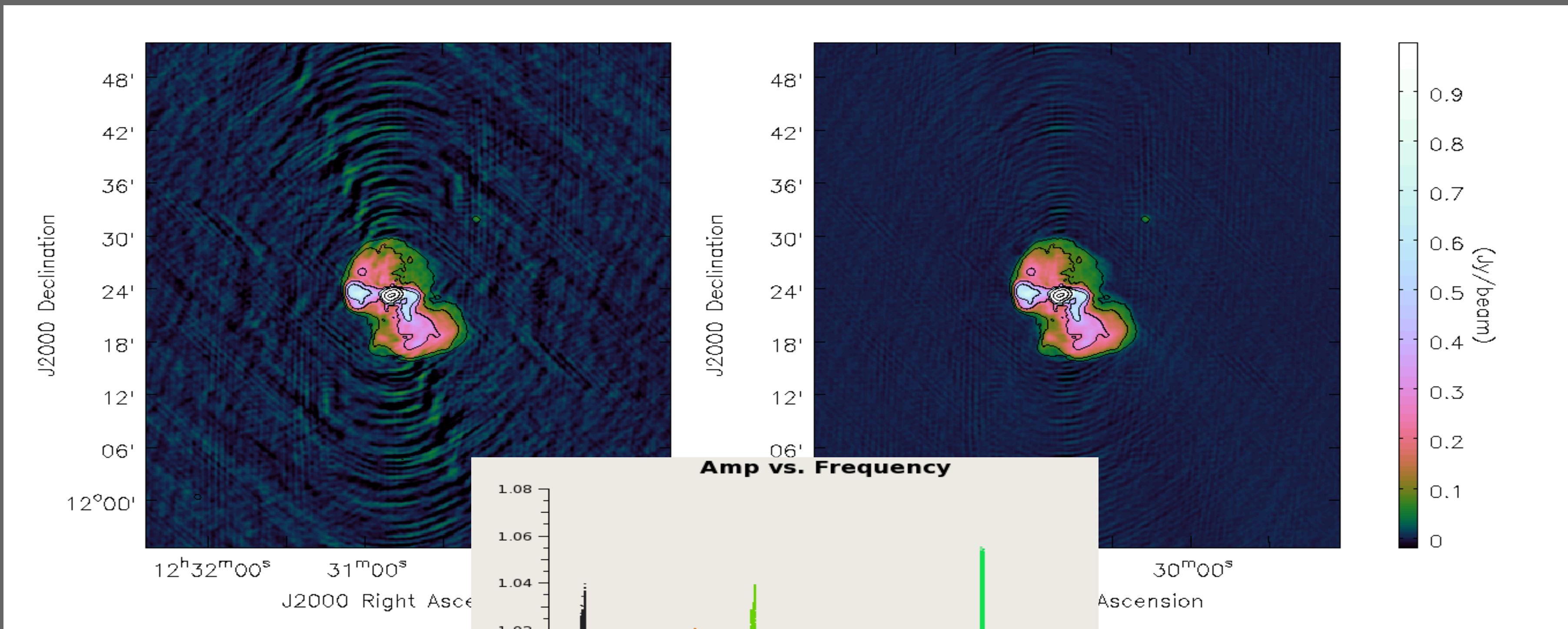


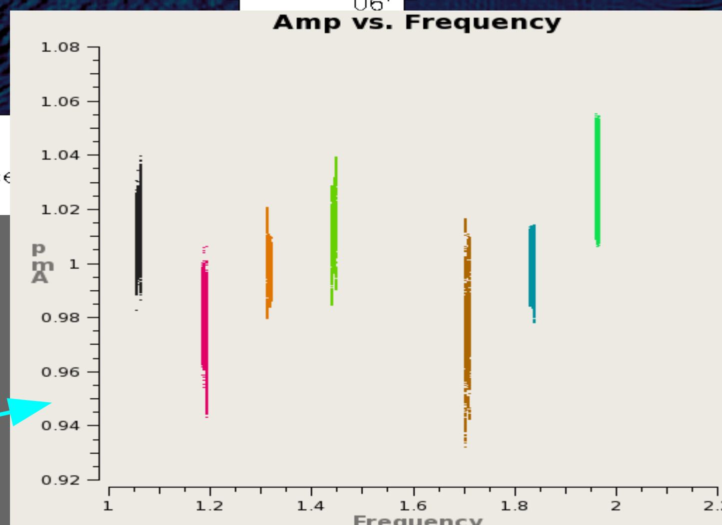
G55.7+3.4 : within the main lobe of the PB



Wide-band Self-calibration (using MS-MFS wideband model)

In CASA, 'clean' saved a wide-band model (calready=True). Or, use 'ft'.





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

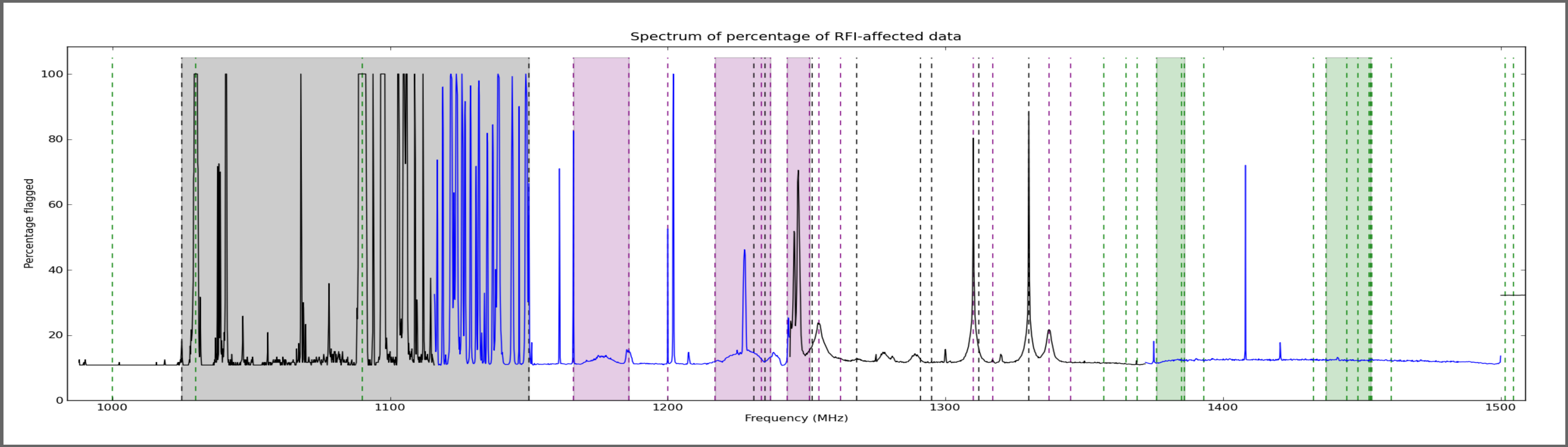
- Can use MS-MFS on your calibrators too, if you don't know their spectra.
- Can also use this wide-band model for continuum subtraction.

Flagging + Examining your data for RFI

Flagging Modes :

– operator logs of known bad antennas and time-ranges / online flags
– shadowing between antennas (elevation-dependent)
– elevation-dependent flags
– known frequency ranges with bad RFI
– exact zeros (from the correlator) , clip very high points, 'automatic flagging '

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

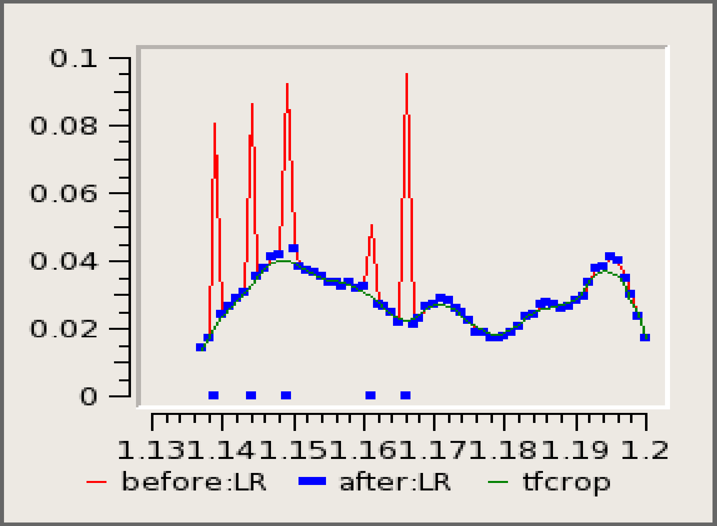


One way to examine your data, is to run 'autoflag' and look at flag counts

– Inspect uncalibrated data to identify 'clean' regions
– Get an estimate of the fraction of total bandwidth usable for imaging.
– Obtain a flagversion to use as a starting point (first calibration/imaging pass).
– Run it on RFI monitoring data – feed-back information about un-documented RFI

Automatic RFI identification and flagging

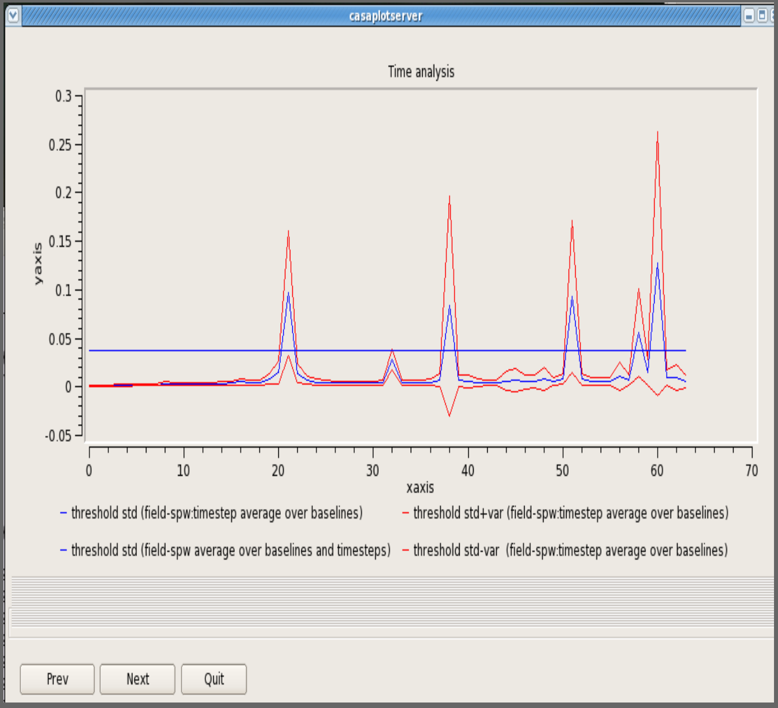
TFCrop : Detect outliers on the 2D time-freq plane.



– Average visibility amplitudes along one dimension
– Fit a piece-wise polynomial to the base of RFI spikes
    -- calculate 'sigma' of data - fit.
– Flag points deviating from the fit by more than N-sigma
– Repeat along the second dimension.
– Grow/extend flags along time, frequency, polarization

Can operate on un-calibrated data + one pass through MS
'testautoflag' in CASA 3.3. 'tflagdata' in CASA 3.4

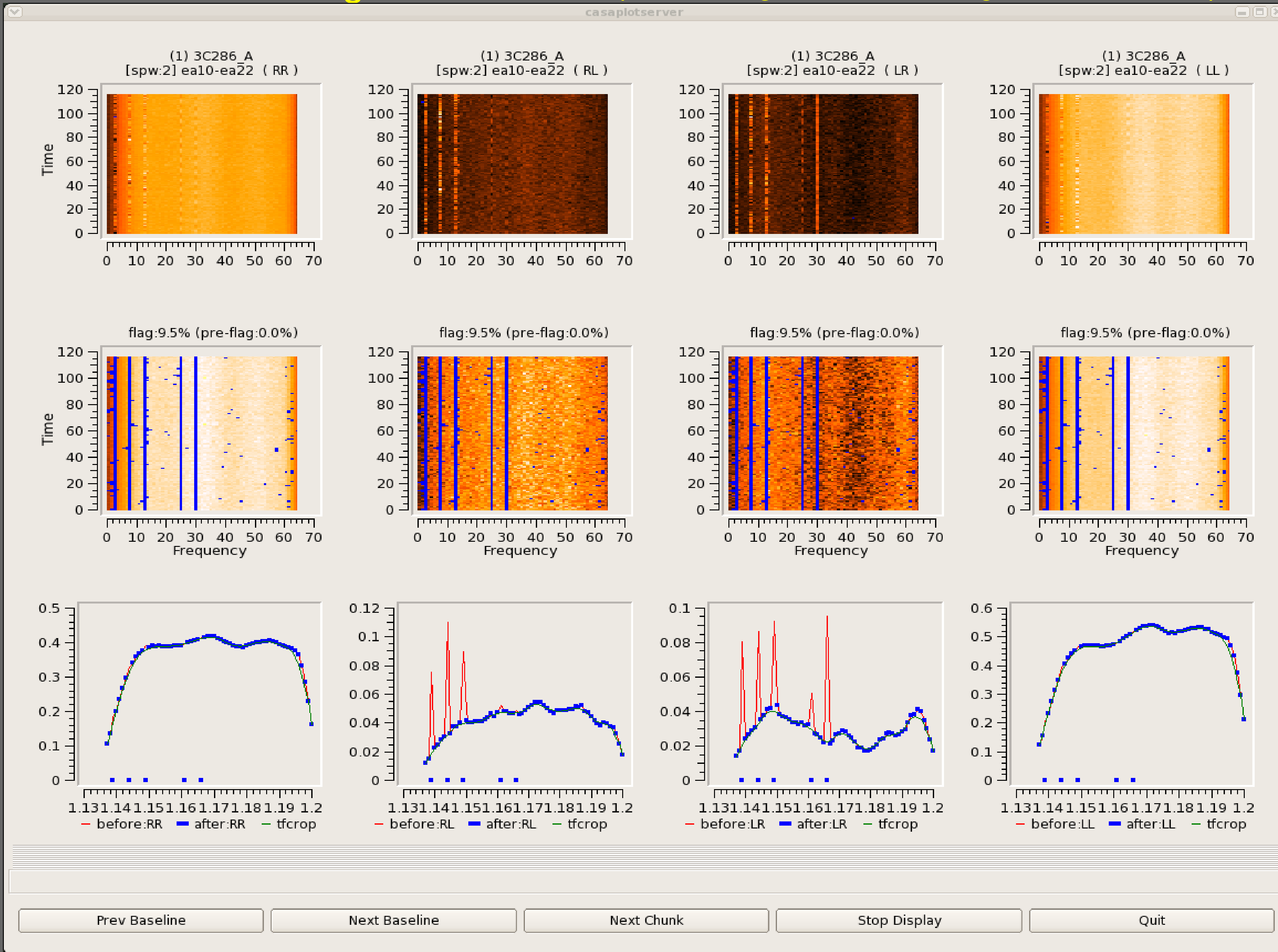
RFLAG : Detect outliers using a sliding-window rms in time



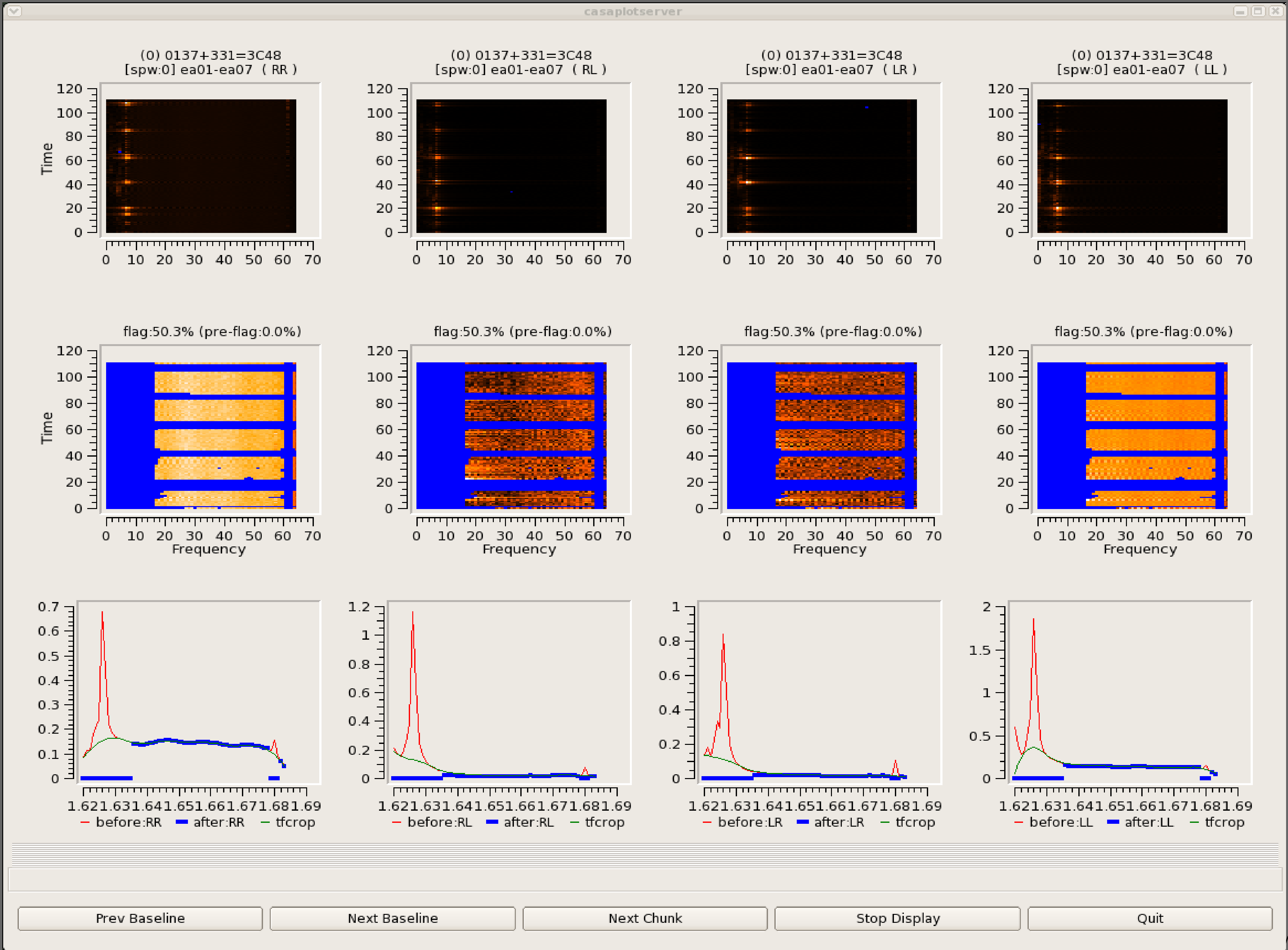
– For each channel,
  – Calculate rms of real and imag parts of visibilities across a sliding time window.
  – Calculate the mean-rms across time, and deviations of these rmss from the mean.
  – Search for outliers
    (local rms > N x (median-rms + median-deviation)
– For each timestep,
  – Calculate a median-rms across channels, and flag points deviating from this median.
– Grow/extend flags (pol, time, freq, baselines)

Needs calibrated data + two passes through data.
“RFLAG” in AIPS. 'tflagdata' in CASA 3.4

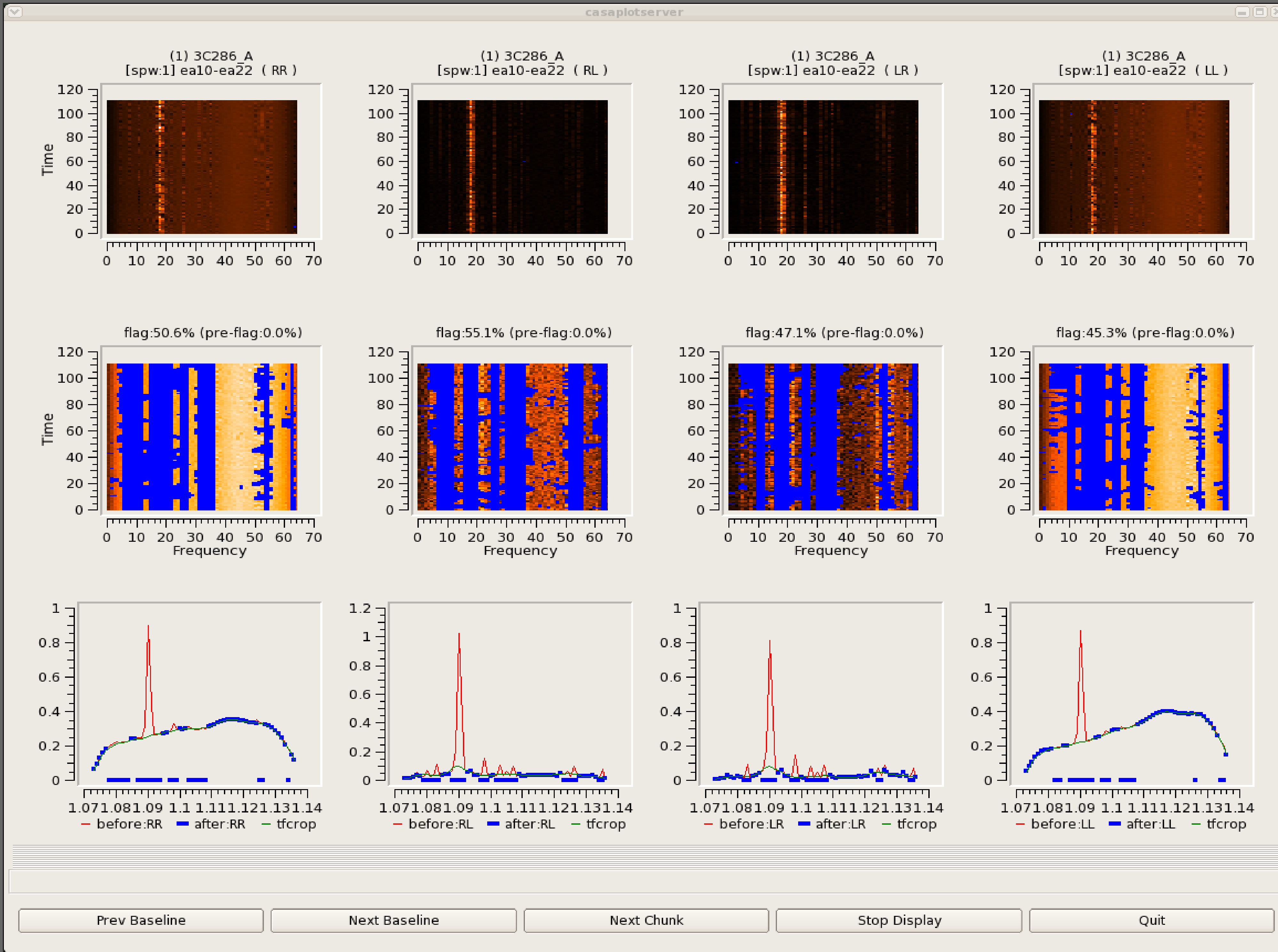
Visualize Data/Flags at run-time (testautoflag in CASA 3.3, tflagdata in CASA 3.4)



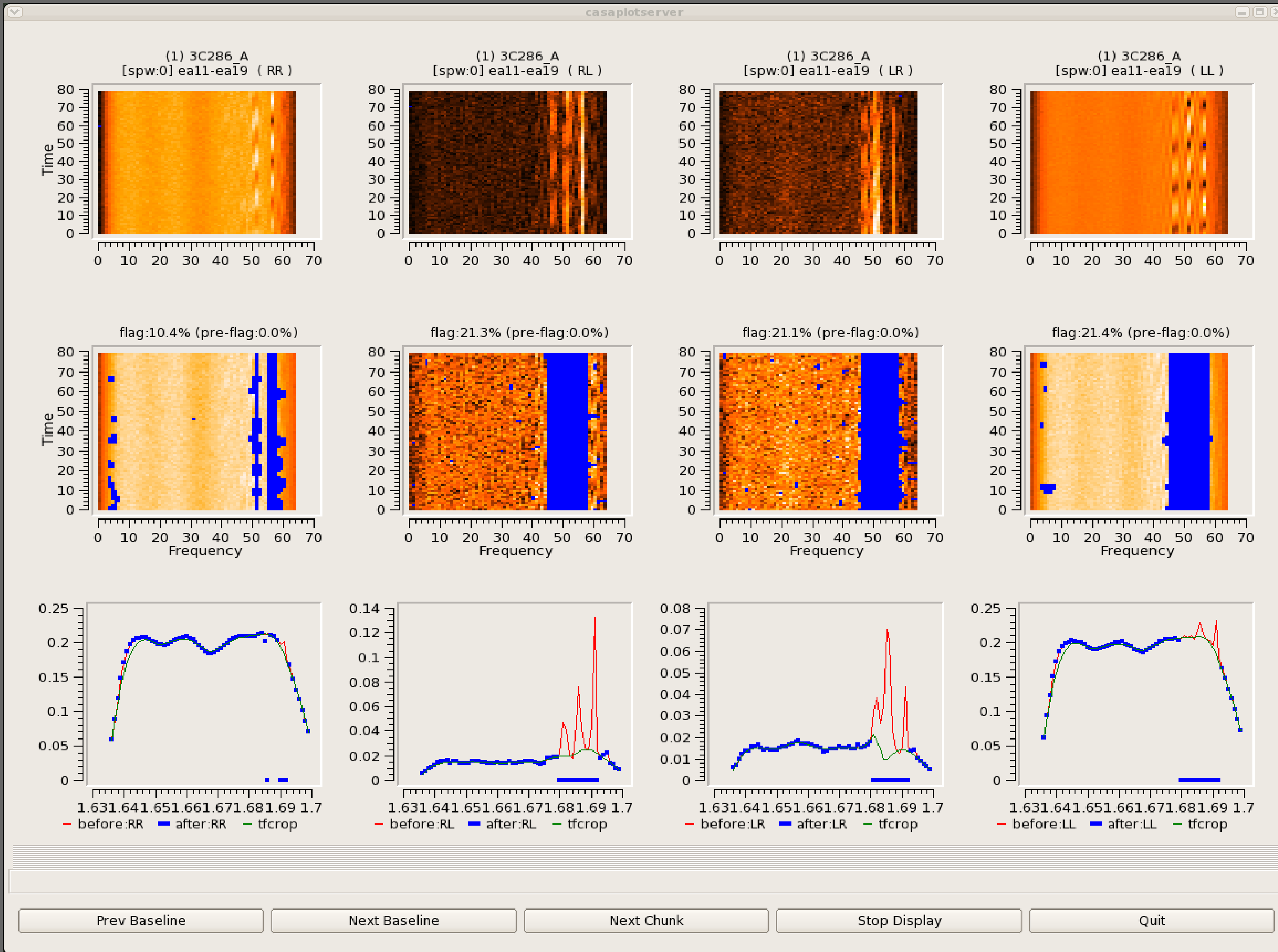
Example 1 (with extension along frequency, and statistics-based flagging)



Example 2 (an example where it is better to flag more than less..)



Example 3 (with broad-band RFI)



RFI identification strategies

– RFI is in-general frequency and direction-dependent (satellites / local/ …)

=> Inspect and decide flagging strategies separately per SPW / IF and Field.
=> Inspect baseline groups (short, mid, long...), especially at higher frequencies

– Choose which correlations to operate on (extend flags to others)

=> RL, LR have higher RFI signal-to-noise, and RR and LL have stronger band-shape information (depends on what you're looking for)

– Operate on bandpass-corrected data

=> Do a bandpass calibration in a separate step, or use methods that account for uneven bandpass levels.

– Hanning Smoothing

=> when there is very strong RFI with ringing in nearby channels.
(for weak RFI, this can spread the RFI to more channels)

Summary

Broad-band receivers
=> better sensitivity

To achieve this sensitivity
=> Careful RFI removal
=> Spatial and spectral image reconstructions along with corrections for wide-field instrumental effects.

User choices (start simple):

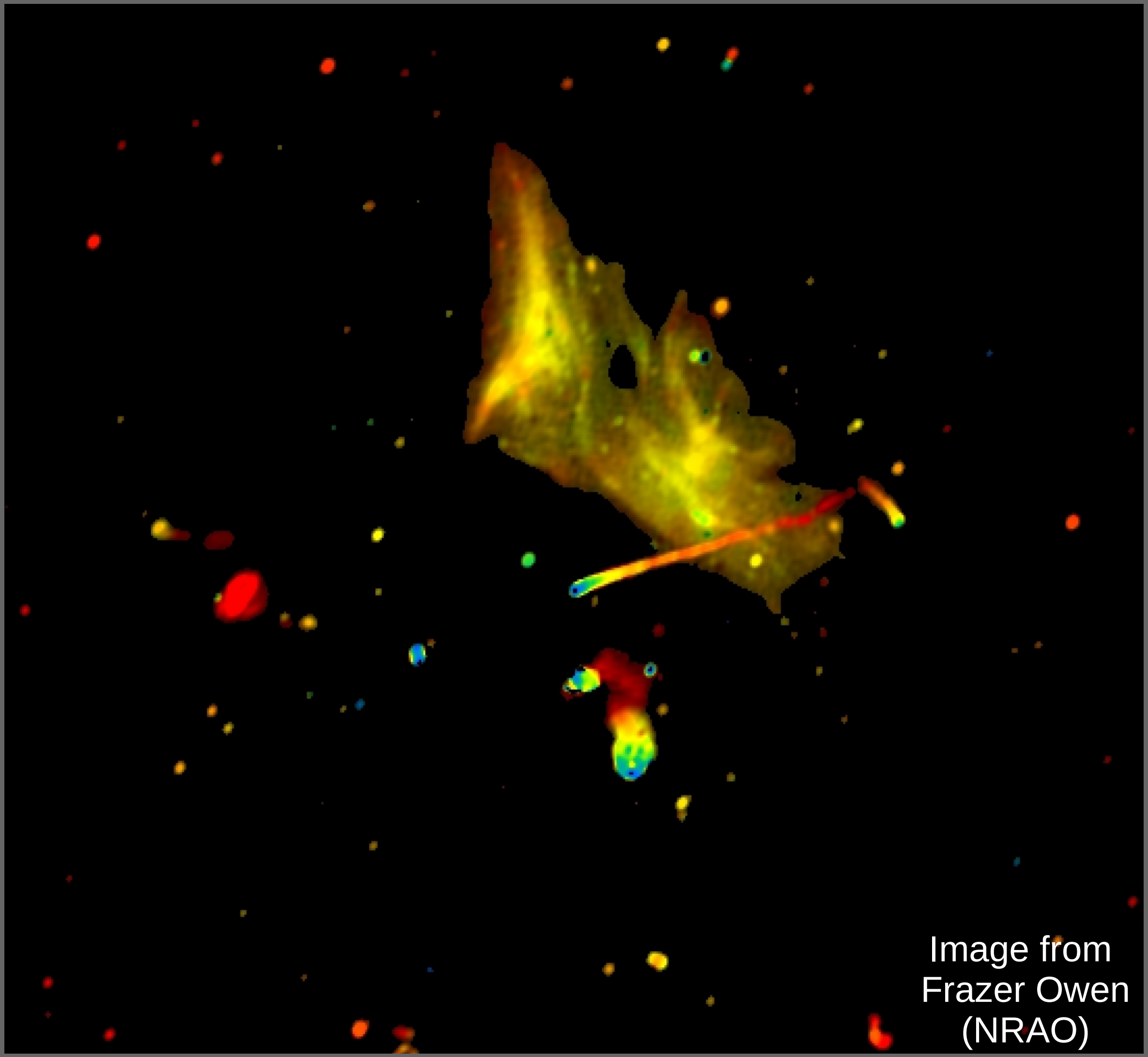
- Will single-SPW imaging suffice ?

- If not, then use MS-MFS :
  N-terms (is there enough SNR ?)
  Multi-scales (measured vs desired)

- Wide Field-of-view ?
  W-term, Primary-beam

Imaging results so far (high SNR) :

- Point sources : OK
- Extended emission : DR of few 1000,
- Spectral-index accuracy : 0.02 ~ 0.2
- Wideband PB-correction : Upto HPBW
- RFI at L-Band : Lose 200 ~ 500 MHz



Abell-2256 : intensity-weighted spectral-index

Ongoing work : HPC methods + more software integration + more efficient minor-cycle algorithms + uncertainty estimates, improving autoflag......