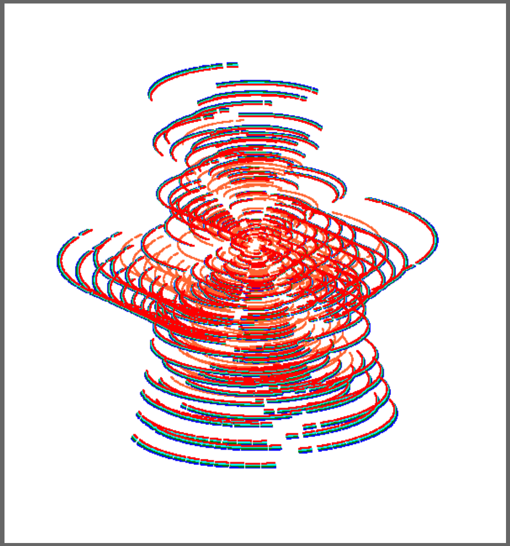
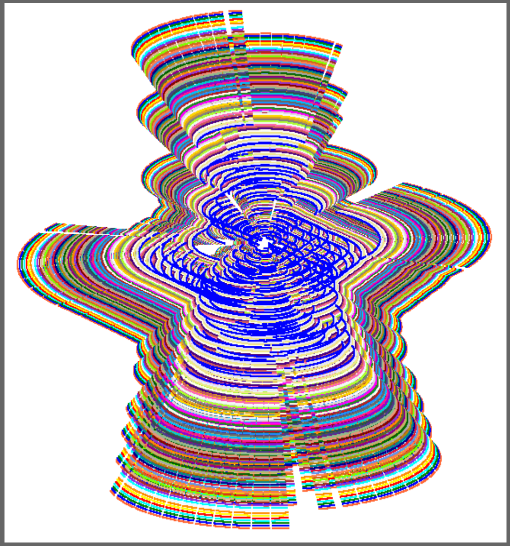
Wide-band wide-field imaging with the EVLA – II





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

– Dynamic-range and accuracy

– Wide-field effects of wide bandwidths

– Wide-band self-calibration

– RFI identification and flagging

Bandwidth and bandwidth-ratio

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

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

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.
(x 4) (x 9) (x 12)

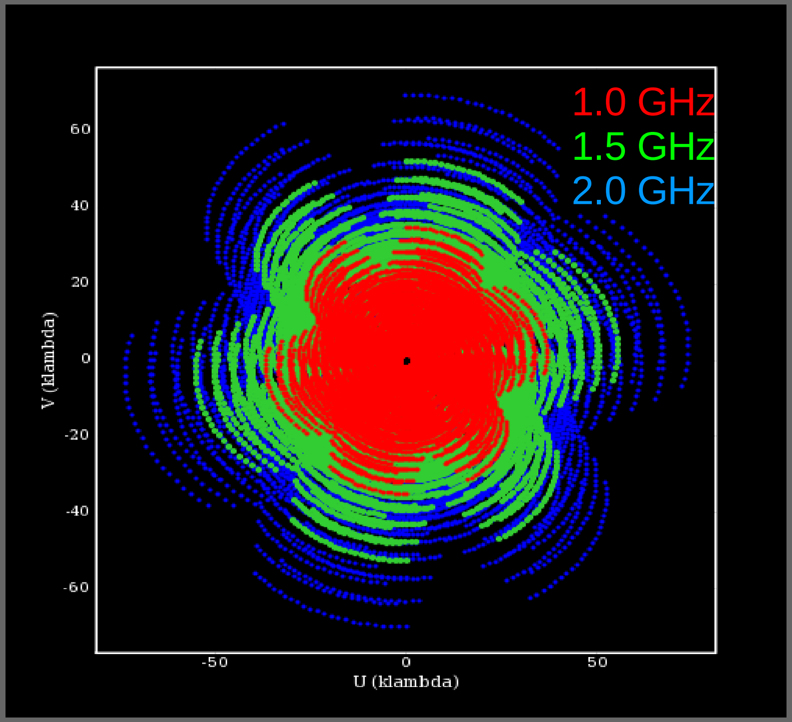
Currently, maximum bandwidth is 2 GHz => (x 6)

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

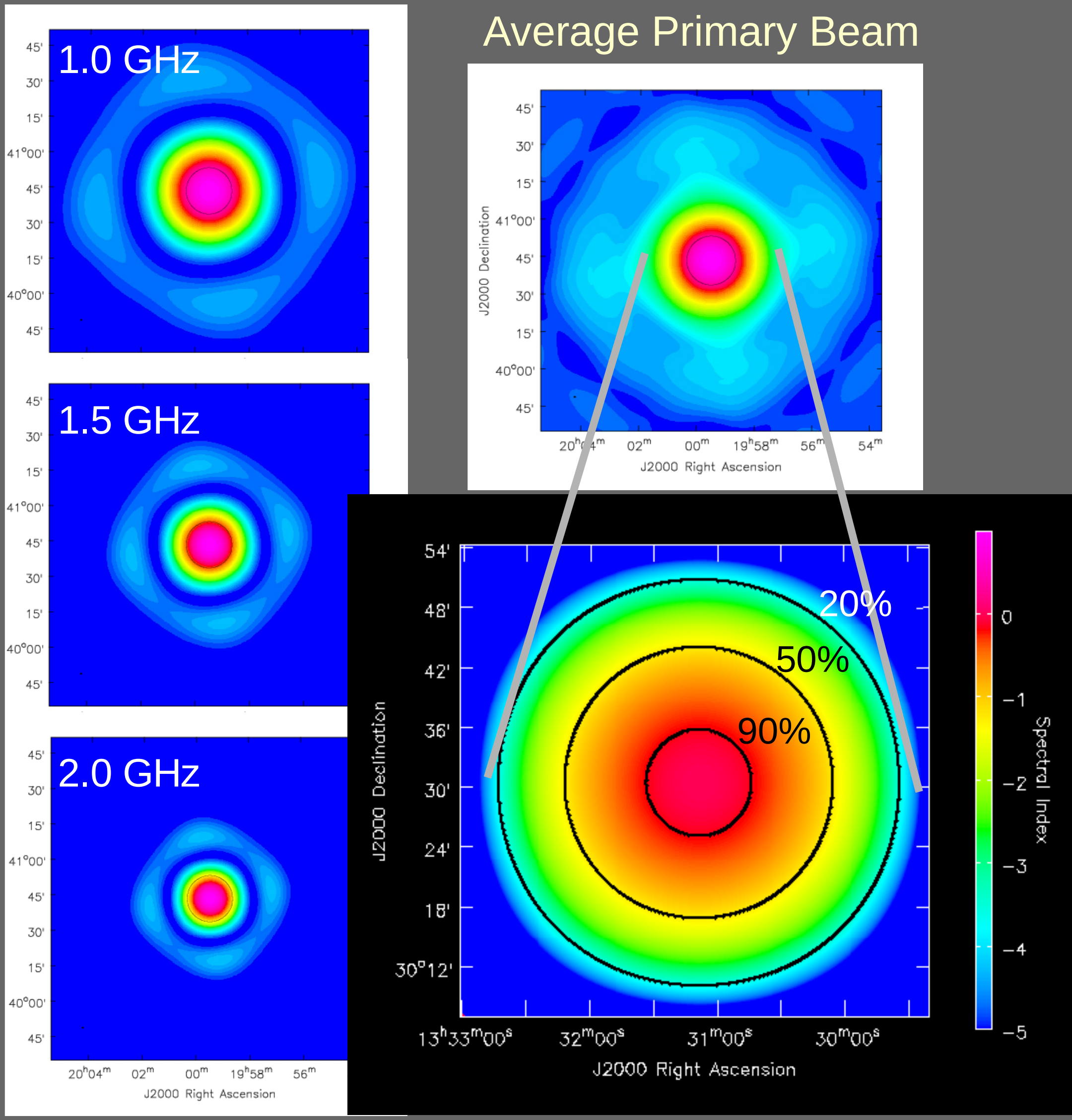
Higher BWR (2:1 at L,S, C bands) => Stronger frequency-dependent effects within the band (sky and instrument)

Frequency-dependence of the instrument and sky

Multi-Frequency UV-coverage



Multi-Frequency Primary Beams



'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

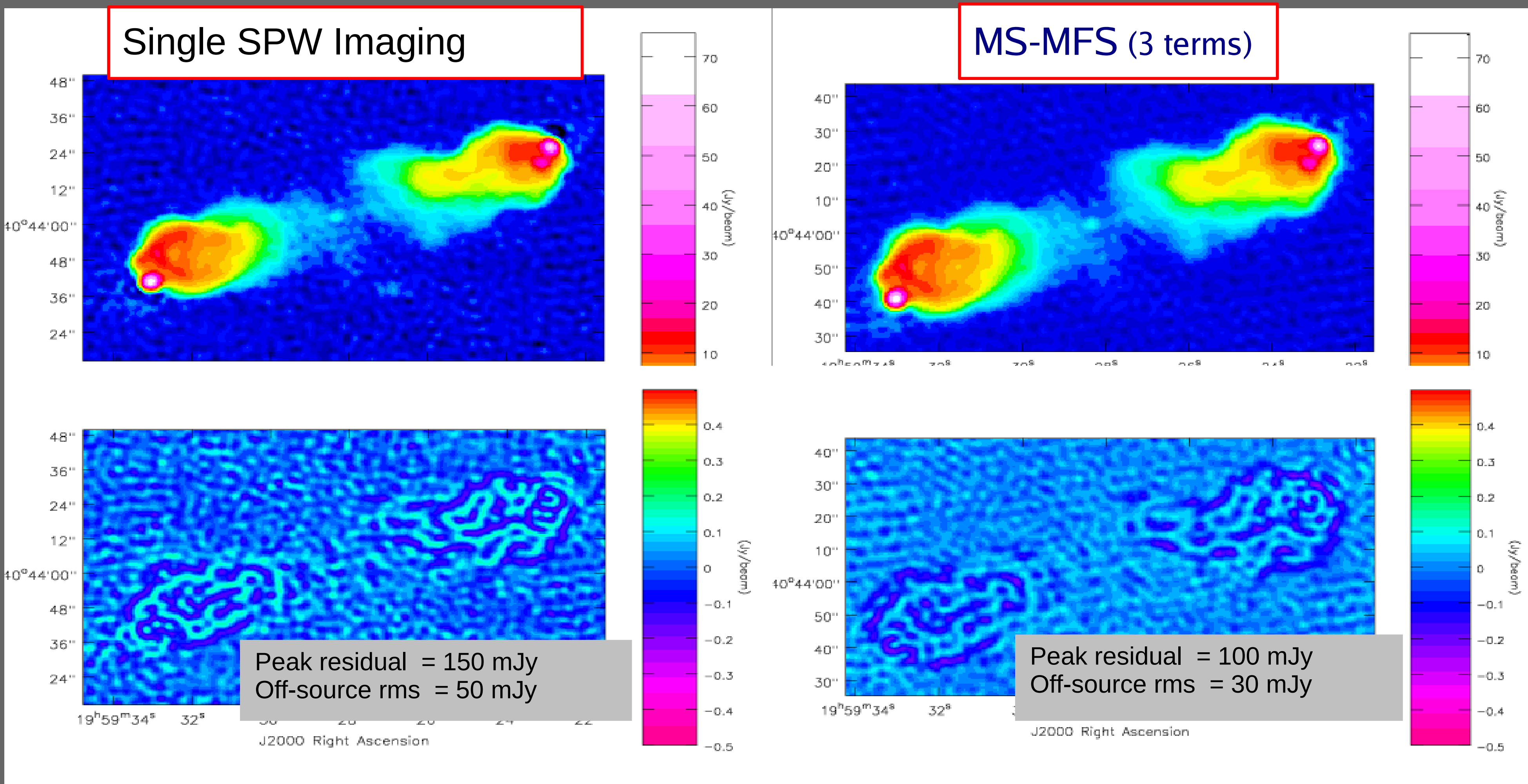
When do you need MFS ?

- 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

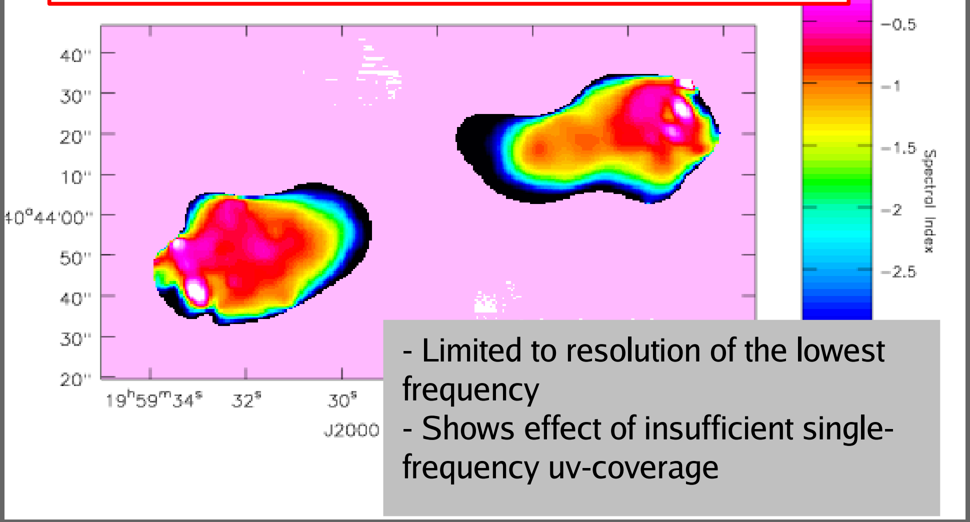
- both methods reconstruct plausible intensity images.
- both have similar residual errors due to deconvolution.

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

Comparison of single-SPW imaging with MFS – Spectral Index

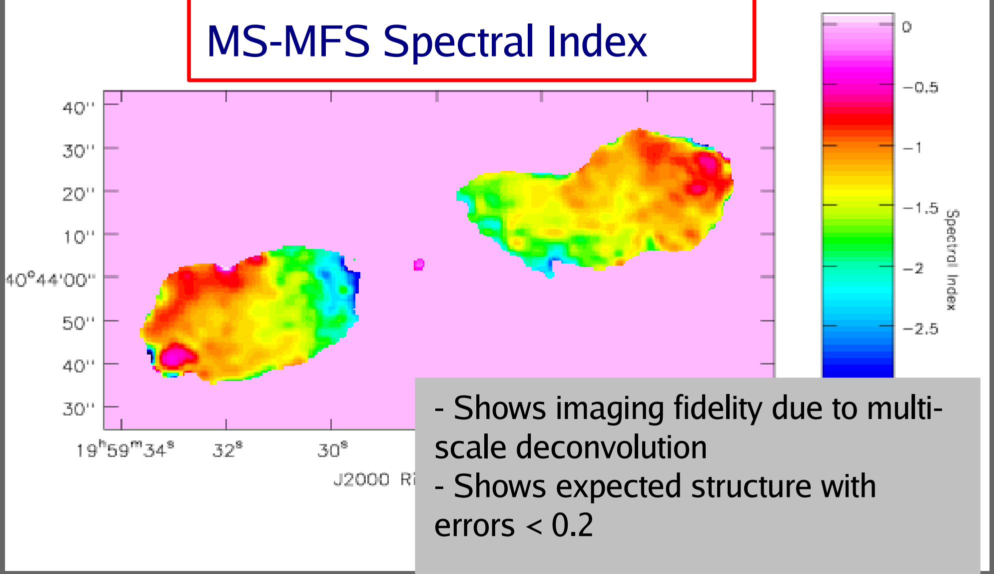
Data : 20 VLA snapshots at 9 frequencies across L-band + wide-band self-calibration

Spectral Index from single-SPW images



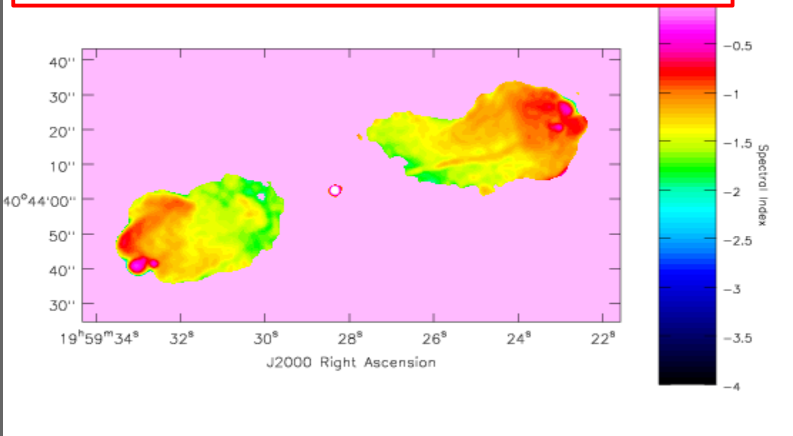
- Limited to resolution of the lowest frequency
- Shows effect of insufficient single-frequency uv-coverage

MS-MFS Spectral Index



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

Two-point spectrum (1.4 –4.8 GHz)



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.

"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

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

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 $I_0, I_1, I_2, \ldots$

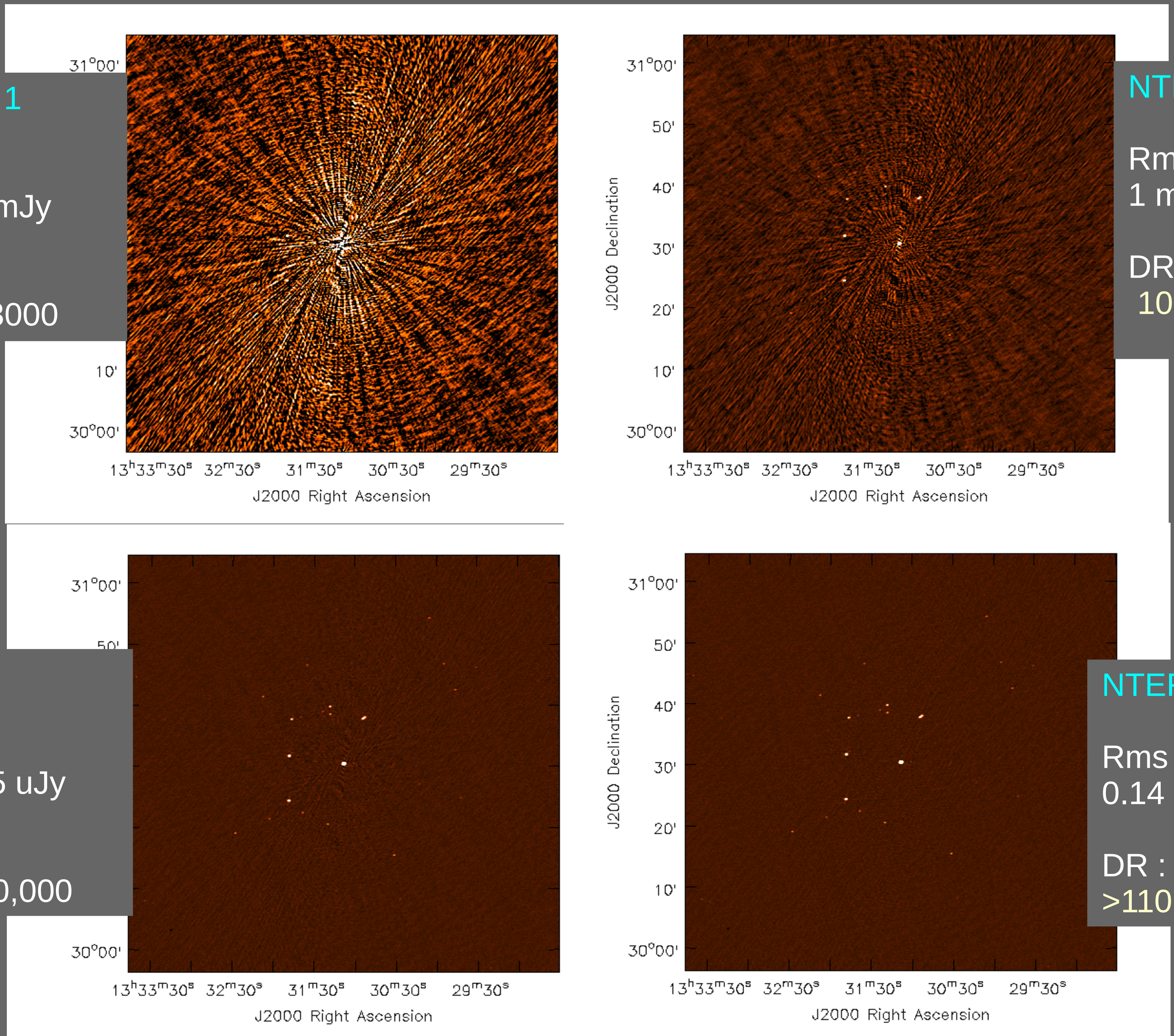
- Interpret in terms of a power-law : spectral index and curvature

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

(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

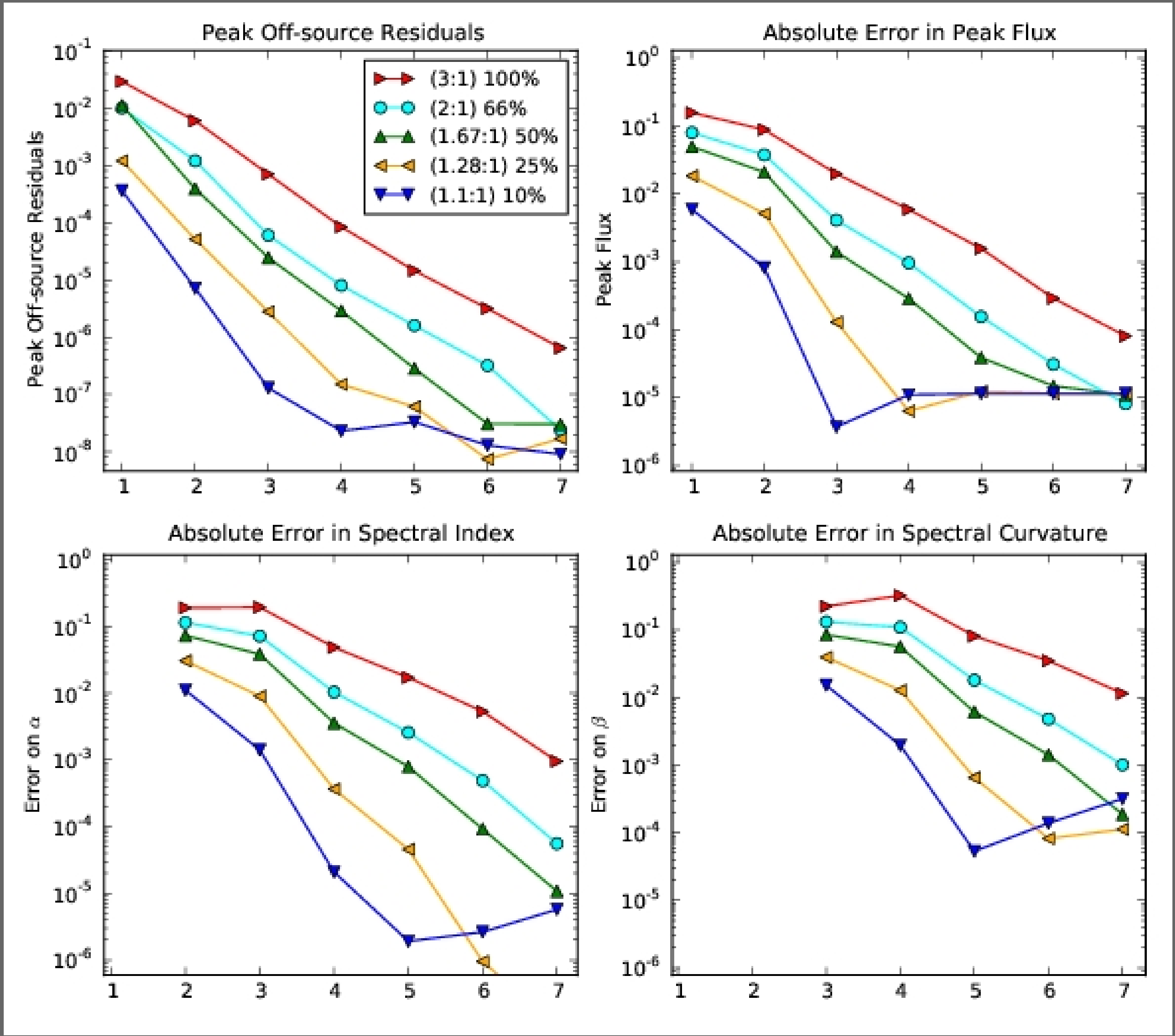
DR :
65,000 -- 170,000

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,

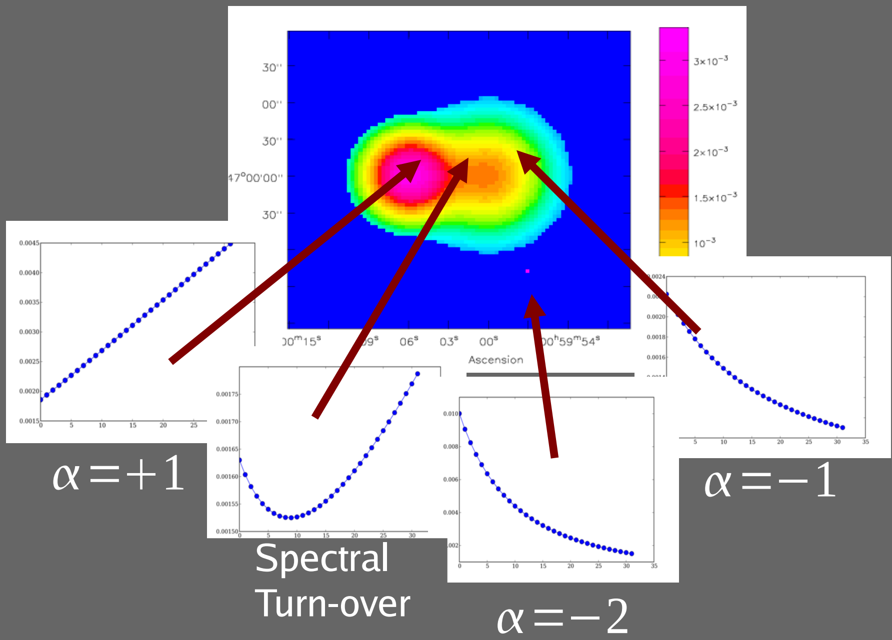
=> more terms gives smaller errors

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

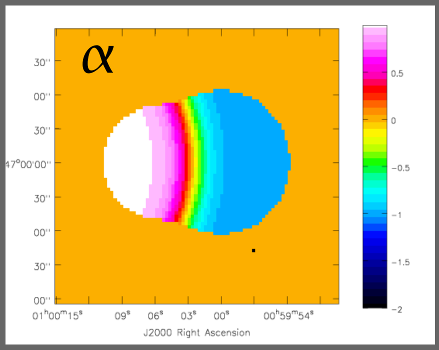
In practice, use nterms>2 only if there is high SNR (>100), and if you can see spectral artifacts in the image with nterms=2

Multi-Scale vs Point-Source model for wideband imaging

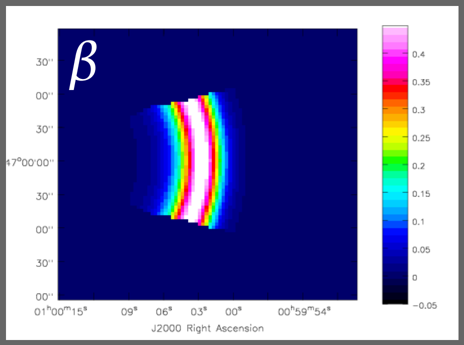
Intensity Image

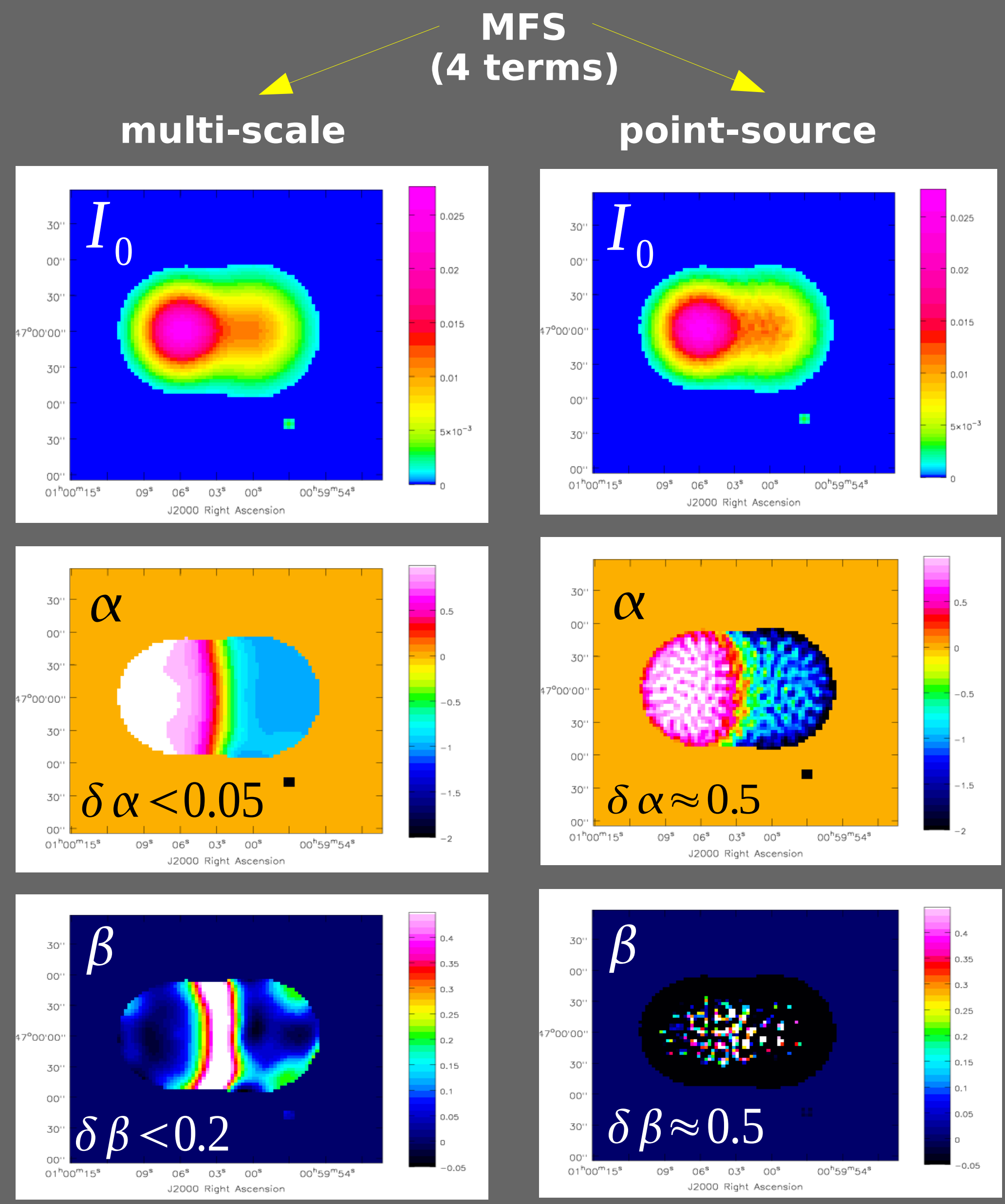


Average Spectral Index



Gradient in Spectral Index



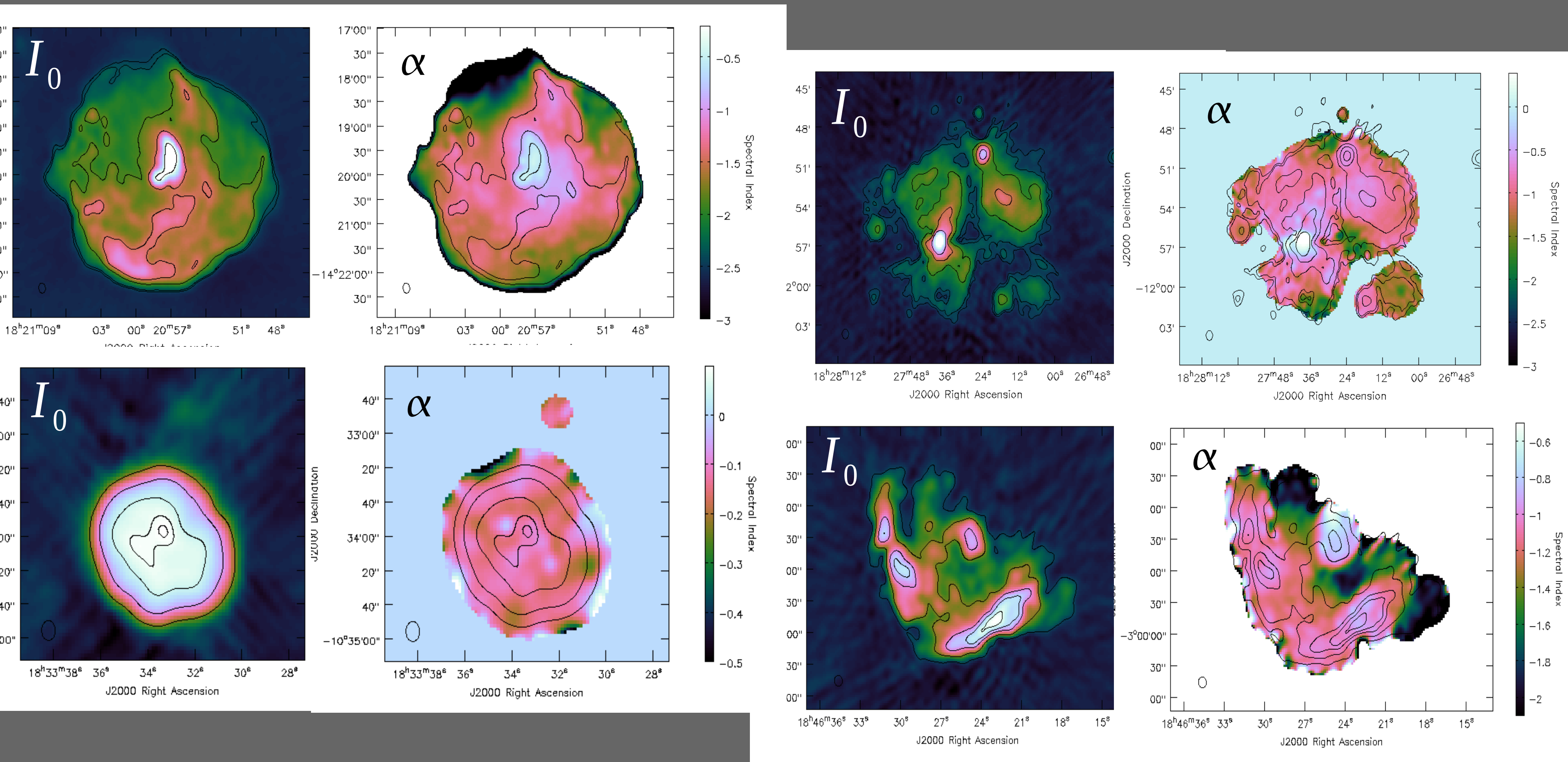


=> For extended emission,

-> 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)



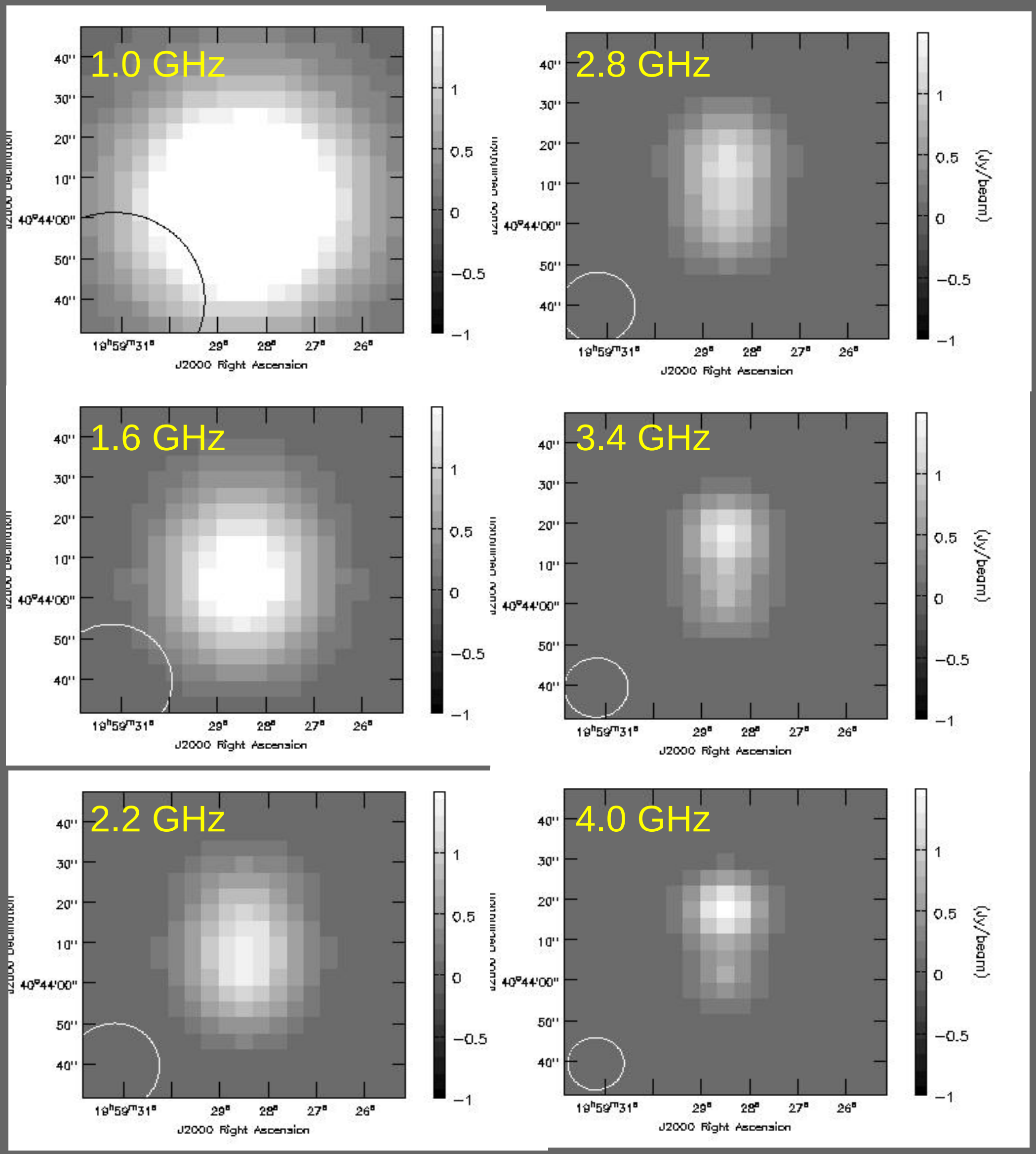
Initial results of a pilot survey (EVLA RSRO AB1345). These examples used nterms=2, and about 5 scales.

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

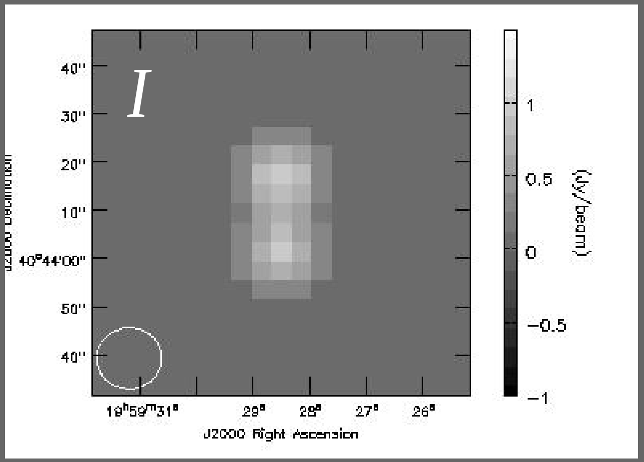
=> These images have a dynamic-range limit of few x 1000

Small spatial-scales - moderately-resolved sources

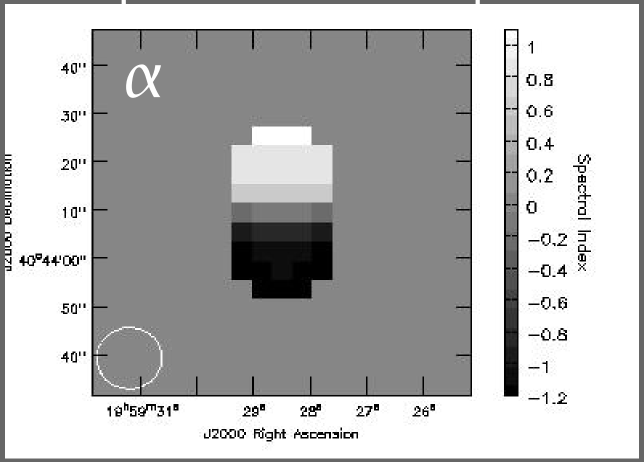
Can reconstruct the spectrum at the angular resolution of the highest frequency



Restored Intensity image

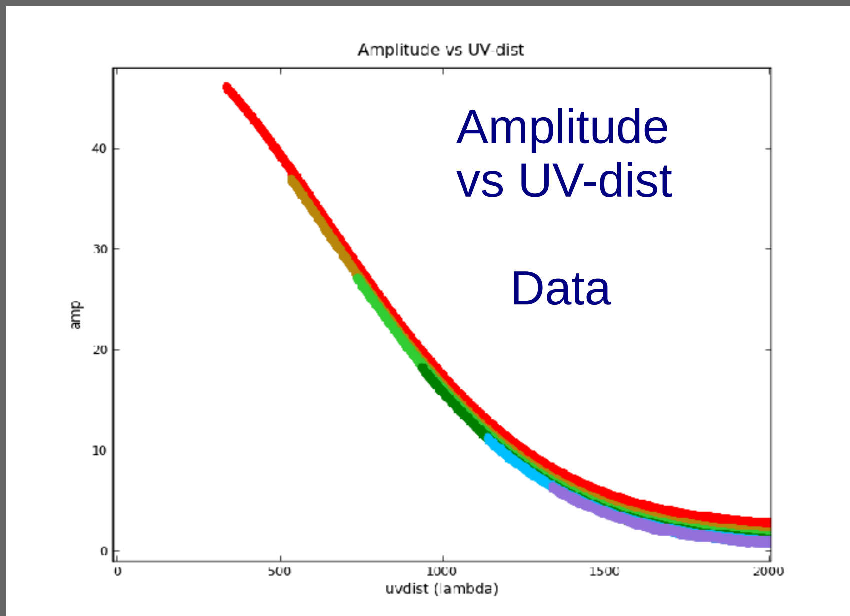


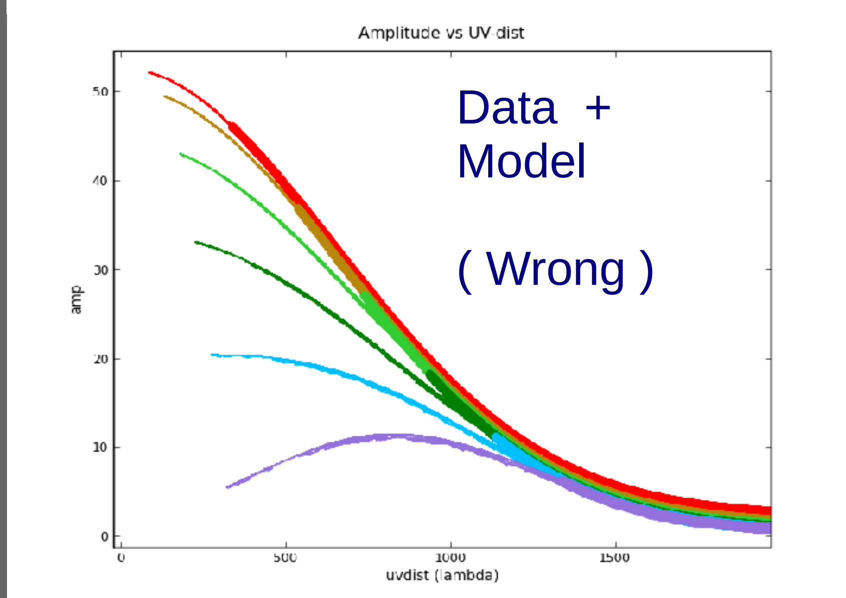
Spectral Index map

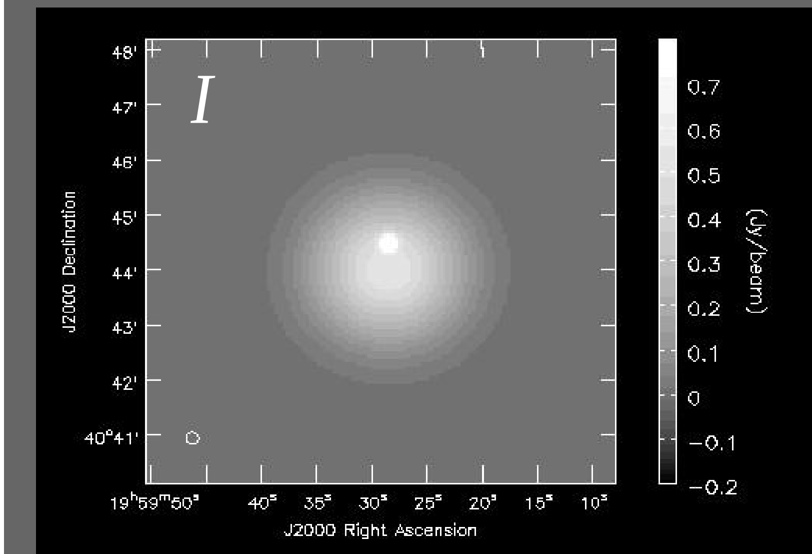


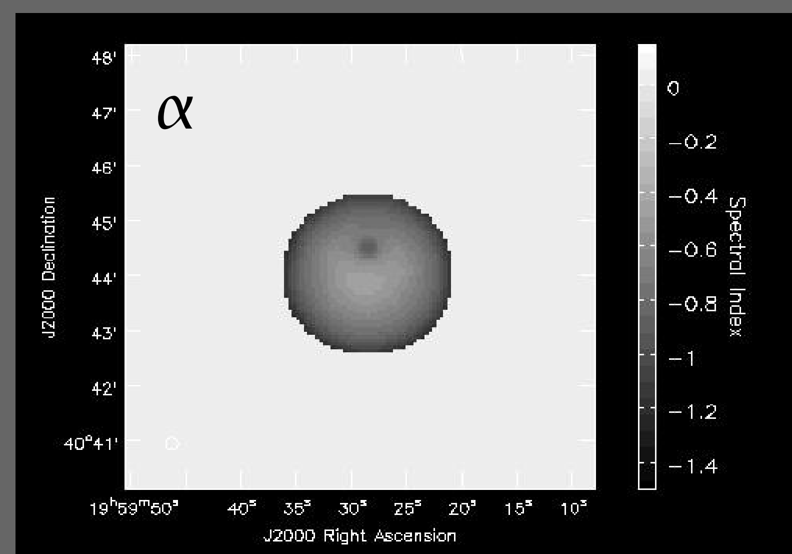
Very large spatial scales - without short-spacing data

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



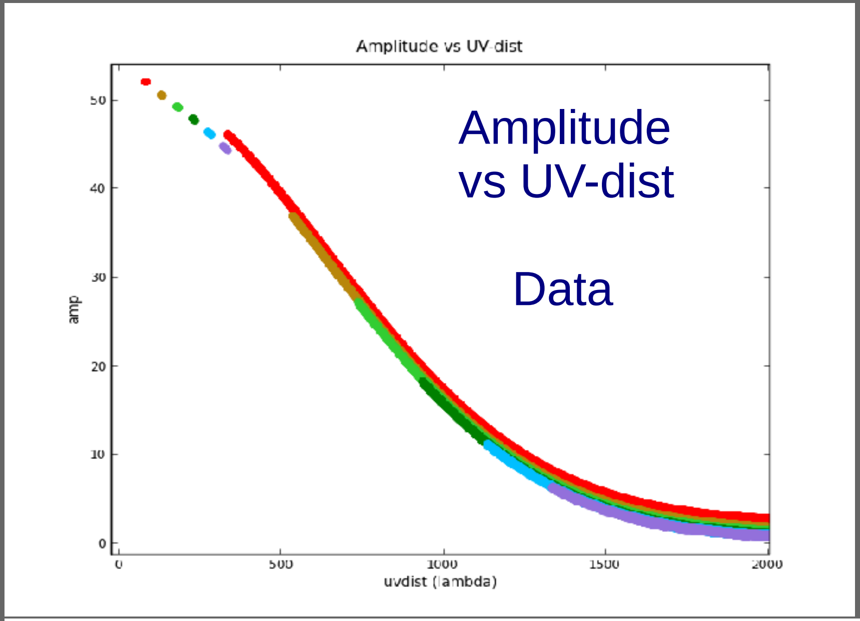


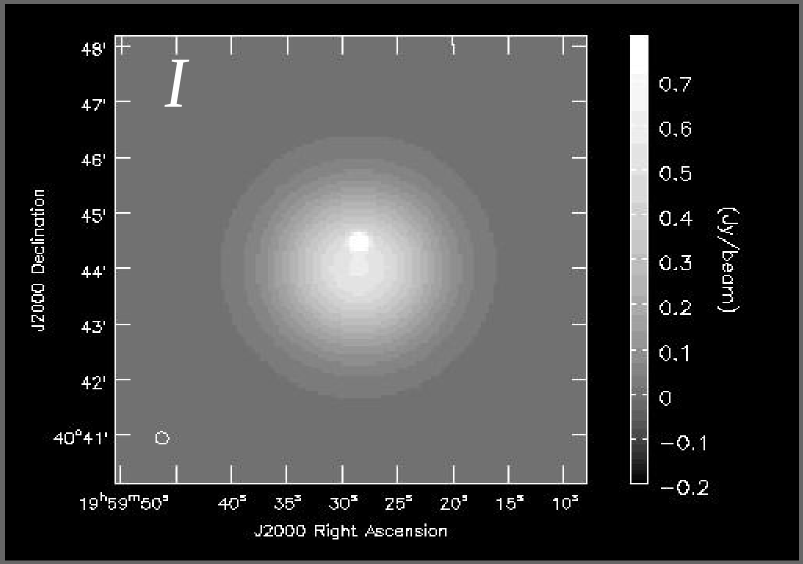


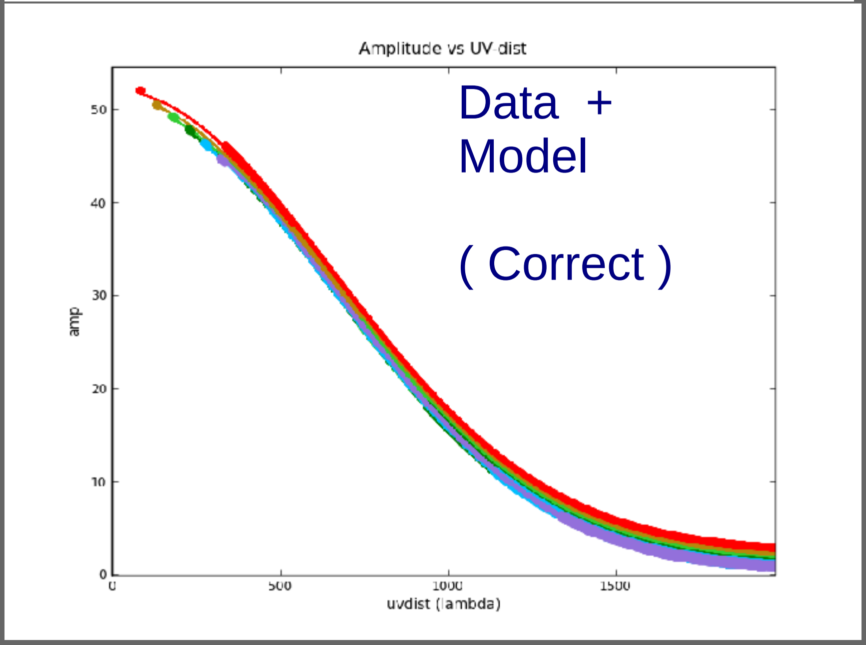


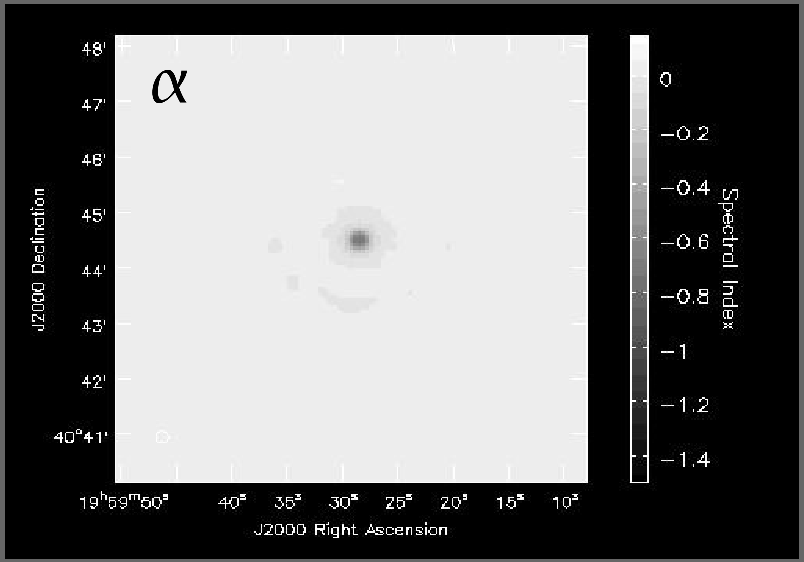
Very large spatial scales – with short-spacing data

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



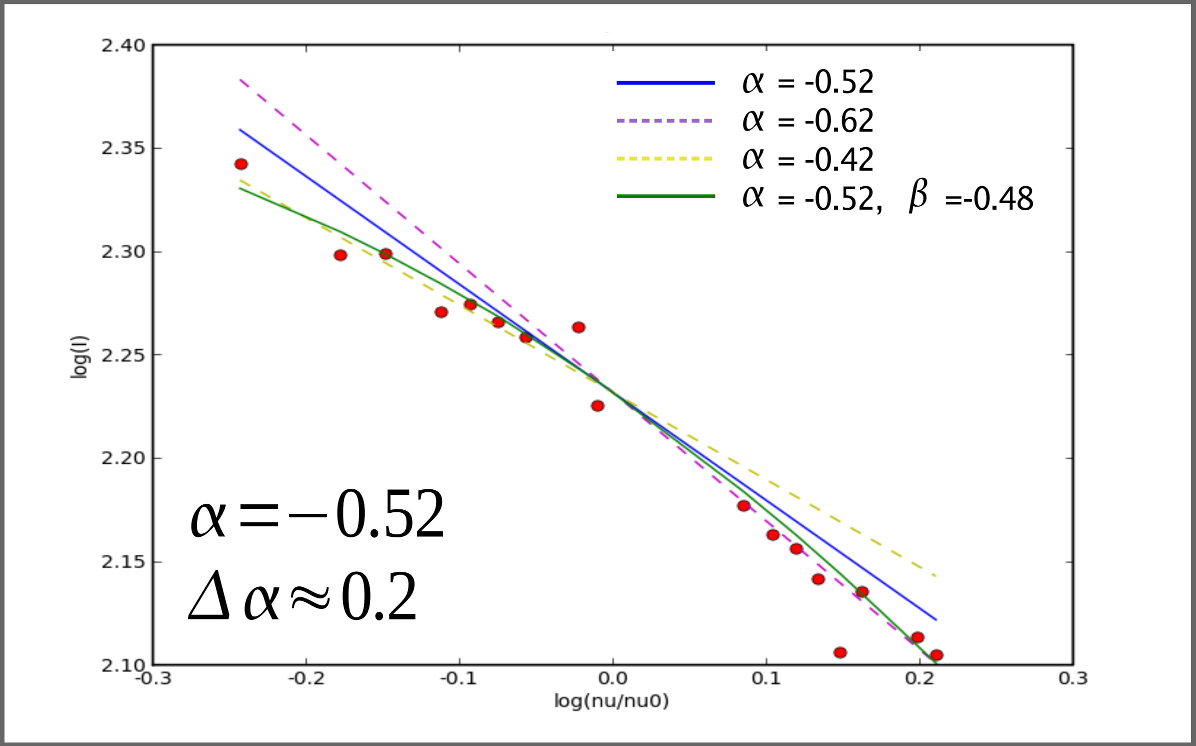


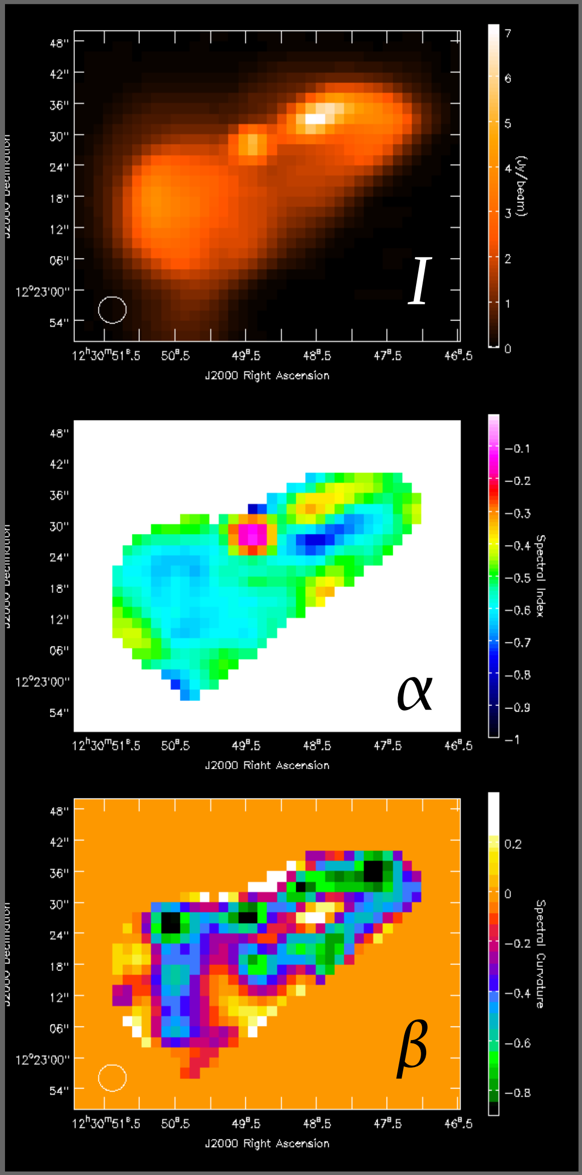




Spectral Curvature : VLA data : M87 1.1-1.8 GHz

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

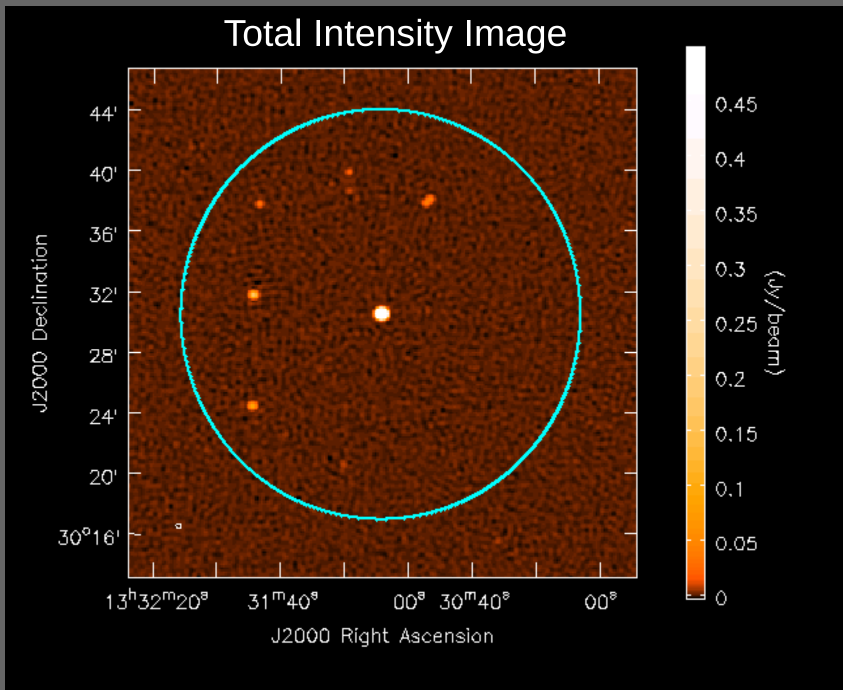
L-C spectral index : -0.5 ~ -0.7

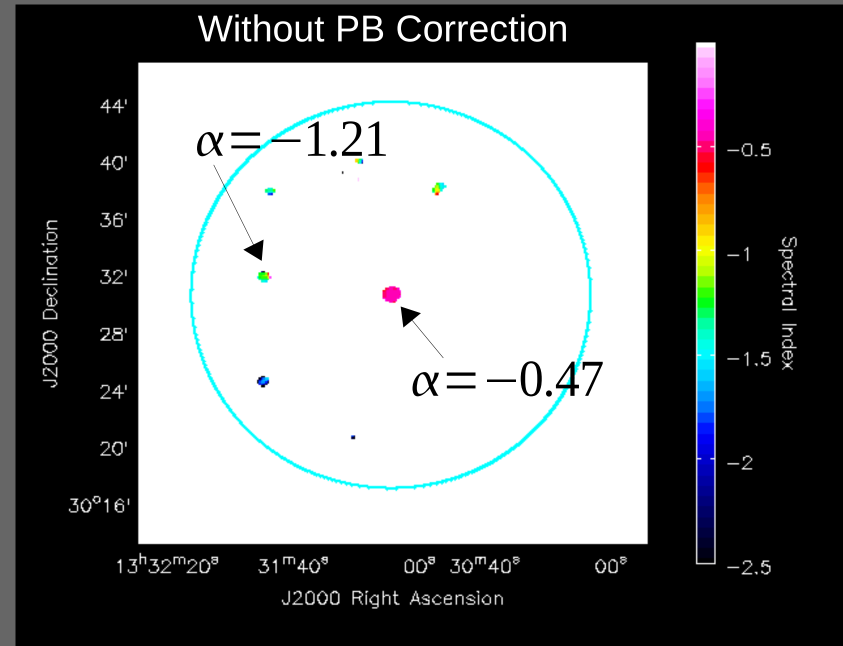
=> Need SNR > 100 to fit spectral index variation ~ 0.2 (at the 1-sigma level ...)

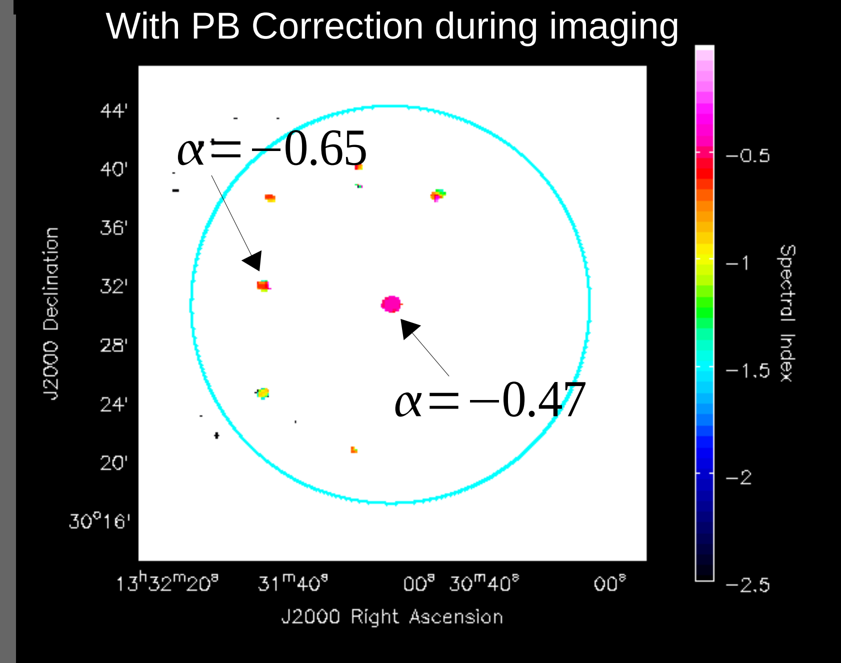
=> Be careful about interpreting β

Wide-Field issues : Wide-band Primary-Beam

3C286 field , C-config , L-band







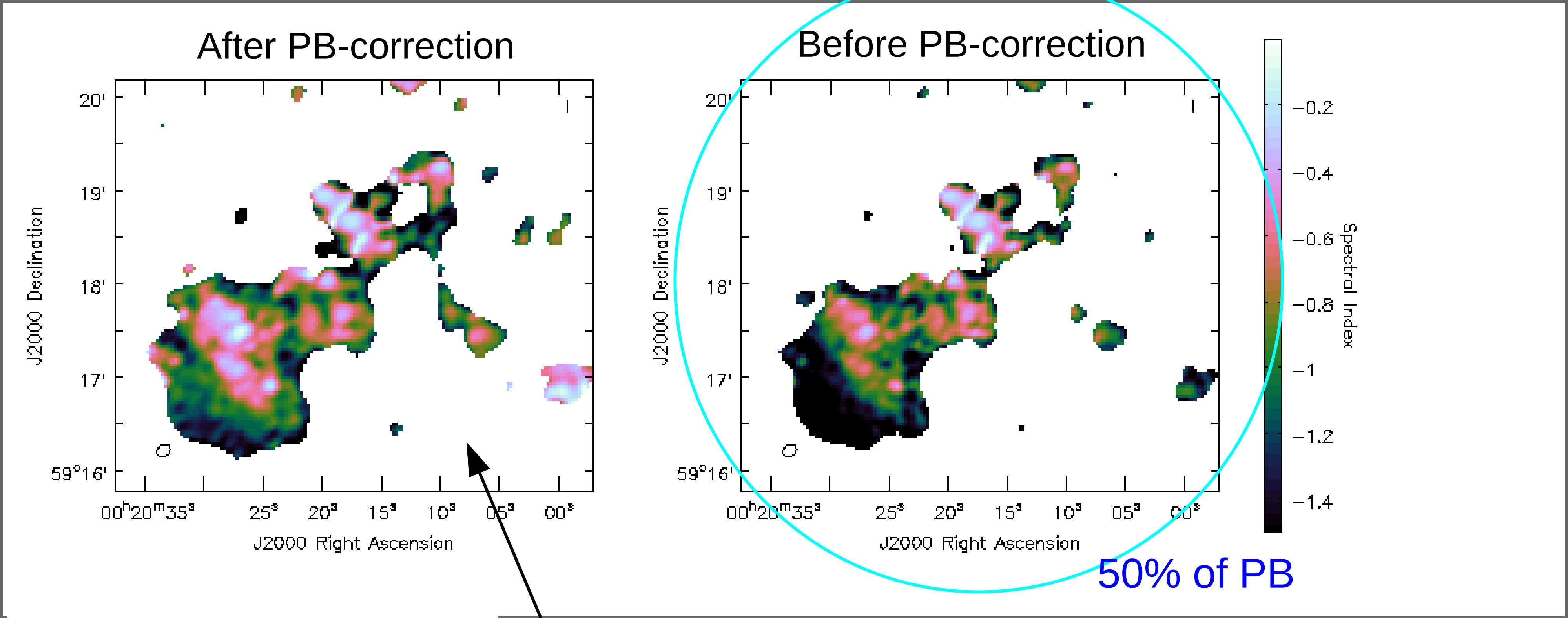
Verified spectral-indices by pointing directly at one background source.

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

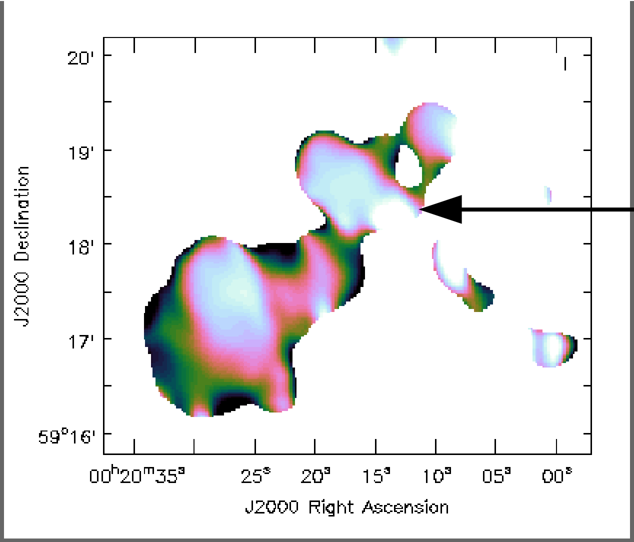
Obtained $\delta\alpha$ = 0.05 to 0.1 for SNR or 1000 to 20

Also verified via holography observations at two frequencies

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).

A Post-deconvolution correction assumes that the primary-beam does not vary / rotate during the observation....

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
  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)

Positive things : 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).

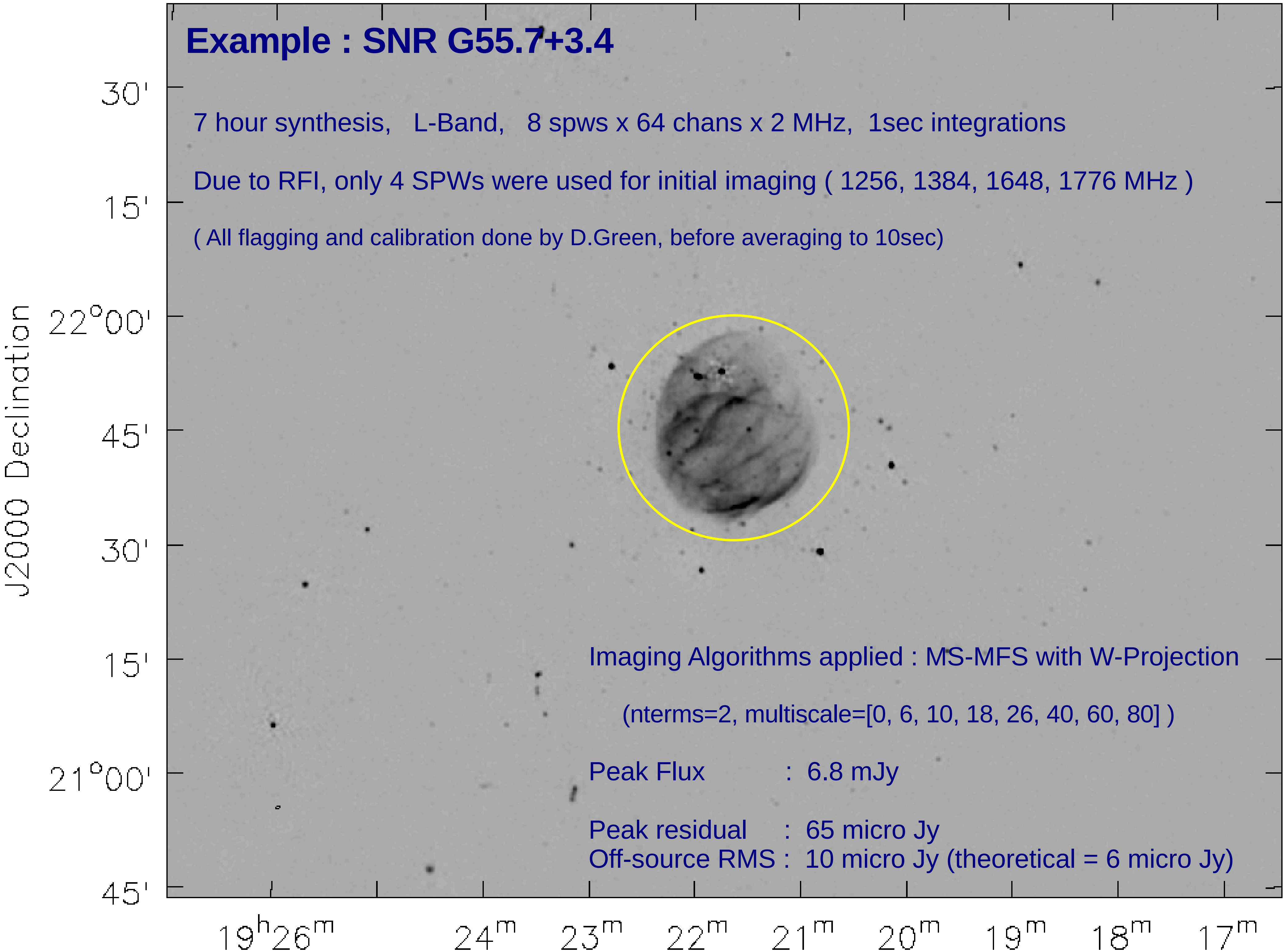
- Minor Cycle runtime x $N_{taylor} N_{scales} N_{pixels}$
- Minor Cycle memory x $\left[0.5\left(N_{taylor} N_{scales}\right)^2 + N_{taylor} + N_{taylor} N_{scales}\right] N_{pixels}$

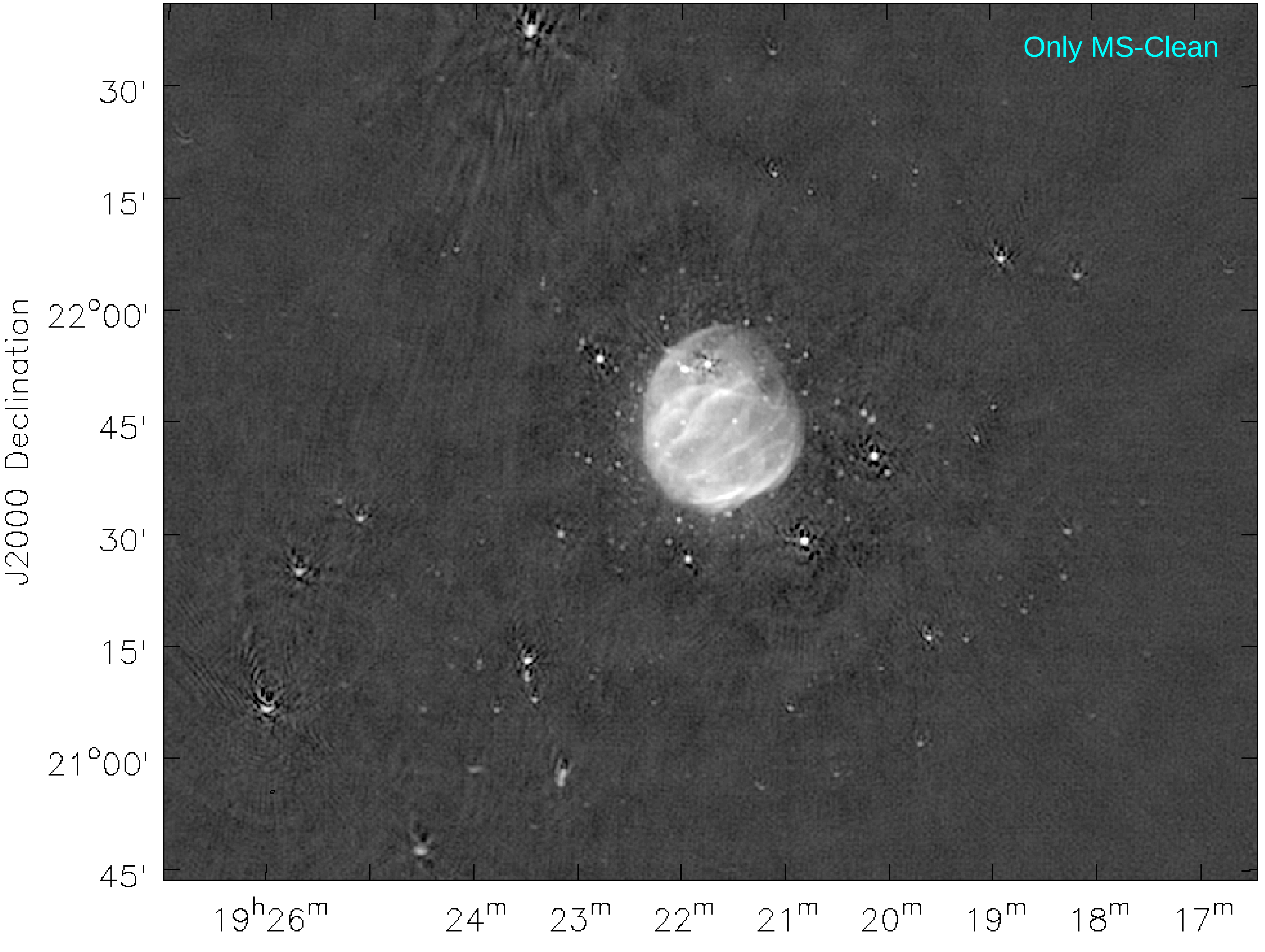
Rate of convergence : Typical of steepest-descent-style optimization algorithms : logarithmic. Can control 'loop gain', 'cleaning depth'

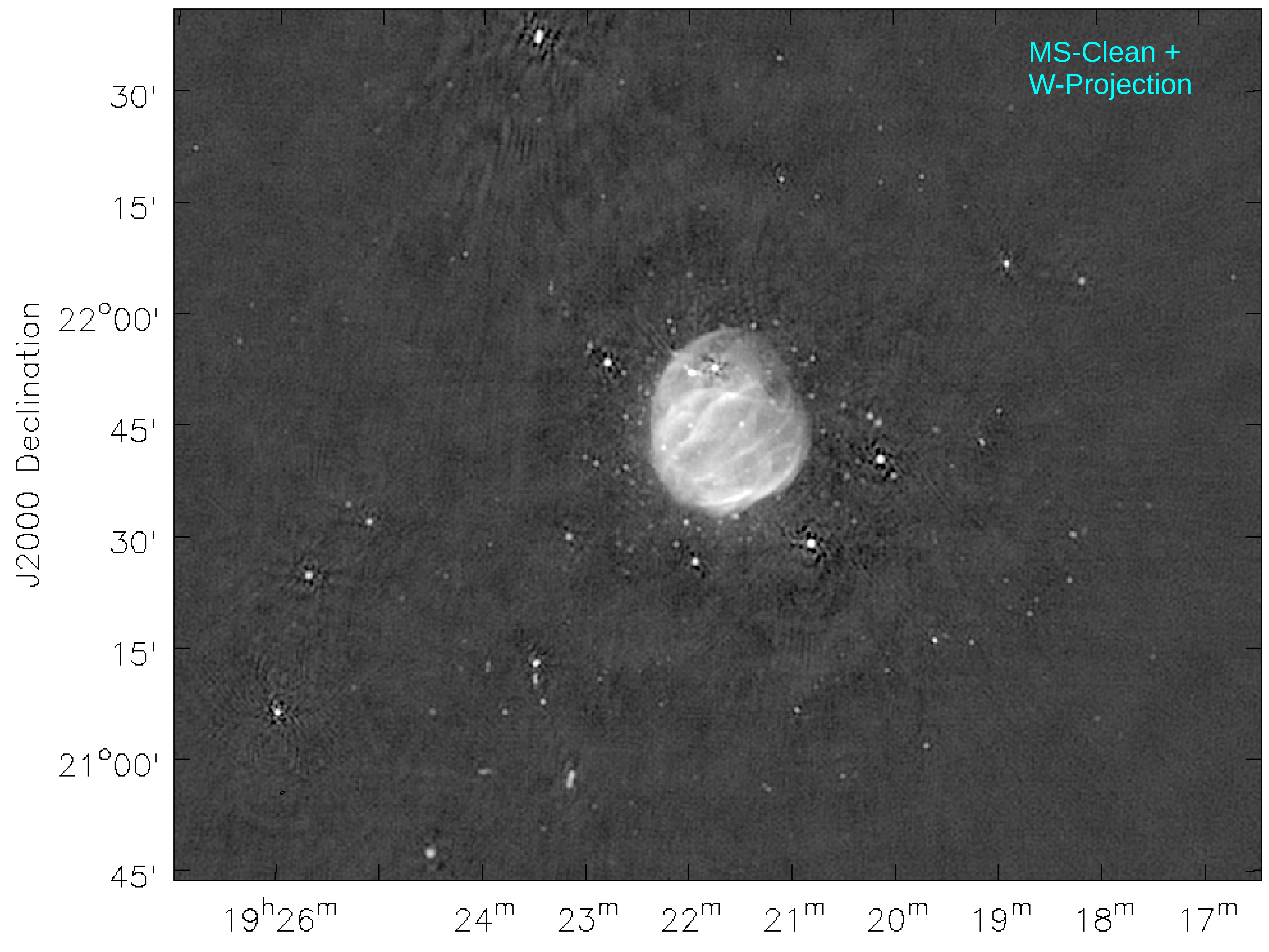
Some source structures will handle loop-gains of 0.3 to 0.5 or more (0.3 is safe).

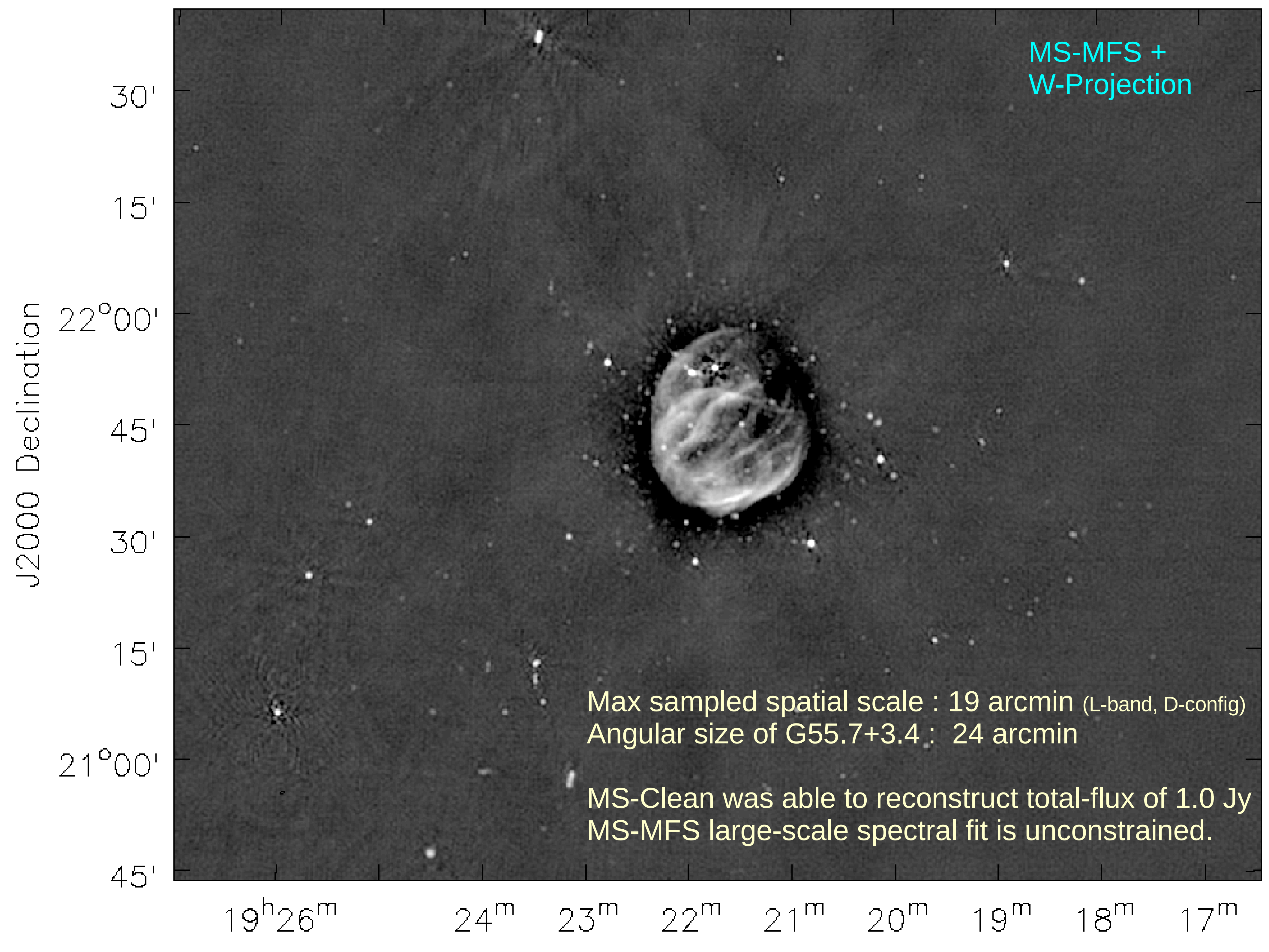
Runtimes reported by different people have ranged from 1 hr to several days.

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

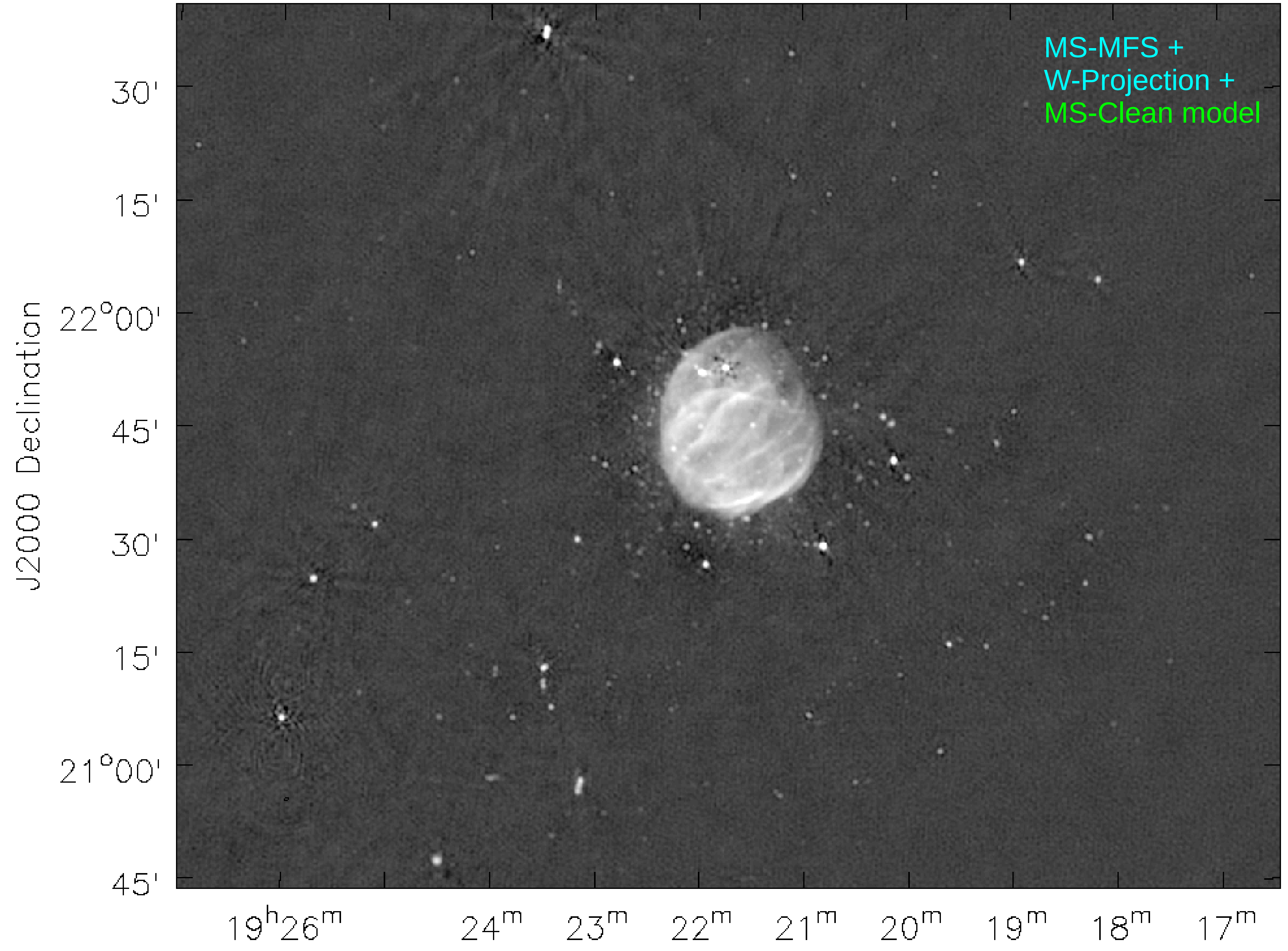

Example : SNR G55.7+3.4
7 hour synthesis,   L-Band,   8 spws x 64 chans x 2 MHz, 1sec integrations
Due to RFI, only 4 SPWs were used for initial imaging (1256, 1384, 1648, 1776 MHz)
(All flagging and calibration done by D.Green, before averaging to 10sec)
Imaging Algorithms applied : MS-MFS with W-Projection
(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


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

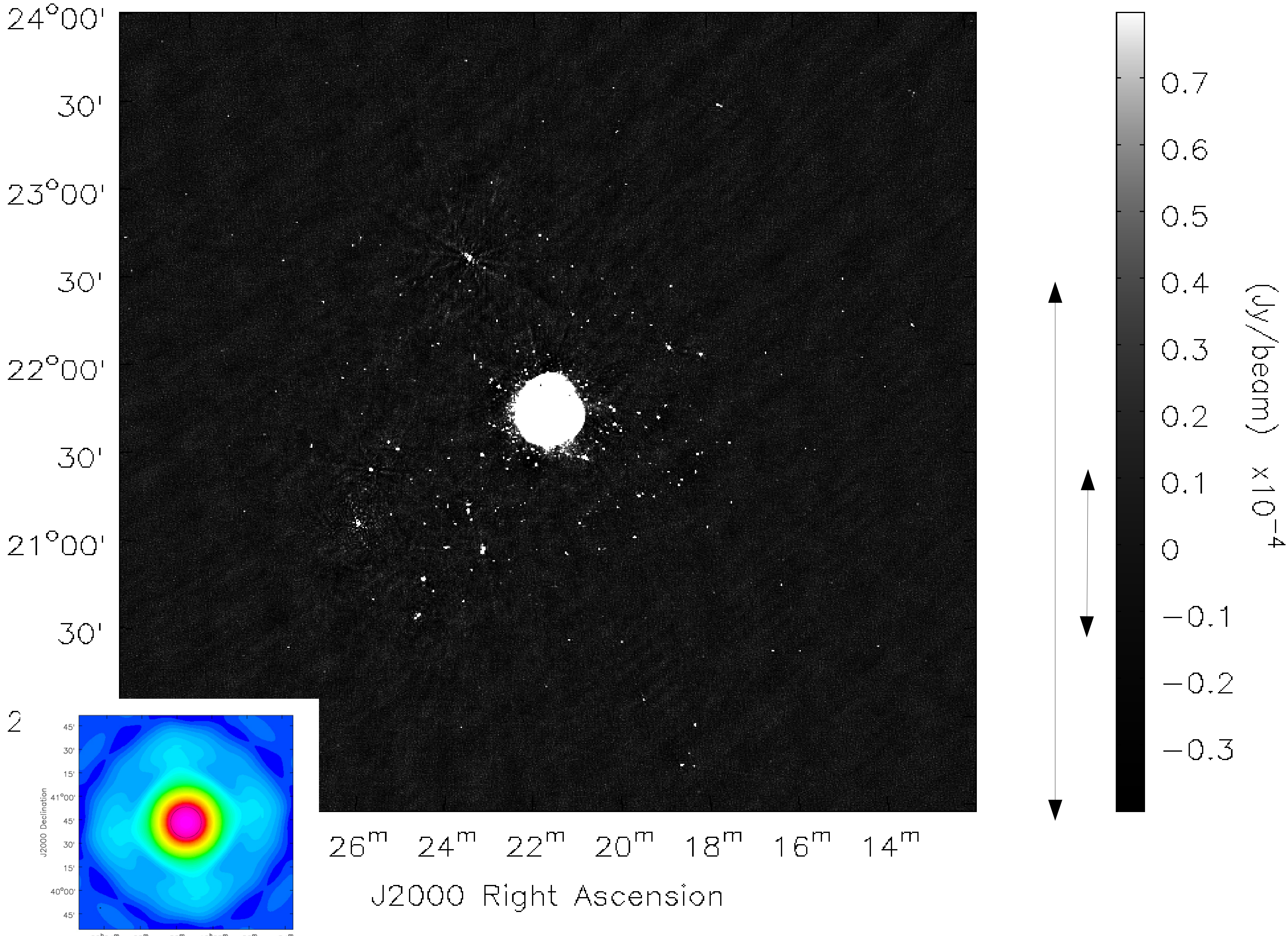

MS-Clean +
W-Projection
J2000 Declination
30'
15'
22°00'
45'
30'
15'
21°00'
45'
19h26m
24m
23m
22m
21m
20m
19m
18m
17m



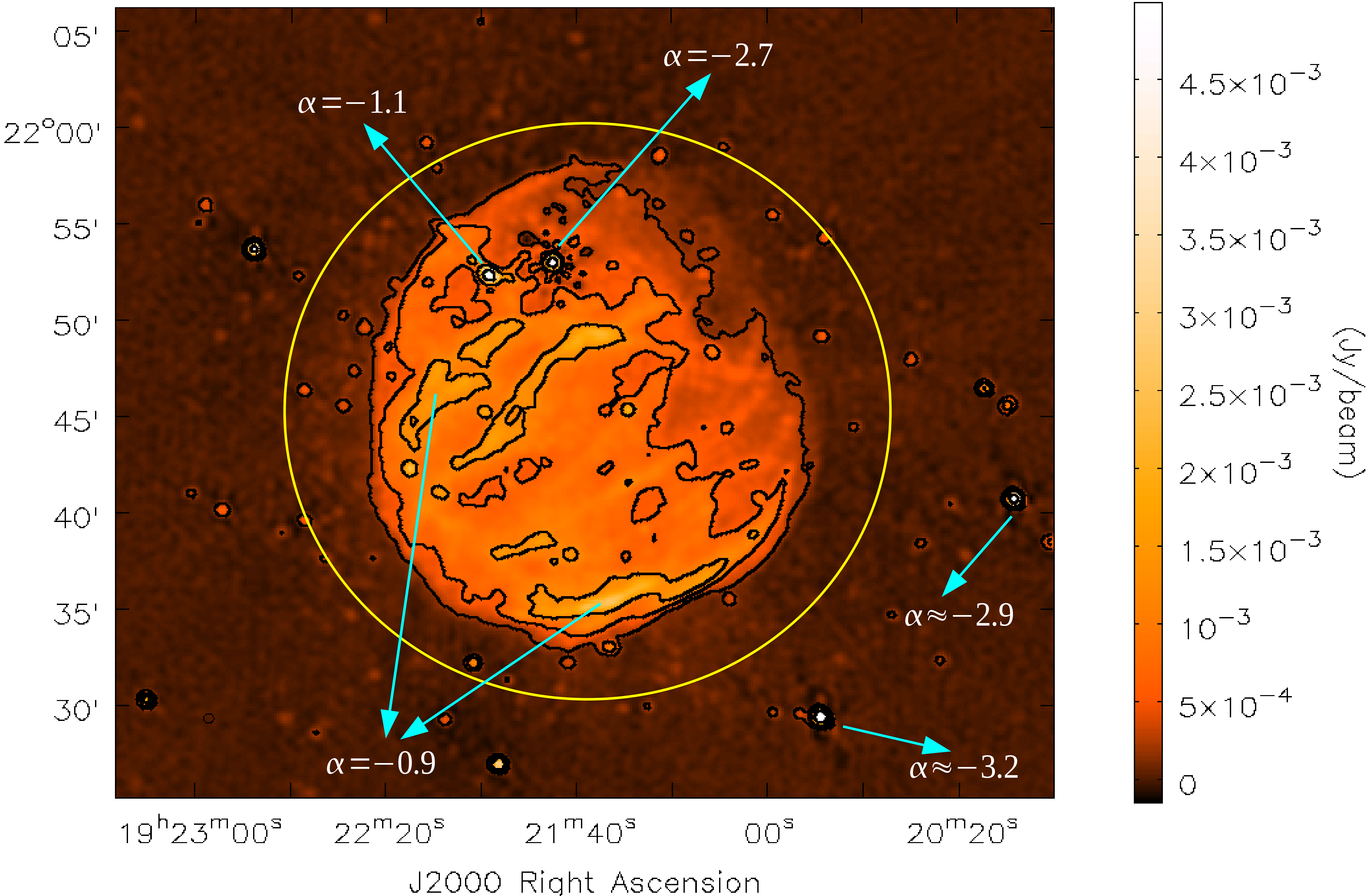
MS-MFS +
W-Projection
Max sampled spatial scale : 19 arcmin (L-band, D-config)
Angular size of G55.7+3.4 : 24 arcmin
MS-Clean was able to reconstruct total-flux of 1.0 Jy
MS-MFS large-scale spectral fit is unconstrained.
J2000 Declination
30'
15'
22°00'
45'
30'
15'
21°00'
45'
19h26m
24m
23m
22m
21m
20m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



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

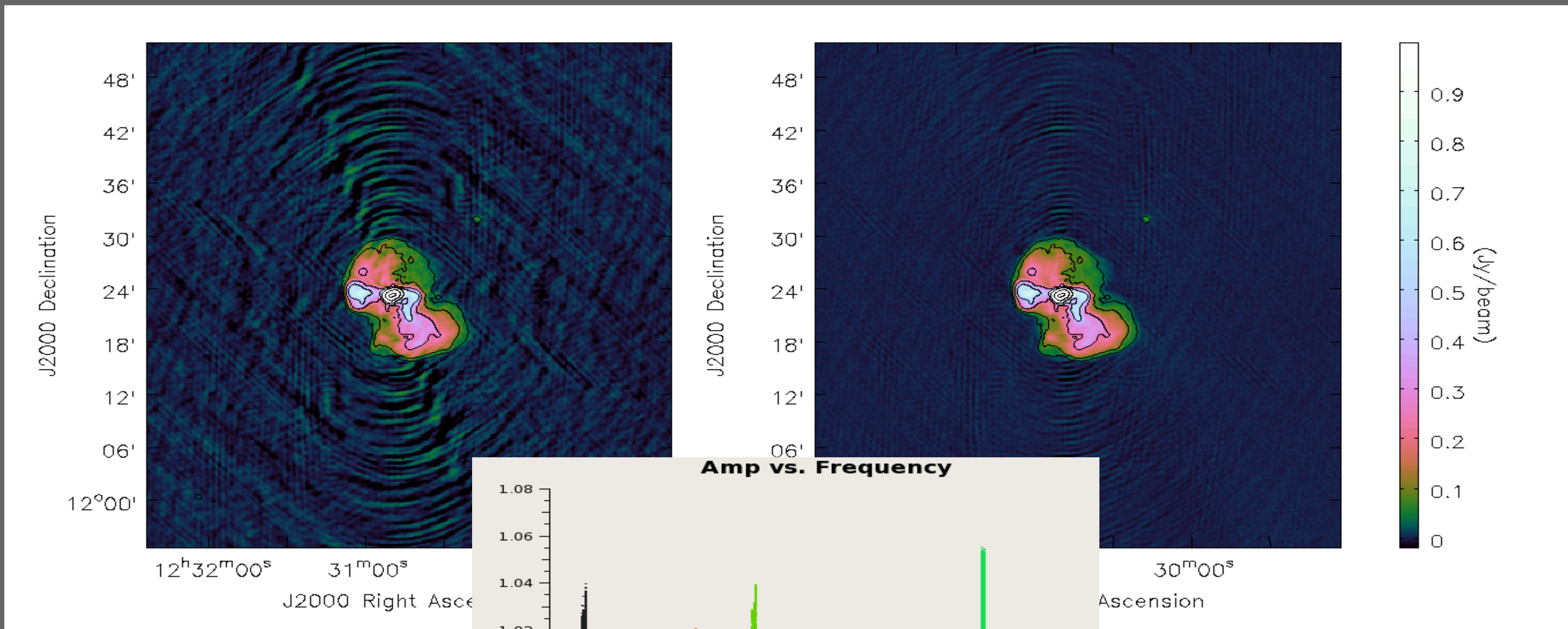

24°00'
30'
23°00'
30'
22°00'
30'
21°00'
30'
2
26m
24m
22m
20m
18m
16m
14m
J2000 Right Ascension
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
−0.1
−0.2
−0.3
(Jy/beam) x10^-4
45'
30'
15'
41°00'
45'
30'
15'
40°00'
45'
J2000 Declination
20h04m
02m
00m
19h58m
56m
54m

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



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

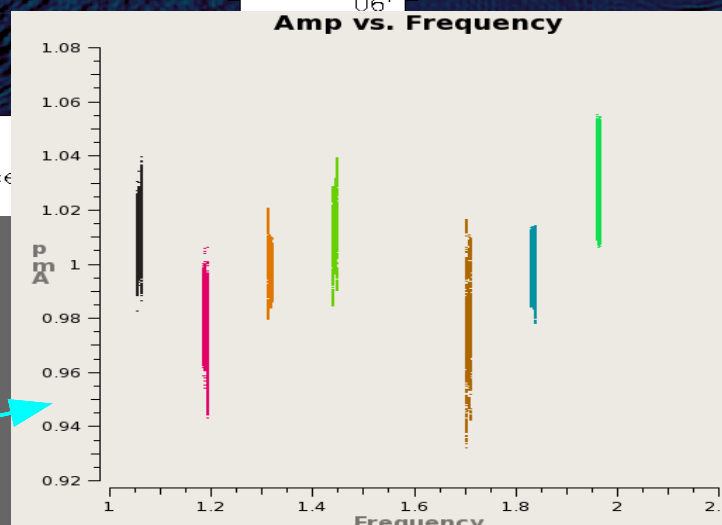
In CASA, 'clean' writes wide-band model visibilities to disk (calready=True). Or, use 'ft'.



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......



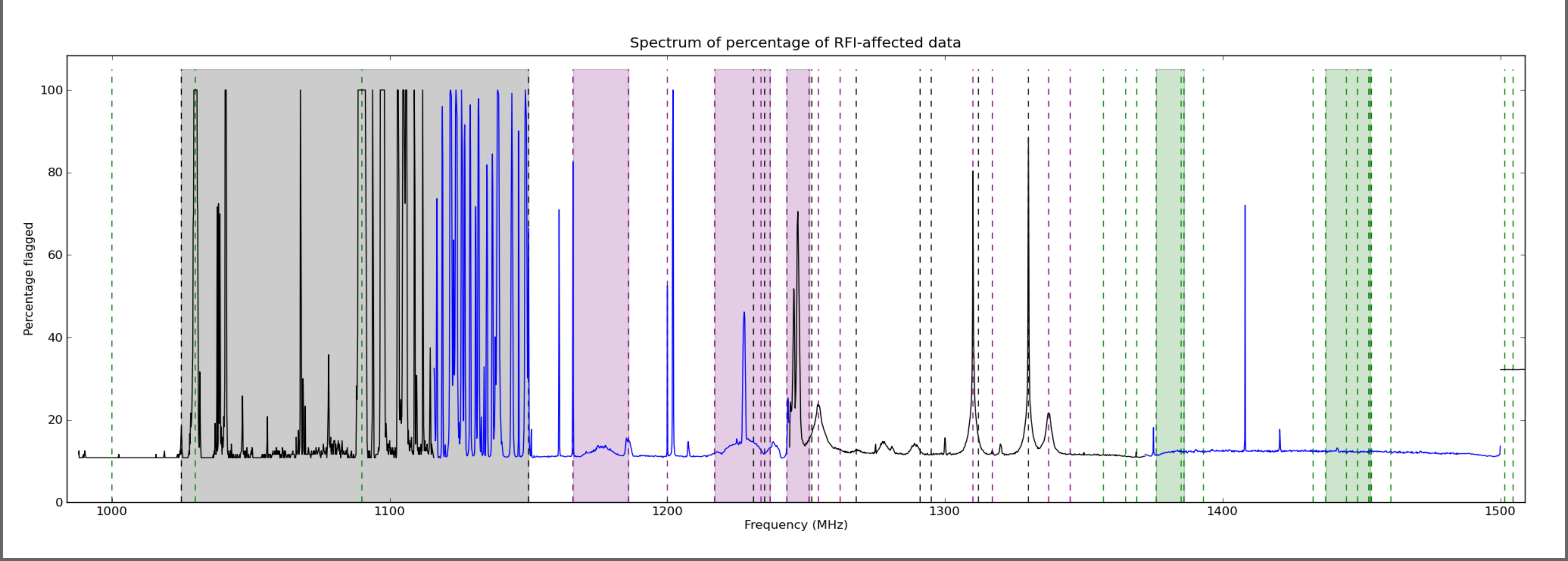
5 chans x 7 spectral-windows

- 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.

RFI and automatic flagging

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

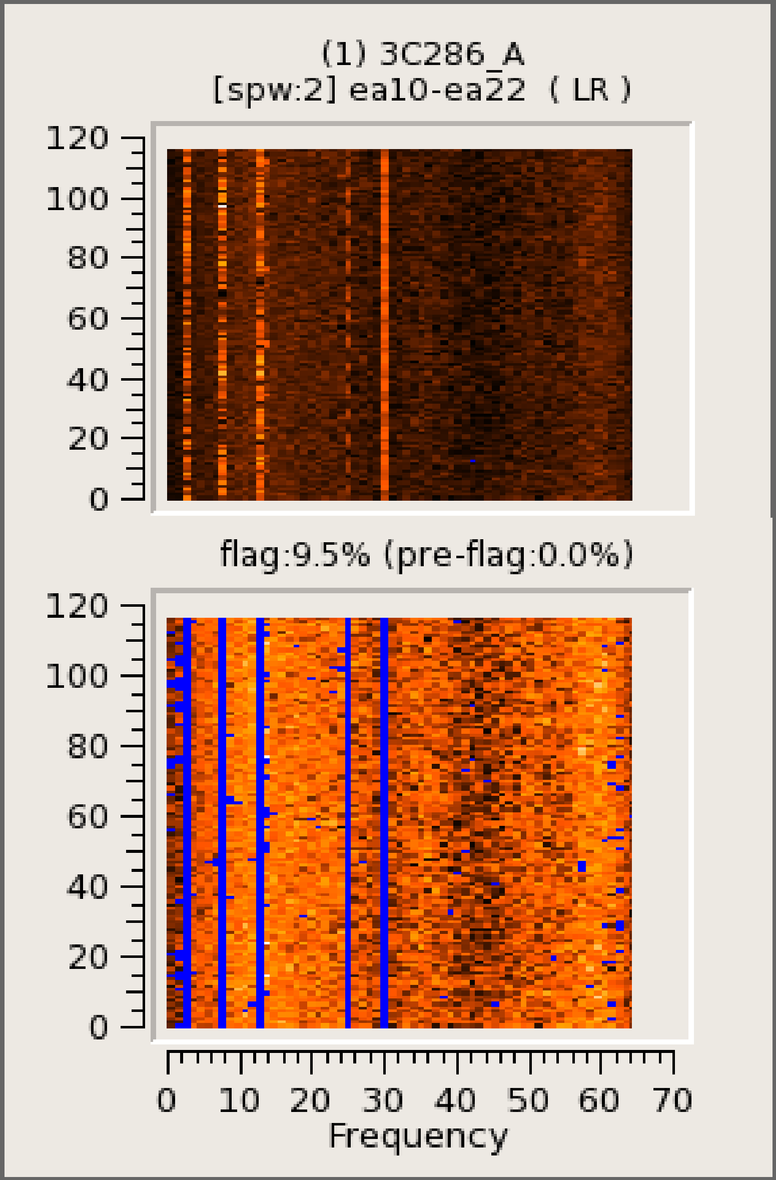
CASA : TFCrop (fit a smooth function to the time-freq plane, and find outliers)
AIPS : RFLAG (statistics-based flagger with automatic threshold-calculation)



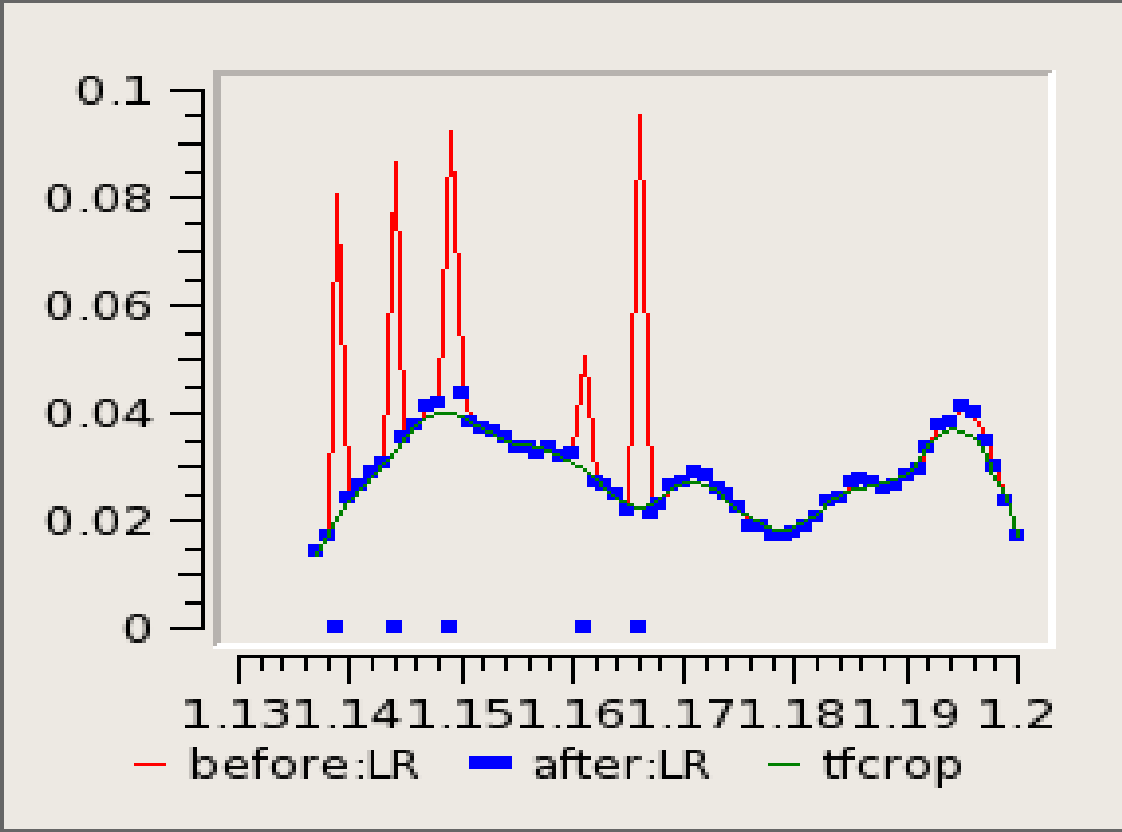
One way to examine your data, is to run 'autoflag' and look at flag counts

– 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

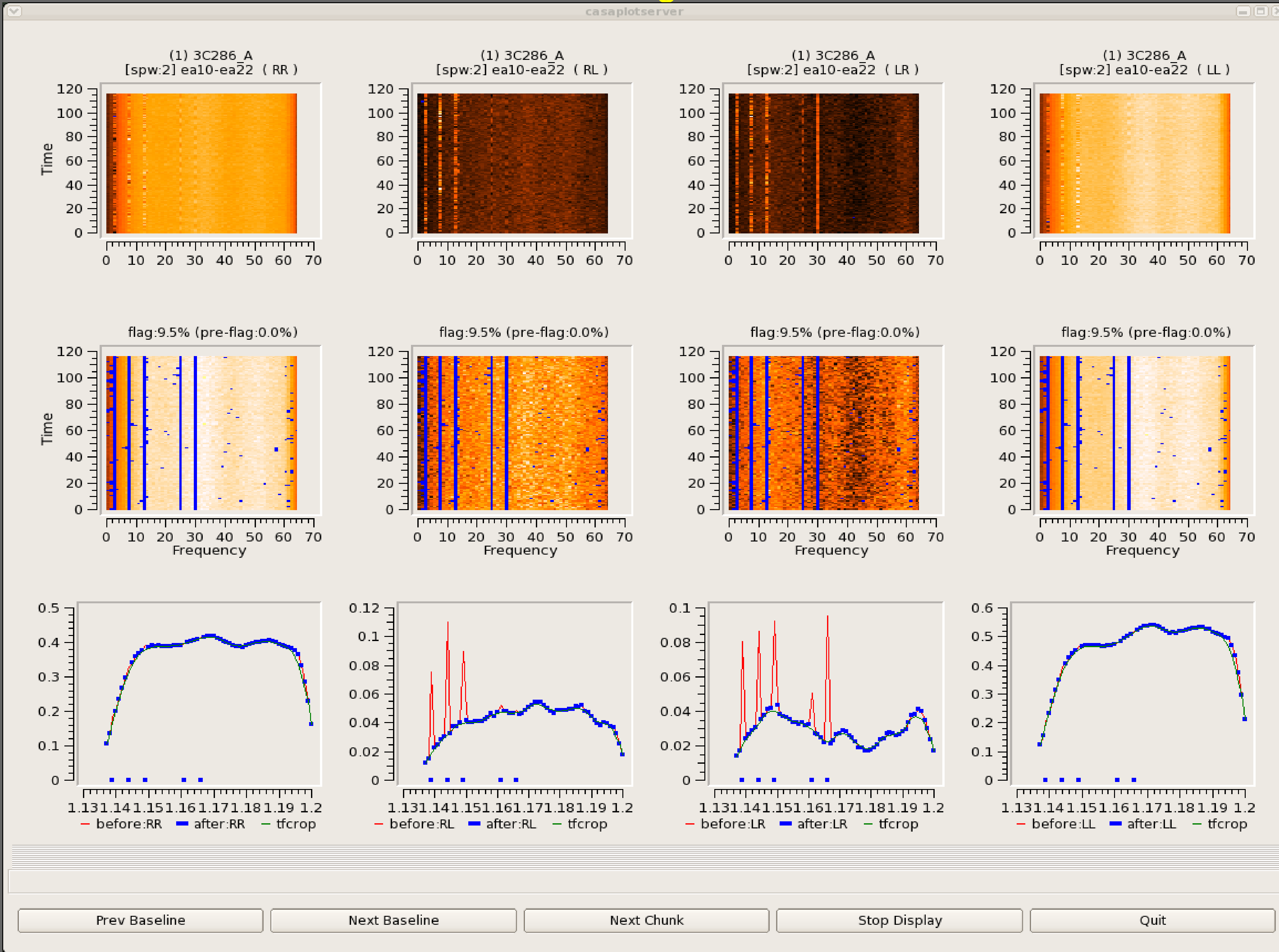
TFCrop : Detect outliers on the 2D time-frequency plane
(testautoflag in CASA)



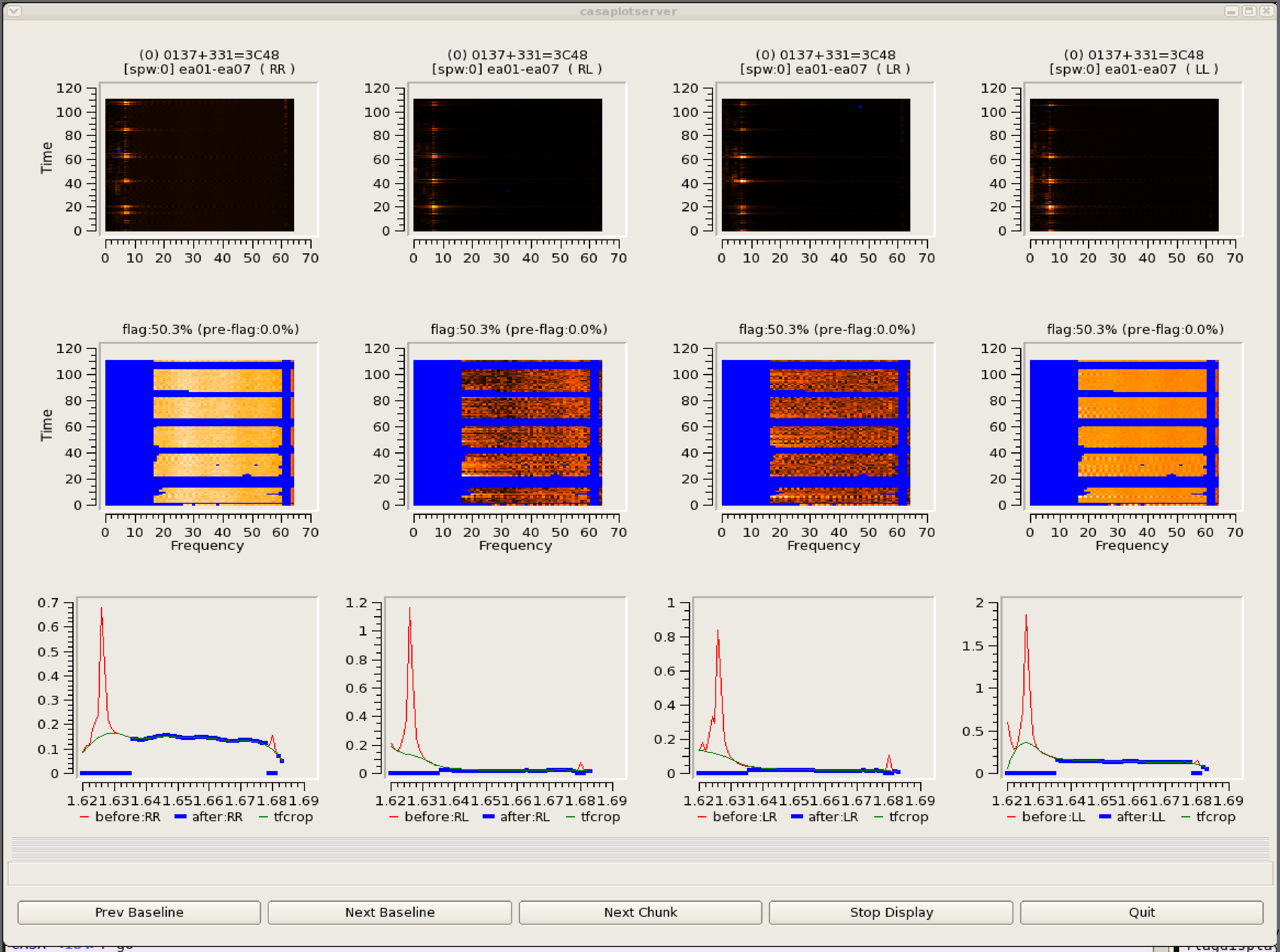
– Average the data along one dimension
– Fit a piece-wise polynomial to the base of RFI spikes
-- calculate 'sigma' of data - fit.
– Flag points deviating from the fit by more than N-sigma
– Repeat along the second dimension.
– Extend flags along time, frequency, polarization



Visualize Data/Flags at run-time

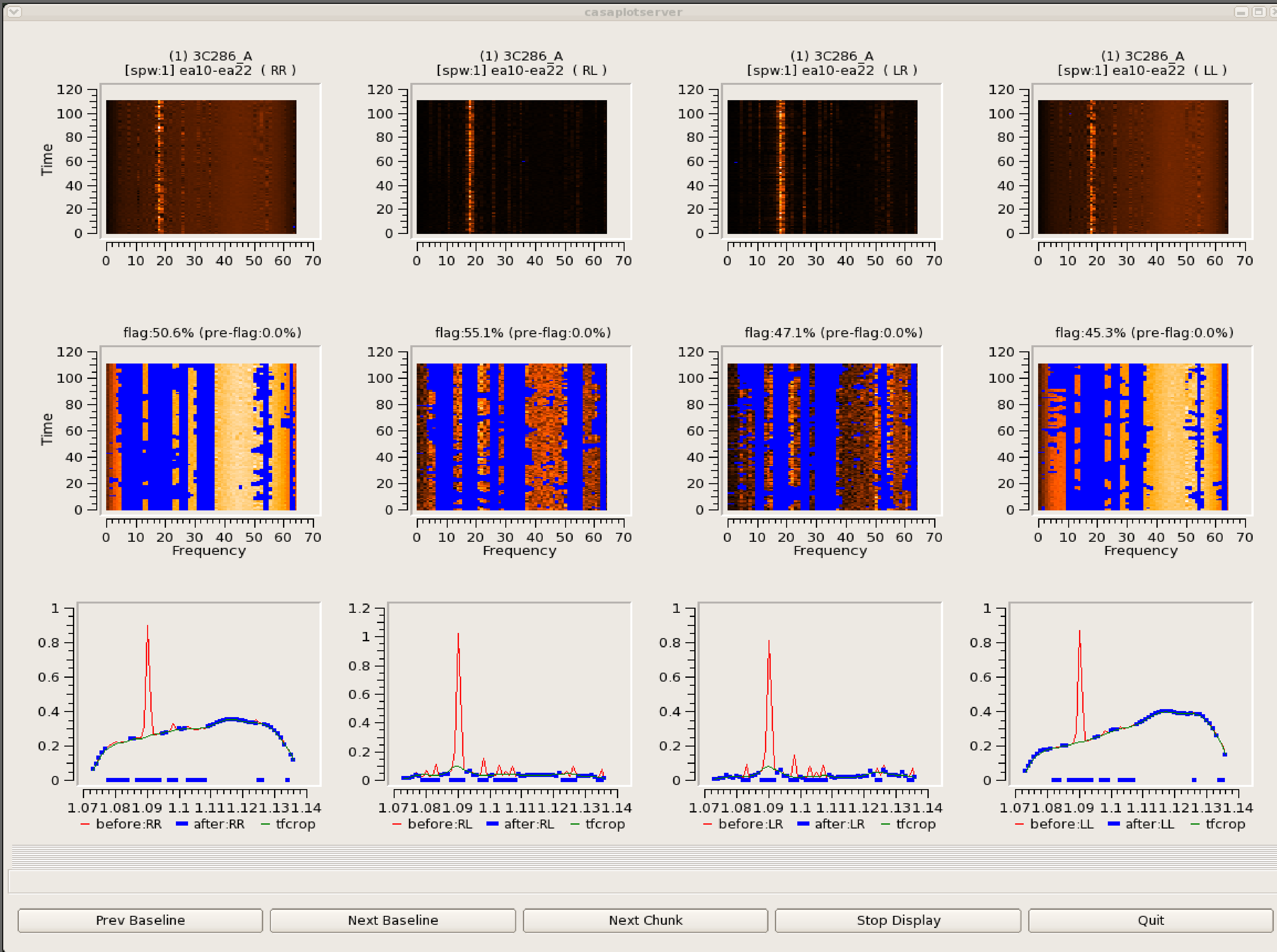


Example 1

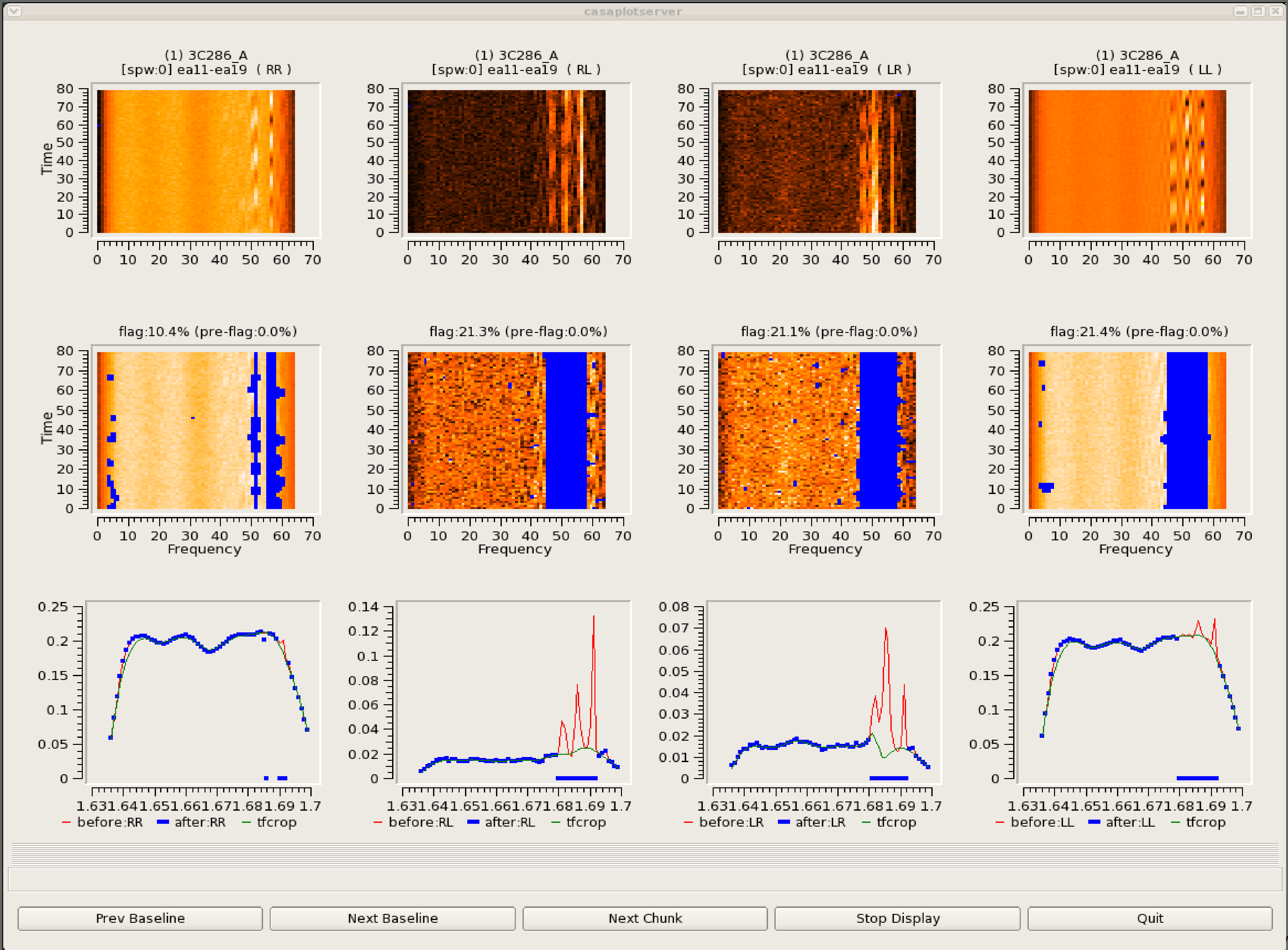


casaplotserver
(0) 0137+331=3C48
[spw:0] ea01-ea07 (RR)
(0) 0137+331=3C48
[spw:0] ea01-ea07 (RL)
(0) 0137+331=3C48
[spw:0] ea01-ea07 (LR)
(0) 0137+331=3C48
[spw:0] ea01-ea07 (LL)
Time
flag:50.3% (pre-flag:0.0%)
Frequency
before:RR
after:RR
tfcrop
before:RL
after:RL
before:LR
after:LR
before:LL
after:LL
Prev Baseline
Next Baseline
Next Chunk
Stop Display
Quit

Example 2


casaplotserver
(1) 3C286_A
[spw:1] ea10-ea22 (RR)
(1) 3C286_A
[spw:1] ea10-ea22 (RL)
(1) 3C286_A
[spw:1] ea10-ea22 (LR)
(1) 3C286_A
[spw:1] ea10-ea22 (LL)
Time
flag:50.6% (pre-flag:0.0%)
flag:55.1% (pre-flag:0.0%)
flag:47.1% (pre-flag:0.0%)
flag:45.3% (pre-flag:0.0%)
Frequency
before:RR after:RR tfcrop
before:RL after:RL tfcrop
before:LR after:LR tfcrop
before:LL after:LL tfcrop
Prev Baseline
Next Baseline
Next Chunk
Stop Display
Quit

Example 3



casaplotserver
(1) 3C286_A
[spw:0] ea11-ea19 (RR)
(1) 3C286_A
[spw:0] ea11-ea19 (RL)
(1) 3C286_A
[spw:0] ea11-ea19 (LR)
(1) 3C286_A
[spw:0] ea11-ea19 (LL)
Time
flag:10.4% (pre-flag:0.0%)
flag:21.3% (pre-flag:0.0%)
flag:21.1% (pre-flag:0.0%)
flag:21.4% (pre-flag:0.0%)
Frequency
before:RR after:RR tfcrop
before:RL after:RL tfcrop
before:LR after:LR tfcrop
before:LL after:LL tfcrop
Prev Baseline
Next Baseline
Next Chunk
Stop Display
Quit

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):

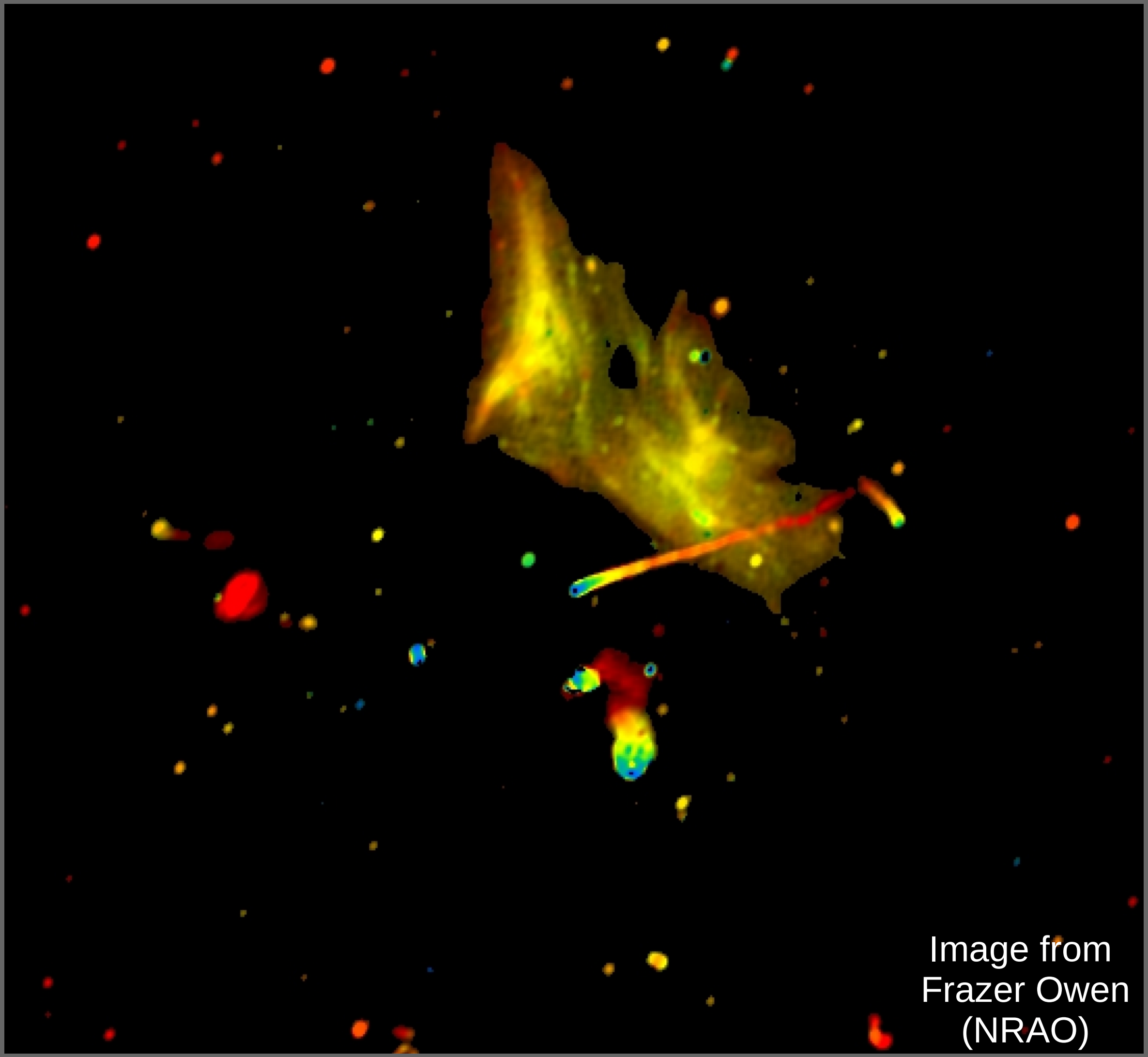
- Will single-SPW imaging suffice ?

- 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......