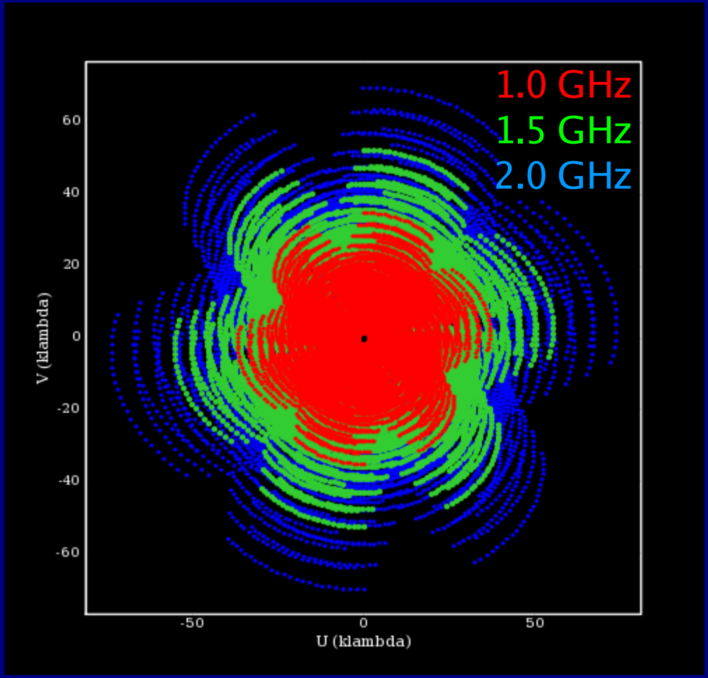
Multi-Frequency Synthesis Imaging with Multi-Scale Deconvolution (EVLA, e-MERLIN)



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(Thesis advisor : T.J.Cornwell (ATNF))

Imaging and Calibration Algorithms for
EVLA, e-MERLIN, ALMA

Oxford, U.K.
December 02, 2008

Outline :

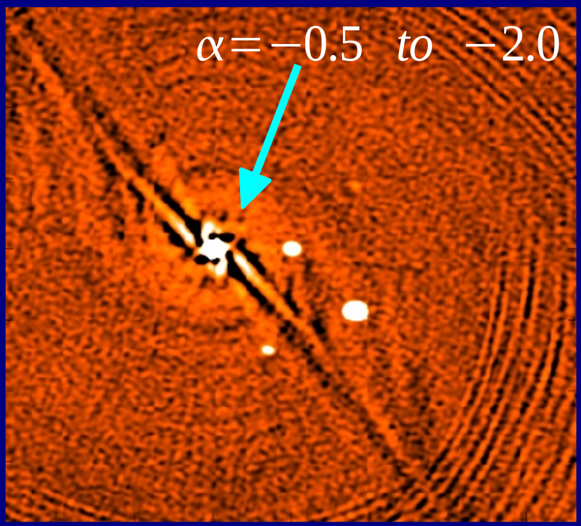
- Comparison of existing algorithms
- A simple extension of spectral-line imaging
- A multi-scale multi-frequency technique that generates spectral index and spectral curvature maps.
- Application to data taken with EVLA receivers and VLA correlator (1 –2 GHz)
- Frequency-dependent primary-beam correction (preliminary results)

MFS for point-source fields (currently used methods)

(U.Rau, T.J.Cornwell, EVLA Memo 101, 2006)

Standard Continuum Imaging

Peak residual : 60 uJy



Dyn range limit ~ 1000
for α ~ -1.0 across 1-2 GHz
(Conway et al, 1990)

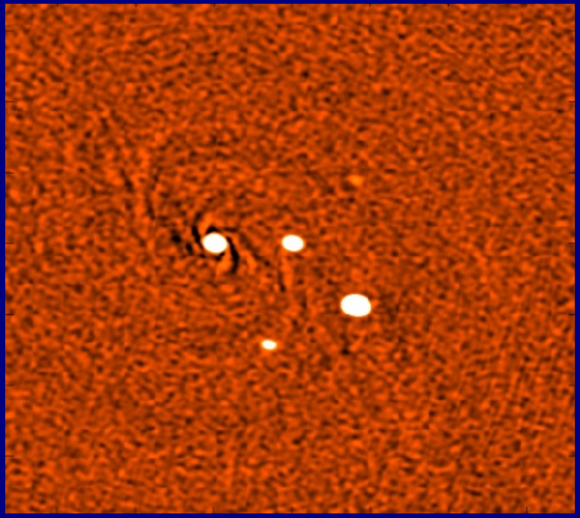
Simulation of 5 point sources :
100mJy, 10mJy, 1mJy, 100uJy, 10uJy

Spectral index of 10mJy source
(800 MHz at 1.4 GHz) : -0.5 to -2.0

Target RMS : 1 uJy

MF-CLEAN (Miriad)

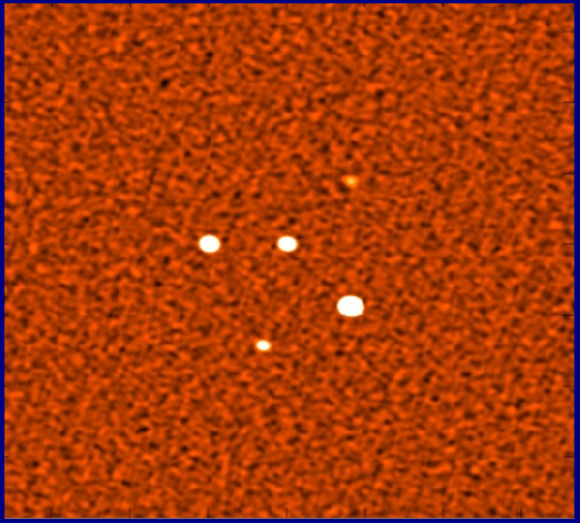
Linear Fit to Spectrum
Peak residual : 10 uJy



Both methods will work for
~ Point-sources.

Spectral-Line Imaging

Peak residual : 2 uJy

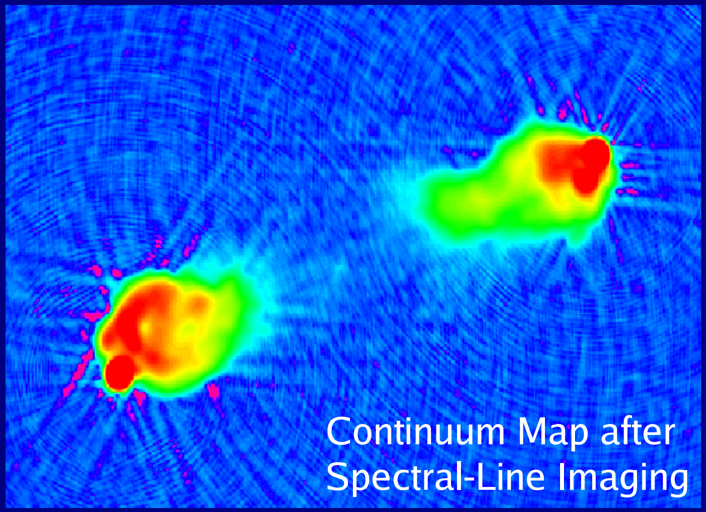


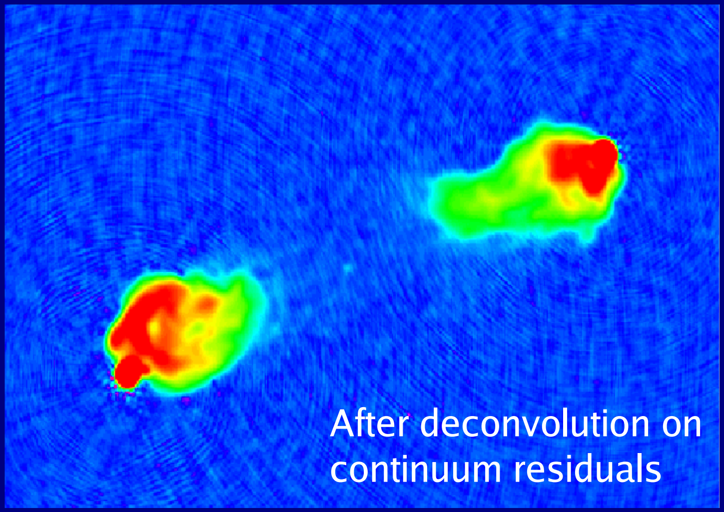
Insufficient for extended sources
and sources whose flux ~ σ_{chan}

Hybrid Algorithm – on extended emission

(U.Rau, T.J.Cornwell, 2008 (in prep))

Spectral-Line Imaging + Deconvolution on continuum residuals





Target dynamic range : 10^6
Target pt-source rms : 10 uJy

Max Dynamic range : 10^6
(component image)

Max Dynamic range : 10^5
(restored image)

Cygnus-A^{+} simulation (40 channels, L-Band to C-Band, 4 hours) => Ideal data

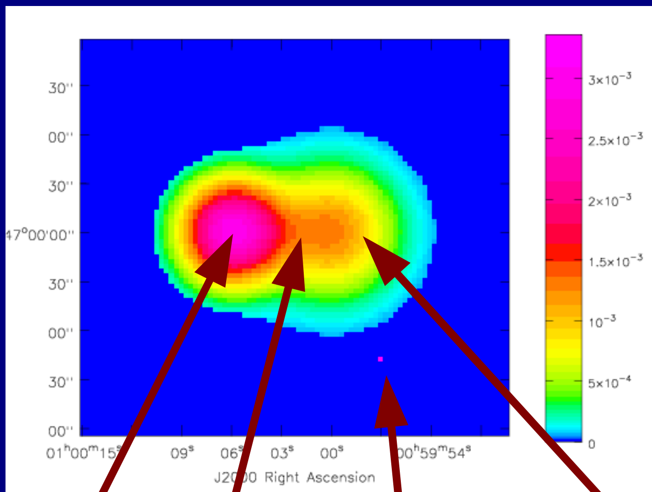
Simple hybrid algorithm can handle arbitrary spectra and will suffice (upto calibration limits)
- for point sources
- for extended sources if there is sufficient uv-coverage per channel

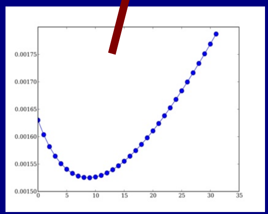
Insufficient uv-coverage per channel
=> solve for total-intensity and spectrum simultaneously.
(MF-CLEAN and other parametric solvers)

Multi-Scale Multi-Frequency-Synthesis *(U.Rau, T.J.Cornwell, 2008 (in prep))*

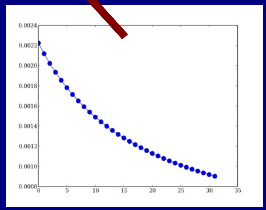
EVLA C-array simulation, 1-2 GHz

Image at Reference Frequency

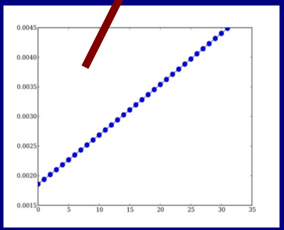




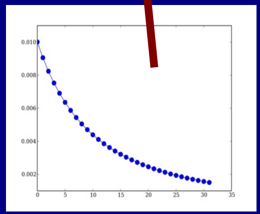
Spectral Turn-over



Gaussian (right) :
α = -1.0
size : 1 arcmin
flux : 1 Jy

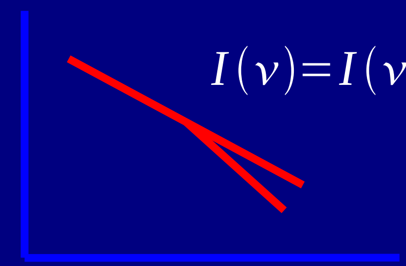


Gaussian (left) :
α = +1.0
size : 0.8 arcmin
flux : 0.5 Jy



Point source :
α = -2.0

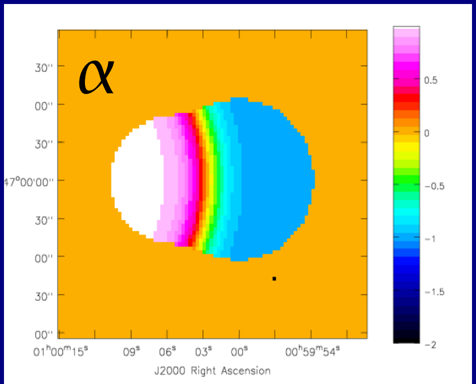
Spectral Flux Model : Power Law with varying index



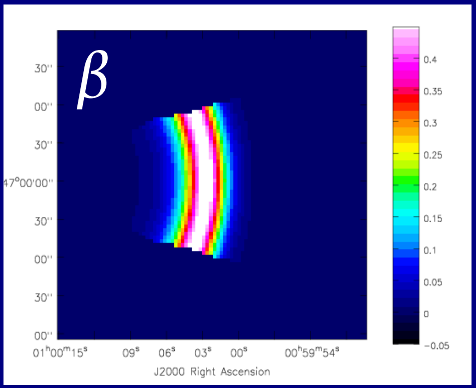
$$I(\nu) = I(\nu_0)\left(\frac{\nu}{\nu_0}\right)^{\alpha + \beta \log(\nu/\nu_0)}$$

$\log I(\nu)$; $\log\left(\frac{\nu}{\nu_0}\right)$

Average Spectral Index



Gradient in Spectral Index



Deconvolution Algorithm :
MS-CLEAN + MF-CLEAN (>2 Taylor terms)
(Cornwell, 2008) *(Sault,Wieringa, 1994)*

True Images

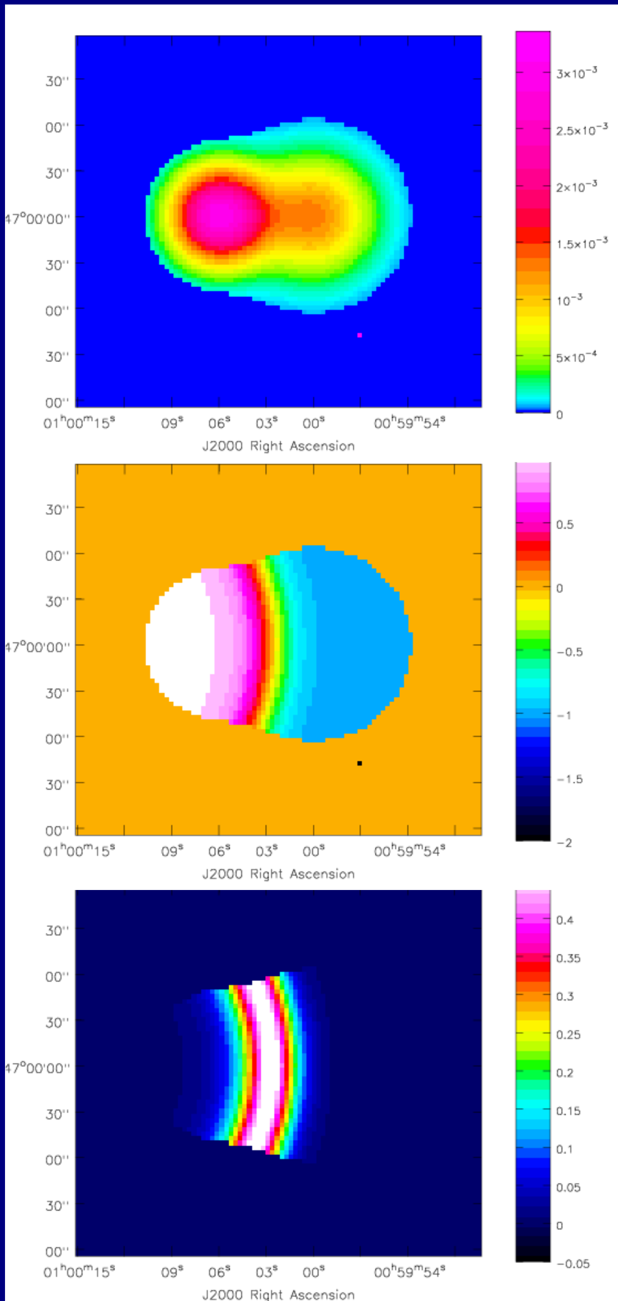


Image at reference frequency

$I(\nu_0)$

Average Spectral Index

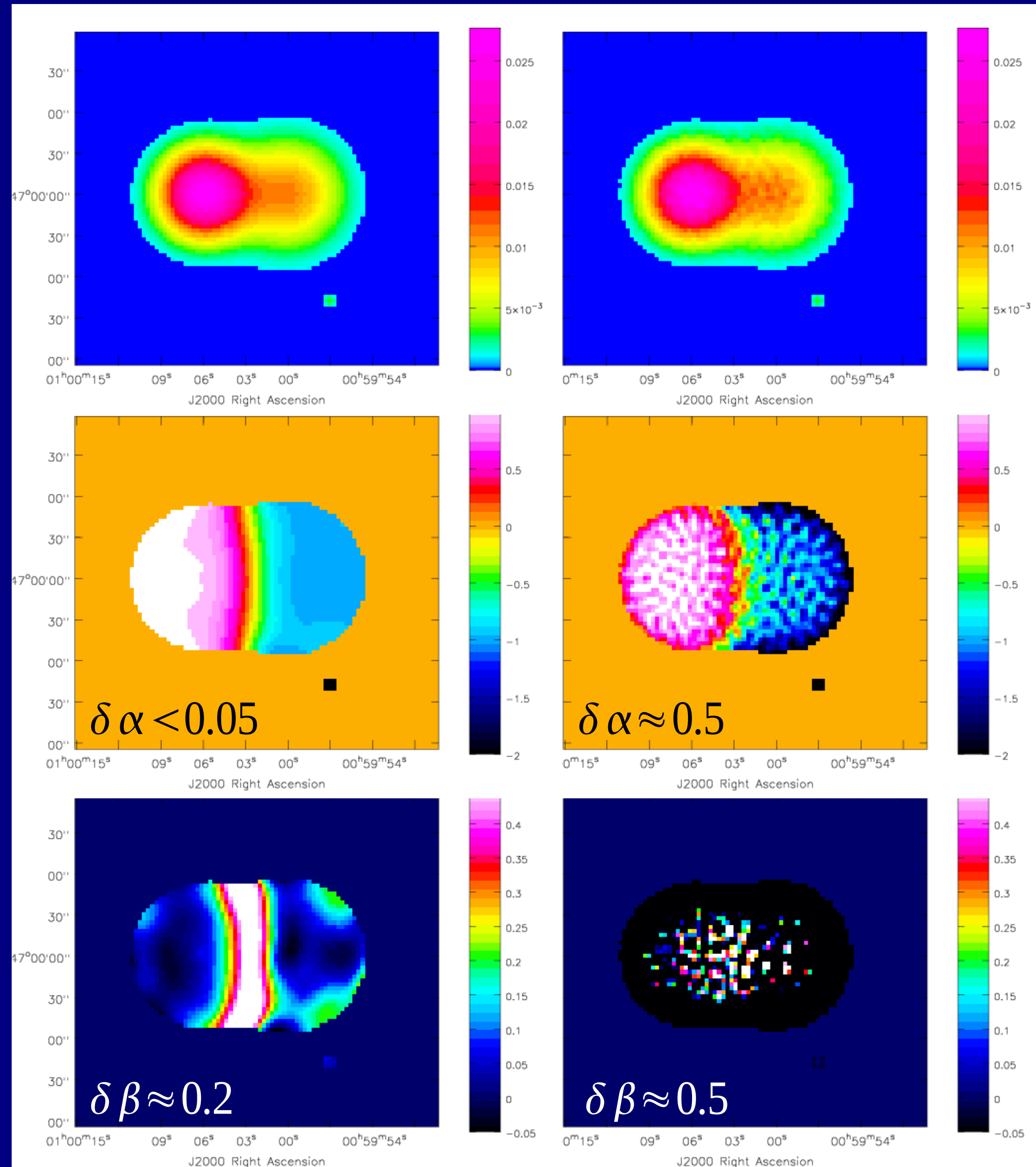
α

Gradient in Spectral Index

β

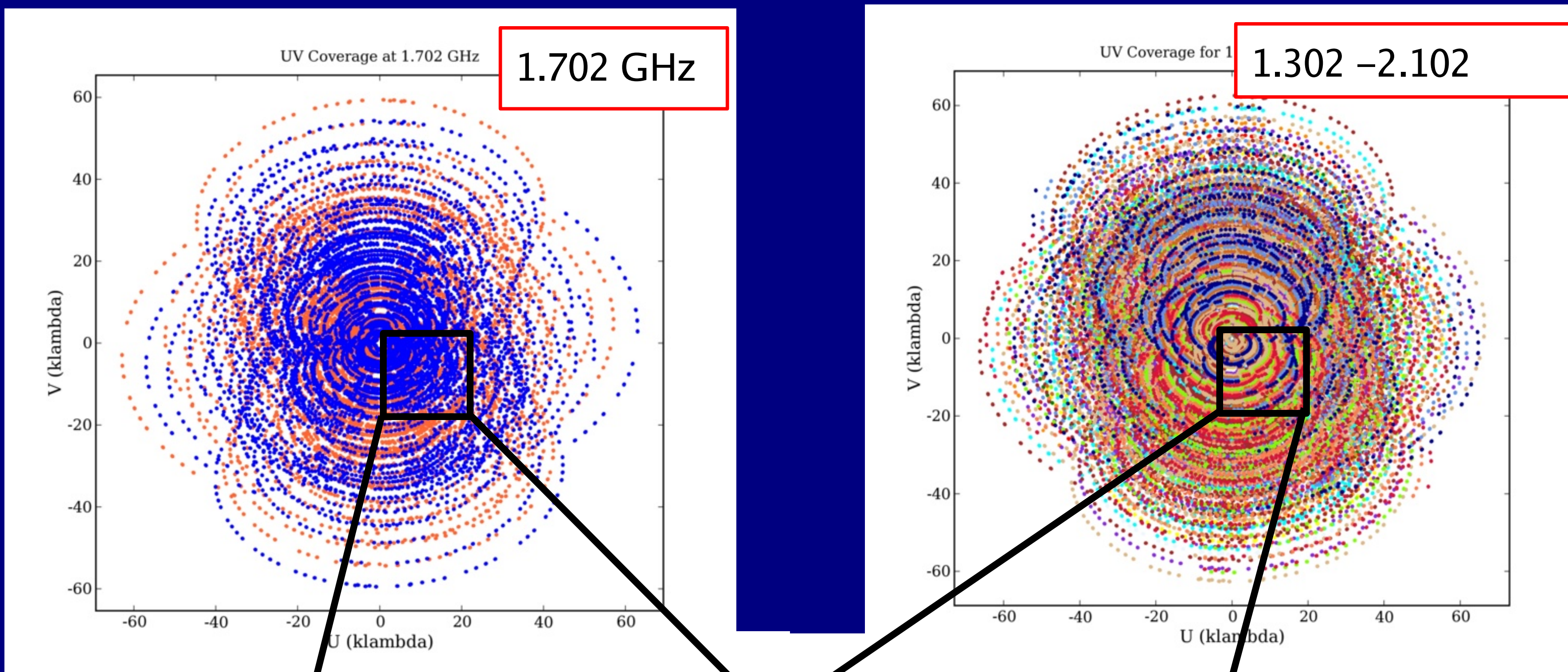
MS- MFS (multi-scale source model)

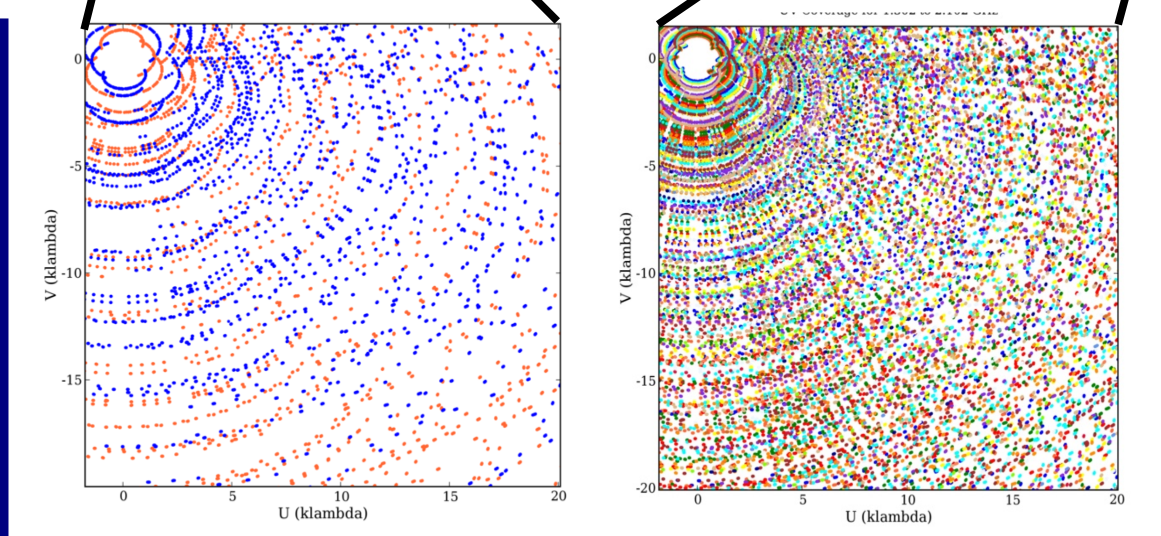
MF-Clean (3 Taylor terms) (point-source pixel model)



Example synthesized wide-band EVLA uv-coverage

CygA : Cycle through 9 frequency bands, 20 one-minute snapshots per band, spread over 8 hours)





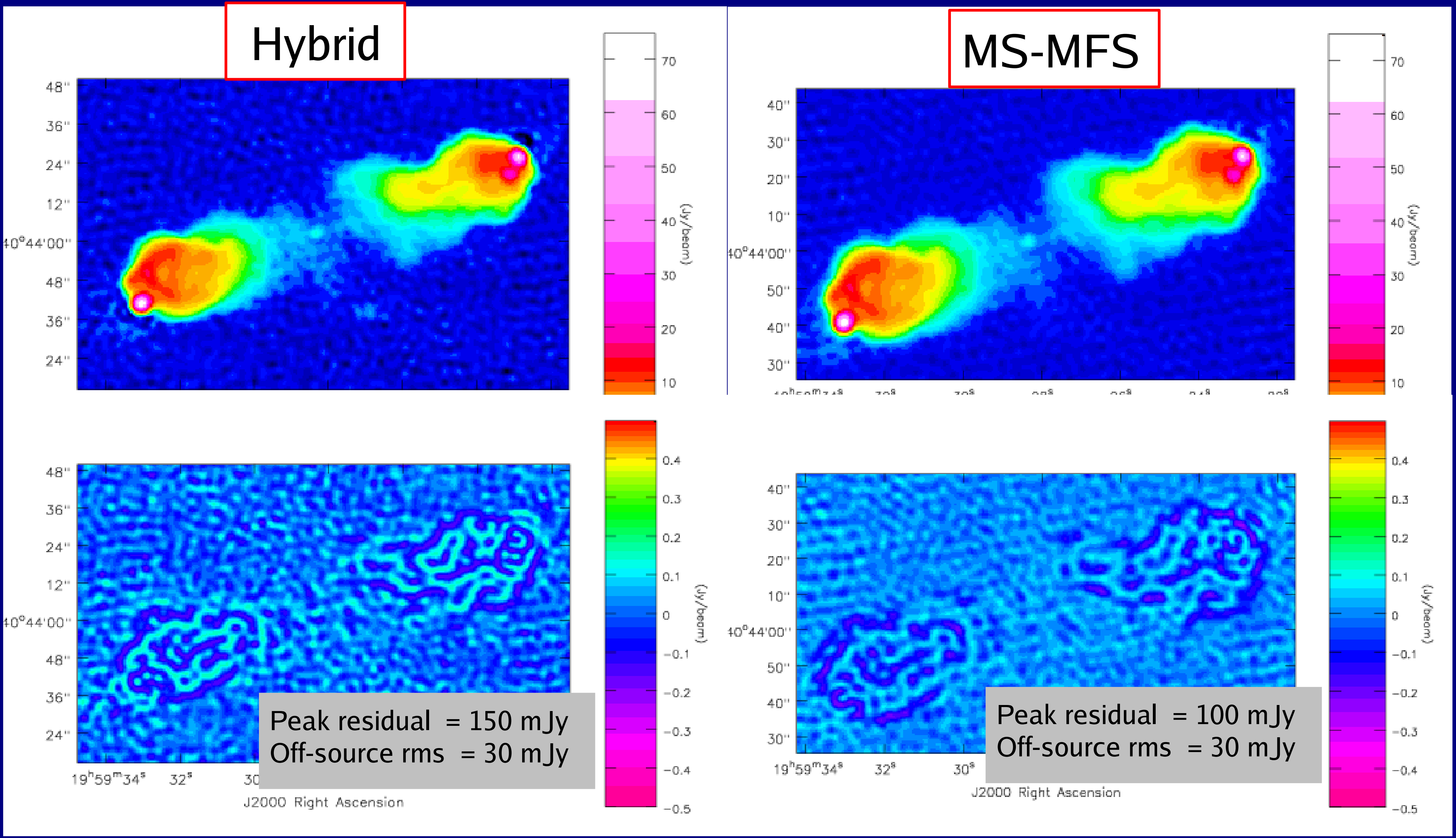
uv-grid cell size
~ 0.2 klambda

< 0.5 visibilities
per uv-grid cell

>1 visibility points
per uv-grid cell

=> Good for Spectral Structure at multiple scales

CygA –Continuum Image and Residuals

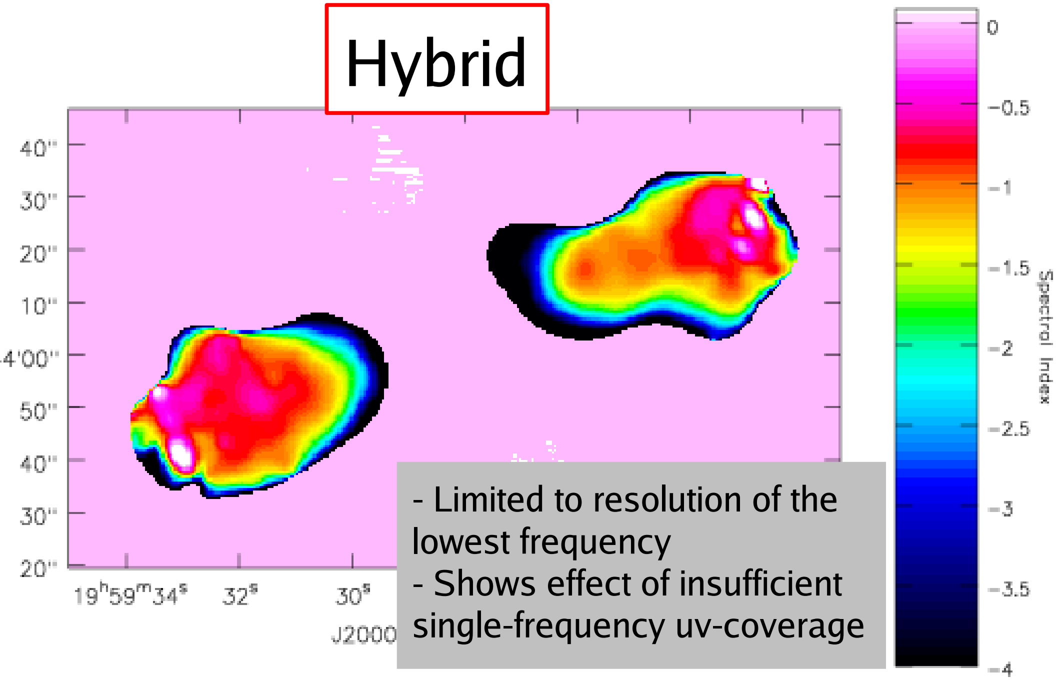


=> Similar results

- both algorithms work well
- both have few-sigma residual deconvolution errors.

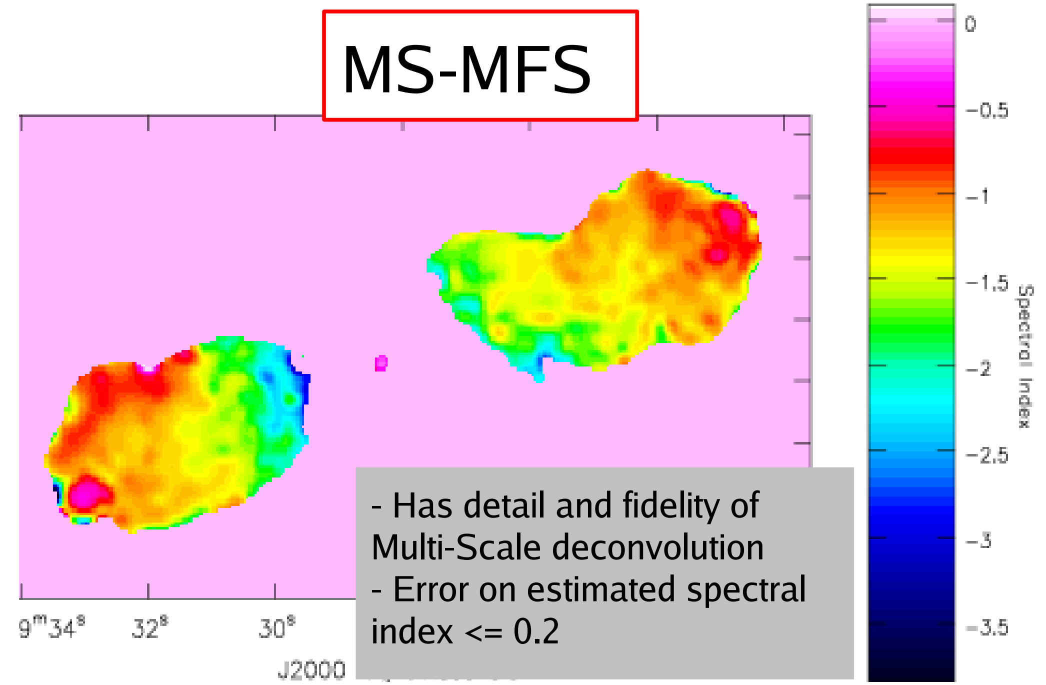
CygA - Spectral Index Images

Hybrid



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

MS-MFS

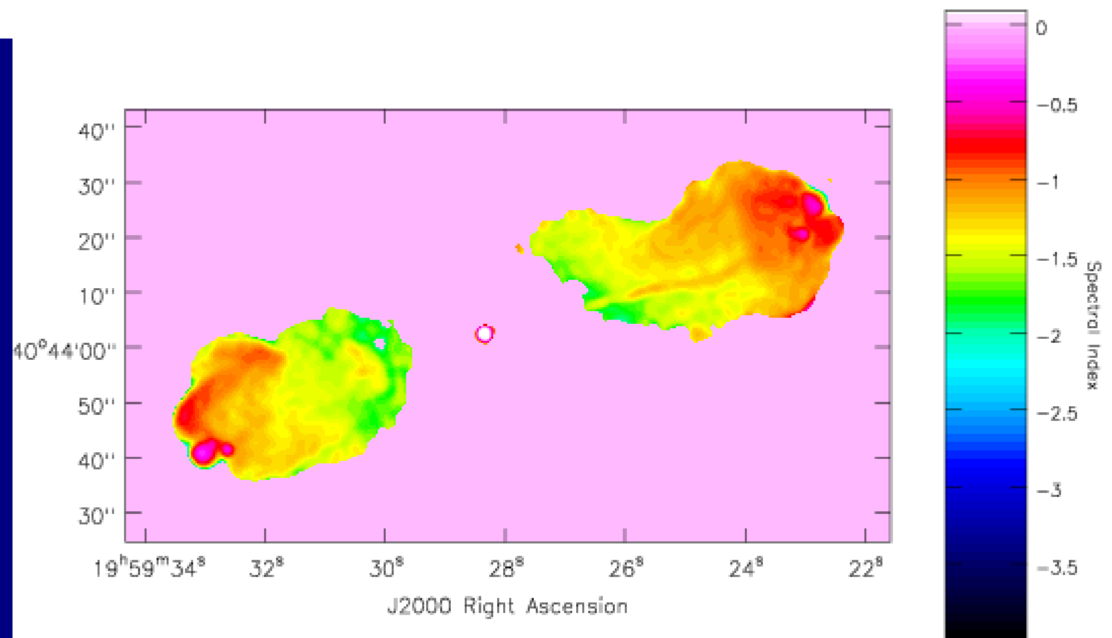


- Has detail and fidelity of Multi-Scale deconvolution
- Error on estimated spectral index <= 0.2

For comparison,

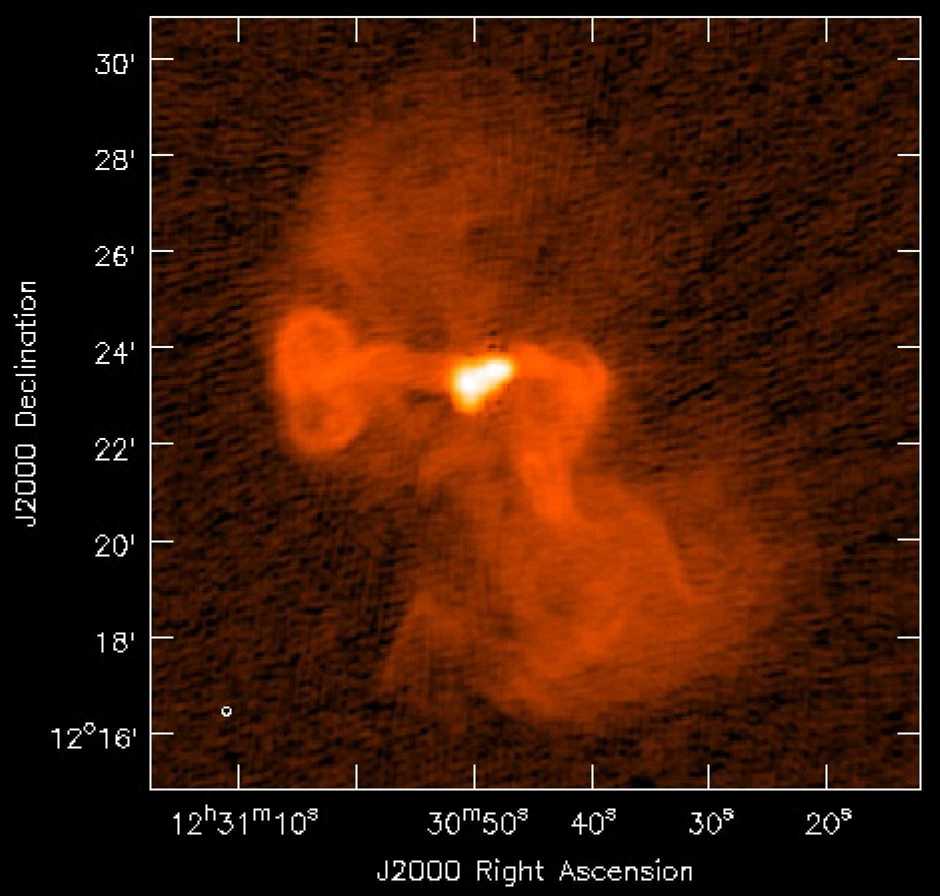
Spectral Index Map constructed from images at 1.4GHz and 4.8GHz, obtained from C.Carilli et al, Ap.J. 1991.
(VLA A,B,C,D Array at L and C band)

Map has been smoothed to 1 arcsec.

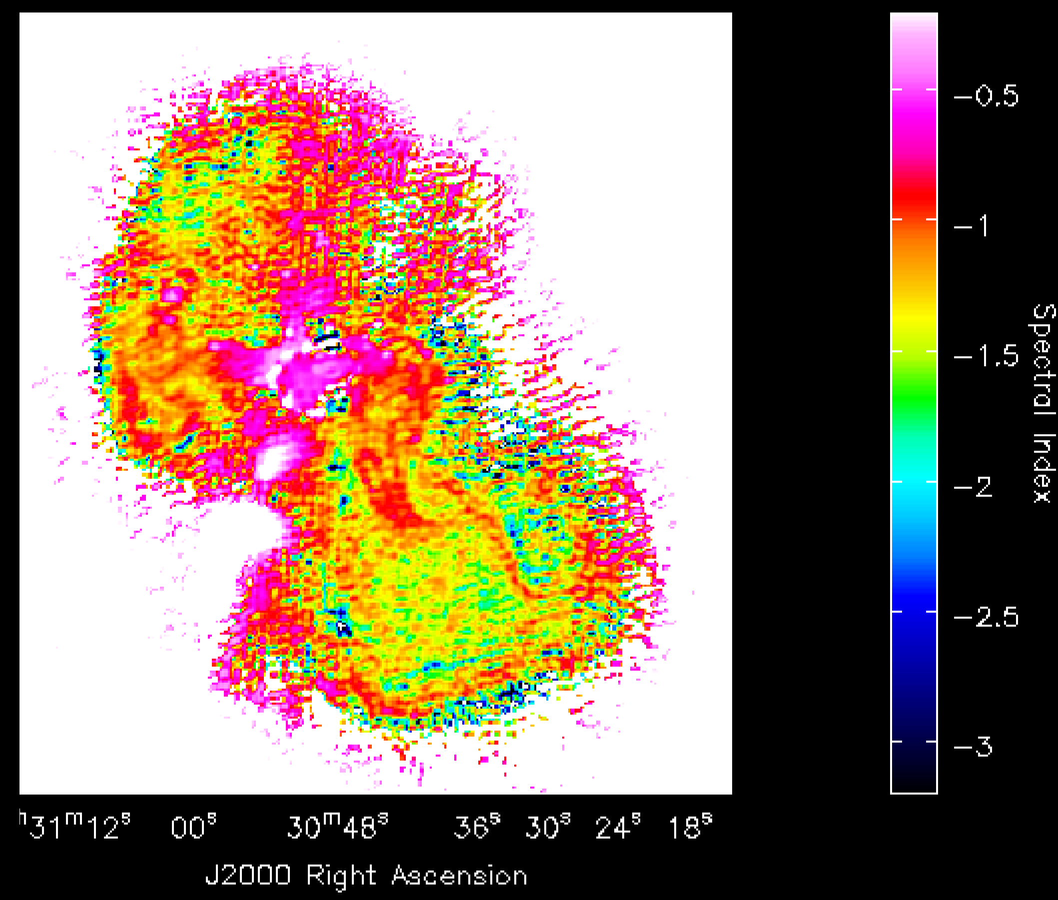


M87 data + images (so far...)

VLA C-array : cycle through 16 frequencies between 1.18 –1.86 GHz, 25MHz bands, RR,LL
~ 30 mins per frequency, spread across 10 hrs => 10 x 3min šnapshots'per frequency



Total Intensity Image



Spectral Index Map

M87 - Spectral Curvature

Points :
from Spectral Line Images

Lines : from MS-MFS

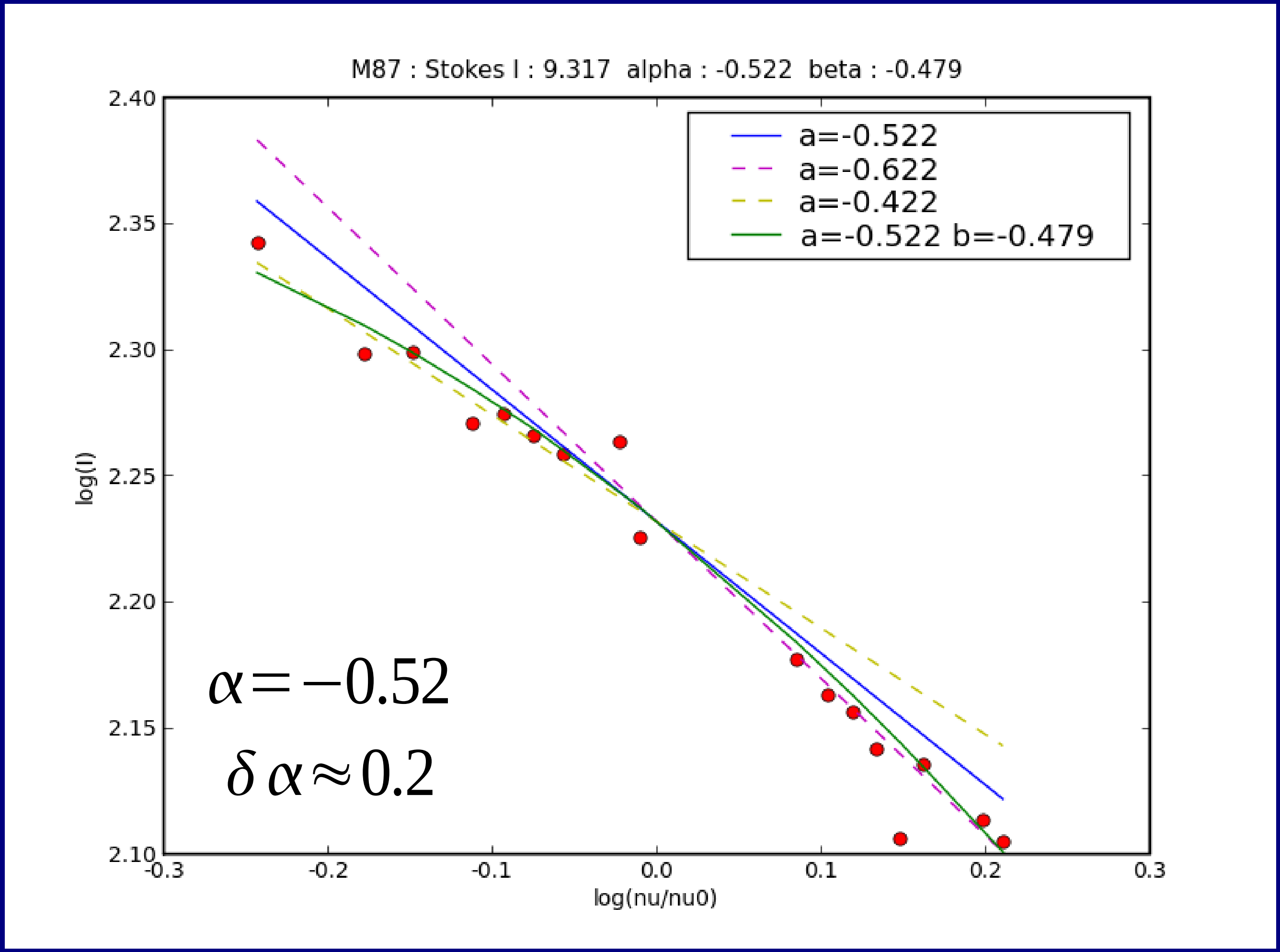
=> Need < 1% error in flux amplitude to fit this spectral curvature.

From a more general error analysis from fitting an exponential with a polynomial (1-2 GHz)

Need SNR > 6 to fit
spectral index ~ 1.0

Need SNR > 100 to fit
spectral index variation ~ 0.2

Spectrum of M87 core + inner jet region (1.18 GHz- 1.86 GHz)



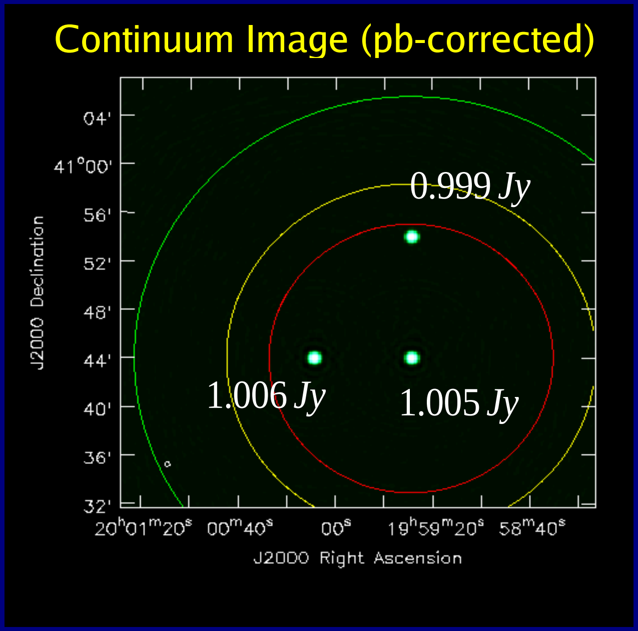
Frequency-Dependent Primary-Beam correction

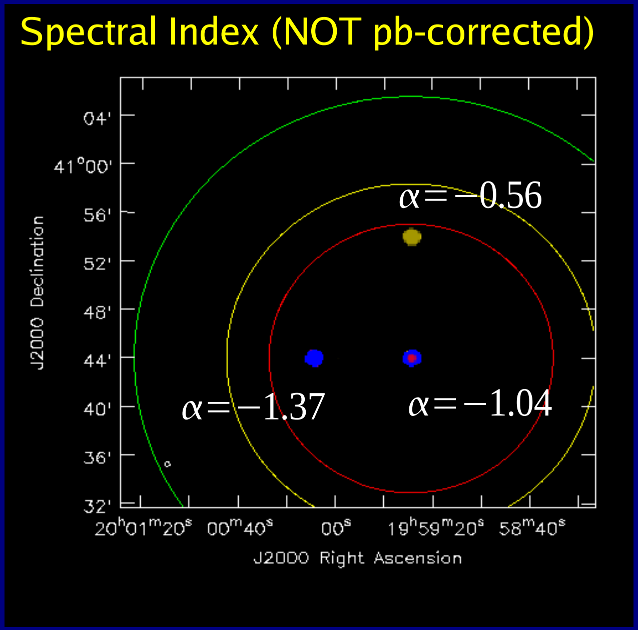
(U.Rau, T.J.Cornwell, 2008 (in prep))

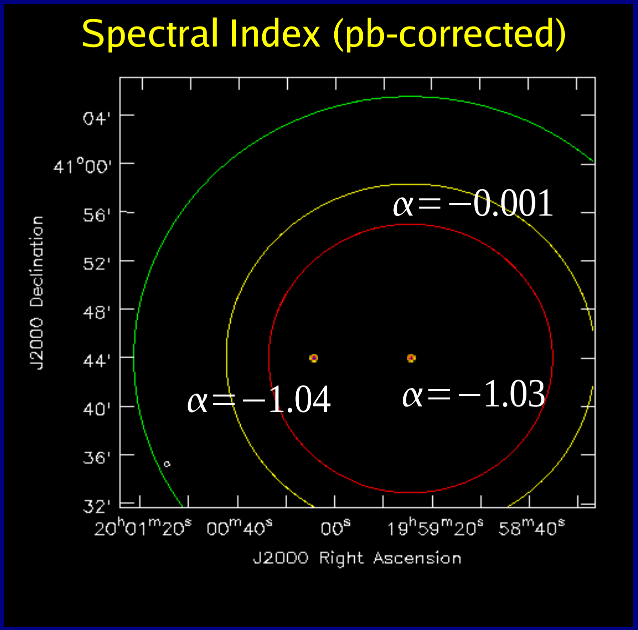
Preliminary results :

Correct the MS-MFS results by a model of the spectral variation of the primary beam.

Below : HPBW at 1.0 GHz (green) , 1.4 GHz (yellow) and 1.8 GHz (red)
3 point sources : 1 Jy each,
Bottom 2 sources have α = -1.0







Work in progress : using CASA / ASKAPSOFT

- Test if this method is adequate for time-varying primary beams and pointing offsets.
- Apply frequency-dependant direction-dependent corrections via gridding convolution functions.

Summary

Wide-Band receivers provide increased uv-coverage and sensitivity and measure spectra.

Hybrid :

- Requires adequate UV-coverage per channel
- Angular resolution of spectral index and curvature : lowest
- Easily parallelizable (Major and Minor cycles)

MS-MFS :

- Can handle sparse UV-coverage per channel *(e-MERLIN !)*
- Angular resolution of spectral index and curvature : highest
- Non-trivial to parallelize the Minor Cycle *(Major cycle parallelized in ASKAPSOFT)*

Spatial Structure :

- Fields of well-separated point-sources : Algorithms can get to 10^6 dynamic range
- Extended emission : Algorithms can get to $>10^5$ dynamic range (limited by multiscale algorithms)

Spectral Structure :

- Can correct for the frequency dependent primary beam *(limits yet to be understood)*
- Error Analysis for a power law spectrum with varying index : (for 2:1 bandwidth)
  Need SNR > 6 to fit spectral index ~ 1.0
  Need SNR > 50 to fit spectral index variation ~ 0.2