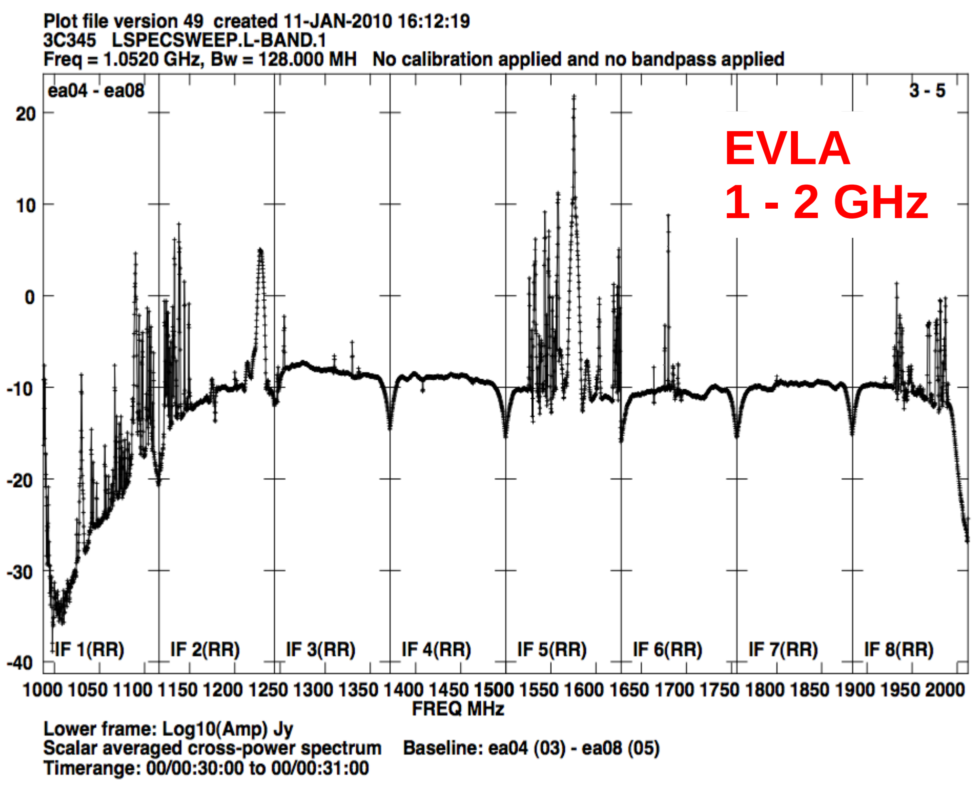
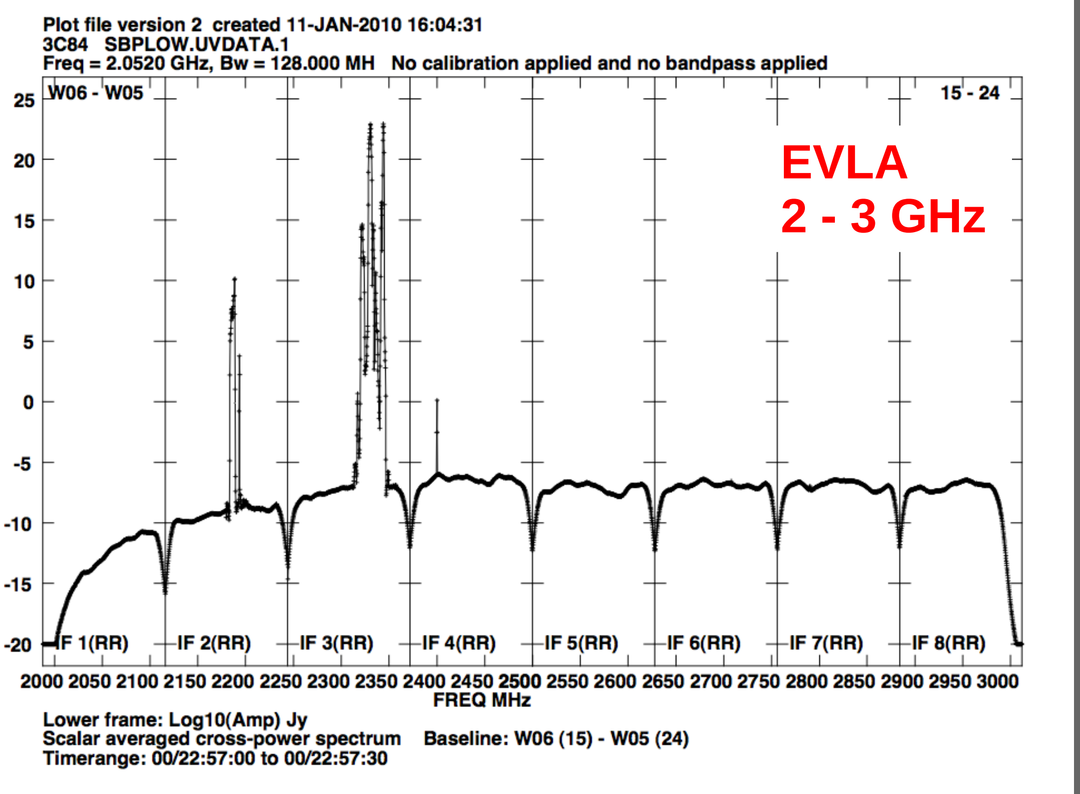
Feasibility of Wide-Band Imaging



EVLA
1 - 2 GHz



EVLA
2 - 3 GHz

Urvashi Rau
National Radio Astronomy Observatory

23 Aug 2010
5th SKA Calibration and Imaging workshop, ASTRON, Dwingelooo

Outline

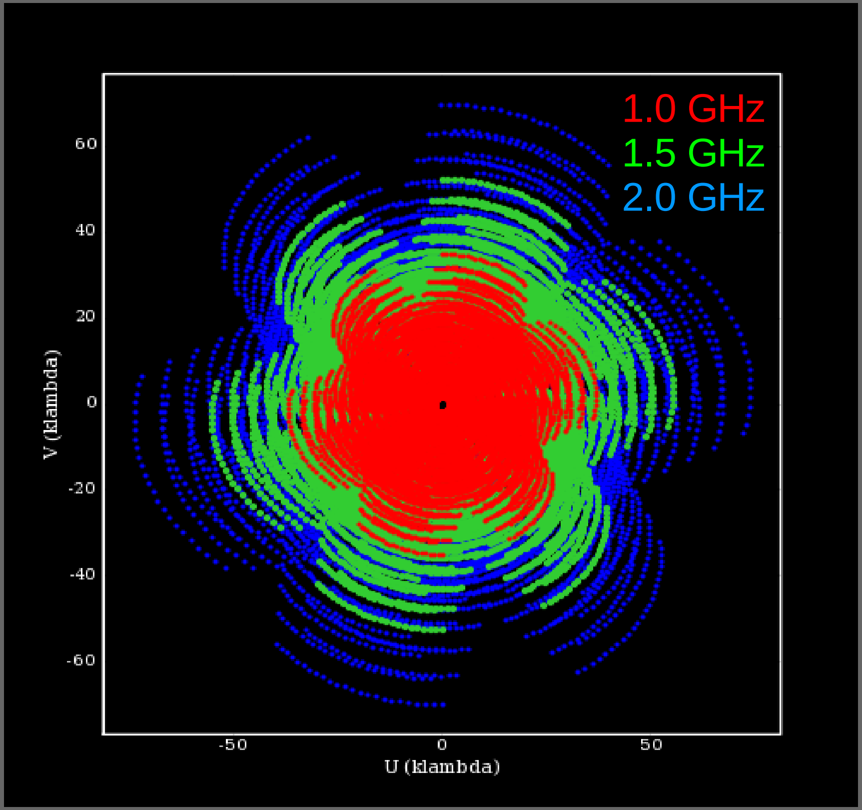
Wide-field wide-band imaging : Problem definition and algorithms

Proof of concept : Simulations and feasibility tests

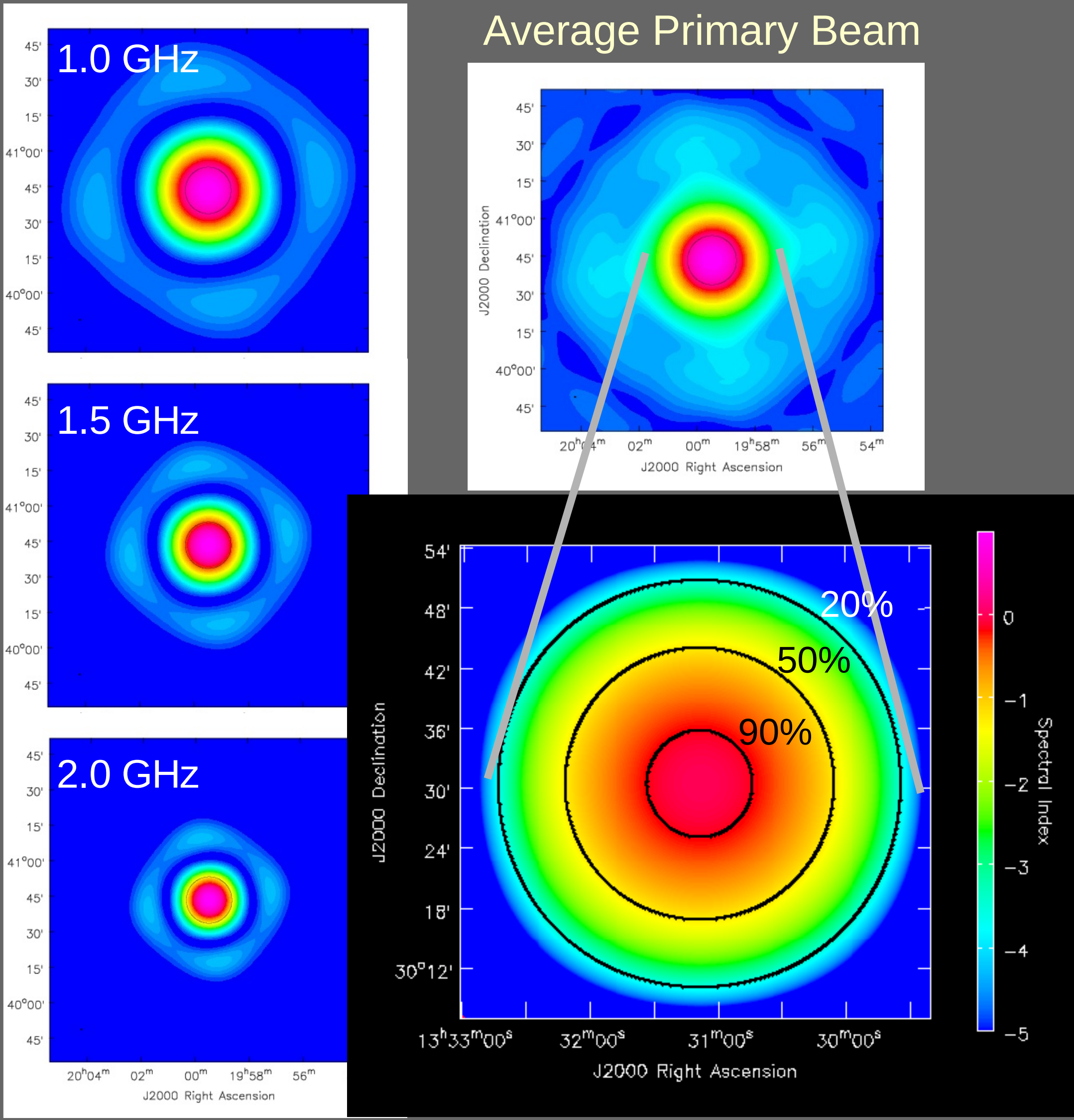
Results : Application to VLA and (initial) EVLA data

Multi-Frequency Synthesis (MFS)

VLA C configuration UV-coverage



Multi-Frequency Primary Beams



Average Primary Beam

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

Evolution of relevant algorithms

	CLEAN *(Hogbom,1974, Clark,1980, Schwab/Cotton,1983)*	Multi-Scale (MS) CLEAN *(Cornwell, 2008 Greisen et al, 2009)*	Multi-Frequency (MF) CLEAN *(Conway et al, 1990 Sault & Wieringa, 1994)*	Wide-Field A-Projection *(Bhatnagar, Cornwell, Golap, Uson, 2008)*	MS-MFS + A-Projection *(Rau, Cornwell, Bhatnagar 2010 - paper in prep.)*
Point source model	Yes	Yes	Yes	Yes	Yes
Multi-scale source model	~ No	Yes	~ No	Yes	Yes
Spectral flux model	No	No	~Yes	~ No	Yes
Primary-beam correction	No	No	No	Yes	Yes

Ph.D. Thesis : Parameterized deconvolution for wide-band radio synthesis imaging

http://www.aoc.nrao.edu/~rurvashi/HTMLfiles/Research.html

Imaging/deconvolution : solving the measurement equation

Standard Imaging : $V=[S][F]\underline{I^{sky}}$ where I^{sky} is a set of $\delta-functions$

Wide-field Imaging with primary-beam correction :

Image-domain correction

$$V=[S][F](P\cdot \underline{I^{sky}})$$

A-projection : visibility-domain

$$V=[S^G][F]\underline{I^{sky}}$$

Multi-Scale Deconvolution : $V=[S][F]I^{sky}$ where $I^{sky}=\sum_s [I_s^{shp} * \underline{I_s}]$

Multi-Frequency Deconvolution : $V_\nu=[S_\nu][F]I_\nu^{sky}$ where $I_\nu^{sky}=\sum_t \underline{I_t}\left(\frac{\nu-\nu_0}{\nu_0}\right)^t$

Minor Cycle : Solve the normal equations (Linear least-squares + Deconvolution)
Major Cycle : Imaging and model-prediction via AW-projection.

http://www.aoc.nrao.edu/~rurvashi/HTMLfiles/Research.html

Multi-scale multi-frequency synthesis + PB-correction

(Sky brightness).(Primary Beam) = Taylor polynomial with multi-scale coefficient images

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

↓

Solve for $I_{s,t}$ (linear least squares) and calculate Taylor coefficients I_t

↓

Remove the primary-beam from the Taylor coefficients (polynomial division) : I_t^{sky}

↓

Interpret the Taylor coefficients :
Power Law with varying index

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

$$I_0^{sky} = I_{\nu_0}^{sky}$$

$$I_1^{sky} = I_{\nu_0}^{sky} \alpha$$

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

Major Cycle :

Multi-Frequency
A-Projection

Outline

Wide-field wide-band imaging : Problem definition and algorithms

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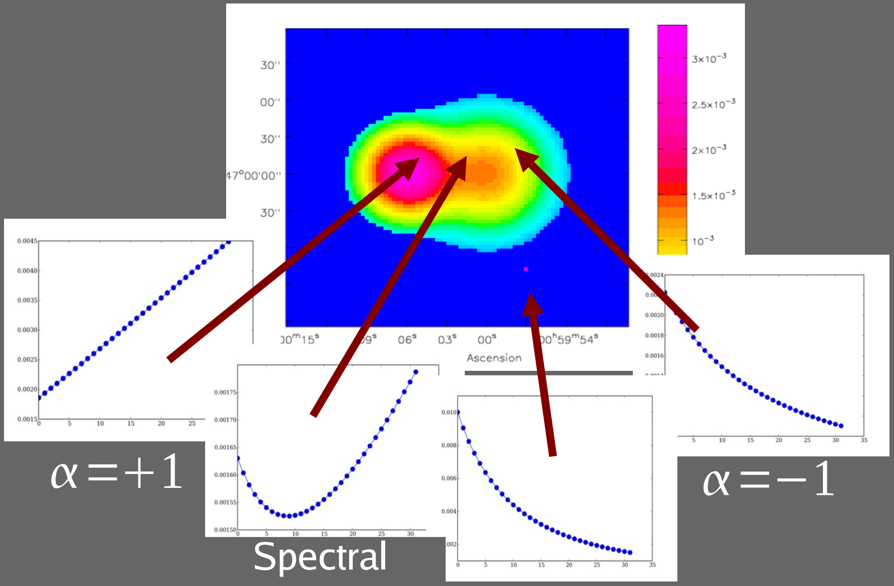
Intensity, Spectral Index, Spectral Curvature

EVLA C-config 1-2 GHz simulation

Intensity Image



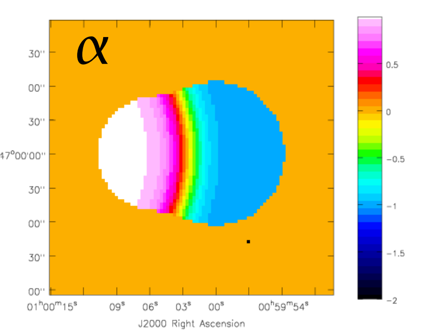
$\alpha = +1$

Spectral Turn-over

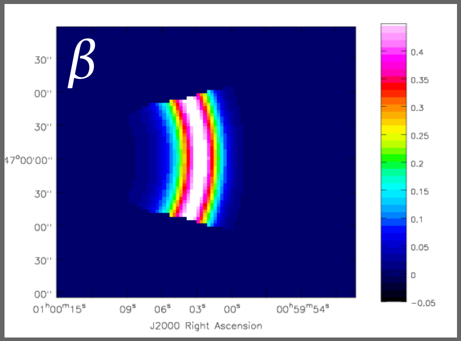
$\alpha = -2$

$\alpha = -1$

Average Spectral Index



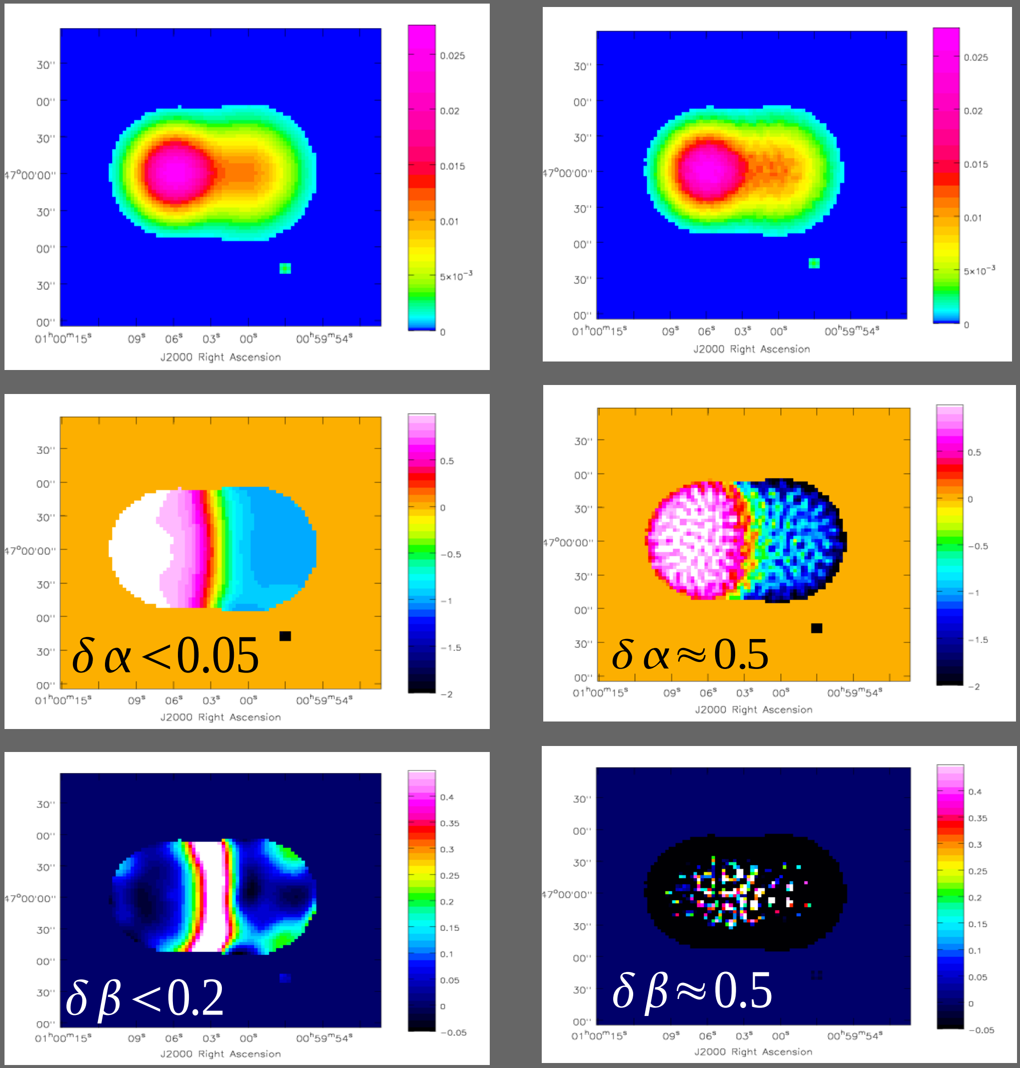
Gradient in Spectral Index



MFS

multi-scale

point-source



$\delta\alpha < 0.05$

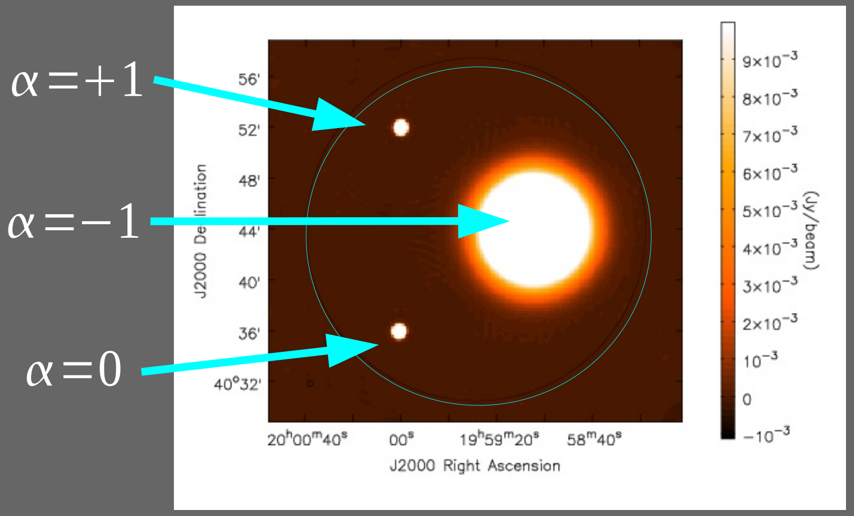
$\delta\alpha \approx 0.5$

$\delta\beta < 0.2$

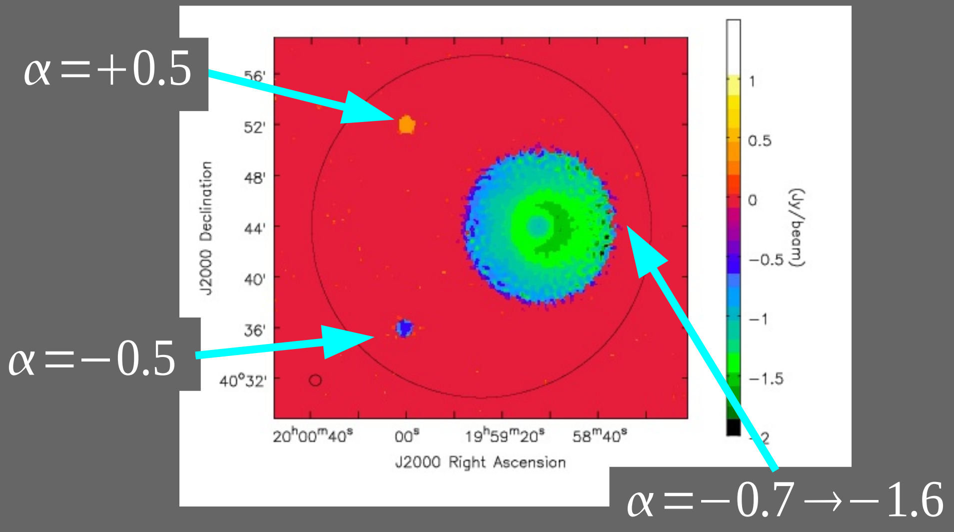
$\delta\beta \approx 0.5$

Wide-band Primary-Beam correction

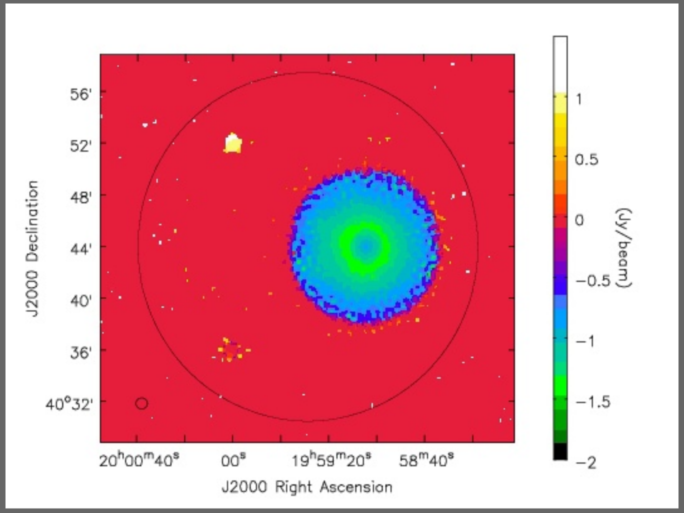
Deconvolved Stokes I image at Ref-Freq.



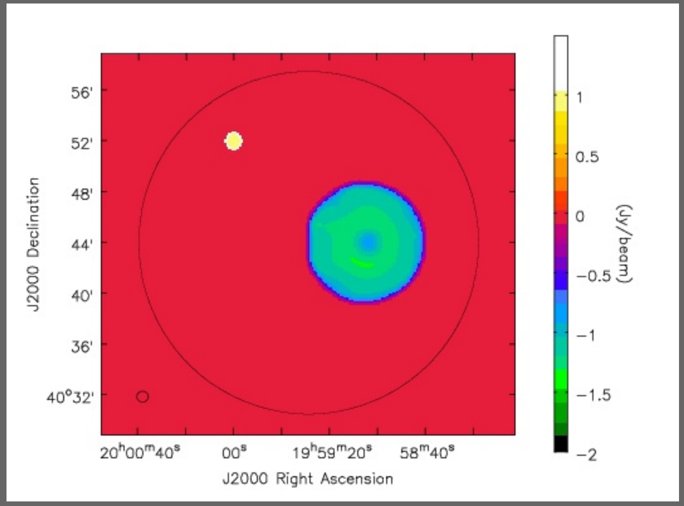
Spectral Index –NO PB-correction



Spectral Index WITH primary beam correction



(1) Post-deconvolution correction



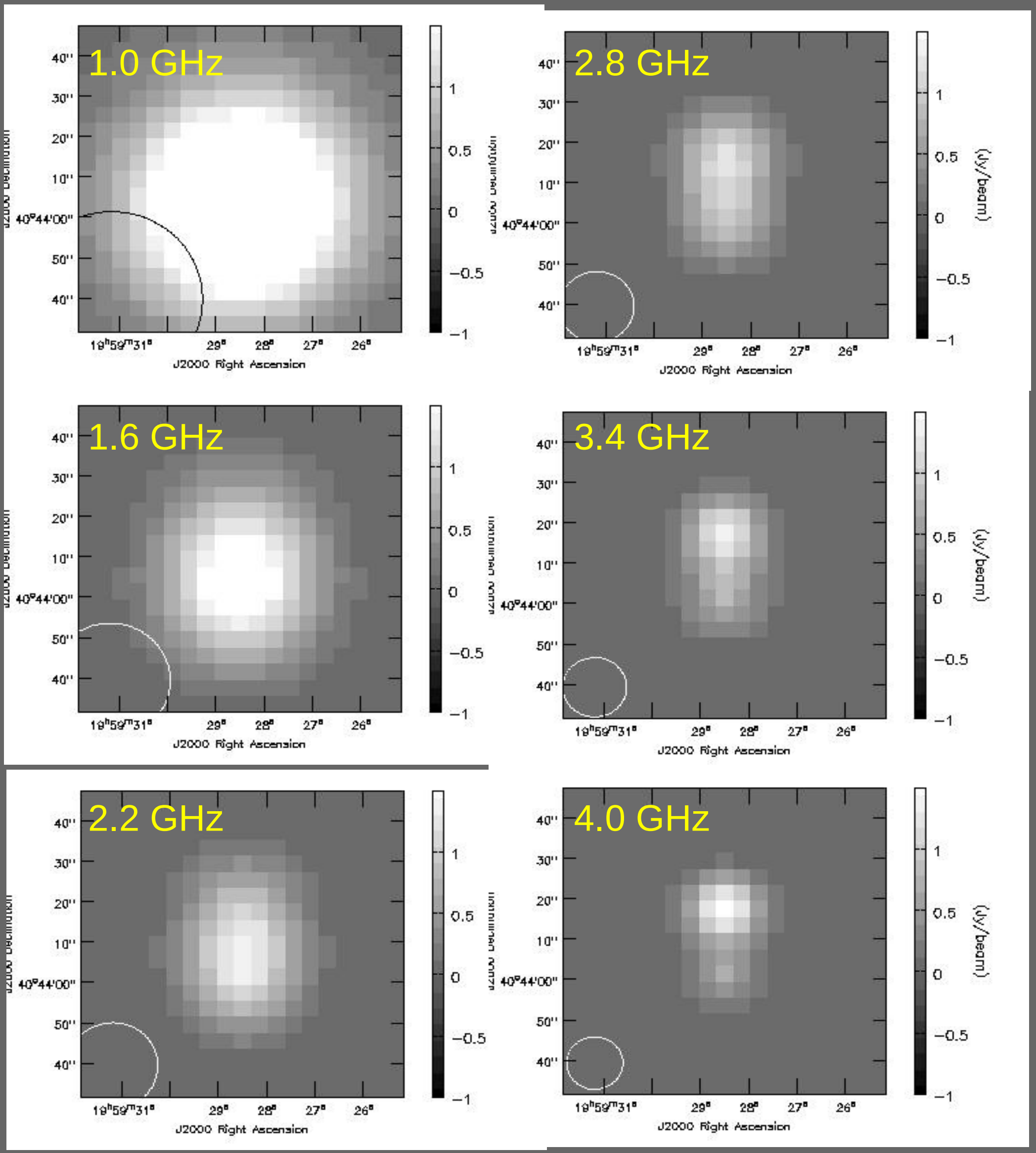
(2) MS-MFS with A-projection

“ remove an average primary beam
and the average frequency dependence “

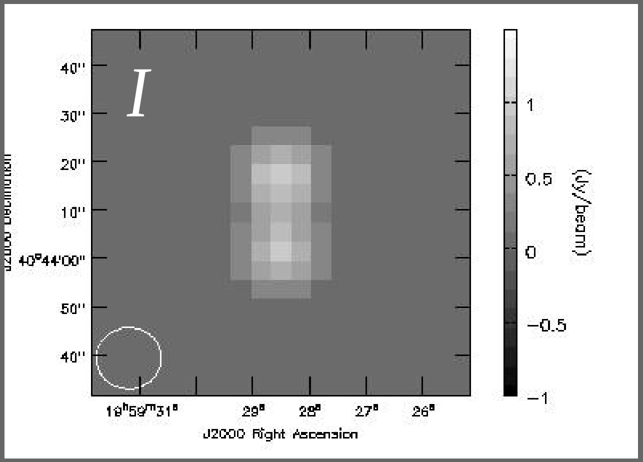
“ remove a time-varying primary
beam and its frequency dependence “

Moderately Resolved Sources

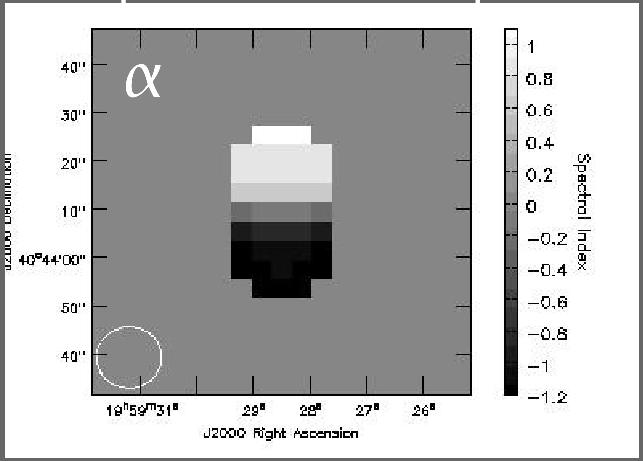
Can reconstruct the spectrum at the angular resolution of the highest frequency



Restored Intensity image



Spectral Index map

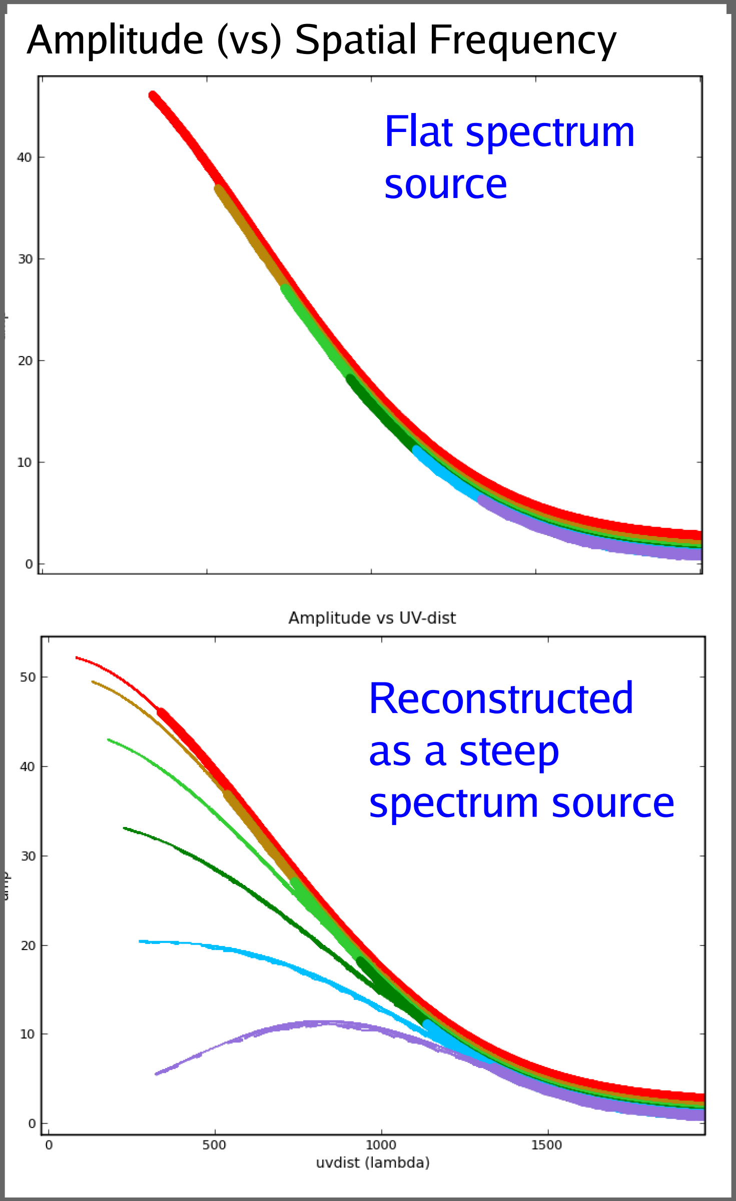


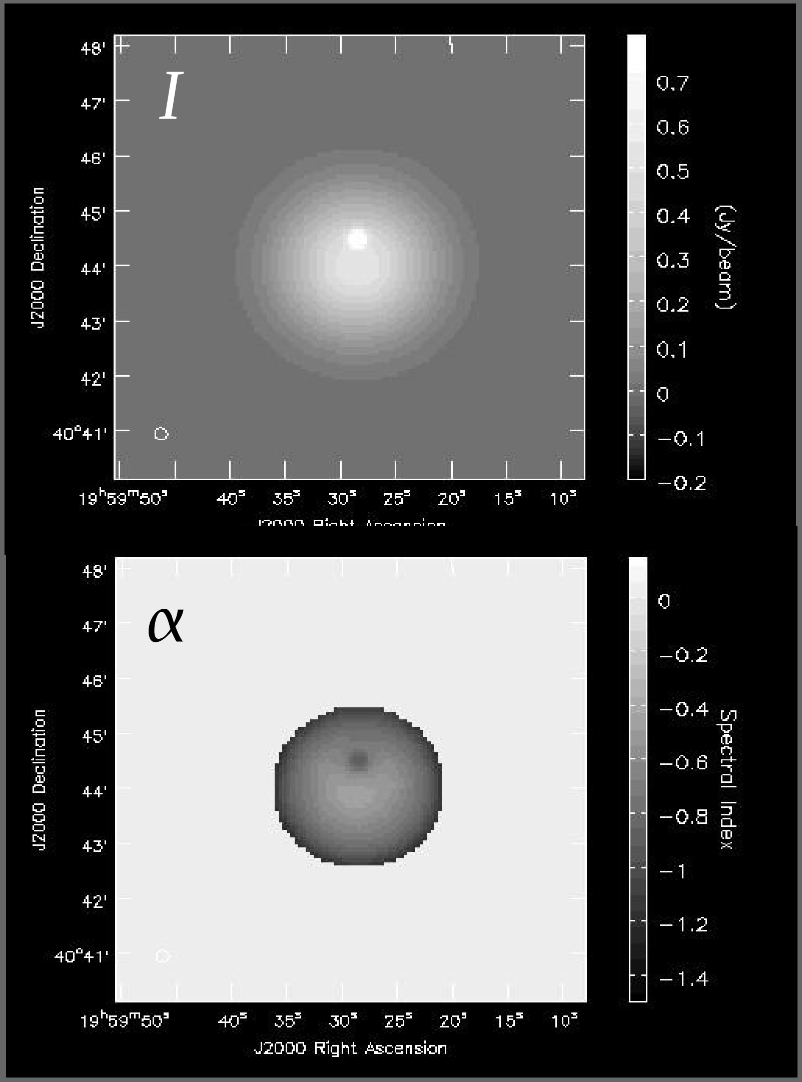
Very large spatial scales – without short-spacing data

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

Data

Data
+
Model



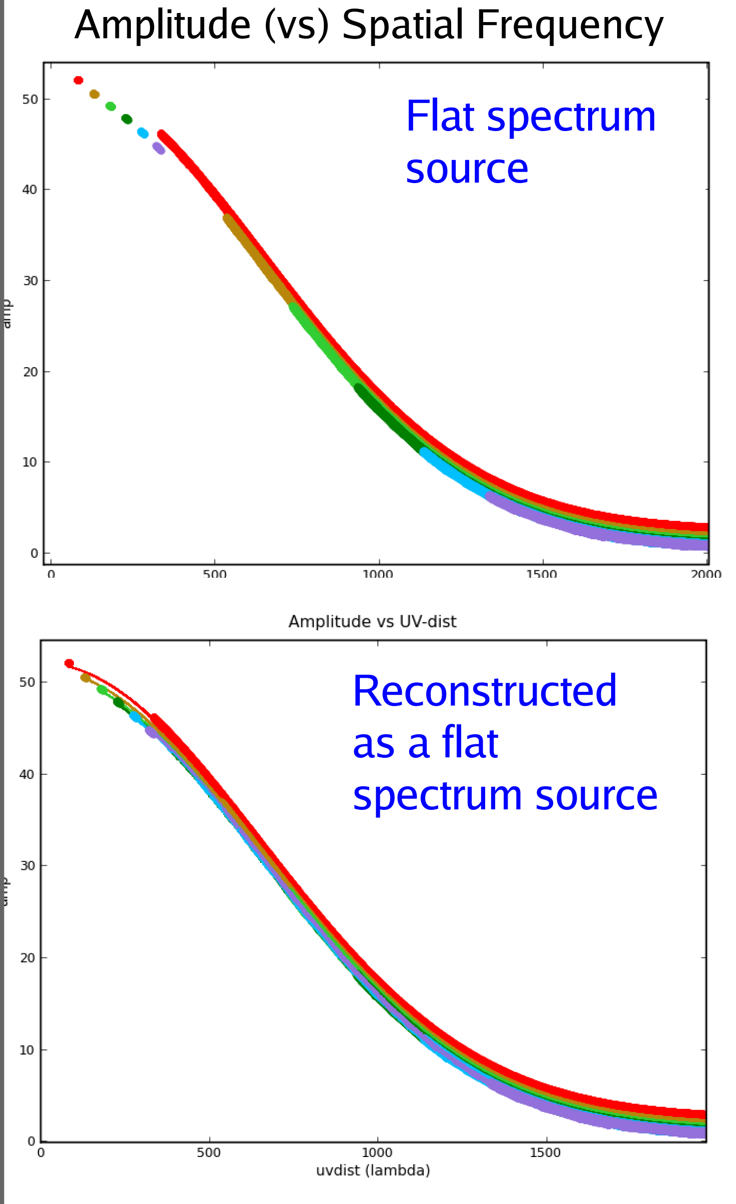


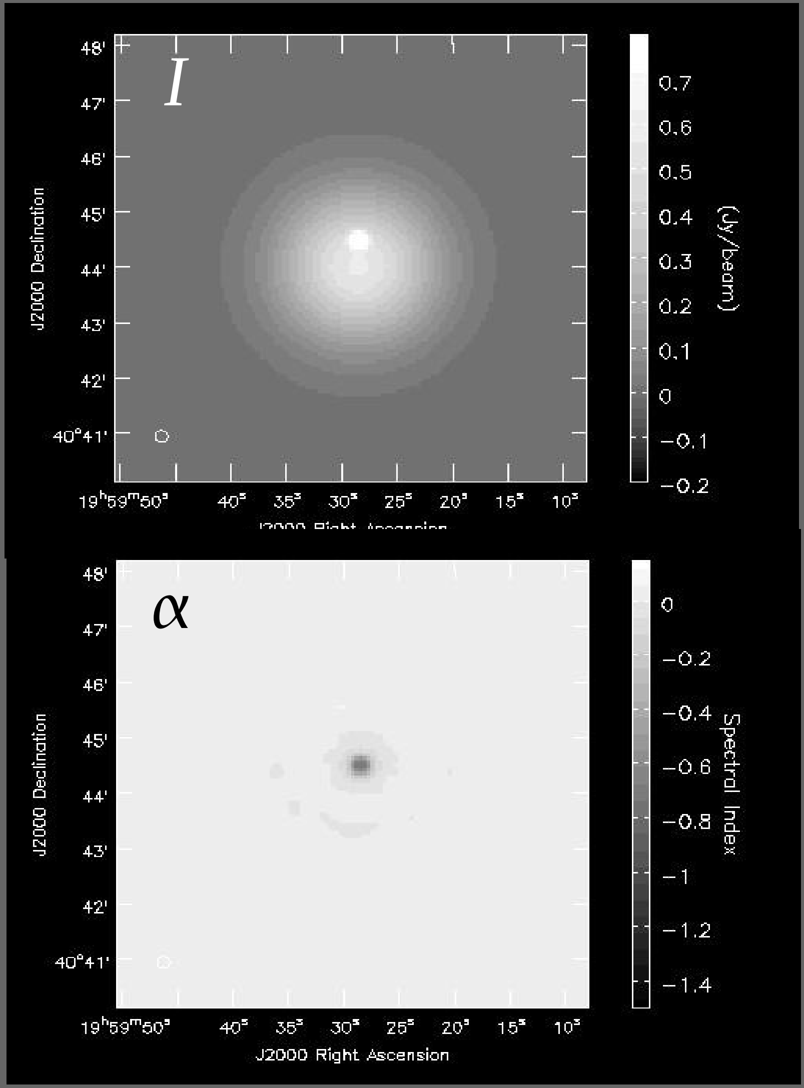
Very large spatial scales – with short-spacing data

Extra short-spacing information can help constrain the spectrum

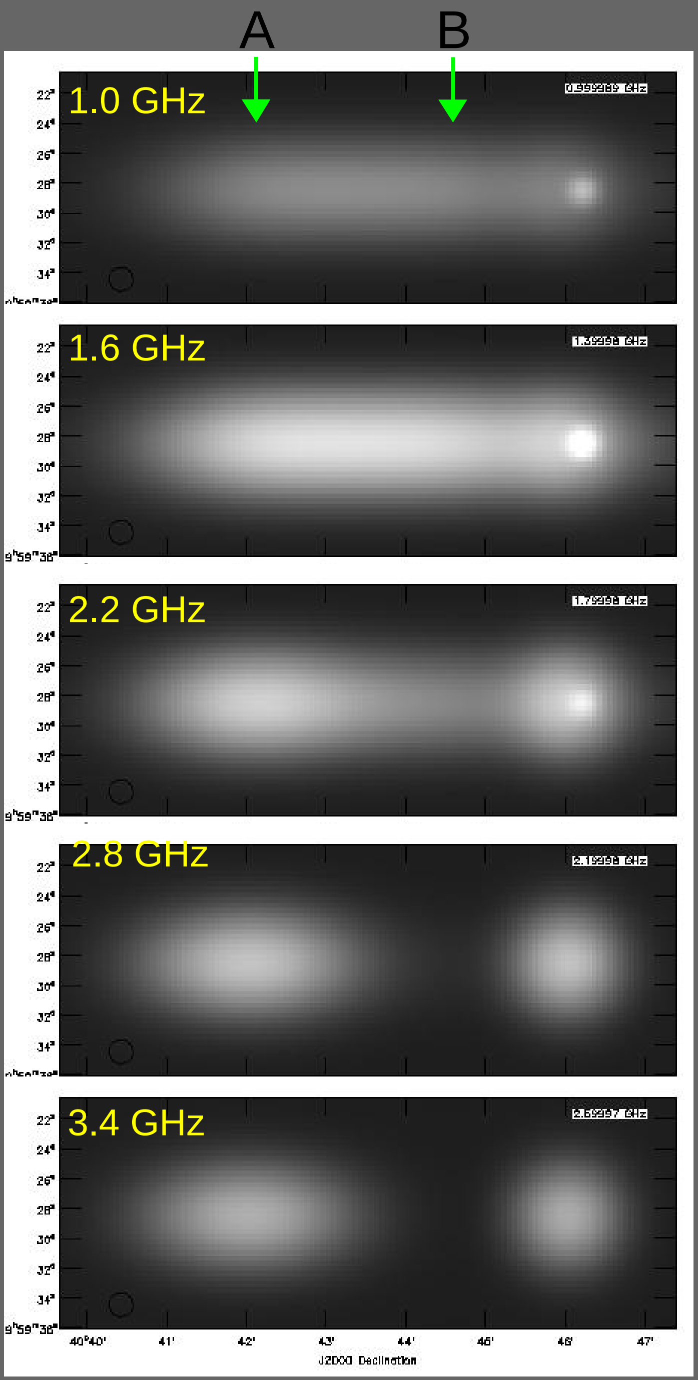
Data

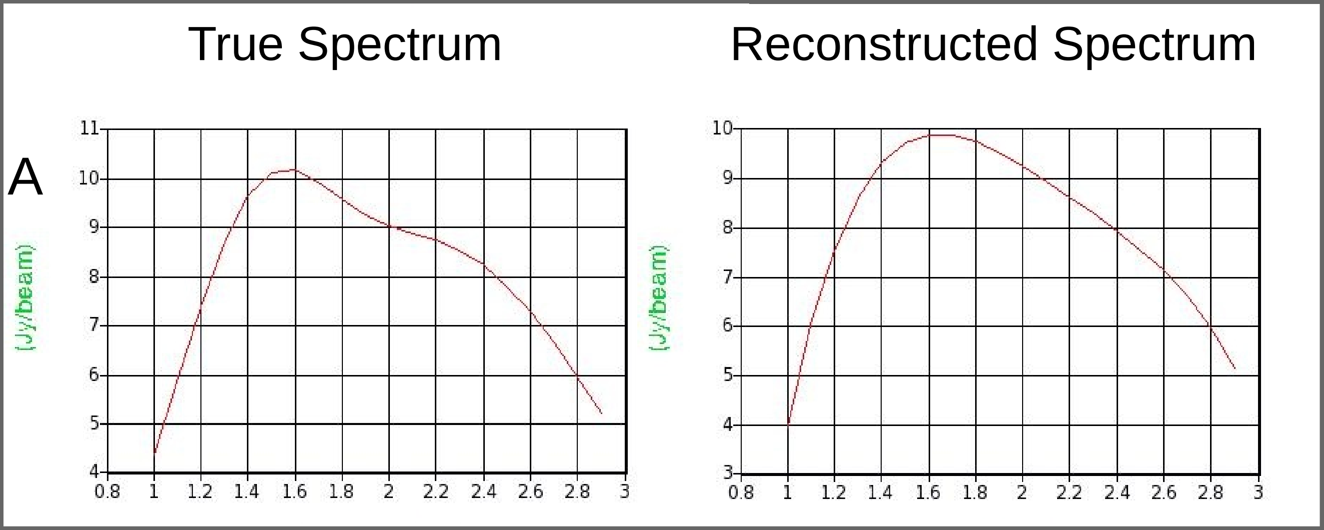
Data
+
Model

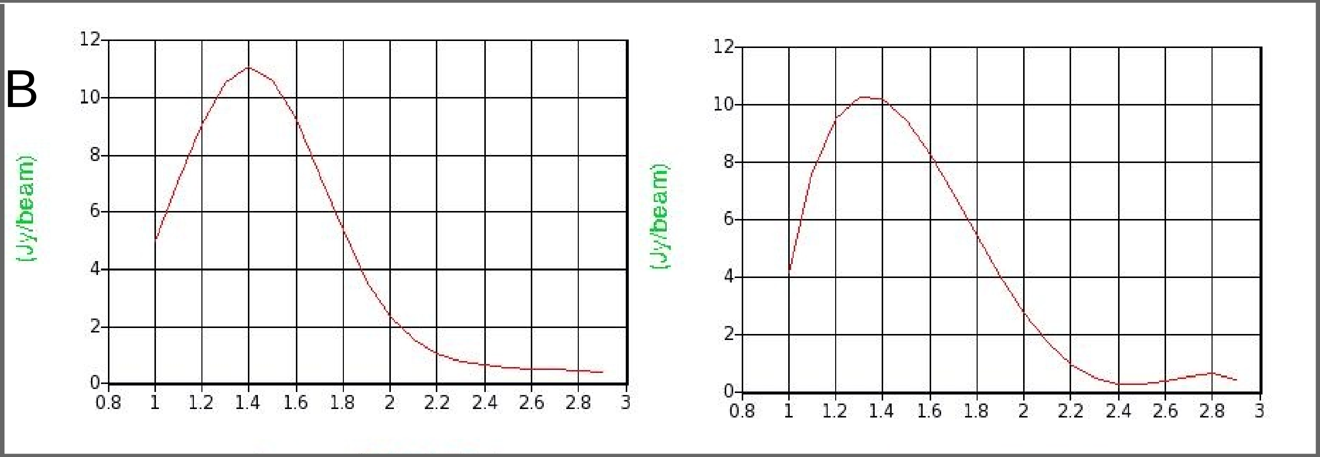




Non power-law spectra and band-limited signals







Angular resolution depends on the highest sampled frequency at which the emission exists.

Outline

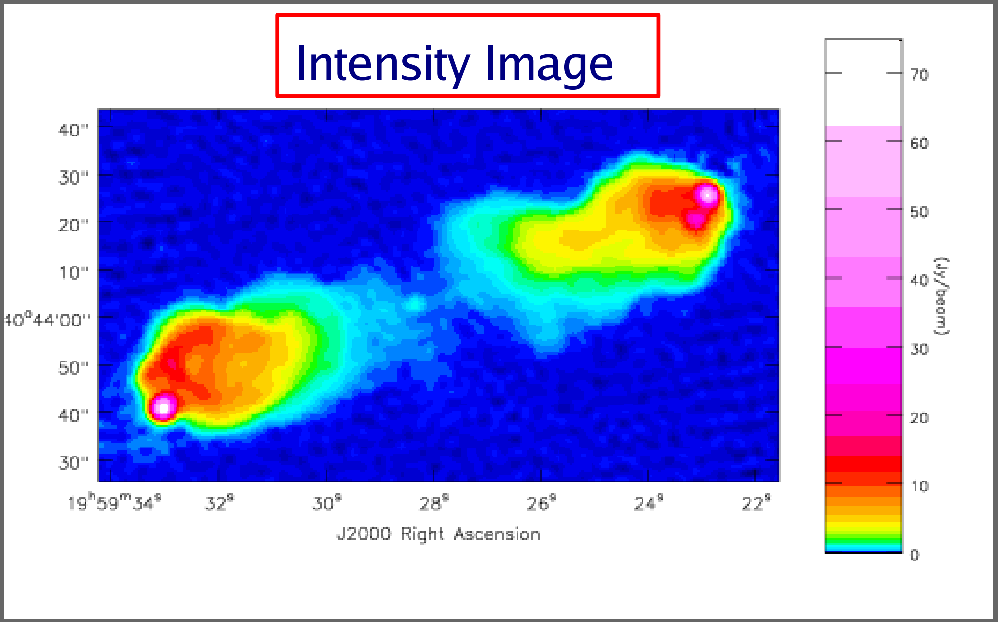
Wide-field wide-band imaging : Problem definition and algorithms

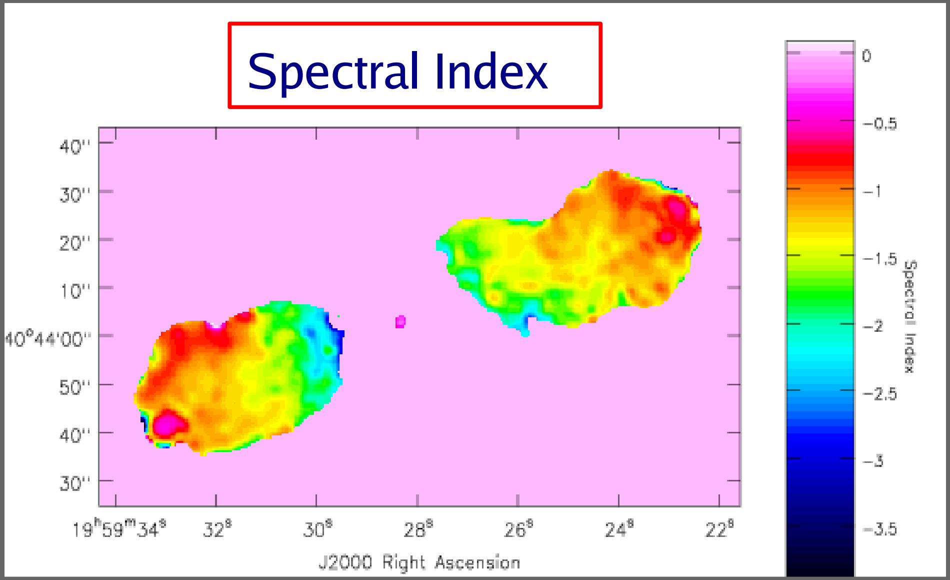
Proof of concept : Simulations and feasibility tests

Results : Application to VLA and (initial) EVLA data

VLA : Cygnus A (Stokes I, Spectral Index)

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

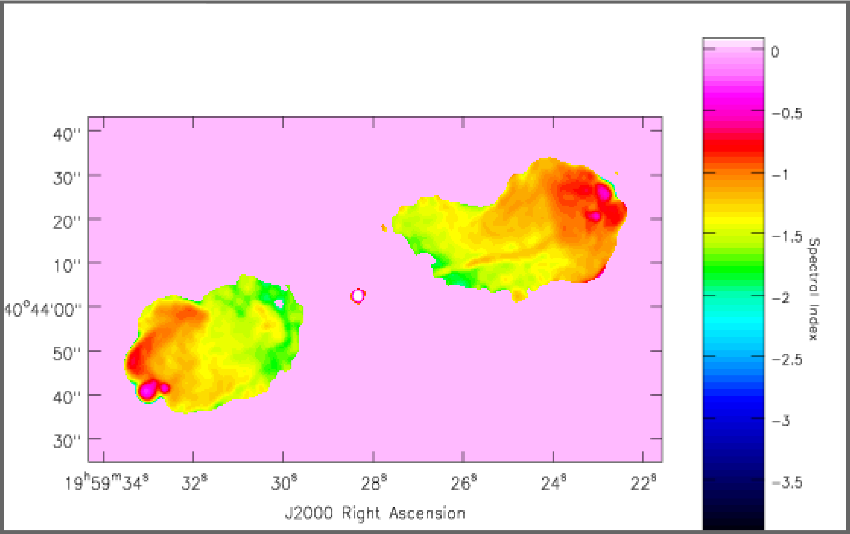




- Has detail and fidelity of Multi-Scale deconvolution
- Error on estimated spectral index <= 0.2

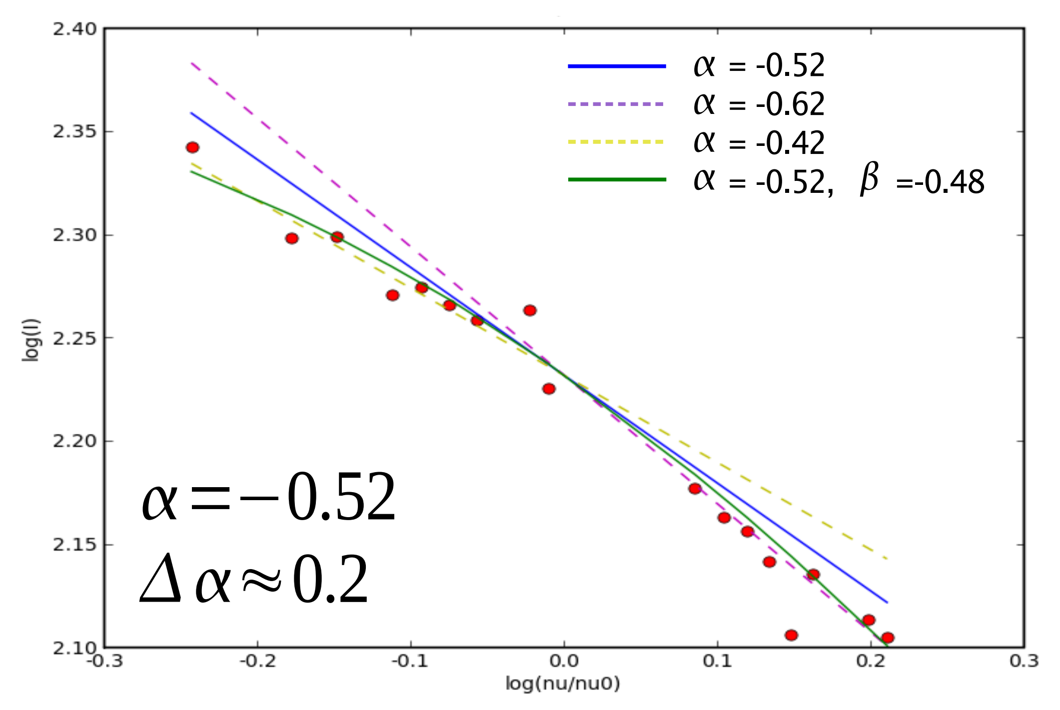
For comparison :

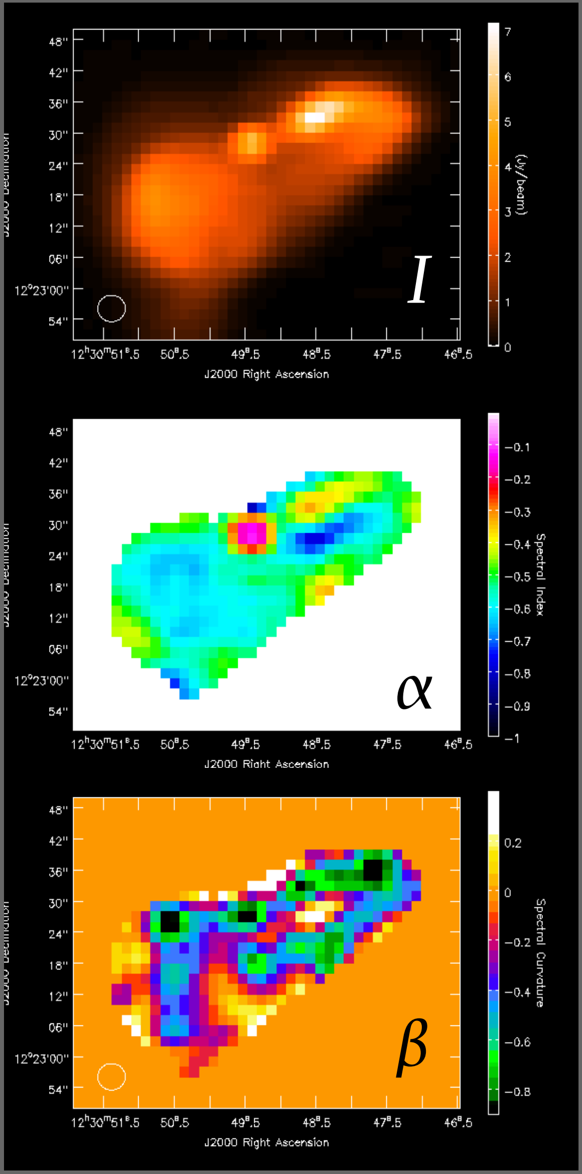
Sp.Ndx. map constructed from 1.4GHz and 4.8GHz, Images obtained from C.Carilli et al, Ap.J. 1991. (VLA A,B,C,D configs at L and C band)



VLA : M87 1.1-1.8 GHz spectral curvature

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





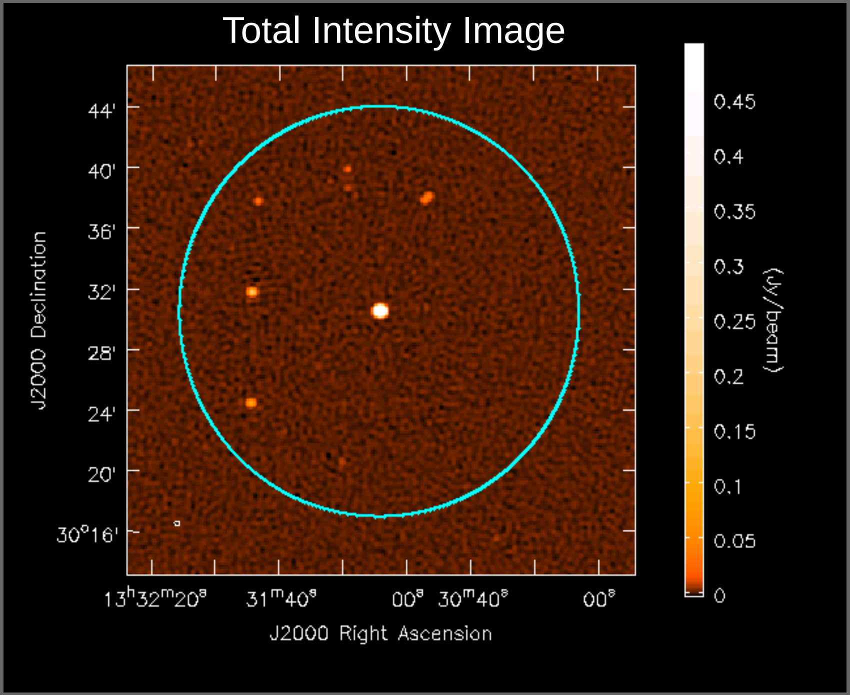
From existing P-band (327 MHz), L-band(1.42 GHz) and C-band (5.0 GHz) images of the core/jet

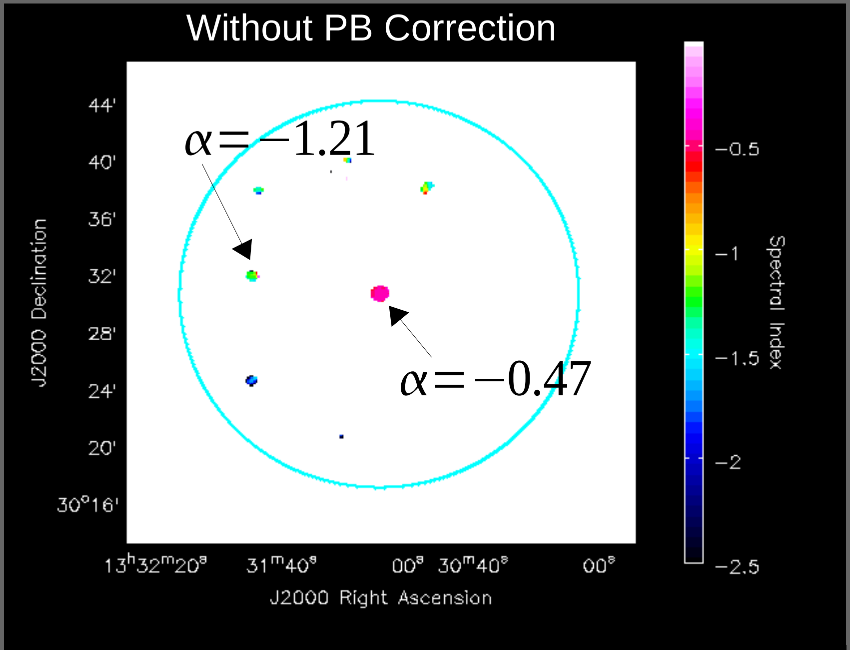
P-L spectral index : -0.36 ~ -0.45

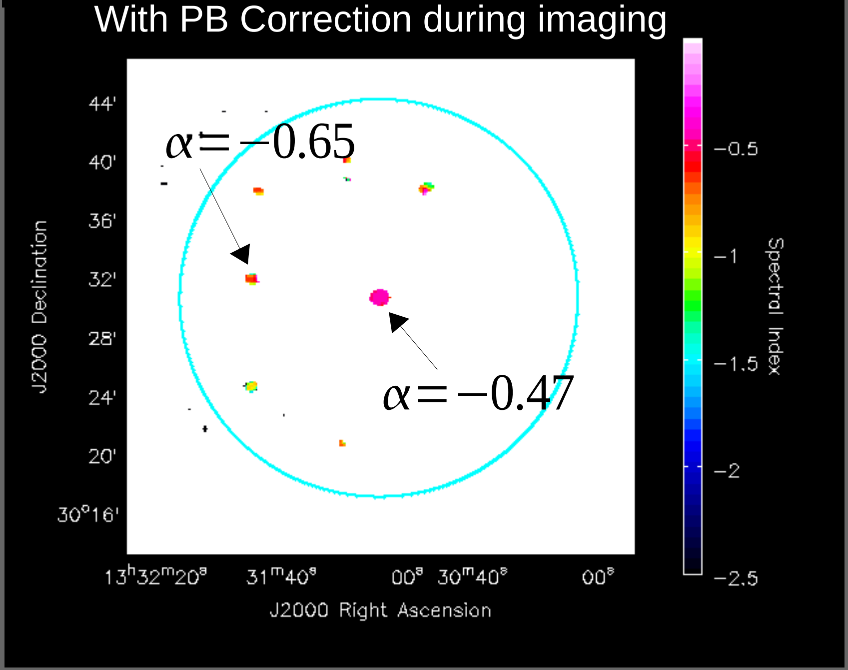
L-C spectral index : -0.5 ~ -0.7

Need SNR > 100 to fit spectral index variation ~ 0.2

VLA : 3C286 field with freq/time-varying PB correction


Total Intensity Image


Without PB Correction


With PB Correction during imaging

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

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

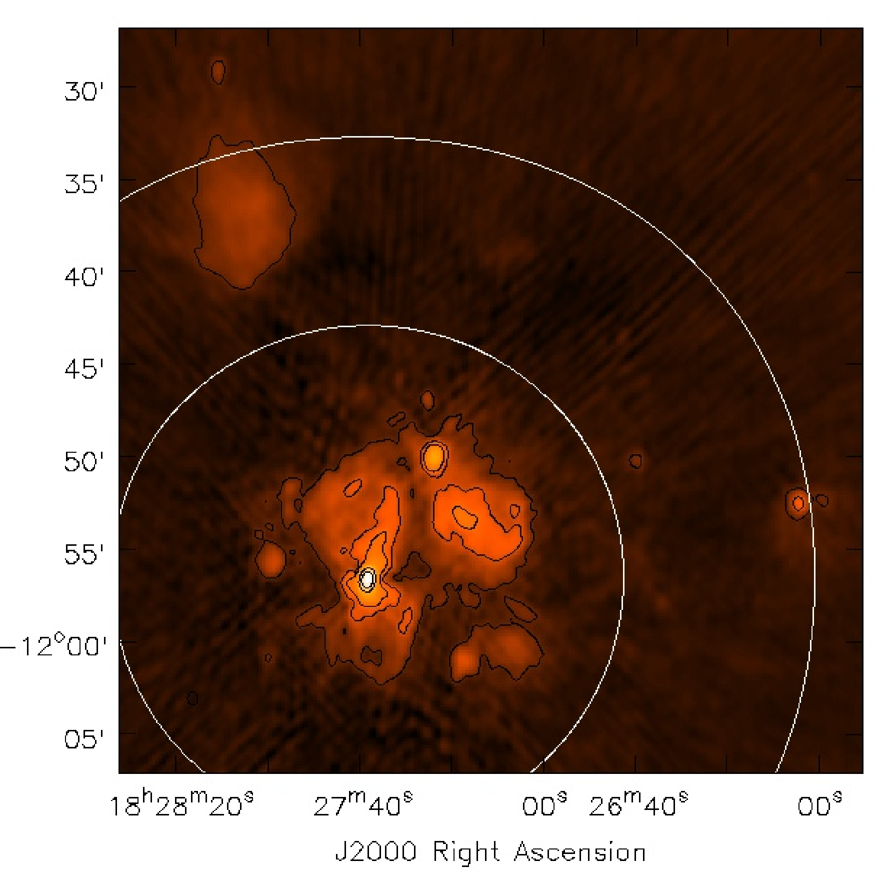
Obtained $\delta \alpha$ = 0.05 to 0.1 for SNR or 1000 to 20

Also verified via holography observations at two frequencies

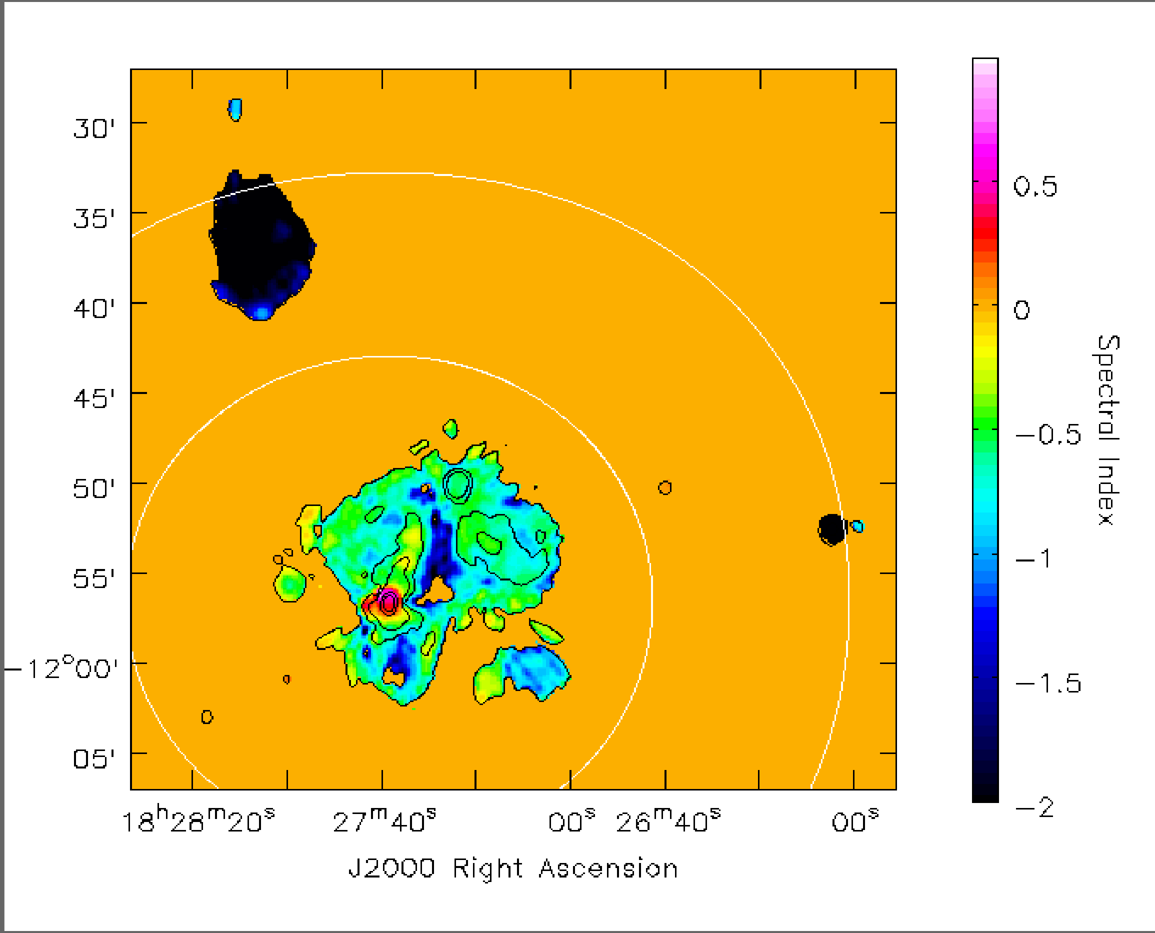
EVLA : G19.6-0.2 Supernova field - no PB correction

EVLA D-config data (128 MHz bands at 1368, 1472, and 1784 MHz)

Continuum Intensity



Spectral Index

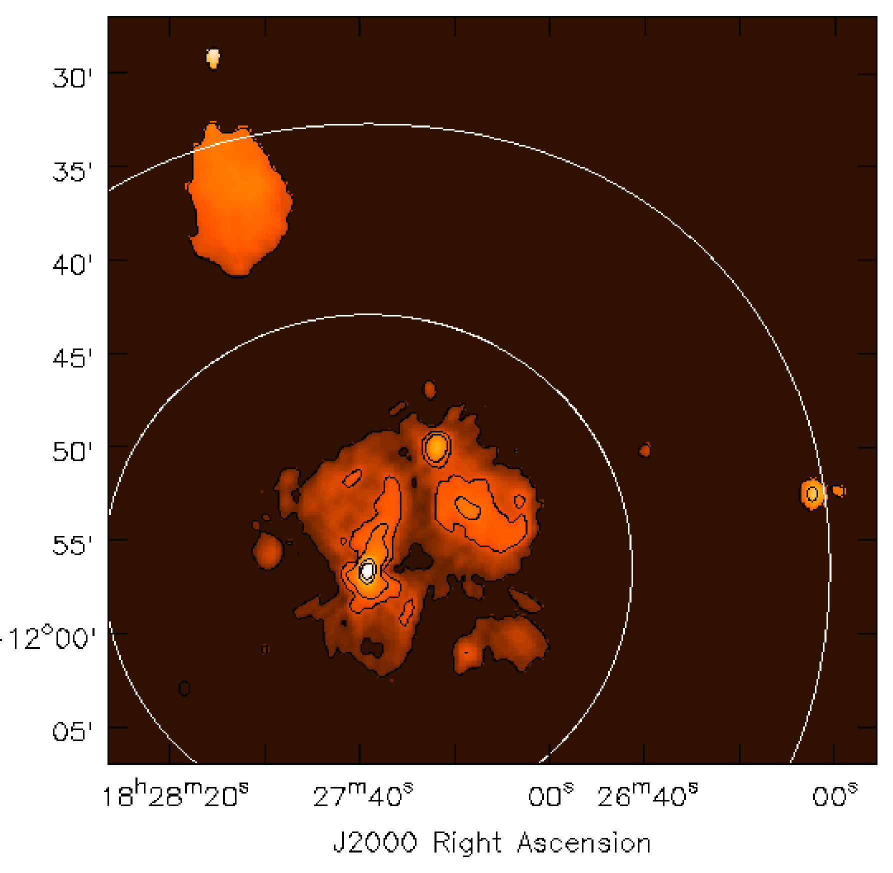


Data : Taken as part of RSRO project AB1345, calibrated and flagged by D.Green
Imaging : CASAPY

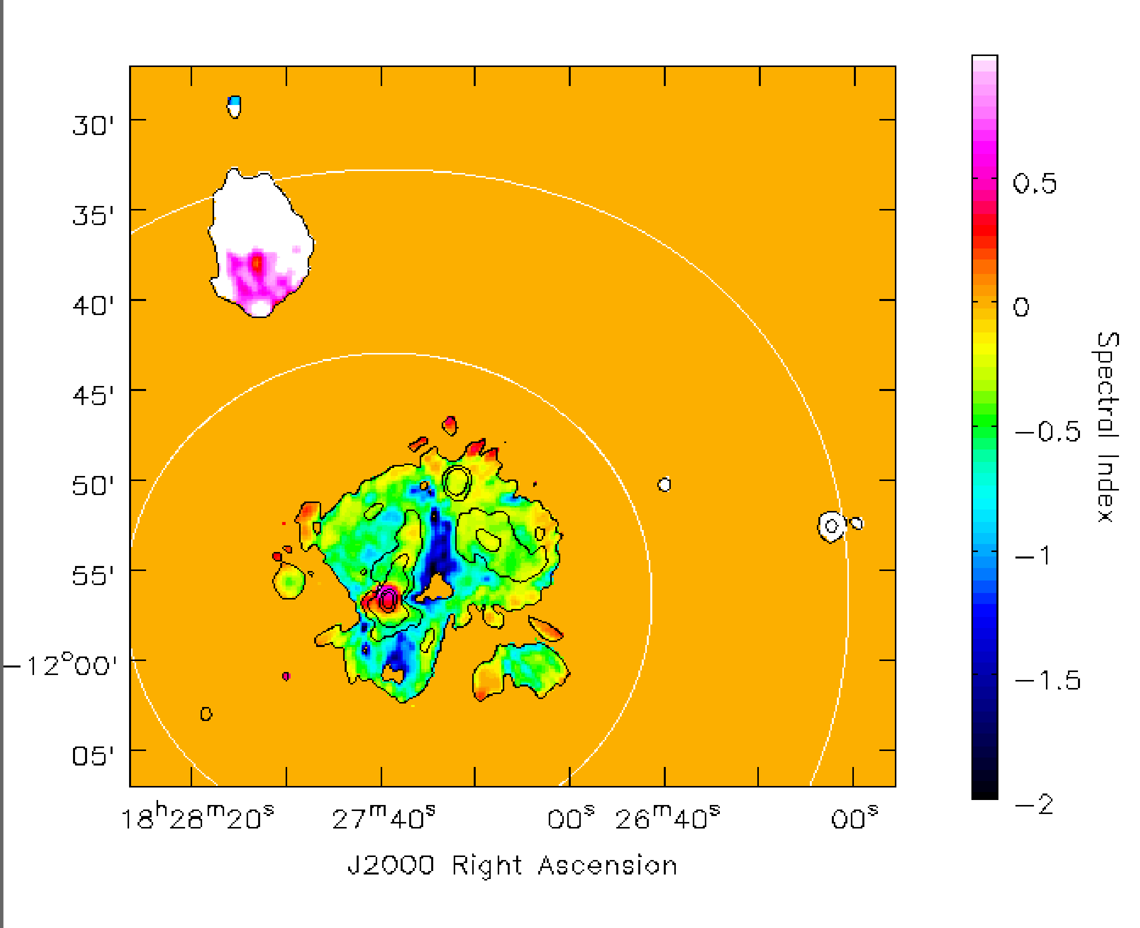
EVLA : G19.6-0.2 Supernova field – image-domain PB correction

EVLA D-config data (128 MHz bands at 1368, 1472, and 1784 MHz)

Continuum Intensity



Spectral Index



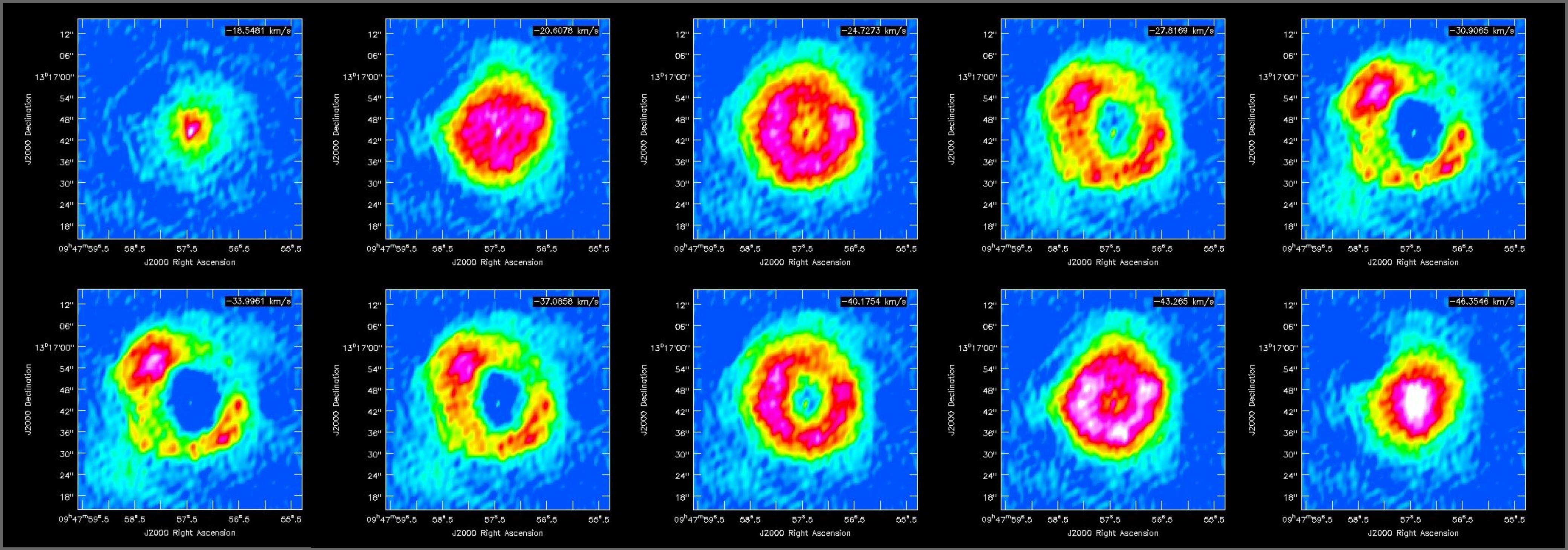
.... next step : run MS-MFS with A-projection

EVLA : IRC10216 – a resolved spectral line (narrow-band data)

H3CN line (36 GHz) traces a 3D expanding shell around a star.

Spectral-line width ~ 3.5 MHz, channel width ~ 100 kHz (35 channels)

MS-MFS with a 5th order polynomial to model the spectrum



CASAPY + calibration scripts compiled by C.Brogan for the NRAO synthesis imaging summer school
(http://casaguides.nrao.edu   EVLA Tutorials)

MS-MFS : as implemented in CASA

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

User Parameters :
- Set of spatial scales (in units of pixels)
- Order of Taylor polynomial
- Reference frequency
- With or without primary-beam correction

Image Reconstruction : Linear least squares + Deconvolution + AW-Projection

Data Products : Taylor-Coefficient images

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

Software : CASA and ASKAPSOFT (via CASAcore libraries)
(MS-MFS without wide-field corrections : released in CASAPY v2.4)
http://casa.nrao.edu

Three sources of error

- Artifacts in the continuum image due to too few terms in the Taylor-series expansion of the spectrum.

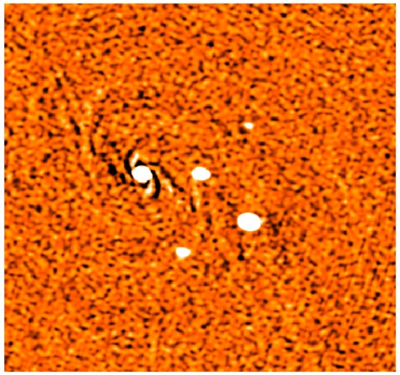
High signal-to-noise : use a higher-order polynomial.

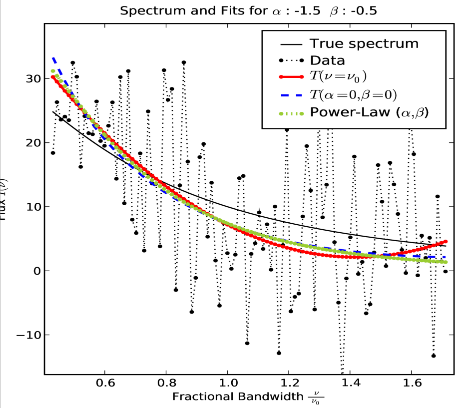
- Error in spectral index and curvature due to low signal-to-noise or unconstrained spectra

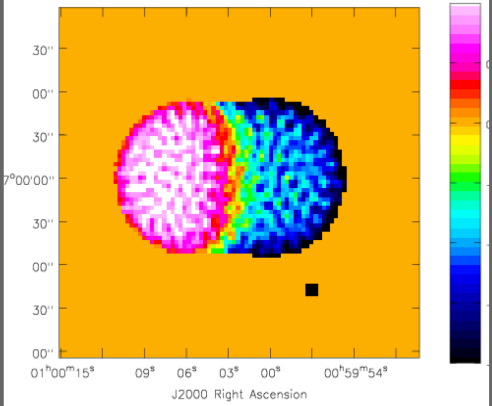
Low signal-to-noise : use a linear approximation.

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

Extended emission : use multiple spatial scales







Conclusion

Summary :

- Can make multi-scale images of continuum intensity, spectral index and curvature (images of coefficients of an Nth-order Taylor-polynomial)

- Can correct for time-varying primary-beam spectrum upto 40% at ref-frequency

(this limit will influence mosaicing)

To do :

✔Test MS-MFS with real wide-band EVLA data ! (continuum sensitivity, processing)

- MS-MFS with primary-beam correction, W-projection and mosaicing, together.
- Wide-band full-polarization imaging (and then wide-field).
- A wide-band extension of the ASP-Clean multi-scale deconvolution algorithm.
- MFS in the presence of spectral lines (and/or RFI).

=> A lot to do before wide-band imaging becomes feasible for the SKA !

Computational Performance and Parallelization (as of 2008)

	Single-Channel Imaging	MS-MFS
Number of deconvolution runs	N_{chan}	1
Data I/O per Major Cycle	N_{vis} / N_{chan}	N_{vis}
Memory Use per deconvolution run (multi-scale)	Image Size x $N_{scales}{}^2$	Image Size x $(N_{taylor} \times N_{scales})^2$
Runtime (for few GB of EVLA data on CygA, M87 and ~2000 iterations)	~ 30 hrs parallelized : ~ 7 hrs (4 nodes) (theoretical)	~ 12 hrs parallelized : ~ 4 hrs (4 nodes) (measured in ASKAPsoft)

Trade-Off between source complexity, available uv-coverage, desired angular resolution of spectral index map, and algorithm simplicity/stability.

Work In Progress : Parallel version of MS-MFS in CASA

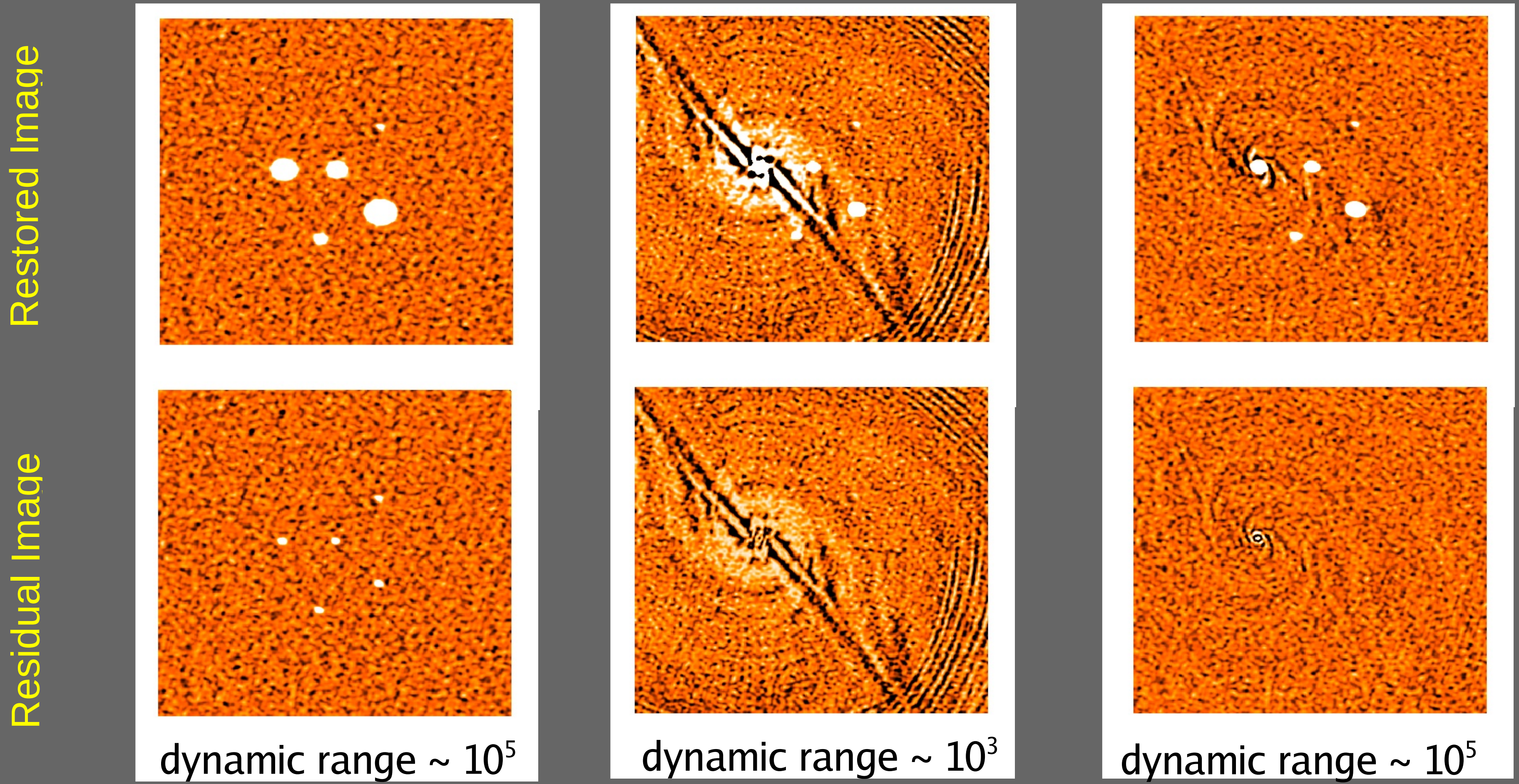
Comparison of existing/older methods

EVLA Memo 101, Rau & Cornwell, 2006

Single-channel CLEAN

CLEAN with MFS

Multi-Frequency
MF-CLEAN (Miriad)



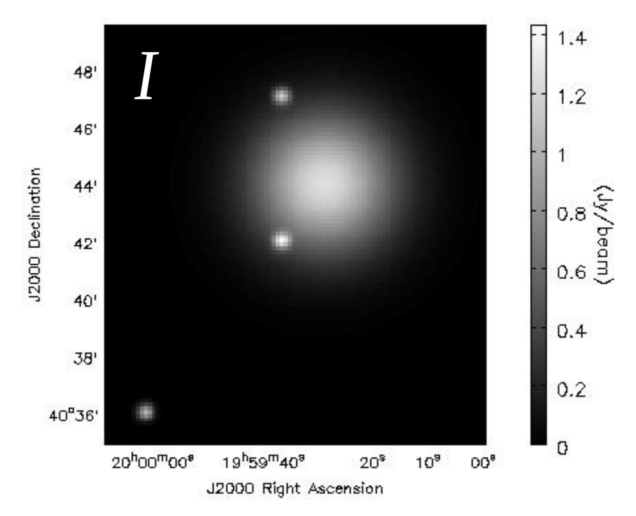
dynamic range ~ 10^5

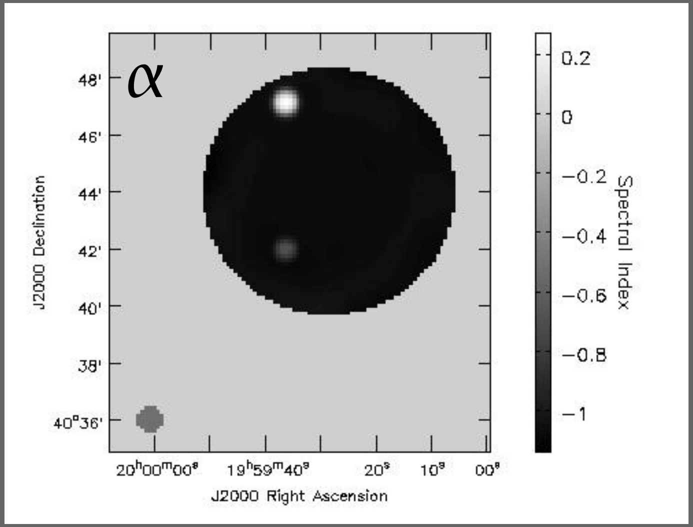
dynamic range ~ 10^3

dynamic range ~ 10^5

These methods will not suffice for emission at multiple spatial scales, non-linear spectra or wide fields-of-view....

Overlapping sources with different spectra





MS-MFS image model naturally separates sources with different spatial scale and spectrum.

Multi-Frequency background subtraction

$$I^{front} = I^{total} - I^{back}$$

$$\alpha^{front} = \frac{I_1^{total} - I_1^{back}}{I_0^{total} - I_1^{total}}$$

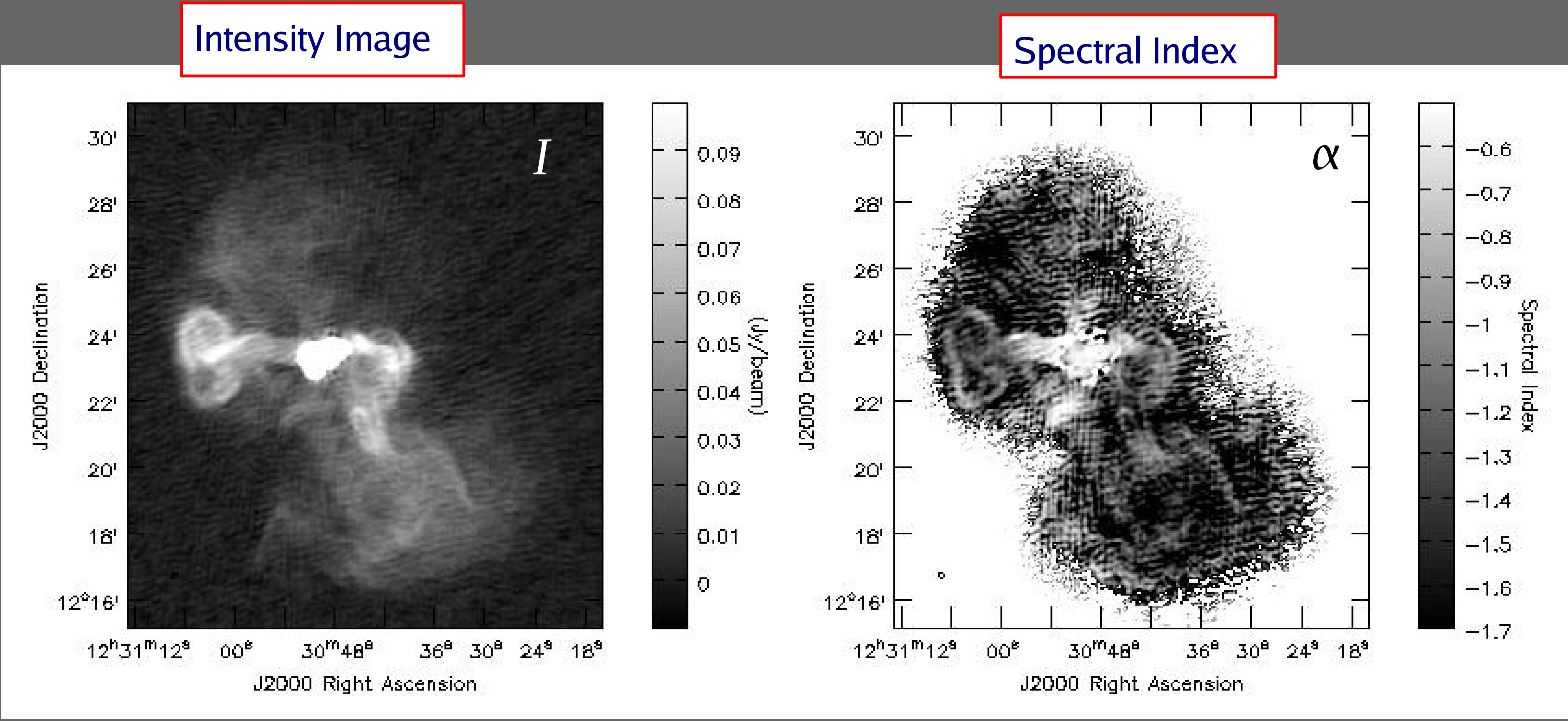
Example : Foreground source : I=1.0, α = -0.5

Measured : I = 1.434, α = -0.68

Background : I = 0.429, α = -1.08

Corrected foreground : I = 1.005, α = -0.51

M87 1.1 – 1.8 GHz (Stokes I , Spectral Index)



Intensity Image

Spectral Index

10 VLA snapshots at 16 frequencies between 1.1 and 1.8 GHz, spread across 10 hrs

- Used existing images of M87 (F.Owen) at 74 MHz, 330 MHz and 1.4 GHz and this spectral index image to constrain the “slope” of the spectrum at 1.4 GHz.
- Fitted spectral evolution models to derive constraints on the dynamical history of the M87 halo.