Wide-field, wide-band and multi-scale imaging - II

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Outline

- WideBand Imaging
  - UV-coverage changes with frequency
  - Modeling wideband sky brightness
    - Point sources + Multi-Scale emission
    - Reconstructing very large spatial scales
  - Wideband primary beams + Mosaics
- Example : Imaging the G55 supernova remnant
- Summary
  - Basic CLEAN vs Wide-field Wide-band imagng
  - Imaging algorithm framework in CASA

Why do we need wide bandwidths ?

Broad-band receivers => Increased 'instantaneous' imaging sensitivity

Continuum sensitivity : (at field-center) $\sigma_{cont} = \frac{\sigma_{chan}}{\sqrt{(N_{chan})}} \propto \frac{T_{sys}}{\sqrt{N_{ant}(N_{ant}-1)\ \delta\tau\delta\nu}}$

50 MHz → 2 GHz => Theoretical improvement : $\sqrt{\frac{2\,GHz}{50\,MHz}} \approx 6$ times.

In practice, effective broadband sensitivity for imaging depends on bandpass shape, data weights, and regions of the spectrum flagged due to RFI. For VLA L-band, we typically use 70% of the band.

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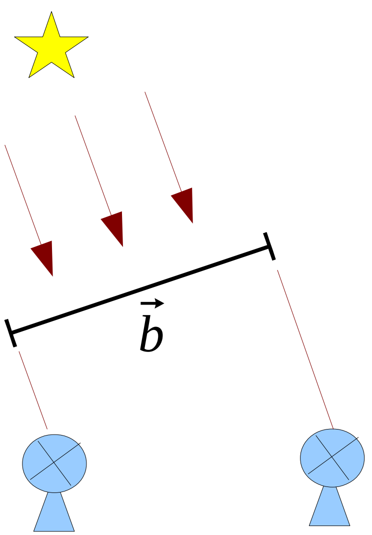
Some bandwidth jargon.....

Frequency Range :	ν_{min}, ν_{max}	(1 – 2 GHz)	(4 – 8 GHz)	(8 – 12 GHz)
Bandwidth :	$\nu_{max} - \nu_{min}$	1 GHz	4 GHz	4 GHz
Bandwidth Ratio :	$\nu_{max} : \nu_{min}$	2 : 1	2 : 1	1.5 : 1
Fractional Bandwidth :	$(\nu_{max} - \nu_{min})/\nu_{mid}$	66%	66%	40%

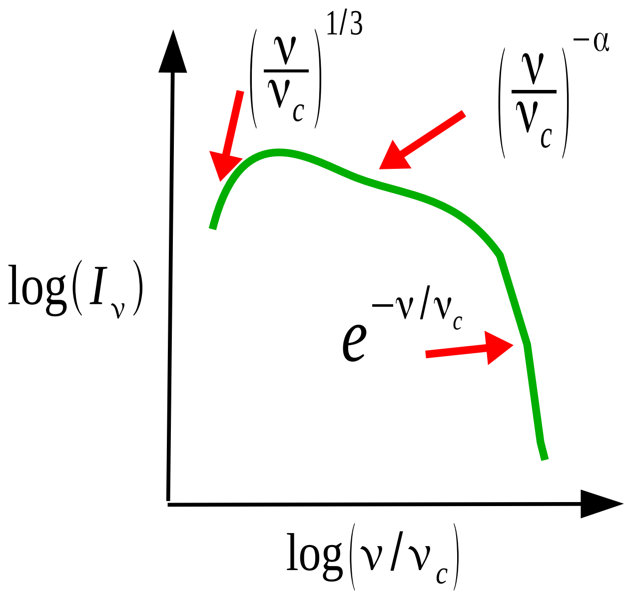
The instrument and the sky change with frequency...

UV-coverage



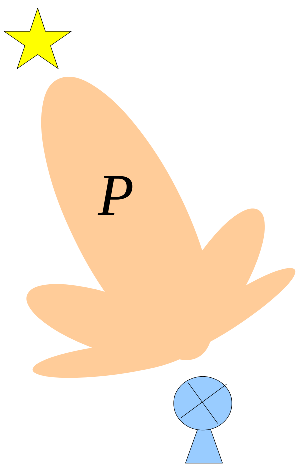
$$S(u,v)_\nu = \frac{\vec{b}}{\lambda} = \frac{\vec{b}\,\nu}{c}$$

Sky Brightness



$$I(\nu)$$

Primary Beam



$$HPBW_\nu = \frac{\lambda}{D} = \frac{c}{\nu D}$$

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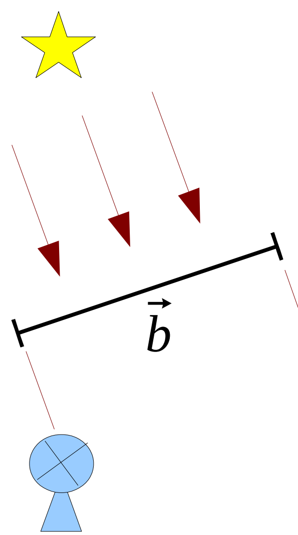
UV-coverage



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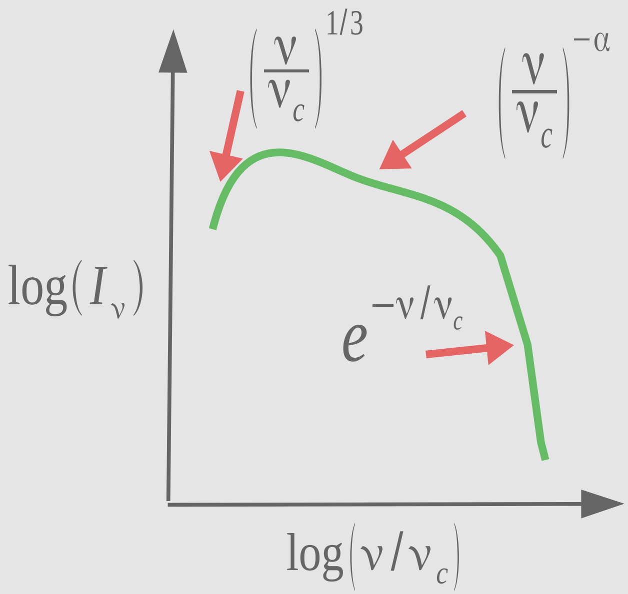

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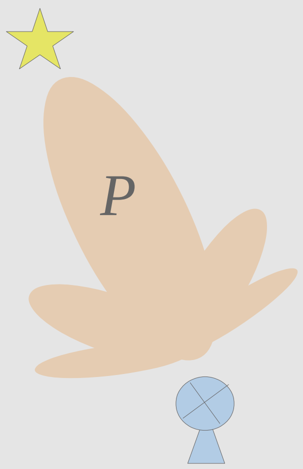
Primary Beam

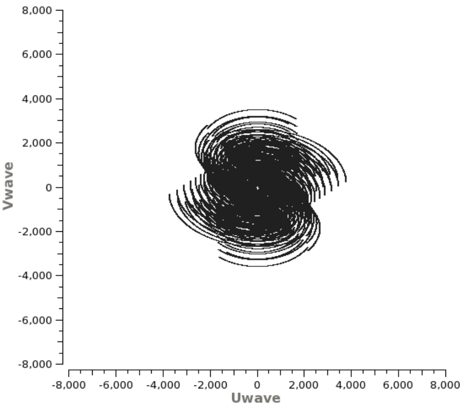


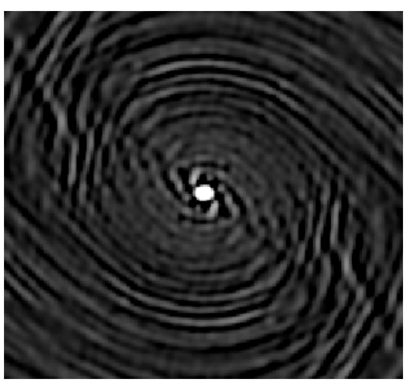
$$HPBW_\nu = \frac{\lambda}{D} = \frac{c}{\nu\,D}$$

Imaging Properties change with frequency

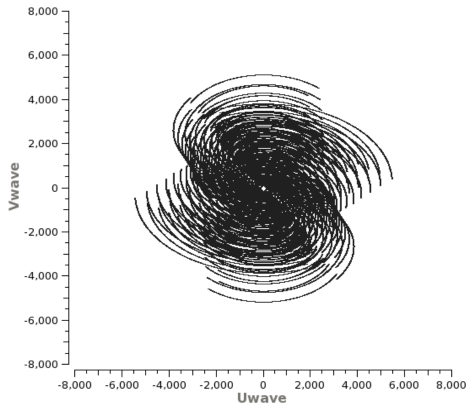
- Angular-resolution increases at higher frequencies
- Sensitivity to large scales decreases at higher frequencies
- Wideband UV-coverage has fewer gaps => lower Psf sidelobe levels

1.0 GHz

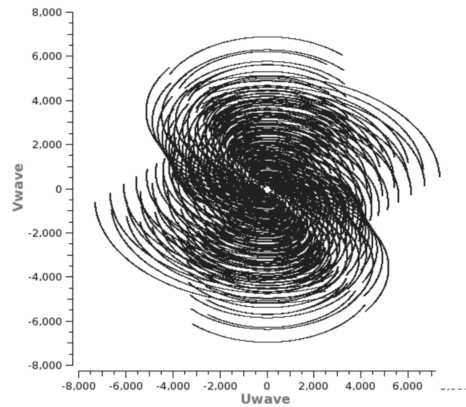




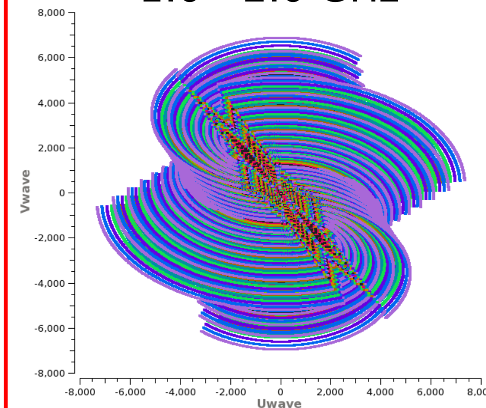
1.5 GHz

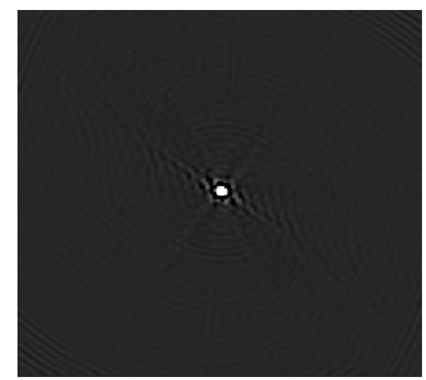


2.0 GHz



1.0 - 2.0 GHz

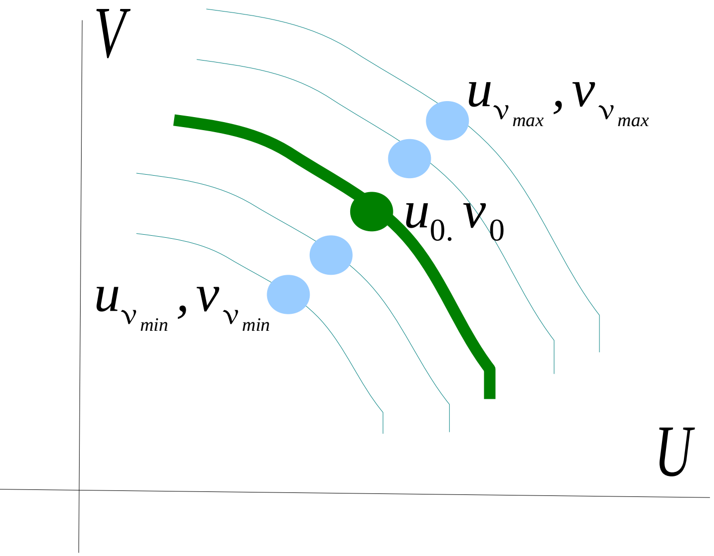




Measure visibilities in frequency ‘channels’ and place them at their correct locations on the UV-plane => Multi-Frequency Synthesis

Bandwidth smearing (chromatic aberration)

Suppose the entire receiver bandwidth was measured in one channel ν_0

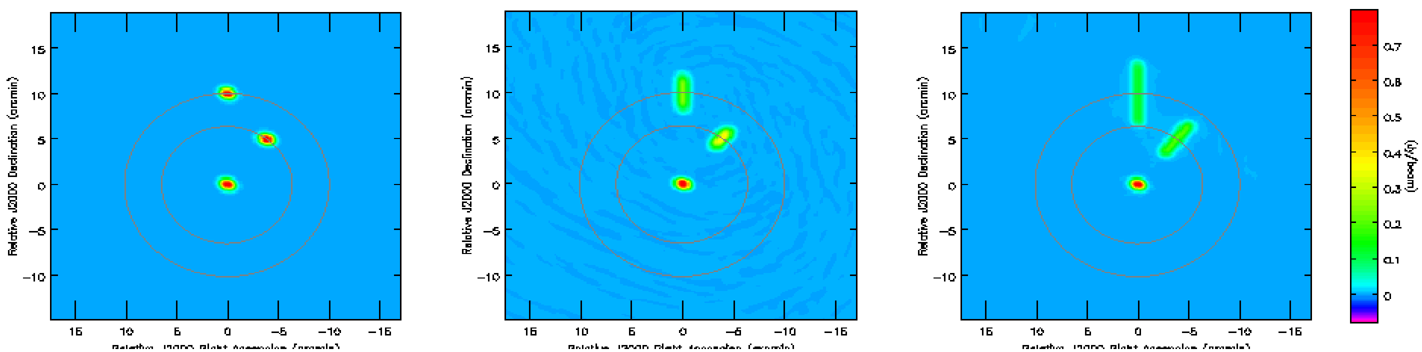


$V(u_\nu)$ is mistakenly mapped to $\frac{\nu_0}{\nu} u_\nu$

Similarity theorem of Fourier-transforms :

Radial shift in source position with frequency.
=> Radial smearing of the sky brightness

2 MHz 200 MHz 1.0 GHz



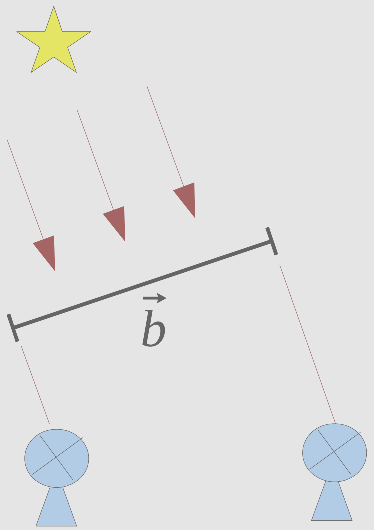
Excessive channel averaging during post-processing has a similar effect.

Bandwidth smearing limit for HPBW field-of-view : $\delta\nu < \frac{\nu_0 D}{b_{max}}$

Bandwidth Smearing limits at L-Band (1.4 GHz),
33 MHz (VLA D-config), 10 MHz (VLA C-config),
3 MHz (VLA B-config), 1 MHz (VLA A-config)

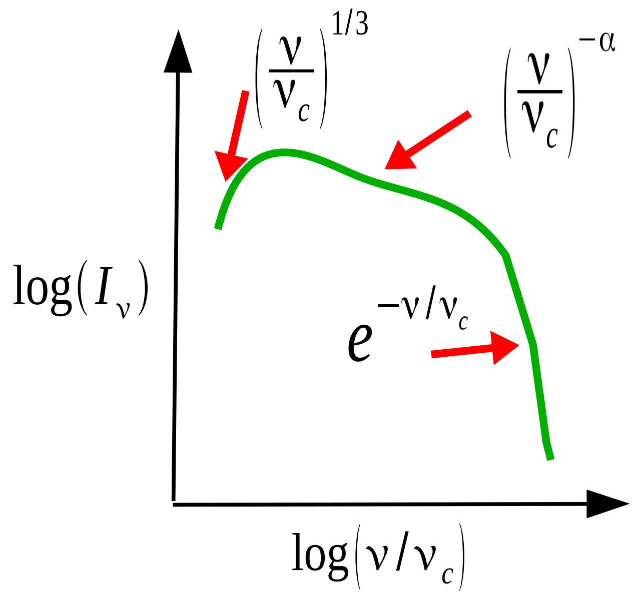
The instrument and the sky change with frequency...

UV-coverage



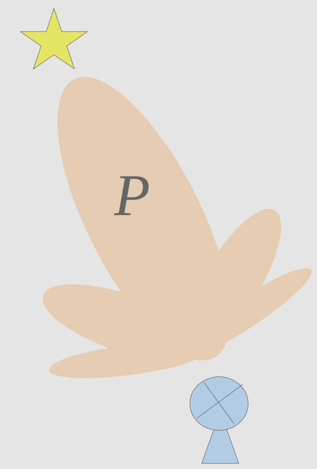
$$S(u,v)_\nu = \frac{\vec{b}}{\lambda} = \frac{\vec{b}\,\nu}{c}$$

Sky Brightness



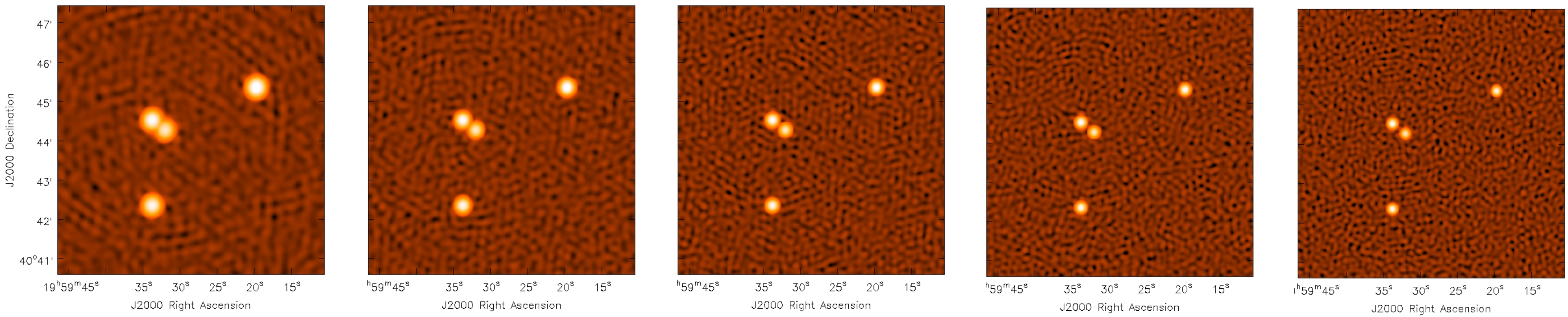
$$I(\nu)$$

Primary Beam



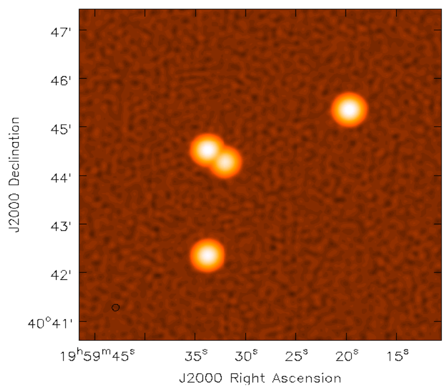
$$HPBW_\nu = \frac{\lambda}{D} = \frac{c}{\nu D}$$

Algorithms : Cube Imaging vs Multi-Frequency Synthesis



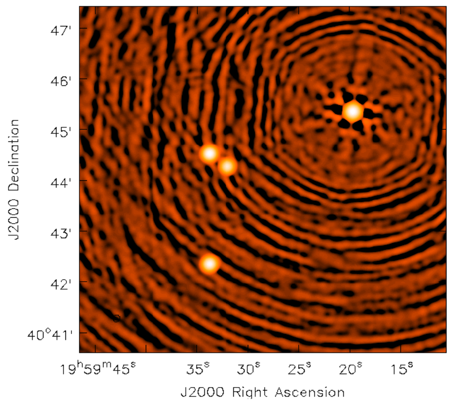
Cube Imaging :

(1) Reconstruct each chan/spw separately
(2) Smooth to the lowest available resolution
(3) Combine to calculate continuum and spectra



Multi-Frequency-Synthesis :

Combine data from all frequencies onto
a single grid and do a joint reconstruction
(assuming flat sky spectra)



Algorithm : Multi-Term Multi-Frequency-Synthesis

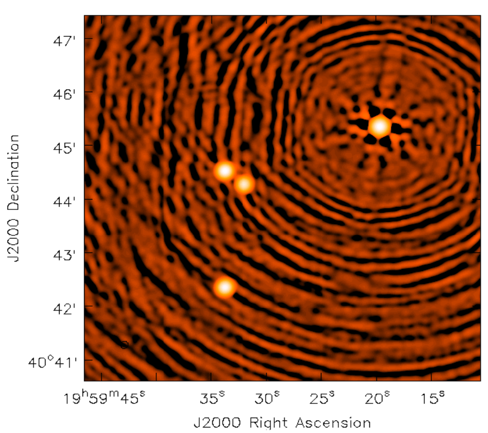
Solve for coefficients of a Taylor polynomial in frequency $I_\nu^{sky} = \sum_t I_t^m \left(\frac{\nu - \nu_0}{\nu_0} \right)^t$

Interpret coefficients as a power-law (spectral index and curvature)

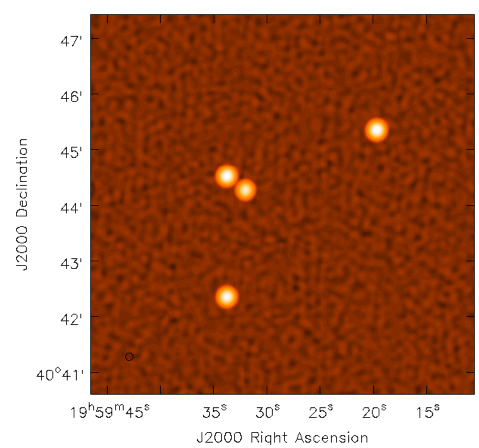
$$I_\nu = I_{\nu_0} \left(\frac{\nu}{\nu_0} \right)^{\alpha + \beta \log(\nu/\nu_0)} \longleftrightarrow \quad I_0^m = I_{\nu_0} \qquad I_1^m = I_{\nu_0} \alpha \qquad I_2^m = I_{\nu_0} \left(\frac{\alpha(\alpha - 1)}{2} + \beta \right)$$

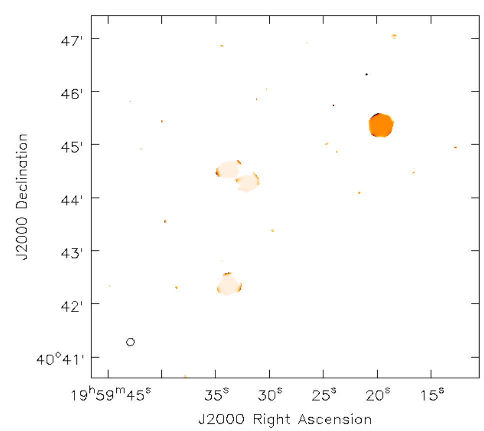
Rau &Cornwell, 2011
Sault &Wieringa, 1994

Nterms=1
(ignore spectra)



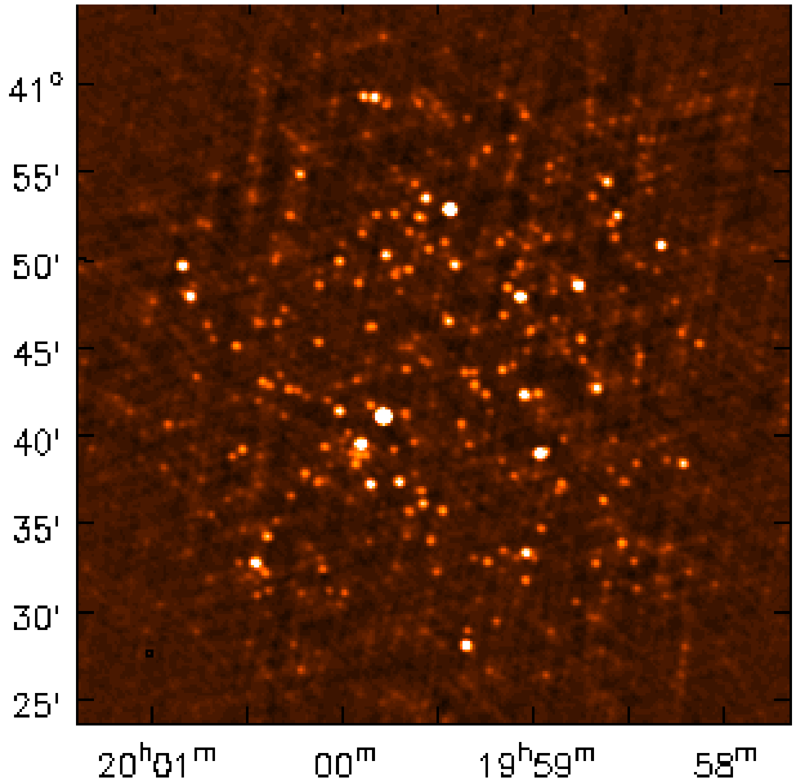
NTerms>1
(Model the spectrum during the reconstruction)



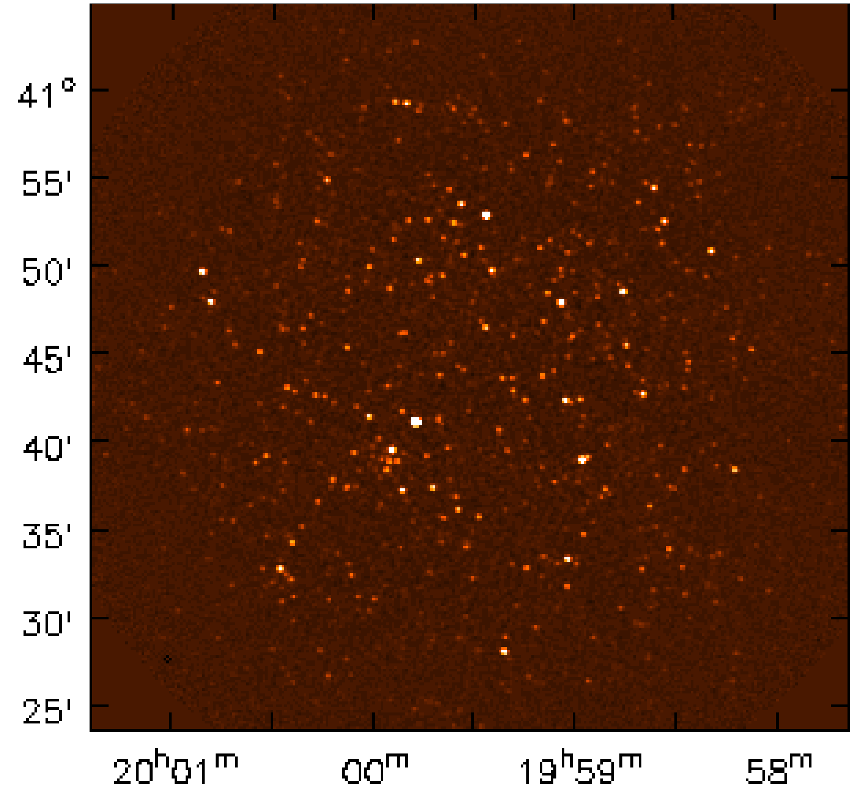


Cube Imaging vs Multi-Frequency-Synthesis

Cube



(MT) MFS



- Low angular resolution
- Weakest sources are not deconvolved enough
- Crowded field may suffer from ‘Clean bias’ due to PSF sidelobes and require careful masking
+ Independent of spectral model

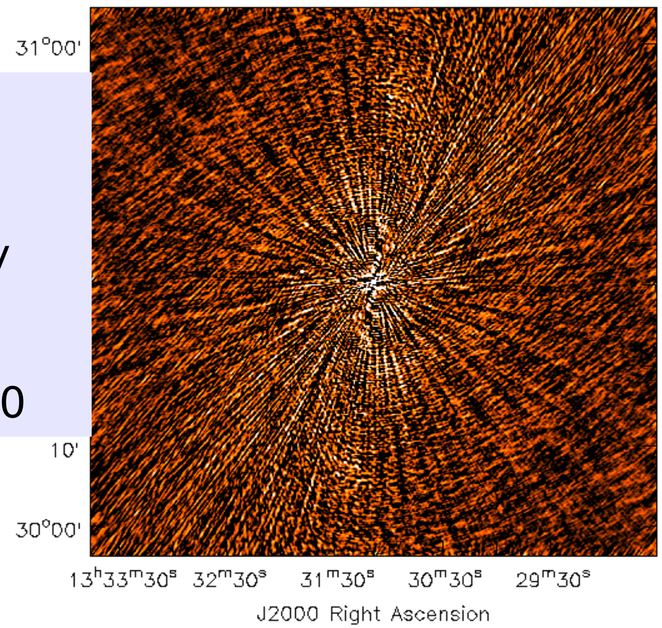
+ High angular resolution
+ Imaging at continuum sensitivity
+ Better PSF and imaging fidelity can eliminate ‘Clean bias’ and the need for masks in crowded fields
- Depends on how appropriate the spectral model is

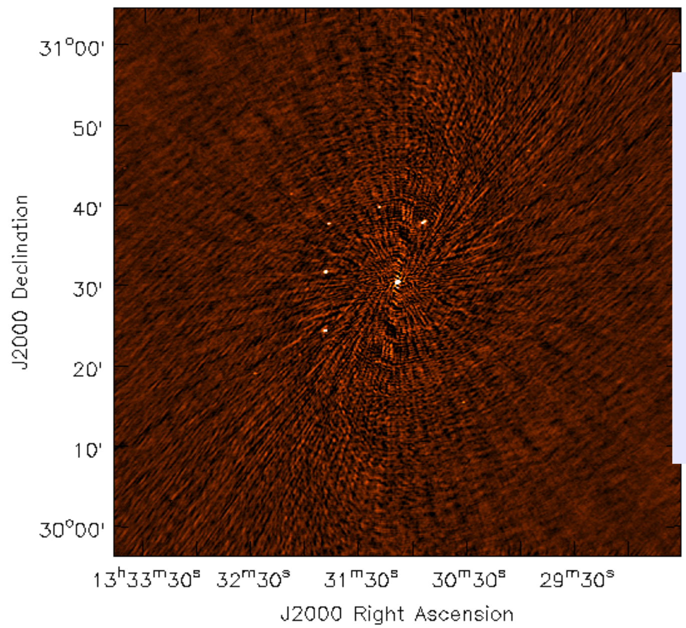
Dynamic-range : 1-2GHz : 3C286 example : Nt=1,2,3,4

NTERMS = 1

Rms :
9 mJy -- 1 mJy

DR :
1600 - 13000





NTERMS = 2

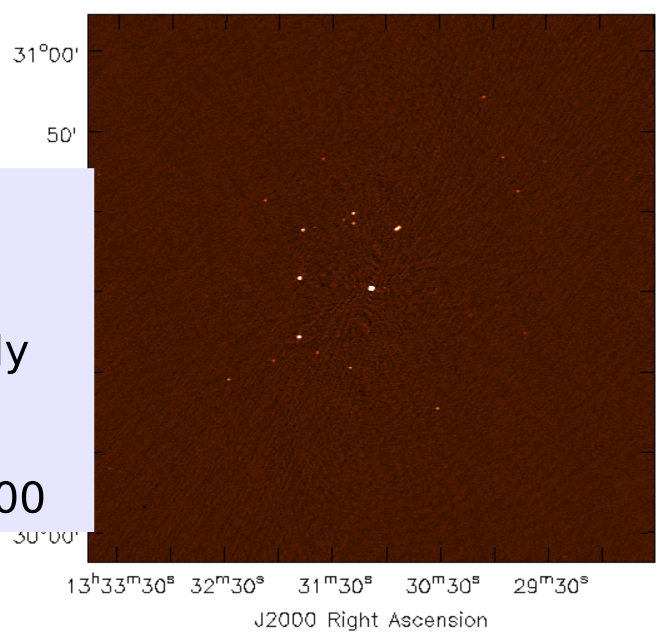
Rms :
1 mJy -- 0.2 mJy

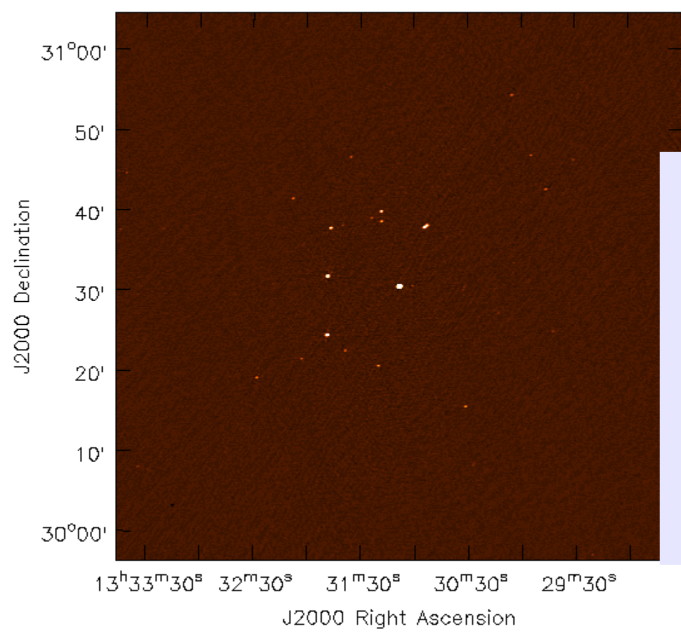
DR :
10,000 - 17,000

NTERMS = 3

Rms :
0.2 mJy -- 85 uJy

DR :
65,000 - 170,000





NTERMS = 4

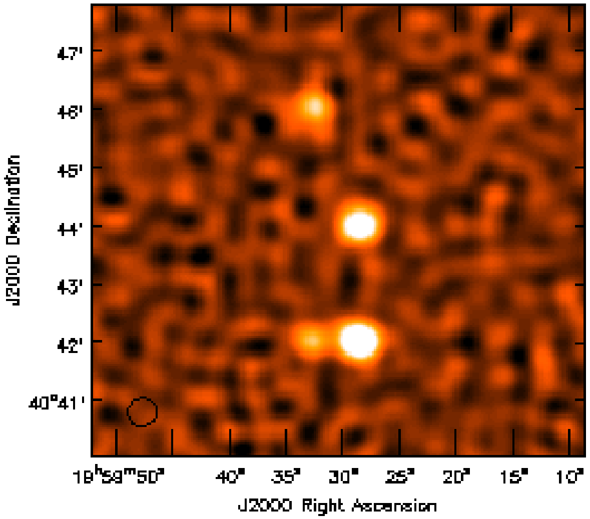
Rms
0.14 mJy -- 80 uJy

DR :
>110,000
- 180,000

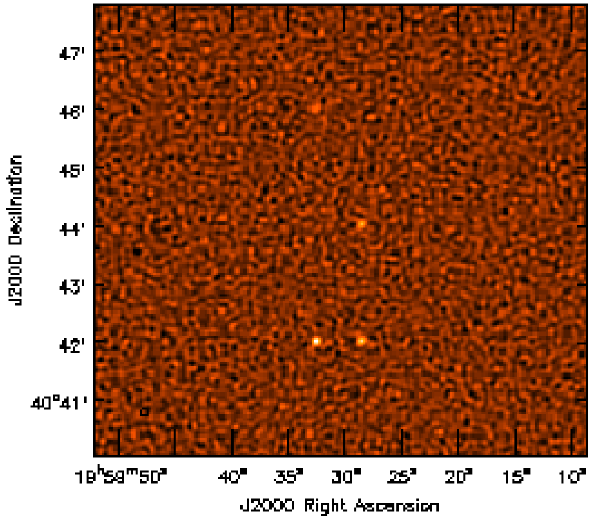
Spectral Index Accuracy (for low signal-to-noise)

Accuracy of the spectral-fit increases with larger bandwidth-ratio

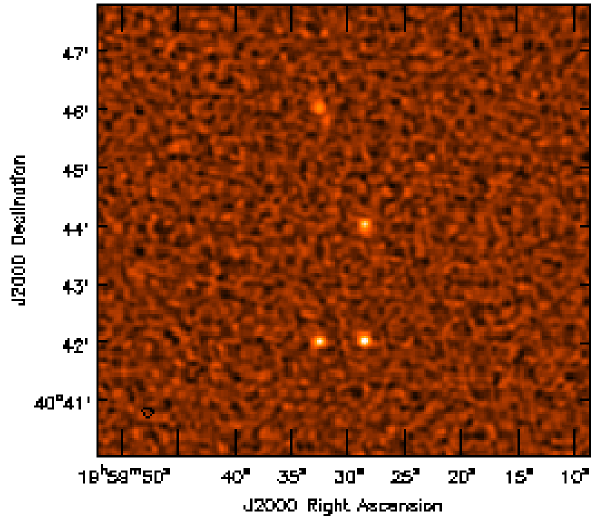
1 – 2 GHz, 4 hr



4 - 8 GHz , 4 hr



1 – 2 GHz, 4 - 8 GHz, 2 hrs each



RMS
5 uJy/bm

Source	Peak Flux	SNR	L alpha	C alpha	LC alpha	True
Bottom right	100 uJy	20	-0.89	-1.18	-0.75	-0.7
Bottom left	100 uJy	20	+0.11	+0.06	+0.34	+0.3
Mid	75 uJy	15	-0.86	-1.48	-0.75	-0.7
Top	50 uJy	10	-1.1	0	-0.82	-0.7

To trust spectral-index values, need SNR > 50 (within one band – 2:1)
For SNR < 50 need larger bandwidth-ratio.

Multi-Scale + Wide-Band image reconstruction

Multi-Scale Sky Model : Linear combination of 'blobs' of different scale sizes

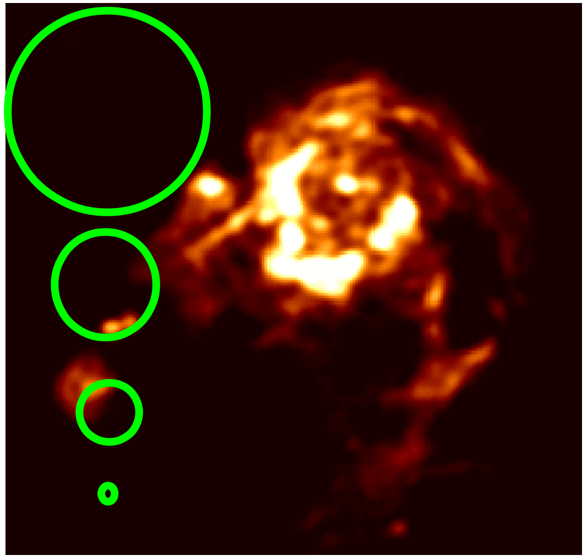
- Efficient representation of both compact and extended structure (sparse basis)

MS-Clean : an iterative scale-sensitive algorithm

(1) Choose a set of scale sizes

(2) Calculate dirty/residual images
smoothed to several scales (basis functions)

– Normalize by the relative sum-of-weights
(instrument's sensitivity to each scale)

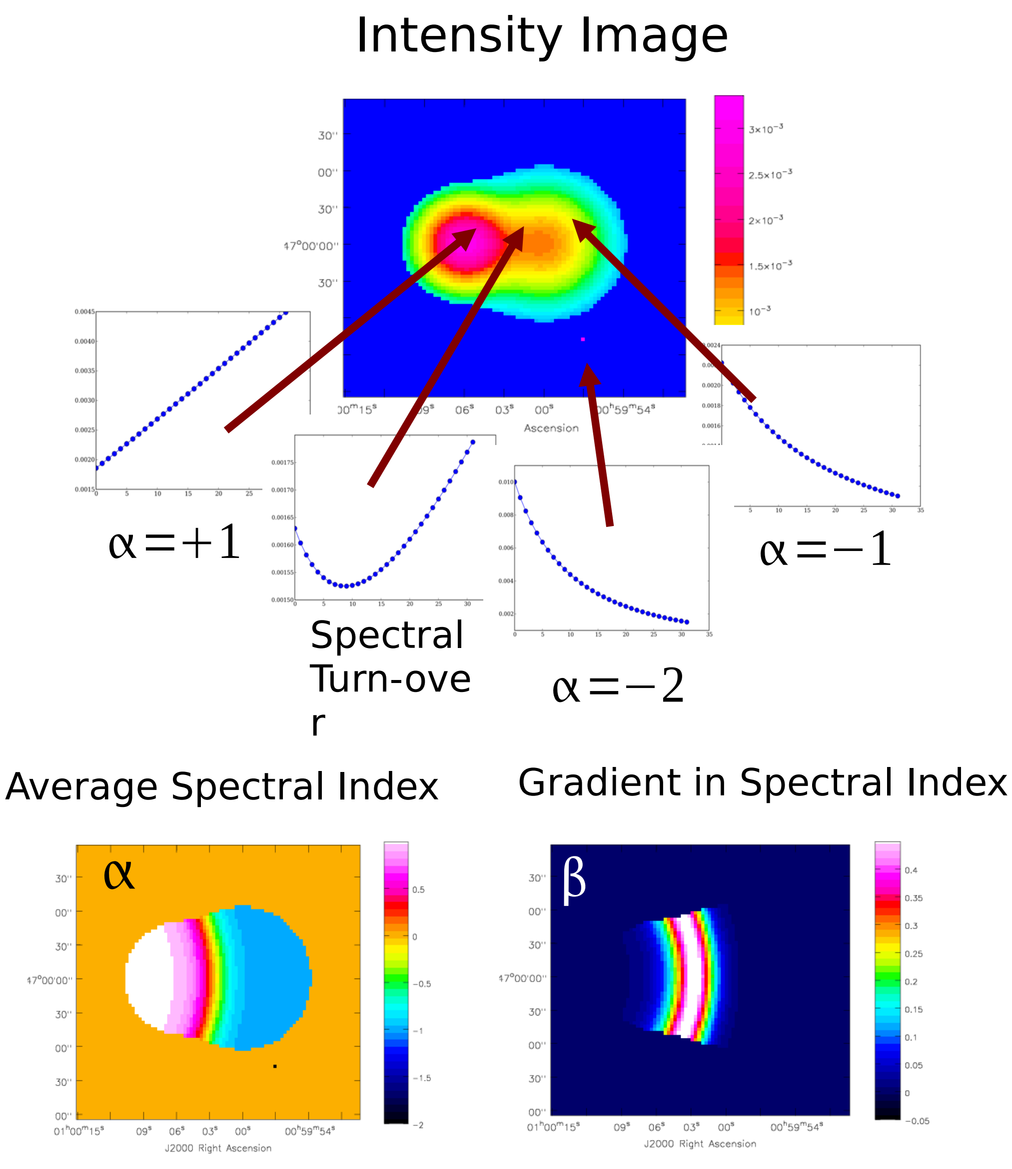


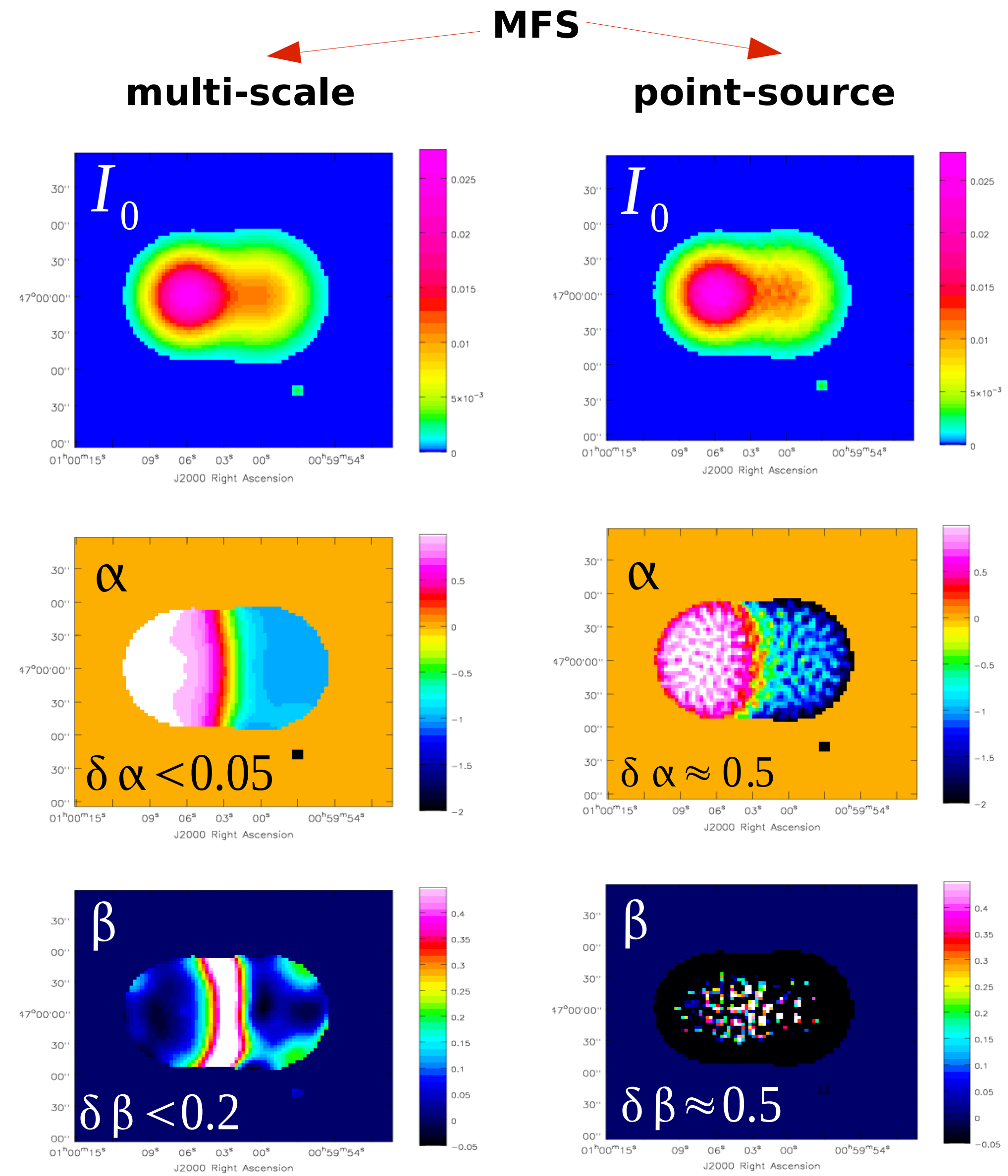
(3) Find the peak across all scales, update a single multi-scale model as well as all residual images (using information about coupling between scales)

Wideband + Multiscale Sky Model : Collection of multi-scale flux components whose amplitudes follow Taylor polynomials in frequency.

(There are several newer MS algorithms that adaptively pick best-fit basis functions. Work is ongoing to include wideband models as well.)

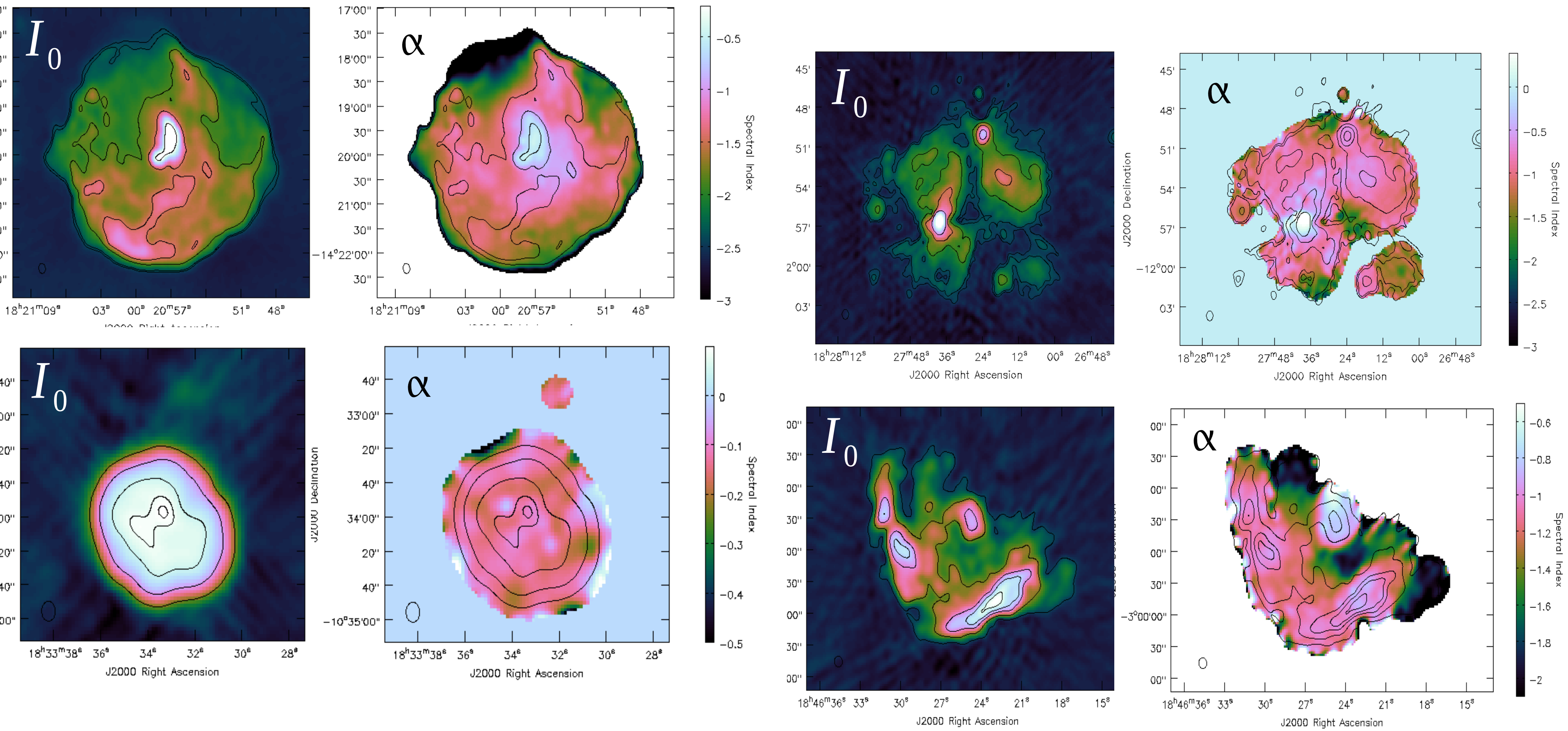
Example of wideband-imaging on extended-emission





=> Spectral-index error is dominated by 'division between noisy images'
– a multi-scale model gives better spectral index and curvature maps

Supernova Remnants at L and C Band [Bhatnagar et al, 2011]

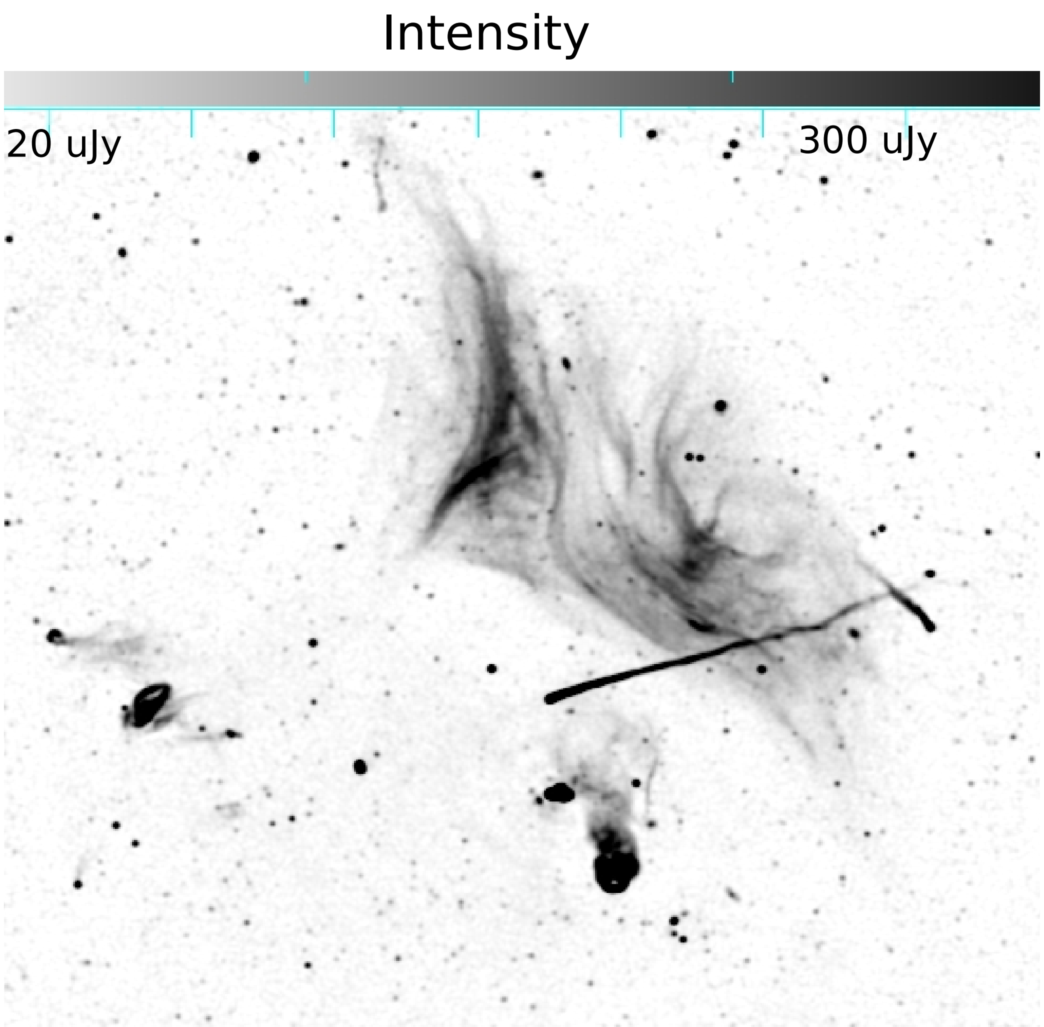


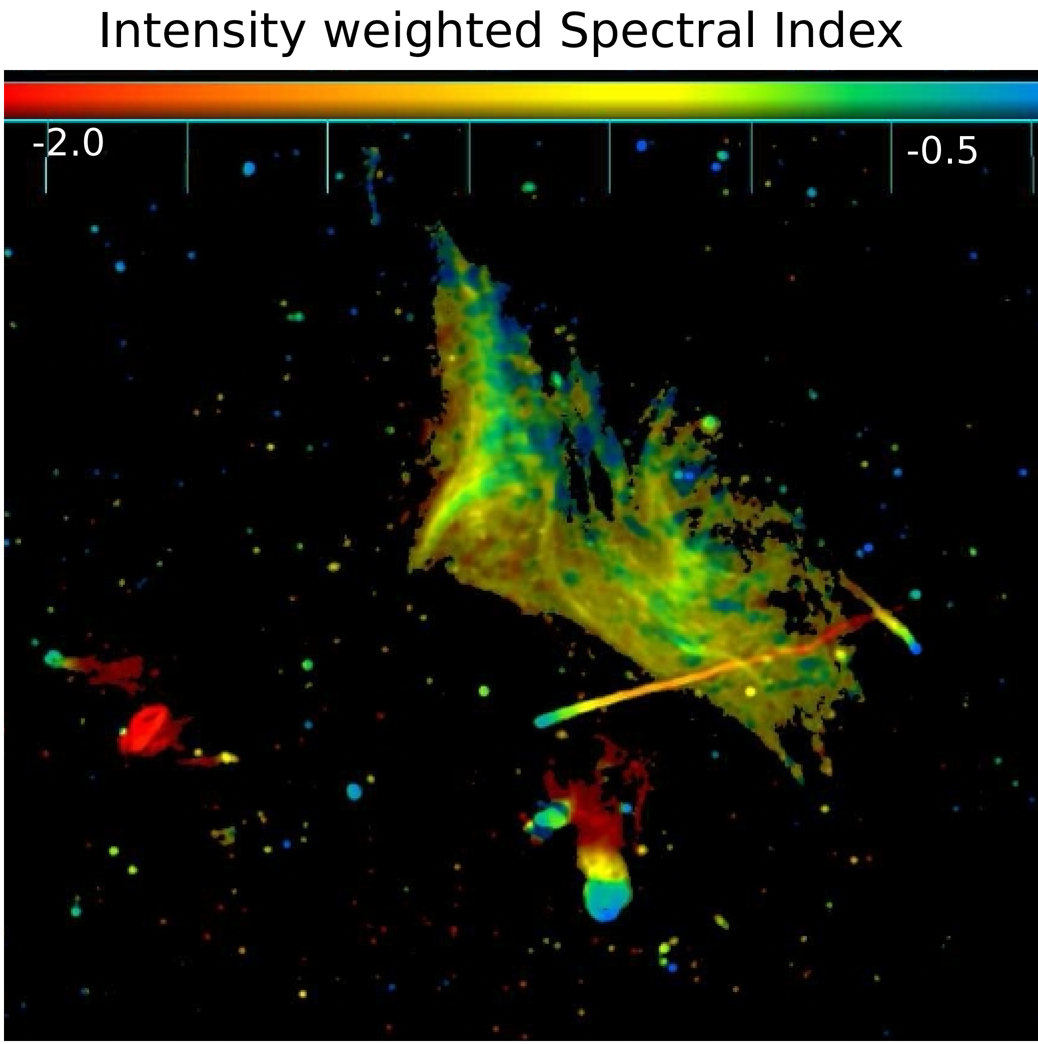
These examples used nterms=2, and about 5 scales.

=> Within 1-2 Ghz and 4-8 GHz, spectral-index error is < 0.2 for SNR>100.

=> Dynamic-range limit of few x 1000 ---> residuals are artifact-dominated

Example : Abell 2256 *[Owen et al, 2014]*



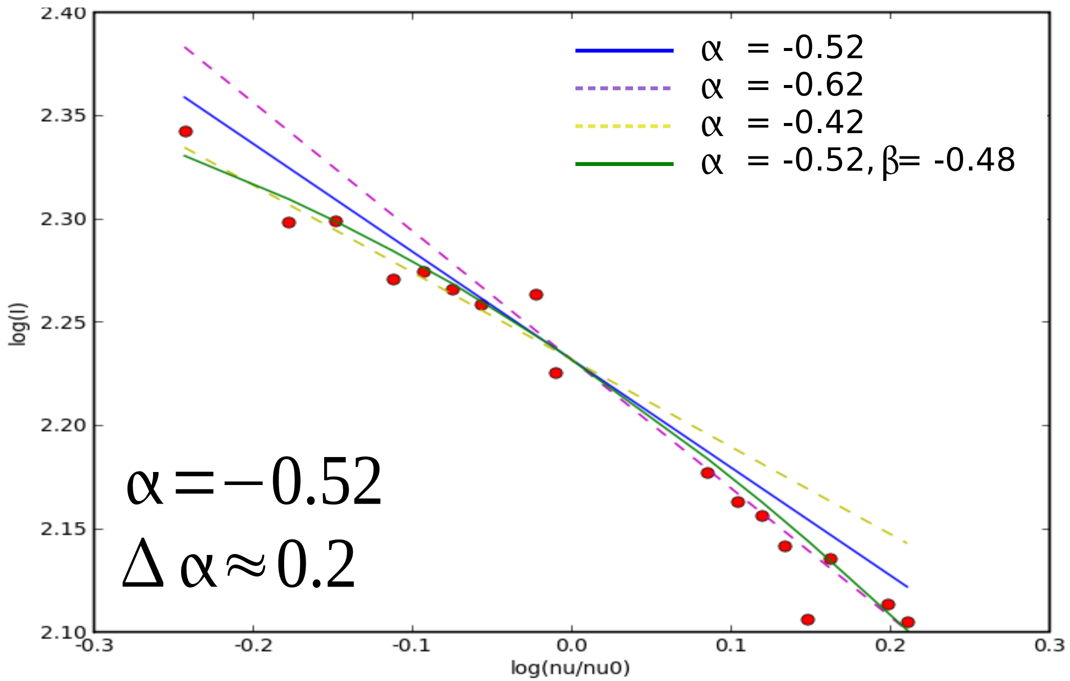


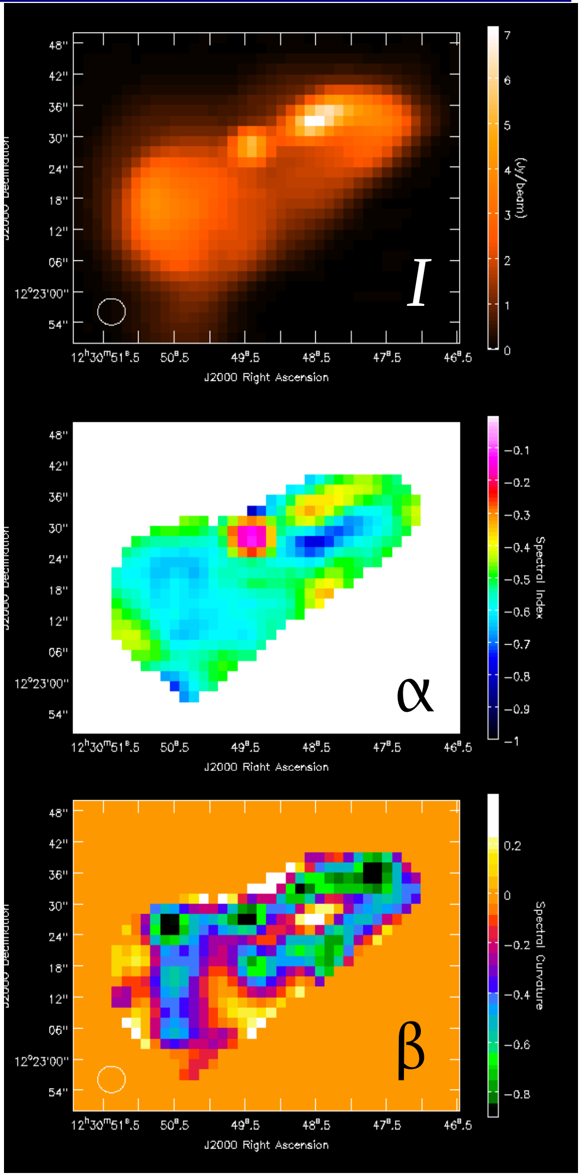
VLA A,B,C,D at L-Band (1-2 GHz), VLA A at S&C bands(2-4, 4-6, 6-8 GHz)

Calibration and Auto-flagging in AIPS. Intensity/Spectral index Imaging in CASA.

Spectral Curvature

Data : 10 VLA snapshots at 16 frequencies (1.2 – 2.1 GHz)





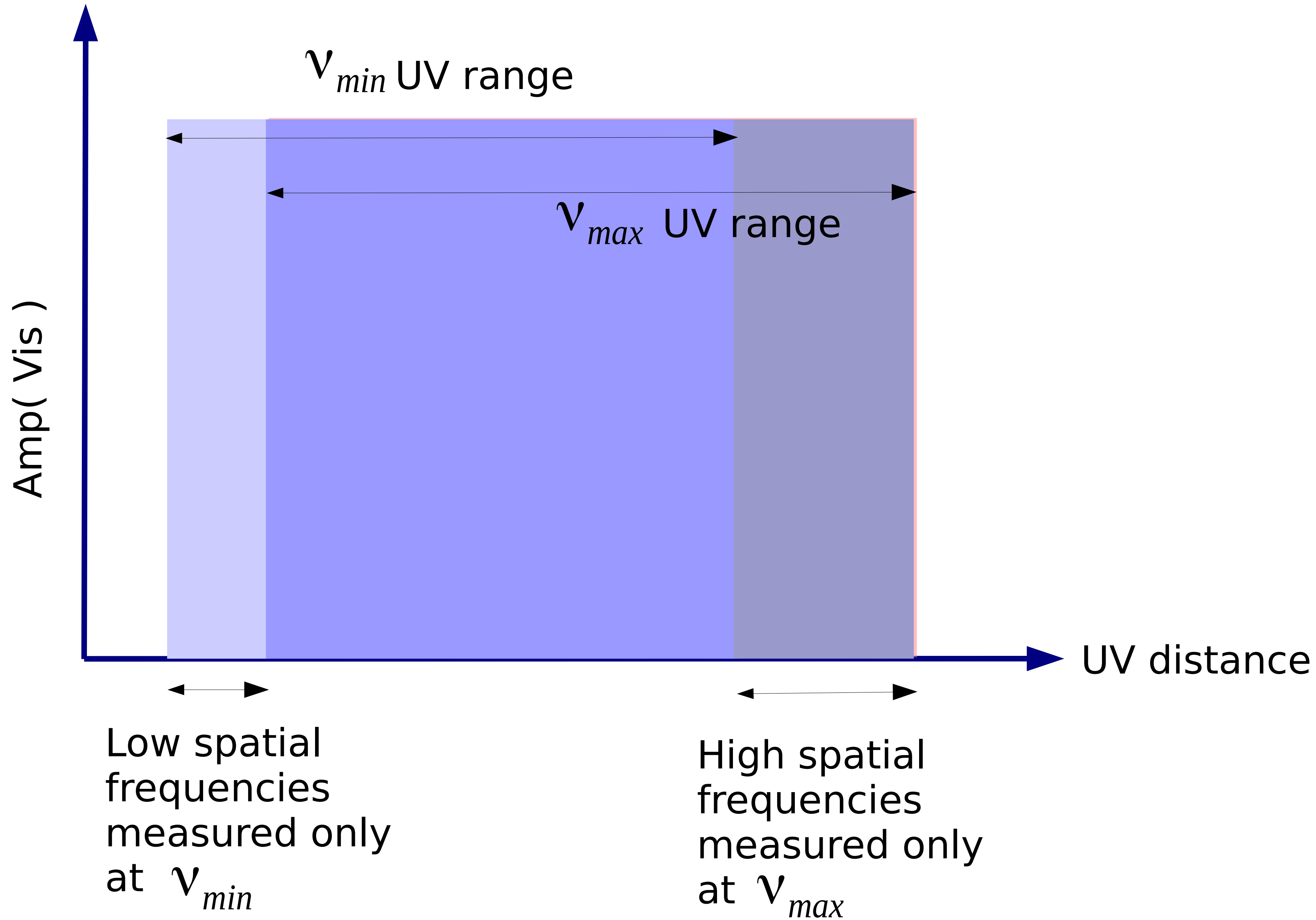
From existing P-band (327 MHz), L-band(1.42 GHz) and C-band (5.0 GHz) images of the core/jet

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

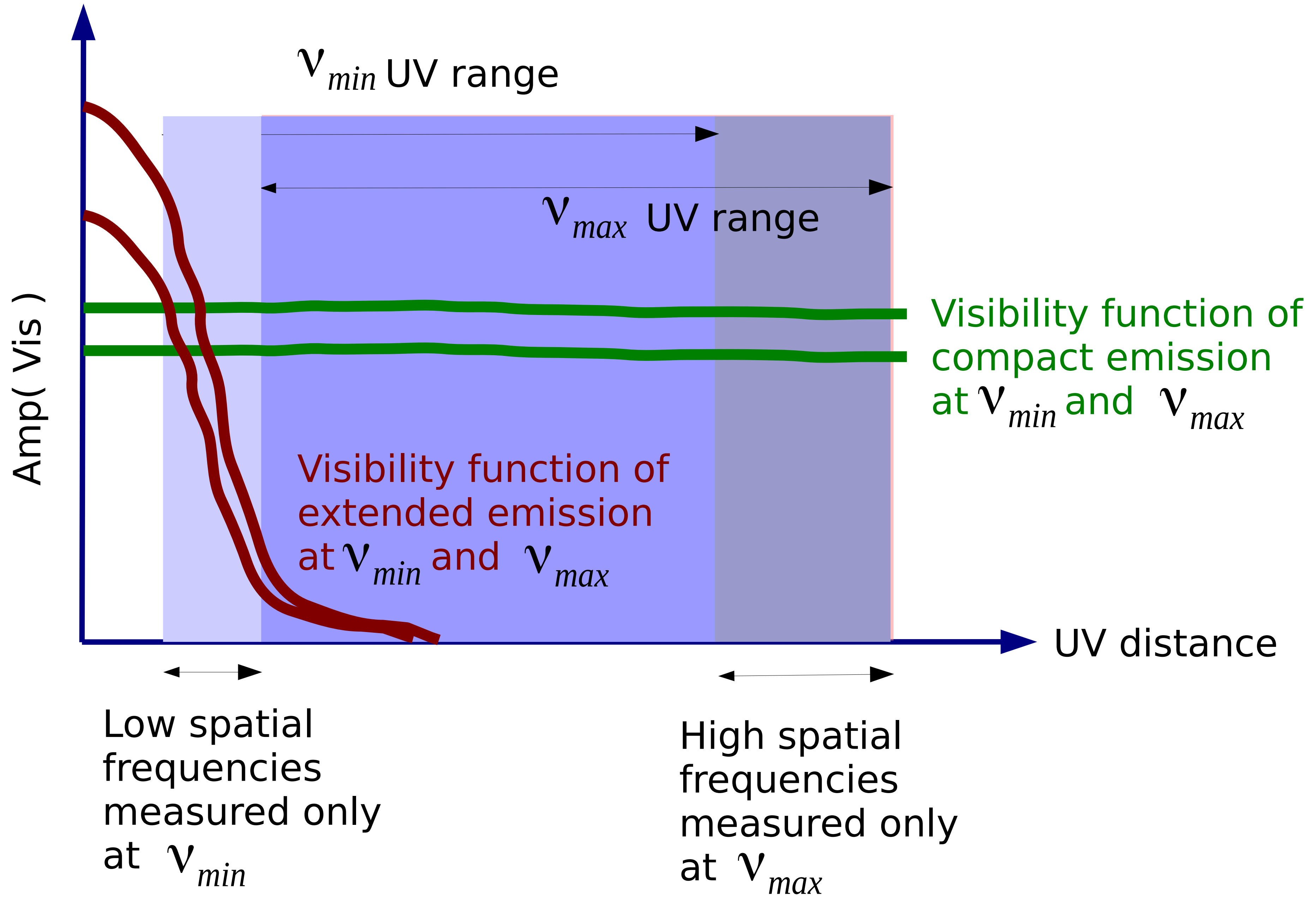
=> Need SNR > 100 to fit spectral index variation ~ 0.2 (at the 1-sigma level ...)

=> Be very careful about interpreting β

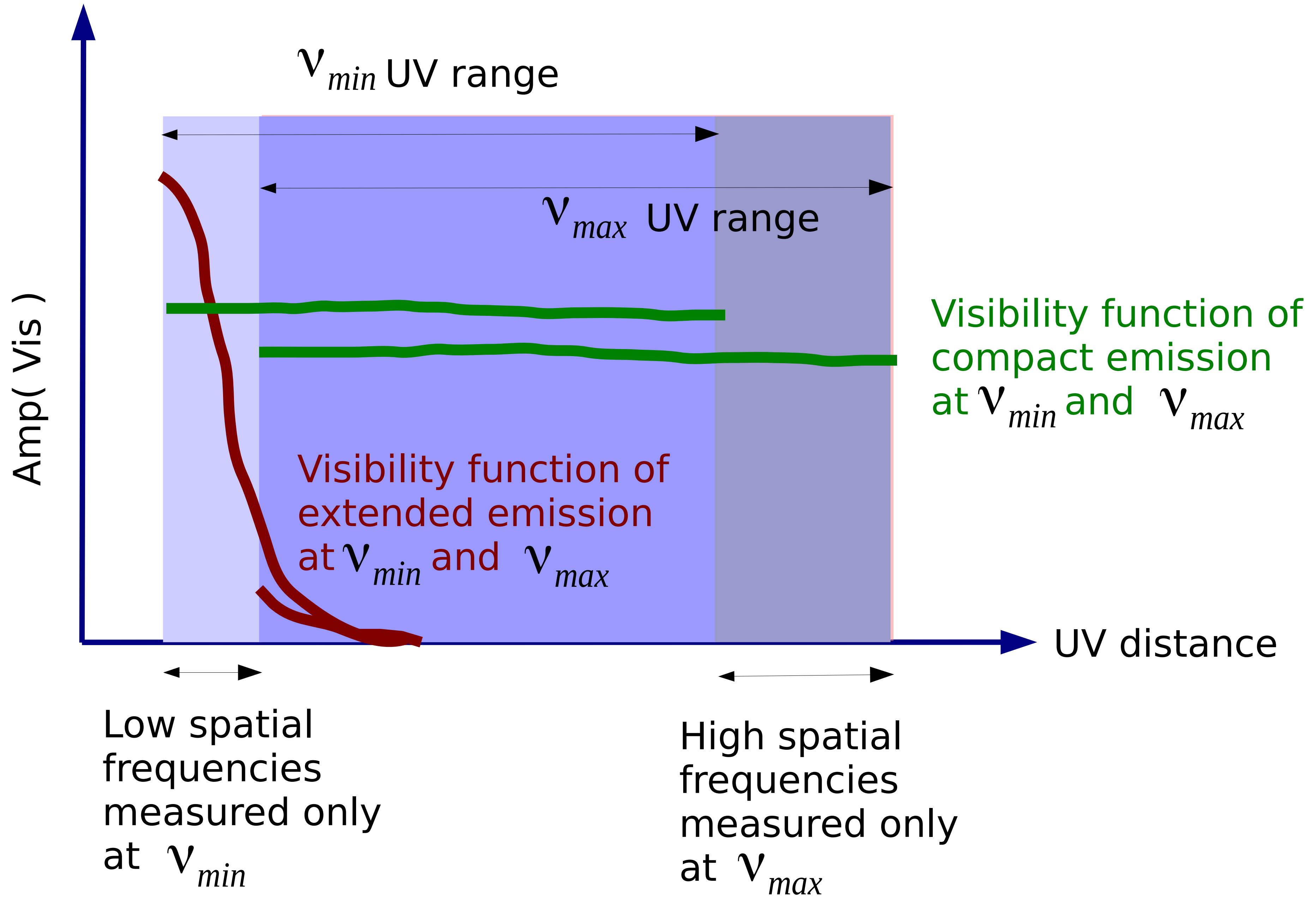
For which scales can we reconstruct the spectrum ?



For which scales can we reconstruct the spectrum ?

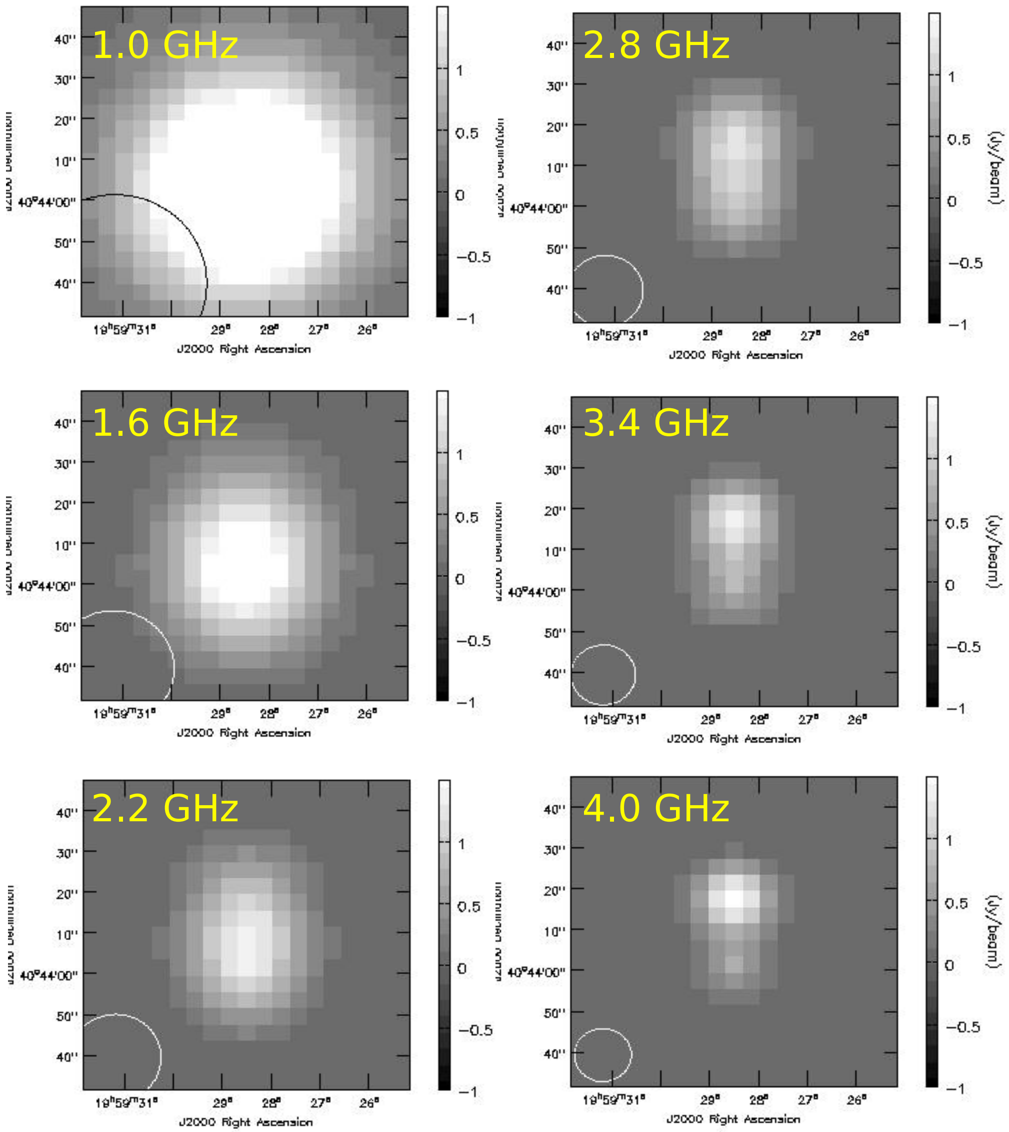


For which scales can we reconstruct the spectrum ?

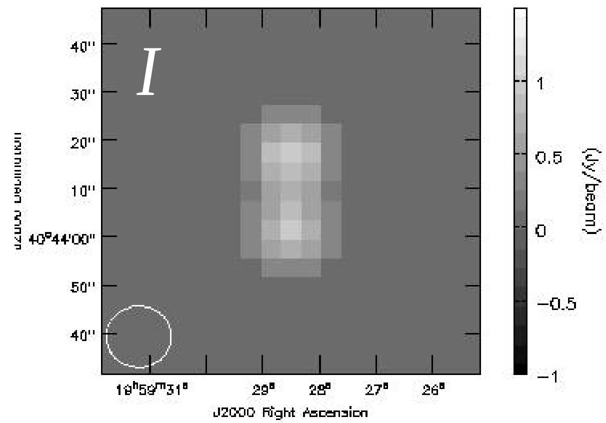


Moderately Resolved Sources + High SNR

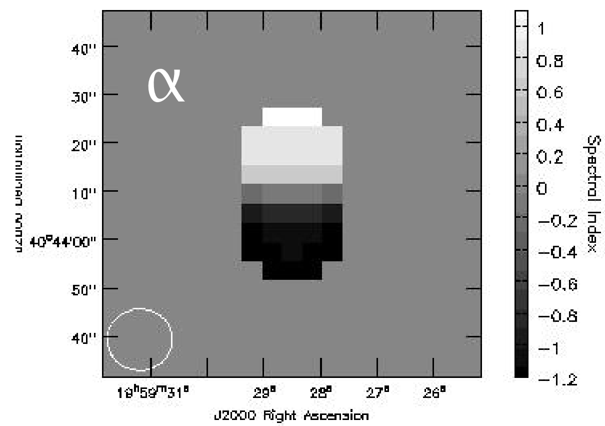
Can reconstruct the spectrum at the angular resolution of the highest frequency (only high SNR)



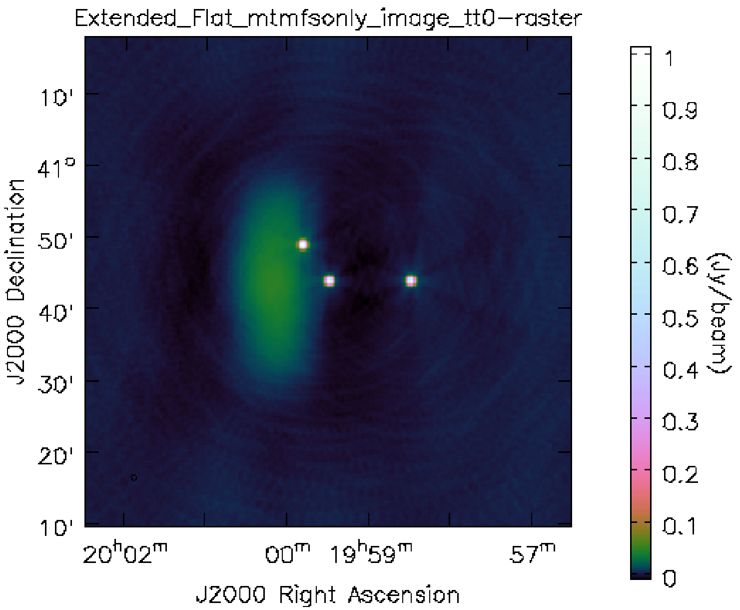
Restored Intensity image

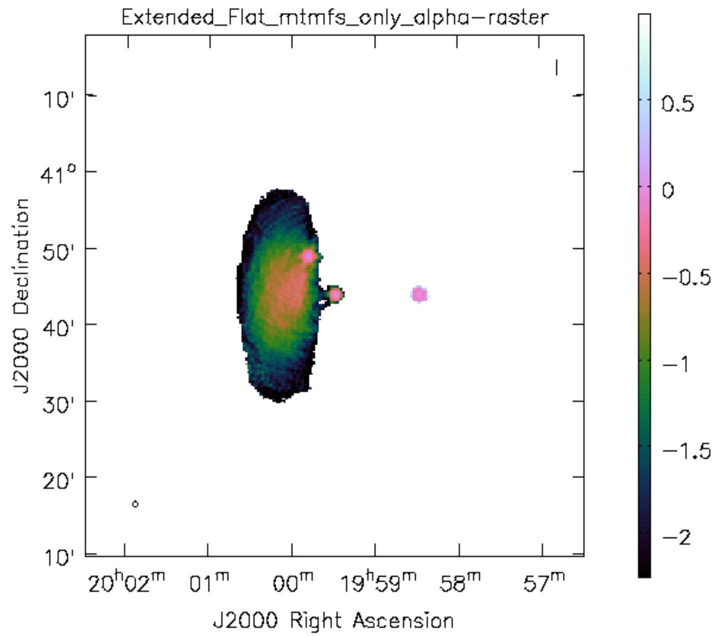


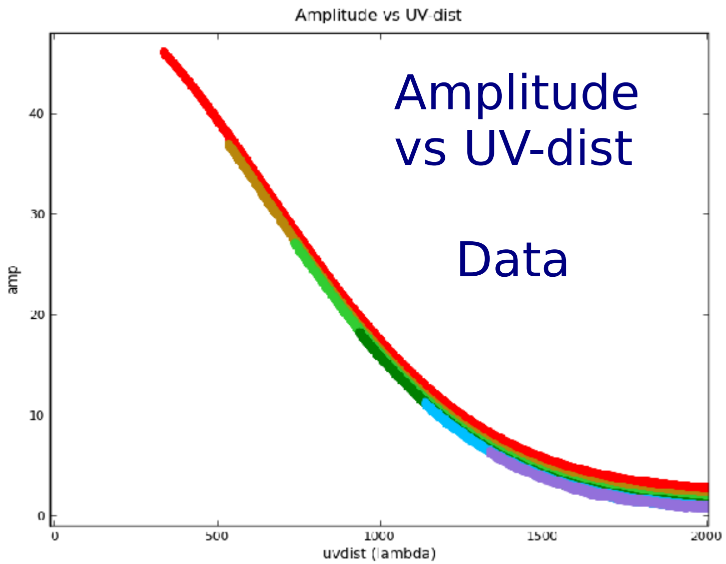
Spectral Index map

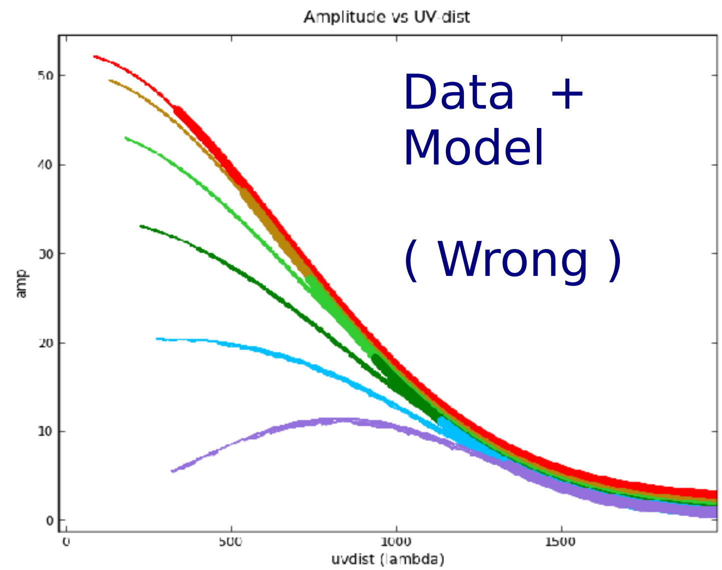


Very large spatial scales : Need wideband single dish data









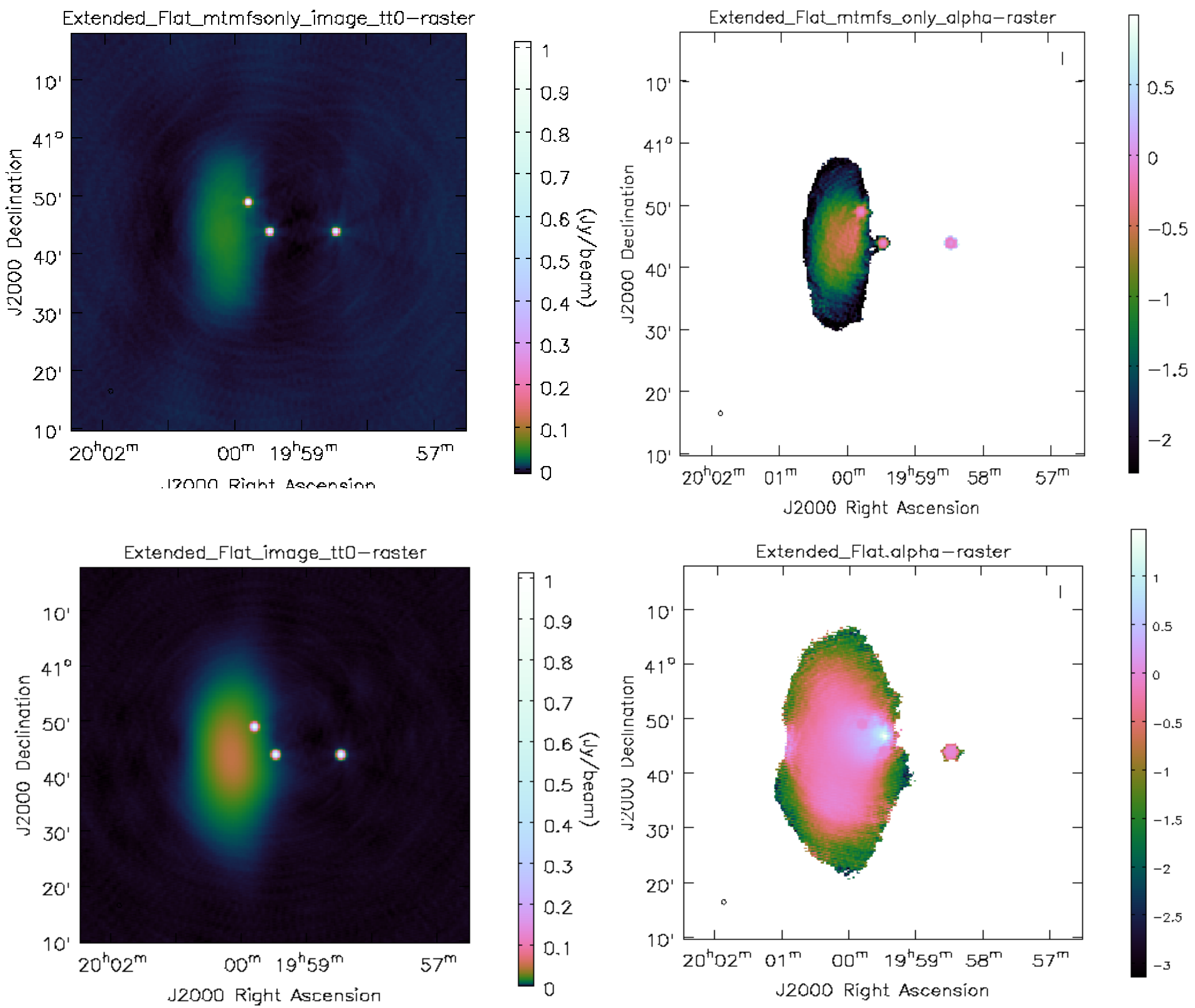
Example : Flat spectrum emission at very large scales

Top : Only interferometer data
=> Negative bowl and artificial steep spectrum

No short spacings to constrain the spectra

=> False steep spectrum reconstruction

Very large spatial scales : Need wideband single dish data



Example : Flat spectrum emission at very large scales

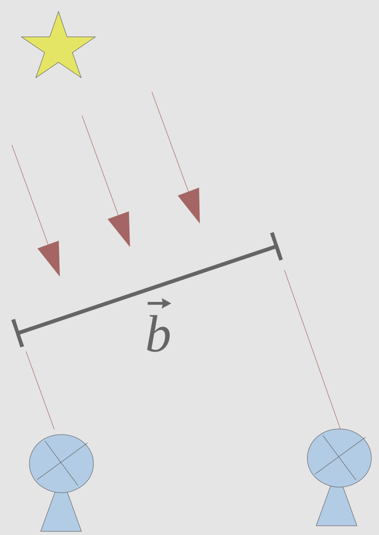
Top : Only interferometer data
=> Negative bowl and artificial steep spectrum

Bottom : Joint wideband reconstruction
=> Recovers more flux and gets accurate spectrum

[Naik & Rau, 2017 (in prep)]

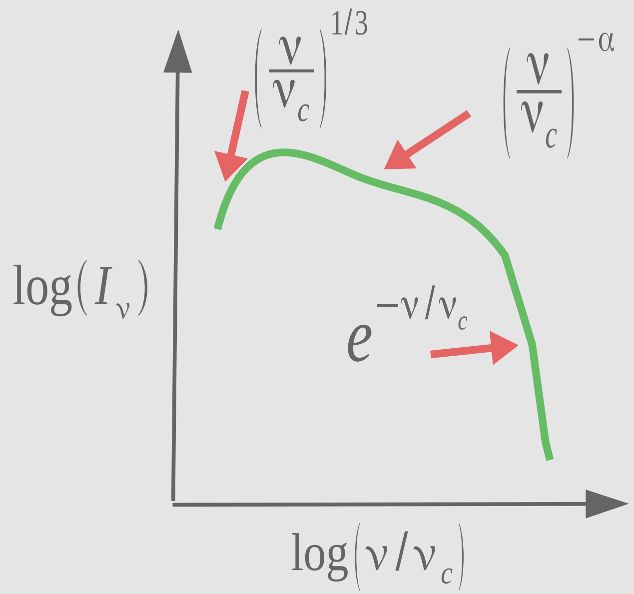
The instrument and the sky change with frequency...

UV-coverage



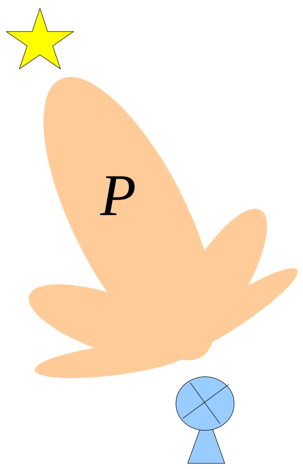
$$S(u,v)_\nu = \frac{\vec{b}}{\lambda} = \frac{\vec{b}\,\nu}{c}$$

Sky Brightness



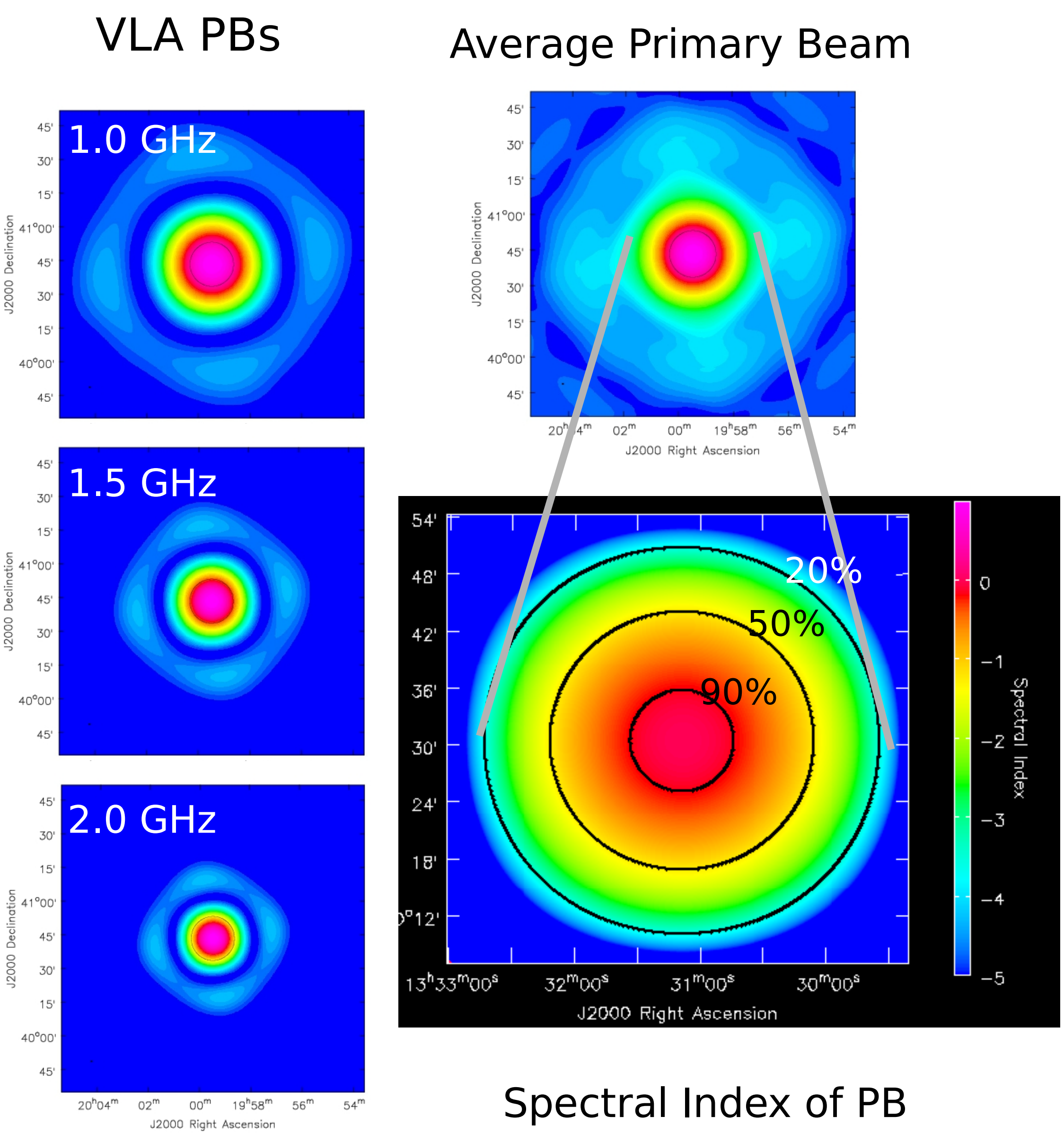
$$I(\nu)$$

Primary Beam



$$HPBW_\nu = \frac{\lambda}{D} = \frac{c}{\nu D}$$

Wide-Band Wide-Field Imaging : Primary Beams



Spectral Index of PB

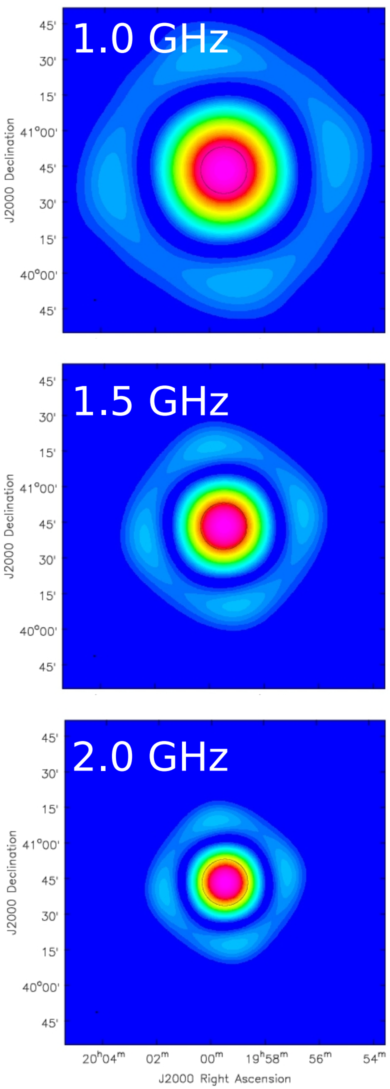
MFS : artificial 'spectral index' away from the center

For VLA L-Band (1-2 GHz)

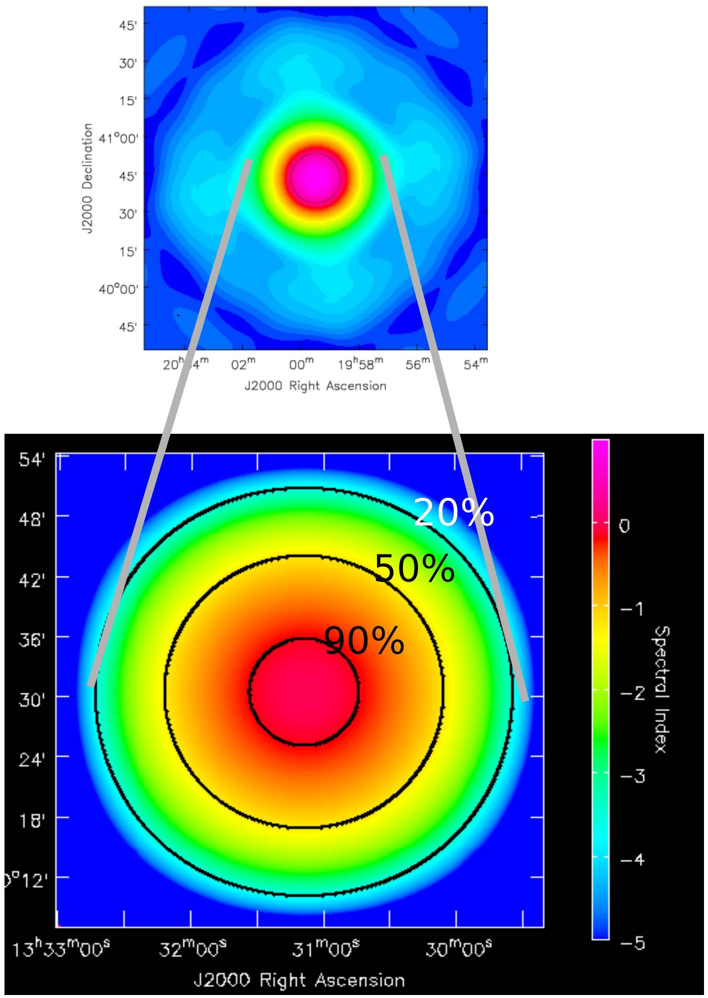
- About -0.4 at the PB=0.8
  (6 arcmin from the center)
- About -1.4 at the HPBW
  (15 arcmin from the center)

Wide-Band Wide-Field Imaging : Primary Beams

VLA PBs



Average Primary Beam



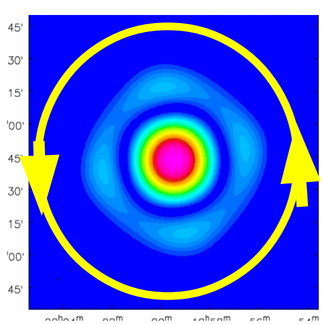
Spectral Index of PB

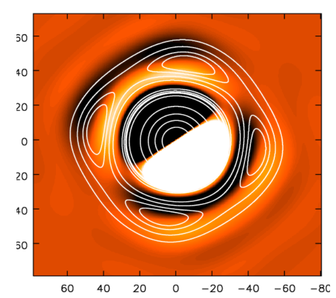
MFS : artificial 'spectral index' away from the center

For VLA L-Band (1-2 GHz)

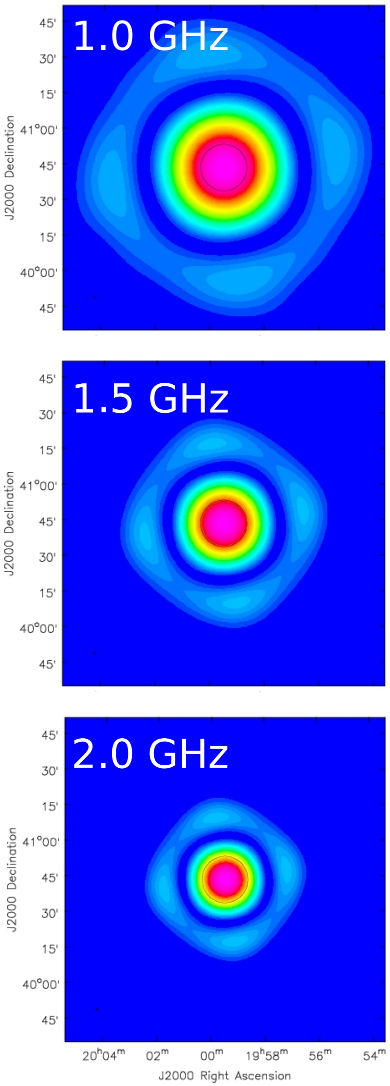
- About -0.4 at the PB=0.8
  (6 arcmin from the center)
- About -1.4 at the HPBW
  (15 arcmin from the center)

Primary beams also
- rotate with time
- have polarization structure
  (beam squint, etc...)





Wide-Band Primary Beam Correction



Cube Imaging

-- Sky model represents $I(\nu)P(\nu)$
-- Divide the output image at each frequency by $P(\nu)$

Multi-Term MFS Imaging

-- Output spectral index represents $I(\nu)P(\nu)$

-- Polynomial division
by PB Taylor coefficients

$$\frac{(I^m_{0,} I^m_{1,} I^m_{2,} \ldots)}{(P_{0,} P_{1,} P_{2,} \ldots)} = (I^{sky}_{0,} I^{sky}_{1,} I^{sky}_{2} \ldots)$$

Wideband A-Projection

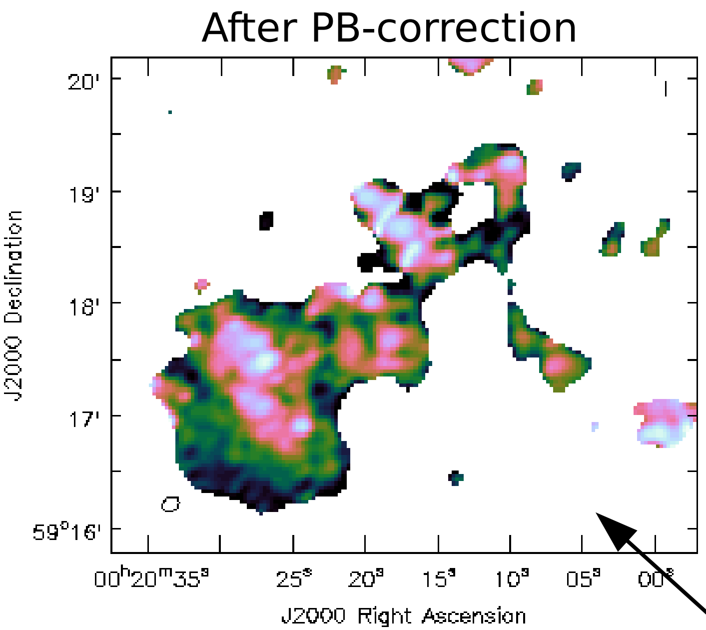
-- Remove $P(\nu)$
during gridding

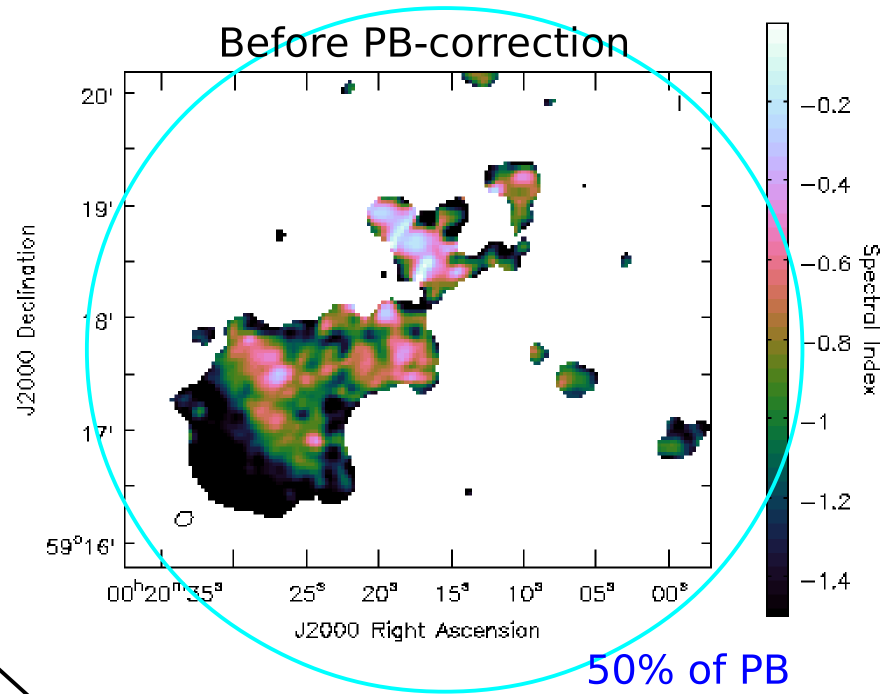
$$P_\nu . P_{\nu_c} \approx P^2_{\nu_{mid}} \qquad A^{-1}_\nu \approx \frac{A^T_{\nu_c}}{A^T_{\nu_c} * A_\nu}$$

-- Output spectral index image represents only the sky

Wideband VLA imaging of IC10 Dwarf Galaxy

[Heesen et al, 2011]



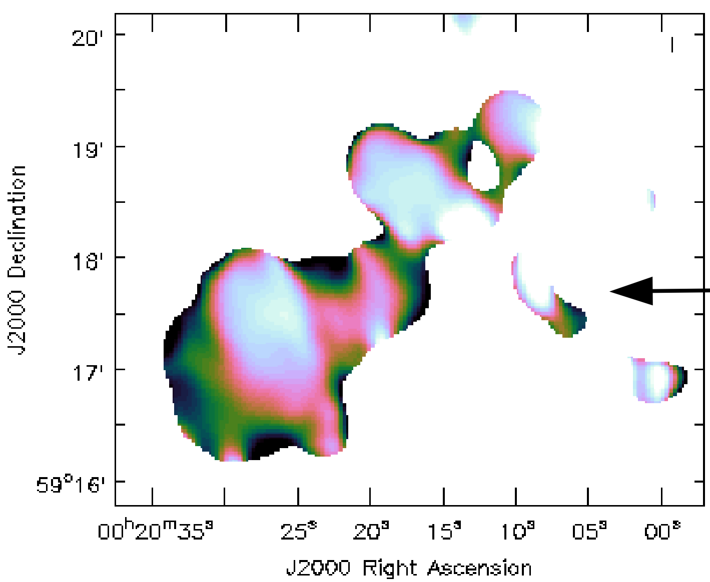


50% of PB

IC10 Dwarf Galaxy :

Spectral Index across C-Band.

Dynamic-range ~ 2000



MT-MFS : Wide-band PB-correction after multi-term multi-scale MFS.

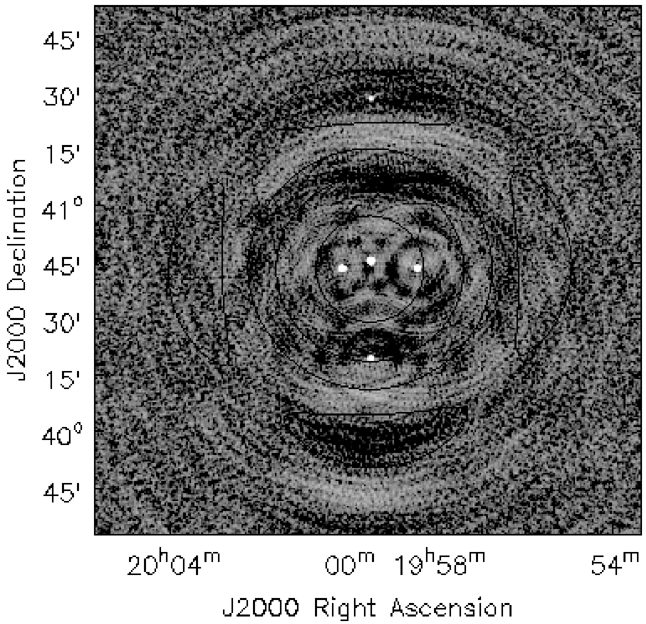
Cube : Spectral-index map made by cube imaging, smoothing to lowest resolution, and spectral fitting.

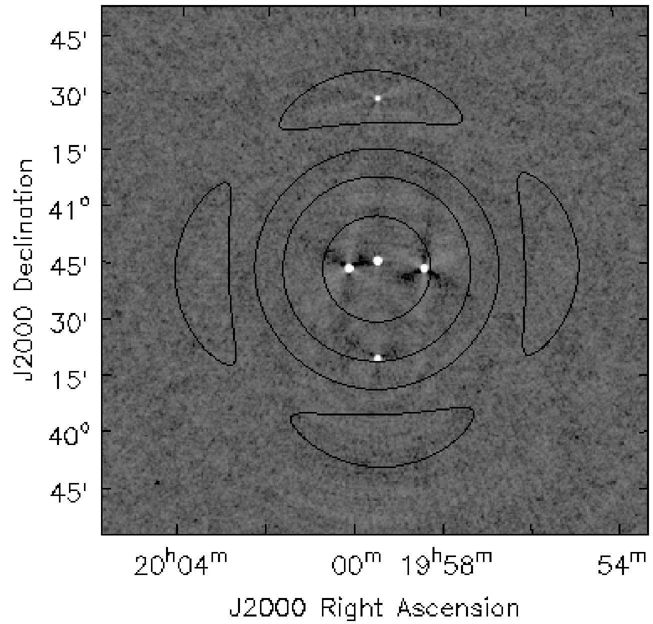
Wide Band Full Beam imaging – Algorithm Comparison

[Bhatnagar et al, 2013]

Basic MFS imaging

(no WB,WF corrections)



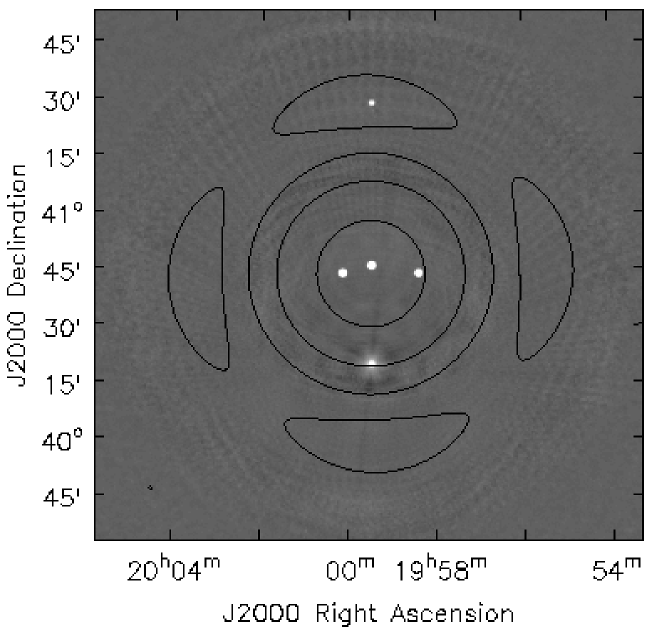


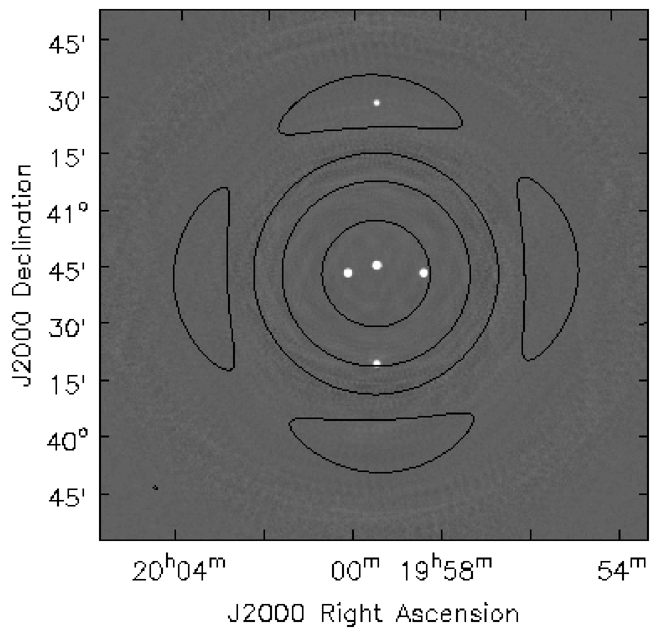
MT-MFS wideband imaging

(No WF corrections, PB freq dependence part of sky model)

MT-MFS wideband imaging + A-Proj

(PB^2 freq dependence part of sky model)



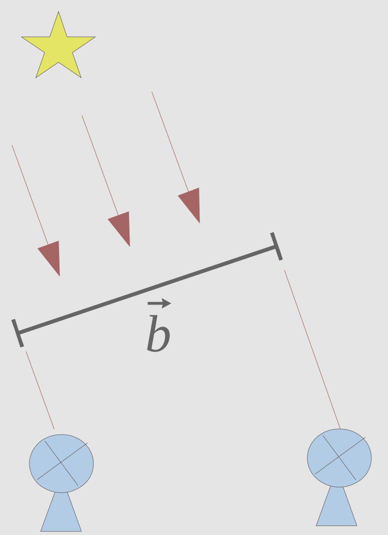


MT-MFS wideband imaging + WB-A-Proj

(PB freq dependence removed during gridding)

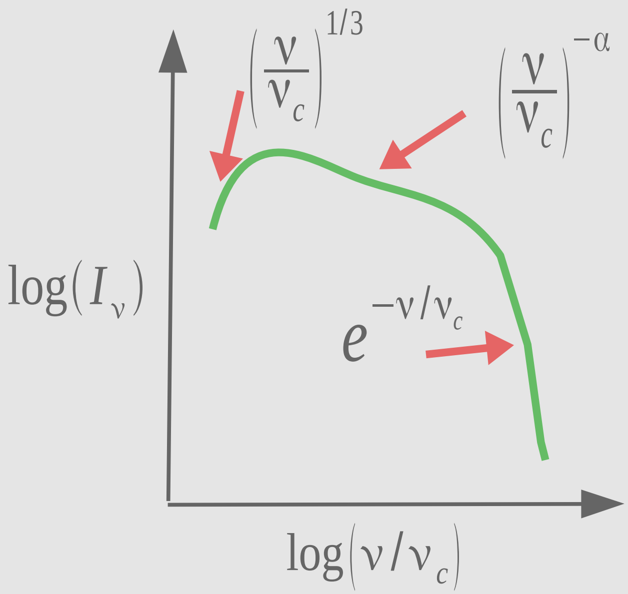
The instrument and the sky change with frequency...

UV-coverage



$$S(u,v)_\nu = \frac{\vec{b}}{\lambda} = \frac{\vec{b}\,\nu}{c}$$

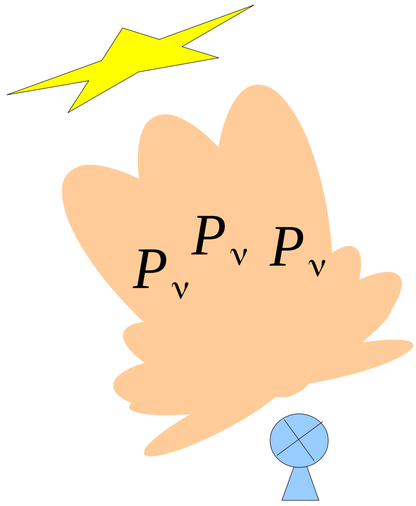
Sky Brightness



$$I(\nu)$$

Primary Beams

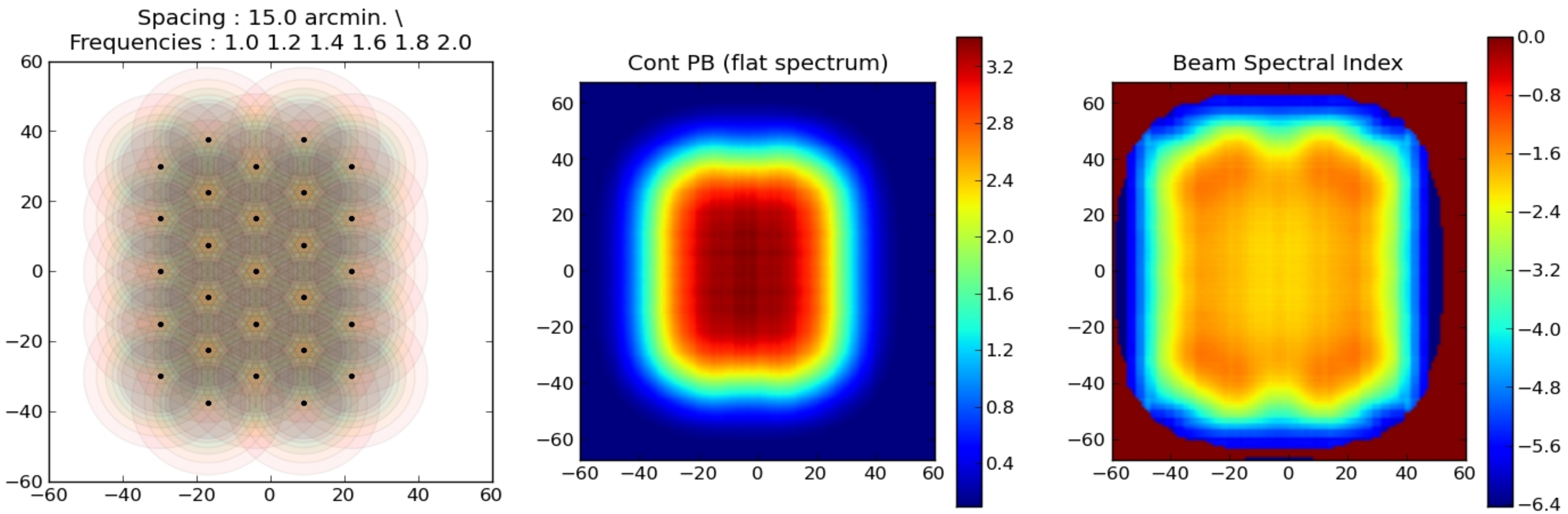
(Mosaic)



$$HPBW_\nu = \frac{\lambda}{D} = \frac{c}{\nu D}$$

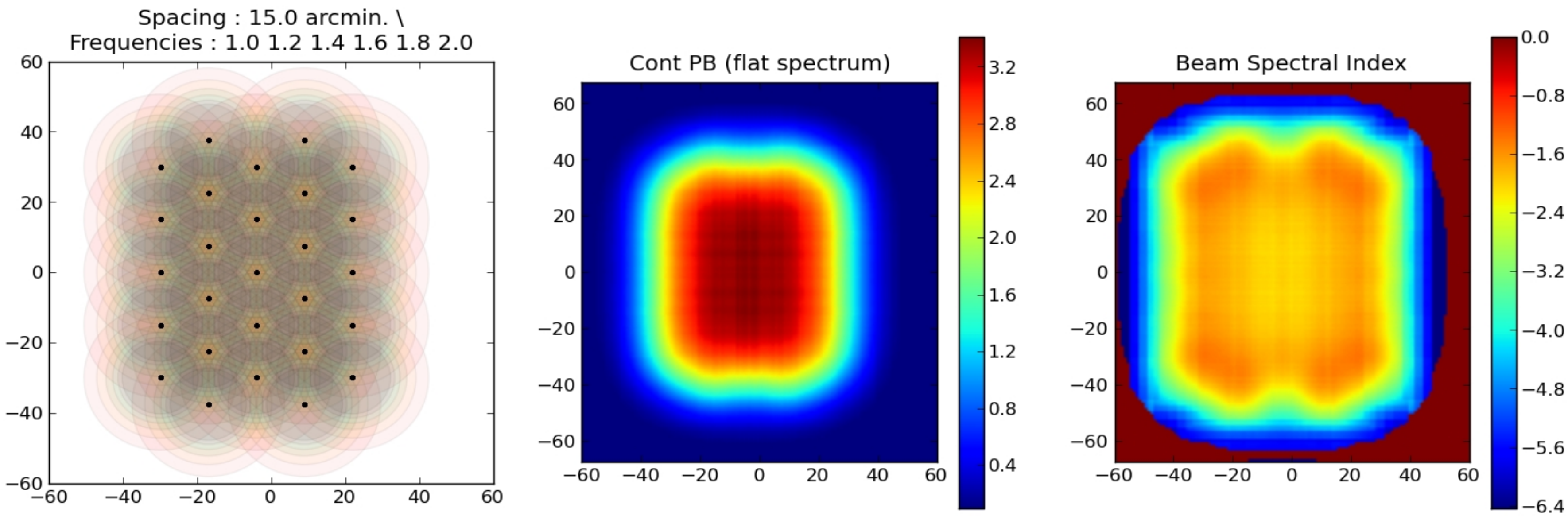
Wide-Band Wide-Field Imaging : Mosaics

The mosaic primary beam has an artificial spectral index all over the FOV



Wide-Band Wide-Field Imaging : Mosaics

The mosaic primary beam has an artificial spectral index all over the FOV



Algorithms :

- Deconvolve Pointings separately or together (Stitched vs Joint Mosaic)
  - Impacts image fidelity, especially of common sources.

- Deconvolve Channels separately or together (Cube vs MFS)
  - Impacts imaging fidelity and sensitivity, dynamic range

- Use A-Projection or not (Accurate vs Approximate PB correction)
  - Impacts dynamic range and spectral index accuracy

[Rau &Bhatnagar, 2017 (in prep)]

Wideband Mosaic Imaging Accuracy

[Rau et al, 2016]

Cube + Joint Mosaic
(with static Primary Beams)

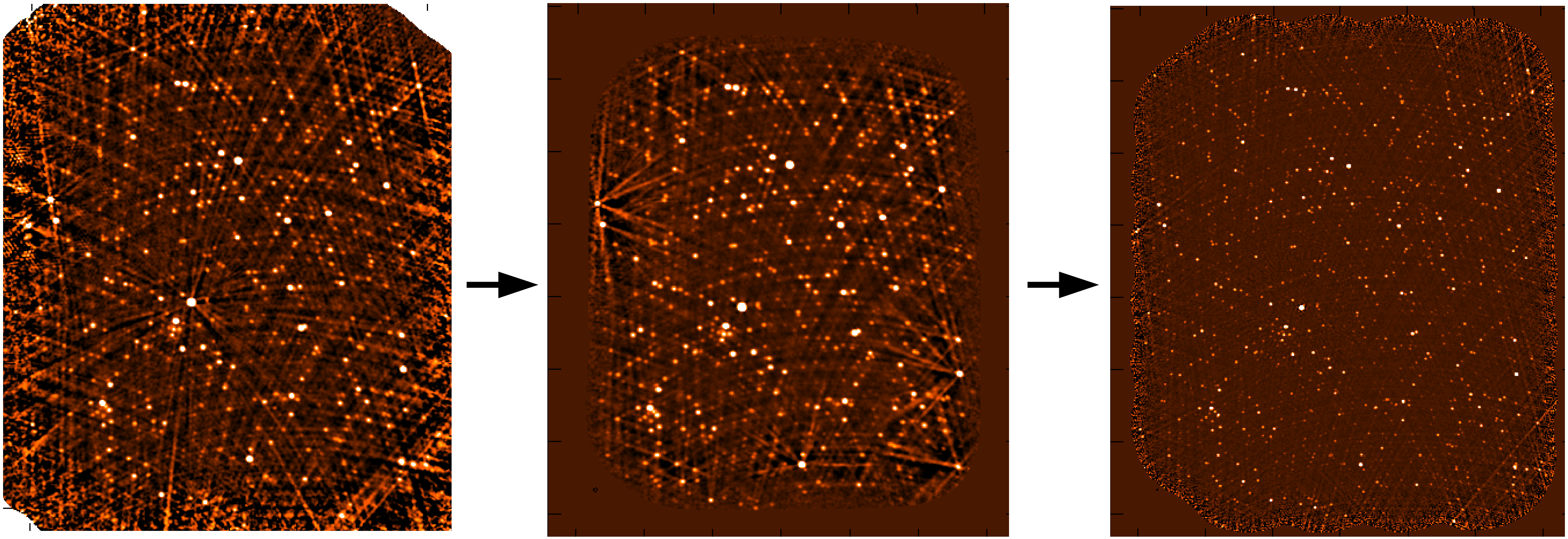
Dyn.Range = 5000:1

Cube + A-Projection + Joint Mosaic

Dyn.Range = 10000:1

Wideband A-Proj + Joint Mosaic + Multi-term MFS

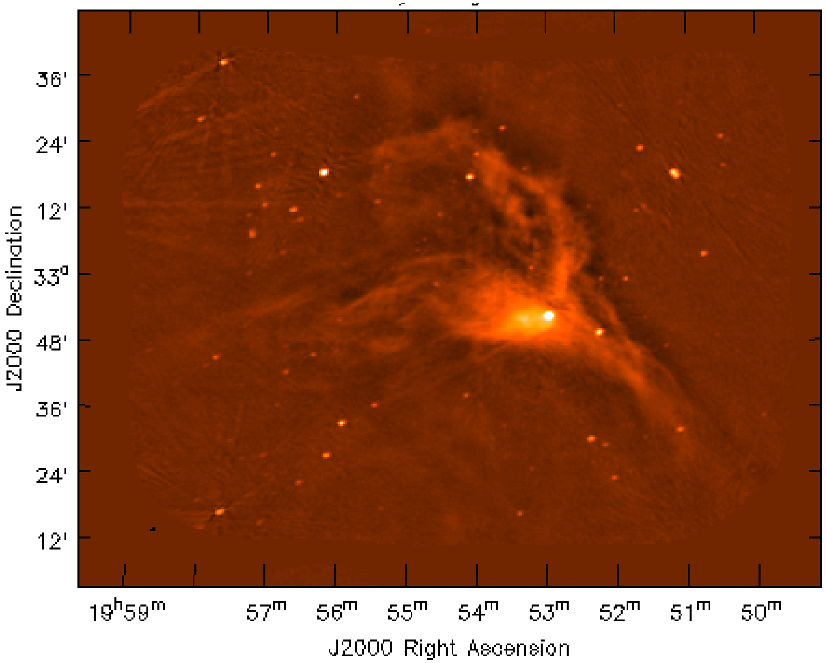
Dyn.Range = 40000:1



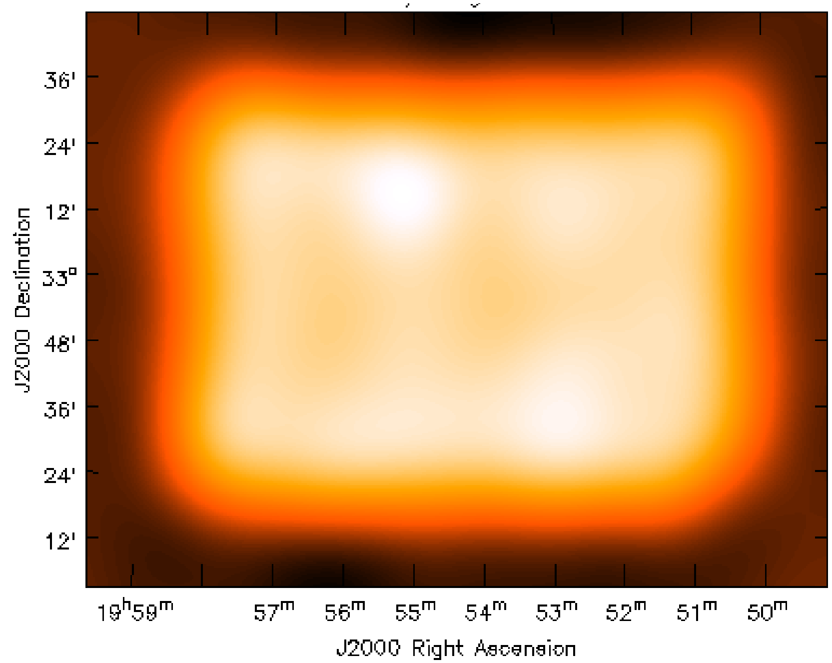
Method Intensity Range	I/I_{true} $> 20\mu Jy$	I/I_{true} $5 - 20\mu Jy$	I/I_{true} $< 5\mu Jy$	$\alpha - \alpha_{true}$ $> 50\mu Jy$	$\alpha - \alpha_{true}$ $10 - 50\mu Jy$
Cube	0.9 ± 0.1	0.9 ± 0.3	0.9 ± 0.5	-0.5 ± 0.2	-0.6 ± 0.5
Cube + AWP	1.0 ± 0.05	1.0 ± 0.2	1.0 ± 0.3	-0.15 ± 0.1	-0.1 ± 0.25
MTMFS + WB-AWP	1.0 ± 0.02	1.0 ± 0.04	1.0 ± 0.15	-0.05 ± 0.05	-0.1 ± 0.2

Wideband Mosaic of CTB80 (1-2 GHz, VLA-D config)

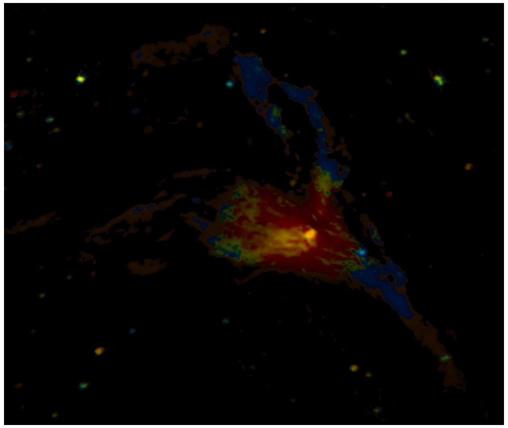
Intensity



Mosaic Primary Beam



Intensity-weighted
Spectral Index

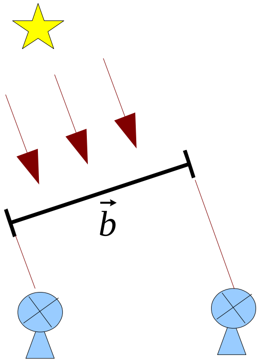


300GB calibrated dataset, 106 pointings over 1.5x2 deg, imaged with MT-MFS (NT=2) and WB-A-Projection.

Major cycle runtime without parallelization : ~10 days.
With 40 processes : 5 hrs   (CASA)

Wide-Band (wide-field) Imaging - Summary

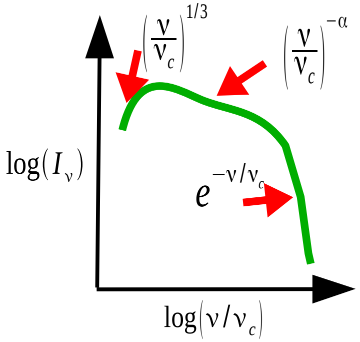
– UV coverage changes with frequency



-- Avoid bandwidth-smearing
-- Use multi-frequency-synthesis

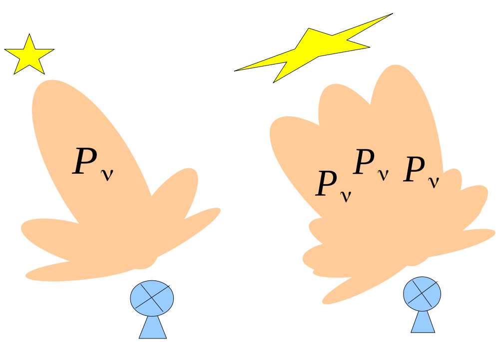
-- to increase the uv-coverage and image-fidelity
-- to make images at high angular-resolution

– Sky brightness changes with frequency



-- reconstruct intensity and spectrum together (MT-MFS)
-- (or) make a Cube of images

– Instrumental primary beam changes with frequency



-- divide PB-spectrum from observed sky-spectrum.
-- apply wide-field imaging techniques to eliminate
the PB frequency dependence during imaging.
-- Stitched vs Joint mosaics

– For very large scales, include single dish data before reconstruction

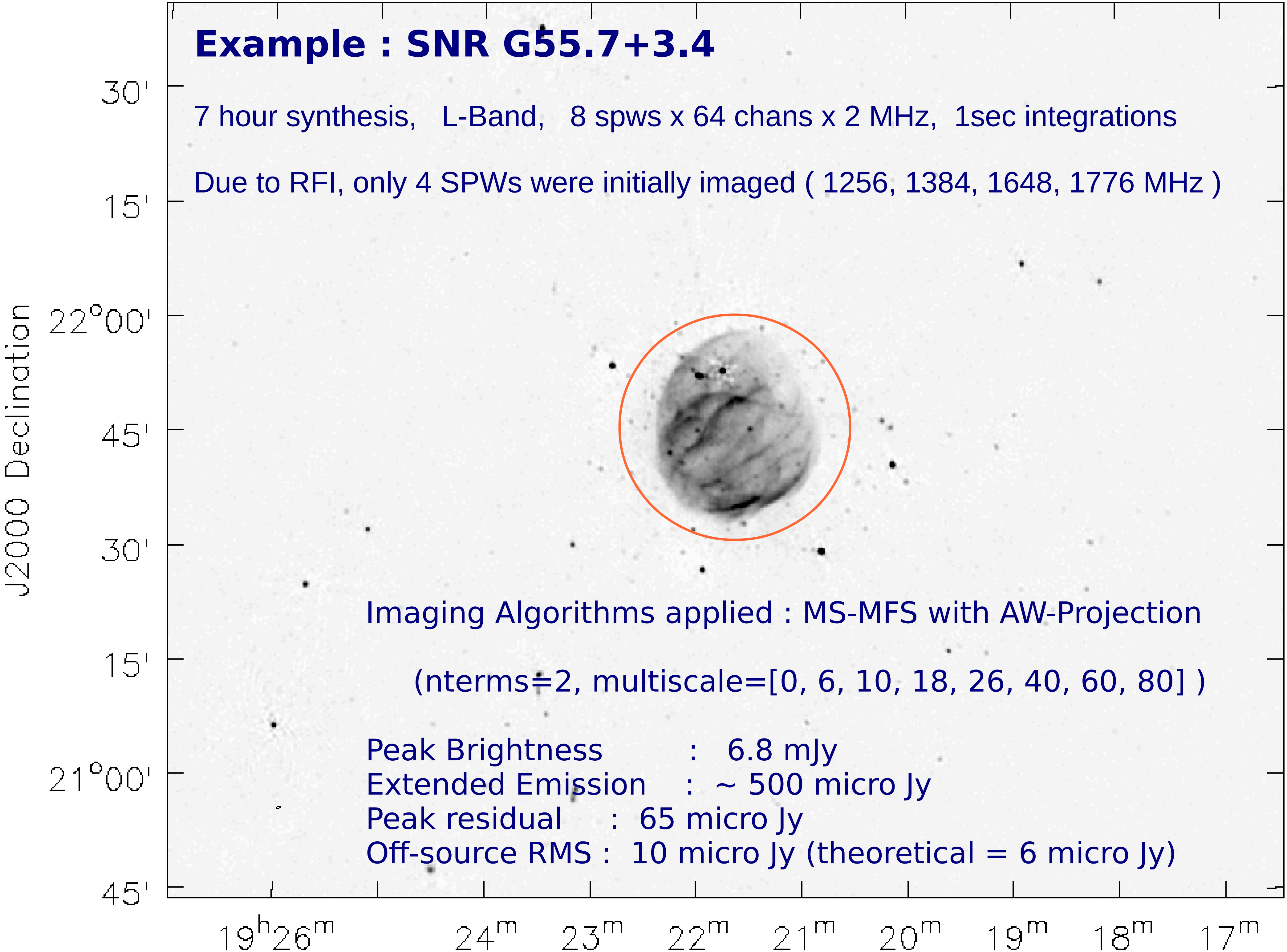
Outline

– WideBand Imaging
  – UV-coverage changes with frequency
  – Modeling wideband sky brightness
    – Point sources + Multi-Scale emission
    – Reconstructing very large spatial scales
  – Wideband primary beams + Mosaics
– Example : Imaging the G55 supernova remnant
– Summary
  – Basic CLEAN vs Wide-field Wide-band imagng
  – Imaging algorithm framework in CASA

Example : SNR G55.7+3.4

7 hour synthesis,   L-Band,   8 spws x 64 chans x 2 MHz, 1sec integrations

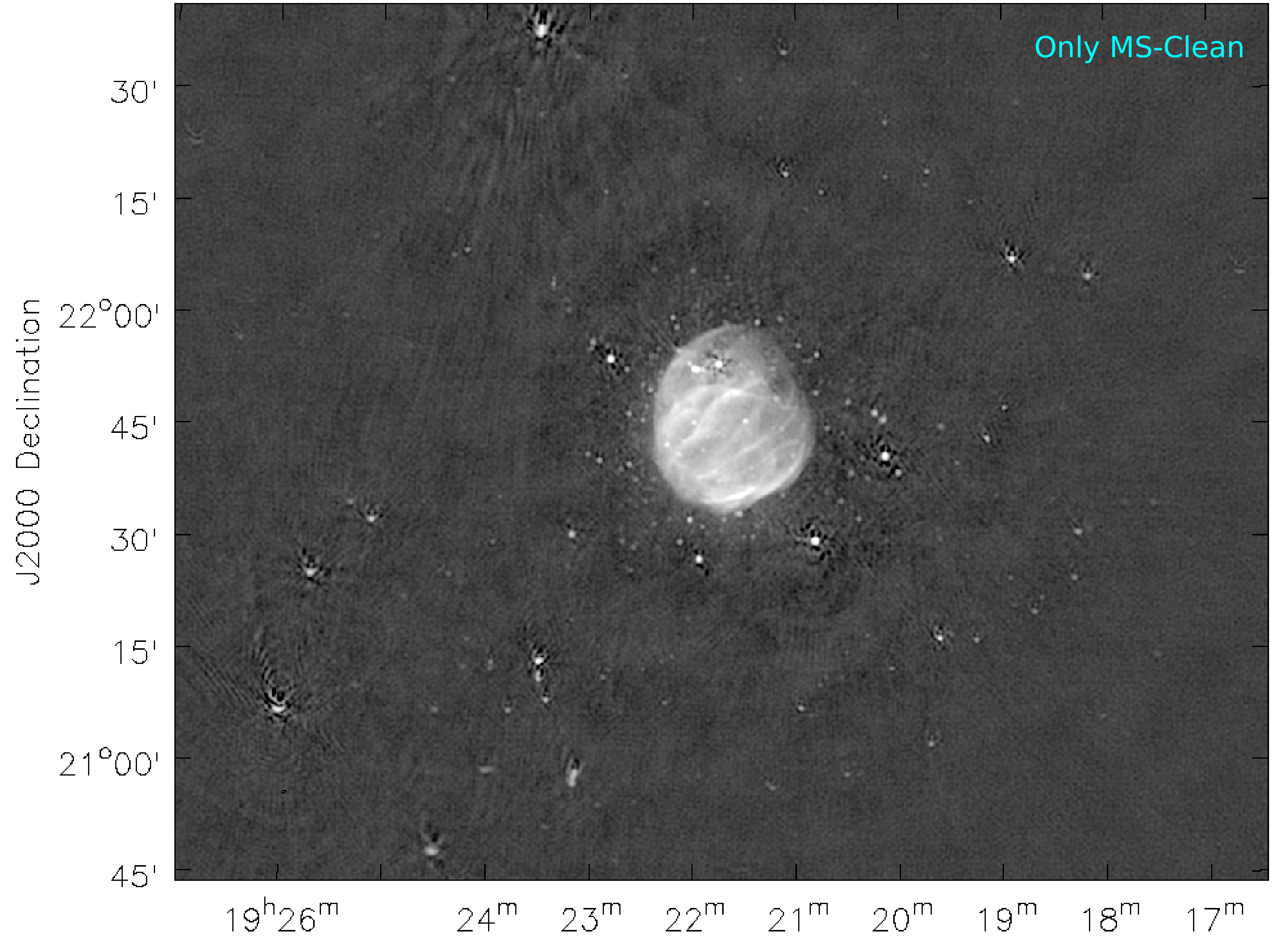
Due to RFI, only 4 SPWs were initially imaged (1256, 1384, 1648, 1776 MHz)

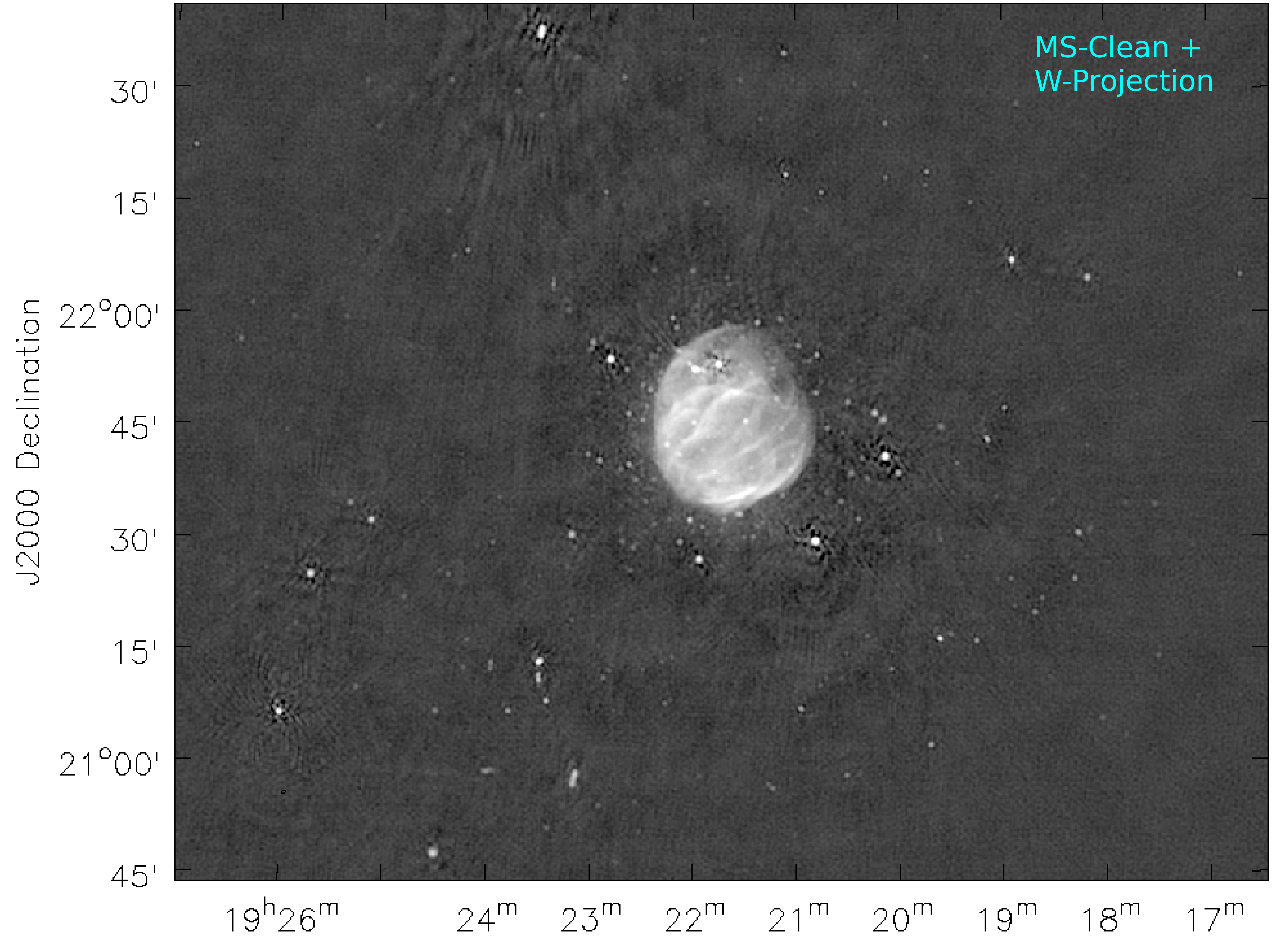


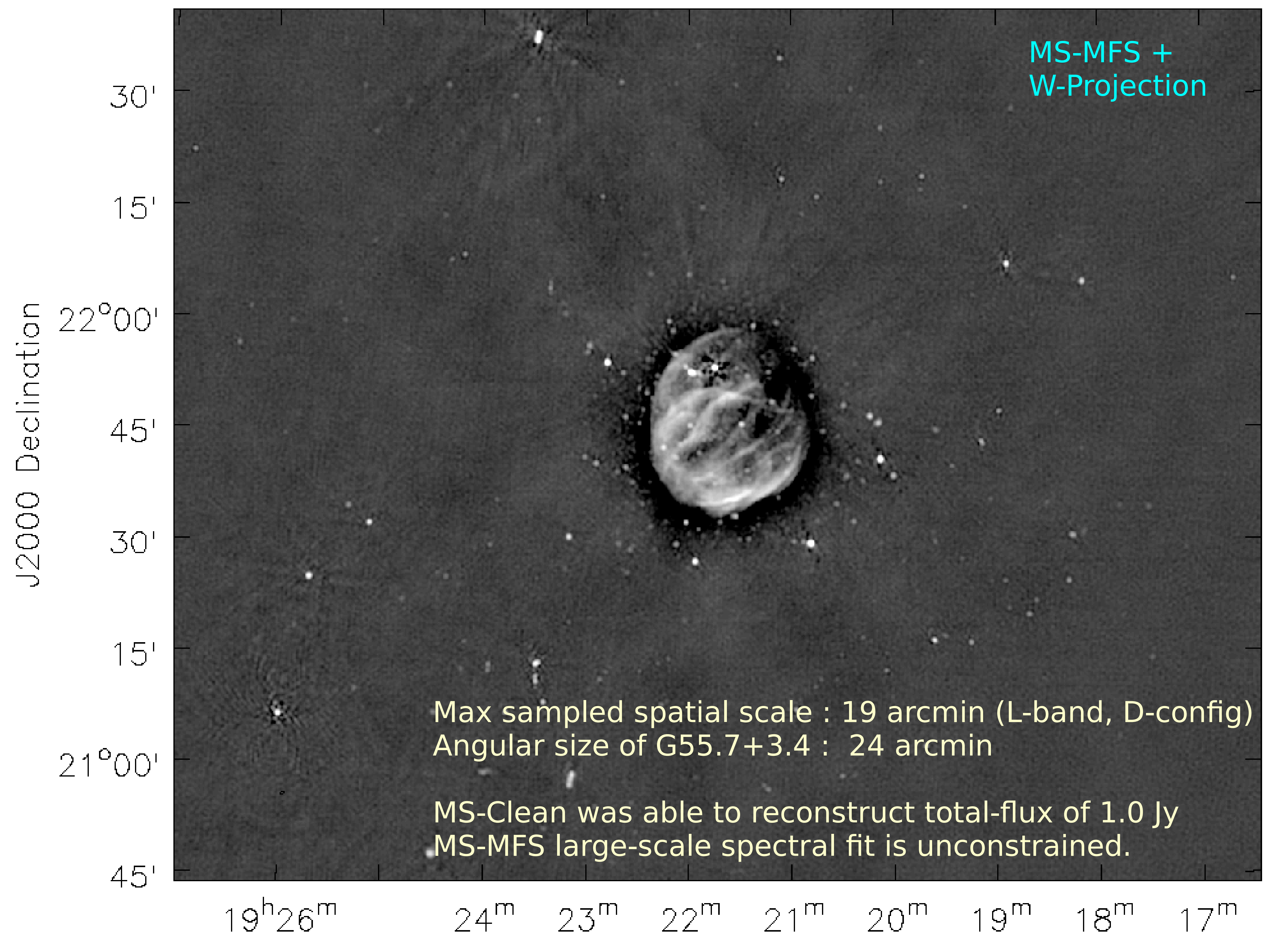
Imaging Algorithms applied : MS-MFS with AW-Projection

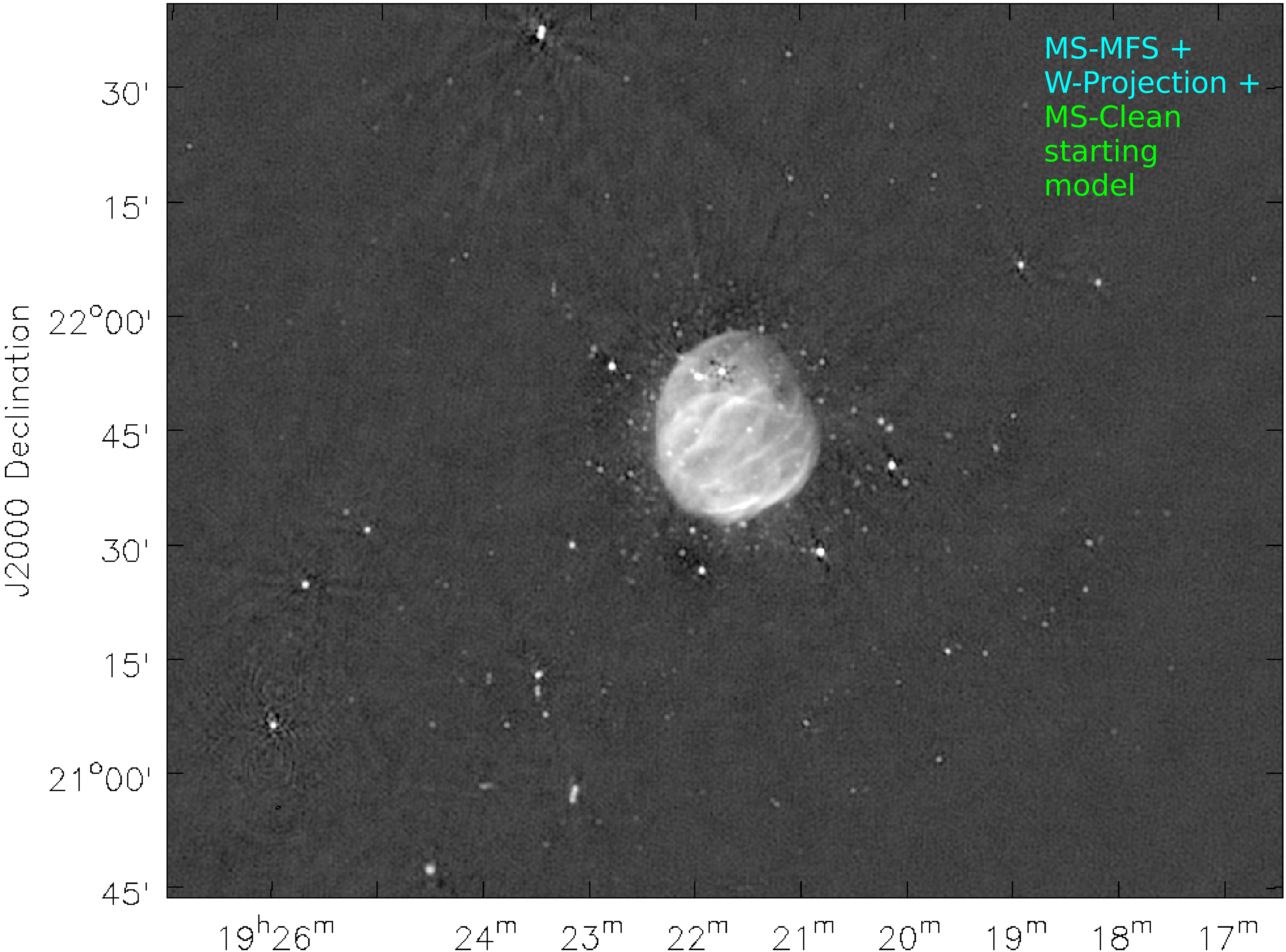
(nterms=2, multiscale=[0, 6, 10, 18, 26, 40, 60, 80])

Peak Brightness : 6.8 mJy
Extended Emission : ~ 500 micro Jy
Peak residual : 65 micro Jy
Off-source RMS : 10 micro Jy (theoretical = 6 micro Jy)


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

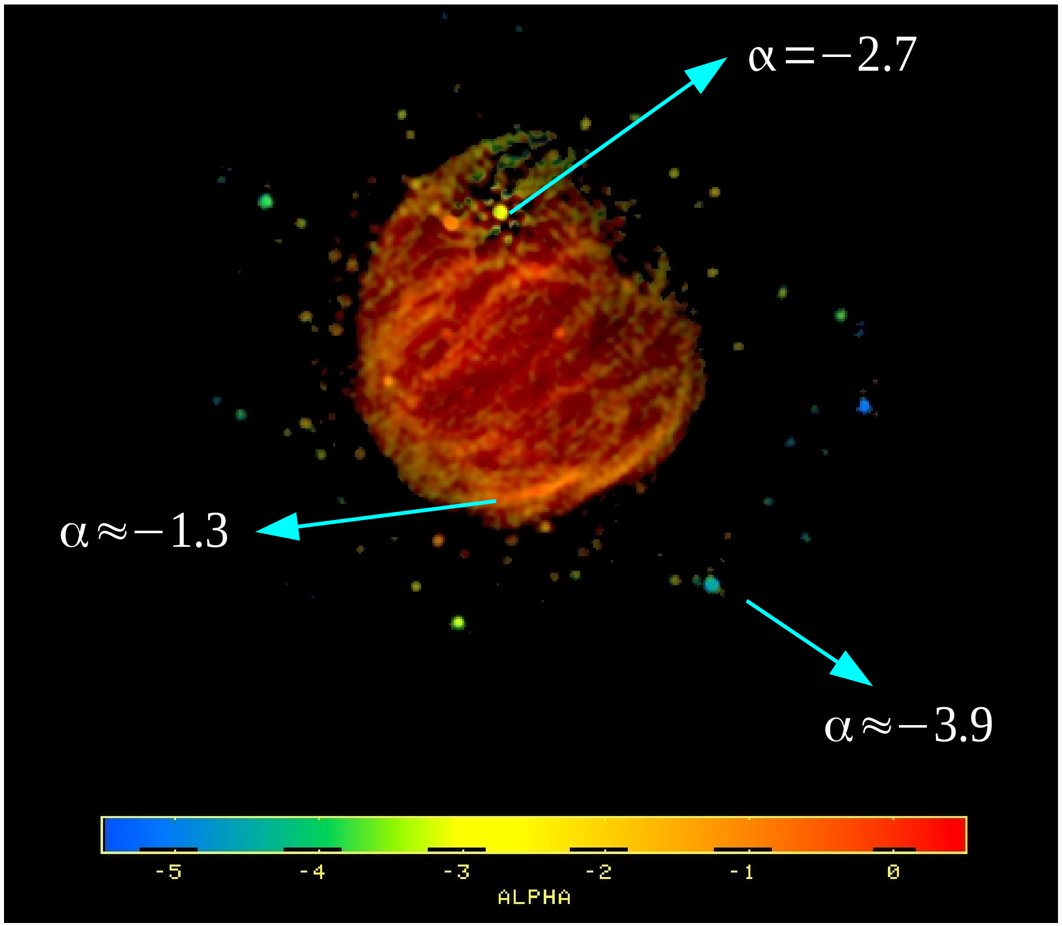

MS-MFS +
W-Projection
Max sampled spatial scale : 19 arcmin (L-band, D-config)
Angular size of G55.7+3.4 : 24 arcmin
MS-Clean was able to reconstruct total-flux of 1.0 Jy
MS-MFS large-scale spectral fit is unconstrained.
J2000 Declination
30'
15'
22°00'
45'
30'
15'
21°00'
45'
19h26m
24m
23m
22m
21m
20m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

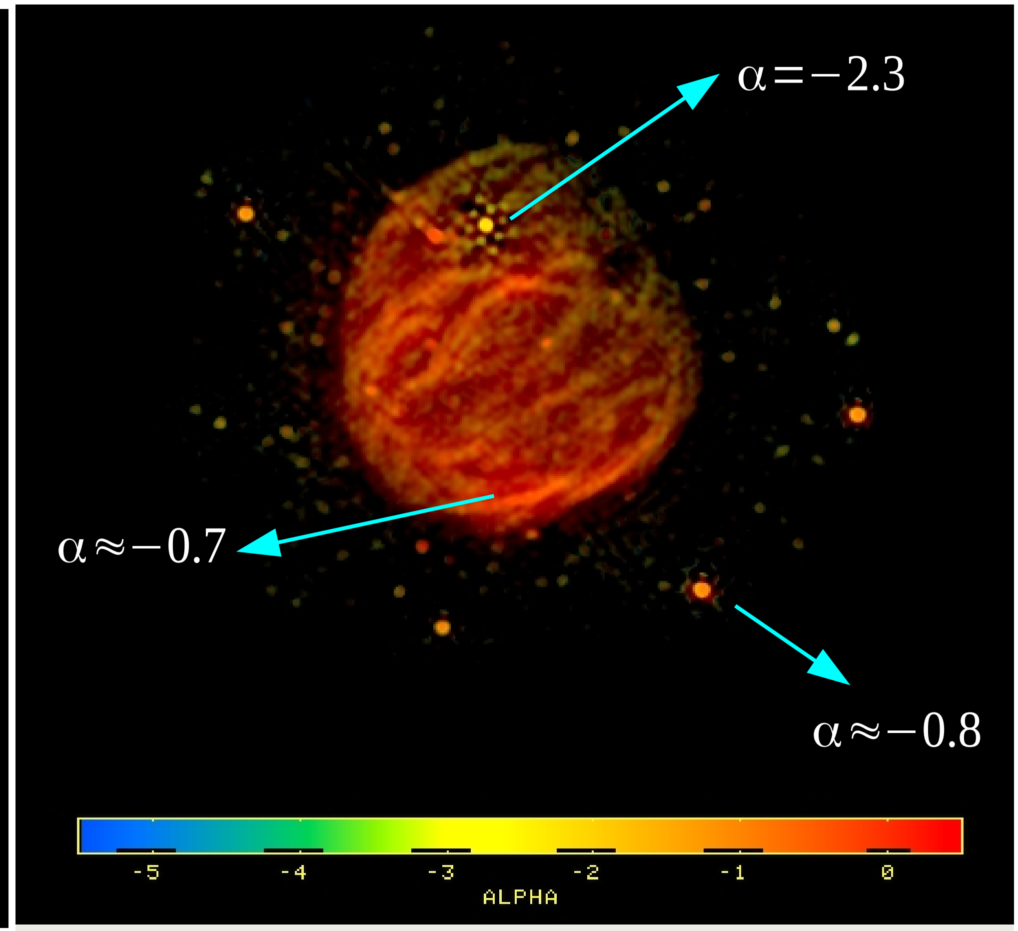

MS-MFS +
W-Projection +
MS-Clean
starting
model
J2000 Declination
30'
15'
22°00'
45'
30'
15'
21°00'
45'
19h26m
24m
23m
22m
21m
20m
19m
18m
17m

Spectral Indices before and after WB-A-Projection

Without PB correction
Outer sources are artificially steep

With PB correction (via WB-AWP)
Outer sources have correct spectra





Intensity-weighted spectral index maps (color = spectral index from -5.0 to +0.2)
(Without single dish information, we can trust only small scale spectral index)

Wide-field sensitivity because of wide-bandwidths

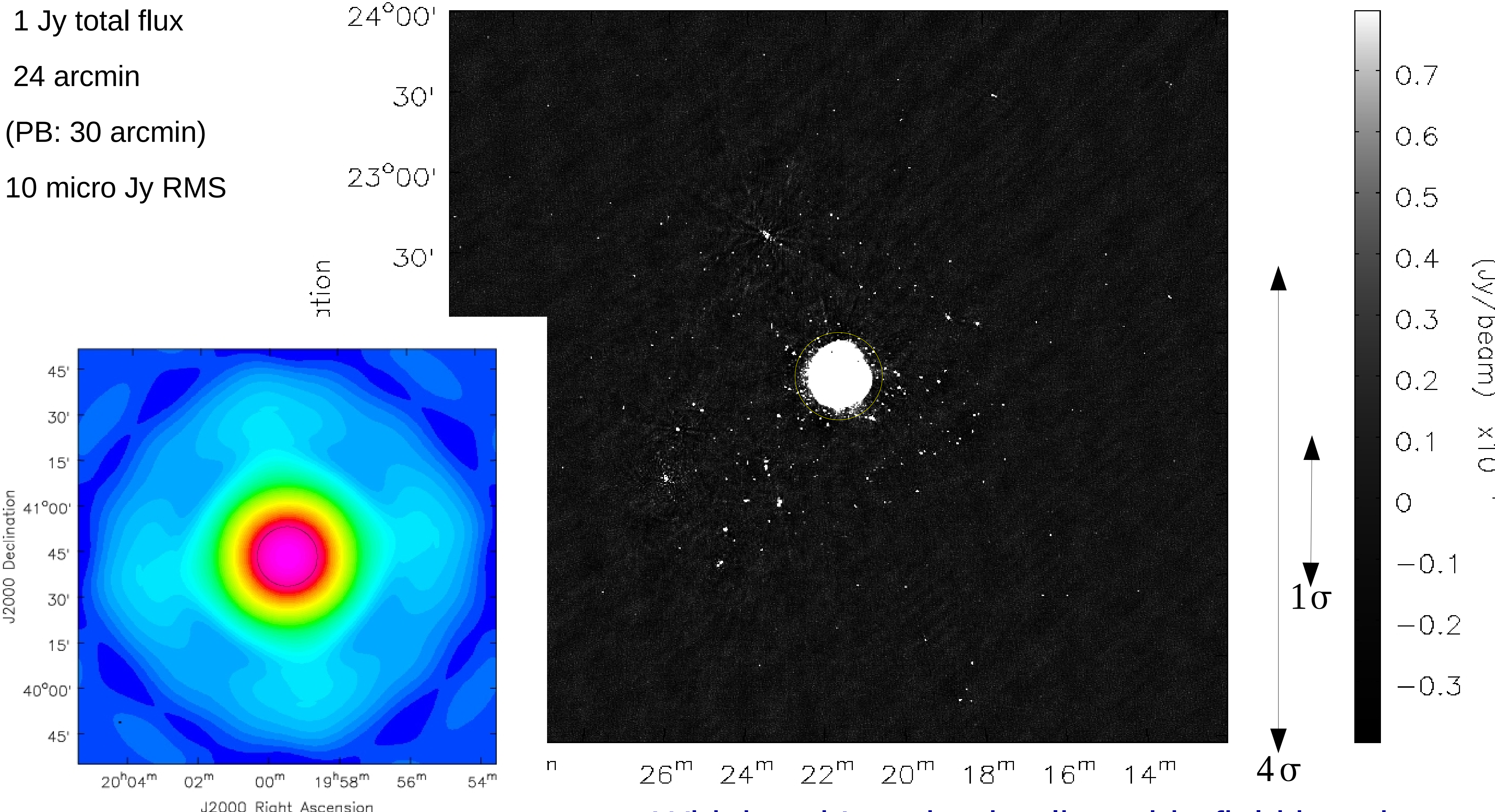
G55.7+3.4 : 4 x 4 degree field-of-view from one EVLA pointing

1 Jy total flux

24 arcmin

(PB: 30 arcmin)

10 micro Jy RMS



=> Wideband Imaging implies wide-field imaging

Outline

- WideBand Imaging
  - UV-coverage changes with frequency
  - Modeling wideband sky brightness
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  - Wideband primary beams + Mosaics
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  - Imaging algorithm framework in CASA

Basic Calibration and Imaging

An interferometer partially measures the spatial Fourier transform of the sky brightness distribution.

$$V_{ij}^{obs}(\nu,t) = \boxed{M_{ij}(\nu,t)}\, S_{ij}(\nu,t) \iint I(l,m)\, e^{2\pi i (ul+vm)}\, dl\, dm$$

Observed visibilities (Data)

Direction Independent Gains

UV sampling pattern

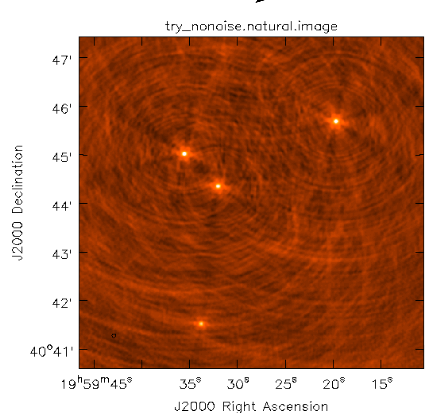
Sky Brightness (Image)

Fourier transform kernel

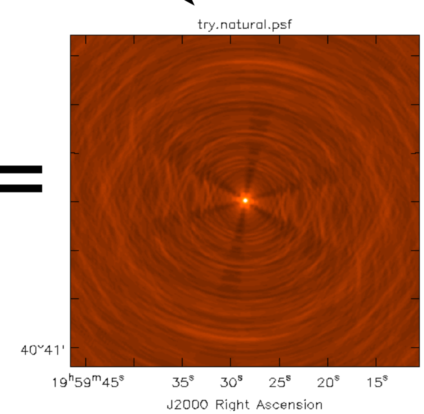
$$I^{obs}(l,m) = I^{PSF}(l,m) * I^{sky}(l,m)$$

Standard calibration eliminates $M_{ij}(\nu,t)$

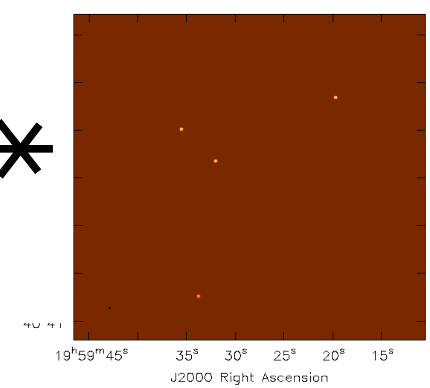
The observed image is a convolution of the PSF with the sky brightness.



=



$*$



Wide Band and Full Beam Imaging

An interferometer partially measures the spatial Fourier transform of the sky brightness distribution.

$$V_{ij}^{obs}(\nu,t) \approx M_{ij}(\nu,t) S_{ij}(\nu,t) \iint I(l,m) e^{2\pi i(ul+vm)} dl\, dm$$

$$V_{ij}^{obs}(\nu,t) = M_{ij}(\nu,t) S_{ij}(\nu,t) \iiint M_{ij}^{s}(l,m,\nu,t) I(l,m,\nu,t) e^{2\pi i(ul+vm+w(n-1))} dl\, dm\, dn$$

Direction Independent Gains

- Eliminated during calibration

Primary Beams

- Power pattern varies with time, frequency and baseline

Sky-brightness varies with frequency (time)

- All sources have spectral structure (some vary with time)

W-Term

-Non-coplanar baselines

-Sky curvature

Direction Dependent Effects

=> The observed image is NOT a simple convolution equation

Wide Band + Full Beam Imaging – Algorithms

The measurement equation of an interferometer (per baseline) :

$$V_{ij}^{obs}(\nu,t) = M_{ij}(\nu,t)\, S_{ij}(\nu,t) \iiint M_{ij}^{s}(l,m,\nu,t)\, I(l,m,\nu,t)\, e^{2\pi i (ul+vm+w(n-1))}\, dl\, dm\, dn$$

Direction Independent Gains

- Eliminated during calibration

Primary Beams

- Power pattern varies with time, frequency and baseline

– PBcor (post-deconvolution)

– A-Projection

- WB-A-Projection

Sky-brightness varies with frequency (time)

- All sources have spectral structure (some vary with time)

– Cube Imaging

– Multi-Frequency Synthesis (MFS)

– Multi-Term-MFS

(point source or multi-scale models)

W-Term

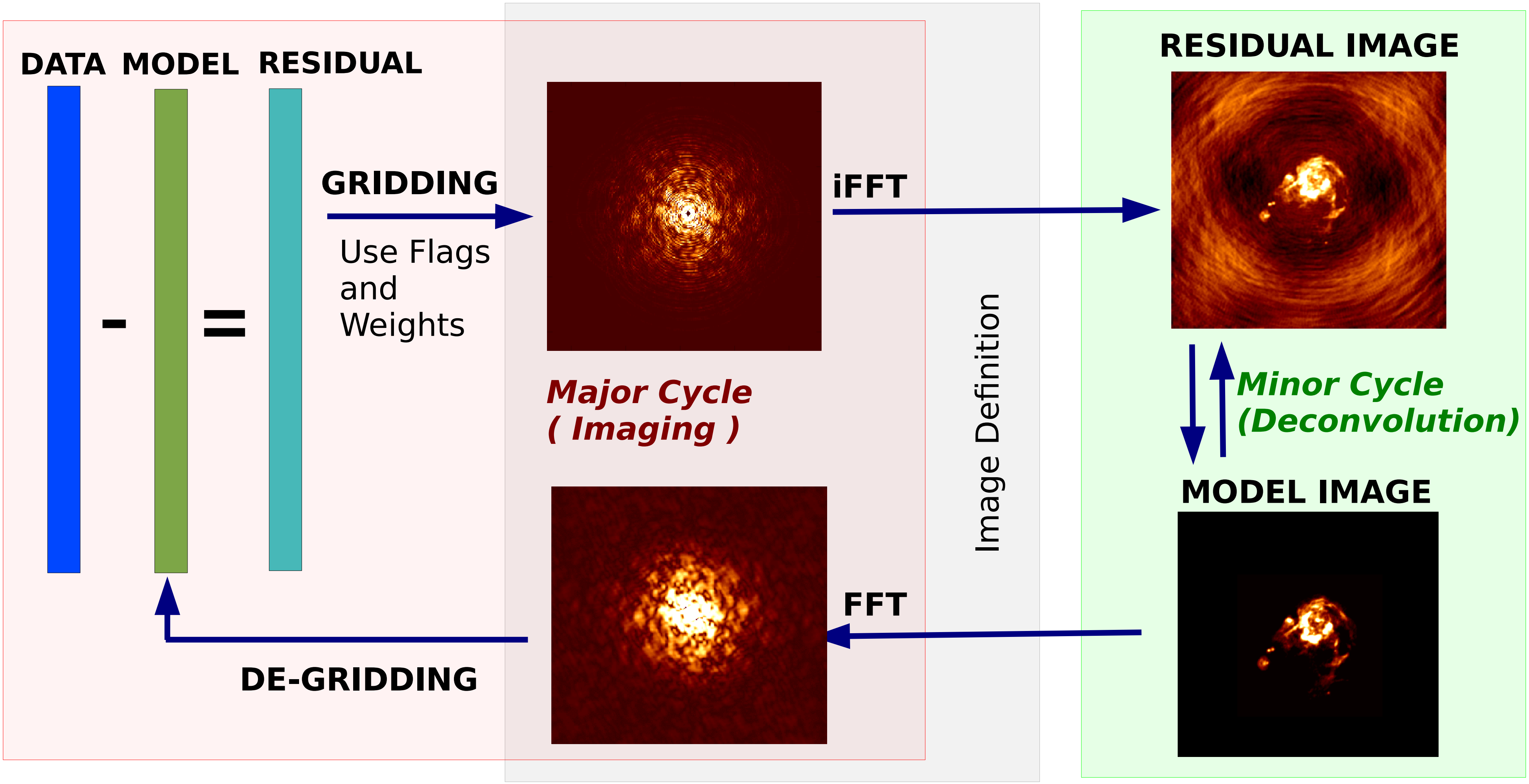
-Non-coplanar baselines

-Sky curvature

– Faceting

- W-Projection

Iterative χ^2 minimization – Major and Minor Cycles in CASA



Standard gridding, W-Projection, (WB)-A-Projection, Joint Mosaics

Cube, MFS, MT-MFS, Faceting, Stokes, Multi-Field

Clean (Hogbom, Clark, MultiScale, MultiTerm, etc...)