Wide Band Imaging

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Wide-Band terminology

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

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Continuum sensitivity
improves with **bandwidth**.

$$\sigma_{cont} = \frac{\sigma_{chan}}{\sqrt{(N_{chan})}} \propto \frac{T_{sys}}{\sqrt{N_{ant}(N_{ant}-1)\ \delta\tau\delta\nu}}$$

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Imaging complexity due to frequency dependence of the sky and instrument increases with **bandwidth ratio**

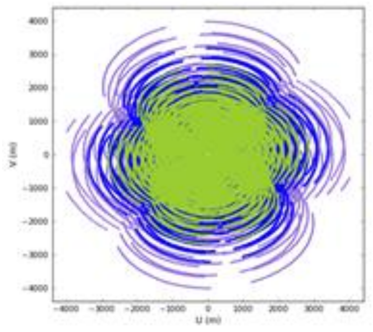
Sky and Instrument are frequency-dependent

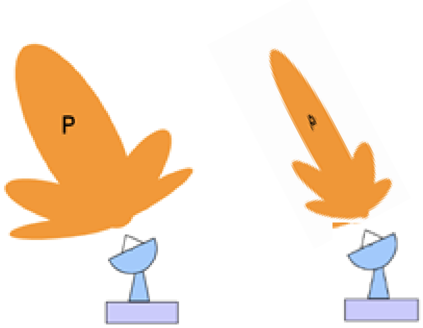
$$V_{ij}^{obs}(\nu,t)=M_{ij}(\nu,t)S_{ij}(\nu,t)\iiint M_{ij}^{dd}(l,m,\nu,t)I(l,m,\nu,t)e^{2\pi i(ul+vm+w(n-1))}dl\,dm\,dn$$

UV coverage

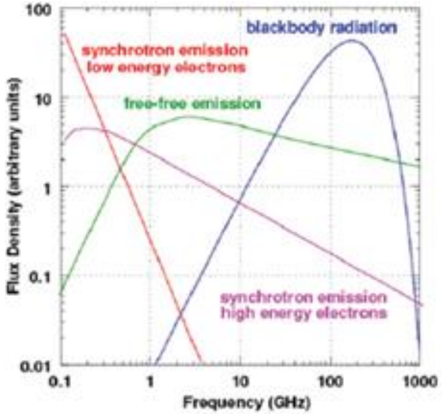
Primary Beam

Sky Brightness

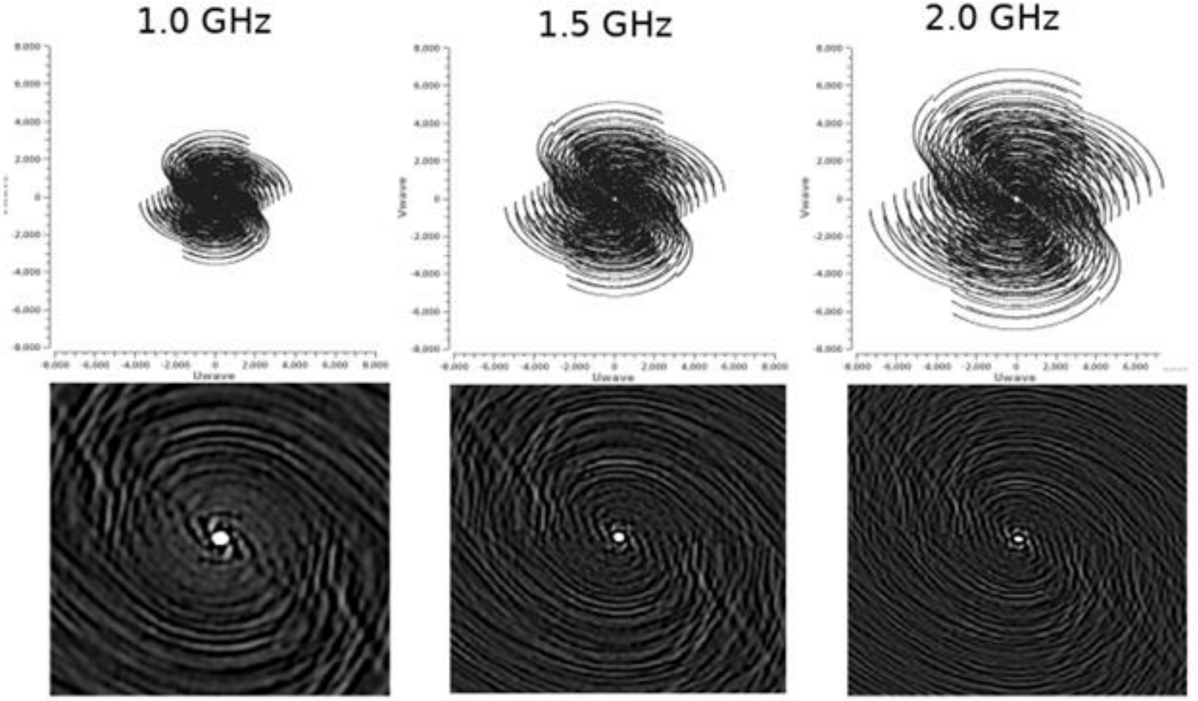




$\nu_1 < \nu_2$



Multi Frequency UV-coverage (and resolution)



Angular resolution changes with frequency.

Observed image : $I_{\nu}^{obs} = I_{\nu}^{sky} * PSF_{\nu}$

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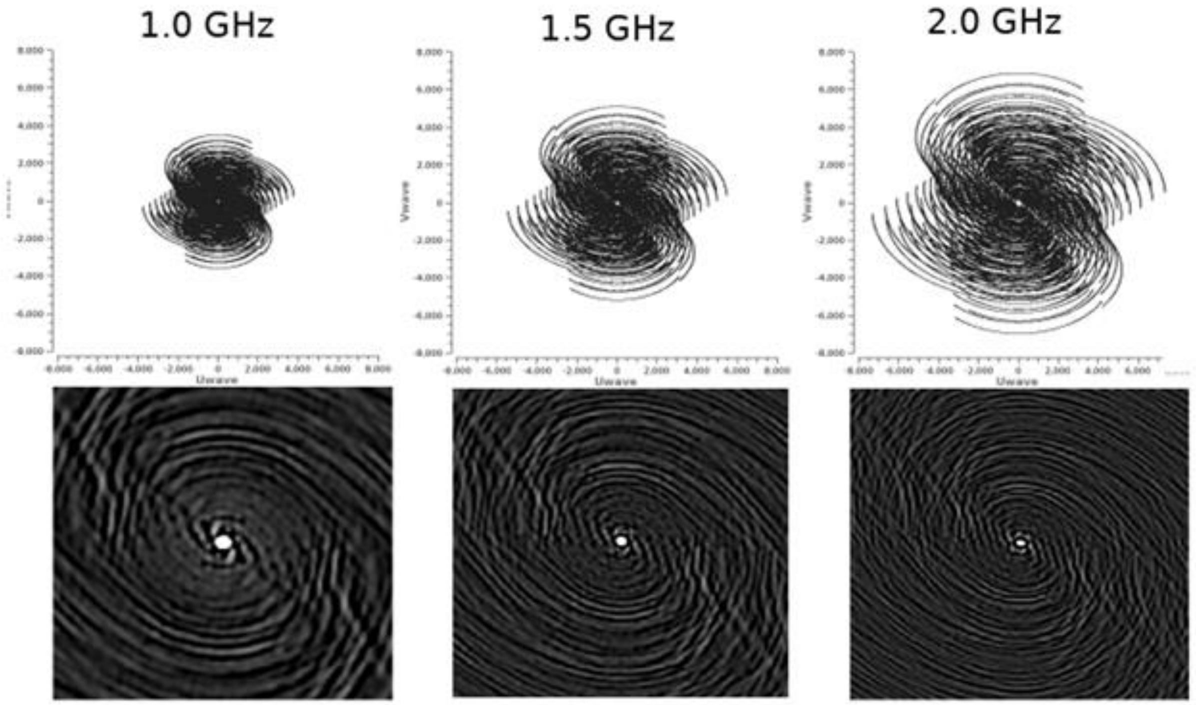


Observed image : $I_\nu^{obs} = I_\nu^{sky} * PSF_\nu$

Angular resolution changes with frequency.

Method 1 : Cube

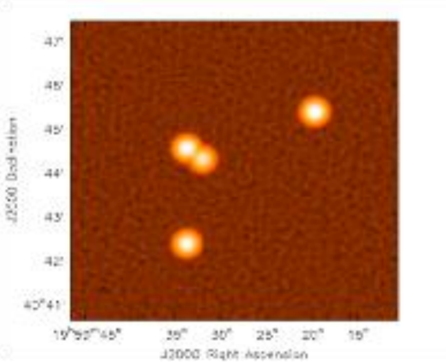
- Image each channel
- Smooth all to match lowest resolution
- Add them together

Simplest technique, but limited angular resolution

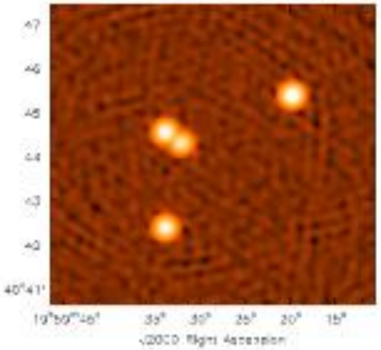
Cube Imaging + Image sum

Method 1 : Cube

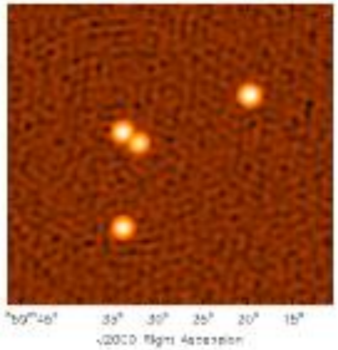
- Image each channel
- Smooth to match lowest resolution
- Add them together



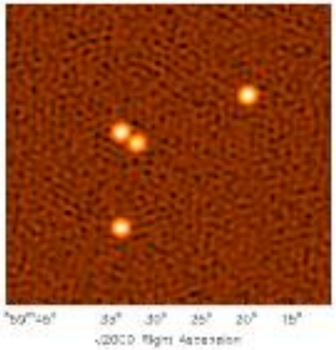
- Lower noise
- Lower resolution



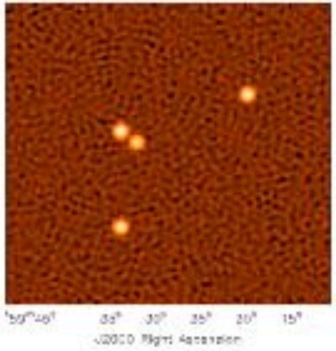
1.0 GHz



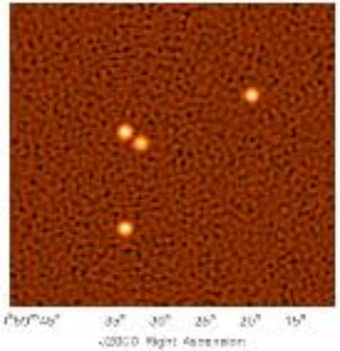
1.2 GHz



1.4 GHz

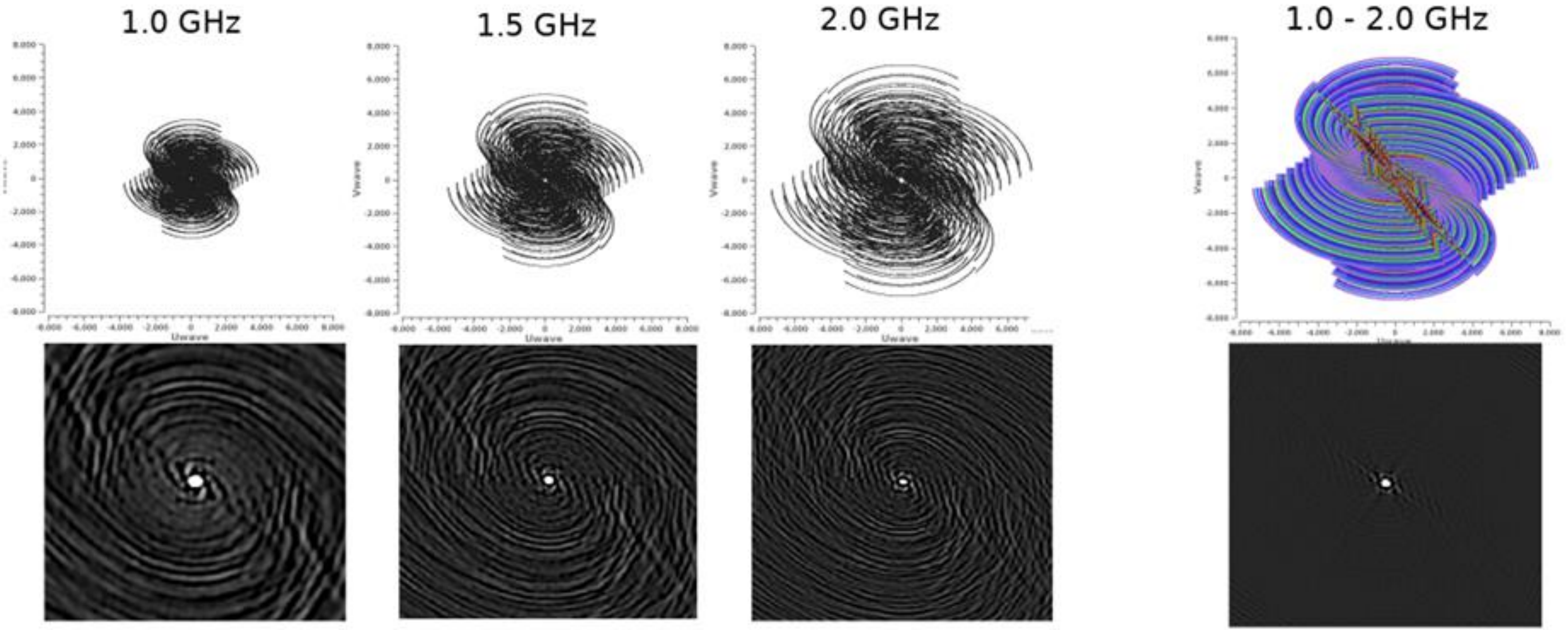


1.6 GHz



1.8 GHz

Multi Frequency Synthesis



Observed image : $I_\nu^{obs} = I_\nu^{sky} * PSF_\nu$

$$I_{wb}^{obs} = \sum_\nu \left[I_\nu^{sky} * PSF_\nu \right]$$

Multi Frequency Synthesis

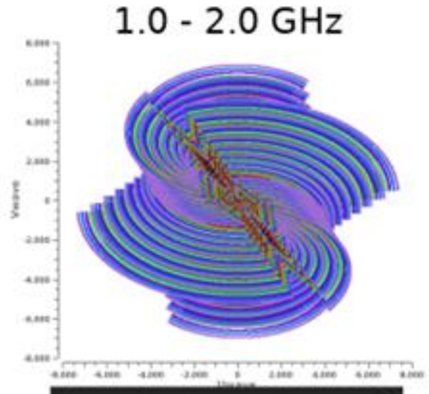
Angular resolution and PSF sidelobe levels
are defined by the combined UV-coverage.

Method 2 : WideBand

- Image and deconvolve all data together

Flat-spectrum Source ⇒ All OK.

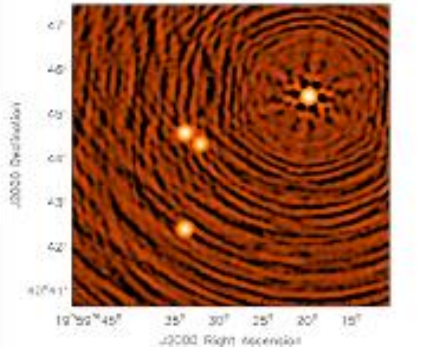
Steep-spectrum source
⇒ Need a wide band sky model



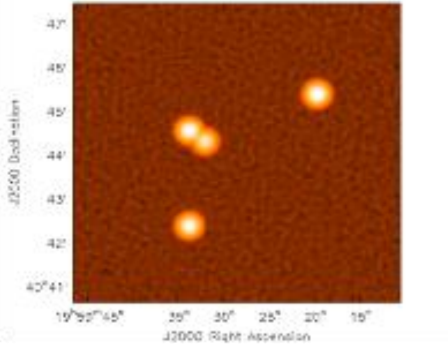
$$I_{wb}^{obs} = \sum_{\nu} \left[I_{\nu}^{sky} * PSF_{\nu} \right]$$

Multi Frequency Synthesis

MFS nterms=0



Cube



Angular resolution and PSF sidelobe levels are defined by the combined UV-coverage.

Method 2 : WideBand

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Steep-spectrum source

$\Rightarrow$ Need a wide band sky model

Multi Frequency Synthesis

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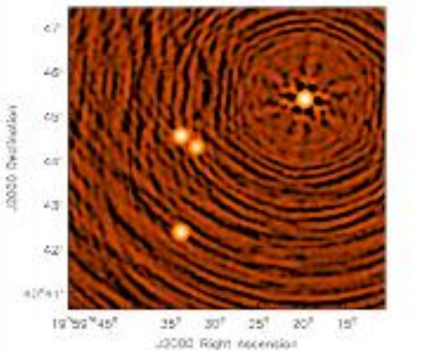
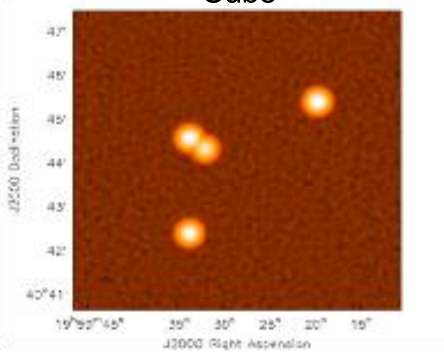
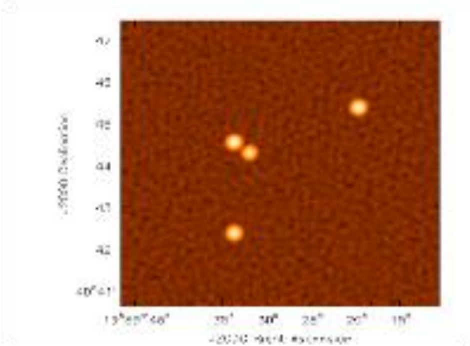
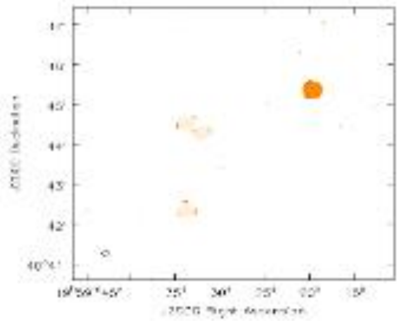


Cube

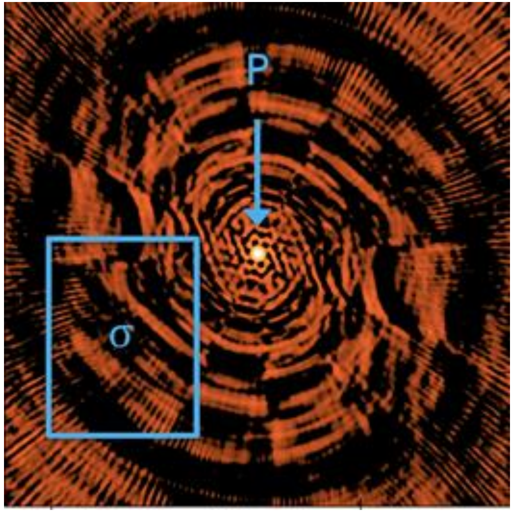


MFS nterms>1 Intensity and Spectral Index





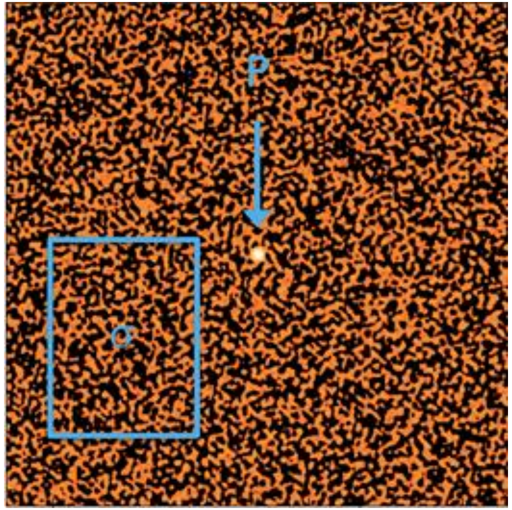
Which sources need wideband modeling ?



- Steep Spectrum source
- Low noise level

Artifacts are visible above the noise.

=> Need a wideband model (nterms>1)



- Steep Spectrum source
- High noise level

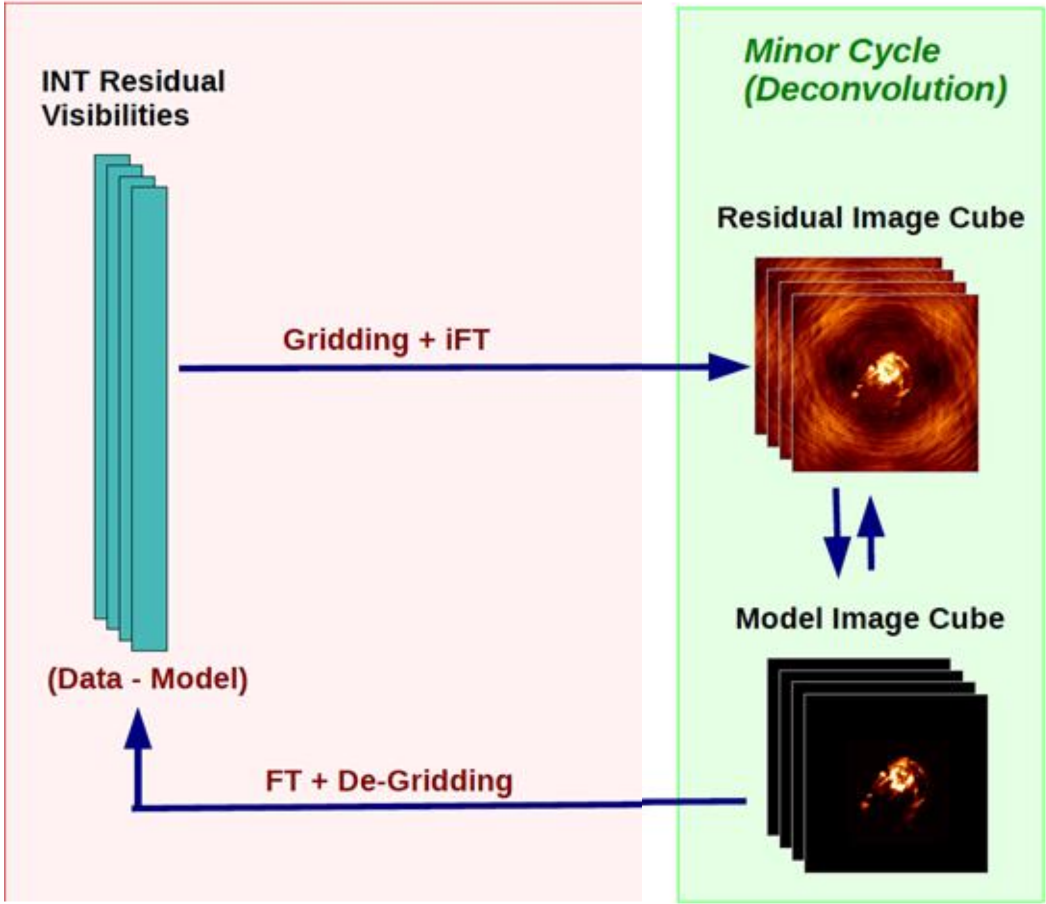
Artifacts are below the noise level

=> Flat-spectrum model will suffice

Images from J.Marvil

Algorithms that make a wide band sky model

Algorithms that make a wide band sky model



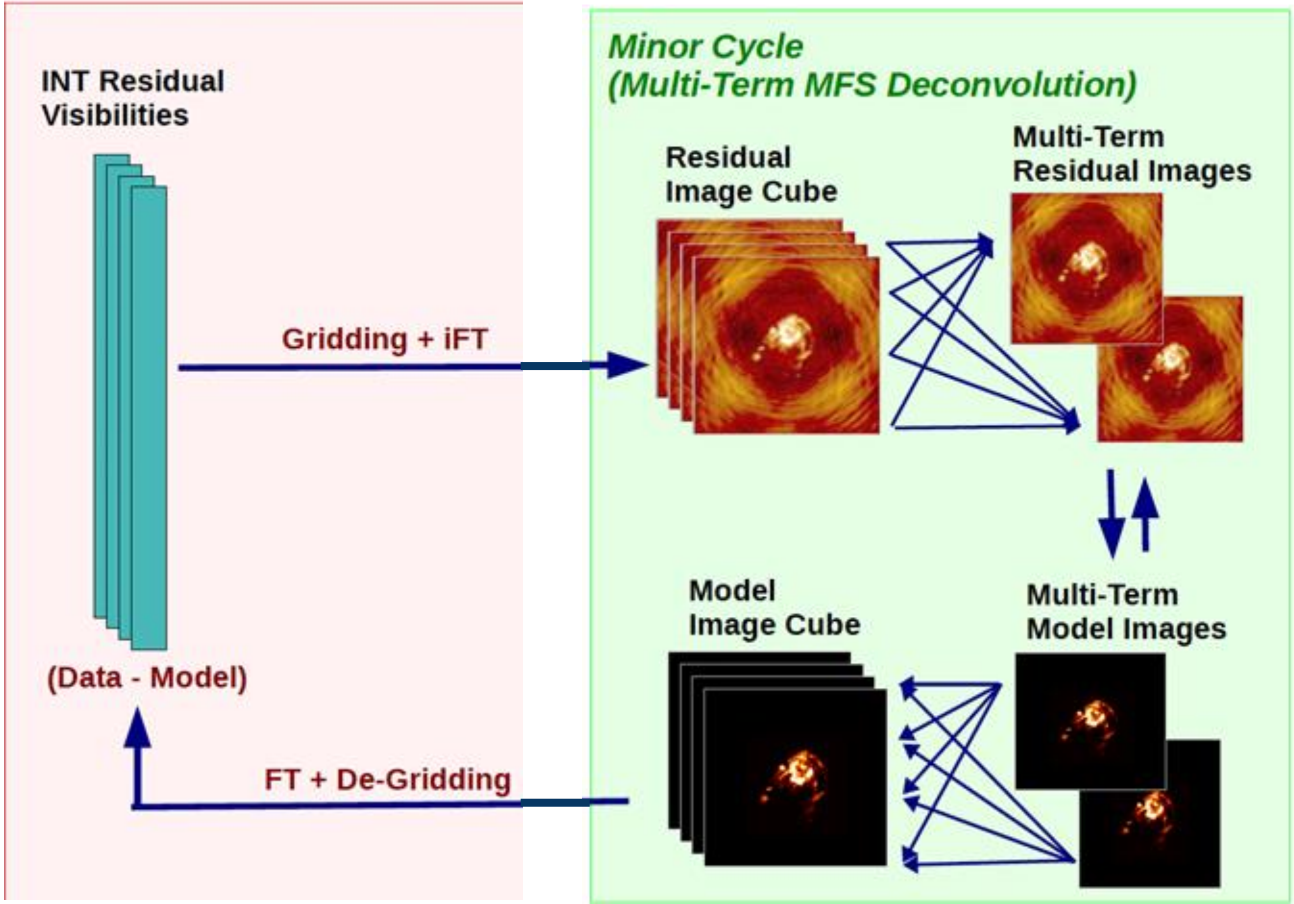
Solve for a sky model independently per channel

Intensity model

- Delta-functions, Gaussians, Paraboloids, etc as ‘atoms’

(Combine channels or fit a spectrum only with the output image cube)

Algorithms that make a wide band sky model



Intensity model

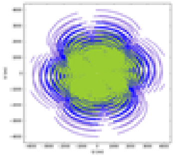
- Delta-fns, Gaussians, Paraboloids, etc as 'atoms'

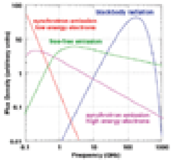
Spectral model (per 'atom')

- Stokes I : Polynomials, Power Laws
- Polarization : Faraday depth structure

Algorithms that make a wide band sky model

Multi-term MFS deconvolution (specmode='mfs' or 'mvc' in CASA tclean)





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

(Multi-term linear least squares)

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

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

Rau &Cornwell, 2011
Sault &Wieringa, 1994

WS-Clean *(Offringa/Smirnov 2017)* & Obit MF-Image *(Cotton, 2025)* :

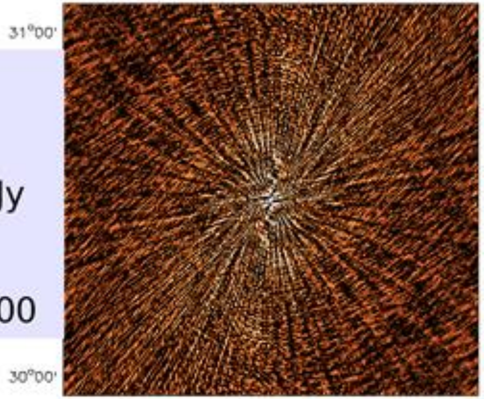
- Other Taylor-term and Cube-based modeling options during the deconvolution step.
- MF-Image also chooses the order of the polynomial, based on the source SNR

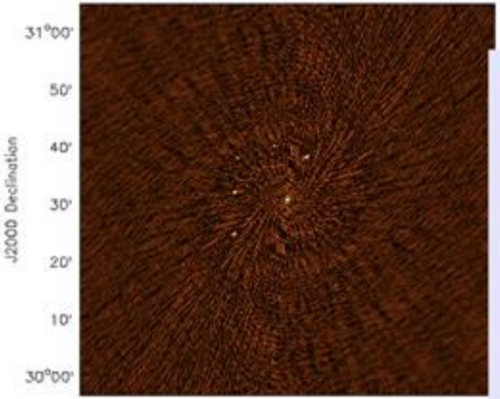
High Dynamic Range Continuum Imaging - 3C286 VLA

NTERMS = 1

Rms :
9 mJy -- 1 mJy

DR :
1600 - 13000

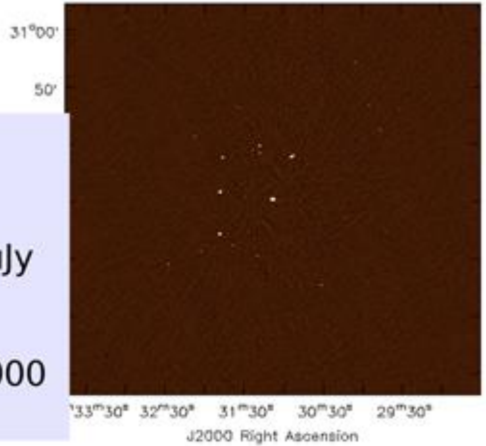




NTERMS = 2

Rms :
1 mJy -- 0.2 mJy

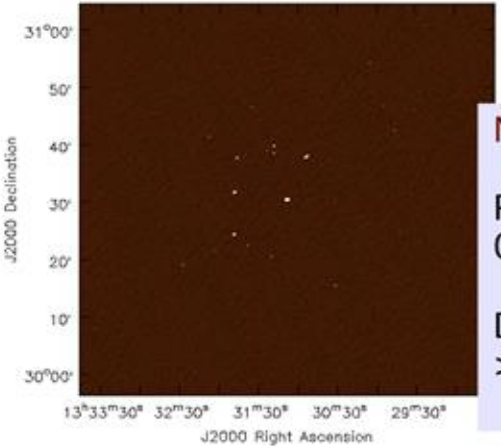
DR :
10,000 - 17,000



NTERMS = 3

Rms :
0.2 mJy -- 85 uJy

DR :
65,000 - 170,000

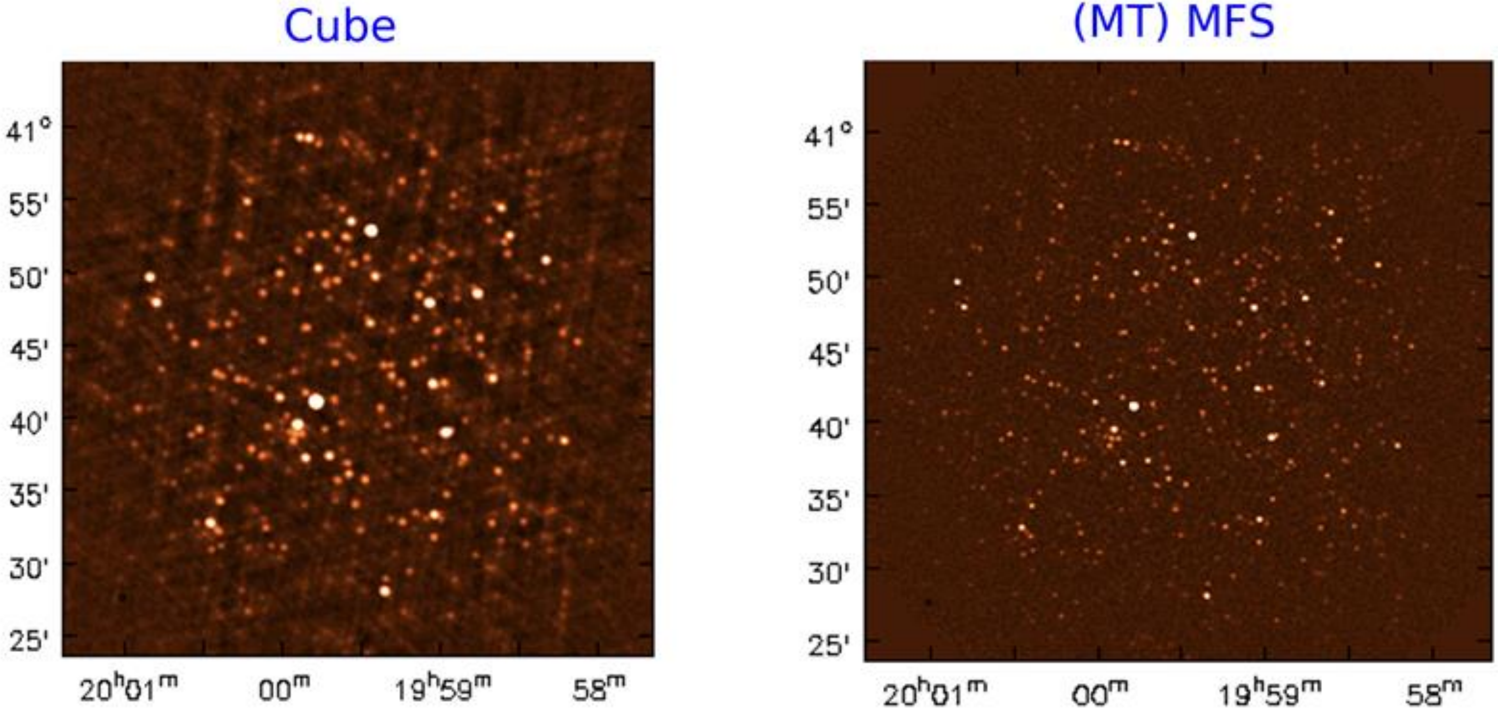


NTERMS = 4

Rms
0.14 mJy -- 80 uJy

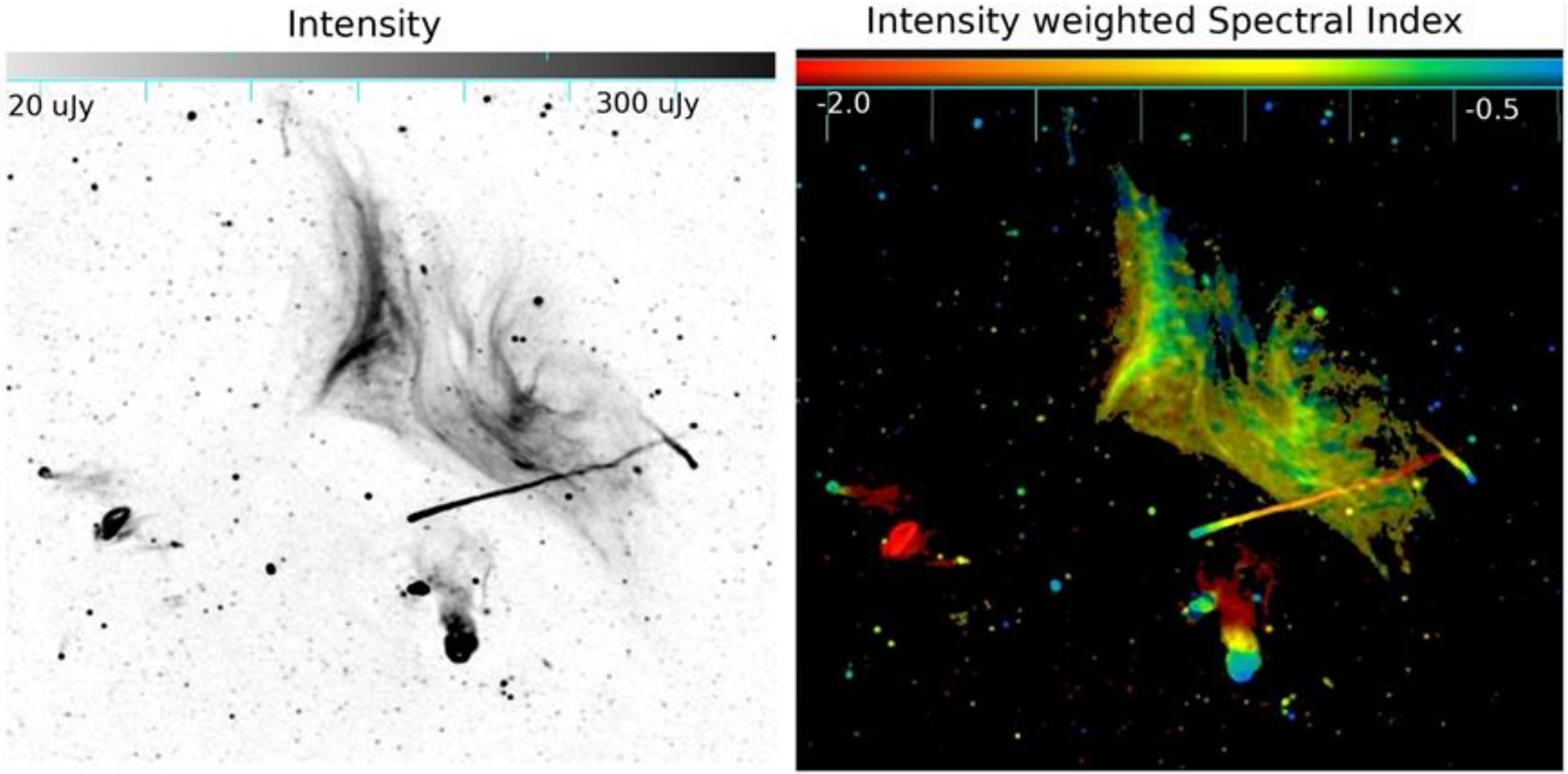
DR :
>110,000
- 180,000

Imaging fidelity with Cube vs Wideband Imaging



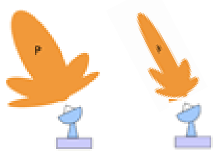
Compare angular resolution and imaging artifacts (**a simulated dataset**)

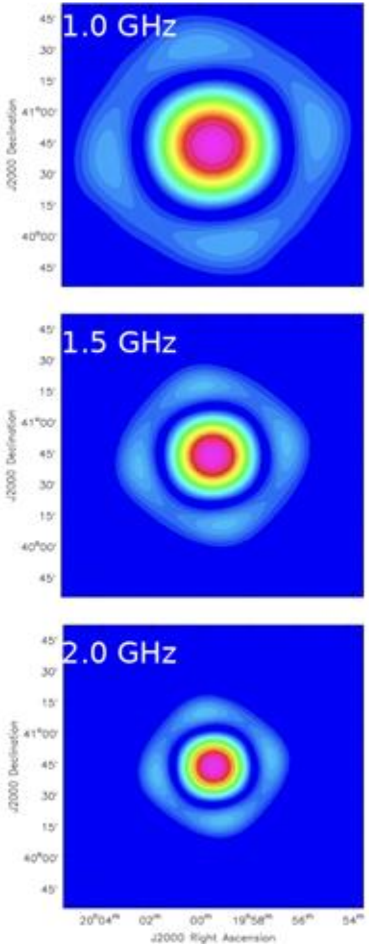
Example : Abell 2256 *(Owen et al, 2014)*



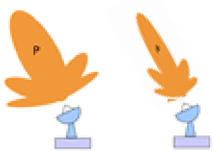
VLA A,B,C,D at L-Band (1-2 GHz), VLA A at S&C bands(2-4, 4-6, 6-8 GHz)

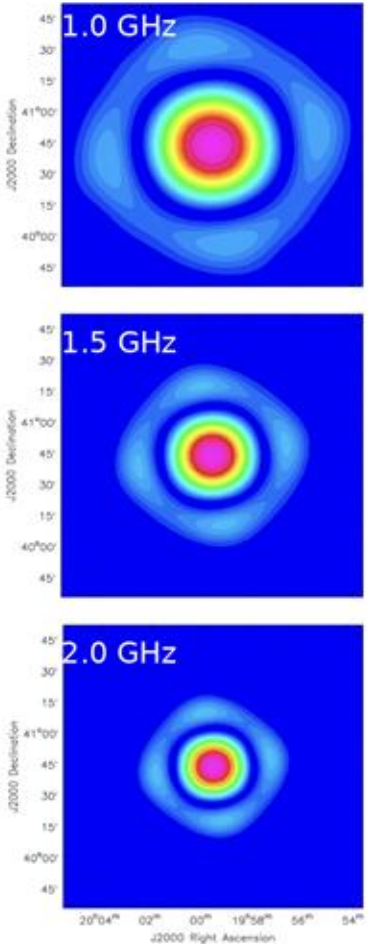
Wide Band Primary Beams

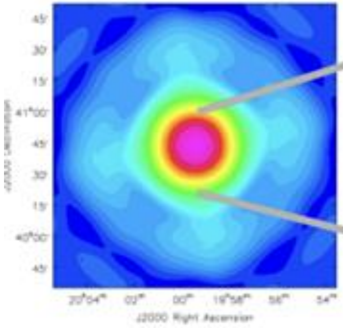




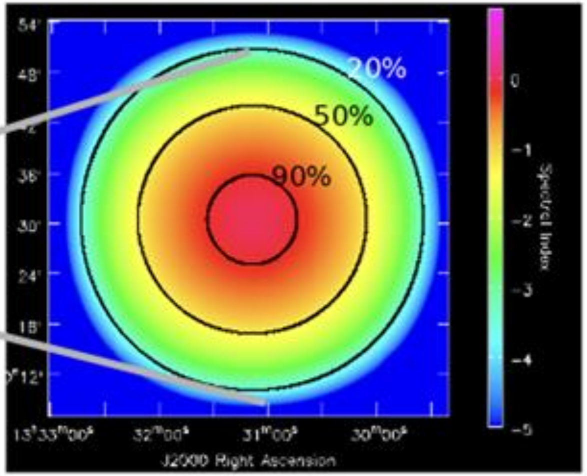
Wide Band Primary Beams







Average PBs

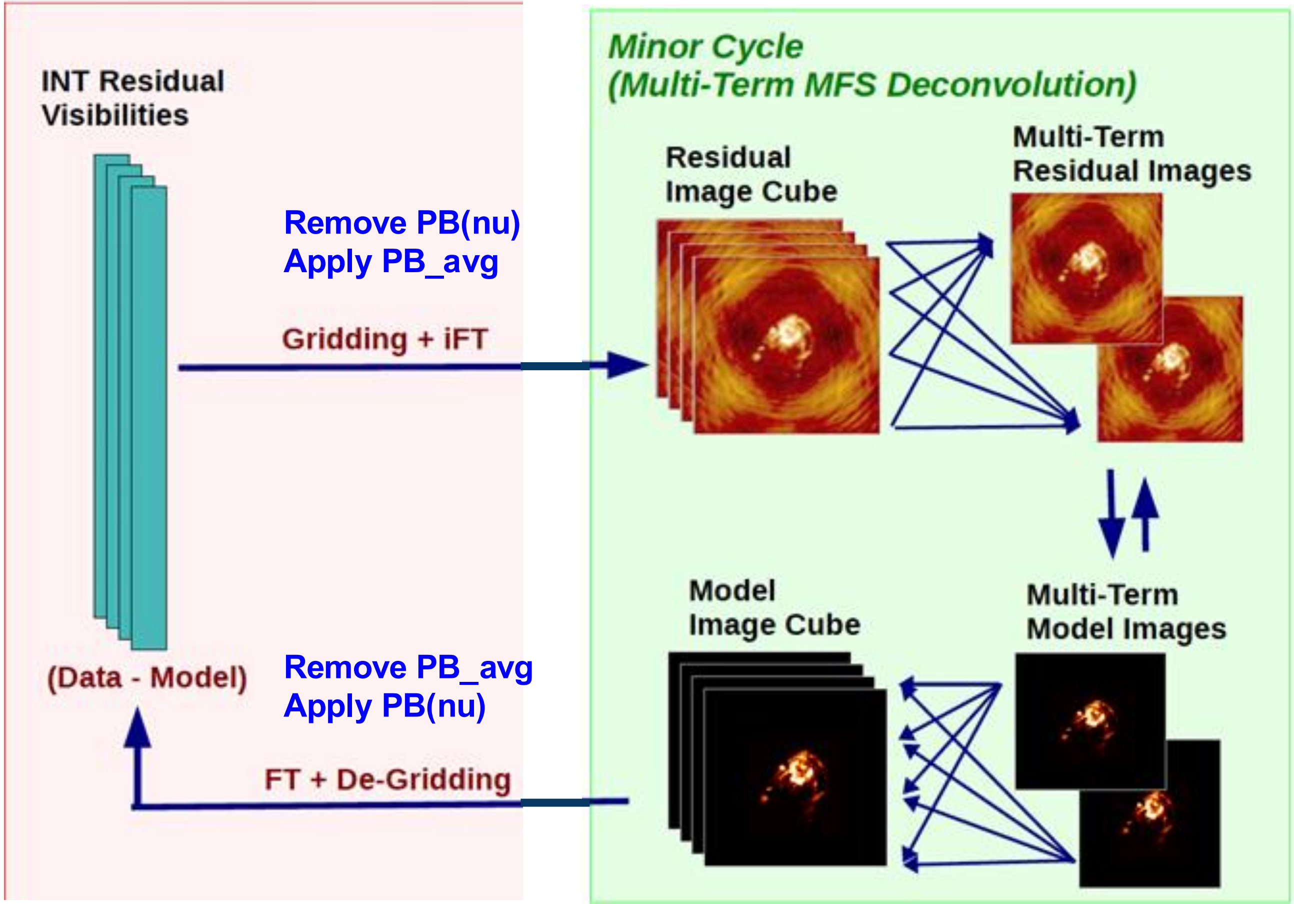


Spectral Index of PB (About -1.4 at the HPBW)

$$I^{obs}_{wf,wb} = \sum_{\nu} \left[\left(P_{\nu} \cdot I^{sky}_{\nu} \right) * PSF_{\nu} \right]$$

Single Pointing Image has an **artificial PB spectral index** away from the pointing center

Handling Wide-Band Primary Beams during imaging



Implemented in CASA tclean as **specmode='mvc'**

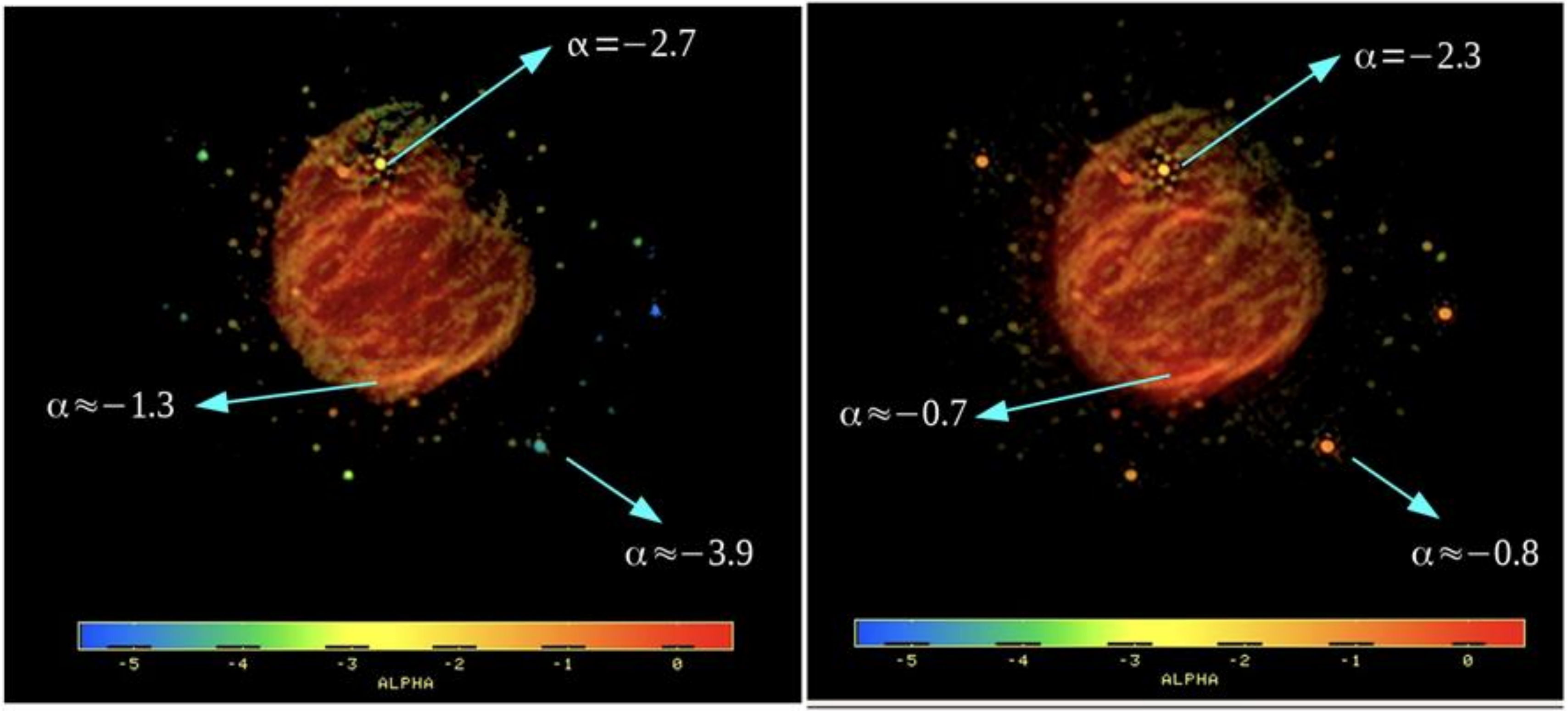
Output Sky model

Intensity : Sky x PB_avg
Spectrum : Sky only

Other options (limited accuracy):

- Apply WB-PB-cor during gridding for MFS imaging (specmode='mfs')
- Do 'widebandpbcor' as a post-deconvolution step only (gridder='standard')

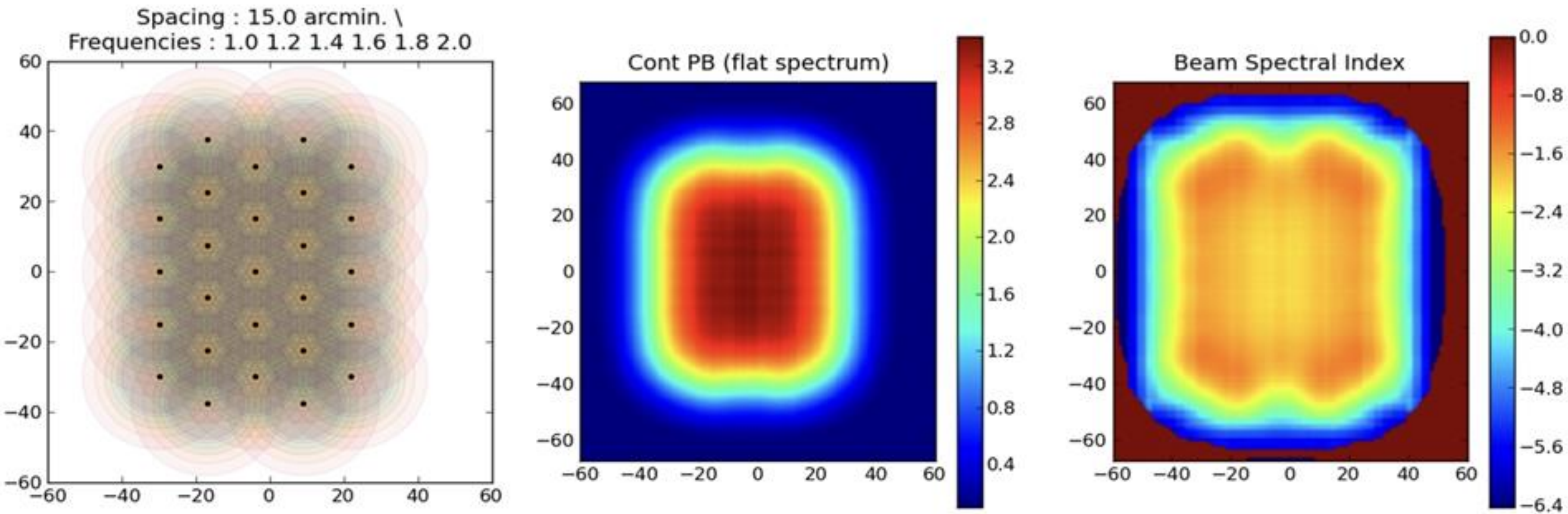
Example : Spectral index in G55 supernova remnant



Without WB PB correction

With WB PB correction

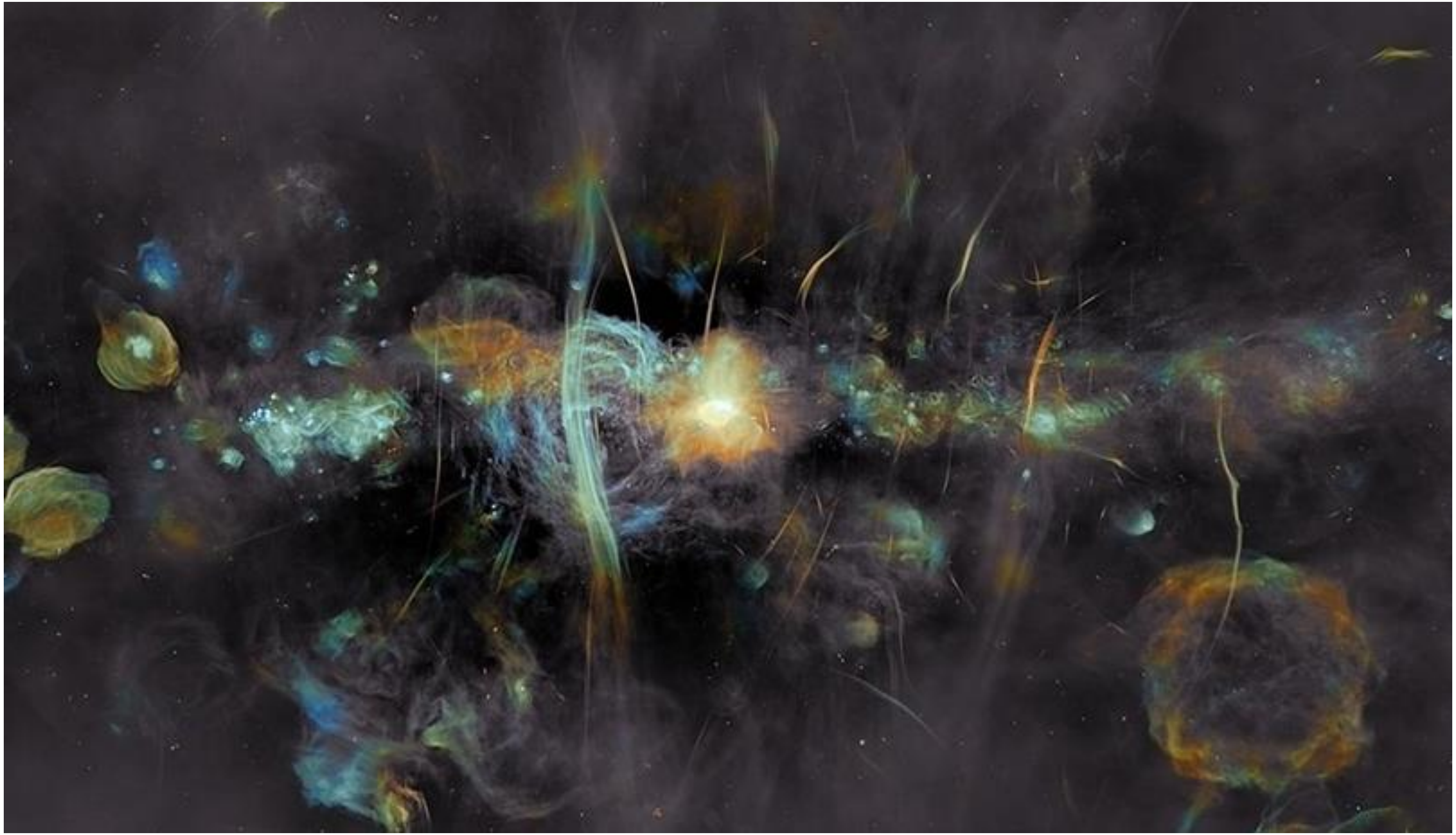
Wide Band Mosaic Primary Beam



The mosaic primary beam has an **artificial spectral index** all over the combined F-O-V

=> Need wide-band PB correction prior to wideband sky modeling and joint deconvolution.
(Implemented in CASA as specmode='mvc' with gridder='mosaic' or 'awp2')

Example : Galactic Center *(SARAO, **I. Heywood** et al 2002, J.C. Munoz-Mateos)*



Wideband Model per pointing

Linear Mosaic

Include single-dish data

Dir-dep Cal

Using MeerKAT's dense UV-coverage

WS-Clean, etc.

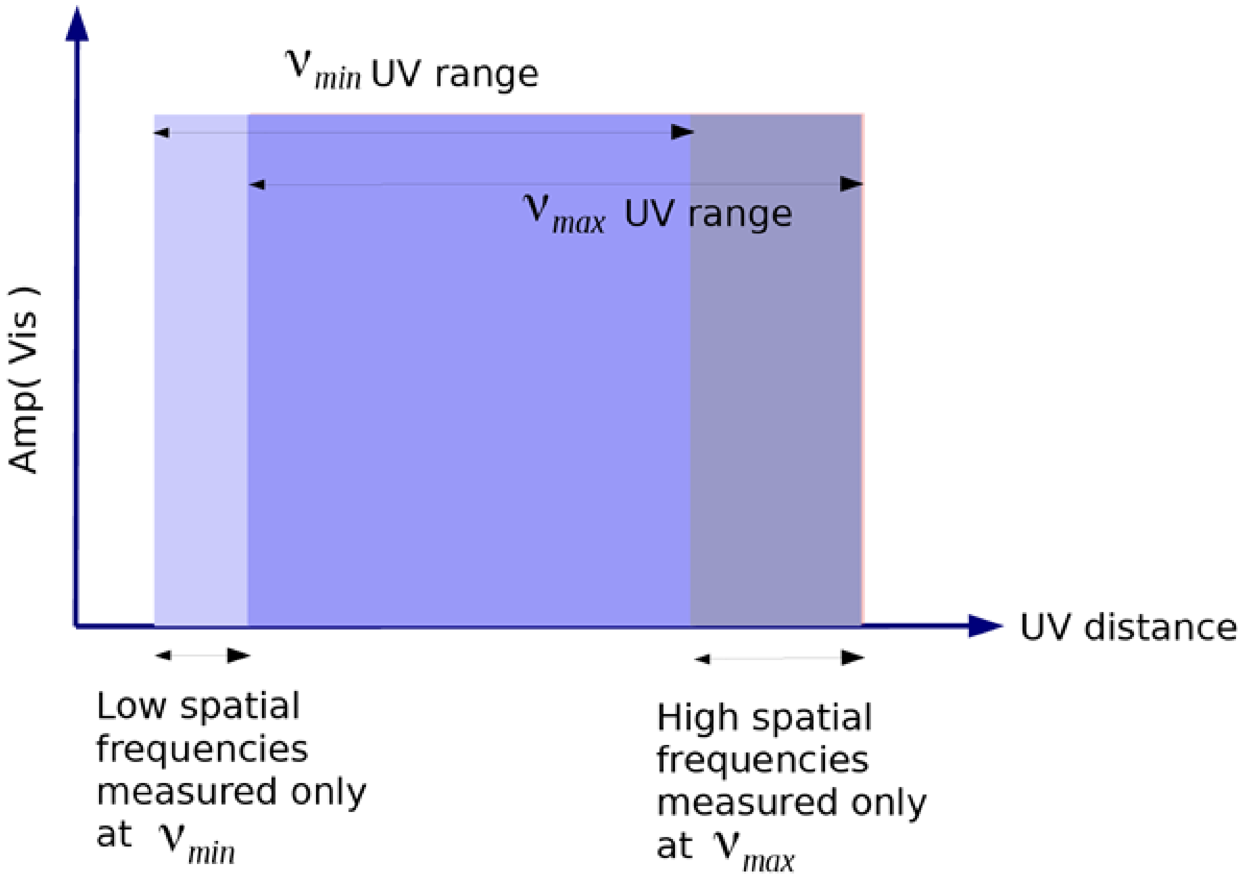
Accuracy of wide-band models

How accurately can we reconstruct sky spectra, at different spatial scales ?

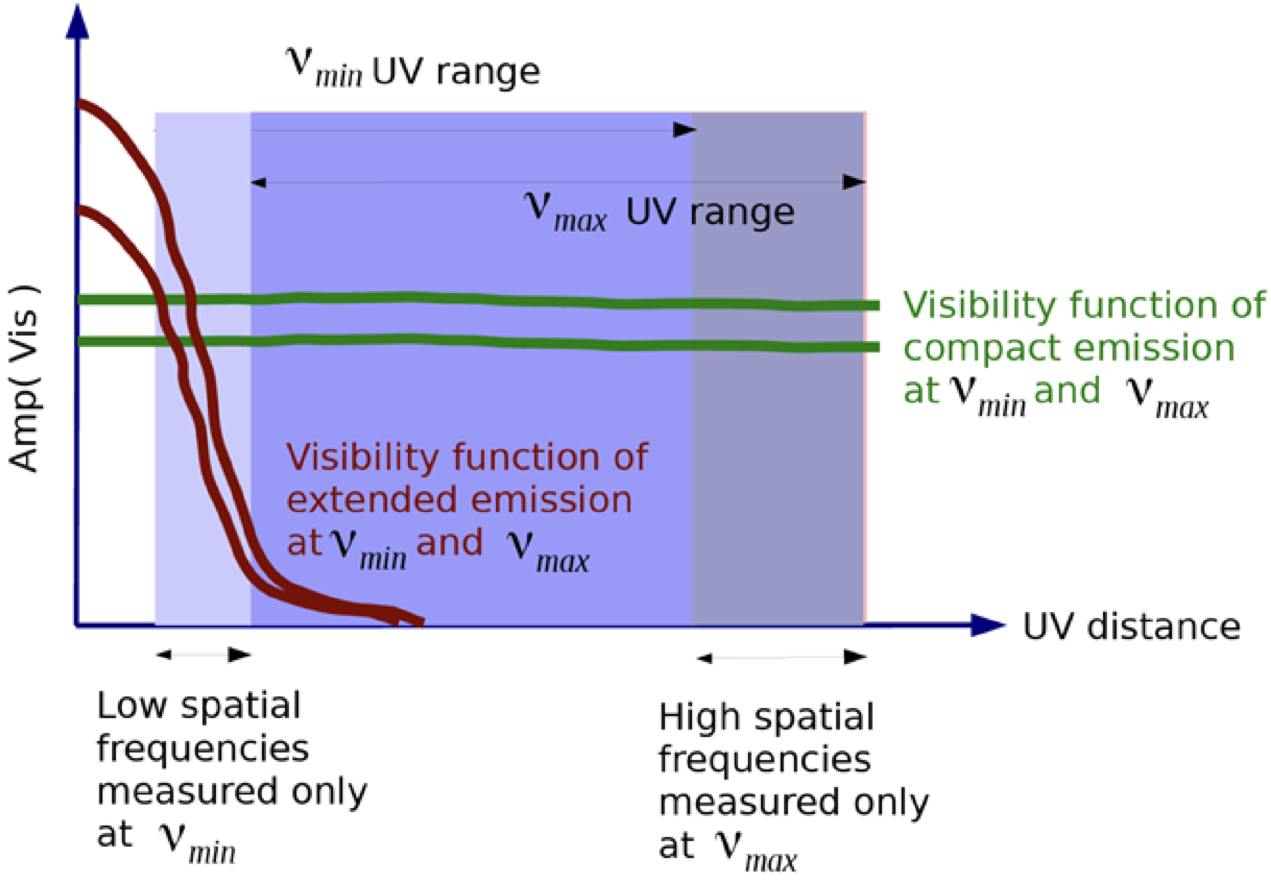
- Point sources
- Extended emission
- Very large scales (spatial scales comparable to the UV hole)

Consider the signature of broadband emission, on the UV-plane.

Range of Spatial Scales



Range of Spatial Scales



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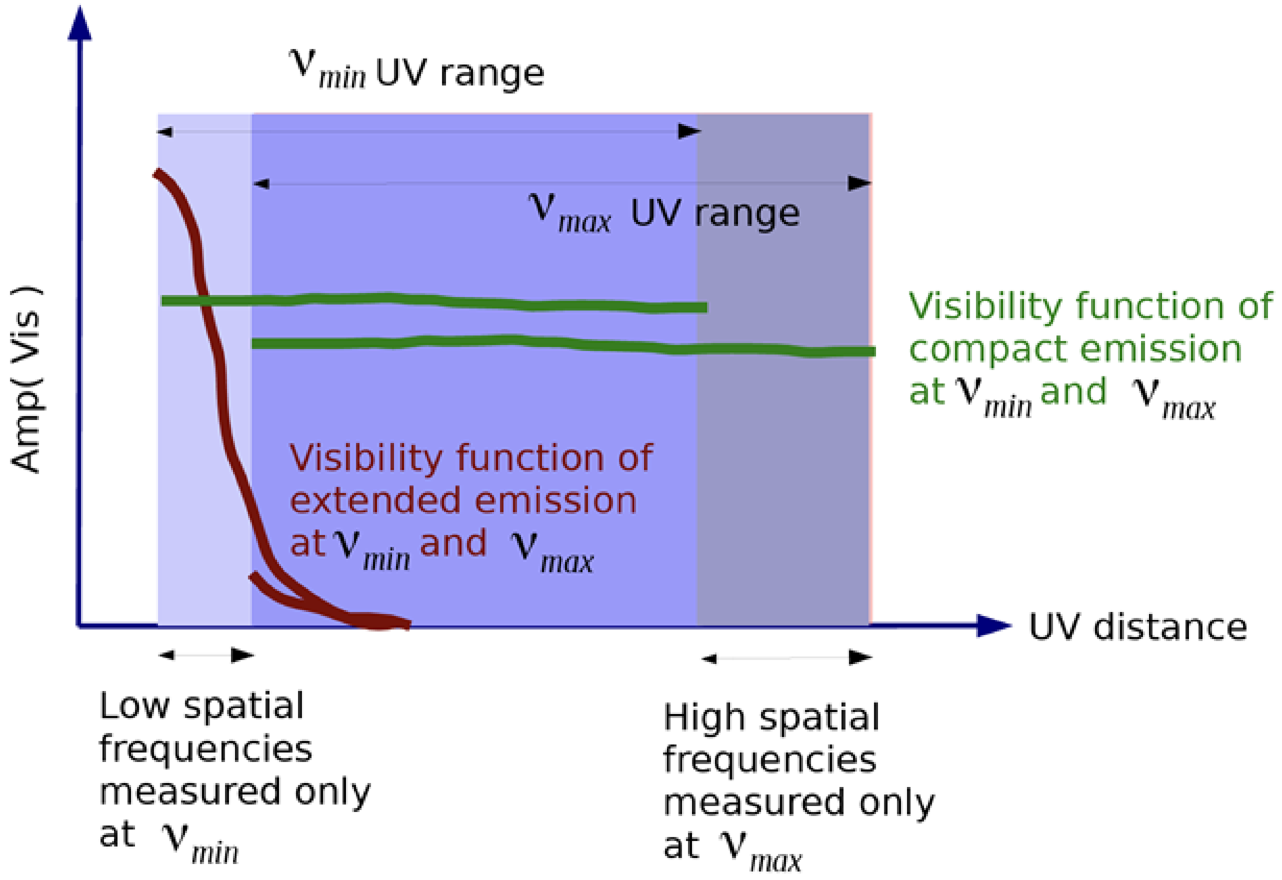
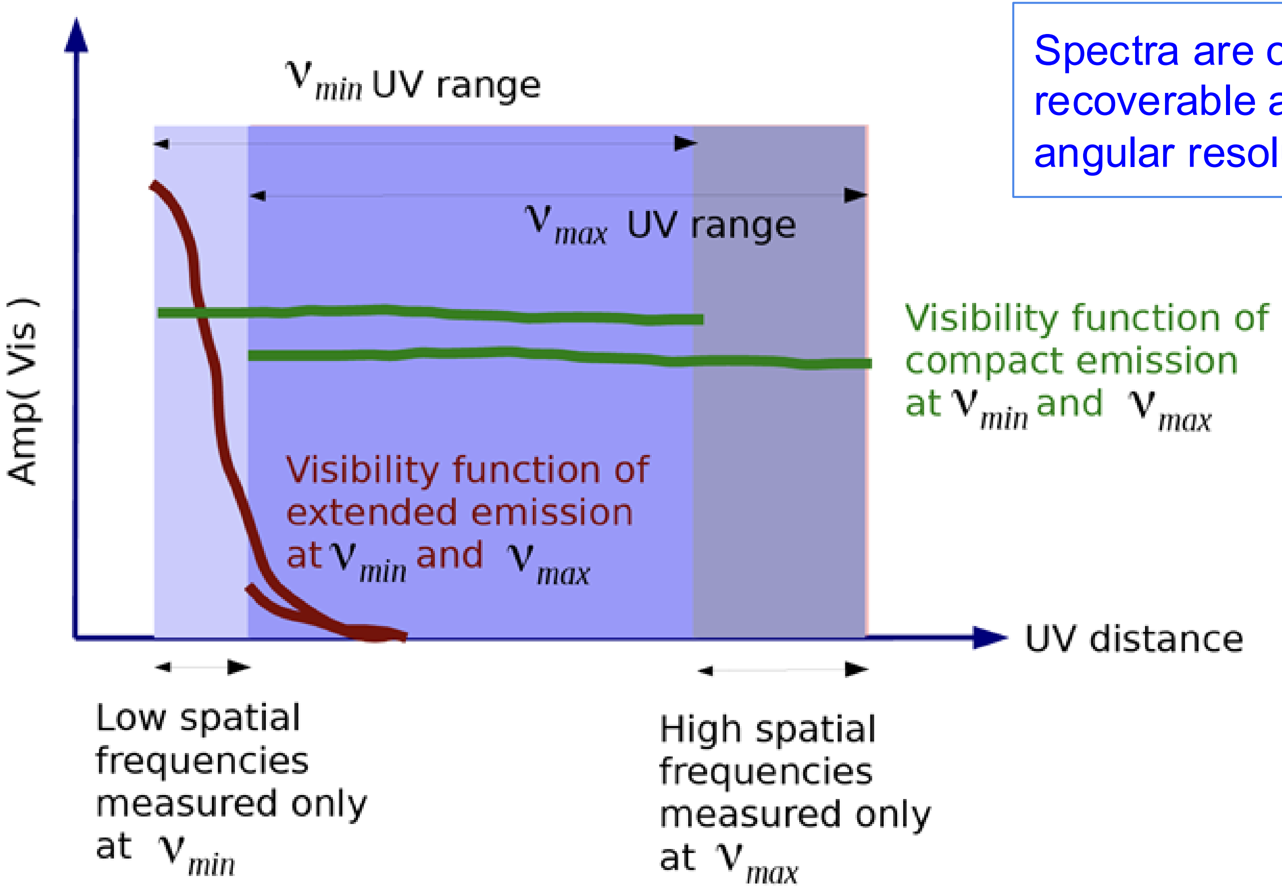


Range of Spatial Scales



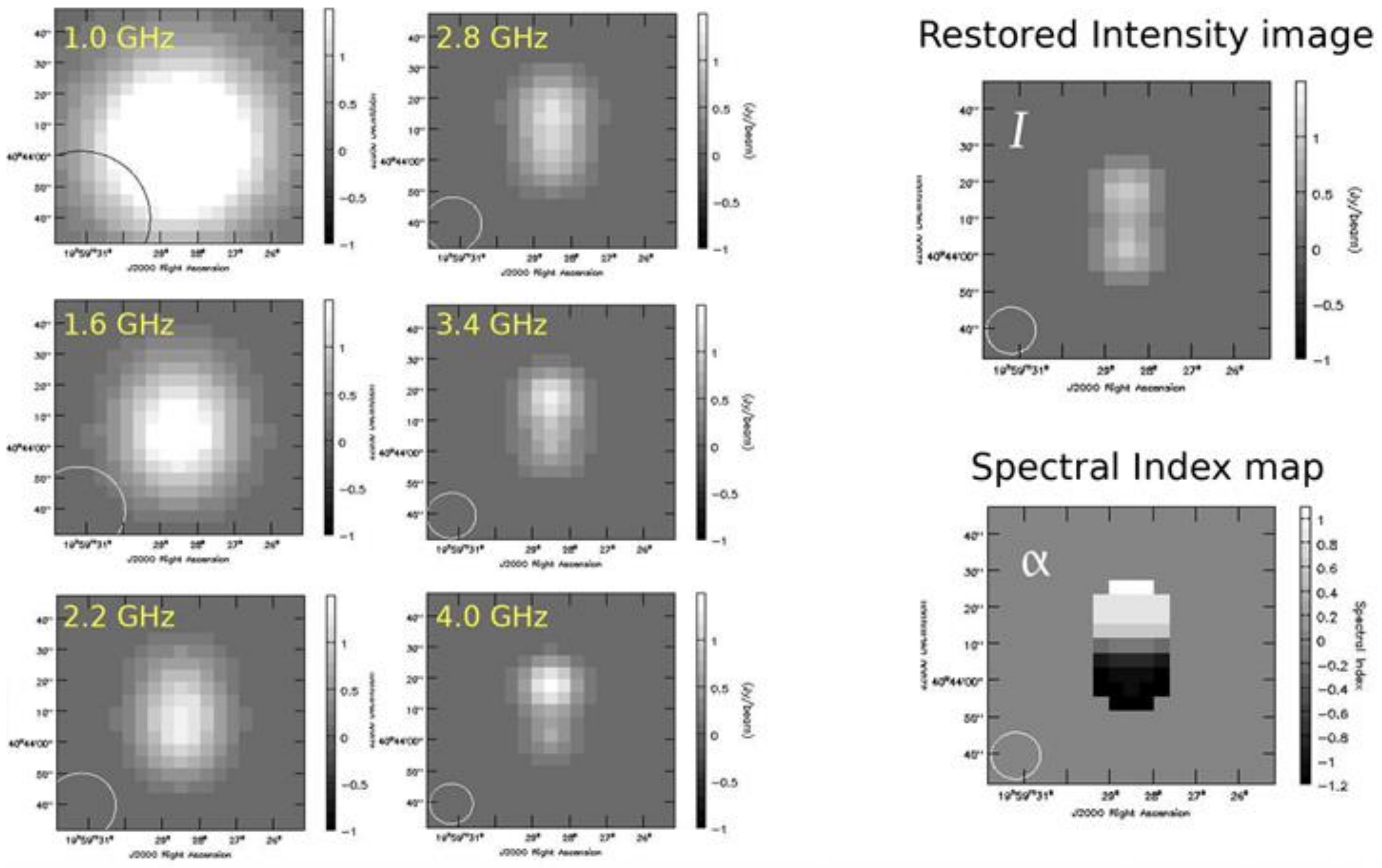
Spectra are often recoverable at high angular resolution

Spectra are unconstrained at the very largest scales

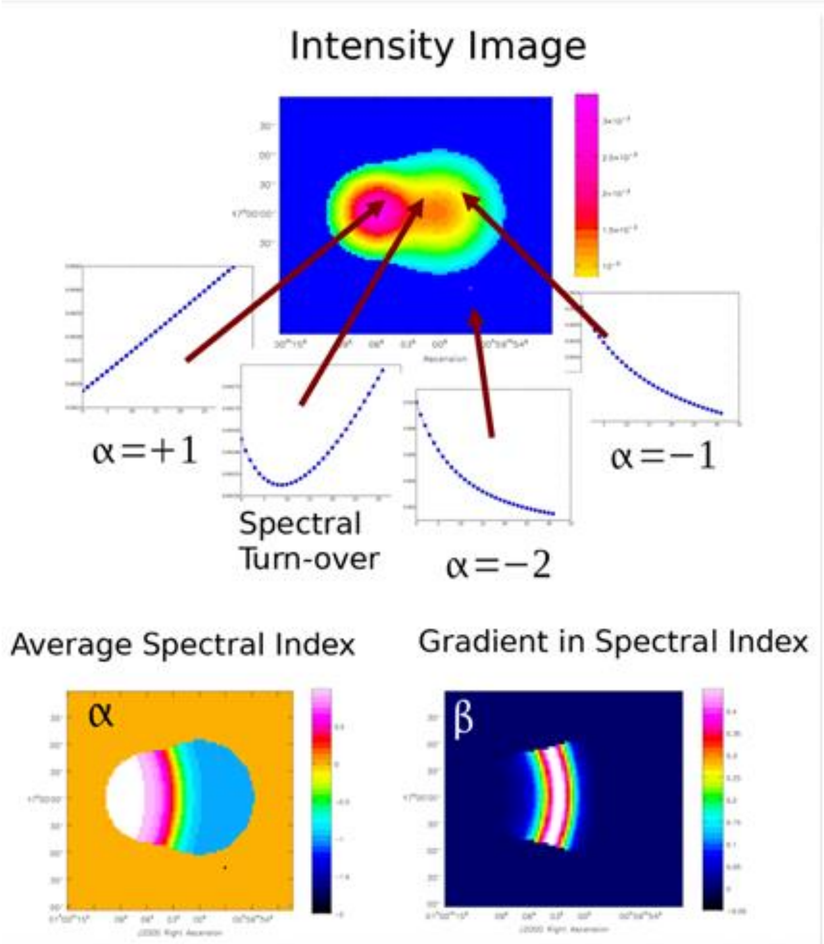
Point Sources – Cube vs WideBand

For most compact sources

Can model the structure and spectrum at high resolution



Extended Emission - Multi-scale spectra



Accuracy depends on how good the multi-scale emission model is.

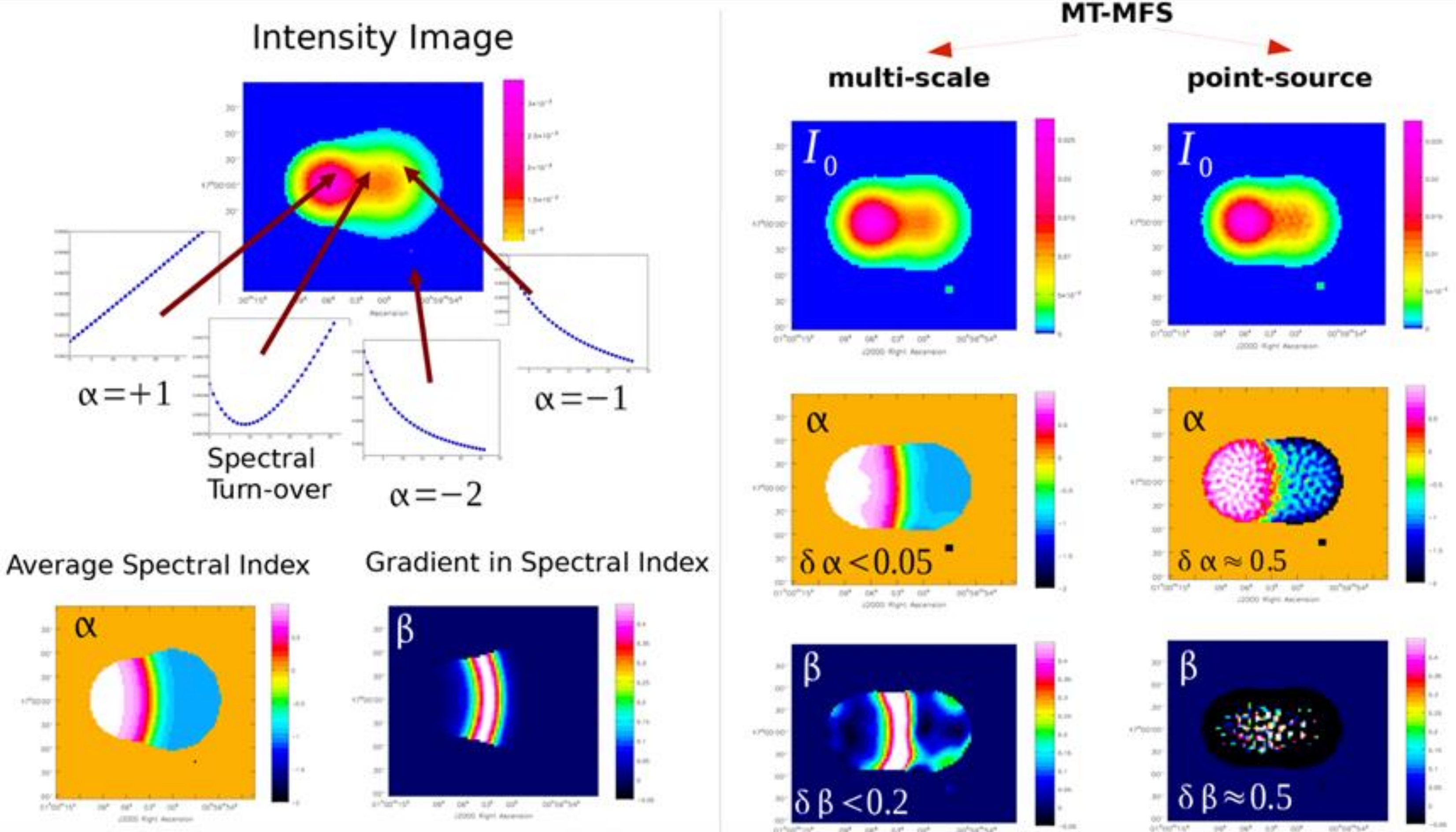
Compare two options :

(1) Multi-scale source model

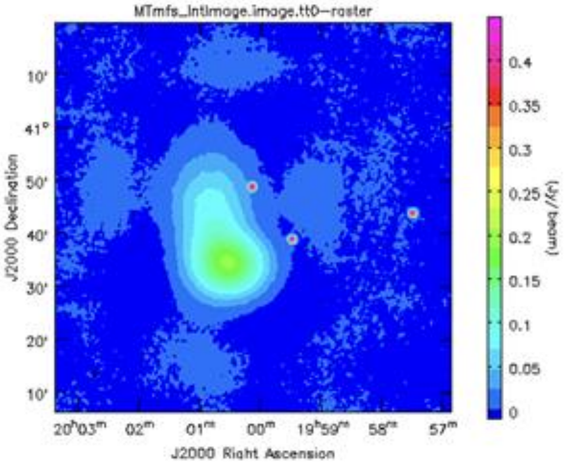
(1) Delta-fn source model

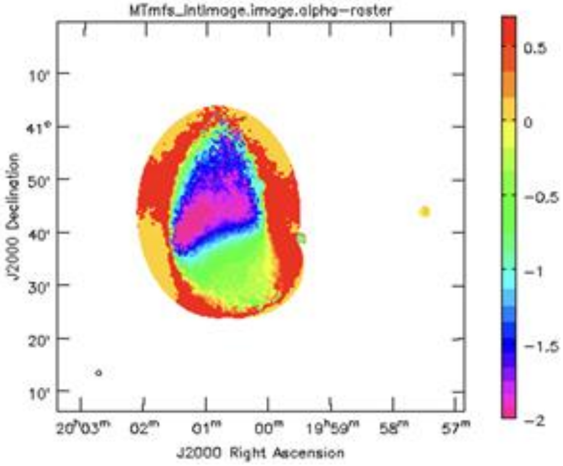
For both : Use a polynomial spectrum per flux component

Extended Emission - Multi-scale spectra



Very Large Spatial Scales – Unconstrained spectrum





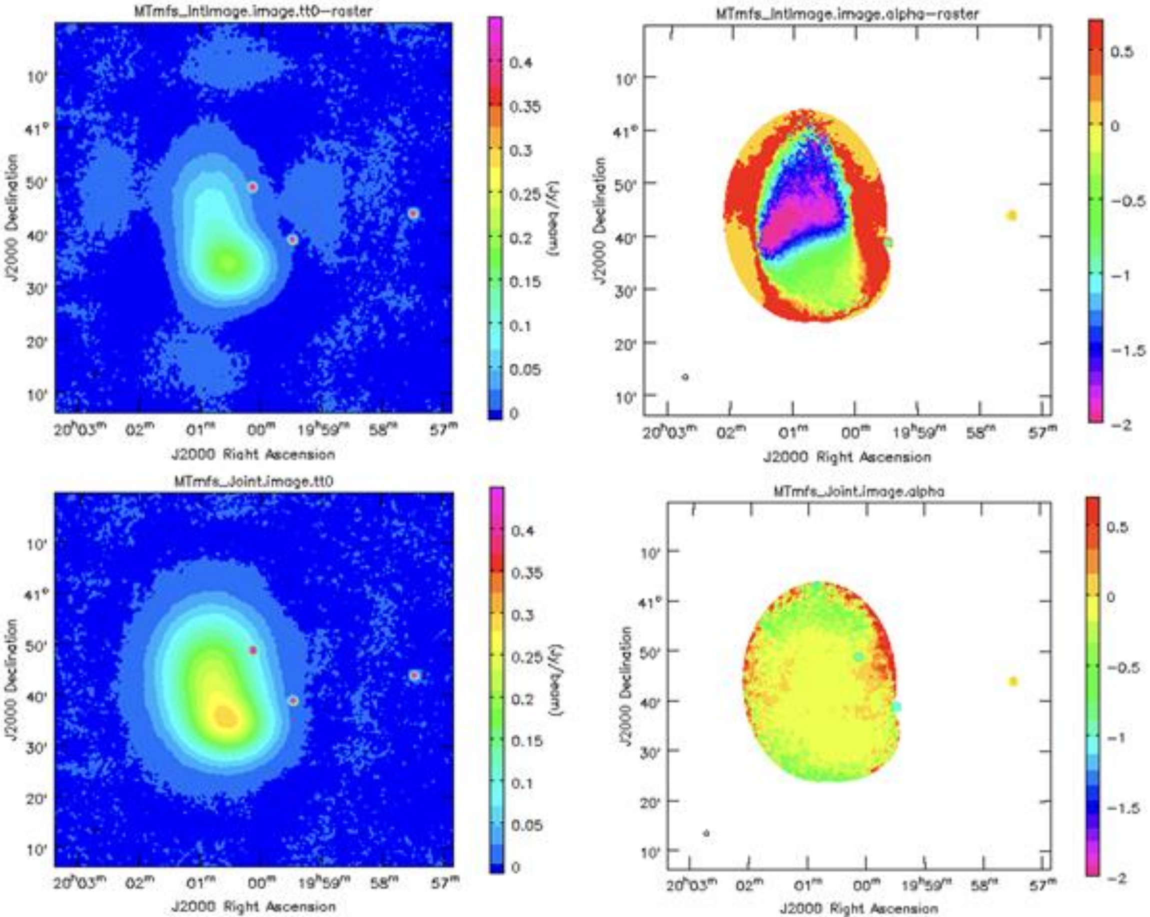
Example : Flat spectrum emission at large scales

With only interferometer data

=> Wideband modeling can get the spectrum wrong.

=> Add wideband single dish data

Very Large Spatial Scales – Constrain with single-dish data



Example : Flat spectrum emission at large scales

With only interferometer data

=> Wideband modeling can get the spectrum wrong.

=> With SD data, better reconstruction of intensity and spectrum at very large scales

Algorithms

- tp2vis *(Koda et al, 2011)*
- SDInt *(Rau, Naik, Braun 2018)*

Other related topics

(1) Wide Band Self Calibration & Continuum Subtraction

(1) Modeling sky polarization effects (e.g. Faraday rotation measure)

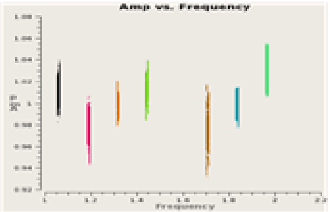
(1) Bandwidth smearing limits

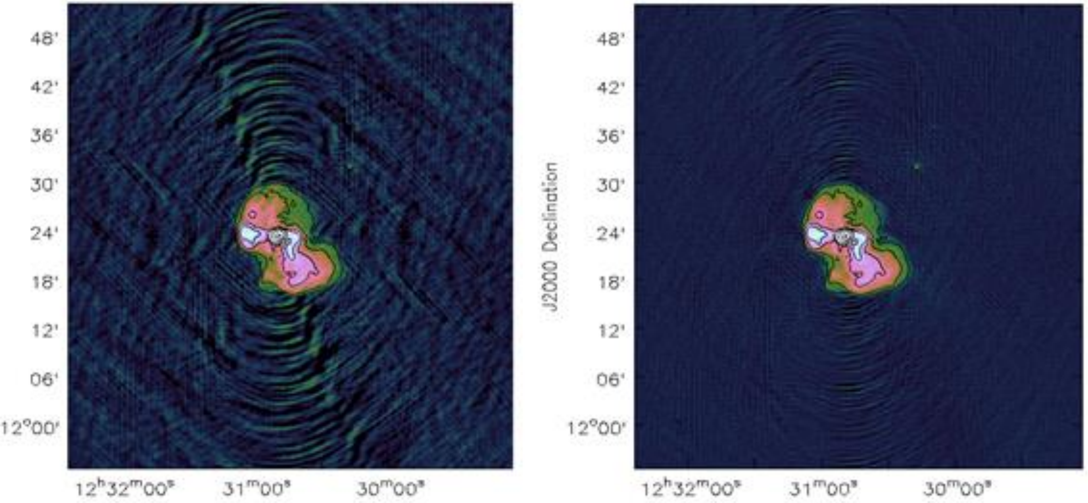
– Relevant when choosing ‘ how much to average your data ‘ to control data volumes

Other uses of Wide Band Sky models

Wide Band Self-Calibration

- Eg: To fix calibration errors across spws

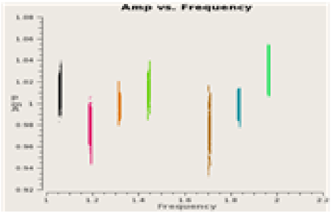


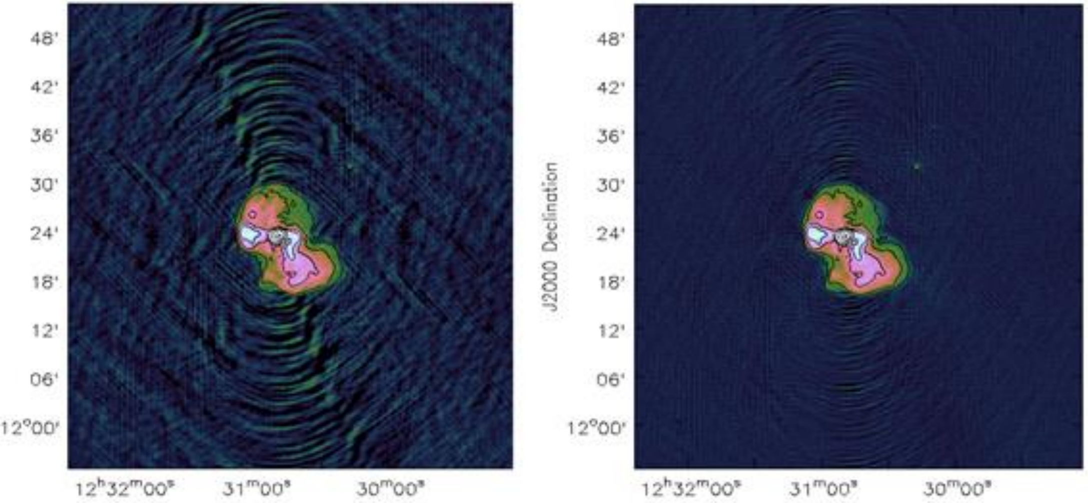


Other uses of Wide Band Sky models

Wide Band Self-Calibration

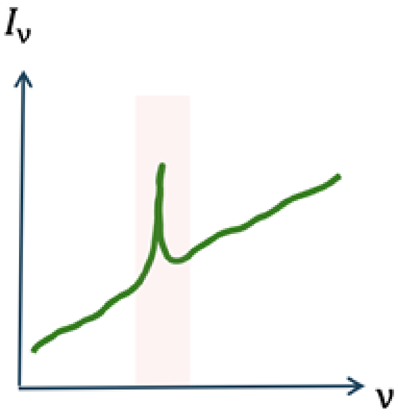
- Eg: To fix calibration errors across spws





Continuum Subtraction

- To fit and remove continuum spectrum from underneath spectral lines of interest



Wide Band Polarization

Stokes Q,U,V can also change with frequency

- If the expected variation < ~1% of the peak, MFS (nt=1) will suffice
- If not, it is safest to make a Cube (as the spectra may not smooth)

Faraday Rotation-Measure Synthesis *Brentjens, 2008, Bell et al, 2013*

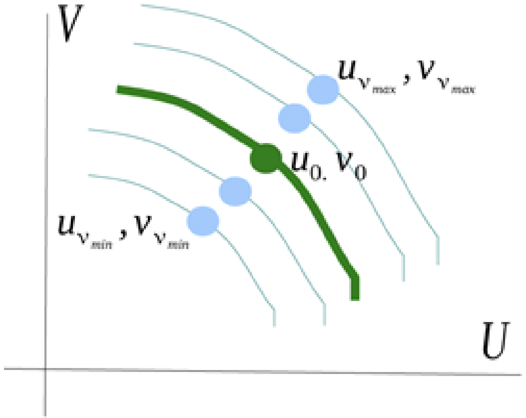
Images of polarized surface-brightness at various Faraday-depths : $F(\varphi)$

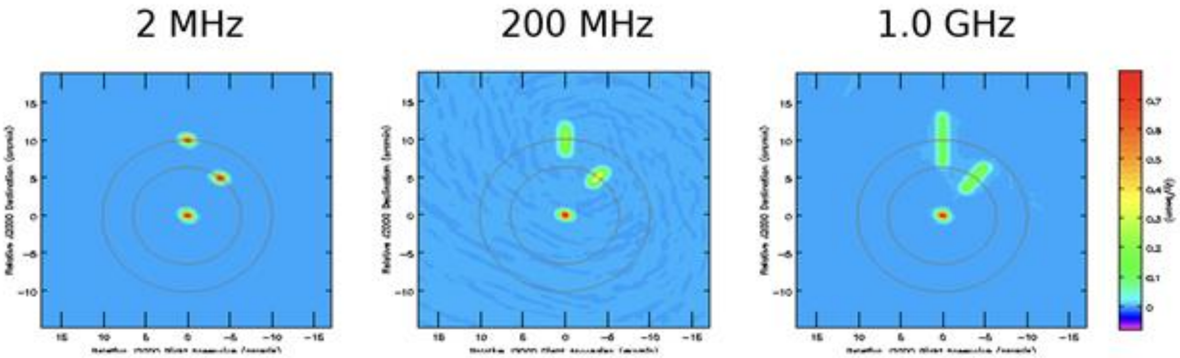
- P = Q + i U : Make spectral cubes for Q and U separately, and calculate P

- For each pixel in the P-cube, solve $P(\lambda^2) = \int F(\varphi) e^{2\pi i \varphi \chi^2} d\varphi$ for $F(\varphi)$

Bandwidth smearing

Excessive channel averaging of visibilities will cause radial smearing





Radial shift of visibilities on the UV plane + Similarity theorem of Fourier transforms

Bandwidth smearing limit for HPBW f-o-v = $\delta\nu < \frac{\nu_0 D}{b_{max}}$ (chan avg limit)

1 MHz for VLA A, 30 MHz for VLA D

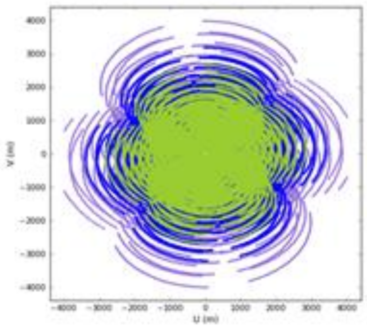
Imaging with frequency-dependent Sky + Instrument

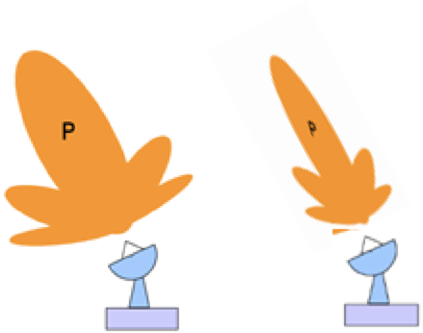
$$V_{ij}^{obs}(\nu,t)=M_{ij}(\nu,t)S_{ij}(\nu,t)\iiint M_{ij}^{dd}(l,m,\nu,t)I(l,m,\nu,t)e^{2\pi i(ul+vm+w(n-1))}\,dl\,dm\,dn$$

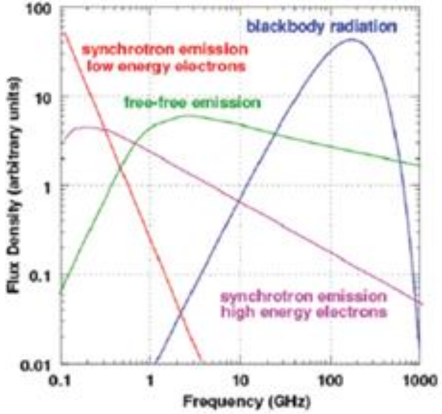
UV coverage

Primary Beam

Sky Brightness



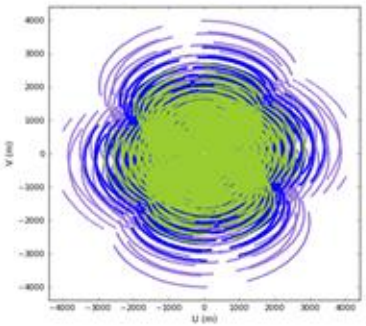




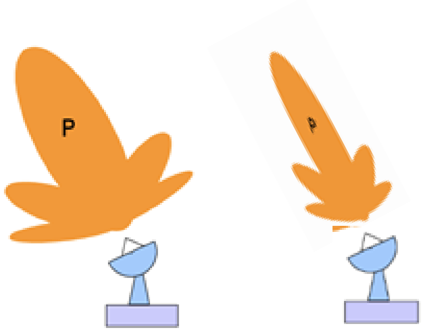
Imaging with frequency-dependent Sky + Instrument

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

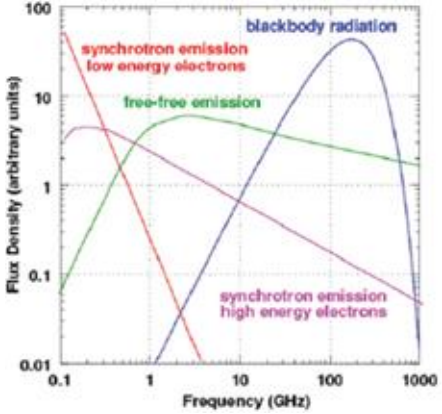
UV coverage



Primary Beam



Sky Brightness



A wide-band sky model during deconvolution

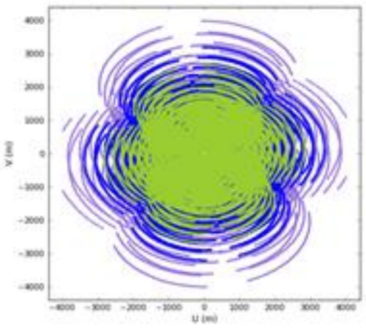
Imaging with frequency-dependent Sky + Instrument

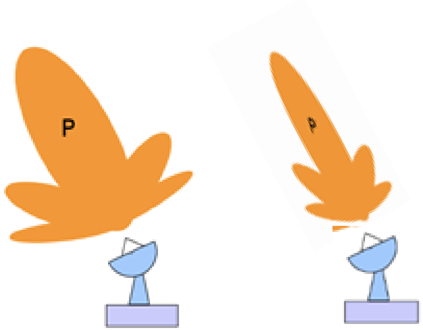
$$V_{ij}^{obs}(\nu,t)=M_{ij}(\nu,t)S_{ij}(\nu,t)\iiint M_{ij}^{dd}(l,m,\nu,t)I(l,m,\nu,t)e^{2\pi i(ul+vm+w(n-1))}dl\,dm\,dn$$

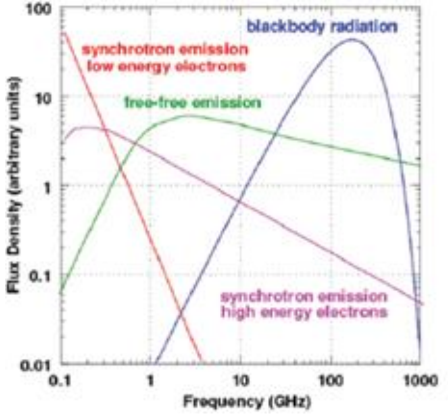
UV coverage

Primary Beam

Sky Brightness







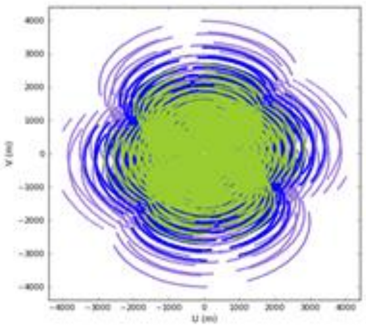
Undo freq-dep PBs before sky modeling

A wide-band sky model during deconvolution

Imaging with frequency-dependent Sky + Instrument

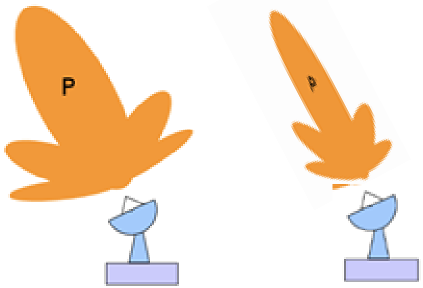
$$V_{ij}^{obs}(\nu,t)=M_{ij}(\nu,t)S_{ij}(\nu,t)\iiint M_{ij}^{dd}(l,m,\nu,t)I(l,m,\nu,t)e^{2\pi i(ul+vm+w(n-1))}dl\,dm\,dn$$

UV coverage



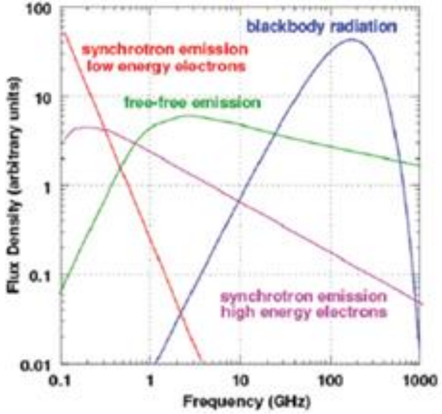
Be aware of how well the multi-freq data constrain the model

Primary Beam



Undo freq-dep PBs before sky modeling

Sky Brightness



A wide-band sky model during deconvolution

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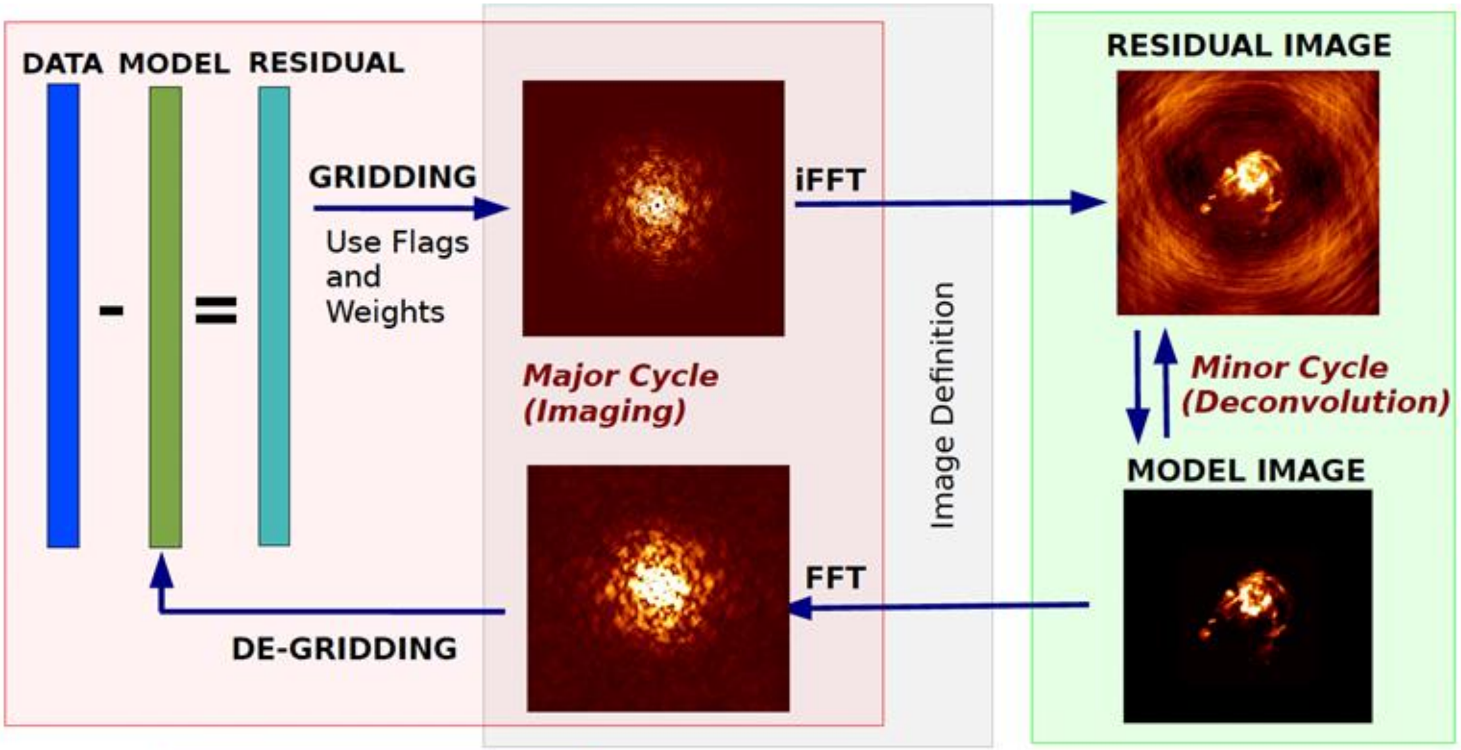
How Image Reconstruction is implemented in software

Iterative Image Reconstruction

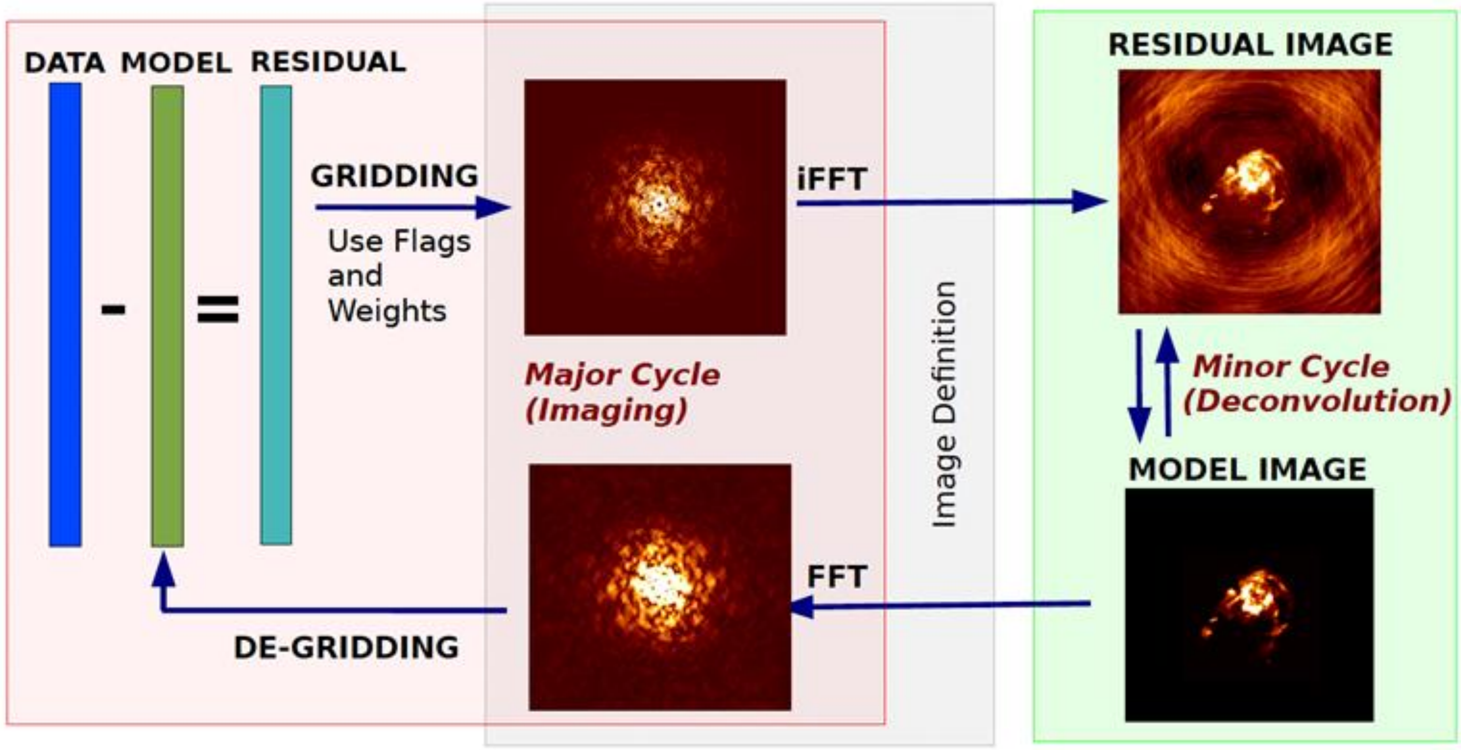


Instrumental Corrections (applied per visibility during gridding)

Mapping of data to Image Shape/Type

Solving for the sky model (non-linear optimization)

Iterative Image Reconstruction



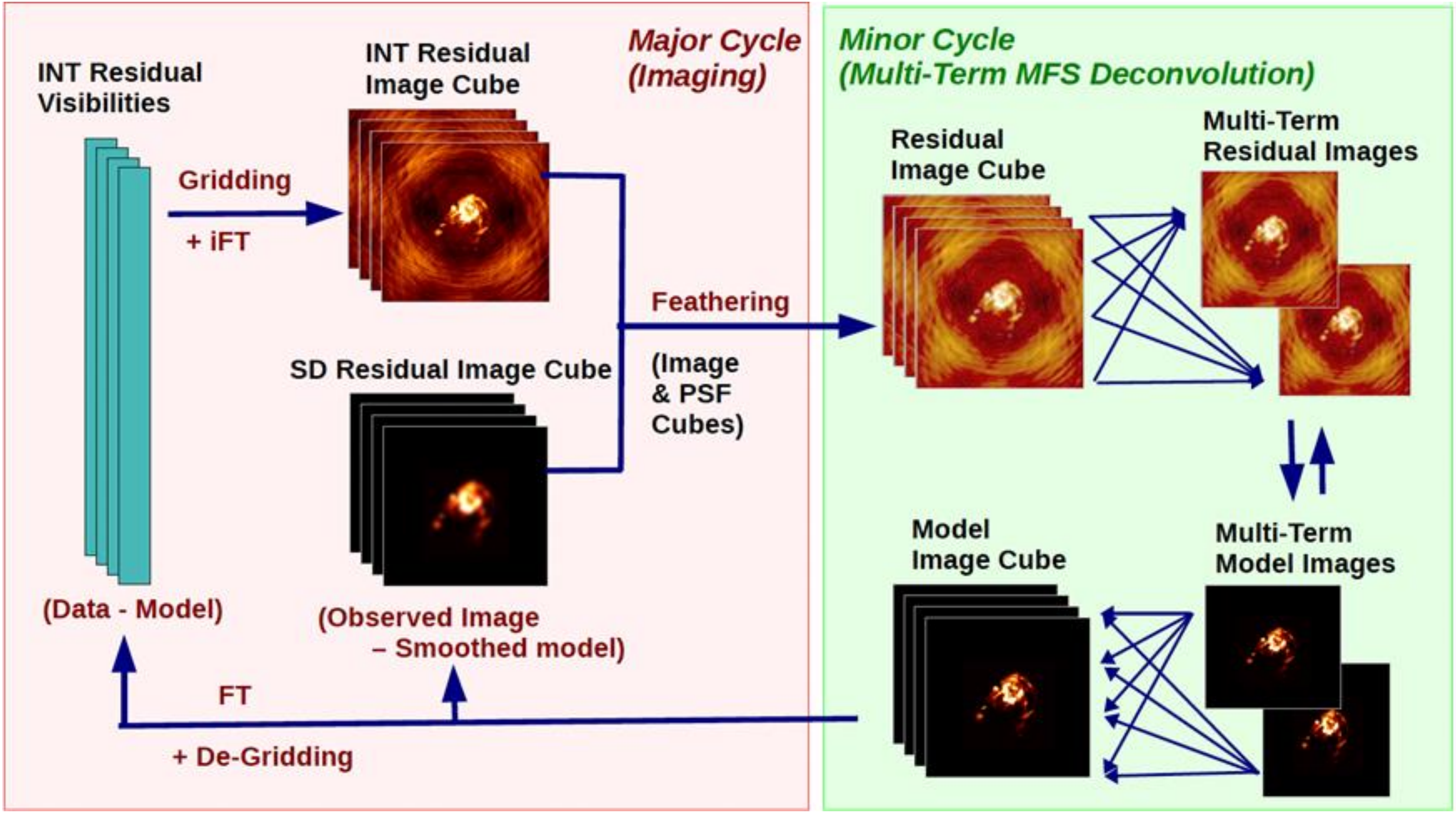
Standard gridding, W-Proj (WB)-A-Proj, Joint Mosaics, (Parallelization)

Cube, MFS, MT-MFS, Faceting,Stokes, Multi-Field, SD+INT Stitched Mosaic

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

Implementation of Cube vs Wideband vs SDINT

Wide-Band Modeling with Single-Dish combination (SDINT)



Example : Wideband PB sensitivity pattern

Wide shelf of sensitivity
per wide-band pointing

G55 : 1 Jy total flux
10 micro-Jy RMS

High dynamic range
wide-band imaging often
needs wide-field
corrections too.