Overview of data combination methods - II

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Improving Image Fidelity on Astronomical Data :
Radio Interferometer and Single-Dish Data Combination

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NRAO

Outline

Imaging Equations

Short Spacing Problem

Combination Methods

- **Image Combination**
- **Starting Model**
- **Joint Reconstruction**

Joint Reconstructions within CASA

Example : Wideband Mosaic : Feathering, StartModel, SDINT

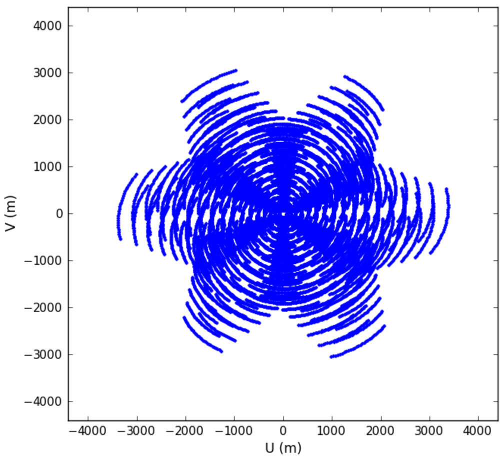
Imaging Equations

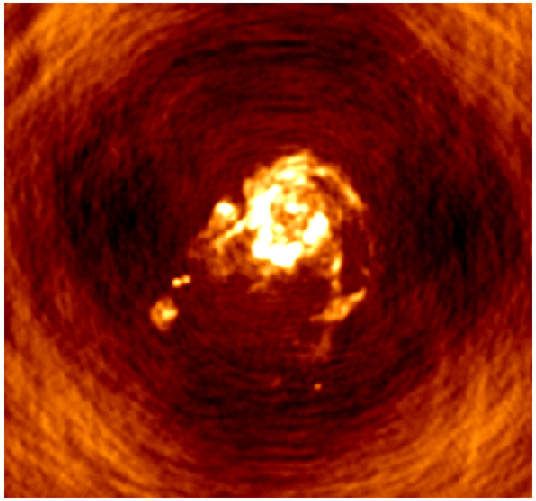
An interferometer samples the spatial Fourier transform of the sky brightness

$$I^{obs}_{INT,\nu} = \left[I^{sky}_{\nu} \cdot P_{\nu}\right] \star I^{psf}_{INT,\nu}$$

Angular res = wavelength / max_baseline

Sampling is incomplete and short spacings (large scales) are not measured



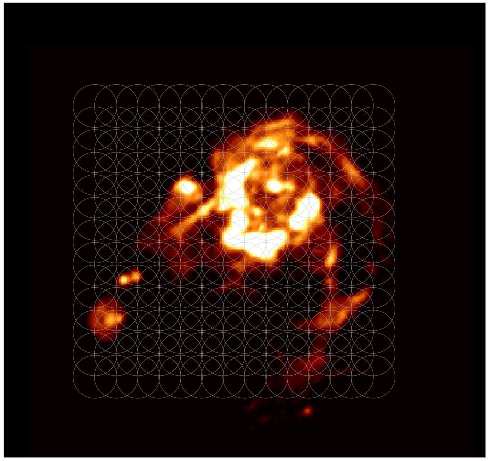


A single dish telescope does a raster scan of a region of sky

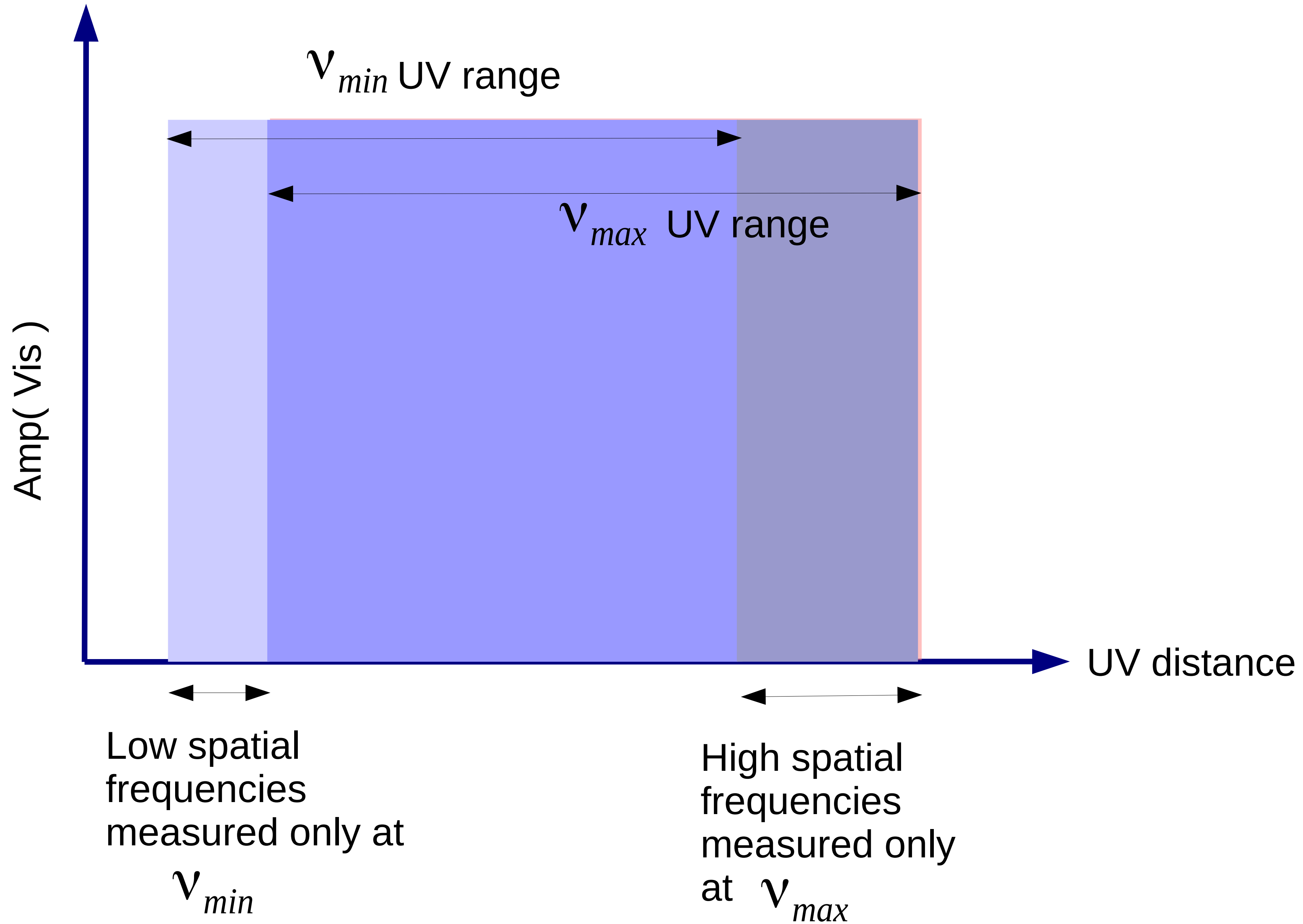
$$I^{obs}_{SD,\nu} = I^{sky}_{\nu} \star I^{psf}_{SD,\nu}$$

Angular res = wavelength / aperture_size

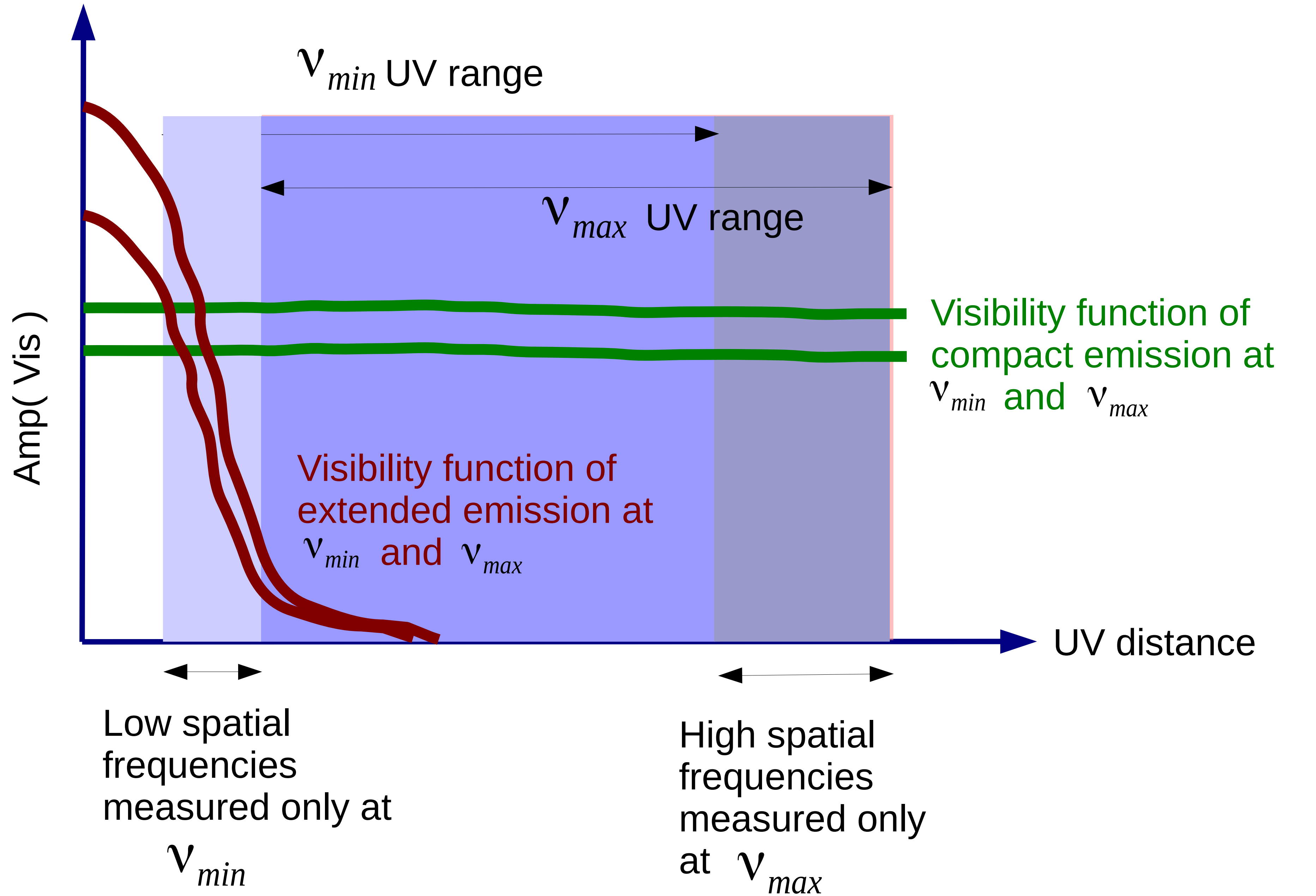
All spatial frequencies lower than that offered by the dish size are measured.



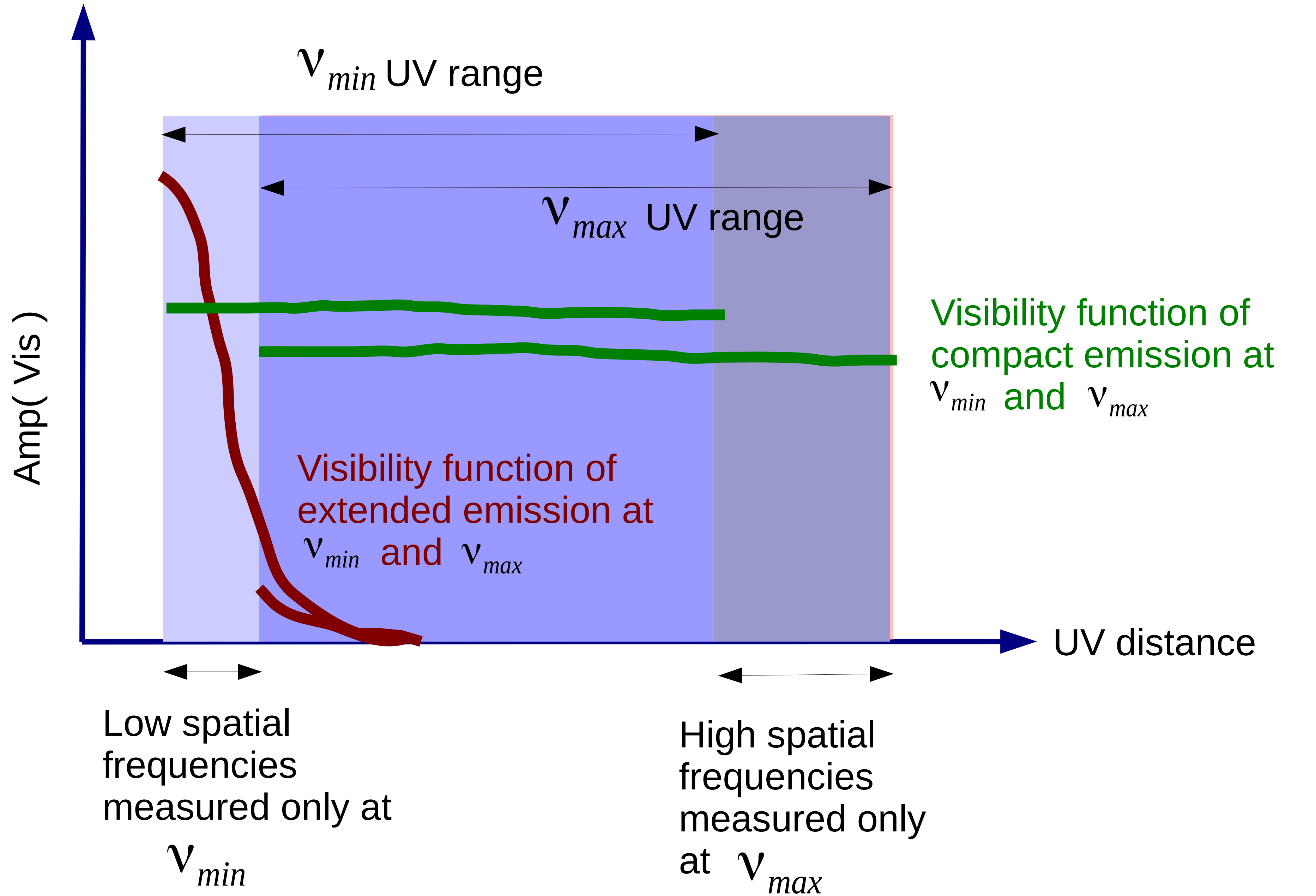
Short-Spacing Problem



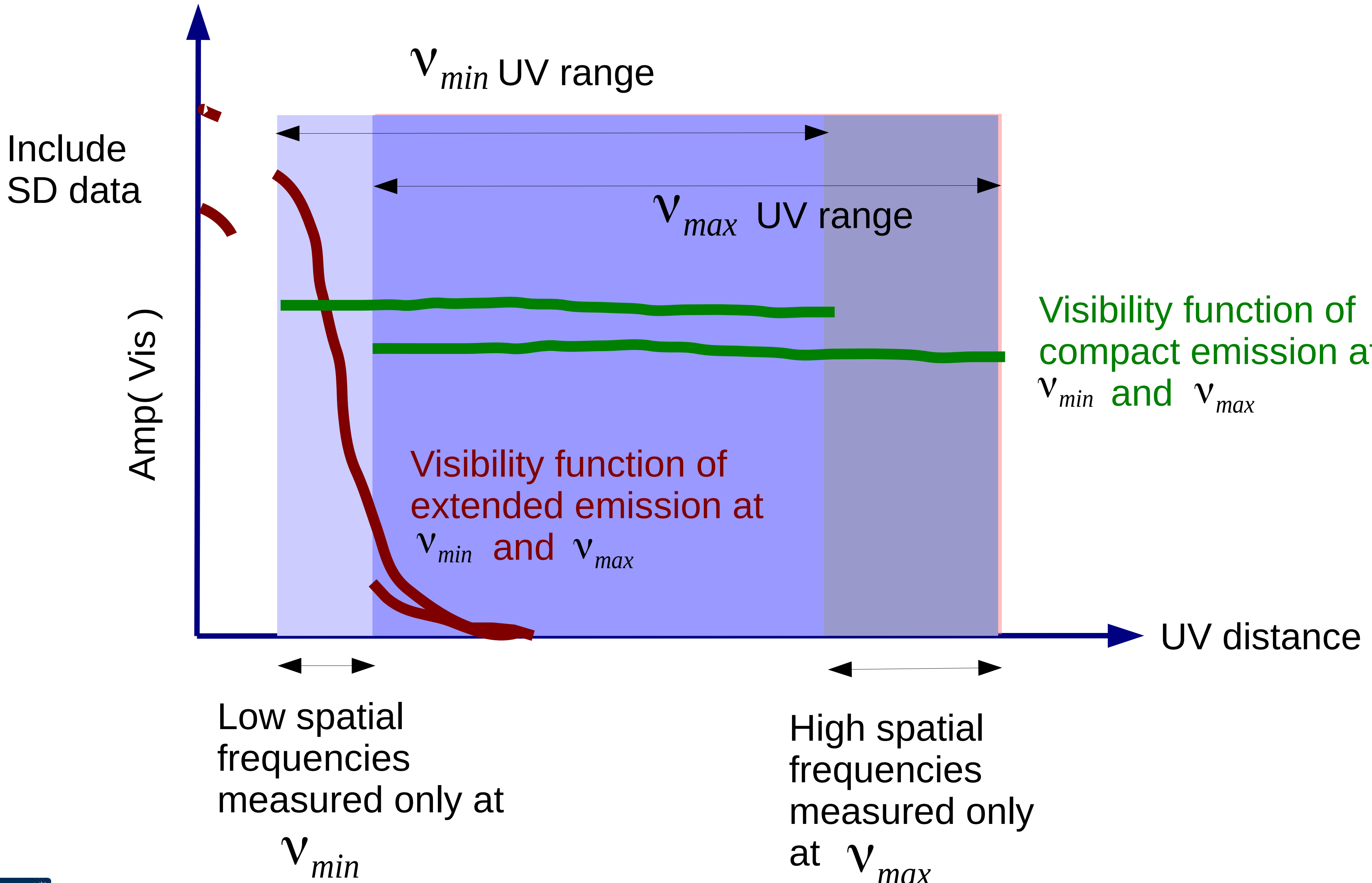
Short-Spacing Problem



Short-Spacing Problem

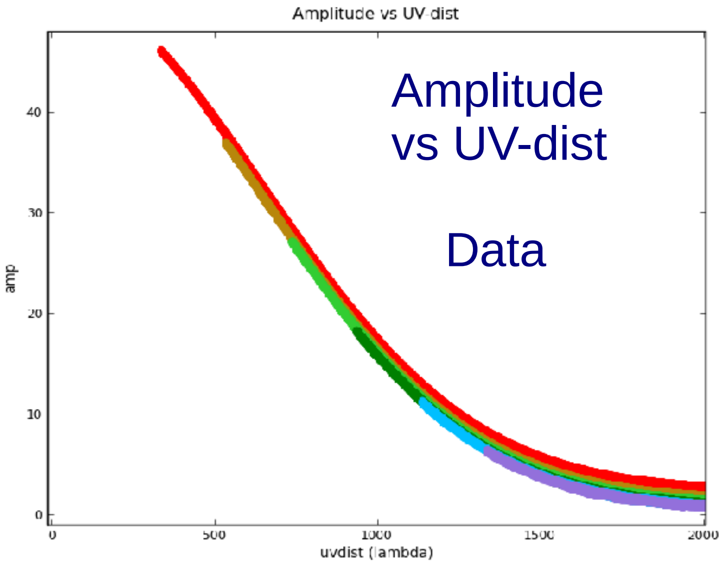


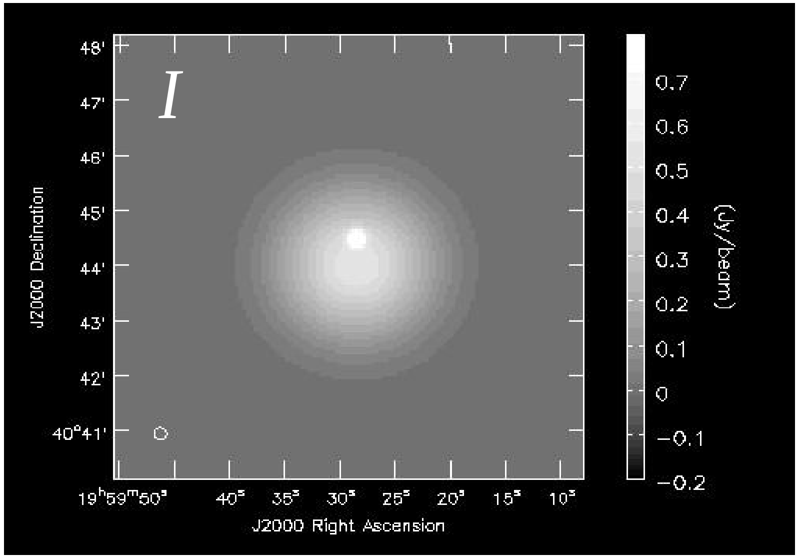
Short-Spacing Problem



Very large scales : Unconstrained Spectrum

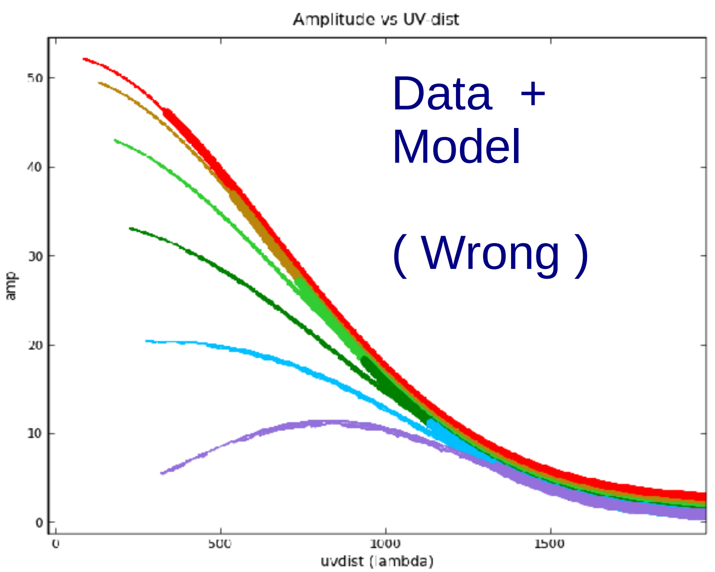
The spectrum at the largest spatial scales is NOT constrained by the data

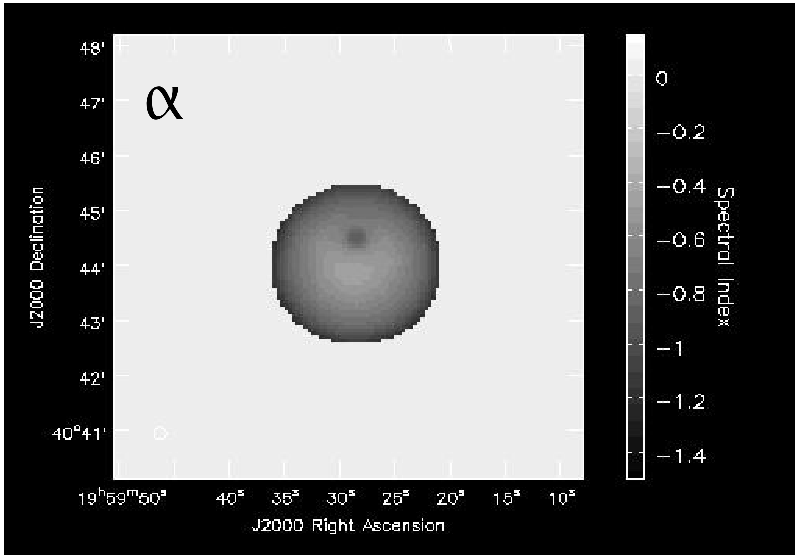




True sky has one steep spectrum point, and a flat-spectrum extended emission

Leave out shortest baselines



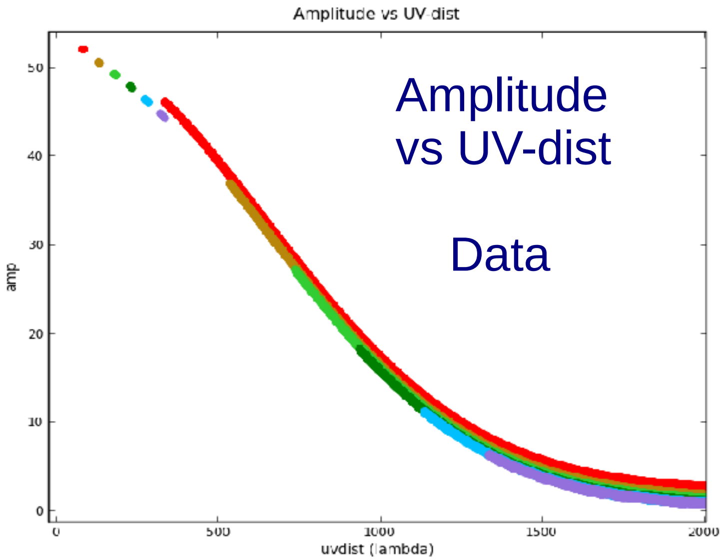


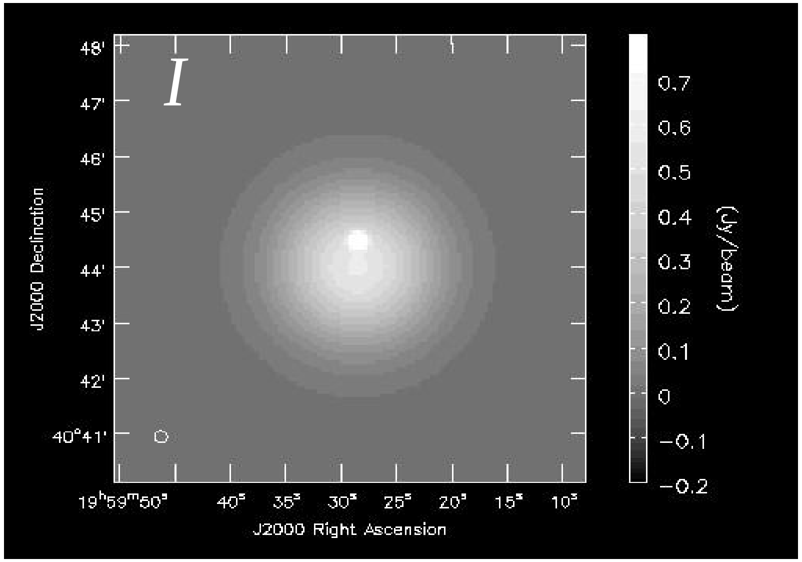
No short spacings to constrain the spectra

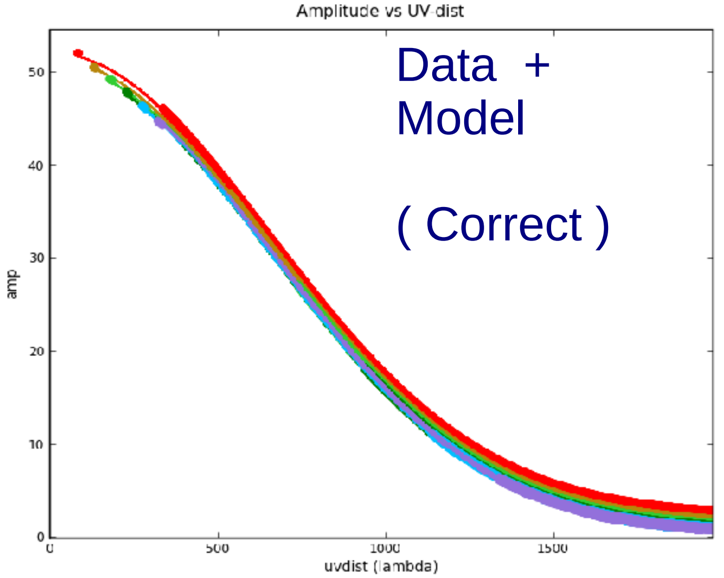
=> False steep spectrum reconstruction

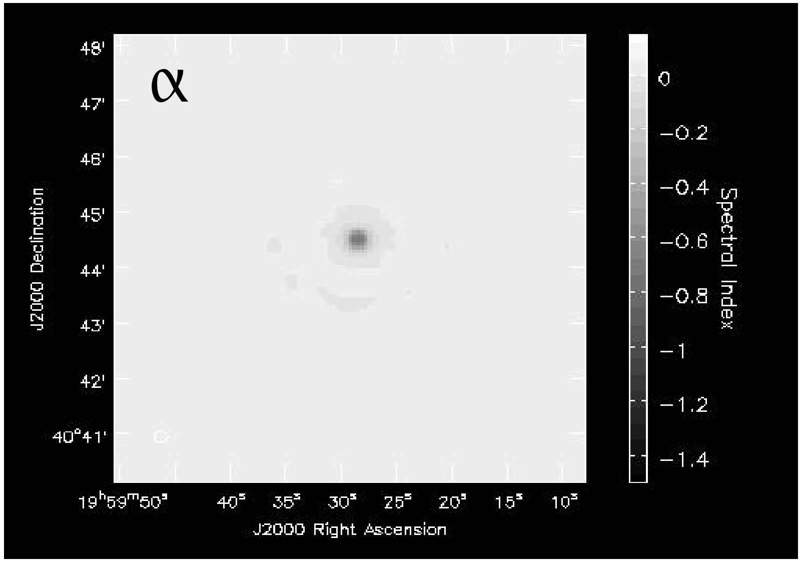
Very large scales : Need additional information

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









True sky has one steep spectrum point, and a flat-spectrum extended emission

Retain some short spacing information.

Correct reconstruction of a flat spectrum

=> So, how to add this information ?

Combination Methods

Image Combination

Starting Model

Joint Reconstructions

Image Combination

Weighted average between the SD image and the reconstructed INT image

AIPS : IMERG $I^{sdint} = F^{-1}\left[F[I^{interf}]_{high\,uv} + F[I^{sd(mod)}]_{low\,uv} + f\left(F[I^{interf}], F[I^{sd(mod)}] \right)_{overlap} \right]$

$$I^{sd(mod)} = I^{sd} \rightarrow Deconvolve(B_{sd}) \rightarrow Convolve(B_{interf})$$

MIRIAD : IMMERGE

CASA : Feather

$$I^{sdint} = F^{-1}\left[(1 - F[B_{sd}])\, F[I^{interf}] + \frac{A_{interf}}{A_{sd}} \cdot F[I^{sd}] \right]$$

NOD3 : Immerge

$$I^{sdint} = I^{interf} + \frac{A_{interf}}{A_{sd}} \left(I^{sd} - I^{interf} \right)$$

+ others

Handling INT Primary Beams : Use Flat-Sky INT image for feathering

(or) Multiply SD image with INT PB before combining

AIPS/MIRIAD have options for automatic flux scale matching within UV annulus

Image Combination

– Straightforward to implement and use.

=> Many successful examples in the literature

– Single step method.

=> Relies on accurate INT-only reconstructions

=> Cannot recover from all INT-only errors due to deconvolution uncertainty

(e.g. : Artifacts in the INT-only image, divergence, etc…)

– Noise/Error levels in the SD image and INT image must be comparable

=> If not, there can be a trade-off between noise and flux accuracy.

=> Considerable care is required in designing relative UV-Weighting functions

[For Wideband Multi-term imaging, combination is to be done on Taylor coefficient maps]

Starting Model

Method :

Use a (deconvolved) Single Dish Image as a starting model for the INT deconvolution.

Primary Beams :

For mosaic INT data, modify the single dish image model with the INT Primary Beam.

E.g. : For a flat-noise minor cycle normalization,

multiply the Single Dish image by the INT Primary Beam

Features :

– Requires sufficient spatial-frequency overlap between SD and INT data

=> Otherwise, it reduces to adding the SD model to the INT-only reconstruction

[For WideBand Multi-Term imaging, a multi-term SD model must first be created]

Joint Reconstructions

Combine constraints from SD and INT data (or images) during deconvolution

MOSMEM :

– Image-domain chi-square constraint with separate terms for the INT and SD images within a Maximum Entropy algorithm (narrow-band imaging only). Has auto-scaling.

TP2VIS :

– Construct pseudo SD visibilities by sampling the FT of the deconvolved SD image according to the UV-sensitivity envelope of the SD measurement. Match meta-data with INT observation.

– Append SD pseudo visibilities to INT dataset and reconstruct together.

Wideband SDINT :

– Combine SD and INT images and PSFs via feathering prior to minor cycle deconvolution, but keep the data (and major cycles) separate. Simple/flexible implementation.

+ others

Joint Reconstructions

– A joint sky model is constructed using information from all scales at once

=> Errors from INT-only reconstructions are not burnt in at any stage.

– The SD beam is also deconvolved from the SD observed image

=> Better resolution than just the SD observed image

– Merge Images and PSFs (feathering as a weighting scheme for deconvolution)

=> Robust to a wide range of choices of scale factors and UV-weighting functions.

– Potentially better handling of high relative error in SD data

=> Less of a trade-off between noise suppression and flux accuracy.

– Watch out for position-dependent PSFs in CLEAN-based wideband mosaics (natural and artificial)

– e.g. RFI-affected frequencies may differ across the field-of-view and telescopes, but algorithms may assume that measurement properties are invariant.

Joint Reconstructions within CASA

TP2VIS (Tuesday talk)

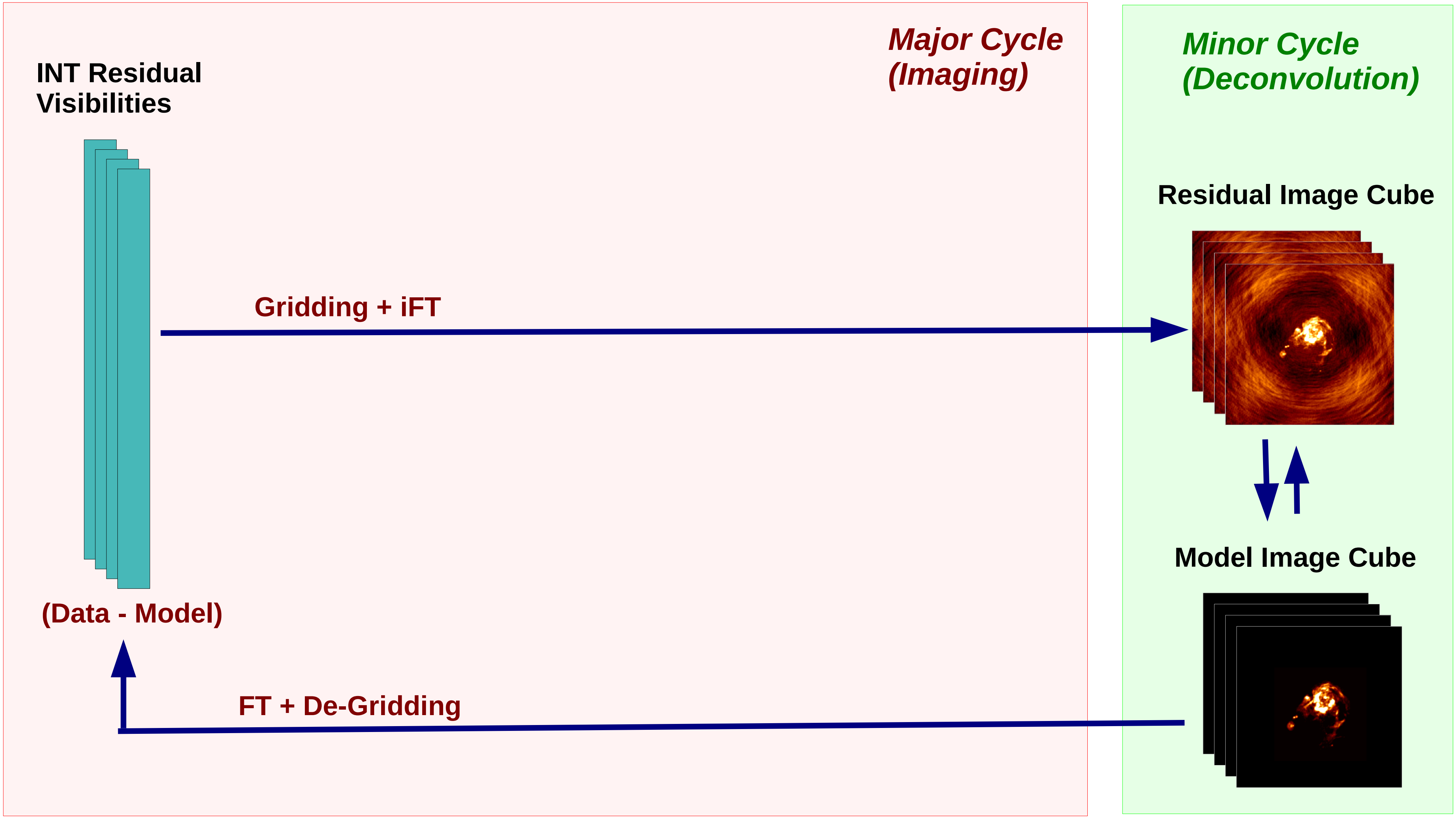
- Make SD pseudo-visibilities and use with CASA tclean

SDINT

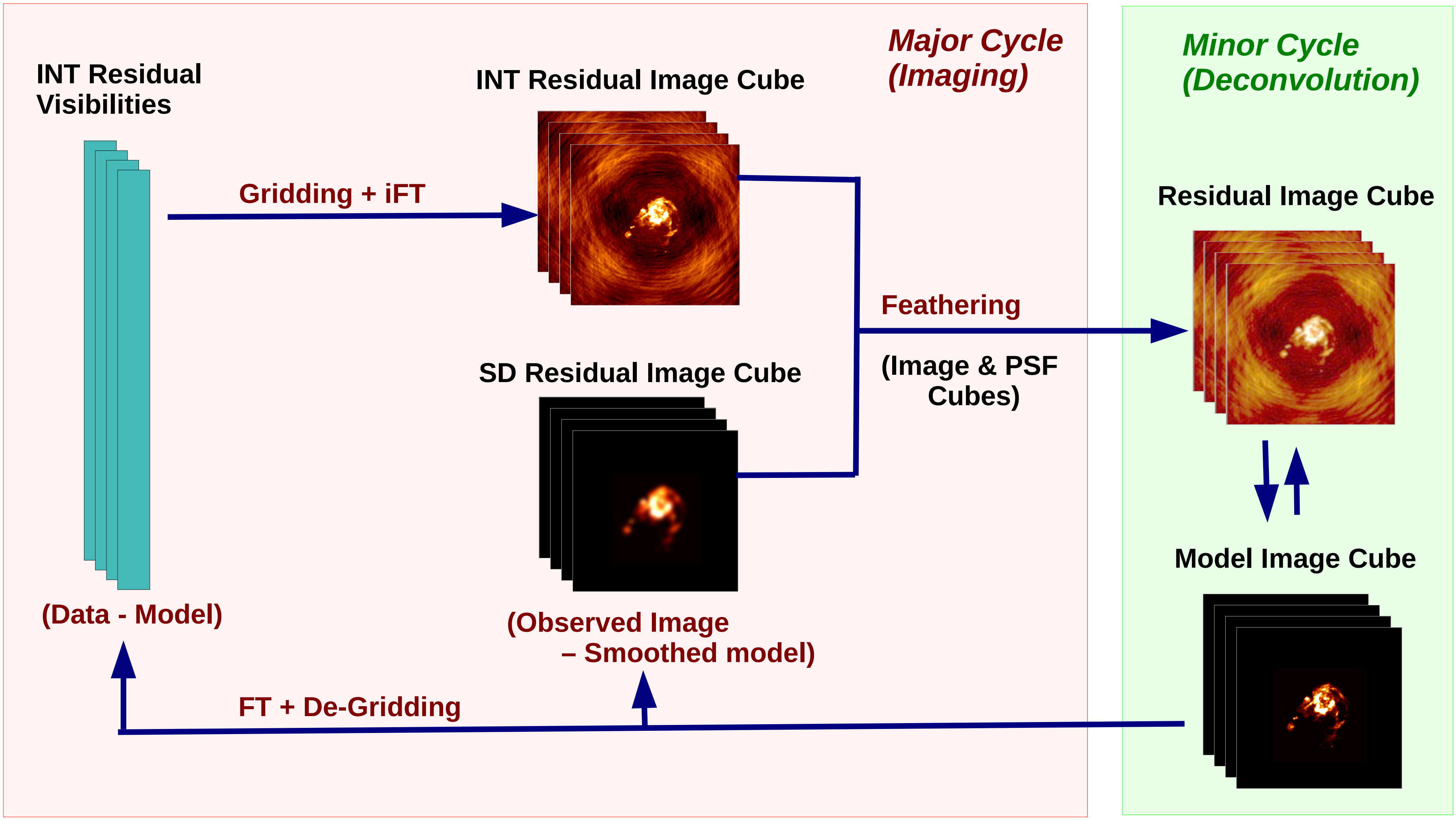
- Uses PySynthesisImager scripting interface
- Modular design for generic data combination
- Scripts and examples : https://github.com/urvashirau/WidebandSDINT
- A CASA task is being designed and evaluated

(Suggestions for features and validation tests are welcome)

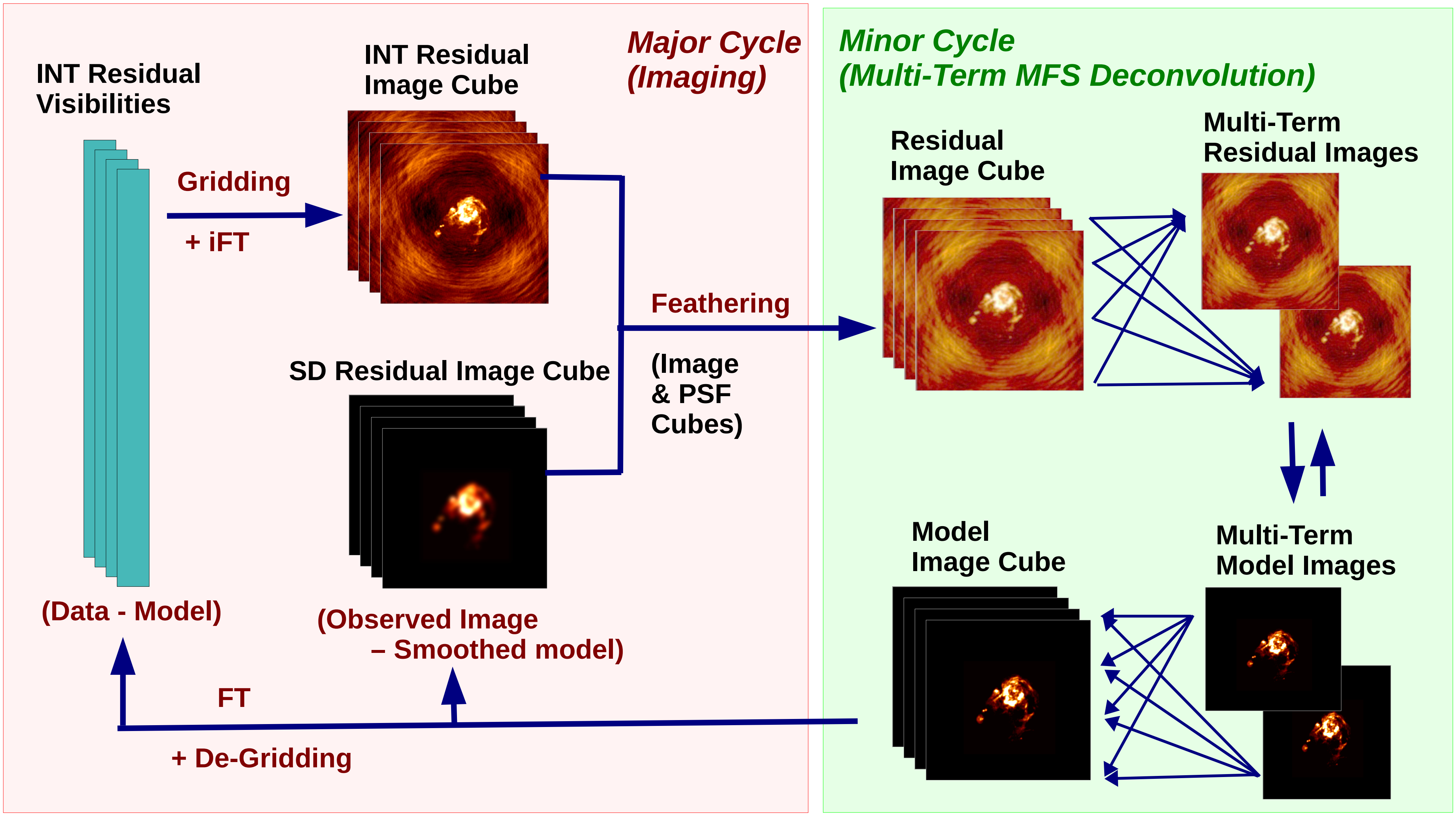
CASA : Spectral Line (Cube) Imaging : INT only



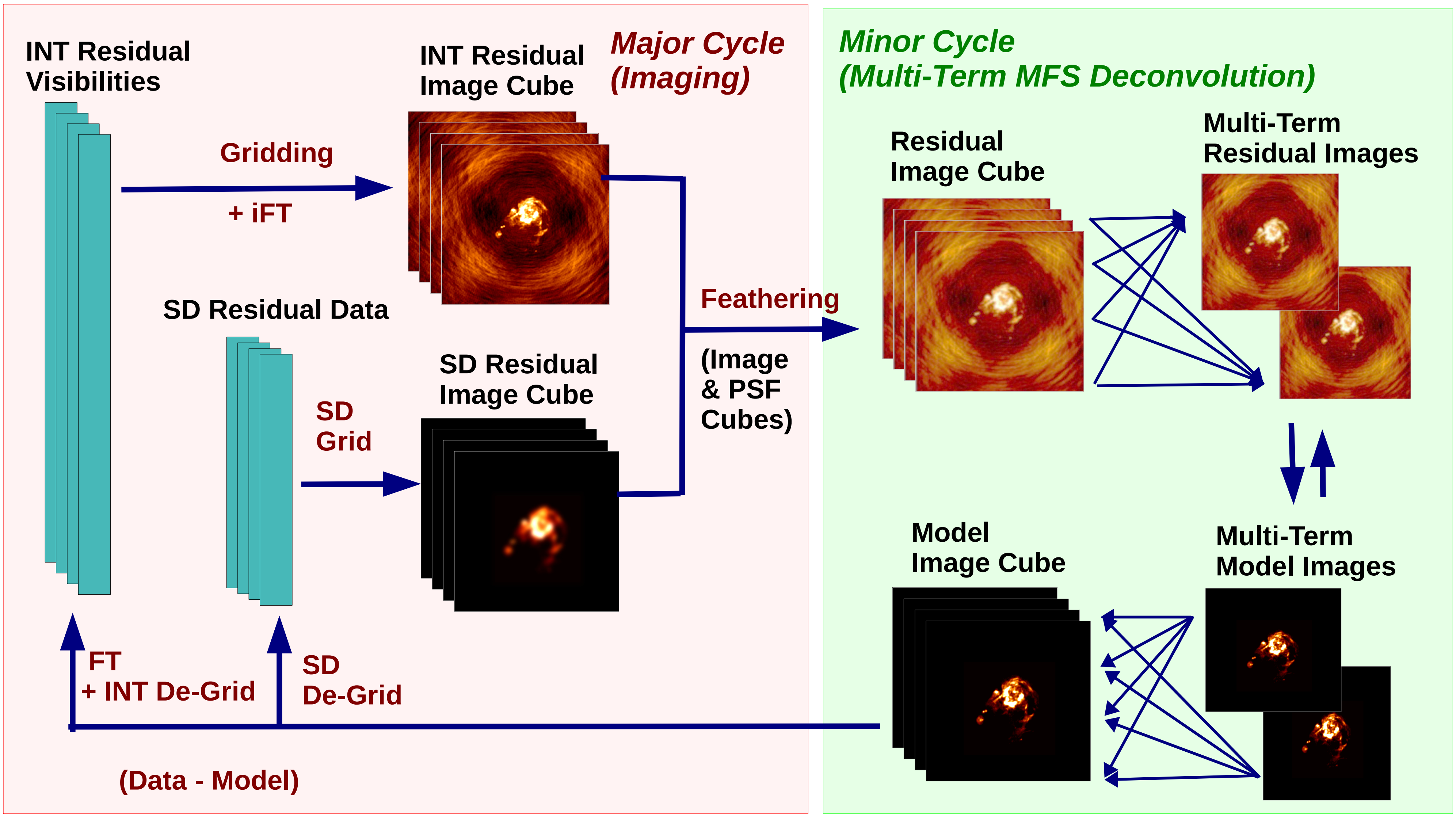
CASA : Spectral Line (Cube) Imaging : Joint INT + SD



CASA : Wideband Multi-Term Imaging : Joint INT + SD



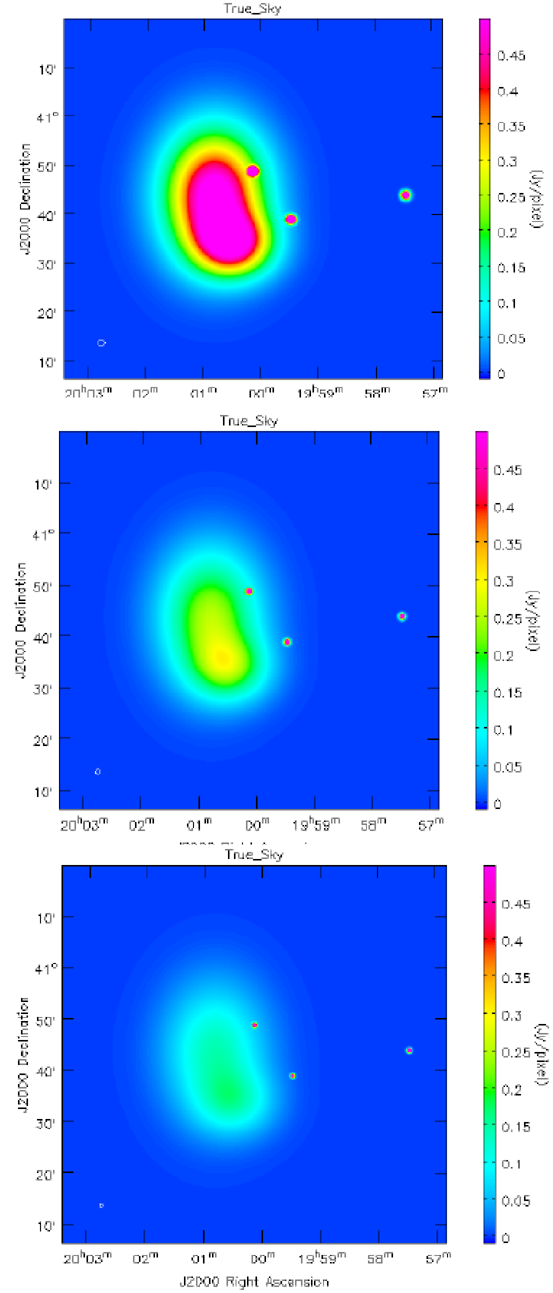
CASA : Wideband Multi-Term Imaging : Joint INT + SD



Data-to-Image transforms can differ across instruments.

Example : Simulation

True Sky, smoothed to INT resolution



Sky Brightness :

Extended : 10 – 20 arcmin Gaussians, Alpha = 0.0

(Max INT scale at 1.5 GHz : 20 arcmin)

Compact : 3 point sources

Alpha of -1.0, -1.0, and 0.0 from left to right.

VLA D-config + GBT :   1.0, 1.5, 2.0 GHz

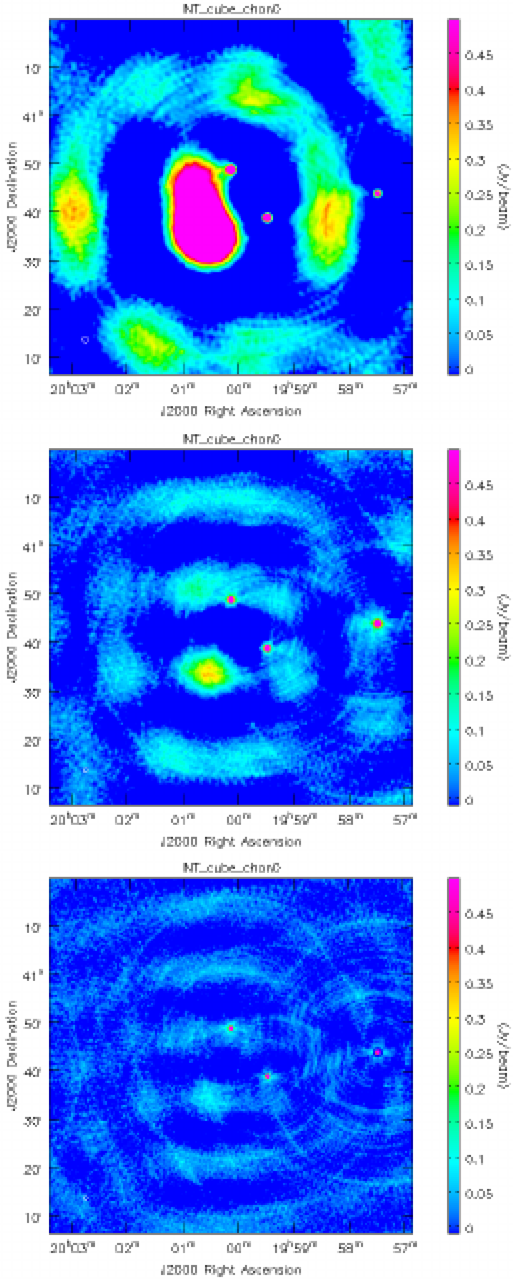
(1) Single Pointing Simulation

- No Primary Beams
- Wideband Short Spacing Problem

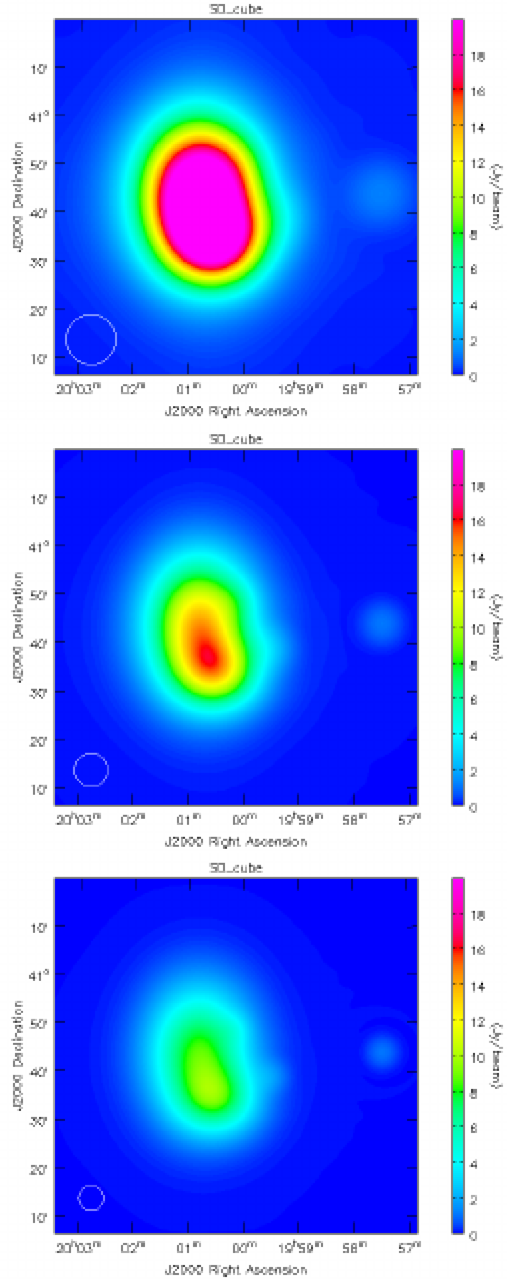
(2) Mosaic Simulation

- 25 Pointings
- Frequency dependent Primary Beams

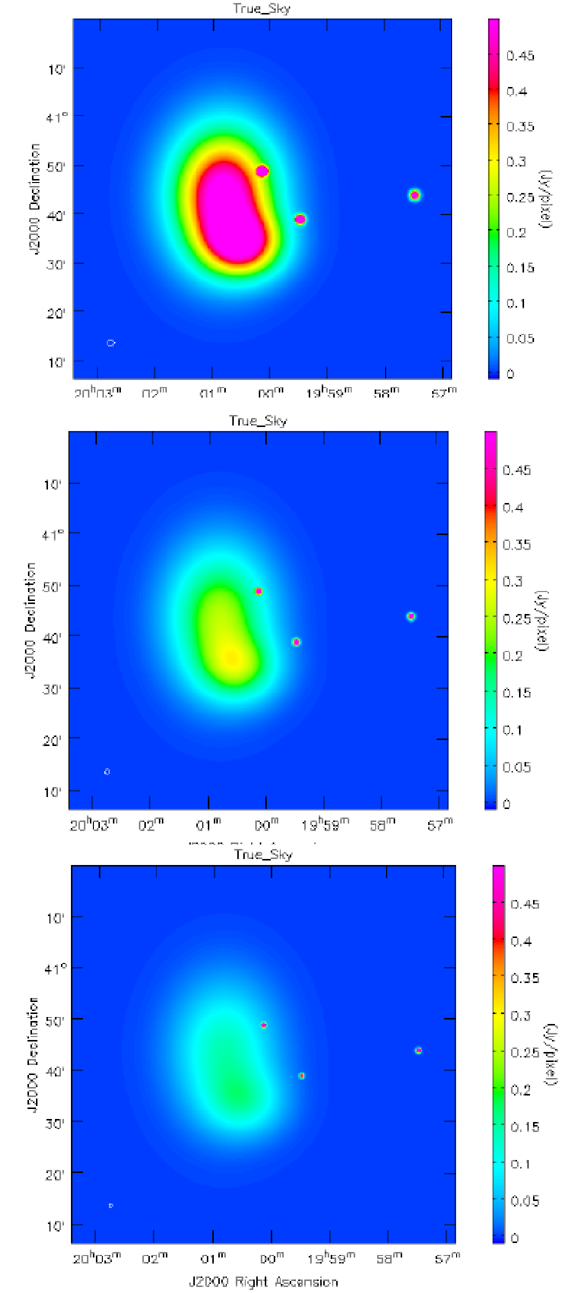
INT Cube



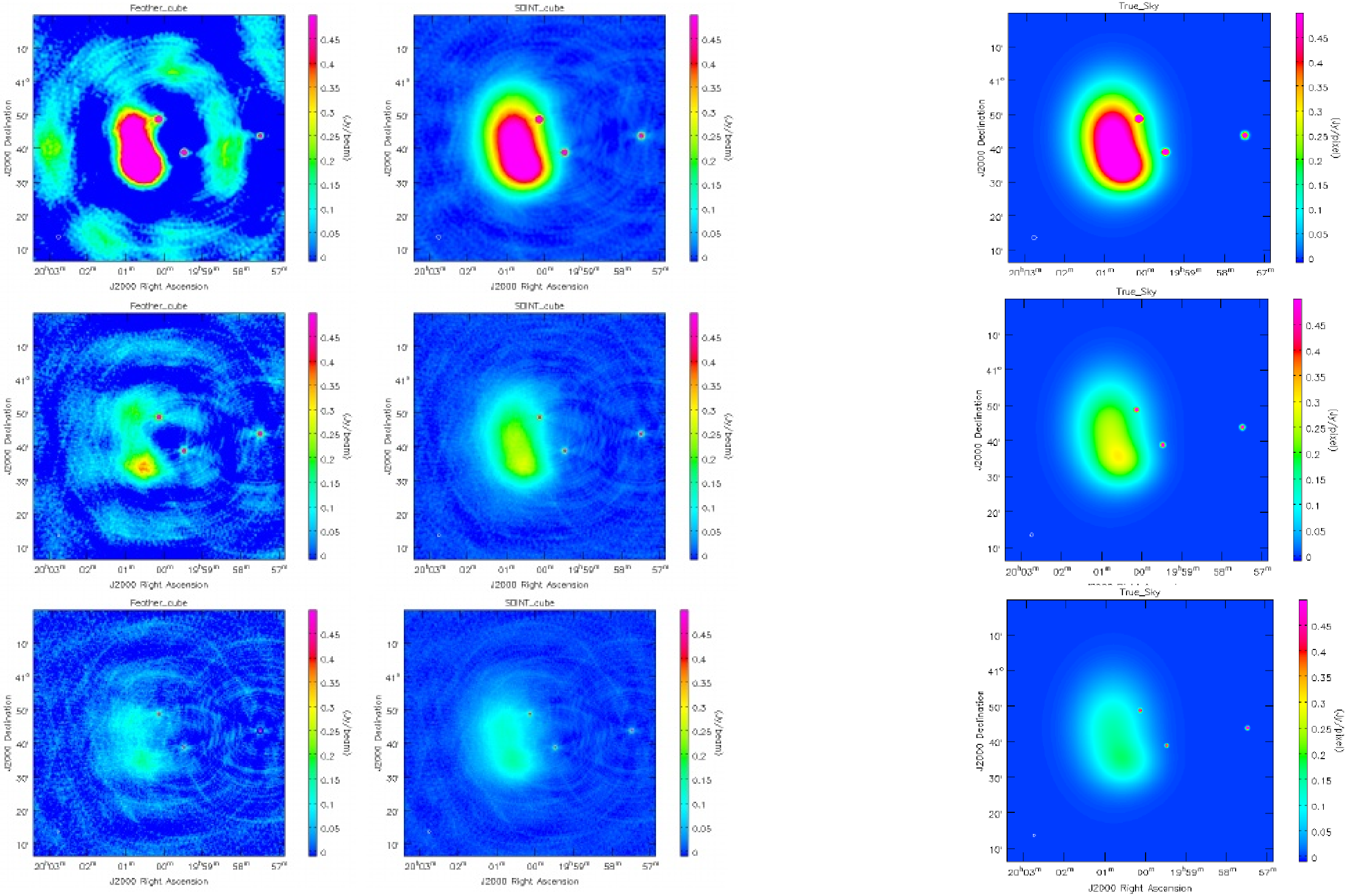
SD Cube



True Sky



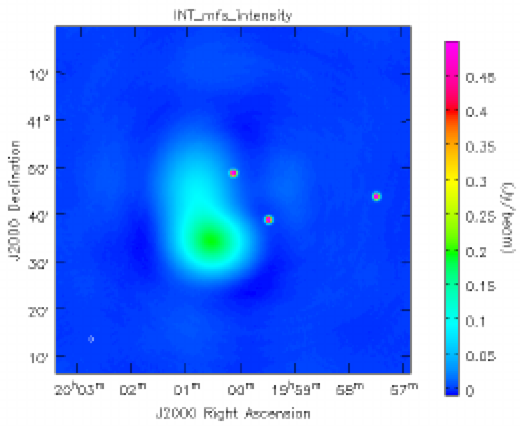
Feather Cube   SDINT Cube   True Sky

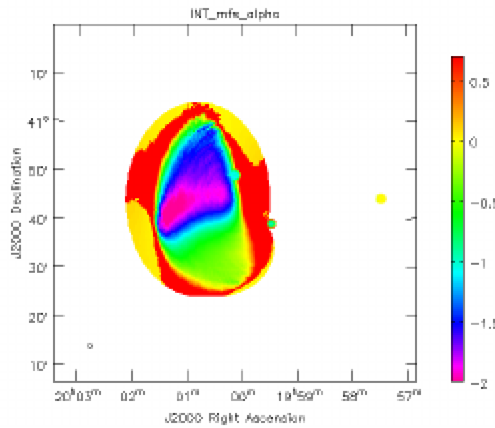


Wideband Imaging – INT , SD , SDINT

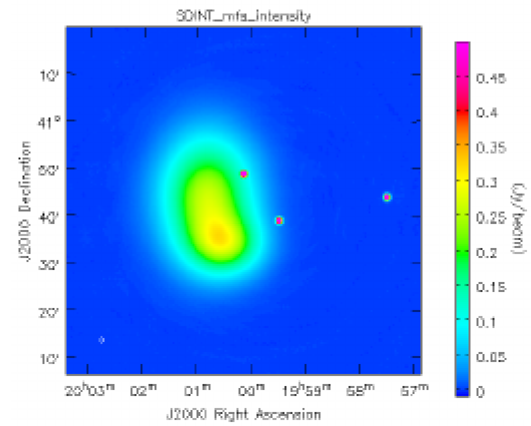
Intensity and Spectral Index (deconvolver='mtmfs', nterms=2)

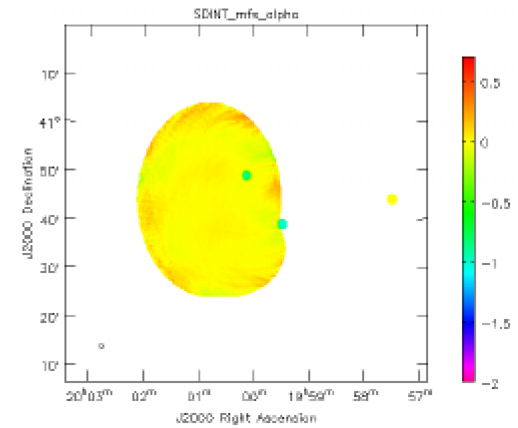
INT only



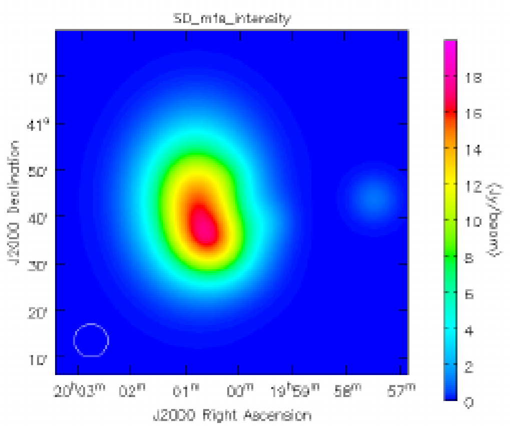


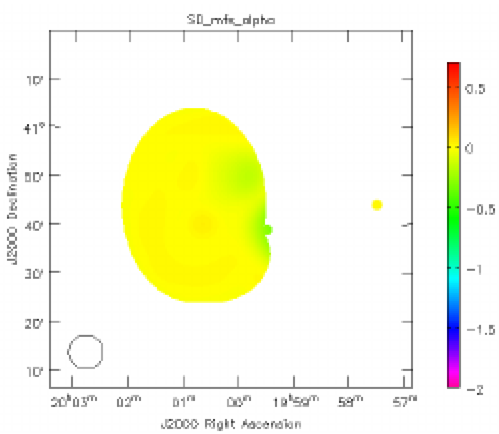
Wideband SDINT





SD only





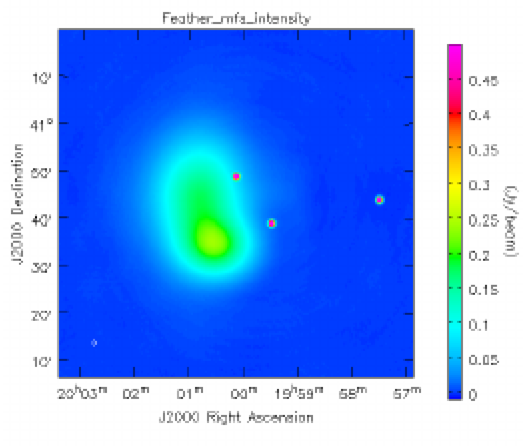
INT-only reconstruction has errors at mid and large scales

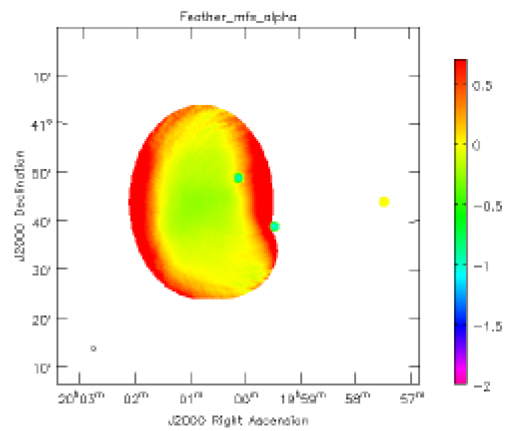
SDINT spectral index is accurate to within 0.15 (typical of any multi-scale result).

Wideband Imaging – Feathering, Startmodel, SDINT

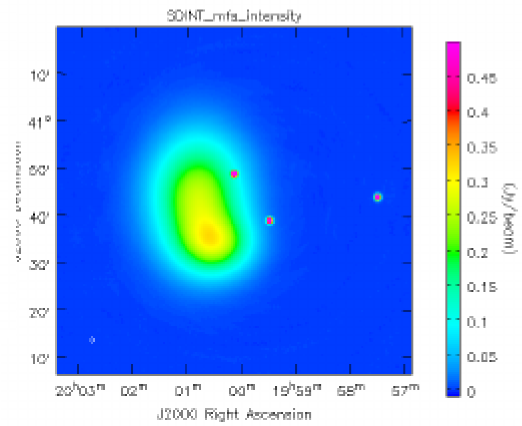
Intensity and Spectral Index (deconvolver='mtmfs', nterms=2)

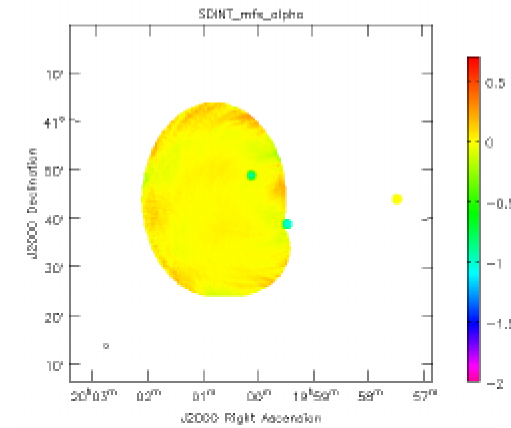
Multi-term Feather



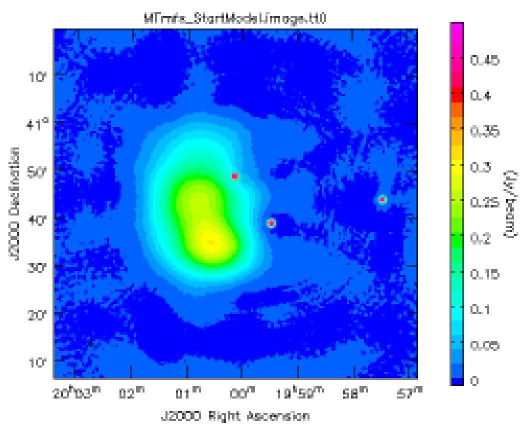


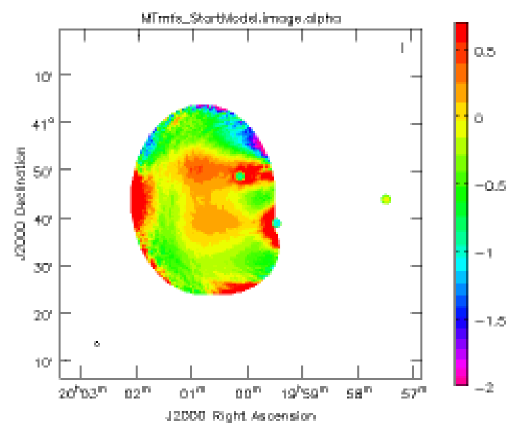
Wideband SDINT





Multi-term StartModel



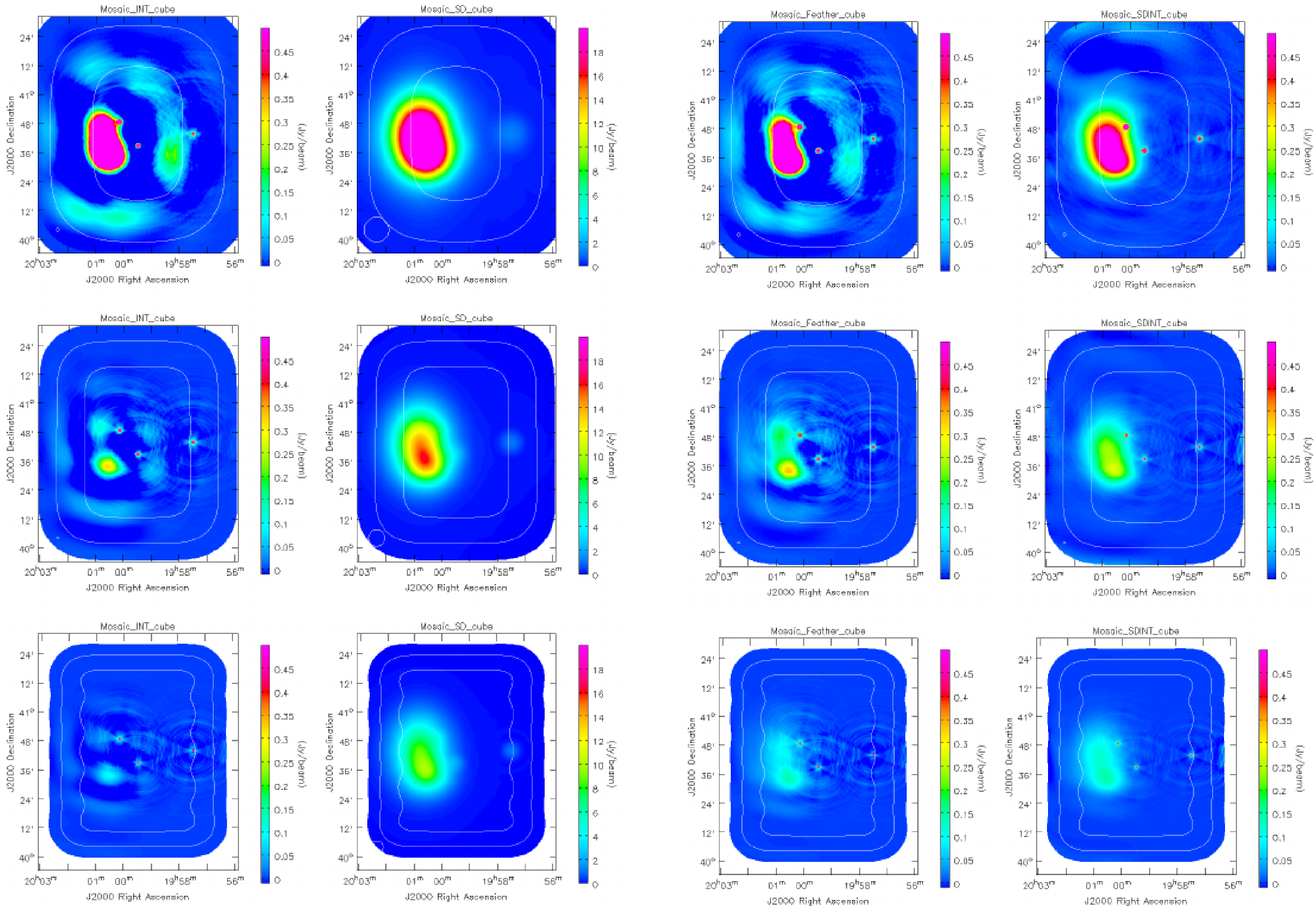


Feathering did not fully recover from INT-only errors on spectral index.

StartModel did not provide sufficient constraints on the INT-reconstruction

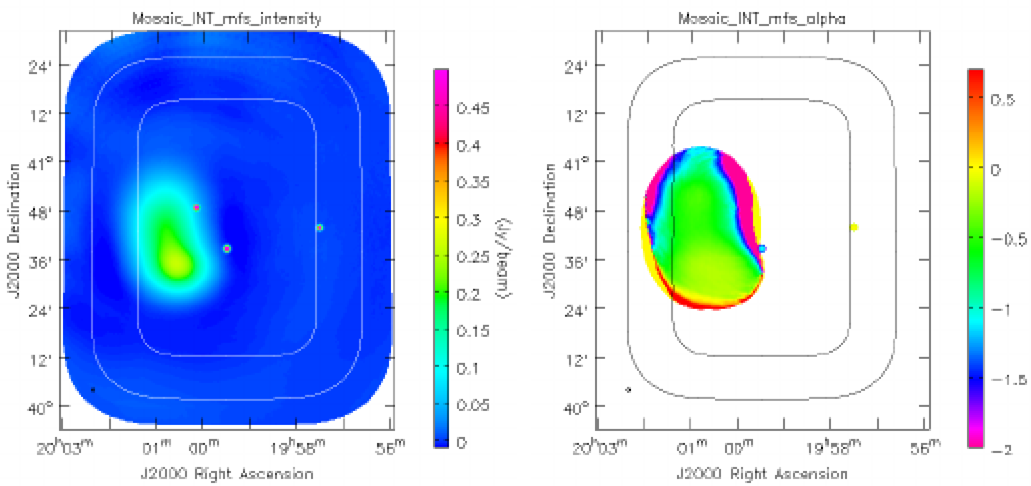
Mosaic Cube

INT SD Feather SDINT

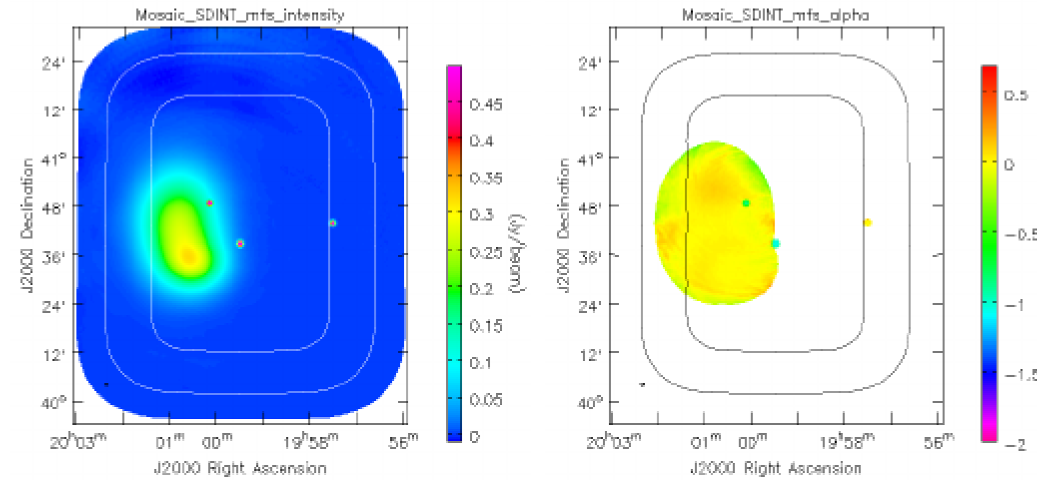


Wideband Mosaic - INT , Feather and SDINT

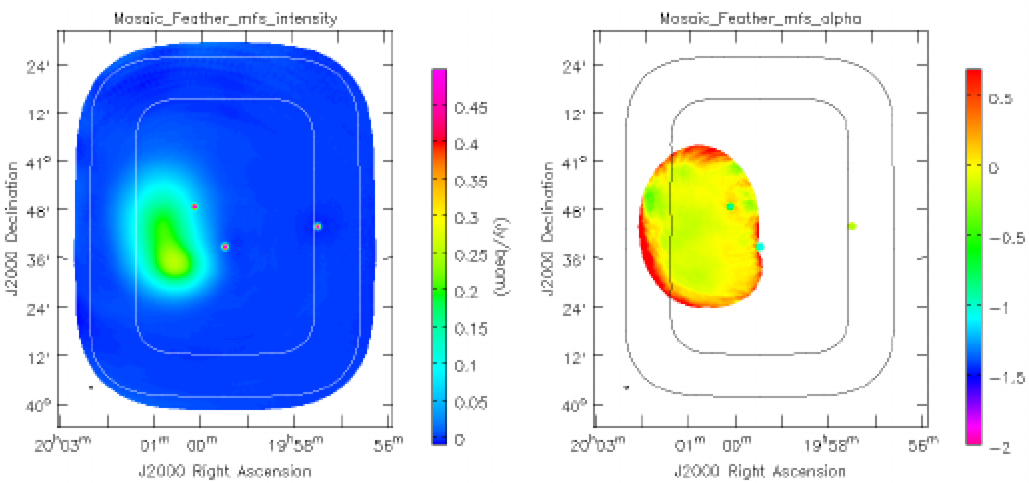
INT-only Multi-term Mosaic



Wideband Mosaic SDINT



Feathered Multi-term Mosaic



With a mosaic, the INT-only spectral index is better but still too steep (-0.5)

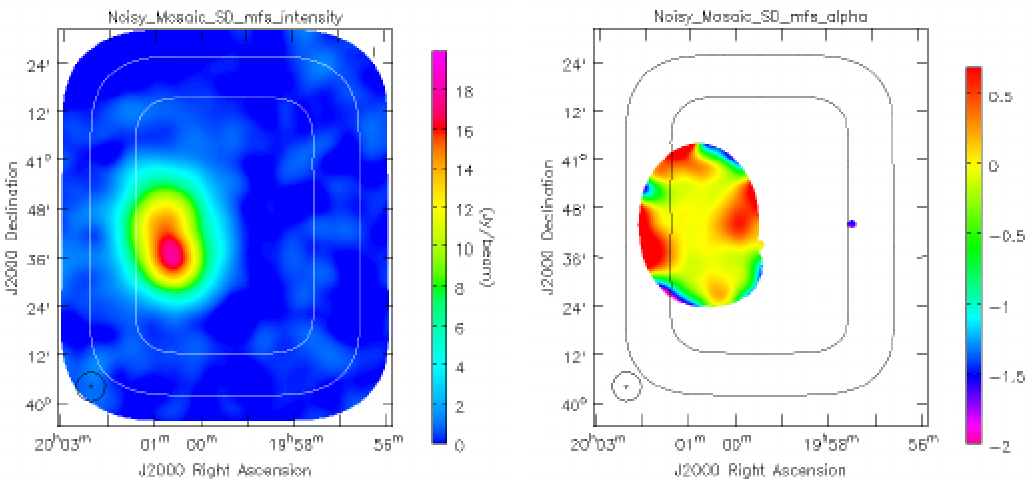
Feathering gets close (err : +/- 0.3)

SDINT gets alpha accurate within +/- 0.15

High relative Single Dish noise

Added random noise to the true sky before convolution with the SD beam.

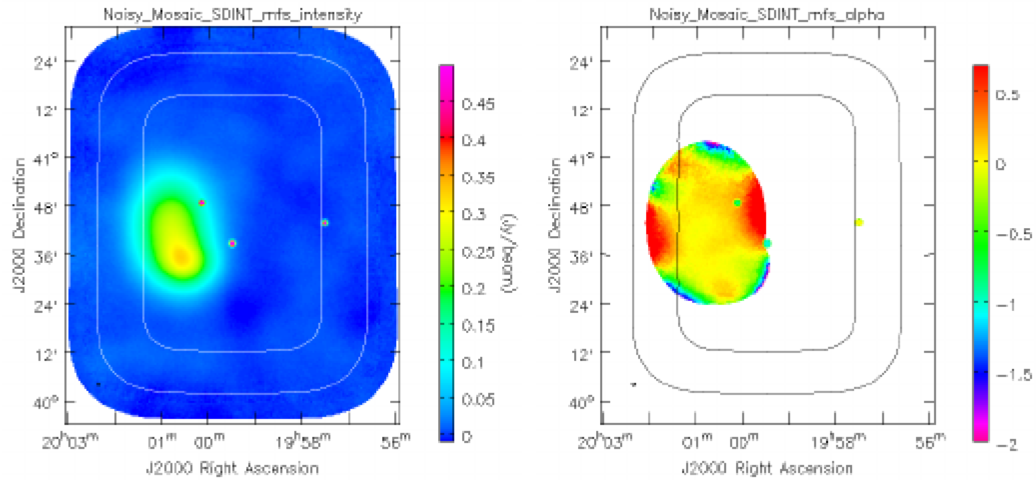
~ Proxy for pointing errors ?



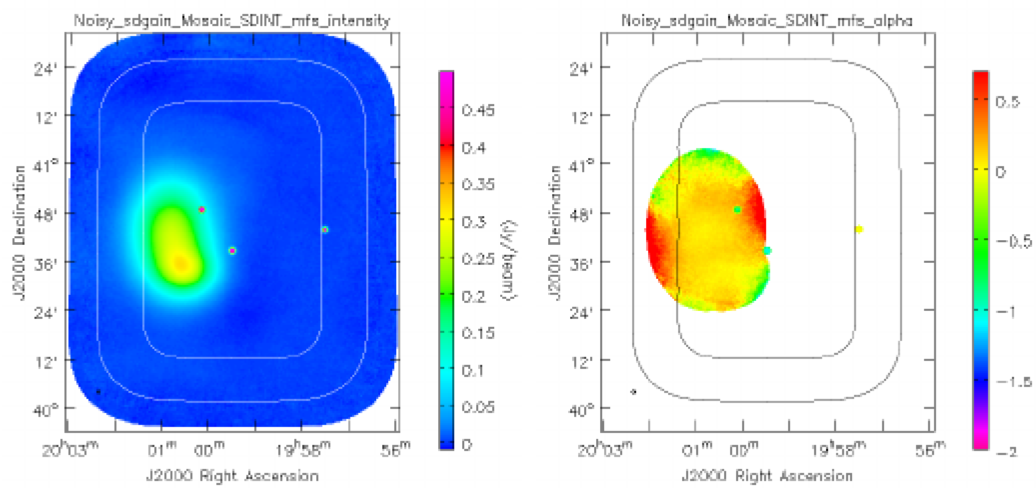
Lower the SD gain by a factor required to match image noise with IN image, but not too much to incur bias in reconstructed flux.

Bias due to weighting is less than due to direct scaling.

SDINT with sdgain=1.0



SDINT with sdgain=0.2



Intensity : Flux is accurate. Noise is down.

Alpha : Minor improvement

Summary of Data Combination Methods

– **Image Combination :** When INT and SD images are both well-behaved

  – Effective and simple

  – Errors arise from trade-offs between flux accuracy and error control.

– **Start Model :** When INT and SD data overlap well in UV-space

  – Easy to use with existing image reconstruction solvers

– **Joint Reconstructions :** When deconvolution just needs more constraints from the data

  – SD+INT, joint mosaics, multi-frequency-synthesis before reconstruction.

  – More robust to relative weighting schemes than a single-step approach

  – Faster convergence, less divergence, less need for masks, more accurate model

  – Instability can occur when the data do not match a uniform instrument model