Combining single dish and interferometer data for joint wideband multi-term deconvolution

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&

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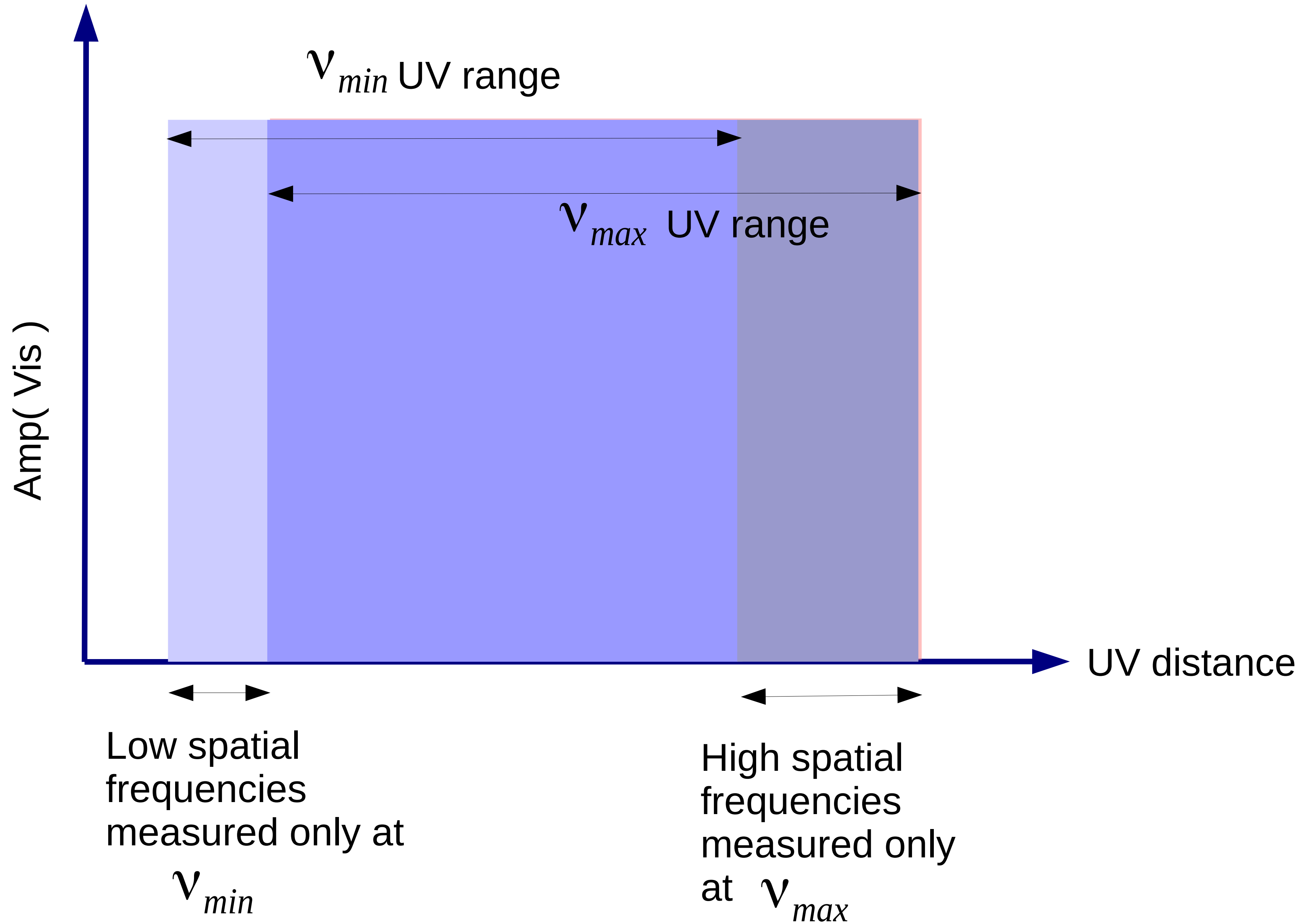
Goals

- Solve the short-spacing problem for wideband multi-term imaging
  - Reconstructions of large scale spectra are particularly error prone with INT-only data
- Prototype a generic algorithmic framework for joint SD+INT reconstructions
  - Retain the benefits of multiple existing algorithms
  - Ensure flexibility in algorithm and image-type choices
- Explore robustness to differing noise levels between SD and INT data/images
  - Is it possible to relax current constraints on required SD observing time ?
  - How much SD uv-coverage (and overlap with INT) is sufficient ?

For which scales can we reconstruct the spectrum



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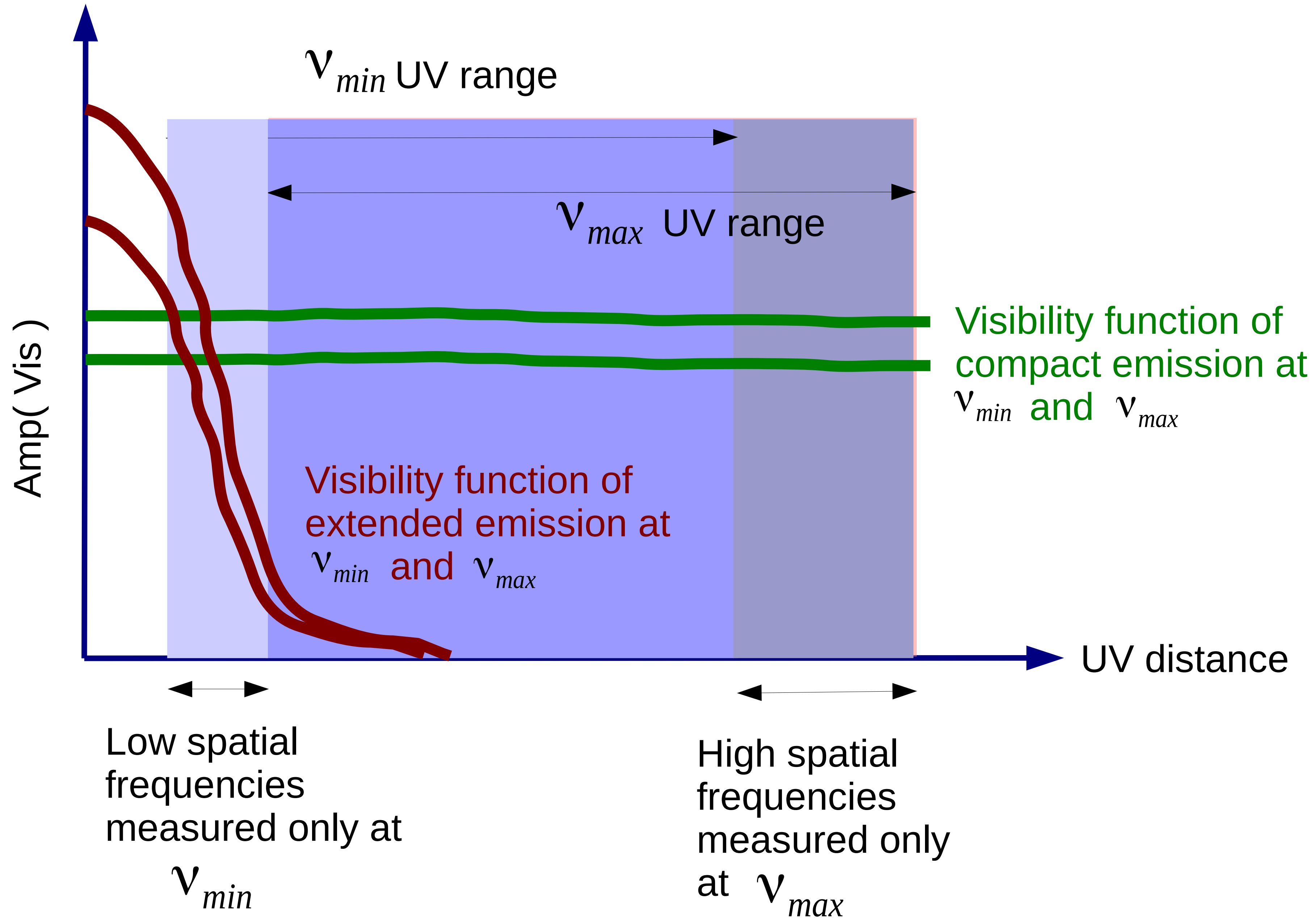
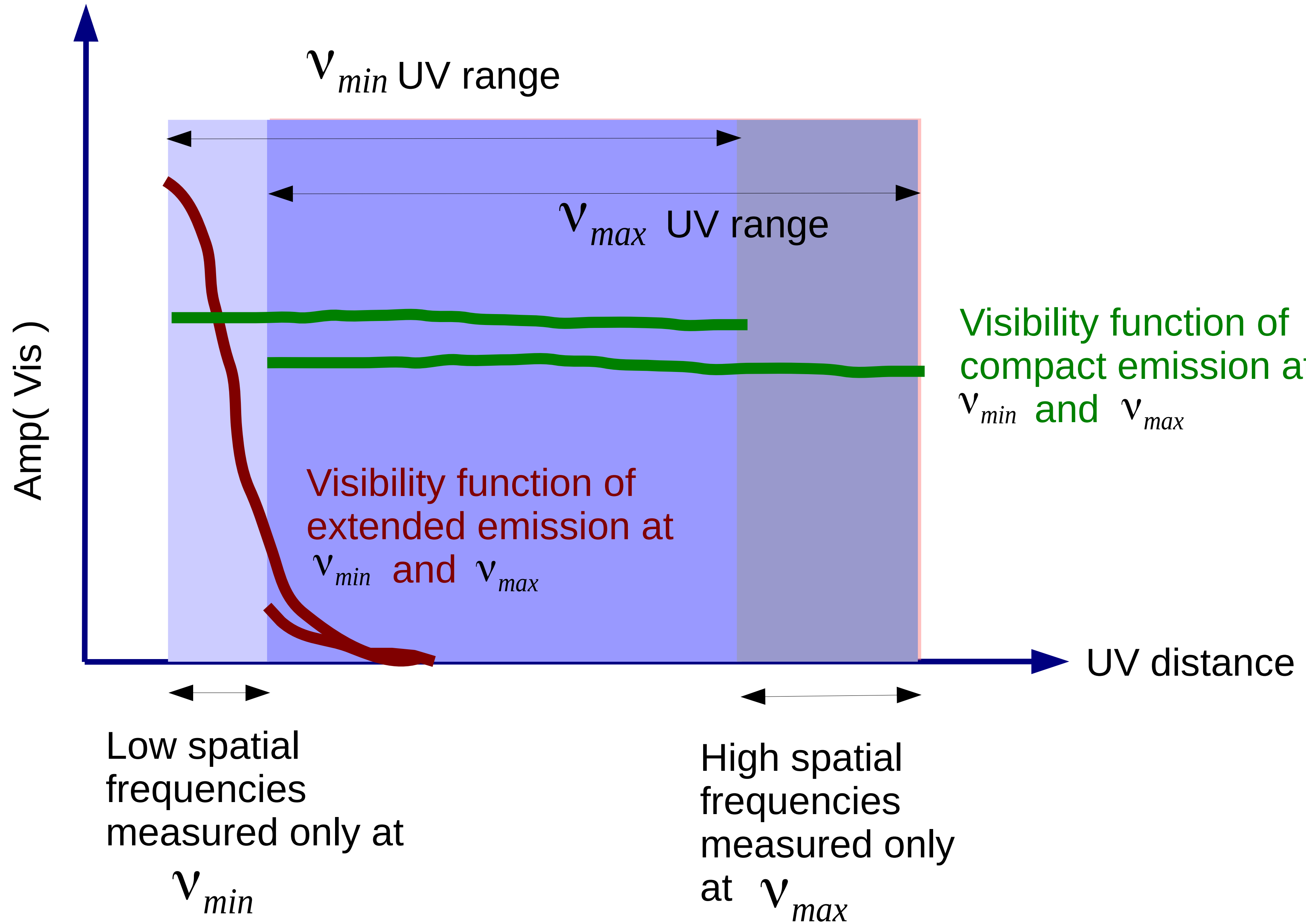
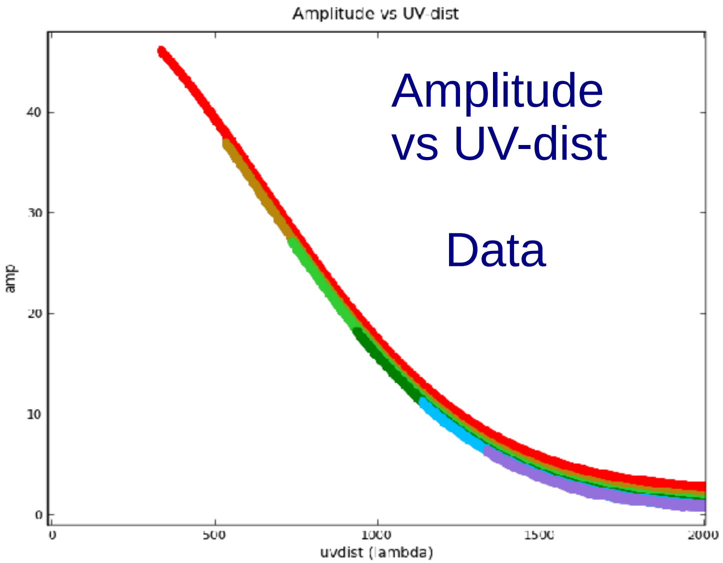


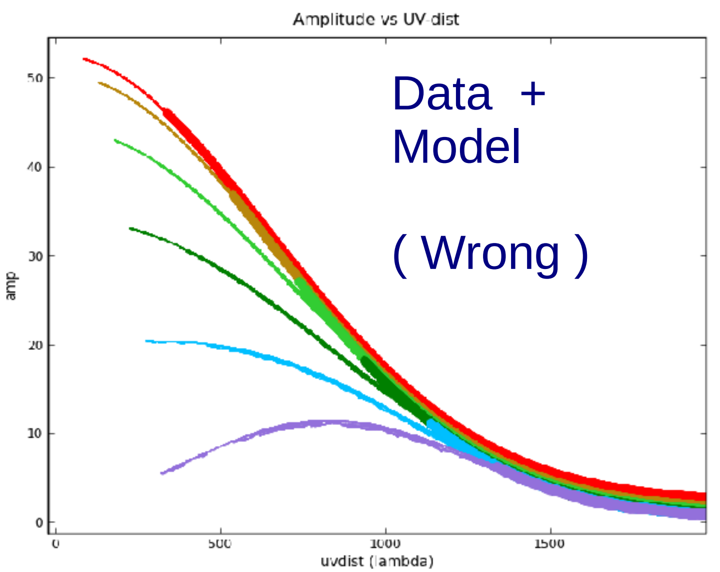
For which scales can we reconstruct the spectrum

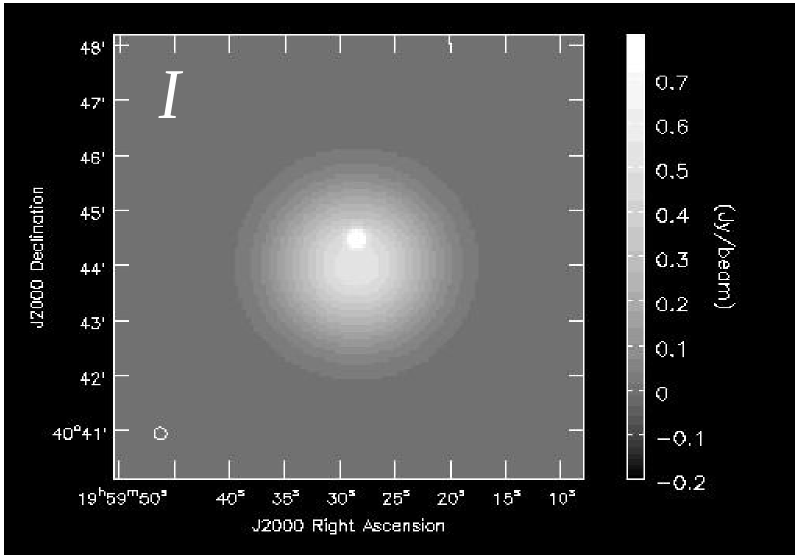


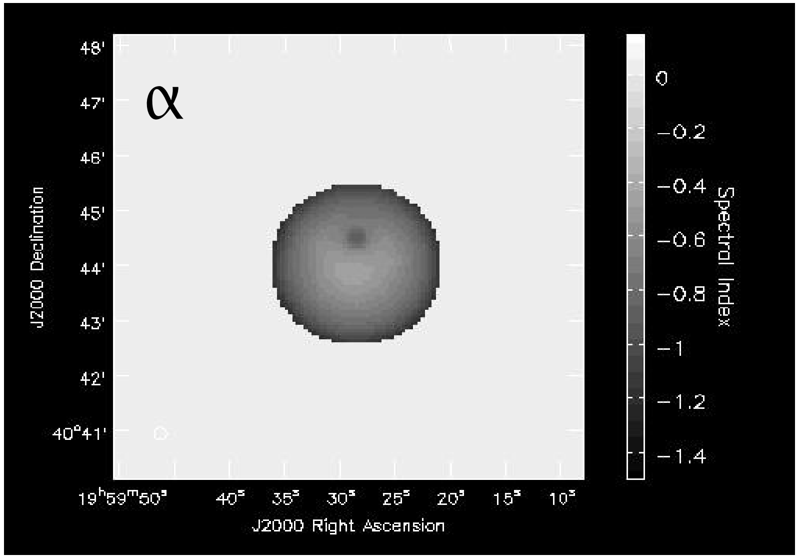
Very large scales : Unconstrained Spectrum

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

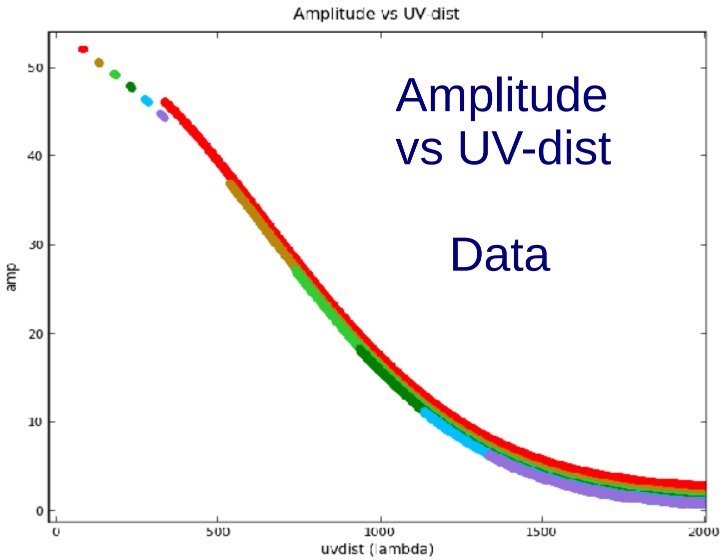
Leave out shortest baselines

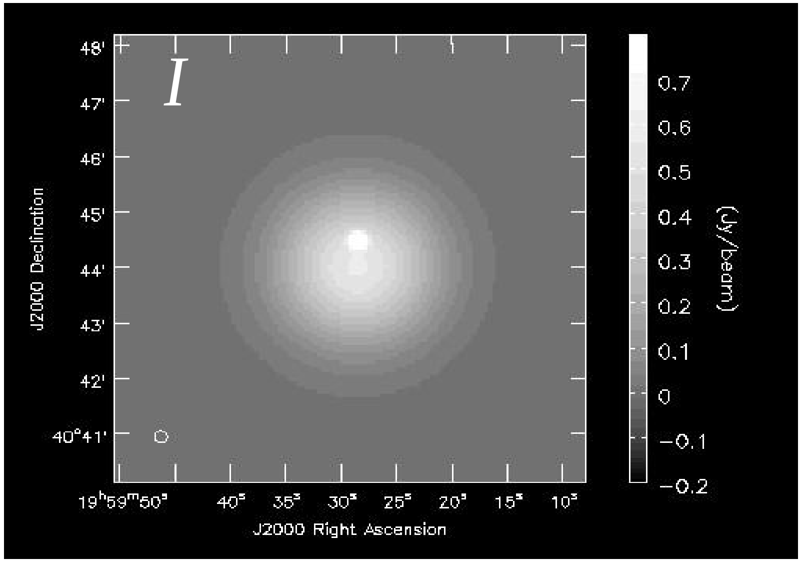
No short spacings to constrain the spectra

=> False steep spectrum reconstruction

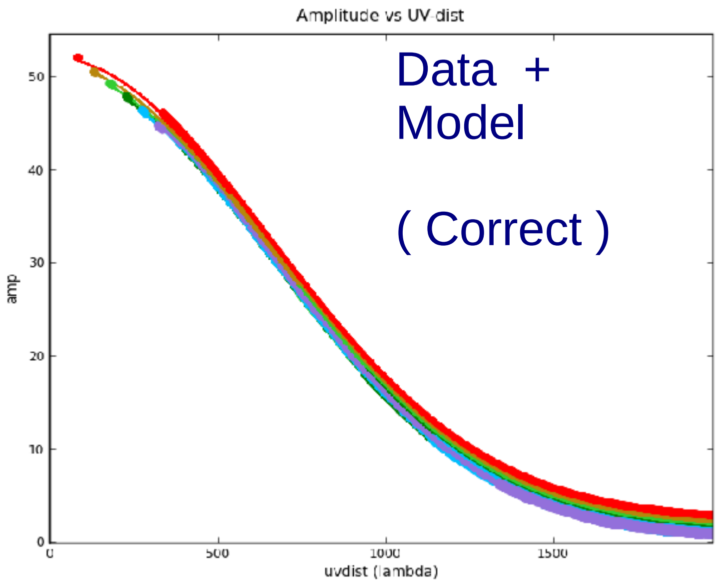
Very large scales : Need additional information

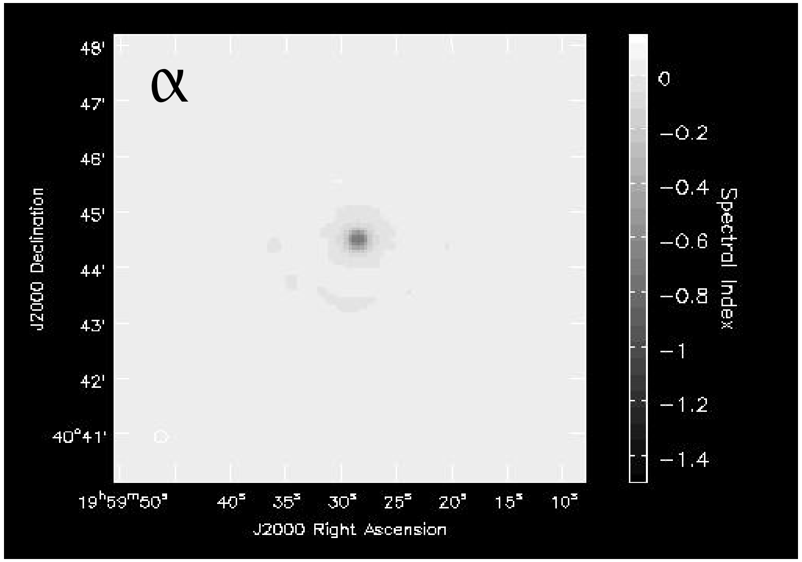
External short-spacing constraints (visibility data, or starting image model)





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



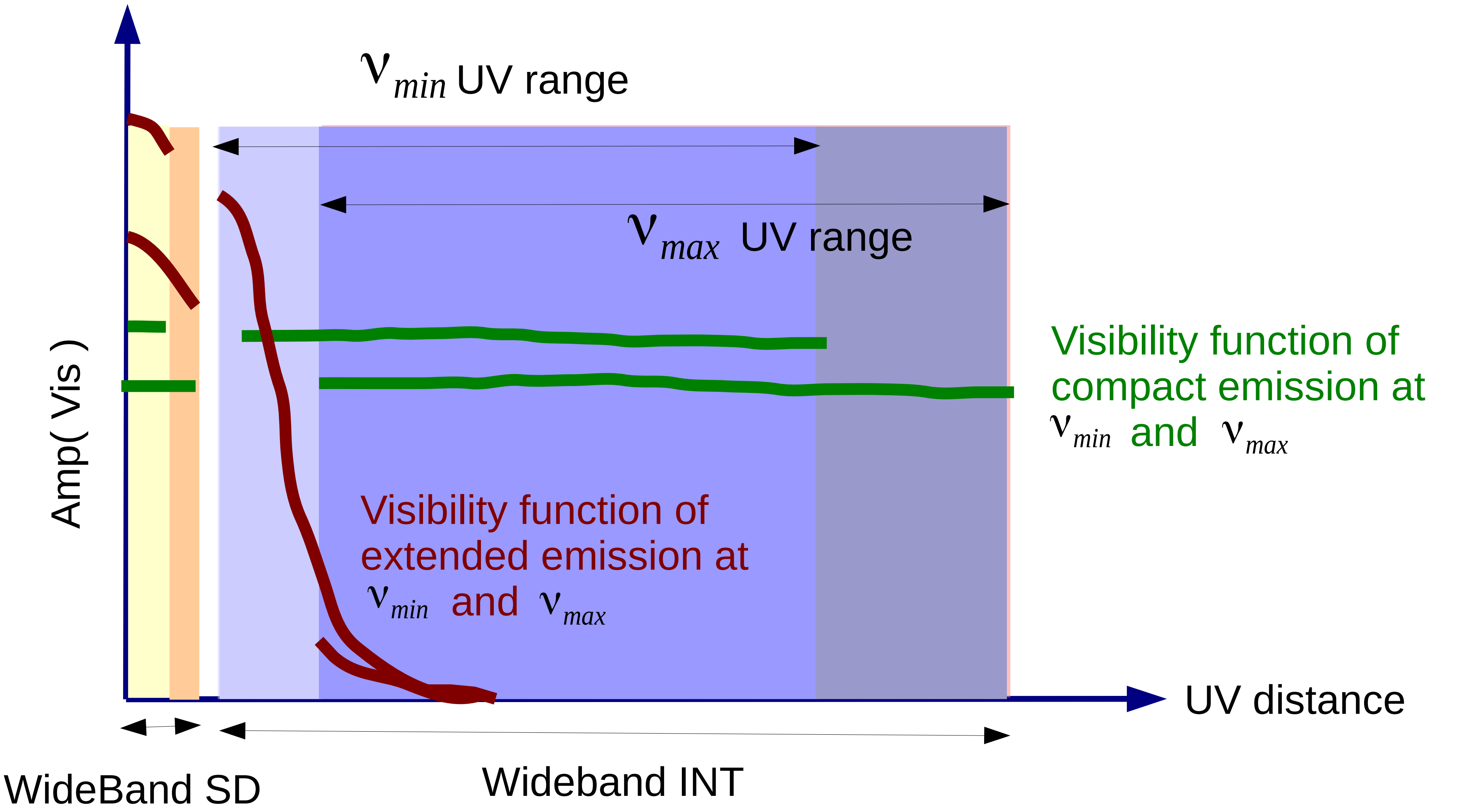


Retain some short spacing information.

Correct reconstruction of a flat spectrum

=> So, how to add this information ?

Wideband data : SD-only vs INT-only vs SD+INT



Degree of overlap between SD and INT depends on single dish diameter
=> Different algorithms apply (post-reconstruction combination vs joint modeling)

Approaches for combining INT and SD data/images

- **[1/3] Feathering** : Combine SD observed image and INT reconstructed image.
  - A weighted sum in the uv-domain
    - The FT of the SD beam is used as the weighting function
    - Scale factor chosen empirically (or as the ratio of beam areas)

    (CASA, AIPS, OBIT, MIRIAD all have slightly different implementations.
    Several other efforts/ideas exist)
  - It is usually used as a post-deconvolution combination
  - The effect of the empirical scale factor is also burnt into the result
    (=> significant art involved in choosing proper relative weighting schemes)

- **[2/3] StartModel** : Use a deconvolved SD image as a starting model for the INT reconstruction
  - Effective when there is significant overlap between INT and SD uv-spacings

Approaches for combining INT and SD data/images

- **[3/3] Joint reconstructions** : Build a sky model using SD+INT together

  Method 1 : Combine SD and INT images **and PSFs** before deconvolution.

  – Scale factors and empirical weight functions enter the reconstruction as a choice of data weighting (robust, uniform, etc)

  Stanimirovic et al, 1999 : Construct an image-domain weighted sum prior to one deconvolution cycle

  Method 2 : Add image-domain constraints to non-linear solvers (e.g. MEM)

  – MOSMEM (miriad) implements a narrow-band version

  MIRIAD task documentation : User-supplied scale factors + auto-matching of visibility levels.

  Method 3 : Create artificial visibilities from single dish data

  – Use a random visibility sampling function within the UV footprint of the SD telescope. Simulate a list of visibilities.

  – Make up meta-data to match what an interferometer measures

  Koda et al 2011, 2017 : Implemented and demonstrated this approach for ALMA via 'tp2vis'.

- Our Approach : Feather SD and INT residual images and PSFs in-between standard major/minor cycle iterations.

Approaches for combining INT and SD data/images

- **Dealing with Interferometer Primary Beams (and mosaics)**

  - INT observed image = (sky . INT_pb) * INT_psf

    INT_model = (sky . INT_pb)

  - SD observed image = (sky) * SD_pb

    SD_model = (sky)

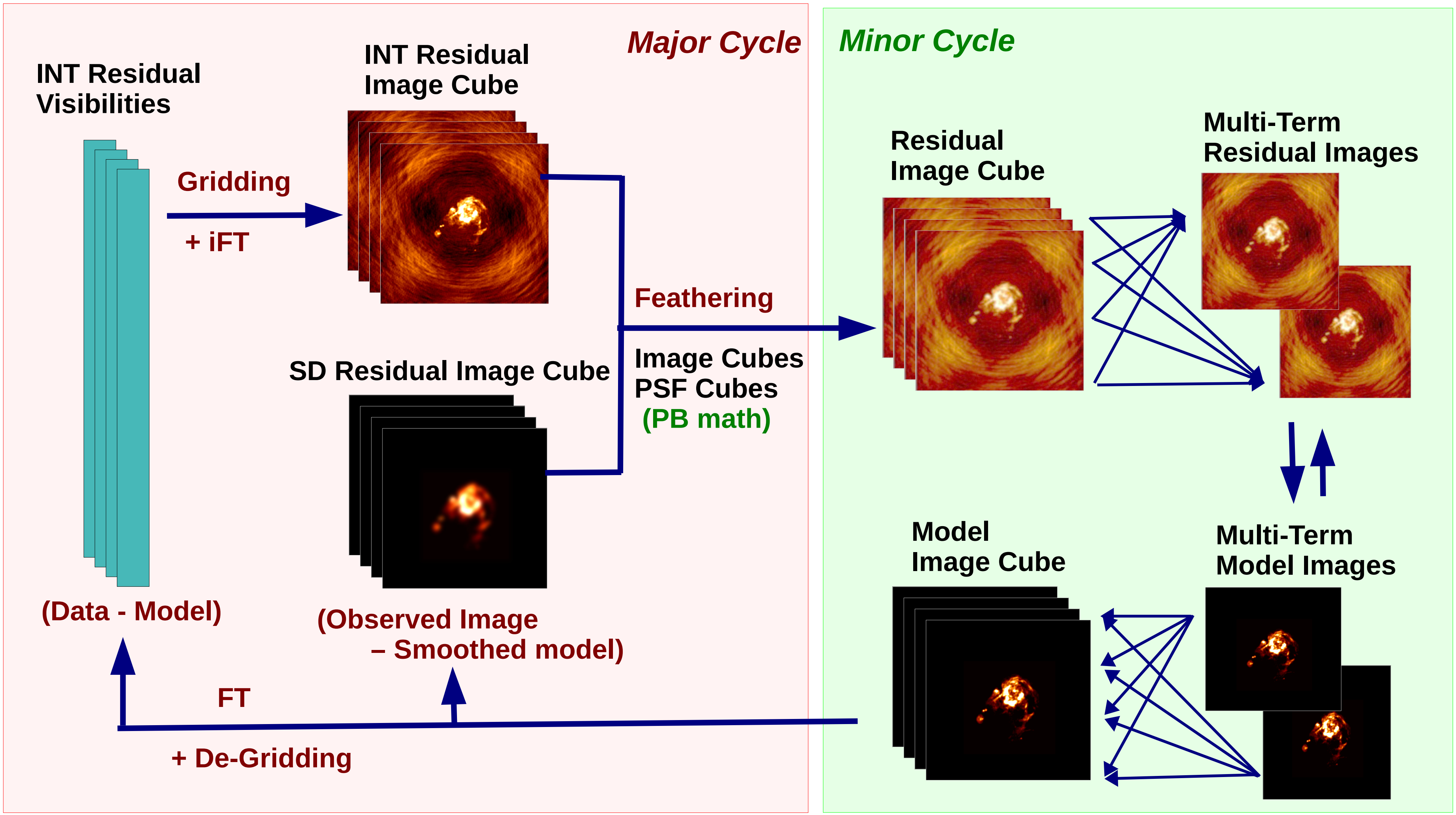
=> Manipulate either the SD or INT images (with INT PB) to match the other

e.g. For Feathering, use (INT_model / INT_pb) with SD_model

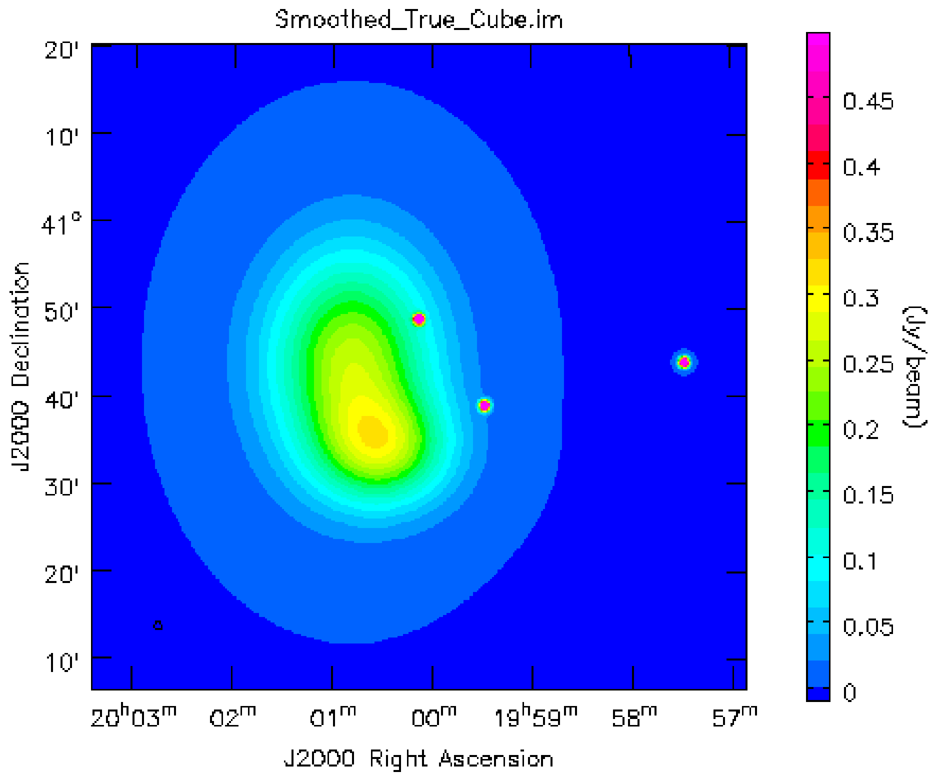
e.g. For Startmodel, use (SD_model . INT_pb) with the INT-only reconstruction with flat-noise normalization

e.g. Details for Joint algos depend on algorithm (and normalization)

Our Choice : Wideband SD+INT Multi-Term Imaging



SD and INT wideband simulations (VLA D-config + GBT)



Two extended Gaussian components

15 x 20 arcmin (largely unsampled by INT)
10 x 12 arcmin (partially sampled by INT)

Spectral index = 0.0

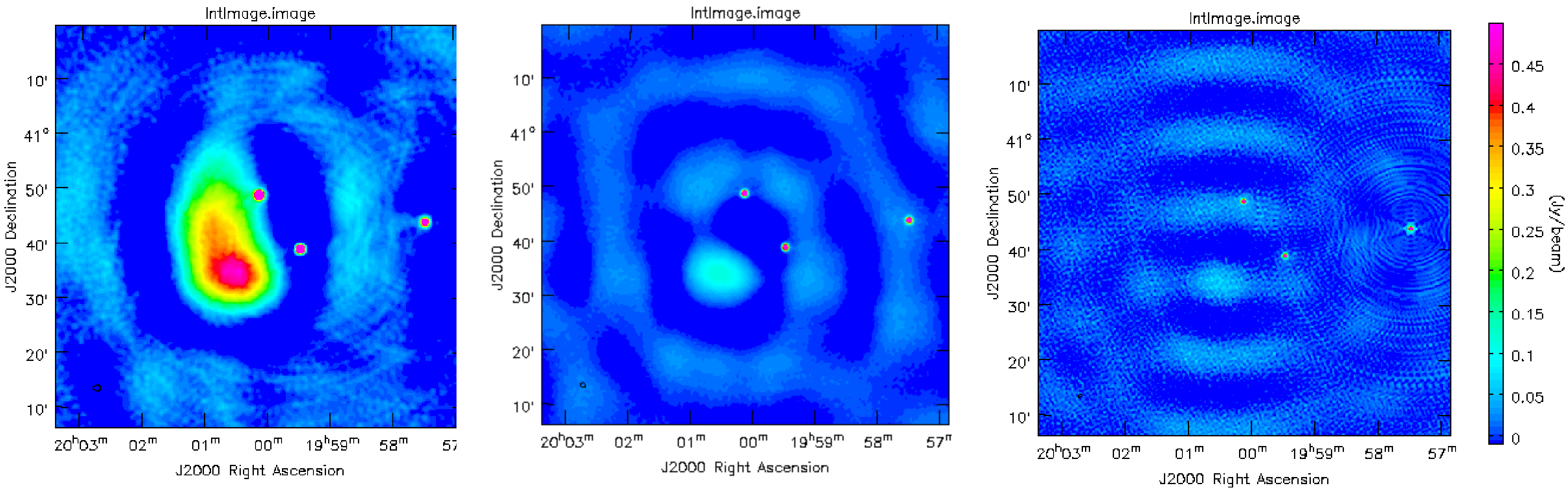
Three point sources

Spectral indices = -1.0, -1.0, 0.0

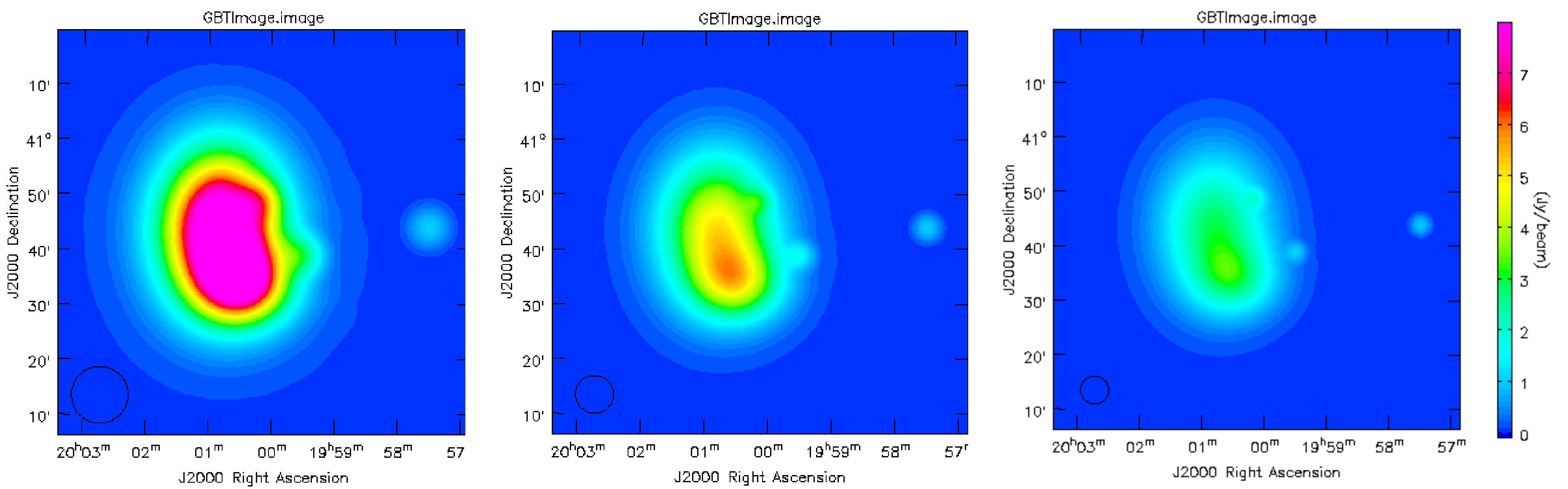
Frequency	1.0 GHz	1.5 GHz	2.0 GHz	Spacing
• INT (resolution)	1.0 arcmin	0.67 arcmin	0.5 arcmin	~ 1030m
• INT (max scale)	30.0 arcmin	19.6 arcmin	14.7 arcmin	~ 35m
• SD (resolution)	10.3 arcmin	6.8 arcmin	5.1 arcmin	~ 100m

Cubes from INT-only and SD-only data

INT Cube



SD Cube

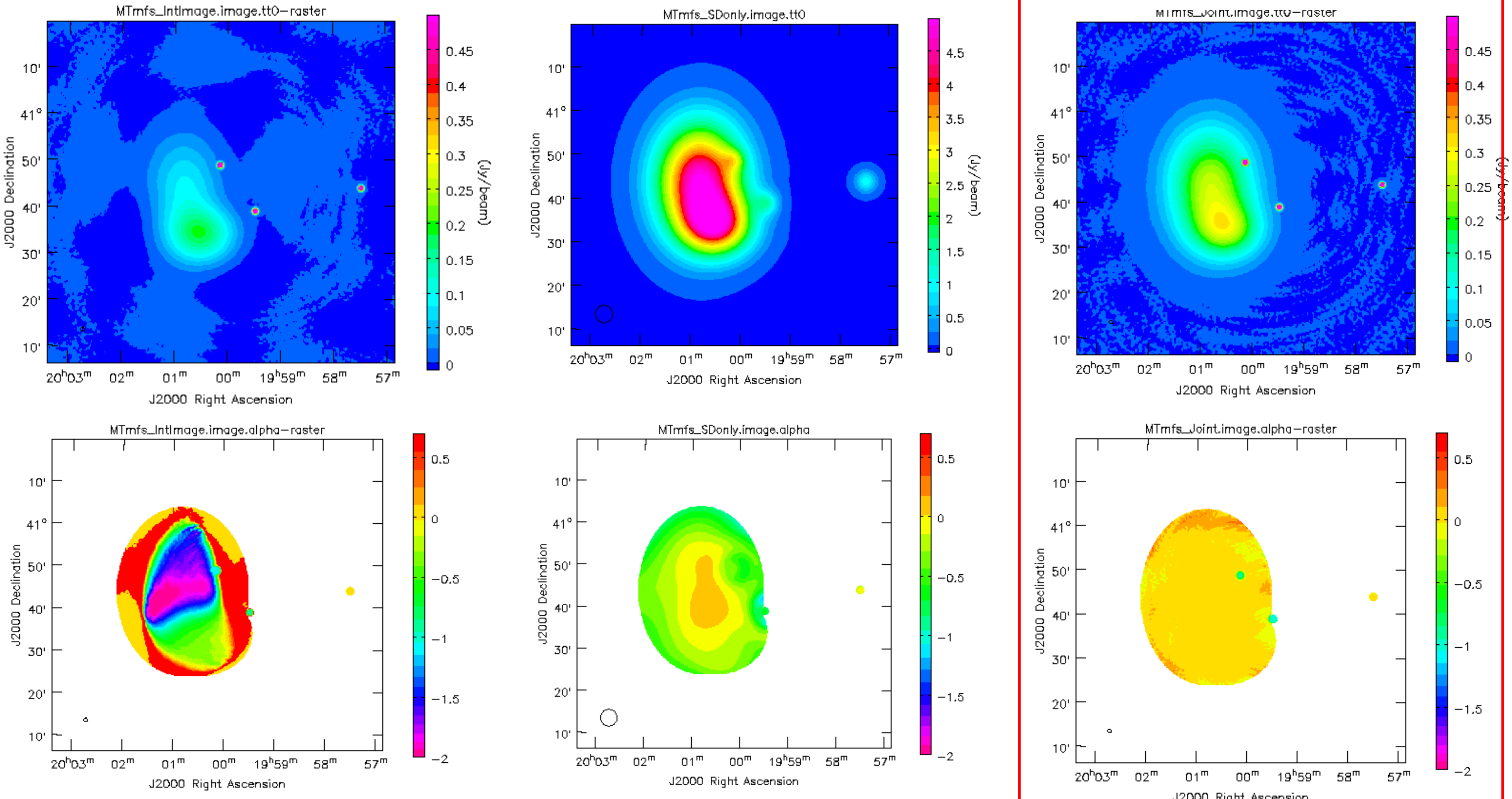


Wideband multi-term imaging : INT, SD, SD+INT

INT only
Multi-Term

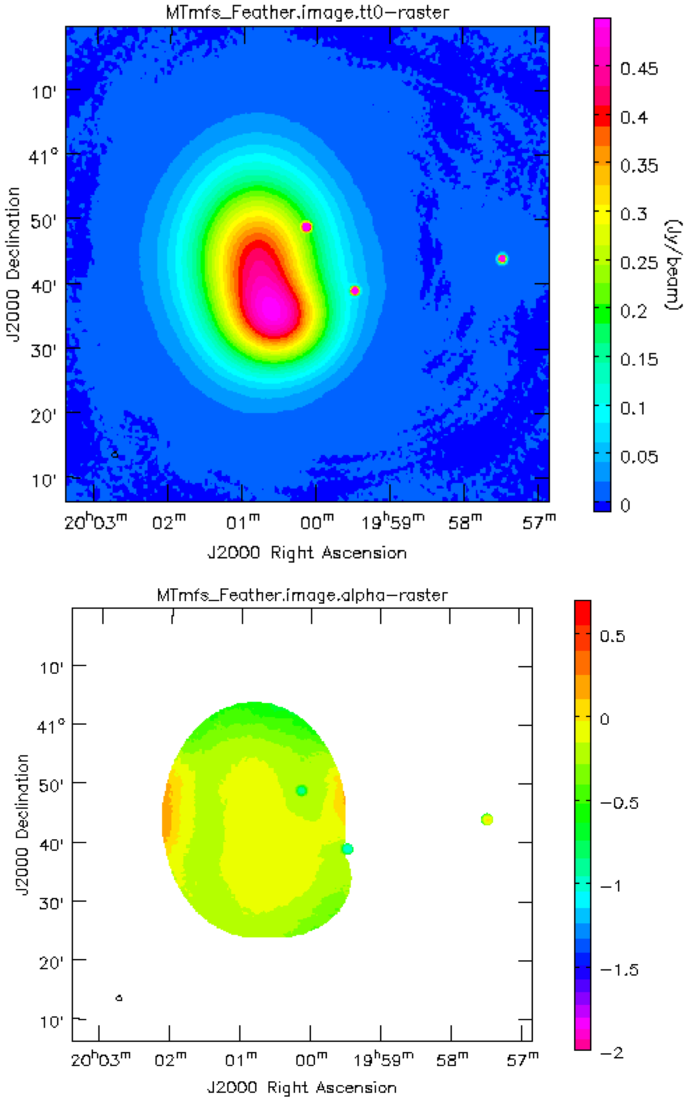
SD only
Multi-Term

SD+INT Joint
Multi-Term

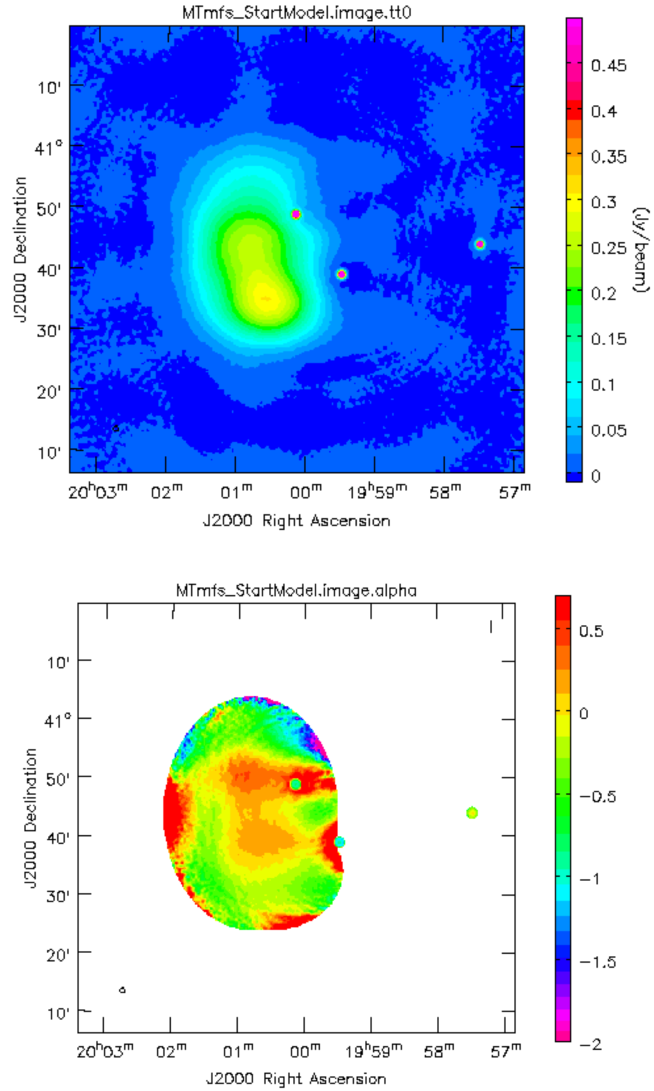


Comparison with Feathering & Startmodel

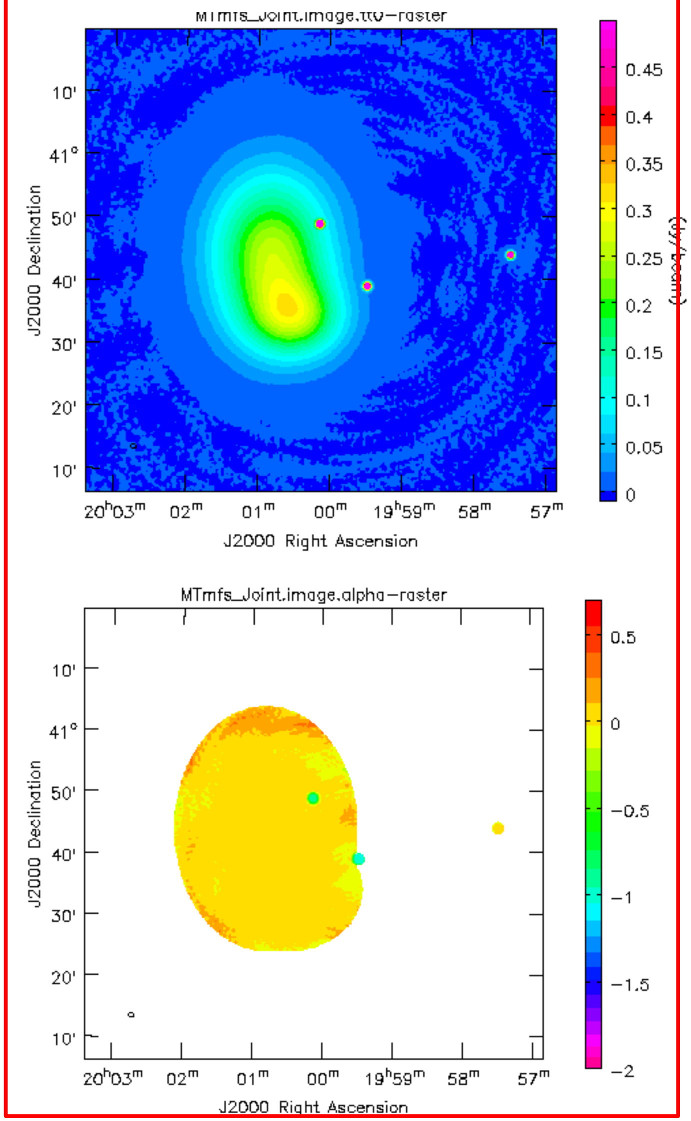
Multi-Term
Feathering



Multi-Term
Start-Model



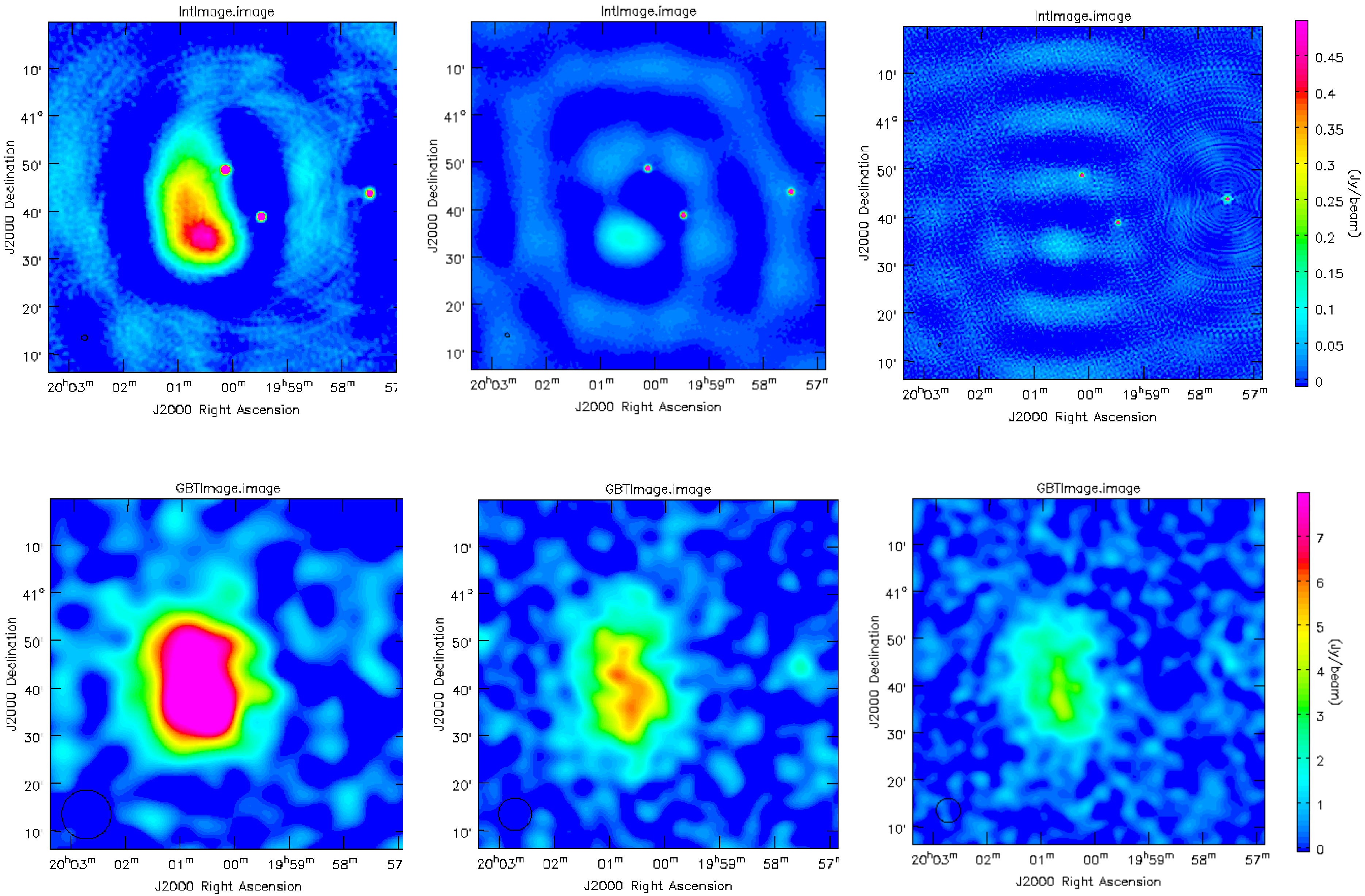
SD+INT Joint
Multi-term



Noisy Data : INT-only and SD-only Cubes

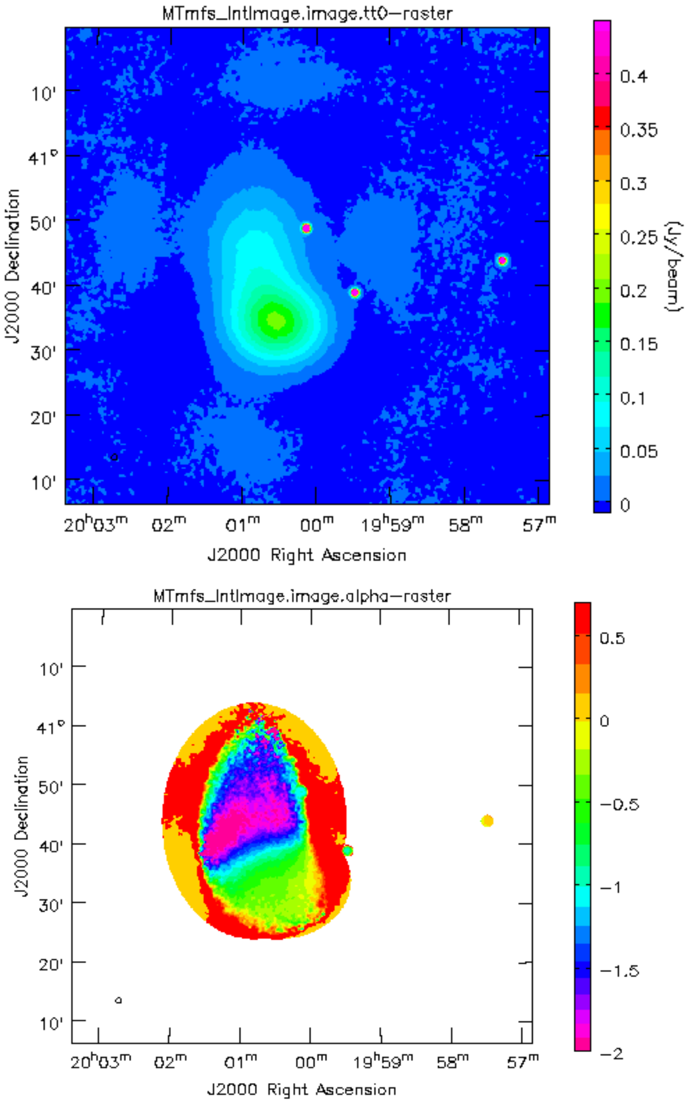
INT Cube

SD Cube

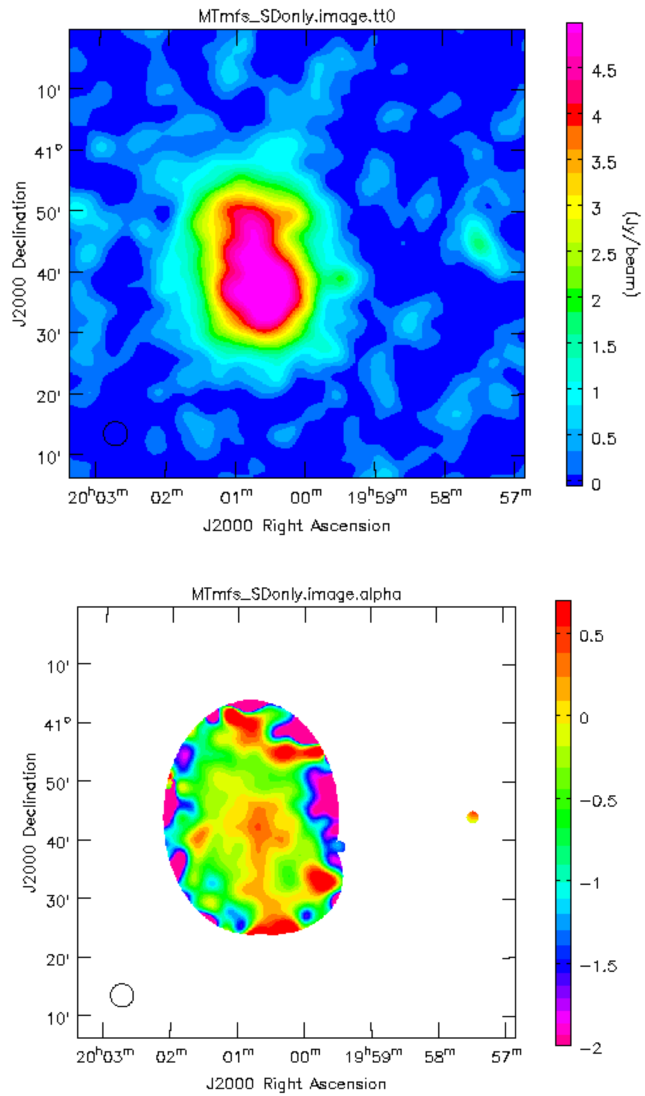


Wideband multi-term imaging : High SD noise

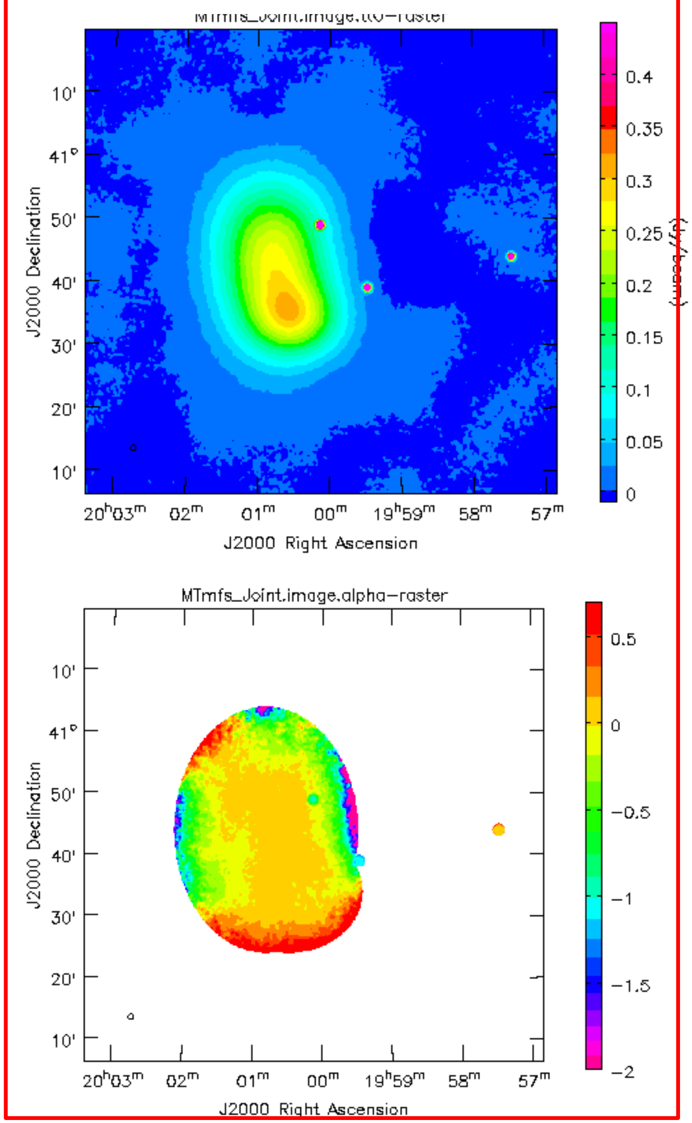
INT only
Multi-Term



SD only
Multi-Term



SD+INT Joint
Multi-Term



Wideband multi-term imaging : High SD noise + weighting

SD-scale = 0.2 during the Feather step

(For residual images and PSFs)

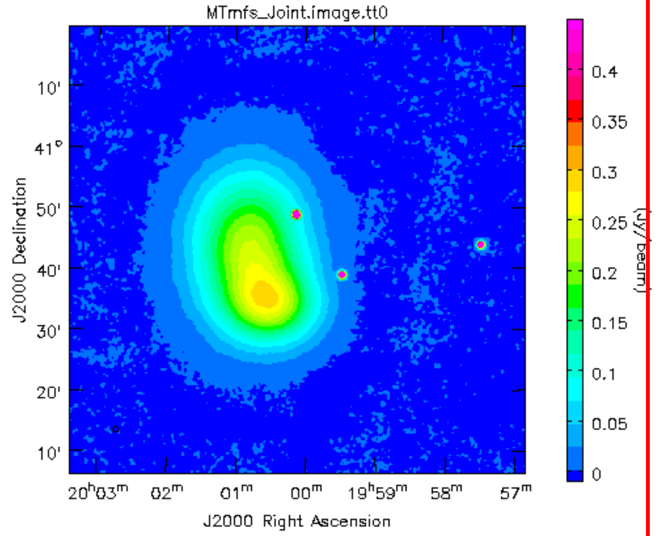
=> Data weighting scheme to match the noise levels

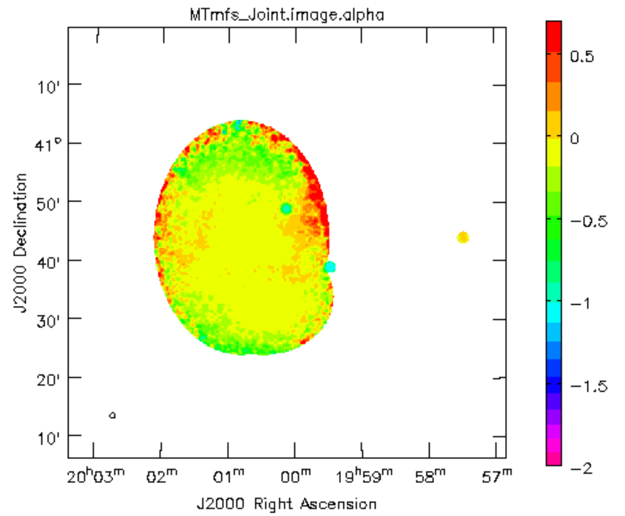
Results :

- Lower Residual noise
- Flux Correctness

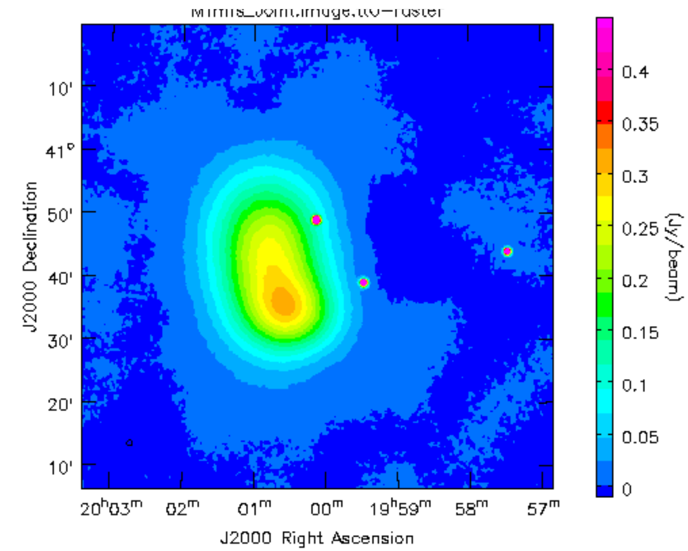
- Accurate alpha
(with frequency-independent feathering functions)

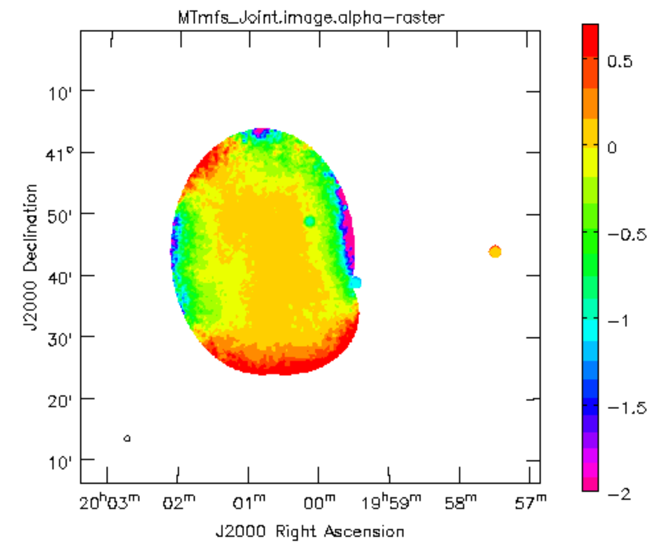
SD+INT Joint Multi-Term with SDscale = 0.2





SD+INT Joint Multi-Term





Summary (so far...)

- Prototyped a generic algorithmic framework for joint SD+INT imaging
  - Spectral Cubes and Wideband Continuum
  - Supports deconvolution for INT-only, SD-only, INT+SD joint.
  - SD data can be handled either as images or SD MeasurementSets
  - Supports the use of custom feathering functions (if needed)
  - Framework allows full range of gridding/deconvolution algorithm choices
    - wide-field gridding (W-Proj/A-Proj), point source or multi-scale

- Demonstrated a solution to the wide-band short-spacing problem

- Promising results for using the implicit weighting scheme to manage SD data with noise levels much higher than INT data.
  - Implications on amount of observing time needed for short-spacing data
- Paper (nearly) ready for submission (Rau & Naik)

Next Steps…..

- A formal implementation within the ARDG code base

- Commissioning the algorithm on several real data sets

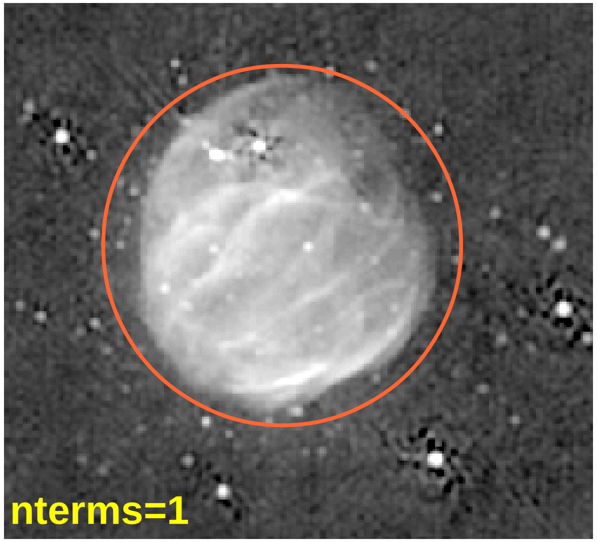
  – G55.7+3.4 SNR, CTB80 SNR, CHANG-ES Galaxy Halos
    - EVLA L-Band Single Pointings and Mosaics
    - GBT VEGAS L-Band Mosaics

  – ALMA M100 Band 3 reference/benchmark dataset
    - 7m ACA + 12m ALMA + 12m TP data
    - Evaluate against standard procedure (joint ACA+ALMA followed by feathering of TP data) and the 'tp2vis' approach.

- Integration into CASA for production release

G55.7+3.4 Supernova Remnant + Pulsar

7 hour synthesis, L-Band, 8 spws x 64 chans x 2 MHz, 1sec integrations (used 4 spws)

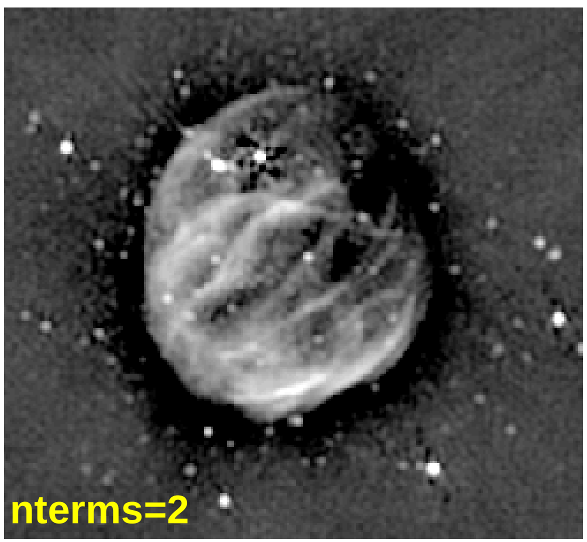


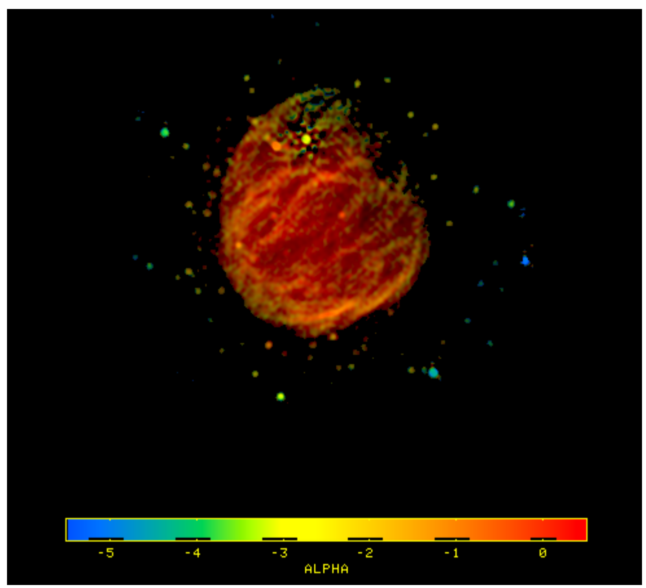
Max sampled spatial scale : 19 arcmin (L-band, D-config)
Angular size of G55.7+3.4 : 24 arcmin
Primary beam at 1.5 GHZ : 30 arcmin

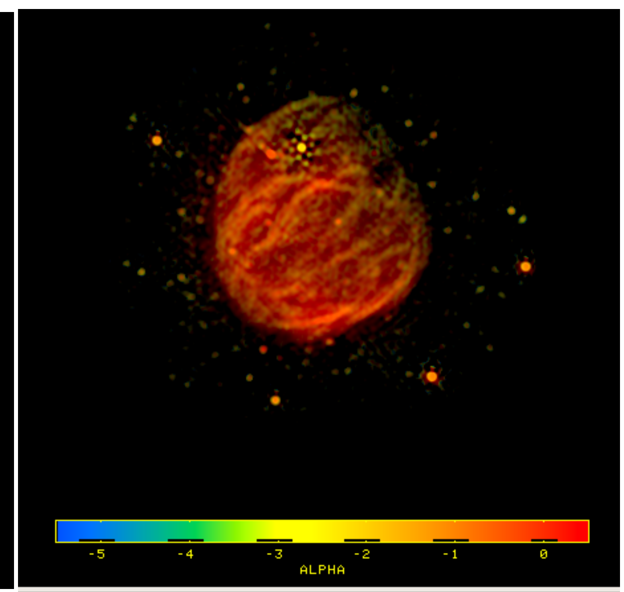
Clear example of wideband short-spacing problem (i.e. only for nterms=2)

Needs wide-field wide-band Primary Beam handling too

In 2016, we obtained GBT VEGAS wideband data.

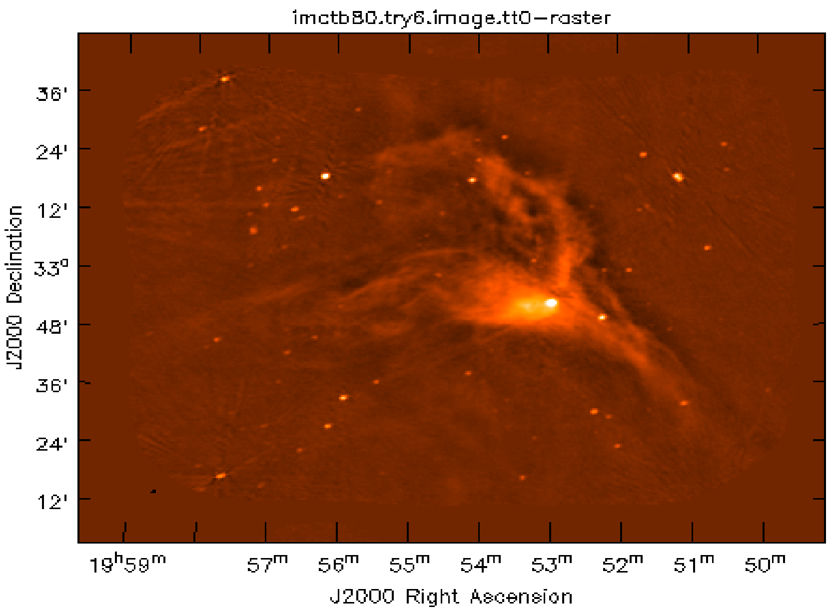




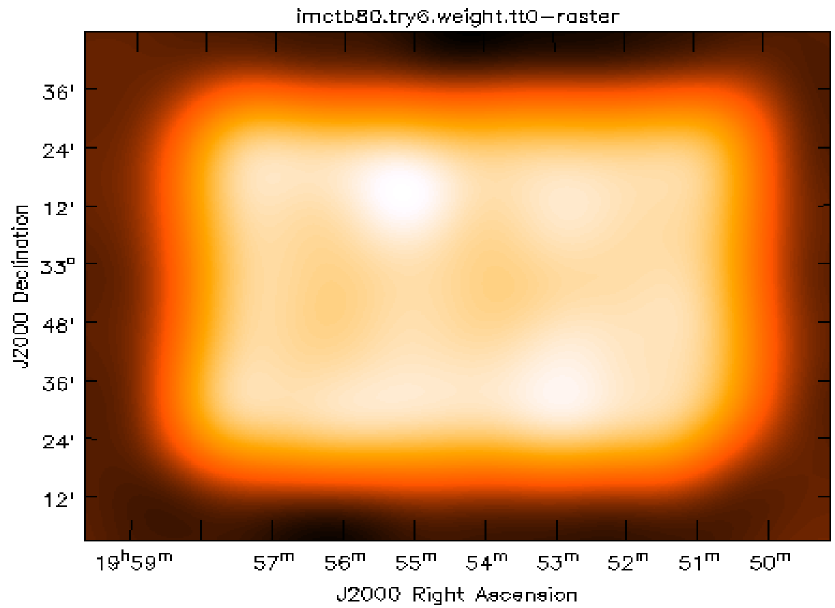


CTB80 wideband mosaic : L-Band EVLA , GBT

Interferometer joint mosaic intensity

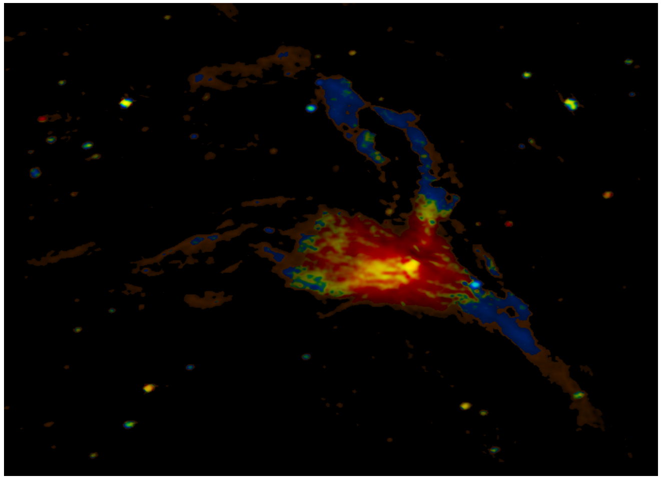


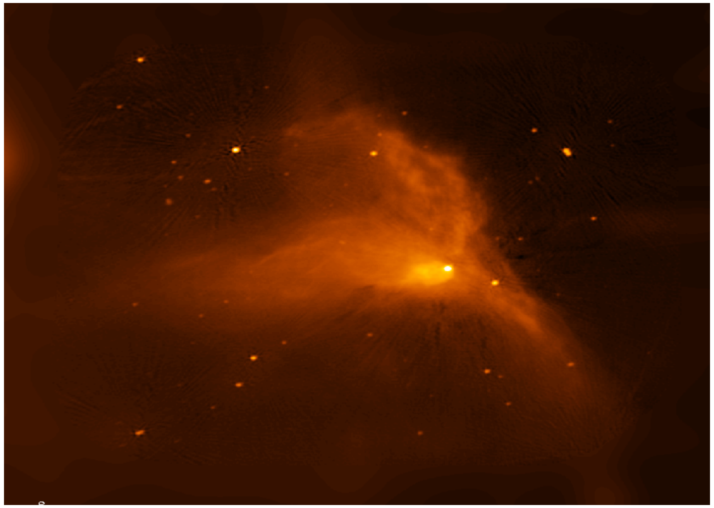
Joint mosaic primary beam from 106 VLA pointings



Wide-Field Spectral Index

(INT only)





Interferometer + Single dish

(Only Intensity, Feathering)