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

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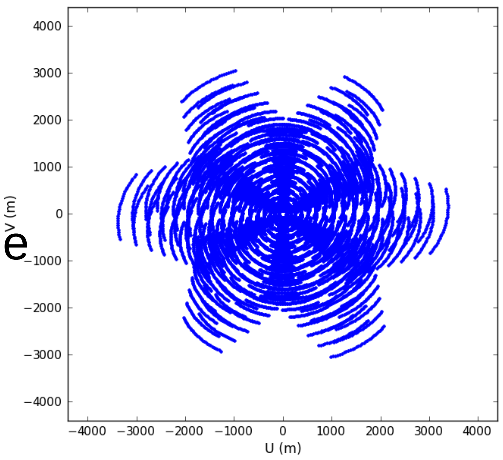
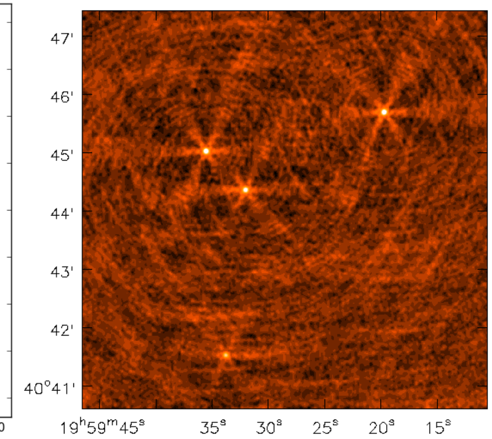
URSI National Radio Science Meeting, Boulder, Colorado, USA
4 Jan 2018

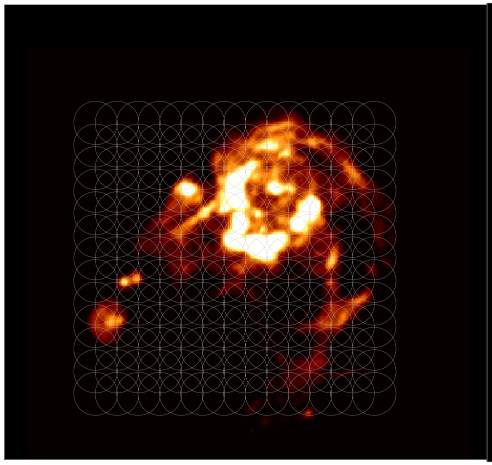
Image formation in radio astronomy

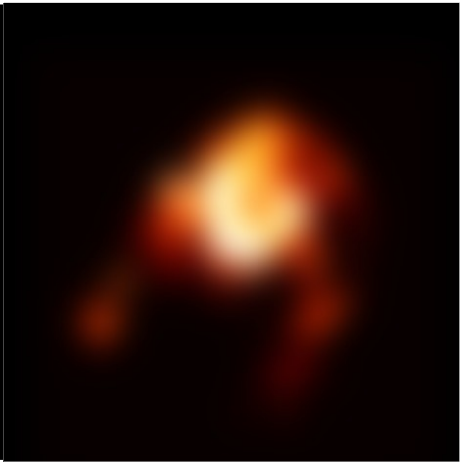
- An interferometer samples the spatial Fourier transform of the sky brightness
- Observed image ~
  (Sky.PB) convolved with the PSF
- Angular resolution = wavelength / max_baseline
- Sampling is incomplete and short spacings (large scales) are not measured at all





- A single dish telescope does a raster scan of a region of sky
- Observed image ~
  Sky convolved with antenna power pattern
- Angular resolution = wavelength / aperture_size
- All spatial frequencies lower than that offered by the dish size (in wavelengths) are measured.





Wideband imaging (single dish and interferometers)

- Data from multiple observing frequencies are combined to increase continuum sensitivity and to study the spectral structure of the sky brightness.
- Instrument response and the sky brightness change with frequency

  (1) Sky brightness model needs to be wideband

  (2) Angular resolution increases with frequency

  (3) For interferometers, largest measured scale also changes.

  => *Large scale spectra are unconstrained by the data*

  (4) For interferometers, array element primary beams also change

  => *Spurious intrumental spectral index*

- Option 1 : Image each channel separately + smooth + combine

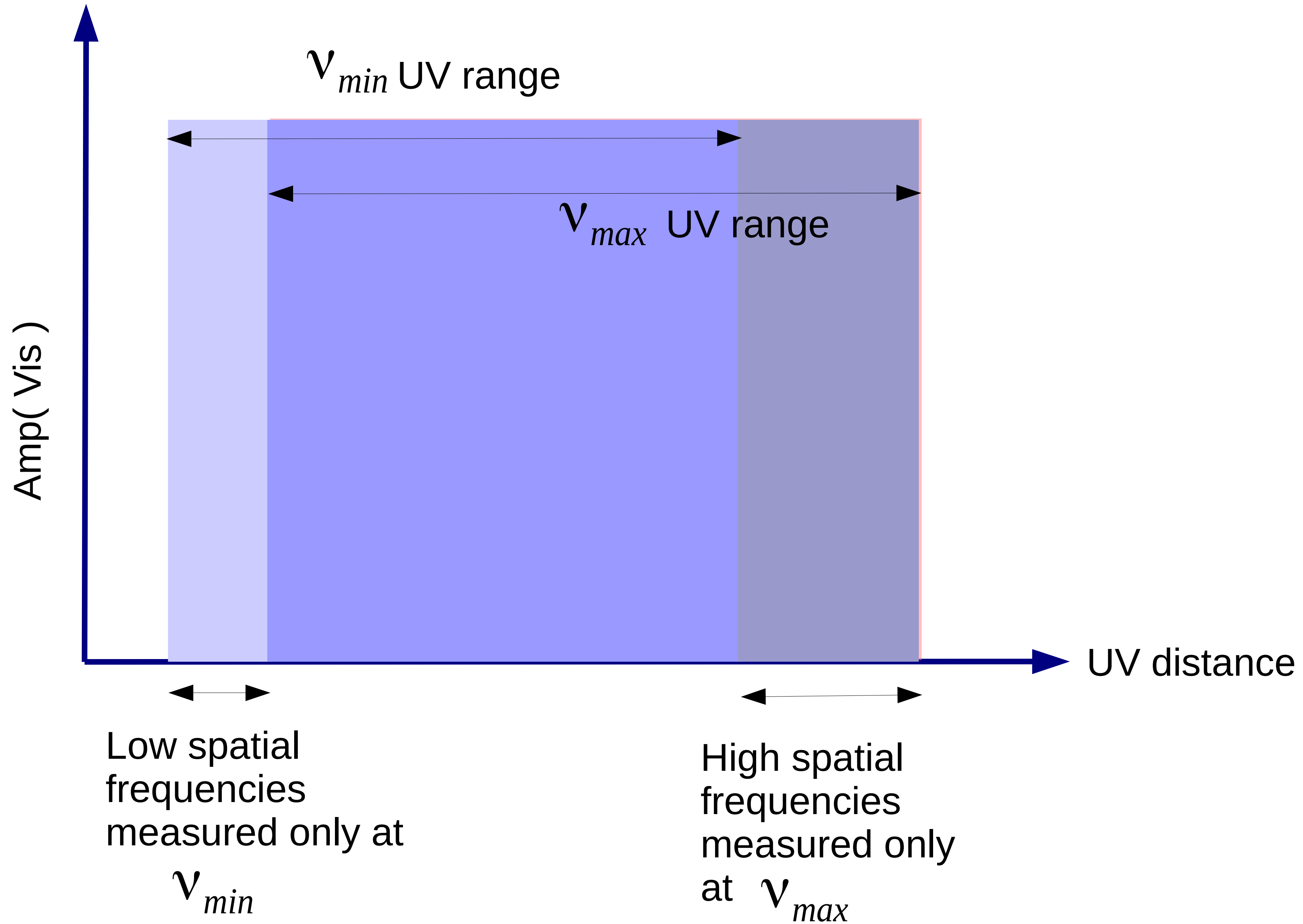
  - Angular resolution is limited to that of lowest frequency

- Option 2 : Joint (multi-term) wideband imaging

  - Solve for the continuum intensity and spectral structure together

  - Angular resolution is given by the joint uv-coverage (close to upper part of the band)

For which scales can we reconstruct the spectrum



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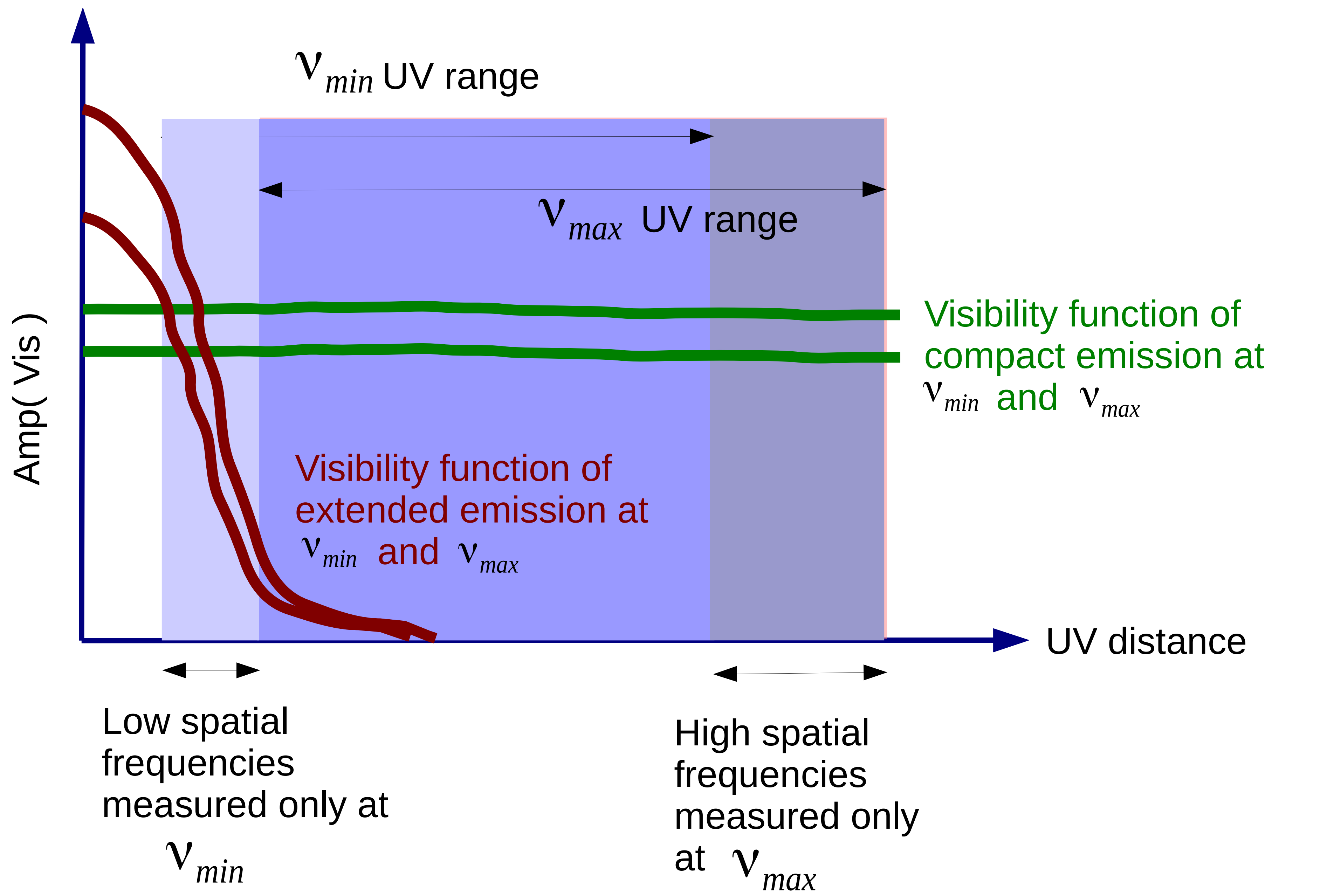

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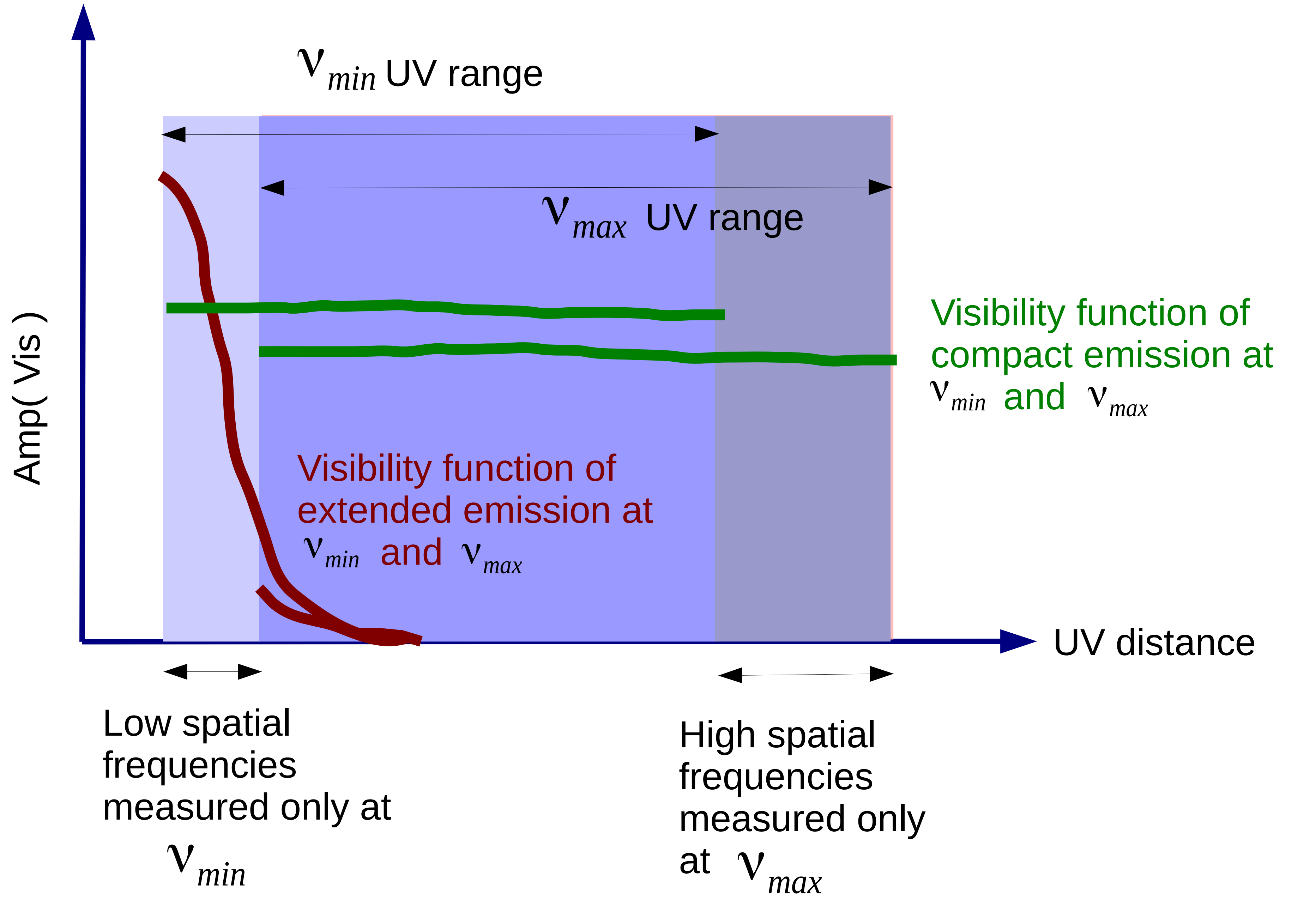
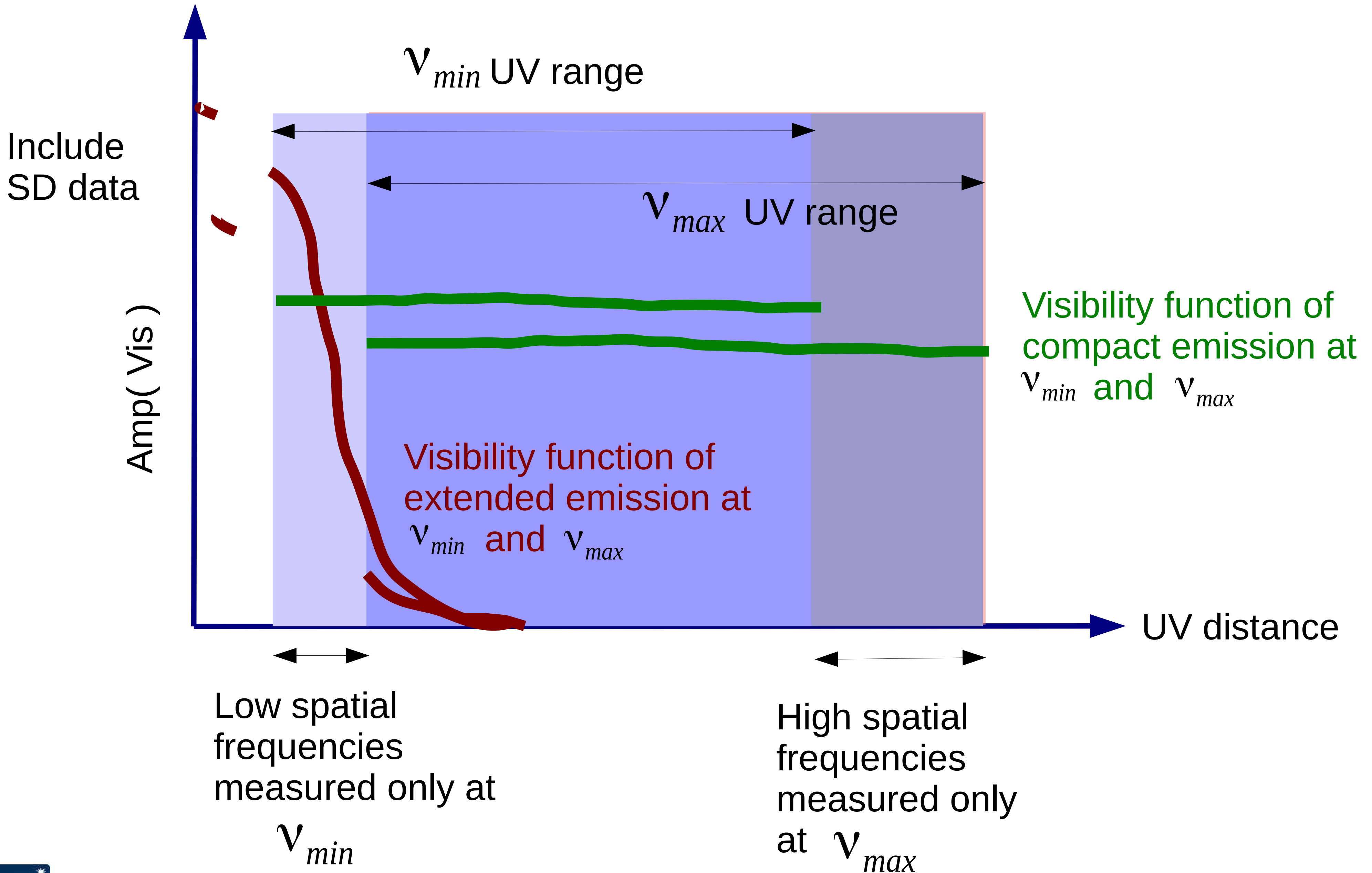
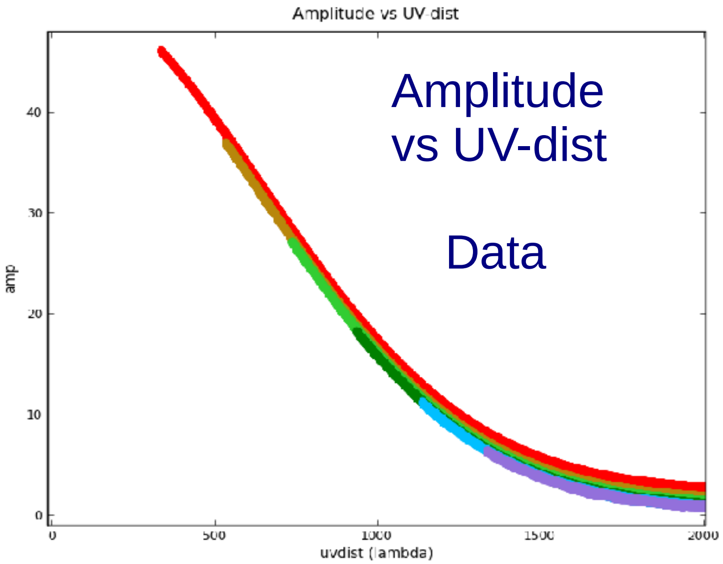


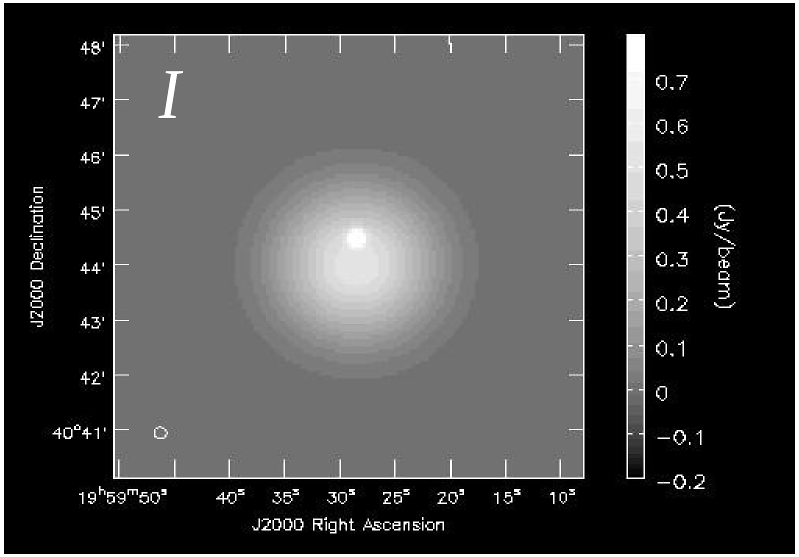
For which scales can we reconstruct the spectrum

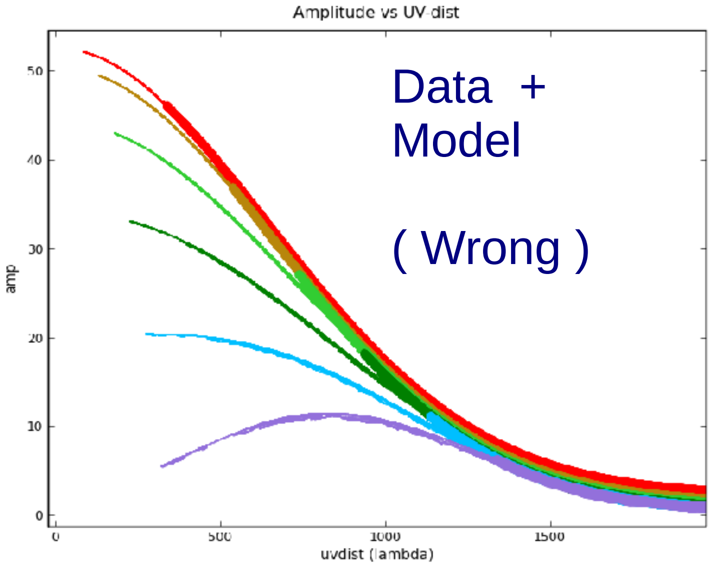


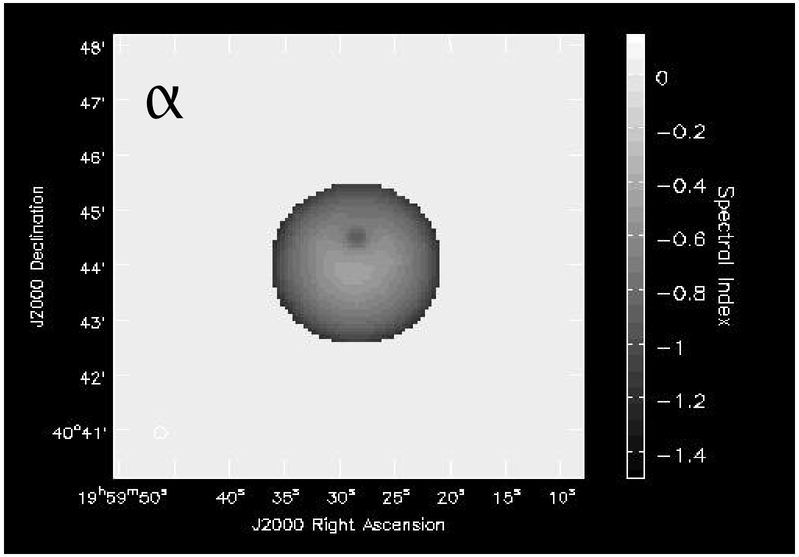
Very large scales : Unconstrained Spectrum

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

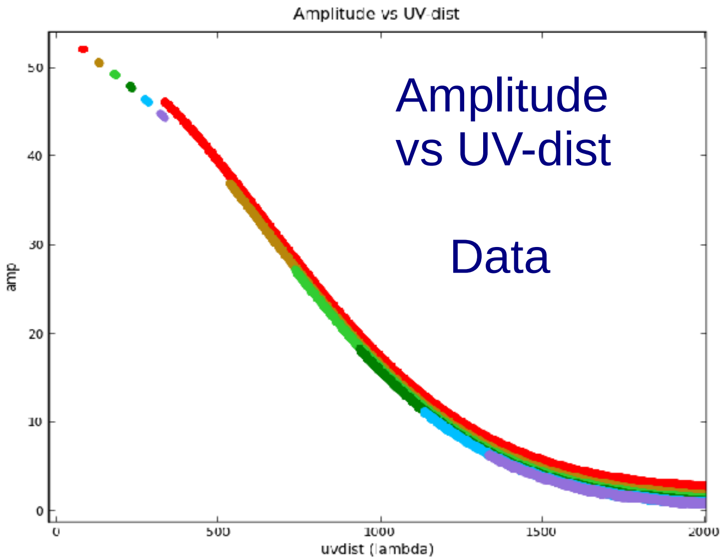
Leave out shortest baselines

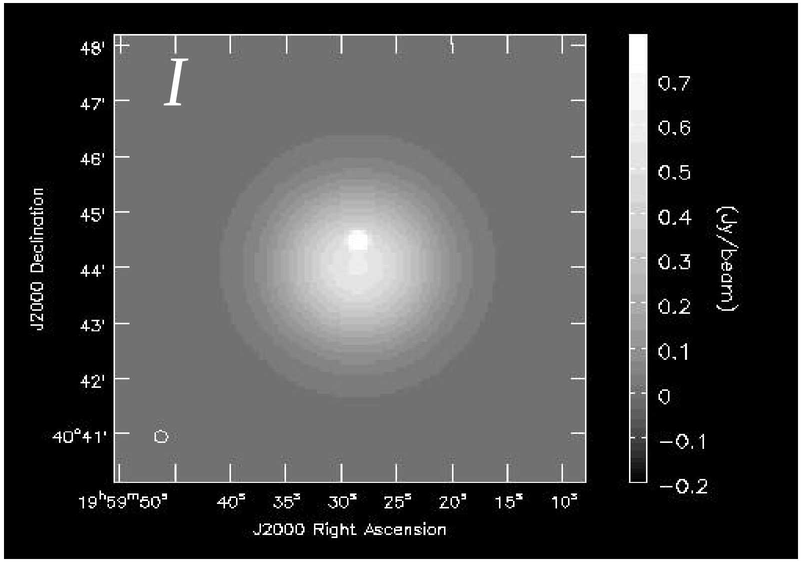
No short spacings to constrain the spectra

=> False steep spectrum reconstruction

Very large scales : Need additional information

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





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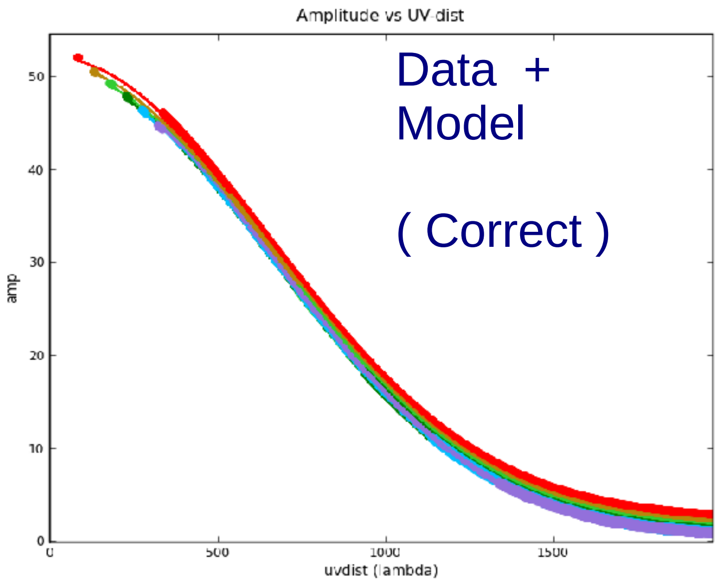
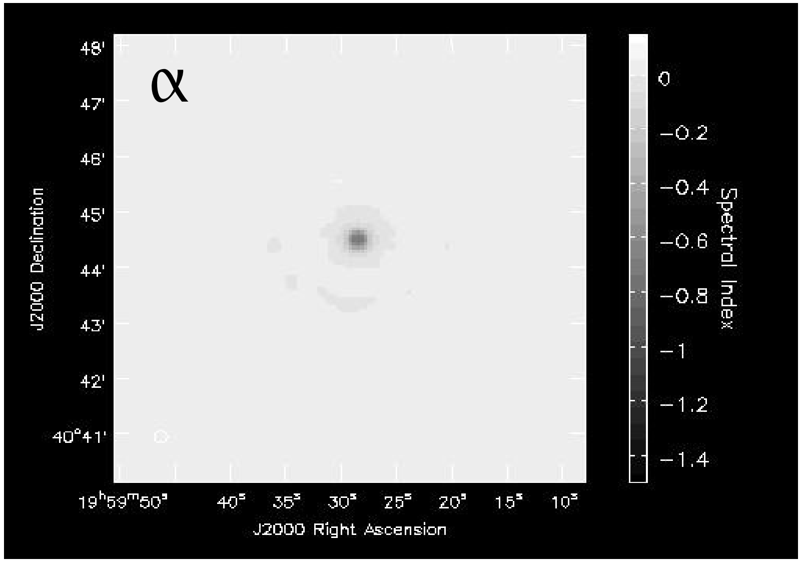




Retain some short spacing information.

Correct reconstruction of a flat spectrum

=> So, how to add this information ?

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

  – C * FT(SD_image) + [[1 – FT(SD_beam)] * FT(INT_reconstructed_image)]

  – The FT of the SD beam is used as the weighting function

  – C is a scale factor often chosen empirically (or as the ratio of beam areas)

  – It is usually used as a post-deconvolution combination, where burnt-in errors cannot be recovered from.

  – The effect of the empirical scale factor is also burnt into the result

- **[2/3]** **StartModel** : Use a deconvolved SD image as a starting model for the INT reconstruction

  – Effective only when there is significant overlap between INT and SD uv-spacings

Approaches for combining INT and SD data/images

- **[3/3] Joint deconvolution** : Combine SD and INT observed images **and PSFs** before deconvolution.

  – Scale factors and empirical weight functions enter the reconstruction simply as a choice of data weighting (similar to uniform/natural/tapered/robust, etc).

  => This approach is robust to a wide range of choices of scale factors

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

  => Better resolution than just the SD observed image

  – 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.

- **Dealing with Interferometer Primary Beams (and mosaics) for all 3 methods**

  – INT observed image = (sky . PB) * INT_psf

  – SD observed image = (sky) * SD_psf

  => Manipulate the SD image to follow the form of the INT observed image before combining with the INT image

Our Choice : Wideband Multi-term Joint Deconvolution

– Feather together the SD and INT observed image cubes and PSF cubes

(the feathering weight function is frequency dependent)

– Perform deconvolution (the minor cycle) using any standard algorithm

  – For Spectral Cubes : Generate a Cube model

  – For Multi-term Wideband imaging :

    – Convert the Joint cubes to Multi-term images and PSFs

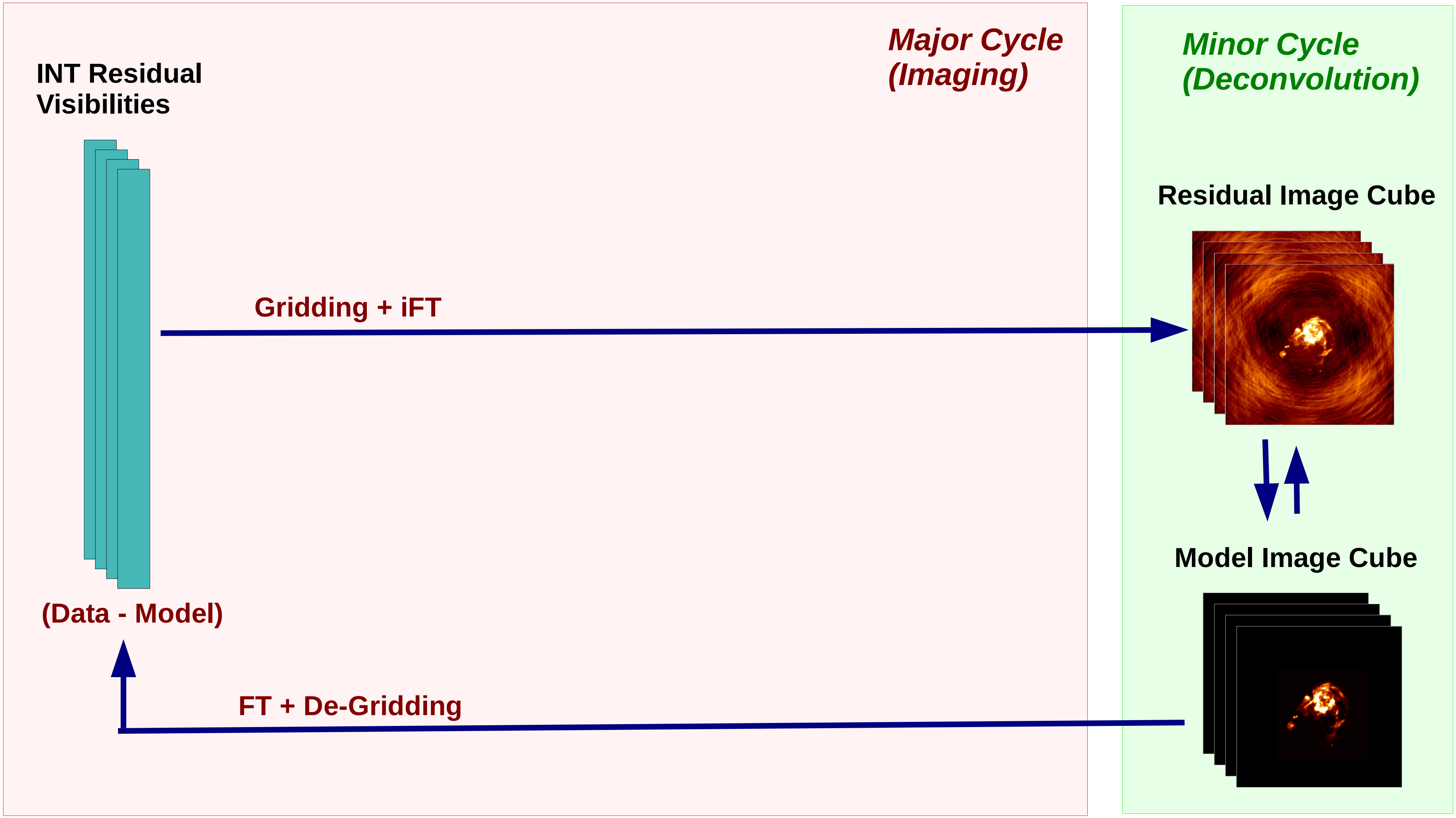
    – Do multi-term deconvolution to get Taylor coefficient images

– Handling wideband primary beams

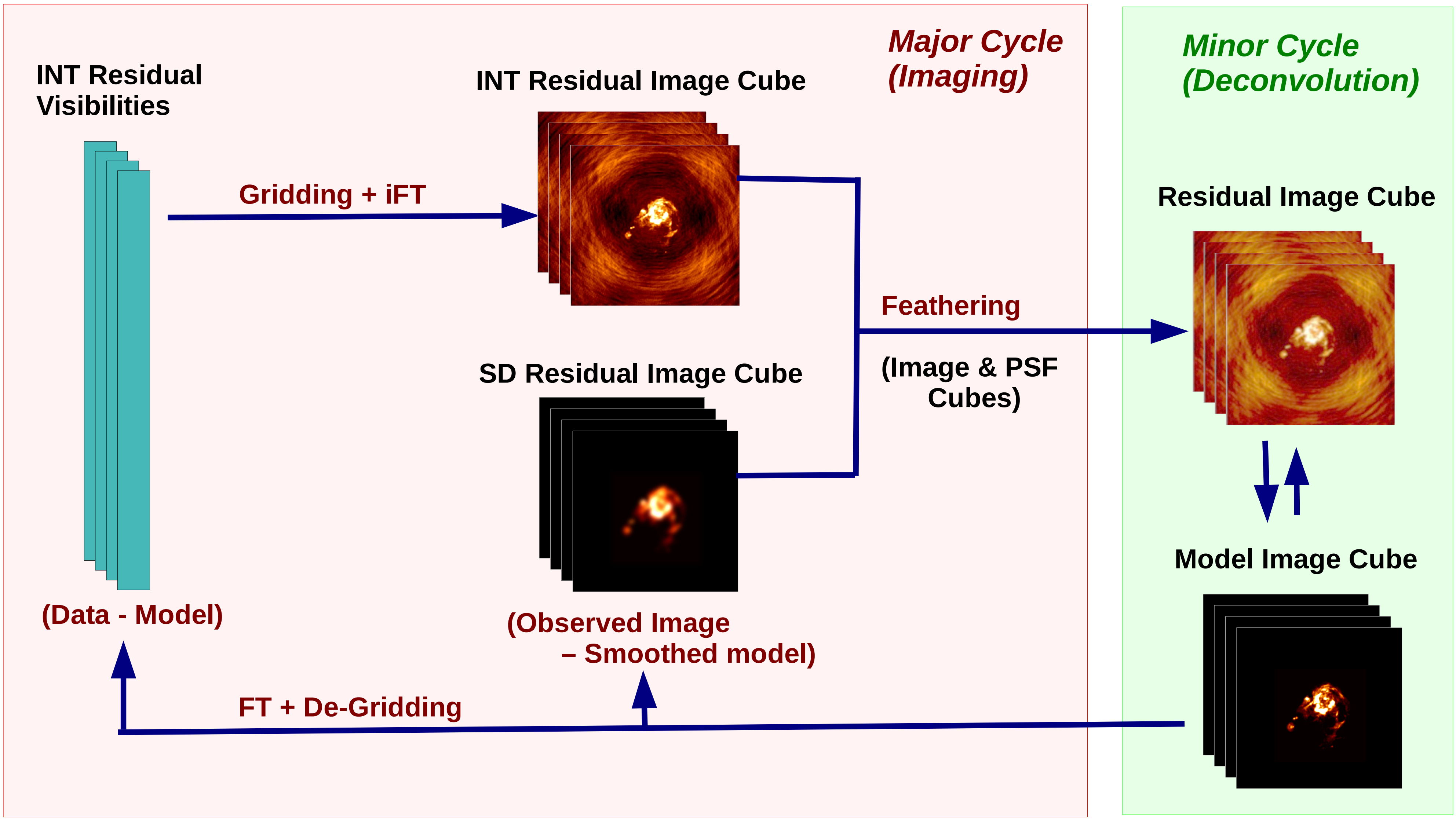
  – Manipulate the SD observed images (per channel) to follow the form of the corresponding INT image (via deconvolution and multiplication by INT_PB)

  – Math depends on the chosen INT gridding algorithm (standard, A-Projection)

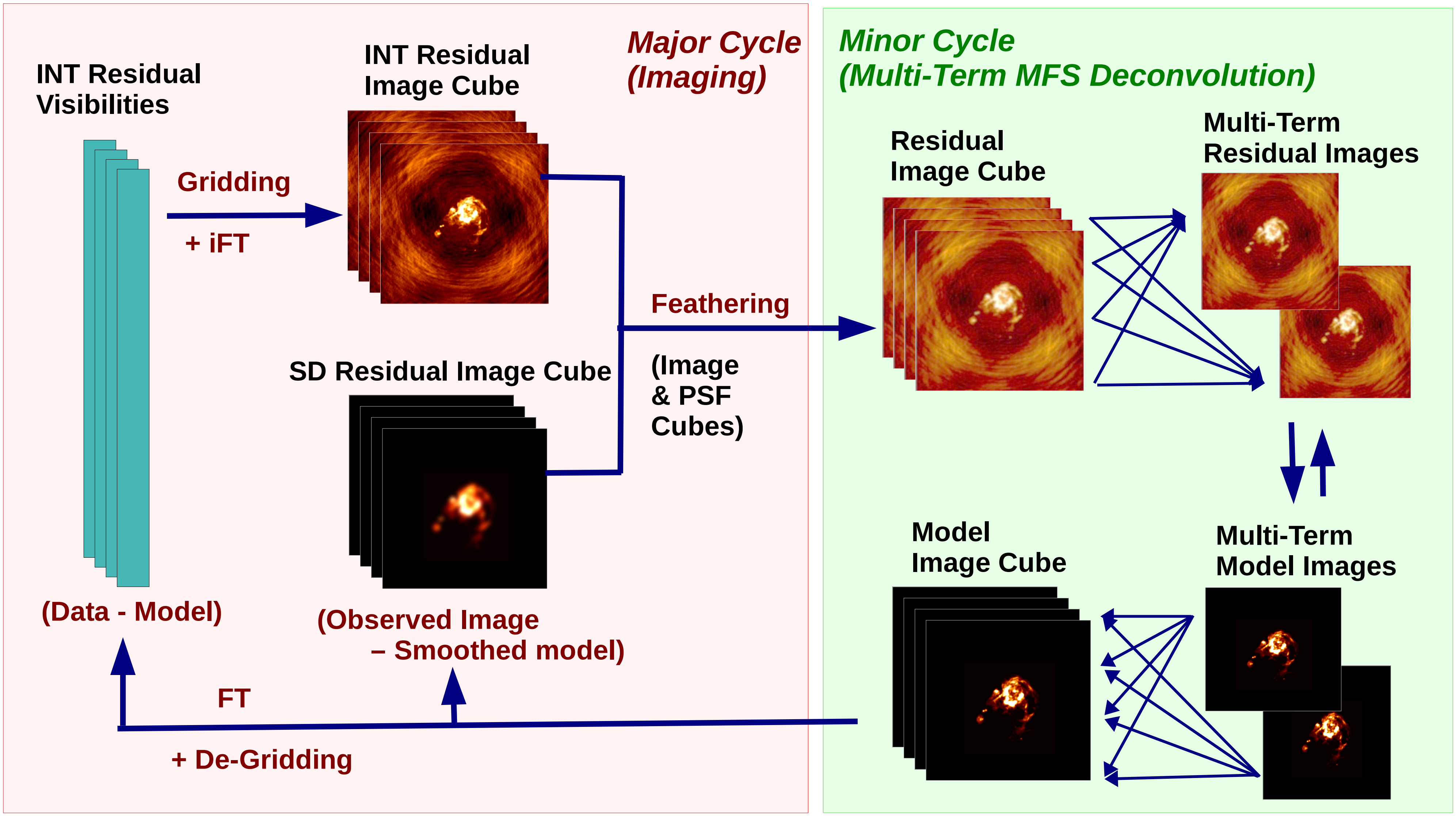
Spectral Line (Cube) Imaging : INT only



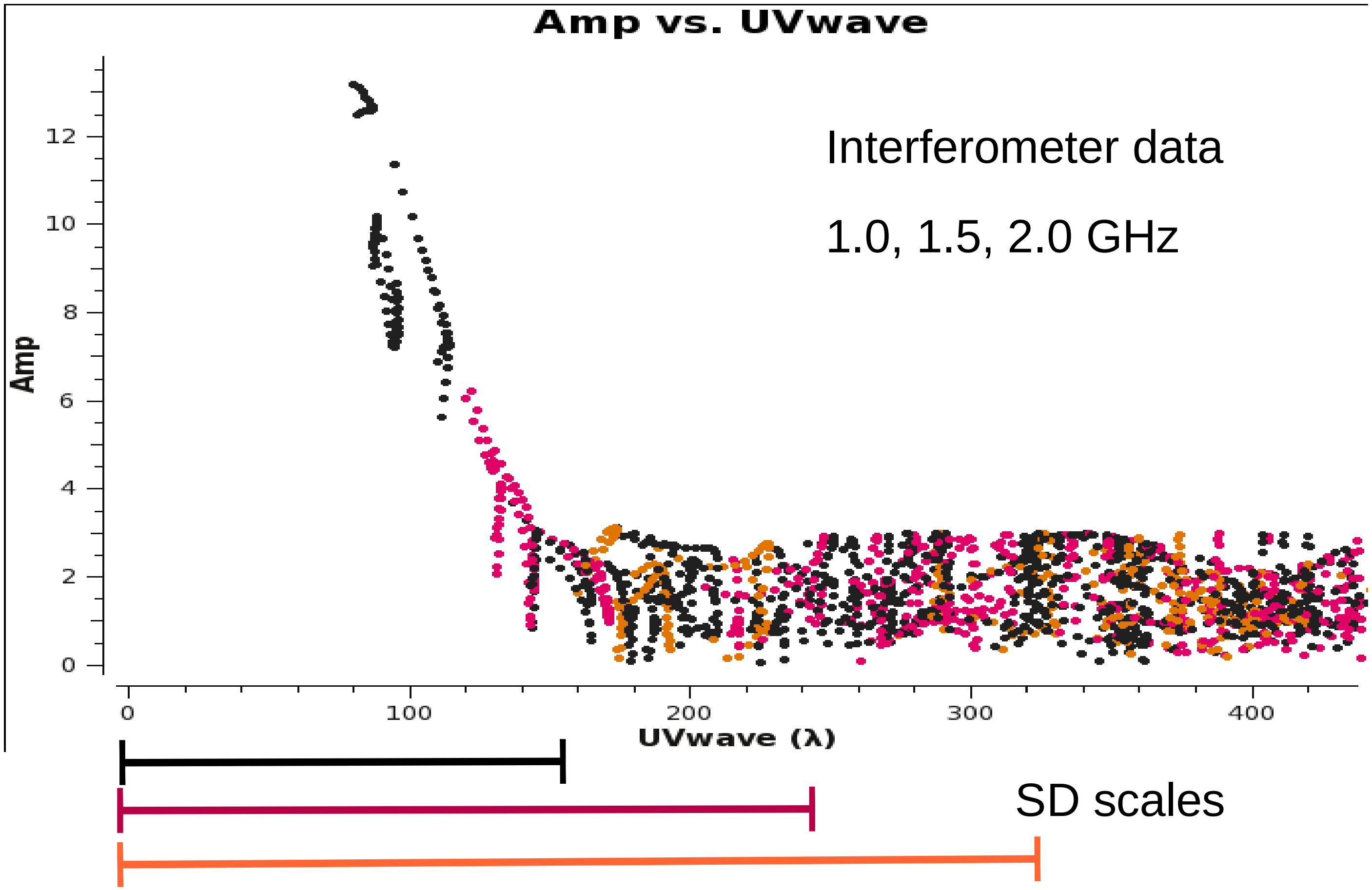
Spectral Line (Cube) Imaging : Joint INT + SD



Wideband Multi-Term Imaging : Joint INT + SD

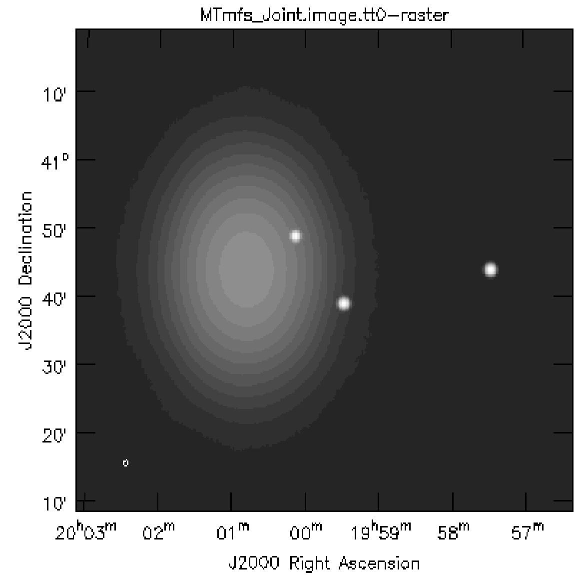


Example : Multi-frequency uv-coverage / resolution



Simlated sky :

Three points and one 15 x 20 arcmin extended source

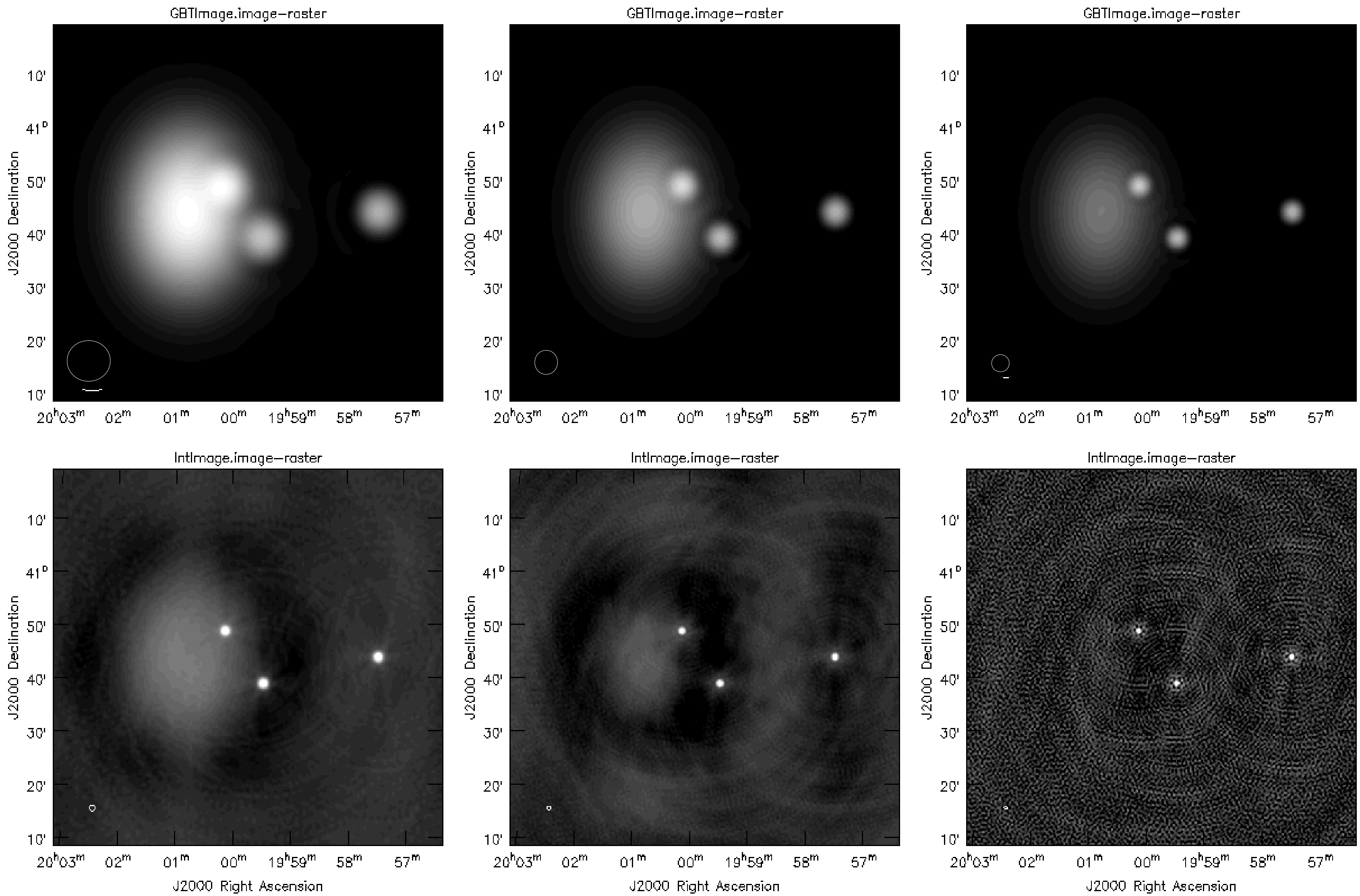


Frequency	1.0 GHz	1.5 GHz	2.0 GHz	Spacing
• INT (resolution)	1.2 arcmin	0.8 arcmin	0.6 arcmin	~ 1000m
• INT (max scale)	40.4 arcmin	27.5 arcmin	19.1 arcmin	~ 25m
• SD (resolution)	10.3 arcmin	6.8 arcmin	5.2 arcmin	~ 100m

Images from SD and INT (3 frequencies)

1.0 GHz | 1.5 GHz | 2.0 GHz

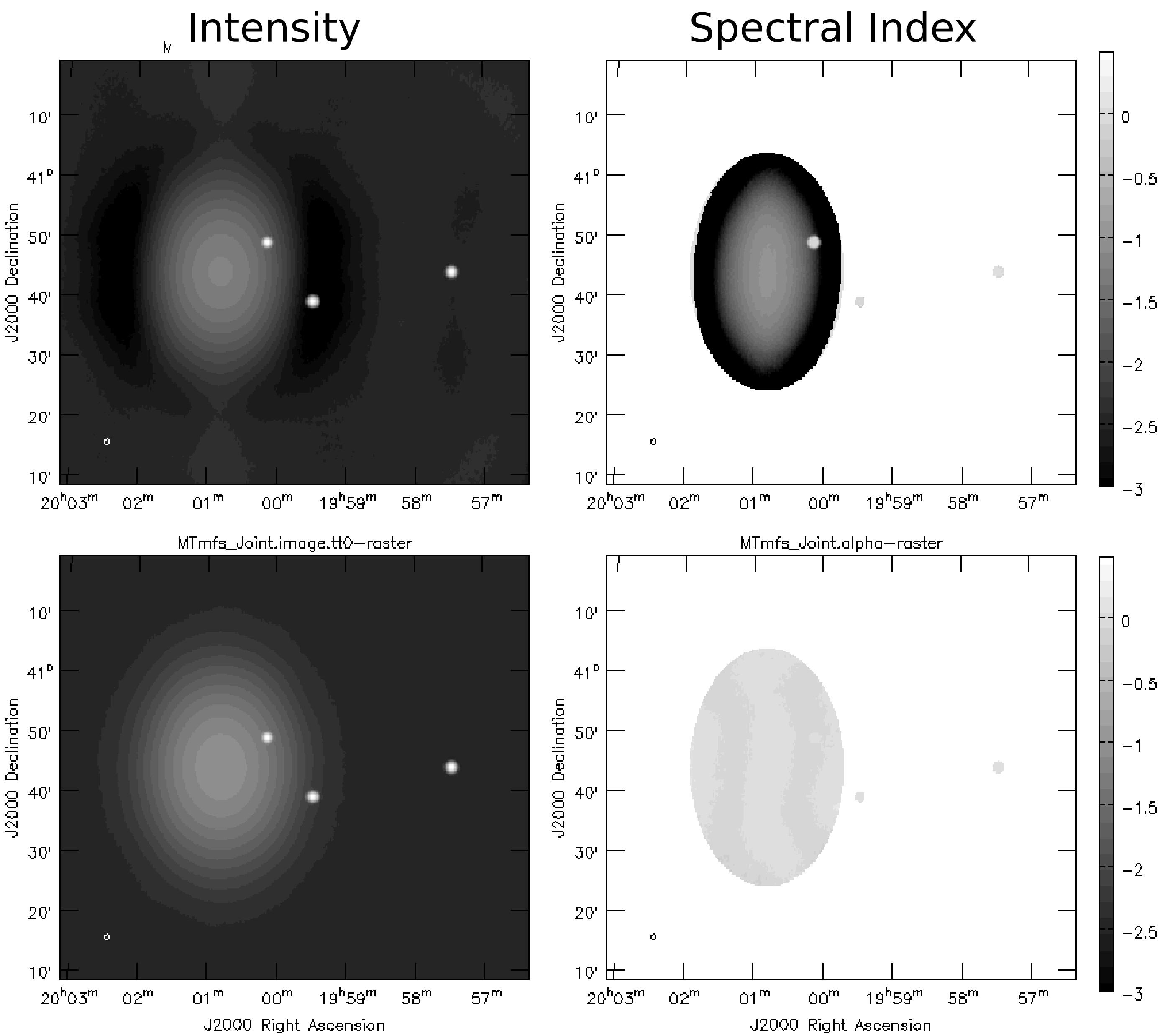
- SD observed Images
- INT reconstructed Images



Example – Wideband imaging (without/with SD data)

- **INT only** : Multi-term wideband images
- Spurious steep spectral structure for the large scales
- Compact sources have correct spectra

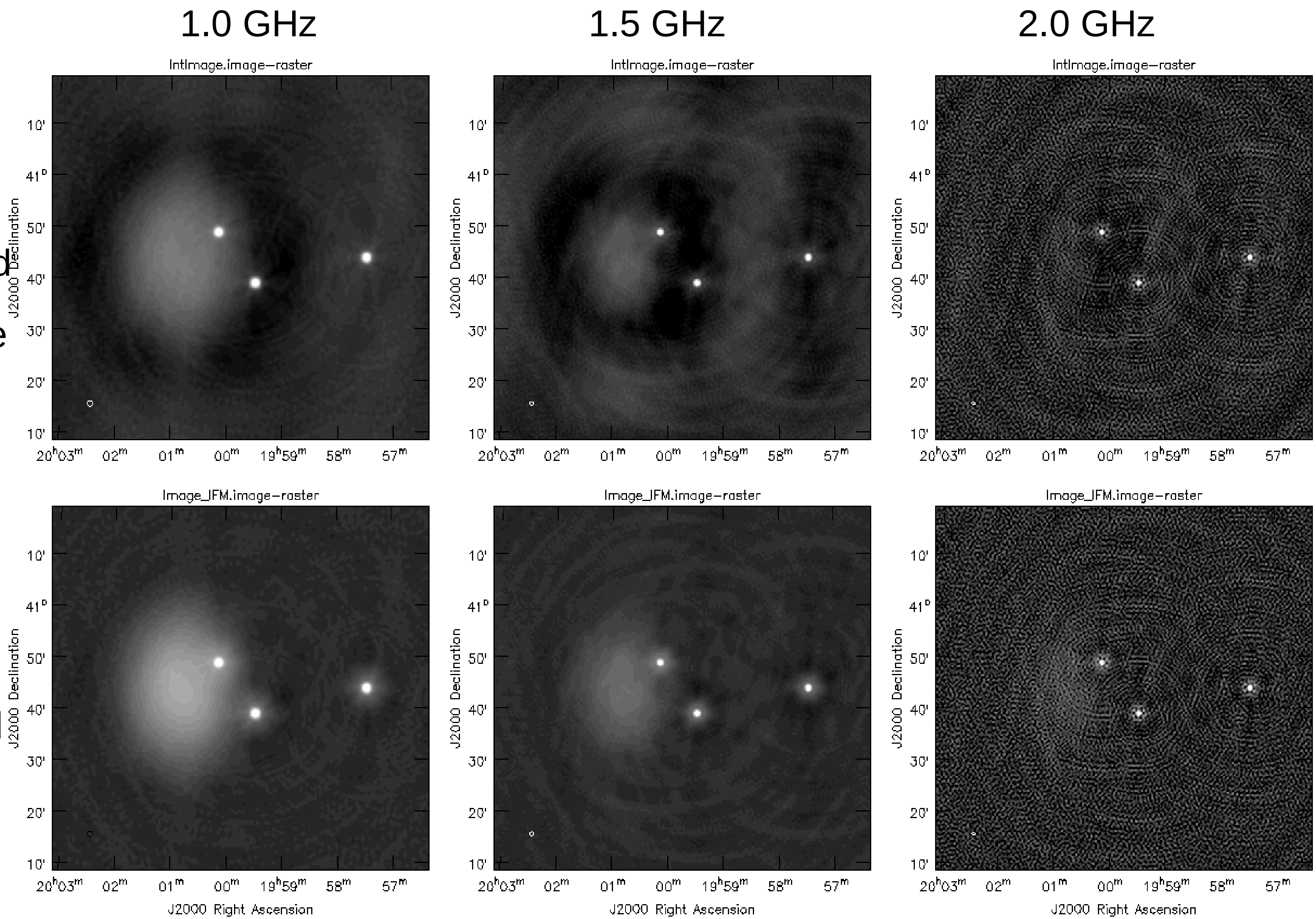
- **INT + SD** : Multi-term wideband images
- All sources have correct (flat) spectra



Other uses - 1 - Spectral Cube Joint Deconvolution

- INT only reconstructed spectral cube

- INT + SD reconstructed spectral cube



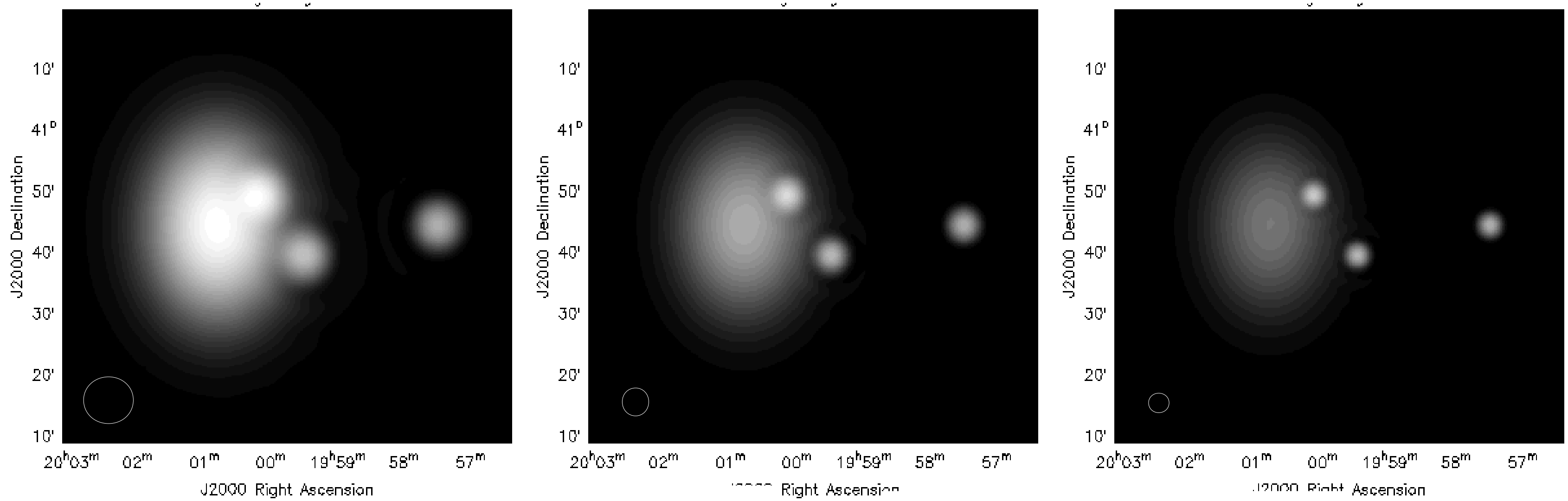
Other uses - 2 – Wideband Single Dish Imaging

- Apply Multi-term wideband deconvolution to SD data only

- SD

  Spectral Cube

1.0 GHz | 1.5 GHz | 2.0 GHz



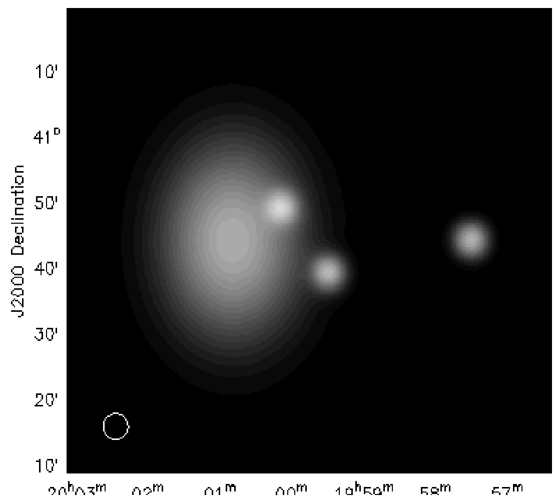
- SD

  Continuum Intensity
  & Spectral Index

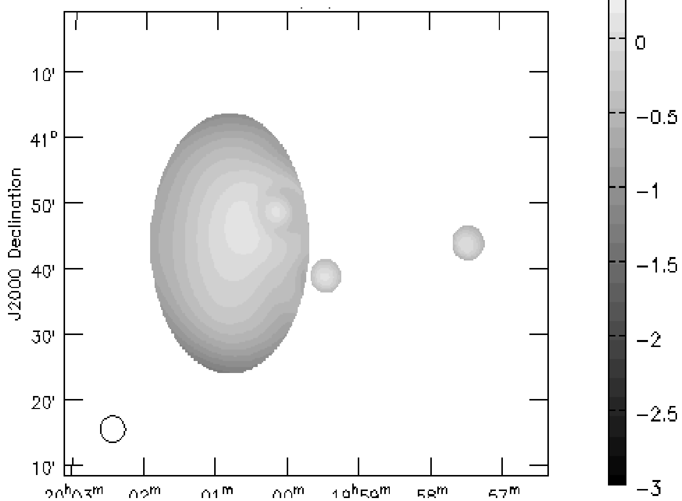
- Better resolution

- Deconvolved SD beam

Intensity



Spectral Index



Summary (so far...)

- Problem : Wideband multi-term interferometric imaging is especially susceptible to the short-spacing effect, not by making artifacts but by producing astrophysically plausible (but wrong!) source spectra at large scales.
- Needed a method that combined data before the wideband sky model is constructed.
- Multi-term Joint Deconvolution : Feather both INT and SD observed images and PSFs before the minor cycle in an iterative image reconstruction scheme. Similarity to a weighting scheme makes this robust to different choices of scale functions.
- Demonstrated successful recovery of large scale spectral structure for an example where wideband INT only got it wrong.
- Two by-products of this algorithm implementation (using CASA scripting)
  - Spectral cube joint reconstructions
  - Multi-term deconvolution of SD-only images (to derive structure at a resolution better than that of the lowest frequency).
- Next steps :

  – Integrate with the A-Projection and WB-Aprojection algorithms for wide-field wide-band imaging (full-beam and mosaic interferometric observations)

  – Demonstrate on VLA+GBT (single pointing and mosaic) data, apply to ALMA+ACA+SD mosaics, evaluate w.r.to ngVLA requirements

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

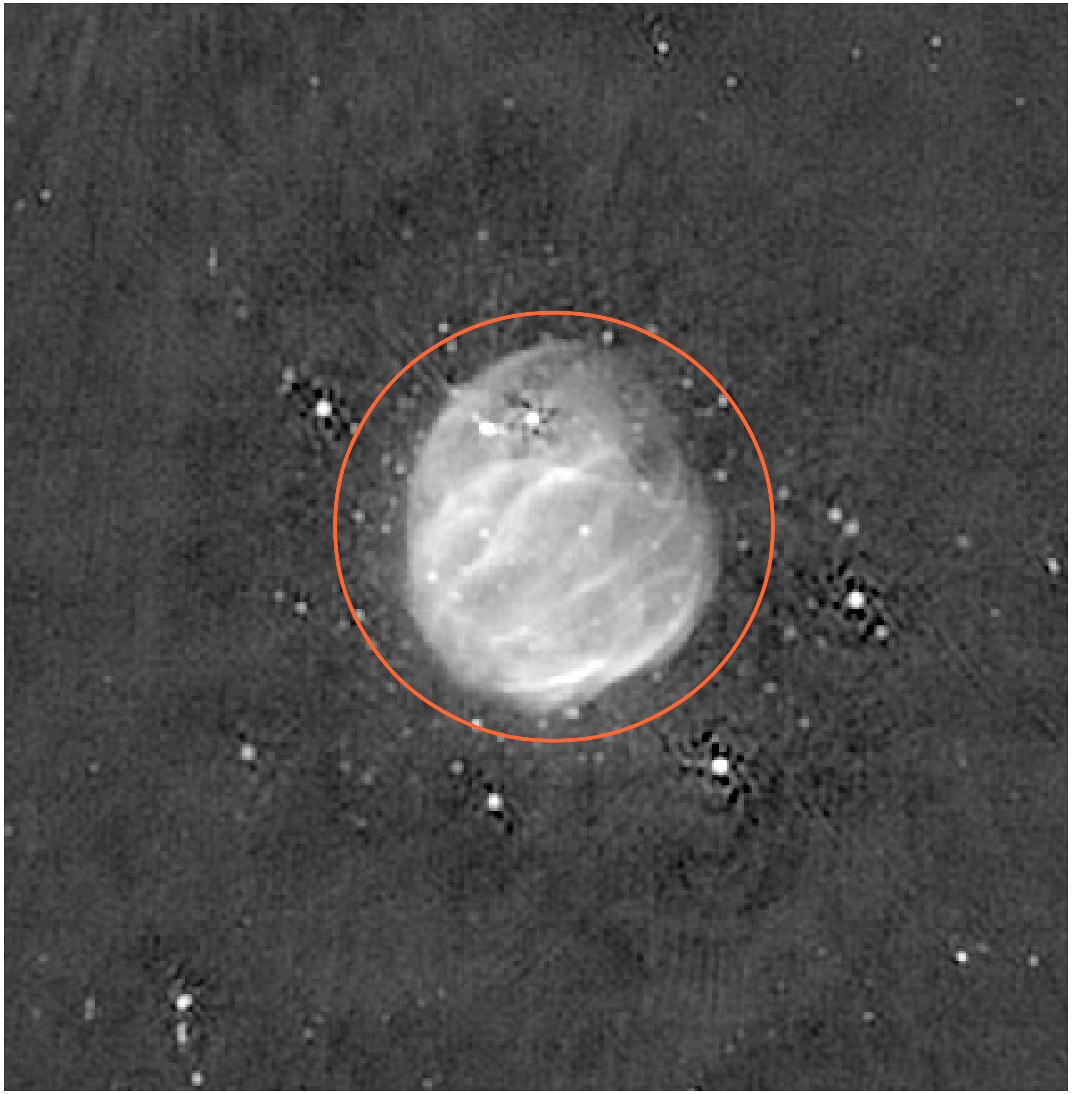
Primary beam at 1.5 GHZ : 30 arcmin

Imaging Algorithms applied :
MT-MFS with A/W-Projection

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

Large scale sizes were chosen based on existing GBT information :
total flux of ~ 1.0 Jy

MS-Clean + W-Projection
(flat spectrum assumption)



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Max sampled spatial scale :
19 arcmin (L-band, D-config)

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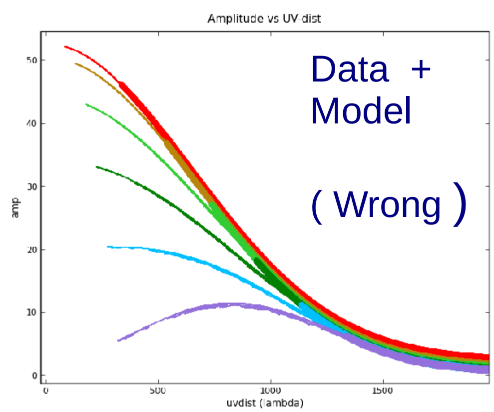
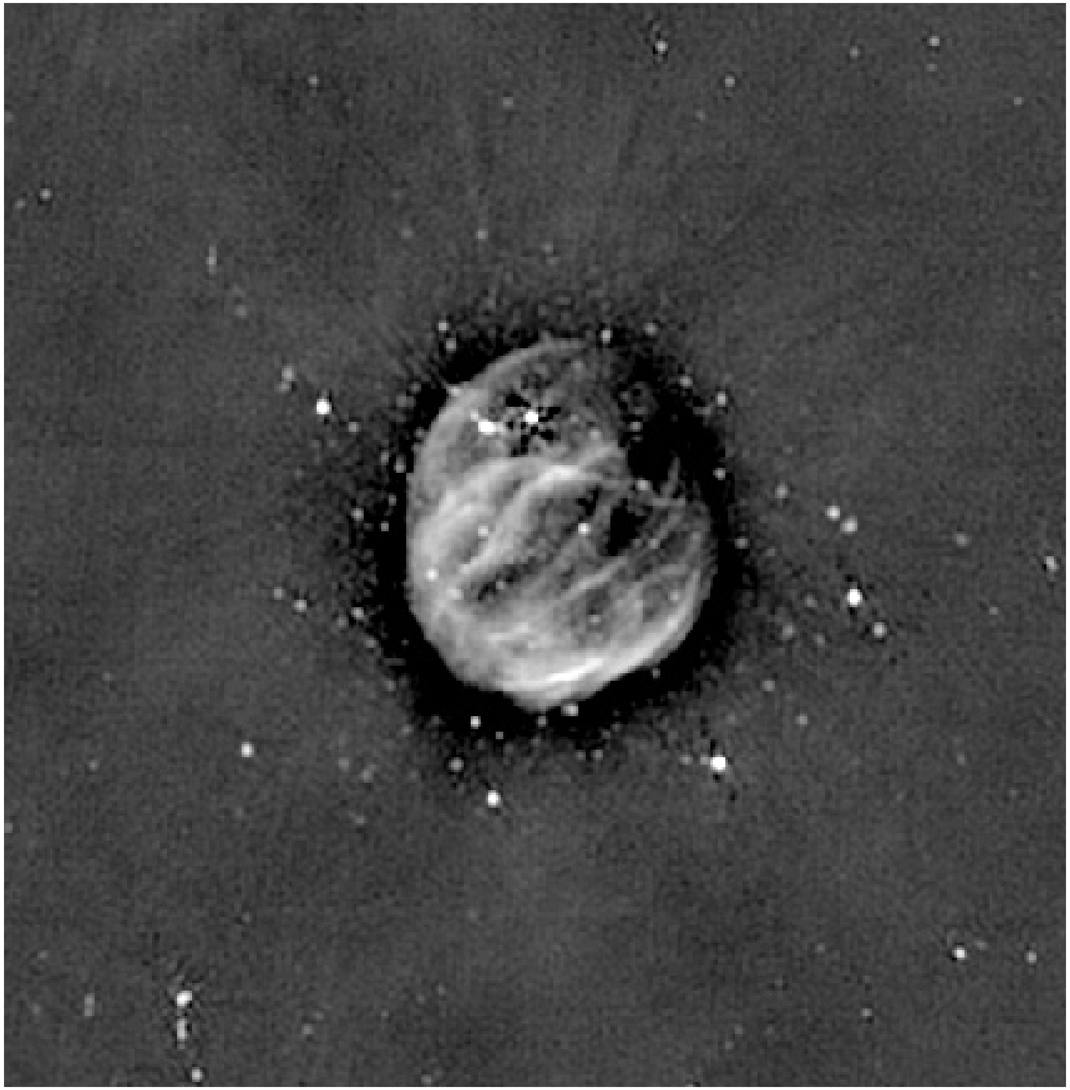
Primary beam at 1.5 GHZ : 30 arcmin

MS-Clean on it's own was able to reconstruct total-flux of 1.0 Jy

MT-MFS large-scale spectral fit is unconstrained and caused part of the reconstructed source flux to go negative at the high end of the band



MT-MFS Clean + W-Projection
(Multi-term wideband model)



G55.7+3.4 Supernova Remnant + Pulsar

Use the MS-Clean (flat spectrum model) as a starting model for the wideband MT-MFS reconstruction.

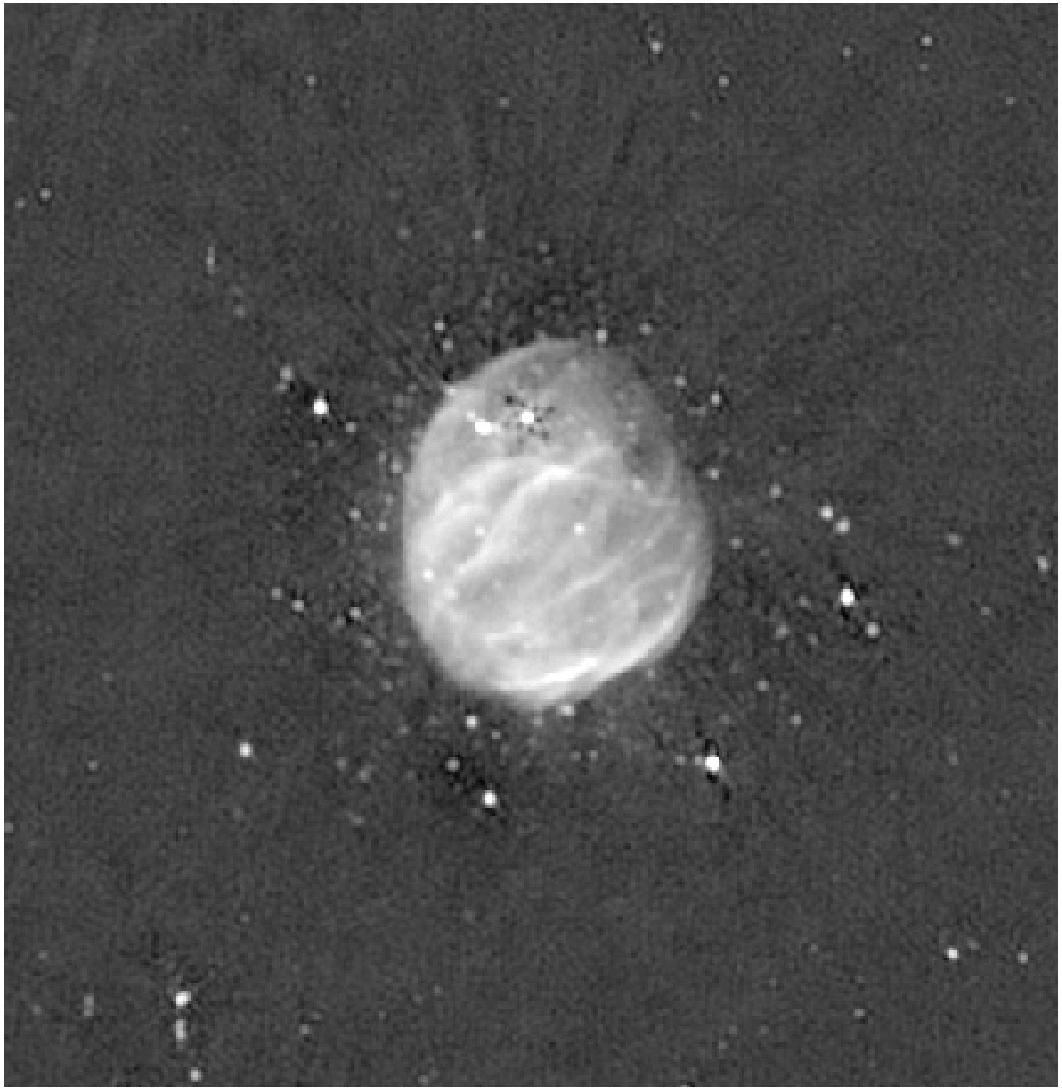
In this example, this was sufficient to recover the correct intensity (total flux of ~ 1.0 Jy) but the spectrum is still unconstrained.

=> Ideal wideband VLA test dataset to demonstrate combination of wideband SD data

Use recently obtained GBT (VEGAS) data between 1 GHz and 2 GHz

Plan :
– Use the pulsar and its known spectrum to calibrate the bandpass
– Try joint wideband deconvolution
– Handle wideband primary beams

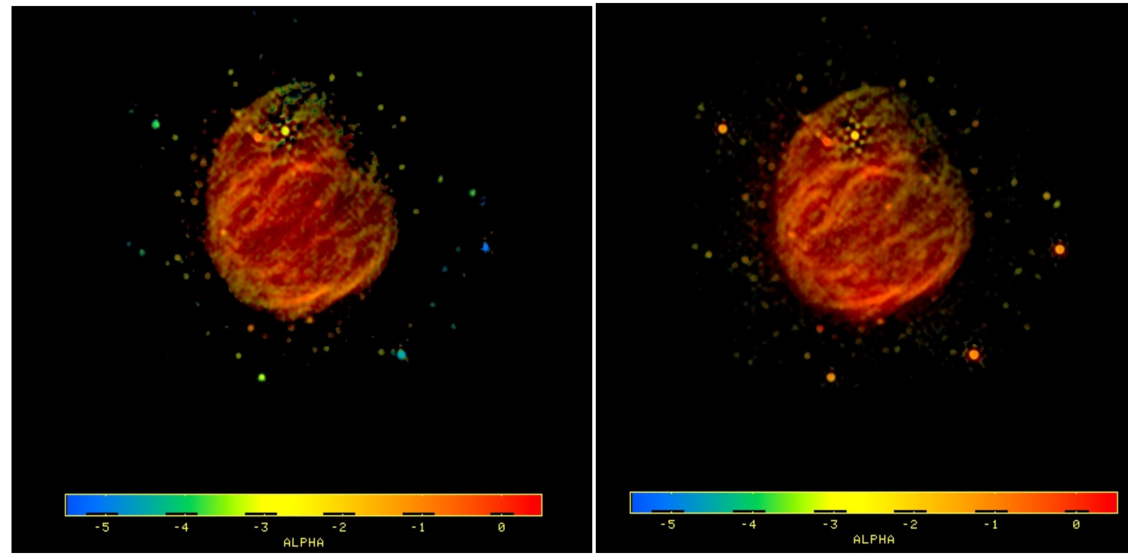
MT-MFS Clean + W-Projection
+ MS-Clean starting model



Wideband Primary Beams – WB-AW-Projection

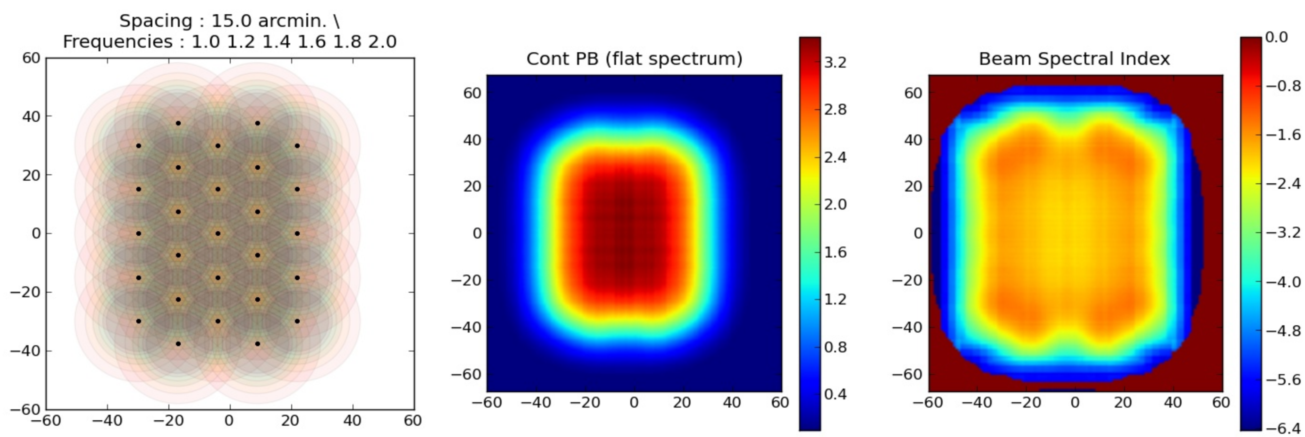
Without wideband PB correction
Outer sources are artificially steep

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



Wideband Mosaic
Primary Beam

Spurious PB spectra
across entire mosaic



=> Joint wideband SD+INT deconvolution approach needs to work with the (WB) A-Projection algorithm to handle wideband primary beams for joint mosaics

(Modify the SD observed images per frequency before combining)

Summary

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- Needed a method that combined data before the wideband sky model is constructed.
- Multi-term Joint Deconvolution : Feather both INT and SD observed images and PSFs before the minor cycle in an iterative image reconstruction scheme. Similarity to a weighting scheme makes this robust to different choices of scale functions.
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