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

Urvashi Rau
National Radio Astronomy Observatory, USA

Nikhil Naik
IIT-Kharagpur, India (2017 NRAO summer intern)

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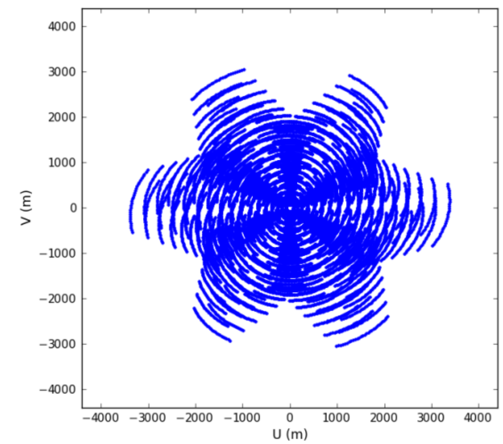
Image formation in radio astronomy

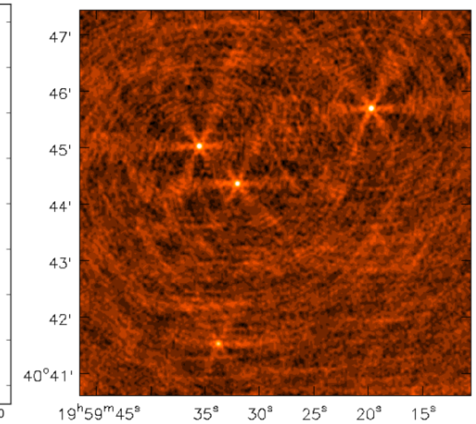
•An interferometer samples the spatial Fourier transform of the sky brightness

•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



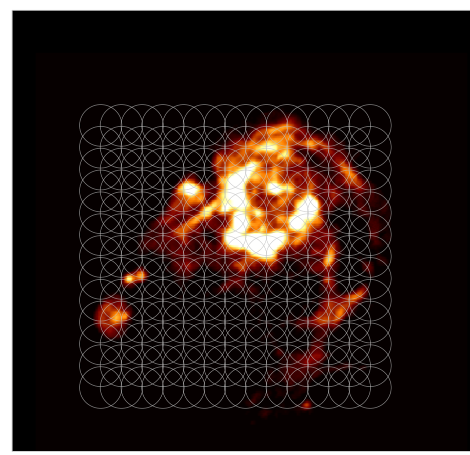


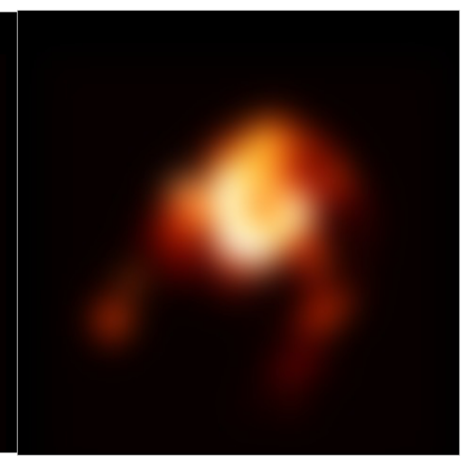
•A single dish telescope does a raster scan of a region of sky

•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.

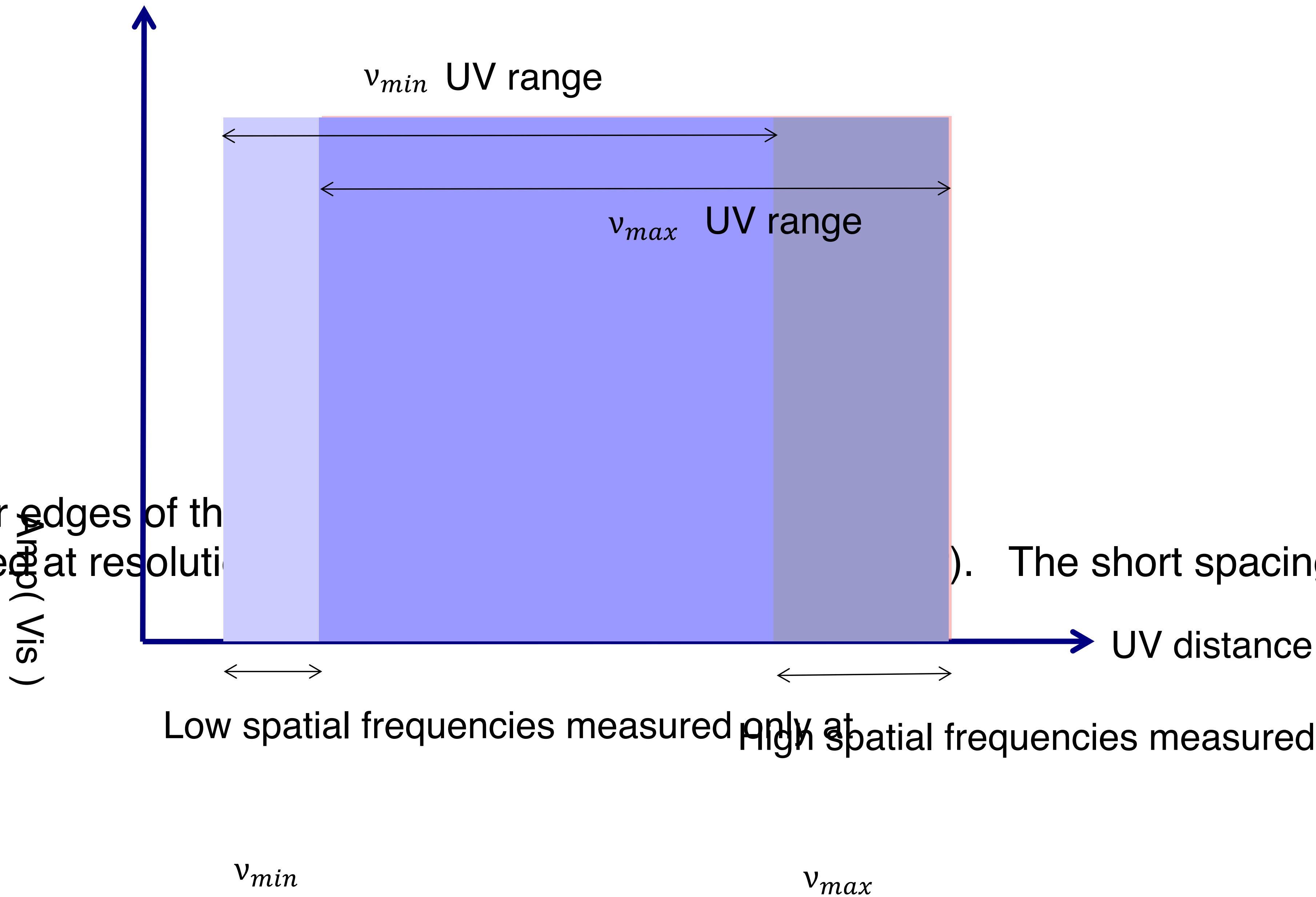




Wideband imaging (single dish and interferometers)

- 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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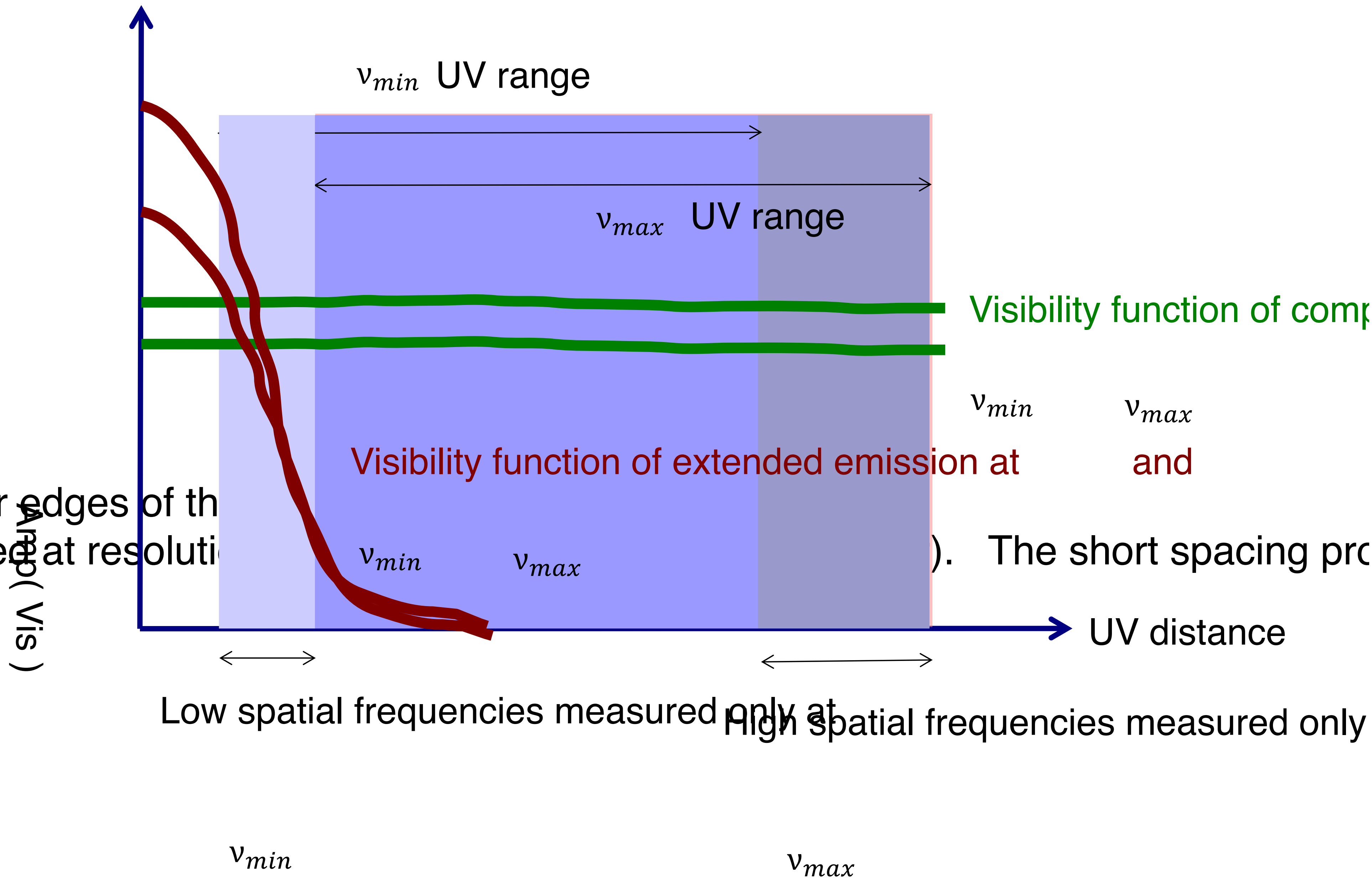
For which scales can we reconstruct the spectrum



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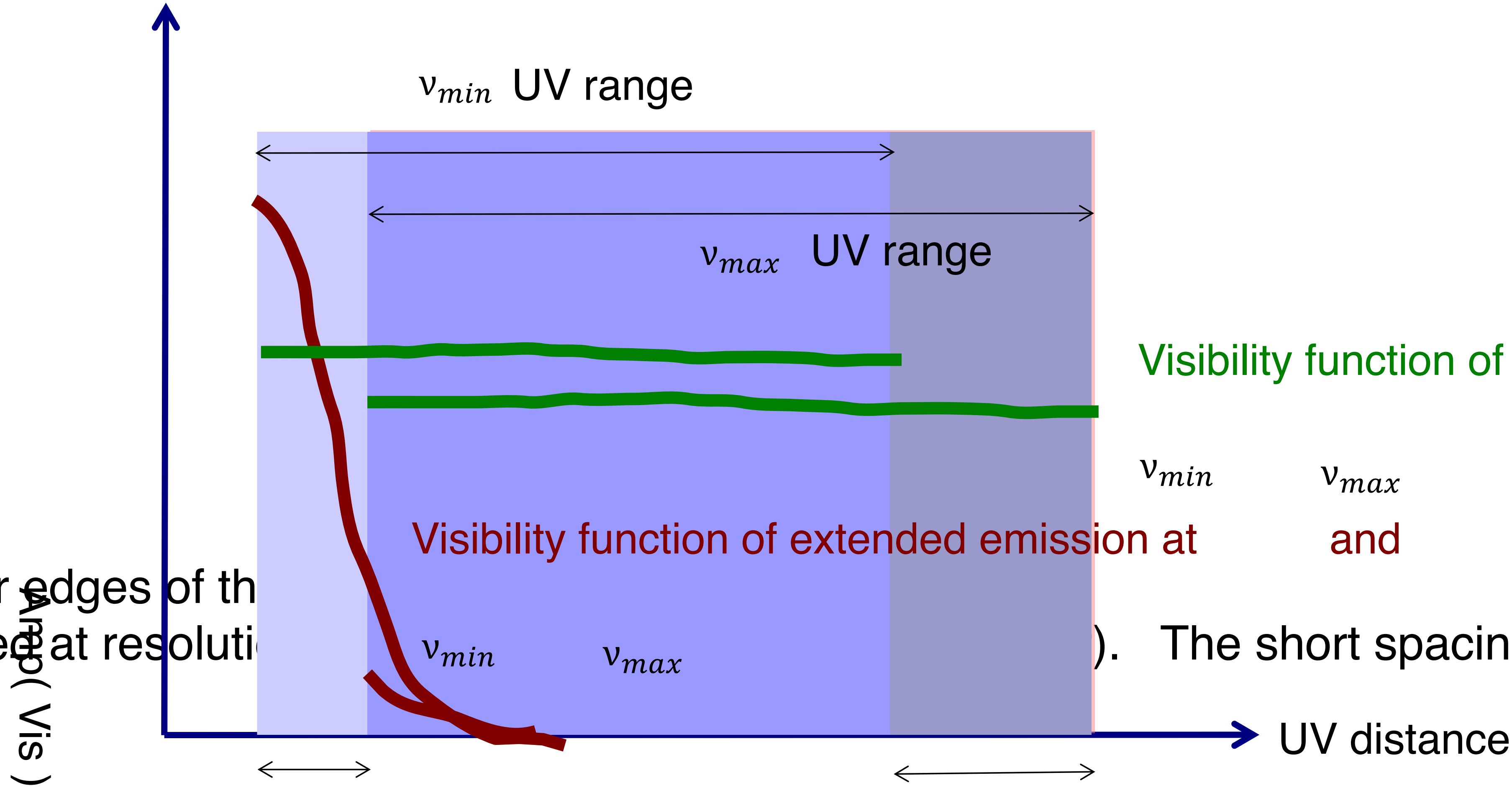

Visibility function of comp

ν_{min} ν_{max}

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outer edges of th

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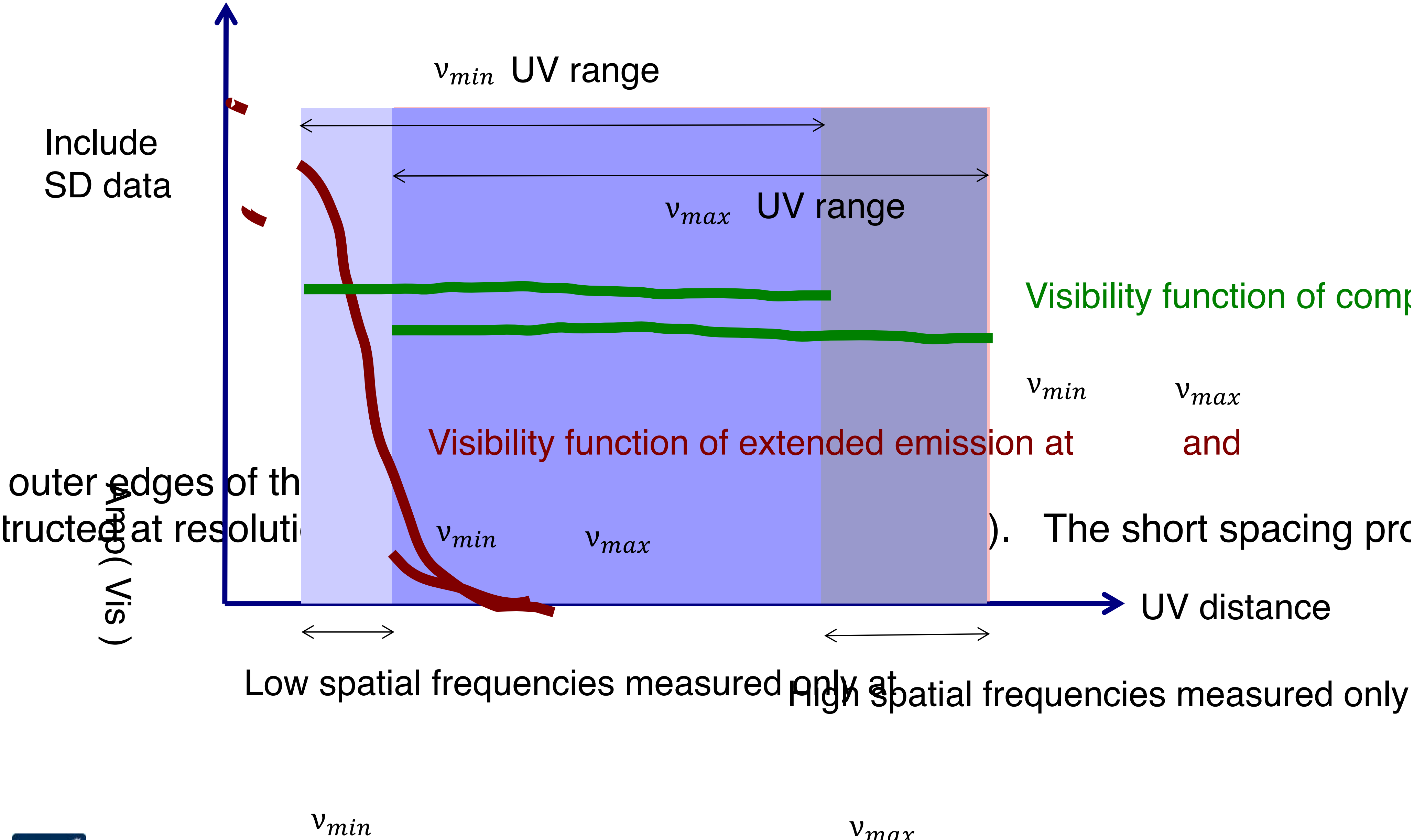
Low spatial frequencies measured only at

High spatial frequencies measured only

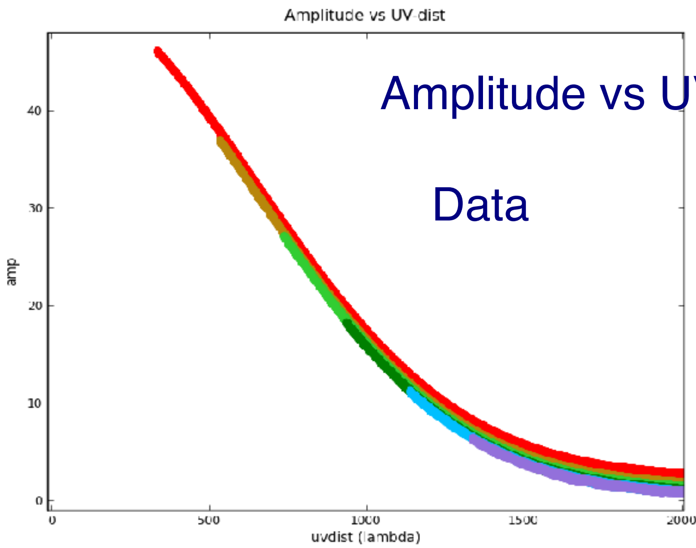
ν_{min} ν_{max}

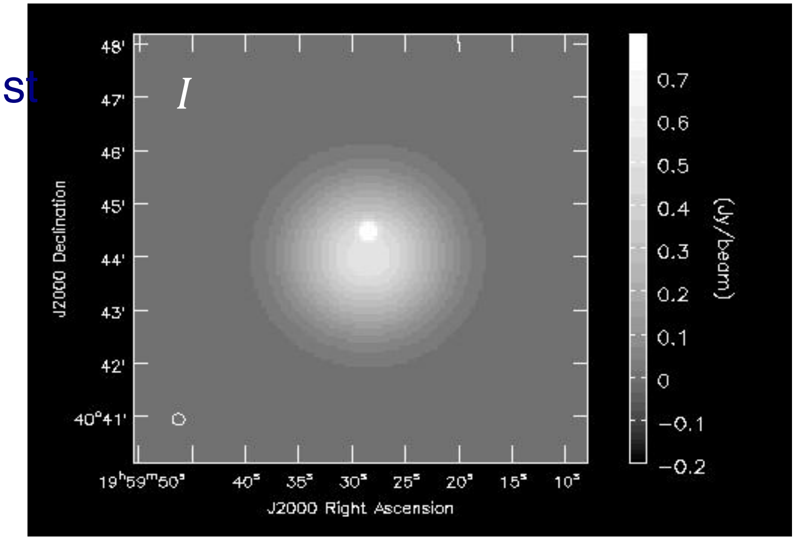
For which scales can we reconstruct the spectrum



Very large scales : Unconstrained Spectrum

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





True sky has one s

Leave out shortest

No short spacings

=> False steep spe

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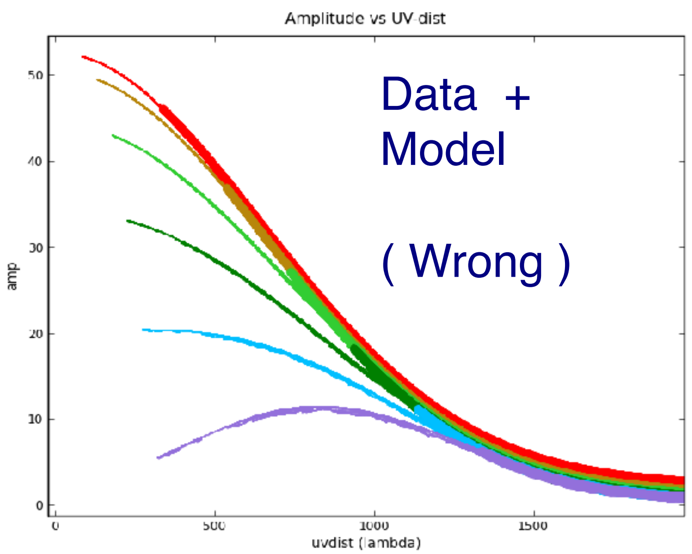
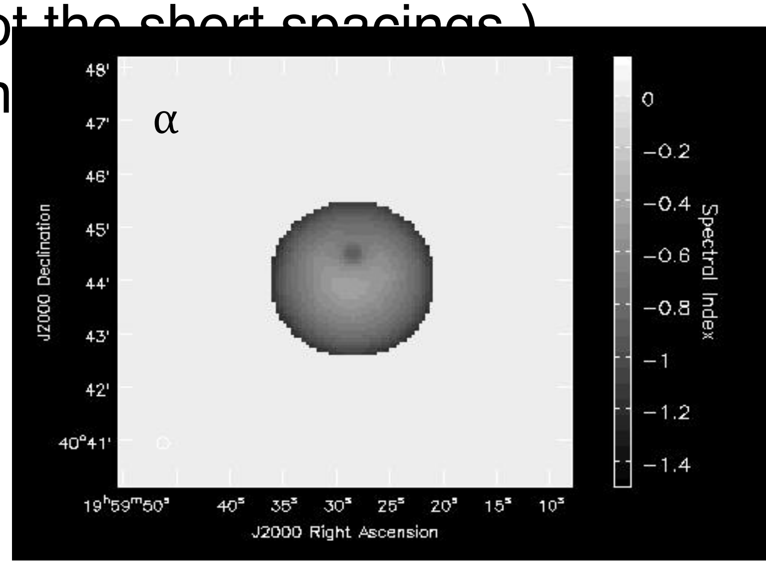
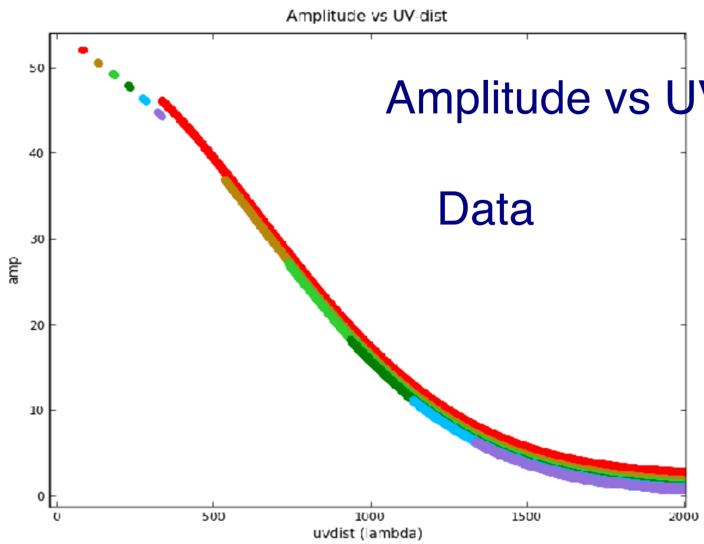
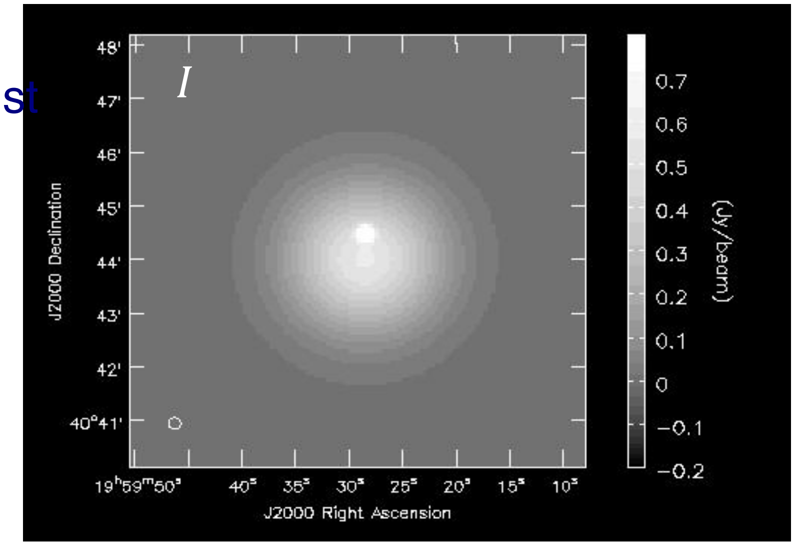




Very large scales : Need additional information

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



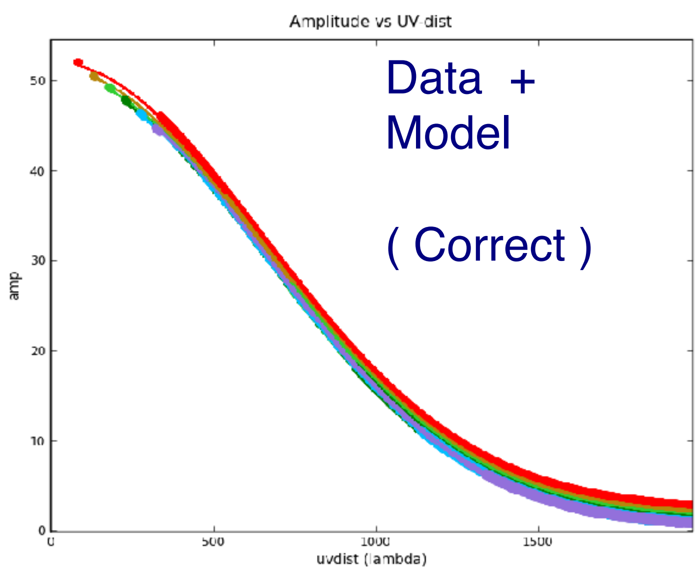


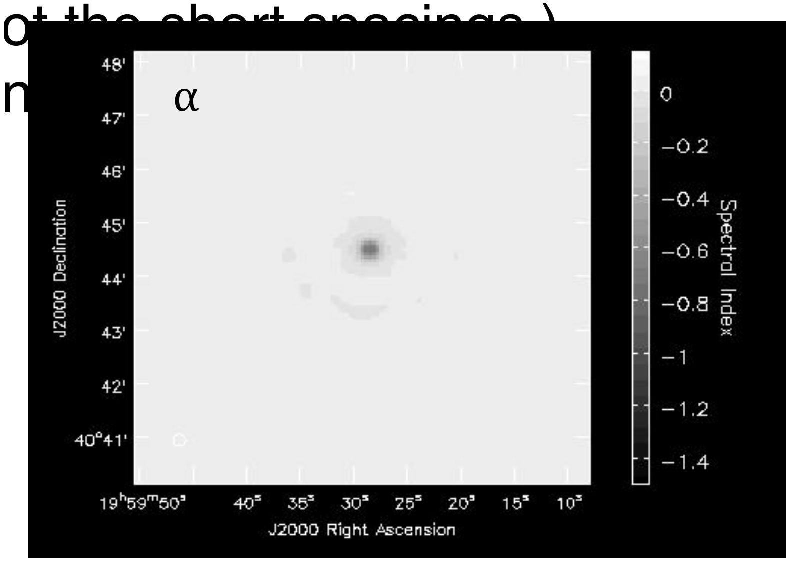
True sky has one s

Retain some short

Correct reconstruc

=> So, how to add





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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

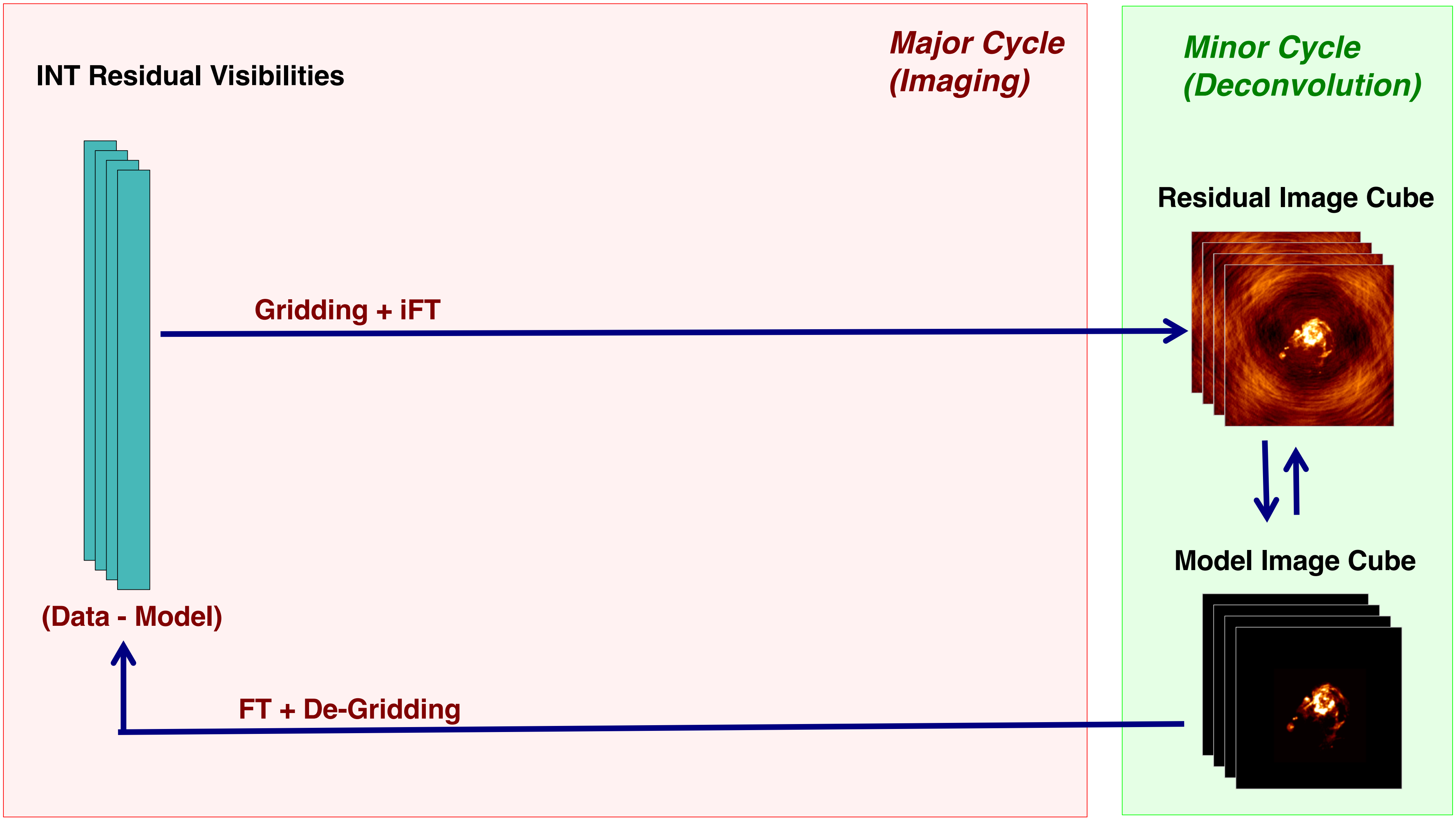
    – Do multi-term deconvolution to get Taylor coefficient images

– Handling wideband primary beams

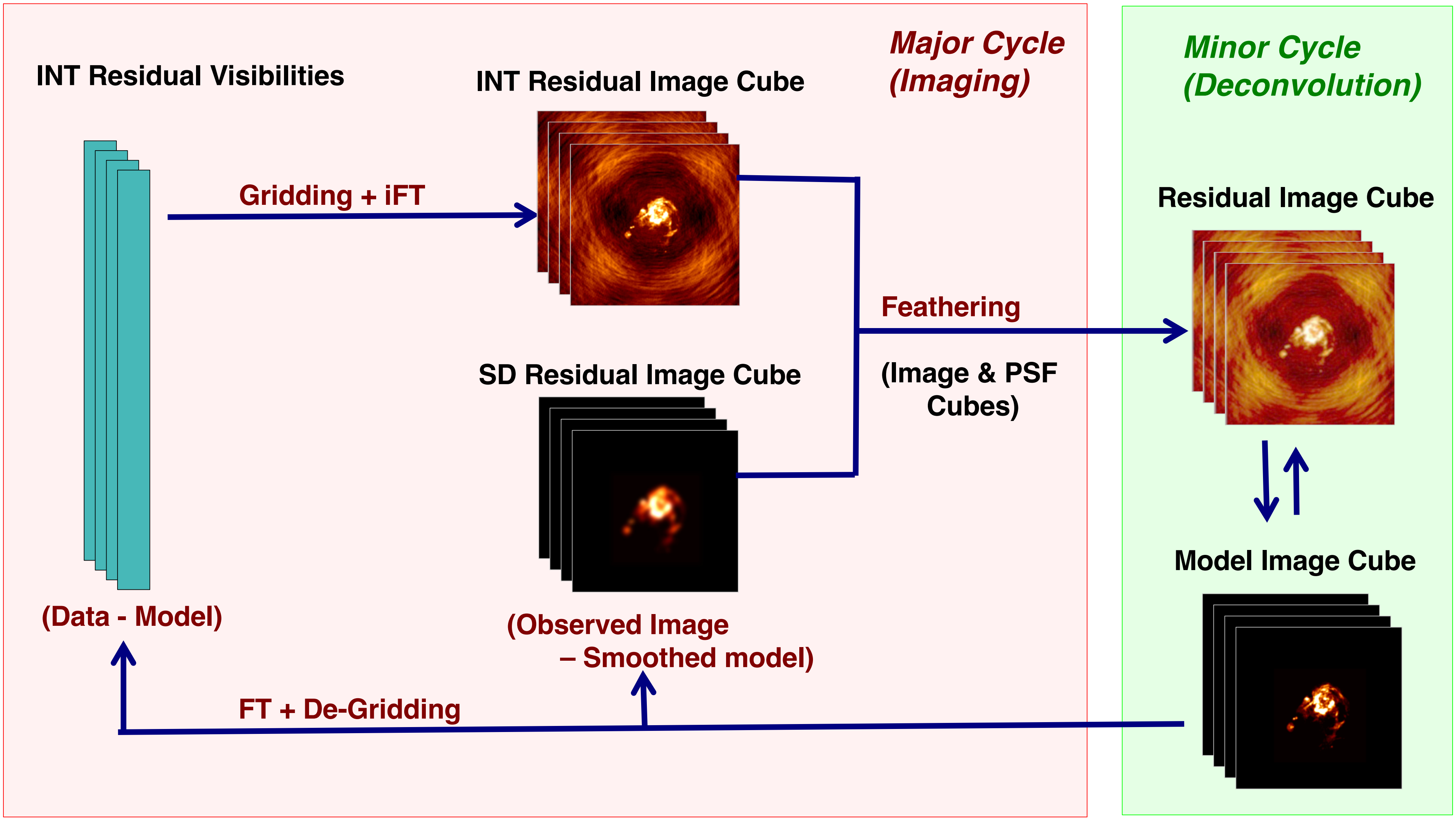
  – Manipulate the SD observed images (per channel) to follow the form of the corresponding INT image (via deconvolution and multiplication by INT_PB)

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

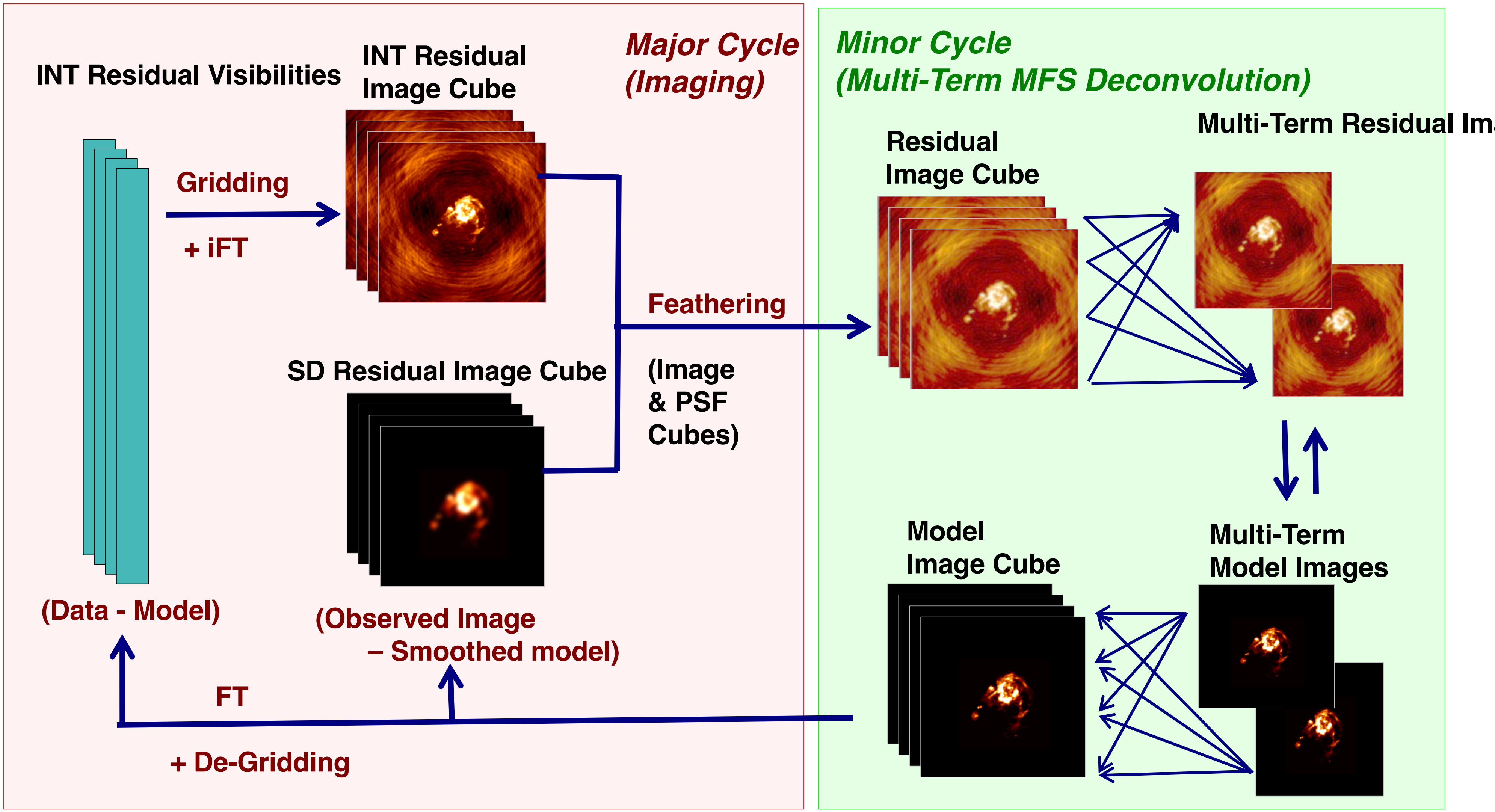
Spectral Line (Cube) Imaging : INT only



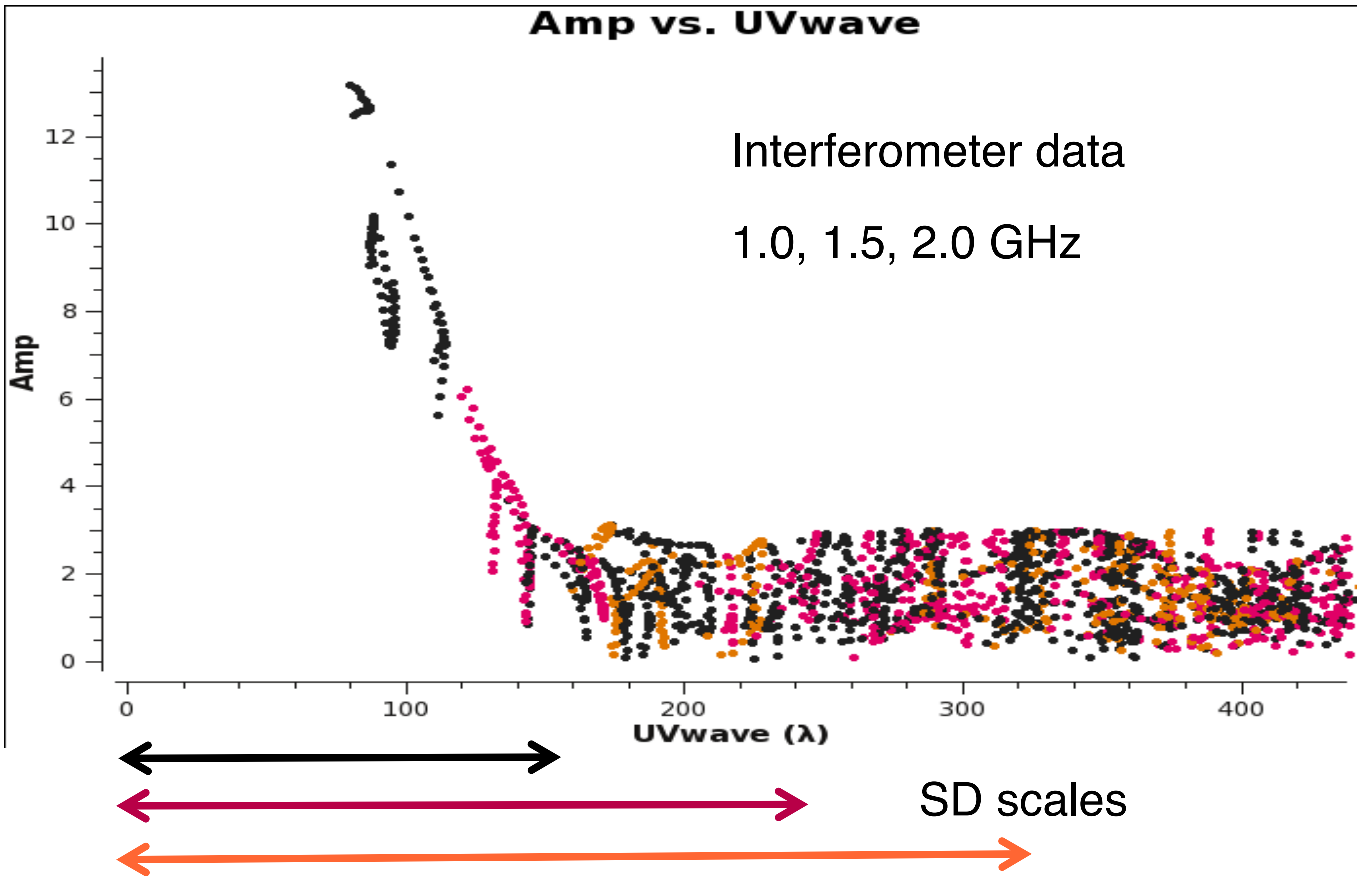
Spectral Line (Cube) Imaging : Joint INT + SD



Wideband Multi-Term Imaging : Joint INT + SD

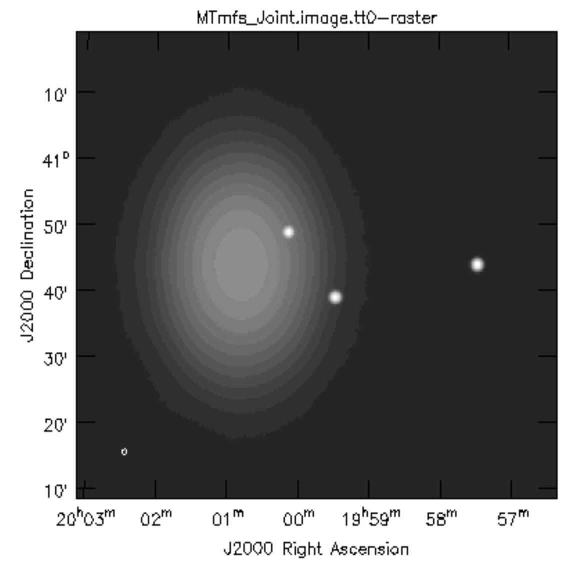


Example : Multi-frequency uv-coverage / resolution



Simlated sky :

Three points and one 1



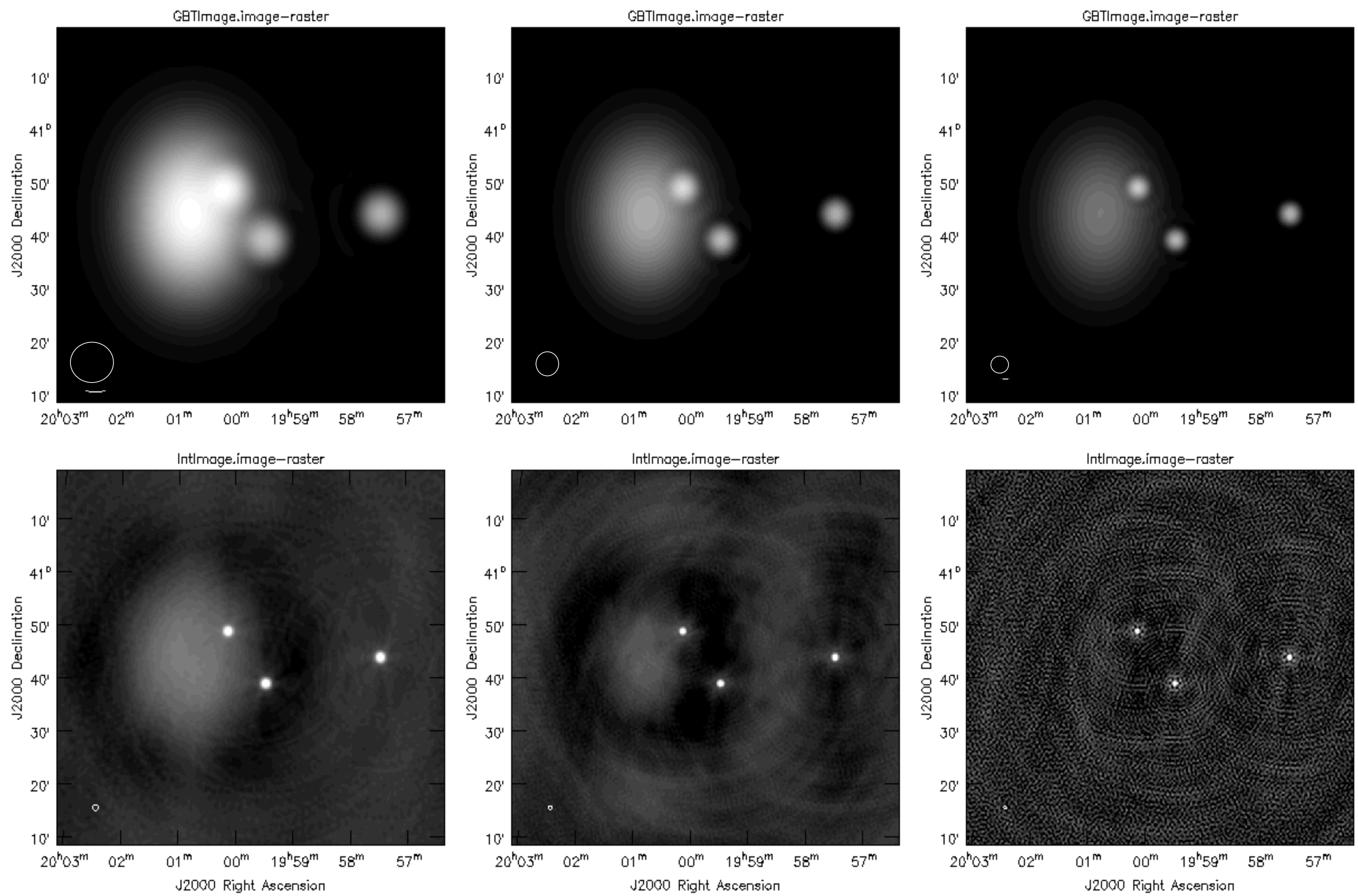
Frequency	1.0 GHz	1.5 GHz	2.0 GHz	Spacing
•INT (resolution)	1.2 arcmin	0.8 arcmin	0.6 arcmin	~ 1000m
•INT (max scale)	40.4 arcmin	27.5 arcmin	19.1 arcmin	~ 25m
•SD (resolution)	10.3 arcmin	6.8 arcmin	5.2 arcmin	~ 100m

Images from SD and INT (3 frequencies)

1.0 GHz 1.5 GHz 2.0 GHz

- SD
- observed
- Images

- INT
- reconstructed
- Images

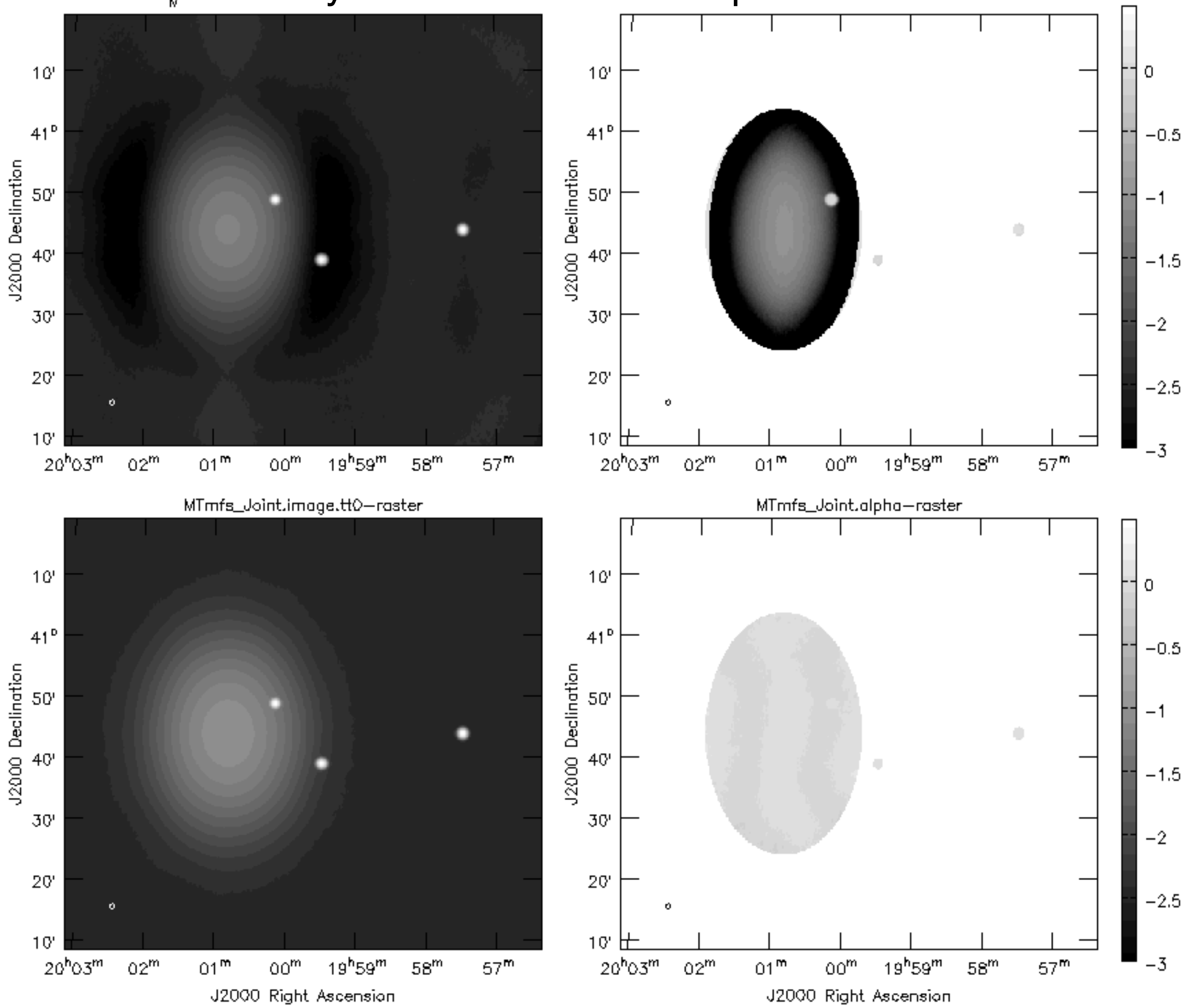


Example – Wideband imaging (without/with SD data)

- **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

Intensity Spectral Index

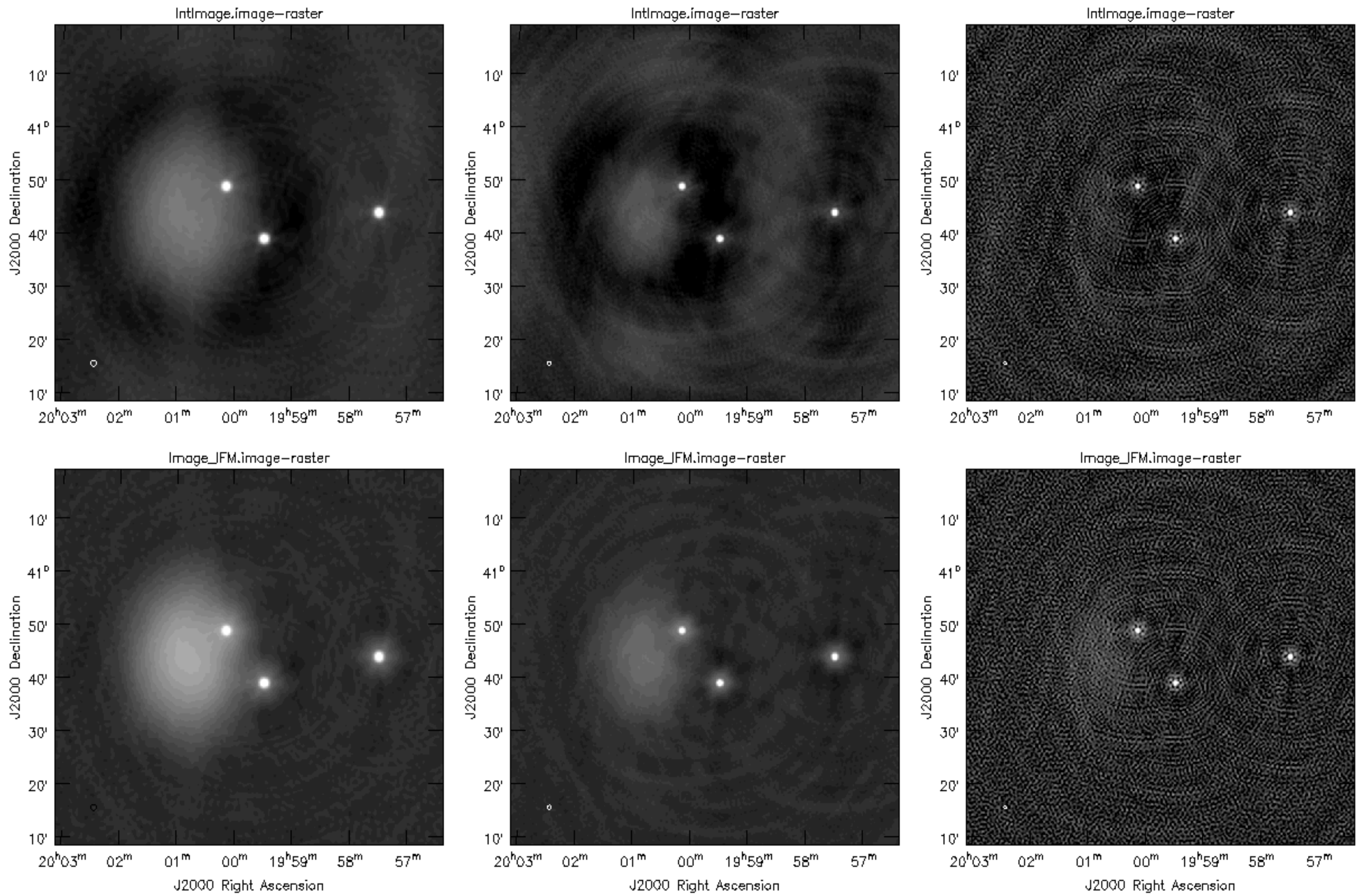


Other uses - 1 - Spectral Cube Joint Deconvolution

1.0 GHz   1.5 GHz   2.0 GHz

- INT only
- reconstructed
- spectral cube

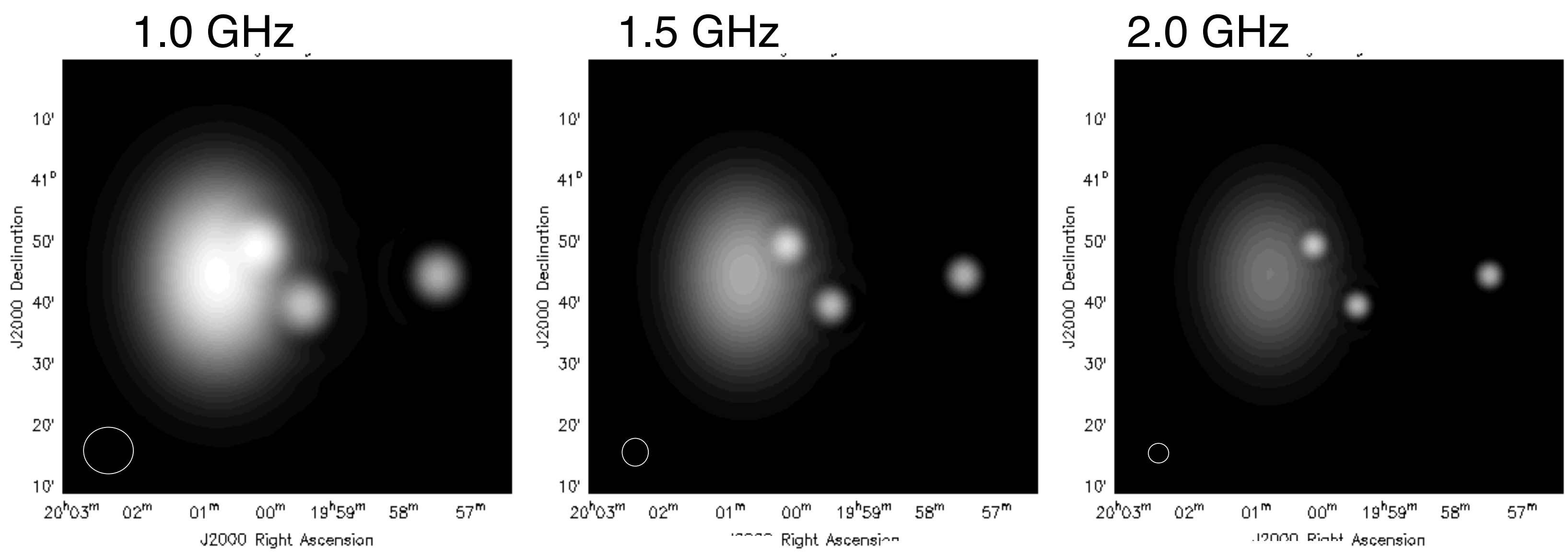
- INT + SD
- reconstructed
- spectral cube



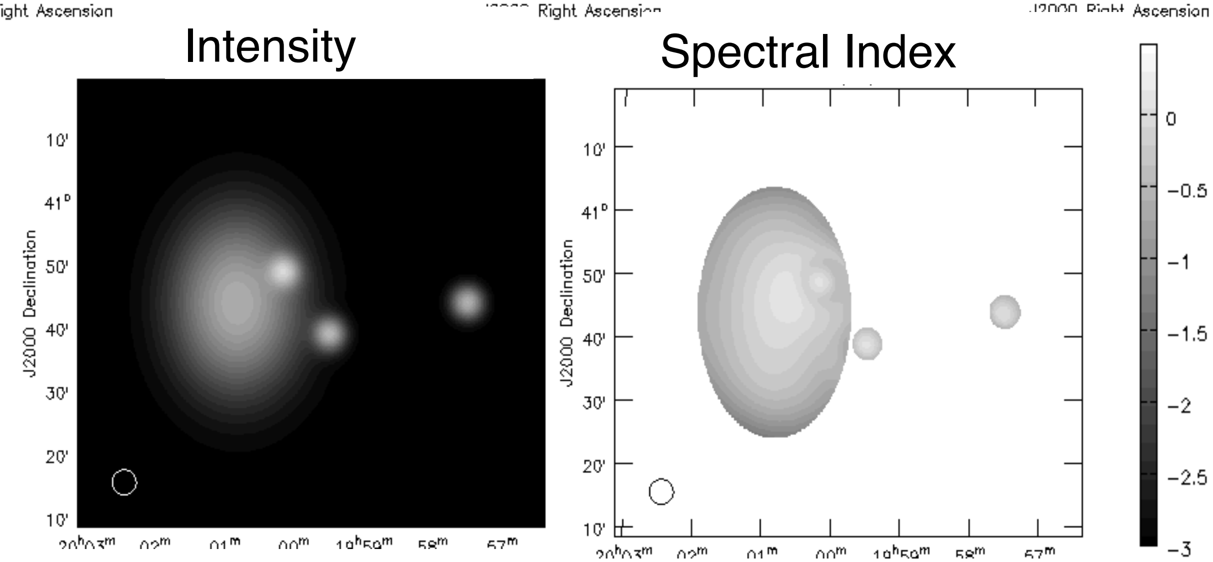
Other uses - 2 – Wideband Single Dish Imaging

- Apply Multi-term wideband deconvolution to SD data only

- SD
- Spectral Cube



- SD
- Continuum Intensity & Spectral Index
- Better resolution
- Deconvolved SD beam



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)

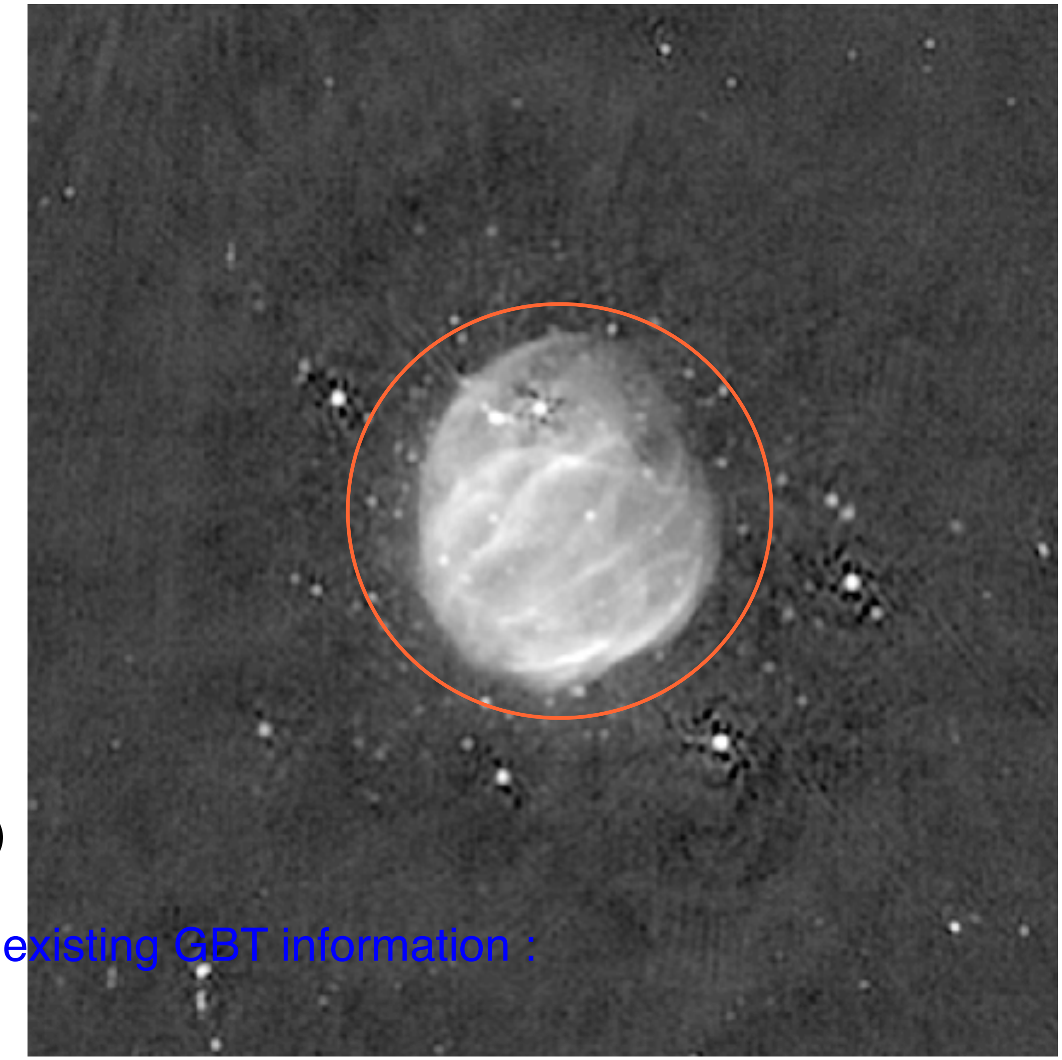
Angular size of G55.7+3.4 : 24 arcmin

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])

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



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

G55.7+3.4 Supernova Remnant + Pulsar

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

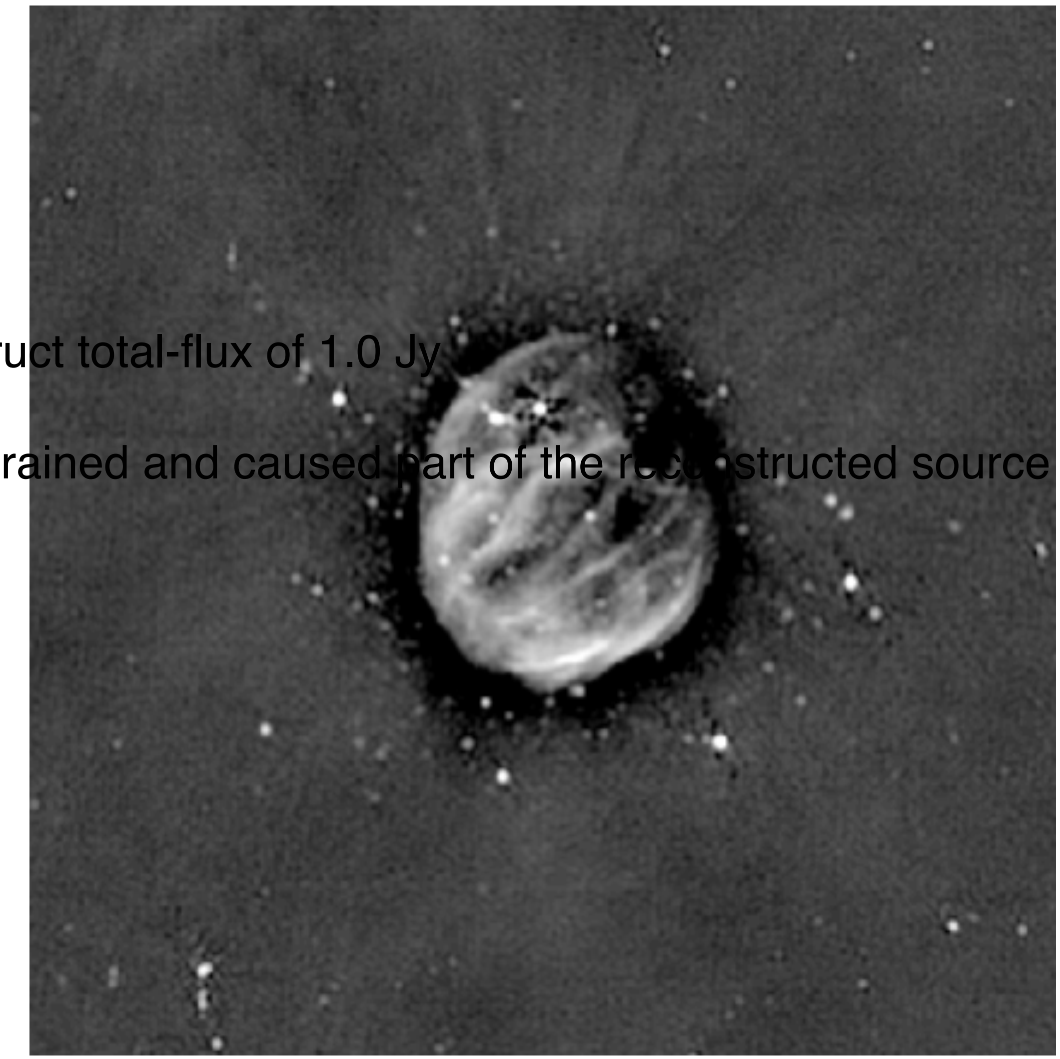
Angular size of G55.7+3.4 : 24 arcmin

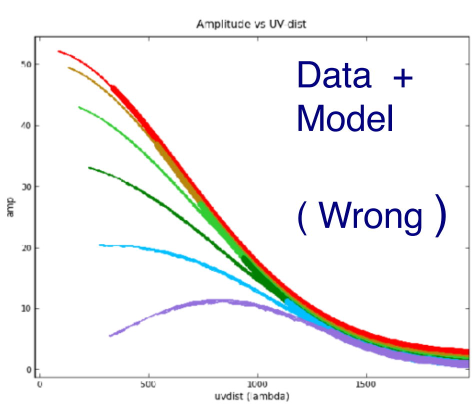
Primary beam at 1.5 GHZ : 30 arcmin

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 flu

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 reconstru

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

=> 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 :

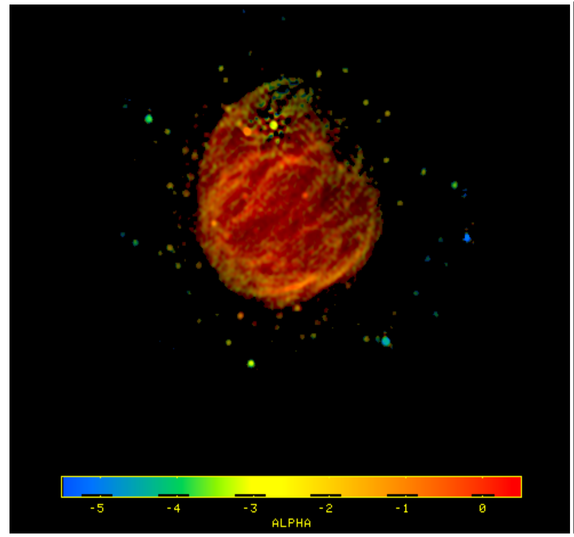
– Use the pulsar and its known spectrum to calibrate the bandpass
– Try joint wideband deconvolution
– Handle wideband primary beams

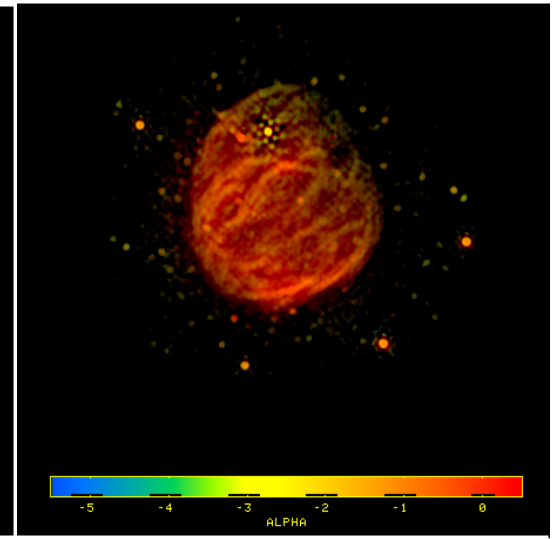
MT-MFS Clean + W-Projection
+ MS-Clean starting model

Wideband Primary Beams – WB-AW-Projection

Without wideband PB correction
Outer sources are artificially steep

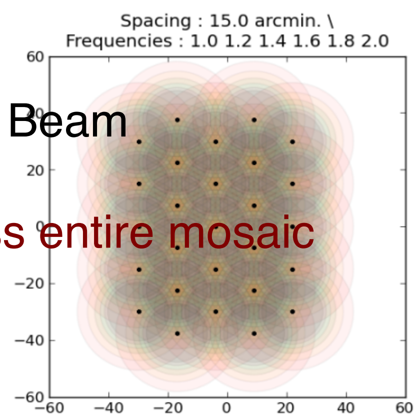
With wideband PB correction (via WB-AWP)
Outer sources have correct spectra

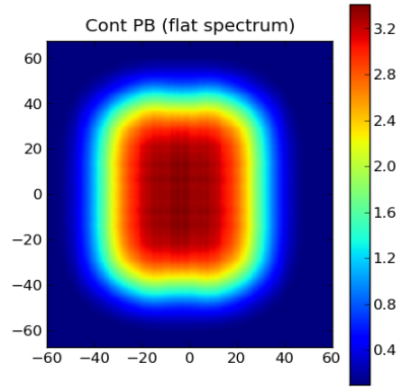


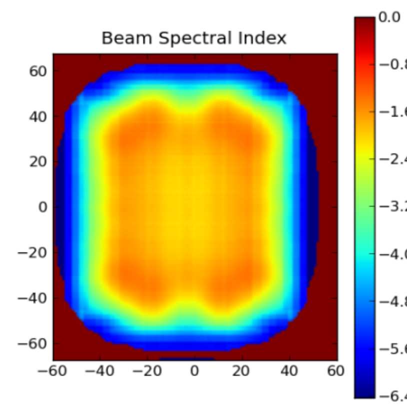


Wideband Mosaic Primary Beam

Spurious PB spectra across entire mosaic







=> Joint wideband SD+INT deconvolution approach needs to work with the (WB) A-Projec

(Modify the SD observed images per frequency before combining)

Summary

- 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.
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