Wide Band Imaging of Multi-Scale Structure

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(Virtual) CHANG-ES Meeting

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Imaging for CHANG-ES

CHANG-ES data :

– Multi-configuration VLA at L-Band and C-band , full pol

– GBT Mosaics at L-Band C-band , full pol (+ 150 MHz LOFAR data)

Imaging Goals :

– Intensity, Spectral and Polarization structure of Galaxy Halos.

– Extended low-brightness emission. Moderate dynamic range.

Hurdles :

– Angular resolution and sky brightness change with frequency
– Antenna primary beams have frequency-dependent gain and leakage
– Missing large scale information
– Accurate modeling of sky emission

=> Overview of algorithms and effects
=> Applicability to CHANG-ES ?

Algorithms relevant to CHANG-ES

– Angular resolution and Sky Brightness change with frequency

Spectral Cube Imaging

Multi-Frequency Synthesis

– Antenna primary beams change with frequency

Wideband Primary Beam correction

Joint Mosaics , Full Pol/Mueller Primary Beam correction

– Missing large scale information

Joint Reconstruction of Single Dish and Interferometer data

[Sky Models : Multi-Scale CLEAN, Multi-Term CLEAN, RM-synthesis...]

Wide-Band Imaging

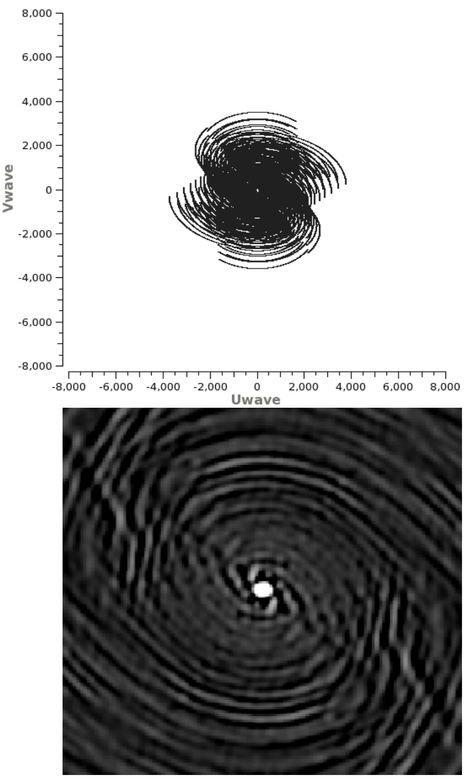
Sky and Instrument change with frequency

Large bandwidth => Better imaging sensitivity

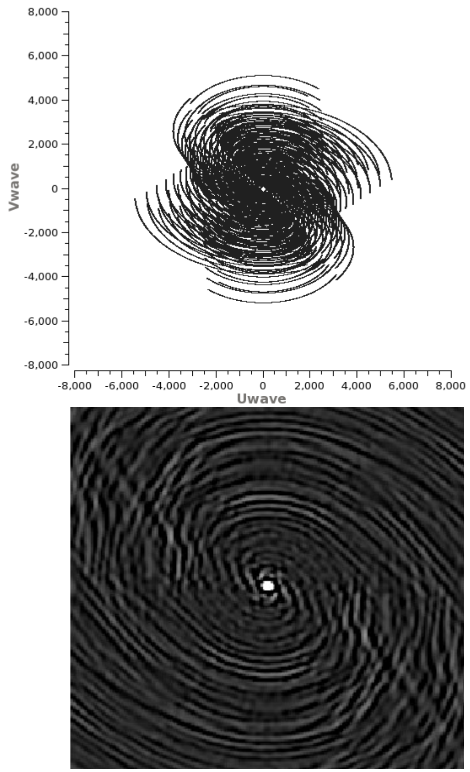
$$\sigma_{cont} = \frac{\sigma_{chan}}{\sqrt{N_{chan}}}$$

Imaging properties change with frequency

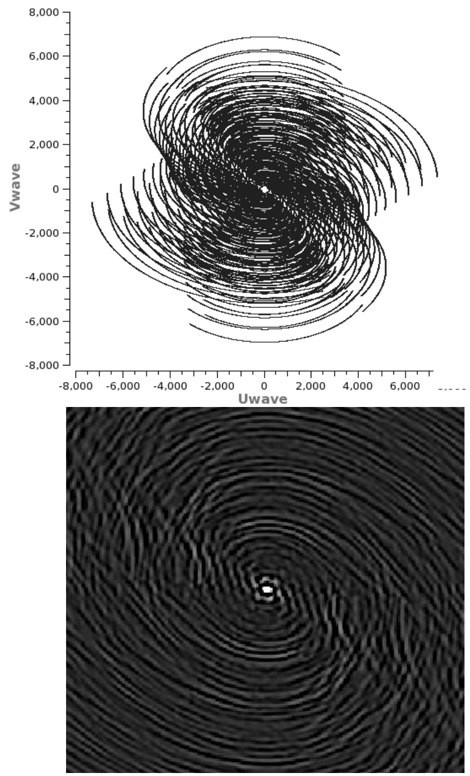
1.0 GHz



1.5 GHz



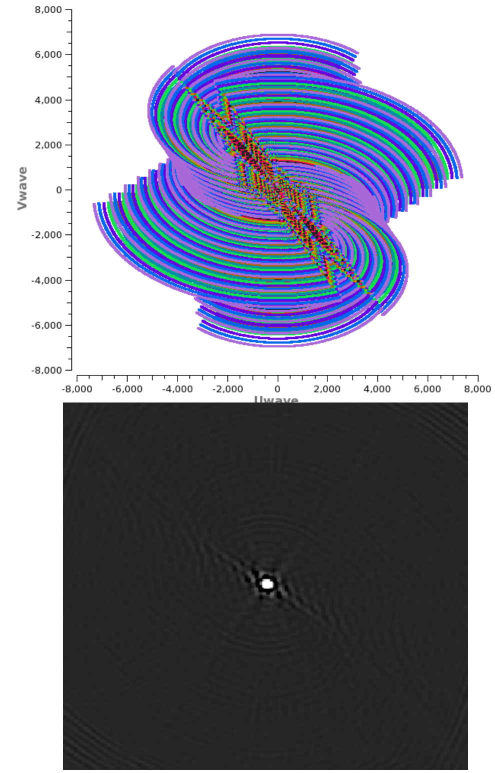
2.0 GHz



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

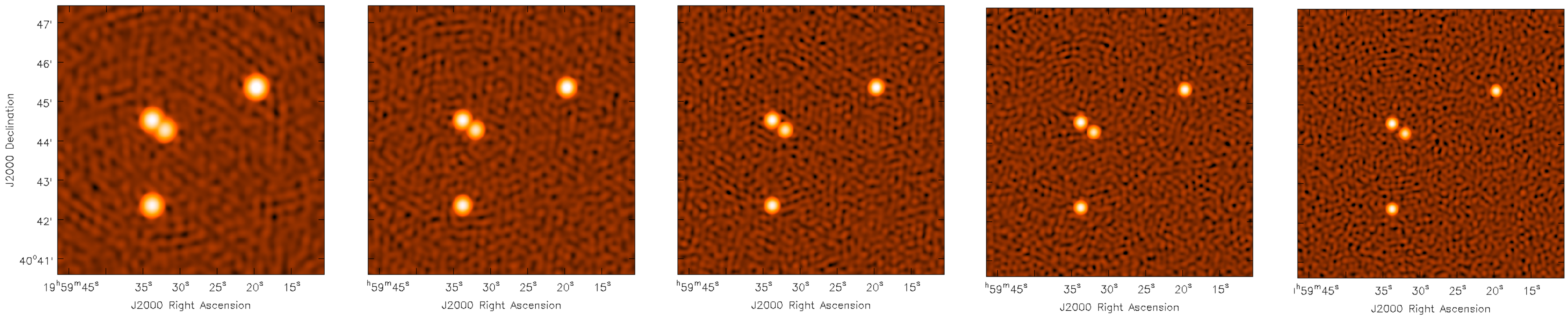
Multi-Frequency Synthesis

1.0 - 2.0 GHz



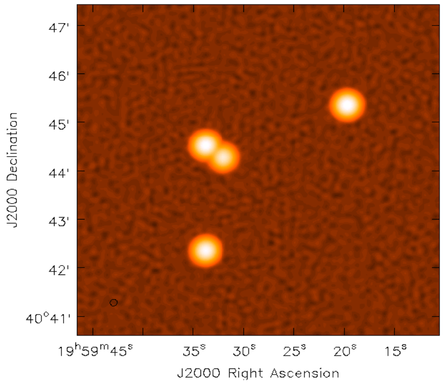
$$I_{wb}^{obs} = \sum_{\nu} \left[I_{\nu}^{sky} * PSF_{\nu} \right]$$

Two wide-band imaging techniques : Cube / MFS



Cube Imaging :

(1) Image each chan/spw separately
(2) Smooth to the lowest resolution
(3) Calc continuum and spectrum

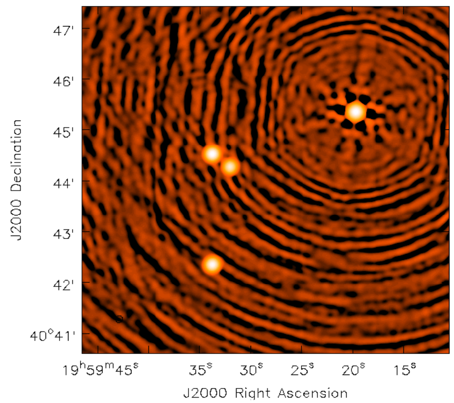


*required for Stokes Q/U
and RM-synthesis

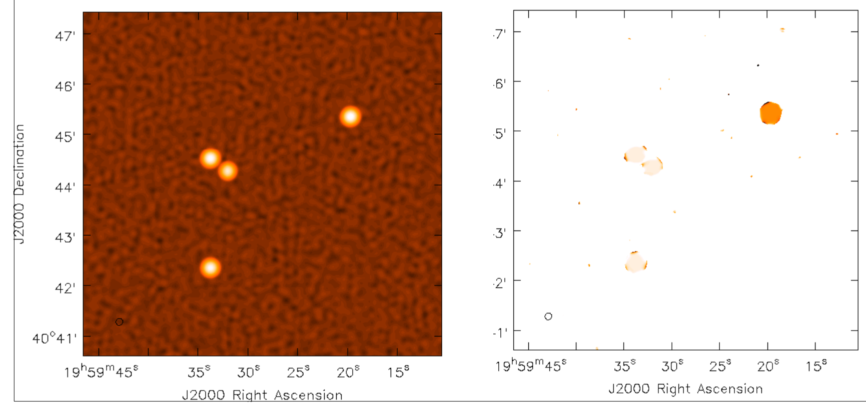
Multi-Frequency-Synthesis (MFS) :

Combine data from all frequencies onto a single grid and do a joint reconstruction

Flat-sky assumption

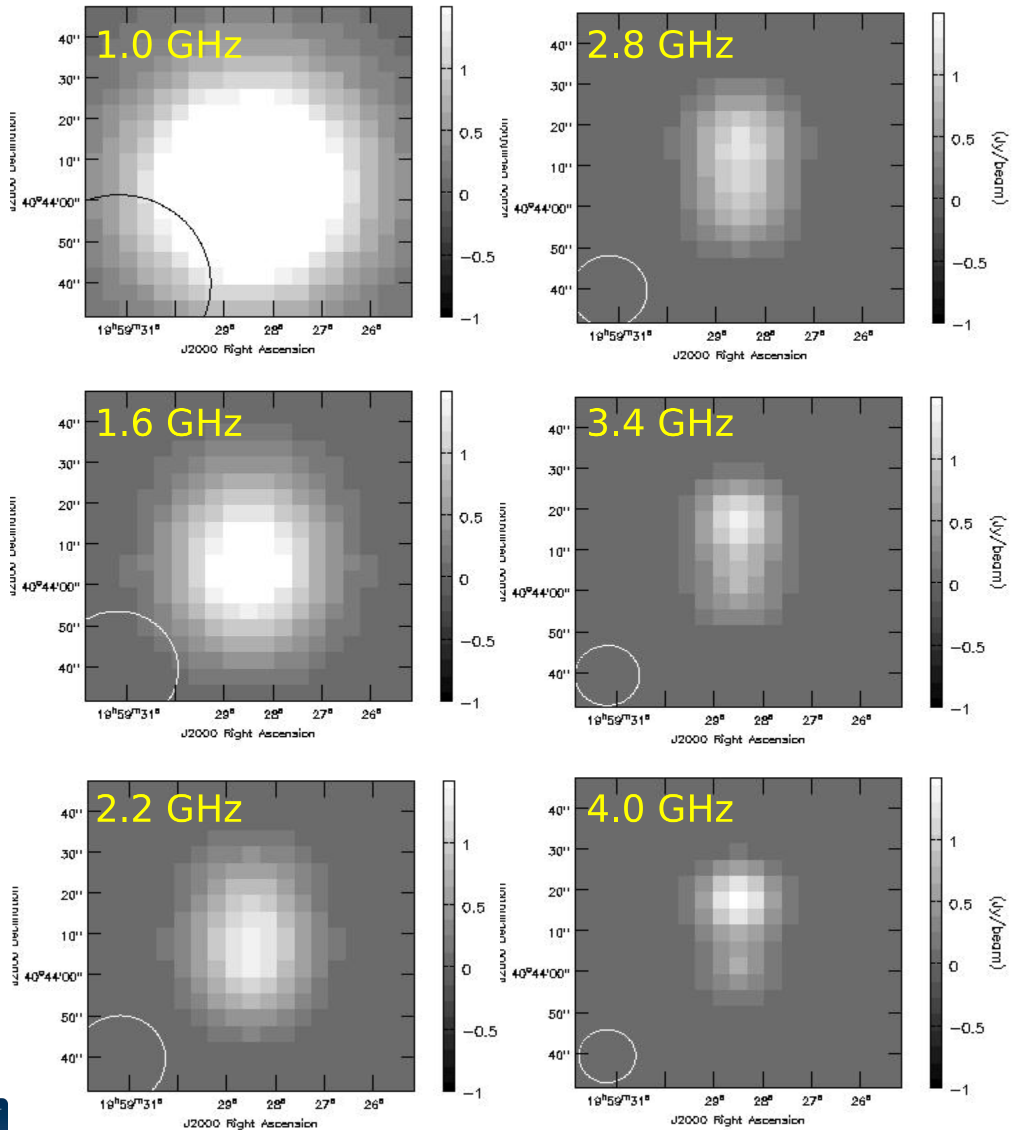


Include a Spectral model
(Stokes I, Spectral Index)

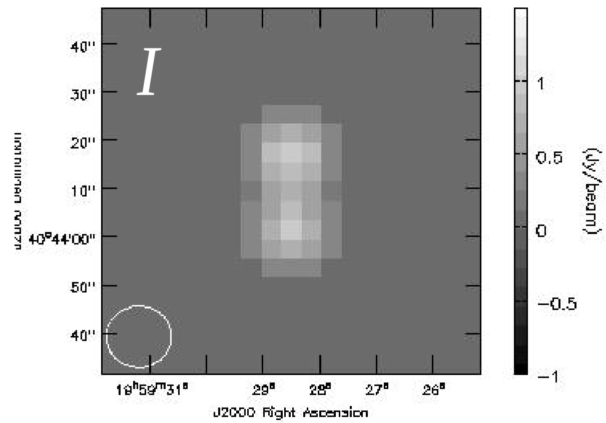


Angular resolution of MFS (wideband) images

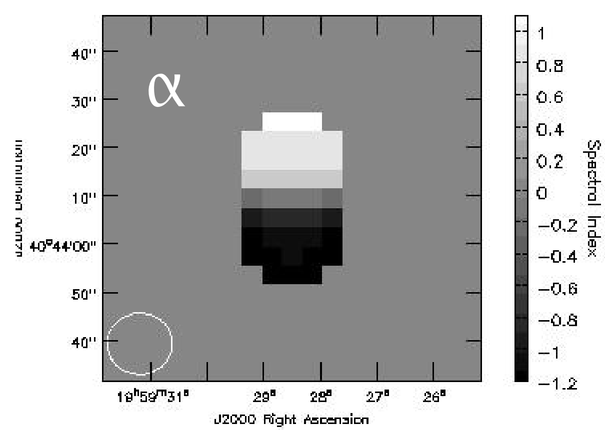
Can model the intensity and spectrum at the angular resolution of the joint UV-coverage



Restored Intensity image



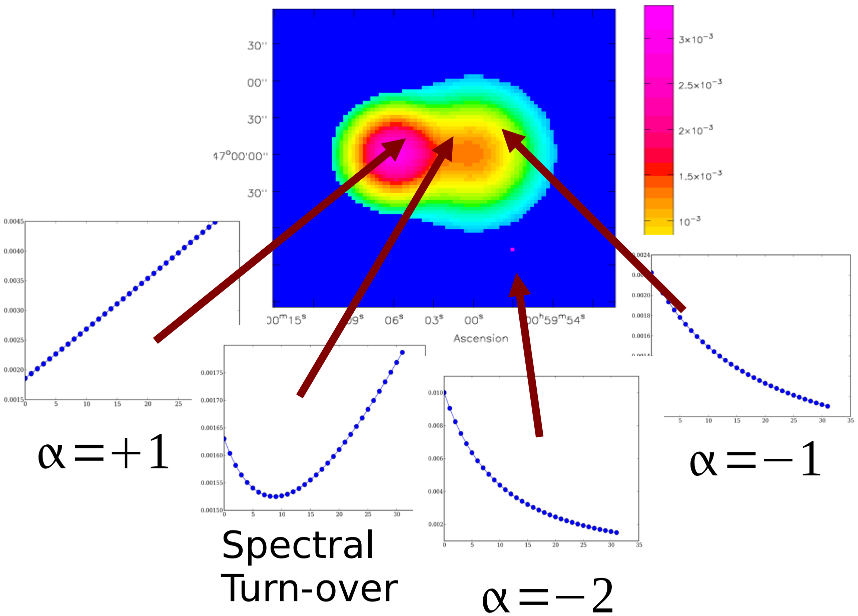
Spectral Index map



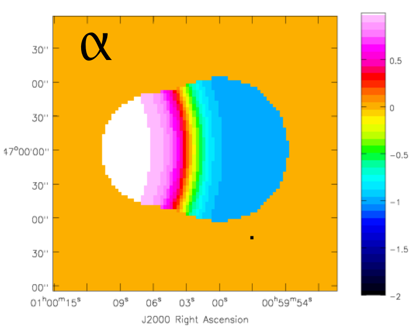
Wideband (MTMFS) imaging of extended-emission

A multi-scale model gives better spectral index and curvature than a point-source model

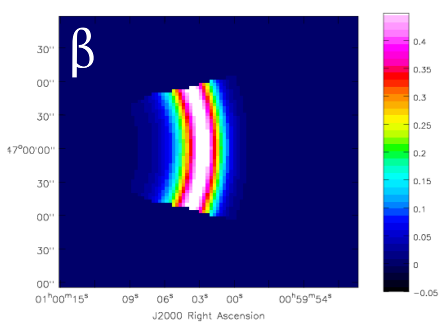
Intensity Image

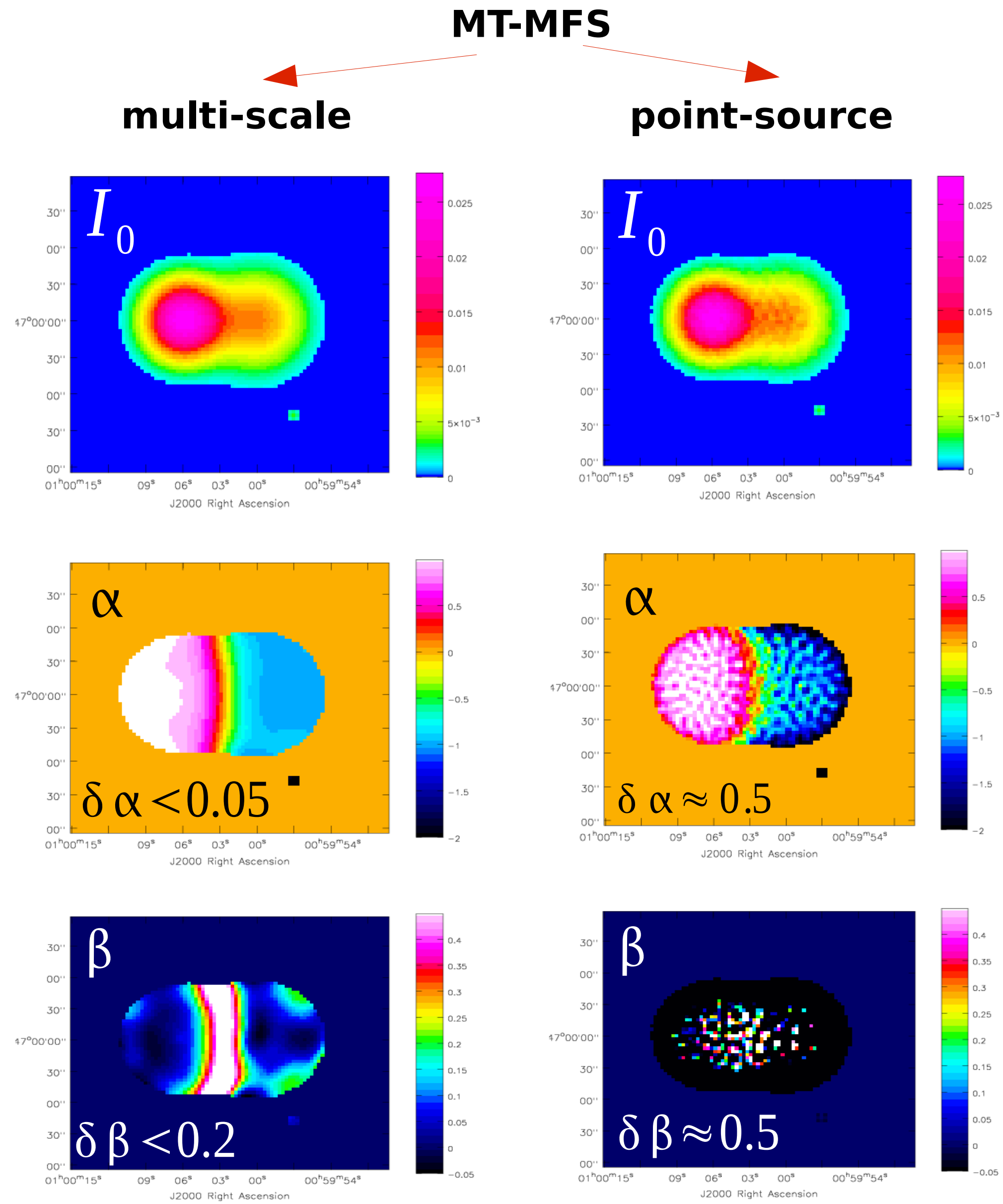


Average Spectral Index



Gradient in Spectral Index

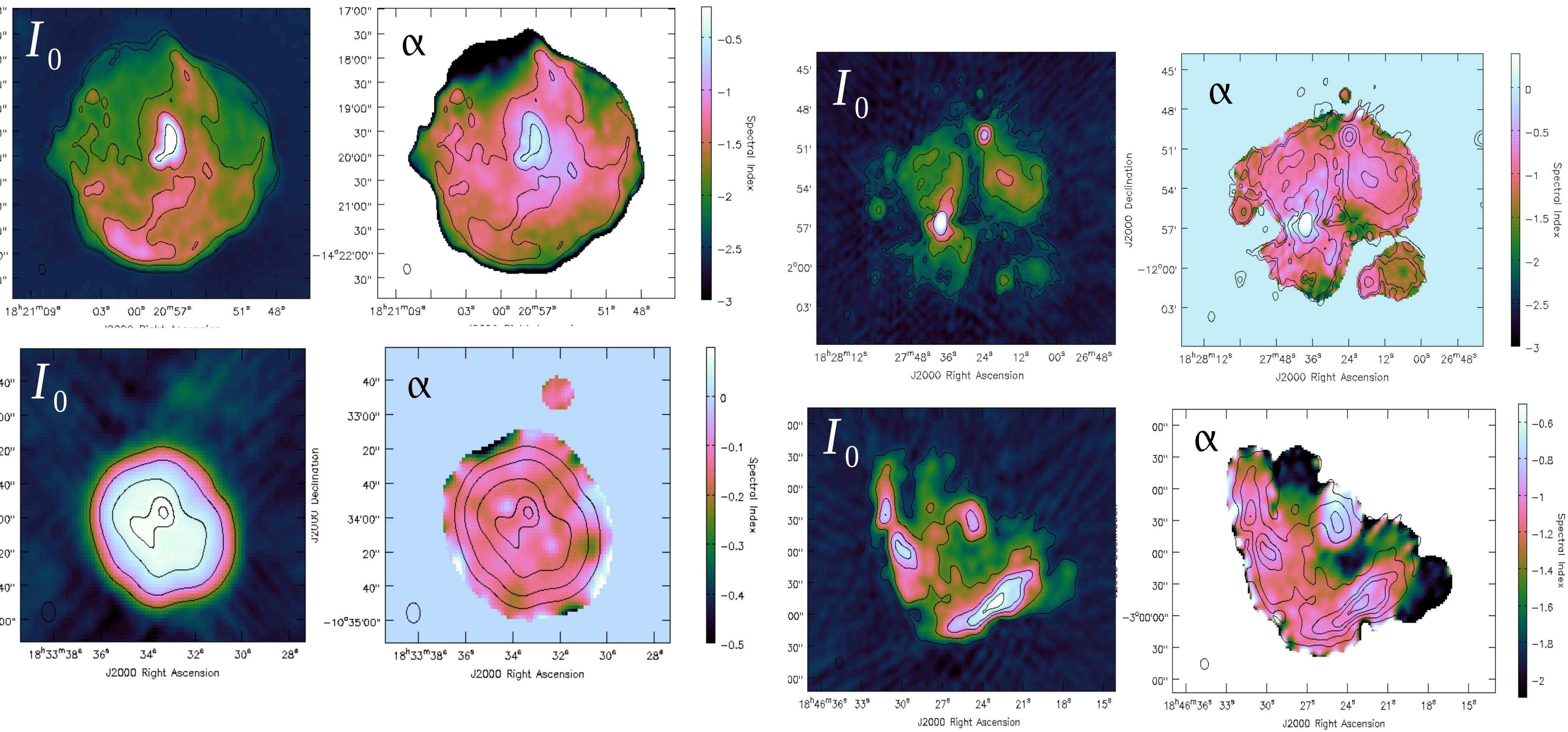




=> Spectral-index error is dominated by 'division between noisy images'

Supernova Remnants at L and C Band *[Bhatnagar et al, 2011]*

Examples of typical accuracy of spectral index maps (extended emission)



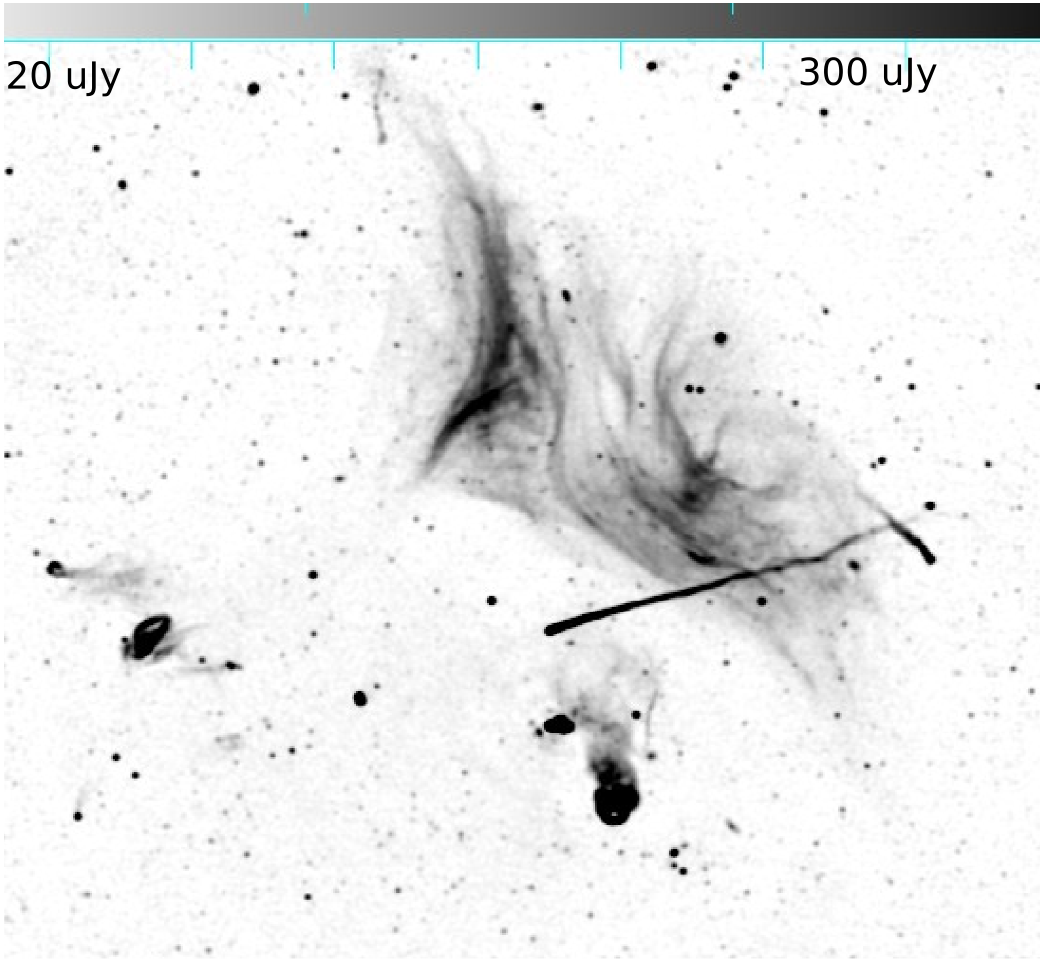
These examples used nterms=2, and about 5 scales.

=> Within 1-2 Ghz and 4-8 GHz, spectral-index error is < 0.2 for SNR>100.
=> Dynamic-range limit of few x 1000   ---> residuals are artifact-dominated

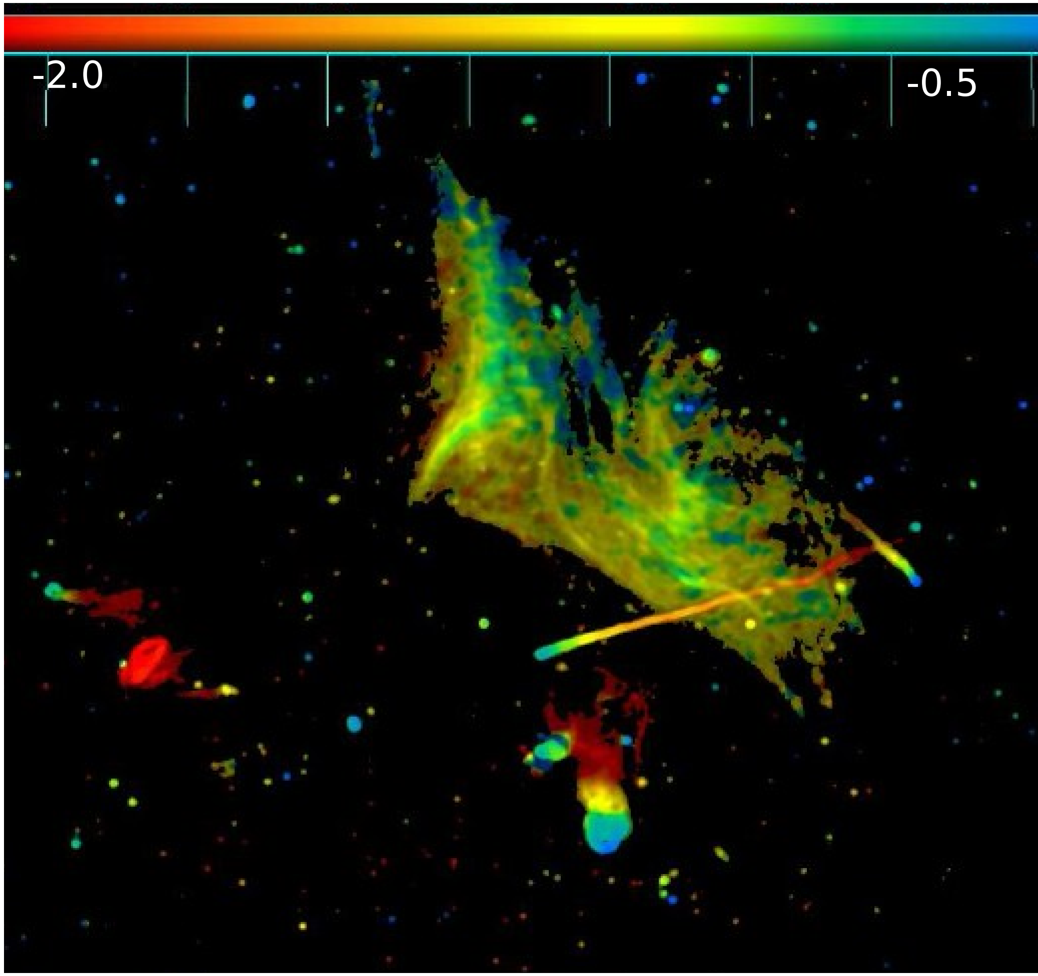
Example : Abell 2256 *[Owen et al, 2014]*

Example of high-fidelity wideband imaging (and, a pretty picture !)

Intensity



Intensity weighted Spectral Index



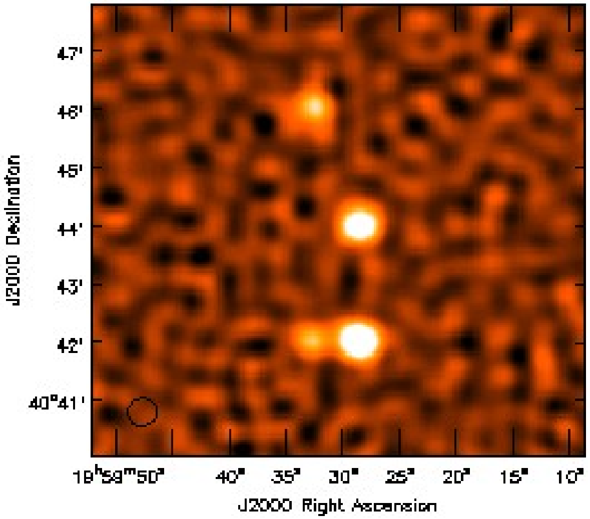
VLA A,B,C,D at L-Band (1-2 GHz) [Intensity included VLA A at S&C bands(2-4, 4-6, 6-8 GHz)]

Calibration and Auto-flagging in AIPS. Intensity/Spectral index Imaging in CASA.

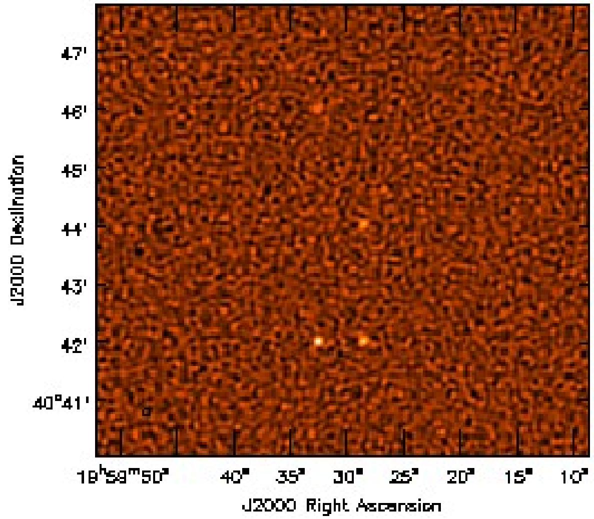
Spectral Index Accuracy (for low SNR)

Accuracy of the spectral-fit increases with larger bandwidth-ratio

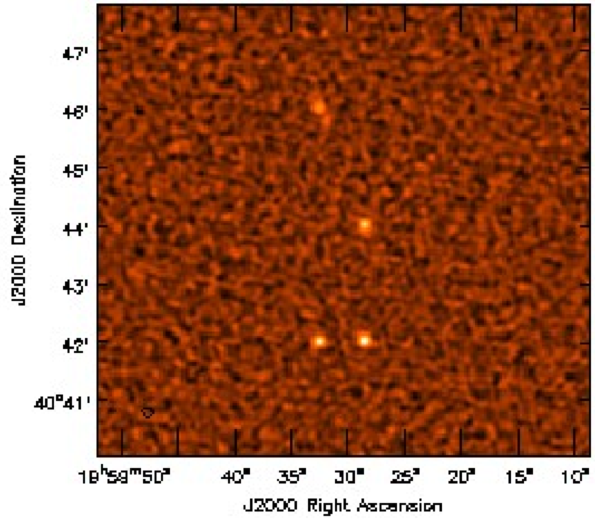
1 – 2 GHz, 4 hr



4 - 8 GHz , 4 hr



1 – 2 GHz, 4 - 8 GHz, 2 hrs each



RMS
5 uJy/bm

Source	Peak Flux	SNR	L alpha	C alpha	LC alpha	True
Bottom right	100 uJy	20	-0.89	-1.18	-0.75	-0.7
Bottom left	100 uJy	20	+0.11	+0.06	+0.34	+0.3
Mid	75 uJy	15	-0.86	-1.48	-0.75	-0.7
Top	50 uJy	10	-1.1	0	-0.82	-0.7

To trust spectral-index values, need SNR > 50 (within one band – 2:1)

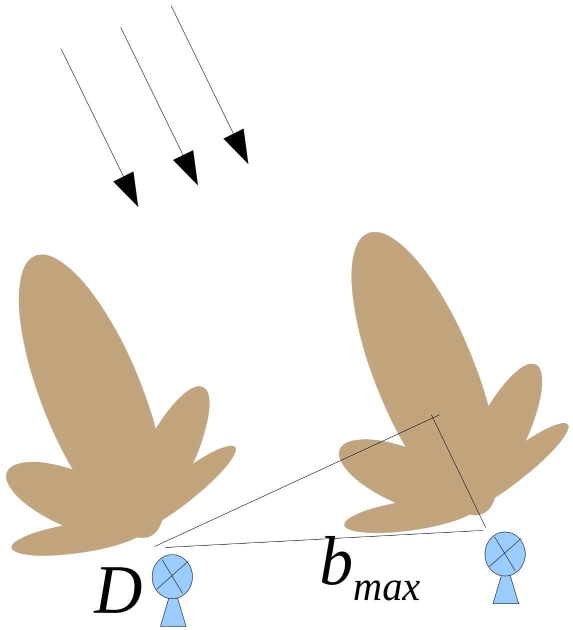
For SNR < 50 need larger bandwidth-ratio : Eg : Joint L and C band imaging

Primary Beams and Mosaics

Wide-Field Imaging – Primary Beams

The Sky is multiplied by a PB, **before** being sampled by each baseline

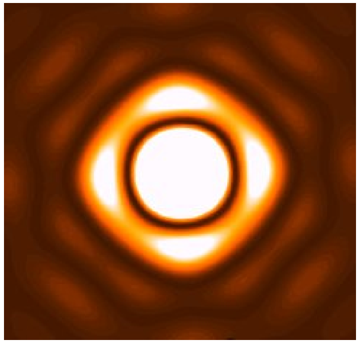
$$I^{obs}(l,m) \approx I^{PSF}(l,m) * \left[P^{sky}(l,m)\cdot I^{sky}(l,m)\right]$$



The antenna field of view :
D = antenna diameter

$$\lambda / D$$

Primary Beam



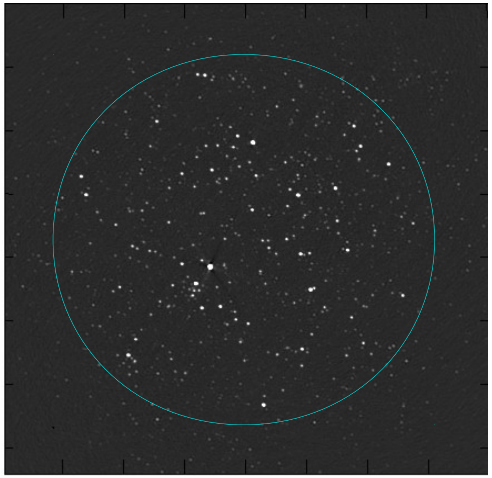
VLA HPBW :

L-Band : 40 – 20 arcmin

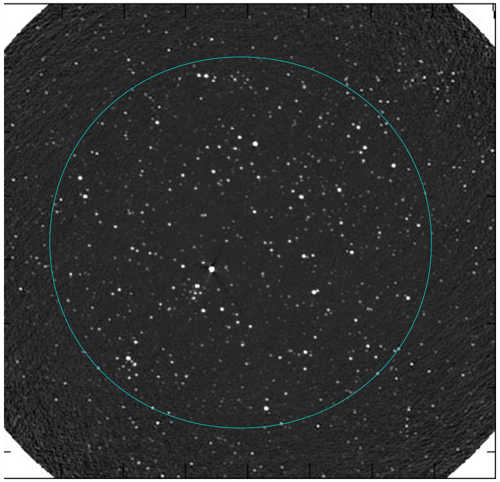
C-Band : 10 – 5 arcmin

CHANG-ES Galaxies :

~ “few” arcmin



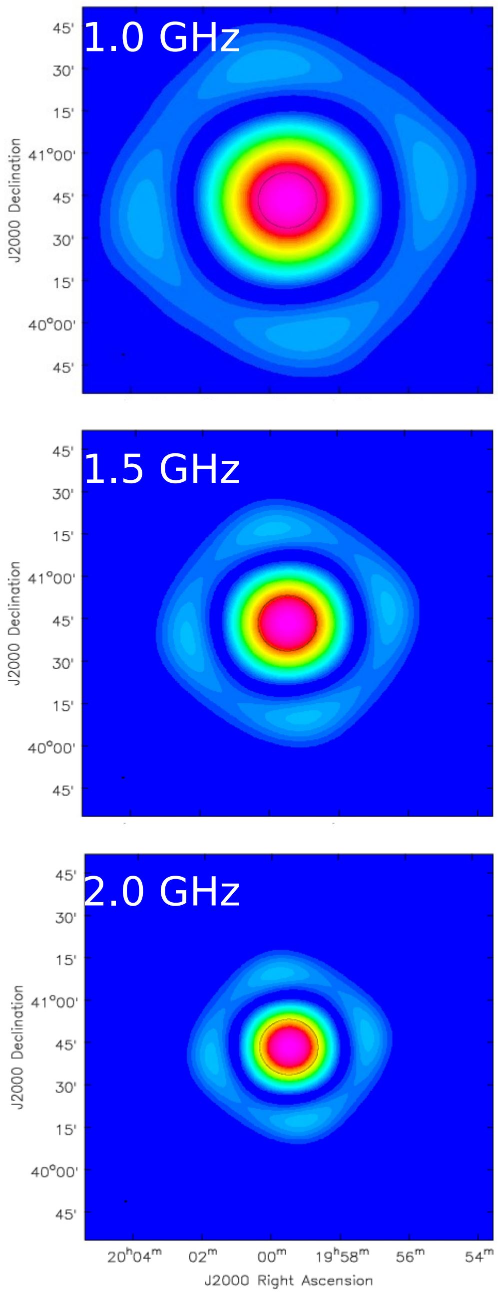
Output Image = Sky x PB



PB-corrected Image : Sky

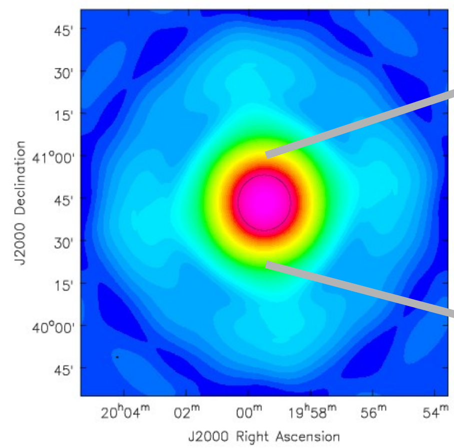
Wide-Band Primary Beams

VLA PBs



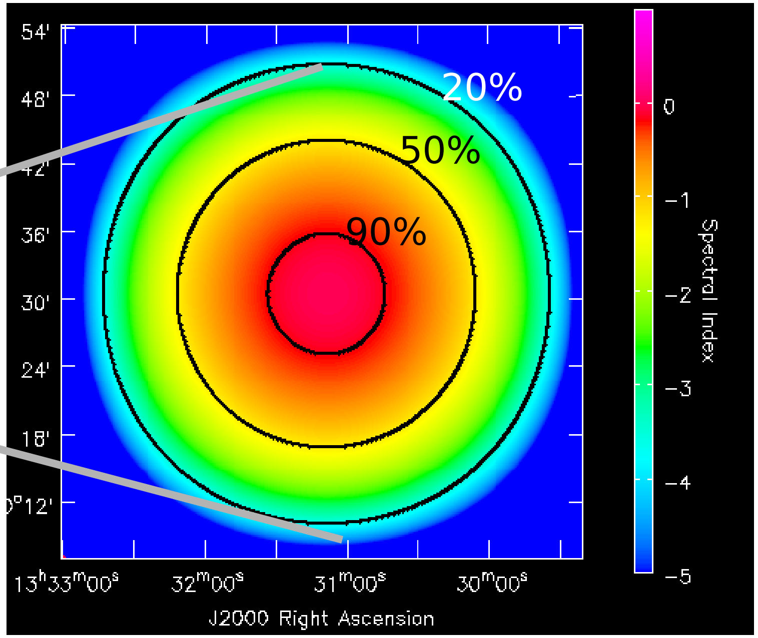
Primary beam scales (or changes) with frequency

Average Primary Beam



A very wide shelf of sensitivity outside the main lobe

Spectral Index of PB (2:1 BWR)



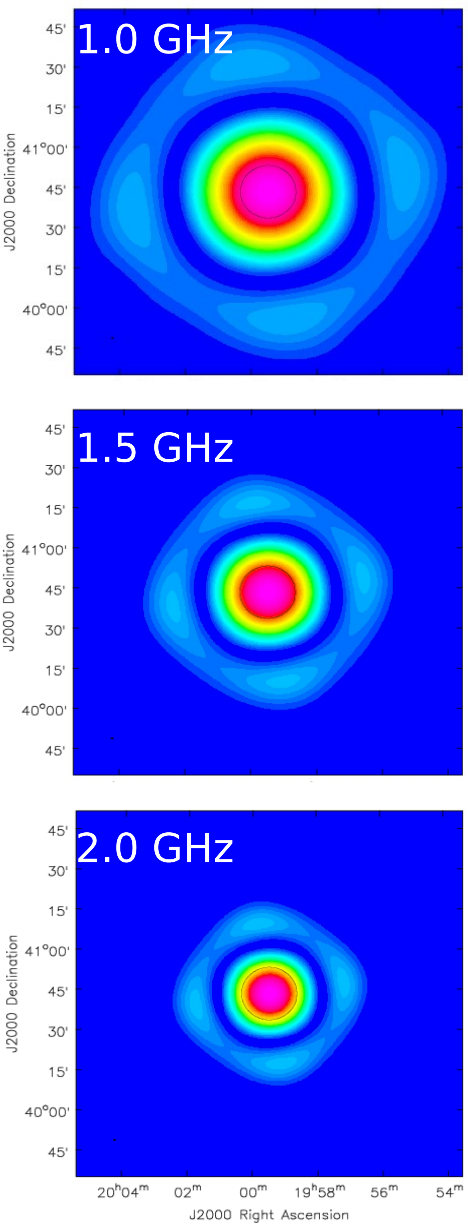
- About -0.4 at the PB=0.8

L : ~ 6 arcmin from the center
C : ~ 2 arcmin from the center

- About -1.4 at the HPBW

L : ~ 15 arcmin from the center
C : ~ 4 arcmin from the center

Wide-Band Primary Beam Correction



Cube Imaging

-- Sky model represents $I(\nu) P(\nu)$
-- Divide the output image at each frequency by $P(\nu)$

Multi-Term MFS + Wideband-PBcor

-- Taylor coefficients represent $I(\nu) P(\nu)$

-- Polynomial division
by PB Taylor coefficients $$\frac{(I^m_{0,} I^m_{1,} I^m_{2,} \dots)}{(P_{0,} P_{1,} P_{2,} \dots)} = (I^{sky}_{0,} I^{sky}_{1,} I^{sky}_{2} \dots)$$

Wideband A-Projection

-- Remove $P(\nu)$ before the wideband deconvolution step and replace it by a frequency-independent PB model

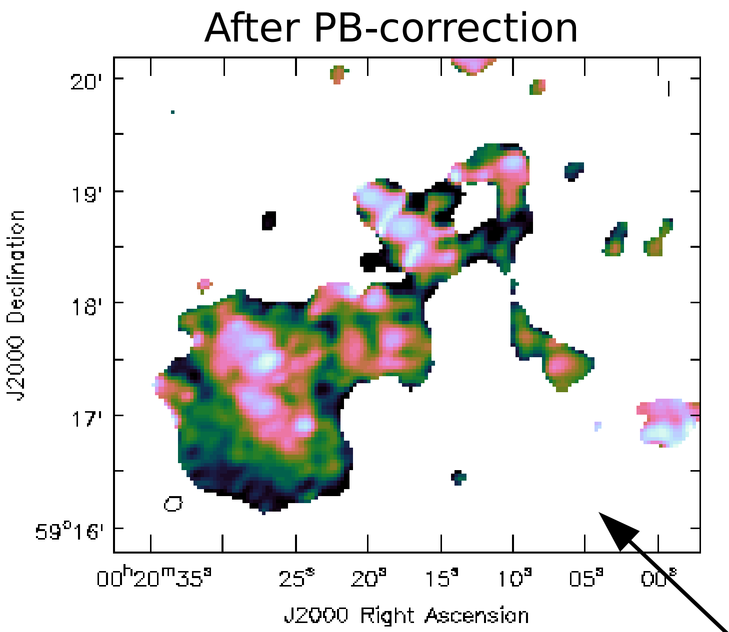
– Option 1 : As part of the gridding convolution function
– Option 2 : Operate on the image cube before/after deconvolution

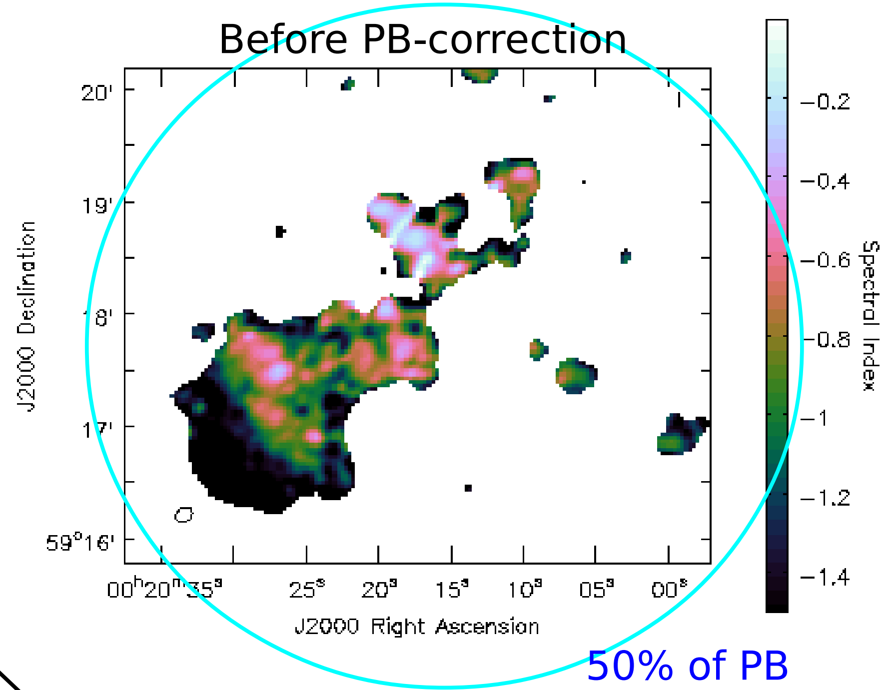
-- Output spectral index image represents only the sky

Bhatnagar et al, 2013

Wideband VLA imaging of IC10 Dwarf Galaxy

[Heesen et al, 2011]

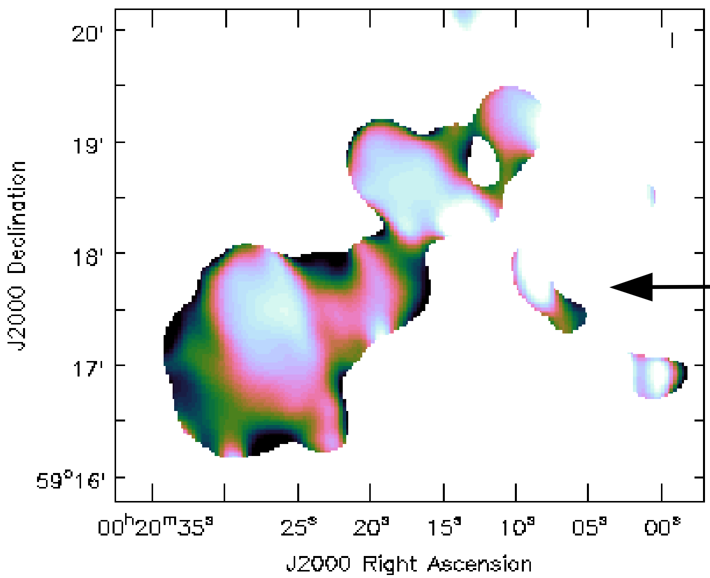




IC10 Dwarf Galaxy :

Spectral Index across C-Band.

Dynamic-range ~ 2000

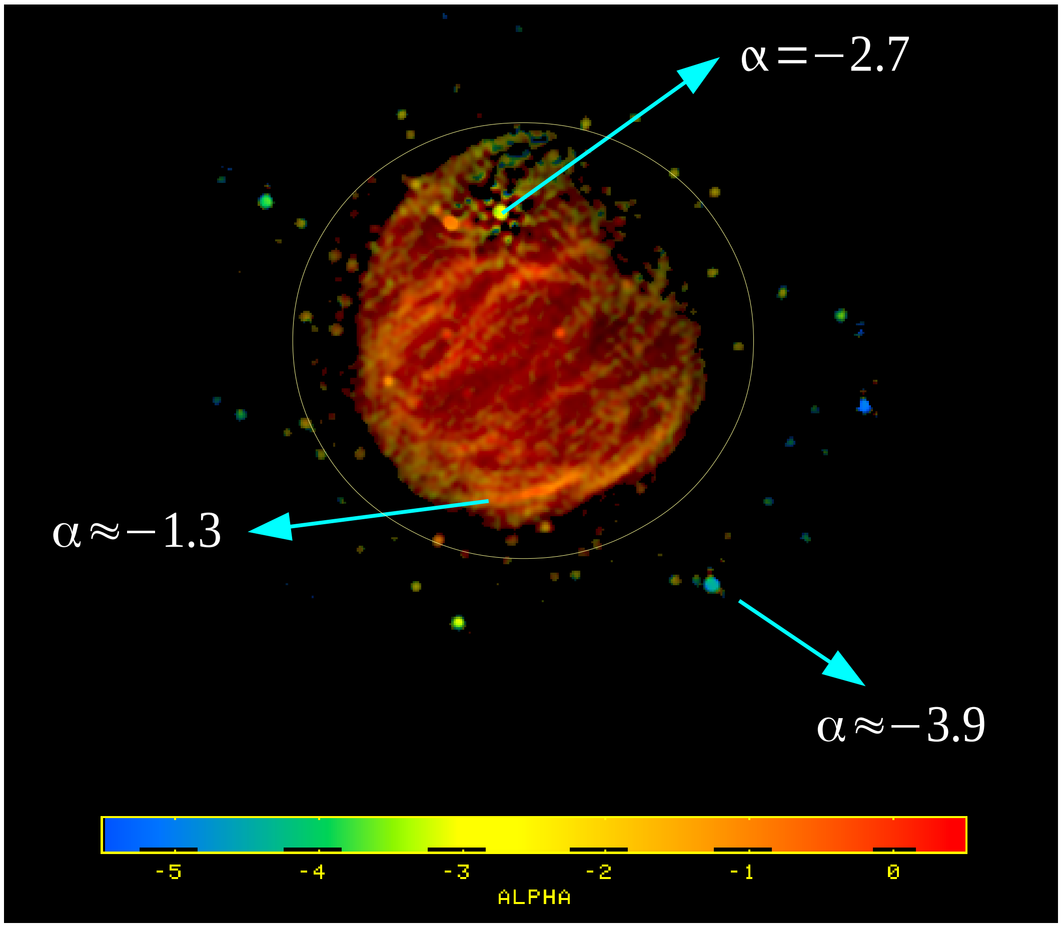


MT-MFS : Wide-band PB-correction after multi-term multi-scale MFS.

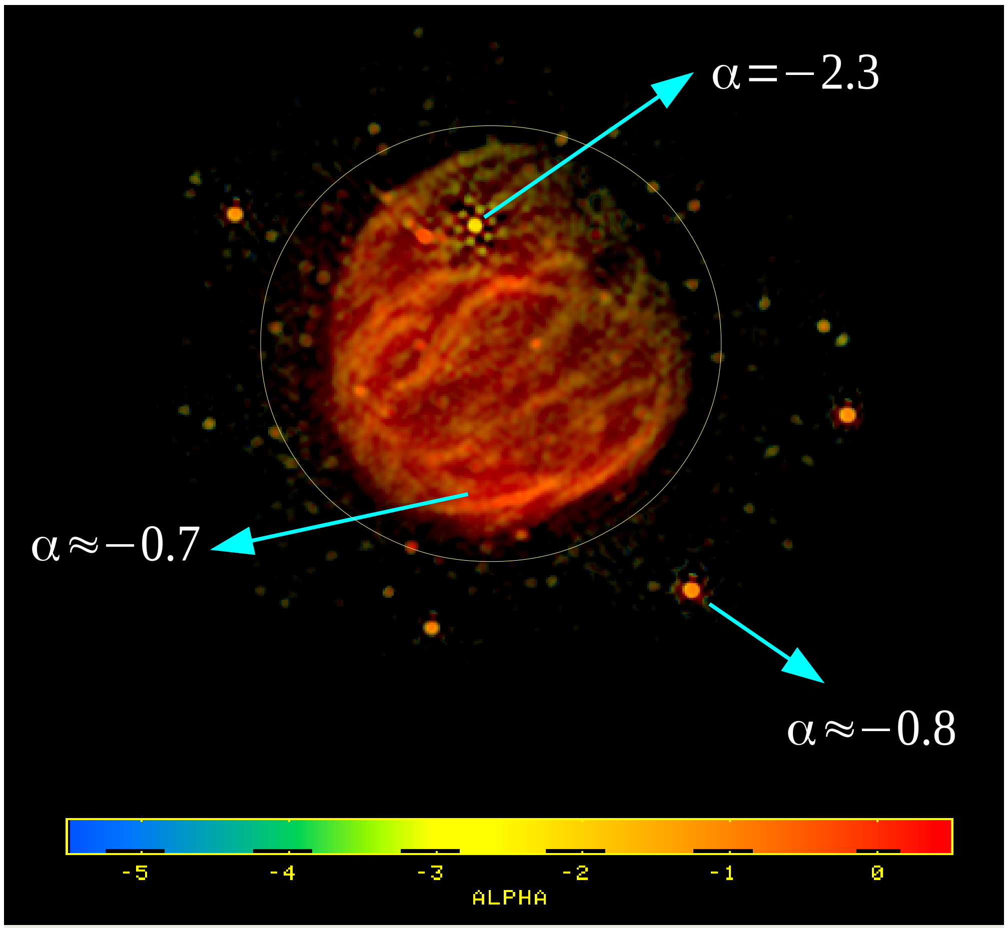
Cube : Spectral-index map made by cube imaging, smoothing to lowest resolution, and spectral fitting.

Spectral Indices before and after WB-A-Projection

Without PB correction
Outer sources are artificially steep



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



Intensity-weighted spectral index maps (color = spectral index from -5.0 to +0.2)

Full Polarization Primary Beams

Full Stokes primary beams :

Shows the magnitude of direction dependent polarization leakage

Colors : Log Scale

PB peak = 1.0

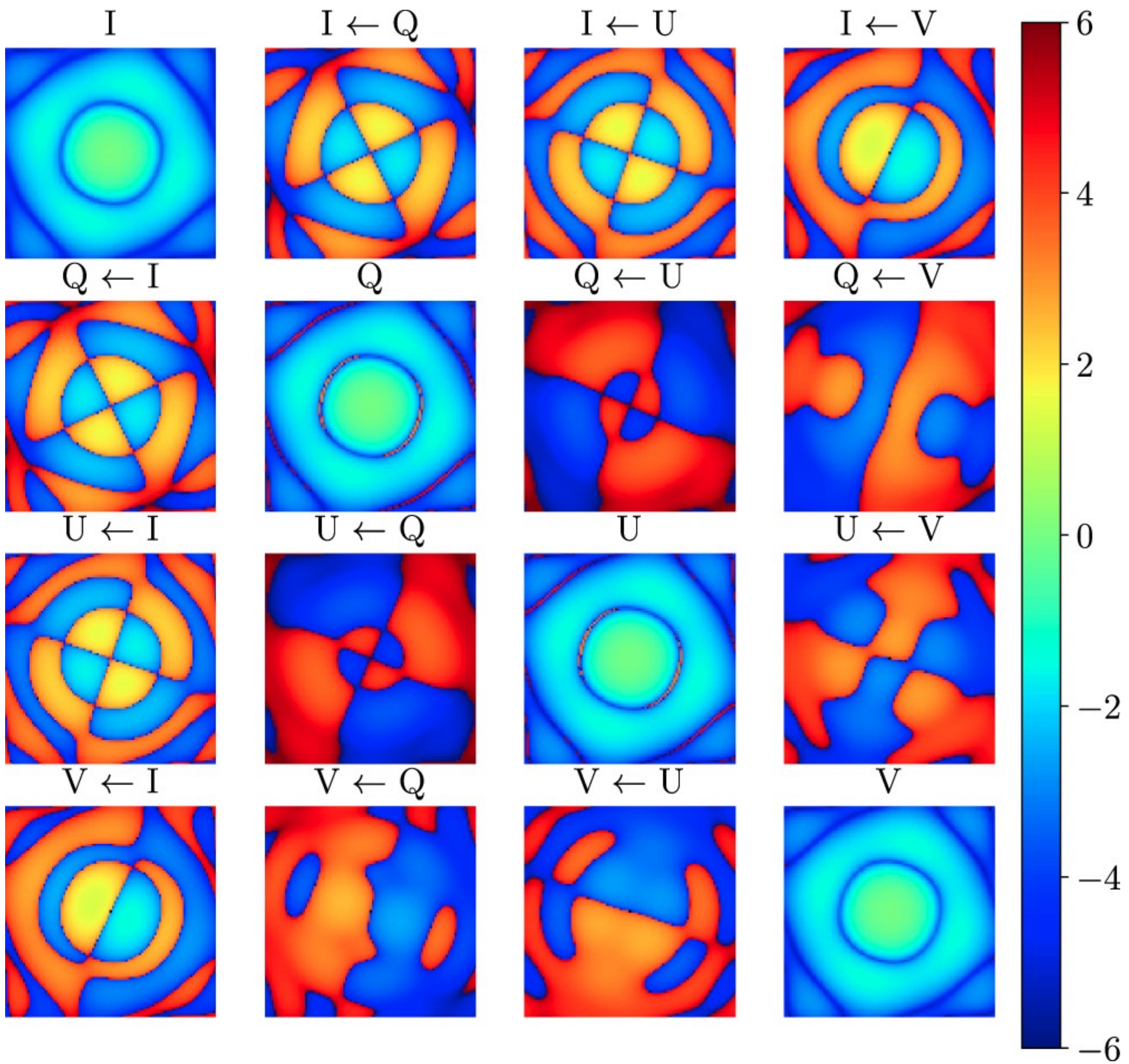
Leakage : I → Q or I → U

Max : 3% of Stokes I at the 0.3 PB level.

- Compare with sky Stokes Q,U signal w.r.to Stokes I

- These patterns also scale with frequency

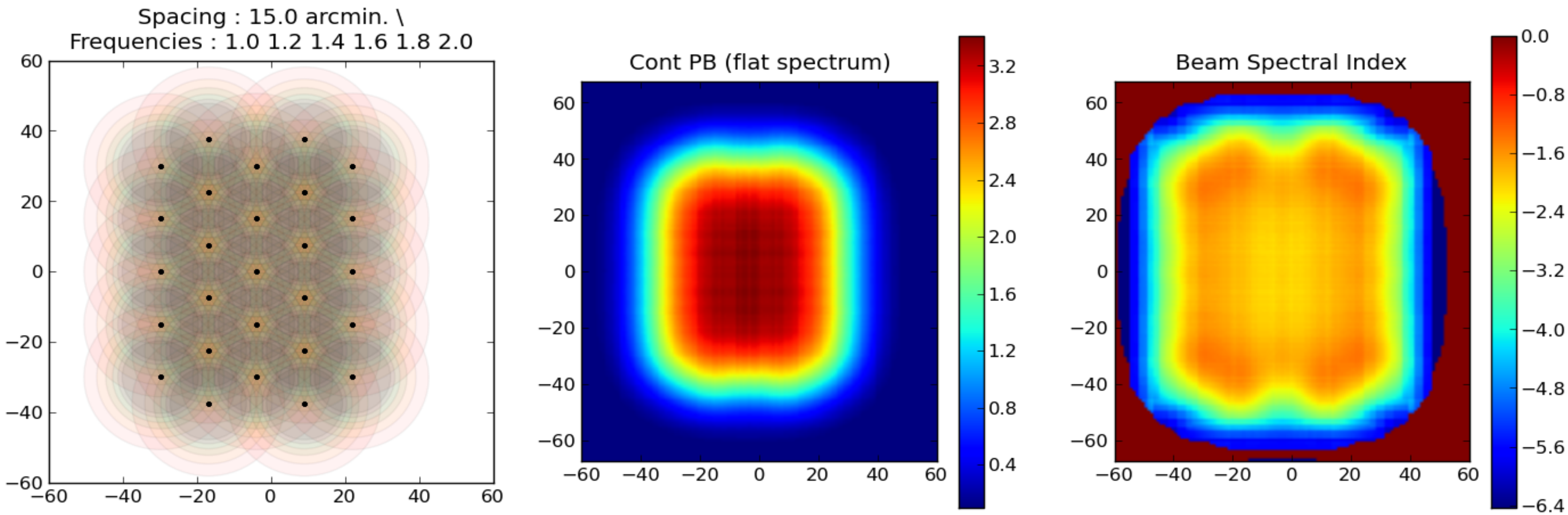
=> Effective PB 'RM'
(in prep, ARDG)



Jagannathan et al, 2017

Mosaic Primary Beam (wideband, full-pol)

The mosaic primary beam has an artificial spectral index all over the mosaic field-of-view.



..... a similar effect for polarization leakage

Algorithms :

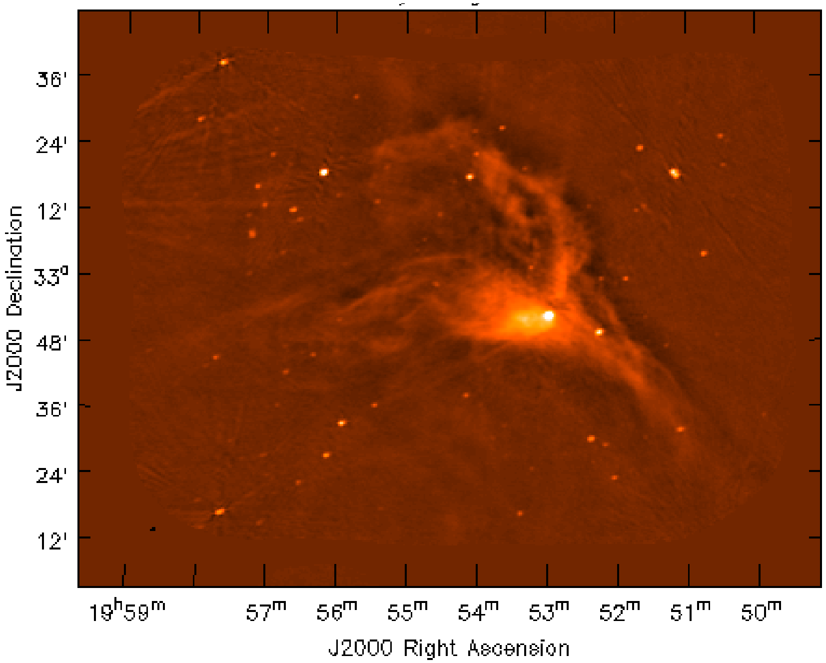
- Deconvolve Pointings separately or together (Stitched vs Joint Mosaic)
    - Impacts image fidelity, especially of common sources.

- Deconvolve Channels separately or together (Cube vs MFS)
    - Impacts imaging fidelity and sensitivity, dynamic range

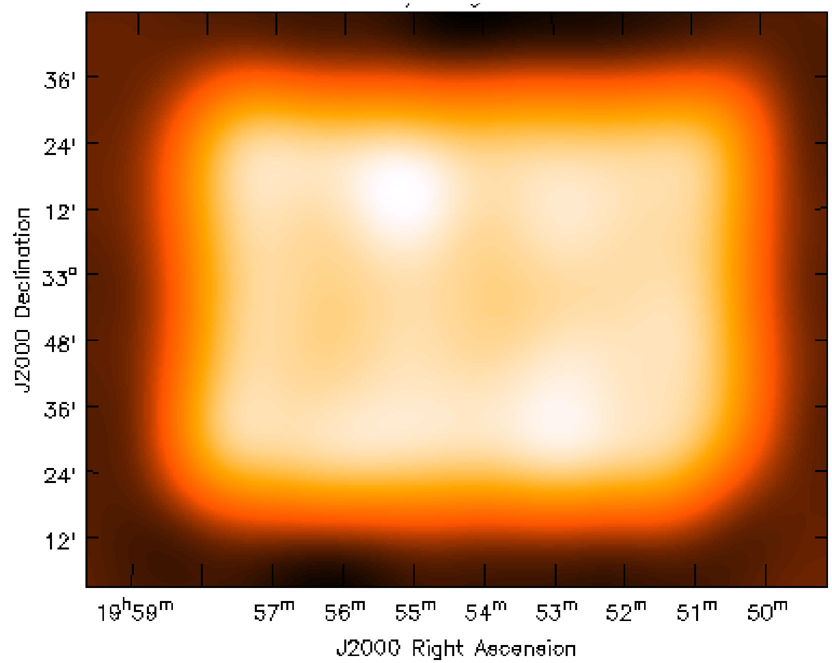
- Use A-Projection or not (Accurate vs Approximate PB correction)
    - Impacts dynamic range, spectral index accuracy, polarization leakage effects

Wideband Mosaic of CTB80 (1-2 GHz, VLA-D config)

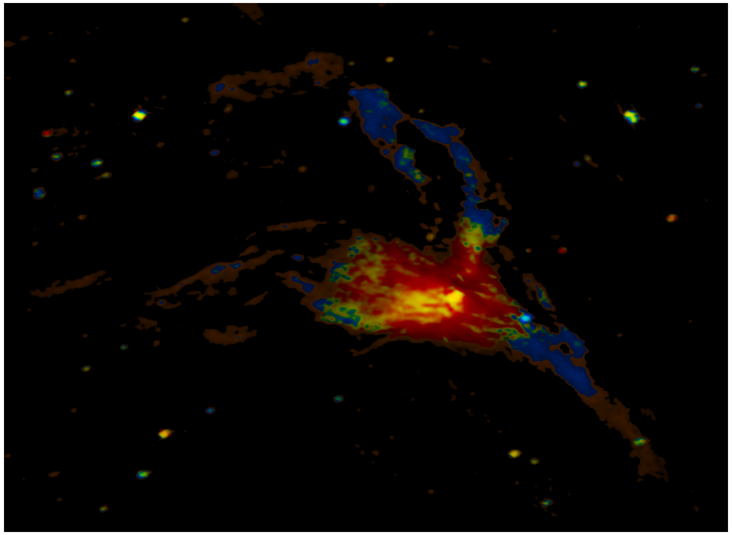
Intensity



Mosaic Primary Beam



Intensity-weighted Spectral Index



300GB calibrated dataset,
106 pointings over 1.5x2 deg,
Imaged with MS-MT-MFS (NT=2) + WB-A-Projection.

=> Mosaic primary beam spectral index of ~ -1.5 has been removed prior to wideband sky model fitting (deconvolution)

(Full-pol mosaics : Algorithm R&D in progress…)

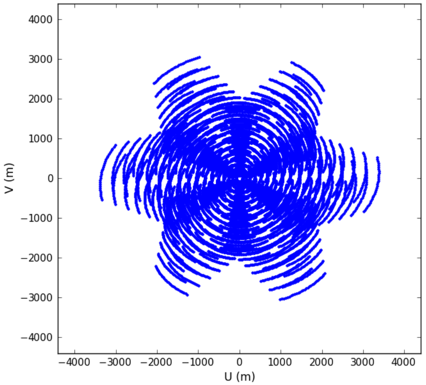
Single Dish + Interferometer

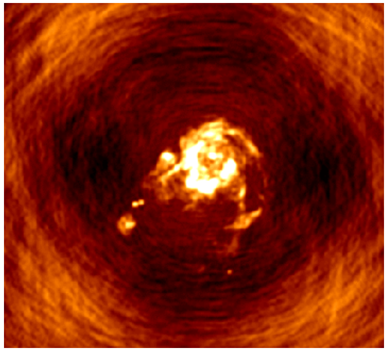
Single Dish data to fill missing short spacings

Interferometer

Observed Image = (Sky . PB) * PSF

Sampling is incomplete and short spacings are not measured at all

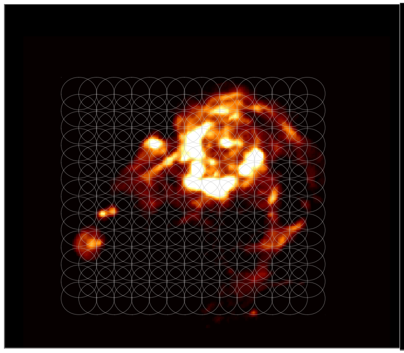


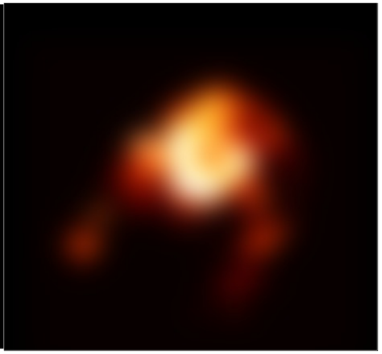


Single dish

Observed Image = Sky * SDbeam

All spatial frequencies lower than the dish size (in wavelengths) are measured.





Algorithms to combine SD and INT data

- Feathering : Single step combination of output SD and INT images

- StartModel : Supply SD image as a startmodel for the INT reconstruction

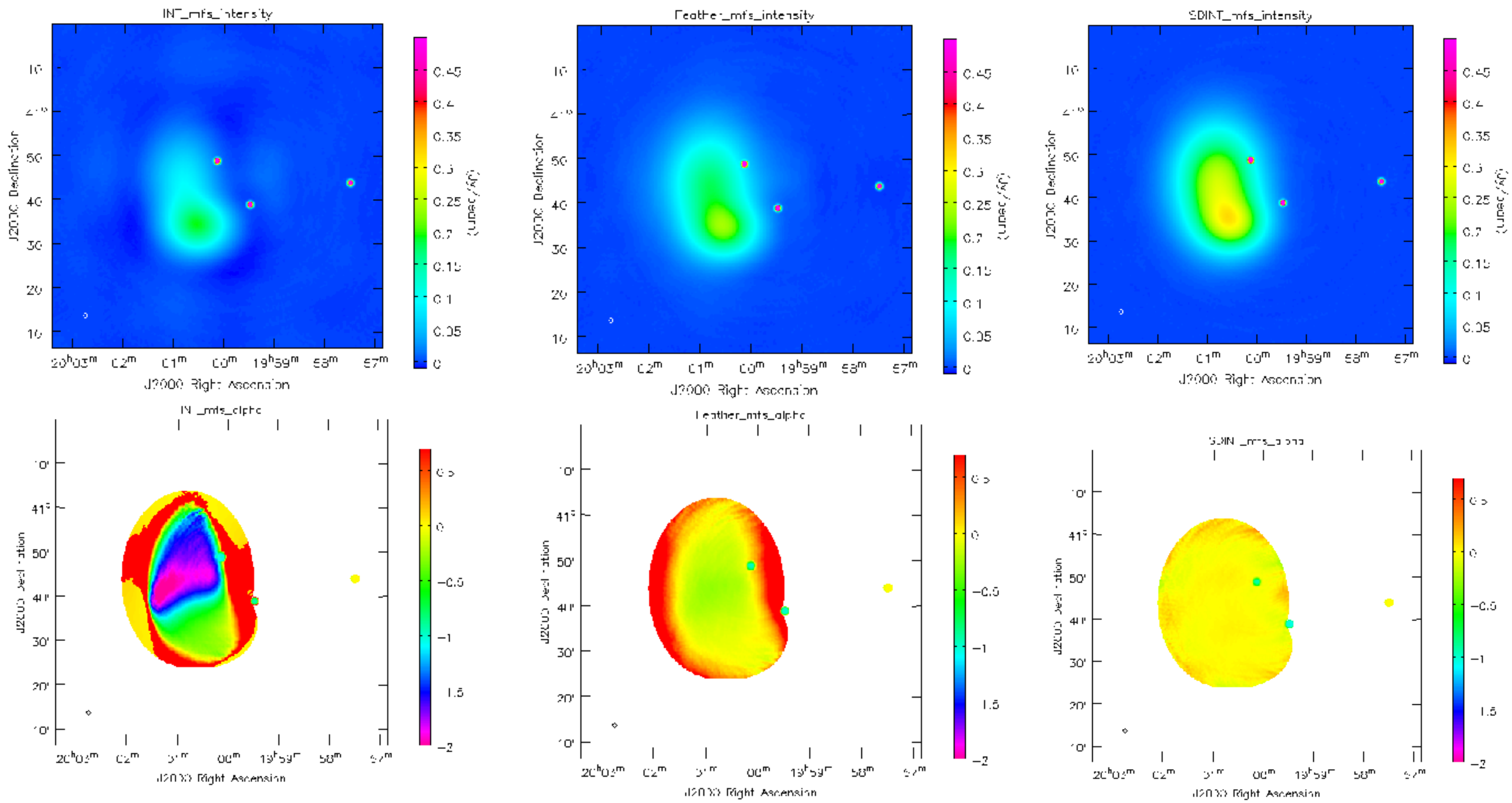
- Joint Reconstruction : Solve for a single sky model using constraints from both datasets

Wideband SD+INT : Multi-term MFS

INT only | Feather | SDINT

Intensity

Spectral Index



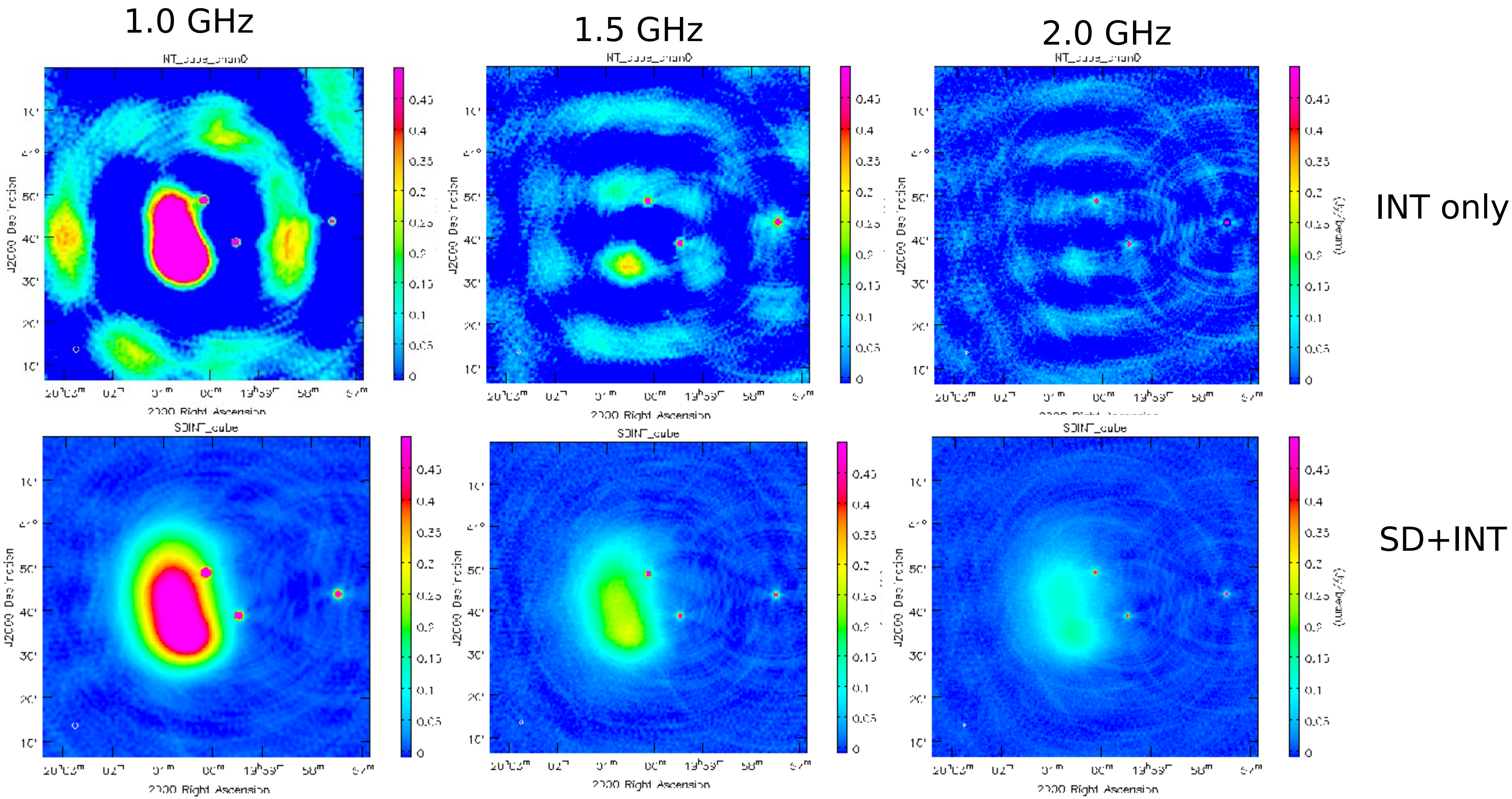
Example : Flat spectrum emission at large scales + flat/steep spectrum point sources

In this case, INT-only errors cannot be fixed in a single feather step.

Requires a joint reconstruction.

Rau, Naik, & Braun, 2019

Wideband SD+INT : Cube Imaging



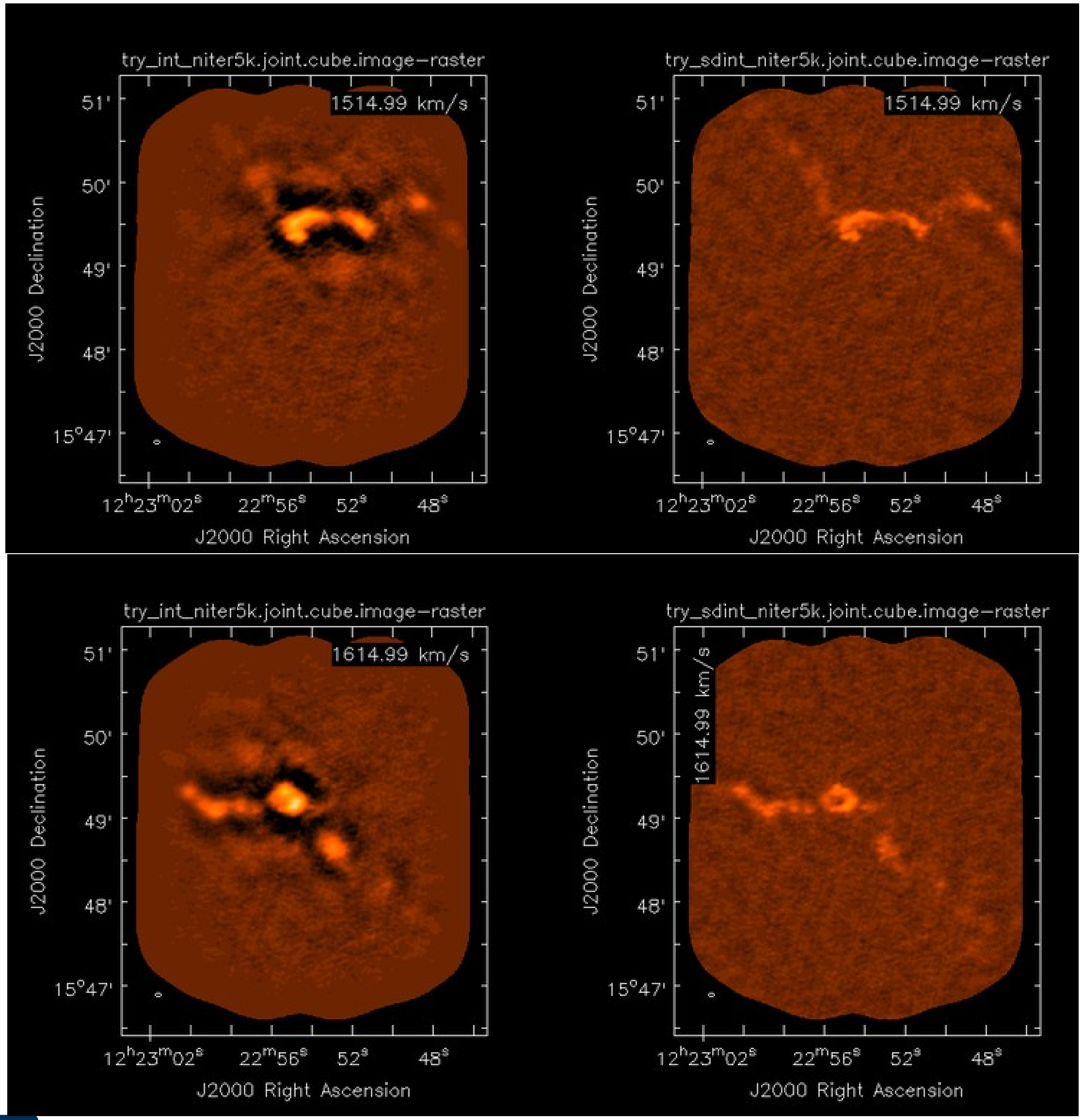
Images shown at native angular resolution.

Negative bowls and missing flux in INT-only cubes have been filled.

ALMA M100 CO 12m + 7m + TP : SDINT Imaging

INT only

SD+INT



Two channels of the cube

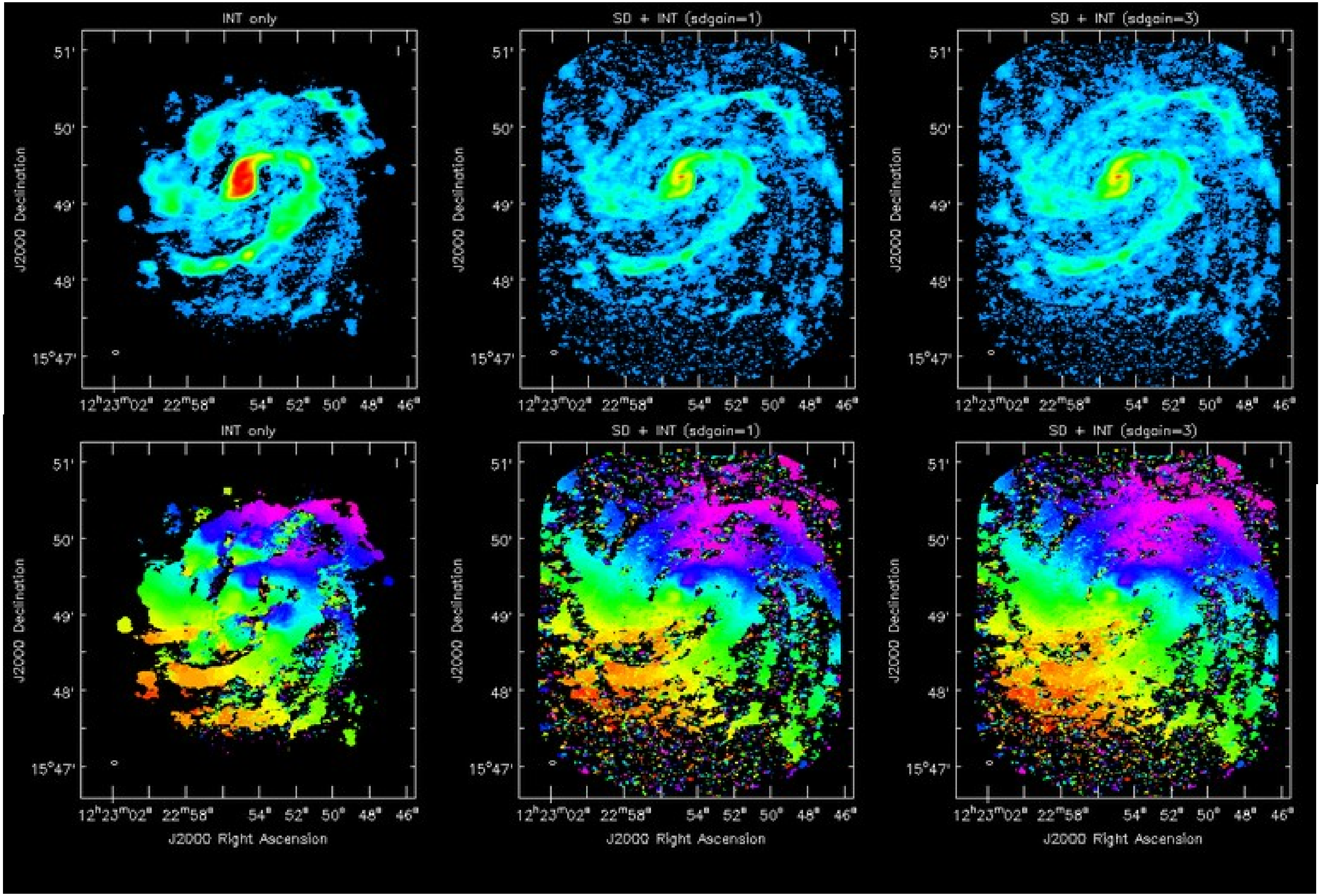
Joint Mosaic, with primary-beam correction built into the algorithm implementation.

ALMA M100 CO 12m + 7m + TP : SDINT Imaging

INT only | SDINT (sdgain=1) | SDINT (sdgain=3)

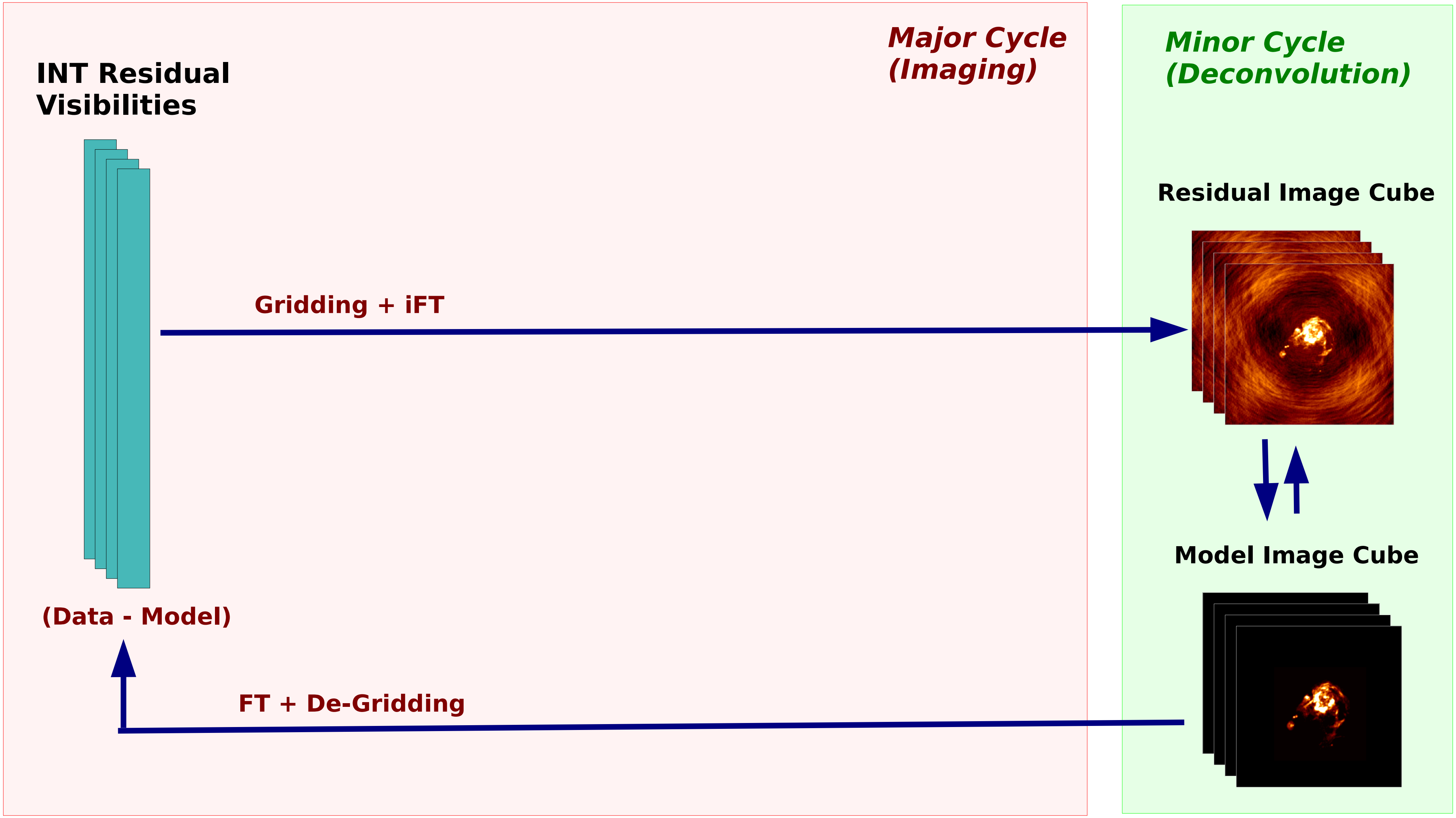
Moment 0

Moment 1

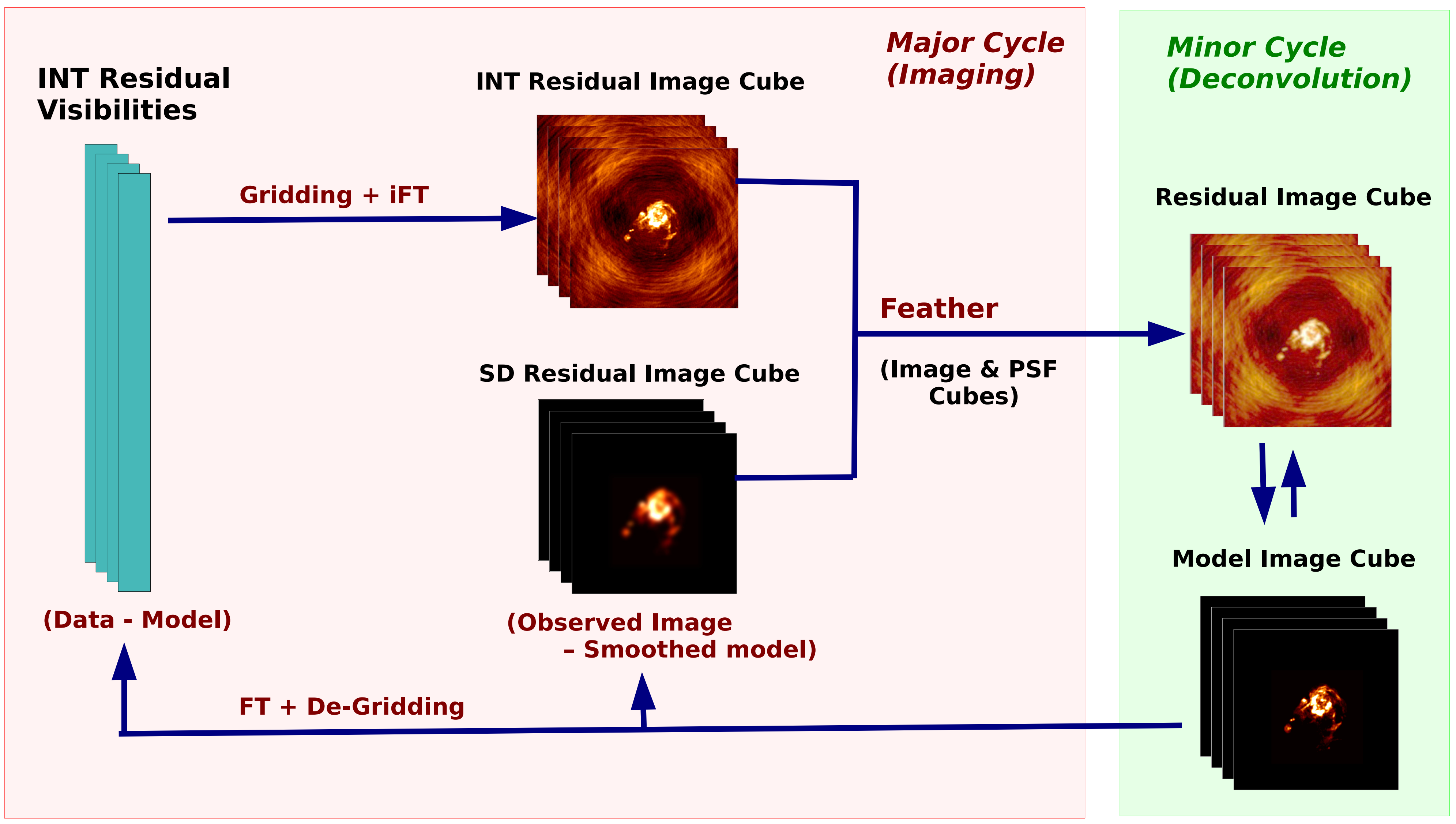


Imaging Algorithm Framework

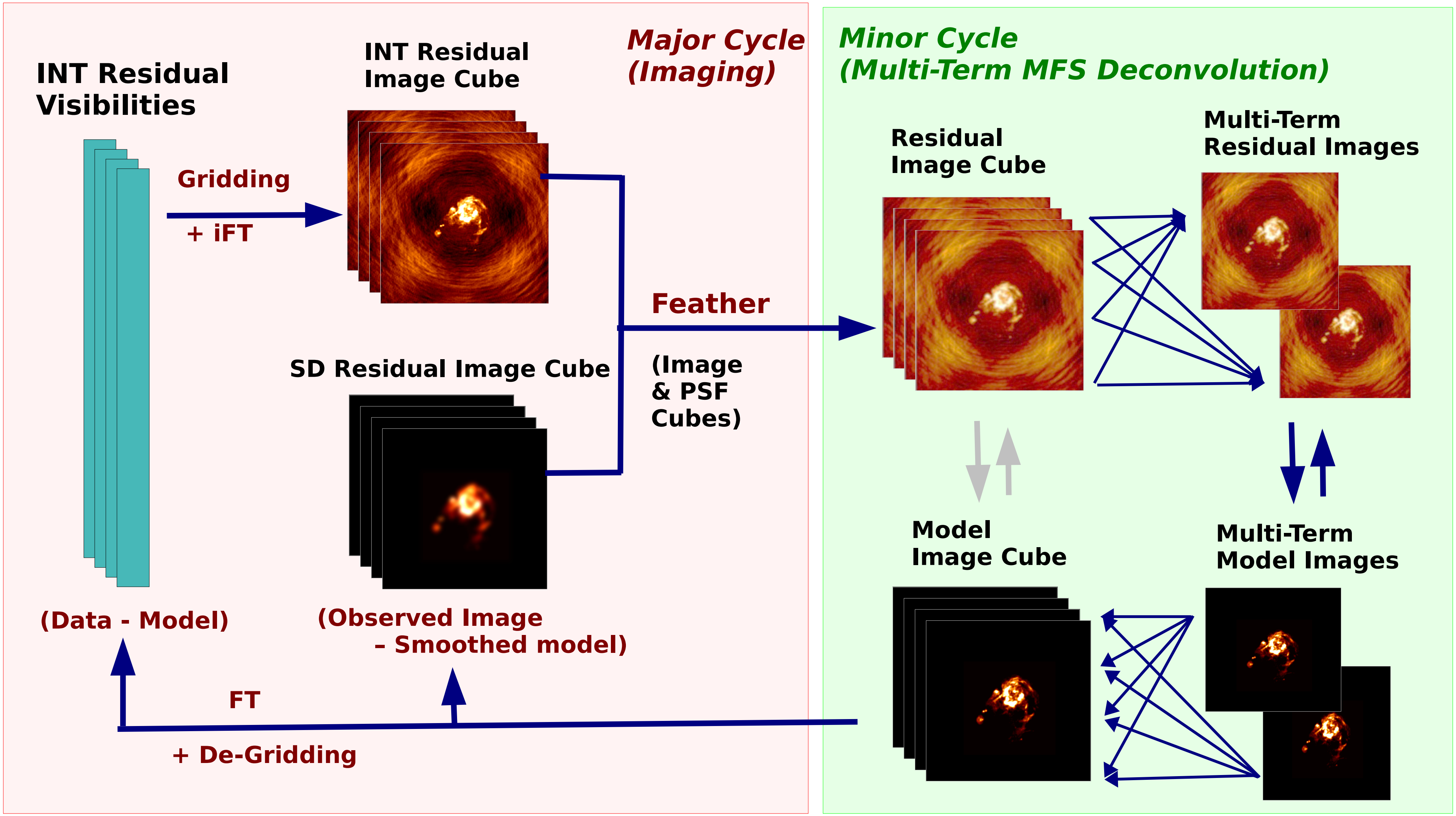
Spectral Line (Cube) Imaging : INT only



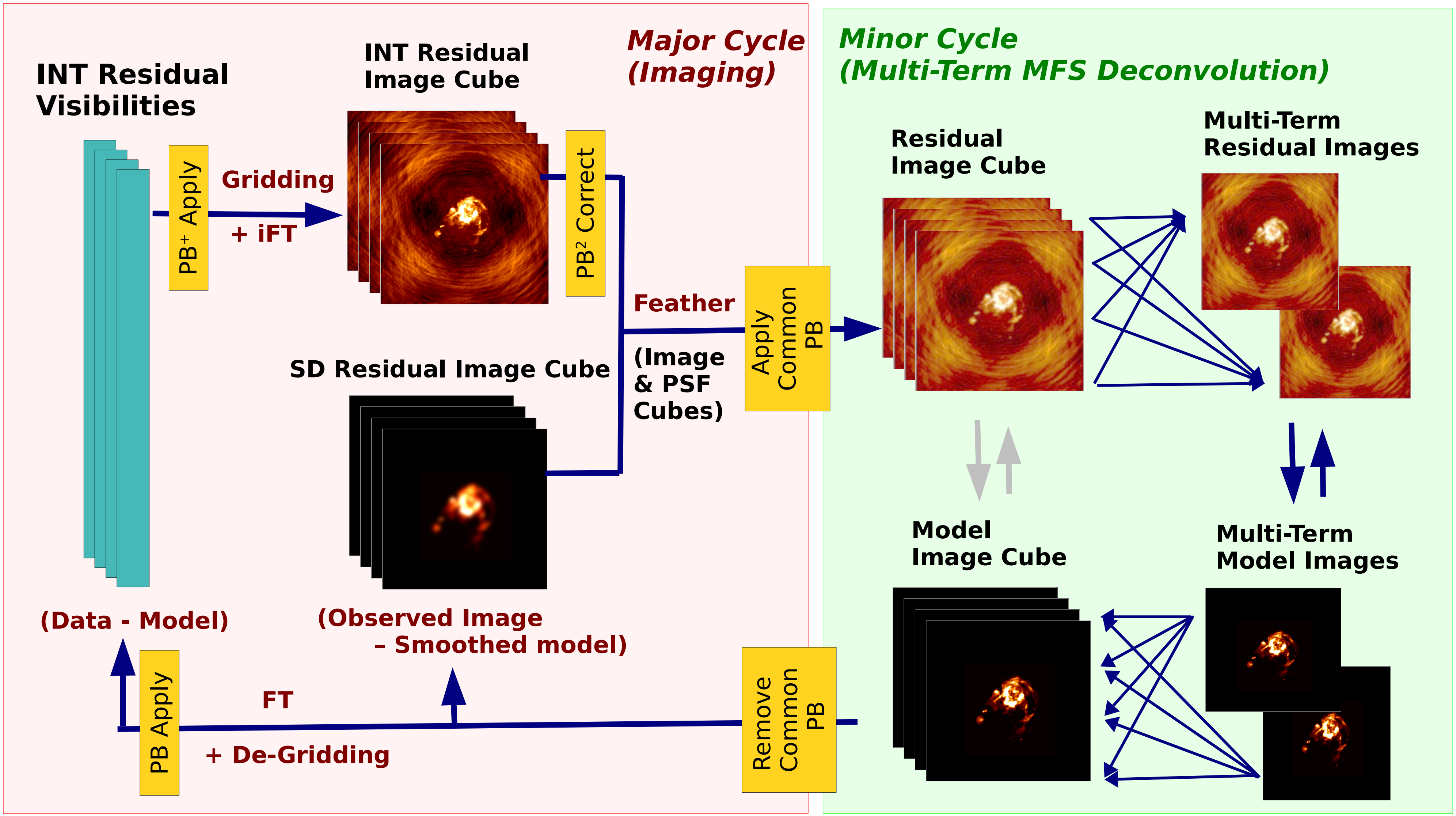
Spectral Line (Cube) Imaging : Joint INT + SD



Wideband Multi-Term Imaging : Joint INT + SD



Wideband Multi-Term Imaging : Joint INT + SD with PBs



"sdintimaging" : Experimental Task in CASA 6.1/5.7

Summary

CHANG-ES Imaging Goals :

– Intensity, Spectral and Polarization structure of Galaxy Halos.

– Extended low-brightness emission. Moderate dynamic range.

In the past few years, algorithms have become available for

– Joint Wideband Mosaics : Intensity + Spectral Index with Wideband PBCor

– Joint Single Dish and Interferometer Reconstructions

Work in progress (NRAO Algorithm R&D group + CASA)

– Full-Mueller PB corrections, Adaptive Multi-scale deconvolution, RM-Synthesis

– All algorithms to be integrated into a single imaging framework.

Question : Are these ideas useful for CHANG-ES ? What is missing ?

- Demonstration of full-pol SD+INT combination
- Ability to jointly image L,S,C band with Primary Beams
- Integrated 3D Clean for RM-synthesis (useful or not?)