How the CASA Imager currently uses the parallelization infrastructure

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Goal : Document and convey to the HPC group the top-level parallelization strategy of CASA Imager

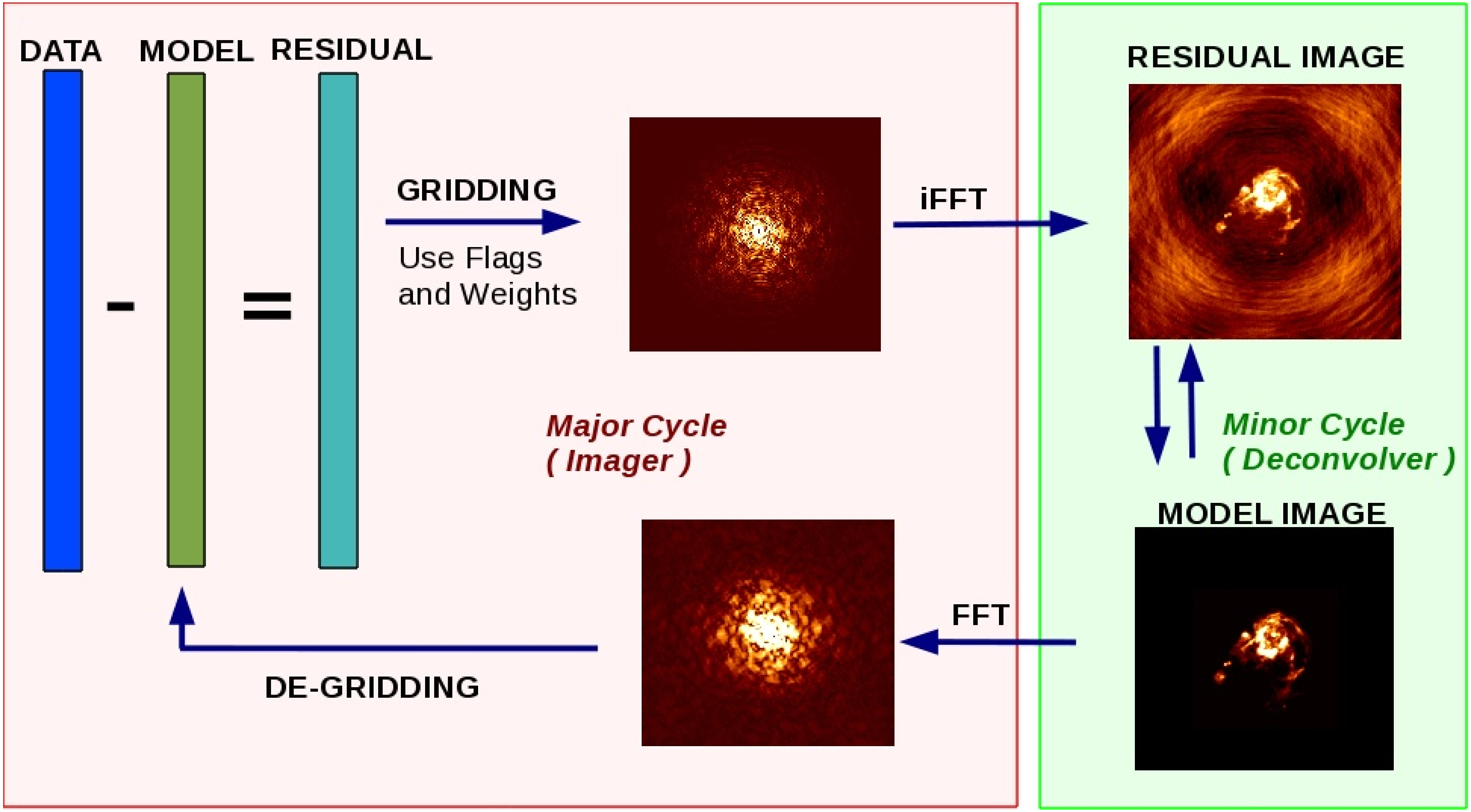
(1) Imaging Basics
- major and minor cycles
- block level code design, inputs/outputs
- functional steps in making an image from visibilities

(2) Main modes : Continuum and Cube
- data to image mapping
- data partitioning for parallelization
- functional steps in a parallel imaging run (messages, scatter/gather)

(3) Algorithmic options to support
- gridding, deconvolution, widefield, stokes, spectral
- relative computing and I/O costs, usage percentage, role of multithreading

(4) Commissioning Tests
- Continuum : wideband multi-scale multi-term joint mosaic with wb-awp
- Cube : TBD

Imaging Process – Iterative χ^2 minimization



Functional Blocks

Basic Functional Unit : 1 Image field, N Frequency planes, M Stokes planes

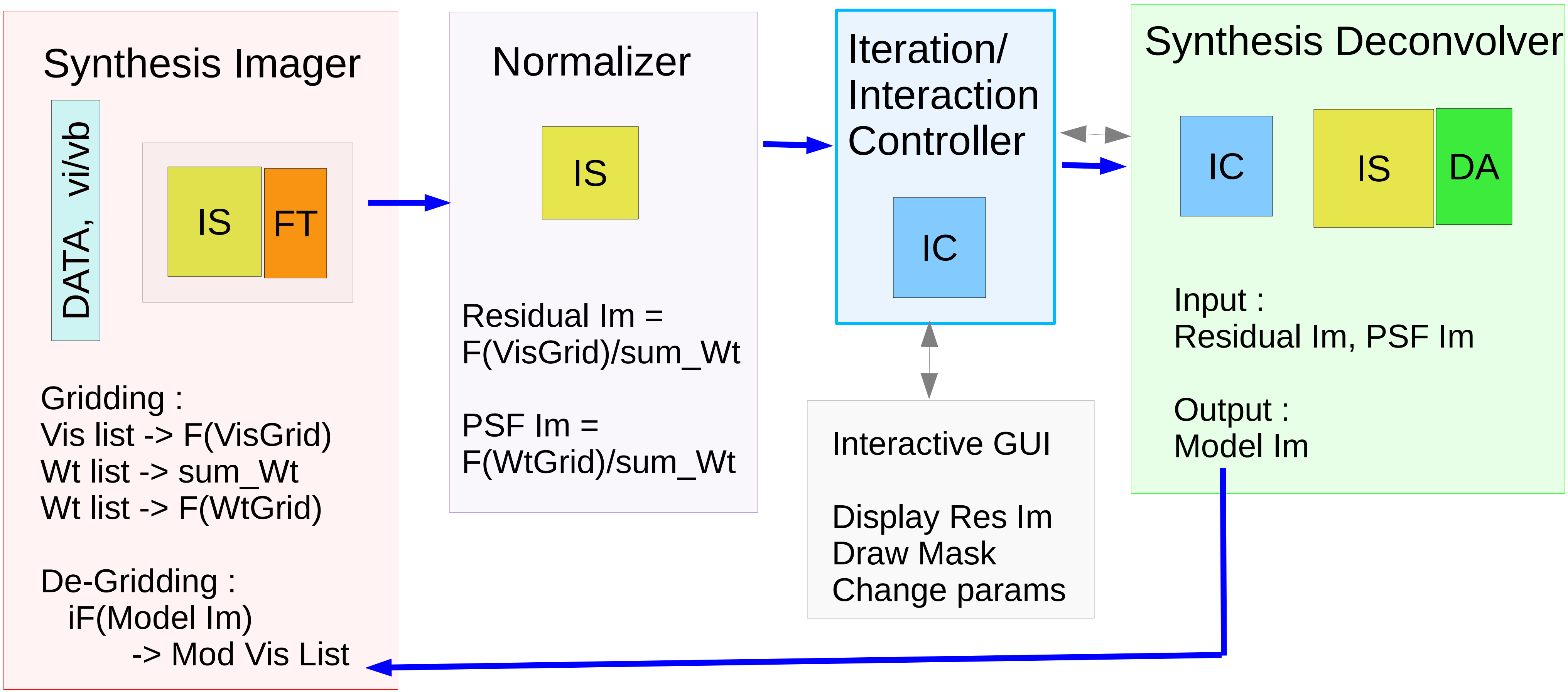
IS — Image Store : Residual, PSF, Model, Weight, Restored, Mask

FT — FTMachine : Gridding / de-Gridding + Convolution Functions

DA — Deconvolver Algorithm : Iteratively reconstruct the sky model

IC — Iteration Controller : Check stopping criterion between Major and Minor cycles + user-interaction

Application Layer



Major Cycle : Read DATA or CORRECTED_DATA from MS on disk
(for each vb) Calculate MODEL_DATA by de-gridding model image
Calculate RESIDUAL=DATA - MODEL and accumulate on grid.

Only last Major Cycle writes MODEL_DATA to MS (if requested)
-- Save FT state as Record inside SOURCE subtable (otf model)
(or) -- Write MODEL_DATA column

Functional Steps – Basic Run

```
SI . select_Data ( Data and selection parameters )
SI . define_Image ( Image Parameters , Gridding parameters )
SN . setup_Normalizer ( Normalization Parameters )
SD . setup_Deconvolution ( Algorithm parameters )
IC . setup_IterationControl ( niter, threshold, gain... )

SI . make_PSF ( )
SN . normalize_PSF ( )

SI . run_Major_Cycle ( )
SN . normalize_Residual ( )

while (  not  IC . has_Converged( ) ) :
    IC . interactive_Mask ( )
    iter,peak = SD . run_Minor_Cycle ( )
    IC . update ( iter, peak )
    SI . run_Major_Cycle ( )
    SN . normalize_Residual ( )

SD . restore ( )
```

Old Code :

Functional layer in C++
=> All modules communicated by casa::imageInterface references.

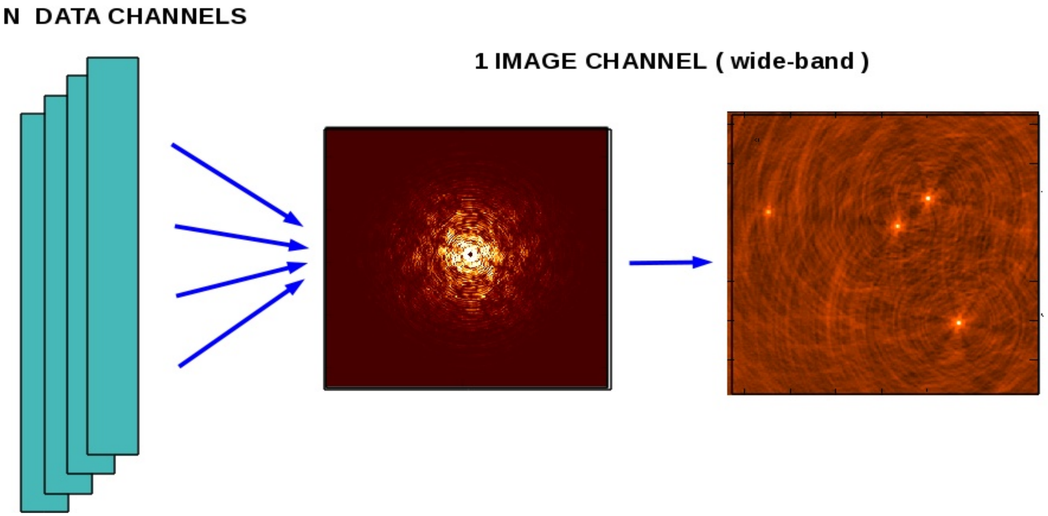
New Code :

Functional layer in Python
=> All modules communicate via image (names) on disk.

--> A design constraint, for serial and parallel runs to use the same code, since at the time of design, parallelization was forced to be in python and not C++. But, can move this layer down into C++ when we can use MPI from there.

Main Imaging modes : Continuum and Cube

Mapping of Data to Image (shapes)

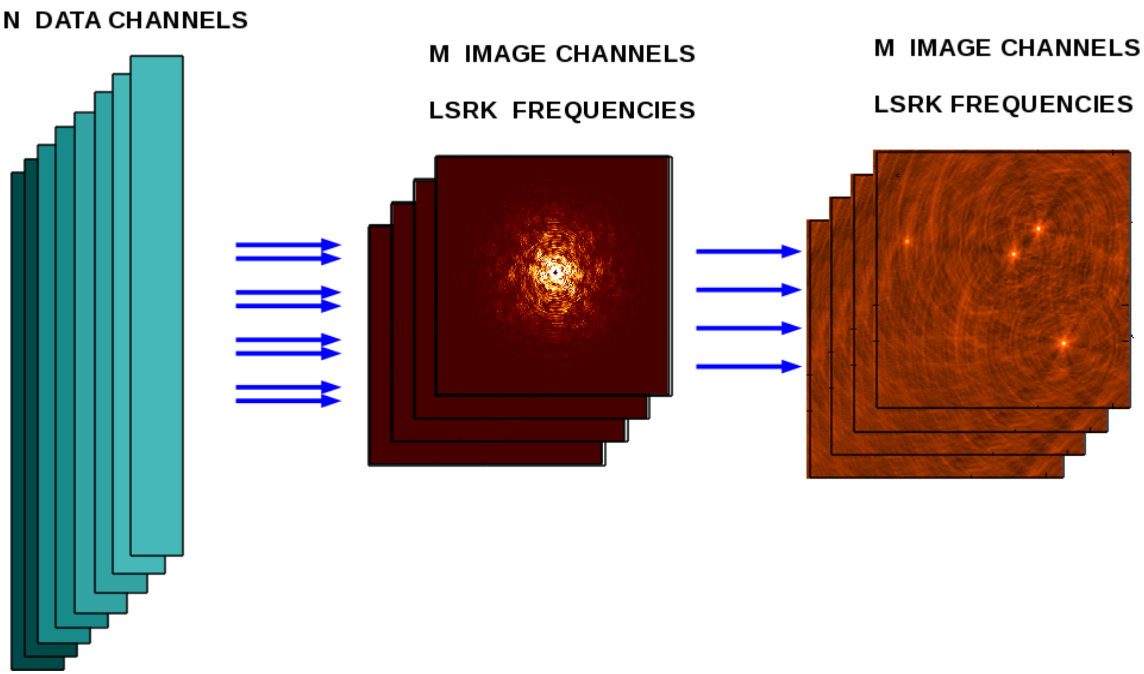


Partitioning for parallelization

Continuum :

Data partitioning can be along any data axis. e.g. row_id
(Preferences can come from algorithmic details.)

All data goes to ONE grid.

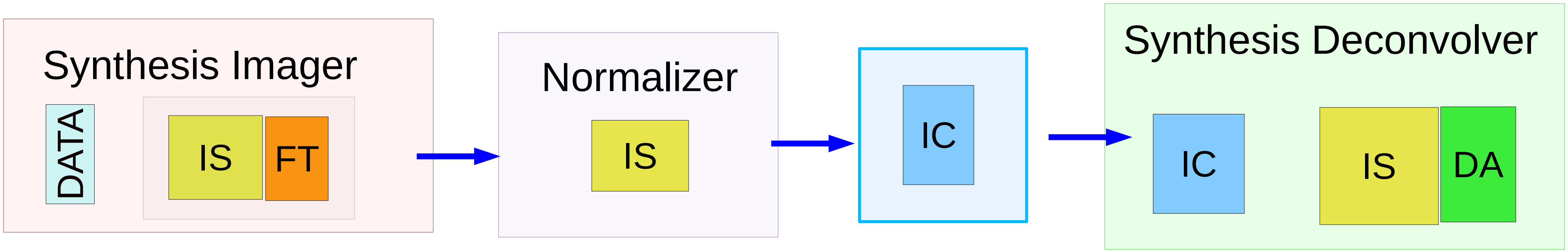


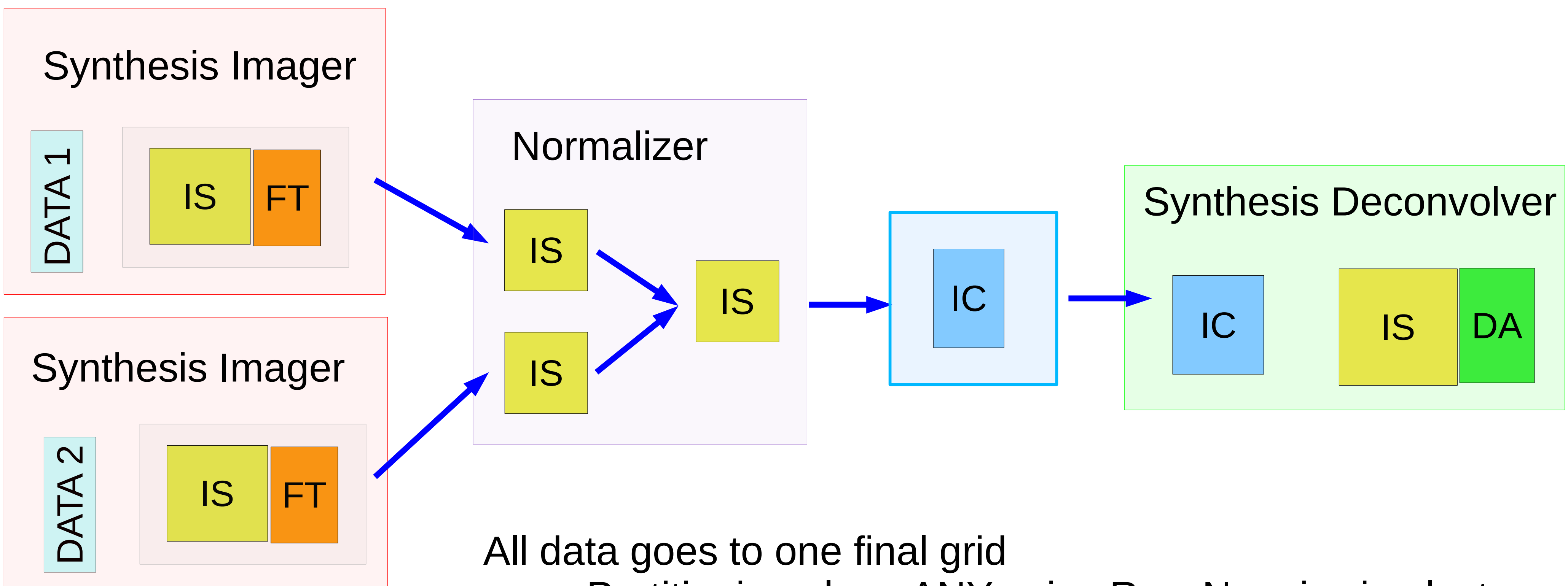
Cube :

Data **and** Image partitioning along Frequency

Each data chunk goes to its own subImage.
(Only slight overlap in data chunks due to software doppler tracking (otf cvel).)

Continuum Imaging : Serial to Parallel





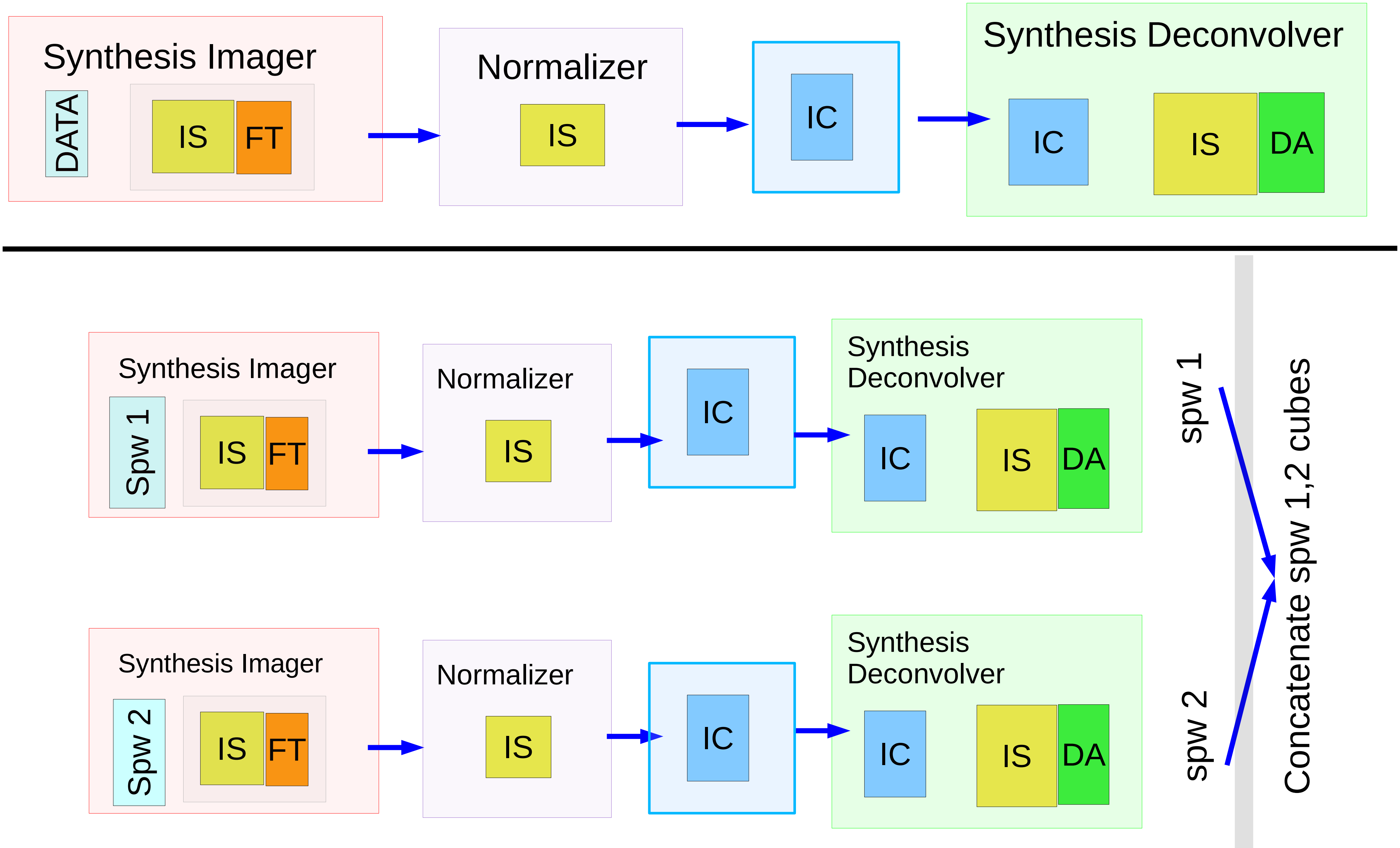
All data goes to one final grid
=> Partitioning along ANY axis. Row Num is simplest.

Messages are only parameters and image names.

Functional Steps : Continuum Data Parallelization

```
continuum_Data_Partition ( ) :
   In : Selection Params , N_Processes, Out : List of N selection parameters

For all processes : SI [proc] . select_Data( ), SI [proc] . define_Image ( )
SN . setup_Normalizer ( )
SD . setup_Deconvolution ( )
IC . setup_IterationControl ( )

For all processes : SI [proc] . make_PSF ( )
SN . gather_normalize_PSF ( )

For all processes : SI [proc] . run_Major_Cycle ( )
SN . gather_normalize_Residual ( )

while (  not  IC . has_Converged( ) ) :
     IC . interactive_Mask ( )
     iter,peak = SD . run_Minor_Cycle ( )
     IC . update ( iter, peak )
     SN . scatter_Model ( )
     For all processes : SI [proc] . run_Major_Cycle ( )
     SN . gather_normalize_Residual ( )

SD . restore ( )
```

Cube Imaging : Serial to Parallel - 1



Mapping of Data Channels to Image Channels => Partitioning along FREQ
(with slight overlap)

Functional Steps – Cube Parallelization - 1

cube_Data_Image_Partition ( ) :
In : Selection Params , Image Cube Parameters, N_Processes
Out : List of N selection parameters, list of N image cube parameters (csys)

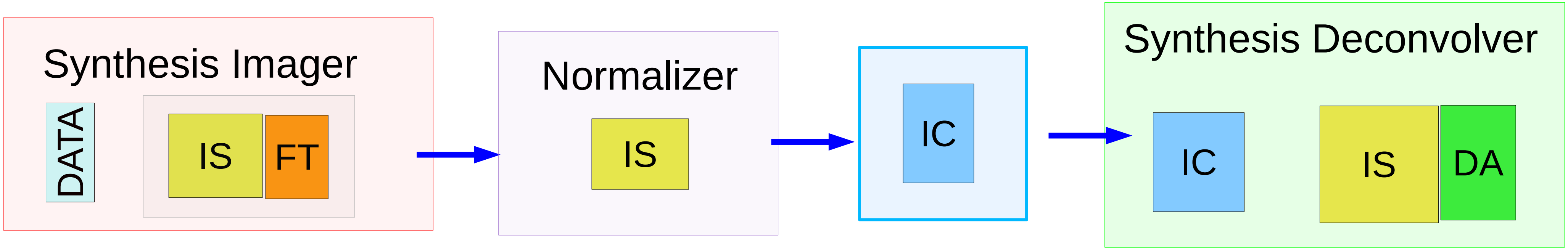
For all processes :
SI [proc] . select_Data(selection parameters for [proc])
SI [proc] . define_Image (image cube definition for [proc])
SN [proc] . setup_Normalizer ( )
SD [proc] . setup_Deconvolution ( )
IC [proc] . setup_IterationControl ( )

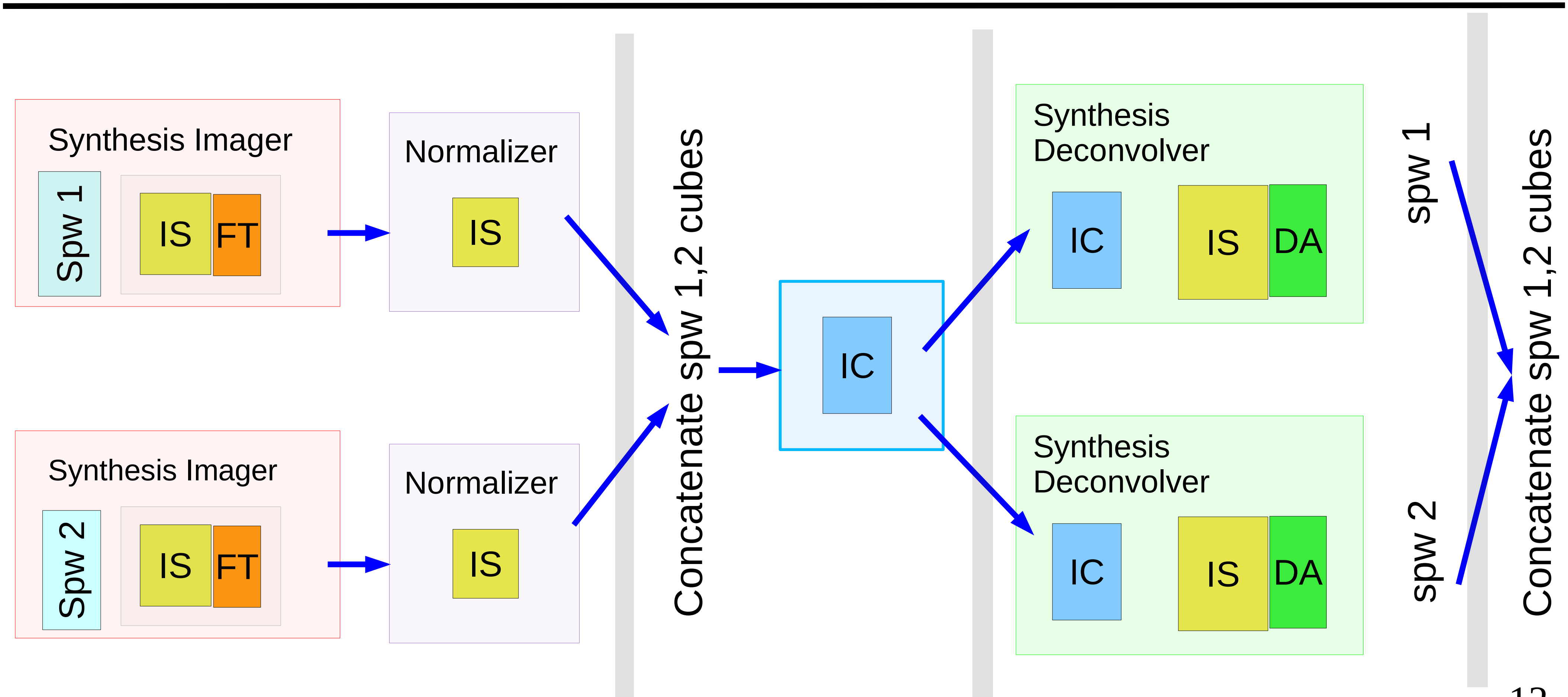
Run Basic Iteration Loops Separately per [proc]

Concatenate all final output sub-Image Cubes into one **large Cube.**

Problems :
-- Last step involves a full copy, and can be slow.
- Exploring option of reference concatenation (KG).
-- Iteration control is separate per chunk => not in sync, for major-cycle triggers
-- No user interaction at runtime, or operate separate viewer/mask per chunk.

Cube Imaging : Serial to Parallel - 2





Functional Steps : Cube Parallelization - 2

cube_Data_Image_Partition ( ) :
In : Selection Params , Image Cube Parameters, N_Processes
Out : List of N selection parameters, list of N image cube parameters (csys)

For all procs : SI [proc] . select_Data( ), SI [proc] . define_Image ( )
SN [proc] . setup_Normalizer ( )
SD [proc] . setup_Deconvolution ( )
IC . setup_IterationControl ( )

For all procs : SI [proc] . make_PSF ( ); SN [proc] . normalize_PSF ( )
SI [proc] . run_Major_Cycle ( ); SN [proc] . normalize_Residual ( )

while (not IC . has_Converged( )) :
IC . interactive_Mask (**concatenated large cube**)
For all procs :
iter[p],peak[p] = SD [proc] . run_Minor_Cycle ( )
IC . update (iter[p], peak[p])

For all procs : SI [proc] . run_Major_Cycle ( ); SN [proc] . normalize_Residual ( )

For all procs : SD [proc] . Restore ( )
Concatenate large cube

Many More Imaging Options...

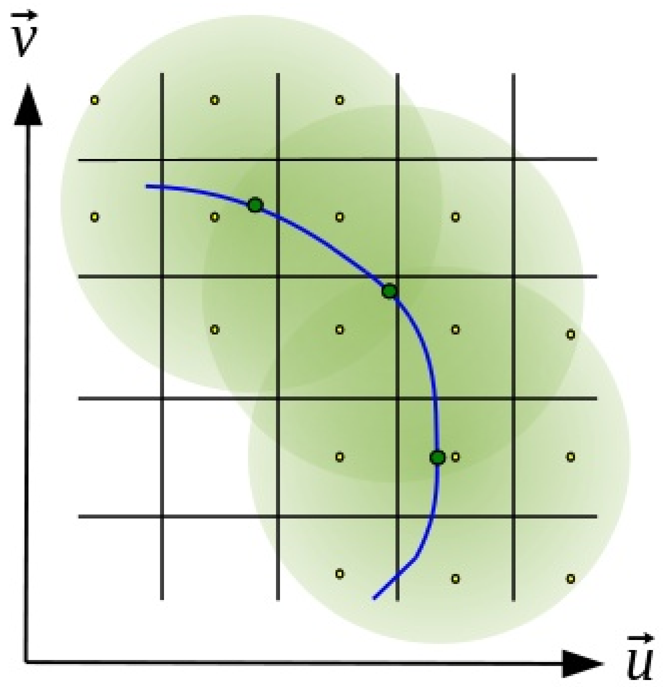
- Gridding Convolution Functions (Standard, W-Proj, A-Proj, …)
- Deconvolution Algorithms (Clark/Hogbom Clean, MS-Clean, ASP, MEM)
- Cube Imaging (vs) Multi-Frequency Synthesis (Nterms = 1 or MTMFS)
- Stokes Parameters (I, Q, U, V, IV, QU,...., RR....., XX,...)
- Multiple Fields, Multiple Facets, Stitched / Joint Mosaics

=> Almost all possible combinations of the above are valid.

User Interaction :

- Create and edit masks during the Minor Cycle (including Auto- and PB- masks)
- Ability to monitor progress and change iteration control parameters at run-time

Gridding (Imaging) Options



Gridding Convolution Function (GCF)

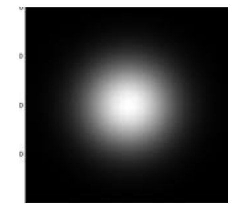
– Several GCF options (algorithms)

Size range : 3x3 to > 100x100 pixels

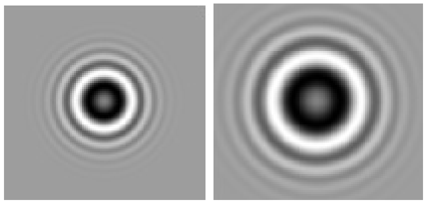
Range in computing cost spans few orders of magnitude, following number of operations per visibility point.

Memory cost also varies.

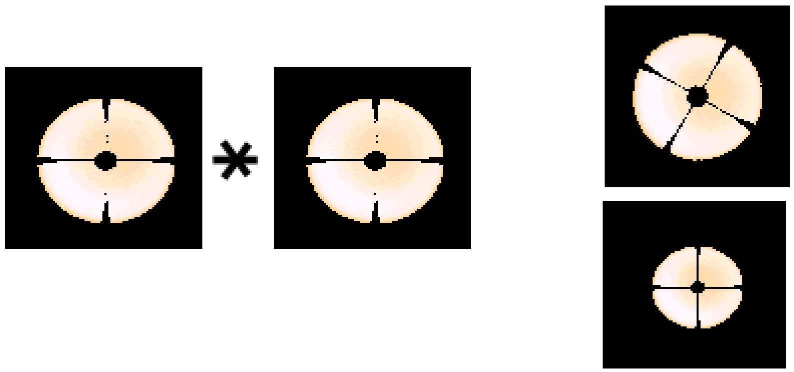
Standard Imaging :
Prolate Spheroidal



W-Projection :
FT of a Fresnel kernel



A-Projection :
Convolutions of Aperture Illumination Funcs
+ phase gradients for joint mosaics



Combined algorithms :
Convolutions of different kernels

Kernels can be different per visibility point, with varying degrees of approximation

Minor Cycle (Deconvolution) Algorithms

For Point Sources :

– Hogbom Clean

– Clark Clean

(simplest, fastest...)

For Point/Extended Sources :

– Maximum-Entropy Method*

– Adaptive-Scale Pixel Clean*

– Multi-Scale-Clean

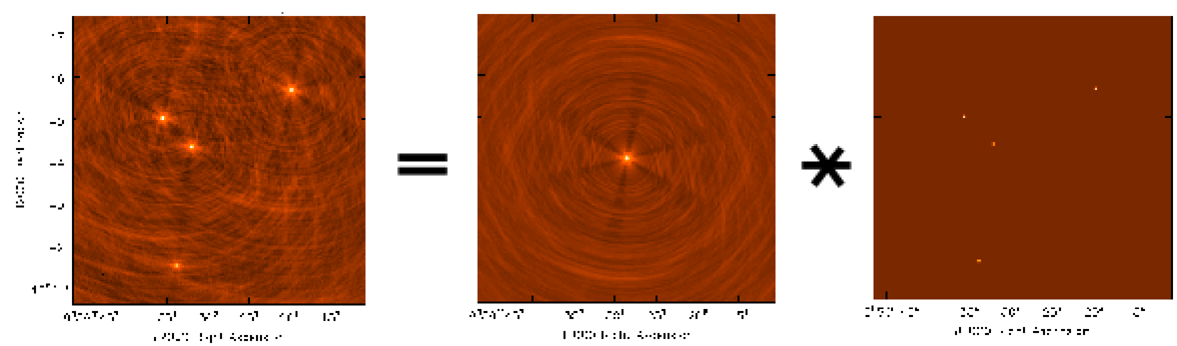
(medium computing cost)

For Wide-band Images

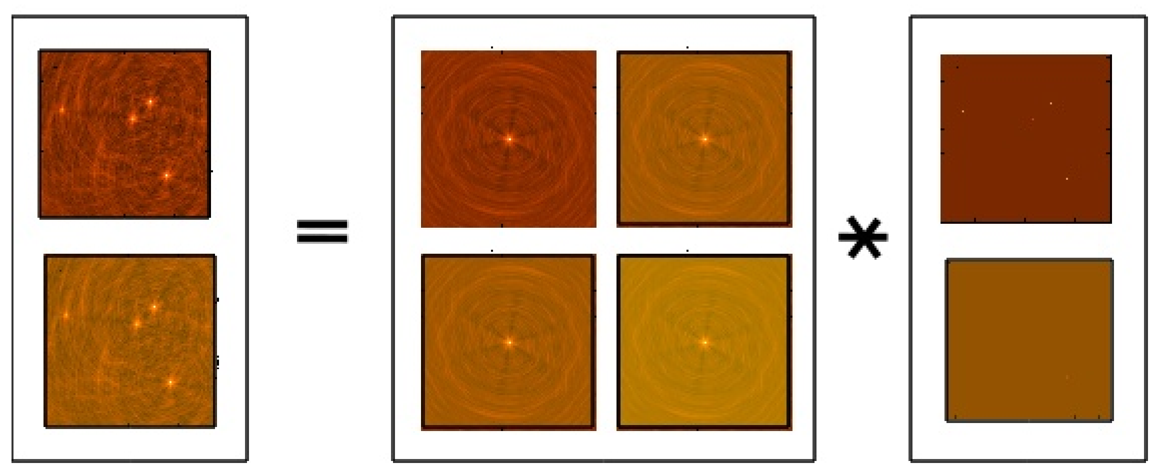
– Multi-Frequency-Clean
(with or without Multi-Scale)

(max computing cost, so far)

Convolution Equation ==> Deconvolution

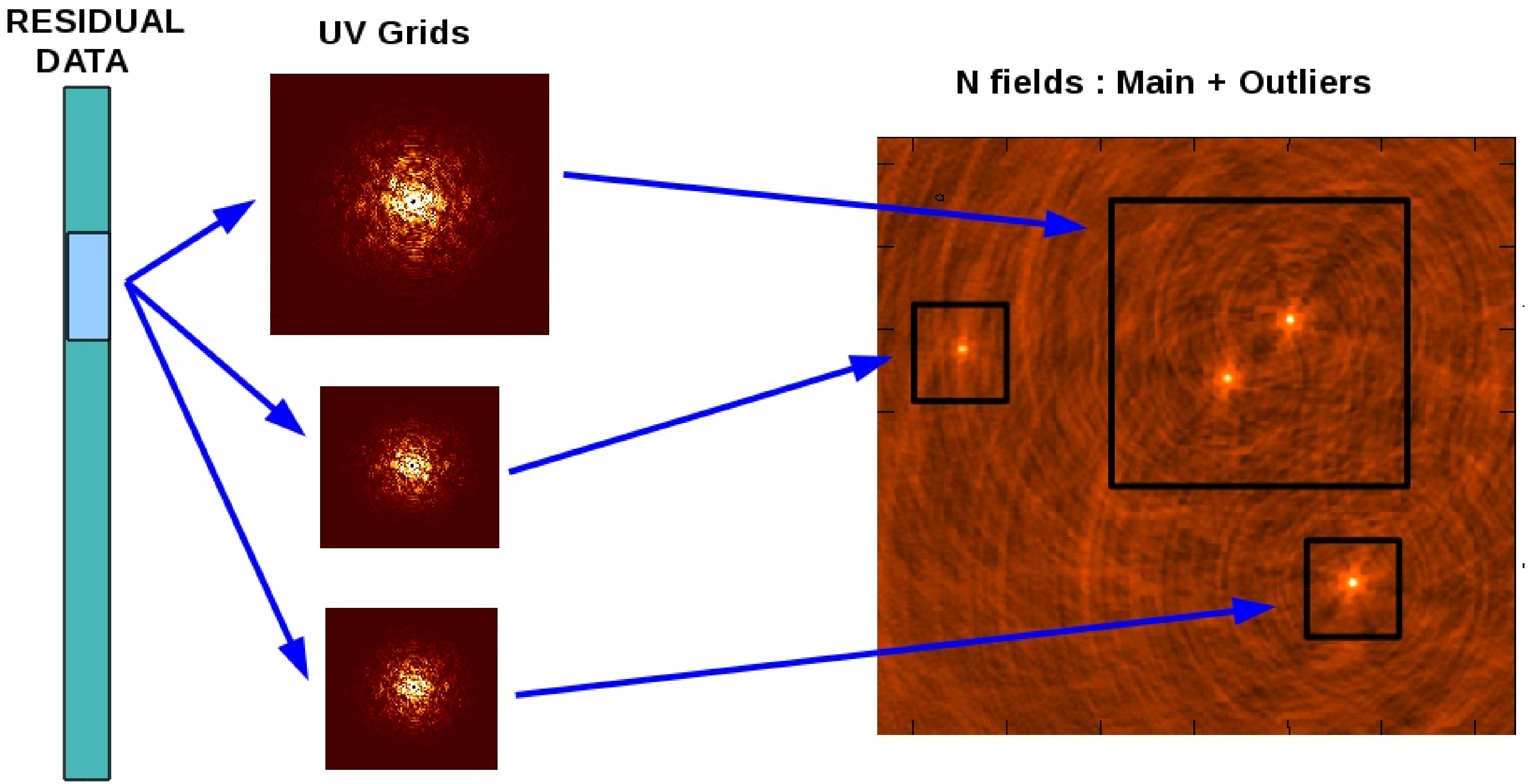


Multi-Term Convolution Equation
==> Joint Deconvolution



(Multi-Term Algorithms can be memory-intensive)

Multiple Fields



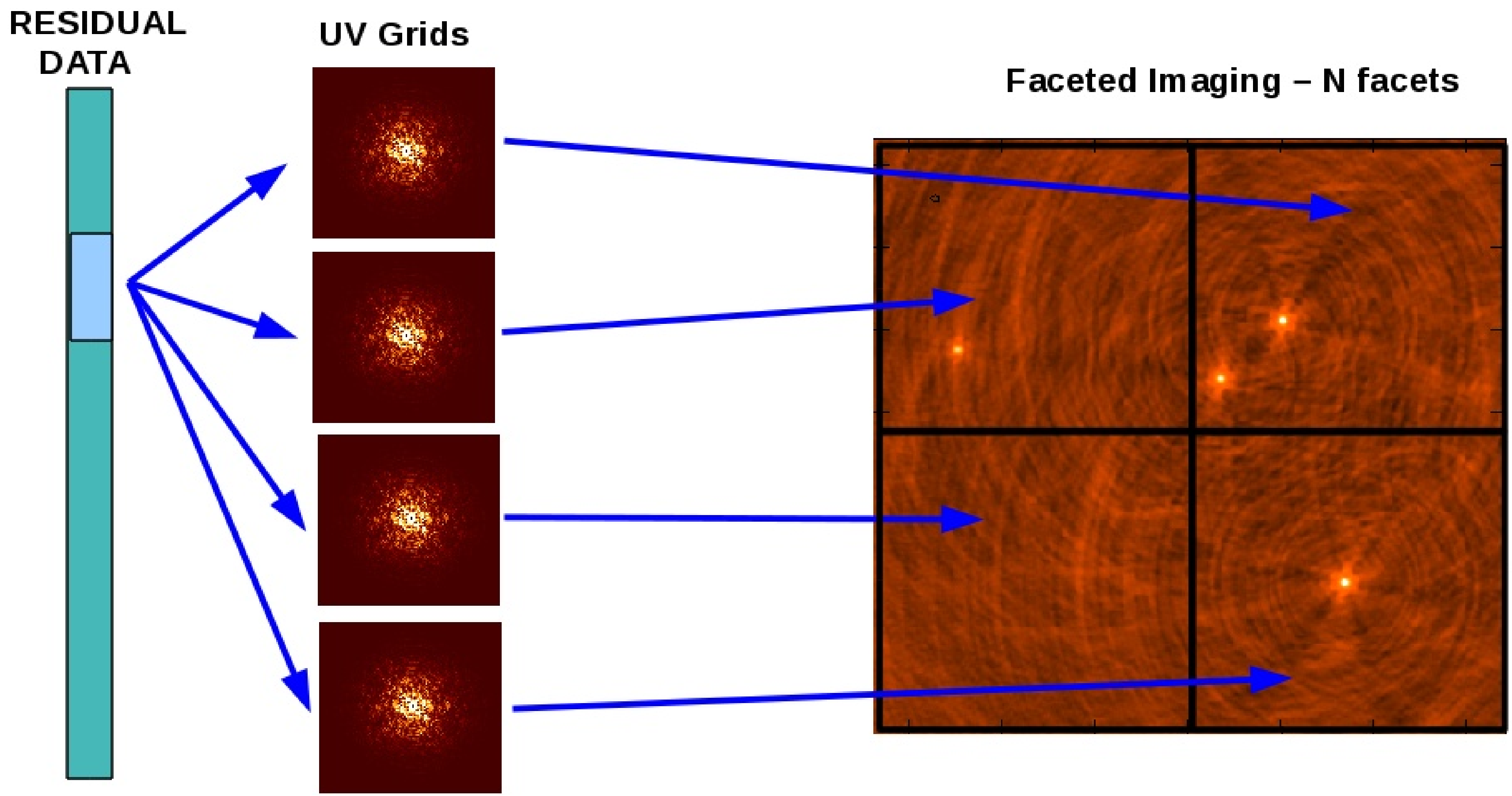
– Work with N smaller sized images (deconvolve N images separately)

– A few outlier sources that must be reconstructed to prevent artifacts from contaminating the main field.

(Usually one large image and several tiny ones)

NOTE : To support this consistently, our code contains LISTS of modules in C++ and Python, with the simplest case being a list of length 1. Major cycle has lists in C++ since all fields share data, and minor cycles have lists at Python level (as they are independent)

Multiple Facets

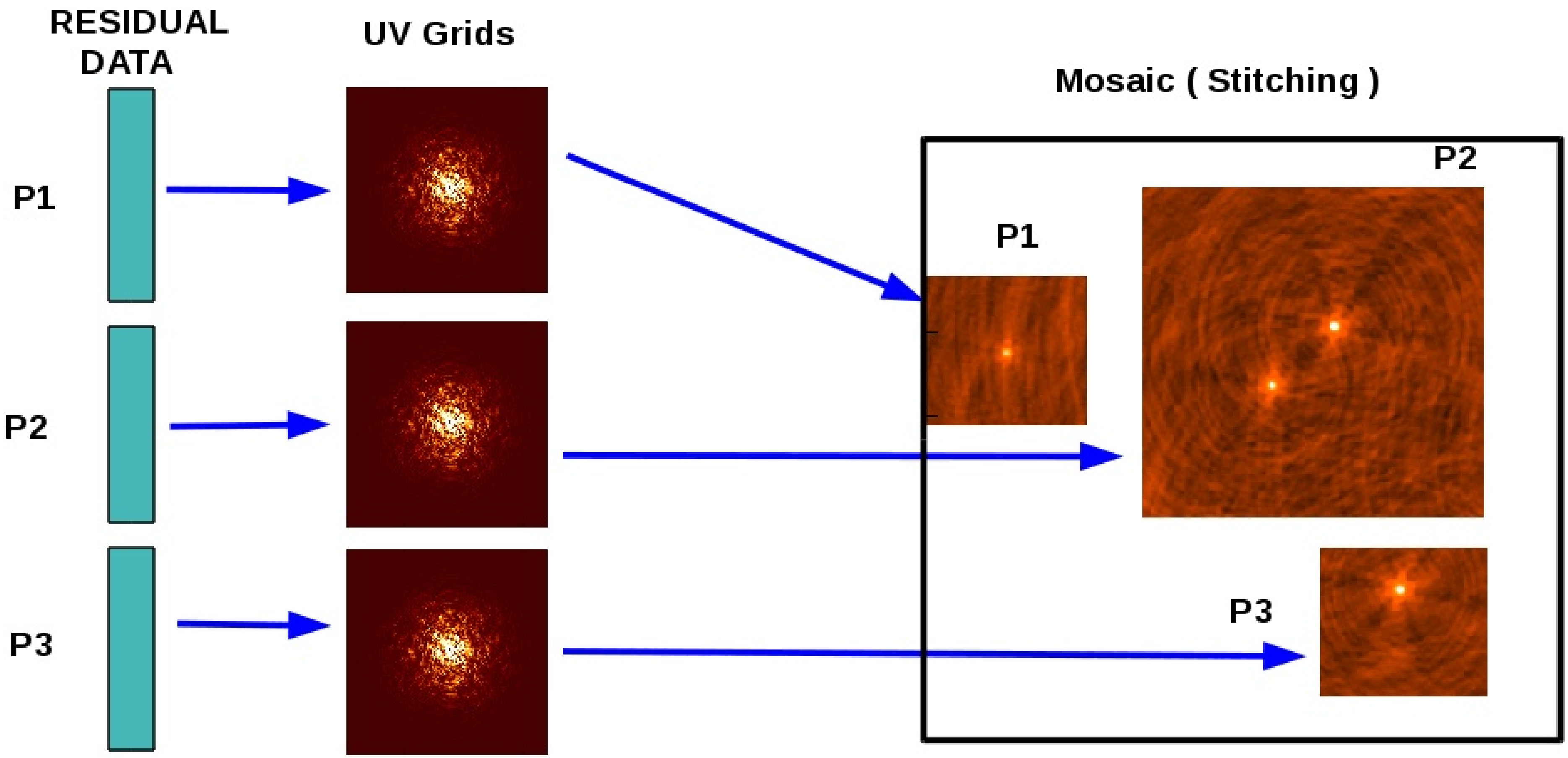


– Wide-field imaging where array non-coplanarity and sky curvature produce artifacts away from the phase-center.

– Work with smaller field-of-view images,
– Deconvolve N facets separately (OR) as 1 single large image.

An (older) alternative to (or addition to) w-projection. Not very commonly used in casa

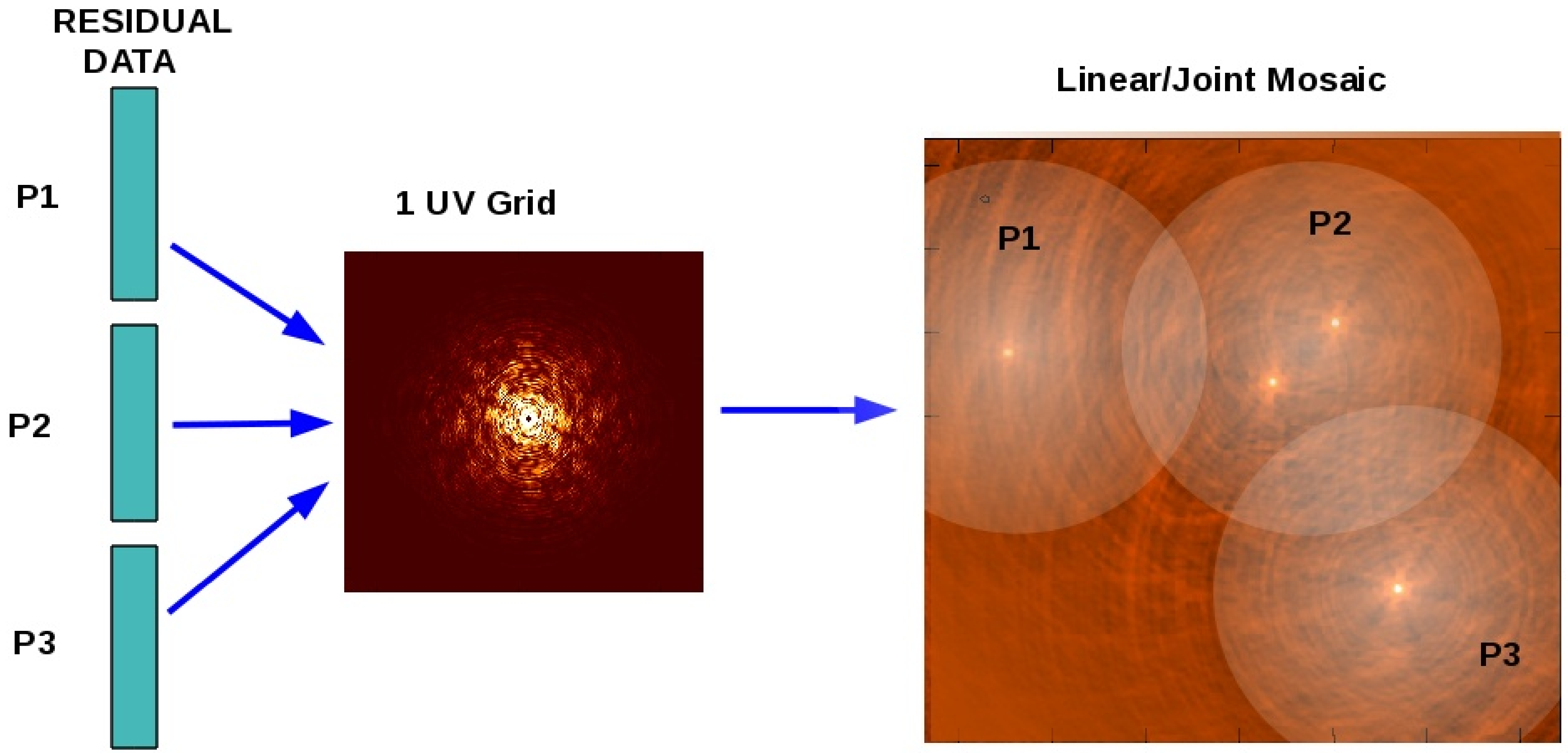
Mosaics – Grid pointings separately



– Deconvolve N images separately, combine restored images : ‘stitched mosaic’
OR
– Grid pointings separately, combine before deconvolution : ‘image domain joint mosaic’
[Use PB model as weights during combination, w/wo PB-cor]

Could parallelize (data and image) on pointings/fields at top level (via tool level)

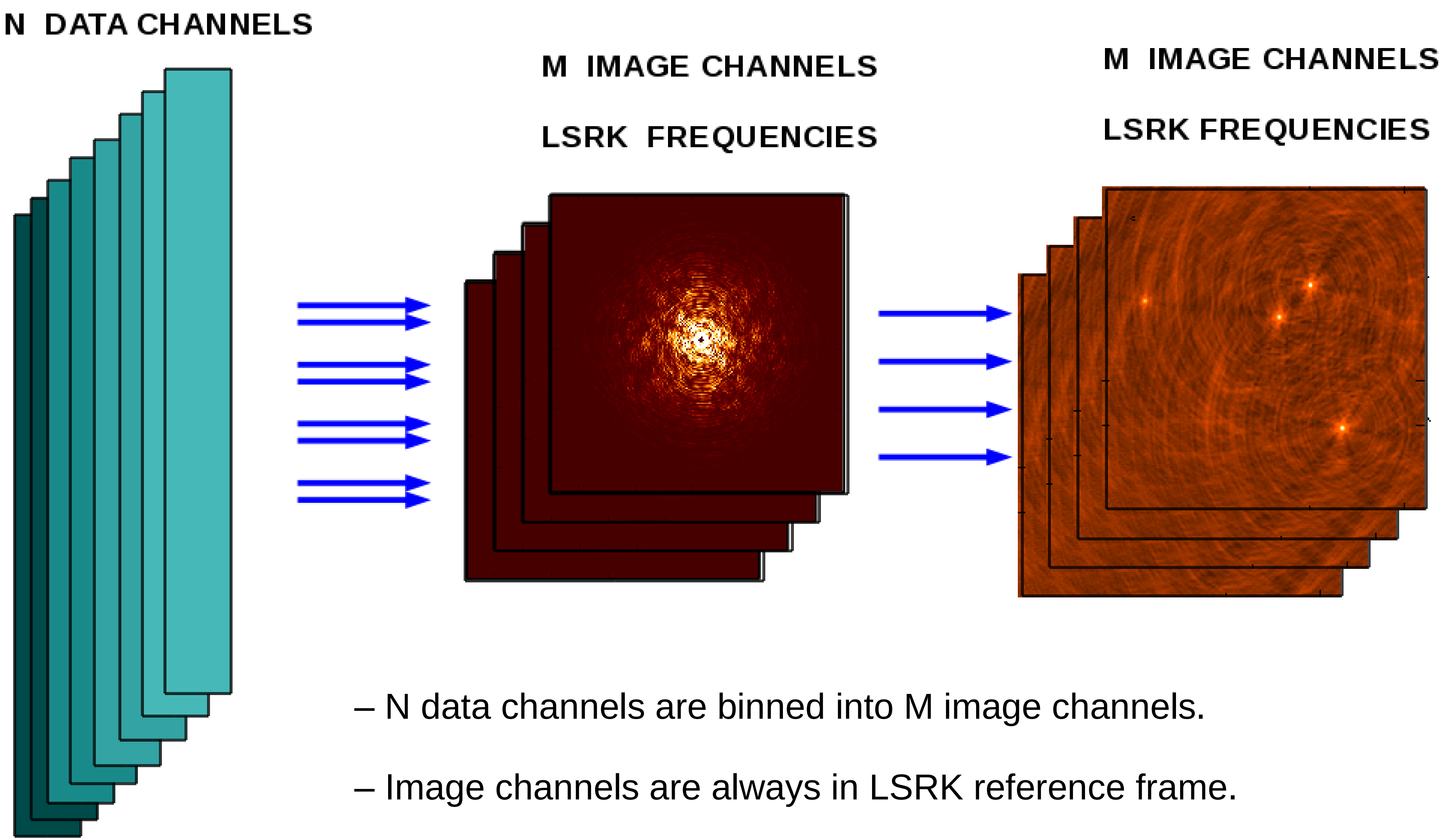
Mosaics – Grid pointings together



- Grid all pointings onto a single UV-grid, using GCFs with appropriate phase gradients. Do a joint deconvolution
- Gridding math is very similar to “ facet ” and “ multi-field ” imaging but using separate data.

Uses standard continuum or cube parallelization .
Uses large gridding convolution fns (A-projection and its approximate forms)

Cube Imaging (Spectral Line)

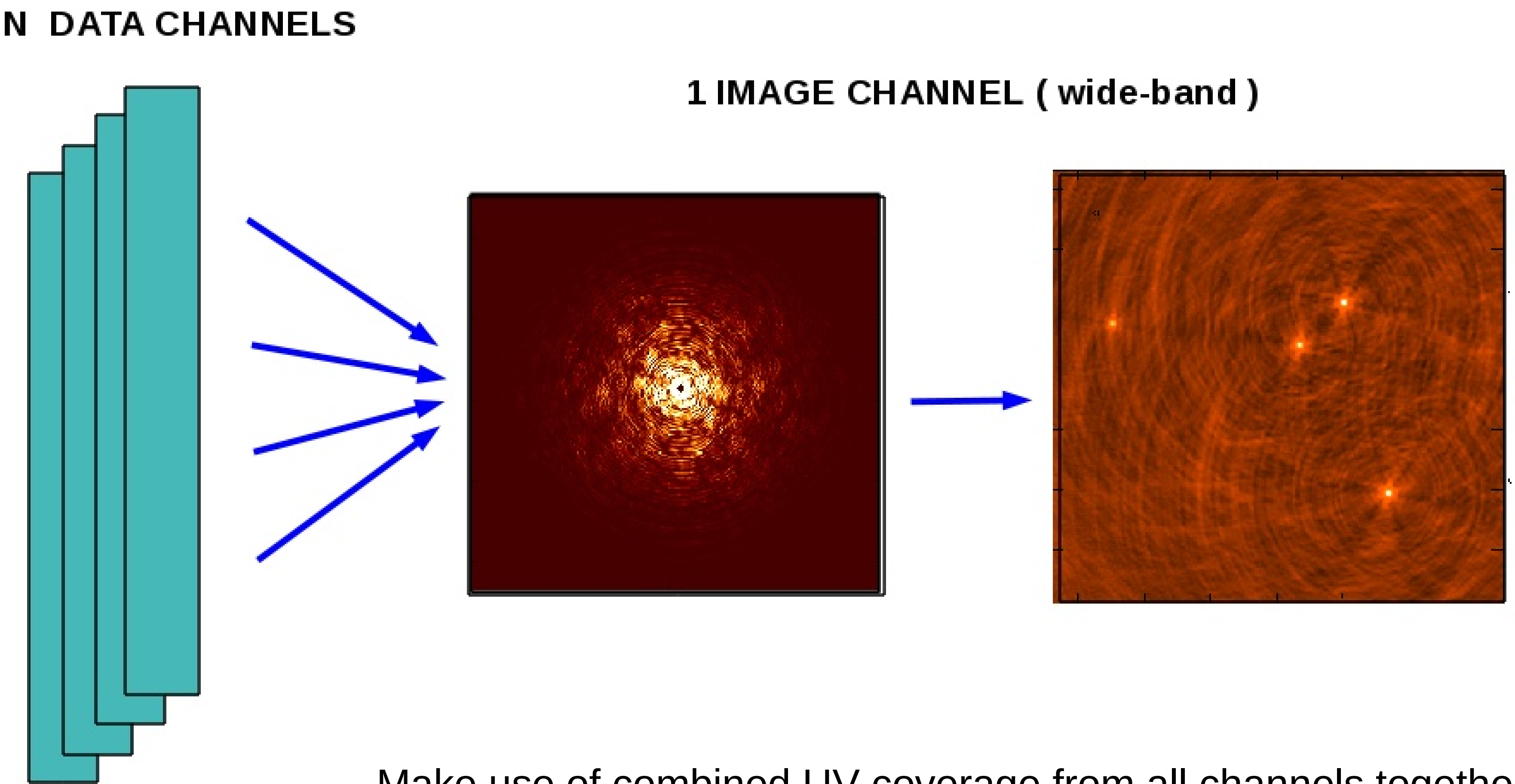


– N data channels are binned into M image channels.

– Image channels are always in LSRK reference frame.

– Conversion to 'velocity', etc is only axis re-labeling (not regridding)

Continuum Imaging (MFS)

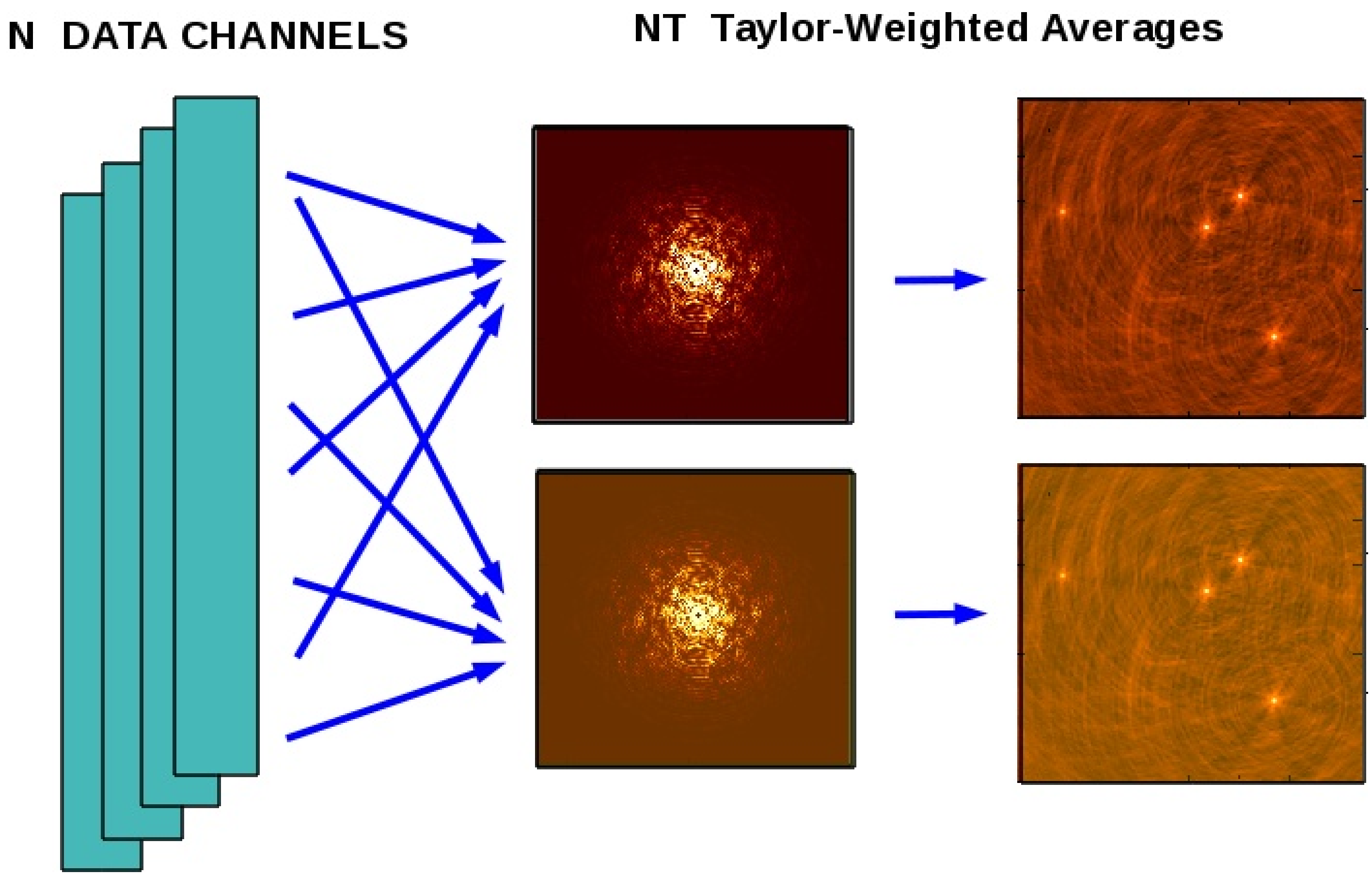


– Make use of combined UV-coverage from all channels together

– Make use of broad-band sensitivity during image reconstruction

– Deconvolve 1 image

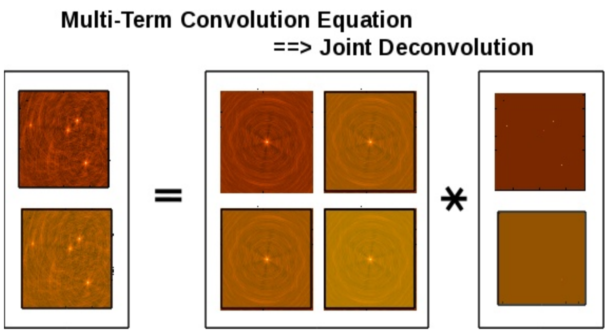
Continuum Imaging (MT-MFS nterms>1)



– Combined UV-coverage and broad-band sensitivity

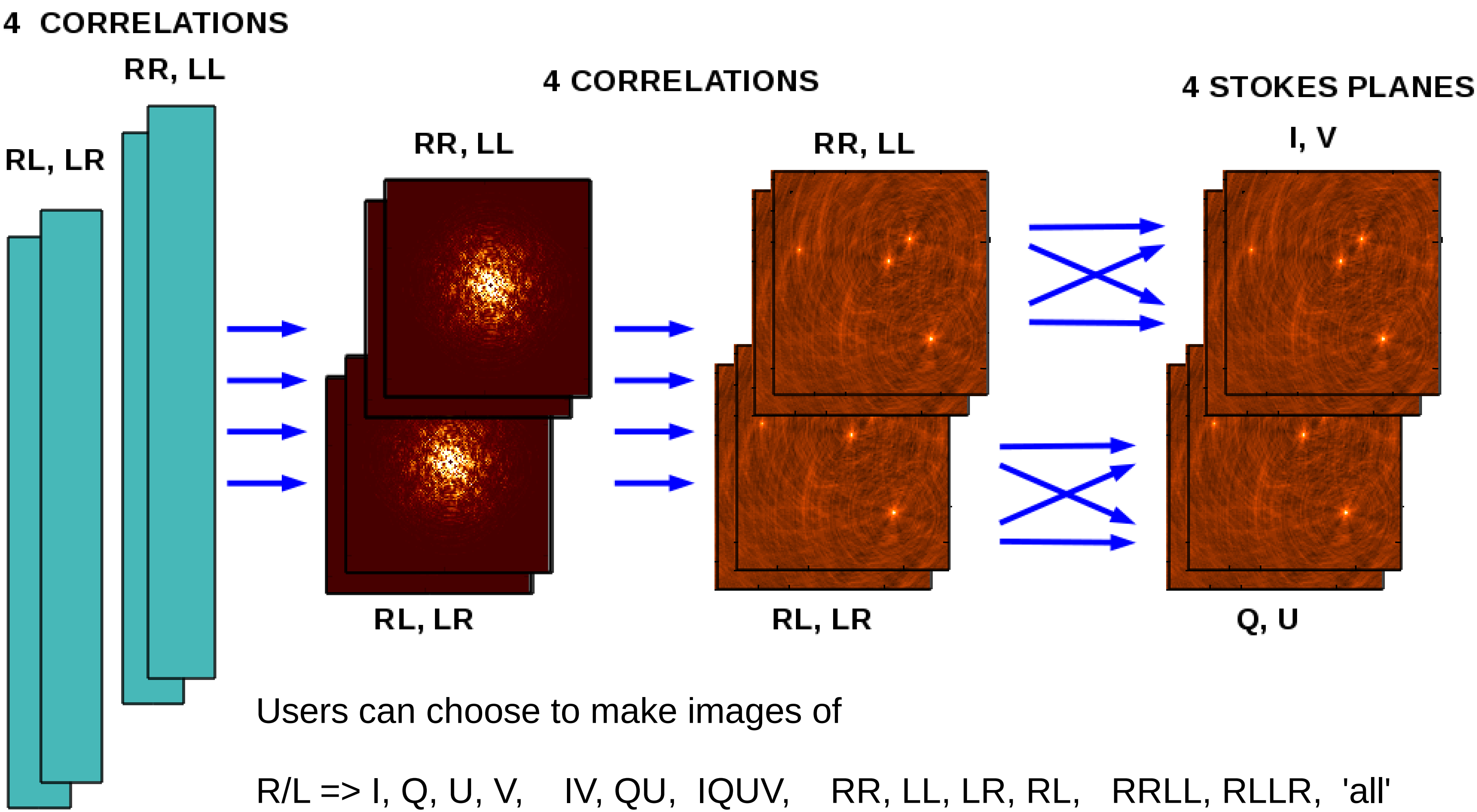
– Solve for sky spectrum as well as intensity.

– Joint multi-term deconvolution of all Taylor coefficients



Data parallelization. Expensive minor cycle.

Correlations / Stokes



Users can choose to make images of

R/L => I, Q, U, V, IV, QU, IQUV, RR, LL, LR, RL, RRLL, RLLR, 'all'

X/Y => I, Q, U, V, IQ, UV, IQUV, XX, YY, XY, YX, XXYY, XYYX, 'all'

(when possible, use data even if some correlations are flagged)

Other Ongoing Performance Improvements

- Multi-threading of gridders (KG)

- Multi-threading of some minor-cycle algorithms (KG,UR)

- Improving efficiency of FFT usage/implementation (KG)

- Smarter W-Projection plane selection (KG)

- Efficient use of Convolution function caches (SB)

- On-the-fly GPU calculations of convolution functions (SB)

- Virtual model column (trade I/O for computing) (KG)

- Efficient cube concatenation (reference/virtual) (KG)

[All of the above apply to both old and new Imagers]

Recent Commissioning Tests - Continuum

Wideband multi-scale multi-term joint mosaic with wideband awprojection.

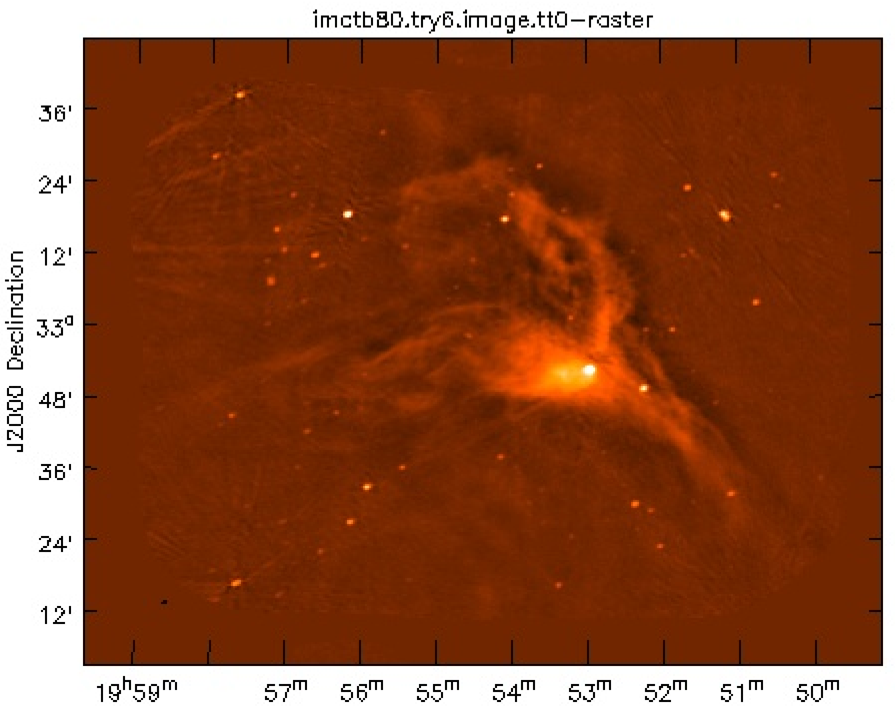
=> 106 pointing mosaic : 300 GB
=> Extended emission spanning multiple primary beams
    => Joint mosaic and multi-scale
=> Wideband 1-2 GHz EVLA data
    => Multi-term imaging to model the intensity and spectrum
    => WB-A-Projection to handle frequency dependent primary beam
=> Bright compact sources on top of diffuse emission : HDR
    => A-Projection with rotating and squint-correcting kernels

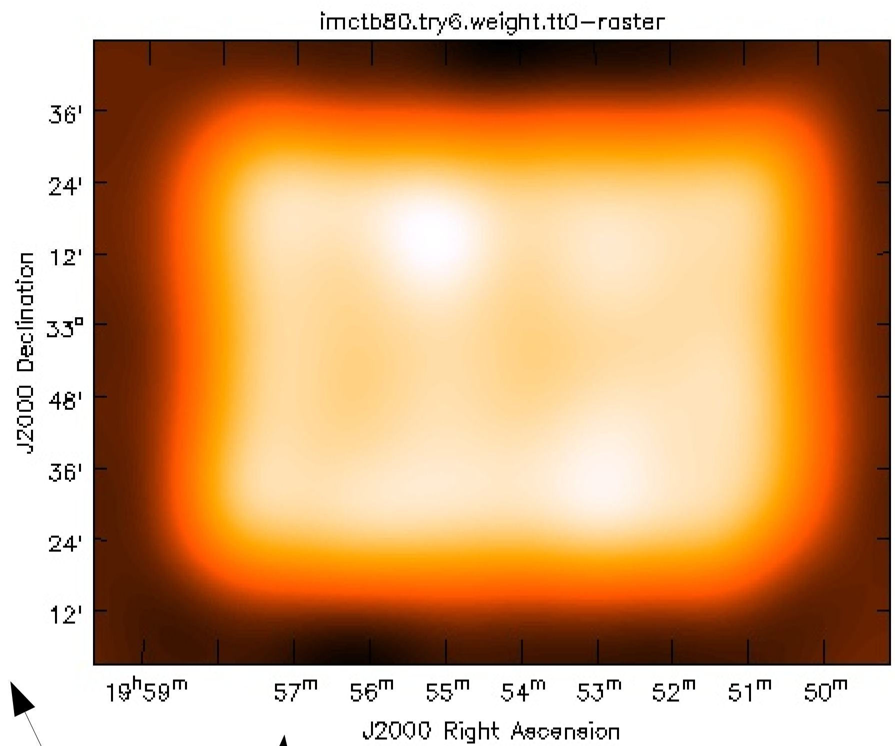
=> Minor Cycle is memory and compute intensive
=> Major Cycle is I/O and compute intensive

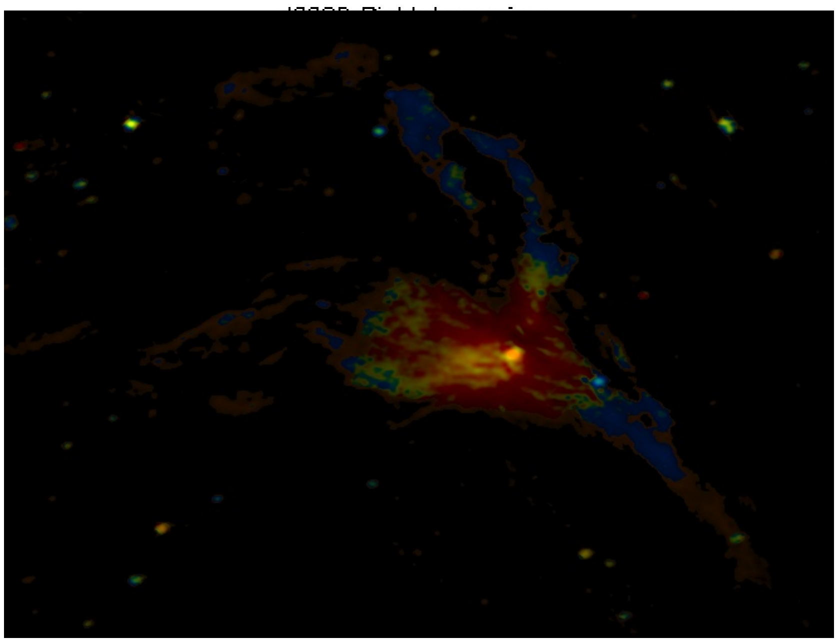
Results : Obtained expected speedup and scaling for major cycle.

(Worked through software issues : MS and image locks, parallel writes on single MS, running on MMS, ability to restart / recover tclean with minimal overhead, etc...)

Recent Commissioning Tests - Continuum







Mosaic Primary Beam

Intensity

Intensity-weighted Spectral Index