Advanced Algorithms

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Plan for the talk

- Re-cap of imaging, need for new/advanced algorithms
- Advances in algorithms for the current telescopes
  - Algorithms for wide-field imaging/ Direction-dependent corrections
  - Algorithms for wide-band imaging
- Computing cost issues to understand and keep in mind
  - Computing complexity / computing resource requirements
  - Understand the algorithmic needs of your scientific goal: Not all imaging needs to trigger the most advanced algorithms
  - Use implementations that allow flexibility in algorithmic choices and combinations
- Next-gen instruments and the next-generation challenges
  - SKA
  - ngVLA
    - » 214 antennas, 1000Km baselines
    - » Fractional bandwidth: up to 60%
    - » Range of scales: mas → 10s arcsec

Telescope sensitivity

- Noise limit for imaging with interferometric radio telescopes

$$Noise \propto \frac{T_{sys}}{A_{eff}\sqrt{\Delta\nu\,\Delta T}}$$

10 – 100x improvement in sensitivity over the past decade!

- Sensitivity improvements achieved by

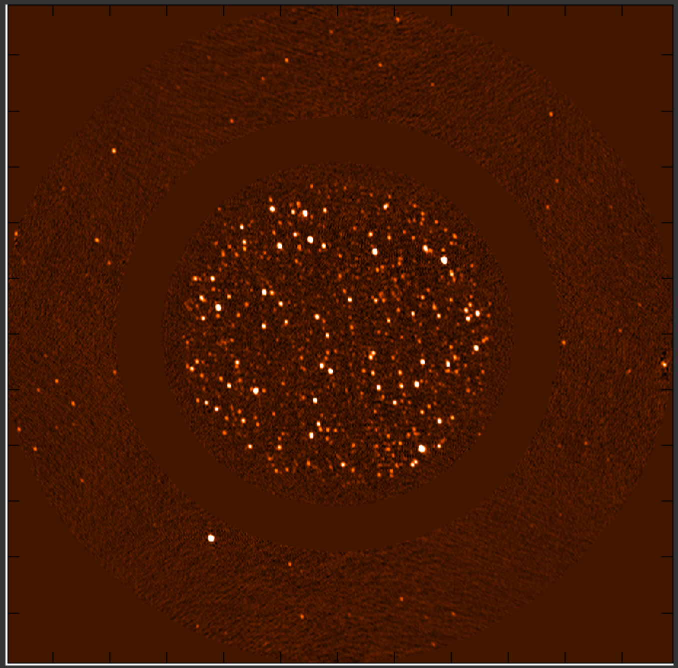
$\Delta\nu$: *Wide band receivers: >60% fractional bandwidth*

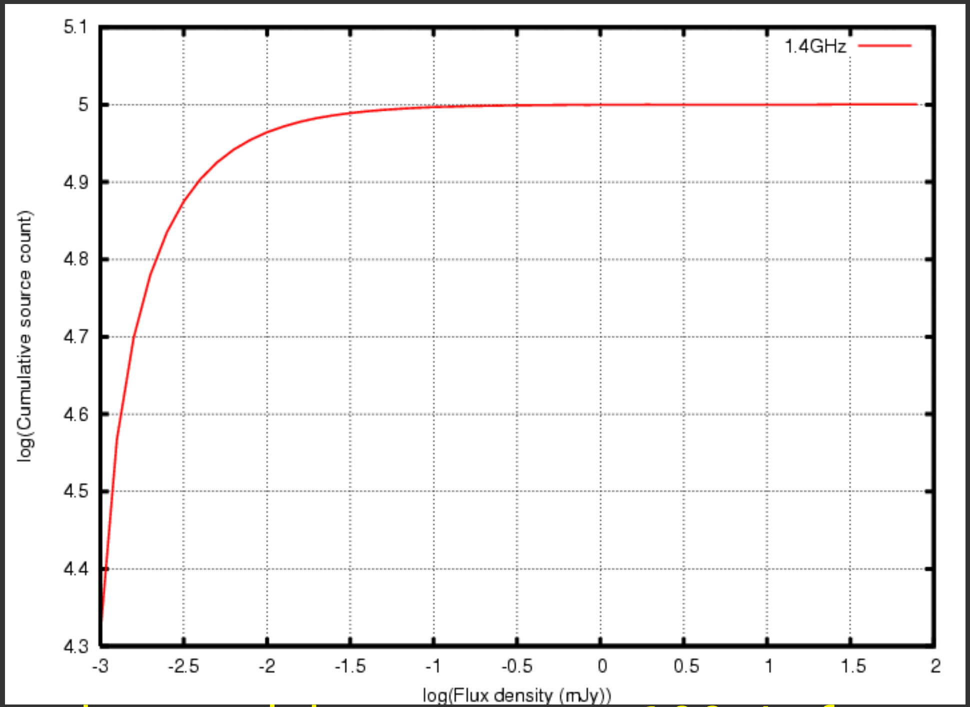
A_{eff}: *More antennas: 30 -- many 100s*

Long baselines: To beat confusion limit

ΔT: *Long integration times: many hours -- months*

Sky at low frequencies: No. of sources

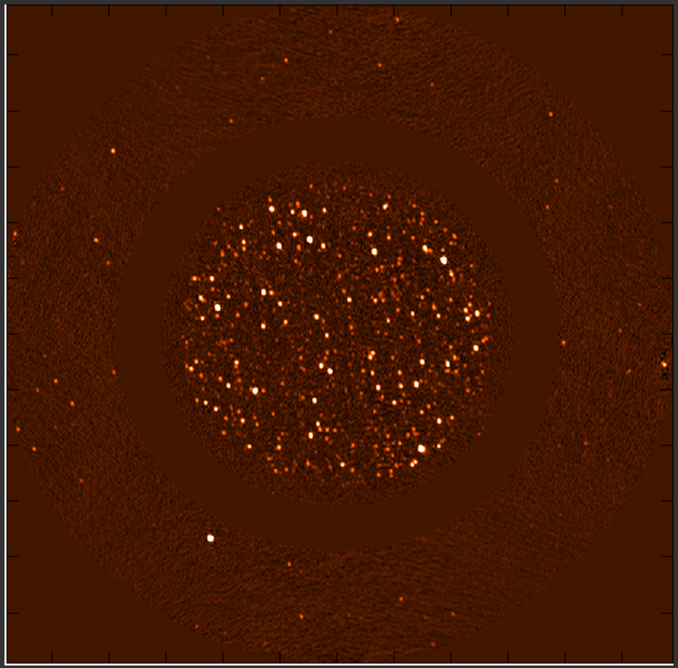


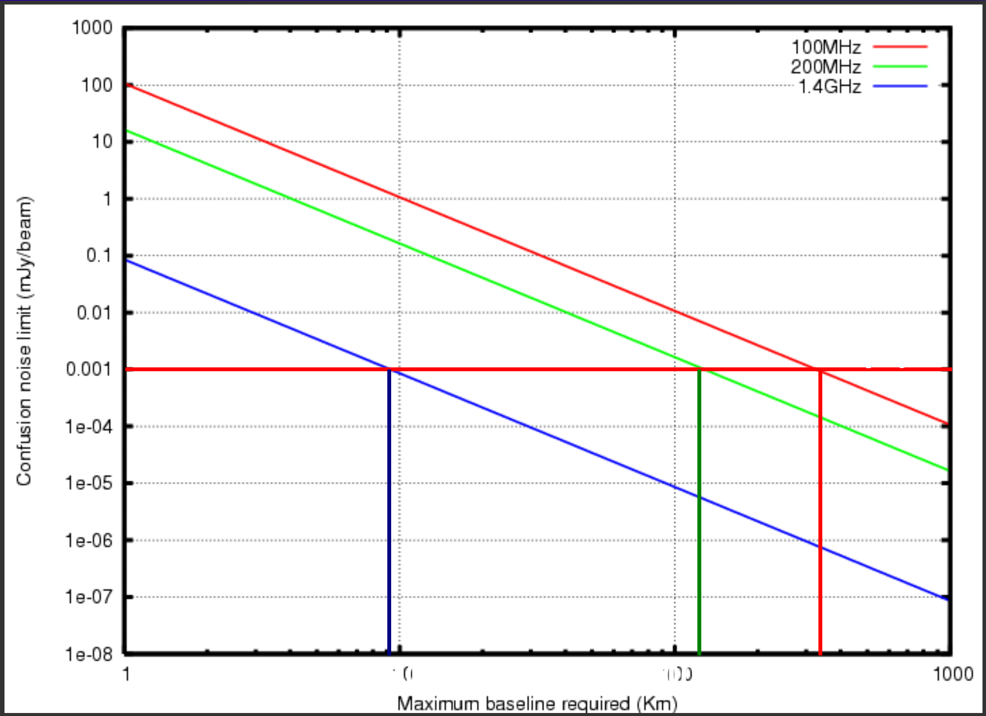


- PSF side-lobe at 1% level requires deconvolving sources >100µJy for 1µJy/beam RMS
- $10^{4\text{-}5}$ sources per deg^2 >10µJy @1.4GHz
  - Source size distribution important at resolution < ~2"
- Implications for imaging
  1. Wide-field imaging
  2. Deconvolution of crowded fields (same problem as deconvolution of extended emission)

     For HDR imaging we need to consider few X 100 mJy – 1 Jy source ~few sq. deg.

Sky at low frequencies: Confusion limit

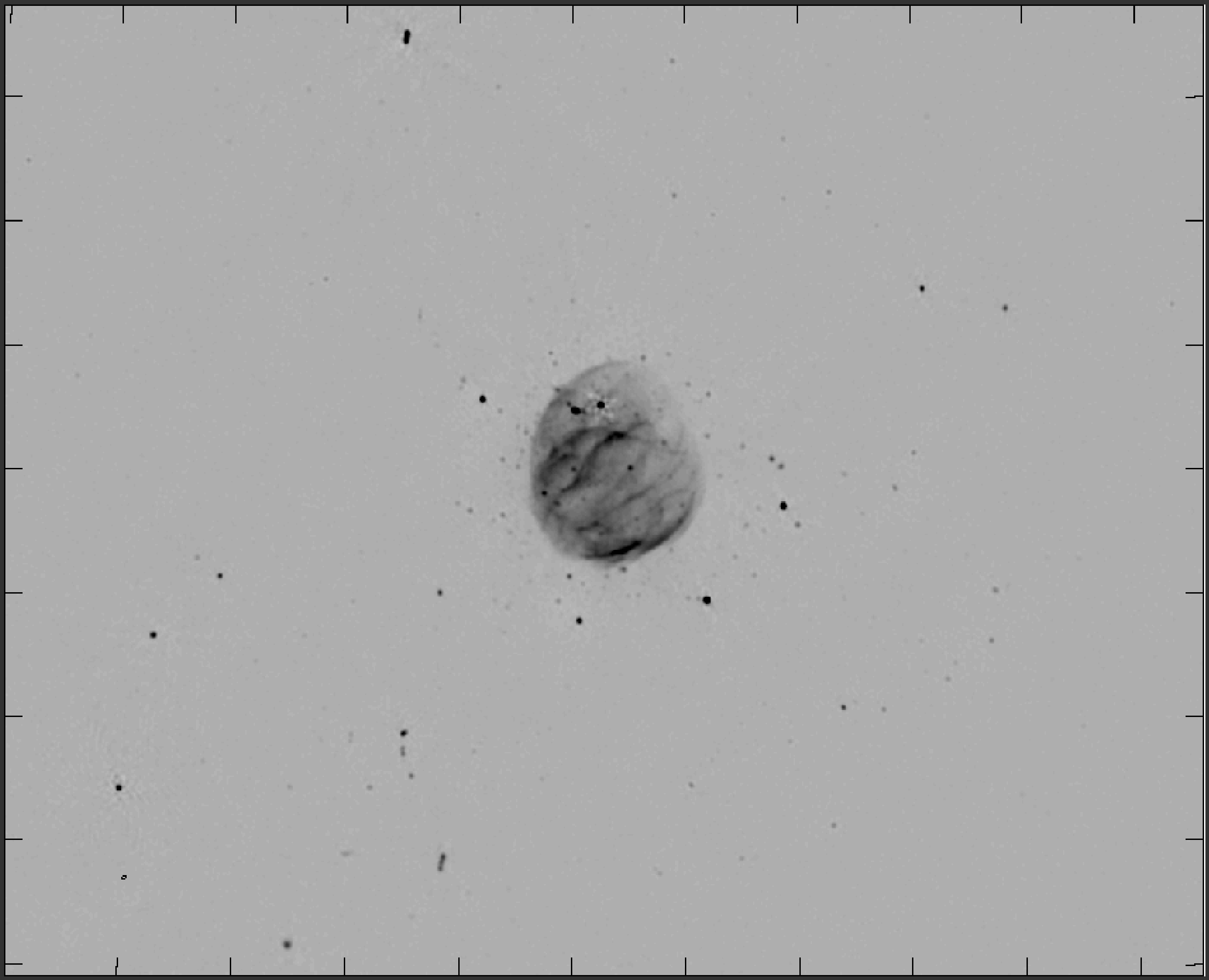




- $\sigma_{confusion} \propto (\nu^{-2.7}/B^2_{max})$: B_{max} ~100 Km at 200MHz for $\sigma_{confusion}$ ~ 1µJy/beam
- Implications for imaging
  1. Long baselines: B_{max} > 2-3 Km & DR > 10^4
  2. Wide-field effects: W-term, PB effects, ionospheric effects
  3. Larger data volume

Wide-field, wide-band, high resolution, HDR imaging using large data volumes is a natural consequence of low frequency and high sensitivity

Wide-band implies Wide-field imaging



- EVLA @L-Band
- BW=600 MHz
  (1.2 – 1.8 GHz)

- Algorithmic Challenge:
  - Time-varying direction-dependent gains
  - Wide-band effects
  - Extended emission with superimposed compact emission
  - Full Stokes + Mosaicking

Imaging challenges

- Challenges in imaging at low frequencies

  1. Wide-field imaging
     - Account for Direction Dependent (DD) effects
     - PB: Time, frequency and poln. dependence
     - W-term
  2. Wide-band imaging
     - All of the above plus...
     - ...frequency dependence of the sky brightness
  3. Sky brightness stronger and complex
     - Multi-Scale deconvolution
  4. Ionospheric effects
     - Requires DD solvers: An algorithmic & computing challenge in itself
  5. Runtime
     - Harvest the vast amount available computing power
     - It is geographically distributed though! ;-)

Direction Dependent (DD) Effects

- DI Calibrated ME

$$V_{ij}^{DI-Cal}(\nu) = \qquad W_{ij} \int P_{ij}(\mathbf{s}, \nu, t) \; I(\mathbf{s}, \nu) \; e^{\iota \mathbf{s}.\mathbf{b}_{ij}} \; d\,\mathbf{s}$$

Data

DI Calibration

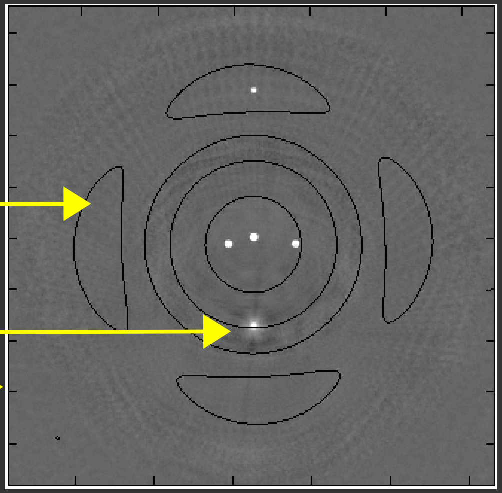
DD Term
Instrumental
Ionospheric

Sky

Geometry

- Removing the effects of the DD terms cannot be separated from imaging

$$I_{continuum}^{Dirty} = \int \int PSF(\nu, t) * \left[PB(\nu, t) \times I^{True} \right] \; d\nu \;\; dt$$



Direction Dependent (DD) Effects

- DI Calibrated ME

$$V_{ij}^{DI-Cal}(\nu) = W_{ij} \int P_{ij}(\mathbf{s}, \nu, t)\; I(\mathbf{s}, \nu)\; e^{\iota\, \mathbf{s}.\mathbf{b}_{ij}}\; d\,\mathbf{s}$$

Data

DI Calibration

DD Term Instrumental Ionospheric

Sky

Geometry

- Standard Imaging assumes:
  - PB is independent of time, frequency and polarization
  - Sky brightness is independent of frequency
  - Geometry is 2D

DD Corrections: Projection Algorithms

- Rewrite $V_{ij}^{DI-Cal}(\nu) = W_{ij} \int P_{ij}(\mathbf{s}, \nu, t)\ I^{True}(\mathbf{s}, \nu)\ e^{\iota\, \mathbf{s}.\mathbf{b}_{ij}}\ d\mathbf{s}$

  as $V_{ij}^{DI-Cal}(\nu) = A_{ij}(\nu, t) * V^{True}(\nu, t)$

- Find an operator X which when applied to the above equation, projects-out the undesirable effects of A?

$$X_{ij}\ V_{ij}^{DI-Cal} = X_{ij}\ A_{ij}\ V^{True}$$

$$such\ that\ X_{ij}\ A_{ij} \approx \mathbf{1}$$

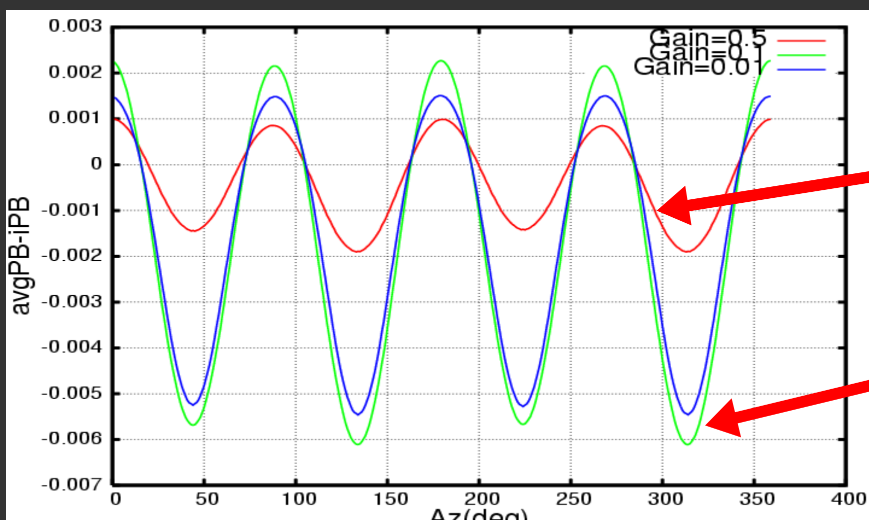
- Then

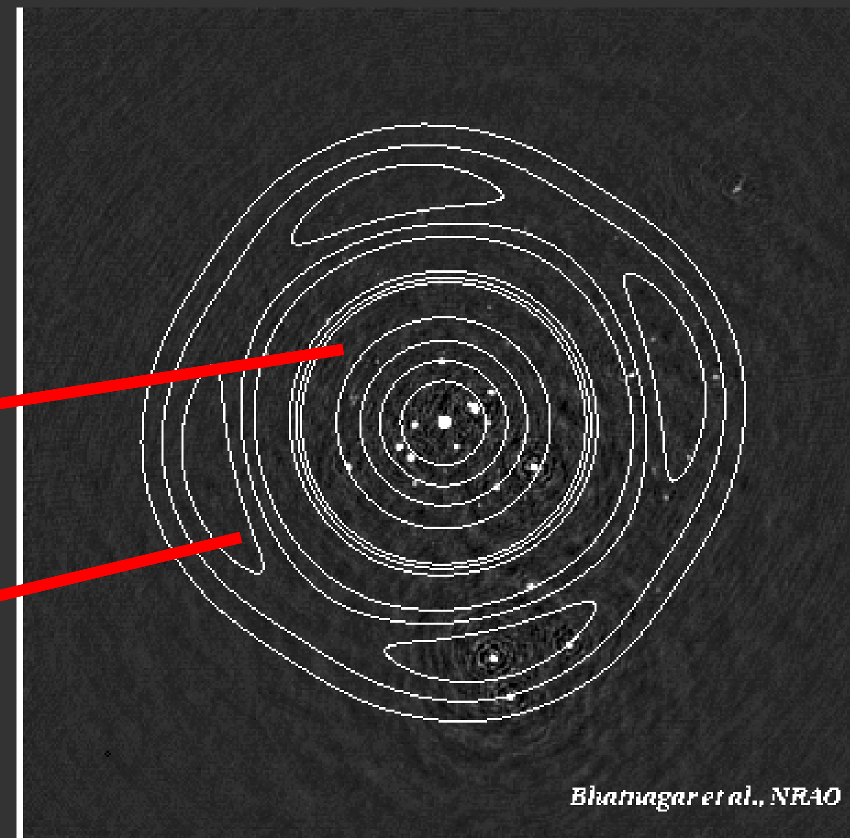
$$F\ X_{ij}\ V_{ij}^{DI-Cal} = F\ V^{True} = I^{True}$$

X encodes the Physics of the problem

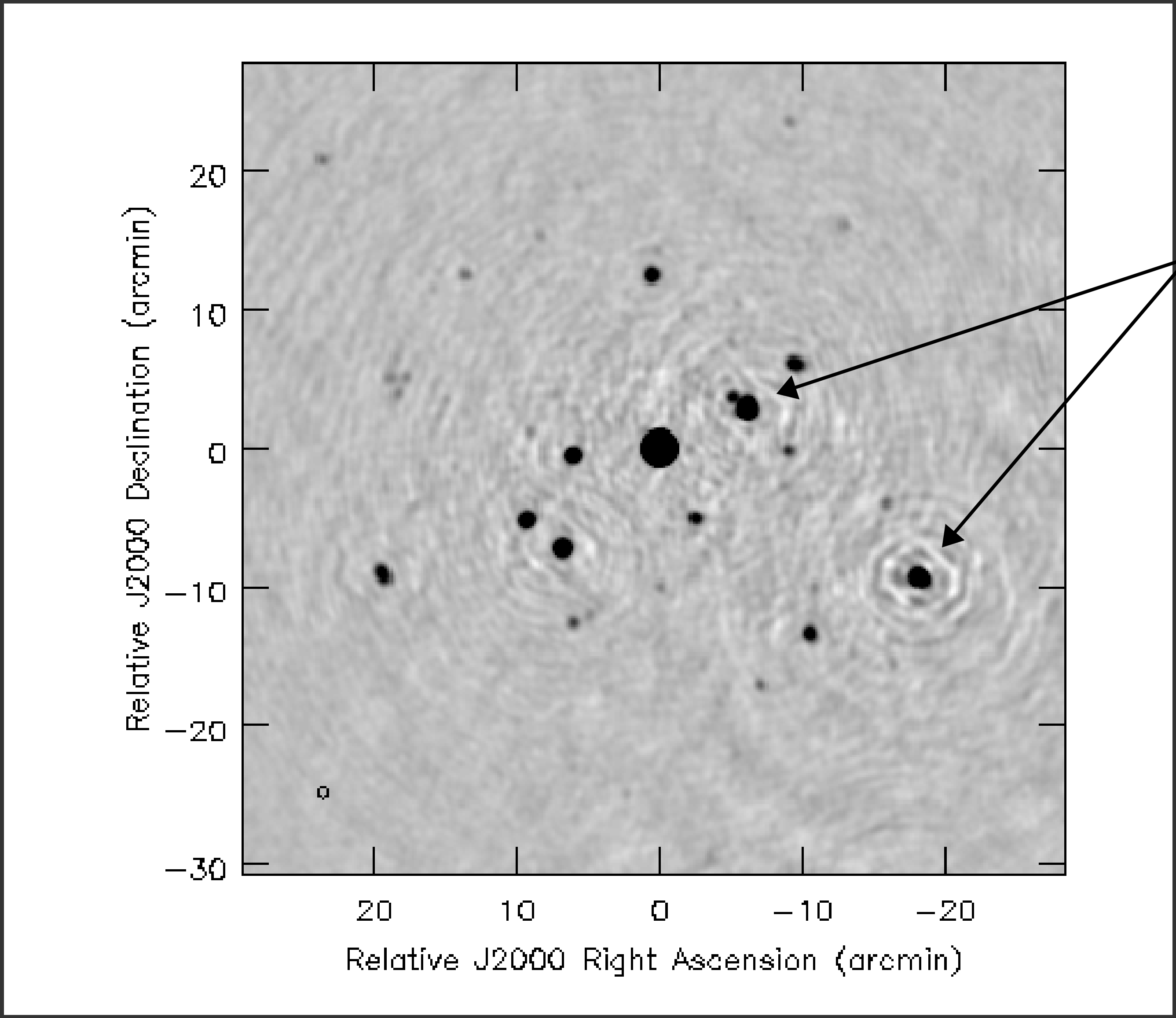
Time dependent terms

- Antenna PB ($The \quad P_{ij}(s,\nu,t)$)
  - Time dependence





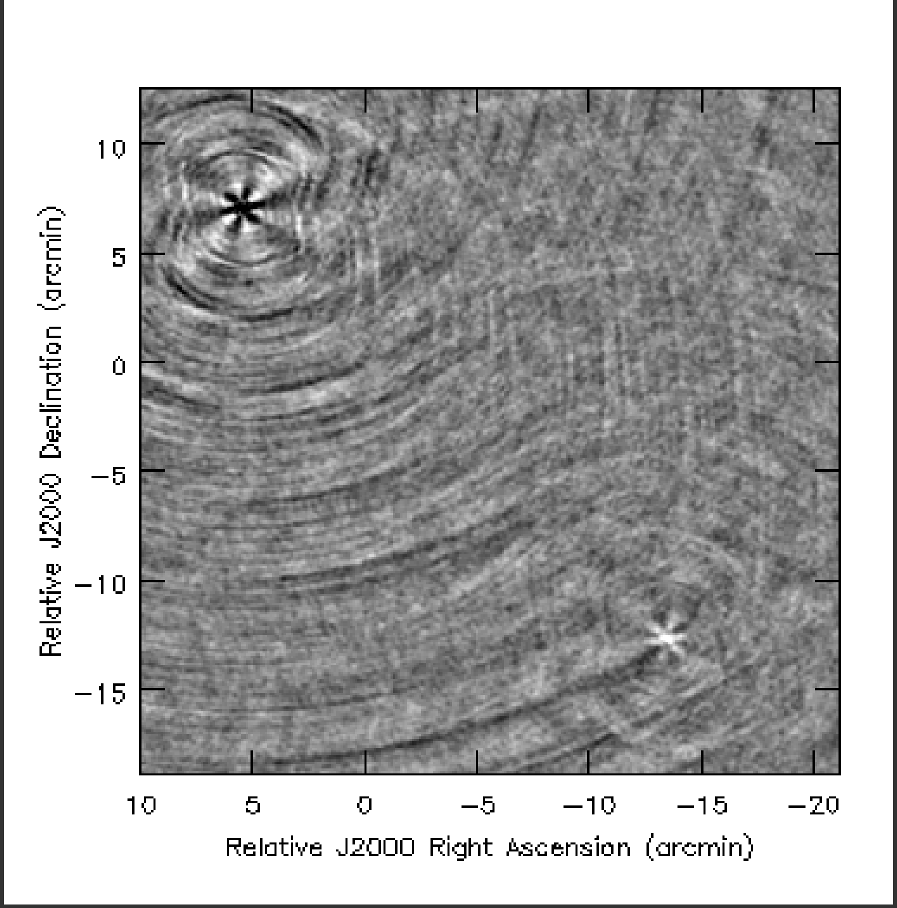
Time+Polarization dependence



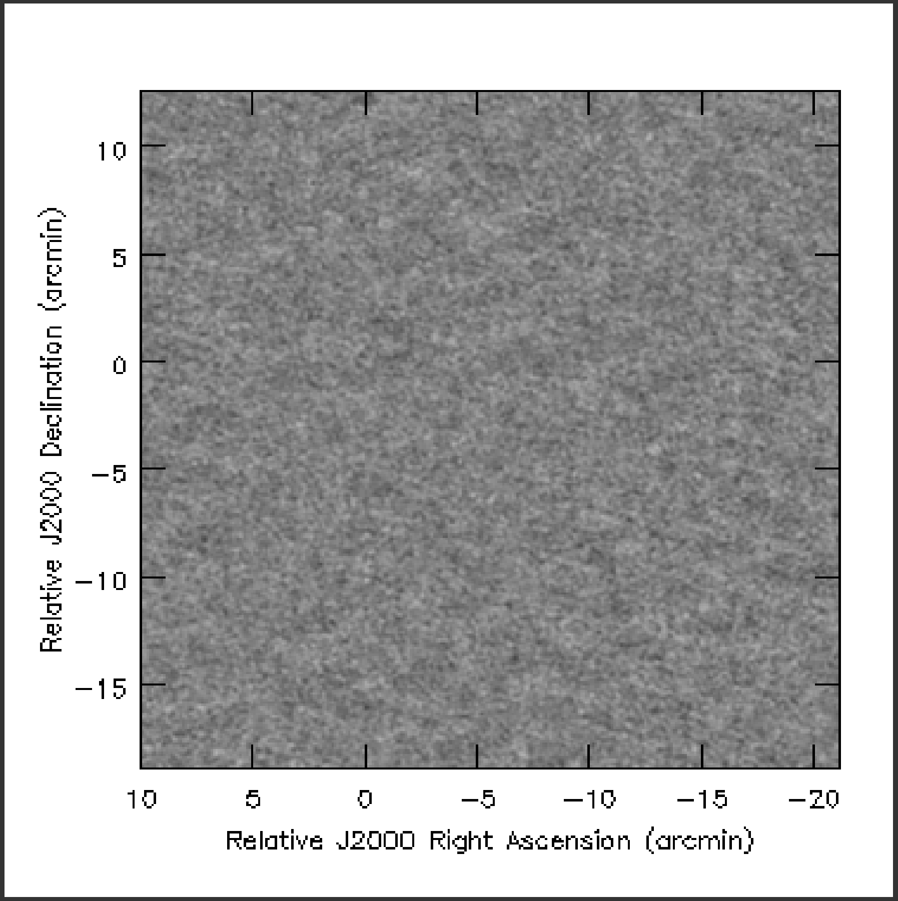
Errors due to PB Squint + Rotation + Pointing errors

PB Polarization Effects

Stokes-V Images



A-Projection →

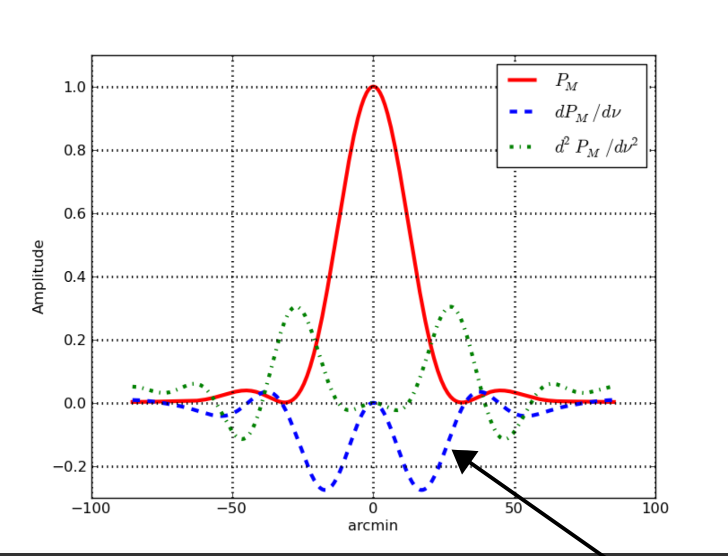


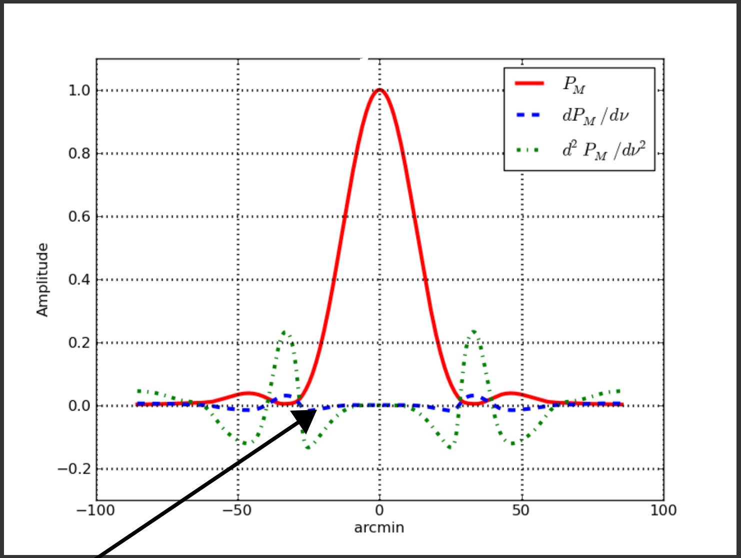
- L-Band VLA imaging
- DR ~ 10^4

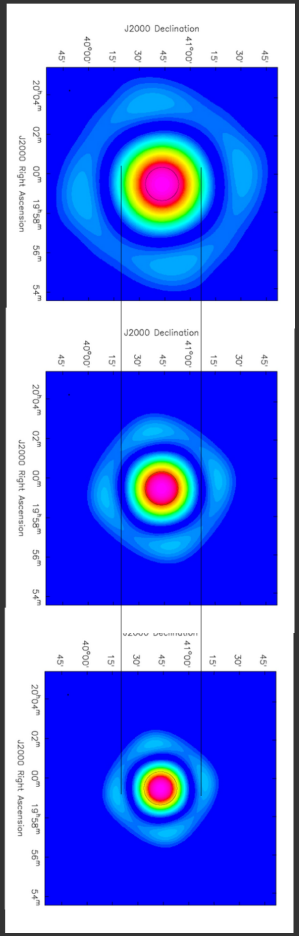
Wide-Band AW-Projection

- Correct for frequency dependence of the PB effects
  - Polarization: Squint + in-beam polarization

$$I^{continuum} = \int P_{ij}(s, \nu, t)\; I(s, \nu)\; d\nu$$







PB Frequency dependence (blue curve)

WB AW-Projection + MT-MFS

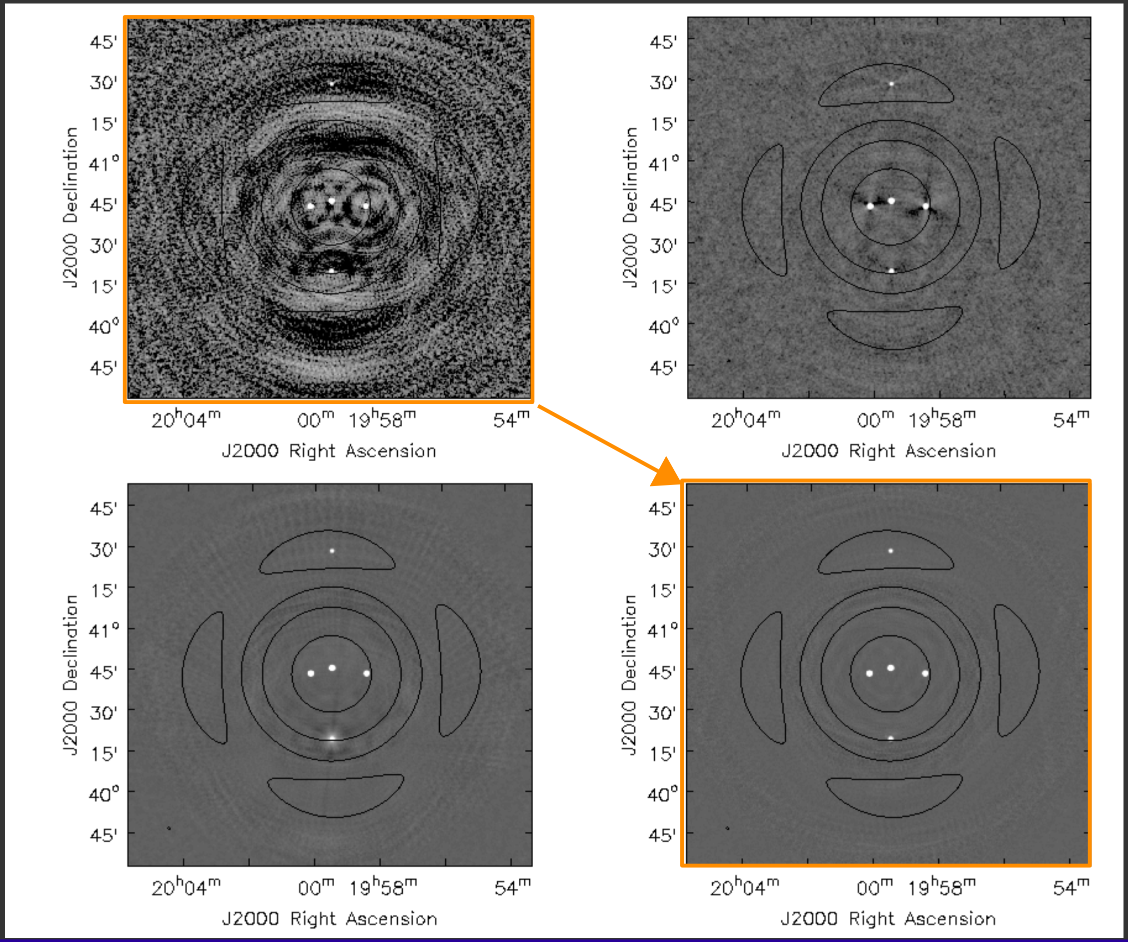
- Simultaneously account for the PB effects and frequency dependence of the sky
  - PB effects corrected by WB A-Projection
  - PB-corrected image used in MT-MFS for model the frequency dependence of the sky brightness

MFS+SI

MT-MFS+SI

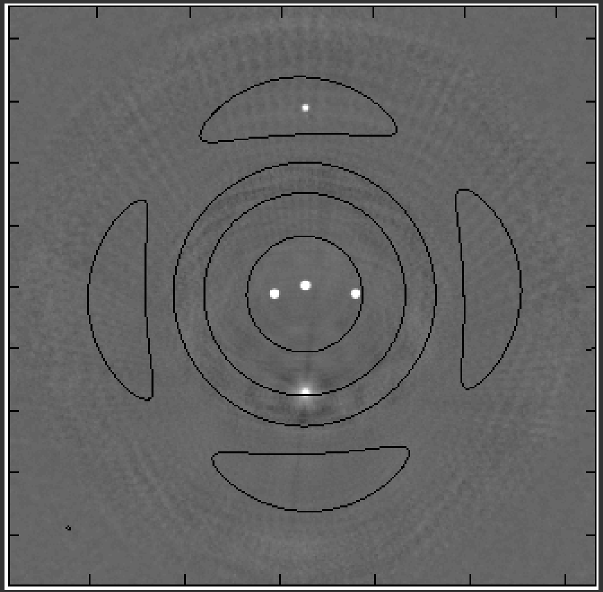
MT-MFS+
A-Projection

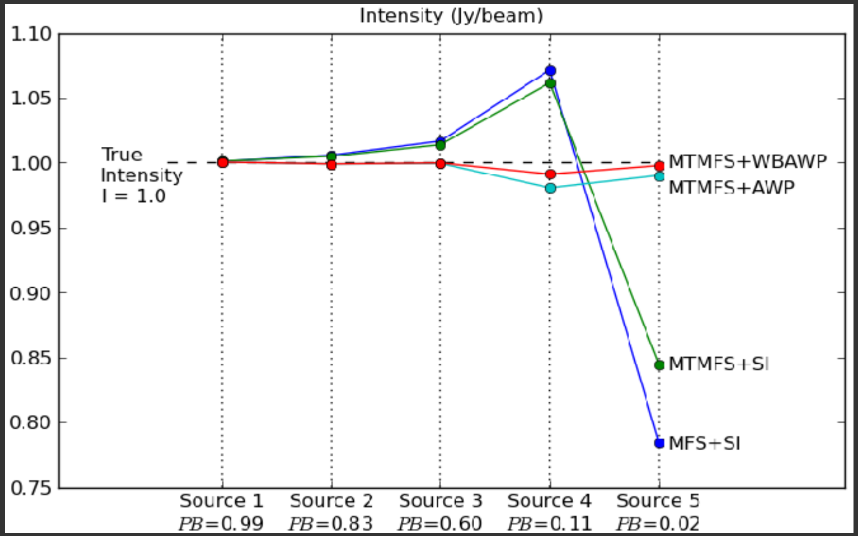
MT-MFS+
WB A-Projection

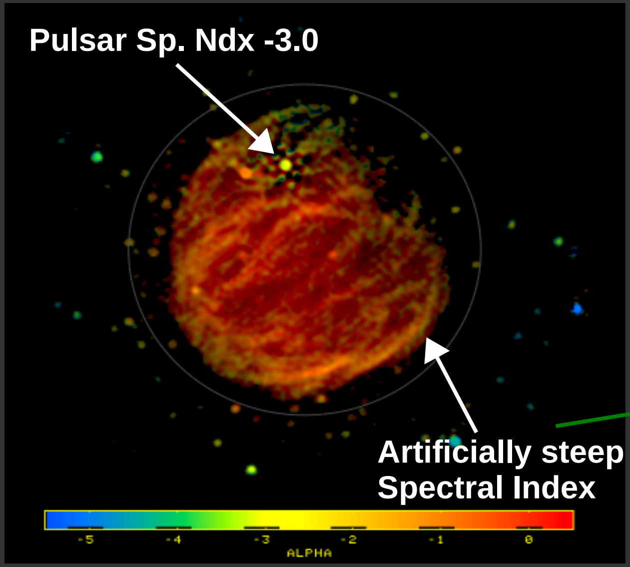


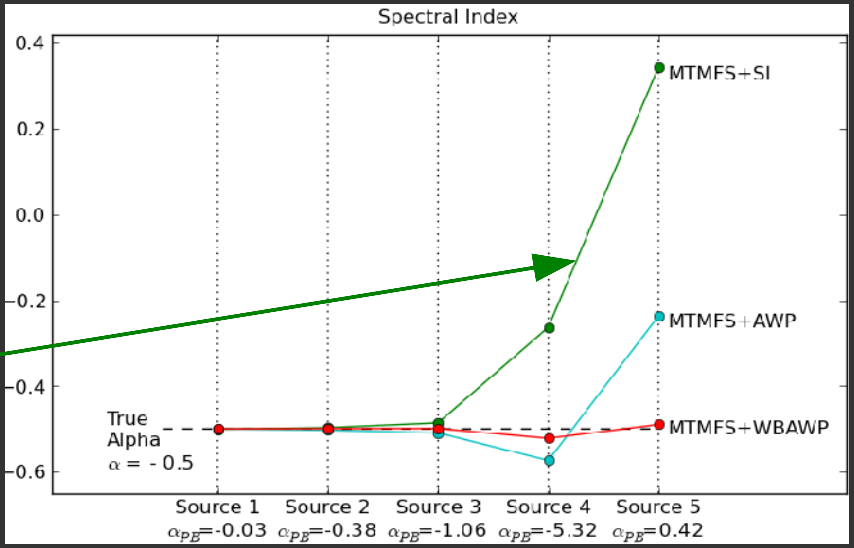
Ap.J., 2013

Instrumental frequency dependence









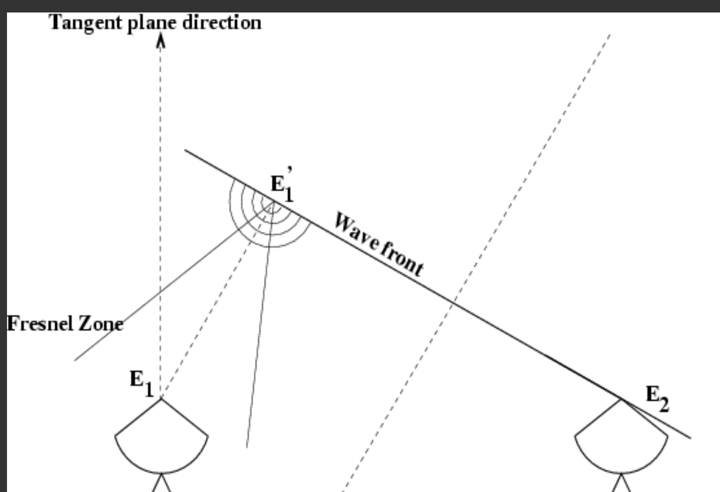
Non co-planar baselines: W-Term

- Imaging

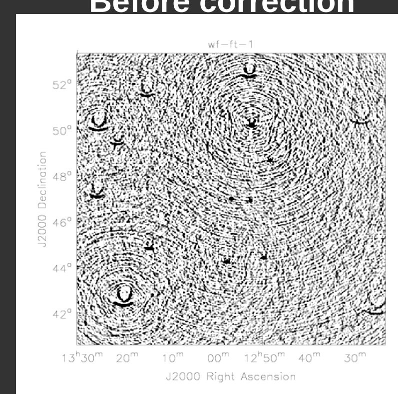
$$V_{ij}^{DI-Cal}(\nu) = W_{ij} \int P_{ij}(\mathbf{s},\nu,t)\; I(\mathbf{s},\nu)\; e^{\iota\, \mathbf{s}.\mathbf{b}_{ij}}\; d\mathbf{s}$$

Data | DI Calibration | DD Term Instrumental Ionospheric | Sky | **Geometry**

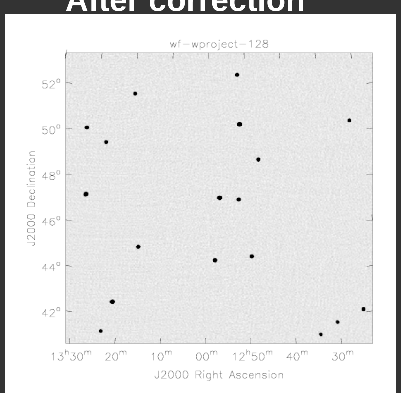
- The geometric term (non co-planar baselines)
  - Transform is no more 2D Fourier Transform



Before correction



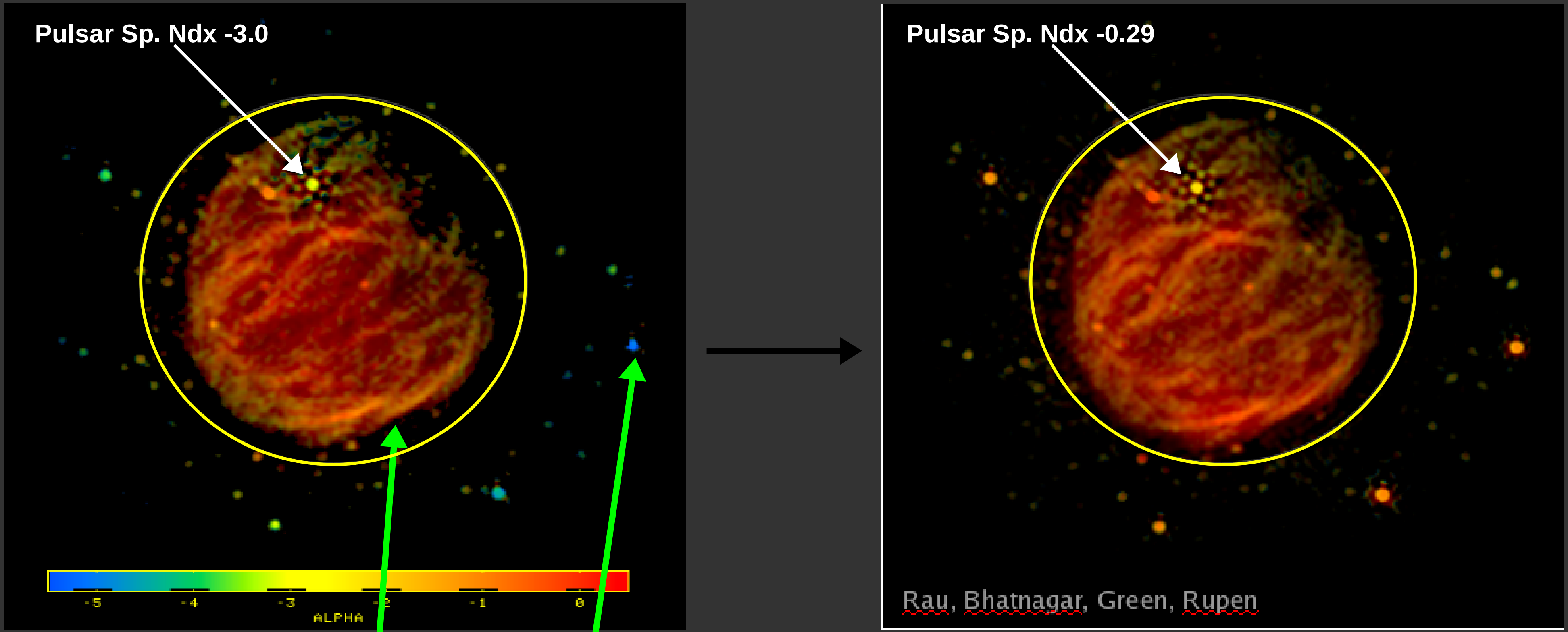
After correction



NRAO

Wide-Band AW-Projection + MT-MFS

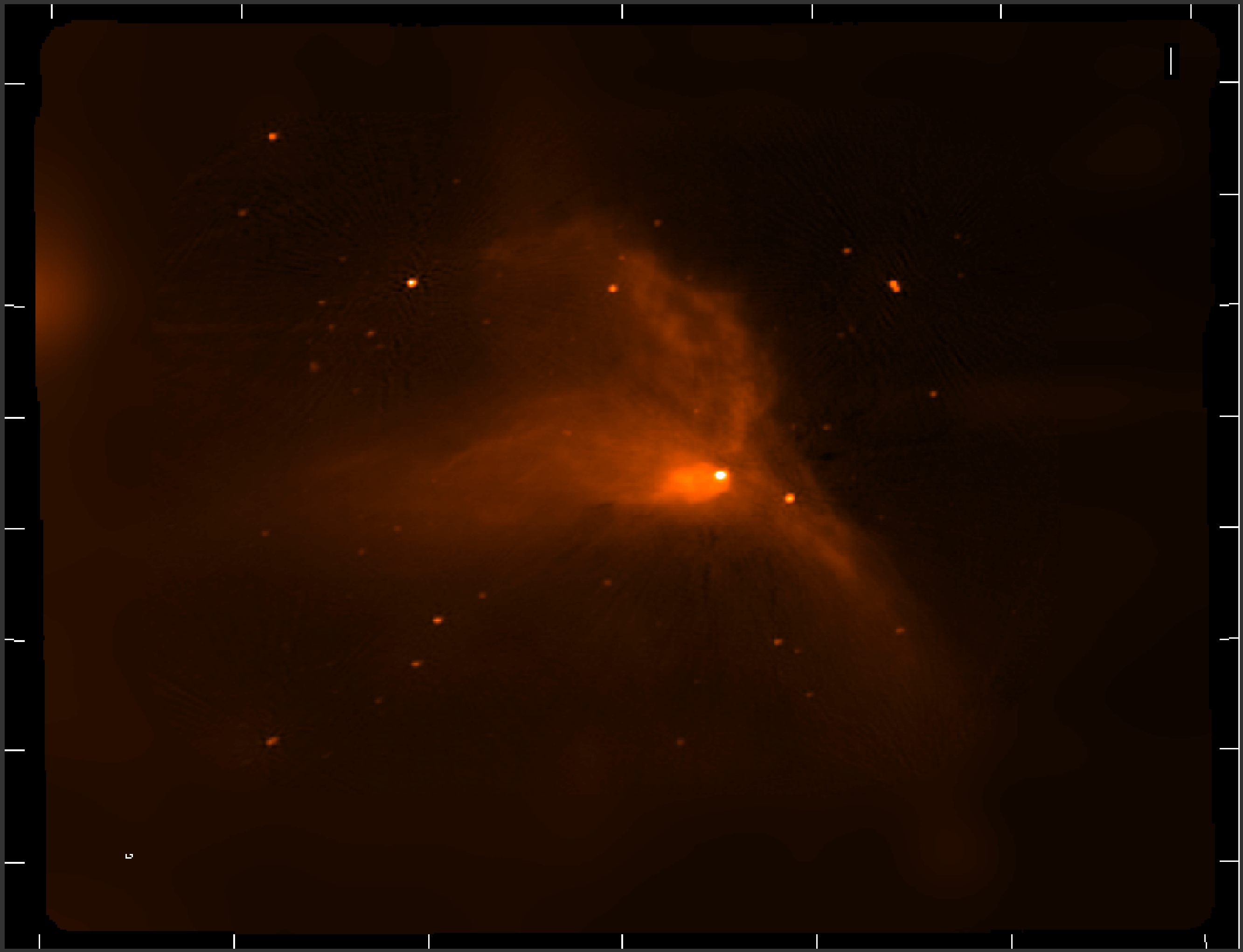
- Intensity weight Spectral Index Map
- Wide-field Spectral Index maps comes out in the wash correctly



Artificially steep (due to PB)

A&A, 2008, ApJ, 2013

Wide-band Mosaic Imaging + SD



- Simultaneous corrections for instrumental effects+ Frequency Dependence of the Sky
- WB AW-Projection + MS-MFS + Mosaic
- Wide-band ~200-pointing mosaic
- EVLA + GBT Feathering (existing algorithm)
- In progress:
  - Mosaic spectral Index mapping
- Parallel execution / Optimization /
- Numerical tests

Status: In production or commission stage

- W-Term correction: Dominant DD term at low frequencies
  - Facted-imaging, W-Projection, W-Stacking
- Extended emission
  - MS-Clean, Asp-Clean, various variants
- Frequency dependence of the sky brightness
  - MT-MFS
- PB corrections
  - A-Projection: Time and polarization dependence
  - WB A-Projection: Also frequency dependence

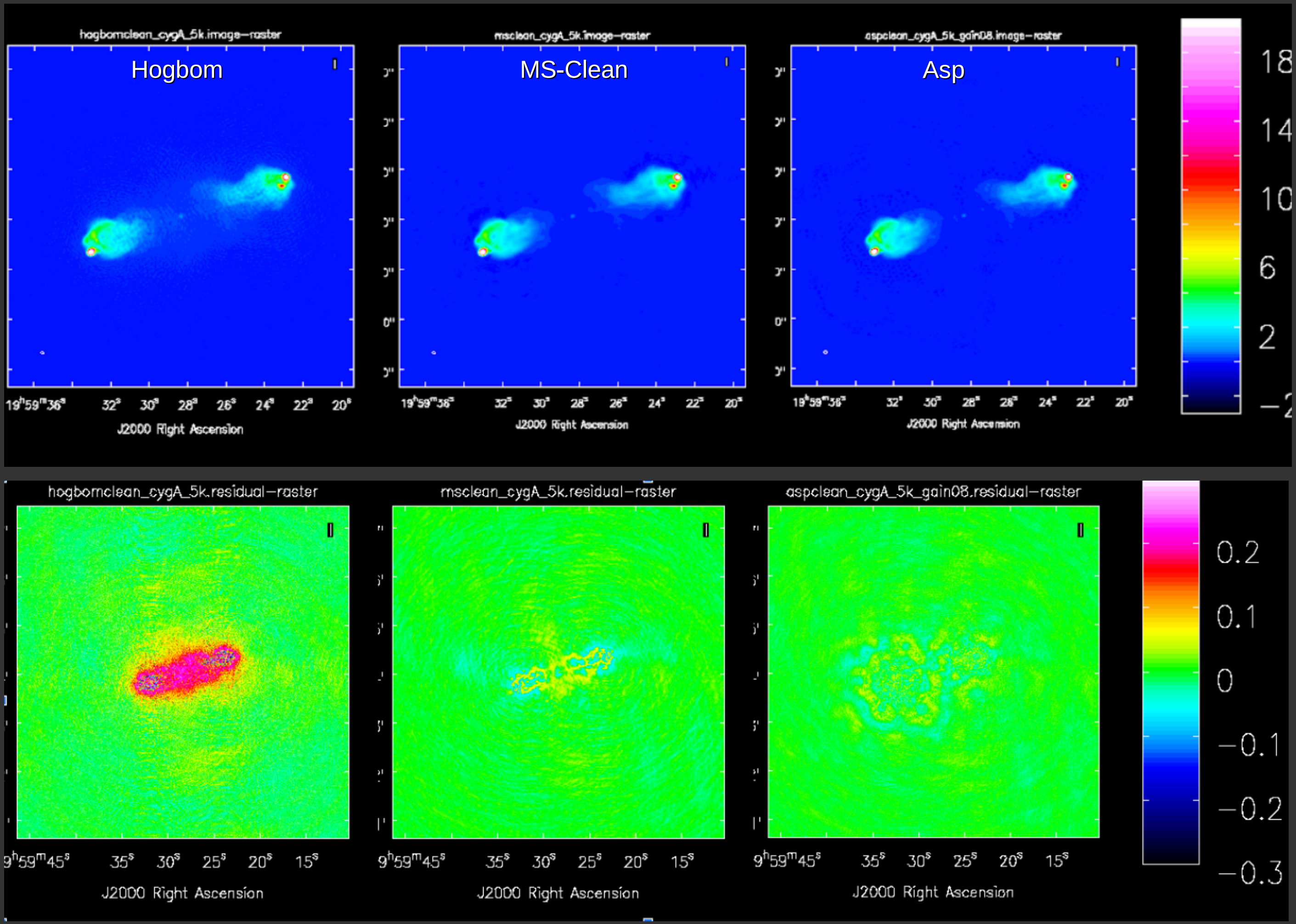
- Recently Commissioned:
  - `W-Term + WB A-Projection + MT-MFS`
    - » Simultaneously account for instrumental and sky terms
  - `Wide-band Mosaic`
    - » All of the above for mosaic imaging (e.g. VLASS)

Status: In active R&D

- Improved scale-sensitive deconvolution algorithms
  - Asp-Clean, WAsp (Wide-band Asp-Clean)
- Full-polarization imaging
  - Extend PB correction to full polarization
  - RM Synthesis at the sensitivity and band-width now available
- Parallelization
  - Many projects takes weeks of computing for imaging
  - Cluster computing: High Performance Computing (HPC), High Throughput Computing (HTC)
  - CPUs, GP-GPUs, FPGAs,...

Asp imaging algorithms

- Adaptive Scale Pixel (Asp): Scale-sensitive image reconstruction of complex emission
  - Asp-Clean: Narrow-band implementation, now in production-CASA
  - WAsp: Wide-band Asp

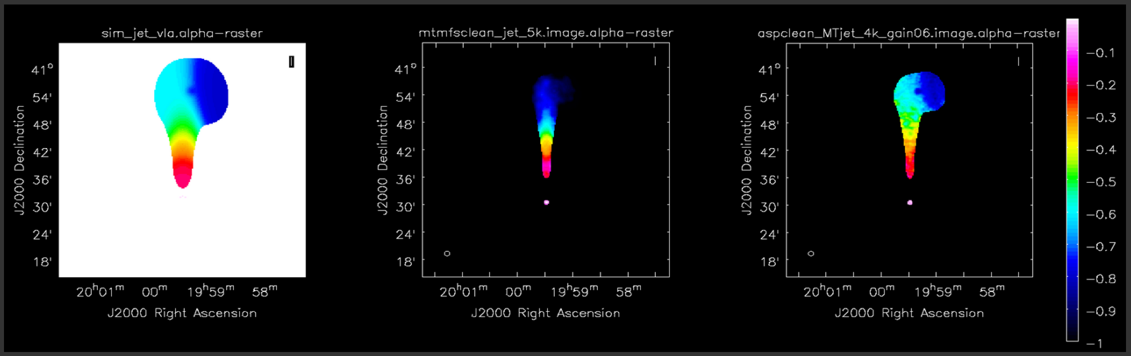


WAsp imaging algorithms

- Adaptive Scale Pixel (Asp): Scale-sensitive image reconstruction of complex emission
  - WAsp: Wide-band Asp

MS-MT-MFS WAsp

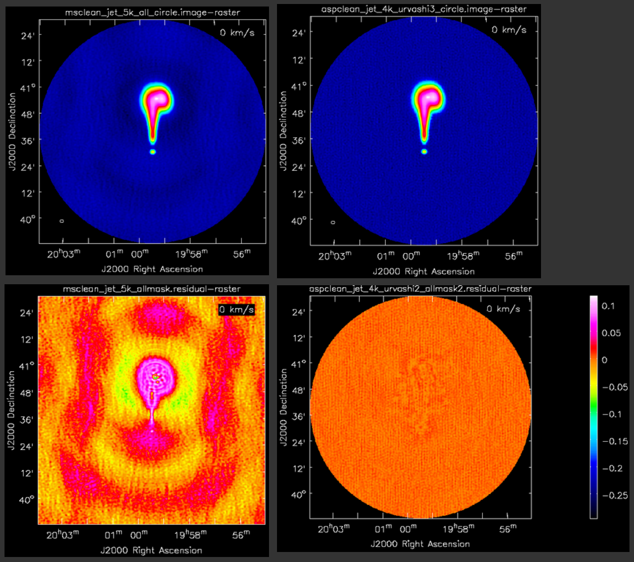
Spectral Index Mapping



MS-MT-MFS WAsp

Stokes-I

Residual



Computing Cost

- Imaging + deconvolution accounts for >90% of the computing cost in a "typical" end-to-end processing

DataArchive → Flagging/Calibration → Imaging-Deconv. → ImageArchive

- Computing Scaling
  - Computing costs: $N^2_{support} \times N_{vis}$: Dominated by Image-making (a.k.a. the "Major cycle")
  - Memory footprint: $N^2_{Scales} + N^2_{Terms}$: Dominated by Deconvolution (a.k.a. "Minor Cycle"

- Large cluster with cheaper CPU/GPU and small memory for the Major cycle

  Faster computers with lots of memory for the Minor Cycle

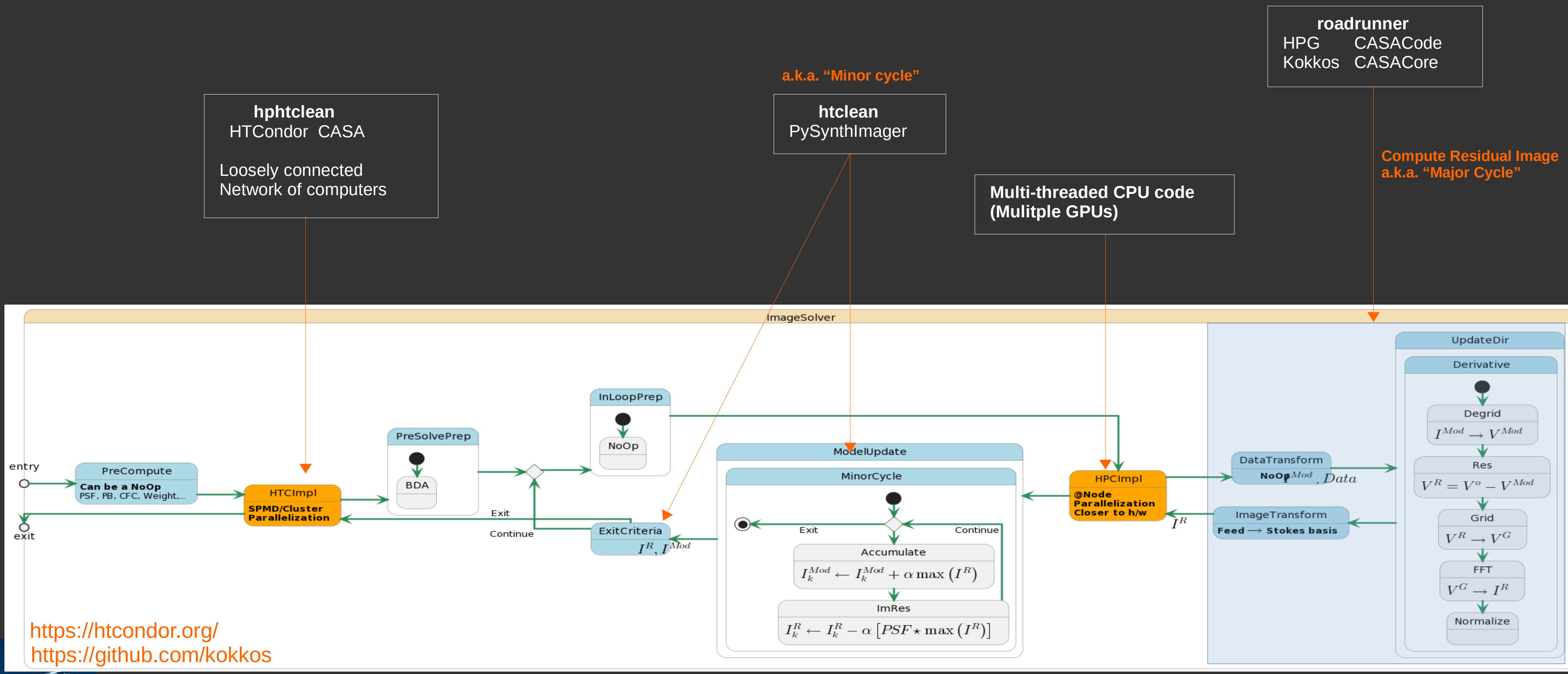
- Imaging : Pleasantly Parallel (a.k.a "Embarrassingly parallel")
  - Scatter-Gather paradigm on the Cluster scale

Scale of computing

- Estimates of the size of computing
- ngVLA
  - 30 – 50 PFLOP/s
  - Currently the largest facility has about 40 PFLOP/s!
  - No. of CPU cores: O(Million)
    - » These have to run 24x7 to keep-up with the data rates!!
- SKA: Latest estimates are similar
- Available computing power:
  - A typical desktop: 0.1 TFLOP/s
  - A typical GPU: 10 TFLOP/s
- Utilization
  - Single-digit percentage is typical
  - 5-7% utilization of the CPU-cluster at NRAO

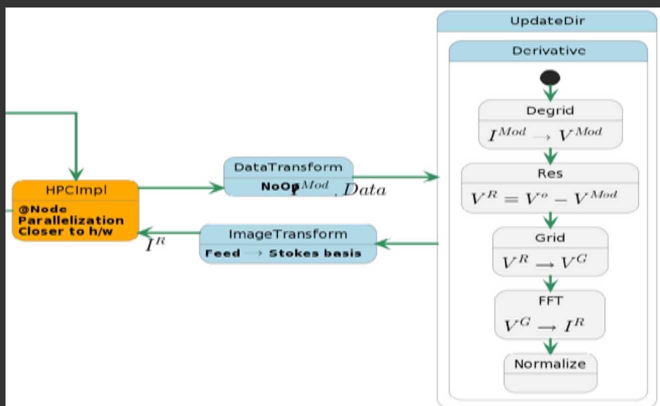
Algorithm Architectural Component

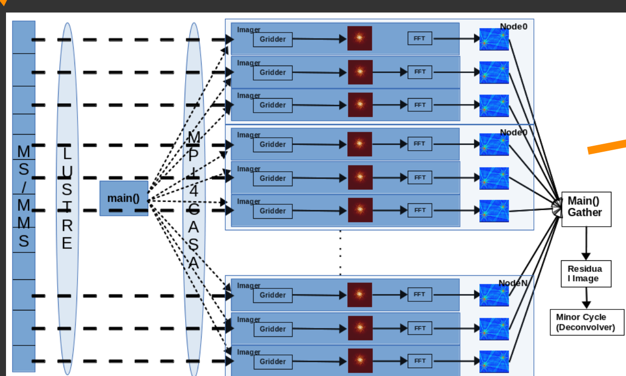
- Both, calibration and imaging as standard χ^2 minimization problem
- Specialization of the framework components deliver various calibration and imaging algorithms
  - Prototypes: CPU single/multi-cores, cluster, variety of GPUs,..., external GPU cluster

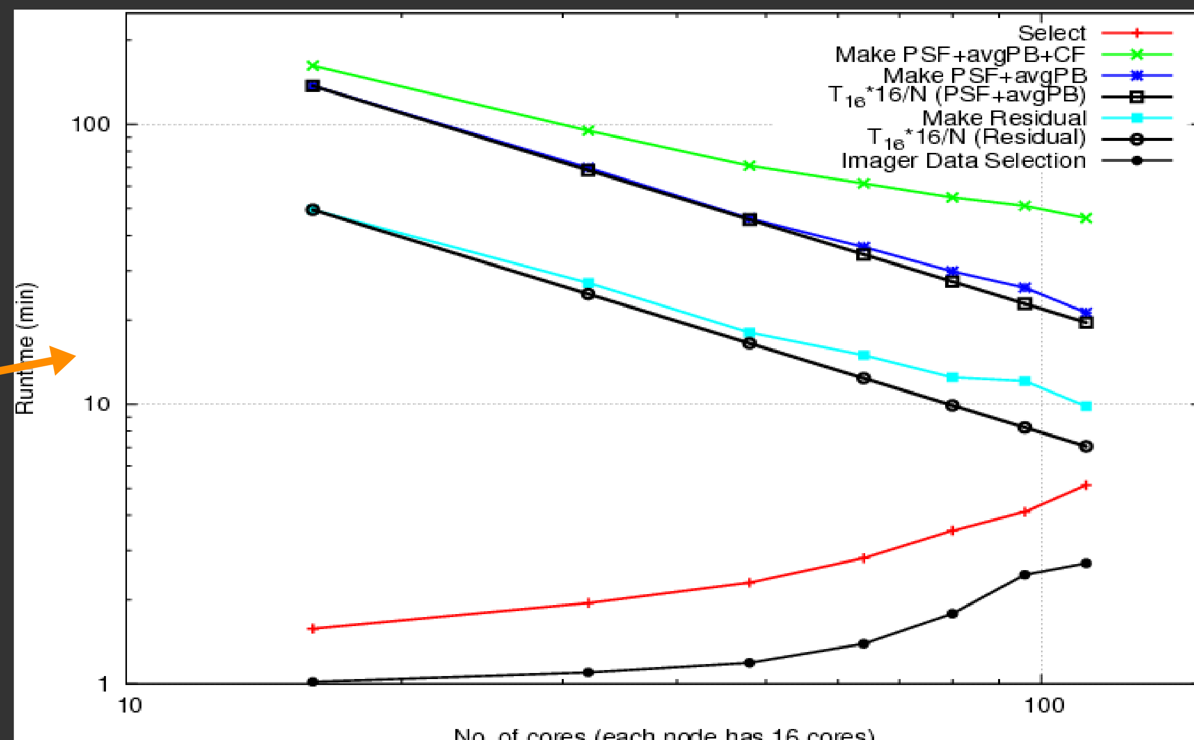


Parallel processing

- High Computational Intensity (FLOP per byte)
  - O(10^{2-3}) FLOP per data point. Number of data points: O(10^{12-15})



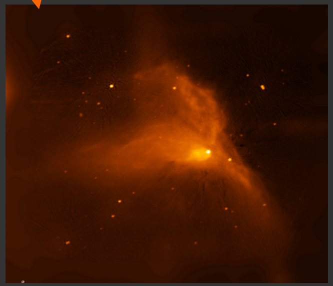


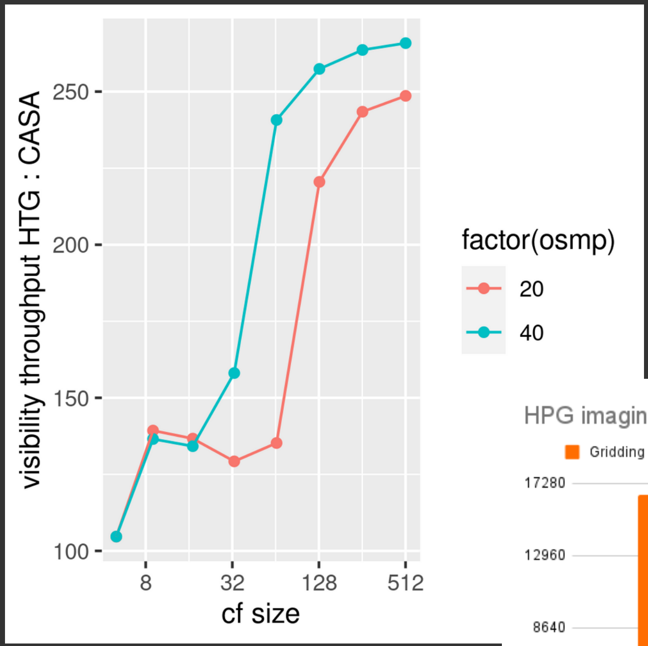


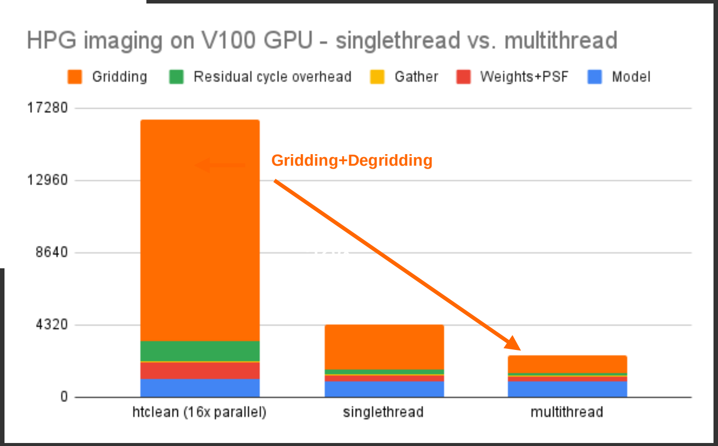
ngVLA will need O(Million)-way parallization!

High Performance Gridder

- A gridder on a GPU connected to a CPU host (NGVLA Memo #05, #07)
  - Measured speed-up: 100 – 200x compared to a single CPU core
  - 200-pointing wide-band mosaic: 7-10 days (parallel tclean) vs 2.5hr (HPG)



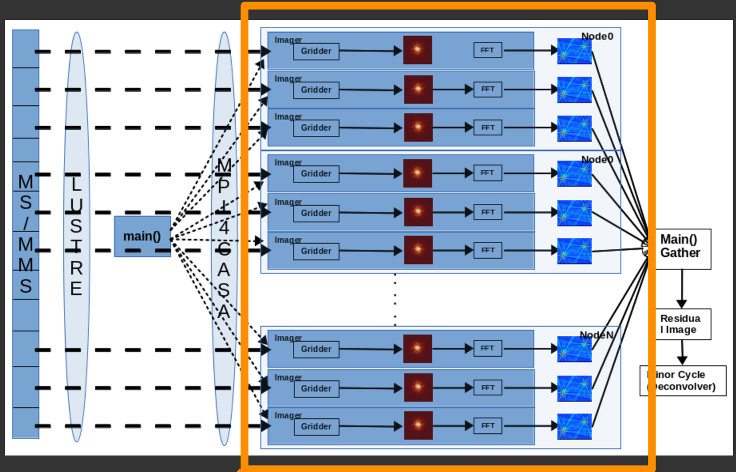




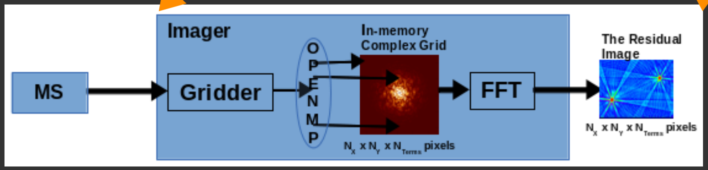
Multi-core CPU

Single CPU-core +GPU

Multi CPU-cores +GPU



runtime complexity reduction

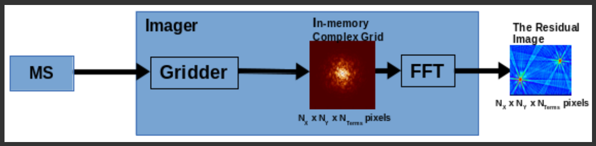


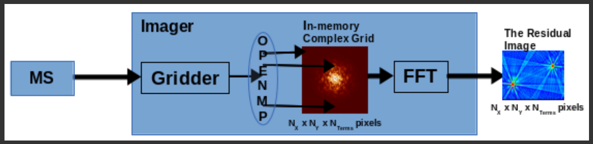
Scientific S/W Complexity

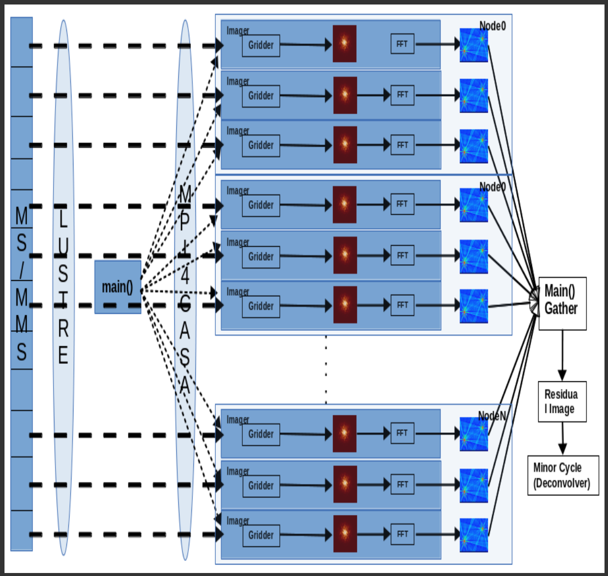
- Imaging is embarrassingly parallel
  - SAMD parallelization architecture measures high efficiency
  - In-coherent gather is OK

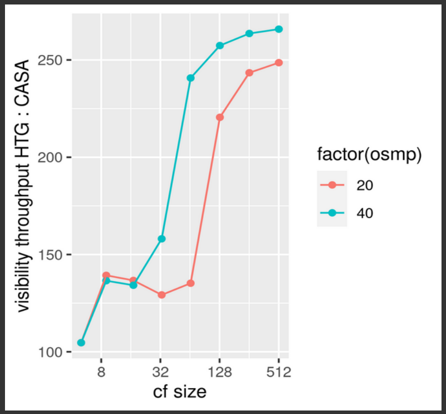
$$I^D=\sum_p FXG_pV_p \quad \text{or} \quad F\sum_p XG_pV_p \quad \text{or} \quad FX\sum_p G_pV_p$$

Node s/w complexity

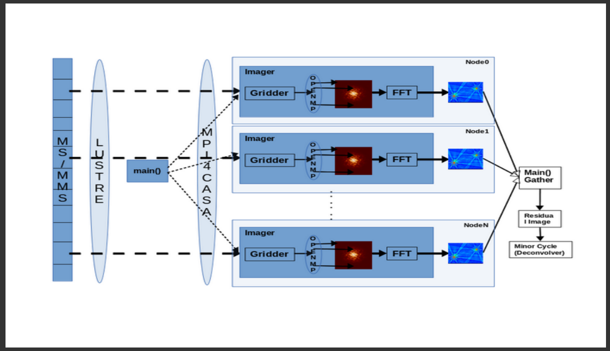








100-200x fewer processes



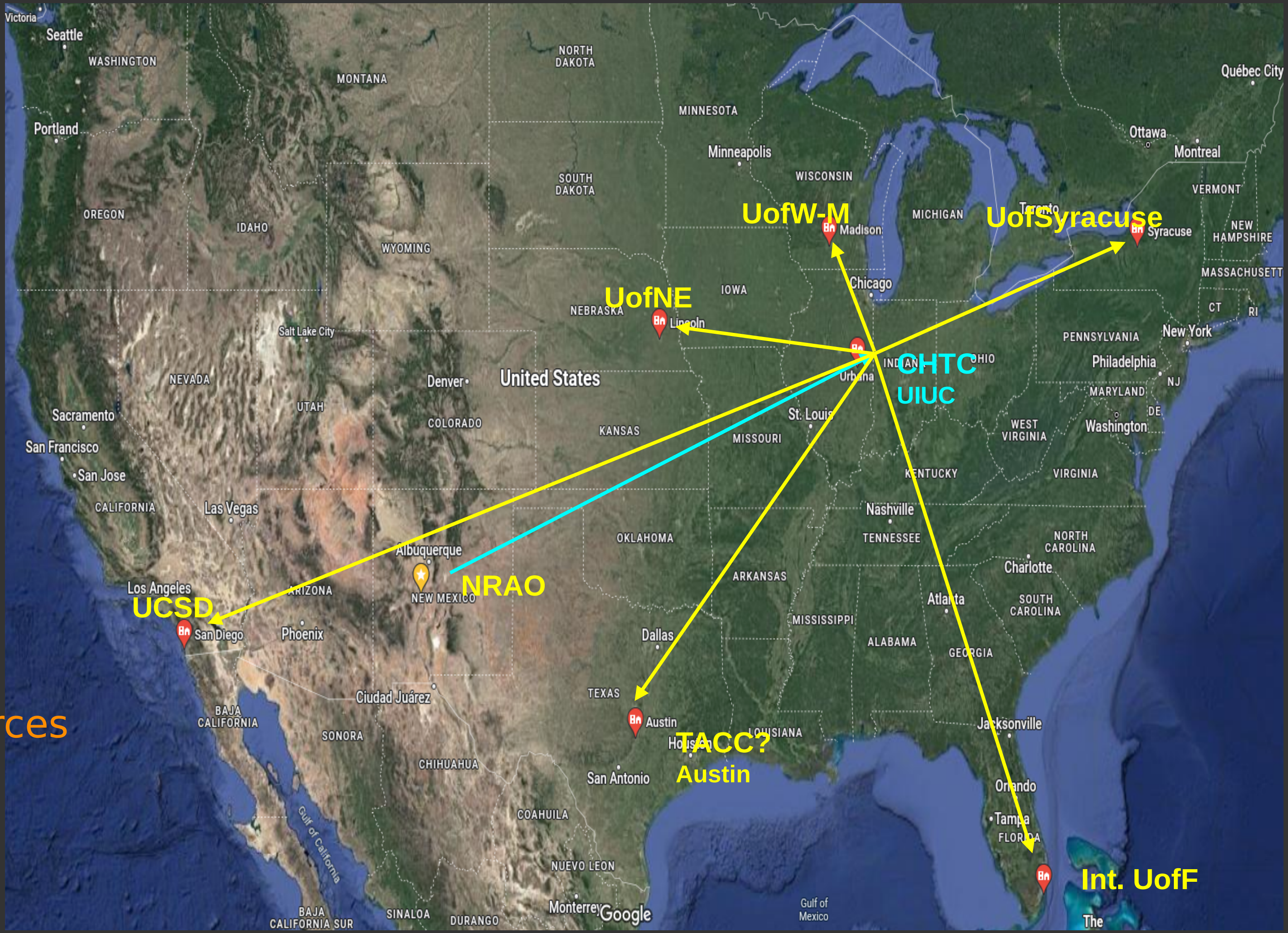
Complexity reduction

O(Million) **$O(10^3)$**

High Throughput Computing Prototype

- <u>Computing at a national scale</u>
- Breakup into smaller problems
- Trigger from NRAO, deploy nationally
- Execute as-n-when resources become available.

Using the HTCondor scheduler software
https://htcondor.org/



- <u>Work in progress</u>
- Get more resources
- Improve reliability, usability of h/w and s/w
- Use international resources

Challenges

- Algorithms
  - Wide-band RM Synthesis
  - DD Solvers: Ionospheric screen
  - Efficient multi-scale algorithms for both imaging & deconvolution

- Computing
  - Optimal use of available computing resources
  - Use of (massively) parallel hardware
    - Multi-core CPUs, GP-GPUs
  - Memory footprint
  - Data I/O: SKA-, ngVLA-class problem
    - Algorithms are fundamentally iterative

Computing Cost

Re-sampling: Uses all data

The Major Cycle

Gridding + Degridding + FFT

Only images

The Minor Cycle

Deconvolution (Hogbom,, MS-Clean, MT-MFS, Asp-Clean,...)

Model the measurements (telescope, ionosphere, etc.)

Projection algorithms

Images corrected for instrumental artifacts

Model the sky brightness distribution

Image modeling (a.k.a. “deconvolution”)

Computing Cost

Standard Imaging

Standard deconvolution

Computing Cost

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Computing Cost

Advanced deconvolution: MS, MT-MFS, MS-MFS

Standard Imaging

Computing Cost

Re-sampling: Uses all data

The Major Cycle

Gridding + Degridding + FFT

Only images

The Minor Cycle

Deconvolution
(Hogbom,, MS-Clean, MT-MFS,
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Model the measurements
(telescope, ionosphere, etc.)

Projection algorithms

Images corrected for instrumental artifacts

Model the sky brightness distribution

Image modeling (a.k.a. “deconvolution”)

Computing Cost

Advanced Imaging: W-, A-, AW-Proj., Heterogeneous, WB

Standard deconvolution

Computing Cost

Re-sampling: Uses all data

The Major Cycle

Gridding + Degridding + FFT

Only images

The Minor Cycle

Deconvolution
(Hogbom,, MS-Clean, MT-MFS,
Asp-Clean,...)

Model the measurements
(telescope, ionosphere, etc.)

Projection algorithms

Images corrected for instrumental artifacts

Model the sky brightness distribution

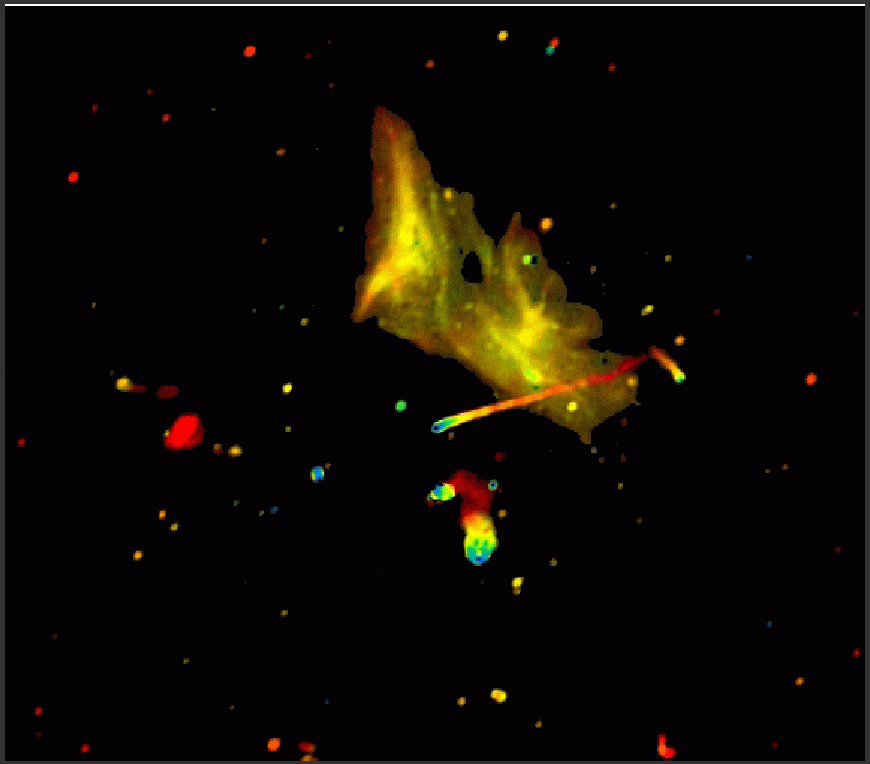
Image modeling (a.k.a. "deconvolution")

Computing Cost

Advanced Imaging: W-, A-, AW-Proj., Heterogeneous, WB

Advanced deconvolution: MS-, MT-MFS, MS-MFS

Imaging with the EVLA @ L-Band



Single pointing, wide-band image

Wide-band ~200 pointing mosaic+Single Dish