# Components of Imaging at Low Frequencies: Status & Challenges

**Dec. 12th 2013**

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NRAO

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# Telescope sensitivity

- Noise limit for imaging with interferometric radio telescopes

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

- Sensitivity improvements achieved by

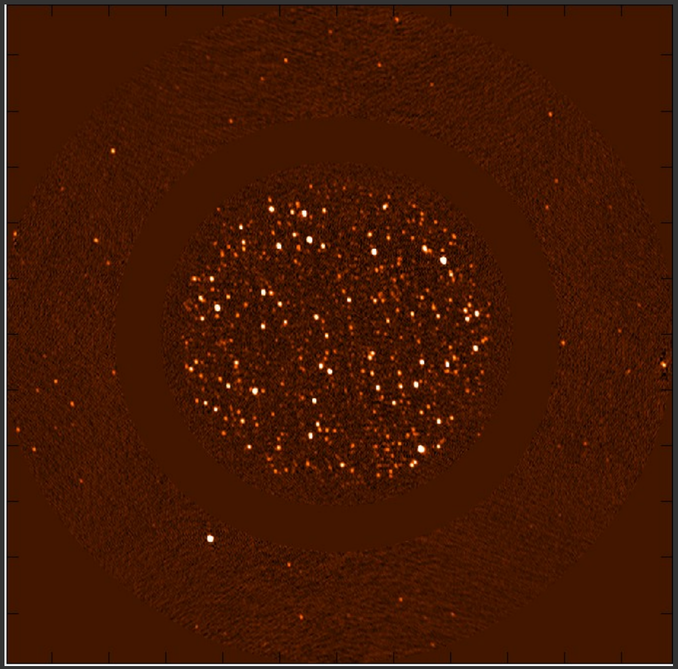
$\Delta\nu$ : *Wide band receivers: >60% fractional bandwidth*

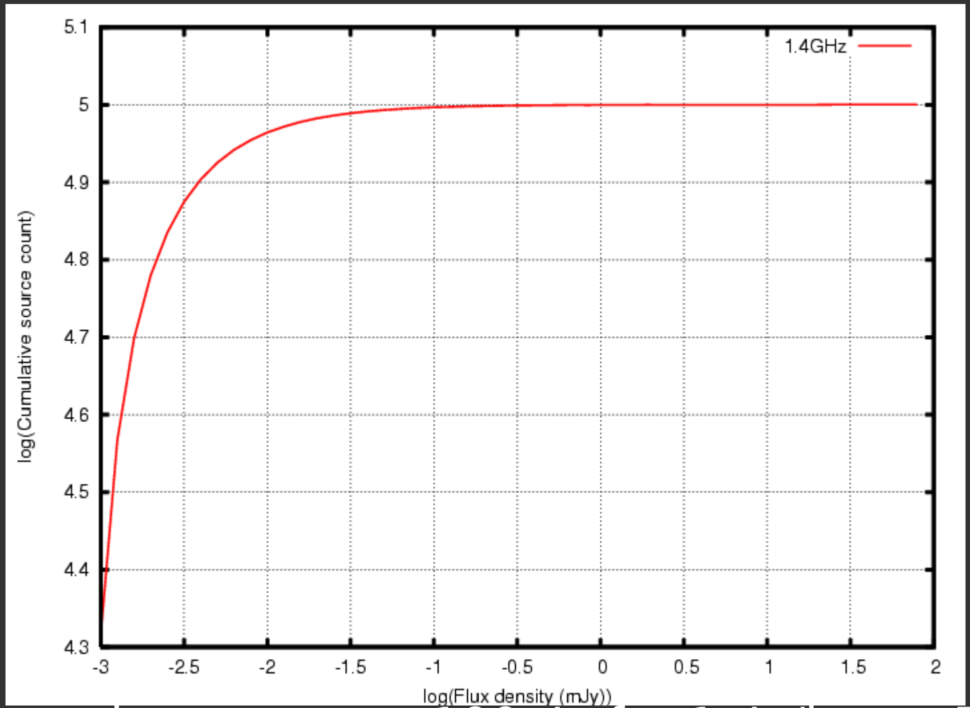
$\Delta T$ : *Long integration times: many hours -- months*

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

*Long baselines: To beat confusion limit*

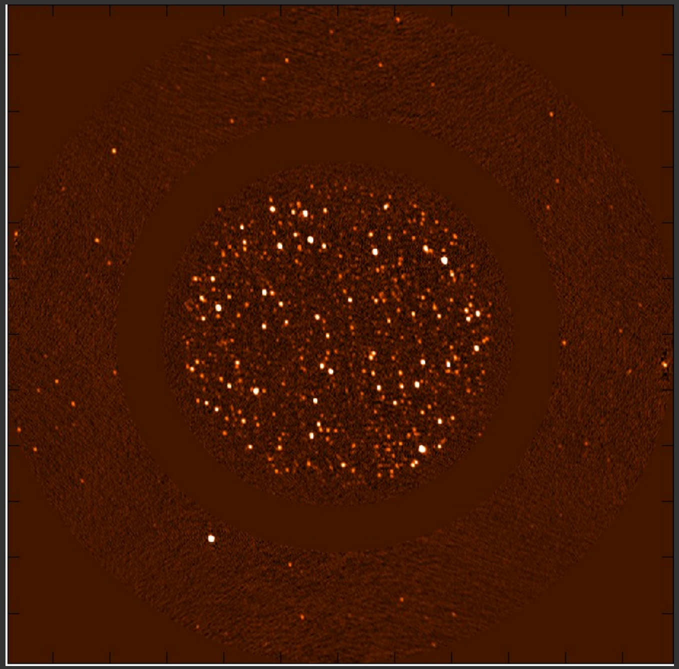
# Sky at low frequencies: No. of sources

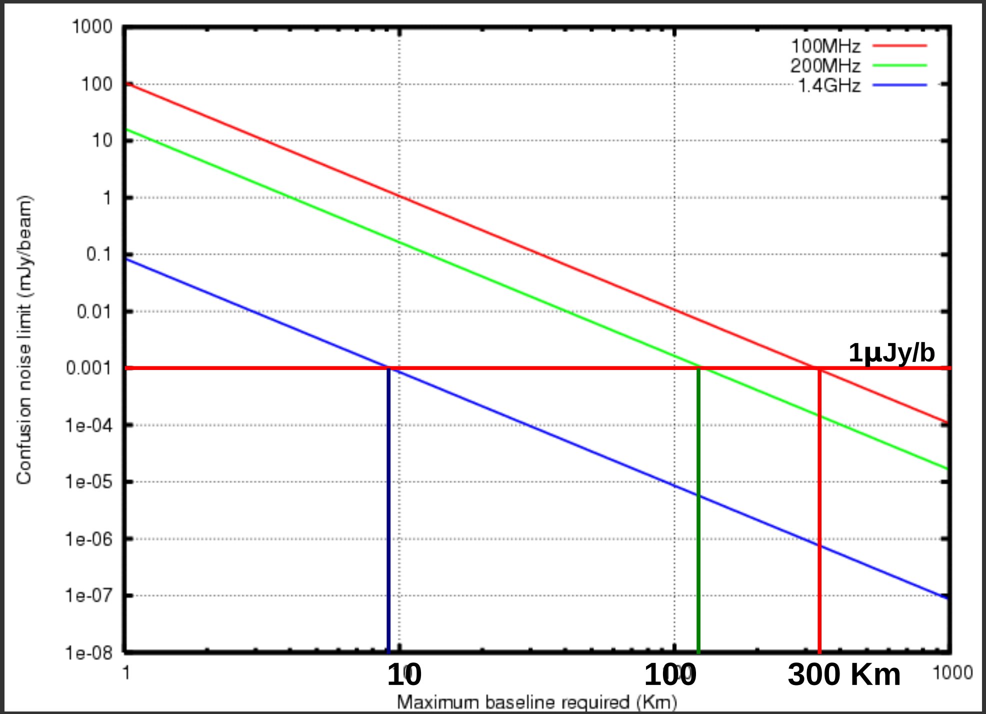





- PSF side-lobe at 1% level → deconvolve sources >100µJy for 1µJy/beam RMS
- $10^{4\text{-}5}$ sources per deg$^2$ >10µJy @1.4GHz
  - Source size distribution important at resolution < ~2"
- Implications for imaging
  1. Wide-field imaging
  2. HDR imaging: few X 100 mJy – 1 Jy source ~few sq. deg.
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

# Sky at low frequencies: Confusion limit

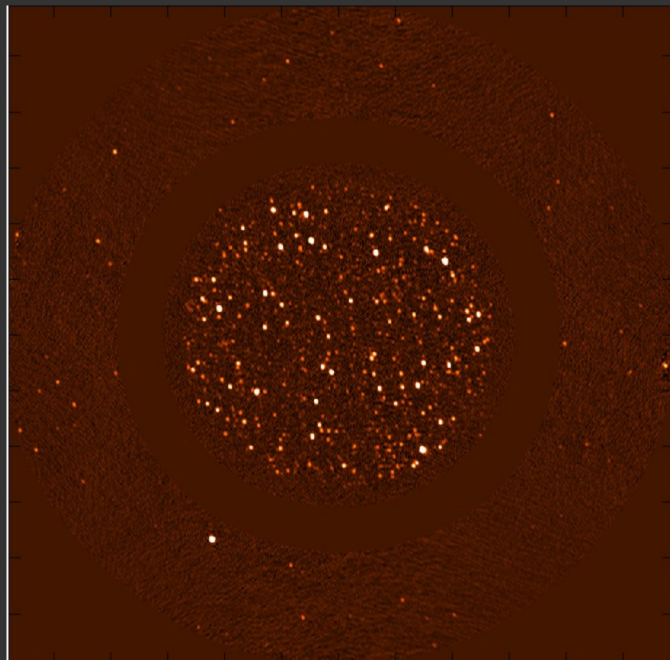


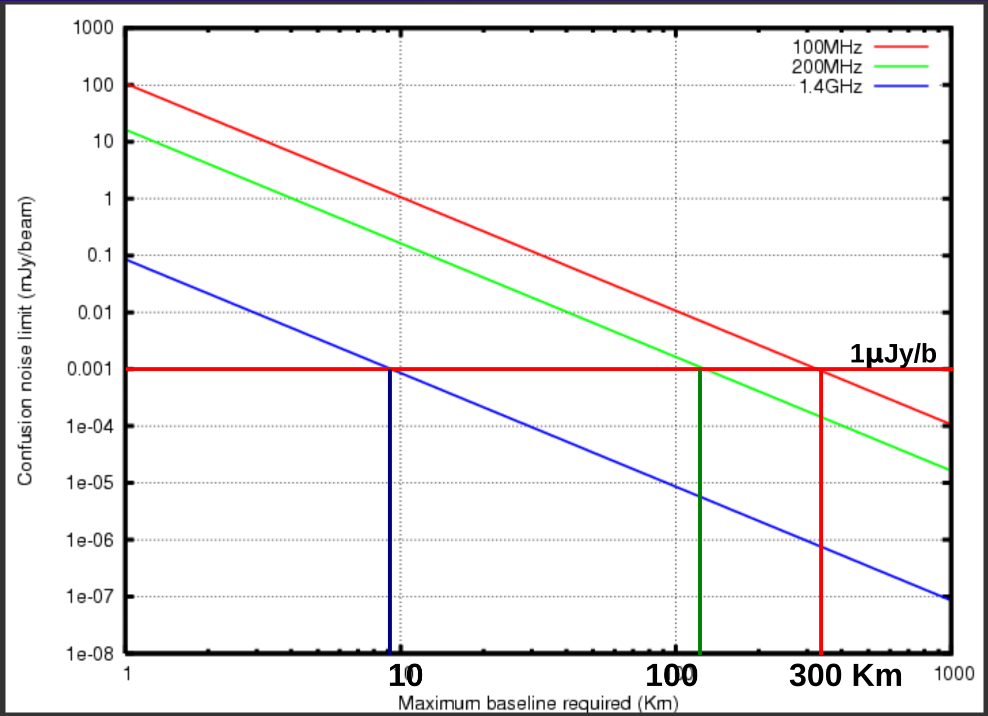



- $\sigma_{confusion} \propto ( \nu^{-2.7}/B^2_{max}) : B_{max}$ ~100 Km at 200MHz for $\sigma_{confusion}$ ~ 1µJy/beam
- Implications for imaging
  1. Long baselines: $B_{max}$ > 2-3 Km & DR > $10^4$
  2. Wide-field effects: W-term, PB effects, ionospheric effects
  3. Larger data volume

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

# 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 fo
  1. Long
  2. Wide- effects
  3. Large

Point source sensitivity 1-sigma 12hr. Synthesis:

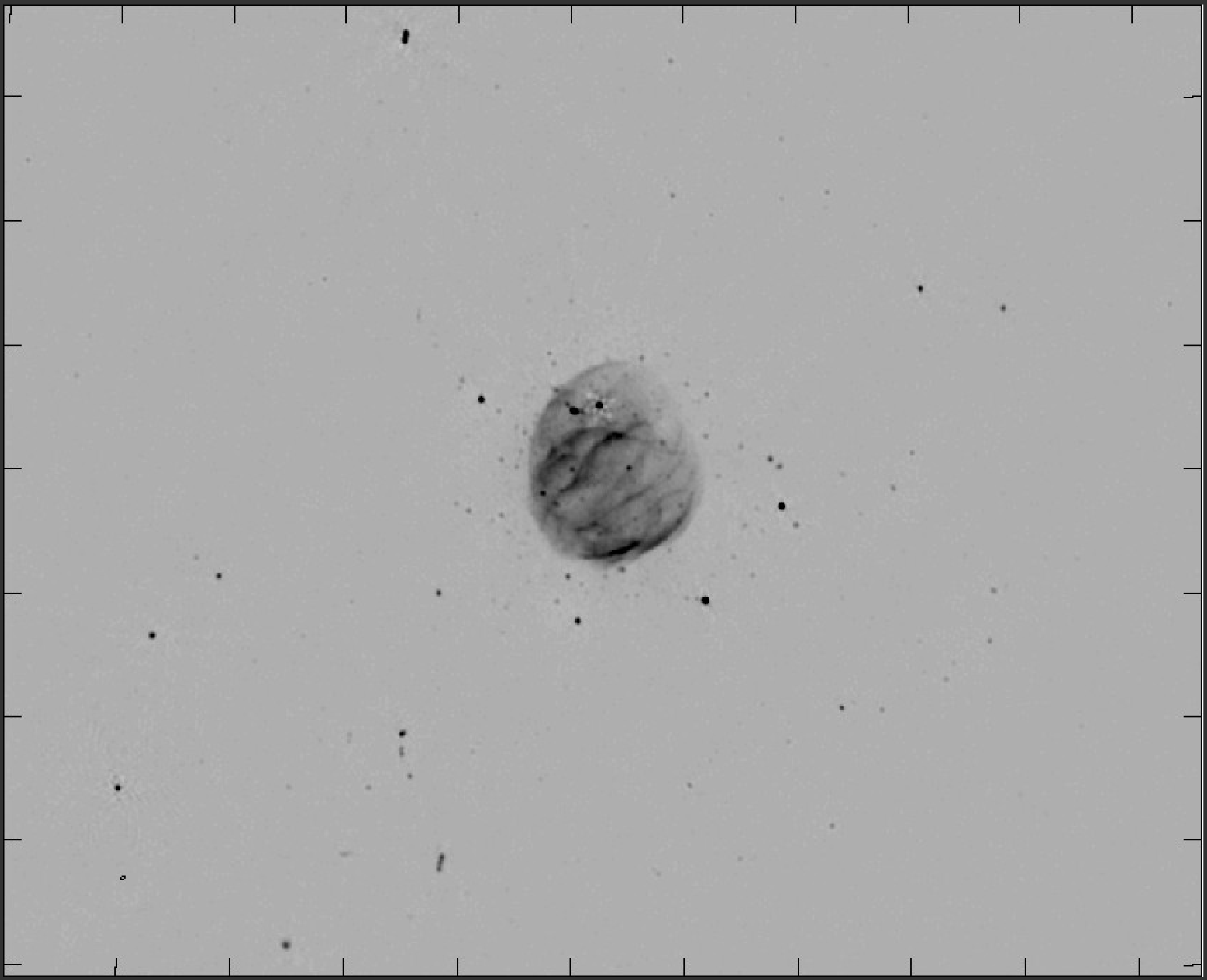
| VLA | EVLA | Factor |
|---|---|---|
| 10uJy | 1uJy | 10 |

Data volume:

| | | |
|---|---|---|
| ~1GB | 100-1000GB | $10^{2-4}$ |

**Wide-field, w... ...sing large data volumes is a natural consequence of low frequency and high sensitivity**

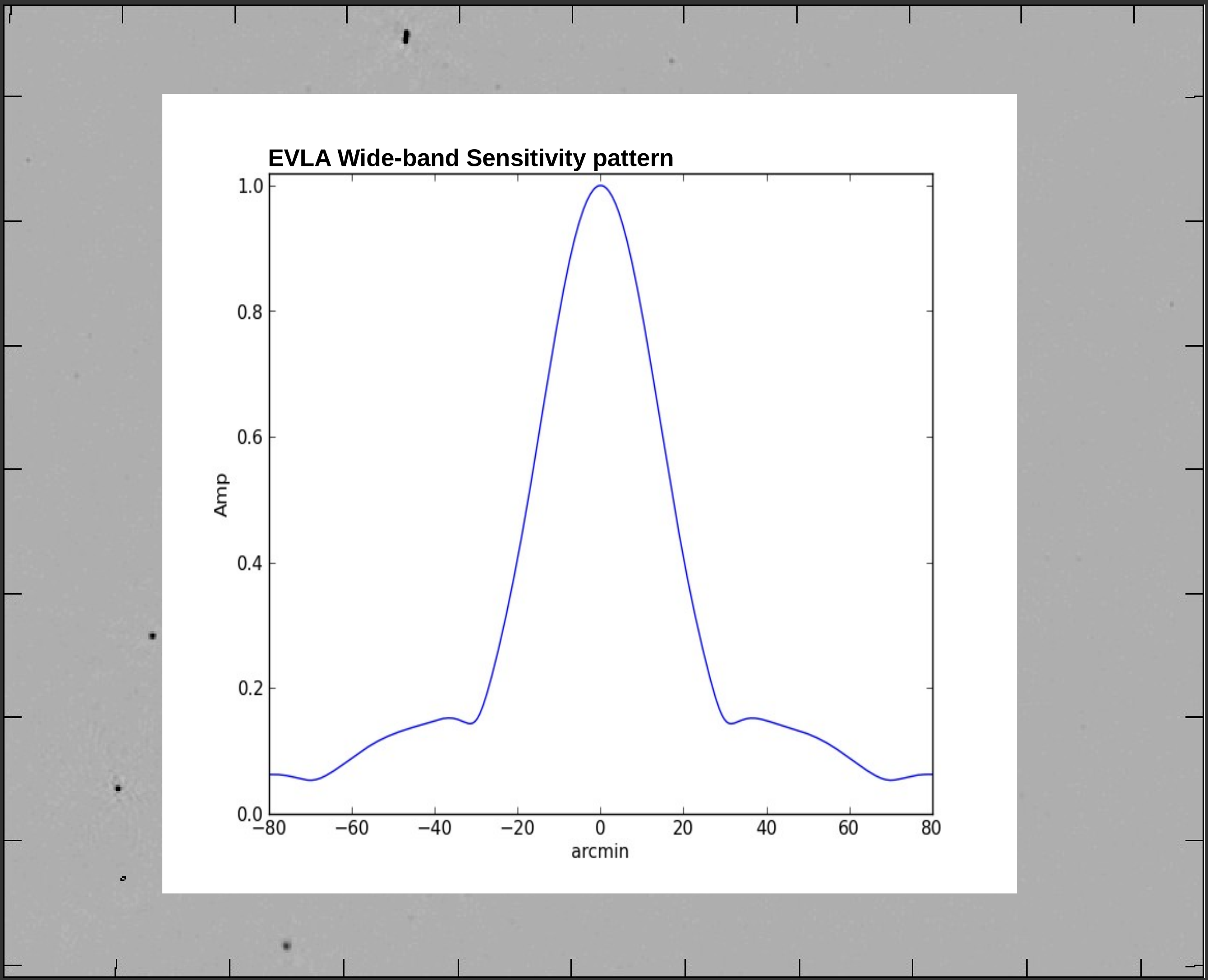
# Wide-band implies Wide-field imaging



- 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

# Wide-band implies Wide-field imaging

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# 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

1. HPC: Data volume proportional to $N^2_{ant} N_{chan}$

1. Sky brightness stronger and complex: Multi-Scale deconvolution
2. Ionospheric effects
   Requires DD solvers: An algorithmic & computing challenge in itself

# 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

- Fastest varying term on the RHS determines the averaging scale (time and frequency)
- Removing the effects of the DD terms cannot be separated from imaging

- Imaging equation:

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

# Direction Dependent (DD) Effects

- DI Calibrated ME

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

**Data**

**DI Calibration**

**DD Term**
**Instrumental**
**Ionospheric**

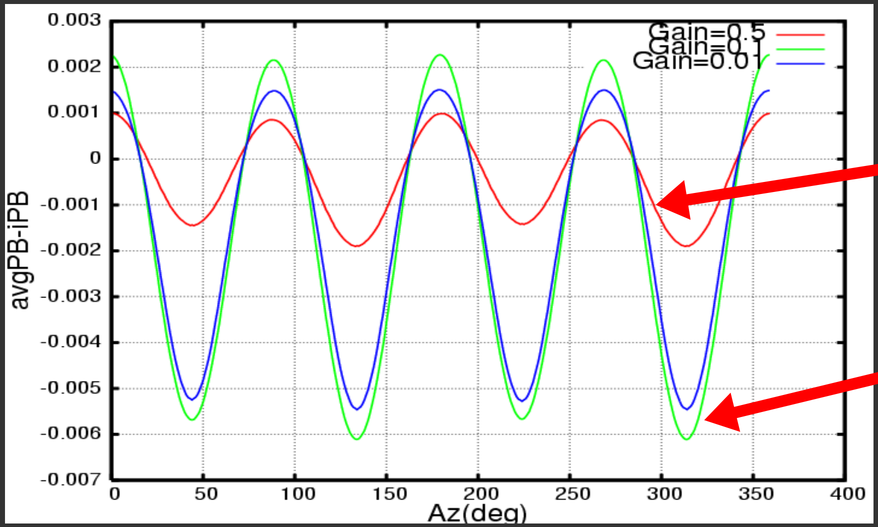
**Sky**

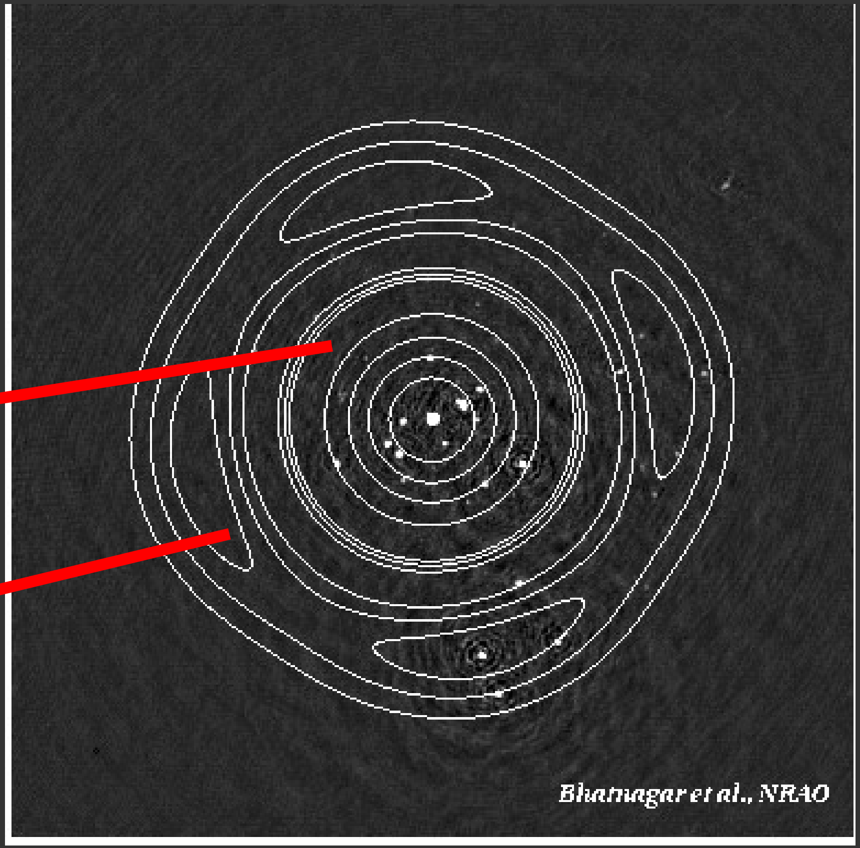
**Geometry**

- Standard Imaging assumes:
  - PB is independent of time, frequency and polarization
  - Sky brightness is independent of frequency
  - Geometry is 2D
- Lets look at the DD-term one at a time (the terms marked in white in the equation above)

# Time dependent terms

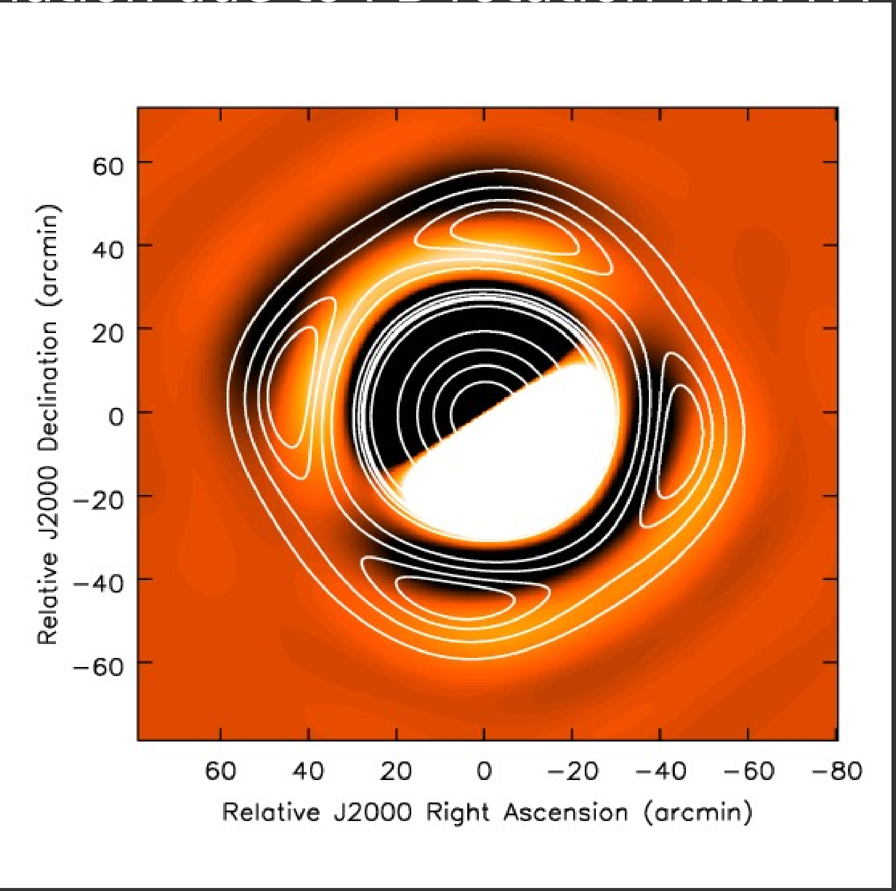
- Antenna PB ( $The\ \ P_{ij}(s,\nu,t)$ )
  - Time dependence
  - Rotation of PB with PA leads to time-varying DD gains



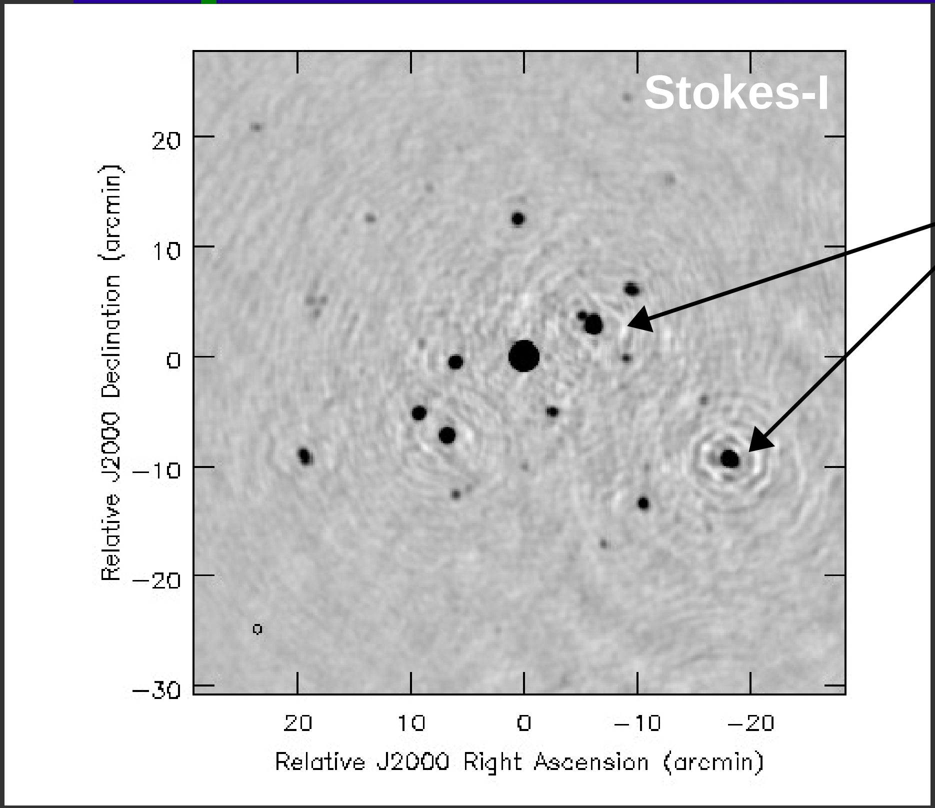
# Polarization dependent terms

- Antenna PB ($The\ \ P_{ij}(\mathbf{s},\nu,t)$)
  - Polarization dependence
  - Off-axis polarization due to antenna optics
  - Time variation due to PB rotation with PA



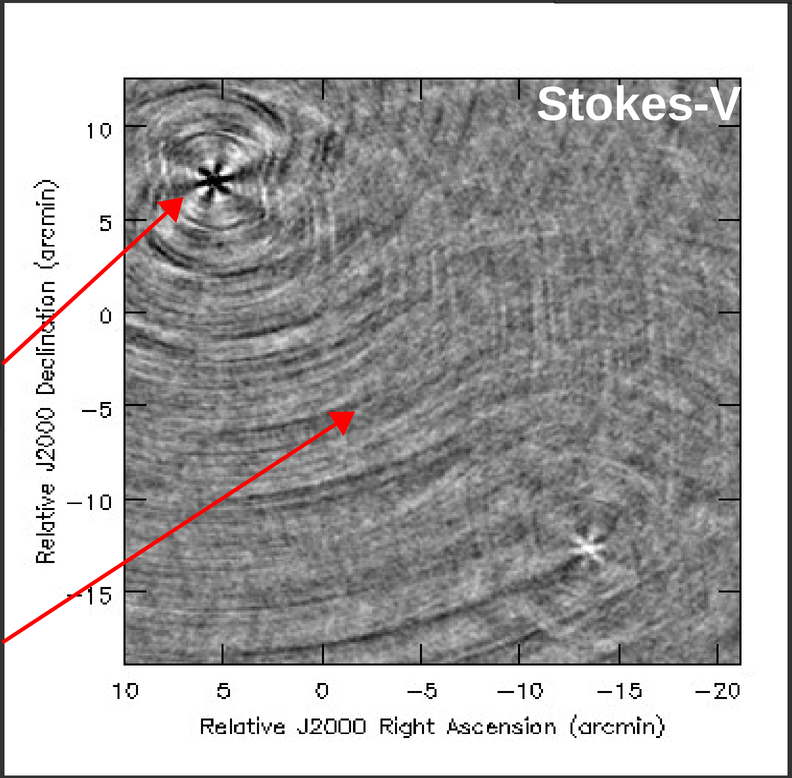

Contours: Stokes-I
Colours: Stokes-V
$PB_{RR}$ - $PB_{LL}$

# Errors due to time+polarization dependence




**Errors due to PB**
**Squint + Rotation + Pointing errors**

**Purely instrumental**
**Stokes-V artifacts**



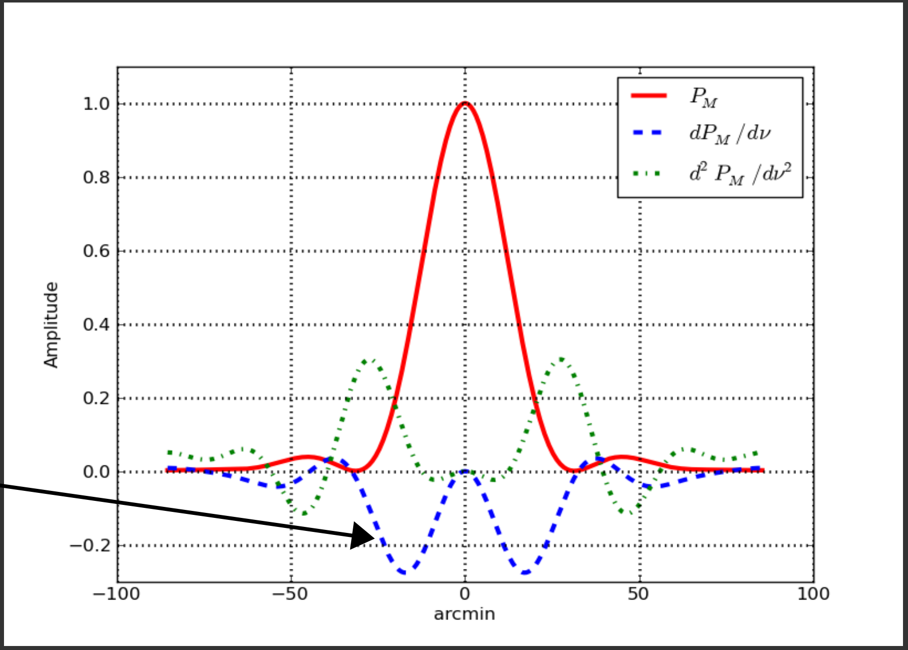

**Due to avg. PB**

**Due to time-variable PB**

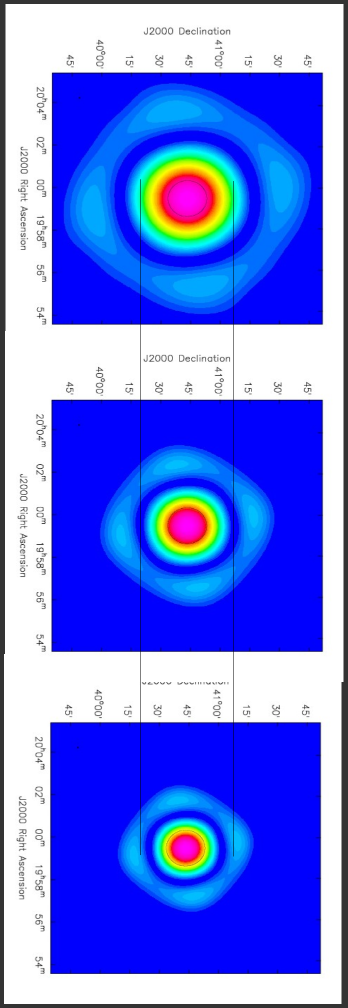
# Instrumental frequency dependence

- Continuum imaging $I^{continuum} = \int P_{ij}(\mathbf{s},\nu,t)\ I(\mathbf{s},\nu)\ d\nu$

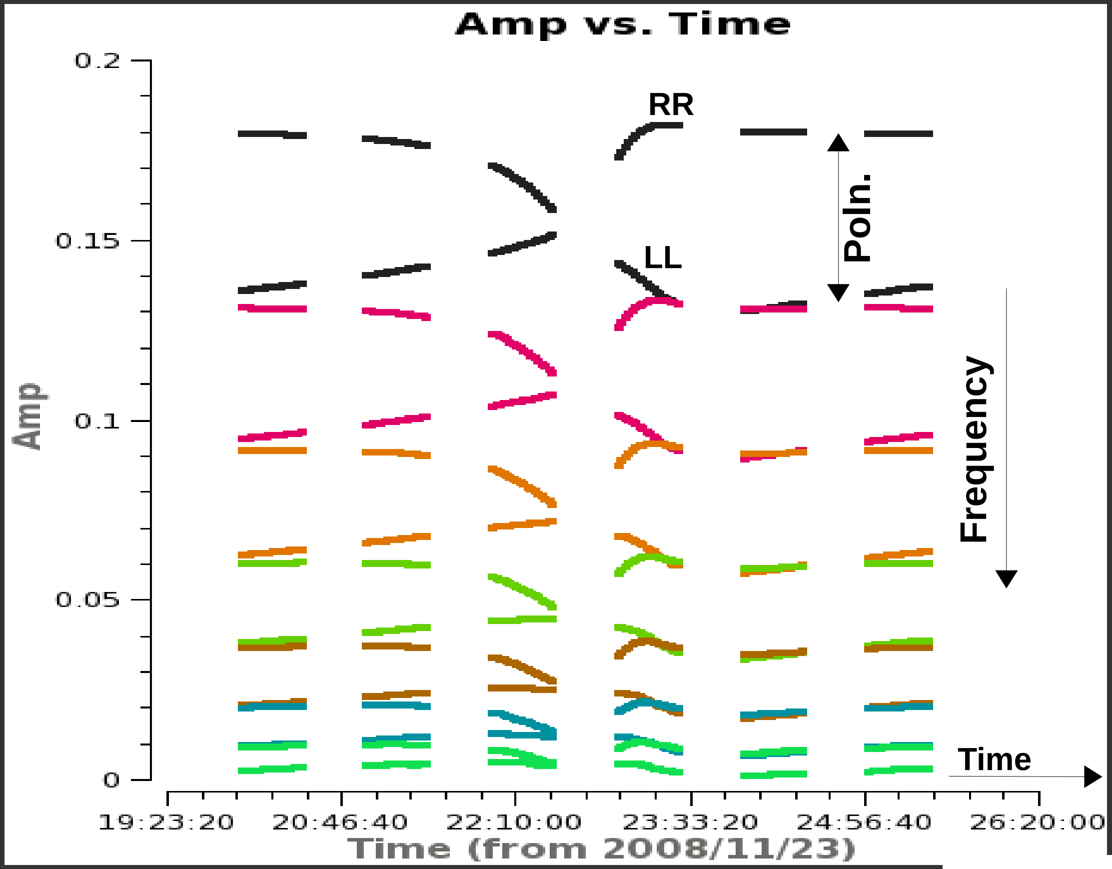
- Antenna PB ($The\ \ P_{ij}(\mathbf{s},\nu,t)$)
  - Frequency dependence
  - First order: scaling with frequency by 2x across the EVLA band

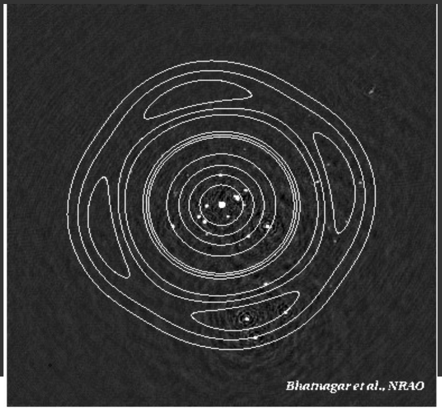


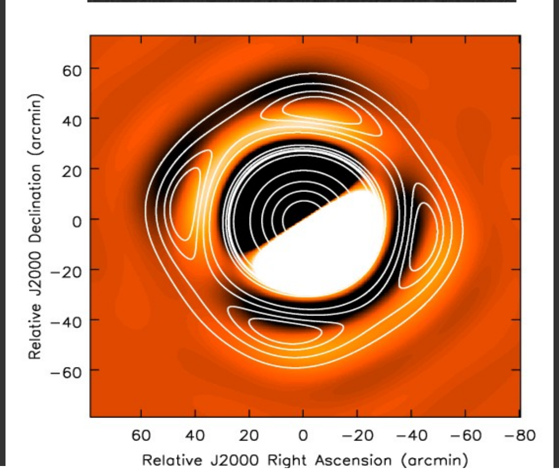

**PB Freq. dependence (blue curve)**

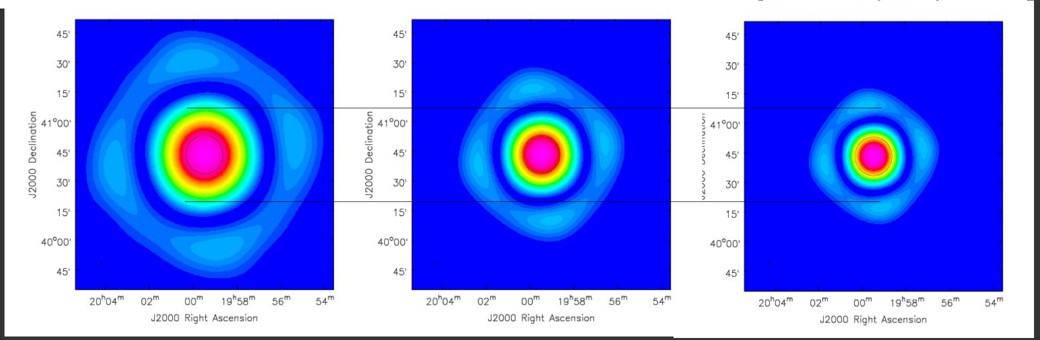


# All PB effects together: Time, Frequency, Polarization effects

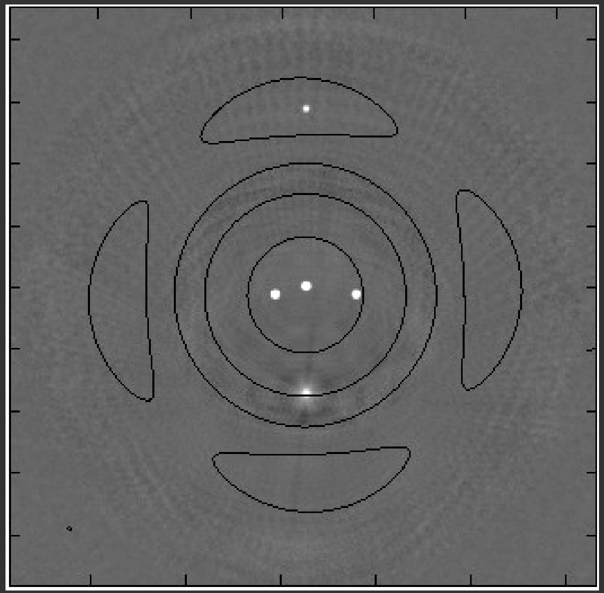


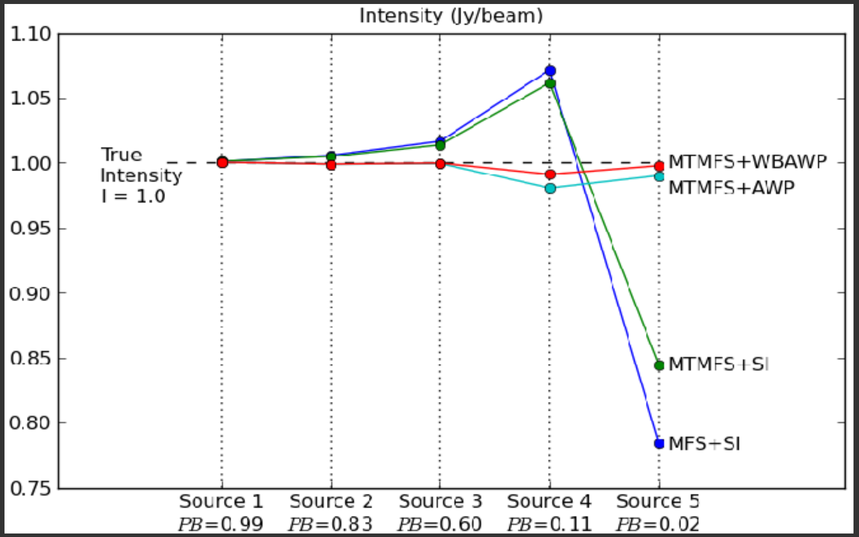



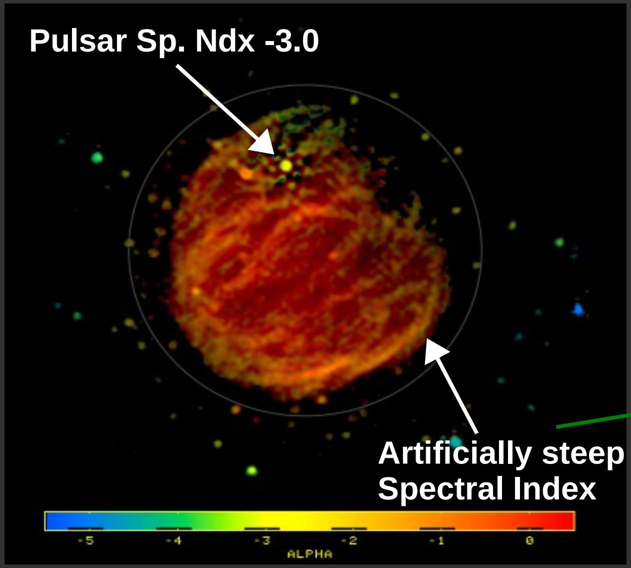



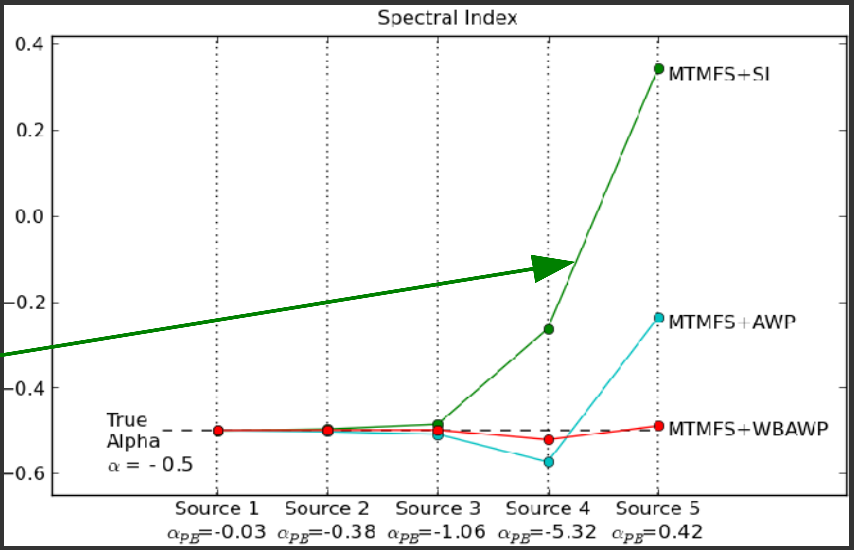



# Instrumental frequency dependence





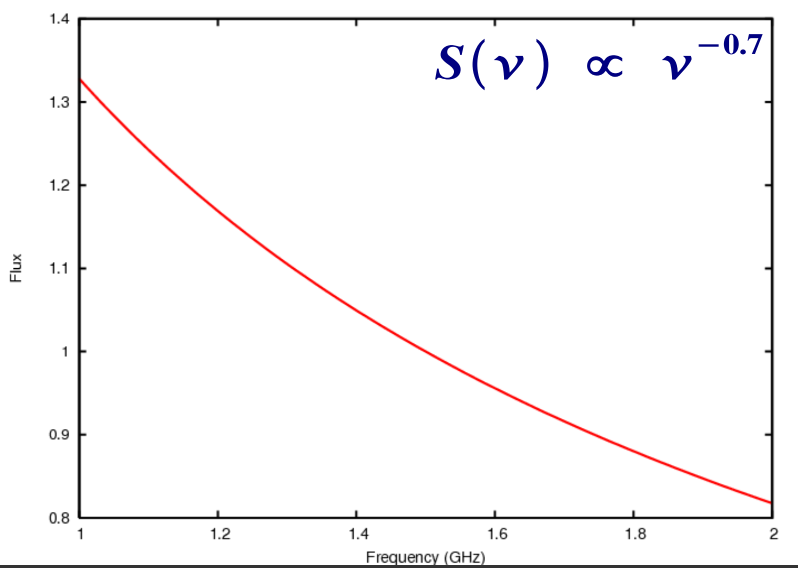



# Sky frequency dependence

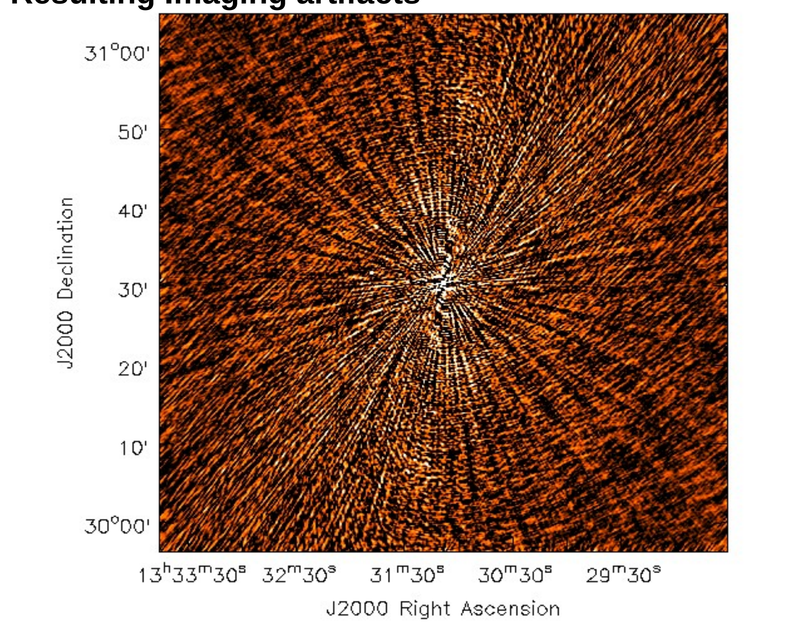
$$V_{ij}^{DI-Cal}(\nu) = \quad W_{ij} \int P_{ij}(s,\nu,t)\; I(s,\nu)\; e^{\iota\, s.b_{ij}}\; ds$$

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

**Variations of sky brightness with frequency**




**Resulting Imaging artifacts**



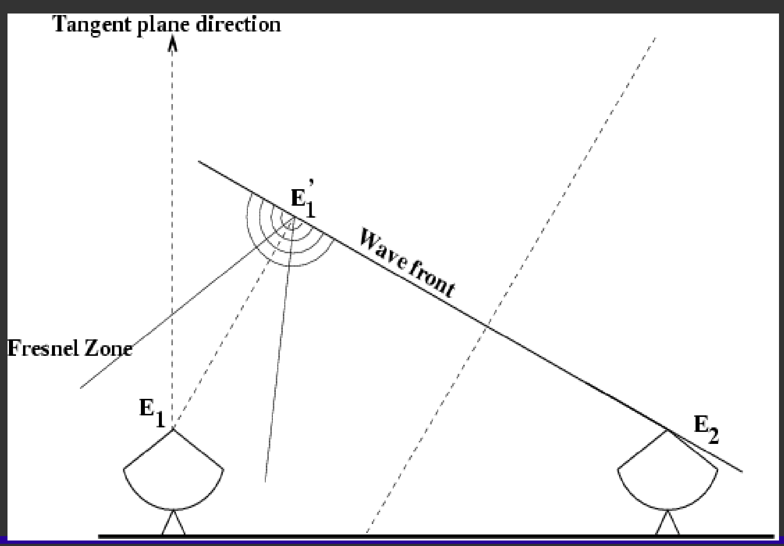
# Non co-planar baselines: W-Term

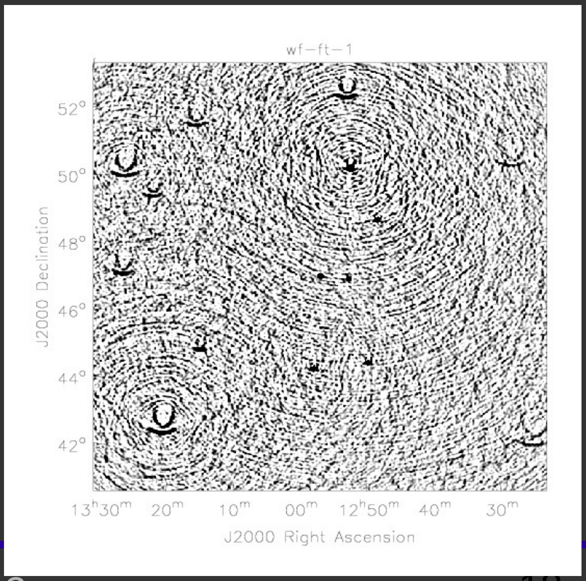
- Imaging

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

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

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

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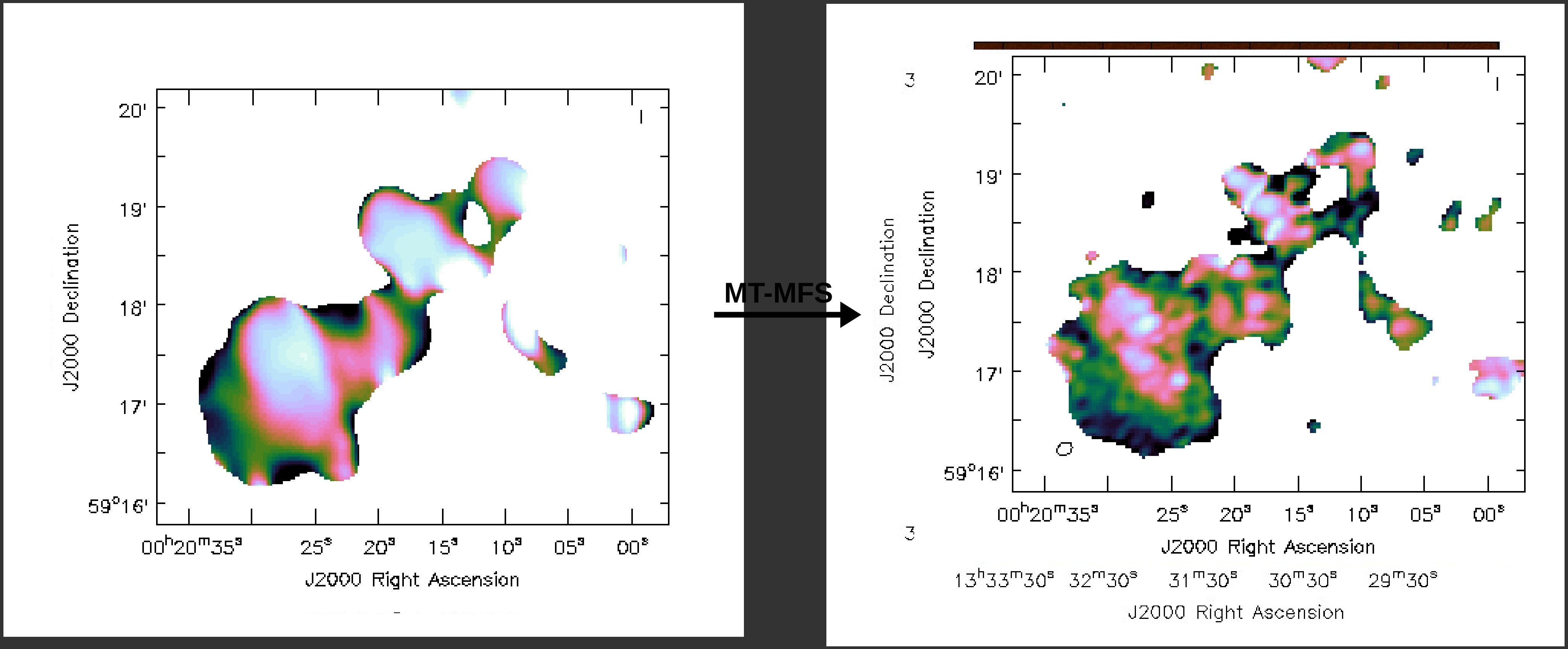
# MT-MFS: Freq. dependence of the sky

- Model the frequency dependence of the sky brightness as a polynomial in frequency
- Solve for the coefficients as a joint deconvolution problem




Rau et al., A&A, 2011

# DD Corrections: Projection Algorithms

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

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

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

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

$$such\ that\ X_{ij} \; A_{ij} = \mathbf{1}$$

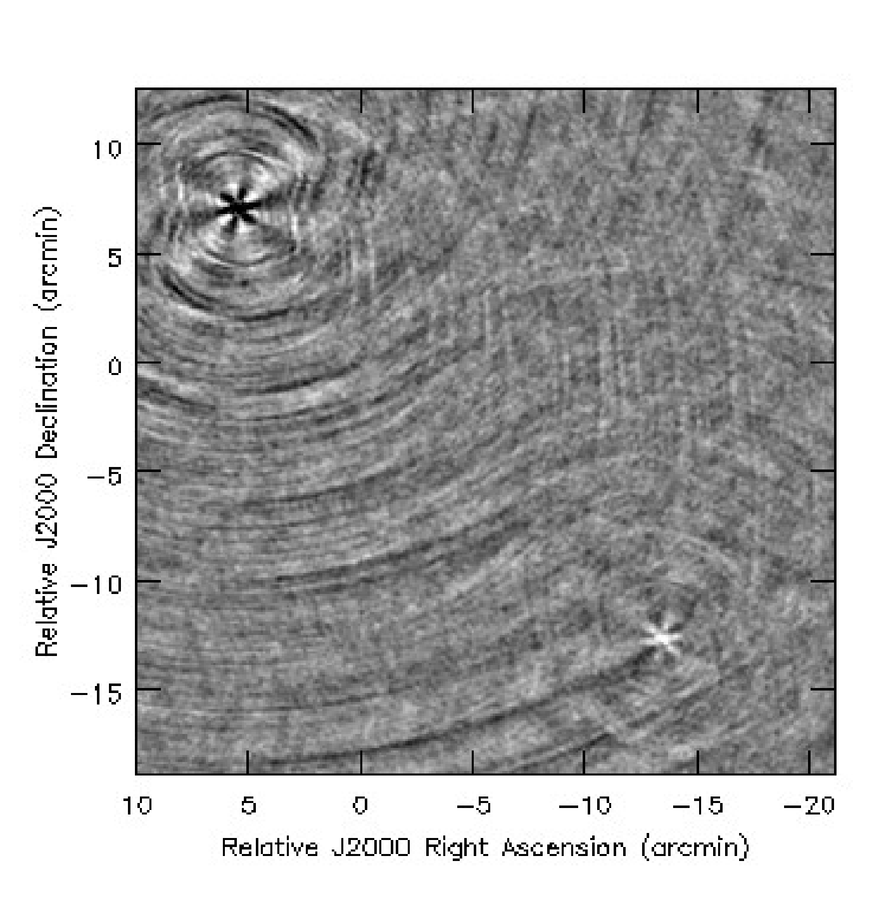
- Then

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

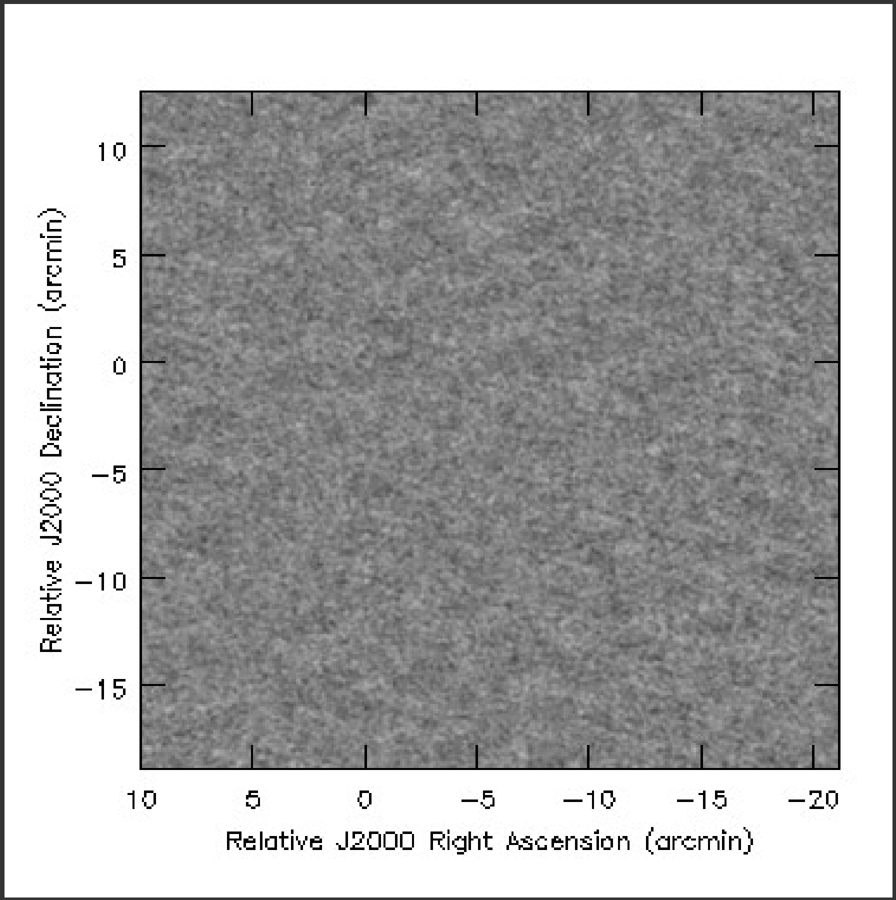
**Understand the Physics of the problem; use mathematical techniques to find a solution**

# PB Polarization Effects

Stokes-V Images



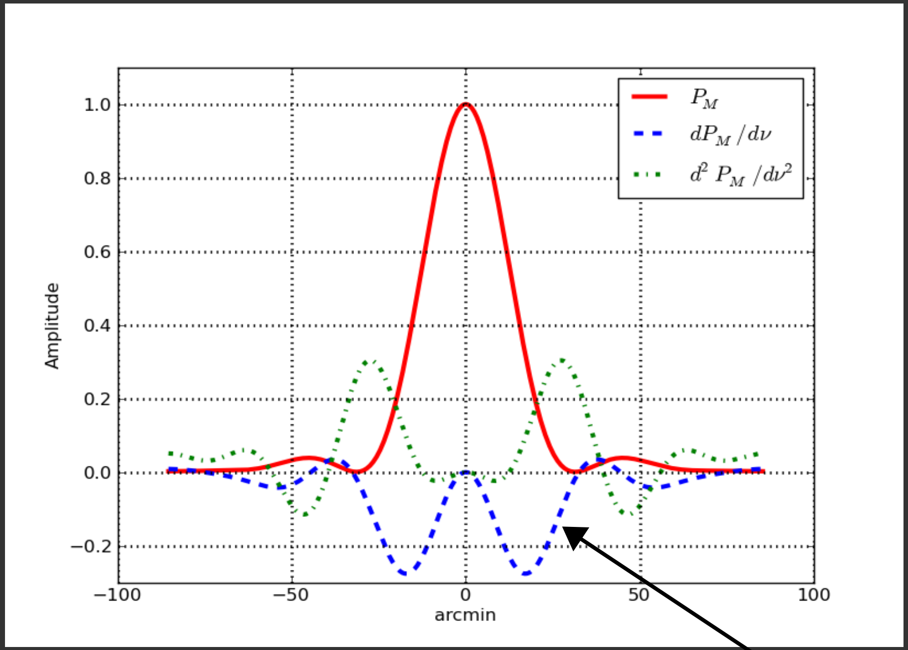

A-Projection

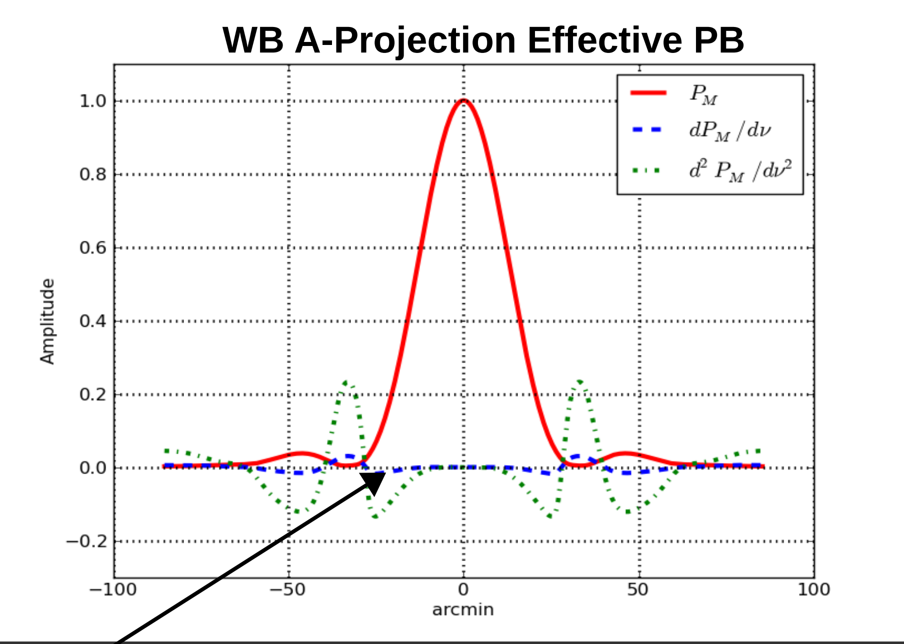



- L-Band VLA imaging
- DR ~ $10^4$

# Wide-Band AW-Projection

- Correct for PB effects + W-term
  - Polarization: Squint + in-beam polarization
  - Time variability: Rotation with Parallactic Angle



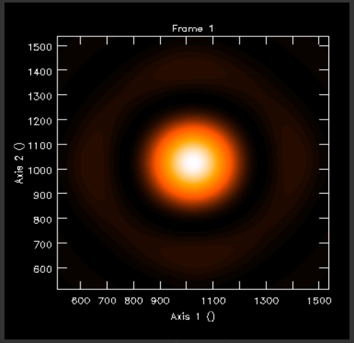




**PB Frequency dependence (blue curve)**

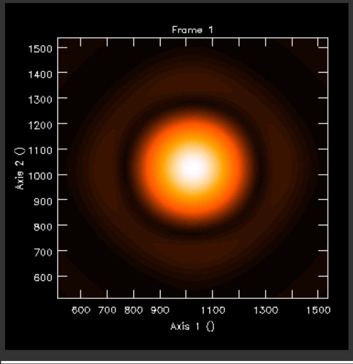
# Wide-Band AW-Projection

$$A_{ij}(\nu_*) \quad where\, \nu_* = \sqrt{2\nu_{ref}^2 - \nu^2}$$

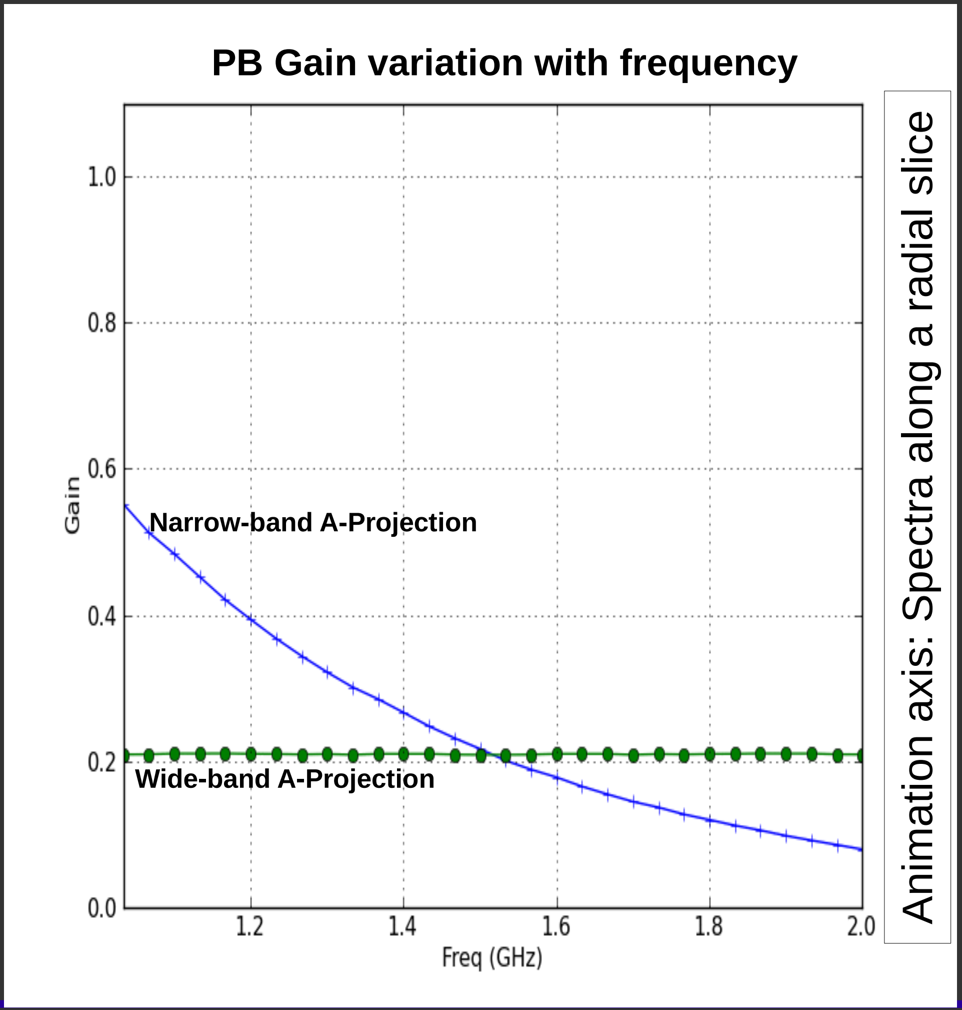
Frequency along the animation axis




$PB(\nu)$

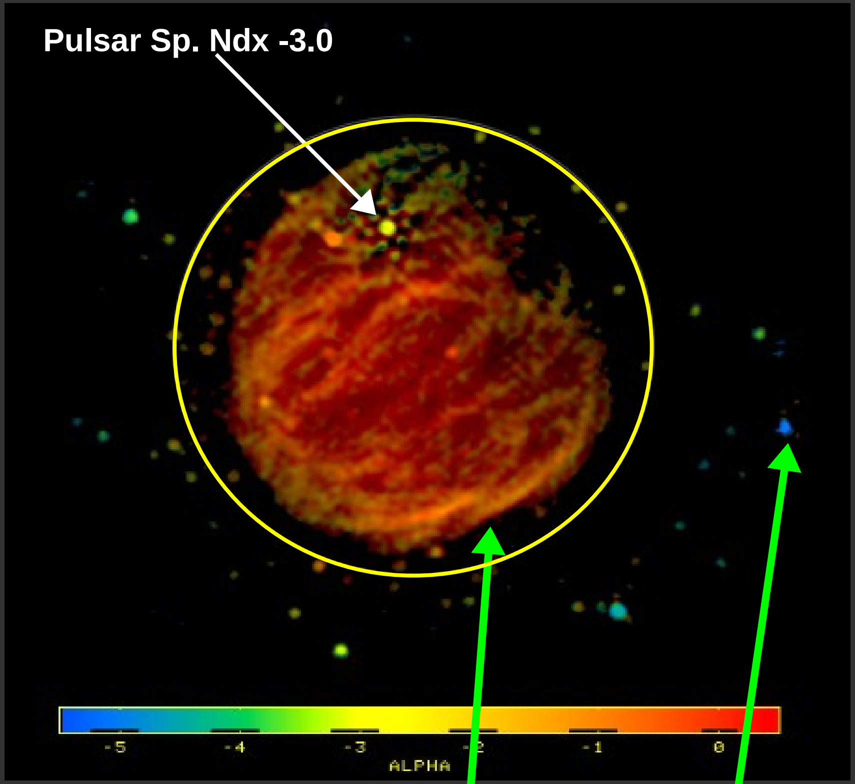


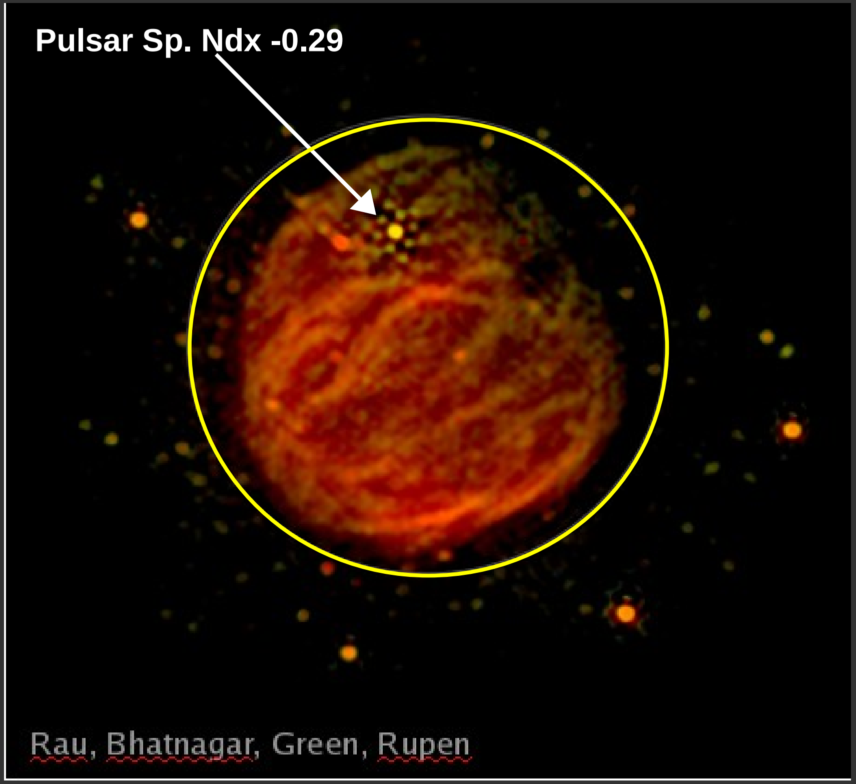

$\sqrt{PB(\nu)\, PB(\nu_*)}$



# 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)

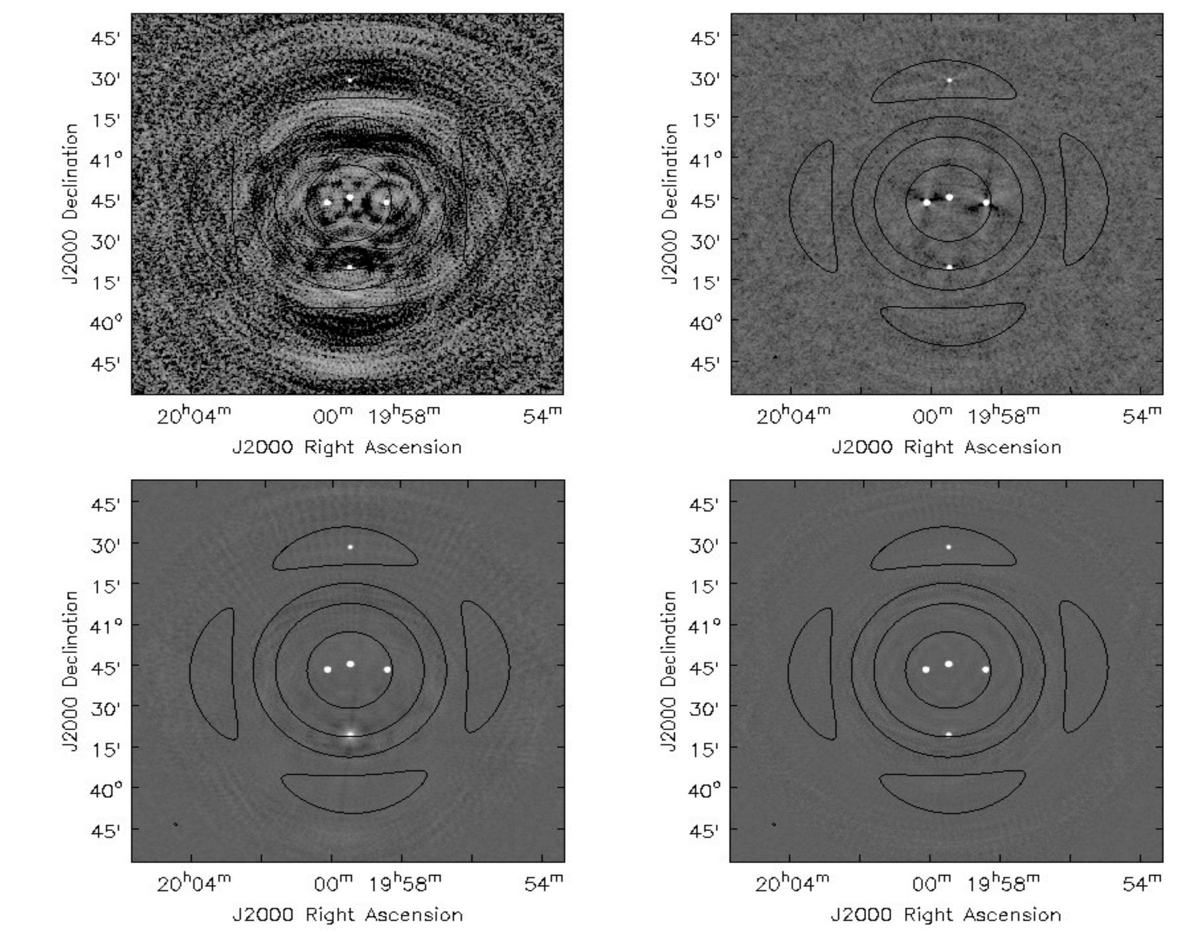
A&A, 2008, ApJ, 2013

# 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

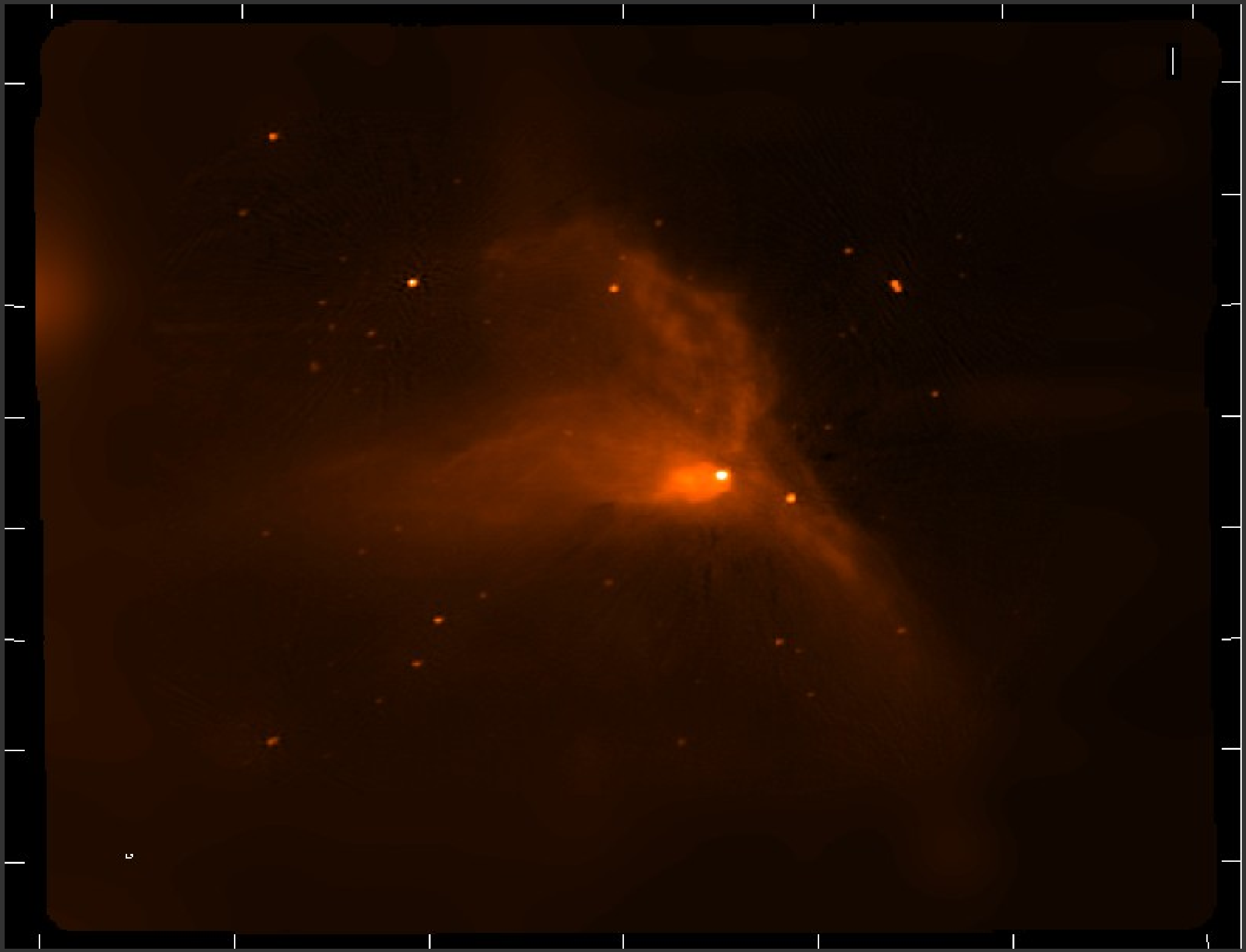
# Status-1

- 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
  - MS-MFS, MT-MFS
- PB corrections
  - A-Projection: Time and polarization dependence
  - WB A-Projection: Also frequency dependence

- W-Term + WB A-Projection + MT-MFS
  - Simultaneously account for instrumental and sky terms

- Wide-band Mosaic
  - All of the above for mosaic imaging (work in progress)

# Wide-band Mosaic Imaging + SD



- Simultaneous corrections for instrumental effects+ Frequency Dependence of the Sky
- WB AW-Projection + MS-MFS + Mosaic
- Wide-band 100-pointing mosaic
- EVLA + GBT Feathering (existing algorithm)
- In progress:
  - Mosaic spectral Index mapping
- Parallel execution / Optimization /
- Numerical tests

# Status-2

- Full-polarization imaging
  - Extend PB correction to full polarization (student PhD project)
  - RM Synthesis at the sensitivity and band-width now available
- Ionospheric phase corrections
  - Corrections:  Can be included as a term in  A-Projection for correction during imaging (Tasse et al., A&A)
  - Ionospheric phase screen solvers
    - » SPAM
    - » Other similar “peeling” based solvers
    - » More generic solvers
- Deployment on HPC platforms
  - Cluster computing
  - Multi-threaded CPUs, GP-GPUs

# Computing Cost

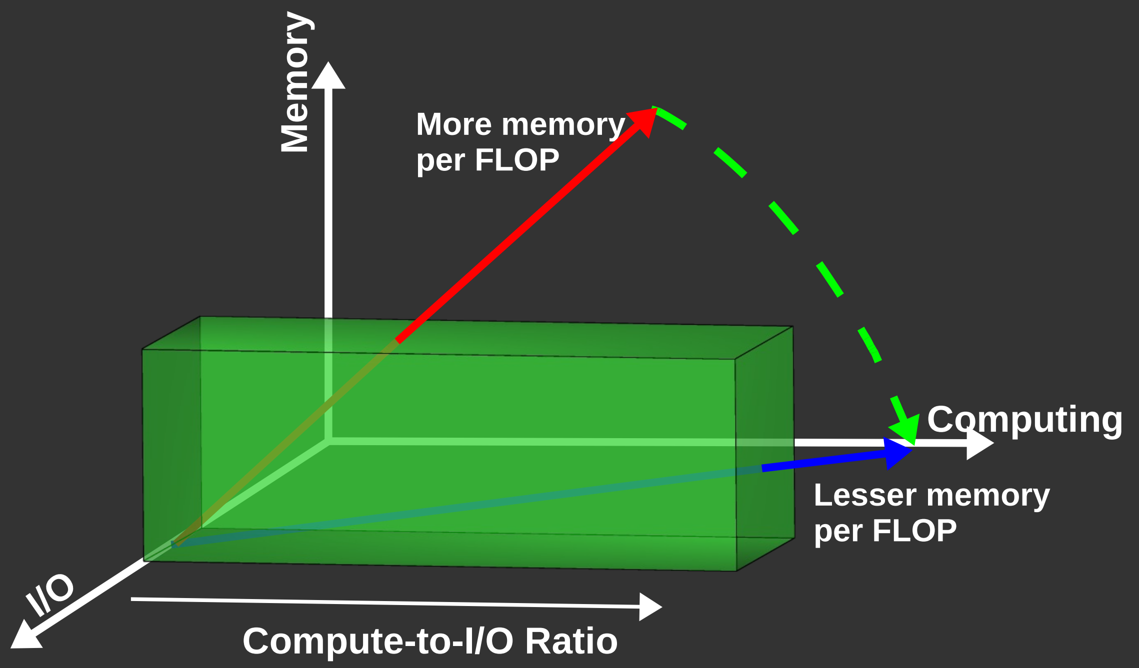
- Imaging + deconvolution accounts for ~70% of the computing cost in an “typical” end-to-end processing

- Computing Scaling
  - Computing costs: $N^2_{support} + N_{vis}$ : Dominated by Projection
  - Memory footprint: $N^2_{Scales} + N^2_{Terms}$ : Dominated by MT-MFS

- Imaging : Embarrassingly parallel
  - Scatter-Gather Paradigm on the Cluster scale

- Optimal utilization of the computing multi-core CPUs is harder
  - Multiple process per node: Limited by total memory footprint
  - Single multi-threaded process: Algorithmically challenging

# Algorithm Design: 3D Parameter space



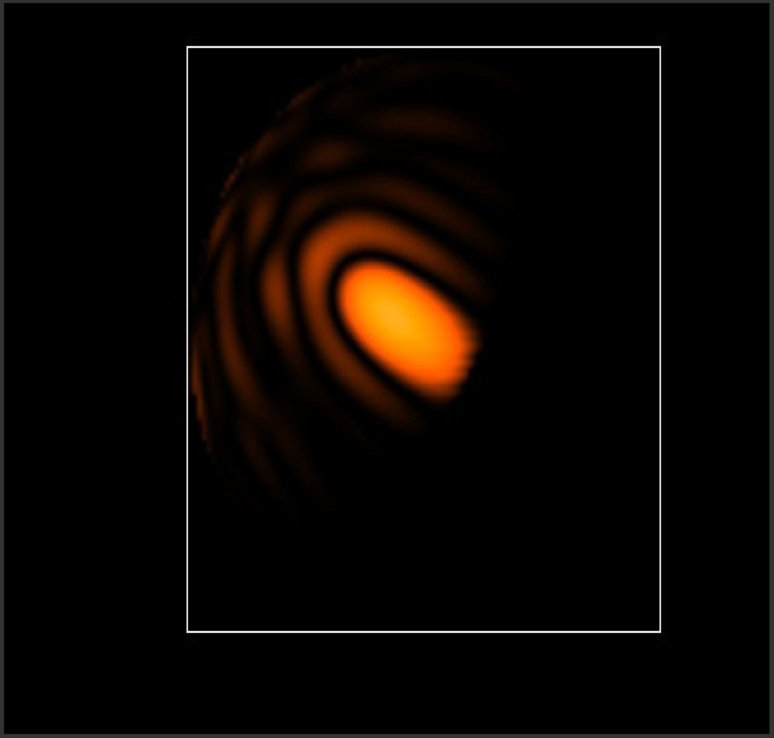

**Algorithm design**

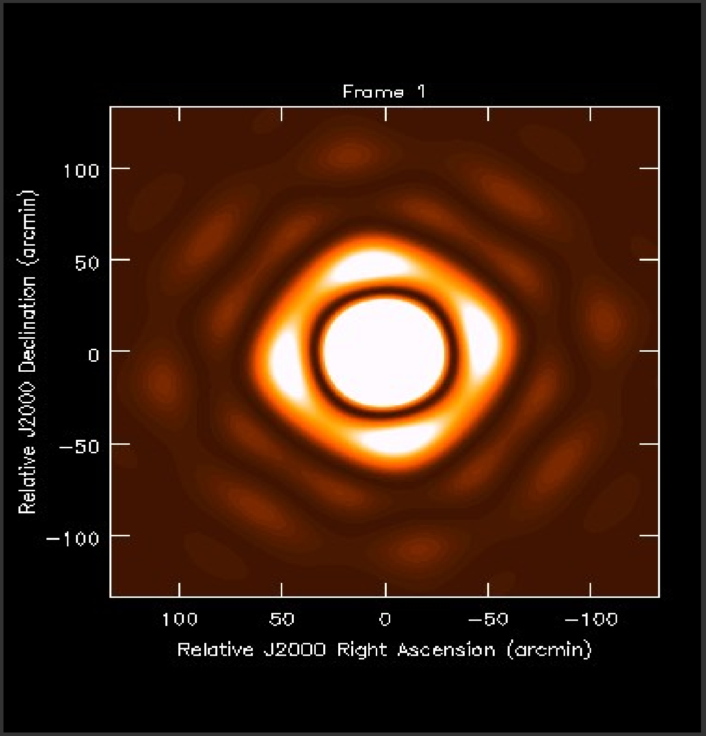
- **Move towards algorithms with higher compute-to-I/O ratio**
- Reduce memory foot print
  - remain inside the Green Box

# Challenges

Aperture Array PB (LOFAR, MWA, LWA)   vs   Antenna PB

Antenna-to-antenna variations






Simulations for LWA @50MHz
(Masaya Kuniyoshi (LWA/NRAO))

Model for EVLA PB at L-Band

# Challenges

- Algorithms
  - Scientific commissioning (in progress)
    - » WB-AWP + MT-MFS + Mosaic
  - All of the above + full Polarization (starting Jan. 2014)
  - Wide-band RM Synthesis
  - DD Solvers: Ionospheric screen, Pointing Errors, ...

- Computing
  - Use of (massively) parallel hardware
    - » Multi-core CPUs, GP-GPUs
  - Memory footprint
  - Data I/O
    - » Algorithms are fundamentally iterative

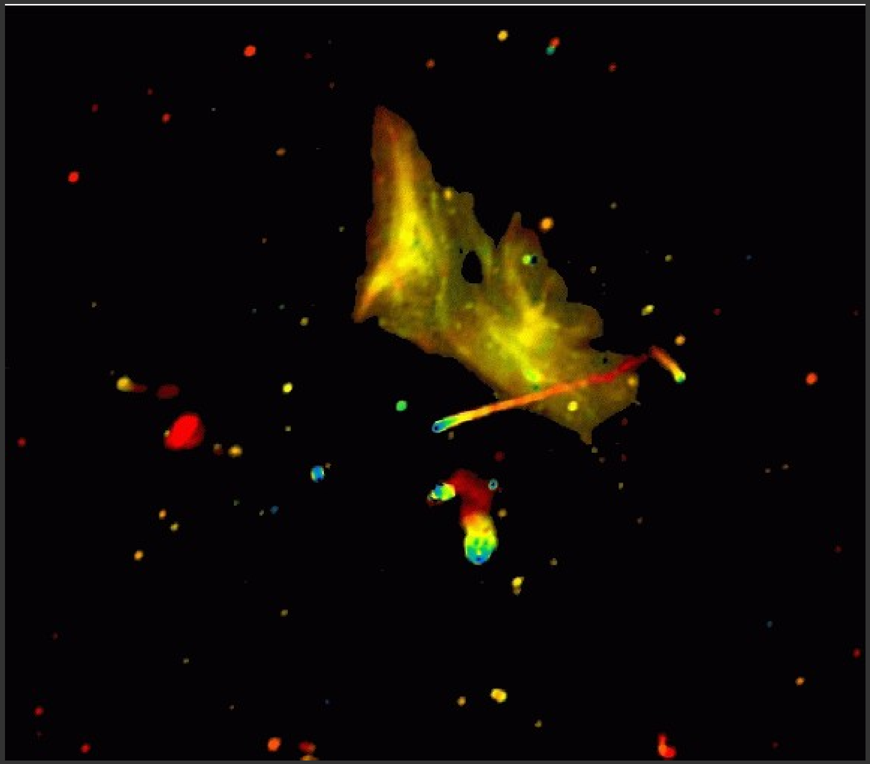
# Challenges

- Current algorithms
  - Performance
  - Efficiency
  - PB variations, Pointing errors, Shape
- Full-polarization treatment
  - 1 vs 2 vs 4x4 Mueller Matrix treatment

- Rate of convergence: Crucial for SKA-scale problems
  - Optimal algorithms, Optimal utilization
- SKA sensitivity → wider-field imaging, expose more error terms
  - Instrumental terms: Measure vs Model vs Solve

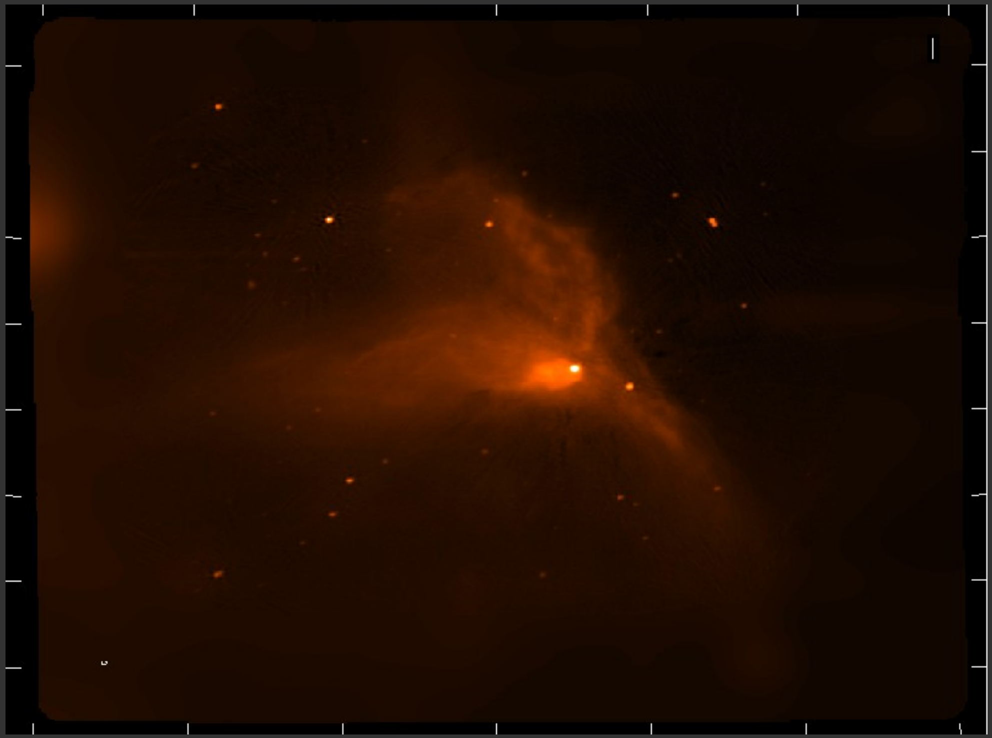
- We collect enormous amounts of data → more information
  - Are we utilizing the available information optimally?
    - » In terms of algorithm design
    - » In terms of extracting astrophysical information

# Imaging with the EVLA @ L-Band



Intensity-weighted Sp. Ndx. Map

Single pointing, narrow field, wide-band image (Owen, Rau)



Wide-band mosaic+Single Dish (GBT)
Working on Stokes-I + Sp.Ndx. Mapping
(Bhatnagar et al.)

# Challenges: Human resources

- Algorithm R&D is not yet main-stream astronomy
  - Algorithm R&D is a service mind-set needs to break

- Data taken under many proposals, but science not achievable without algorithm commissioning work
- Many telescopes in construction, with ambitious scientific and time-line goals around the Globe

- Appeal to the young-guns
  - Think of ambitious scientific goals, do not be shy of technical work (telescope debugging, algorithms R&D, commissioning)
  - It's great fun.  Mind-liberating, scientific-horizon widening
  - “...it does not work” kind of gripes are insufficient
- Appeal to the seniors
  - Policy changes: Encourage & support multidisciplinary research – at least at the observatories!