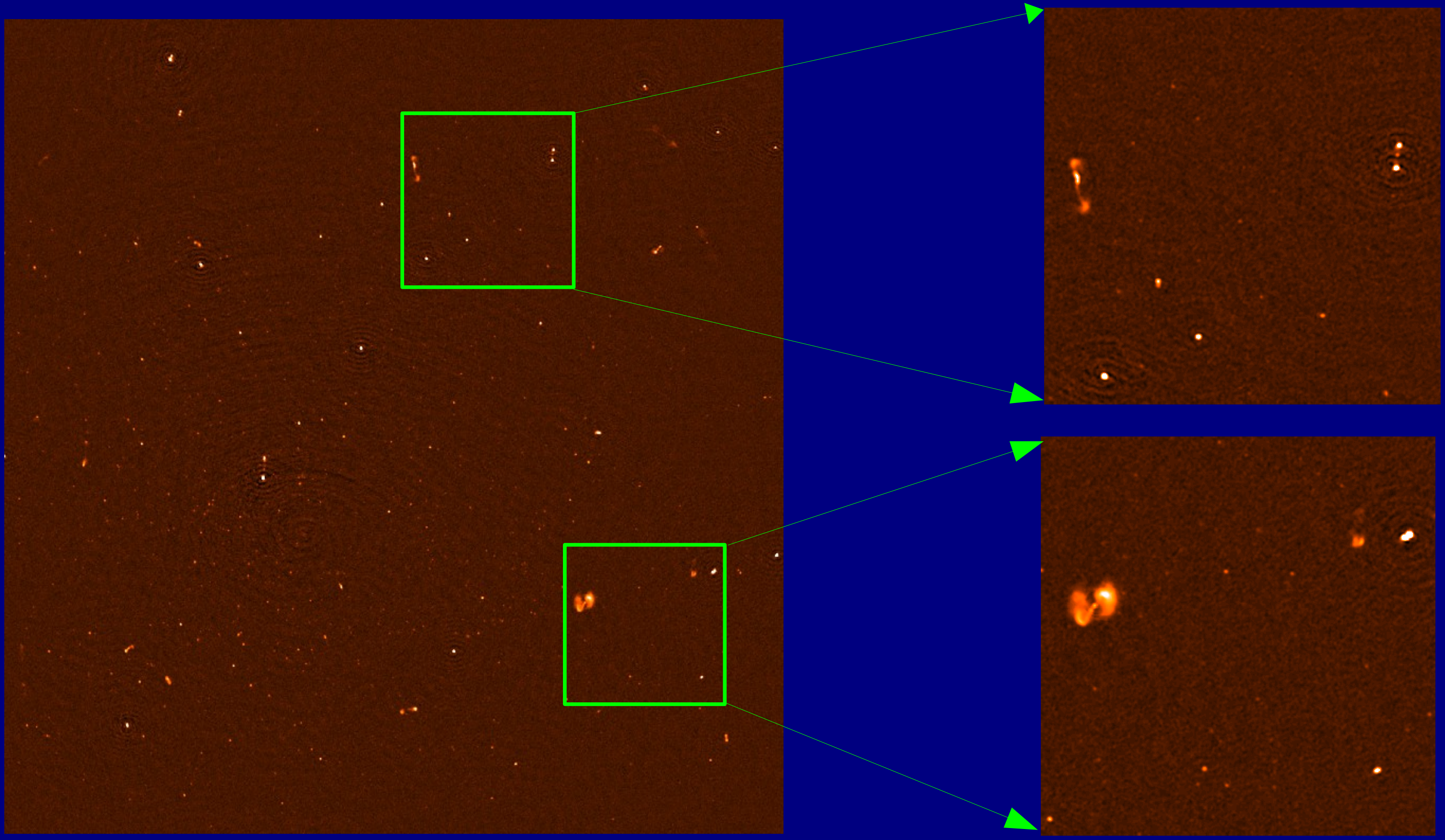
Low Frequency Imaging Challenges



S. Bhatnagar

NRAO, Socorro

Challenges

- Radio sky at low frequencies
  - Typically stronger, more complex
    - Deconvolution errors, Pixelation errors
  - Spectral index variations across the sky
- Direction dependent (DD) effects
  - Primary beam effects
    - Time and frequency dependent
    - Polarization response
  - Pointing errors
  - Long, non co-planar baselines (w-term)
  - Ionospheric phase screen
  - FPA calibration/stability
- Computing and I/O loads

Challenges

- Strong RFI
  - Some algorithms/schemes exist
- Weak RFI
  - Very difficult to detect and remove
  - Will/does affect high dynamic range imaging
- Near field problems
  - Remains correlated
  - Not the same at all baselines
  - Variable in time & frequency
- Self Interference

The Measurement Equation

- Generic Measurement Equation: [HBS papers]

$$V_{ij}^{Obs}(\nu) = J_{ij}(\nu, t) W_{ij} \int J_{ij}^{S}(\mathbf{s}, \nu, t) \; I(\mathbf{s}, \nu) \; e^{\iota \mathbf{s}.\mathbf{b}_{ij}} \; d\mathbf{s}$$

Data — Corruptions — Sky — W-term

- Corruptions: $J_{ij} = J_i \otimes J_j^{*}$:direction independent corruptions
  - Electronics

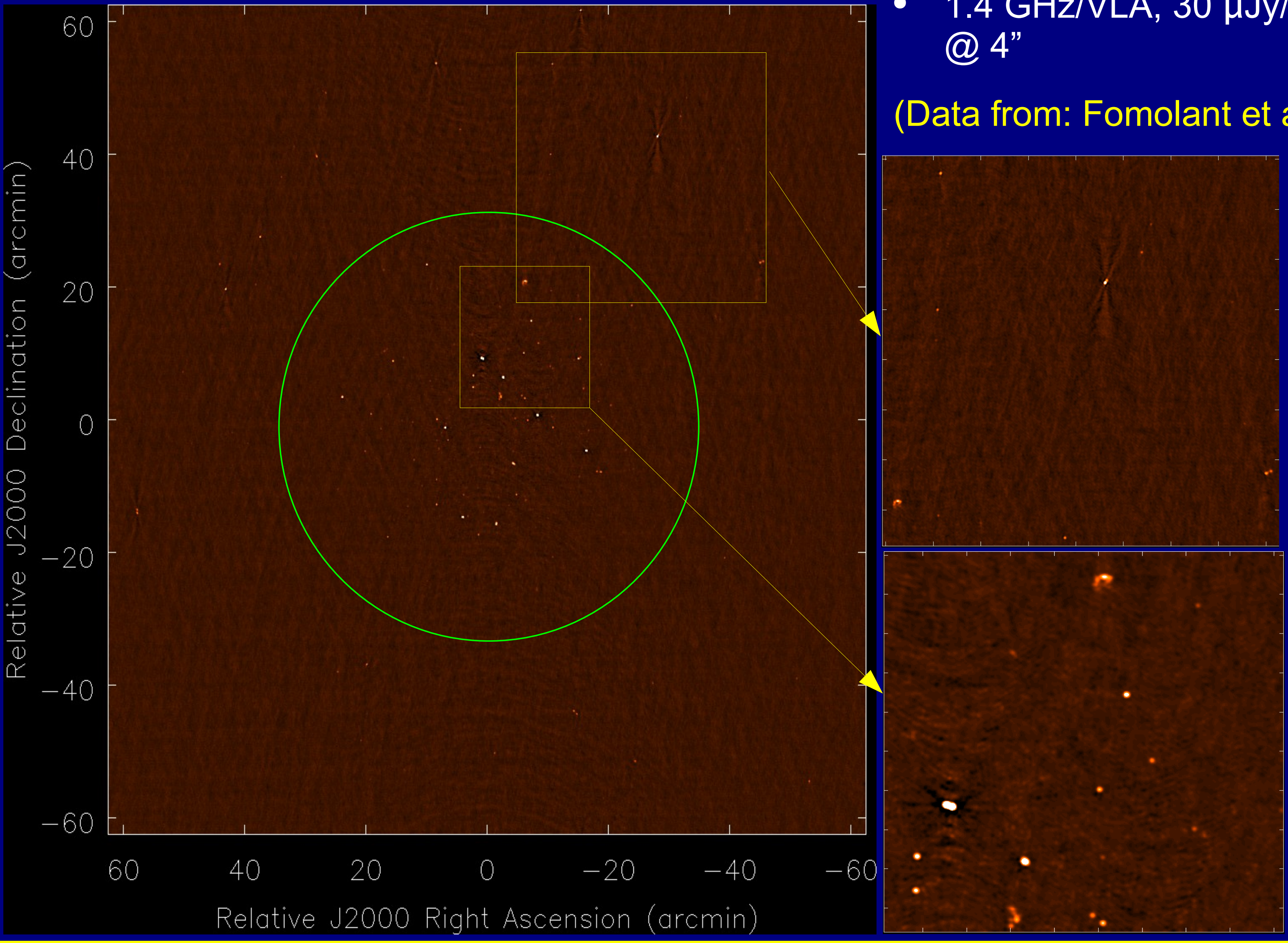
  $J_{ij}^{s} = J_i^{s} \otimes J_j^{s*}$:direction dependent corruptions
  - Primary Beam errors, pointing errors,....
- Sky: Frequency dependent sky: $I(s, \nu) = I(s, \nu_o)\left(\frac{\nu}{\nu_o}\right)^{\alpha}$
- W-term: $e^{\iota s.b_{ij}} = e^{\iota[ul + vm + w(\sqrt{1 - l^2 - m^2} - 1)]}$: Not a FT kernel

  (a.k.a. non co-planar array)

Pieces of the puzzle

- Unknowns:
  - J_{ij}, J^s_{ij}: *Electronics, Primary Beams, Antenna pointing, ionosphere,...*
  - I^M : *Extended emission, spectral index variations, polarization,...*
- Need Efficient Algorithms:
  - *Correct for image plane effects*
  - *Decompose the sky in a more appropriate basis*
    - Frequency sensitive (combine with MFS)
  - Solvers for the "unknown" direction dependent effects (pointing, PB shape, ionospheric effects,...)
    - As expensive as imaging!
- Needs (Computing):
  - Parallel computing & I/O
  - Scalable algorithms & software

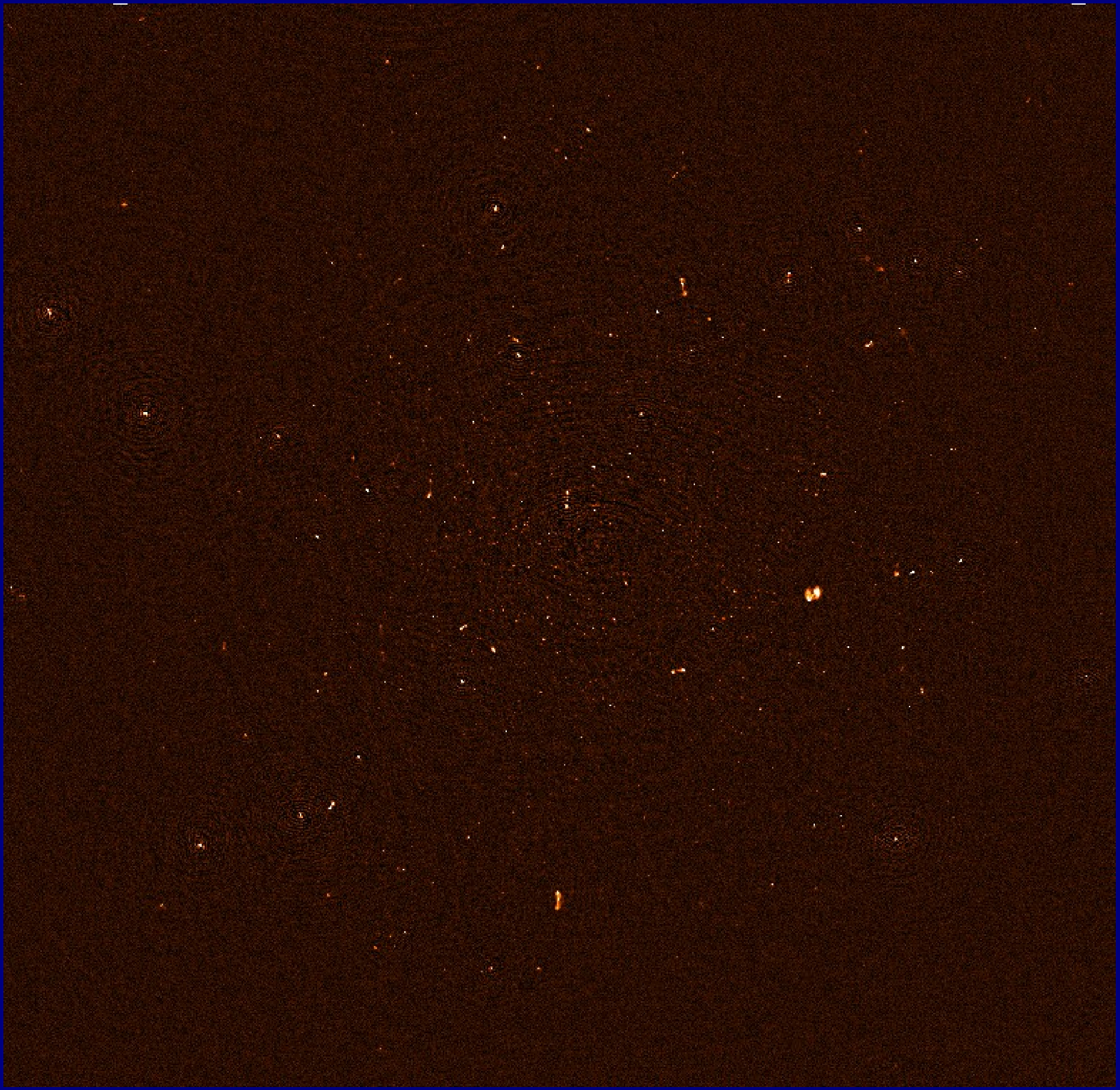
Sky at low frequencies: Stronger/complex



- 1.4 GHz/VLA, 30 μJy/b @ 4”

(Data from: Fomolant et al.)

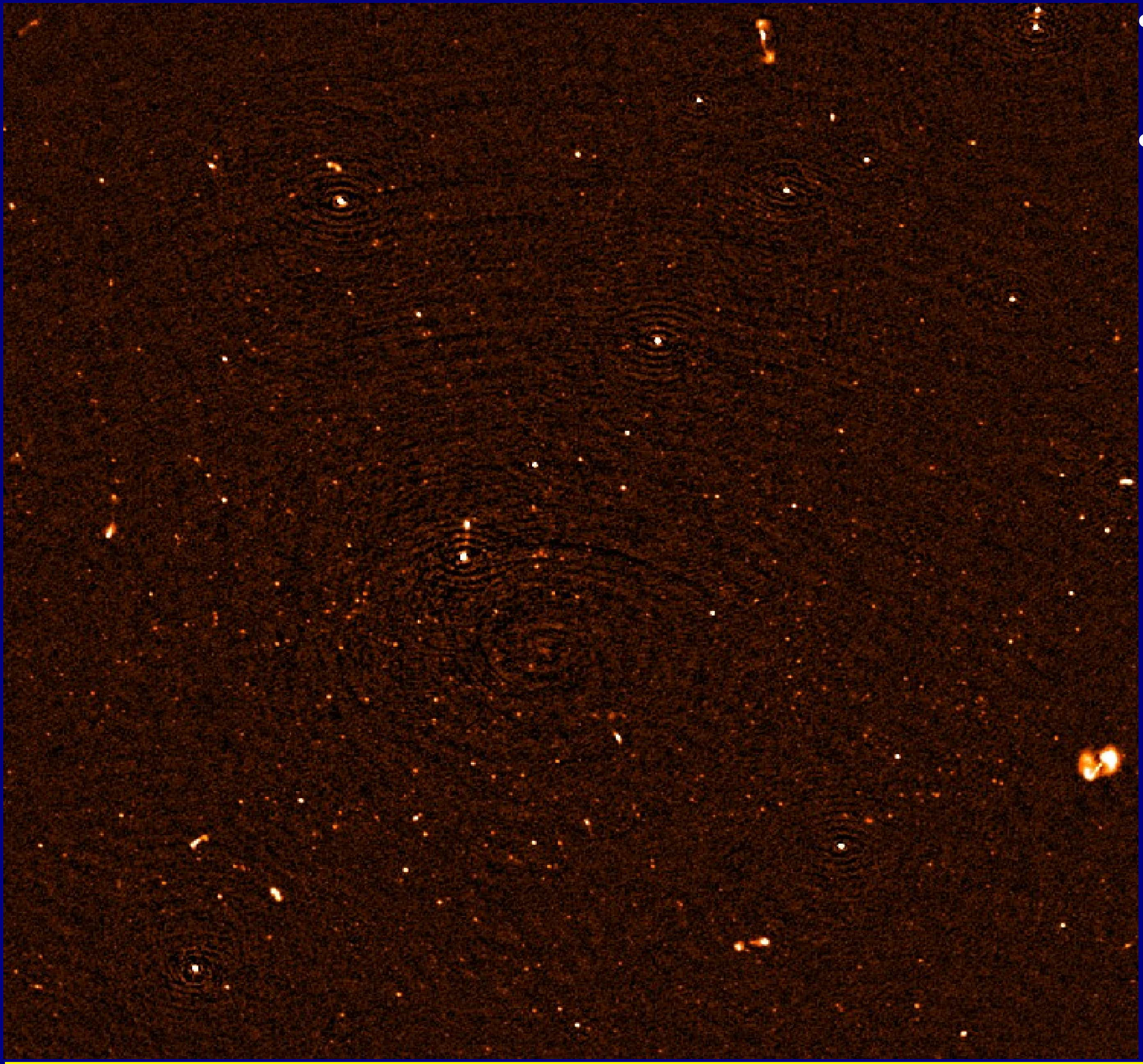
Sky at low frequencies: Stronger/complex



- 610MHz/GMRT 20µJy/b @ 4”
- Peak: 40mJy/b
- Errors are direction dependent
- Significant flux in the first sidelobe
- Limited by
  - PB errors
  - Pointing errors
  - Deconvolution errors

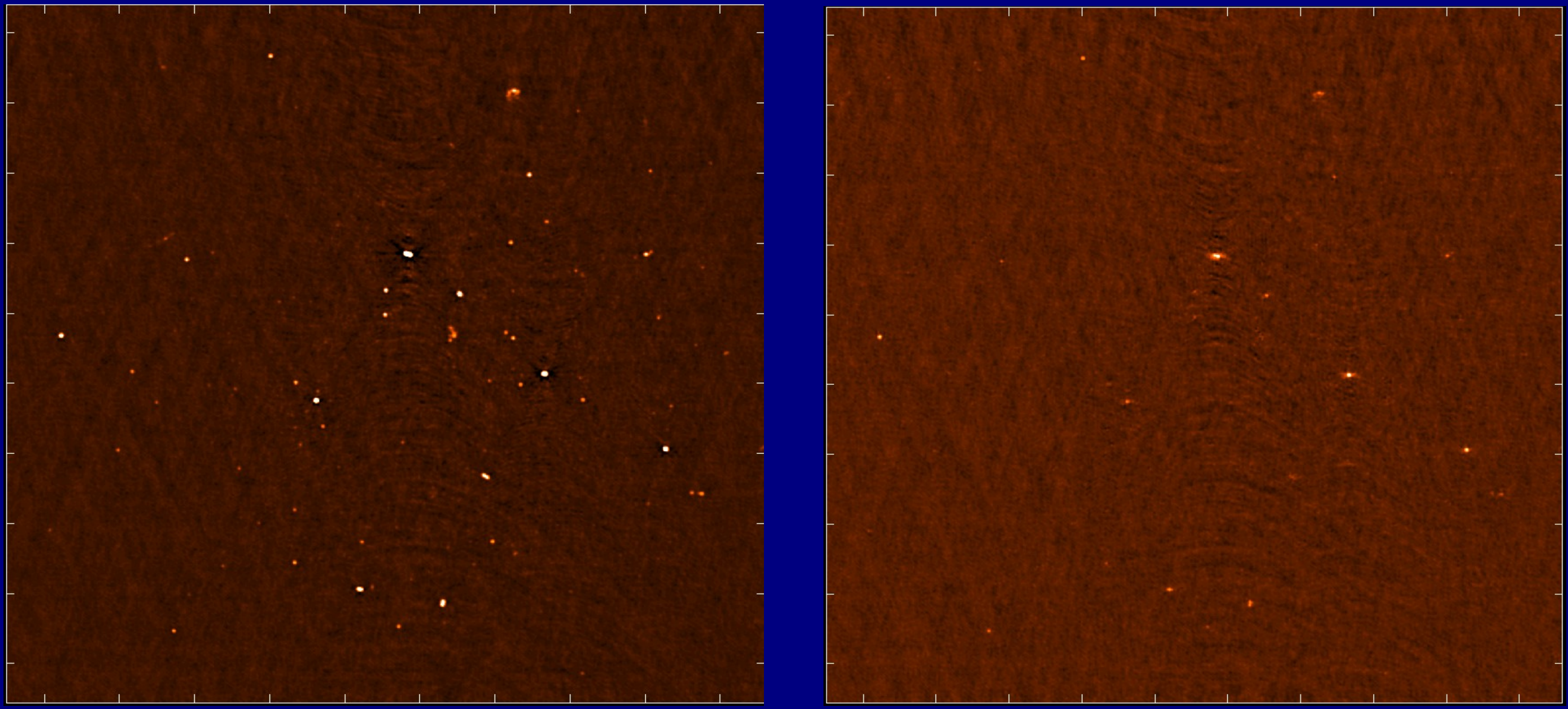
(Data from: Owen, et al.)

...sky more complex



- PB main lobe zoomed in
- Note:
  - Many resolved sources
  - Sky more filled
  - Errors are direction dependent

Sky at low frequencies: Frequency dependence



1.365GHz   I(1.365GHz)-I(1.435GHz)

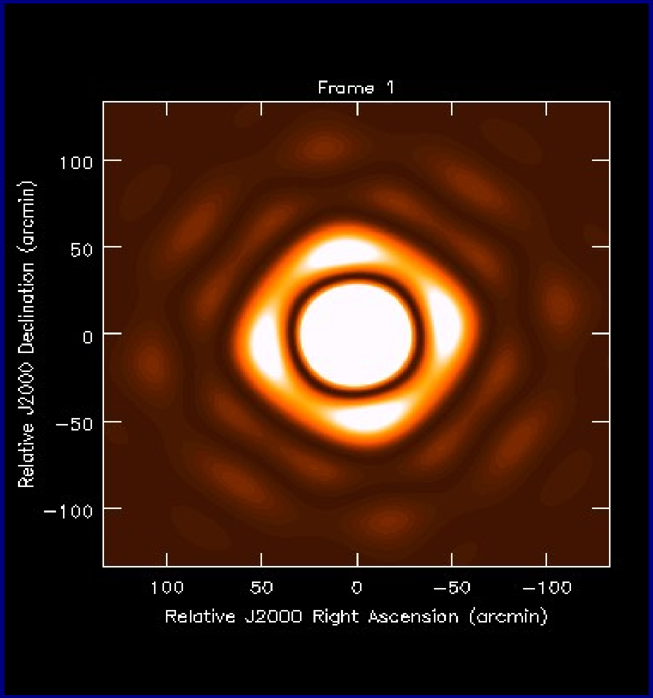
- Direction & Frequency Dependent errors
  - Sky spectral index? PB effects? Pointing? Pixelation errors?
- Errors not coherent across frequency
  - Will affect spectral line signals (EoR)

More details in talks next week!

Primary Beam Effects

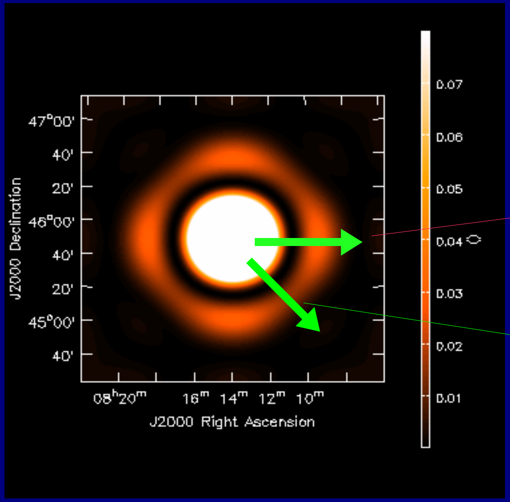
- EVLA full beam, full band, single feed

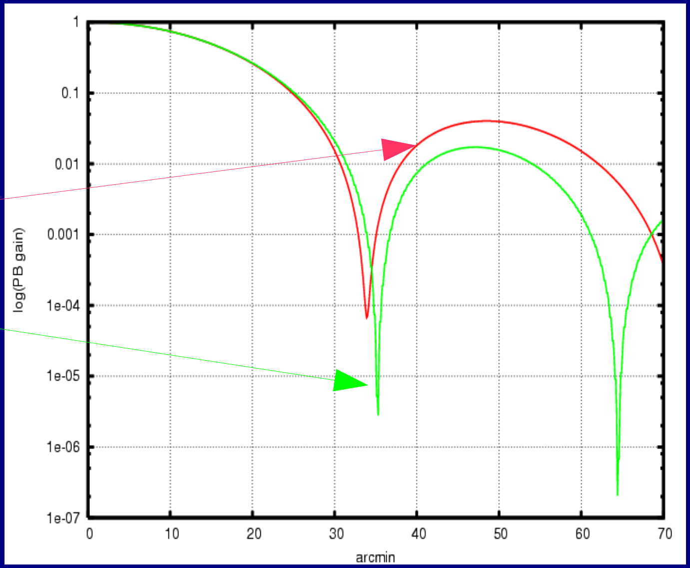
PB rotation, pointing errors

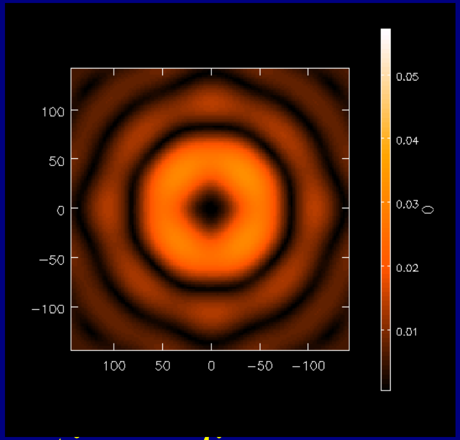


PB variation across the band

EVLA: Sources move from main-lobe to side-lobes







Cross hand power pattern

PB gain varies as a function time, frequency and direction in the sky

PB errors: Full beam imaging limits

- Limits due to rotation of asymmetric PB
  - In-beam max. error @~10% point
  - DR of few x10^{3-4}:1
  - Errors larger in the first sidelobe

- Limits due to antenna pointing errors
  - In-beam max. error at half-power points
  - DR of few x10^{3-4}:1
  - Limits for mosaicking would be worse
    - Significant flux at half-power and side-lobes for many pointing

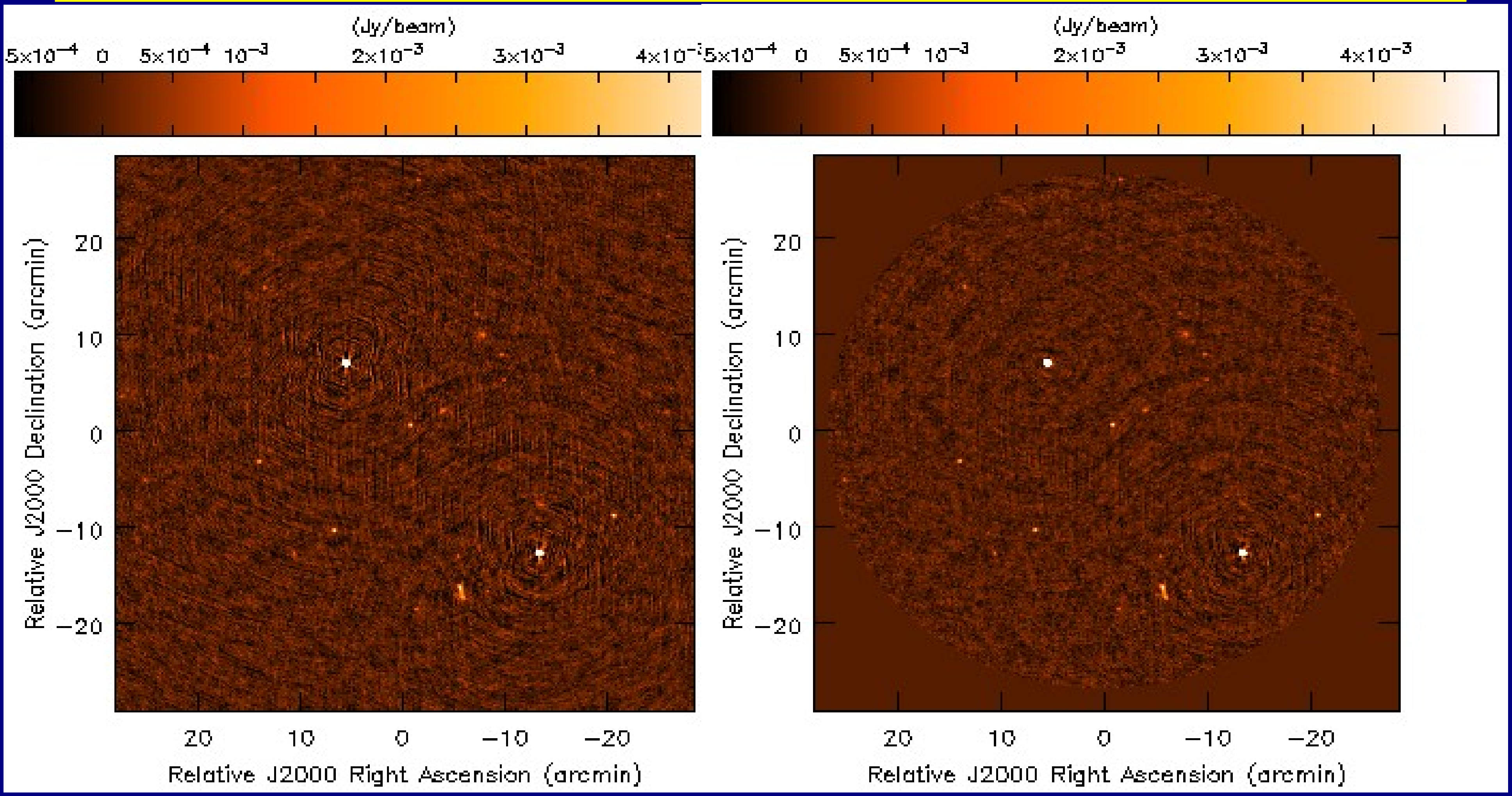
PB correction: A-Projection algorithm

- Corrections in the visibility plane (Bhatnagar, Cornwell, Kolap, Uson, A&A)
  - $V_{ij}^{Obs} = E_{ij}(t) * FFT(I^M) \quad where \quad E_{ij}(t) = E_i(t) * E_j^*(t)$
  - No assumption about the sky
  - Scales well with image complexity
  - Straightforward to integrate with algorithms that correct for other errors (MFS, W-Projection, MS-Clean, ASP-Clean).

✗ Requires a model for the PB

More details in talks next week!

Example: 1.4GHz/VLA, Stokes-I Imaging

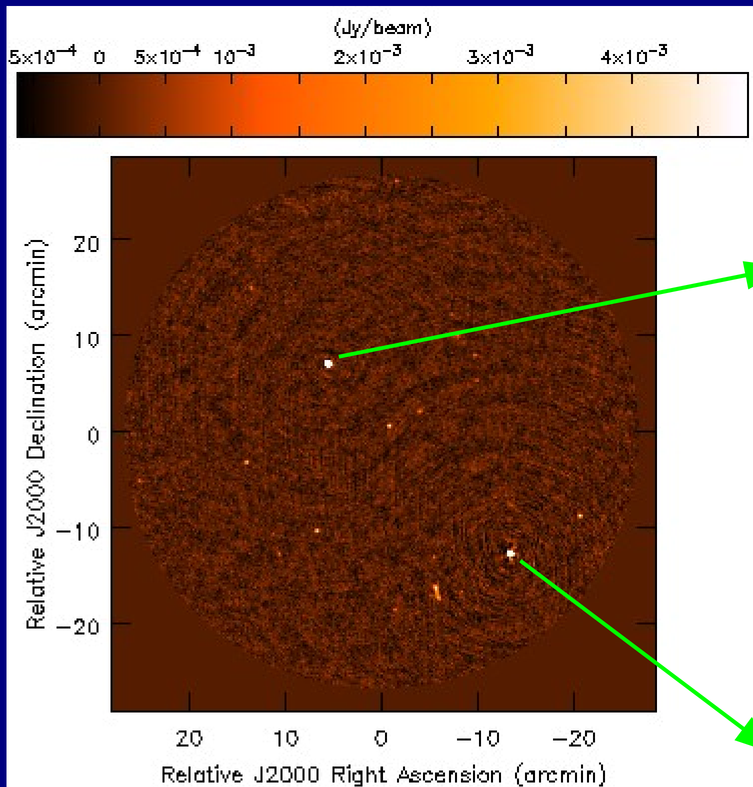


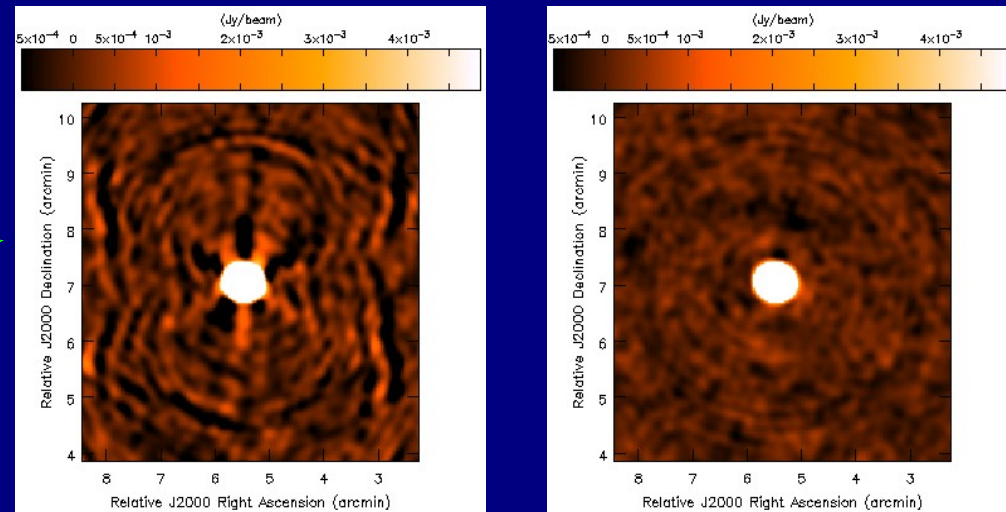
Post-deconv. PB correction:
Strong sources located at ~HP limit the dynamic range

PB correction during imaging:
Limited by pointing errors? PB knowledge? (100µJy/b)

(Data from: Matthews & Uson)

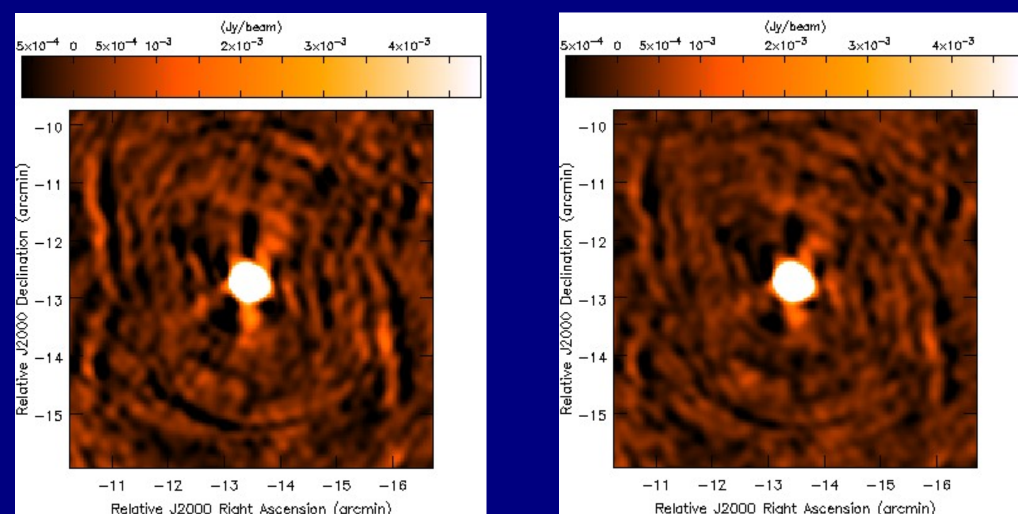
During vs. Post deconvolution PB correction





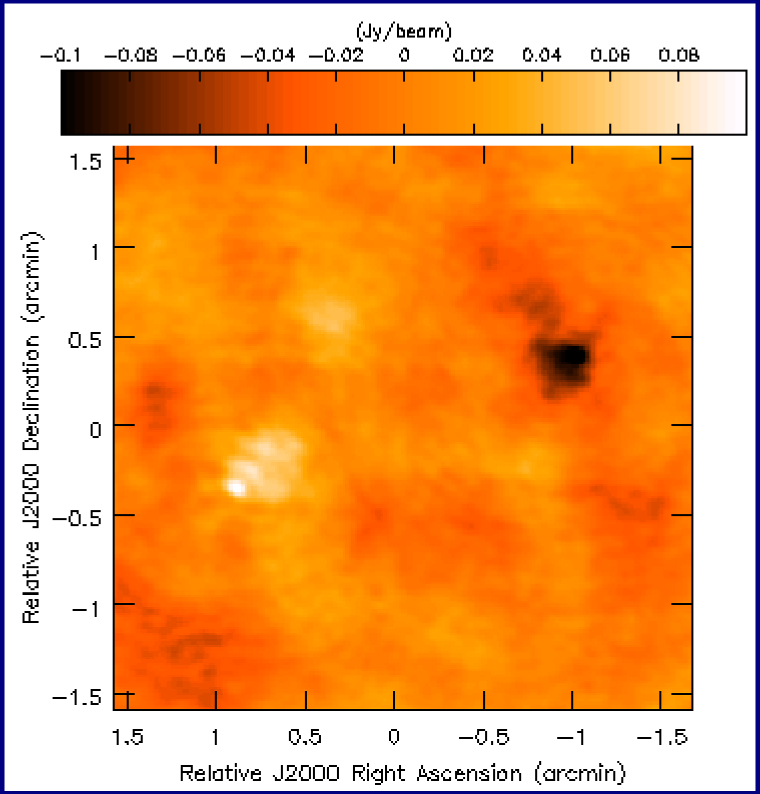
Post-deconvolution PB correction

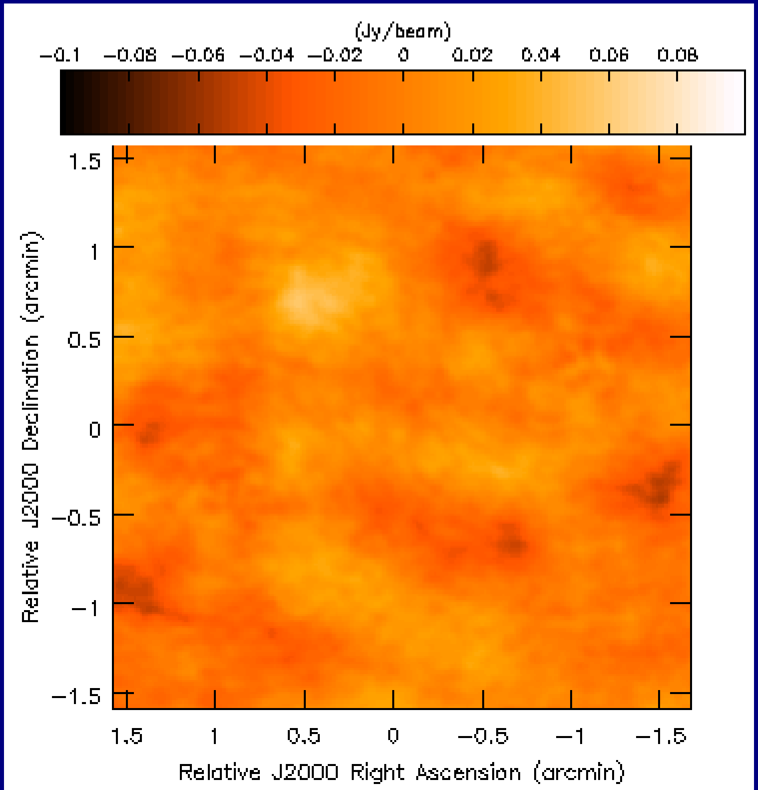
PB correction during deconvolution



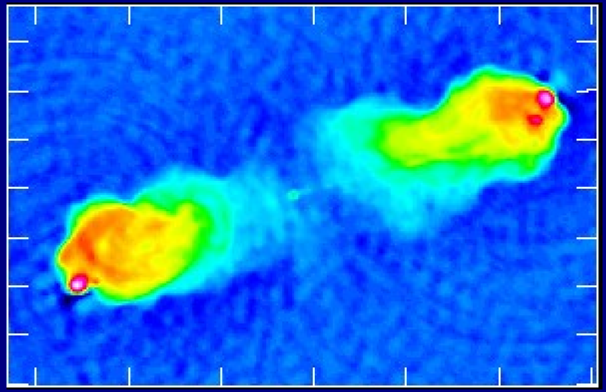
- PB errors can easily limit imaging DR
- Errors are non-random
- Stable PB will be helpful
  - Dipole arrays vs. rigid structure

Extended Emission

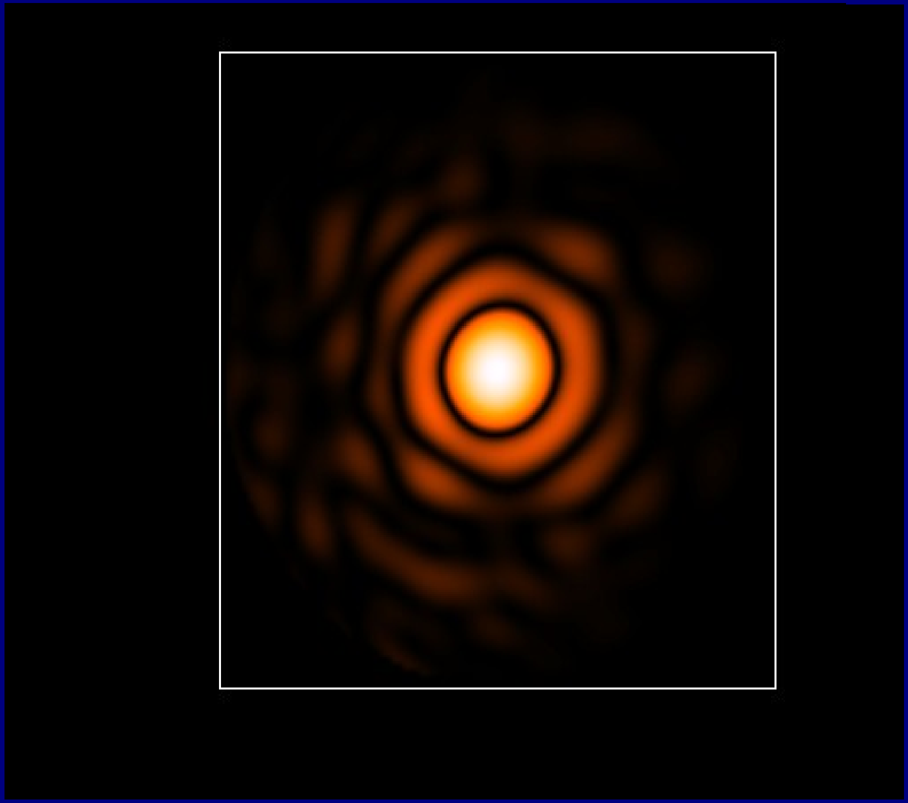




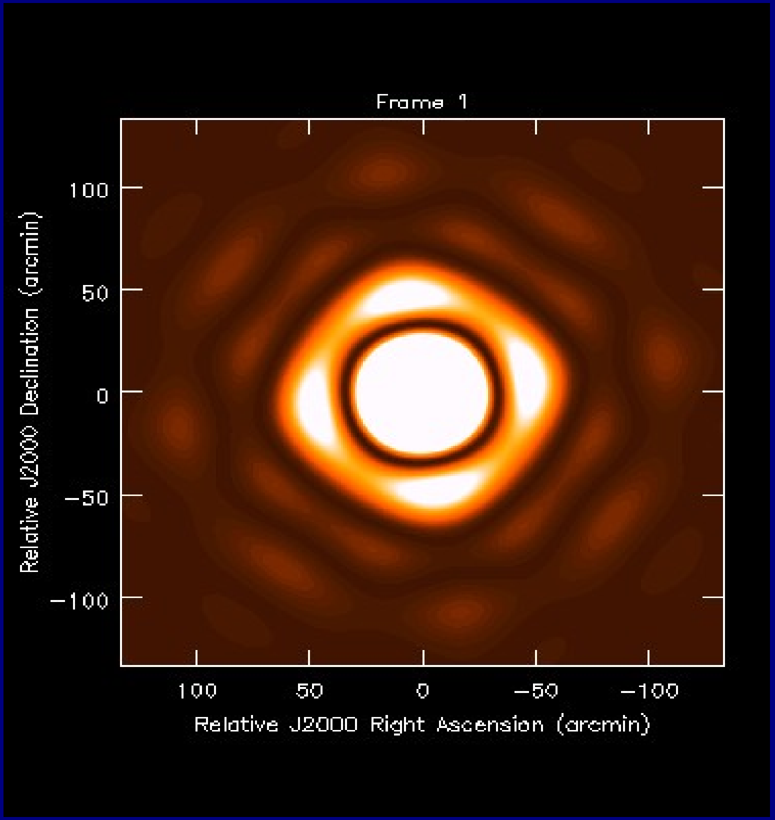
- **Stokes-V imaging of extended emission**
  - **Algorithms designed for point sources will not work**
  - **Need more sophisticated modeling of the extended emission**



Antenna: Dipole arrays vs. Solid Steel



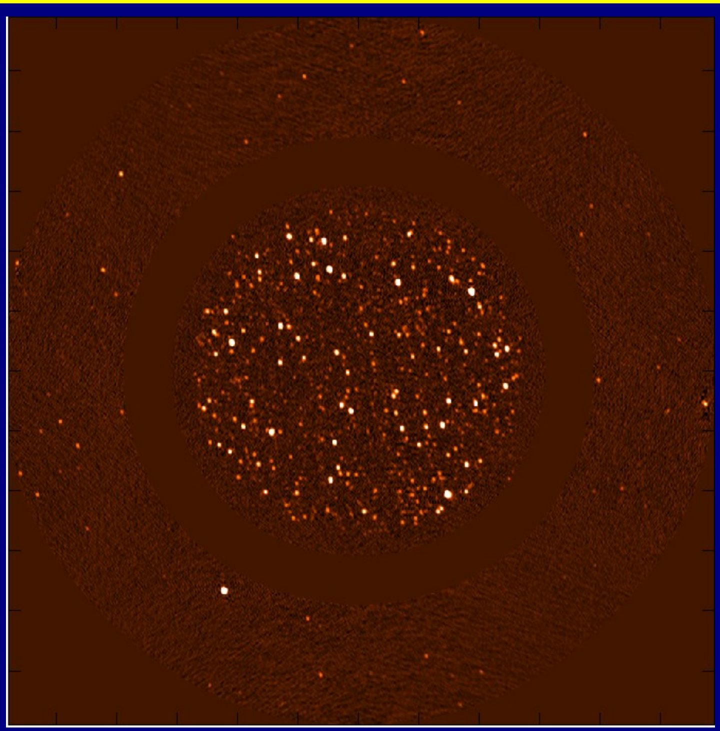
Simulation of LWA station beam
@50MHz
(Masaya Kuniyoshi, UNM/AOC)

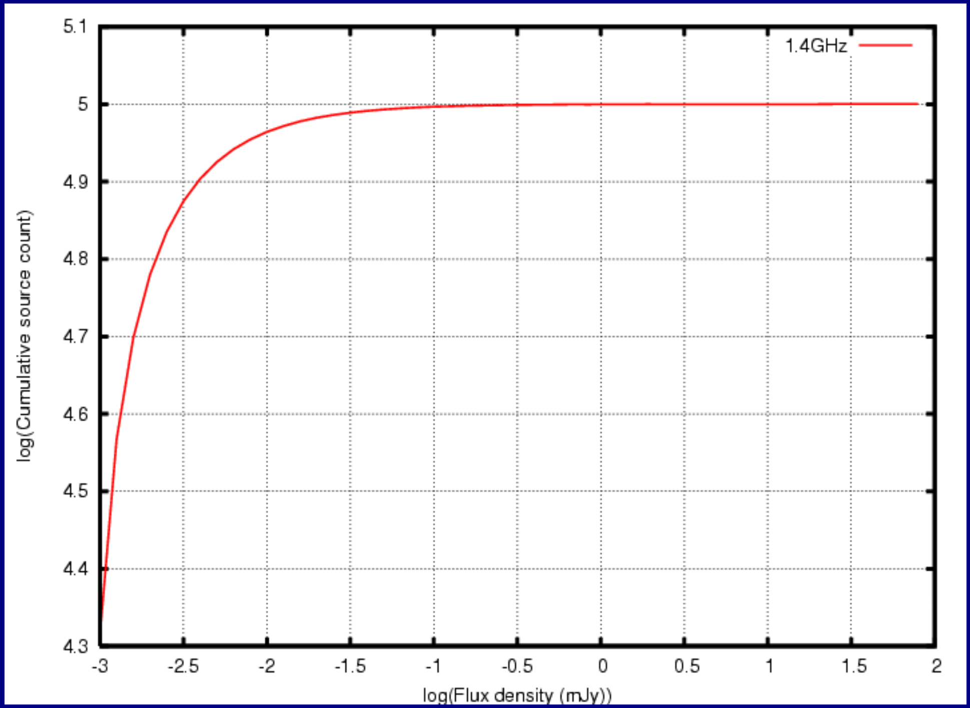


EVLA antenna PB rotation with
Parallactic Angle

More details in talks next week!

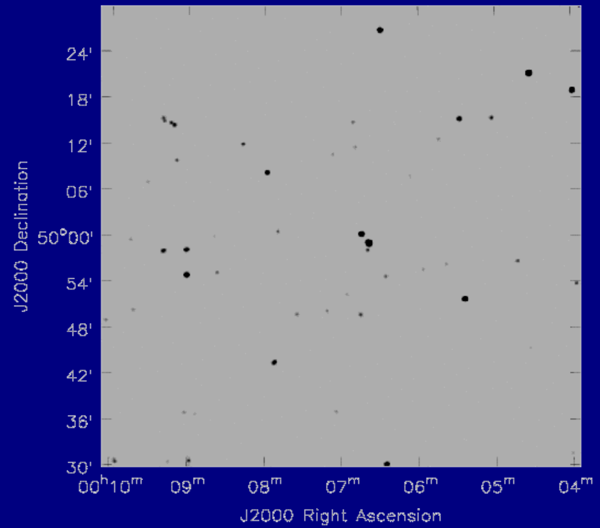
Number of sources @ 1.4GHz



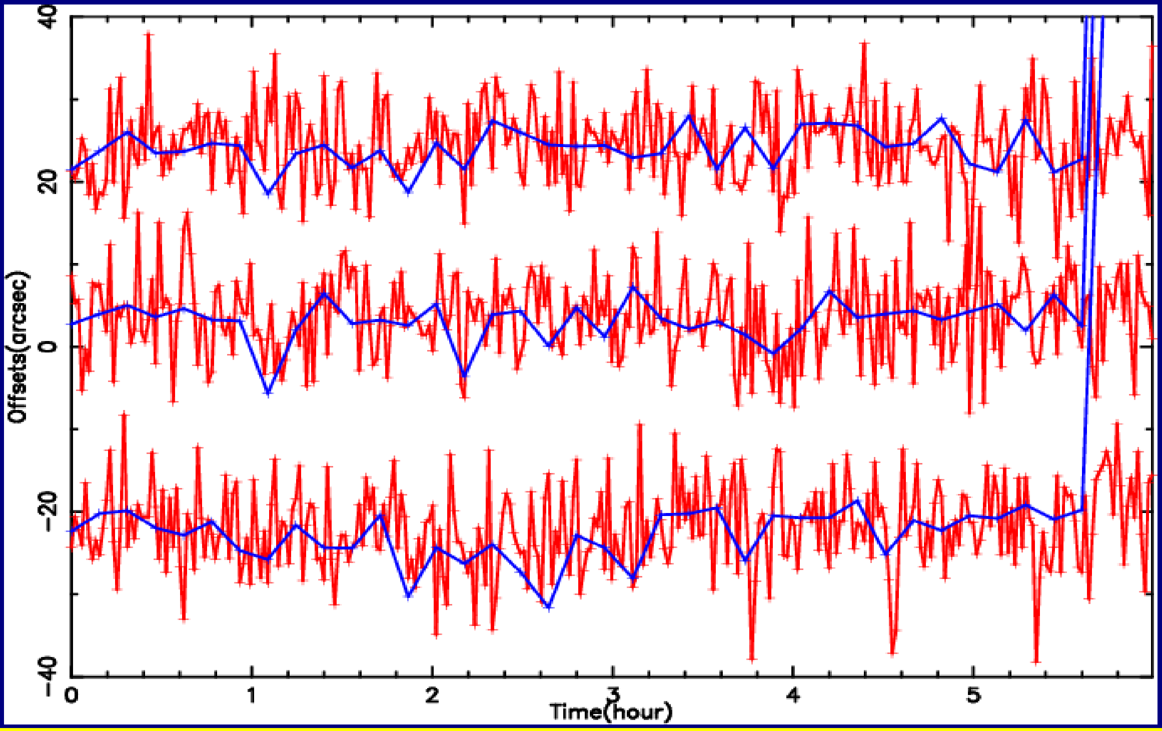


- Assuming max. PSF side-lobe at 1% level, need to deconvolve sources >100μJy to get RMS(1σ) =1μJy/beam
- $10^{4\text{-}5}$ sources per deg^2 >10μJy @1.4GHz
  - Brighter at lower frequencies (α ~ -0.8)
  - Source size distribution important at resolution < ~2"
- High precision, efficient algorithms for imaging required!

Pointing SelfCal: Example



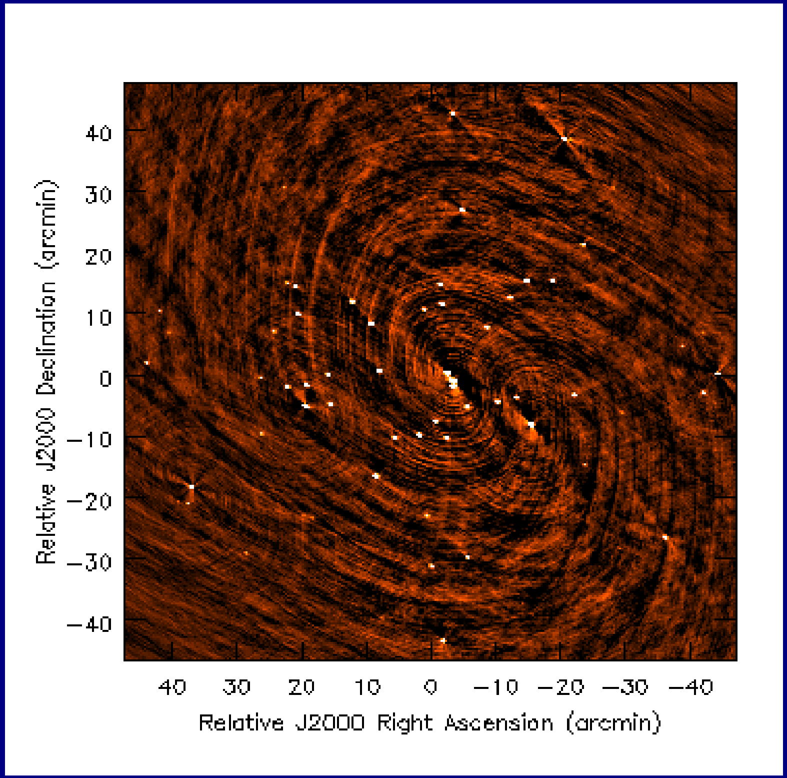
Model image: 59 sources from NVSS. Flux range ~2-200 mJy/beam



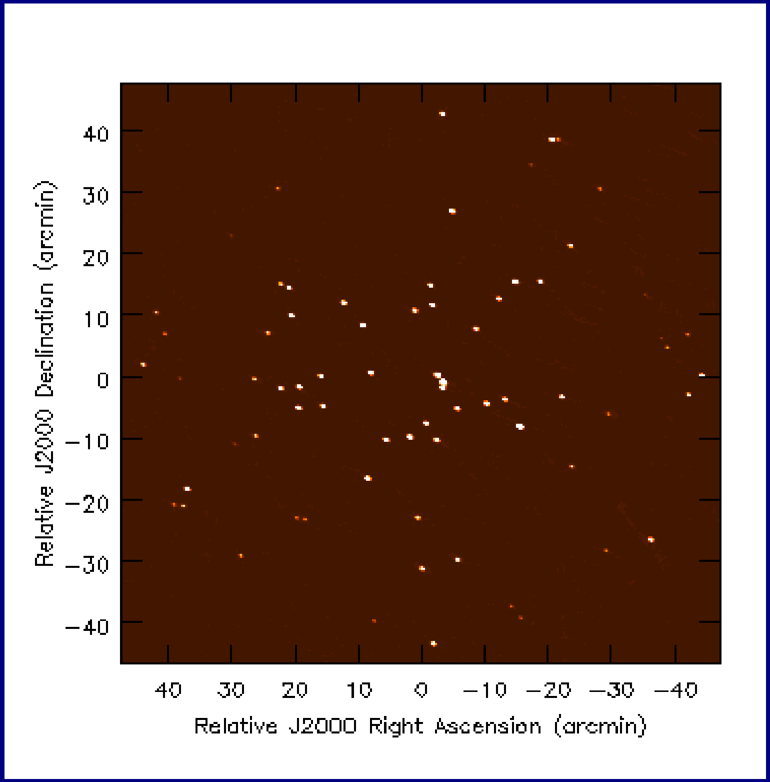
Red: Typical antenna pointing offsets for VLA as a function of time

Blue: Solved antenna pointing errors

Pointing SelfCal: Test performance



- No pointing correction:
- RMS ~ 15μJy/b



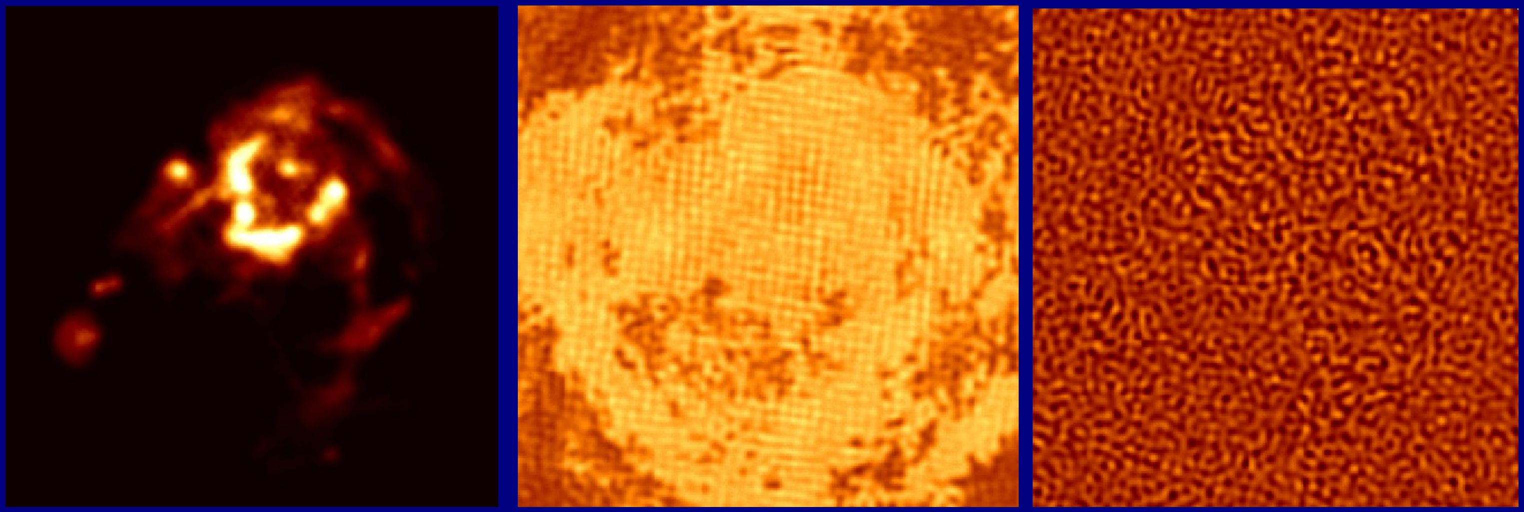
- After pointing correction:
- RMS ~ 1μJy/b

(Bhatnagar, Cornwell & Kolap, EVLA Memo #84/paper in prep.)

Imaging extended emission: Asp-Clean

- Pixel-to-pixel noise in the image is correlated
- *Keep the DoF in control!*
  - *Sub-space discovery*
- Asp-Clean (Bhatnagar & Cornwell, A&A,2004)
  - Search for local scale, amplitude and position

Asp-Clean | Clean Residuals | Asp-Clean Residuals



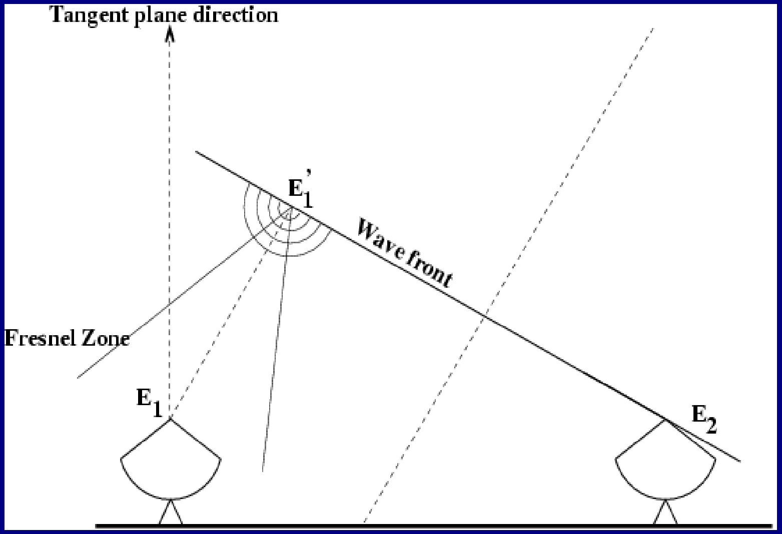
Non coplanar baselines

- $V(u,v,w) = G(u,v,w) * V(u,v,w=0)$

  $$\text{where}\ \overline{G}(l,m,w) = e^{2\pi\iota\left[w\left(\sqrt{1-l^2-m^2}\right)\right]}$$

- $E_1 = E'_1(u,v,w)$ propagated using Fresnel diffraction theory.

- Away from the phase center, sources are distorted



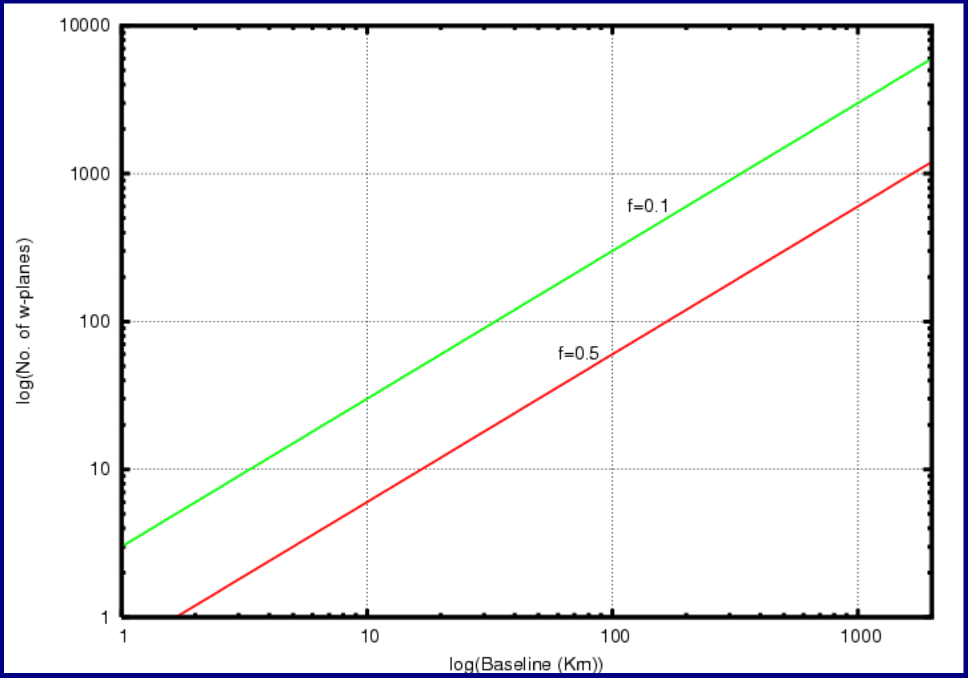
- Problem for long baselines
  - $N = 2\, B_{max} / f\, D^2$

  N: No. of W-planes

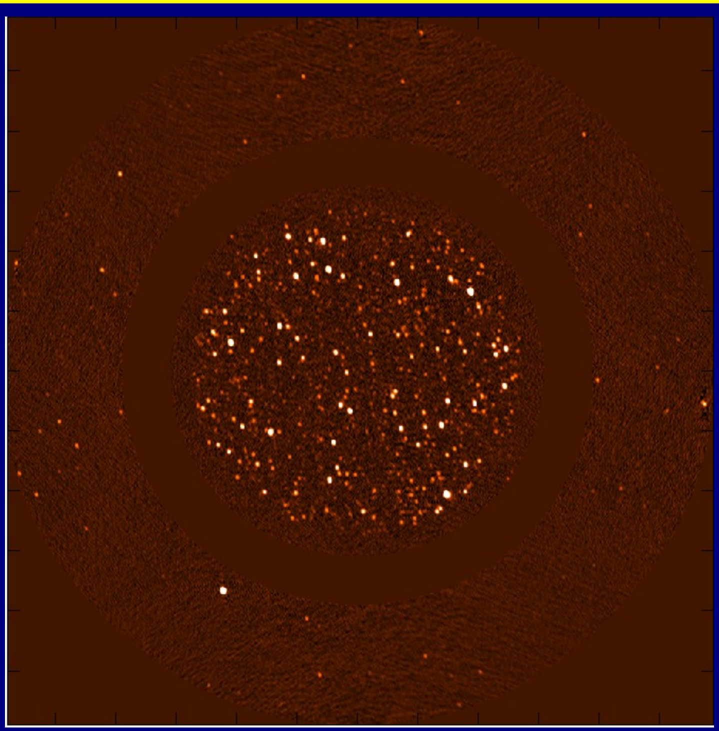
  B_{max}:Max. Baseline

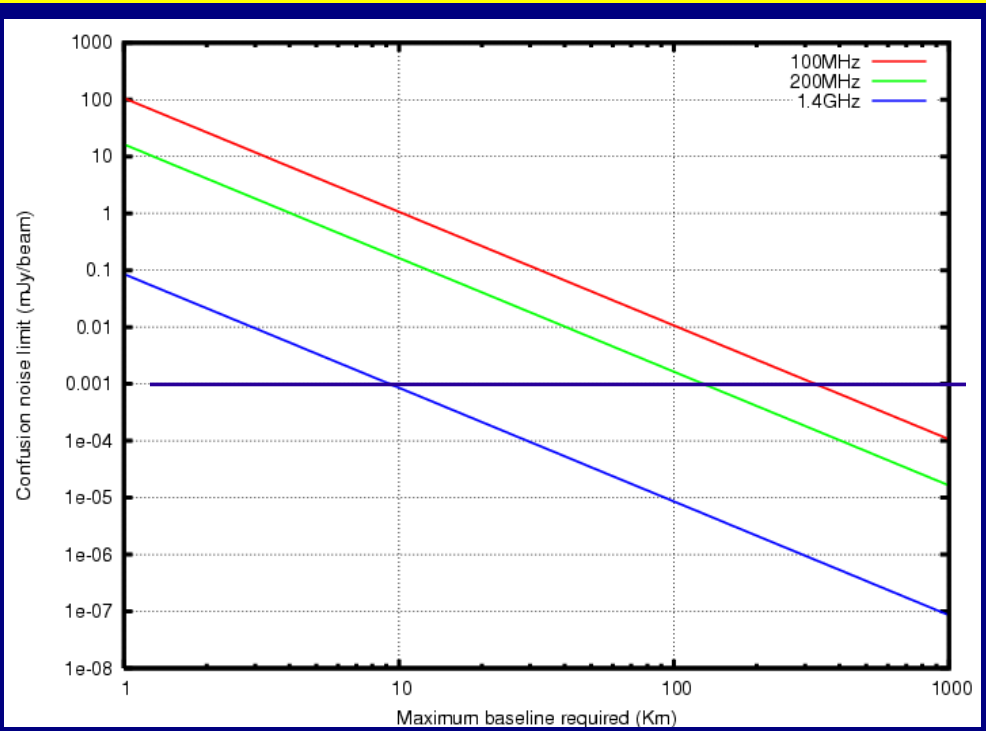
  D: Antenna diameter

  f: <1.0 for high DR (>= 10^4)

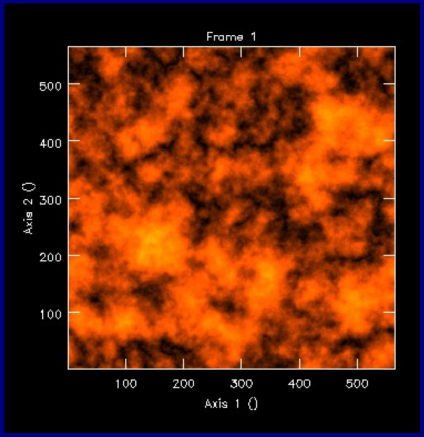


Confusion limit vs. resolution

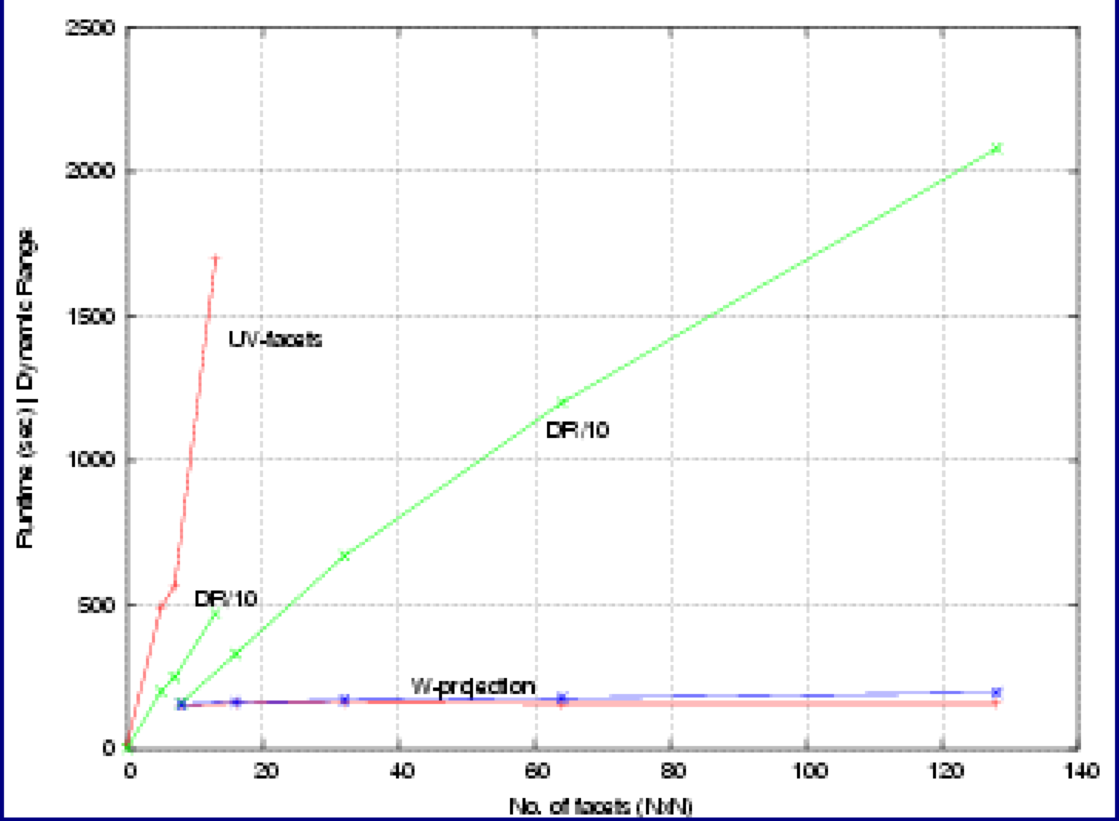


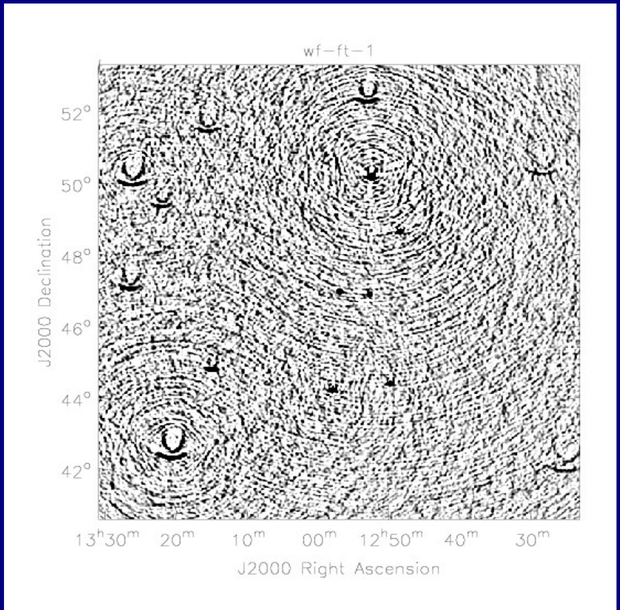


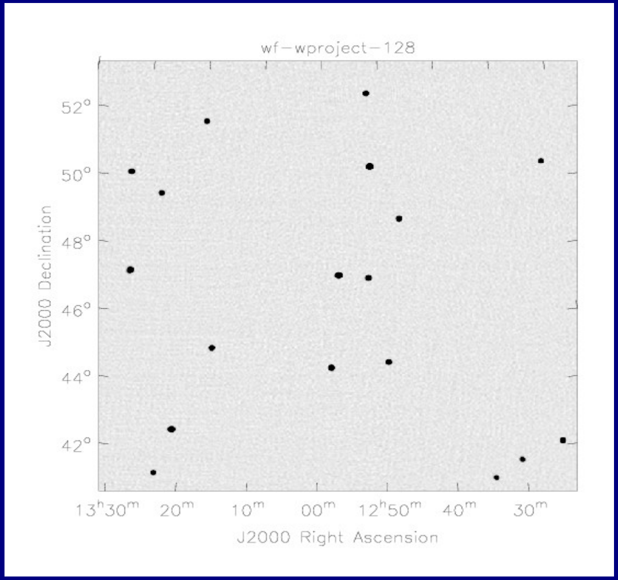
- $\sigma_{confusion} \propto (\nu^{-2.7}/B^2_{max})$
- B_{max} ~100 Km at 200MHz for $\sigma_{confusion}$ ~ 1µJy/beam
- Challenges:
  - W-term an issue for B_{max} > 2-3Km & DR > 10^4
  - Ionospheric calibration: Even field based calibration fails for B_{max} > 3Km



W-projection algorithm: Scaling laws





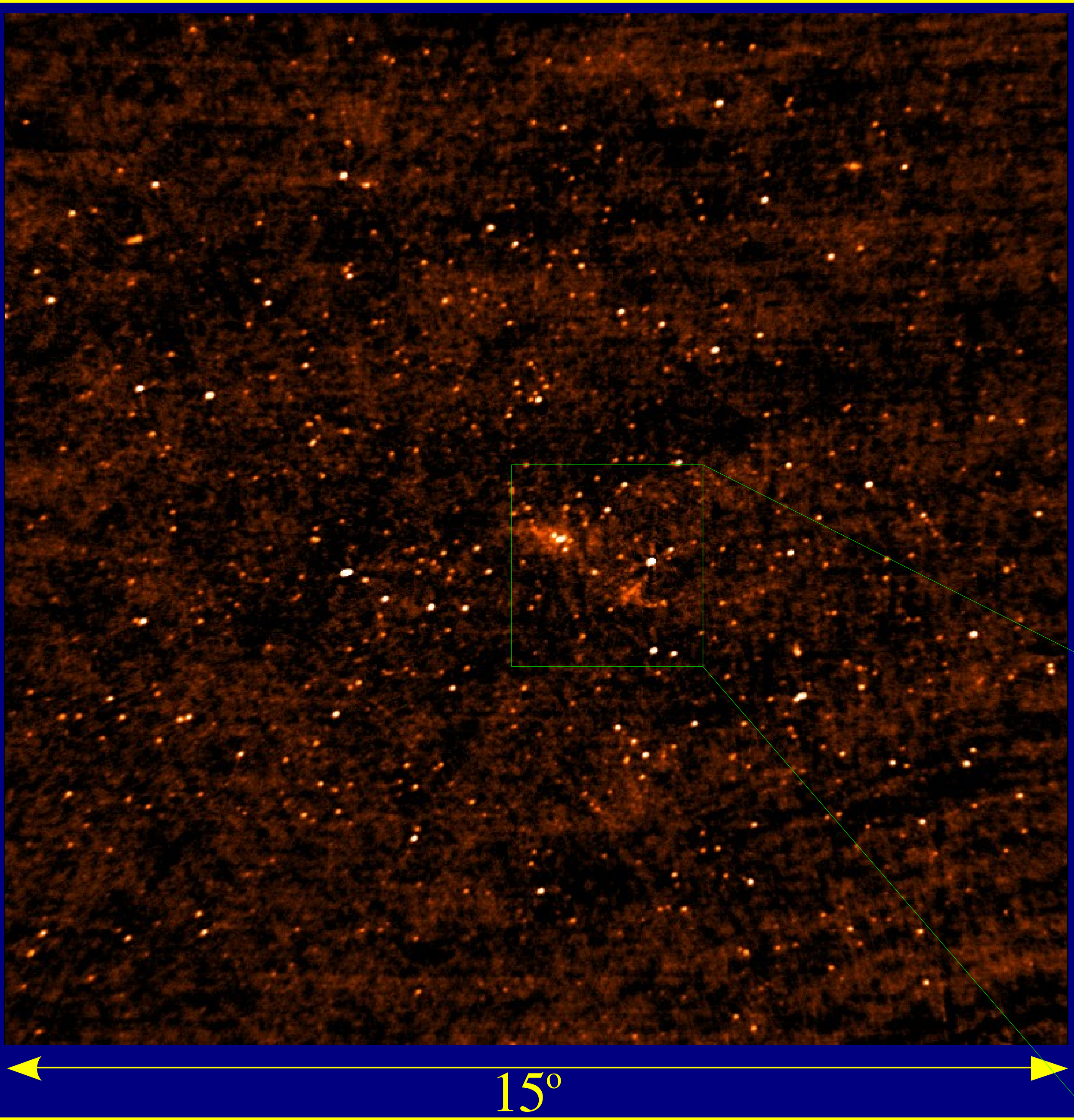


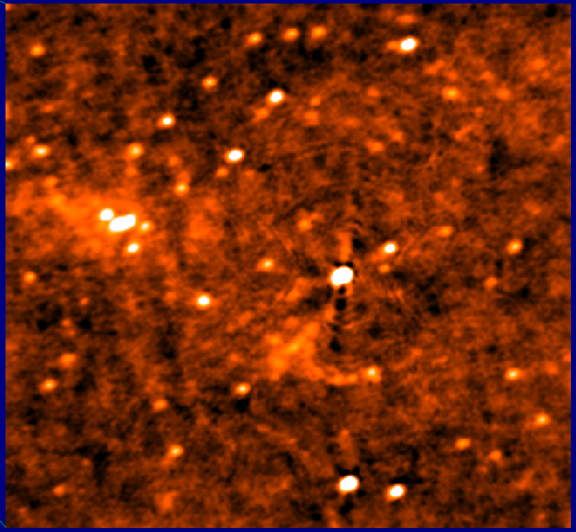
W-projection: $(N^2_{wproj} + N^2_{GCF})\,N_{vis}$

UV-facet: $N^2_{facets}\,N^2_{GCF}\,N_{vis}$

(Cornwell, Kolap & Bhatnagar, paper submitted)

W-Projection: Example

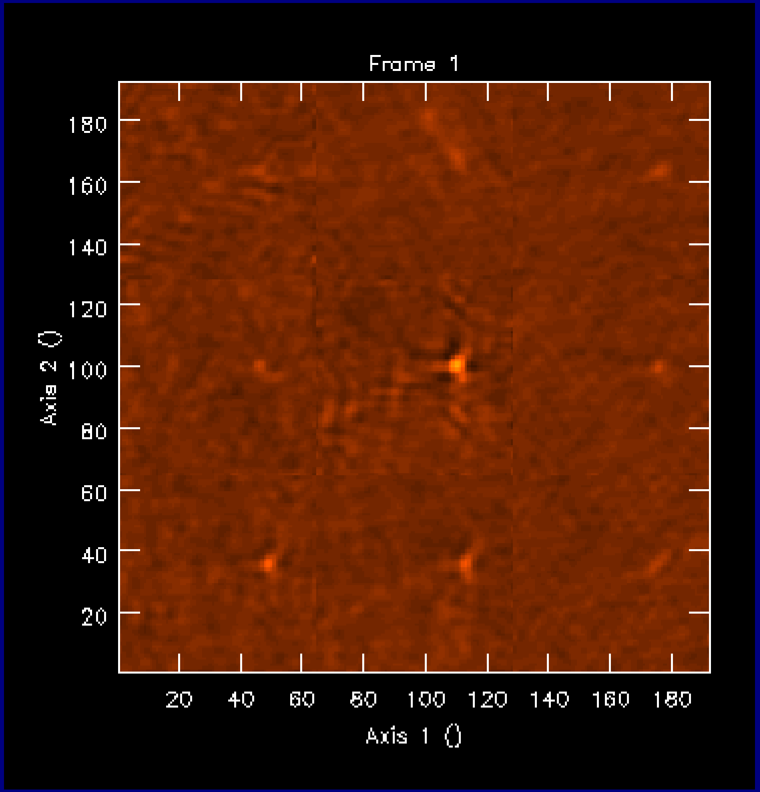




- Coma cluster at 74 Mhz/VLA
- 30 arcsec resolution, RMS ~30mJy/beam
- Imaged using the W-projection algorithm (Golap)

Ionospheric phase screen

- Ionospheric phase varies across the FoV
- For short baselines (1-3Km) at 74MHz/VLA, field based calibration helps (Cotton et al. 2004)
  - Corrects of phase gradients only
- De-focusing significant at baselines >3Km.
  - No known algorithm for this
  - Solutions will probably be computationally expensive
- Imaging DR limits not reliably known
  - Simulation work with realistic ionosphere in progress



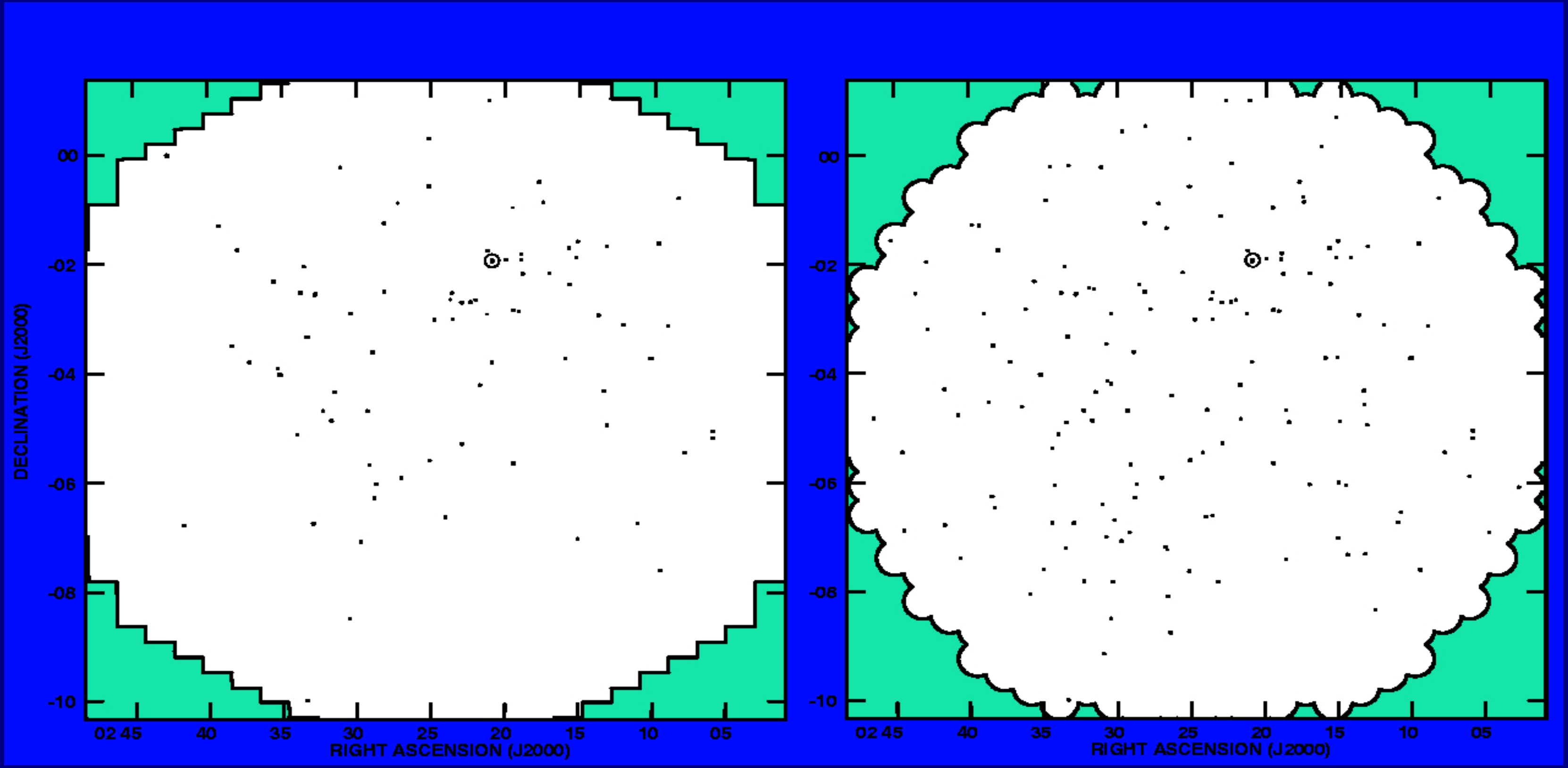
Non-isoplantic ionospheric effects (by Cotton). Note: Differential source wandering + de-focusing.

Ionosphere: Field Based Calibration

- Find shifts of strong sources from snapshot images
- Fit 2nd order Zernike polynomials to get phase screen model
- Correct for the phase screen during imaging

➔ De-focusing not handled

➔ Limited to snapshot imaging sensitivity (Cohen et al., AJ, 2007)



Computing & I/O costs

- Higher sensitivity ==> more data + correction of more error terms
  - Needs more sophisticated parameterization
  - Significant increase in computing and I/O loads
- Imaging:
  - Correction for PB variations, Pointing errors, ionosphere
  - Better modeling of extended emission
- Calibration: solve for direction dependent effects
  - As expensive as imaging
  - PB shape, pointing, ionosphere
- Processing cost dominated by forward and backward transforms (gridding)
  - I/O time comparable to computing time

Development challenges

- Software development costs will be significant
  - Need (many) more, highly skilled FTEs
- Investment in research
  - Basic algorithms research
  - Development of scalable algorithms
    - Scaling with computing & DR
- Software
  - Design and implement scalable software (non trivial)
  - Large teams in space-time
- Management
  - Expect attrition: Design and implement accordingly
  - Attract new talent: Algorithms & software development mainstream RA!

Summary

- Improvements in algorithms for imaging & calibration required for high dynamic range
- High DR ==> longer baselines ==> challenges
- Many effects are direction dependent
  - Need efficient algorithms which correct for these
- Good progress in some areas
  - W-Projection (W-stacking), A-Projection, Pointing selfcal, MS-Clean/Asp-Clean, Wide field imaging, Ionosphere
- Need “system” integration and tests
- Ionospheric calibration and correction at high resolution/DR a difficult, largely unsolved problem (some works in progress)
- Need to change how we work (software development)

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Yes We Can! **Message of Hope** (Obama et al. 2008; www.barakobama.org)