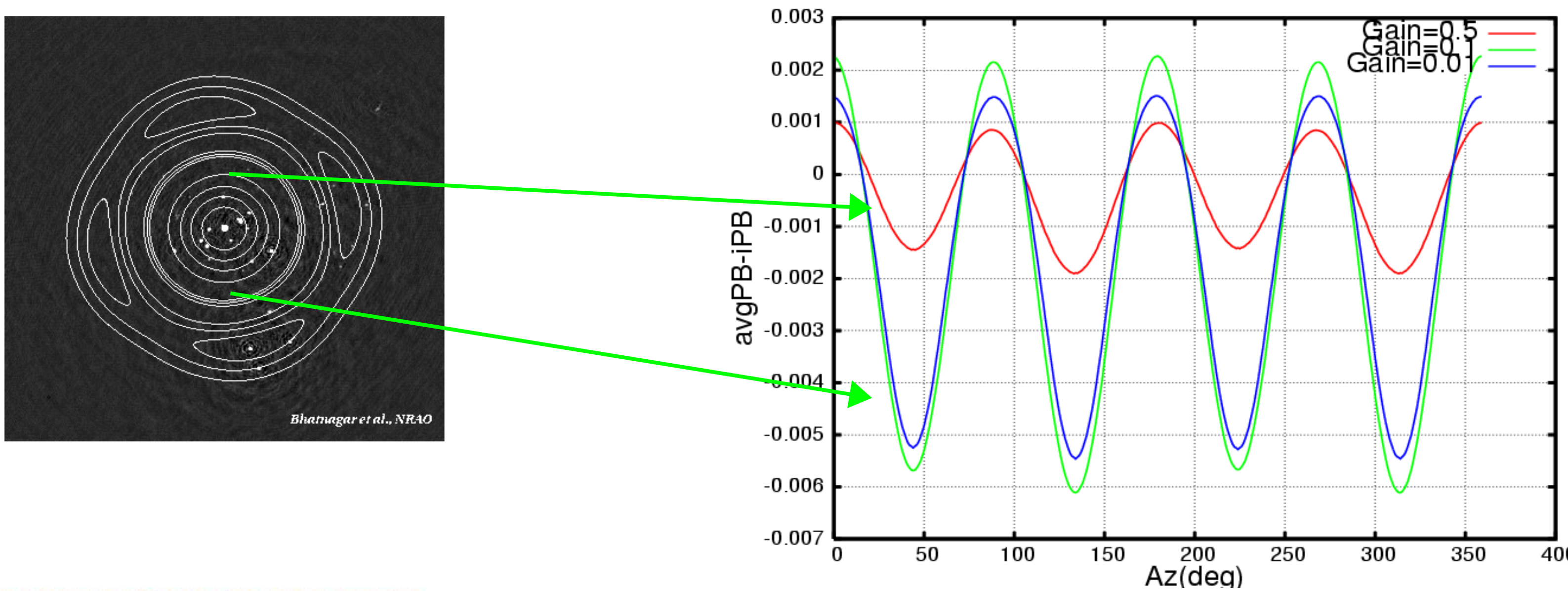
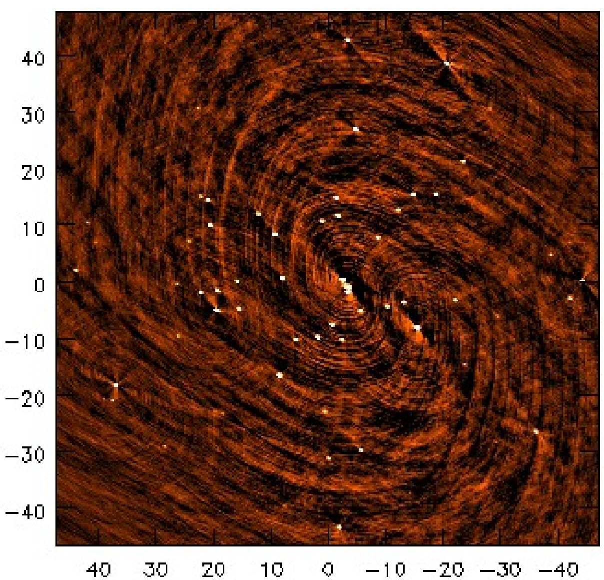
Wide-field Wide-band Full-polarization Imaging:

Impact of Direction Dependent PB effects

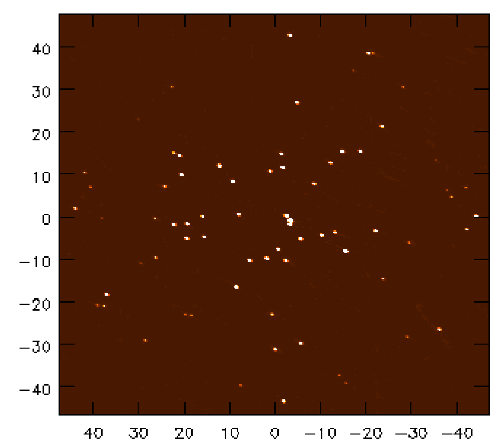
S. Bhatnagar, U. Rau, P. Jagannathan, K. Kundart

What is wide-field?



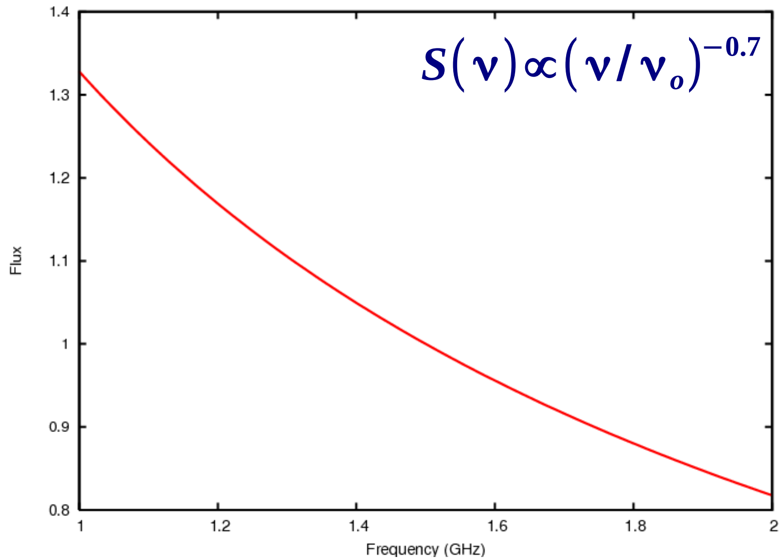


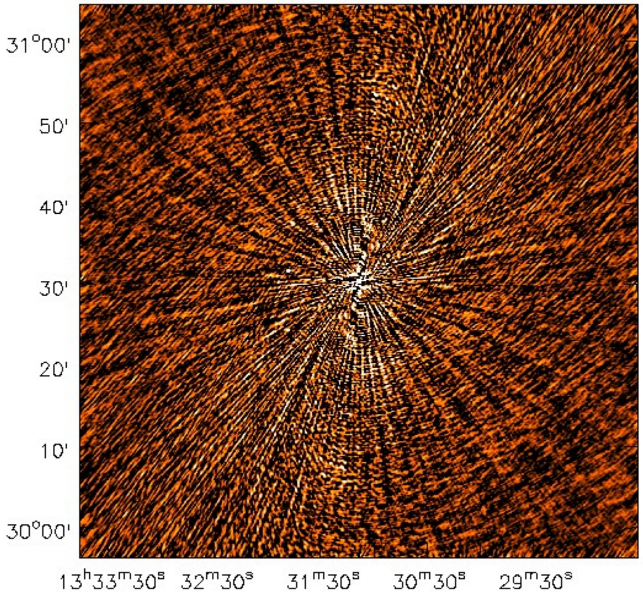
"True" sky



What do we call wide-band?

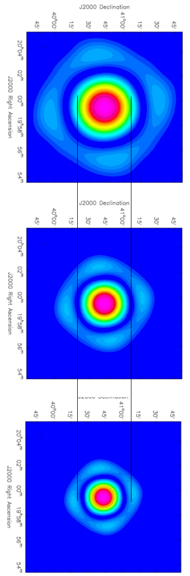
- When fractional signal bandwidth used for imaging > ~20%
  - Plus source spectral index >= -1.0
  - Plus target dynamic range > 1000
- Spectral effects for higher source spectral index will become significant at lower bandwidth ratios
  - Empirical Dynamic range : $\frac{I\alpha}{100}$
  - Spectral line imaging, by definition, does not require wide-band imaging algorithms

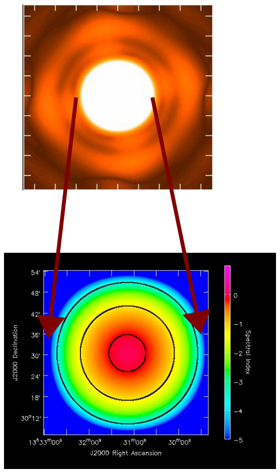




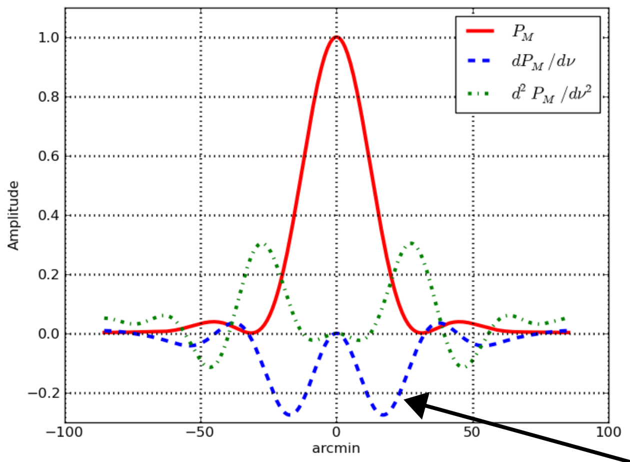
Wide-band Wide-field Imaging

- Wide band data to image beyond the ~50% point of the PB at a reference frequency
  - Bandwidth ratio > ~20%
  - FoV > ~HPBW @ reference frequency
  - Variable PB:
    - Long integration (rotation), Mosaicking (pointings at different PA), in-beam polarization is large (AA)





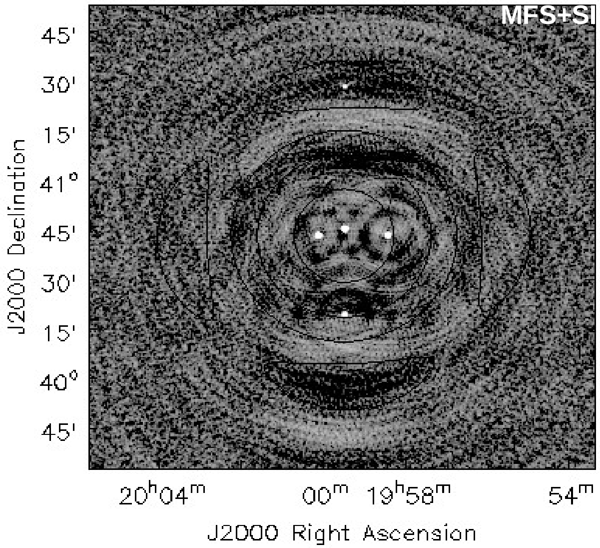
PB “Spectral Index”

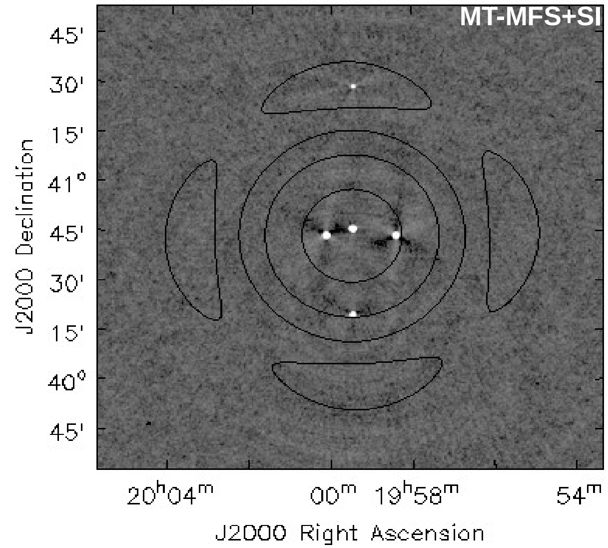


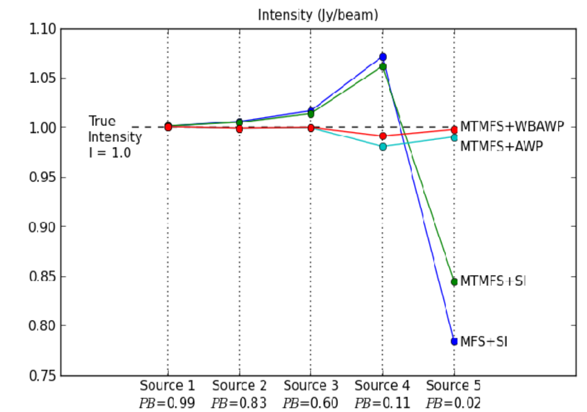
PB Frequency dependence (blue curve)

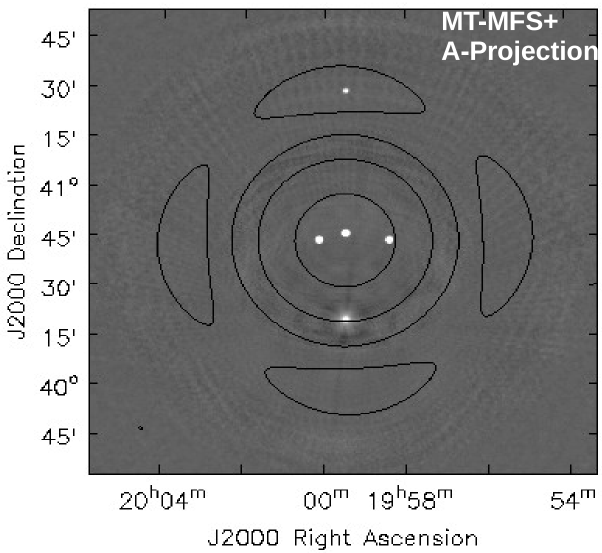
Wide-band Wide-field Imaging

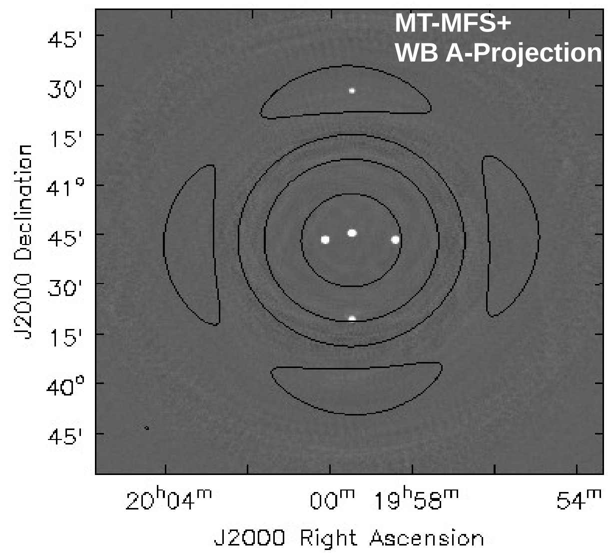
- Characterization of the (WB) A-Projection + MT-MFS

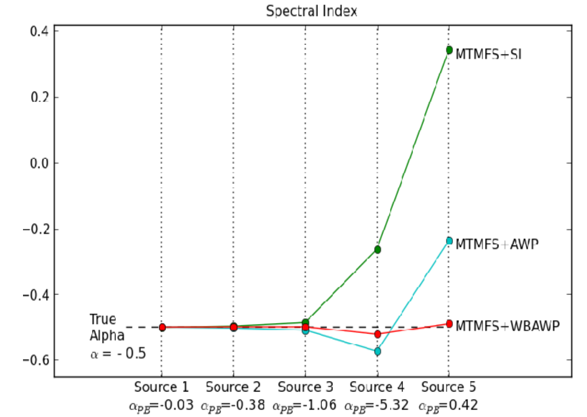








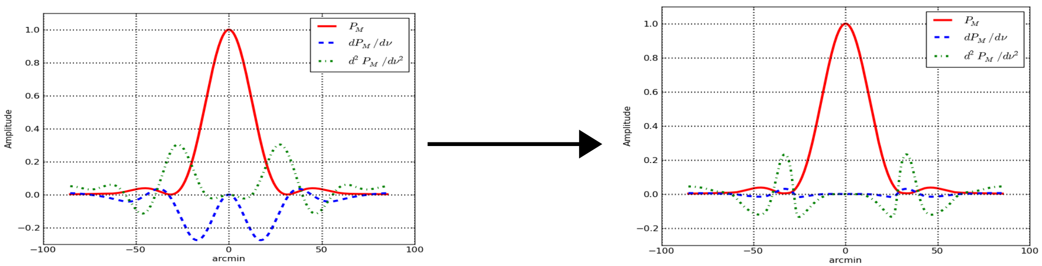




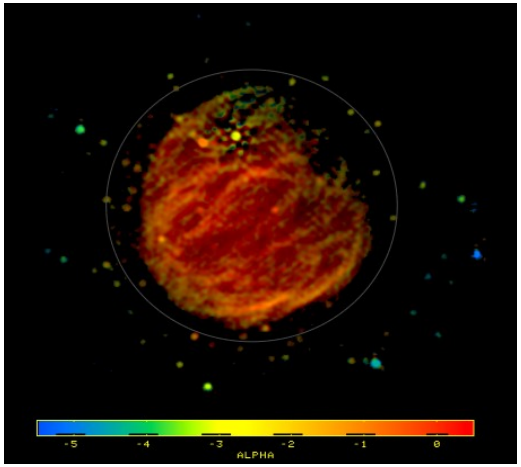
2016, AJ (accepted) [arXiv:1605.07640]

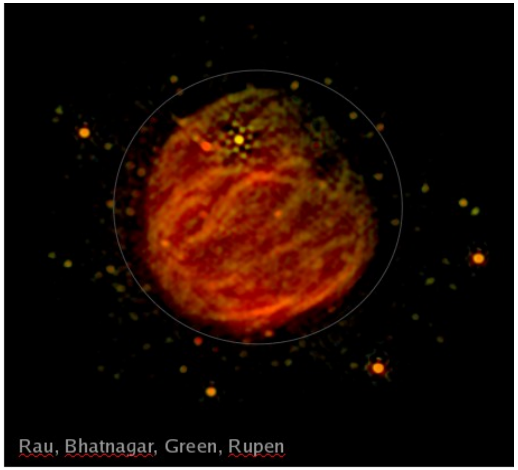
Wide-band Wide-field Imaging

- WB A-Projection + MT-MFS
  - WB A-Projection for PB



  - MT-MFS for sky





(2011, ApJ, 739, L20 [arXiv:1106.2796v2])

Full-Mueller (Polarization) WF-WB Imaging

- Direction Dependent (DD) Measurement Eq. (ME) in the image domain:

$$\boldsymbol{I}^{Obs} = [\boldsymbol{M}] \cdot [\boldsymbol{I}^{o}]$$

$$\begin{bmatrix} I_I^{Obs} \\ I_Q^{Obs} \\ I_U^{Obs} \\ I_V^{Obs} \end{bmatrix} = \begin{bmatrix} M_{11} & M_{12} & M_{13} & M_{14} \\ M_{21} & M_{22} & M_{23} & M_{24} \\ M_{31} & M_{32} & M_{33} & M_{34} \\ M_{41} & M_{42} & M_{43} & M_{44} \end{bmatrix} \cdot \begin{bmatrix} I_I^{o} \\ I_Q^{o} \\ I_U^{o} \\ I_V^{0} \end{bmatrix}$$

- Diagonal: “pure” poln. products
- Off-diagonal: Include poln. leakage

- DD ME in the visibility domain:

$$\boldsymbol{V}_{ij}^{Obs} = \left[\boldsymbol{A}_i \otimes \boldsymbol{A}_j^{T}\right] * \left[\boldsymbol{V}_{ij}^{o}\right] = \left[\boldsymbol{A}_{ij}\right] * \left[\boldsymbol{V}_{ij}^{o}\right]$$

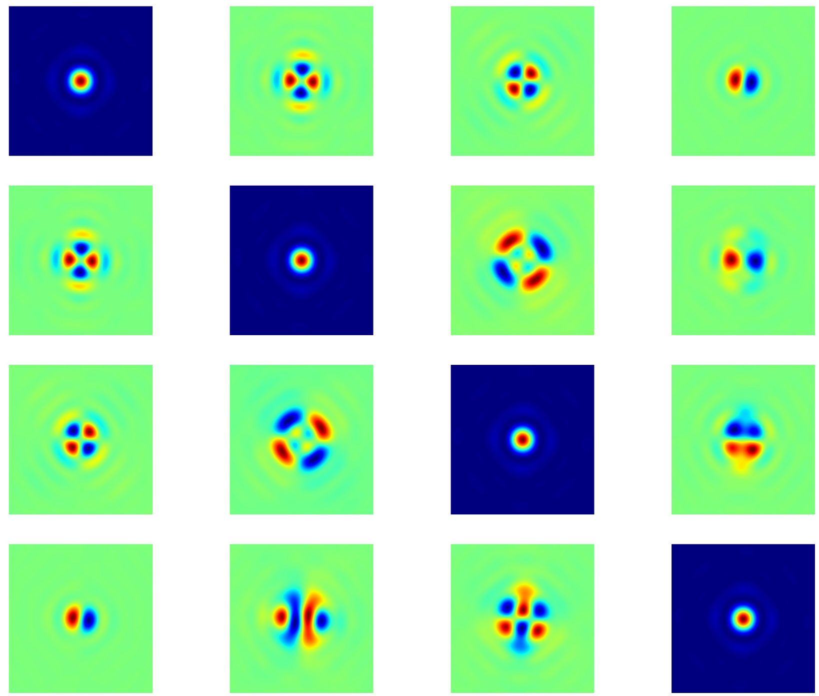
where $\boldsymbol{A}_i = \begin{bmatrix} \boldsymbol{A}_p & \boldsymbol{A}_{p \to q} \\ \boldsymbol{A}_{q \to p} & \boldsymbol{A}_q \end{bmatrix}$

Antenna Aperture Illumination

DD Effects in Full-pol. Imaging

- DD “Mueller” matrix:

$$\begin{bmatrix} I_I^{Obs} \\ I_Q^{Obs} \\ I_U^{Obs} \\ I_V^{Obs} \end{bmatrix} =$$



Stokes Basis

$$\cdot \begin{bmatrix} I_I^{o} \\ I_Q^{o} \\ I_U^{o} \\ I_V^{0} \end{bmatrix}$$

- Affects DR at the $10^{3\text{-}4}$ level
- PB Stokes-Q, -U is few% of Stokes-I

[Jagannathan, Bhatnagar, Rau & Taylor]

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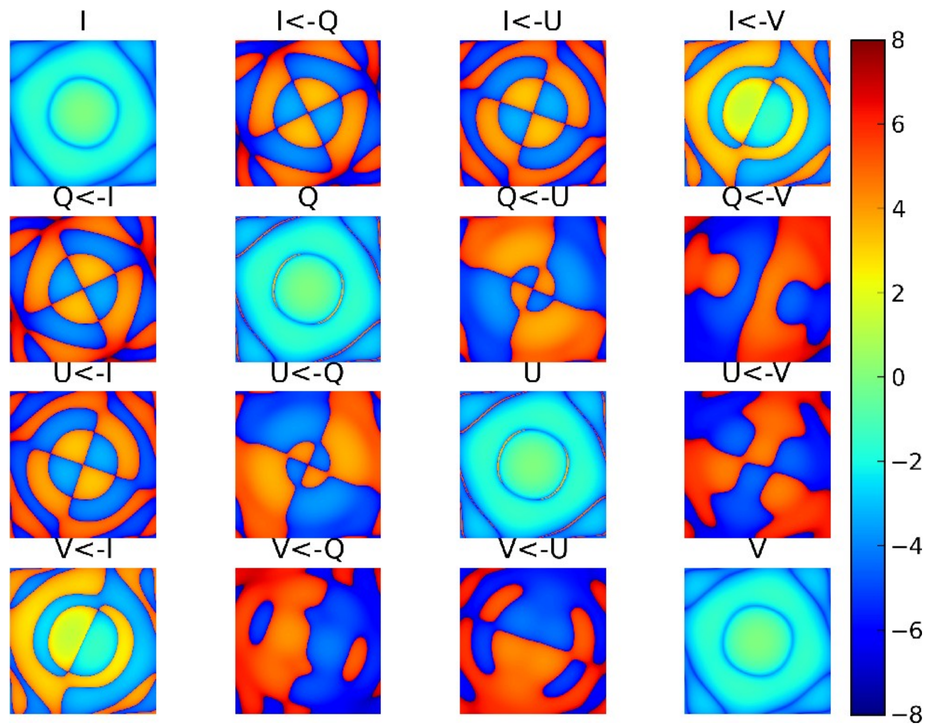

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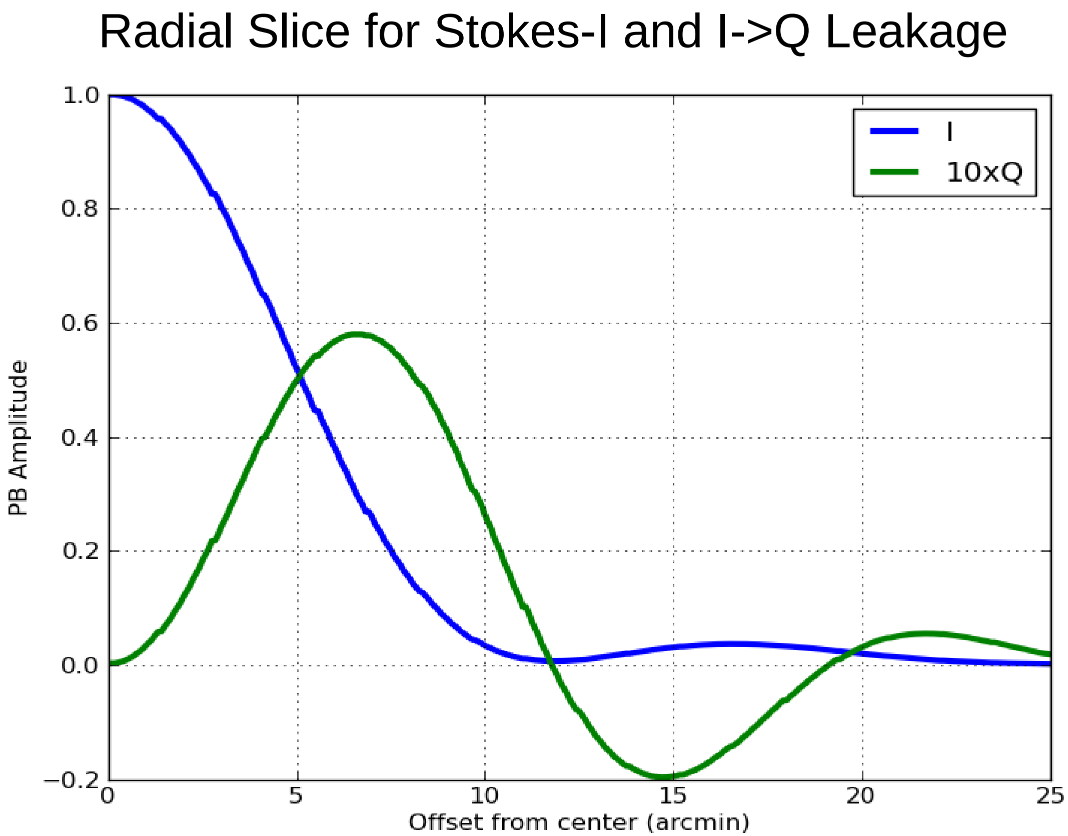
[Jagannathan, Bhatnagar, Rau & Taylor]

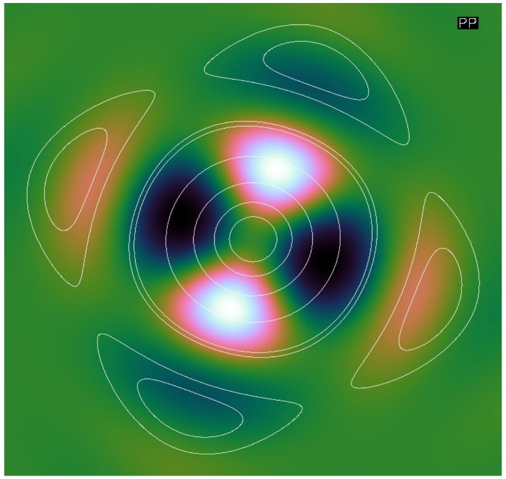
Issues in Wide-field Wide-band Full-Pol. Imaging

- PB Effects
  - In-beam effects : DD Leakage
  - Parametric Aperture Illumination model (Holographic measurements not sufficient)
  - Pointing Errors
  - Mosaic patterns
- Variations with frequency
  - Frequency dependence of intrinsic Q and U
  - Frequency dependence due to PB
- Computing load
  - Fundamentally more expensive : Larger CF support
  - Larger memory footprint: Fundamentally required, any which way you cut it

Full-pol. Imaging: In-beam Leakages

- Leakage (Off-diagonal elements of the Mueller matrix)
  - Vary with direction (position in the beam), Parallactic Angle (time) and frequency





[Jagannathan, Bhatnagar, Rau & Taylor]

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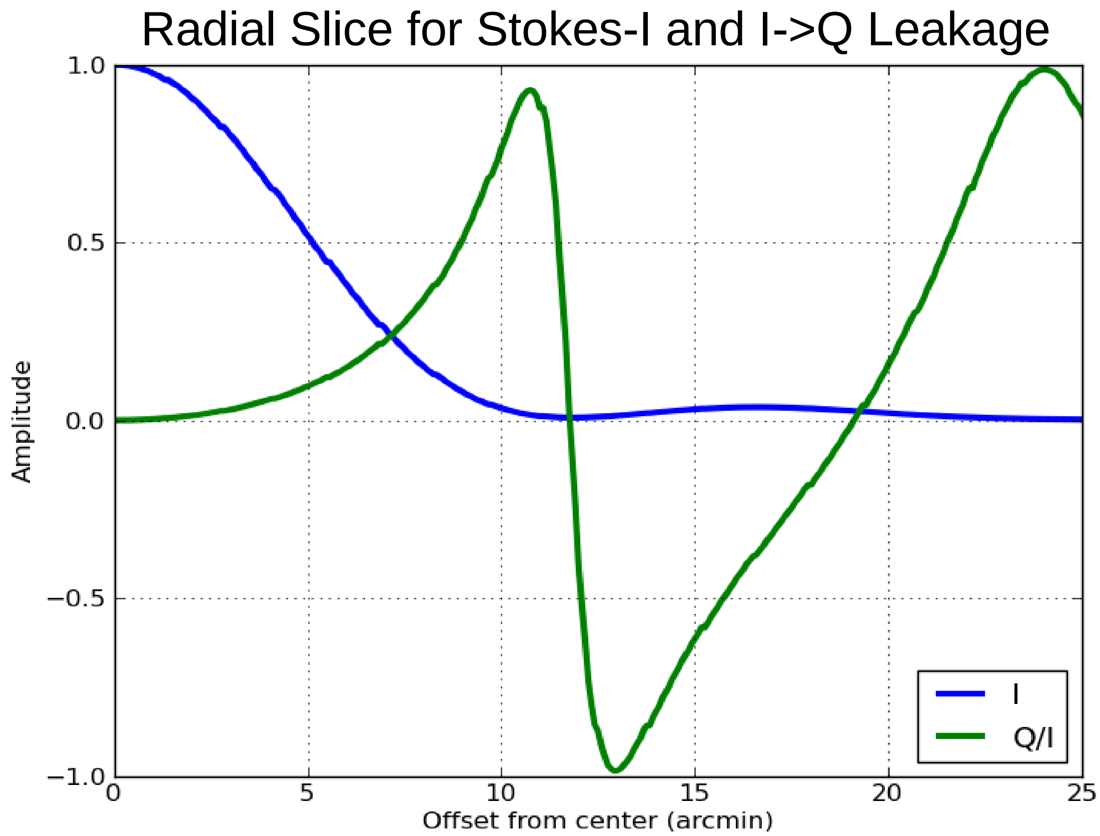
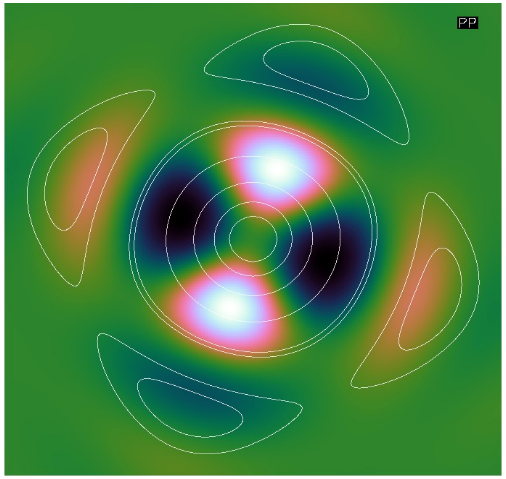
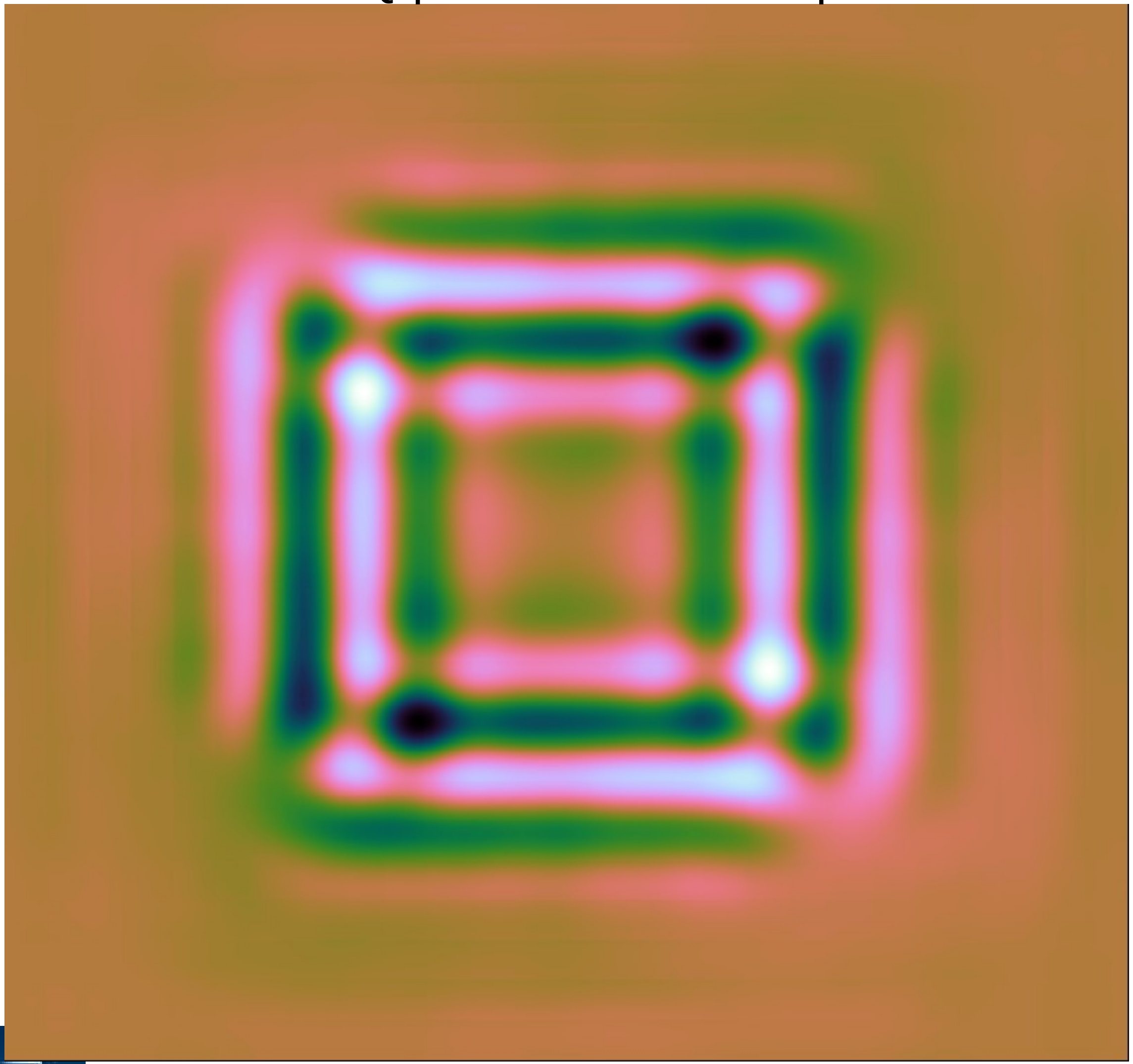




[Jagannathan, Bhatnagar, Rau & Taylor]

Full-pol. Imaging: Mosaic Sensitivity Pattern

In-beam Stokes-Q pattern for a 11x11 point mosaick



- Heterogeneous case; rotation due to PA change also ignored

- The resulting pattern is combination of overlapping Clover-leaf pattern of each pointing

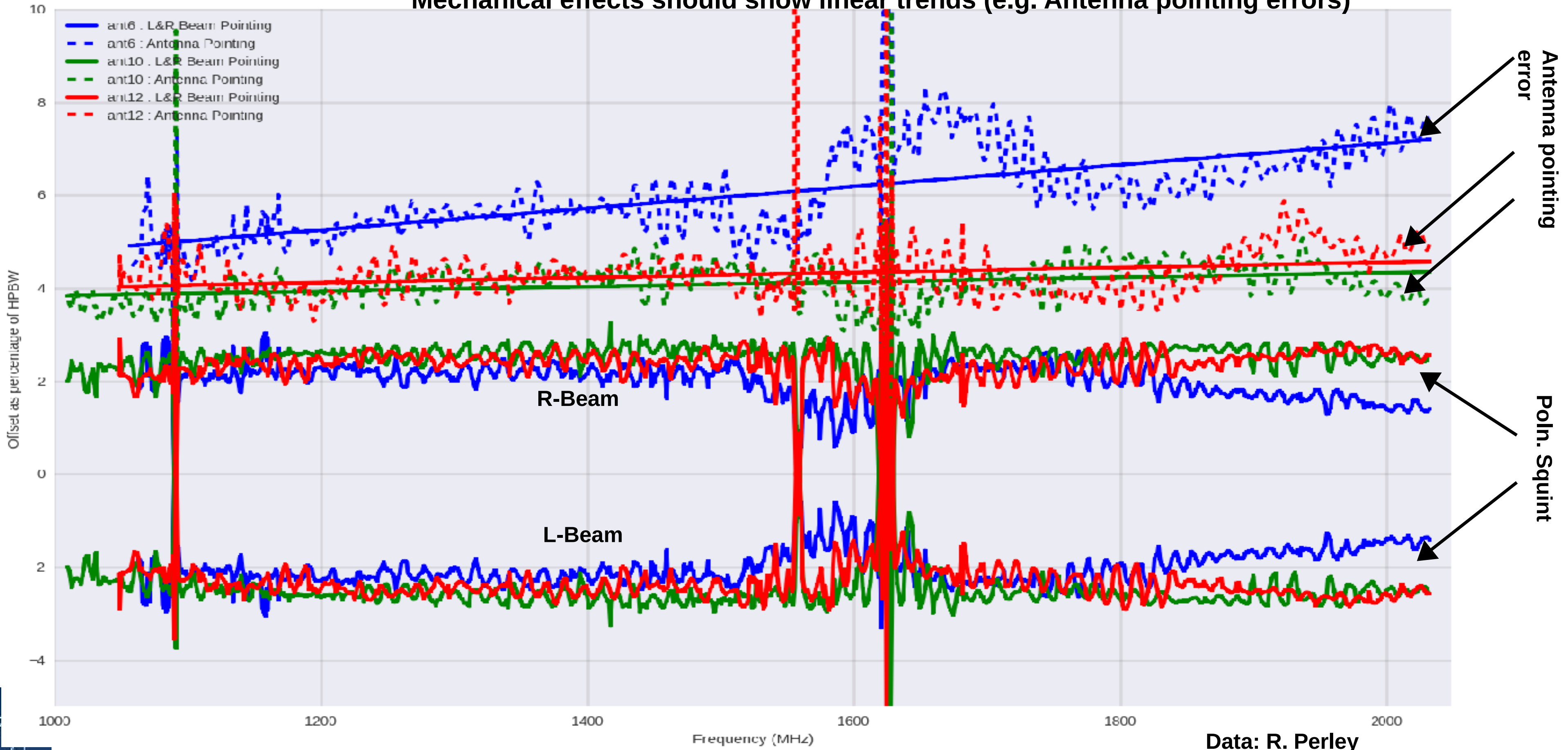
- In-beam DD leakage spreads all across the mosaicked region.

[Jagannathan, Bhatnagar, Rau & Taylor]

Full-pol. Imaging: PB Effects

- Parametric model of antenna Aperture Illumination
  - Difference between Ant6 and Ant10 in “homogeneous array”

In the graph below: Optical effects should be independent of frequency (e.g. Poln. Squint)
Mechanical effects should show linear trends (e.g. Antenna pointing errors)

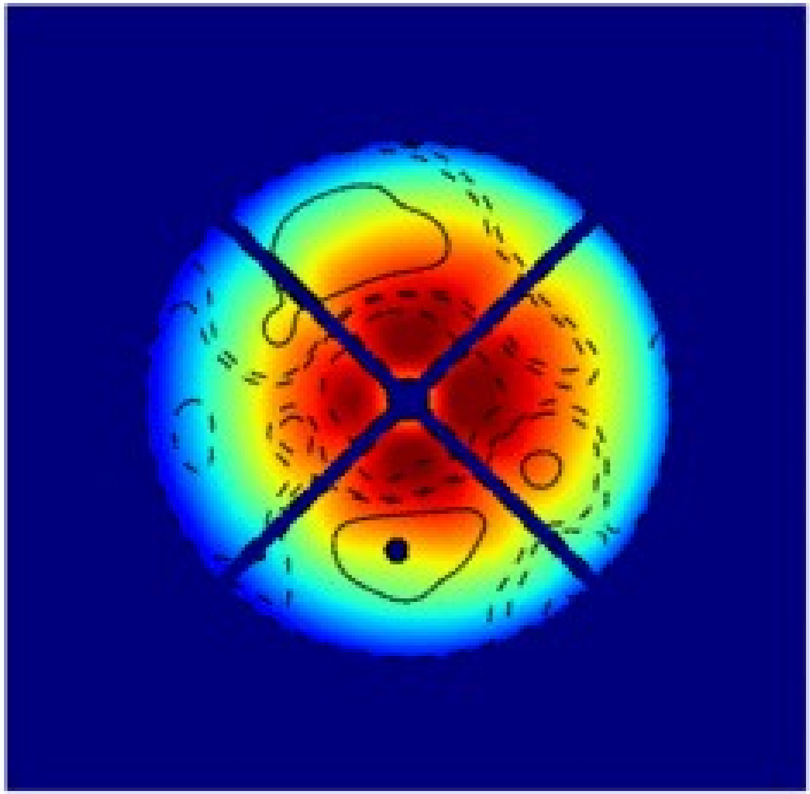


Data: R. Perley
Analysis: P.Jagannathan, S.Bhatnagar

Full-pol. Imaging: PB Effects

- Parametric model of antenna Aperture Illumination

Aperture Illumination



- Strongest effects
  - Antenna size,Pointing errors
  - Quadrapods
  - Antenna-to-antenna variations

[Kundert et al. IEEE Trans. (in review)]

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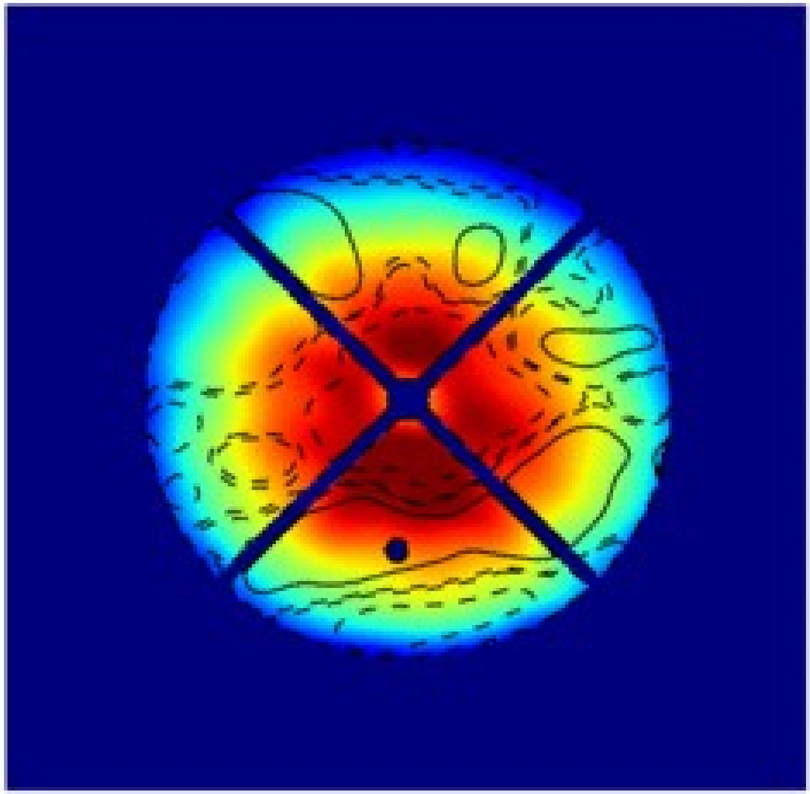

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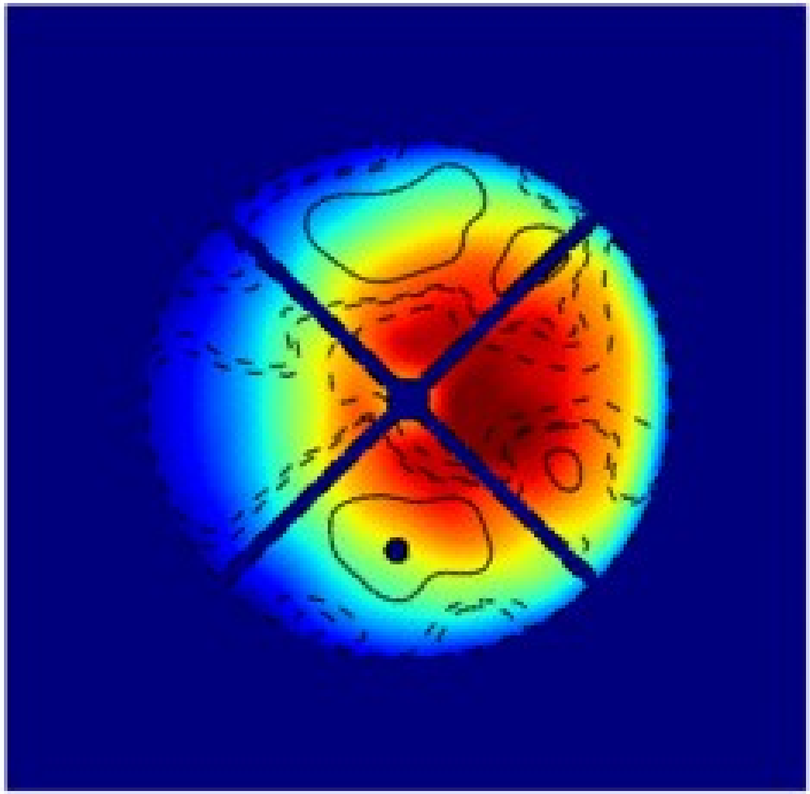

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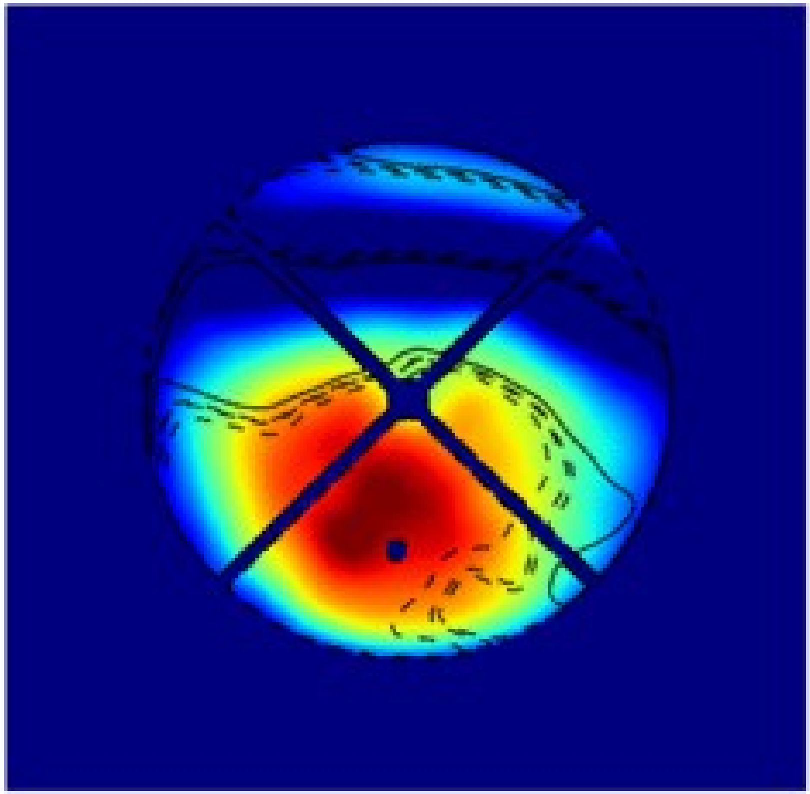

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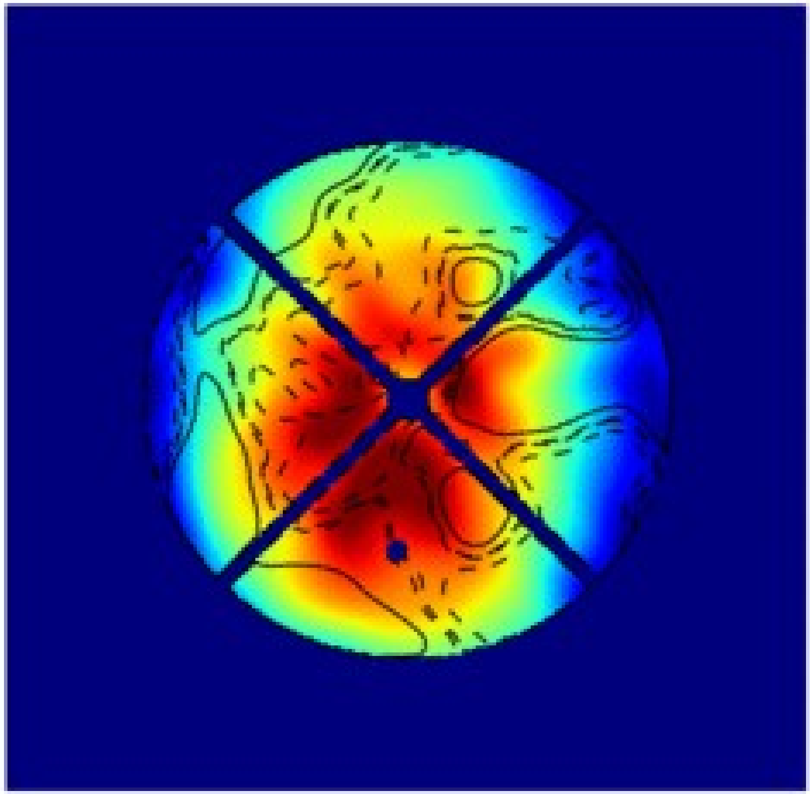

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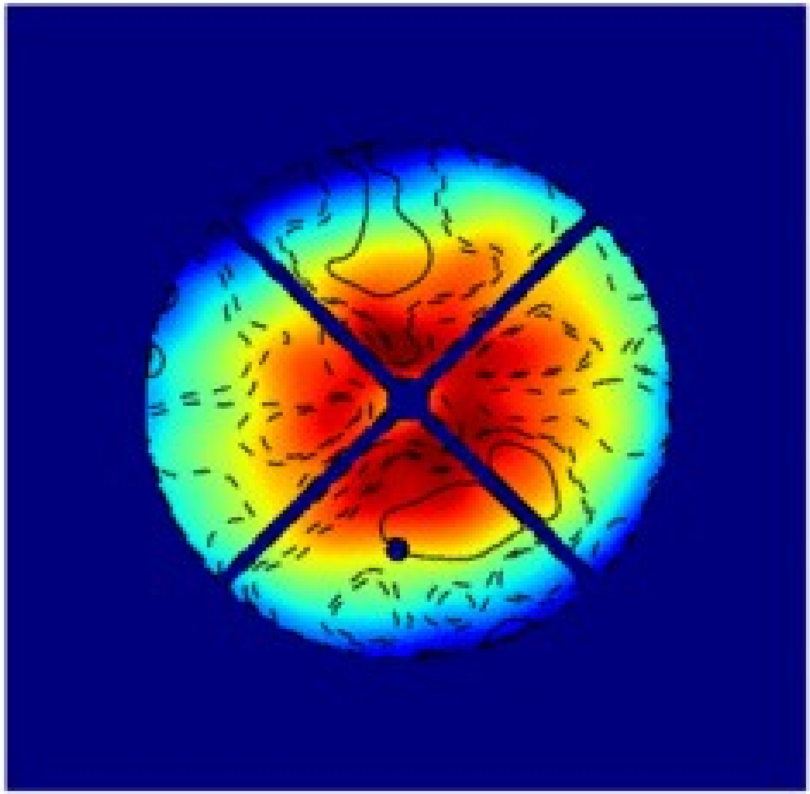

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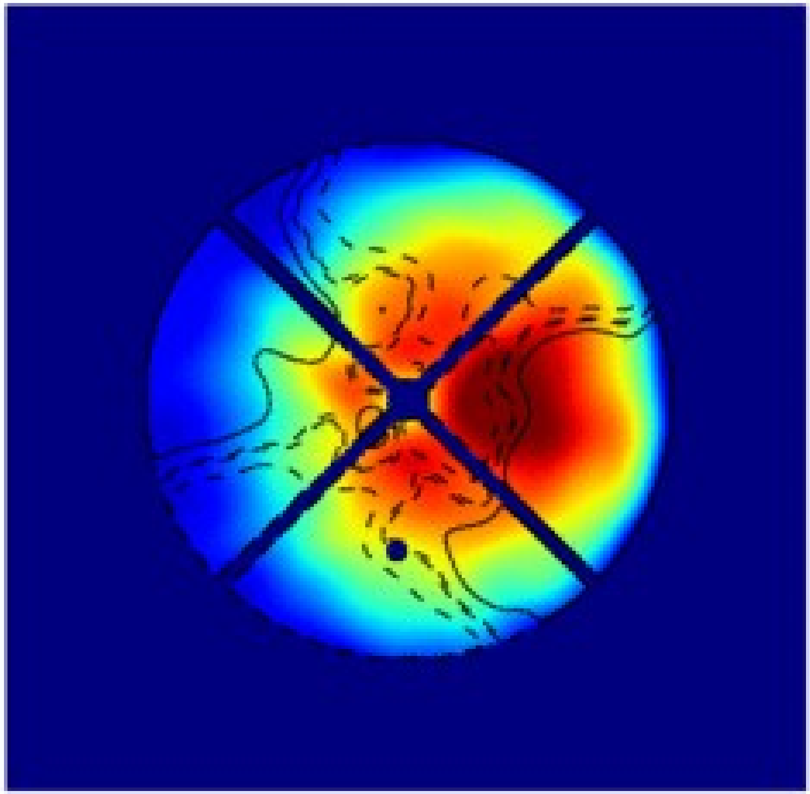

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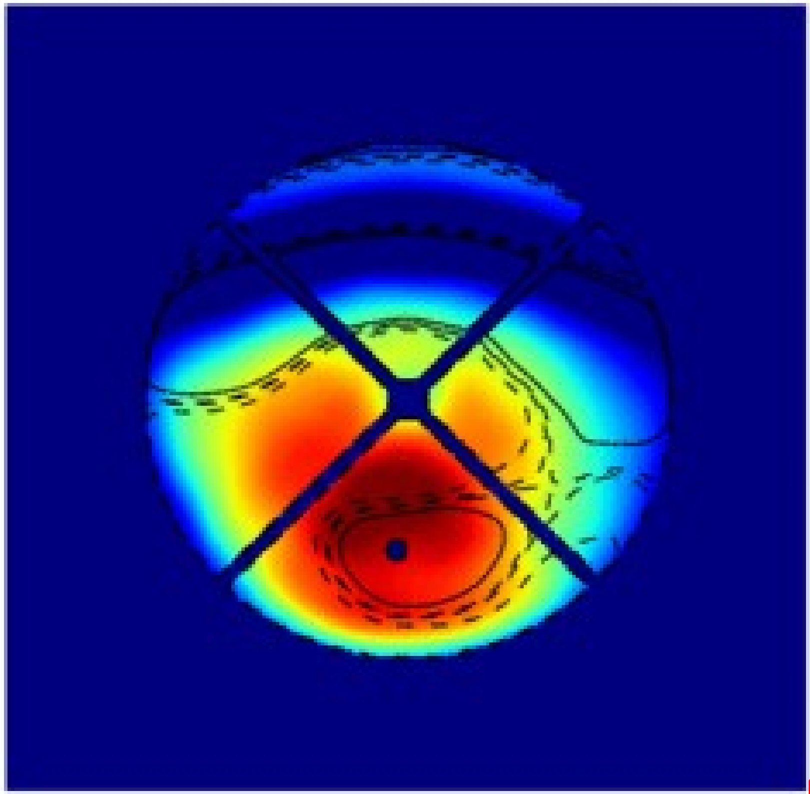

- Strongest effects
  - Antenna size,Pointing errors
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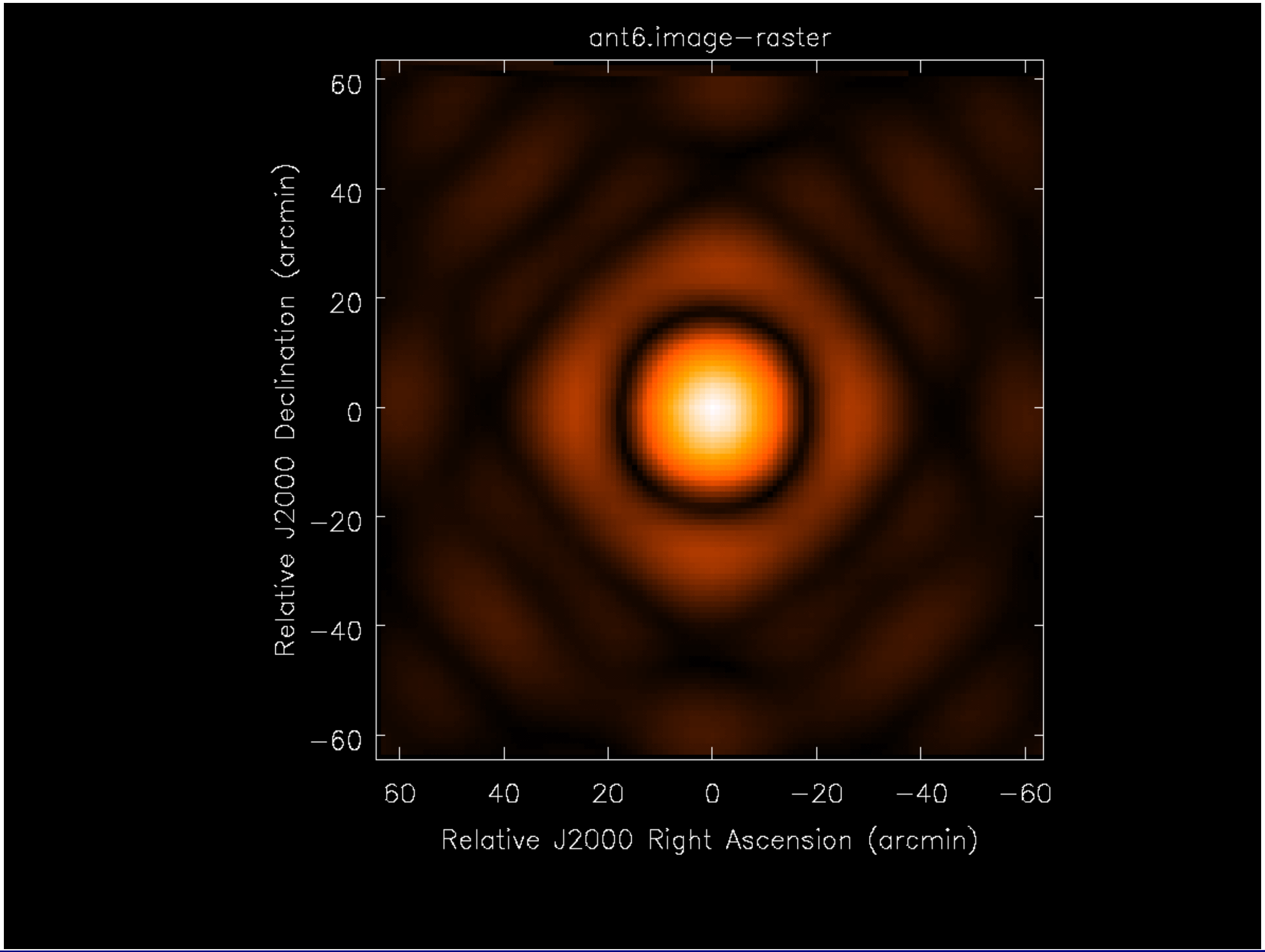
[Kundert et al. IEEE Trans. (in review)]

- Cost equations
  - Cheaper to fix the hardware?
  - Cheaper to handle in post processing?

Full-pol. Imaging: PB Effects

- EVLA Squint
  - Expected: Lateral translation between RR- and LL-beams
  - Measure: Translation + Rotation (~1 deg!)



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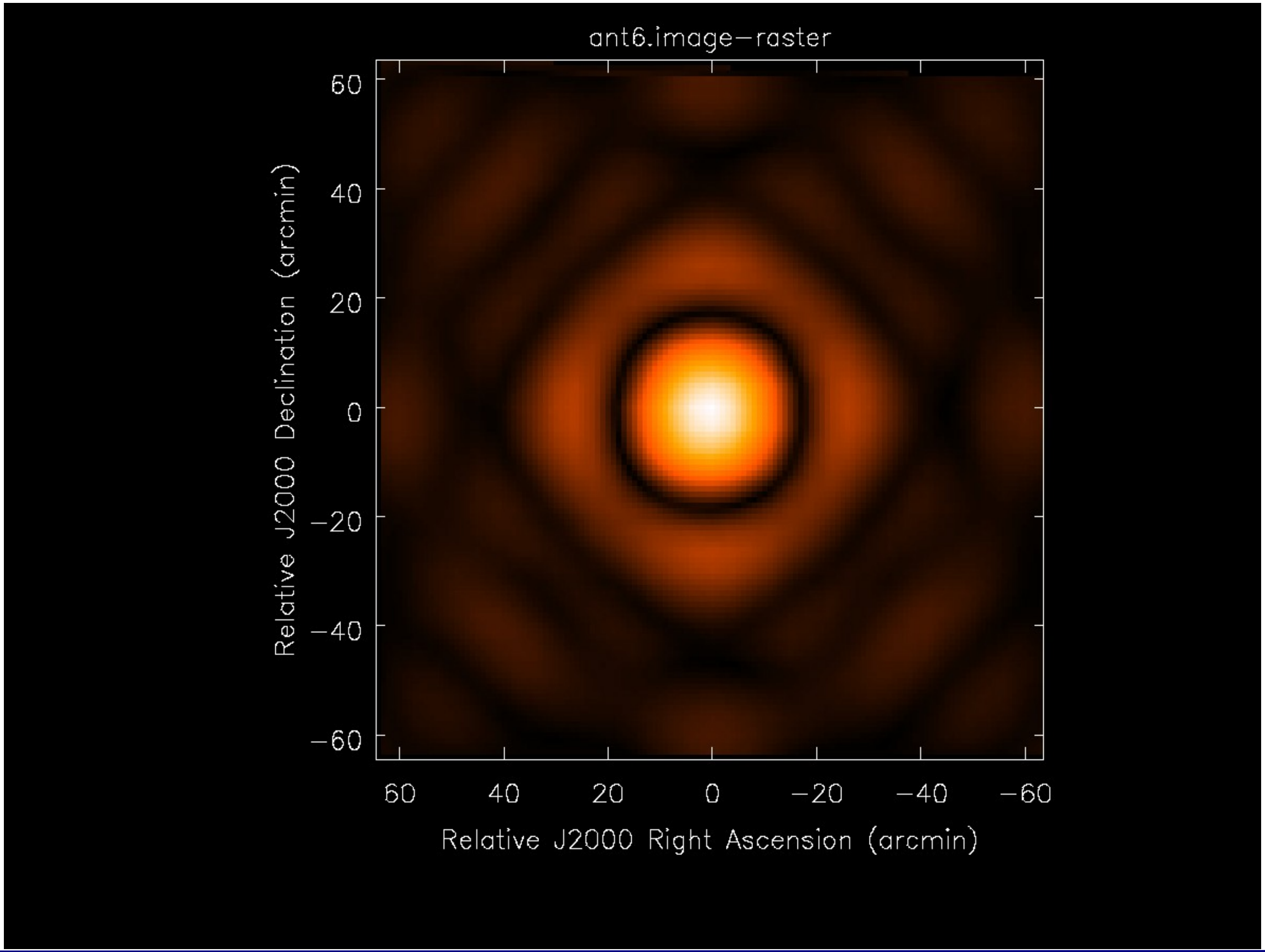
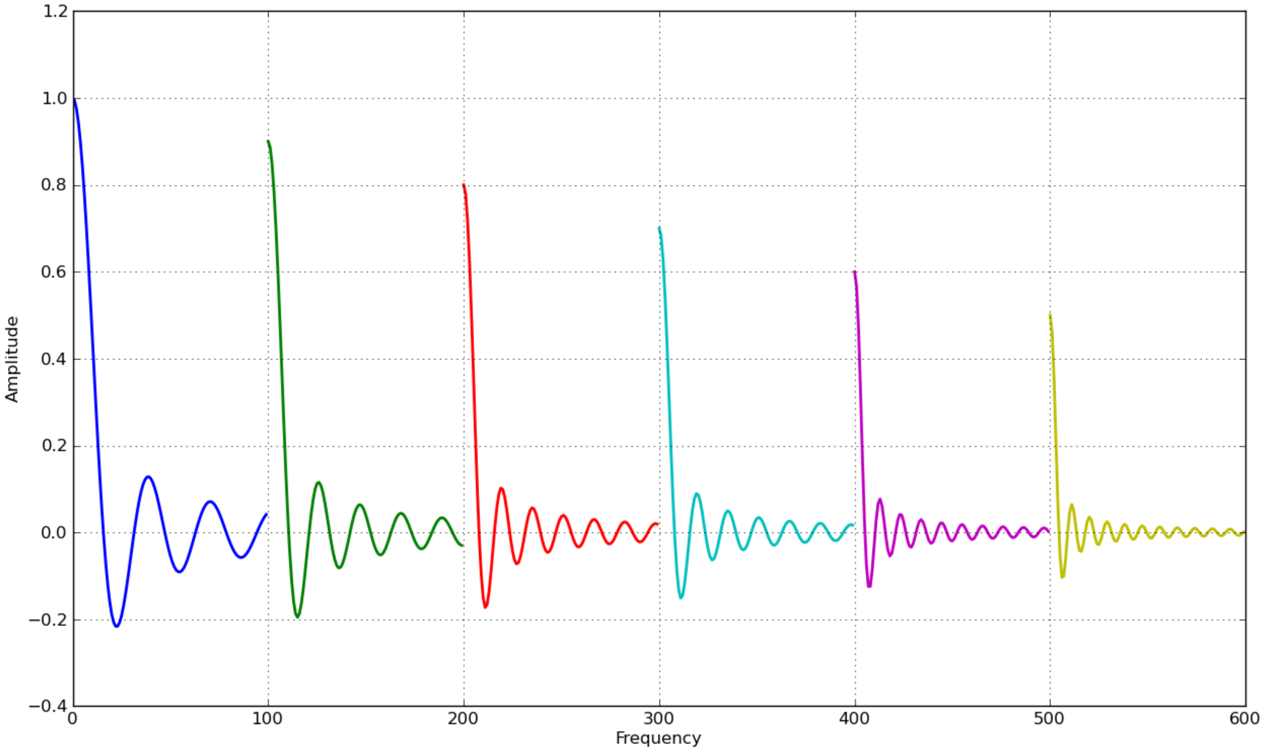


Full-pol. Imaging: Q/U vs. Frequency

- MFS approach to gain from WB sensitivity

  - PSF structure scales with frequency
  - Effective PSF amplitude also changes with frequency (Sp. Ndx., PB scaling)



[Jagannathan, Bhatnagar, Rau & Taylor]

Full-pol. Imaging: Q/U vs. Frequency

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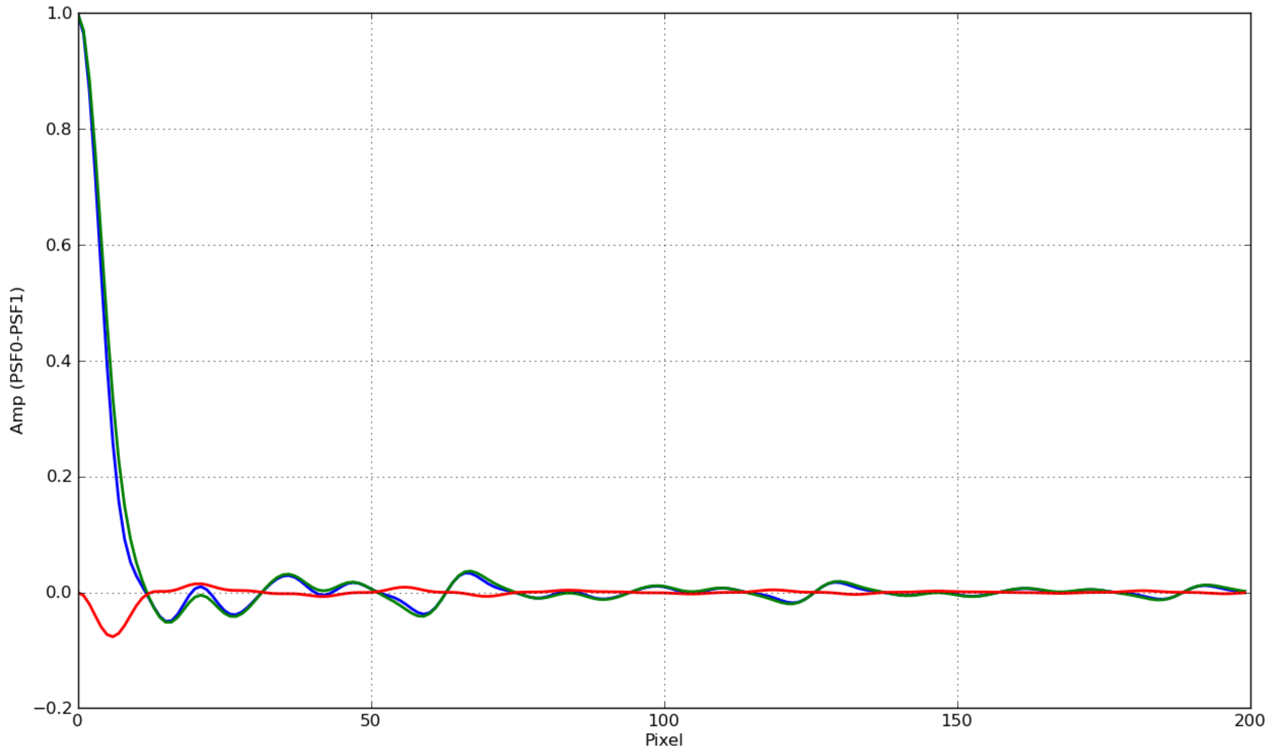
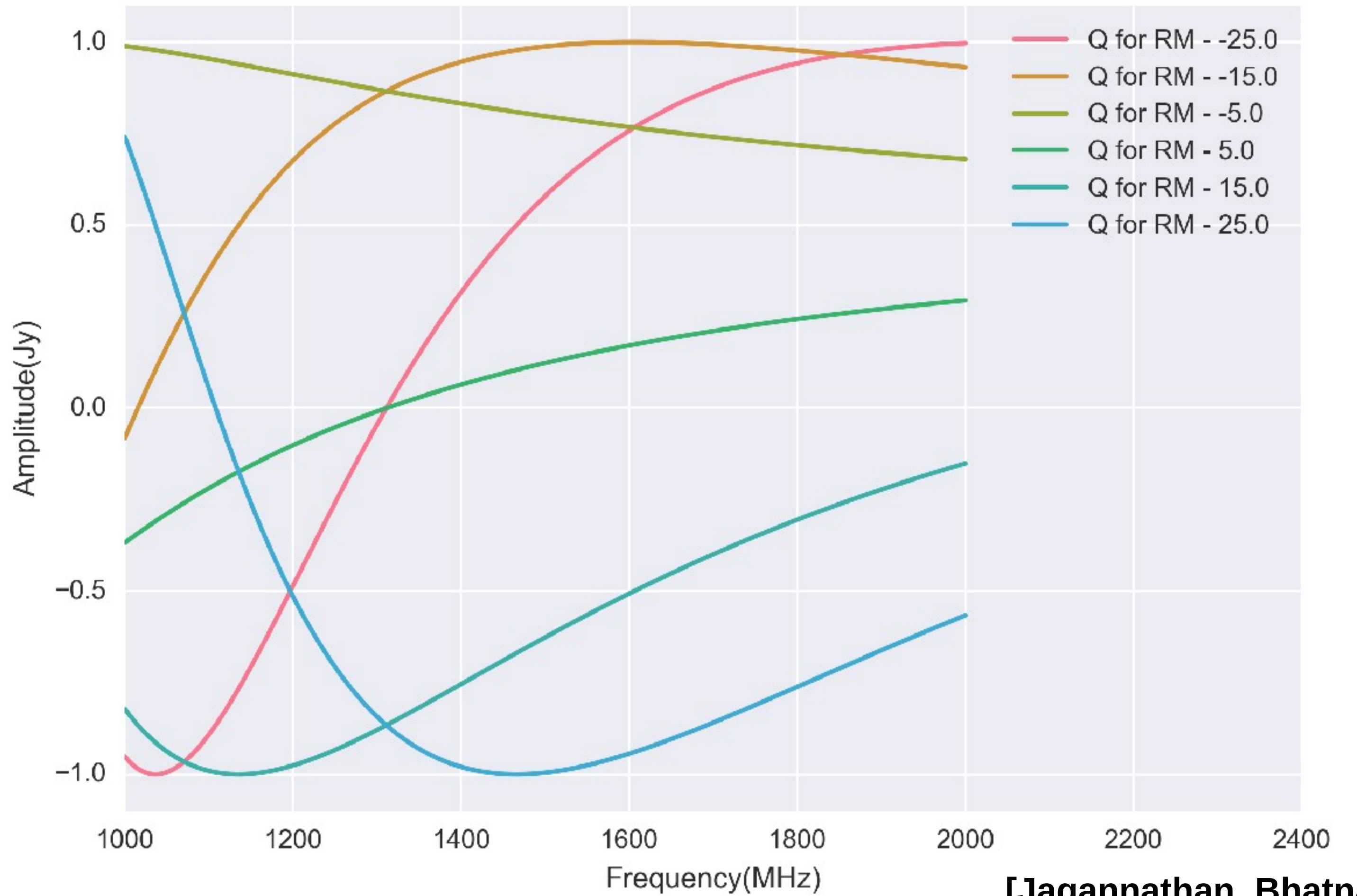
$$PSF(x_o)_{Continuum} = \sum_{\nu} I(x_o, \nu)\, PSF(x - x_o, \nu)$$



[Jagannathan, Bhatnagar, Rau & Taylor]

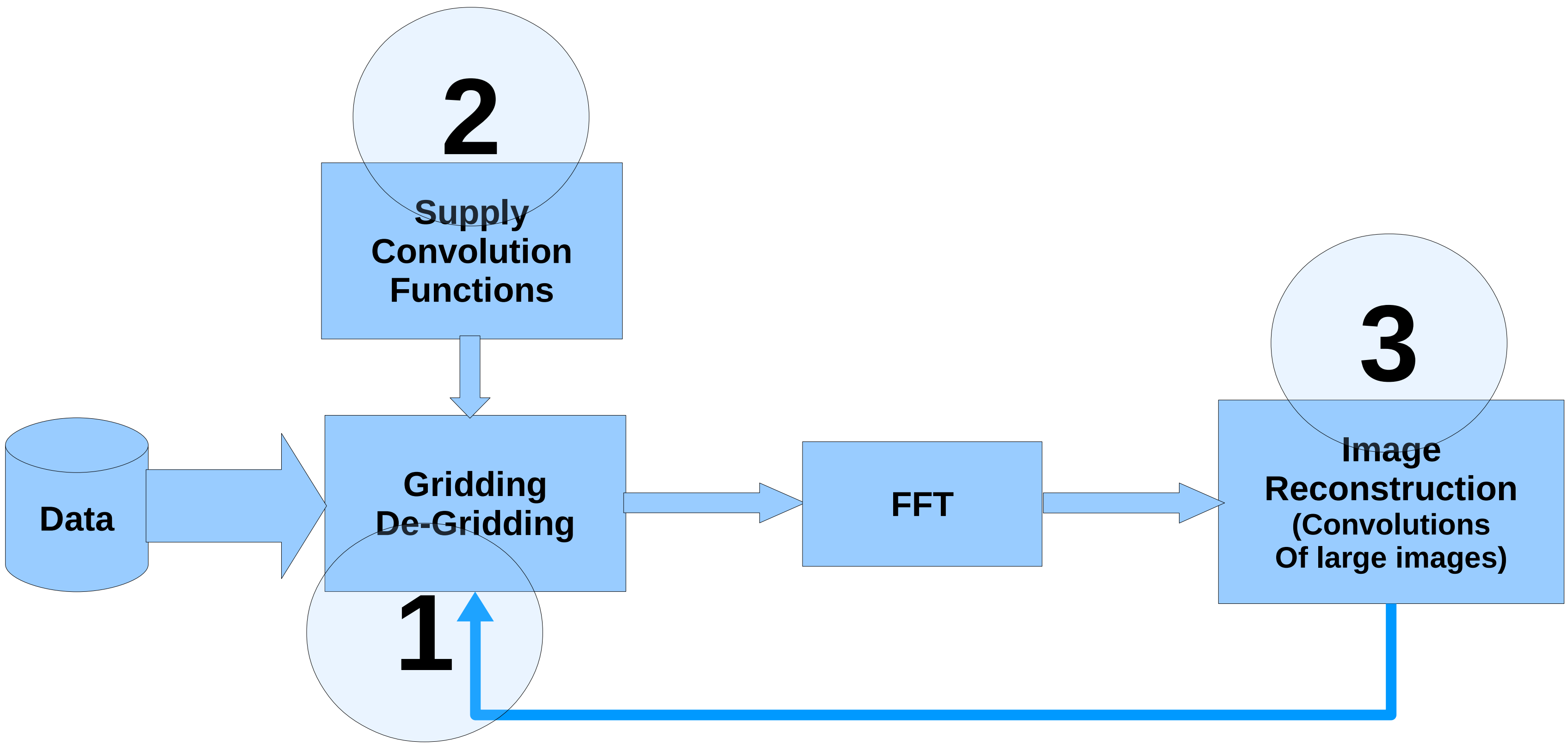
Full-pol. Imaging: Q/U vs. Frequency

- Possible to use MT approach on Q and U for low RM cases
  - Polynomial model (a la MT-MFS) tested for RM = -25 to +25
  - Even easier for ALMA frequency range



[Jagannathan, Bhatnagar, Rau & Taylor]

The Hot-spots



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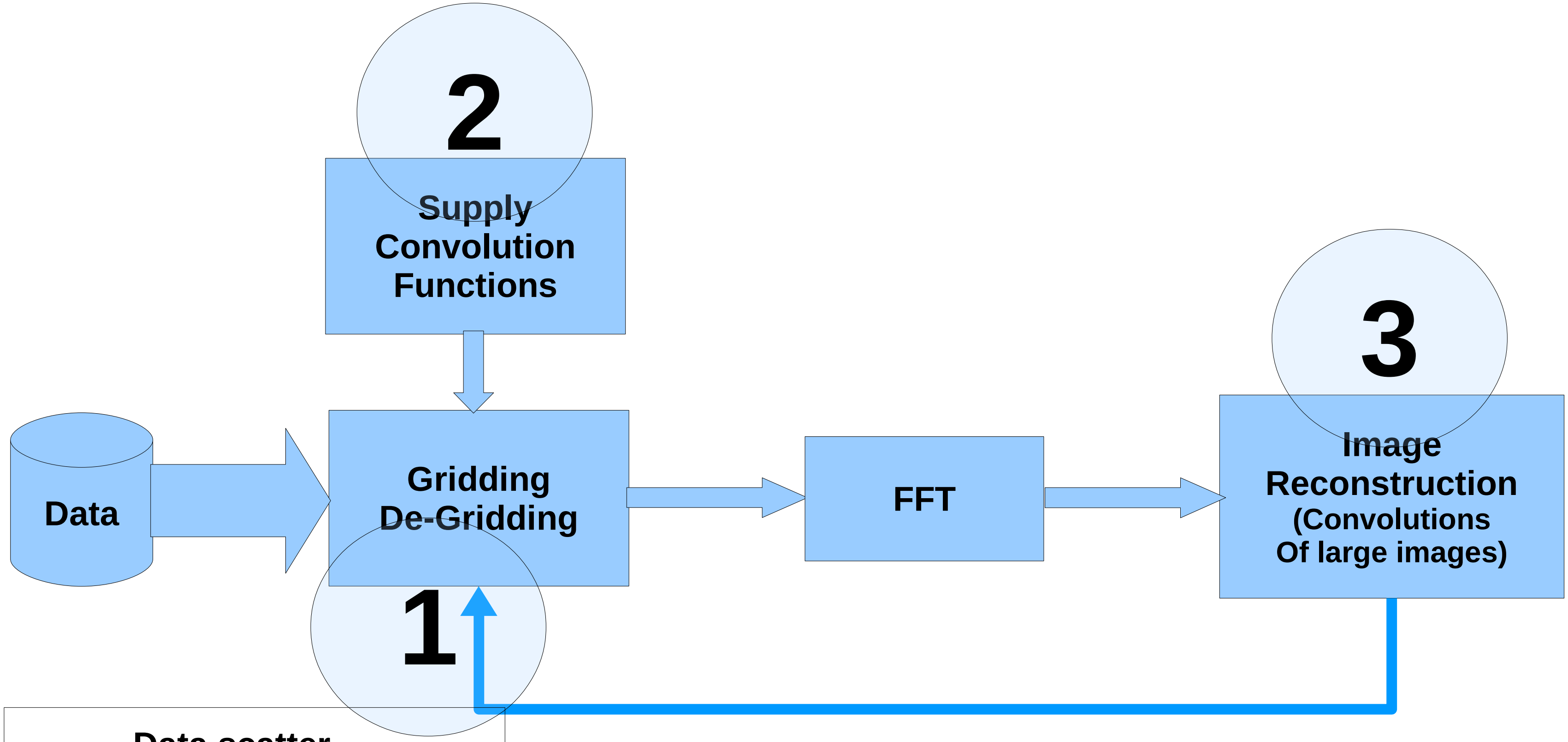
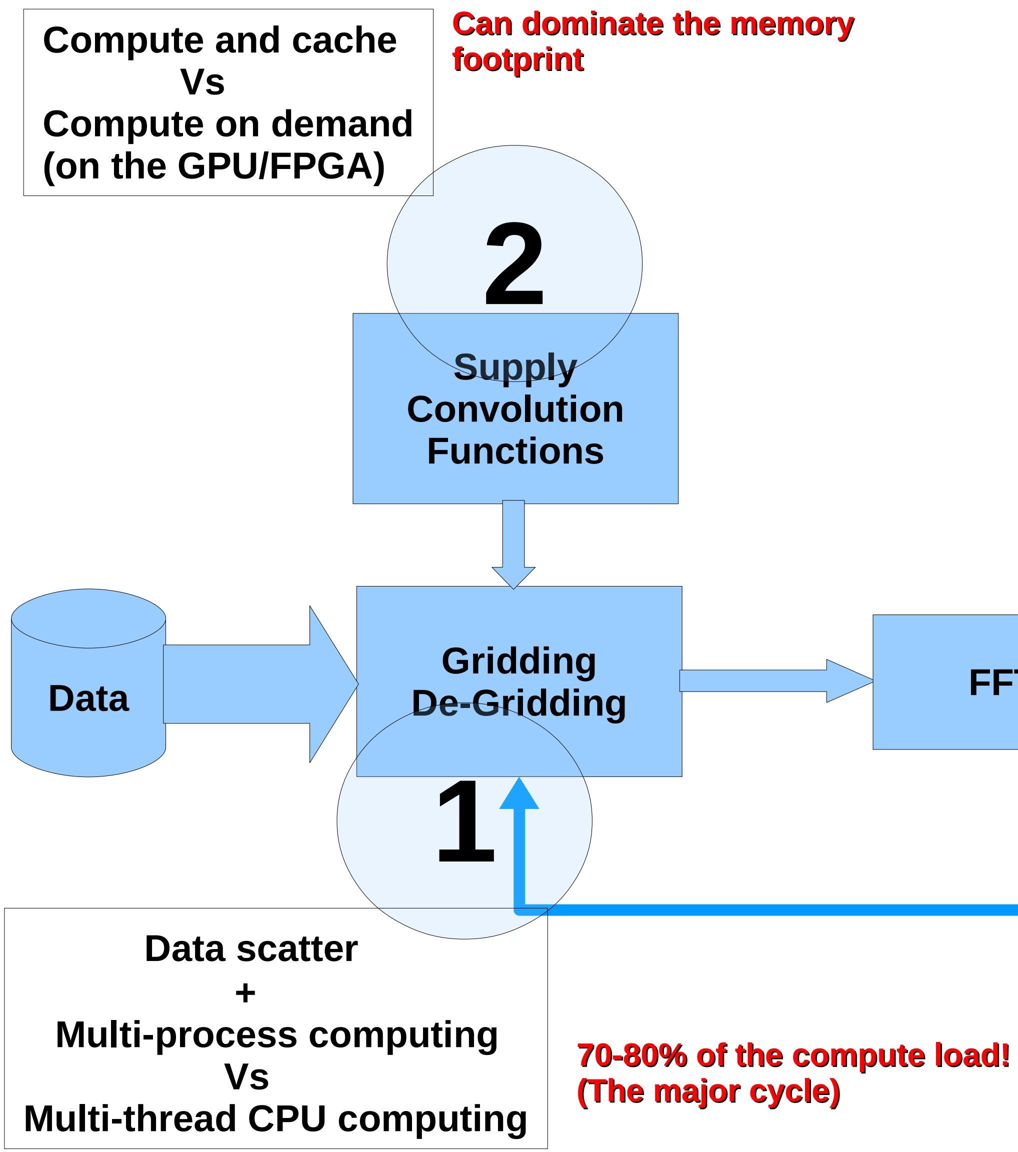


Data scatter
+
Multi-process computing
Vs
Multi-thread CPU computing

70-80% of the compute load!
(The major cycle)

The Hot-spots



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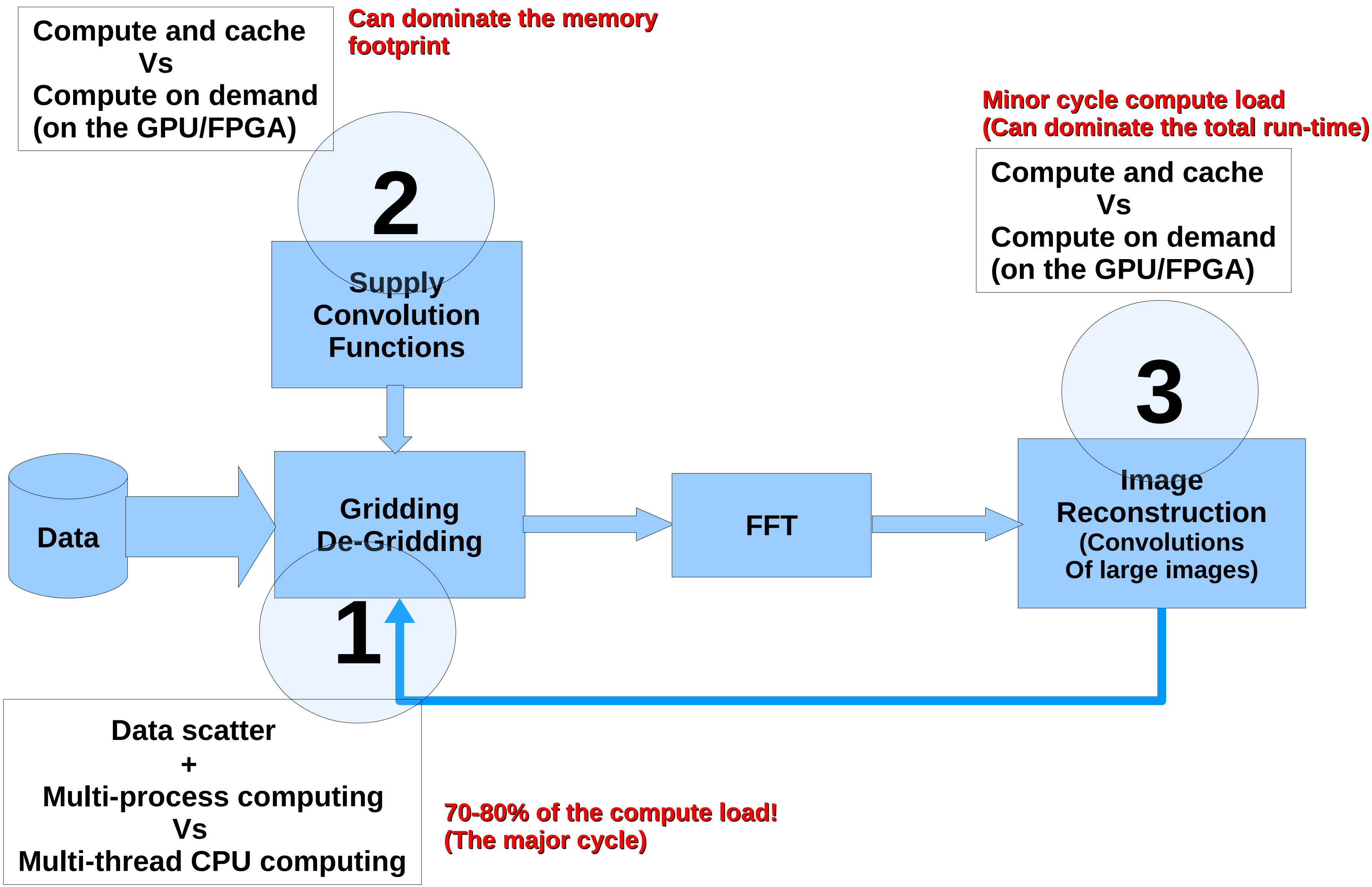
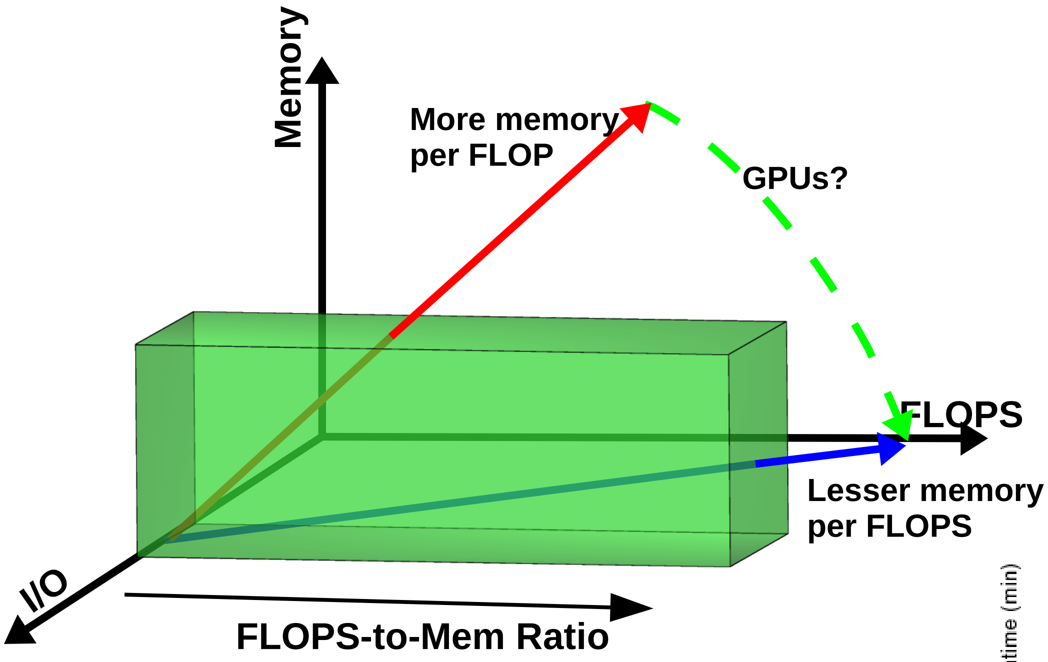
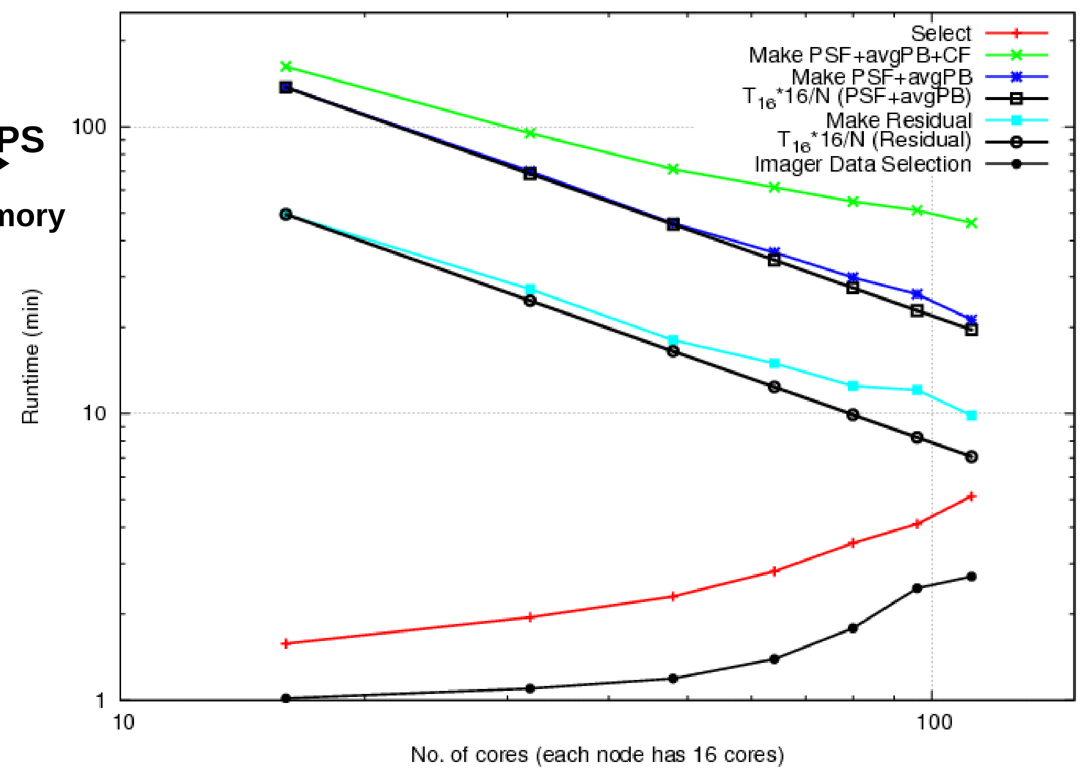


Algorithm architecture





Algorithm design

- **Move towards algorithms with higher compute-to-I/O ratio**
- **Use cheap massively parallel h/w (low memory footprint at the cost of higher computing)**

Issues in Wide-field Wide-band Full-Pol. Imaging

- PB Effects
  - Develop parametric models for antenna aperture illumination
  - Extend full Mueller imaging tools for heterogeneous array case
    - Full-pol imaging for EVLA under test as part of P. Jagannathan's thesis

- Variations with frequency
  - Assess extension of MT-MFS for full pol.
    - Improved multi-scale algorithms in general
  - Assess the range of freq. dependencies of the PB to be included

- Computing load
  - Computing: Parallel processing on a routine basis
  - Memory footprint: Use heterogeneous hardware (CPUs + GPUs, etc.)
  - Use Cloud Computing as an effective development platform.